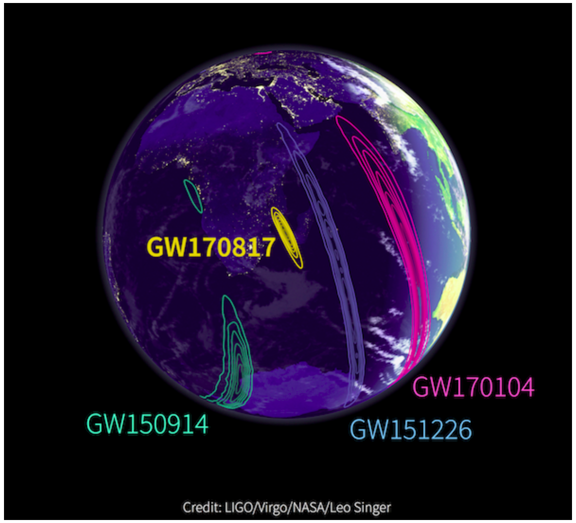
Les ondes gravitationnelles dans les prochaines decennies



Marie Anne Bizouard, ARTEMIS

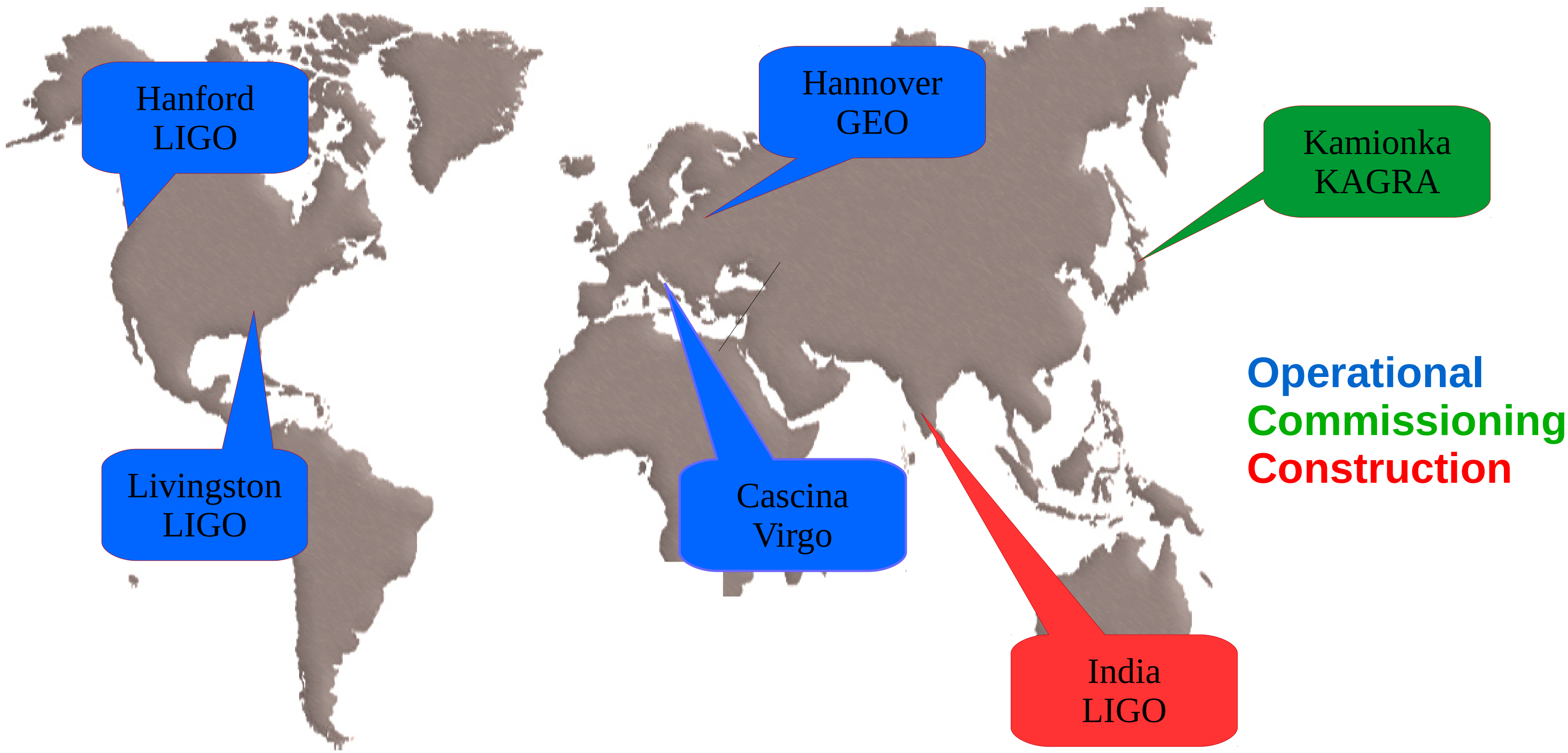
Journées OG
12 fevrier 2019, Lyon

Outline

- The future detectors
  - 2G updates : Advanced LIGO, advanced Virgo and Kagra
  - Spaceborne mission : LISA.
  - 3G ground based detectors.
  - Other detectors : atomic interferometers, PTA, ...

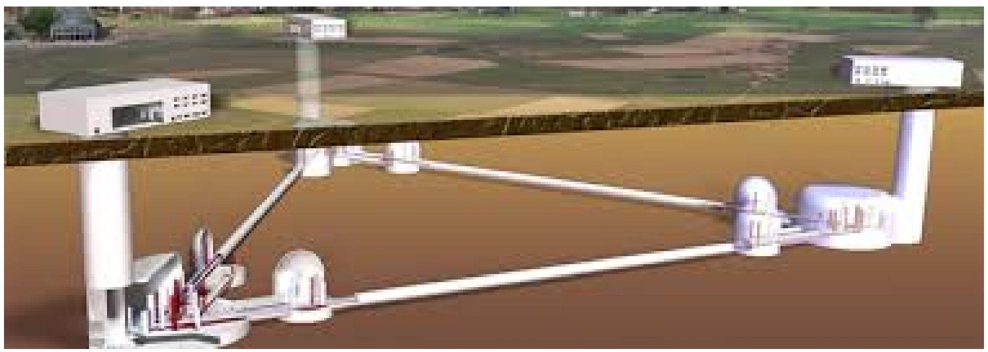
- For which science ?
  - Science case defined in :
    - LISA proposal [ArXiv:1702.00786]
    - 3G Science Book (to be released soon)

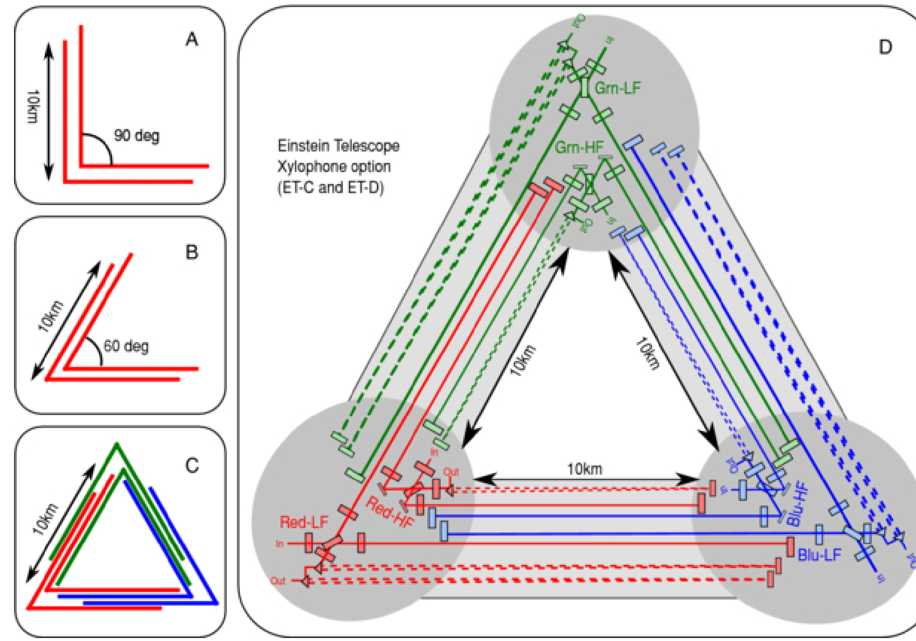
Network of 2G ground detectors in the next decade



