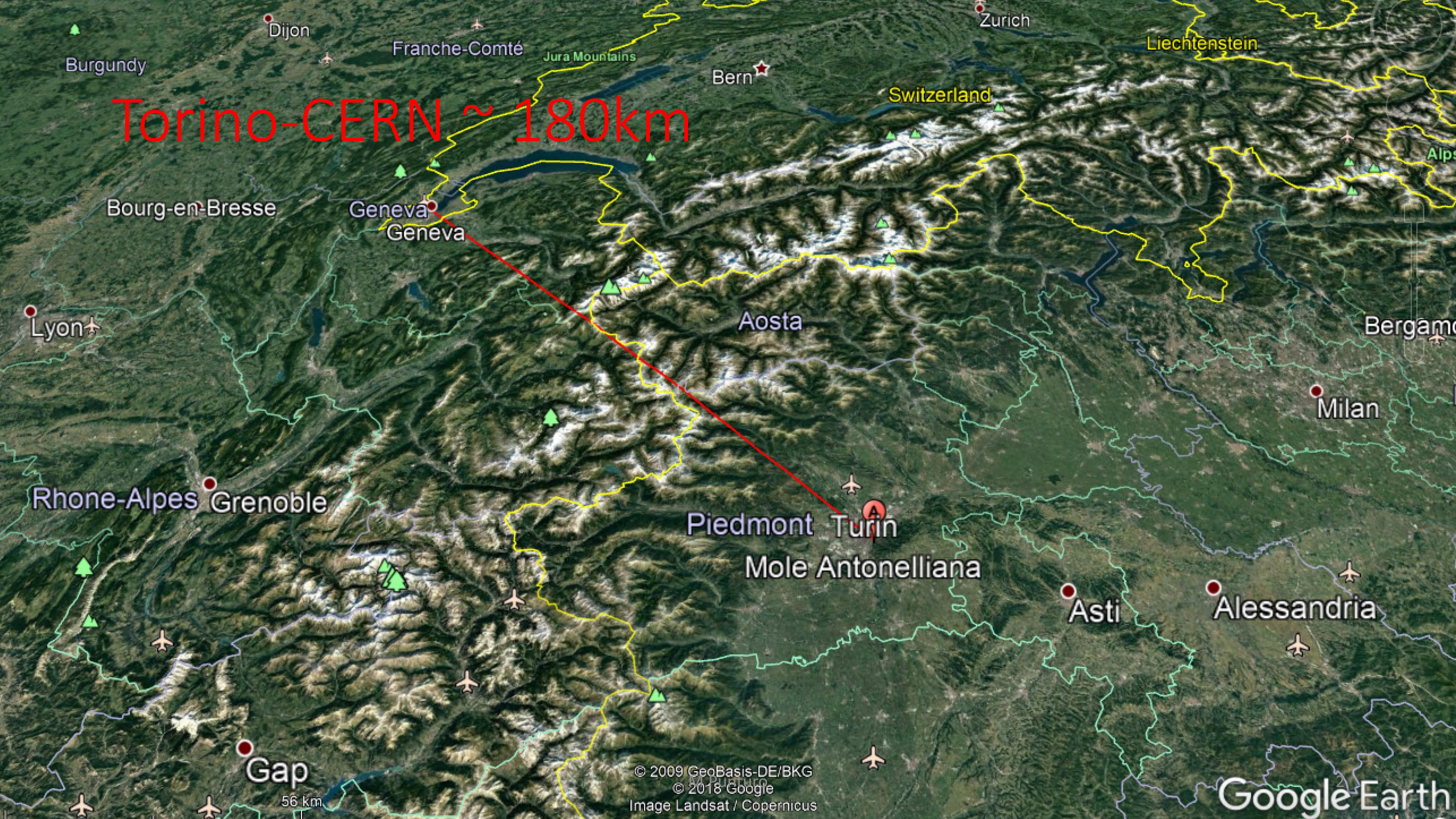
Gravitational Waves: From the current detectors to Einstein Telescope

Michele Punturo
INFN Perugia



Torino-CERN ~ 180km
Dijon
Burgundy
Franche-Comté
Jura Mountains
Bern
Zurich
Liechtenstein
Switzerland
Alps
Bourg-en-Bresse
Geneva
Geneva
Lyon
Aosta
Bergamo
Milan
Rhone-Alpes
Grenoble
Piedmont
Turin
Mole Antonelliana
Asti
Alessandria
Gap
56 km
© 2009 GeoBasis-DE/BKG
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Image Landsat / Copernicus
Google Earth

Modello Standard delle Particelle

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- Le interazioni fra i componenti base della materia, il comportamento dell’intero Universo è regolato da 4 (?) interazioni fondamentali

Interazioni Fondamentali:

Interazione **elettromagnetica**, che caratterizza gli atomi e le molecole

Nucleare debole, che entra in gioco nei decadimenti radioattivi

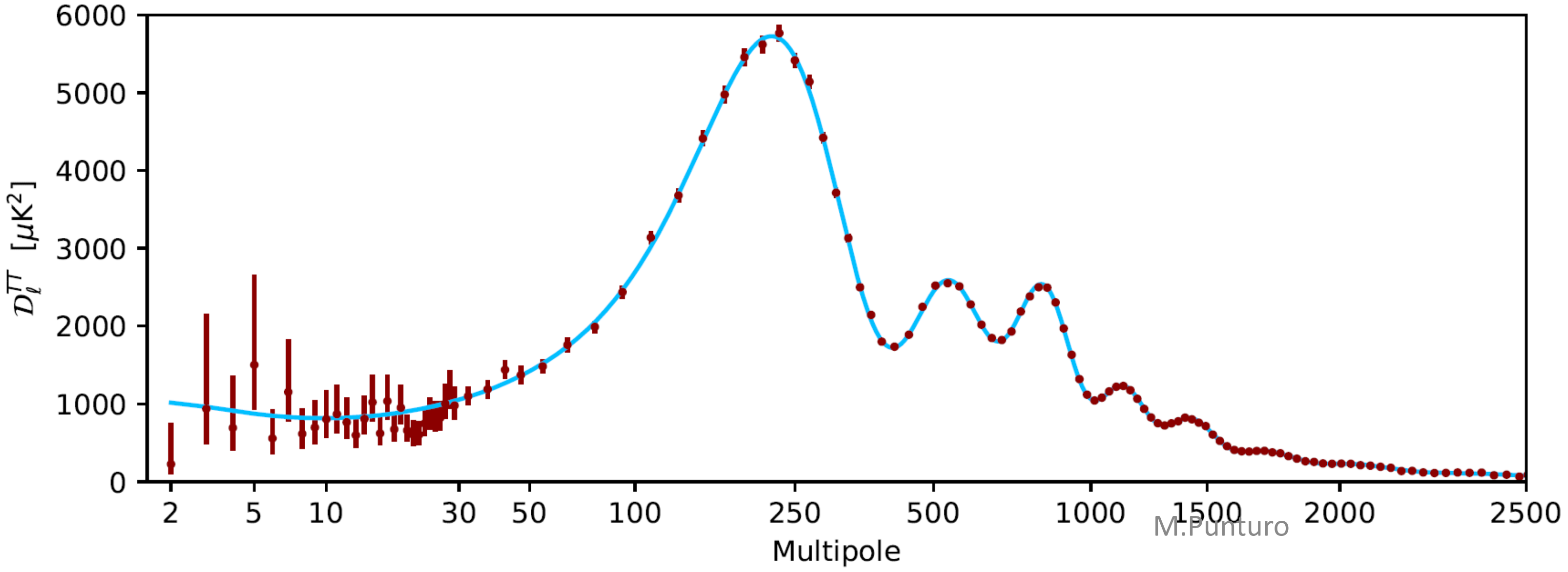
Nucleare forte, che tiene uniti i quark e i nucleoni

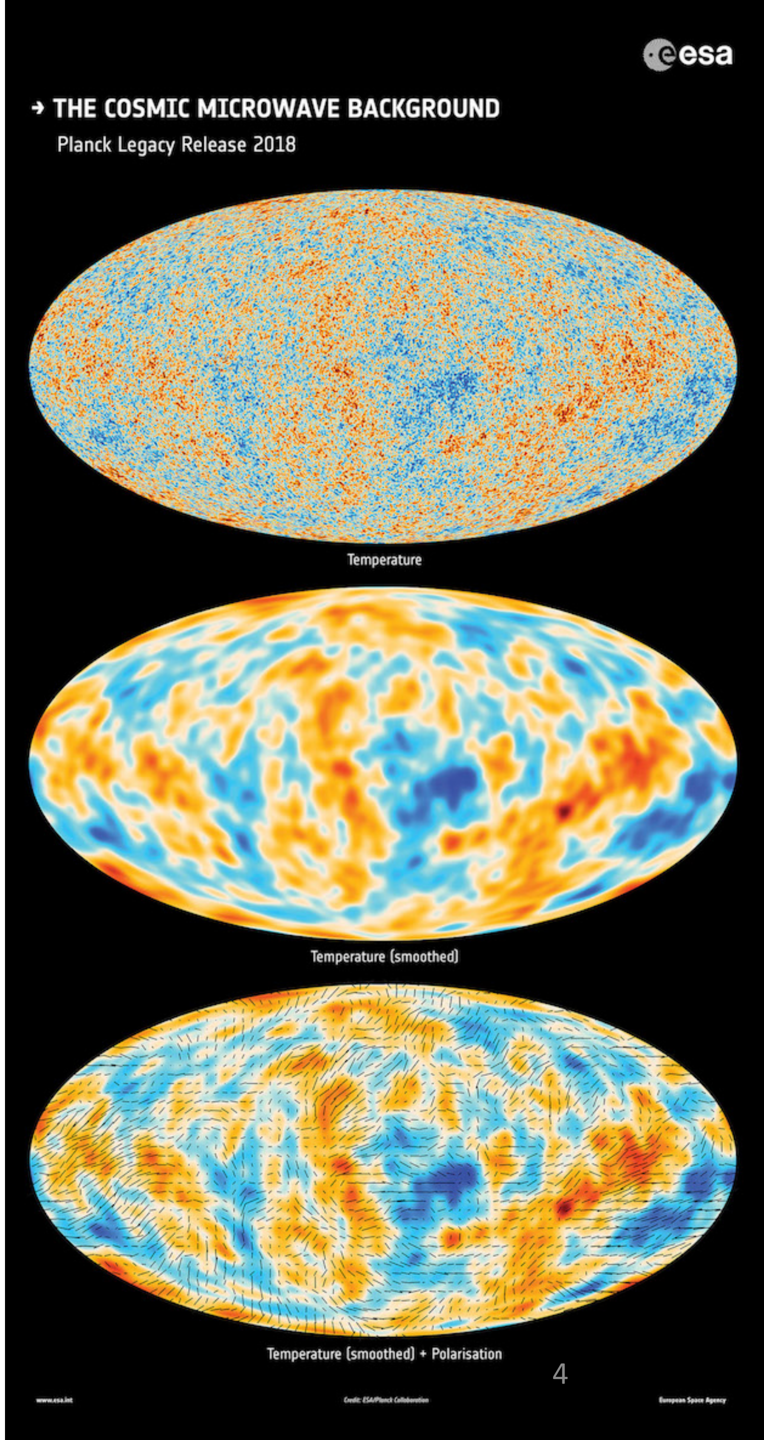
Interazione **Gravitazionale**

Componenti elementari della materia

The Cosmological Standard Model

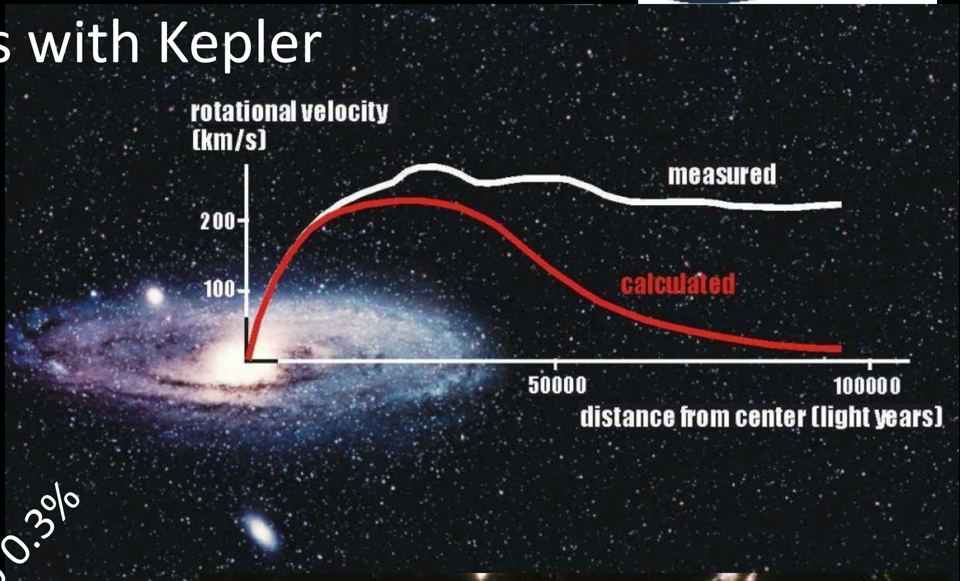
- Observation of the Universe “substantially” confirms the “standard” cosmological model
- Λ-CDM + “simple inflation”
- The agreement between Λ-CDM and the Plank mission data on the angular power spectra for temperature of the Cosmic Microwave Background (CMB)is impressive

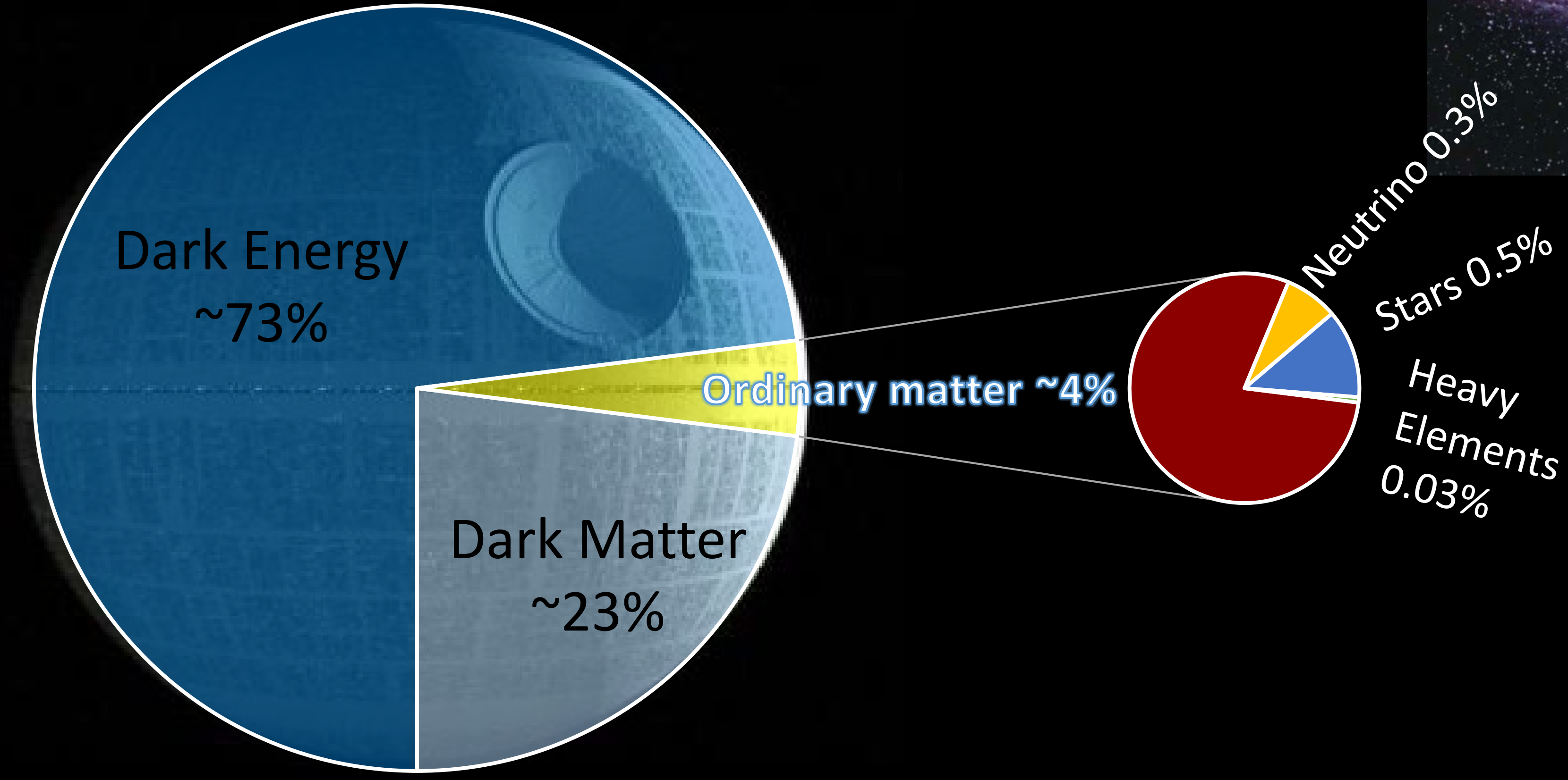


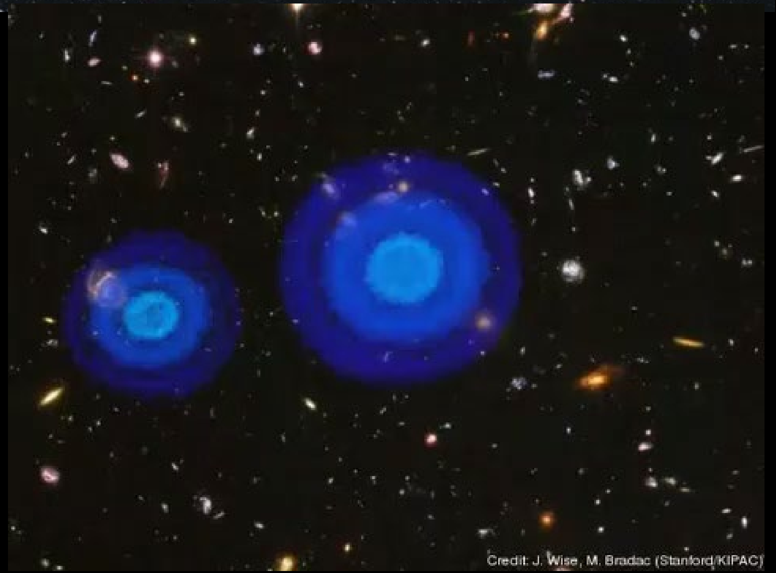


The Dark Side of the Universe

- To reconcile the observed rotational velocity of the galaxies with Kepler prediction from visible mass → Dark Matter
- To explain the observed acceleration of the Universe expansion we need to introduce a repulsive “gravitational” energy → Dark Energy





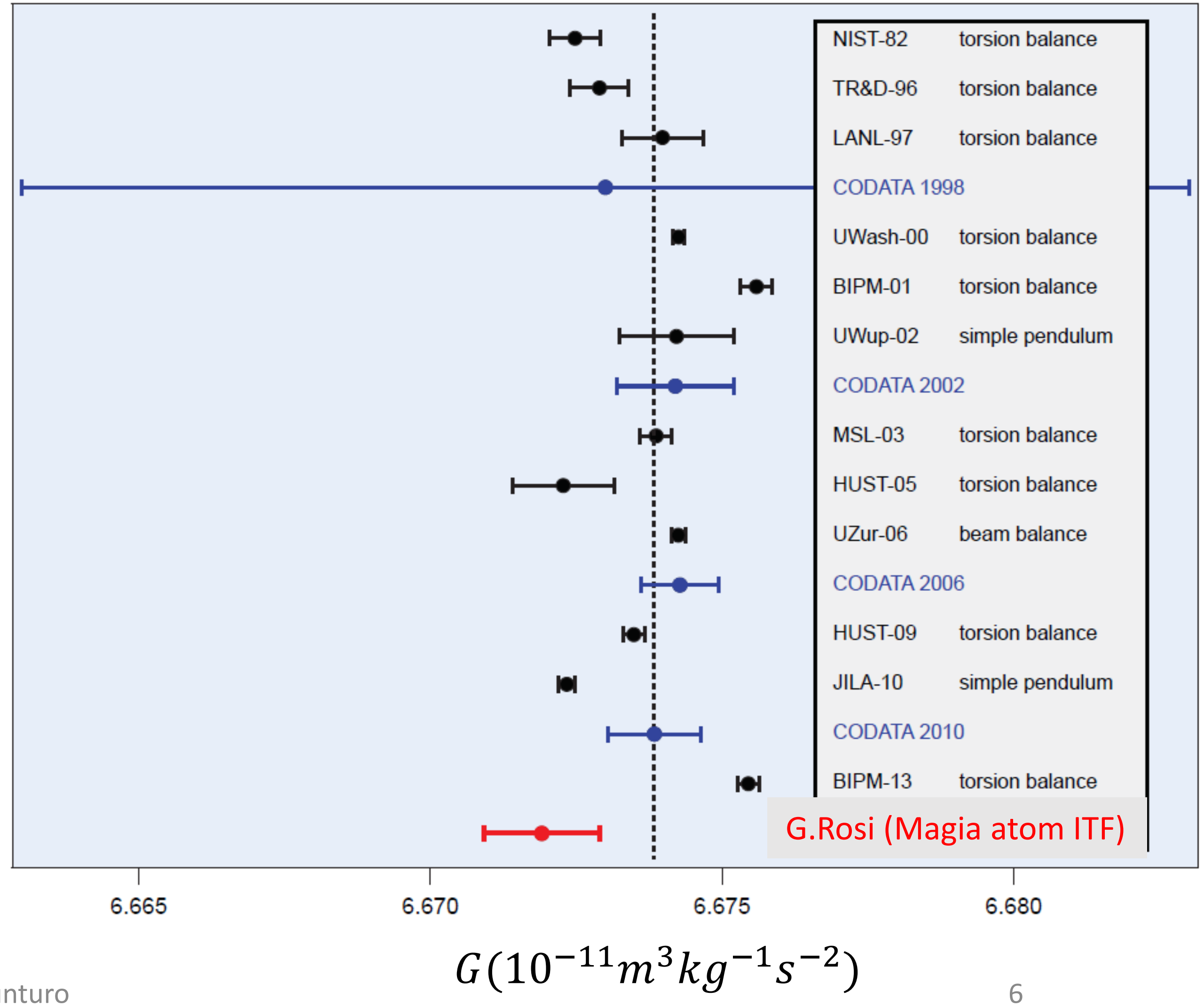


Then, … do we really know gravity?

$$F = -G\frac{m_1 \cdot m_2}{r^2}$$

- Despite the fact that the first measurement of G has been made by Cavendish in 1798, the G value is poorly known
- The comparison with the other “fundamental” constants in physics is impressive

G. Rosi et al., Nature 510, 518-521 (2014)



CODATA 2014

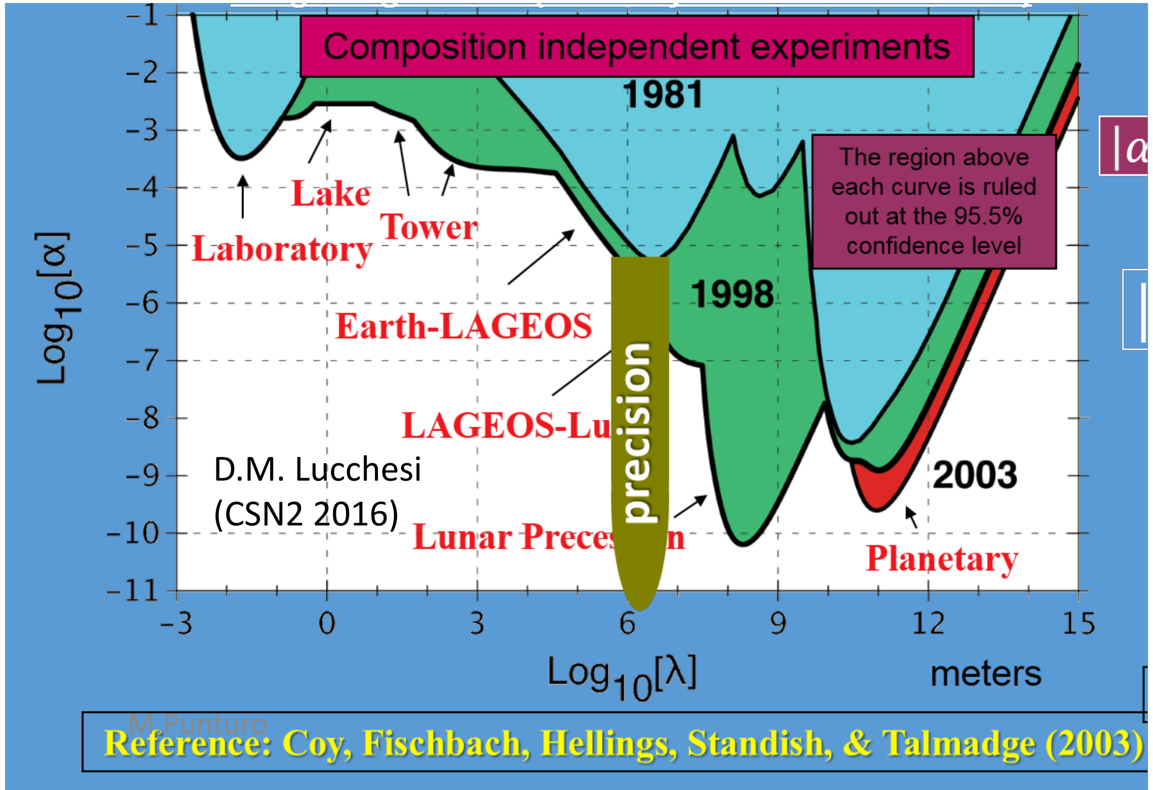
TABLE I An abbreviated list of the CODATA recommended values of the fundamental constants of physics and chemistry based on the 2014 adjustment.

Quantity	Symbol	Numerical value	Unit	Relative std. uncert. u_r
speed of light in vacuum	c, c_0	299 792 458	m s^{-1}	exact
magnetic constant	μ_0	$4\pi \times 10^{-7}$	N A^{-2}	
		$= 12.566\,370\,614... \times 10^{-7}$	N A^{-2}	exact
electric constant $1/\mu_0 c^2$	ϵ_0	$8.854\,187\,817... \times 10^{-12}$	F m^{-1}	exact
Newtonian constant of gravitation	G	$6.674\,08(31) \times 10^{-11}$	m^3 kg^{-1} s^{-2}	4.7×10^{-5}
Planck constant	h	$6.626\,070\,040(81) \times 10^{-34}$	J s	1.2×10^{-8}
$h/2\pi$	$\hbar$	$1.054\,571\,800(13) \times 10^{-34}$	J s	1.2×10^{-8}
elementary charge	e	$1.602\,176\,6208(98) \times 10^{-19}$	C	6.1×10^{-9}
magnetic flux quantum $h/2e$	Φ_0	$2.067\,833\,831(13) \times 10^{-15}$	Wb	6.1×10^{-9}
conductance quantum $2e^2/h$	G_0	$7.748\,091\,7310(18) \times 10^{-5}$	S	2.3×10^{-10}
electron mass	m_e	$9.109\,383\,56(11) \times 10^{-31}$	kg	1.2×10^{-8}
proton mass	m_p	$1.672\,621\,898(21) \times 10^{-27}$	kg	1.2×10^{-8}
proton-electron mass ratio	m_p/m_e	$1836.152\,673\,89(17)$		9.5×10^{-11}
fine-structure constant $e^2/4\pi\epsilon_0\hbar c$	α	$7.297\,352\,5664(17) \times 10^{-3}$		2.3×10^{-10}
inverse fine-structure constant	α^{-1}	$137.035\,999\,139(31)$		2.3×10^{-10}
Rydberg constant $\alpha^2 m_e c/2h$	R_∞	$10\,973\,731.568\,508(65)$	m^{-1}	5.9×10^{-12}
Avogadro constant	N_A, L	$6.022\,140\,857(74) \times 10^{23}$	mol^{-1}	1.2×10^{-8}
Faraday constant $N_A e$	F	$96\,485.332\,89(59)$	C mol^{-1}	6.2×10^{-9}
molar gas constant	R	$8.314\,4598(48)$	J mol^{-1} K^{-1}	5.7×10^{-7}
Boltzmann constant R/N_A	k	$1.380\,648\,52(79) \times 10^{-23}$	J K^{-1}	5.7×10^{-7}
Stefan-Boltzmann constant $(\pi^2/60)k^4/\hbar^3 c^2$	σ	$5.670\,367(13) \times 10^{-8}$	W m^{-2} K^{-4}	2.3×10^{-6}
		Non-SI units accepted for use with the SI		
electron volt (e/C) J	eV	$1.602\,176\,6208(98) \times 10^{-19}$	J	6.1×10^{-9}
(unified) atomic mass unit $\frac{1}{12}m(^{12}\mathrm{C})$	u	$1.660\,539\,040(20) \times 10^{-27}$	kg	1.2×10^{-8}

Is really $F \propto r^{-2}$?

- Let use the Gravitational potential → $$\phi(r) = -G\frac{M}{r}$$
- Let suppose to have a modification according to a Yukawa-like interaction $$\phi(r) = -G\frac{M}{r}\left(1+\alpha e^{-r/\lambda}\right)$$
- λ is the Compton wavelength of the interaction boson ("graviton"):

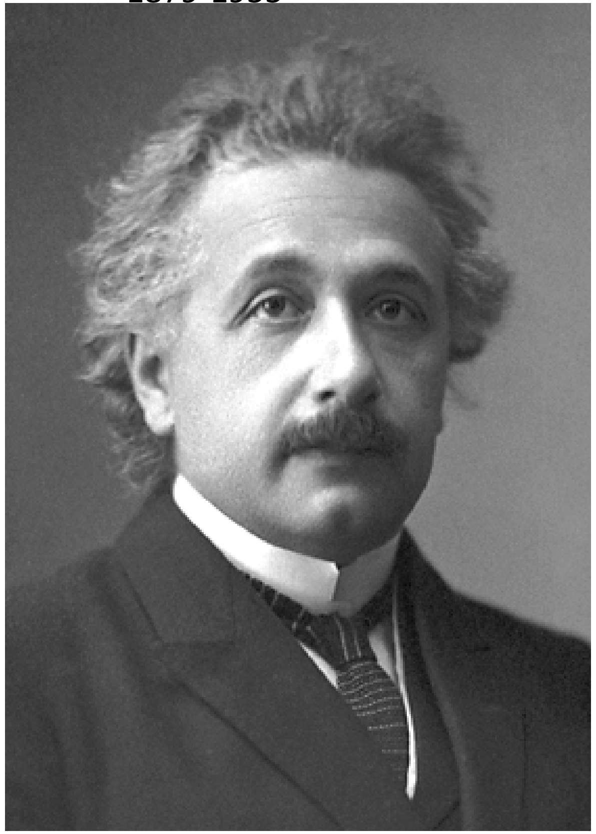
$$\lambda = \frac{\hbar}{m_g c}$$



Albert Einstein

- In fisica, come in molti ambienti dove la creatività è elemento cruciale, i momenti di crisi sono i più produttivi per una svolta nella conoscenza
- 1905 – Annus Mirabilis
  - Tesi di dottorato: “Nuova determinazione delle dimensioni molecolari”
  - Sviluppi sul moto “Browniano”
  - “Sull'elettrodinamica dei corpi in movimento” (Relatività Ristretta $E=mc^2$)
  - Effetto Fotoelettrico (Premio Nobel)

Albert Einstein
1879-1955



Ma nella Teoria della Relatività ristretta manca un ingrediente fondamentale: la Gravità

General Relativity

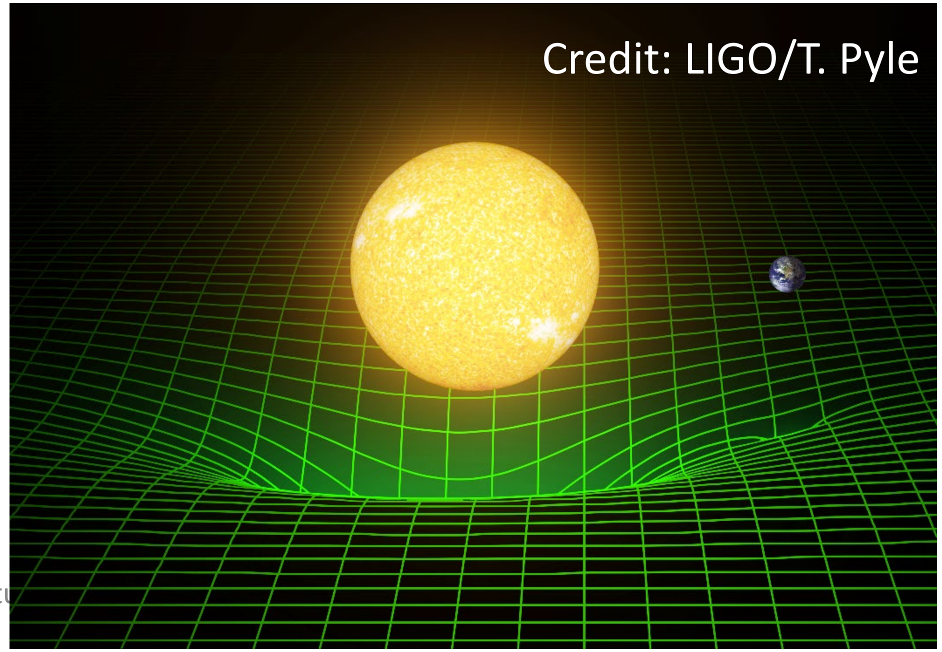
Theory of the gravitation

Carl Friedrich Gauss
1777-1855

Bernhard Riemann
1826-1866

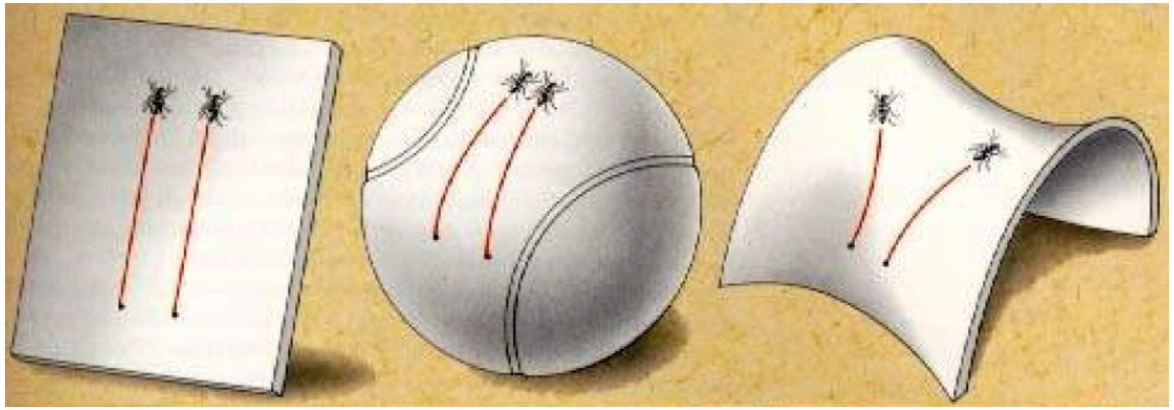
1915 – GR is "the" gravitation theory where space-time is no more flat, but curved by the presence of masses:

> "Mass tells space-time how to curve, and space-time tells mass how to move." (John Wheeler)"



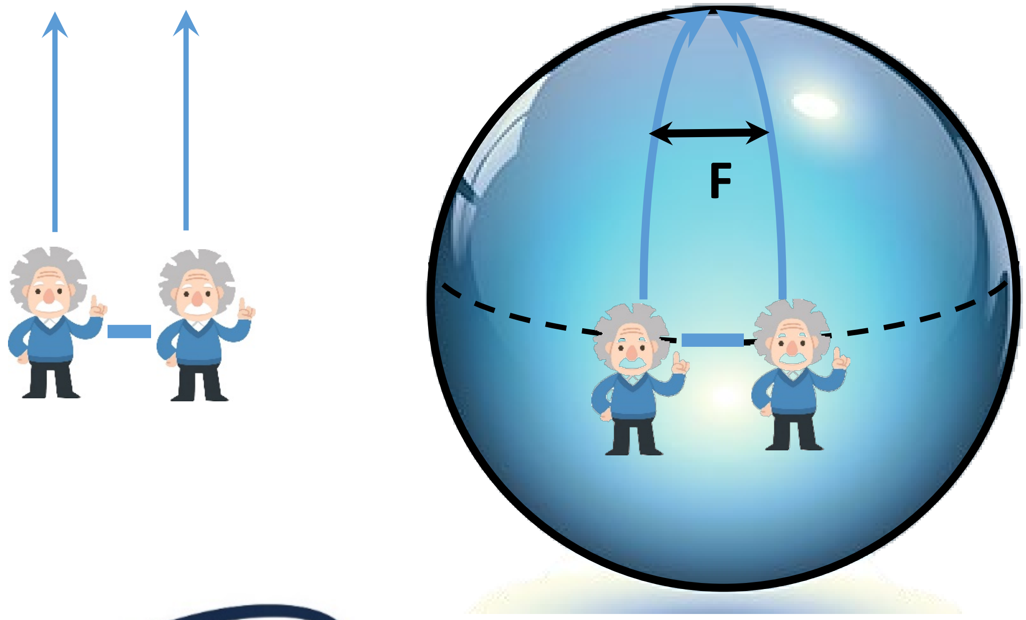
Curved Geometry = Force?

Trajectories (worldlines) of particle which are not being acted upon any non-gravitational force are generalised to curved path named **geodesics**



Sphere: positive intrinsic curvature. The geodesics converge

Saddle: negative intrinsic curvature. The geodesics diverge



The **acceleration** of the deviation between neighbouring geodesics is the signature of space-time curvature due to the presence of a non-uniform (tidal) gravitational fields

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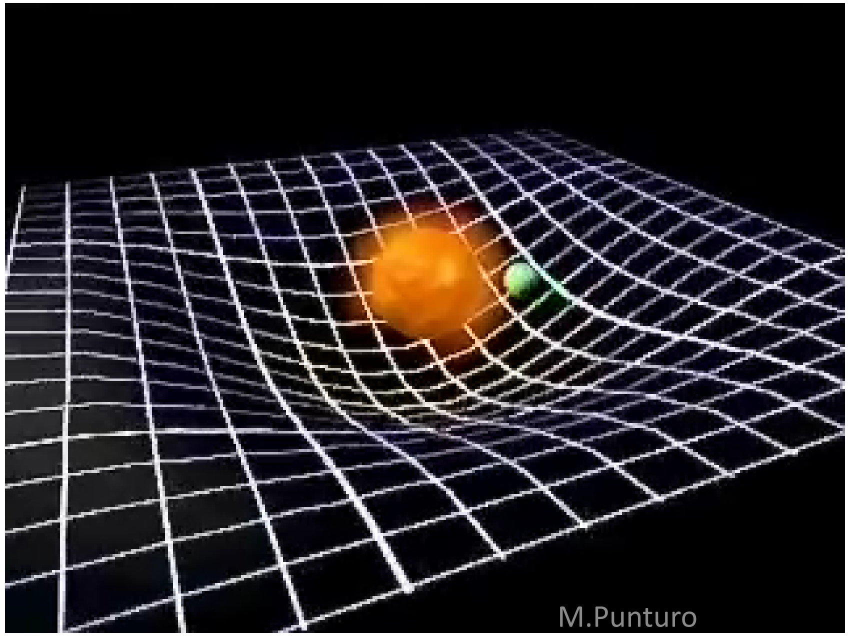
GR Field Equation

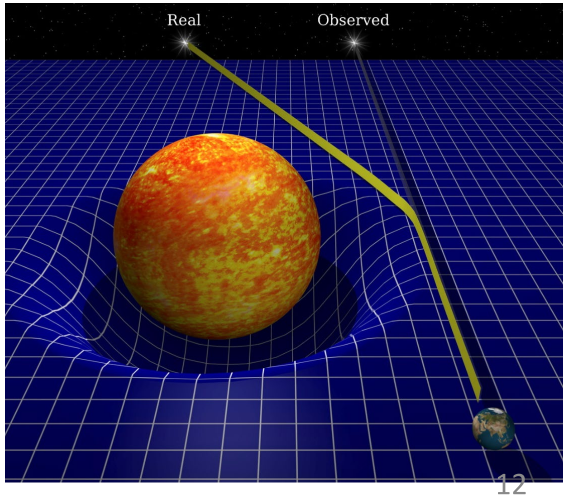
- Gravitational field equation in General Relativity:

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu} \Rightarrow G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

Curvature of the space-time

Energy-Momentum Tensor





Eddington 1919

GW: propagation of the space-time curvature

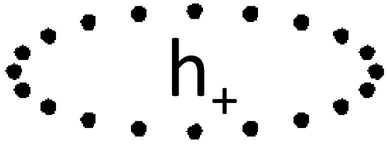
- (1916) Field equation solution for near flat space-time (far field $T_{\mu\upsilon} = 0$)

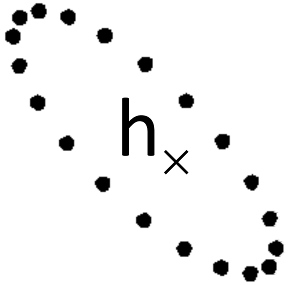
$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu} \Rightarrow \left(-\frac{1}{c^2}\frac{\partial^2}{\partial t^2} + \nabla^2 \right) h_{\mu\nu} = 0$$

- The space-time curvature propagates as a wave at the speed «c»

$$h_{ij}^{TT}(t,z) = \begin{pmatrix} h_+ & h_\times & 0 \\ h_\times & -h_+ & 0 \\ 0 & 0 & 0 \end{pmatrix}_{ij} \cos\left[\omega\left(t - z/c\right)\right]$$

Two polarisations h_+ and h_x



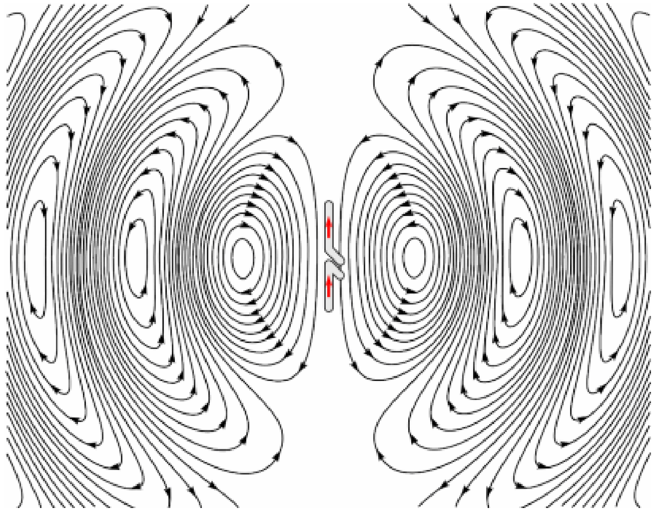


$$\Delta L = h \cdot L$$

Emission of GW

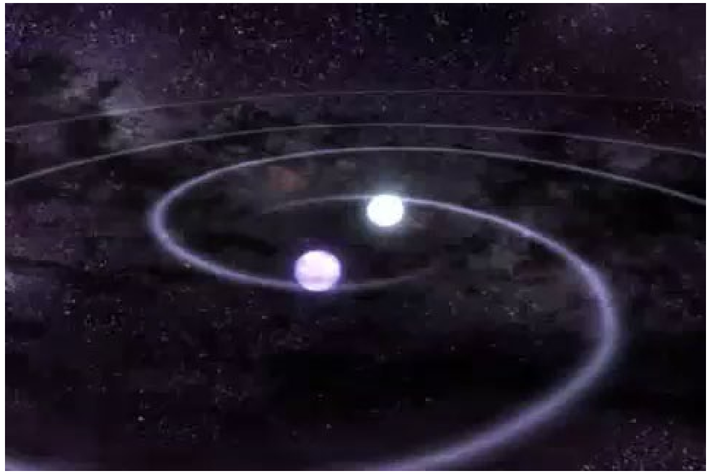
Electromagnetic waves

- Accelerated charges are emitting e.m. waves: dipole emission



Gravitational Waves

- Accelerated masses are emitting GW waves: quadrupole emission



Retarded potential: $h_{\mu\nu}(t,\vec{x}) = -\frac{\kappa}{4\pi}\int \frac{T_{\mu\nu}\left(t-|\vec{x}-\vec{x}'|,\vec{x}'\right)}{|\vec{x}-\vec{x}'|} d^3x'$

Developing in Taylor's series $\frac{1}{|\vec{x}-\vec{x}'|}$ and arresting it to the quadrupolar term:

$$\left|h_{kl}^{TT}(t,\vec{x})\right|_{quad} = -\frac{\kappa}{8\pi r}\frac{1}{3}\ddot{Q}_{kl}^{TT}(t-r/c) = \frac{1}{r}\frac{2G}{c^4}\frac{1}{3}\ddot{Q}_{kl}^{TT}(t-r/c)$$

1/r

$1.6\times10^{-44}\ m^{-1}kg^{-1}s^2$

GW: expected signal shape

- Obviously the signal shape depends upon the source
- Let consider a CBC (Coalescence of a Compact Binary system):
  - BNS or BBH
  - Newtonian approximation:

$$h_+(t) = \frac{4}{r}\left(\frac{GM_c}{c^2}\right)^{\frac{5}{3}}\left(\frac{\pi f_{gw}(t_{ret})}{c}\right)^{\frac{2}{3}}\frac{1+\cos^2 i}{2}\cos(\phi(t_{ret}))$$

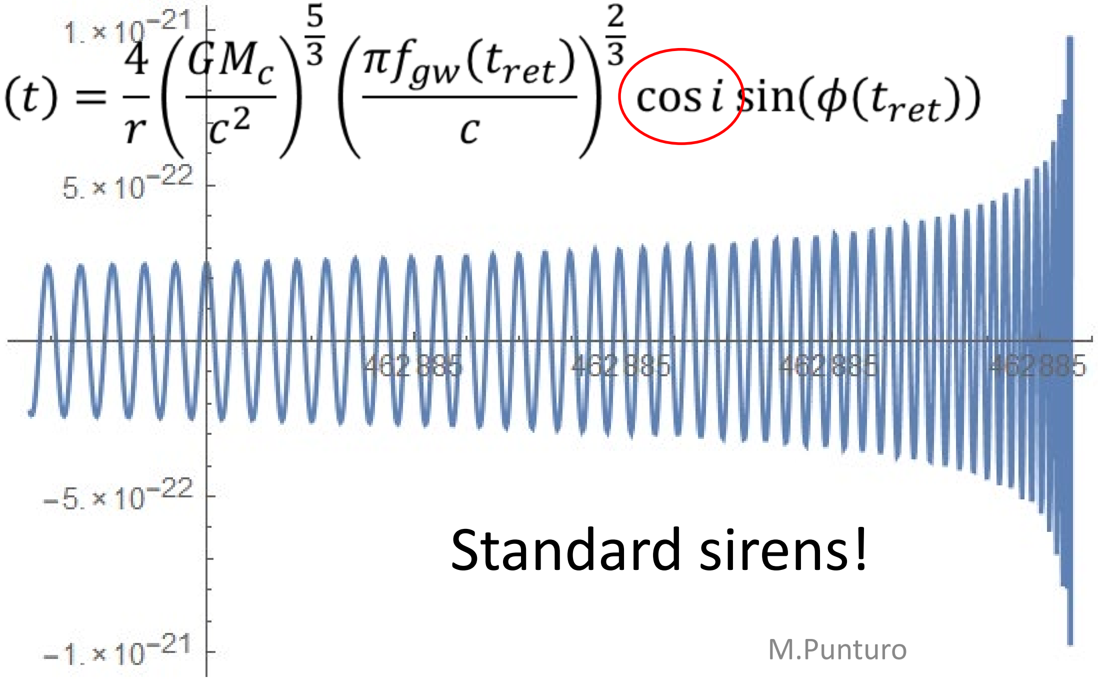
$$h_\times(t) = \frac{4}{r}\left(\frac{GM_c}{c^2}\right)^{\frac{5}{3}}\left(\frac{\pi f_{gw}(t_{ret})}{c}\right)^{\frac{2}{3}}\cos i\,\sin(\phi(t_{ret}))$$

Red shift!

