Gravitation and Cosmology
-Experiments II -

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integration notes to presentations
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ii. Intro to main facts about GWs

We will focus on LIGO and Virgo. LIGO started to observe in 2015, after a stop of about 5 years. LIGO started the observations on the first of September, while officially the run should have started on the 20^{th} or something. Then we had the discovery on the 15^{th} of September, before the starting of the run. Marco Drago was the first who saw the signal.
The second detection happened in December and the community that we were indeed observing something.

Virgo joined the two USA interferometers in the second run. Having more interferometers is very important for sky localization. Now we also have KAGRA in Japan, which started the observations in 2020, but it isn't very sensitive and so didn't participate with LIGO and Virgo.
Now all the detectors, LIGO, Virgo and KAGRA, are off and there is a year of upgrading. We will restart in June 2022.
Every time there is a stop, there is an increase in sensitivity, so that when they will restart we will be able to see a larger volume of the Universe. This will also increase the rate of detections.

ii.1 Detections

On the first run we had 3 detections of BBH mergers, with no EM emission. These are stellar mass BHs, tens of solar masses. We do not know yet the relation between stellar mass BHs and the BHs at the center of galaxies (AGNs). There's a theory that states that intermediate mass BHs could be the seeds of SMBHs.
These detections are very important, because we didn't know about BHs in binary systems. It was the first evidence. We also didn't know that these systems we were able to merge within a Hubble time. Actually, everyone was expecting as a first signal a BNS. This was a bias linked to our knowledge of the EM side which predicted a smaller mass. All the counts predicting rates were based on the mass. We discovered BHs that were higher mass, therefore higher signal and as a consequence a larger volume of the Universe.
So we expected BNS, but BHs are higher mass, so we observe a larger volume of the Universe and a higher rate of BBHs than BNSs.
In reality, the BNS rate is higher than the BBH merger rate, but from the detector point of view we detect more BBHs because we are able to go to larger volumes because their signal is more loud.
Moreover, the stellar mass BHs that we observe are heavier than we expected and this challenges our knowledge about the evolution of stars. Not many models were able to predict so massive BHs. This had a big impact in astrophysics on the theory of BHs and stellar evolution.

During the second run we had 11 detections and we also saw a BNS merger (the first one!) with an EM emission.
During the first part of O3 we had like 50 events. This changes a lot our knowledge of compact objects. Before we didn't know about the distribution of mass of BHs, about their spin or channel formation. There are 2 possibilities:

1. These BHs form from isolated binaries of high mass stars

2. They form in very dense environments (cluster of stars) through dynamical interactions

What's more is that we didn't know about the existence of intermediate mass BHs and what we detected were 2 BHs of masses larger than $60M_\odot$ (in the so called pair instability mass gap, where we didn't expected BHs). The resulting BH was $140M_\odot$. It was the first observational evidence of an intermediate mass BH. This may tell us something about the relation between stellar mass BHs and SMBHs: if we detect something in the early Universe, maybe with ET or LISA.

We also detected a signal from a BNS alongside a gamma ray emission. There was a large campaign of EM observations in all bands and we discovered the optical emission, the X-ray and the radio one.
It had a big impact on the knowledge of GRBs (they were discovered in '70s by chance by USA satellites monitoring the sky to see whether Russians were making nuclear tests; they saw these brief -seconds- emissions with a huge energy).
GRBs were puzzling for many years (near or far objects?). There are 2 families: short and long.
In any case the merger of two neutron stars is related to short GRBs and these emit relativistic jets of matter and energy. GW170817 was the most close detection of a short GRB and this allowed us to really know better about the structure of the jets, a big impact on relativistic astrophysics.

ii.2 Kilonovae

When 2 neutron stars are merging they can be tidally disrupted when they are very close and we have some material around which is slower wrt the jet (subrelativistic material $\sim 0.3c$). This material is rich in neutrons and there is the neutron capture process (**the r-process**) and we form heavy elements that radioactively decay heating the material around and we have the so called kilonova emission.
GW170817 was the first evidence of kilonova emission. From the properties of this emission we can understand how many elements form during the merger of NSs. We now know that this is the major channel of formation of heavy elements (also gold). We do not know precisely which heavy elements form.
Using both GW and EM side we can constrain the NS EOS. Increasing the sample of detections will allow us to identify the EOS (impact on nuclear matter physics).
Another important impact is in cosmology: from the GW signal we can know the distance and from the EM counterpart, if any, we can measure the redshift of the galaxy (the EM part is usually useful for identifying the galaxy, then from its spectrum we can measure the redshift). Using distance and redshift we can have an estimate of the Hubble constant. We have a huge error since we had only one signal.
There's a tension in the Hubble constant value (we know the universe is accelerating but we do not know the rate of expansion). The supernovae give a certain Hubble constant, the CMB gives another (lower). Having a huge sample of EM counterparts joint with GW signals, we can really determine the expansion of the local universe and if there is some new physics in these results.
Last, GW170817 was a close signal (40Mpc), so it was very easy to study the galaxy. Unfortunately, this was the only signal. It answered a lot of questions, but opens even more.

ii.3 GW sources in LIGO-Virgo band

A self-gravitating system has a natural dynamical frequency, associated to its mean density:

$$f_{\text{dyn}} = \sqrt{\frac{G\bar{\rho}}{4\pi}} \sim \left(\frac{GM}{16\pi R^3}\right)^{1/2} \tag{1}$$

where we made the approximation $3/\pi \sim 1$.

Fun fact: Weisskopfian

When a factor of order one is omitted from an expression it is called Weisskopfian, after Victor Weisskopfian, who perfected this style of calculation.

If we put inside some numbers of mass and radius, we can see what is the range of frequencies where the sources emit GWs. The important factor is M/V.

- for a neutron star
$$\begin{aligned} M_{NS} &\sim 4M_\odot \\ R_{NS} &\sim 10\text{km} \end{aligned} \implies f_{\text{dyn}} \sim 2\text{kHz} \tag{2}$$
- for a black hole
$$\begin{aligned} M_{BH} &\sim 10M_\odot \\ R_{BH} &\sim 30R_{\text{sh}} \end{aligned} \implies f_{\text{dyn}} \sim 1\text{kHz} \tag{3}$$

We see that more massive objects have smaller frequencies. This is due to the mass-radius relation. In a binary system R is the semi-major axis. It's the Kepler law in the end. The GW frequency can be approximated as twice the dynamical frequency. From the quadrupole formula we can write the GW amplitude:

$$h \sim 2\left(\frac{GM}{Rc^2}\right)\left(\frac{GM}{rc^2}\right) \tag{4}$$

The amplitude has a $1/r$ dependence, where the EM goes as $1/r^2$. This is important because if we increase the distance by a factor 10, this means a factor 10^3 in the volume and in the rate. Each increase n sensitivity is much more effective than a similar increase in the EM part.

If we take a binary system of 2 NSs with an approximation of $1.4M_\odot$, 90km separation between them and take the distance to the Virgo cluster (the largest cluster close to us, $\sim$ 15Mpc), we have emission of GWs, the orbit shrinks. We have three phases:

1. **Inspiral**: LIGO and Virgo are able to see only the last part of the inspiral
2. **Merger**
3. **Ringdown**: here we ave the so called *chirp*, where the amplitude increases and so does the frequency

We can easily calculate the frequency of the merger to be $\sim$ 100Hz. Using the parameters for a BH, we would obtain a smaller frequency.

So when we have a signal in the detector, on the basis of the frequency and other properties we are able to say whether we have a BH or a NS (also from the duration of the signal). On the other hand, we have that the amplitude is directly related to the distance, so we can have information on this one.

Schutz made an interesting plot on the emission frequencies from different types of sources (1990), as a function of mass and radius. We have three lines corresponding to different frequencies: (10^4Hz, 1Hz, 10^{-4}Hz). Ground based interferometers have a lower limit of 20Hz. With ET seismic noise will be considerably reduced.

At GSSI there is the idea of building a seismometer on the Moon: measuring the vibrations of the Moon, it could be possible to measure GWs. It's in the LISA band, but it will be able to arrive at 1Hz.
An interesting line is the grey one corresponding to the boundary for a BH: we cannot have BHs under this line!
Ground based interferometers are not able to see all the BHs, but only those up to $10^4M_\odot$, if we will be able to arrive at 1Hz with ET. For more massive BHs we need to go in space. With ground based interferometers we are able to see only the last part of the inspiral.
The inspiral phase is really well modeled using post-Newtonian approximation (we know well the waveform). The waveform is also known in the merger and ringdown phases, but with less precision and moreover the detection is done mostly in the inspiral phase. The energy emission during the inspiral is huge (10^{-2}).

Other sources in the LIGO-Virgo band are also core-collapse of massive stars, expected typically at a frequency of 100Hz or less. We expect a burst but we don have a model. It's difficult to model the microphysics of this event. We do not have precise waveforms. The difficulty is similar to modeling tidal deformabilities of 2 NSs at the last stage of their merger. We need a full GR simulation.
Another source that can emit in the LIGO-Virgo band is isolated NS instabilities. When we have a starquake in the NS, this can generate GWs. Also in this case the waveform is very uncertain and we do not know the amount of the emitted energy neither, though it should be much smaller than a BNS merger. Therefore, we would be able to detect them only when they are very close. For core collapse of massive stars we should be able to see them only in our Galaxy or up to the Local Group in the most optimistic scenario (1 every 100 years in our Galaxy).

Knowing the waveform we can use the match-filter model search: we use models to extract signal from the noise. In the case of core collapse massive stars and isolated SNe we need to use unmodeled searches.

When we know the waveform, we know that it depends on:

- **intrinsic parameters**: mass, spins, eccentricity, compactness and tidal deformability for neutron stars (these are directly linked to the NS EOS)
- **extrinsic parameters**: location (the region wrt the detectors), distance, merger time, system orientation (the orbital plane wrt the detectors)

On the basis of these parameters we can build a template pf waveforms, exploring different ranges of parameters. These are then compared to observations. We also have the noise model. The template that gives the highest SNR is the one used to make the detection.
When a detection happens we need to be very rapid (we have an online analysis), mainly for the multi-messenger work, because we have rapid emission in case of NS merger (prompt emission of GRB). It's important to send the alert to astronomers very quickly. To do a rapid online detection we use few parameters (masses and fixed spins). After the detection the whole source parameter reconstruction can be made.