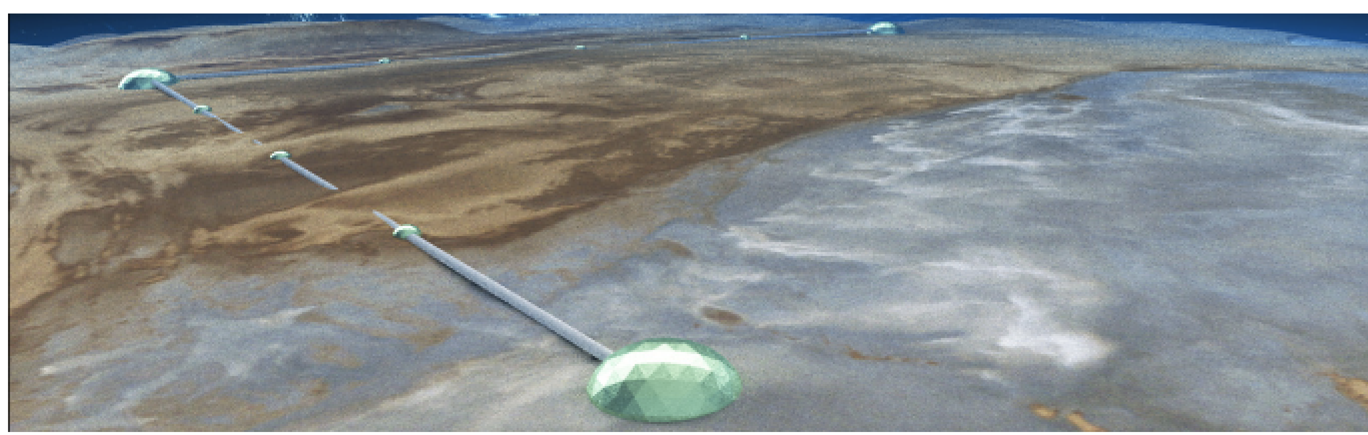
Future detectors : 3G ground detectors

Einstein Telescope : 10 km triangle



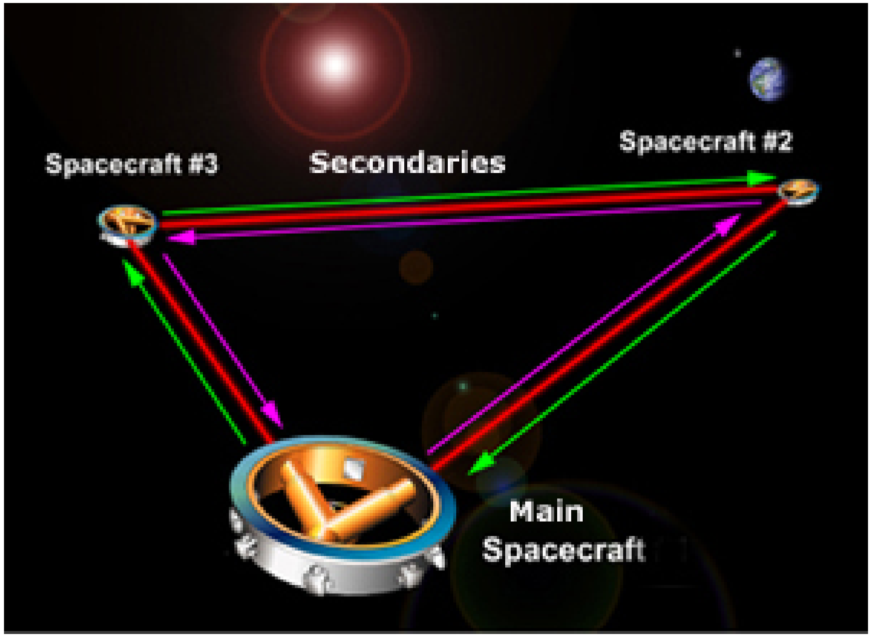


Cosmic Explorer : 40 km

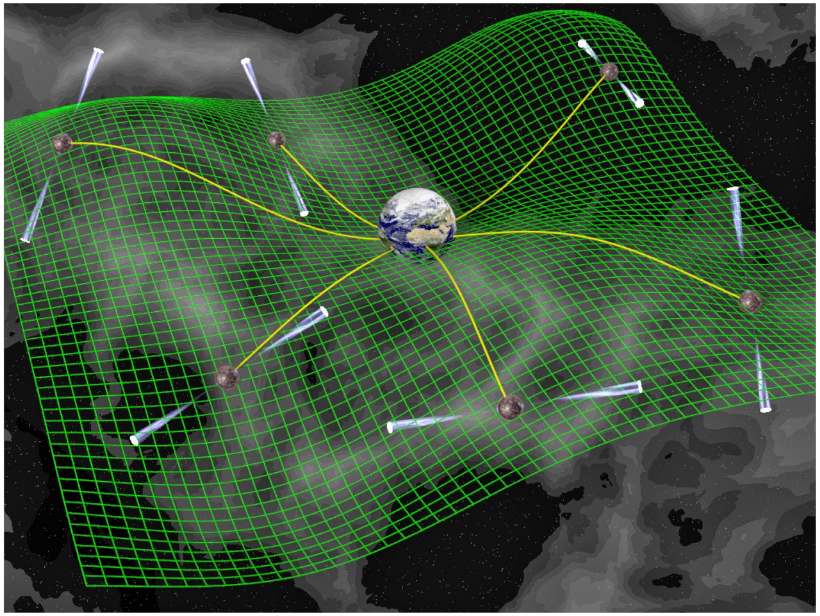


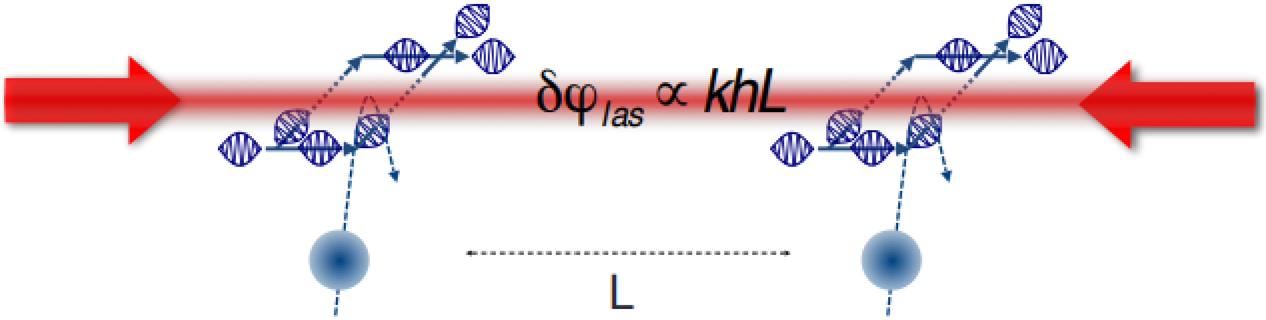
Future detectors

LISA : launch 2034



Pulsar timing array

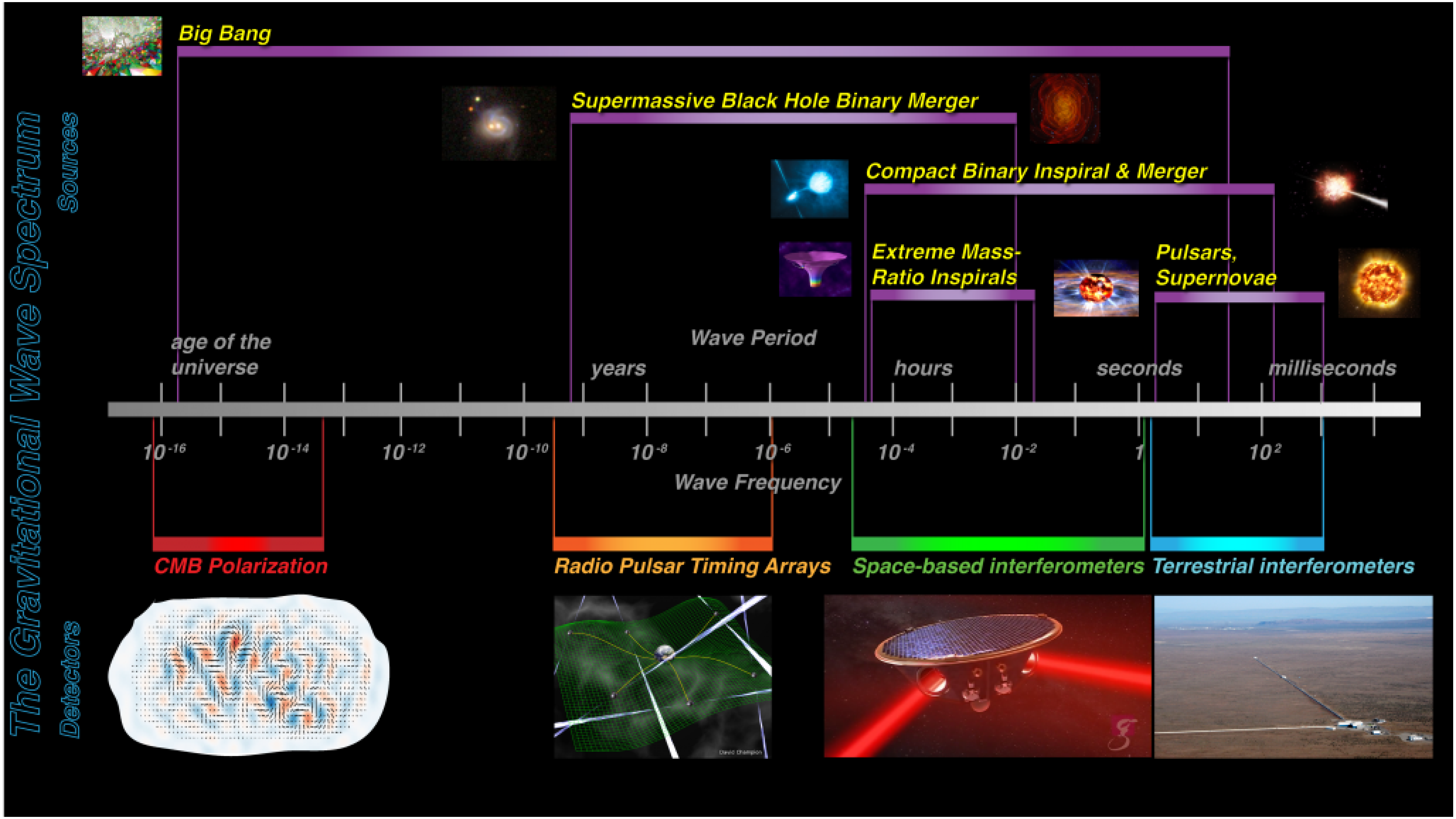




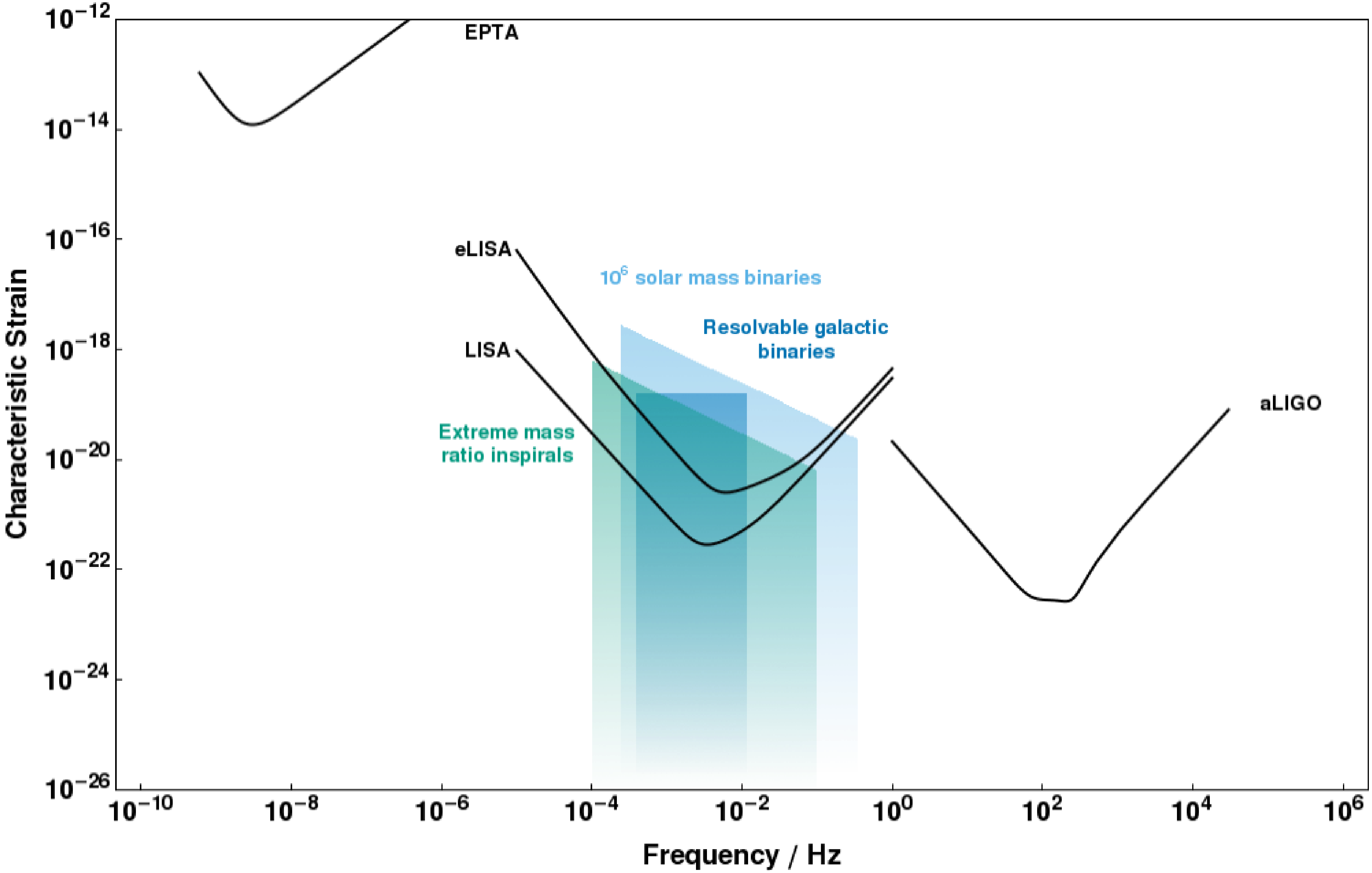
MIGA
Atomic interferometry : inertial sensor

Discrimination between GW effects and gravity gradients using the spatial resolution of the antenna

