Observing gravitational waves from space with LISA

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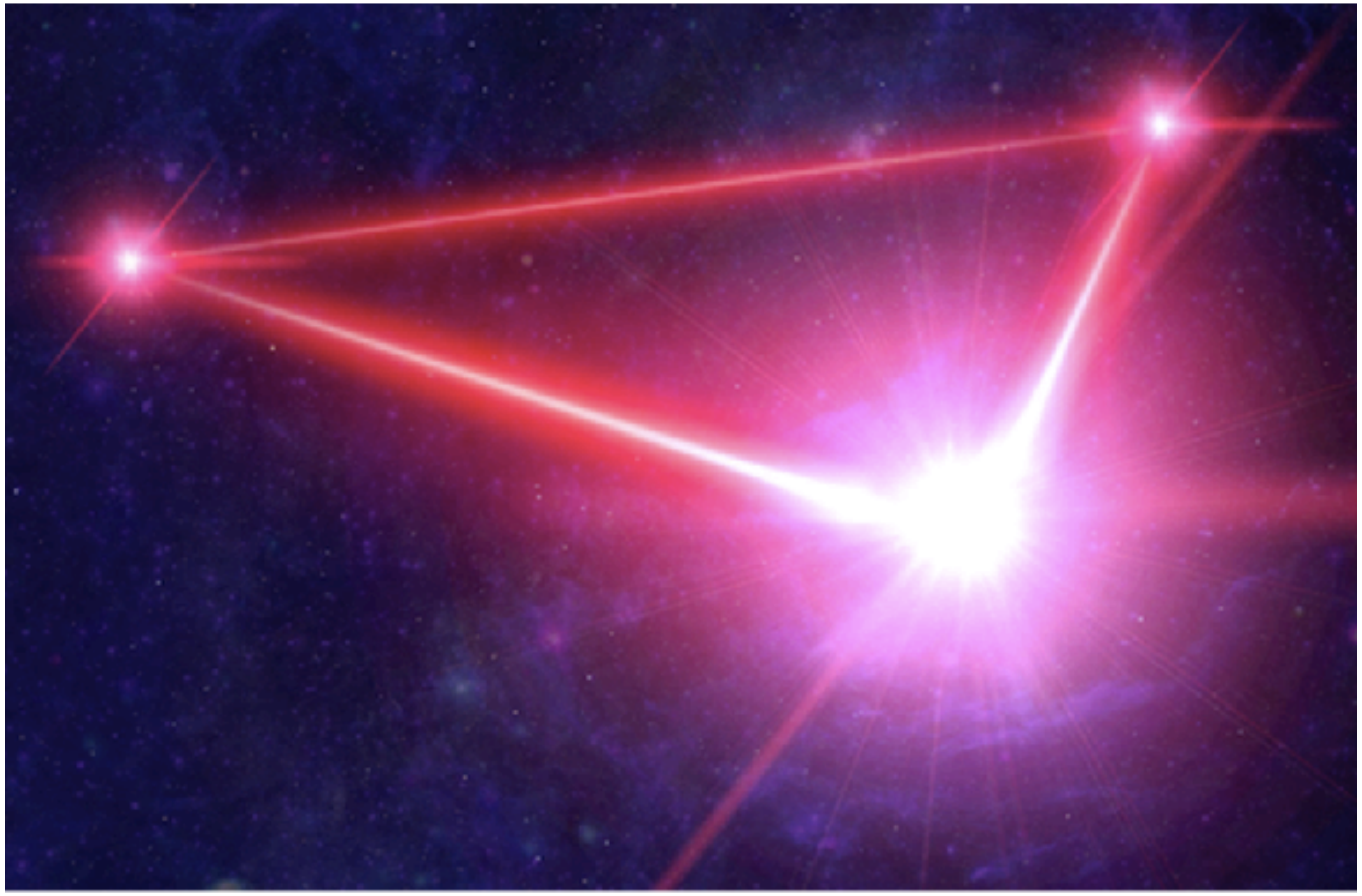
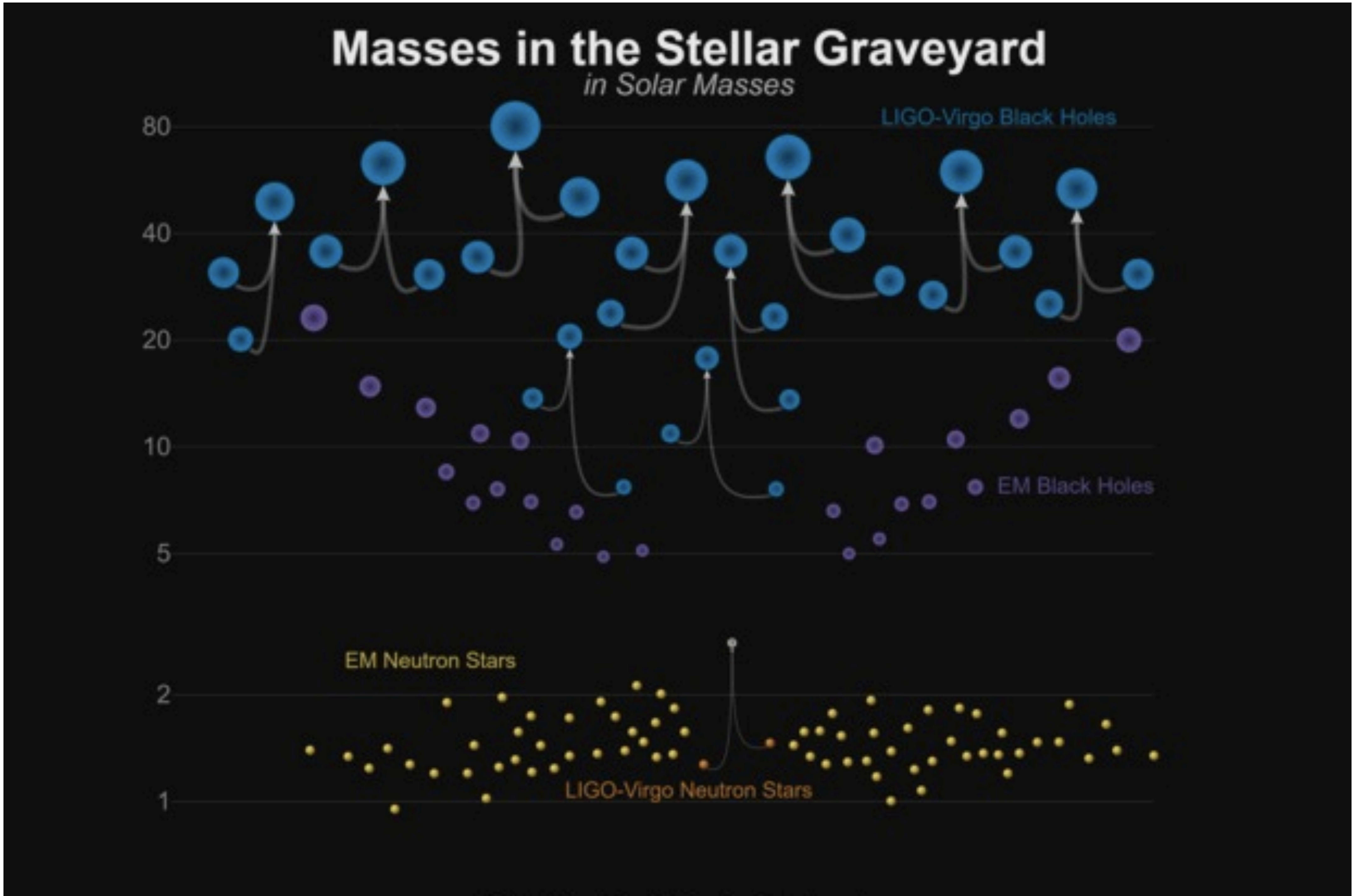


the birth of GW astronomy

- 11/2/16: announcement of the first GW detection by the Earth-based interferometers LIGO
- GW emitted by the merging of two black holes of about 30 $M_\odot$
- since: 9 black hole mergers + 1 neutron star merger detected



LIGO website

this seminar in a nutshell

- GW direct detection from Earth is a great theoretical and experimental achievement
- GW detections are a new mean to test the universe, relevant both for astrophysics and cosmology
- GW detections can provide observational access to many new physical phenomena
- the science of LISA: the space-based gravitational wave observer of the European Space Agency
- review of gravitational wave sources in the LISA band: from the Galaxy to Hubble scales, from the present time to the very early universe
- LISA is a discovery mission that can test fundamental physics, and can be complementary to cosmological observations and particle colliders

Gravitational waves

Einstein's equations have a wave solution in linearised theory

$$G_{\mu\nu} = 8\pi G \, T_{\mu\nu}$$

space-time metric

Newton constant

Energy momentum tensor

GW EMERGE "NATURALLY"

Newtonian gravitation theory + special relativity =
causal theory (General Relativity)

