Onde gravitazionali e progetto Einstein Telescope

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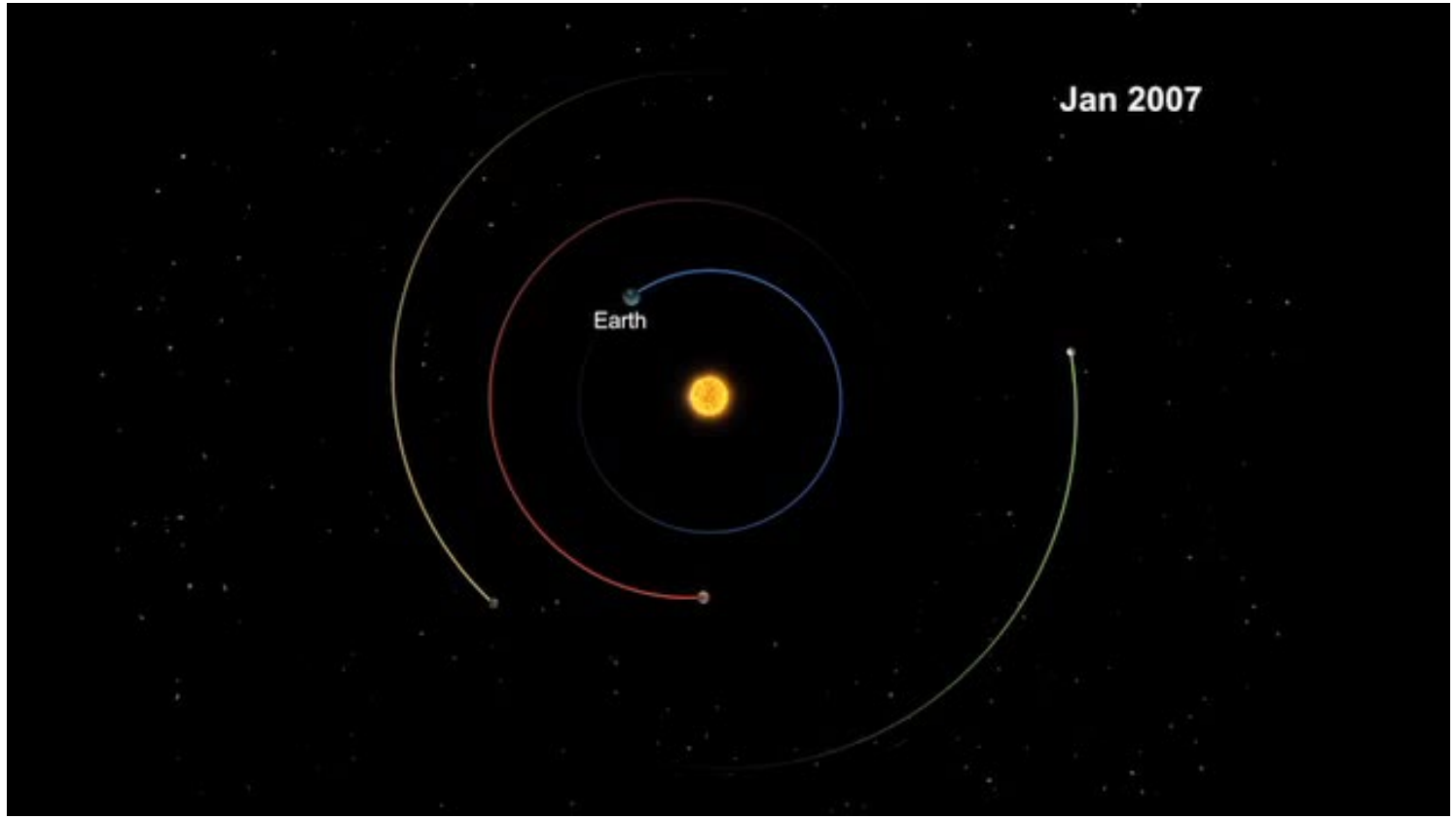
Attuale comprensione dell'Universo

- Il modello interpretativo di tutto ciò che ci circonda è basato su due pilastri fondamentali:
  - Il modello standard delle particelle (infinitamente piccolo), basato sui canoni della fisica quantistica
  - Il modello cosmologico dell'Universo (infinitamente grande), basato sulla relatività generale di Albert Einstein
- Ma le assunzioni di base (fisica quantistica e relatività generale) sono tra loro «incompatibili» e portano a conseguenze «non comprese» nel nostro modo di spiegare ciò che ci circonda.

La gravitazione di Newton

$$F = -G\frac{m \cdot m'}{r^2}$$

- Pietra miliare nel cammino di comprensione della gravità è la teoria della gravitazione universale di Newton, che tuttora, nel sistema solare, rappresenta un buon modello.



Istituto Nazionale di Fisica Nucleare

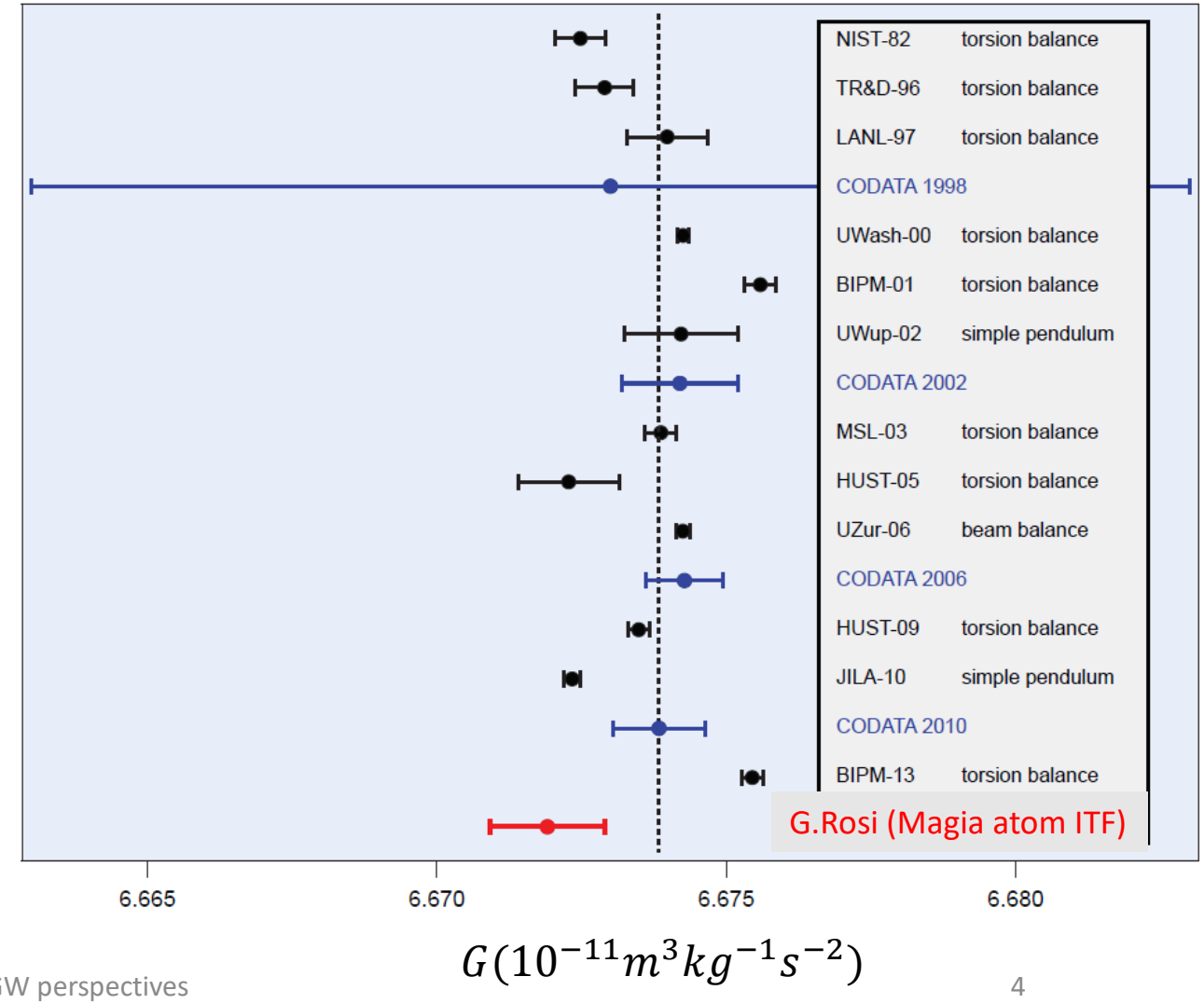
Ma conosciamo veramente la gravità?

- Iniziamo dalla costante di Newton

$$G = (6{,}67430 \pm 0{,}000015) \times 10^{-11} \frac{m^3}{kg \cdot s^2}\ ^*$$

- Nonostante che la prima misura di G è stata fatta da Cavendish nel 1798, conosciamo relativamente poco il valore di G
- Il confront con le altre costanti "fondamentali" è impietoso

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



*CODATA 2018

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 $\frac{1}{12}m(^{12}C)$	u	$1.660\,539\,040(20) \times 10^{-27}$	kg	1.2×10^{-8}

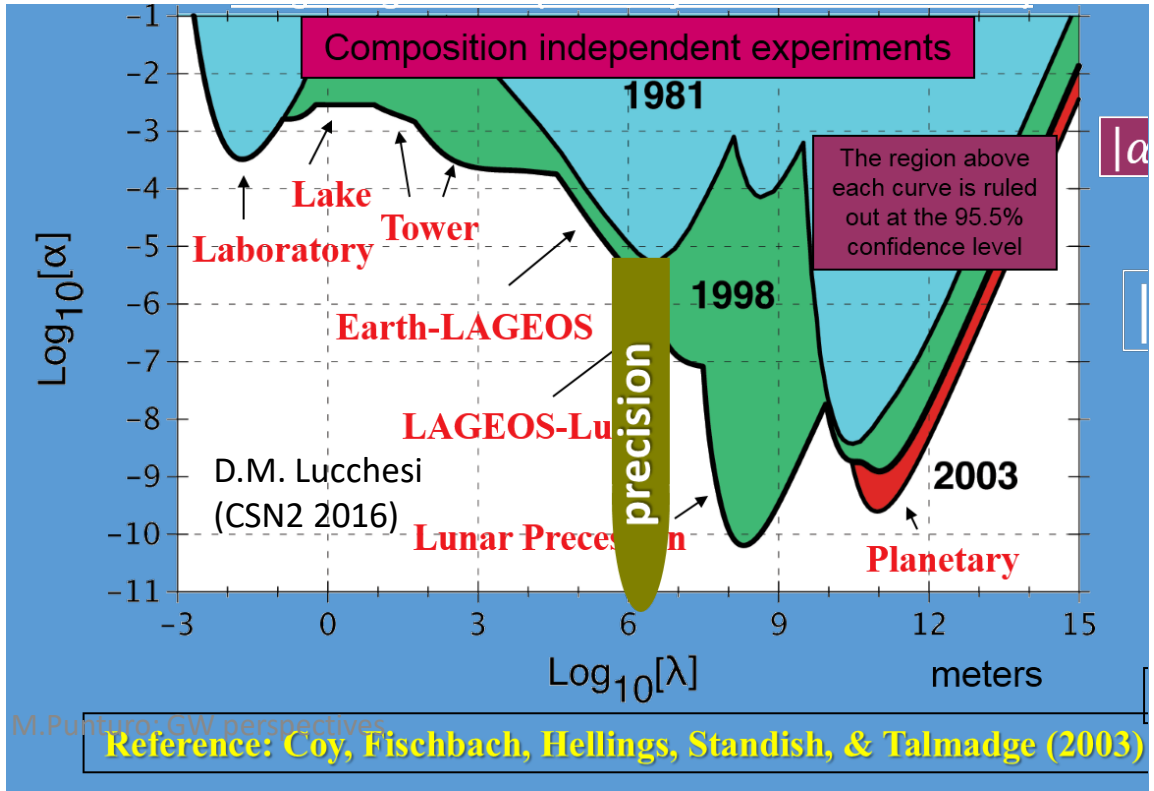
Is really $F \propto r^{-2}$?

- 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"):

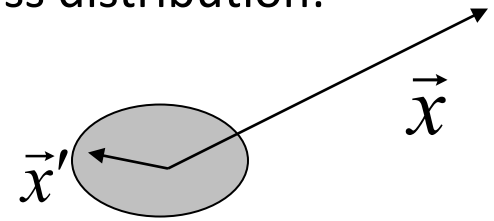
$$\lambda = \frac{\hbar}{m_g c}$$



Gravitational Potential of a mass distribution [1]

- Let consider a continuous distribution of mass having density $\rho(x')$. To evaluate the value of the potential $\phi(\vec{x})$ in un point $\vec{x}$ external to the mass distribution:

$$\phi(\vec{x}) = -\int_V \frac{G \cdot \rho(x')}{|\vec{x} - \vec{x}'|} d^3x'$$



- Being $\vec{x}$ external to the mass distribution, we can Taylor-expand $1/|\vec{x}-\vec{x'}|$ in multi-poles around $\vec{x'} = 0$:

$$\frac{1}{|\vec{r} - \vec{r'}|} = \frac{1}{\sqrt{(x-x')^2 + (y-y')^2 + (z-z')^2}} \equiv f(x', y', z')$$

$$f(x,y,z) = \sum_{n_x=0}^{\infty} \sum_{n_y=0}^{\infty} \sum_{n_z=0}^{\infty} \frac{(x-x_0)^{n_x} (y-y_0)^{n_y} (z-z_0)^{n_z}}{n_x!\, n_y!\, n_z!} \left[\frac{\partial^{n_x+n_y+n_z}}{\partial x^{n_x} \partial y^{n_y} \partial z^{n_z}} f(x,y,z) \right]_{(x_0, y_0, z_0)}$$

Multivariable Taylor series

$$n_x = n_y = n_z = 0 \Rightarrow \frac{1}{|\vec{r} - \vec{r'}|_{r'=0}} = \frac{1}{r}$$

Gravitational Potential of a mass distribution [2]

$$n_x = 1, \quad n_y = n_z = 0 \Rightarrow x' \left[\frac{1}{2} \frac{2(x - x')}{\left|\vec{r} - \vec{r}'\right|^3} \right]_{r'=0} = \frac{x'x}{r^3}$$

And similarly for *y* and *z*

$$n_{x,y} = 1, \quad n_z = 0 \Rightarrow x'y' \frac{\partial^2 f}{\partial x' \partial y'} = x'y' \left[\frac{\partial}{\partial y'} \frac{(x - x')}{\left|\vec{r} - \vec{r}'\right|^3} \right]_{r'=0} = 3 \frac{x'y'xy}{r^5}$$

And similarly for $n_{x,z}=1$ *and* $n_{y,z}=1$

$$n_x = 2, \quad n_y = n_z = 0 \Rightarrow x'^2 \frac{\partial^2 f}{\partial x'^2} = x'^2 \left[\frac{\partial}{\partial x'} \frac{(x - x')}{\left|\vec{r} - \vec{r}'\right|^3} \right]_{r'=0} = \ldots$$

- Where $x^{1,2,3}=x,y,z$ and $r = \sqrt{x^2 + y^2 + z^2}$

  - The gravitational potential becomes:

$$\varphi(\vec{x}) = -\frac{GM}{r} - \frac{G}{r^3} \sum_{k=1}^{3} x^k D^k - \frac{G}{2} \sum_{k,l=1}^{3} Q^{kl} \frac{x^k x^l}{r^5} + \ldots$$

Quadrupolar terms of the gravitational potential

$$\phi(\vec{x}) = -\frac{GM}{r} - \frac{G}{r^3}\sum_k x^k D^k - \frac{G}{2}\sum_{k,l} Q^{kl}\frac{x^k x^l}{r^5} + \ldots$$

- where: $M = \int_V \rho(x')d^3x'$ $\quad D^k = \int_V x'^k \rho(x')d^3x'$ $\quad Q^{kl} = \int_V \left(3x'^k x'^l - r'^2\delta_l^k\right)\rho(\vec{x}')d^3x'$

- Note: it is possible to find a reference system where the center of mass terms (dipole) D^k vanishes
- If the quadrupolar terms of the mass distribution are $Q^{kl} \neq 0$, a term $\propto r^{-3}$ in $\phi(\vec{x})$ (r^{-4} in force) remains.
- Earth has a relative difference between the polar and equatorial diameters of 3×10^{-3} and this impacts on the orbits of the satellites (precession of the orbits)
- Extending the series, in general we use the spherical harmonics Y_{lm} expansion:

$$V(\vec{x}) = \sum_{l=0}^{\infty}\sum_{m=-l}^{l} Q_{lm}\frac{Y_{lm}(\theta,\varphi)}{r^{l+1}}$$

where Q_{lm} are the moments of the system

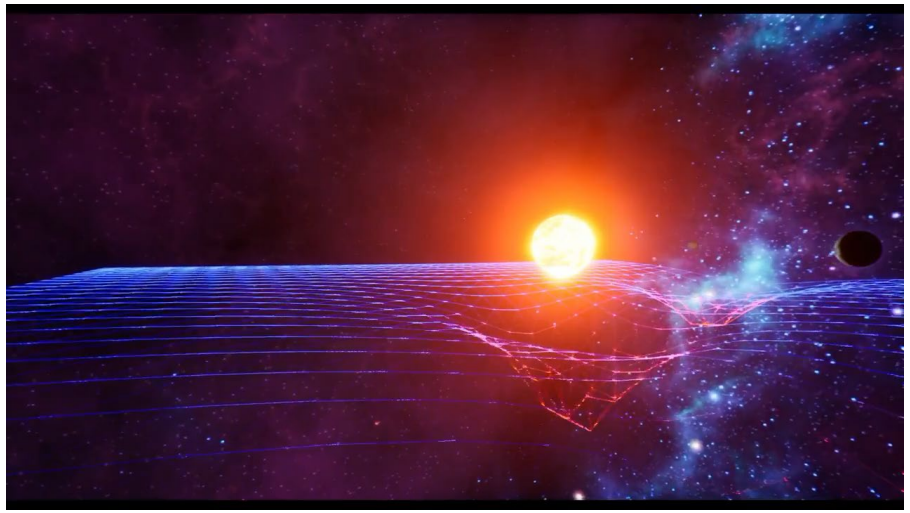
The “right” theory of Gravitation

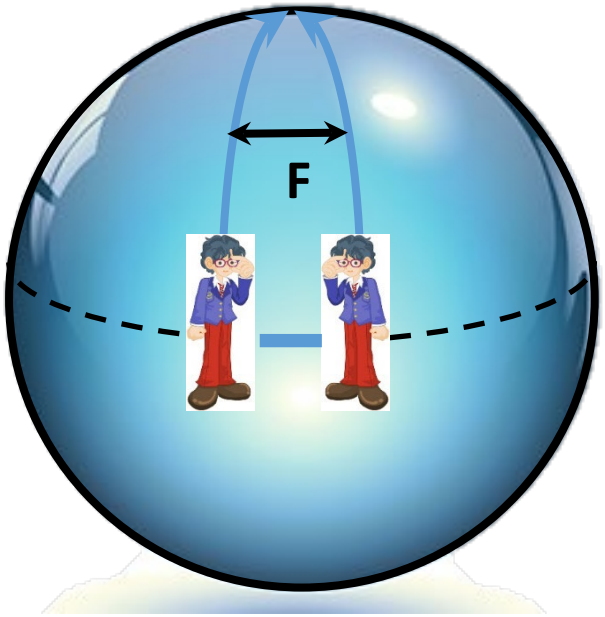
- OK what is the “best” theory of the Gravitation we have currently?
  - Einstein General Relativity

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

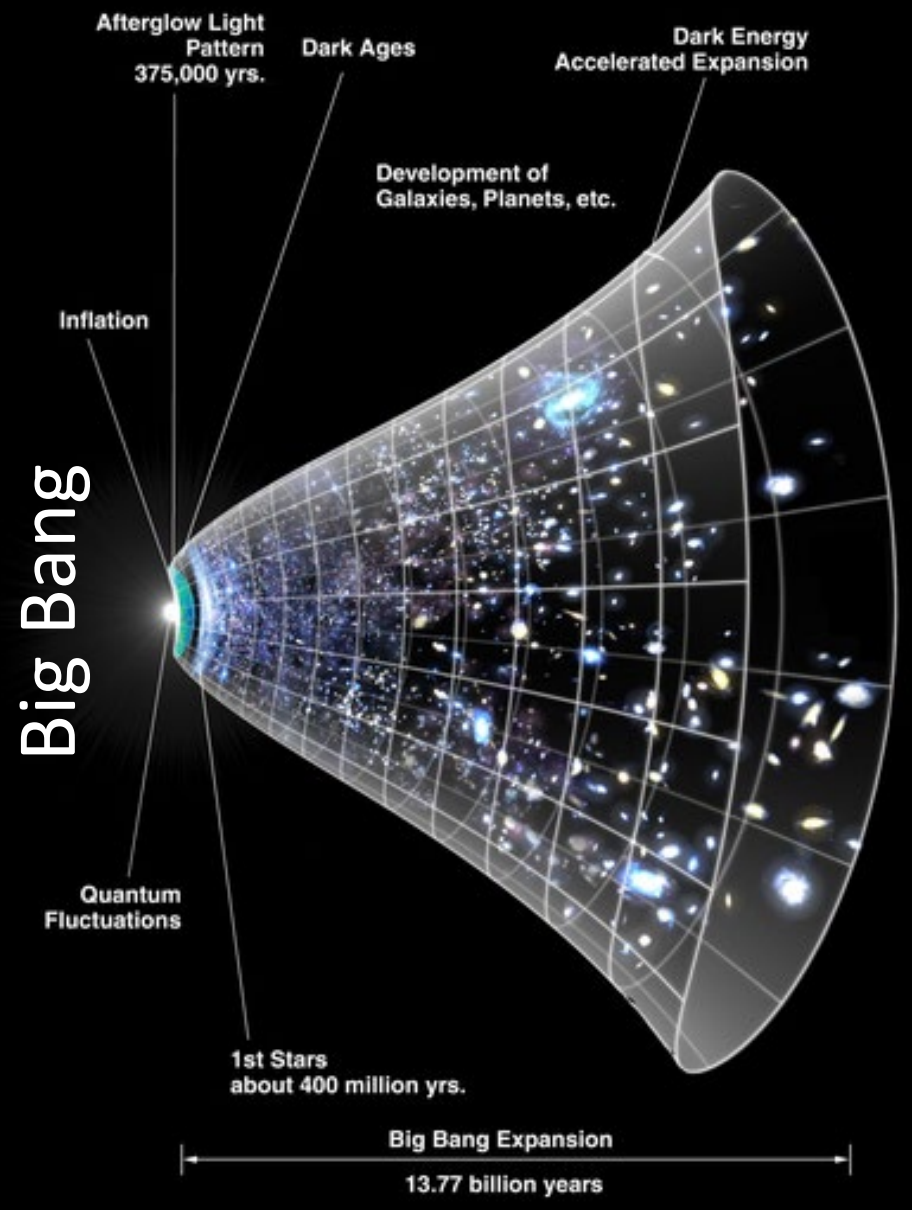
Curvature of the space-time “The Einstein Tensor”

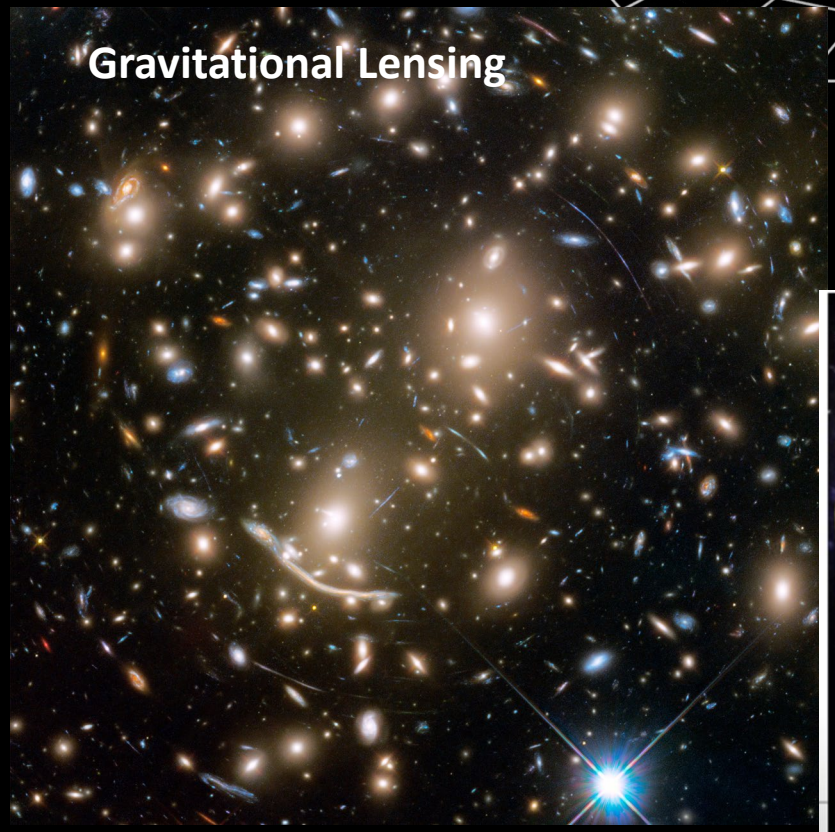
Energy-Momentum Tensor

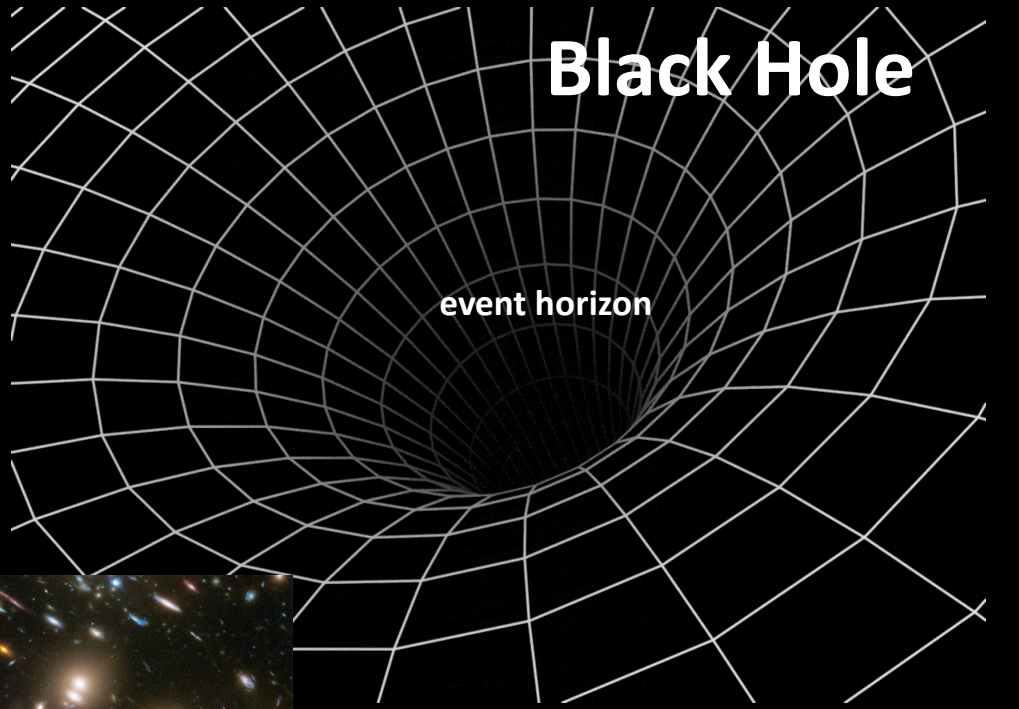


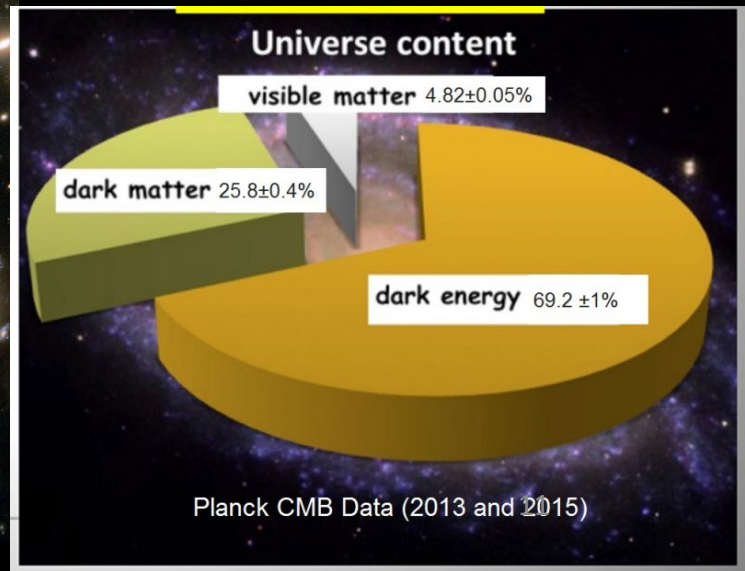


The GR Universe



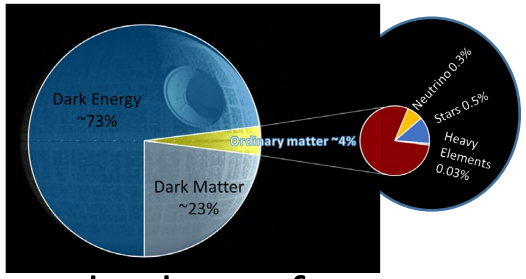






The “right” theory of Gravitation

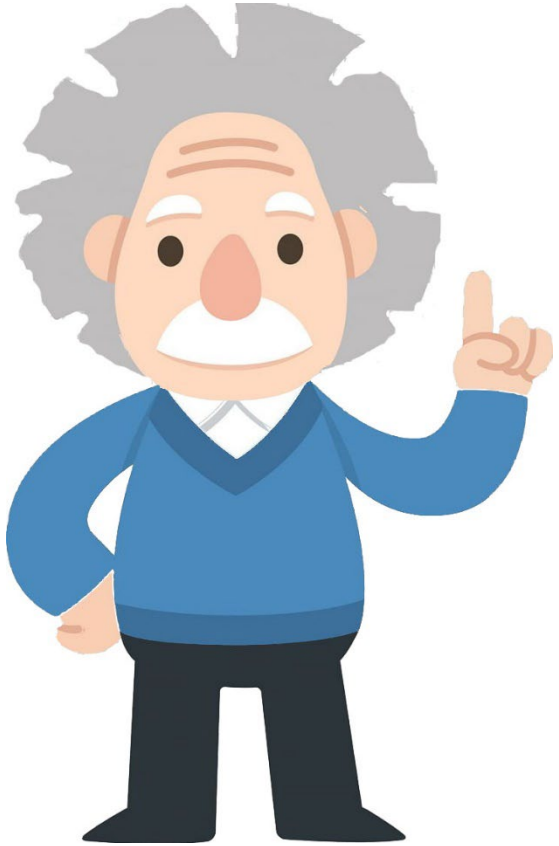
- Despite the incredible success of the theory, we have a series of difficulties:
  - GR is a purely classical theory
    - GR is not renormalizable in the standard quantum field theory sense
      - Strong-field modifications may provide a solution to this problem:
        - the theory becomes renormalizable if we add quadratic curvature terms – i.e., high-energy/high-curvature corrections
        - High-energy corrections can avoid the formation of singularities unavoidable in GR
  - Dark Matter/Dark Energy
    - Is it true that we understand only the 4% of the Universe?
  - Cosmological Constant problem (vacuum catastrophes)
    - Cosmological Constant → Dark Energy
    - Up to 120 order of magnitude of difference between the observed values of vacuum energy density (the small value of the cosmological constant) and theoretical large value of zero-point energy suggested by quantum field theory.
    - GR is incredibly well tested at intermediate length regime:
      - Any additional degrees of freedom must modify the theory at low and/or high energies while being consistent with GR in the intermediate-energy regime



GW: propagation of the space-time curvature

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

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

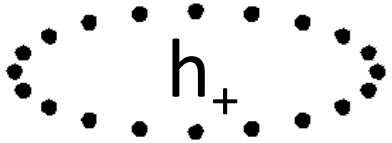


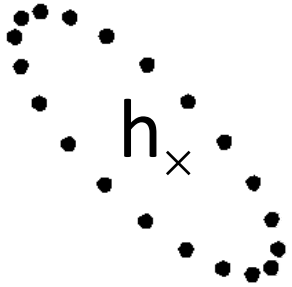
$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu} \Rightarrow \boxed{\left(-\frac{1}{c^2}\frac{\partial^2}{\partial t^2} + \nabla^2 \right) h_{\mu\nu} = 0}$$

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

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

Two polarisations h_+ and h_x



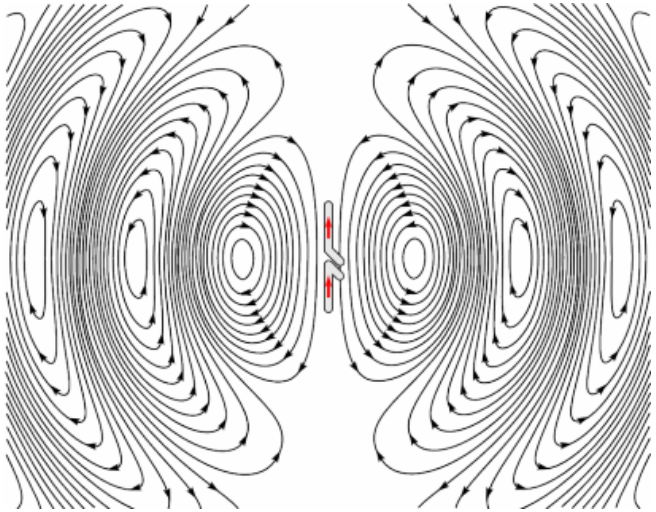


$$\Delta L = h \cdot L$$

Emission of GW

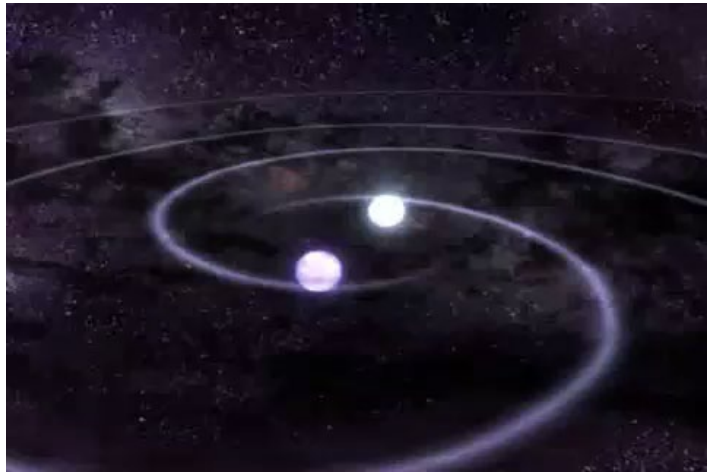
Electromagnetic waves

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



Gravitational Waves

- Accelerated masses are emitting GW waves: quadrupole emission



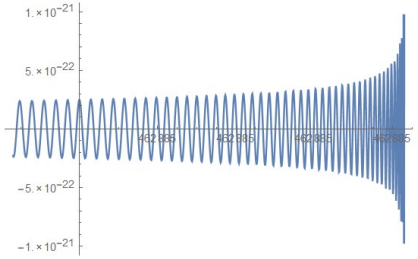
Retarded potential: $h_{\mu\nu}(t,\vec{x}) = -\frac{\kappa}{4\pi}\int \frac{T_{\mu\nu}\left(t-|\vec{x}-\vec{x}'|,\vec{x}'\right)}{|\vec{x}-\vec{x}'|} d^3x'$

