A status on gravitational waves detection and some prospects

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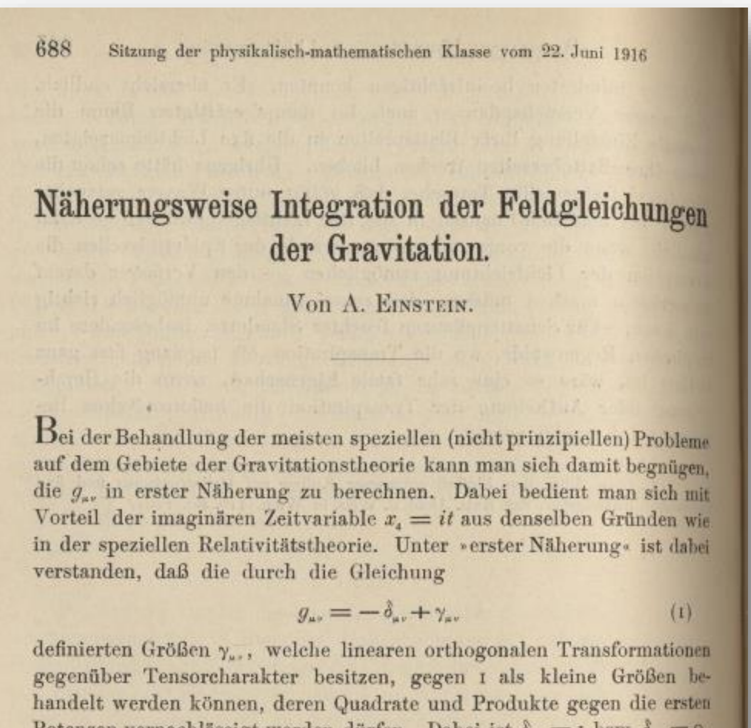
LHC Days in Split, september 2024

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

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

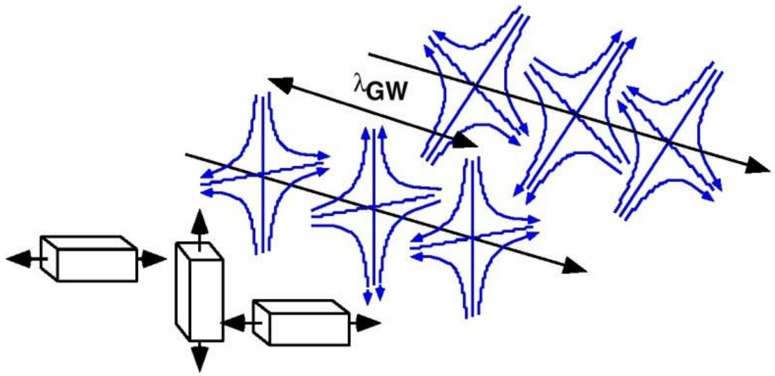
definierten Größen $\gamma_{\mu\nu}$, welche linearen orthogonalen Transformationen gegenüber Tensorcharakter besitzen, gegen 1 als kleine Größen behandelt werden können, deren Quadrate und Produkte gegen die ersten

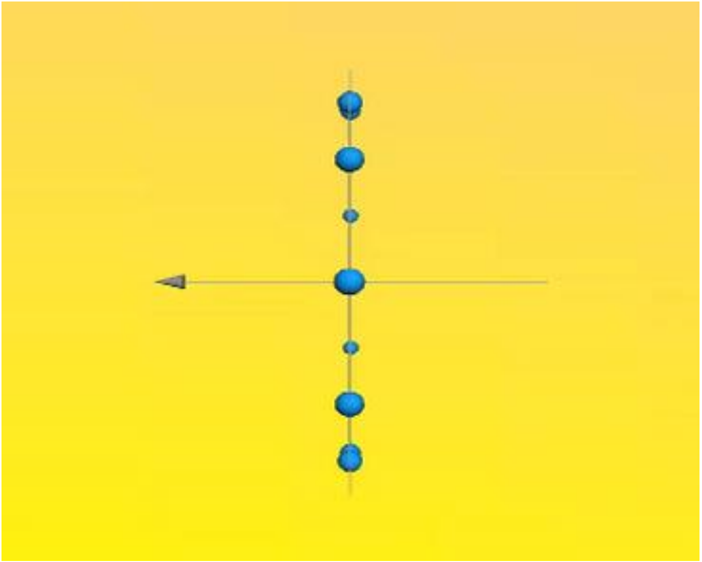
- Develop small perturbations $h_{\mu\nu}$ around a flat (Minkowski) metric
- => wave equation

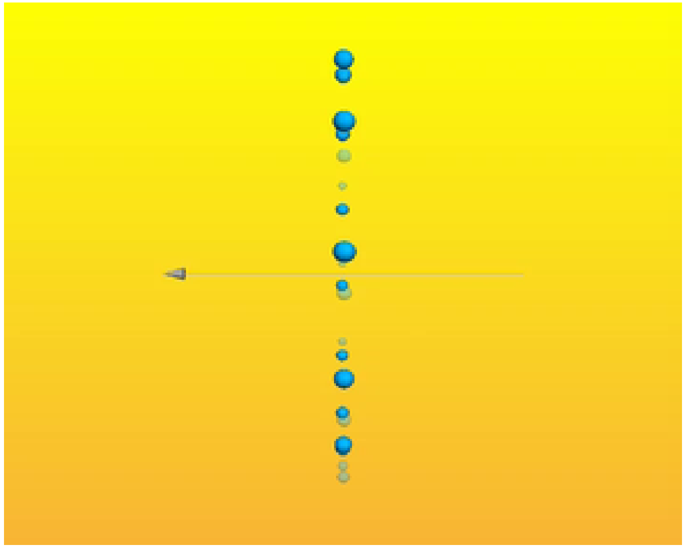
$$(\nabla^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t^2})h_{\mu\nu} = 0$$

Gravitational waves

- Effect on a set of (free) “test” mass



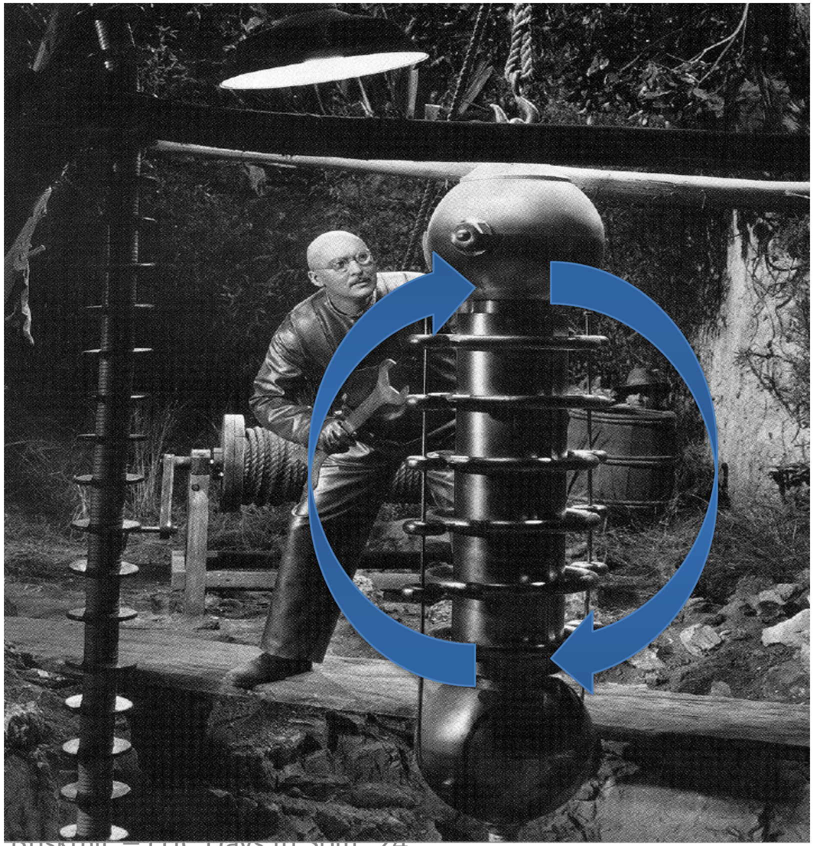




Gravitational waves

- Production :

  - Distribution of masses : acceleration of quadrupolar moment



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

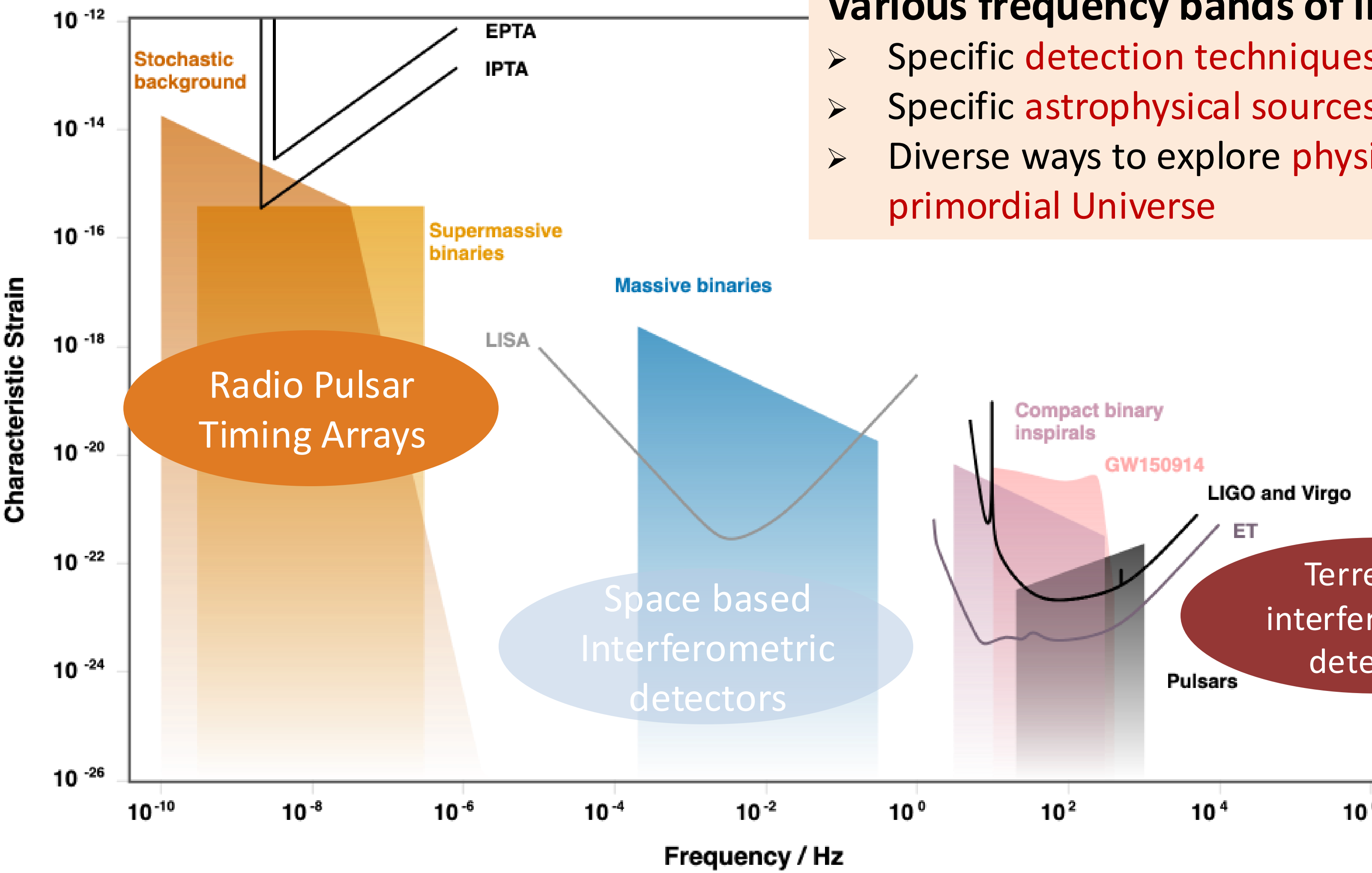
- Examples
  - M = 1000 kg, R = 1 m, f = 1 kHz, r = 300 m

    $h \sim 10^{-35}$

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

    $h \sim 10^{-21}$

Gravitational waves sources and detectors



Various frequency bands of interest

- Specific detection techniques
- Specific astrophysical sources
- Diverse ways to explore physics of primordial Universe

