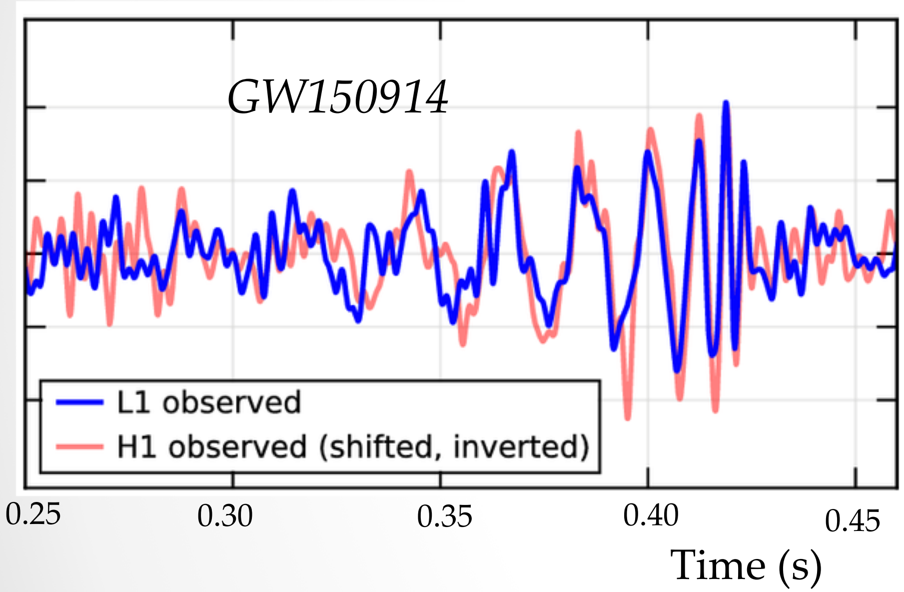
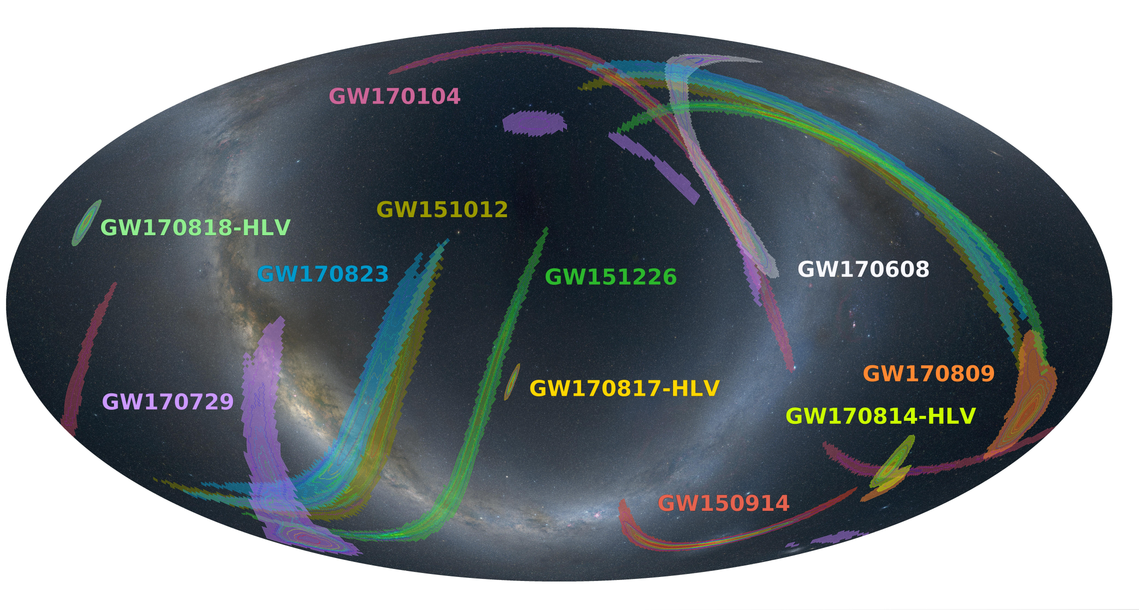
Gravitational wave : recent results and future of the field

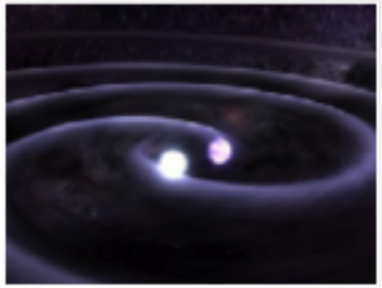




Nicolas Leroy
Laboratoire de l'accélérateur linéaire d'Orsay

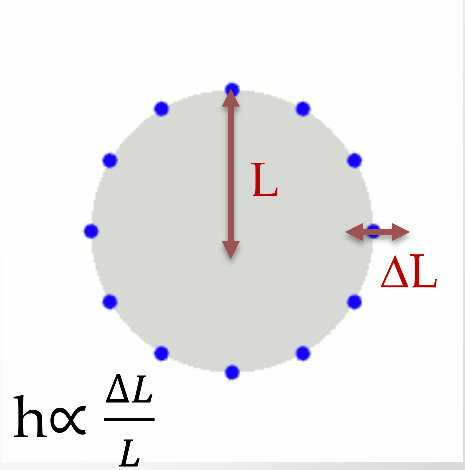
Cosmic explosions 2019 – 30 May 2019

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



1916-2016: a century of progress

Theoretical developments

- ❖ 1916: GW prediction (Einstein)

1957 Chapel Hill Conference (Bondi, Feynman, Pirani, etc.)

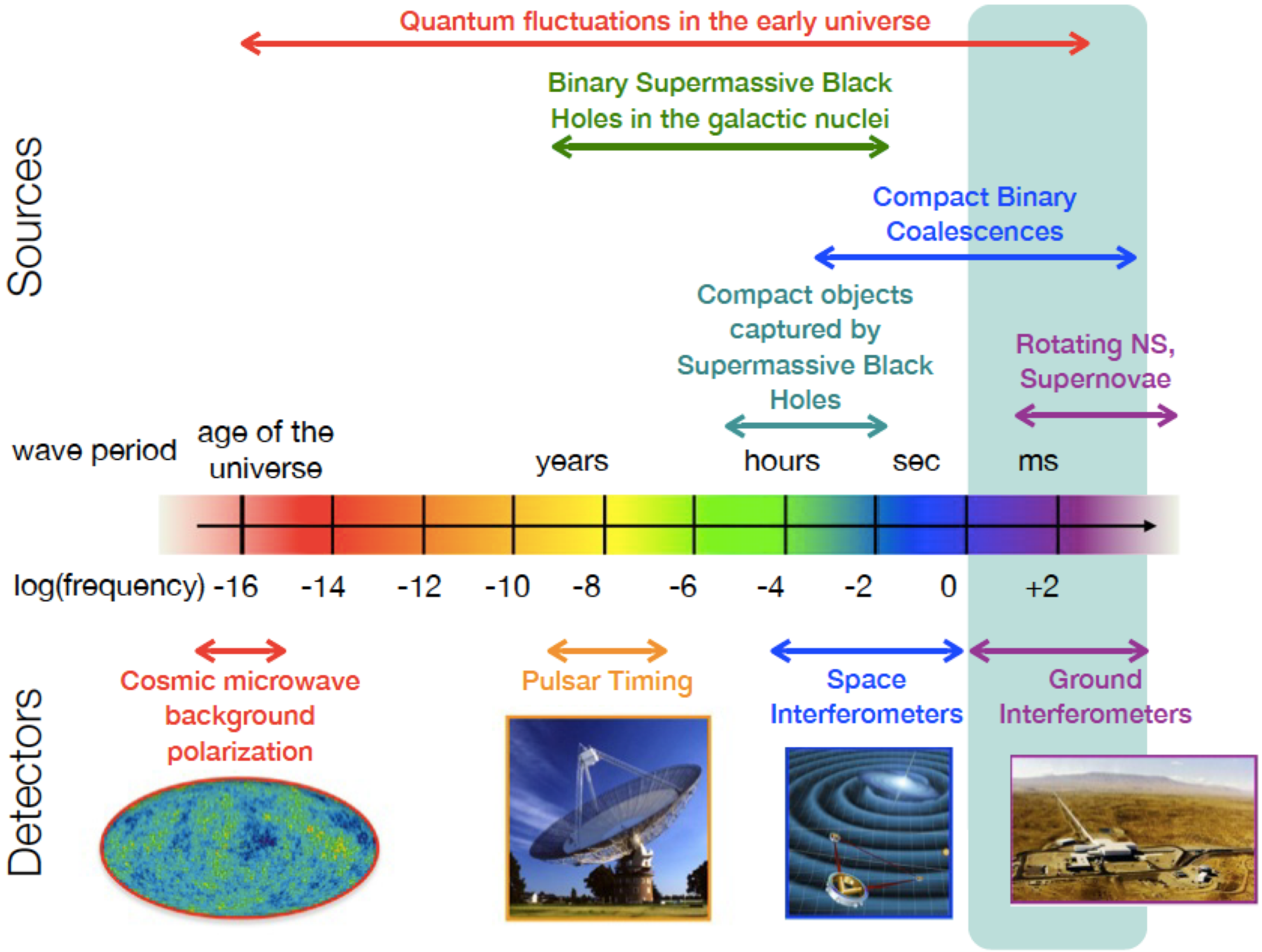
- ❖ 1963: rotating BH solution (Kerr)
- ❖ 1990's: CBC PN expansion (Blanchet, Damour, Deruelle, Iyer, Will, Wiseman, etc.)
- ❖ 2000: BBH effective one-body approach (Buonanno, Damour)
- ❖ 2006: BBH merger simulation (Baker, Lousto, Pretorius, etc.)

See E. Porter's lecture

Experiments

- ➢ 1960's: first Weber bars
- ➢ 1970: first IFO prototype (Forward)
- ➢ 1972: IFO design studies (Weiss)
- ➢ 1974: PSRB 1913+16 (Hulse & Taylor)
- ➢ 1980's: IFO prototypes (10m-long)
- ➢ (Caltech, Garching, Glasgow, Orsay)
- ➢ End of 1980's: Virgo and LIGO proposals
- ➢ 1990's: LIGO and Virgo funded
- ➢ 2005-2011: initial IFO « science » » runs
- ➢ 2007: LIGO-Virgo Memorandum Of Understanding
- ➢ 2012 : Advanced detectors funded
- ➢ 2015: First Advanced LIGO science run

The Gravitational Wave Spectrum



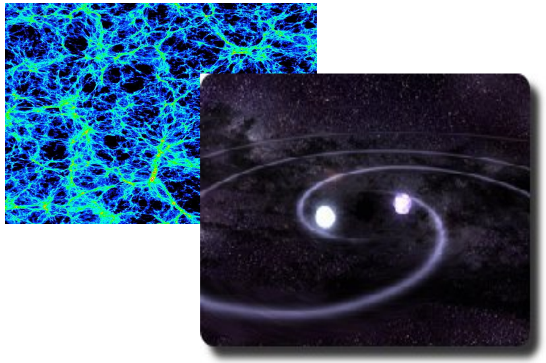
[Inspired from http://science.gsfc.nasa.gov/663/research/]

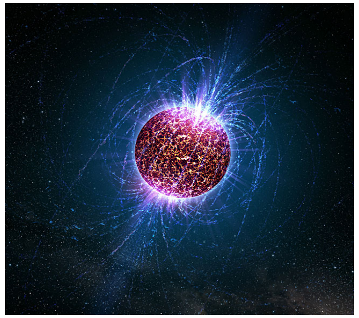
GW zoology

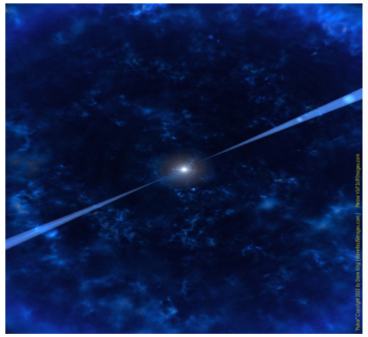
Short duration (1sec)

Long duration (∞)

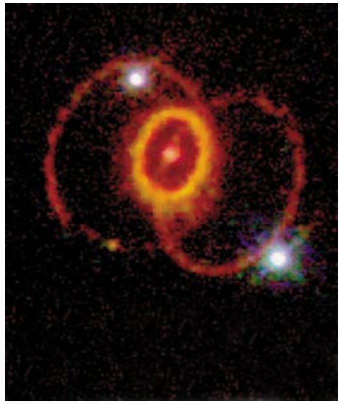
Waveform known



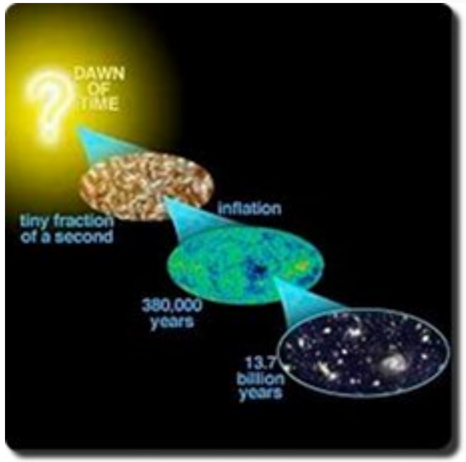




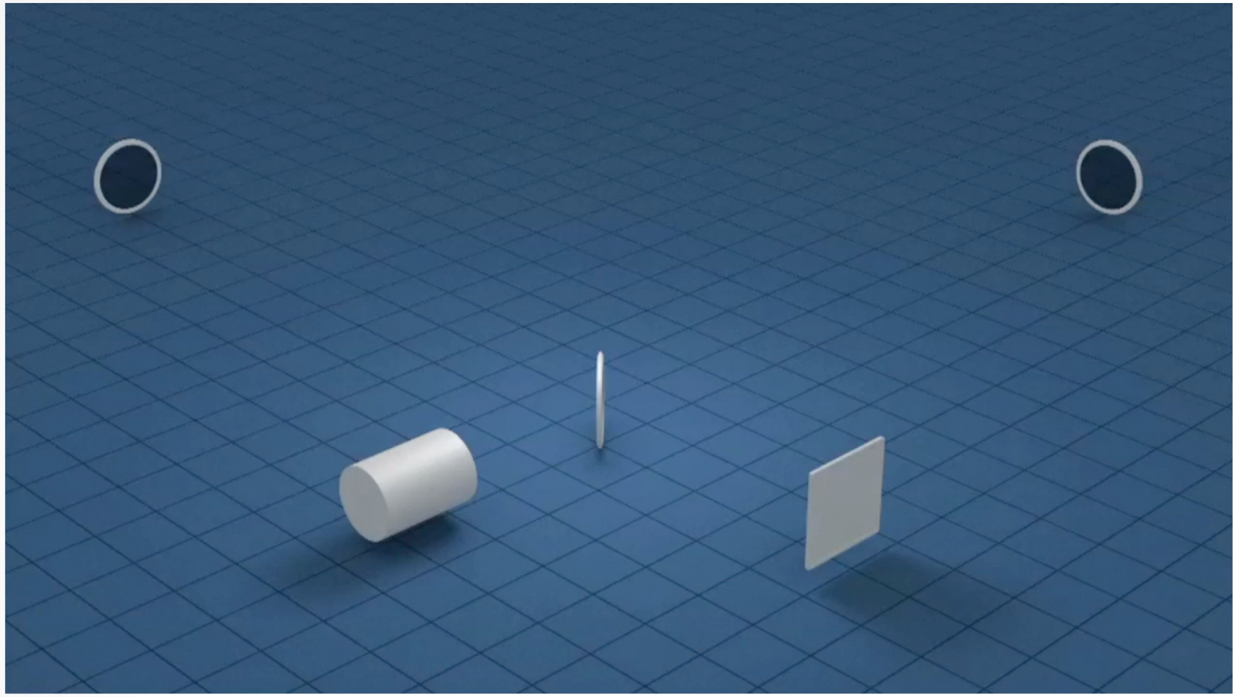
Waveform unknown



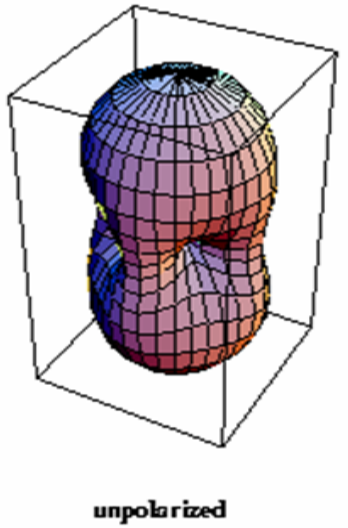
?