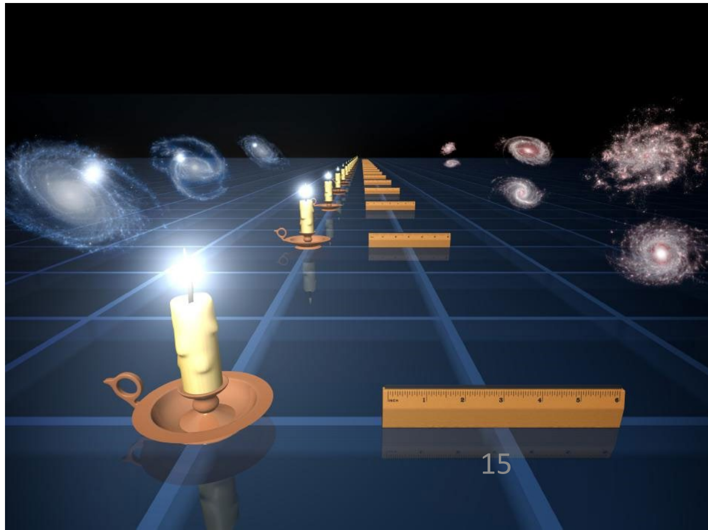
$$f_{gw}(\tau_0) = \frac{1}{\pi}\left(\frac{5}{256}\frac{1}{\tau_0}\right)^{\frac{3}{8}}\left(\frac{c^3}{GM_c}\right)^{\frac{5}{8}}$$

Chirp mass:

$$M_c = \mu^{\frac{3}{5}}M^{\frac{2}{5}} = \frac{(m_1 m_2)^{\frac{3}{5}}}{(m_1+m_2)^{\frac{1}{5}}}$$

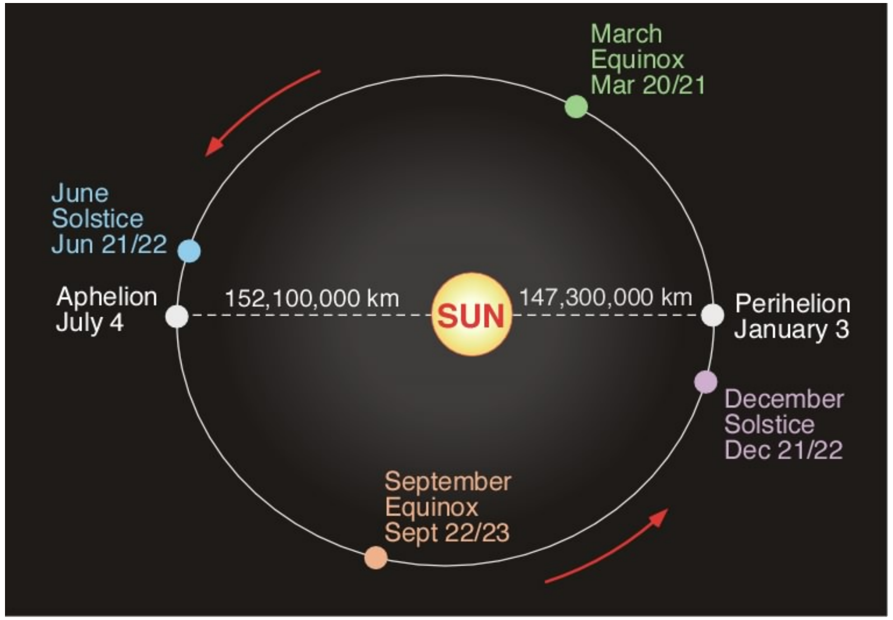


Standard sirens!



GW: expected amplitude

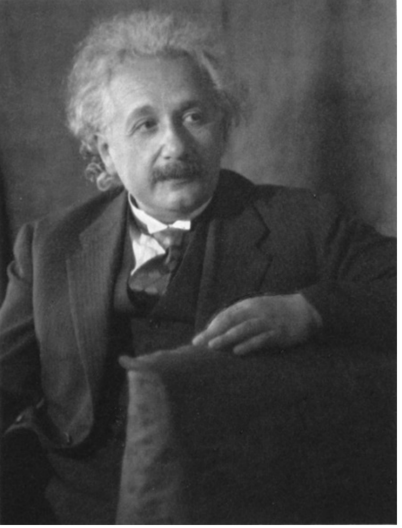
$$\left.\begin{aligned} m_1 &= m_2 = 1.4 M_\Theta = 1.4 \cdot \left(2 \cdot 10^{30} kg\right) \\ r &= 40\text{MPc} = 40 \cdot 10^6 \cdot \left(3 \cdot 10^{16} m\right) \\ f &= 100 Hz \end{aligned}\right\} \Rightarrow h \approx 1.0 \times 10^{-22} \left(\frac{f}{100 Hz}\right)^2 \rightarrow \Delta L = hL \approx 3 \times 10^{-19} m$$



It corresponds to the modulation of the distance Earth-Sun by the size of one atom

A. Einstein: *«the effect is of no practical interest since it is too small to be detected»*

One century of research, study and R&D

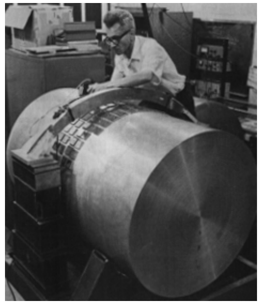


1915 GR

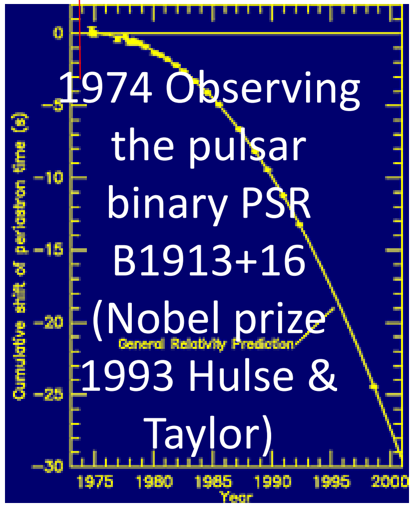
1916-1918 GW

1937 GW correct equation

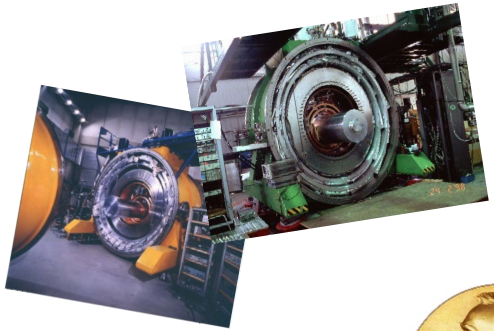
1957 GW are transporting energy



1966 J.Weber: beginning of the experimental GW era



1974 Observing the pulsar binary PSR B1913+16 (Nobel prize 1993 Hulse & Taylor)



’80-’90: Cryogenic resonant bars

1986: B.Schutz (standard sirens), PPN templates …

1993

INFN

1994: approval of the Virgo experiment

1999+ Templates: EOB, Numerical relativity

1999+ beginning of LIGO and Virgo (+4y) operations

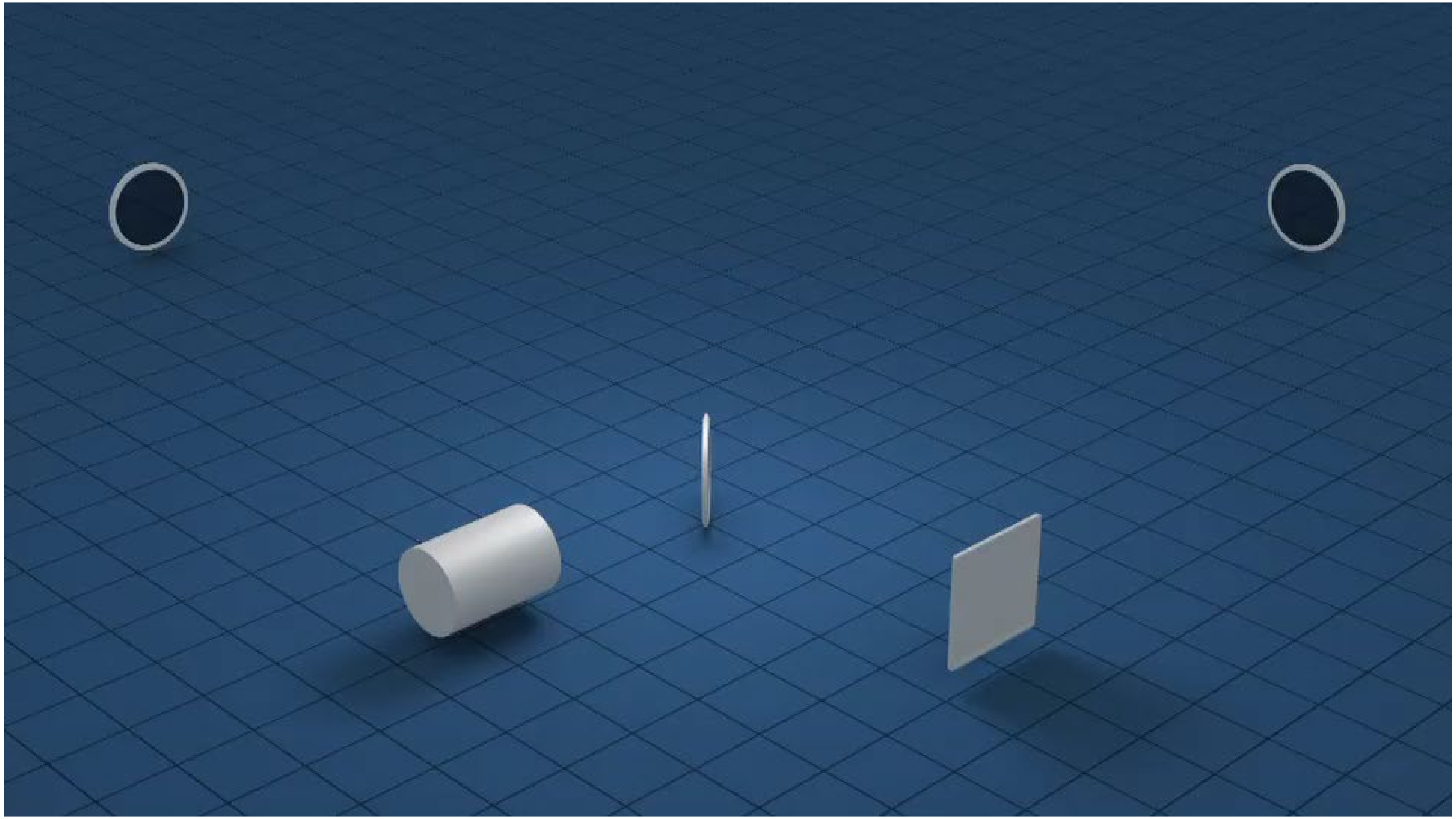
2015: beginning of aLIGO operativity: GW detection

2017 beginning of Advanced Virgo operativity: GW from BNS

t

Working principle of a GWD

- Laser interferometry

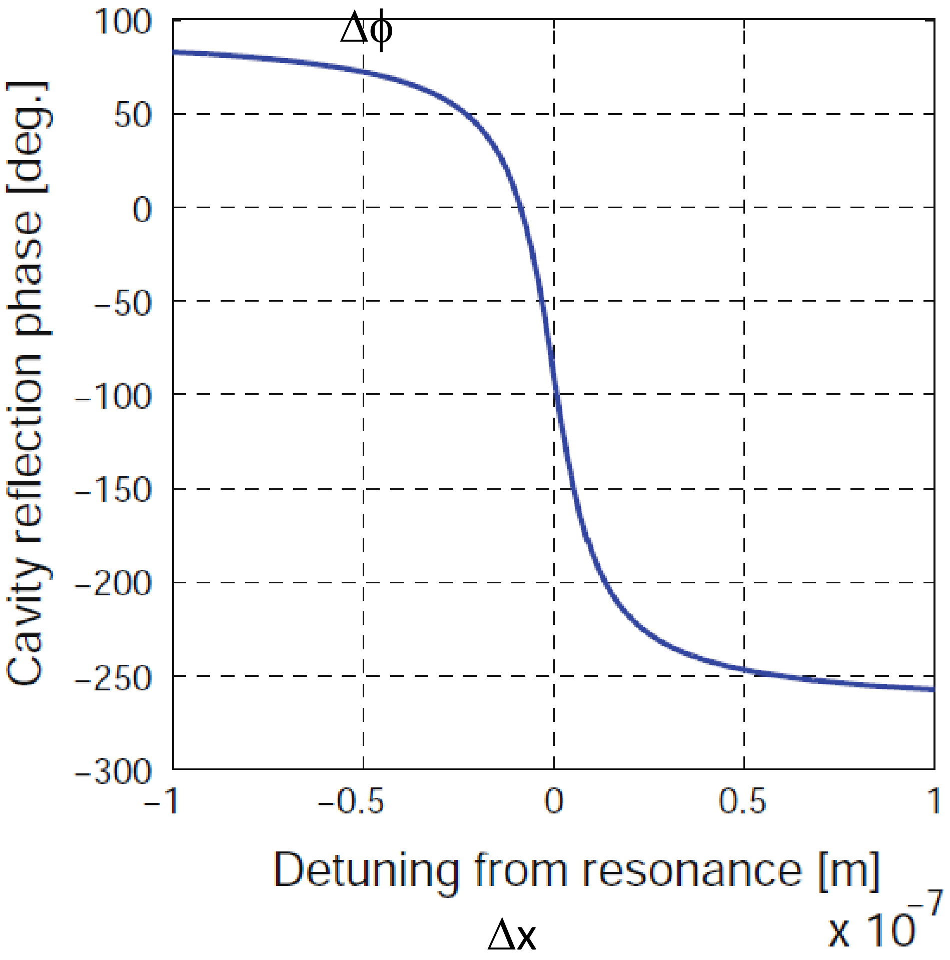


Complex optical layout: FP cavities

$$t_2 - t_0 = \frac{2L_x}{c} + \frac{1}{2}\int_{t_0}^{t_2} h_+(t')\,dt'$$

A Fabry-Perot is a resonant optical cavity

We are interested to $\frac{\partial \phi}{\partial x}$: we are blind far the resonance, but extremely more sensitive (with respect to a Michelson) around the resonance



$$\frac{\partial \phi_{Mic}}{\partial x} = \frac{2\pi}{\lambda}$$

$$\left.\frac{\partial \phi_{FP}}{\partial x}\right|_{reson} = \frac{2\mathcal{F}}{\pi}\frac{2\pi}{\lambda}$$

Where $\mathcal{F}$ is named Finesse and its is defined through the transmitted power

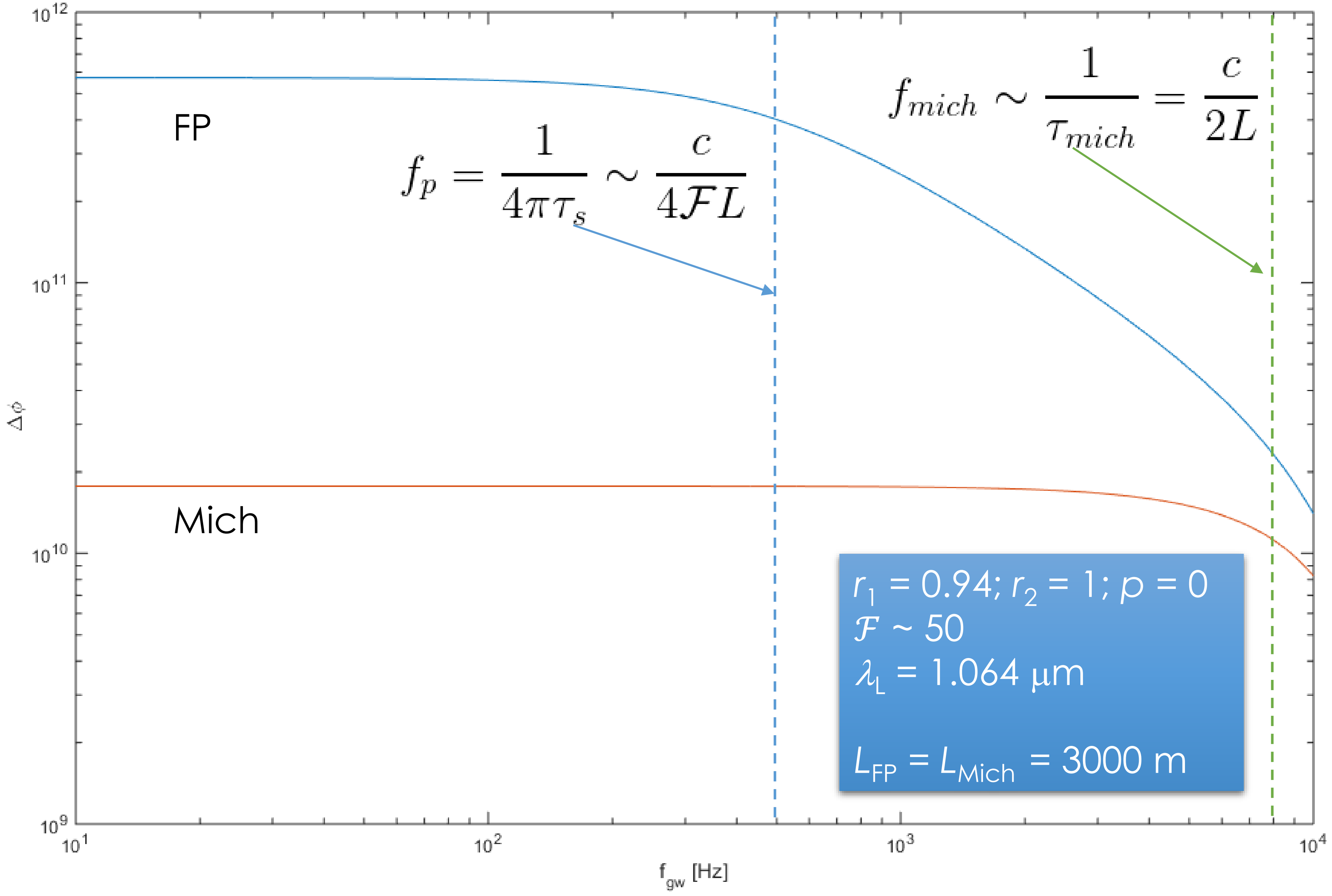
$$|E_t|^2 = E_0^2 \frac{(t_1\, t_2)^2}{1 + (r_1\, r_2)^2 - 2\, r_1 r_2 \cos 2k_L L}$$

Response to the GW passage

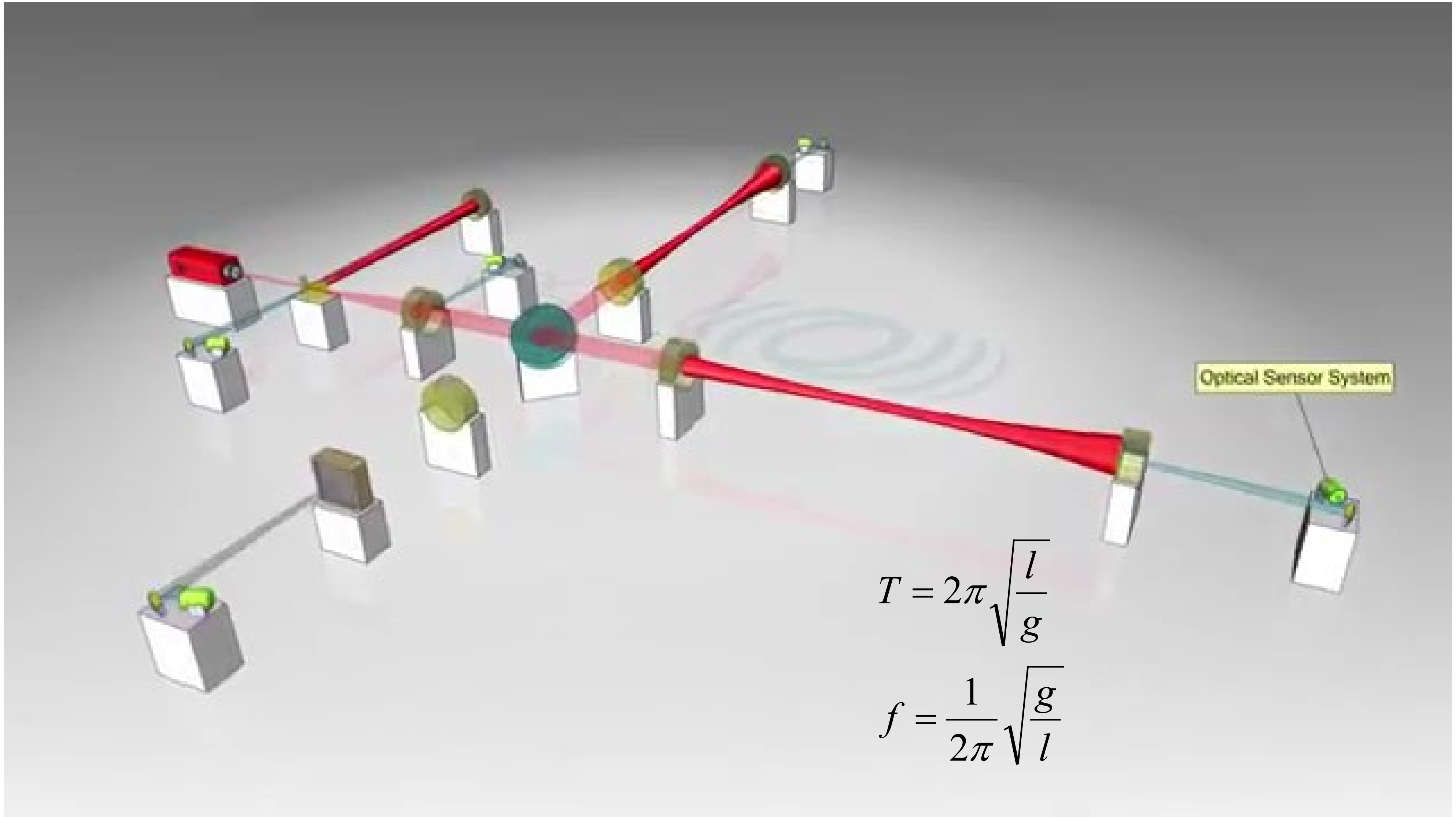
- We seen that the FP amplifies the response in $\Delta\phi$ with respect to a Michelson:
  - Its response to a GW is roughly corresponding to the response of a Michelson having the arms $2\mathcal{F}/\pi$ longer
  - This is true at the first approximation, but we need to consider the storage time and the low pass filtering behaviour of the cavity:

$$\left|\Delta\phi_x\right|_{reson} \approx h_0 2k_L L \frac{\mathcal{F}}{\pi} \frac{1}{\sqrt{1+ f_{gw}^2 / f_p^2}}$$

where $$f_p = \frac{1}{4\pi\tau_s} \approx \frac{c}{4\mathcal{F} L}$$


FP
Mich
$f_p = \frac{1}{4\pi\tau_s} \sim \frac{c}{4\mathcal{F}L}$
$f_{mich} \sim \frac{1}{\tau_{mich}} = \frac{c}{2L}$
$r_1 = 0.94$; $r_2 = 1$; $p = 0$
$\mathcal{F} \sim 50$
$\lambda_L = 1.064\ \mu m$
$L_{FP} = L_{Mich} = 3000$ m
$\Delta\phi$
f_{gw} [Hz]
10^{12}
10^{11}
10^{10}
10^{9}
10^{1}
10^{2}
10^{3}
10^{4}

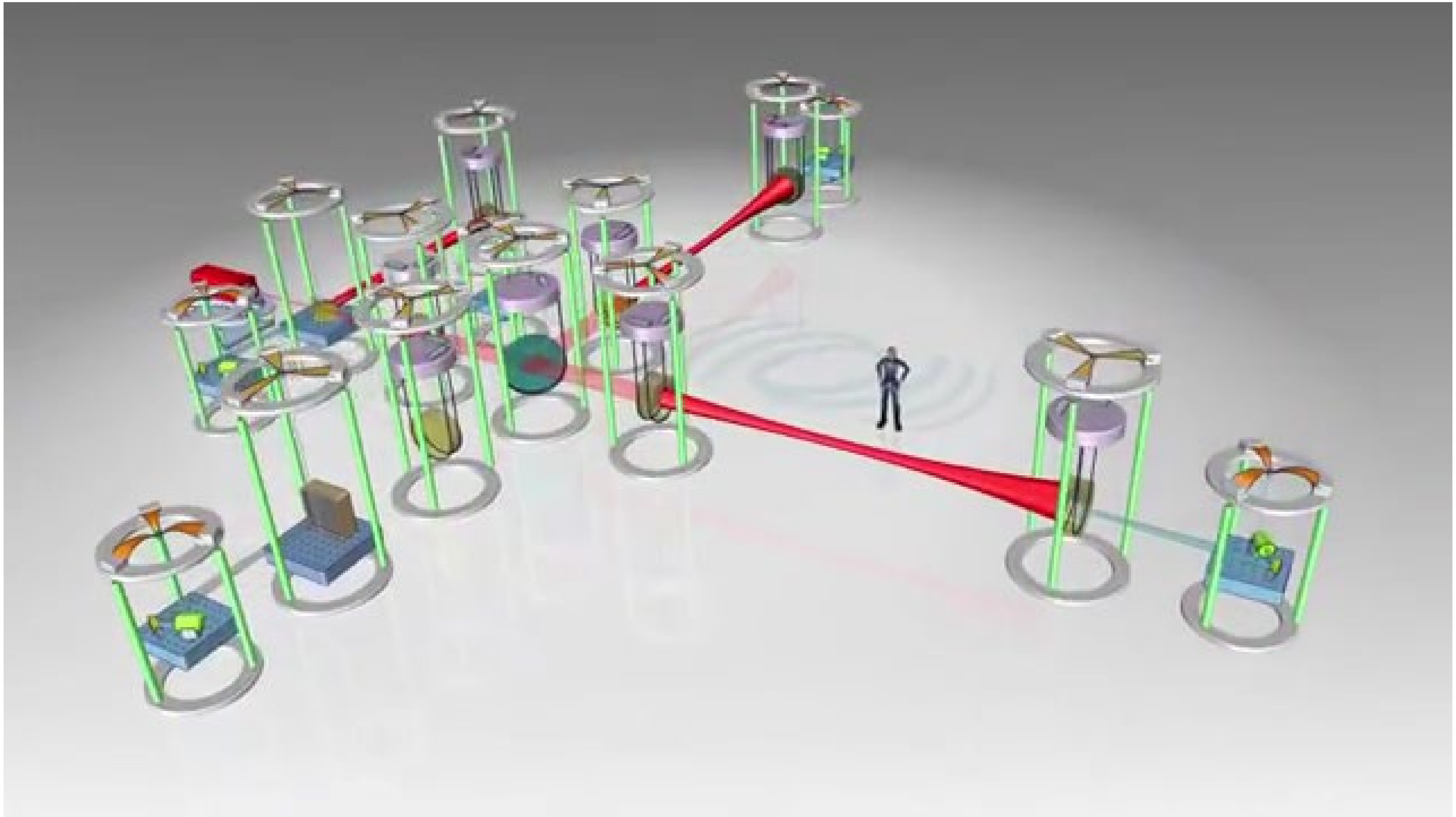
Seismic filtering



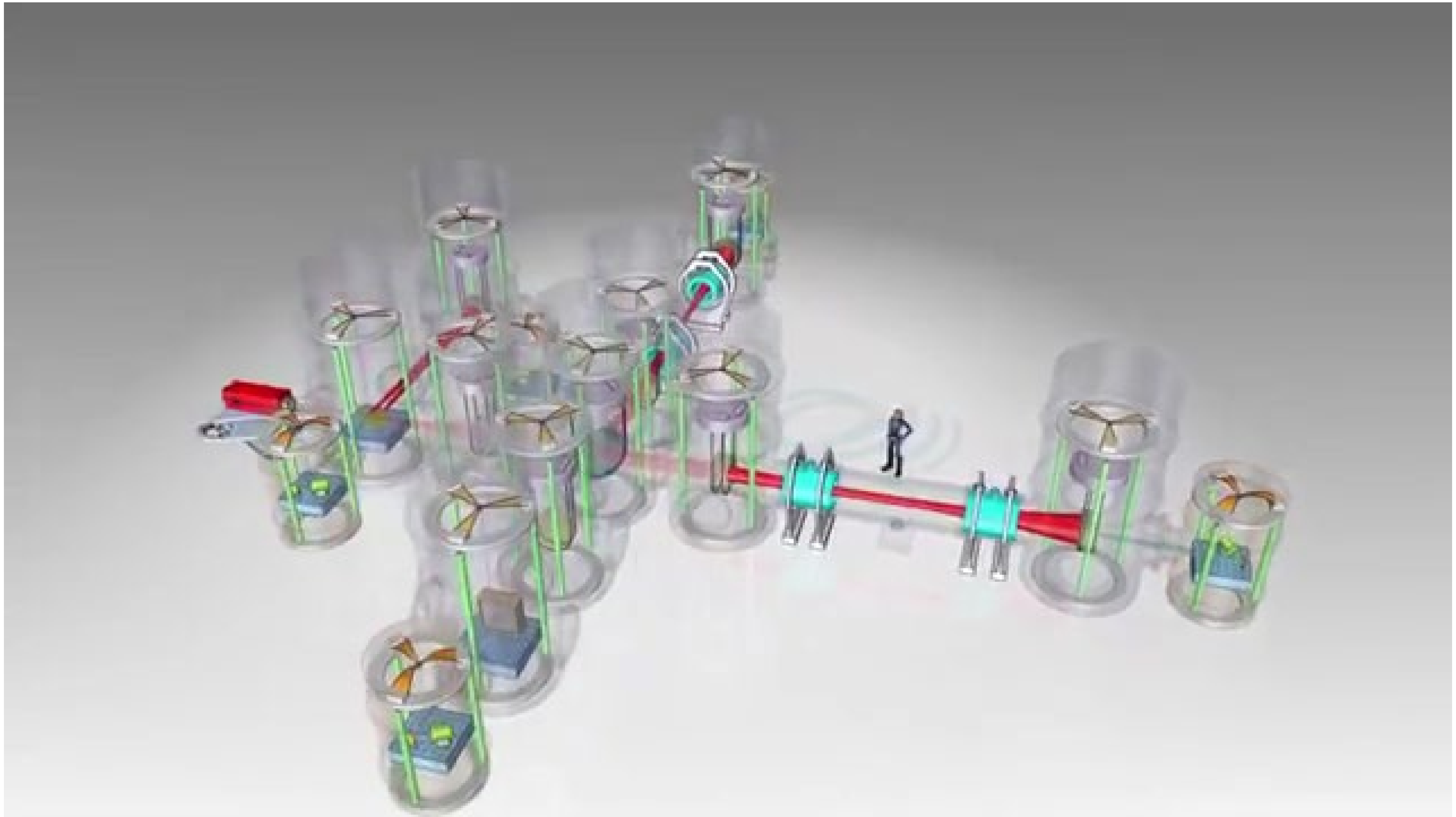
$$T = 2\pi\sqrt{\frac{l}{g}}$$

$$f = \frac{1}{2\pi}\sqrt{\frac{g}{l}}$$

Under vacuum

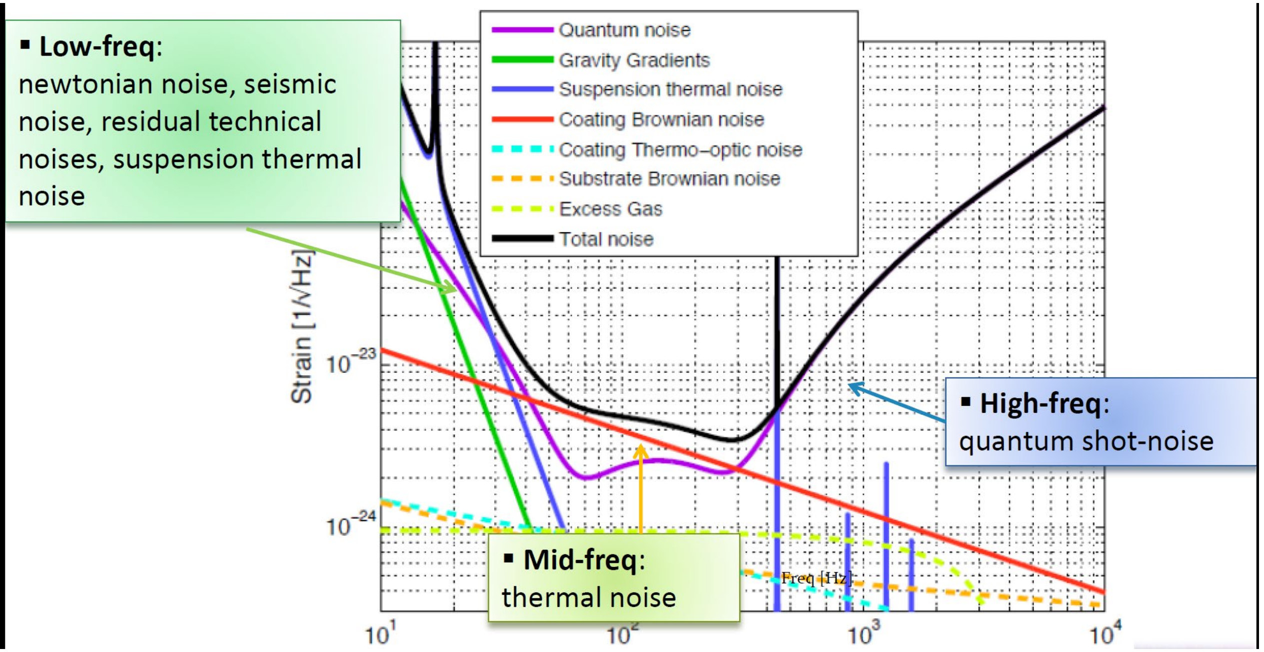


Giant!

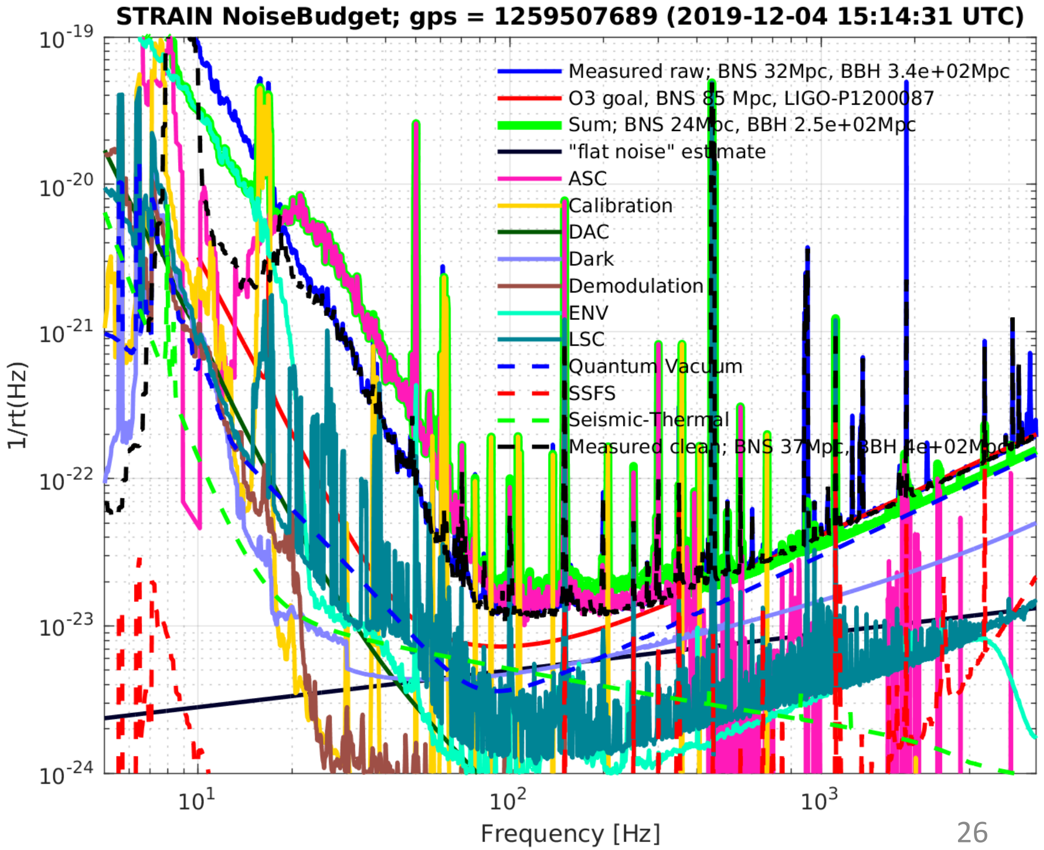


Noise Budget

The theory



The reality

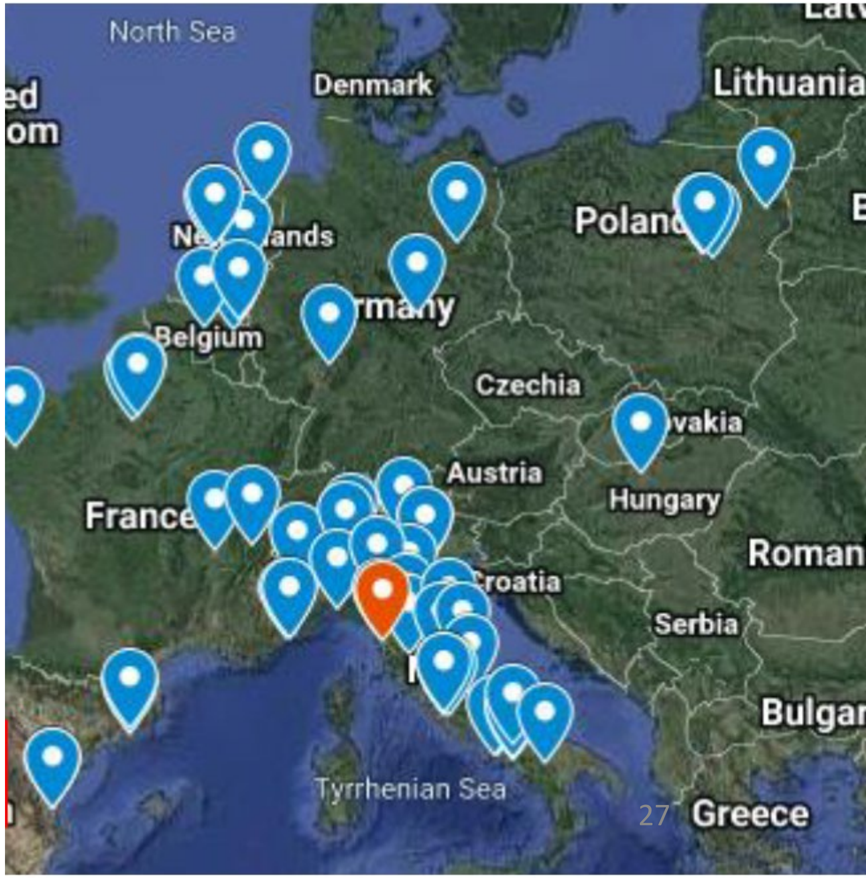


Virgo Collaboration

- Virgo experiment has been founded by INFN and CNRS
- Advanced Virgo (AdV) and AdV+: upgrades of the Virgo interferometric detector implemented by the (larger) Virgo collaboration
- Virgo is a European collaboration with 502 members, 352 authors, and 98 institutes
- Participation by scientists from France, Italy, Belgium, The Netherlands, Poland, Hungary, Spain, Germany
- Institutes in Virgo Steering Committee

  - APC Paris
  - ARTEMIS Nice
  - IFAE Barcelona
  - ILM and Navier
  - INFN Firenze-Urbino
  - INFN Genova
  - INFN Napoli
  - LAPP Annecy
  - LKB Paris
  - LMA Lyon
  - Maastricht University
  - Nikhef Amsterdam
  - POLGRAW(Poland)
  - University Nijmegen
  - INFN Perugia
  - INFN Pisa
  - INFN Roma Sapienza
  - INFN Roma Tor Vergata
  - INFN Trento-Padova
  - IPHC Strassbourg
  - LAL Orsay ESPCI Paris
  - RMKI Budapest
  - UCLouvain, Uliege, UAntwerp
  - Univ. of Barcelona
  - University of Sannio
  - Univ. of Valencia
  - University of Jena

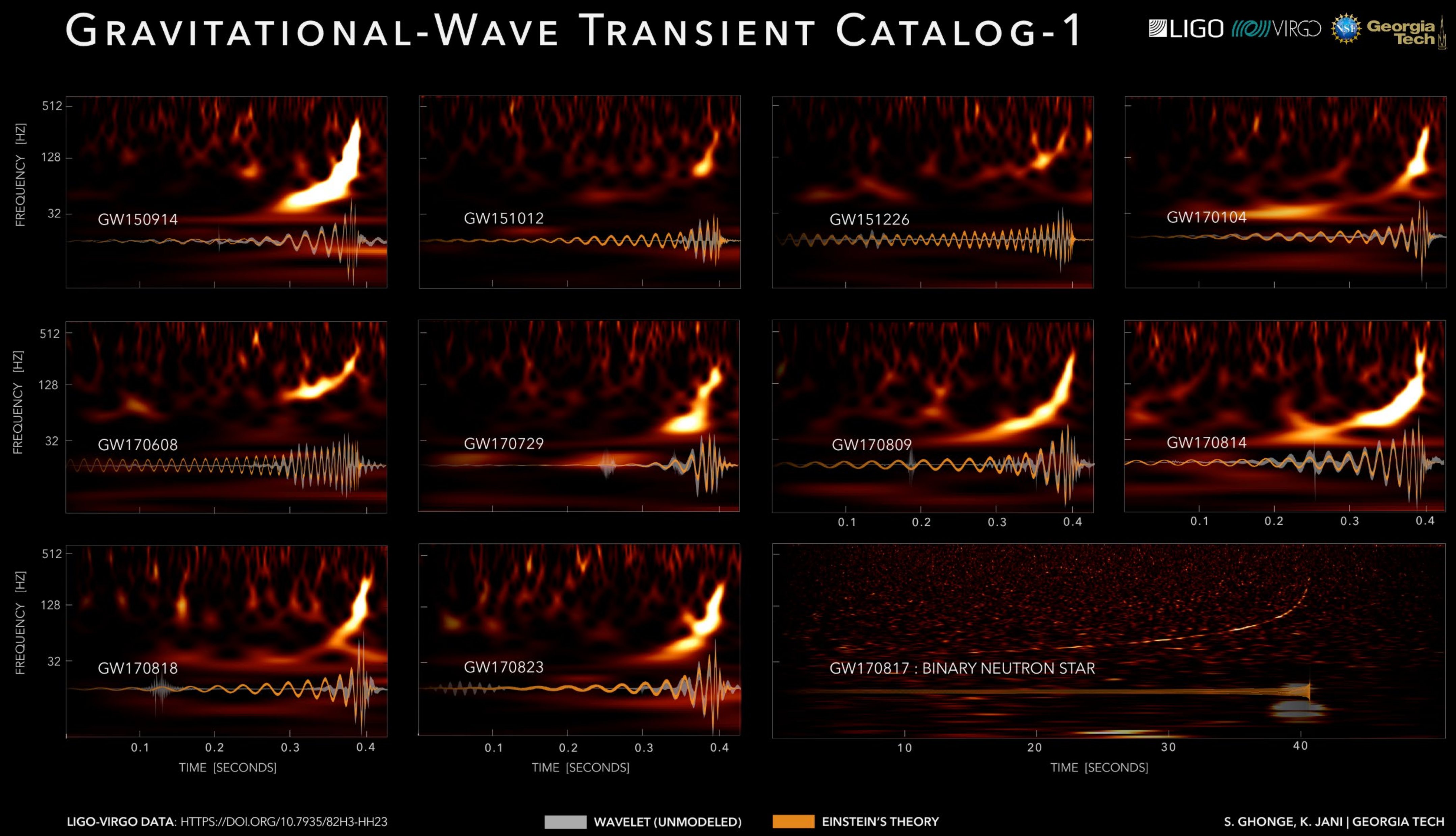
- New/in progress/ applying
  - INFN Torino
  - INFN GSSI
  - IFAE Barcelona



GWD network + E.M. followers

Scientific runs

- **O1: 12 Sep 2015 → 19 Jan 2016**
- **O2: 30 Nov 2017 → 25 Aug 2017 (Virgo: 1 Aug 2017 → 25 Aug 2017)**
- **Total observation time: 0.46 y; 118 days double coincidence; 15 days triple coincidence**



B. P. Abbott, et al., (LIGO Virgo Collaboration), "GWTC-1: A Gravitational-Wave Transient Catalog of Compact Binary Mergers Observed by LIGO and Virgo during the First and Second Observing Runs" , PRX, 9, 031040 (2019)

B. P. Abbott, et al. (LIGO Virgo Collaboration), PRX, 9, 031040 (2019)

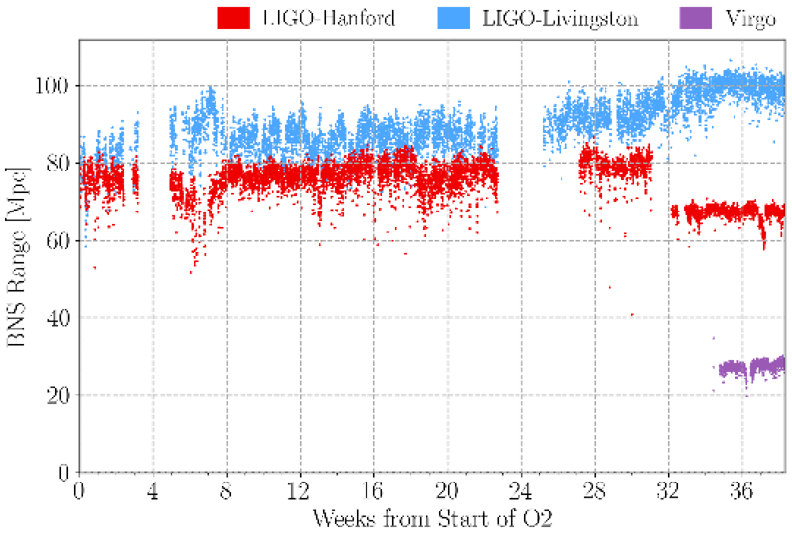
The O1-O2 Catalog

Information on masses, spins, energy radiated, position, distance, inclination, polarization.
Population distribution may shed light on formation mechanisms

