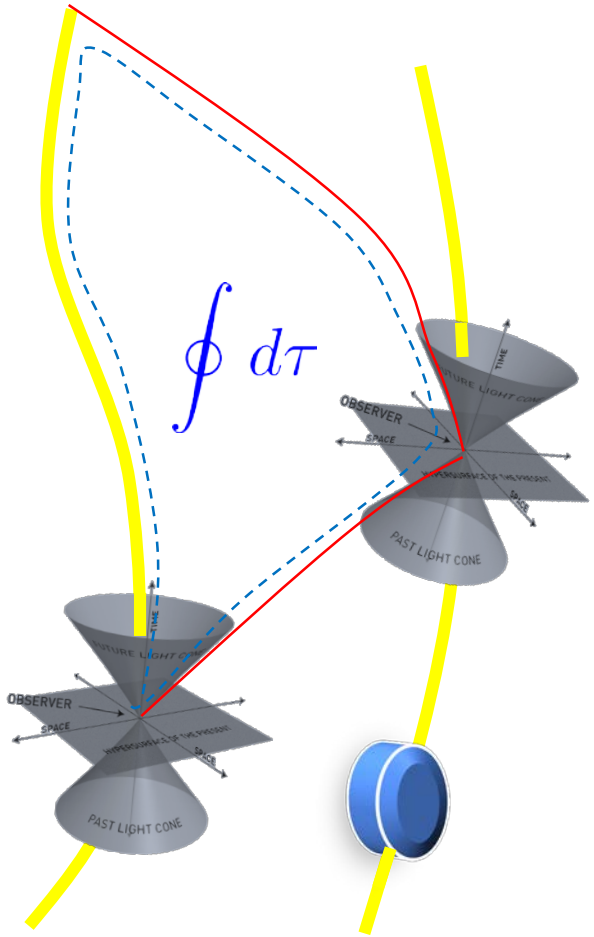
Results of LIGO-VIRGO

Giancarlo Cella - INFN Sez. Pisa & LVC

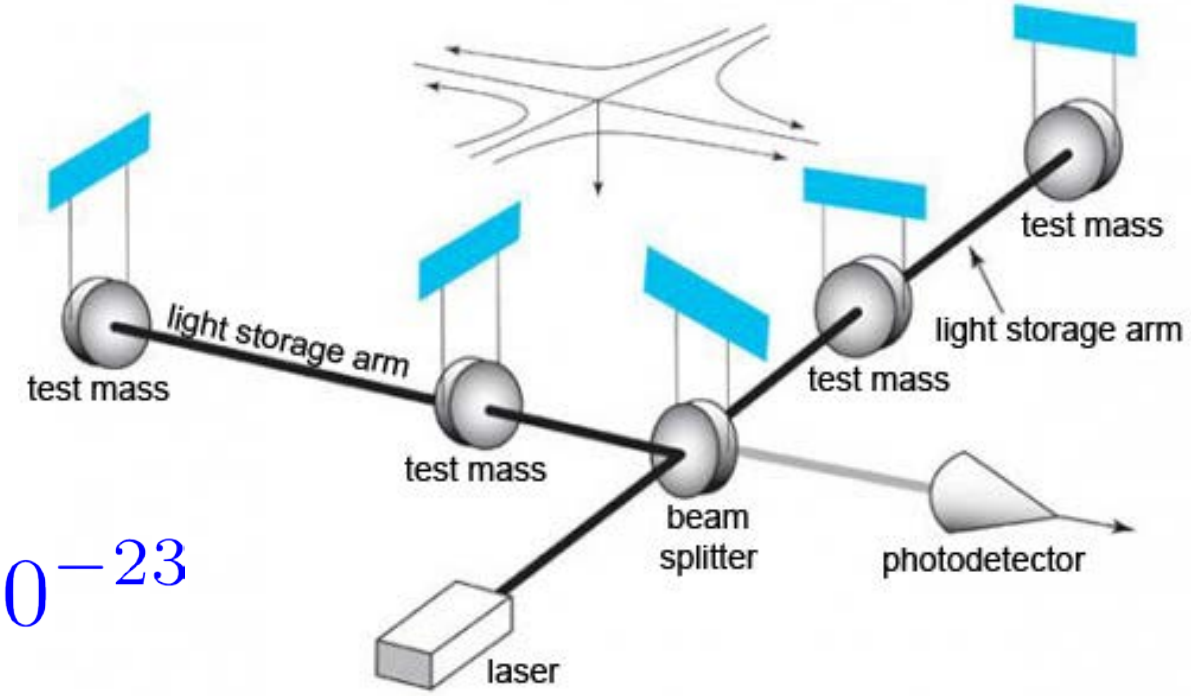
53rd Rencontres de Moriond
ELECTROWEAK INTERACTIONS AND UNIFIED THEORIES
La Thuile
March 10th - March 17th, 2018.

Interferometric detectors of gravitational waves



- The description of interaction between detector and GW is coordinate dependent
- Physical effect is not.
- Intuitive picture ($\lambda_{GW} \gg L$)

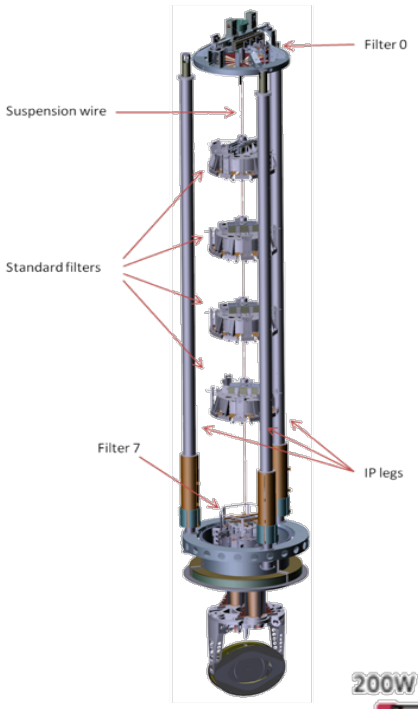
$$F_i = \frac{1}{2} m \frac{d^2 h_{ij}^{TT}}{dt^2} L_j$$



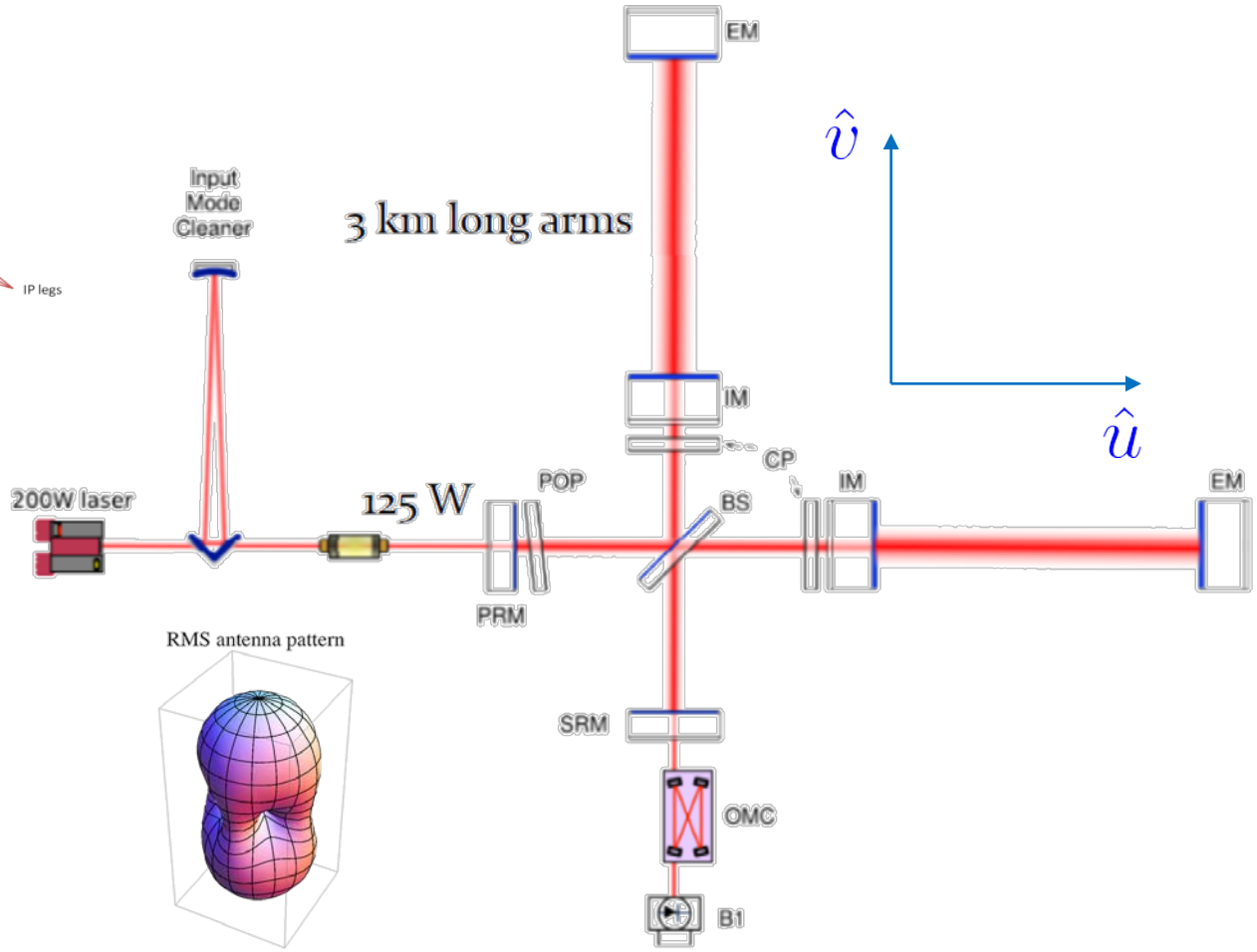
$$\frac{\Delta L}{L} < 10^{-23}$$

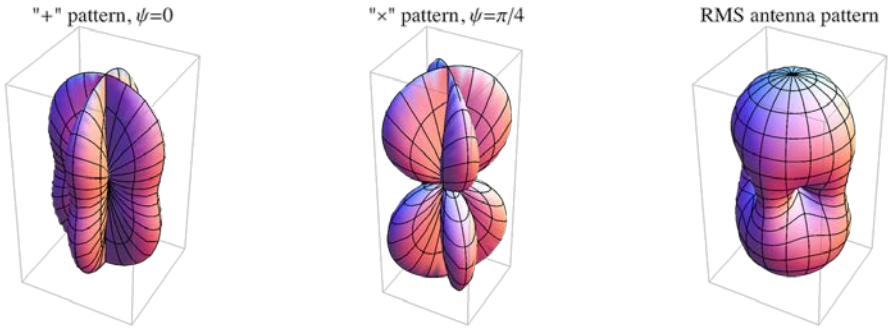
Advanced detectors

- Larger beams ($\times$ 2.5)
- Heavier mirrors ($\times$ 2)
- Optical quality improved (residual rugosity < 0.5 nm)
- Improved coating
  - absorption < 0.5 ppm
  - scattering < 10 ppm
- Larger Finesse ($\times$ 3)
- Thermal control of optical aberrations
- Diffused light mitigation
- Improved vacuum ($\times 10^{-2}$, 1×10^{-9} mbar)
- *Laser 200 W*
- *Signal recycling*

