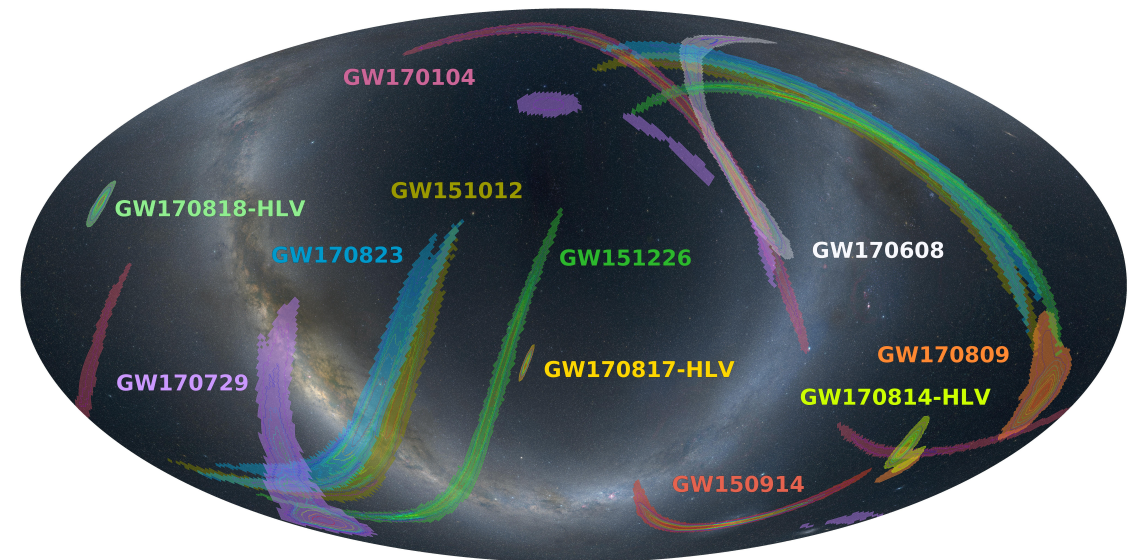
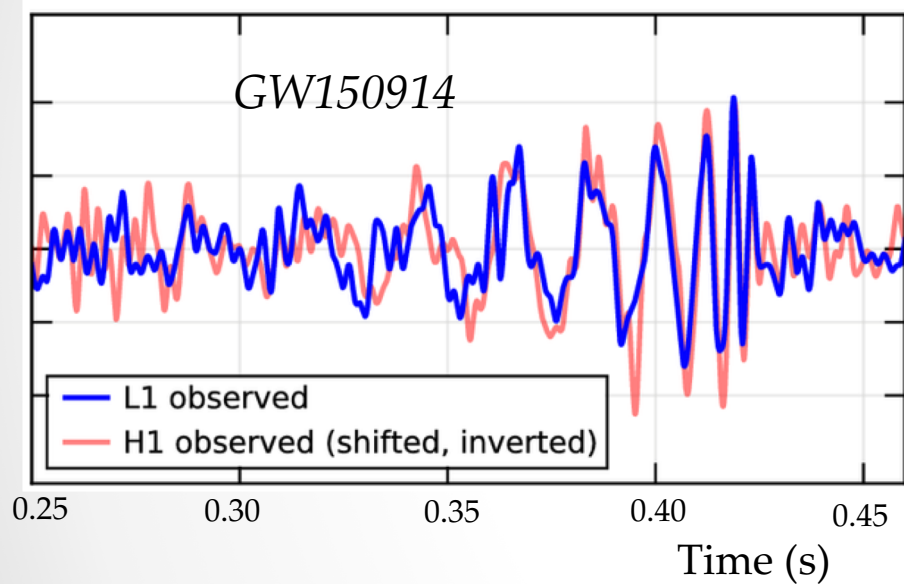


Gravitational wave : a new astronomy

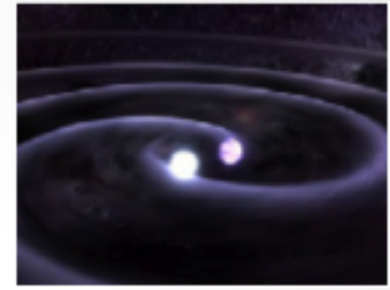


Nicolas Leroy

Laboratoire de l'accélérateur linéaire d'Orsay

Promotion Vera Rubin – 22 July 2019

What are Gravitational waves ?

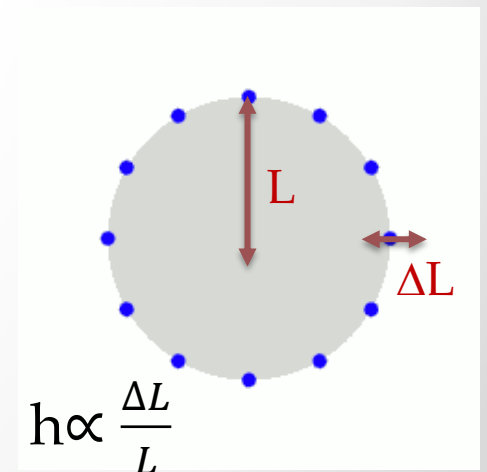


- Solution from General Relativity derived by A. Einstein in 1916
- Far from sources then can be seen as a perturbation of the metric
- They are ripples of space-time produced by rapidly accelerating mass distributions
- Provide info on mass displacement
- Weakly coupled – access to very dense part of objects
- Main properties:

- Propagate at speed of light
- Two polarizations '+' and 'x'
- Emission is quadrupolar at lowest order

Needs to have

- Compact object : $R \sim R_s$
- Relativist : $v \sim c$
- asymmetric



1916-2016: a century of progress

❖ **1916: GW prediction (Einstein)**

1957 Chapel Hill Conference

❖ **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.)**

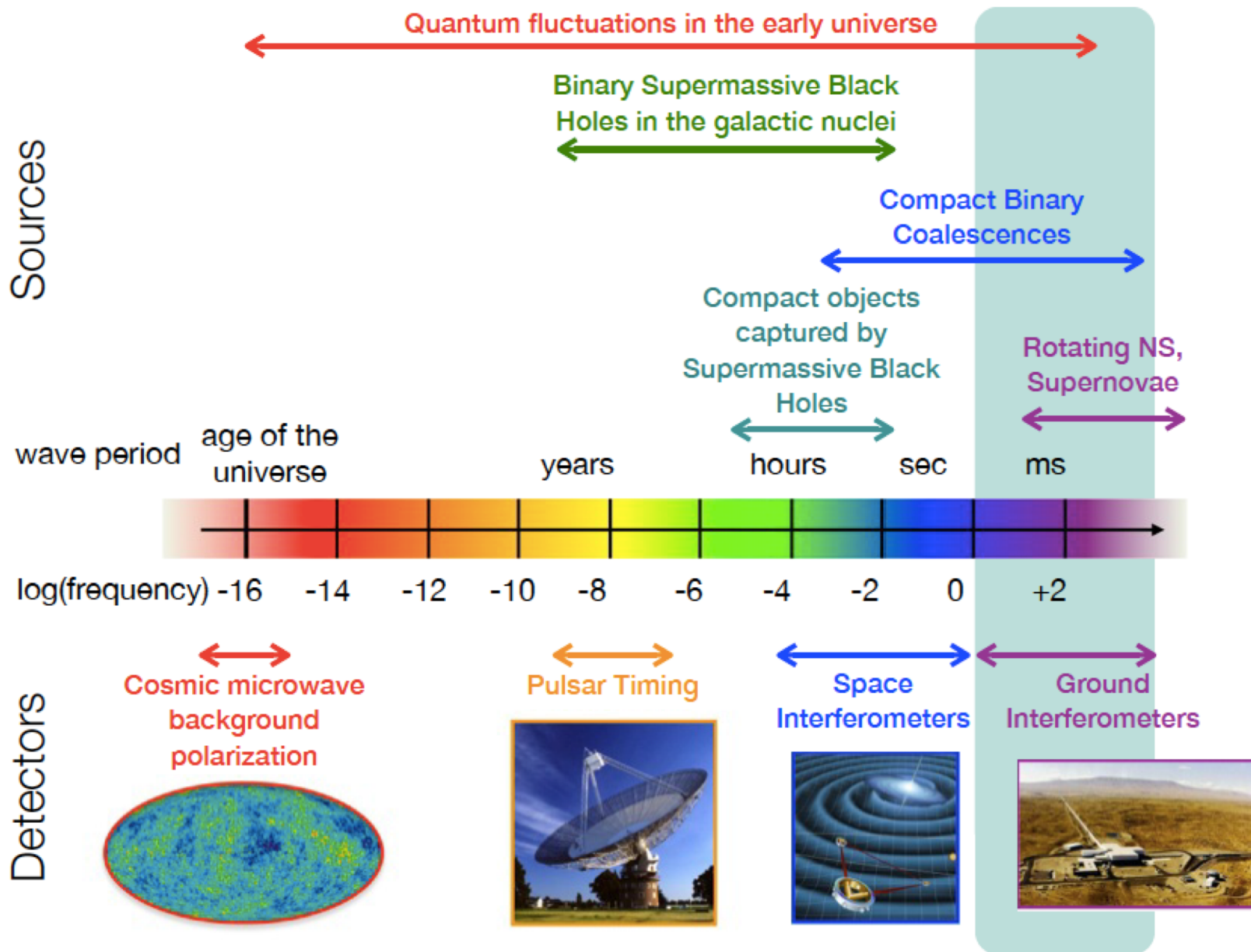
(Bondi, Feynman, Pirani, etc.)

- **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**
- **2017 : Nobel Prize**