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

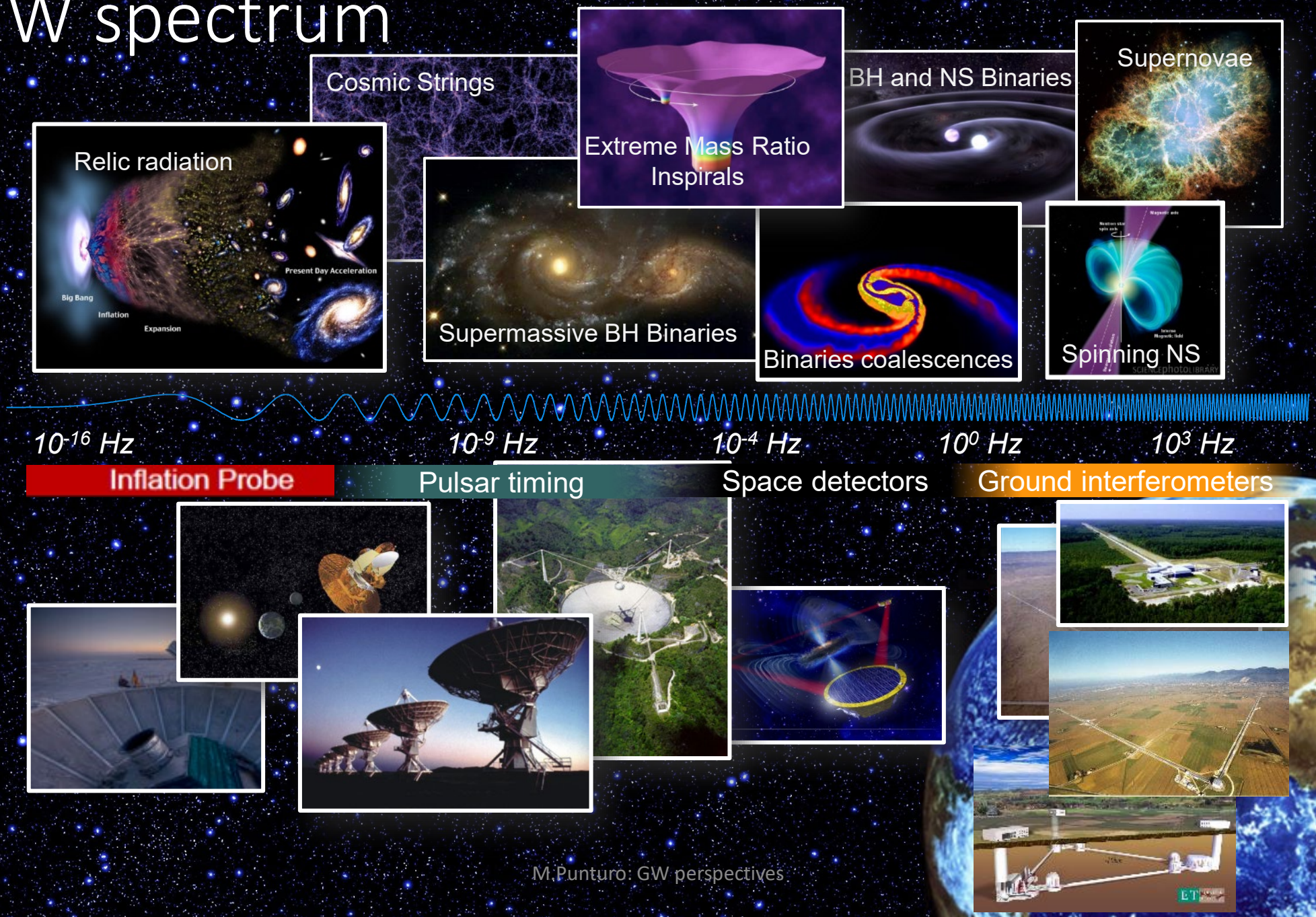
$$\left|h_{kl}^{TT}(t,\vec{x})\right|_{quad} = -\frac{\kappa}{8\pi r}\frac{1}{3}\ddot{Q}_{kl}^{TT}(t-r/c) = \frac{1}{r}\frac{2G}{c^4}\frac{1}{3}\ddot{Q}_{kl}^{TT}(t-r/c)$$

1/r

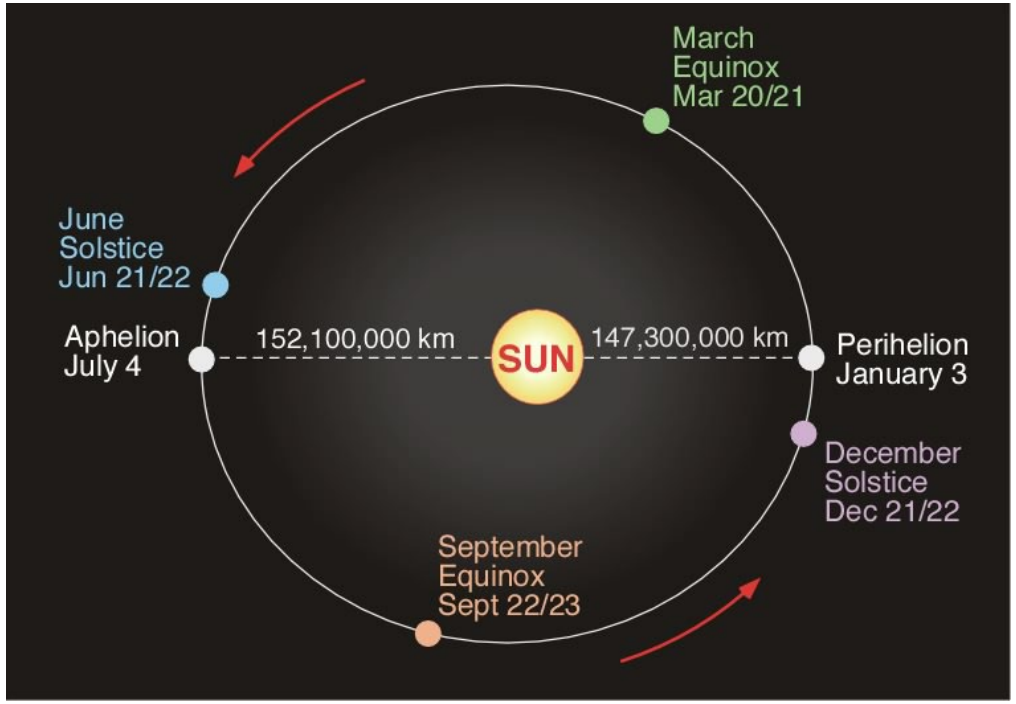
1.6×10^{-44} $m^{-1}kg^{-1}s^2$



The GW spectrum



$$\left.\begin{aligned} h &\approx 10^{-22} - 10^{-21} \\ \delta L &\approx h \cdot L_0 \\ L_0 &\approx 1km \end{aligned}\right\} \Rightarrow \delta L \approx 10^{-18} - 10^{-19}\, m$$

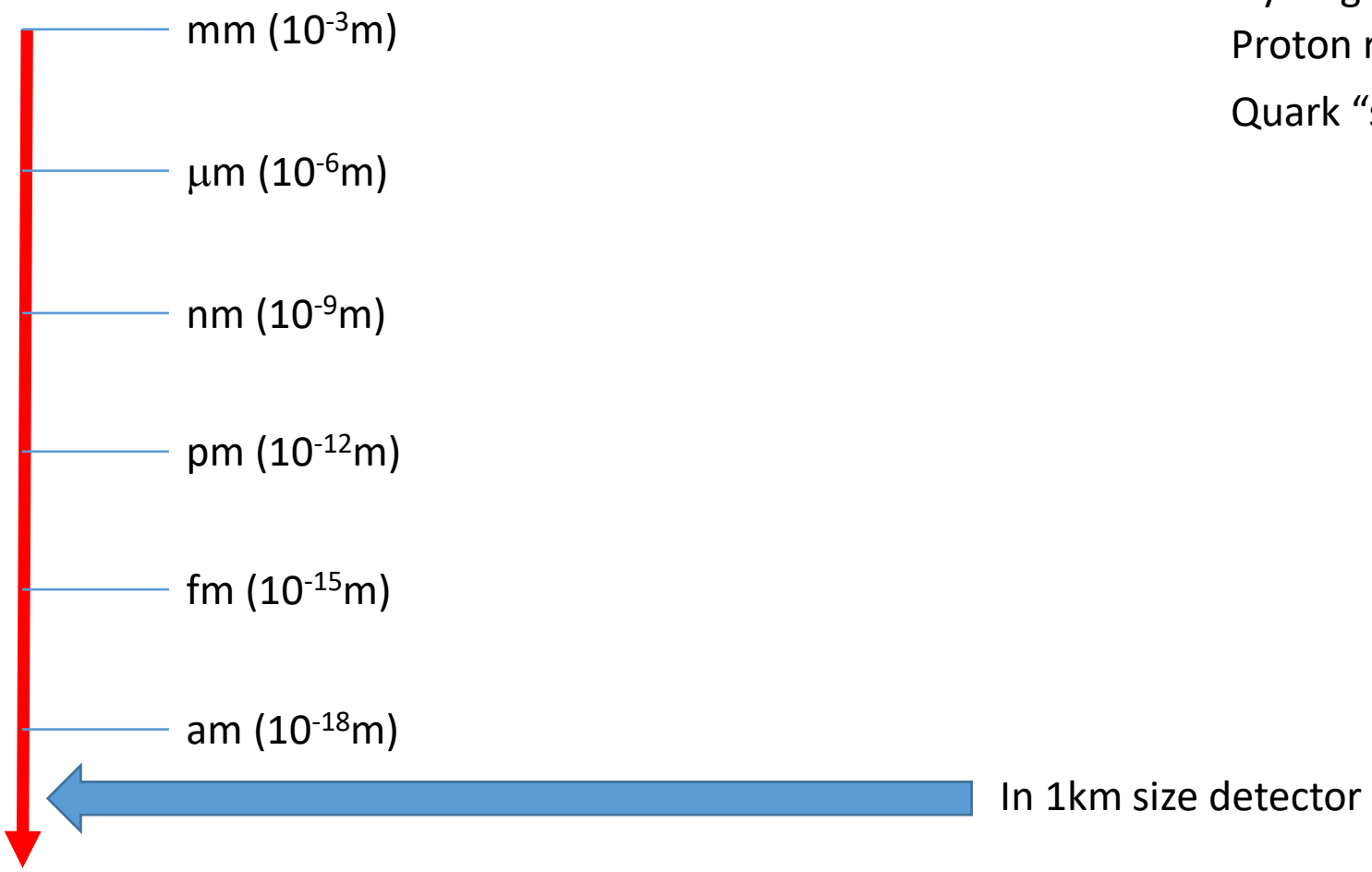


Distanza Terra-Sole variata per la dimensione di un atomo

Oppure 10^{-19} m su 1km

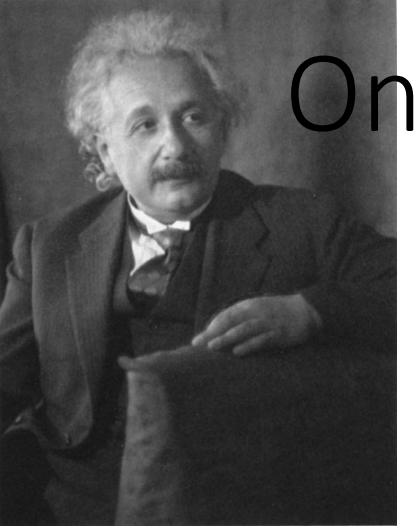
Cosa significa 10^{-19}m?

ΔL atteso in Virgo ~10^{-19}m



Human cells
Hydrogen atom
Proton radius
Quark "size"

One century of research, study and R&D

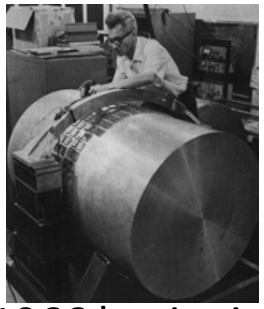


1915 GR

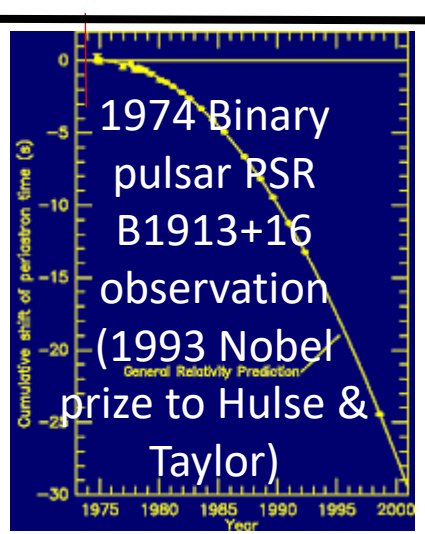
1916-1918 GW

1937 rigth GW equation

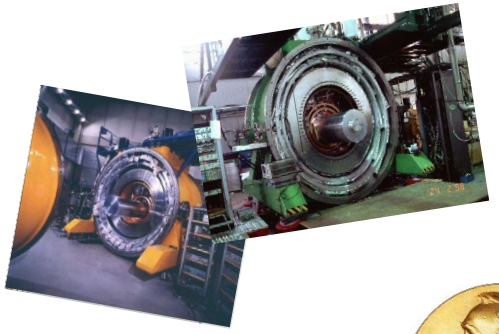
1957 GW transports energy



1966 beginning of the «experimental» era thanks to the J.Weber resonant bar



1974 Binary pulsar PSR B1913+16 observation (1993 Nobel prize to Hulse & Taylor)



'80-'90: Cryogenic Resonant Bars

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

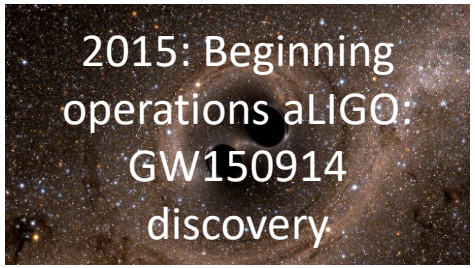
INFN

1994: Virgo project approval

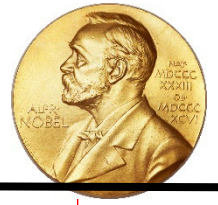
1993

1999+ Templates: EOB, Numerical relativity

1999+ Beginning operations LIGO and (+4y) Virgo



2015: Beginning operations aLIGO: GW150914 discovery



2017 Beginning operations Advanced Virgo: first BNS GW signal discovery: GW170817

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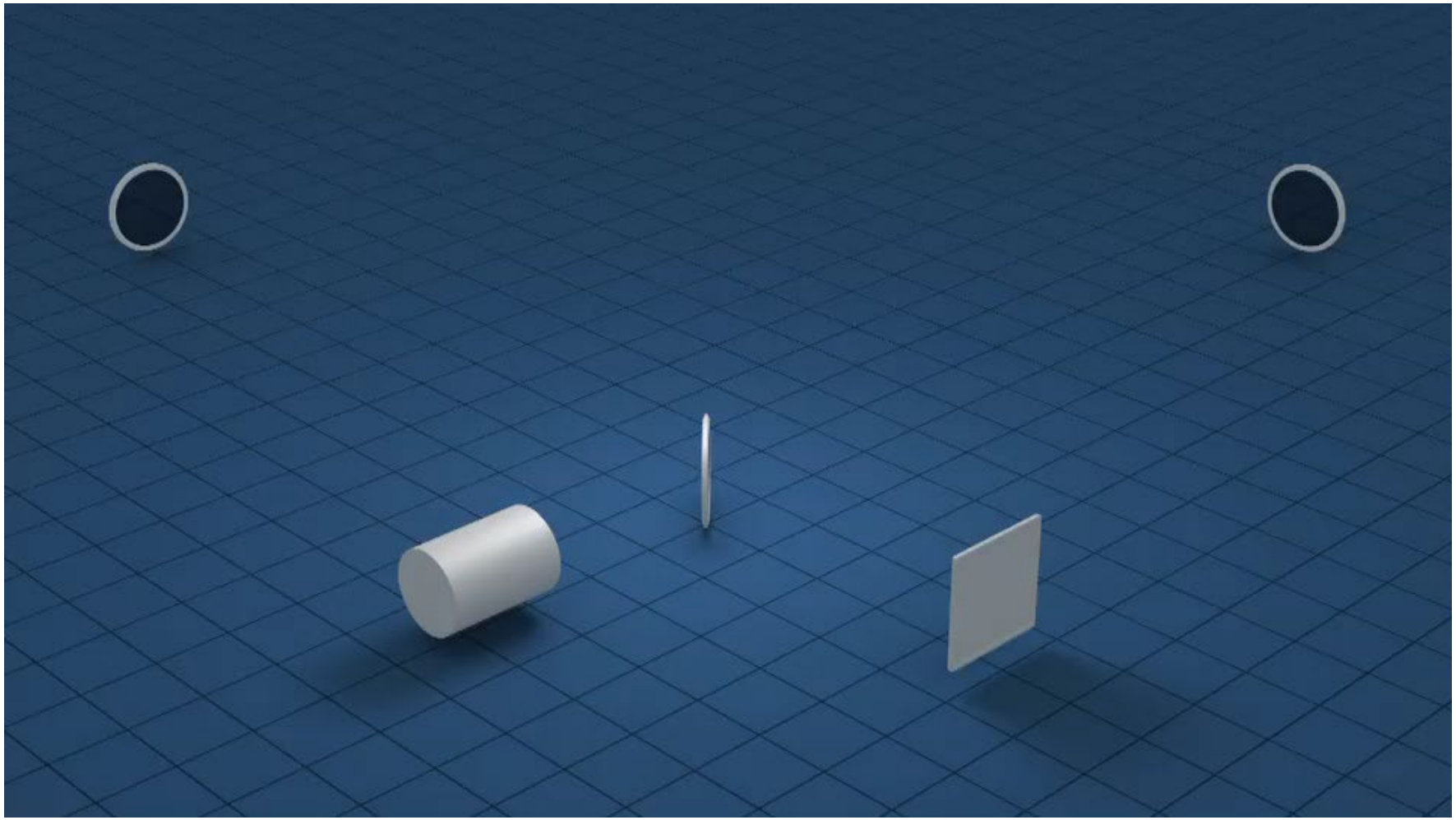
Monumental Scientific Successes of the GW Detectors Advanced LIGO and Advanced Virgo

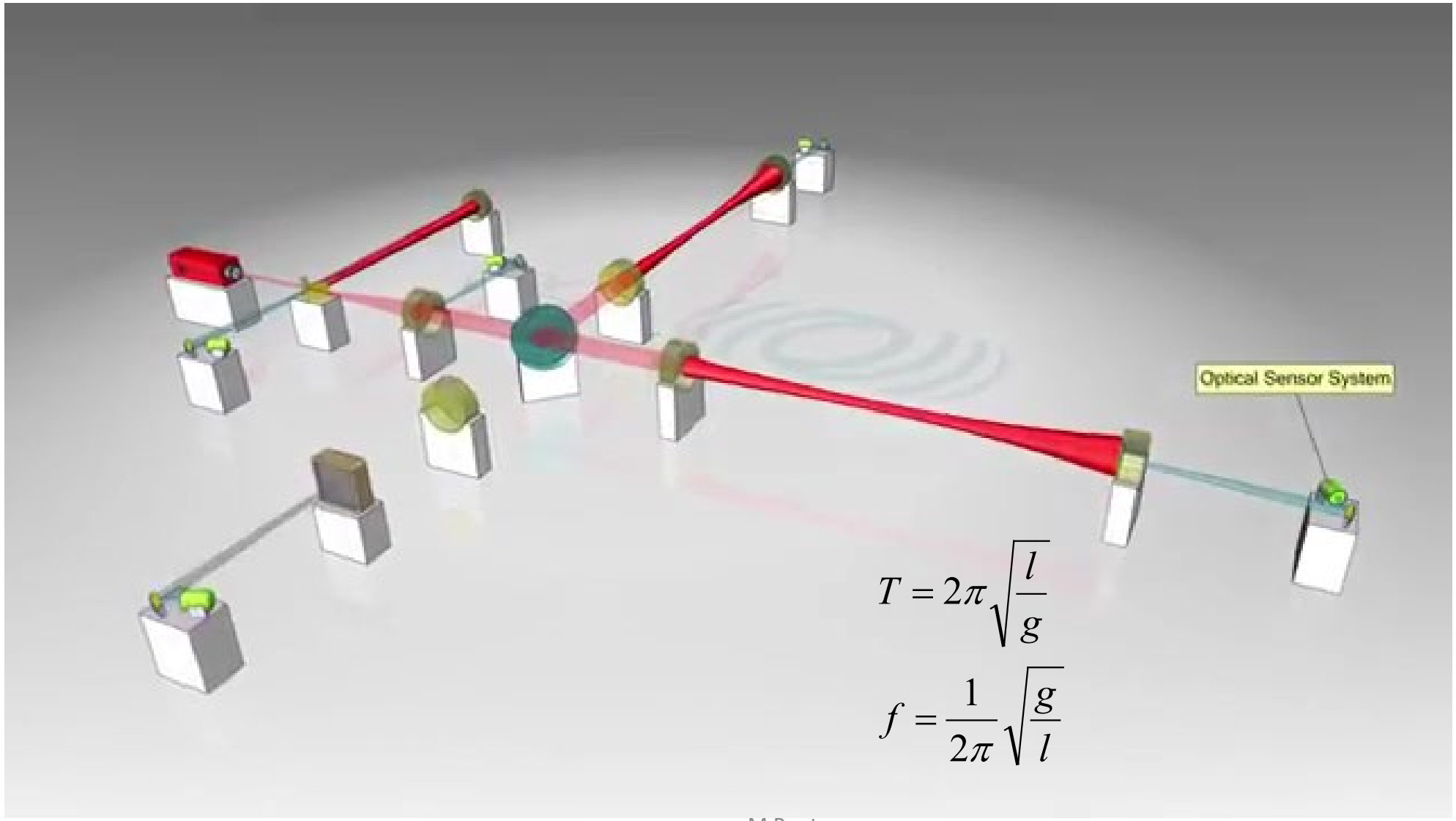
Principio funzionamento GWD

- Il principio base è l'interferometria laser



Costruiamo un GWD: Layout ottico

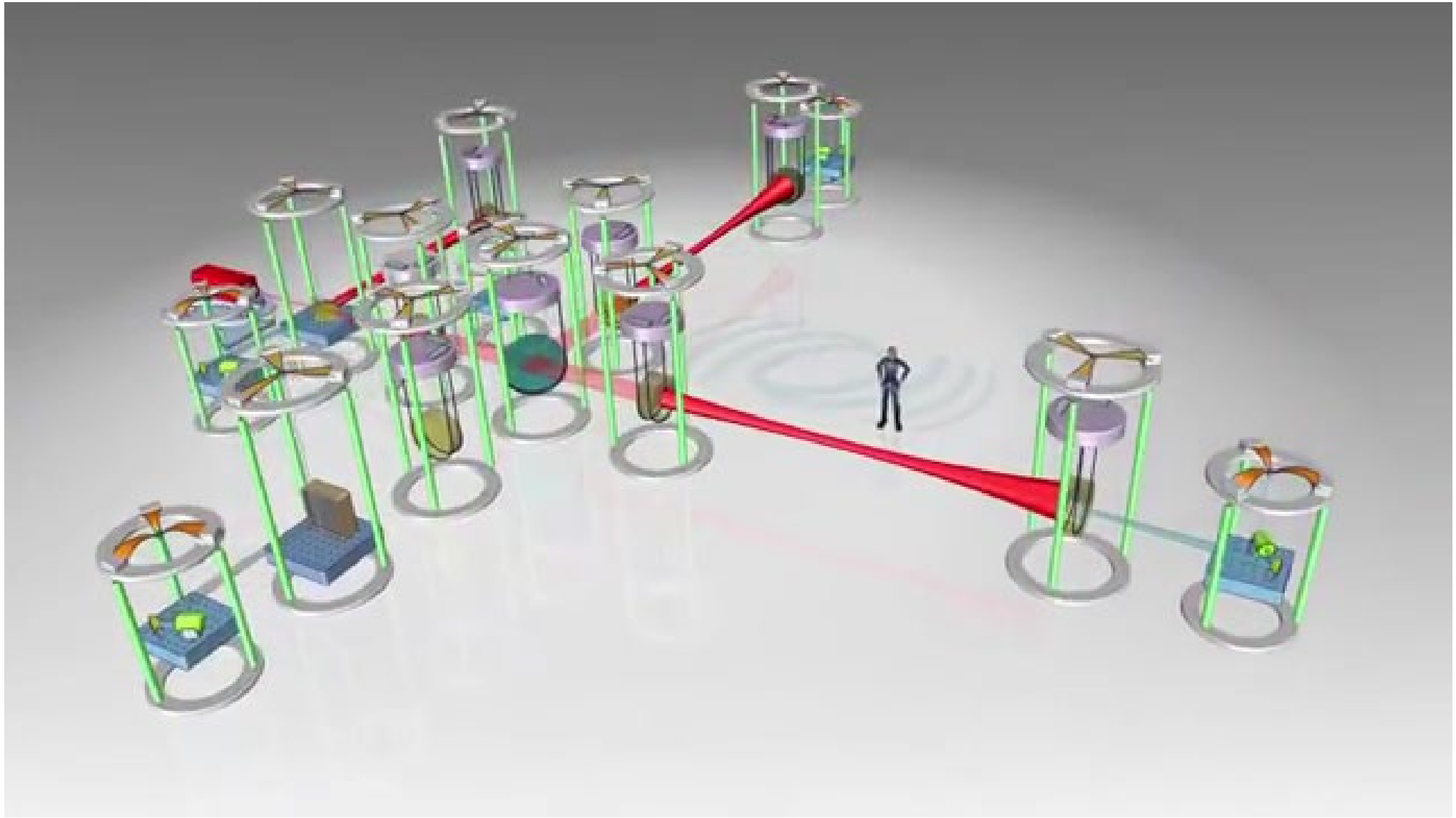
Costruiamo un GWD: filtraggio sismico



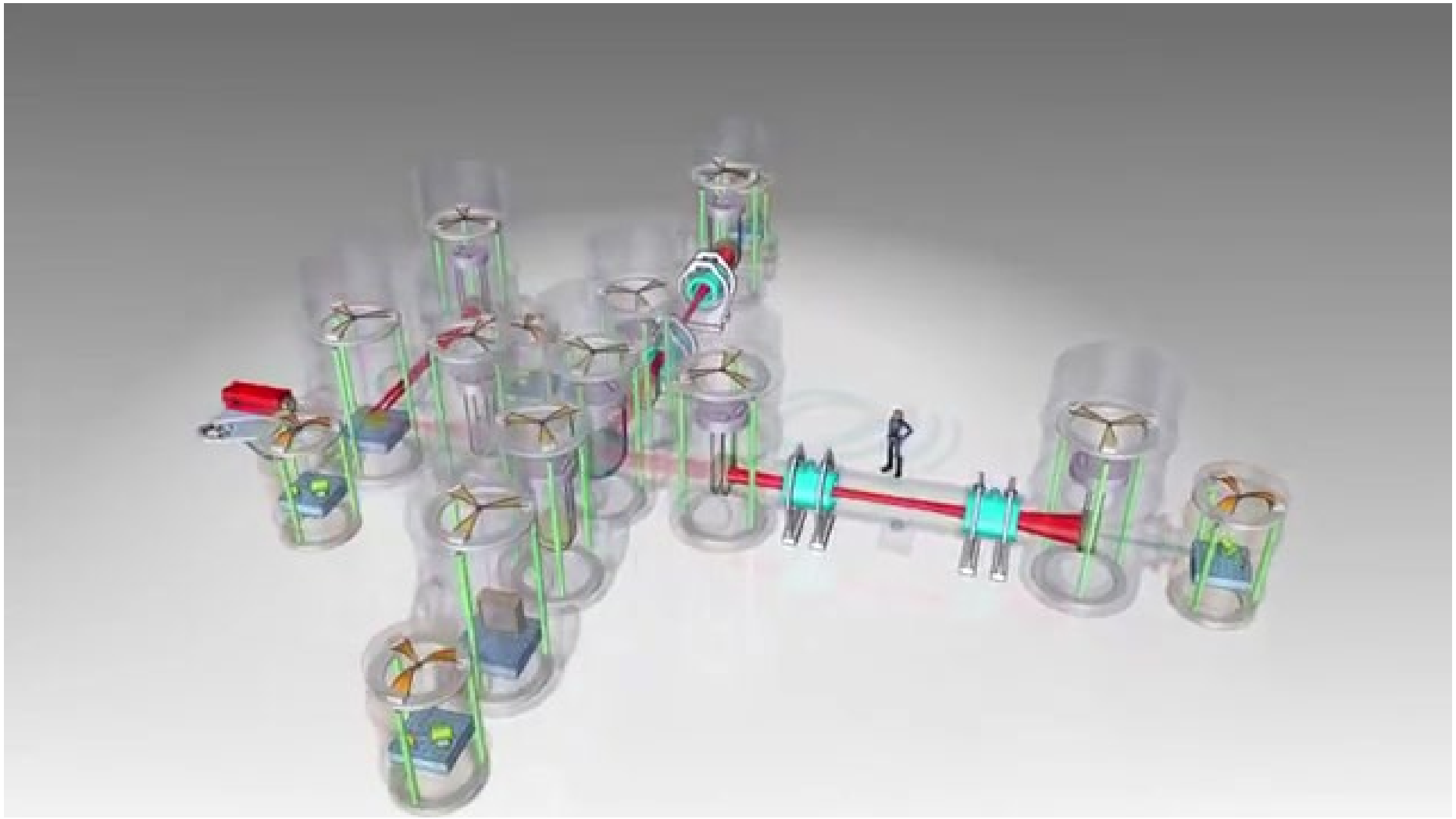
$$T = 2\pi\sqrt{\frac{l}{g}}$$

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

Costruiamo un GWD: sotto vuoto



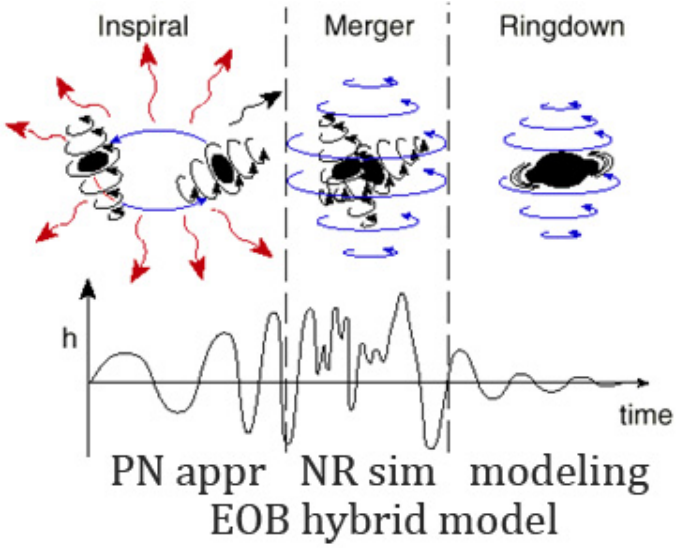
Costruiamo un GWD: Gigantismo

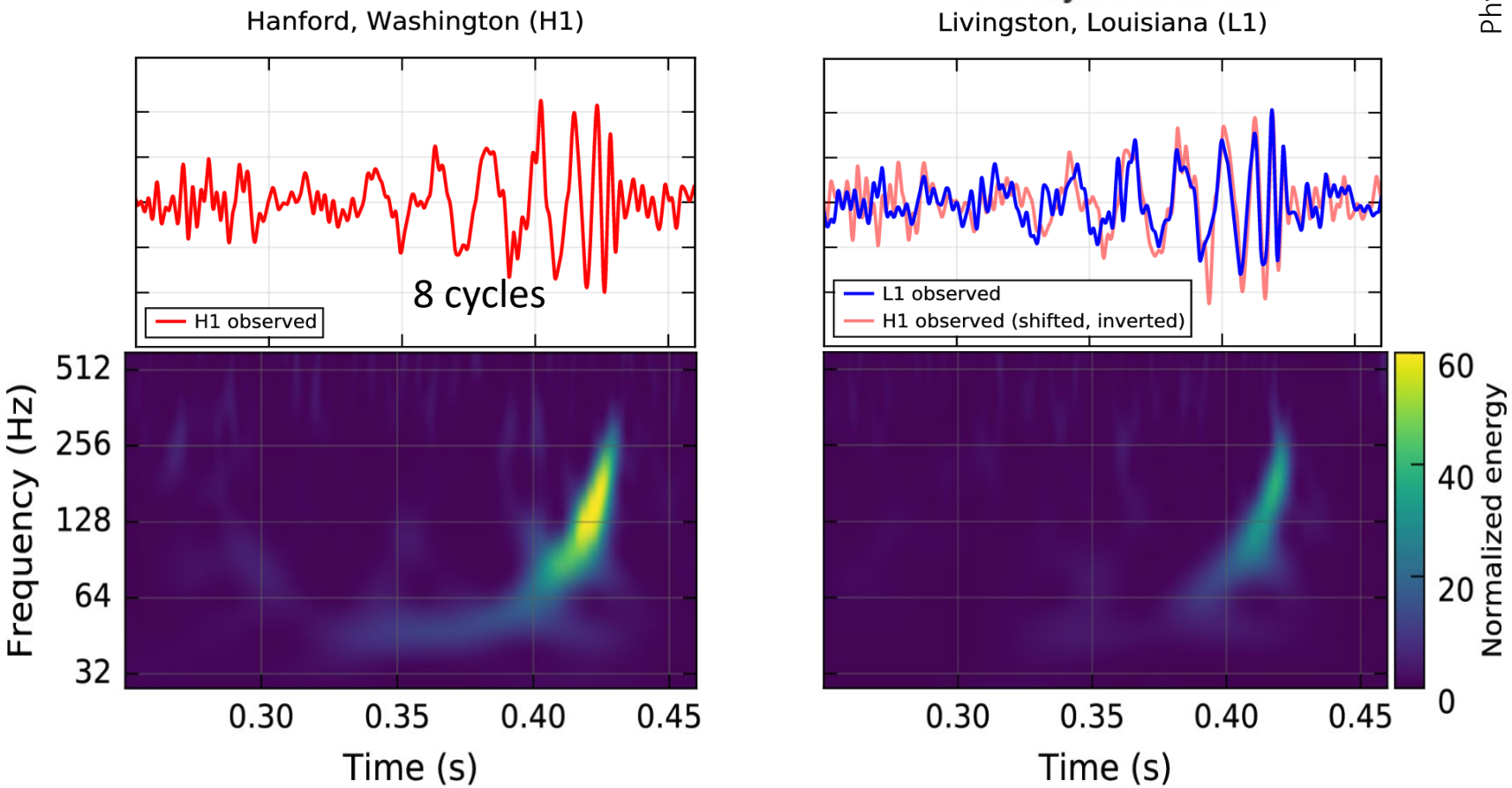


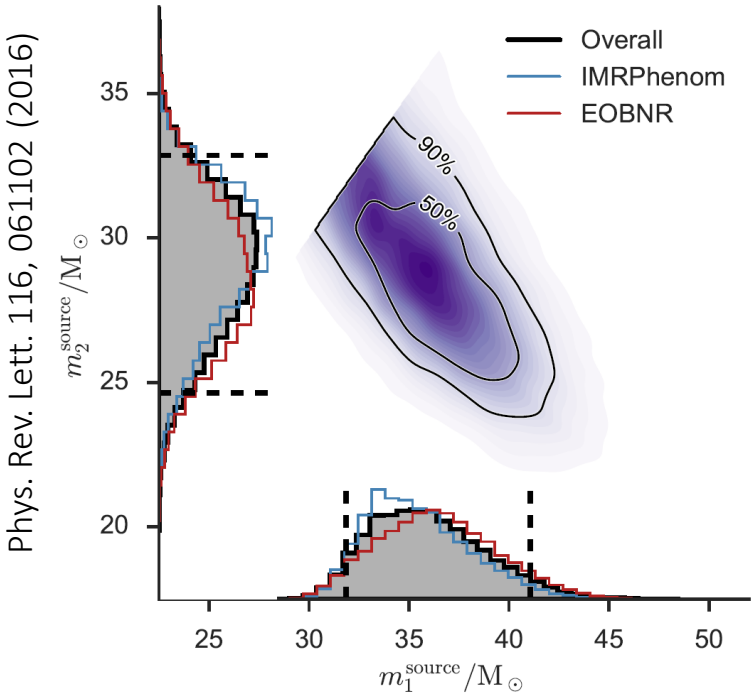
La scoperta delle onde gravitazionali

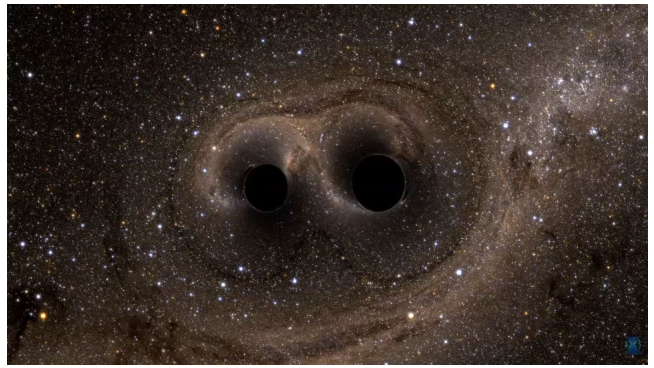
GW150914
The first detection
by the LIGO interferometers

Two BHs: $M_1 = 35.6 M_\Theta$, $M_2 = 30.6 M_\Theta$
$d_L = 440\ Mpc, \Delta\Omega = 182\ deg^2$