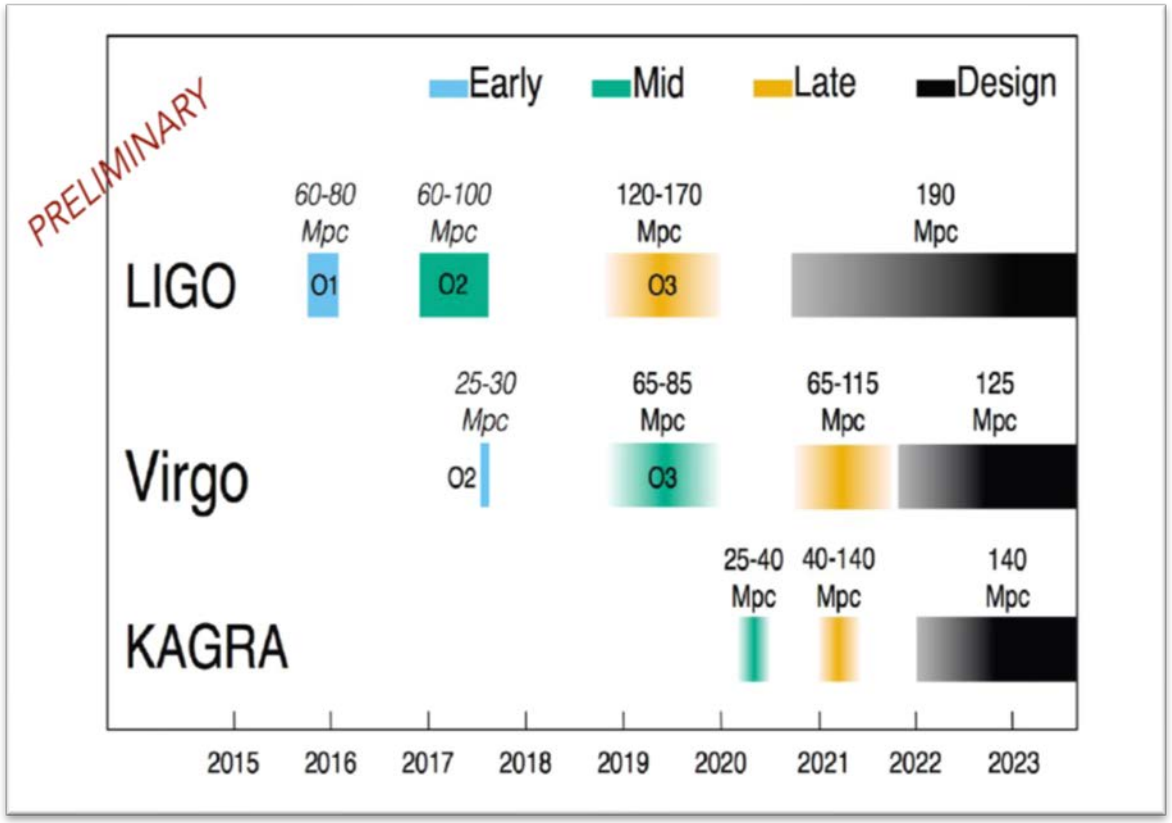


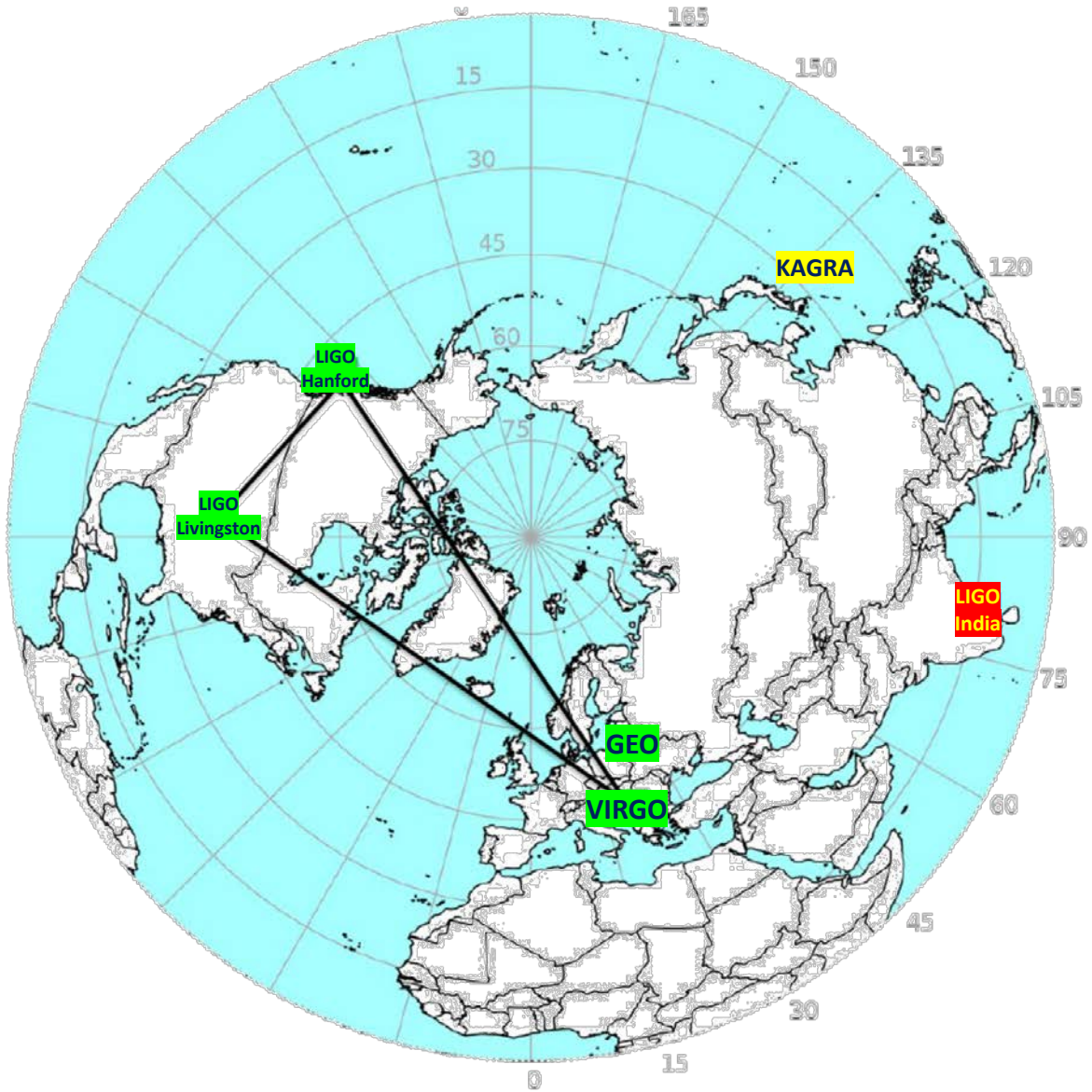
$$h(t) = D^{ij} h_{ij}^{TT} \quad D^{ij} = (u^i u^j - v^i v^j)$$





A network of detectors

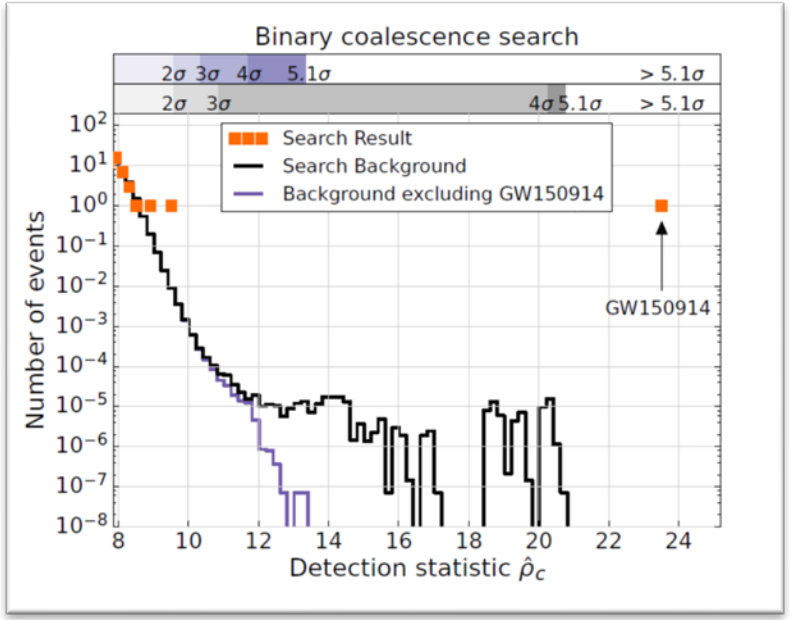


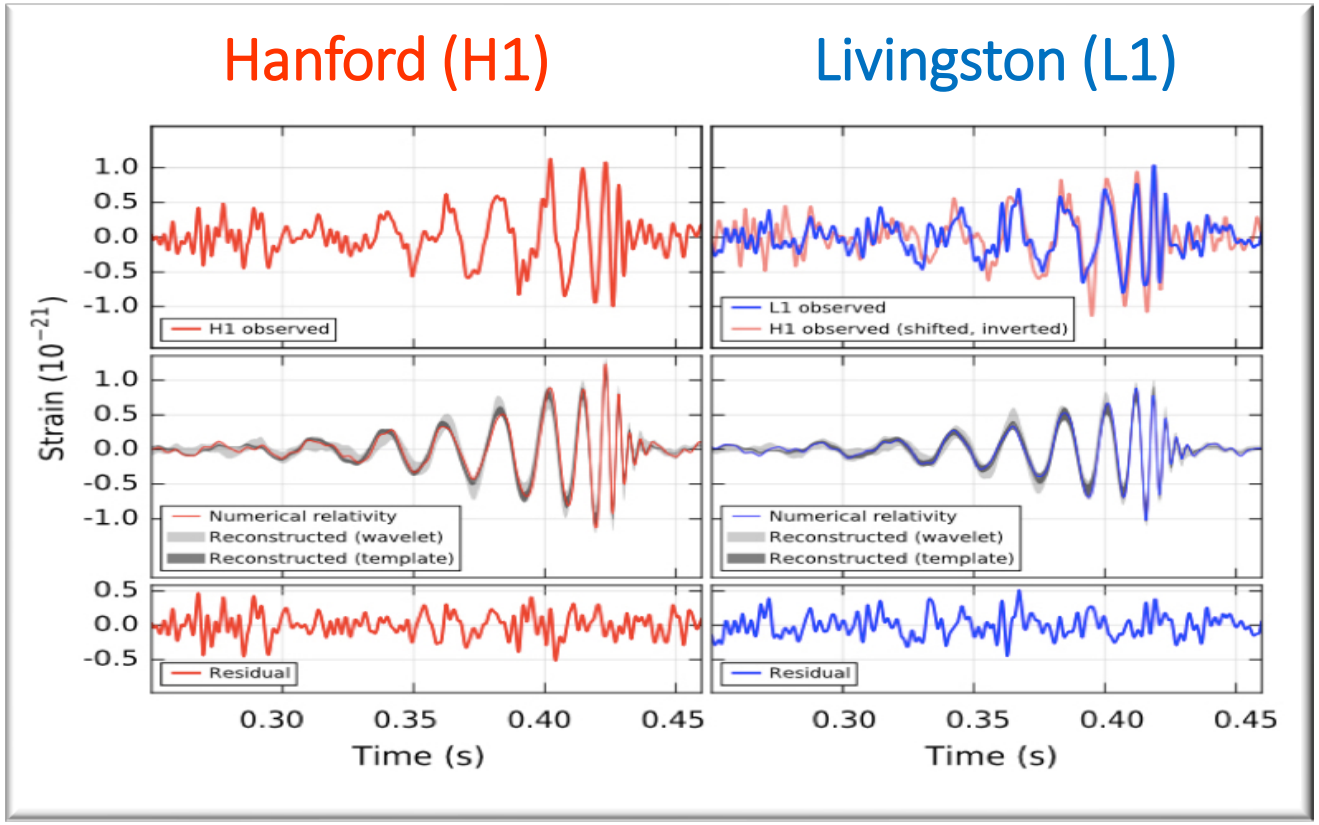


Living Rev. Relativity 19 (2016), 1

GW150914

Primary black hole mass	$36^{+5}_{-4}\,M_\odot$
Secondary black hole mass	$29^{+4}_{-4}\,M_\odot$
Final black hole mass	$62^{+4}_{-4}\,M_\odot$
Final black hole spin	$0.67^{+0.05}_{-0.07}$
Luminosity distance	410^{+160}_{-180} Mpc
Source redshift, z	$0.09^{+0.03}_{-0.04}$





- P_{FA} = 1/203000 yr^{-1}
- Significativity > 5.3σ

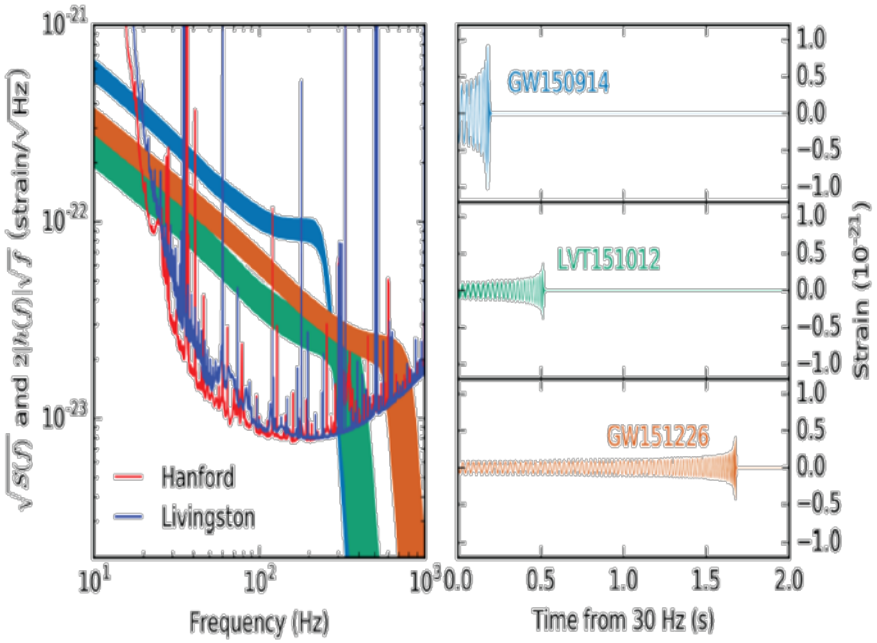
Interpretation: BBH coalescence

Other similar events in the following:

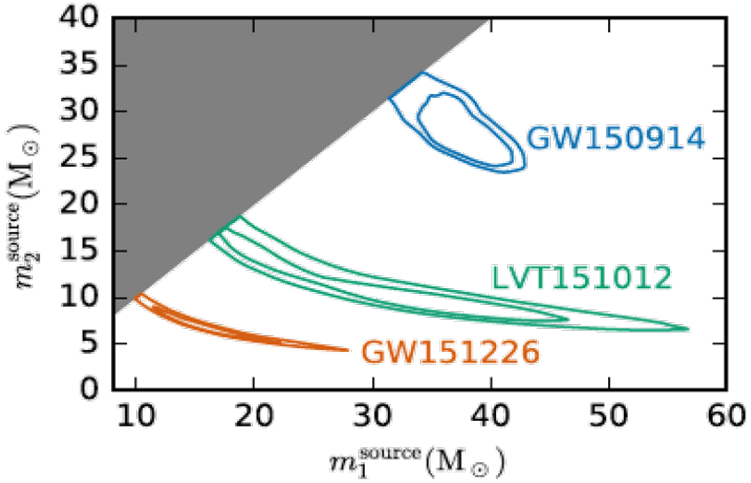
- GW151226 (December 26 2015)
- GW170104 (January 4 2016)

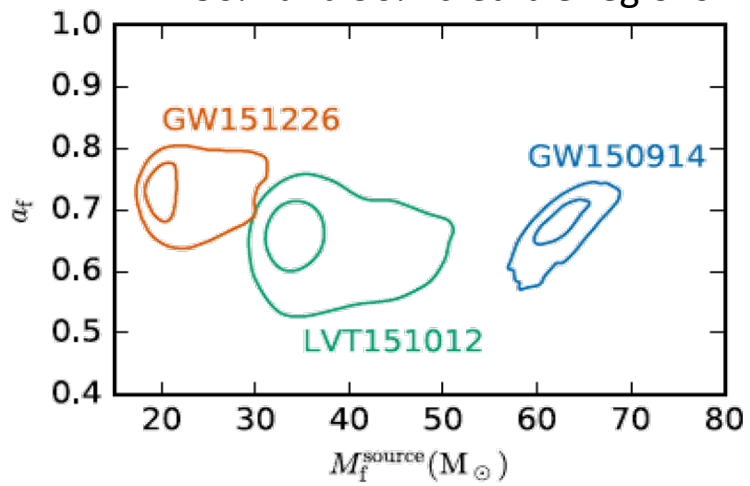
Phys. Rev. Lett. 116, 131103 (2016)
Phys. Rev. D 93, 122003 (2016)
Phys. Rev. Lett. 116, 241103 (2016)
Phys. Rev. X 6, 041015 (2016)
Phys. Rev. Lett. 118, 221101 (2017)