Interferometer and GW



Sensitivity : almost full sky



Averaged beam antenna

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

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

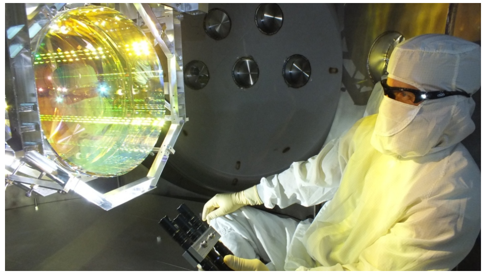
Detected signal proportional to h(t)

Advanced generation detectors

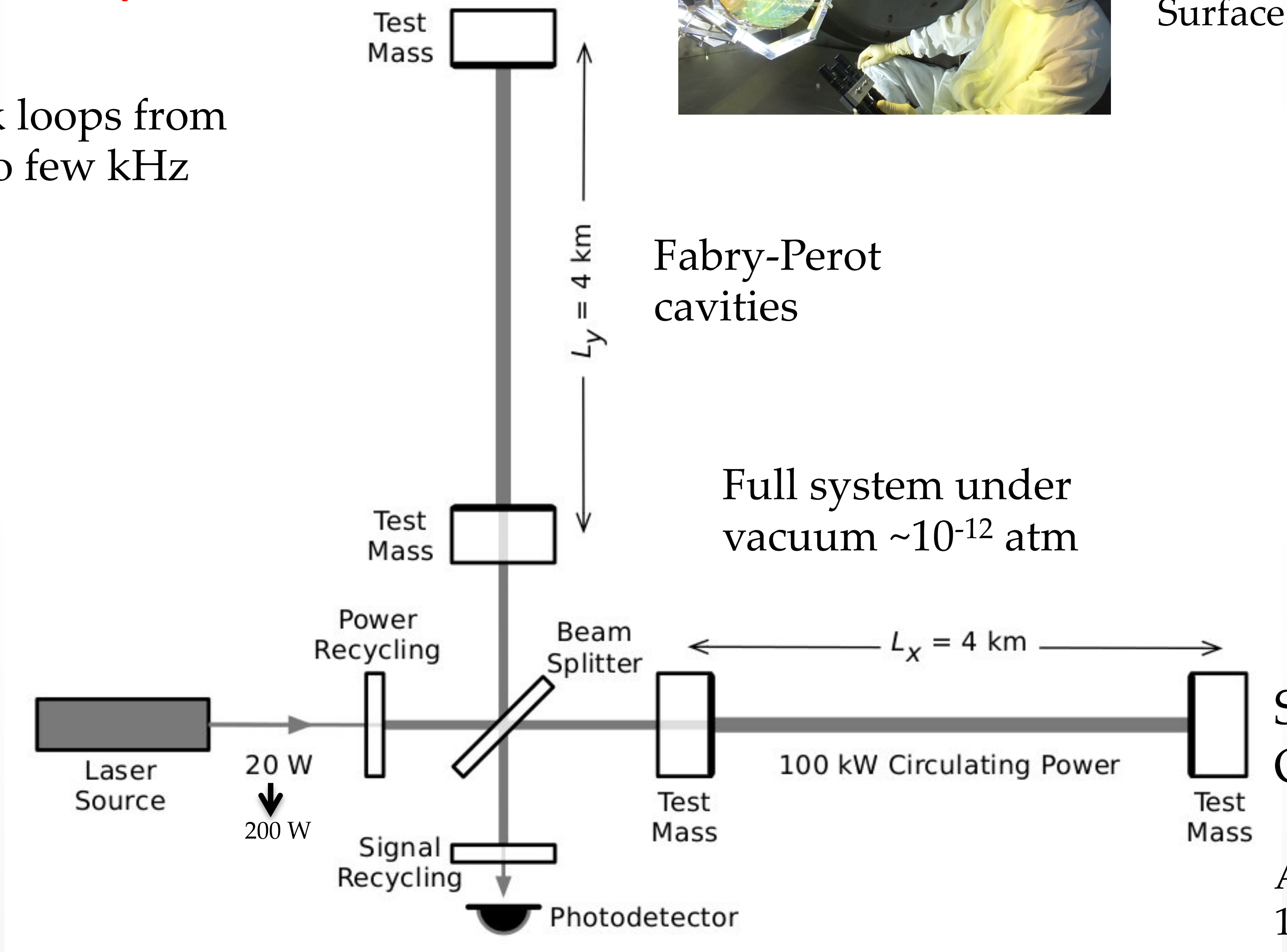
Michelson interferometer

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

Feedback loops from few Hz to few kHz



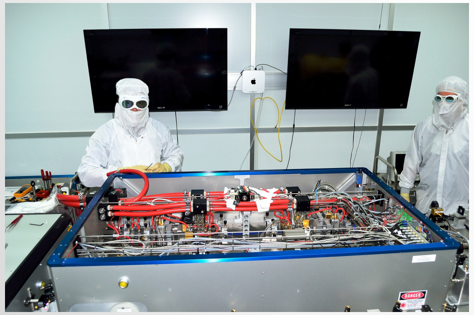
High quality optics – 40 kg
Surface RMS ~nm



