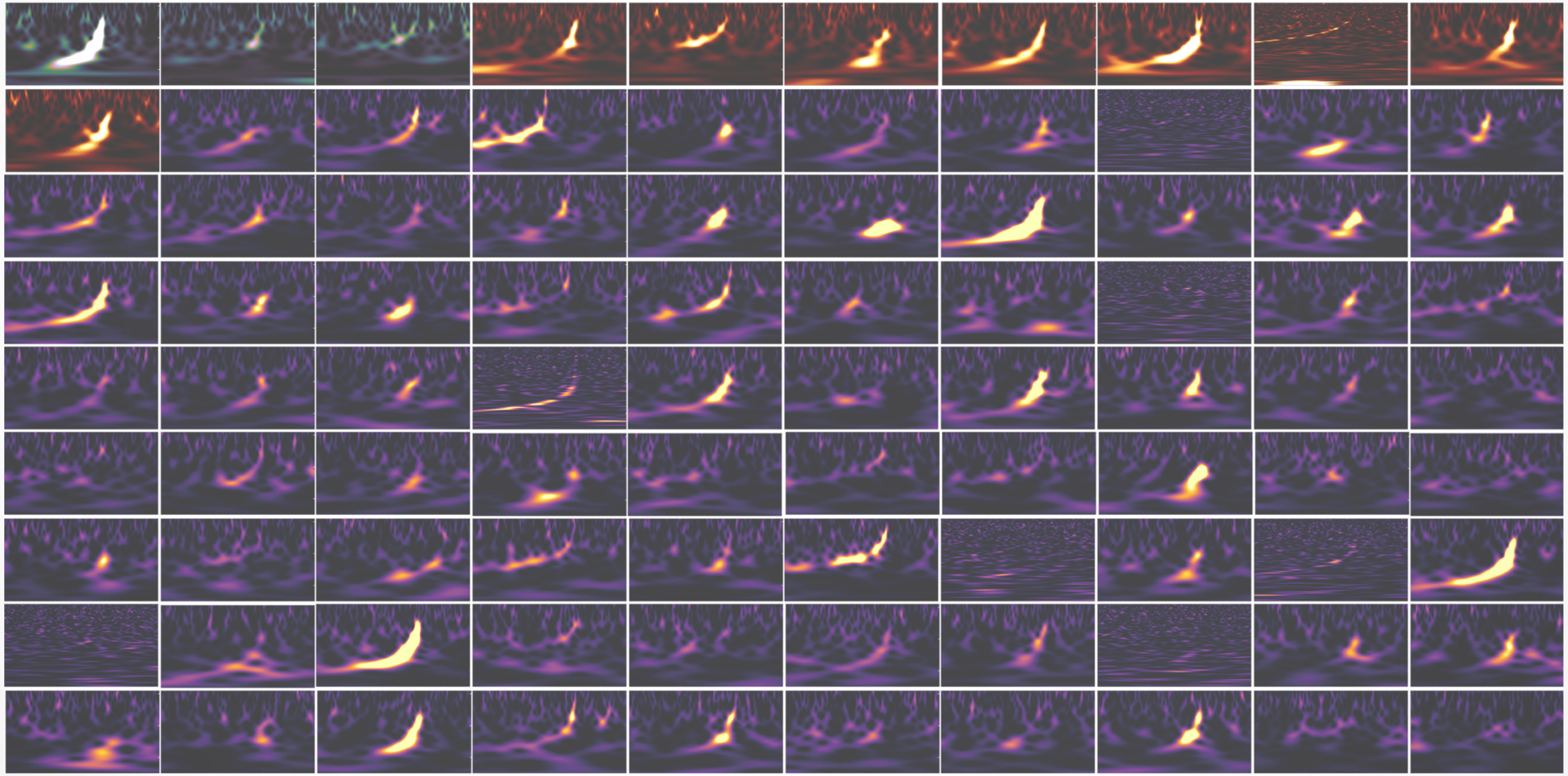
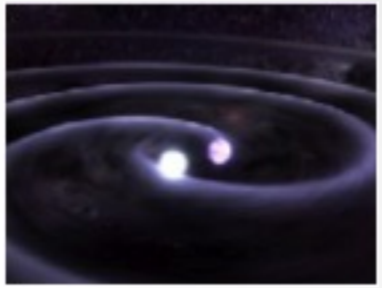
Gravitational wave : recent results and future of the field



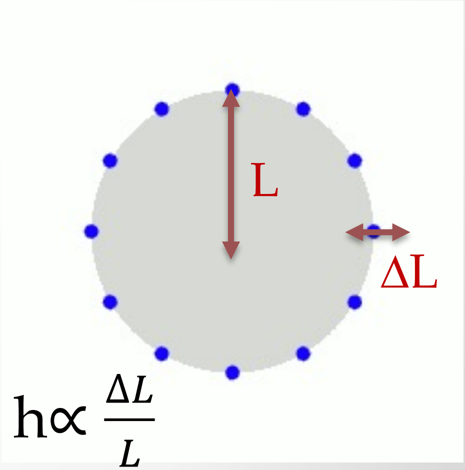
Nicolas Leroy – IJCLab – ISAPP 2022

What are Gravitational waves ?

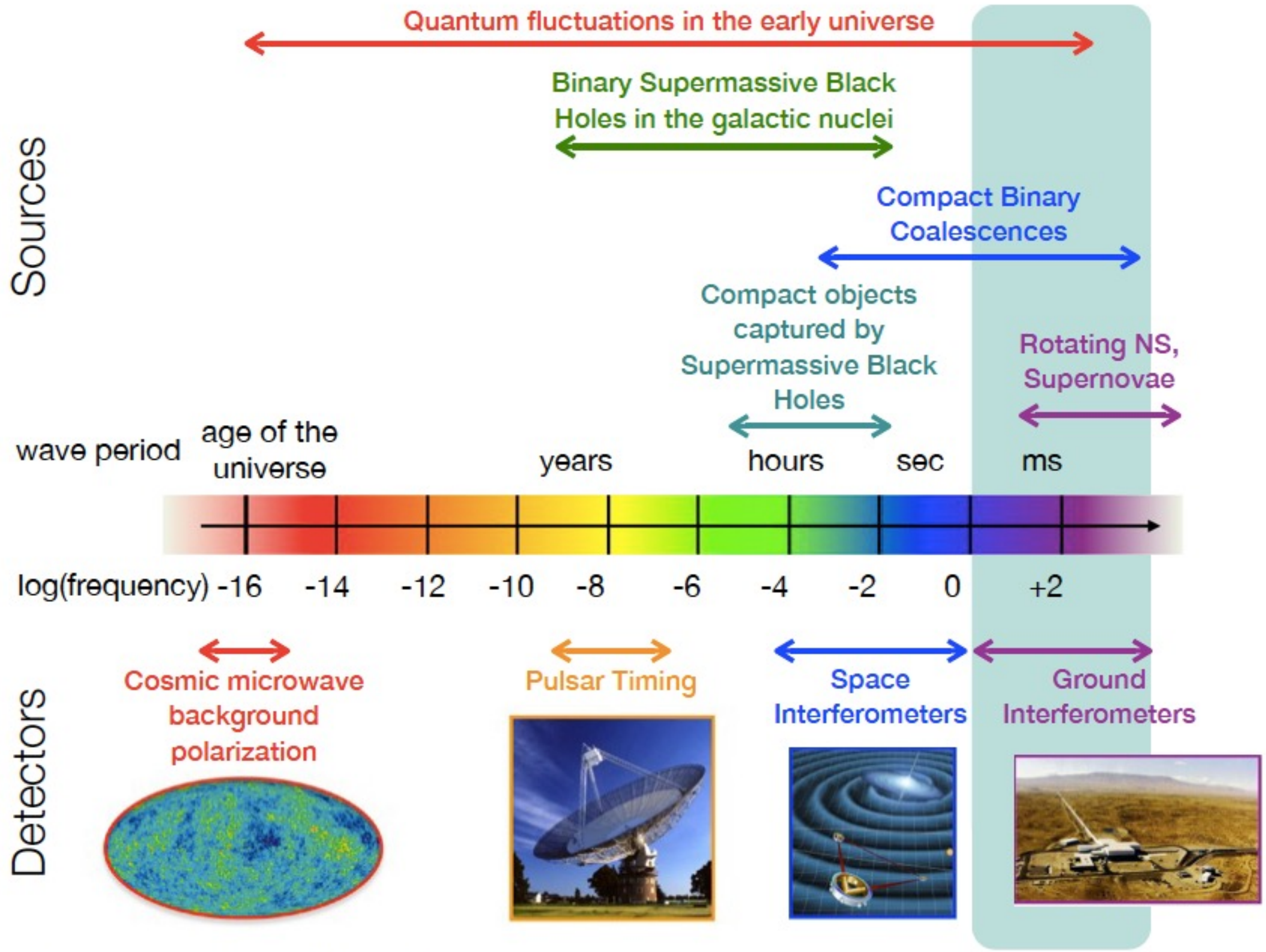


- Solution from General Relativity derived by A. Einstein in 1916
- Far from sources then can be seen as a perturbation of the metric
- They are ripples of space-time produced by rapidly accelerating mass distributions
- Provide info on mass displacement
- Weakly coupled – access to very dense part of objects
- Main proprieties:
  - Propagate at speed of light
  - Two polarizations '+' and 'x'
  - Emission is quadrupolar at lowest order

Needs to have
- Compact object : R~Rs
- Relativist : v ~ c
- asymmetric

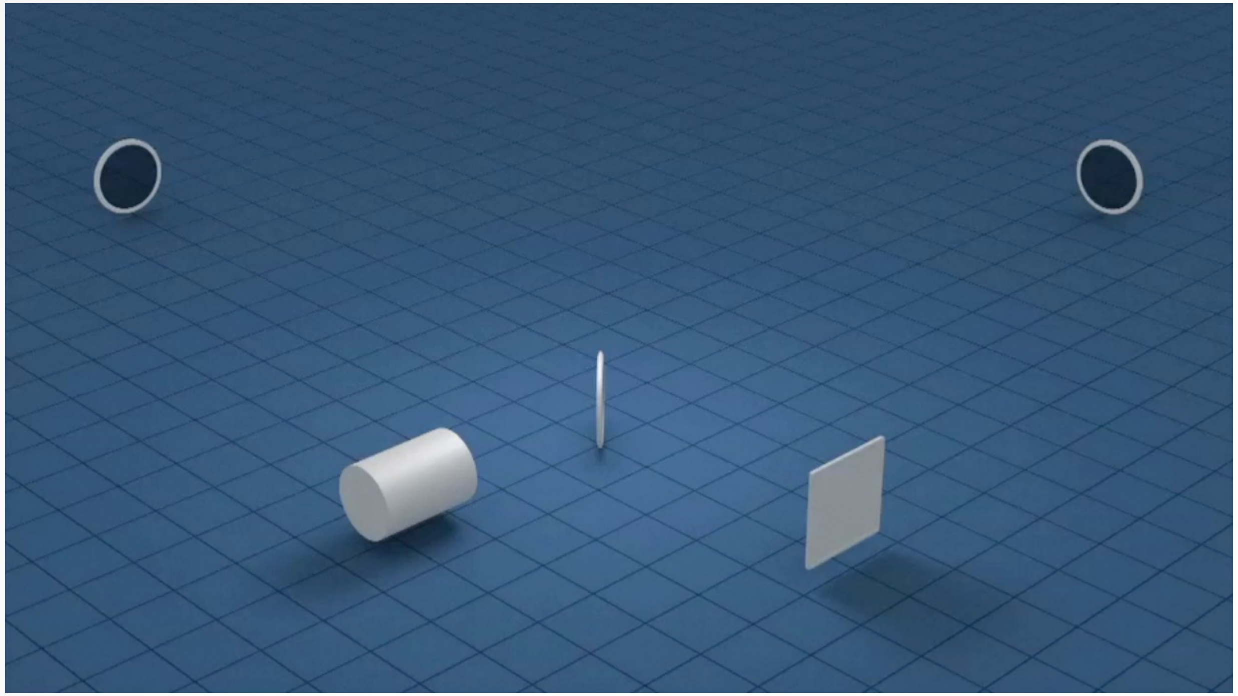


The Gravitational Wave Spectrum

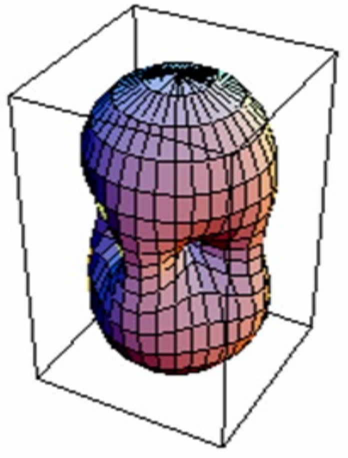


[Inspired from http://science.gsfc.nasa.gov/663/research/]

Interferometer and GW



Sensitivity : almost full sky



Averaged beam antenna

$$\Delta\phi = \Delta\phi_{OP} + \delta\phi_{GW}(t) = \frac{2\pi\,\Delta L}{\lambda} + \frac{4\pi\,L\,h(t)}{\lambda}$$

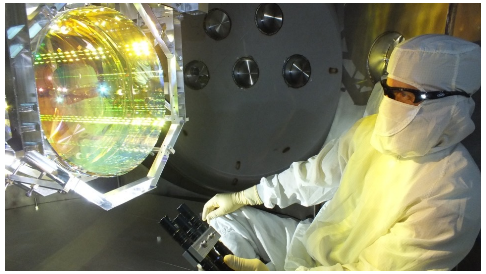
$$P_{det} \approx \frac{P_{in}}{2}\left[\,1 + \cos(\Delta\varphi_{OP}) - \sin(\Delta\varphi_{OP})\times\delta\varphi_{GW}(t)\,\right]$$

Detected signal proportional to h(t)

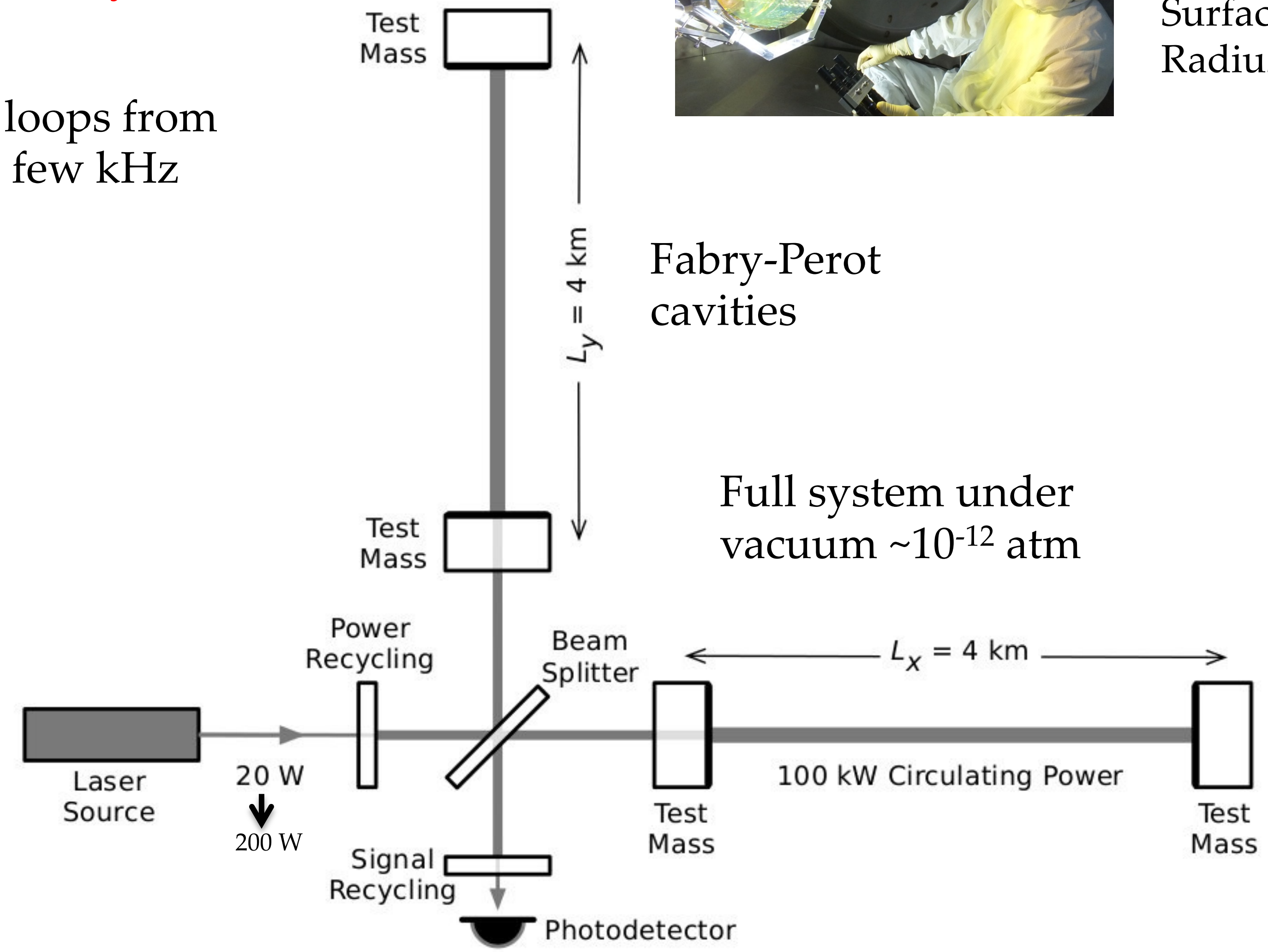
Advanced generation detectors

Michelson interferometer
Goal : $(L_x-L_y)/L_x = 10^{-23}$

Feedback loops from few Hz to few kHz



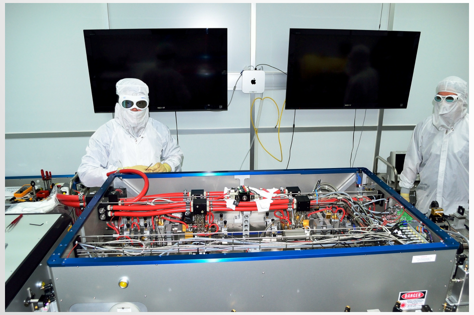
High quality optics – 40 kg
Surface RMS ~nm
Radius of curvature : 2m on 1.5 km