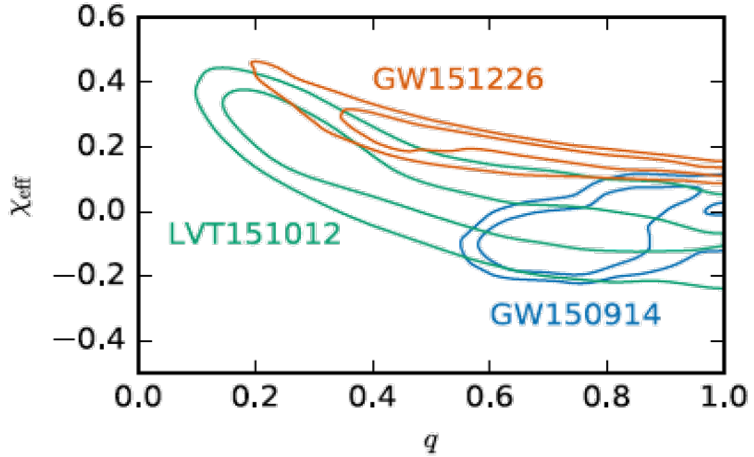
Parameters of the BBH systems

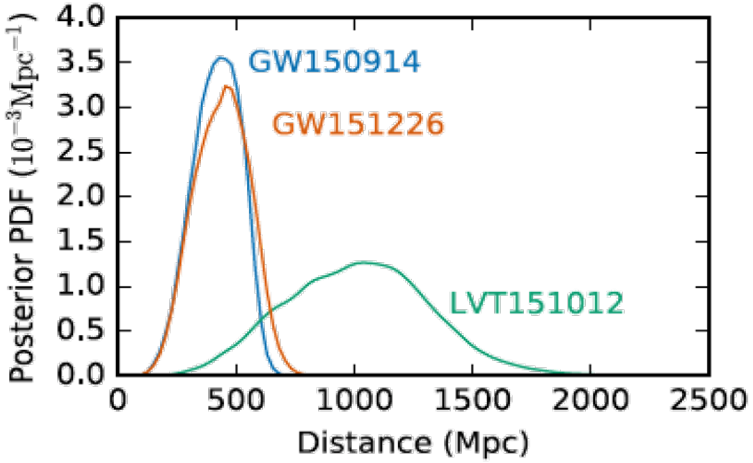


50% and 90% credible regions



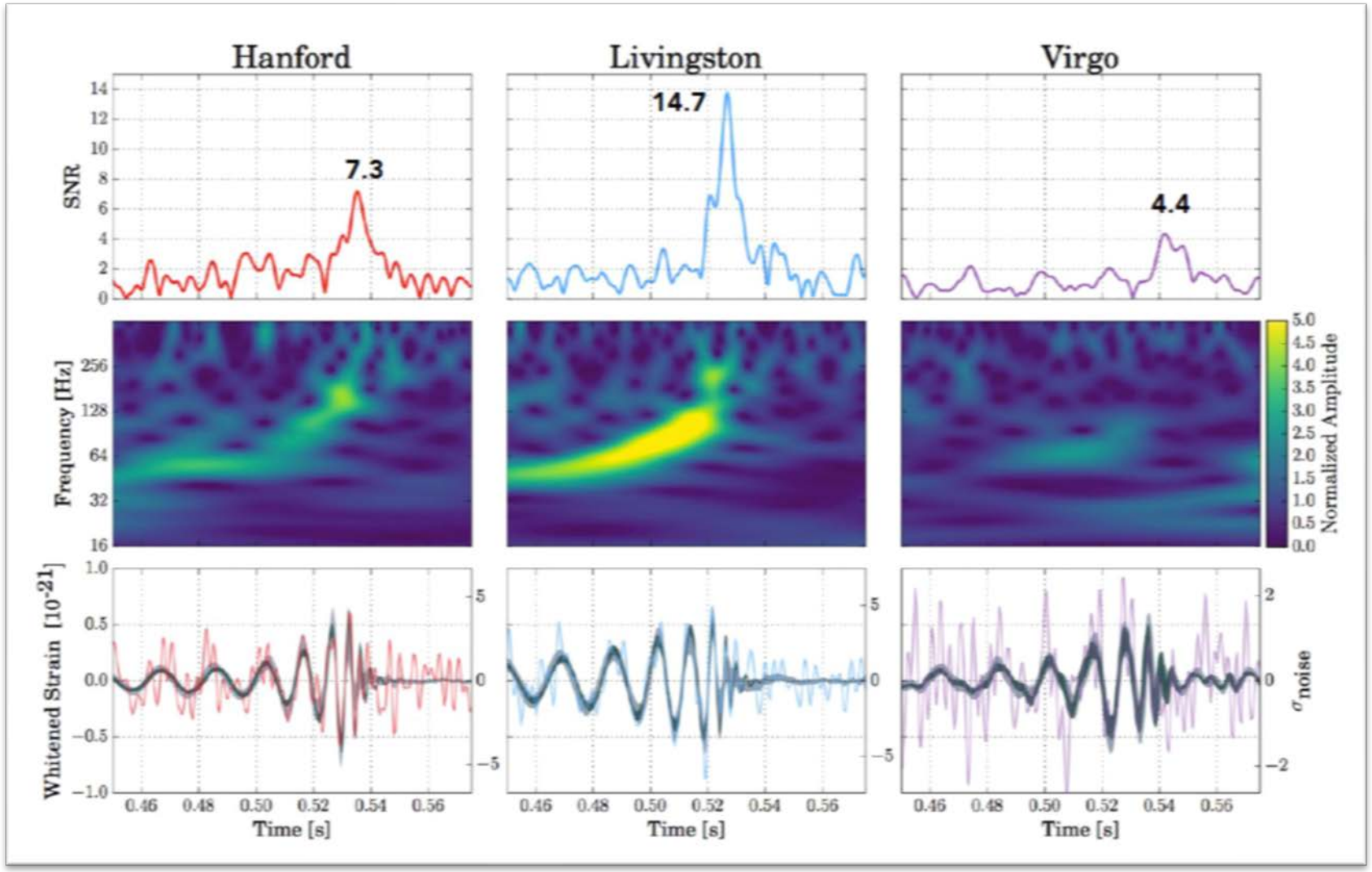






Phys. Rev. X 6, 041015 (2016) Phys. Rev. Lett. 116, 241103 (2016)

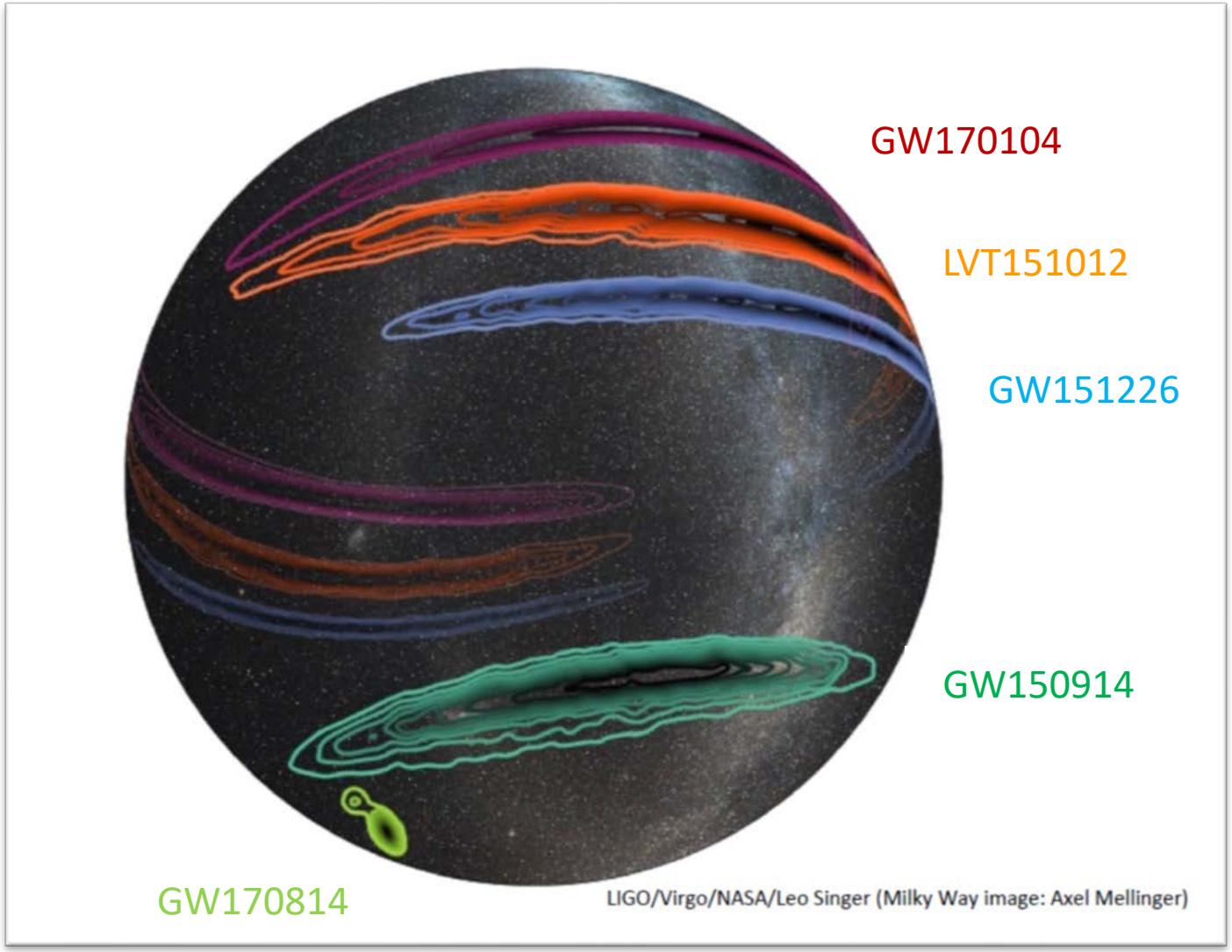
GW170814

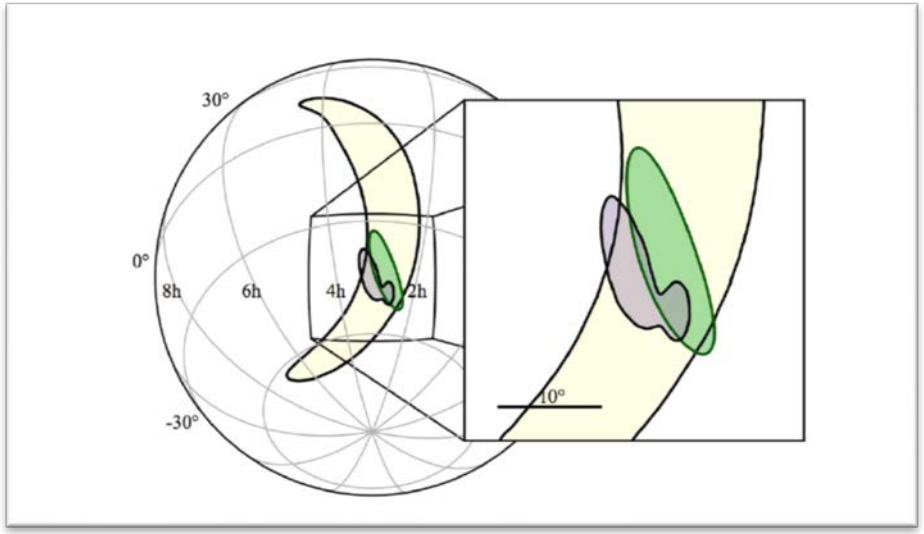


- «Still» a BBH coalescence.
- Three detectors detection:
  - Localization
  - Polarization

Phys. Rev. Lett. 119, 141101 (2017)

Localization



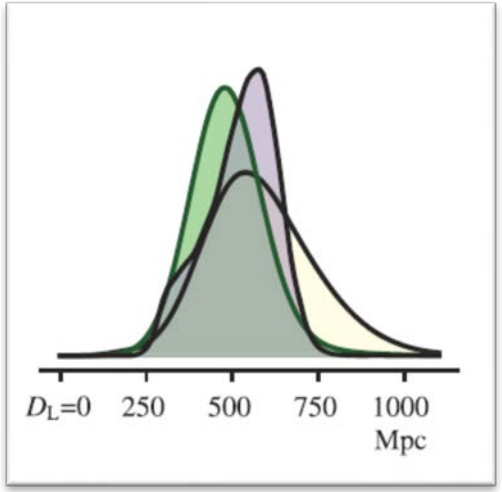


LIGO:
1160 deg^2 (90% CL)

LIGO+VIRGO:
60 deg^2 (90% CL)

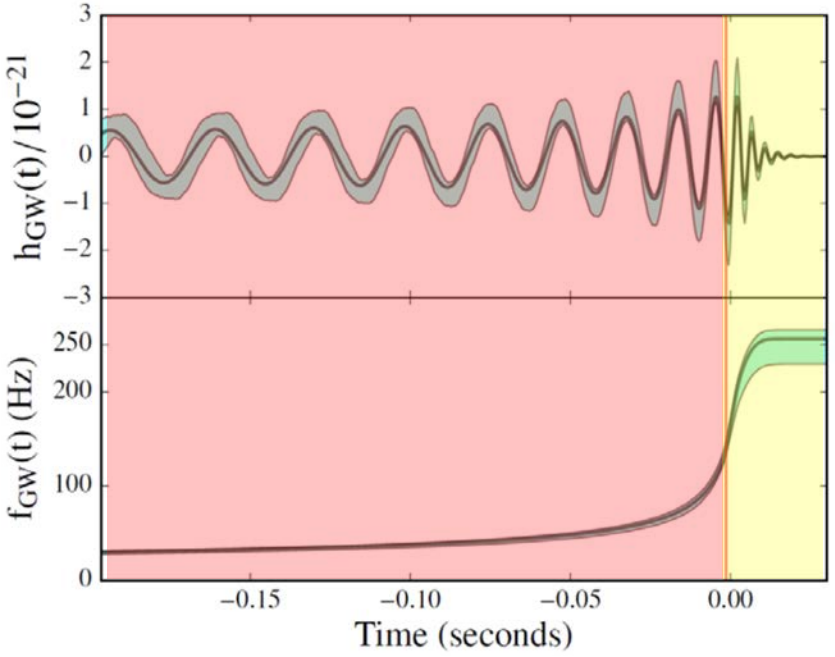
No expected counterparts....

