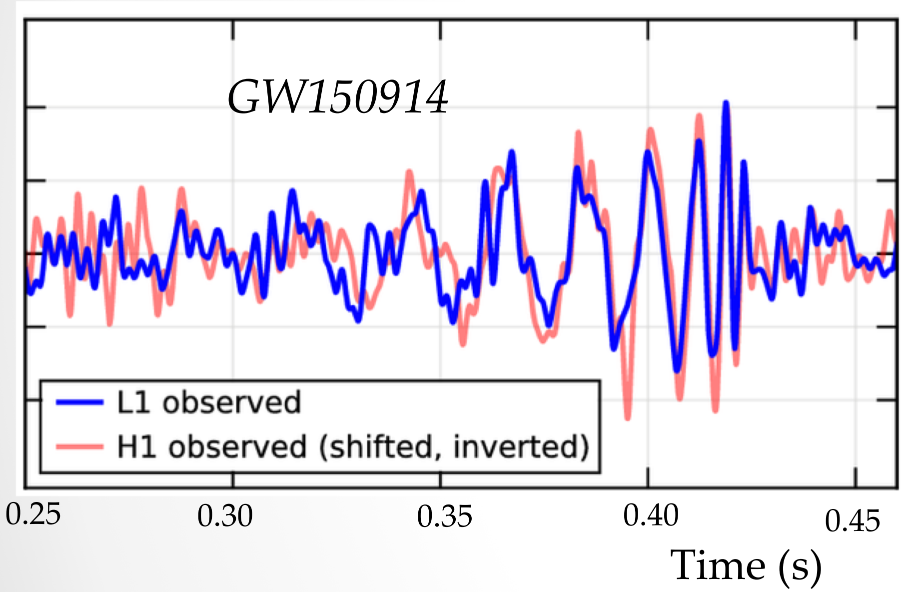
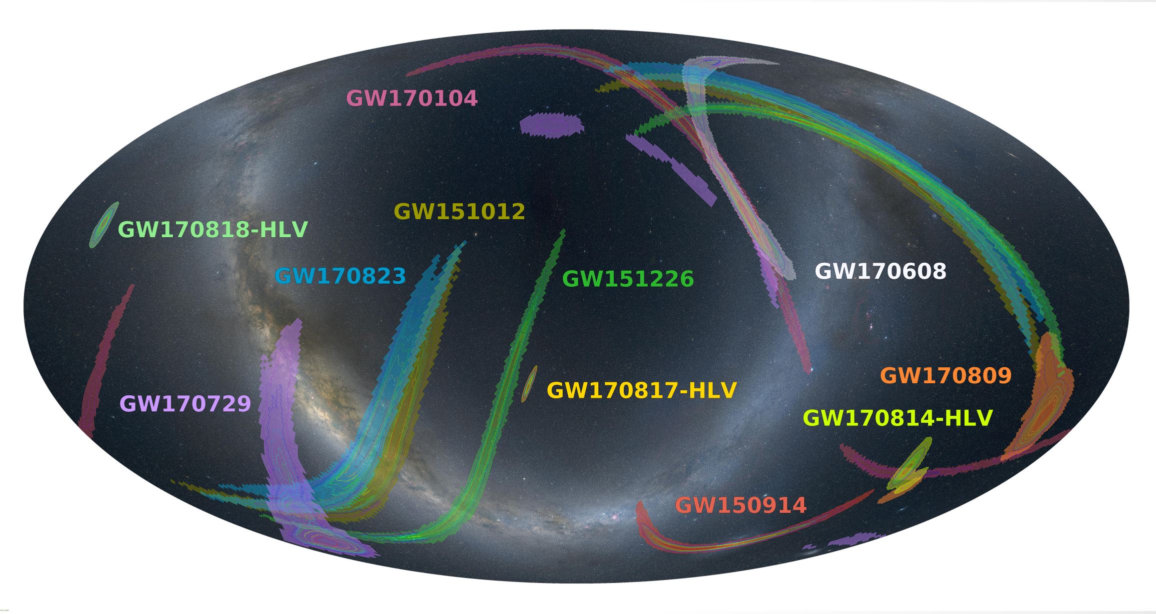
Gravitational wave : recent results and future of the field

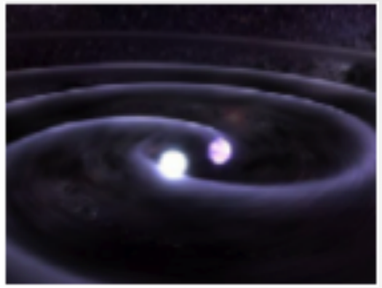




Nicolas Leroy
Laboratoire de l'accélérateur linéaire d'Orsay

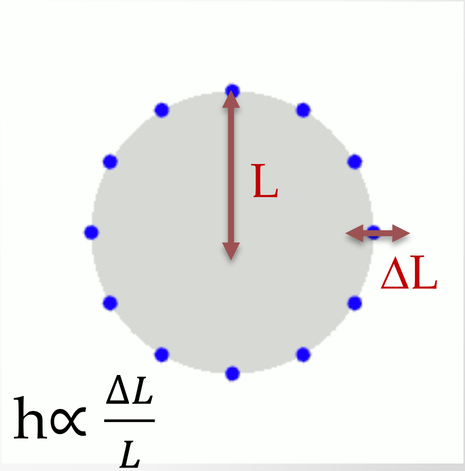
Journée P2I-PHOM – 20 June 2019

What are Gravitational waves ?

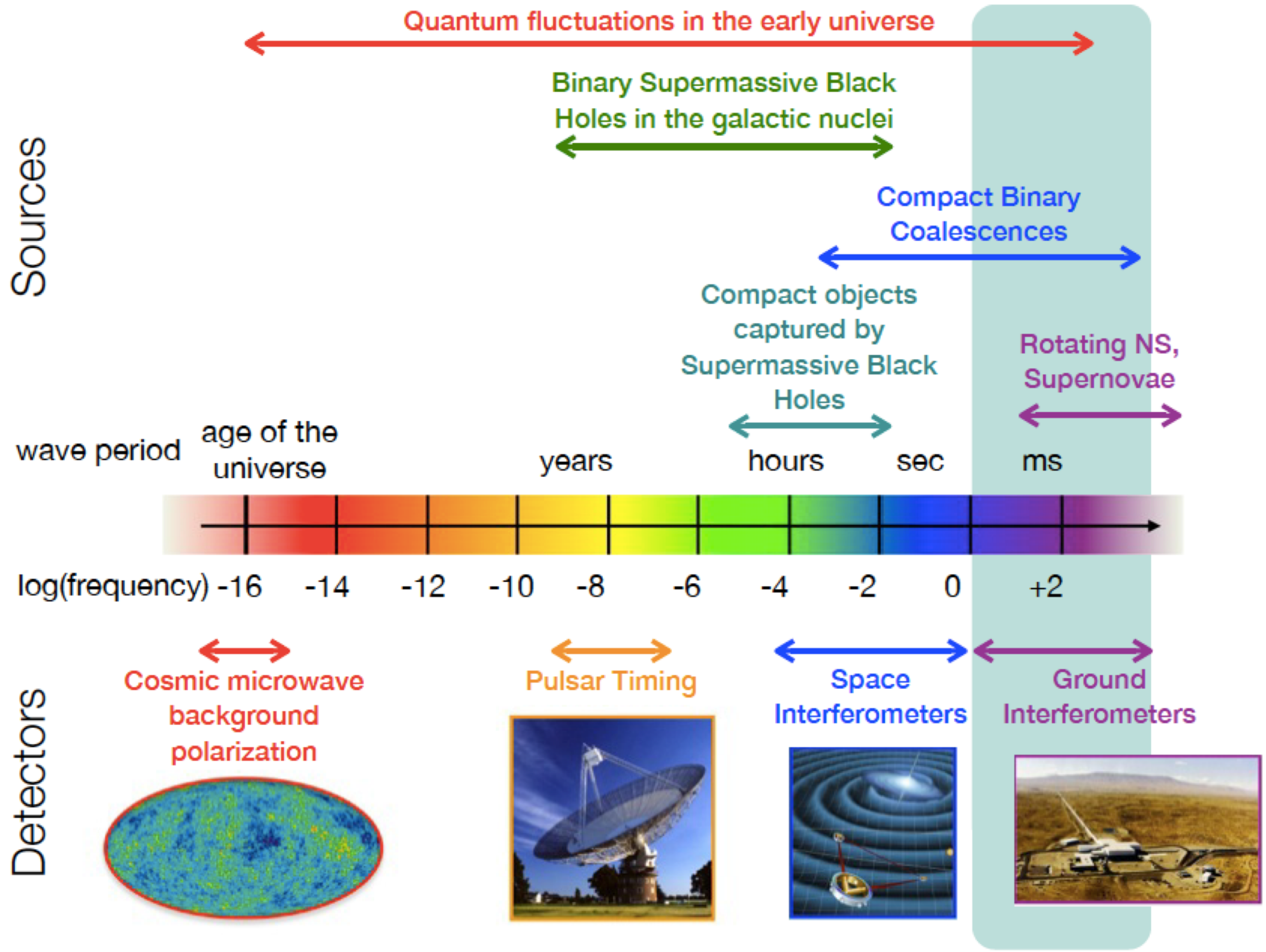


- Solution from General Relativity derived by A. Einstein in 1916
- Far from sources then can be seen as a perturbation of the metric
- They are ripples of space-time produced by rapidly accelerating mass distributions
- Provide info on mass displacement
- Weakly coupled – access to very dense part of objects
- Main proprieties:
  - Propagate at speed of light
  - Two polarizations '+' and 'x'
  - Emission is quadrupolar at lowest order

Needs to have
- Compact object : R~Rs
- Relativist : v ~ c
- asymmetric



The Gravitational Wave Spectrum

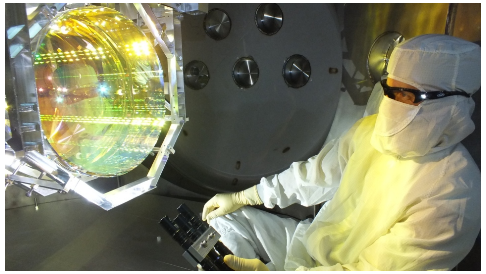


[Inspired from http://science.gsfc.nasa.gov/663/research/]

Advanced generation detectors

Michelson interferometer

Goal : $(L_x - L_y)/L_x = 10^{-23}$



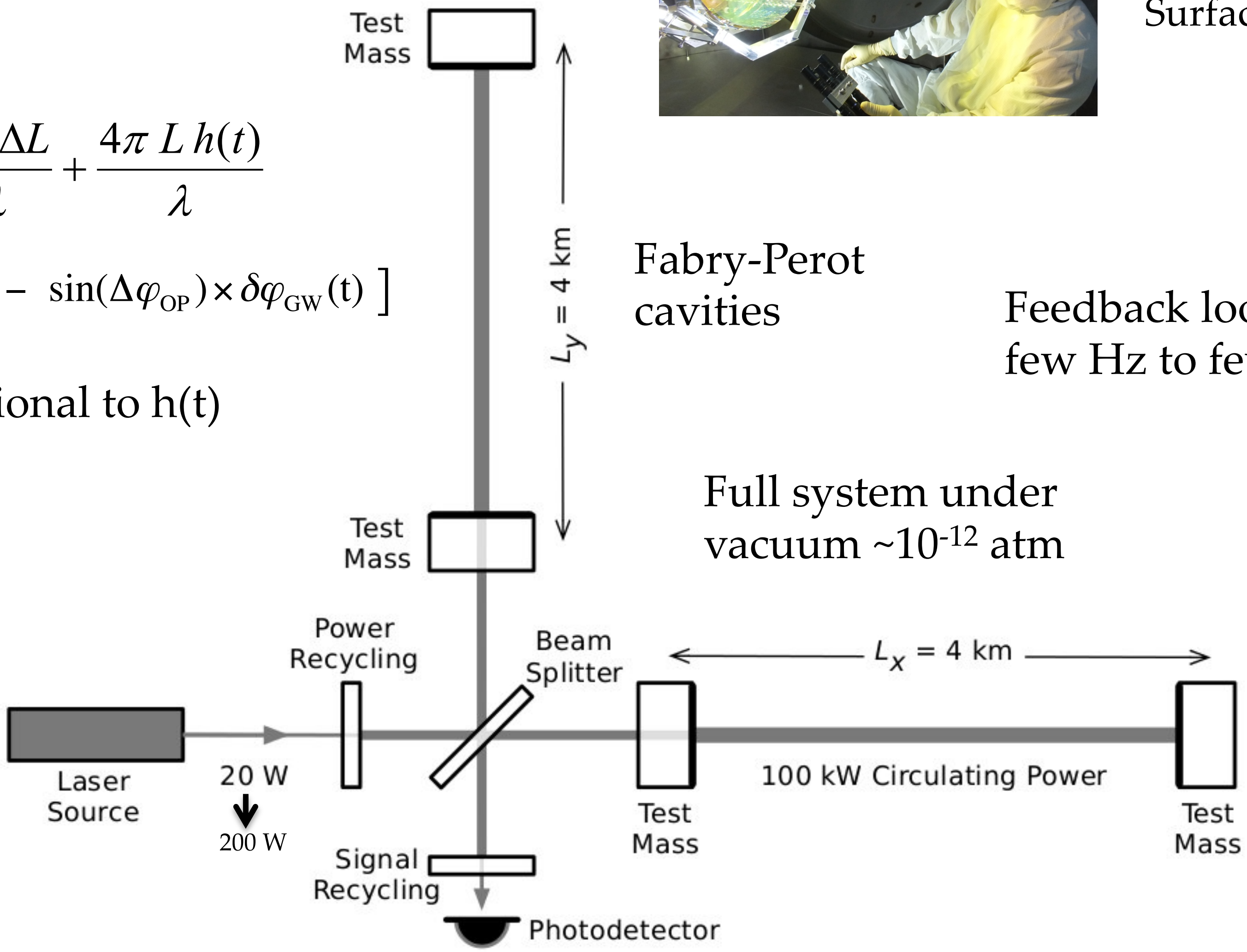
High quality optics – 40 kg

Surface RMS ~nm

$$\Delta\phi = \Delta\phi_{OP} + \delta\phi_{GW}(t) = \frac{2\pi\,\Delta L}{\lambda} + \frac{4\pi\,L\,h(t)}{\lambda}$$