http://gwplotter.com

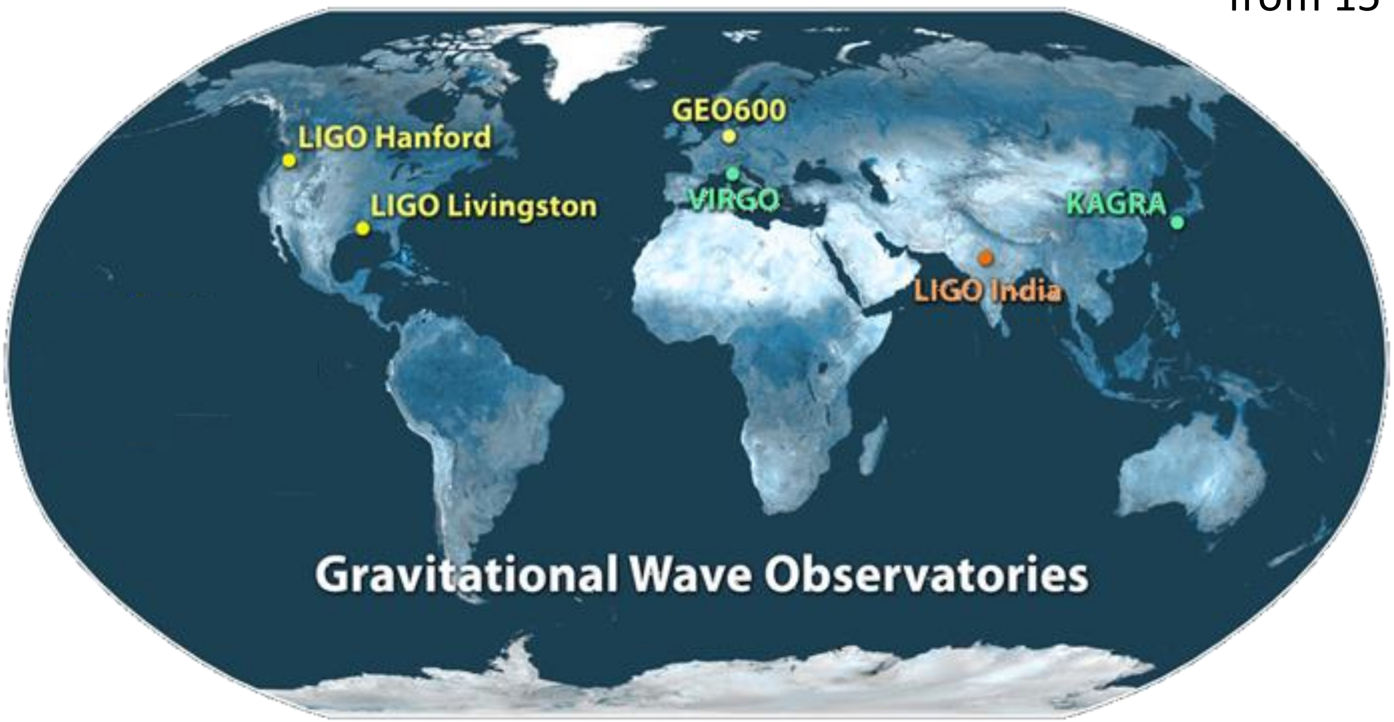
The observed : LIGO-Virgo-Kagra results

LVK Gravitational waves detector network

Virgo : ~800+ members
129 institutions
from 16 pays

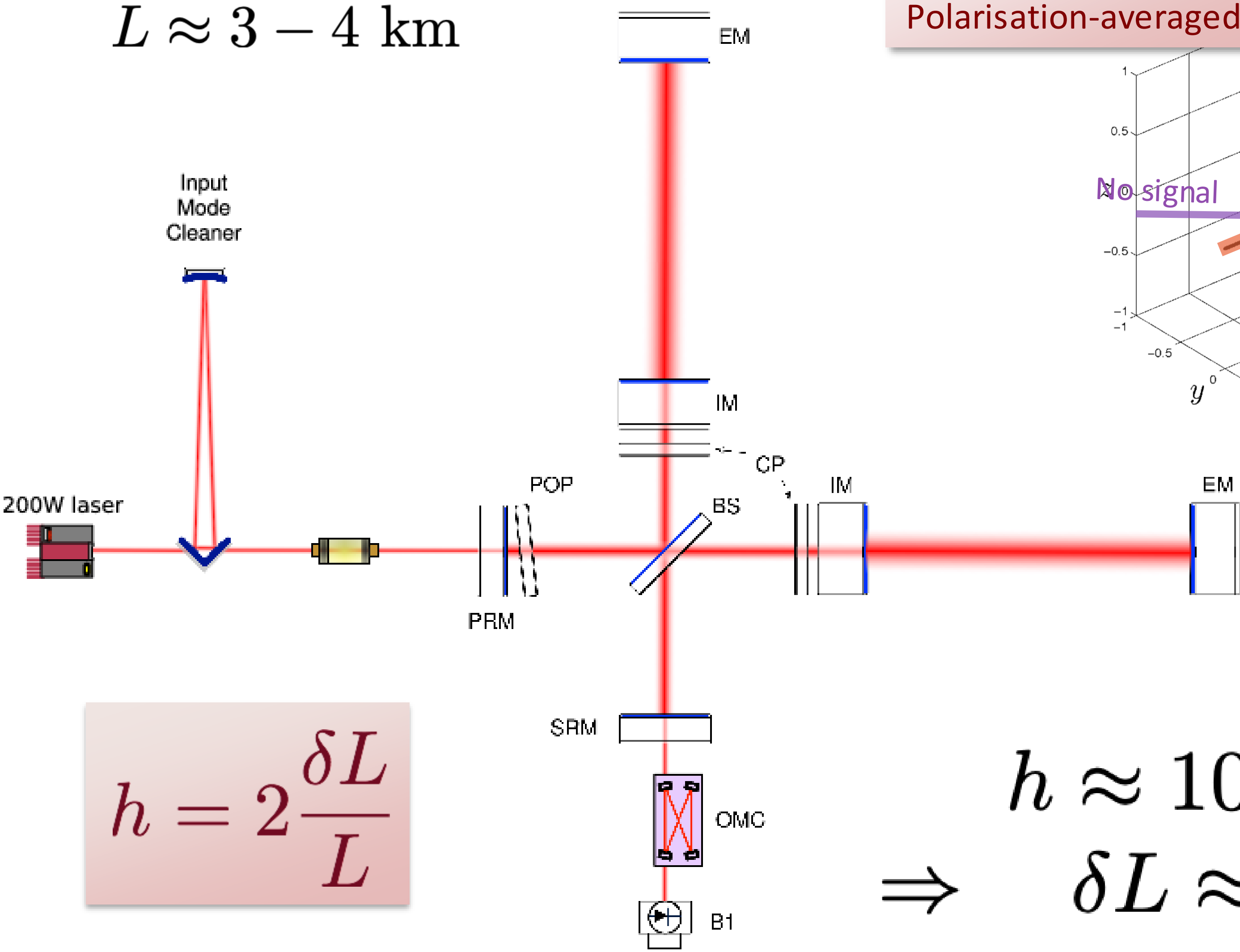
LSC : ~1500+ members
~127 institutions
from ~19 countries

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



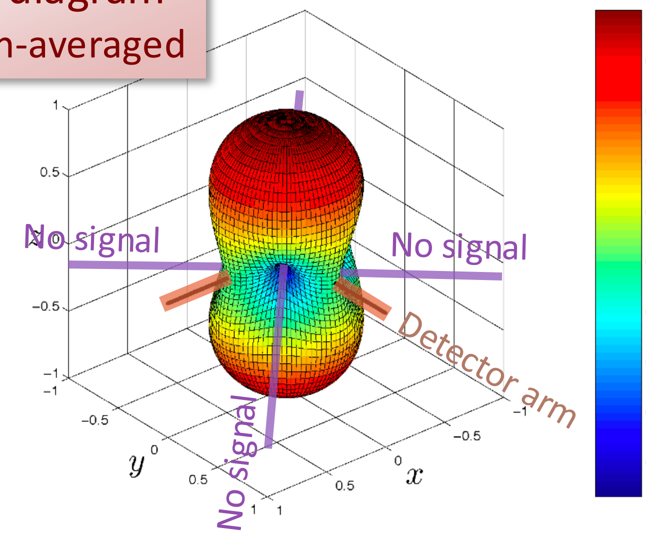
Michelson interferometer : a "sensor" of gravitational waves

