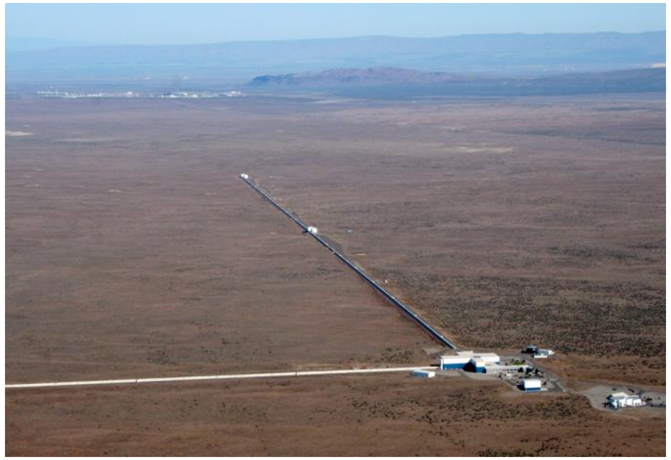
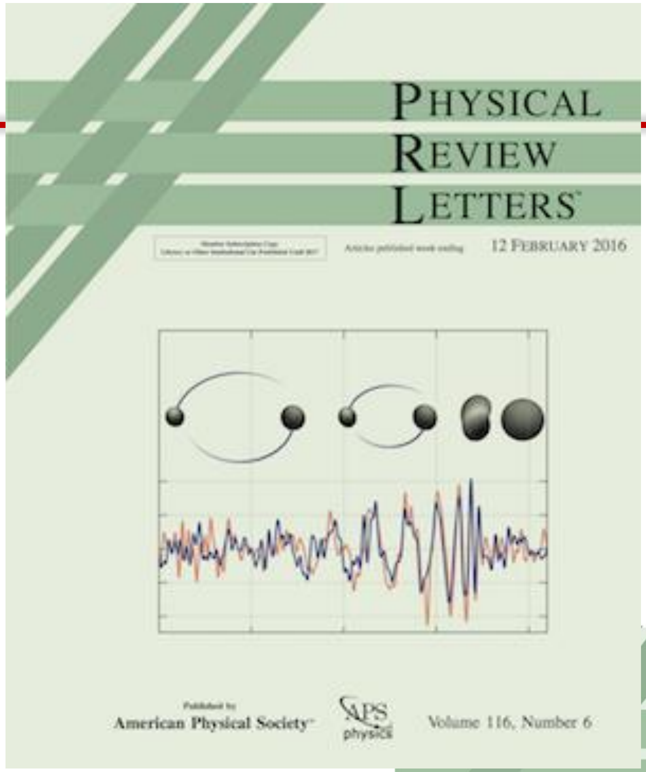
Gravitational Wave Transients from Compact Binary Coalescences

Giovanni Andrea Prodi
Università di Trento e INFN,
Virgo Collaboration,
on behalf of LSC and Virgo



- **LIGO-Virgo Detectors**

- **Black Hole coalescences and related discoveries** limited to astrophysical properties and tests of General Relativity



LIGO-Virgo data release to public
losc.ligo.org

why chasing Gravitational Waves ?

- **Fundamental Physics:**
  - **Gravity and Space-Time**
    - ✓ strong Field Gravity & relativistic motion
    - ✓ Black Hole properties and Event Horizon
    - ...
  - **Equation of State of matter beyond nuclear density**
    - Neutron Star Physics
    - ...

?

General Relativity
vs
Quantum Mechanics

vacuum field

no hair theorem
for Black Holes

Hubble flow

- **Cosmology**
  - **Dark Energy and accelerated expansion**
  - **Dark Matter**
  - **...**

quark/hyperon/neutron star

- **Astrophysics**
  - **Compact Objects and stellar evolution**
  - **Nucleosynthesis of elements**
  - **Gamma Ray Bursts**
  - **...**

evolution of stars and
structures

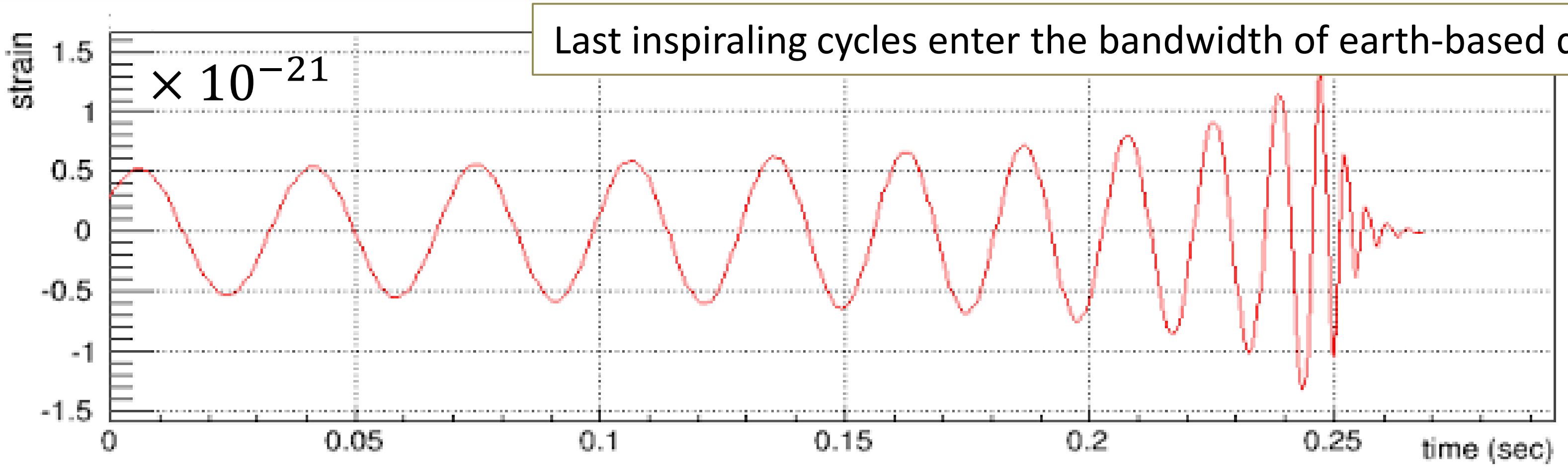
Formation of super massive
Black Holes

GWs from compact binary coalescences

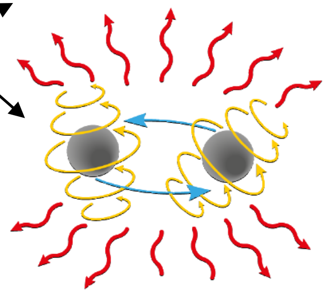
- The most efficient emitters among expected GW sources
  - Up to ~ **10%** total mass converted in gravitational radiation

h

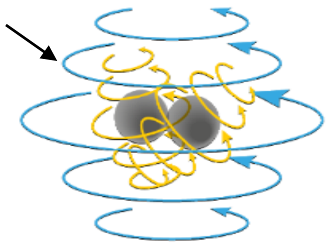
at least 15 parameters in the waveform model (BBH circular orbit)



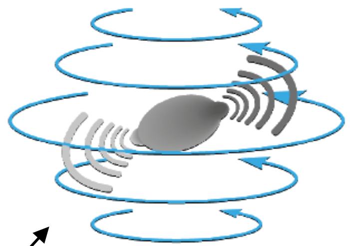
INSPIRAL
GW emission described by quadrupole formula. Analytical solution available