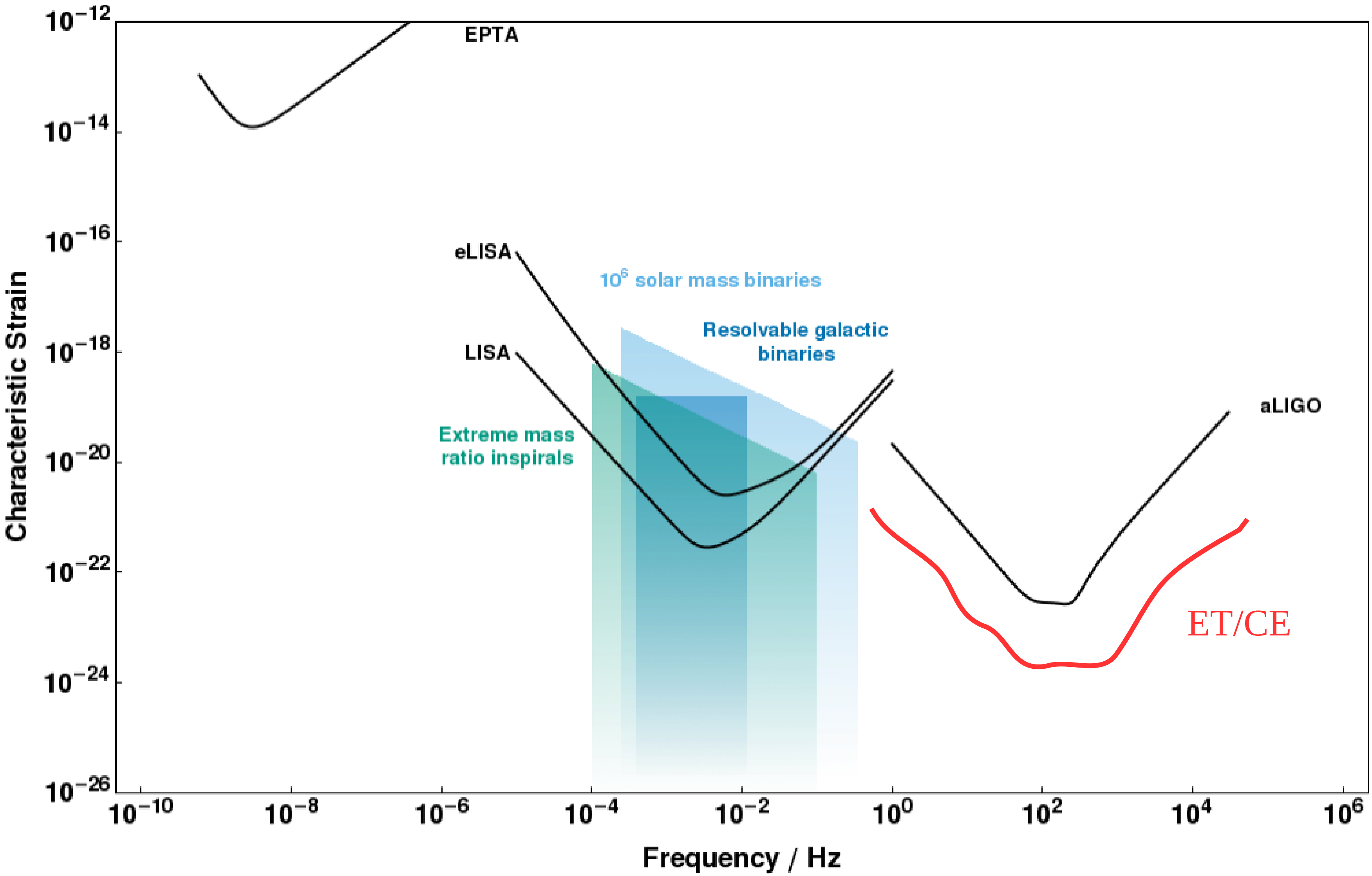
GW spectrum


The Gravitational Wave Spectrum
Sources
Detectors
Big Bang
Supermassive Black Hole Binary Merger
Compact Binary Inspiral & Merger
Extreme Mass-Ratio Inspirals
Pulsars, Supernovae
Wave Period
age of the universe
years
hours
seconds
milliseconds
10^{-16}
10^{-14}
10^{-12}
10^{-10}
10^{-8}
10^{-6}
10^{-4}
10^{-2}
1
10^{2}
Wave Frequency
CMB Polarization
Radio Pulsar Timing Arrays
Space-based interferometers
Terrestrial interferometers

Expected sensitivities



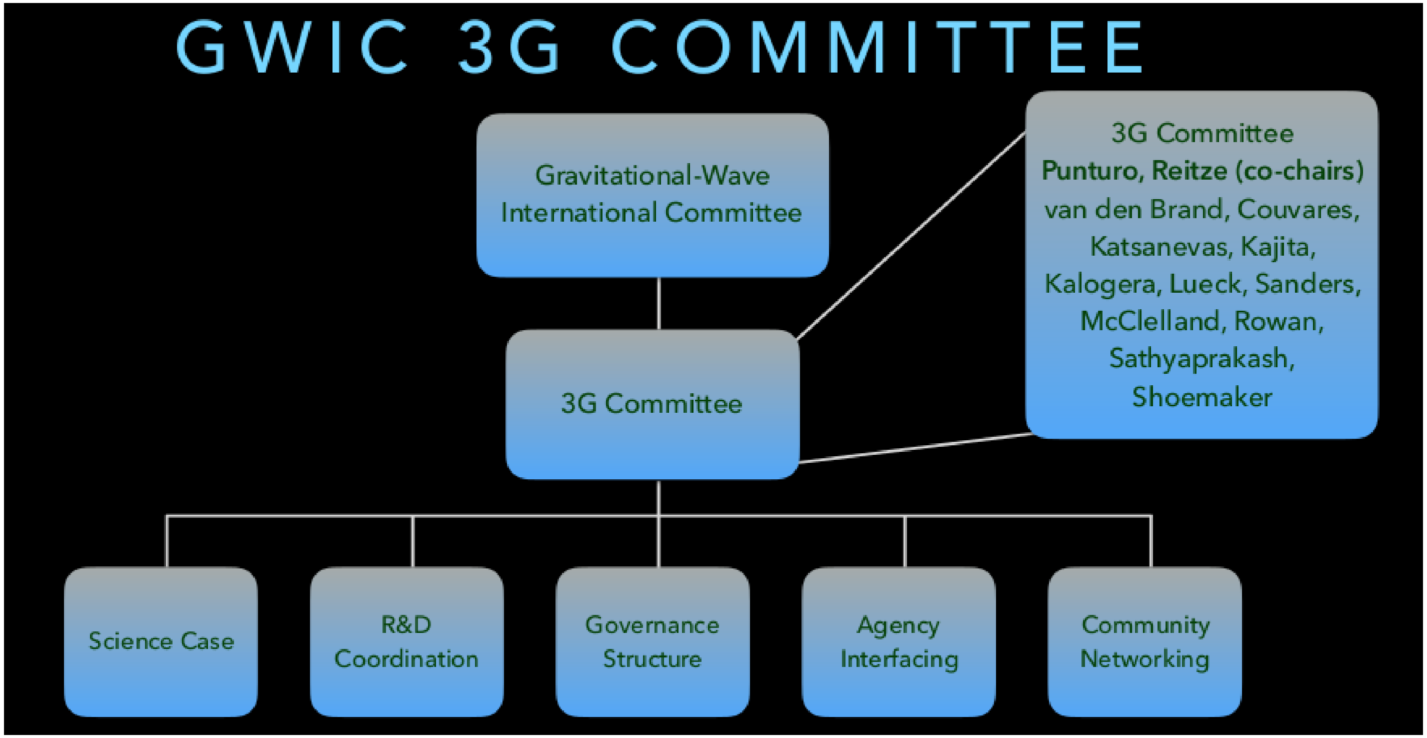
Expected sensitivities



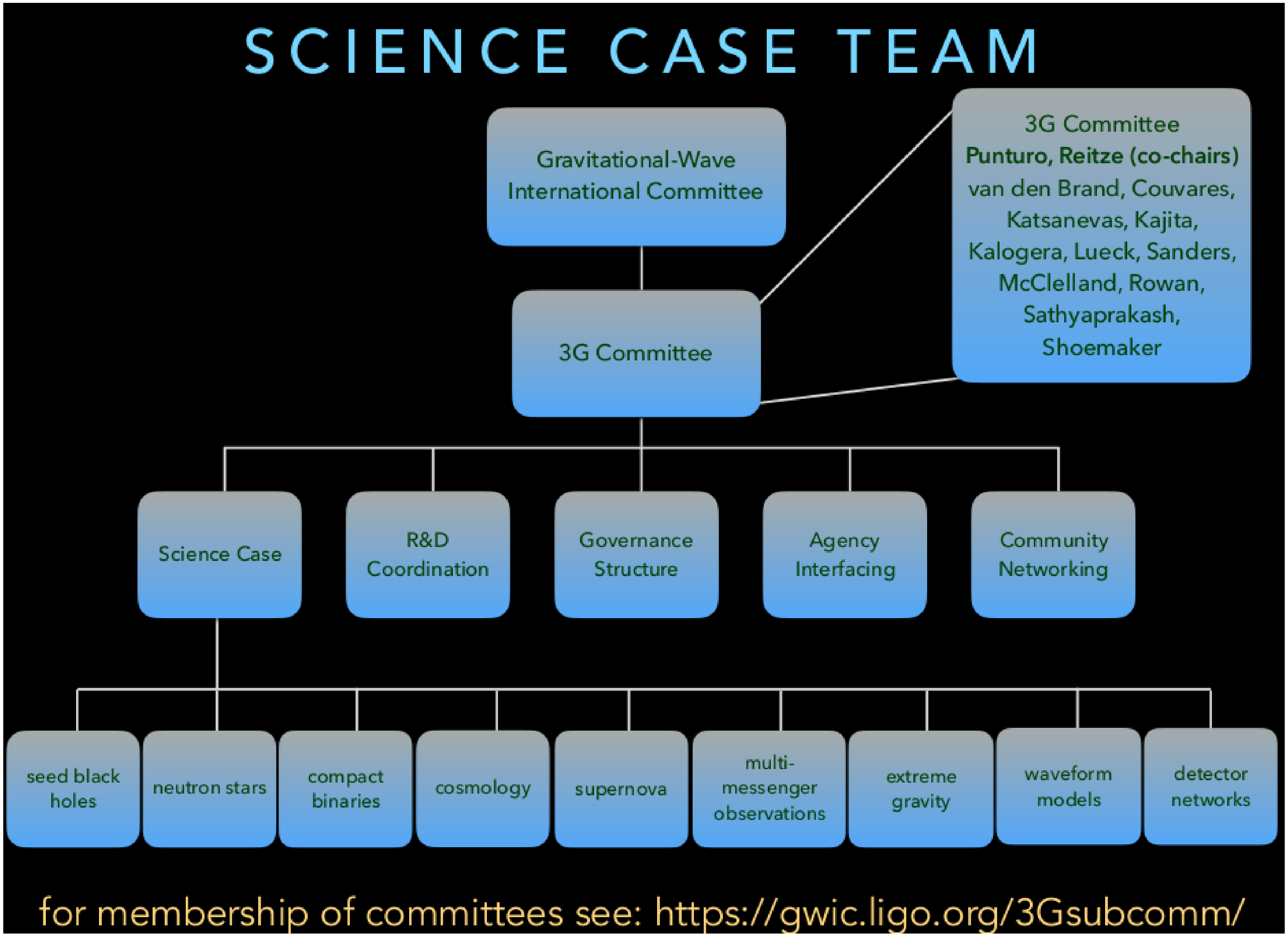
The GWIC

https://gwic.ligo.org/

- Gravitational Wave International Comittee.
- Goal : defining the road map for future detectors. That includes all types of ground based detectors but mainly laser interferometric detectors.
- Has formed a 3G committee that has appointed a subcommittee to write the 3G Science Book.