Theoretical developments

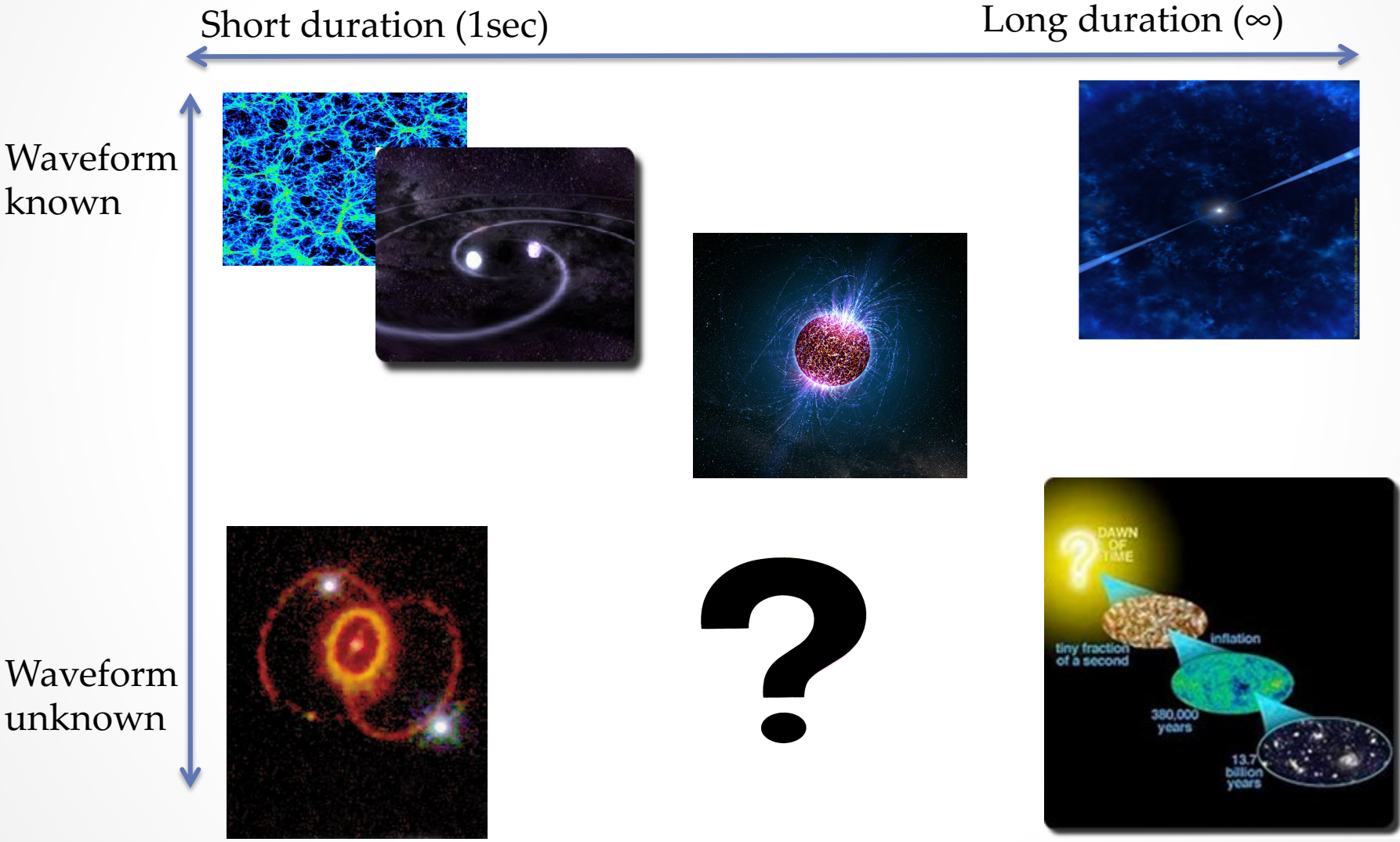
Experiments

The Gravitational Wave Spectrum

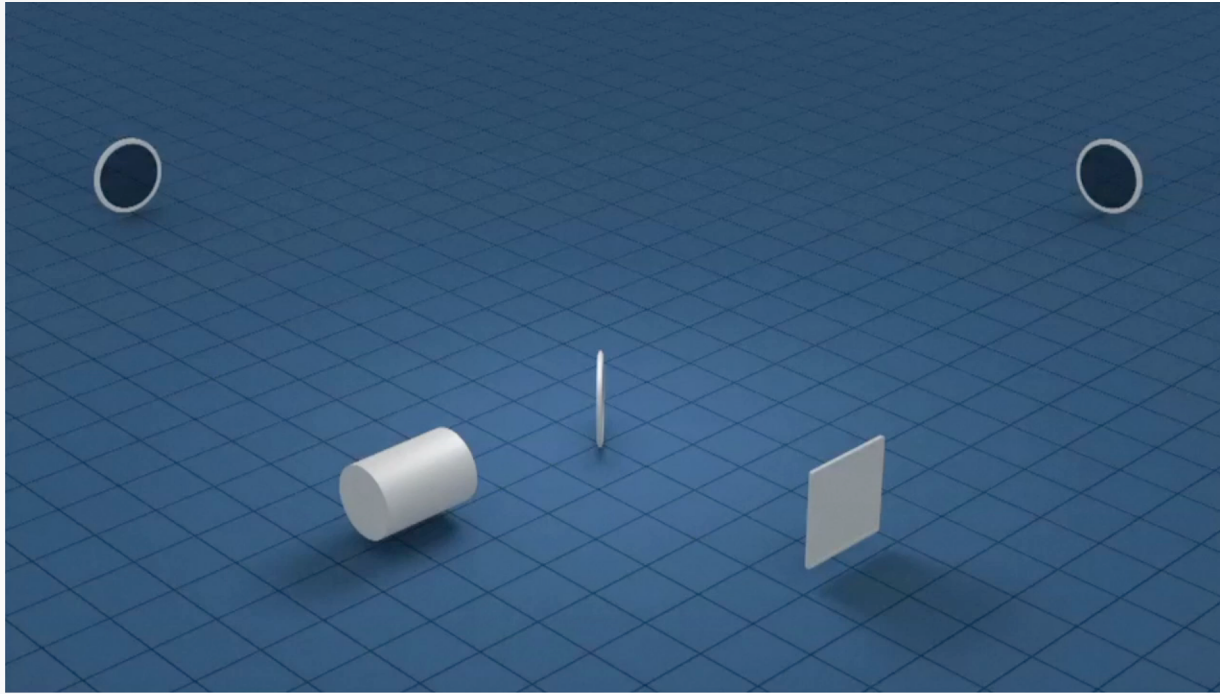


[Inspired from <http://science.gsfc.nasa.gov/663/research/>]

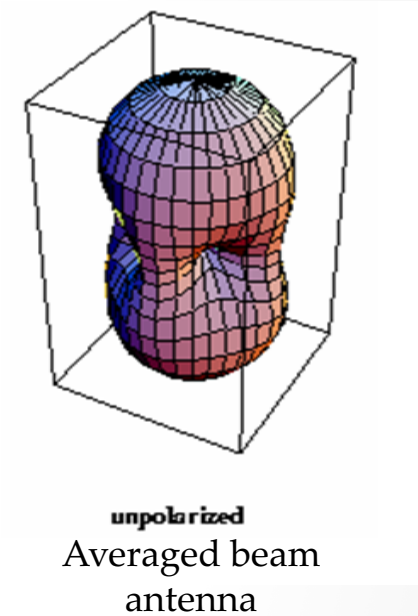
GW zoology



Interferometer and GW



Sensitivity : almost full sky



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

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

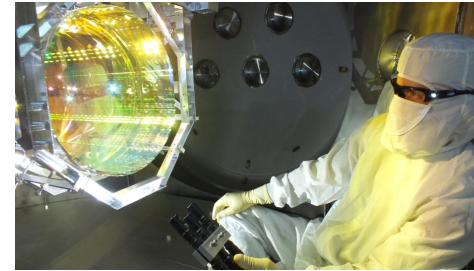
Detected signal proportional to $h(t)$

Advanced generation detectors

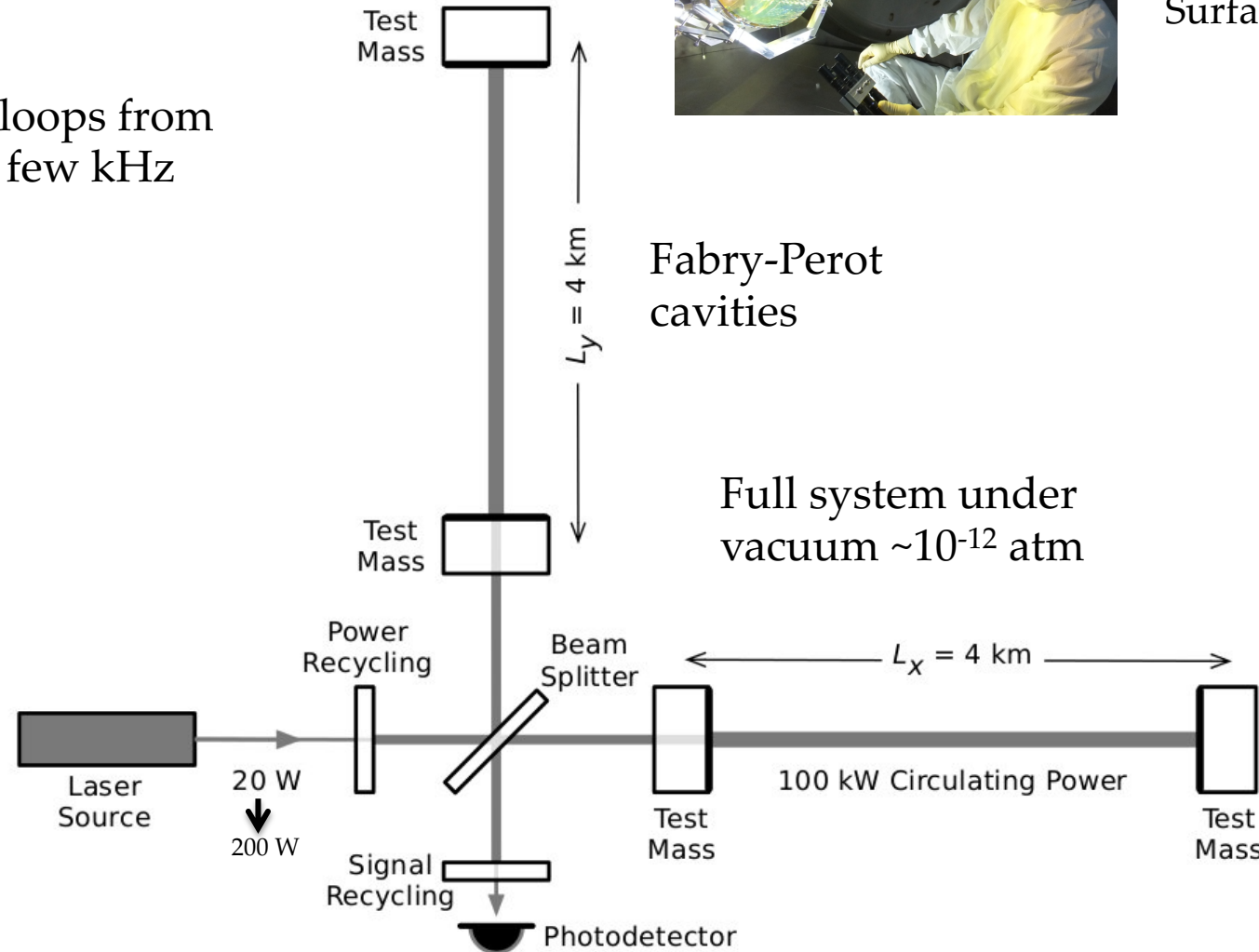
Michelson interferometer

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

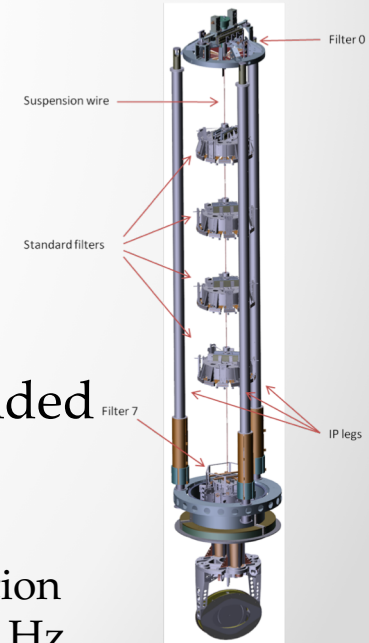
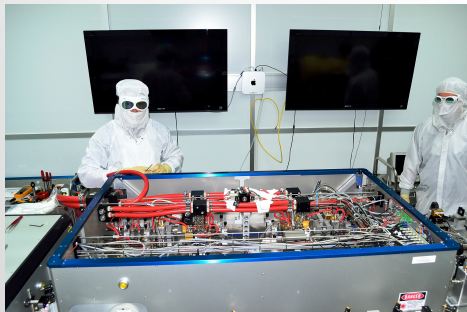
Feedback loops from
few Hz to few kHz



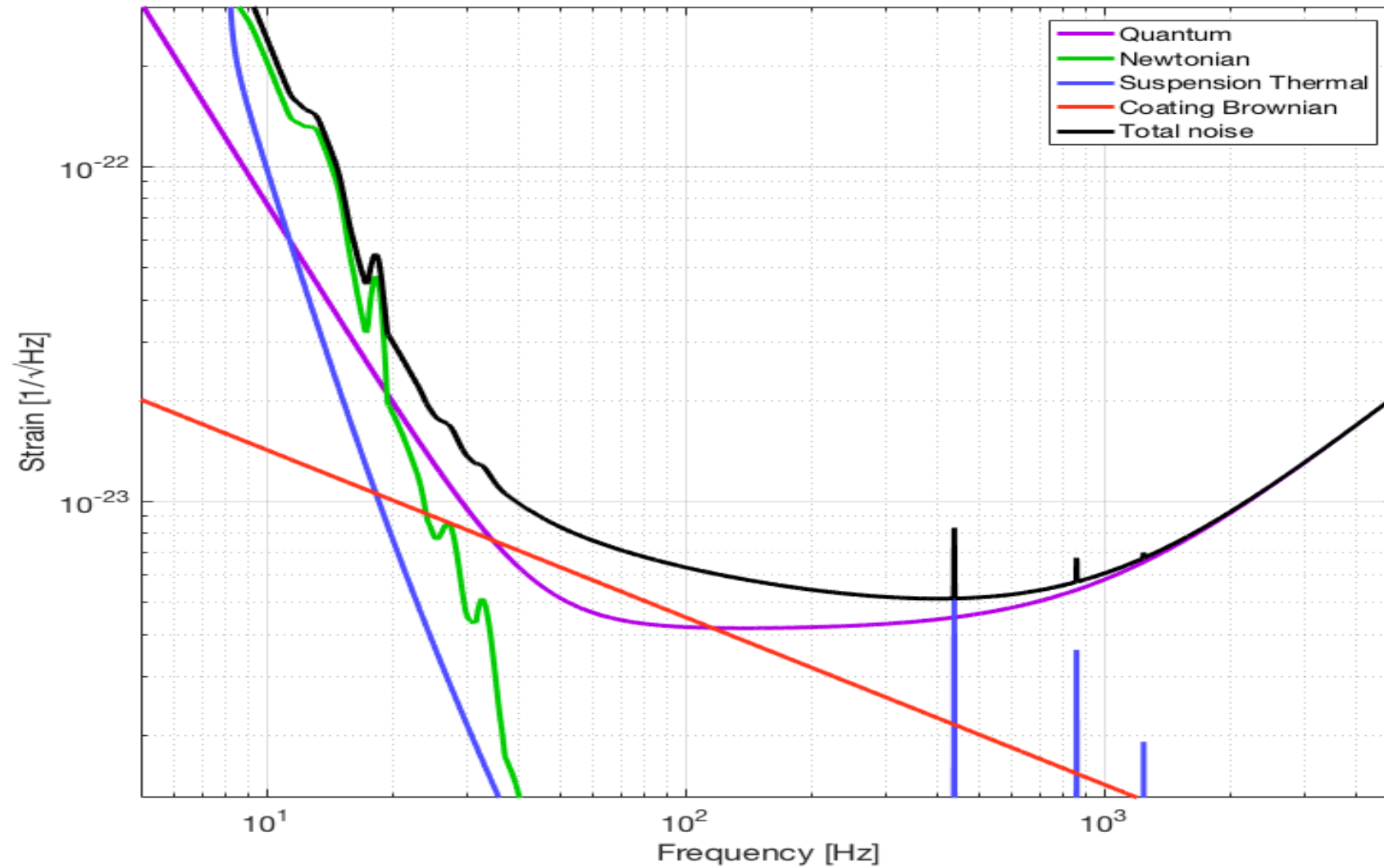
High quality
optics – 40 kg
Surface RMS ~nm