As for the sources for which we do not have a model, we use unmodeled searches, that search only for a burst (for intermediate mass BHs, cosmic strings and very massive BHs). Unmodeled searches look for excess pf power wrt the noise in the time frequency (1ms to 1s). Here the search is more difficult because we have contaminant glitches, similar to our signal. If we have more detectors we can have a coherent search: we can exclude all the signal that do not have correspondencies in other detectors. To eliminate noise fluctuations we do time shifts of the data that we take so that to remove any possible real signal and have an estimate of the noise. Once we have an estimate of the noise we can recover all the signals that are over the threshold wrt the noise.

ii.4 Some useful definitions

Range is the volume and orientation averaged distance at which the compact binary coalescence gives an SNR of 8 in a single detector.
Usually a detector is not sensitive in all the sky and what this range means is that you average the sensitivity of the detector in all the parts of the sky. Another effect is linked to the orientation of the system:

- **Face-on**: orbital plane is perpendicular to the line of sight (the emission is strong)
- **Edge-on**

Horizon means the best region from the point of view of sensitivity and also face-on systems: it's the best place and the best setup of our system to see a GW signal

$$\text{horizon} = \text{range} \times 2.26 \tag{5}$$

for LIGO and Virgo.
When we see a GRB from a face-on system, we expect the jet to be perpendicular to the orbital plane. To know

which is the maximum distance at which we can see a face-on object we need

$$\text{range} \times 1.5 \tag{6}$$

We estimate the range for:

- binary neutron stars: 200Mpc
- binary balck hole neutron star: 400Mpc
- binary black hole: 1Gpc

For larger masses these distances are larger.

ii.5 Events

The first signal, GW150914, was already visible in the row data. The peak of the frequency was at 150Hz and it lasted 0.2s.
The second event, GW151226, was much weaker. It's difficult to see the chirp. In this case it is very impotratnt the matched filtering.

In a waveform modeling we have 15 parameters:

1. Inspiral: analytic solution
2. Merger: numerical solution
3. Ringdown: perturbative and numerical methods

The inspiral depends a lot on the chirp mass. It can be derived estimating the frequency and the derivative of the frequency at the highest frequency. Using Kepler laws and the frequency we can estimate the distance.

II. Lesson 2

i. Extracting info from GW signal

There's an easy way to extract some basic info from the signal, like to understand if we are dealing with a BBH or a BNS. From the signal we can extract the frequency and its derivative. From this we can extract the chirp mass. For the first signal we obtain $\mathcal{M} = 30M_\odot$. Assuming equal mass we can extract the total mass:

$$M = 70M_\odot \tag{7}$$

and bigger for inequal mass. In cannot be a BNS!
From M we can extract the sum of the Schwarzschild radii.
An interesting info is the maximum frequency, 150Hz. So the orbital one is 75Hz. So at merger the objects were 300km apart. This needs to be compared to R_S, if it is smaller that R_S the objects are already merged.
In conclusion we can say that these are 2 BHs.

ii. Compactness

The **compactness** is defined as

$$C = \frac{\text{Newtonian separation between the centers}}{\text{sum of Schwarzschild radii}} \tag{8}$$

For GW150914 it is 1.7. For 2 NSs we would obtain a larger compactness $(2-5)$. This also tells us that we are dealing with a BH.
If we take into account the mass ratio we see that at zero eccentricity increasing q the compactness decreases: we have smaller separation between the objects once R_S is fixed.
Compactness equal to one means that the orbital separation equals the sum of the two radii. If it is less than one the objects are already merged.

iii. Signals

At first LVT151012 was classified as a transient because it had a small SNR. But after O2 knowing better the noise the SNR of this event became larger.
A high amplitude in the signal gives better info on the masses of the components. Usually from the inspiral we get info on the chirp mass.
Before GWs our knowledge was limited by EM emission and stellar mass BHs were thought to have a mass lower than $20M_\odot$.
The first evidence of BH comes from seventies from Cygnus X-1 in an X ray binary: the companion star loses mass and it forms an accretion disk around the BH. Viscous phenomena heat the disk which emit in X ray. We had 22 observations of X ray binaries before GW signals. The majority of them were in our Galaxy because we needed enough resolution.

iv. Sky localization and low latency

There are 2 types of searches for GWs: model search that uses waveforms and unmodeled which tries to find an excess in the amplitude. It is extremely important to have this pipeline running in low latency because we want to give alerts to astronomers to point telescopes. LIGO and Virgo developed low latency pipelines that are able to detect the signal that are candidate events (significant wrt the noise) and they are doing this in less than 1 minute. There are also attempts to give a pre-merger alert. We need to check the data quality and define the sky localization. All this process typically takes 30 minutes because there is also human validation. In the last run we were able to

remove the human validation. So the alert is send to astronomers in few minutes. People then discuss on line to decide if to retract or not the event.
Then there is the PE that can require also many months. One of the most important things for astronomers is sky localization. A single GW detector is an all sky monitor (some places in the sky are more sensitive than other and 4 points in which it is blind). More or less it is able to see everywhere not like a telescope, But it's not a pointing instrument. We can constrain the data because the waveform depends on sky localization.
Using time delay between 2 interferometers we obtain an anulus in the sky. With three detectors we have 3 anulus and the localization is the intersection: we have 2 regions one the mirror of the other. With a fourth detector we can resolve the degeneracy. It's important to have a network.
Another thing that can improve sky localization is the SNR. Having a higher SNR we in general can do better PE.

When we have a binary system we not only use time delay but also phase and amplitude of the signal. We use the fact that we know the waveform and we use what we expect in the interferometers. This removes some regions in the anulus.
The very rapid sky localization we use is called Bayestar. The detection pipeline doesn't use all the templates (only mass and aligned spins). We have a fast sky localization in the beginning. Then it improves.
The field of view of an optical telescope considered wide is like $1 - 10$ deg^2.

III. Lesson 3

i. Electromagnetic emission

It's the counterpart of GW emission. We analyse the most promising sources of the ground based detectors, the ones that we already detected. For sure we detected a BNS, GW170817 and GW190425, one candidate for NSBH, and BBHs. For BBH we do not expect matter around to have EM emission, even though there are some exotic models that predict EM emission also for BBHs.
We are talking about stellar mass BHs. These are different from SMBHs because here we expect matter around and EM emission. This does not happen with stellar mass BHs, we have only the interstellar medium.

We concentrate on BNSs and on BHBNs. There are also core collapses of massive stars and isolated neutron star instabilities. We send alerts to astronomers which are usually burst alerts.
The emission we expect are short GRBs. It's a non thermal emission, it's a beamed emission in a jet. This is due to relativistic material. Bu t we also have sub-relativistic material around the merger which gives rise to a more isotropic emission, called kilonova, due to radioactive decay of heavy elements. We have different components of kilonova.
Extremely important i also the remnant: in some cases we have a direct formation of a BH but we can also have a formation of a NS. If there is a NS we have some emission due to spin down of this object: the NS rotates really fast and if there is a strong magnetic field we have the so called magnetar and we have also a source of emission in the EM band.
If we have the core collapse of massive star (with mass $< 40M_\odot$) we have a SN explosion (very bright in the optical band). It emits in various bands: the first emission is in X-ray/UV band (the shock break out), it's very close to the explosion time. The optical emission takes time because there is a lot of material around the SN which needs time to expand to become optically thin, the SBO is almost immediate (minutes to hours). There are no observations of SBO. There will be future instruments, which are wide field i UV and X-ray that will discover many of them. In the optical band we have a problem for SN: the radiation is absorbed, while in the UV and more in the X-ray they are less absorbed. We will have a larger number of SN detected by these X-ray and UV instruments.
When material decelerates we also have the radio emission. Linked to core collapse of massive stars we have all the EM emission in all the bands. They are also associated with long GRBs.

Isolated NS instabilities are associated with soft gamma ray repeaters and the so called anomalous X-ray pulsars. We know that there are these X-ray flares linked to magnetars and the interpretation of these flares, that sometimes are repeated and sometimes not, is linked to NS quake[1]. This is something that we expect associated with this type of sources.
Observing the pulsars in radio and gamma there also from time to time these glitches and also these are associated with star quakes.

These are the EM emission expected from different sources. We try to observe them, we point the telescope and observe things after the GW emission. If there is a SN in the sky, we try to come back to the time of the explosion and we use in GW data an analysis that fixes some parameters: we observe an explosion in the optical (typically non distance $\sim$ 10Mpc), we know the position in the sky, sometimes the distance (we also extrapolate the time of the explosion from the optical observation, typically the optical emission is weeks after the explosion). So we fix time, distance and position and we can be more effective in the research and detect also sub-threshold events. If we detect SBO we are close to the explosion time (reduce the time window where to search).
We do the same with flares of gamma rays: we use this information in the GW analysis.

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[1] There is a class of short GRBs related to NS quakes, the so called magnetars. We have oscillations in the crust which are amplified bu the strong magnetic field. These are the fast GRBs. They are also associated with large amount of energy release. We do not understand these phenomena well yet

II. BNS-BHNS: dynamical and accretion phases

What is the most important moment that determine the EM emission? It's the last phase of the inspiral, when tidal effects start to be important. This happens in the last orbits, when objects are around 50km from one another. We are talking about several tens of ms, which determine the whole EM emission, because it determines how much mass of the NS is disrupted. This is called dynamical phase.
Another important phase is the creation of a temporary accretion disk. When we are in the last phase of the merger, we have disruption of mass. Part of the mass is dynamically ejected (no more bound to the central remnant). Some mass remains bound and creates an accretion disk, which powers the jet.