GWIC 3G science case



3G Science Book

Fundamental physics

- Nature of gravity
- Nature of compact object
- Nature of dark matter

Astrophysic of compact objects

- NS physics
  - Max mass of NS
  - EOS of matter at supranuclear density
- Core collapse supernova
- Seed black holes and their growth
- Extreme mass ratio insoiral and SMBH environment
- Multi-messenger analysis
  - Jet physics
  - Cosmic ray acceleration
  - nucleosynthesis

Cosmology & cosmography

- Test of inflation models
- Cosmic strings
- Cosmological parameters and dark energy with standard sirens

3G detectors sensitivity

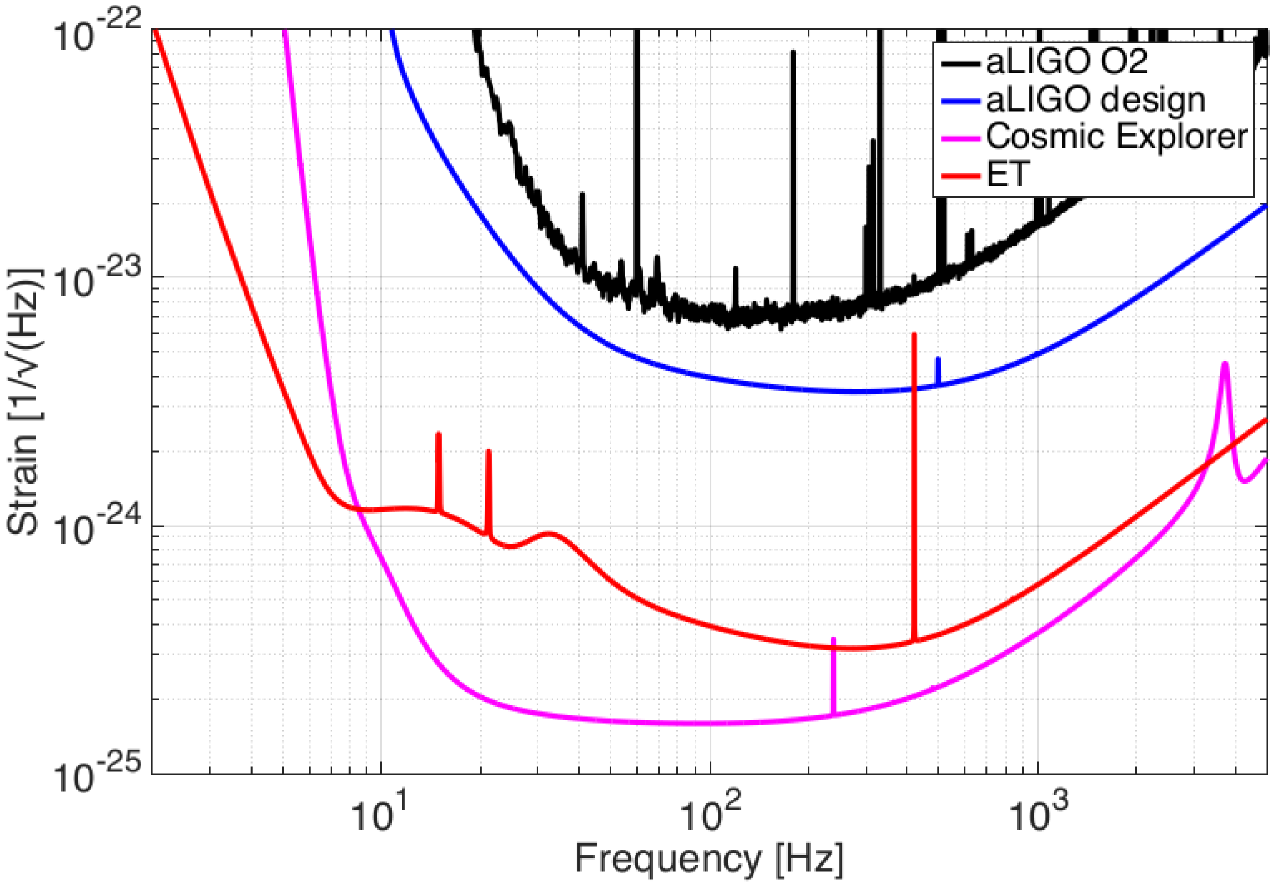
- Factor 10 improvement

  → 1000 times more sources than 2G

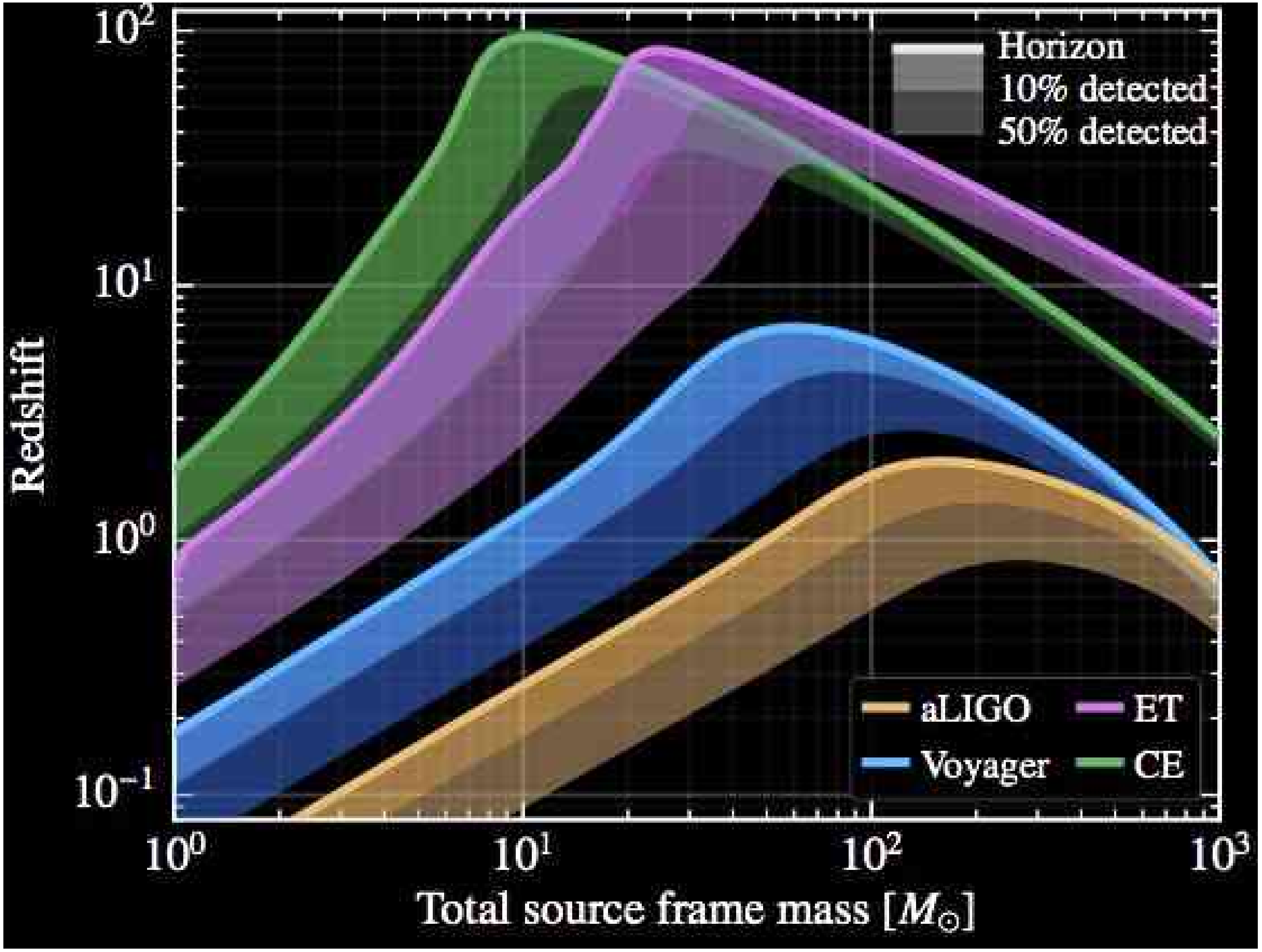
  → 1 % statistical accuracy for binary related measurements

- Shifting towards lower cuttoff frequency

- Einstein Telescope and Cosmic explorer sensitivity comparison can be misleading (triangle vs linear)

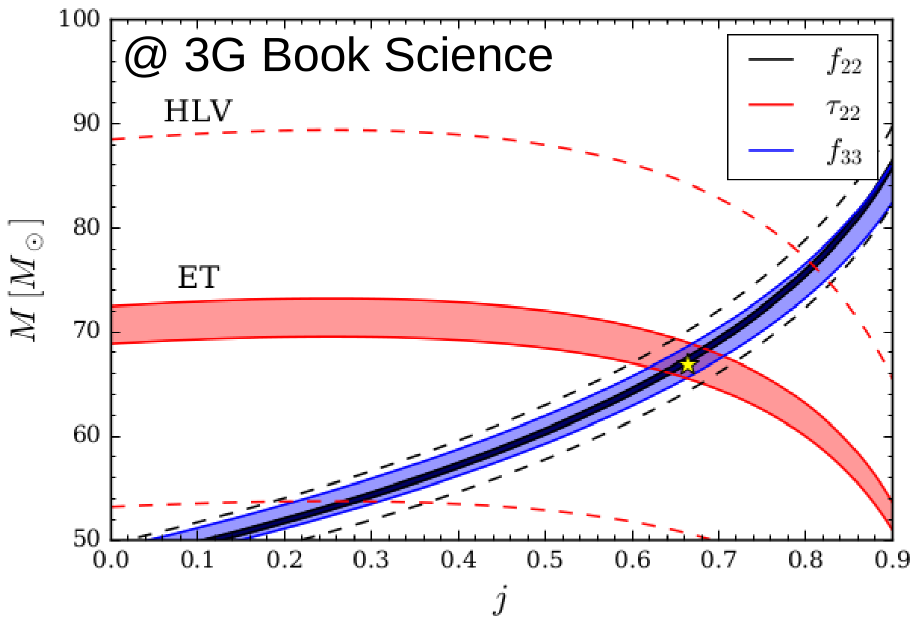


3G detectors sensitivity



Fundamental physics : nature of gravity

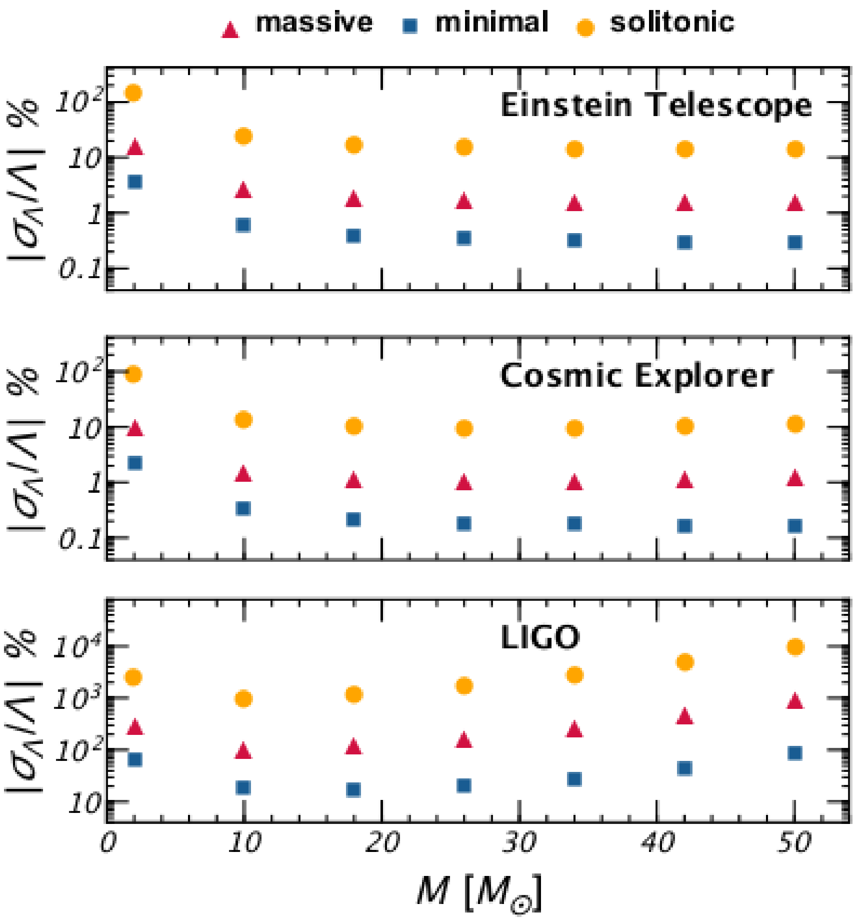
- Is GR the fundamental theory ?
  - GW allows to constrain alternative gravity theories
  - Non tensorial radiation
  - Lorentz symetry violation
- Test black hole conjecture : QNM, absence/presence of horizon