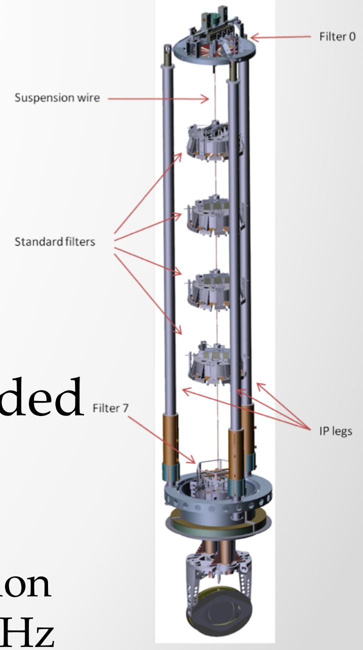
Fabry-Perot cavities

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

High power laser

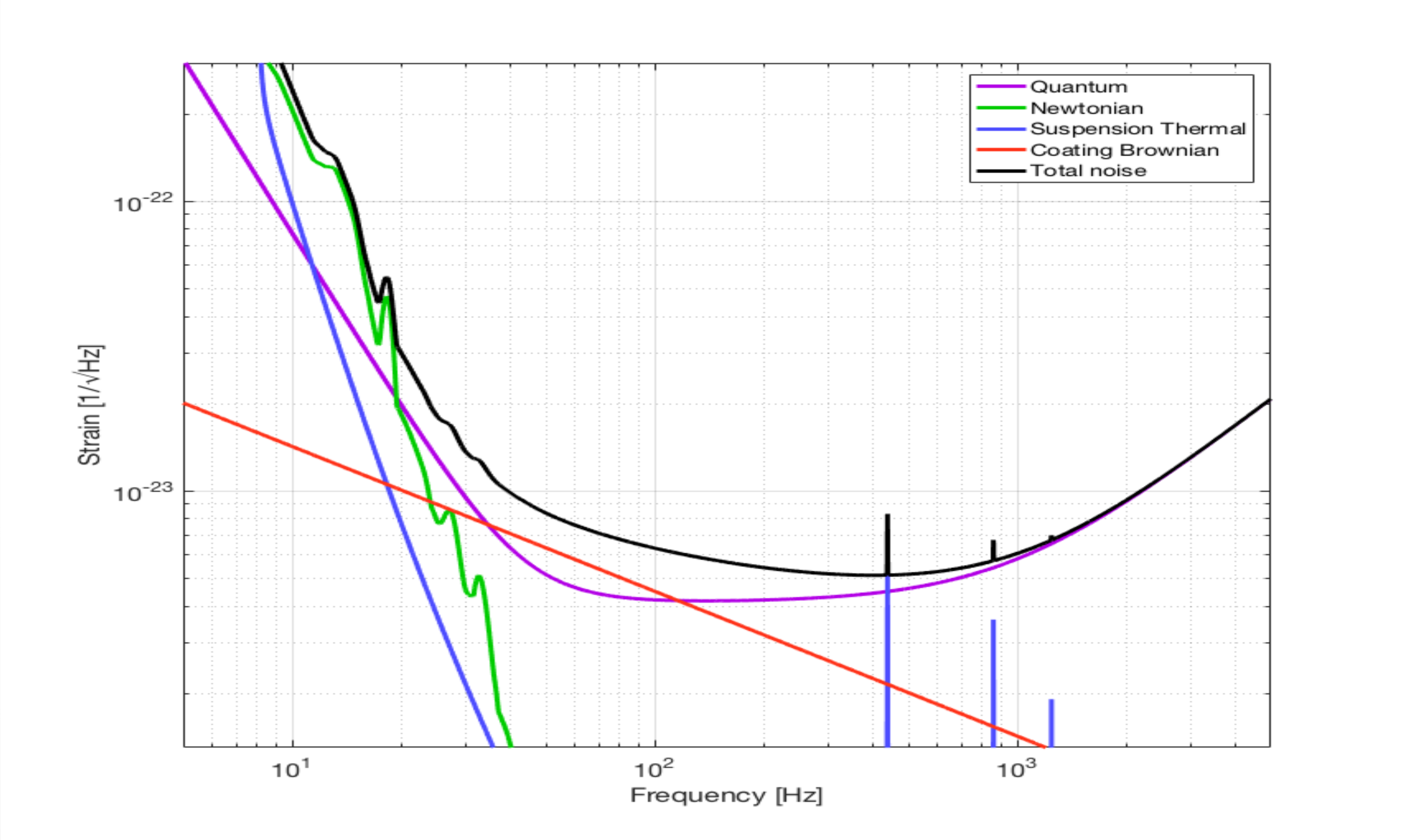


Suspended Optics



Attenuation 10^{14} @ 10 Hz

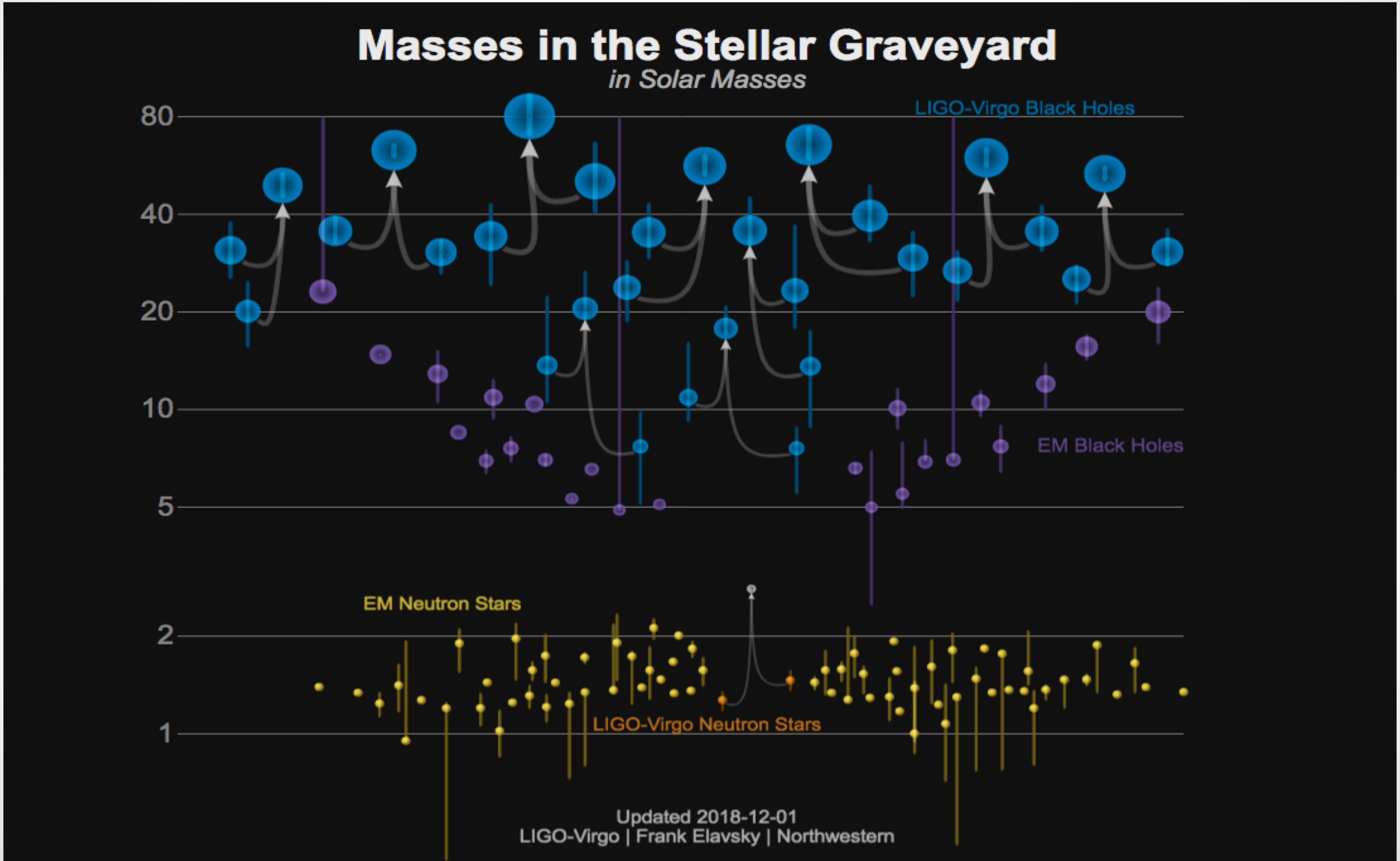
Sensitivity



GW network

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

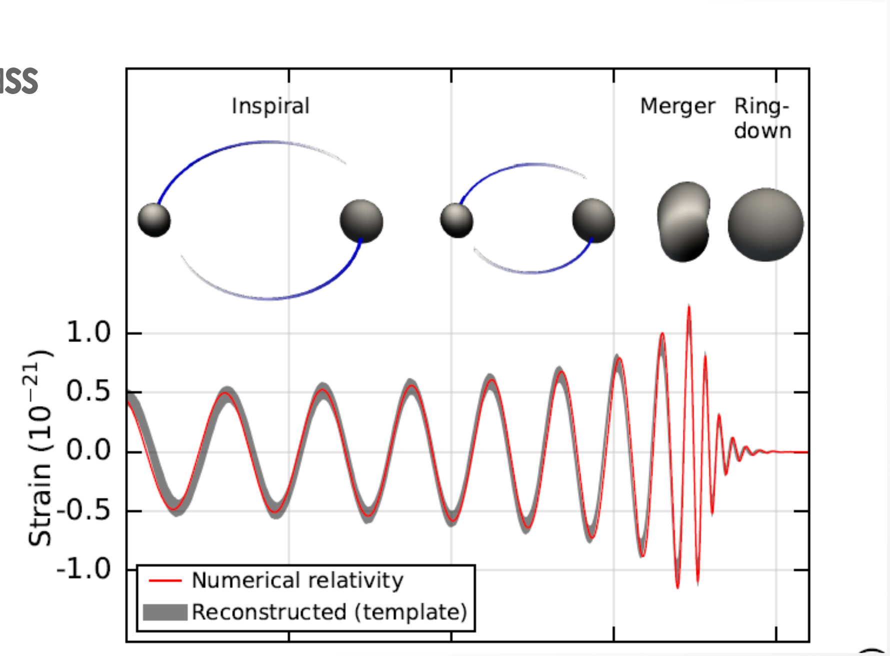
GW detections



Coalescing binaries

See E. Porter's lecture

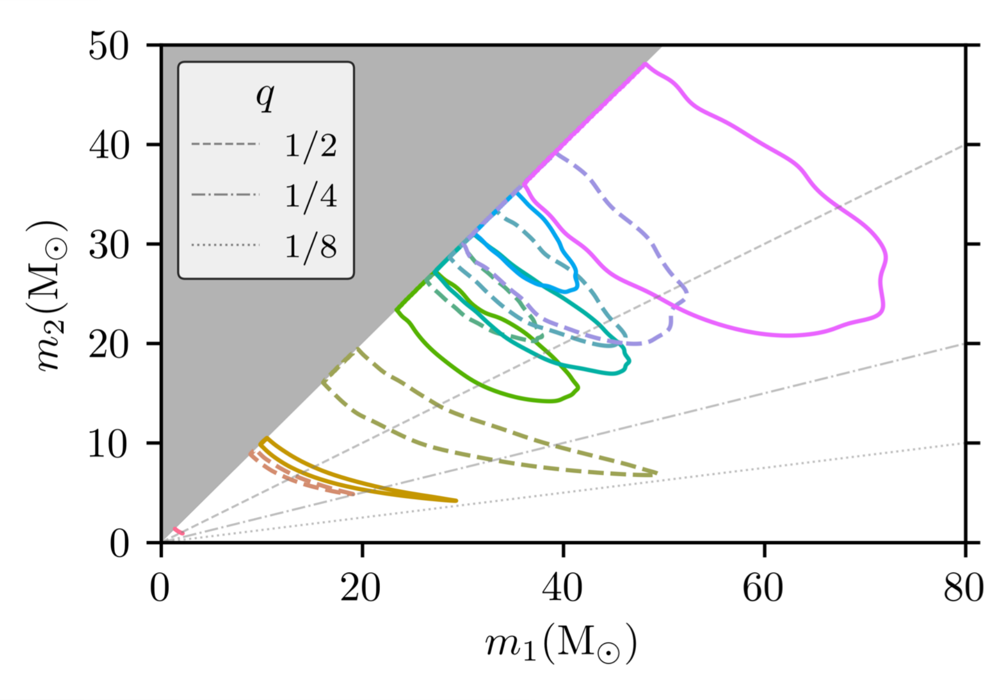
- Searching for objects containing black holes (BH) and neutron stars (NS)
- Possible electromagnetic emission if one object is a NS
- Known waveforms from analytical model or numerical relativity simulations
- Waveform allow to retrieve :
  - Masses : ratio (chirp mass) and total mass
  - Spins : initials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

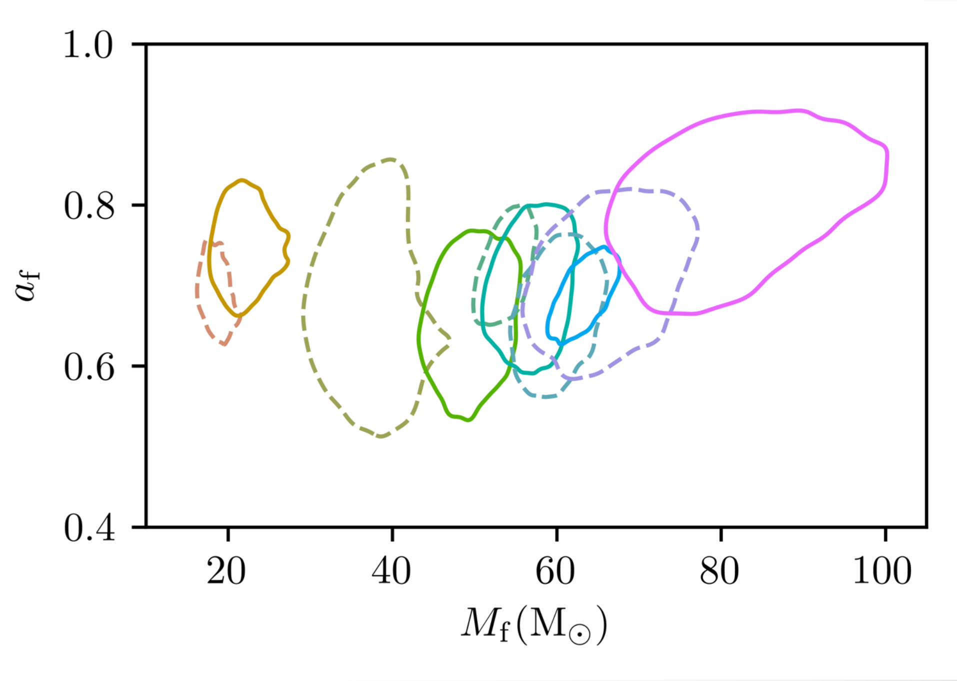


Detecting black holes

See S. Markoff, E. Porter's lectures

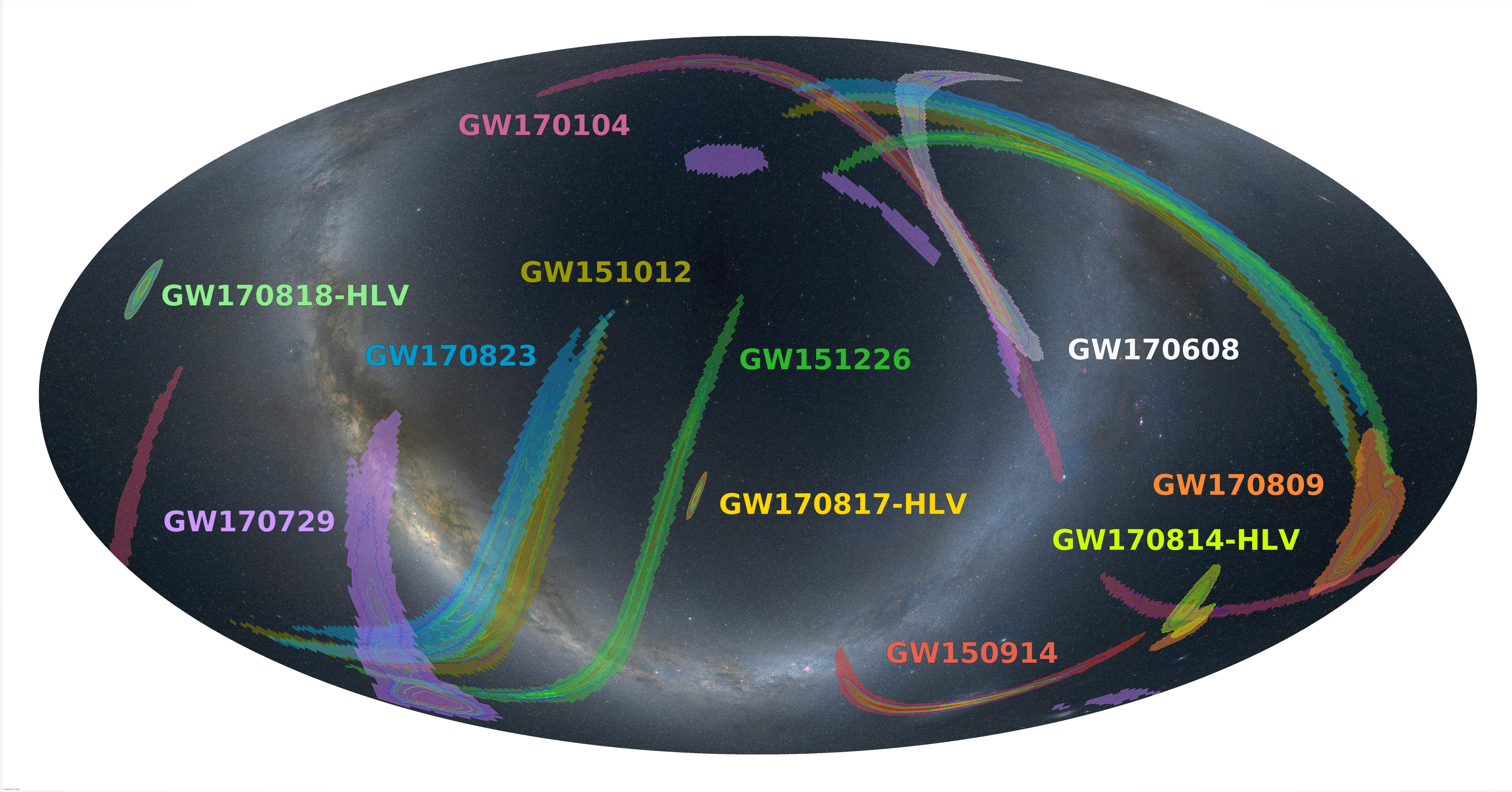
- Detected Binary Black Holes in the mass range : 5 – 50 $M_{\odot}$
- Detection range up to ~Gpc, mostly ~450 Mpc
- Rate : R = 9.7 – 101 $Gpc^{-3}\ yr^{-1}$
- A large fraction of energy in GW : 1 to 3 $M_{\odot}$
- No large constraint on spins





Abbott et al, PRX 9 (2019)

Sky error regions

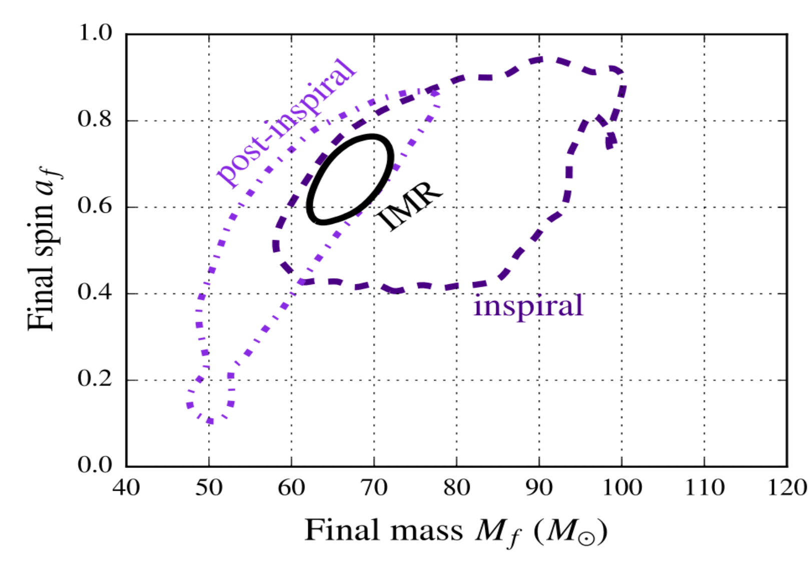


Sky map reconstructed with time of flight technic

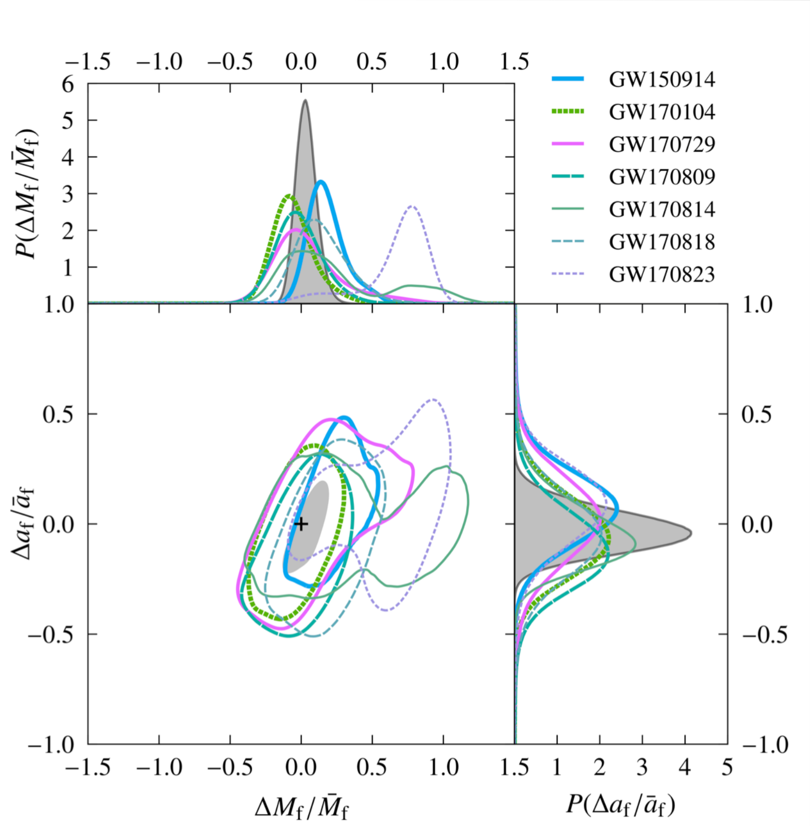
Large improvement since Virgo joined data taking