....but the demonstration that multimessenger era can start.....

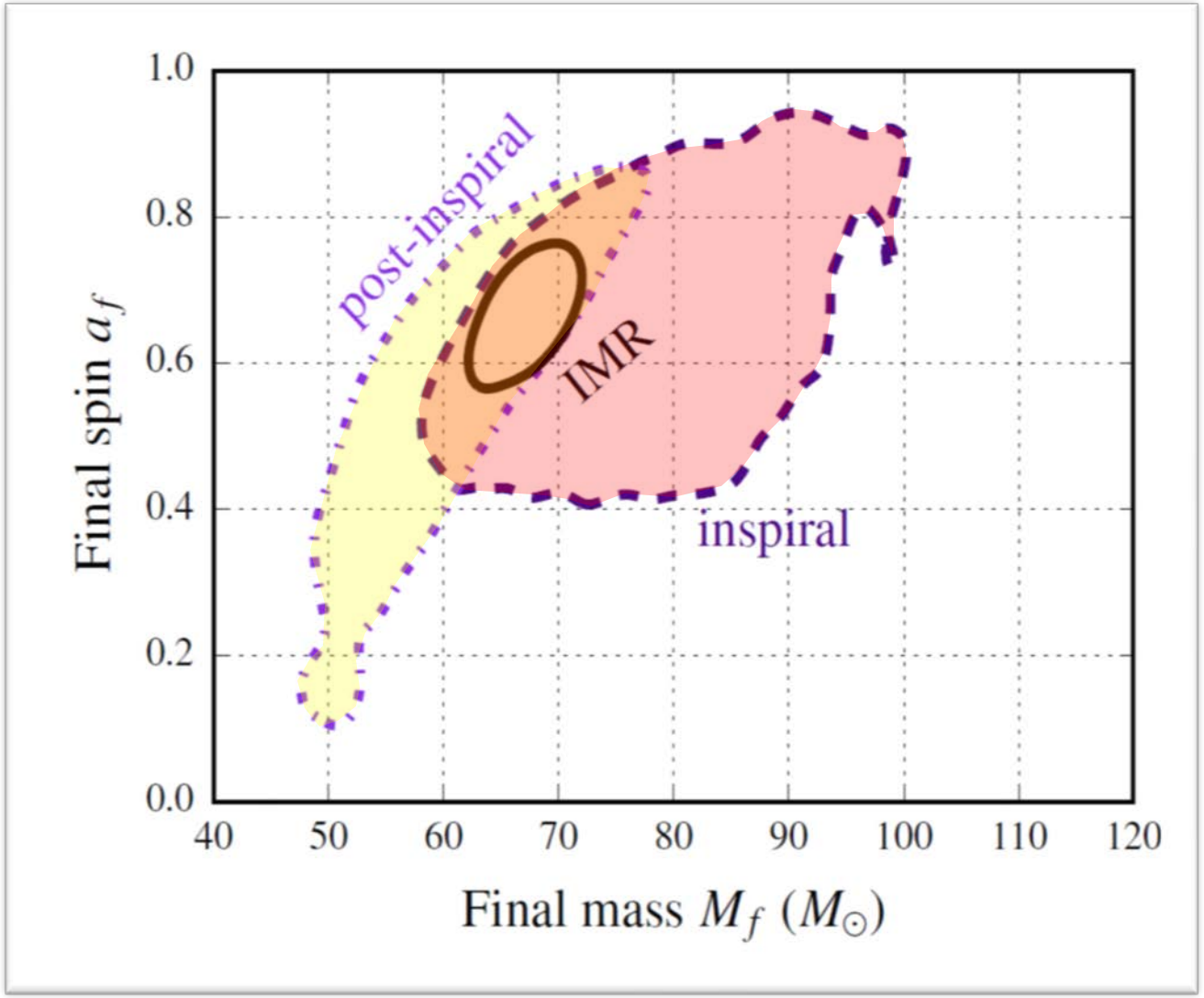


Astrophys.J. 826 (2016) no.1, L13

Consistence between different regimes



1. Mass & final spin estimation using only the inspiral signal $SNR_{det} \simeq 19.5$
2. Mass & final spin estimation using only the inspiral signal & ringdown signal $SNR_{det} \simeq 16$
3. Comparison



Phys. Rev. Lett. 116, 221101 (2016)

Quasi Normal Modes

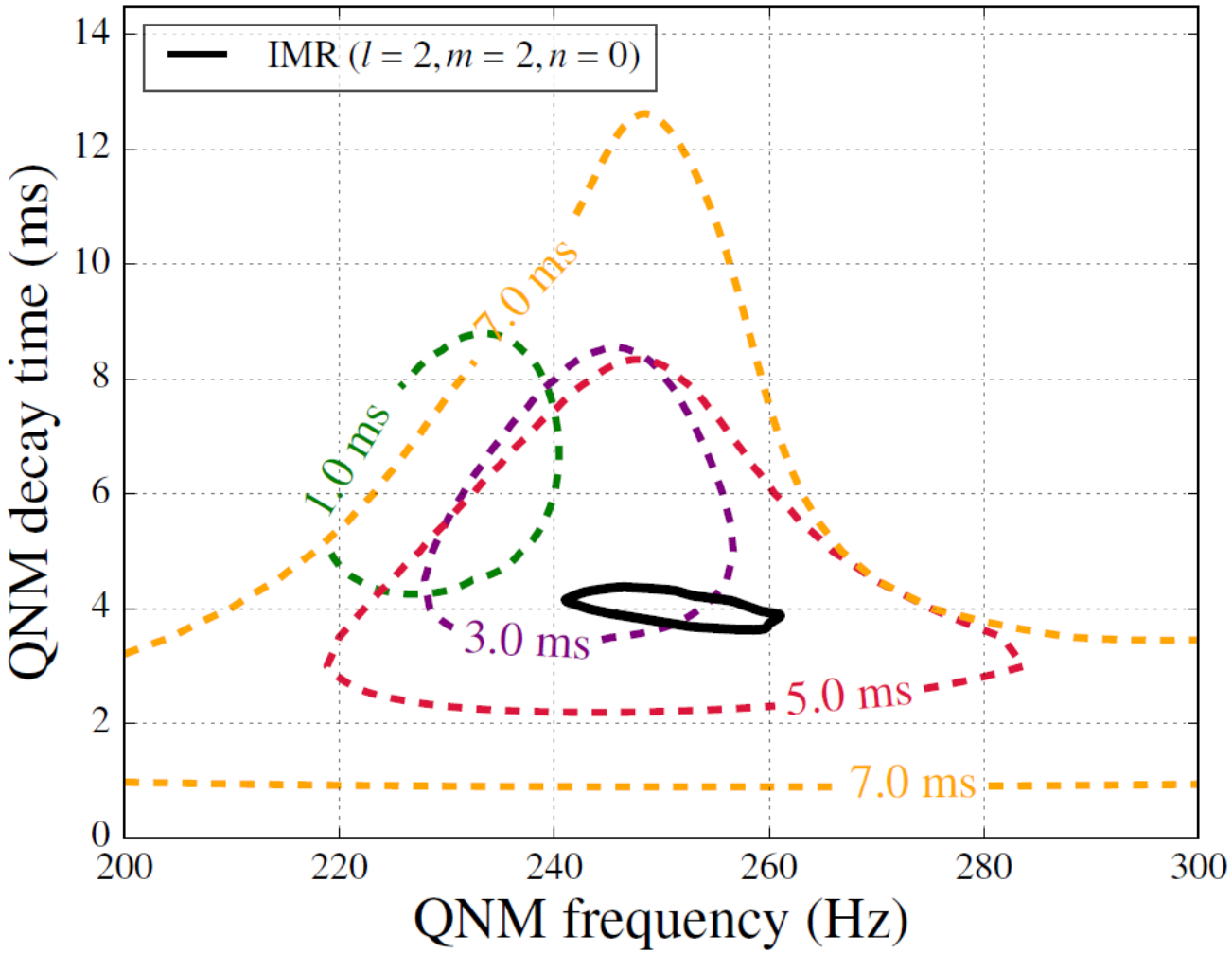
Phys. Rev. Lett. 116, 221101 (2016)

Only 1 mode
(Higher Q factor one)

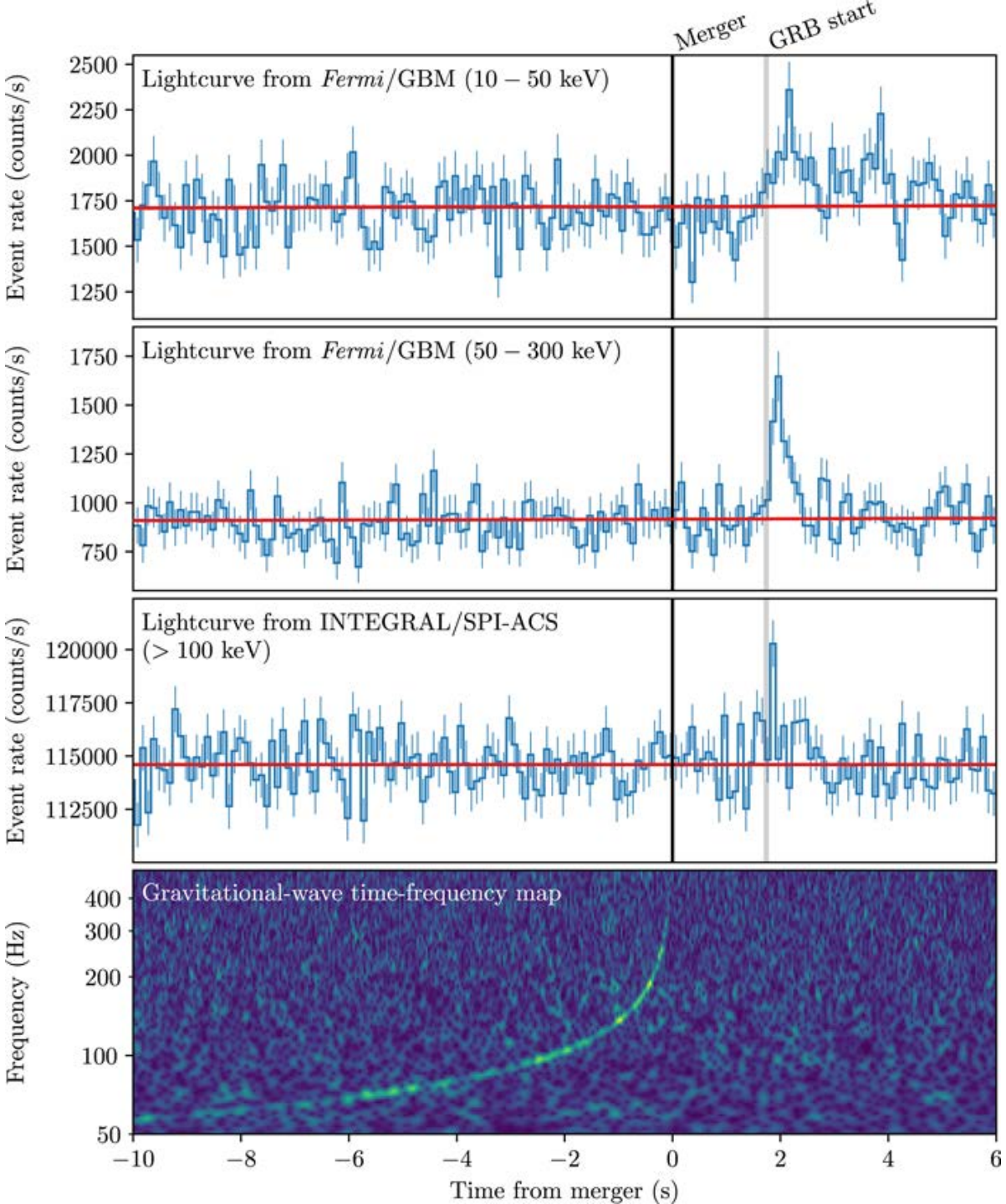
$$h(t) = A\,\theta(t-t_0)e^{-(t-t_0)/\tau}\cos\left[\omega_0(t-t_0)+\phi_0\right]$$