What are the properties of the EM emission? How much mass is dynamically ejected? How much mass is the accretion disk?
For BNSs we have full GR simulations that give us some numbers (ten years ago simulations made poor approximations on the mater side, now we have simulations that put together both sides, GW and matter). For BNS the expected amount of unbound mass is of order of $10^{-4} - 10^{-2} M_{\odot}$. This depends strongly on total mass, mass ratio, EOS and eccentricity. The geometry depends on mass ratio. With high eccentricity we have a higher amount of mass ejected.
For NSBH binary the unbound mass is higher, up to $0.1 M_{\odot}$, but the mass is strongly dependent on the ration between the tidal disruption radius and ISCO. ISCO and r_{tidal} depend on mass ratio, BH spin and NS compactness, which is defined as mass over radius.
Mass and spin of BH define the ISCO orbit. When the NS goes close to the BH, the tidal force increases and the structure of NS is really important. For a non rotating Schwarzschild BH, the isco is three times the Schwarzschild radius. If the BH rotates ISCO has a strong dependence on spin. Increasing the spin the ISCO decreases.
The BH spin can be aligned or misaligned with the orbital angular momentum. Anti-aligned configuration means larger ISCO.

In the Foucart plot we see spin versus mass ratio: three different regions of ejected mass quantity. If we have a large spin, we have a small ISCO, so the tidal radius tend to be larger wrt the ISCO and we tend to have a disruption of the star and we have EM emission.
High mass ratio, larger ISCO, the NS tend to plunge without disruption.

The other plot gives information on compactness (linked to the EOS). The EOS relates pressure and density: $p \propto \rho^{\alpha}$. When we have a small α we have a soft EOS and these are easier to compress. Large α means large pressure to small changes in density. T
There a unique relation between radius and mass, depending only on the EOS. Soft EOS do not arrive at large mass. If we fix mass for soft EOS we have smaller radii, larger for stiff EOS. On the basis of NS compactness, soft EOS are more compact.

For fixed spin, larger compactness means no mass, smaller compactness means large ejected mass (stiff EOS) and large EM emission. Knowing EM emission we can put constrain on ejected mass and constrain on the EOS.

III. Accretion disk

When mass has enough angular momentum to be bound to the central remnant. The disk mass can be up to $0.3 M_{\odot}$. The mass that gives rise to the disk depends on mass ratio, spins, EOS and the total mass. The geometry and the amount of mass in the outflow influences the EM emission, the properties, the brightness, the geometry.
Also the remnant influences the EM emission. If we have a NSBH for sure the remnant is a BH. If we have 2 NSs the remnant can be different: it depends mainly on the total mass. If it is high we have direct collapse to BH. Otherwise we can have a formation of a NS (hyper massive supported by differential rotation or super massive supported by uniform rotation) that then collapse into a BH. The super massive NSs can survive for hours, the hypermassive for

seconds. The NS that forms can also be a stable one, that doesn't collapse to a BH. The threshold on the total mass that gives these different scenarios depends on the EOS. We have different thresholds of total mass for different EOS. Again, knowing the remnant is again a way to constrain the EOS. From GW signal we know the total mass estimate, then we know what is the remnant and we know the threshold and we can have constrain on the EOS.

From GW signal we have info on mass, spin and eccentricity, some information on tidal deformability (linked to EOS and compactness), info on system orientation and luminosity distance. We can also have info on EM emission. We have simulations that tell us what to expect from the EM point of view. We also have EM observations, from which we know if we are looking at a beamed or isotropic emission, we know the energetics, we have info on nucleosynthesis, jet astrophysics. Observations help us to put constraints on the modeling.

IV. Modeling of EM emission

The luminosity is link to the flux density by

$$L(\nu) = 4\pi D^2 S(\nu) \tag{9}$$

We will see that when going to cosmological distance we need the correction and use the luminosity distance.

We have both continuum emission and line processes. In the continuum we have the thermal black body and bremsstrahlung, and synchrotron and inverse Compton which are non thermal. We will mostly talk about synchrotron.

Brightness is the flux density per solid angle measured at observer's location.
In the Wien approximation the peak depends on the temperature (higher temperature higher peak). For higher temperature at each frequency we have a higher brightness. From the brightness, through the Stefan-Boltzmann law, we can know the temperature, in the Railegh-Jeans approximation.
This can be done also for non thermal emission. But only for a black body this radiation is the same at all frequencies. Also the first day of emission from GW170817 was approximated as black body.

V. Synchrotron emission

When we have ultra-relativistic electrons in a magnetic field. If we have an energy distribution for particles like $N(E) = N_0 E^{-\delta}$ then we expect a spectral distribution of the type

$$S(\nu) = S_0 \left(\frac{\nu}{\nu_0}\right)^{-\alpha} \tag{10}$$

with $\alpha = (\delta - 1)/2$.
This type of emission is a power law: so it's non thermal!
The energy radiated by each electron (the frequency depends on the γ factor) is super-posed.
For every emission process we also have absorption process. So we have also part where we have absorption. This is linked to the fact that brightness temperature can never exceed kinetic temperature. The typical synchrotron spectrum has a part when it is self-absorbed and a part where it is optically thin in which we have the power law.

VI. Gamma Ray Bursts

These are the non thermal emission. These are not really gamma rays, but more X-ray emission.
The first question about GRB was: are they galactic or cosmological? The satellite that answered this question was BATSE. It showed an isotropic distribution of these sources. This was the first evidence that they are cosmological. To have a spherical distribution in the sky we need to go to cosmological distances. If we look at galactic objects the distribution is not spherical!

What these sources are? The smoking gun satellite for GRBs was BeppoSAX. It has 2 instruments: a scintillator for gamma rays and a wide field for X-ray. When the scintillator observed gamma rays the wide field camera was able to observe at he same time X-rays. We were able to make good localization. A detection in X ray means a 5 arcminute resolution: we can point telescope from Earth and try to make a spectra, i.e. measure the distance of these objects and therefore try to understand their energetics and also the environment.
In 1997 BeppoSAX was able to see a gamma ray also in the X-ray and a very well localized X-ray afterglow (a very good sky localization). There was observation also in the optical band. This was really important! There were studies about the host galaxy: the spectrum of the galaxy and the redshift of this distant object. This paper was the first redshift taken for a GRB.
Another important satellite for GRBs was Swift. It's also active now. The Swift data are full of new discoveries. Swift is 3 instruments together: gamma-ray, XRT is 5 arcseconds resolution (we really have the sky localization). It's also very rapid to turn. For BATSE we need that the wide field camera took the X-ray emission. We can also point the UV telescope. This increased a lot the knowledge of the X ray emission in the early phase. We can study all he steps of the X ray emission. Swift gave the possibility to observe a lot of galaxies for the GRBs and have a lot pf information on the environment of GRBs.

GRBs can be split in 2 based on duration of the prompt emission (burst in the gamma ray!). We have a double peak distribution: a peak on less than 1s and another on more than 2s. These are also linked to a different spectrum. The hardness ration is the ratio between higher energy photons and lower energy photons. There are 2 populations in the hardness ratio: this is used when we do not ave good spectra and we look at all the photons in the high energy and all the photons in softer energy. We see that the short GRBs are hard (a higher fraction of high energy photon wrt lower energy photons).
We have 2 populations with different duration of prompt emission and with different properties of the spectra. For long GRBs there was something that let people understand what they were: they were observed in the same region where SNe type 1C were observed, the ones related to collapse of massive stars. This was a strong observational evidence that the progenitors of these sources are the collapse of massive stars.
For the short GRBs was a long enigma and a smoking gun observation was GW170817. There were indications that these sources could be associated with BNS or BHNS mergers: the evidence was no SNe present. Moreover, if study the nearby star population it was older wrt long GRBs. Also their position wrt the center of galaxy was more distance from the center wrt to long GRBs.
The explosion of SNe is associated with young population and high SFR. The massive stars have a fast evolution and explode very rapidly. On the other hand, if we think about BNSs we need time that they arrive to the merger. Wrt the formation of a NS after the SN explosion we need time to merge. That's why they are associated to old population: we need time to arrive to the merger. Why they are more distant from the galactic center? This is because of the kick due the explosion of the SN: the system after the kick starts to move and moves distance from the center. The distribution is not concentrated like for long GRBs.

The GRB emission is a synchrotron emission (a power law) and what people observed was a bump. This was explained with a SN emission. People were sure about the SN because when they see a bump they also found a typical spectrum of a SN. The bump is thermal emission.

Long GRBs are typically in bluer galaxies (brighter in blue, color of young stars). Galaxies of long GRNs are younger. The long ones are also low metallicity and also ongoing star formation activity.
For short GRBs the emission is fainter and it is not so easy to find the host galaxy (up till now we have like 40 short GRBs with the hist galaxy).
If we look at the type of the galaxy short GRBs are also in early type (the elliptical, the older population) and a large fraction in spirals, similar to the long one. But in spirals with short GRB there is less SFR. Also due to the kick the object could have gone so distant that we are no more able to associate it with a galaxy.
The redshift distribution shows that long GRBs has higher redshift, which is linked to the delay wrt the star

formation (peak of star formation around $z = 1.5 - 2.0$). Long GRBs are in the peak of star formation. Short GRBs peak later, because of the delay for the merger.

VII. Jet

NSBH or BNS mergers can give rise to a BH or a magnetar and can give rise to a relativistic jet. The same happens to a core collapse: the mechanism for the jet is very similar after the merger or after the collapse. It's not clear how this can launch a jet. In any case there is a relativistic. We have a prompt emission due to internal shock (we have relativistic shells with different velocities, they go one over the other, accelerate particle and we have emission in the gamma within seconds - less than 2s for short and up to one hundred seconds for long-).
Then we have the relativistic jet interacting with the ISM and we have the afterglow emission, which is in all the bands: X-ray, then optical (after days) and radio (after months). for GRB we observe it in gamma ray and we point on Earth telescope to observe them in the optical. So these objects are on axis.

