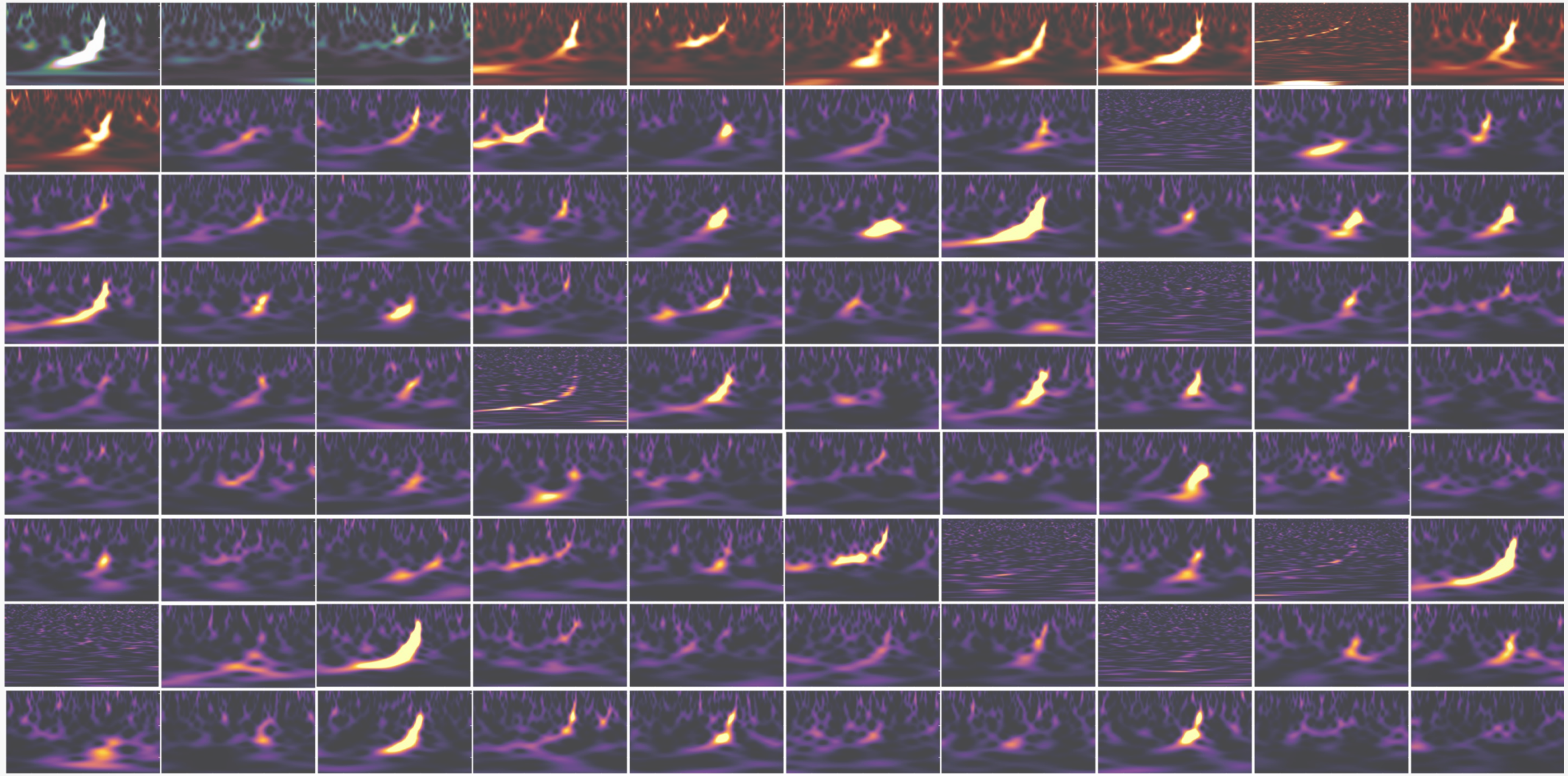
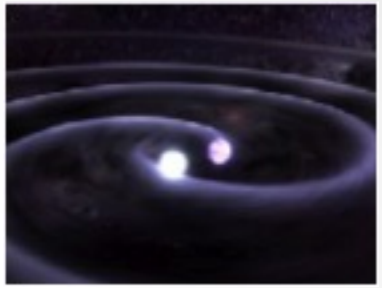
Recent observations in GW



Nicolas Leroy – IJCLab
for the LIGO Scientific, Virgo and KAGRA collaborations
IPA 2022

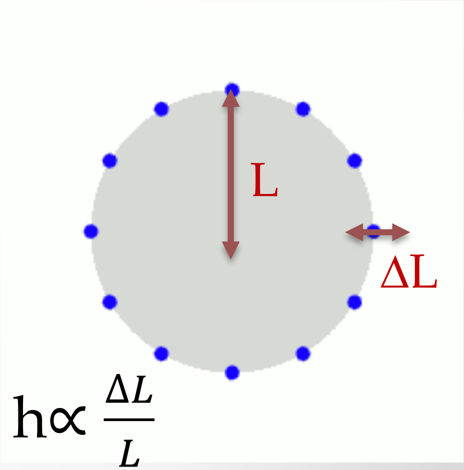
LIGO DCC-G2201356 – VIR-0825A-22

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

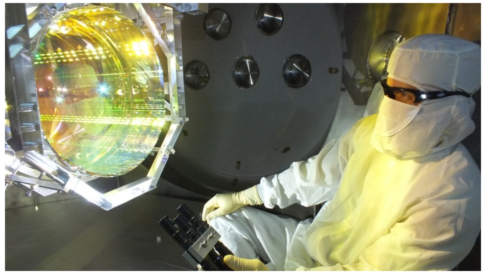
Needs to have
- Compact object : R~Rs
- Relativist : v ~ c
- asymmetric



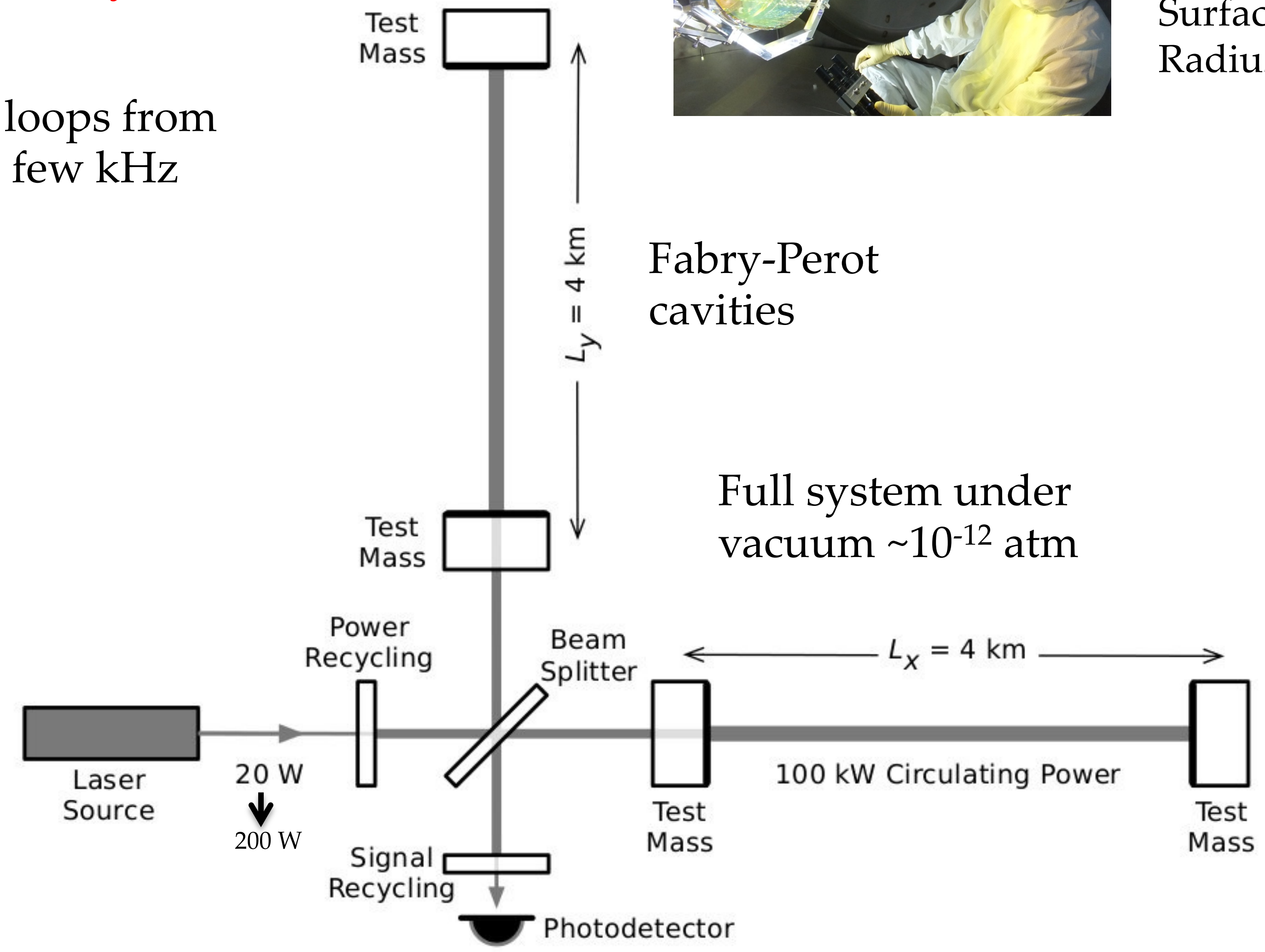
Advanced generation detectors

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

Feedback loops from few Hz to few kHz



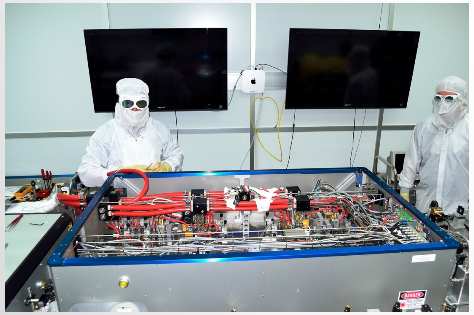
High quality optics – 40 kg
Surface RMS ~nm
Radius of curvature : 2m on 1.5 km