GR needs a radiation field that carries information at the speed of light

Gravitational waves

Einstein's equations have a wave solution in linearised theory

perturb around
flat space-time

$$G_{\mu\nu} = 8\pi G\, T_{\mu\nu}$$

$$g_{\mu\nu}(x) = \eta_{\mu\nu} + h_{\mu\nu}(x) \qquad |h_{\mu\nu}(x)| \ll 1$$

exploit invariance under slowly varying infinitesimal coordinate transformation and choose the Lorentz gauge to find the wave equation

$$\Box \bar{h}_{\mu\nu} = -16\pi G\, T_{\mu\nu}$$

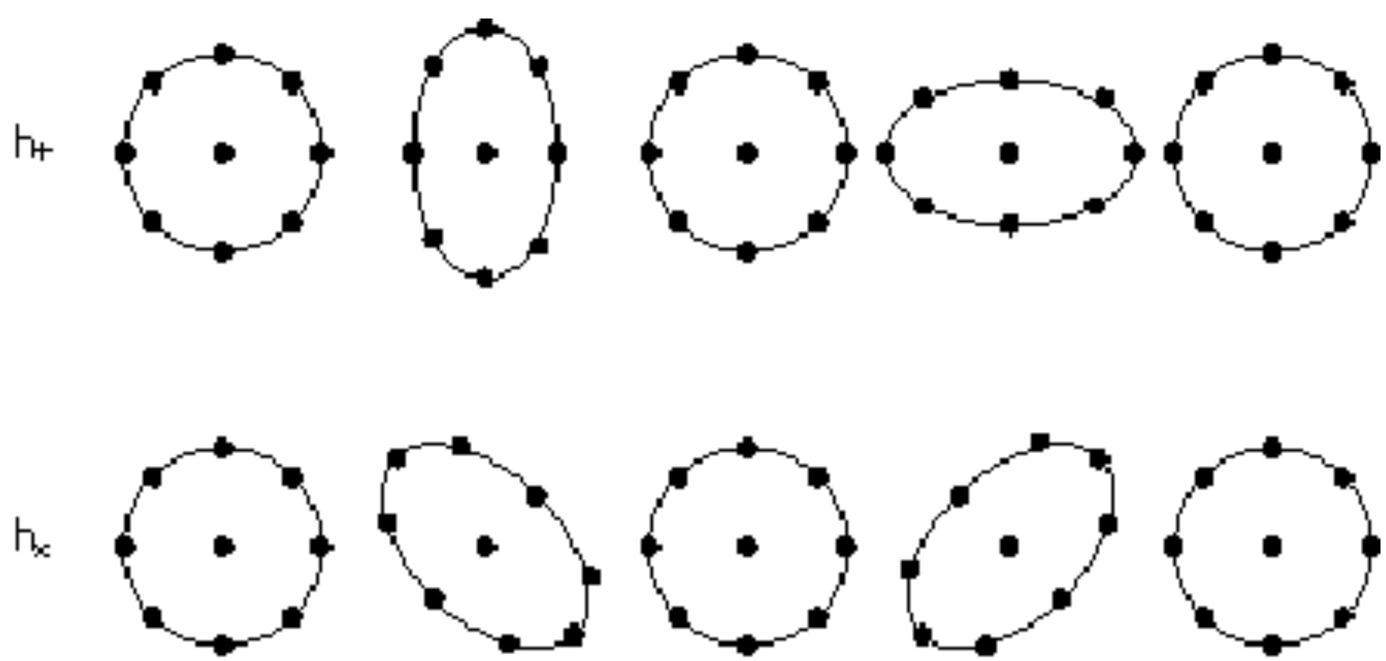
Gravitational waves

TRANSVERSE TRACELESS GAUGE: two physical wave degrees of freedom

$$h_{\mu 0} = 0 \qquad h^i{}_i = 0 \qquad \partial_i h_{ij} = 0$$

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

$$ds^2 = -dt^2 + dz^2 + (1+h_+)dx^2 + (1-h_+)dy^2 + 2h_\times dx dy$$



$$\ddot{x}^i = \frac{1}{2}\,\ddot{h}_{ij}^{\mathrm{TT}}\,x^j$$

Gravitational waves

GW are generated by
ACCELERATED MASS DISTRIBUTIONS
possessing at least
A QUADRUPOLE MOMENT

$$h_{ij}(t, \mathbf{x}) = \frac{2G}{r} \Lambda_{ijk\ell}(\hat{n}) \ddot{Q}_{k\ell}(t - r) + \ldots$$

distance to the source

Transverse Traceless projector

quadrupole moment of the source mass density

monopole and dipole radiation do not occur because of the spin 2 nature of the GW

Gravitational waves

GW are generated by
ACCELERATED MASS DISTRIBUTIONS
possessing at least
A QUADRUPOLE MOMENT

$$h_{ij}(t, \mathbf{x}) = \frac{2G}{r} \Lambda_{ijk\ell}(\hat{n}) \, \ddot{Q}_{k\ell}(t - r) + \dots$$

amplitude: $\ddot{Q}_{k\ell} \sim M = 30 M_{\odot}$

$r = 400\,\mathrm{Mpc}$

$h_{ij} \sim 10^{-20}$

the gravitational interaction is weak:
very massive objects moving relativistically still produce small amplitudes

HOW TO DETECT GW?

Indirect detection with binary pulsars

- binary of neutron stars emitting beamed EM waves
- detected by a radio telescope at very precise time intervals
- from the rate of the pulses infer the orbital period
- compare variation of orbital period with GR prediction

$$\dot{T} = -\frac{192\pi\, f(e)}{5}\,\frac{G^{5/3}\mu\, M^{2/3}}{c^5}\left(\frac{2\pi}{T}\right)^{5/3}$$

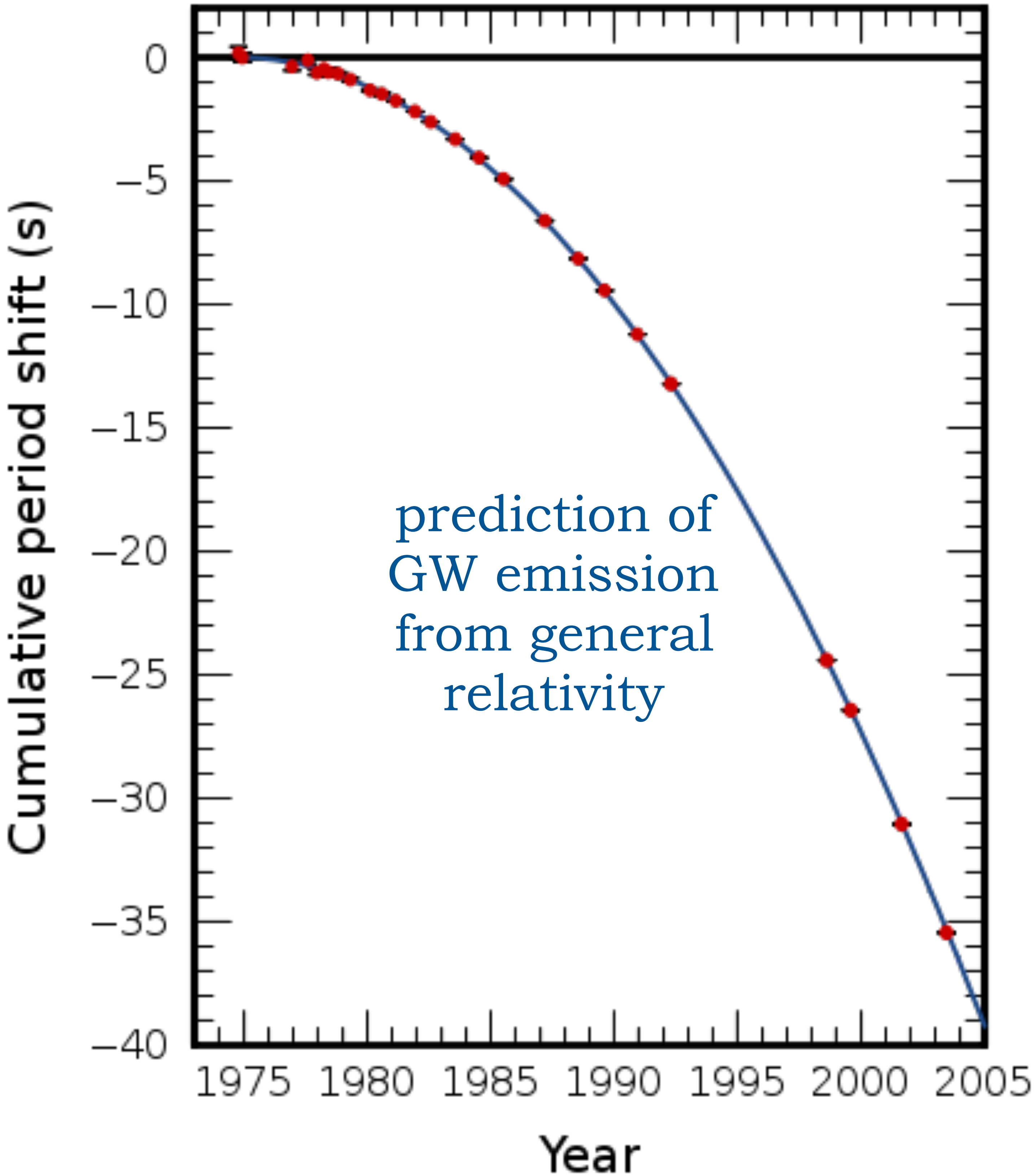
method used with the Hulse-Taylor binary pulsar