$$P_{det} \approx \frac{P_{in}}{2}\left[\,1 + \cos(\Delta\varphi_{OP}) - \sin(\Delta\varphi_{OP}) \times \delta\varphi_{GW}(t)\,\right]$$

Detected signal proportional to h(t)

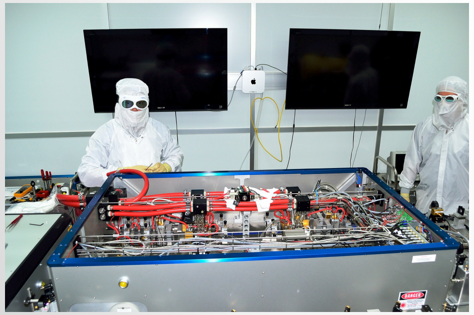


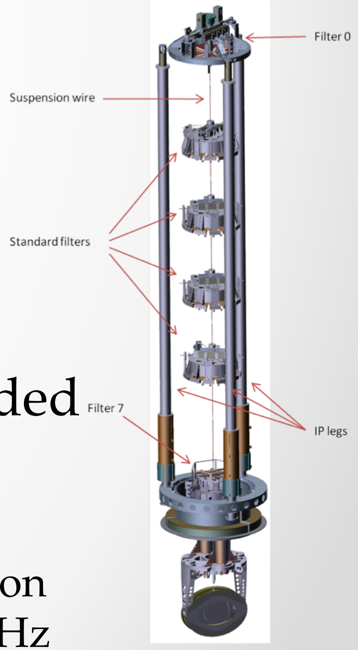
Fabry-Perot cavities

Feedback loops from few Hz to few kHz

Full system under vacuum ~10^{-12} atm

High power laser

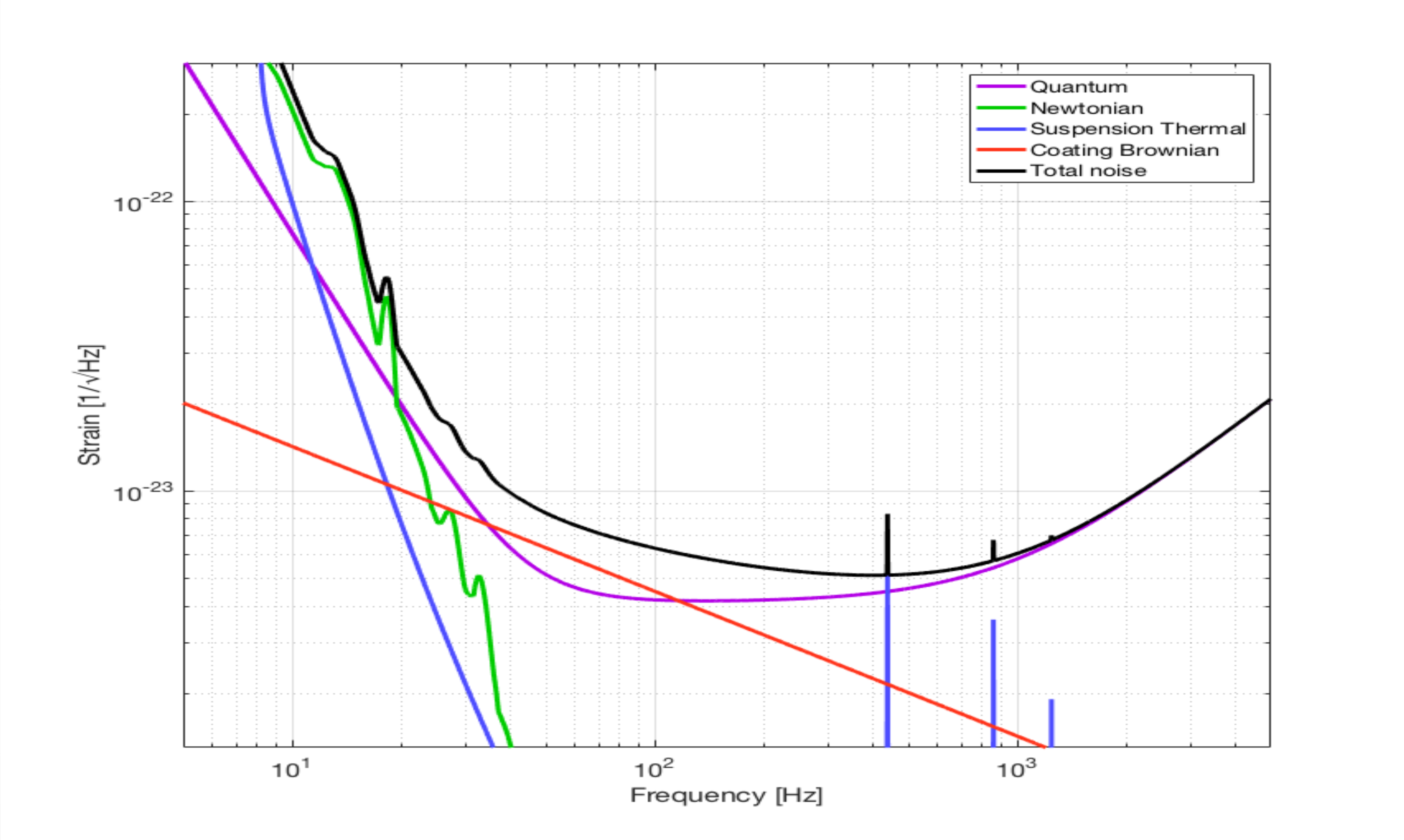


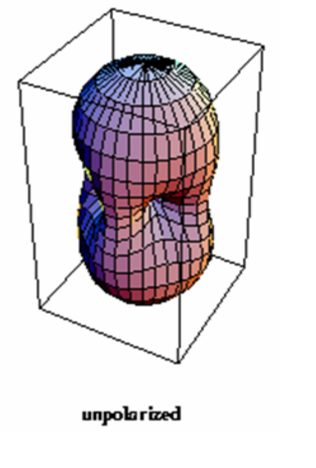


Suspended Optics

Attenuation 10^{14} @ 10 Hz

Sensitivity

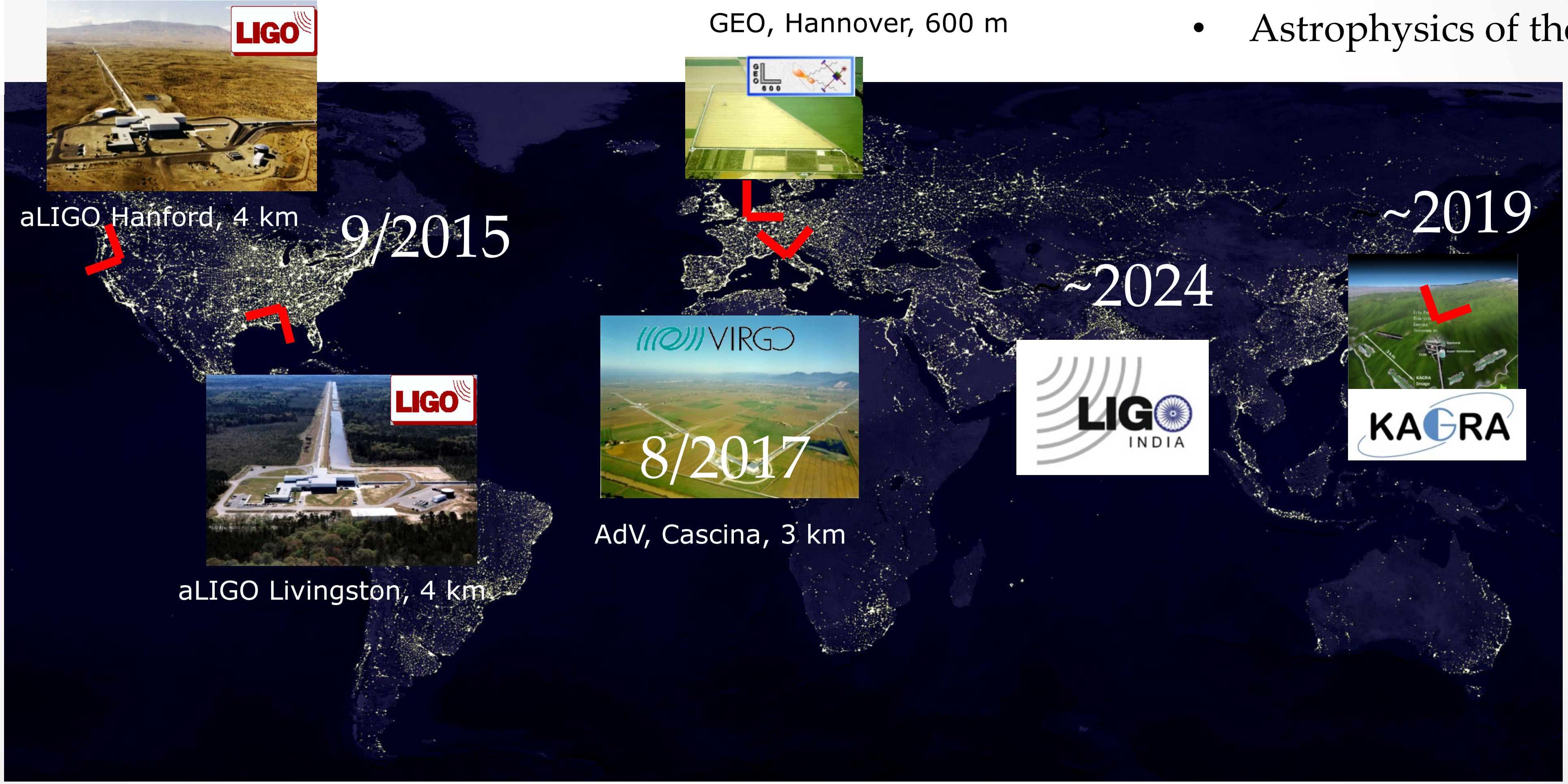




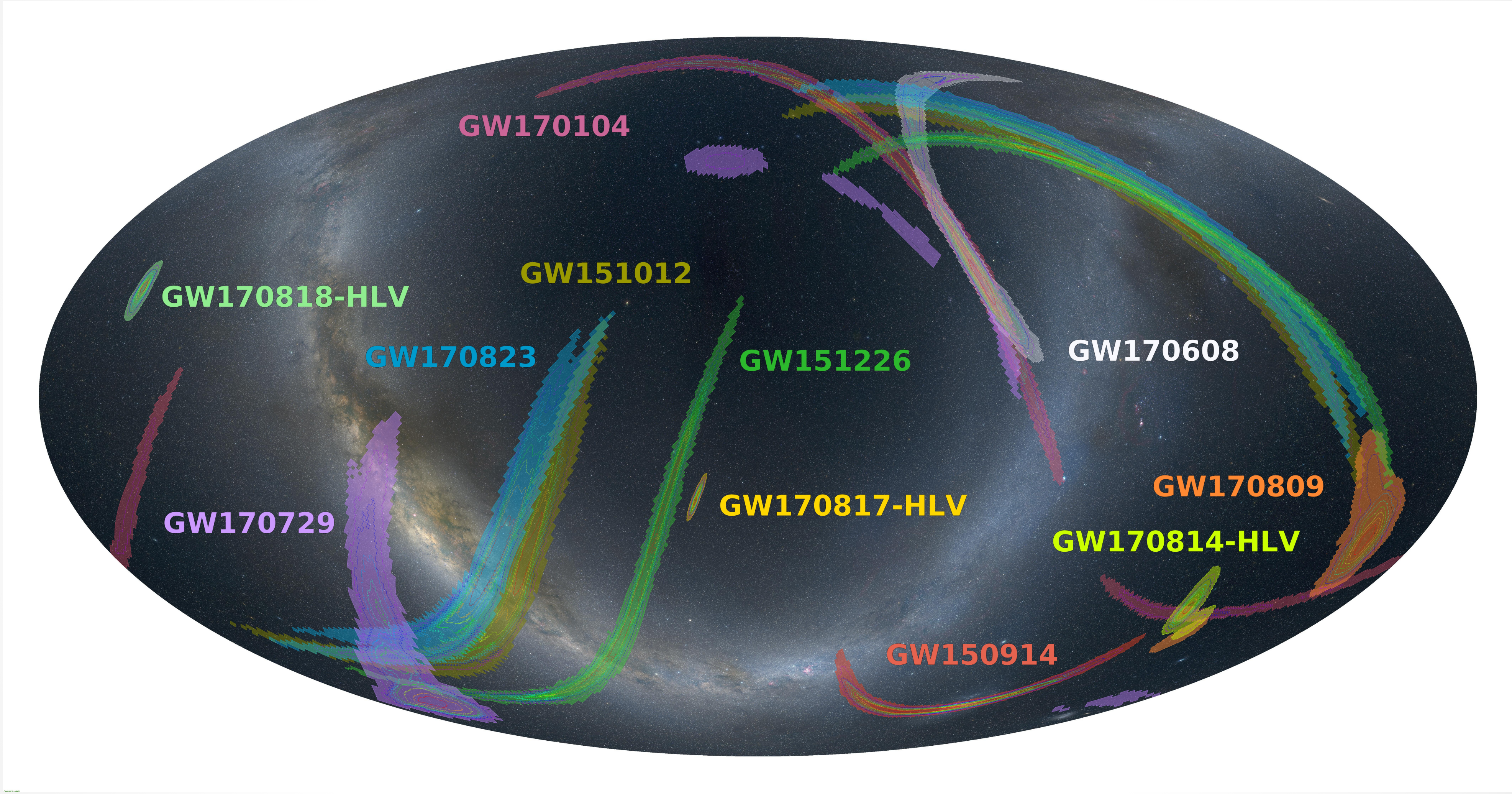
Averaged beam antenna

GW network

- Increase the detection confidence
- Source sky localization
- Source parameters inference
- GW polarization determination
