A status on gravitational waves detection

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For the LSC – LIGO Scientific Collaboration –
Virgo and Kagra collaborations

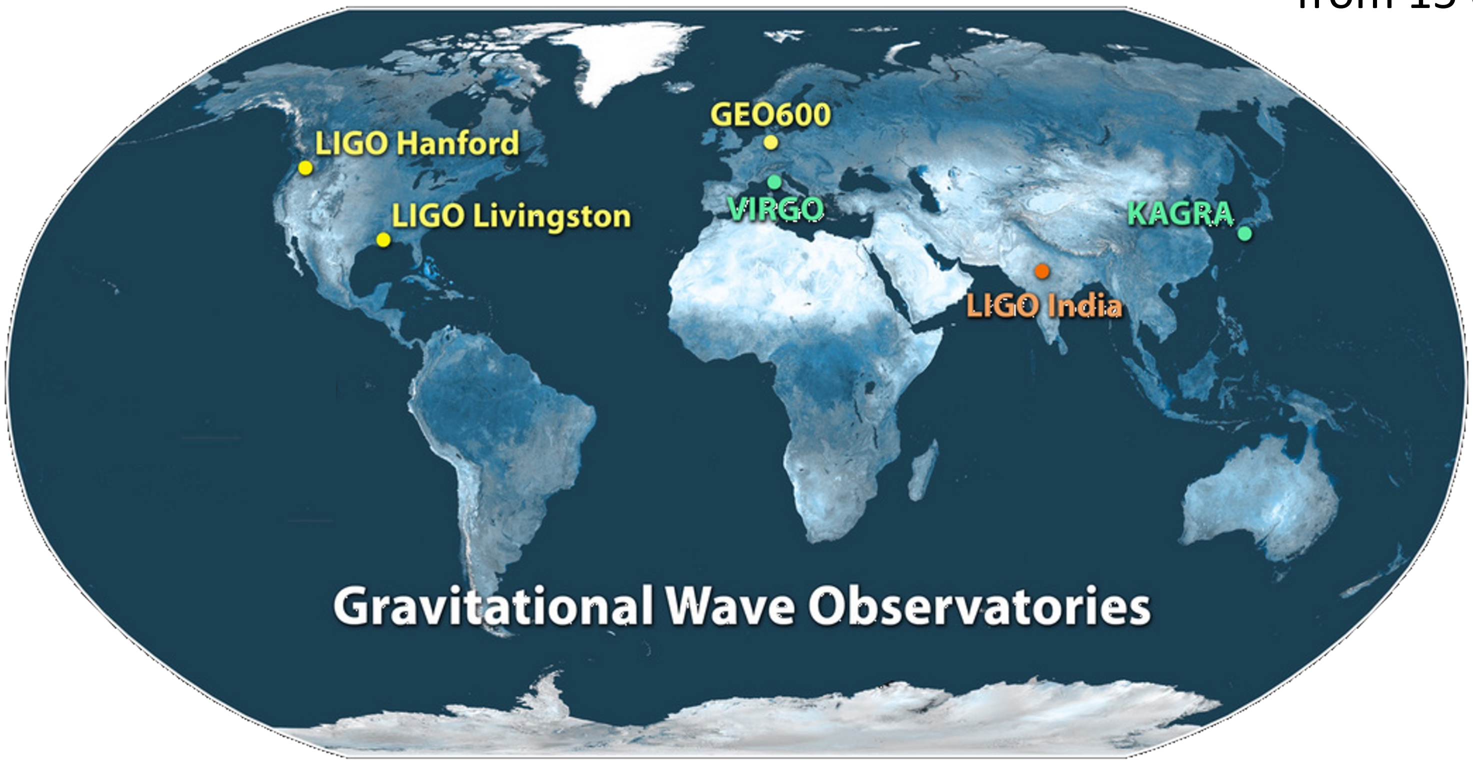
LHC Days in Split, september 2022

Gravitational waves detector network

Virgo : ~700+ members
129 institutions
from 16 countries

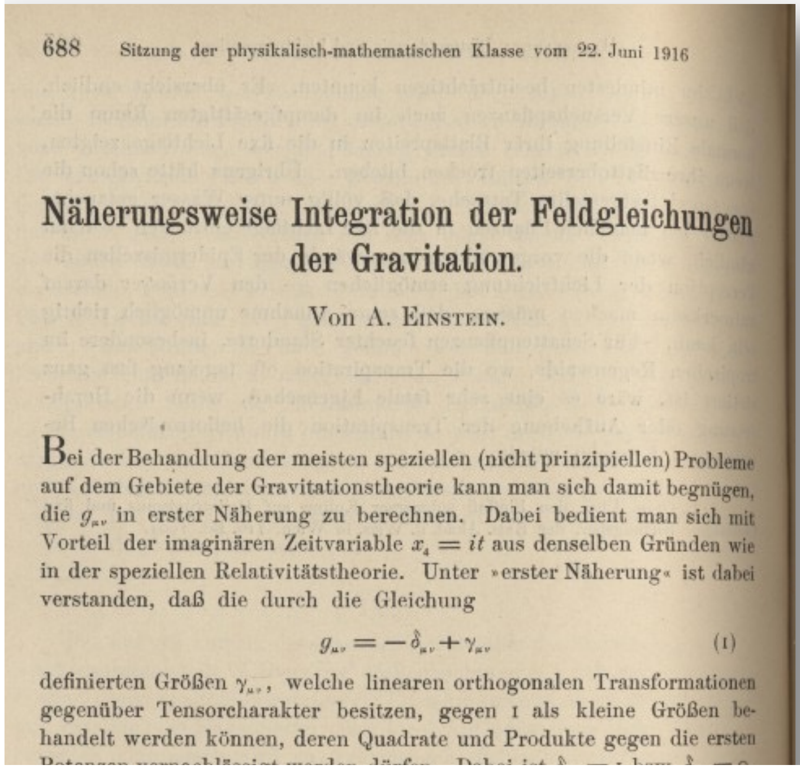
LSC : ~1400+ members
~127 institutions
from ~19 countries

KAGRA : ~400+ members
110 institutions
from 15 countries
or regions



Gravitational waves

- Consequence of the theory of General Relativity (GR)
- Einstein 1916 – 1918
  - Geometric theory of gravitation
  - Describes the curvature of space-time
    and interaction btw space-time and energy-matter



688 Sitzung der physikalisch-mathematischen Klasse vom 22. Juni 1916

Näherungsweise Integration der Feldgleichungen der Gravitation.

Von A. Einstein.

Bei der Behandlung der meisten speziellen (nicht prinzipiellen) Probleme auf dem Gebiete der Gravitationstheorie kann man sich damit begnügen, die $g_{\mu\nu}$ in erster Näherung zu berechnen. Dabei bedient man sich mit Vorteil der imaginären Zeitvariable $x_4 = it$ aus denselben Gründen wie in der speziellen Relativitätstheorie. Unter »erster Näherung« ist dabei verstanden, daß die durch die Gleichung

$$g_{\mu\nu} = -\delta_{\mu\nu} + \gamma_{\mu\nu} \qquad (1)$$

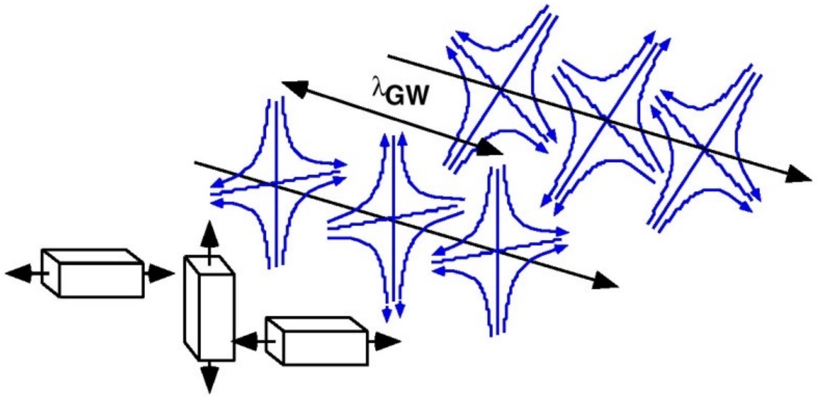
definierten Größen $\gamma_{\mu\nu}$, welche linearen orthogonalen Transformationen gegenüber Tensorcharakter besitzen, gegen 1 als kleine Größen behandelt werden können, deren Quadrate und Produkte gegen die ersten

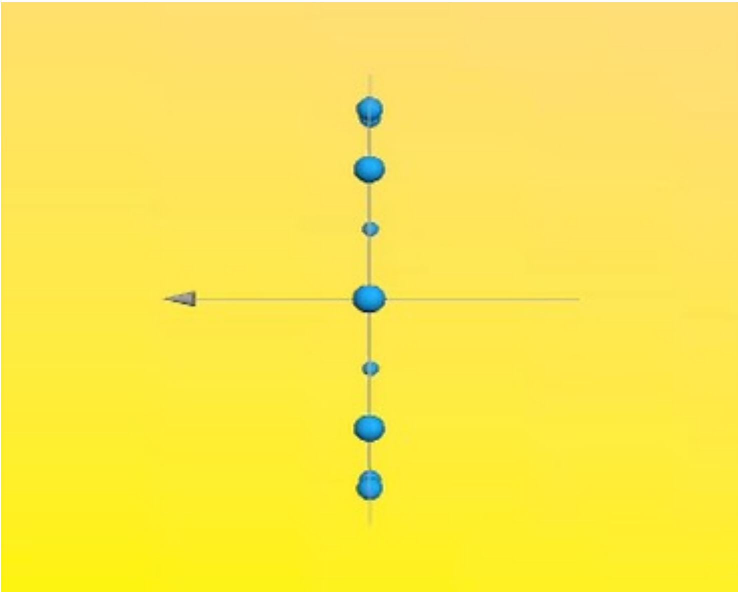
- Develop small perturbations $h_{\mu\nu}$ around a flat (Minkowski) metric
- => wave equation

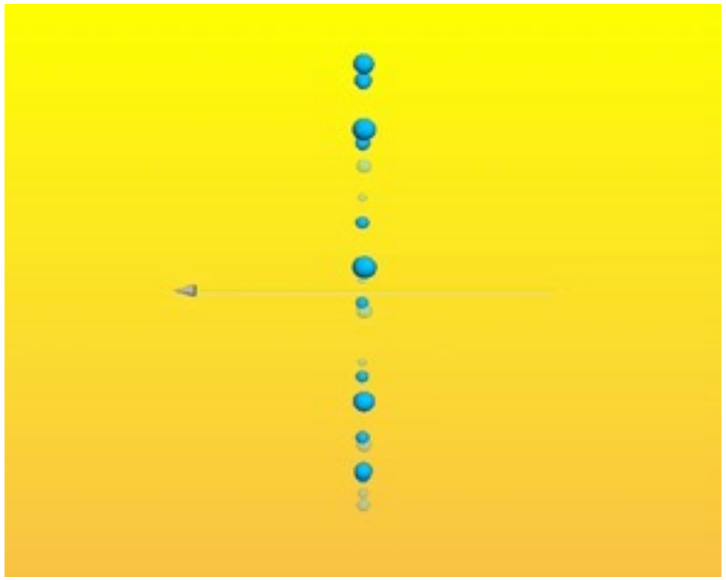
$$(\nabla^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t^2})h_{\mu\nu} = 0$$