Fabry-Perot cavities

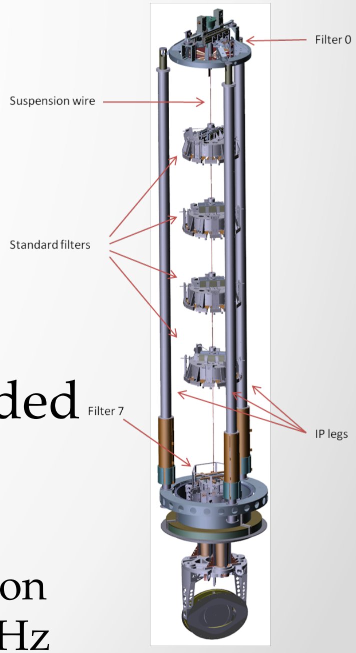
Full system under vacuum ~10^{-12} atm

High power laser

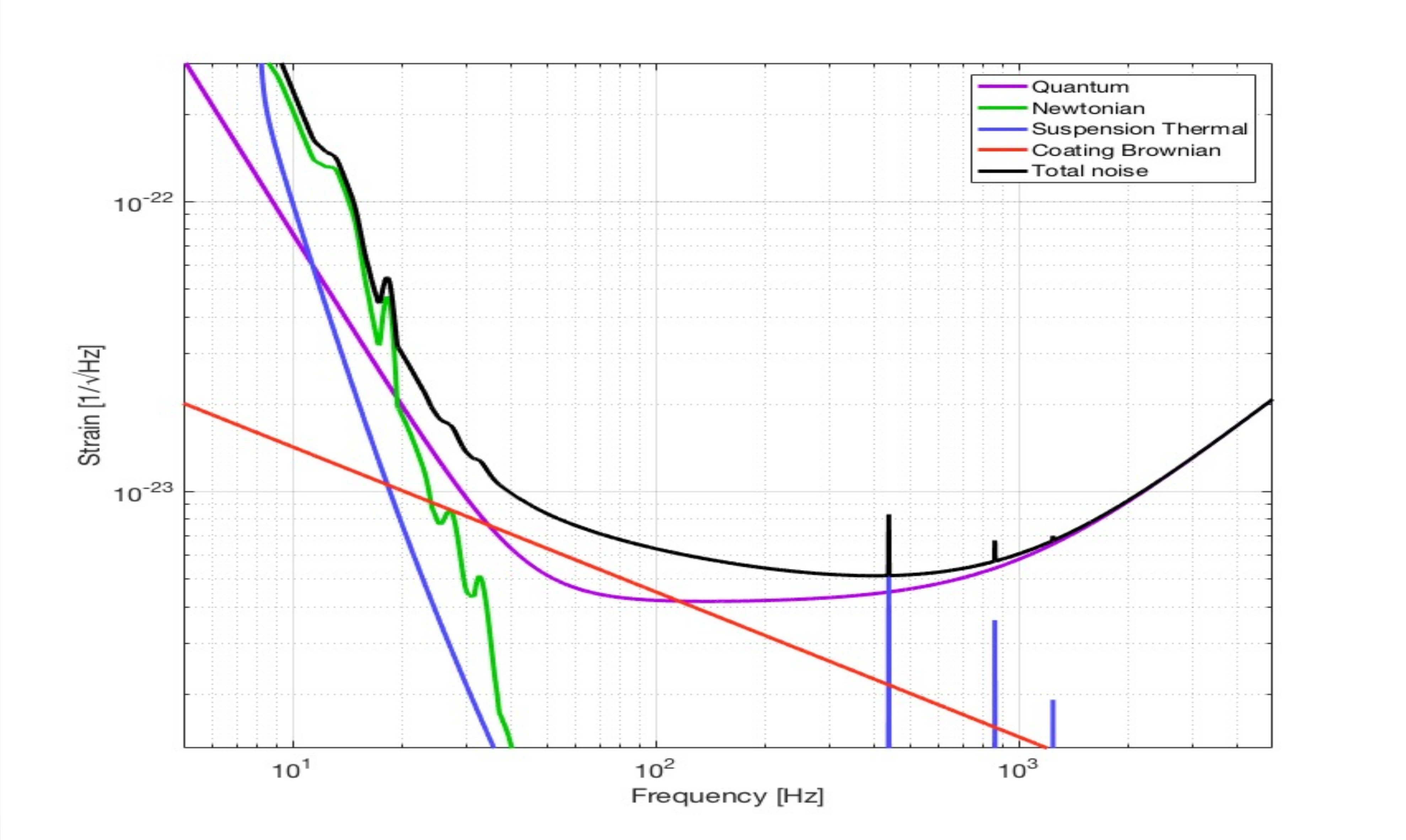


Suspended Optics

Attenuation 10^{14} @ 10 Hz

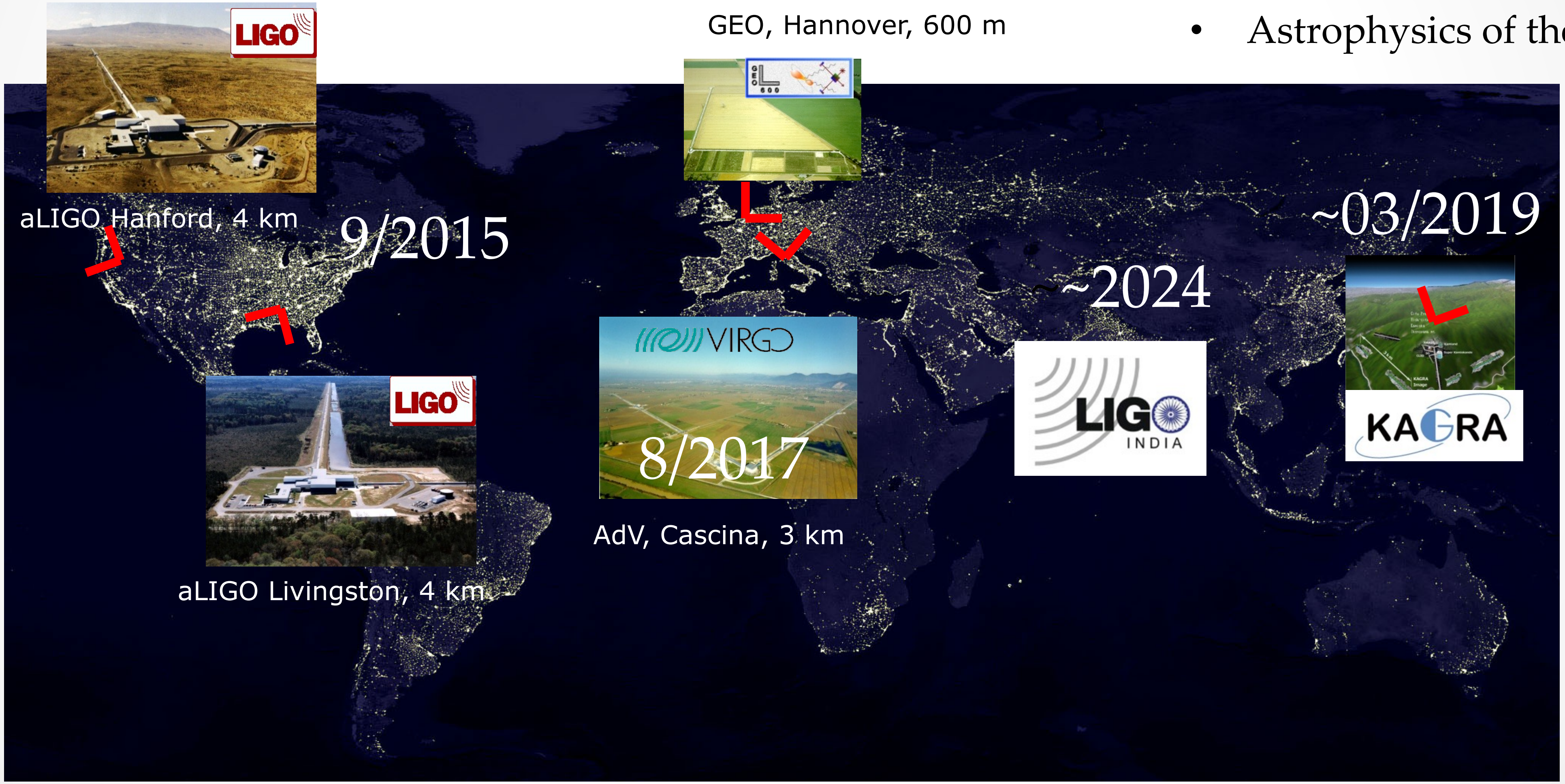


Sensitivity

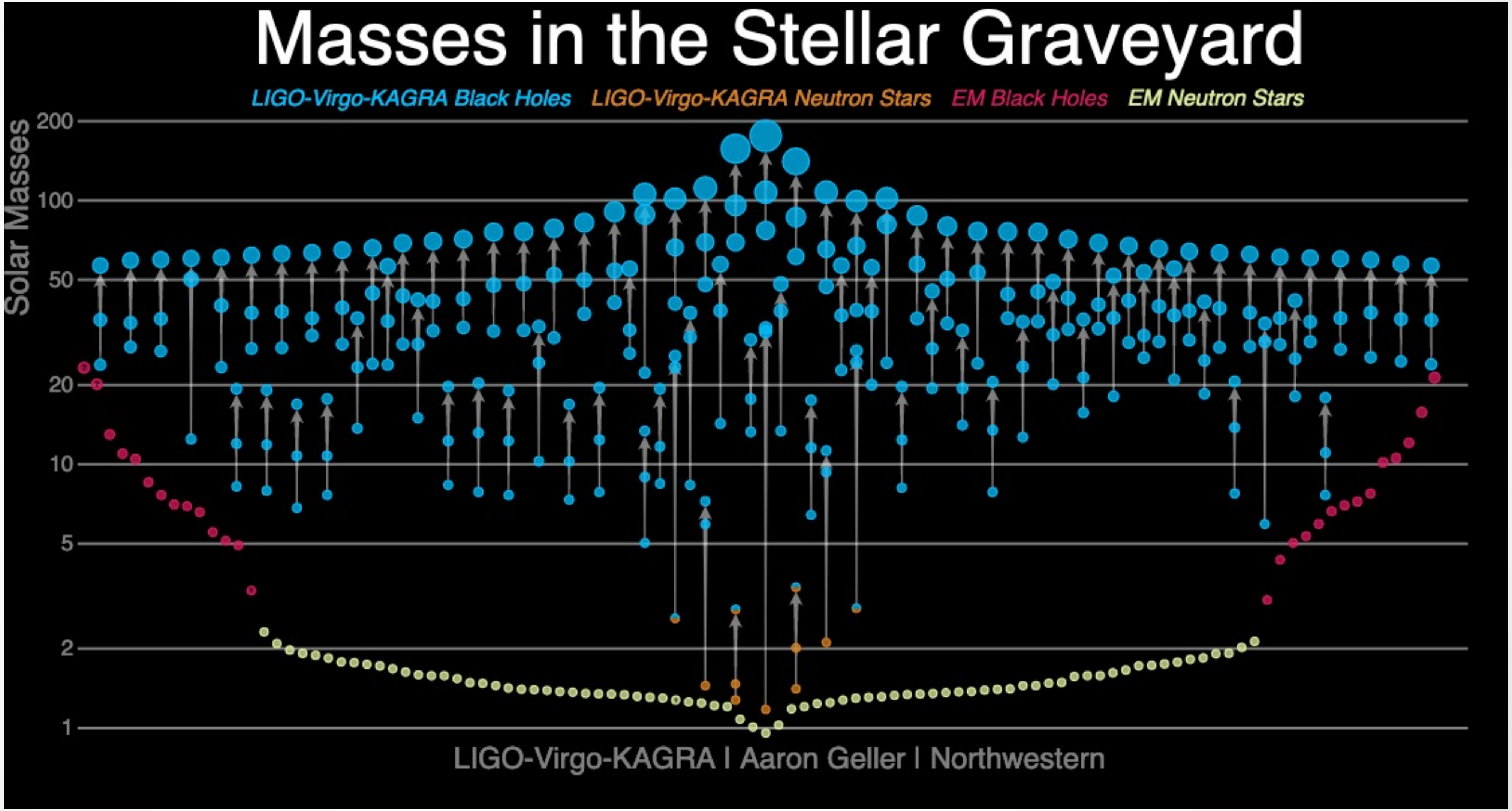


GW network

- Increase the detection confidence
- Source sky localization
- Source parameters inference
- GW polarization determination
- Astrophysics of the sources

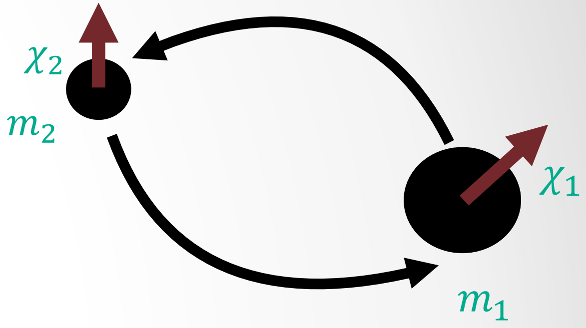


GW detections



Coalescing binaries

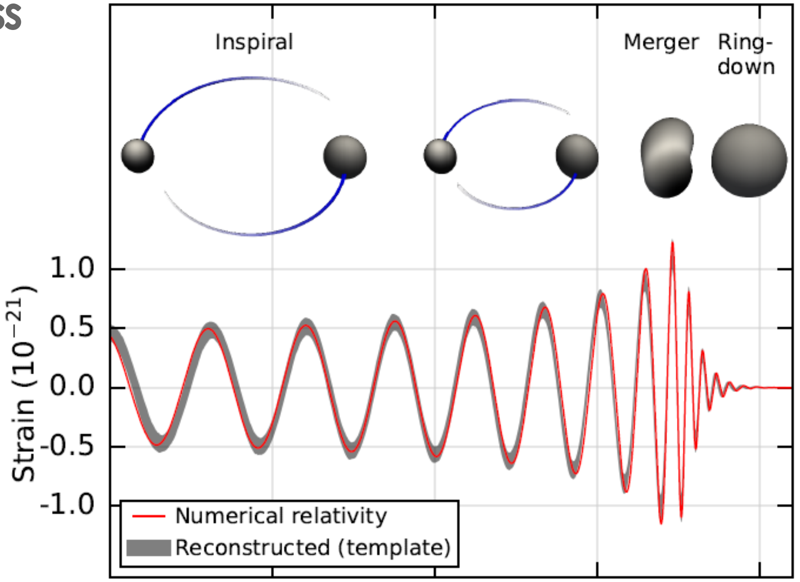
- Searching for objects containing black holes (BH) and neutron stars (NS)
- Possible electromagnetic emission if one object is a NS
- Known waveforms from analytical model or numerical relativity simulations
- Waveform allow to retrieve :
  - Masses : ratio (chirp mass) and total mass
  - Spins : initials and final object(s)
  - Geometry of the system
  - Distance
  - Total energy dissipated
- Can be used to test GR



$$\mathcal{M} = (m_1 m_2)^{3/5} / (m_1 + m_2)^{1/5}$$

$$\chi_{\rm eff} = \frac{(m_1 \boldsymbol{\chi_1} + m_2 \boldsymbol{\chi_2}) \cdot \hat{\boldsymbol{L}}}{m_1 + m_2},$$

$$q = m_2 / m_1$$



GWTC-3 :

Better sensitivity and a high duty cycle :
142 days with at least one detector observing

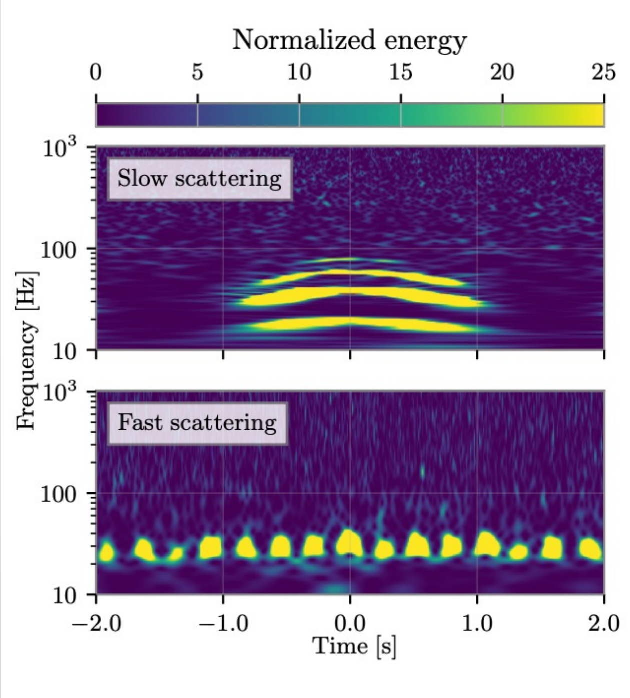


Fig4 : *Spectrograms of glitches caused by scattered-light*

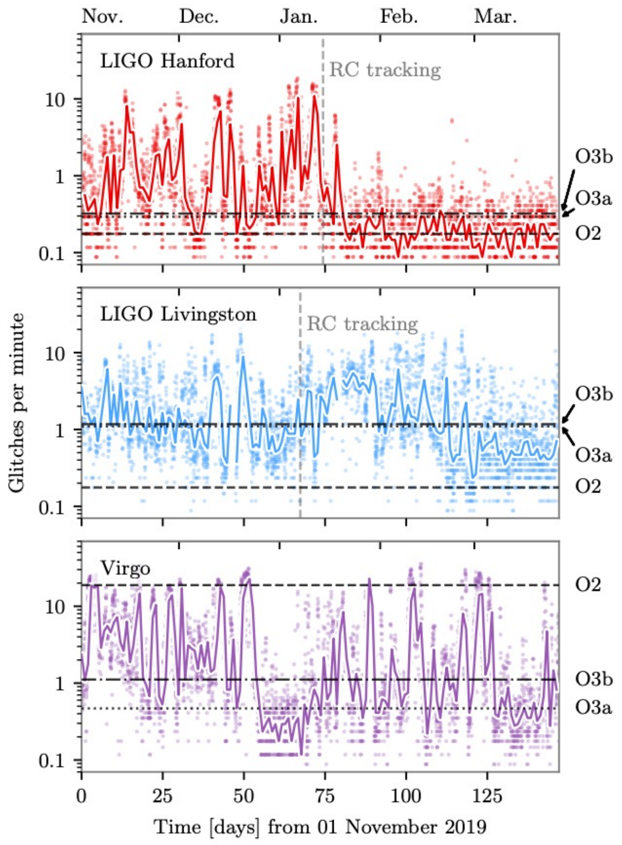
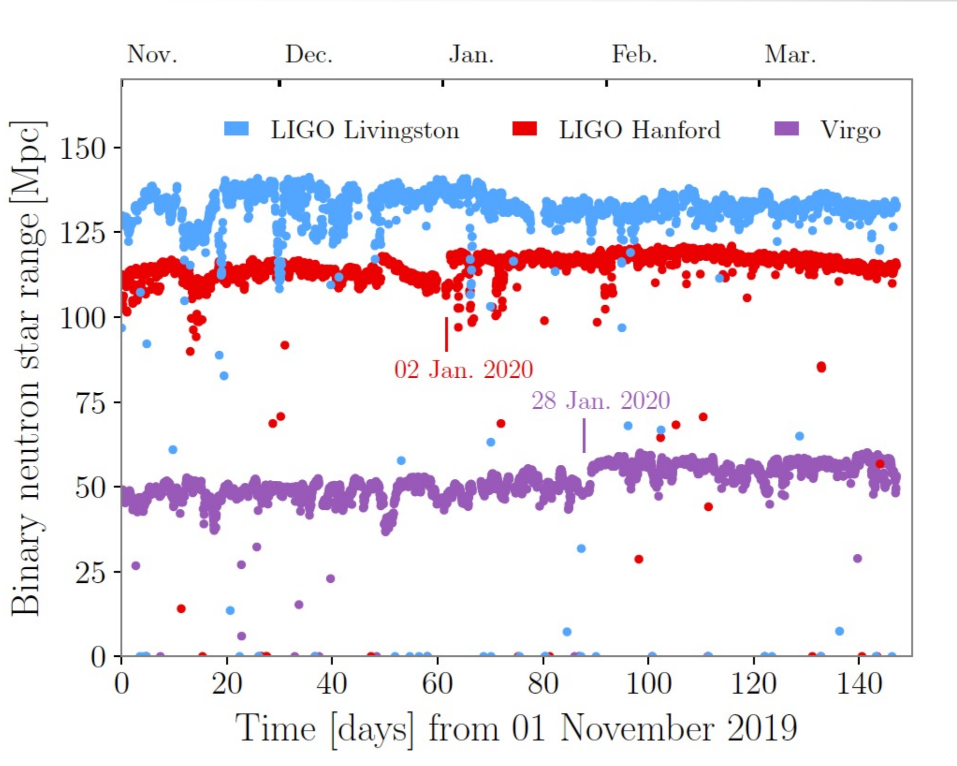


Fig5 : *Rate of single-interferometer glitches*



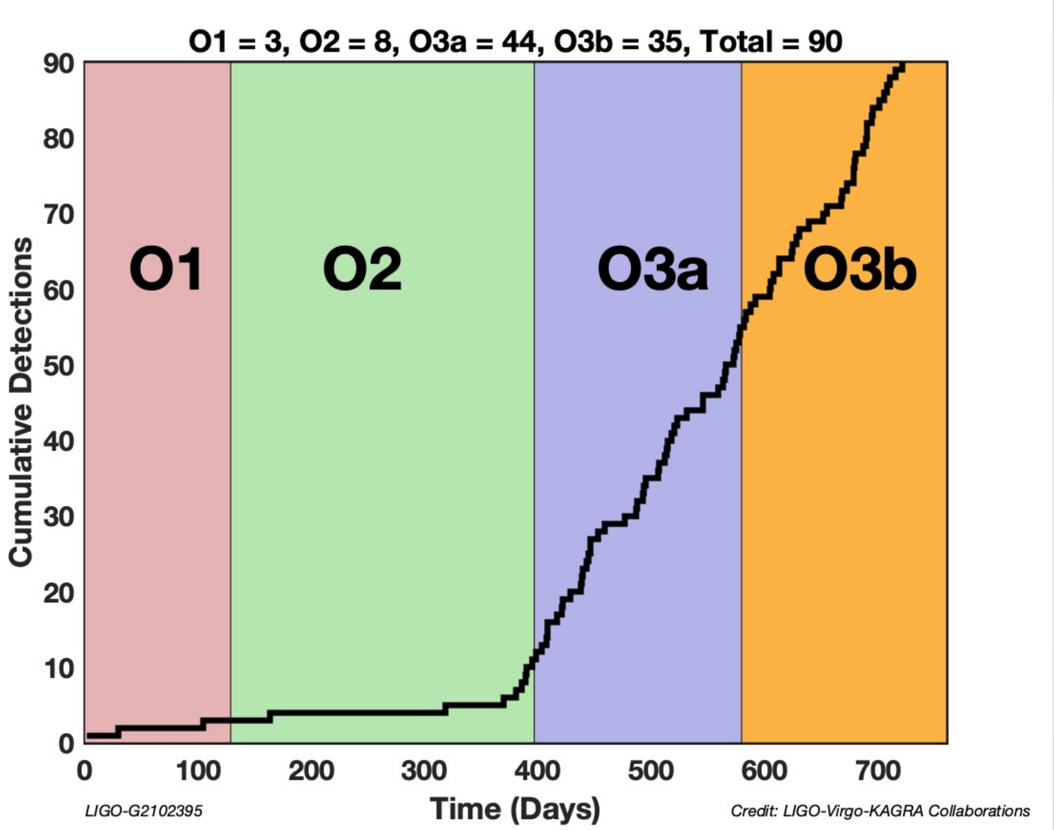
Measure of detector sensitivity: The binary neutron star range represents the distance a detector is able to detect a signal from a 1.4-1.4 solar mass binary

https://arxiv.org/pdf/2111.03606.pdf

GWTC-3 : candidates

Procedure :

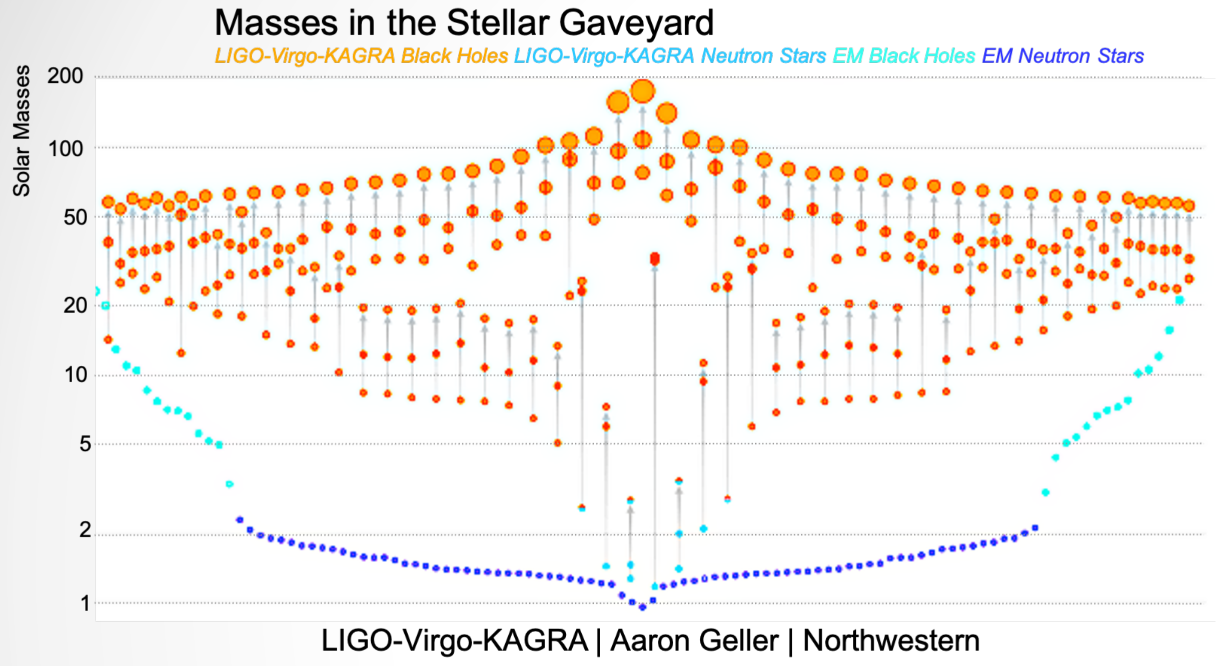
- Search method : Modeled searches (PyCBC GstLal, MBTA ...) & Minimally modeled search (cWB)
- Candidates events identification
- Validation by checking for evidence that they were caused by one or more detector noise artifacts following the same procedure as for previous catalogs
- Parameter estimation
- Main list (35 events): candidates with a probability of astrophysical origin (p-astro) > 0.5
- Marginal list** (7 events): p-astro < 0.5 but FAR < 2 per year

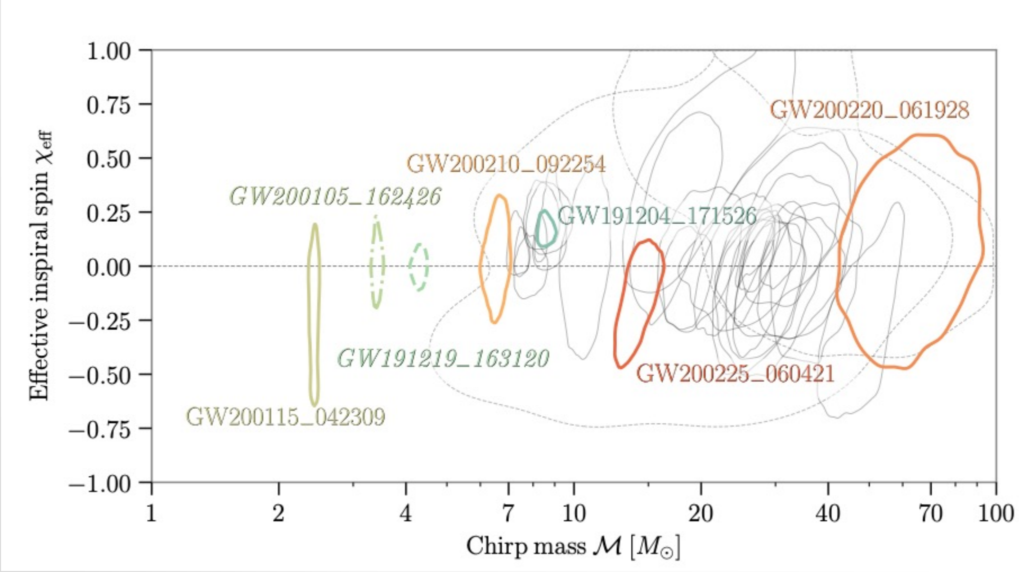


Likely instrumental artifacts :