$$m_p = 1.4414\, M_\odot$$
$$m_c = 1.3876\, M_\odot$$
$$e = 0.6171338$$

$$T = 0.322997448930\,\mathrm{days}$$
$$\dot{T} = -2.4055 \cdot 10^{-12}$$

Weisberg and Taylor astro-ph/0407149

Indirect detection with binary pulsars



$$\frac{\dot{T}_{\rm obs}}{\dot{T}_{\rm GR}} = 1.001$$

first indirect detection of GW

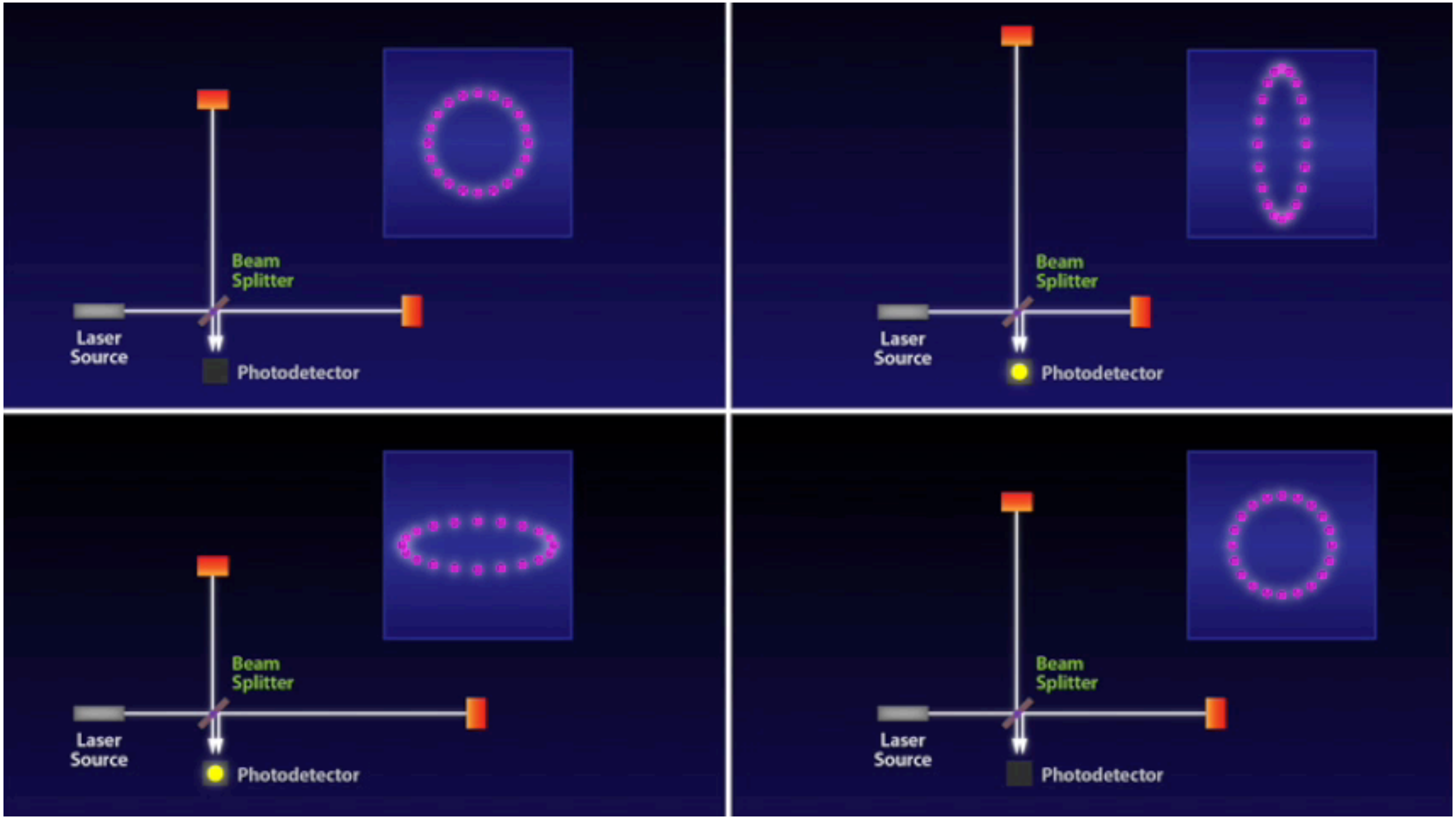
NOBEL PRIZE IN 1993 TO HULSE AND TAYLOR

Weisberg and Taylor astro-ph/0407149

Direct detection with interferometers

$$|E_x + E_y|^2 = E_0^2 \sin[\omega_\gamma (t_x - t_y)/2]$$

$$ds^2 = (\eta_{\mu\nu} + h_{\mu\nu}) dx^\mu dx^\nu = 0 \qquad \delta\varphi = \omega_\gamma \, \delta L \simeq \omega_\gamma \, L \, h_+(t - L)$$



LIGO website

Advanced LIGO/Virgo interferometers

arm length L = 4 km
laser power 20 W
beam radius about 6 cm
test masses 40 kg
laser wavelength 0.1µm

$$h \simeq \frac{\delta L}{L} \simeq 10^{-21}$$

displacement of the mirrors :
(collective - averaged over beam size)

$$\delta L \sim 2 \cdot 10^{-18}\,\mathrm{m}$$

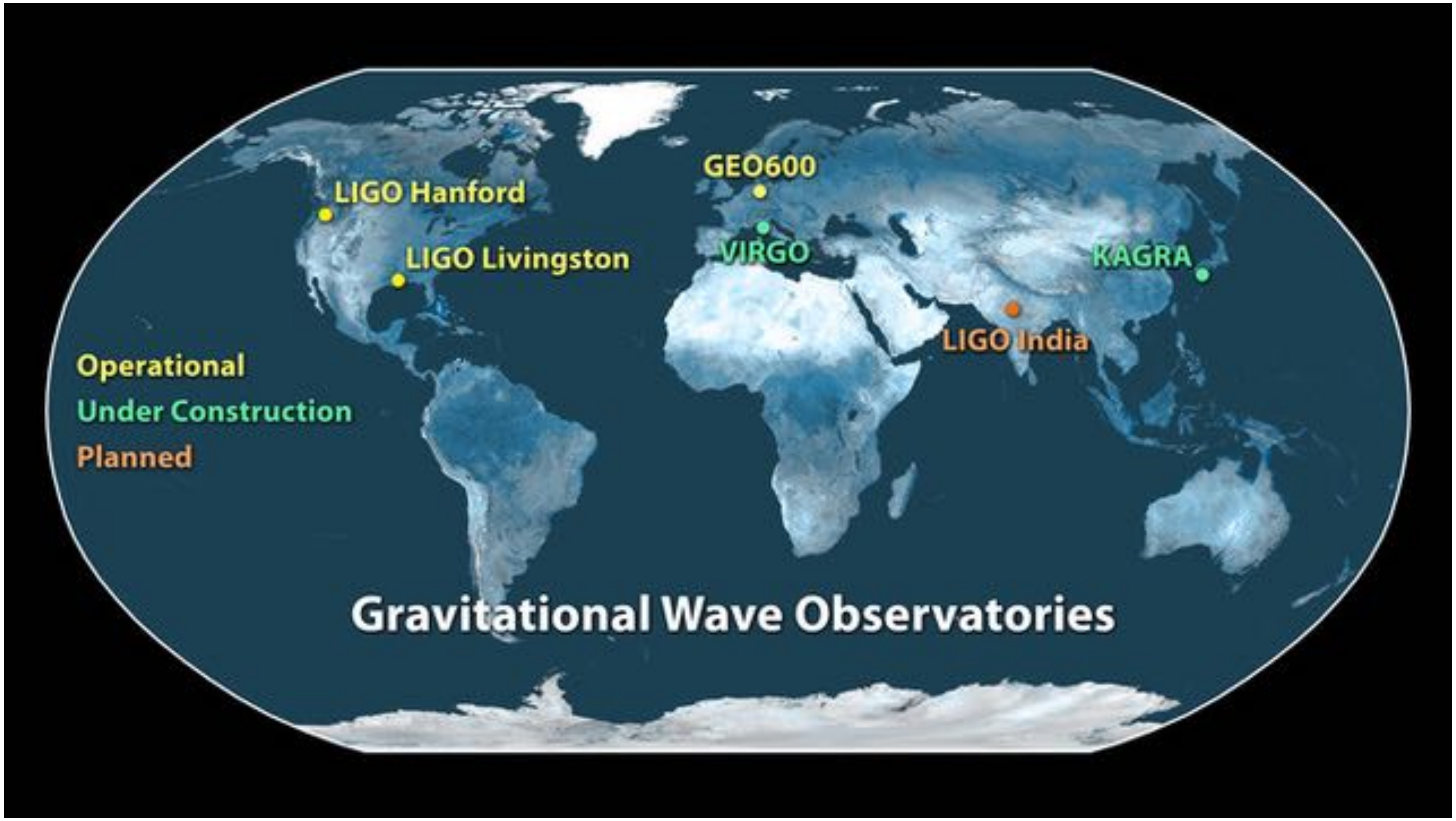
dephasing :

$$\delta\varphi \simeq \omega_\gamma\, L\, h\, \mathcal{F} \simeq 10^{-8}\,\mathrm{rad}$$

noise sources:
seismic, thermal,
radiation pressure,
shot noise

M. Maggiore, 2007

Earth-based gravitational wave detectors worldwide



LIGO website

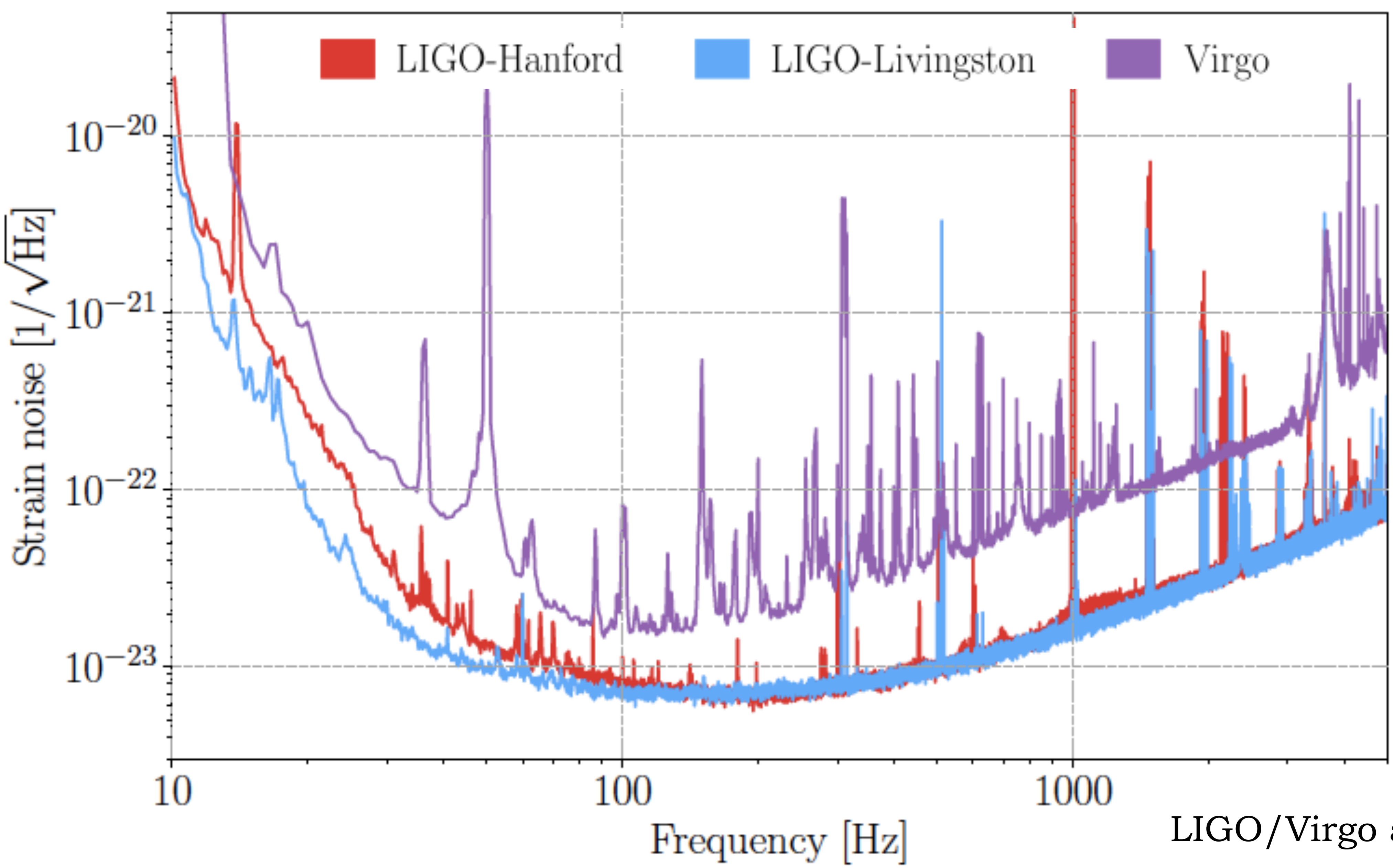
need a network of detectors

- cross-correlation to distinguish the signal from the noise
- the same signal should be seen after a time interval (max 10 msec for the two LIGO detectors, 3700 km)
- at least three detectors to localize the source and measure the polarization