MERGER
Only numerical solution available



RINGDOWN
Perturbative and numerical solutions

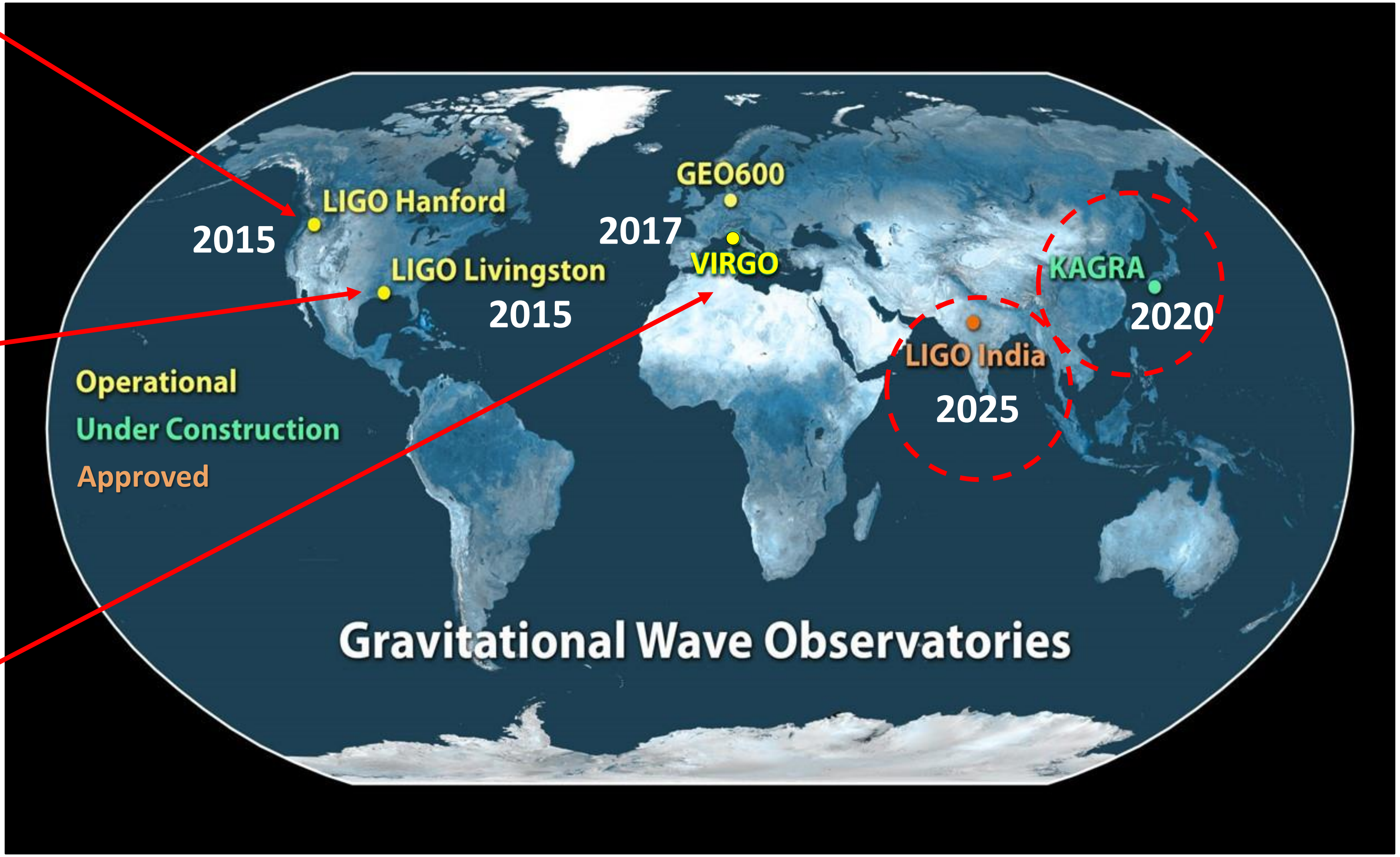


GW can be used as a standard candle.

Chirp Mass $(m_1\, m_2)^{3/5}\, (m_1 + m_2)^{-1/5}$

General Relativity in strong field
highly non-linear regime
NS would bring more physics (Equation of State, ...)

The Network of Gravitational Wave Detectors



Increase detection confidence

Better source localization

Enhance sky coverage

Reduce downtime

More reliable source parameter estimation

Directional Sensitivity of Detectors

Each interferometer senses only one of the two GW polarizations:

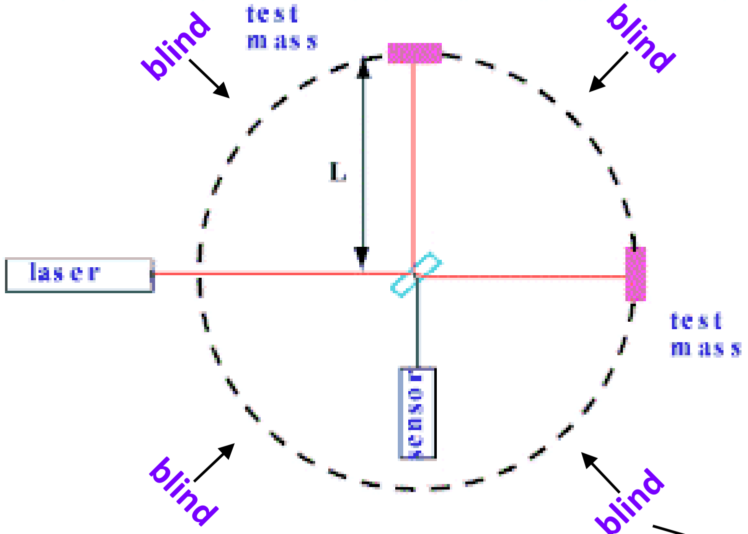
- measures the linear combination

$$h_{det} = F_+ h_+ + F_\times h_\times$$

$$F_{+,\times}(\text{sky direction})$$

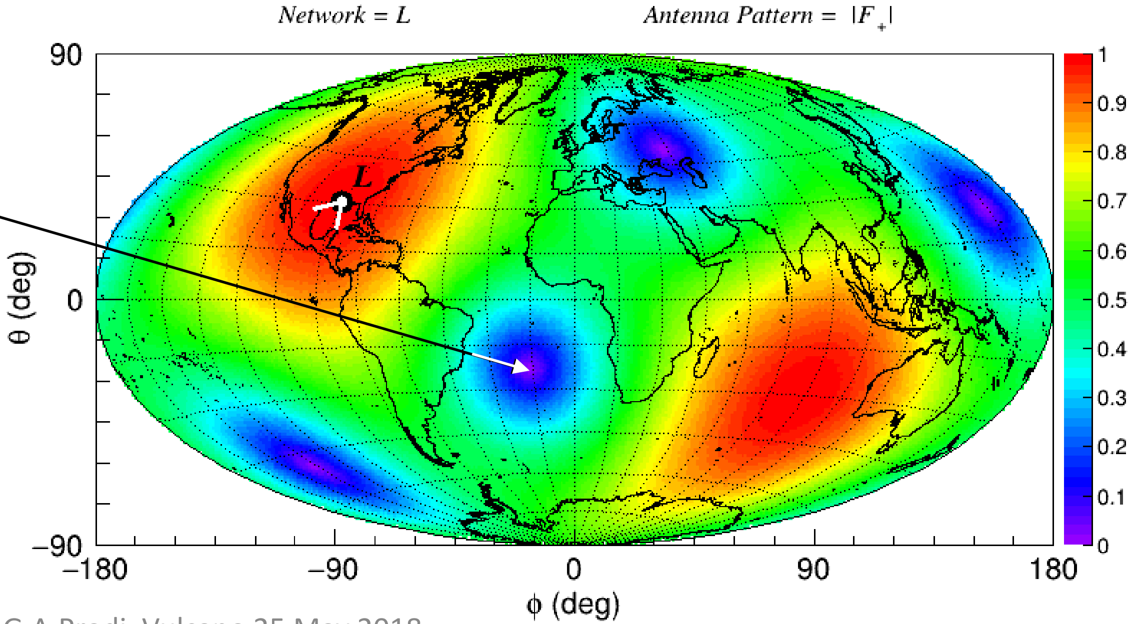
antenna patterns for + and x

- misses the orthogonal combination



Broad directional sensitivity:

LIGO Livingston



The LIGO network of two detectors

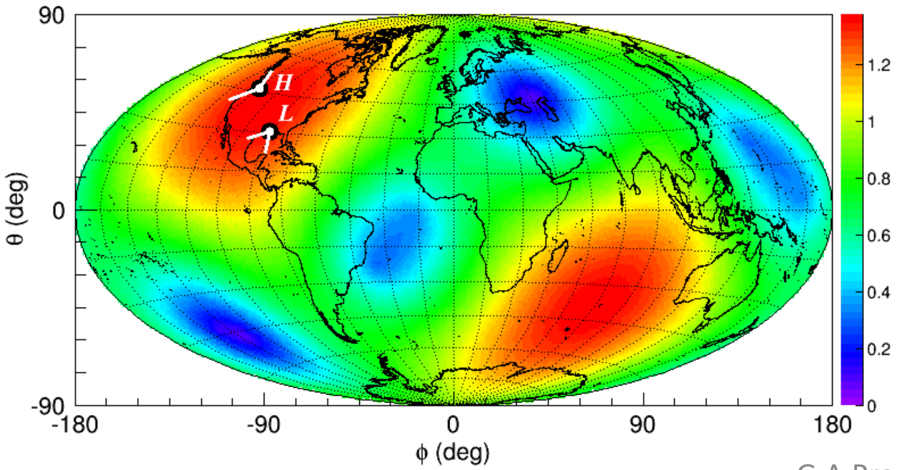
- **Detection confidence: discriminate GW candidates from noise fluctuations**
  - ✓ **At least two detectors in coincidence observation are required**
    unless for searches of persistent and well parametrized signals, e.g. periodic GWs
  - ✓ multimessenger searches with other detectors can help