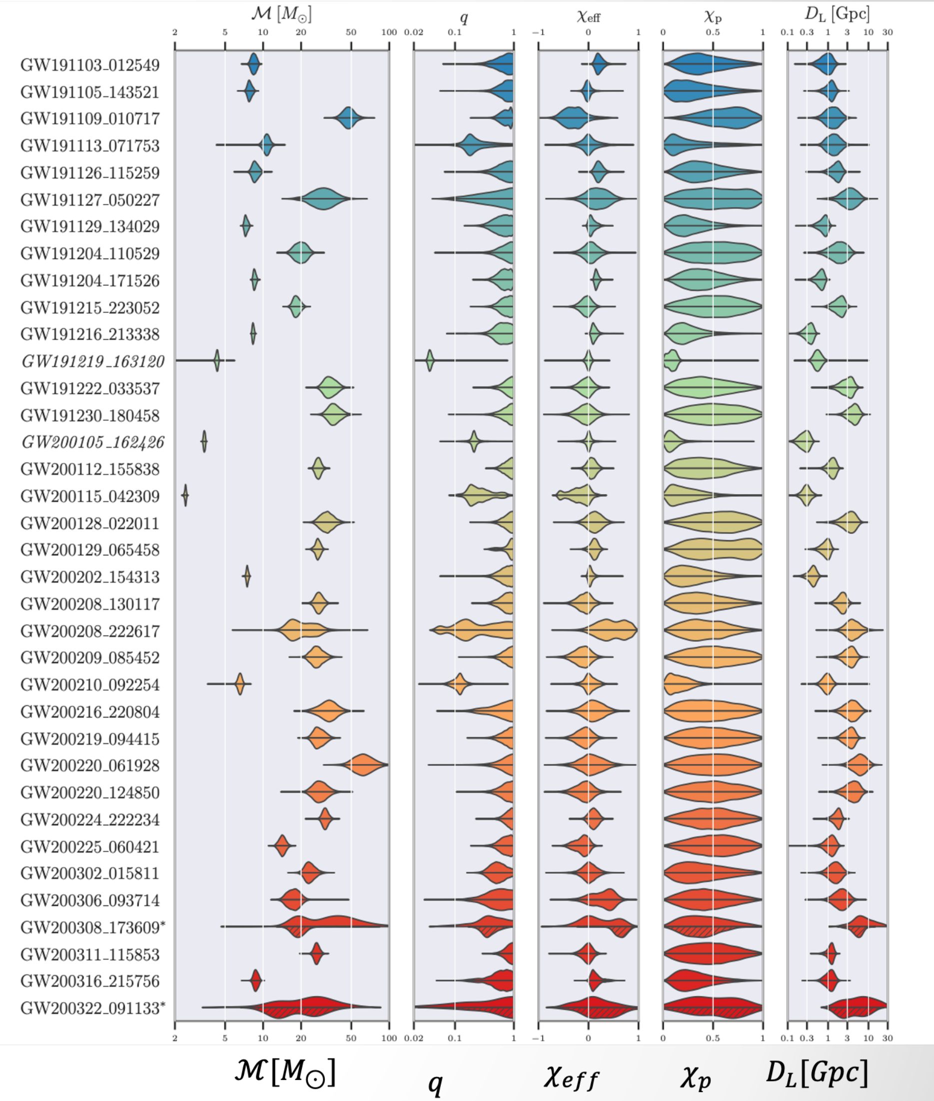
- Main list : 0
- Marginal candidates list : 3

GWTC-3 : properties





Credible-region contours in the plane of chirp mass M and effective inspiral spin χeff for O3b candidates with p-astro > 0.5 plus GW200105-162426



Marginal posterior distributions for the source properties for O3b

https://arxiv.org/pdf/2111.03606.pdf

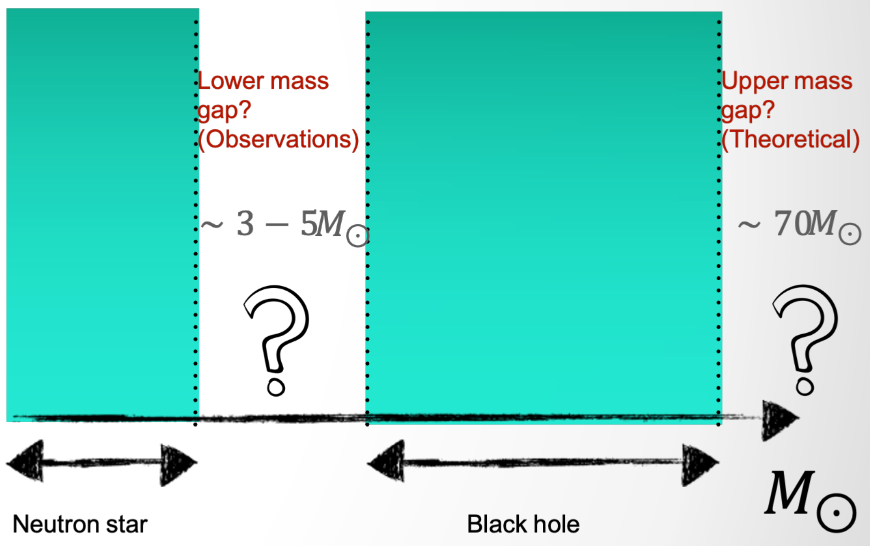
Astrophysical population

Population properties of 76 compact binary mergers detected with gravitational waves below a false alarm rate of 1 per year through GWTC-3

- Masses, spins, distances of these events inferred from the GW signal
- Several mass models, 3 spins models, one distance model

Fundamental questions :

- Which types of mergers are we seeing? In terms of formation channels?
- How many are happening in the Universe ?
- What is the mass distribution of BH and NS ?



Astrophysical population - Rate

How many are happening in the Universe ?

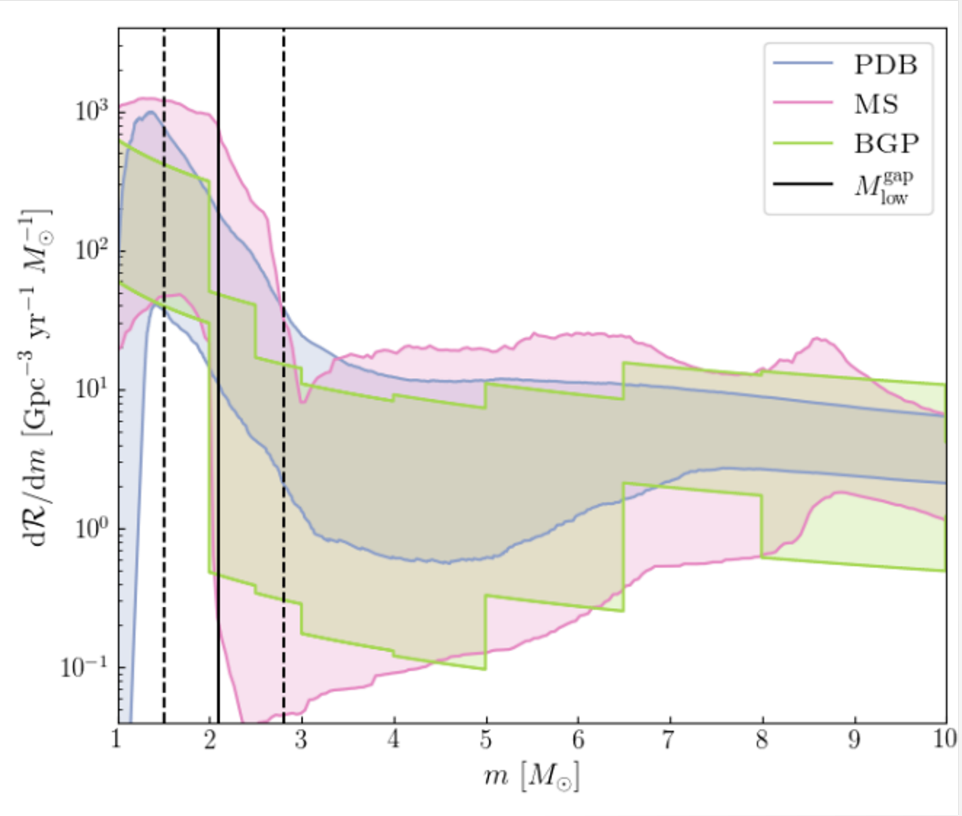
Multiple models but consistent with the same results :

$$\mathcal{R}_{\text{total}} = 470^{+830}_{-300}\ \text{Gpc}^{-3}\text{yr}^{-1}$$

$$\mathcal{R}_{\text{BNS}} = 250^{+640}_{-200}\ \text{Gpc}^{-3}\text{yr}^{-1}$$

$$\mathcal{R}_{\text{NSBH}} = 170^{+150}_{-89}\ \text{Gpc}^{-3}\text{yr}^{-1}$$

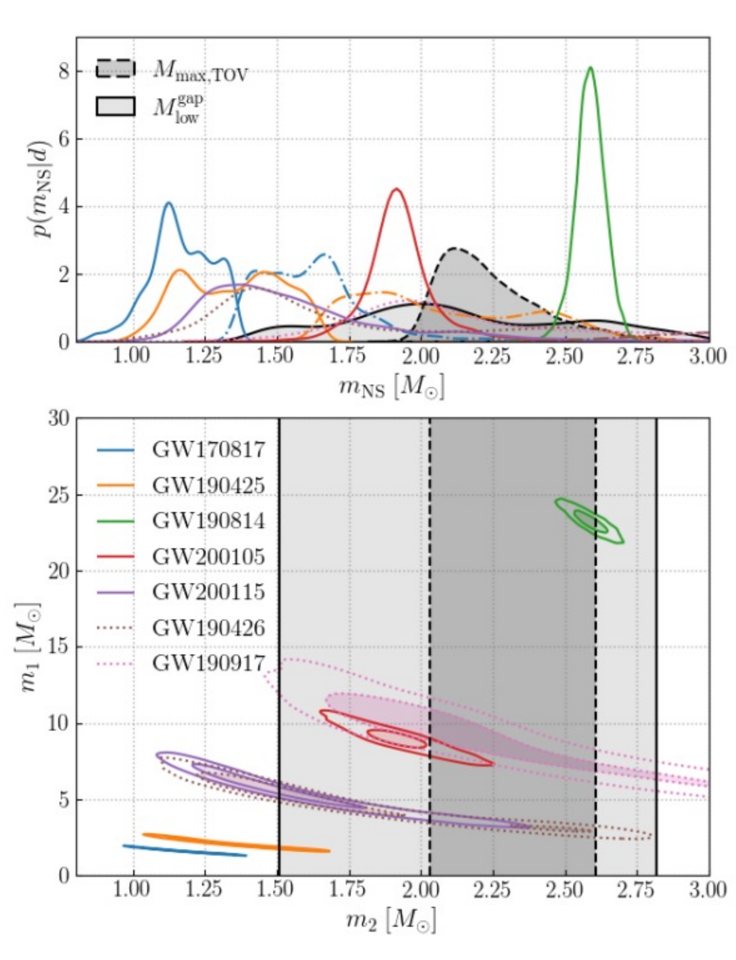
$$\mathcal{R}_{\text{BBH}} = 22^{+9}_{-6}\ \text{Gpc}^{-3}\text{yr}^{-1}$$



Different models

Differential merger rate as a function of component mass for the PDB, MS, and BGP model (from https://arxiv.org/pdf/2111.03634.pdf)

Astrophysical population – NS properties

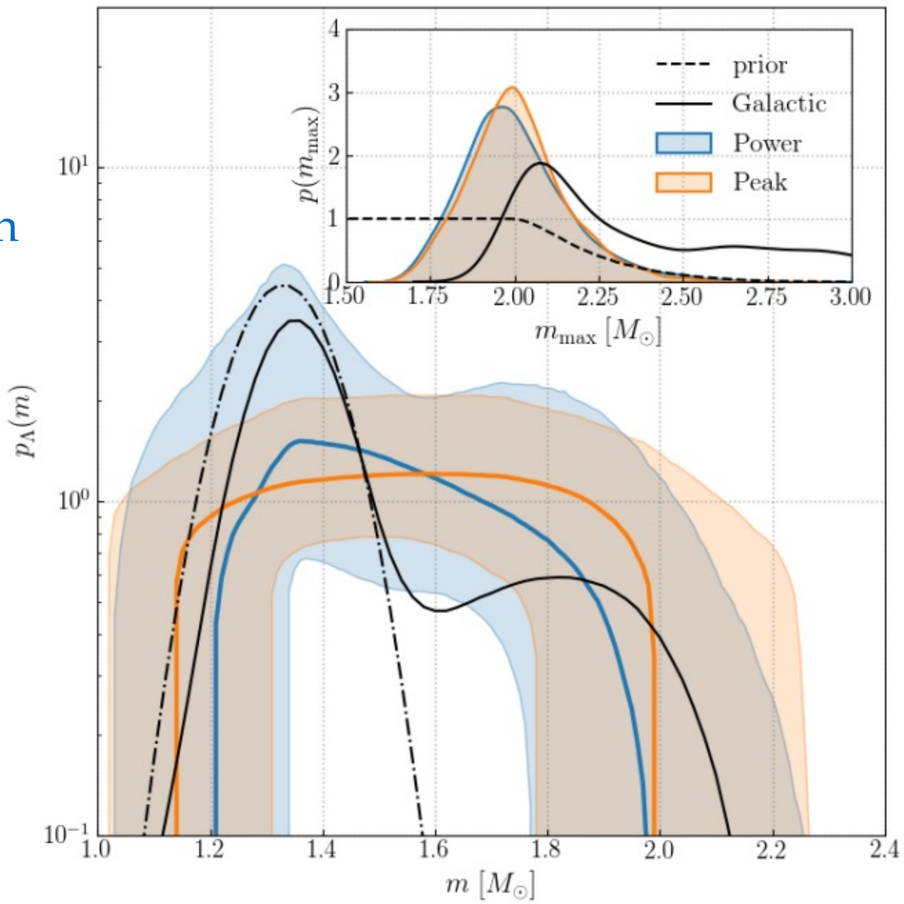


Masses for events with at least one candidate neutron

Maximum mass observed in the NS population : $m_{max} = 2.0^{+0.3}_{-0.2} M_\odot$

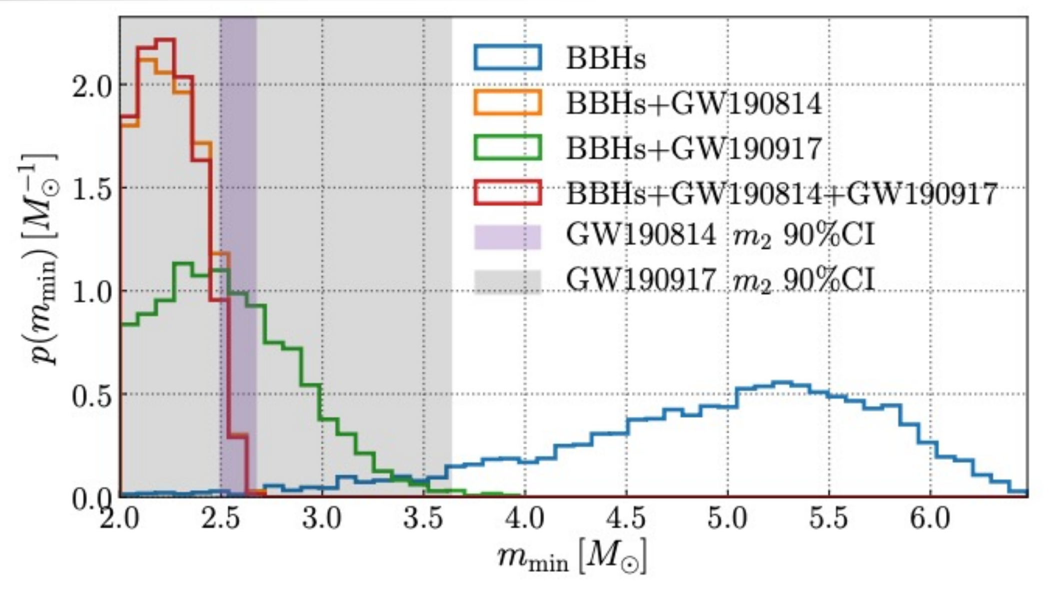
Consistent with the mass found with the equation of state & Galactic pulsars

Minimum NS mass in the gravitational wave population inferred to be $m_{min} = 1.2^{+0.1}_{-0.2} M_\odot$ in both the Power and Peak models.



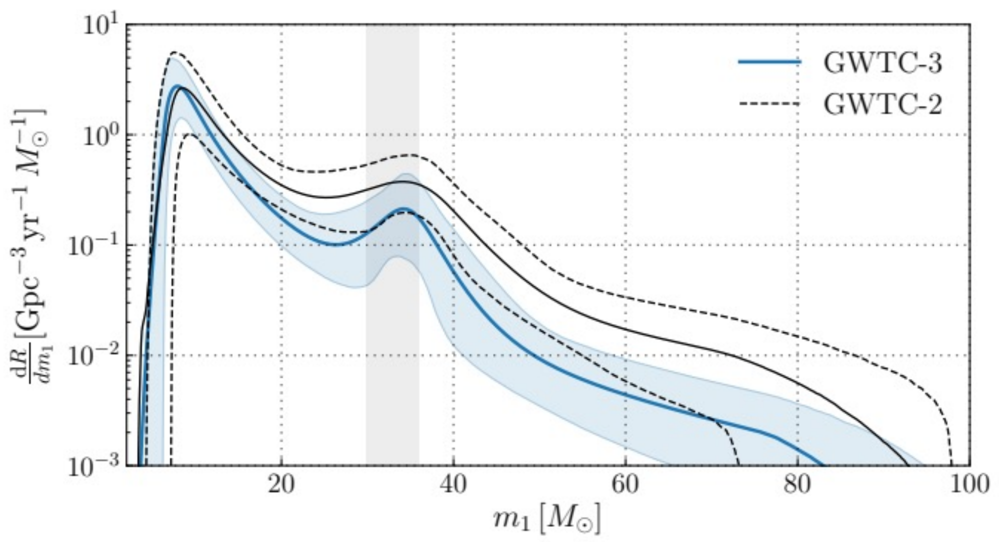
https://arxiv.org/pdf/2111.03634.pdf

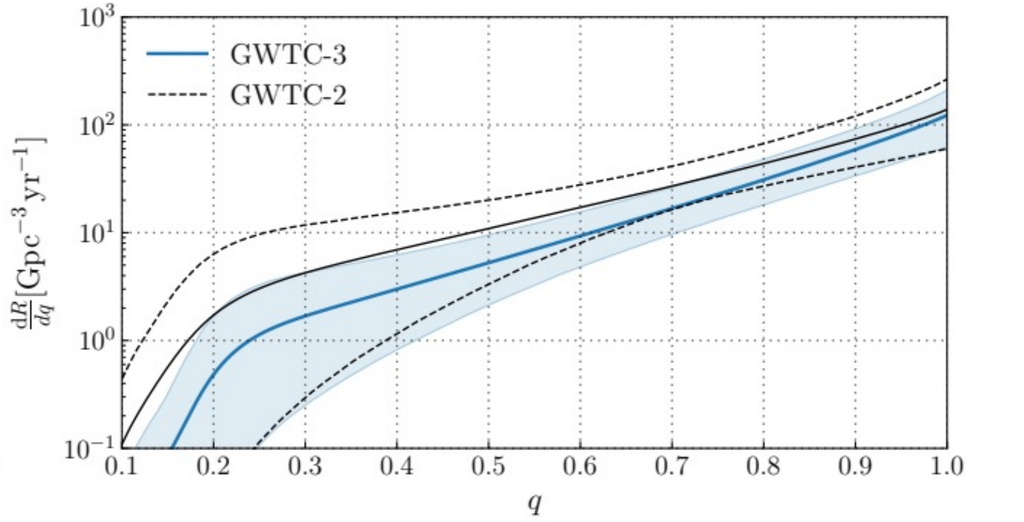
Astrophysical population – BBH mass



Posterior distribution on the minimum mass truncation parameter m_{min}

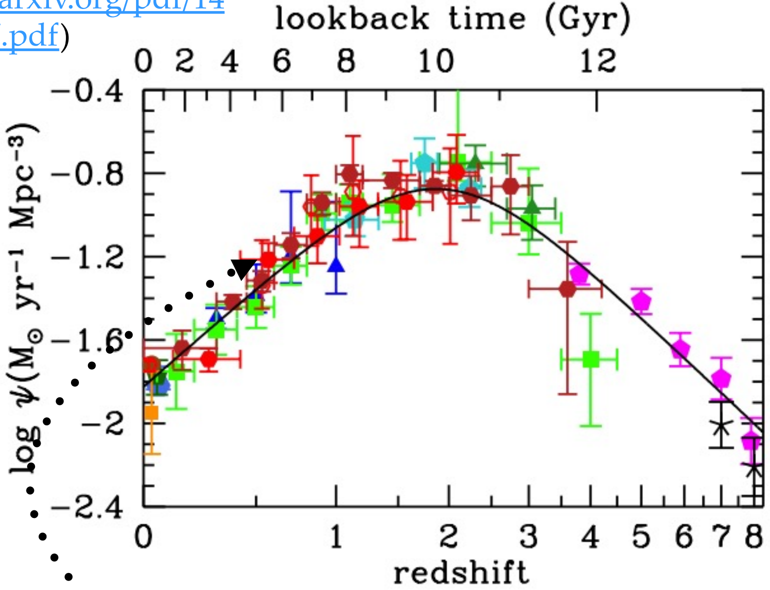
Results consistent between GWTC-2 & GWTC-3

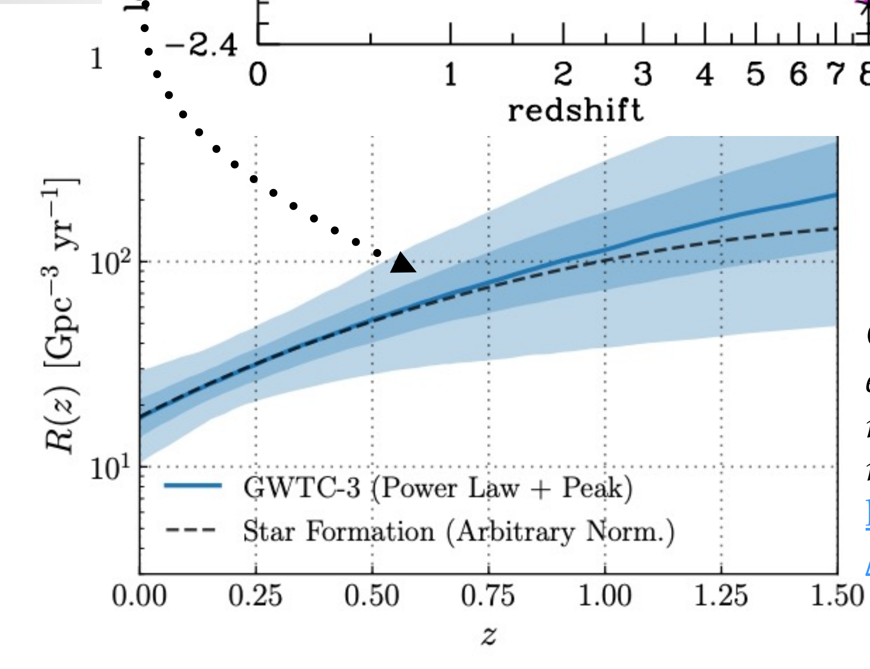




Astrophysical population – BBH vs redshift

The history of cosmic star formation (from https://arxiv.org/pdf/1403.0007.pdf)





Constraints on the evolution of the BBH merger rate with redshift (from https://arxiv.org/pdf/2111.03634.pdf)

