Gravitational wave astronomy with Virgo and the GW detectors network

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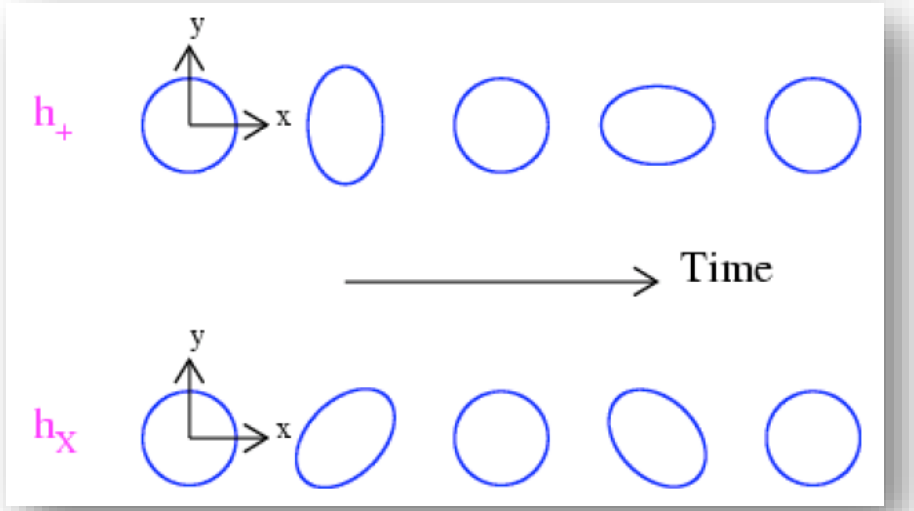
for the Virgo collaboration

Virgo document: VIR-0650A-18

Primer on gravitational waves

- *Wave-like perturbation of space-time that travel at the speed of light*
  - Predicted by Einstein in 1916
  - Result from linearization of General Relativity field equations
- *Produce a change in proper distance between geodesics*
  - Act in plane orthogonal to direction of propagation
  - Two independent polarization
  - Relative distance change (strain)
- *Generated by systems with non-zero second derivative of the mass quadrupole moment*
  - accelerated, non-symmetric mass distributions (i.e. binary systems)
- *Typical effect from astronomical sources is very small!*

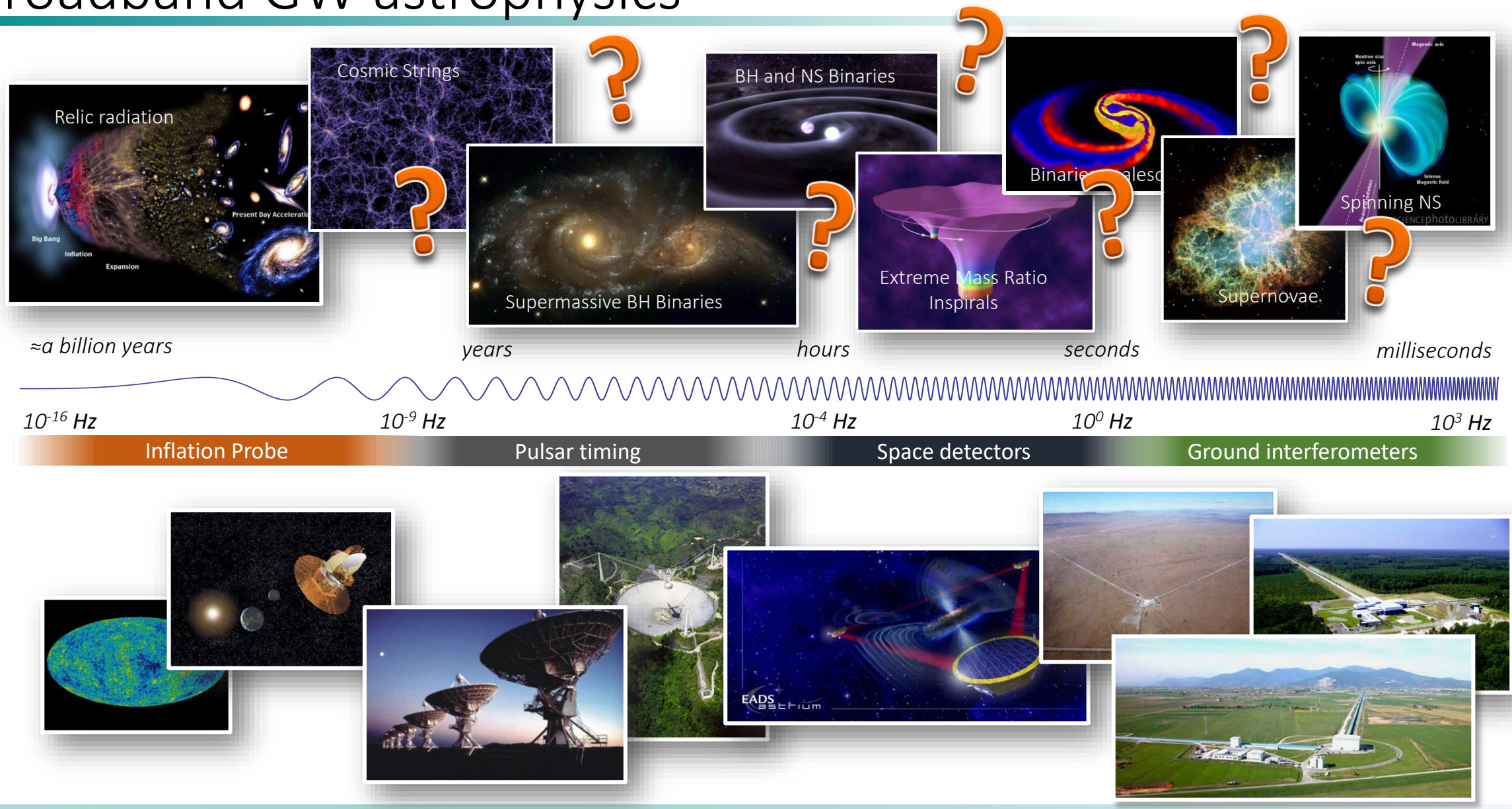


$$Q_{jk} = \int \rho x_i x_k d^3x \qquad h_{jk} = \frac{2}{r}\ddot{Q}_{jk}$$

$$h_{ab} = \begin{pmatrix} h_+ & h_\times \\ h_\times & -h_+ \end{pmatrix}$$

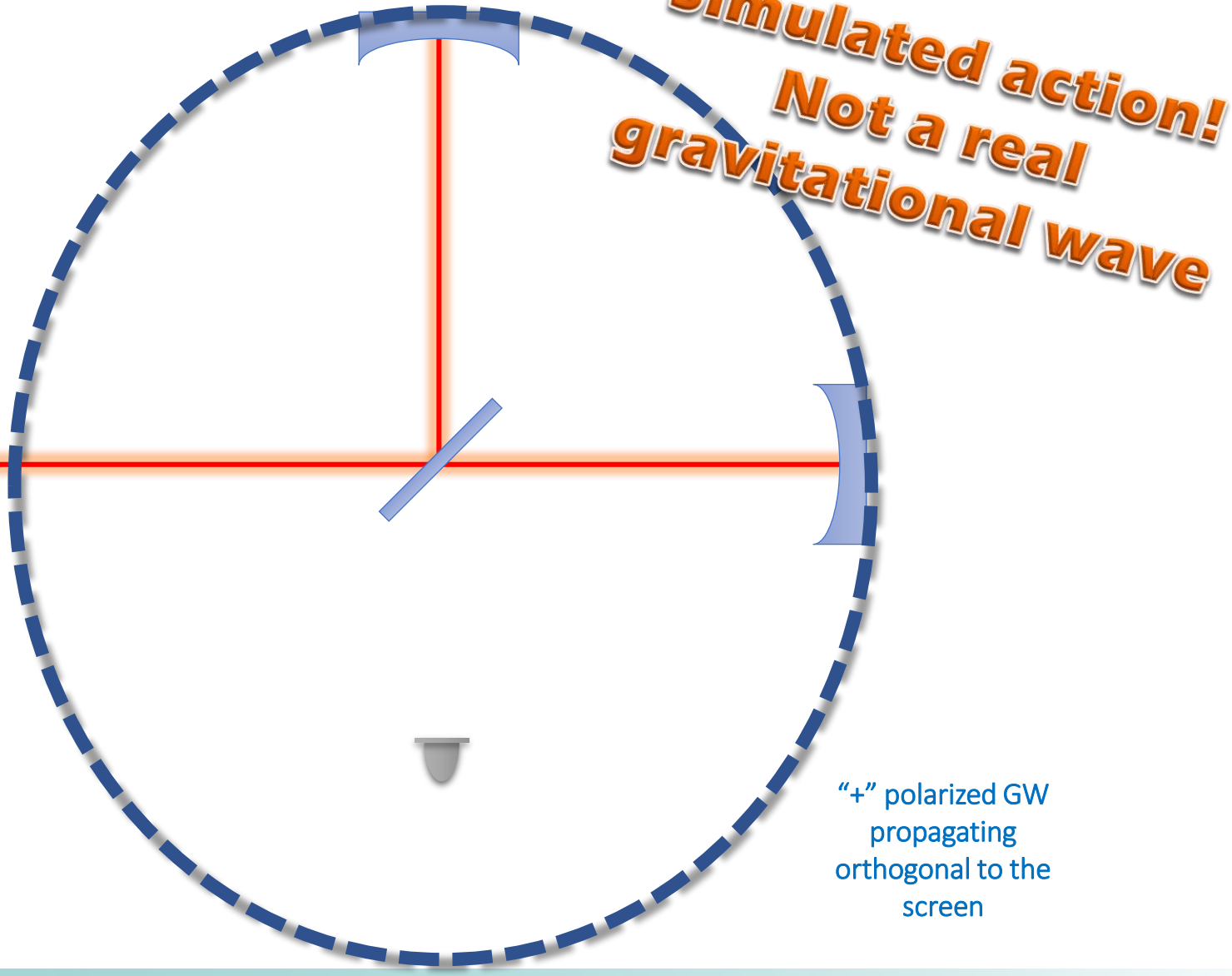
$\Delta L/L \sim 10^{-21}$

Broadband GW astrophysics



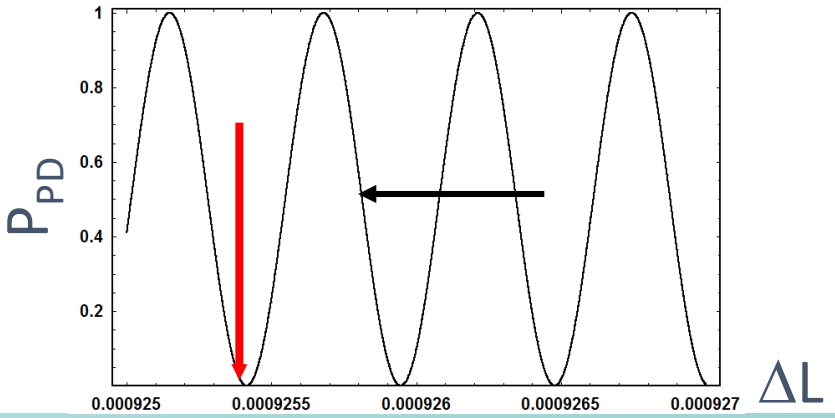
Laser interferometers

- Inherently differential
- Broad band
- Long baseline



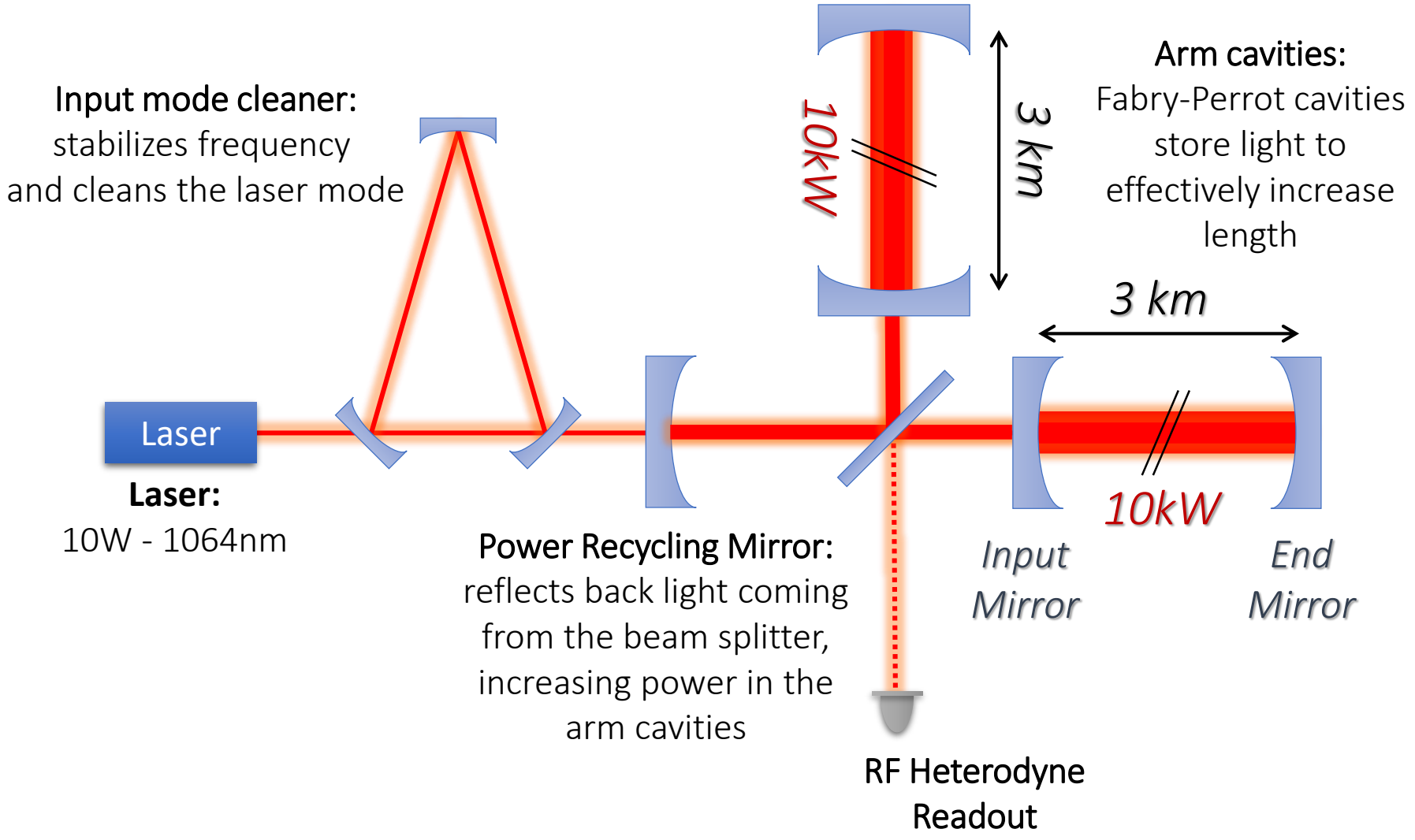
Phase: $\phi = 4\pi\,(L_x - L_y)\,/\lambda \sim \Delta L$

