Latest news from the gravitational wave detector projects

Andrzej Królak

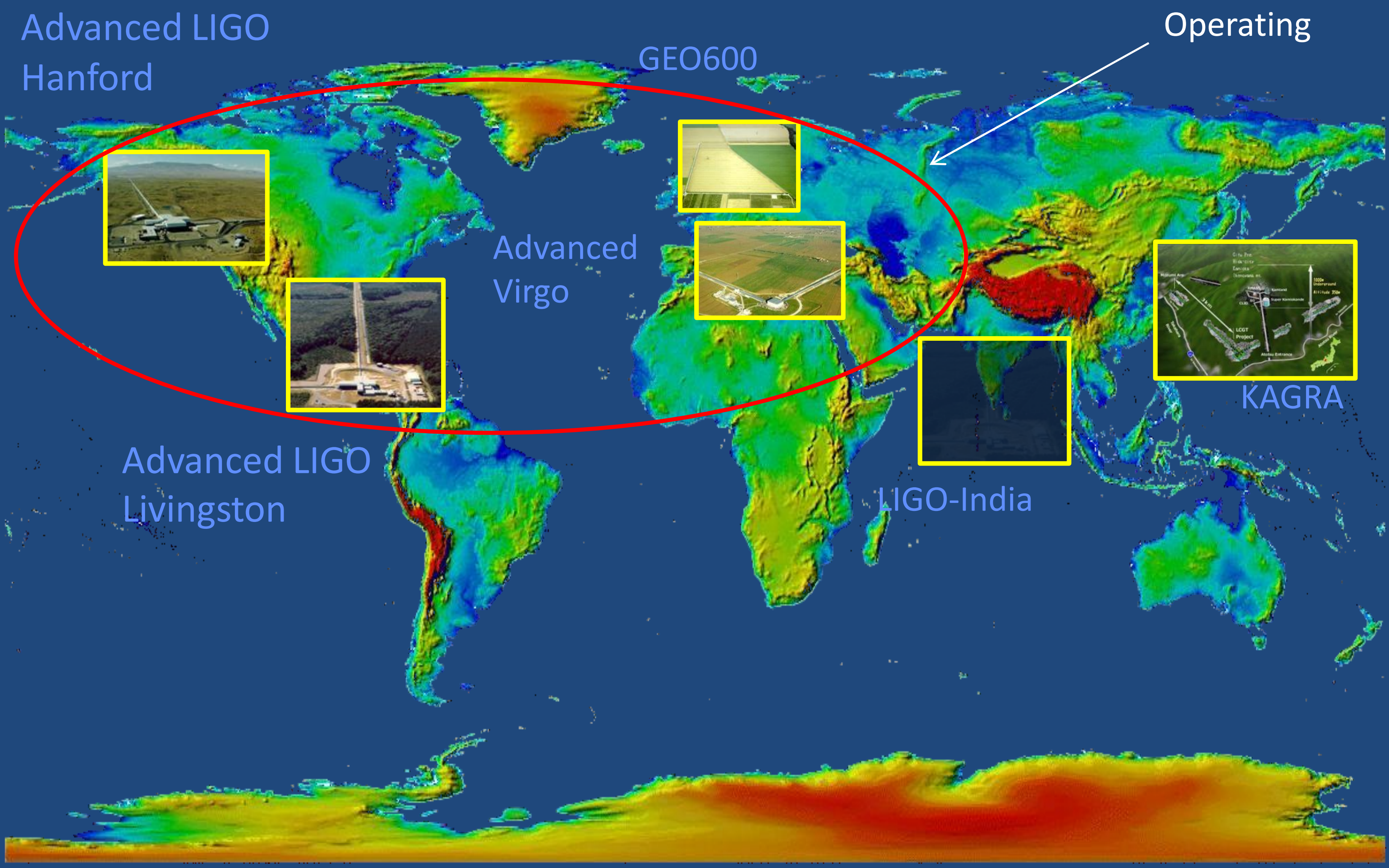
INSTITUTE OF MATHEMATICS
Polish Academy of Sciences

NATIONAL CENTRE for NUCLEAR RESEARCH
Świerk

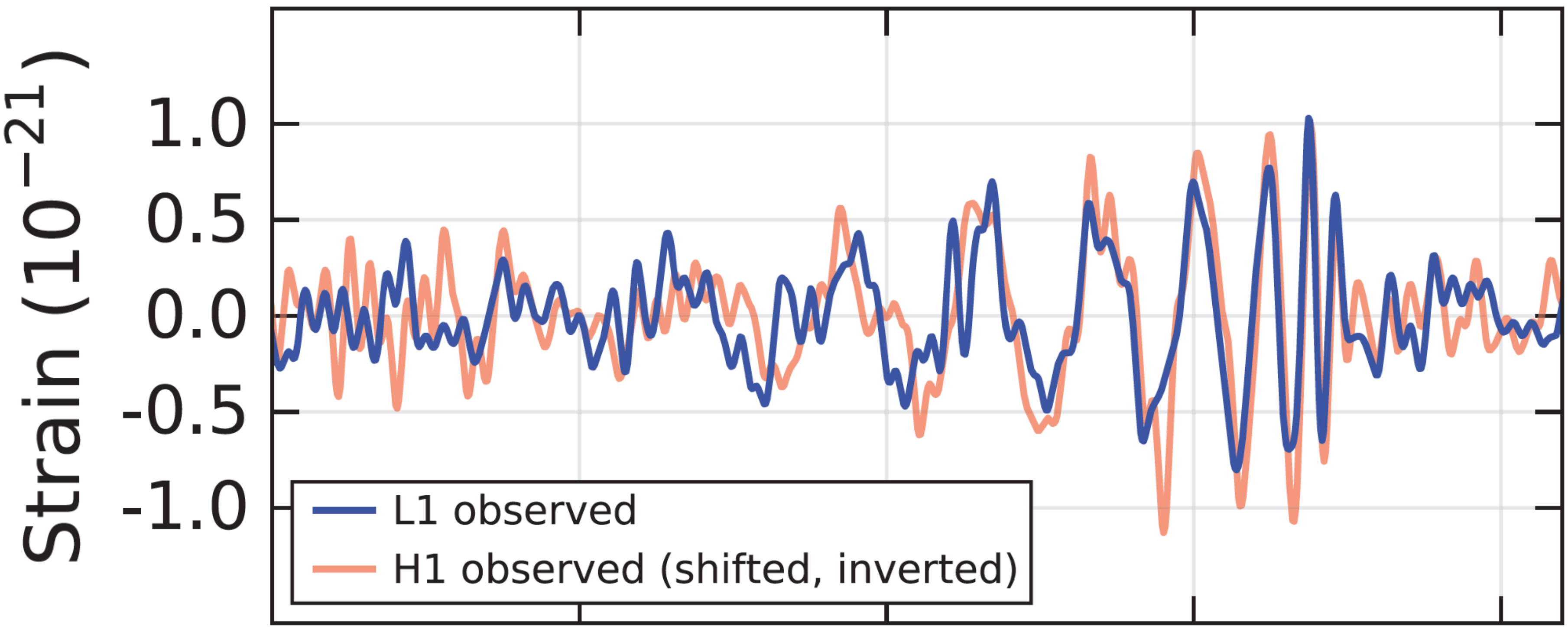
Contents

- Present network of ground based GW detectors
- Recent detections
- Results of the observations
- Activities of Polgraw-Virgo group
- Plans for the future

Network of gravitational wave detectors



On September 14, 2015 at 09:50:45 UTC the two detectors of the Laser Interferometer Gravitational-Wave Observatory (LIGO) caught the first gravitational-wave signal



2017 Nobel prize in physics

Advanced Virgo

Virgo is a European collaboration with about 280 members

Advanced Virgo (AdV): upgrade of the Virgo interferometric detector

Participation by scientists from France, Italy, Belgium, The Netherlands, Poland, Hungary, Spain, Germany

- 22 laboratories, about 280 authors
  - APC Paris
  - ARTEMIS Nice
  - EGO Cascina
  - INFN Firenze-Urbino
  - INFN Genova
  - INFN Napoli
  - INFN Perugia
  - INFN Pisa
  - INFN Roma La Sapienza
  - INFN Roma Tor Vergata
  - INFN Trento-Padova
  - LAL Orsay – ESPCI Paris
  - LAPP Annecy
  - LKB Paris
  - LMA Lyon
  - Nikhef Amsterdam
  - POLGRAW(Poland)
  - RADBOUD Uni. Nijmegen
  - RMKI Budapest
  - UCLouvain
  - ULiege
  - Univ. of Barcelona
  - Univ. of Valencia
  - University of Jena