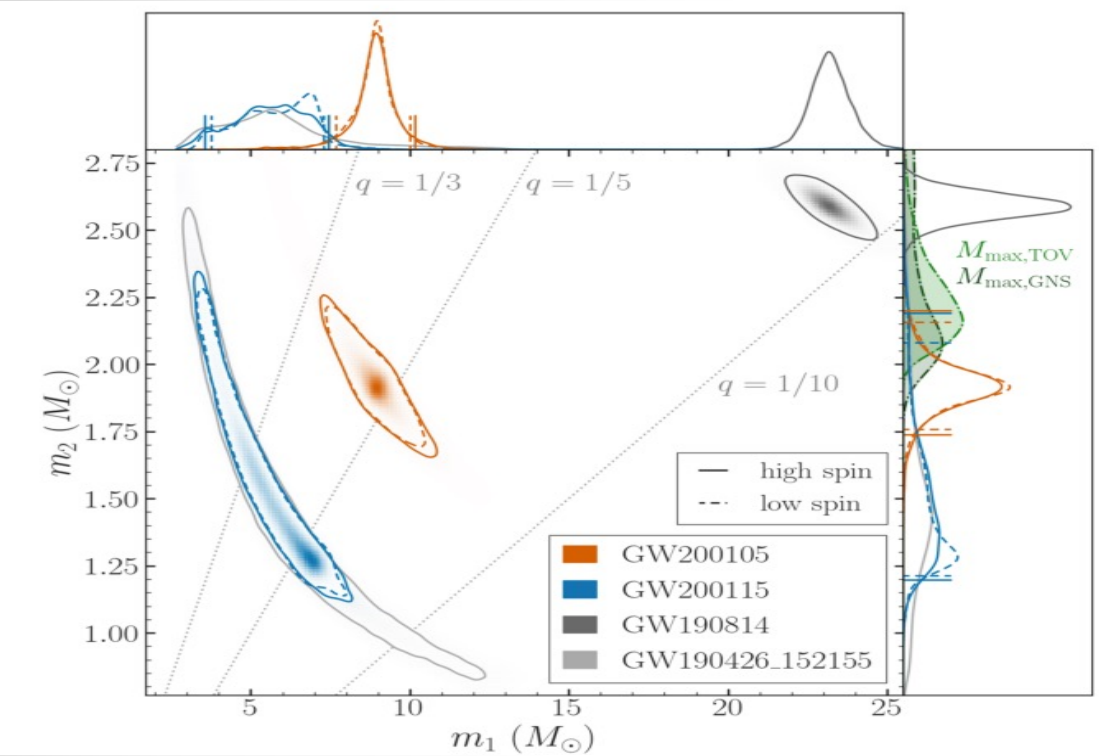
- Merger rate density increases with redshift
  ~$(1+z)^{2.7}$ for z<1

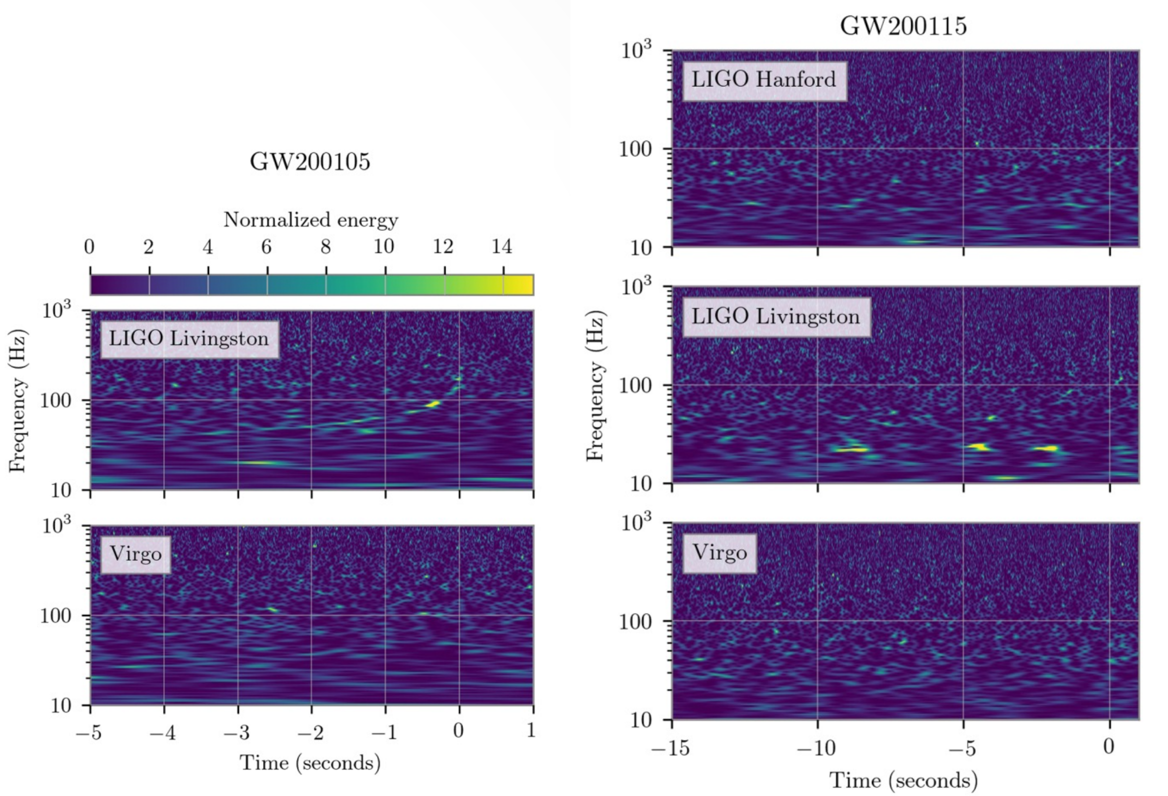
- In most plausible formation scenarios : we do not expect R(z) to continue growing with arbitrarily high z.

  Instead, we anticipate that R(z) will reach a maximum beyond which it turns over and falls to zero.
  —> not observed yet, maybe with Einstein Telescope ?

- Study formation scenarios

The missing piece – NSBH coalescence





	m1	m2
GW200105	$8.9^{+1.2}_{-1.5} M_\odot$	$1.9^{+0.3}_{-0.2} M_\odot$
GW200115	$5.7^{+1.8}_{-2.1} M_\odot$	$1.5^{+0.7}_{-0.3} M_\odot$

m2: Consistent with maximum NS mass

m1 : BH identified

GW200115 m1: 30% probability of falling in the mass gap

Note :

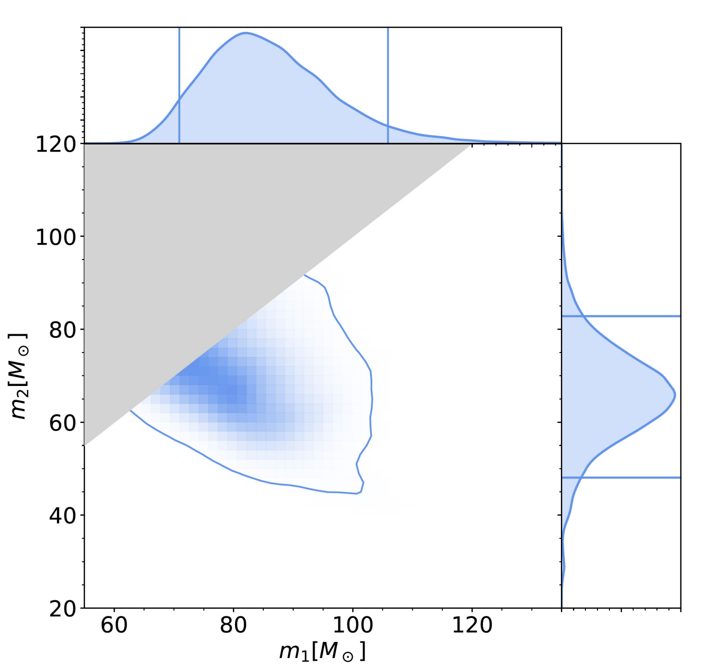
- Spectrograms do not always show the track of the signal
- To detect a CBC we use matched-filtering methods but the SNR is not always enough to estimate the significance of a trigger so we also compute the χ^2

https://iopscience.iop.org/article/10.3847/2041-8213/ac082e/pdf

Intermediate mass BBH

GW190521 :
→ Heaviest progenitor: 85 Msun + 66 Msun → 142 Msun

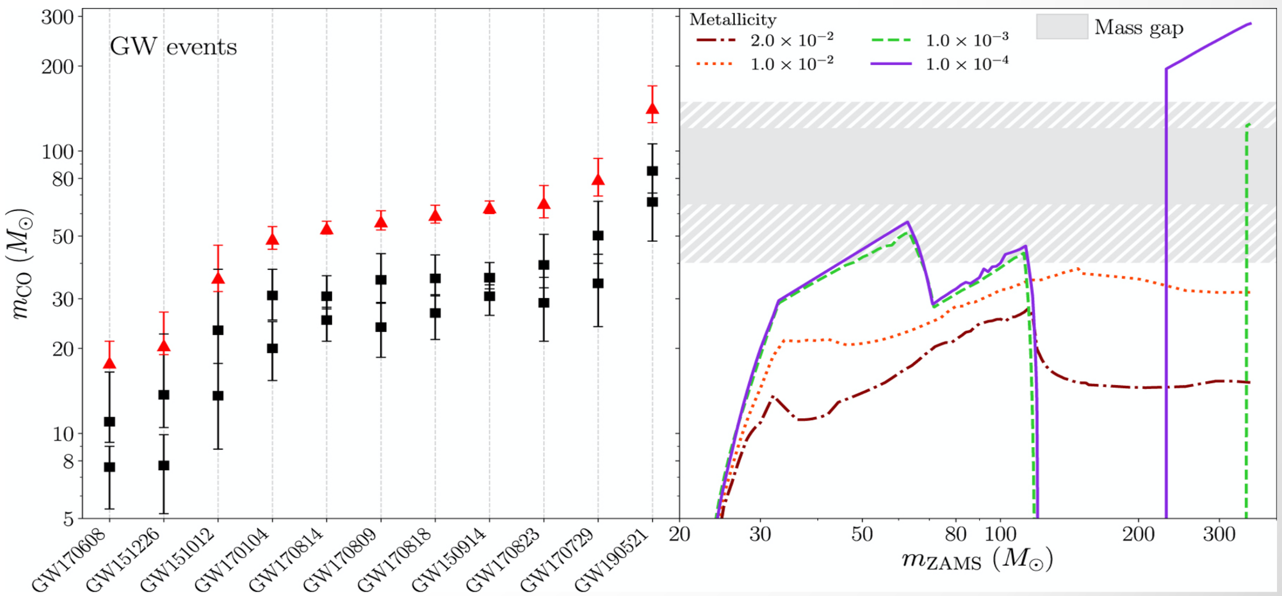
→ Cosmological distance: 5.3 Gpc



Mass gap predicted by pair-instability (PI) supernova theory : 65 – 120 Msun

→ Low likelihood for the primary black holes to originate from stellar collapse

Final black hole = intermediate mass (100 – 105 Msun)
→ First detection in this mass range

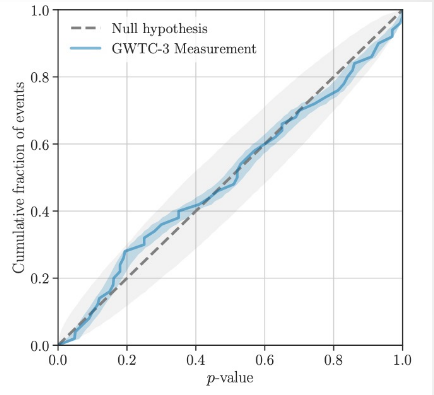
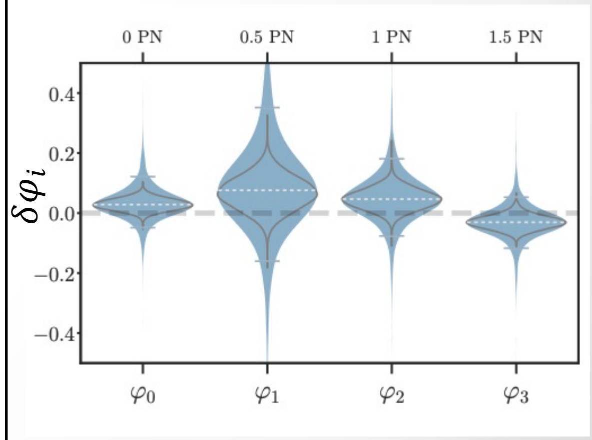


Testing GR

- The model waveform is constructed using the predictions of General Relativity.
- Gravitational-wave sources offer us unique testbeds for probing strongfield, dynamical and nonlinear aspects of gravity
- Tests predictions of General Relativity by introducing small modifications to our currently available waveform models and compare the data with these "distorted" waveforms
- Three theory-agnostic tests (parameterized tests, inspiral-merger-ringdown consistency tests, and gravitational-wave propagation tests)

Testing GR – examples

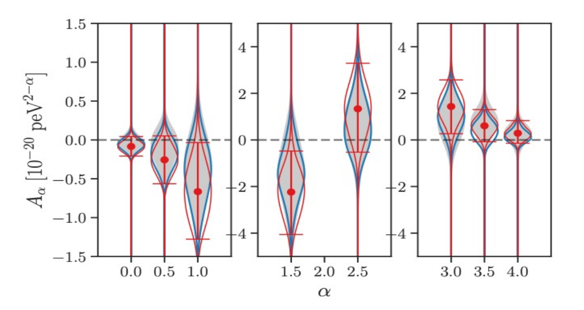
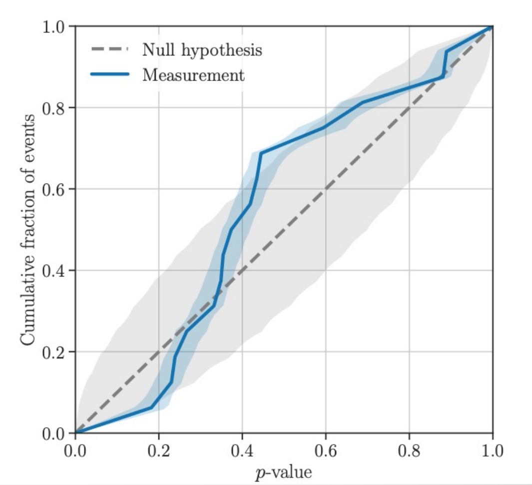
https://arxiv.org/pdf/2112.06861.pdf

Tests	Question to answer	Description	Results
Residual Test	Are the residual consistent with detector noise?	Subtracts the best-fit GR waveform from the data and asks whether there is any statistically significant residual power.	 **No evidence for violation of GR**
Parametrized test	Is the inspiral phase consistent with GR ?	Inspiral can be treated perturbatively within the post-Newtonian framework. PN coefficients : measurable parameters of the waveform —> sensible consistency test of GR	 **No evidence for violation of GR**

$$\varphi_{\rm PN}(f) = 2\pi f t_c - \varphi_c - \frac{\pi}{4} + \frac{3}{128\eta}(\pi\tilde{f})^{-5/3}\sum_{i=0}^{7}\left[\varphi_i + \varphi_{il}\log(\pi\tilde{f})\right](\pi\tilde{f})^{i/3}$$

Testing GR – examples

https://arxiv.org/pdf/2112.06861.pdf

Tests	Question to answer	Description	Results
Modified dispersion	Modified theory predict dispersion of GW	Affect the morphology of the signal —> effective dephasing of the GW signal can be measured. $$E^2 = p^2c^2 + A_\alpha p^\alpha c^\alpha$$ Different choices of α —> leads to a deviation in the GR phasing formula. Mass of the graviton : $m_g = \sqrt{A_0}/c^2$	 **Improved bounds on graviton mass with respect to GWTC-2** $m_g < 1.27{\times}10^{-23} eV/c^2$
Test for GW echoes	If the merger remnant is not a classical BH but an exotic compact object without an event horizon but a reflective surface	Search for post-merger echoes in a morphology independent way.	 **No evidence for echoes**

Testing GR - summary

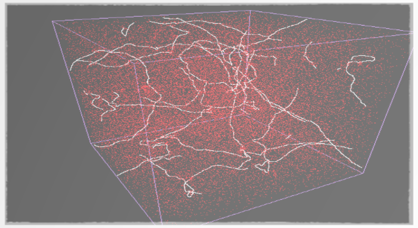
Many more tests of General Relativity have been done :

- Spin-induced quadrupole moment test
- GW polarizations test
- BH remnant test
- Ringdown test
- …

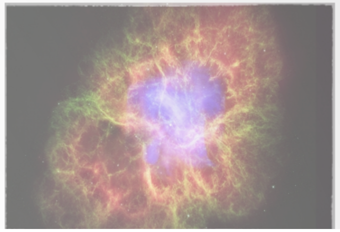
- Found no statistically significant evidences for any deviation from GR

- Update bounds on deformation parameters in the case of parametrized tests

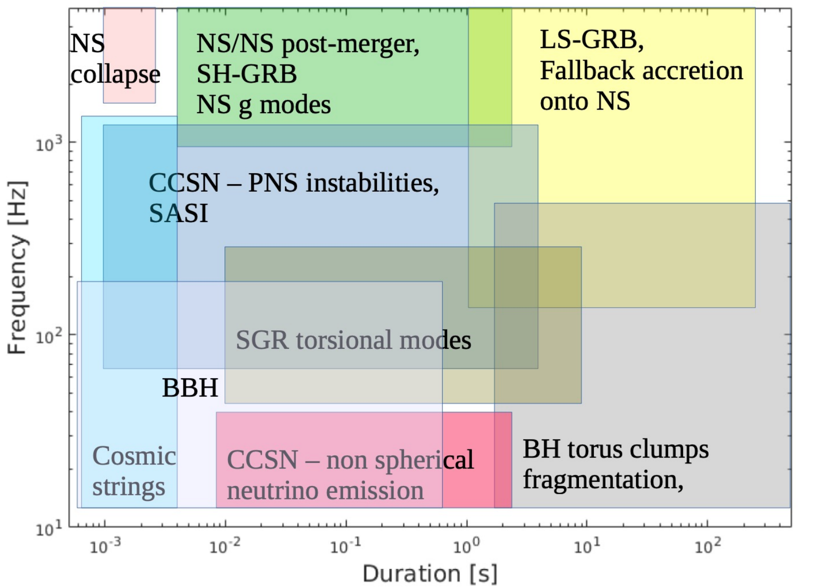
- Testing GR is very hard, even if a deformation is found:
  - Is it really GR that is deformed ?
  - A problem in the data qualify models ?
  - Waveform not enough precise ?



Short transients searches

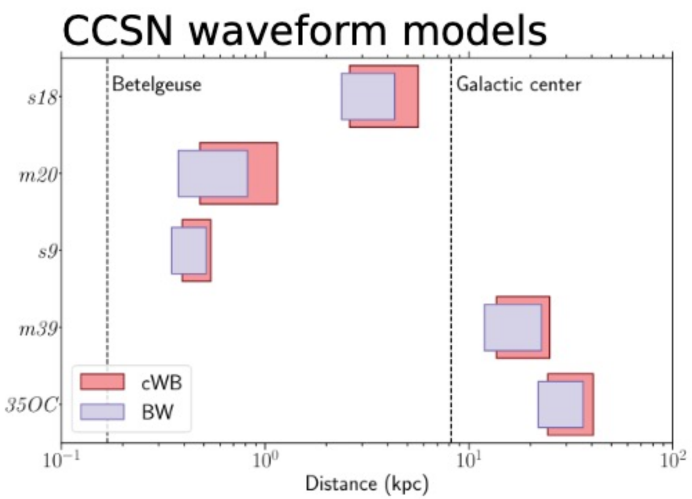


- There are several plausible sources of short-duration GW transients (GW bursts) that have not yet been observed, such as core-collapse supernovae, neutron star excitations, non-linear memory effects, or cosmic string cusps and kinks



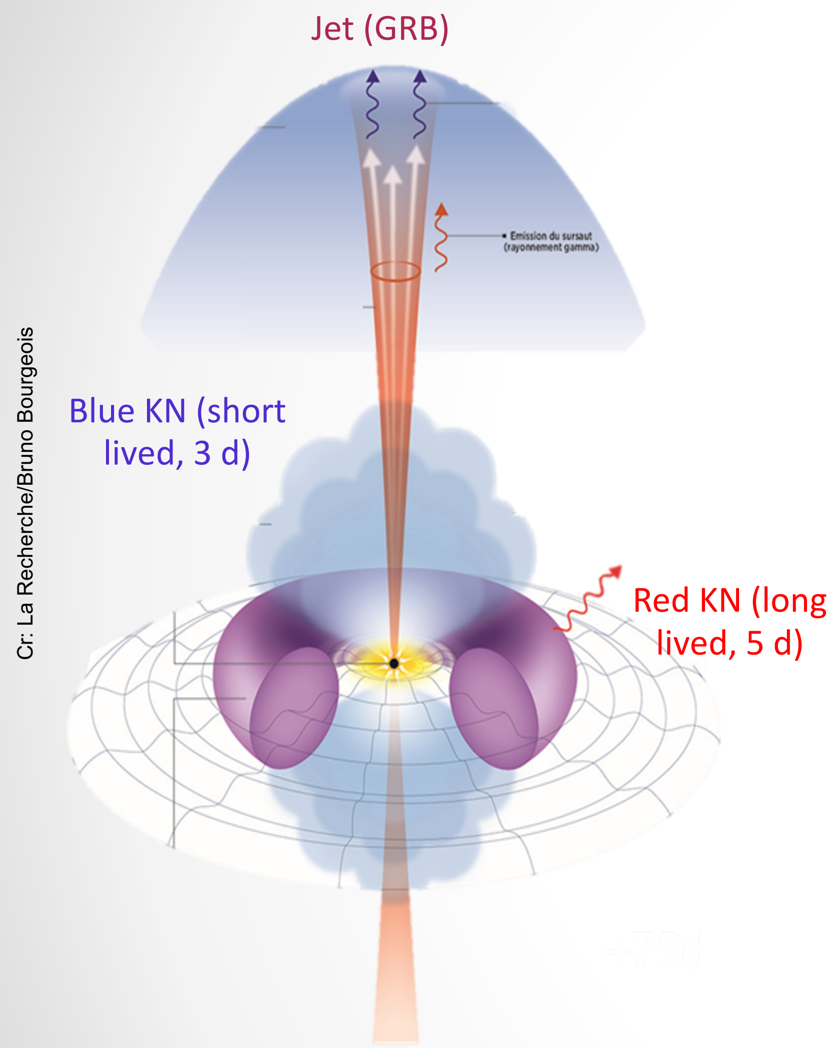
- All-sky search looks for signals arriving at any time from any sky direction : short-duration GW transients, up to a few seconds duration , and longer GW transients, up to $\sim 10^3$ s duration

- 2 independently developed search algorithms deployed: coherent WaveBurst (cWB) and BayesWave (BW).



Null result of this search :
 - Allows setting of rate density upper limits at an inverse false alarm rate threshold of 100 years
- Estimate sensitivity to certain classes of GW signals: CCSNe and isolated NS excitations.