$$L \approx 3 - 4 \text{ km}$$



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

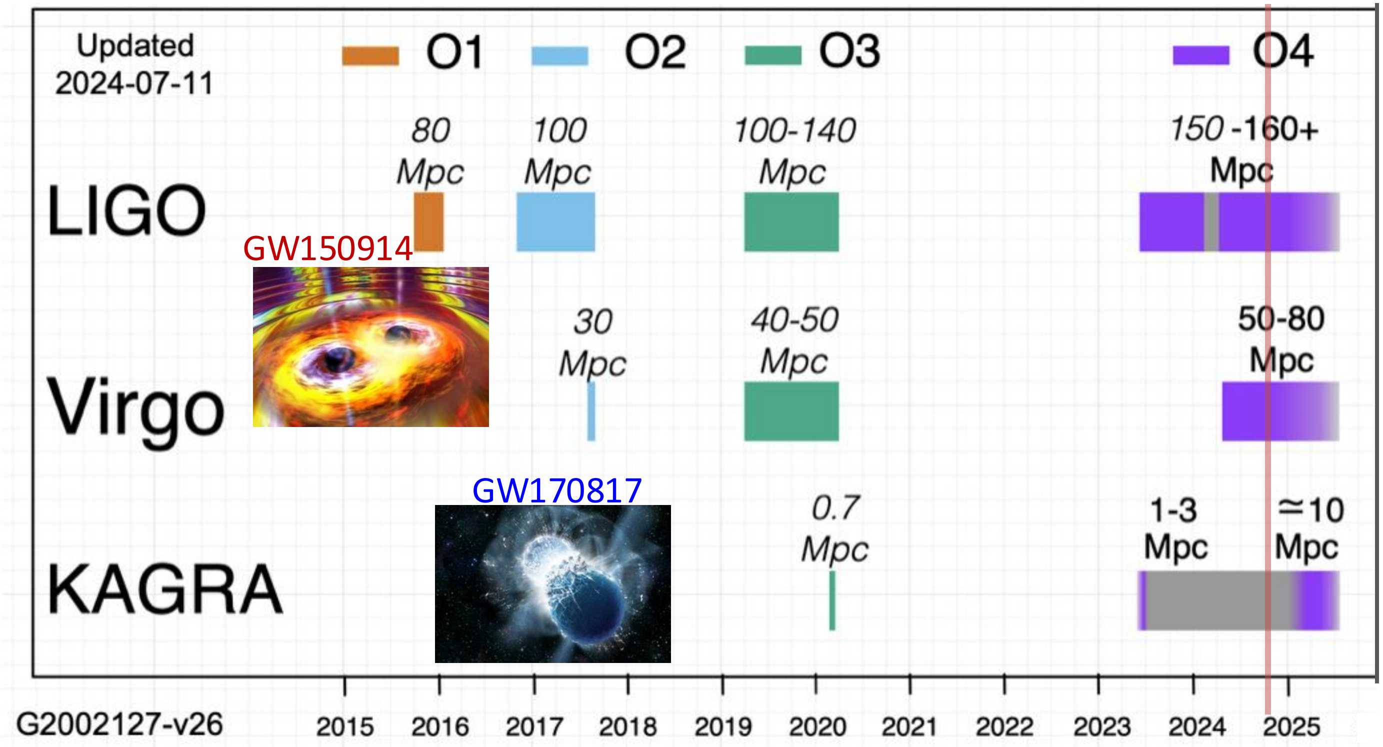
Antenna diagram
Polarisation-averaged



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

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

LIGO-Virgo Observing Runs

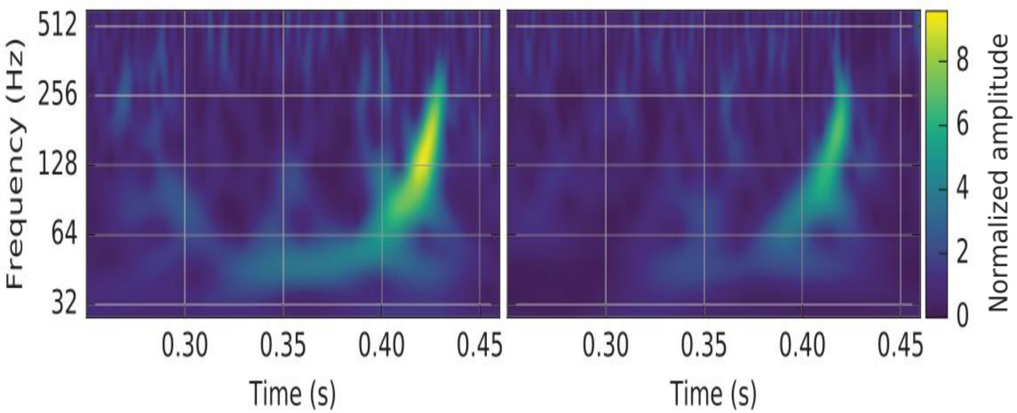


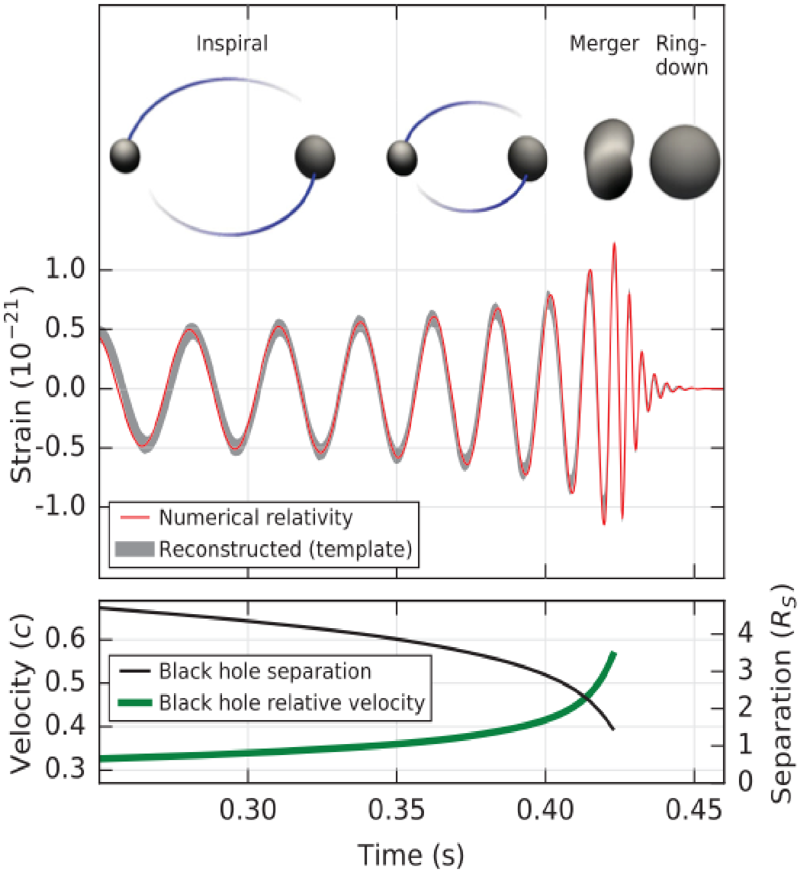
https://observing.docs.ligo.org/plan/

- « 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

The observed : compact binary coalescences

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



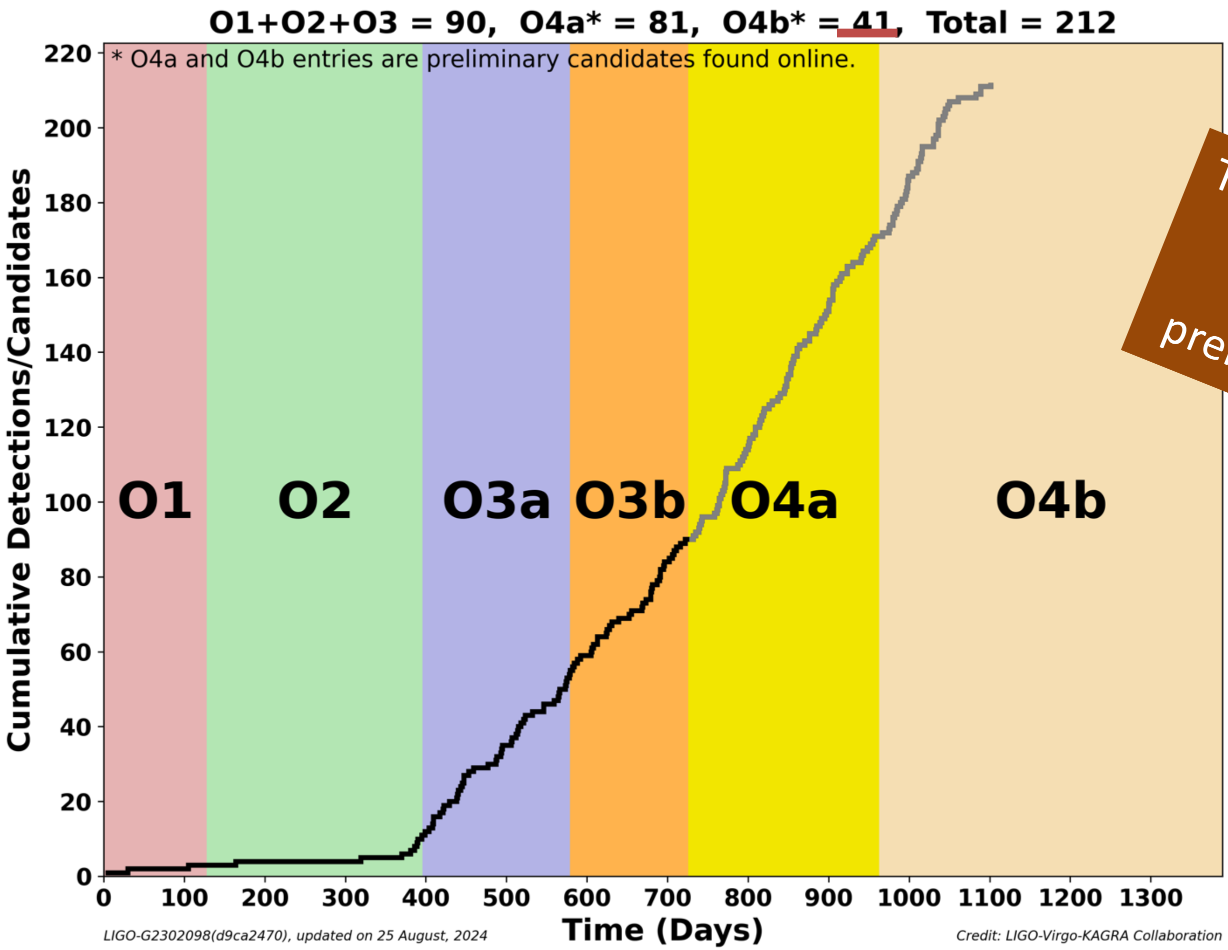


- Single observations allow studies on:
  - Binary dynamics and component nature
  - Non linear dynamics of space-time
  - Final object nature
  - Tests of GR

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

A path to astronomy

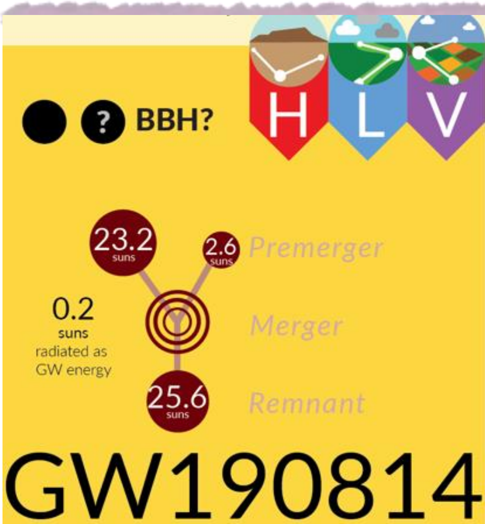
- Cumulative detections of binary coalescences



Today (30/09/24) in O4:
141
preliminary candidates

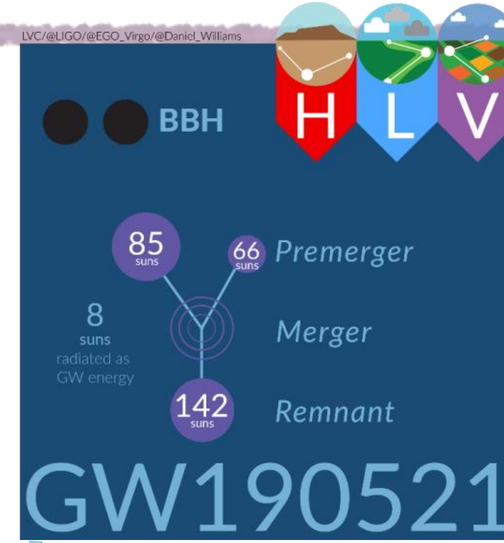
https://gracedb.ligo.org/superevents/public/O4/

A few interesting events



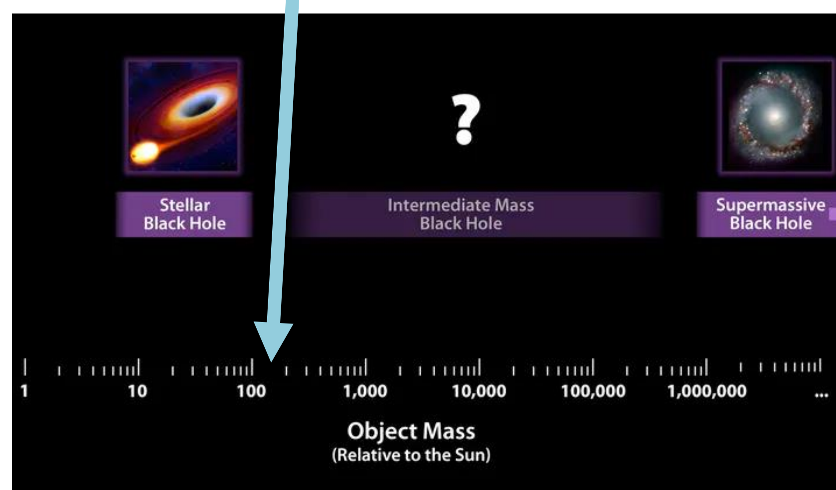
ApJL 896 L44 (2020)

ApJL 970 L34 (2024)



PRL 125, 101102 (2020)

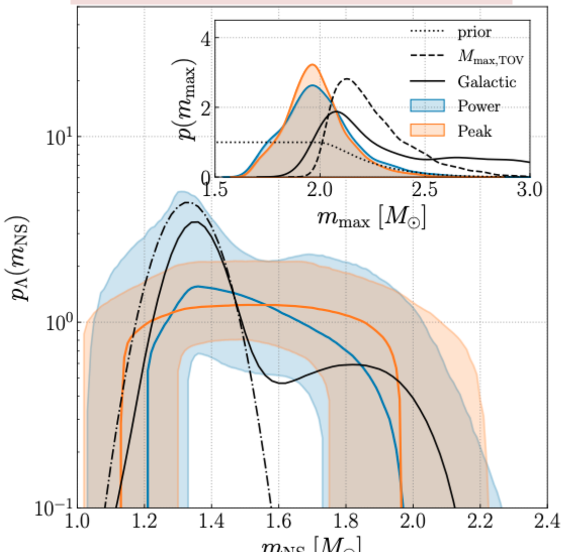
- GW190814's secondary and GW230529's primary are either heavy neutron stars or light black holes
- GW190521's remnant is an intermediate-mass black hole

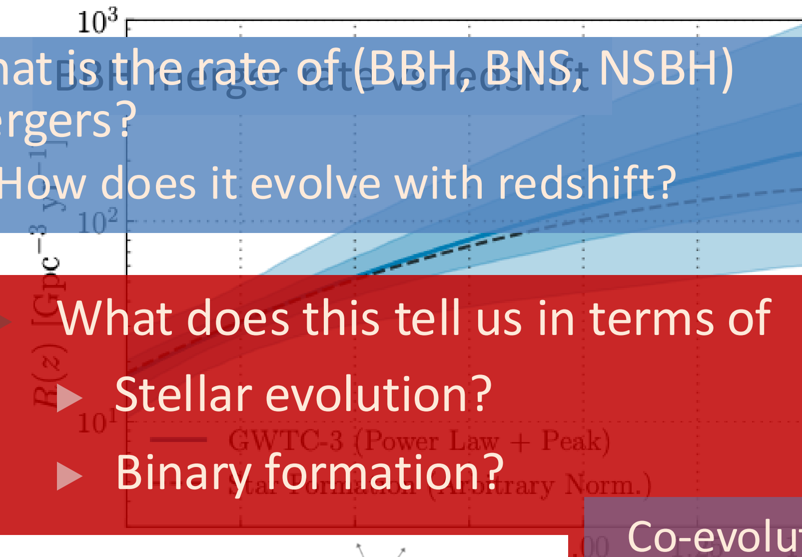


Astrophysics with GW

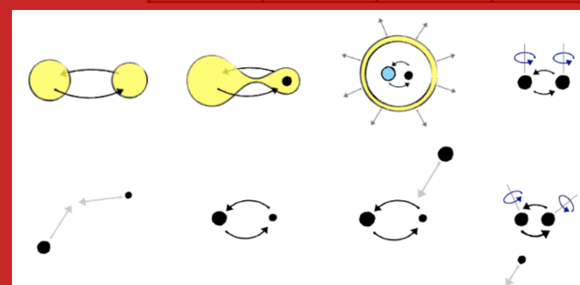
arXiv:2111.03634

NS mass distribution





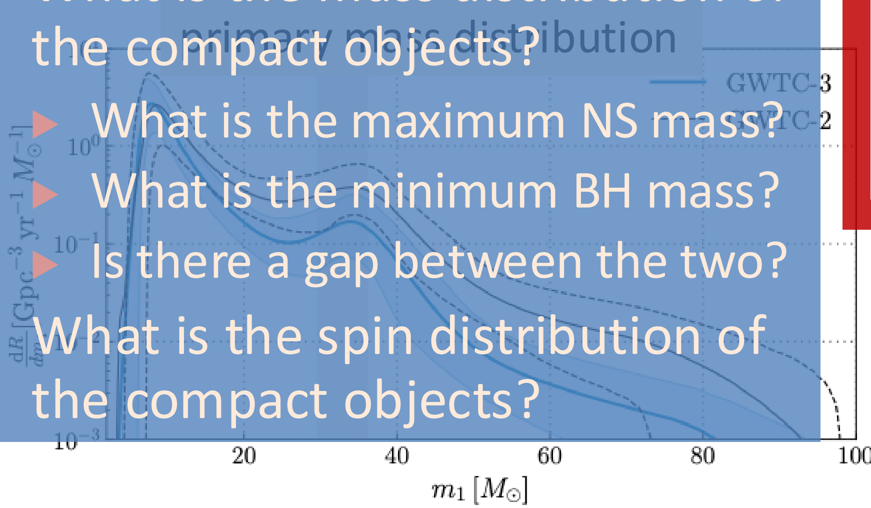
- What is the rate of (BBH, BNS, NSBH) mergers?
  - How does it evolve with redshift?
- What does this tell us in terms of
  - Stellar evolution?
  - Binary formation?



Co-evolution in isolated binaries

vs

Dynamical formation



- What is the mass distribution of the compact objects?
  - What is the maximum NS mass?
  - What is the minimum BH mass?
  - Is there a gap between the two?
- What is the spin distribution of the compact objects?

Probe strong interaction in ultra-dense neutron-star matter

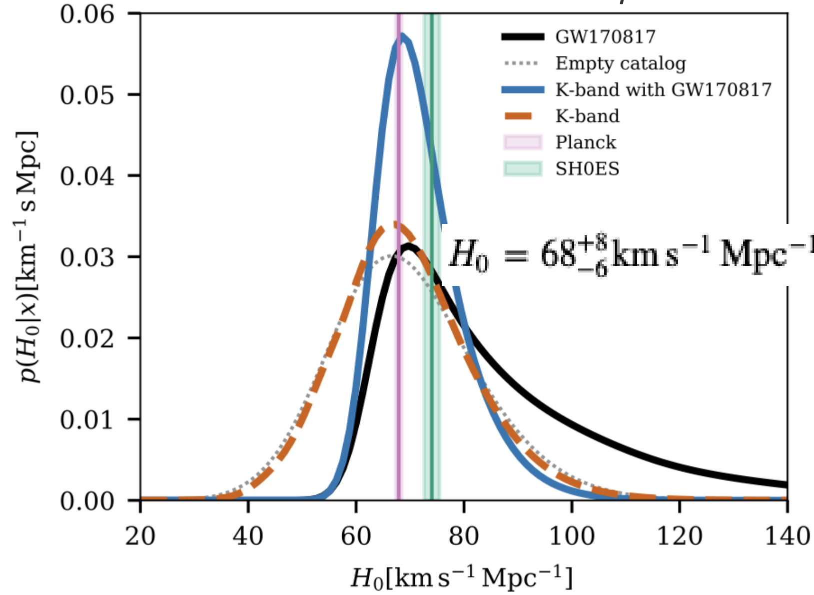
- Impact of tidal effects on inspiral will be measured for 100s of events in the future