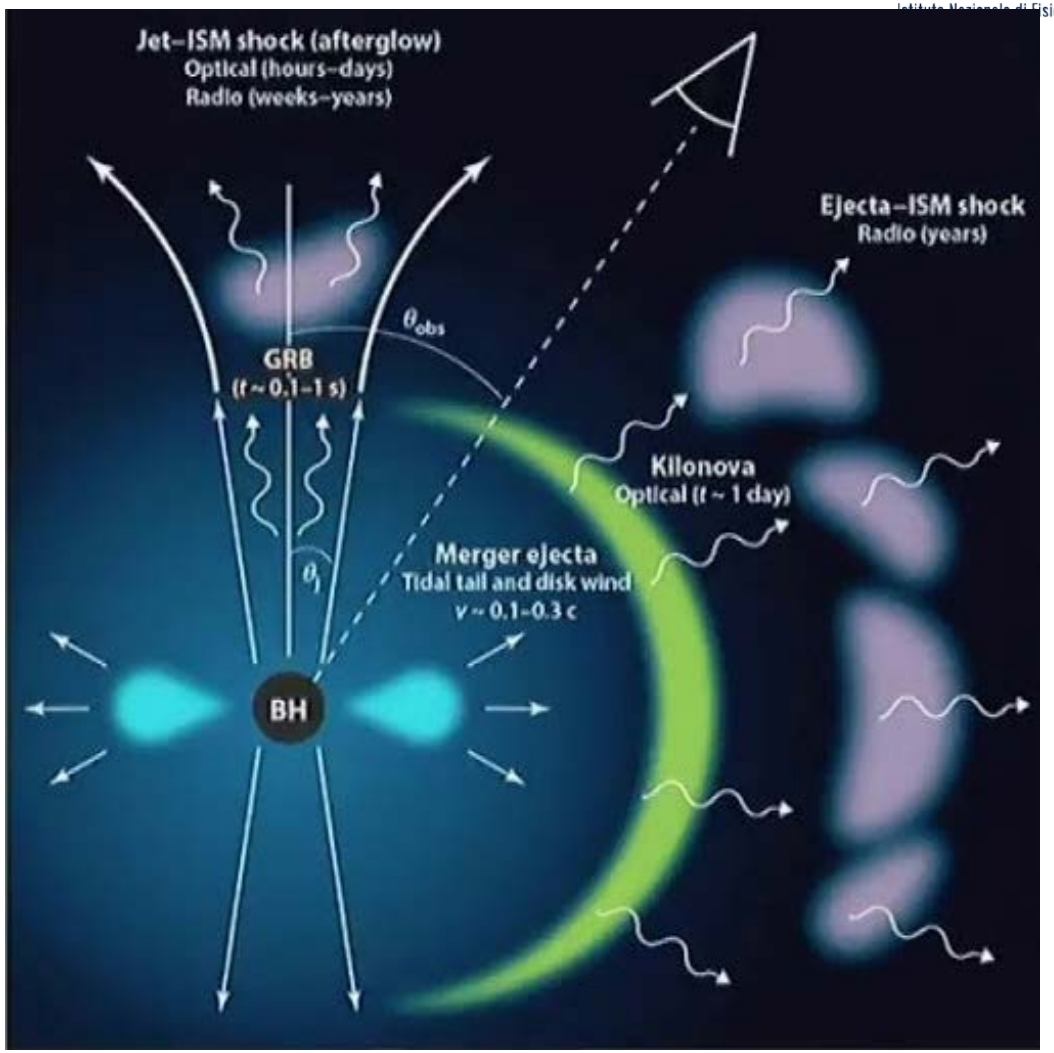
$$t_0 = t_M + \Delta t$$

- Contours: 90% confidence
- Variation of Δt
- Black contour: prediction based on parameters estimated from Inspiral+Merger+Ringdown



GW170817

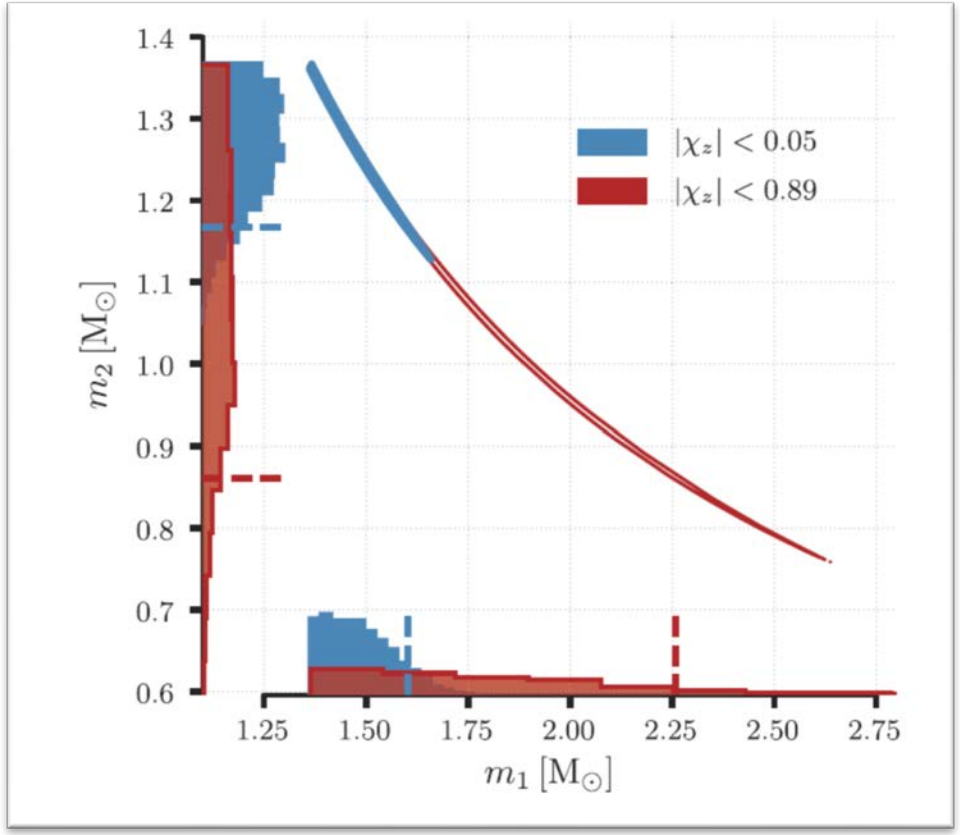




Credit: Metzger

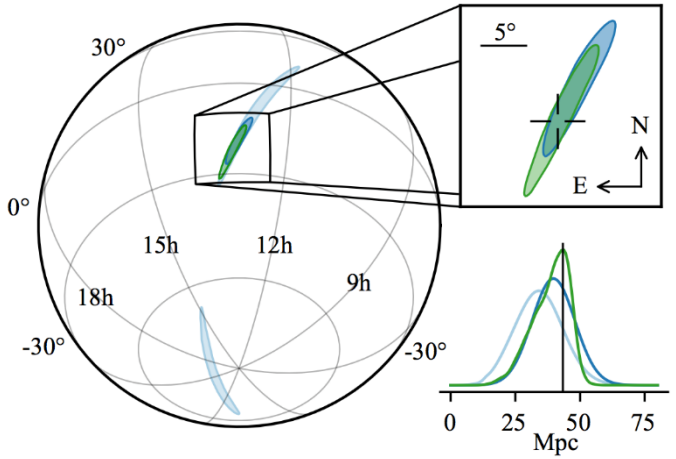
[Phys. Rev. Lett. 119, 161101 (2017)]
[Astrophys. J. Lett. 848, L13 (2017)]
[Astrophys. J. Lett. 848, L12 (2017)]

Parameter estimation



SNR 32.4
P_{FA}=1/80000 yr^{-1}
D_L=85-160 Mly

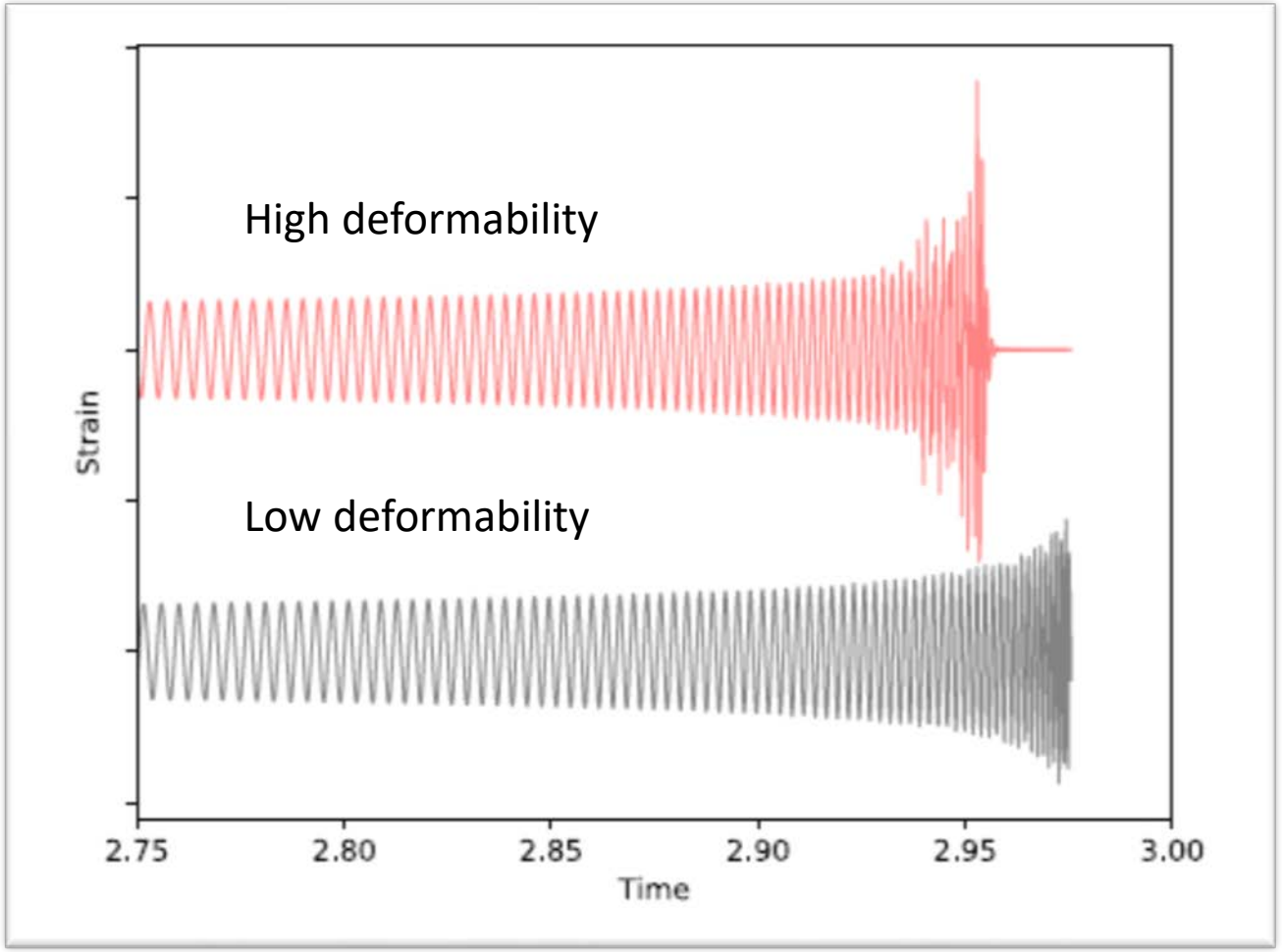
- GRB170817A: matter is present
- Mass consistent with binary NS
- Deformability

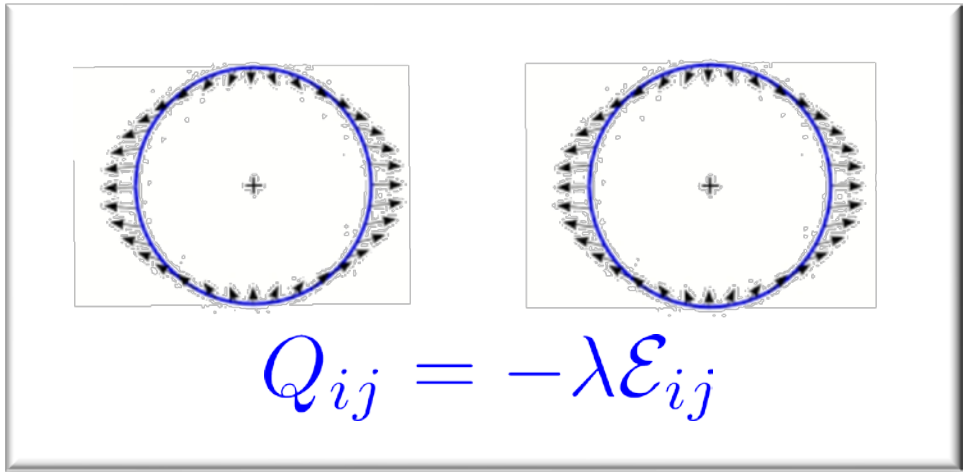


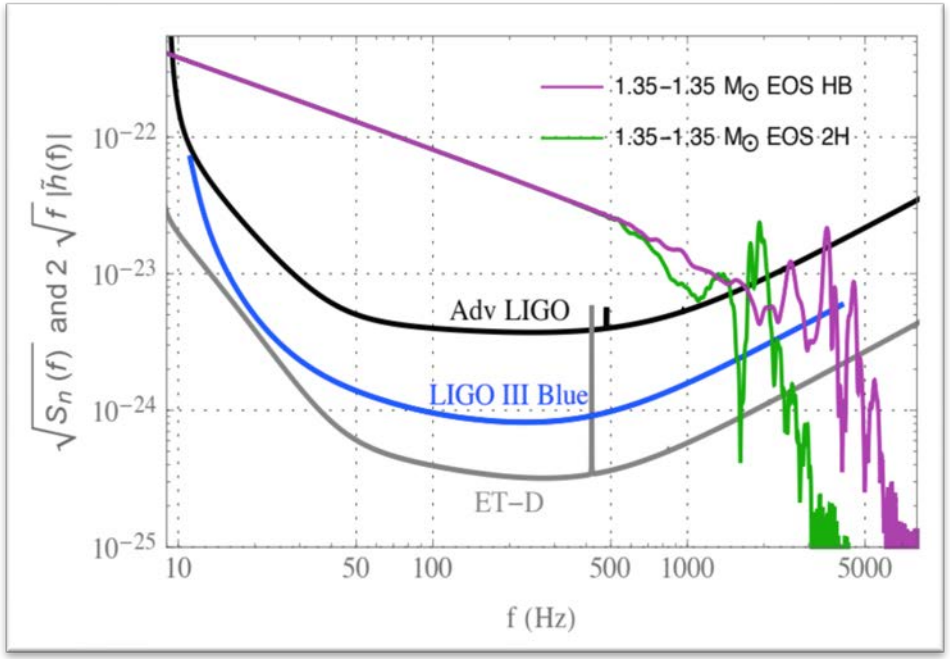
	Low-spin priors ($\lvert\chi\rvert \leq 0.05$)	High-spin priors ($\lvert\chi\rvert \leq 0.89$)
Primary mass m_1	1.36–1.60 $M_\odot$	1.36–2.26 $M_\odot$
Secondary mass m_2	1.17–1.36 $M_\odot$	0.86–1.36 $M_\odot$
Chirp mass $\mathcal{M}$	$1.188^{+0.004}_{-0.002} M_\odot$	$1.188^{+0.004}_{-0.002} M_\odot$
Mass ratio m_2/m_1	0.7–1.0	0.4–1.0
Total mass m_{tot}	$2.74^{+0.04}_{-0.01} M_\odot$	$2.82^{+0.47}_{-0.09} M_\odot$
Radiated energy E_{rad}	$> 0.025 M_\odot c^2$	$> 0.025 M_\odot c^2$
Luminosity distance D_L	40^{+8}_{-14} Mpc	40^{+8}_{-14} Mpc
Viewing angle Θ	$\leq 55°$	$\leq 56°$
Using NGC 4993 location	$\leq 28°$	$\leq 28°$
Combined dimensionless tidal deformability $\tilde{\Lambda}$	≤ 800	≤ 700
Dimensionless tidal deformability $\Lambda(1.4 M_\odot)$	≤ 800	≤ 1400