For the afterglow emission, the short GRBs are fainter. In the flux-time plot we see that mostly all GRBs have the same decay, $time^{-\alpha}$, with $\alpha \sim 1 - 1.5$. In the X-ray this different. The lightcurve is very particular in the X ray, while in the optical we have more or less a clean power law.
The relativistic beaming angle is $1/\Gamma$. When the jet decelerates the emitting surface increases. An observer that is off-axis, at the beginning is not able to observe the emission. If we increase the viewing angle wrt the jet we observe the emission later (we need the jet to decelerate more and more to become larger) and it is fainter. It is more easy to find an on axis GRB because we observe the X ray emission (prompt emission).
What determines the afterglow emission is also the density of the ISM. For smaller densities we have fainter emissions. The properties of the emission depend on the intrinsic energy and on the properties of the environment plus the observation angle wrt the jet.

For short GRBs afterglows, we see that for X-ray we have more information on early emission: the X-ray is the first emission and we are also biased with observations because we are able to readily point at the source.
Before Swift we had prompt emission and after a gap! The fact that Swift was very rapid to point XRT helped to fill the gap. The spectrum is crazy: steep decay, flat and then a power law. Some show also flares.
After GW170817 we discovered that the jet is structured and the plateau is explain only with a structure of the jet.

IV. Lesson 4

i. Thermal emission

We form during the merger a jet of relativistic matter, but around there is also subrelativistic material. In particular it comes from NS and it is rich in neutrons. The temperature are very high. This is the ideal place to form heavy elements for r-process nucleosynthesis. These elements, when they form, they radioactively decay, they heat the material around and when this material is enough expanded we have an emission called kilonova.

- In particular, when we form very heavy elements, lanthanides, the opacity is very high and this emission is expected in the near IR and to peak after one week and then to decline. This is only one of the **kilonova**.
- Another component of the ejecta giving rise to the kilonova is in the interface between the 2 NSs and these ejecta are called **shock heated ejecta**.
- Then we form an accretion disk which can lose matter and again we have an **ejecta due to wind outflow**.
- Another component is due to viscous effects in the accretion disk (also the heating from the center of the merger) and these are called **secular ejecta**.

The difference between these ejecta and the tidal one are due to different conditions of temperature: for the former the higher temperature and the presence of neutrino flux makes weak interactions important. We have neutrino absorption and electron/positron capture that make the number of neutron smaller and increase the number of electrons. We cannot form the very heavy elements. The opacity is different from the tidal ejecta: we expect a blue transient peaking two days after merger and again we have the decline.

ii. Nucleosynthesis

Elements heavier than iron are typically produced in 2 processes:

1. **s-process**: the neutron capture timescale is very long wrt the decay
2. **r-process**: the neutron capture timescale is very short wrt the decay

Neutron capture means the system captures a neutron and we have the same elements with a higher mass number. At the same time we have β decay, because we create non stable isotopes and what happens is that we have that a neutron becomes a proton (with an emission of an electron and a anti-neutrino).
During r-process neutron capture is very fast: we move to very high mass number nuclei. At the same time we have decay. The unstable elements go to the stability line. We have also α decay and fission which brings to the stability line.

Before GW170817 it was not clear what was the site of these heavy elements production (iridium, platinum, gold, lead). Another channel is SN explosion but in simulations we were not able to form very heavy elements. But SN are more frequent. But they were not able to produce the actinides and lanthanides.

iii. R-PROCESS

When T is high we form a lot of electrons and positrons and these activate weak interactions:

$$\begin{aligned} e^+ + n &\to p + \bar{\nu}_e \\ p + e^- &\to \nu_e + n \end{aligned} \tag{11}$$

Since the density of neutrons at the beginning is very high the first reaction is more likely. We have the capture of a lot of neutron, we increase the proton number, the positrons and neutrons are converted and so we have an increase of the **electron fraction**. When we have shock ejecta and wind, we are in this condition: we are not able to from

the very heavy elements as we decreased the number of neutrons.
The same happens if we have a high neutrino flux: we form protons:

$$\nu_e + n \rightarrow p + e^- \tag{12}$$

We again decrease the number of neutron and increase the one of protons. This is what we call the **blue component**. It is blue because we have an opacity of elements that are not so heavy.
So we have different ejecta corresponding also to different timescales at which they start to emit:

1. **tidal ejecta**: it is cold wrt to the other (even if the T is higher than 10^9K); we have a low electron fraction, here we form very heavy elements; it's distributes equatorially and it is more isotropic the more equal mass are the progenitors
2. **shock-heated ejecta**: this is high T, it's more on the polar axis (perpendicular to the orbital plane of the two objects), we have a higher electron fraction and here we are not able to form lanthanides and actinides.
3. **neutrino-driven winds**: we have an accretion disk and material is ejected through neutrino-driven winds, we have a high flux of neutrinos, the electron fraction is high and we are not able to form very heavy elements
4. **secular ejecta**: due to viscous phenomena in accretion disk, it has a broad range in electron fraction

If electron fraction is smaller and smaller we can also produce lanthanides and actinides. The electron fraction determines what elements we form. On the basis of the elements we form we have material with different opacity. With no lanthanides we have a lower opacity. With lanthanides and actinides present we have a higher opacity.

iv. Main ingredients of the kilonova emission

- **Opacity**: it determines the color of the emission, the spectrum of the emission
- **mass ejected**
- **Velocity** of the ejecta

The peak of the emission depends on the ejected mass, its velocity and the opacity. If we have a larger mass ejected we have a delayed peak. This is inversely proportional to velocity. The pea is also later if the opacity is larger.
We told that the blue emission peaks after a day, and the red after a week. This is due to opacity because the red emission is the one corresponding to lanthanides and the opacity is larger.
The luminosity of the peak is inversely proportional to opacity and directly proportional to velocity and ejected mass .

So the main ingredients are the ejected mass and velocity which depend on astrophysics, the opacity which depends on atomic physics and also on the radioactive heating rate and this depends on nuclear physics (how this energy is effective to heat material around and have an EM emission).
The lightcurve is the variation of luminosity with days. It is a function of the formation of heavy elements. With a larger ejected mass we have a more luminous object (a brighter one). When we have r-process elements (formation of lanthanides) the IR part of spectrum are increased wrt iron emission, whereas the UV are decreased.
The unstable elements are disintegrated through α, β and fission. We do not know which is the major channel, but all of them take place. We do not know the energy deposition rate of the kinetic energy of the decay products. This changes a lot luminosity. Using different proportions of decay, the emission is different.

The kilonova emission is a multi-component emission with a geometry. On the basis on where we observe it we can observe different components. The red kilonova is linked to tidal emission (due to material unbound by hydrodynamics and gravitational torques, we have a lot of r-process and formation of lanthanides and actinides), whereas the blue is related to disk winds and shocked-heated ejecta (here we do not form lanthanides and actinides). The secular emission is between blue and red.

The remnant also influences the EM emission. When there is direct collapse into a BH: blue, red and IR. If there is the formation of a stable NS (or an unstable one surviving for minutes/hours) we have an increase of neutrino flux which makes the component in the blue and red higher (the IR is the same). Typically the blue is predominant also wrt the red. It is expected that a remnant increases the blue part.

The first observed kilonova was GW170817. There was also an evidence before: a discovery linked to a short GRB. They discovered in the near IR making the subtraction 9 and 30 days later. In the X ray we have a typical power law of the afterglow (non thermal), we have the same in the optical. We have the 2 orange curves corresponding to kilonova emission with different ejecta mass.
The first kilonova models took into account only iron.

When the material of the kilonova expands, it decelerates and heats the ISM and we have a radio emission. This is due to the kilonova can happen months and also years after the merger. The radio remnant peaks really later (200-300 days later). For GW170817 we didn't detect it. People are still searching. But we detected the kilonova remnant in X rays. Studies are still ongoing.
The more energetic jet gives a higher emission. Another important ingredient to understand luminosity is the ISM density. At smaller densities the emission is fainter. What are the expected densities? Short GRBs are detected not at the center of galaxies, differrently from long GRBs. Short GRBs are expected not in dense environments, less than 0.01. We need to look for faint emission. The radio afterglow was detected for short GRBs but only on axis. This type of sources is not yet detected.

Another EM counterpart not yet detected is an emission in the X ray (HE) due to the formation of a NS. When we have that the remnant NS is stable or at least stable for some time, we expect a spin down energy, extracted from the NS which can give rise to a soft X ray emission ($0.2-10$keV) and this emission can be pretty high. The signal is expected to peak up to few hours after the merger. This is interesting because like the kilonova emission, it is not beamed. It is isotropic, bright and long lasting (few hours).
Looking at Swift archive we find a lot of short GRBs showing a plateau in the emission. It could be a stable NS. Maybe there are other reasons.
We expect a plethora of emissions with very different timescales for the emission. We need a network of multi-wavelength observatories in all the bands (ground based and satellites), covering large portions of the sky. We really need a lot of help from theory, because we need to know where to point the telescope.

BBHs are not expected to have material around: we don't expect to have enough barionic matter to power an EM emission. For binary stellar mass BHs we only have ISM around. We do not expect EM emission. For the first event Fermi observed a very weak signal, which was not confirmed by other satellites. This stimulated a lot the theorists that tried to explain it as connected to GW. There can be scenarios with high density around the BHs (some material coming from the progenitors). We can also have a star around which is tydally destroyed by the BH binary. Or the BBH can be in the accretion disk of an AGN (less exotic hypothesis).
Some say they found an optical counterpart to one of binary BH and that it was close to an AGN. But this signal was detected one and a half month after the GW merger and the sky position had one thousand of squared degrees of uncertainty. So this association is not so strong.