Power: $P_{PD} = P_{BS} \sin^2\phi$

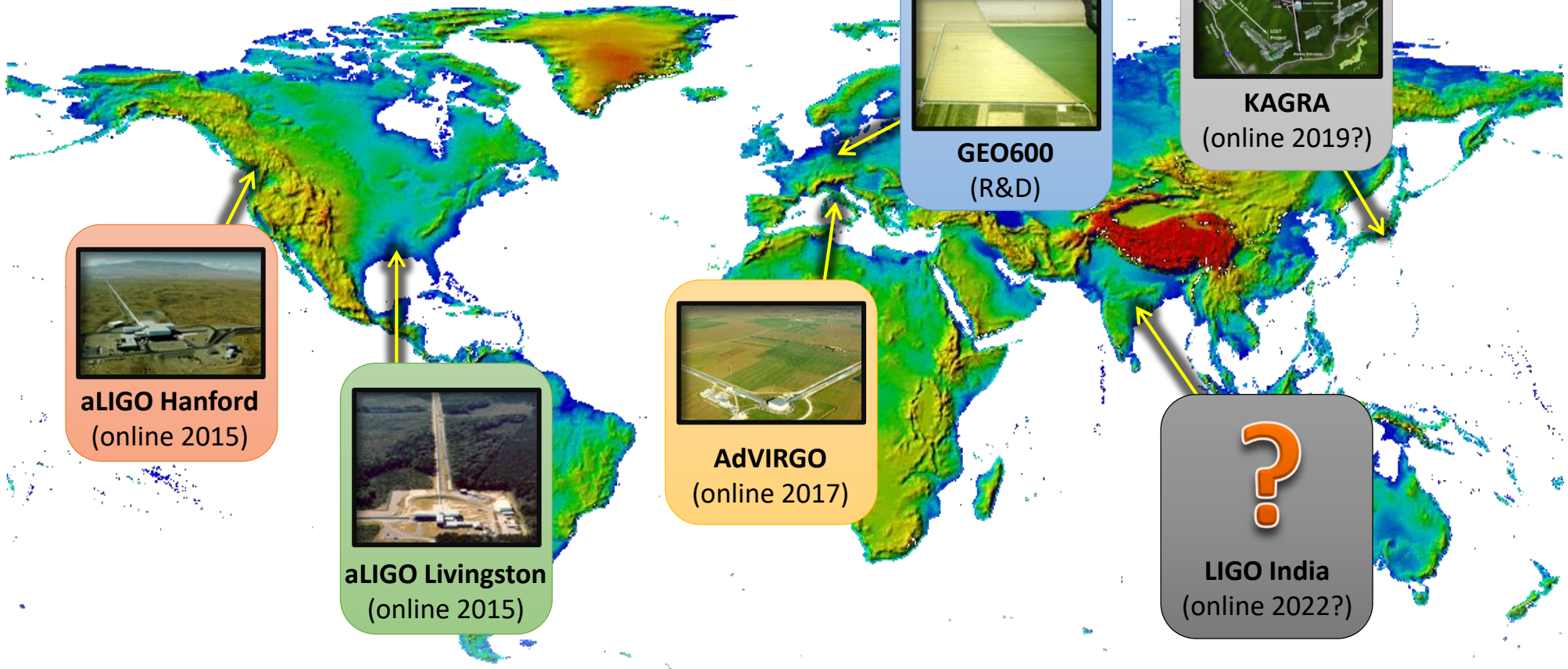


"+" polarized GW propagating orthogonal to the screen

Initial detectors: not just Michelson interferometers…



A planetary network



Coincidence: increased detection confidence

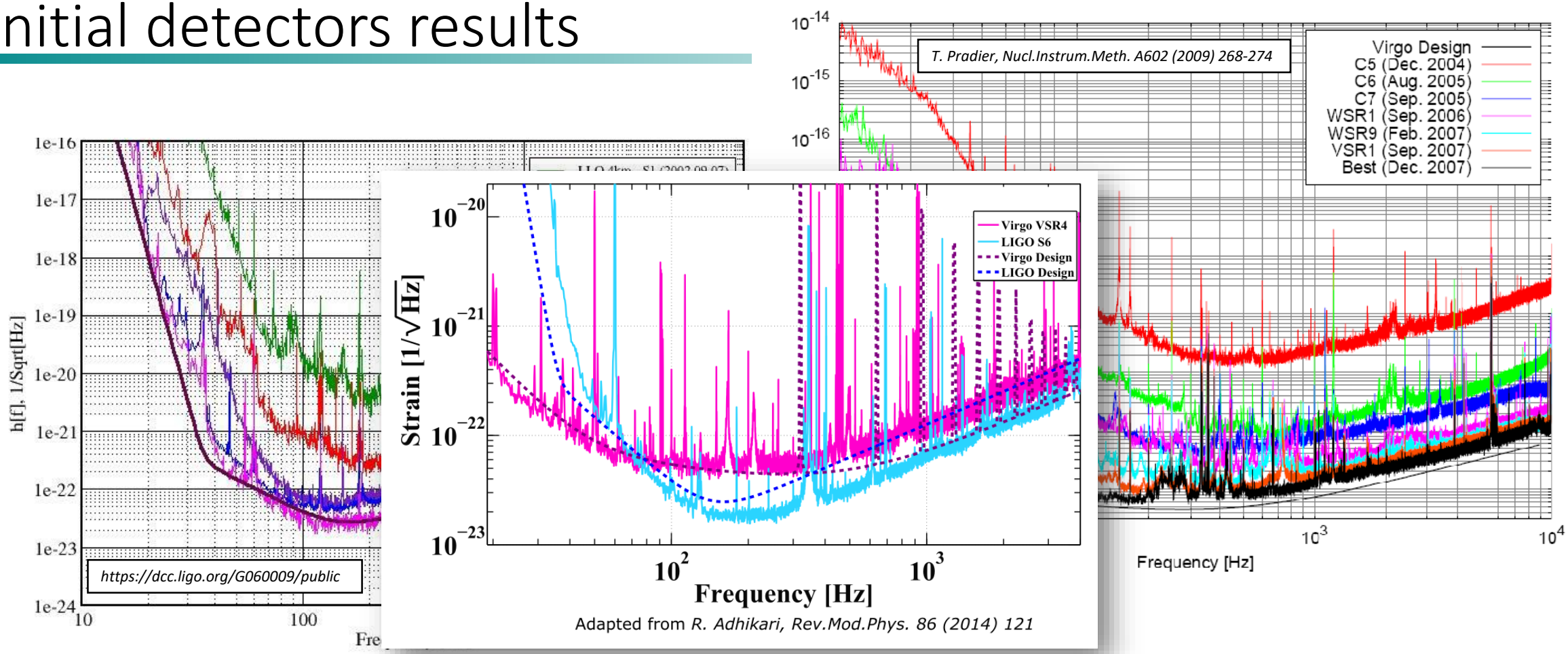
Triangulation: source localization

Enhanced sky coverage

More reliable source parameters estimation

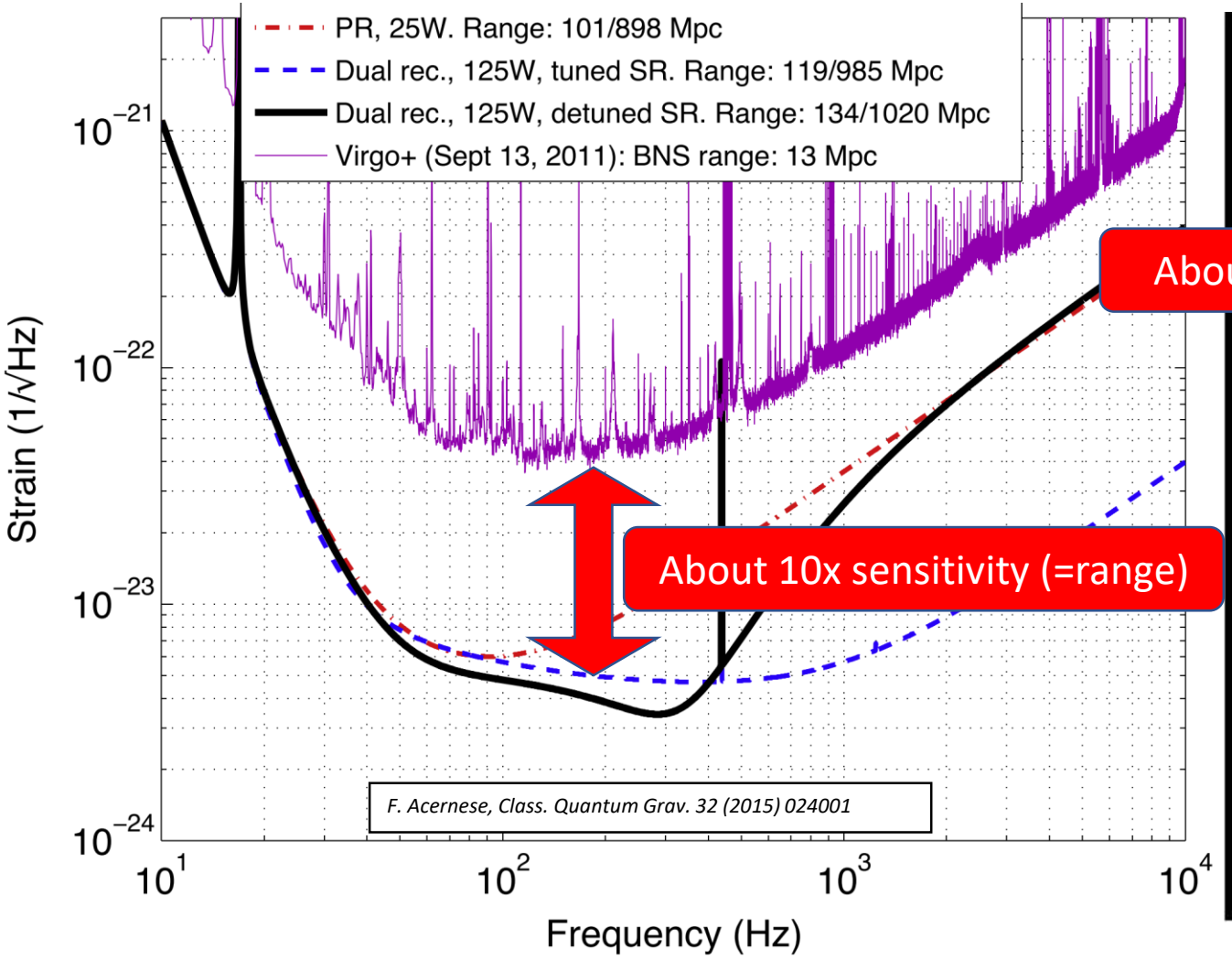
Reduced downtime

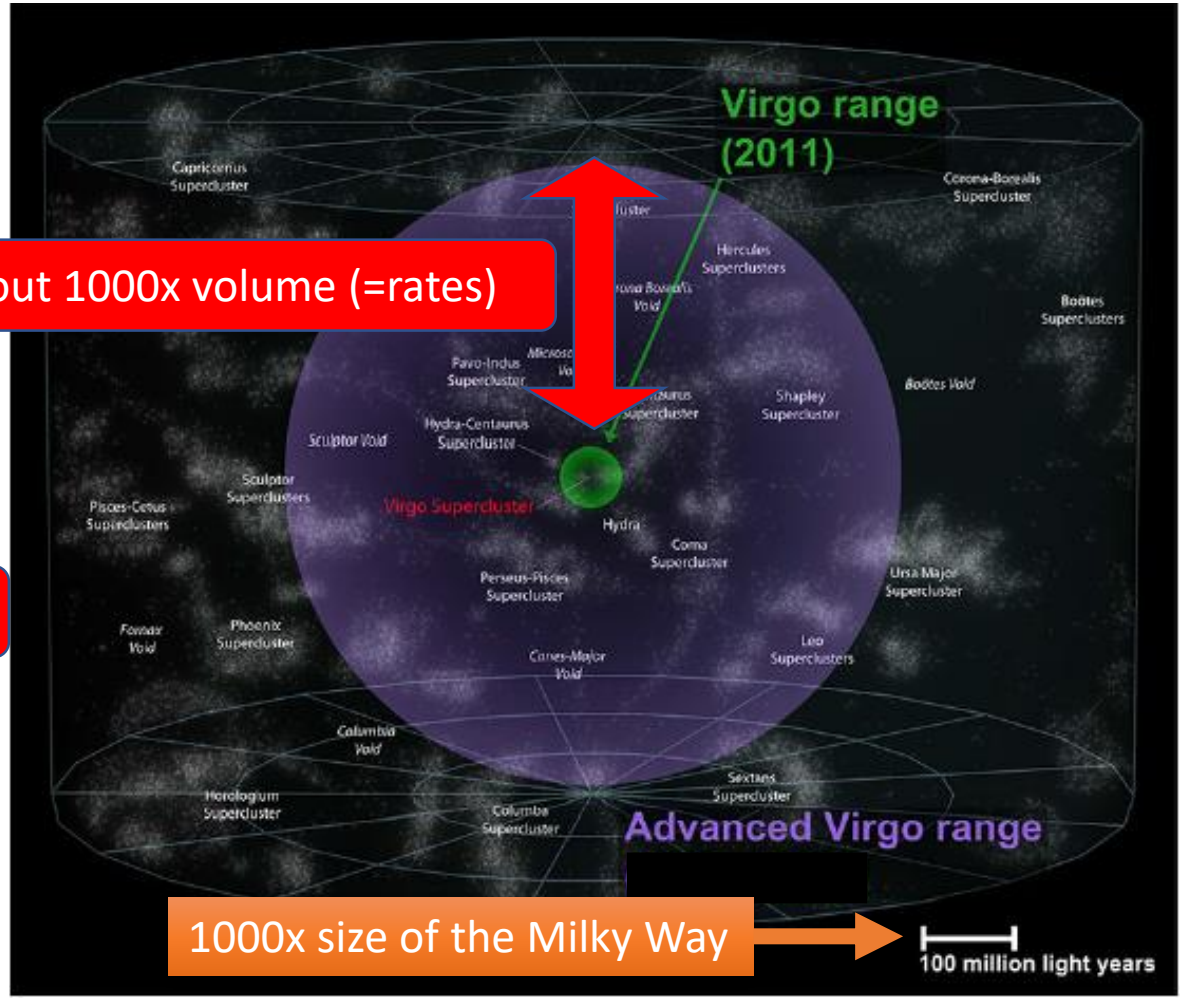
Initial detectors results



- Showed that such instruments can be successfully operated
- Set upper limits on GW emission from several sources
- Paved the (scientific, political and financial) way for Advanced Detectors