Cosmology and tests of GR with GW

Measure the expansion rate of the Universe

- Compact binary coalesces are *standard sirens*
- Probe cosmological model

R. Abbott *et al* 2023 *ApJ* **949** 76



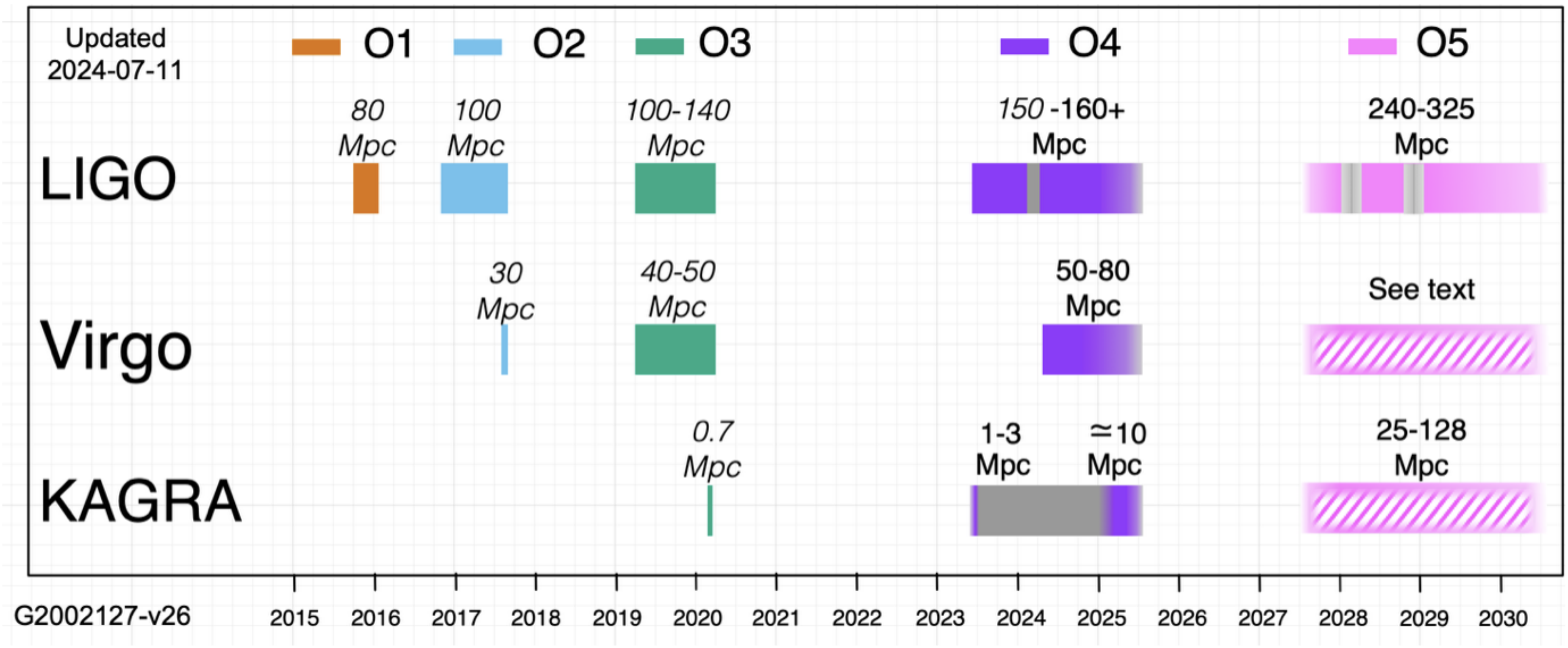
Test General Relativity

- GW propagation
  - Already tight constraints from GW170817 et al.
    - GW and light propagate at the same speed
    - GW and light are affected by background gravitational potentials in the same way
  - Any sign of dispersion – waveform distortion due to different frequencies propagating at different speeds?
    - Constrain hypothetical graviton mass!

$$m_g \leq 1.27 \times 10^{-23} \mathrm{eV}/c^2$$

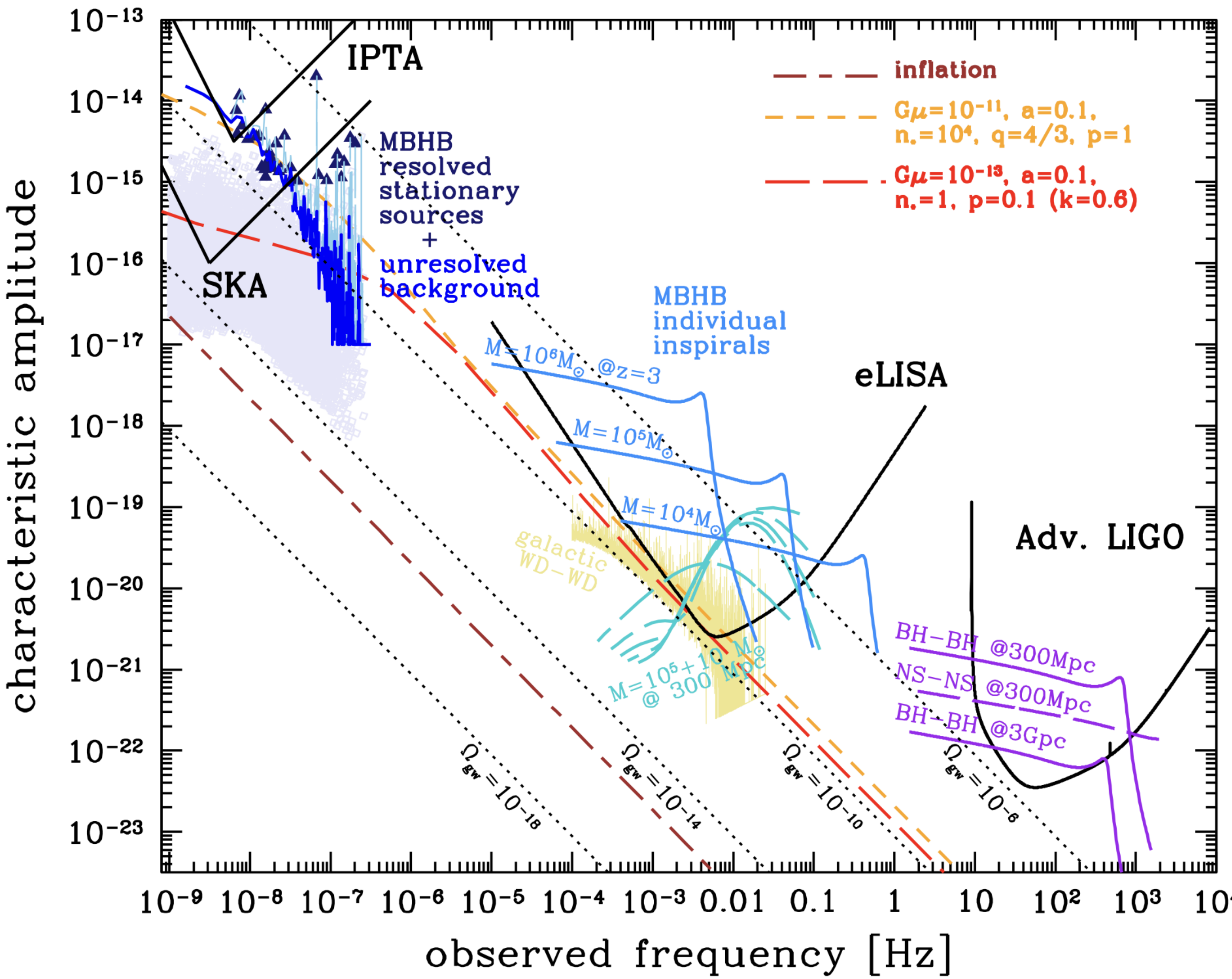
- GW polarization
  - Are signals recorded in different detectors consistent with two tensor polarizations?
- Source dynamics
  - Waveforms consistent with GR prediction?
  - Test BH no-hair theorem via ringdown spectroscopy