95 % confidence intervals on 2 QNM frequencies for GW150914 like event

Fundamental physics : nature of compact object

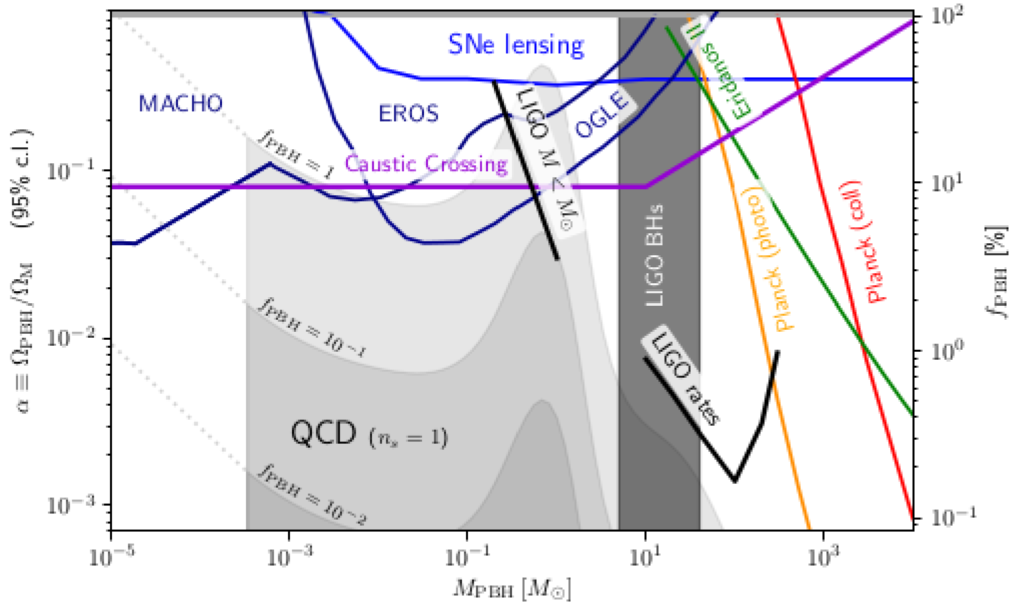
- Search for exotic compact objects : worm holes, bosonic clouds, cosmic strings
  - Spin induced quadrupole moment
  - Tidal deformability (distinguish a BNS from a boson star merger)
- Exploring particle physics theories : axions, ultra-light bosons, consequence of new interactions on two-body dynamics and population characteristics



Bound on ECO's tidal deformability

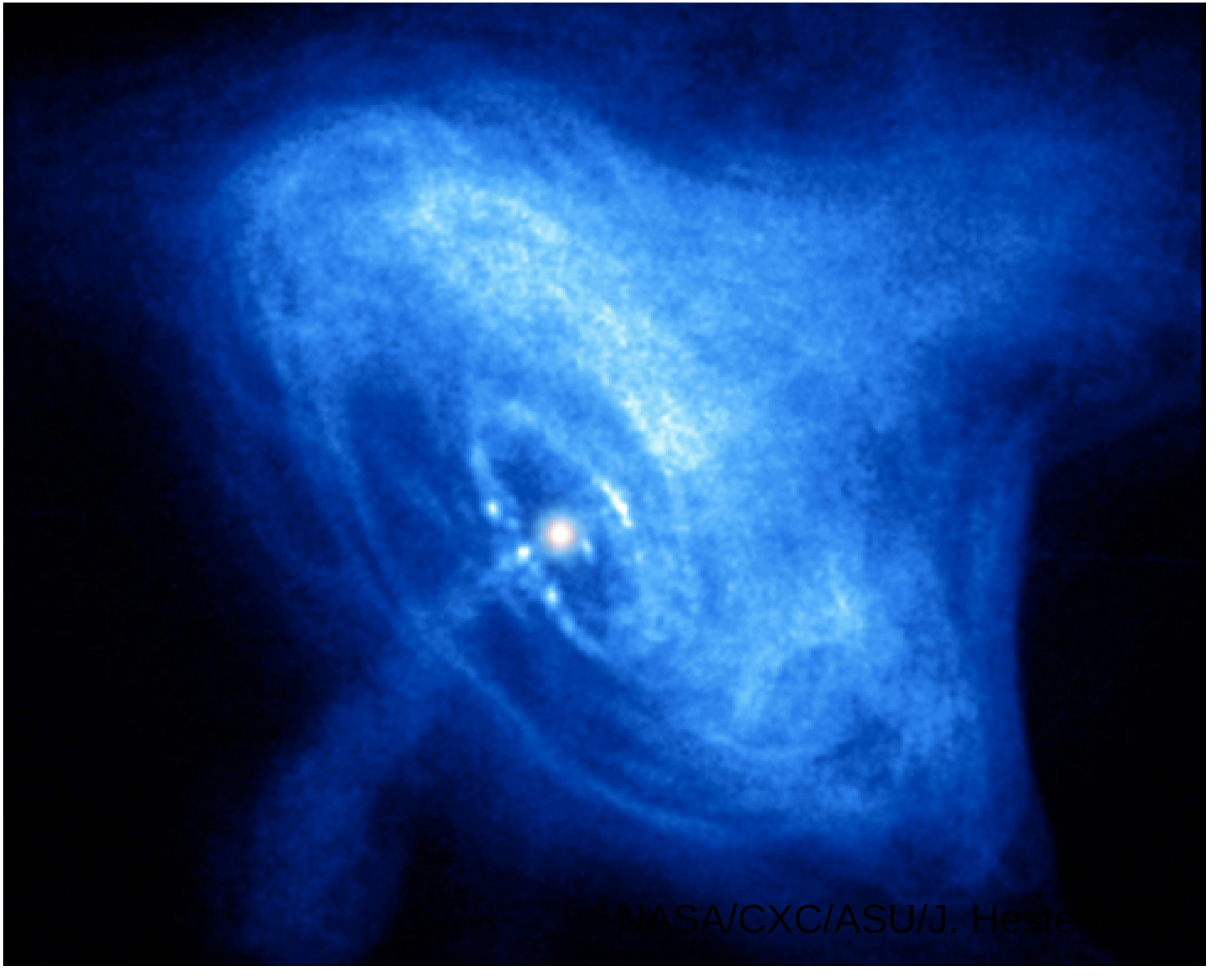
Fundamental physics : nature of dark matter

- Can dark matter be BH ?



- Can we detect particule like dark matter with compact objects ?
  - Gravitational drag will affect the binary dynamics

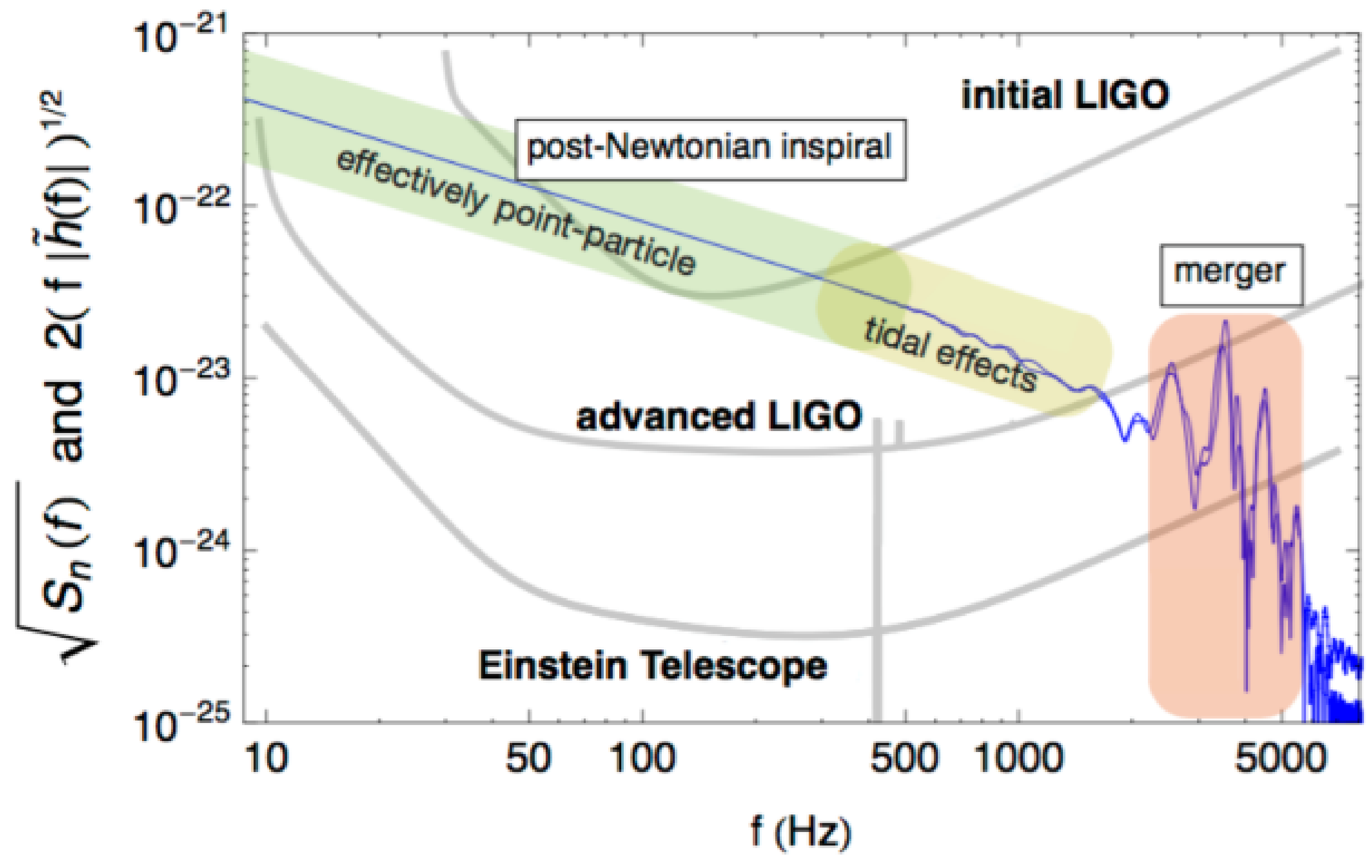
Astrophysics of compact objects



Neutron stars

- Binary mergers involving neutron stars
  - EOS, finite temparatures, phase transitions
  - microphysics input: neutrino transport and interactions, applicability of MHD
  - modeling mergers
    - hydrodynamics and MHD, neutrino radiation, EM signals
  - post-merger oscillations, stability extraction of radius, mass and compactness
- Continuous wave sources
  - EOS, elasticity (mountains) of phases; deformations and precession
  - microphysics input: transport in cold matter (shear, bulk viscosities), neutrino cooling
  - GR modeling of oscillations, stability and dependence on EoS
  - effect of magnetic fields, spin-evolution, magnetically induced deformations
  - binary systems: dynamics, X-rays, spin-evolution, QPOs

Neutron stars



Neutron stars

- Transients
  - EOS of cold matter, superfluidity for glitches and relaxations, hot-matter in core-collapse.
  - Microphysics of neutrino interactions in core-collapse, mutual friction superfluids.
  - Modelling magnetar oscillations and bursts.
  - Modelling pulsar glitches, precessions.
- Beyond the standard model
  - Effect of dark matter particules
  - Testing GR in a matter environment

Core collapse supernovae (ground detectors)

- Understanding the explosion mecanism mystery :
  - Role of neutrinos
  - Role of Standing Accretion Shock Instability
  - Role of rotation
  - Role of progenitor mass
  - Mass accretion rate after shock
  - Asymetry of the explosion
- EOS measurement in proto-neutron star
  - Time frequency evolution of PNS oscillation modes
- Fate of the explosion : NS or BH ?