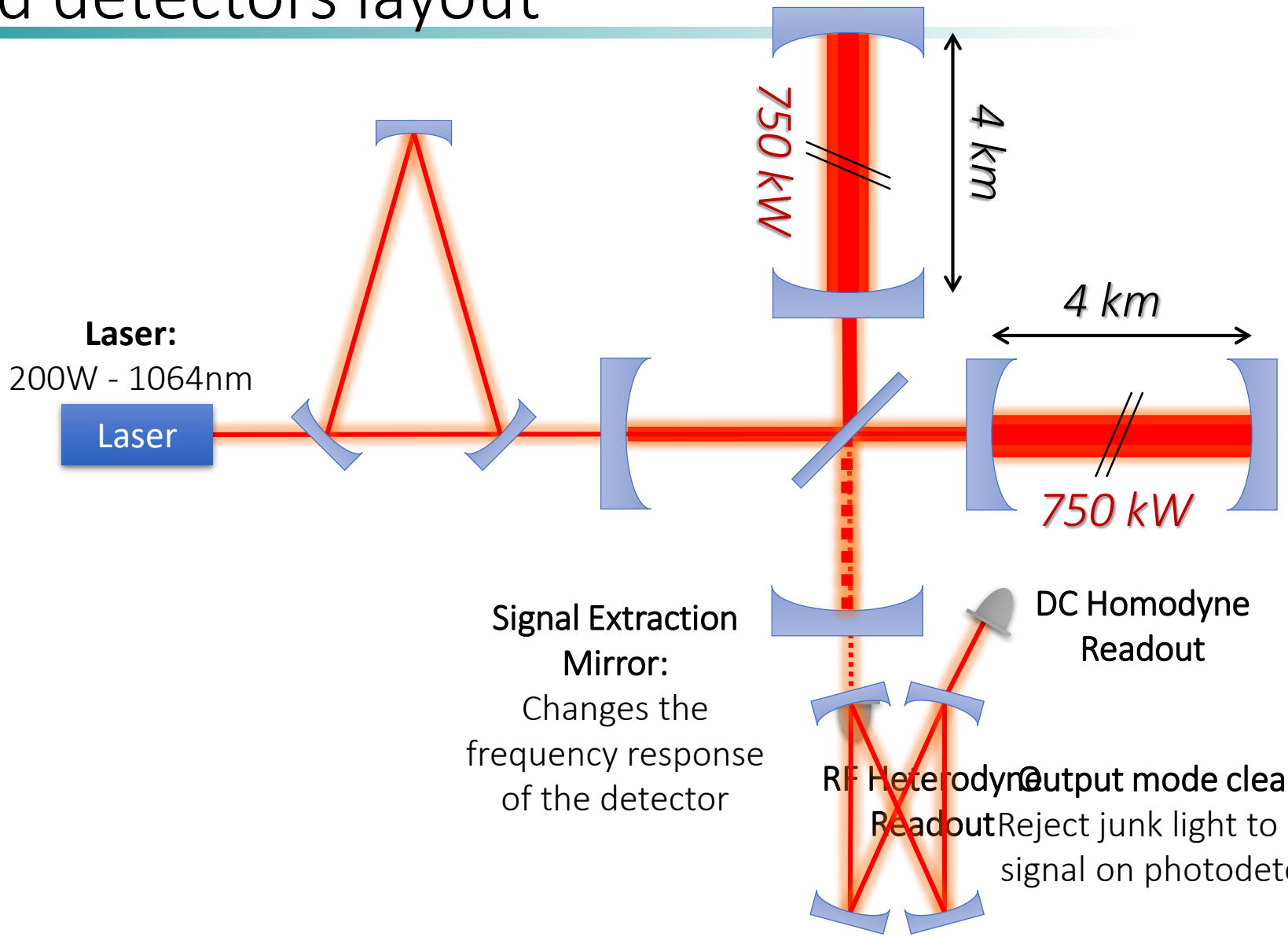
From Initial to Advanced





Design sensitivity to BNS merger with SNR = 8

Advanced detectors layout

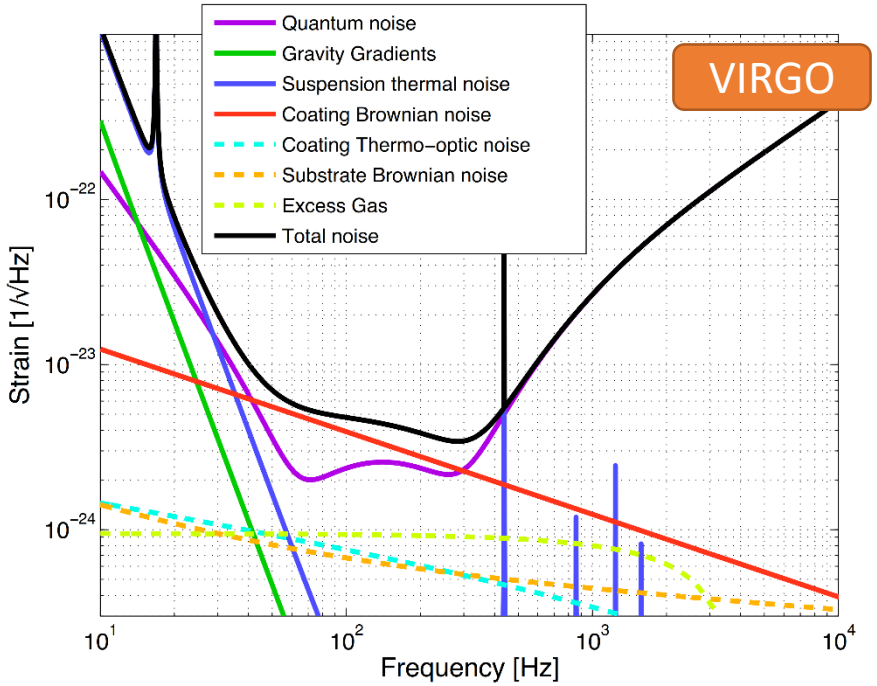


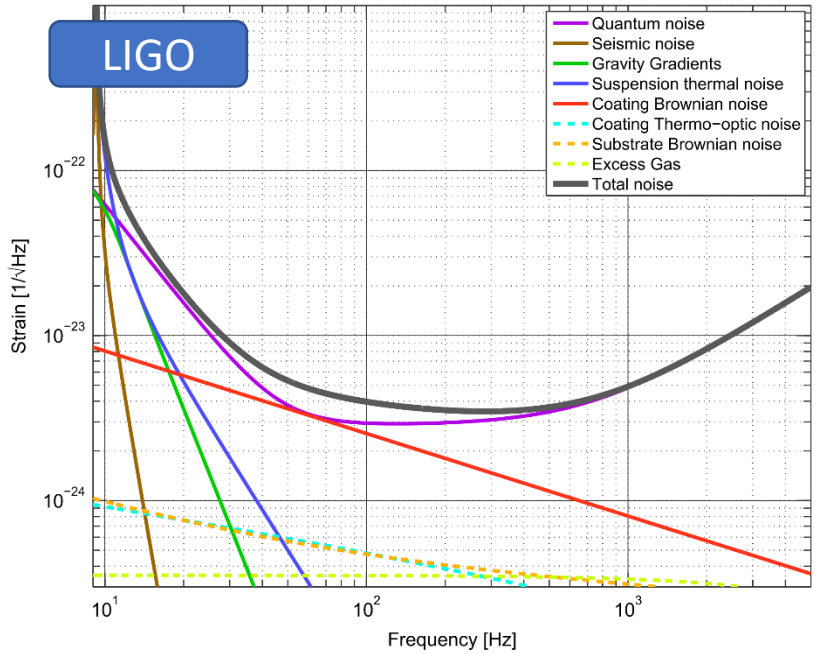
From Initial to Advanced (design values)

	Input Laser	Mirrors	Topology	Seismic isolation	Mirror susp.	Readout	Sensitivity
iLIGO	10W (10 kW arm)	10 kg	Power-Recycled Fabry-Perot	Single pendulum (LF cutoff ≈ 40 Hz)	Steel-wire	RF etherodyne	3 10^{-23} $Hz^{-1/2}$
aLIGO	**180W (>700 kW arm)**	**40 kg**	**Dual-Recycled Fabry-Perot**	**Quadruple pendulum (LF cutoff ≈ 10 Hz)**	**Monolithic SiO_2**	**DC homodyne**	**5 10^{-24} $Hz^{-1/2}$ broadband (tunable)**
Virgo	10W (10 kW arm)	21 kg	Power-Recycled Fabry-Perot	Superattenuators (LF cutoff few Hz)	Steel-wire (SiO_2 in En. Virgo)	RF etherodyne	5 10^{-23} $Hz^{-1/2}$
AdVirgo	**125W (>600 kW arm)**	**42 kg**	**Dual-Recycled Fabry-Perot**	**Superattenuators (LF cutoff few Hz)**	**Monolithic SiO_2**	**DC homodyne**	**5 10^{-24} $Hz^{-1/2}$ broadband (tunable)**

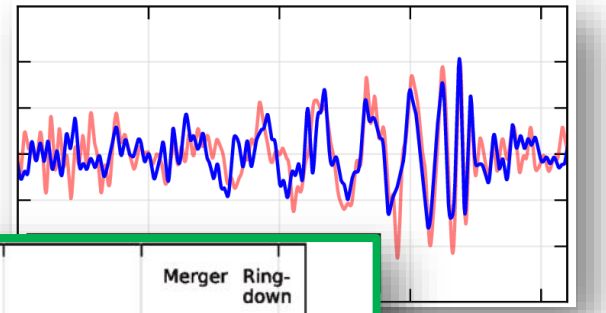
Also improved:

- Beam size
- mirror polishing and coatings
- compensation of thermal effects
- Vacuum
- Stray light control





14 September 2015: the birth of GW astronomy

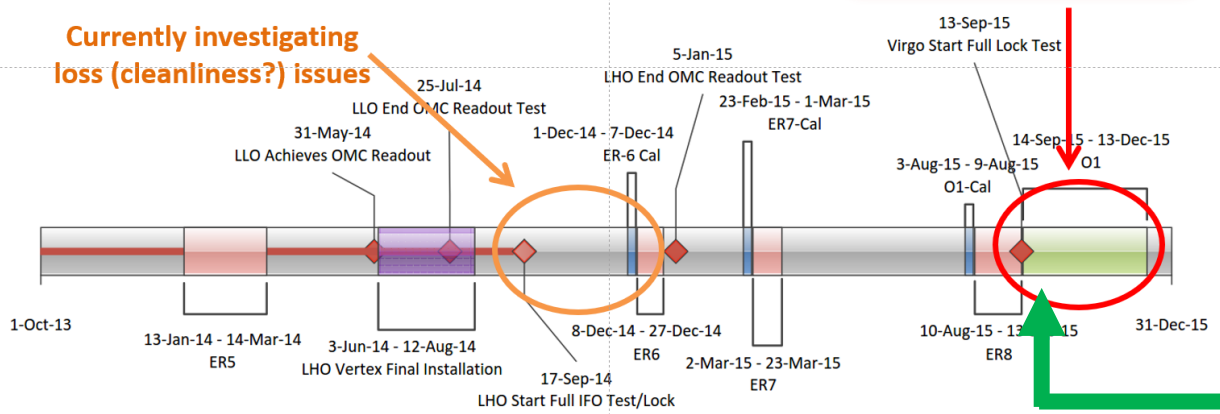


The near future

- Engineering run (ER6) ongoing at LLO
- Working towards 2 hours full lock at Hanford
- Ongoing commissioning
- First coincident Engineering Run: early 2015?

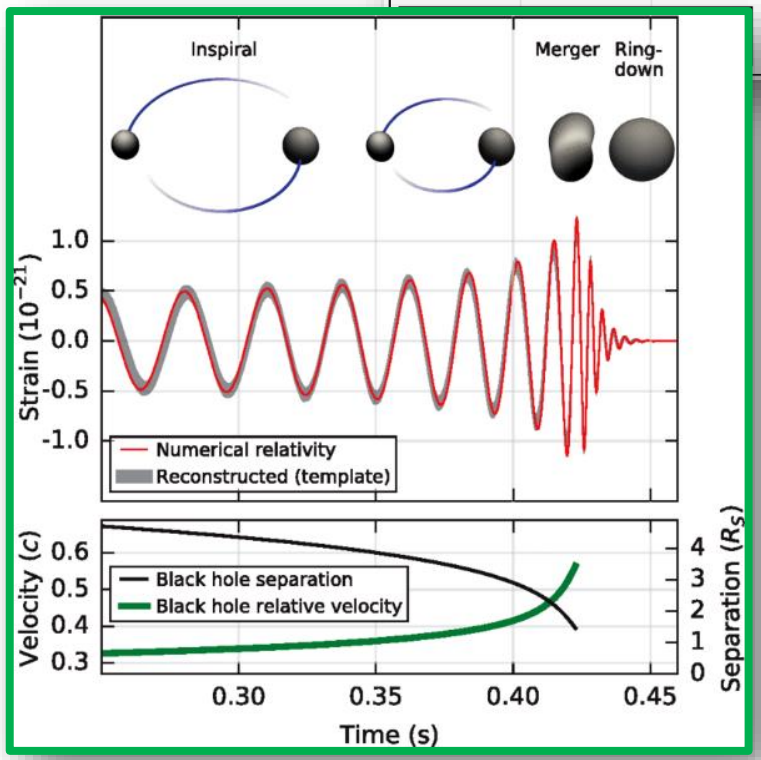
We could be listening to the universe!

- **First coincident Observation Run: late 2015?**



Dec 19th, 2014 – CGC Conference in Fort Lauderdale | Giacomo Ciani for the LSC | LIGO-G1401371 | 21

Physical Review Letters **116**, 061102 (2016)