The (near) future for LVK



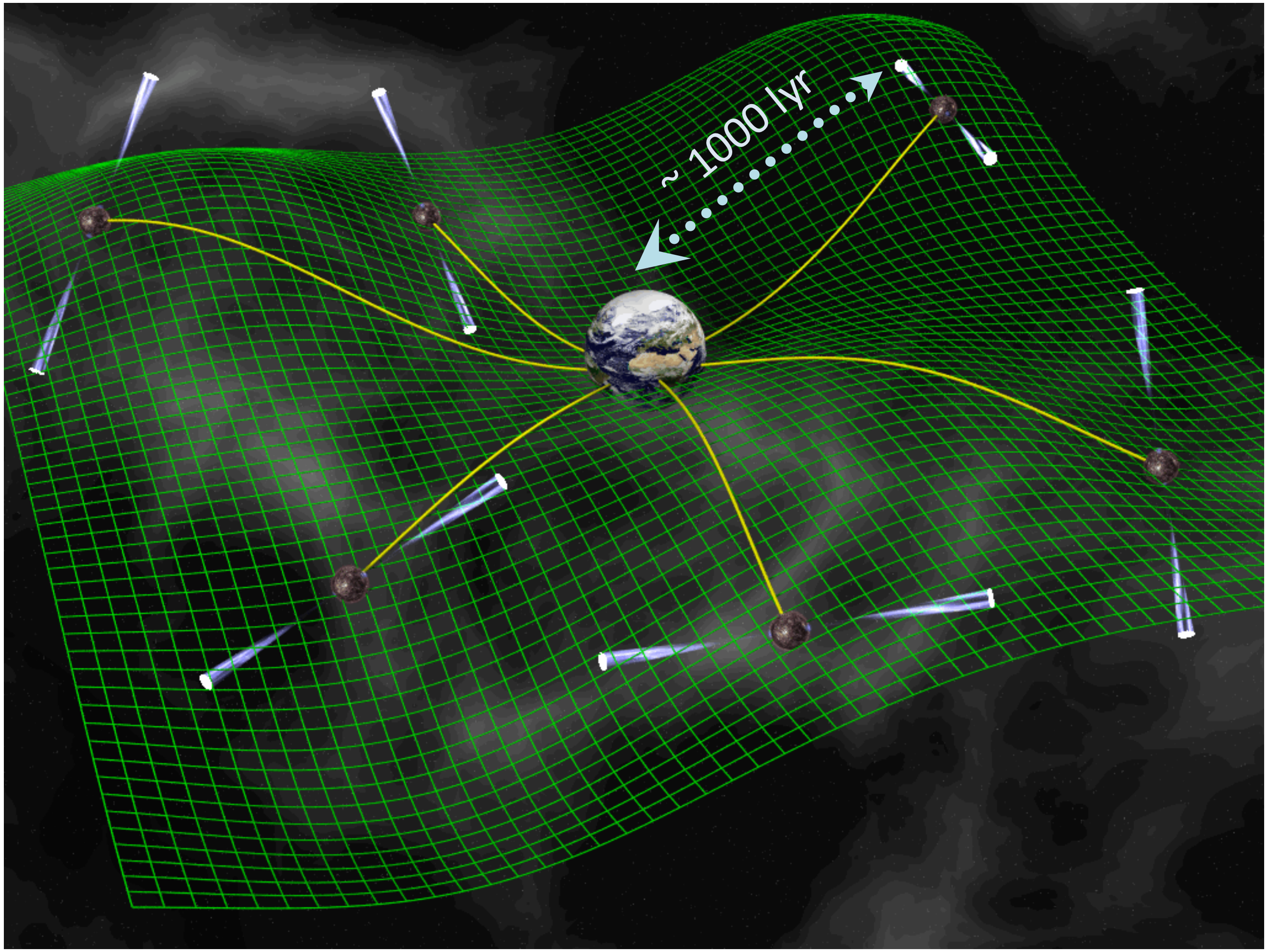
https://observing.docs.ligo.org/plan/

The quasi-observed : Pulsar Timing Arrays



arXiv:1501.00127

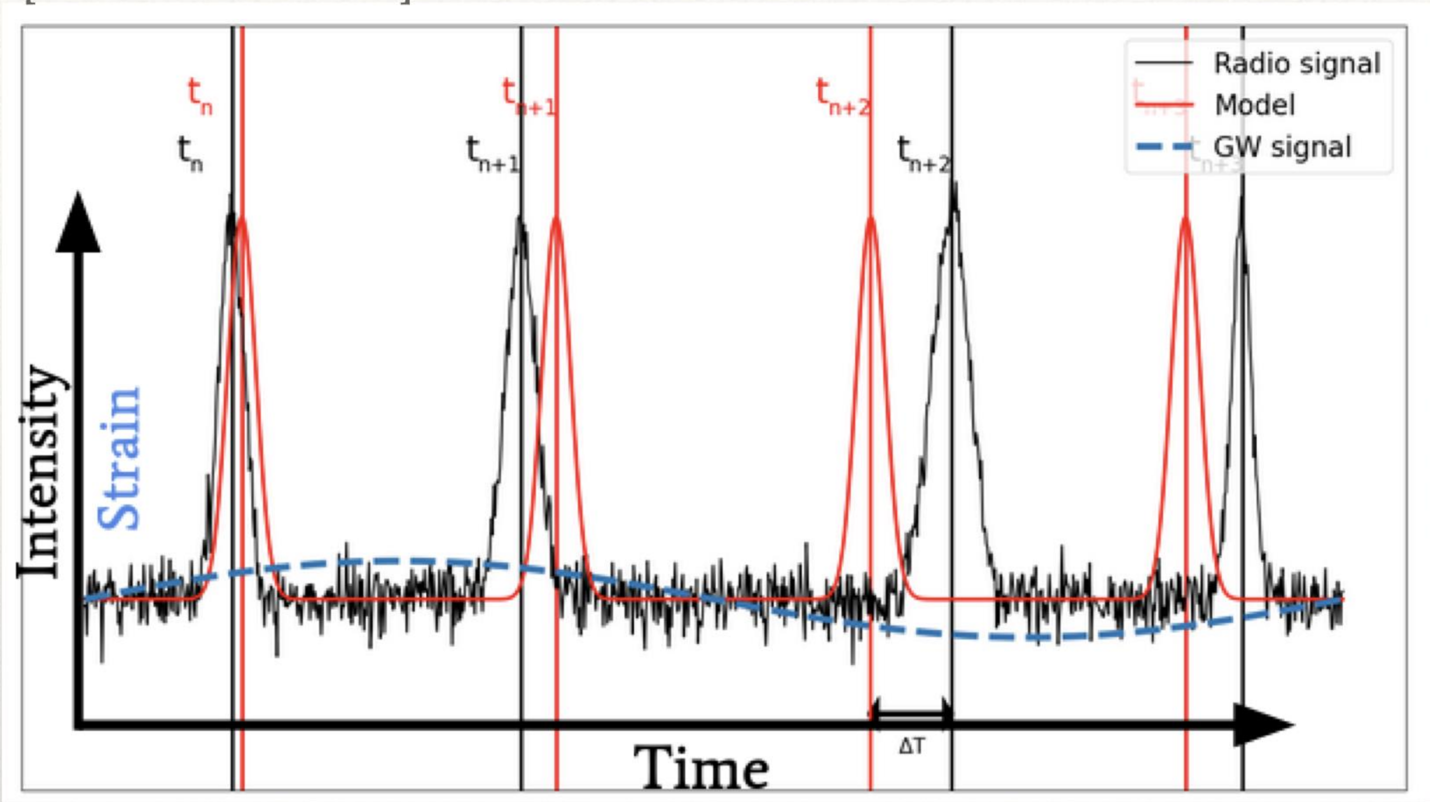
Looking at many pulsars



Ingredient : ToA and residuals

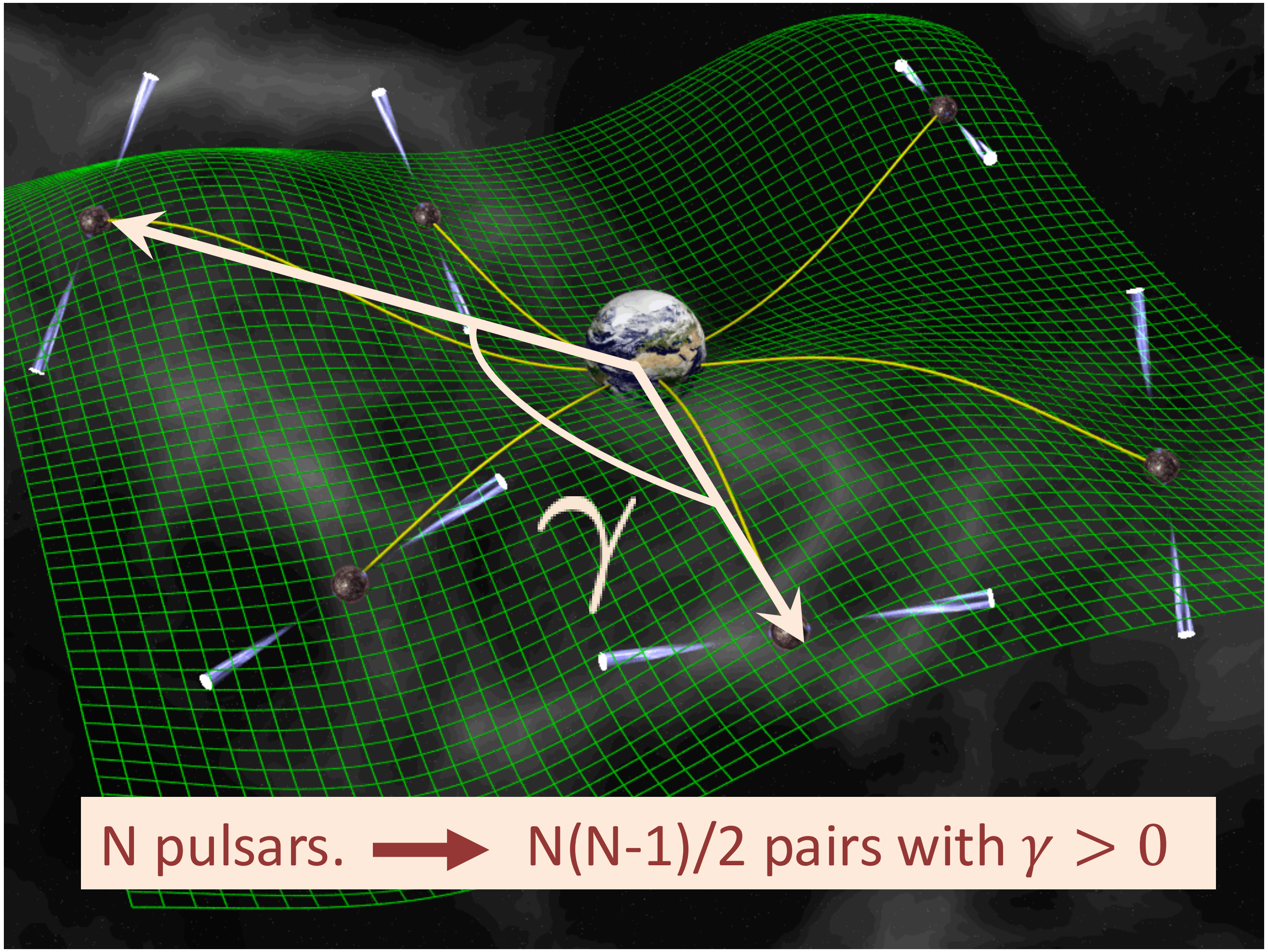
- Radio pulses -> ToA (time of arrival)
  - Predict arrival time -> timing residuals

[credits: Mikel Falxa]



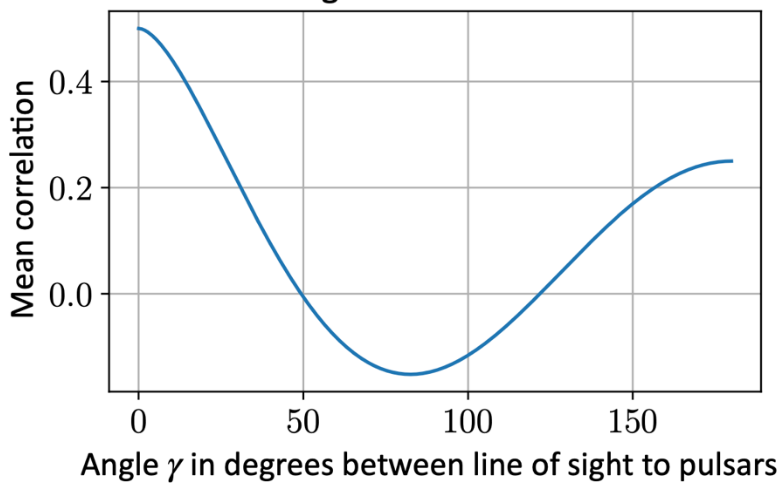
Ingredient : Hellings and Downs

- Correlation of residuals between two pulsars

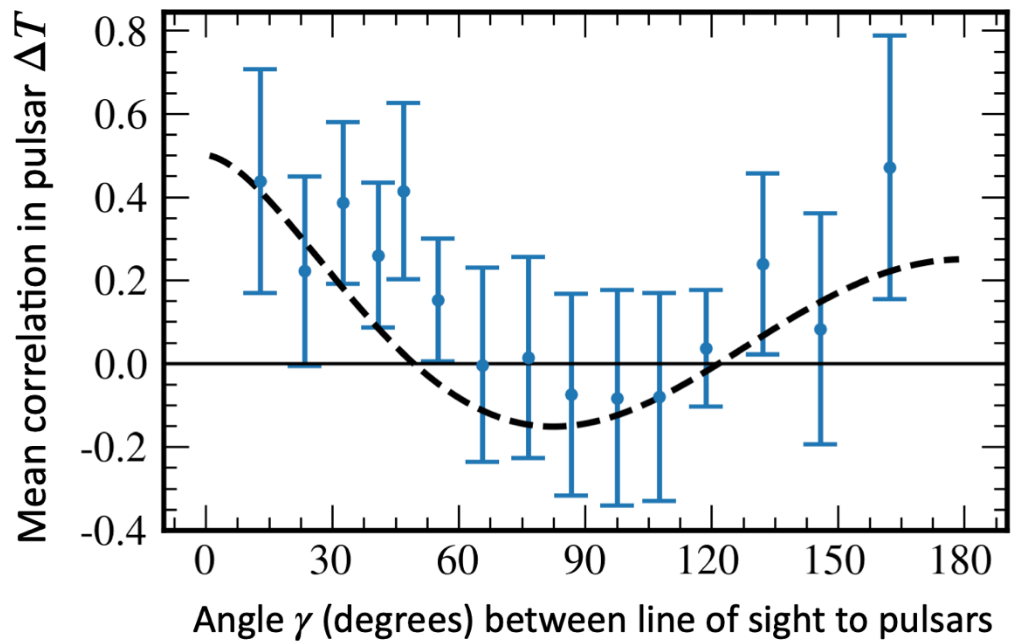


Ingredient : Hellings and Downs

Hellings and Downs curve



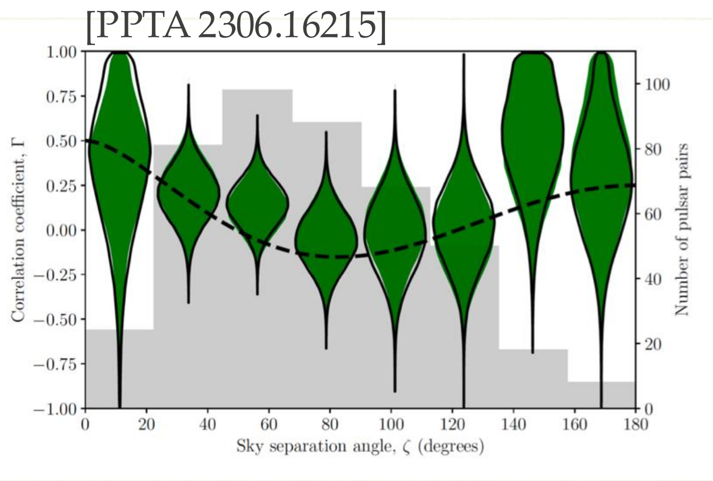
NANOGrav reconstruction with N = 67 pulsars



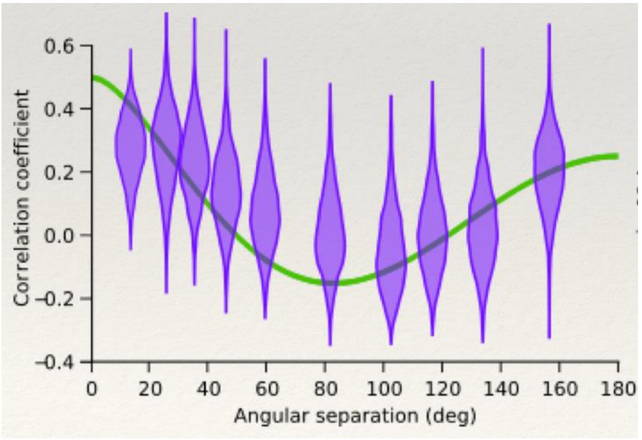
- Example : NANOGrav 15 years data
  - 67 pulsars => 2211 pulsar pairs
  - 15 angular bins => 2211/15 = 147 pairs per bin on average
  - Deviations from the H-D curve due to :
    - Measurement noise
    - Finite set of pulsars
    - Cosmic variance

Various PTAs

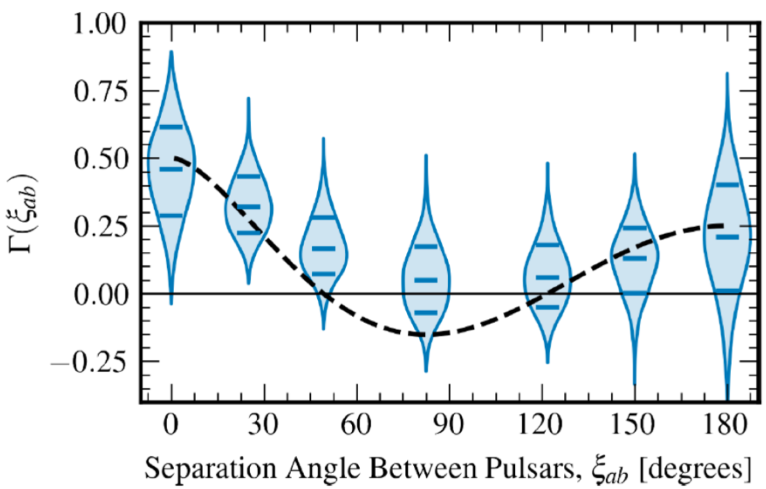
Individual results of various PTAs



PPTA
18 yrs, 30 pulsars, 2 σ



EPTA+InPTA
14 yrs, 25 pulsars, 3 σ



arXiv:2309.00693

NANOGrav
15 yrs, 68 pulsars, $3-4\ \sigma$

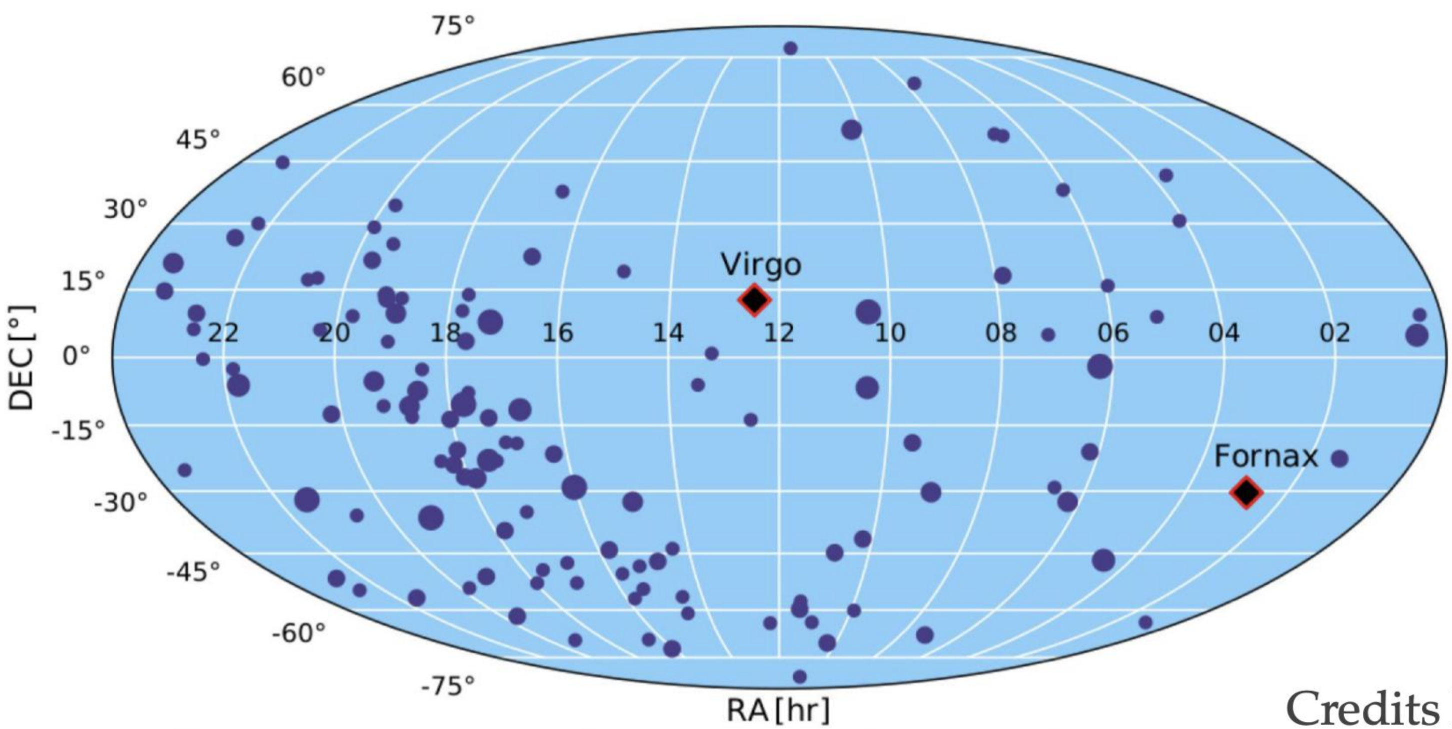
Interpretation

- Very difficult to interpret :
  - any quadrupolar perturbation that falls in the nHz band is good

- Stochastic gravitational waves background (SGWB)
- Could be :
  - GW signal from the population of super massive black hole binaries (SMBHB) in the local Universe ?
  - Network of cosmic strings ?
  - Superposition of continuous gravitational waves (CGW) ?
  - Due to inflation, phase transitions, primordial black holes… ?
  - Anything else ?