Multimessenger



EM counterpart to GW **needs matter***

Binary neutrons stars are the most promising MMA source

GRB : Powered by on-axis jet

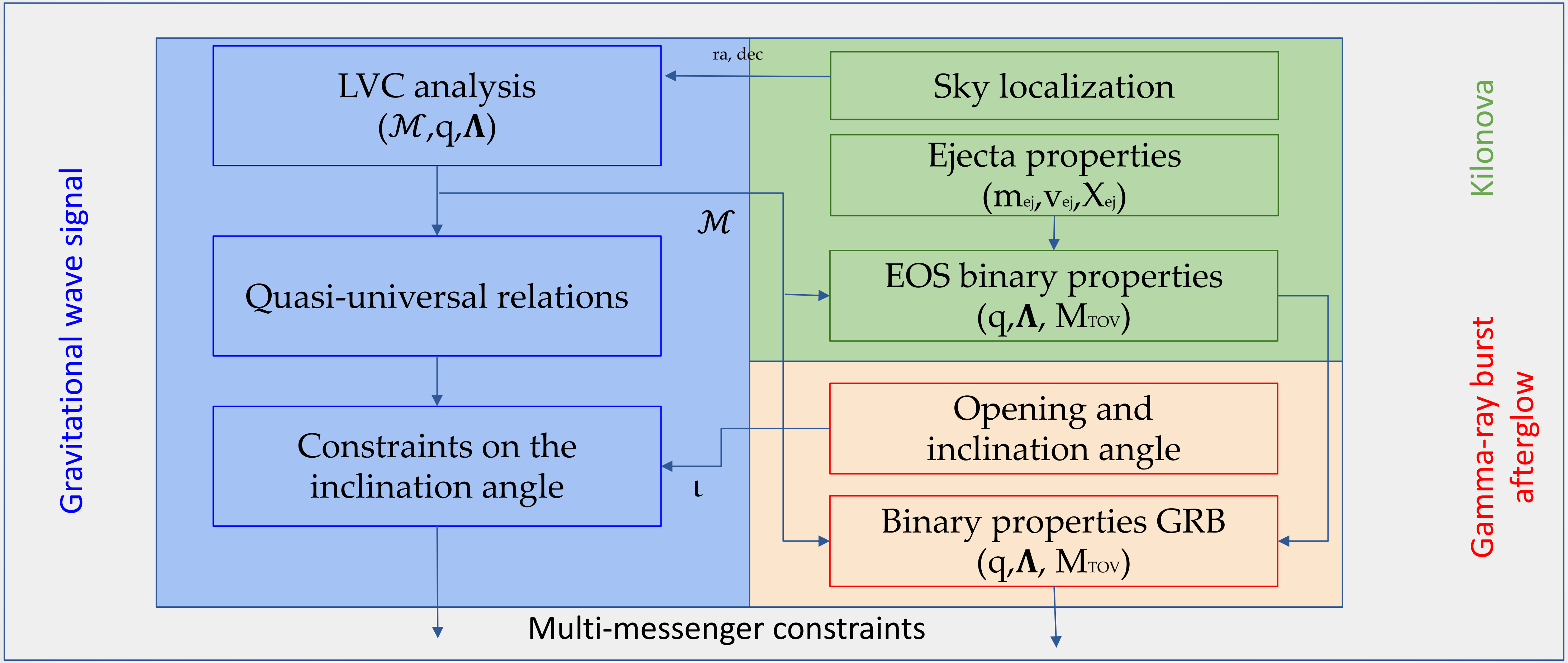
Kilonova (KN): **Optical** and **NIR** transient **powered by r-process** in **neutron rich** environment. Only **one** clear confirmed event (**AT2017gfo**)

- 40 Mpc
- Localized in NGC4993
- Identified by LVK in 39 deg2
- *~10 Galaxy compatible*
- Absolute 16 mag in K-band mag
- Fading at 0.5 mag per day

Topics possible with MMA

1. **Cosmology**
   - **Independent measure of H_0** (LVK et al. 2017, *Dietrich et al. 2020, Coughlin et al. 2020)*
2. **Nuclear Astrophysics**
   - **r-Process** : lanthanide and actinide synthesis (*Barnes et al., Dvorkin et al.)*
   - **Dense matter EOS of NS** : MM sample + numerical simulation (*Essick et al.)*
3. **High Energy Astrophysics**
   - **GRB population associated to GW** : GW observation favors on-axis jet
   - **Host galaxy information** : Which type of galaxy for short GRBs
4. **GW Sources**
   - **GW progenitor** : KN color evolution to discriminate NS-BH
   - **Post-merger object** : Discriminate between NS & BH remnant

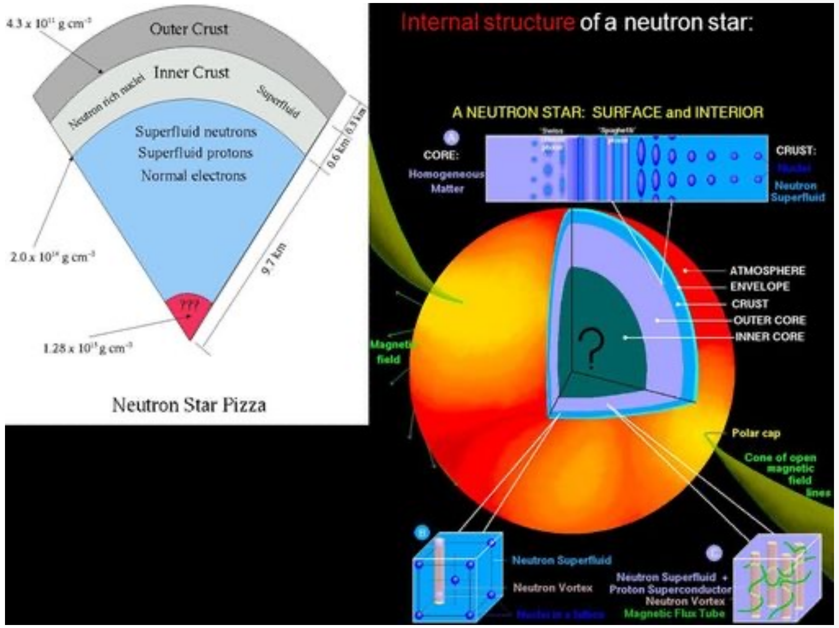
Multimessenger



Need to access both GW side and EM observatories on a large fraction of the electromagnetic band

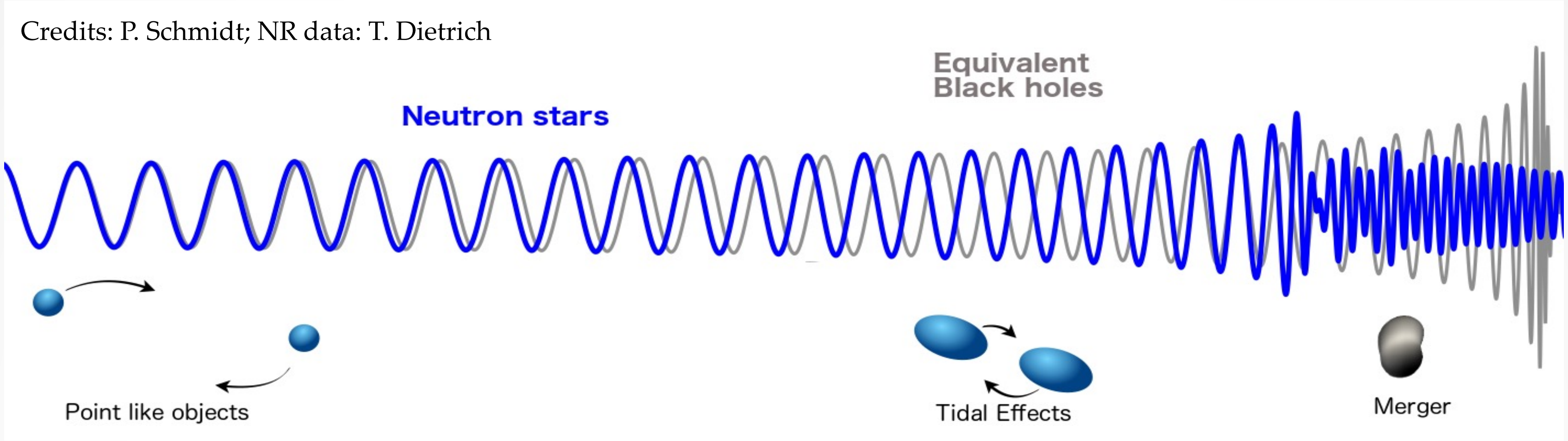
Equation of state of nuclear matter

- Among the most densest objects in the Universe
- Large uncertainties on their structure
  - Structure of the crust
  - Neutron superfluid in outer core
  - Deep core composition ?
  - Magnetic fields



- GW information complementary to the LHC
- Equation of state influence :
  - Pressure as function of density
  - Mass as function of radius
  - Tidal deformability
  - Impact on post merger

Constraints on EOS

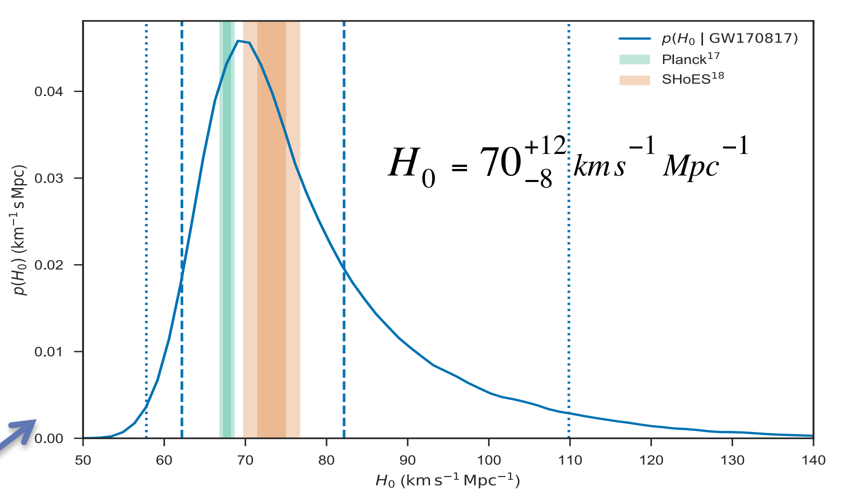


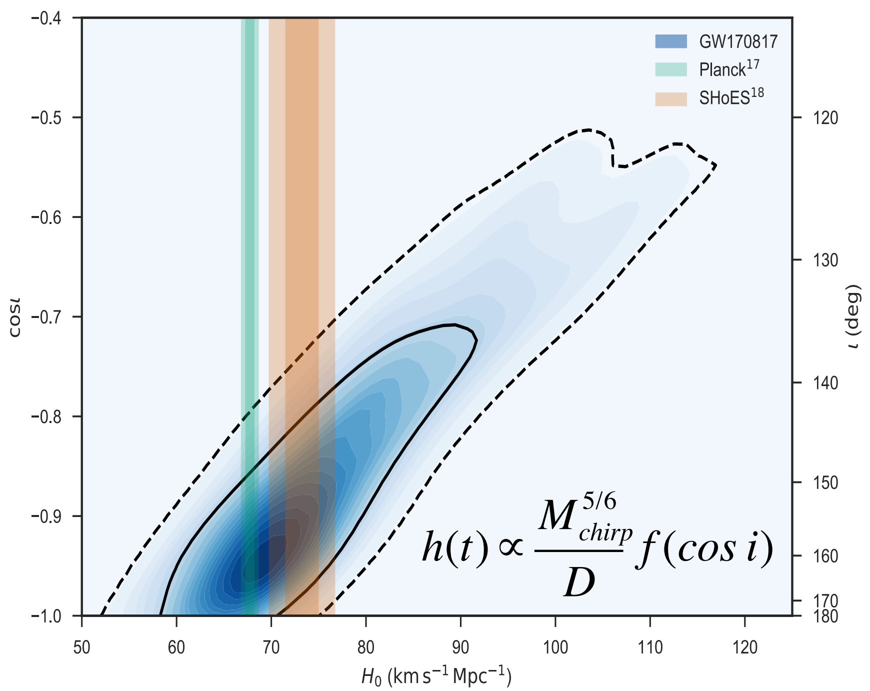
- Tidal effects when stars are close
- Affect the GW waveform

- Compact stars are favored
- Consistent with radius below 14 km
- 10s of detections to distinguish between the models
- First detections of spinning neutron stars (pulsars) will also add constraints

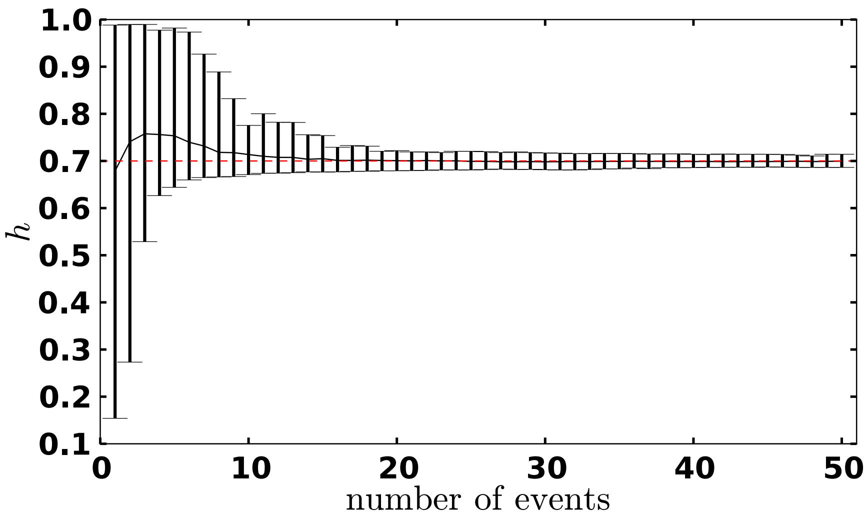
Hubble constant measurement

- For closed-by source : $v=H_0D$
- EM counterpart found in NGC4993, can then measure redshift
- GW : Distance and orientation are correlated
- 10s of common detections to reach few % precision



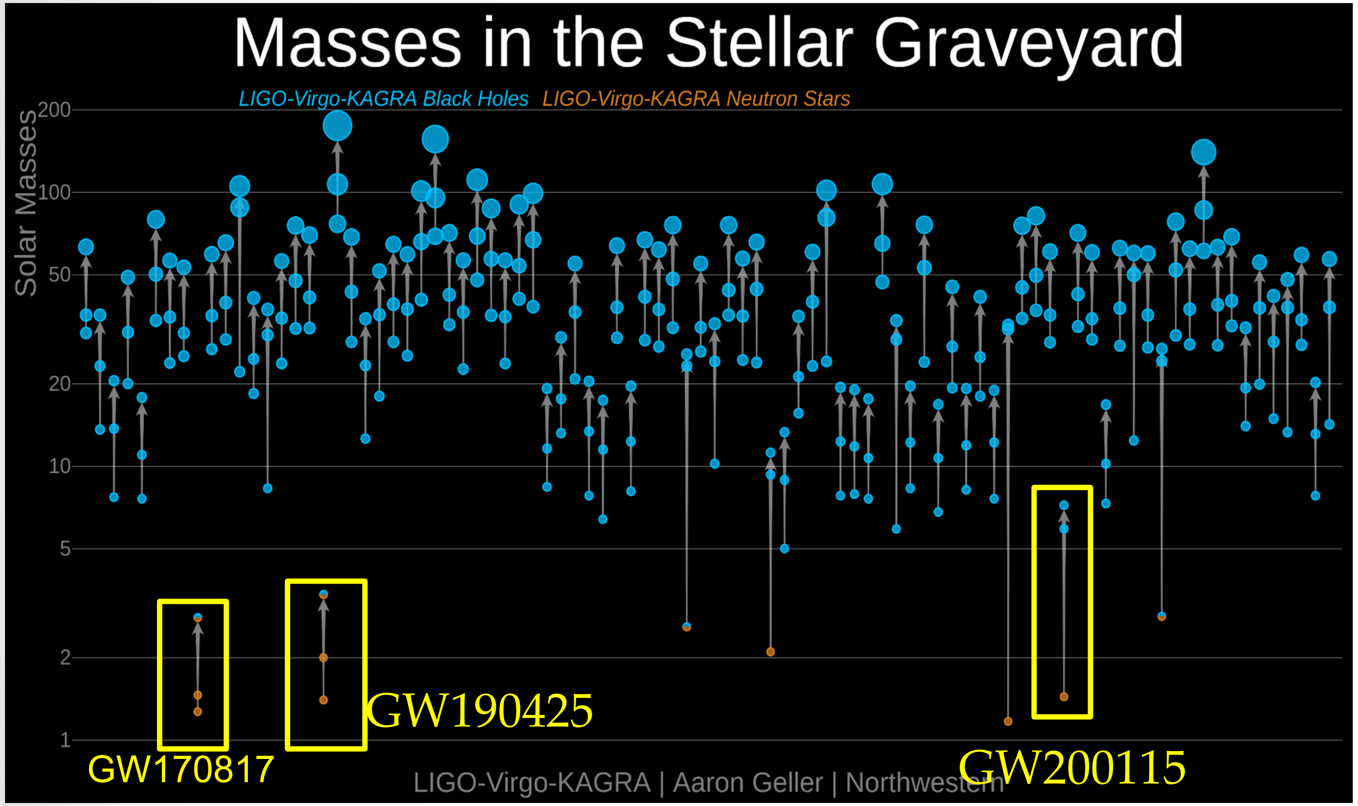


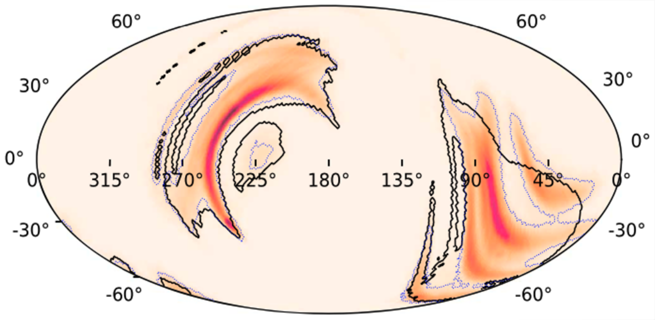
"A standard siren measurement of the Hubble constant with GW170817", Nature 551, 85 (2017)



Del Pozzo, PRD 86, 043011 (2012)

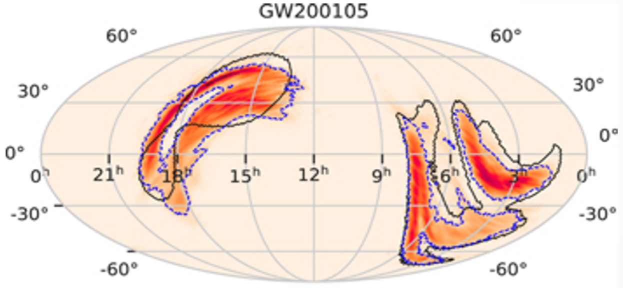
NS during O3





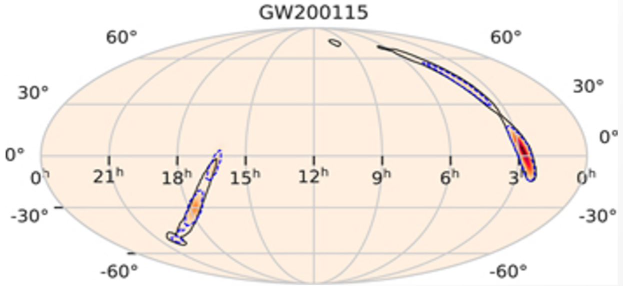
O3 BNS

D ~ 160 Mpc



Two NSBHs in O3:

D ~ 280 Mpc
(Marginal event)



D = 300 Mpc

Few events …
Large distance ….
Not well localized …….

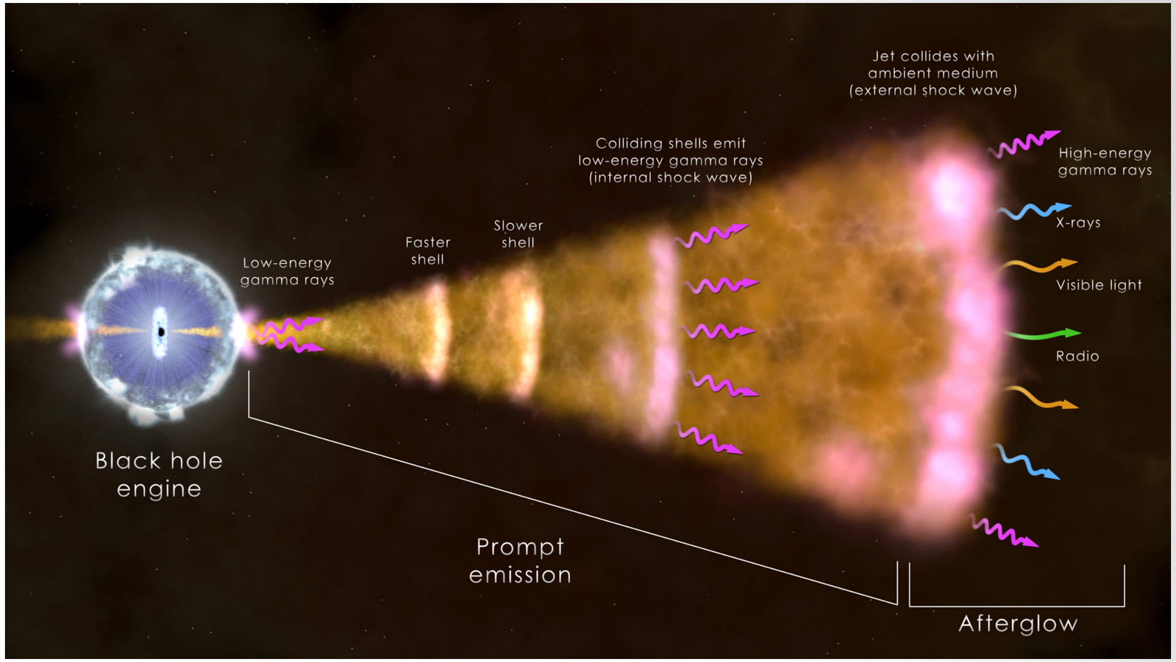
Gamma-ray bursts

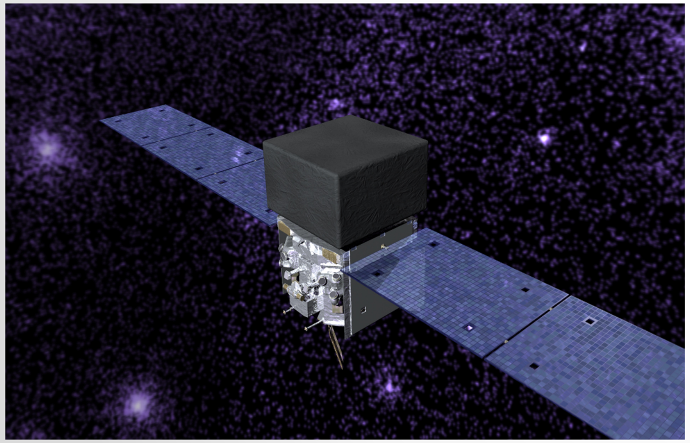
Classified into **2 categories** :

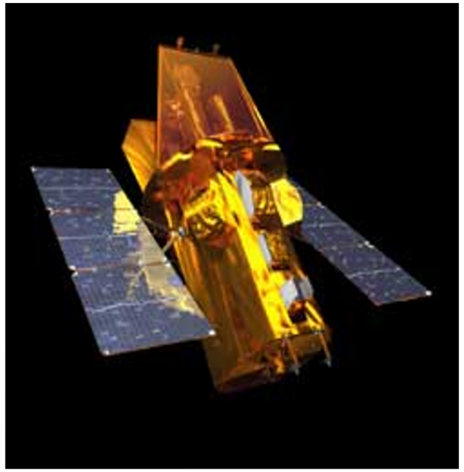
- **Long** GRBs (T>2s) : linked to CCSN
- **Short** GRBs : Linked to CBC (GRB170817A)

2 main instruments for the GWs searches :

Fermi-GBM & **Swift-BAT**







Characteristics of GRB170817A :

- One of the closest GRB : 40 Mpc
- Low energy : 2-6 orders of magnitude less energetic than usual

Contributions of GRB170817A :

- Confirmation of the sGRB/CBC link
- First hints of a Structured jet
- Ruled out "Top Hat Jet"
- Constraints on speed of gravity

GW search on GRBs

Modeled search

Only CBC signals : Expected with sGRBs

Template banks for signal search :

- BH mass in [2.8, 25] $M_\odot$
- NS mass in [1, 2.8] $M_\odot$ - cutoff based on NS equation of state
- BH Spins < 0.998 (theory based)
- NS spins < 0.05 (observation based)

Generic transient search

3 types of waveform injected for sensitivity estimation :

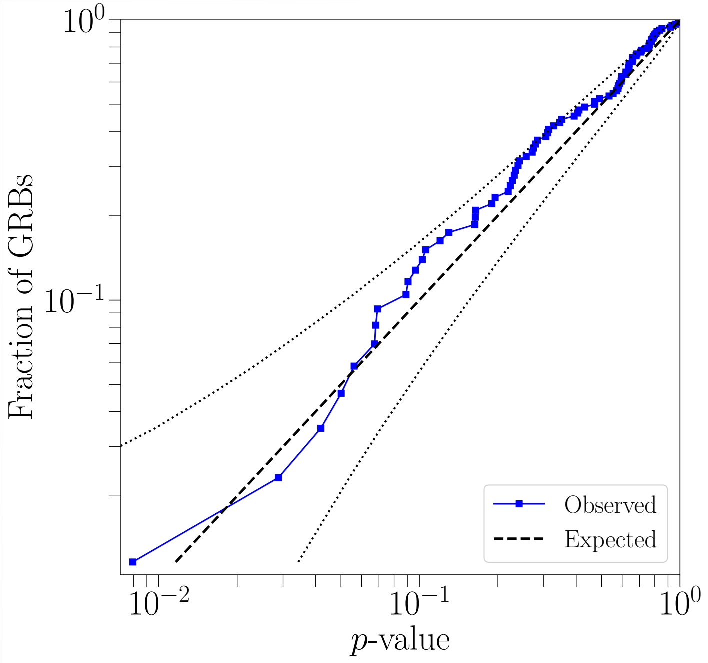
- Circular Sine-Gaussian (CSG) : describes SN bursts
- CBC : BNS and NSBH
- Accretion Disk Instabilities (ADI): Long duration signal describing instabilities produced in torus around rapidly spinning BH

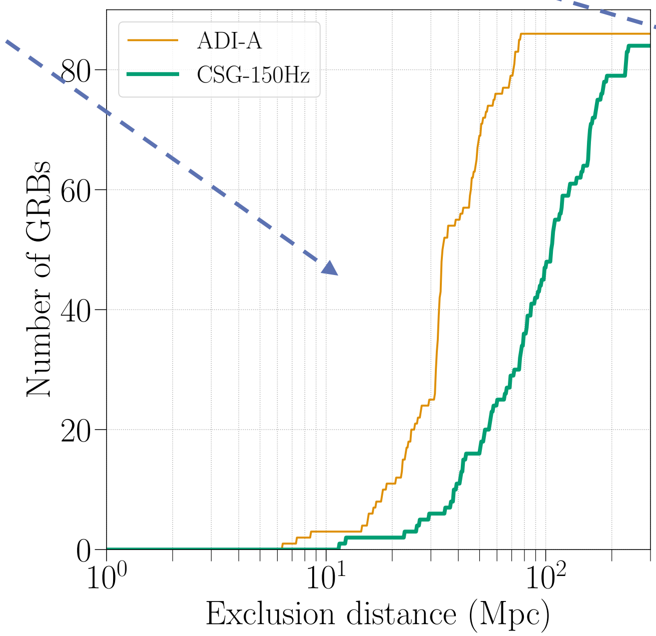
p-value : **fraction** of background events with **SNR** > **loudest trigger**
$\mathbf{D_{90}}$: **Distance** up to which < **90% injections** are **recovered** with a ranking statistics superior to the loudest trigger. Act as an lower limit on the distance of the source.