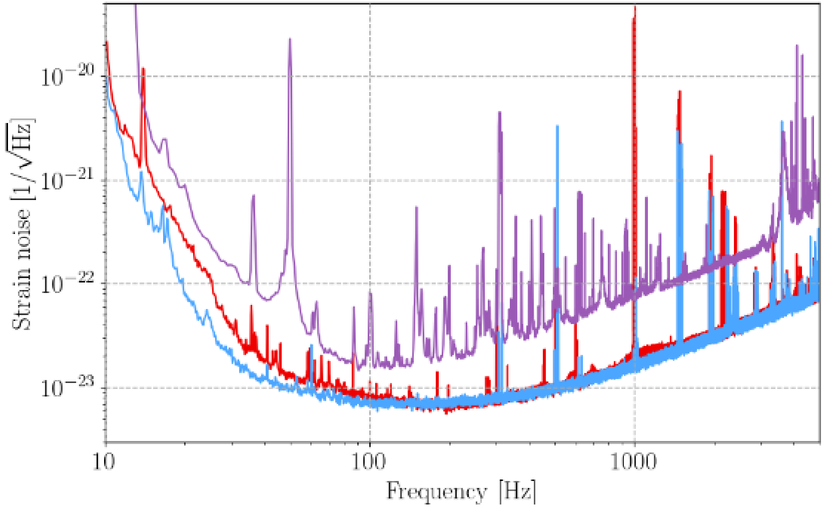
Event	$m_1/M_\odot$	$m_2/M_\odot$	$\mathcal{M}/M_\odot$	$\chi_{\rm eff}$	$M_f/M_\odot$	a_f	$E_{\rm rad}/(M_\odot c^2)$	$\ell_{\rm peak}/({\rm erg\,s^{-1}})$	d_L/Mpc	z	$\Delta\Omega/{\rm deg}^2$	
GW150914	$35.6^{+4.7}_{-3.1}$	$30.6^{+3.0}_{-4.4}$	$28.6^{+1.7}_{-1.5}$	$-0.01^{+0.12}_{-0.13}$	$63.1^{+3.4}_{-3.0}$	$0.69^{+0.05}_{-0.04}$	$3.1^{+0.4}_{-0.4}$	$3.6^{+0.4}_{-0.4} \times 10^{56}$	440^{+150}_{-170}	$0.09^{+0.03}_{-0.03}$	182	
GW151012	$23.2^{+14.9}_{-5.5}$	$13.6^{+4.1}_{-4.8}$	$15.2^{+2.1}_{-1.2}$	$0.05^{+0.31}_{-0.20}$	$35.6^{+10.8}_{-3.8}$	$0.67^{+0.13}_{-0.11}$	$1.6^{+0.6}_{-0.5}$	$3.2^{+0.8}_{-1.7} \times 10^{56}$	1080^{+550}_{-490}	$0.21^{+0.09}_{-0.09}$	1523	O1
GW151226	$13.7^{+8.8}_{-3.2}$	$7.7^{+2.2}_{-2.5}$	$8.9^{+0.3}_{-0.3}$	$0.18^{+0.20}_{-0.12}$	$20.5^{+6.4}_{-1.5}$	$0.74^{+0.07}_{-0.05}$	$1.0^{+0.1}_{-0.2}$	$3.4^{+0.7}_{-1.7} \times 10^{56}$	450^{+180}_{-190}	$0.09^{+0.04}_{-0.04}$	1033	
GW170104	$30.8^{+7.3}_{-5.6}$	$20.0^{+4.9}_{-4.6}$	$21.4^{+2.2}_{-1.8}$	$-0.04^{+0.17}_{-0.21}$	$48.9^{+5.1}_{-4.0}$	$0.66^{+0.08}_{-0.11}$	$2.2^{+0.5}_{-0.5}$	$3.3^{+0.6}_{-1.0} \times 10^{56}$	990^{+440}_{-430}	$0.20^{+0.08}_{-0.08}$	921	
GW170608	$11.0^{+5.5}_{-1.7}$	$7.6^{+1.4}_{-2.2}$	$7.9^{+0.2}_{-0.2}$	$0.03^{+0.19}_{-0.07}$	$17.8^{+3.4}_{-0.7}$	$0.69^{+0.04}_{-0.04}$	$0.9^{+0.0}_{-0.1}$	$3.5^{+0.4}_{-1.3} \times 10^{56}$	320^{+120}_{-110}	$0.07^{+0.02}_{-0.02}$	392	
GW170729	$50.2^{+16.2}_{-10.2}$	$34.0^{+9.1}_{-10.1}$	$35.4^{+6.5}_{-4.8}$	$0.37^{+0.21}_{-0.25}$	$79.5^{+14.7}_{-10.2}$	$0.81^{+0.07}_{-0.13}$	$4.8^{+1.7}_{-1.7}$	$4.2^{+0.9}_{-1.5} \times 10^{56}$	2840^{+1400}_{-1360}	$0.49^{+0.19}_{-0.21}$	1041	
GW170809	$35.0^{+8.3}_{-5.9}$	$23.8^{+5.1}_{-5.2}$	$24.9^{+2.1}_{-1.7}$	$0.08^{+0.17}_{-0.17}$	$56.3^{+5.2}_{-3.8}$	$0.70^{+0.08}_{-0.09}$	$2.7^{+0.6}_{-0.6}$	$3.5^{+0.6}_{-0.9} \times 10^{56}$	1030^{+320}_{-390}	$0.20^{+0.05}_{-0.07}$	308	O2
GW170814	$30.6^{+5.6}_{-3.0}$	$25.2^{+2.8}_{-4.0}$	$24.1^{+1.4}_{-1.1}$	$0.07^{+0.12}_{-0.12}$	$53.2^{+3.2}_{-2.4}$	$0.72^{+0.07}_{-0.05}$	$2.7^{+0.4}_{-0.3}$	$3.7^{+0.4}_{-0.5} \times 10^{56}$	600^{+150}_{-220}	$0.12^{+0.03}_{-0.04}$	87	
GW170817*	$1.46^{+0.12}_{-0.10}$	$1.27^{+0.09}_{-0.09}$	$1.186^{+0.001}_{-0.001}$	$0.00^{+0.02}_{-0.01}$	≤ 2.8	≤ 0.89	≥ 0.04	$\geq 0.1 \times 10^{56}$	40^{+7}_{-15}	$0.01^{+0.00}_{-0.00}$	16	
GW170818	$35.4^{+7.5}_{-4.7}$	$26.7^{+4.3}_{-5.2}$	$26.5^{+2.1}_{-1.7}$	$-0.09^{+0.18}_{-0.21}$	$59.4^{+4.9}_{-3.8}$	$0.67^{+0.07}_{-0.08}$	$2.7^{+0.5}_{-0.5}$	$3.4^{+0.5}_{-0.7} \times 10^{56}$	1060^{+420}_{-380}	$0.21^{+0.07}_{-0.07}$	39	
GW170823	$39.5^{+11.2}_{-6.7}$	$29.0^{+6.7}_{-7.8}$	$29.2^{+4.6}_{-3.6}$	$0.09^{+0.22}_{-0.26}$	$65.4^{+10.1}_{-7.4}$	$0.72^{+0.09}_{-0.12}$	$3.3^{+1.0}_{-0.9}$	$3.6^{+0.7}_{-1.1} \times 10^{56}$	1940^{+970}_{-900}	$0.35^{+0.15}_{-0.15}$	1666	

*BNS

O2 run characteristics



BNS range for each instrument during O2



Representative amplitude spectral density of the total strain noise in O2

O2 data were recalibrated (post run) and cleaned (available ~march 2018)

+20% sensitivity in LHO (arXiv:1806:00532)

Final calibration benefited from post-run measurements and lines removal

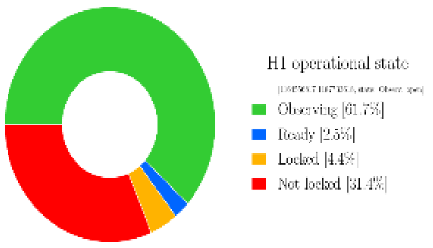
LIGO calibration error: ~3% in amplitude; ~2 deg in phase

Virgo calibration error: ~5% in amplitude; ~2 deg in phase

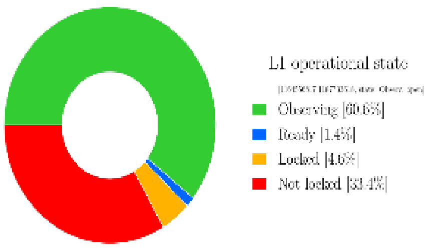
Duty cycle:

LIGO detectors: ~60%

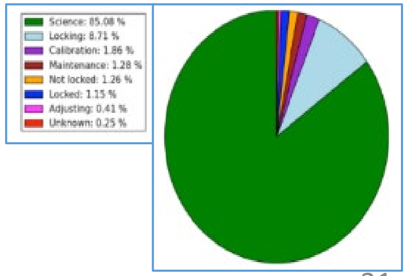
Virgo: ~80%



H1



L1

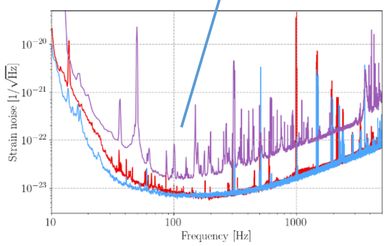


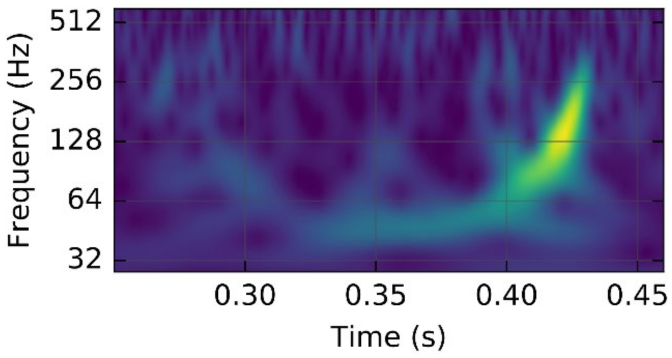
V1

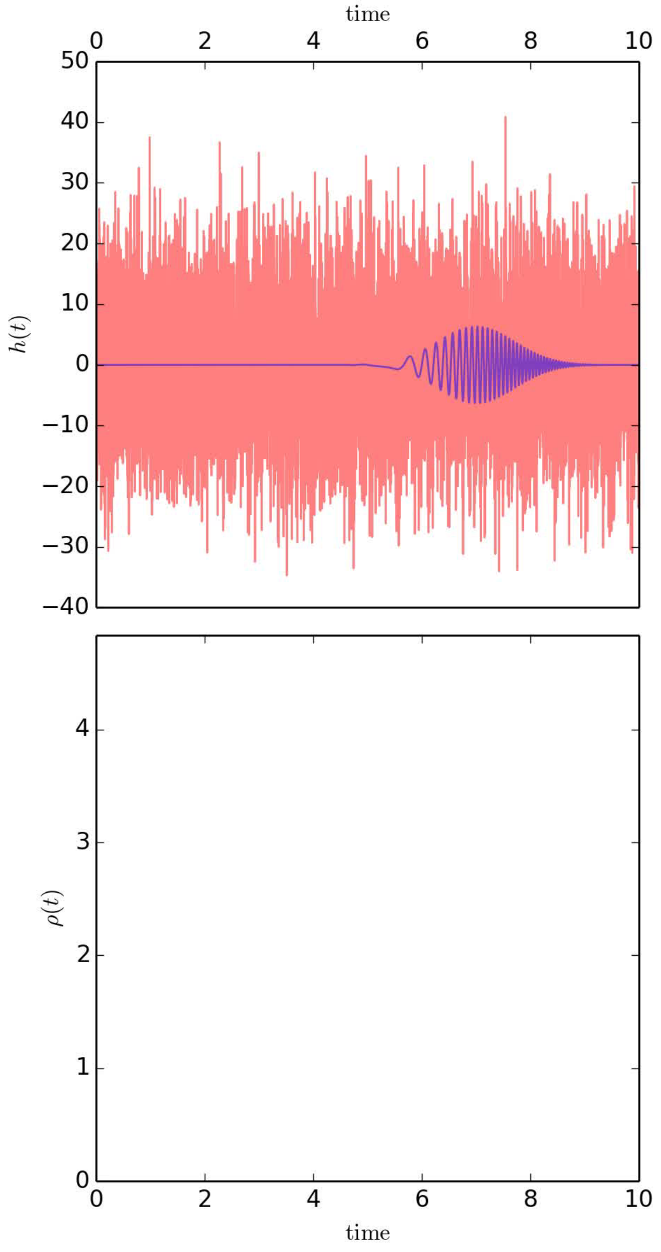
The analysis method

- Search based on 3 detection pipelines:
  - Two-matched-filter (modelled) searches
    - GstLAL: 2-400$M_{\odot}$, templates in time, ranks candidates using the logarithm of the likelihood-ratio, $\mathcal{L}$, a measure of how likely it is to observe that candidate if a signal is present compared to if only noise is present; in O2 worked on LHV
    - PyCBC: 2-500$M_{\odot}$, templates in frequency, uses the SNR of the single detector, in O2 operated on LH
  - One un-modelled (weakly modelled) search
    - cWB: it searches for “generic” short signals (excess of power), chirping in frequency; less sensitive but signal independent

$$\rho = \int_{-\infty}^{+\infty} df \, \frac{\tilde{s}\widetilde{\boldsymbol{h}}^{*}}{S_n(f)}$$



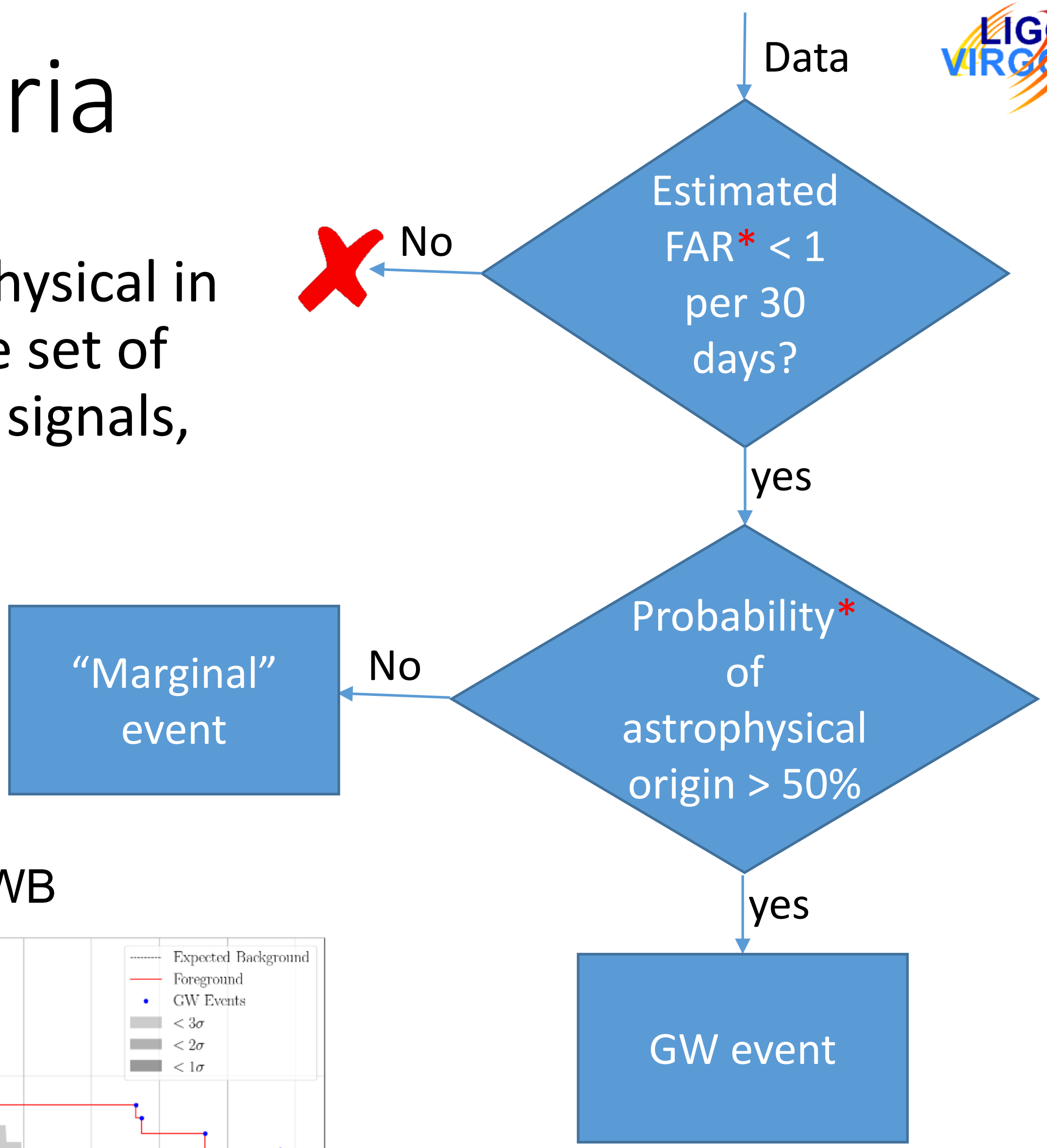




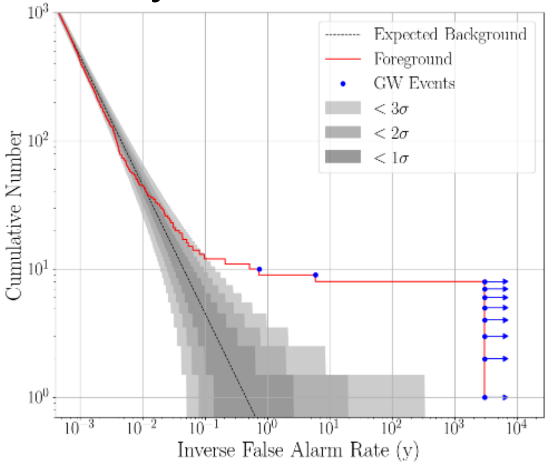
Event Selection Criteria

- Aim:
  - Identify all events that are confidently astrophysical in origin, and additionally provide a manageable set of marginal triggers that may include some true signals, but certainly also includes noise triggers

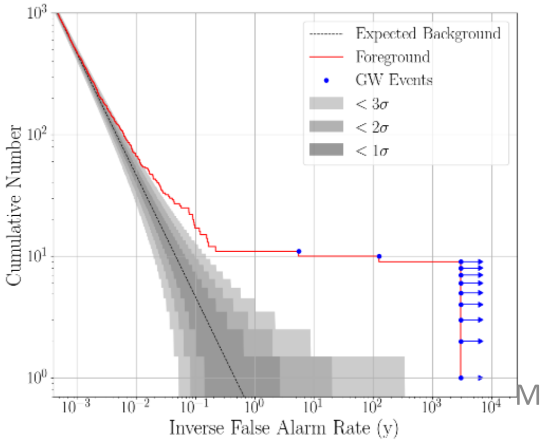
- Marginal events could contain experimental artefacts (and for some of them we have indications given by auxiliary channels)
- But they could contain real astrophysical events



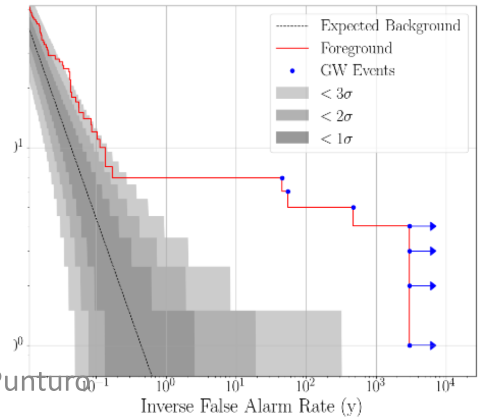
PyCBC



GstLAL

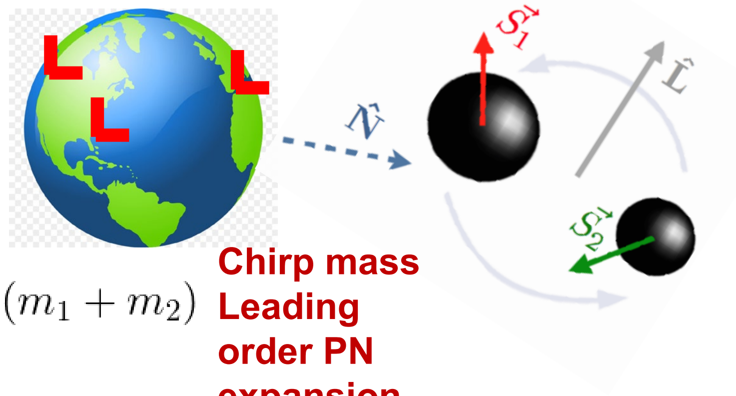


cWB



*the condition must be satisfied in at least one modelled search

Parameter estimation



- Extrinsic parameters:
  - Sky location:
    - Right ascension α and declination δ
    - Luminosity distance d_L
  - Orbital inclination ι
  - Polarisation angle ψ
  - Time t_c and phase ϕ_c at coalescence
- Intrinsic parameters:
  - In case of BBHs we have 8 parameters:
    - 2 masses and 2 spin 3D vectors
  - For BNS we should account also the deformability

$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1+m_2)^{1/5}} = \left[\frac{q}{(1+q)^2}\right]^{3/5} (m_1+m_2)$$

$$q = \frac{m_2}{m_1} \leq 1$$

Chirp mass Leading order PN expansion

$$\vec{\chi}_i = \frac{c\,\vec{S}_i}{G\,m_i^2} \qquad a_i = |\vec{\chi}_i| = \frac{c\,|\vec{S}_i|}{G\,m_i^2}$$

Dimensionless spin (spin-spin coupling 2PN)

$$\chi_{eff} = \frac{(m_1\vec{\chi}_1 + m_2\vec{\chi}_2)\cdot\vec{L}_N}{m_1+m_2}$$

Effective aligned spin (spin-orbit coupling 1.5PN)

$$\chi_p = \frac{1}{B_1 m_1^2}\max(B_1 S_{1\perp}, B_2 S_{2\perp})$$

$$B_1 = 2 + \frac{3q}{2} \qquad B_2 = 2 + \frac{3}{2q}$$

Effective precession spin parameter (2PN) arXiv:1308.3271

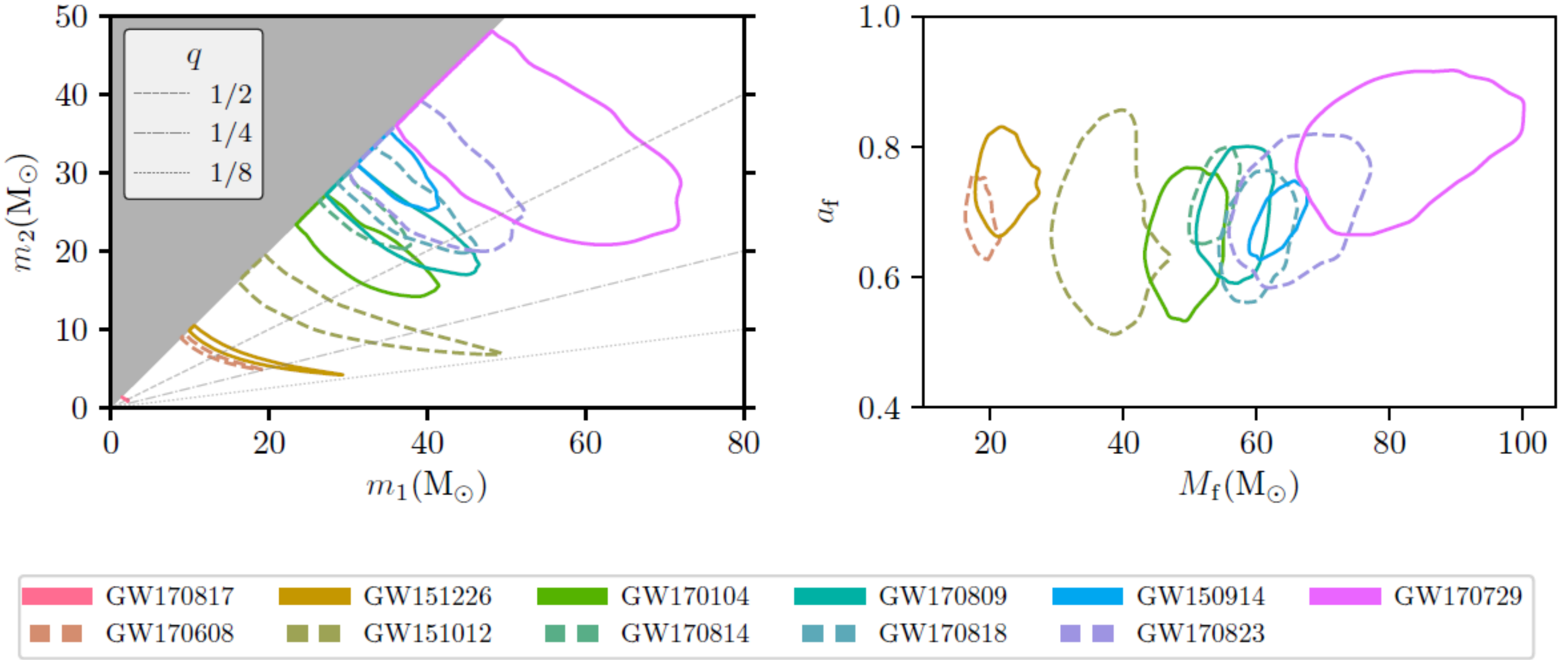
$$\Lambda = \frac{2}{3}k_2\left(\frac{c^2}{G}\frac{R}{m}\right)$$

Dimensionless tidal deformability

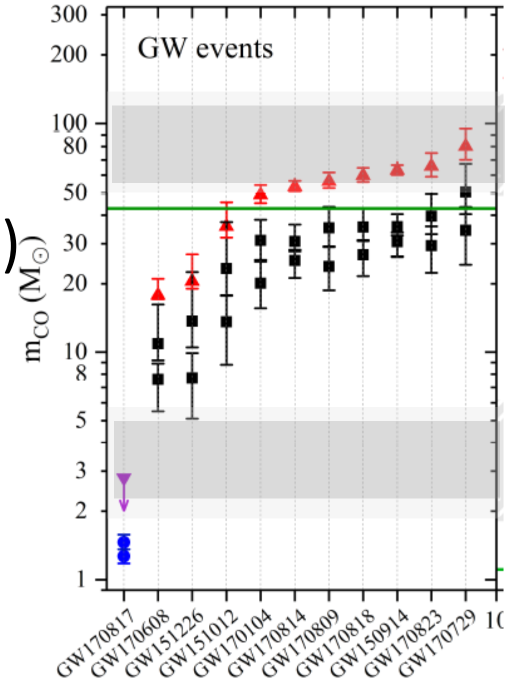
$$\tilde{\Lambda} = \frac{16}{13}\frac{(m_1+12m_2)m_1^4\Lambda_1 + (m_2+12m_1)m_2^4\Lambda_2}{M^5}$$

Effective tidal deformability parameter (5PN)

Masses and (posterior) spin



- Component masses 5-70 $M_\odot$ → Stellar-mass black holes
- The heavier component of the heaviest BBH GW170729 ($50.6^{+16.6}_{-10.2} M_\Theta$) grazes the lower boundary of the possible mass gap expected from pulsational pair instability and pair instability supernovae at ($\sim 60 - 120 M_\Theta$)
- The lowest-mass BBH systems, GW151226 and GW170608, have 90% credible lower bounds on m_2 of 5.6 and 5.9 $M_\odot$, respectively, → above the propose band gap 2-5 $M_\odot$.
- Only 2%-7% of the binary total mass is radiated in GW
- Peak luminosity depends on q and spin.

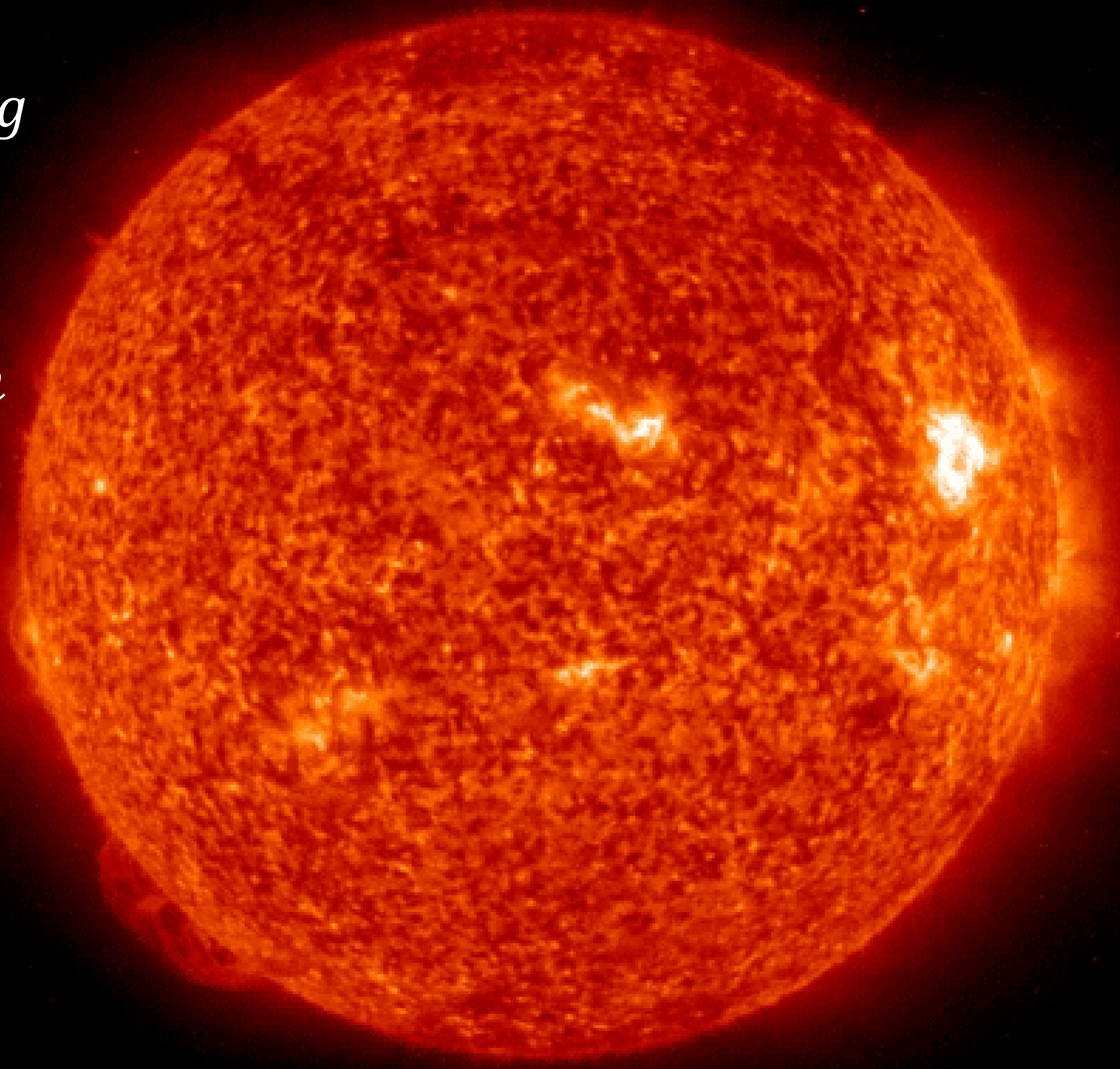


Sun

$M_\Theta = 1.989 \times 10^{30} kg$

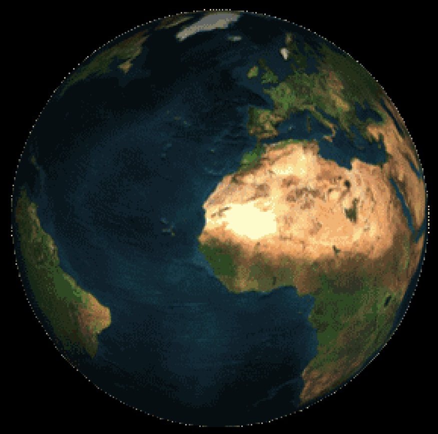
$R_\Theta = 695510\ km$

$$R_{sc} = \frac{2GM}{c^2} \simeq 2.9\ km$$



Not in scale:

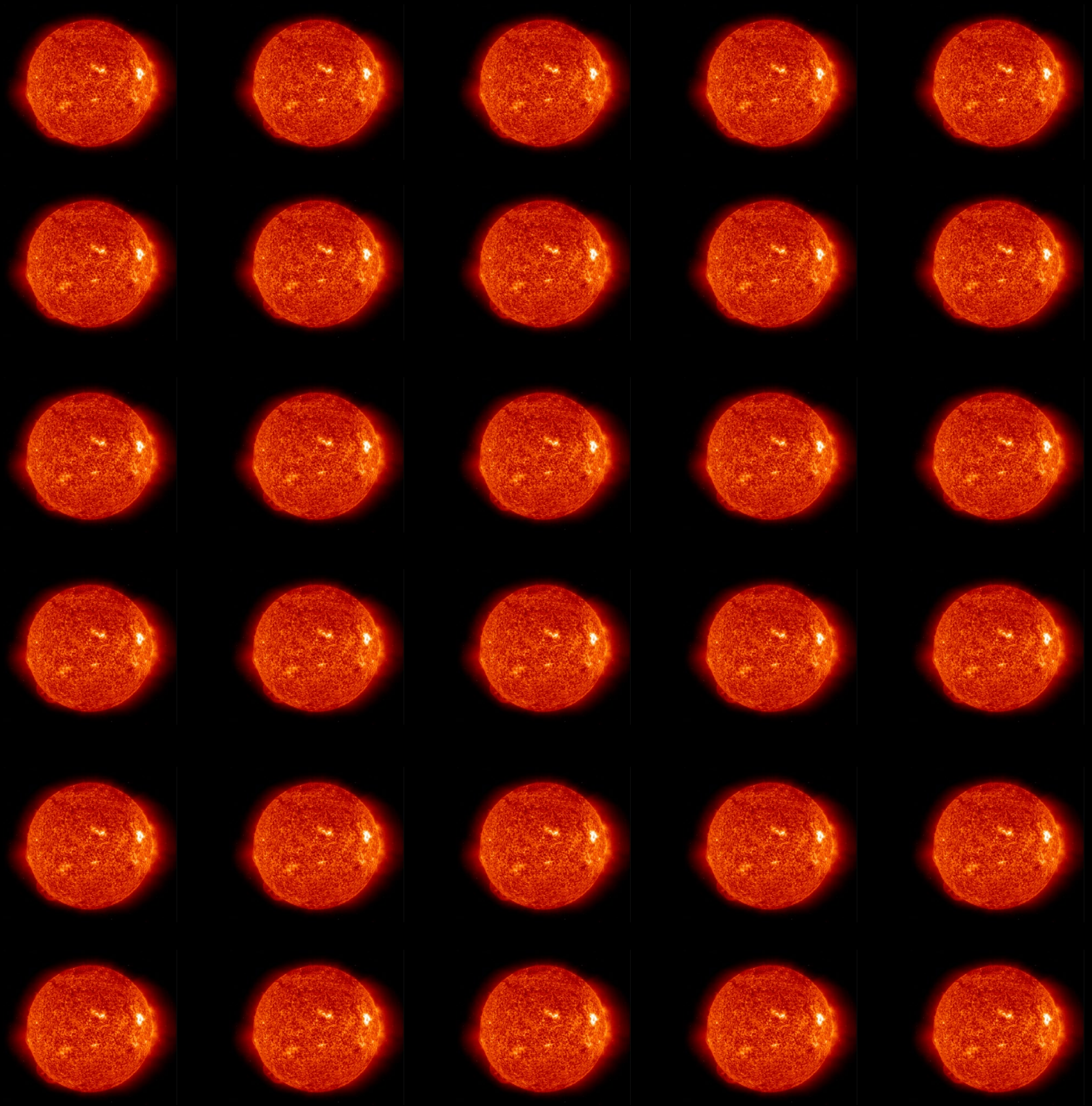
$R_\Theta \sim 110\ R_H$



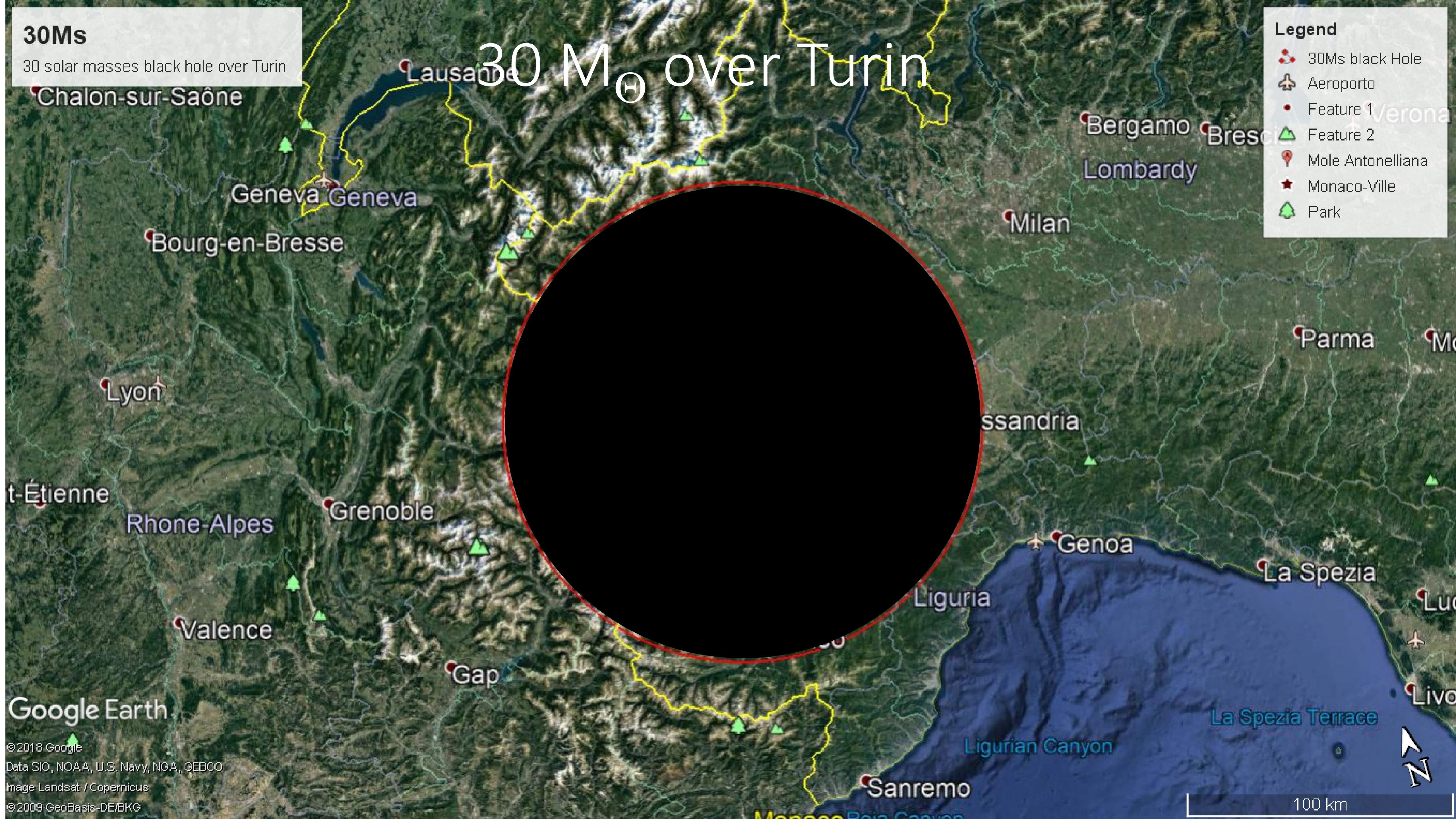
A 30 M_Θ BH

$$M_{BH} = 30M_\Theta$$

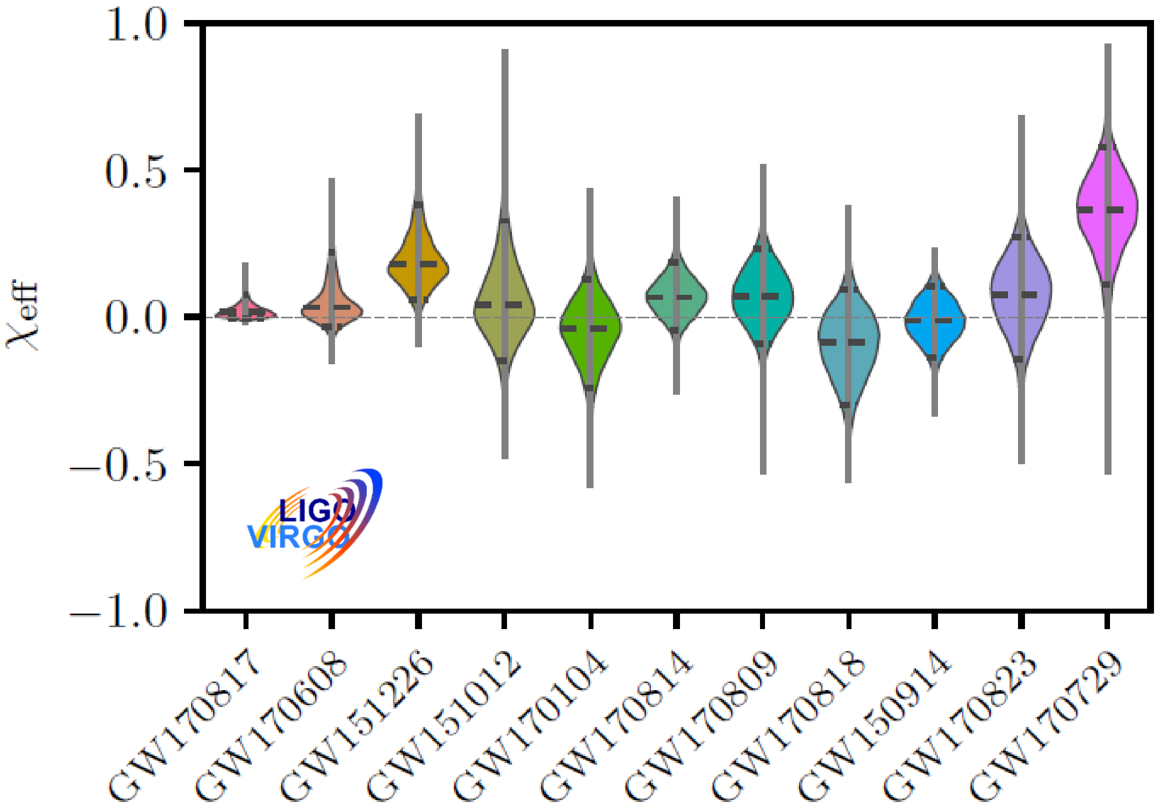
$$R_{sc} = 88\ km$$



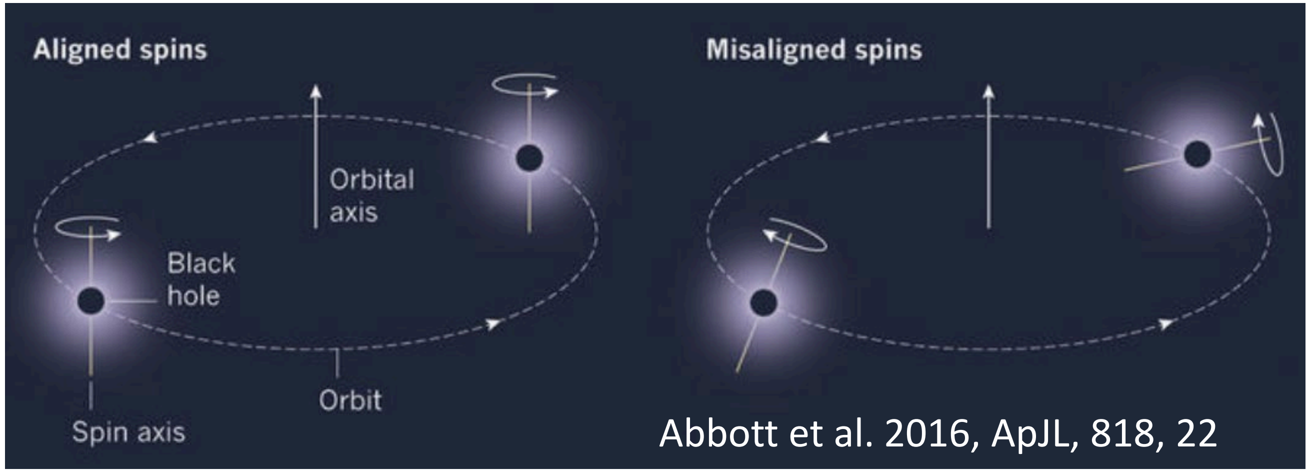
30 $M_{\odot}$ over Turin



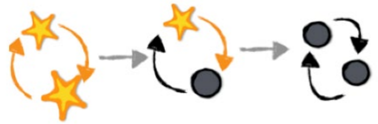
Spins



How the BHs form a binary system?

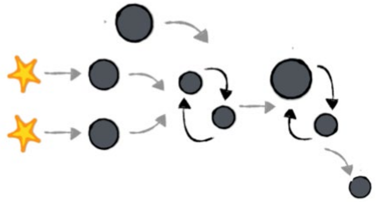


Isolated binary



→ spins preferentially aligned with the binary orbital angular momentum

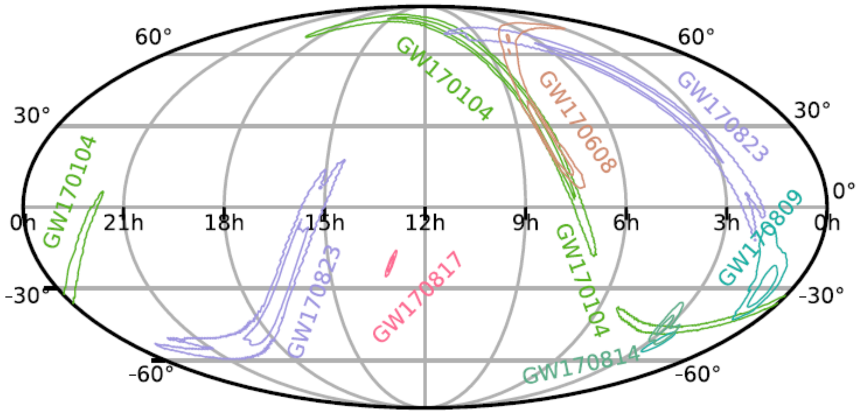
Cluster binary



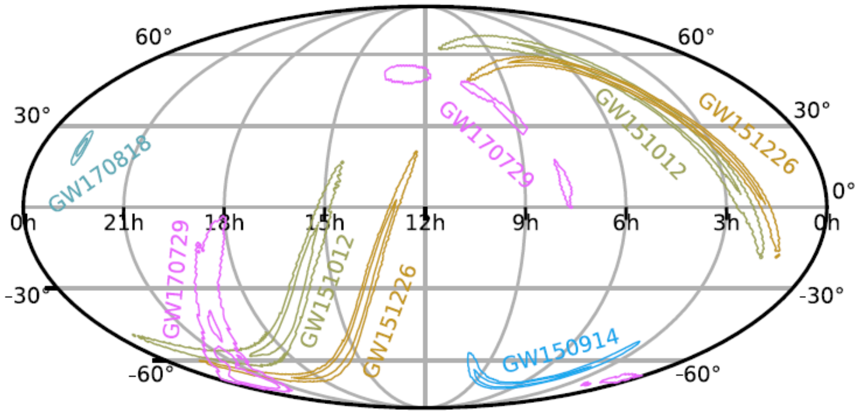
→ isotropic spin orientations

- Posteriors of χ_{eff} peak around zero
- The posteriors for GW151226 and GW170829 exclude $\chi_{eff} = 0$ at 90% confidence
- Degeneracy between q and χ_{eff} makes impossible to measure single BH spin. Currently we disfavour scenarios in which most black holes merge with large spins aligned with the binary's orbital angular momentum

Localisation



O2 GW events for which alerts were sent to EM observers



O1 events along with O2 events (GW170729, GW170818) not previously released to EM observers

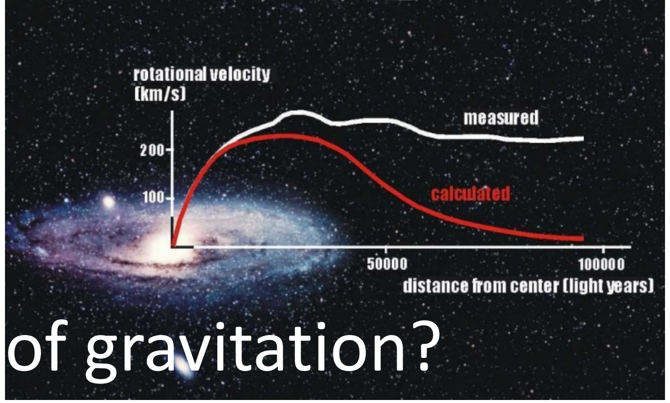
- Sky areas scale inversely with SNR^2
- Inclusion of Virgo improves sky localization: importance of a global GW detector network for accurately localizing GW sources
- Virgo Detections
  - ➢ GW170814 (BBH) with a 90% area of 87 deg^2
  - ➢ GW170817 (BNS) with a 90% area of 16 deg^2
  - ➢ GW170818 (BBH) with a 90% area of 39 deg^2

OK, where is the (fundamental) physics?