Next : IPTA

- Yet to come :
  IPTA Data Release 3
- 121 pulsars
  « the biggest dataset ever made »



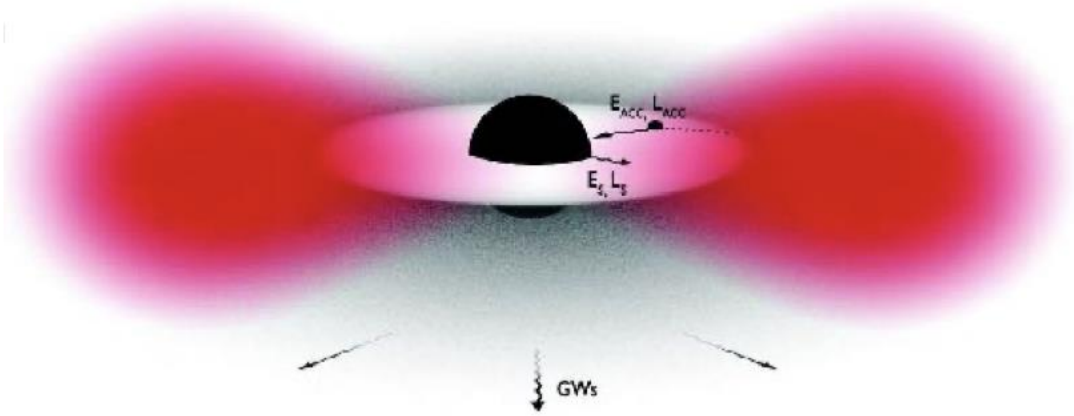
Credits Kuo Liu

The yet unobserved : dark matter searches

Boson cloud superradiance

- Utralight bosons
  - predicted under multiple theoretical frameworks
  - scalar or vector or massive tensor
  - Dark Matter candidates

- Can form clouds around rotating black holes
  - emit gravitational waves by a superradiance mechanism
  - quasi-continuous
  - short duration



Brito et al

Boson cloud superradiance

- Utralight bosons
  - produced by quantum fluctuations near the BH horizon

- Conditions for superradiant instability
  - Superradiance : $\omega_V < m\Omega_{BH}$ (*m* = azimuthal index)
  - Confinement : $\lambda_V \approx r_{BH}$
  - => boson field forms a resonant cavity
  - extracts energy from the rotation of the BH
  - cloud dissipates through gravitational wave emission

- Continuous Waves search methods

Direct searches for ultralight bosonic dark matter

- **Dark photon :** massive vector exerting force on test masses.
  - Changes in lengths of cavities [1, 2, 3]
  - Composition-dependent force on different mirrors in KAGRA [4, 5]

- **Dilaton** : massive scalar exerting force on test masses.
  - Changes in lengths of cavities [6, 7]
  - Varying widths of mirrors [8, 9, 10]

- **Axion** : massive scalar particle modulating polarization of laser light [11, 12]

- Searched with Continuous Waves techniques

References

[1] A. Pierce, K. Riles, Y. Zhao, PRL **121**, 061102 (2018). [2] *SM et al.*, PRD **103** 5, L051702 (2021). [3] LVK, PRD **105**, 063030 (2022).
[4] Y. Michimura *et al.,* PRD **102**, 102001 (2020). [5] LVK, PRD **110**, 042001 (2024). [6] *SM* and T. Suyama, PRD **100**, 123512 (2019).
[7] K. Fukusumi, *SM*, and T. Suyama, PRD **108**, 095054 (2023). [8] H. Grote and Y. V. Stadnik, PRR **1**, 033187 (2019).
[9] S. M. Vermeulen *et al.*, Nature 600, 424–428 (2021). [10] A. S. Göttel *et al.*, PRL **133,** 101001 (2024).
[11] K. Nagano *et al.*, PRL **123**, 111301 (2019). [12] K. Nagano *et al.*, PRL **123**, 111301 (2019).

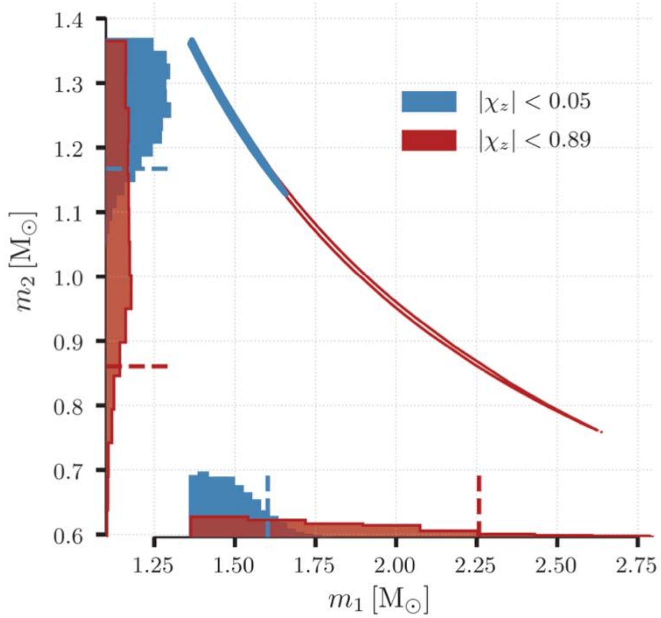
Summary

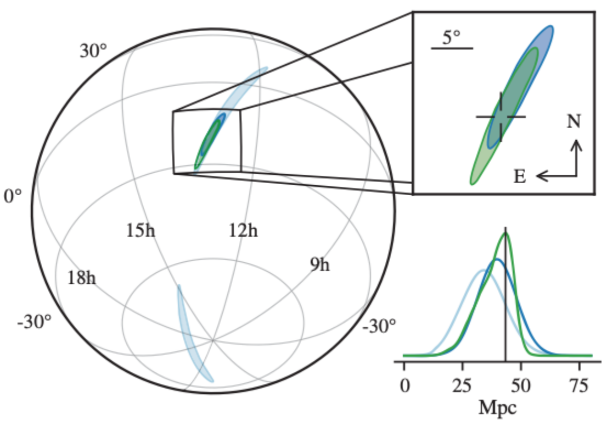
- Extremly successful three observing runs of LIGO / Virgo
  - ~ 200 BBH, 2 NS-BH, 2 BNS
  - Insights on gravity, black holes, cosmology, nuclear physics,…
- GW170817 BNS event was a fundamental milestone… and still is
- O4 run ongoing
  - A few (2-5) BBH detections per week
  - No other multimessenger observation… yet
- Searching for other GW signals
  - (quasi-)Continuous Waves from rotating neutron stars or other sources
  - SGWB with LIGO-Virgo-Kagra and various PTAs
- Searching for some dark matter particles

Spares

BNS systems

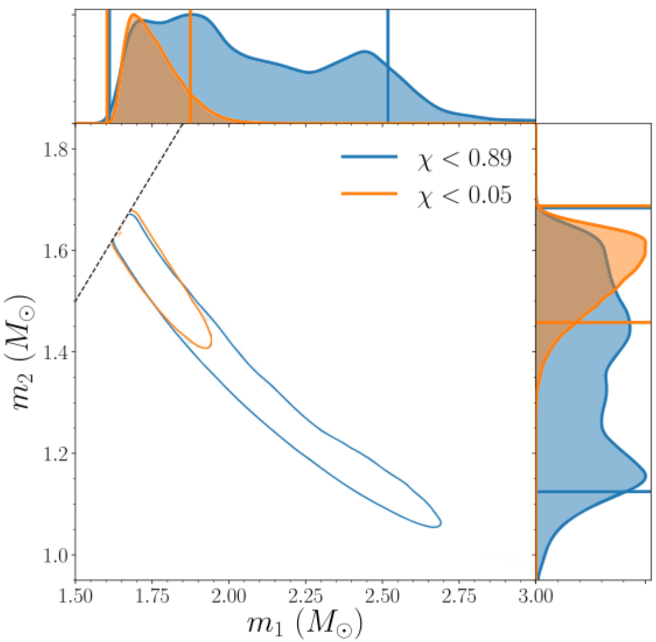
- GW170817

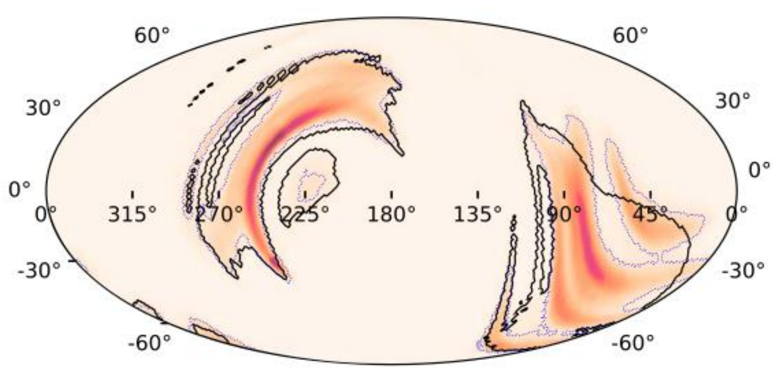




arXiv:1710.05832, PRL 119, 161101 (2017)