Advanced LIGO/Virgo interferometers

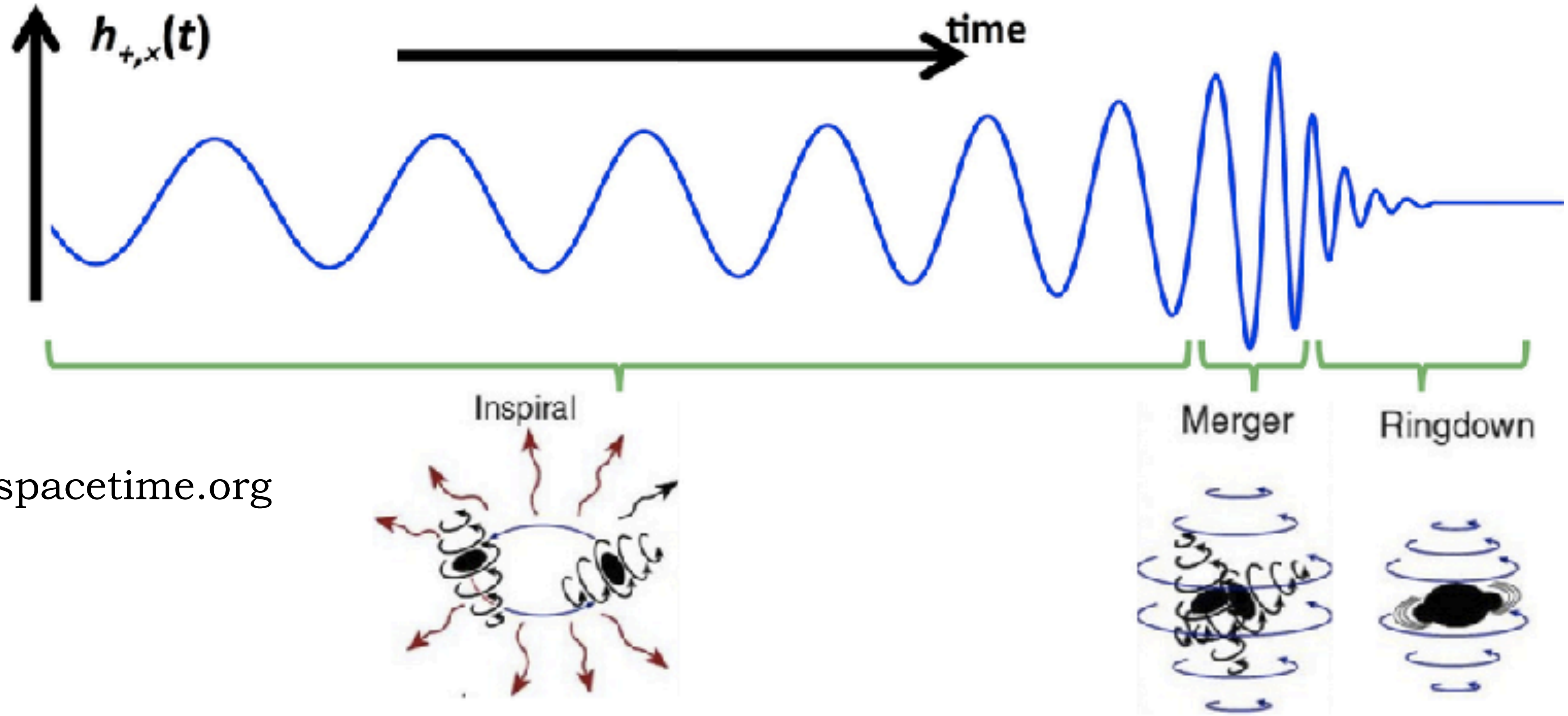
frequency range of detection: $10\,\mathrm{Hz} < f < 5\,\mathrm{kHz}$

- Black hole coalescing binaries of masses few to dozens solar masses
- Neutron Star binaries (electromagnetic counterpart)
- NS-BH binaries



LIGO/Virgo arXiv:1811.12907

GW emission from the inspiral of a binary system



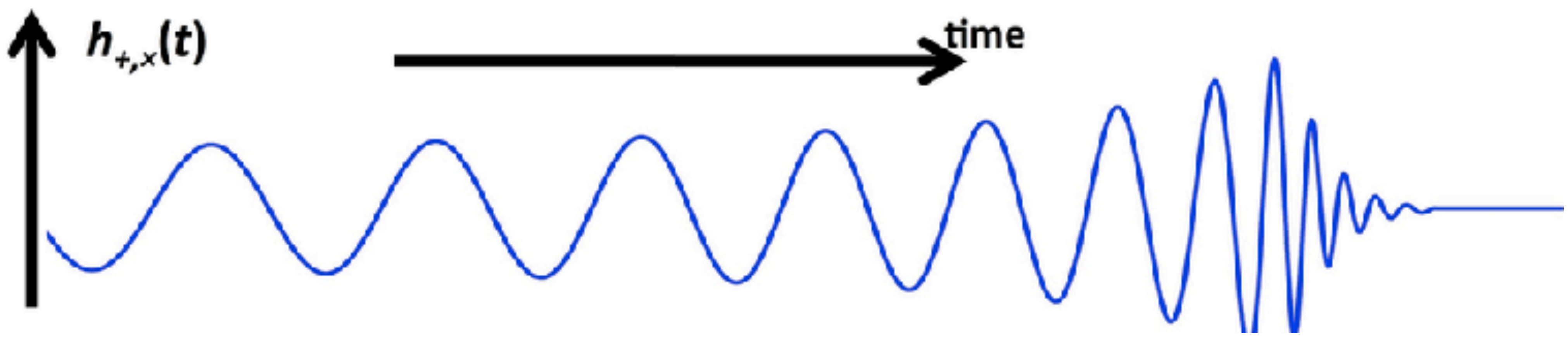
soundofspacetime.org

$$-\frac{dE_{\rm orbit}}{dt} = P_{\rm quad} = \frac{G}{5c^5}\,\langle \dddot{Q}_{ij}\dddot{Q}_{ij}\rangle\Big|_{t_{\rm ret}}$$

variation of the angular frequency

third time derivative of the mass quadrupole

GW emission from the inspiral of a binary system



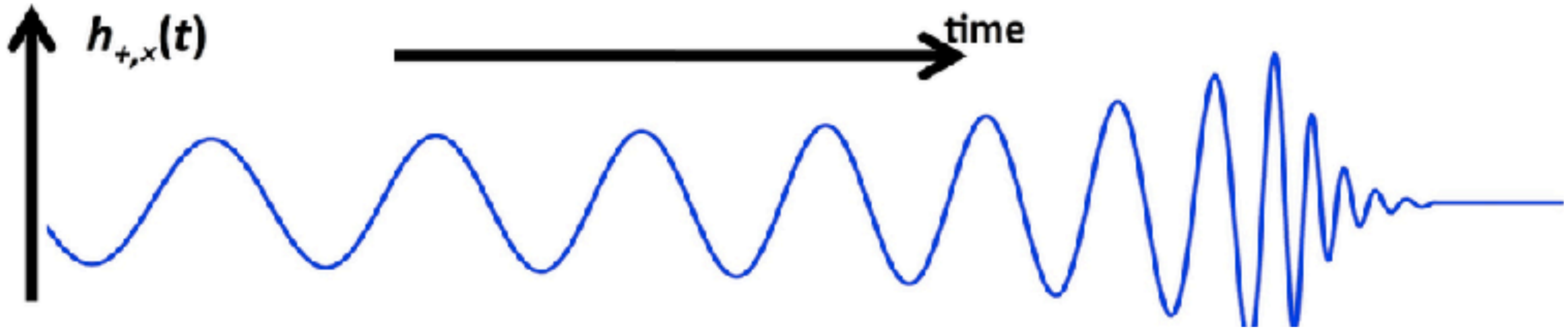
$$\frac{df}{dt} = \frac{96}{5}\pi^{8/3}\left(\frac{GM_c}{c^3}\right)^{5/3} f^{11/3}$$

$$M_c = \frac{(m_1\, m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$$

- measure f and df/dt -> get chirp mass
- from chirp mass get a minimal total mass
- from minimal total mass get minimal Schwarzschild radius -> BH, NS…

$$R_s = \frac{2\,G}{c^2} M = 2.95\,\mathrm{km}\,\frac{M}{M_\odot}$$

GW emission from the inspiral of a binary system



$$h_+(t) = \frac{4}{r}\left(\frac{GM_c}{c^2}\right)^{\frac{5}{3}}\left(\frac{\pi f}{c}\right)^{\frac{2}{3}}\frac{1+\cos^2\imath}{2}\cos[\Phi(t)]$$

$$h_\times(t) = \frac{4}{r}\left(\frac{GM_c}{c^2}\right)^{\frac{5}{3}}\left(\frac{\pi f}{c}\right)^{\frac{2}{3}}\cos\imath\,\sin[\Phi(t)]$$

ι orbit inclination

$$\Phi(t) = -2\left(\frac{5GM_c}{c^3}\right)^{-\frac{5}{8}}\tau^{\frac{5}{8}} + \Phi_i \qquad f(\tau) = \frac{1}{\pi}\left(\frac{G\,M_c}{c^3}\right)^{-5/8}\left(\frac{5}{256\,\tau}\right)^{3/8}$$