Phys. Rev. Lett. 119, 161101 (2017)

Nuclear matter EOS

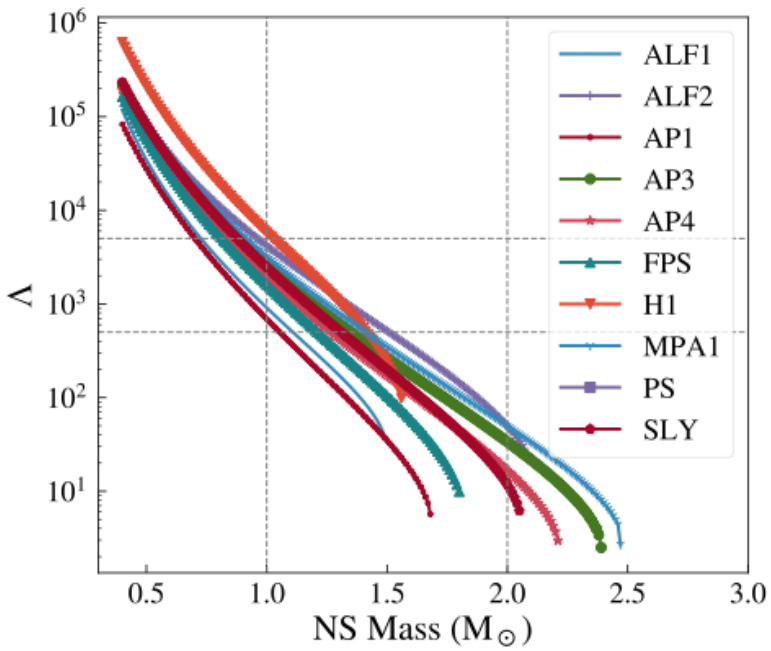


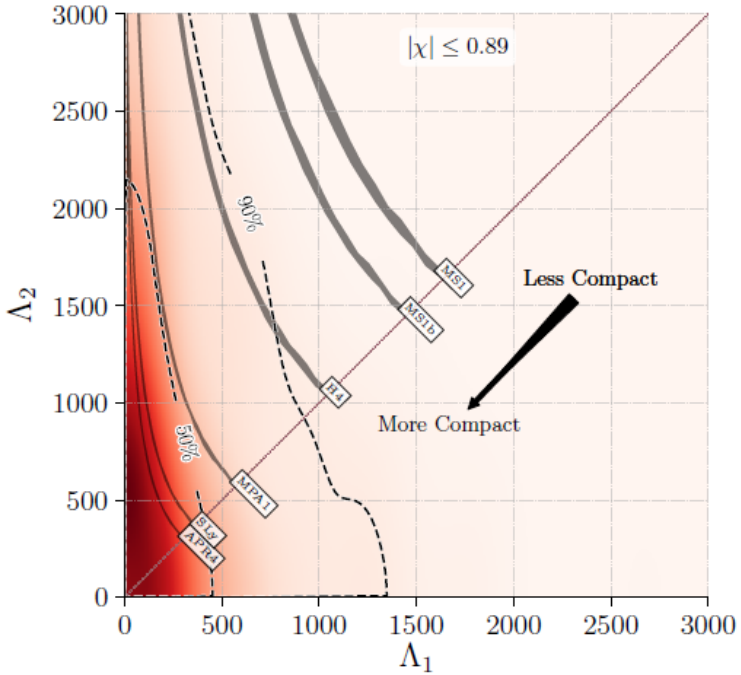


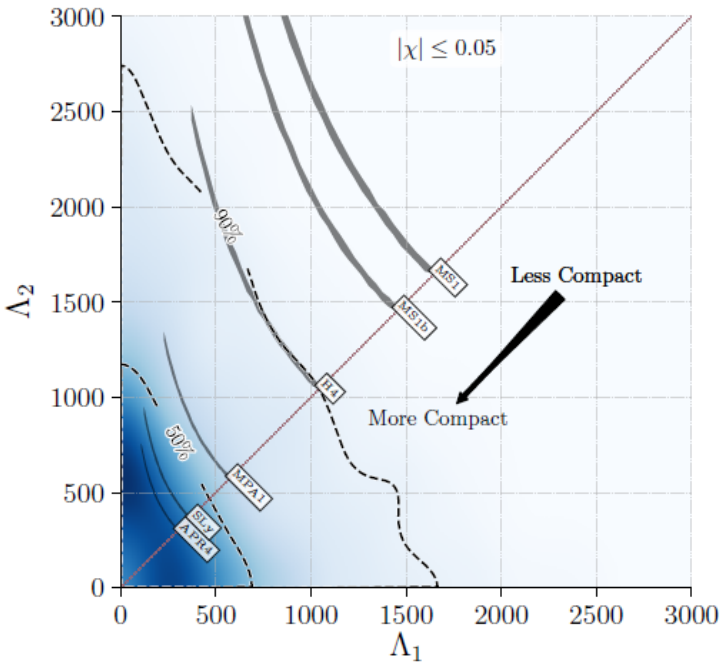


Phys. Rev. Lett. **111**, 071101

Deformabilità: informazioni sulla equazione di stato



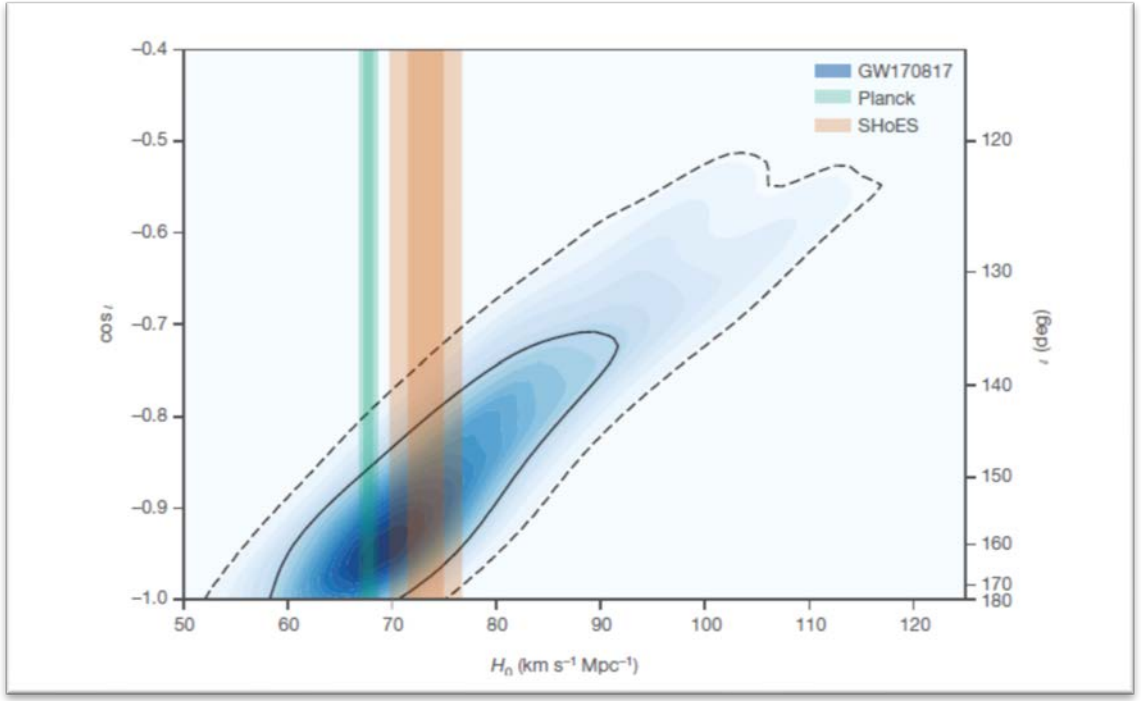


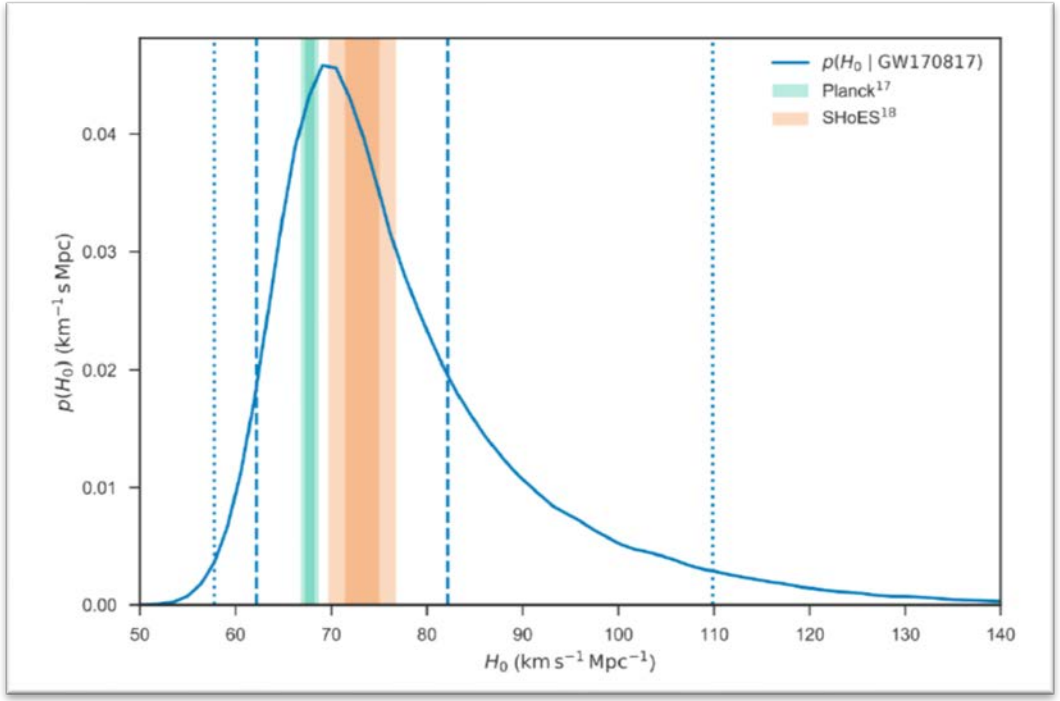


$$\lambda = \frac{2}{3} k_2 R^5$$

$$\Lambda = \lambda \left(\frac{c^2}{GM} \right)^5$$

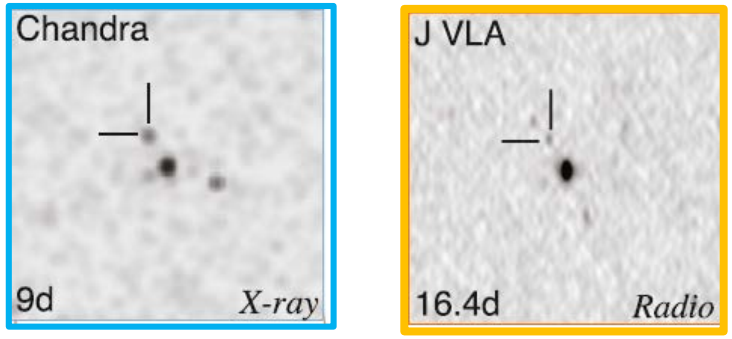
Hubble parameter





Nature 551, 85 (2017)