Advanced Virgo project has been formally completed on July 31, 2017

Part of the international network of 2nd generation detectors

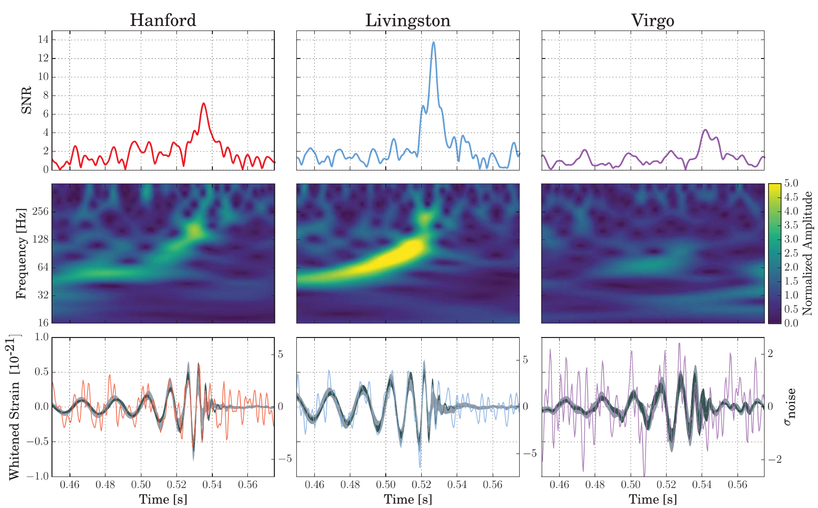
Joined the O2 run on August 1, 2017

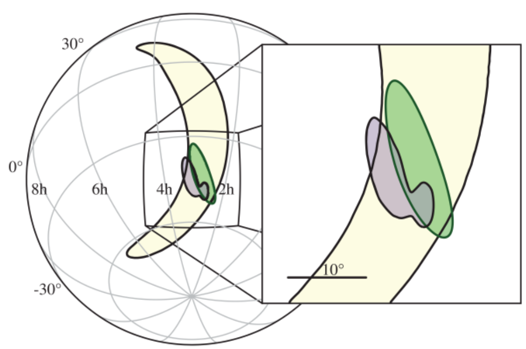
8 European countries

Credit: Jo van den Brand

2017: Advanced Virgo joins the network

14th August 2017



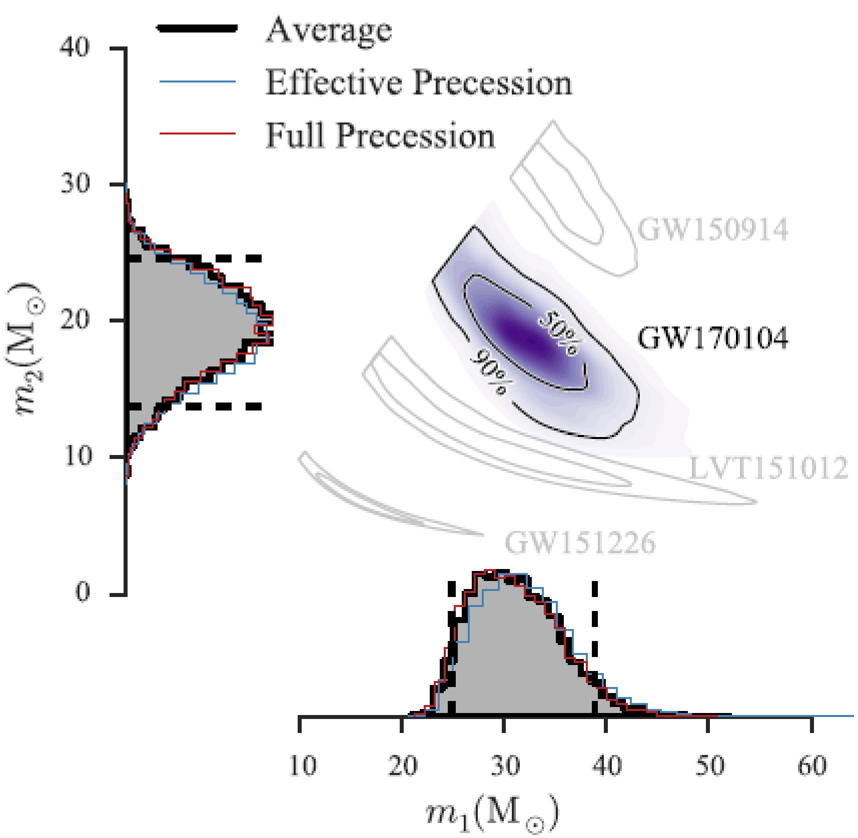


LIGO+Virgo, PRL **118**, 221101 (2017)

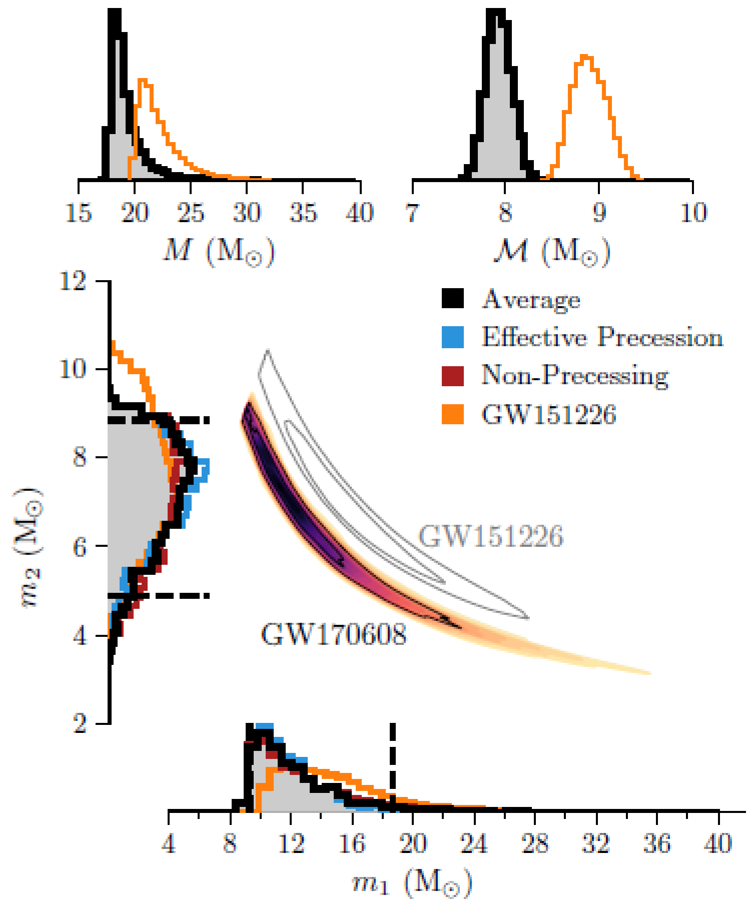
- 3-detector network:
  - LIGO Hanford
  - LIGO Livingston
  - Virgo
- 14 August:
  First observation of a gravitational wave signal by LIGO and Virgo together
- Demonstration of dramatically improved sky localization with a three detector network

Black hole masses

(Abbott et al. PRL 118 (2017) 221101)



(Abbott et al. ApJ 851 (2017) L35)



- Chirp mass is best measured. Individual masses can be better measured if merger is observed, because total mass is measured at merger.