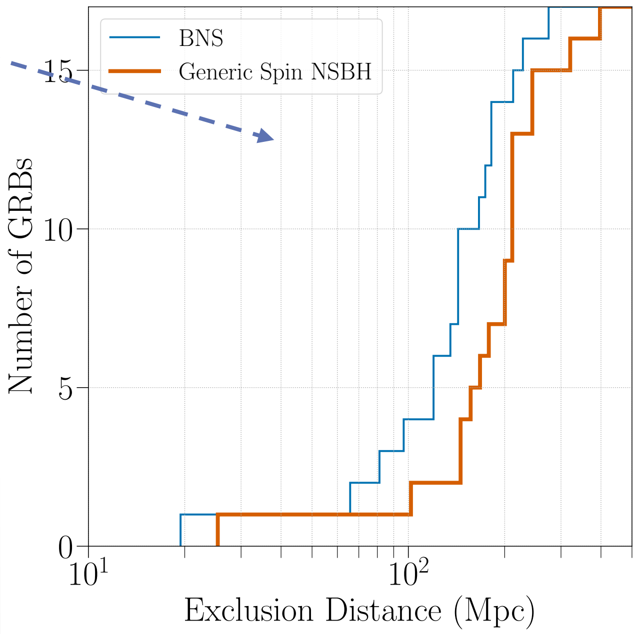
GRBs : Results on O3b

O3a	Modeled search	32 GRBs	No coincidence found :(
	Generic transient	105 GRBs	
O3b	Modeled search	17 GRBs	
	Generic transient	86 GRBs	

- Better constraints on O3b for the 2 searches :
  - **Modeled** : GRBs in average more in the most sensitive area of LV. **10-30%** improvement
  - **Generic** : Veto method improved short duration signals sensitivity + LV improvements (more sensitive + Less glitches) **50%** improvement





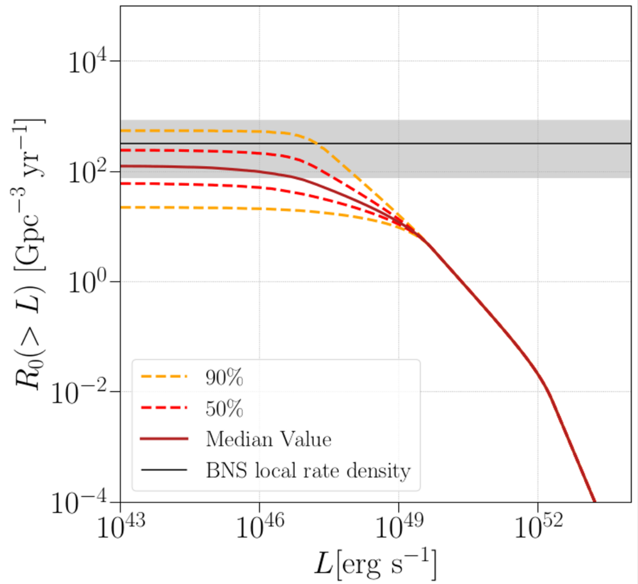


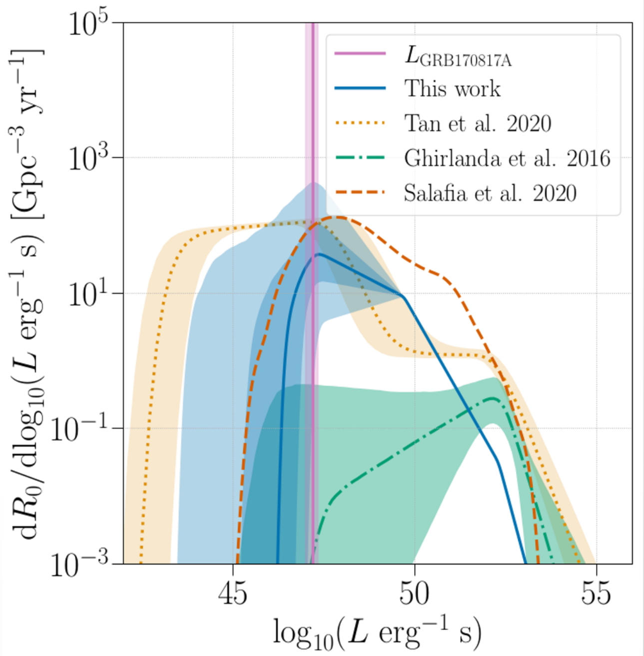
GRBs : population study

Inference on the rate of detection of a joint GW/GRB with Fermi-GBM considering:

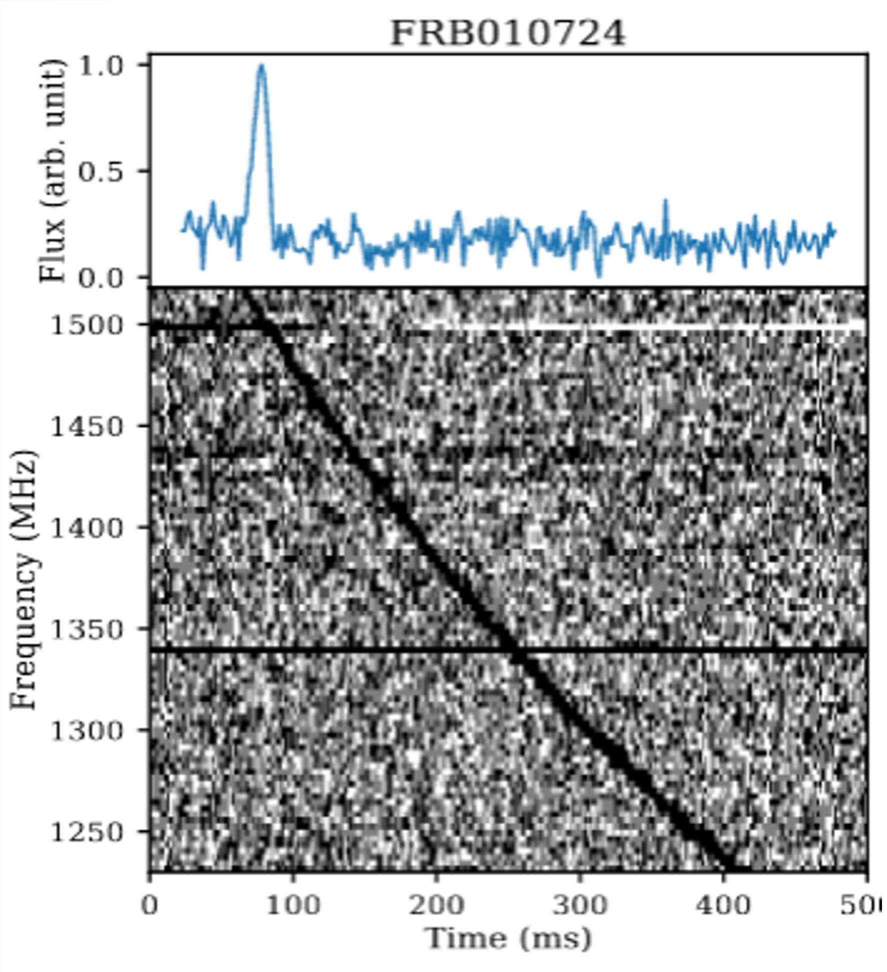
- No detection in O1 and O3
- 1 detection in O2
- A 170817-like luminosity ($L_{170817} \sim 10^{47}$ erg.s^{-1})
- Only BNS as sGRB progenitor

Predicted rate : $$R^{O4}_{GW-GRB} = 1.04^{+0.26}_{-0.27}\, yr^{-1}$$





Fast radio bursts - FRB



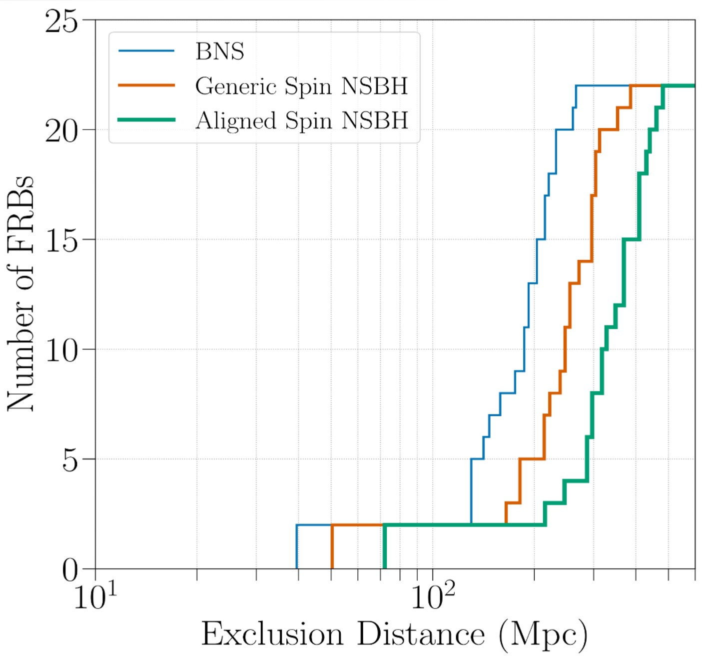
Fast Radio Burst (FRB) : ms radio pulses

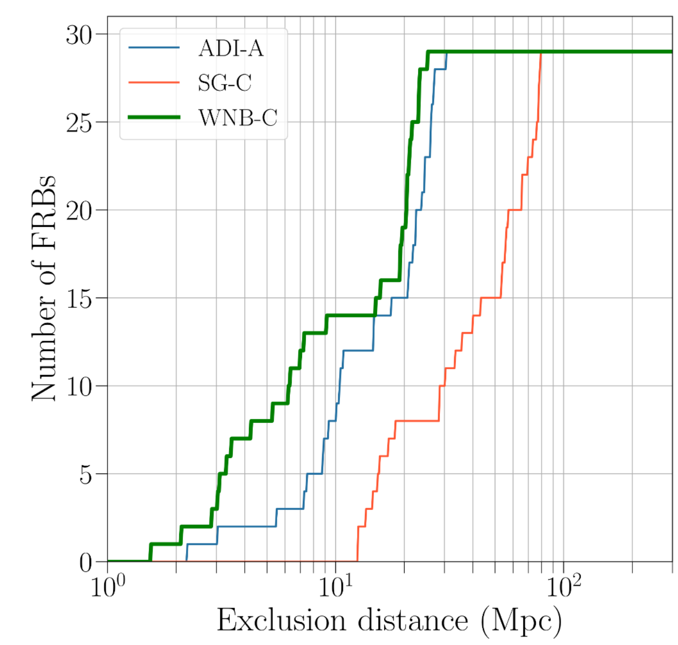
- Robust association with **magnetar** - **Other progenitors unknown**
- Some **models** predicts **FRB/GW association**

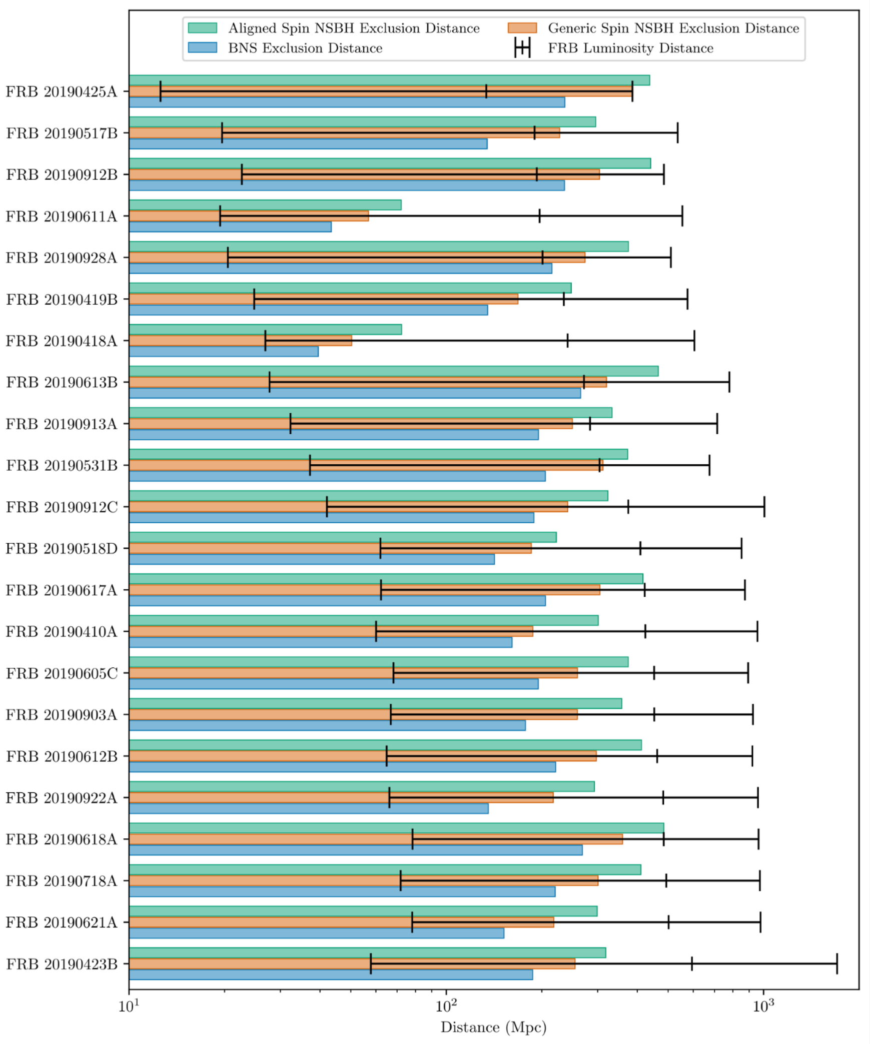
LIGO/Virgo conducted 2 GRB-like searches FRB triggers from CHIME

FRB – results on O3a

- **No confident association** in any search
- Modeled search exclusion distance **can not rule out** any **CBC** model -> Mostly due to the large uncertainties on FRBs distance estimations



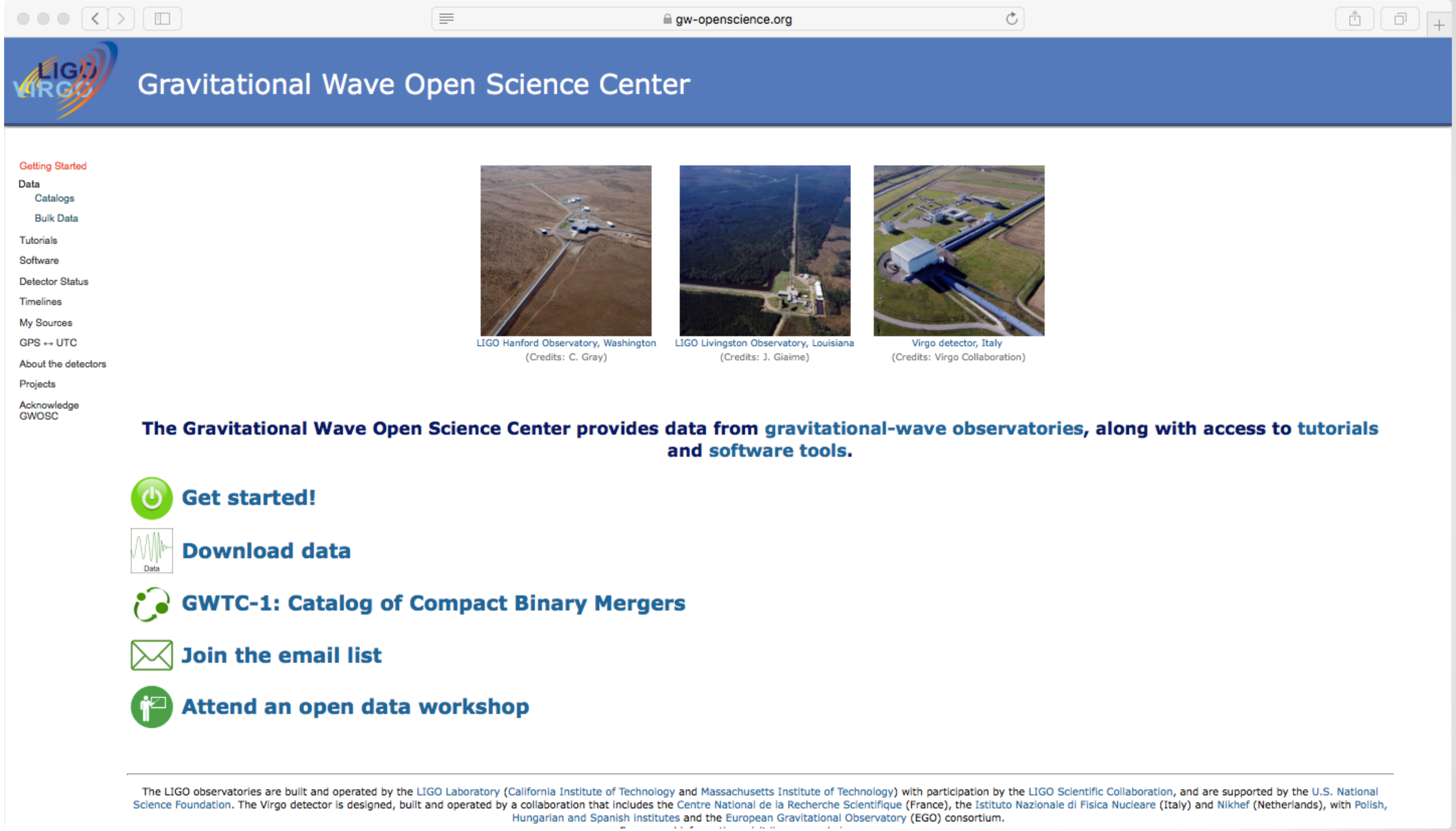




Accessing data of GW detectors

https://www.gw-openscience.org/about/

- Data will be released in two steps :
  - If publication is done on a given event : release one hour around the event
  - After each publication release also posterior distributions
  - We release 6 months block with an 18 months latency – may be reduced in the future



Challenges for O4

O4 Predicted rate for BNS and BHNS mergers based on O3 :

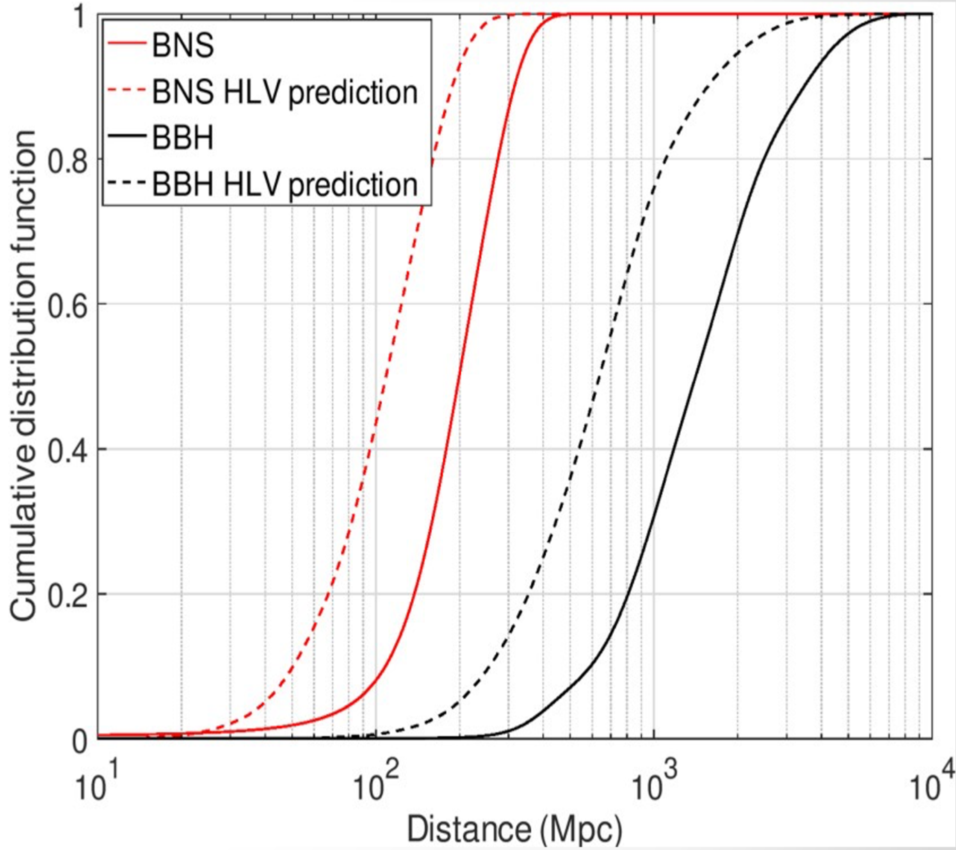
- **34 (+78 -25) per year (BNS)**
- **72 (+75 -38) per year (NSBH)**

GW170817 at 40 Mpc -> Rare event

Up to **1 GW alert per day** in O4 (HLV prediction)