Some of the questions addressed by GW (AdV+, ET)

- Fundamental questions in Gravity: **HEPP** Fundamental interactions, Dark matter, dark energy
  - New/further tests of GR
  - Exploration of possible alternative theories of Gravity
  - How to disprove that Nature black holes are black holes in GR (e.g. non tensorial radiation, quasi normal modes inconsistency, absence of horizon, echoes, tidal deformability, spin-induced multipoles)
- Fundamental questions in particle physics **HEPP** Inflation, additional interactions, dark matter
  - Axions and ultralight particle through the evaluation of the consequences of new interactions, their impact on two bodies mechanics, in population and characterisics of BHs, NSs
- Probing the EOS of neutron stars **HEPP** Nuclear physics, quark-gluon plasma
- Exotic objects and phenomena (cosmic strings, exotic compact objects: boson stars, strange stars/gravastars, …)
- Cosmology and Cosmography with GWs **HEPP** Cosmology
- Accurate Modelling of GW waveforms
- GW models in alternative theory of gravitation **HEPP** Cosmology
- The population of compact objects discovered by GWs is the same measured by EM? Selection effects on BHs and NSs?
- What is the explosion mechanism in Supernovae? **HEPP** Nuclear physics
- What is the history of SuperMassive black holes?
- GW Stochastic Background? Probing the big bang? **HEPP** Cosmology, inflation
- Multimessenger Astronomy in 3G? **HEPP** Astroparticle, GRB, Neutrino Physics

Some of the fundamental questions



- Is Einstein's General Relativity THE theory of gravitation?
  - Test of GR
  - Polarisations
  - Mass of the "graviton"
- Do we need Dark Matter?
  - Wimps, Axions or black holes?

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu} \Rightarrow G_{\mu\nu} = \frac{8\pi G}{c^4}\left(T_{\mu\nu} + T_{\mu\nu}^{DM}\right)$$

$$T_{\mu\nu}^{WIMP} \quad T_{\mu\nu}^{axion} \quad T_{\mu\nu}^{BH}$$

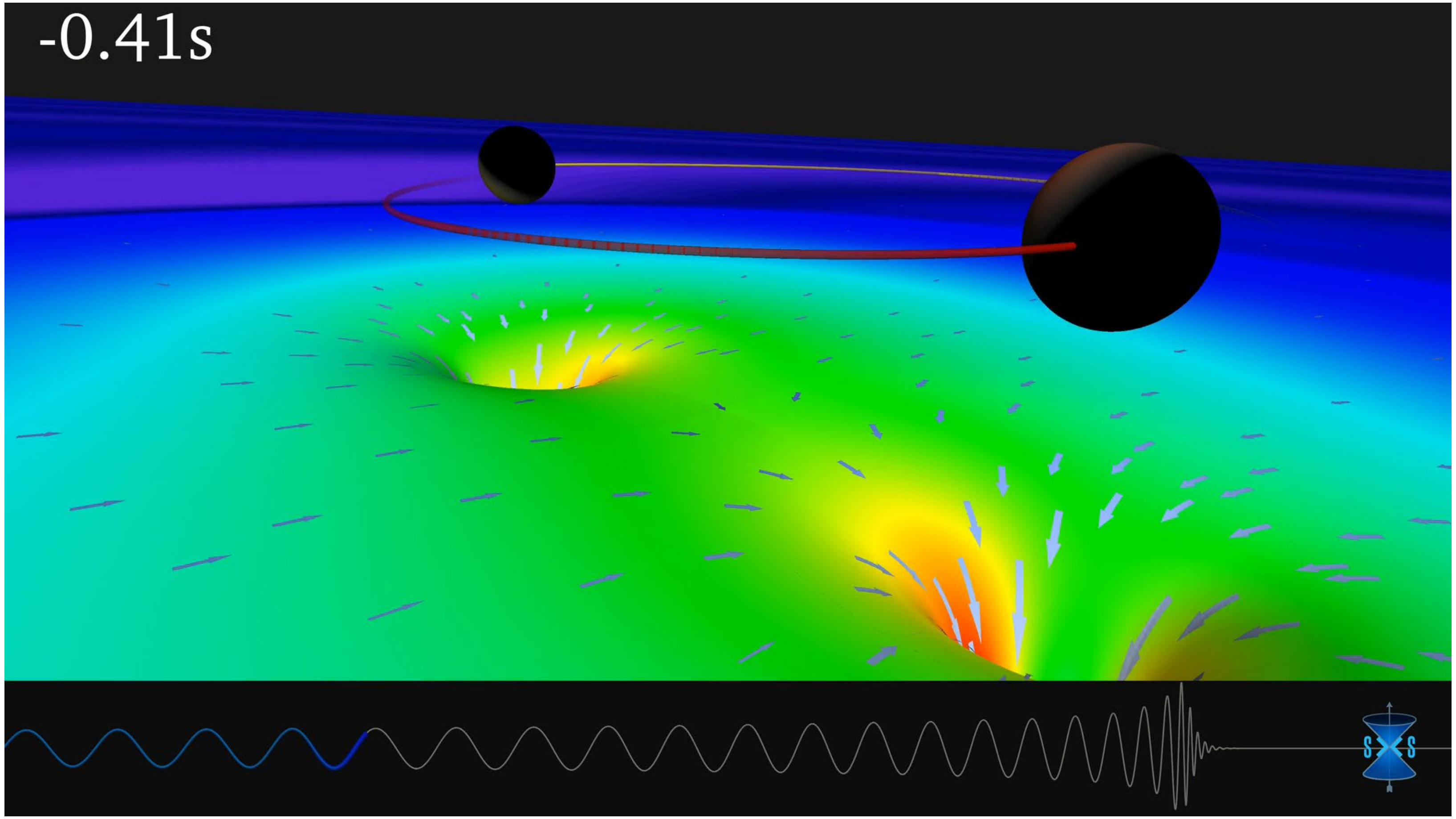
- Do we need Dark Energy?
  - Alternative theories of Gravity

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu} \qquad G_{\mu\nu} + G_{\mu\nu}' = \frac{8\pi G}{c^4} T_{\mu\nu}$$

Alternative theories of Gravity

- Are Neutron Stars "strange"?
  - EOS of NS

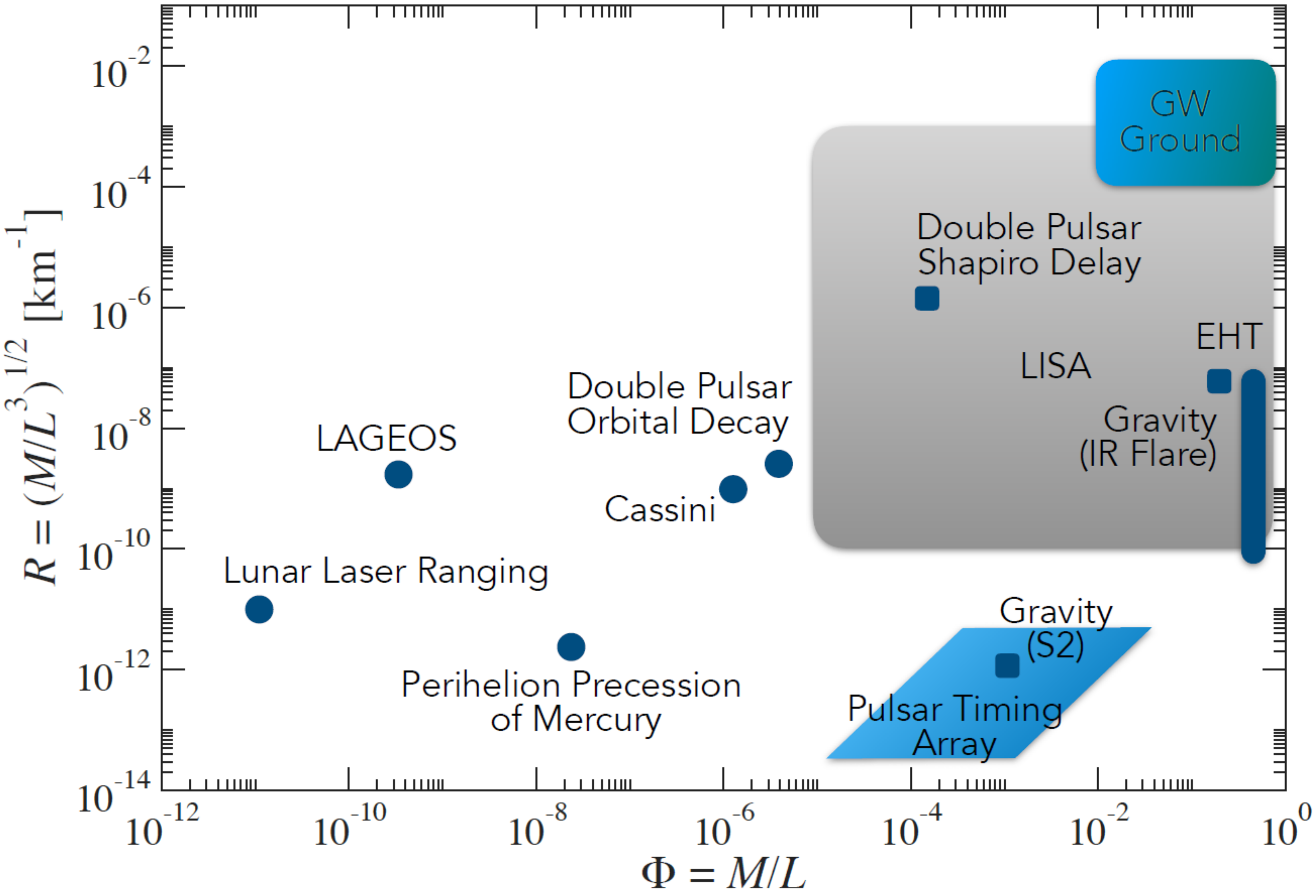
GW150914 … and BBH coalescences



Probing GR in strong field conditions

- BBH coalescences allow to test GR in strong field conditions

Yunes N. et al.
Phys. Rev. D 94, 084002 (2016)
Edited by ET science case team

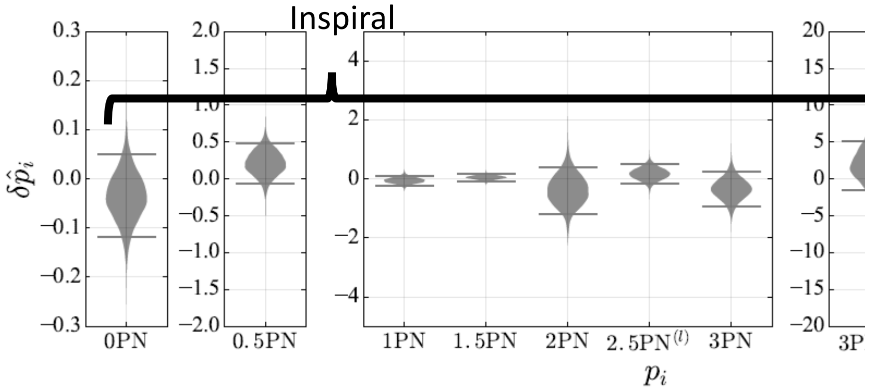


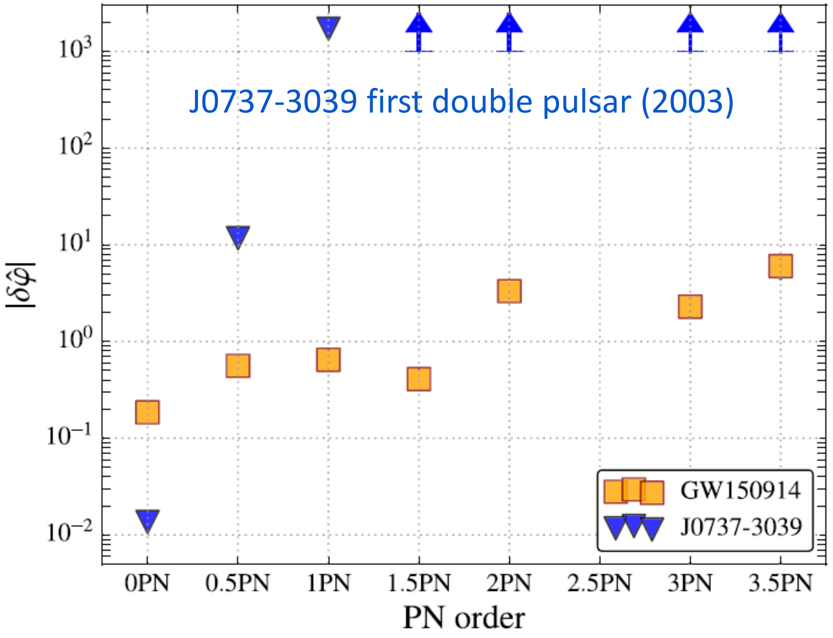
Test of GR: PN approximation

- Going in strong field regime, allow to constrain eventual discrepancies with respect to PN approximation of the GR
- BBH template

$$\Psi(f) = 2\pi f t_c - \varphi_c - \frac{\pi}{4} + \sum_{j=0}^{7} \left[\psi_j + \psi_j^{(l)} \ln f \right] f^{(j-5)/3},$$

$$\psi_j \rightarrow (1 + \delta p_j)\psi_j$$

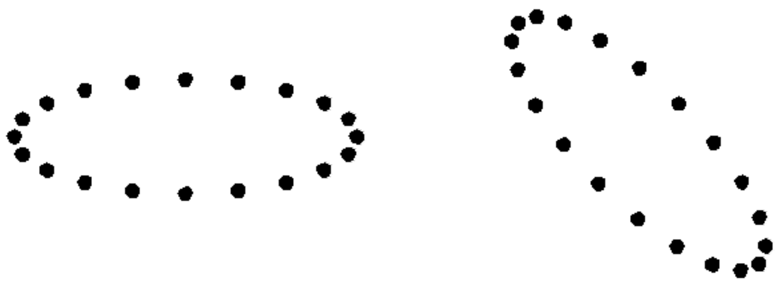


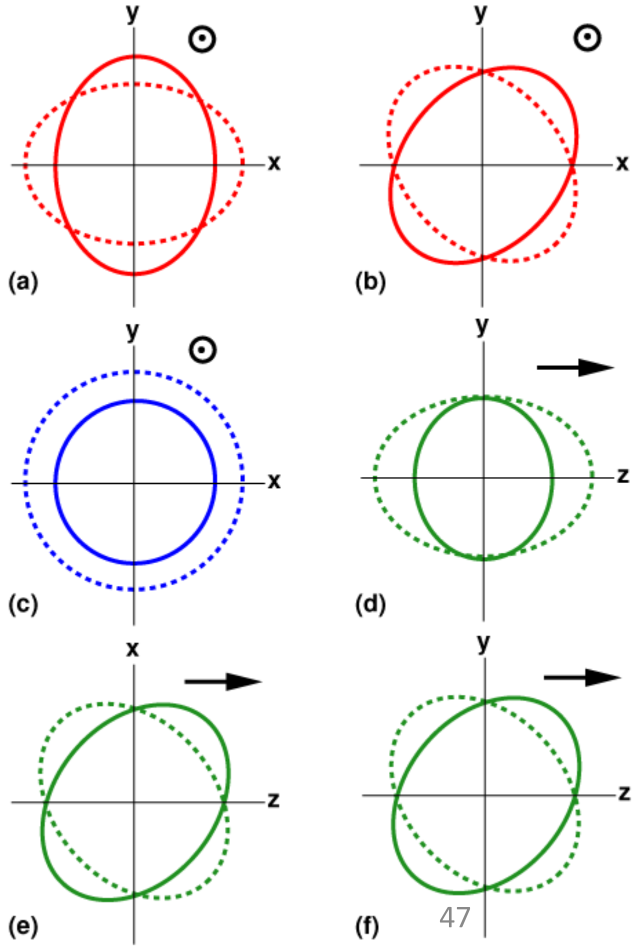


B. P. Abbott et al. (LIGO Scientific and Virgo Collaboration)
Phys. Rev. Lett. 118, 221101 – supplement material

Alternative theories of Gravity: polarisations

- GR predicts a tensorial nature of GW with two polarisations
  - Alternative theories of gravity could predict extra polarisations of GW (up to 6)

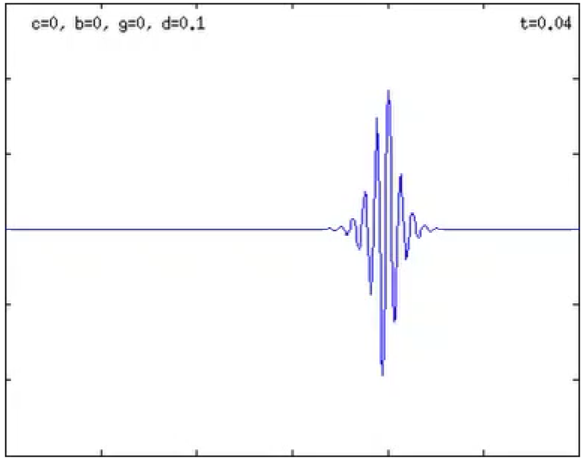


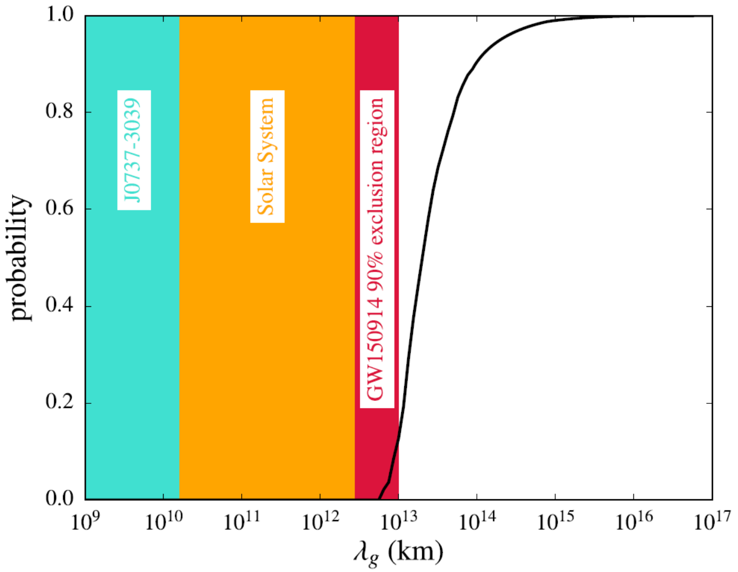


- Present and future GW detectors are setting stringent limits
  - GW170814:
    - Thanks to the presence of Virgo has been possible the evaluate the contribution of extra polarisations in the detected GW resulted disfavoured

Is the Graviton massless?

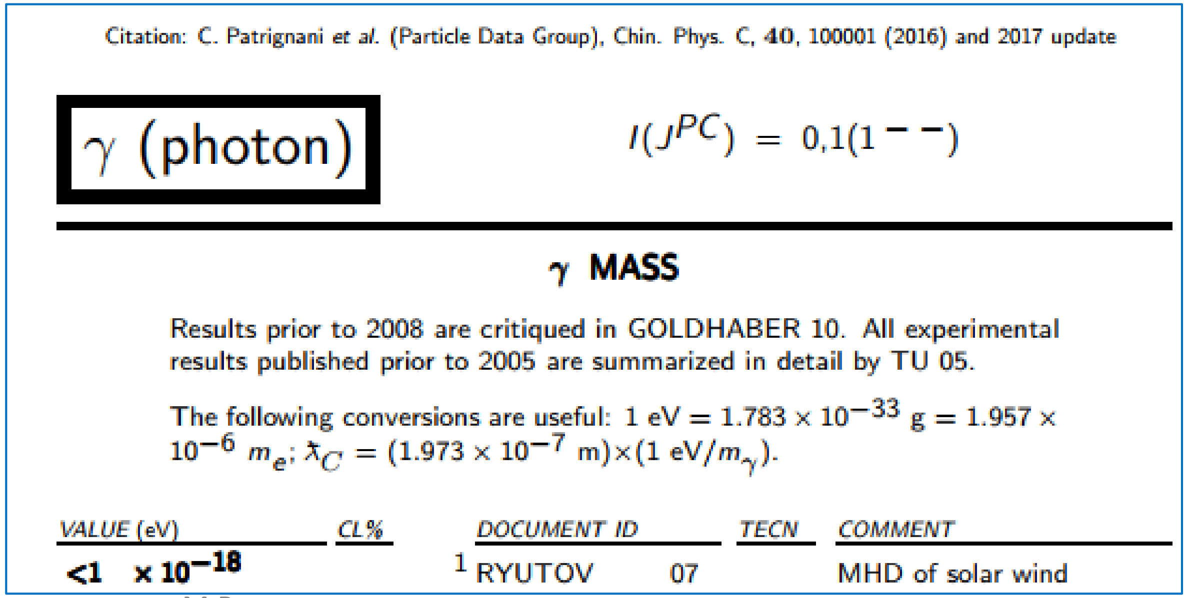
- If the graviton has mass>0 the GW propagates slowly and with dispersion





- Dispersion relation: $E^2 = p^2c^2 + m_g^2c^4$
- $\lambda_g = h/(m_g c)$
- Thanks to **GW170104**, measured at about 3 billions of light years it is possible to set an upper limit:

$$\lambda_g > 1.6\times10^{13}\,km \Rightarrow \quad m_g < 7.7\times10^{-23}\,eV/c^2$$



Citation: C. Patrignani *et al.* (Particle Data Group), Chin. Phys. C, **40**, 100001 (2016) and 2017 update

γ (photon) $\quad I(J^{PC}) = 0,1(1^{--})$

γ MASS

Results prior to 2008 are critiqued in GOLDHABER 10. All experimental results published prior to 2005 are summarized in detail by TU 05.

The following conversions are useful: 1 eV = 1.783 × 10^{-33} g = 1.957 × 10^{-6} m_e; $\bar{\lambda}_C$ = (1.973 × 10^{-7} m)×(1 eV/m_γ).

VALUE (eV)	CL%	DOCUMENT ID	TECN	COMMENT
<1 × 10^{-18}		[1] RYUTOV	07	MHD of solar wind

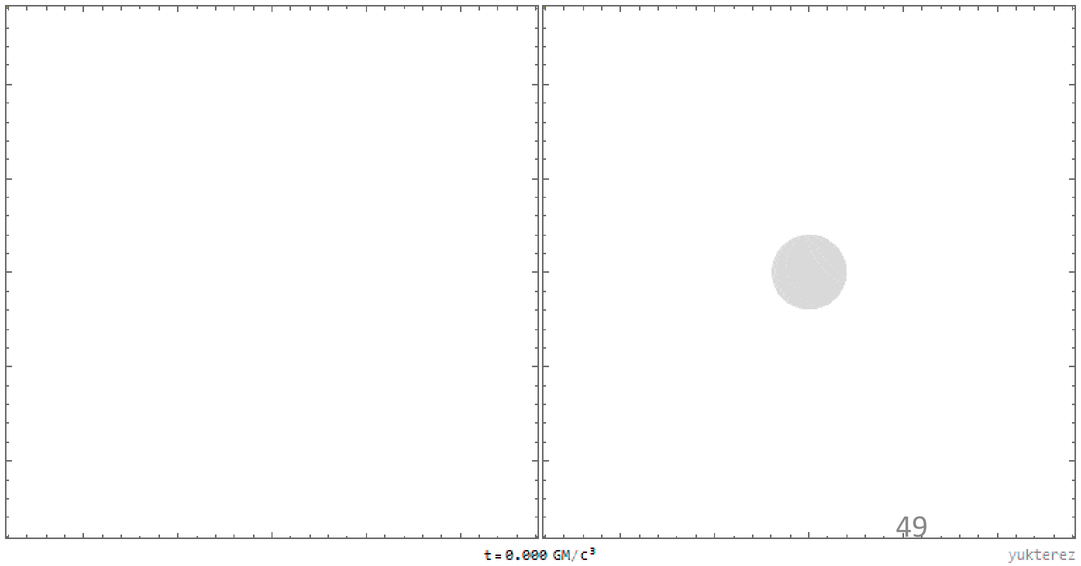
Multimessenger Astronomy and Fundamental Physics

- The beginning of the multimessenger astronomy, marked by GW170817 allowed several fundamental physics tests
  - Constrain the difference of speed between γ and GW: $-3\times10^{-15} \leq \frac{v_{GW}-v_{\gamma}}{v_{\gamma}} \leq 7\times10^{-16}$
  - Test the equivalence principle and discard families (tensor-scalar) of alternative theories of gravity
    - Shapiro effect predicts that the propagation time of massless particles in curved spacetime, i.e., through gravitational fields, is slightly increased with respect to the flat spacetime case:

$$\delta t_{\mathrm{S}} = -\frac{1+\gamma}{c^3}\int_{\mathbf{r}_{\mathrm{e}}}^{\mathbf{r}_{\mathrm{o}}} U(\mathbf{r}(l))dl,$$

$\mathbf{r}_o$ observation point
$\mathbf{r}_e$ emission point
U(**r**) gravitational potential

$$-1.2\times10^{-6} \leq \gamma_{\mathrm{GW}} - \gamma_{\mathrm{EM}} \leq 2.6\times10^{-7}$$



- The γ factor parametrises the coupling of the density energy with the curvature; in the Einstein General Relativity $\gamma_{GW} = \gamma_{EM} = 1$

Dark Energy and Dark Matter after GW170817

GW170817 had consequences for our understanding of Dark Energy and Dark Matter

GWs: many models of modified gravity ruled out!

	Viable after GW170817 (c_g=c)	Not Viable after GW170817 ($c_g \neq c$)
Horndeski	General Relativity	Quartic/quintic Galileon
	Quintessence/K-essence	“Fab-Four”
	K-mouflage	de Sitter Horndeski
	Brans-Dicke/f(R)	$G_{\mu\nu}\phi^{;\mu}\phi^{;\nu}$, Gauss-Bonnet
Beyond H.	DHOST with A_1=0=B_i=G_5	DHOST with $A_1 \neq 0$ or $B_i \neq 0$ or $G_5 \neq 0$
	Derivative Conformal	Quintic GLPV

Also, e.g.,
- Massive gravity

Also strongly affected:
- Vector Dark Energy
- Einstein Aether theories
- Some sectors of Horava gravity
- TeVeS
- MOND-like theories
- Generalized PROCA theories

See, e.g., Ezquiaga & Zumalacarregui ’17; Baker et al. ’17; Creminelli & Vernizzi ‘17

Nicola Bartolo, private communication

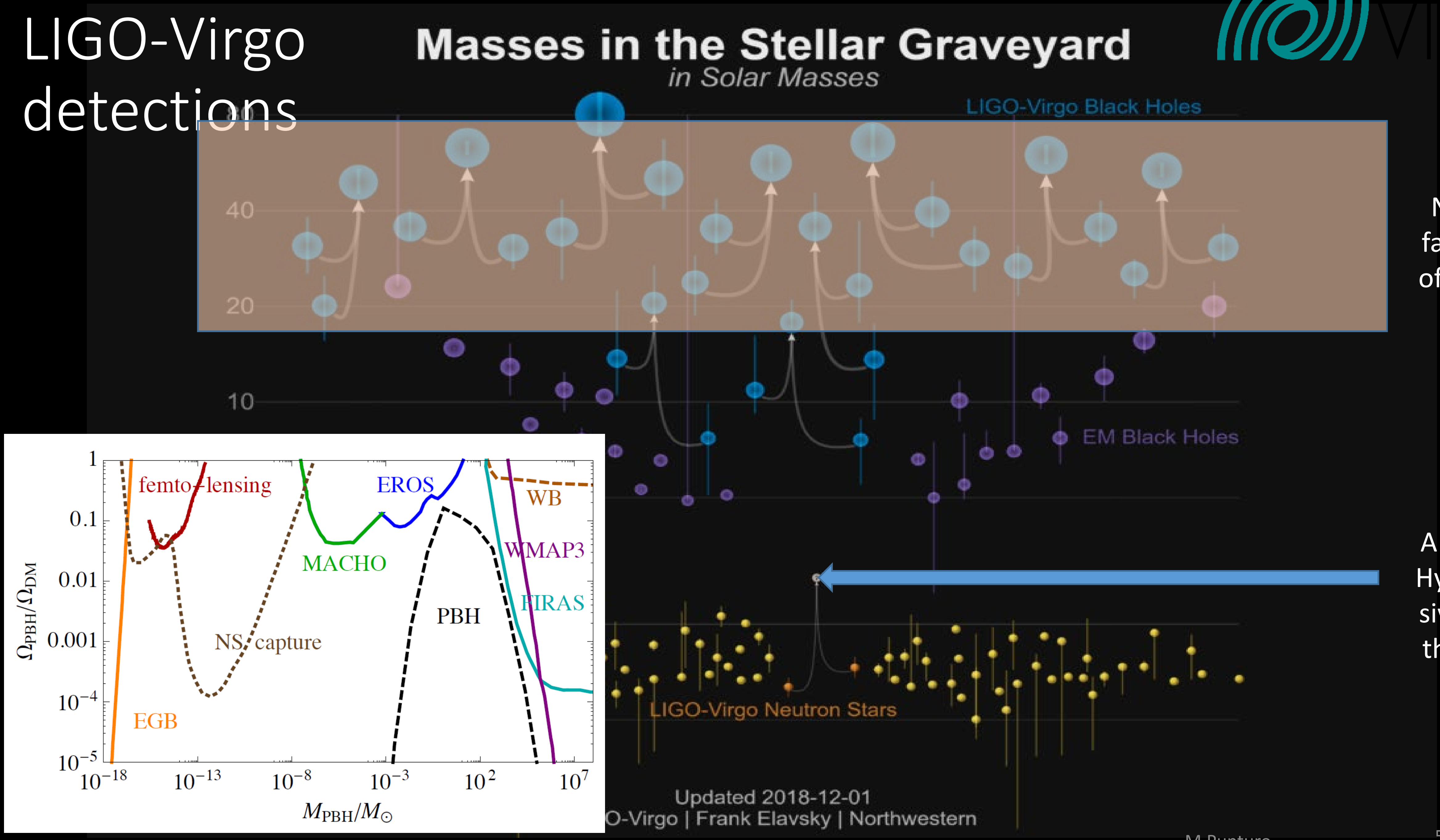
What is the nature of the Dark Matter?

$$T_{\mu\nu}^{WIMP} \quad T_{\mu\nu}^{axion}$$

$$G_{\mu\nu} = \frac{8\pi G}{c^4}\left(T_{\mu\nu} + T_{\mu\nu}^{DM}\right)$$

$$T_{\mu\nu}^{BH}$$

LIGO-Virgo detections



New family of BH?

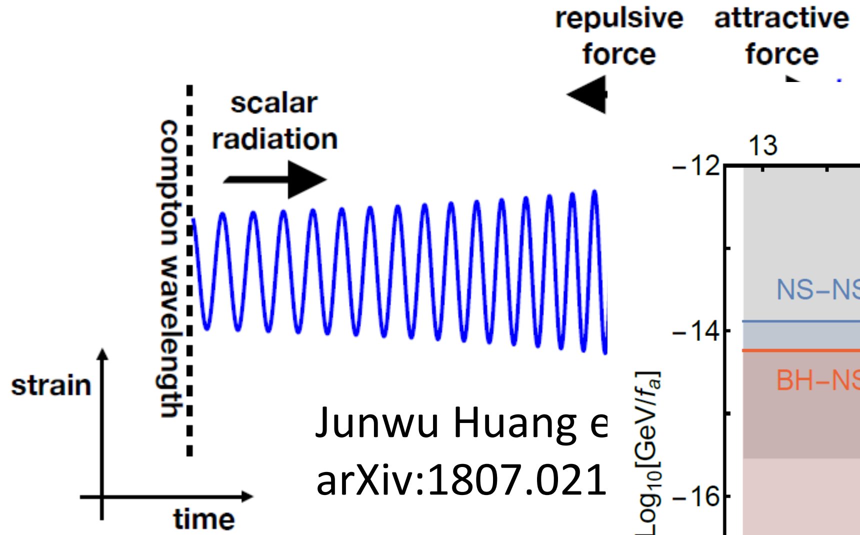
A BH or a Hypermassive NS in the mass gap?

Juan García-Bellido 2017 J. Phys.: Conf. Ser. 840 012032

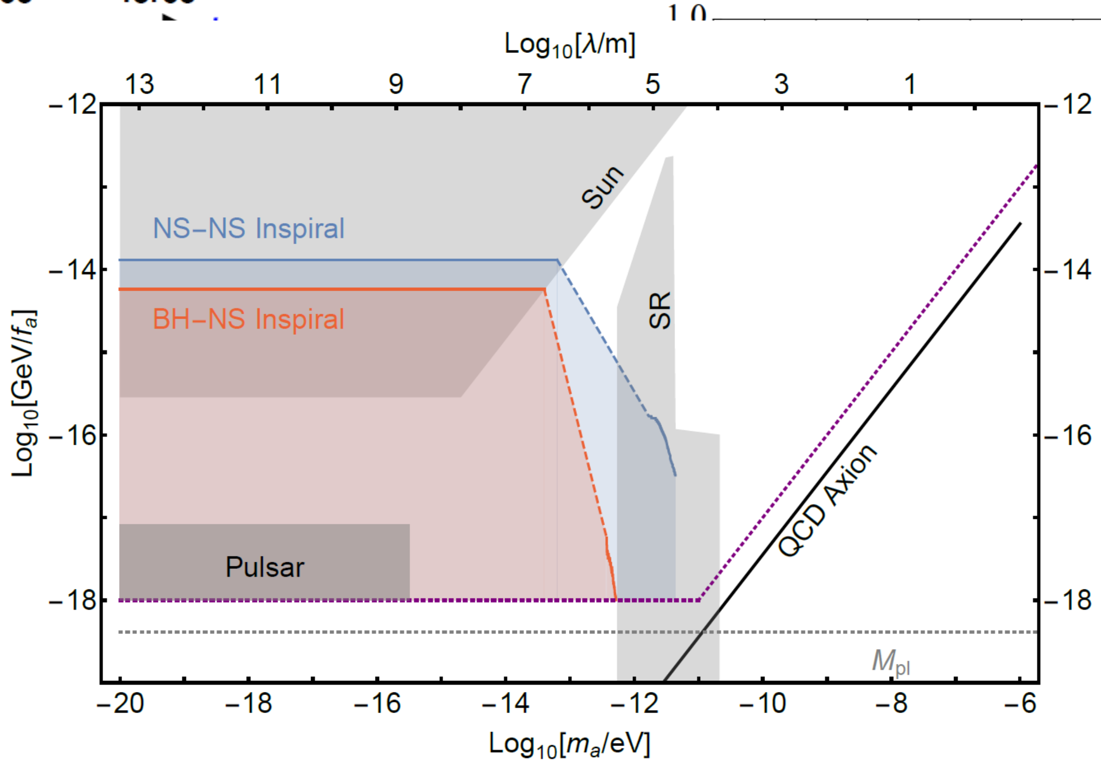
Axions and GW

- Axions or, in general, light scalar fields are a possible extension of the Particle standard model and they could be a component of the dark matter or dark energy
  - Axions could provide an inflation mechanism
- What GW could tell about Axions?

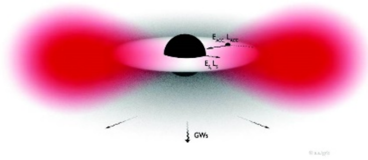
BNS coalescence

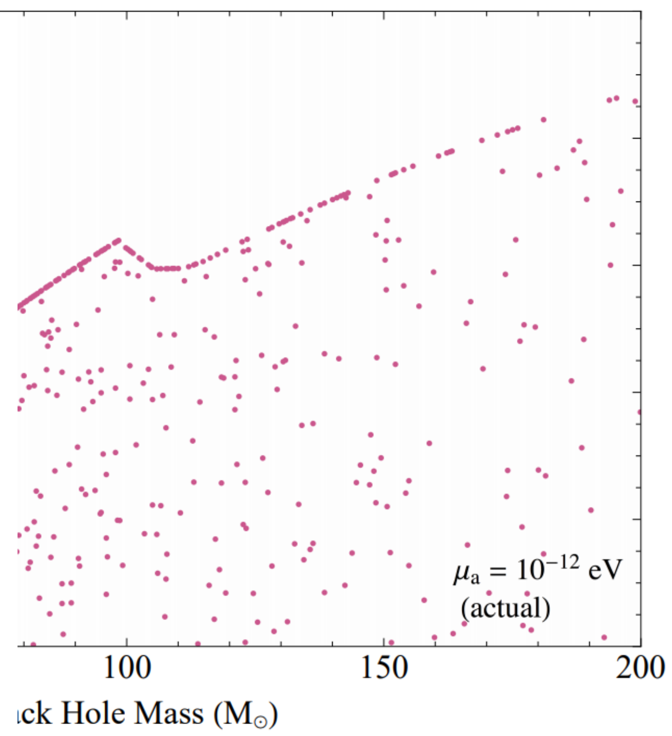


Junwu Huang e
arXiv:1807.021



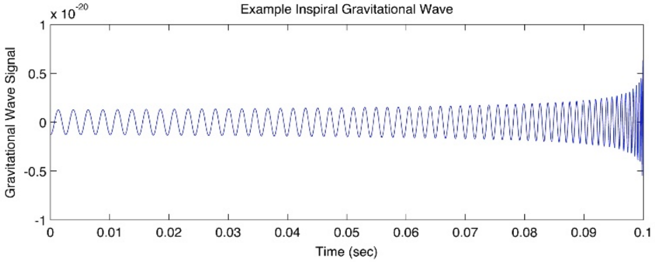
BH superradiance





Measure of H_0

- GW by coalescence of compact bodies are standard ~~candles~~ sirens
- GW170817 has been the first taste of the potential of the multimessenger astronomy in cosmology:
  - Measure of the Hubble constant with an independent method $H_0 = 70.0^{+12.0}_{-8.0}\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$



From GW: redshifted mass and luminosity distance

$$\Psi(f) \propto 2\pi f t_c - \Phi_c - \frac{\pi}{4} + \frac{3}{128}(\pi \mathcal{M}_z f)^{-5/3}[1 + \ldots]$$

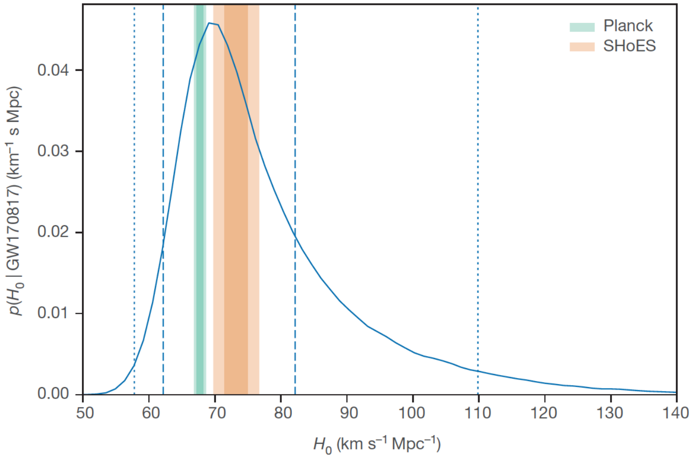
$$\tilde{h}_+(f) \propto A_0 \frac{\mathcal{M}_z^{5/6}}{D_L}\left[1+\cos^2\iota\right] f^{-7/6} e^{i\Psi(f)}$$

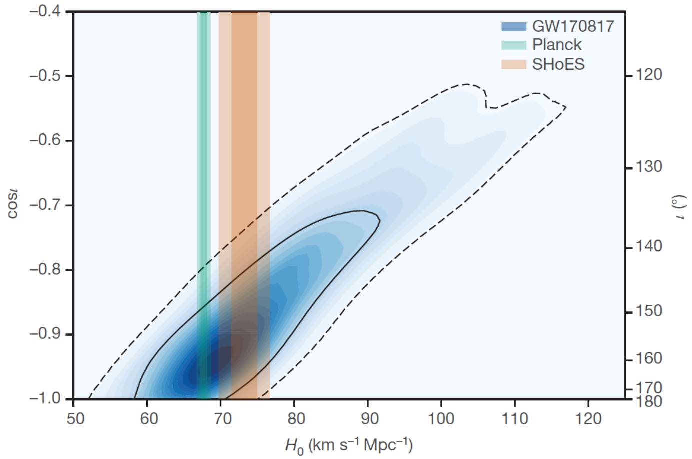
Inclination angle introduces degeneracy, which will be removed by measuring the 2 polarizations

LIGO+Virgo *et al.*, Nature 551, 85 (2017)

$$H_0 d_L = cz$$

$$H_0 = 70^{12.0}_{-8.0}\ \mathrm{km\ s^{-1}Mpc}$$

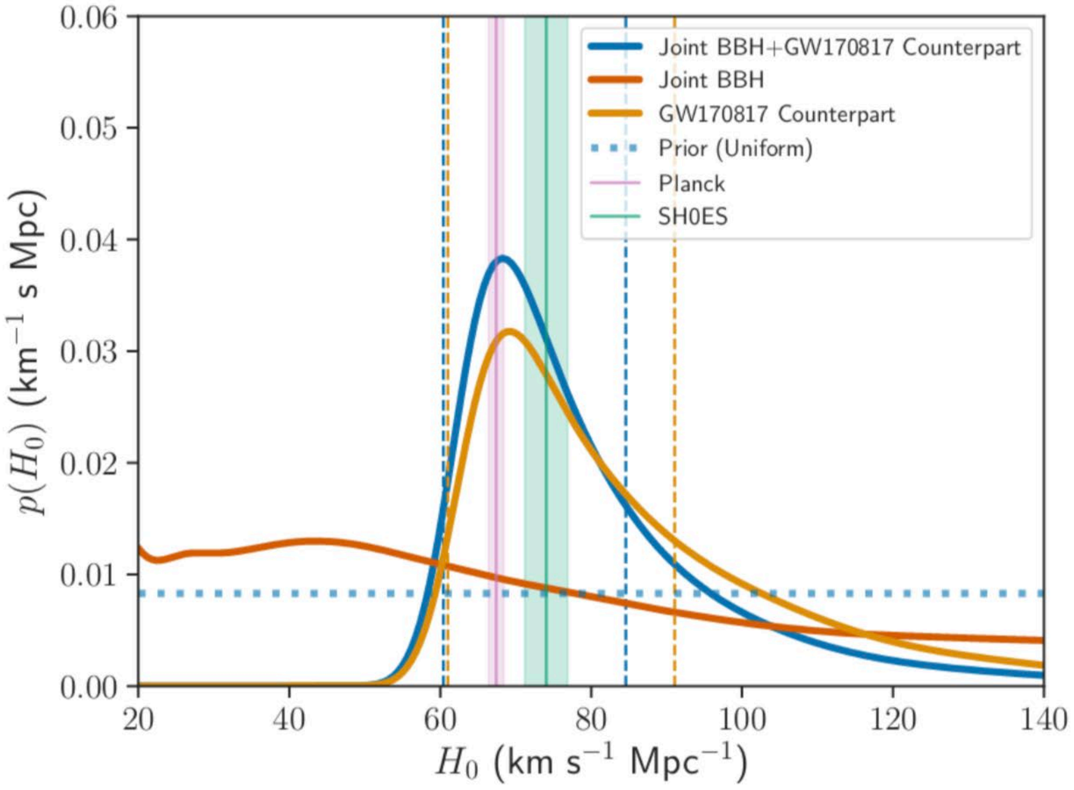




New Measure of H_0

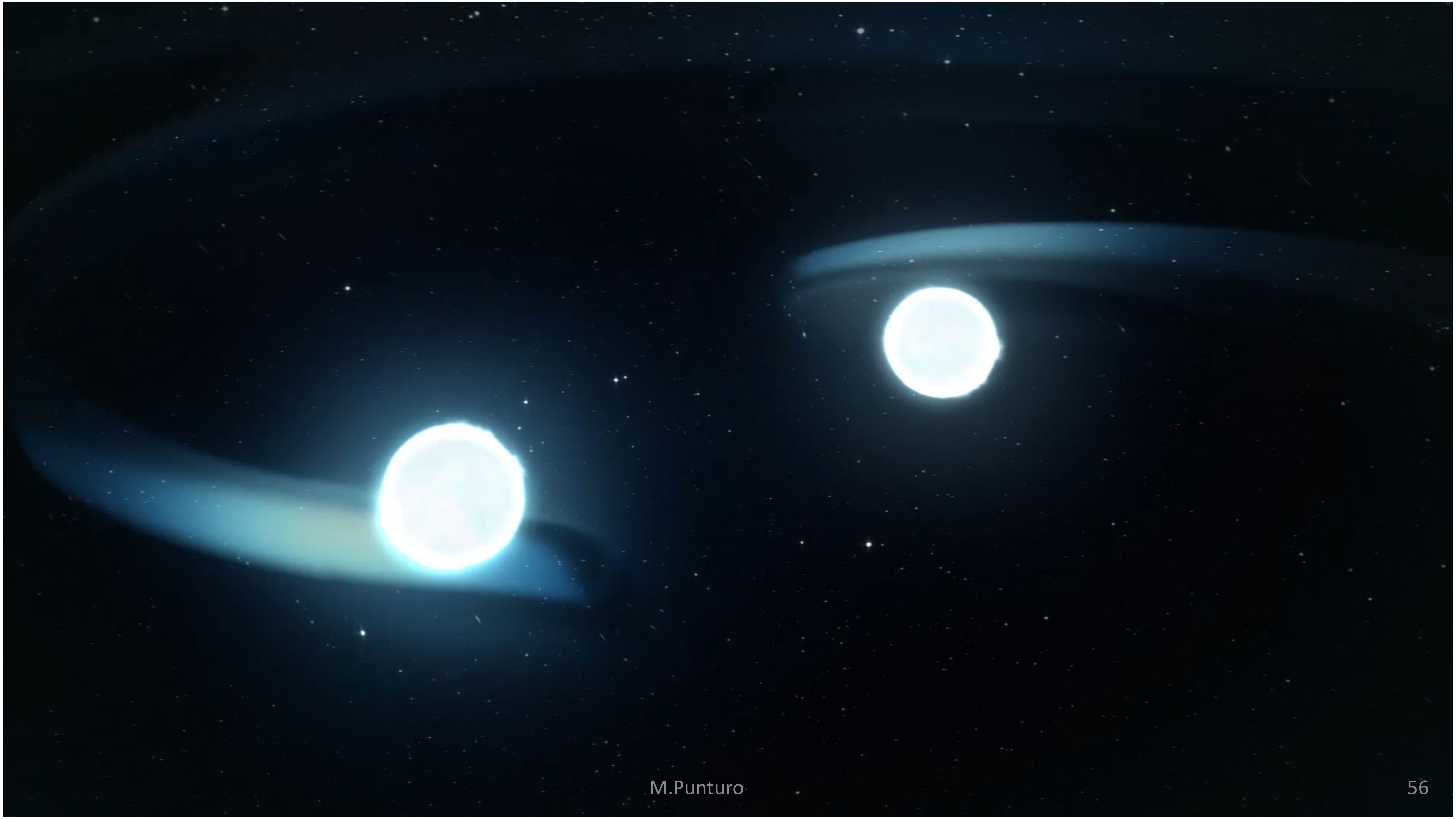
New measurement of H_0 using the O1+O2 detections and galaxy catalogs

arxiv:1908.06060



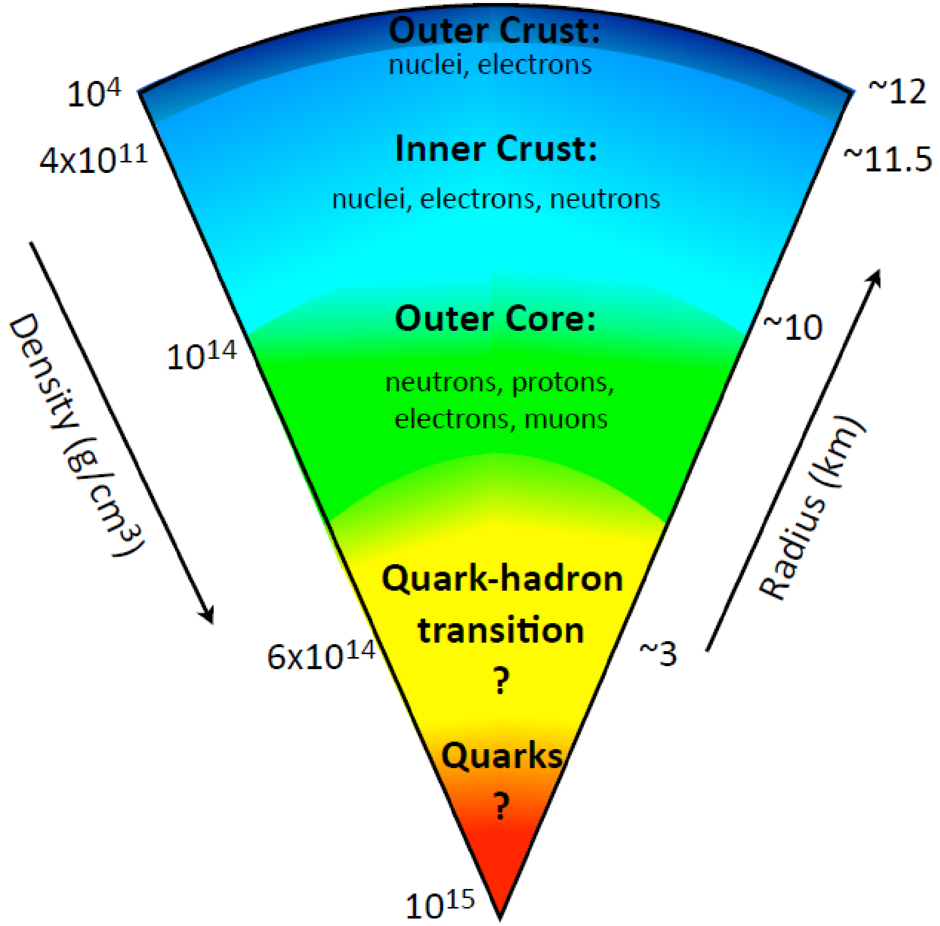
$$H_0 = 68^{+14}_{-7}\ \mathrm{km\ s^{-1}\ Mpc^{-1}}$$