Credit: A. Buonanno

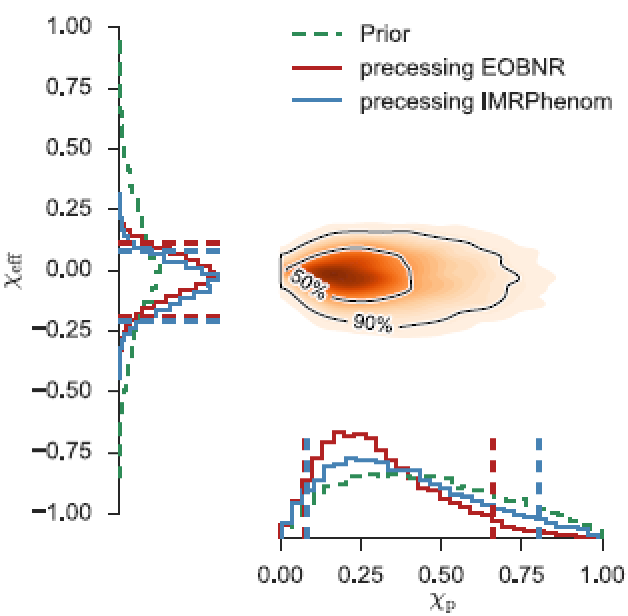
Black hole spins

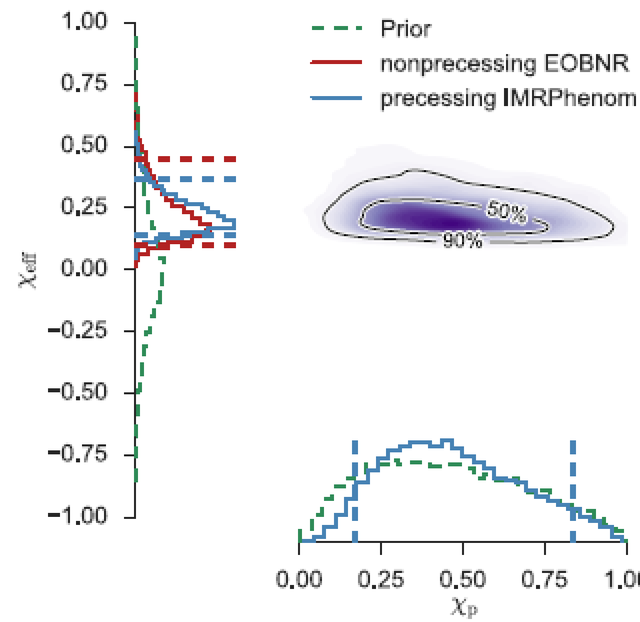
(measurements @ 25Hz)

GW150914

GW151226

(Abbott et al. PRX 6 (2016) 041014)





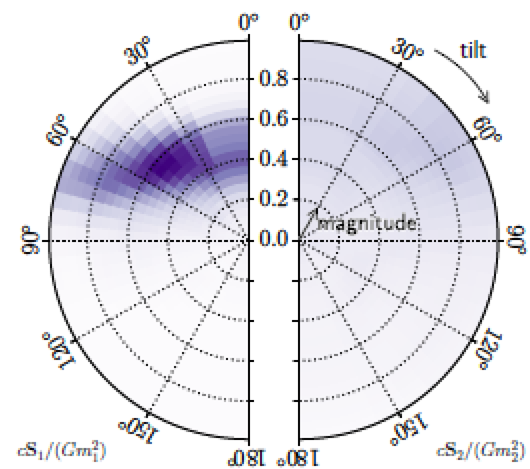
(Abbott et al. PRL 116 (2016) 241103)

$$\chi_{\rm eff} = \frac{c}{GM}\left(\frac{\boldsymbol{S}_1}{m_1}+\frac{\boldsymbol{S}_2}{m_2}\right)\cdot\frac{\boldsymbol{L}}{|\boldsymbol{L}|}$$

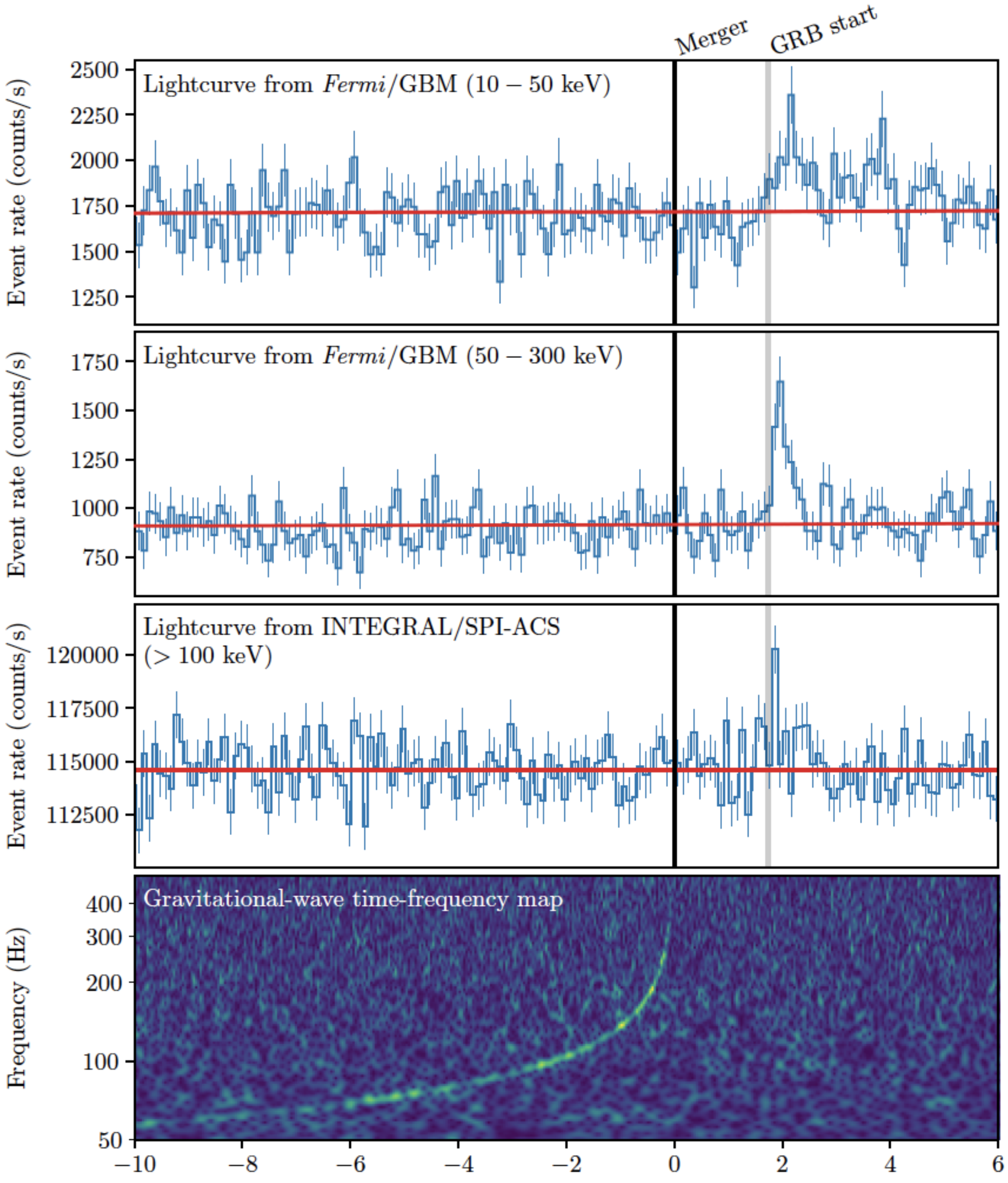
(constant through 2PN order)

- BHs' **spins not maximal**, and for GW151226 **one BH's spin larger than 0.2** at 99% confidence.

- **Spins < 0.7. No information** about **precession.**



GRB 170817A



GRB 170817A occurs (1.74 ± 0.05) seconds after GW170817

It was autonomously detected in-orbit by Fermi-GBM (GCN was issued 14s after GRB) and in the routine followup search for short transients by INTEGRAL SPI-ACS

Probability that GW170817 and GRB 170817A occurred this close in time and with location agreement by chance is 5.0×10^{-8} (Gaussian equivalent significance of 5.3σ)

BNS mergers are progenitors of (at least some) SGRBs

B. P. Abbott et al., *Gravitational Waves and Gamma Rays from a Binary Neutron Star Merger: GW170817 and GRB 170817A*, 2017, ApJL 848, L13

Multimessenger Observations

Approximate timeline:

GW170817 - August 17, 2017 12:41:04 UTC = $\mathbf{t_0}$

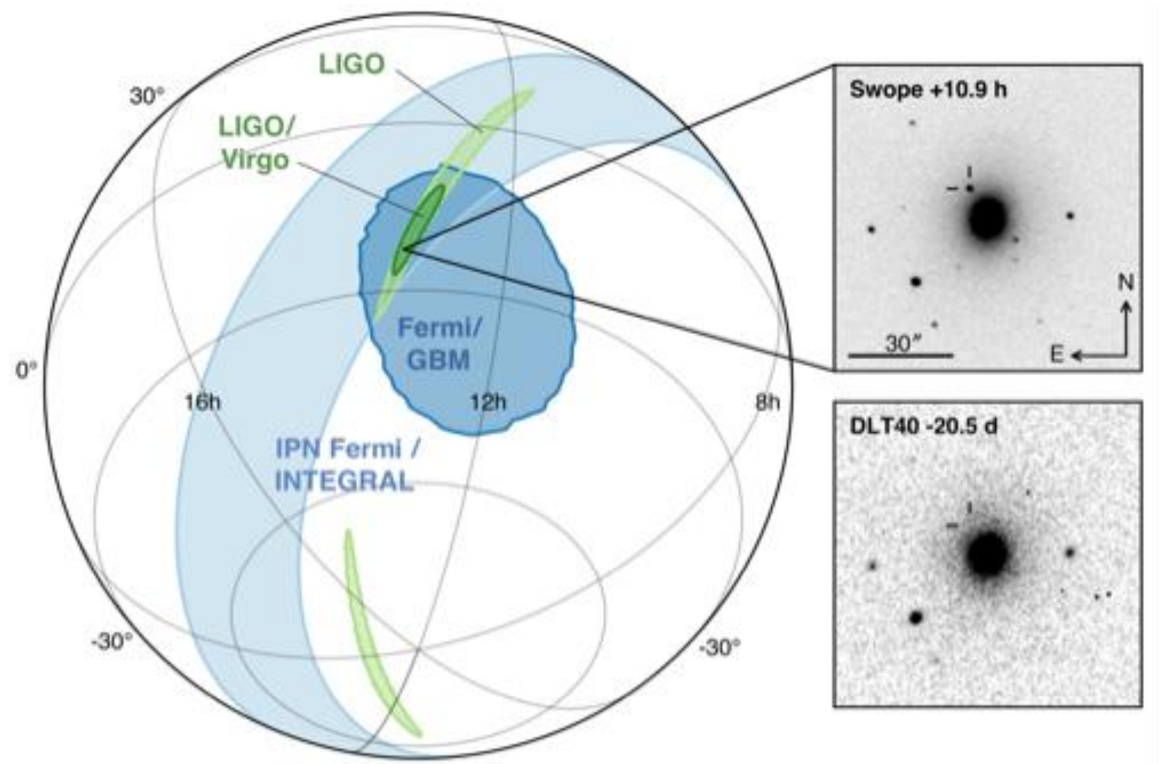
GRB 170817A
t_0 + 2 sec

LIGO signal found
t_0 +6 minutes

LIGO-Virgo GCN reporting BNS signal associated with the time of the GRB
t_0 +41 minutes

SkyMap from LIGO-Virgo
t_0 + 4 hours

Optical counterpart found
t_0 + 11 hours



- The localisation region became observable to telescopes in Chile 10 hours after the event time (wait for nightfall!)
- Approximately 70 ground- and space- based observatories followed-up on this event

B. P. Abbott, *Multi-messenger Observations of a Binary Neutron Star Merger*, 2017, ApJL in press. doi:10.3847/2041-8213/aa91c9

GW170817: A string of "firsts"

- First observation of a binary neutron star merger
  - Also loudest gravitational wave signal to date!
- Confirmation that short, hard gamma ray bursts are associated with binary neutron star mergers
  - Fermi/INTEGRAL GRB observation 1.74 seconds after gravitational waves
- Confirmation that the speed of gravity equals the speed of light
  - The same to within ~1 part in 10^{15}
- Confirmation of the origin of heavy elements
  - Observation of "kilonova" in X-rays, UV, optical, infrared, radio
- First direct measurement of the neutron star equation of state
  - More compact neutron stars are favored
- A new measure of distances in the Universe
  - Distance can be inferred directly from the gravitational wave signal

Hubble constant measurement

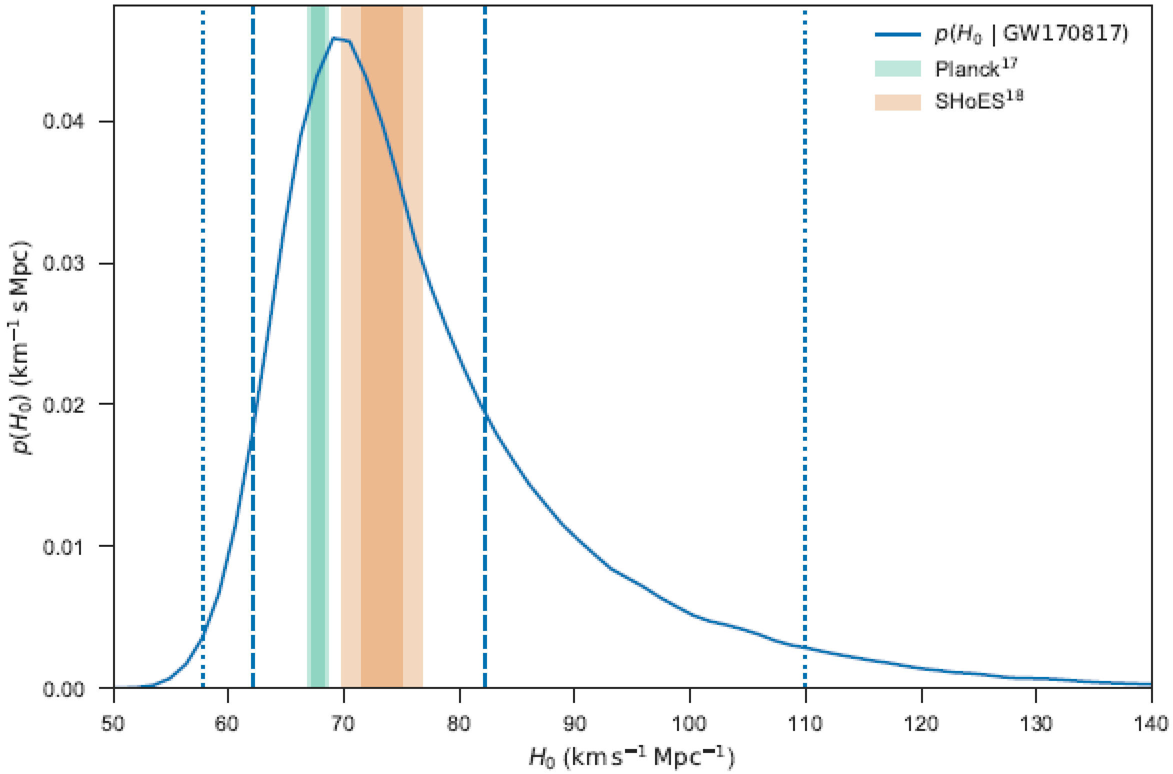
GW measurement:

Luminosity distance d_L

Galaxy localization:

Redshift **z**

Hubble constant: H_0

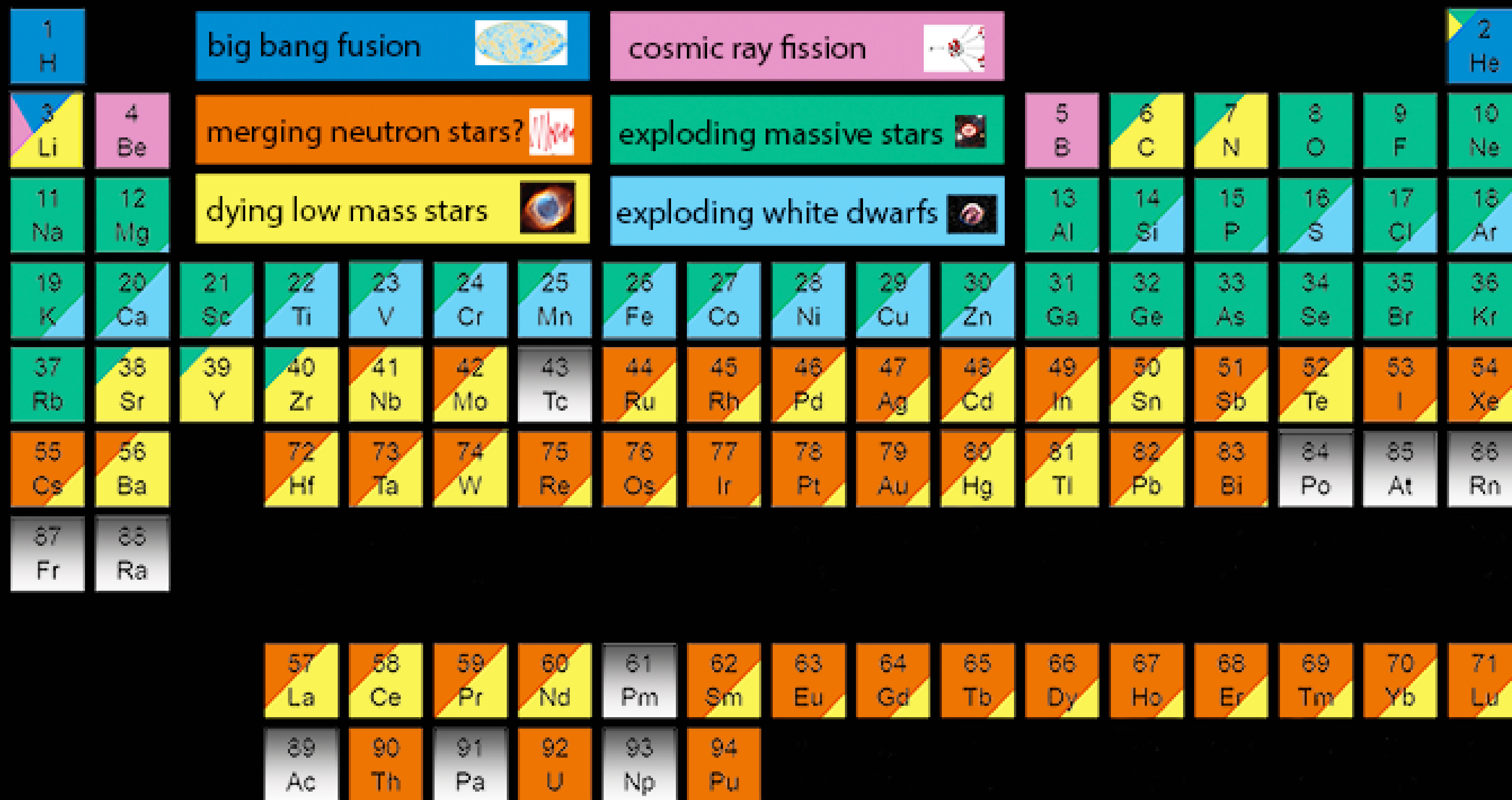


GW170817 measurement of H_0.

Marginalized posterior density for H_0 (blue curve).

Nature **551**, 85–88 (02 November 2017)

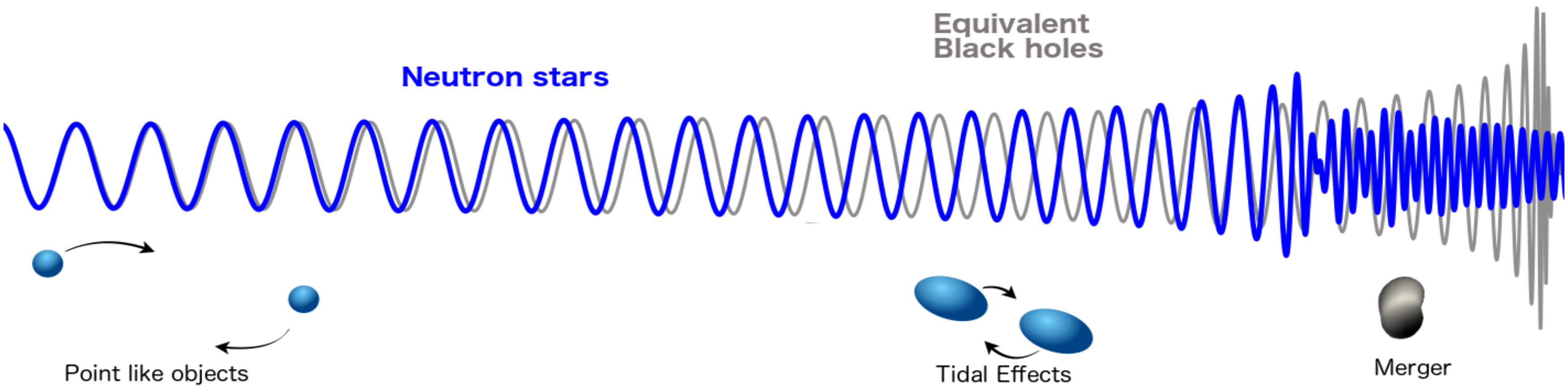
The Origin of the Solar System Elements



Graphic created by Jennifer Johnson
http://www.astronomy.ohio-state.edu/~jaj/nucleo/

Astronomical Image Credits:
ESA/NASA/AASNova

Properties of nuclear matter



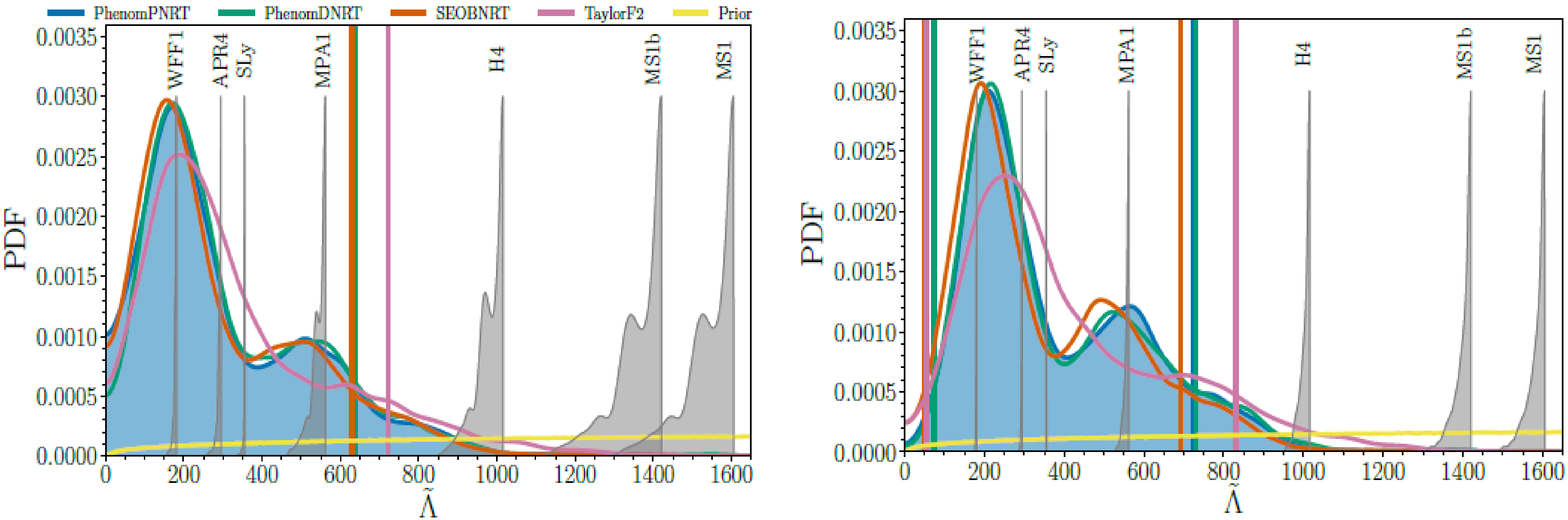
Credits: P. Schmidt; NR data: T. Dietrich

NS equation of state (EOS) affects gravitational waveform during late inspiral, merger and postmerger.

Constraints on NS EOS

More compact <- Less compact

More compact <- Less compact



PDFs of the combined tidal parameter for the high-spin (left) and low-spin (right) priors.