Core collapse supernovae (ground detectors)

P. Cerda-Duran et al, Astrophys.J. 779 (2013) L18

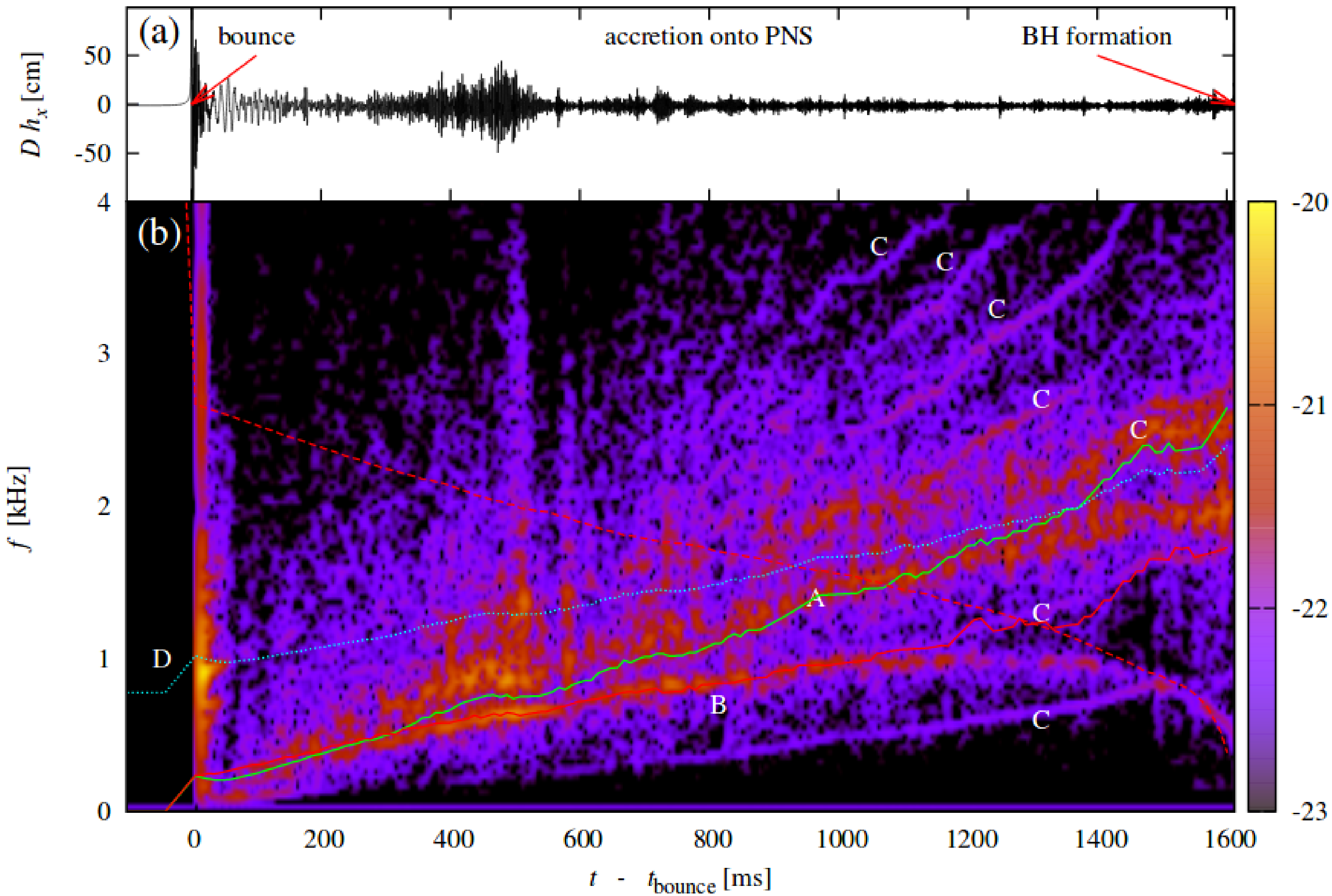
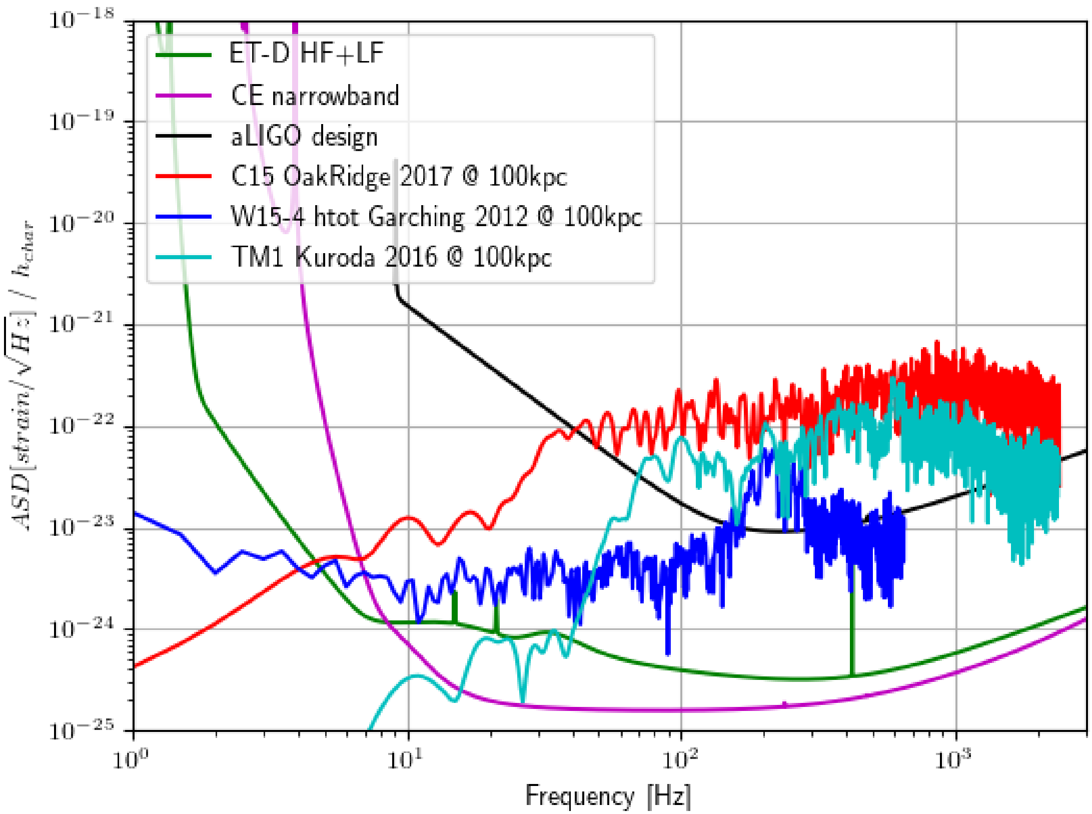


FIG. 3.— Waveform (a) and spectrogram (b) of the characteristic gravitational wave signal for the *fiducial model* at $D = 100$ kpc. We overplot estimates for the frequency evolution of g-modes at the surface of the PNS (solid-green line), g-modes in the cold inner core (solid-red line), quasi-radial mode (dashed-red line) and f-mode (dotted-blue line). Capital letters point to features described in the main text.

Core collapse supernovae (ground detectors)



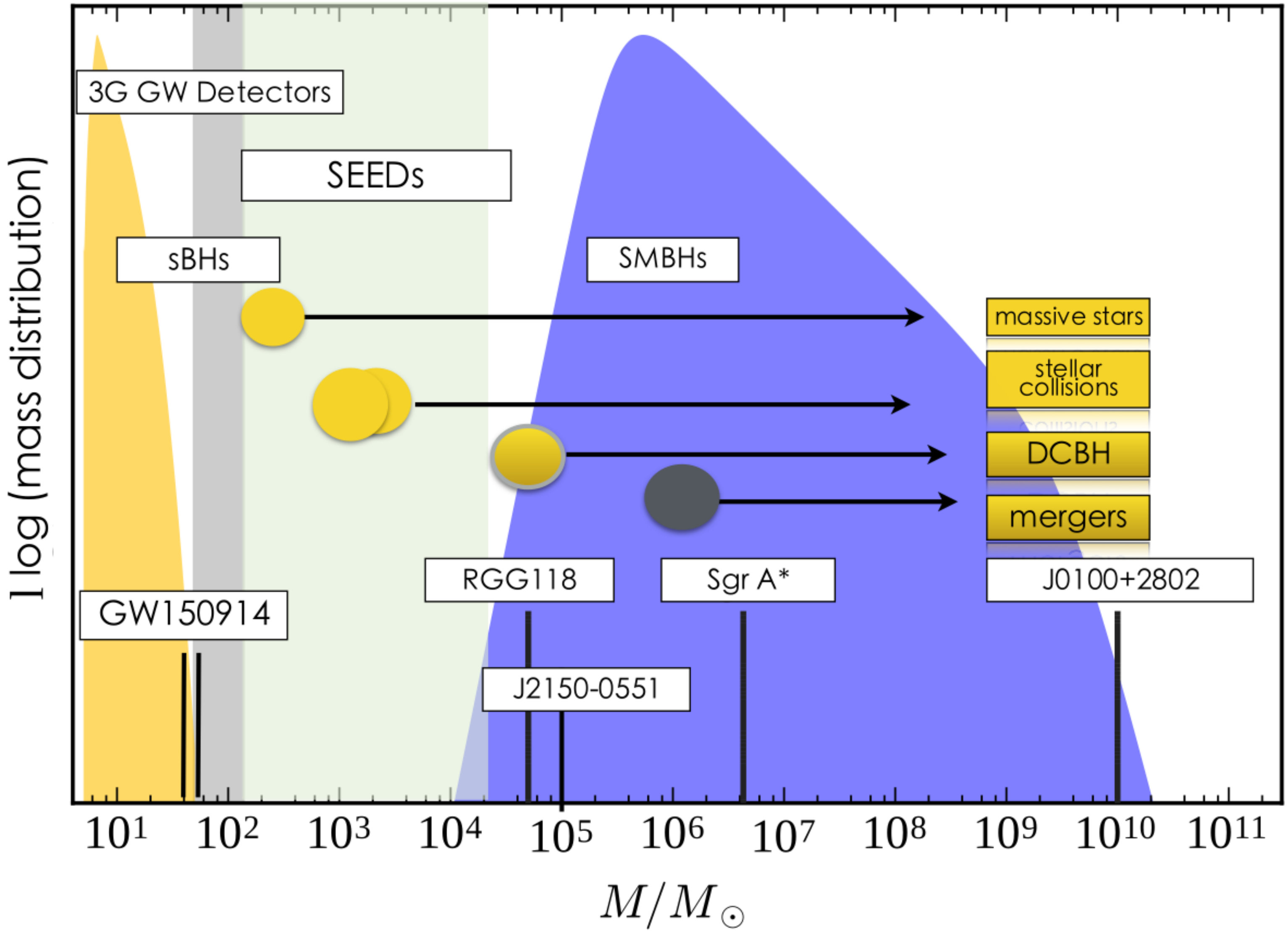
	Yakunin 2017	Mueller 2012			Kuroda 2016	
	C15	L15-3	N20-3	W15-1	SFHX	TM1
ET-D	54	12	4	6	24	18
CE	129	26	11	11.5	51	37
aLIGO	5.9	1.3	0.4	0.6	2.7	2.0

Table 4.1: Matched-filter SNRs of six 3D neutrino-driven explosion simulations for a source located at 100 kpc recorded in 1) the Einstein Telescope (ET-D), 2) the Cosmic Explorer (CE), and 3) and advanced LIGO at design sensitivity (aLIGO) are provided here. The matched-filter SNRs do not include a detector's antenna function.