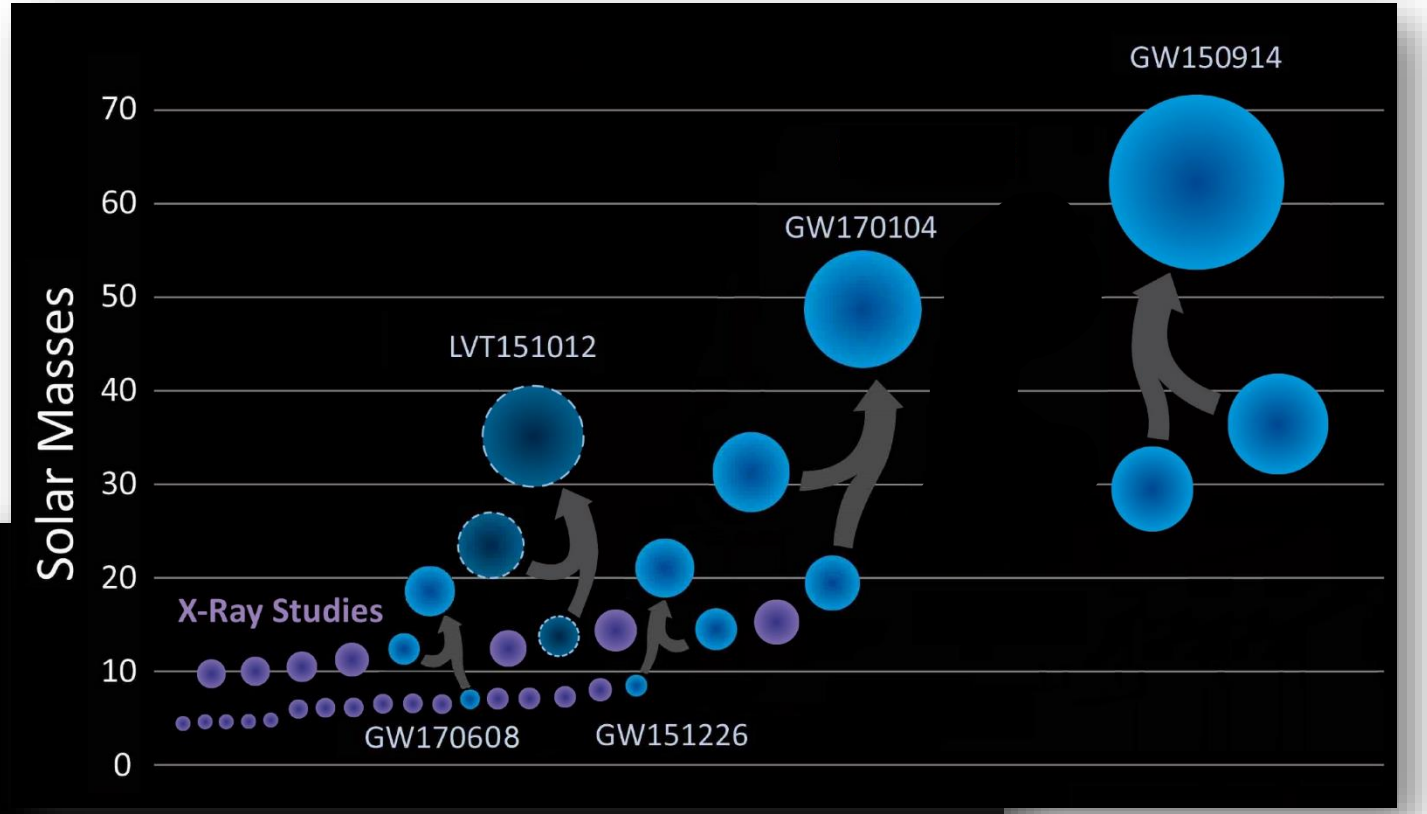


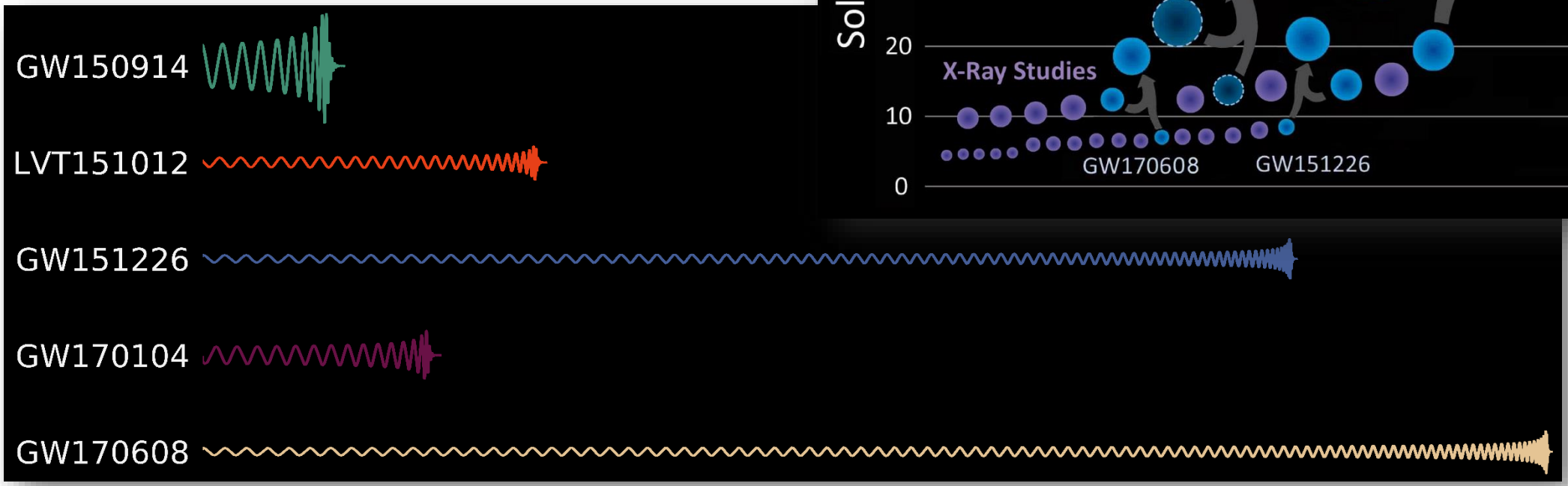
GW150914: a lucky first!

- Clear detection
- Unexpected source
- Important physical and **astrophysical** consequences

LIGO: O1 and O2… up to August 2017

- 4 Binary Black Hole detections and one likely candidate
- 12 (15) new Black Holes observed
- Unexpected mass range
- LIGO-Virgo Collaboration effort, despite only LIGO instruments being online





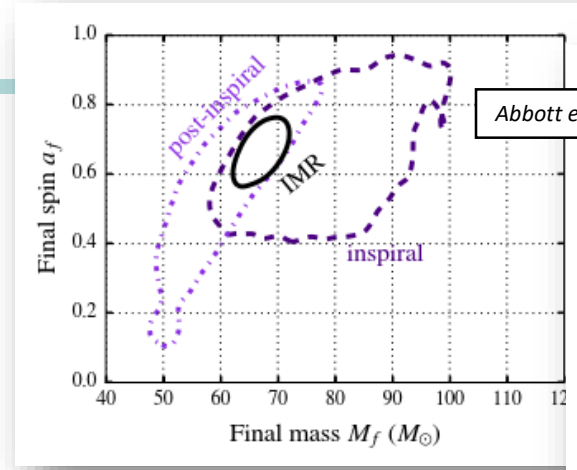
Tests of General Relativity

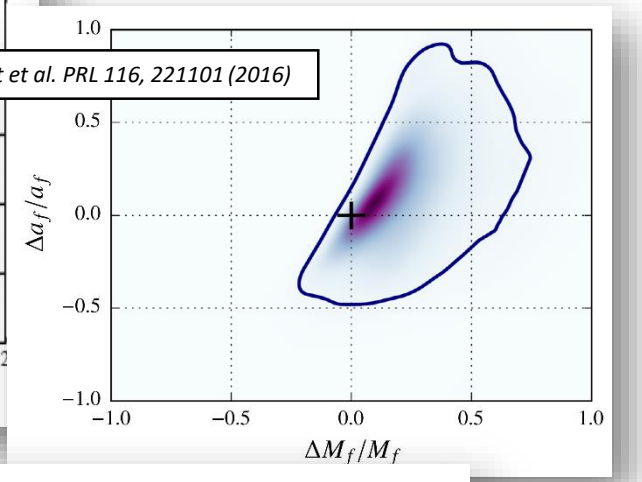
- GW exists! No big surprise here…
- Signal vs GR models:
  - Deviation in residuals from random noise: <4%
  - Parameter inferred from pre- and post-merger phase are consistent
- No evidence of deviation in PN parameters
- Test of modified GW dispersion relation:

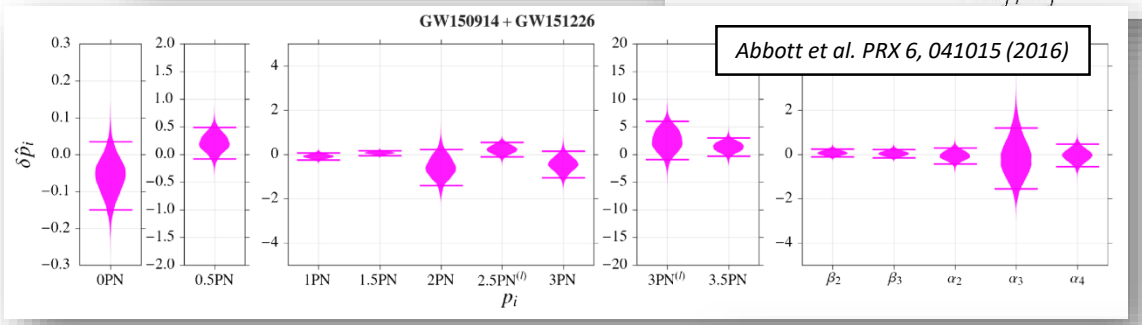
$$E^2 = p^2c^2 + Ap^\alpha c^\alpha$$

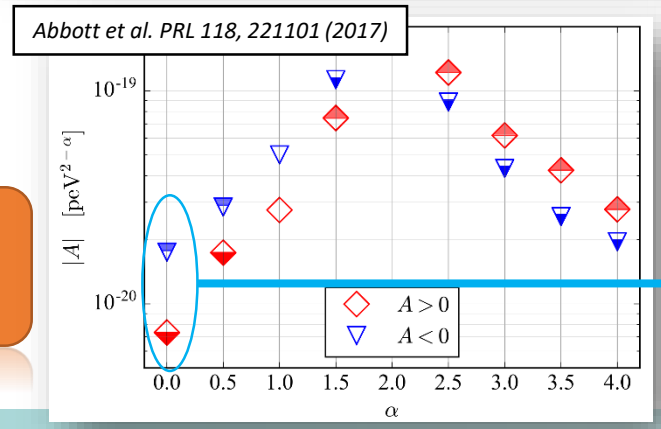
  - Upper bounds on graviton's mass

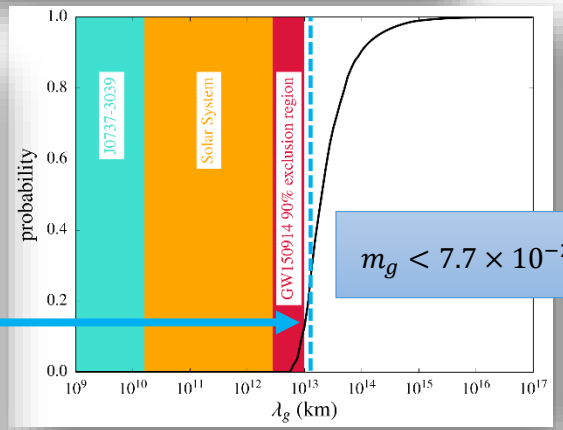
We didn't see new physics either!
But we are happy about it… ☺











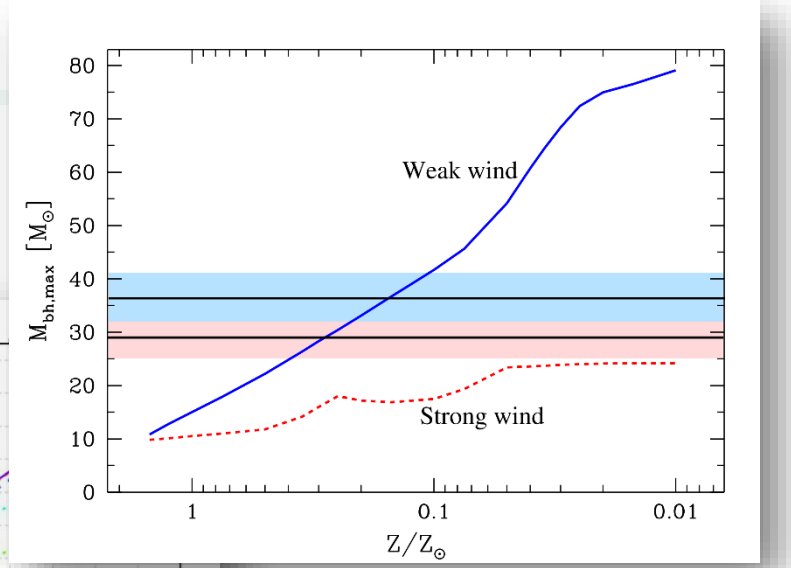
$m_g < 7.7 \times 10^{-23} \frac{\text{eV}}{\text{c}^2}$

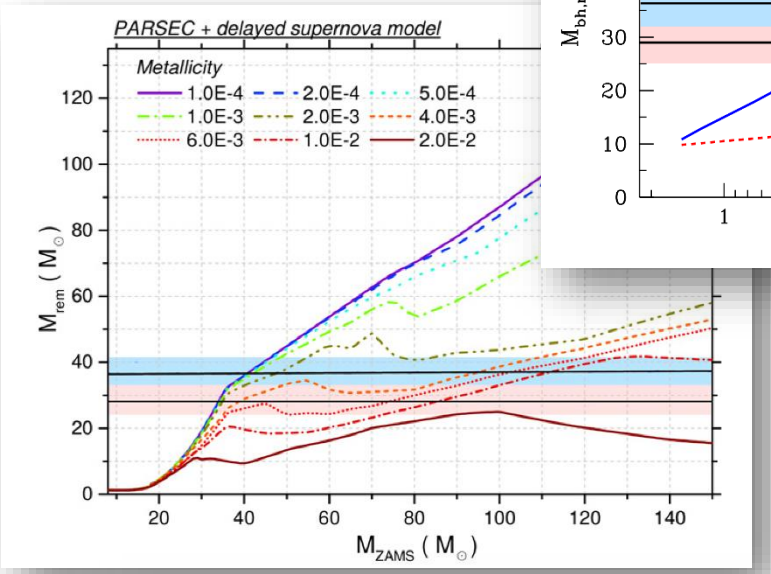
Astrophysical results

- Bounds on merger rates:
  $12 - 230\ \mathrm{Gpc^{-3}yr^{-1}}$

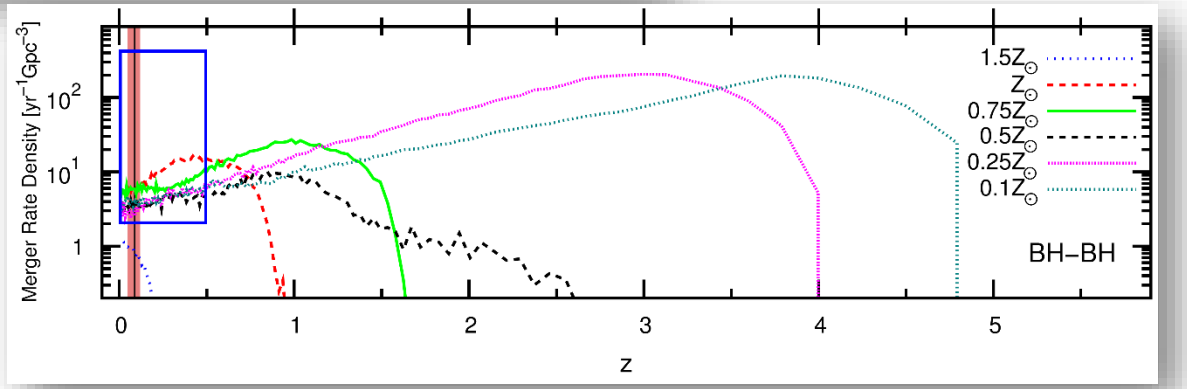
- Observed black holes in unexpected mass range
  - Hints on formation mechanisms and environment
  - Estimates of mass distribution law
  - Population estimates (needs more data)

- Hints on formation channels
  - Low-metallicity needed for high-mass BH remnant
  - Rates too high for some formation channels (but could contribute to total)
  - Misaligned spins slightly favored