- GW190425

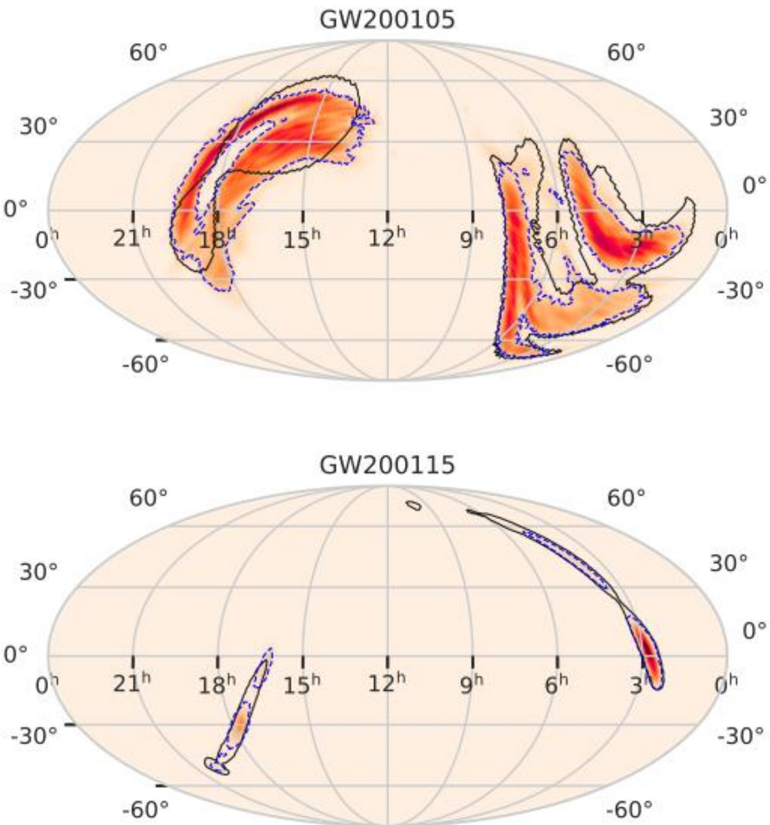


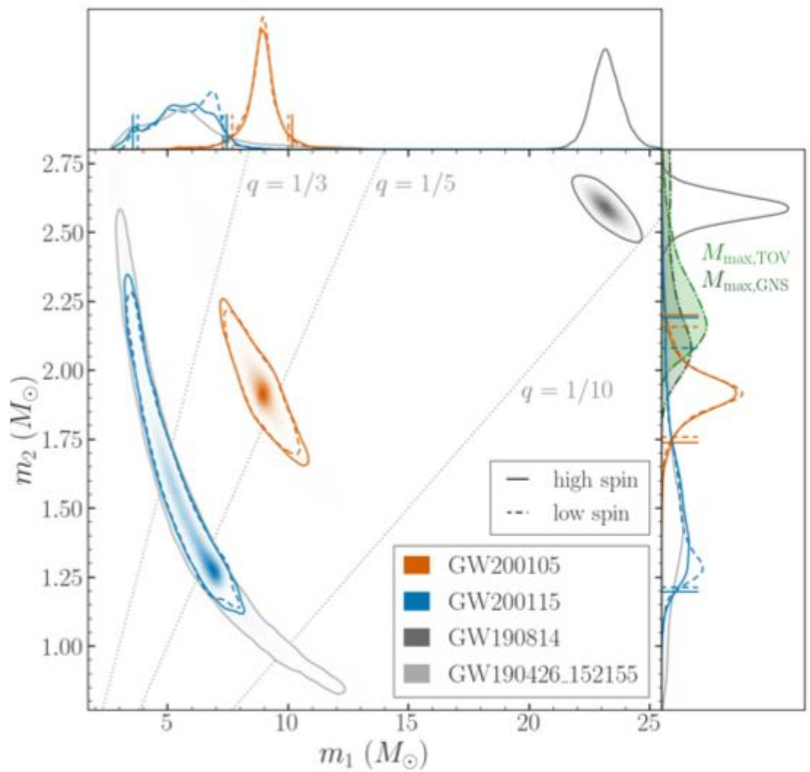


arXiv:2001.01761, ApJ Letters, 892:L3 (24pp), 2020 March 20

Two NS-BH binaries

- Two events
- Poor localization

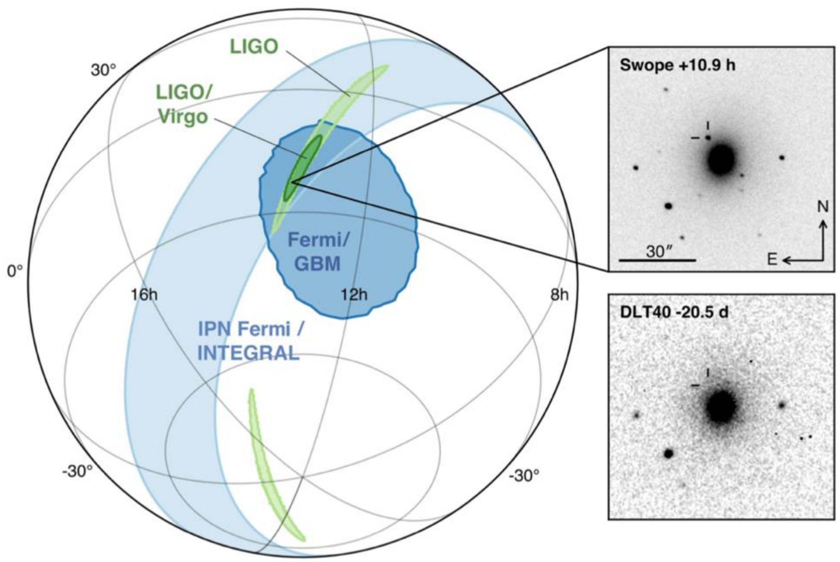


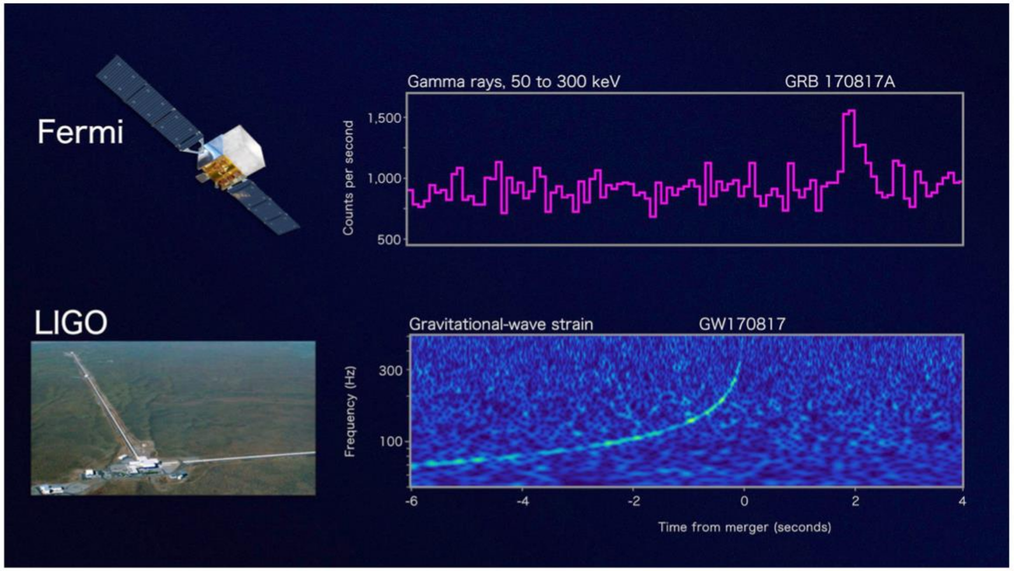


- Spins loosely constrained

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

First BNS system : GW170817

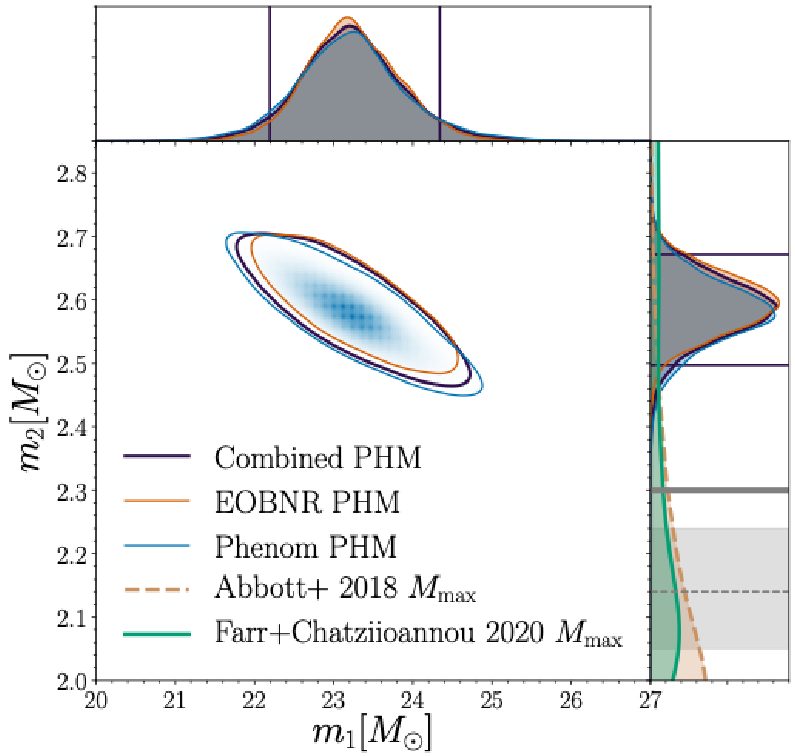




- Coincident short GRB
- First direct evidence
  some BNS mergers ⬄ progenitors of short GRBs

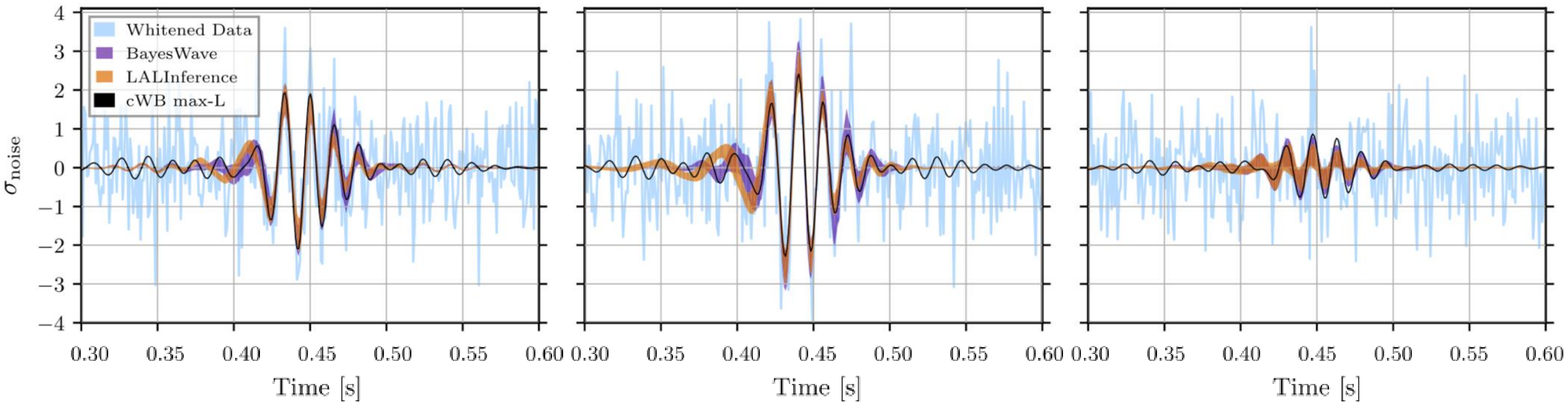
A curious event : GW190814

- 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)?

GW170817 : EM counterpart

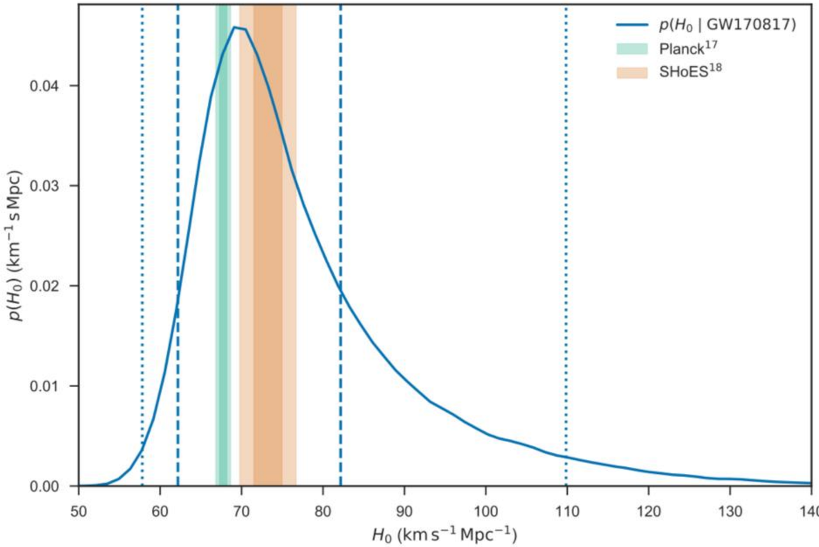
- Observed optical/UV/infrared counterpart
  - Origin : NGC4993 galaxy
  - Kilonova (arXiv:1710.05833, ApJ Letters, 848:L12 (59pp), 2017 October 20)
  - Speed of GW (arXiv:1710.05834, ApJ Letters, 848:L13 (27pp), 2017 October 20)

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

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

  - 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)

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

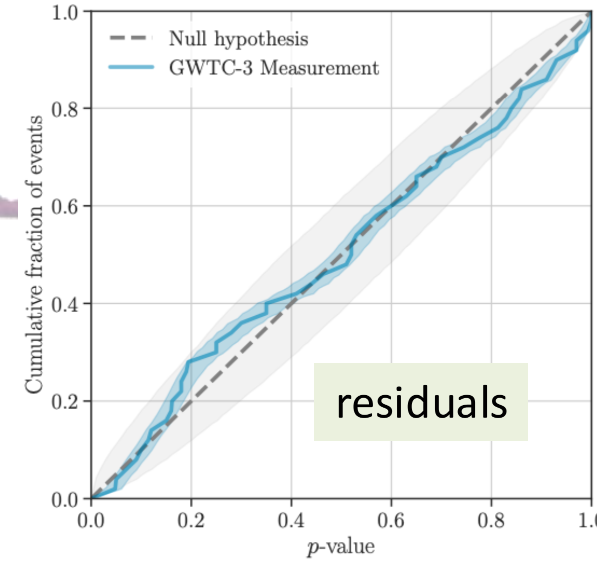
GWs + GRBs, optimistic approach

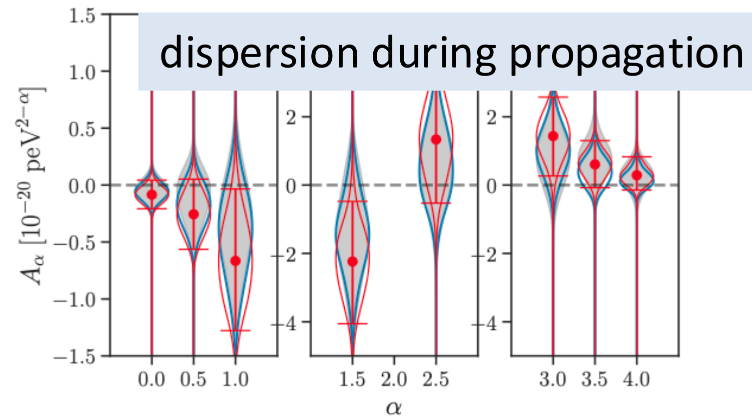
model	$\mathcal{R}(0)$	GW	GW+EM (prompt)							
			Swift/BAT		Fermi/GBM		INTEGRAL/IBIS		SVOM/ECLAIRs	
			uniform	structured	uniform	structured	uniform	structured	uniform	structured
	$Gpc^{-3}yr^{-1}$	yr^{-1}	yr^{-1}	yr^{-1}	yr^{-1}	yr^{-1}	yr^{-1}	yr^{-1}	yr^{-1}	yr^{-1}
A1	31	5	0.002 (0.01)	0.05-0.08	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

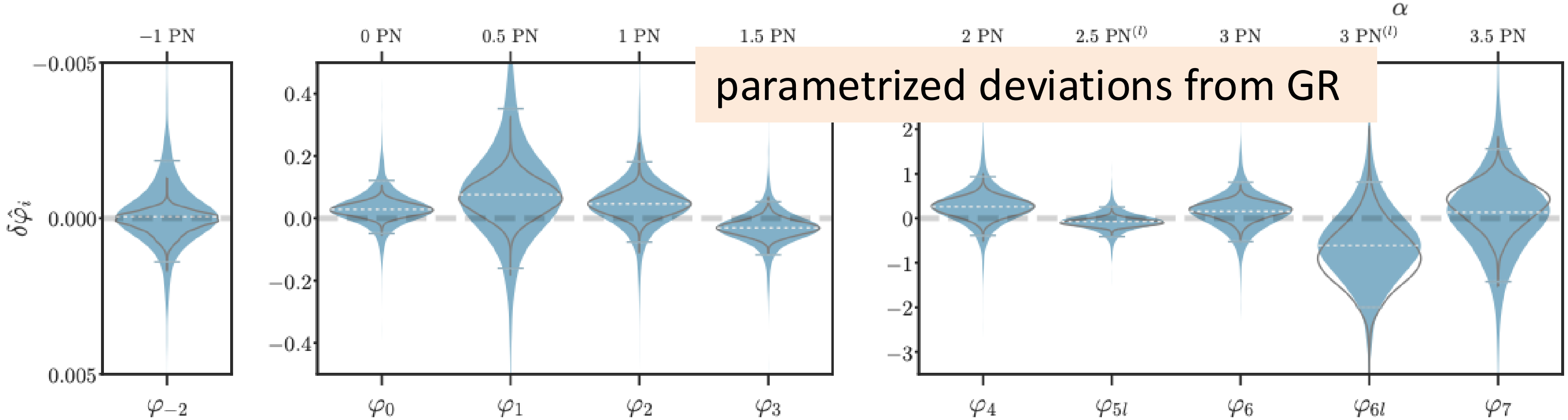
Testing GR

- 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

Expected rates and localization

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

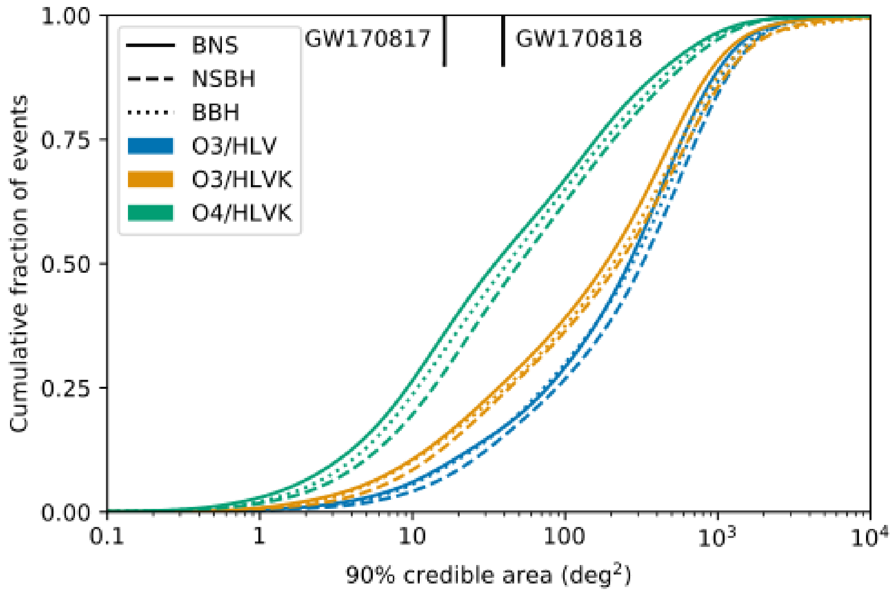
$$d : 100\,\text{Mpc} \rightarrow\ 160\,\text{Mpc} \quad \Rightarrow \quad R_D \times 4$$