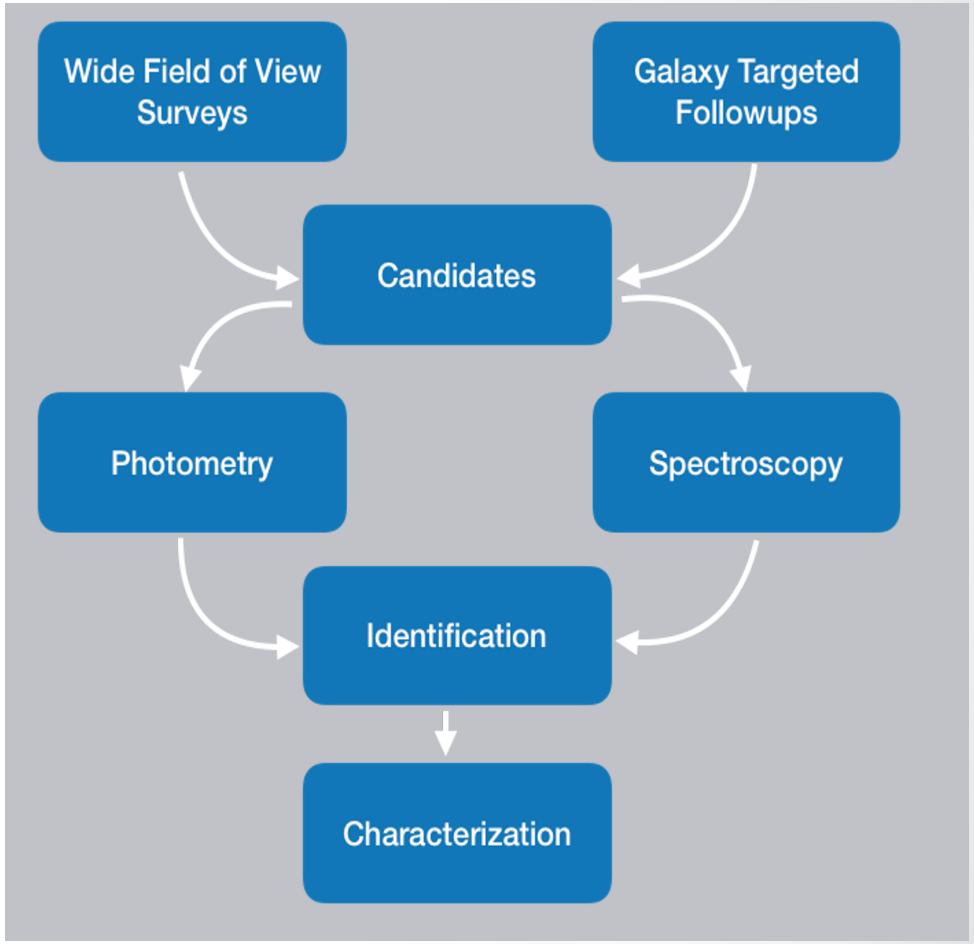
KN **peak magnitude > 20.5** mag for a BNS merger within **200 Mpc**

GRB: < 1 GW + GRB per year observable by Fermi



Find and characterize the EM transient

Kilonova Challenge	Solution
Short lived - Hours up to days	Quick reaction
Faint - Peak at 20.5 mag at 200 Mpc	Deep Observations
Rapid Color Evolution	Observation in g and r (adding i if possible)
Large localisation uncertainties + Many alerts to follow + Well sampled lightcurves	No duplication Coordination of Observations Careful alerts selection



Need a **Network** of **Telescopes** and **People** (EM & GW)

Example of follow-up GRANDMA collaboration

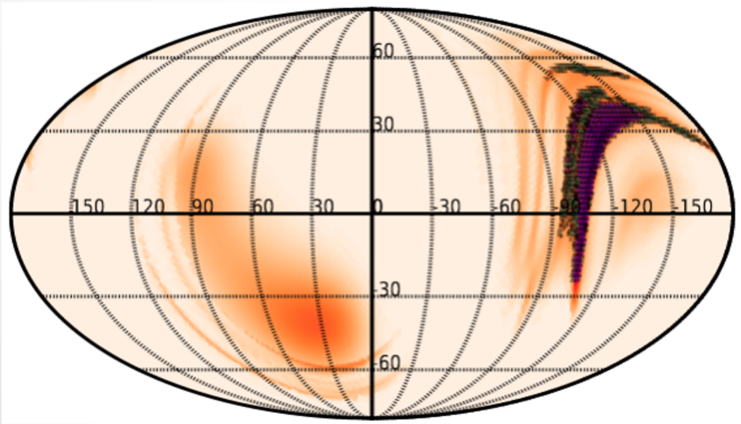
Already a large Community
29 groups - 14 countries
80 scientists
CNRS/- APC - IAP - IJClab -
CPPM - IRAP – LAM - IPHC

Wide-fields up to 20 mag, EM candidates ~ 23 mag in photometry, 22 mag in spectroscopy

Observation strategy

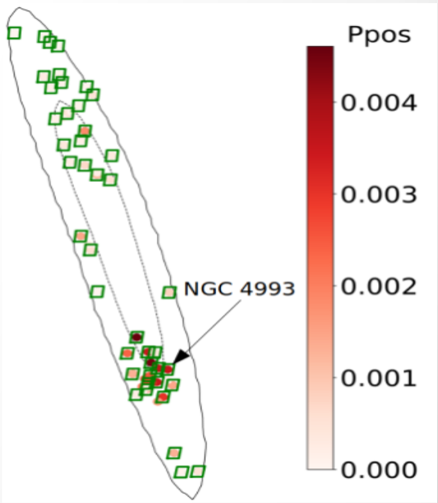
Tilling

- Cover the sky localisation map of GW
- Look for new object that are related to the GW
- Best suited for large FoV (>1deg²) instruments
- Widely used by current survey (PAN-STARRS, ZTF, TAROT,...)



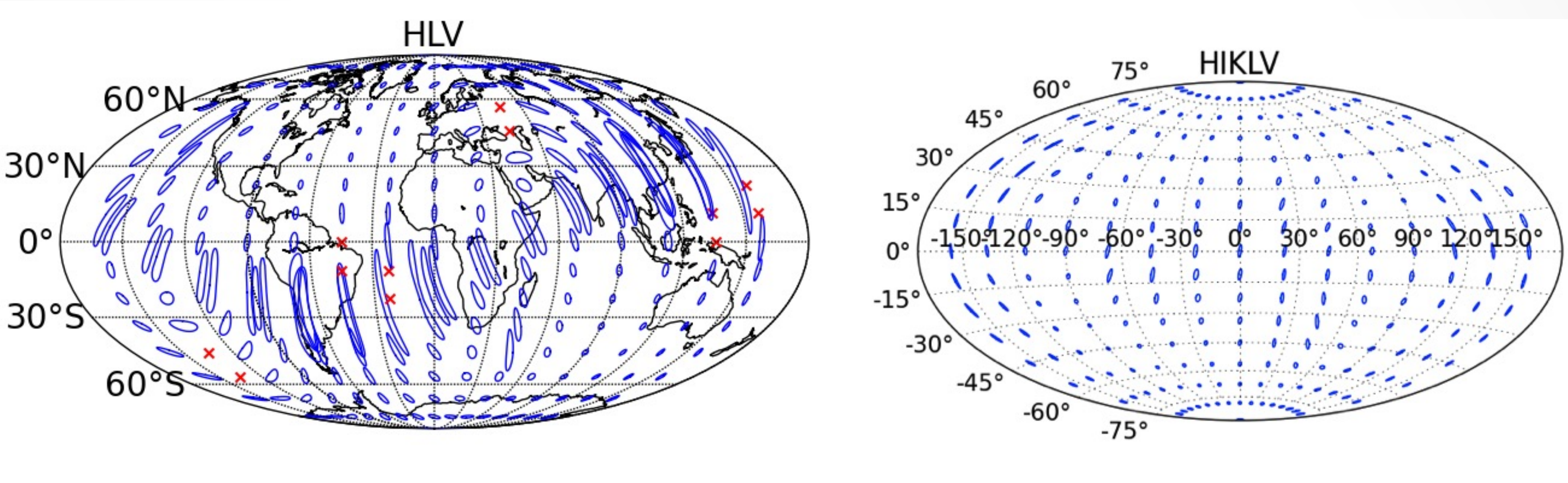
Galaxy Targeting

- Observed the galaxy compatible with the spatial information provided by GW
- Galaxies classified with
  - spatial information
  - Stellar mass estimation
- Catalog developed at IJClab : MANGROVE [8]
- Best suited for small FoV instruments
- Technique used for 170817

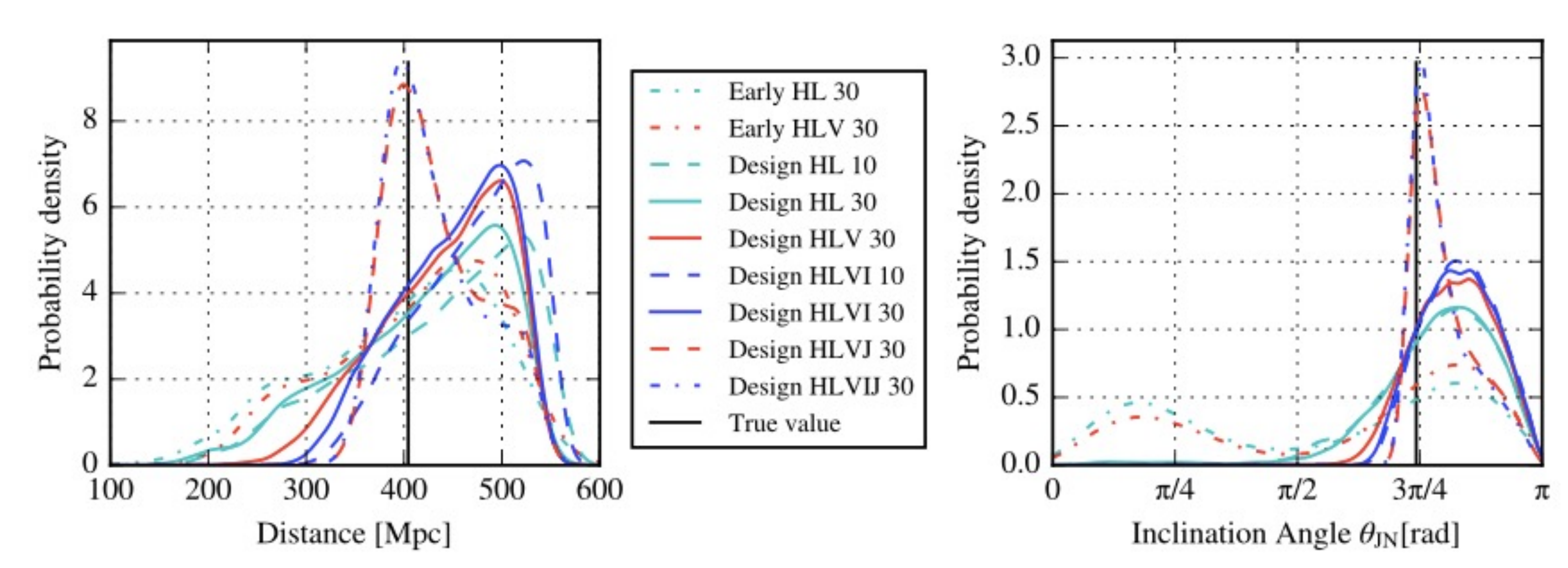


Adding new instruments : parameters inference

Comparison between 3 and 5 detectors for sky localization



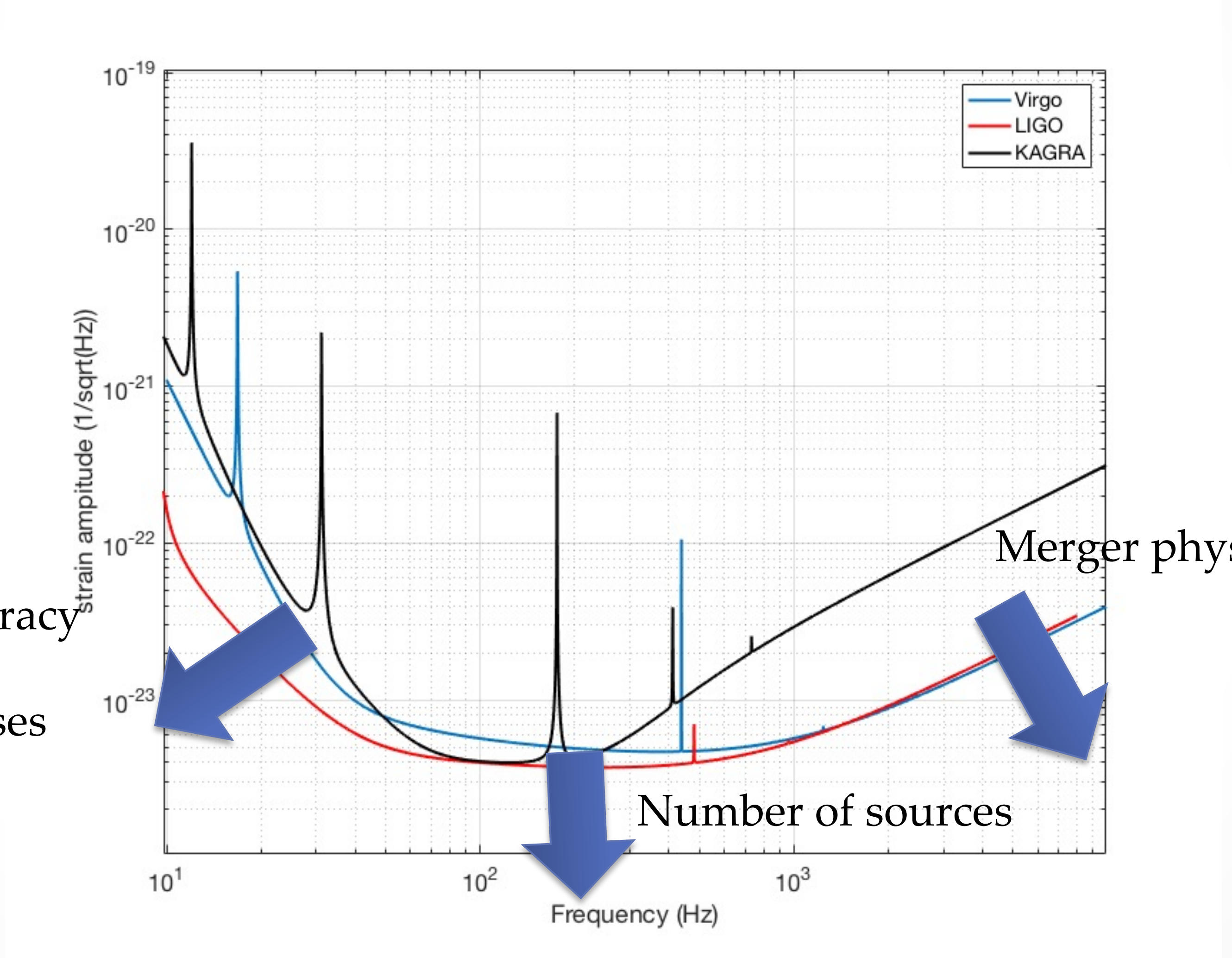
Fairhurst, proceedings of ICGC2011 conference



S M Gaebel and J Veitch 2017 Class. Quantum Grav. 34 174003

Improving sensitivity

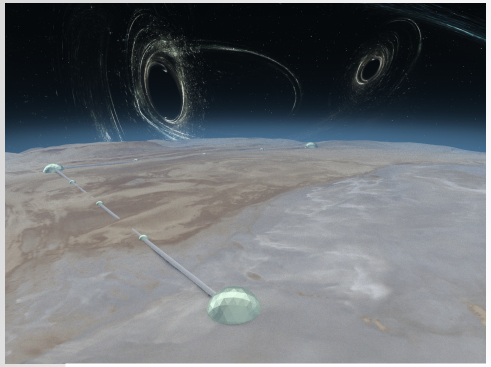
Mass accuracy
High z
High masses

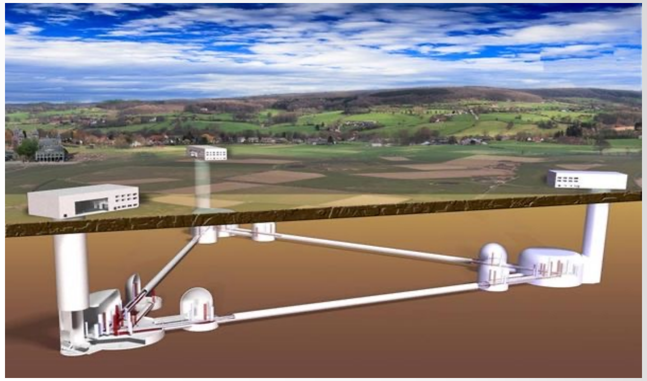


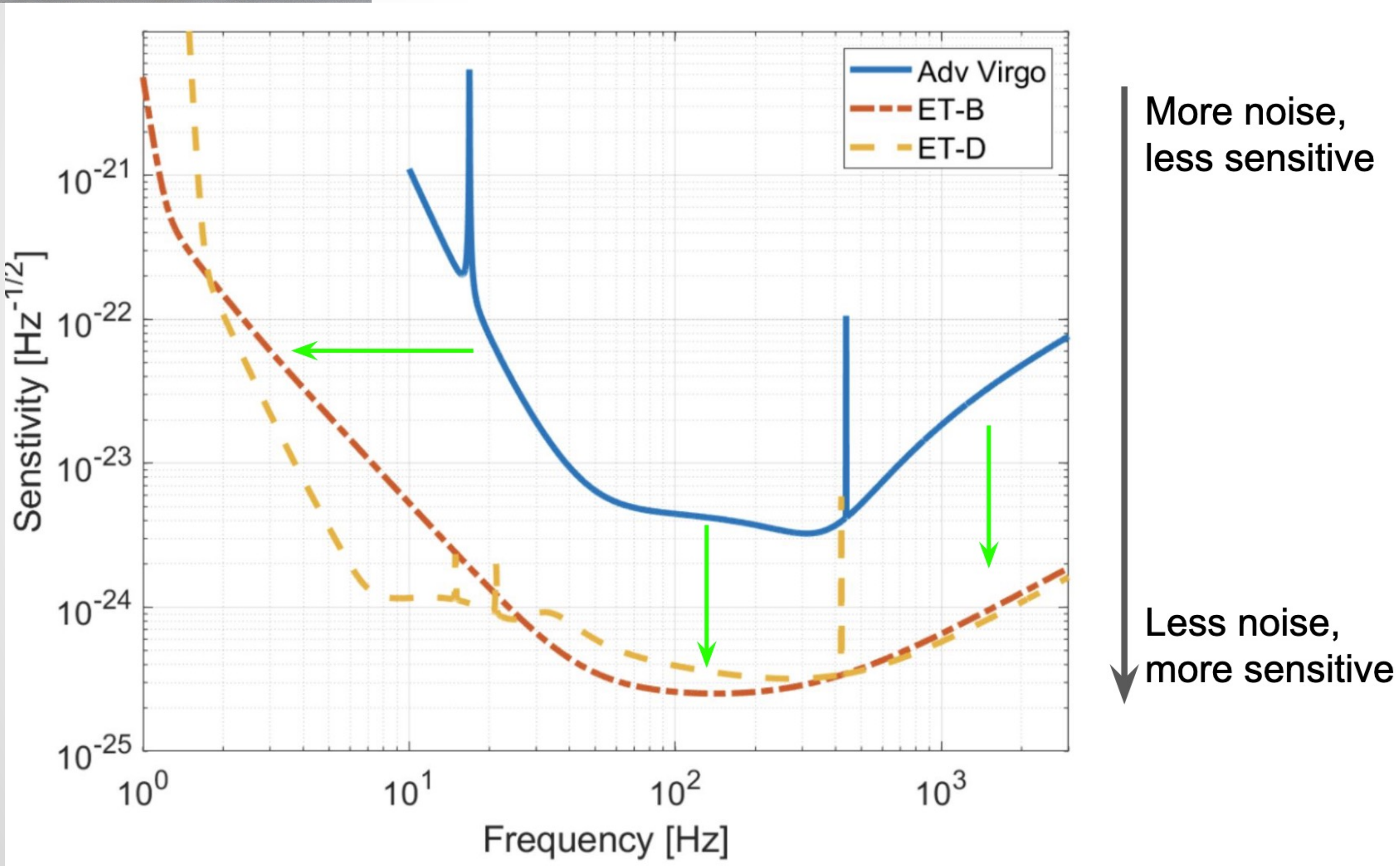
Merger physics

Number of sources

Towards 3G (2030-2035)







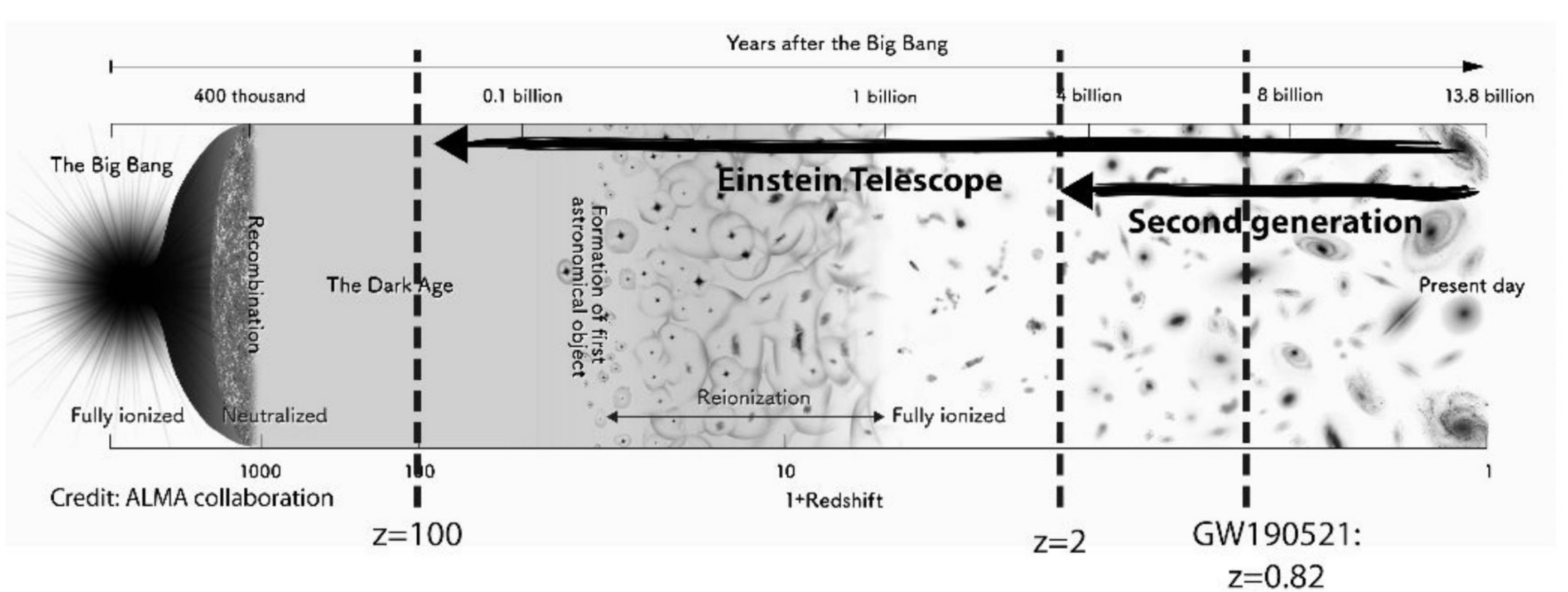
Going underground 10km - ET or surface 40 km – CE