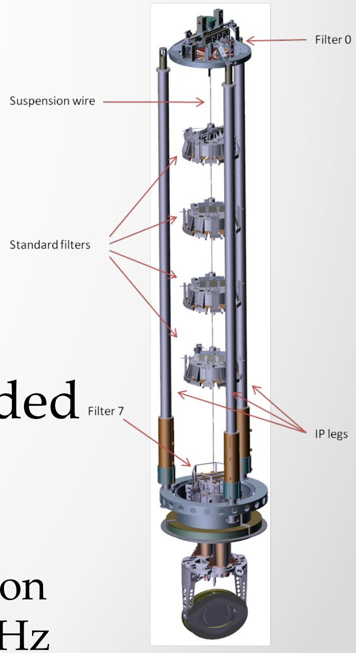


Fabry-Perot cavities

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

High power laser



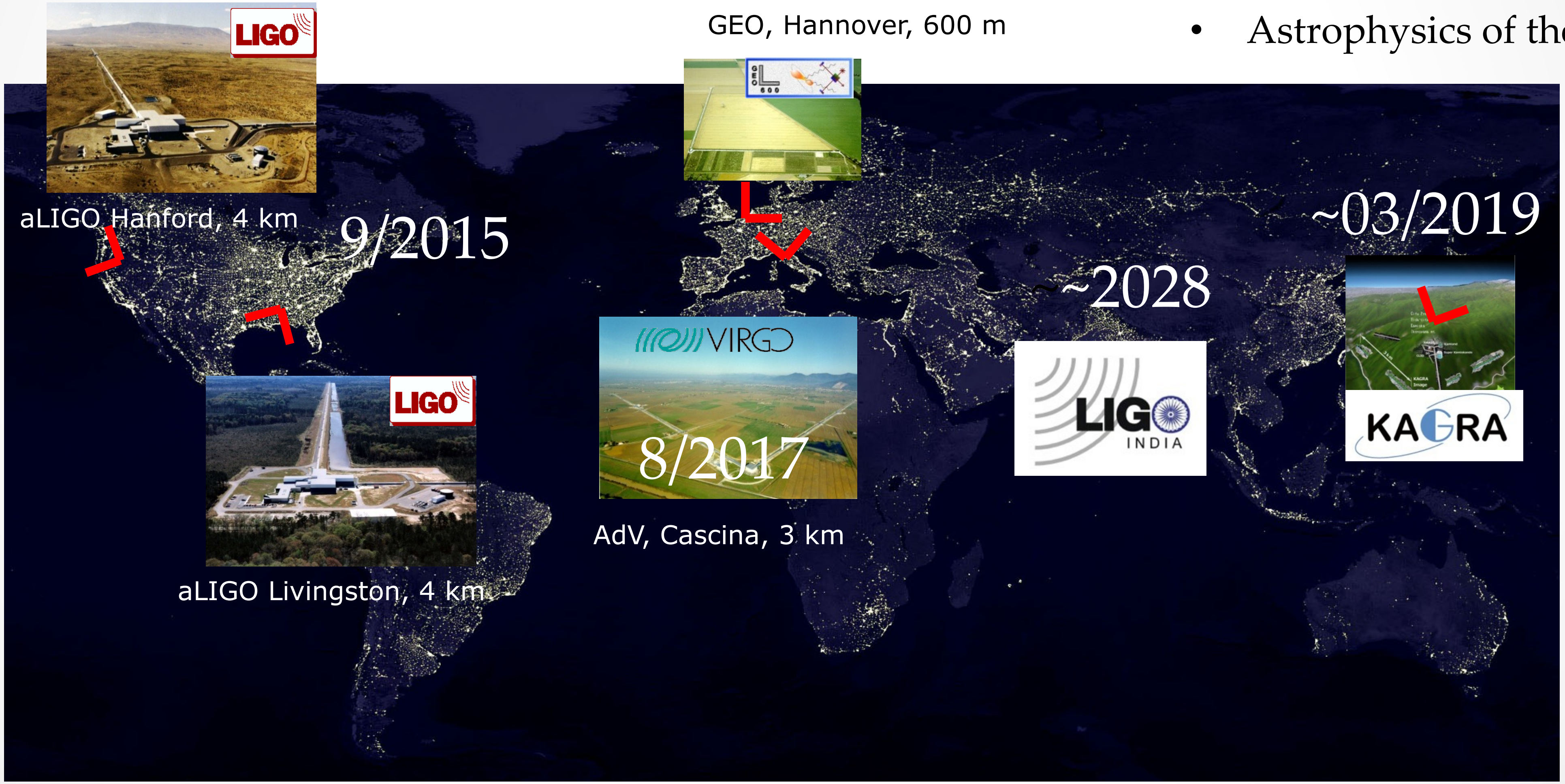


Suspended Optics

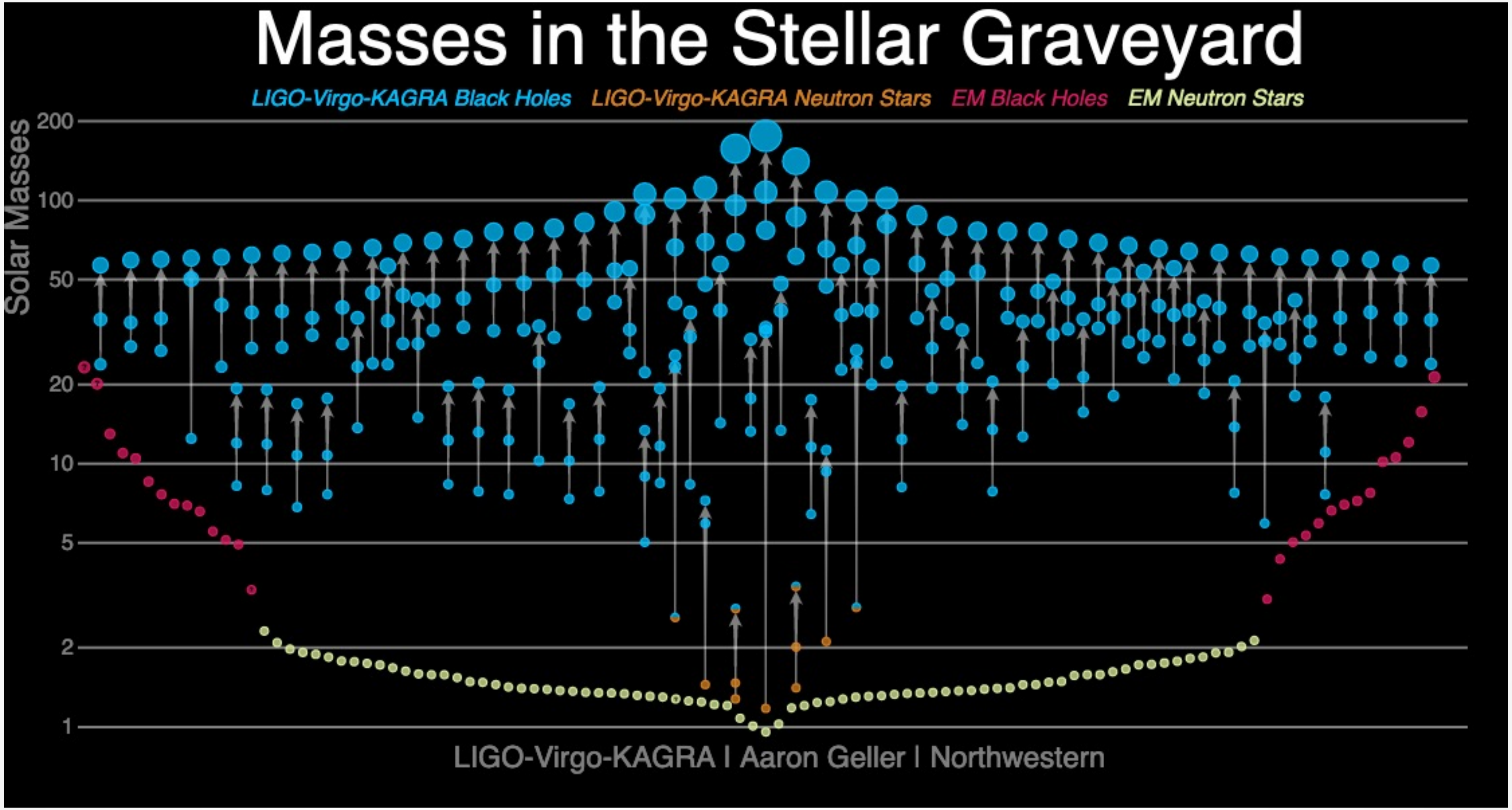
Attenuation 10^{14} @ 10 Hz

GW network

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



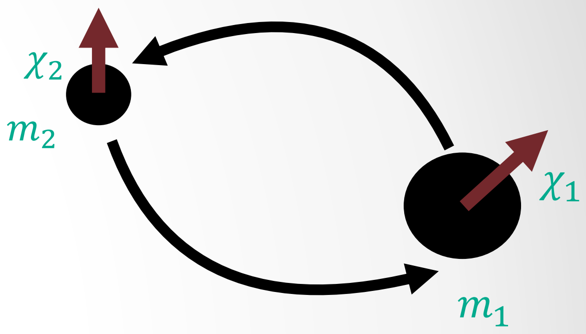
GW detections

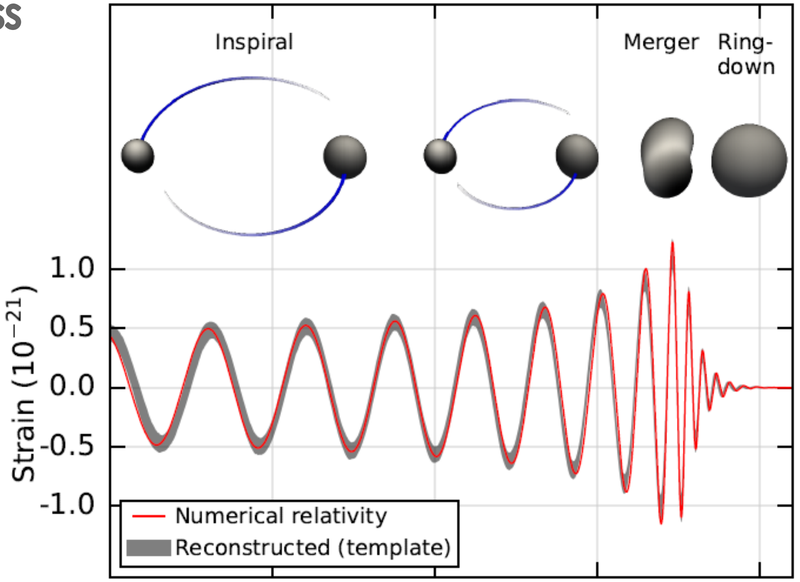


Only found coalescing binaries so far

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





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

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

$$q = m_2 / m_1$$

GWTC-3 :