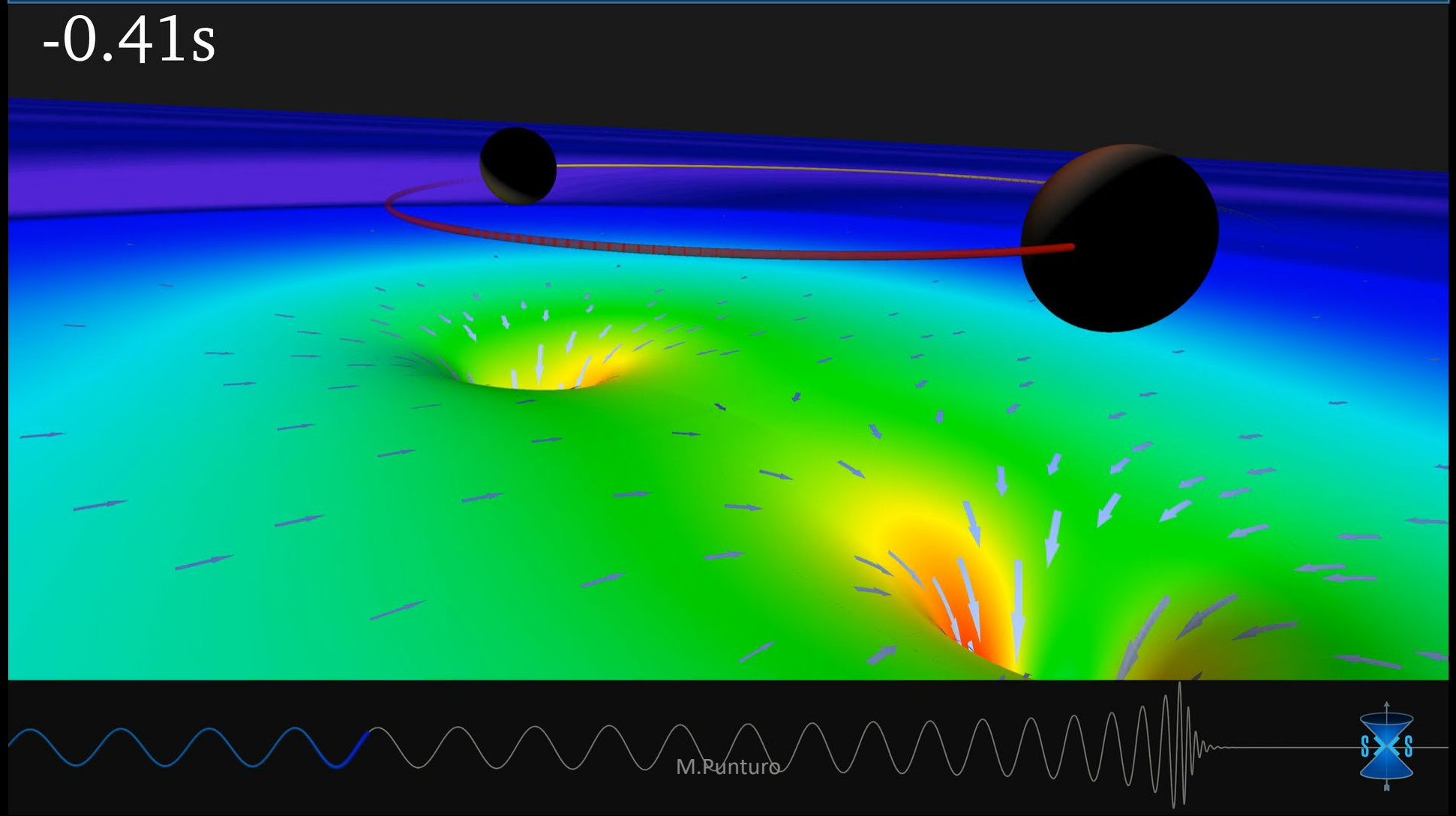




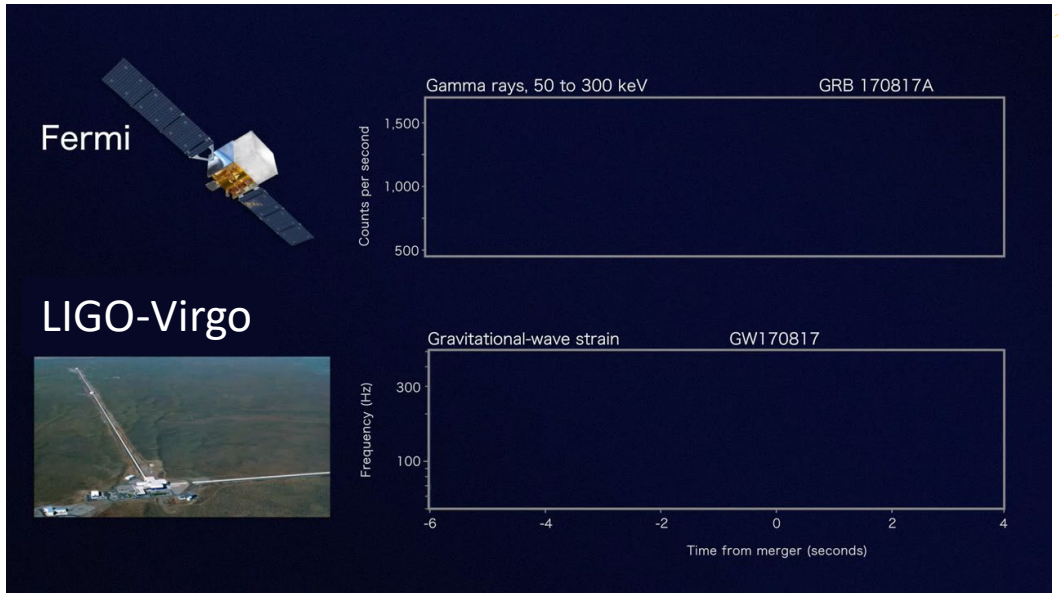




Nell’ultima frazione della collisione, la potenza emessa è pari a 100.000 miliardi di miliardi di soli

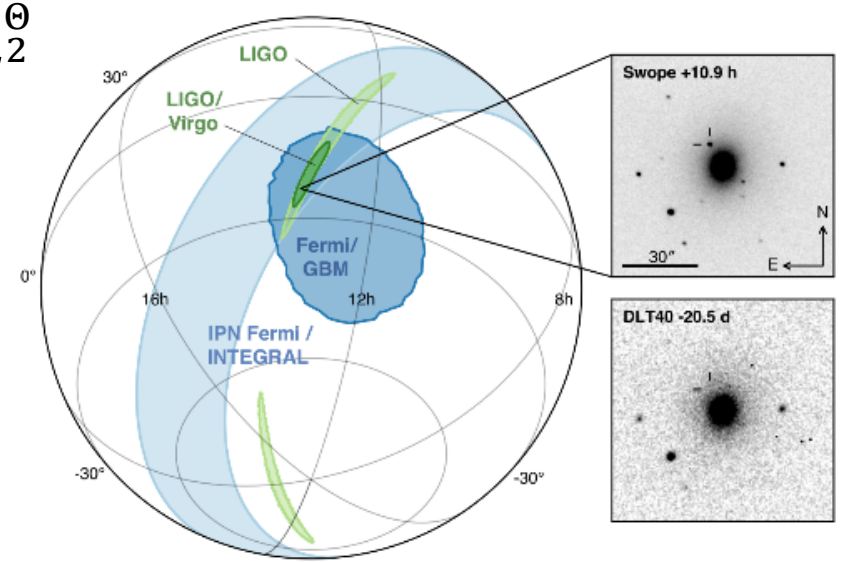


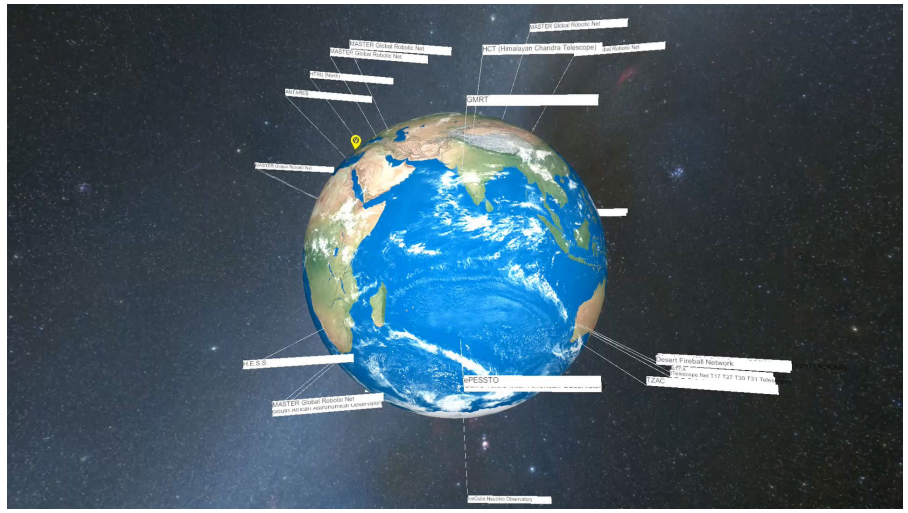
GW170817-The multimessenger era



Two Neutron Stars:

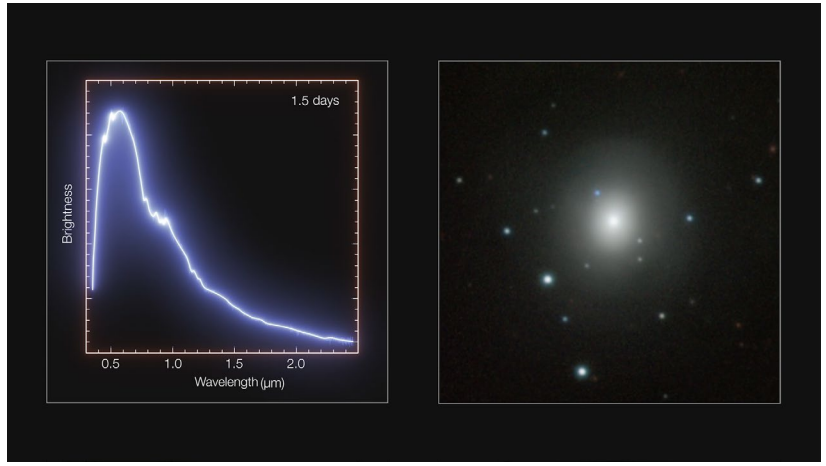
$$M_1 = 1.46 M_\Theta \, , M_2 = 1.27 M_\Theta$$
$$d_L = 40 \; Mpc, \Delta\Omega = 16 \; deg^2$$

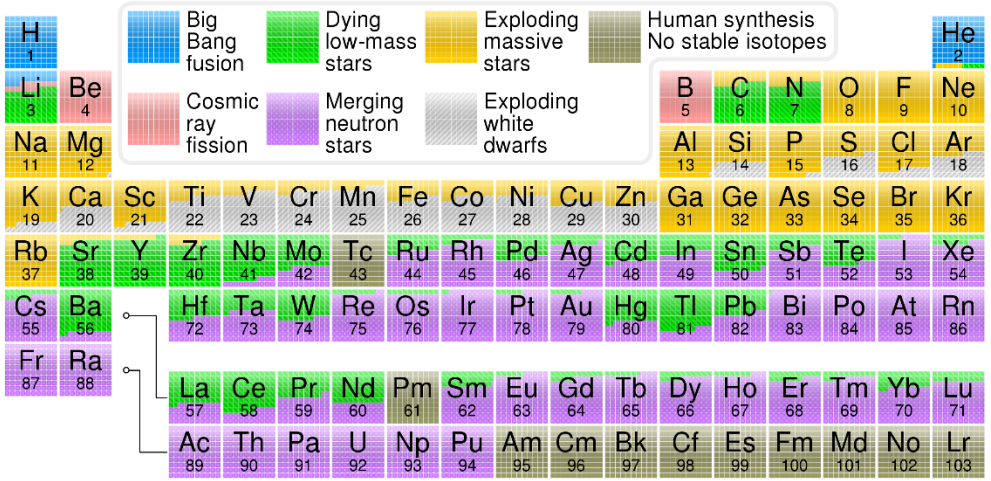


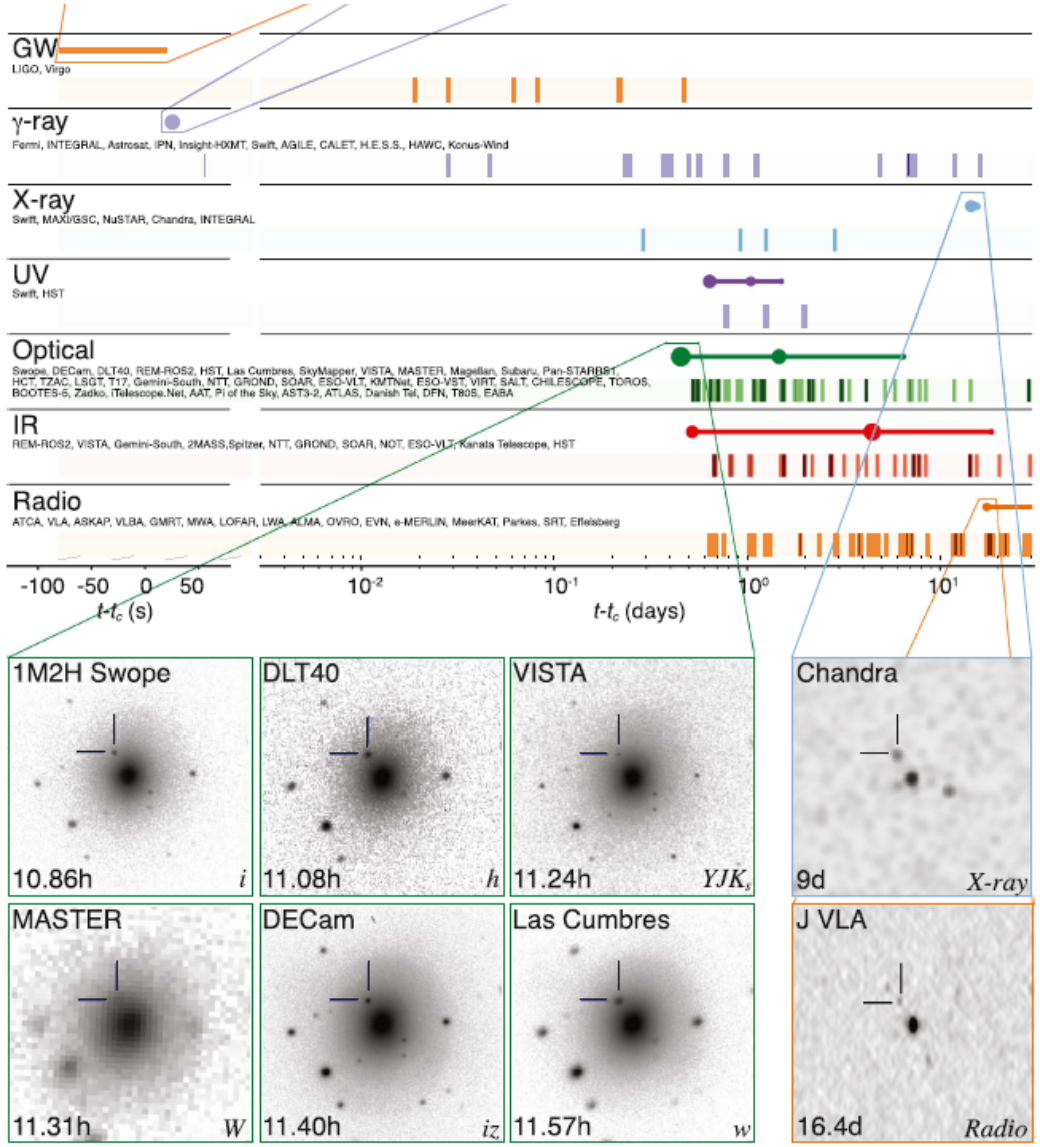


The dawn of the Multimessenger astronomy

- (since) few hours later 70 telescopes and detectors observed the emission in (progressively) all the frequency bands of the EM spectrum

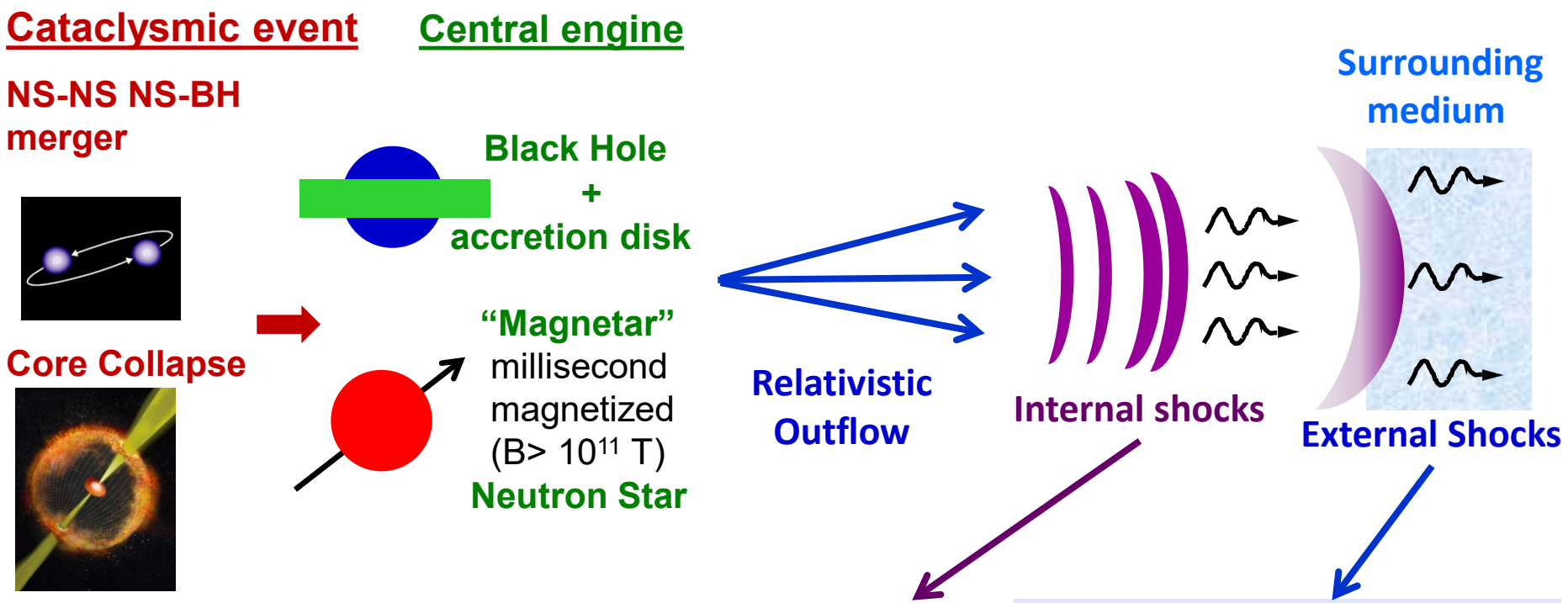






Electromagnetic Follow-up

- Steps in the generation of the e.m. follow-up



Prompt emission

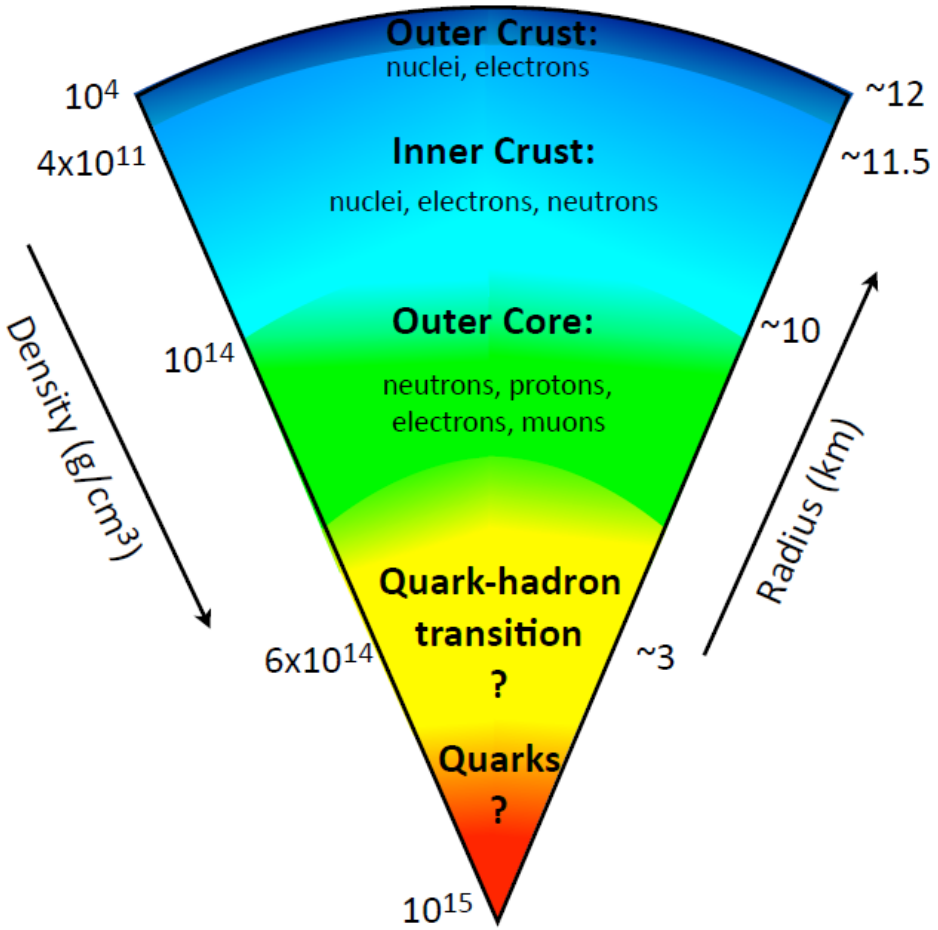
ϒ-ray - within seconds

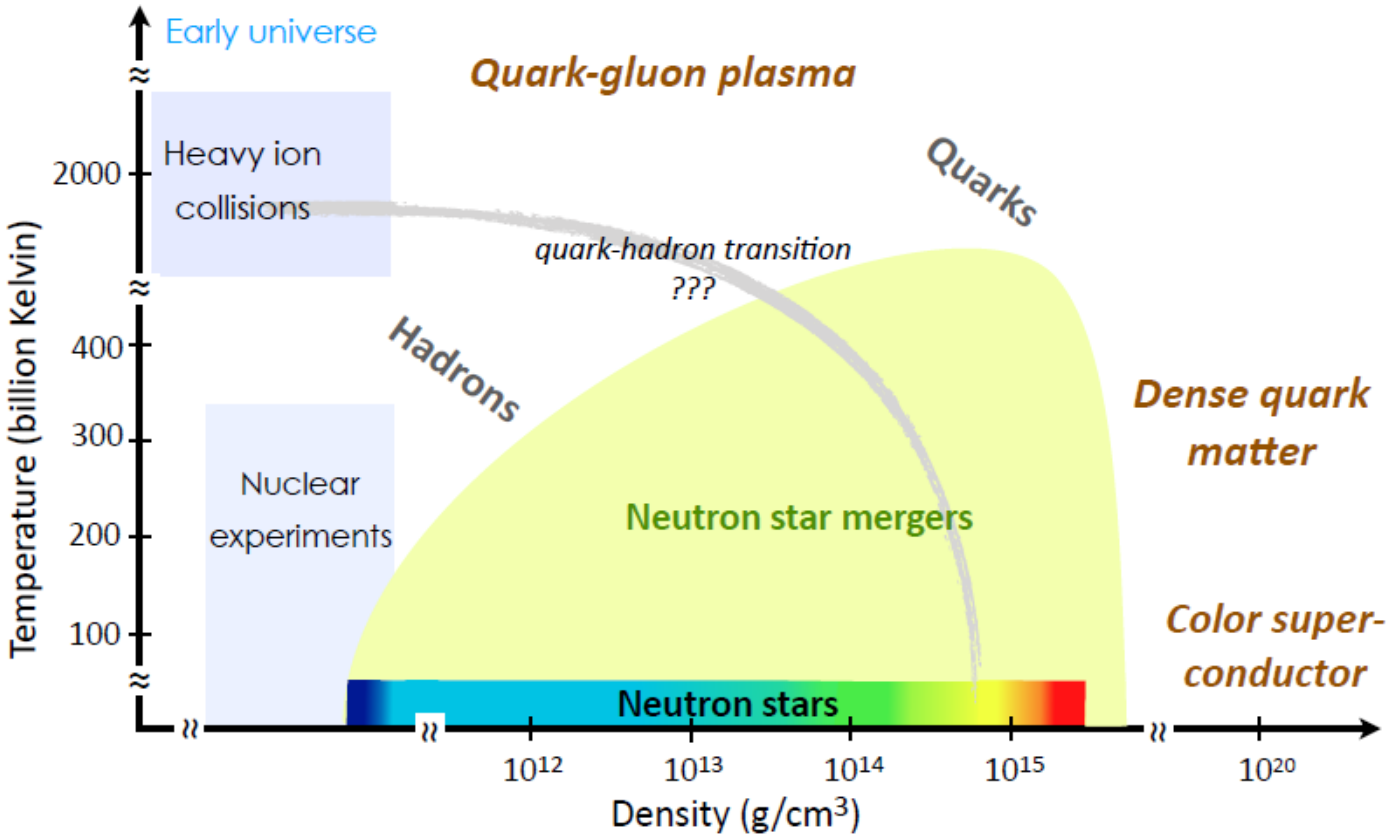
Afterglow emission

Optical, X-ray, radio - hours, days, months

Neutron Star is a nuclear physics lab

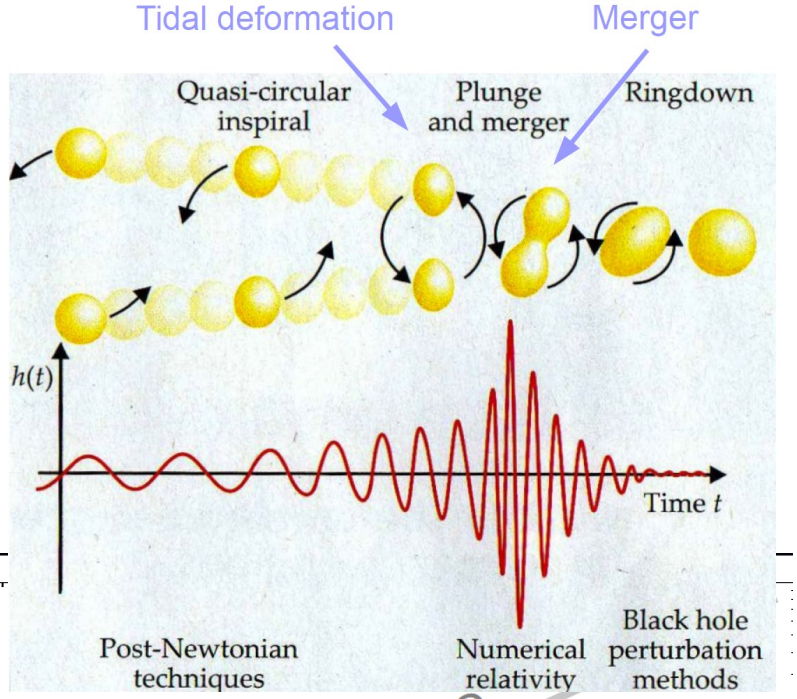
- Neutron stars are an extreme laboratory for nuclear physics
  - The external crust is a Coulomb Crystal of progressively more neutron-reach nuclei
  - The core is a Fermi liquid of uniform neutron-rich matter ("Exotic phases"? Quark-Gluon plasma?)

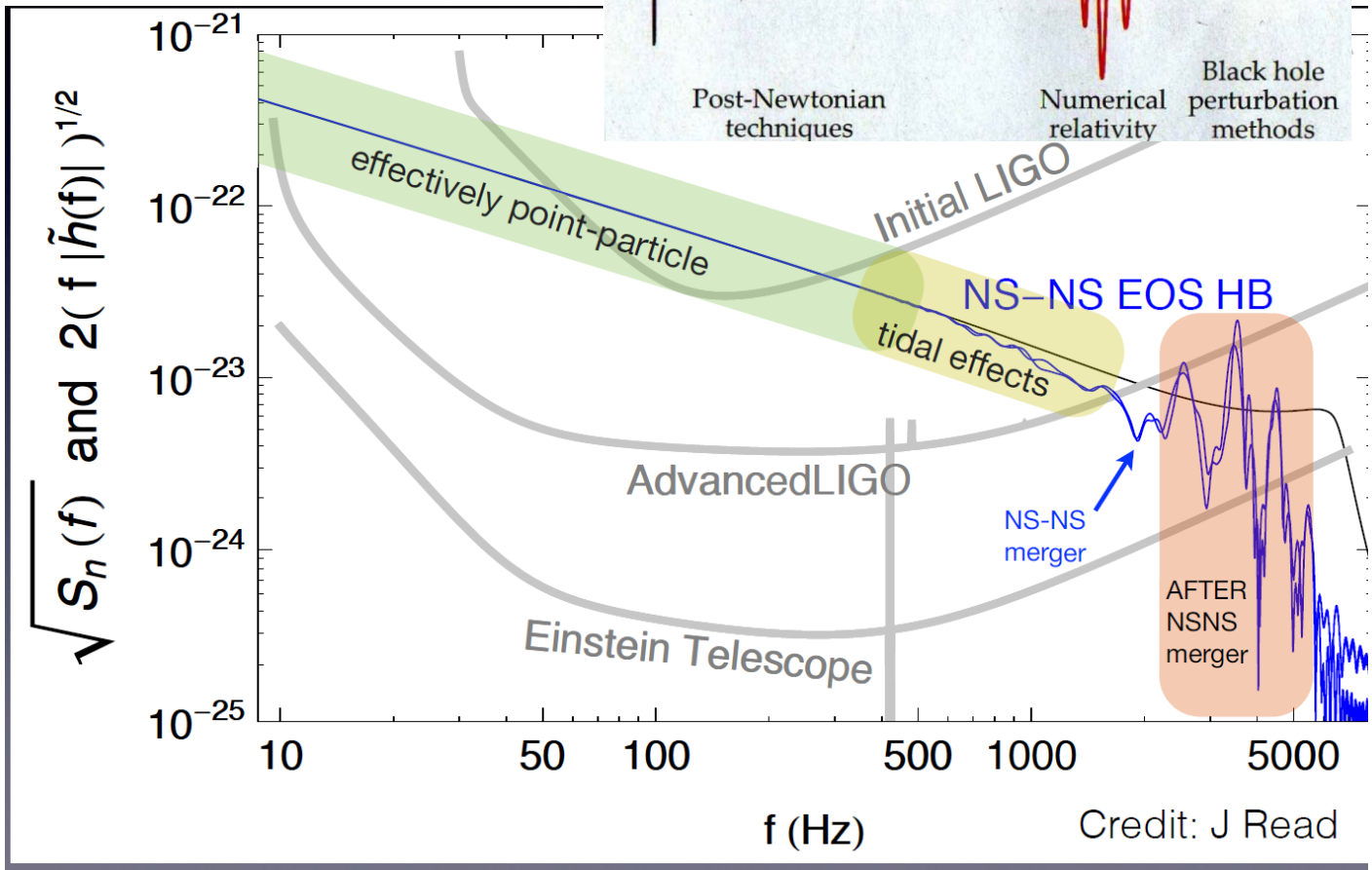




Observing BNS deformation

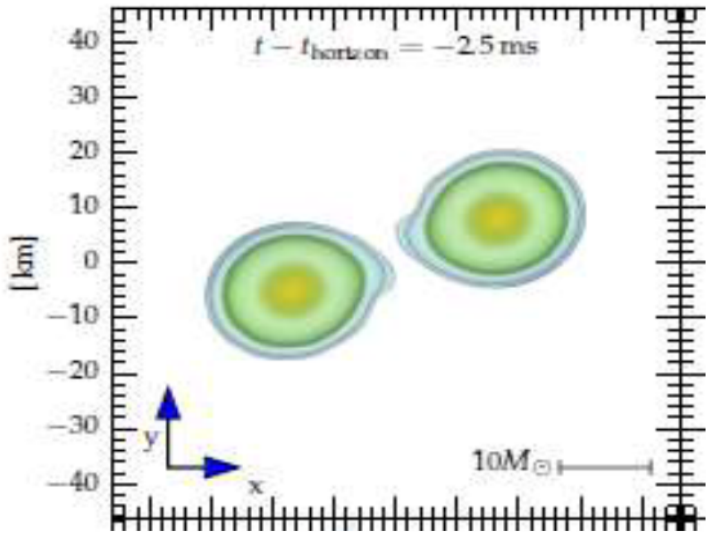
- GW observation from NS coalescing binaries could constrain the EOS:
  - Tidal deformation λ of the NS under external field is related to its EOS and it affects the binary orbital evolution
  - Crucial:
    - High quality templates
    - high SNR





Tidal deformation in BNS mergers

Neutron star in an external, inhomegeneous gravitational field becomes tidally deformed

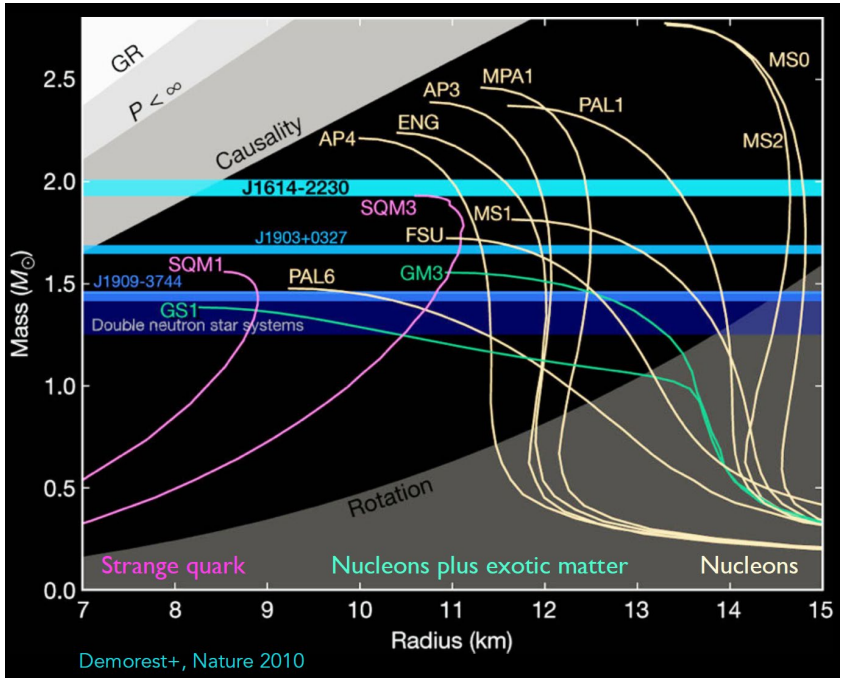


Haas+16

$$Q_{i,j} = -\lambda \mathcal{E}_{i,j}$$

$$\lambda = \left(\frac{2}{3}\frac{R^5}{G}k_2\right)$$

- $Q_{i,j}$ quadrupolar moment
- $\mathcal{E}_{i,j} = \frac{\partial^2 \Phi}{\partial x_i \partial x_j}$ tidal field
- k_2 quadrupolar tidal polarizability
- R radius of the star

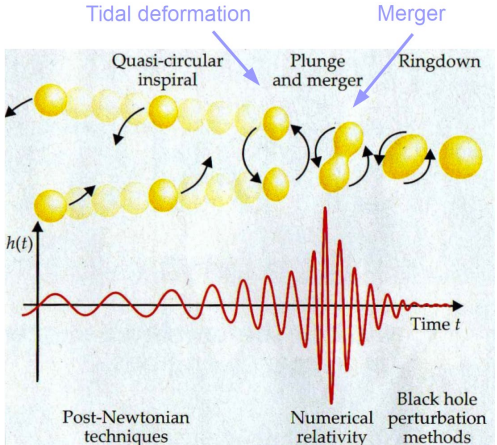


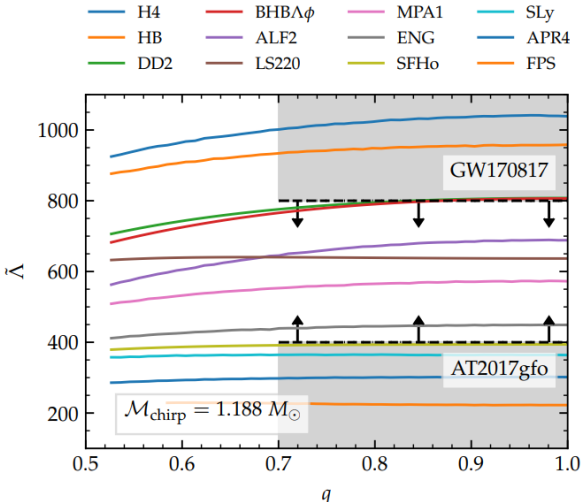
Demorest+, Nature 2010

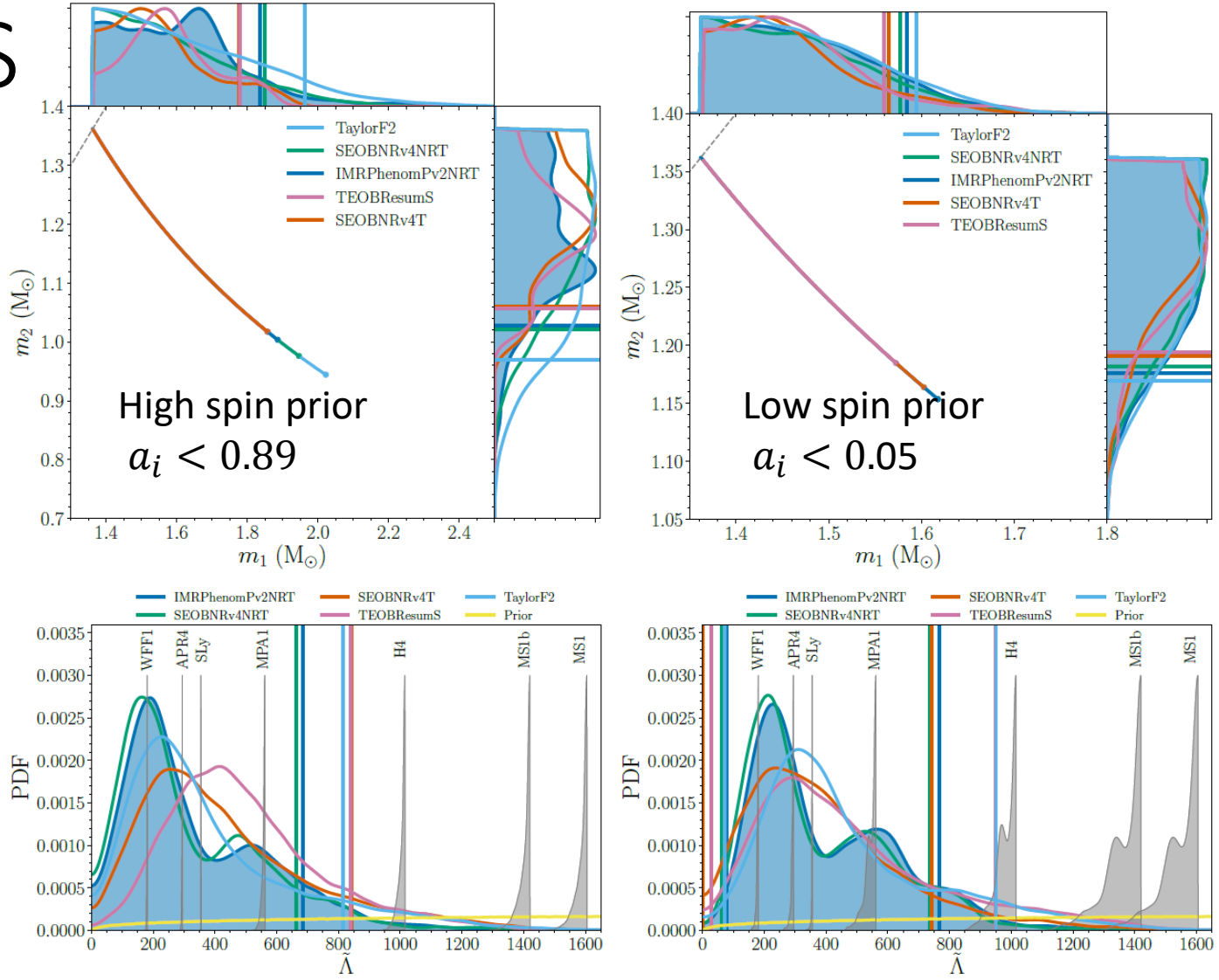
- $R = R(\mathrm{EOS}, M) \quad \Rightarrow \quad \lambda = \lambda(M, EOS)$
- combination of λ's of the two NS in the GW signal