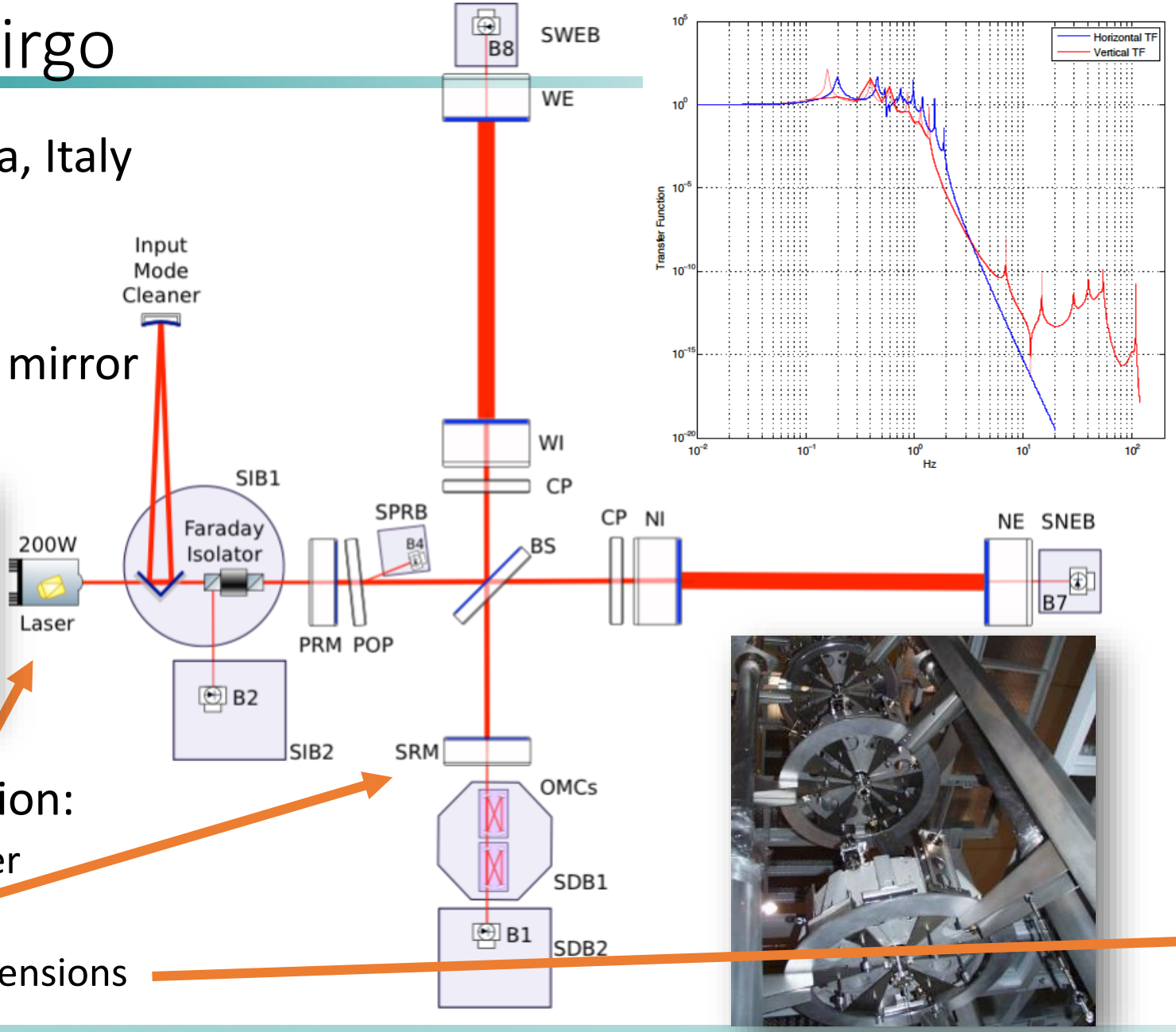
Abbott et al. APJL 818:L22 (2016)

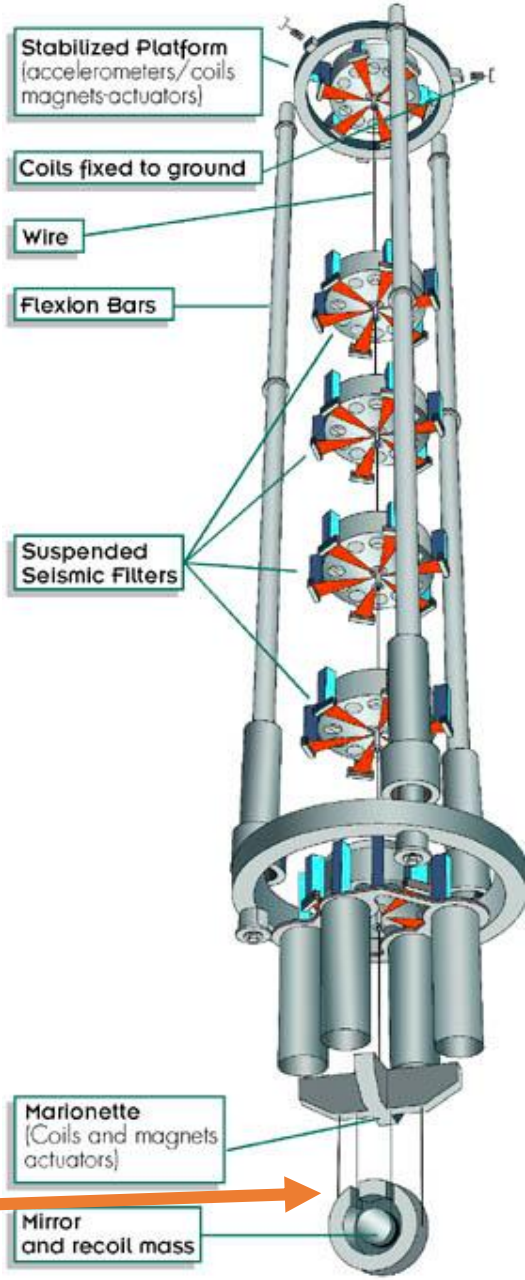


Advanced Virgo

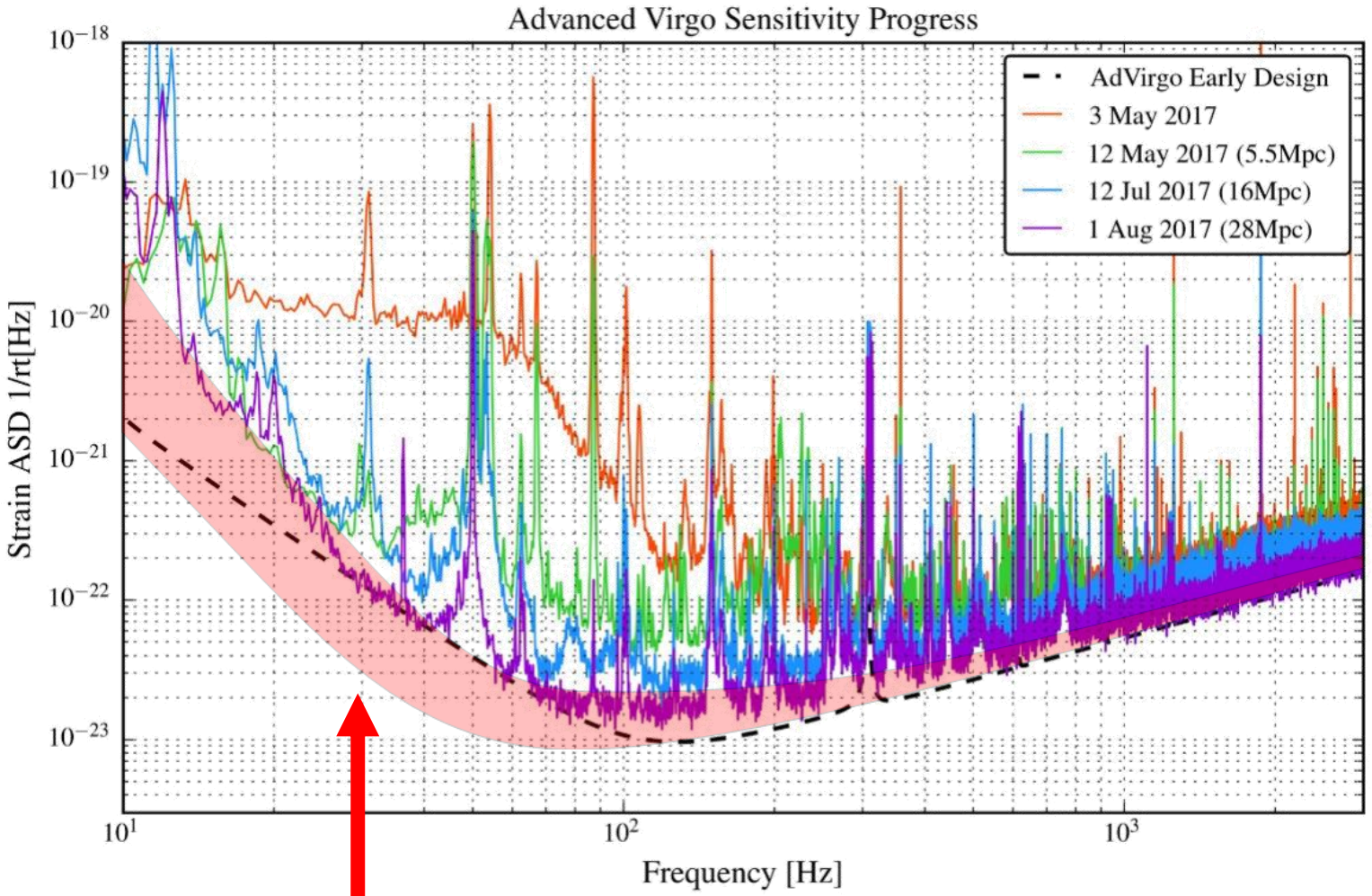
- Located near Pisa, Italy
- 3 km long arms
- Unique *superattenuator* mirror suspensions

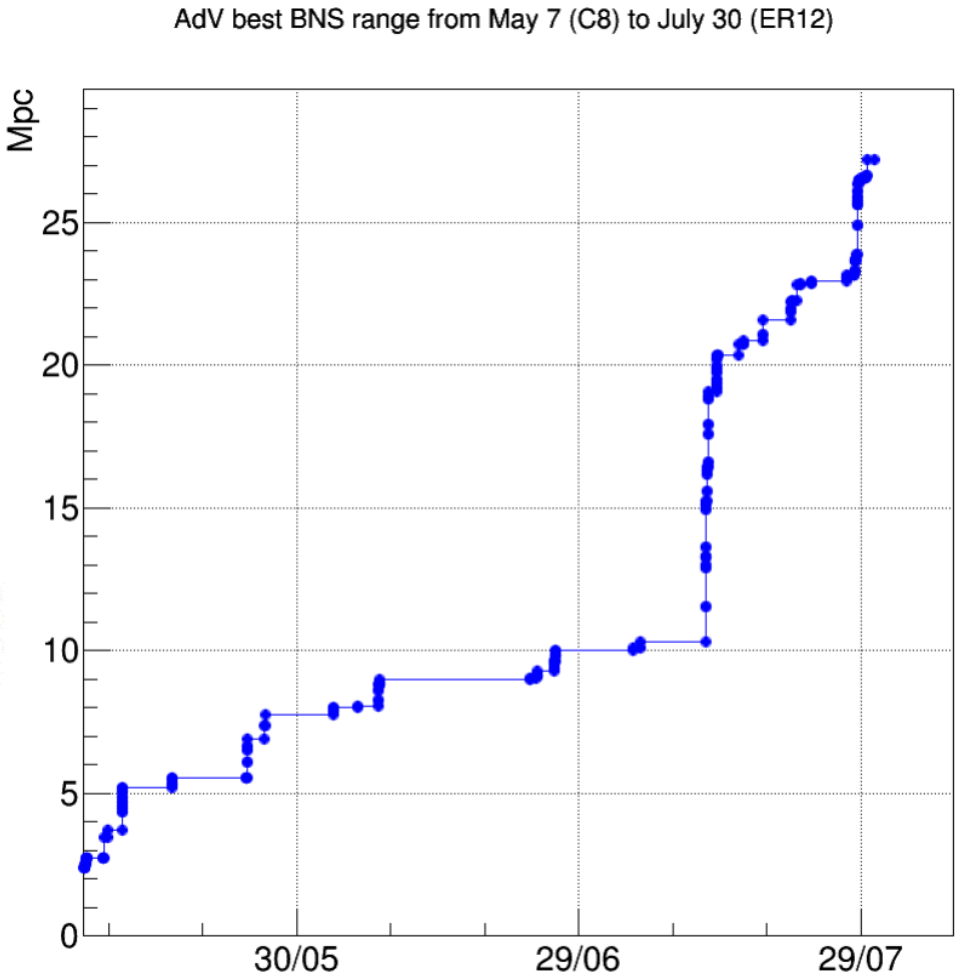
- Initial configuration:
  - Low-power laser
  - No SRM
  - Steel-wire suspensions