- Astrophysics of the sources



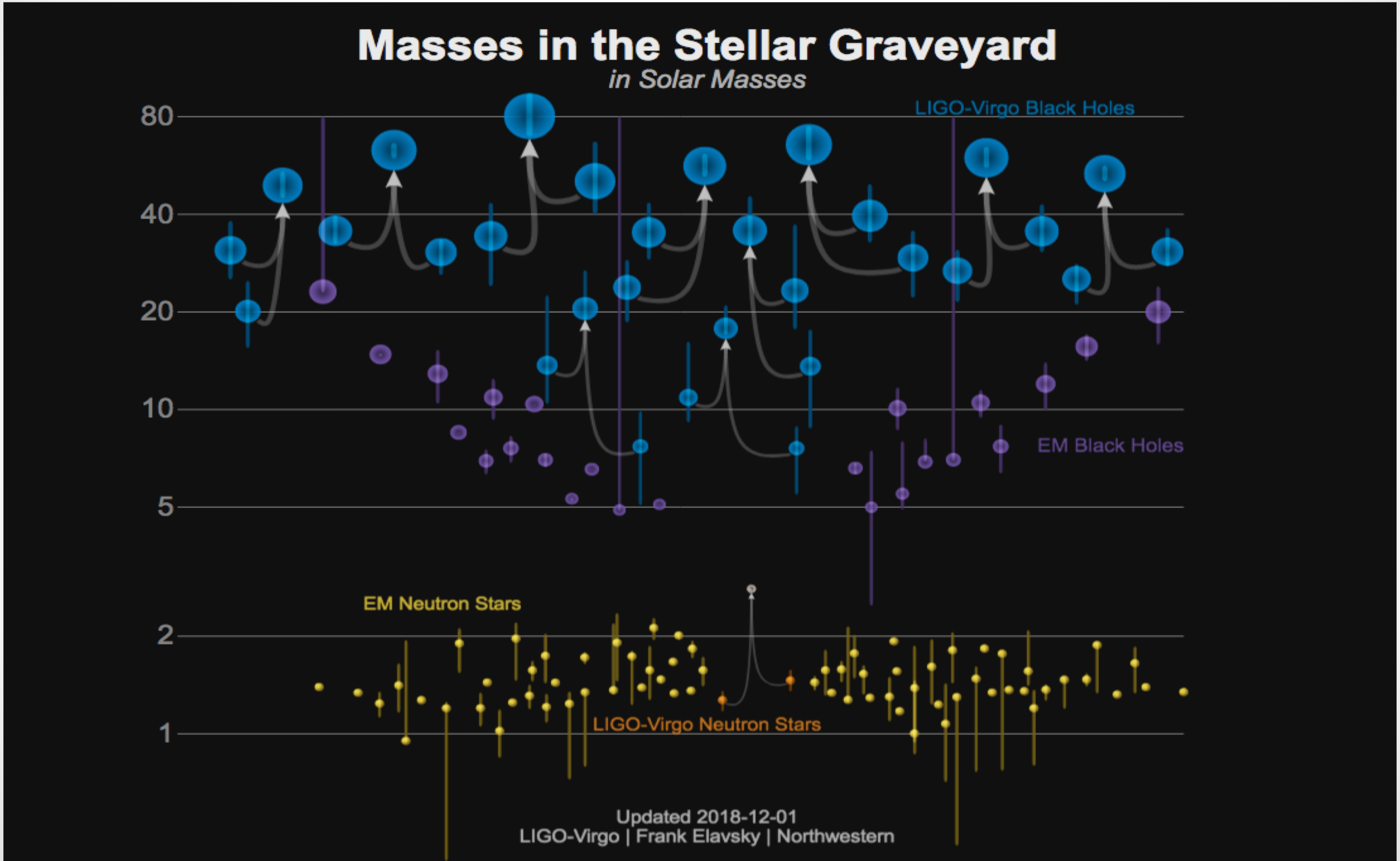
Sky error regions



Sky map reconstructed with time of flight technic

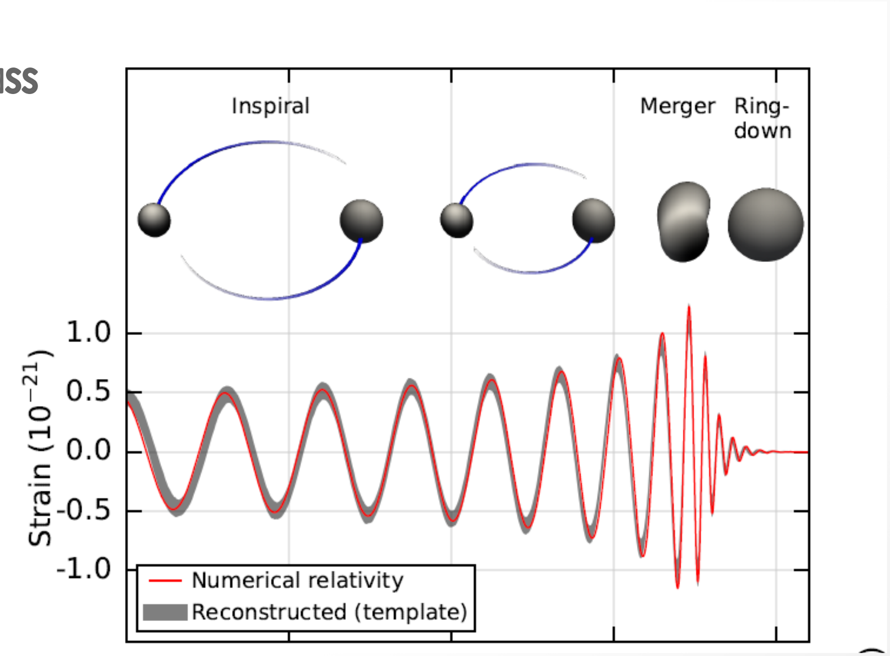
Large improvement since Virgo joined data taking

GW detections



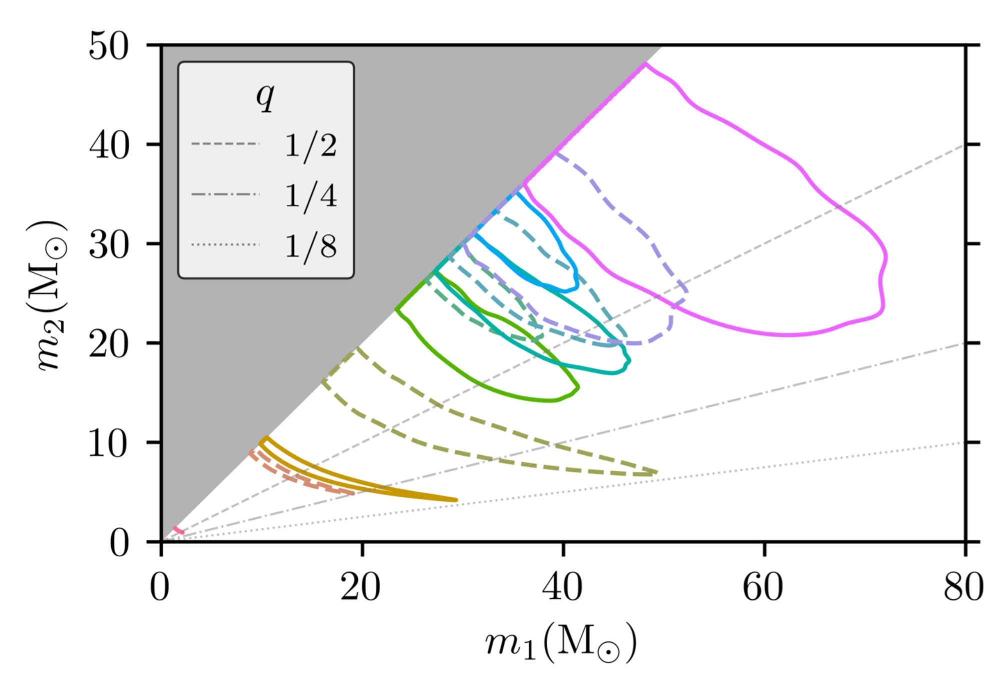
Coalescing binaries

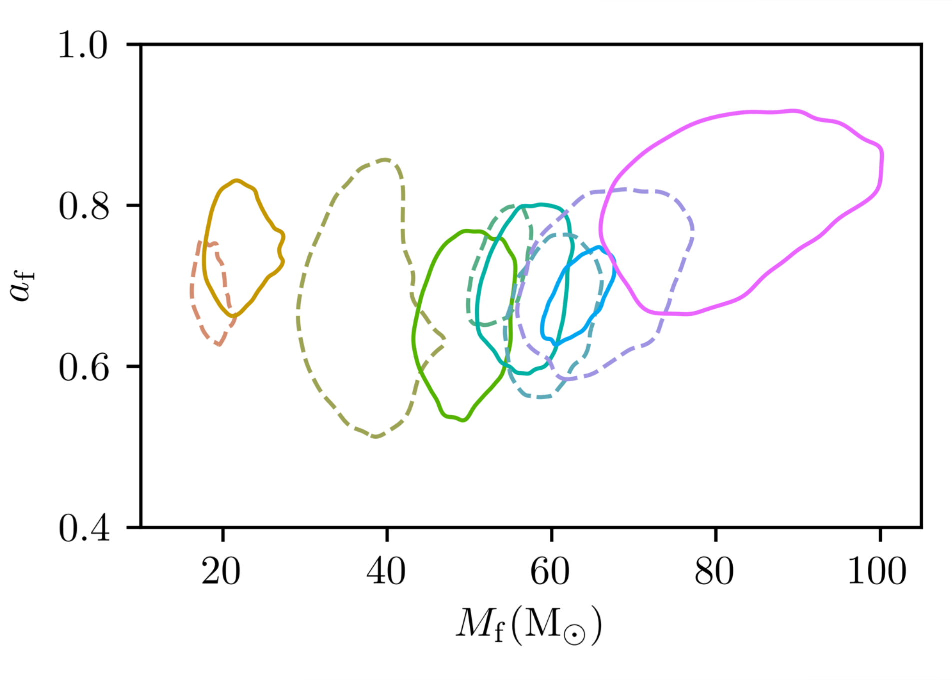
- Searching for objects containing black holes (BH) and neutron stars (NS)
- Possible electromagnetic emission if one object is a NS
- Known waveforms from analytical model or numerical relativity simulations
- Waveform allow to retrieve :
    - Masses : ratio (chirp mass) and total mass
    - Spins : initials and final object(s)
    - Geometry of the system
    - Distance
    - Total energy dissipated
- Can be used to test GR