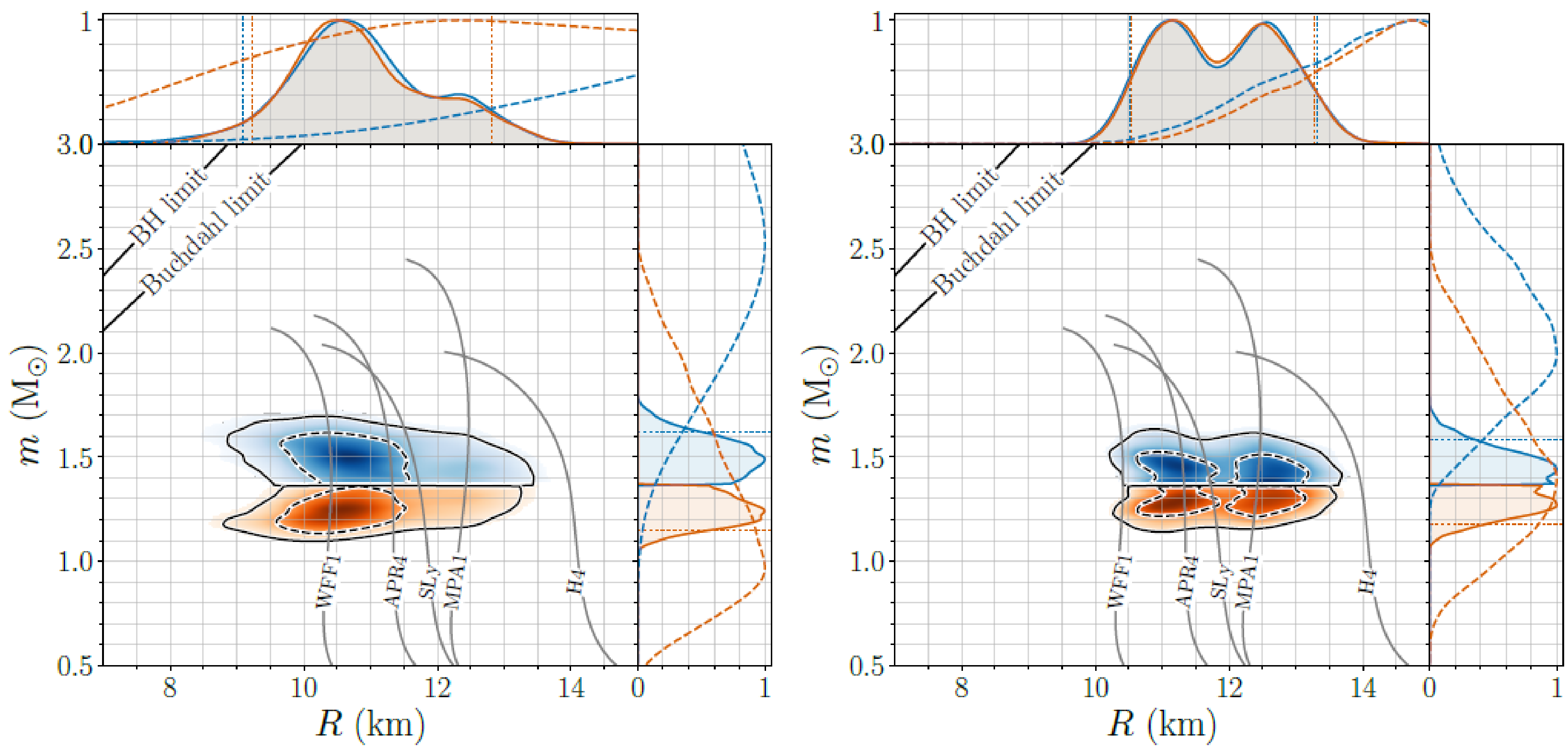
$$\Lambda = (2/3)k_2[(c^2/G)(R/m)]^5$$

Λ_1 Λ_2 : Love numbers

$$\tilde{\Lambda} = \frac{16}{13}\frac{(m_1 + 12m_2)m_1^4\Lambda_1 + (m_2 + 12m_1)m_2^4\Lambda_2}{(m_1 + m_2)^5}$$

https://arxiv.org/abs/1805.11579

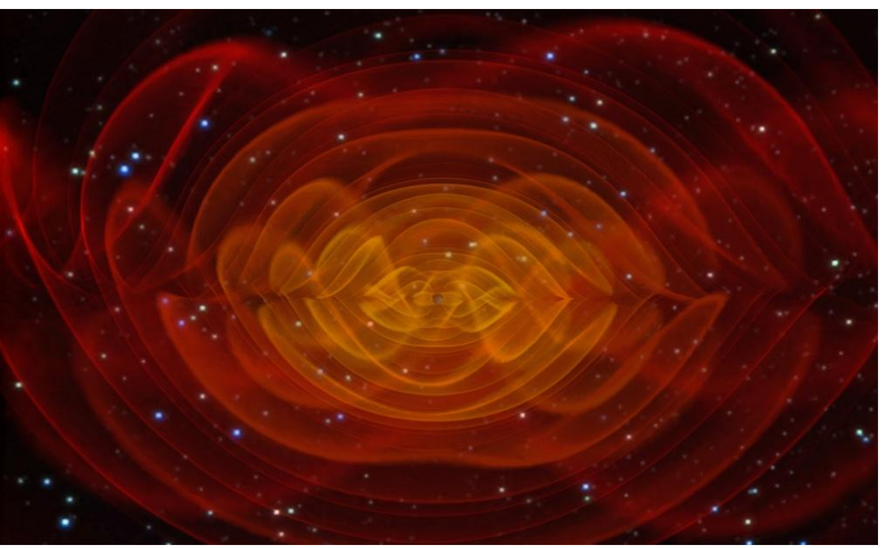
Constraints NS radius



Marginalized posterior for the mass m and areal radius R of each binary component using EOS-insensitive relations (left panel) and a parametrized EOS where we impose a lower limit on the maximum mass of 1.97M (right panel).

https://arxiv.org/abs/1805.11581, accepted to PRL

Does the speed of gravity equal the speed of light?



- Gamma rays reached Earth 1.74 seconds after end of gravitational wave inspiral signal
- Consider two extremes:
  - The gamma rays were emitted at the same time as end of GW

  ⇢ Light moved slower than gravity
  - The gamma rays were emitted 10 seconds after the end of GW

  ⇢ Light moved faster than gravity
- Conservative lower bound on distance from GW signal: 26 Mpc

$$-3 \times 10^{-15} < \Delta v / v_{EM} < +7 \times 10^{-16}$$

LIGO+Virgo+Fermi+INTEGRAL, ApJ **848**, L13 (2017)

What the LIGO-Virgo Detections Tell Us About the Validity of General Relativity

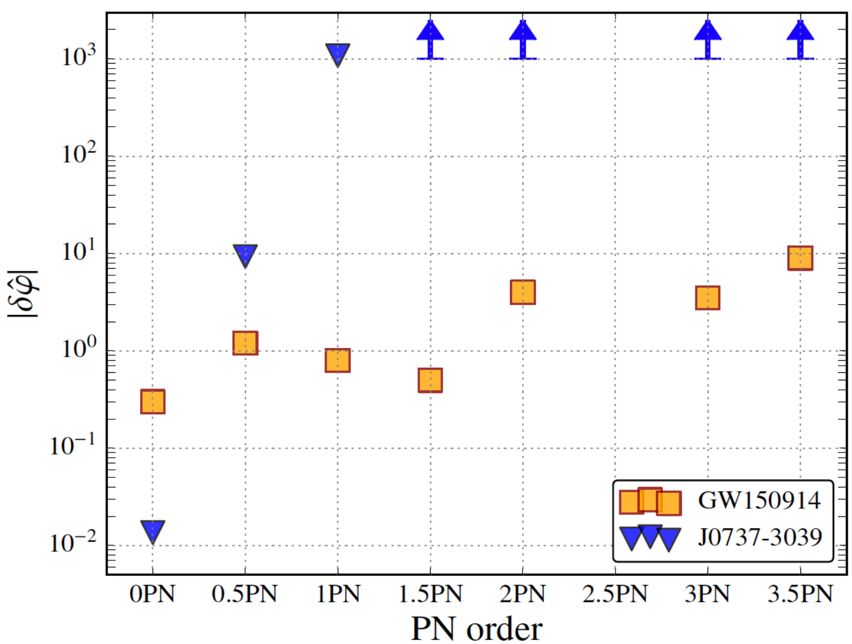
Post-Newtonian Approximation to GR

$$h(f) = A(f)e^{i\phi(f)}$$

$$\phi(f) = \phi_{ref} + 2\pi f t_{ref} + \phi_{Newton}(Mf)^{-5/3} + \phi_{0.5PN}(Mf)^{-4/3}$$