High power laser



Sensitivity



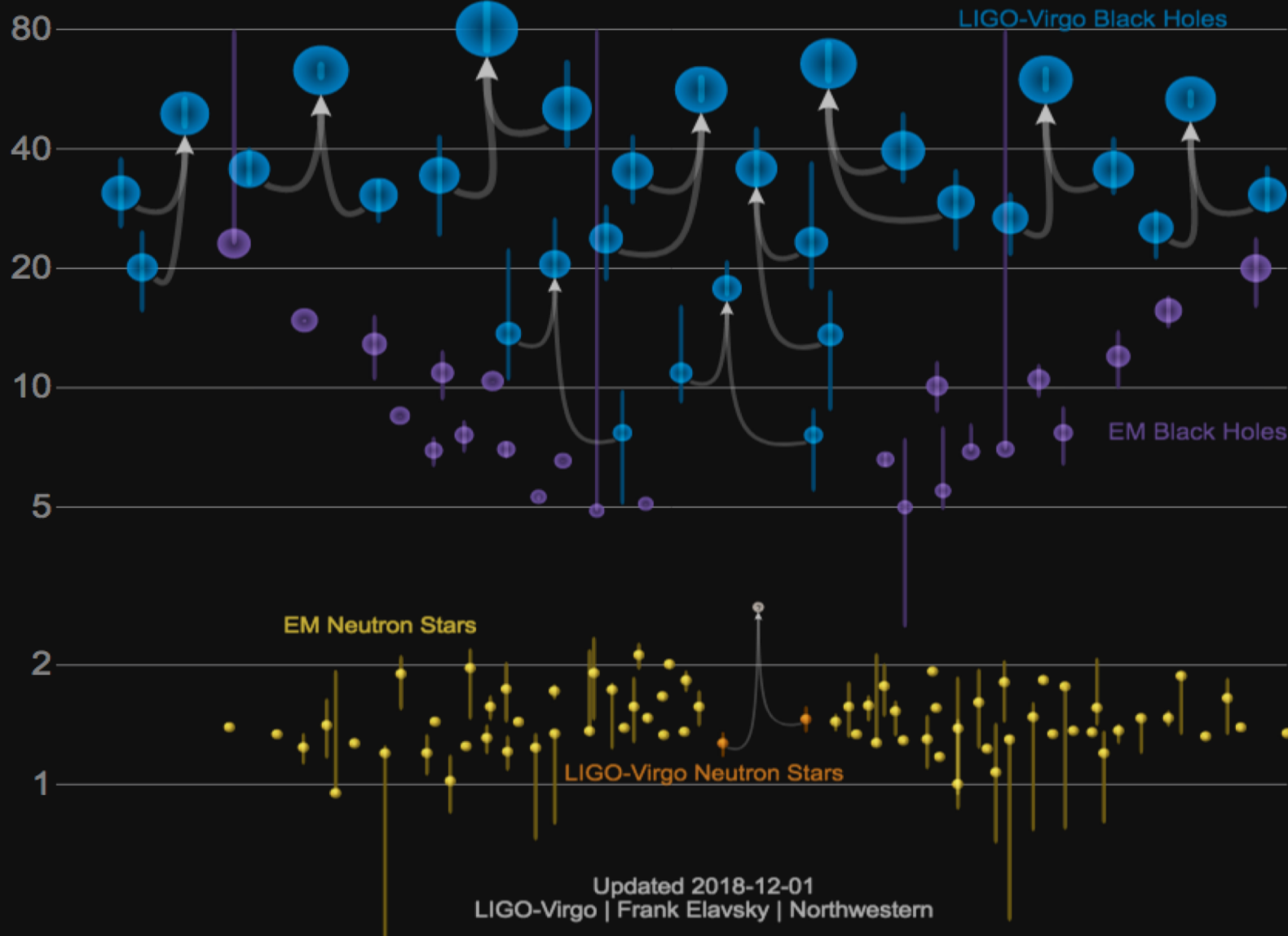
GW network

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



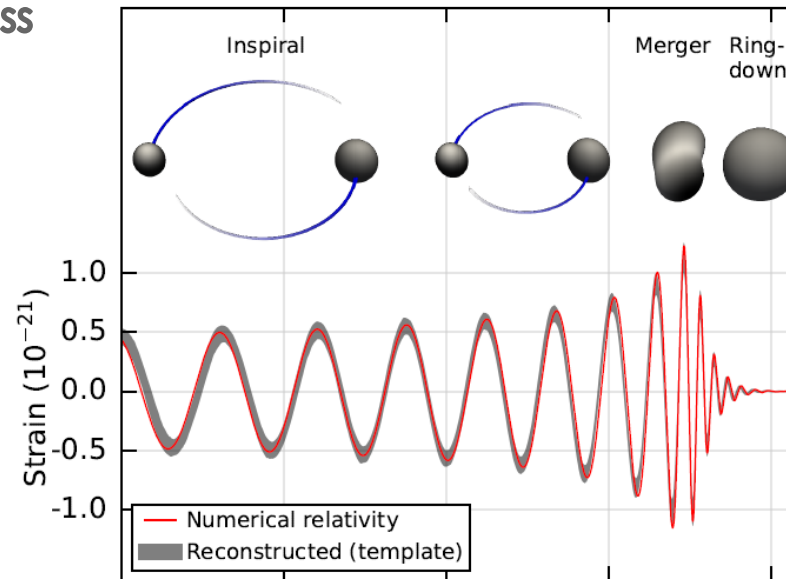
GW detections

Masses in the Stellar Graveyard *in Solar Masses*

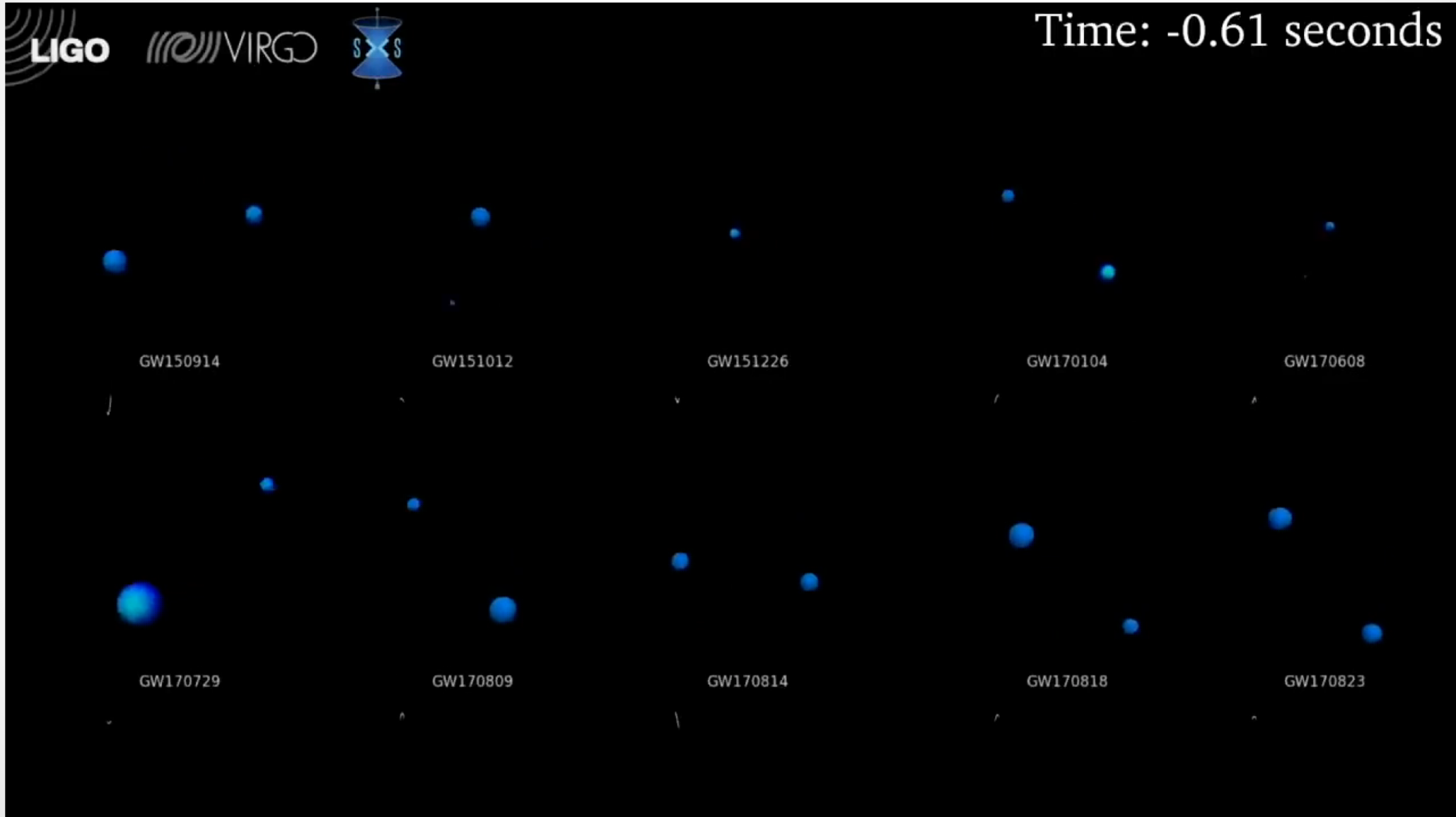


Coalescing binaries

- 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

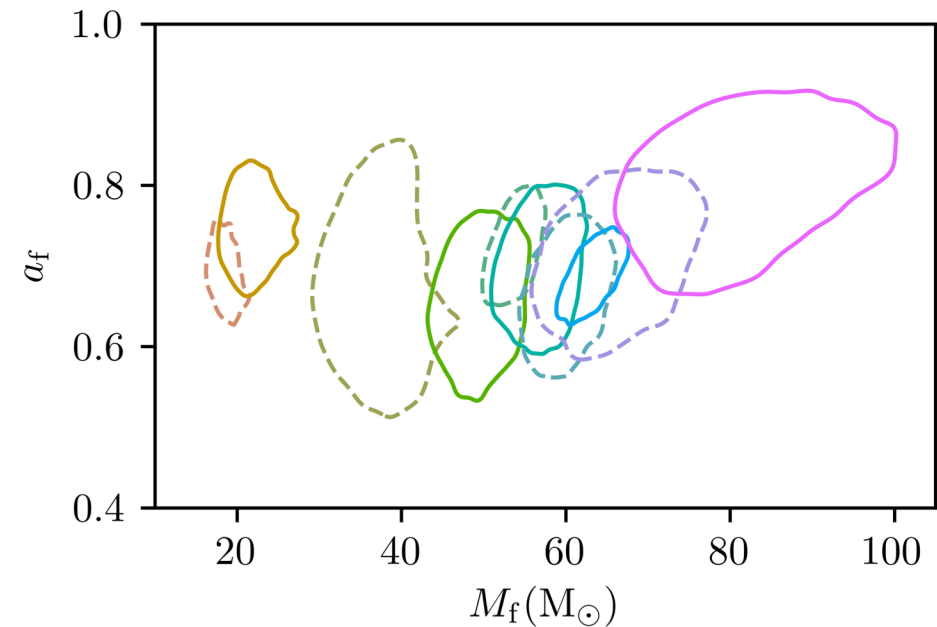
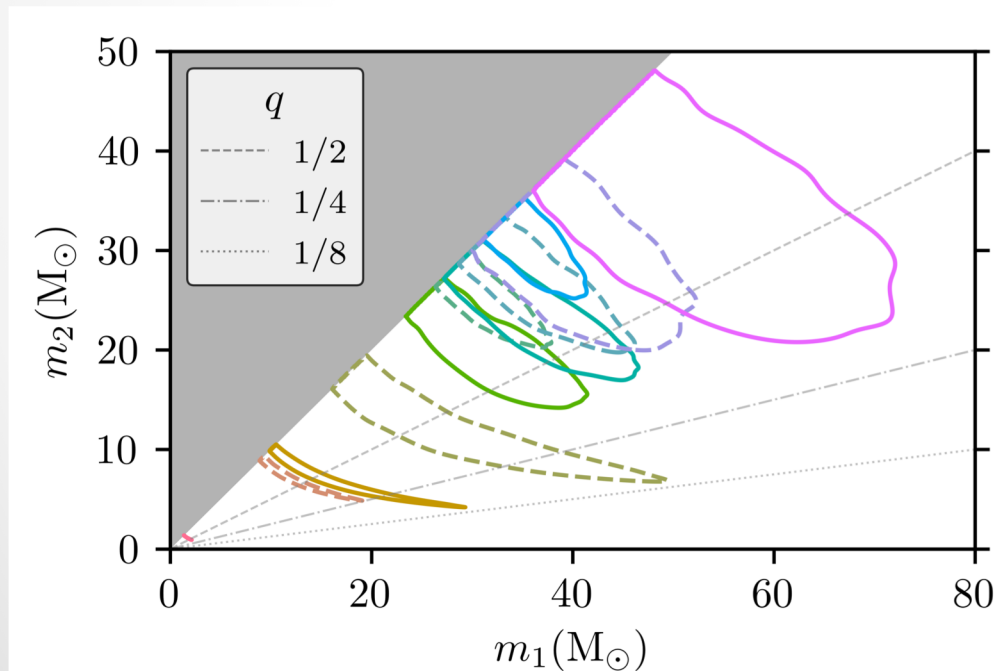