Detecting black holes

- Detected Binary Black Holes in the mass range : 5 – 50 $M_\odot$
- Detection range up to ~Gpc, mostly ~450 Mpc
- Rate : R = 9.7 – 101 $Gpc^{-3}\,yr^{-1}$
- A large fraction of energy in GW : 1 to 3 $M_\odot$
- No large constraint on spins

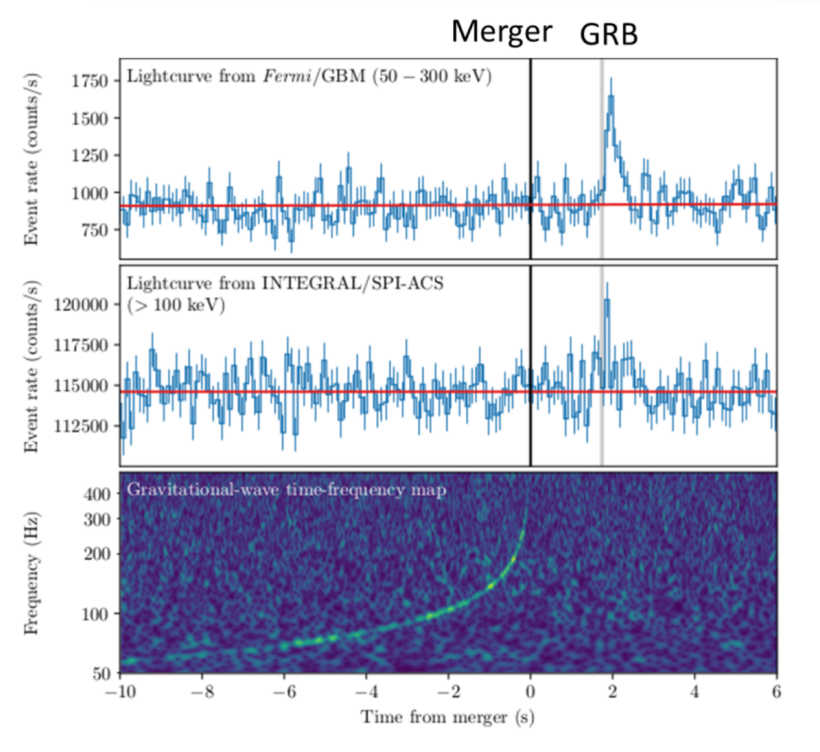


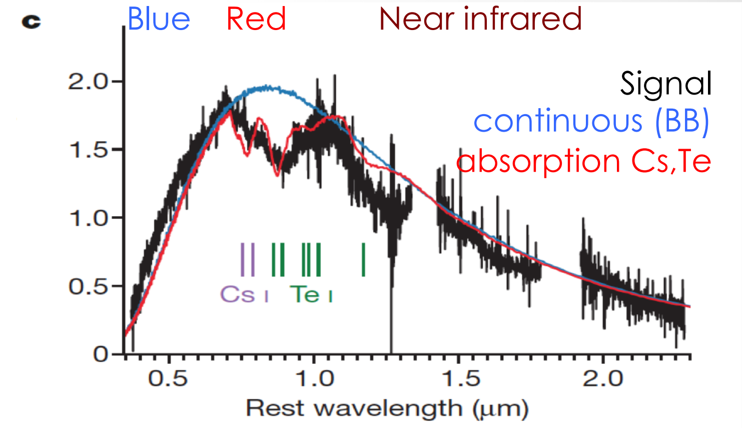


Abbott et al, PRX 9 (2019)

GW170817 :First binary neutron stars

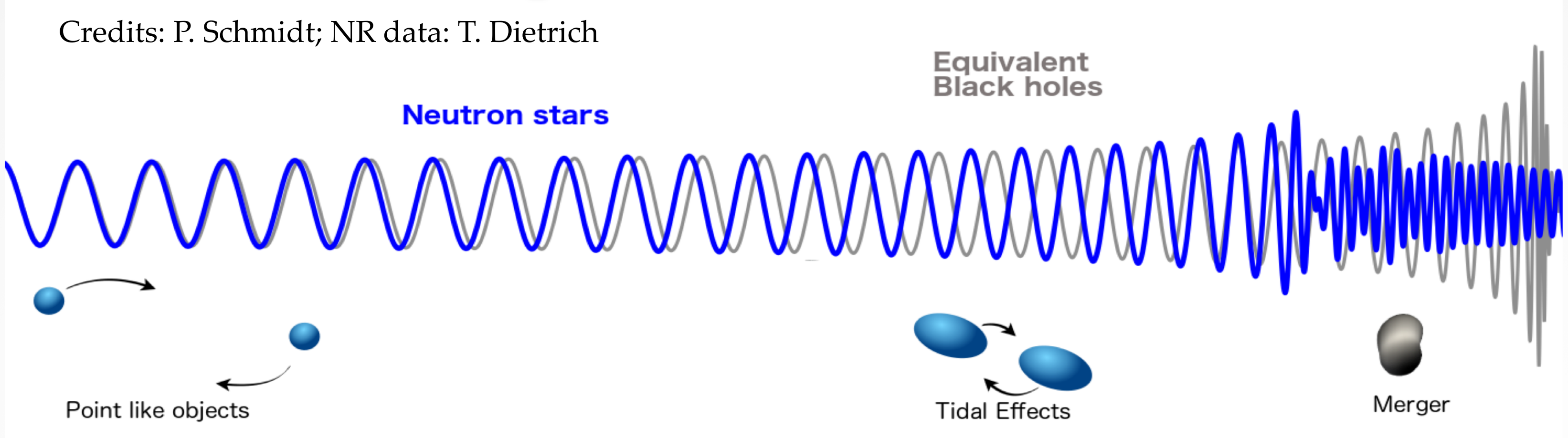
- SNR ~ 32.4,
- FAR <1 10^{-4} /year
- Long event (~100 secs)
  - light masses system !
- Was quickly determined as Binary neuron stars system
- Electromagnetic counterpart found !
  - Association to a gamma-ray burst (> 5.3 σ) within 1.7s and same sky region
  - Including the 3 interferometers -> 28 deg^2
  - Radio to X-rays counterpart found (latency hours to days)
  - Found in NGC4993, distance determined between EM and GW compatible
  - Kilonova emission





ePESSTO - Spectrum ESO/VLT & Gemini

Constraints on Equation of state of nuclear matter



- Neutron star : among the most densest objects in the Universe
- Large uncertainties on their structure

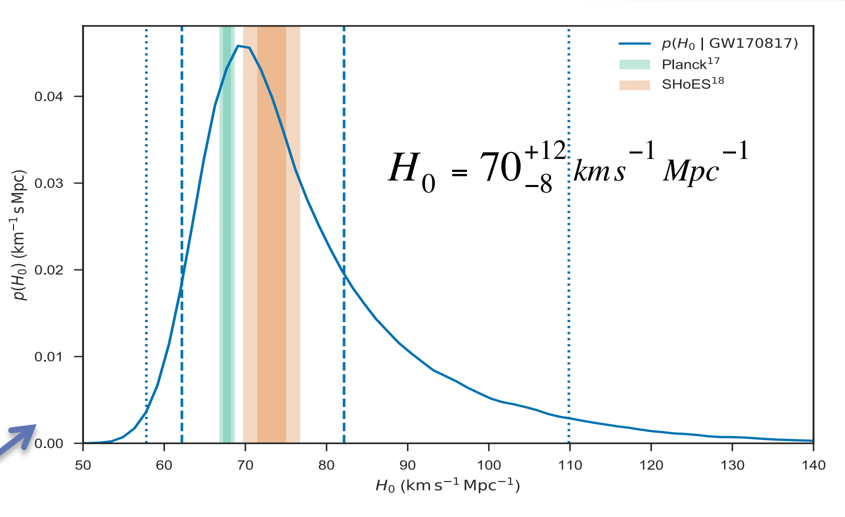
- Equation of state influence :
  - Pressure as function of density
  - Mass as function of radius
  - Tidal deformability
  - Impact on post merger

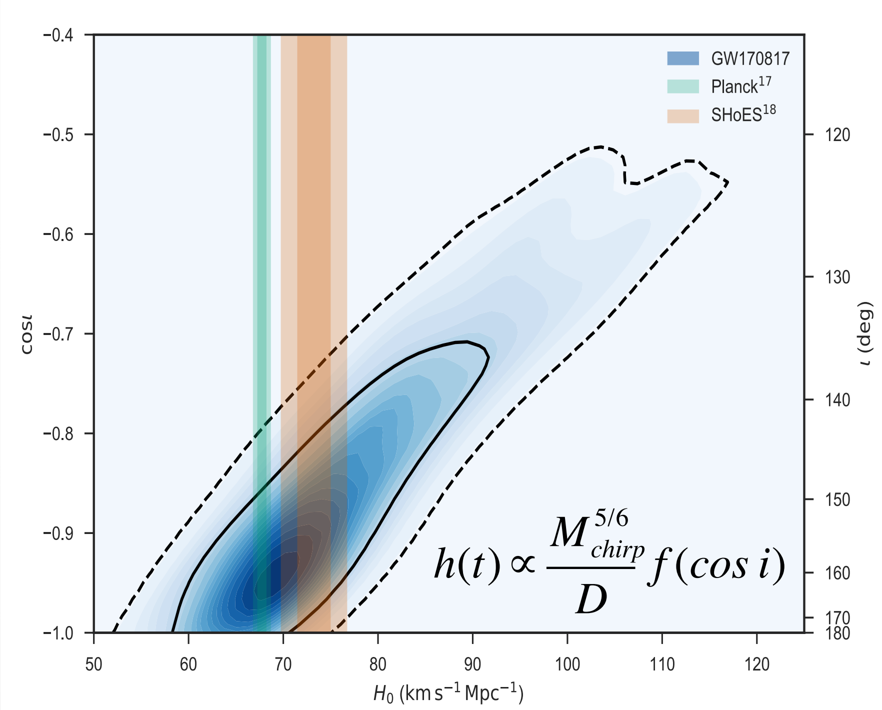
- Tidal effects when stars are close
- Affect the GW waveform

- Compact stars are favored
- Consistent with radius below 14 km
- 10s of detections to distinguish between the models
- First detections of spinning neutron stars (pulsars) will also add constraints

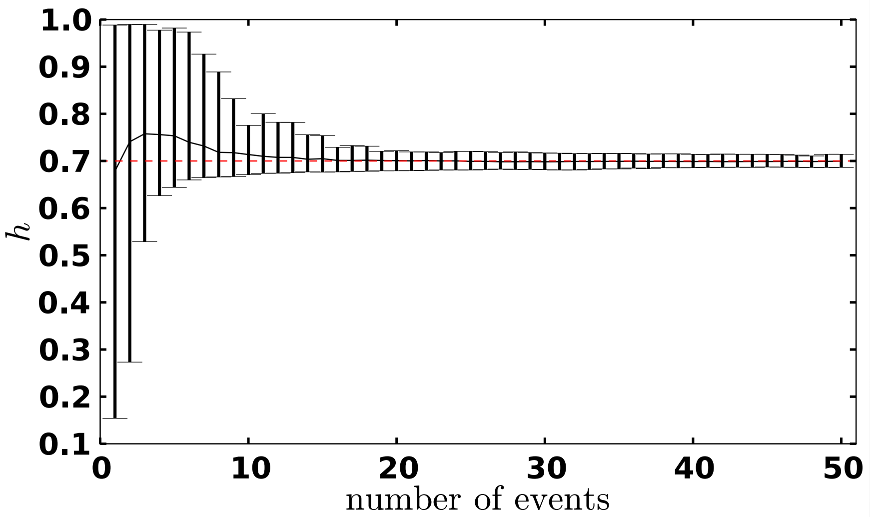
Hubble constant measurement

- For closed-by source : $v=H_0D$
- EM counterpart found in NGC4993, can then measure redshift
- GW : Distance and orientation are correlated
- 10s of common detections to reach few % precision