τ time to coalescence

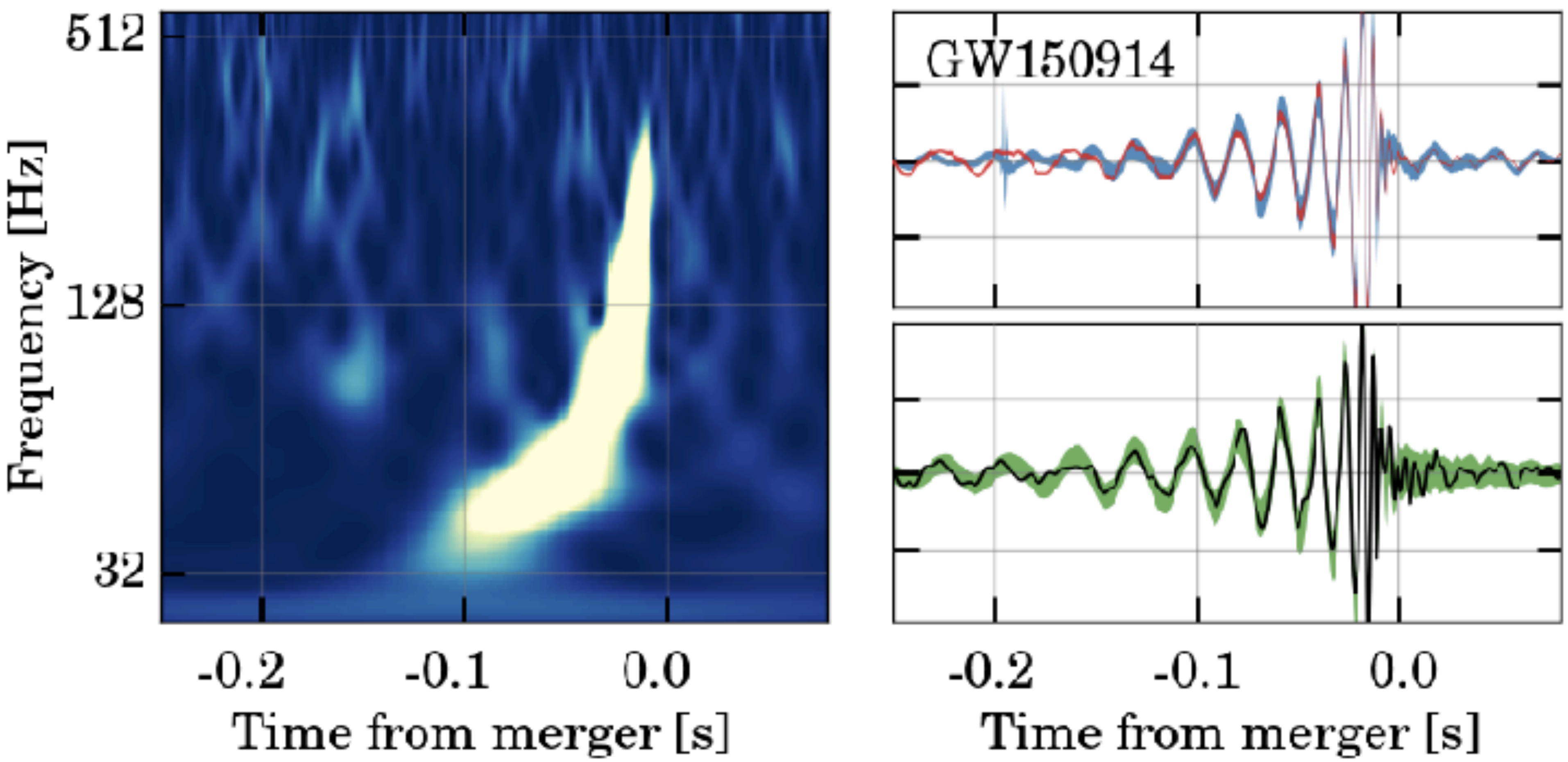
GW emission from the inspiral of a binary system

$$M_c = 25\,\mathrm{M}_\odot \qquad \tau = 0.2\,\mathrm{sec} \qquad \longrightarrow \qquad f = 37\,\mathrm{Hz}$$

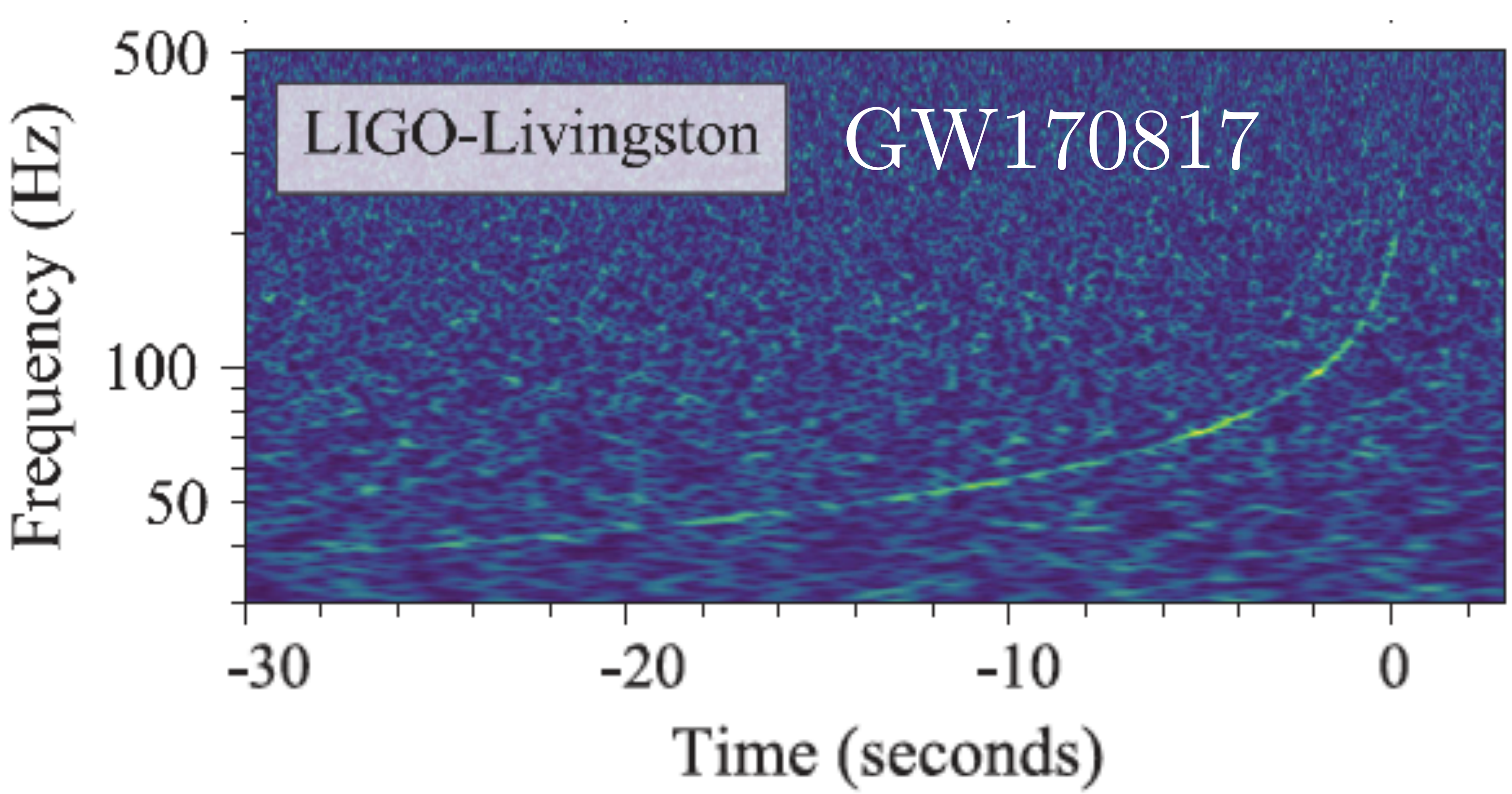
$$M_c = 1.2\,\mathrm{M}_\odot \qquad \tau = 30\,\mathrm{sec} \qquad \longrightarrow \qquad f = 38\,\mathrm{Hz}$$

$$f(\tau) = \frac{1}{\pi}\left(\frac{G\,M_c}{c^3}\right)^{-5/8}\left(\frac{5}{256\,\tau}\right)^{3/8}$$

two examples of detection from Earth-based interferometers



$$m_1 = 35.6^{+4.8}_{-3.0}\, M_\odot$$
$$m_2 = 30.6^{+3.0}_{-4.4}\, M_\odot$$
$$M_c = 28.6^{+1.6}_{-1.5}\, M_\odot$$
$$d_L = 430^{+150}_{-170}\,\mathrm{Mpc}$$



$$m_1 = 1.36 - 1.60\, M_\odot$$
$$m_2 = 1.17 - 1.36\, M_\odot$$
$$M_c = 1.188^{+0.004}_{-0.002}\, M_\odot$$
$$d_L = 40^{+8}_{-14}\,\mathrm{Mpc}$$

LIGO/Virgo arXiv:1811.12907

GW emission from the inspiral of a binary system

$$M_c = 25\,\mathrm{M}_\odot \qquad \tau = 0.2\,\mathrm{sec} \qquad \longrightarrow \qquad f = 37\,\mathrm{Hz}$$

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GW emission from the inspiral of a binary system

$$M_c = 25\,\mathrm{M}_\odot \qquad \tau = 0.2\,\mathrm{sec} \qquad \longrightarrow \qquad f = 37\,\mathrm{Hz}$$

$$M_c = 1.2\,\mathrm{M}_\odot \qquad \tau = 30\,\mathrm{sec} \qquad \longrightarrow \qquad f = 38\,\mathrm{Hz}$$