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



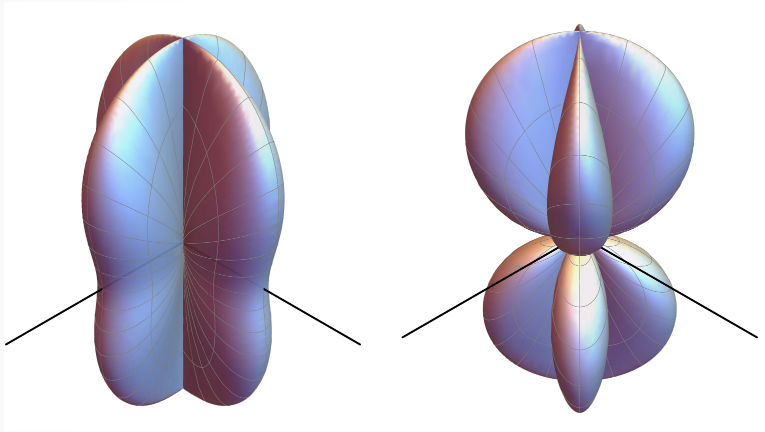
Abbott *et al.* 2019 submitted

Polarization in GR

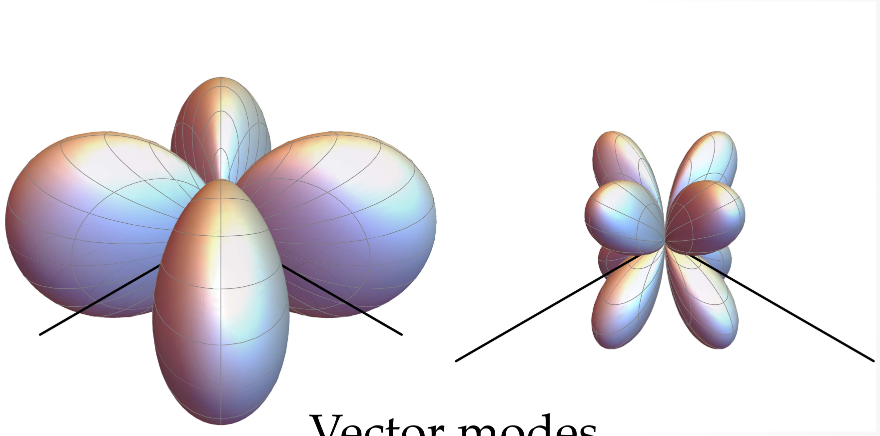
- Generic theories predict up to 6 polarizations states
- With a third detector (non aligned) : test new types of polarizations

Only ones expected with GR

Allowed by other gravitation theories



Tensor modes

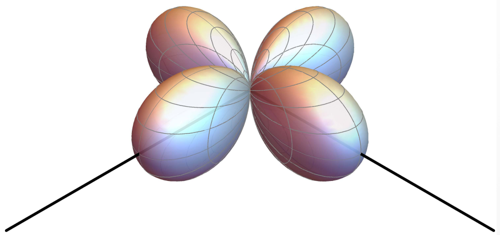


Vector modes

Antenna pattern

Favor pure tensor vs pure vector or scalar

Cannot conclude on mixed version

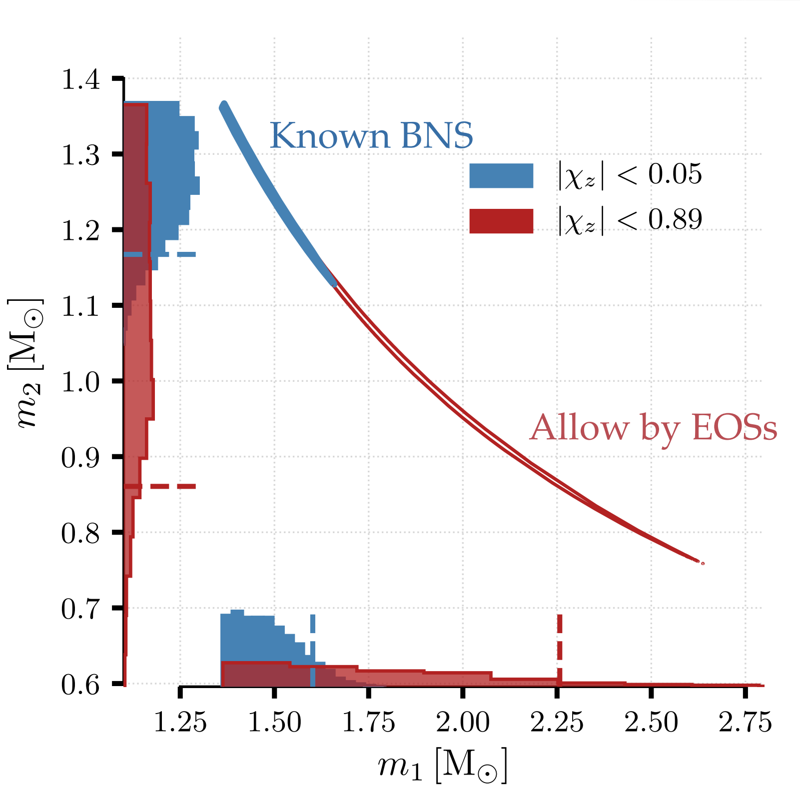


Scalar modes

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

GW170817 :First binary neutron star

- SNR ~ 32.4,
- FAR <1 10^{-4} /year
- Long event (~100 secs)
  - light masses system !
- Probability to have at least one neutron star is important
- Possible electromagnetic counterpart !



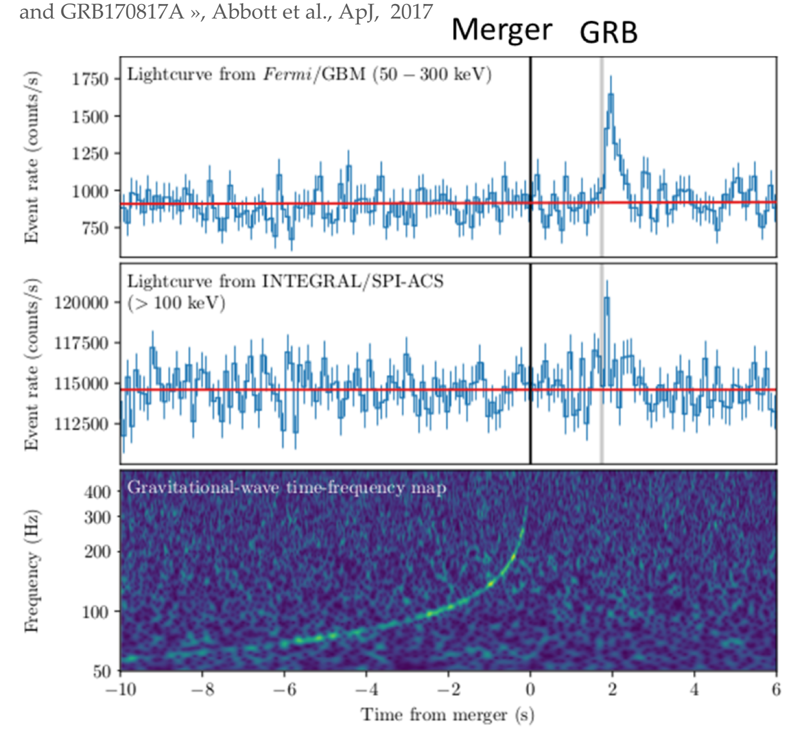
$$M_{Chirp} = \frac{(m_1 m_2)^{3/5}}{(m_1+m_2)^{1/5}} = 1.188^{+0.004}_{-0.002} M_\odot$$

GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral , Abbott *et al.* , PRL 119, 161101

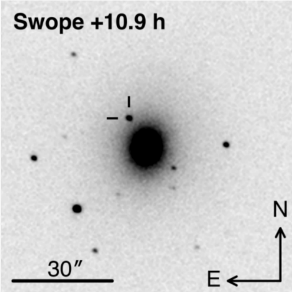
A first electromagnetic counterpart

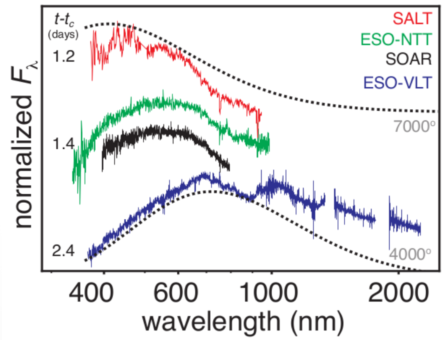
See F, Daigne's lecture

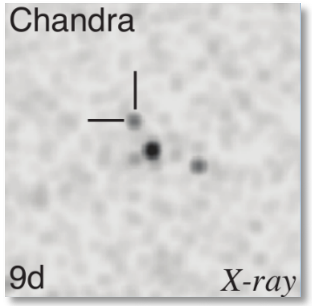
« Gravitational waves and Gamma-rays from binary neutron star merger: GW170817 and GRB170817A », Abbott et al., ApJ, 2017

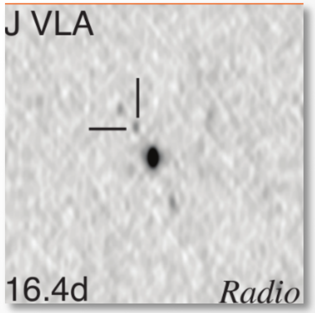


- Association to a gamma-ray burst (> 5.3 σ) within 1.7s and same sky region
- Including the 3 interferometers -> 28 deg²
- Radio to X-rays counterpart found (latency hours to days)
- Found in NGC4993, distance determined between EM and GW compatible
- Kilonova emission





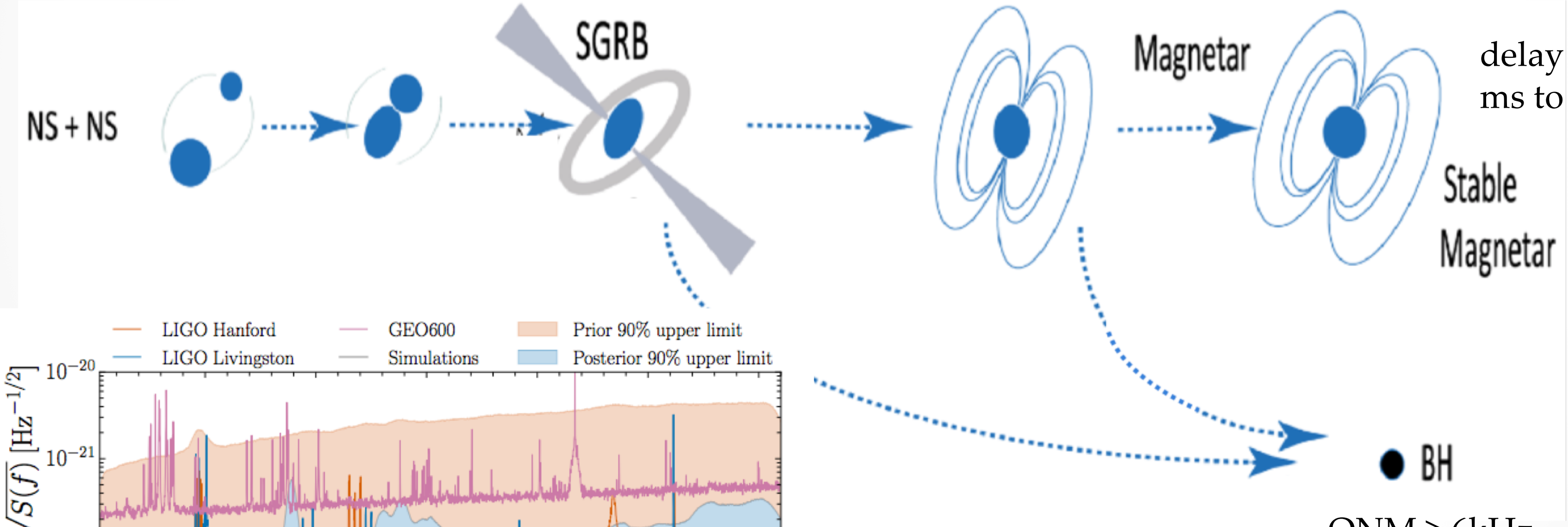




Remanent object

- Different scenarios are possible
- Not yet possible to conclude with GW signal only