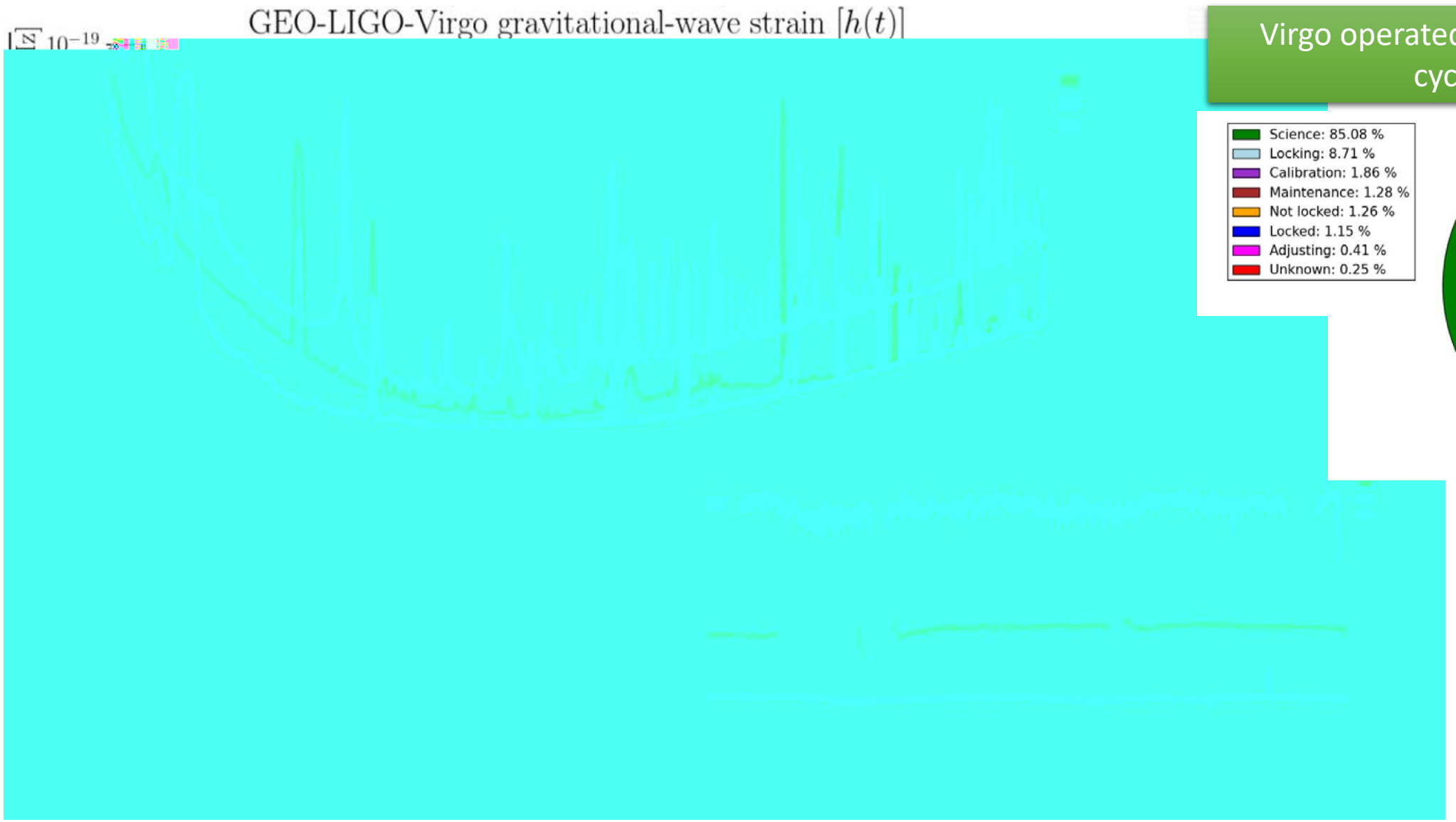
AdV quest to join O2



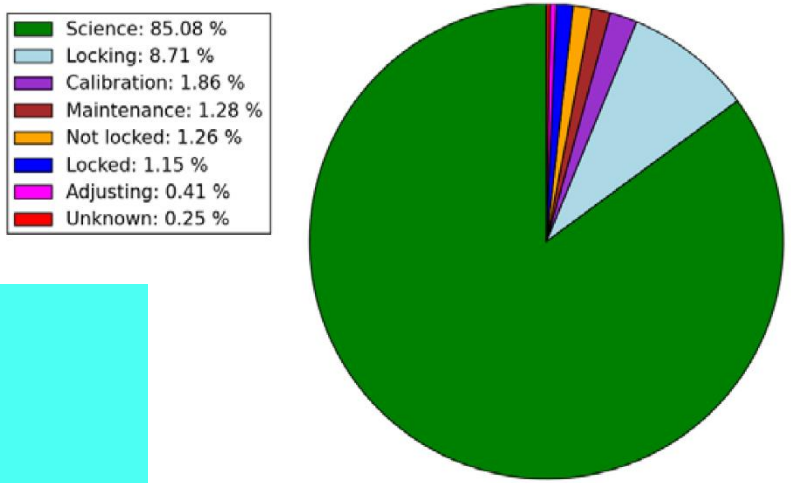


20 Mpc target sensitivity set to (meaningfully) join O2

Detectors sensitivity in O2



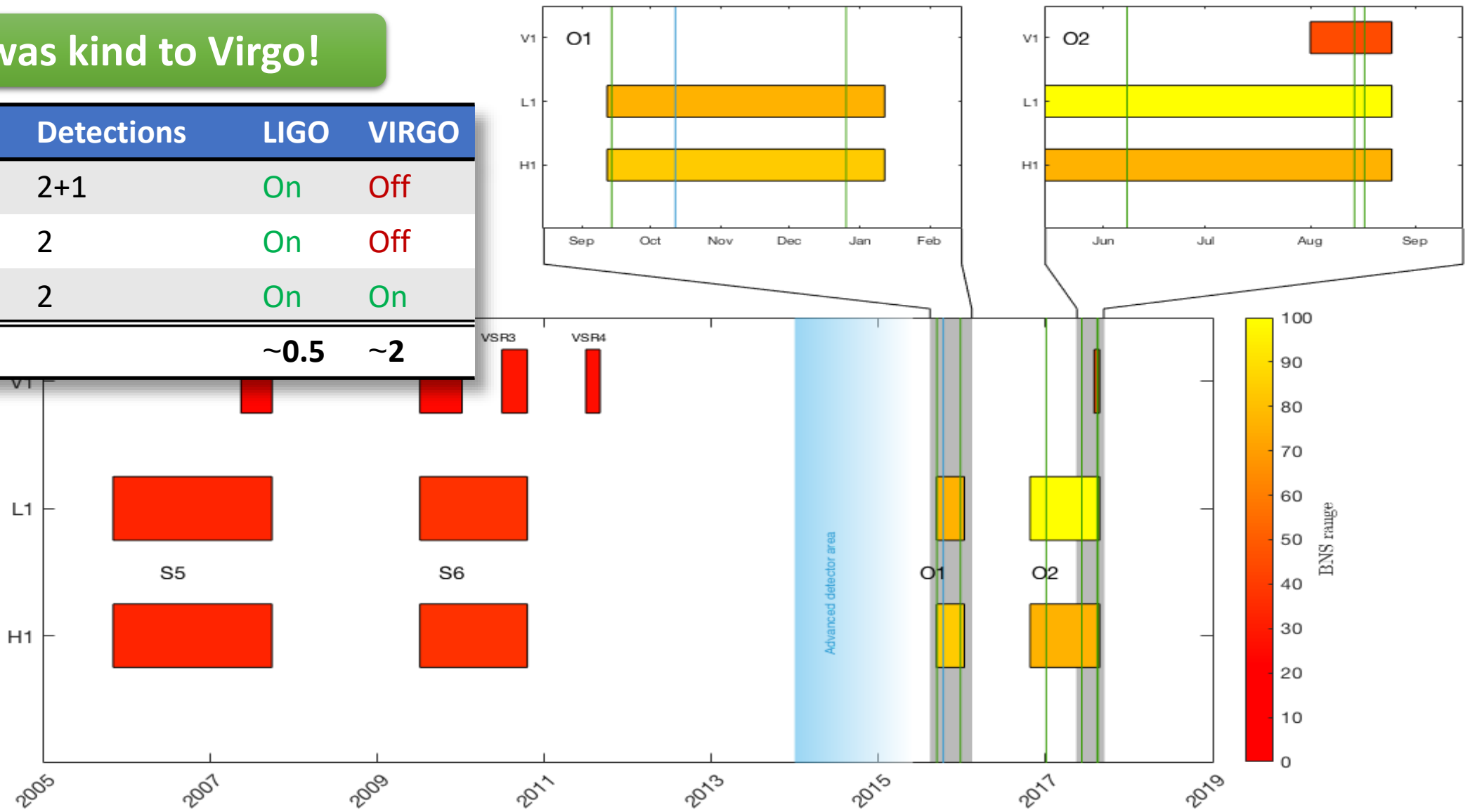
Virgo operated with very high duty cycle (~85%)



LIGO: O1 and O2… up to August 2017

Nature was kind to Virgo!

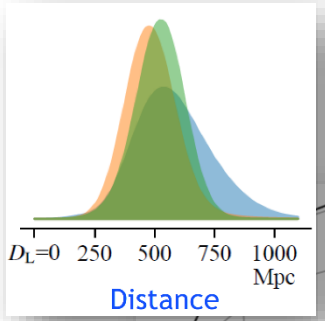
RUN	Duration	Detections	LIGO	VIRGO
O1	~4 mo.	2+1	On	Off
O2a	~8 mo.	2	On	Off
O2b	~1 mo.	2	On	On
Detections/month			**~0.5**	**~2**



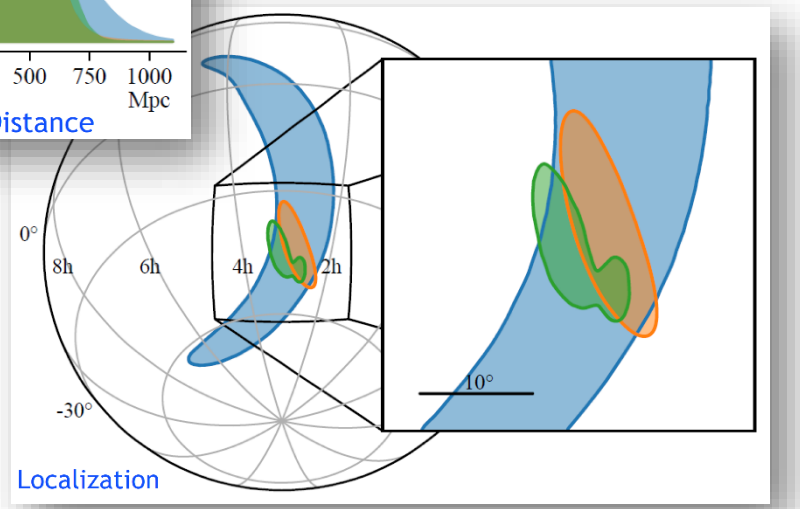
GW170814: 3-detectors BBH observation

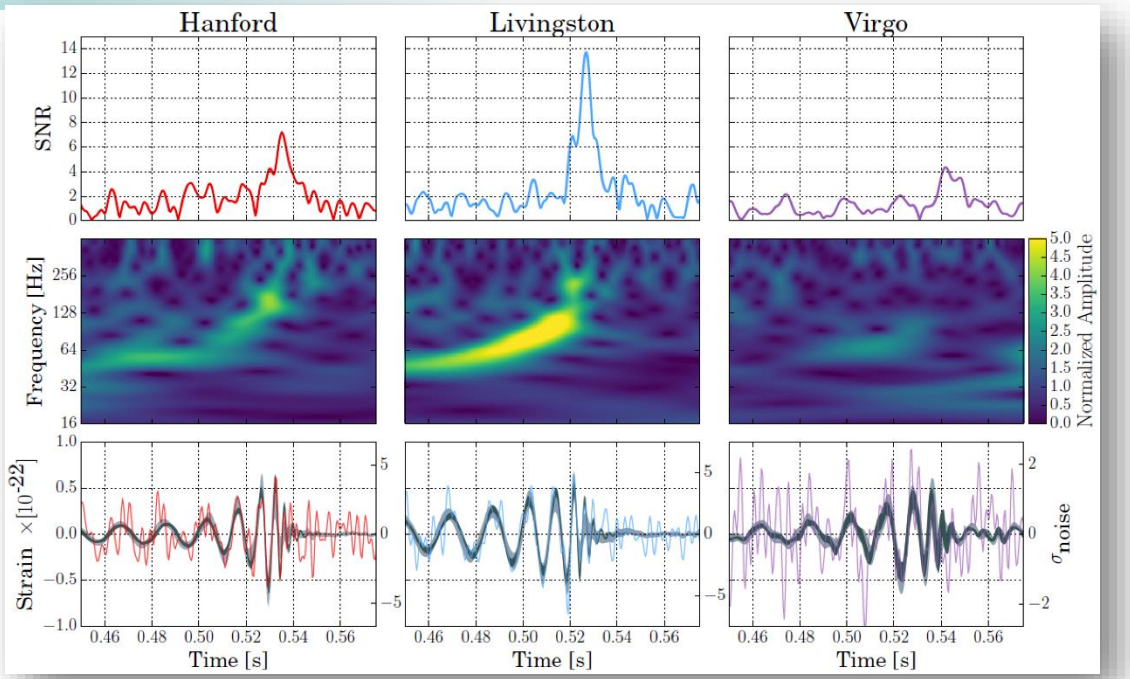
Abbott et al. PRL 119, 141101 (2017)

- 31 + 25 solar masses BBH coalescence
- Virgo contribution:
  - Improved sky localization
  - First ever polarization studies

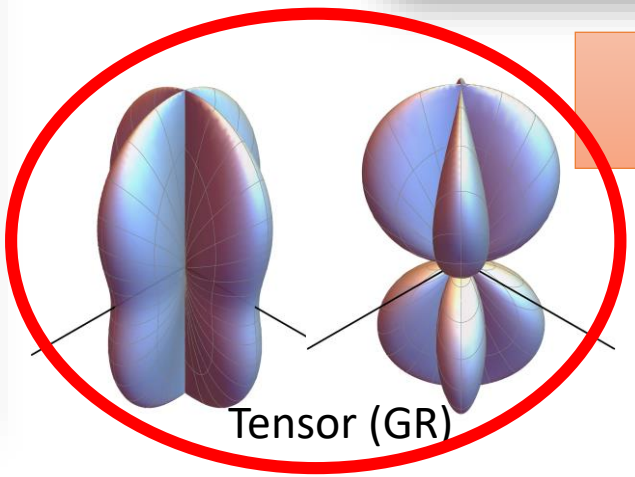


Abbott et al. PRL 119, 141101 (2017)

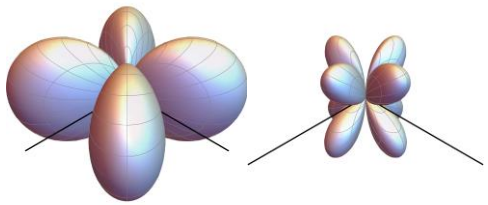


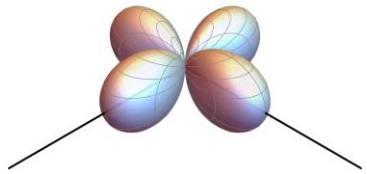


Strongly favored



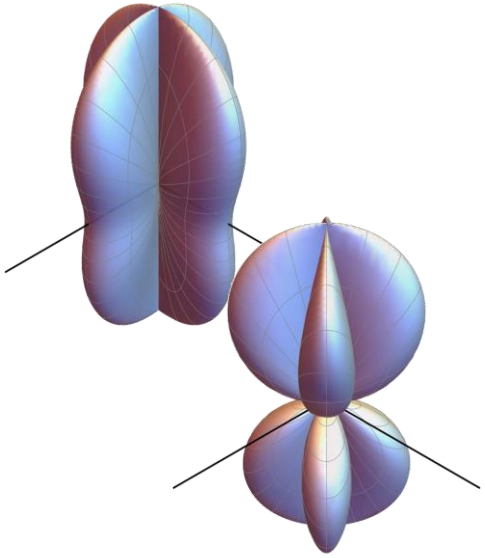
Detectors antenna patterns for GW polarizations