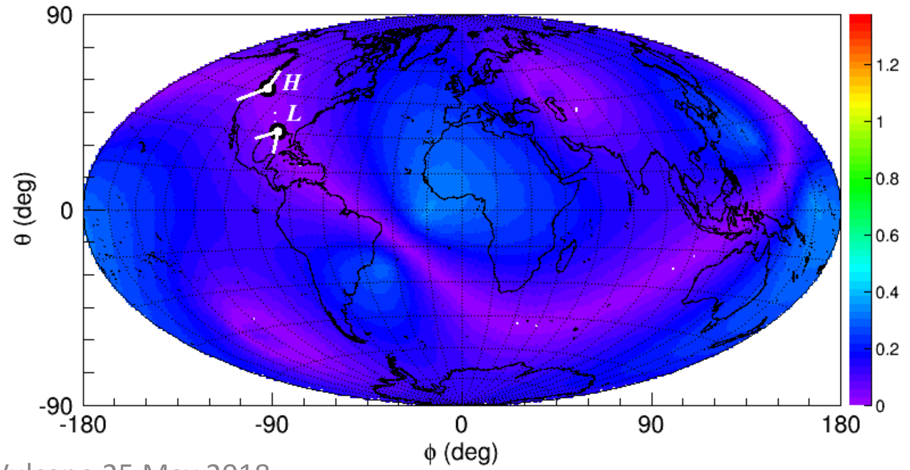
LIGOs arms are almost aligned

- **Sky coverage of LIGOs is very similar to that of a single detector**

  $\Rightarrow$ **almost blind to one GW polarization per each direction:**

$|\vec{F}_{+}|$ LIGO Hanford + LIGO Livingston $|\vec{F}_{\times}|$





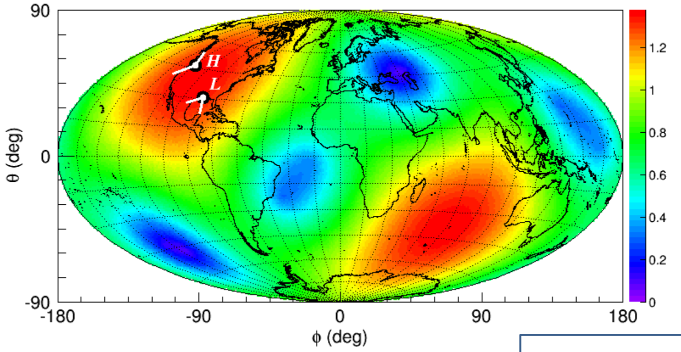
Benefits of adding Virgo detector

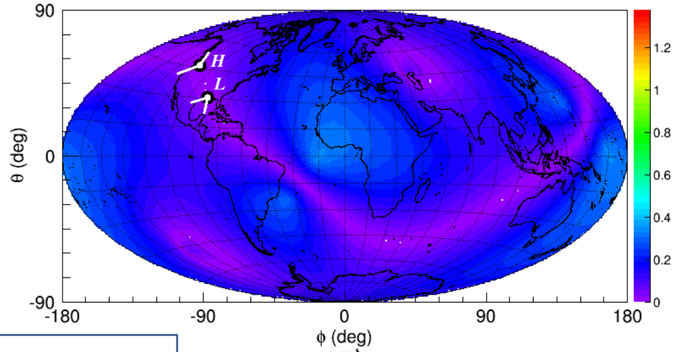
- **Detection confidence**: lower background and higher Signal-to-Noise Ratio
- Increased **time coverage of the survey** by detector pairs
- **coverage of sky and both GW polarizations**: better waveform reconstruction

$|\vec{F}_{+}|$

LIGO H1 + LIGO L1

$|\vec{F}_{\times}|$

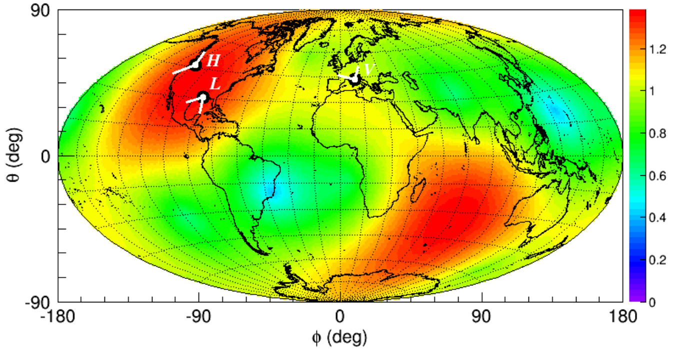




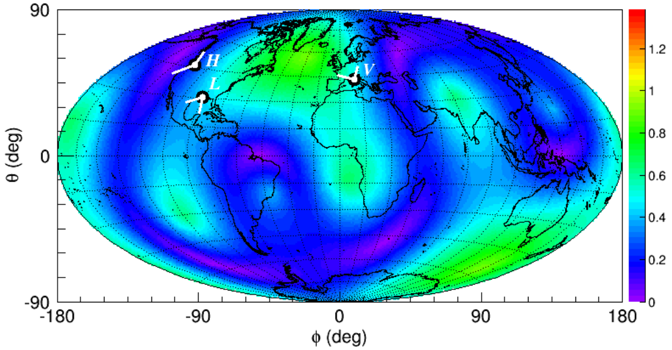
LIGO H1 + LIGO L1 **+ Virgo**

$|\vec{F}_{+}|$

$|\vec{F}_{\times}|$



assuming same spectral sensitivity



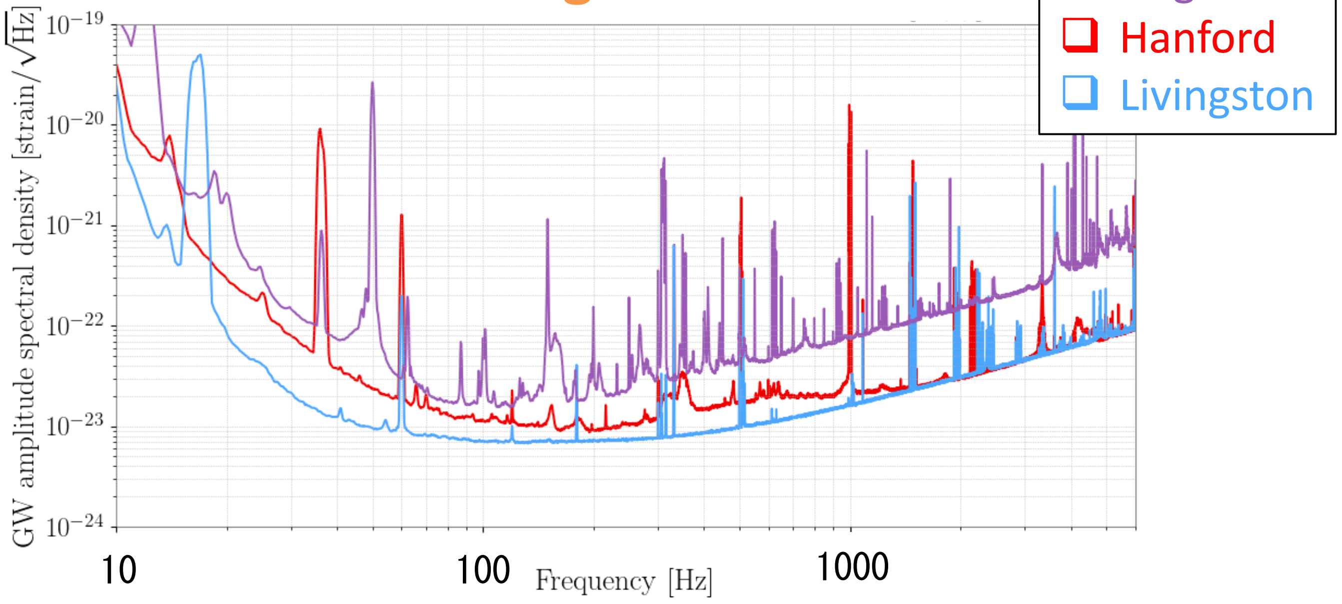
Recap of recent observational campaigns

- O1 $\sim 49\ days$ of coincident **LIGO** data
- O2 $\sim 120\ days$ of coincident **LIGO** data
  $\sim 16\ days$ of coincidence with Virgo data
  10 GW alerts for EM follow-up