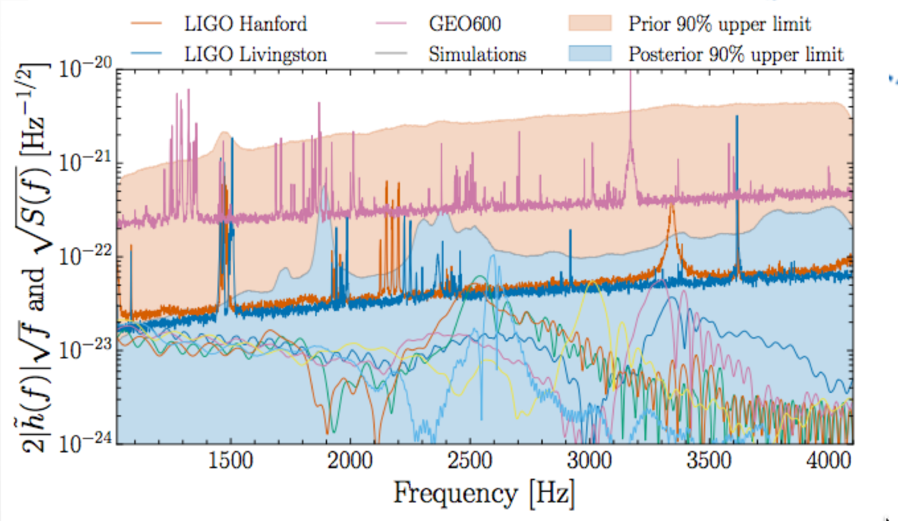
Signal from ms to 10s ks



delay between
ms to 10s of ks

QNM ≥ 6kHz

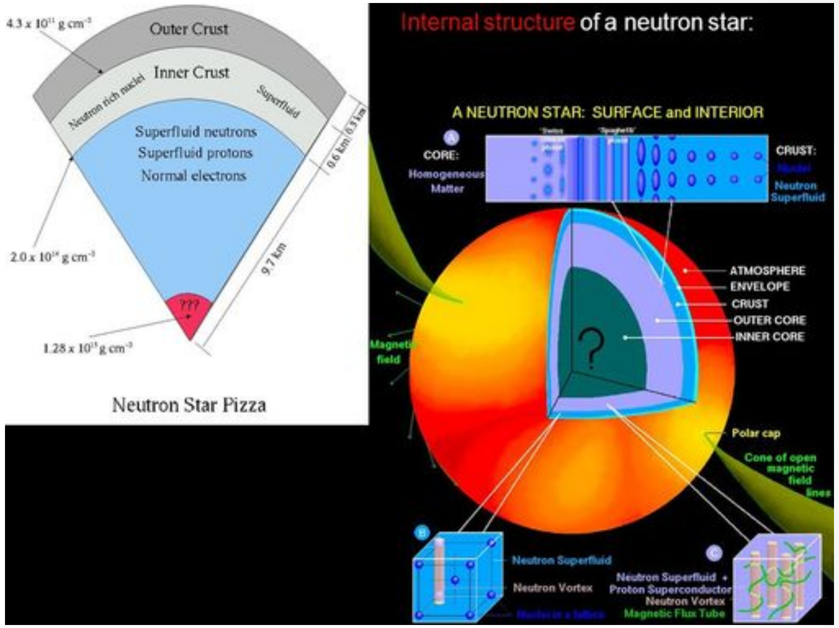
Signal ~ ms



Properties of the binary neutron star merger GW170817, Abbott et al, submitted to PRX, 2018

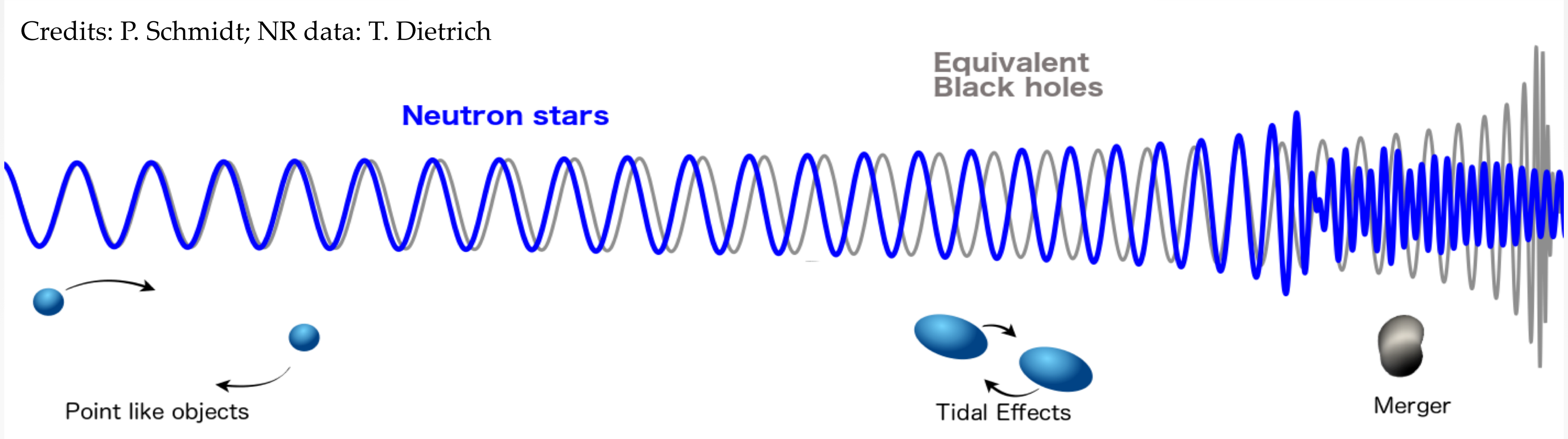
Equation of state of nuclear matter

- Among the most densest objects in the Universe
- Large uncertainties on their structure
  - Structure of the crust
  - Neutron superfluid in outer core
  - Deep core composition ?
  - Magnetic fields



- GW information complementary to the LHC
- Equation of state influence :
  - Pressure as function of density
  - Mass as function of radius
  - Tidal deformability
  - Impact on post merger

Constraints on EOS



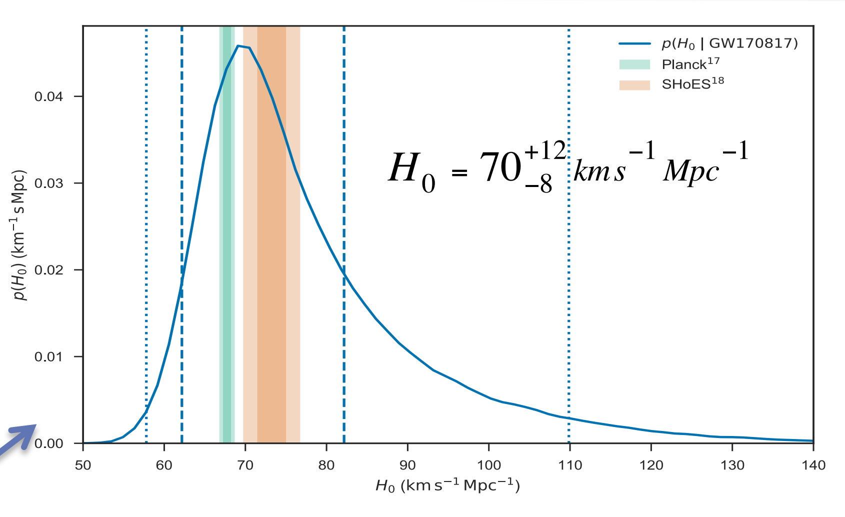
- Tidal effects when stars are close
- Affect the GW waveform

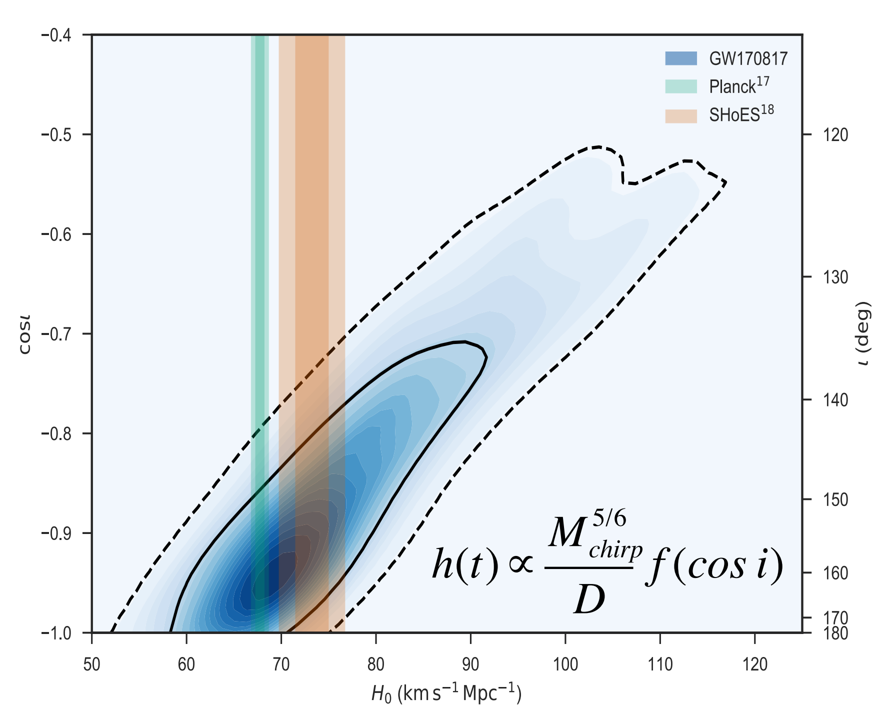
- Compact stars are favored
- Consistent with radius below 14 km
- 10s of detections to distinguish between the models
- First detections of spinning neutron stars (pulsars) will also add constraints

Hubble constant measurement

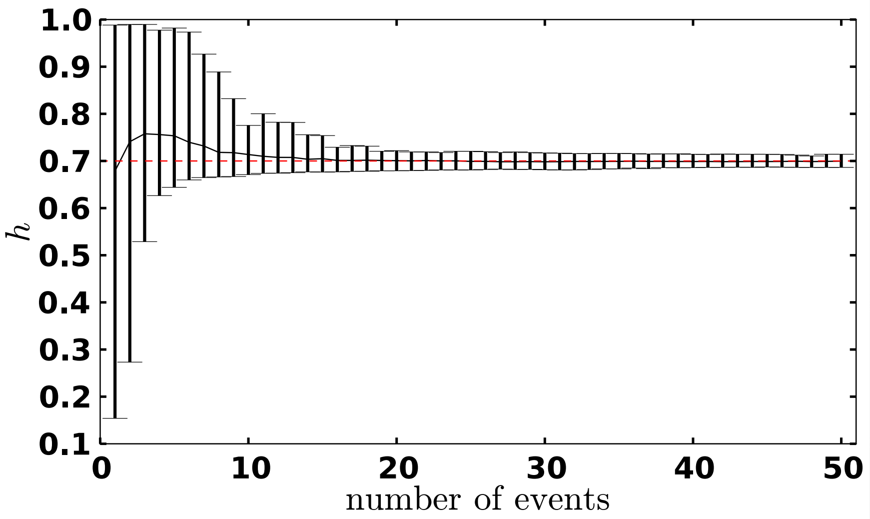
See M. Rigault 's lecture

- 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 using time delay and source distance

- Speed of gravity : $$-3\,10^{-15} \leq \frac{v_{GW} - v_{EM}}{v_{EM}} \leq +7\,10^{-16}$$

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

gravitational potential

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

Deviation to Einsten-Maxwell

- Lorentz Invariance violation :

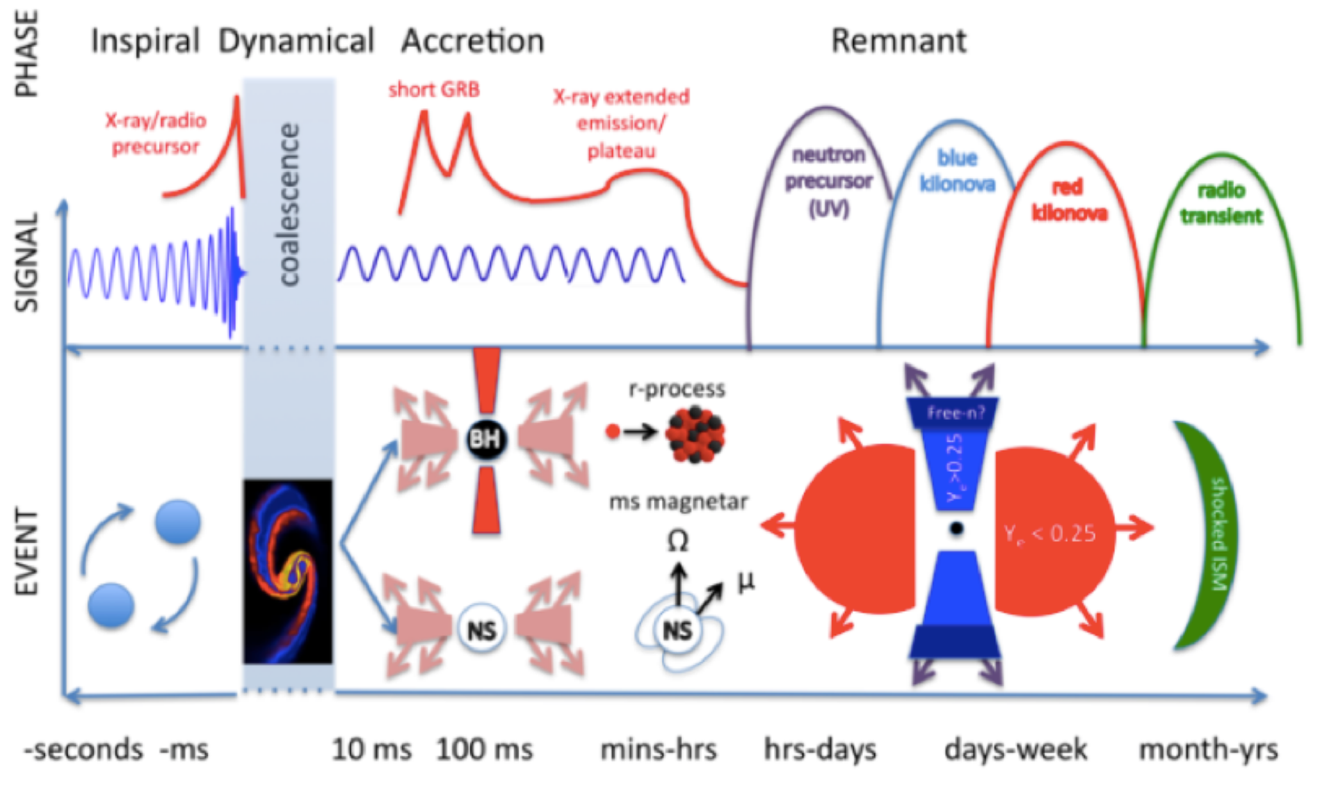
Improve between a factor 2 and 10^{10} previous constraints

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)