- For O4

Rates

  - $O(100)$ BBH detections / year
  - $O(1-10)$ BNS detections / year
  - Counterparts for BNS highly uncertain (arXiv:2204.12504)

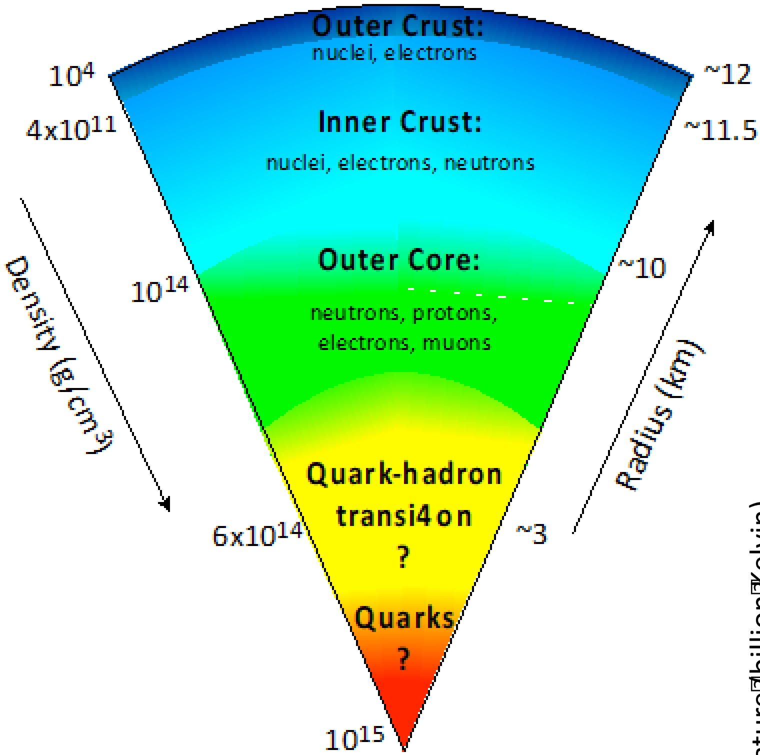
Localization

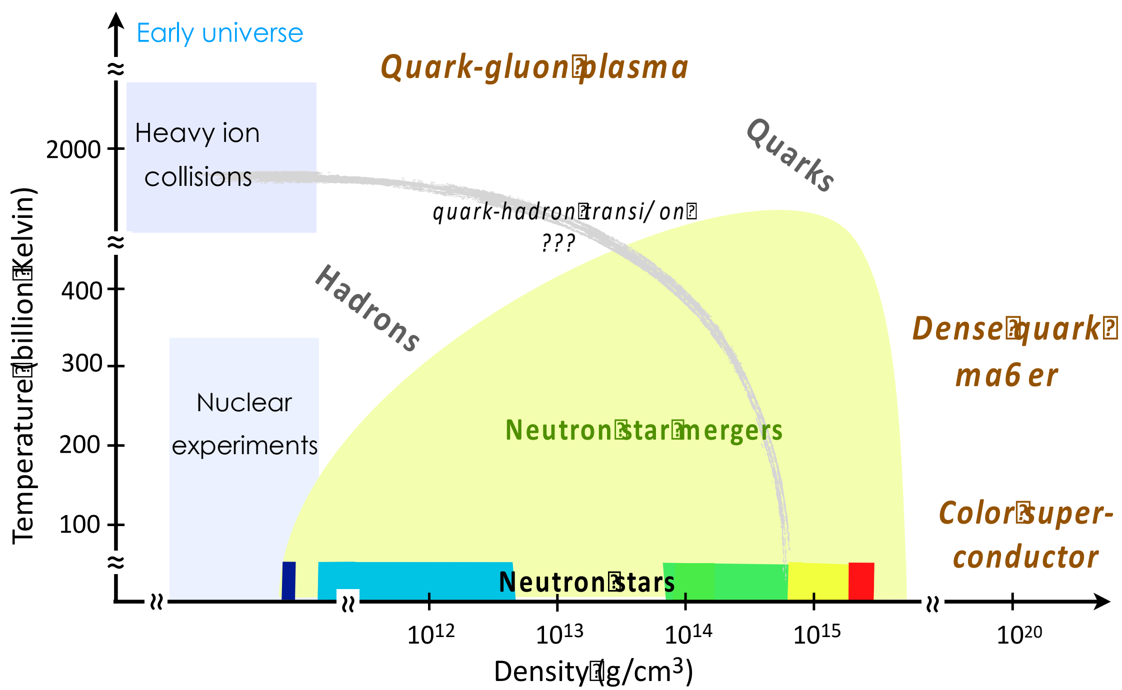


https://dcc.ligo.org/public/0094/P1200087/058/ObservingScenarios.pdf

Neutron stars: internal structure

- Density

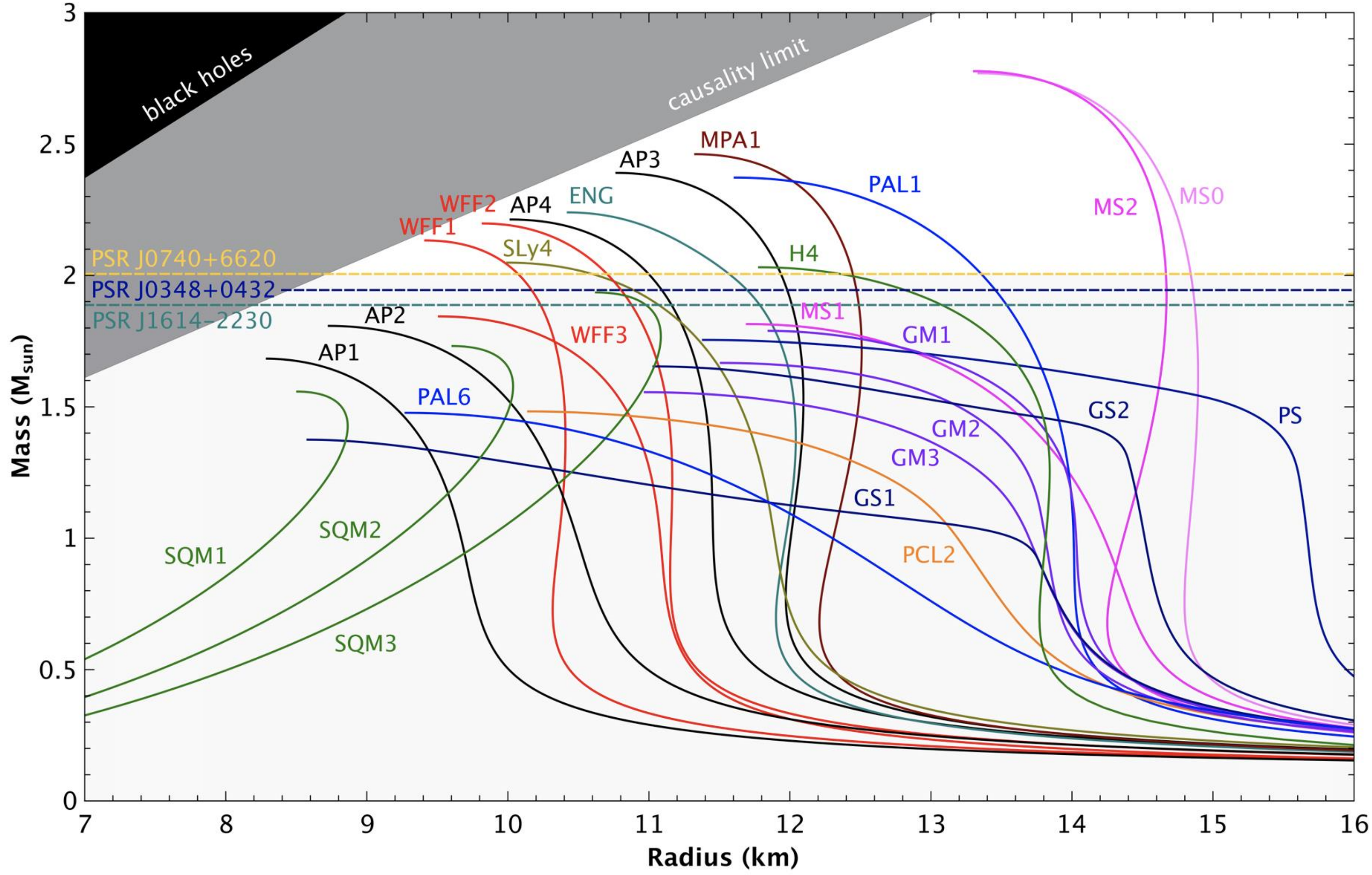




41

Neutron stars: internal structure

- Equation(s) of state



http://www3.mpifr-bonn.mpg.de/staff/pfreire/NS_masses.html arXiv:1603.02698 **[astro-ph.HE]** 42

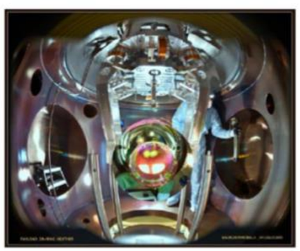
Advanced Virgo+

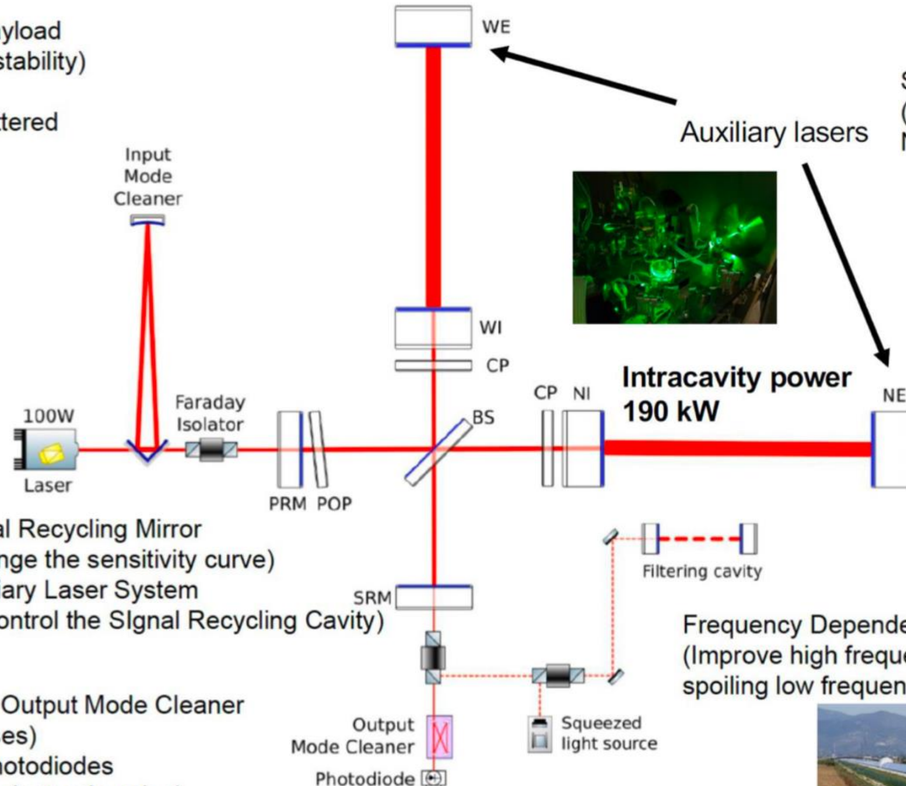
Path towards O4: reduce quantum noise, hit against thermal noise.

credits: V. Fafone, EAS 2022

New Input Mode Cleaner Payload
(Improve controllability and stability)
Instrumented Baffle
(Direct measurement of scattered light)

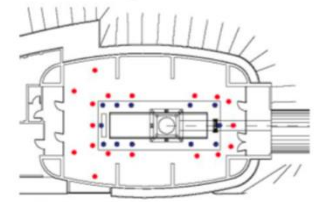
High-power Laser
(Increase the circulating power)

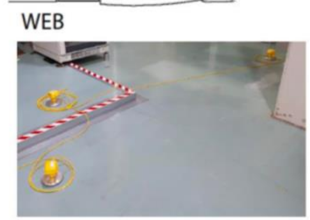




Auxiliary lasers

Seismometer Array
(Measurement and cancellation of Newtonian Noise)





Signal Recycling Mirror
(Change the sensitivity curve)
Auxiliary Laser System
(To control the SIgnal Recycling Cavity)

Frequency Dependent Squeezing
(Improve high frequencies without spoiling low frequencies)

Goal: 4.5 dB

High-finesse Output Mode Cleaner
(Reduce losses)
Low-noise photodiodes
(Reduce the electronic noise)