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

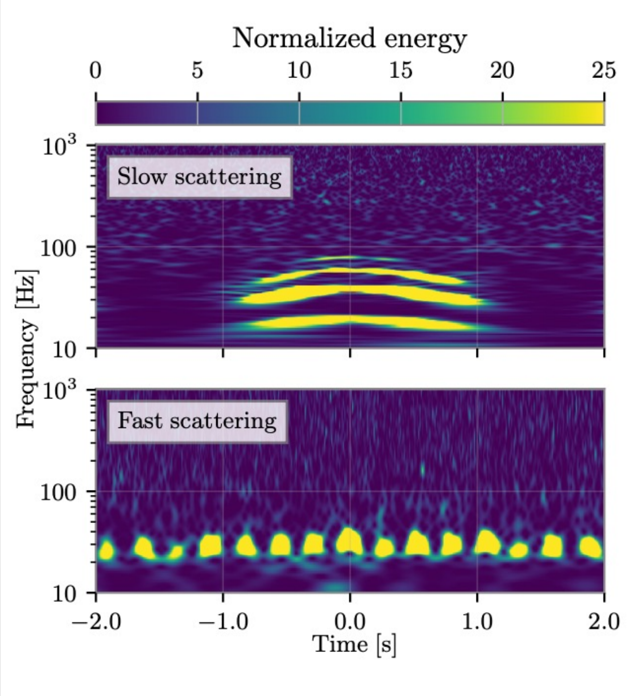


Fig4 : *Spectrograms of glitches caused by scattered-light*

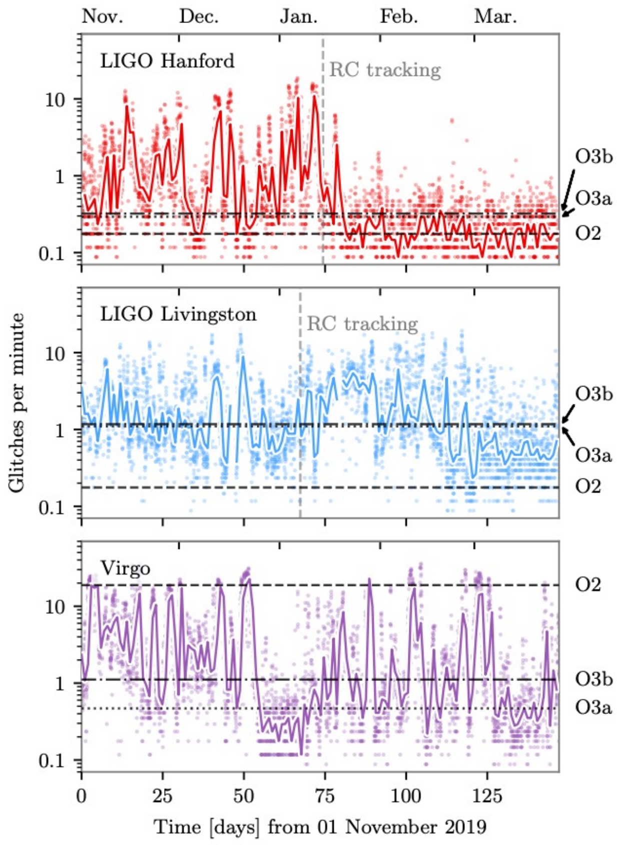
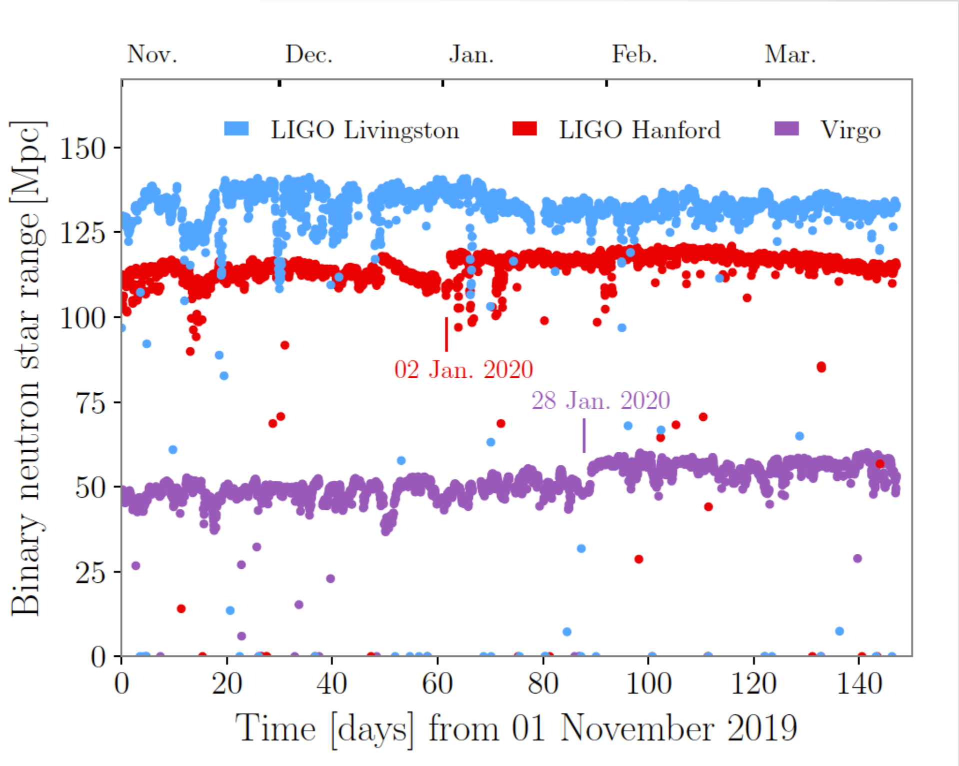


Fig5 : *Rate of single-interferometer glitches*



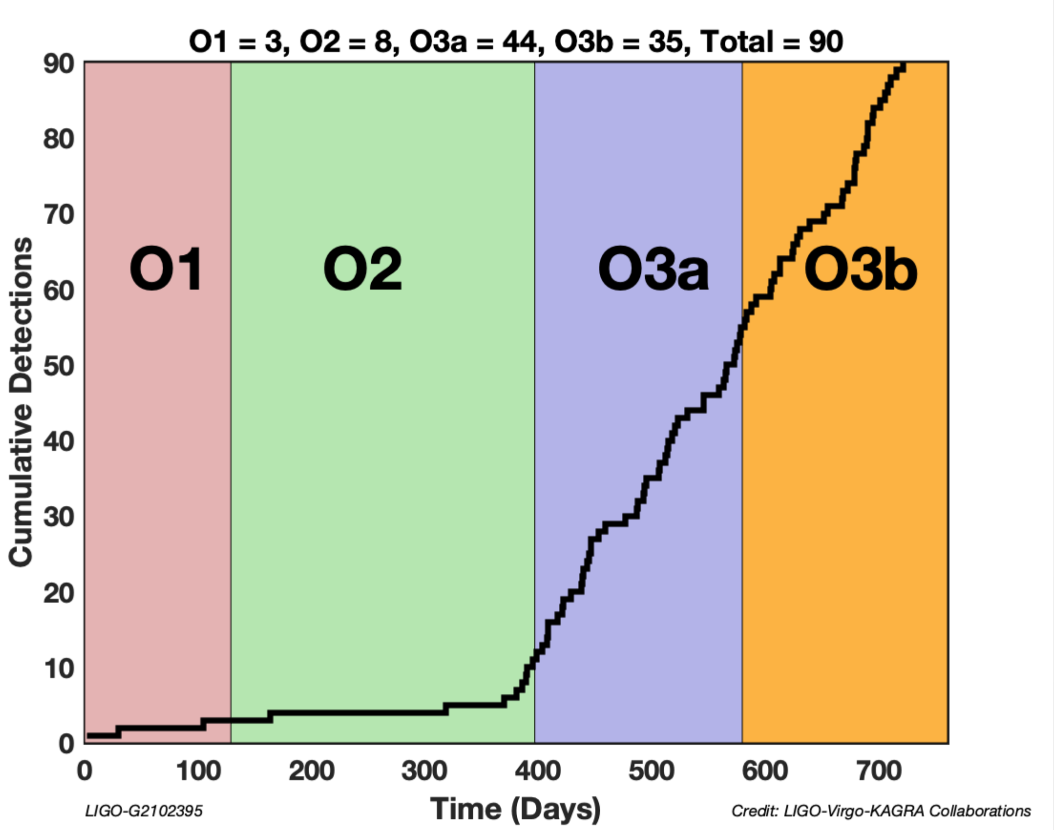
Measure of detector sensitivity: The binary neutron star range represents the distance a detector is able to detect a signal from a 1.4-1.4 solar mass binary

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

GWTC-3 : candidates

Procedure :

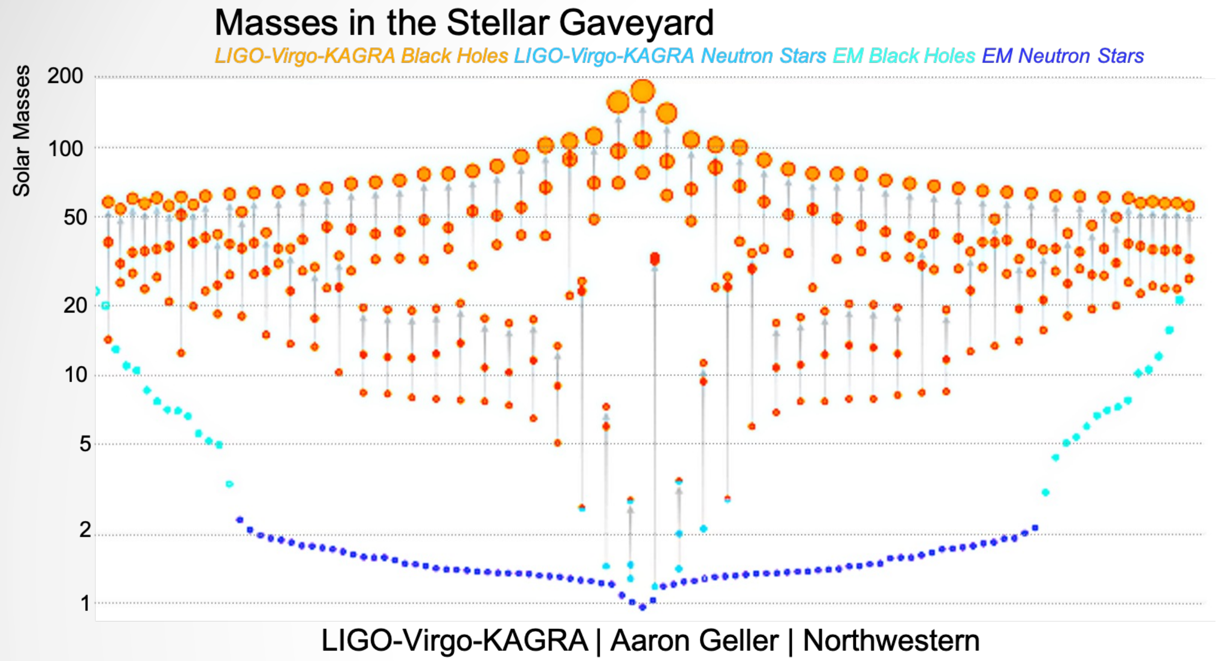
- Search method : Modeled searches (PyCBC GstLal, MBTA …) & Minimally modeled search (cWB)
- Candidates events identification
- Validation by checking for evidence that they were caused by one or more detector noise artifacts following the same procedure as for previous catalogs
- Parameter estimation
- 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

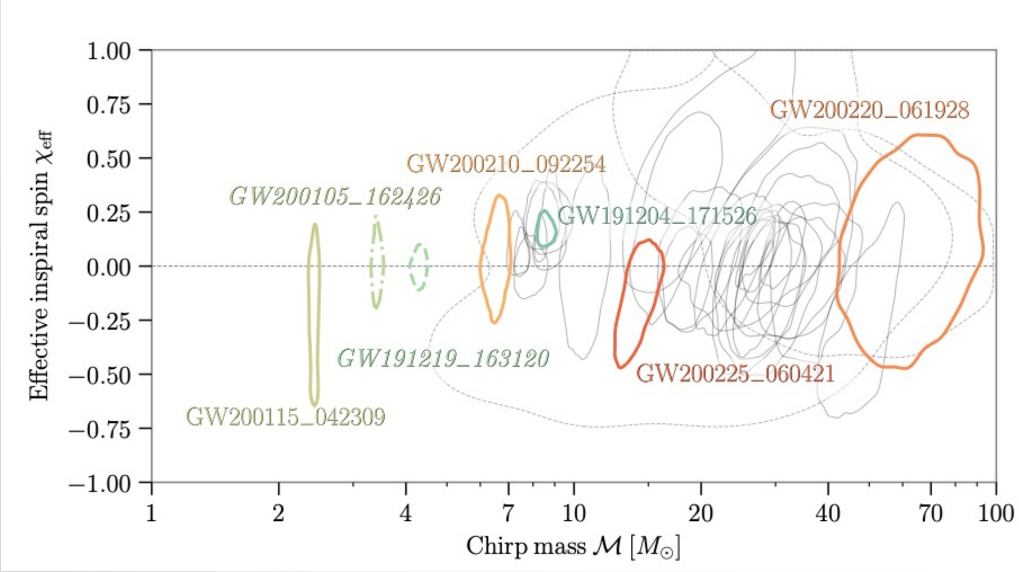


Likely instrumental artifacts :