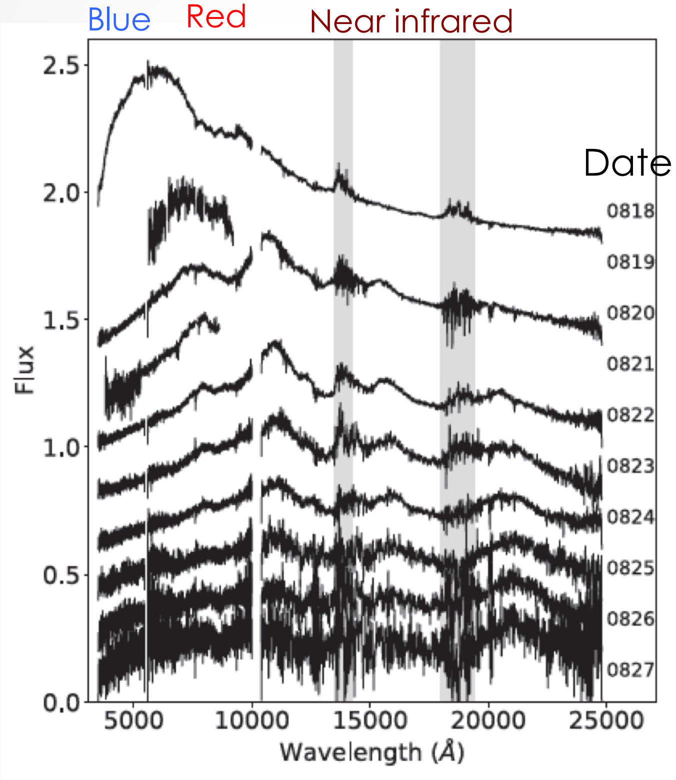
Kilonova

- 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

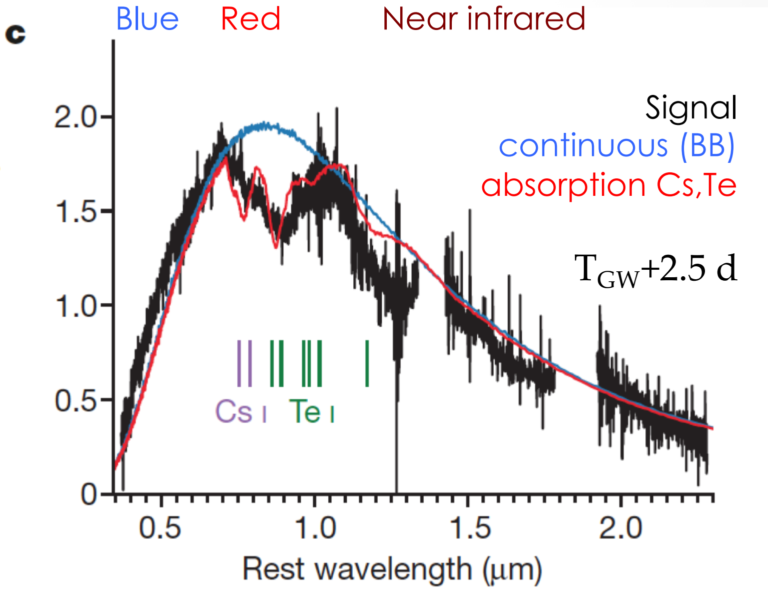


Fernandez and Metzger, A.. Rev. Nuc. Part. Sci. 2016, 66

Kilonova – spectral observations



Grawita Spectrum ESO/VLT & Gemini



ePESSTO - Spectrum ESO/VLT & Gemini

- Spectrum favor a relativistic ejecta
- Rule out supernova hypothesis
- 11000 K at day 1, 5000 K a day later, 1400 K 10 days later
- Spectrum show contributions from heavy elements

GW detectors in the next months

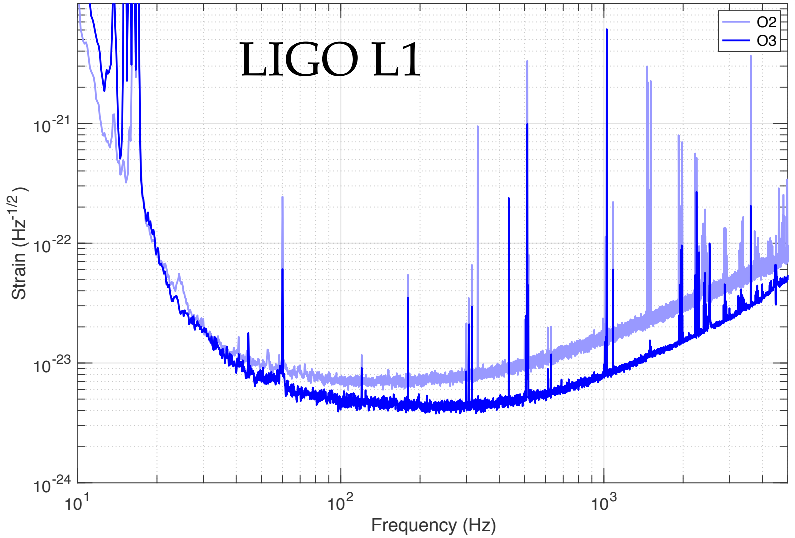
O3 is planned for one year

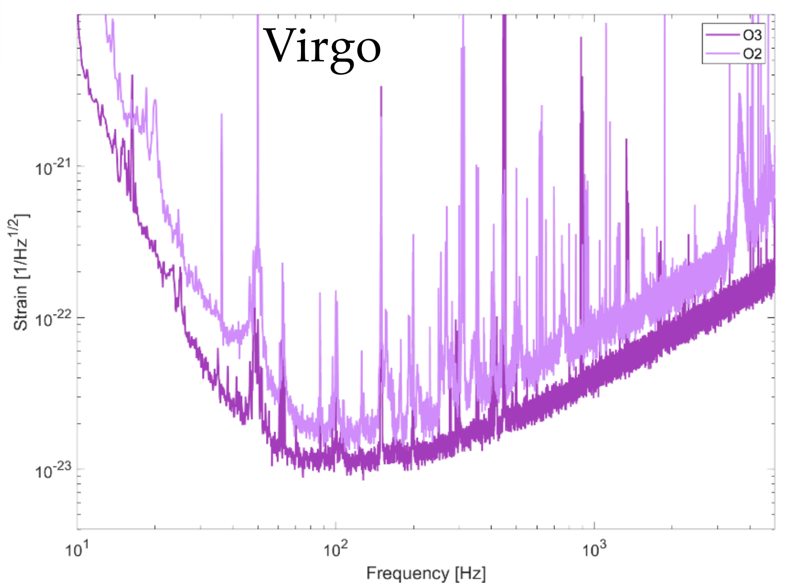
Range BNS :

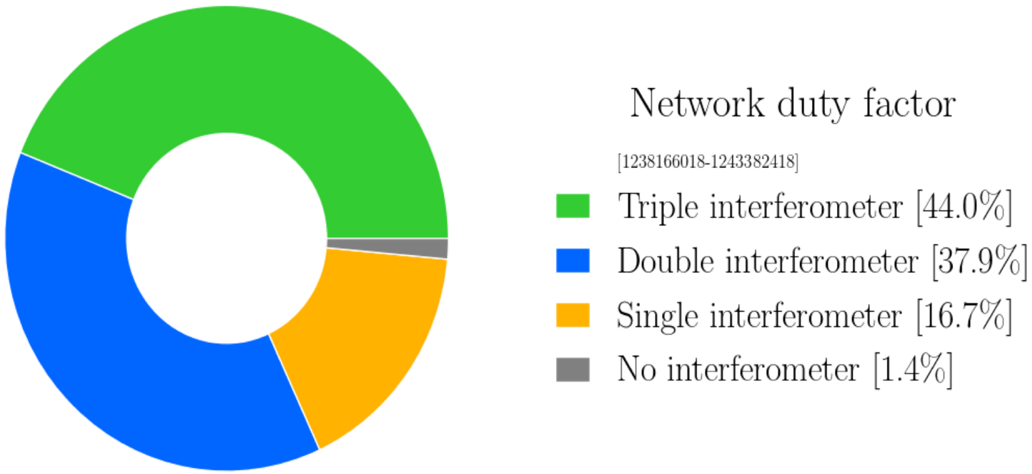
- 100-140 Mpc LIGO
- ~50 Mpc Virgo

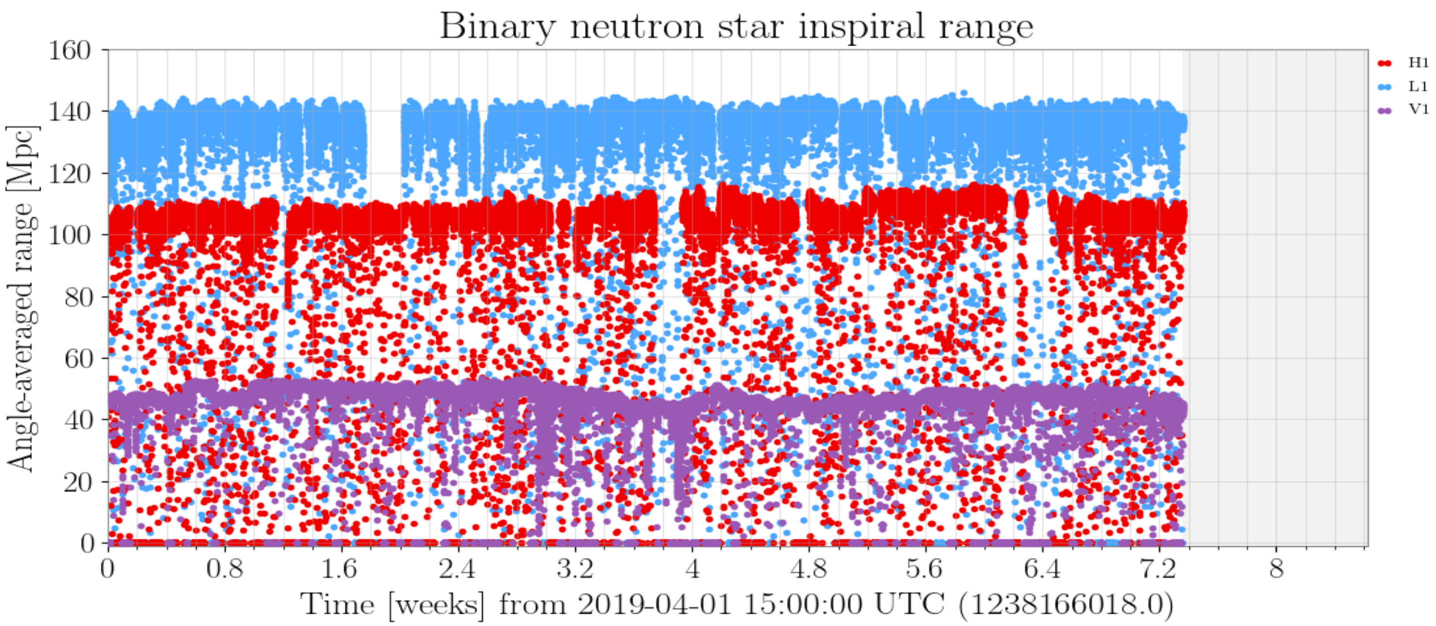
Already 13 alerts

(11 BBHs + 1 BNS + 1 NSBH)





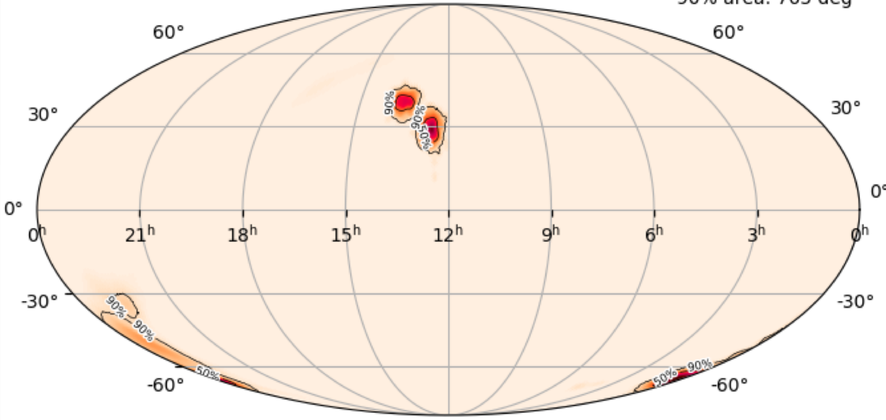




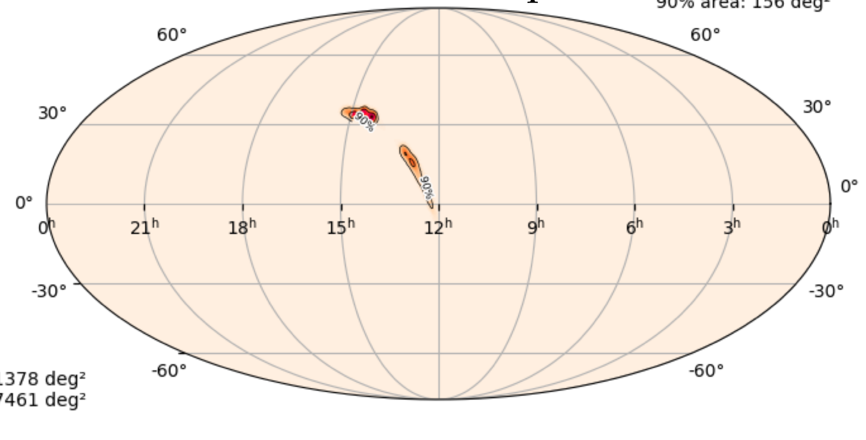
First public alerts – not confirmed detections !

Only few examples !!!