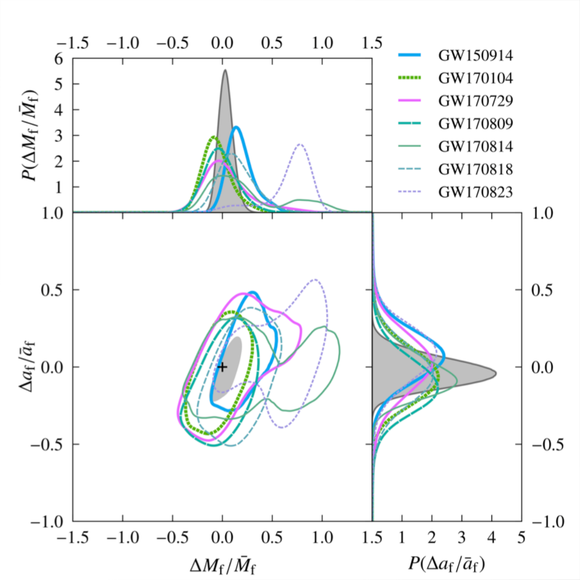


"A standard siren measurement of the Hubble constant with GW170817", Nature 551, 85 (2017)



Del Pozzo, PRD 86, 043011 (2012)

Test for fundamental physics



GW170817

- No deviation observed with BBH data
- Compatible with GR polarization
- Speed of gravity :

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

- Equivalent principle (Shapiro effect) :

$$-2.6\,10^{-7} \le \gamma_{GW} - \gamma_{EM} \le 1.2\,10^{-6}$$

Deviation to Einsten-Maxwell

$$\delta t_S = -\frac{1+\gamma}{c^3}\int_{r_e}^{r_o} U(r(l))\,dl$$

gravitational potential

- Lorentz Invariance violation :

Improve between a factor 2 and 10^{10} previous constraints

Falsify most of models predicting a difference with c

"Gravitational Waves and Gamma Rays from a Binary Neutron Star Merger: GW170817 and GRB 170817A", ApJL (2017)

GW detectors in the next months

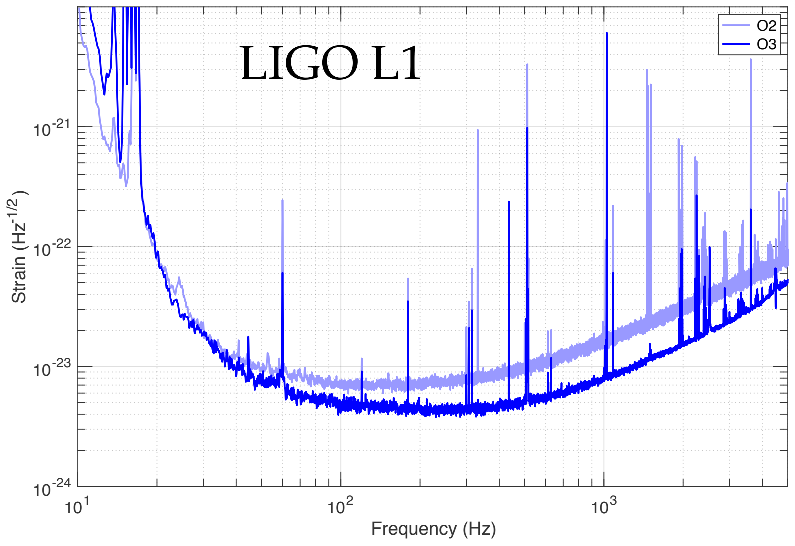
O3 is planned for one year

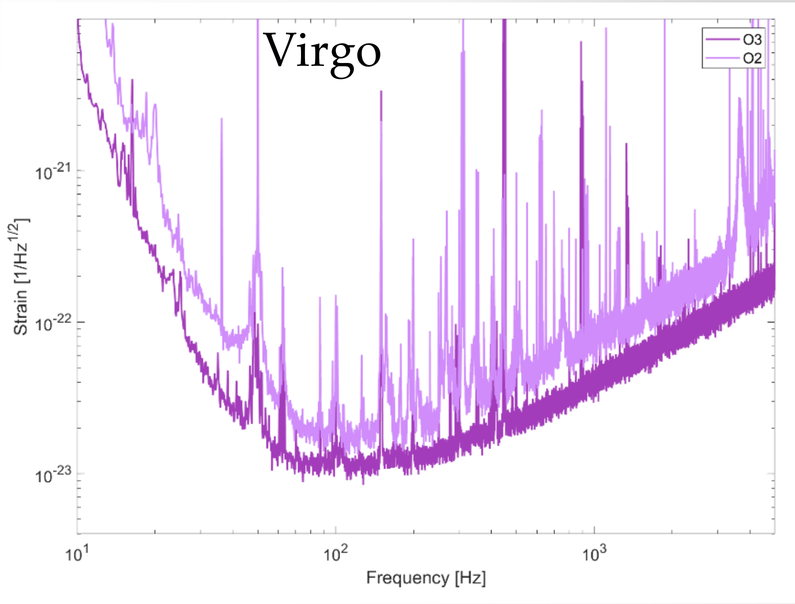
Range BNS :

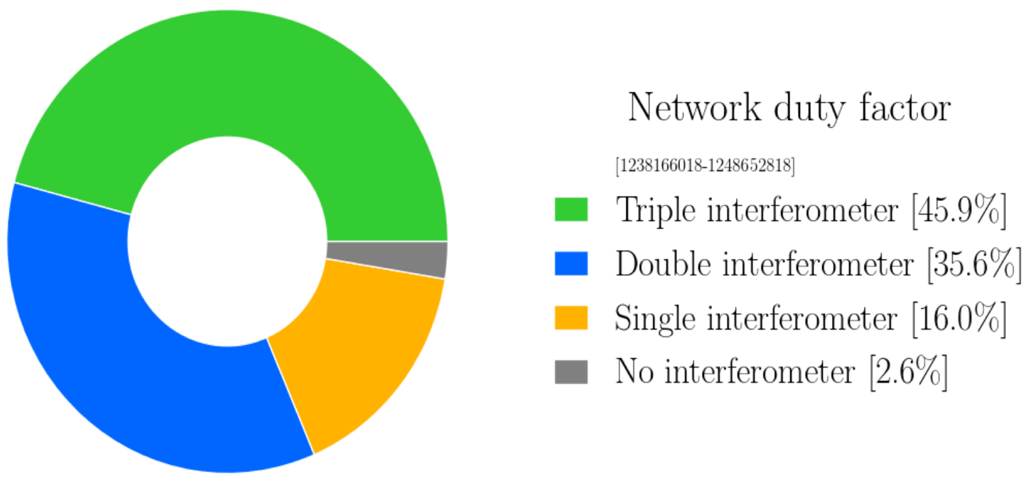
- 100 - 140 Mpc LIGO
- 40 - 50 Mpc Virgo

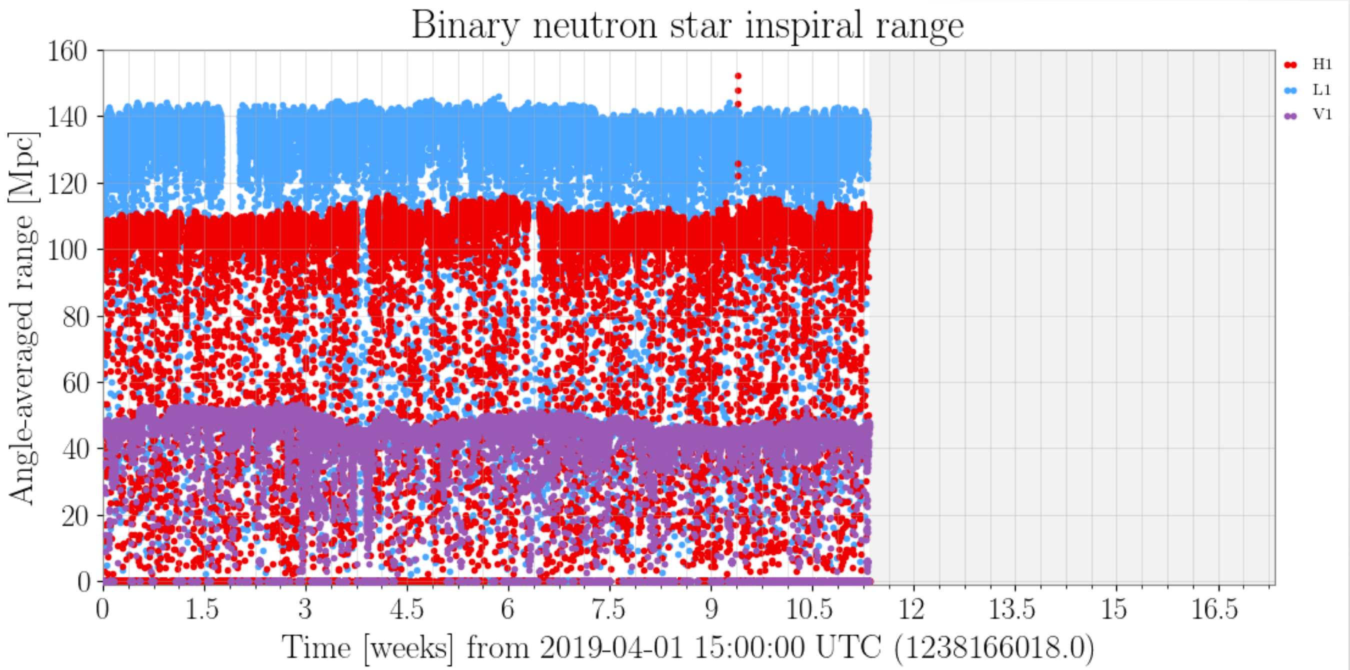
Already 14 alerts

(12 BBHs + 1 BNS + 1 NSBH)