Constraining the NS EOS

- Measuring the tidal deformation through the dephasing in the GW signal is possible to constrain the EOS of the NS
- Critical elements
  - Number of detections
  - Quality of the templates
  - SNR







arXiv:1811.12907

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

Multimessenger fundamental physics

Speed of GW vs speed of light

- GW and GRB arrived with a $\triangle t = t_{GW} - t_{\gamma} = 1.74 \pm 0.05$ s
- Knowing the distance D of the GW170817 event it is possible to measure the difference of speed between GW (graviton) and light (photon):

$$\frac{\Delta v}{v_{\gamma}} \approx v_{\gamma} \frac{\Delta t}{D}$$

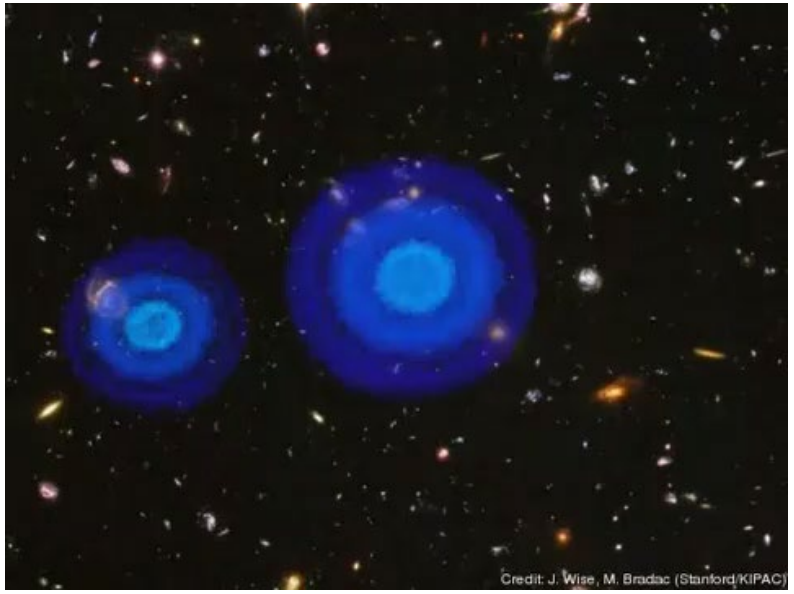
- Where $\triangle v = v_{GW} - v_{\gamma}$
- Considering the emission of light either simultaneous with the emission of GW or within 10 s of delay, it is possible to constrain the difference of speed

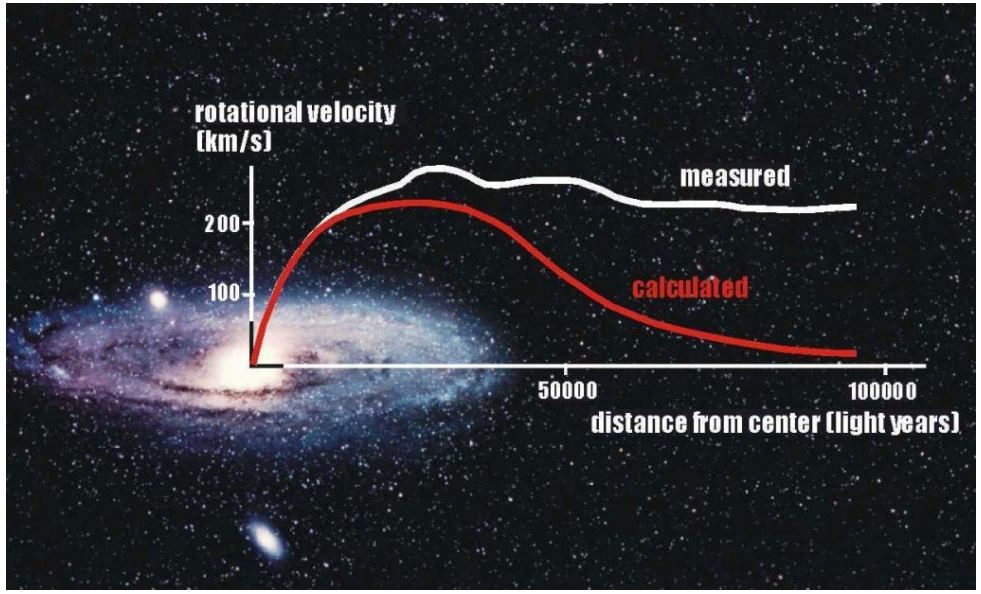
$$-3 \times 10^{-15} \leq \frac{\Delta v}{v_{\gamma}} \leq 7 \times 10^{-16}$$

Multimessenger fundamental physics

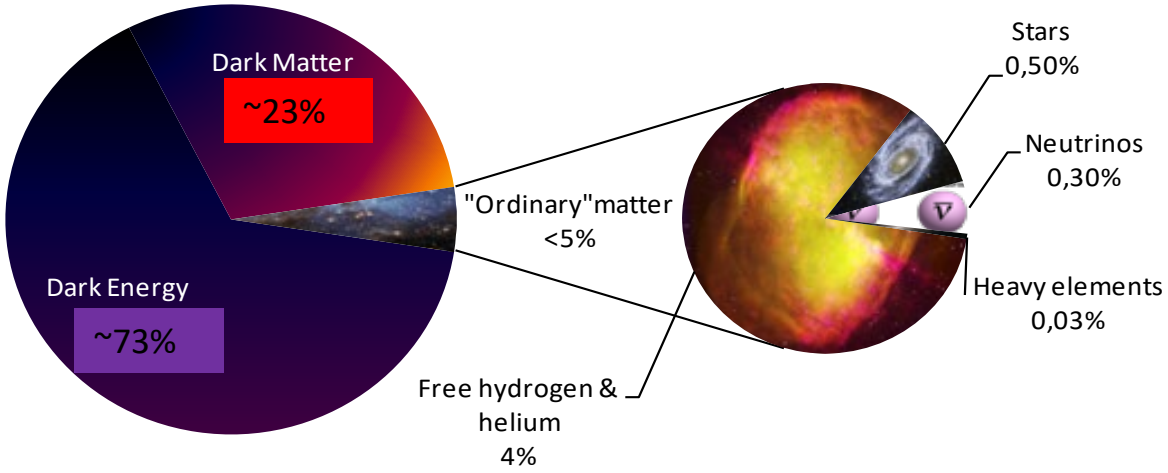
Principle of equivalence, Modified Gravity theories and Dark Matter

Bullet cluster





- Because of these observations and from the increasing velocity of universe expansion Dark Matter and Dark Energy have been introduced



Multimessenger fundamental physics

Principle of equivalence, Modified Gravity theories and Dark Matter

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

- The introduction of Dark Matter is essentially a way to keep the Einstein Equation of field , modifying the «matter» part:

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

- But it isn't the only way to do; we can act on the «curvature» part:

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

- For example, this is done by replacing the Ricci's tensor R with a function f(R)
- *f(R)* theories are quite interesting because it is possible to introduce effects like *G=G(t)*, or Yukawa-like gravitational potential, massive graviton and Dark matter
- Defining $f(R) \equiv \frac{\partial f(R)}{\partial R}$ the field equation becomes

$$f'(R(g))\, R_{\mu\nu}(g) - \frac{1}{2} f(R(g)) g_{\mu\nu} - \nabla_\mu \nabla_\nu f'(R(g)) + g_{\mu\nu} \Box f'(R(g)) = \kappa T_{\mu\nu}$$

Higher order Gravity (4tn)!

High order part can be treated as a scalar (from here the name tensor-scalar theories) and it "replaces" Dark Matter

2nd order part that resembles Einstein tensor and reduces to it if *f(R)=R*

4th order "curvature" part, that reduces to zero if *f(R)=R*

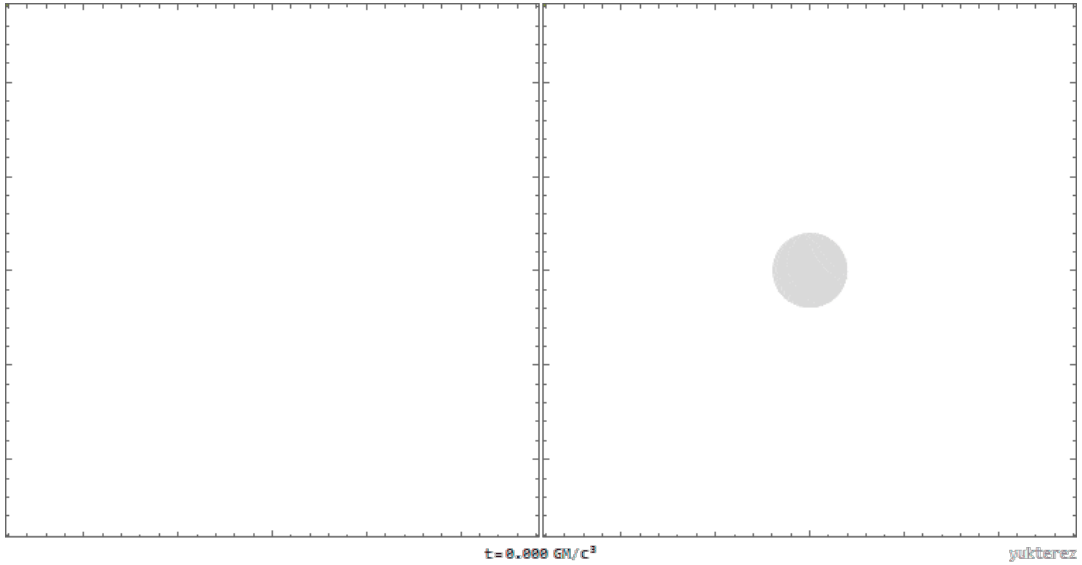
Multimessenger fundamental physics

Principle of equivalence, Modified Gravity theories and Dark Matter

- 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:

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

r$_o$ observation point
r$_e$ emission point
U(**r**) gravitational potential



- The factor γ parametrises the coupling of the wave with the spacetime curvature and then the departure from the Einstein General Relativity where $\gamma_{GW} = \gamma_{EM} = 1$

Multimessenger fundamental physics

Principle of equivalence, Modified Gravity theories and Dark Matter

- To compute g measuring δ_{ts} we need to know *U* from here to the GW170817 sources, but to define an upper limit is enough to consider the Milky Way mass outside a sphere if 100kpc

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

- The best absolute bound on γ_{EM} is $\gamma_{EM} - 1 = (2.1 \pm 2.3) \times 10^{-5}$, obtained with radio wavelength and the Cassini spacecraft
- The measured correspondence between γ_{EM} and γ_{GW} implies:
  - A confirmation of the Equivalence principle
  - The suppression of many alternative (tensor-scalar) gravity theories that require a different behaviour of gravitons and photons in a gravitational field

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!

Horndeski

Beyond H.

Viable after GW170817 (c_g=c)	Not Viable after GW170817 ($c_g \neq c$)
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
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

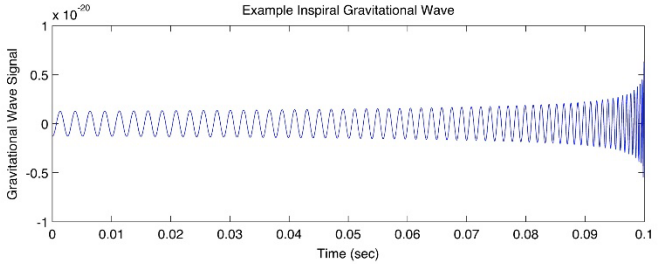
Also strongly affected:
- Vector Dark Energy
- Einstein Aether theories
- Some sectors of Horava gravity
- TeVeS
- MOND-like theories
- Generalized PROCA theories

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

Nicola Bartolo, private communication

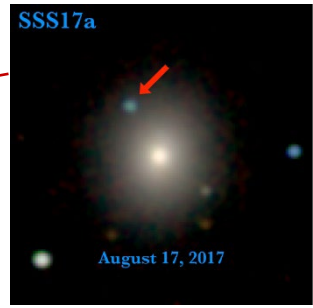
Measure of H_0

- 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 $H_0 = 70.0^{+12.0}_{-8.0}\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$



$$H_0 d_L = cz$$

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



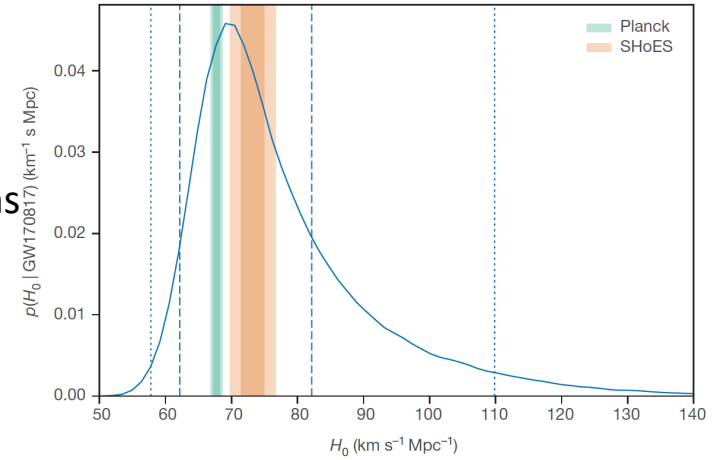
From GW: redshifted mass and luminosity distance

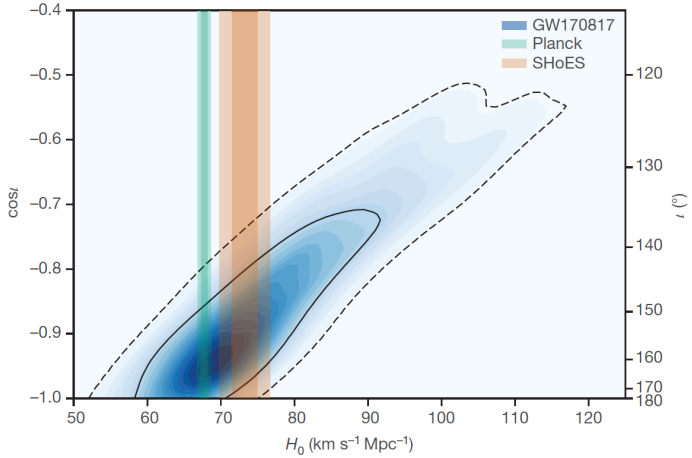
$$\Psi(f) \propto 2\pi f t_c - \Phi_c - \frac{\pi}{4} + \frac{3}{128}(\pi \mathcal{M}_z f)^{-5/3}\,[1 + \ldots]$$

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

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

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

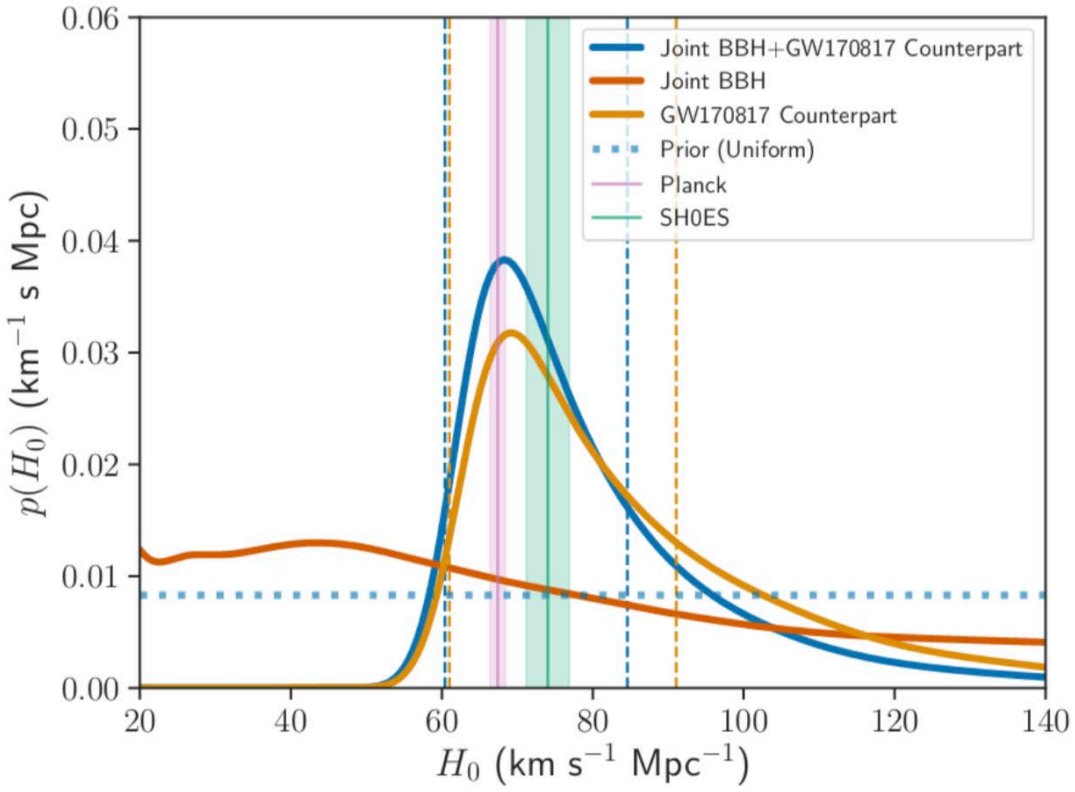




New Measure of H_0

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

arxiv:1908.06060

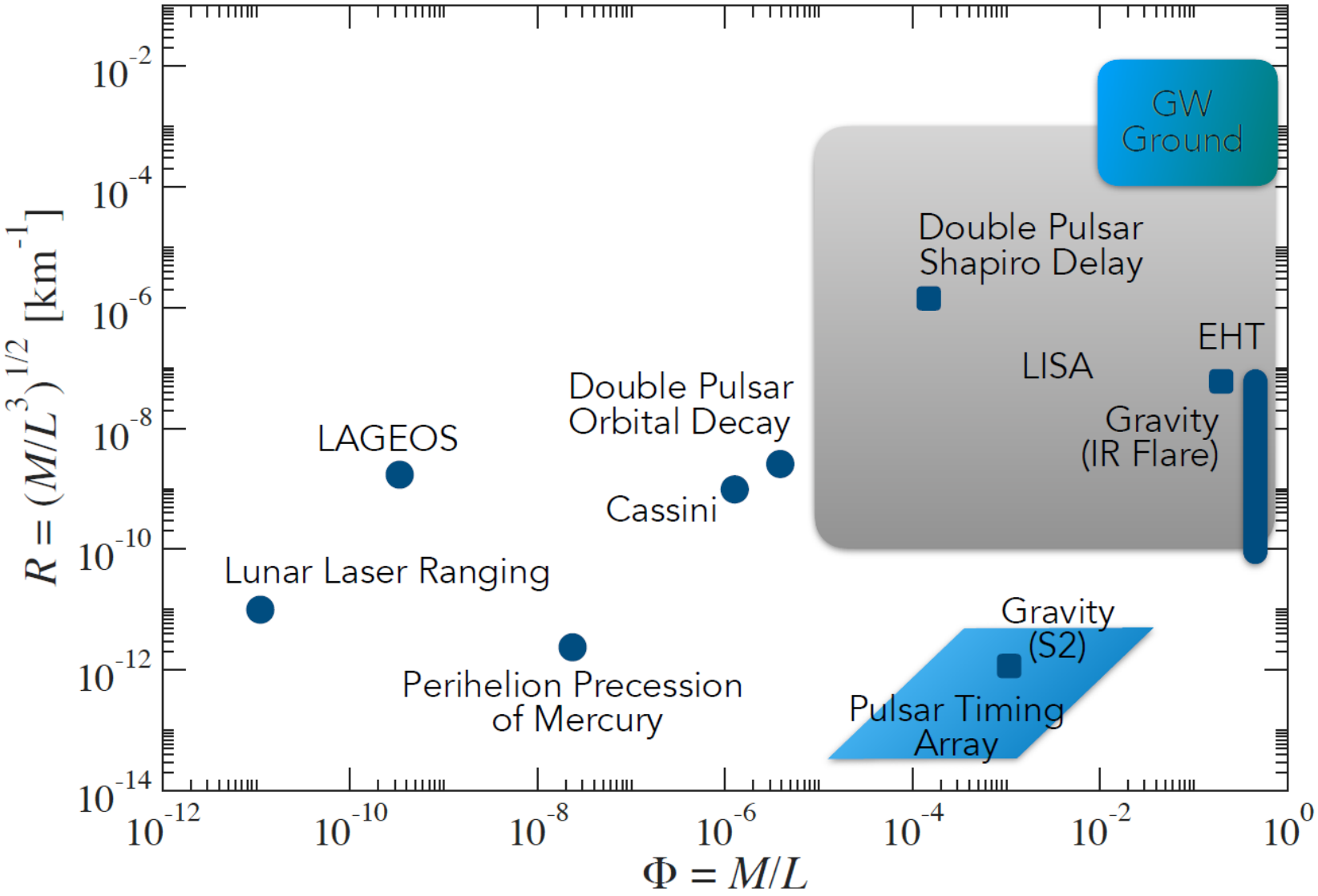


$$H_0 = 68^{+14}_{-7} \text{ km s}^{-1} \text{ Mpc}^{-1}$$

Probing GR in strong field conditions

- BBH coalescences allow to test GR in strong field conditions

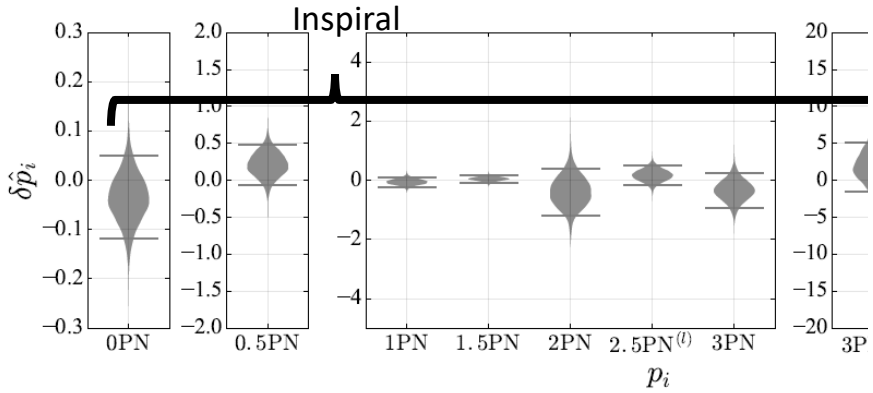
Yunes N. et al.
Phys. Rev. D 94, 084002 (2016)
Edited by ET science case team



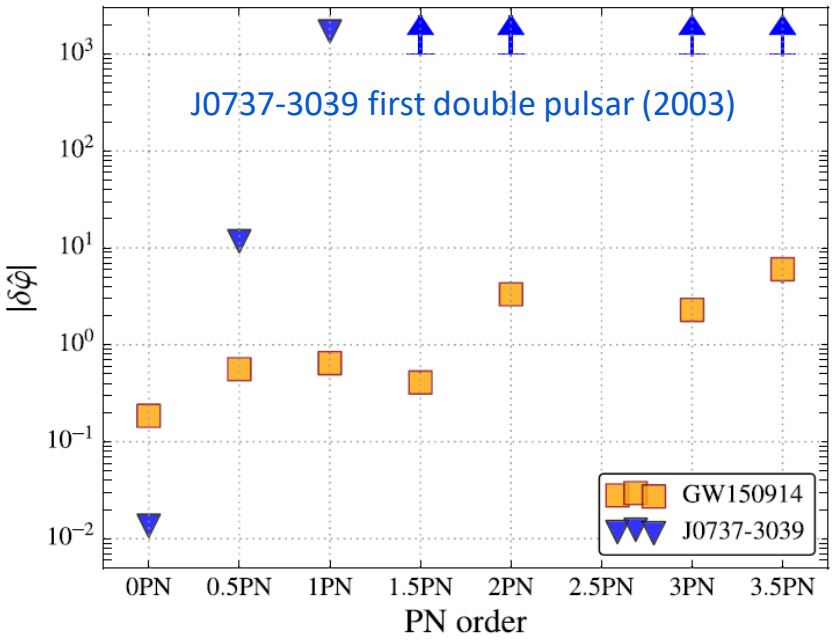
Test of GR: PN approximation

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

$$\Psi(f) = 2\pi f t_c - \varphi_c - \frac{\pi}{4} + \sum_{j=0}^{7} \left[\psi_j + \psi_j^{(l)} \ln f\right] f^{(j-5)/3}, \qquad \psi_j \to (1+\delta p_j)\psi_j$$



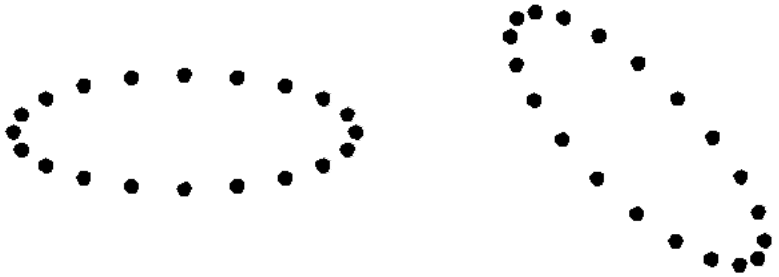
B. P. Abbott et al. (LIGO Scientific and Virgo Collaboration)
Phys. Rev. Lett. 118, 221101 – supplement material

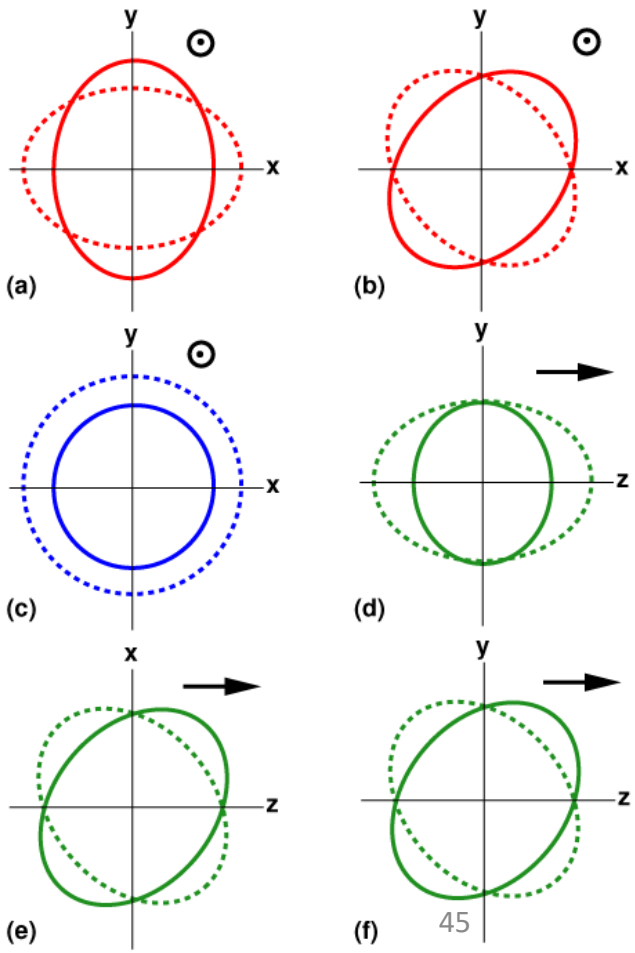


To be updated with O3 data, see R.Abbott et al (LIGO and Virgo Collaboration), arXiv:2004.08342, 27 April 2020

Alternative theories of Gravity: polarisations

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

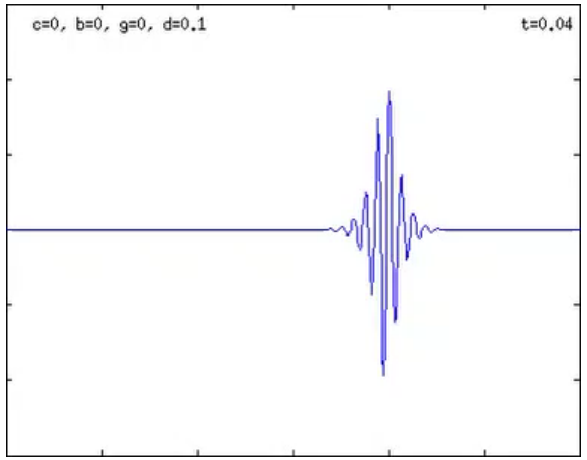




- Present and future GW detectors are setting stringent limits
  - GW170814:
    - Thanks to the presence of Virgo has been possible the evaluate the contribution of extra polarisations in the detected GW resulted disfavoured

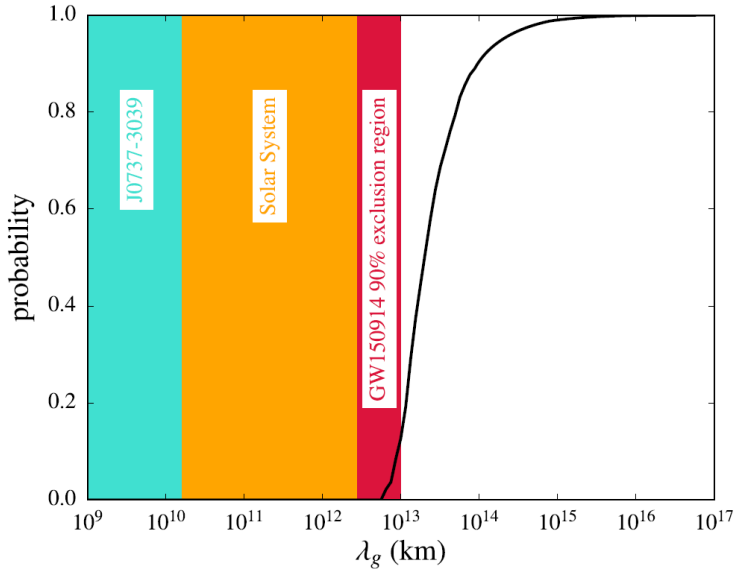
Massive Gravity: Is the Graviton massless?

- 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; $\lambda\!\!\!^{-}_C = (1.973 \times 10^{-7}$ m$)\times(1$ eV$/m_\gamma)$.

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

GWD network + E.M. followers

Scientific runs

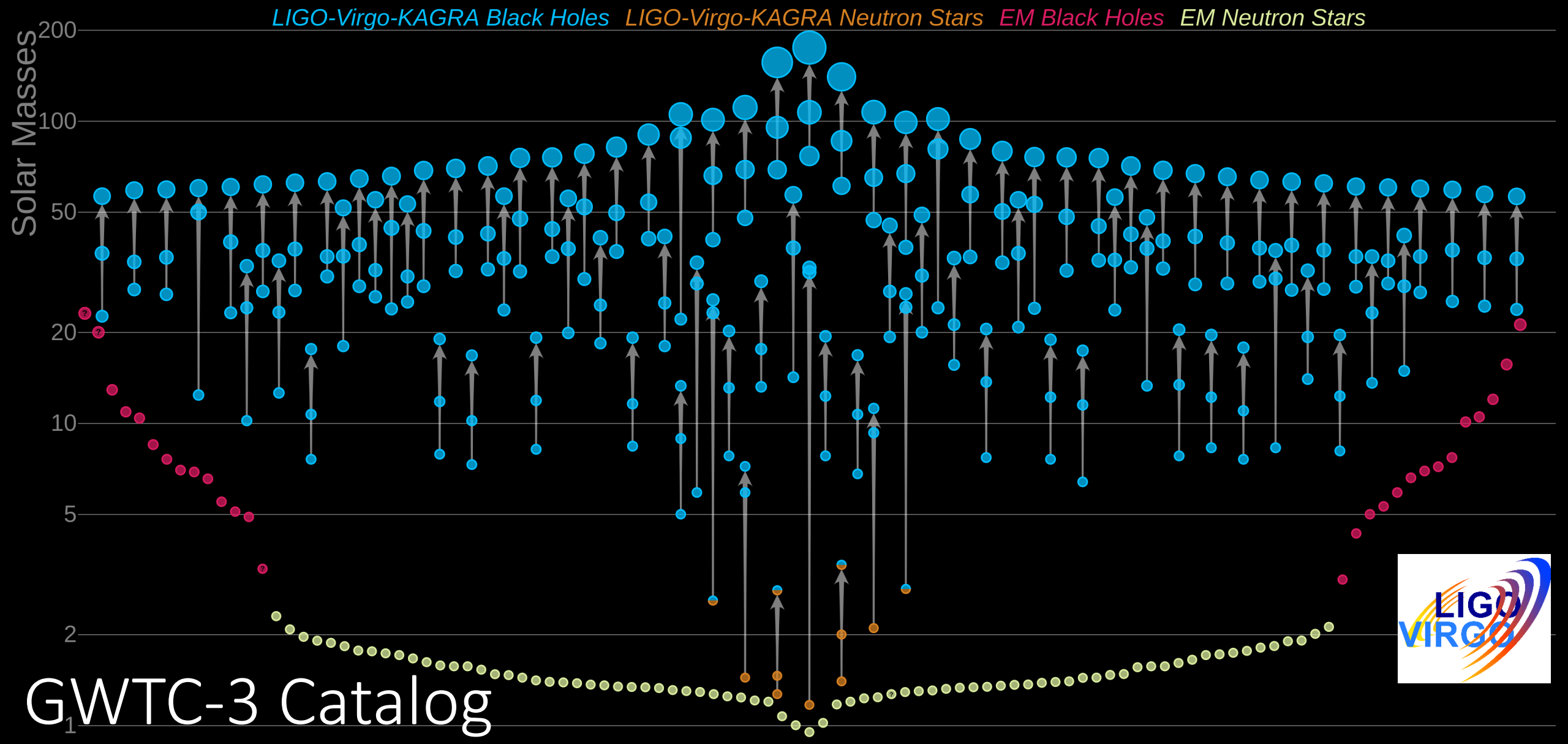
O1: 12 Sep 2015 → 19 Jan 2016
O2: 30 Nov 2016 → 25 Aug 2017 (Virgo: 1 Aug 2017 → 25 Aug 2017)

Published: Open data

O3:
O3a Apr 1 2019 → Oct 1 2019
O3b: Nov 1 2019 → ~~May 1~~ March 27 2020 (due to COVID-19)

Published discovery events and catalogue

Masses in the Stellar Graveyard

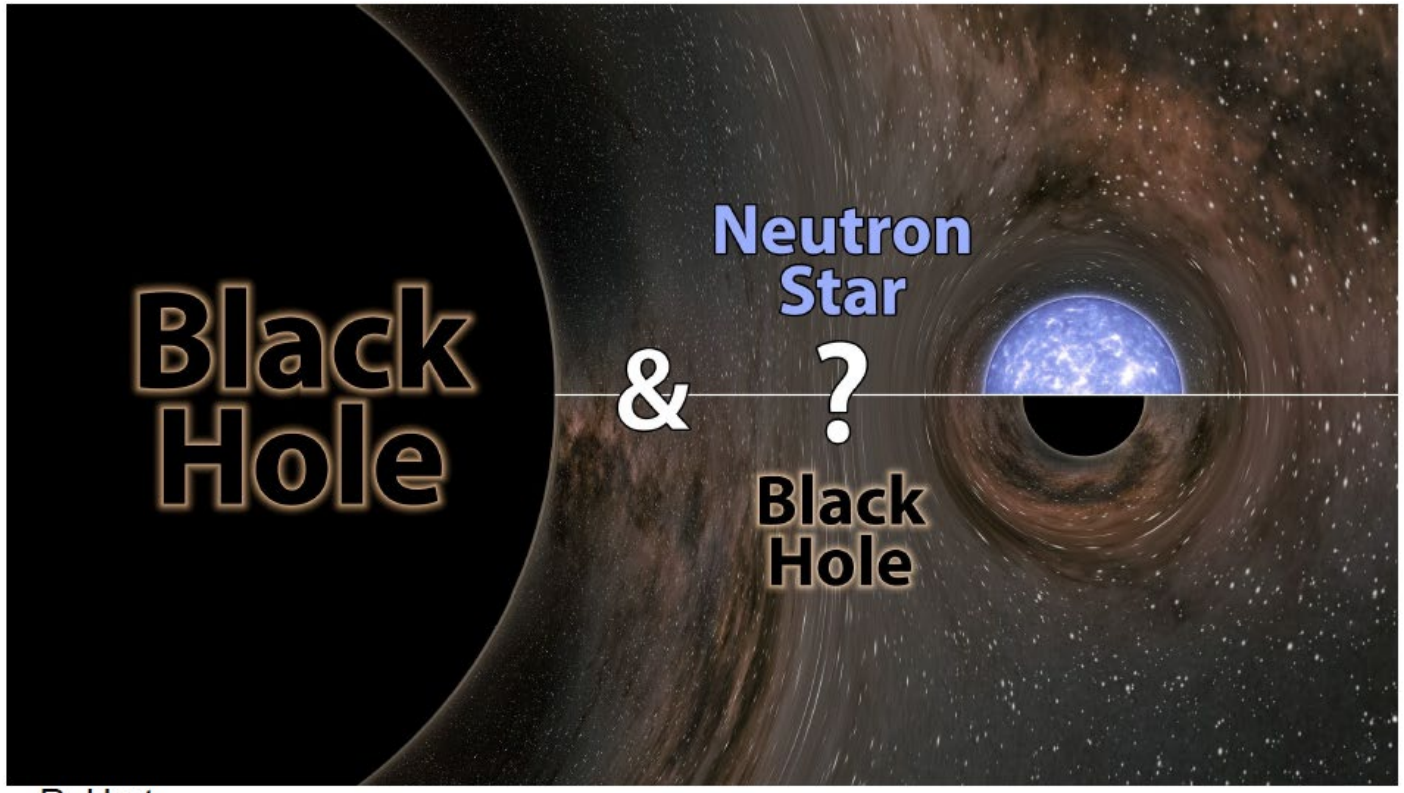


GWTC-3 Catalog

GW190814 – What is that?