Coalescing binaries



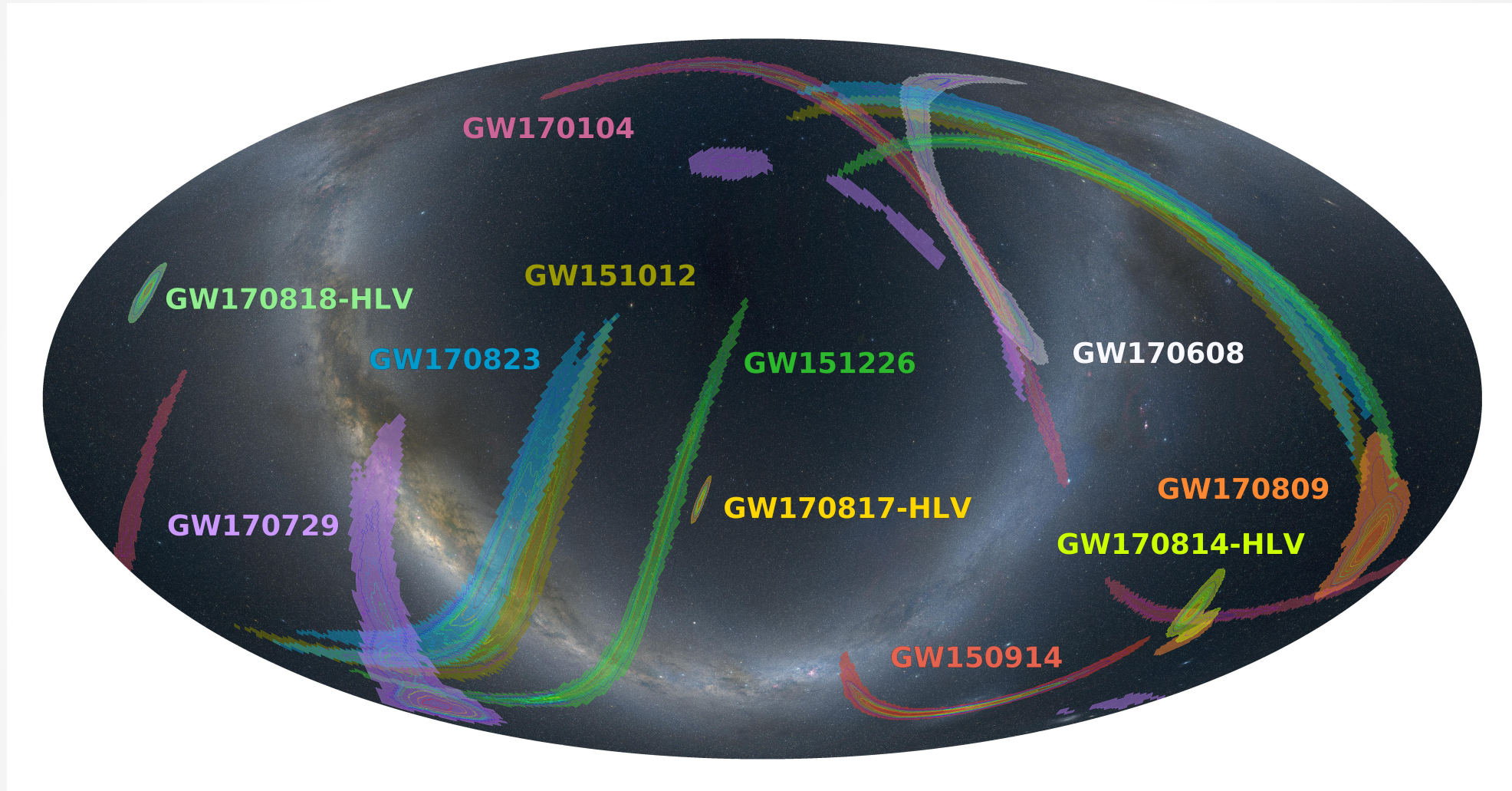
Detecting black holes

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



Abbott et al, PRX 9 (2019)

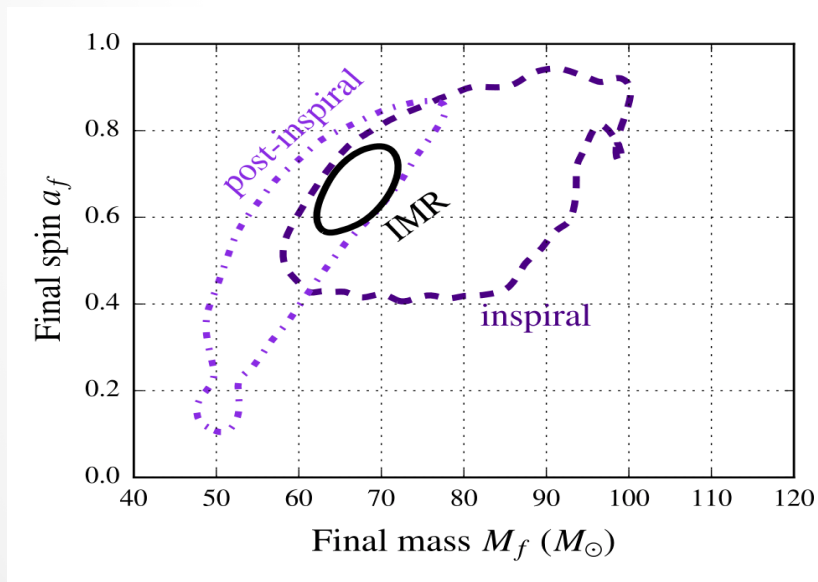
Sky error regions



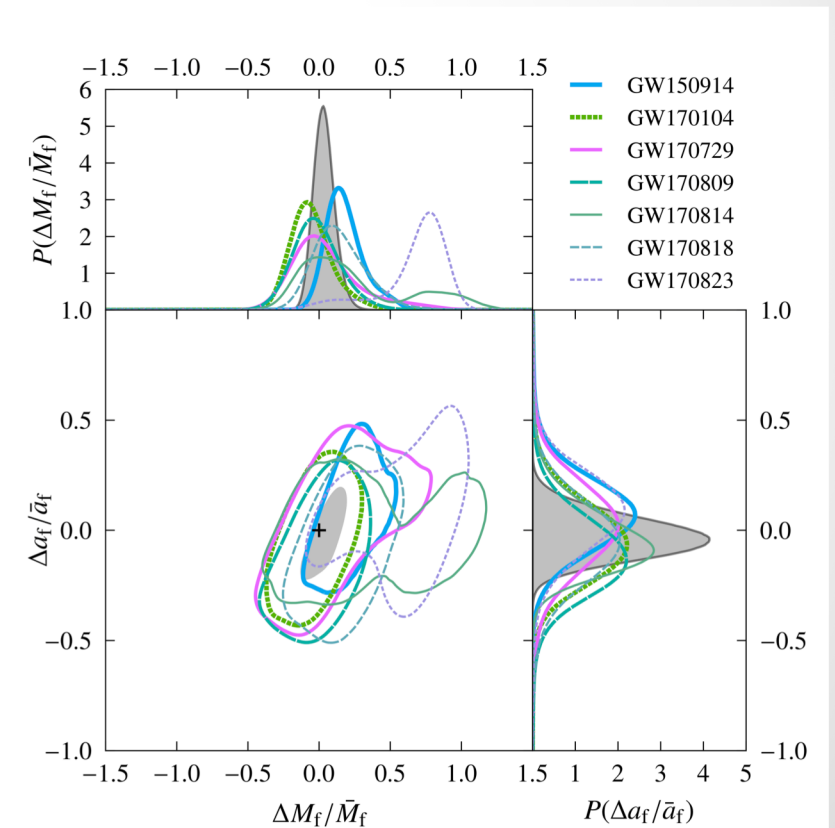
Sky map reconstructed with time of flight technic
Large improvement since Virgo joined data taking

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 performed :
 - 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

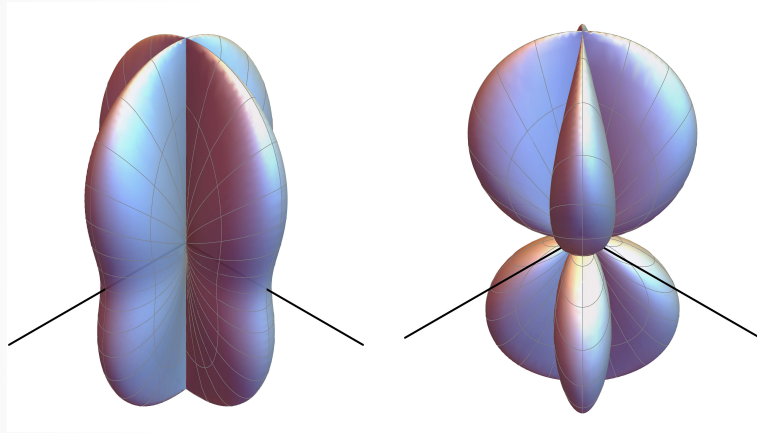


Abbott *et al.* 2019 submitted

Polarization in GR

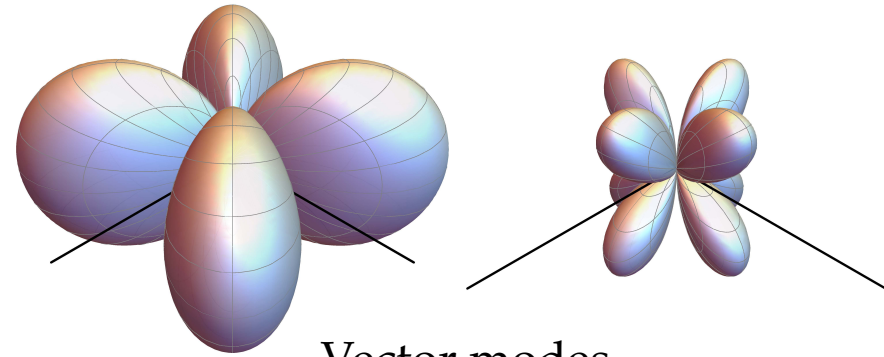
- Generic theories predict up to 6 polarizations states
- With a third detector (non aligned) : test new types of polarizations

Only ones expected with GR



Tensor modes

Allowed by other gravitation theories

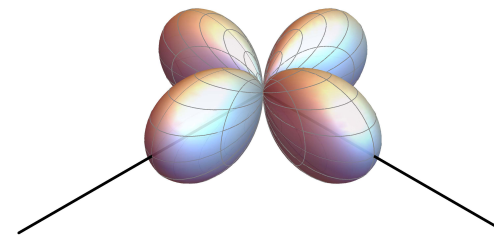


Vector modes

Antenna pattern

Favor pure tensor vs pure vector or scalar

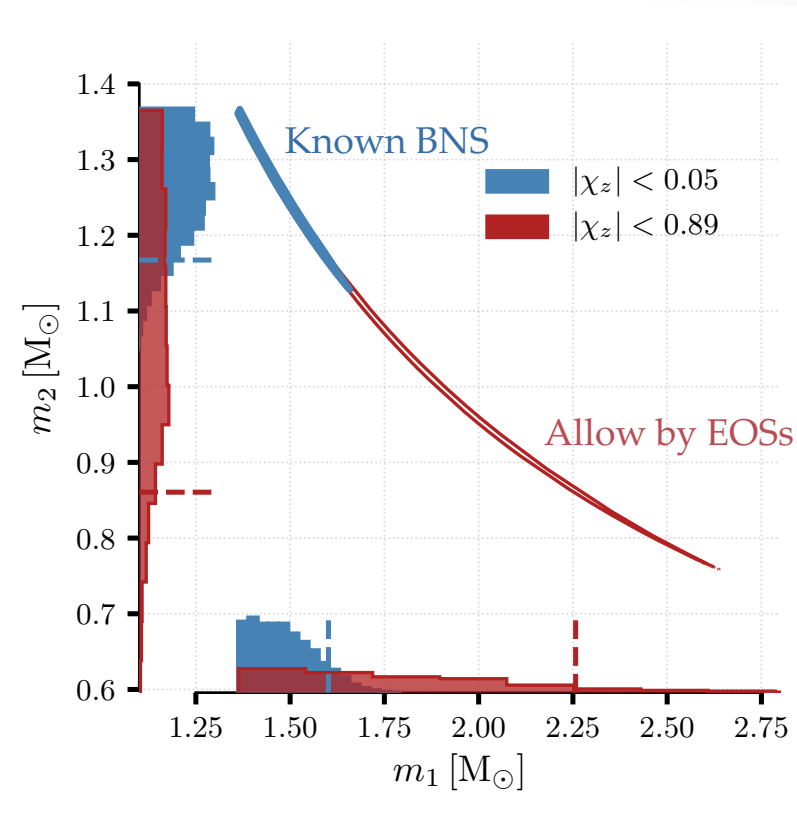
Cannot conclude on mixed version



Scalar modes

GW170817 :First binary neutron star

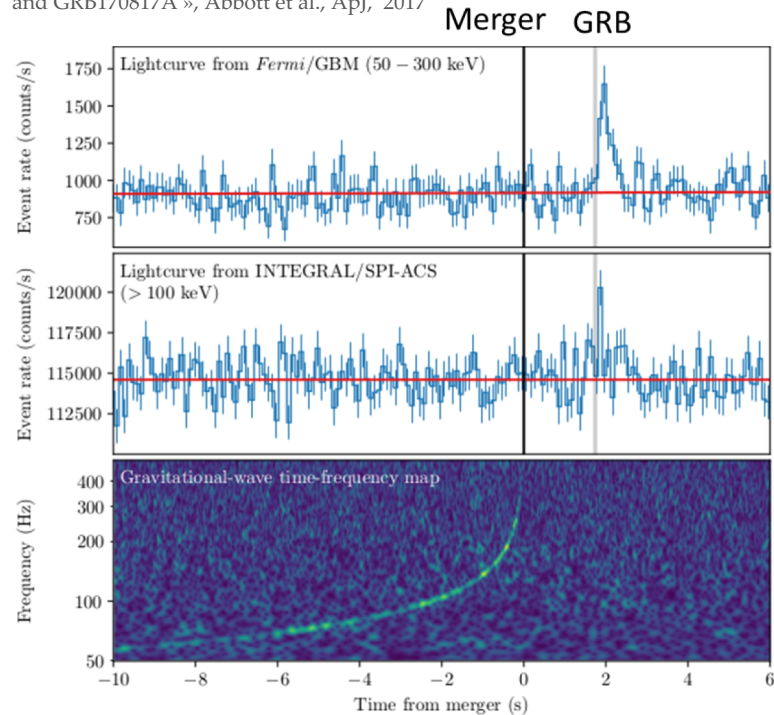
- SNR ~ 32.4 ,
- FAR $< 1 \cdot 10^{-4}$ /year
- Long event (~ 100 secs)
 - light masses system !
- Probability to have at least one neutron star is important
- Possible electromagnetic counterpart !