V. GW170817

We apply all this to this event. The signal was one minute (this is evident that it includes a NS). Fermi detected a GRB in gamma and this was confirmed in a few hours also by Integral. We wanted to detect the signal in all the bands. There was a problem in Livingston detector: there was a glitch which prevented us from having a good sky localization. We need to model the glitch! People worked against time. The best telescopes are in Cile for the

optical band. After 5 hours we had the sky localization.
Virgo started to observe from the first of August (really lucky event!). On the 14^{th} there was also a BBH detection, which showed that Virgo was able to observe.
It was also a close event (14Mpc): 50 galaxies to be observed. It was also lucky because it was in the blind spot of Virgo (this allowed to well locate it). On the basis of SNR in LIGO, Virgo should have seen something: that's why it should be in the blind spot! From there started the most extensive observing campaign ever: 100 telescopes were observing. Still now we are observing this galaxy.

v.1 GW observables

The most mportant parameter GW are able to see is the mass. We are in the region of NS mass ($1 - 2M_{\odot}$).
Another thing saying these are NSs is the tidal deformability, a parameter saying how the gravitational potential of a NS is changed by the companion star. A higher tidal deformability means a higher ejected mass. We can measure the tidal deformability of the 2 components. Zero (which means BH) is not completely excluded: this means that we cannot exclude that one of the two sources was a BH.
This however allows to exlude some EOS, the harder ones. We can exclude the most stiff EOS from the GW side. EM allow to exclude some soft EOS.

We searched for the post merger remnant. We expect a high frequency signal (4kHz) for the ringdown, but here we have a lot of noise in the detectors. We do not have the sensitivity to say what was there. Third G detectors will help us to identify the remnants.

v.2 Non thermal emission

What Fermi detected was a short GRB. It had the typical hardness ratio. When we use the distance, this object is much fainter than the typical short GRB, or also long GRB. Is it the first short GRB seen off-axis?
We observed an increase of flux for 150 days. This removed the uniform (same velocity in all the jet) jet and the uniform isotropic blast wave (for both of these we expected a decline).
We have a non thermal synchrotron emission from mildly relativistic ejecta. How can we explain this for many months? This increase can be explained with a jet with a velocity distribution: higher energy and velocity towards the center. Also radial distribution for the isotropic blast wave. Both models account for the observations.
Radio observations could discriminate.

V. LESSON 5

I. RECUP

Let's review the EM counterpart connected with a system of binary neutron star or neutron star-black hole. The beamed jet is the GRB, we have the shock heated ejecta getting rise to the blue kilonova, the super-relativistic material that gives rise to the red kilonova, the wind.
Then there is also the **cocoon**: some call it the slower part of the jet that has a structure. Some think it is the blue kilonova that shocks the material around and so it is a different emission wrt the jet.

II. SHORT GRBS

So a short GRB is associated to binary systems of NSs, GW170817 was the smoking gun to confirm this scenario. What about the emission? The emission of long and short GRBs is very similar: we have a prompt emission that lasts for seconds, and then we have the emission in all the bands, the so called afterglow phase. The afterglow goes from X-ray, optical and radio bands with different time.
What is the main scenario trying to explain the huge emission of GRBs? When we have a NSBH or BNS merger we have a temporary formation of an accretion disk which is expected to power relativistic matter. The physical mechanism able to launch the jet is still not completely understood, as like as the nature of the central engine, which can be a stellar mass BH or a NS. The most famous mechanism to launch the jet was developed in '77, **Blandfrod-Zanayek mechanism**, which tries to explain the launch with this accretion disk and it is based on the extraction of BH angular momentum through a strong magnetic field that seems in this scenario sustained by currents present in the accretion disk. The simulations so far are not able to launch the jet.

The difference between prompt and afterglow emission: the prompt emission is the dissipation of the kinetic energy of the jet. The most common model is the internal shock scenario also called fireball scenario. From the central engine we have some outflow that has different Lorentz factor. So we have shells of relativistic matter with different Lorentz factors: the faster one catches the slower one producing shock which is the one converting the kinetic energy of the ejecta into particle acceleration. This shock also increases the local magnetic field. The mechanism of acceleration is the Fermi acceleration across the shock. At this point with a high B we have electron cooling with synchrotron radiation. So we have synchrotron emission and inverse Compton. This is the favored model of prompt emission.

For the afterglow emission happening later, the jet starts to interact with the surrounding medium which gives rise to shock in the ISM and in particular we expect a forward shock going into the material and a shock going back into the ejecta, which is called reversed shock. Again we have synchrotron emission and on the basis of the energy of the electrons we expect the peak of the emission at HE. At the beginning we expect X ray, than optical emission and last radio emission. In this model the emission is beamed, we have a relativistic jet, and the beaming angle is inversely proportional to the bulk Lorentz factor of the jet.
With GW170817 we detected the non thermal emission, for days we observed only upper limits and no detection. This no detection in X ray and radio band was indicative of something off axis. What was very significant was a flux increasing for many many months. Another important observation was in radio, we were able to measure of the size of the source which was very small and so indicative of the presence of a jet. After GW170817 what we know is that we observed a jet off axis, with an angle between jet and observer estimated to $15-20°$. We also discovered that we need a **structured jet**, a jet that has an angular velocity distribution, a non uniform jet. GW170817 was also the first observed non structured jet. It was also the first connection between short GRB and BNS merger.

III. RELATION BETWEEN SHORT GRBS AND BNSS MERGER

We know the population of short GRBs as we have 40 years of observations. We know what are the distributions of redshift, we also know the galaxies for some of them. Now we also have a channel to study BNSs. Now is how these two populations are connected? We want to know the astrophysical rate of BNSs, and we also want to know if all BNS mergers are able to power a jet and give rise to a short GRB. Another important thing is to know the structure of the jet.

First we want to understand if there is a connection in the rate. We have 2 distances for GWs. One is called the range which is the distance up to which we are able to detect BNSs averaged on volume (the detector has different sensitivities in different parts of the sky) and at the same time we average on the system orientation. In the case of short GRB the face on system are louder than edge on ones. To understand the distance up to which we can observe face one systems we average on the sky volume: we need to multiply the range by 1.5. For BNSs advanced detectors in design sensitivity are expected to have a range for $1.4M_\odot$ NSs of 200Mpc.

What is the relation between these 2 populations? A short GRB is a beamed emission, an emission emitted in a cone. So to understand the relation between short GRBs and BNSs mergers we need to make a geometrical evaluation. We can define the beaming factor as the ration between the volume of the 2 cones wrt the volume of the sphere:

$$f_b = \frac{2 \times \frac{2\pi r^3}{3}(1-\cos\phi)}{\frac{4\pi r^3}{3}} = 1 - \cos\theta_{jet} \tag{13}$$

where θ_{jet} is half of the opening angle. Given that BNS are progenitors of short GRBs, we have to divide the rate of GRBs for the volume of the volume of the 2 cone and multiply by the volume of the sphere (divide by the beaming factor). If not all BNS produce GRBs we have that the rate of BNSs is larger wrt the rate of GRB divided by the beaming factor.

The energy of GRBs is typically given as isotropic equivalent, the energy release is given assuming that the GRB radiates isotropically. To have the real energy and luminosity we have to multiply the isotropic ones by the beaming factor.

Before GW170817 we knew the observe GRB population for which we knew the luminosity distribution and also the so called luminosity function that is the number of GRB as a function of luminosity. It's something we do not know well at low luminosity and there different works studying the luminosity function.

The main works before GW170817 were:

- Ghirlanda, which predicted a lower number of short GRBs wrt to Wnaderman and Piran
- Wanderman & Piran

The local rate based on the luminosity function given by observations is 0.4 for Ghirlanda and 4 for the other one. These are the extremes. On the basis of the range and distance, to know the number of GRBs associated to GW detected by LIGO/Virgo we need to take the rate of short GRBs and multiply it by the volume that LIGO/Virgo are able to observe. Since they are face-on we need to multiply the range by 1.4 and then by the volume corresponding to 200Mpc. We expect in design sensitivity $0.04 - 0.4$ per year. These are on axis GRBs. For the rate of total BNS, we need to start from the rate of GRBs and divide by the beaming factor which depends a lot on the θ_{jet}, on the dimension of the cone. If the cone is very narrow we will have a larger rate of BNSs, if the cone is larger the number of BNSs will be more similar to the rate of GRBs. The half angle for short GRB is typically taken to be $10°$ and so we expect a BNSs rate of $0.9 - 10$ per year, which is consistent with our current observations.

How big is the jet opening angle? It influences a lot the relation between the number of BNSs and the number of short GRBs. There is a way to measure the jet opening angle. We have already seen that the relativistic opening angle is $\theta_b = 1/\Gamma$ and when the jet decelerates the emitting region increases (the Lorentz factor decreases). At some point θ_b will be equal to θ_{jet}: we see a more rapid decrease of the flux. It's something purely geometrical: we have no more emission behind. How can we connect the Lorentz factor to the break. If we observe this time break (in all the bands!), we can evaluate the θ_{jet}, the dimension of our cone. It is difficult to measure it for short GRBs which are fainter: we do not see the break! For only 4 short GRBs we were able to measure it. It is really difficult to know the relation between the number of short GRBs and the number of BNSs.

GW170817 changed the scenario. The jet is not uniform but structured and so the previous count is too much semplicistic. We need to take into account that the jet is structured. The works of Ghirlanda and Wanderman use different observables and give us the number of GRB per year and Gpc^3 in different luminosity bins. Ghirland is more flat and gives a higher numebr of short GRBs at higher luminosity. Wanderman predicts a larger number of short GRBs at lower luminosity.