Averaged distances to which Binary Neutron Star could be detected

VIRGO : 26 Mpc
HANFORD : 55 Mpc
LIVINGSTON : 100 Mpc

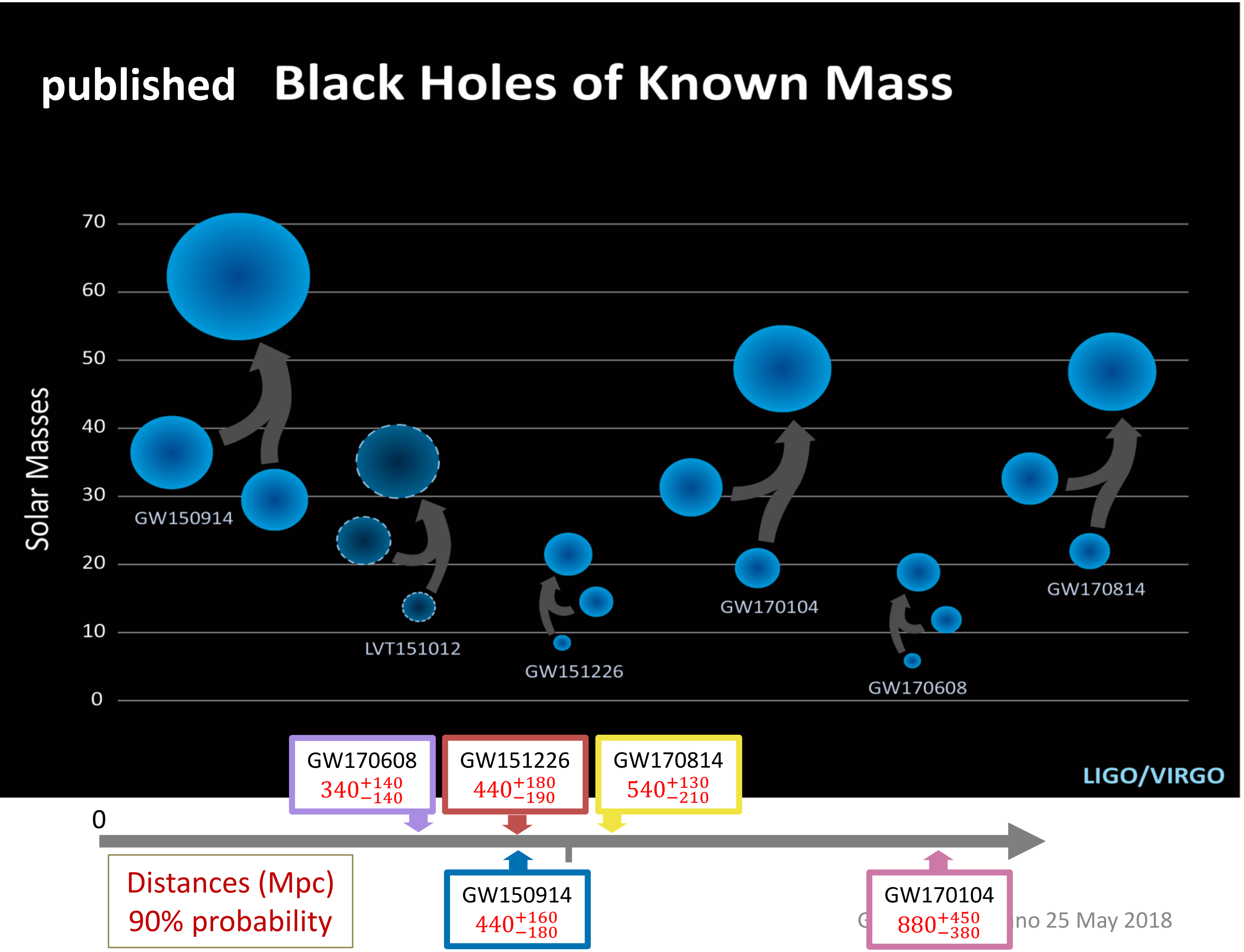
LIGO – Virgo Sensitivities



❑ observations 2015-17 vs 2010:
averaged observable volume of Universe : **~100x** gain for **BBH** like GW150914
~30x gain for **BNS** coalescence events

LIGO-Virgo Black Holes

Data Release: losc.ligo.org

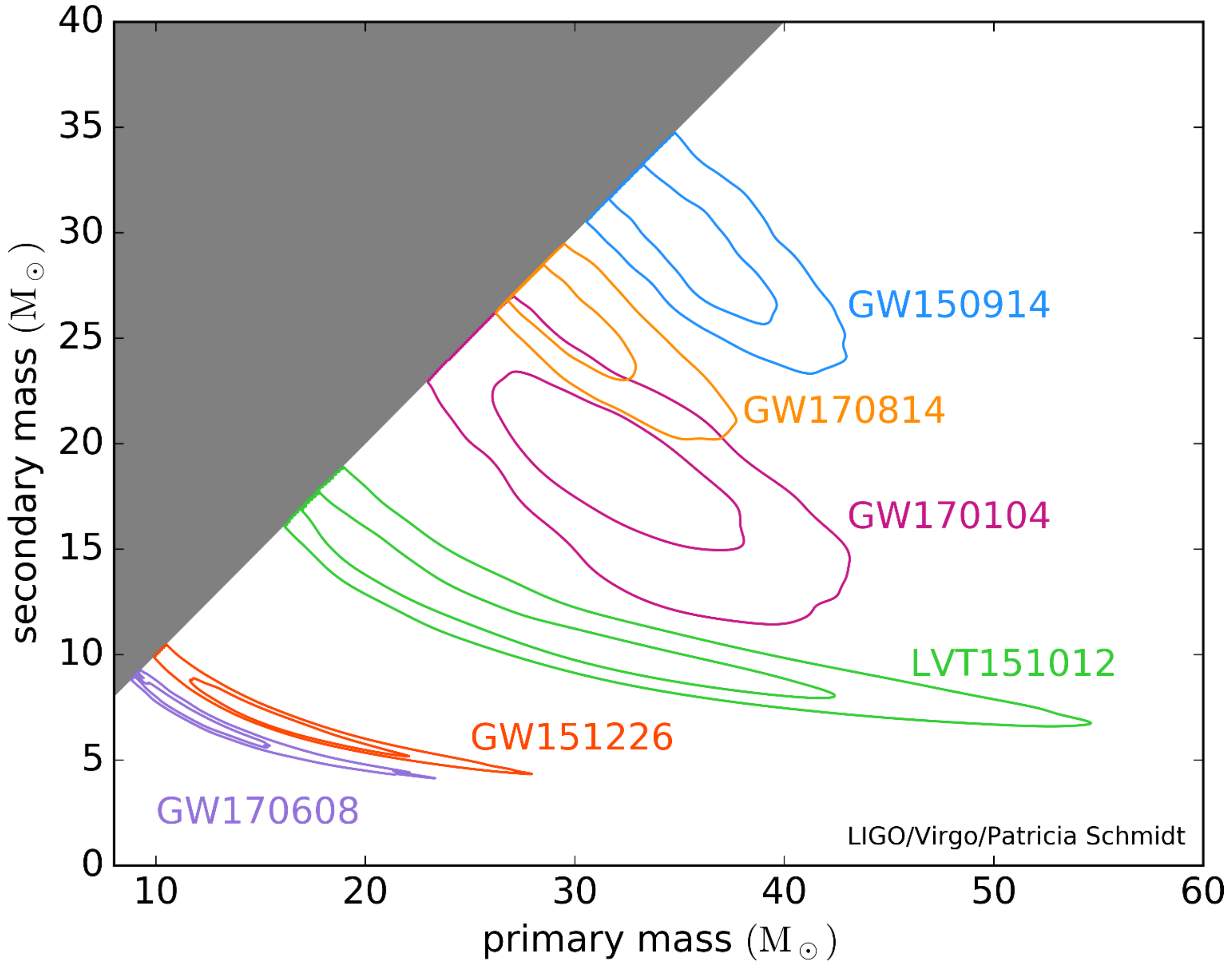


unexpected population of Binary Black Holes:

- higher mass
  x-ray binary BHs are lighter
- merger rate compatible with highest expectations
  12-213 Gpc^{-3} yr^{-1}
- testbed for checking General Relativity
- no related electromagnetic emission found

LIGO-Virgo Black Holes

Data Release: losc.ligo.org



unexpected population of Binary Black Holes:

- higher mass

  x-ray binary BHs are lighter
- merger rate compatible with highest expectations

  12-213 Gpc^{-3} yr^{-1}
- testbed for checking General Relativity
- no related electromagnetic emission found

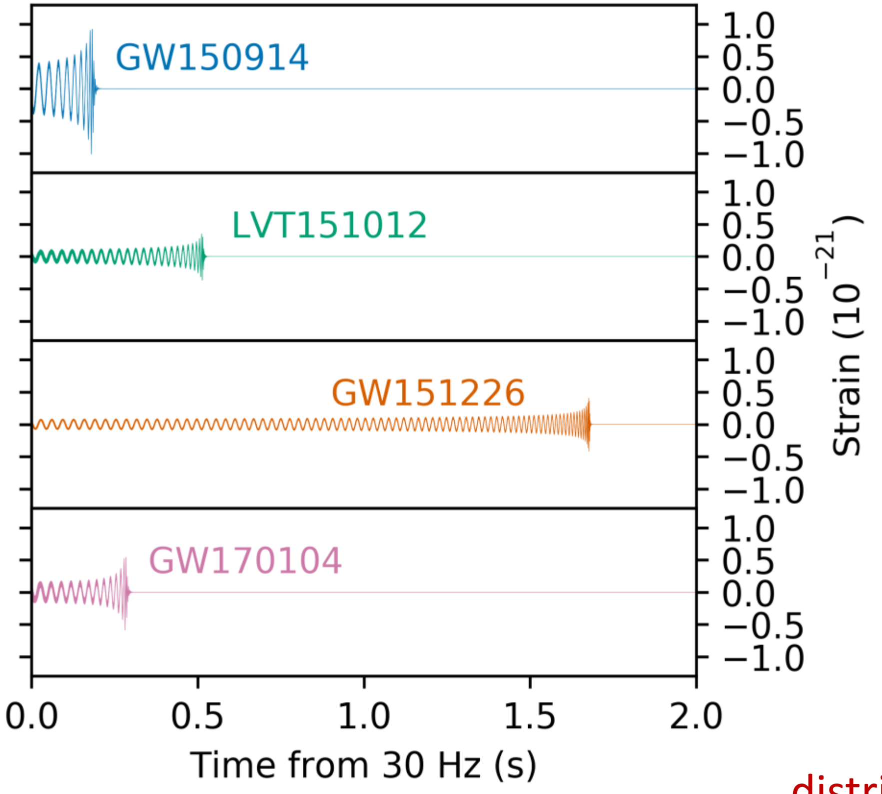
PRL 118, 221101 (2017)