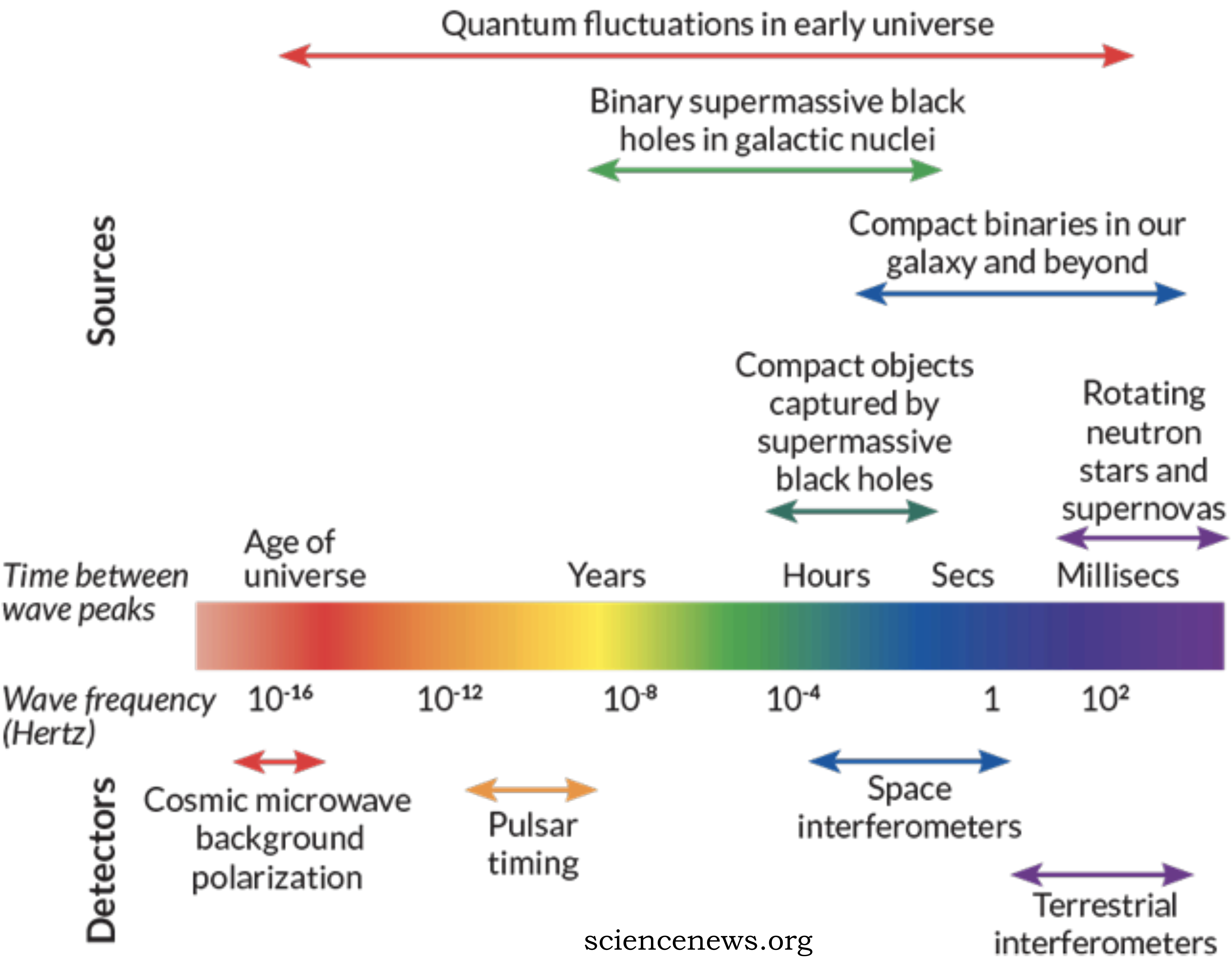
$$M_c = 25\,\mathrm{M}_\odot \qquad \tau = 10\,\mathrm{year} \qquad \longrightarrow \qquad f = 0.01\,\mathrm{Hz}$$

$$M_c = 10^6\,\mathrm{M}_\odot \qquad \tau = 1\,\mathrm{hour} \qquad \longrightarrow \qquad f = 1\,\mathrm{mHz}$$

$$M_c = 10^9\,\mathrm{M}_\odot \qquad \tau = 10^5\,\mathrm{year} \qquad \longrightarrow \qquad f = 7 \cdot 10^{-9}\,\mathrm{Hz}$$

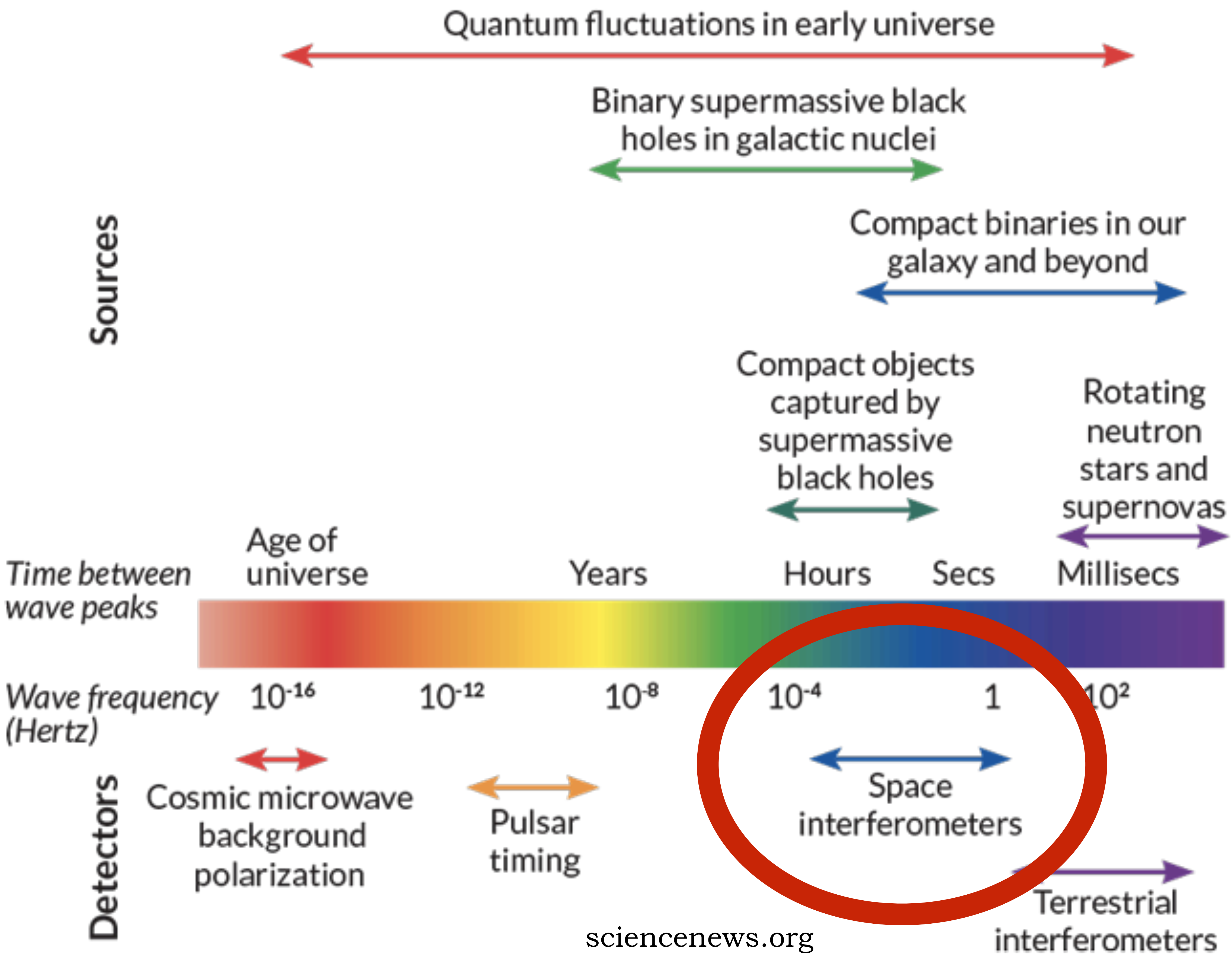
$$f(\tau) = \frac{1}{\pi}\left(\frac{G\,M_c}{c^3}\right)^{-5/8}\left(\frac{5}{256\,\tau}\right)^{3/8}$$

the GW "spectrum"



sciencenews.org

the GW “spectrum”



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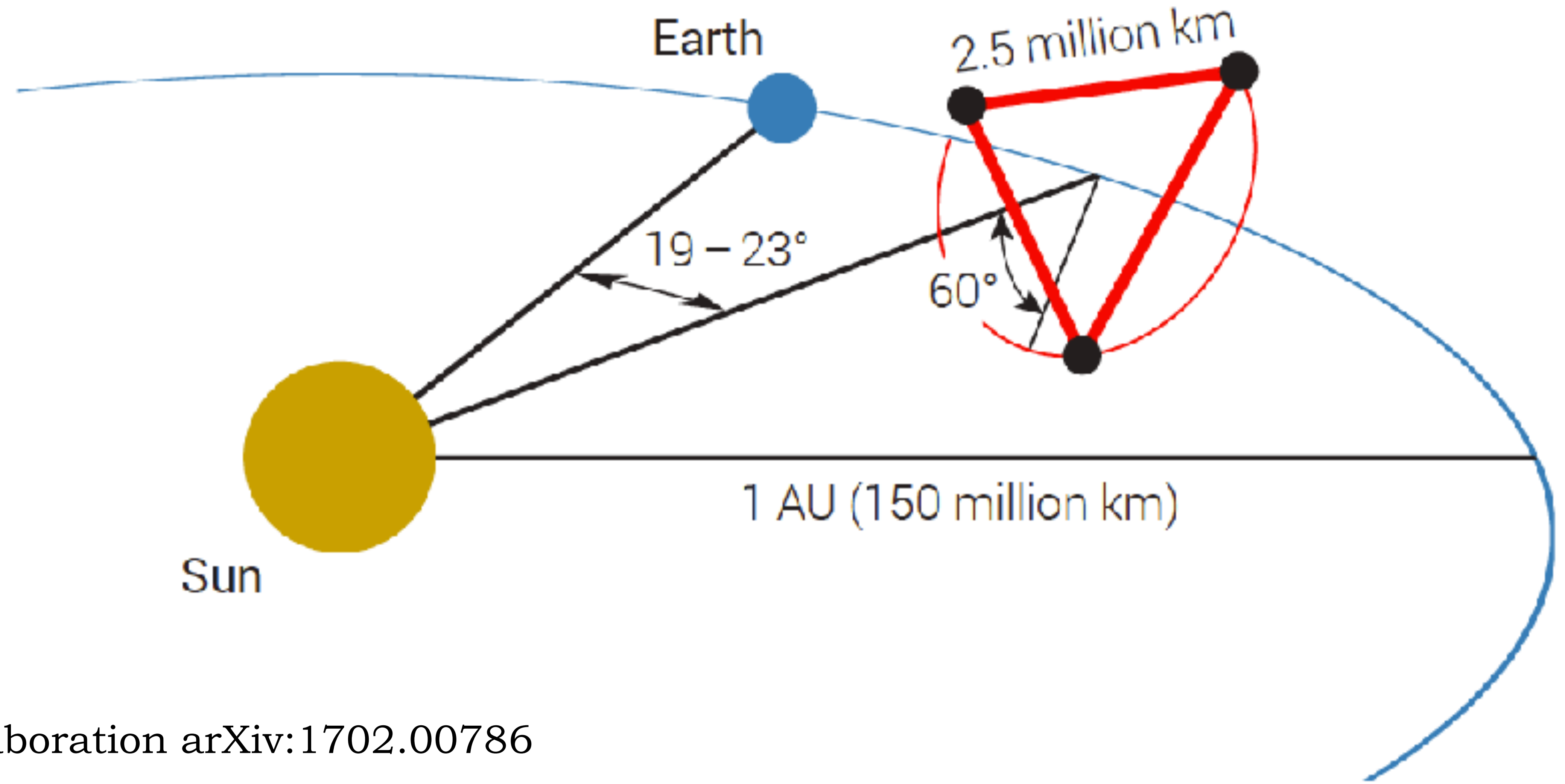
LISA: Laser Interferometer Space Antenna