Gravitational waves

- Effect on a set of (free) "test" mass

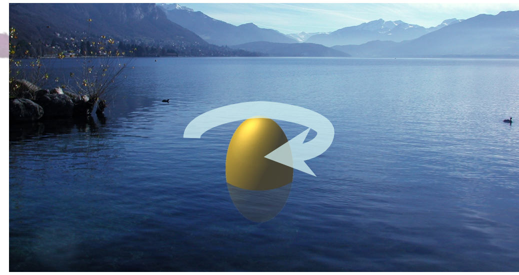




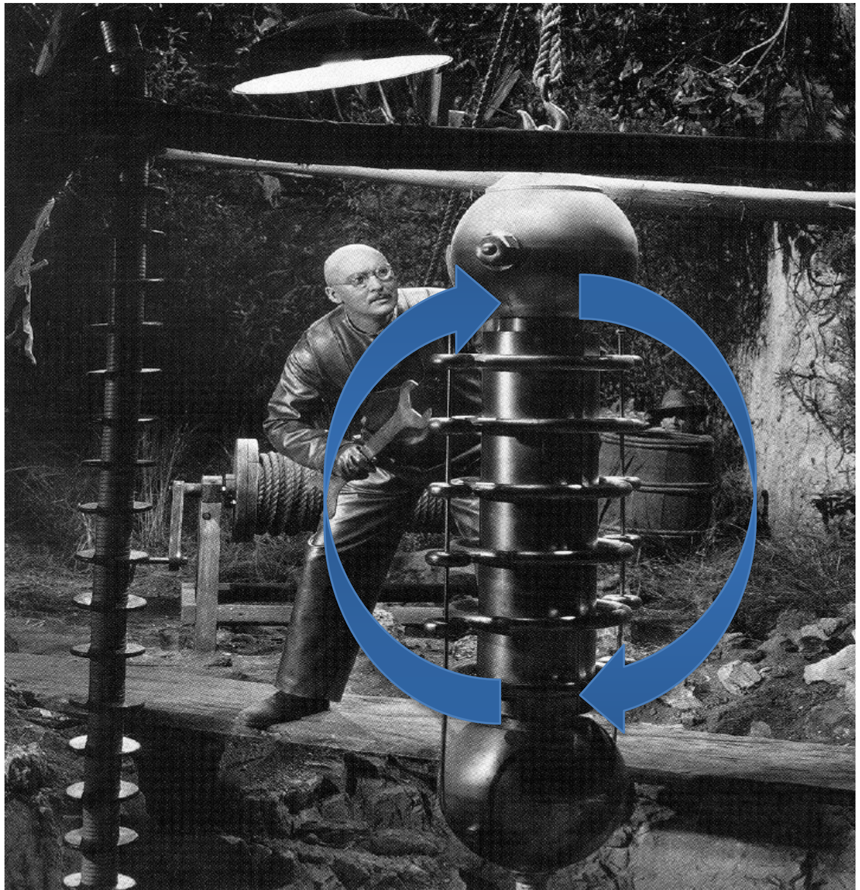


Gravitational waves

- **Production :**




  - Distribution of masses : acceleration of quadrupolar moment



$$h \approx 32\pi^2 \cdot \frac{G}{c^4} \cdot \frac{1}{r} \cdot M \cdot R^2 \cdot f_{orb}^2$$

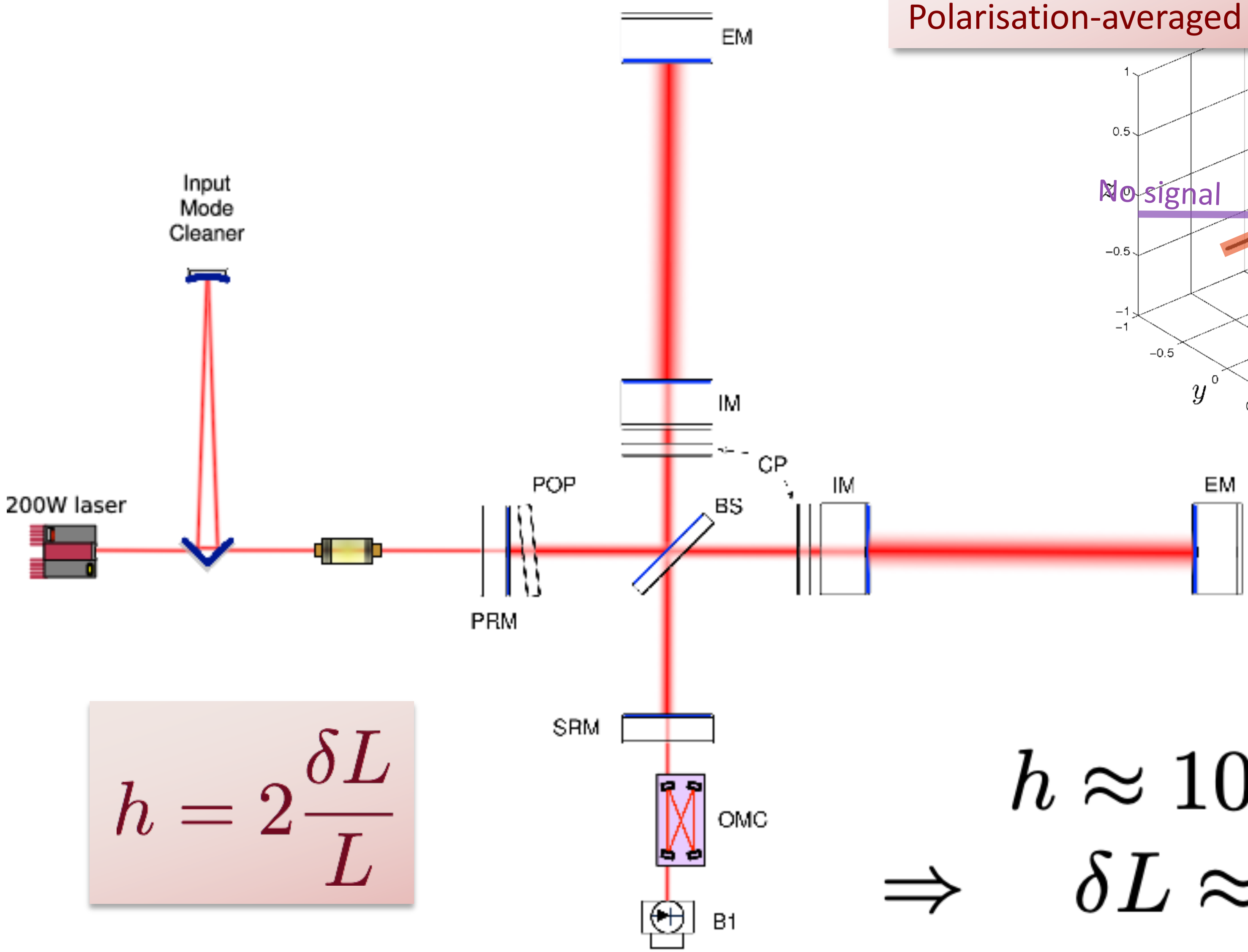
- Examples
  - M = 1000 kg, R = 1 m, f = 1 kHz,
    r = 300 m

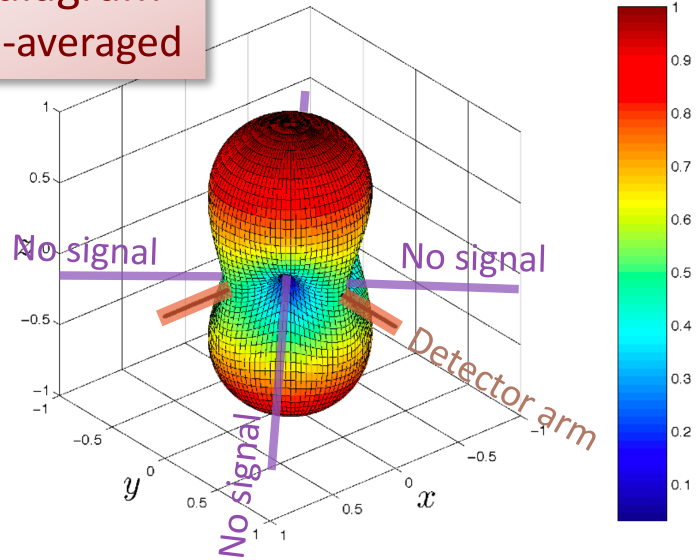
    $h \sim 10^{-35}$

  - $M = 1.4\ M_\odot$, R = 20 km, f = 400 Hz,
    $r = 10^{23}$ m (15 Mpc = 48,9 Mlyr)