GW170104 and previous

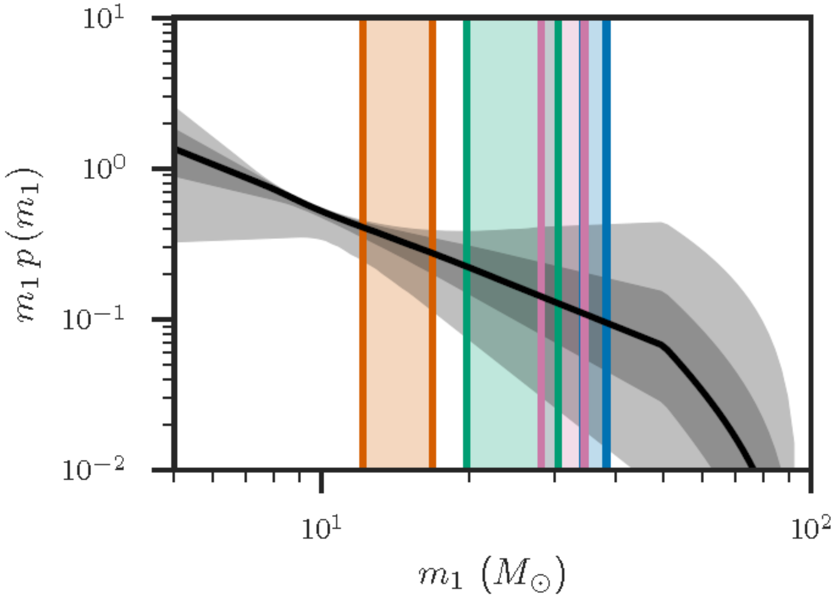
Data Release:
https://losc.ligo.org/events/GW170104/

➢ Selected BH Binary Properties:

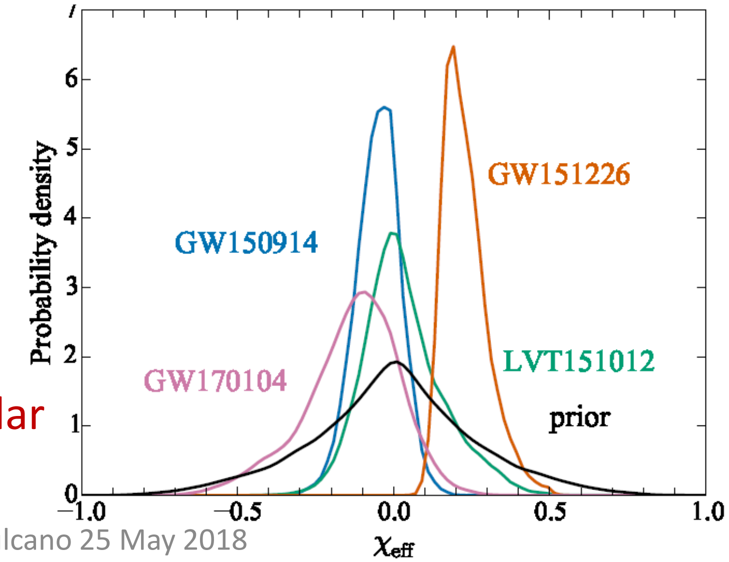
matching templates comparison:



distribution of primary BH component mass



distribution of effective BH spin along orbital angular momentum



GW170608
Astrophys. J. Lett. 851, L35 (2017)
very similar to GW151226

BBH Formation Models

dynamical interaction

isolated binary evolution

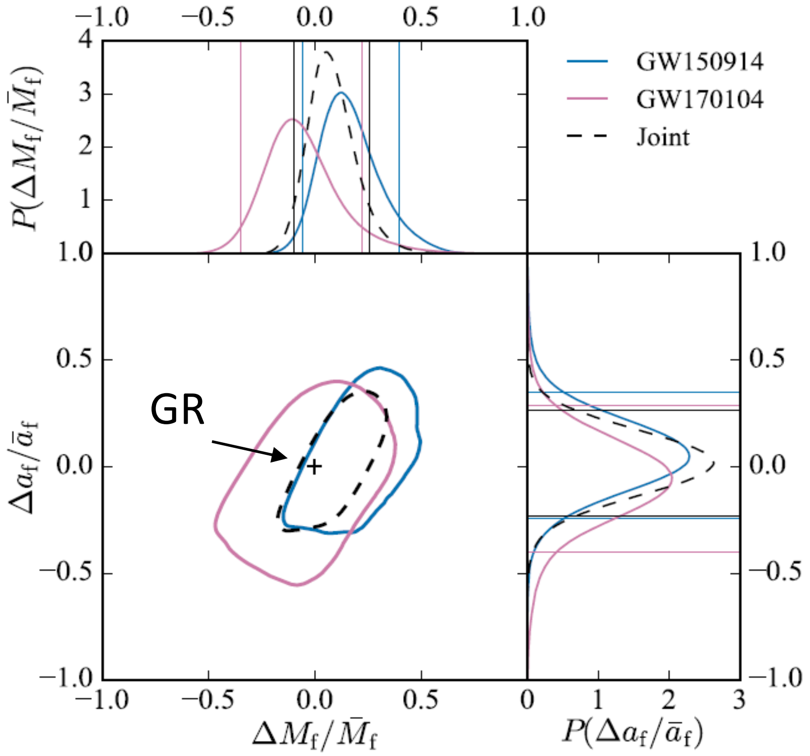
… ? primordial

PRL 118, 221101 (2017)

GW170104 and previous detections

➢ **selected tests of consistency with General Relativity:**

self-consistency test on reconstructed remnant mass and spin as inferred from different parts of the signal (inspiral and merger-ringdown phases)



upper bound on graviton mass

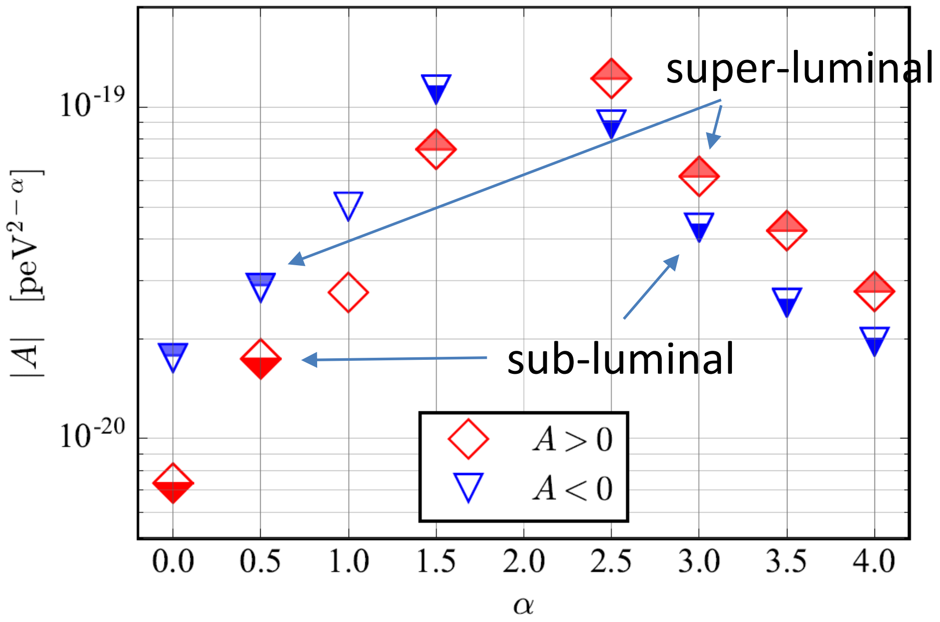
$$m_g \leq 7.7\ 10^{-23} eV \quad , 90\%$$

testing the dispersion relation

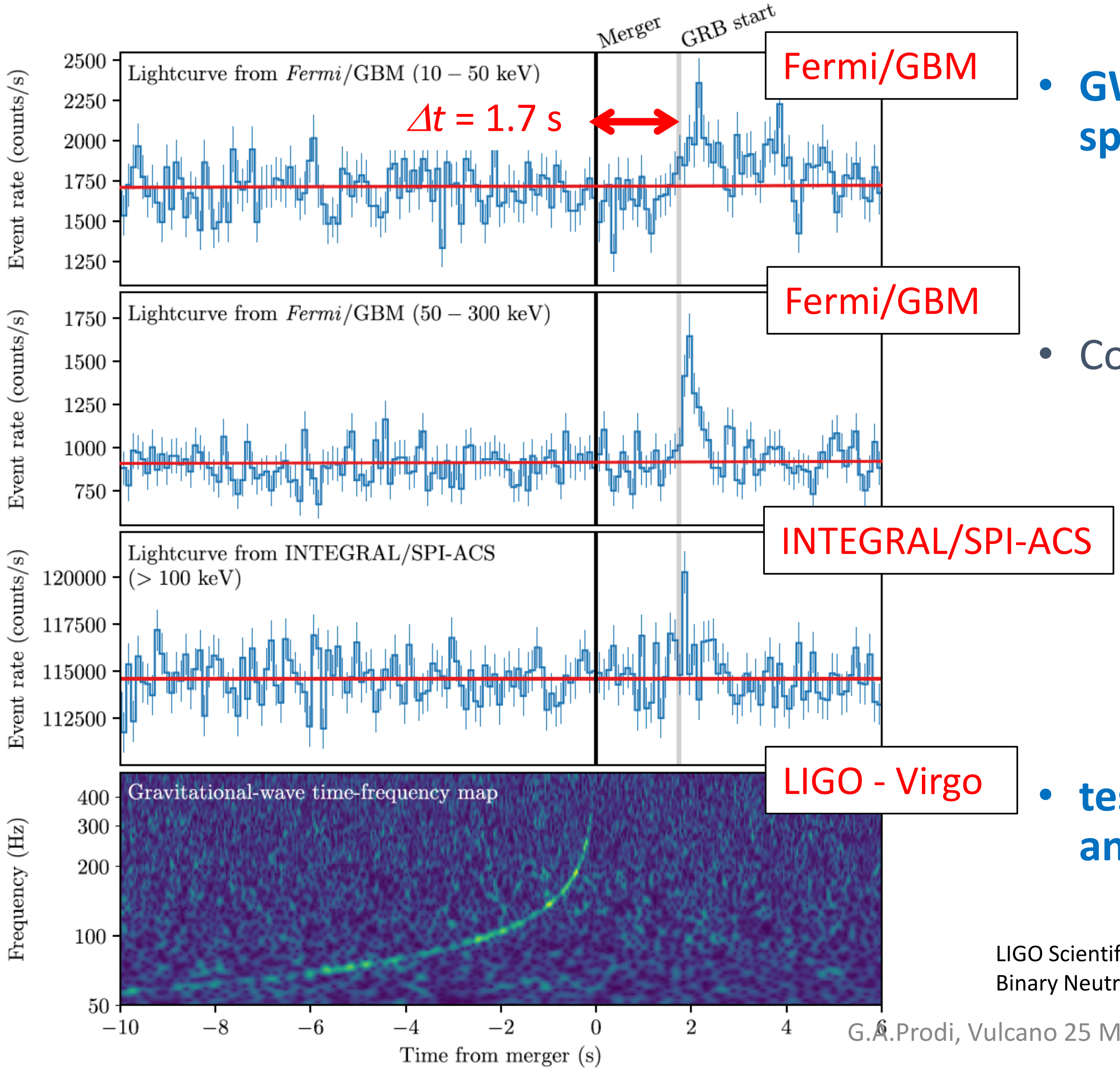
$$E^2 = p^2c^2 + Ap^\alpha c^\alpha \quad with\ \alpha \geq 0$$