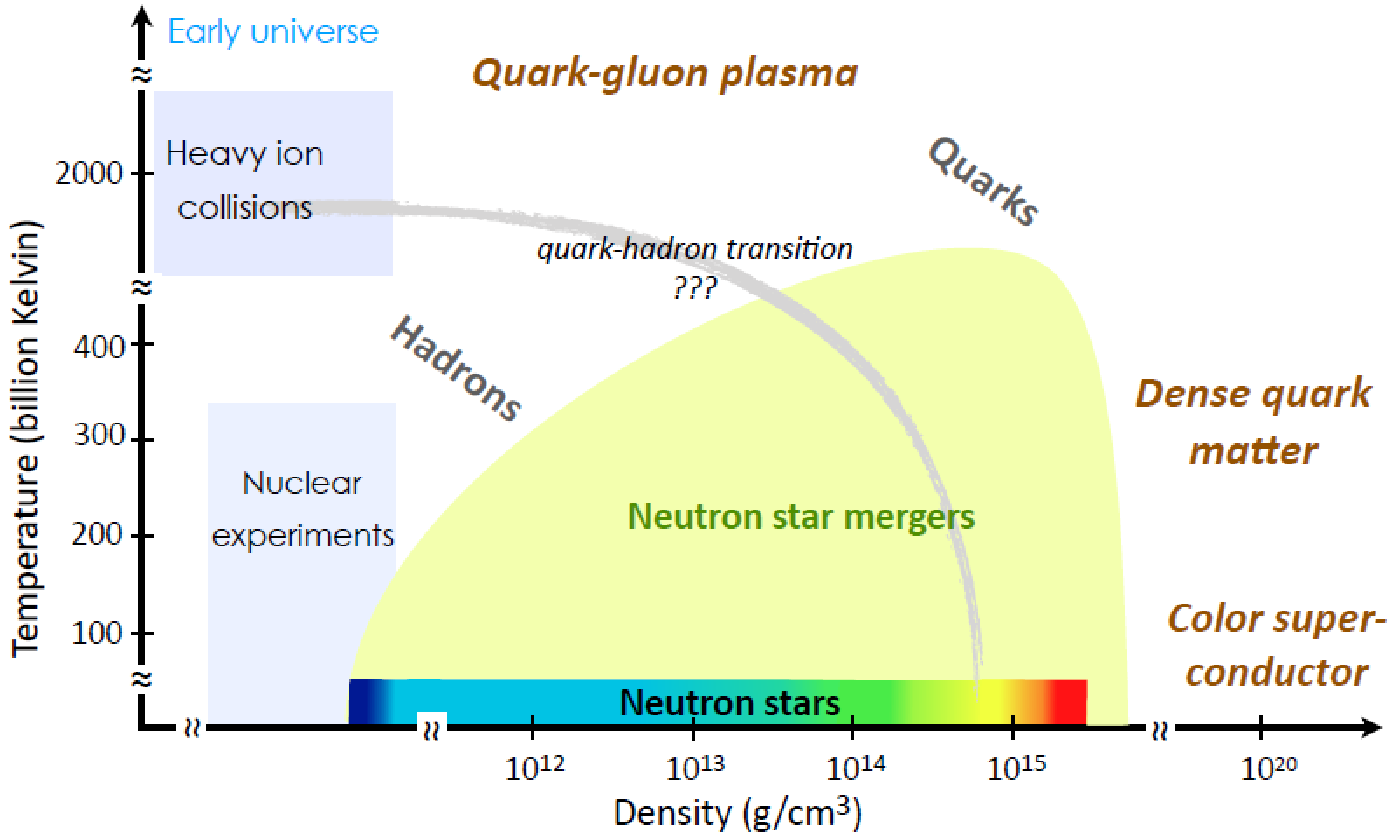
Our Collider



Neutron Star is a nuclear physics lab

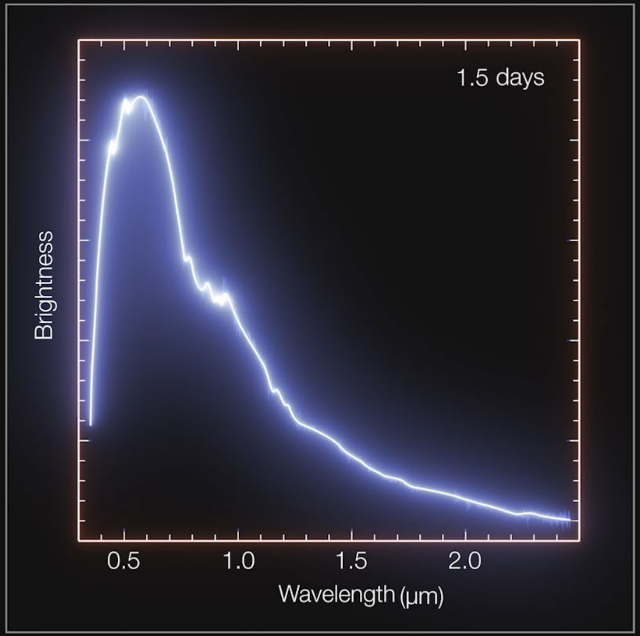
- Neutron stars are an extreme laboratory for nuclear physics
  - The external crust is a Coulomb Crystal of progressively more neutron-reach nuclei
  - The core is a Fermi liquid of uniform neutron-rich matter (“Exotic phases”? Quark-Gluon plasma?)





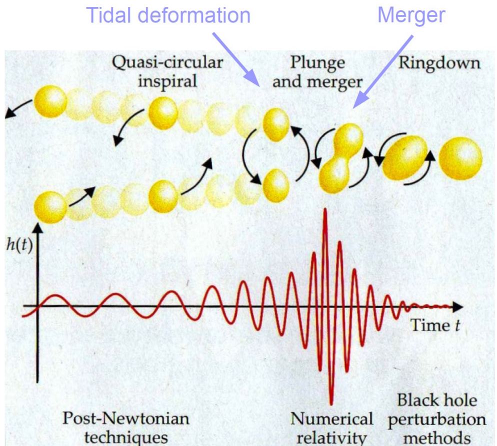
GW170817: Nuclear Physics “experiment”

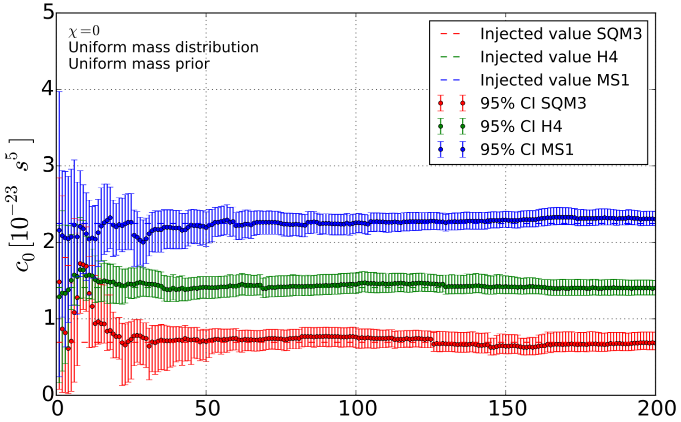
- The collision of two NS in GW170817 has been a complex nuclear physics experiment, where it has been possible
  - The accurate measure the mass and radius of the NS through the tidal deformation of the star → Constrain the EOS
  - To observe the production of heavy elements through r-processes

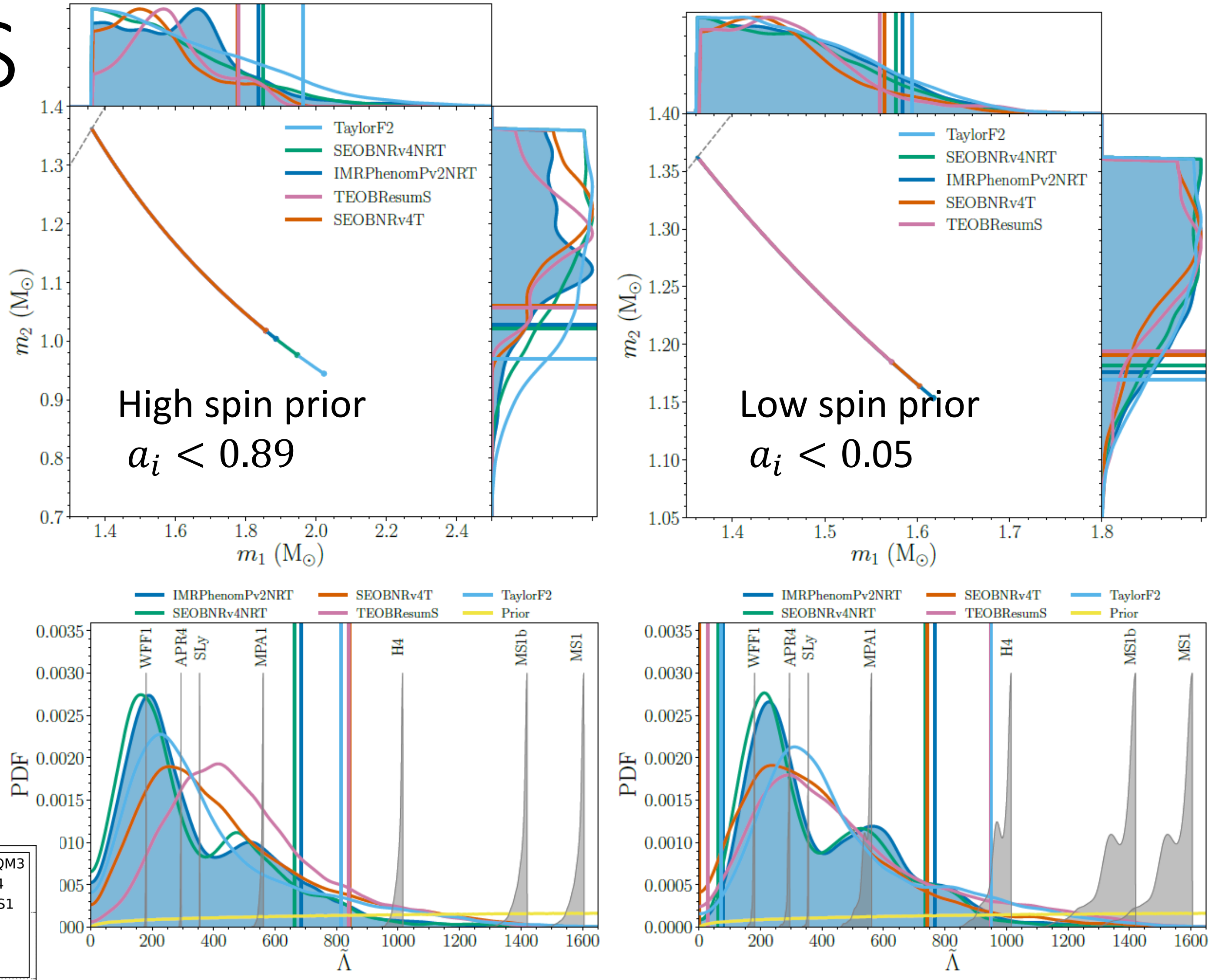


Constraining the NS EOS

- Measuring the tidal deformation through the dephasing in the GW signal is possible to constrain the EOS of the NS
- Adding the em information helps to impose more stringent constrain
  - Knowing the EOS it is possible to describe the status of the matter in the over-critical pressure condition in the NS







arXiv:1811.12907

M. Agathos et al, Phys. Rev. D 92, 023012 (2015)

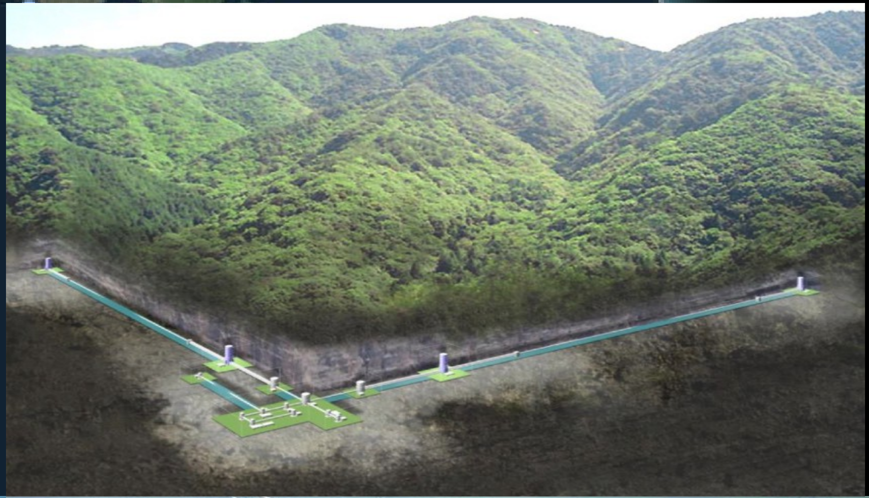
The Present

KAGRA

The O3 run

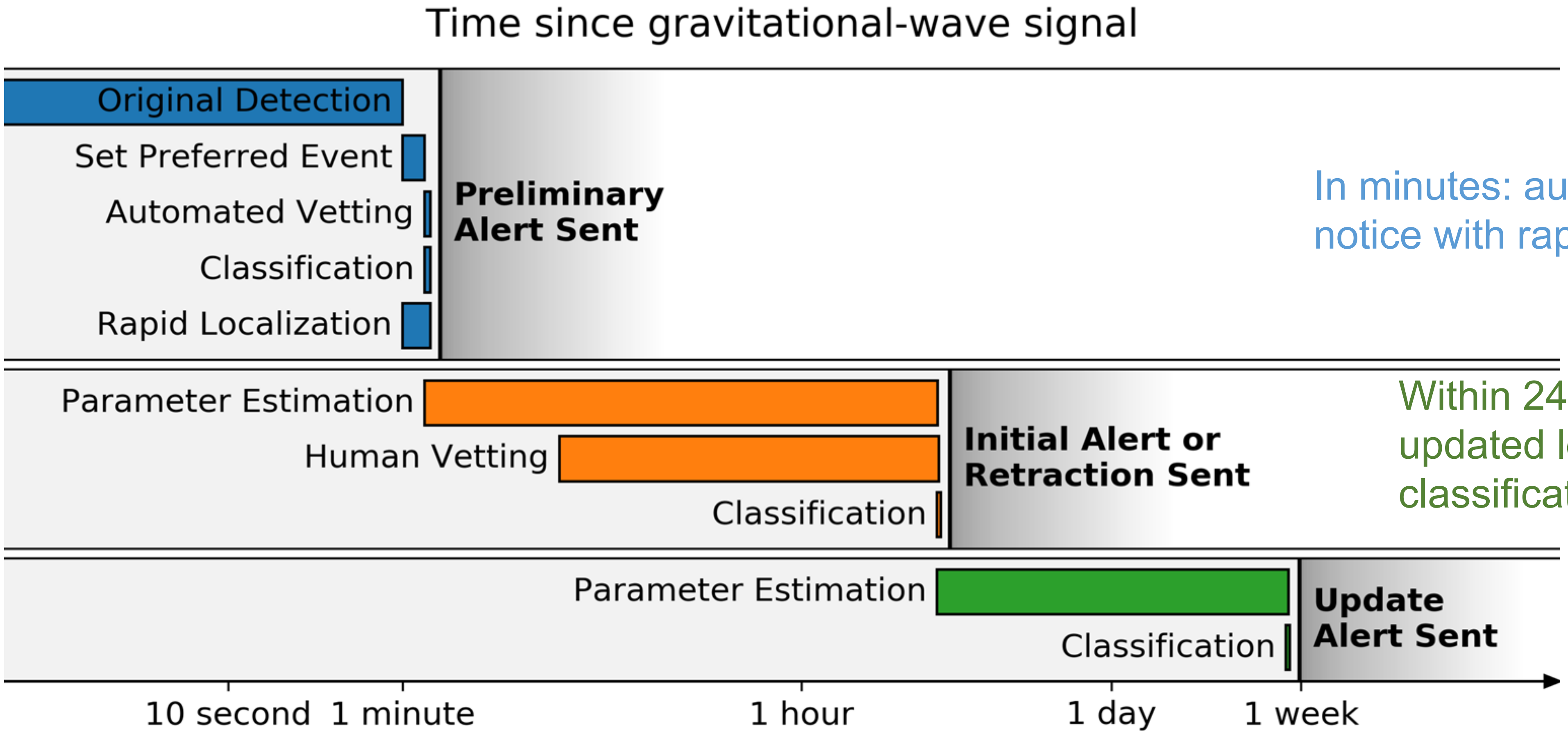
O3a: Apr 1 2019 → Oct 1 2019

O3b: Nov 1 2019 → May 1 2020 (with KAGRA)



Open Public Alerts

LIGO-Virgo will issue Open Public Alerts during the O3 run



In minutes: automatic preliminary notice with rapid localization

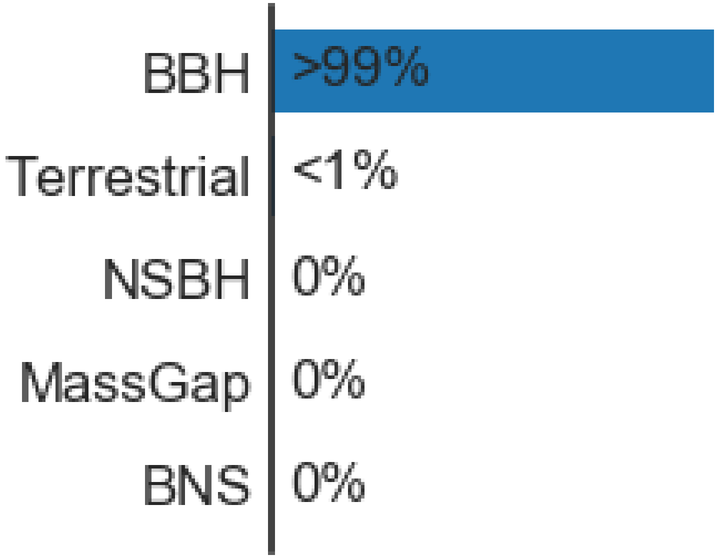
Within 24 hrs: retraction or updated localization, source classification

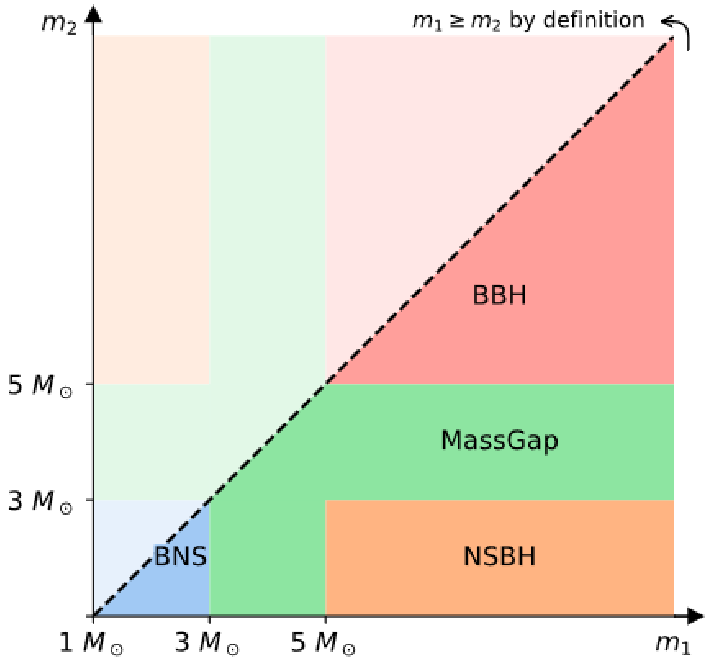
Significant updates

Open Public Alerts

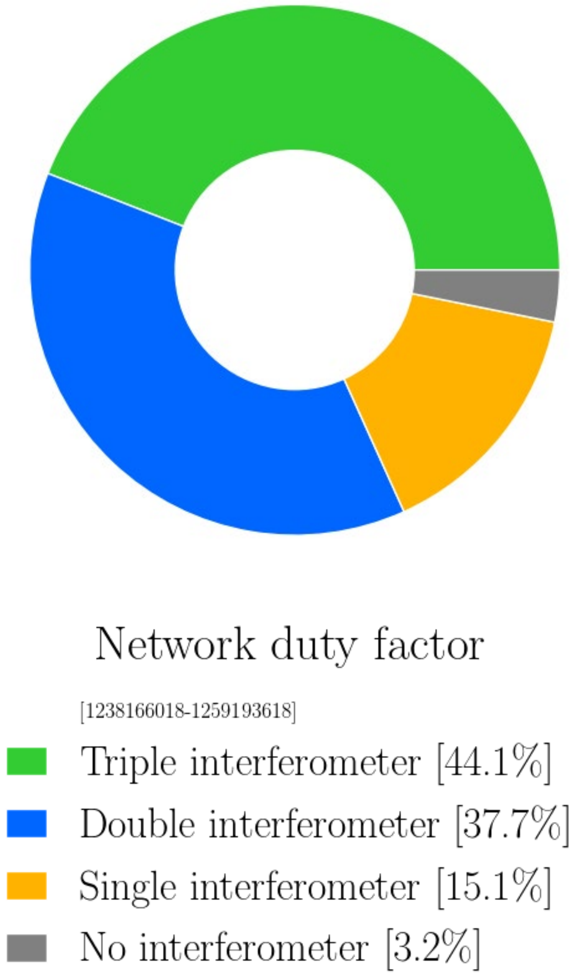
- **Localization:** 3D map for follow-up
- **Classification**: Five numbers, summing to unity, giving probability that the source belongs to five categories
  - This assumes that terrestrial and astrophysical events occur as independent Poisson p

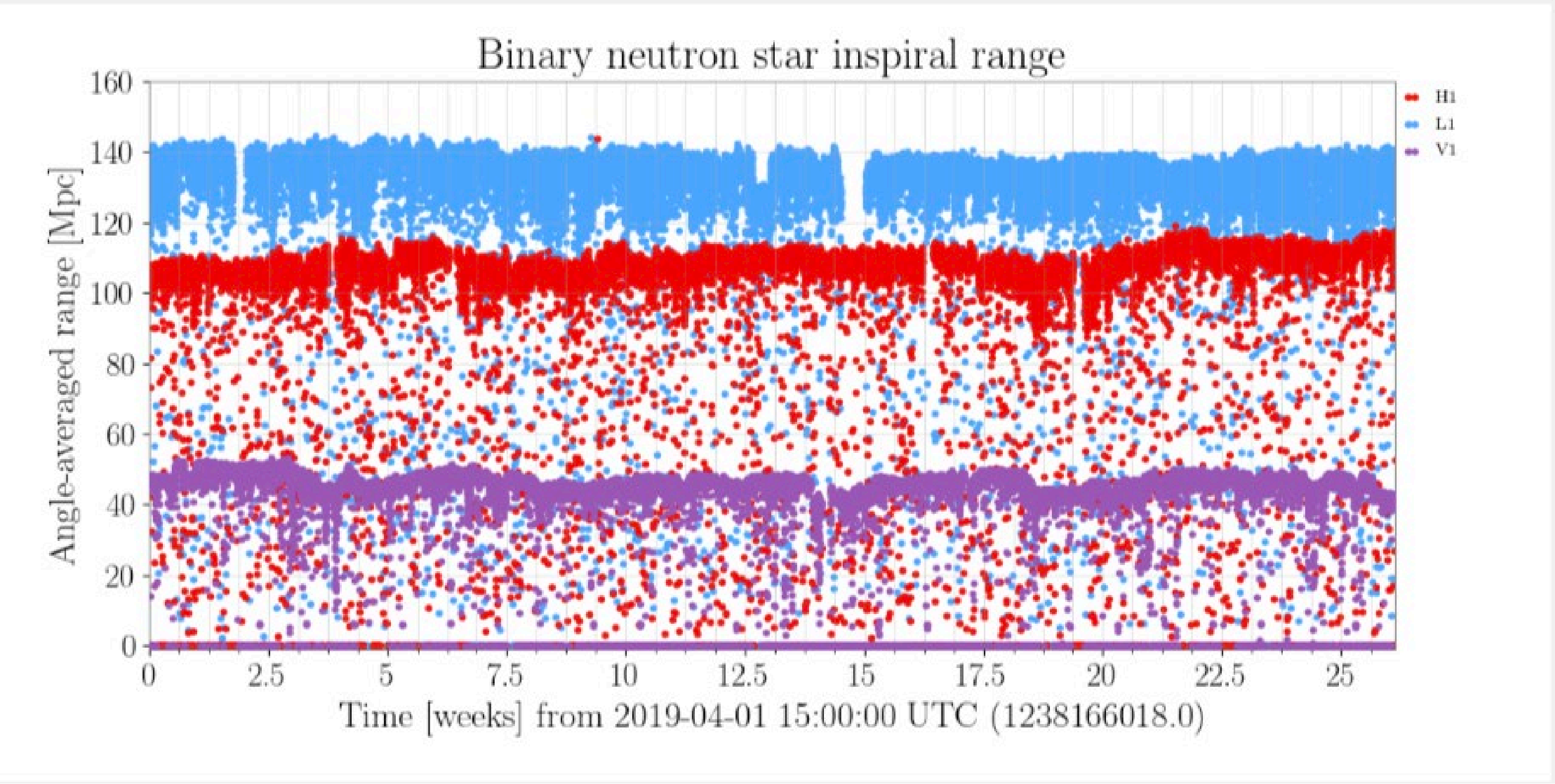
arXiv:1903.06881



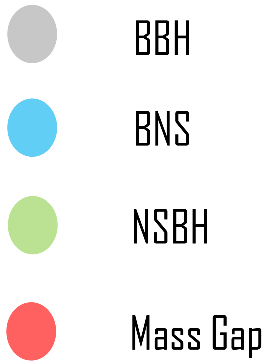


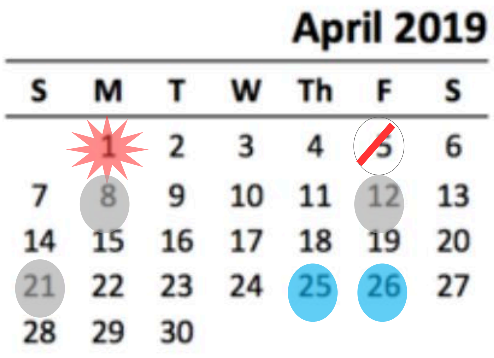
O3

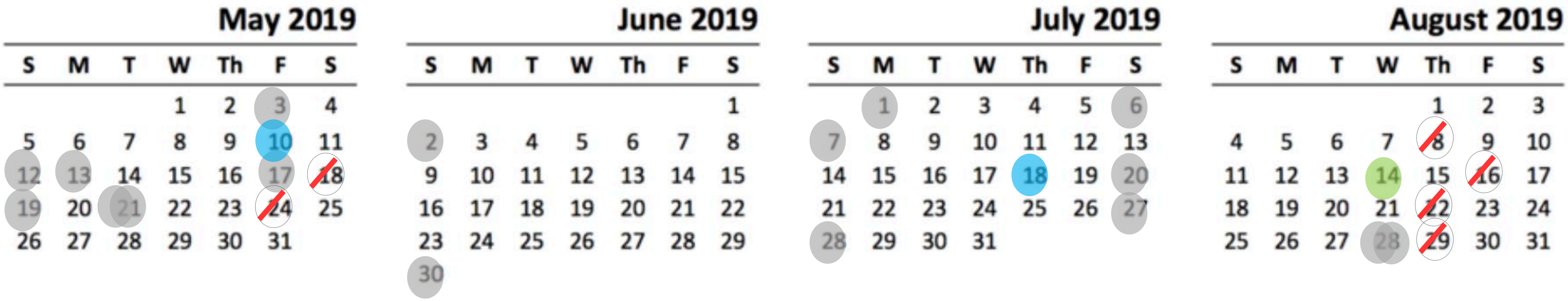

Network duty factor
[1238166018-1259193618]
Triple interferometer [44.1%]
Double interferometer [37.7%]
Single interferometer [15.1%]
No interferometer [3.2%]


Binary neutron star inspiral range
H1
L1
V1
Angle-averaged range [Mpc]
0
20
40
60
80
100
120
140
160
0
2.5
5
7.5
10
12.5
15
17.5
20
22.5
25
Time [weeks] from 2019-04-01 15:00:00 UTC (1238166018.0)

O3a – Summary of public alerts





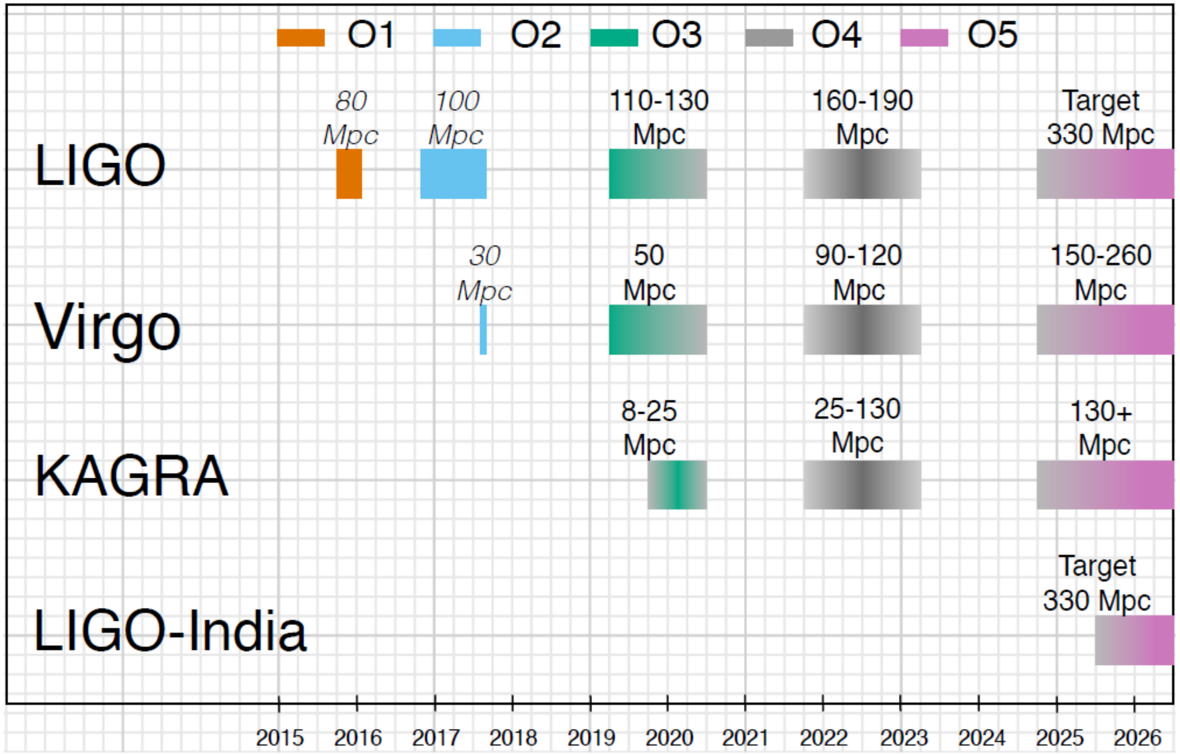


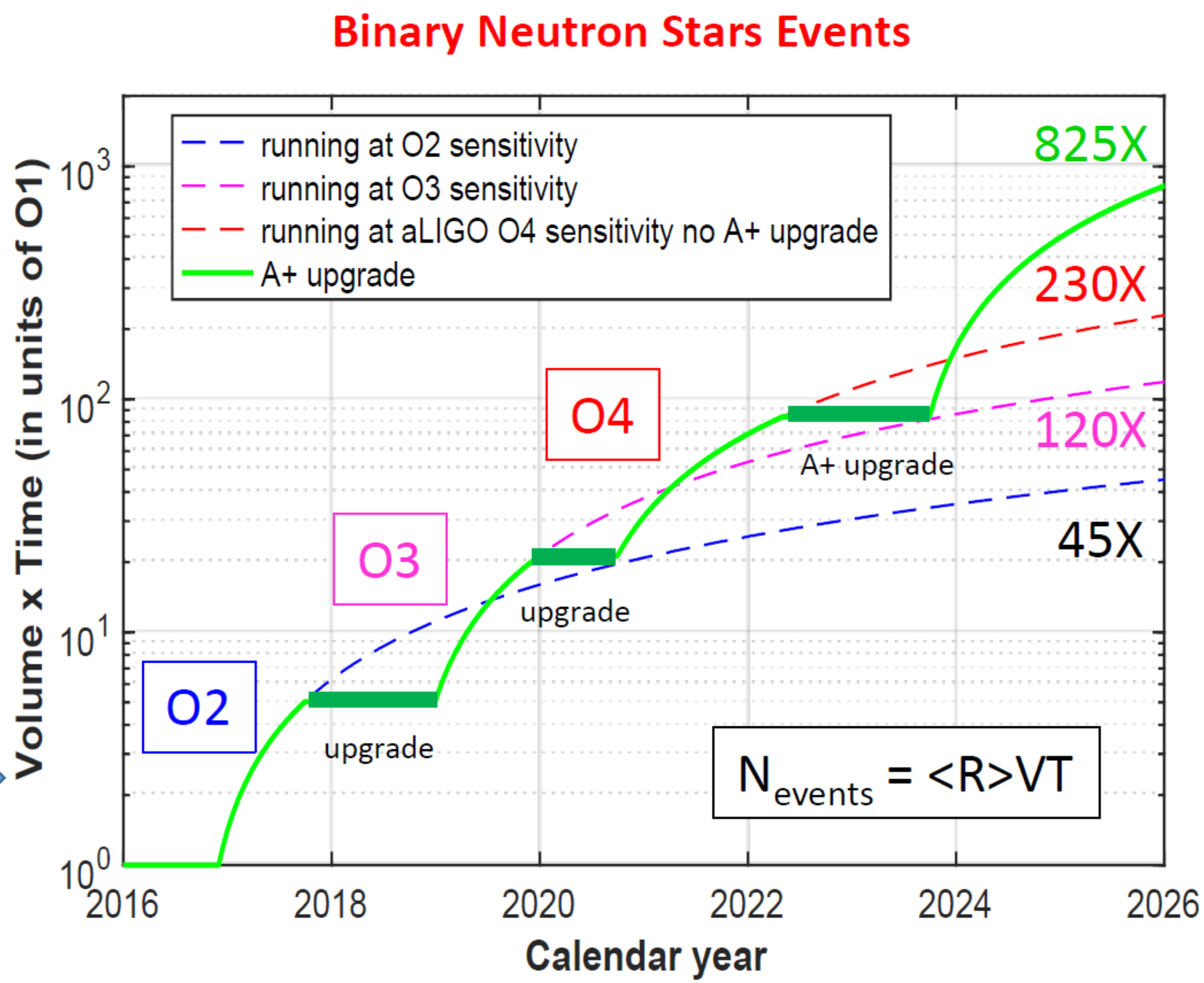
Observation Run	Network	Expected BNS Detections	Expected NSBH Detections	Expected BBH Detections
O3	HLV	2^{+8}_{-2}	0^{+19}_{-0}	15^{+19}_{-10}
O4	HLVK	8^{+42}_{-7}	2^{+94}_{-2}	68^{+81}_{-38}

https://arxiv.org/abs/1304.0670

Next Future

Plans for LIGO-KAGRA-Virgo runs





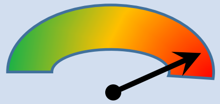
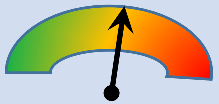
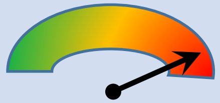
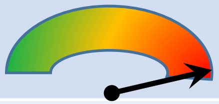
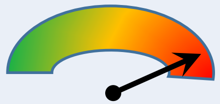
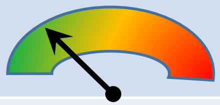
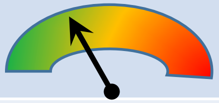
HEPP physicists?

- Luminosity $\mathcal{L}$
- Branching ratio $\mathcal{R}$

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

2029 outlook

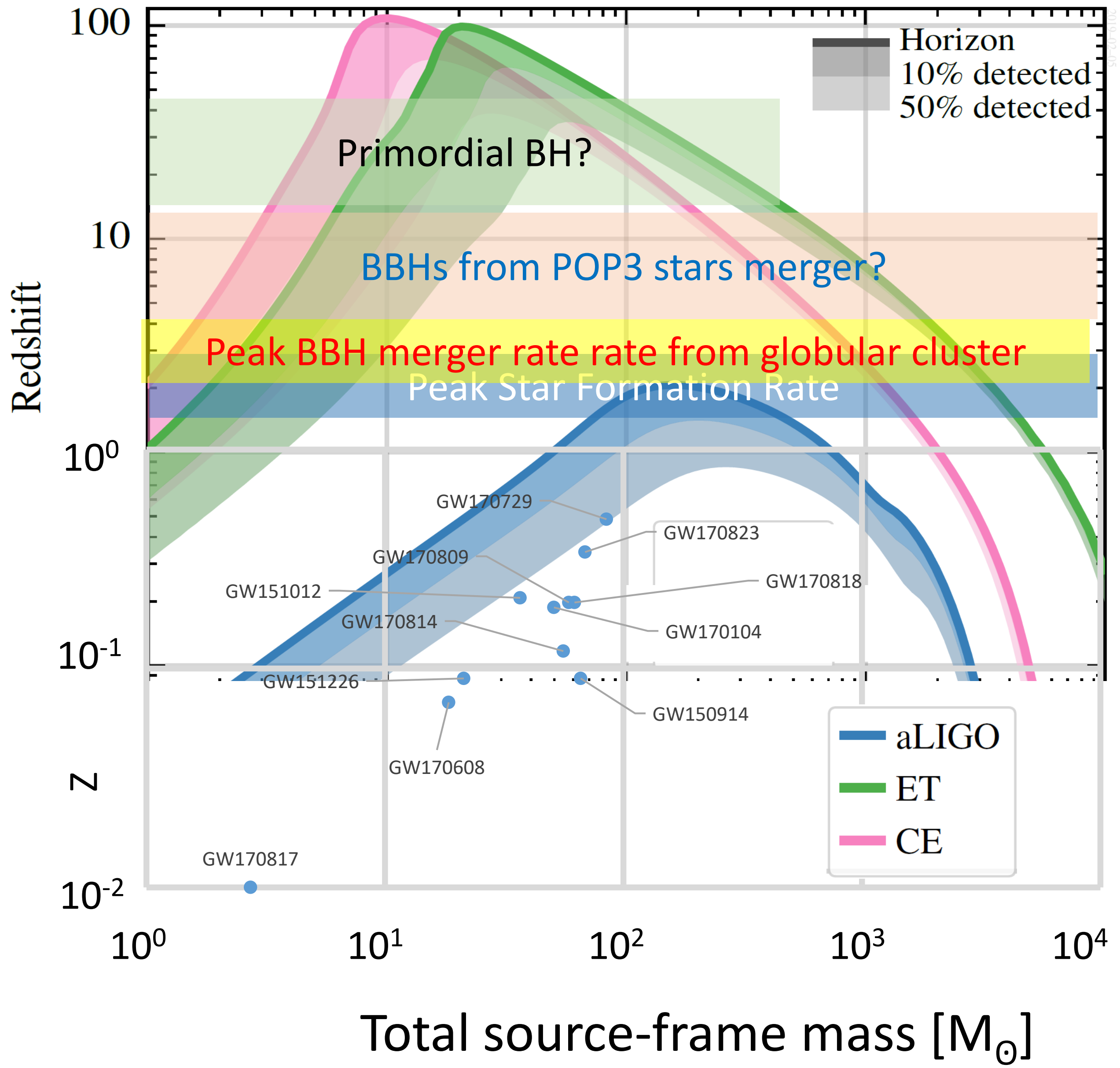
- In 2029 we will have a really heterogeneous 2.xG network
  - The concepts of “obsolescence” and “limit of the infrastructure”, that are driving the quest for new research infrastructures (rather more than a new detector) apply differently to the different continents

Continent	Detector	Obsolescence	Limits
America	LIGO H1		
	LIGO L1		
Europe	GEO600		
	Virgo		
Asia	KAGRA		
	LIGO India		

OK, all done?

- aLIGO and AdV achieved awesome results with a reduced sensitivity
- When they will reach or over-perform their nominal sensitivity can we exploit all the potential of GW observations?