    $h \sim 10^{-21}$

Michelson interferometer : a “sensor” of gravitational waves



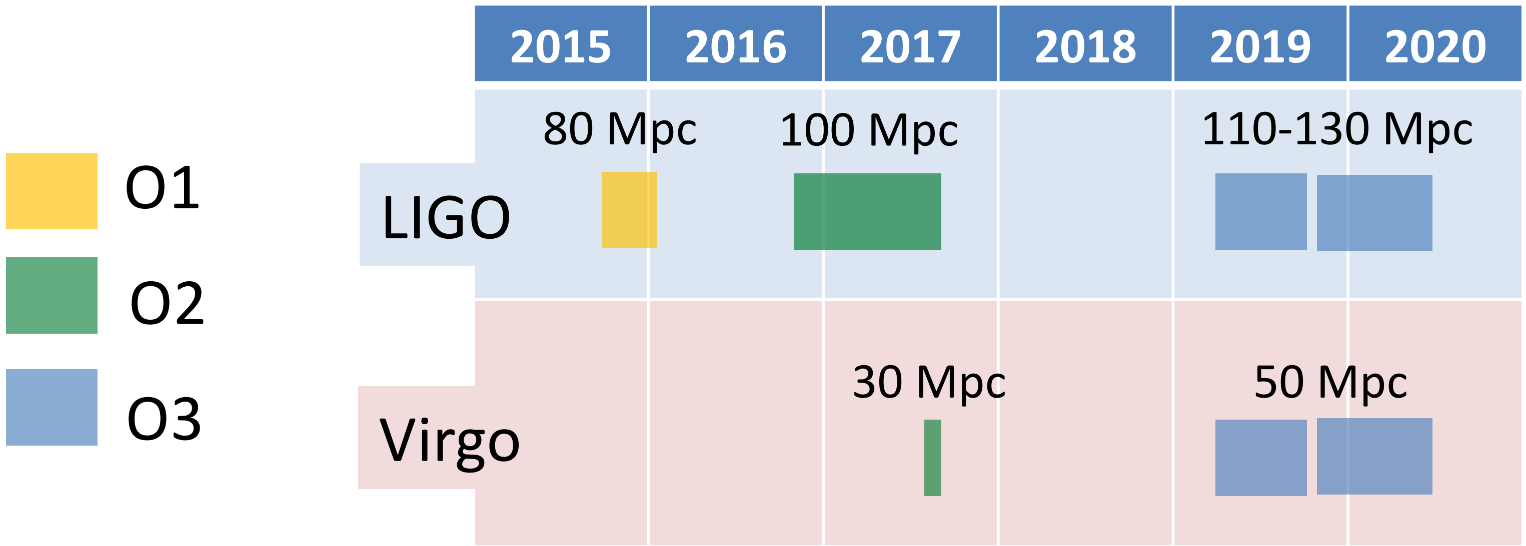


$$h = 2\frac{\delta L}{L}$$

$$h \approx 10^{-23}$$

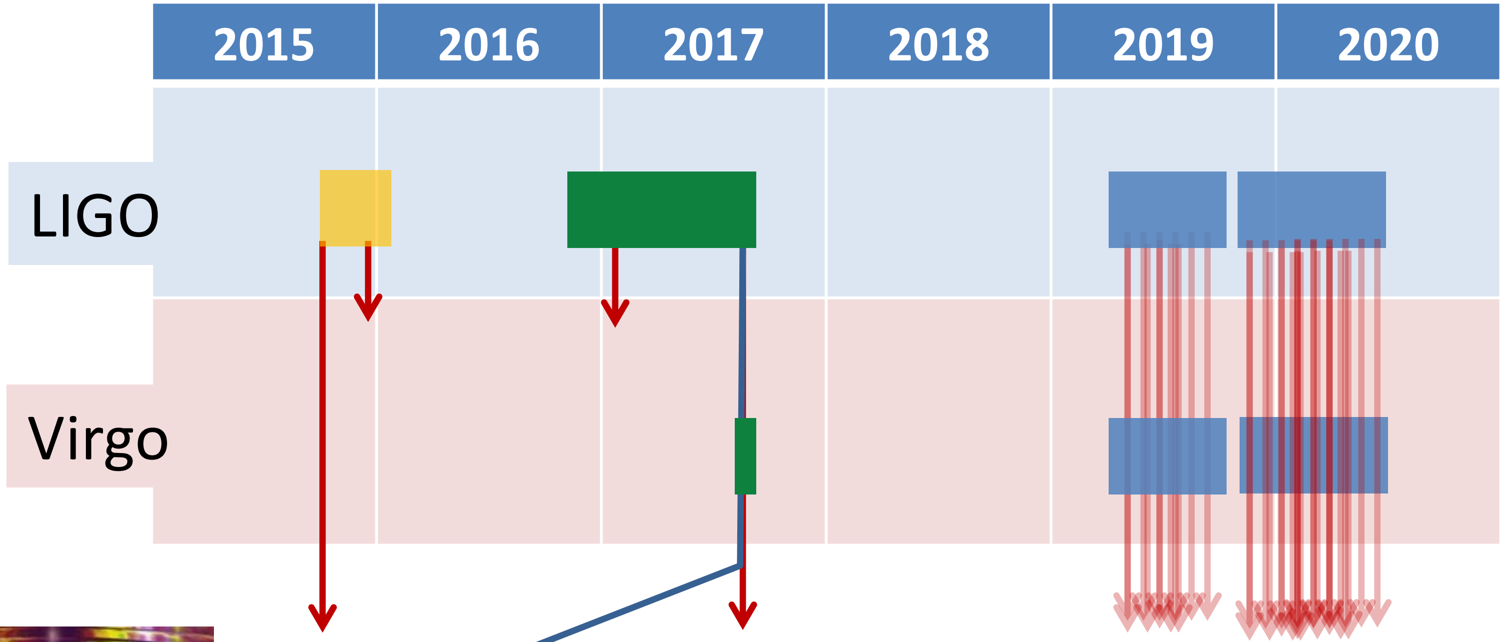
$$\Rightarrow \quad \delta L \approx 10^{-20}\ \text{m}$$

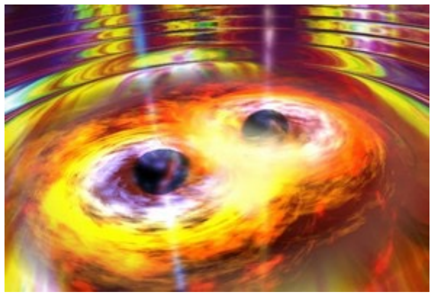
LIGO-Virgo Observing Runs



- « Horizon » distance :
  - Distance at which a particular reference event emitted a signal which can be detected with Signal over Noise Ratio (SNR) = 8
- Reference event = binary neutron star coalescence with 1.4 $M_\odot$ for each component

Events and alerts





GW150914

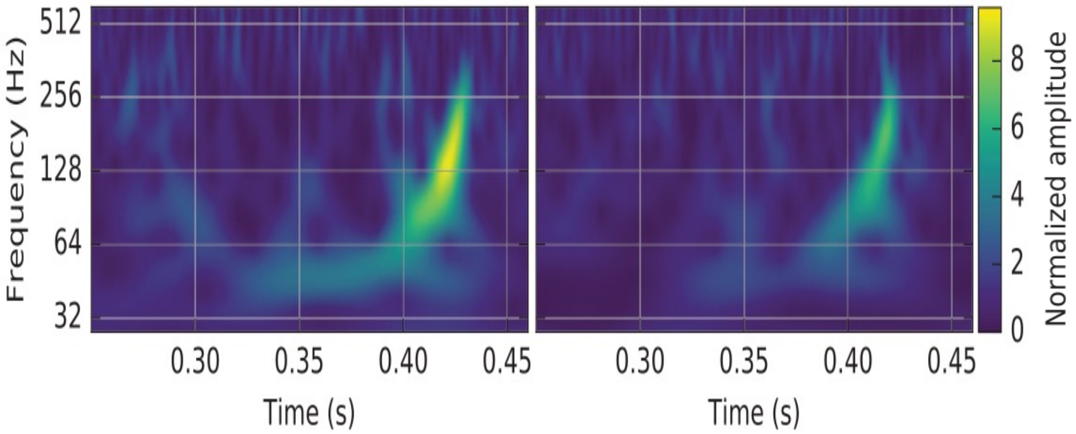
GW170814
First event with
Virgo!

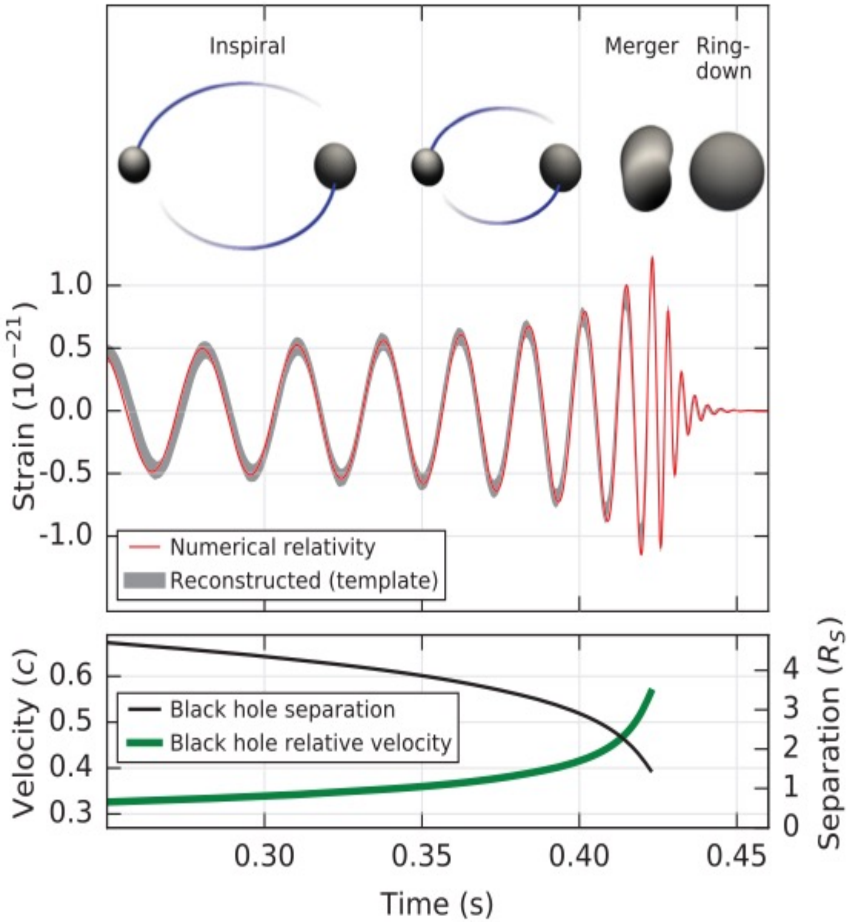
During O3, 79 alerts of which
binary black hole (BH) coalescences,
coalesc. of two neutron stars (NS),
coalescences of NS + BH

GW170817
+ multi-messenger detection!

The discovery : GW150914

Following slides : loosely inspired by W. Del Pozzo, Fermi LAT Coll. Meeting, Pisa 2022



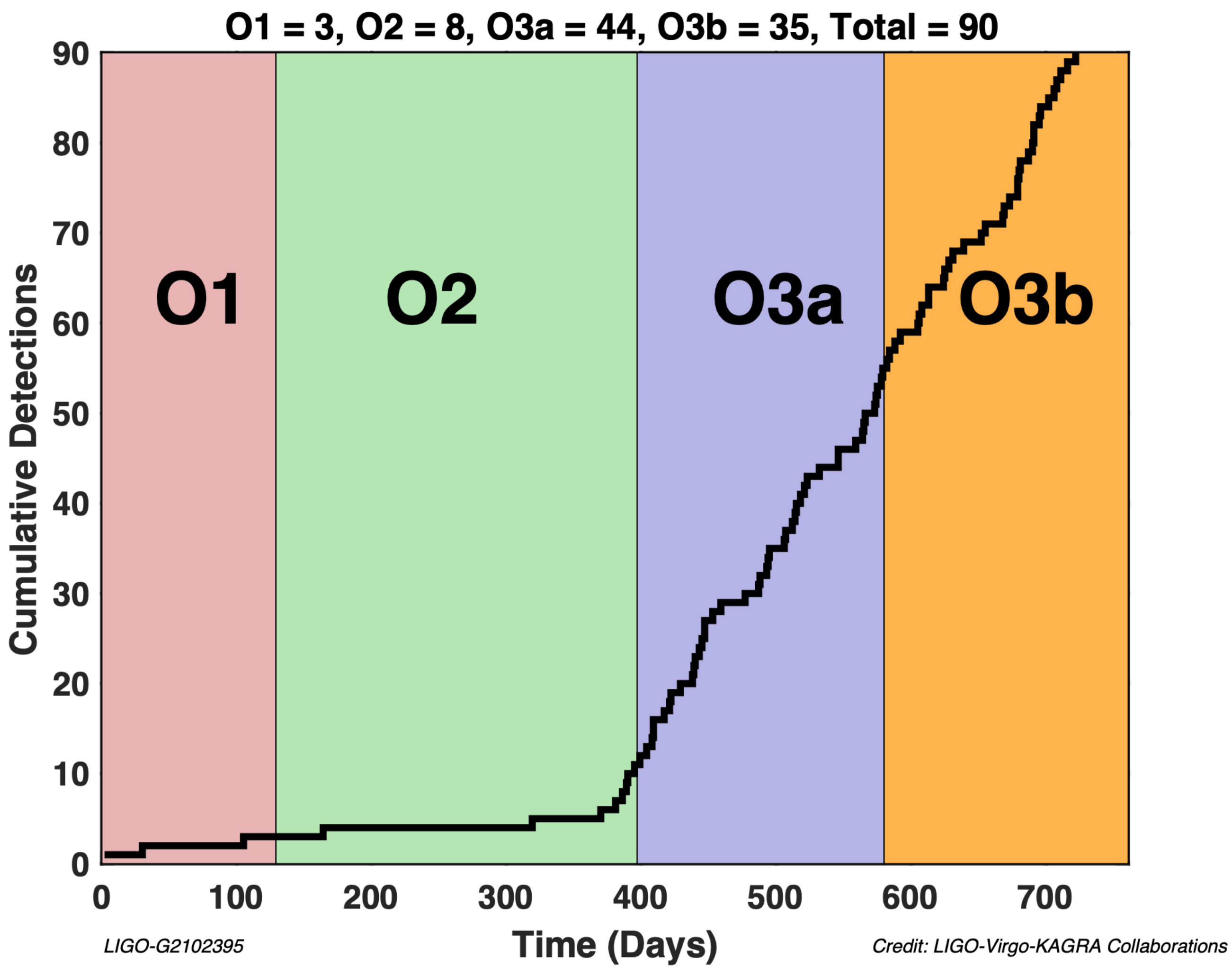


- First observation :
  - Binary dynamics and component nature
  - Non linear dynamics of space-time
  - Final object nature
- And… first tests of GR