GR A=0, massive graviton (α=0 , A>0), …

first local Lorentz invariance test in the Gravitational Sector



Association of GW170817 and GRB170817A & Fundamental Physics



- **GW170817 provides a stringent test of the speed of gravitational waves**

$$\frac{v_{GW} - c}{c} \approx \frac{c\Delta t}{D}$$

- Conservative assumptions
  - t_{GW} - t_{EM} at emission in [-10, 0] sec
  - $D \approx$ 26 Mpc
    - Conservative limit – use 90% confidence level lower limit on GW source from parameter estimation

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

- ***testing violations of local Lorentz Invariance and Equivalence Principle***

LIGO Scientific Collaboration and Virgo Collaboration, Gravitational Waves and Gamma-Rays from a Binary Neutron Star Merger: GW170817 and GRB 170817A" Astrophys. J. Lett., 848:L13, (2017)

GW170104 and previous detections

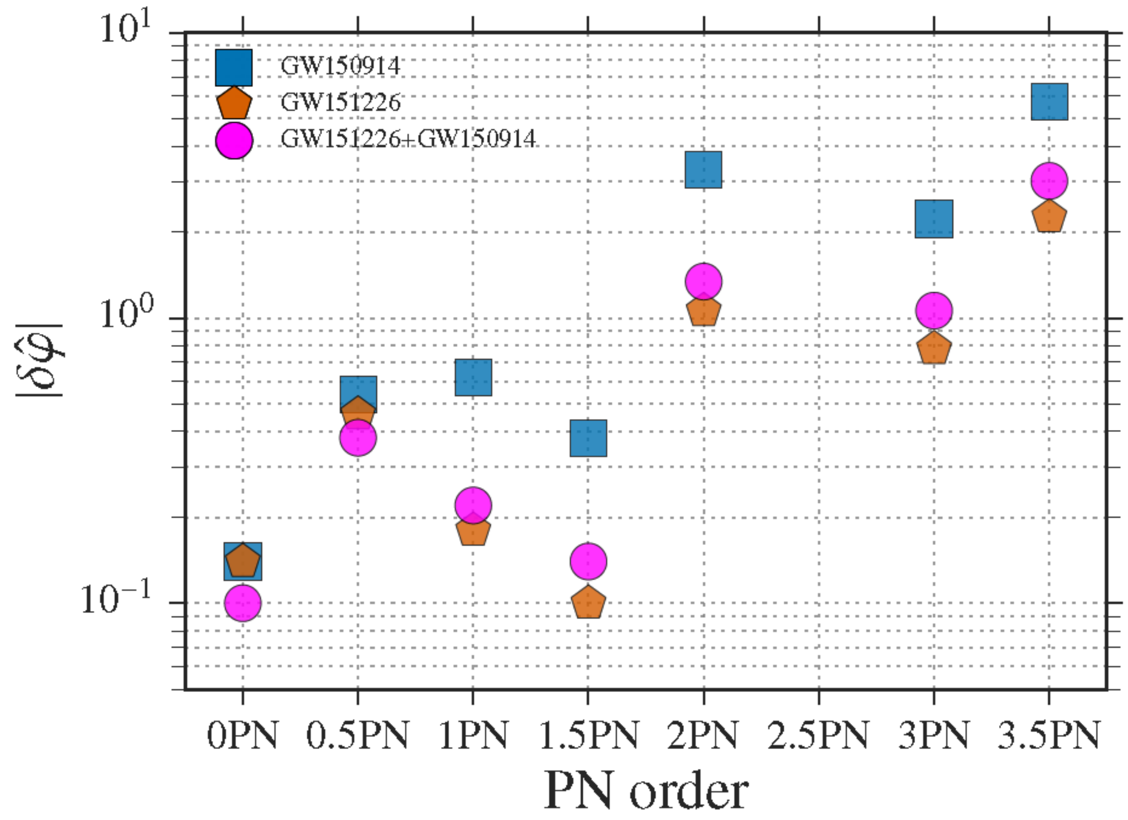
First test of GR in strong field and highly relativistic speed
by checking the phase evolution of the inspiral

90% upper limits on $|\delta\varphi|$

$\delta\varphi$ describes possible deviations from GR prediction per each Post Newtonian order to the quadrupolar emission formula (considering one PN at a time)

New upper limits have been set for each PN order up to 3.5 except for 2.5 PN, unmeasurable with inspiral signal (degenerate with reference phase evolution)

limits from 10 years of double pulsar J0737-3039 are better only for the quadrupolar order 0PN

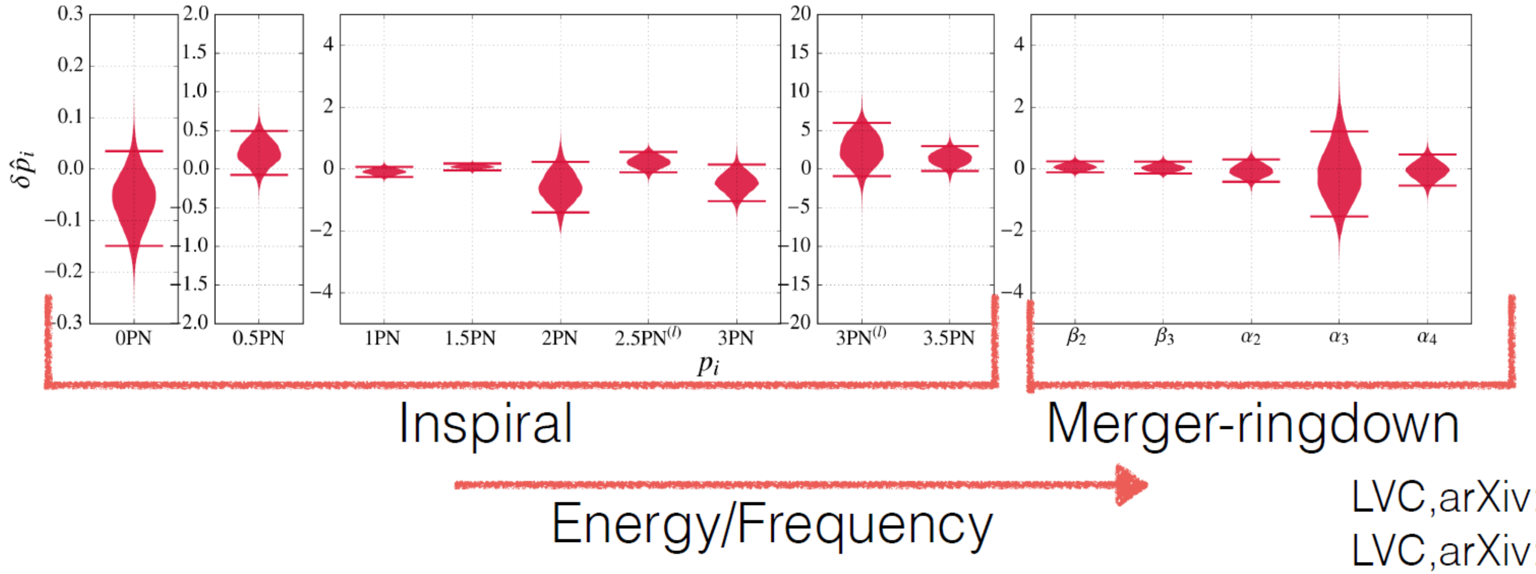


GW170104 and previous detections

First test of GR in strong field and highly relativistic speed
by checking the **phase evolution of the entire BBH coalescences**
posteriors on $\delta\varphi$

waveform regime	parameter	f–dependence	
early-inspiral regime	$\delta\hat{\varphi}_0$	$f^{-5/3}$	post-Newtonian
	$\delta\hat{\varphi}_1$	$f^{-4/3}$	
	$\delta\hat{\varphi}_2$	f^{-1}	
	$\delta\hat{\varphi}_3$	$f^{-2/3}$	
	$\delta\hat{\varphi}_4$	$f^{-1/3}$	
	$\delta\hat{\varphi}_{5l}$	$\log(f)$	
	$\delta\hat{\varphi}_6$	$f^{1/3}$	
	$\delta\hat{\varphi}_{6l}$	$f^{1/3}\log(f)$	
	$\delta\hat{\varphi}_7$	$f^{2/3}$	
intermediate regime	$\delta\hat{\beta}_2$	$\log f$	effective
	$\delta\hat{\beta}_3$	f^{-3}	
merger–ringdown regime	$\delta\hat{\alpha}_2$	f^{-1}	
	$\delta\hat{\alpha}_3$	$f^{3/4}$	
	$\delta\hat{\alpha}_4$	$\tan^{-1}(af+b)$	