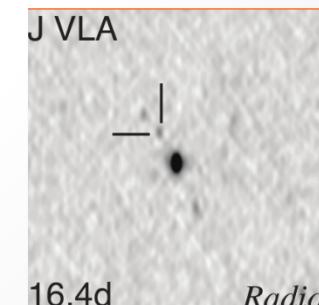
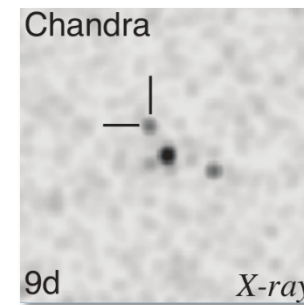
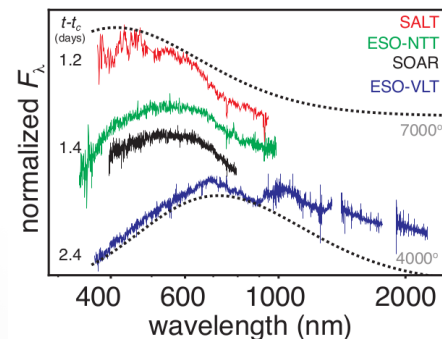
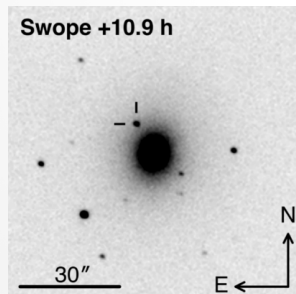
$$M_{Chirp} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}} = 1.188^{+0.004}_{-0.002} M_{\odot}$$

A first electromagnetic counterpart

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

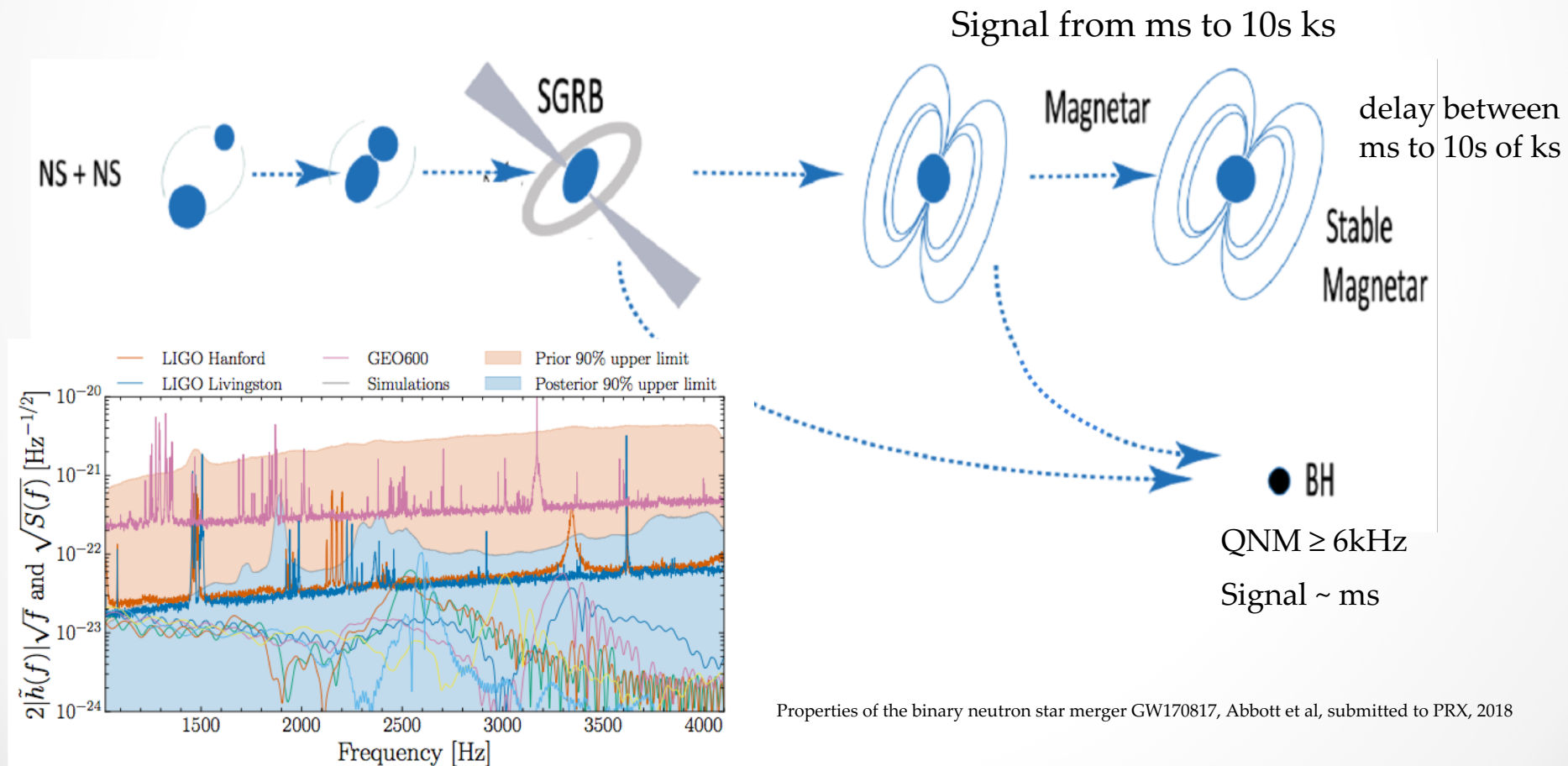


- Association to a gamma-ray burst ($> 5.3 \sigma$) within 1.7s and same sky region
- Including the 3 interferometers $\rightarrow 28 \text{ deg}^2$
- Radio to X-rays counterpart found (latency hours to days)
- Found in NGC4993, distance determined between EM and GW compatible
- Kilonova emission



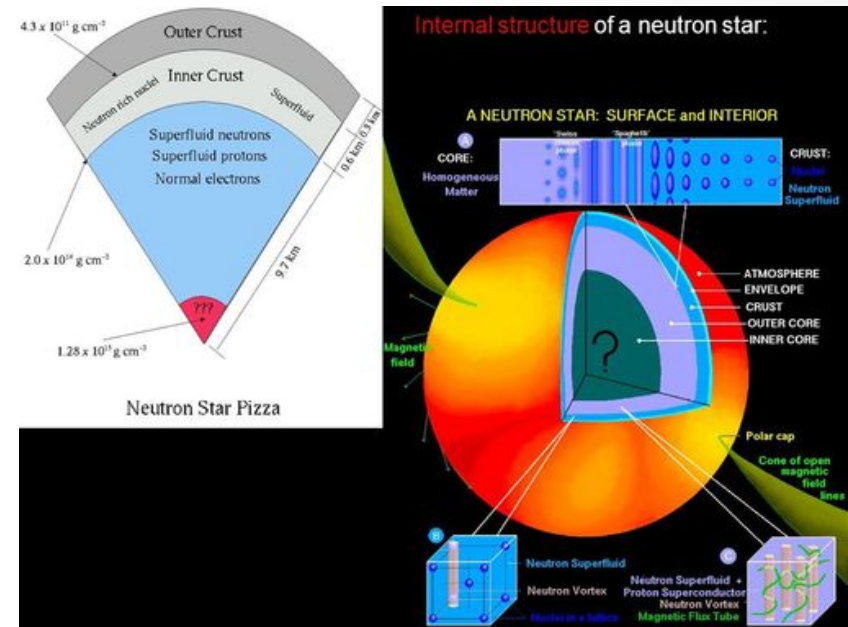
Remanent object

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



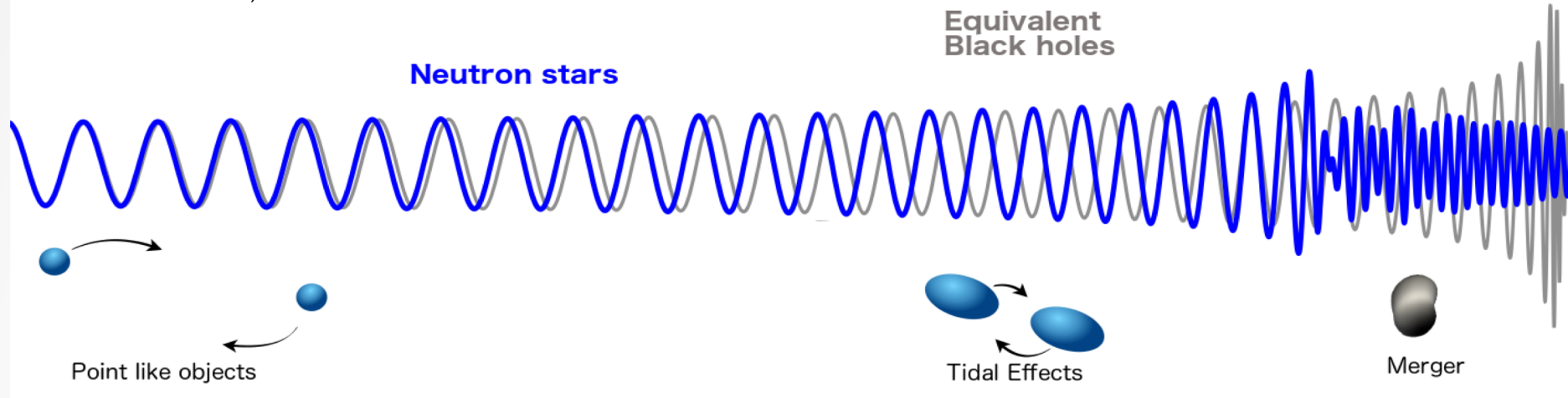
Equation of state of nuclear matter

- 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

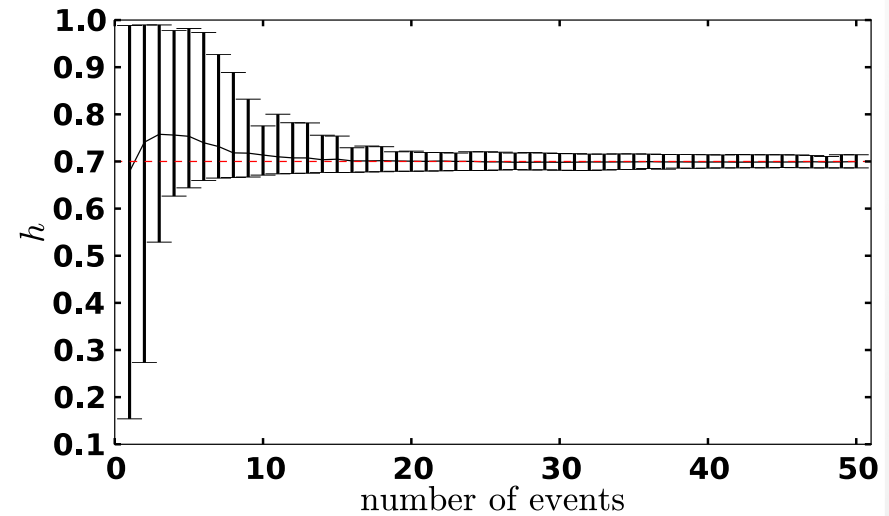
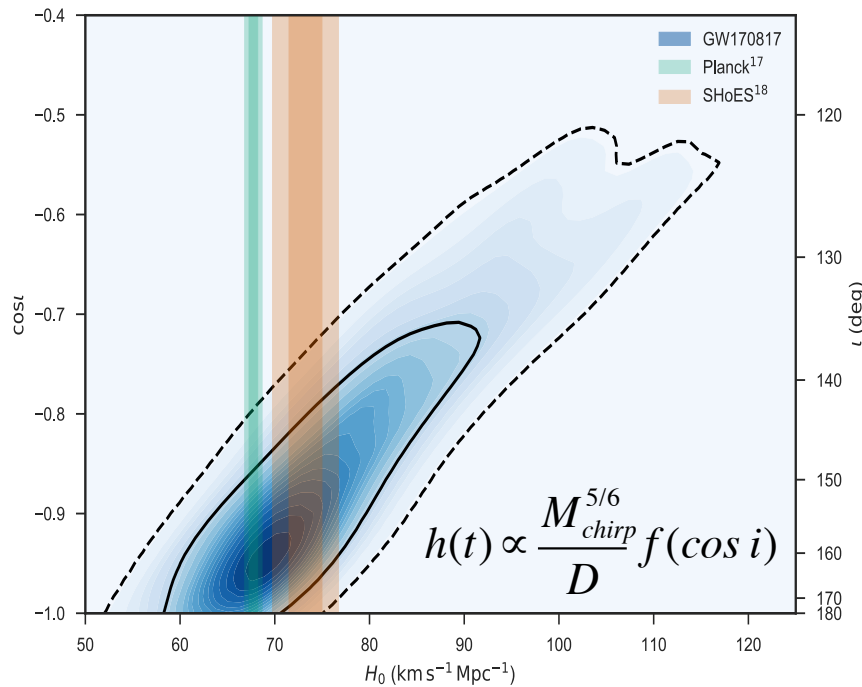
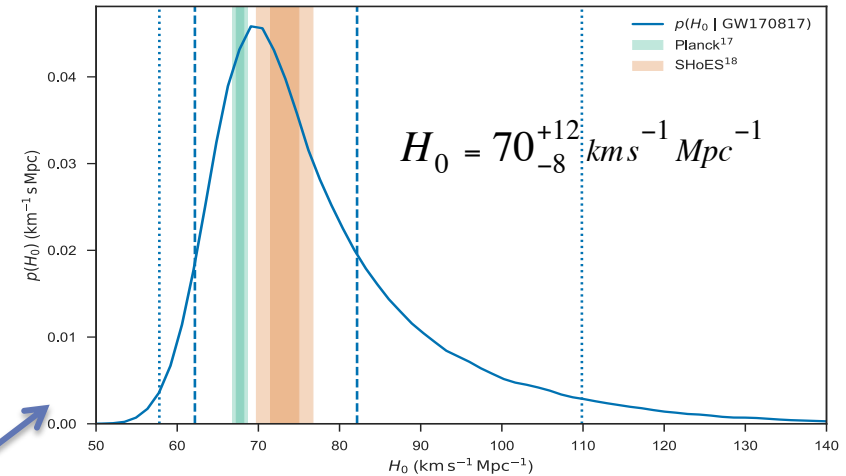
Credits: P. Schmidt; NR data: T. Dietrich