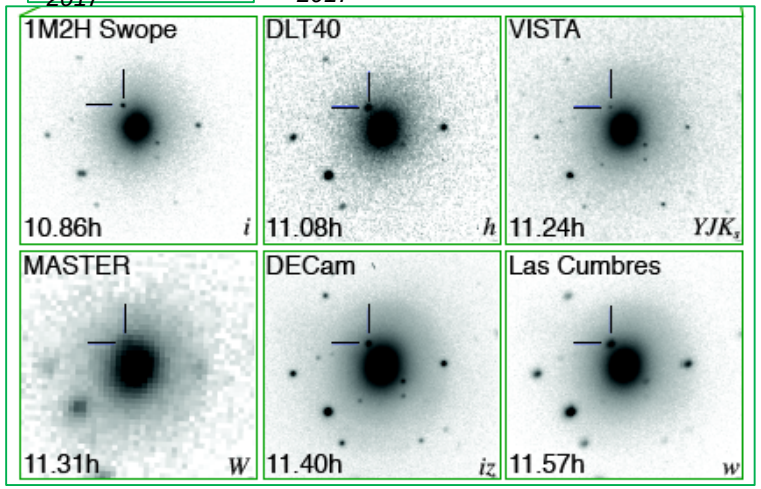
Counterparts



Coulter et al. 2017

Yang et al. 2017

Tanvir et al. 2017

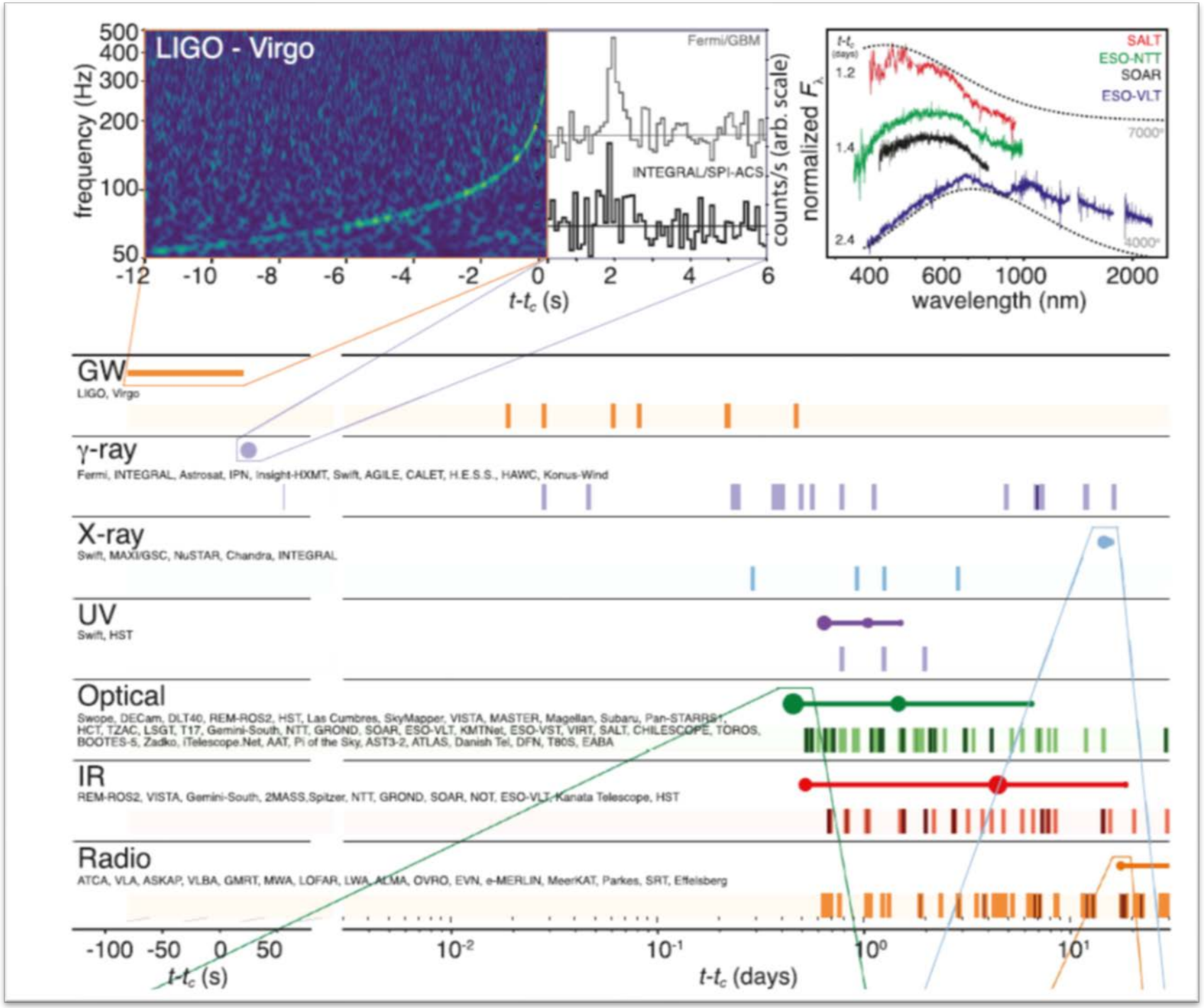


Lipunov et al. 2017

Allam et al. 2017

Accavi et al. 2017

Astrophys. J. Lett. 848, L12 (2017)

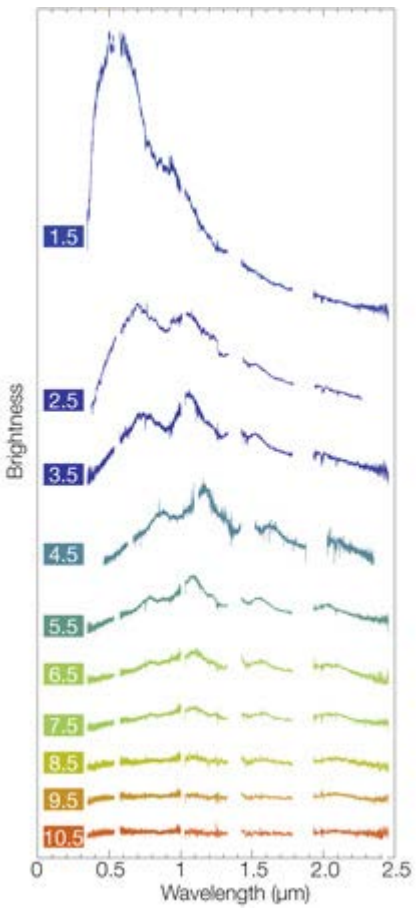


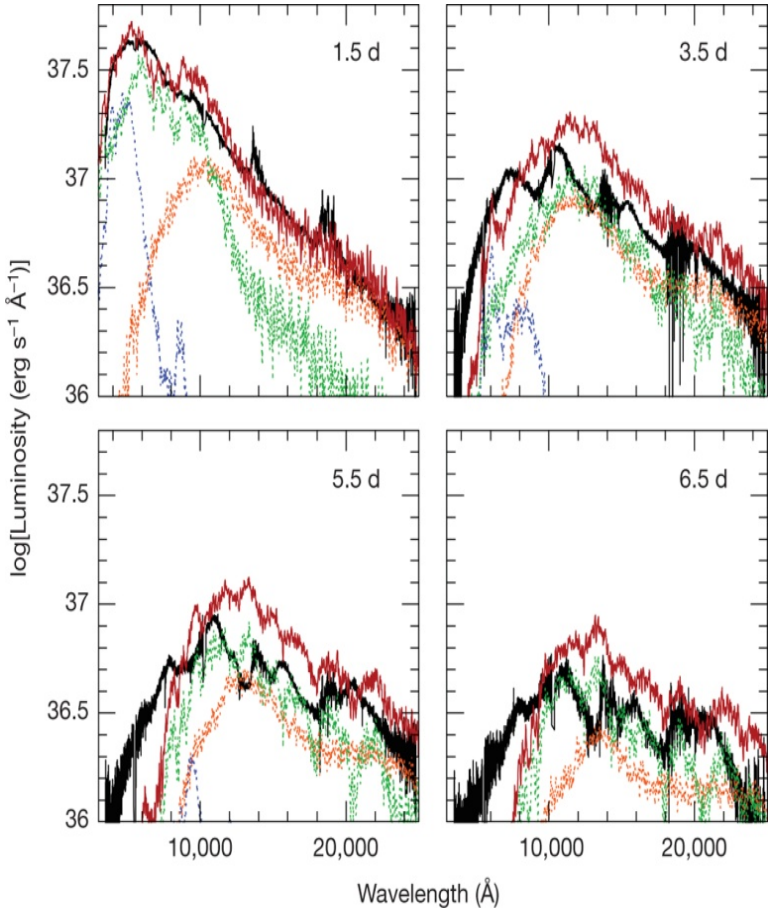
Kilonova

Siegel & Metzger 2017b, arXiv:1711.00868

Siegel & Metzger 2017a, PRL, arXiv:1705.05473

Credits: Eso/E. Pian et al./S. Smartt & ePessto



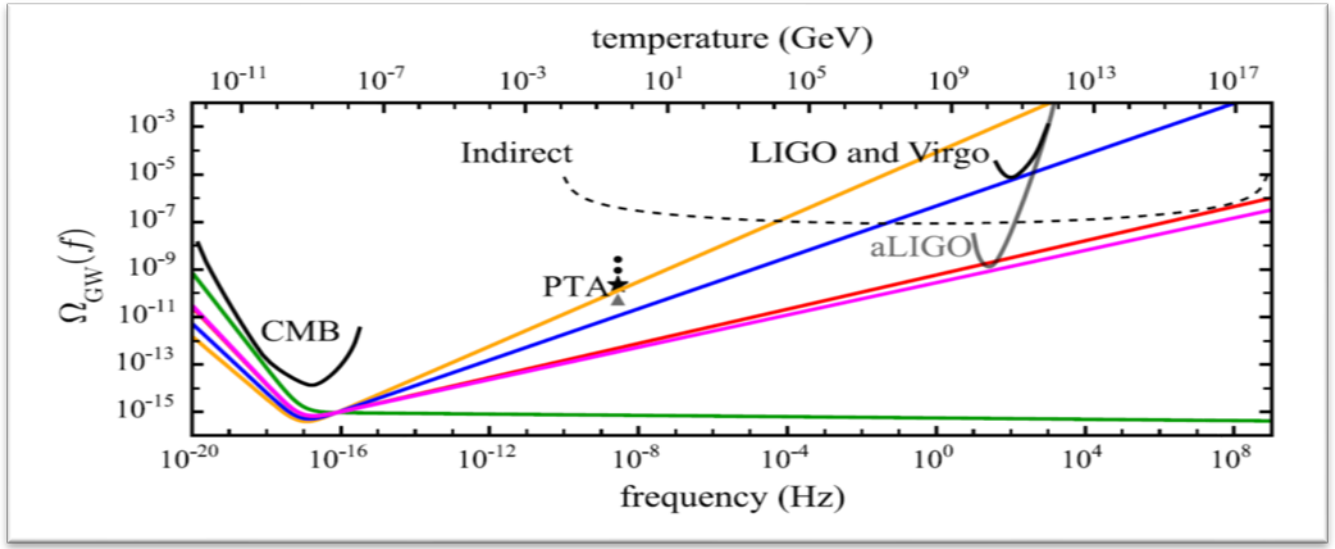


E Pian *et al. Nature* **551,** 67–70 (2017)
doi:10.1038/nature24298

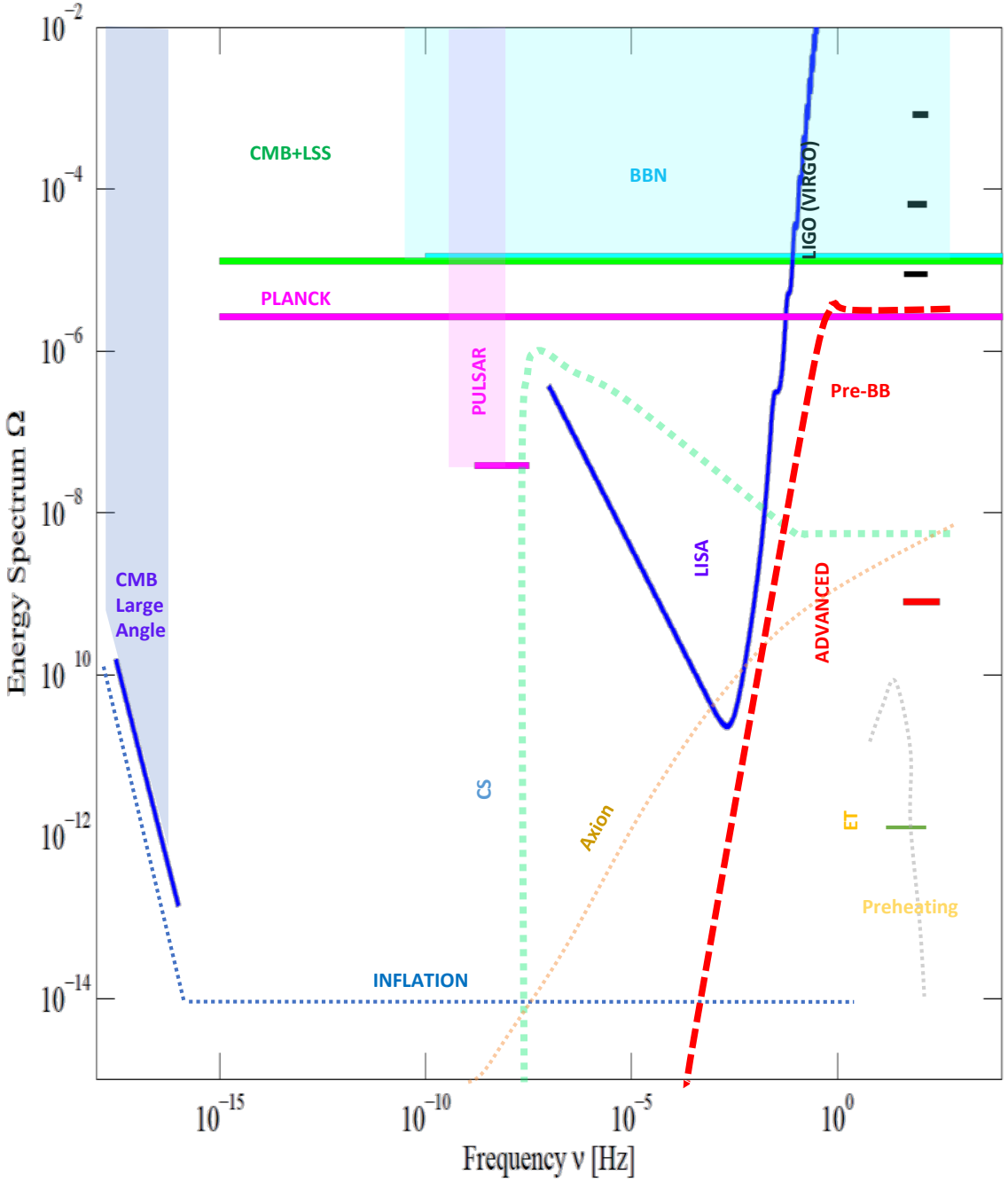
Matter ejected in the post-merger phase undergoes r-process

Stochastic background

- Upper limits and GW observations set constraints in very different frequency bands
- Still no detections
- Interseting upper limits (improving)
- Interesting perspectives
- Future:
  - Anisotropies
  - Astrophysical SB
  - Correlations
  - …….