LVC, arXiv:1602.03841

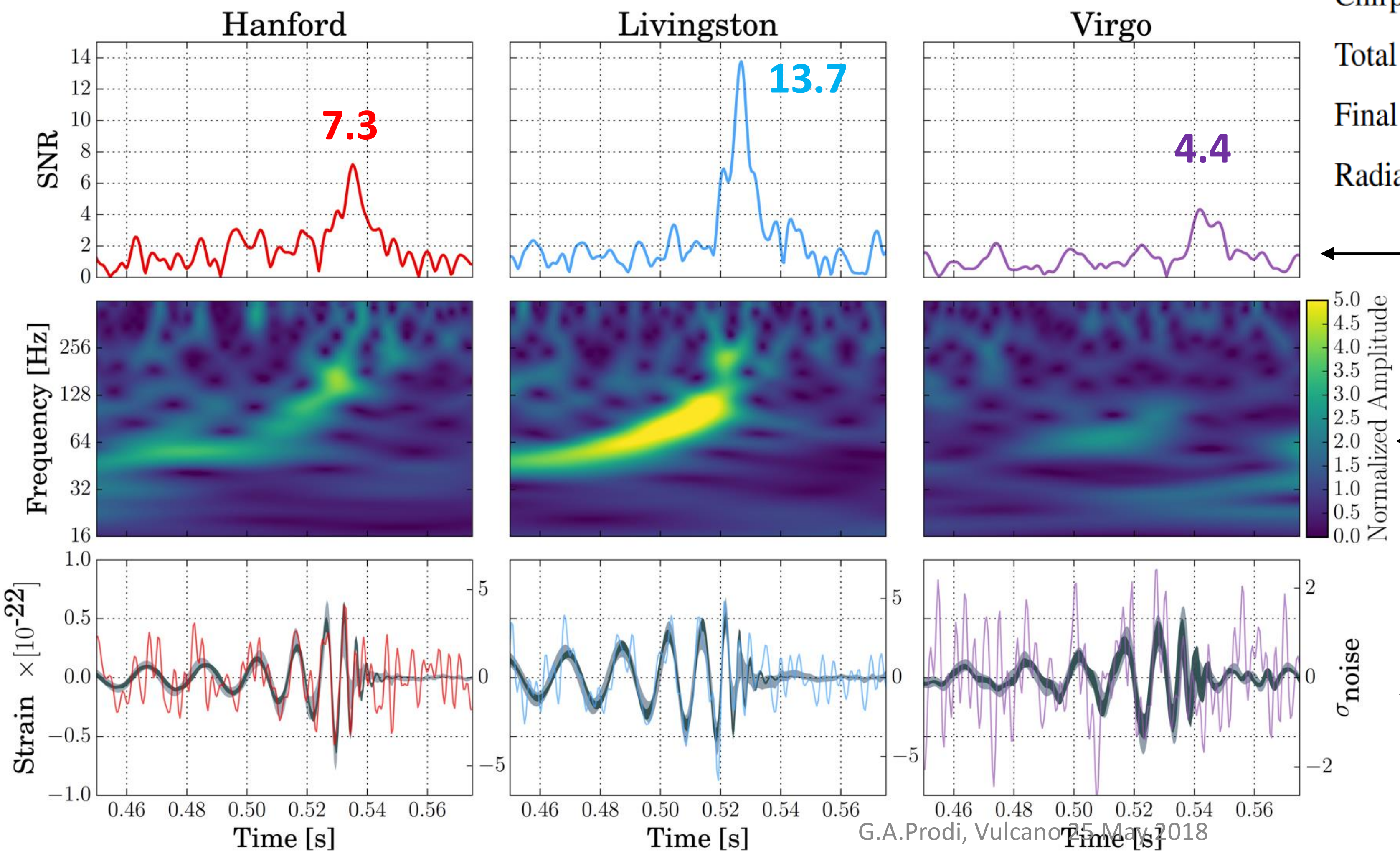


LVC,arXiv:1602.03841
LVC,arXiv:1606.04856

GW170814 : Virgo is in the game!

On August 14, 2017 at 10:30:43 UTC, Virgo & LIGO detected the first triple coincidence BBH event

Primary black hole mass m_1	**30.5** $^{+5.7}_{-3.0}\,M_\odot$
Secondary black hole mass m_2	**25.3** $^{+2.8}_{-4.2}\,M_\odot$
Chirp mass $\mathcal{M}$	$24.1^{+1.4}_{-1.1}\,M_\odot$
Total mass M	$55.9^{+3.4}_{-2.7}\,M_\odot$
Final black hole mass M_f	**53.2** $^{+3.2}_{-2.5}\,M_\odot$
Radiated energy E_{rad}	**2.7** $^{+0.4}_{-0.3}\,M_\odot c^2$



SNR time series using the best matching template

Time-frequency representation of the strain data around the time of GW170814

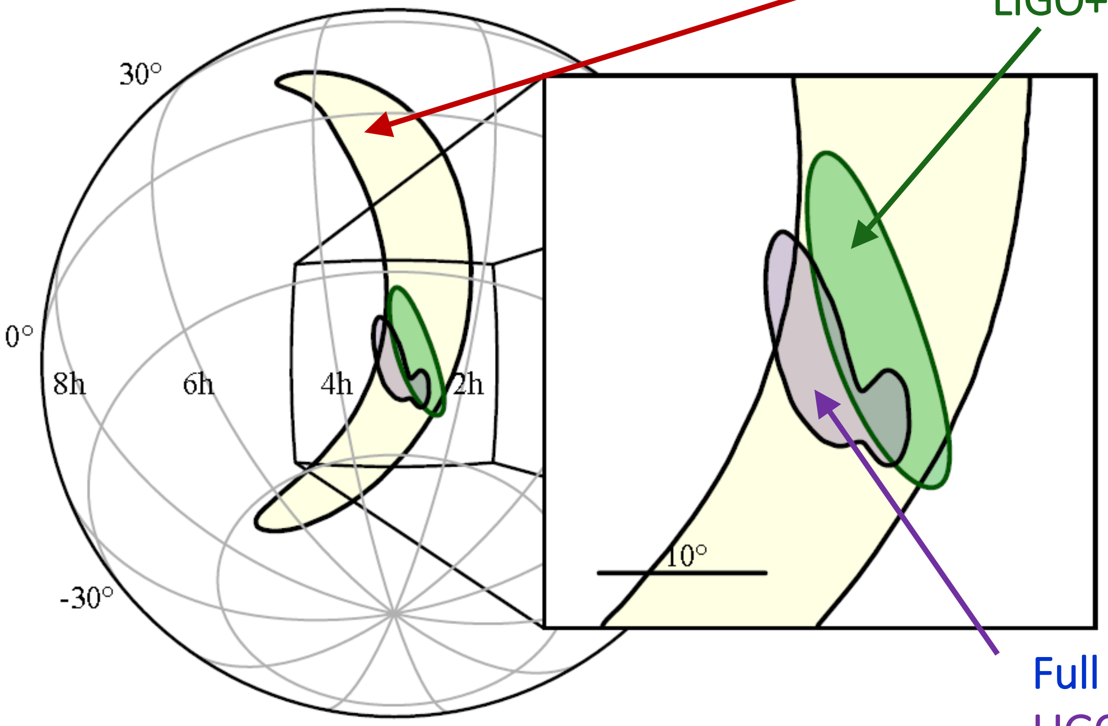
Reconstructed waveforms
- BBH model (dark gray)
- Unmodel (light gray)
- Whitened data (color)

GW170814 : Sky localization & GW polarizations

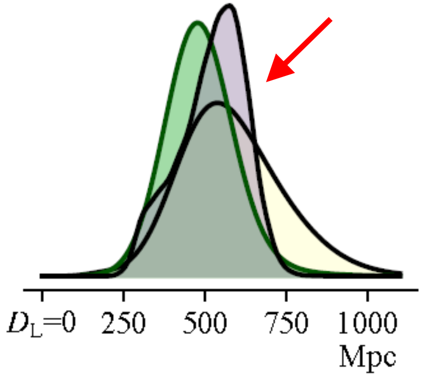
Sky localization prediction greatly improved with Virgo
No electromagnetic or neutrino counterpart reported

PRL 118, 221101 (2017)