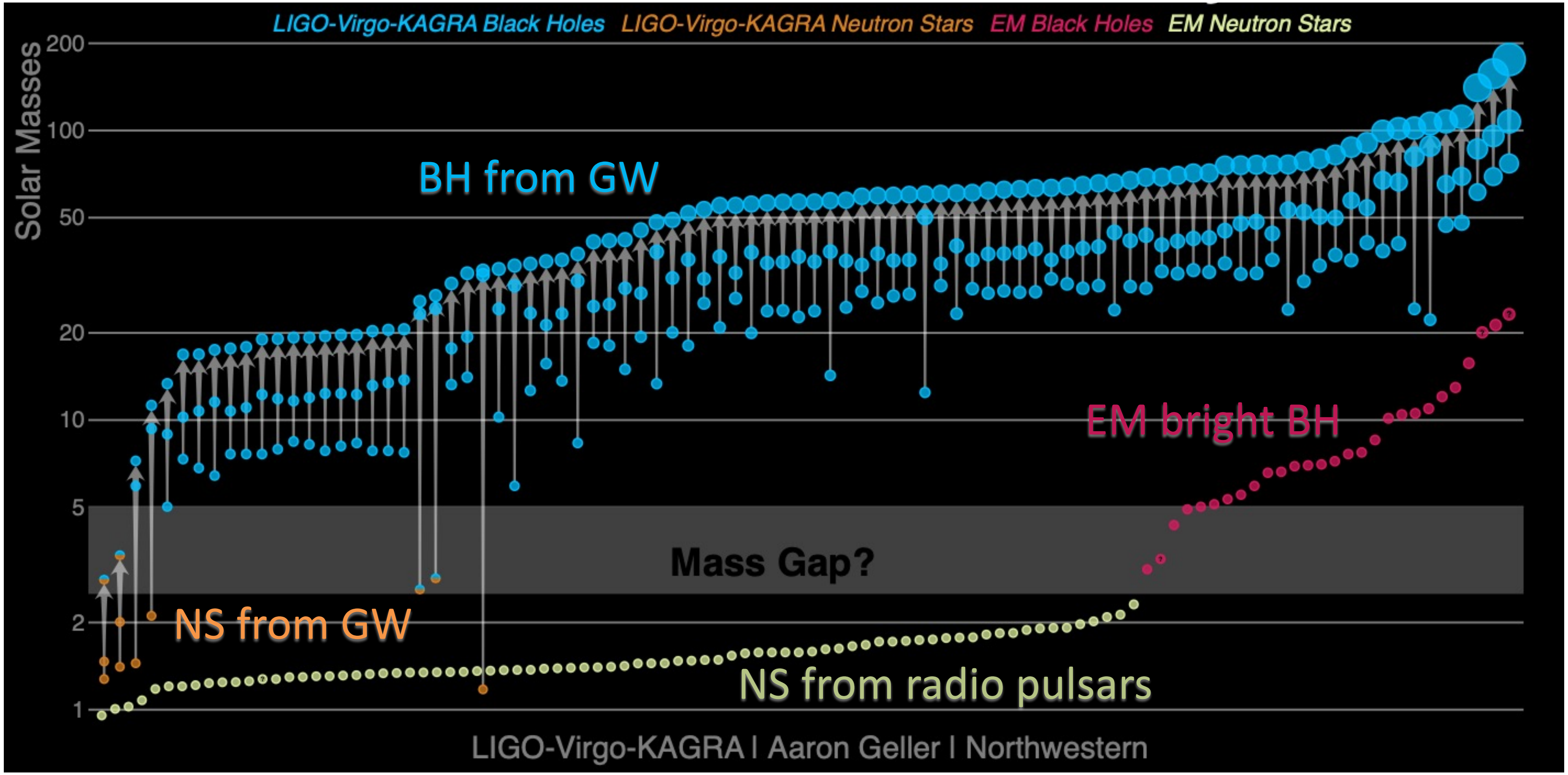
LVC, arXiv:1602.03837, Phys. Rev. Lett. 116, 061102 (2016)

A path to astronomy

- Cumulative detections of binary coalescences



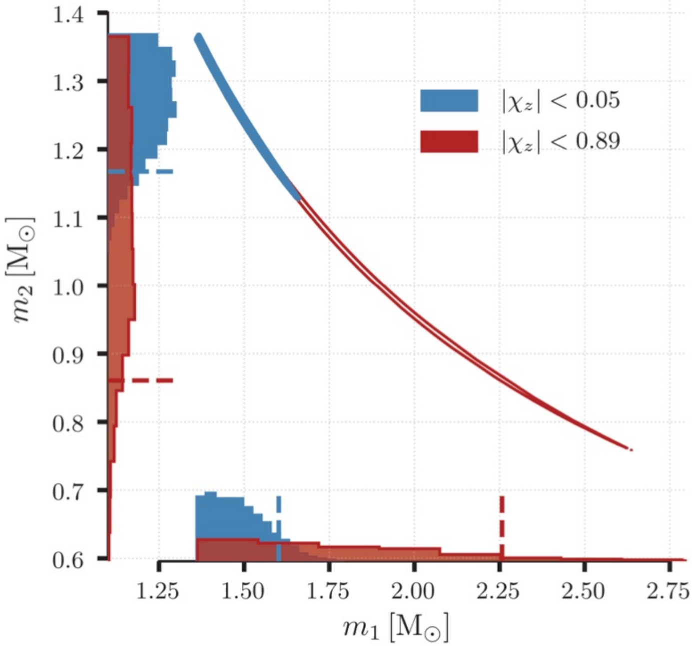
Compact objects

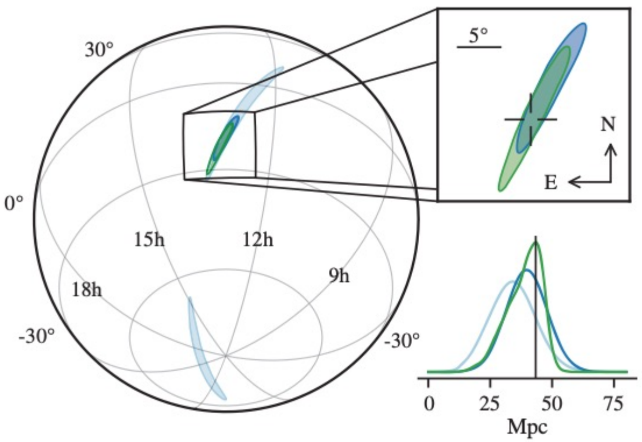


https://ligo.northwestern.edu/media/mass-plot/index.html

BNS systems

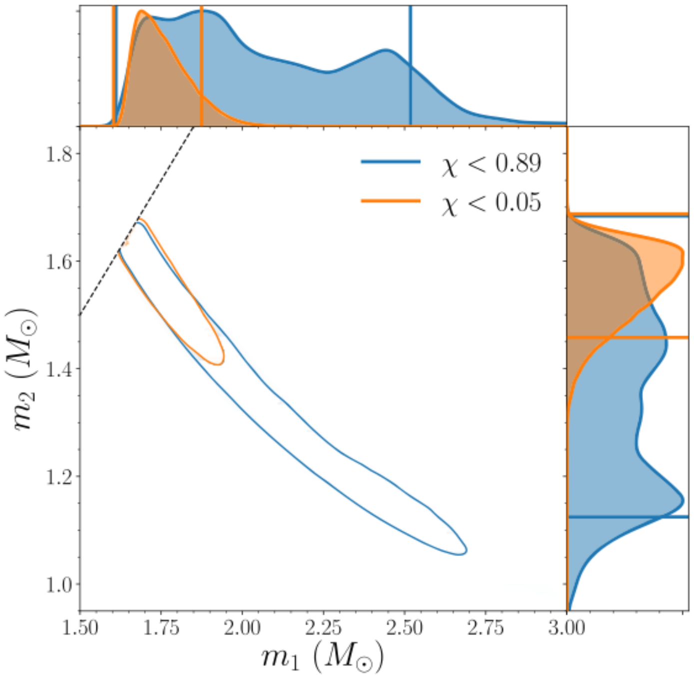
- GW170817

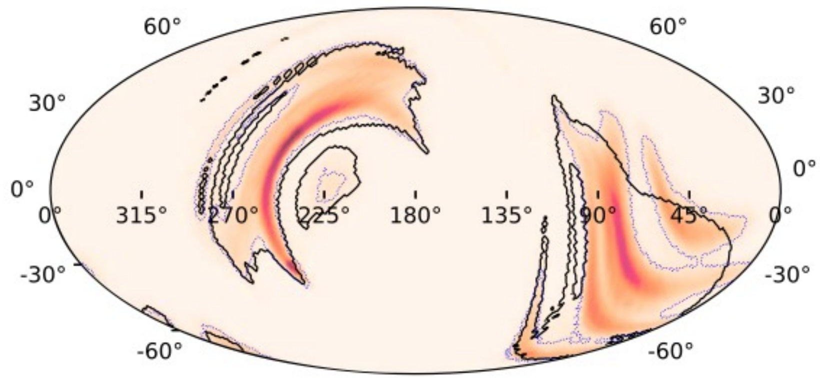




arXiv:1710.05832, PRL 119, 161101 (2017)