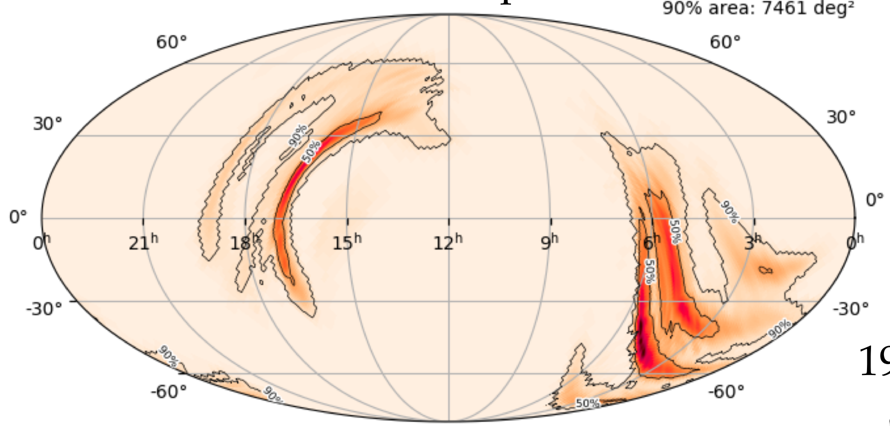
190521g BBH – ~4 Gpc



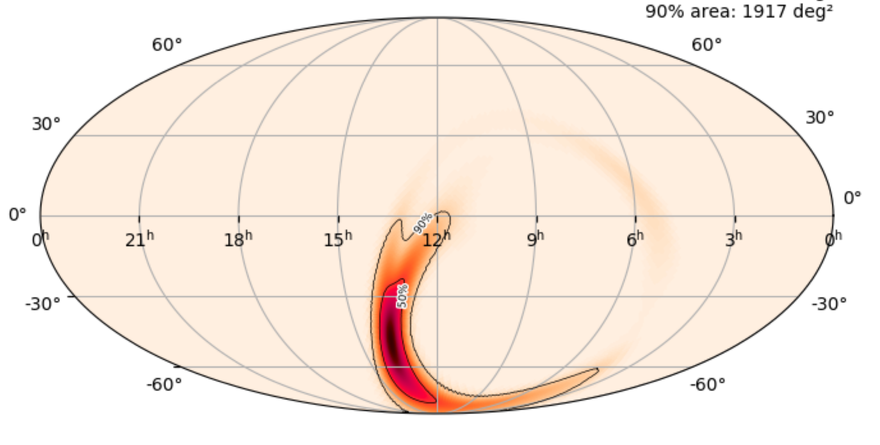
190412 BBH – ~810 Mpc



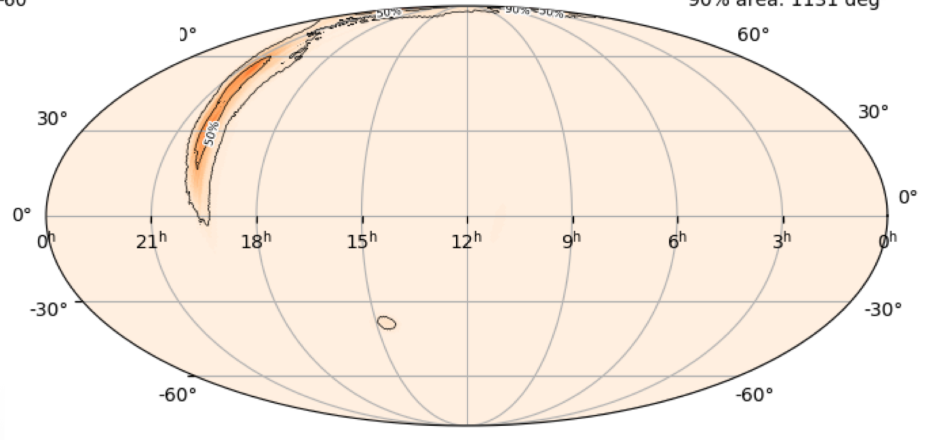
190425 BNS – ~150 Mpc



190421 BBH - ~2.3Gpc



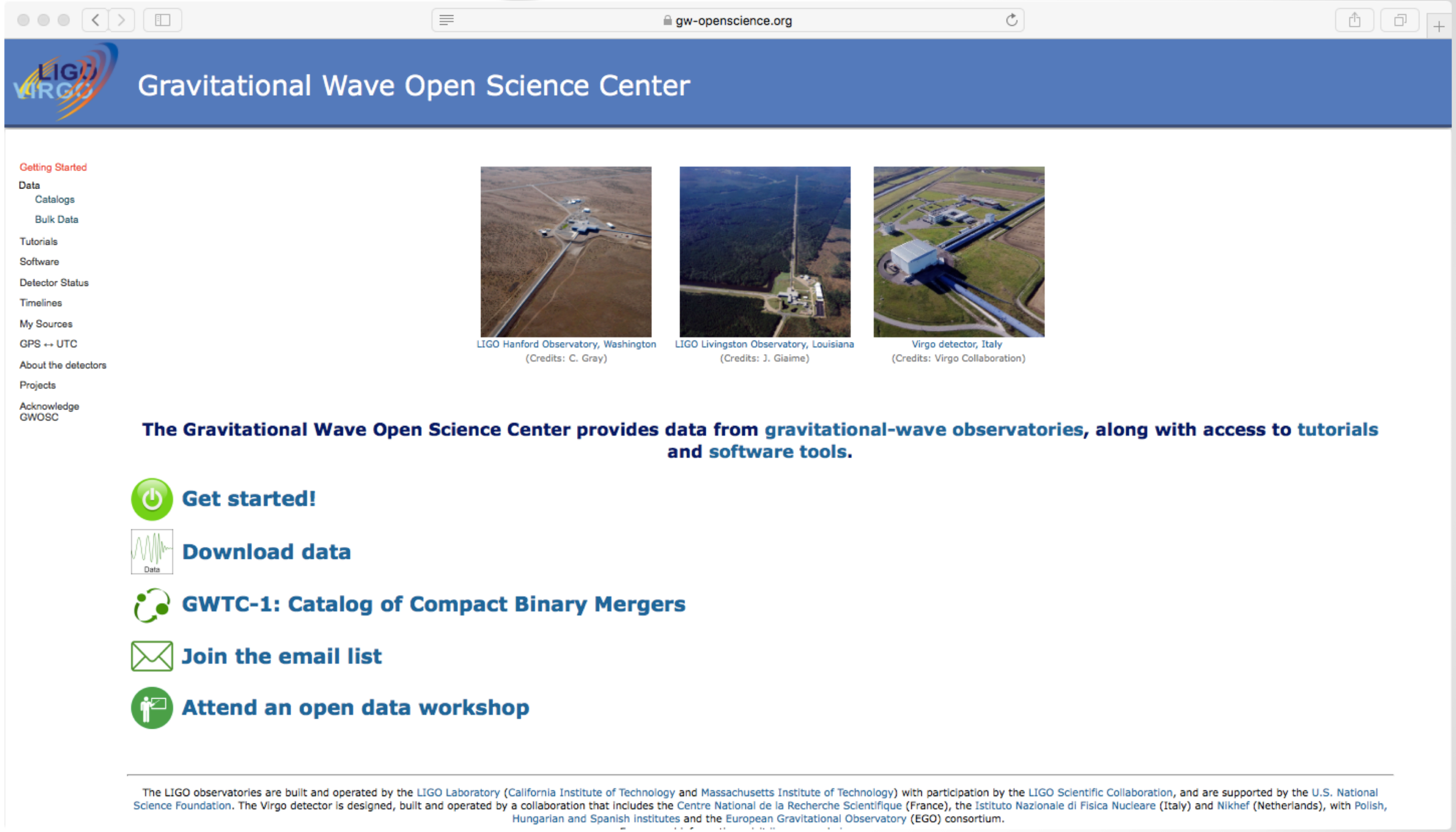
190426 NSBH - ~380 Mpc



Accessing data

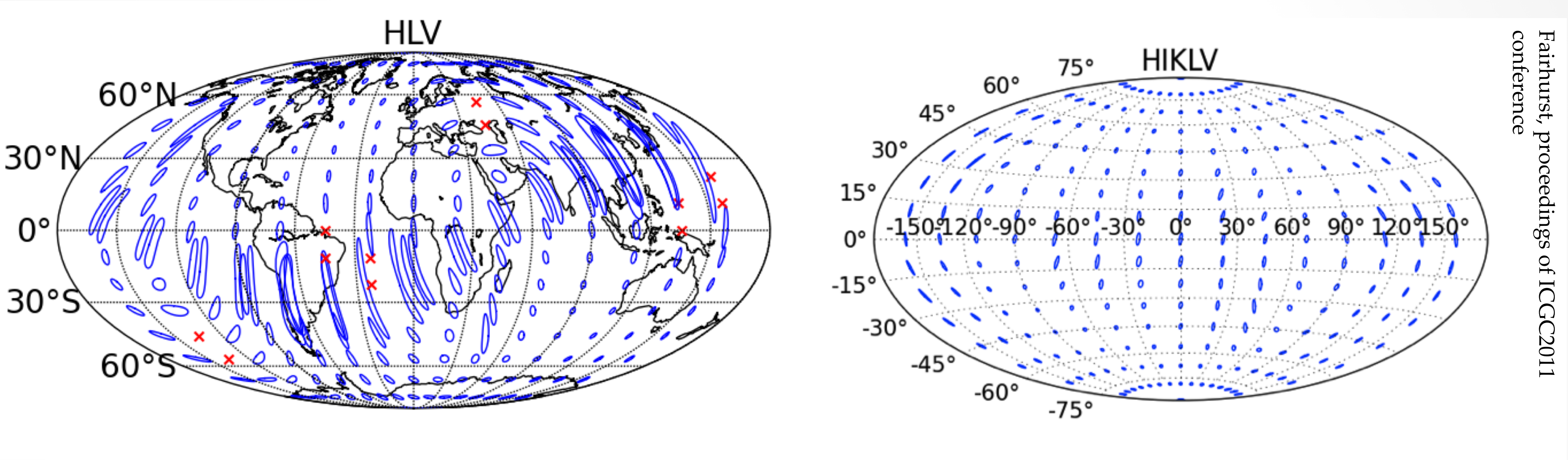
https://www.gw-openscience.org/about/

- Data will be released in two steps :
  - If publication is done on a given event : release one hour around the event
  - After each publication release also posterior distributions
  - We release 6 months block with an 18 months latency