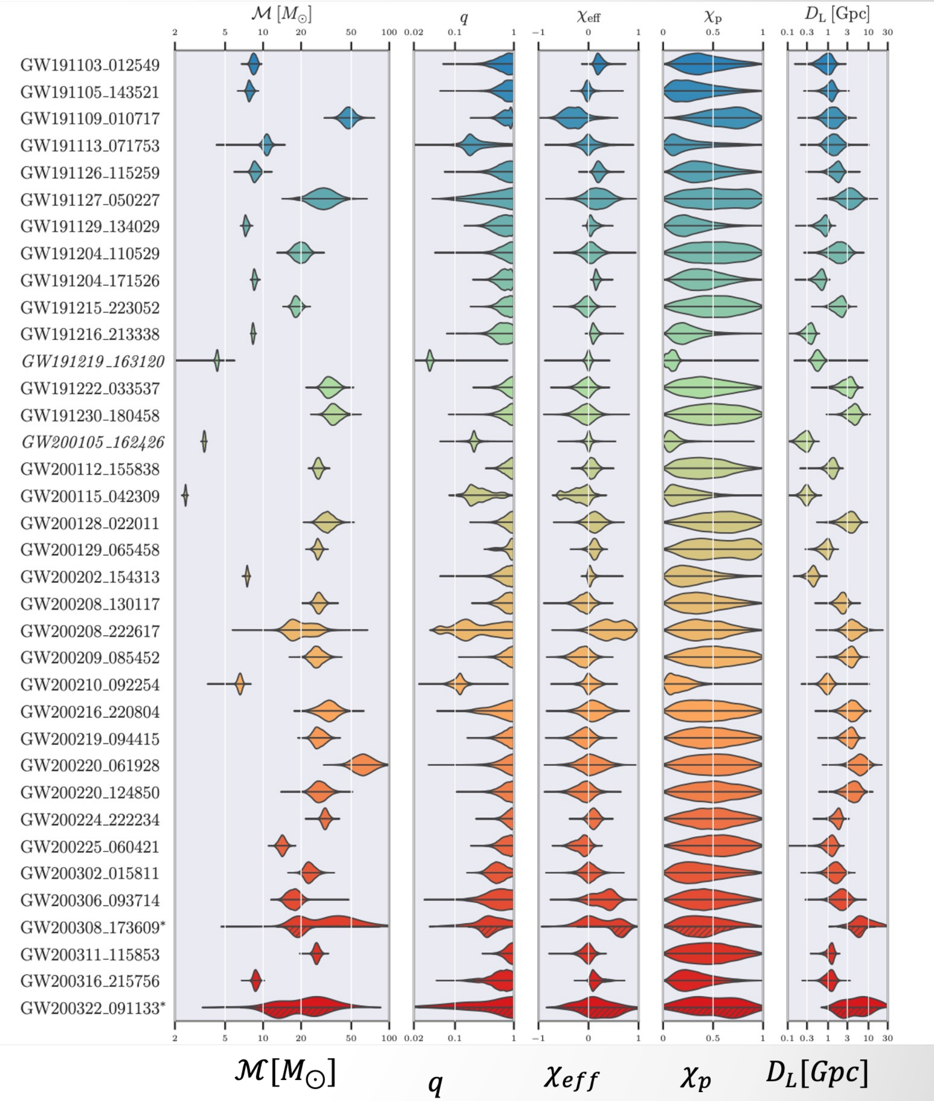
- Main list : 0
- Marginal candidates list : 3

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

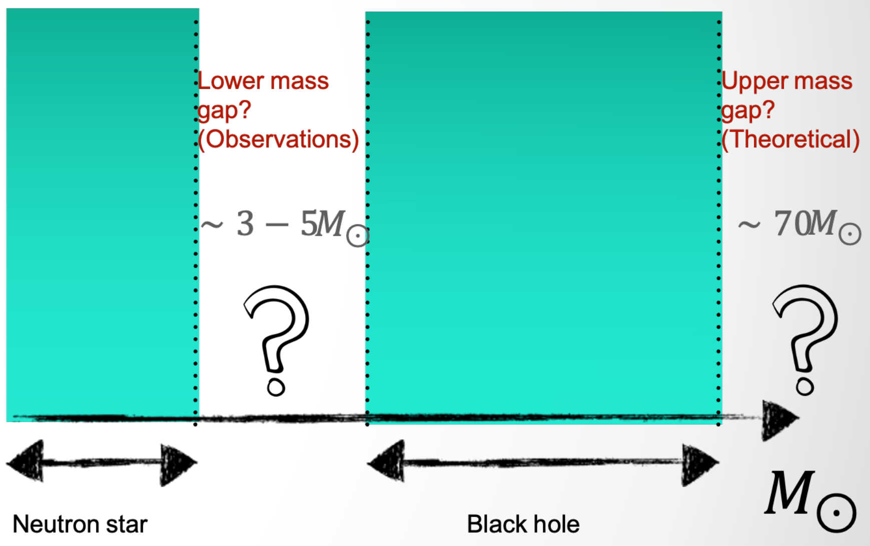
Astrophysical population

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 ?

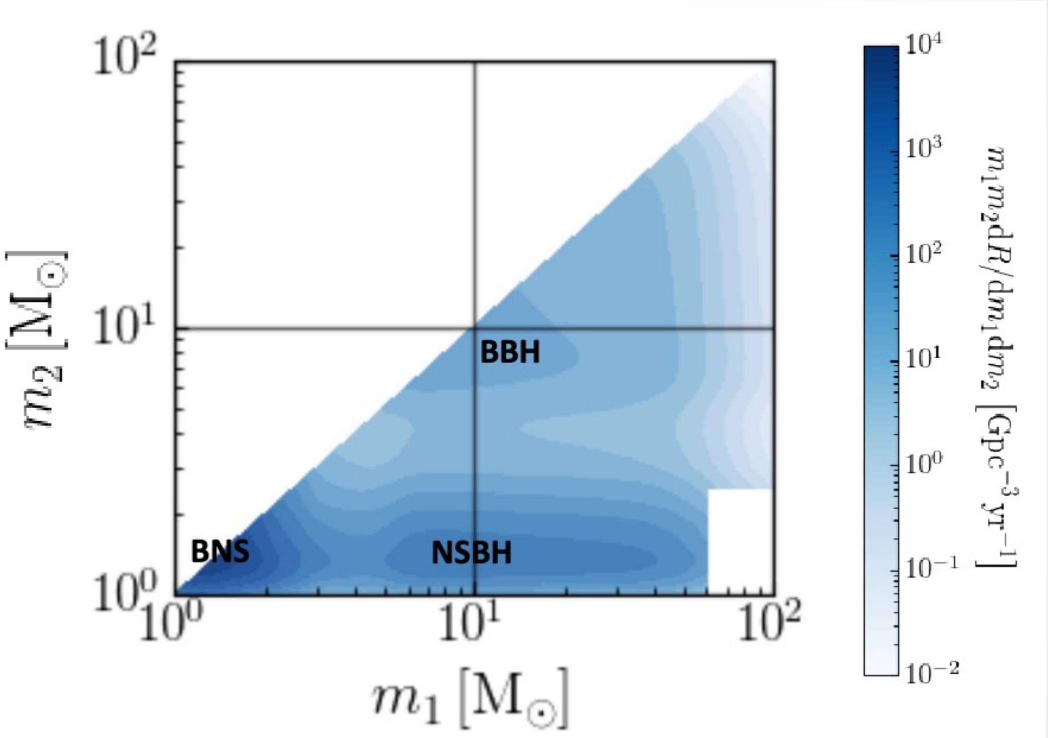
Multiple models but consistent with the same results :

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

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

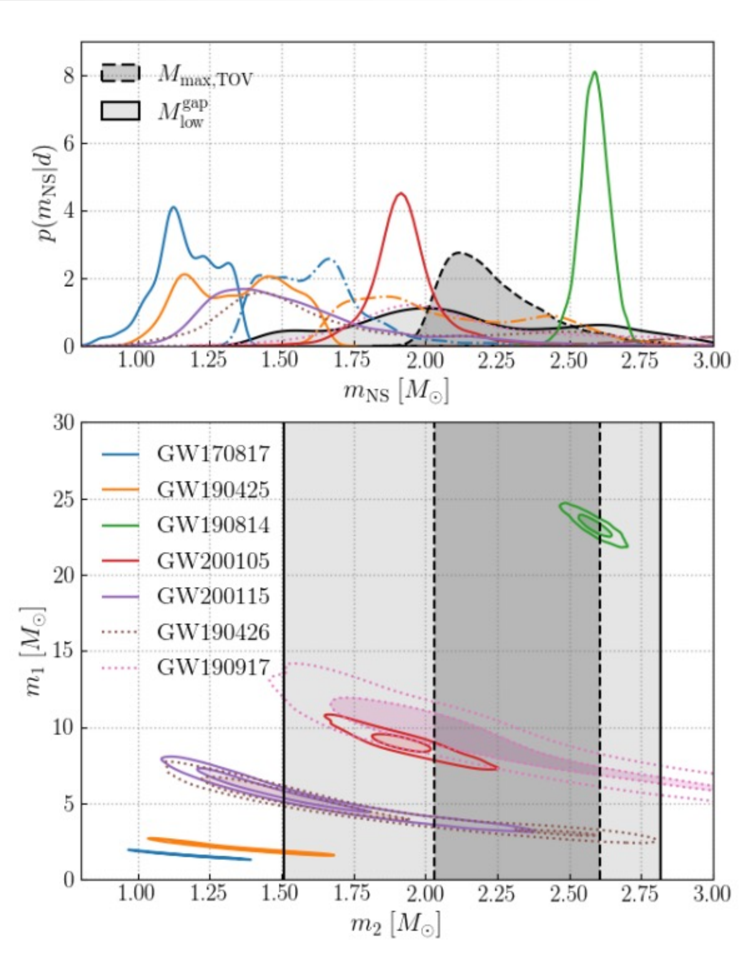
$$\mathcal{R}_{\text{NSBH}} = 170^{+150}_{-89}\ \text{Gpc}^{-3}\text{yr}^{-1}$$

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



Rate density as a function of component masses
(from https://arxiv.org/pdf/2111.03634.pdf)