How can we interpret the luminosity function using the structured jet? Let's start with the rate. What was observed with GW170817 was a very faint GRB (now we know it was off axis) with a luminosity of 10^{47}erg. Observationallly we can try to understand what are the astrophysical rates of these faint GRBs. We can use 9 years of Fermi observations: we observed only 1. Through the archive other 2 candidates were discovered. We are taken into account also the duty cycle: Fermi is not able to observe the whole sky because it is occulted by Earth. So the duty cycle is 0.5. We want to estimate the rate of short GRBs, we say up to what distance we are able to observe this luminosity (10^{47}erg) and we find 65Mpc. The rate of short faint GRB is 190.
Assuming all GRB have a core luminosity of 10^{51}, we can explain the luminosity function using structured jet and different observers. The rate of GRBs is consistent with the luminosity function of structured jets. Going to lower energies we are going to the isotropic case. Nevertheless the BNS rate is always larger than the short GRBs rate: at least 10% of BNS is not able to launch a jet! The rate of BNSs is very uncertain because it depends on the mass distribution.
Having many GW detections and short GRBs will constrain the structure of the jet.

iv. Back to thermal emission

We go back to kilonova emission. We know that we have different components of this sub-relativistic material. We have the tidal ejecta, rich of neutrons with a small electron fraction where we can form lanthanides and it peaks after one week in the red. It is equatorial and more isotropic when we have equal mass.
The blue component is due to the shock heated ejecta in the interphase between the two neutron stars and we can also have mass ejecta from the accretion disk. The electron fraction is higher and weak interactions become very important. The peak is after $1-2$ days and it is blue.
Then we have secular ejecta due to the unbound matter thanks to viscous phenomena. There is a range of electron fraction, between tidal and the shock heated and disk winds. The fraction of lanthanides really influences the luminosity as a function of time. If they are small we have a peak at higher luminosity in the first days. For high fraction of lanthanides the emission is distributed over more days. Without lanthanides we have a peak in the optical band, with more lanthanides the peak is more in the IR band.
For GW170817 we observed both the blue and the red components. The blue component with a high electron fraction and the red component with a small electron fraction. What we observed was very similar to the expectations from models. We also observed absorption features we expect from heavy elements.
We also observed features consistent with r-process nucleosynthesis.
We do not know if this event was exceptional. The first day the observations couldn't tell if it was a SN or the counterpart of a GW event. The only interesting thing was that this object was found in a galaxy at the same distance of the GW signal (40Mpc). It can also be a contaminant, because very similar to a young SN. The clues are time coincidence and distance. All the telescopes were pointed there with spectra taken 1.5 and 3.5 days later. Here we saw how different these spectra were wrt the SN ones.
How much is different kilonova wrt the SN? We have component with high velocity $0.2-0.3$c, for a SN the velocities are much smaller. We have broad lines and it is impossible to identify a single element. We have a forest of elements: it is impossible to identify a single line. We cannot say what precise elements are formed.

We also have a mix of components moving at different velocities: it is extremely hard to have synthetic spectra able to understand the data.

What are the basic parameters we can extract form the spectra? The first thing we can do is to approximate the spectrum to that of a black body with different T. We see the rapid decline in the first days in T. We can study the bolometric luminosity decline: we have a rapid expansion and cooling.
In the first days the observations are consistent with a amount of r-process elements of $0.01M_{\odot}$, after it corresponds to $0.05M_{\odot}$. So at the beginning with have a lower r-process elements amount.
Using Stefan-Boltzmann we can make some estimates of T: we start with very high T and then a rapid decline corresponding to the expansion of the object. The measured opacity is linked to lanthanides, but we also have the recombination. We have ionized elements that recombine. After recombination the opacity decreases and e have a photosphere that reduces, moves inwards. The recombination of heavy elements is what reduces opacity and in particular T becomes asymptotic. All this is due to the recombination of the shell lanthanides elements and reduce of the opacity and move inward of the photosphere.

What is really difficult is to understand the spectra that we have over ten days and so far we have no model able to explain all the evolution. So far we have a 3 component model:

1. **lanthanide-free**: polar
2. **lanthanide-mixed**: more similar to secula ejecta
3. **lanthanide-rich**: dynamical ejecta

We considered an observer at 15° from the polar axis. Combining the three components, the first days are very well approximated. Going to the evolution in 1 days the model is less and less good. The main issue is that we do know well the geometry and the different components of the ejecta. We need more observations.

We try also to understand what elements are formed. Assuming some components and velocity distributions we try to understand if there are some features corresponding to some specific elements. The first paper was about cesium and tellurium, but we are not sure they were there. The same structures can be interpreted also with other elements.
It's very difficult to have synthetic spectra because heavy elements have forests of lines and we really don't know the atomic data for lanthanides. The other thing is that we are dealing with relativistic velocities that make the lines extremely broad. We are neither sure about the gold! We cannot identify it there,
A work by Watson is based on strontium. They were able to identify it even if it is not son heavy and also produced in SNe. We were able to reproduce strontium with GR simulations tuned to properties of GW170817.
Let's understand why BNS merger are the main formation channel of heavy elements. On the basis of observation we are able to say how much mass was ejected. On the basis of what we know about nucleosynthesis we are able to say what fraction of this ejected mass corresponds to some specific elements. On the basis of different models we can know how much europium was formed there. The different amounts come out from different estimates of the ejected mass.

We can try to understand what are the merger rates that give the abundances we observe in our Galaxy. With a lower mass of Eu we expect a larger rate (the errors are very big!), and with large mass in Eu we expect a smaller number for the rate. Both are consistent with the BNSs rate measured with LIGO/Virgo. So we are able to explain the galactic abundance using the ejected mass and the merger rate we know form LIGO/Virgo. This tells that the abundance with big uncertainties are able to reproduce the abundances in our Galaxy.

v. MULTI-MESSENGER STUDIES

NSs are something extremely interesting because they are the natural laboratory to study cold high density nuclear matter. The EOS determines the tidal deformability which is directly connected to the ejected mass. The higher the tidal deformability the more ejected mass. If we are able to measure from GWs tidal deformability we can constrain the EOS and from the ejecta mass we again can have information on tidal deformability and so on the EOS.
We measure the different phases of inspiral, merger and ringdown. During the inspiral we are really good at measuring the chirp mass, while at later phase we are able to measure quantities as the mass ratio.
The EOS is important for the remnant. The threshold for total mass of the remnant is determined by the EOS.

For GW170817 we see that we can exclude stiffer EOS using GWs. Using the EM emission we can see that Λ. We can constrain the ejected mass on the basis of the brightness. We can exclude direct collapse in BH: we form a NS that at a later time collapses to a BH. We also exclude the softer EOS with EM emission. We didn't observed the spin down emission: that is why we can say that a NS formed and after minutes/hours collapsed.
Many open questions were solved with only one event!

VI. Lesson 6

i. GRB/GW cosmology

One of the most important things was to use the delay between the GW burst (maximum amplitude) and the GRB burst observed by Fermi and Integral. From this we can constrain the speed of gravity. We saw that they propagate at light speed. This ruled out many modified gravity models.
The delay of 1.7s is something happening at the source because the GRB requires time to escape from the matter.

The detection was very close 40Mpc and this allowed to study also the host galaxy. Typically short GRBs are at higher redshift, the one that is most close is 400Mpc. We deep images of the galaxy. We were able to study its morphology, SFR and metallicity. This gives us info on the population. This relates to chennel of formation of binary systems of compact objects.
MUSE allows to make spectra in 3d having very detailed info on the gas in the galaxy. The hist galaxy is NGC4993 and it is a lenticular galaxy. It shows some features which mean that it comes from a recent merger, that could have enhanced the SFR in the galaxy. Now this galaxy shows all the properties of an old population. There are also no star clusters, nor globular or young. Very likely this system, GW170817, was not formed dynamically but an isolated system of very massive stars that evolved in a BNS system.

i.1 Neutrino searches

Neutrinos were the missing messenger. We did searches in a 500s window and also delayed searches, 14days after the merger. There are some candidates not consistent with the position of GW170817.
Why searching for neutrinos? When we have the jet we have the prompt emission, the afterglow emission, we have dissipation of energy which is distributed between protons, electrons an magnetic field. We have the bulk kinetic energy radiated by synchrotron and inverse Compton due to shock accelerated electrons: internal shocks for prompt emission and external shocks for the afterglow at later times. This process of particle acceleration is expected also to accelerate protons to ultra-high energy (10^{19}eV). The interaction of these protons with the prompt and afterglow radiation gives rise to the production of charged pions, that then decay and produce neutrinos: this is the reason why we expect neutrinos. We expect the EM emission to be beamed in the jet and so we expect the neutrino flux that is mainly along the jet. We didn't have detection. But we had upper limit wrt this non detection with Antares, Auger and IceCube.
If the GRB were on axis (actually it was $10-15°$ off axis) IceCube could have constrained something.

An important name is Edwin Hubble the one who discovered that the universe is expanding. He was able to measure the recession velocity from the Doppler shift of the spectral lines of galaxies. He also measured the distance from flux measurements. Hubble took galaxies and measured their recession velocity and their distance using them as standard candles. This gives the Hubble constant.
The redshifts are easy to measure spectroscopically. Not so easy in the close Universe because we do not have only recession velocity but also peculiar velocities (all the galaxies are attracted to the Virgo cluster) and we need to correct for the local movement.
The distance is difficult, it depends a lot on finding standard candles. The easy scenario is when we an object for which we know the intrinsic luminosity and we evaluate the flux.

$$L_{obs} = \frac{L_{em}}{(1+z)^2} \tag{14}$$

We have different Hubble diagrams for different models of the universe.

II. Standard candles: SN type 1A

Standard candles that are typically used are SN type 1A. It's not clear what the progenitor are, but for sure there is a white dwarf involved (mass of the sun in a volume like Earth). When the white dwarf exceeds the Chandrasekhar mass it explodes and the CO core is converted in iron. We do not know what is the companion. We have a single-degenerate scenario (the companion is not a white dwarf) or double degenerate (another white dwarf).
We know these are standard candles. They have the same intrinsic luminosity. In reality, this is not totally correct but we can standardize them: they have different brightness, but the brighter ones are also the ones that have a broader lightcurve. Normalizing for this effect we can standardize them and then measure the distance knowing the peak. It's complicated to calibrate and the systematics is not perfectly clear. Also the brightness depends on the environment, the host galaxy.
Also GRBs can be used as standard candles, even if they are not so precise and there is alos a suggestion to use kilonovae.