- Gravitational Waves from the Coalescence of a 23 $M_\odot$ Black Hole with a 2.6 $M_\odot$ Compact Object (at 241^{+41}_{-45} Mpc)

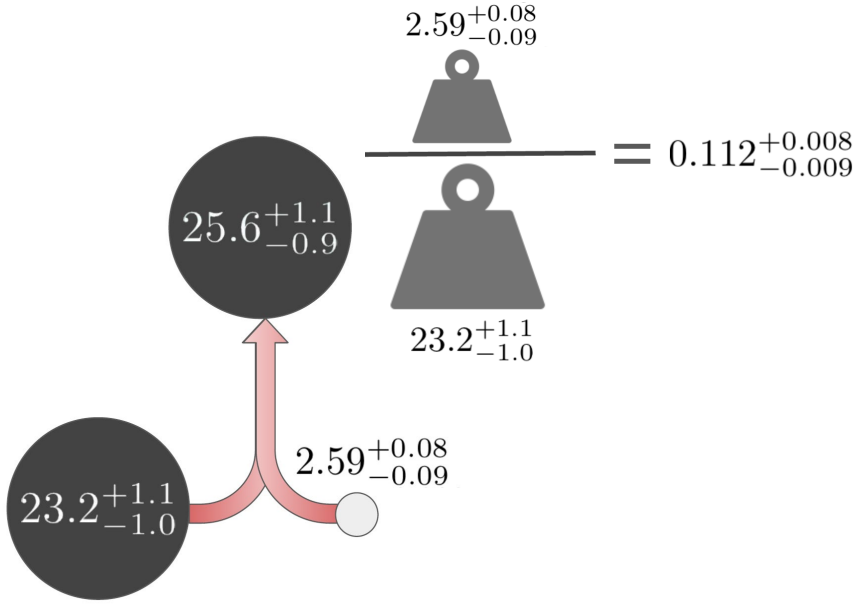
The APJ Letter, 896:L44, June 2020

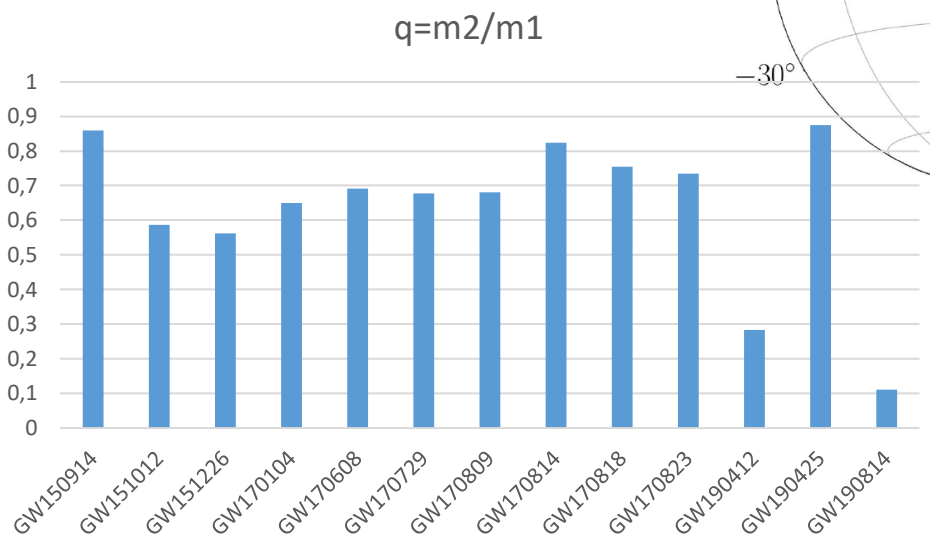


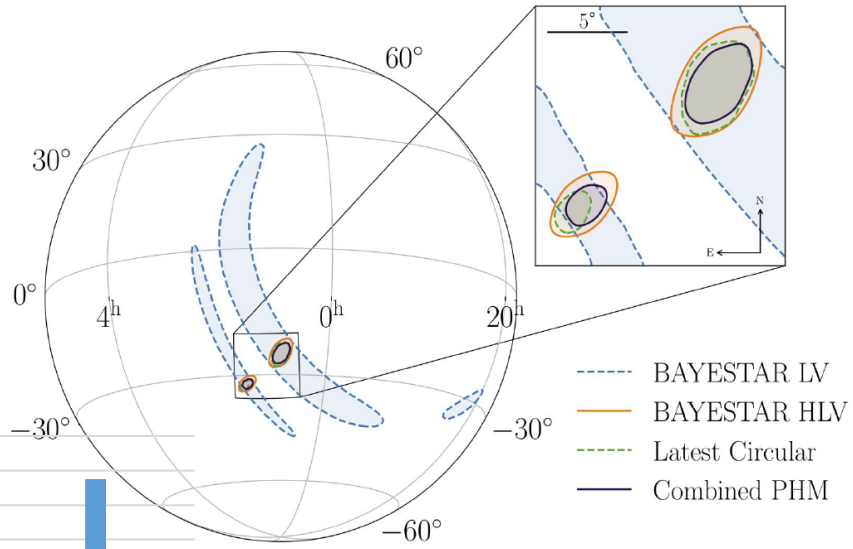
R. Hurt

GW190814 – Loud event

- Detected online by Livingstone and Virgo, Hanford in commissioning mode, but undisturbed
  - Hanford data recovered offline
  - Best localised source (green skymap 23 deg^2)
  - The most mass asymmetric GW event detected

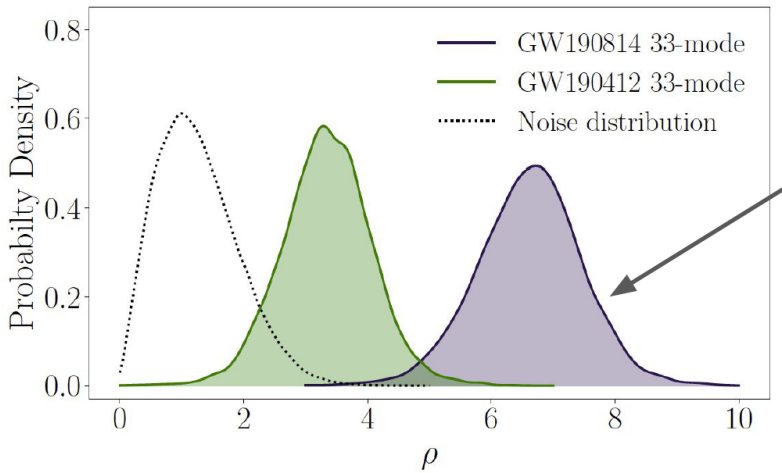






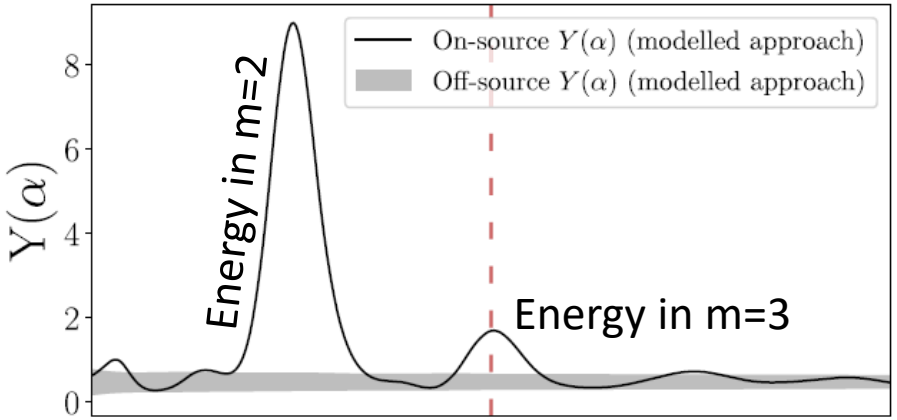
GW190814 – Higher order multipoles

- Being the mass distribution so asymmetric:

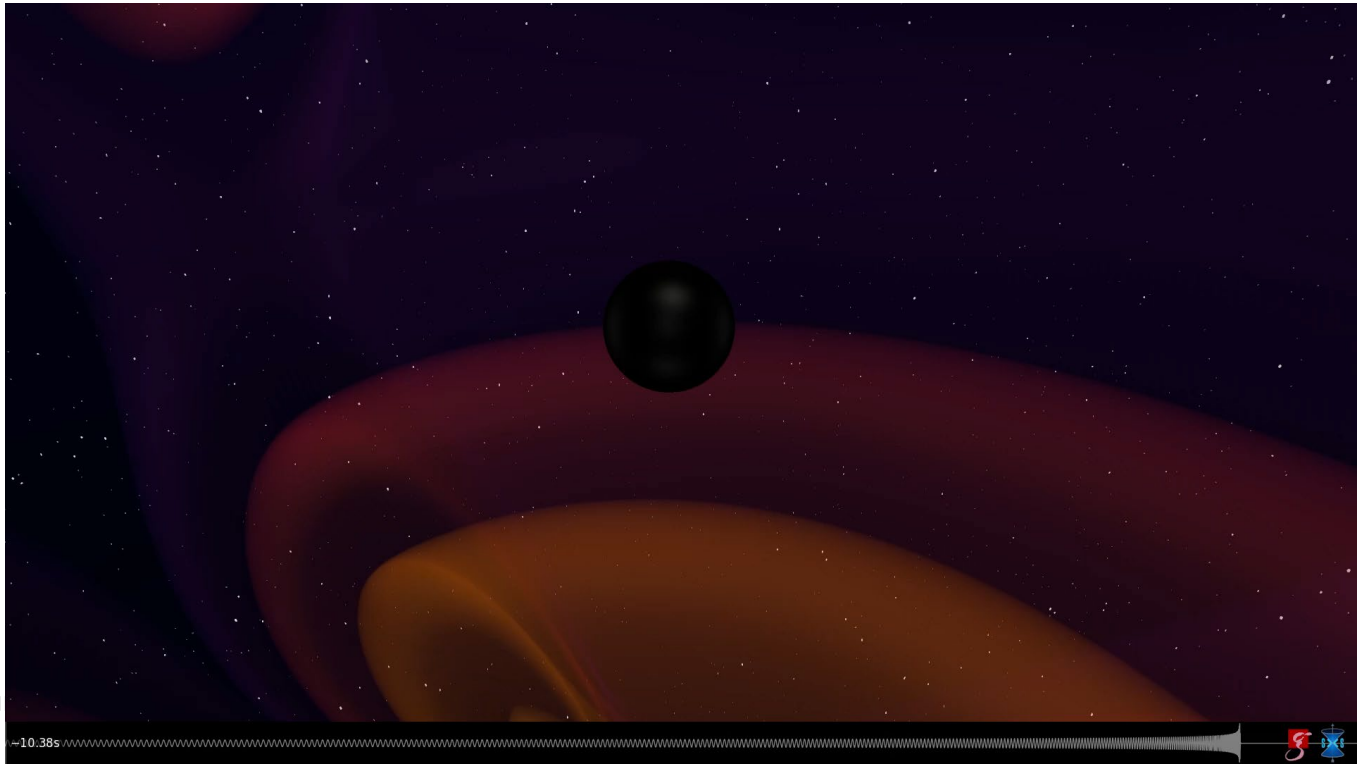


GW190814 has the strongest evidence for Higher order multiples that we have ever detected.

SNR in 33 multipole nearly as high as the total SNR of GW151012



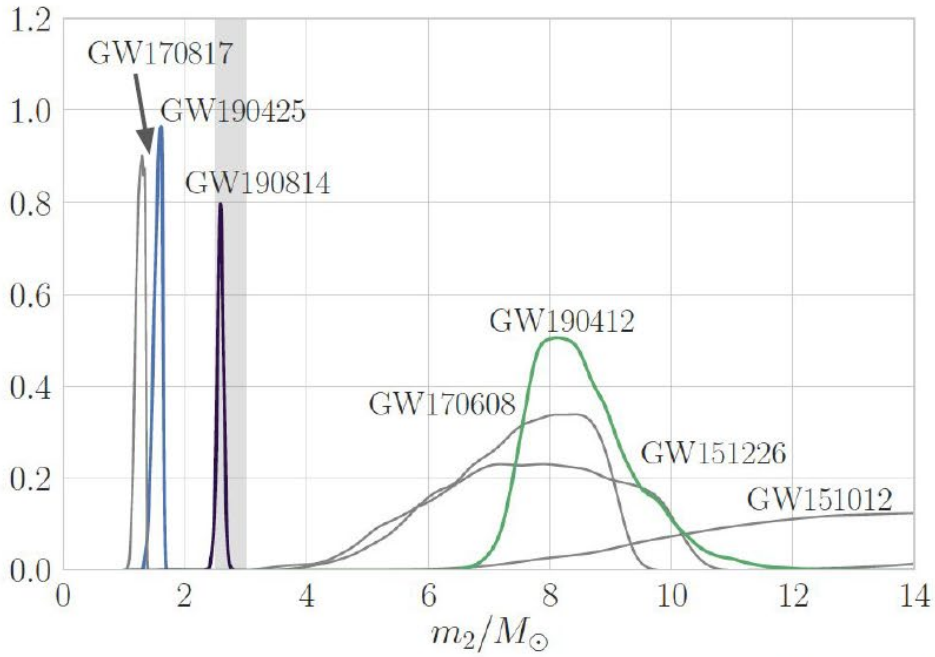
- Test of GR on strongly asymmetric mass distribution (GR "validated")

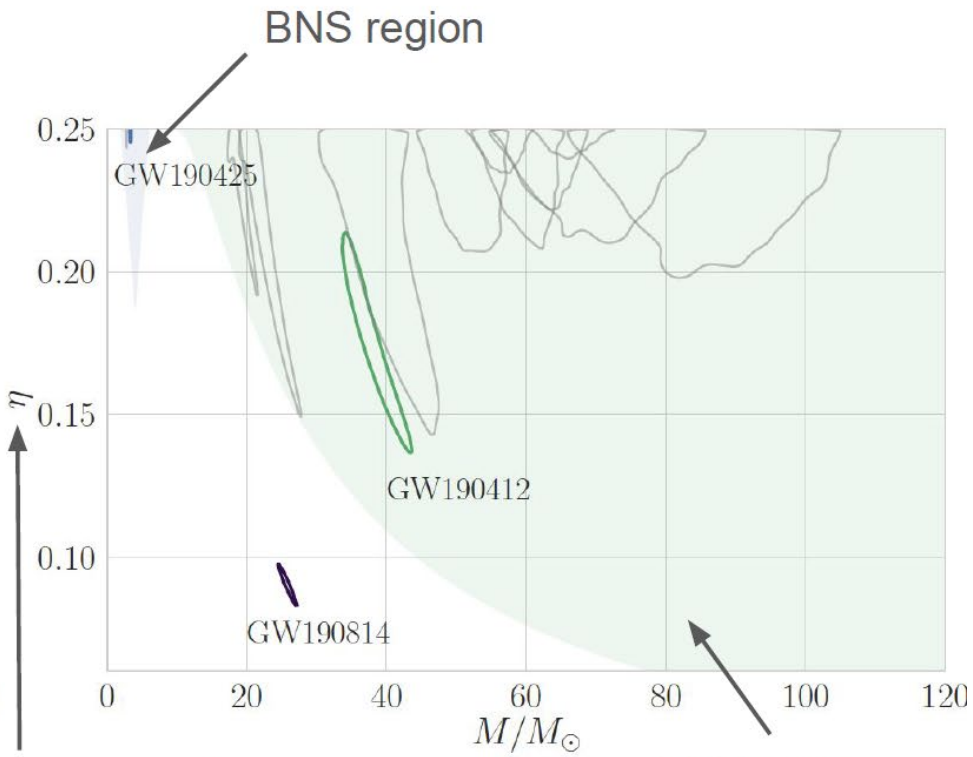


M.Puntu

GW190814 – New class of compact binary mergers

GW190814 - Source frame masses





GWTC-1: LIGO Scientific Collaboration, and Virgo Collaboration (2019)
GW190425: LIGO Scientific Collaboration, and Virgo Collaboration (2020)
GW190412: LIGO Scientific Collaboration, and Virgo Collaboration (2020)

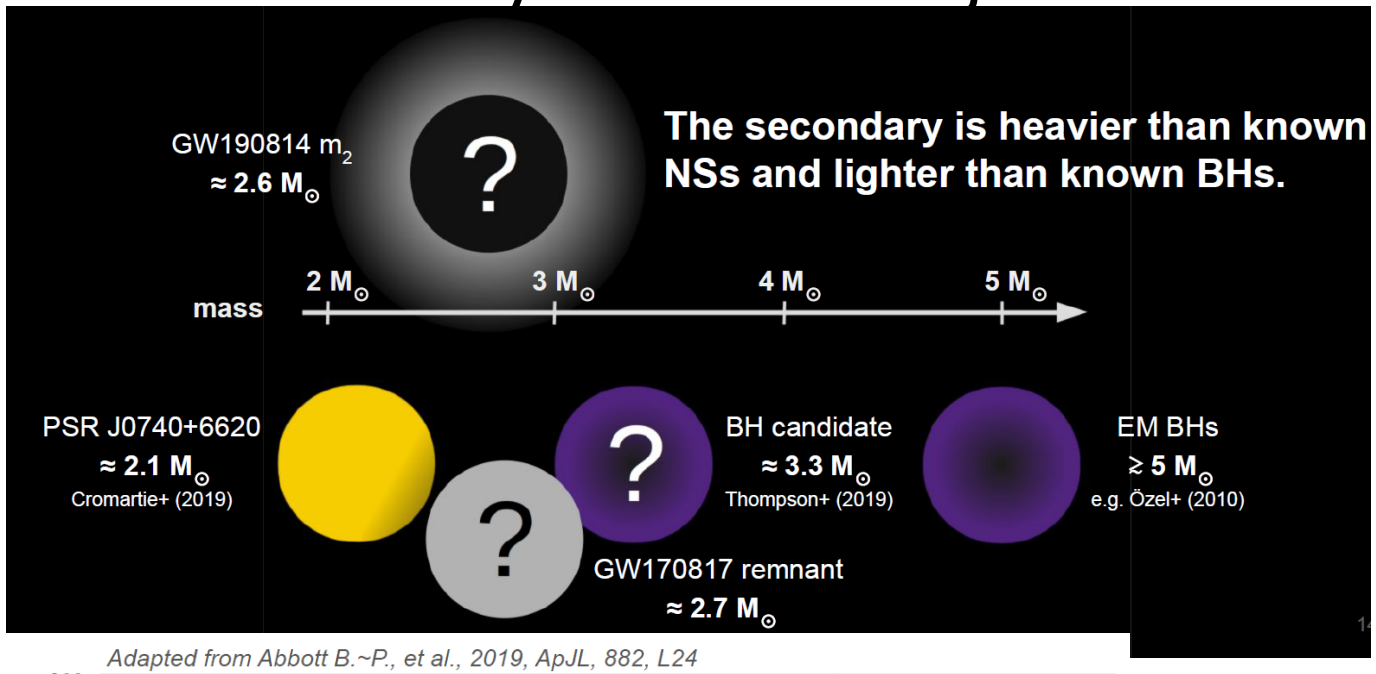
Symmetric mass ratio

$$\eta \equiv \frac{m_1 m_2}{(m_1 + m_2)^2}$$

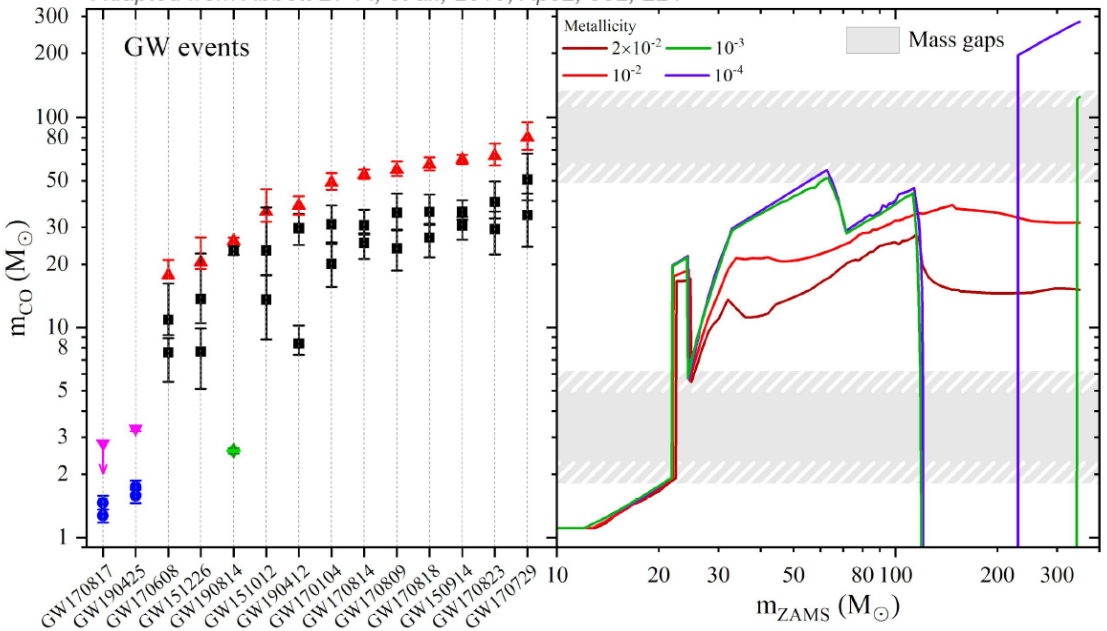
9

GW190814 - What is the secondary mass object?

- What is m_2?
- How is it formed?
  - Implications of the Supernova explosion mechanisms
- It is in the mass gap:
  - Implications on the existence of the lower mass gap



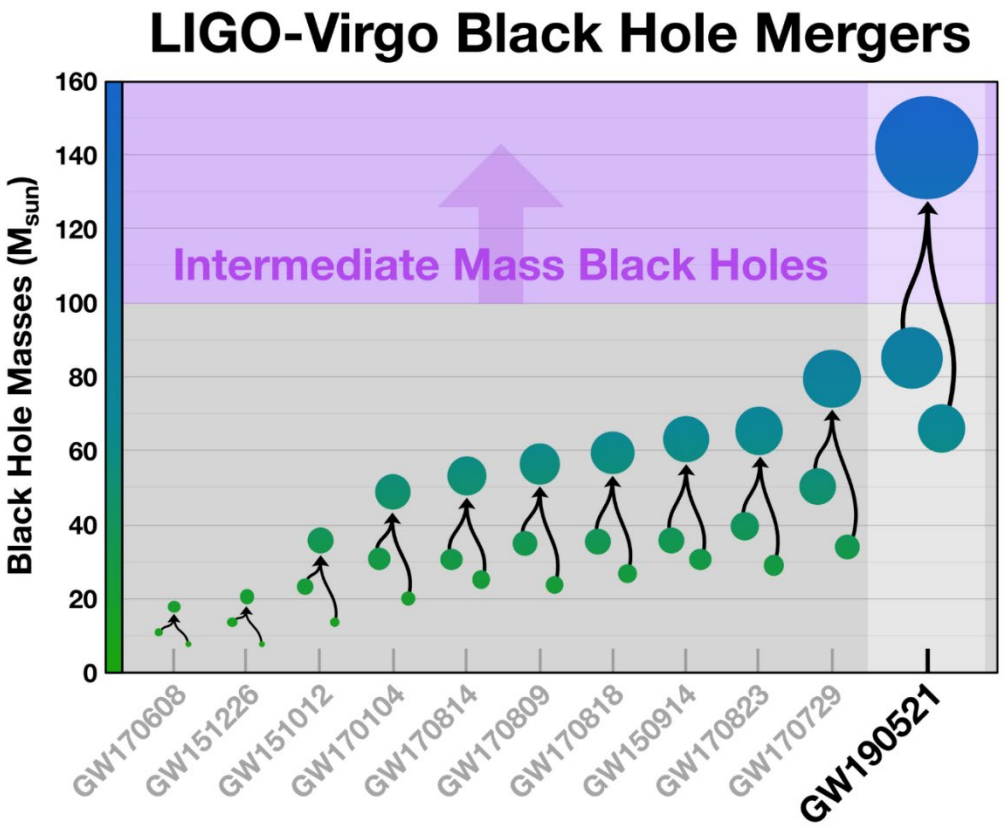
Adapted from Abbott B.~P., et al., 2019, ApJL, 882, L24



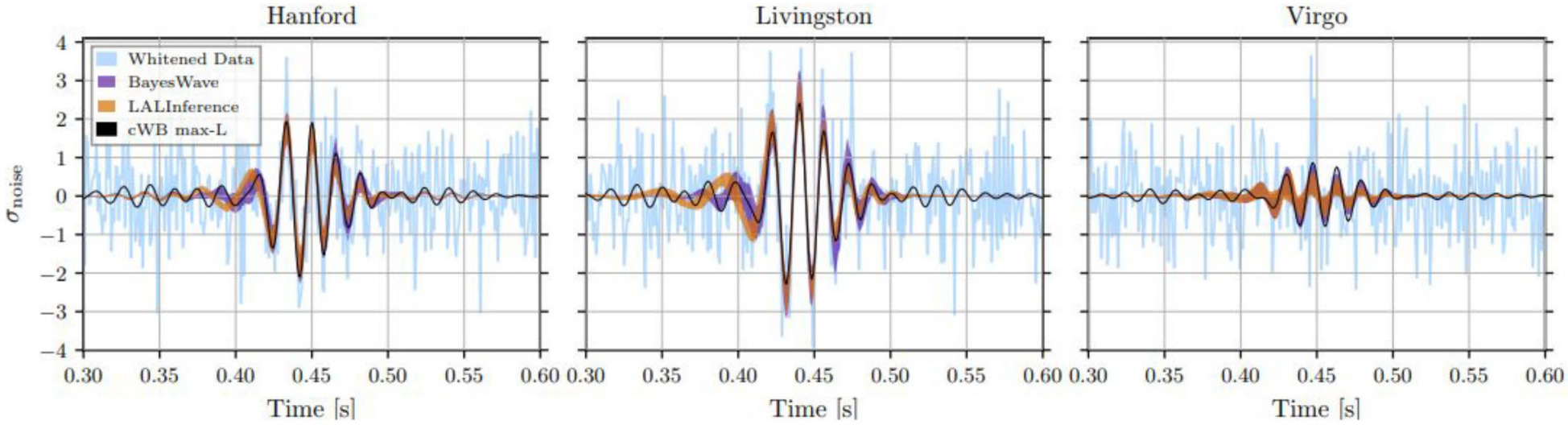
GW190521

$M_1 = 85^{+21}_{-14} M_\Theta$, $M_2 = 66^{+17}_{-18} M_\Theta$
at $z \sim 0.82$ (5.3Gpc)
Remnant $M_f = 142^{+28}_{-16} M_\Theta$

- Very special event:
  - M_1, the black hole that should not exist
  - M_f, the first IMBH ever seen

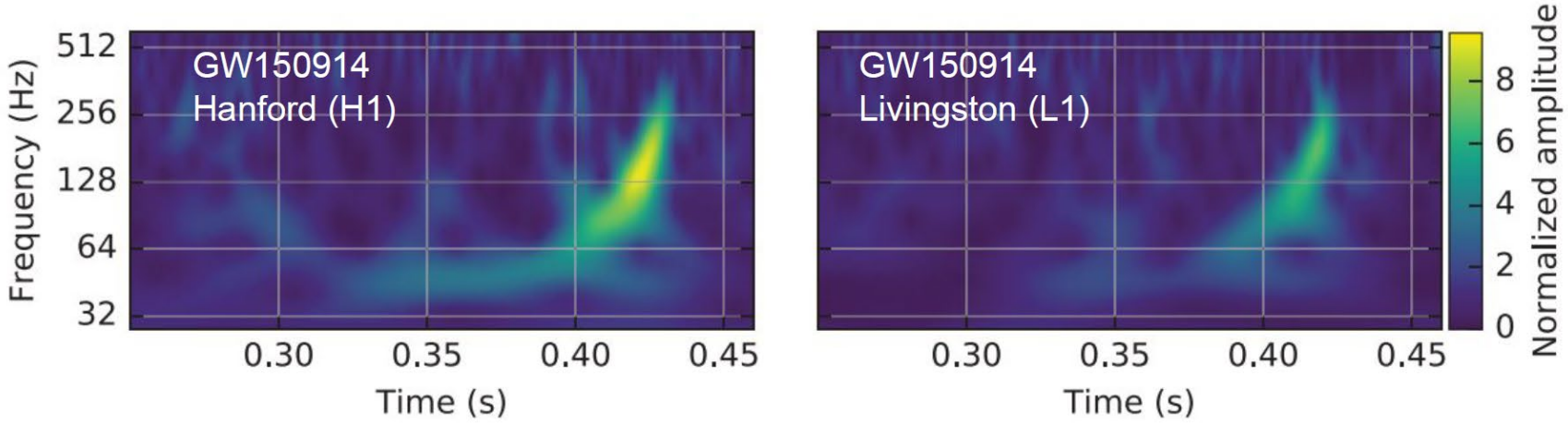


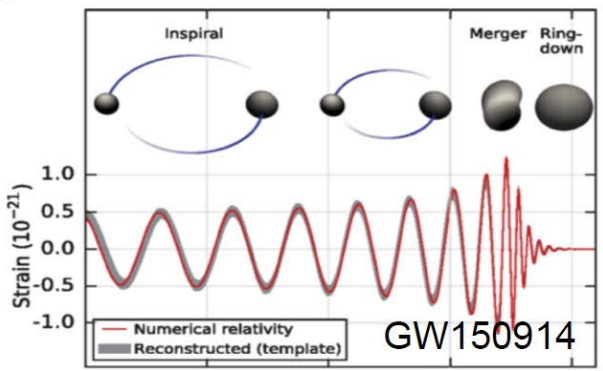
Phys. Rev. Lett. 125, 101102 (2020)
Astrophys. J. Lett. 900, L13 (2020)

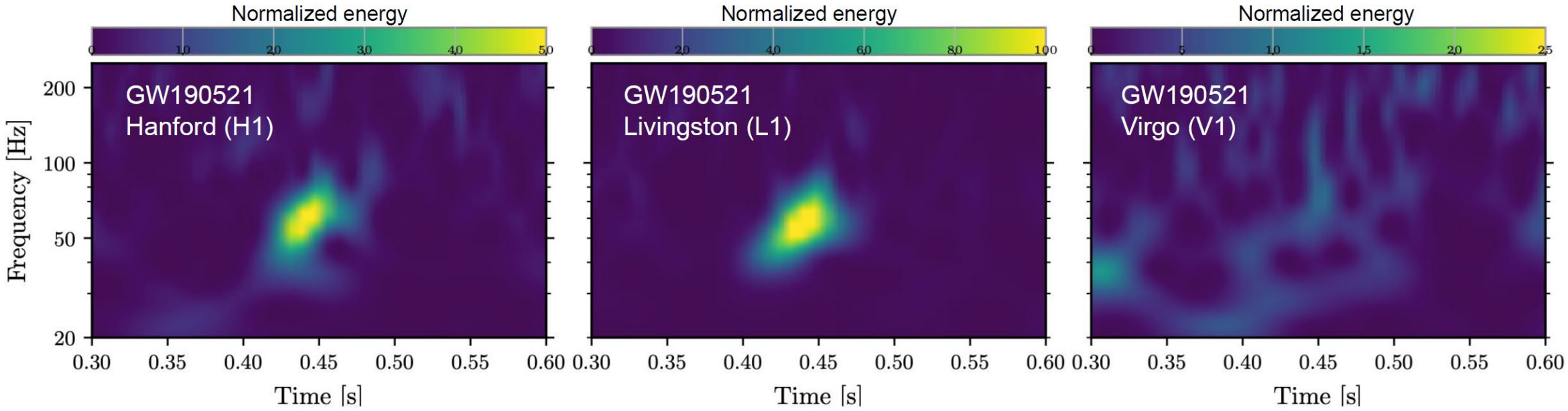


Where is the chirp?