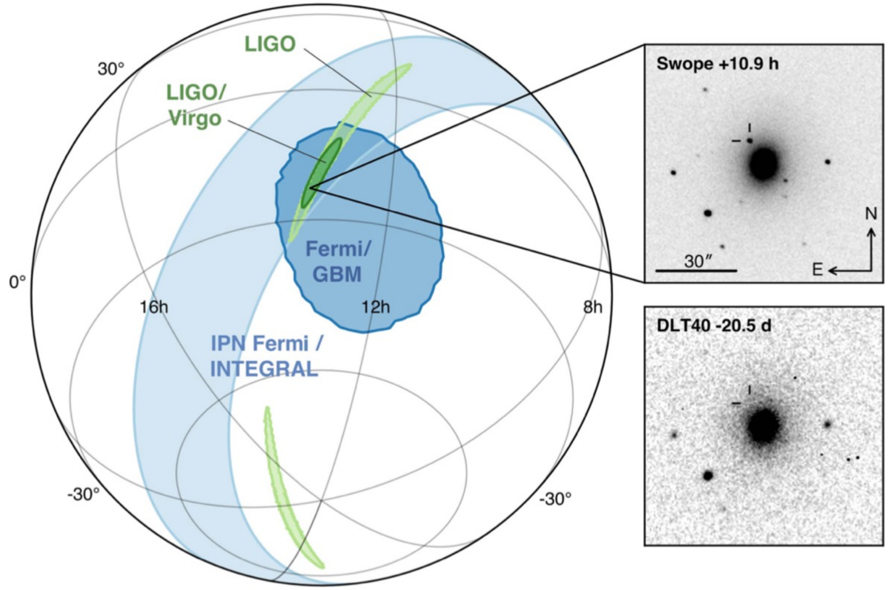
- GW190425

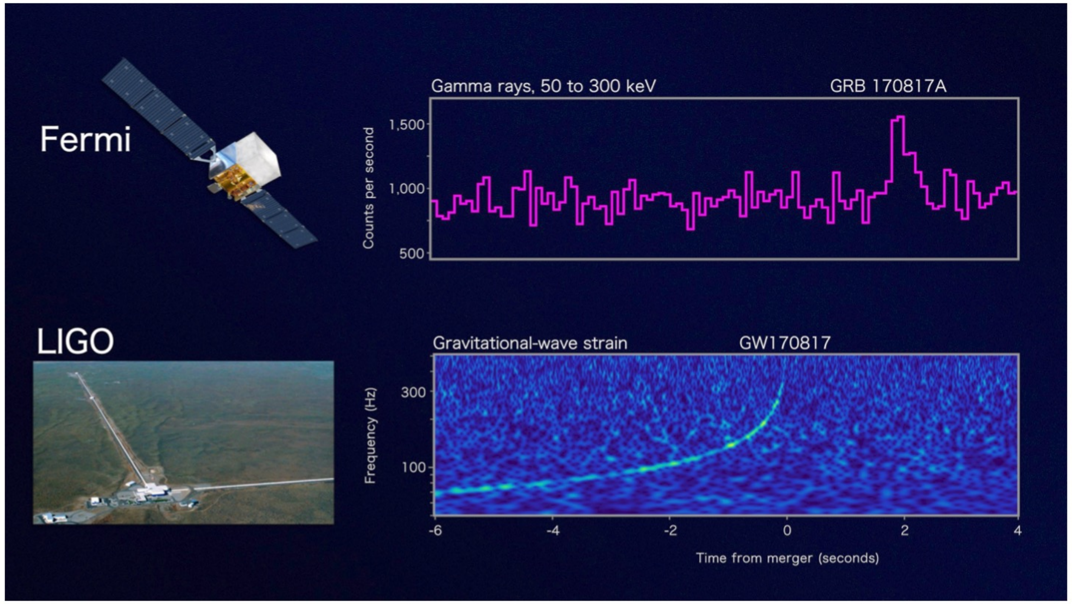




arXiv:2001.01761, ApJ Letters, 892:L3 (24pp), 2020 March 20

First BNS system : GW170817





- Coincident short GRB
- First direct evidence
  some BNS mergers ⬄ progenitors of short GRBs

GW170817 : EM counterpart

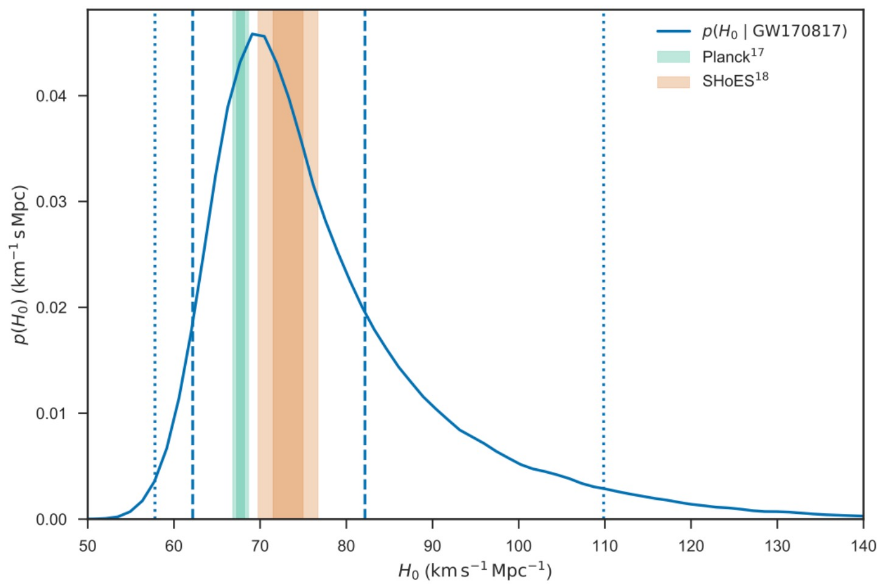
- Observed optical/UV/infrared counterpart
  - Origin : NGC4993 galaxy
  - Kilonova (arXiv:1710.05833, ApJ Letters, 848:L12 (59pp), 2017 October 20)
  - Speed of GW (arXiv:1710.05834, ApJ Letters, 848:L13 (27pp), 2017 October 20)

$$-3 \times 10^{-15} \leqslant \frac{\Delta v}{v_{\mathrm{EM}}} \leqslant +7 \times 10^{-16}$$

$$\Delta v = v_{\mathrm{GW}} - v_{\mathrm{EM}}$$

  - Other outcomes :
    - EoS constraints
    - Jet morphology
  - Cosmology : H_0
    - NGC4993 spectroscopic redshift
    - Cosmic-ladder-Independent H_0 measurement

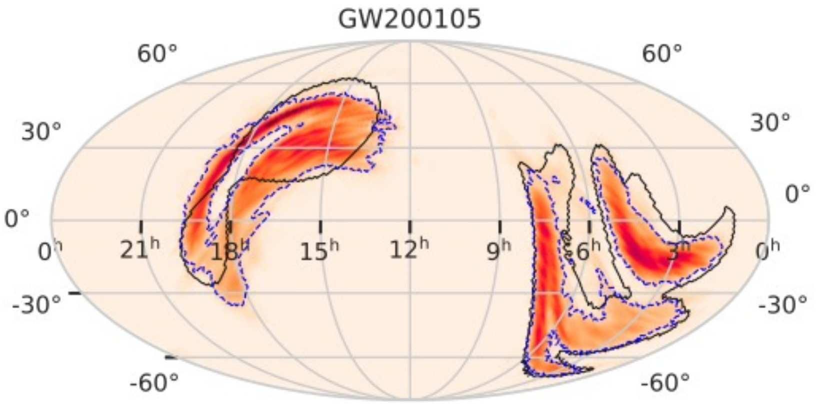
$$H_0 = 70^{+12}_{-8}\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$$

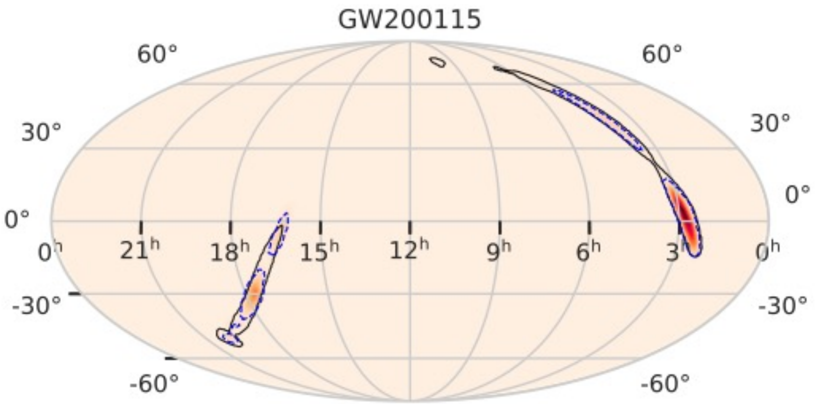


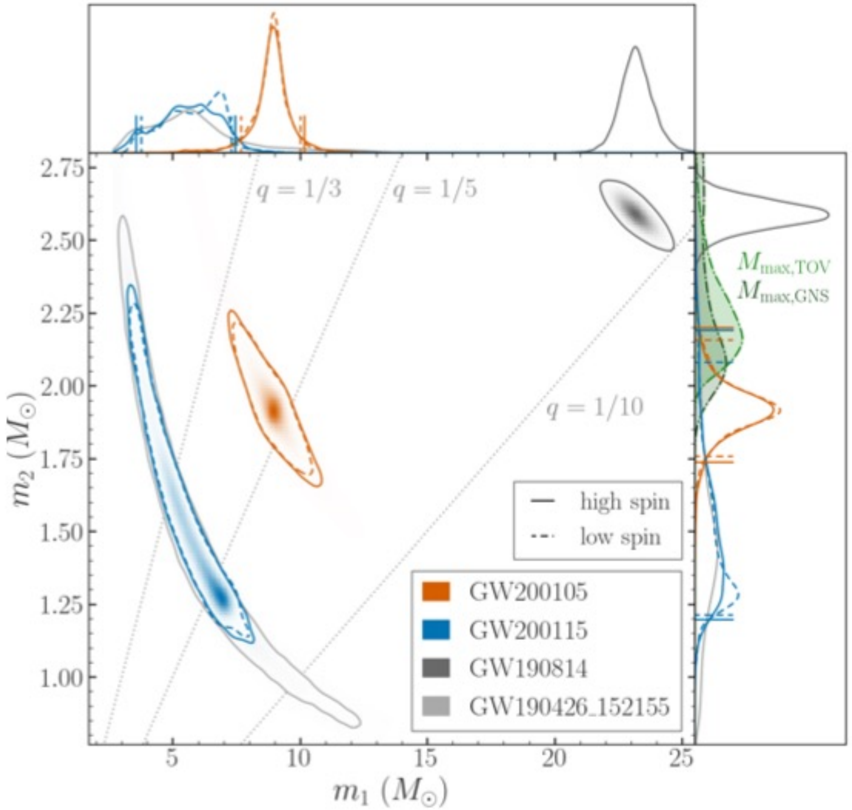
arXiv:1710.05835, LVC, *Nature* **551**, 85–88 (2017)