There's a big tension (5σ) for the Hubble constant estimates from SNe and from CMB. We are not able to completely exclude systematics. CMB uses the early universe, not like SNe.
GWs are extremely important because they can say something about this tension. They have a totally different systematics.
GWs are called standard sirens. When measuring the GW signal we have a direct measurement of distance. From the phase we can extract the redshifted mass and we can insert it the strain amplitude and we can obtain the luminosity distance. There is a degeneracy with the orbital plane. Having D_L from GWs and z from EM we can estimate the Hubble constant! We did it for GW170817 (we knew the recession velocity of the galaxy), we measured the distance and estimated the Hubble constant which resulted in between CMB and SNe, but the error is really big. But there is this degeneracy between distance and orientation of the orbital plane!!! We need to remove the degeneracy to reduce the error or we need a lot of observations.
How can we improve the H_0 estimates? increasing statistics or removing the degeneracy. One way to break the degeneracy is making more precise measurements of the distance from the EM side. Anther way is to use inclination info: from GRB knowing the observing angle wrt the jet can give info on the orbital plane, assuming the jet is perpendicular to the orbital plane.
Or knowing the geometry of the kilonova and use the observation angle of the kilonova to constrain the orientation of the orbital plane.
There is also another way that is a statistical estimate of H_0 using standard candle without EM emission. We know the sky localization with a GW signal and we try to identify the most probable host galaxy in our error box (we need to know well the distribution of the galaxies). In this way we can also use BBHs with no EM emission. It's less effective than having the real galaxy but if we have many of them it could be interesting.

III. The third run

Increase in sensitivity means a larger observable volume: in O3a we had 1 event per week and we expect in O4 to have 1 event per day. In O3a we identified 39 candidates with a contamination less than 10%, which means that among these events only $3-4$ could be noise. Among these 39 candidates 26 were sent in latency, reported in the GCN, the alert used in astronomical community to spread the info that there is a transient so that all the telescopes know they have to point because there is a transient. This system was invented for GRBs.
13 candidates were found off line, less significant events that came out only with a better calibration of the data and a better knowledge of the noise.

In the first run we had only 3 detections, and now we have 50. The population we know better is BBHs. We know the distribution of masses and the frequency of these mergers in the universe. It's impressive what happened in only 5 years.

- GW190425 was the second BNS. It is high mass and with no EM counterpart. The distance is really large 160Mpc. We need to search for a very faint EM emission, which wasn't detected. The reason is that sky localization was thousand f square degrees: find a faint object in a huge region!
- GW190814: we have a $23M_\odot$ massive object and another of $2.6M_\odot$, which we do not know if it is really massive NS or a really light BH. The mass ratio is really big, which we do not expect. Isolated binaries are expected to be equal mass, so this is an indication that it formed in a cluster of stars. It is also very distant: 200Mpc. We also search for tidal effects (which signal the presence of a NS), but there were no evidence for tidal effects. The sky localization was really good 20deg^2, but no Em emission was detected. This observation is consistent with both a low mass BH and a NS. In case of NS the ISCO is much larger than the tidal radius so that NS directly plunges without being disrupted and there are no EM effects.
  There was an EM campaign with results before the knowledge of masses and of the big mass ratio. The optical campaign of Engrave (GSSI is part of it) was split in 2 campaigns: one concentrated on large field of view (VST and Atlas)using mosaic of sky localization; near IR with Vista and a small field of view. We set nlu upper limits, we were not able to see anything. VST gave the best upper limit along with Panstar. We extrapolated GW170817 to larger distance to make a comparison. From brightness we can estimate the ejected mass. From the upper limit we put some constraints. The conclusion is that we were able to exclude a kilonova with an ejected mass larger than $0.01M_\odot$ with a 90% confidence.
- GW190426 could be a BHNS but it has a high FAR so it can be a contamination. There are also similar sources in O3b
- GW190521 most massive BBH discovered (birth of intermediate mass BH!). The 2 BHs are consistent to be a second generation merger products. One of the scenario explaining this BBH is that they can form in the accretion disk of a SMBH. This favors more massive BHs that merge in a shorter time. So we can have second generation BHs that then merge in intermediate mass BHs. There was a detection of ZTF (Zwicky Transient Facility in California, Palomar Observatory): maybe a counterpart? They found a flare near an AGN in the sky localization of the event 34 days after the GW event.

IV. NEXT OBSERVATIVE RUNS

There will be an improvement in the sensitivity. O4 will start not before June 2022 and will start for one year. The sky localization will change!
We can also estimate the merger rate. The best estimate is for BBHs. It also depends on the knowledge of the distribution of mass of these objects.
We also see that the astrophysical rate of BNSs is larger wrt BBHs, but we observe more BBHs because the signal is louder and we can observe a larger volume and a larger number of events.

We are consistent with our estimates. The median for O4 is good but we need to reduce the extremes.
What we saw during O3a was an intermediate mass BH and maybe a NSBH. We didn't detected the astrophysical and cosmological background (superposition of many events). We are hopeful for the continuous emission from the spin down of NSs.

For the FAR we count only on the background. We count the number of the events that have the energy correspondent to the events but due to noise.

VII. Lesson 7

i. Star evolution

The stability condition for a star is hydrostatic equilibrium. We see that the variation in pressure depends on the density.
The EOS is what connects pressure, density and temperature. Making a very rude approximation we can think of derivative as incremental ration and set the pressure at the star surface equal to zero and consider average pressure and density inside the star. We also consider the mass within half radius, $R/2$.
From hydrostatic equilibrium we arrive at:

$$-\frac{GM\rho}{r^2} = \frac{dp}{dr} \sim \frac{p}{R/2} \tag{15}$$

After a bit of algebra we find:

$$\frac{p}{\rho c^2} \sim \frac{R_S}{R} = f(\rho, T) \tag{16}$$

This ratio is exactly the EOS depending on density and temperature. When the star is in the main sequence this EOS depends only on T. When we have a degenerate star this quantity depends only on the density.
For main sequence we can use the EOS of a perfect gas. The star is mainly hydrogen:

$$f(\rho, T) = \frac{k_B T}{m_p c^2} \tag{17}$$

Inserting typical temperatures for main sequence stars:

$$\frac{R_S}{R} \sim 10^{-6} \tag{18}$$

So the size depends on the total mass of the star and temperature.
A star is in MS when we have the burning of H, nuclear fusion of H in He. It's the most populated region (90% of their life is spent in MS) in the HR diagram. Large size stars evolve more rapidly, they have a high fusion rate. Depending on the mass we have objects that have a different evolution from the MS.
From MS they become red giants, when they finish H. They have no more pressure against gravity, they have a collapse: release of gravitational potential energy that heats the outer layer of the star, the luminosity increases and we have an expansion and the object cools down. We increase the size and so the luminosity. the star starts to burn He, and then also the CNO cycle begins. When we finish He, there is not enough mass to start another reaction and a star like Sun evolves into a white dwarf and we have a collapse in a degenerate star: a very hot and small size. There is no more internal fusion. The object is cooler and cooler.
For more massive stars, after the CNO, we have fusion of these material we form Fe in the core and we form supergiants.

When the star is at the end of its life in the MS we have no more fuel, the star starts to cool, but the release of gravitational potential energy makes an expansion of the shell and the evolution into red giants (decrease of T and increase of R). If the star continues to cool the internal energy is no more able to balance gravity and the star collapses.

i.1 Gravitational collapse

In Newtonian physics the collapse stops when all the matter has collapsed in one point. The collapse time can be evaluated and we can assume that it corresponds to the moment at which the pressure goes to zero and the free fall collapse starts. We have to write the EOM of a mass point from the surface to the center. The acceleration increases with time. Integrating this equation we can evaluate the collapse time, which depends only on the initial density of the object, not on its size!

II. EOS FOR DEGENERATE MATTER

If during the collapse the nuclear density becomes extremely high, the star cannot be approximated with a perfect gas. The pressure is determined by electrons and neutrons and becomes totally independent of the temperature. The EOS only depends on density. We are dealing with a degenerate star: white dwarfs and neutron stars.
Fermi gas is a gas with high density conditions. The smaller the distance between electrons the higher their Fermi energy. We are in the condition of Fermi gas when the Fermi energy is much larger than the kinetic energy due to the temperature:

$$\epsilon_F \gg k_B T \tag{19}$$

Fermi enrgy is larger for lighter particles and so for electrons. To evaluate the EOS for degenerate matter we substitute $k_B T$ with the Fermi energy. What we obtain is that the pressure is determined by electrons while the protons contribute mainly to gas rest energy. d is the average distance between electrons.

When we are close to the critical density we have that the electron impulse is equal to $p_F = m_e c$. When it is larger than critical density electrons become relativistic and the electron energy becomes $p_F c$.
The final degenerate EOS is given by:

$$f(\rho) =\sim \frac{m_e}{m_p} \left(\frac{\rho}{\rho_c}\right)^{n/3} \tag{20}$$

with $n = 2$ for $\rho < \rho_c$ and $n = 1$ for $\rho > \rho_c$.

III. WHITE DWARF

These stars are supported by electron degeneracy pressure. Here we are in the conditions where the EOS only depends on density. We can obtain the Chandrasekhar mass imposing $\rho = \rho_c$. So we obtain that the white dwarf mass is given by:

$$M(\rho) = M_{Ch} \left(\frac{\rho}{\rho_c}\right)^{1/2} \tag{21}$$

for $\rho < \rho_c$. If $\rho > \rho_c$ the mass reaches the maximum which is the Chandrasekhar mass.
We can also evaluate the radius, as the EOS directly connects mass and radius. We have a critical radius. The radius decreases when density increases.

IV. NEUTRON STAR

The theory was developed by Oppenheimer and Volkoff. We have a lot of electrons. We have inverse β decay:

$$e + p \to n + \nu_e \tag{22}$$

We decrease the number of electrons and increase the number of neutrons. The electron pressure decreases and the star collapses and the neutrons take the role of electrons. Now the Fermi energy is the one of neutrons and we have to substitute the electron mass with the neutron mass.
We obtain similar equations for the Chandrasekhar mass.