- 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 : $v=H_0 D$
- 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 :
$$-3 \cdot 10^{-15} \leq \frac{v_{GW} - v_{EM}}{v_{EM}} \leq + 7 \cdot 10^{-16}$$
- Equivalent principle (Shapiro effect) :
$$\delta t_s = -\frac{1+\gamma}{c^3} \int_{r_e}^{r_o} U(r(l)) dl$$

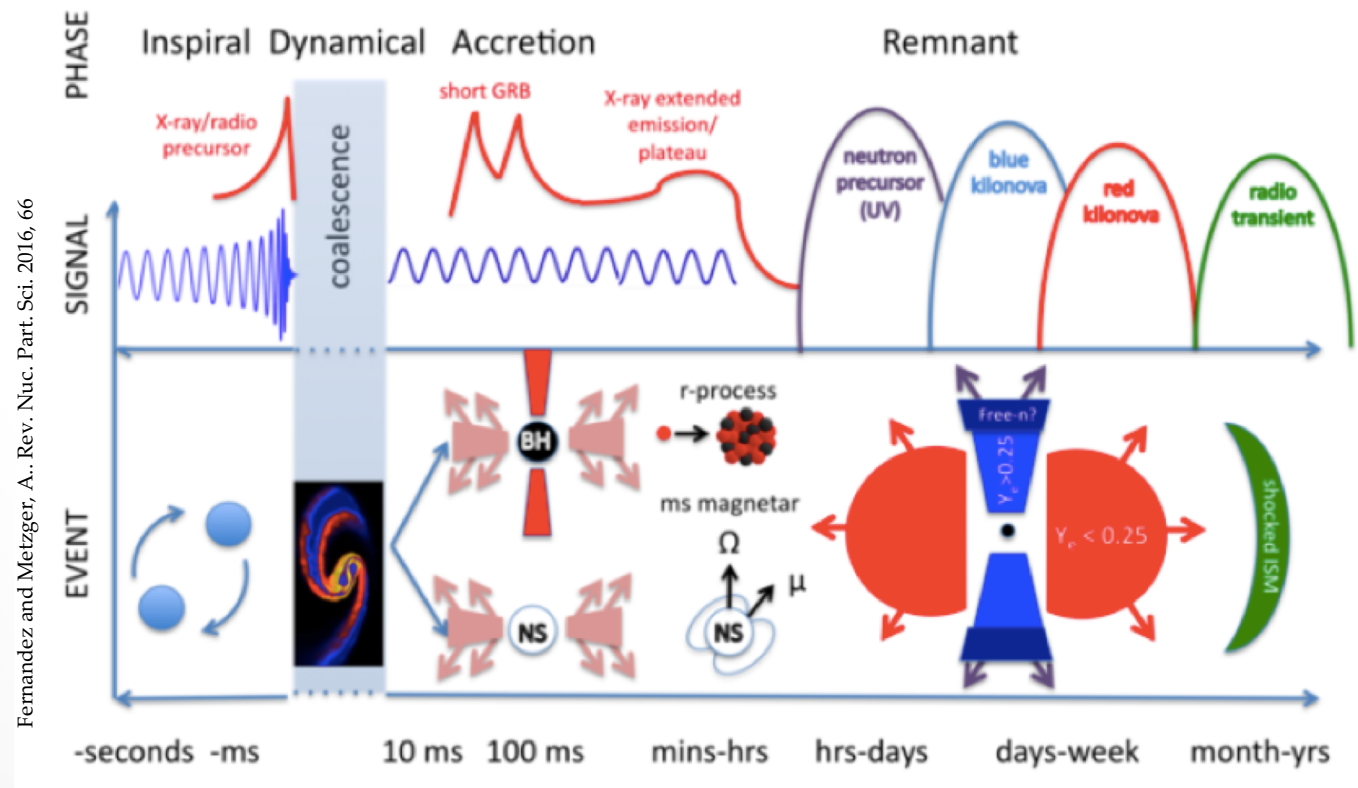
$-2.6 \cdot 10^{-7} \leq \gamma_{GW} - \gamma_{EM} \leq 1.2 \cdot 10^{-6}$
Deviation to Einstein-Maxwell

↑
gravitational
potential
- Lorentz Invariance violation :
Improve between a factor 2 and 10^{10}
previous constraints

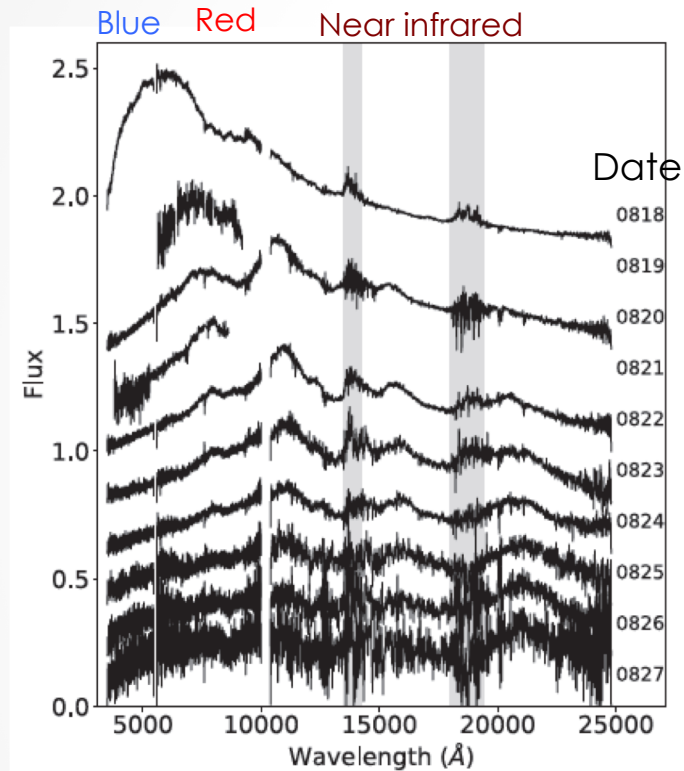
Falsify most of models predicting a difference with c

Kilonova

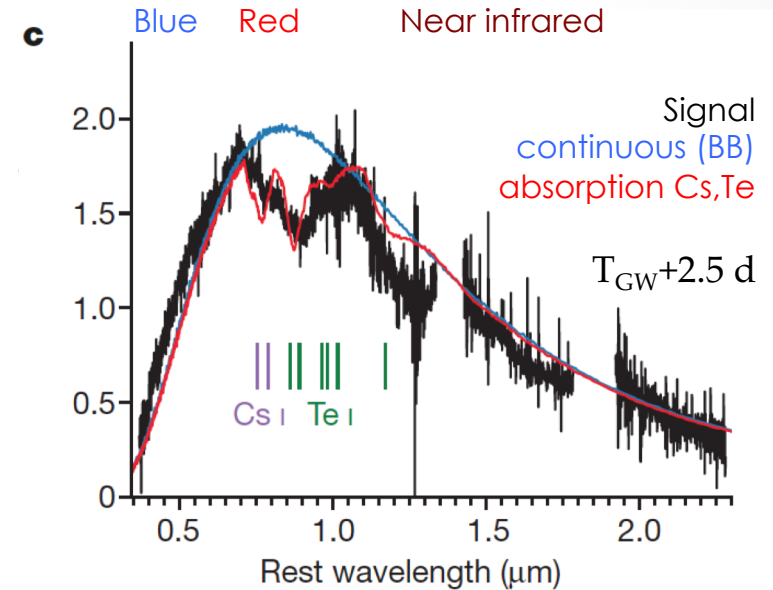
- During merger phase rich neutrons matter could produce heavy elements by neutron capture (r-process)
- Quasi isotropic emission, heated by radioactivity, emission expected to shift from blue to red during cooling



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

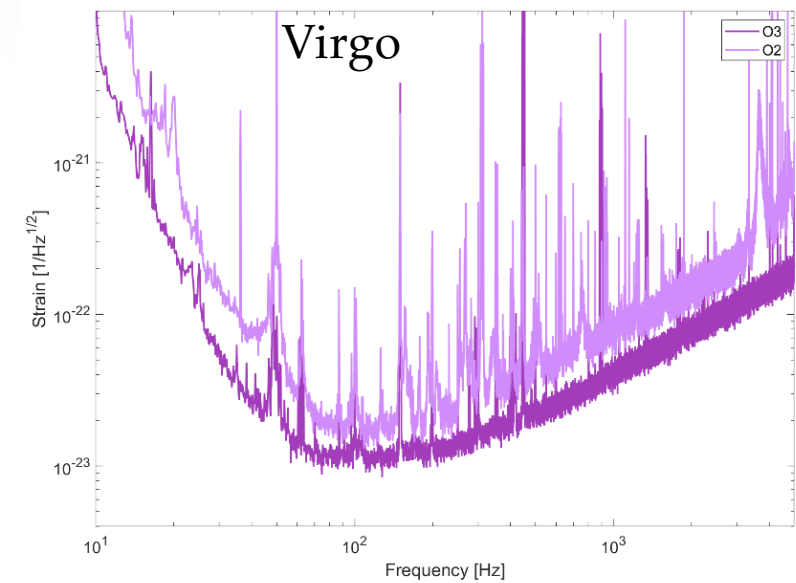
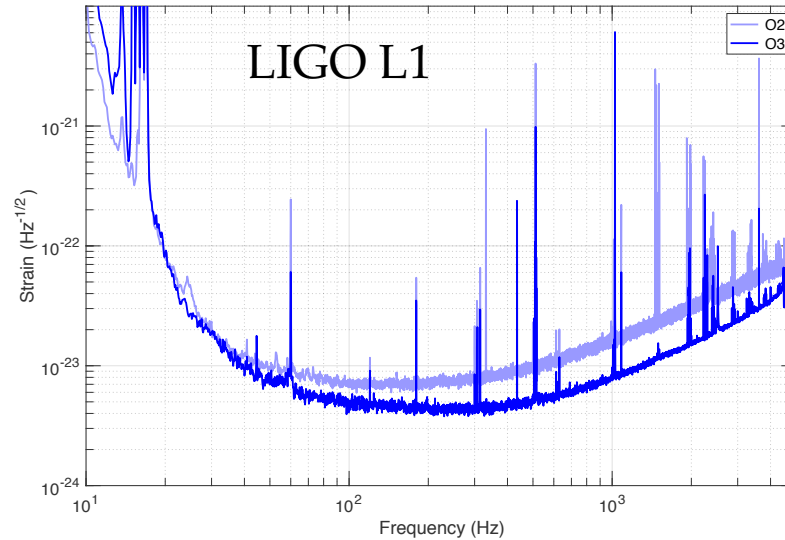
O3 is planned for one year

Range BNS :