Phys. Rev. X 6, 011035 (2016)



Isotropic upper limits

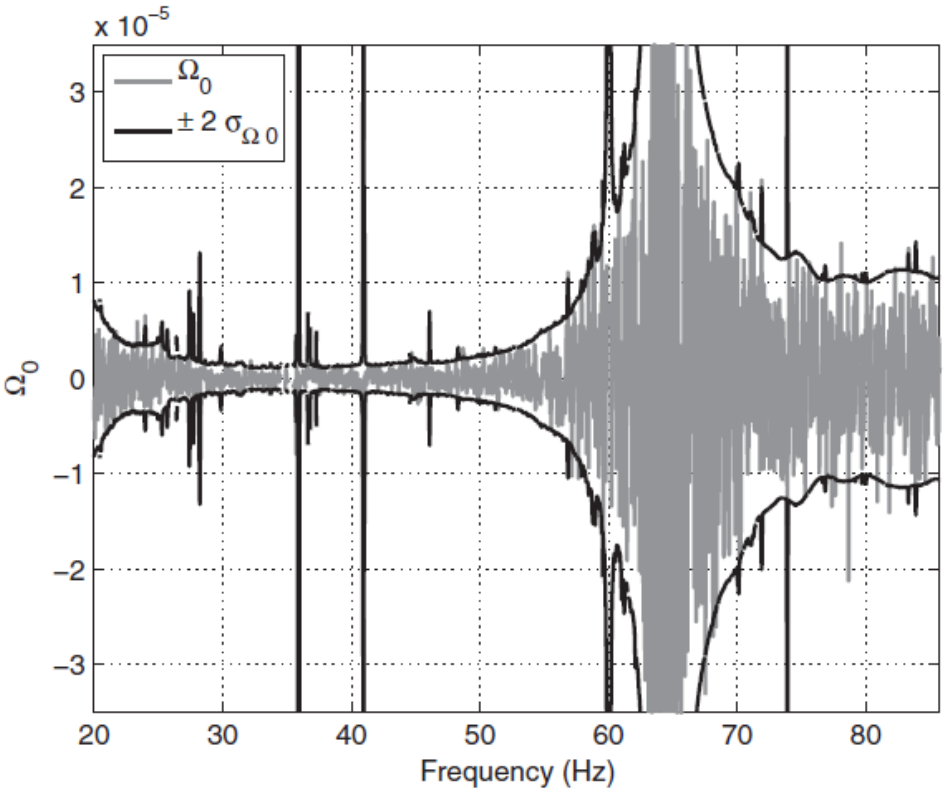


FIG. 1. We show the estimator for Ω_0 in each frequency bin, along with $\pm 2\sigma$ error bars, in the frequency band that contains 99% of the sensitivity for $\alpha = 0$. The loss of sensitivity at around 65 Hz is due to a zero in the overlap reduction function. There are several lines associated with known instrumental artifacts which do not lead to excess cross-correlation. The data are consistent with Gaussian noise, as described in the Results section.

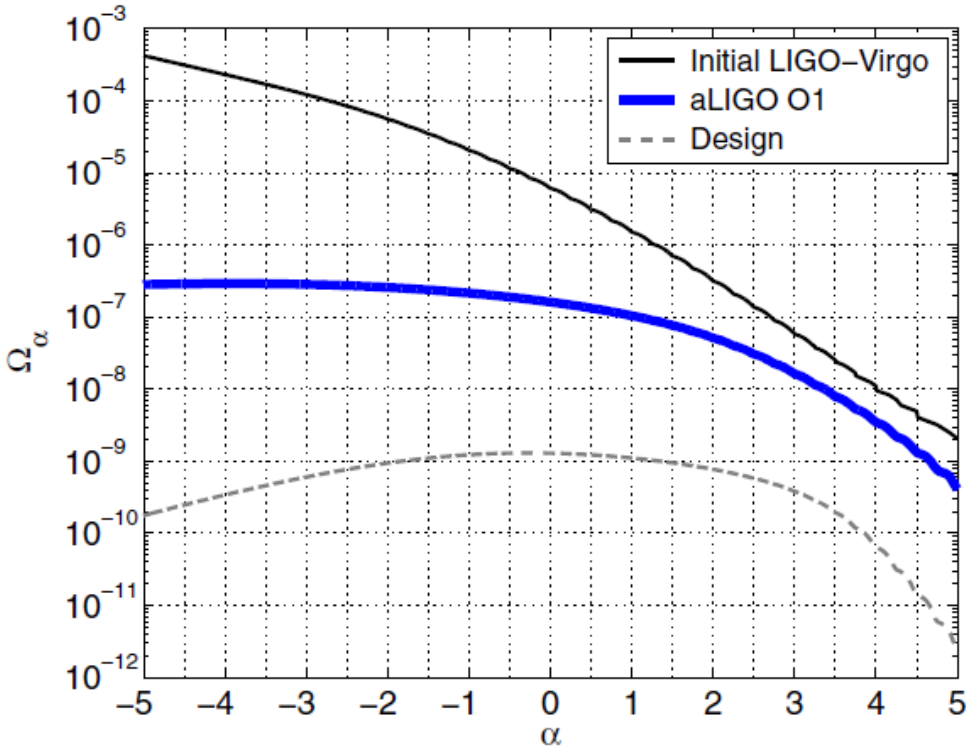
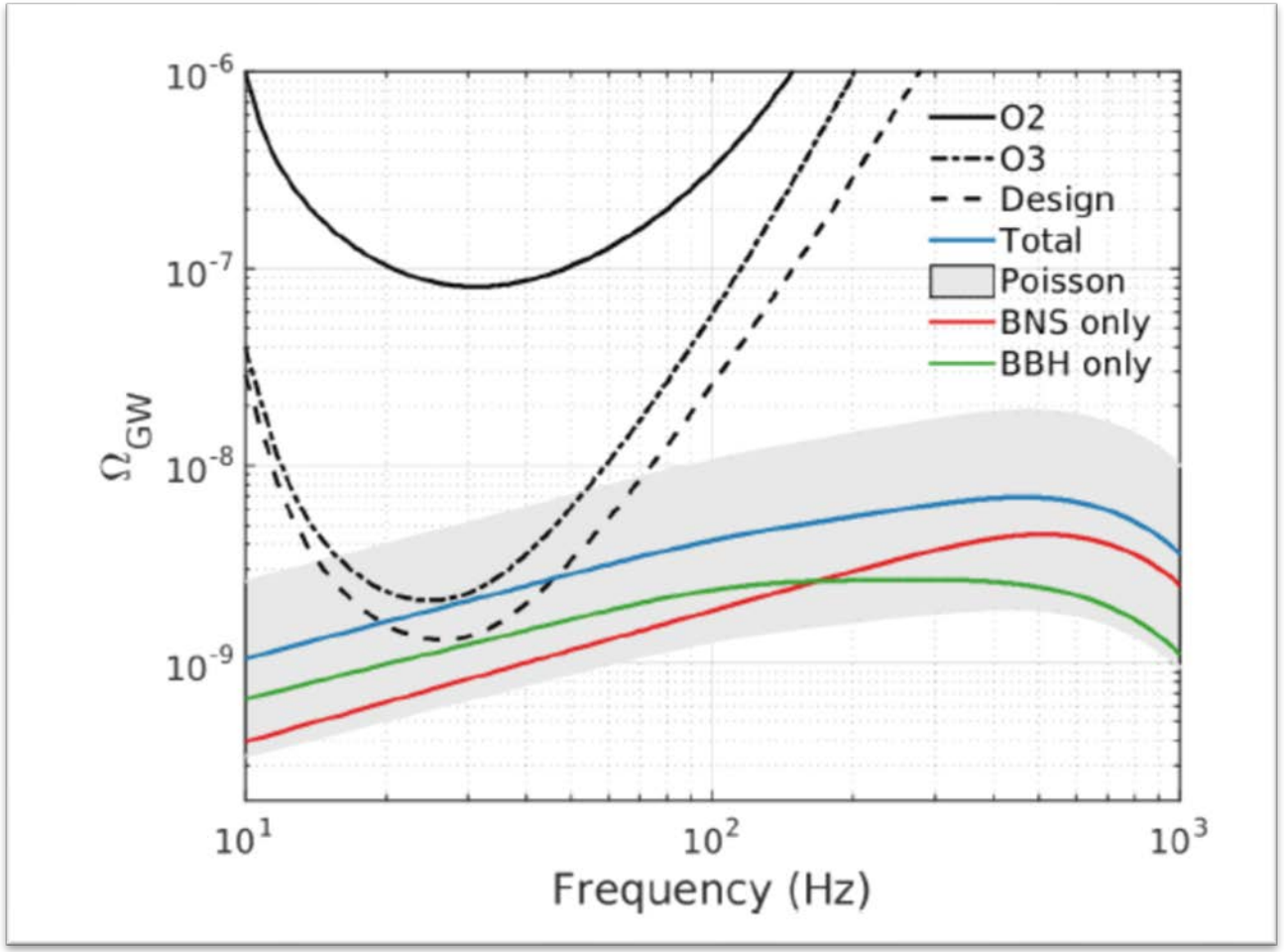


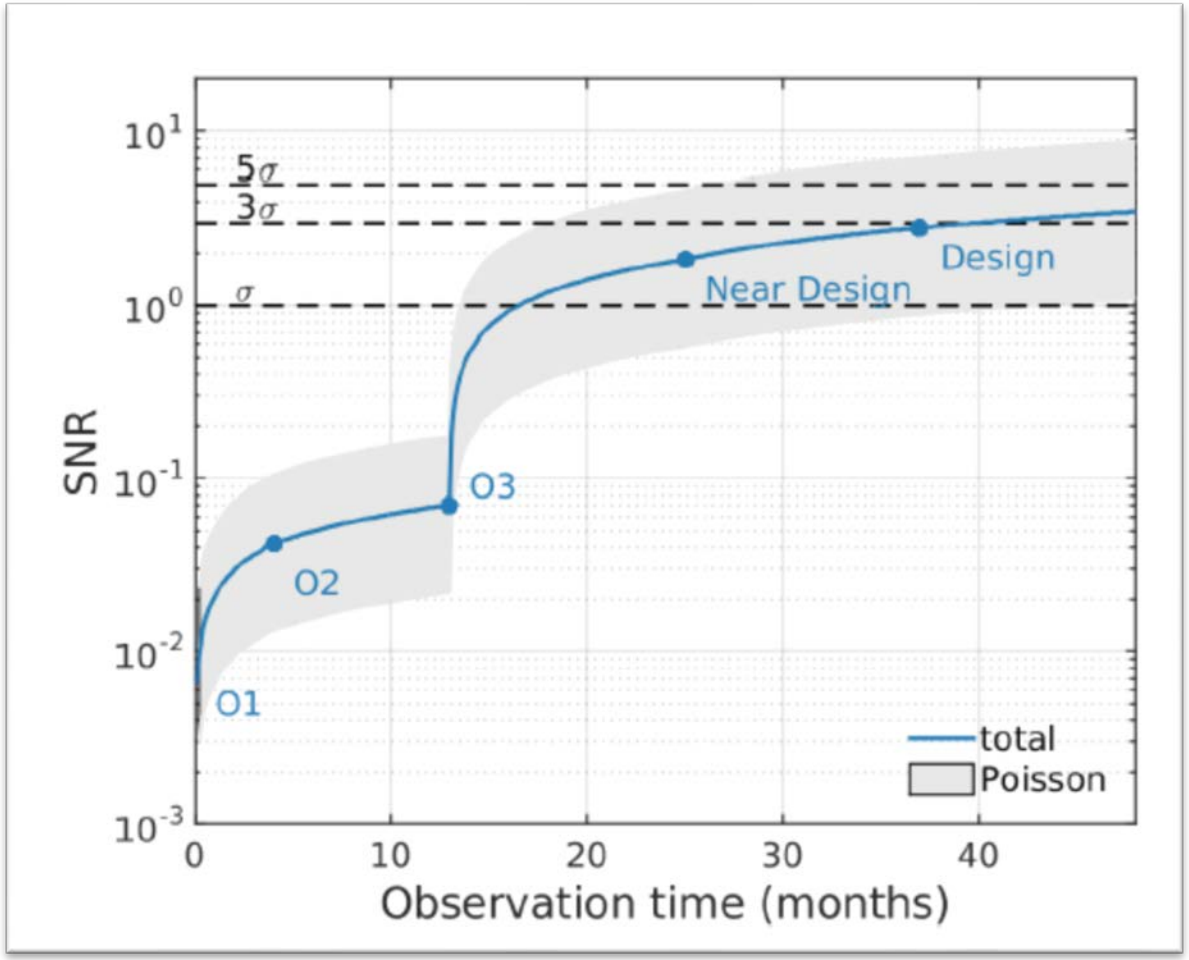
TABLE I. The frequency bands with 99% of the sensitivity are shown, along with the point estimate and standard deviation for the amplitude of the background, and 95% confidence level upper limits using O1 data for three values of the spectral index, $\alpha = 0, 2/3, 3$. We also show the previous upper limits using Initial LIGO-Virgo data.

Spectral index α	Frequency band with 99% sensitivity	Amplitude Ω_α	95% C.L. upper limit	Previous limits [36]
0	20–85.8 Hz	$(4.4 \pm 5.9) \times 10^{-8}$	1.7×10^{-7}	5.6×10^{-6}
2/3	20–98.2 Hz	$(3.5 \pm 4.4) \times 10^{-8}$	1.3×10^{-7}	–
3	20–305 Hz	$(3.7 \pm 6.5) \times 10^{-9}$	1.7×10^{-8}	7.6×10^{-8}

Phys. Rev. Lett. 118, 121101 (2017)

GW170817 : implications for the stochastic background





10.1103/PhysRevLett.120.091101

Conclusions

- August 2017:
  - First detection of BNS coalescence
  - Multi-messenger astronomy: gravitational channel opened
  - Association between BNS – short γ ray burst
  - Kilonova
  - No-degenerate network of GW detectors available
- Tomorrow?
  - O3 run with improved sensitivity
  - Design sensitivity
    - Higher event rates
    - Best parameter estimation
- The day after tomorrow?
  - Precision gravitational astronomy
  - New sources: pulsar, supernovae, fondi stocastici (maybe tomorrow!)
  - …….

A new way of looking at the universe is born