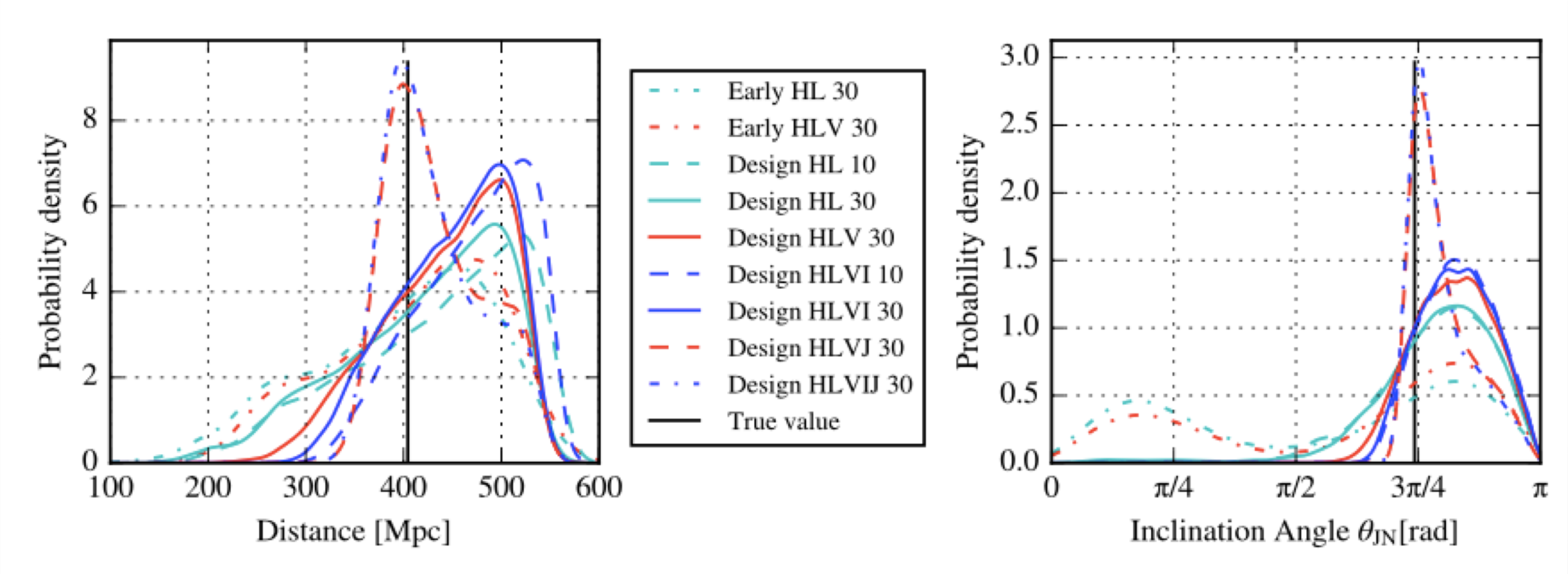


Adding new instruments : parameters inference

Comparison between 3 and 5 detectors for sky localization

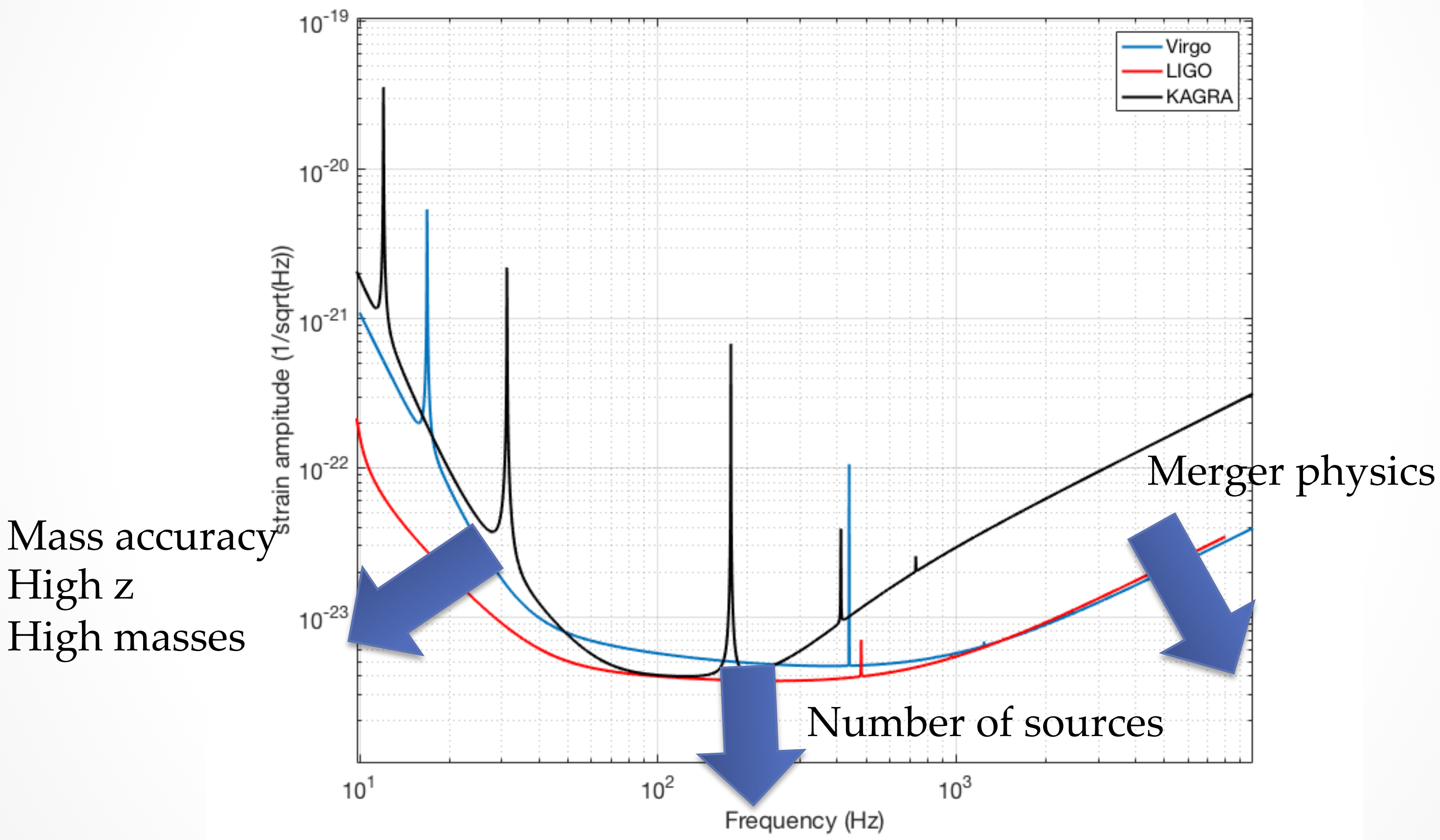


Fairhurst, proceedings of ICGC2011 conference

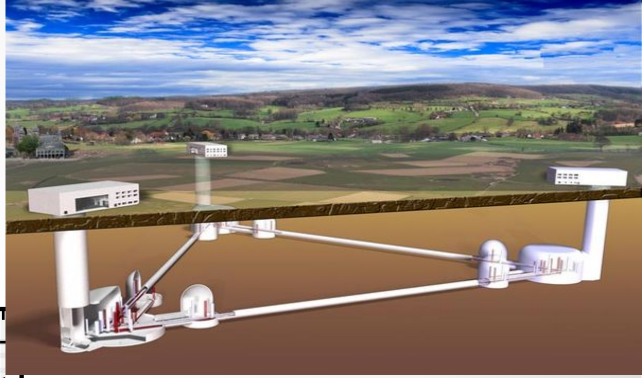


S M Gaebel and J Veitch 2017 Class. Quantum Grav. 34 174003

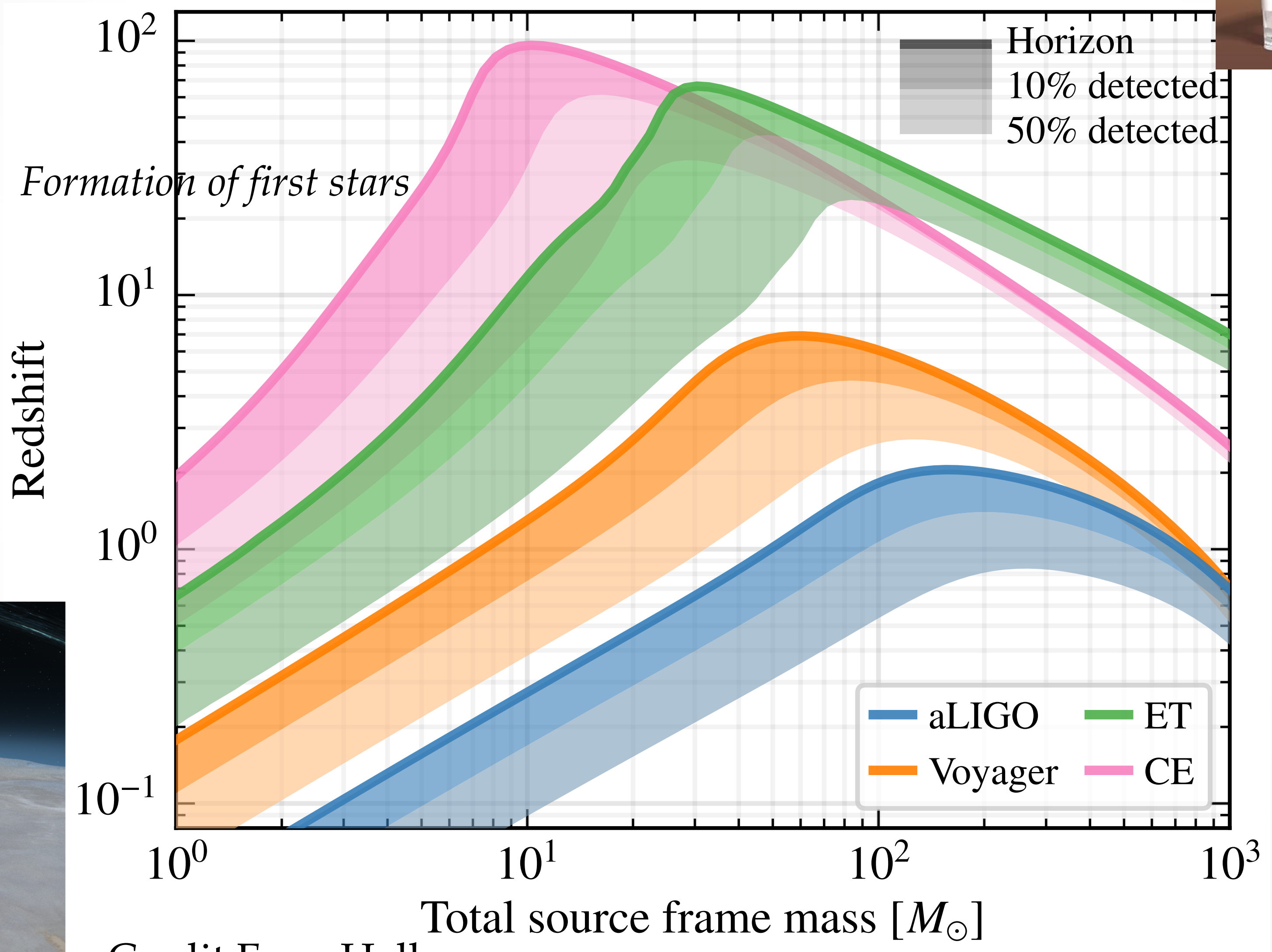
Improving sensitivity

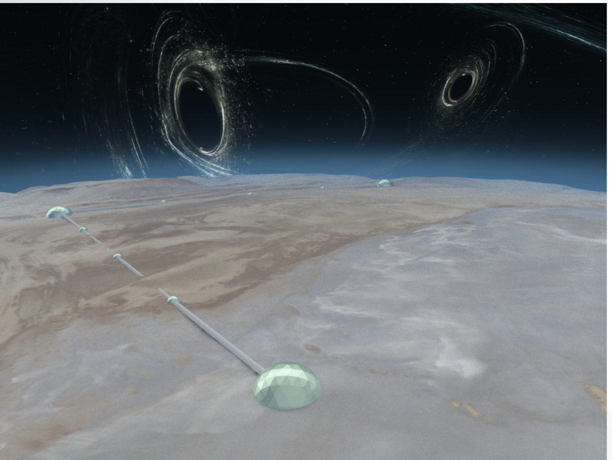


Towards 3G (2030-2035)



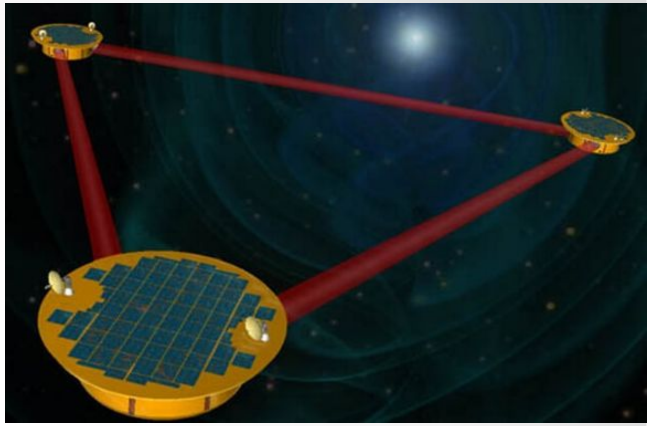
Maximal distance for coalescing objects





Credit Evan Hall

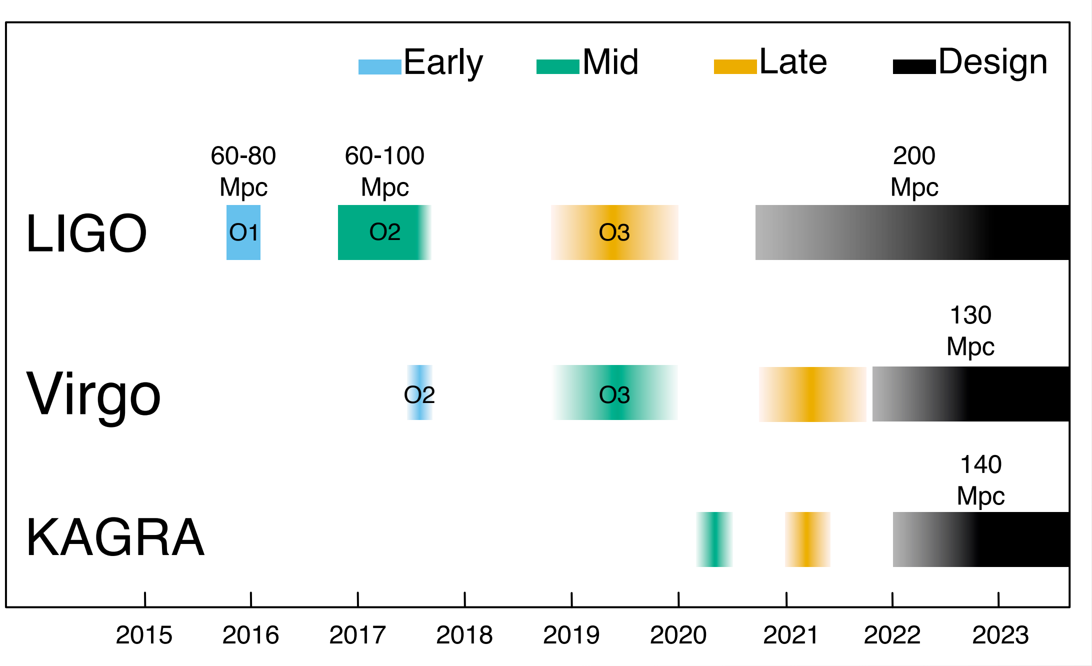
Going into space : LISA



- 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

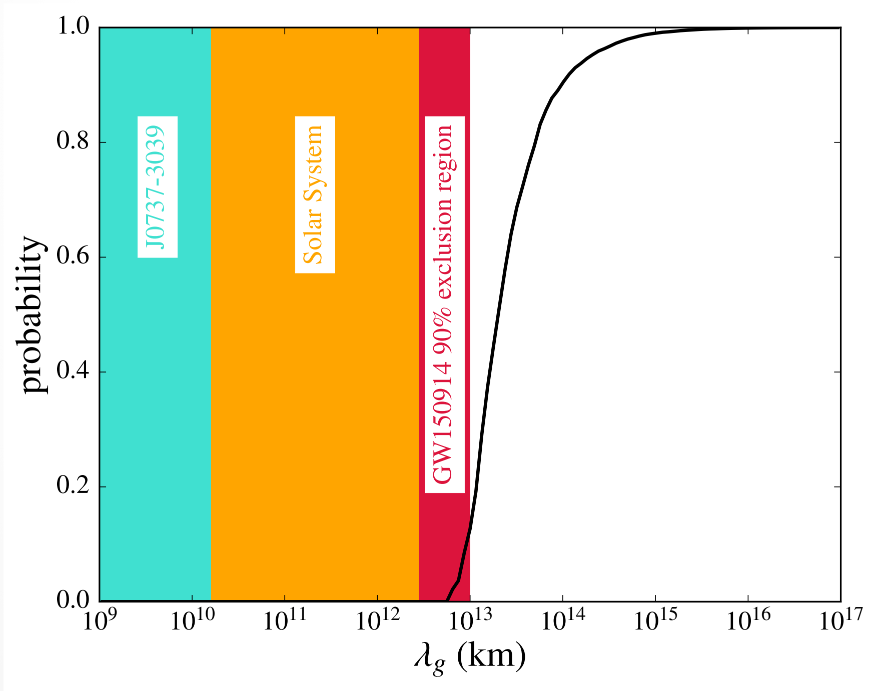


Backup

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

Abbott *et al.* PRL 116, 221101



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

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

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

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

GW170817 parameters

	Low-spin prior ($\chi \leq 0.05$)	High-spin prior ($\chi \leq 0.89$)
Binary inclination θ_{JN}	146^{+25}_{-27} deg	152^{+21}_{-27} deg
Binary inclination θ_{JN} using EM distance constraint [108]	151^{+15}_{-11} deg	153^{+15}_{-11} deg
Detector-frame chirp mass $\mathcal{M}^{\mathrm{det}}$	$1.1975^{+0.0001}_{-0.0001}$ $M_\odot$	$1.1976^{+0.0004}_{-0.0002}$ $M_\odot$
Chirp mass $\mathcal{M}$	$1.186^{+0.001}_{-0.001}$ $M_\odot$	$1.186^{+0.001}_{-0.001}$ $M_\odot$
Primary mass m_1	(1.36, 1.60) $M_\odot$	(1.36, 1.89) $M_\odot$
Secondary mass m_2	(1.16, 1.36) $M_\odot$	(1.00, 1.36) $M_\odot$
Total mass m	$2.73^{+0.04}_{-0.01}$ $M_\odot$	$2.77^{+0.22}_{-0.05}$ $M_\odot$
Mass ratio q	(0.73, 1.00)	(0.53, 1.00)
Effective spin χ_{eff}	$0.00^{+0.02}_{-0.01}$	$0.02^{+0.08}_{-0.02}$
Primary dimensionless spin χ_1	(0.00, 0.04)	(0.00, 0.50)
Secondary dimensionless spin χ_2	(0.00, 0.04)	(0.00, 0.61)
Tidal deformability $\tilde{\Lambda}$ with flat prior	300^{+500}_{-190} (symmetric)/300^{+420}_{-230} (HPD)	(0, 630)

Abbott et al PRX 9, 2019

Image Credit: NASA Goddard Space Fight Center / CI Lab

Coalescing binaries