Astrophysical population – NS properties

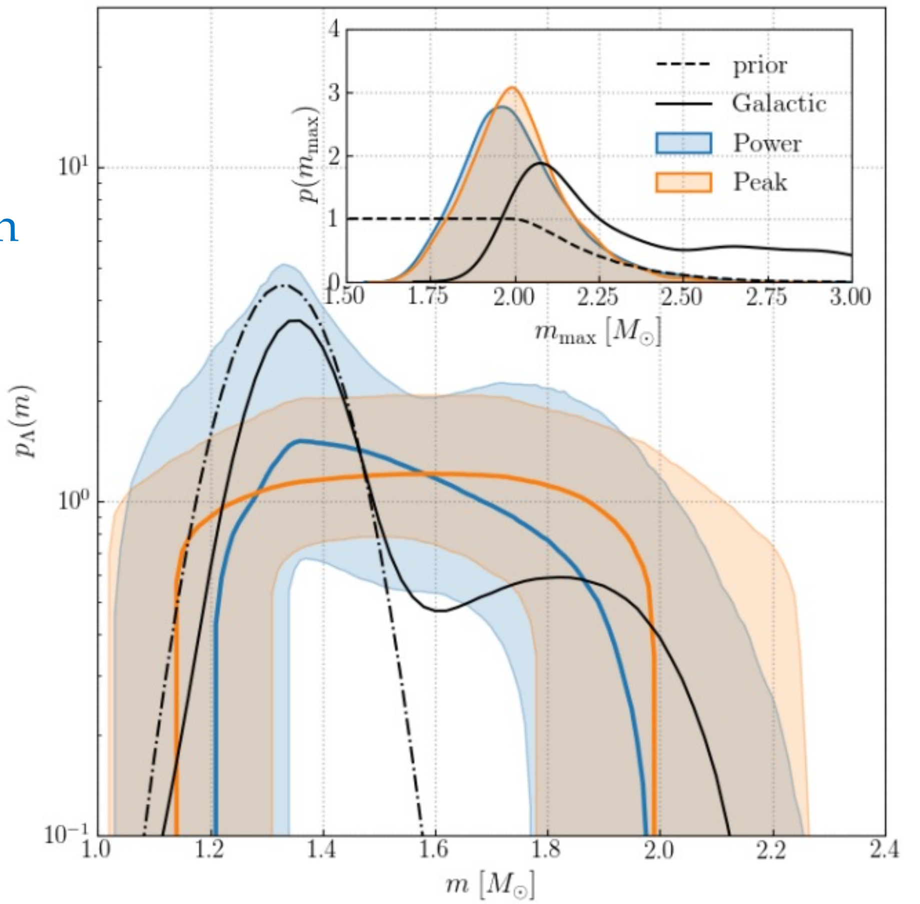


Masses for events with at least one candidate neutron

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

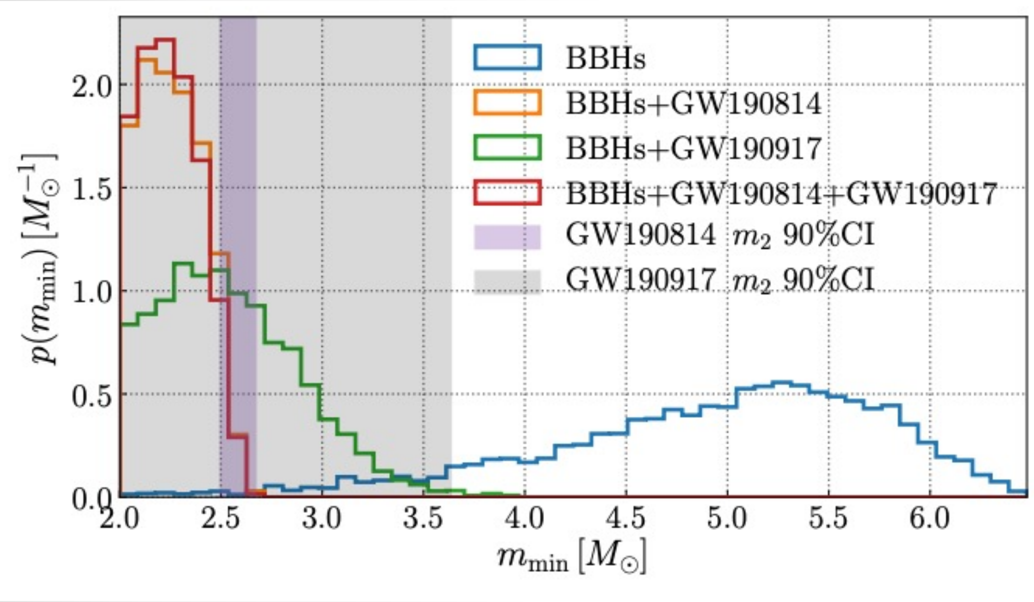
Consistent with the mass found with the equation of state & Galactic pulsars

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.

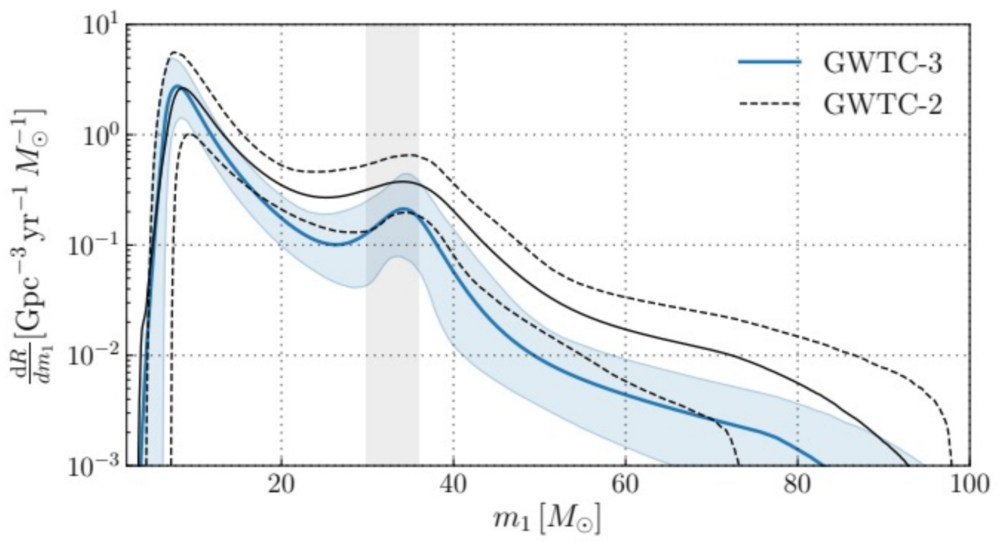


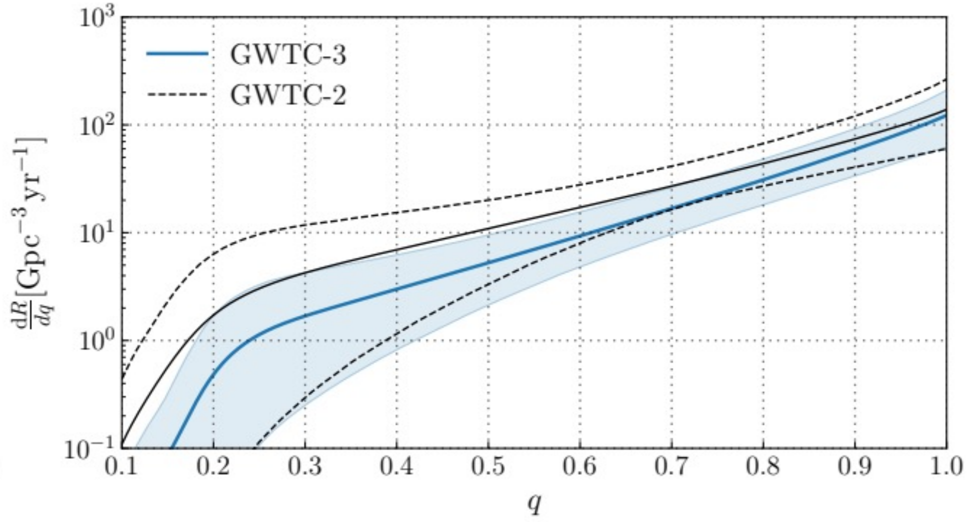
https://arxiv.org/pdf/2111.03634.pdf

Astrophysical population – BBH mass



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

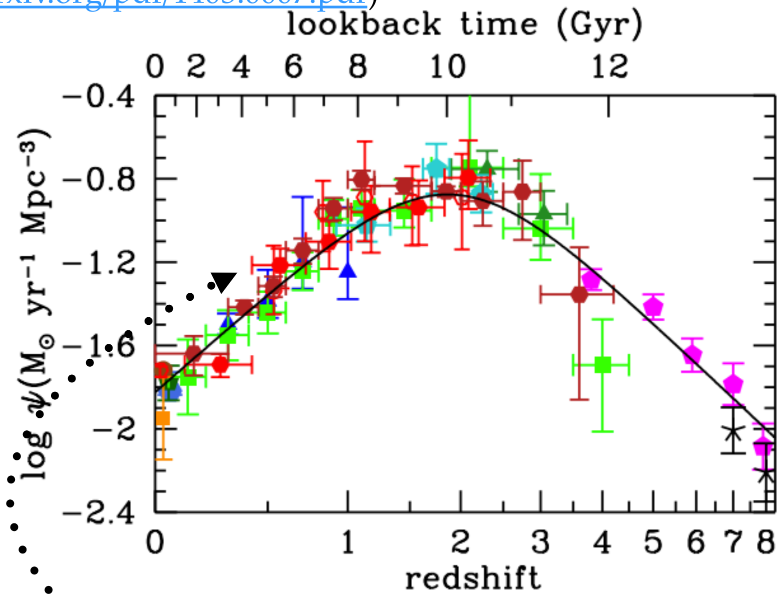


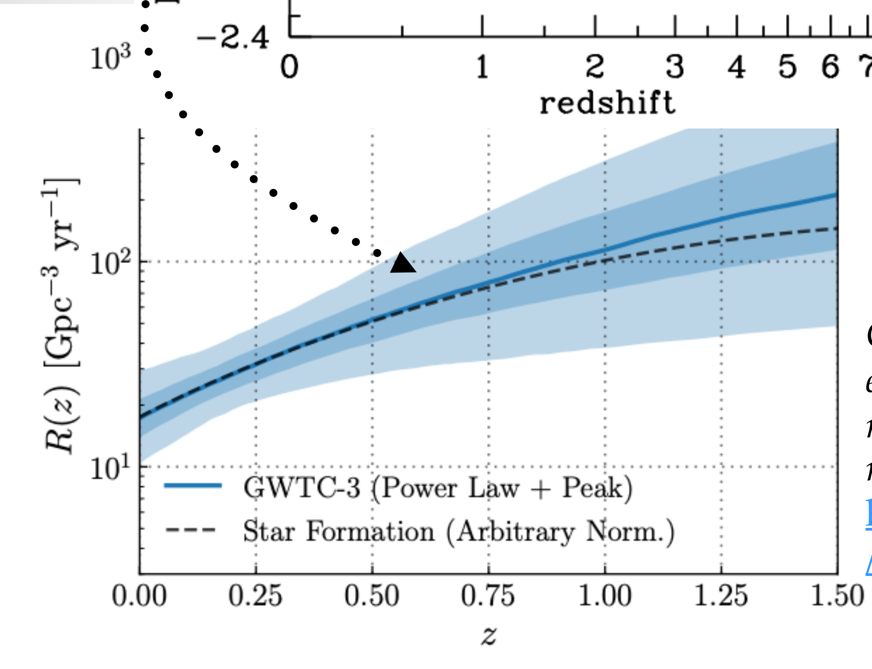


Results consistent between GWTC-2 & GWTC-3:
Inference on astrophysical primary mass distribution: fiducial power law + Gaussian peak at 34 $M_\odot$

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)

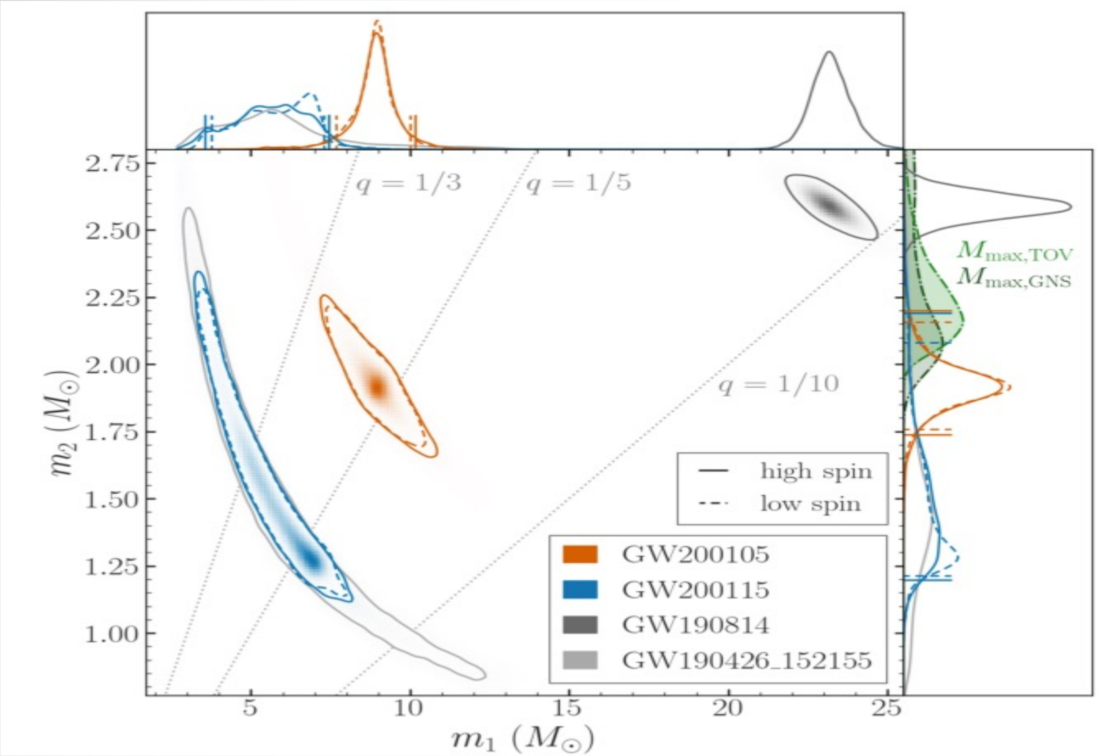
- Merger rate density increases with redshift $\sim(1+z)^{2.7}$ for z<1