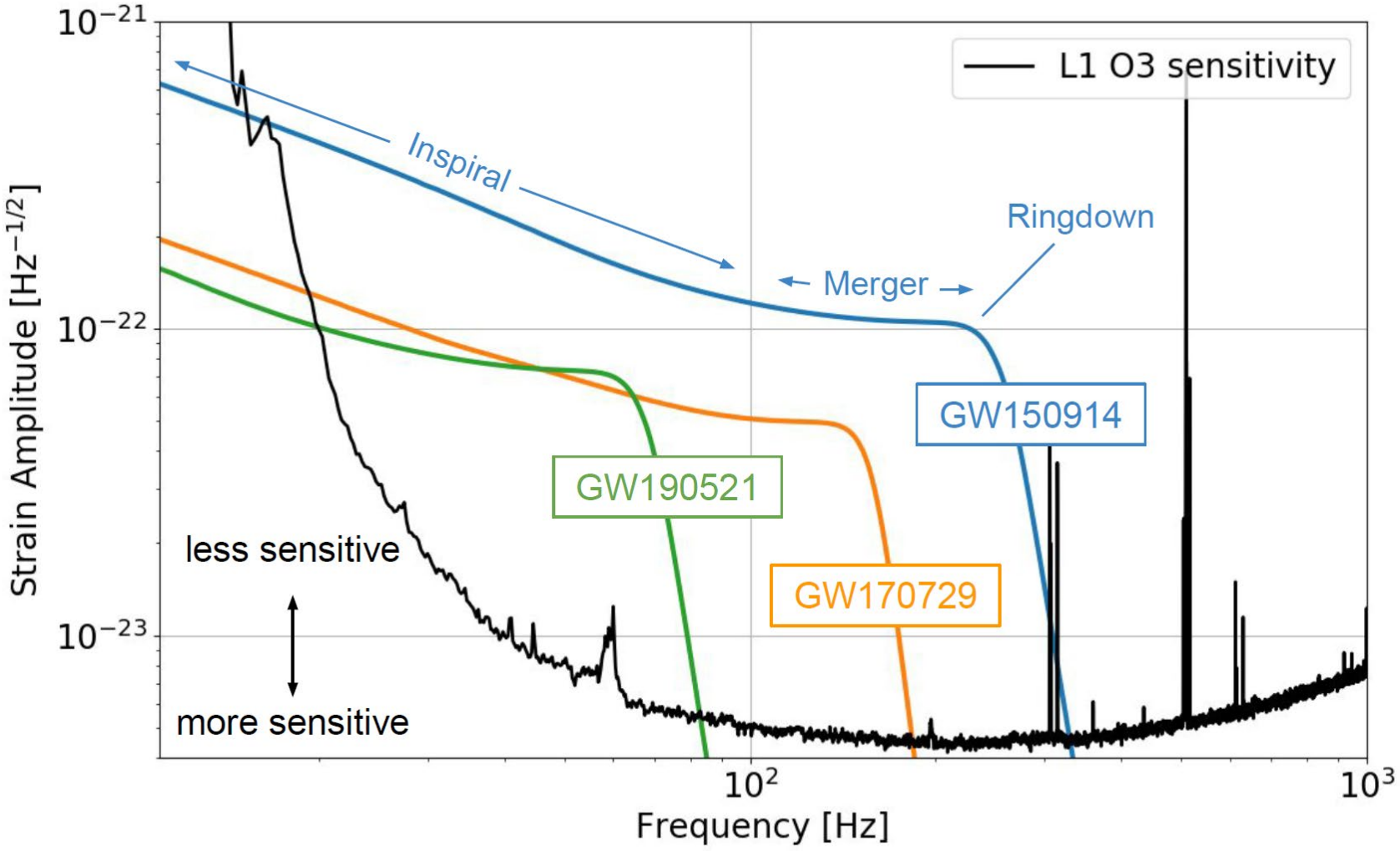
GW190521: signal morphology







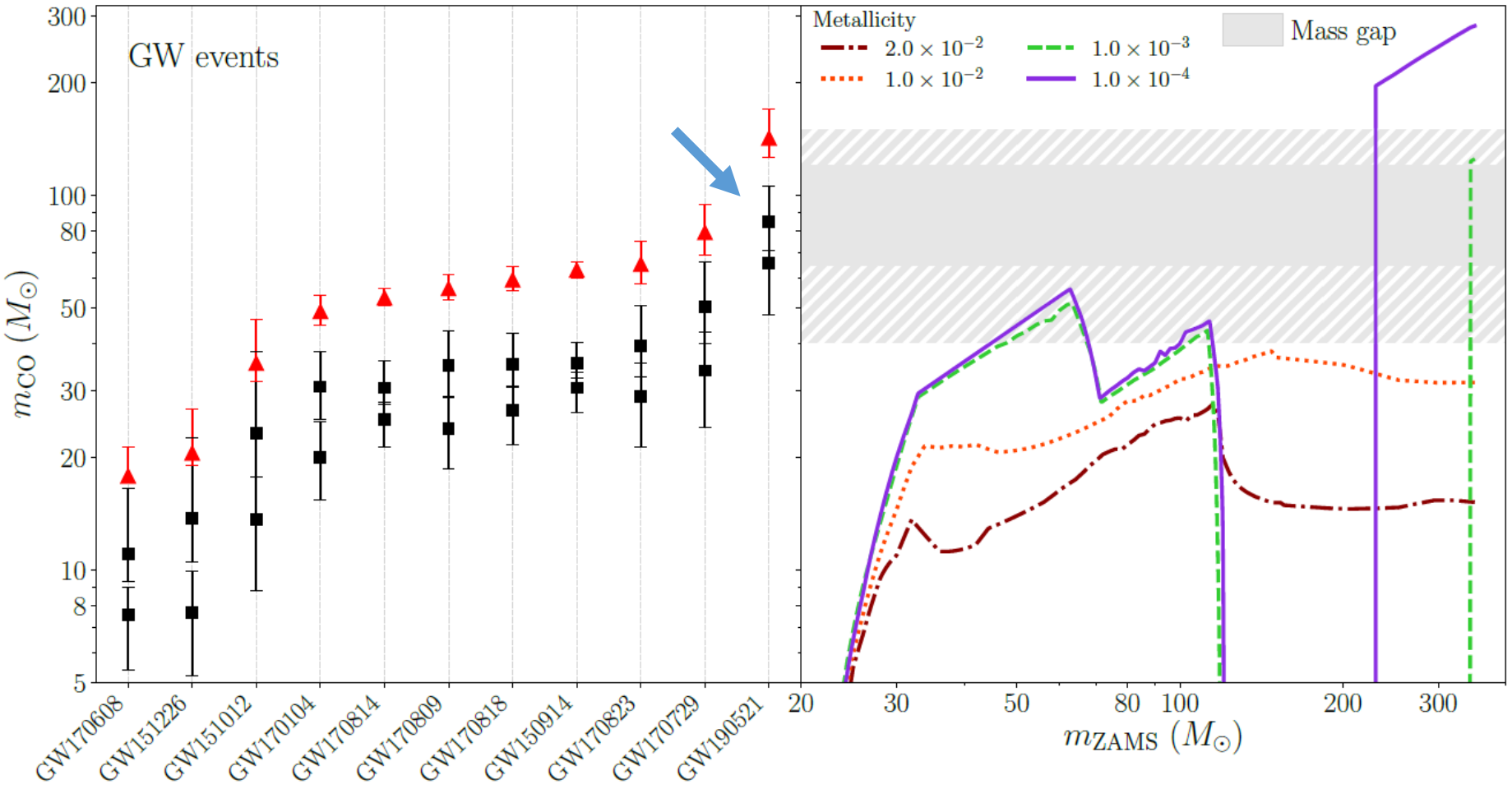
GW190521: LIGO-Virgo sensitivity to the BBH merger



- Higher masses correspond to lower frequency GW emission

GW190521: M_1, what is that?

- M_1 has a mass of $M_1 = 85^{+21}_{-14} M_\Theta$
  - It falls in the upper gap for black hole formation, due to Pair Instability (PI) and Pulsation Pair Instability (PPI)

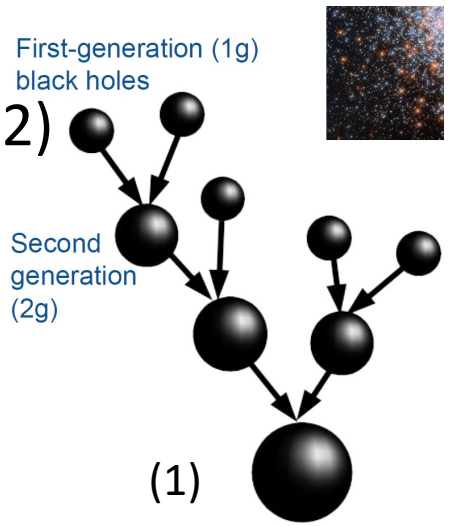


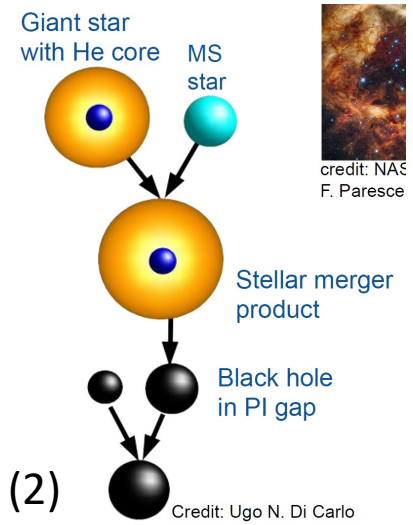
Pair Instability (PI)

- PI develops in a star when the effective production of electron-positron pairs in the stellar core softens the equation of state, removing pressure support
  - This leads to a contraction of the core, raising the internal temperature up to the ignition of oxygen or silicon, and the star becomes unstable.
- PI is expected to develop in stars with helium core mass $\gtrsim 32 M_{\odot}$
- For helium cores $32 \lesssim M_{He}/M_{\odot} \lesssim 64$ this instability manifests as pulsational pair instability (PPI):
  - the star undergoes a number of oscillations that eject material and remove the stellar envelope, bringing the star back to a stable configuration after the resulting mass loss
  - After PPI, the star ends its life with a core-collapse supernova or with direct collapse, leaving a compact object less massive than expected in the absence of PPI

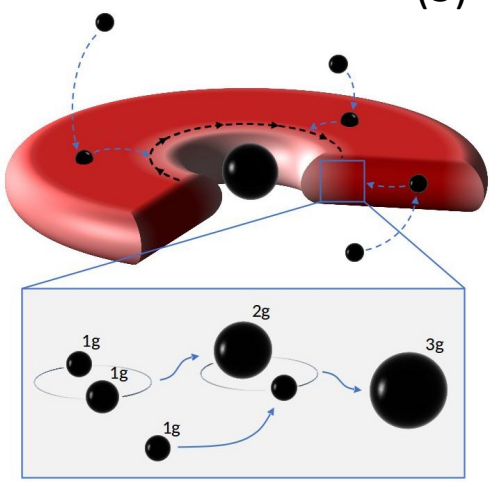
Pair Instability (PI)

- For helium cores $64 \lesssim M_{He}/M_{\odot} \lesssim 135$ PI leads to a complete disruption of the star, leaving no compact object
- For even larger helium cores PI drives a direct collapse to a BH.
- The combined effect of PI and PPI is expected to carve a mass gap in the BH mass function, with lower boundary $\sim 40 - 65 M_{\odot}$ and upper boundary $\gtrsim 120 M_{\odot}$
- The challeng is to explain the formation of M1; several hypothesis
  - Hierarchical mergers (1)
  - Stellar mergers in young star clusters (2)
  - Active galactic nucleus (AGN) disks (3)

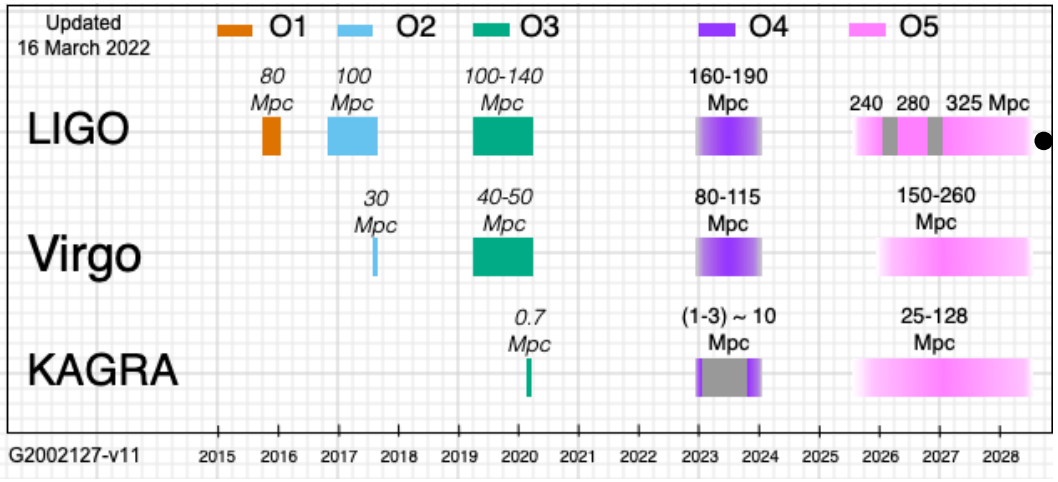




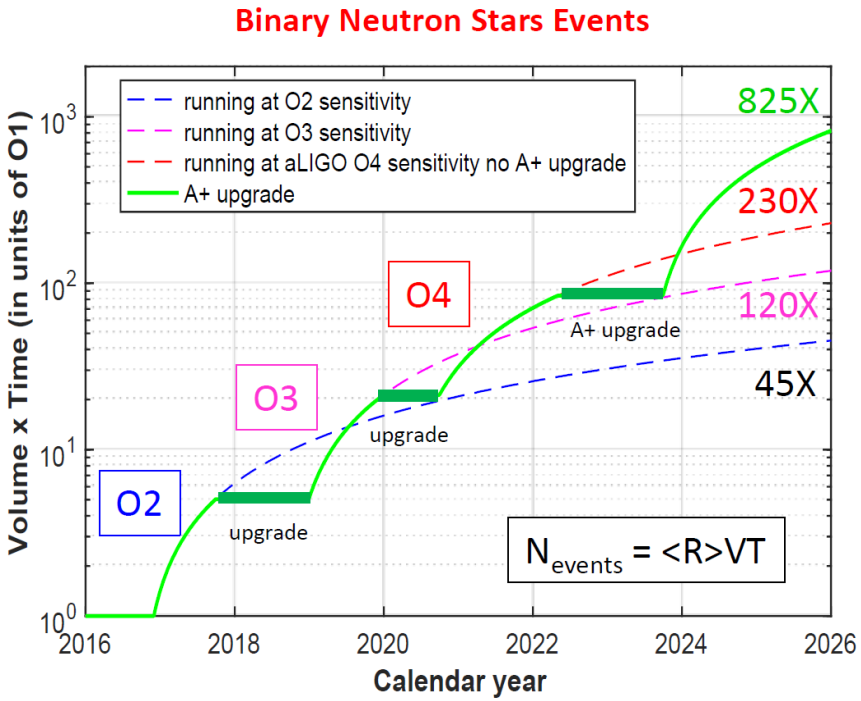
(3)

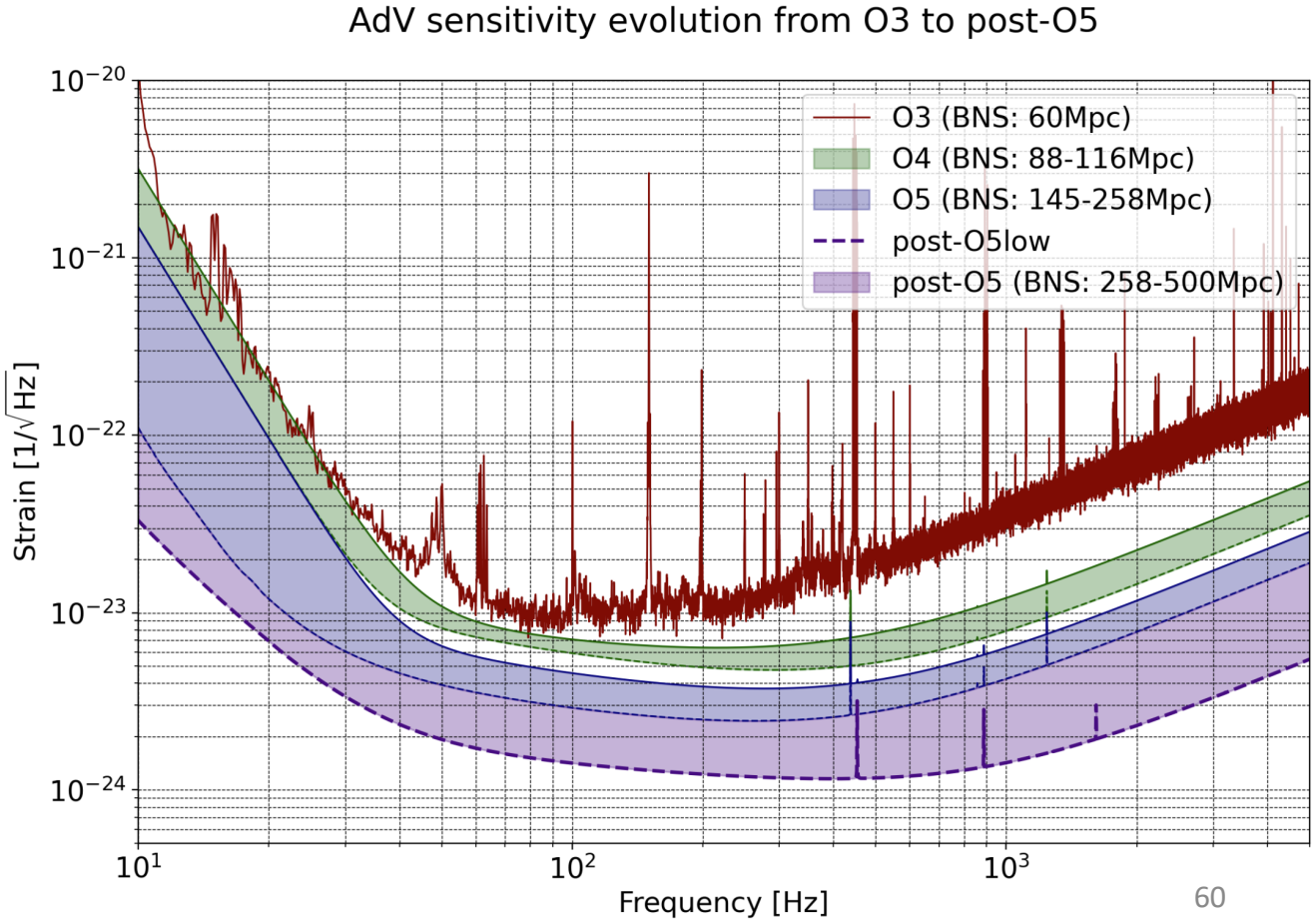


Near future



- O4 run, including the Advanced LIGO, Advanced Virgo and KAGRA detectors should start at the end of 2022
- Current detectors have a well defined plan of upgrades and science runs

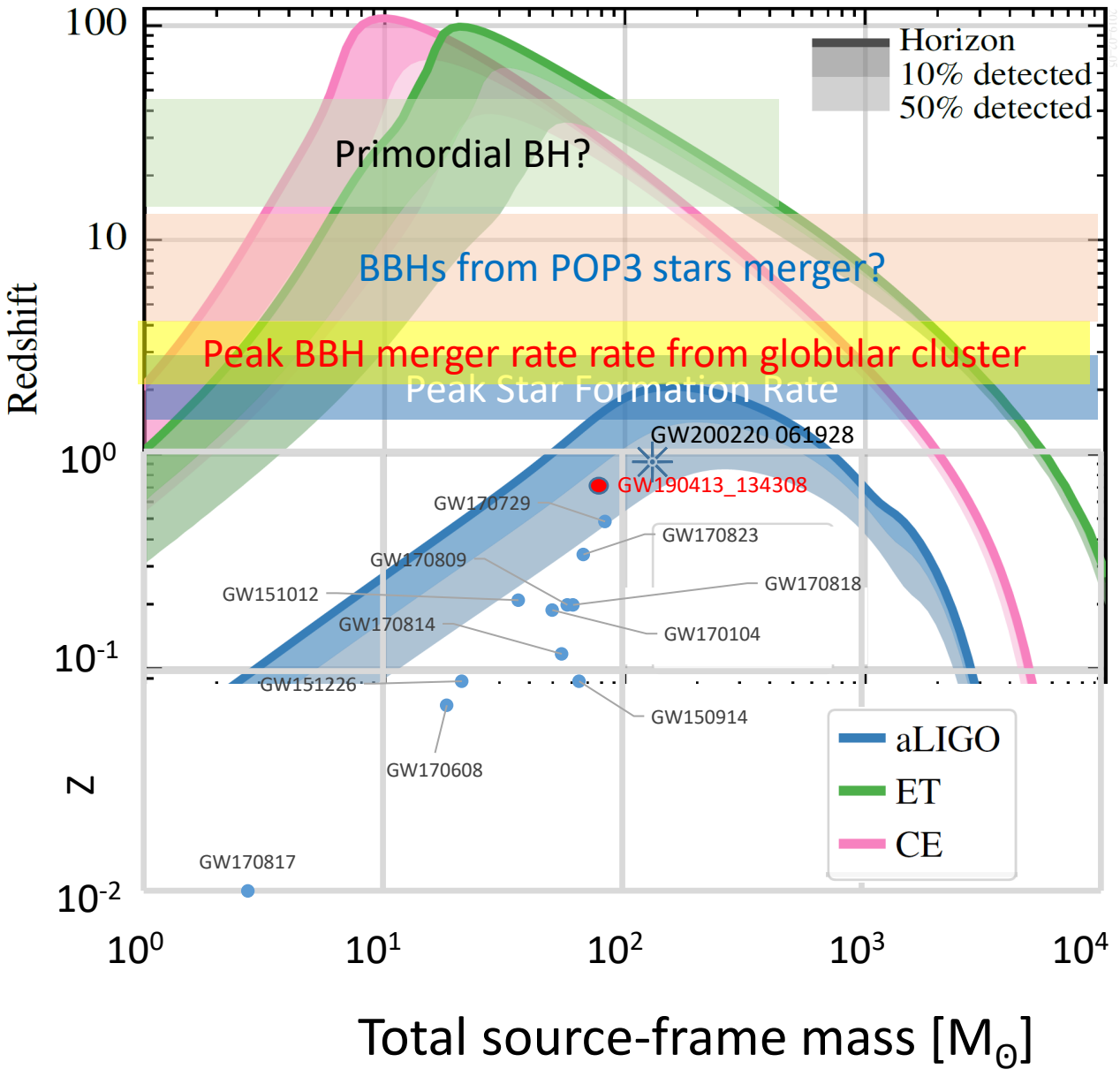




OK, all done?

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

- 2nd generation GW detectors will explore the local Universe, even in their post-O5 configuration, initiating precision GW astronomy, but to have cosmological investigations a factor of 10 improvement in terms detection distance is needed



Detection distance of GWD

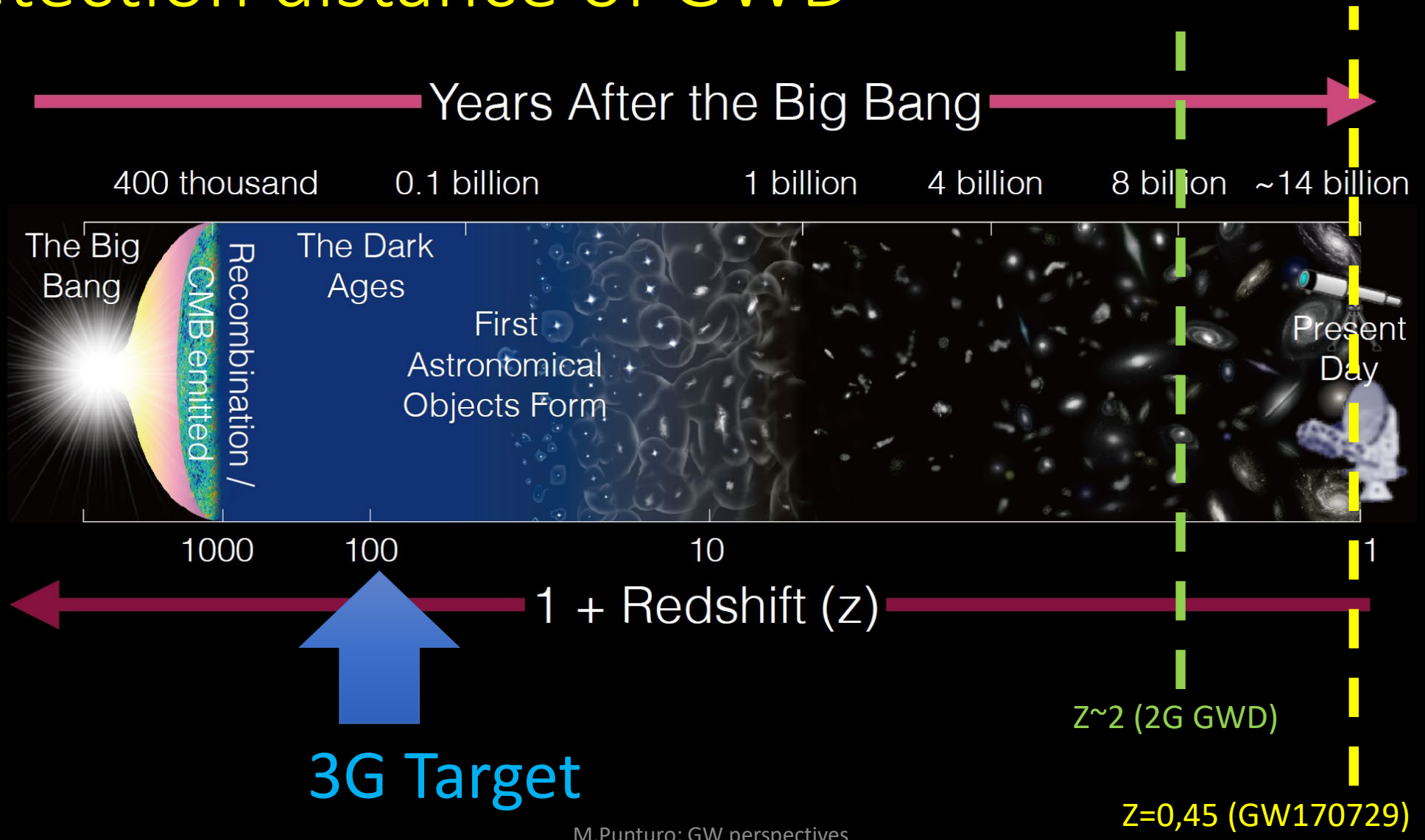
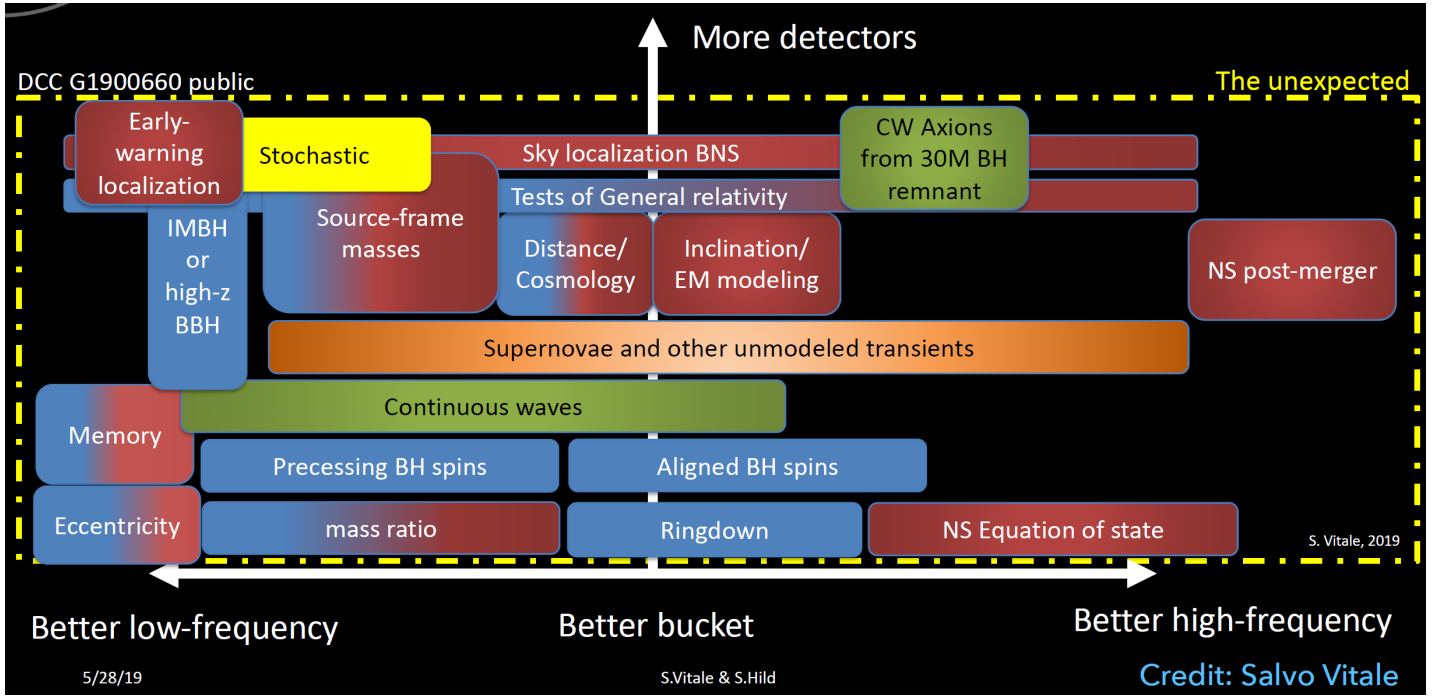


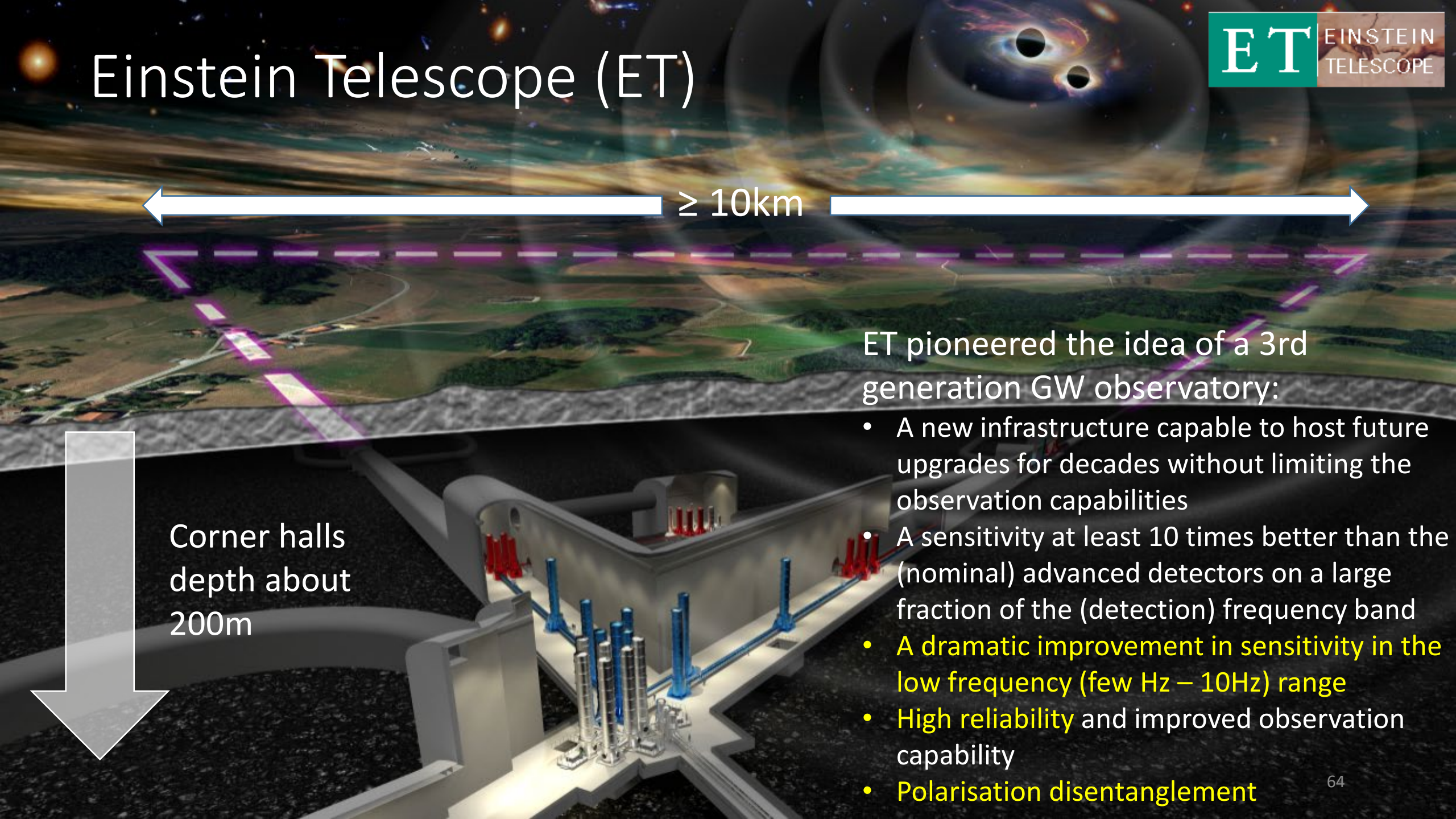
Image credit: NAOJ/ALMA http://alma.mtk.nao.ac.jp/

Where to look for new physics?

- Terrestrial interferometric detectors have access roughly to the [few, few×10^3] Hz frequency interval of the GW signal
- GW sources produce signals in different GW ranges
- Discovery machines must have the widest possible frequency range
- Precision measurement machines should have the best sensitivity
- 3G GW observatories must have both

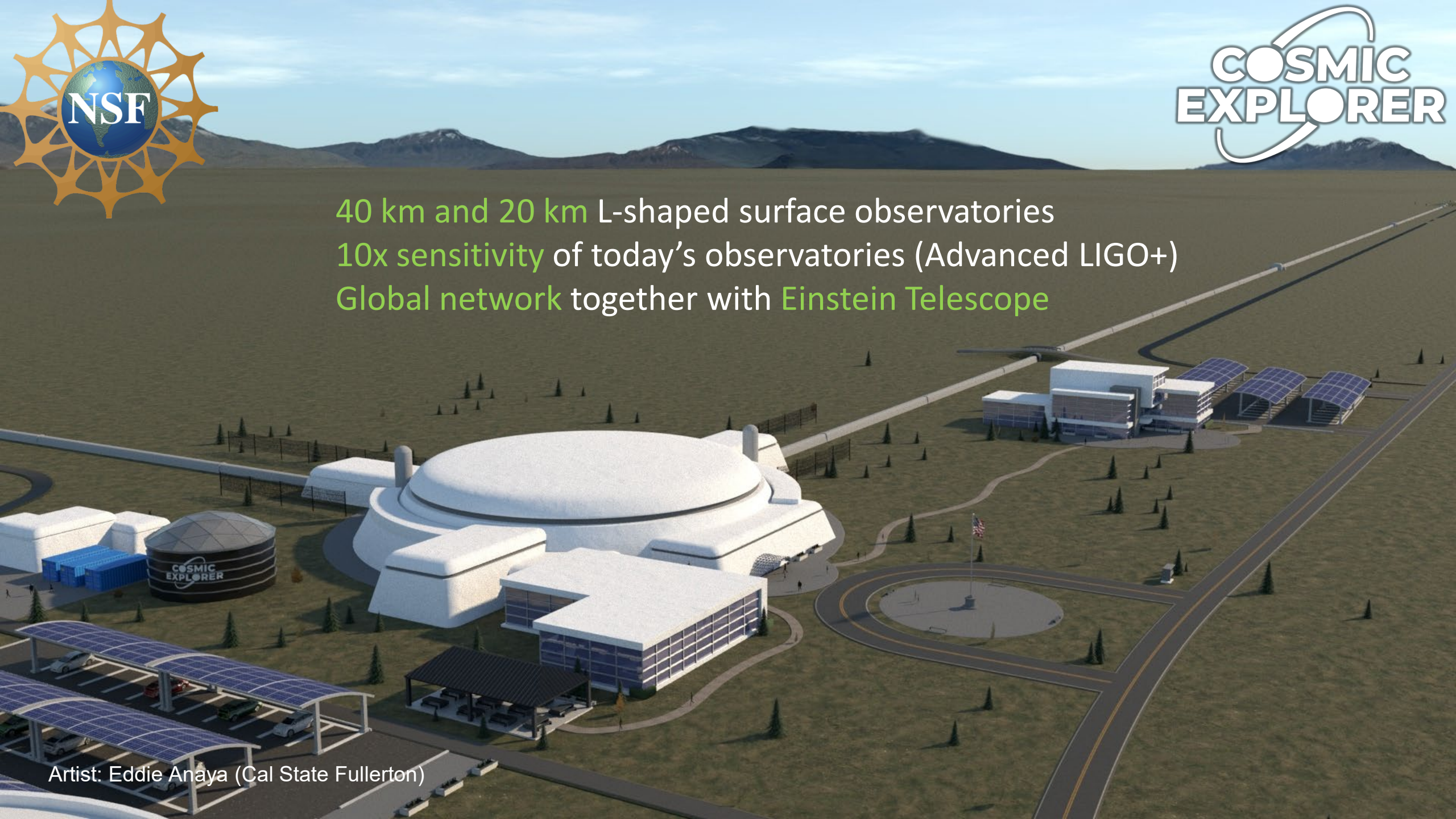


Einstein Telescope (ET)



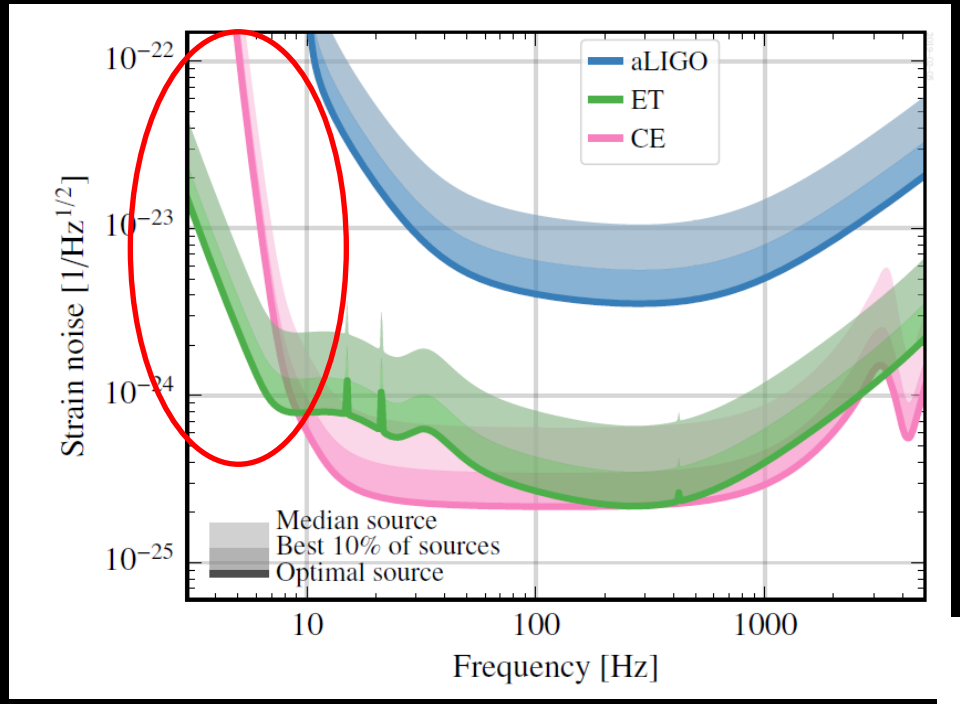
ET pioneered the idea of a 3rd generation GW observatory:

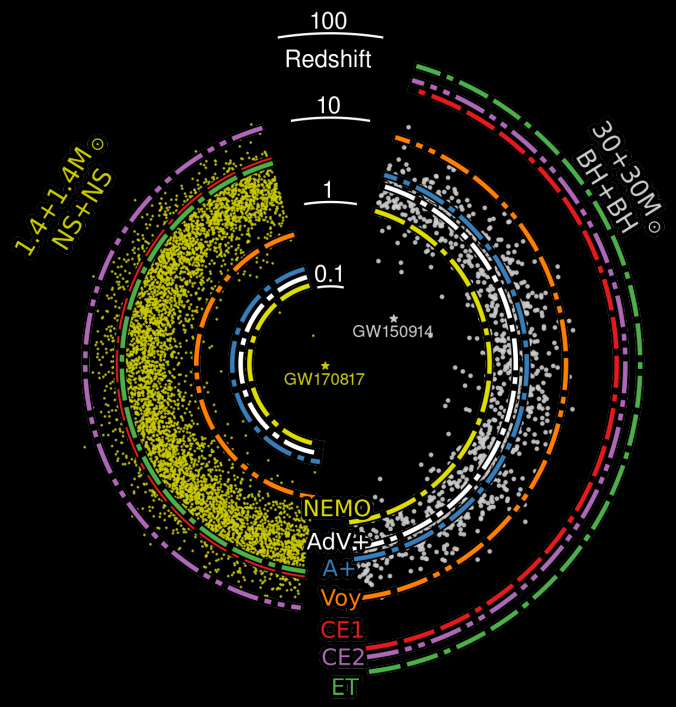
- A new infrastructure capable to host future upgrades for decades without limiting the observation capabilities
- A sensitivity at least 10 times better than the (nominal) advanced detectors on a large fraction of the (detection) frequency band
- A dramatic improvement in sensitivity in the low frequency (few Hz – 10Hz) range
- High reliability and improved observation capability
- Polarisation disentanglement

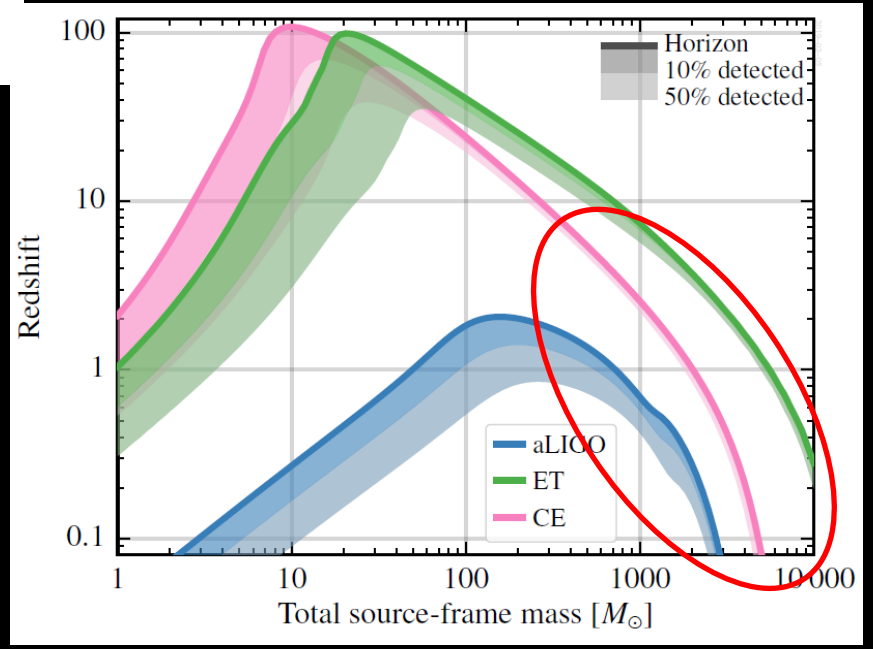

40 km and 20 km L-shaped surface observatories
10x sensitivity of today's observatories (Advanced LIGO+)
Global network together with Einstein Telescope
Artist: Eddie Anaya (Cal State Fullerton)

Observation performance of ET & CE

- BBH up to z~50-100
- 10^5 BBH/year
  - Masses $M_T \gtrsim 10^3\ M_\odot$
- BNS to z~2
  - 10^5 BNS/year
  - Possibly O(10-100)/year with e.m. counterpart
- High SNR







ET Science in a nutshell

ET EINSTEIN TELESCOPE

ASTROPHYSICS

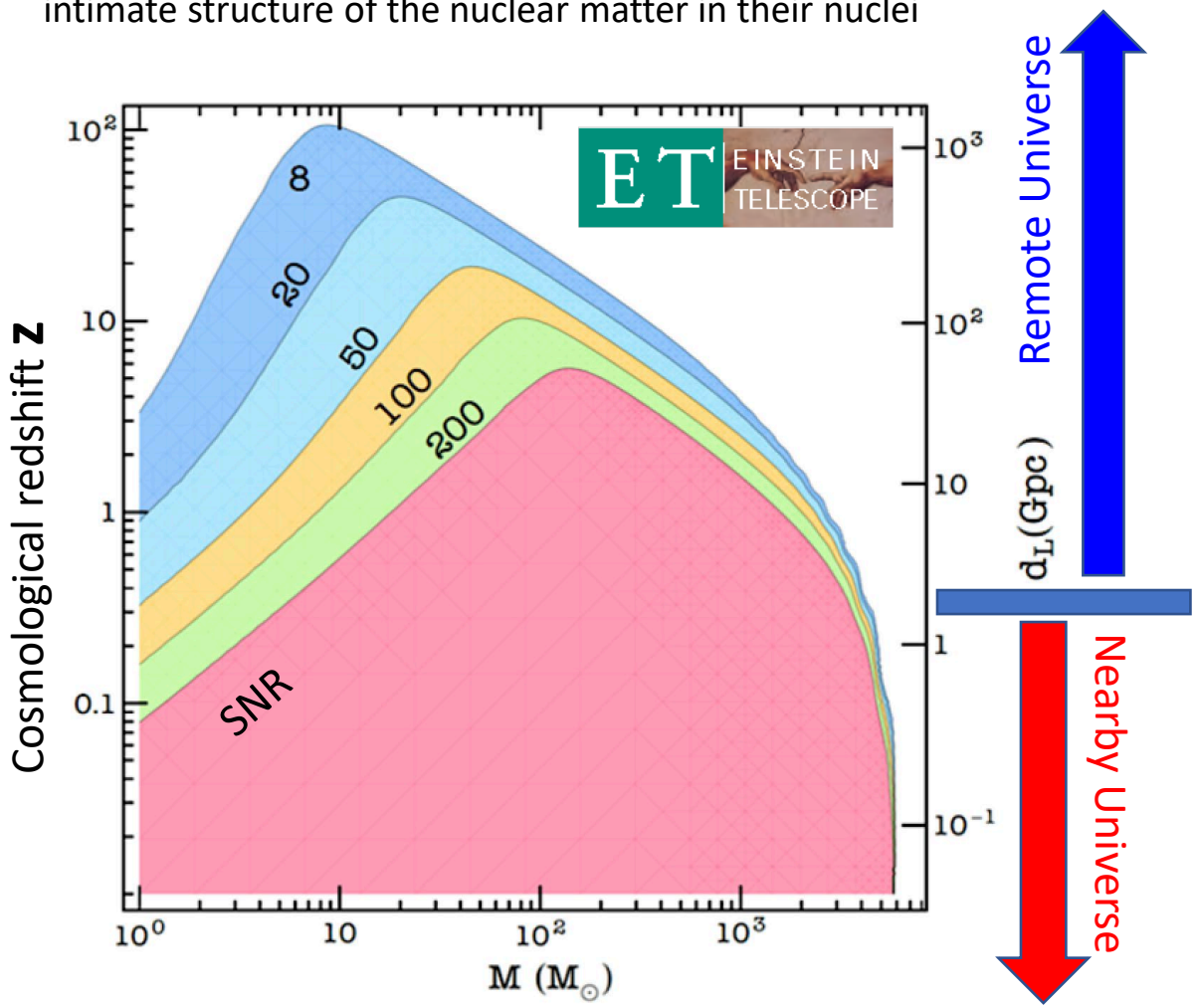
- **Black hole properties**
  - origin (stellar vs. primordial)
  - evolution, demography
- **Neutron star properties**
  - interior structure (QCD at ultra-high densities, exotic states of matter)
  - demography
- **Multi-band and -messenger astronomy**
  - joint GW/EM observations (GRB, kilonova,...)
  - multiband GW detection (LISA)
  - neutrinos
- **Detection of new astrophysical sources**
  - core collapse supernovae
  - isolated neutron stars
  - stochastic background of astrophysical origin

FUNDAMENTAL PHYSICS AND COSMOLOGY

- **The nature of compact objects**
  - near-horizon physics
  - tests of no-hair theorem
  - exotic compact objects
- **Tests of General Relativity**
  - post-Newtonian expansion
  - strong field regime
- **Dark matter**
  - primordial BHs
  - axion clouds, dark matter accreting on compact objects
- **Dark energy and modifications of gravity on cosmological scales**
  - dark energy equation of state
  - modified GW propagation
- **Stochastic backgrounds of cosmological origin**
  - inflation, phase transitions, cosmic strings

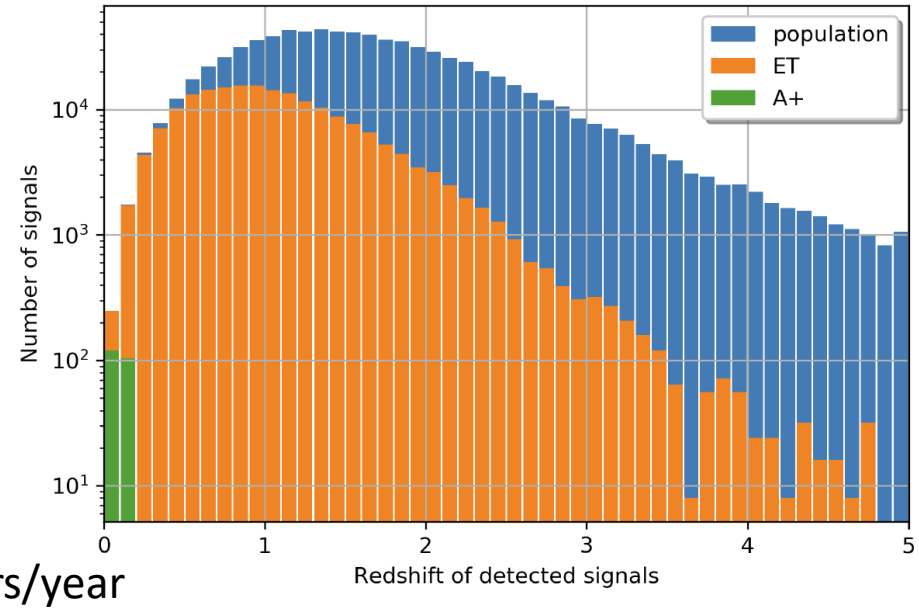
ET Science in a nutshell

- ET will explore almost the entire Universe listening the gravitational waves emitted by black hole, back to the dark ages after the Big Bang
- ET will detect, with high SNR, hundreds of thousands coalescences of binary systems of Neutron Stars per year, revealing the most intimate structure of the nuclear matter in their nuclei



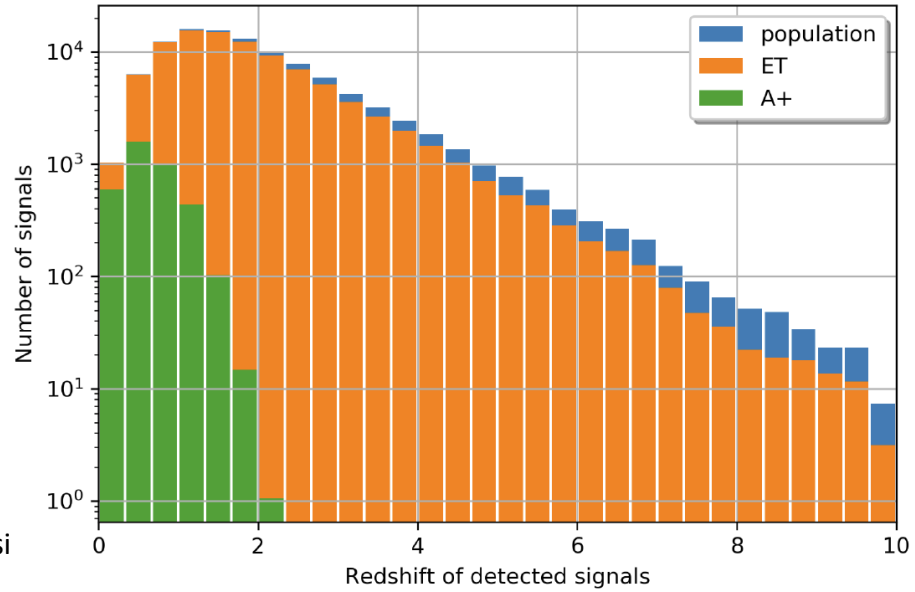
Compact Object Binary Populations

BNS mergers



O(10^5) mergers/year

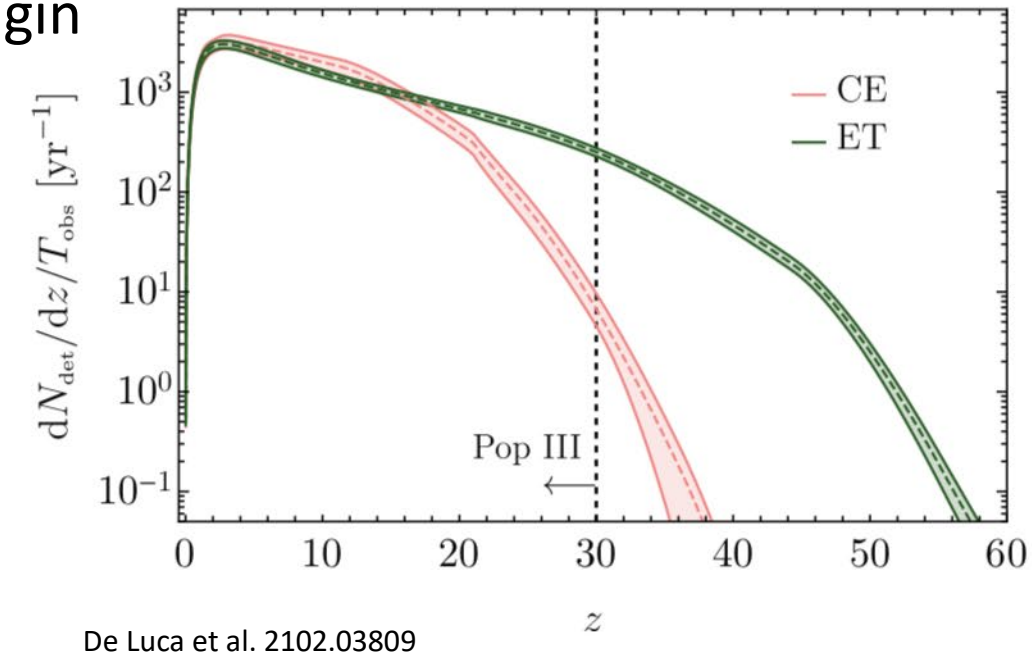
BBH mergers



Credit: M.Branchesi

Primordial BHs

- ET (and CE) will detect BH well beyond the SFR peak z~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)
  - Any BBH merger at z>30 will be of primordial origin

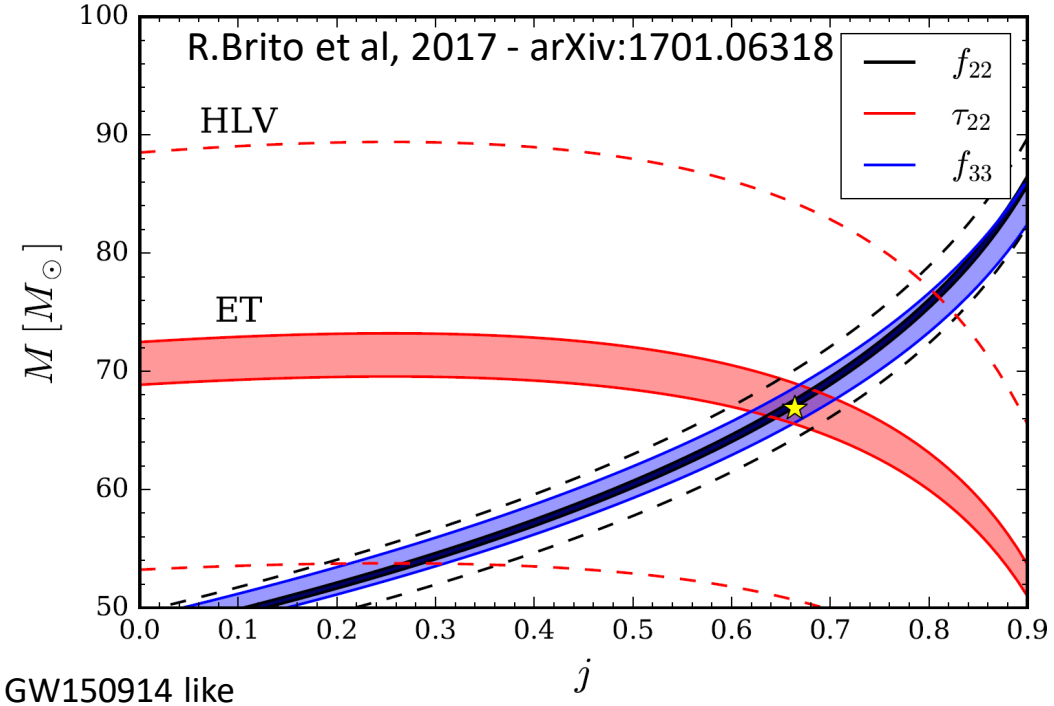


De Luca et al. 2102.03809

Extreme gravity

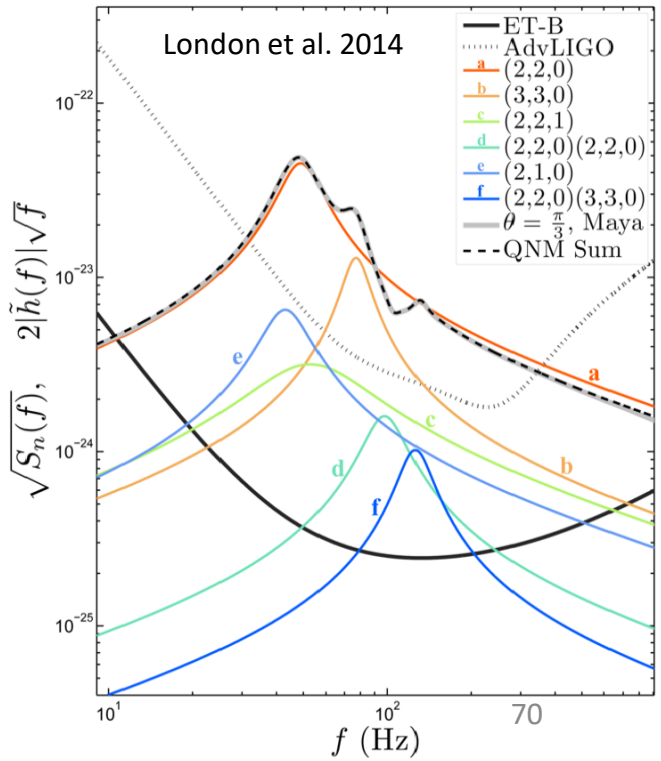
- In GR, no-hair theorem predicts that BHs are described only by their mass and spin (and charge)
  - However, when a BH is perturbed, it reacts (in GR) in a very specific manner, relaxing to its stationary configuration by oscillating in a superpositions of quasi-normal modes, which are damped by the 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



GW150914 like

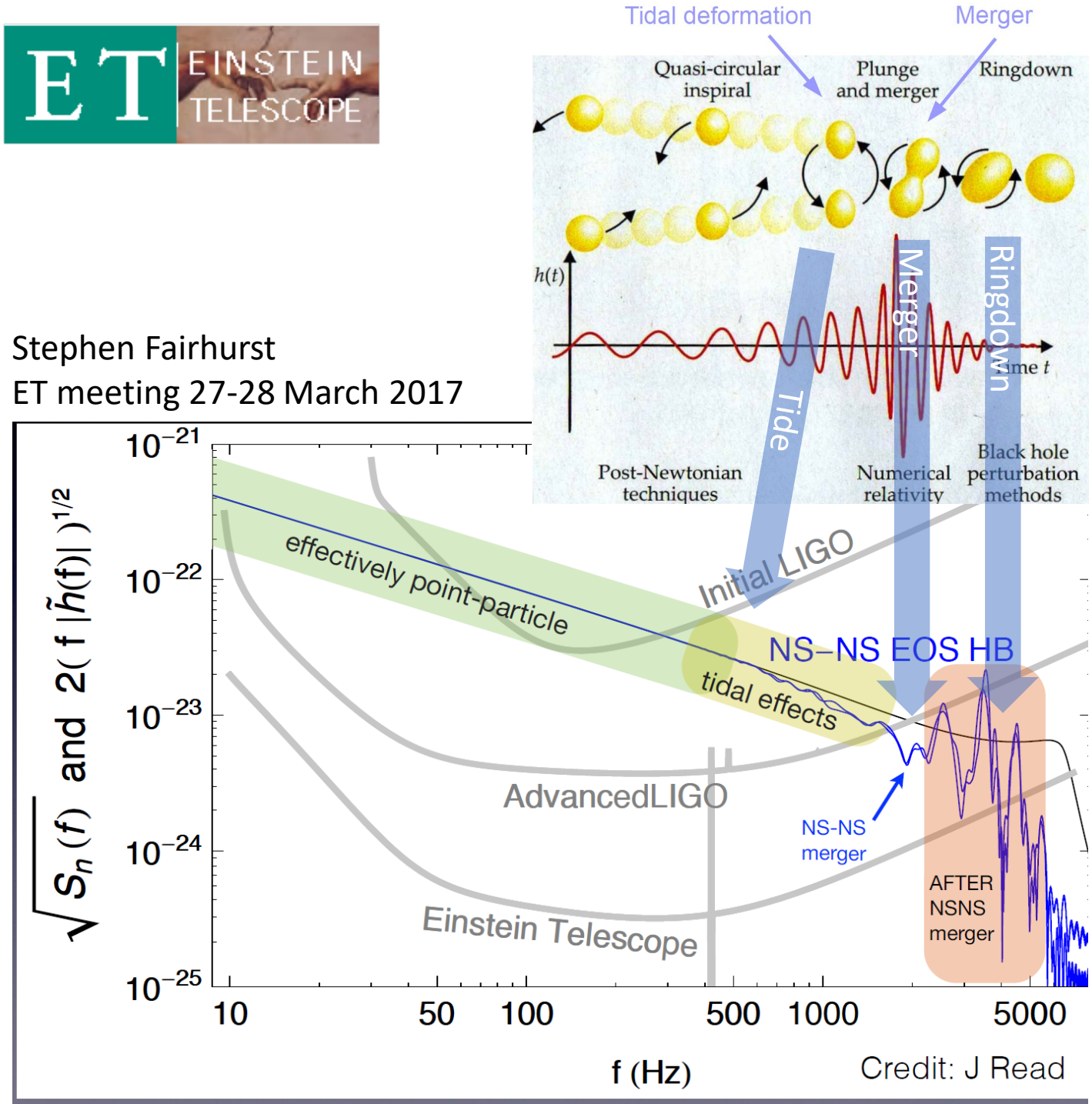
350 Msun binary @ 100 Mpc

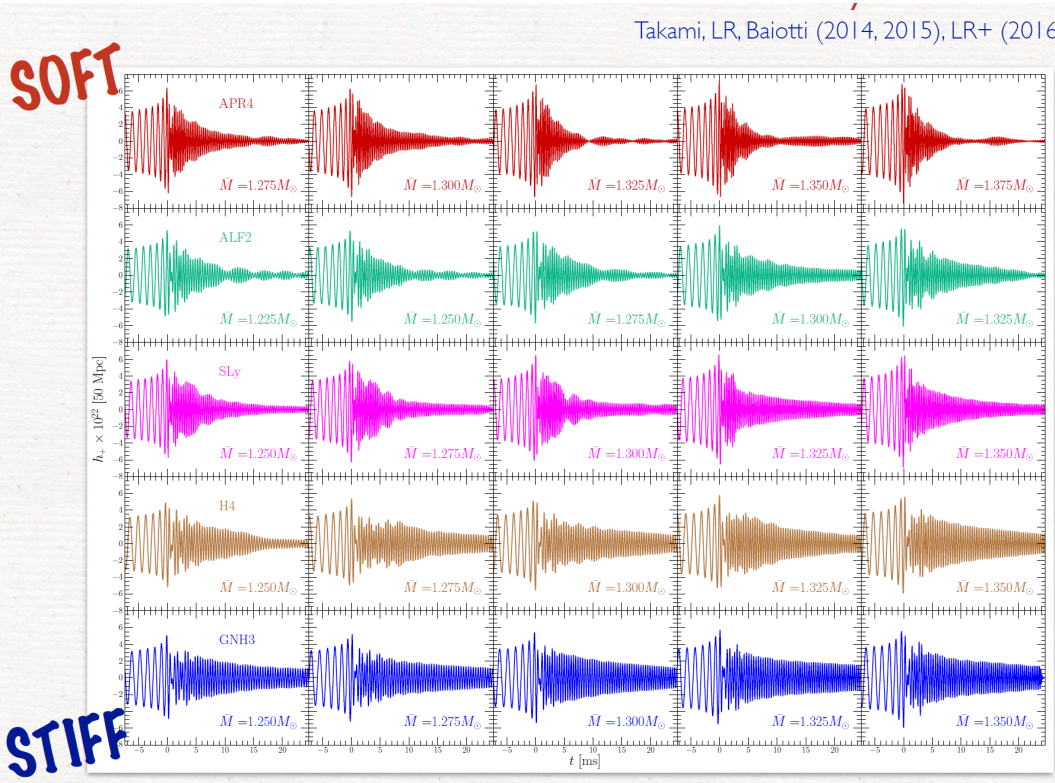


$J=J/M^2$ dimensionless spin

Structure of a Neutron Star

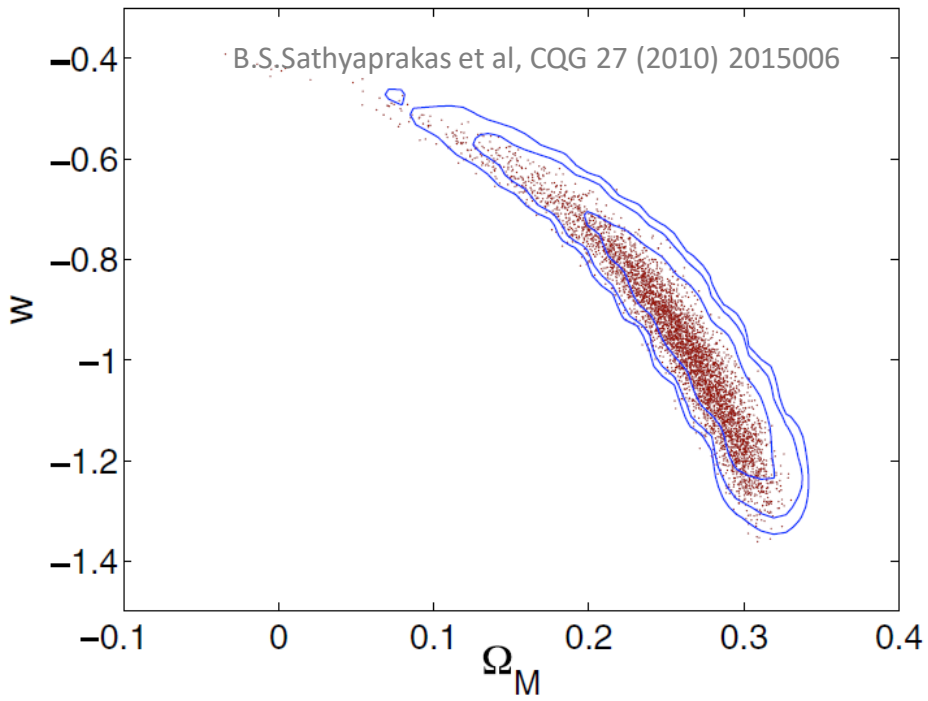
Stephen Fairhurst
ET meeting 27-28 March 2017

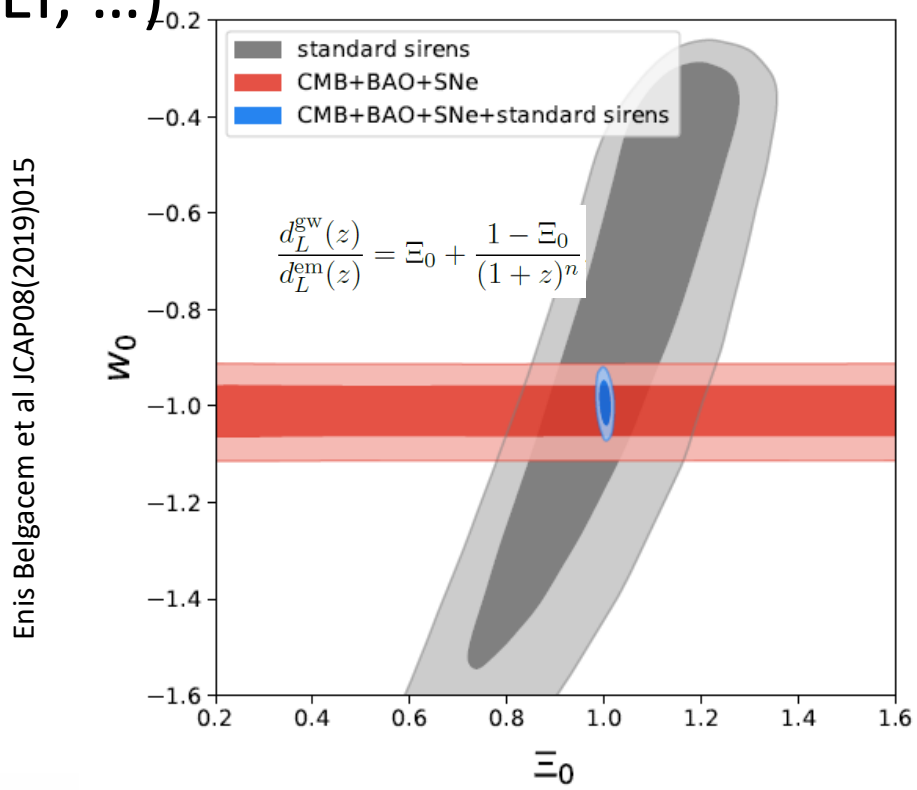




Cosmology/Cosmography with ET

- ET will reveal 10^5 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, …)



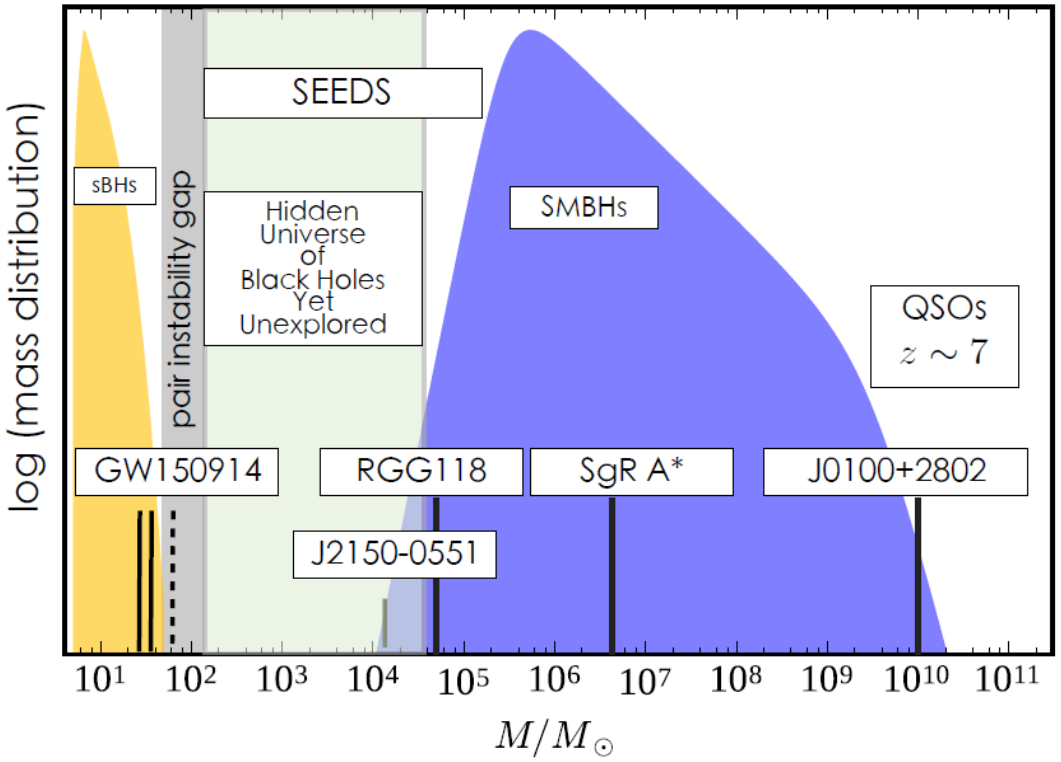


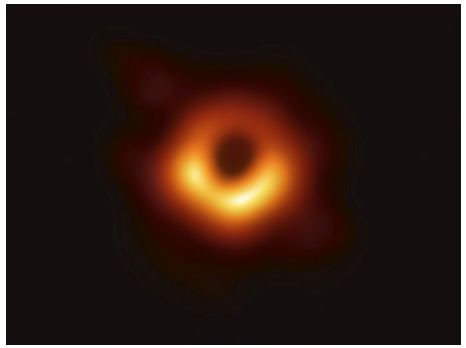
$$D_L(z) = \frac{c(1+z)}{H_0}\int_0^z \frac{dz}{\left[\Omega_M(1+z)^3 + \Omega_\Lambda(1+z)^{3(1+w)}\right]^{1/2}}$$

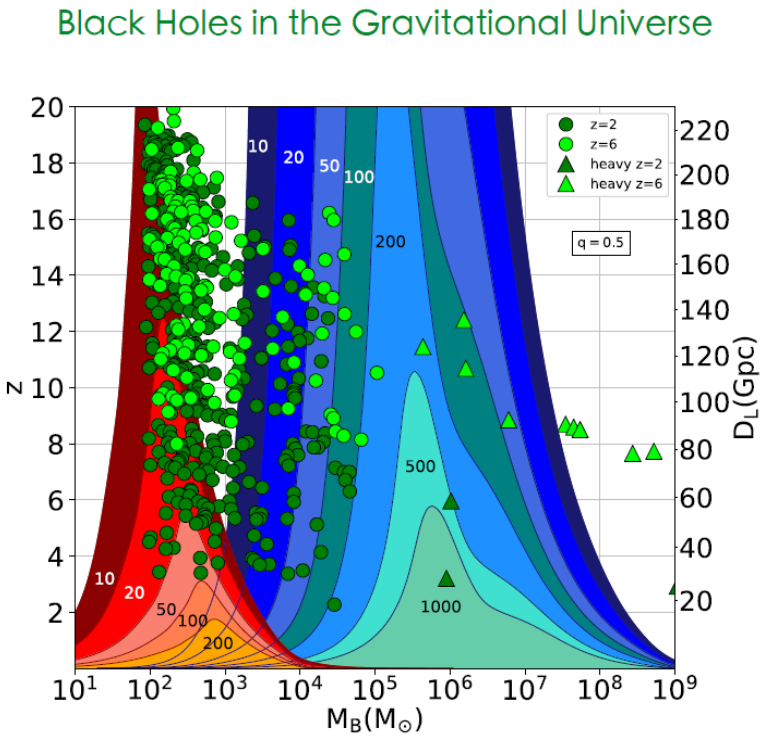
Investigating the DE sector in modified theories of gravity