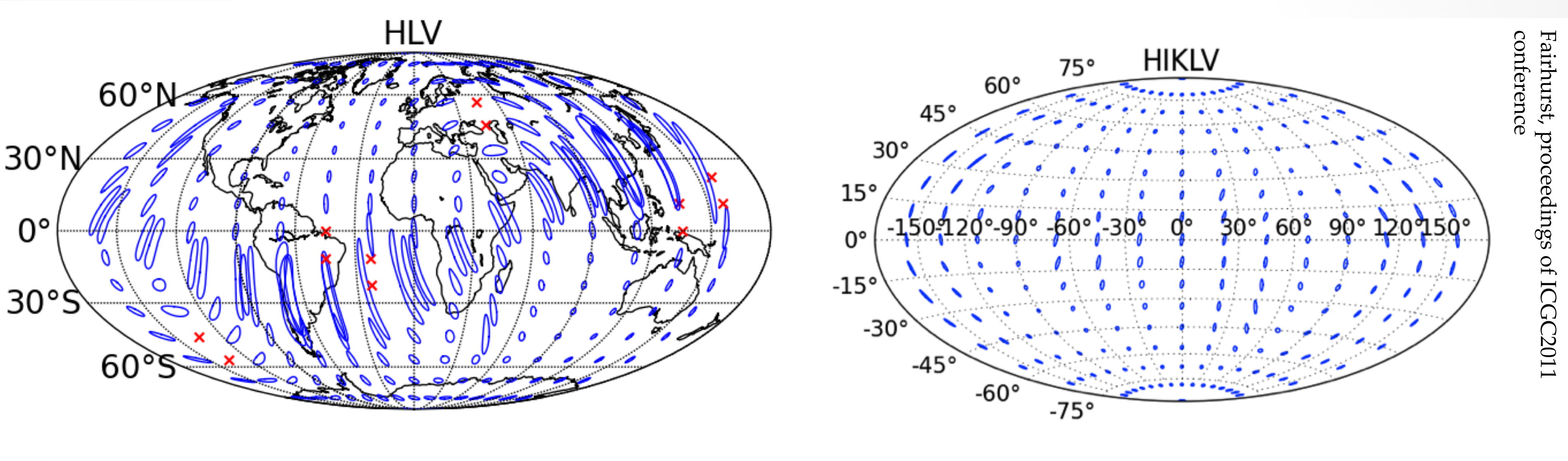




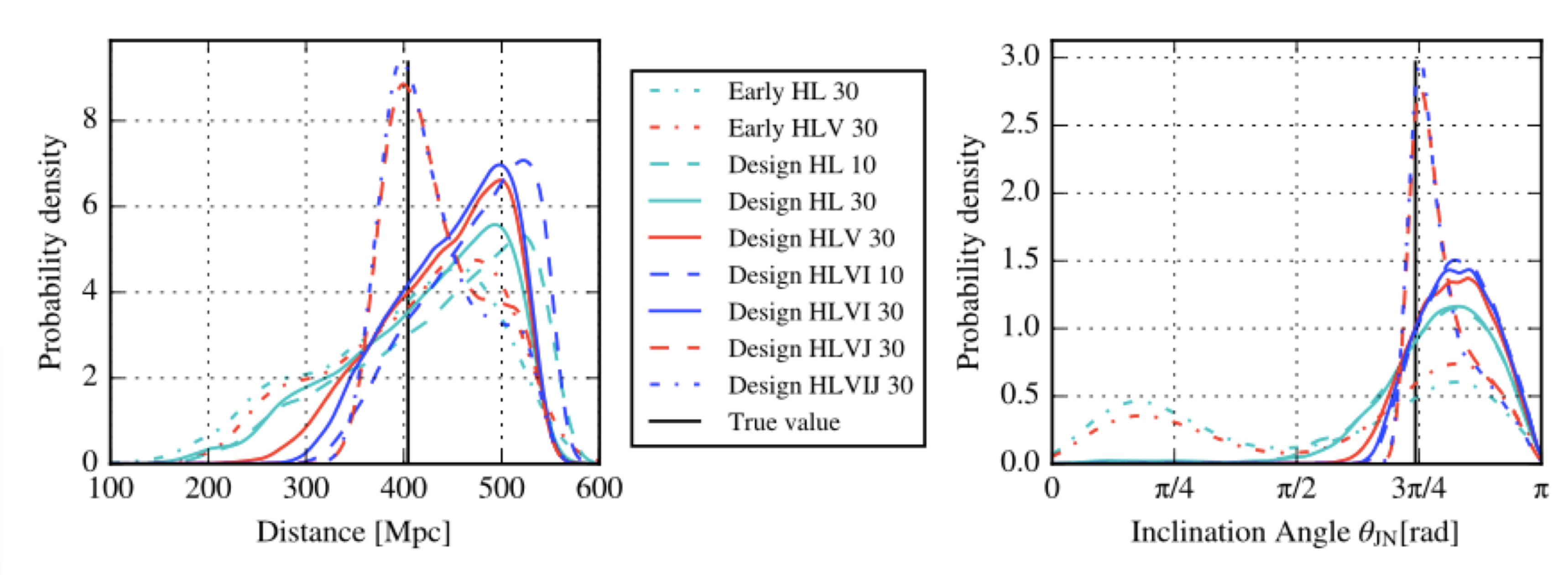


Adding new instruments : parameters inference

Comparison between 3 and 5 detectors for sky localization

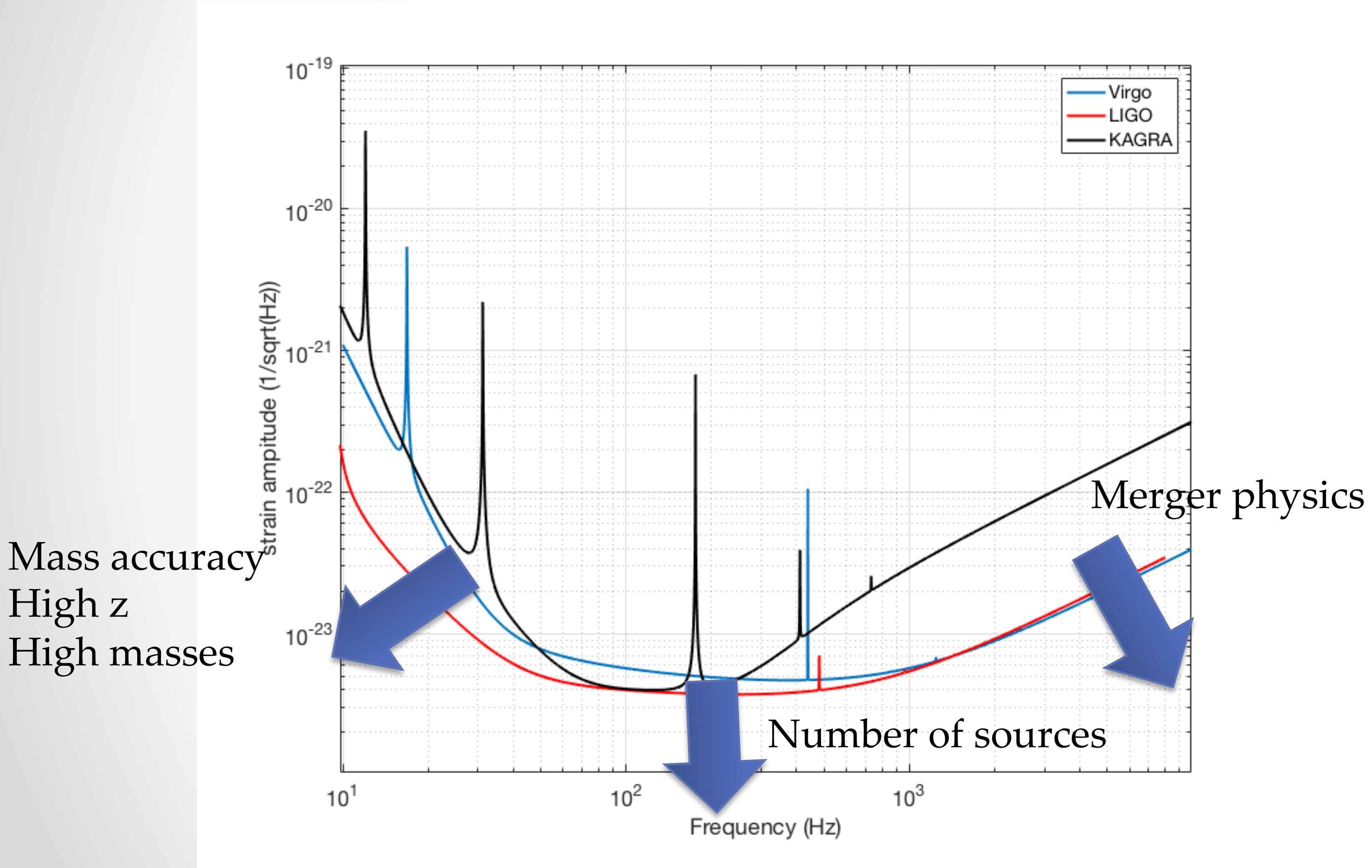


Fairhurst, proceedings of ICGC2011 conference



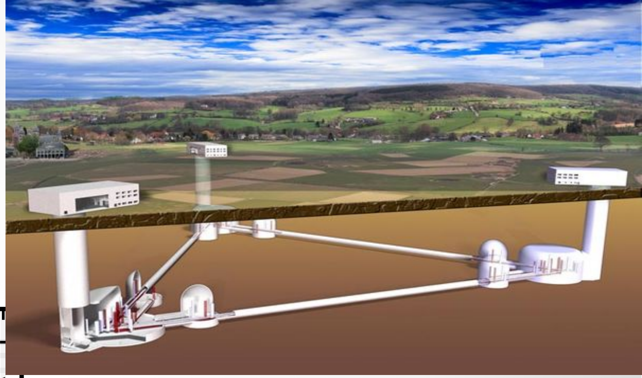
S M Gaebel and J Veitch 2017 Class. Quantum Grav. 34 174003

Improving sensitivity



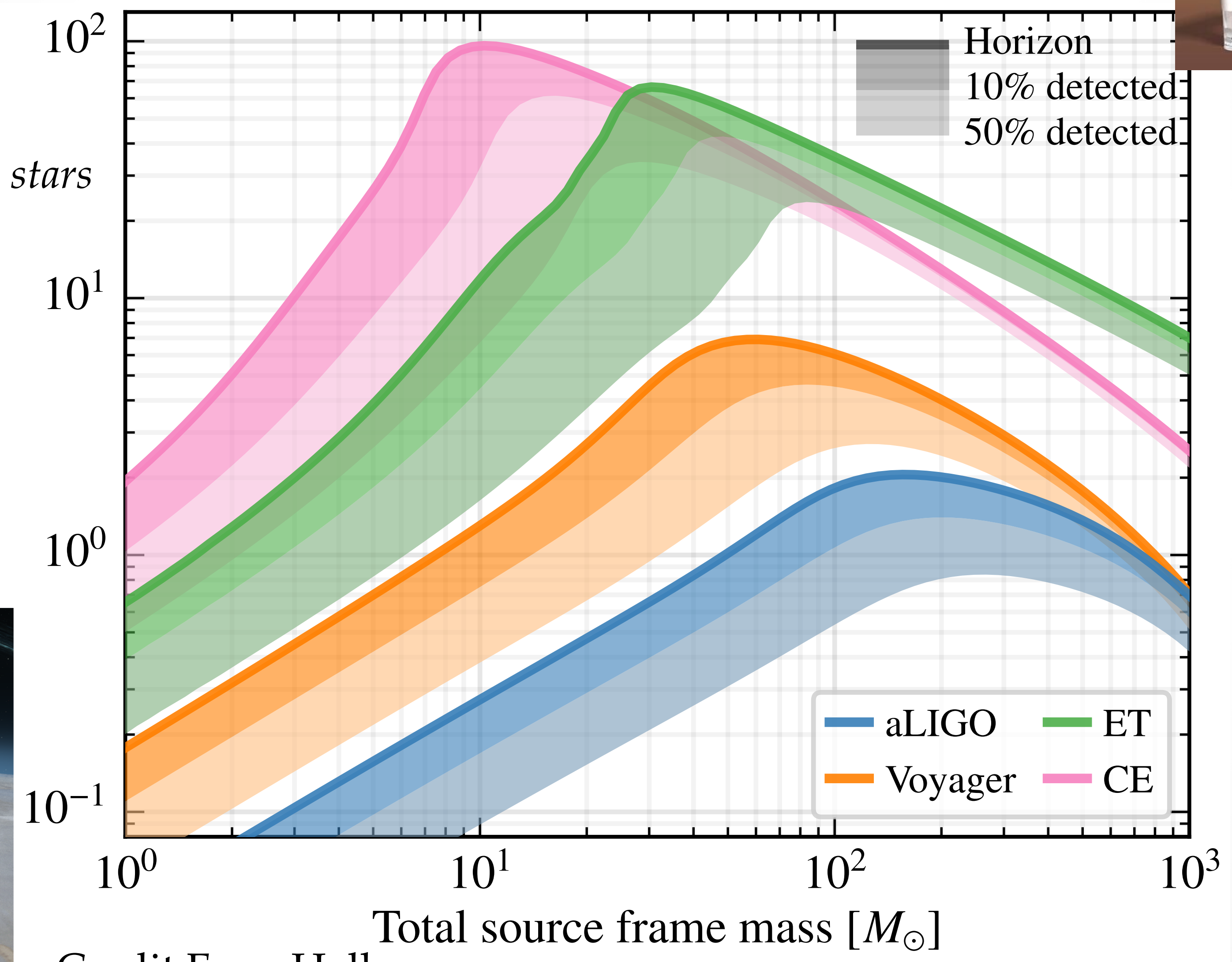
- Larger mirrors
- Higher laser power
- Squeezing light
- Cryogenic interferometer
- Better optics and coating – moving to 2 um ?
- Underground interferometer

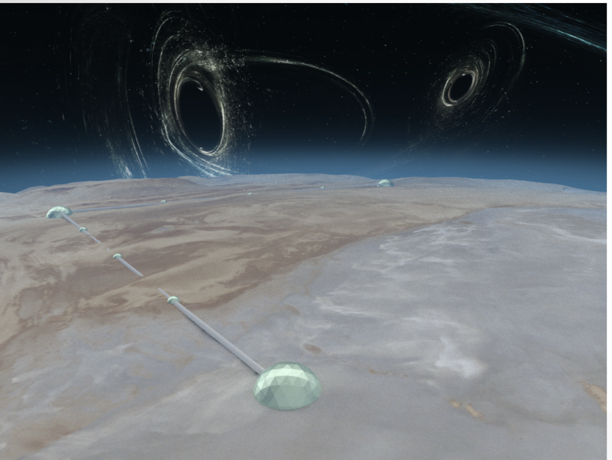
Towards 3G (2030-2035)