VIII. Lesson 8

i. 3G detectors

We will describe what will be the next 10 years. The fact that ET is triangular allows ET to work alone and to have a certain sky localization. Maybe it will be in Sardinia or in the region between Belgium, Netherlands and Germany. It will start observing in 2035. Italy is the country driving the proposal. It is also supported by Spain, Netherlands and Poland. Germany and France haven't signed yet.

In the USA they have a different project, Cosmic Explorer an L shaped detector of 40km. It doesn't go to low frequency, but the long arms improve at high frequency. It's better in detecting NSs wrt ET.

ET will explore a much larger universe than 2G detectors. It will be possible to observe binary systems up to the early universe. We would see what happened from the point of view of first structures and we will be able to do this for all type of massive starting from intermediate mass BHs to NS. Moreover we can monitor these objects along the cosmic history of the universe. It's a huge improvement: larger distribution of masses and go to early universe. It's like going from Galileo telescope to Hubble Space Telescope.
We will have a 10 times better SNR: we will search for exotic compact objects and make tests of GR with much more precision. This is a really big improvement. We are limited by the noise pf LIGO/Virgo in making these tests. Also the EOS of dense nuclear matter can be better constrained. And we will be able to constrain not only the effective spin but also the precession spin.

LSST and Euclid will monitor the large structure of the Universe and we will be able to evaluate the cosmological parameters. The same is with ET because we can use binary systems to monitor and probe the large scale structure. We will also have more possibility to observe SNe even though we won't be able to go to very large distance (limited to 10Mpc). It's difficult because the rate is not large, also in the local volume. What will be discovered first will be the remnant: we know the explosion pf SN brings to the formation of a NS ($10 - 20\%$ of SNe) and then will have a signal in GW due to the spin down of the NS which typically lasts for a few days. This is very promising and it is more likely that we will detect the GW signal from the spin down and not from the core collapse. In reality, it is possible that we see or not the optical counterpart because it is very absorbed, but in the next years we will have a lot wide field of view instruments in the X ray. So it is possible that we will detect GW form the spin down and the shock break out that is in the UV-X ray.

What are the main multi-messenger search goals for the 3G detectors? First of all study of population and then try to see, since we will see objects up to early universe, if there is a connection between binary NS and BHNS and GRBs, star formation history of the universe (do GRBs come from pop III stars?). Also see if in the early universe there are intermediate mass BH mergers and if these can explain the first SMBHs. Another important thing is that we can start to observe the merger remnant which is very important for the EOS of NSs. We will make both cosmology and cosmography (GWs can be used to estimate cosmological parameters and not only H_0). We can really start to have with GWs estimates of all cosmological parameters.

The main step forward for advanced detectors is that for close objects there will be very high SNR which is a big advantage. Moreover, going to large distance we can have a big sample of detections. We can really make population studies and try to understand better the formation and origin of compact objects in connection with star formation history. When we make population study we can disentangle intrinsic parameters from geometrical effects. The statistics will be crucial to understand better the kilonova components and also the structure of the jet.

We will have a huge improvement in sensitivity wrt LIGO. ET is really able to go to lower frequency. Voyager is an upgrade of LIGO. It's not clear it will be done. ET and CE are 1 billion euros. There is a debate if pass through Voyager or to pass directly to CE.

We will explore a huge parameter space with ET and CE. For BNS we can arrive to $z = 2$. At $1M_\odot$ black holes we can arrive at $z = 100$ and we can explore the entire universe. For close objects an increased SNTR corresponds to a better parameter estimation. We can also understand better the role of kilonova and nucleosynthesis. We do not know if SNe associated with long GRBs can give rise to nucleosynthesis with an important r-process elements. With Engrave we recently detected an object that indicates some r-process nuclosynthesis also in SNe. We need to understand the role of kilonova wrt other sources.
For GRBs we can constrain a lot the jet properties and what is the number of events unable to produce jets and also understand the role of magnetars in the emission mechanisms of GRBs linked to star formation history. We will be able to probe better the emission mechanism of kilonova and GRBs and make cosmology. ET alone will have 10^6 BBHs per year and 10^5 BNSs per year.

With ET we will be able to detect the signal from the remnant. The GW observables will have a much better parameter estimation.
Another interesting thing for multi-messenger studies is that we will be able to detect sources before the merger because we will have access to low frequency and we can start to observe the signal well before wrt LIGO/Virgo. In general, we can detect a BNS hours before merger. If we have a not bad sky localization we can point a telescope there before. So we can have images before the merger which is important to make subtractions of images to find the new object and be prepared to make a mosaic of sky localization at the moment of the merger, crucial to detect the early GW emission.

To understand detection capabilities of ET for different sources we need to have a population of these objects. From them we take the expected population of compact objects and make simulations to understand what we are able to detect. We also combine this with the detection efficiency in the EM band. For BNSs the common envelope gives the major errors, for BBHs it is the metallicity. We took the population and made injections and got the detection efficiency as a function of z. Going on axis we have a louder GW signal. We are able to detect more on axis events up to a larger distance.

We also made simulations of sky localization capabilities of ET. We made 2 types of simulations: one in the local universe and another one in the entire volume considering one year of observations. If ET will operate with HLVKI we will have a big number of events with a good sky localization.

For high z it will be the detectors for GRBs to give the sky localization.

On axis we are dominated by the GRB, going more off axis the other components become important. Going more off axis we see the red component of the kilonova, but the kilonova is faint and we won't be able to observe it up to high z. Going to higher z and taking into account the range of EM observatories in the local universe we can detect kilonova and off axis events, but on larger distances we will be dominated by on axis events.

The future instruments for EM observations will be SKA (radio counterpart of GRB), Vera Rubin (former LSST, extremely fast and multi-filter -from near IR to blue-, it will detect very faint transients up to 25 of magnitude), Ultrasat (2025 launch, wide field in UV band able to detect kilonova in the early phase when it is blue and observe SBO from SNe), Theseus and Hermes, and CTA (VHE, the future for Cherenkov telescope, evolution of Magic.
For the follow up we will have ELT (operative in 2028-2029, the largest telescope in the world with adaptive optics, 39 m telescope with resolution comparable to space telescopes), James Webb Space Telescope (similar to Hubble but more on the near IR part), Athena (step forward wrt the current generation of small field X ray telescopes as XMM or Chandra, it will detect very high z off axis afterglow in the X ray also at later times, it has also spectroscopy capability to observe eventually lines in the kilonova emission).

II. EM and GW joint detections

We see the kilonova emission, but what happens going to larger and larger distance? In this plot we see GW170817 in a model thant takes into account both the red and blue kilonova and this model is shifted to different distances. We see a range of models corresponding to different ejected mass. Going to larger distances the object becomes fainter and we also have the limit for the Vera Rubin observatory. ELT will be able to see farther but this is a pointing telescope (only for arcsecond localized sources) not a large field of view. We won't be able to detect this emission up to large z.
The kilonova is a faint counterpart and it will be difficult to detect it and if there is a large sky localization we need to find something very faint and in a big patch of sky: the problems of contaminants will be huge. The joint detection of ET and optical emission is limited by the optical instruments because the optical emission is really faint. Vera Rubin observatory will be able to detect kilonova up to 1Gpc and it will observe only the southern sky.

For ET plus 2G detectors we will probably have several tens of joint detections per year. This is an optimistic number. ET will have a better parameter estimation and we will be able to constrain the EOS from pre-merger and post-merger observations. The improvement is not such the more detections but the better PE.

III. Why high energy?

It's important because there are GRBs. We know we are able to observe GRBs up to high z, and in HE there is a small number of contaminants. In the next years there are also promising mission concepts in the X rays, both hard and soft. These instruments are expected to fly at the time of ET and they are also able to make very good sky localization.
Now we have Fermi and Swift. Fermi detected a lot of GRBs but the sky localization is not very good. Swift has detected GRBs but has not a wide field of view in the X ray. Improving sky localization and a wide field in soft X can increase a lot the number of detections of X ray counterparts.
Going to larger distance is good because we will increase the number of samples of detections on axis. And on axis we know that we are able to observe GRBs.

IV. Theseus

One of these instruments is Theseus in which GSSI is involved. This mission was selected by ESA cosmic vision science program, it's a medium class mission and was selected along with other 2 missions. The competitors are EnVision Venus (a mission to Venus) and Spica (a near IR). Spica was removed because the investments in near IR was in Wfirst. The competition is netween Theseus and EnVision Venus.

Theseus is 3 instruments together: soft X ray with a big field of view and very good sky localization; X ray spectrometer large field of view; IR telescope important for GRBs, it has broad fielf of view and accurate sky localization, prompt reaction.
Theseus will expand a lot the number of GRBs with fainter flux and so we will really be able to go to higher z. It will detect between one and two order of magnitude more GRBs than all of the instruments that are now on line. It will be able to detect 12 short on axis GRBs. It is also able to detect off axis GRBs.

V. High latitude emission

A lot of Swift GRBs show a plateau and it can be a sign of a magnetar so a presence of a new born neutron star or maybe a high latitude emission from a structured jet.
Before GW170817 people were considering a uniform jet so that the beaming angle was the same and the emitting surface was a sphere. After it was clear that the jet is structured. We no more have the same Lorentz factor and so different beaming angles. This corresponds to an emitting surface that is no more spherical. At fixed viewing angle,

photons coming from a spherical surface are smaller wrt the other case. Using a structured jet we were able to have the plateau. We do no need a magnetar. Measuring the plateau can put constraints on the structured jet. The plateau it is found only in the X ray and not in the optical, thing that is very difficult to explain with a magnetar model because we expect a plateau both in X ray and in the optical band.

What happens if we observe a high latitude emission from a structured jet off axis? This is a very promising counterpart for GW signal. We can observe them up to a certain viewing angle. It can also be observed many hours after the merger.
In an optimistic scenario we can have up to one hundred joint detections per year.

VI. HERMES

Now a lot of space missions will be done with cube satellites, because they are cheaper. Hermes pathfinder will fly in 2022. The entire constellation of cube satellite will be in 2030. They are good in making a good temporal resolution. The only problem for Hermes wrt Theseus is sky localization that can drive all the follow up in the optical band.