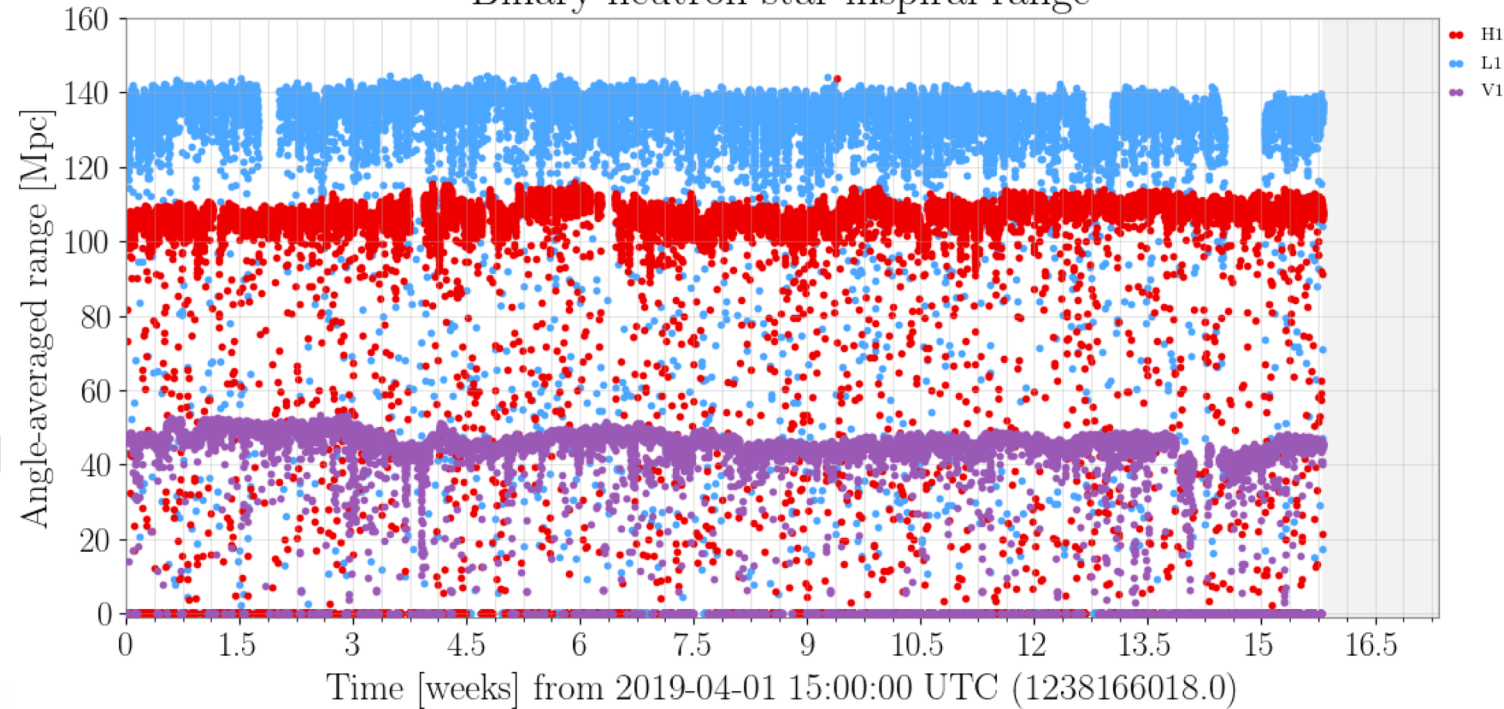
- 100-140 Mpc LIGO
- ~40-50 Mpc Virgo

Already 20 alerts

(17 BBHs + 3 BNS?)



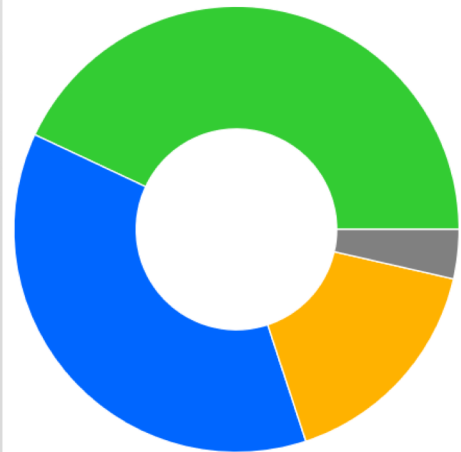
Binary neutron star inspiral range



Network duty factor

[1238166018-1248652818]

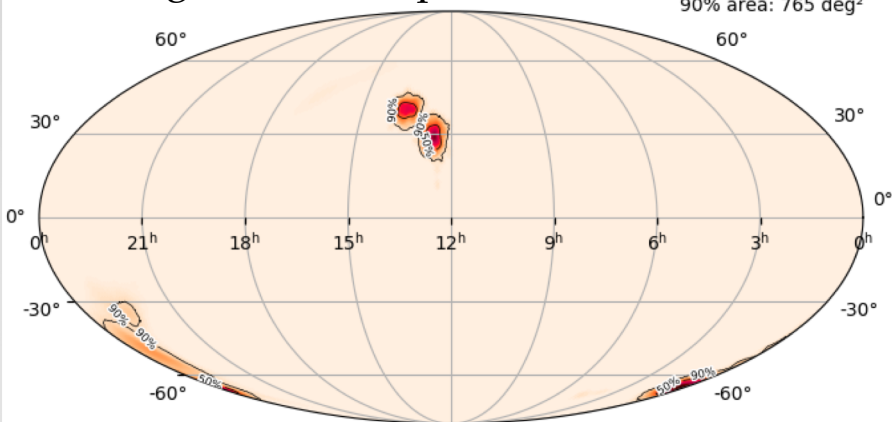
- Triple interferometer [43.0%]
- Double interferometer [37.0%]
- Single interferometer [16.4%]
- No interferometer [3.6%]



First public alerts – not confirmed detections !

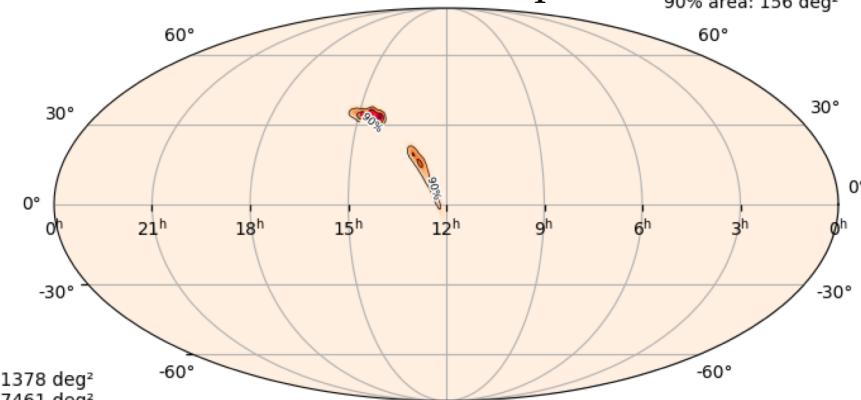
190521g BBH – ~4 Gpc

50% area: 144 deg²
90% area: 765 deg²



190412 BBH – ~810 Mpc

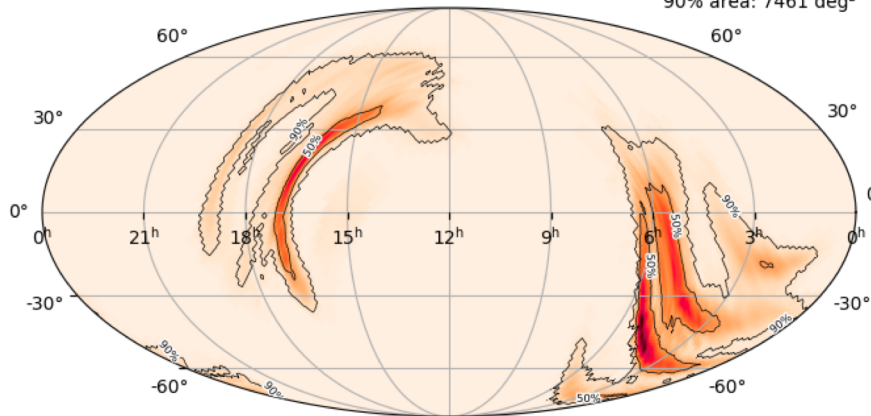
event ID: G329483
50% area: 37 deg²
90% area: 156 deg²



Only few
examples !!!

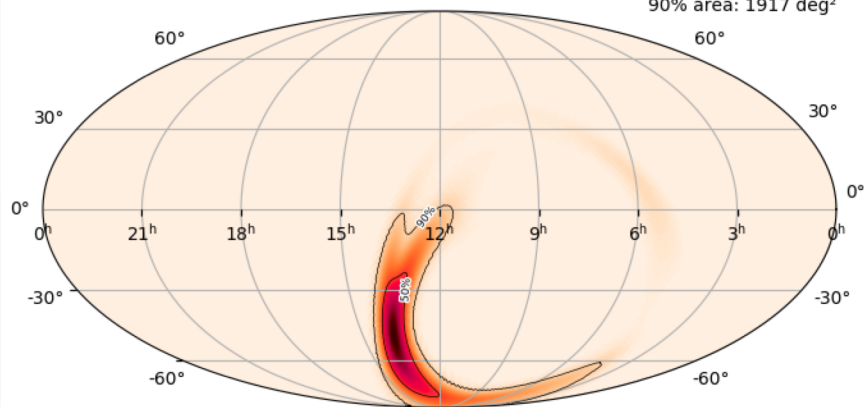
190425 BNS – ~150 Mpc

50% area: 1378 deg²
90% area: 7461 deg²



190421 BBH - ~2.3Gpc

event ID: G330308
50% area: 447 deg²
90% area: 1917 deg²

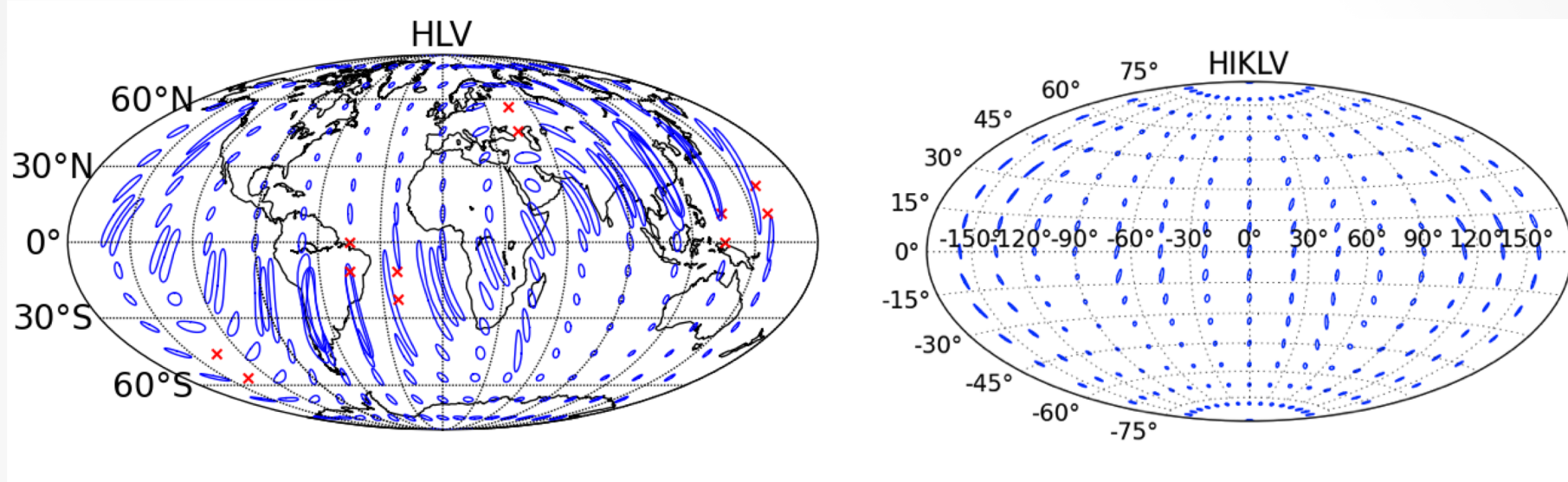


Candidates :

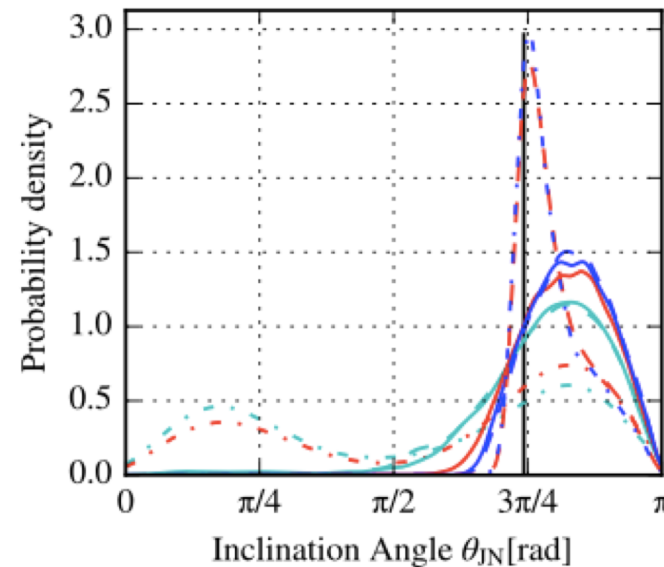
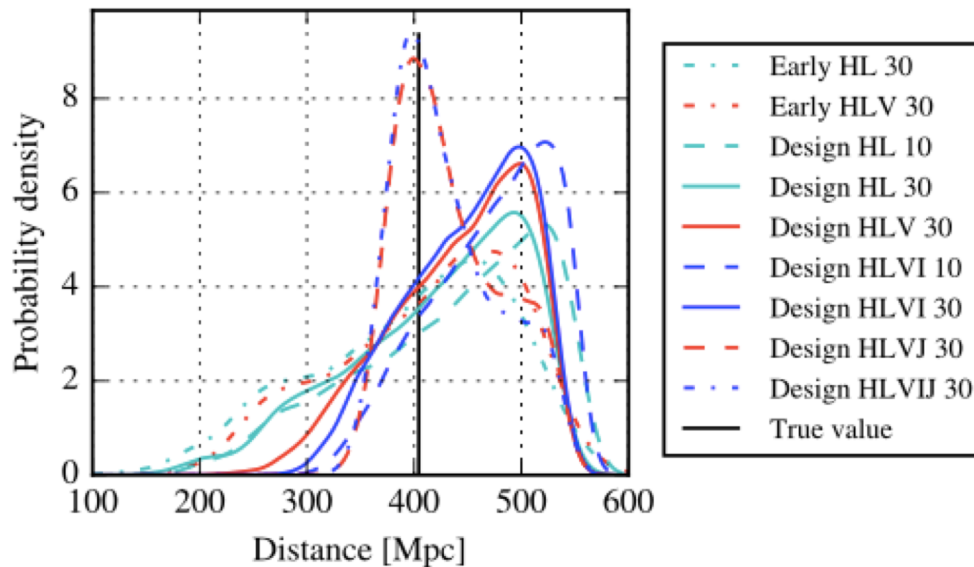
- 1/week for BBH
- 1/month for BNS