Two NS-BH binaries

- Two events
- Poor localization





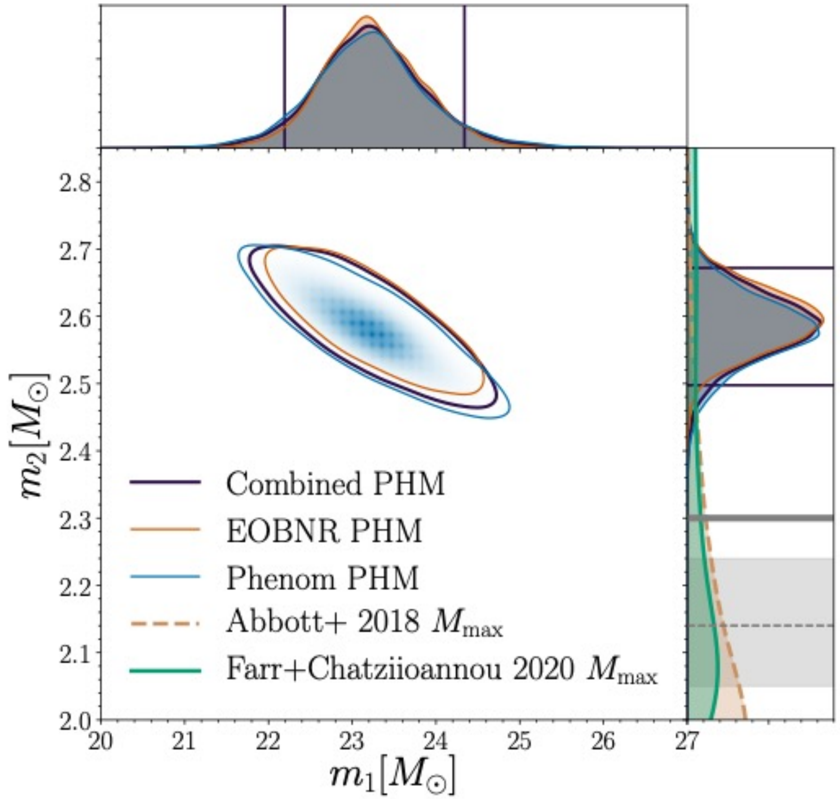


- Spins loosely constrained

arXiv:2106.15163, ApJL, 915, L5 (2021)

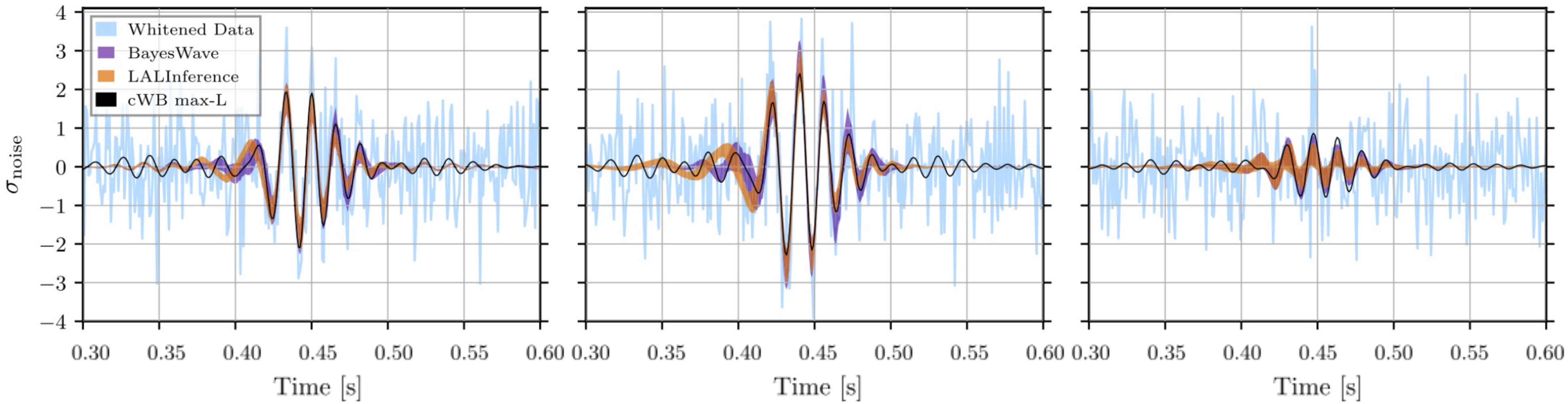
A curious event : GW190814

- Primary mass : $m_1 \sim 23\, M_\odot$
- Secondary mass : $m_1 \sim 2.6\, M_\odot$
- Sec. mass in the hypothesized mass gap $2.5 - 5\, M_\odot$
- New low mass BH population ?
- Extreme NS population ?
  - Exotic object ?
  - Equation of state ?



arXiv:2006.12611, ApJL 896 L44

The heaviest : GW190521



arXiv:2009.01075

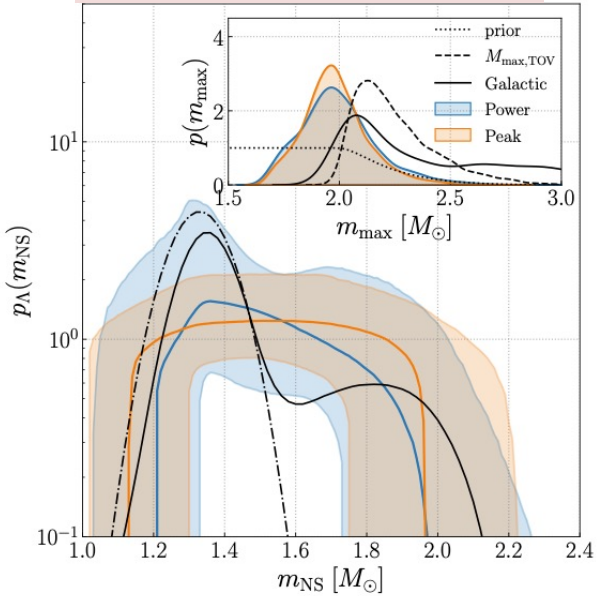
- Merger => $m_1(85\,M_\odot) + m_2(66\,M_\odot) \;\rightarrow\; m_f(145\,M_\odot)$

- Studies :
  - Possible eccentricity ? (e.g. Iglesias et al, arXiv:2208.01766)
  - Possible dynamical capture ? (Gamba et al, arXiv:2106.05575)?