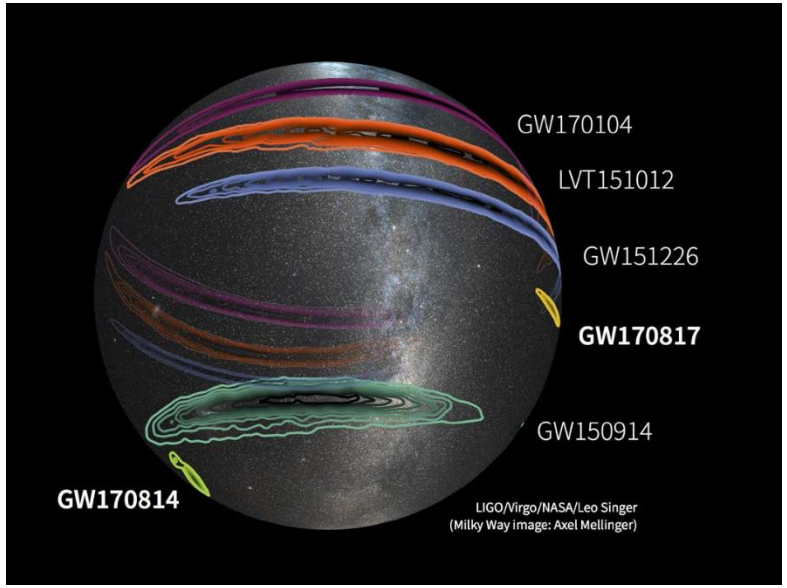


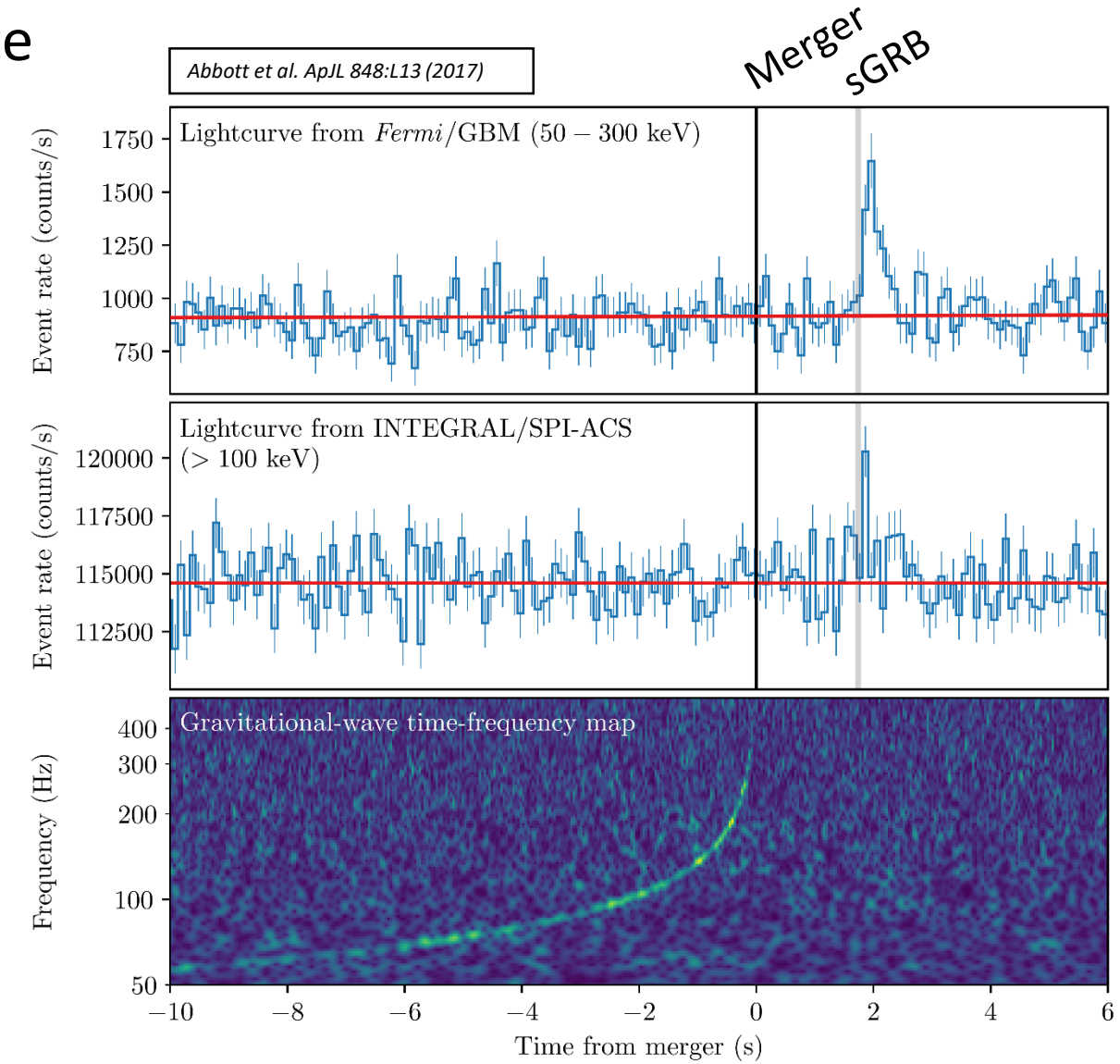


GW170817: the birth of multi-messenger astronomy

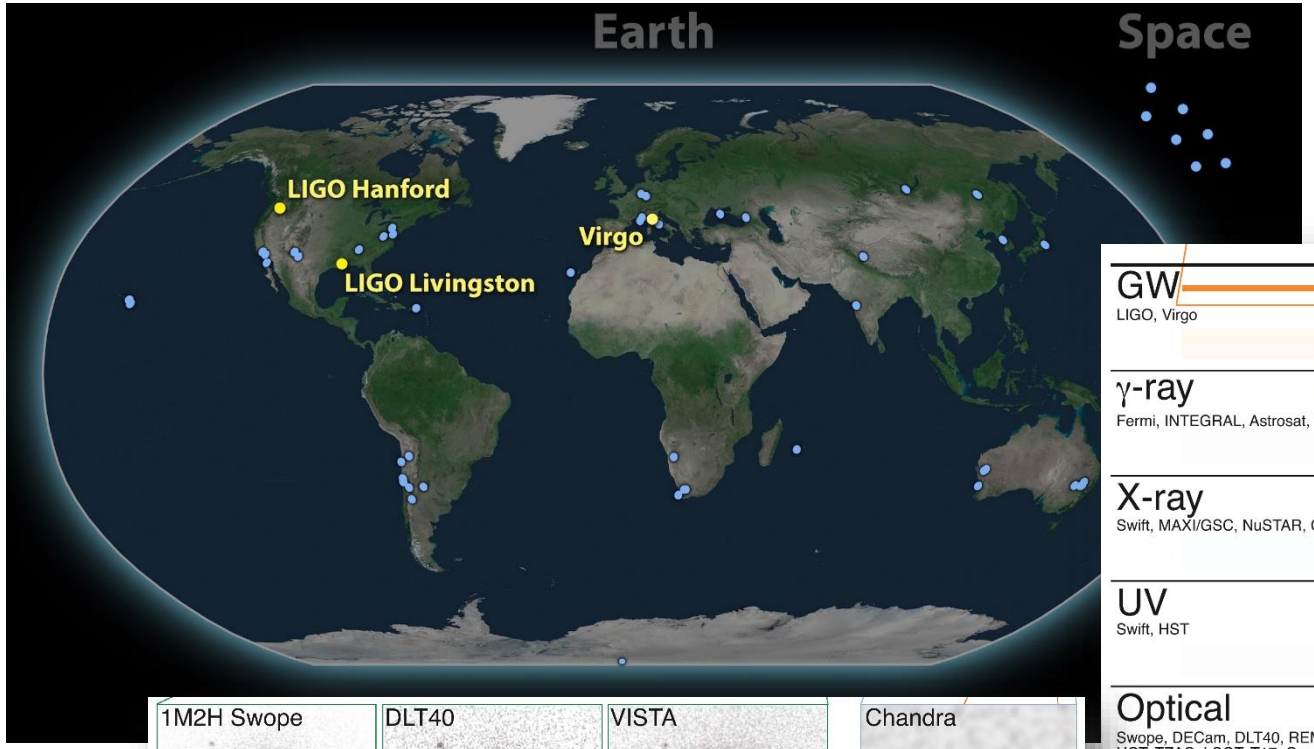
- Signal promptly recognized as BNS candidate
  - Long duration
  - High merger frequency
- Smoking gun: short gamma ray burst coincidence
- Virgo ***non-detection***!
  - Accurate localization by accounting for antenna pattern

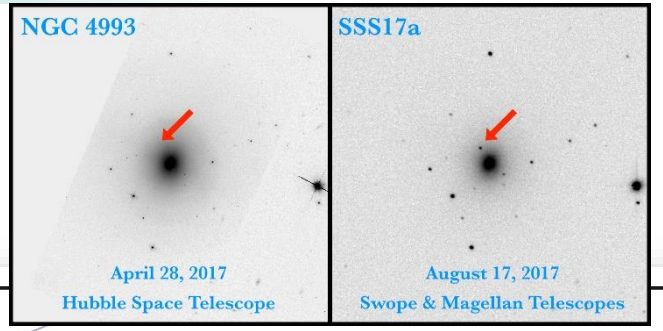


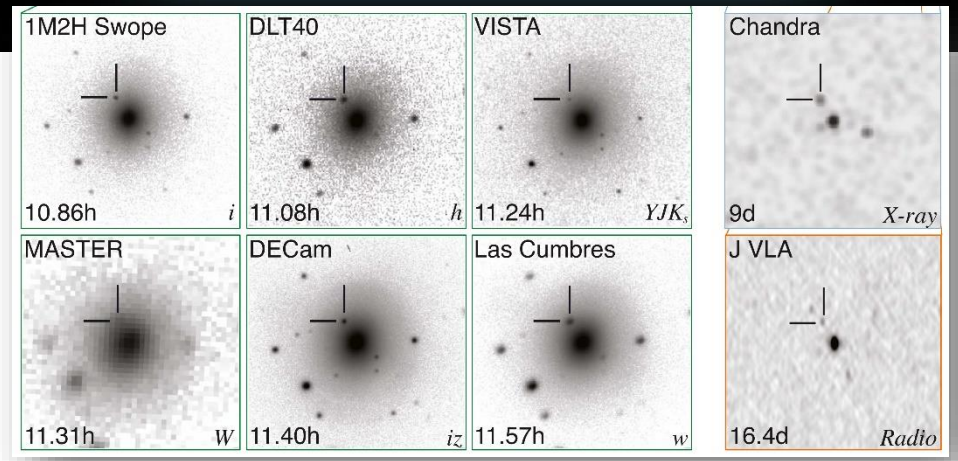


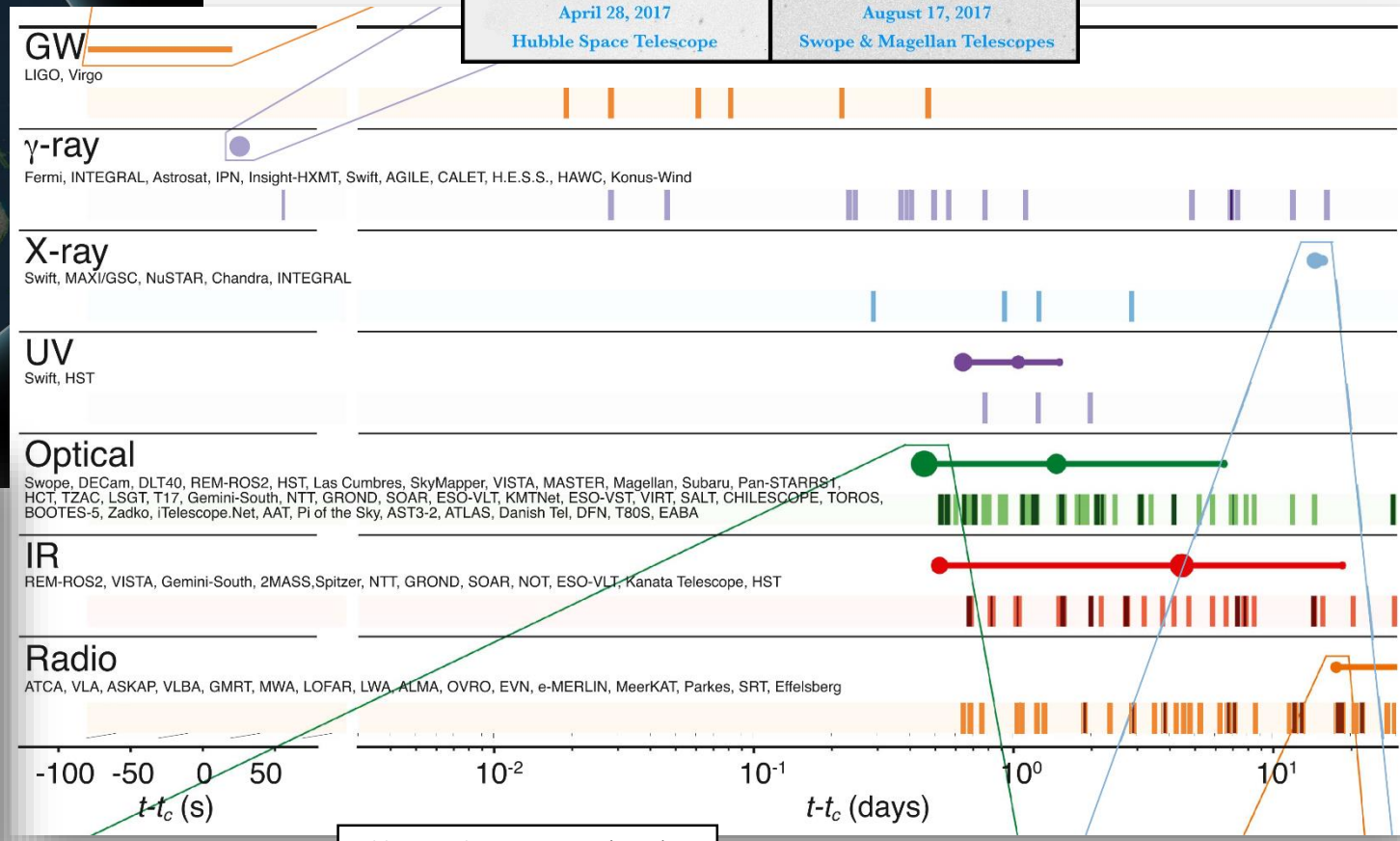


An unprecedented coordinated observational campaign





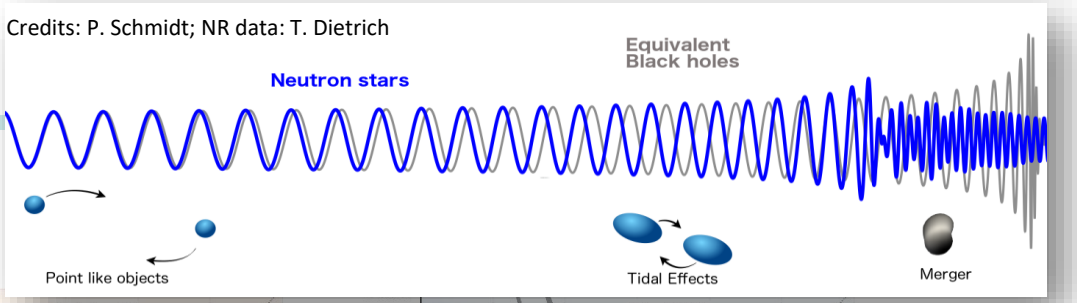


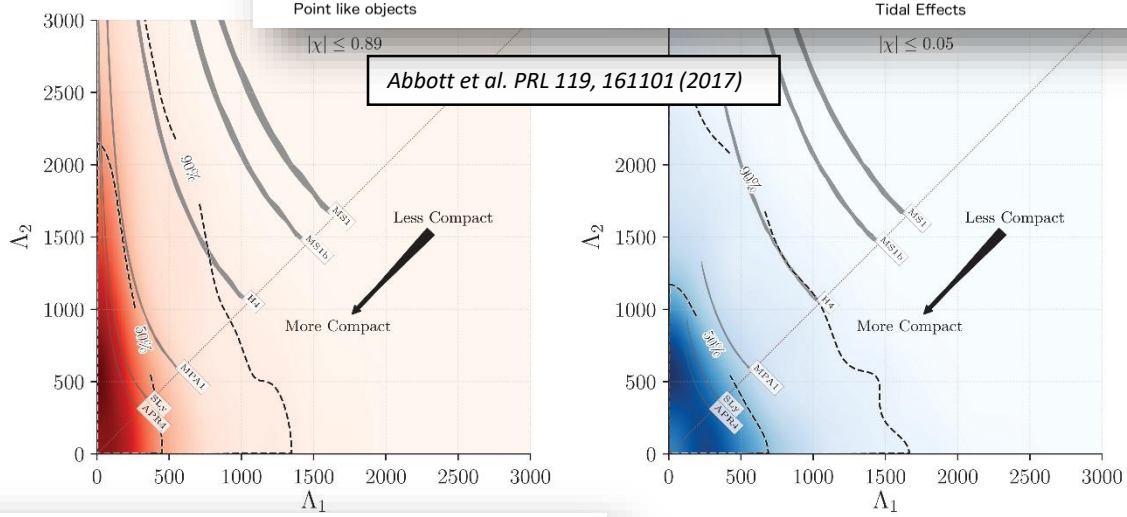


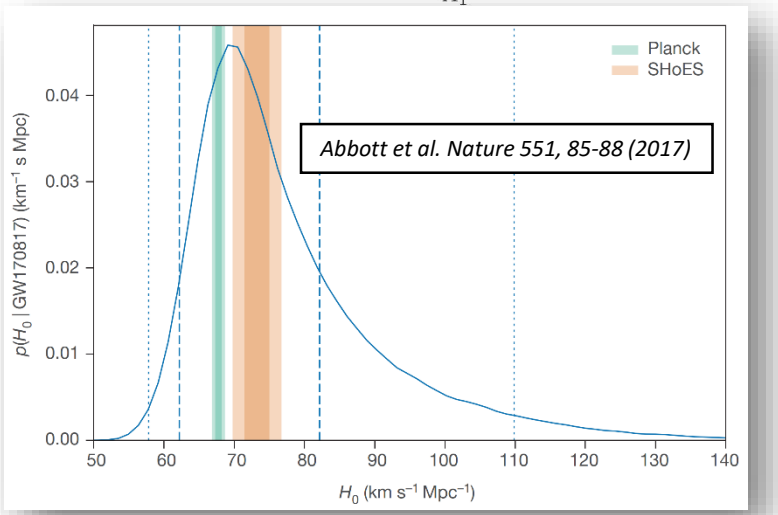
Abbott et al. ApJL 848:L12 (2017)