- 2nd generation GW detectors will explore local Universe, initiating the precision GW astronomy, but to have cosmological investigations a factor of 10 improvement in terms detection distance is needed



GWTC-1: A gravitational-wave transient catalog of compact binary mergers observed by LIGO and Virgo during the first and second observing runs - arXiv:1811.12907 [astro-ph.HE]

Detection distance of GWD

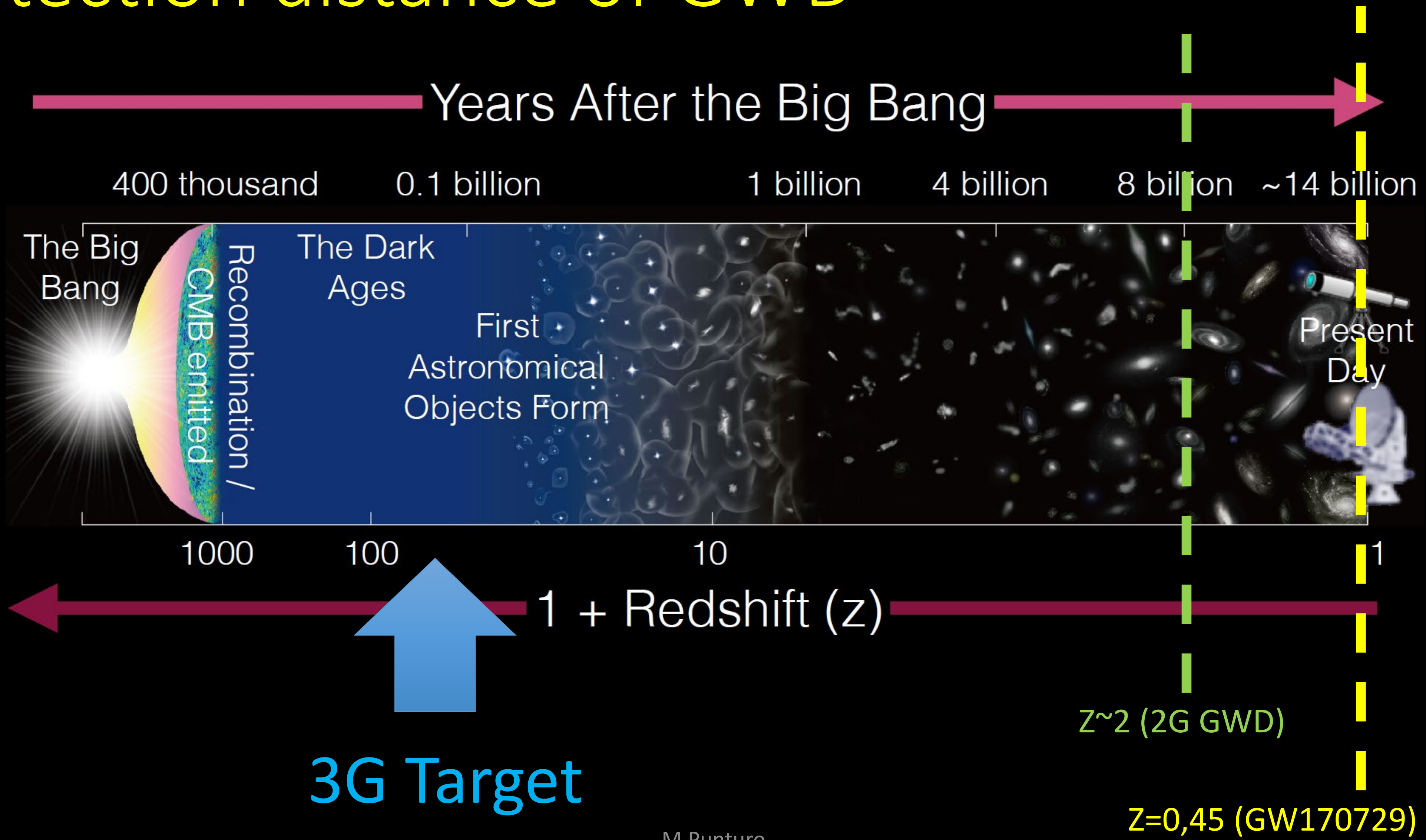
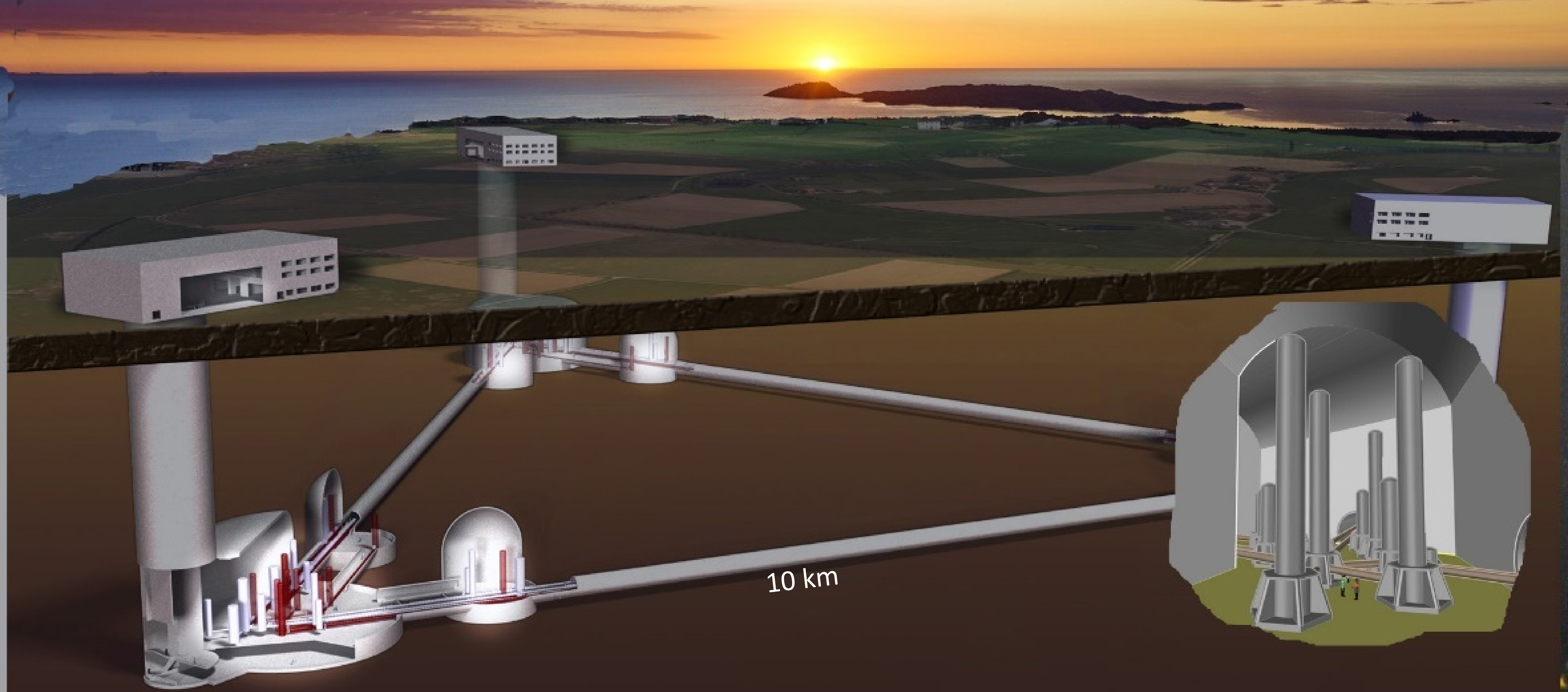


Image credit: NAOJ/ALMA http://alma.mtk.nao.ac.jp/

The Einstein Telescope



The 3G/ET key points

- ET is THE 3G new GW observatory
  - 3G: Factor 10 better than advanced (2G) detectors
  - New:
    - We need a new infrastructures because
      - Current infrastructures will limit the sensitivity of future upgrades
      - In 2030 current infrastructures will be obsolete
  - Observatory:
    - Wide frequency, with special attention to low frequency (few HZ)
      - See later
    - Capable to work alone (characteristic to be evaluated in the international scenario)
      - (poor) Localization capability
      - Polarisations (triangle)
      - High duty cycle: redundancy
    - 50-years lifetime of the infrastructure
      - Compliant with the upgrades of the hosted detectors

Science targets of ET

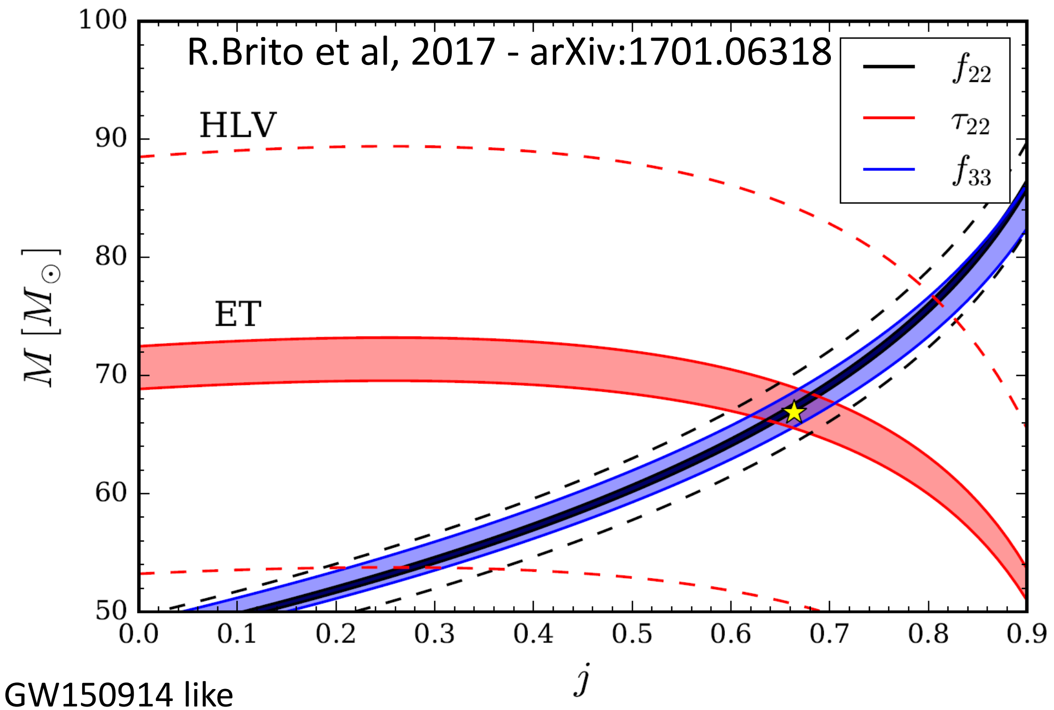
- ET will extend the science potential of 2G/2G+ and will introduce new science targets
- Few examples are hereafter described

Extreme gravity

- In GR, no-hair theorem predicts that BHs are described only by their mass and spin (and charge)
  - However, when a BH is perturbed, it reacts (in GR) in a very specific manner, relaxing to its stationary configuration by oscillating in a superpositions of quasi-normal modes, which are damped by the emission of GWs.
  - A BH, a pure space-time configuration, reacts like an elastic body → Testing the "elasticity" of the space-time fabric
  - Exotic compact bodies could have a different QN emission and have echoes

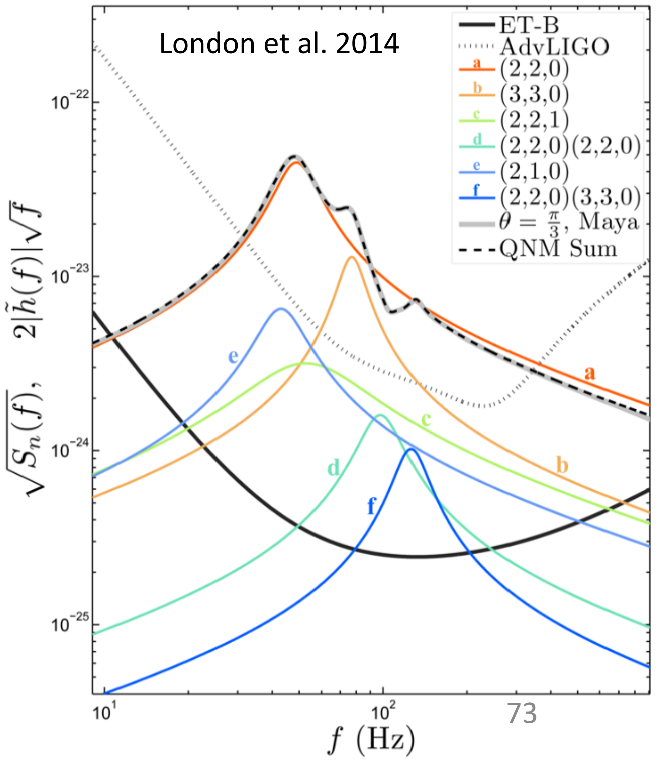
ET will resolve QN emission by BH

J=J/M² dimensionless spin



GW150914 like

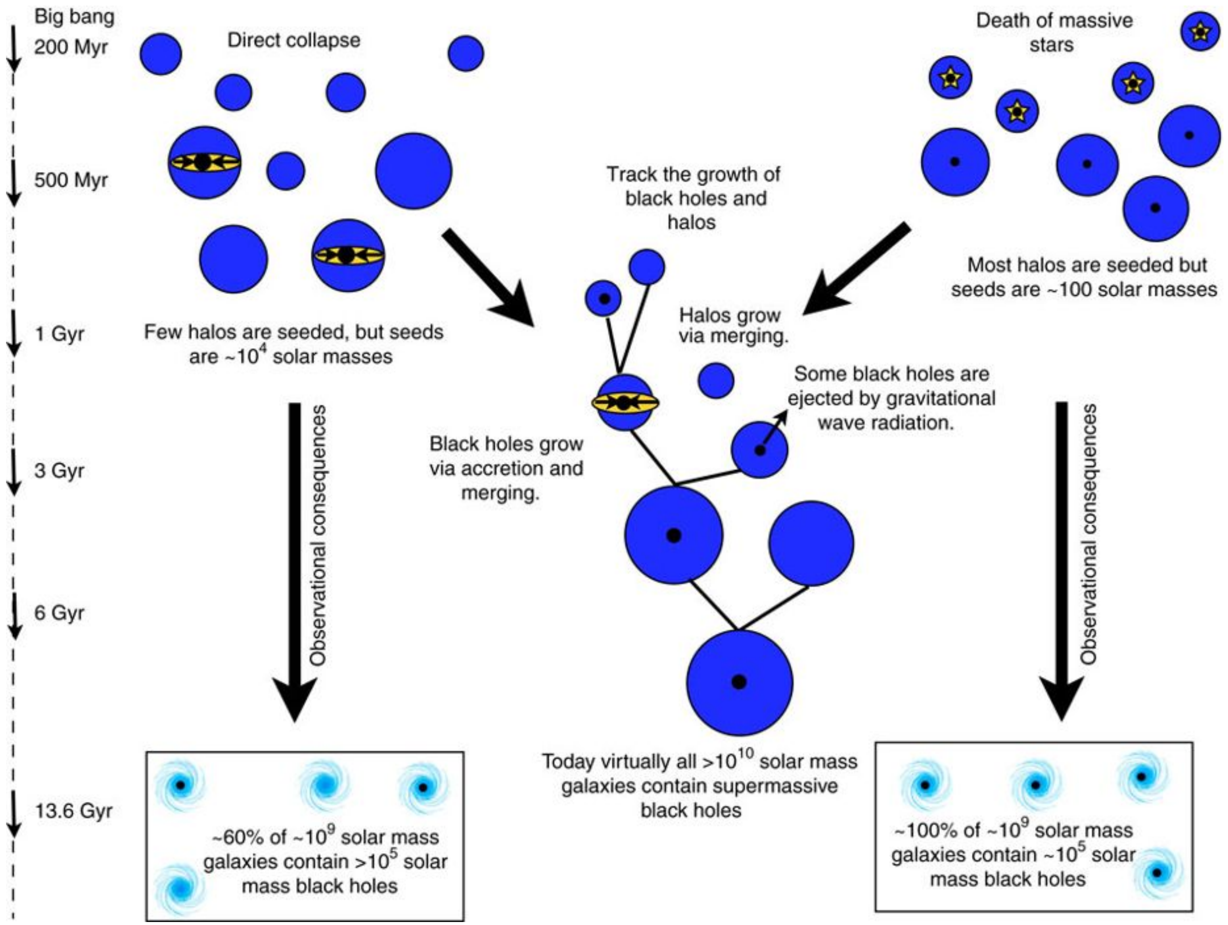
350 Msun binary @ 100 Mpc

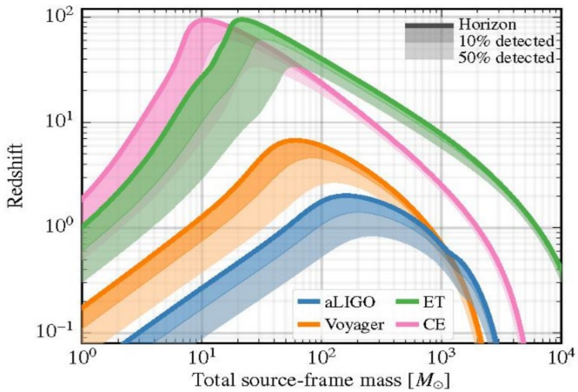


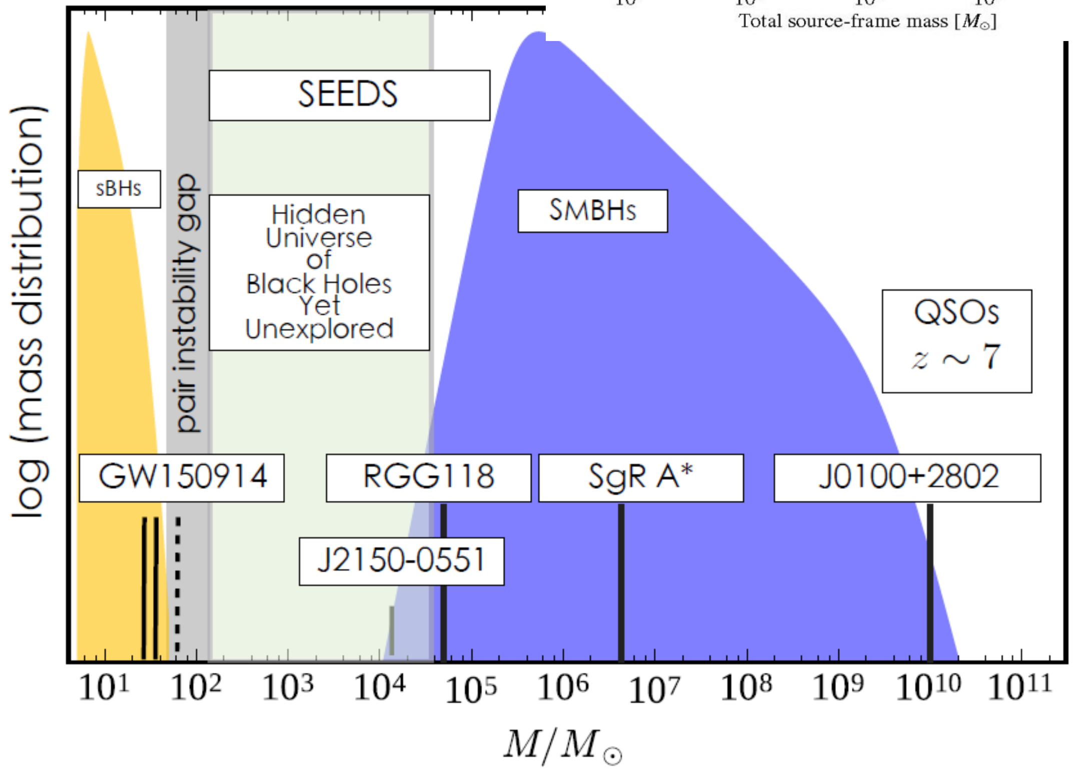
M.Punturo

Seeds and Supermassive Black Holes

- Supermassive Black Holes (SMBHs) are present at the center of many galaxies:
  - What is their history? How they formed? What are the seeds?

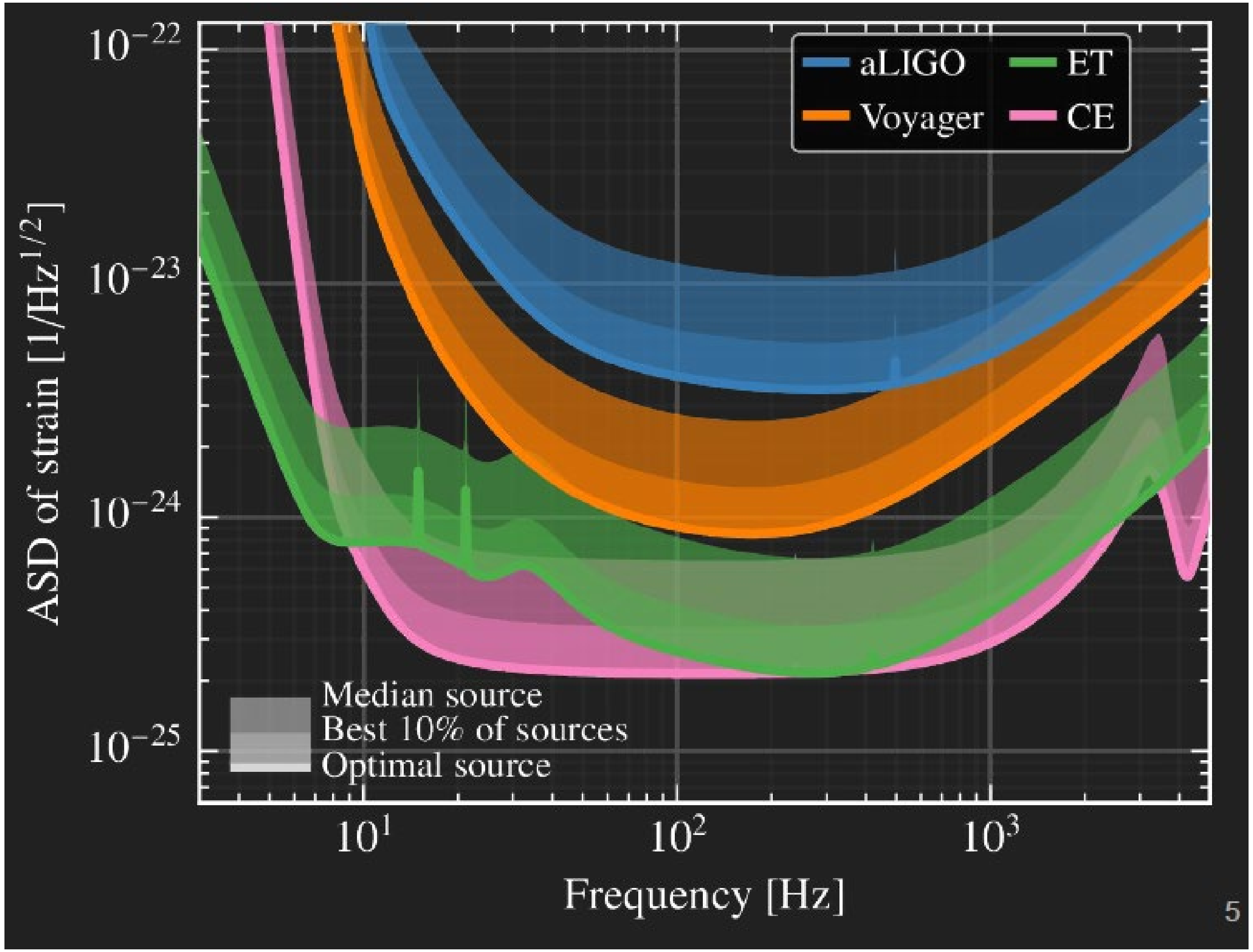


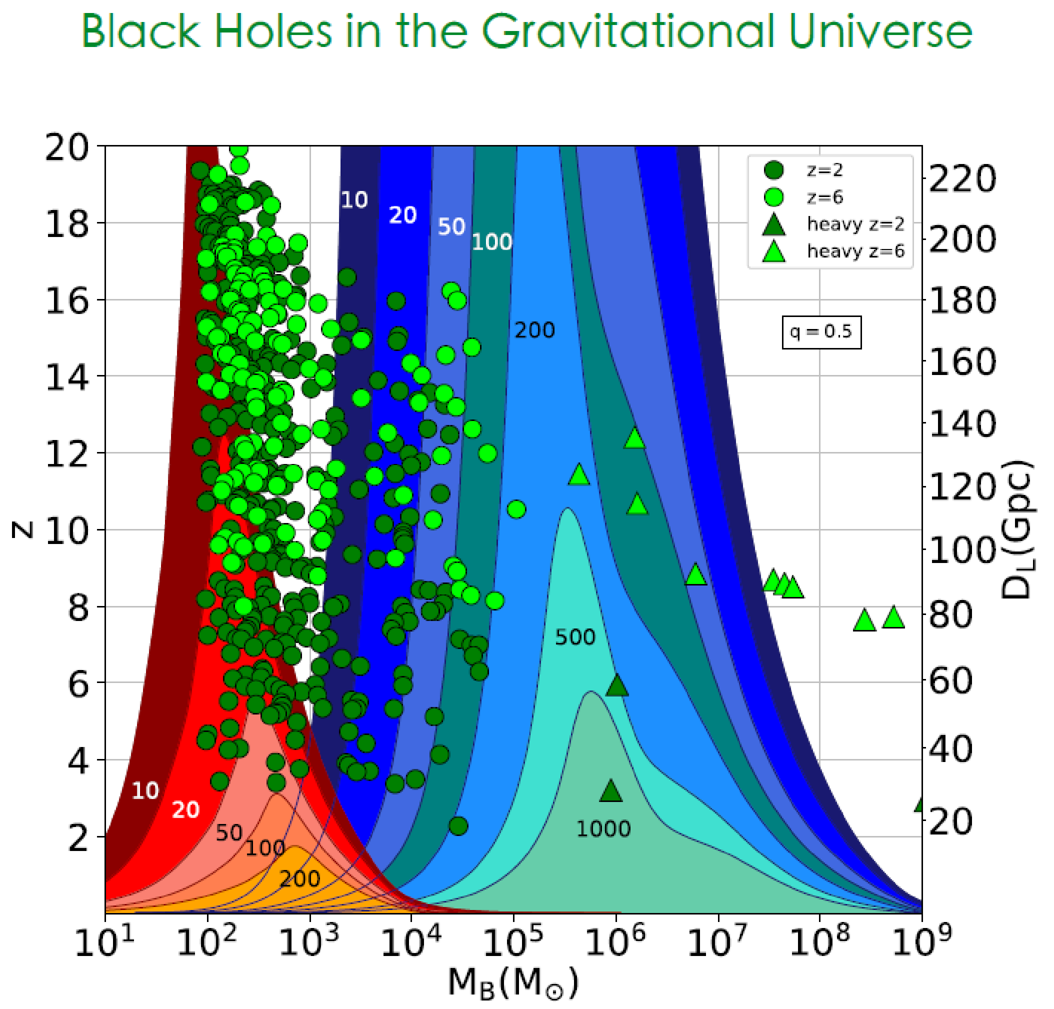




Seeds and Supermassive Black Holes

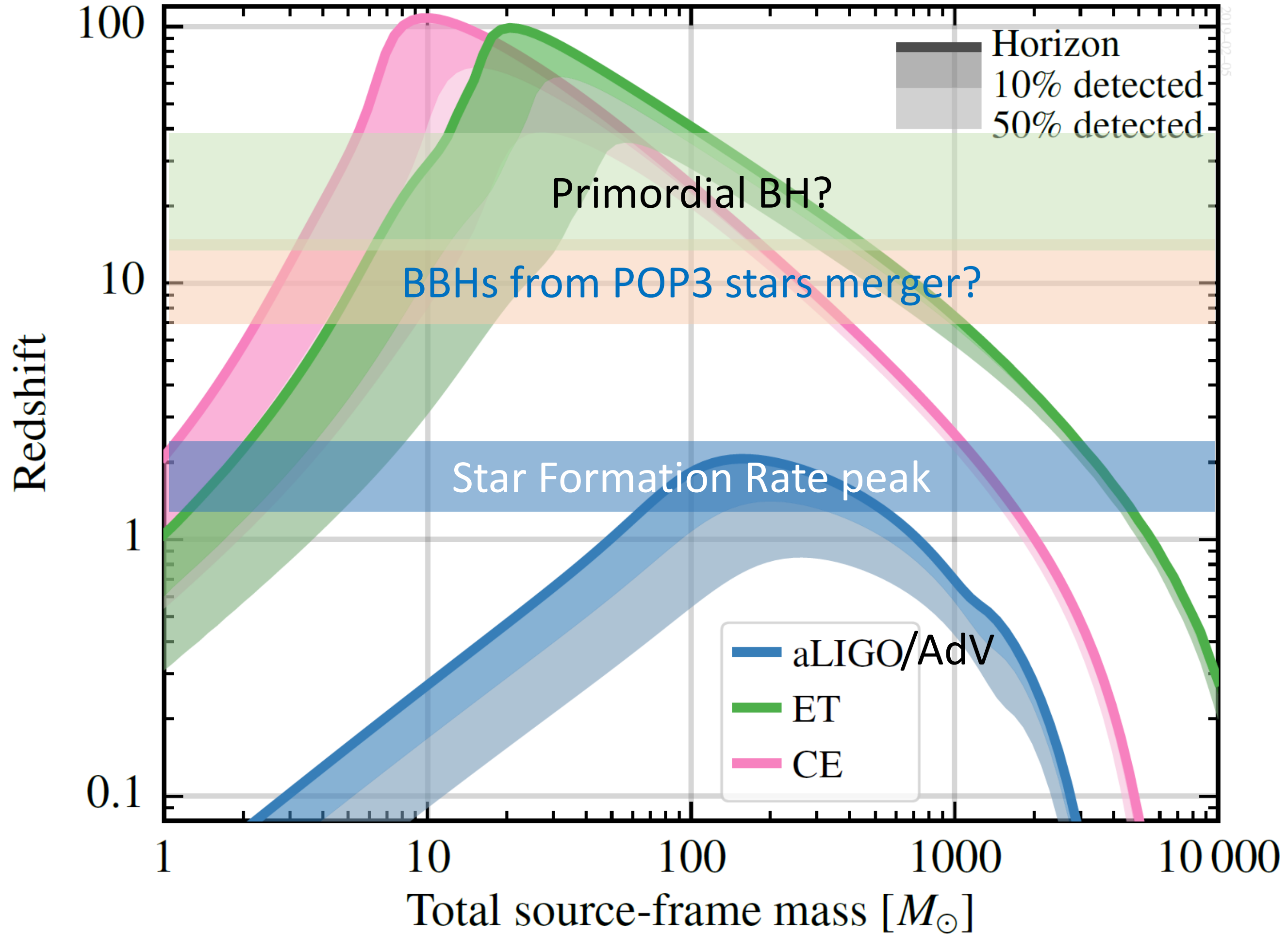
- LISA will detect the coalescences of SMBHs, but what about the seeds?



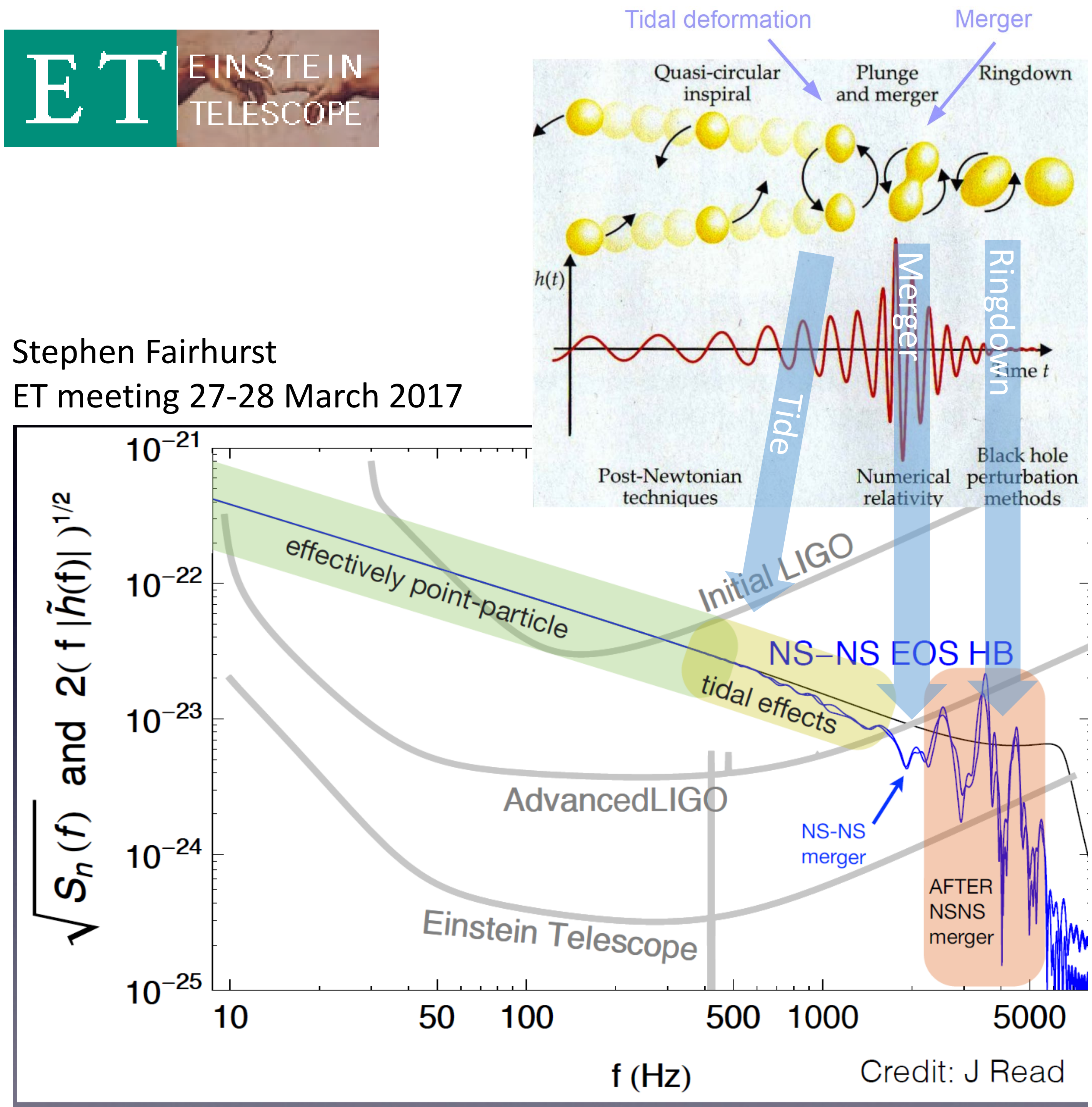


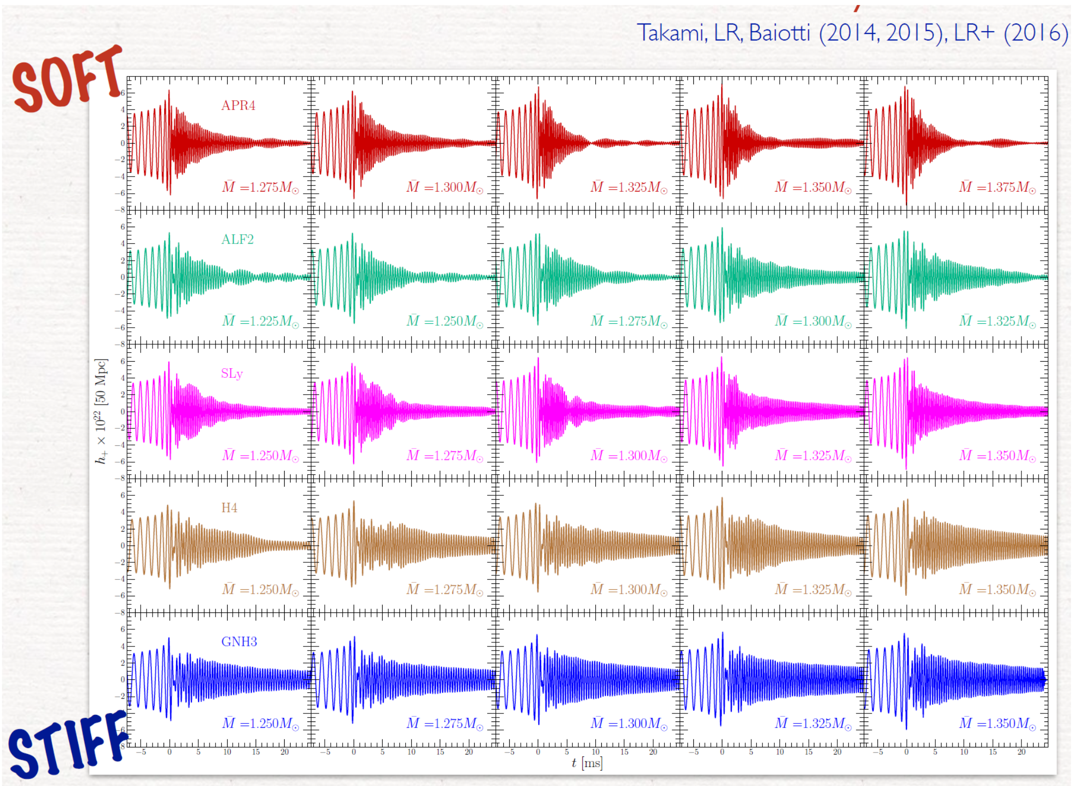
Primordial BHs in ET

- ET will detect BH well beyond the SFR peak $z{\sim}2$
  - comparing the redshift dependence of the BH-BH merger rate with the cosmic star formation rate it will be possible to disentangle the contribution of BHs of stellar origin from that of possible BHs of primordial origin (whose merger rate is not expected to be correlated with the star formation density)
  - The huge number of detections in ET will allow to perform cross-correlations between the detected GW events and large-scale structures, providing another clue to the origin of the observed BHs.
  - Primordial BHs of mass around a solar mass could have formed at the QCD quark-hadron transition via gravitational collapse of large curvature fluctuations generated during the last stages of inflation.
    - This could explain not only the present abundance of dark matter but also the baryon asymmetry of the universe.



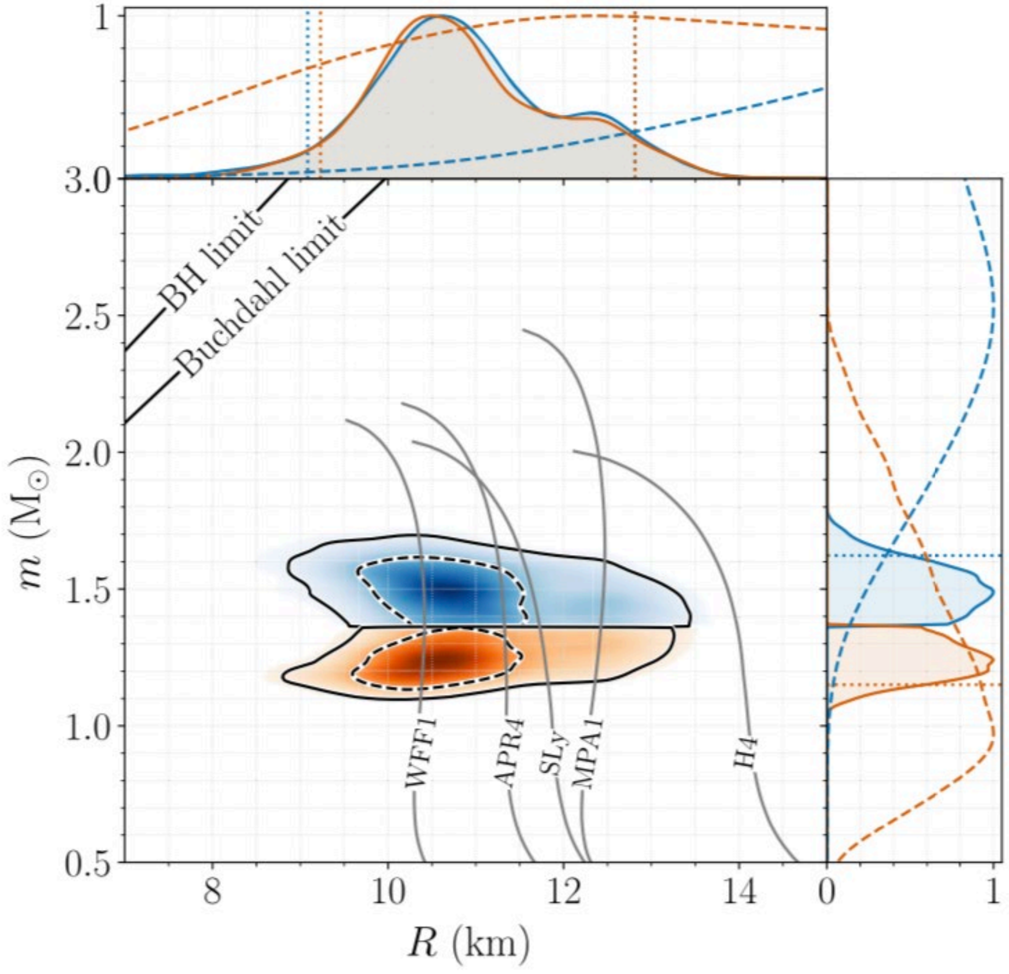
Structure of a Neutron Star



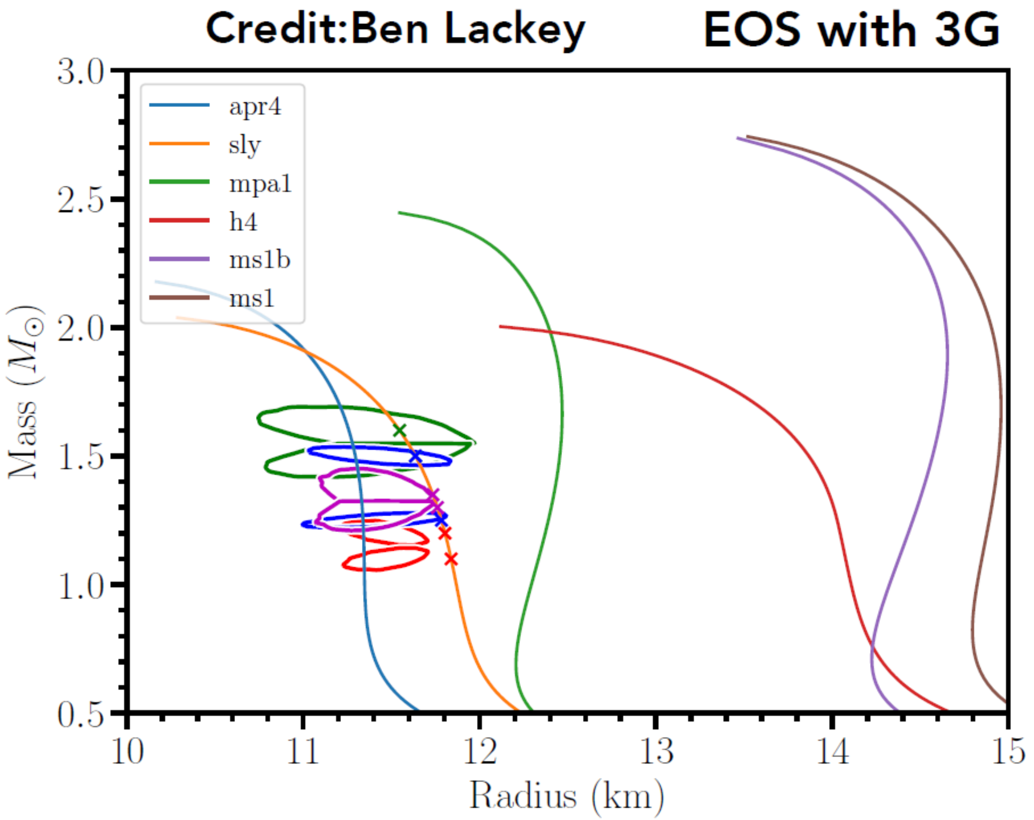


Constraining the EOS of the NS

LIGO/Virgo GW170817



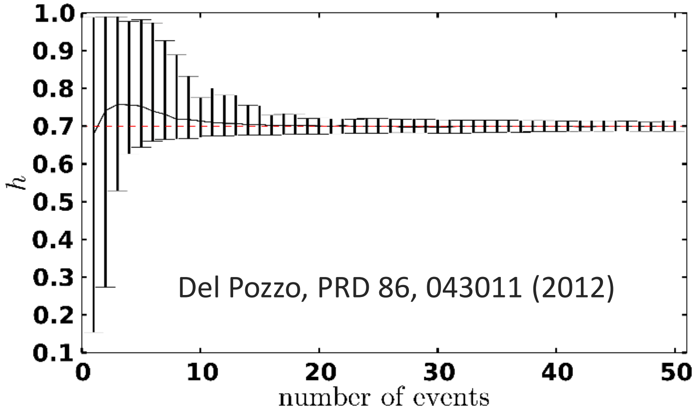
3G-ET

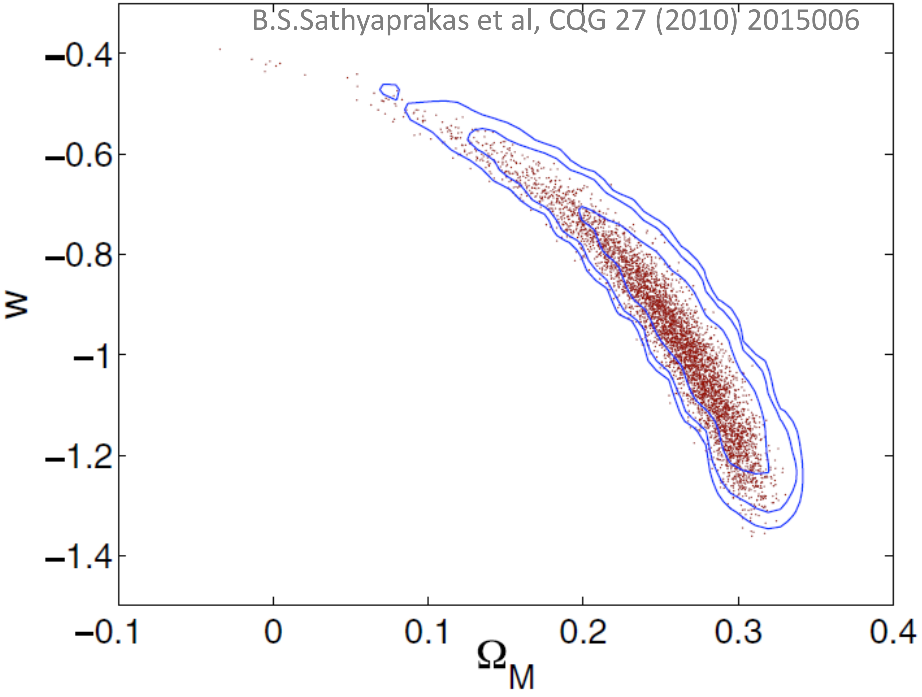


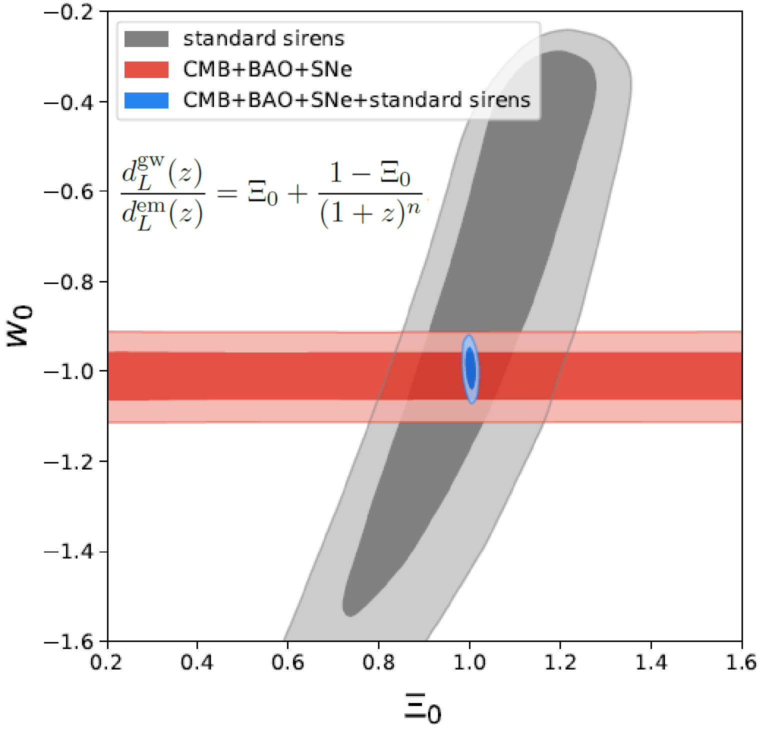
3G detectors promise to constrain the radius of NS below 100m

Cosmology with ET

- ET will reveal 10^5-10^6 BBH/BNS coalescences per year
- A fraction (about 10^3/year?) of the BNS will have a electromagnetic counterpart (thanks also to new telescopes like THESEUS, E-ELT, …