2 to 3 interferometers on the same site

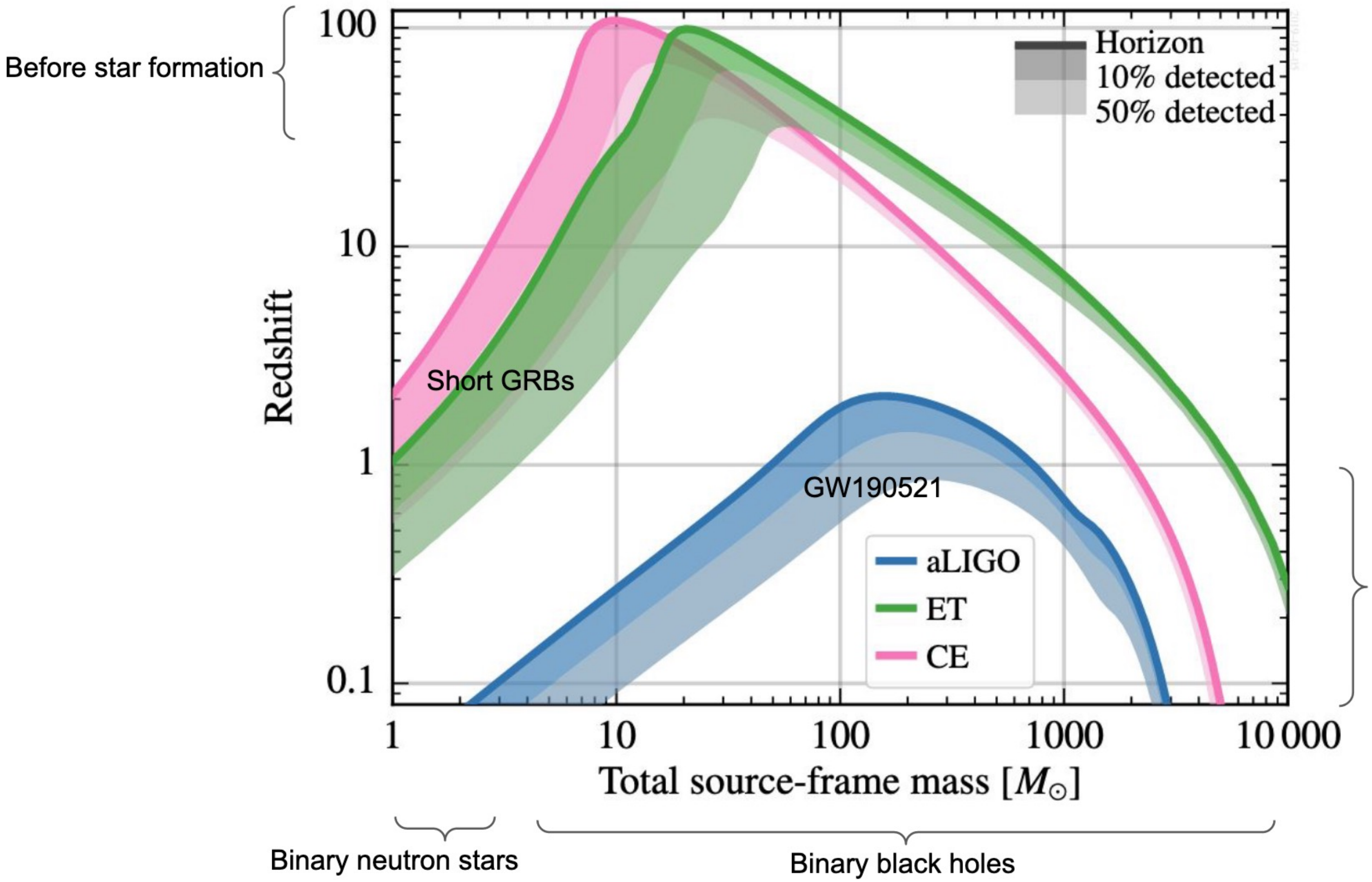
Cryogenic mirrors for low frequency

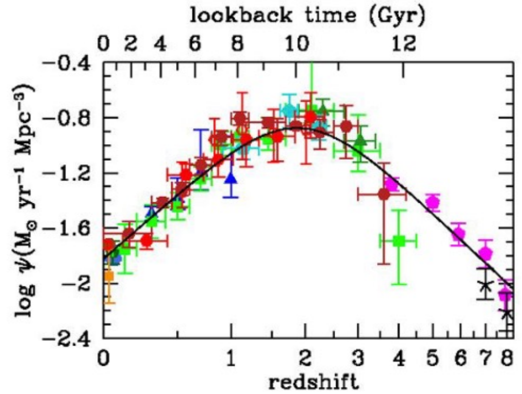
Impact for compact binaries coalescences

- Increase volume by 1000
  - Millions of events per year for BBH
  - 10000 events per year for BNS
- Longer signals
  - BNS signals observable for hours -> pre-merger localization !



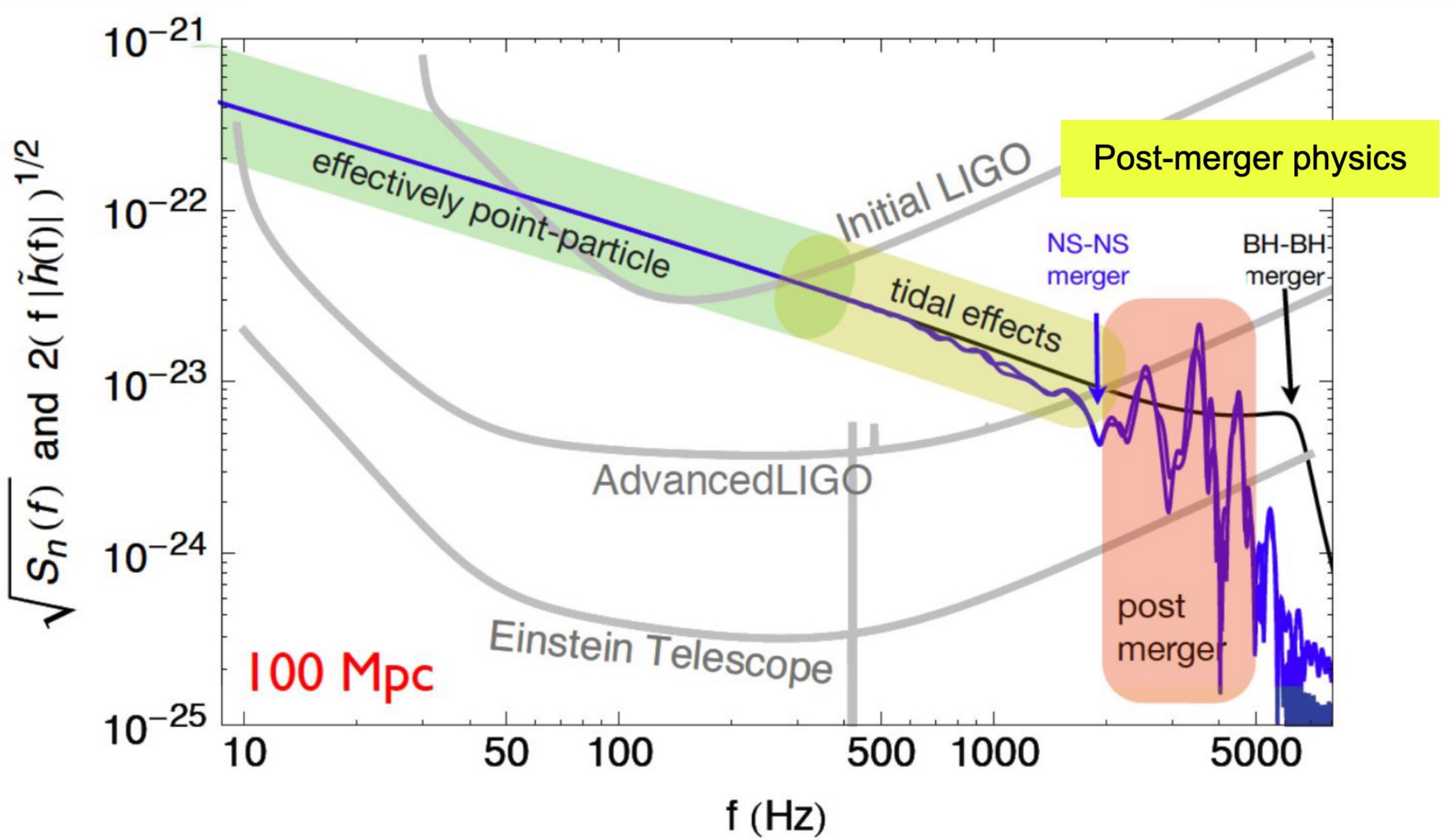
Distance



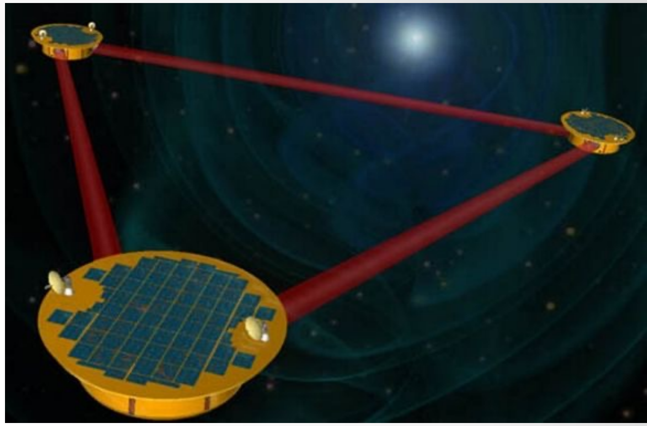


Star formation rate

Physics of neutron stars

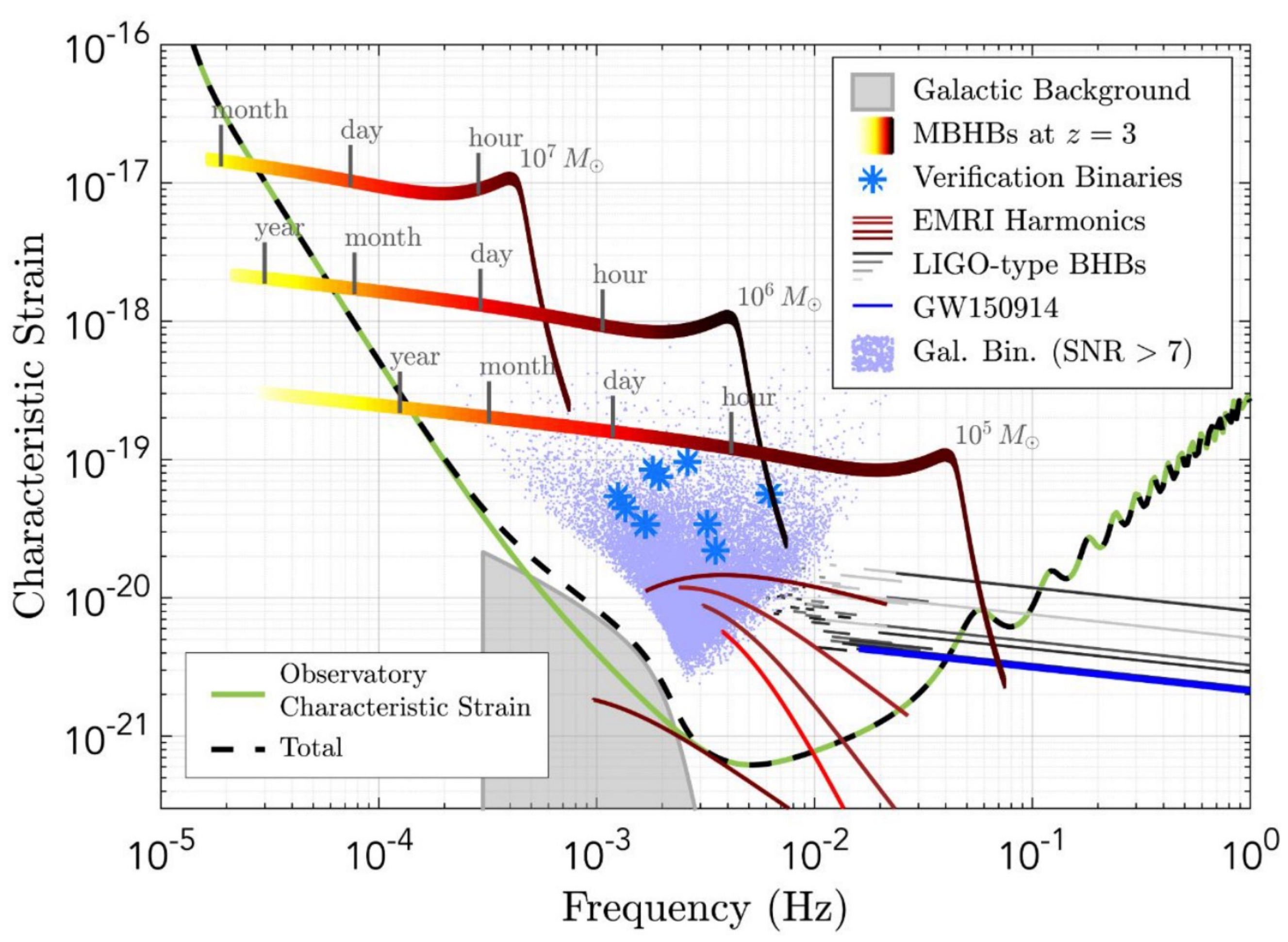


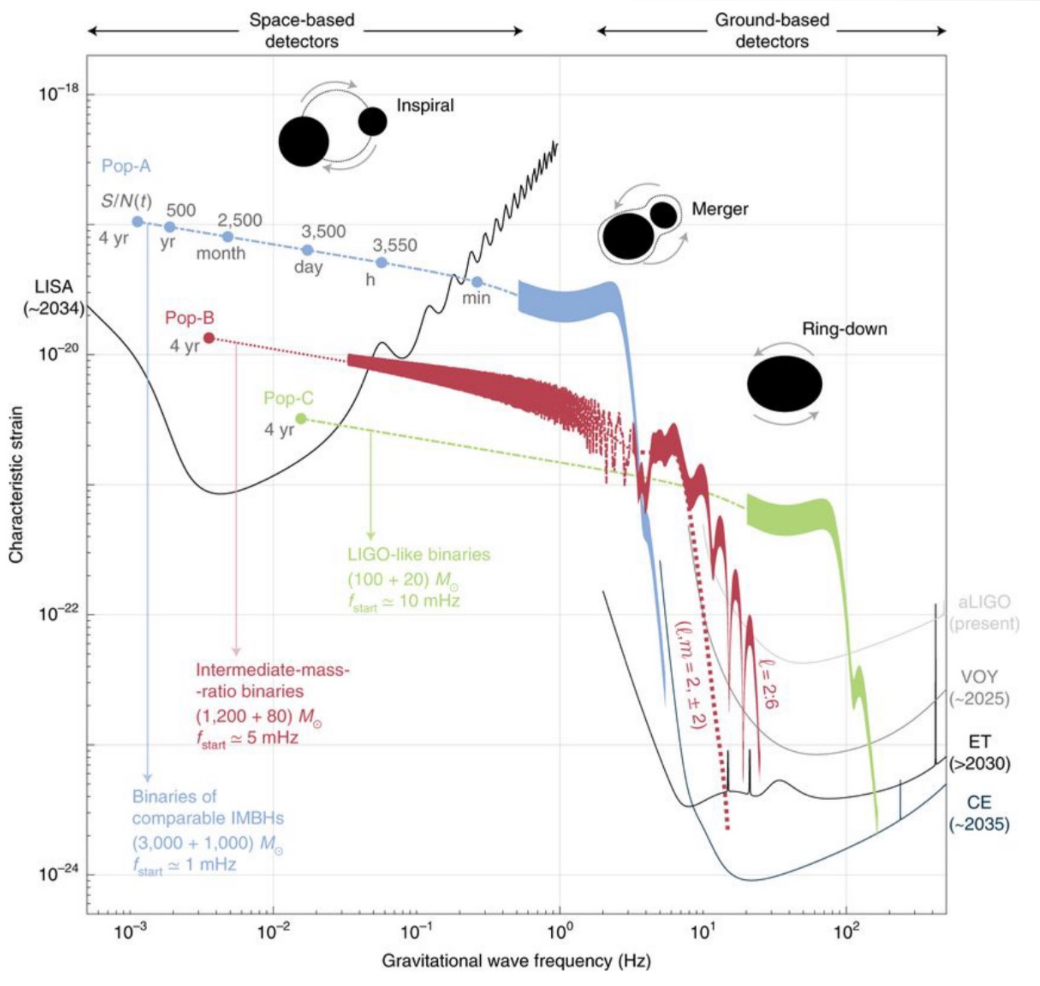
Going into space : LISA



- 3 satellites, time delay interferometry
- Arms with few millions km
- Scientific case:
  - Merger of supermassive black holes
  - Compact solar masses binaries (WD and NS), observe accurately the inspiral phase
  - Extreme mass ratio inspirals , mass ratio > 200
  - BBH, can predict merger time for ground based detectors one year in advance
  - Stochastic background
- Test mission (Pathfinder) showed the readiness of the technics
- Planned for the period 2028-2034

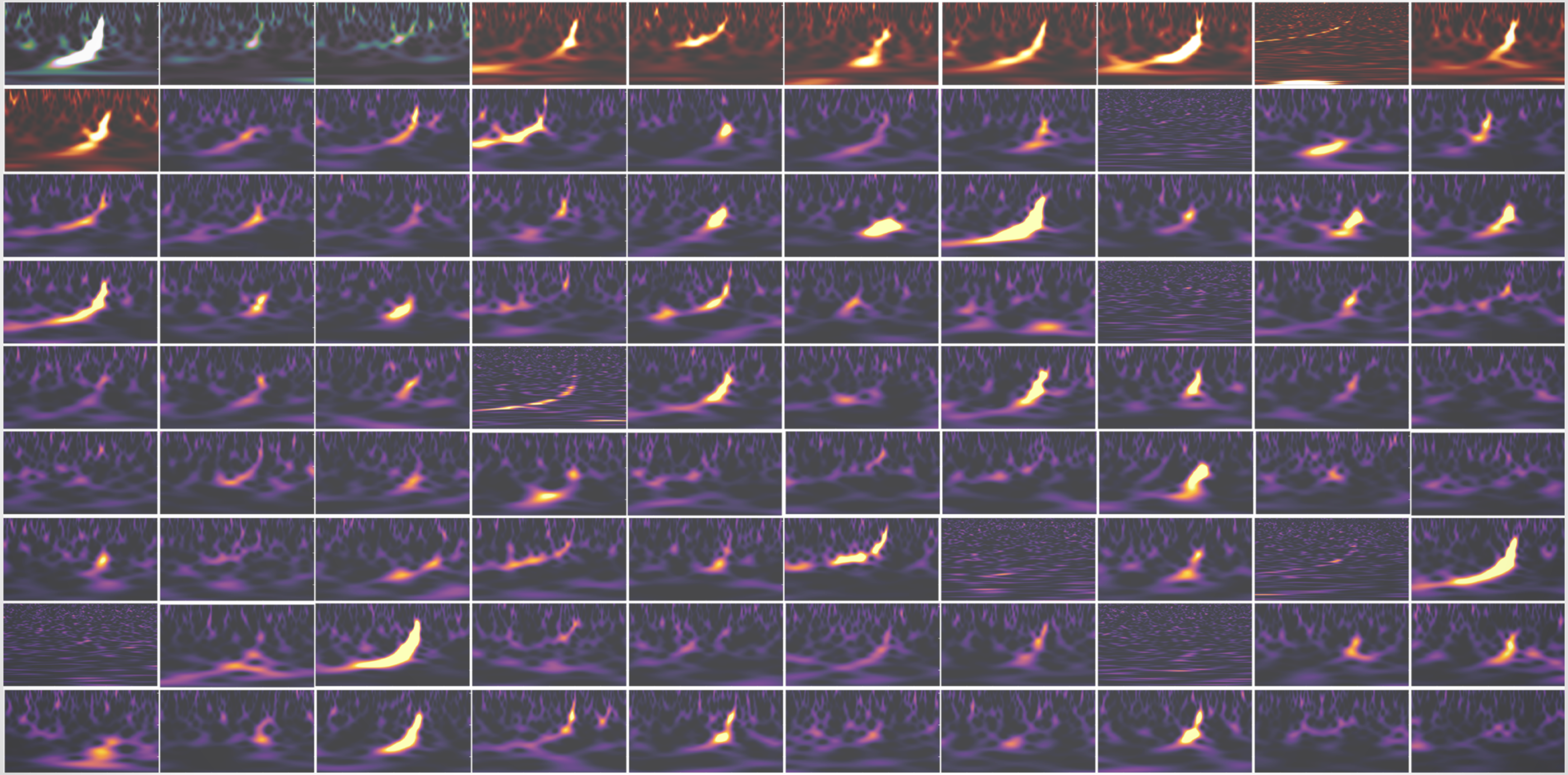
Some highlights with LISA





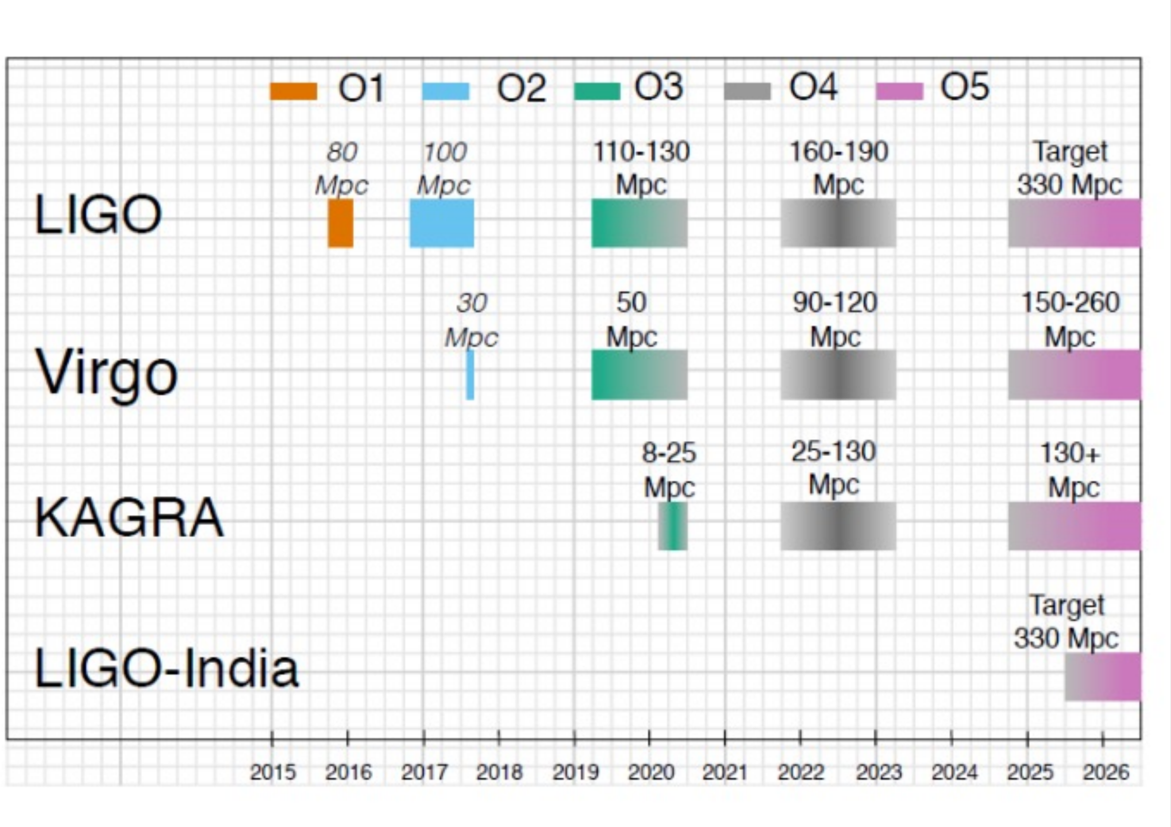
Conclusions

- 90 confirmed detections up to now
  - Black holes with large masses
  - First binary neutron star merger, observed in coincidence with a short gamma-ray burst
  - First NSBH events
  - Test on GR passed
  - First H0 measurement



Conclusions

- 90 confirmed detections up to now
  - Black holes with large masses
  - First binary neutron star merger, observed in coincidence with a short gamma-ray burst
  - First NSBH events
  - Test on GR passed
  - First H0 measurement
- New run O4 for one calendar year
  - 3 detectors at beginning
  - KAGRA will perform some data taking during the period with a reduced sensitivity
  - Detection rate : ~1/day (BBH)
- Plans for O5 and beyond
- 3G already in discussion



Observing scenarios with targeted sensitivities (from https://arxiv.org/pdf/2105.09247.pdf)