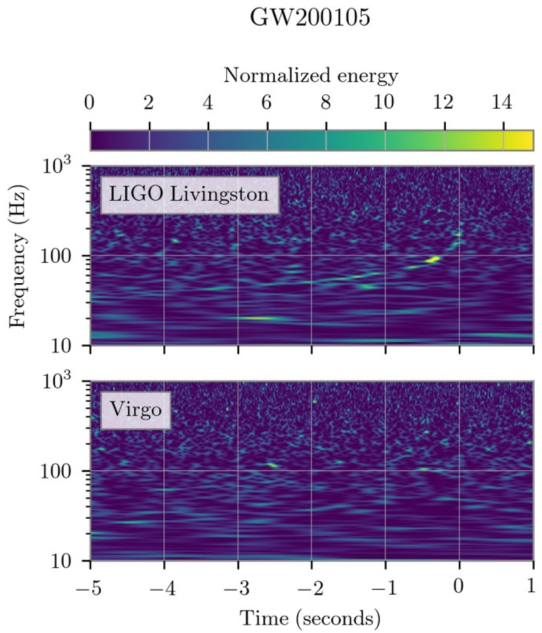
- In most plausible formation scenarios : we do not expect R(z) to continue growing with arbitrarily high z.

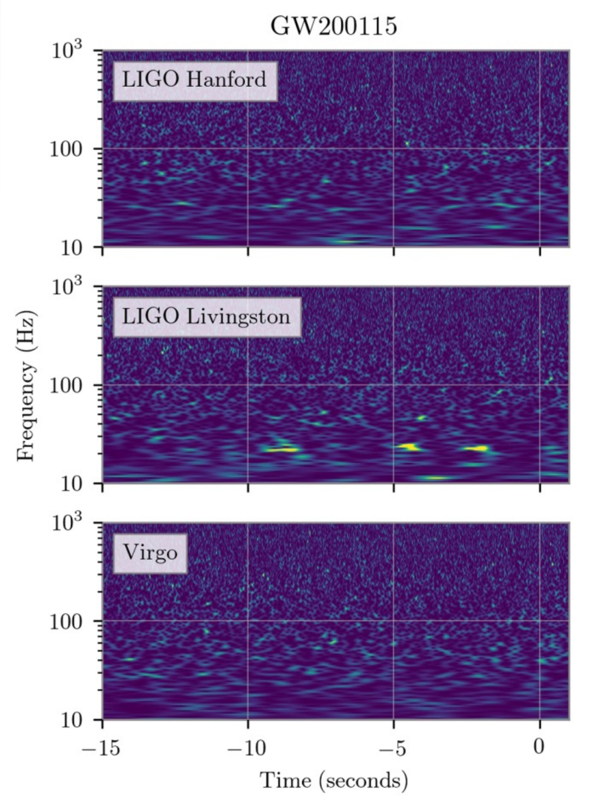
  Instead, we anticipate that R(z) will reach a maximum beyond which it turns over and falls to zero.
  —> not observed yet, maybe with Einstein Telescope ?

- 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

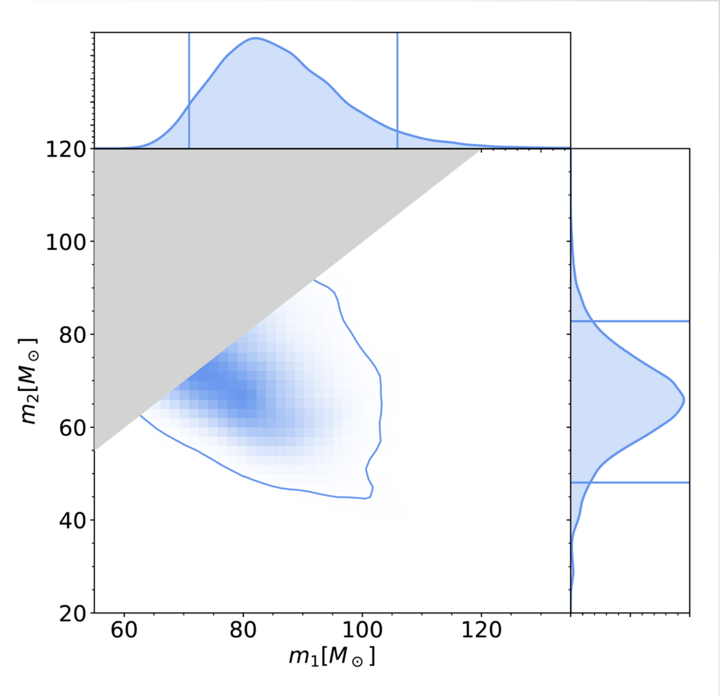
GW200115 m1: 30% probability of falling in the mass gap

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

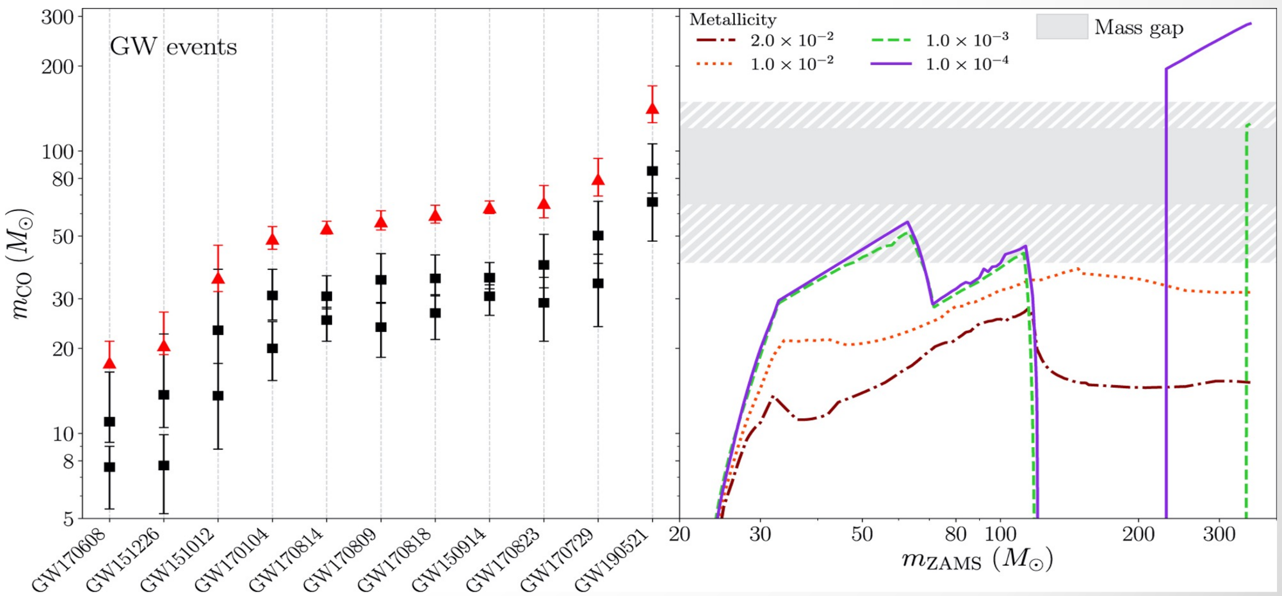
→ Cosmological distance: 5.3 Gpc

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

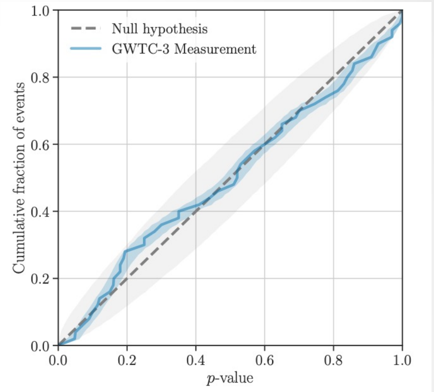
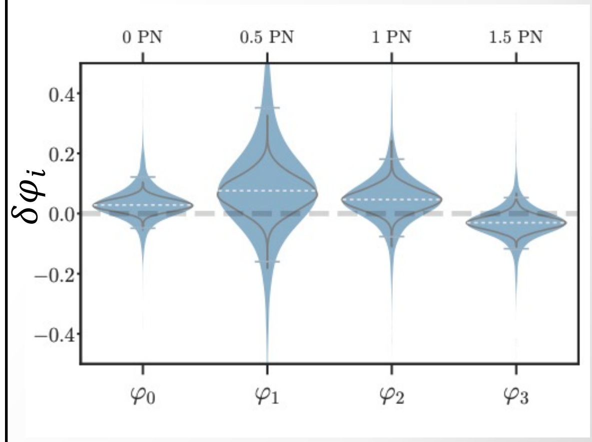


Testing GR

- 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

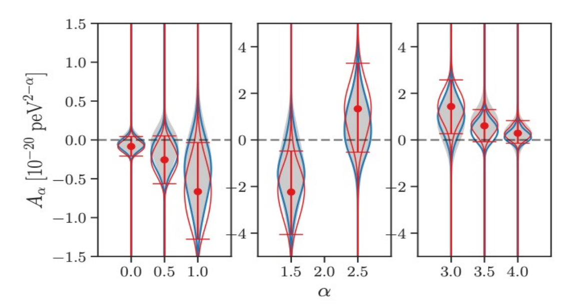
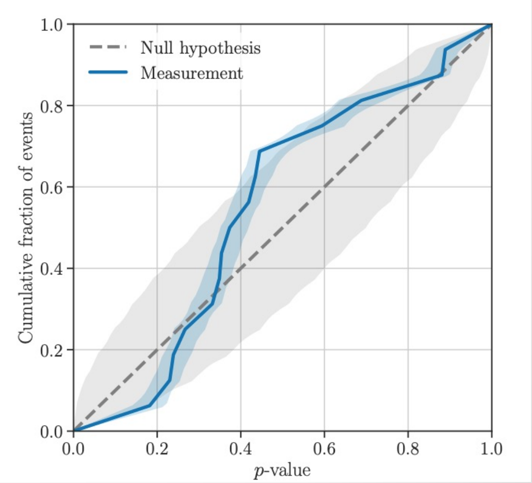
https://arxiv.org/pdf/2112.06861.pdf

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**

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

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** $$m_g < 1.27\times10^{-23} eV/c^2$$
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