Seeds and Supermassive Black Holes

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

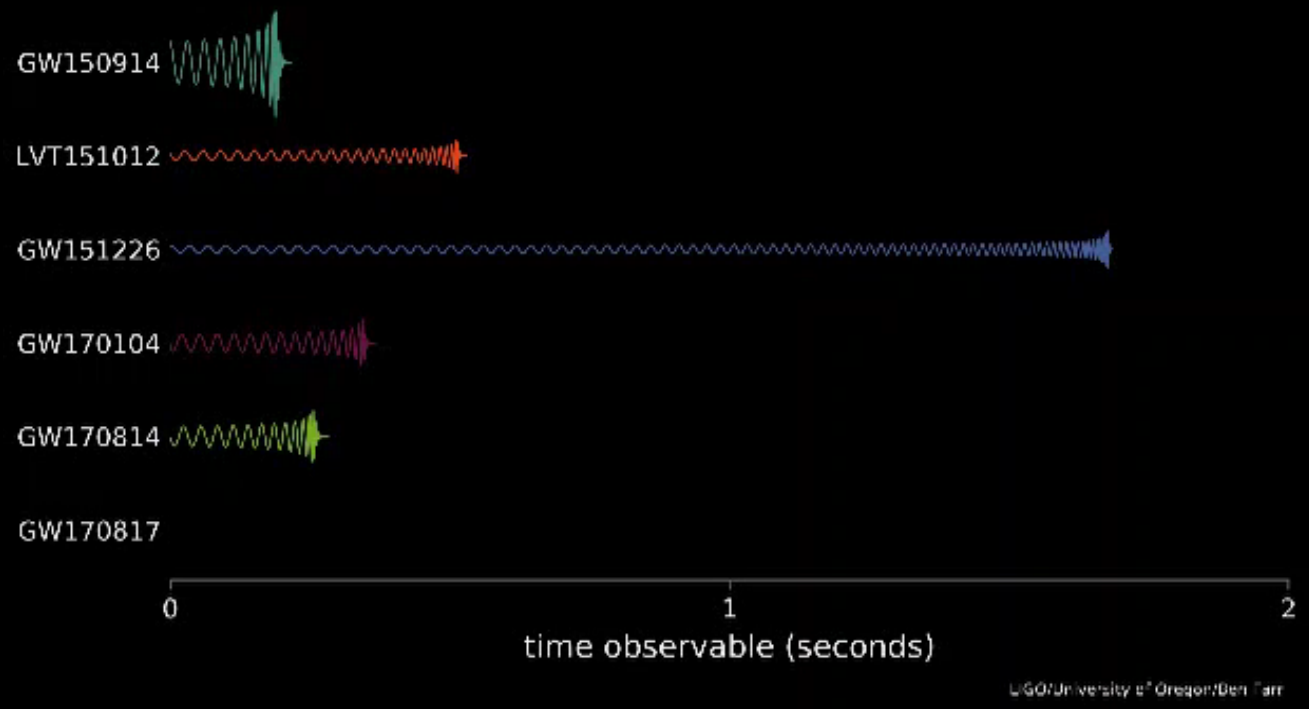


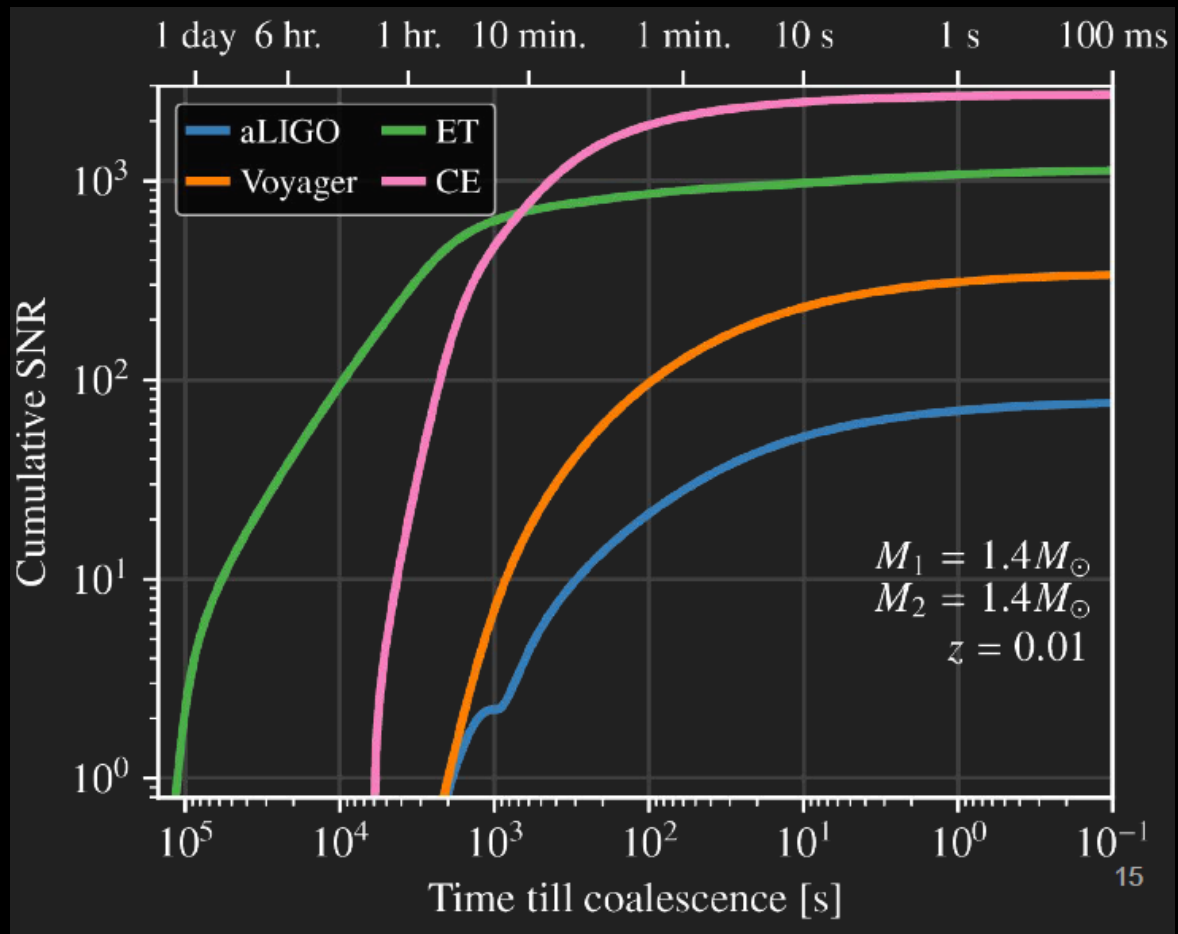




Low frequency: Multi-messenger astronomy

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





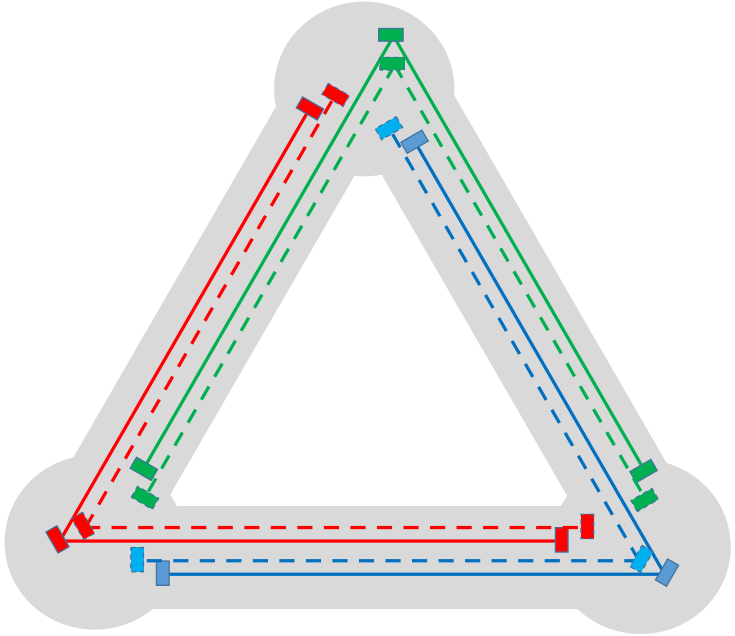
ET key elements

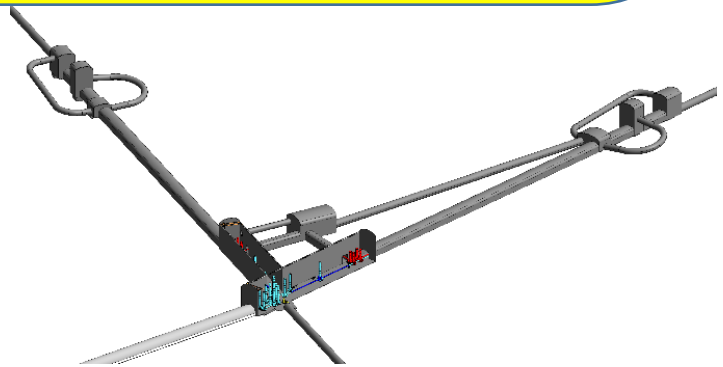
Requirements

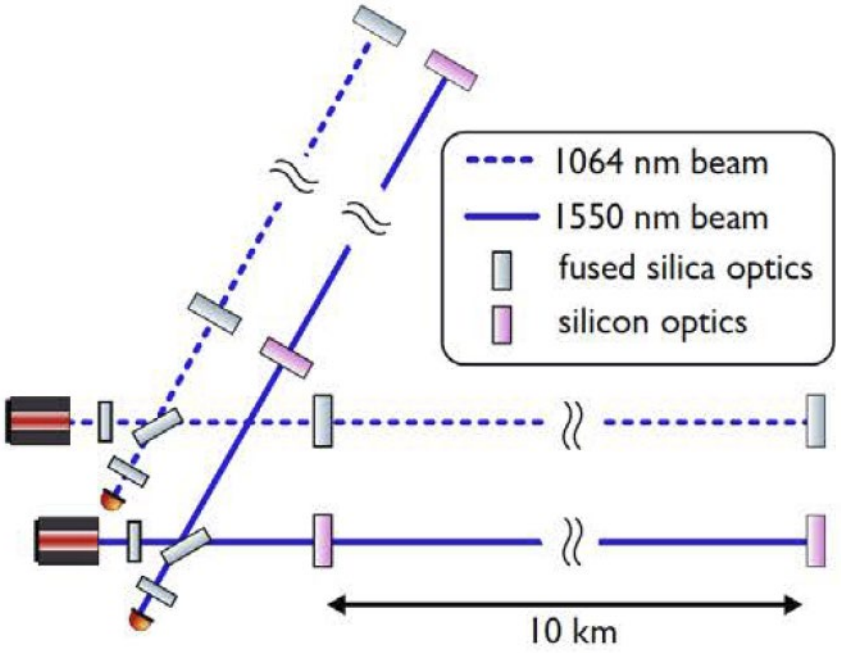
- Wide frequency range
- Massive black holes (LF focus)
- Localisation capability
- (more) Uniform sky coverage
- Polarisation disentanglement
- High Reliability (high duty cycle)
- High SNR

Design Specifications

- Xylophone (multi-interferometer) Design
- Underground
- Cryogenic
- Triangular shape
- Multi-detector design
- Longer arms







ET EINSTEIN TELESCOPE

ET Enabling Technologies

- The multi-interferometer approach asks for 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

Parameter	ET-HF	ET-LF
Arm length	10 km	10 km
Input power (after IMC)	500 W	3 W
Arm power	3 MW	18 kW
Temperature	290 K	10-20 K
Mirror material	fused silica	silicon
Mirror diameter / thickness	62 cm / 30 cm	45 cm/ 57 cm
Mirror masses	200 kg	211 kg
Laser wavelength	1064 nm	1550 nm
SR-phase (rad)	tuned (0.0)	detuned (0.6)
SR transmittance	10 %	20 %
Quantum noise suppression	freq. dep. squeez.	freq. dep. squeez.
Filter cavities	1×300 m	2×1.0 km
Squeezing level	10 dB (effective)	10 dB (effective)
Beam shape	TEM_{00}	TEM_{00}
Beam radius	12.0 cm	9 cm
Scatter loss per surface	37 ppm	37 ppm
Seismic isolation	SA, 8 m tall	mod SA, 17 m tall
Seismic (for $f > 1$ Hz)	$5 \cdot 10^{-10}$ m/f^2	$5 \cdot 10^{-10}$ m/f^2
Gravity gradient subtraction	none	factor of a few

Challenging engineering

New technology in cryo-cooling

New technology in optics

New laser technology

High precision mechanics and low noise controls

High quality opto-electronics and new controls

Evolved laser technology

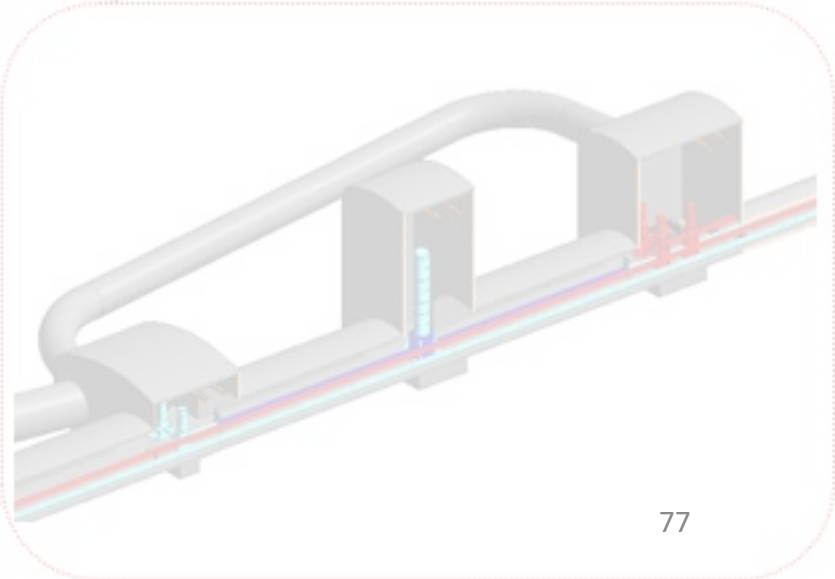
Evolved technology in optics

Highly innovative adaptive optics

High quality opto-electronics and new controls

Challenging Engineering: key points

- **~30km of underground tunnels**
  - Safety (fire, cryogenic gasses, escape lanes, heat handling during the vacuum pipe backing)
  - Noise (creeping, acoustic noise, seismic noise, Newtonian noise)
  - Minimisation of the volumes, but preservation of future potential)
  - Water handling, hydro-geology and tunnels inclination
  - Cost
- **Large caverns**
  - In addition to the previous points:
  - Stability
  - Cleanliness
  - Thermal stability
  - Ventilation and acoustic noise



Cryo-cooling

ET operative temperature ~10K

Key issues

- Acoustic and vibration noises
- Laser absorption and heat extraction
- Cleanliness and contamination
- Cooling time (large masses, commissioning time, …)
- Infrastructures
- Technology (gasses or cryo-coolers)
- Materials
- Safety

Low Frequency special focus

- Underground infrastructure
- 17m tall seismic filtering suspensions
  - Large impact on cavern engineering and costs
- R&D in active-passive filtering systems and seismic sensors

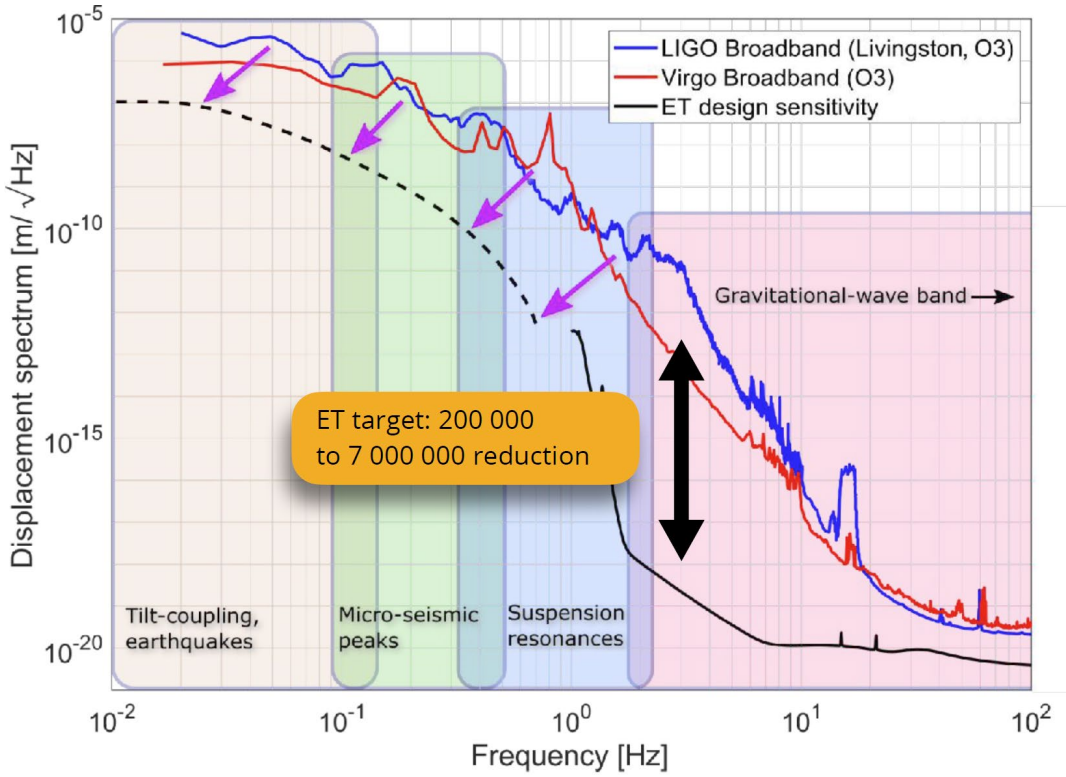
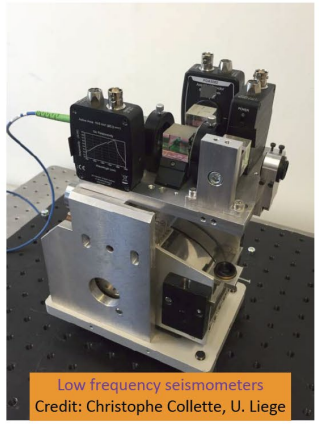
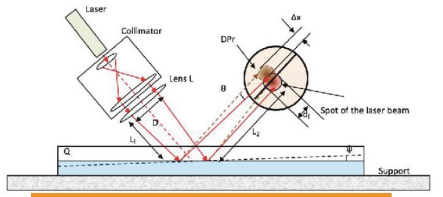
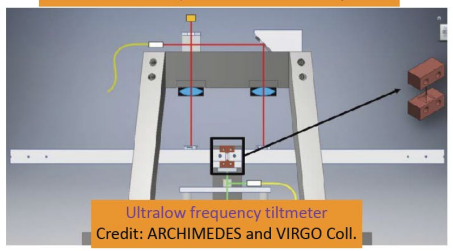


Image: Conor Mow-Lowry


6-D interferometric readout inertial sensor
Credit: Conor Mow-Lowry, VU Amsterdam


Low frequency seismometers
Credit: Christophe Collette, U. Liege

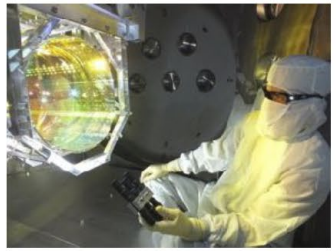

Laser inclinometer, Credit: B. Di Girolamo, CERN

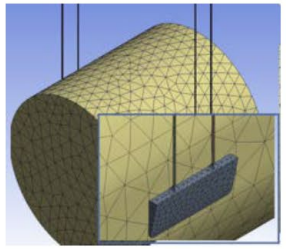

Ultralow frequency tiltmeter
Credit: ARCHIMEDES and VIRGO Coll.

Credits: A.Freise

Credits: A.Freise

New Optics



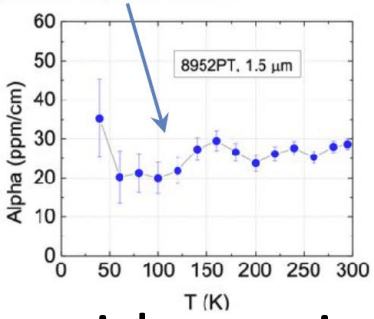


Advanced LIGO – 40 kg / ET 200 kg

Nikon SiO_2

Absorption of "best 45 cm" MCZ Si: 1.5um

Stanford/Glasgow/Berkeley/Caltech 2019



- Substrates Challenge:
  - Substrate (ET-HF silica / ET-LF silicon) of 200 kg-scale, diam≥45cm, with required purity and optical homogeneity/abs.
  - Silicon Challenge:
    - Czochralski (CZ) method produced test masses could have the required size, but show absorption excesses due to the (crucible) contaminants
    - Float Zone (FZ) produced samples show the required purity, but of reduced size (20cm wrt ≥45cm required)
    - Magnetic Czochralski (mCZ) could be the possible solution?
- Coating Challenge:
  - major challenge over recent years:
    - Amorphous dielectric coating solutions often either satisfy thermal noise requirement (3.2 times better than the current coatings) **or** optical performance requirement (less than 0.5ppm) – not both
    - AlGaAs Crystalline coatings could satisfy ET-LF requirements, but currently limited to 200mm diameter.

New Laser and Opto-Electronic Technology

Virgo and LIGO developed CW low noise lasers at 1064nm

- In ET-HF their evolution toward higher power will be investigated

In ET-LF we will use a different wavelength because of the Silicon test masses:

- λ=1.55μm or 2μm?

New electro-optic components:

- High quantum efficiency photodiodes
- Low absorption e.o.m.
- Low dissipation faraday isolators

Other relevant challenges

- Auxiliary optics, adaptive optics and thermal compensation of optical aberrations
- Precision mechanics, alignment and positioning
- **Vacuum** (*the largest volume under UHV in the World*):
  - More than 120km of vacuum pipes
    - ~1 m diameter, total volume 9.4×10^4 m^3
    - 10^{-10} mbar for H_2, 10^{-11} mbar for N_2 and less than 10^{-14} mbar for Hydrocarbons
  - Joint development with CERN involving ET and CE
- Low noise controls
- Computing
  - Computation intensive, not data intensive
- Governance & Organisation

European Strategy Forum on Research Infrastructures

ESFRI Roadmap

ET EINSTEIN TELESCOPE

Proposal submitted by:

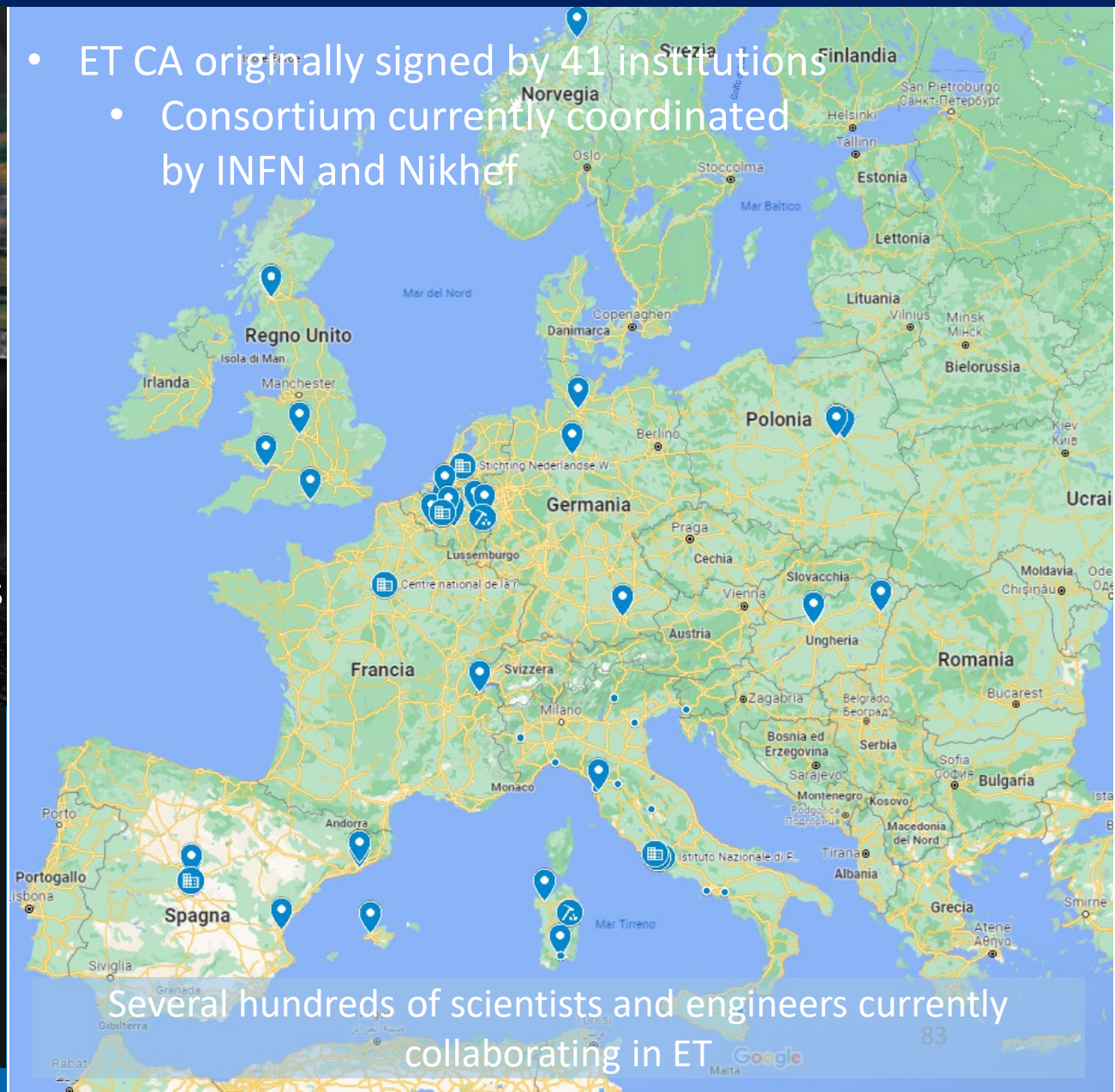
- **Italy** (Lead Country)
- Belgium
- Netherlands
- Poland
- Spain

The project and the collaboration activities now also include agencies and institutions belonging to:

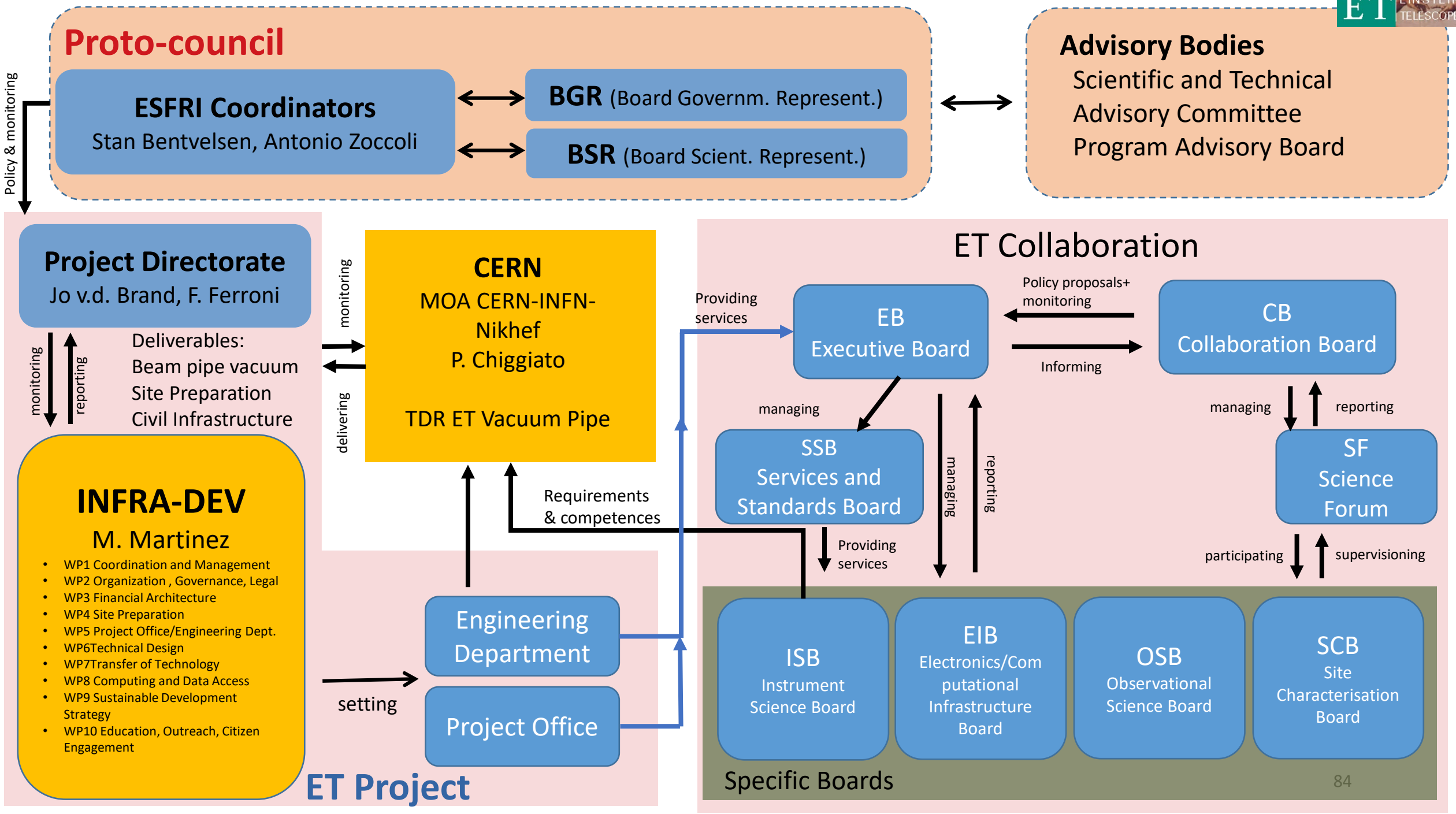
- **Austria**
- **France**
- **Germany**
- **Hungary**
- **Switzerland**
- **UK**

Large preparatory funds available in some country (IT, NL, …), an EU INFRA-DEV proposal just submitted and an EU INFRA-TECH proposal in preparation

- ET CA originally signed by 41 institutions
  - Consortium currently coordinated by INFN and Nikhef



Several hundreds of scientists and engineers currently collaborating in ET


Proto-council
ESFRI Coordinators
Stan Bentvelsen, Antonio Zoccoli
BGR (Board Governm. Represent.)
BSR (Board Scient. Represent.)
Advisory Bodies
Scientific and Technical Advisory Committee
Program Advisory Board
Policy & monitoring
Project Directorate
Jo v.d. Brand, F. Ferroni
monitoring
reporting
Deliverables:
Beam pipe vacuum
Site Preparation
Civil Infrastructure
monitoring
delivering
CERN
MOA CERN-INFN-Nikhef
P. Chiggiato
TDR ET Vacuum Pipe
INFRA-DEV
M. Martinez
WP1 Coordination and Management
WP2 Organization , Governance, Legal
WP3 Financial Architecture
WP4 Site Preparation
WP5 Project Office/Engineering Dept.
WP6Technical Design
WP7Transfer of Technology
WP8 Computing and Data Access
WP9 Sustainable Development Strategy
WP10 Education, Outreach, Citizen Engagement
setting
Engineering Department
Project Office
ET Project
Requirements & competences
Providing services
ET Collaboration
EB Executive Board
Policy proposals+ monitoring
Informing
CB Collaboration Board
managing
SSB Services and Standards Board
managing
reporting
managing
reporting
SF Science Forum
Providing services
participating
supervisioning
ISB Instrument Science Board
EIB Electronics/Computational Infrastructure Board
OSB Observational Science Board
SCB Site Characterisation Board
Specific Boards

ET site(s)

- Currently there are two sites, in Europe, candidate to host ET:
  - The Sardinia site, close to the Sos Enattos mine
  - The EU Regio Rhine-Meusse site, close to the NL-B-D border
- A third option in Saxony (Germany) is under discussion

ET sites under characterisation

Euregio Meuse-Rhine

- A 250-m deep borehole has been excavated and equipped
  - Seismic data under acquisition and analysis
- A set of other boreholes under excavation
- Extensive active and passive site characterisation with sensor arrays in 2021
- Good seismic noise attenuation given by the particular geological structure
- Characterisation funded through Interreg grants
- Large proposal O(1G€) for funding the infrastructure submitted to the Dutch government

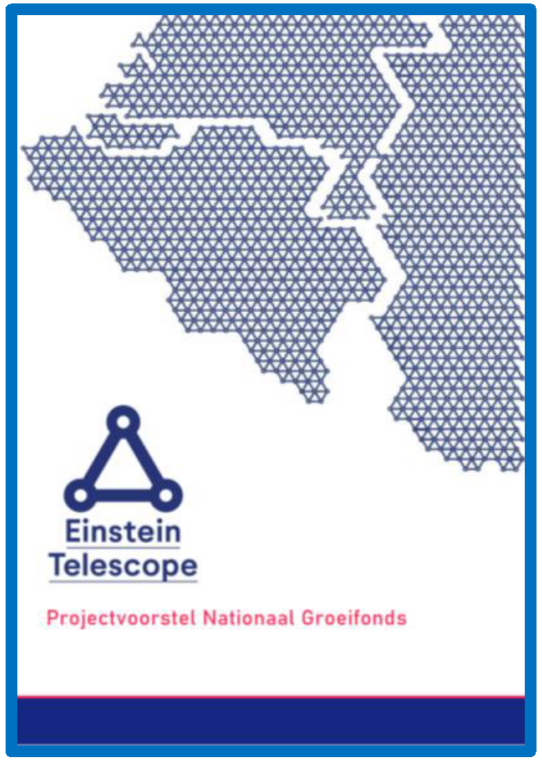
Sardinia

- Long standing characterisation of the mine in one of the corners continuing
  - Seismic, magnetic and acoustic noise characterisation ongoing at different depth in the mine
- Underground laboratory under preparation (SarGrav)
- Two ~290m boreholes have been excavated, equipped and data taking is ongoing
- A set of other boreholes expected in 2022
- Intense & international surface investigations programme ongoing
- Characterisation funded on regional and national funds
- Large proposal O(100M€) for technology development and engineering design submitted to the Italian government; O(1G€) infrastructure realisation under discussion.

Einstein Telescope in Euregio Meuse-Rhine (EMR)

Connected institutions in:
Belgium,
Germany &
the Netherlands

Nationaal Groeifonds (the Netherlands)



Emphasis on potential socio-economic Impact

Submitted by OCW Ministry
(EZK Ministry support)

Supported by ~70 Dutch Industries/institutions

In October 2021 the Netherlands submitted large funding proposal within context of the '*Nationaal Groeifonds*'. Decision on April 2022.

Approved

Includes 42 M€ for geology, R&D & organization
as well as possible Dutch share towards ET realization

ETIC – Einstein Telescope Infrastructure Consortium

Next Generation EU Investment proposed 100M€ focused on ET enabling technology and Sardinian site candidature support

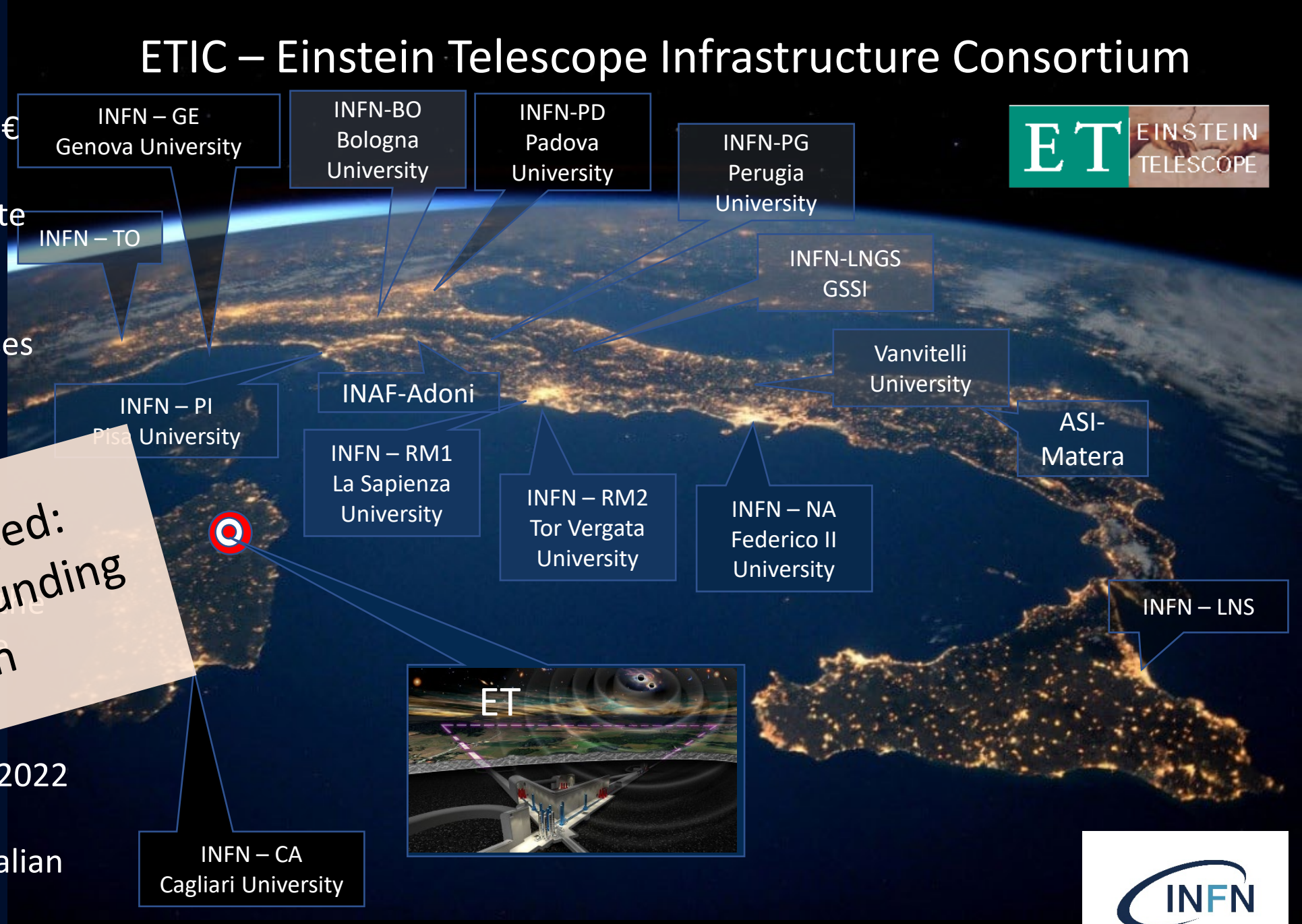
- 8% Human Resources
- 30% Scientific apparatuses
- 12% Distributed Infrastructures
- 28% ET design
- 12% Training

Additional funding for the same framework for the site characterization

Feedback expected in June 2022

Discussion ongoing on an Italian share toward ET realization

Ranking published: Negotiation for funding starts soon



XII Einstein Telescope Symposium

Budapest, 7-8 June 2022: Birth of the ET Scientific Collaboration