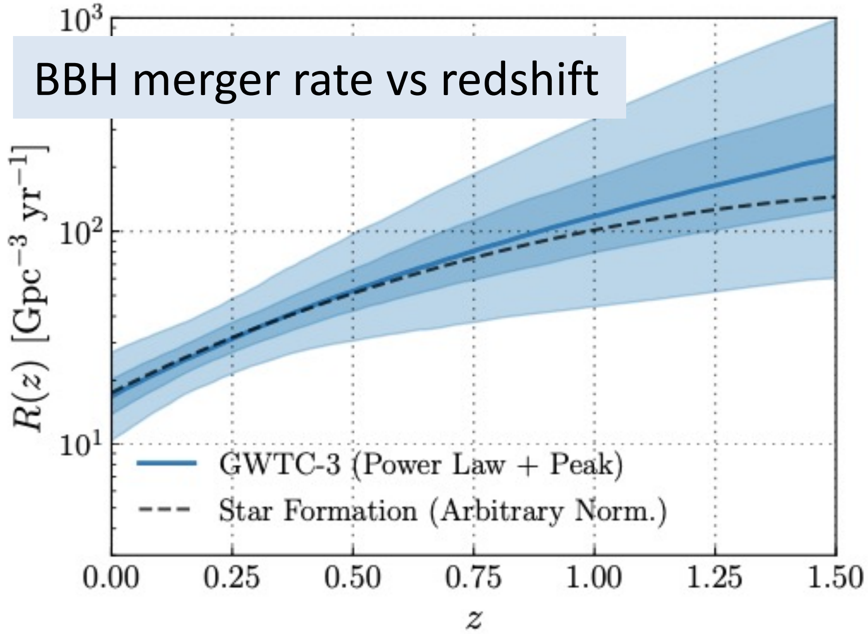
Astronomy with GR

arXiv:2111.03634

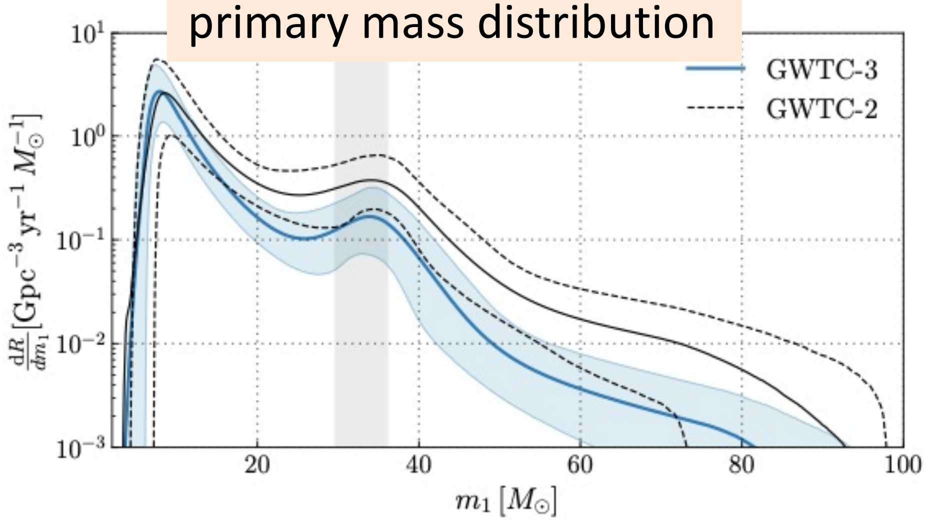
NS mass distribution



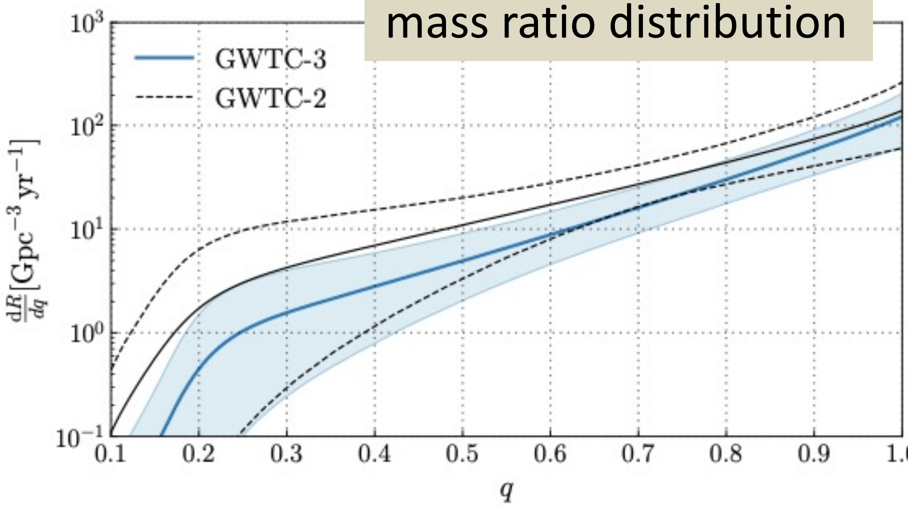
BBH merger rate vs redshift



primary mass distribution

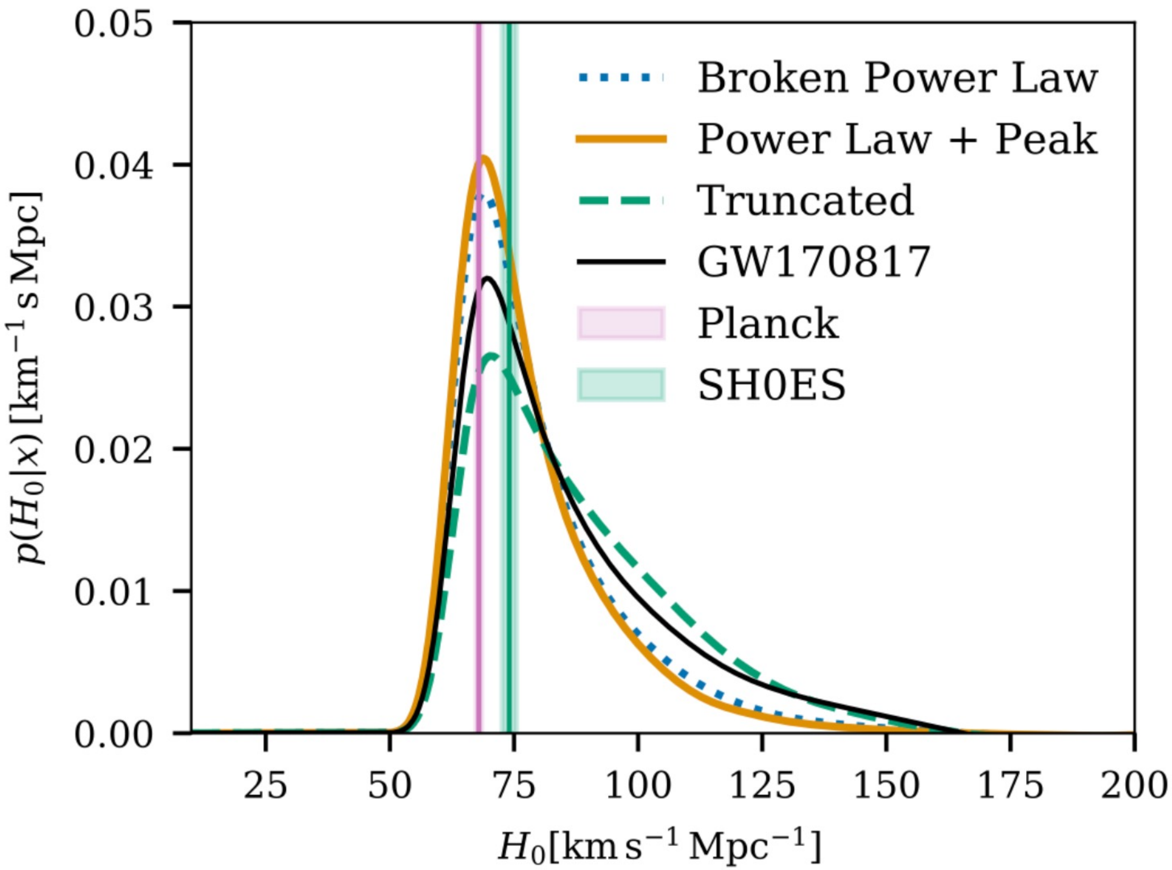


mass ratio distribution



Cosmology with GR

arXiv:2111.03604



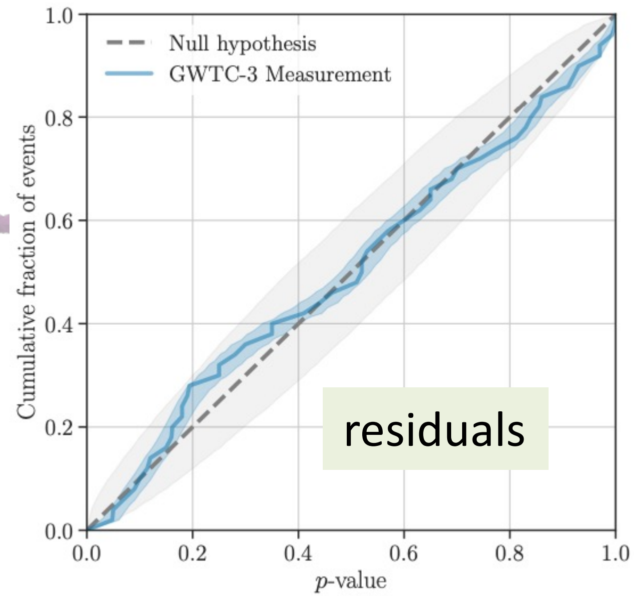
- BBH can also bring information to H0
- Association method :
  - GW event associed with its probable host galaxy (catalog GLADE+)
  - Marginalizes over the redshifts of each event's potential hosts

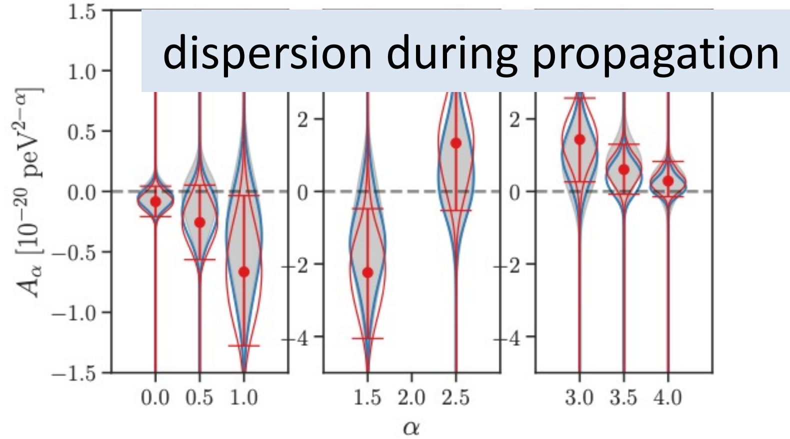
$$H_0 = 68^{+8}_{-6} \mathrm{km\,s^{-1}\,Mpc^{-1}}$$

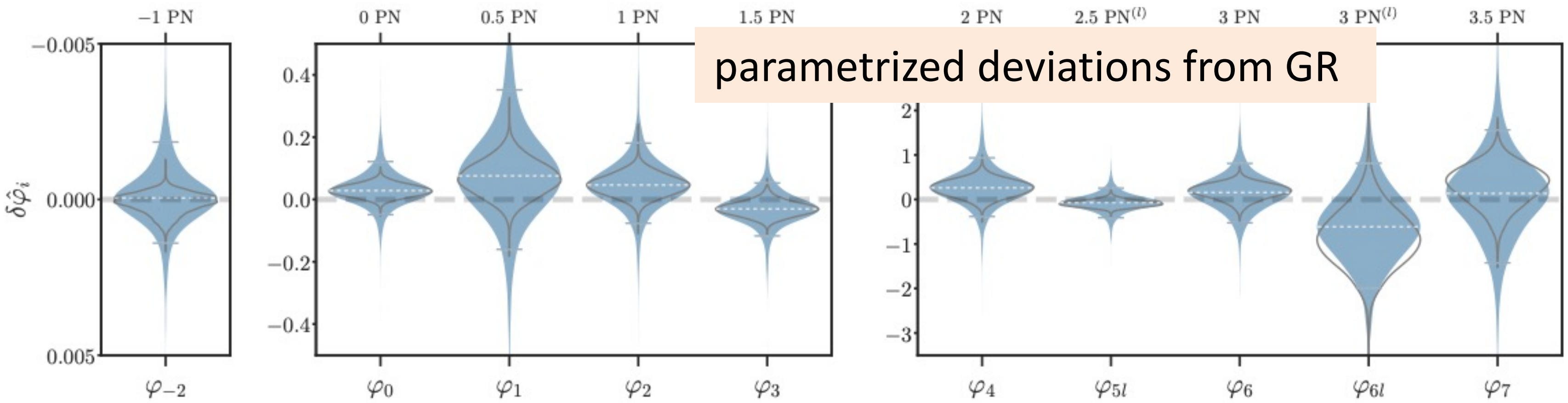
Testing GR

- Test consistency of predictions vs data
  - residuals (when wavef. removed from data)
  - checks of GW emission model
    - using different portions of waveforms (inspiral / merger / ringdown)
  - Remnant properties
  - GW propagation (testing beyond GR)

- No evidence of non-GR physics

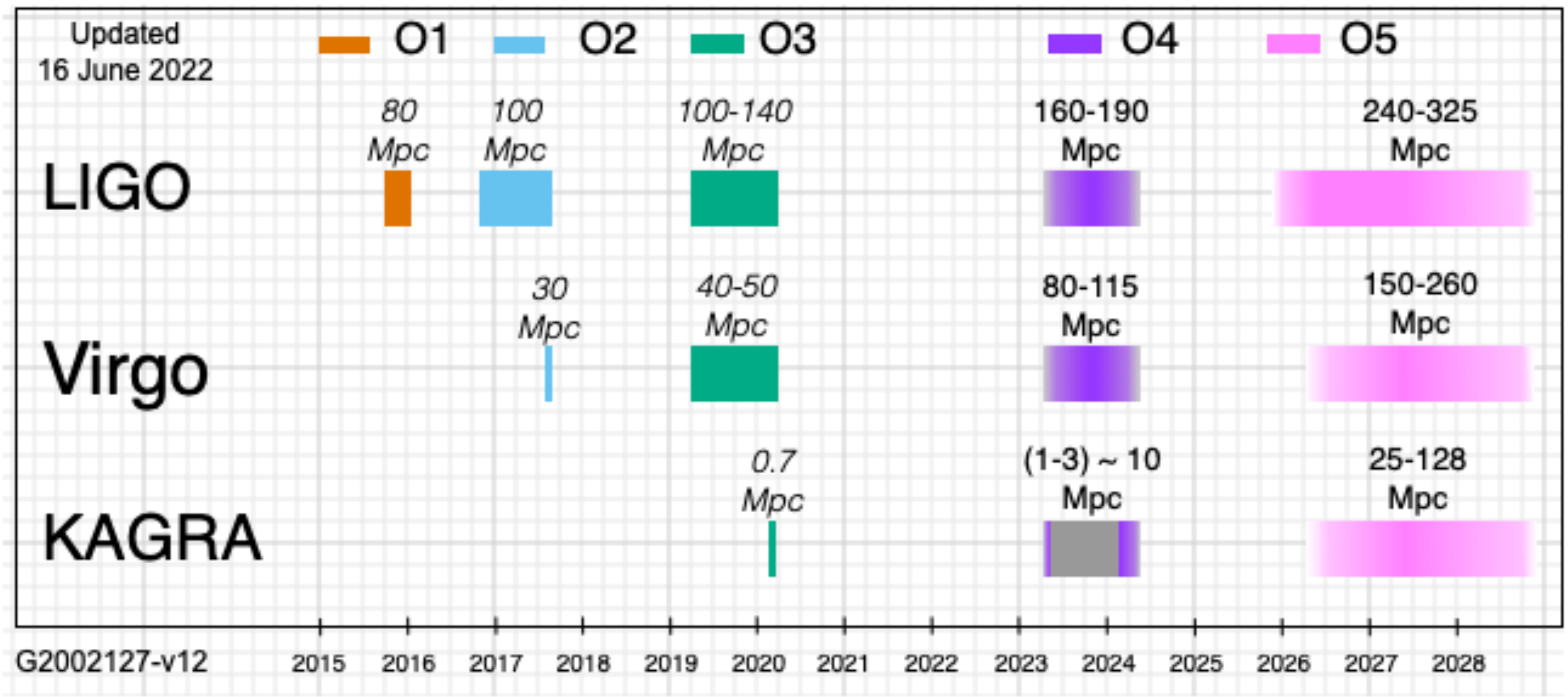






arXiv:2112.06861

The future



https://observing.docs.ligo.org/plan/

Expected rates and localization

- $R_D(=\text{detection rate}) \propto d(=\text{range})^3$
- Example :

$$d : 100\,\text{Mpc} \rightarrow\ 160\,\text{Mpc} \quad \Rightarrow \quad R_D \times 4$$