Maximal distance for coalescing objects

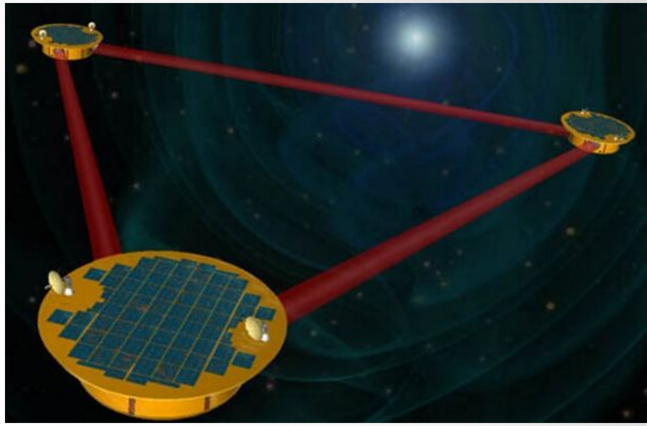
Formation of first stars





Credit Evan Hall

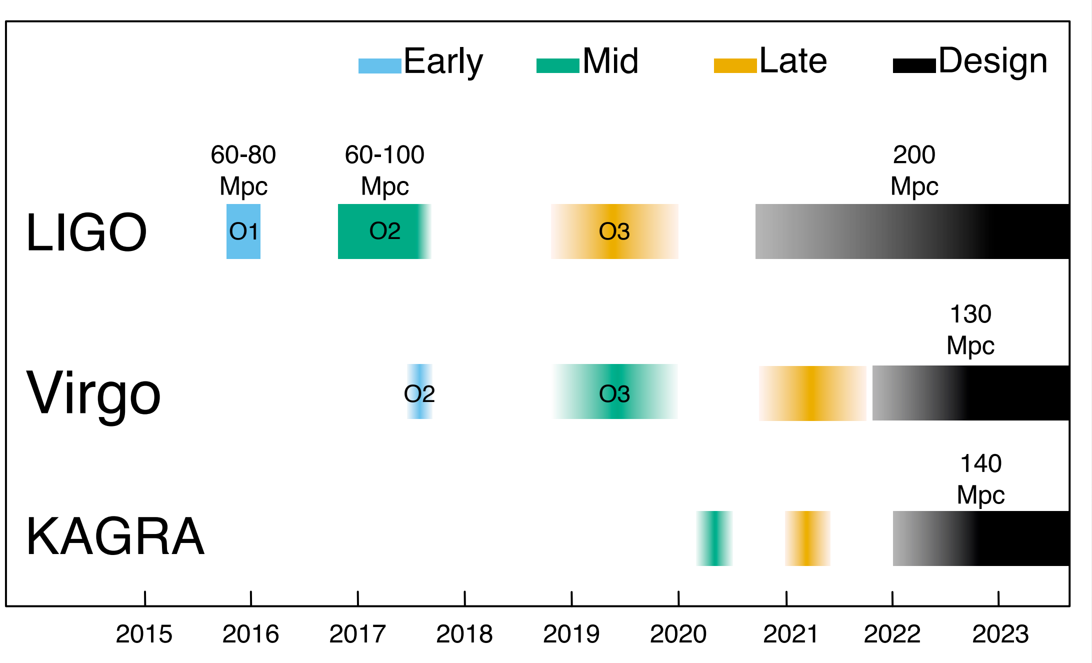
Going into space : LISA



- 3 satellites, time delay interferometry
- Arms with few millions km
- Scientific case:
  - Merger of supermassive black holes
  - Compact solar masses binaries (WD and NS), observe accurately the inspiral phase
  - Extreme mass ratio inspirals , mass ratio > 200
  - BBH, can predict merger time for ground based detectors one year in advance
  - Stochastic background
- Test mission (Pathfinder) showed the readiness of the technics
- Planned for the period 2028-2034

Conclusions

- 11 confirmed detections up to now
  - Black holes with large masses
  - First binary neutron star merger, observed in coincidence with a short gamma-ray burst
  - Test on GR passed
  - First H0 measurement
- New run O3 for one calendar year
  - 3 detectors at beginning
  - KAGRA may join before the end of the data taking
  - Detection rate : ~1/week (BBH)
  - Already 13 candidates publicly released
- 3G already in discussion



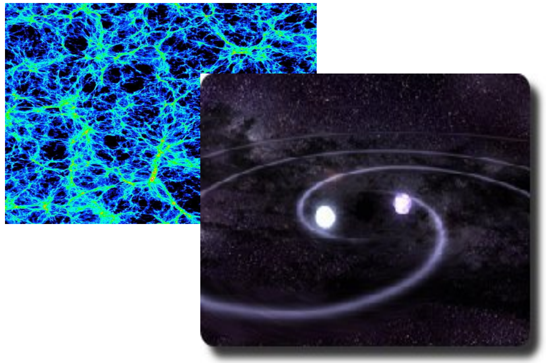
Backup

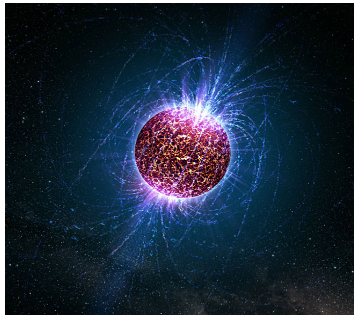
GW zoology

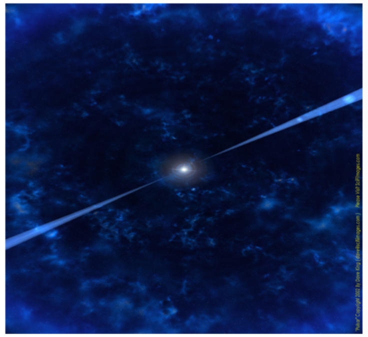
Short duration (1sec)

Long duration (∞)

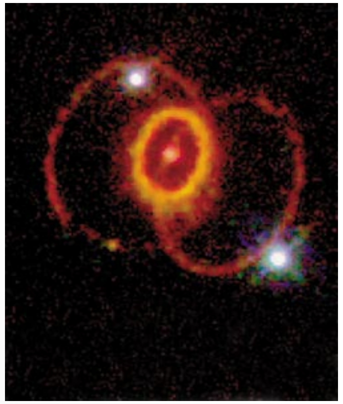
Waveform known



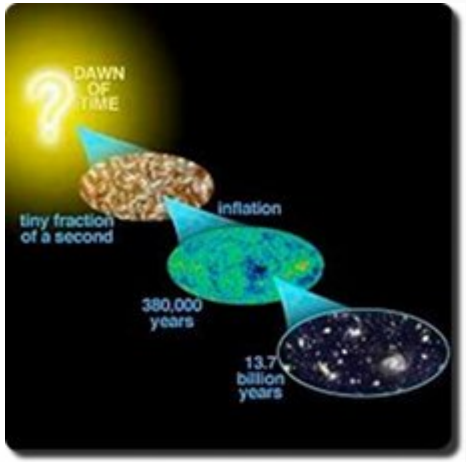




Waveform unknown

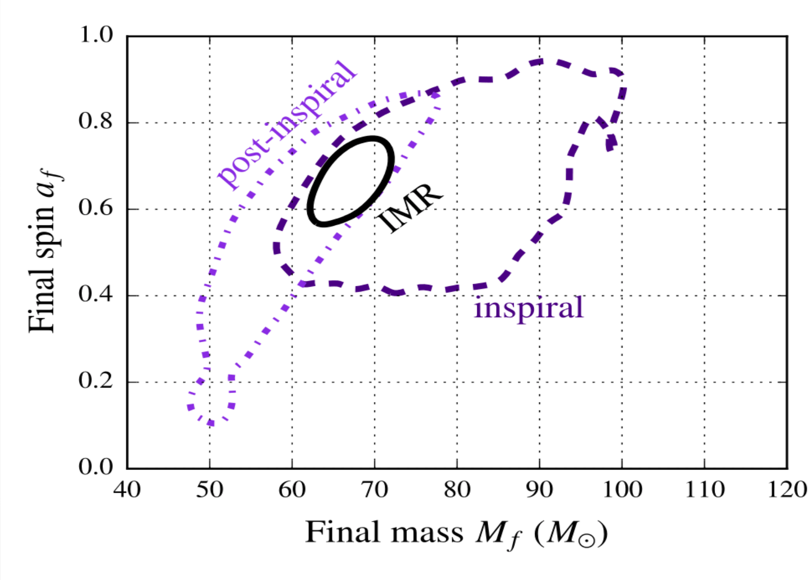


?

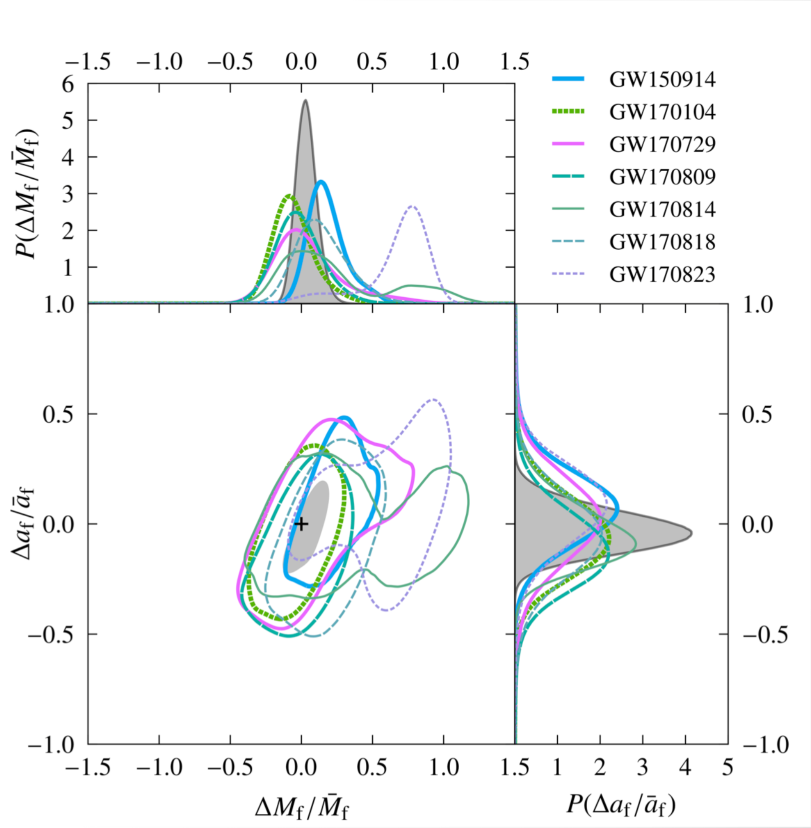


Testing General relativity in a new regime

- We have for the first time test under highly relativistic and non linear conditions
- Different tests can be peformed :
  - Remove waveform and see any deviation from noise in the data : possible deviations less than 4 %
  - Check the consistency of the waveform if:
    - Look only the pre merger phase
    - Use the remaining time serie



Abbott *et al.* PRL 116, 221101



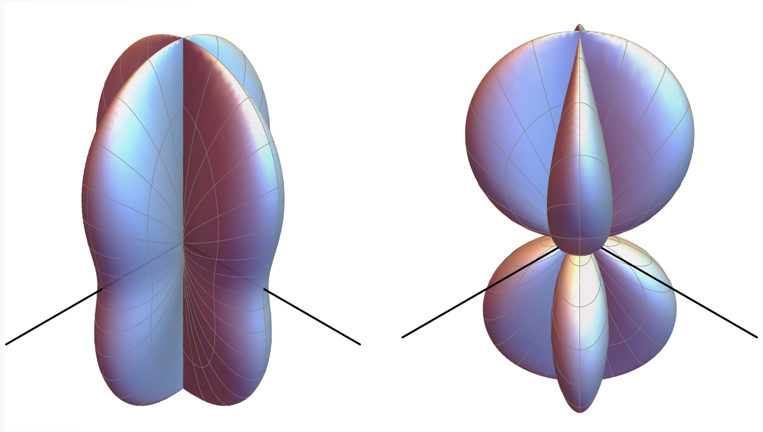
Abbott *et al.* 2019 submitted

Polarization in GR

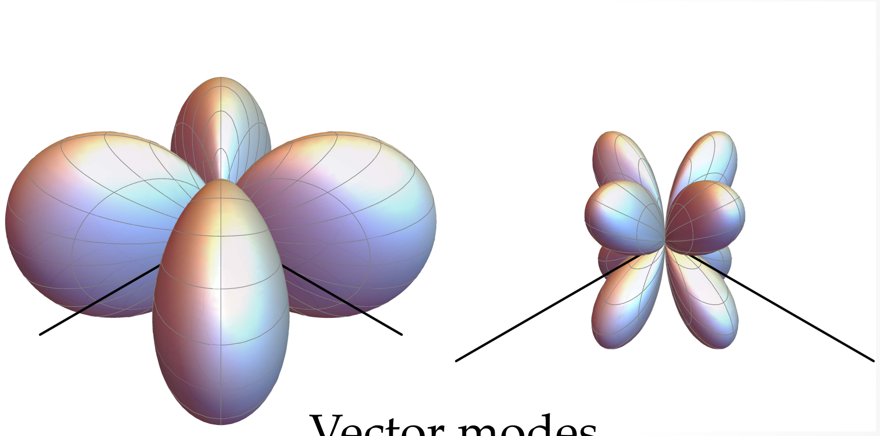
- Generic theories predict up to 6 polarizations states
- With a third detector (non aligned) : test new types of polarizations