GW170817: scientific highlights

- Confiremed BNS mergers as sources of sGRB
  - Chace association probability $> 5.3\ \sigma$
- (weak) constraints on NS Equation of State
  - Less compact stars disfavored
- Independent measurement of the Hubble Constant
  - By comparison of GW distance with source redshift
- Measurement of the speed of GW (compared to EM)







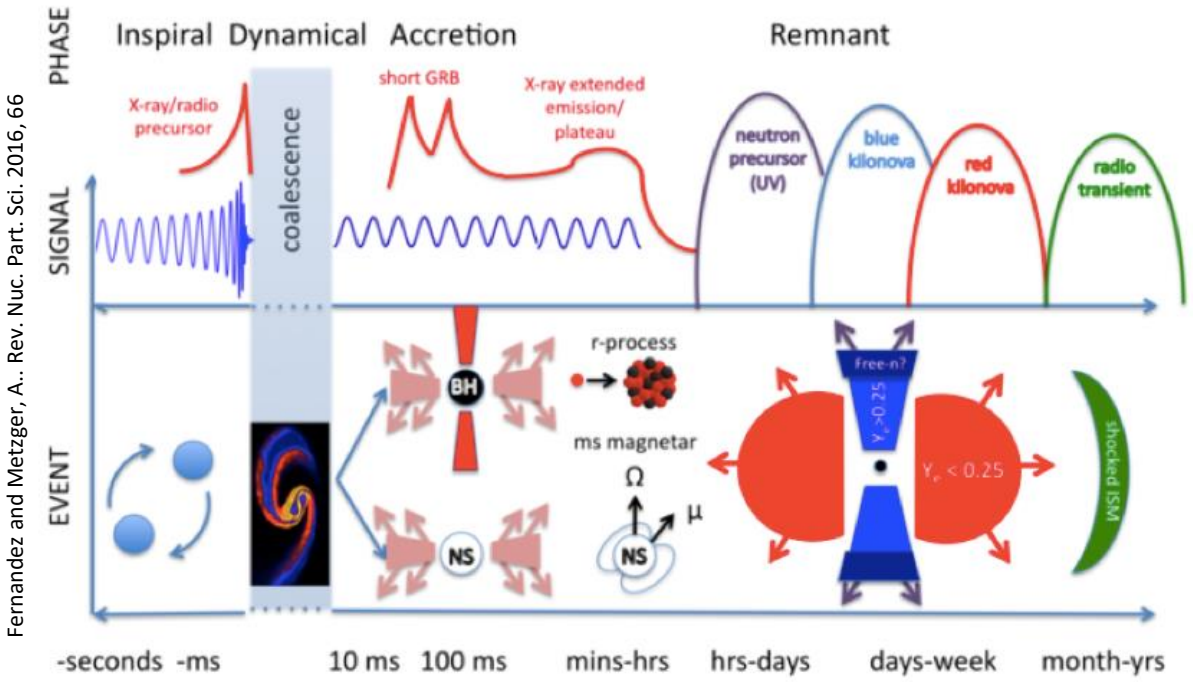
1.7 s delay after a journey of 1.3×10^8 years:

$$-3\ 10^{-15} \leq \frac{v_{GW} - v_{EM}}{v_{EM}} \leq +7\ 10^{-16}$$

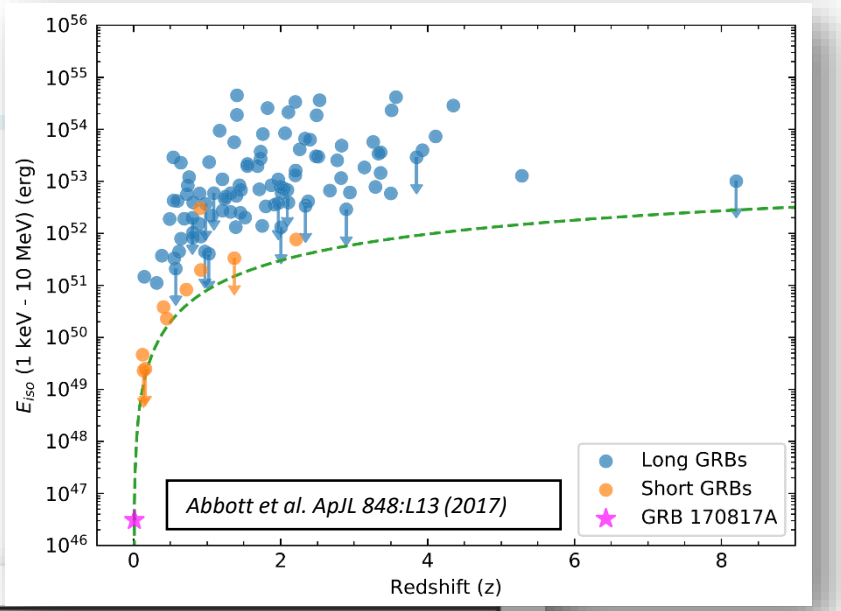
Rules out many alternative theories of gravity!

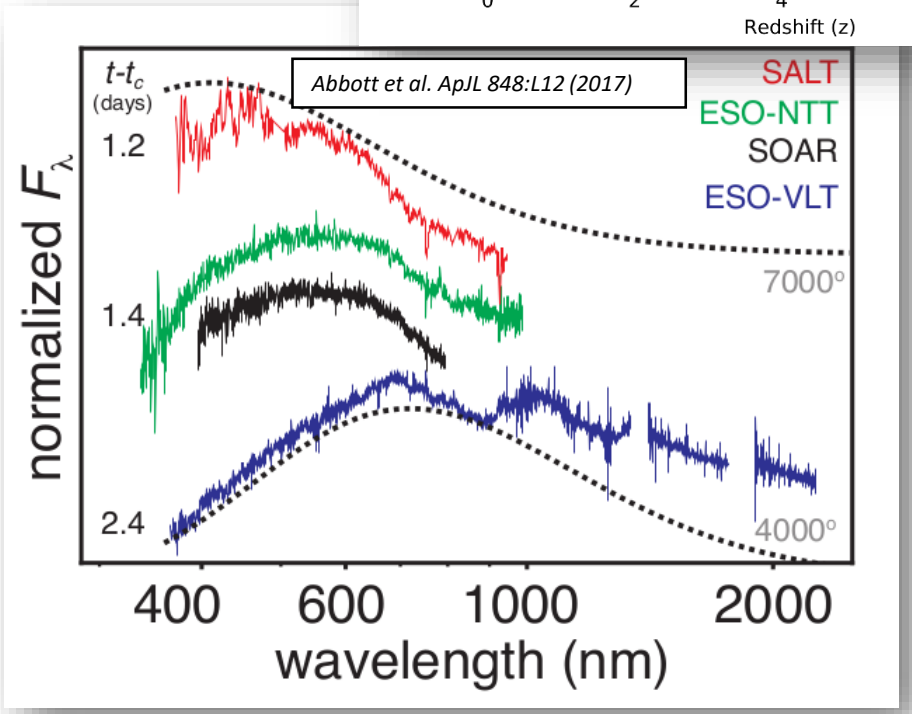
GW170817: kilonova emission

- Contribution of heavy elements observed in emission spectrum
  - Support hypothesis of formation by neutron capture (r-process)
- Evidence supports kilonova event
  - Atypical luminosity vs distance

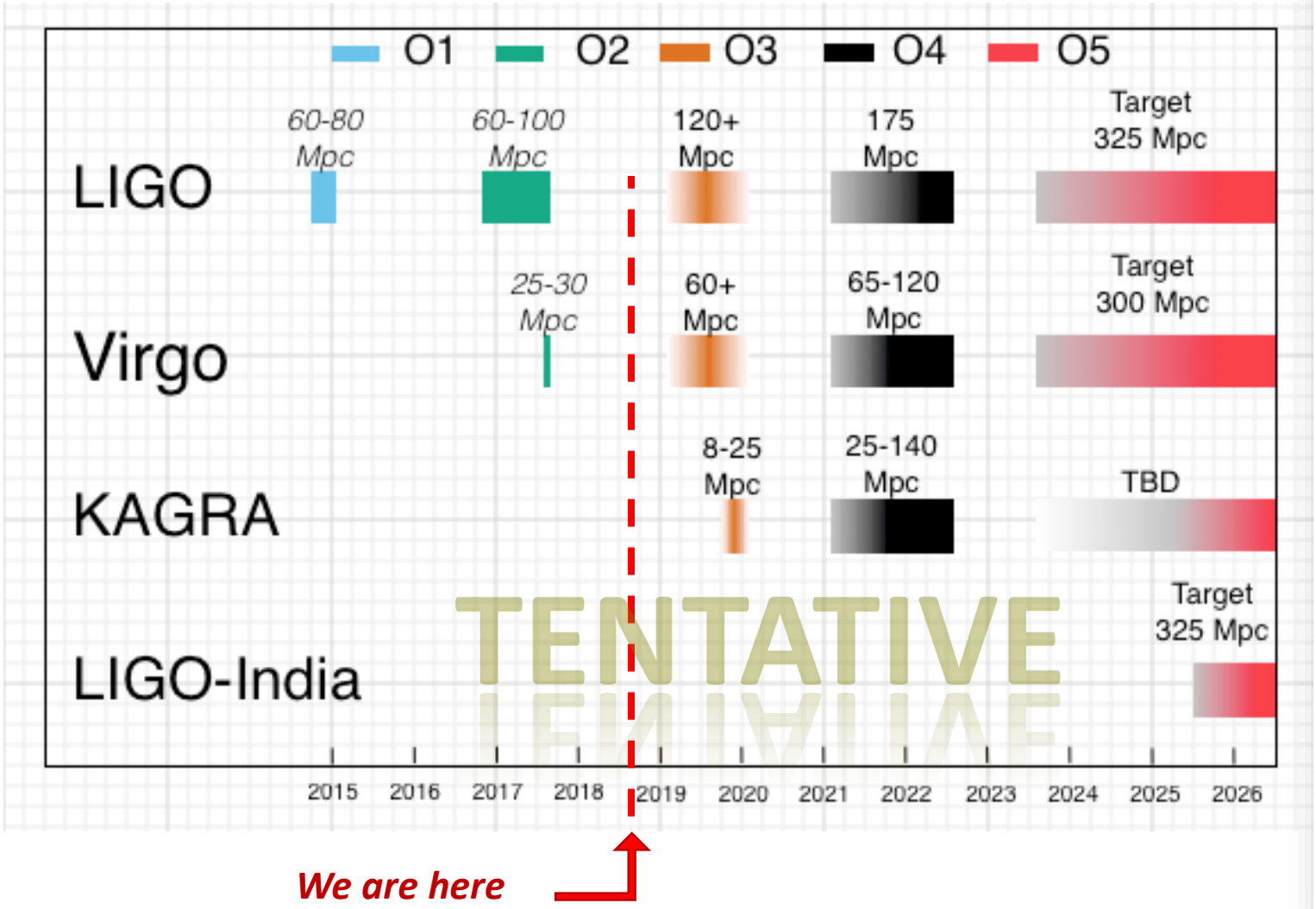


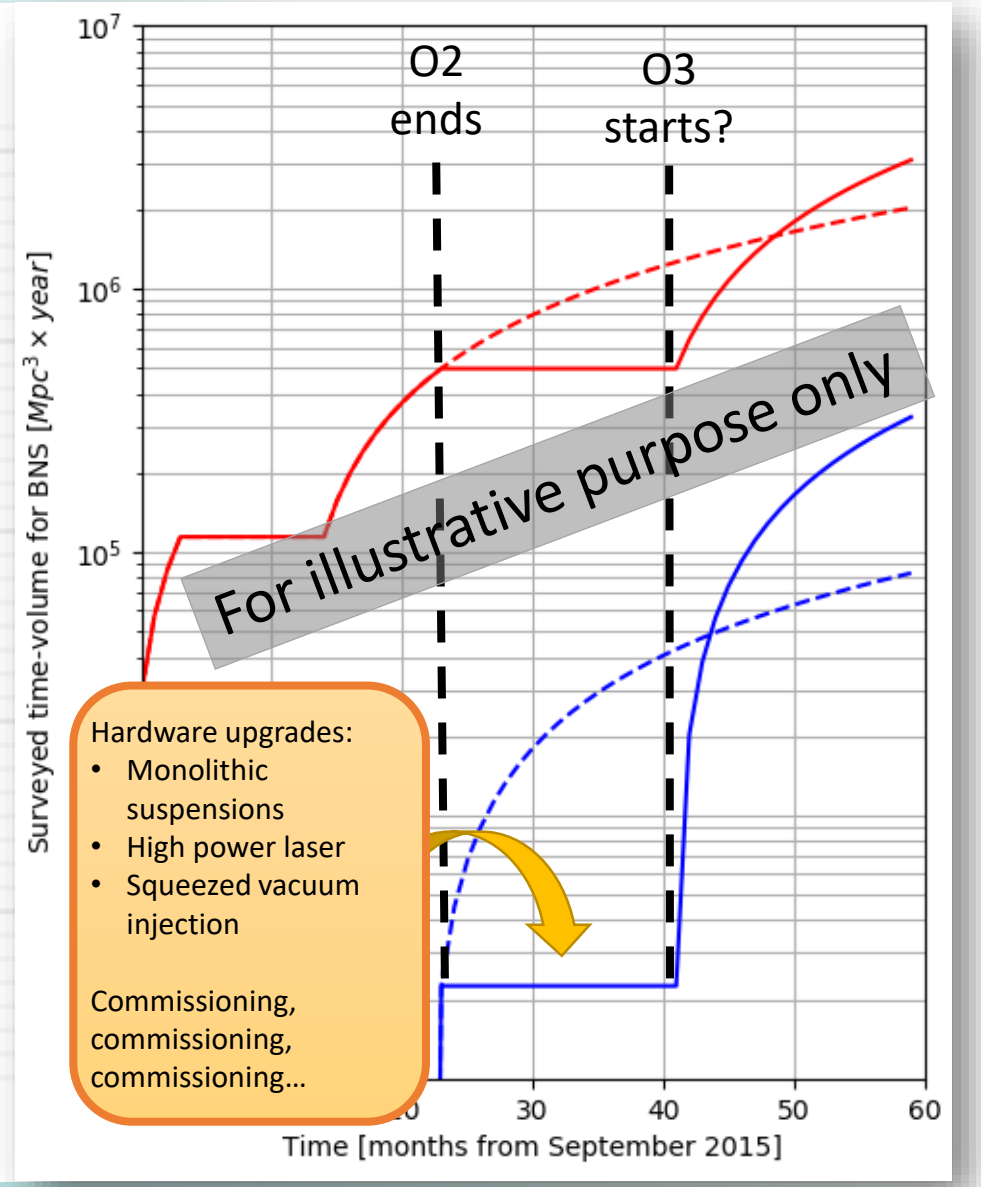
Fernandez and Metzger, A.. Rev. Nuc. Part. Sci. 2016, 66





To observe or to improve? This is the question…





Gravitational wave observatories are here to stay (and be useful)!

- We now have a proven network of gravitational wave ***observatories***
  - "Routine" detection demonstrated
  - A roadmap exist for a steady increase in sensitivity:
    - Detection rates to increase steadily and substantially run-by-run

- Virgo is an essential complement to the LIGO detectors
  - Improved parameter estimation
  - More precise sky localization -> **Multi-messenger astronomy**
  - More detectors will join in the future

- Extremely ***rich scientific output*** even with few GW detections
  - Consequences in fundamental physics, astrophysics, astronomy…

Thanks for listening… to the tune of gravitational waves!