$$+\phi_{1PN}(Mf)^{-1} + \phi_{1.5PN}(Mf)^{-2/3} + \ldots$$

Post-Newtonian Approximation to GR

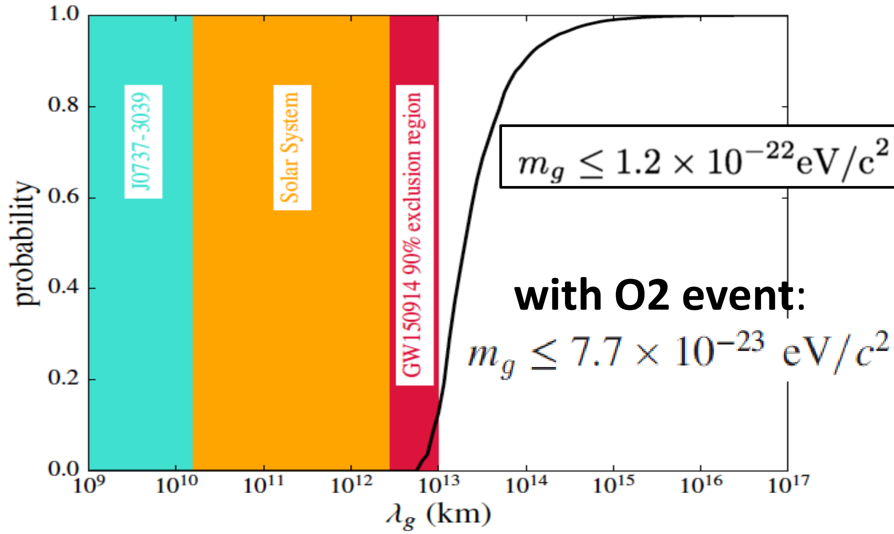


Upper Bound on the Graviton Mass

$$E^2 = p^2c^2 + m_g^2c^4 \qquad \lambda_g = \frac{h}{m_g c}$$

$$\frac{v_g^{\,2}}{c^2} \approx 1 - \frac{h^2c^2}{\lambda_g^2 E^2}$$

Compton Wavelength of the Graviton



Abbott, et al. ,LSC and Virgo, "Tests of general relativity with GW150914", Phys. Rev. Lett. 116, 221101 (2016), Binary Black Hole Mergers in the first Advanced LIGO Observing Run, https://arxiv.org/abs/1606.04856

Searches for other GW sources

(upper limits only)

Bursts (Supernovae) Phys. Rev. D 95, 042003 (2017)

All-sky search for short gravitational-wave bursts in the first Advanced LIGO run

h_{UL} 10x less than for 1st generation of detectors

Other binary systems (NSBH) ApJL, L21 (2016)

Upper limits on the rates of binary neutron star and neutron-star--black-hole mergers from Advanced LIGO's first observing run

NSBH MBH > 5 M_s detectable to 110Mpc

Periodic signals (pulsars)

Astrophys.J. 839 (2017) no.1, 12

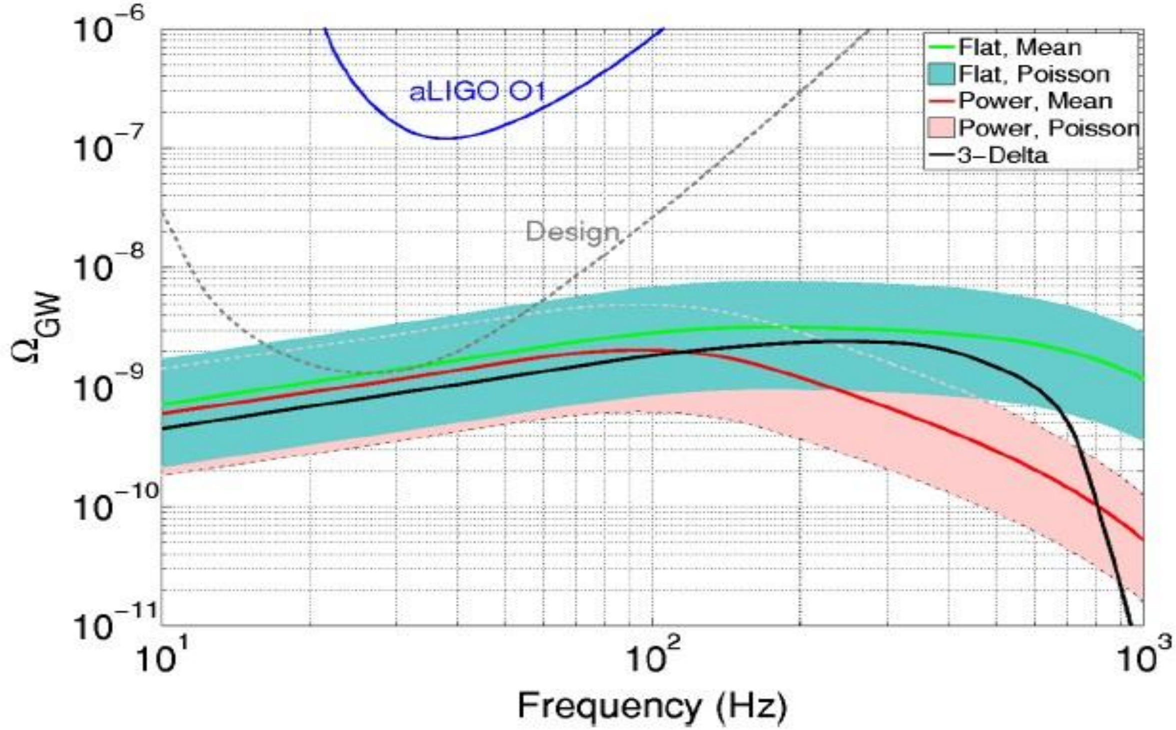
Crab pulsar : Energy in GW < 0.002 $E_{TotalRadiated}$
Vela pulsar : Energy in GW < 0.01 $E_{TotalRadiated}$

Phys. Rev. D 96, 062002 (2017), Phys. Rev. D **97**, 102003 (2018)

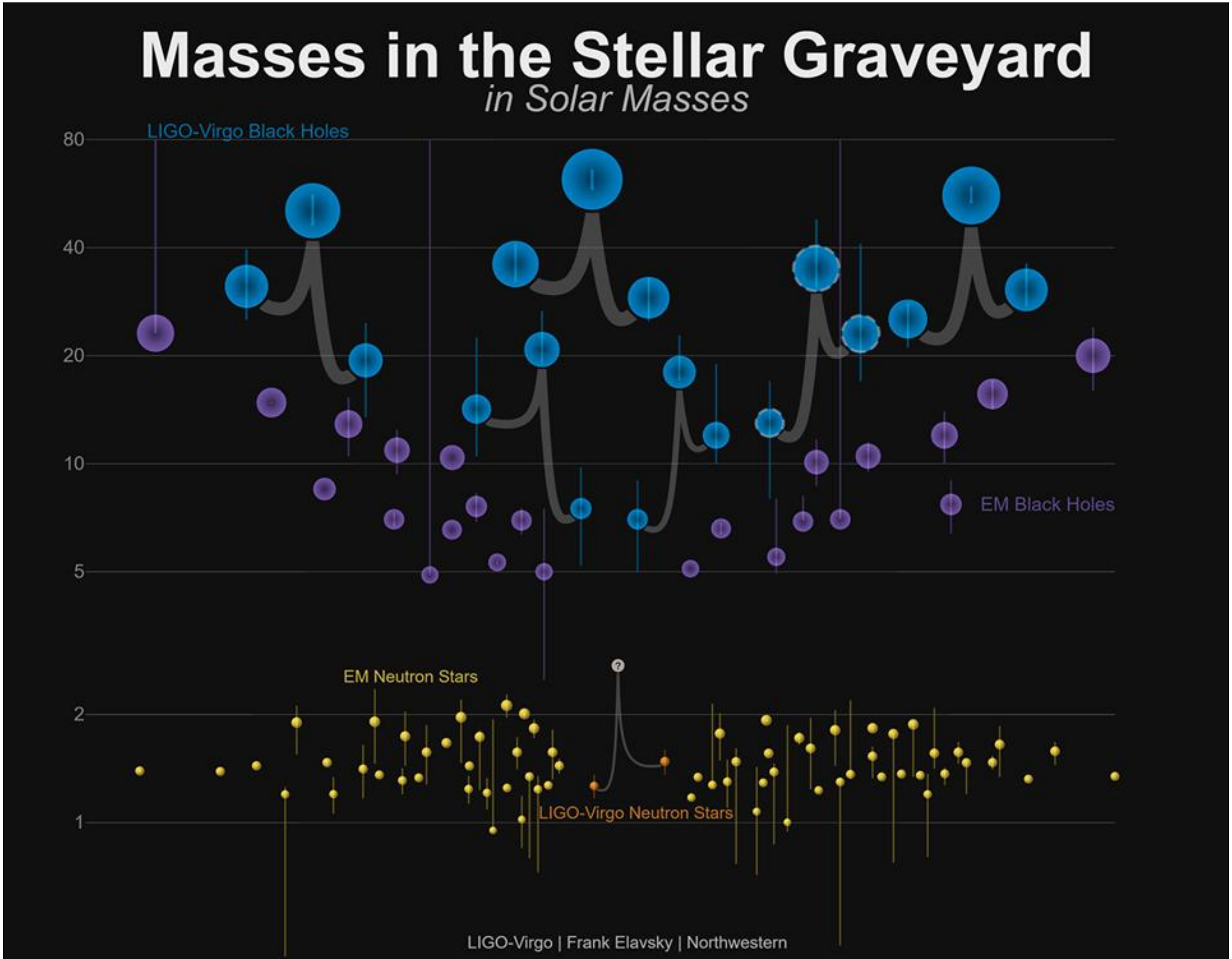
Blind searches h_{GW} < $4e^{-25}$ at 170 Hz