Origin and evolution of compact object binaries

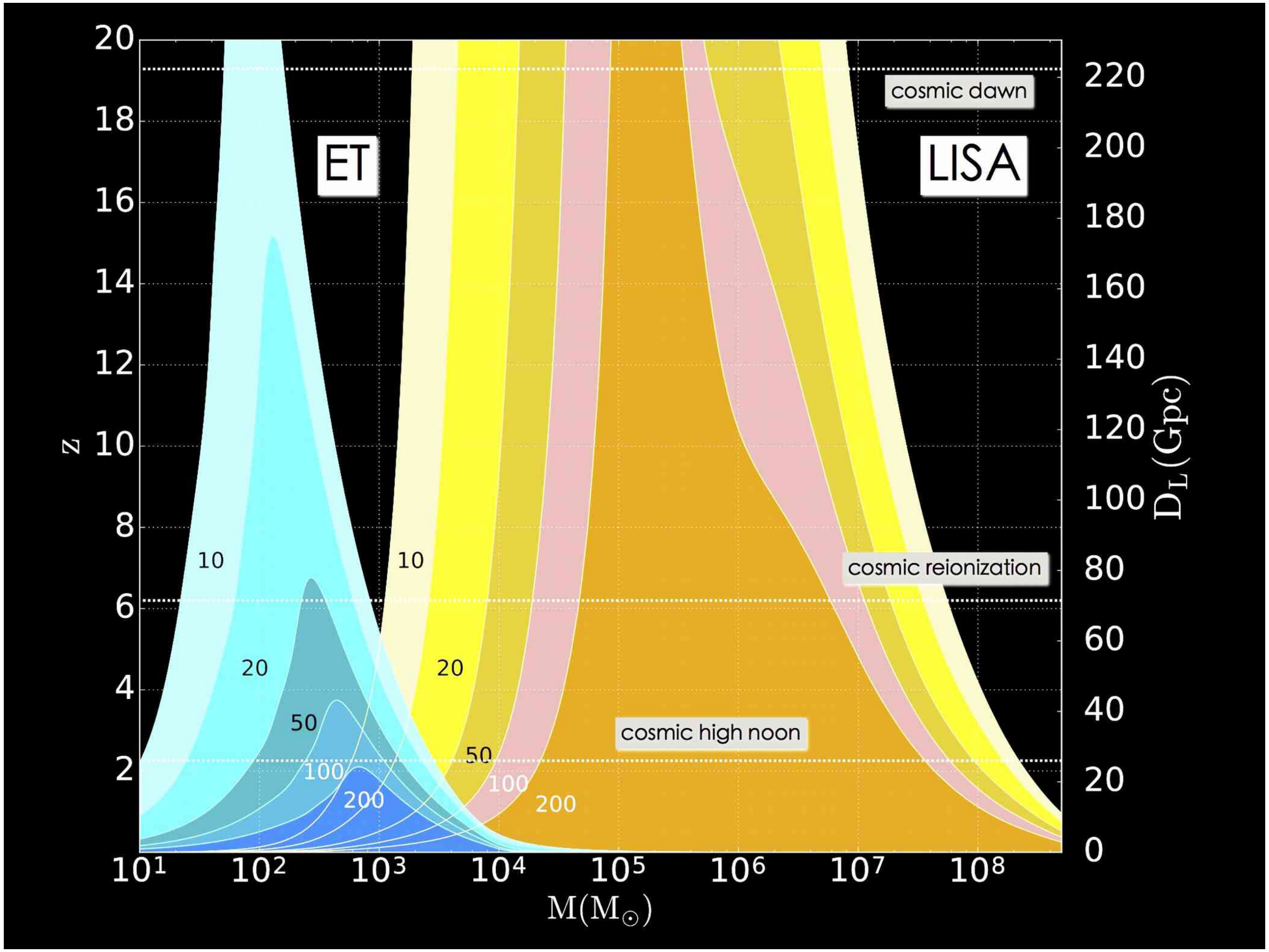
- Key question : binary formation scenario
  - Close compact binaries form from the evolution of massive stellar binaries through a common envelope phase or through chemically homogenuous evolution.
  - Dynamical formation : triple systems, star cluster or galactic nuclei.
  - BH formed from instabilities in the early universe.
- What is important to measure ?
  - Mass distribution, rate and spins.
- Observation of >100 Msun mergers at high redshift is only accessible to 3G
  - Comoving merger rate density of stellar born compact object is predicted to depend on the cosmic star formation rate. Star formation peaks a z~2.
  - 3G will be able to test wether merging binaries scales with the cosmic star formation rate.
- Complement other measurements :
  - SKA (radio) : maps of neutral gas up to very early ages.
  - James Webb telescope (near IR) : image light of galaxies up to z~7.

Origin of seed black holes



Origin of seed black holes

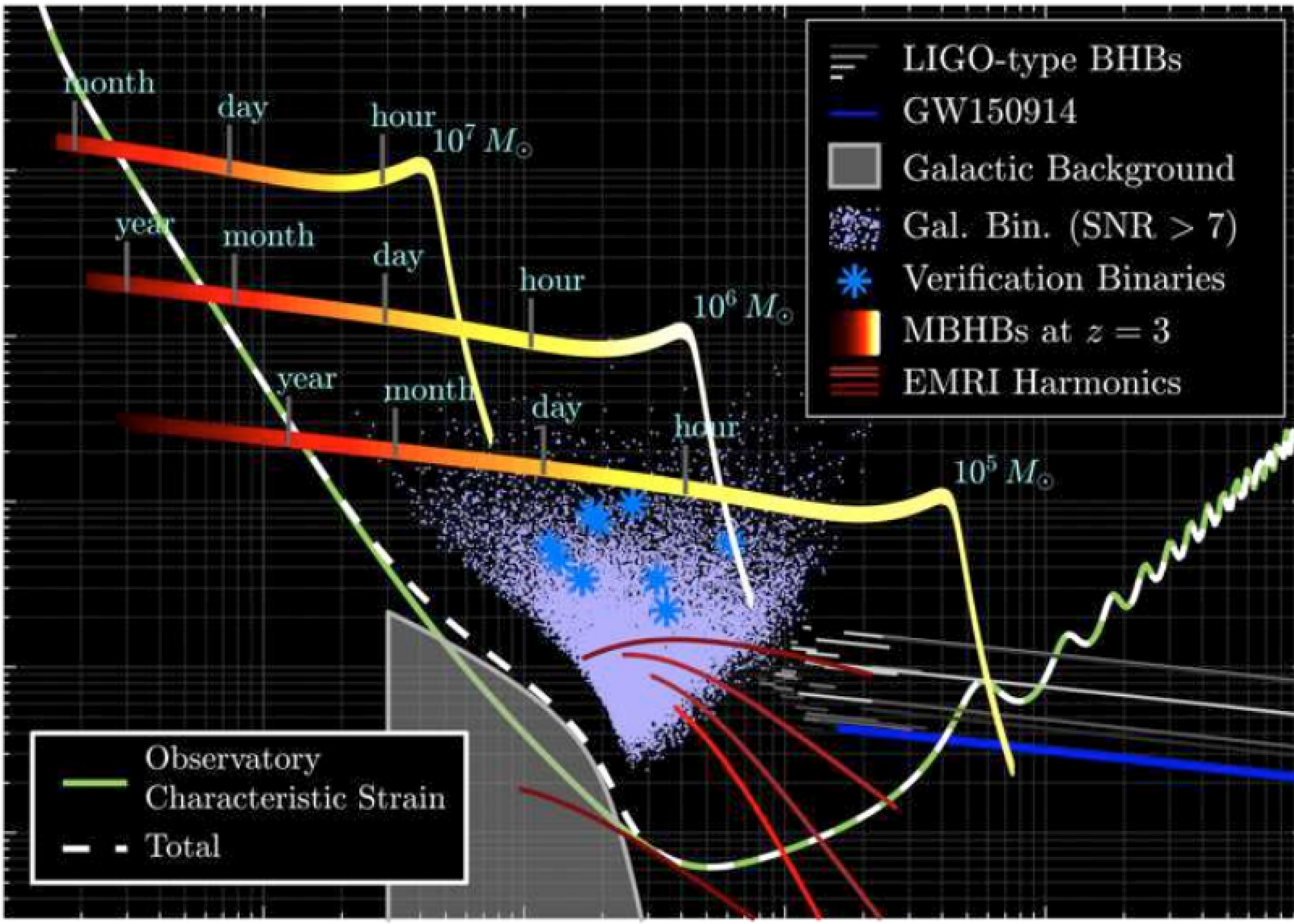
- Are stellar mass BH at high z BH that seed super massive black holes ?
- How do they form ?



IMBH

- Intermediate mass region : 100-1000 Msun accessible by 3G and LISA
  - Is there a gap ?
  - Could be failed seed
  - Redshift distribution would help to understand their role as seeds
- LISA band :
  - 600 M_{sun} 10^4 M_{sun} up to z~1 (equal mass).
  - Parameters estimated at ~30 %

LISA sources



EMRIs and SMBH (LISA)

- Extreme mass ratio inspirals (EMRI)
  - Long lasting inspiral and plunge of a 10-60 M_{sun} BH into a 10^5-10^6 M_{sun} BH in the centers of galaxies.
  - Orbits are generic but highly eccentric.
  - Use « gloden » EMRIs to probe the multipolar structure of MBHs (deviation to Kerr BH).
  - Uncertain rate.
- SMBH environment
  - Will complement EM observations

Cosmology & cosmography

- Primordial backgrounds
  - Inflationary and early universe : phase transitions, cosmic strings and superstrings

    → stochastic background of relic GWs.
- Astrophysical backgrounds
  - Remove binary mergers background and dig deeper
  - Correlating large-scale structure maps with GW stochastic background maps
- Standard siren cosmology
  - Hubble constant, dark energy, EOS

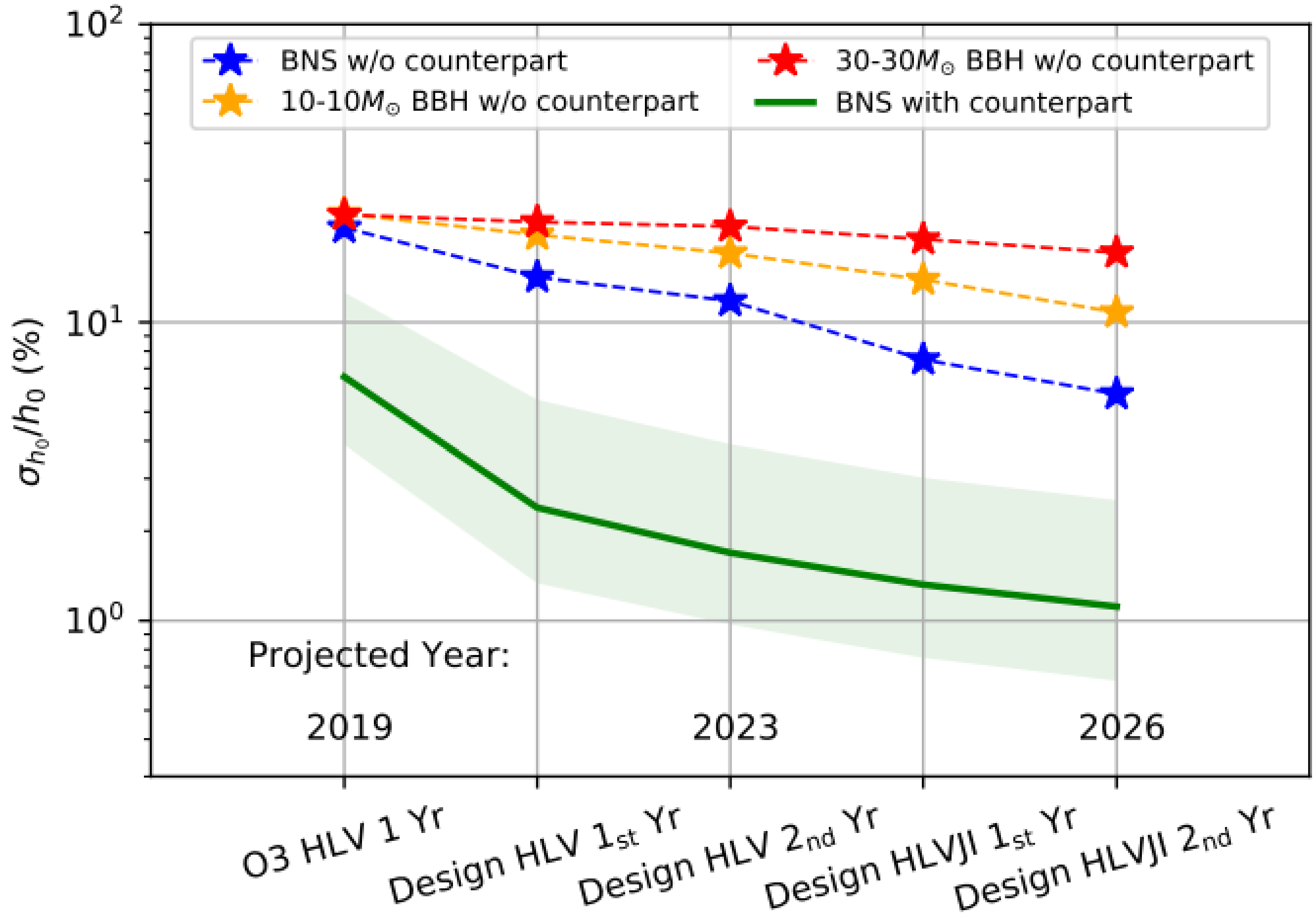
$$d_L(z) = \frac{1+z}{H_0} \int_0^z \frac{d\tilde{z}}{\sqrt{\Omega_M (1+\tilde{z})^3 + \rho_{\rm DE}(\tilde{z})/\rho_0}},$$