Adding new instruments : parameters inference

Comparison between 3 and 5 detectors for sky localization

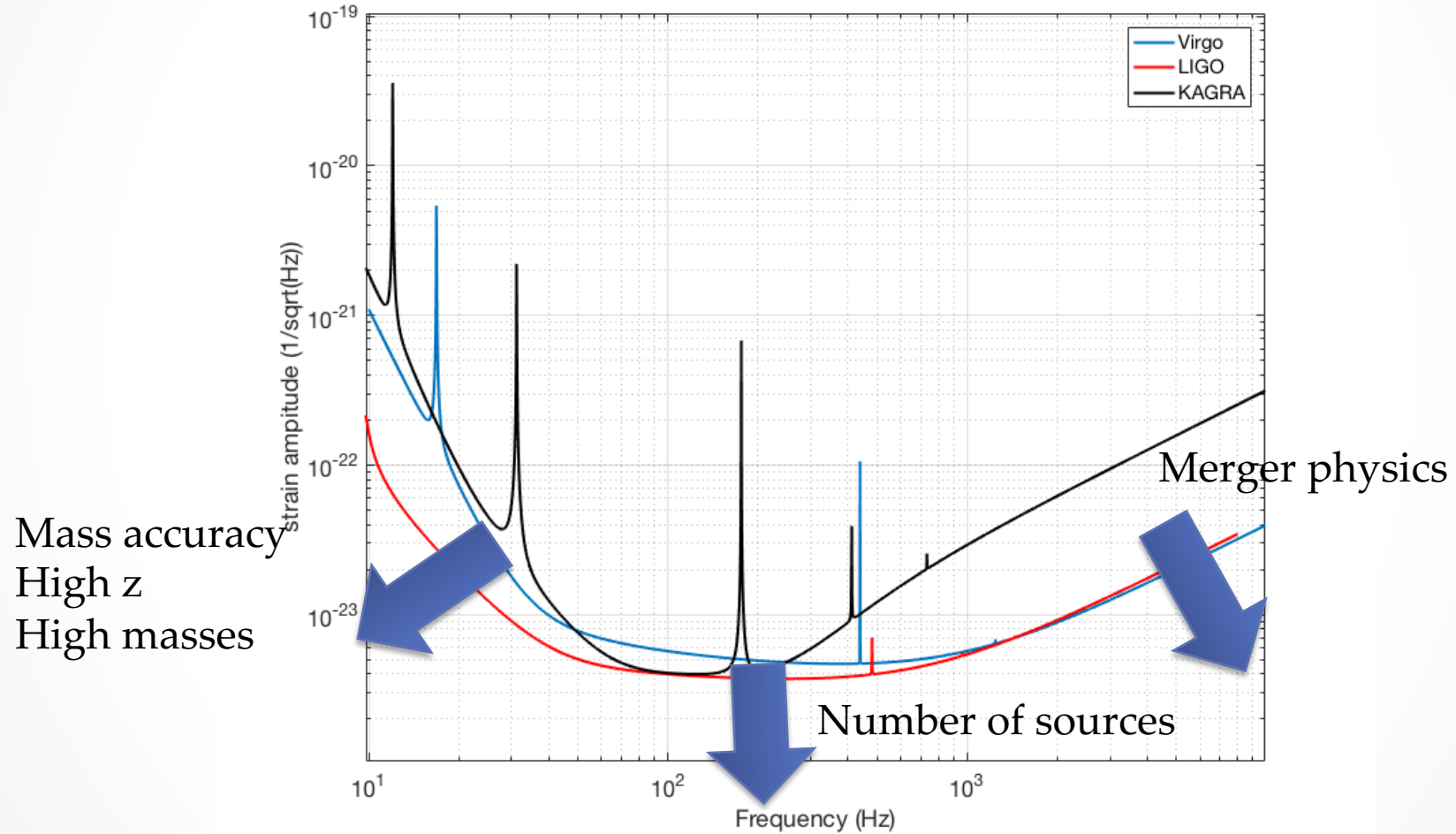


Fairhurst, proceedings of ICGC2011 conference



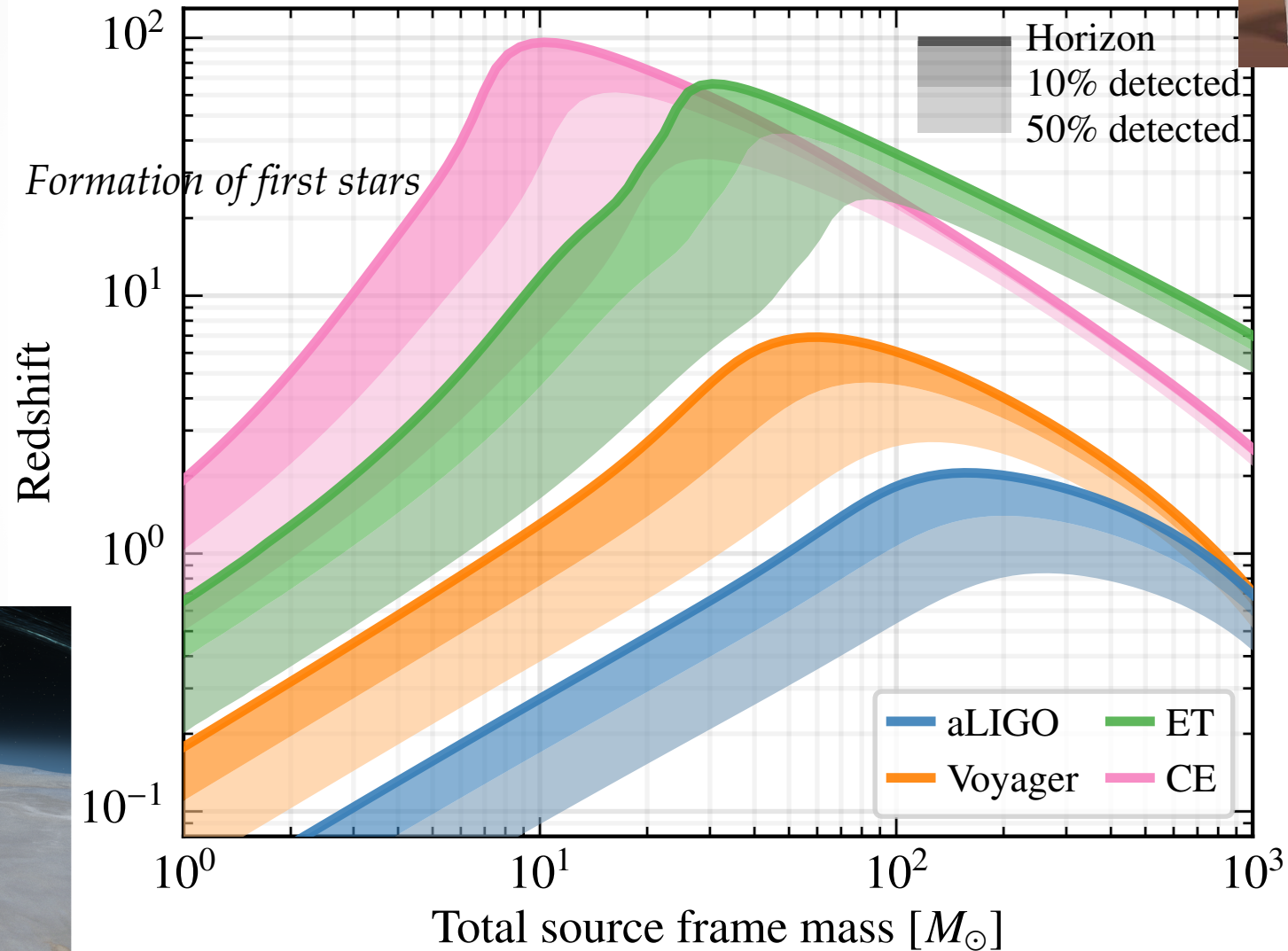
S M Gaebel and J Veitch 2017
Class. Quantum Grav. 34
174003

Improving sensitivity

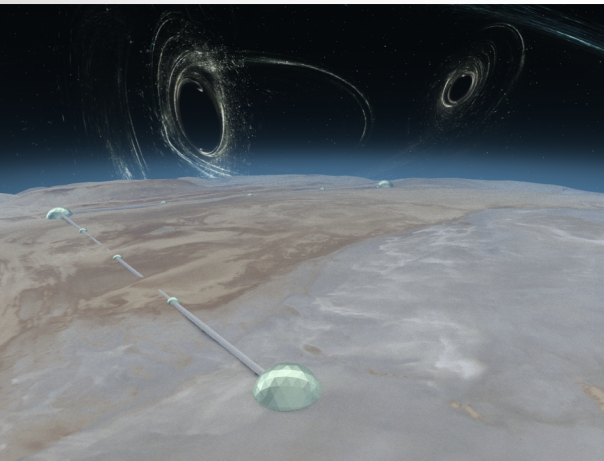
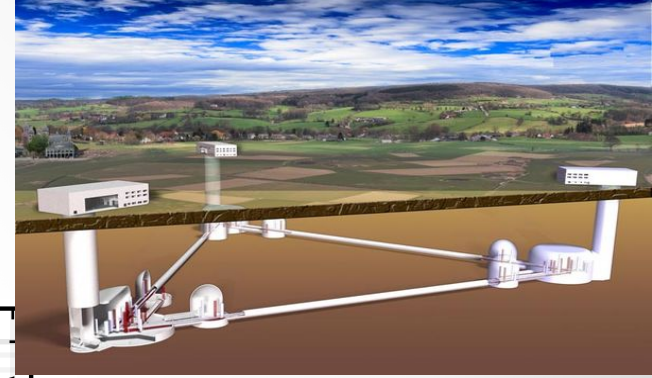


Towards 3G (2030-2035)

Maximal distance for coalescing objects

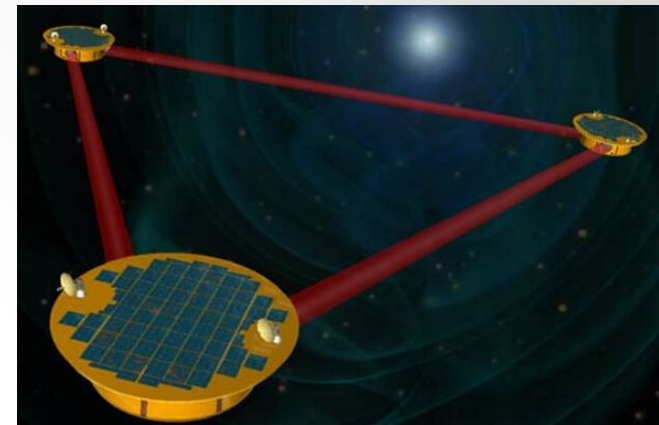


Credit Evan Hall



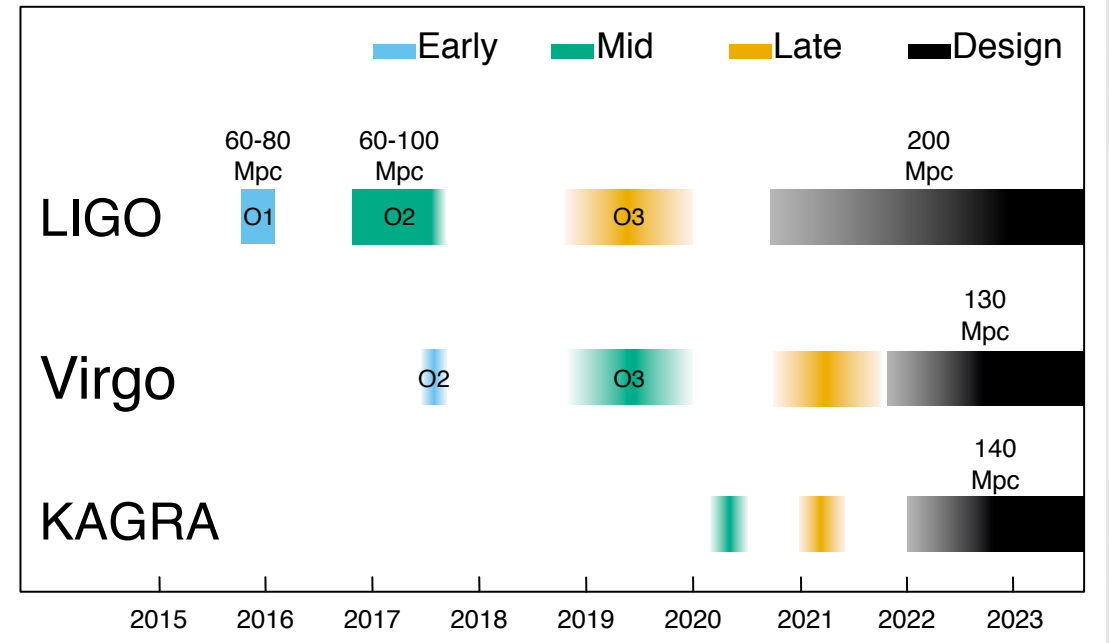
Going into space : LISA

- 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 H_0 measurement
- New run O3 for one calendar year
 - 3 detectors at beginning
 - KAGRA may join before the end of the data taking
 - Detection rate : $\sim 1/\text{week}$ (BBH)
 - Already 20 candidates publicly released
- 3G already in discussion



Backup

...

Image Credit: NASA Goddard Space Flight Center / CI Lab