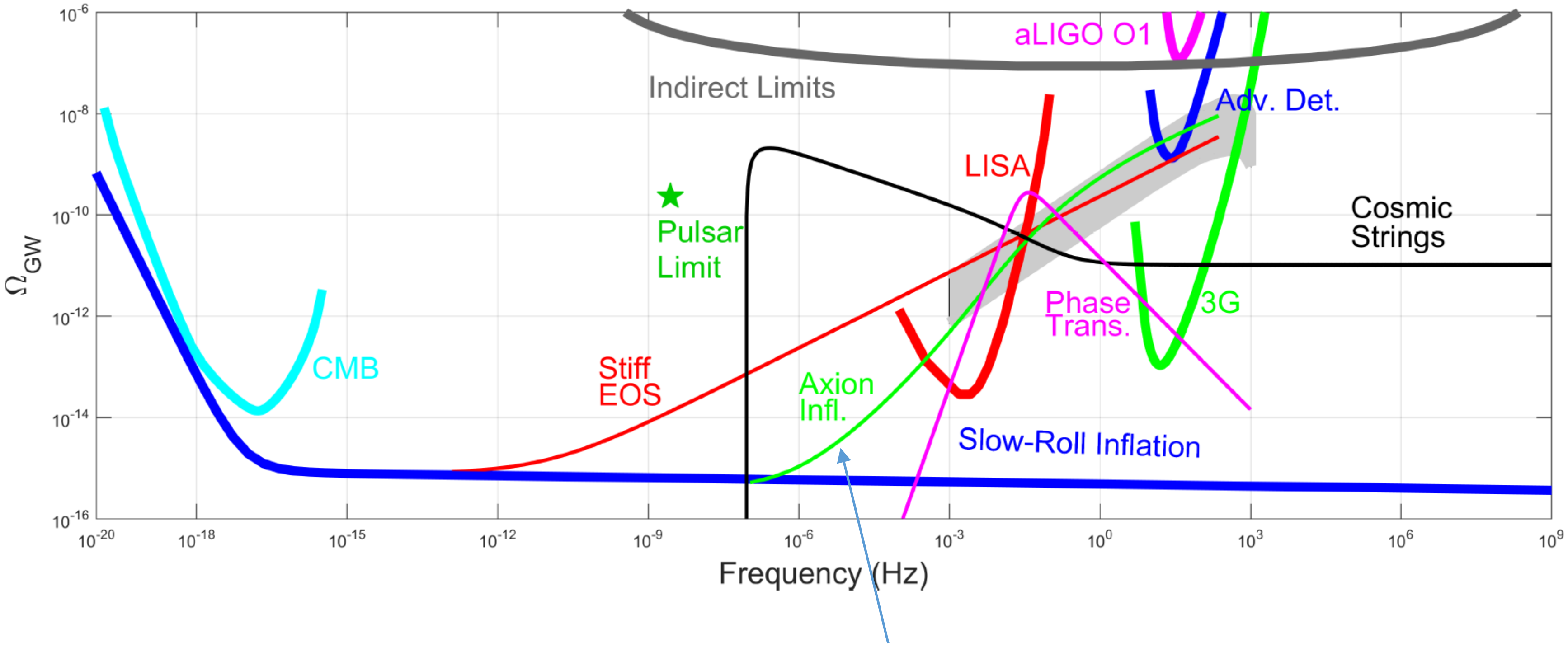


$$D_L(z) = \frac{c(1+z)}{H_0}\int_0^z \frac{dz}{[\Omega_M(1+z)^3 + \Omega_\Lambda(1+z)^{3(1+w)}]^{1/2}}$$

Investigating the DE sector in modified theories of gravity

GW Stochastic Background and inflation

- Inflation, reheating, preheating models could be distinguishible in the GW stochastich background in case of some blue-shift mechanism
  - information on: new additional degrees of freedom, interactions and/or new symmetry patterns underlying high energy physics of early universe

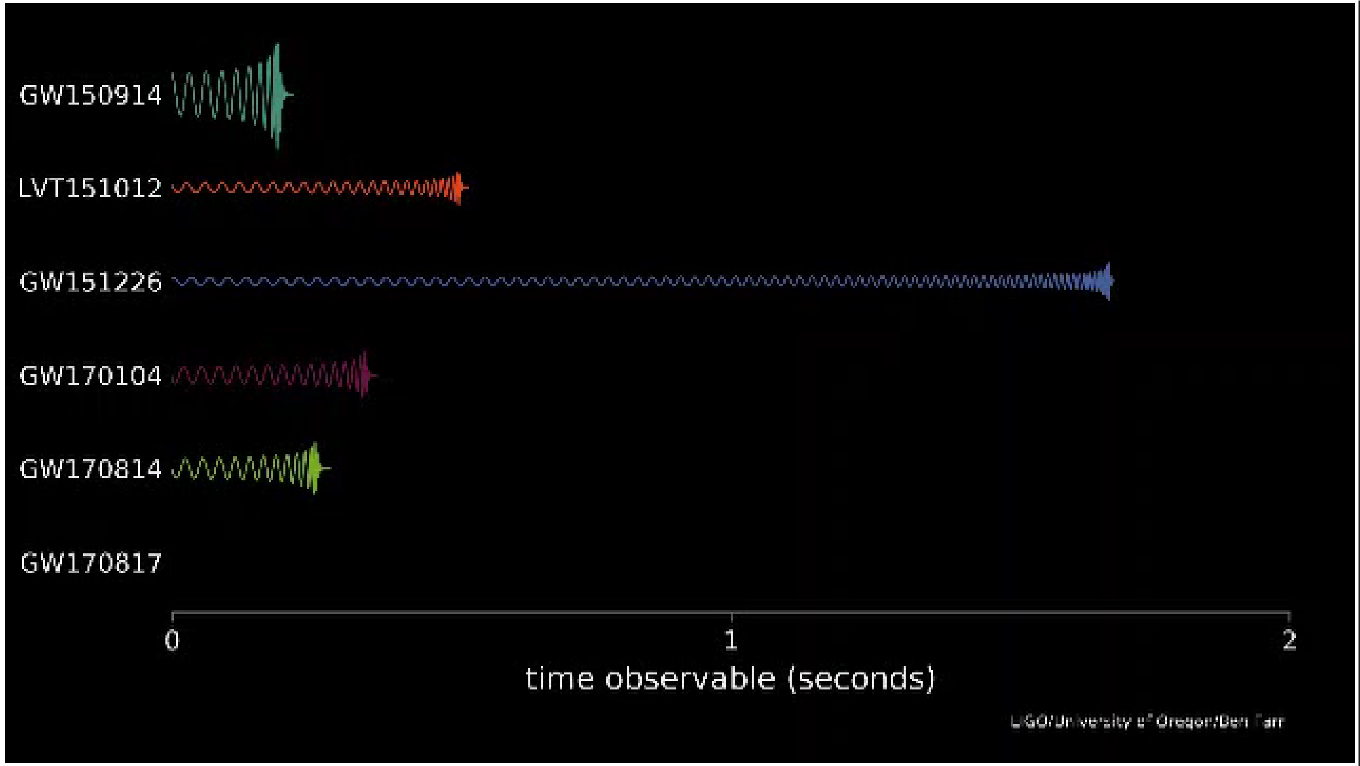


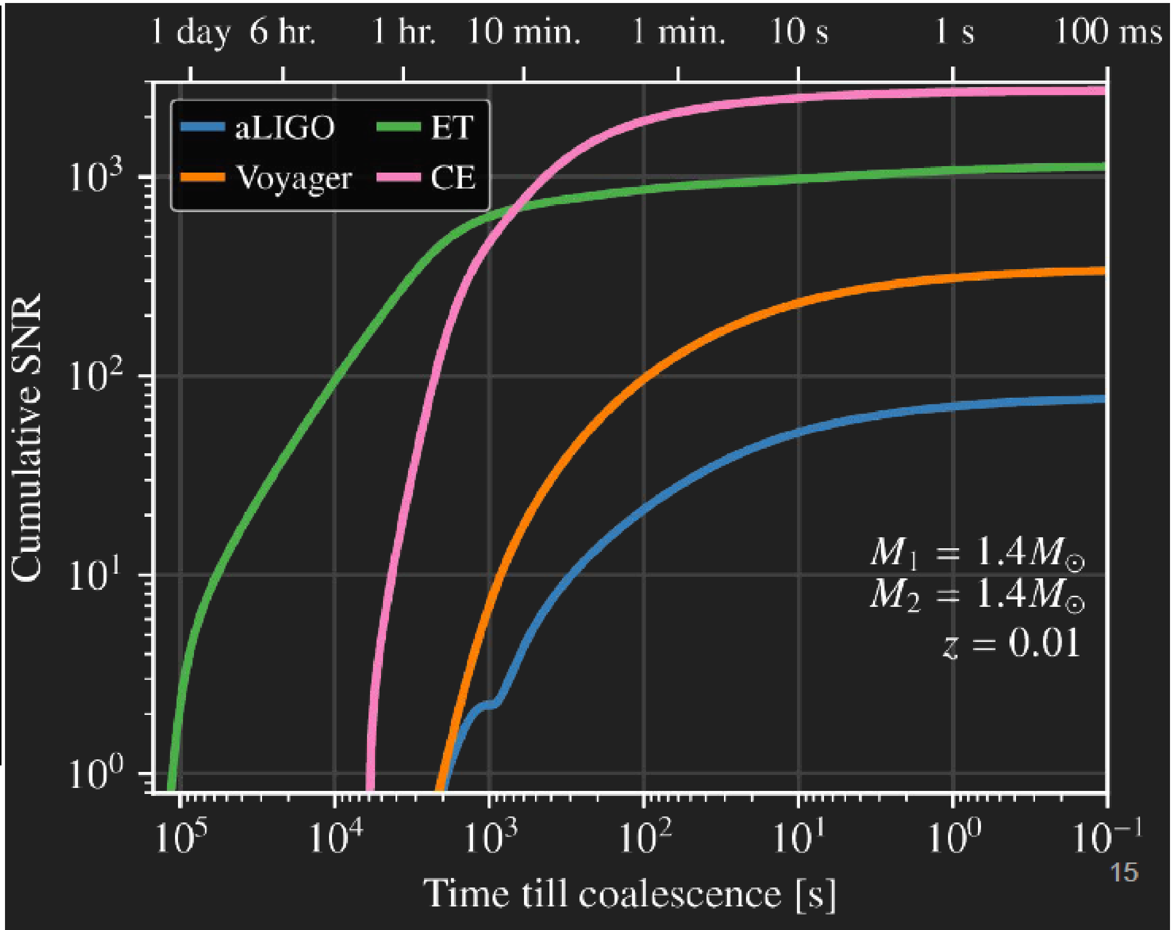
Abbot, B.P. et al, Phys Rev Lett 118 (12), 2017, 121101

Axion inflation
(see for example V. Domcke arXiv:1704.03464)

Low frequency: Multi-messenger astronomy

- If we are able cumulate enough SNR before the merging phase, we can trigger e.m. observations before the emission of photons
- Keyword: low frequency sensitivity:





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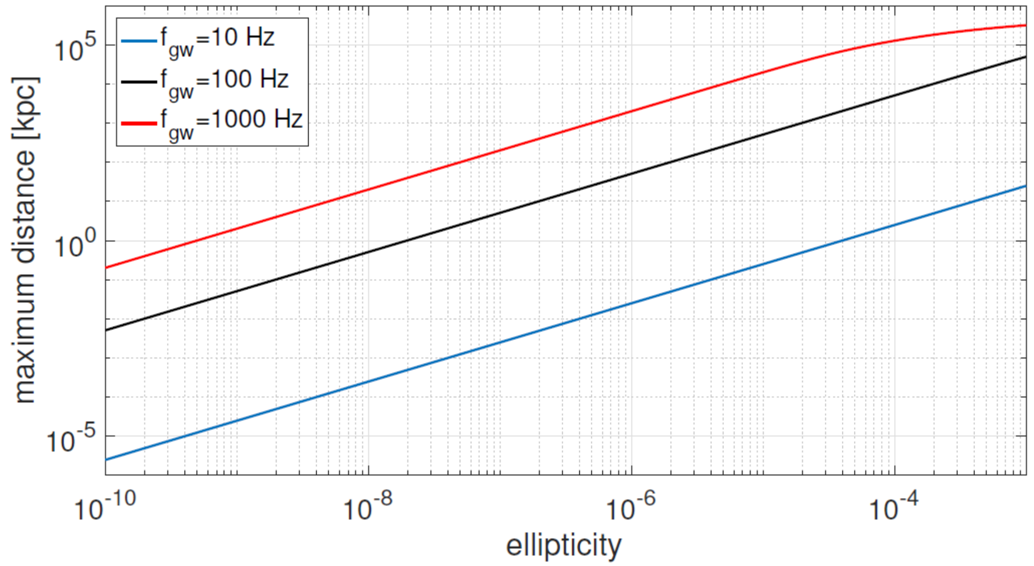
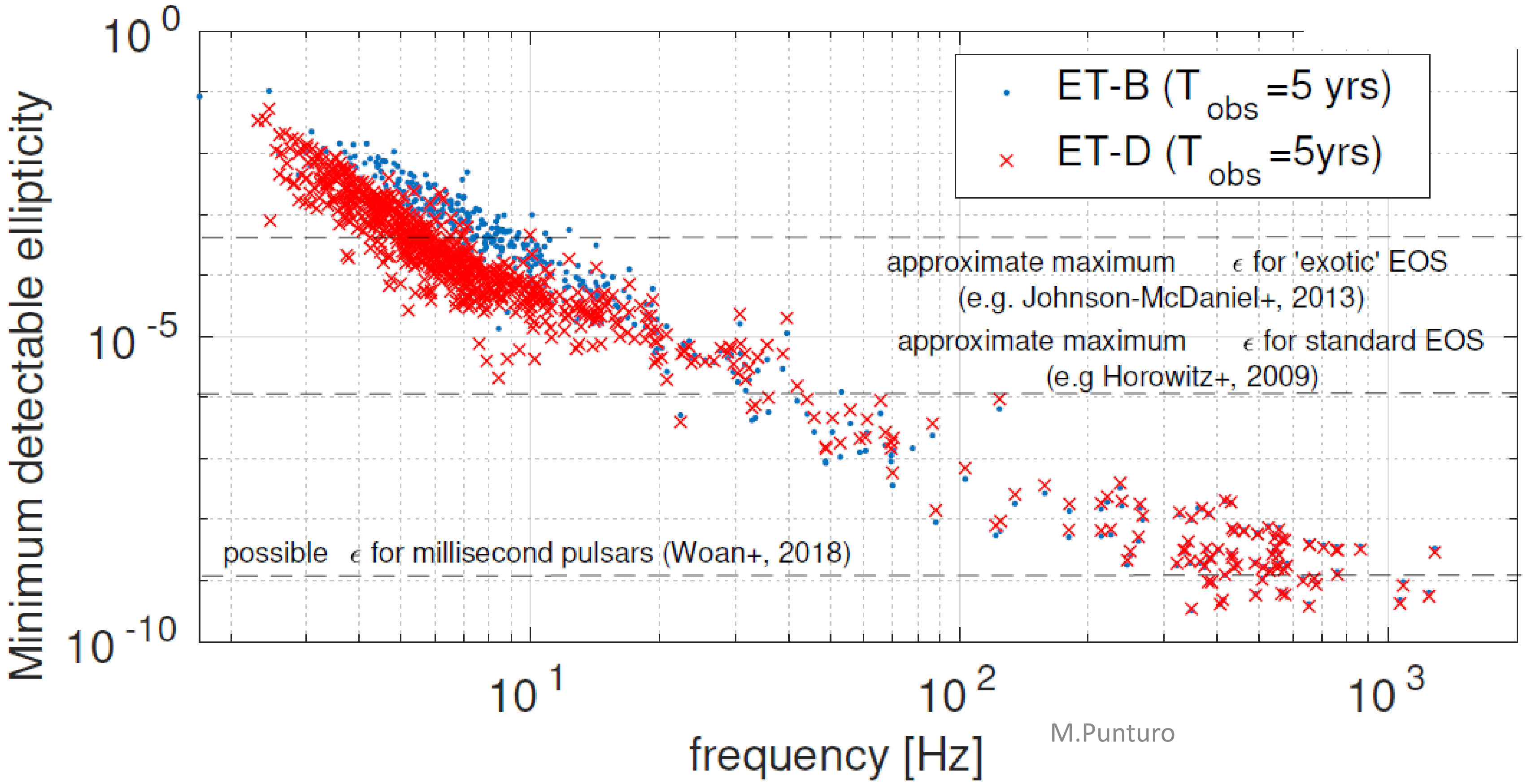
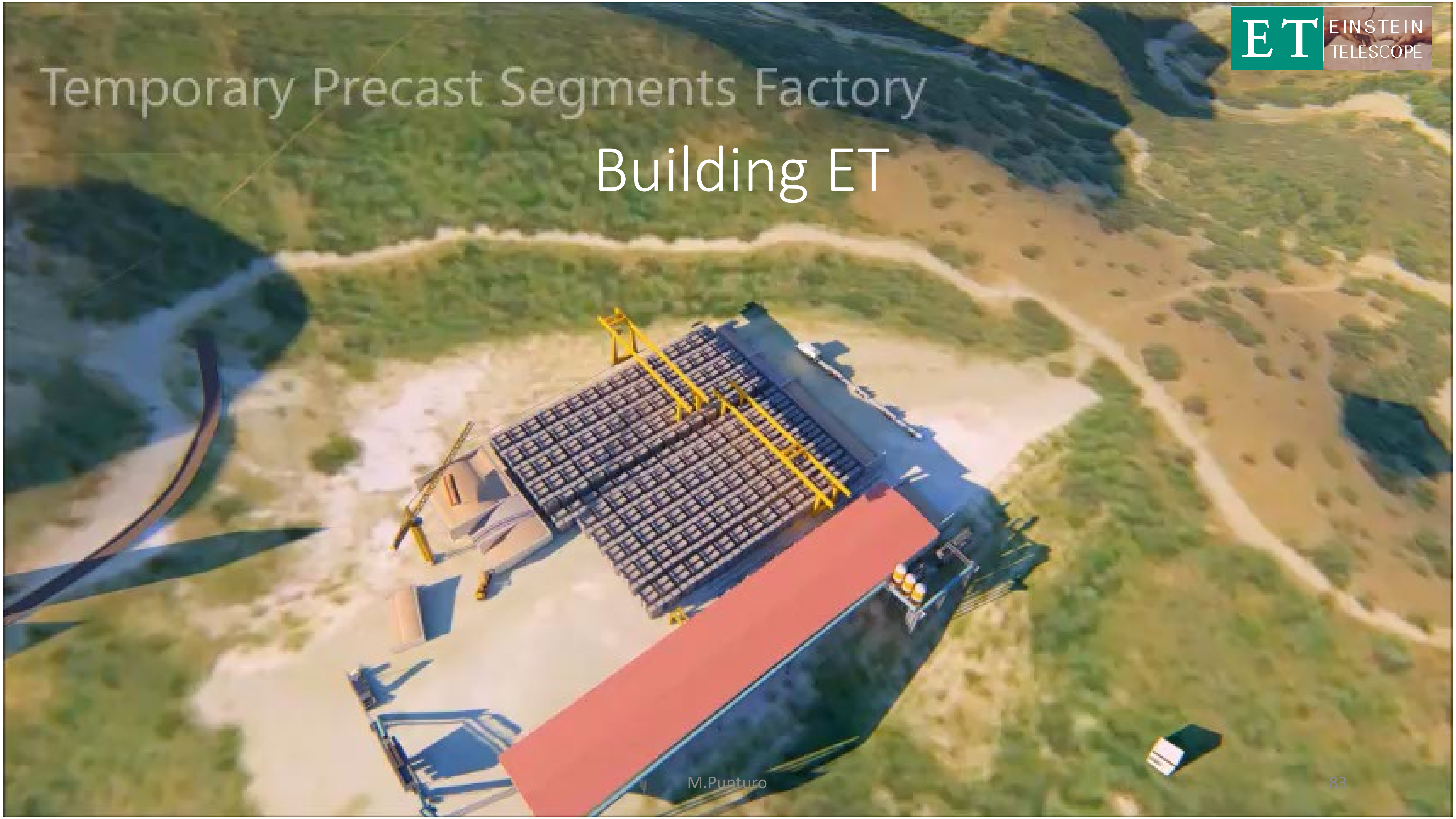
Isolated NS (pulsars)

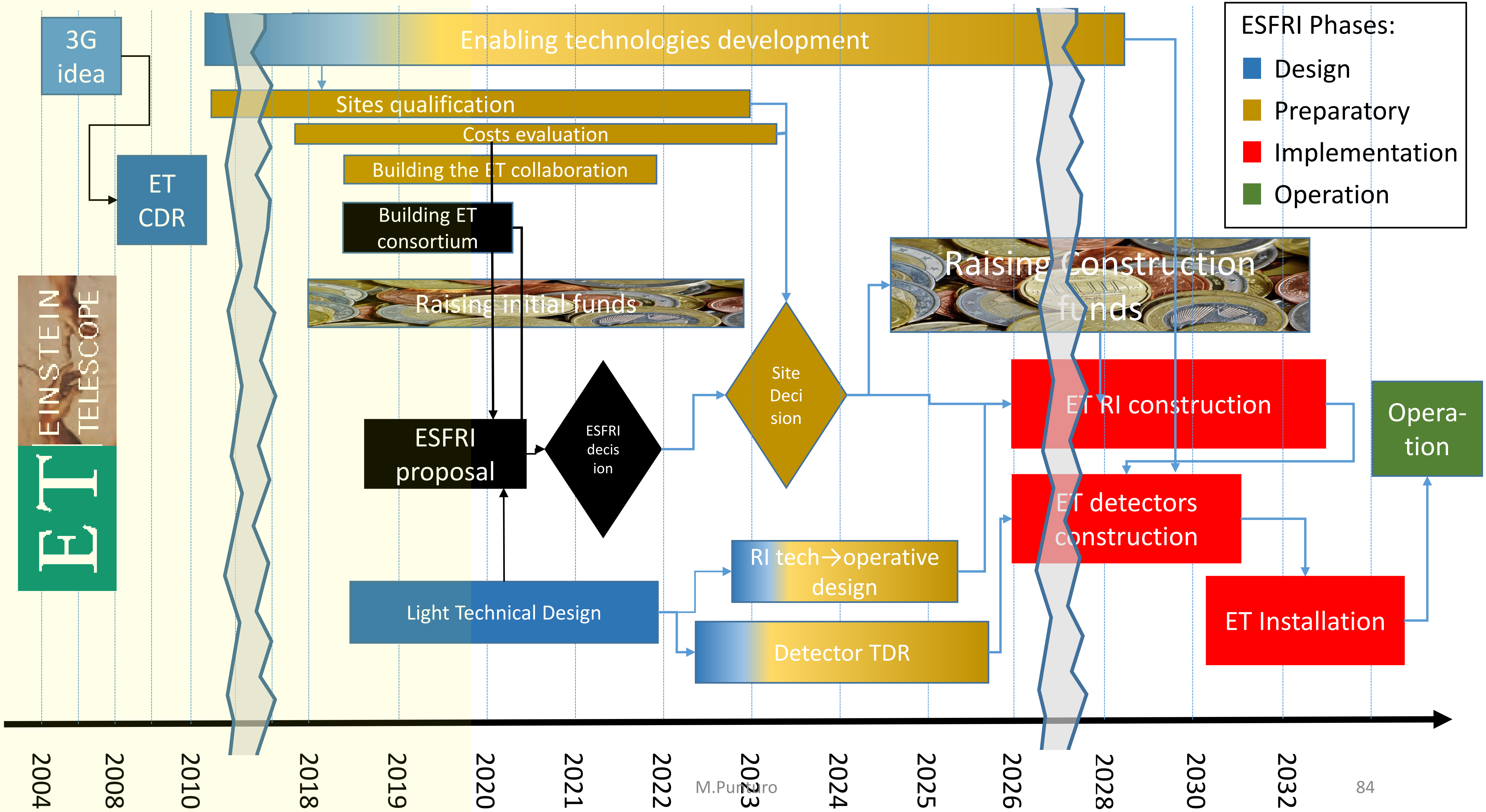




$\epsilon = 10^{-7}$ corresponds to a “mountain” of 1 mm on the NS surface

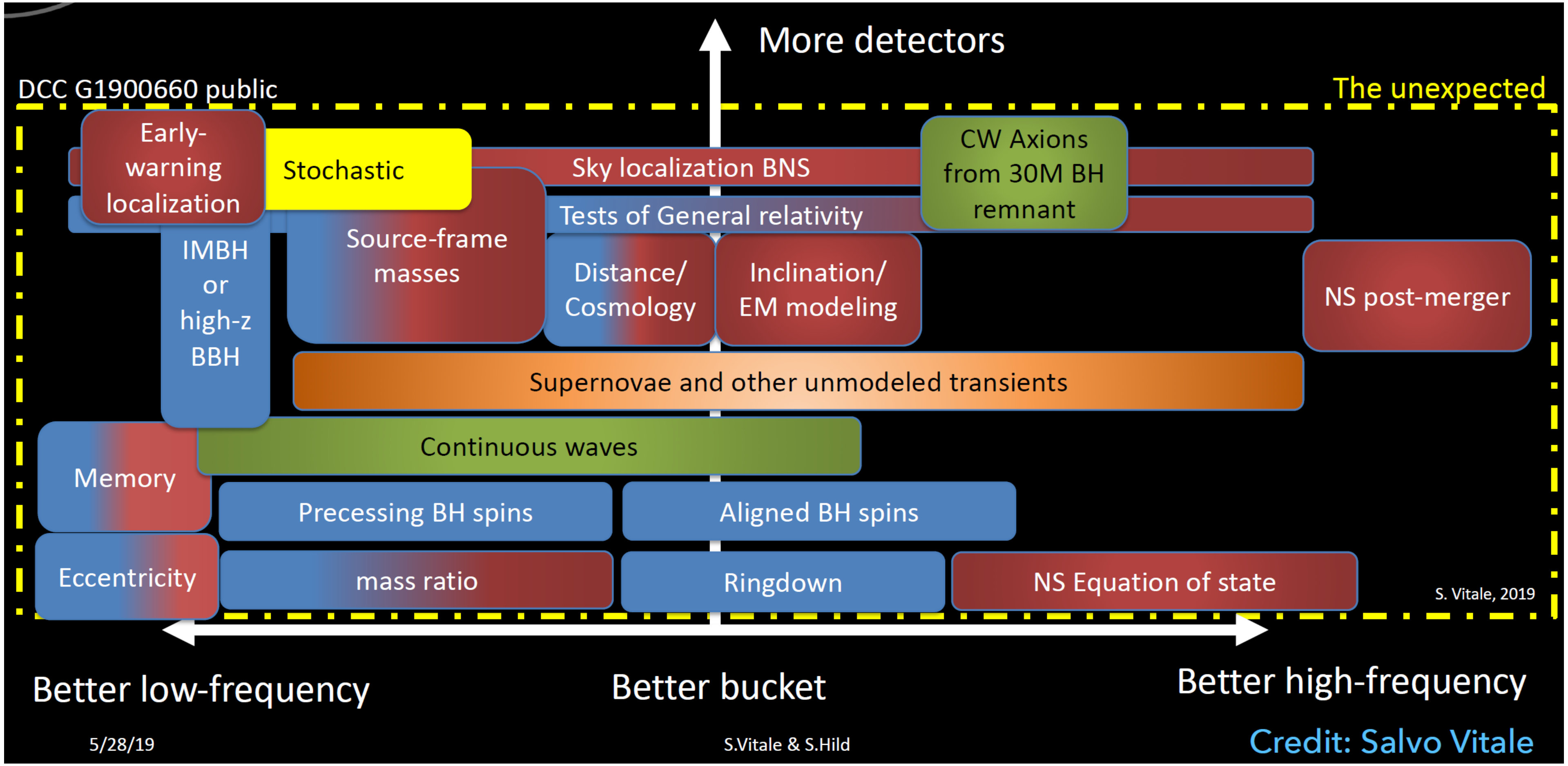
Building ET




ESFRI Phases:
Design
Preparatory
Implementation
Operation
3G idea
ET CDR
EINSTEIN TELESCOPE
ET
Enabling technologies development
Sites qualification
Costs evaluation
Building the ET collaboration
Building ET consortium
Raising initial funds
ESFRI proposal
ESFRI decis ion
Site Deci sion
Raising Construction funds
ET RI construction
ET detectors construction
Opera-tion
ET Installation
RI tech→operative design
Detector TDR
Light Technical Design
2004
2008
2010
2018
2019
2020
2021
2022
2023
2024
2025
2026
2028
2030
2032

Wideband or Narrow band?

- The design of the ET observatory is driven by the physics objectives
  - At what frequency are they?

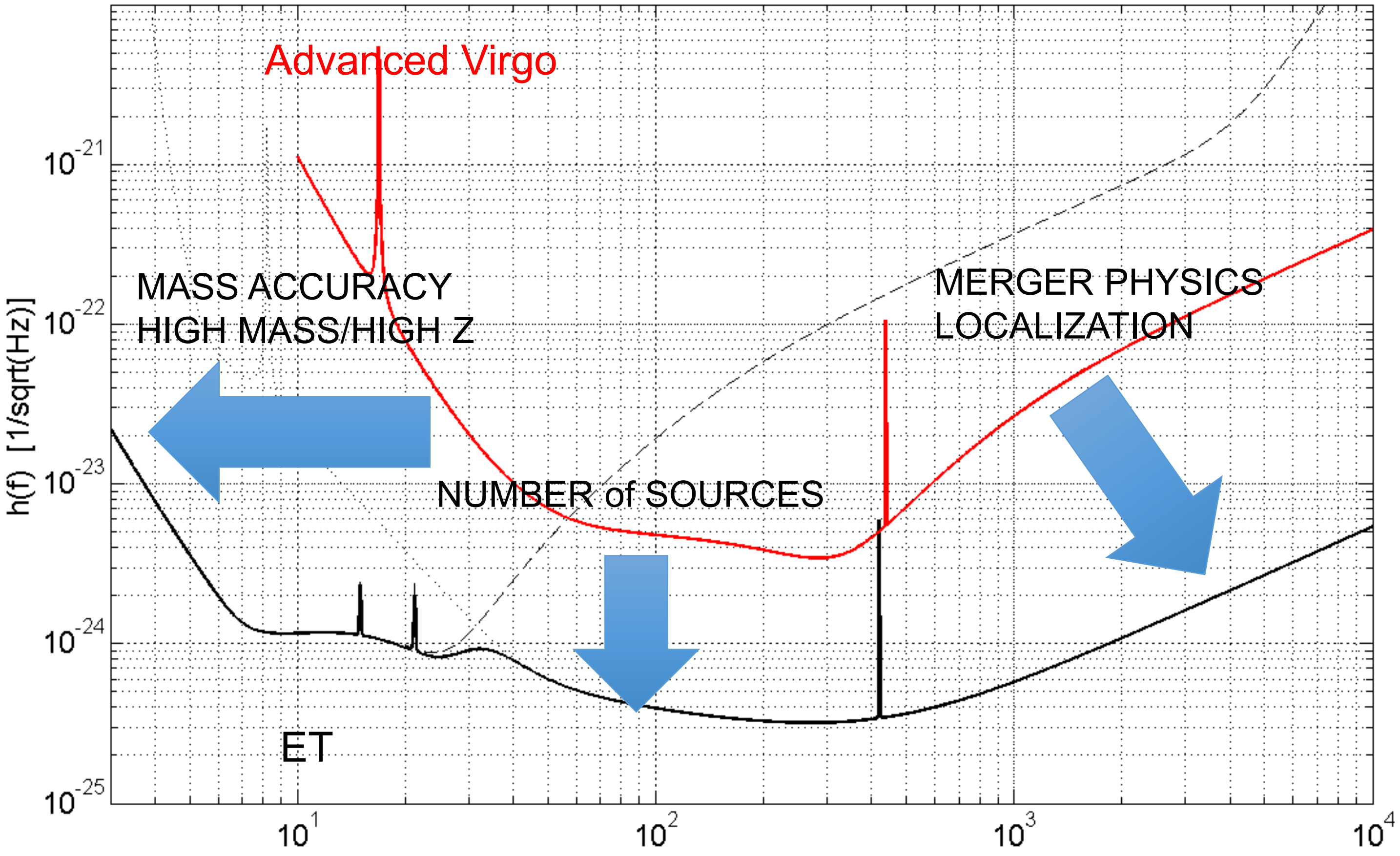


Everywhere!

We need a wide band observatory (with special attention to low frequency)

From 2G to 3G

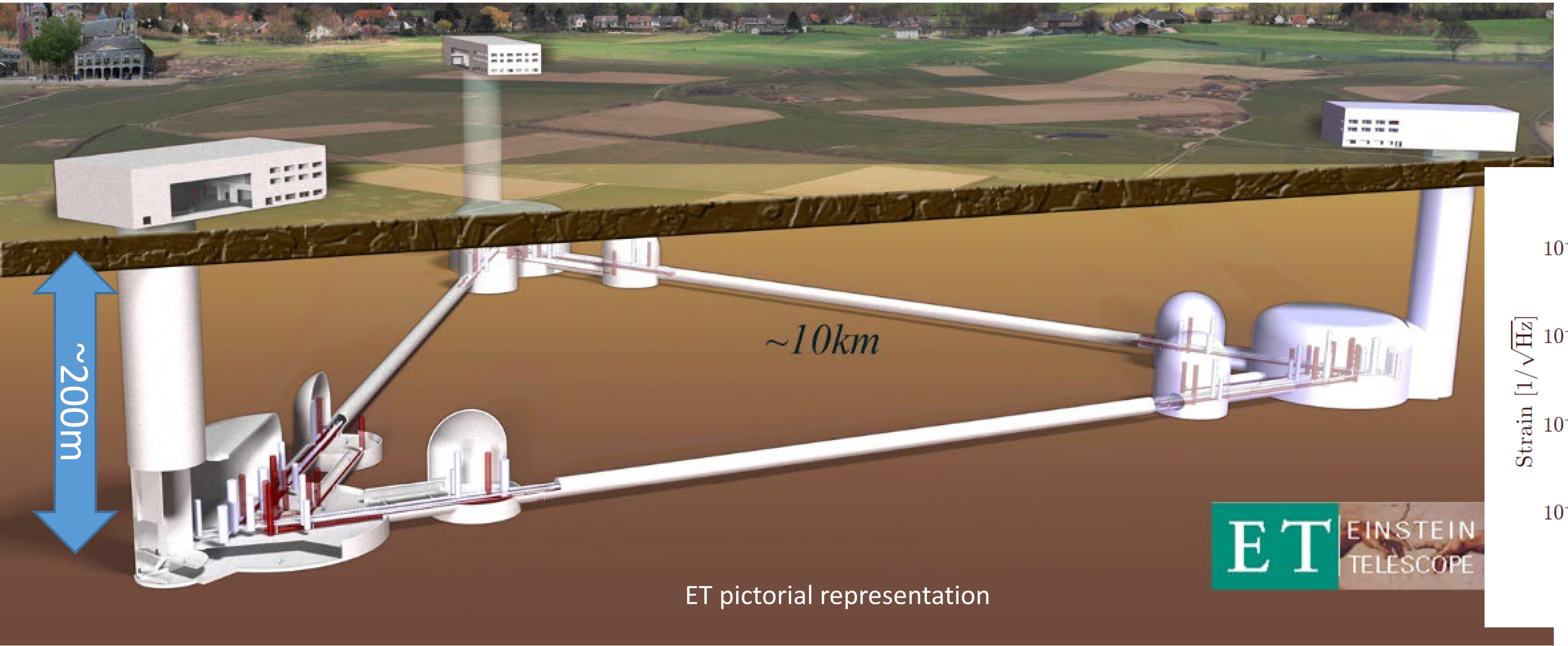
- To achieve the expected targets of physics, ET must gain about an order of magnitude of frequency wrt the 2G detectors



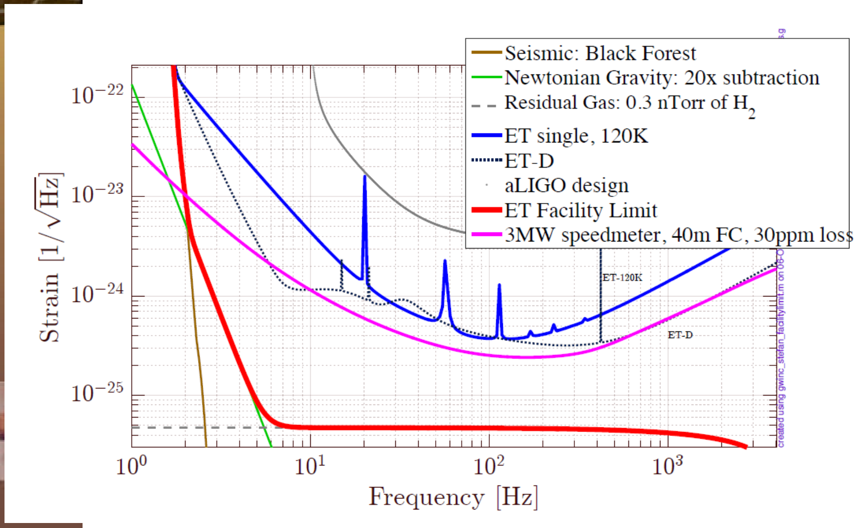
- This is obtaining mixing up 3 ingredients:
  - Infrastructure
  - Detector design
  - Technology

The ET underground infrastructure

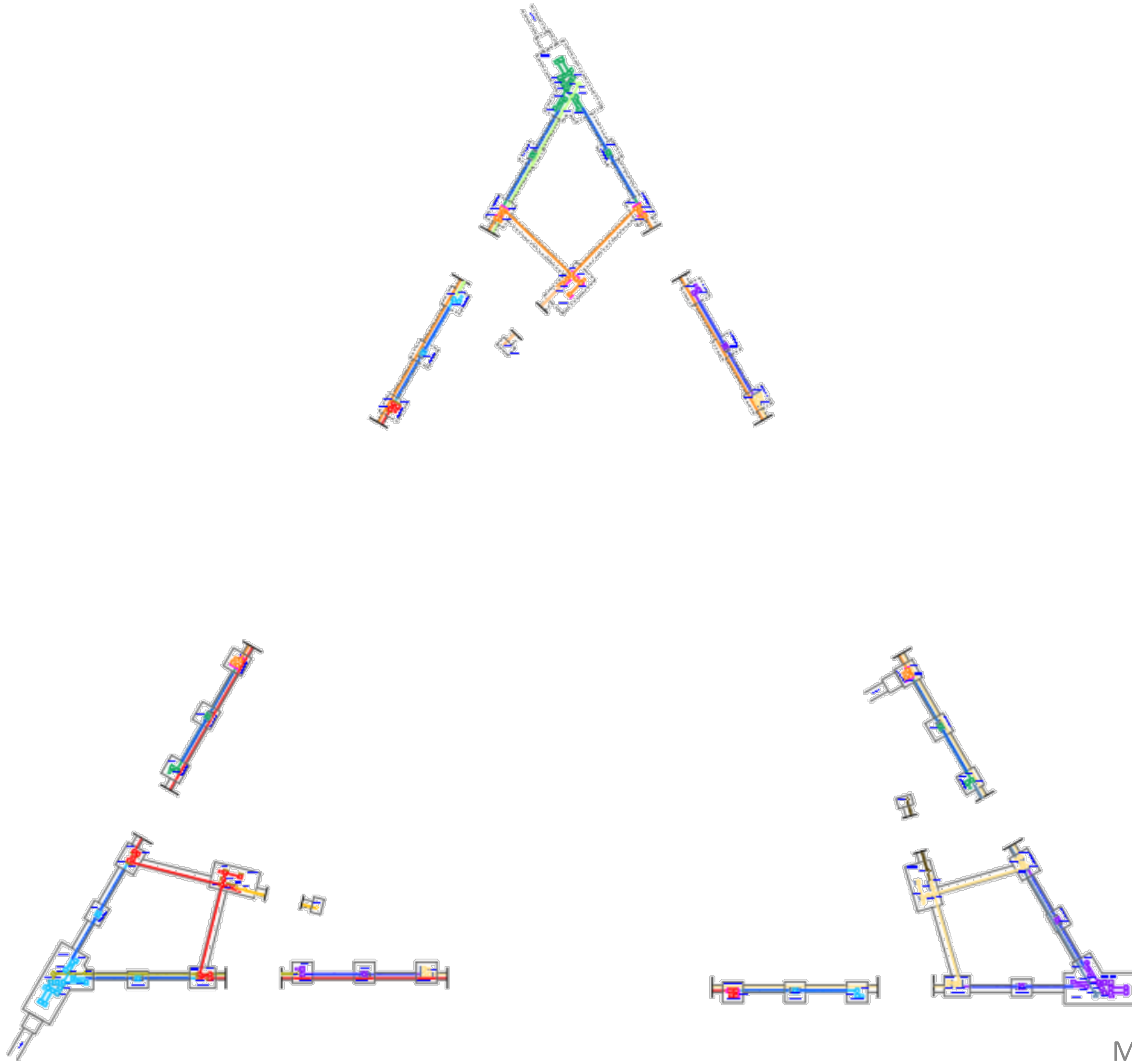
- GW detectors sensitivity scales linearly with the length of the arms:
  - From 3km of AdV to 10km of ET
- To reduce the impact of the environmental disturbances (seismic, acustic, electromagnetic) the ET infrastructure is located underground



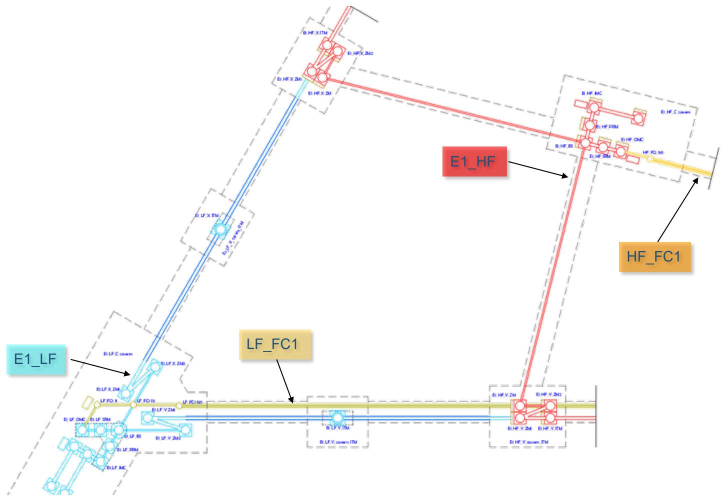
ET pictorial representation



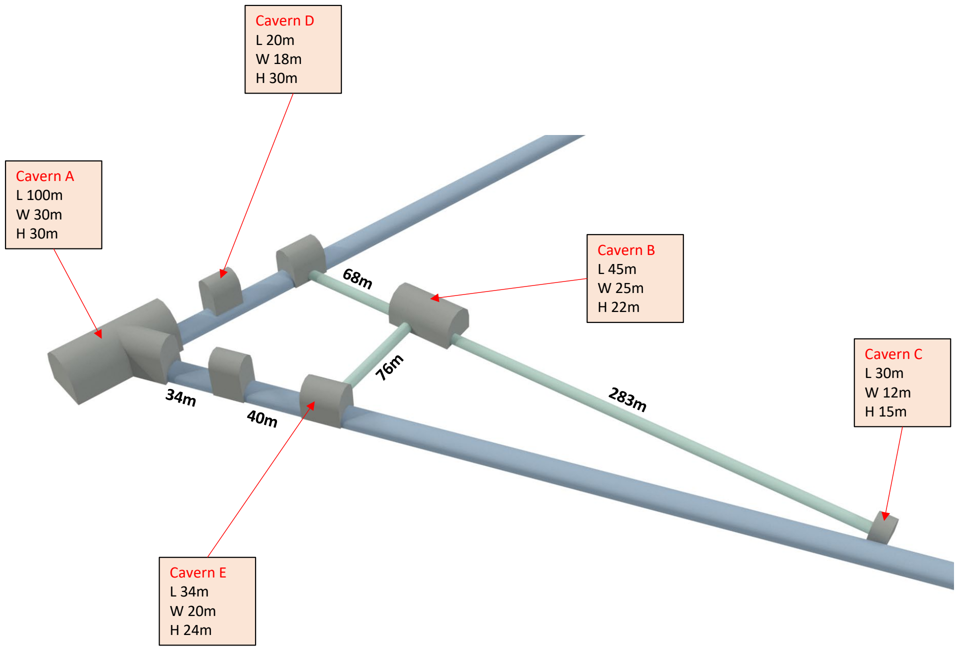
2D design of the infrastructure



2D scheme – Detail – Corner A1

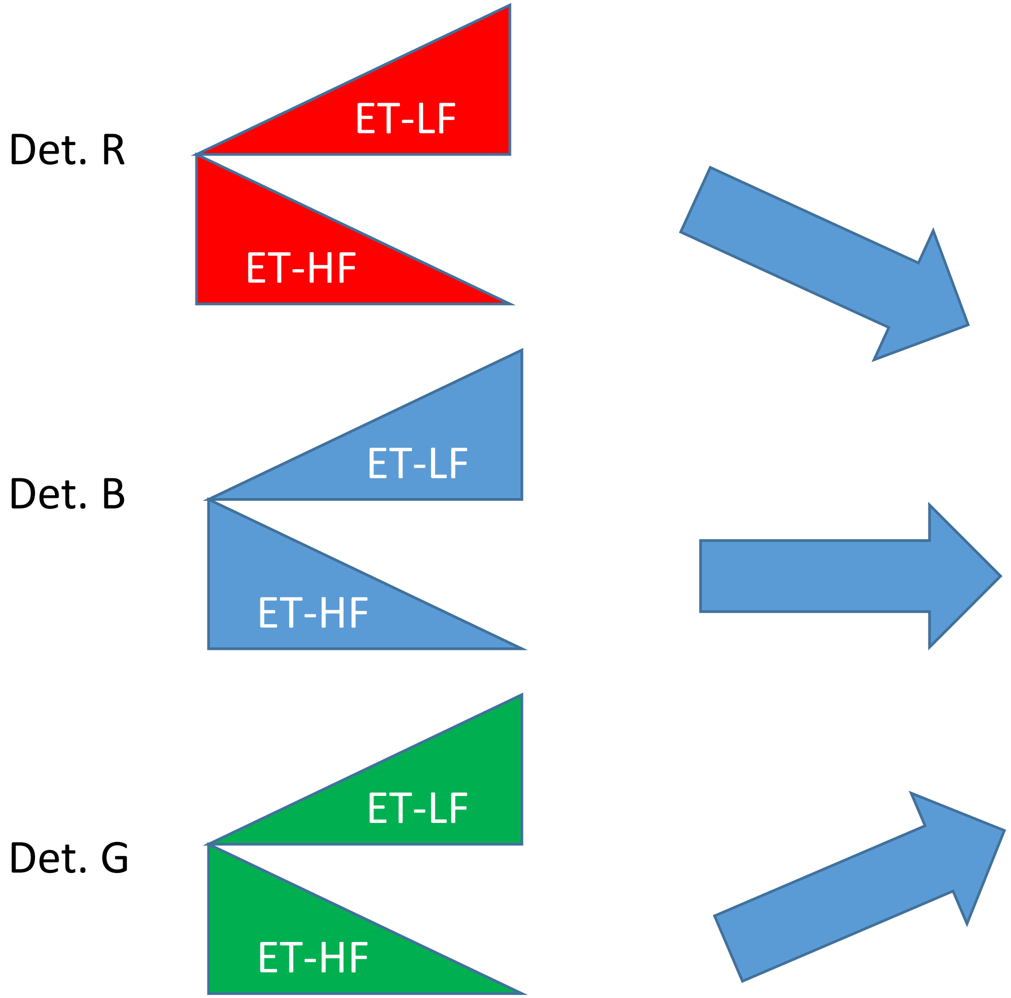


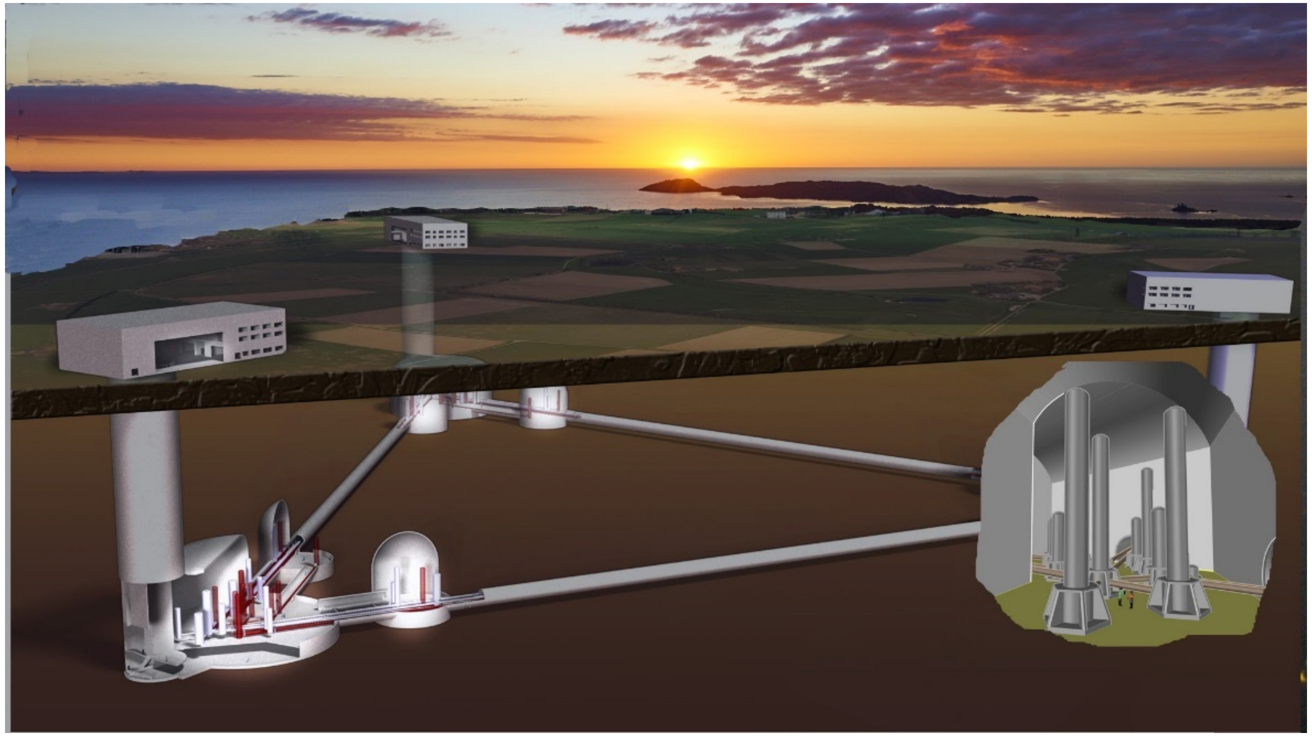
3D sketch - Corner detail 1



Detector Design

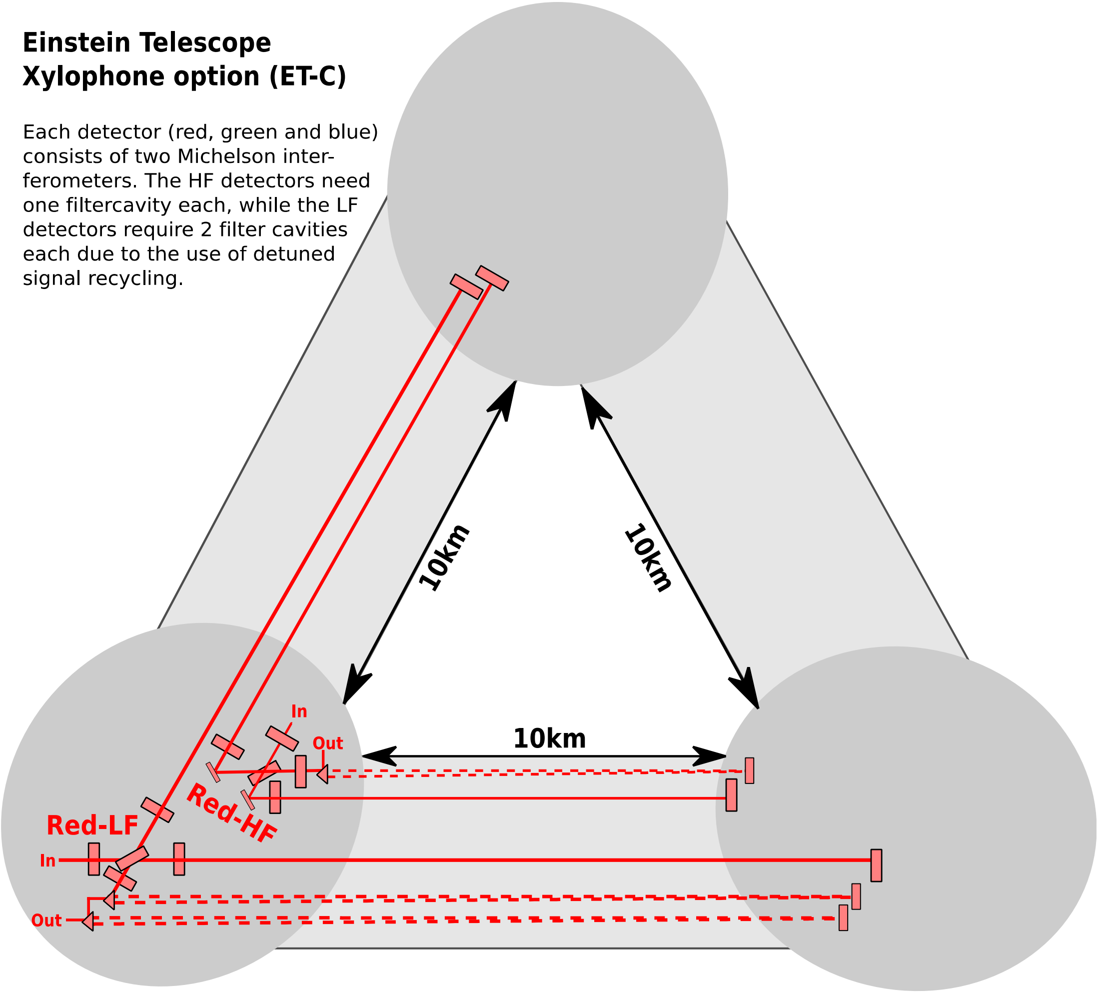
- The second ingredient to gain sensitivity and science potential in ET wrt 2G detectors is the detector design:
- ET is an Observatory
  - The Observatory is composed by 3 detectors
    - Each detector is composed by two interferometers