  - Cosmological perturation effects on GW luminosity distance
  - Strongly-lensed GW

Cosmology & cosmography

[1712.06531]

2G detectors



Multi-messenger analysis

- Compact binary mergers
  - r-process production of heavy elements via NS-NS and NS-BH mergers
  - Are there differences in kilonovas from BNS and NSBH
  - NS max mass
  - Jet physics
- Continuous wave sources
  - Curst and magnetosphere from coherence of GW and EM observations
  - Crust physics from magnetar flares and outbursts
- Supernovae
  - Production of heavy elements
  - neutrinos

Conclusion

Fundamental physics

- Nature of gravity
- Nature of compact object
- Nature of dark matter

Cosmology & cosmography

- Test of inflation models
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Astrophysic of compact objects

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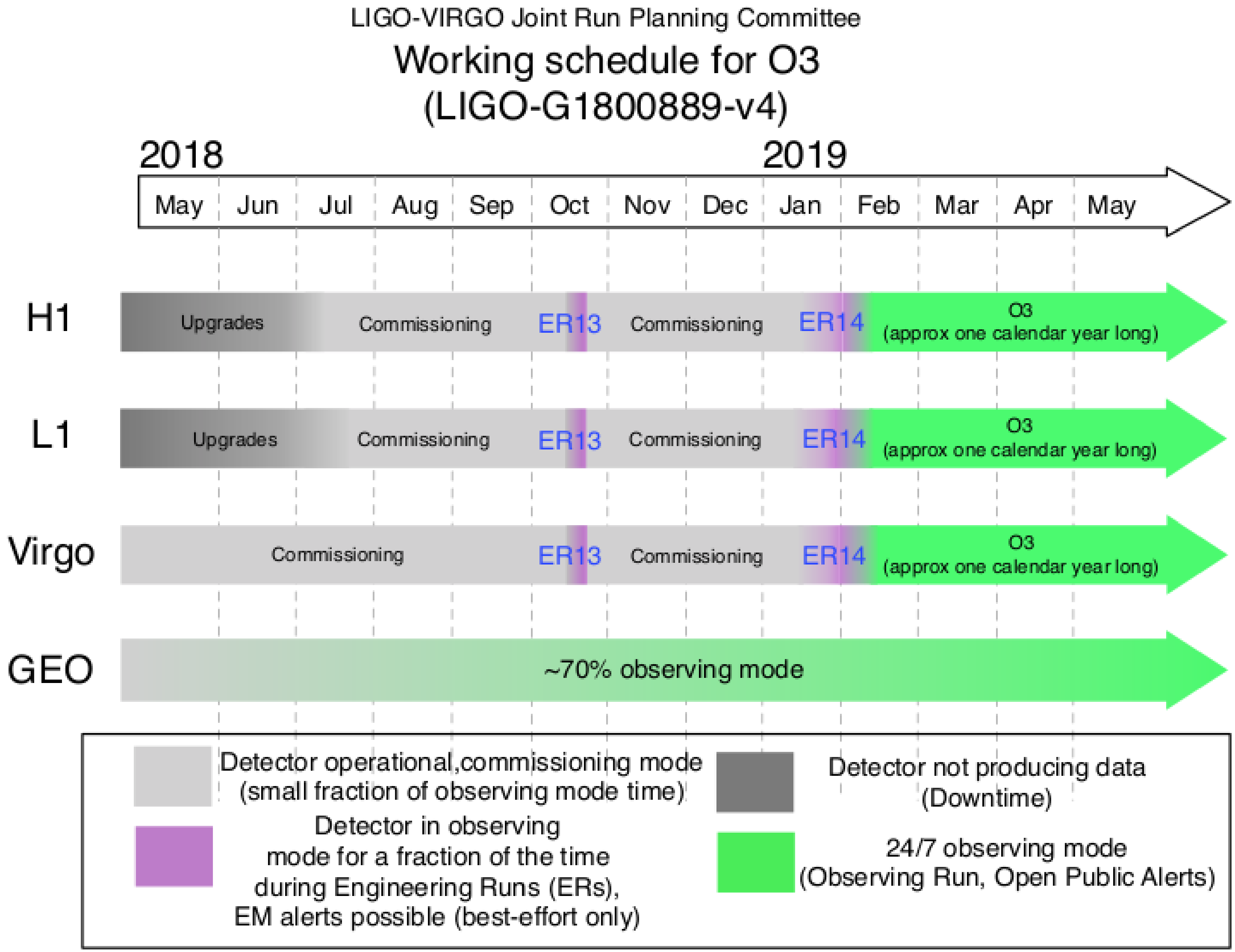
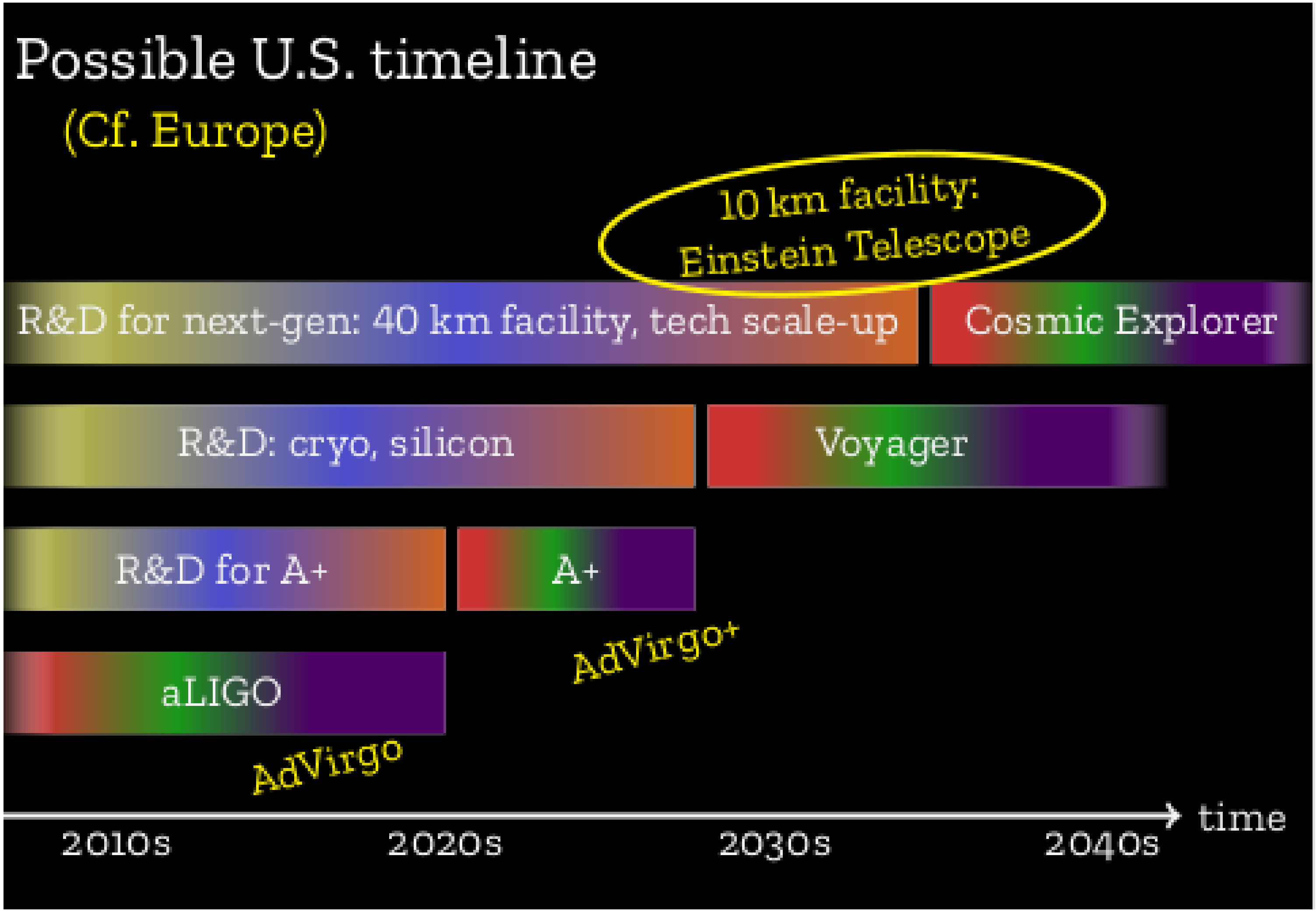
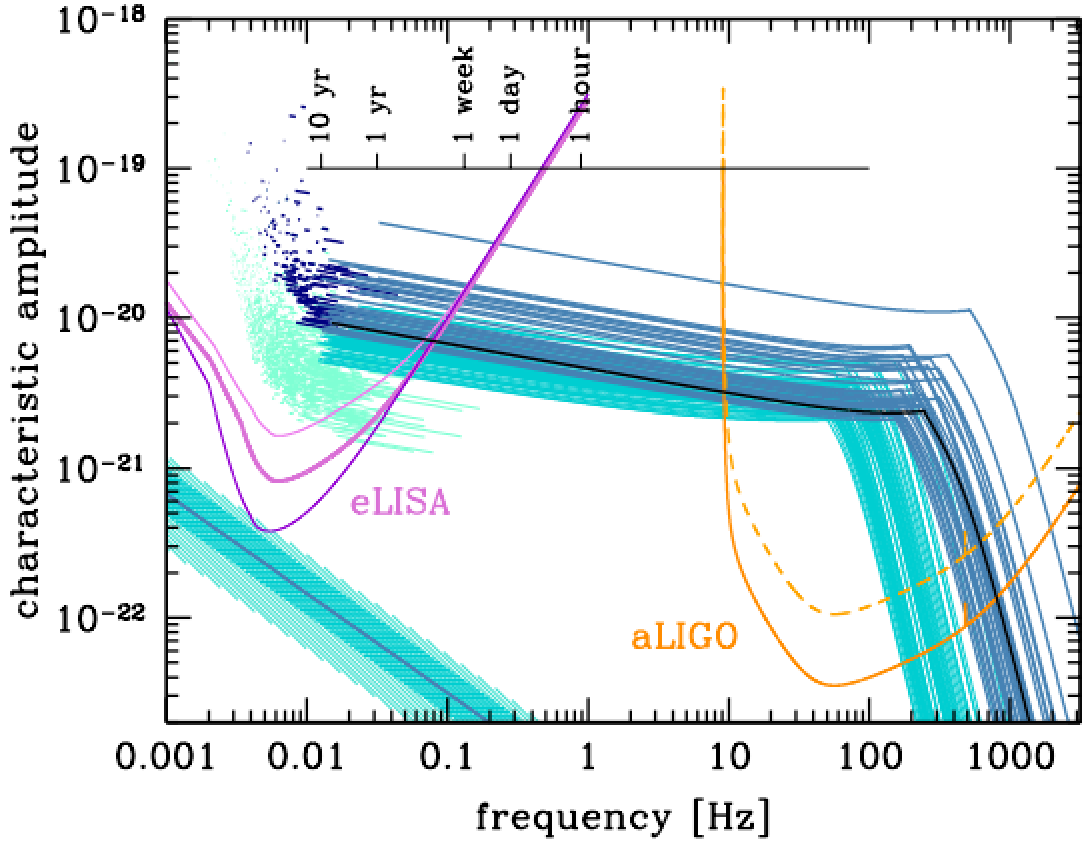
  - Cosmic ray acceleration
  - nucleosynthesis

2G detectors timeline



3G Cosmic Explorer/Einstein Telescope





characteristic amplitude
frequency [Hz]
10^{-18}
10^{-19}
10^{-20}
10^{-21}
10^{-22}
0.001
0.01
0.1
1
10
100
1000
10 yr
1 yr
1 week
1 day
1 hour
eLISA
aLIGO