Rapid Analysis – 90% confidence
Only LIGO : 1160 deg^2
LIGO+Virgo : 100 deg^2



Estimated Distance
540 Mpc



Full Analysis – 90% confidence
LIGO+Virgo : 60 deg^2

- **The volume** for GW170814 localization **is 30 times smaller** with the 3-detector network wrt the LIGO only network

GR polarization vs
non-GR polarization

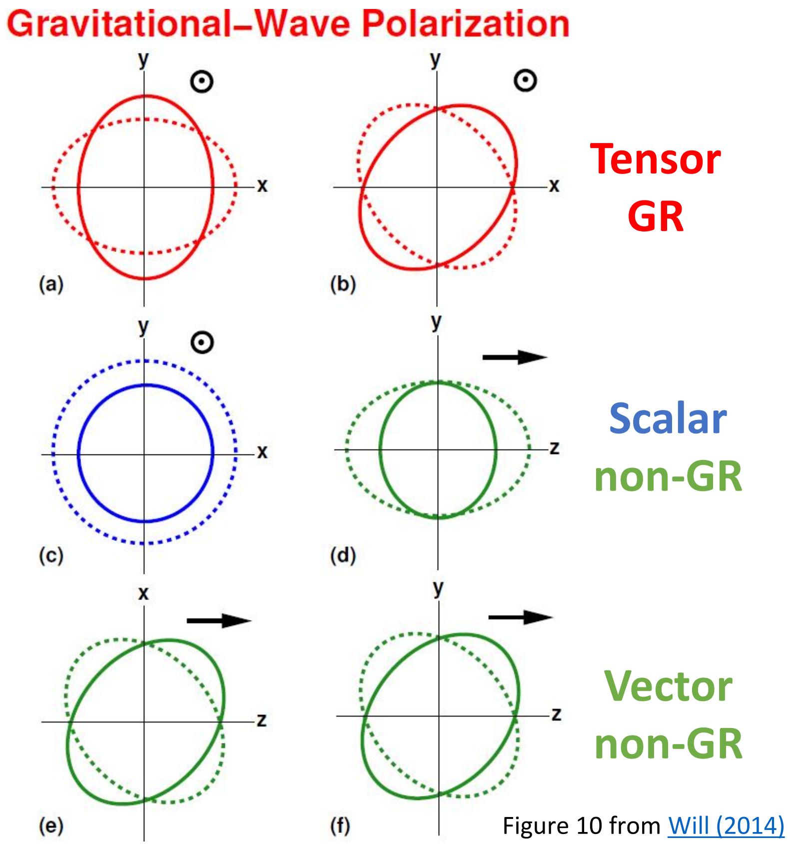
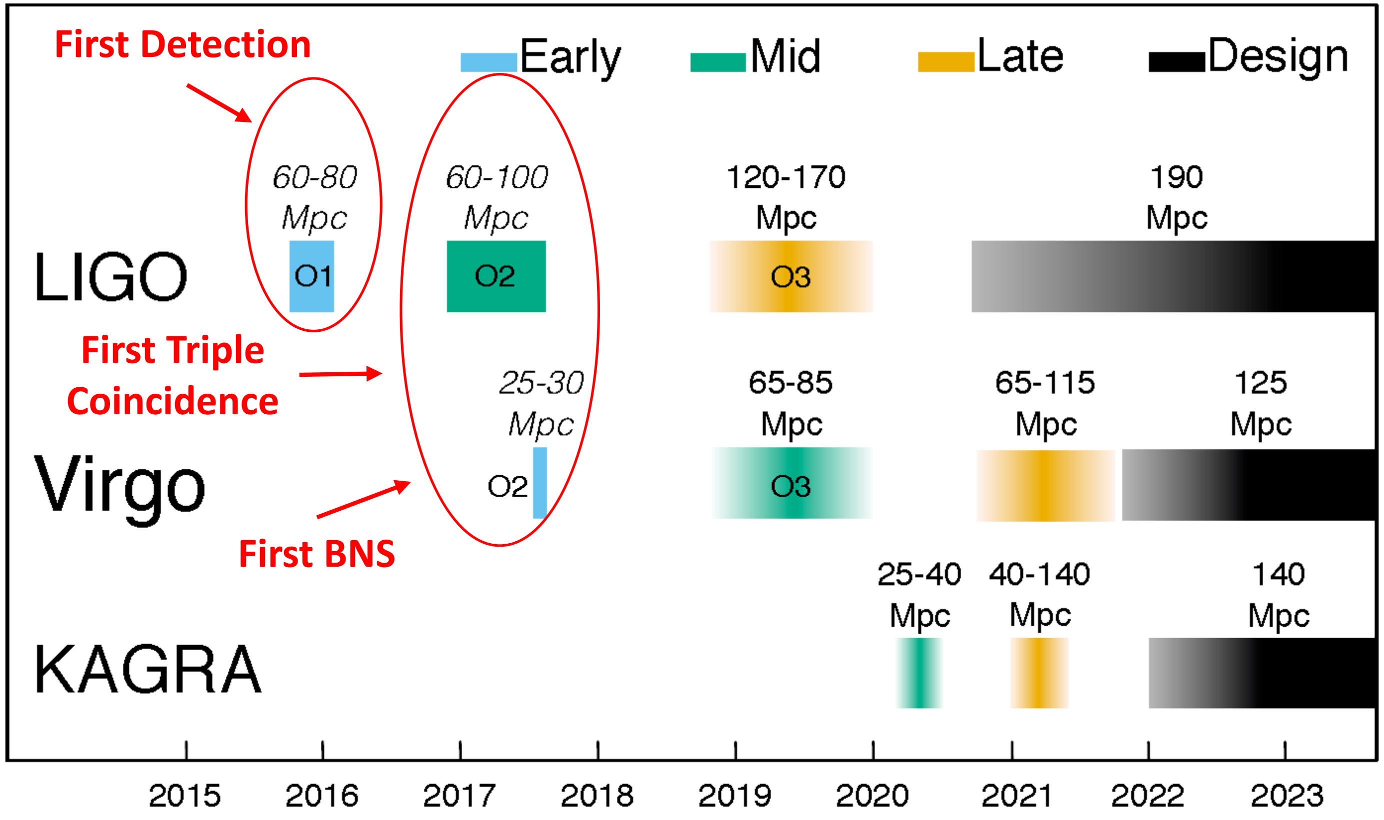


Figure 10 from Will (2014)

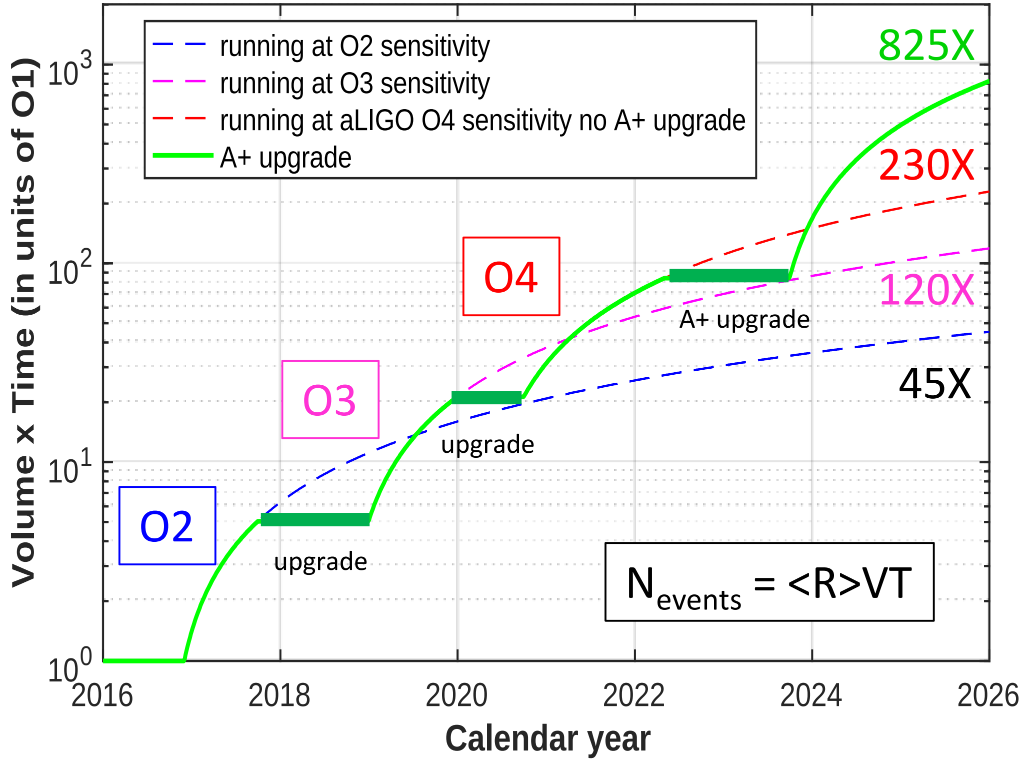
3 detector network enables investigations on GW polarizations.
The tensor polarizations are preferred

Plans for LIGO-Virgo-KAGRA Surveys

arXiv: 1304.0670v4 KAGRA & LIGO & VIRGO



Binary Neutron Stars Events



Design sensitivity:

- **1000x gain** in surveyed volume of the Universe with respect to first generation detectors
- **Binary BH detection rate: 50 - 500 /year**
- **Binary NS detection rate: 10 -300 /year**

- <R> average astrophysical rate
- V volume of the universe probed → $(\text{Range})^3$
- T coincident observing time