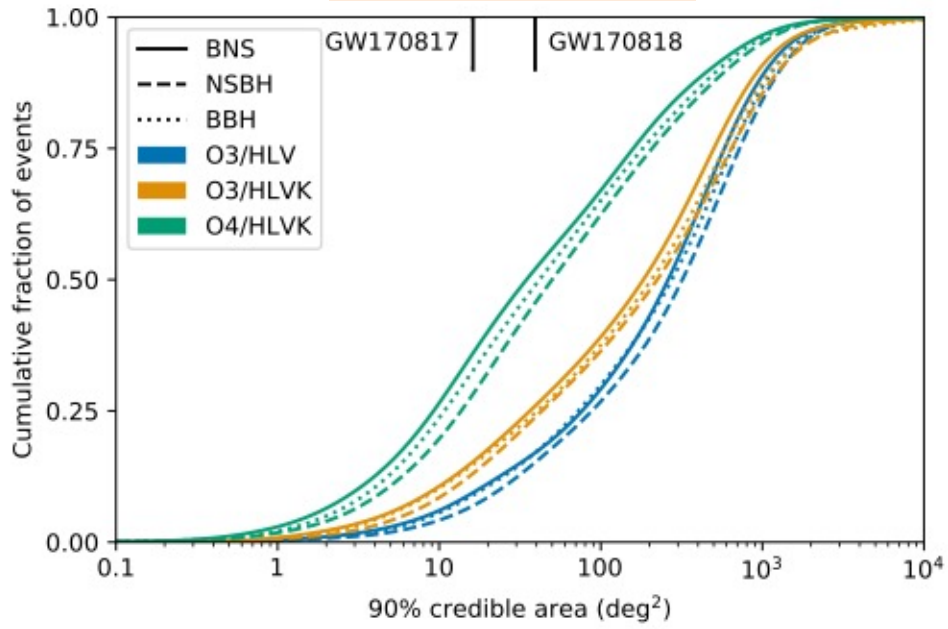
- For O4

Rates

  - $O(100)$ BBH detections / year
  - $O(1-10)$ BNS detections / year
  - Counterparts for BNS highly uncertain

(arXiv:2204.12504)

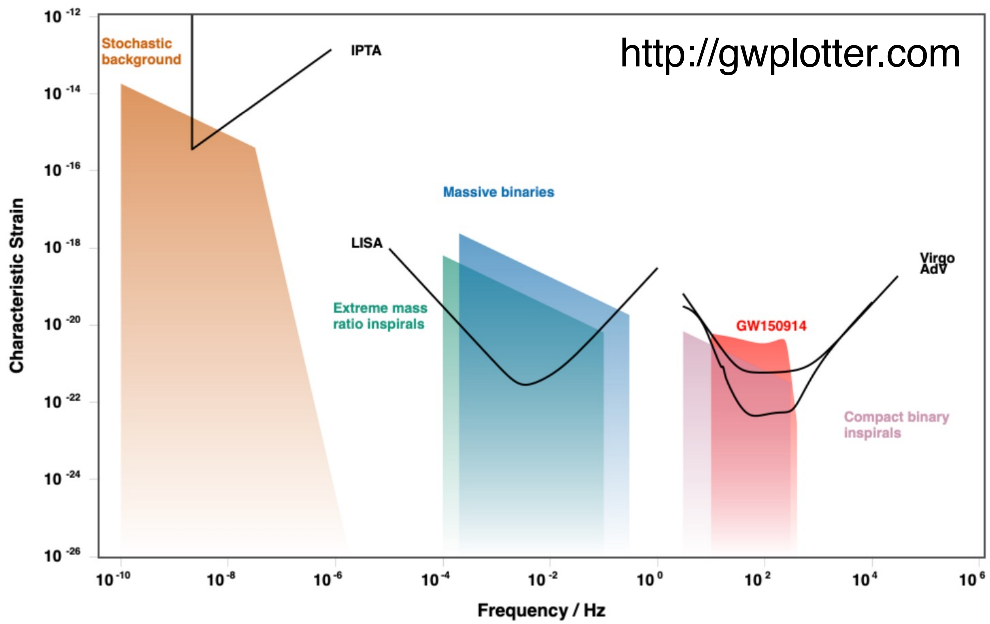
Localization



https://dcc.ligo.org/public/0094/P1200087/058/ObservingScenarios.pdf

Summary

- Extremly successful first three observing runs
  - 90 BBH, 2 NS-BH, 2 BNS
  - Insights on gravity, black holes, cosmology, nuclear physics,…
- GW170817 BNS event was a fundamental milestone
- O4 run scheduled for the beginning of 2023
  - A few (2-5) BBH detections per week
    -> hope one per day
  - Possibly
    1 or more multi-messenger detections
- More to come !



Spares

GWs + GRBs, conservative approach

model	$\mathcal{R}(0)$	GW	GW+EM (prompt)							
			Swift/BAT		Fermi/GBM		INTEGRAL/IBIS		SVOM/ECLAIRs	
			uniform	structured	uniform	structured	uniform	structured	uniform	structured
	$Gpc^{-3}yr^{-1}$	yr^{-1}	yr^{-1}	yr^{-1}	yr^{-1}	yr^{-1}	yr^{-1}	yr^{-1}	yr^{-1}	yr^{-1}
A1	31	1	0.0006 (0.0023)	0.014-0.020	0.003 (0.013)	0.070-0.11	0.0001 (0.0004)	0.0024-0.0035	0.0005 (0.0019)	0.013-0.017
A3	258	5	0.003 (0.01)	0.07-0.10	0.017 (0.068)	0.35-0.54	0.0005 (0.002)	0.01-0.02	0.002 (0.01)	0.06-0.08
A7	765	13	0.008 (0.031)	0.18-0.26	0.045 (0.18)	0.91-1.42	0.001 (0.005)	0.031-0.046	0.006 (0.025)	0.17-0.22

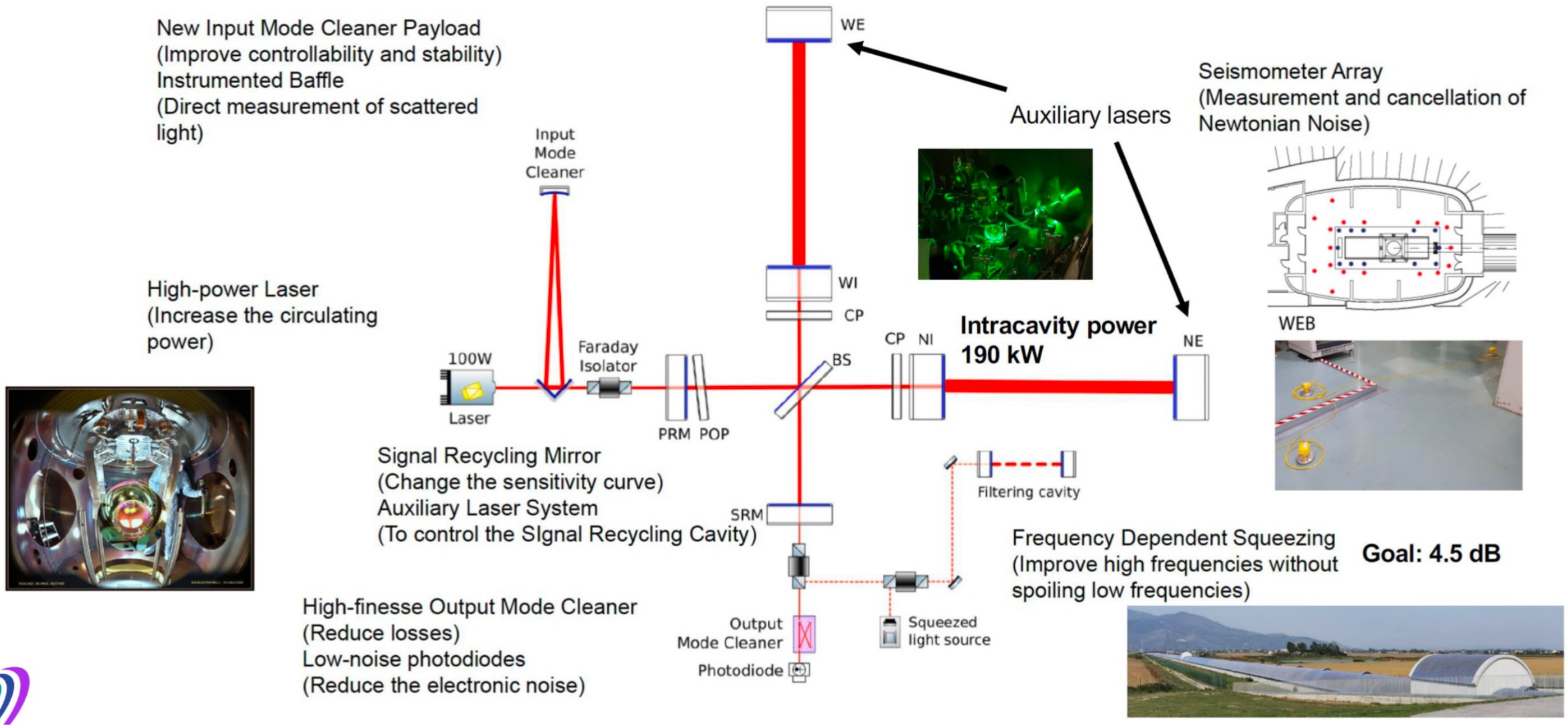
GWs + GRBs, optimistic approach

model	$\mathcal{R}(0)$	GW	GW+EM (prompt)							
			Swift/BAT		Fermi/GBM		INTEGRAL/IBIS		SVOM/ECLAIRs	
			uniform	structured	uniform	structured	uniform	structured	uniform	structured
	$Gpc^{-3}yr^{-1}$	yr^{-1}	yr^{-1}	yr^{-1}	yr^{-1}	yr^{-1}	yr^{-1}	yr^{-1}	yr^{-1}	yr^{-1}
A1	31	5	0.002 (0.01)	0.05-0.08	0.014 (0.06)	0.27-0.46	0.0005 (0.002)	0.009-0.014	0.002 (0.008)	0.05-0.07
A3	258	22	0.01 (0.04)	0.24-0.37	0.06 (0.26)	1.17-2.00	0.002 (0.008)	0.04-0.06	0.009 (0.04)	0.22-0.32
A7	765	61	0.03 (0.12)	0.67-1.05	0.18 (0.74)	3.28-5.65	0.006 (0.02)	0.11-0.18	0.02 (0.10)	0.63-0.90

Advanced Virgo+

Path towards O4: reduce quantum noise, hit against thermal noise.

credits: V. Fafone, EAS 2022



Advanced Virgo+