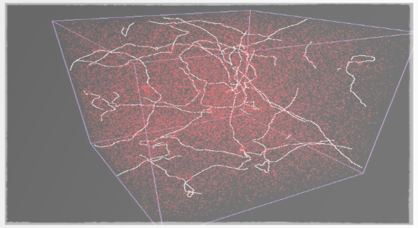
Many more tests of General Relativity have been done :

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

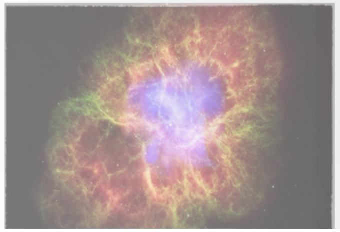
- Found no statistically significant evidences for any deviation from GR

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

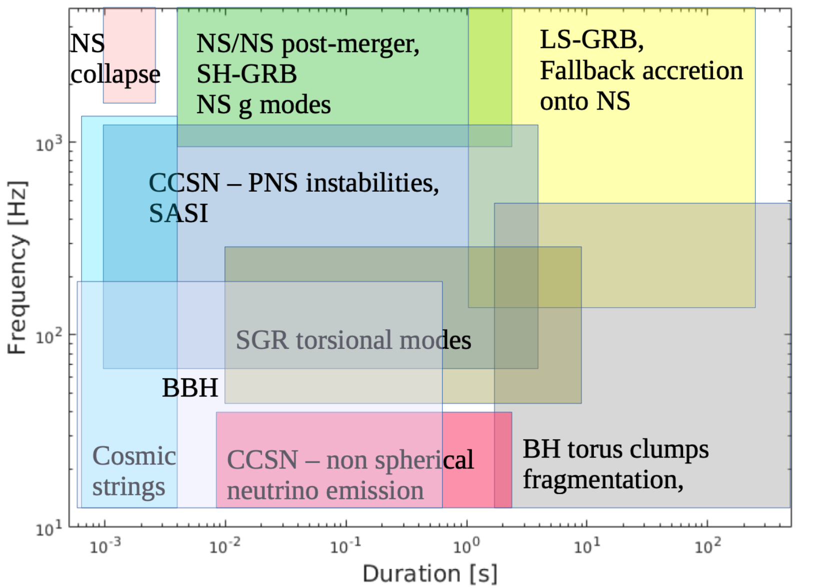
- Testing GR is very hard, even if a deformation is found:
  - Is it really GR that is deformed ?
  - A problem in the data qualify models ?
  - Waveform not enough precise ?



Short transients searches

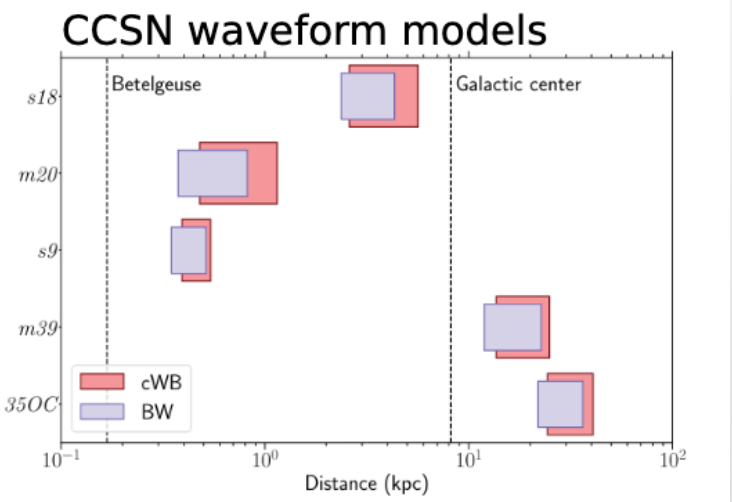


- There are several plausible sources of short-duration GW transients (GW bursts) that have not yet been observed, such as core-collapse supernovae, neutron star excitations, non-linear memory effects, or cosmic string cusps and kinks



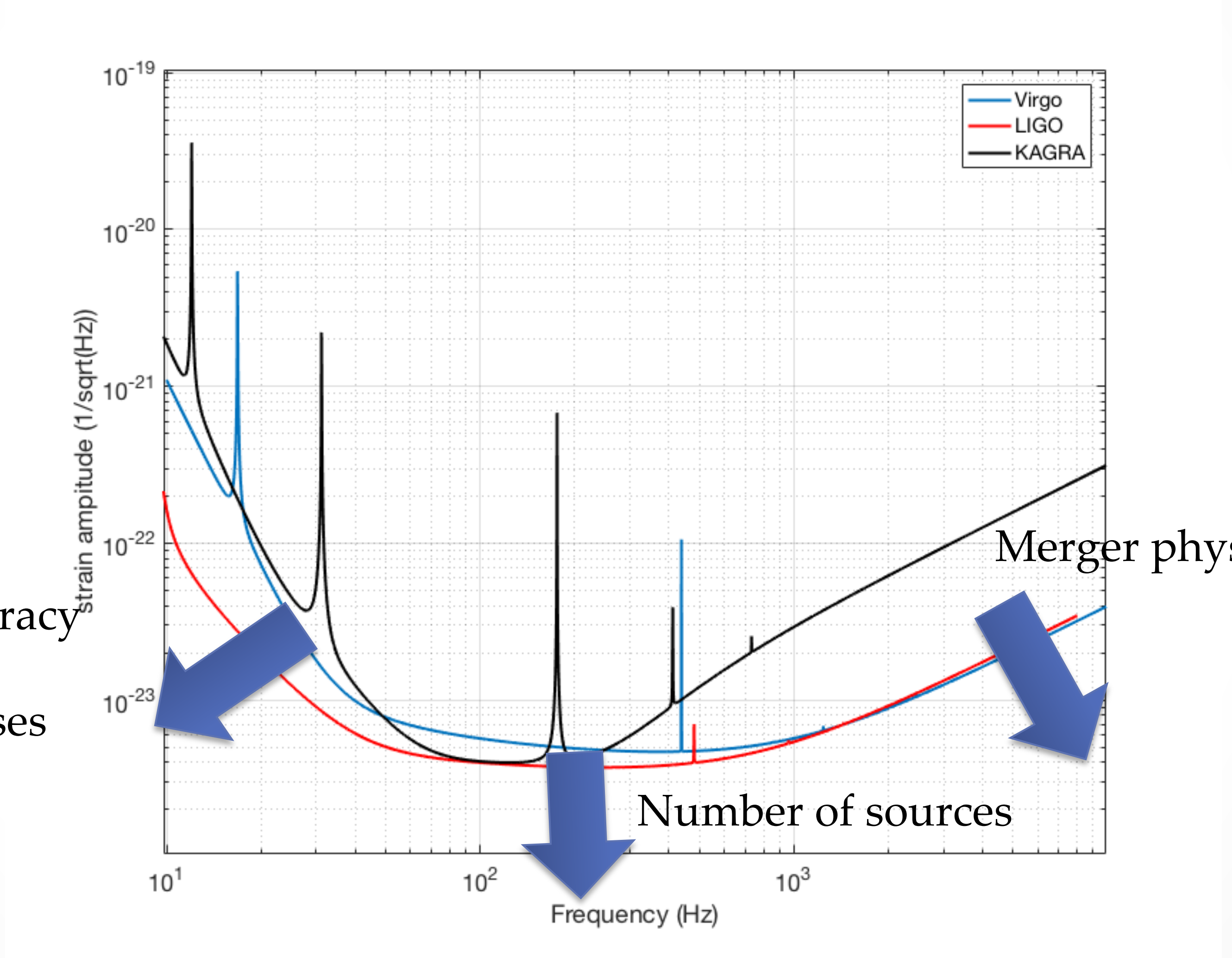
- All-sky search looks for signals arriving at any time from any sky direction : short-duration GW transients, up to a few seconds duration , and longer GW transients, up to $\sim 10^3$ s duration

- 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.

Improving sensitivity



Mass accuracy
High z
High masses

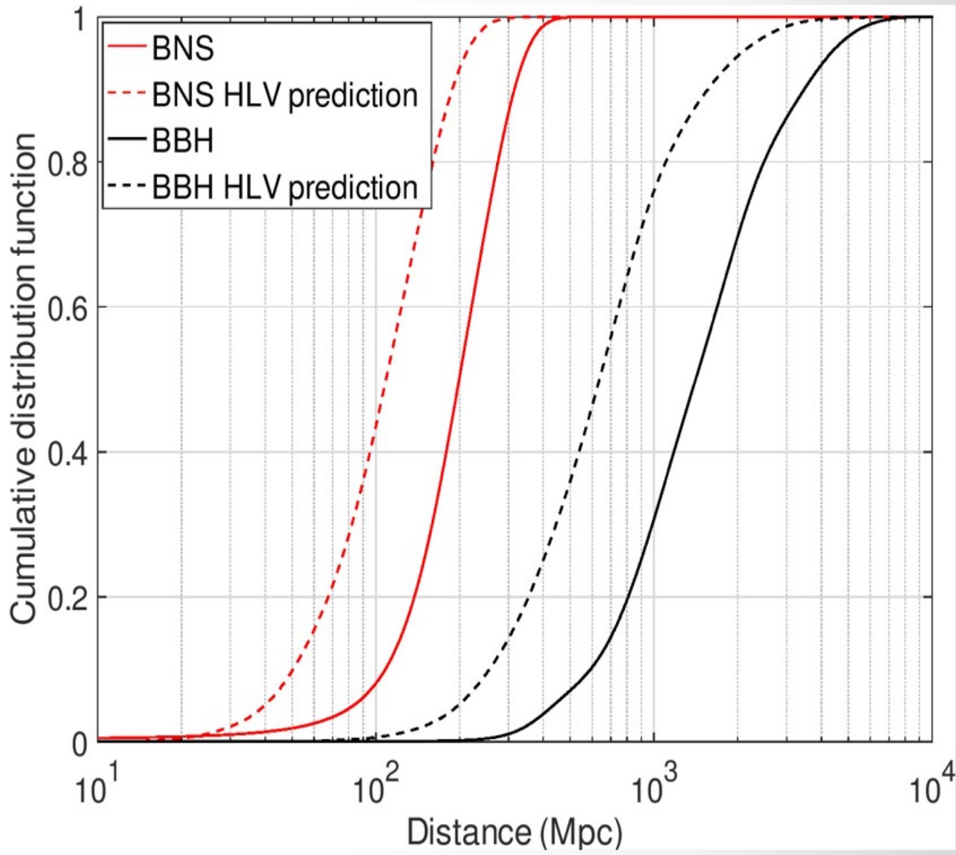
Merger physics

Number of sources

Challenges for O4

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

- **10 (-10 +52) per year (BNS)**
- **1 (-1 +91) per year (NSBH)**
- **79 (-44 +89) per year (BBH)**