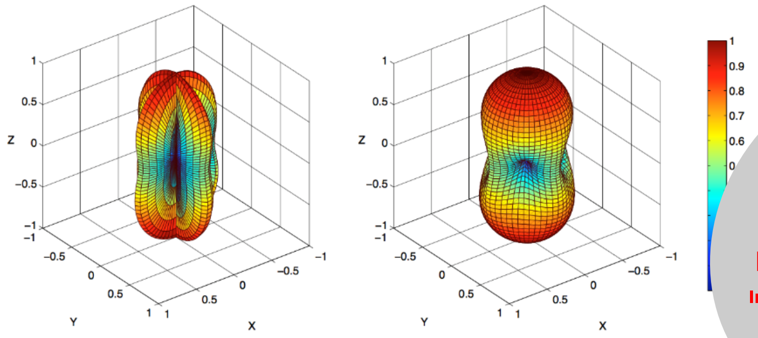
STAND-ALONE OBSERVATORY

- Start with a single (xylophone) detector

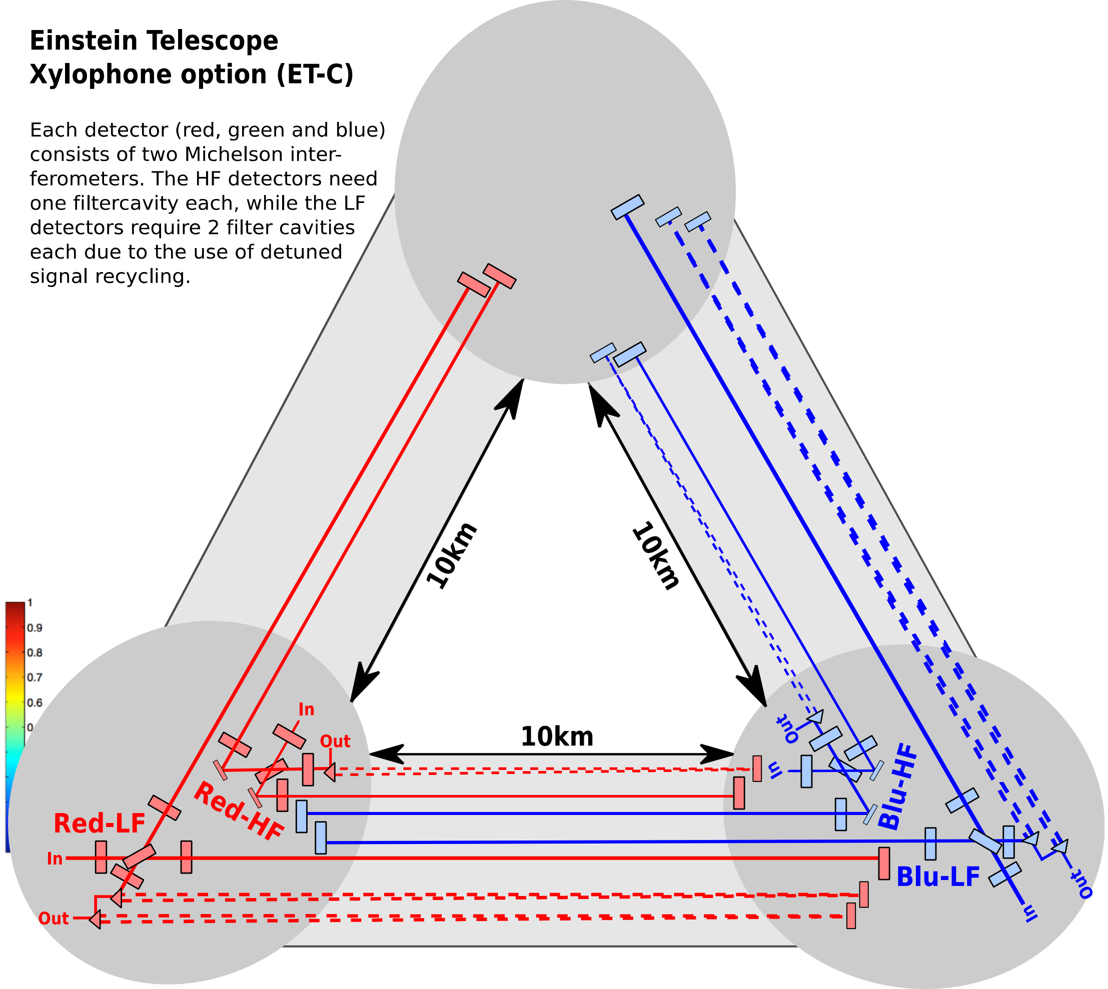


STAND-ALONE OBSERVATORY

- Start with a single (xylophone) detector
- Add a second one to fully resolve polarizations

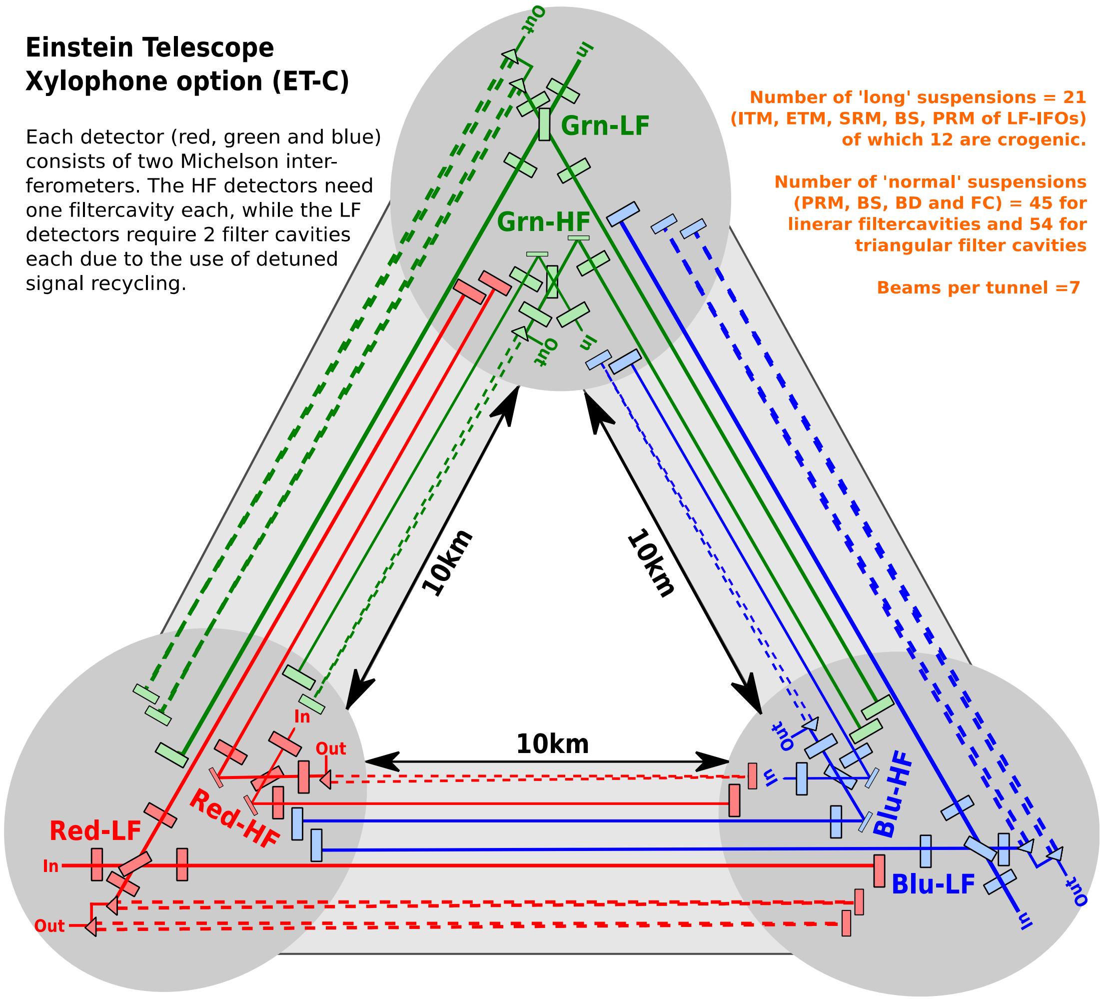


Antenna pattern for a polarized GW: simple "L" (left) vs Triangle (right)



STAND-ALONE OBSERVATORY

- Start with a single (xylophone) detector
- Add a 2nd one to fully resolve polarization
- Add a 3rd one for null stream and redundancy



Enabling Technologies

- The Xylophone approach needs two parallel technology developments:

- ET-LF:
  - Underground
  - Cryogenics
  - Silicon (Sapphire) test masses
  - Large test masses
  - New coatings
  - New laser wavelength
  - Seismic suspensions
  - Frequency dependent squeezing
- ET-HF:
  - High power laser
  - Large test masses
  - New coatings
  - Thermal compensation
  - Frequency dependent squeezing

Challenging engineering

New technology in cryo-cooling

New technology in optics

New laser technology

High precision mechanics

High quality opto-electronics and new controls

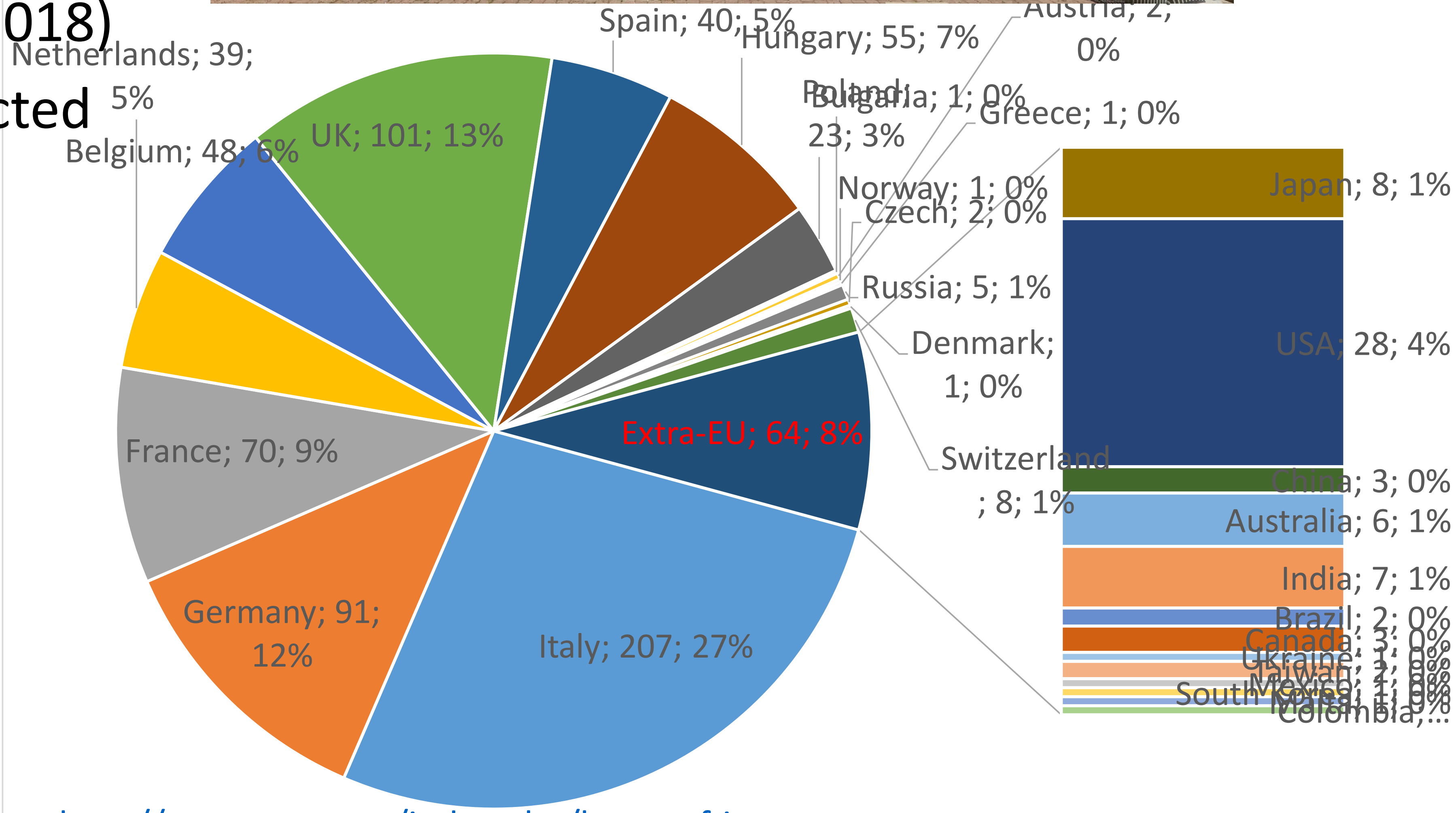
New laser technology

New technology in optics

High quality opto-electronics and new controls

ET collaboration

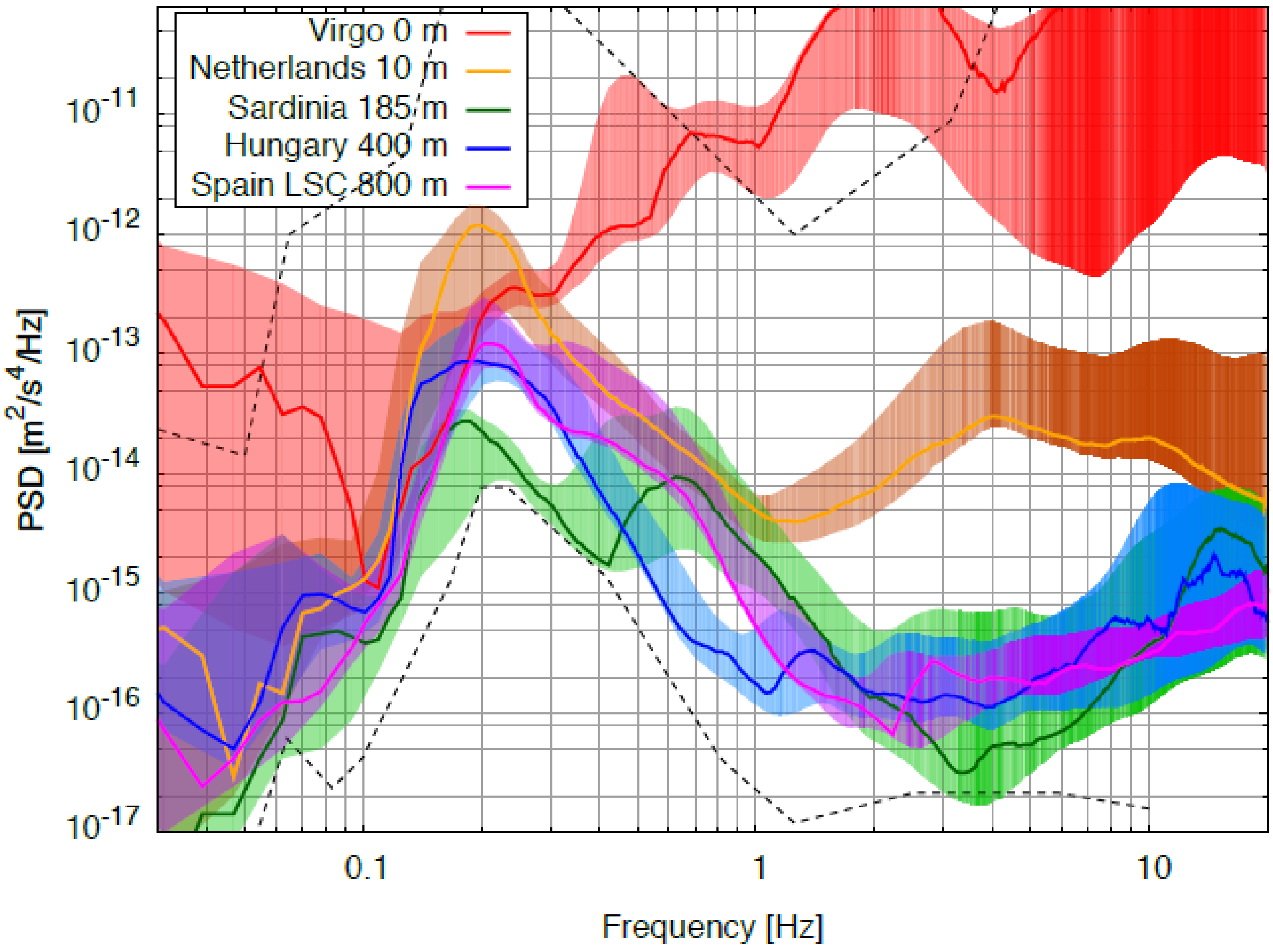
- Launched the ET letter of intent @ the 9th ET symposium (April 2018)
- Currently, we collected 759 signatories



http://www.et-gw.eu/index.php/letter-of-intent

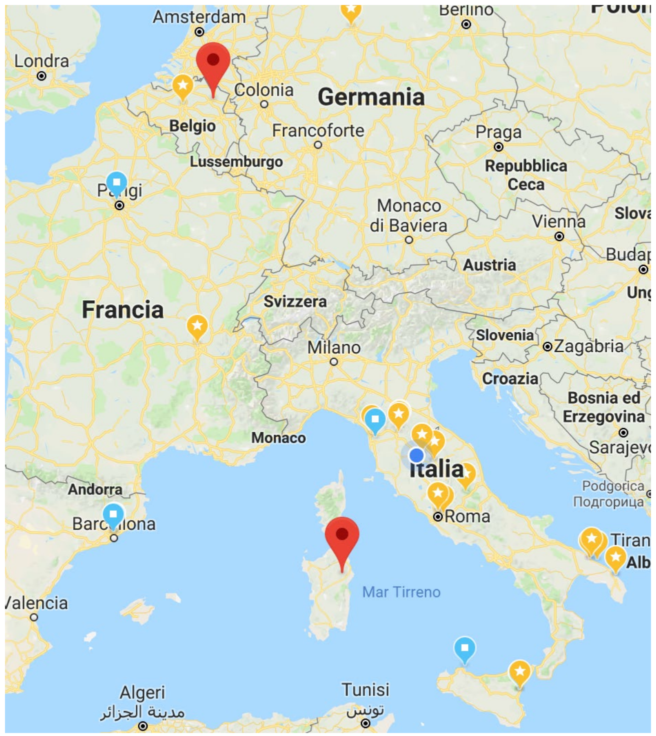
ET site: 2 candidates

Horizontal spectral motion at various sites



- 3 borders site (NL-B-DE)
- Sardinia site (IT)

M.Punturo



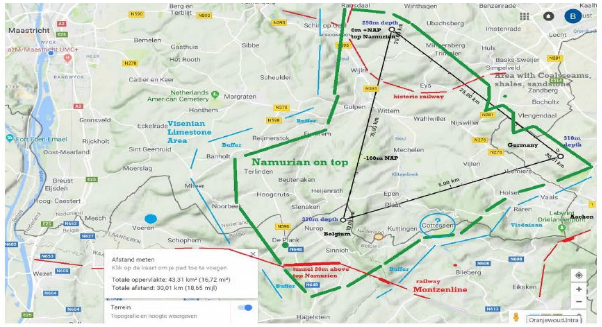
Sites qualification

- What are the technical selection parameters?
  - Define what are the important parameters needed to compare the sites (GSSI/INFN leadership)
    - Geology
    - Seismology
    - Natural radioactivity
    - Water content
  - Suggest a list of tests to be realised
- How the sites match these parameters?
  - Complete the qualification for Sardinian site
    - Team of qualification in the underground mine
      - University of Rome, University of Sassari, INFN, INGV, GSSI
  - Perform the qualification for the 3 borders site:
    - 1 month of data analysed

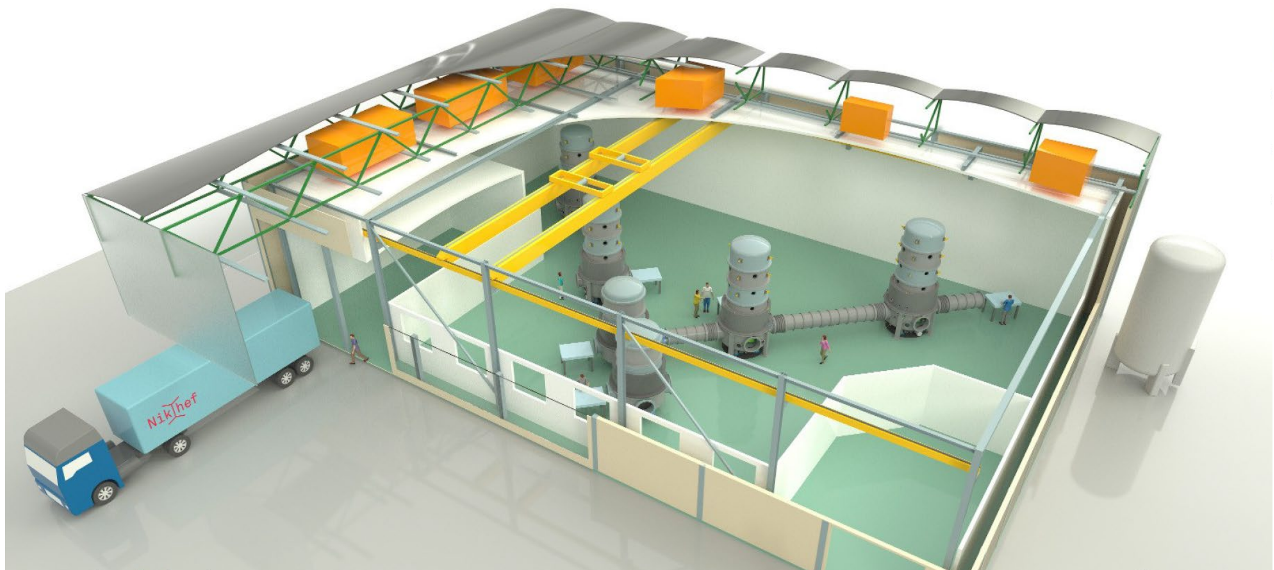
Initial funds raising

- The site qualifications, the engineering studies, the enabling technologies development require initial funding
- Some initial funding has been delivered in the most proactive countries to realise facilities and to candidate the sites

ET Pathfinder activities



ET Pathfinder in Maastricht



Bas Swinkels
on behalf of many people

GWADW
Elba, 21/05/2019

Nikhef

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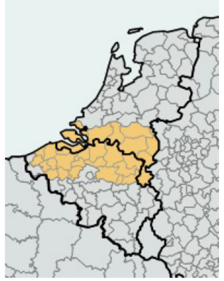
Funding & partners

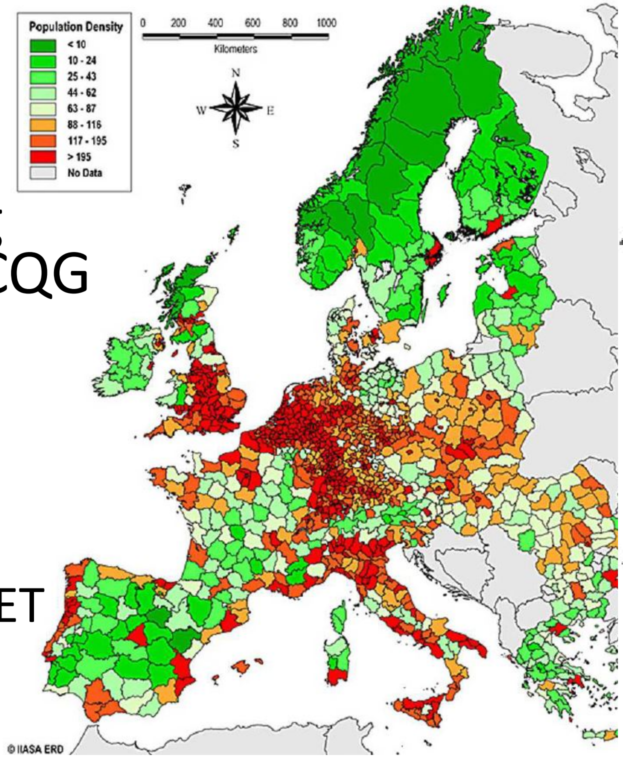


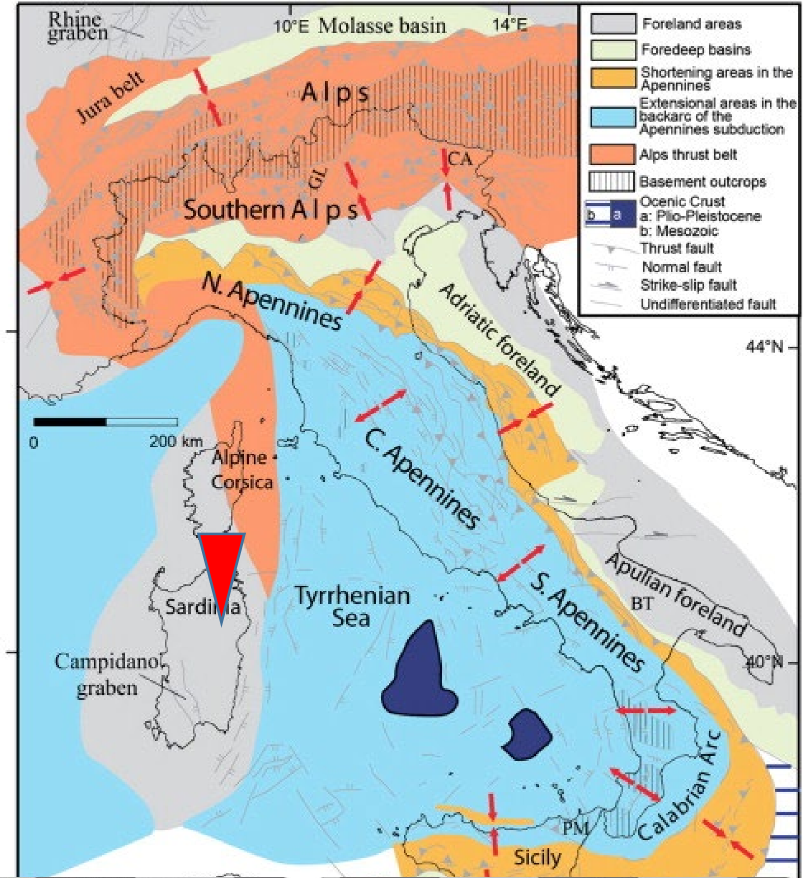
Interreg
EUROPESE UNIE
Vlaanderen-Nederland
Europees Fonds voor Regionale Ontwikkeling

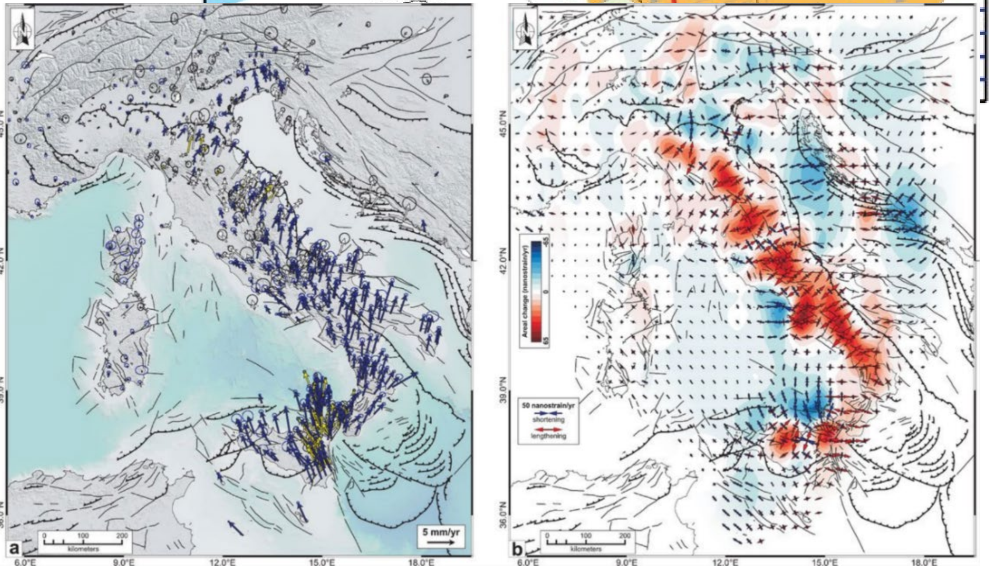
- Obtained ~14.5 MEuro funding from unconventional sources:
  - InterReg Flanders-South of NL (European fund for cross-border development)
  - Province of Limburg (NL), Dutch and Belgian national ministries
  - Matched contribution by partners
- Partners: Nikhef, universities of Antwerpen, Eindhoven, Ghent, Hasselt, Leuven, Maastrich
- Satellite partners: Aachen, Brussels, Fraunhofer, Liège, Louvain la Neuve, Twente, TNO
- Additional input from Glasgow, AEI, Perugia ...
- 100+ person-years (staff scientists and engineers) committed over the next 5 years
- New collaborators are welcome

Sardinia - Italy

- Site (preliminarily) qualified with a long measurement campaign, published in CQG
- Very high quality geological, seismic, constructive and environmental characteristics
- Support of the Italian Government
  - 17 M€ promised to support AdV+ and the ET site candidature
    - 5.5M€ delivered in 2018
  - 3.5M€ delivered by Sardinia region
  - 1M€ from Research Ministry (PRIN)
- Direct involvement of the largest academic institutions in Italy:
  - INFN, INAF, INGV
  - University La Sapienza Rome
- Direct involvement of the Sardinian Universities:
  - UniSS, UniCa







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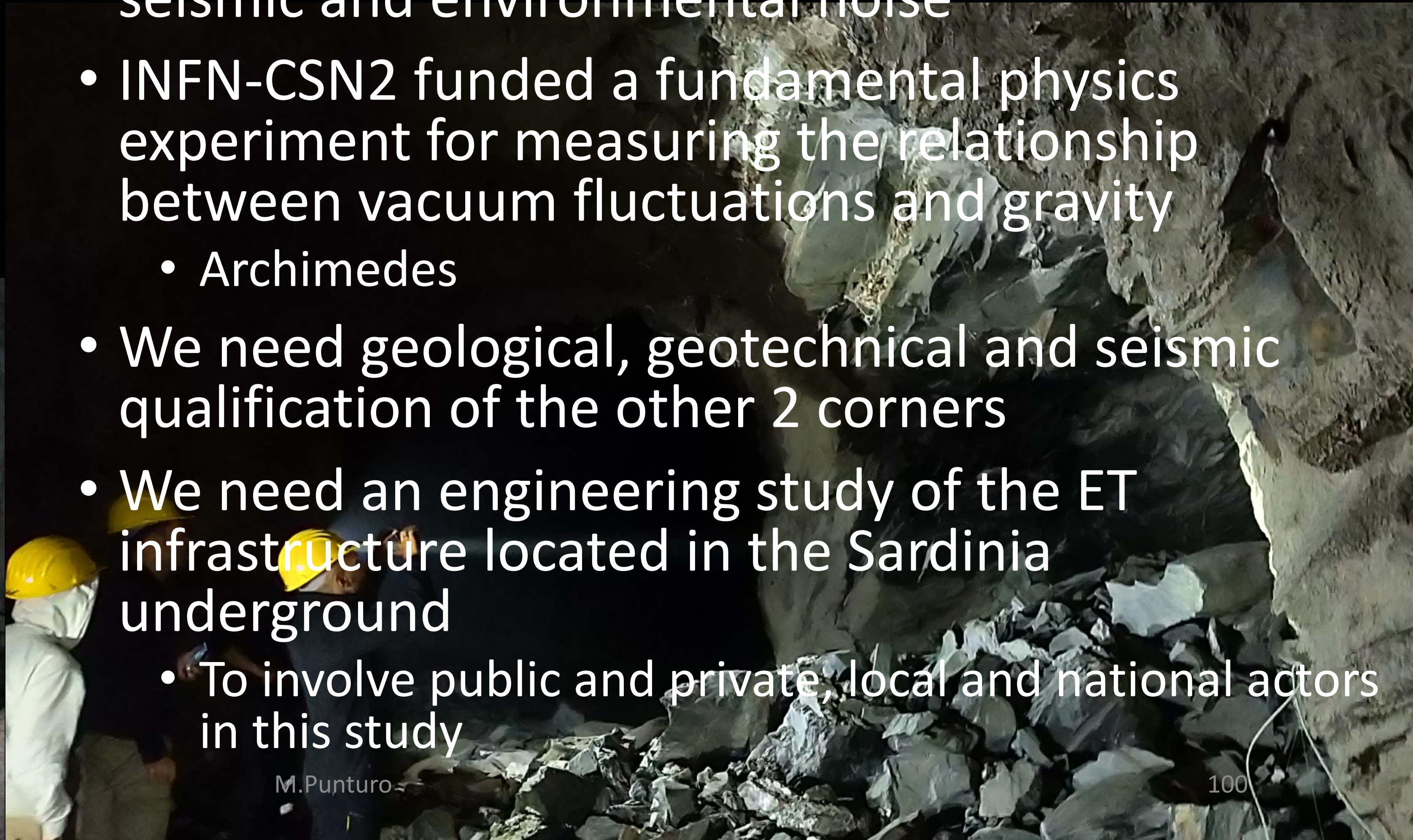
Activities at the Sos Enattos site

- The site needs to be further qualified with seismic and environmental measures
- Thanks to the support of the Regione Sardegna is under construction an underground lab (SarGrav) for experiments that need very low level of seismic and environmental noise
- INFN-CSN2 funded a fundamental physics experiment for measuring the relationship between vacuum fluctuations and gravity
  - Archimedes
- We need geological, geotechnical and seismic qualification of the other 2 corners
- We need an engineering study of the ET infrastructure located in the Sardinia underground
  - To involve public and private, local and national actors in this study



Latest news on ET ESFRI proposal

- There is a general (informal) agreement (at scientists, agencies and Ministries level) to submit the ET ESFRI proposal in the following configuration:
  - Italy is the leading country
  - Netherlands, Belgium and now also France are perspective countries
  - INFN (…) is the coordinator of a consortium of about 30-35 Agencies and Institutions form Belgium, France, Germany, Hungary, Italy, Netherland, Poland, Spain, Switzerland and UK
  - EGO is the headquarter of the project
- In the following countries the decision for a political support to ET is progressing apparently in the right direction:
  - Germany, Spain, Poland and UK
- We have a very dense calendar:
  - France, 09/12/2019, EoI
  - Italy 16/12/2019, EoI
  - Poland, 31/12/2019, National deadline
  - France, 10/01/2020, National deadline
  - Germany, 17/01/2020, National deadline
  - UK, 10/02/2020, National deadline
  - Italy, 15/02/2020, National deadline
  - Netherlands, 18/02/2020, National deadline
  - Belgium, 18/02/2020, National deadline
  - Spain, 28/02/2020, National deadline

Europe – 05/05/2020 – Final deadline

Conclusions

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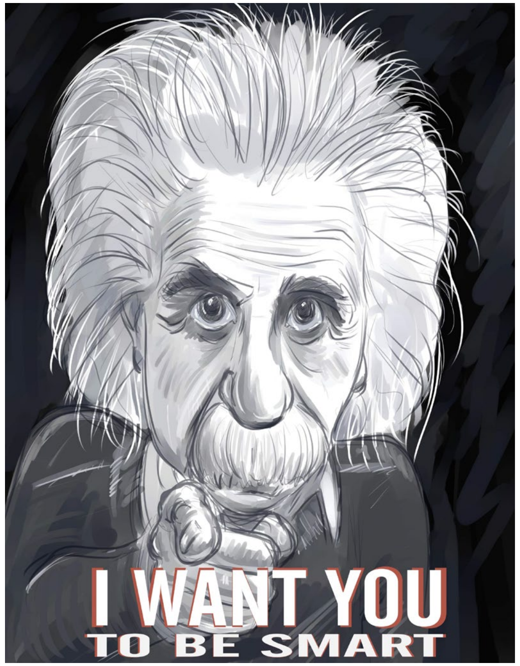
- GW is one of research sector the highest discovery potential in this moment
- We will have a rapid evolution in the next decades and we expect great scientific achievements
- If you like challenges, the 3G project is what you are looking for
- The payoff for the success is a new understanding of the Universe and real new physics

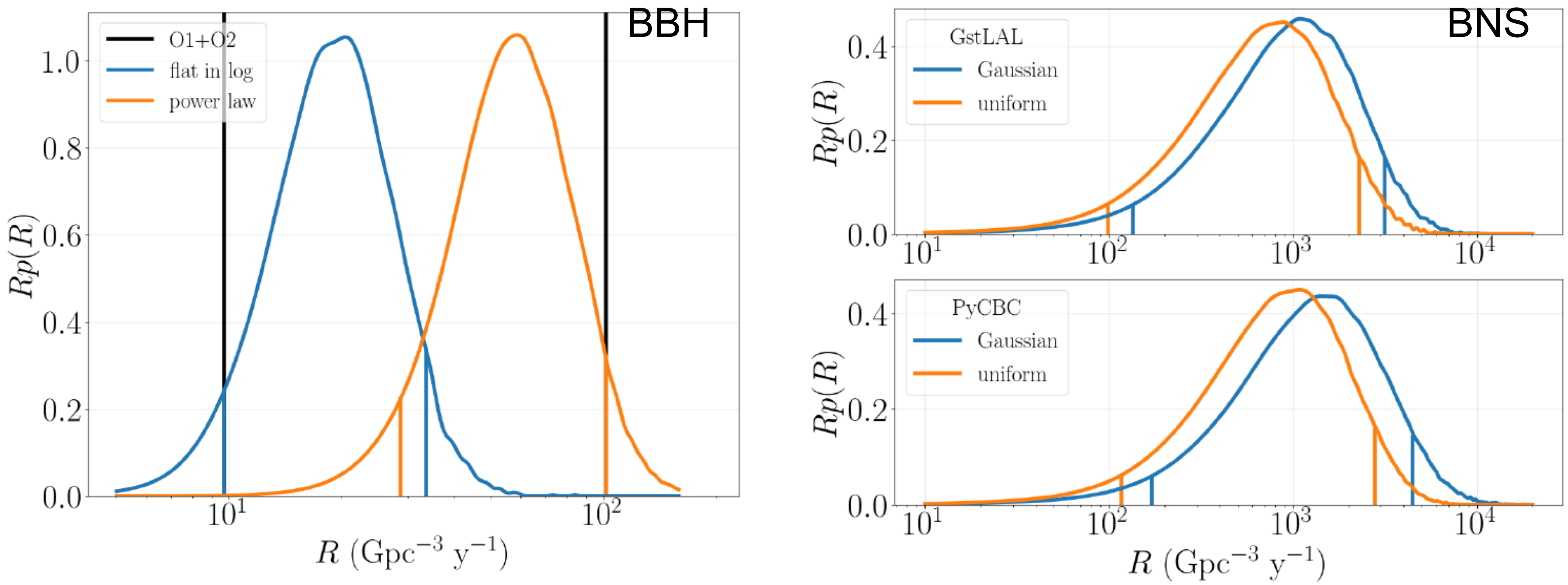
GWs Want You!



ET Wants You!

End

BBH and BNS merger rates



- **BBH event rates:** for the mass distributions of the primary mass m_1 flat in log (blue) and power-law (orange)
  Union of the interval R_{BBH} in [9.7,101] Gpc^{-3} y^{-1}

- **BNS event rates:** for uniform or Gaussian component mass distributions
  Union of the interval R_{BNS} in [110,3840] Gpc^{-3} y^{-1}

- **NSBH rates** (no detection): **R_{NSBH} < 610 Gpc^{-3} y^{-1} @90% confidence**
  factor of 2 better than O1 results, starts to be interesting

Materials for cryogenic test masses

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Sapphire

- Used in KAGRA
- Pro:
  - No need to change laser wavelength
  - Capability to realise a cryogenic monolithic payload demonstrated in KAGRA (Sapphire suspension fibres, silicate bonding)
- Cons:
  - Large diameter test masses unavailable
  - High optical absorption value and spread
  - Birifrangence

Silicon

- Target material for ET, CE2 and Voyager
- Pro:
  - It is possible to find large samples in silicon (almost true, large if produced by through Czochralski grown method, ~45cm diam if produced through Full Zone method)
  - Low optical absorption (few ppm) for full zone or Magnetic Czochralski method produced test masses
  - Thermal expansion coefficient almost null around 120K and at 10K
- Cons:
  - Technology still immature
    - No large test mass produced
    - Monolithic fiber production technology still unavailable
  - Opaque at 1064 nm, to be used at 1550 or 2000nm

Enabling Technologies

We could profit of "excellences" available in Europe

- The Xylophone approach needs two parallel technology developments:

Specific R&D needed

Technology developed at MPG

- ET-LF:
  - Underground
  - Cryogenics
  - Silicon (Sapphire) test masses
  - Large test masses
  - New coatings
  - New laser wavelength
  - Seismic suspensions (*)
  - Frequency dependent squeezing (*)
- ET-HF: (*)
  - High power laser
  - Large test masses
  - New coatings
  - Thermal compensation
  - Frequency dependent squeezing

(*) AdV+ is a pathfinder for these technologies