Only ones expected with GR

Allowed by other gravitation theories

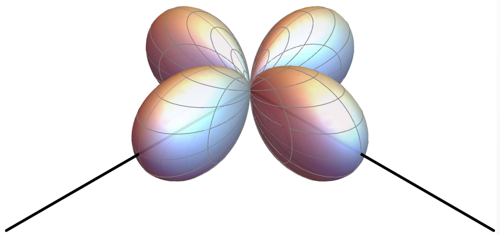


Tensor modes



Vector modes

Antenna pattern



Scalar modes

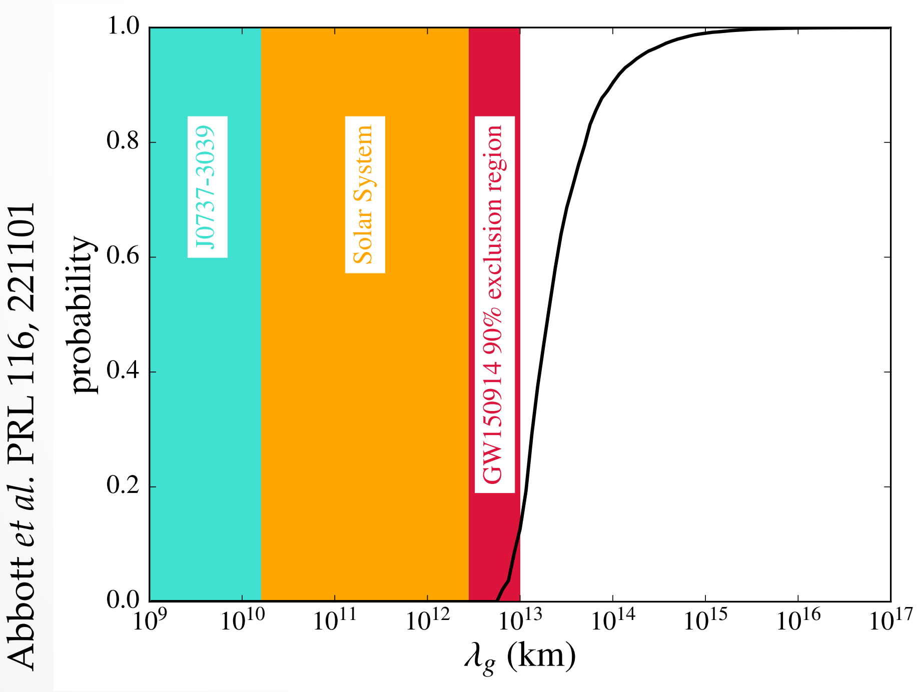
Favor pure tensor vs pure vector or scalar

Cannot conclude on mixed version

GW170814: A Three-Detector Observation of Gravitational Waves from a Binary Black Hole Coalescence, Abbott *et al.* , PRL 119, 141101

Can we say something on graviton ?

- If we postulate a massive graviton we need to take into account Yukawa type correction to Newtonian potential
- This will induce a dispersion depending of the frequency and can tested with 1 PN order



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

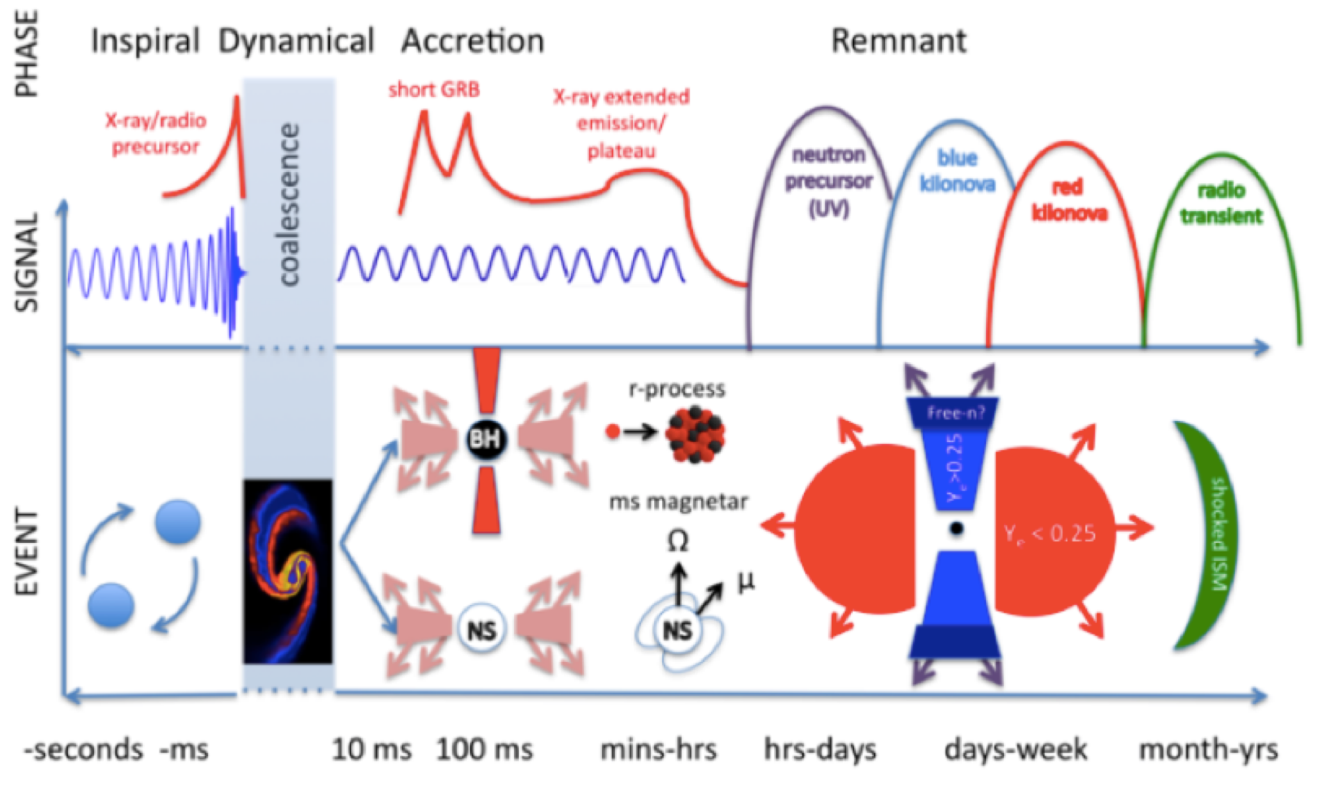
$$\lambda_g = \frac{h}{m_g c}$$

$$\lambda_g > 10^{13} km$$

$$m_g < 10^{-22} eV$$

Kilonova

- During merger phase rich neutrons matter could produce heavy elements by neutron capture (r-process)
- Quasi isotropic emission, heated by radioactivity, emission expected to shift from blue to red during cooling



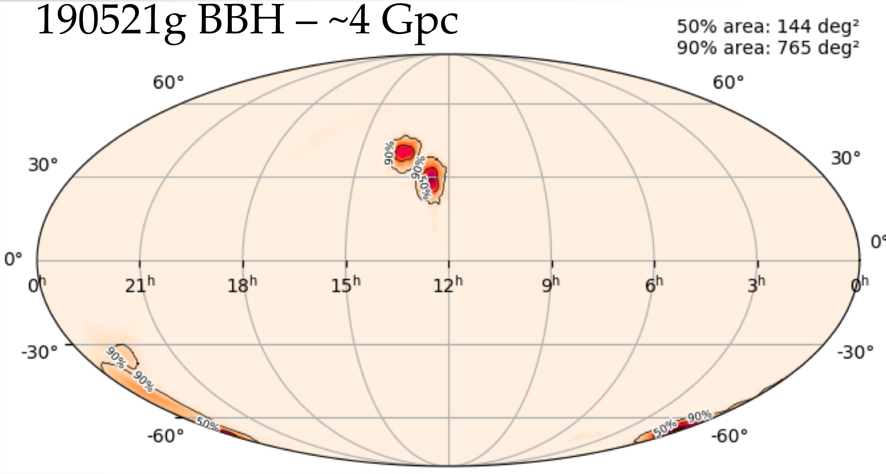
Fernandez and Metzger, A.. Rev. Nuc. Part. Sci. 2016, 66

Image Credit: NASA Goddard Space Fight Center / CI Lab

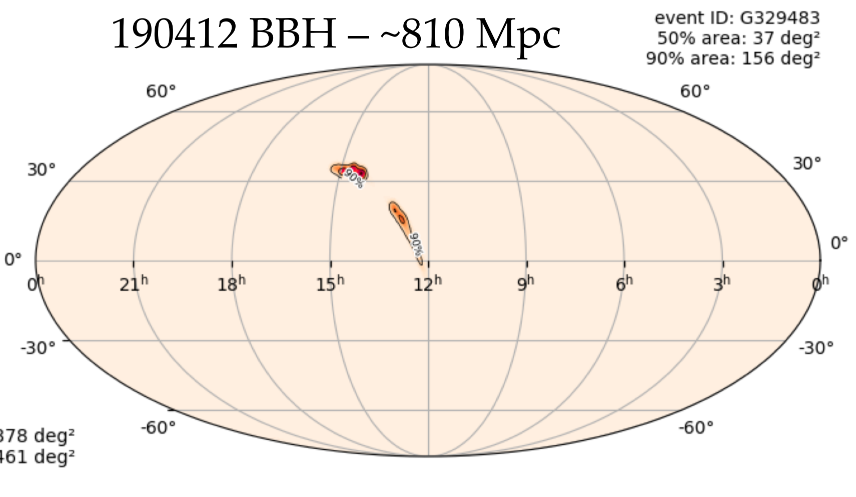
First public alerts – not confirmed detections !

Only few examples !!!

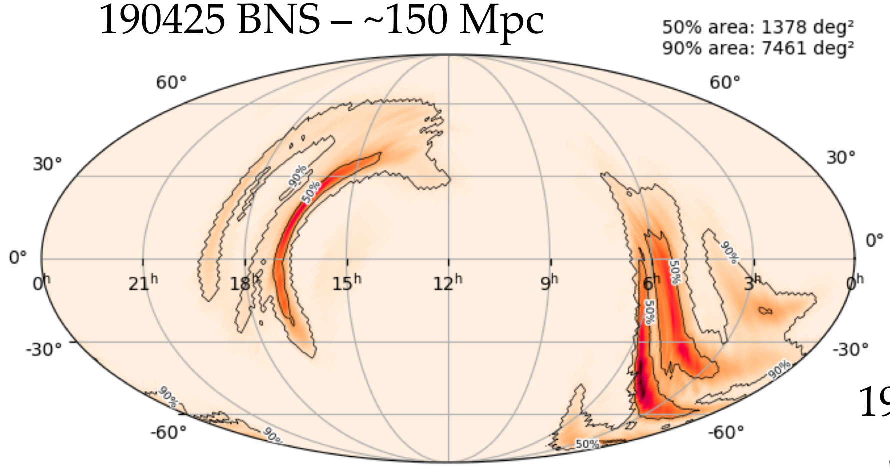
190521g BBH – ~4 Gpc



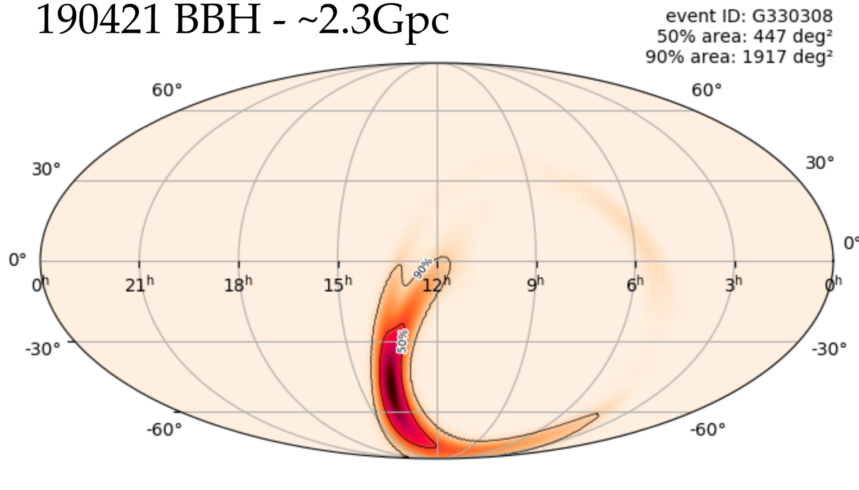
190412 BBH – ~810 Mpc



190425 BNS – ~150 Mpc



190421 BBH - ~2.3Gpc



190426 NSBH - ~380 Mpc