GW170817 at 40 Mpc -> Rare event

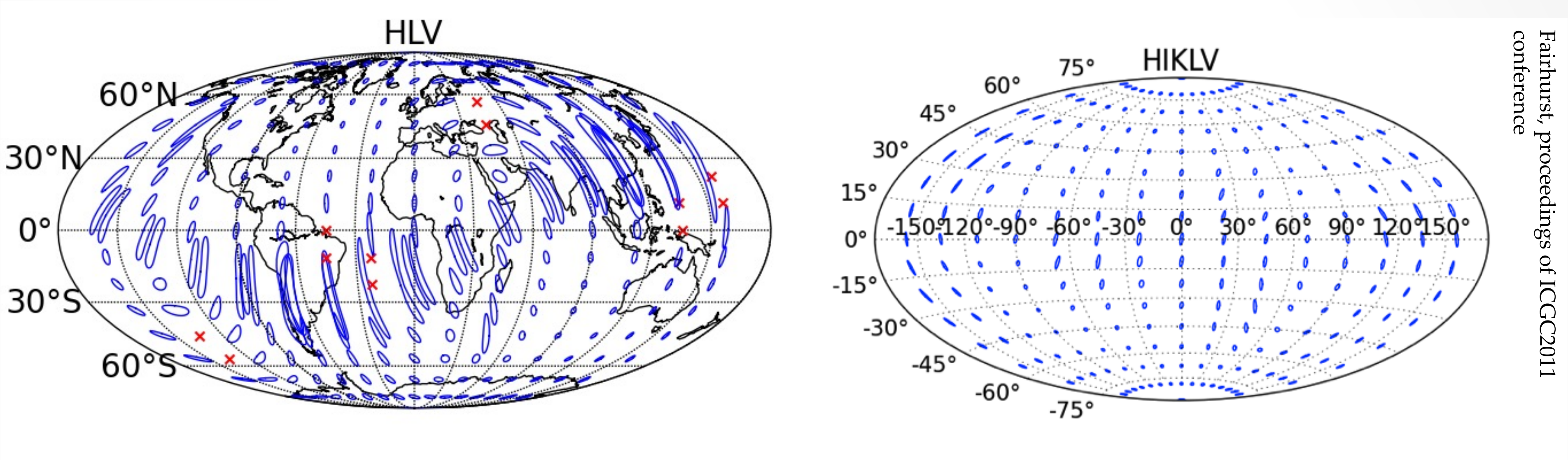
Up to **1 GW alert per day** in O4 (HLV prediction)

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

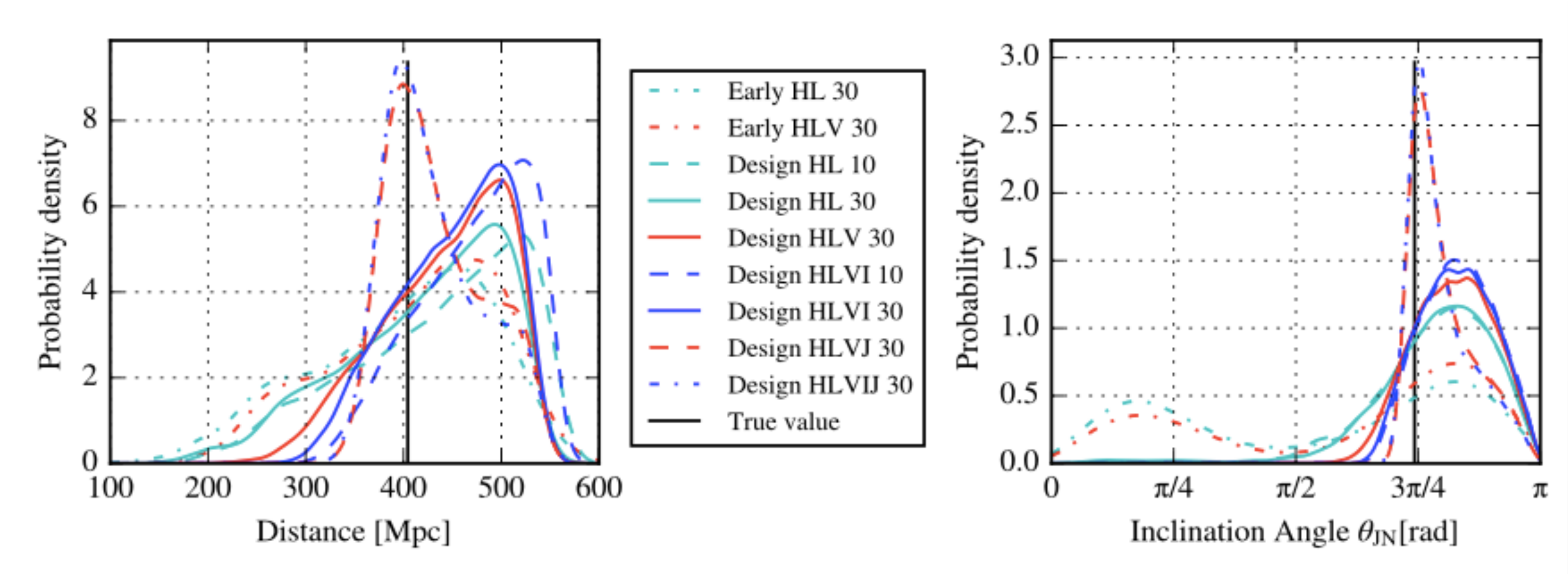
GRB: < 1 GW + GRB per year observable by Fermi

Going beyond :Adding new instruments - parameters inference

Comparison between 3 and 5 detectors for sky localization



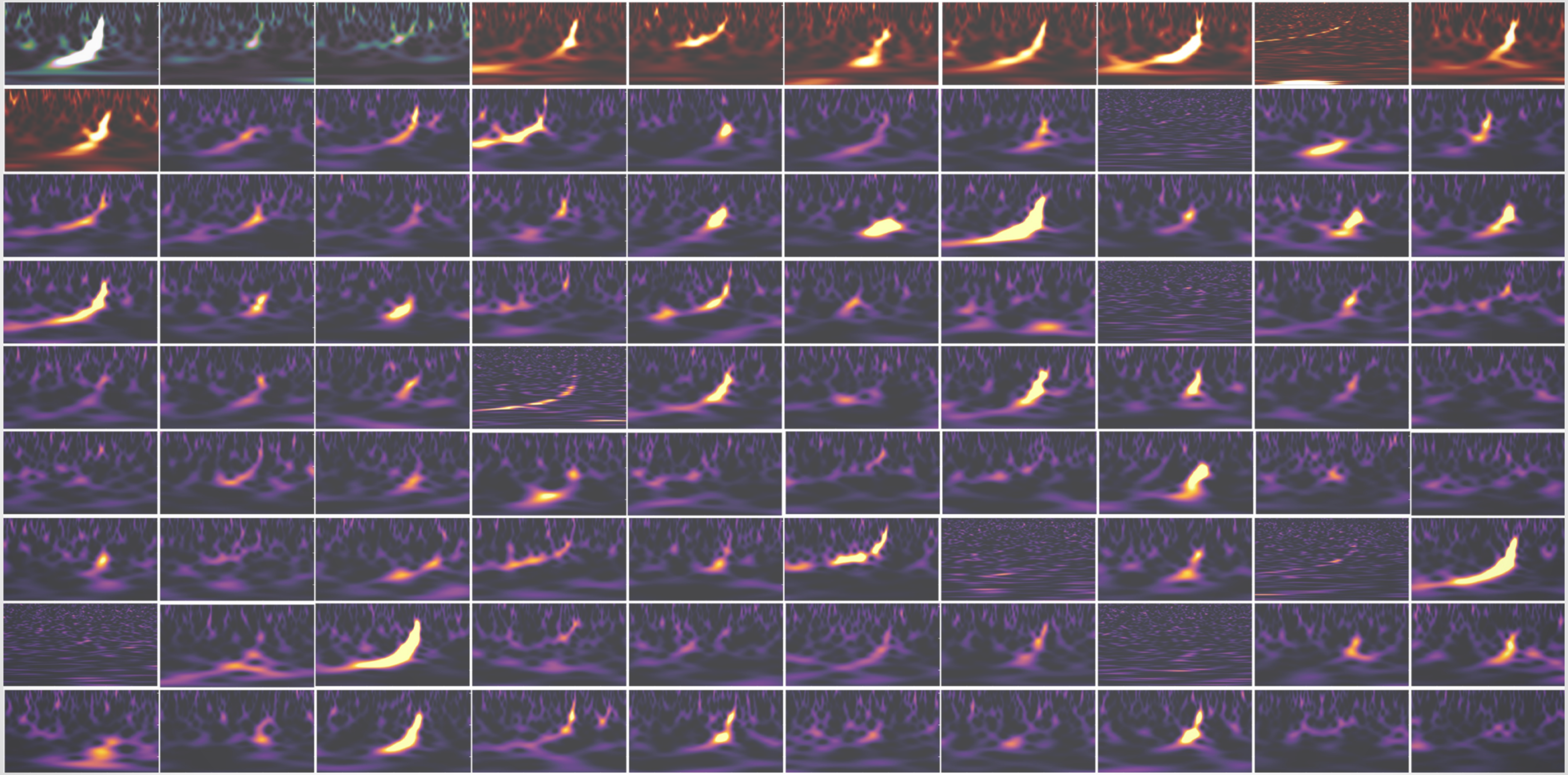
Fairhurst, proceedings of ICGC2011 conference



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

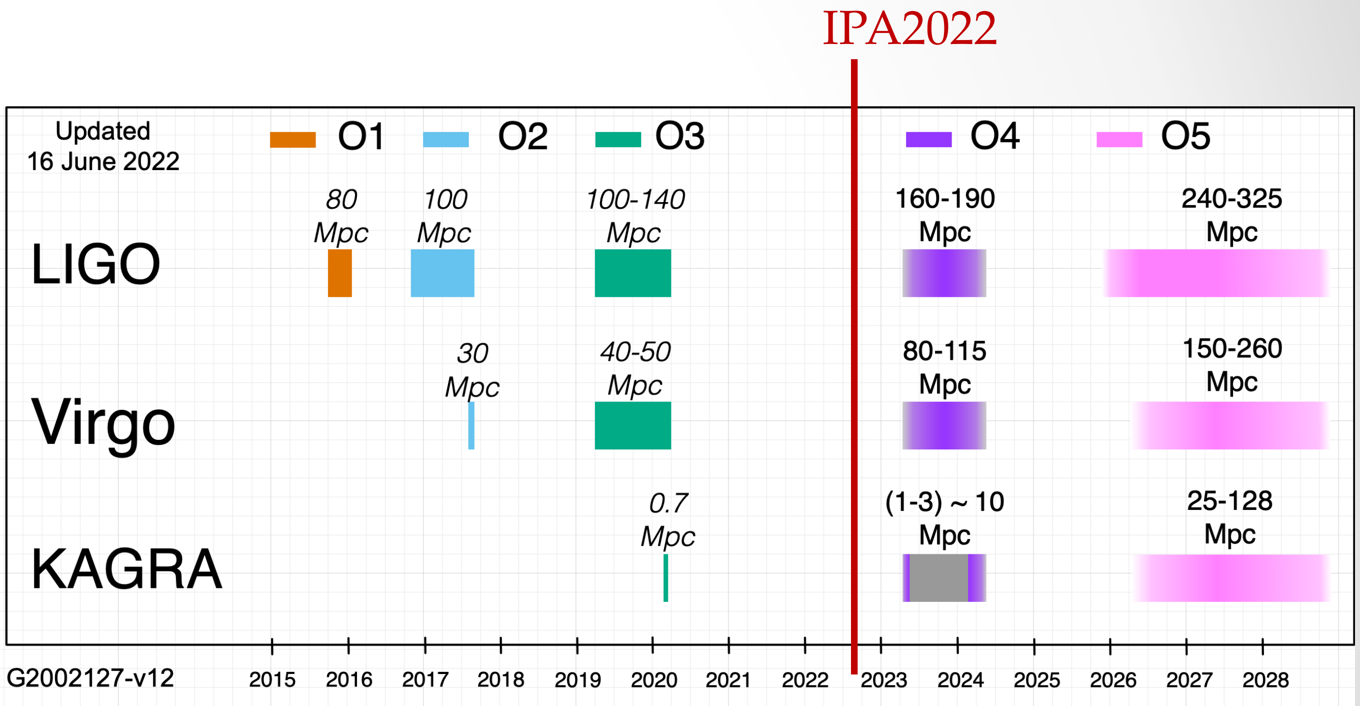
Conclusions

- 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://observing.docs.ligo.org/plan/)

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