Stochastic background

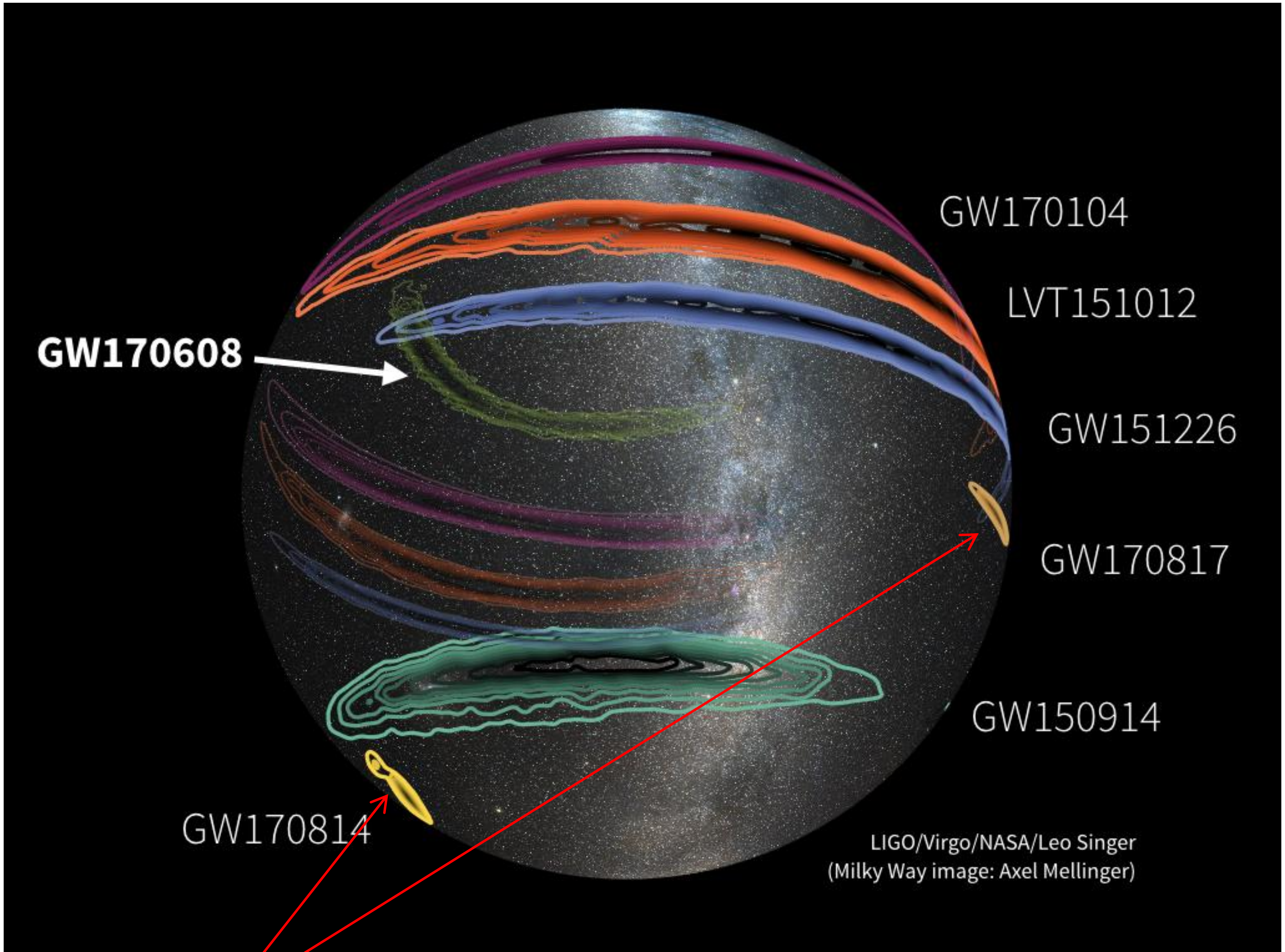
Upper limit: dimensionless energy density $\Omega_{GW} < 1.7x10^{-7}$(33 better than before) [Phys. Rev. Lett. 118, 121101 (2017)]



GW detections



Sky positions



Virgo data included

Activities of Polgraw-Virgo group

•Two body problem to high PN order (P. Jaranowski) :

G. Schaefer and P.Jaranowski,

Living Reviews in Relativity (2018) 21:7.

•Searches for GW from rotating neutron stars (A. Królak et al):

Searches of O2 LIGO data -

a) All-sky searches

b) Targeted searches

•Hardware contribution to improve sensitivity of the Virgo detector (T. Bulik et al): **Newtonian noise cancellation.**

Summary

- Analysis of O2 run data close to be finished
- 6 detections up to now
  - Black holes with large masses
  - First binary neutron star merger observed in coincidence with a short gamma-ray burst
  - Test of GR passed
  - First H_0 measurement

Conclusion

Next run (O3) at the beginning of 2019 with 3 detectors and KAGRA joining later on.

Expected BBH detection every week and BNS detection every month.

Observing Timeline

Binary Neutron Star Range

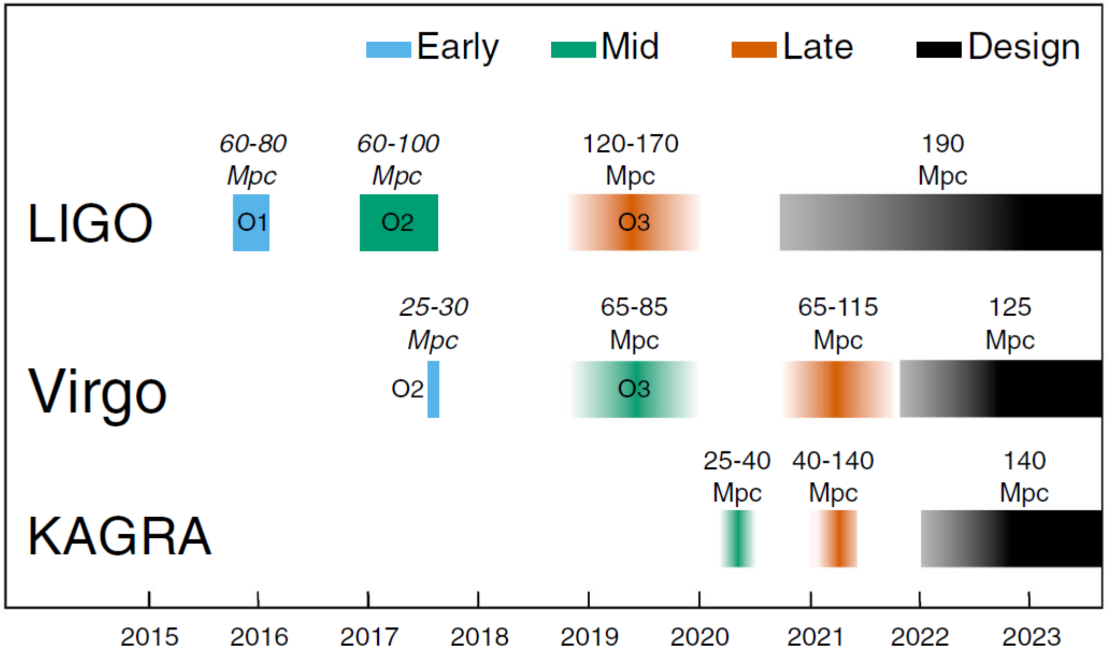


Figure 2 from B. P. Abbott et al., *Prospects for Observing and Localizing Gravitational-Wave Transients with Advanced LIGO, Advanced Virgo and KAGRA*, 2018, Living Rev. Relativity 21