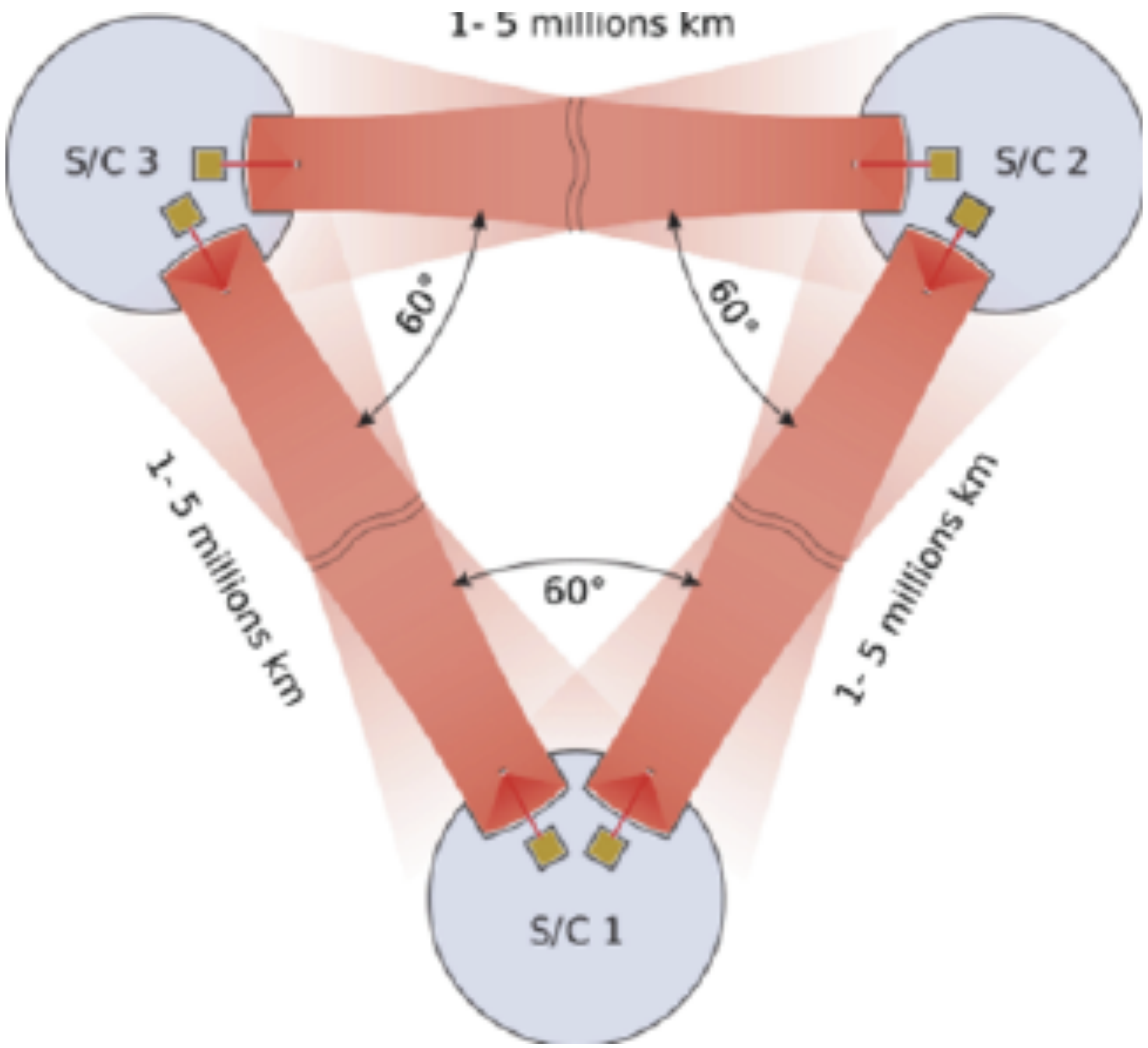
- no seismic noise
- much longer arms

frequency range of detection: $10^{-4}\,\mathrm{Hz} < f < 1\,\mathrm{Hz}$



LISA collaboration arXiv:1702.00786

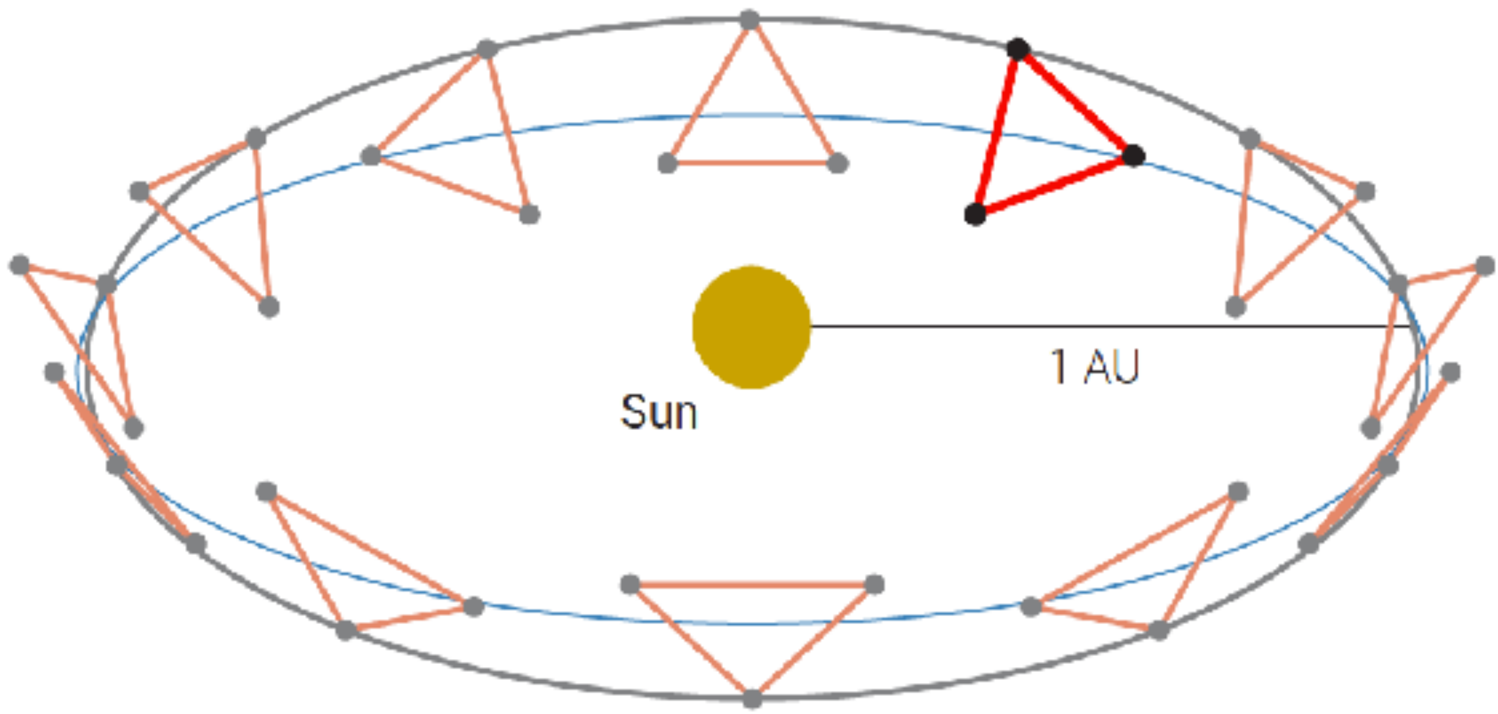
LISA: Laser Interferometer Space Antenna



- two masses in free fall per spacecraft
- 2.5 million km arms
- picometer displacement of masses

it is a survey instrument:

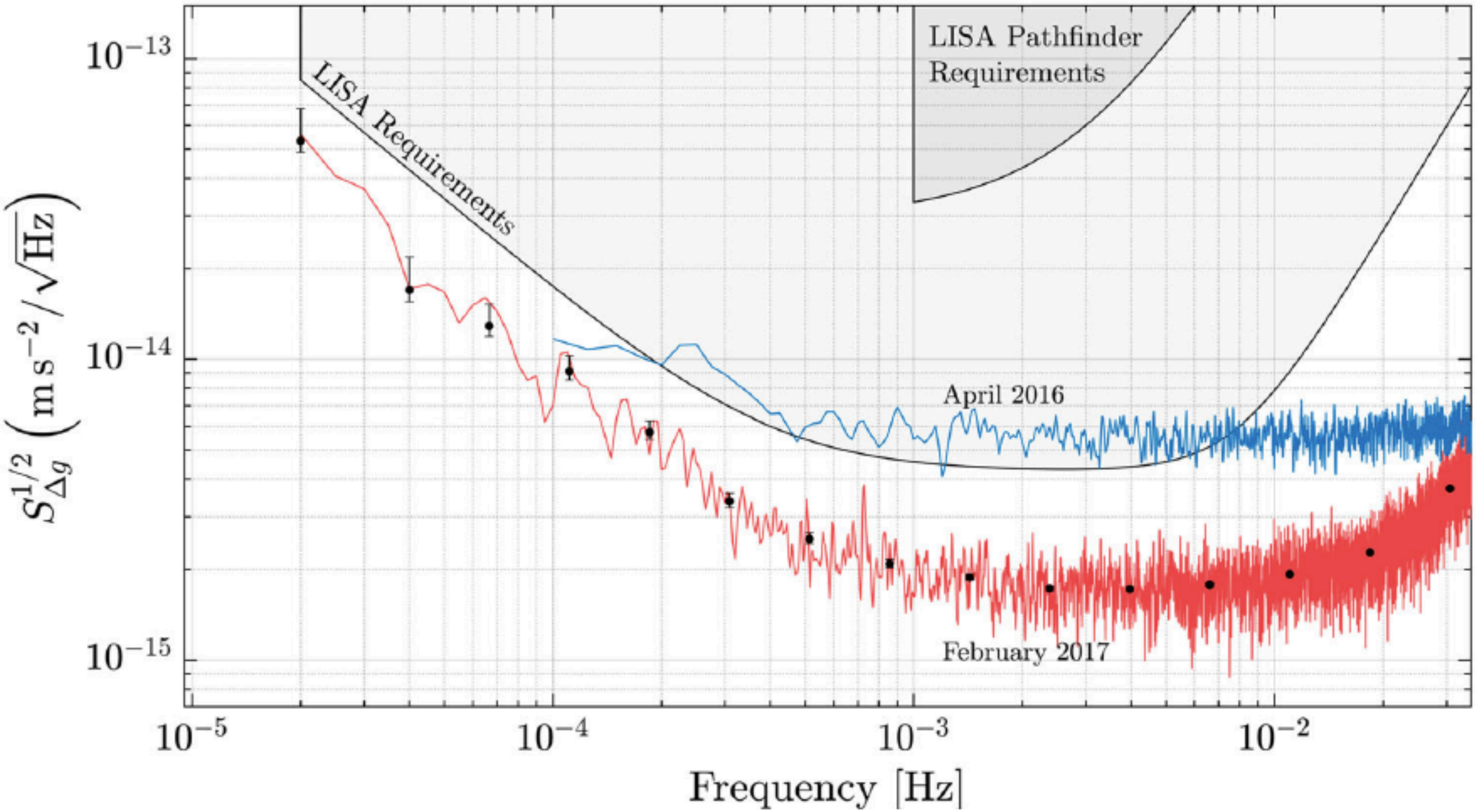
no pointing
continuous sky observation



LISA collaboration arXiv:1702.00786

LISA Pathfinder

- launch Dec 2015, operations March 2016 -> July 2017
- one LISA arm reduced in one spaceship
- test the ability to put two masses in free fall: measure the differential acceleration among them



Armano et al, PRL 120 (2018)

LISA chronology

- 2013: ESA selects LISA scientific theme for L3: “the gravitational universe”
- 2013 - 2016: studies of different configurations and refinement of the scientific case
- LISA Pathfinder : 2016-2017, it demonstrates the feasibility of LISA

- 1/2017: LISA Consortium submits the LISA proposal (3 arms), approved by ESA

- 3/2017 - 3/2018 : ESA Phase 0 study, NASA contributes to LISA
- 3/2018 - ~2019 : ESA Phase A study (with industries)
- Reboot of the Consortium: ~1000 membres
- ~2019 - ~2020: preparation of industrial implementation
- ~2021: ESA mission adoption
- ~8.5 years: mission construction
- ~2032: launch (Ariane 6)

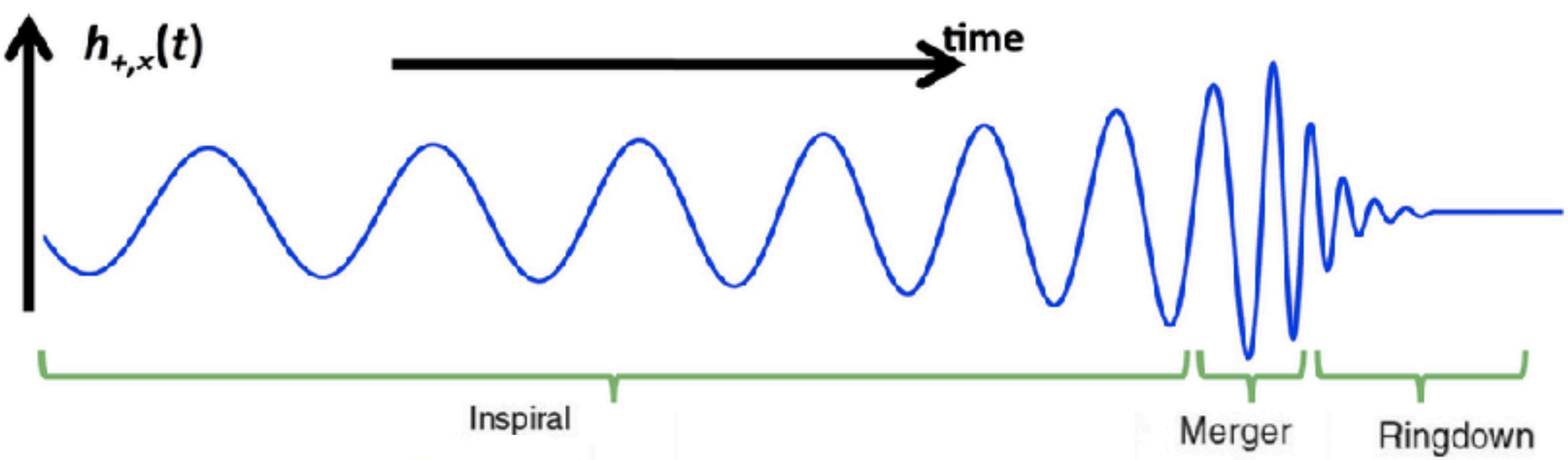
- nominal mission duration 4 years, tested extension up to 10 years, cost: 1050 M€

What LISA measures

1. The gravitational wave strain from the inspiral and merger of compact binaries

$$h(t) \sim 2\,\frac{\Delta L}{L}$$

LISA target :
- BH binaries, massive (high SNR) and LIGO-like
- galactic binaries
- Extreme Mass Ratio Inspirals



What LISA measures

2. the stochastic background of gravitational waves

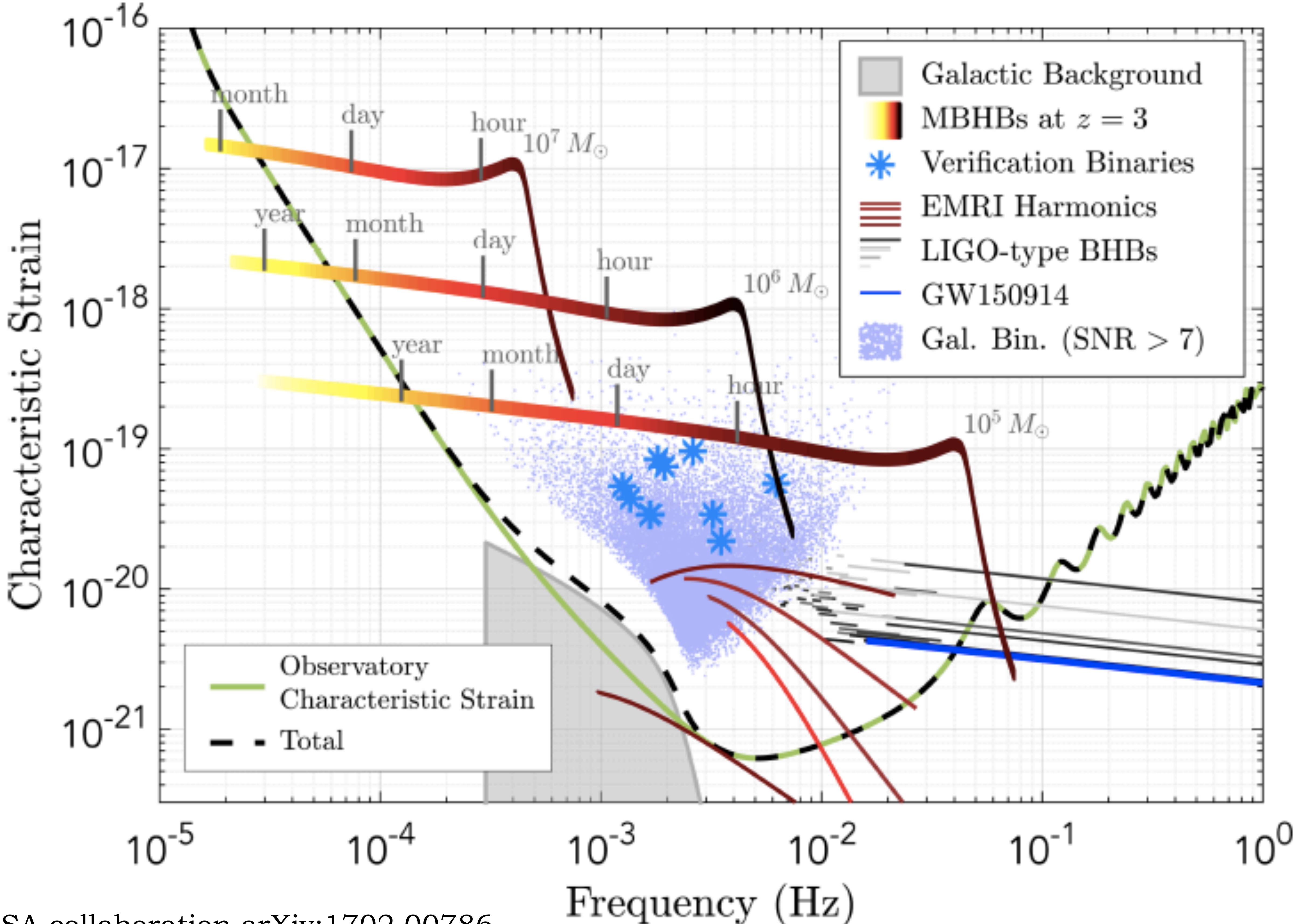
the superposition of sources that cannot be resolved individually

- binaries too numerous and with too low SNR to be identified
- signals from the early universe with too small correlation scale (typically horizon at the time of production) with respect to the detector resolution

$$\Omega_{\rm GW} = \frac{\rho_{\rm GW}}{\rho_c} = \frac{\langle \dot{h}_{ij} \dot{h}_{ij} \rangle}{32\pi G\, \rho_c} = \int \frac{{\rm d}f}{f} \frac{{\rm d}\Omega_{\rm GW}}{{\rm d}\ln f}$$

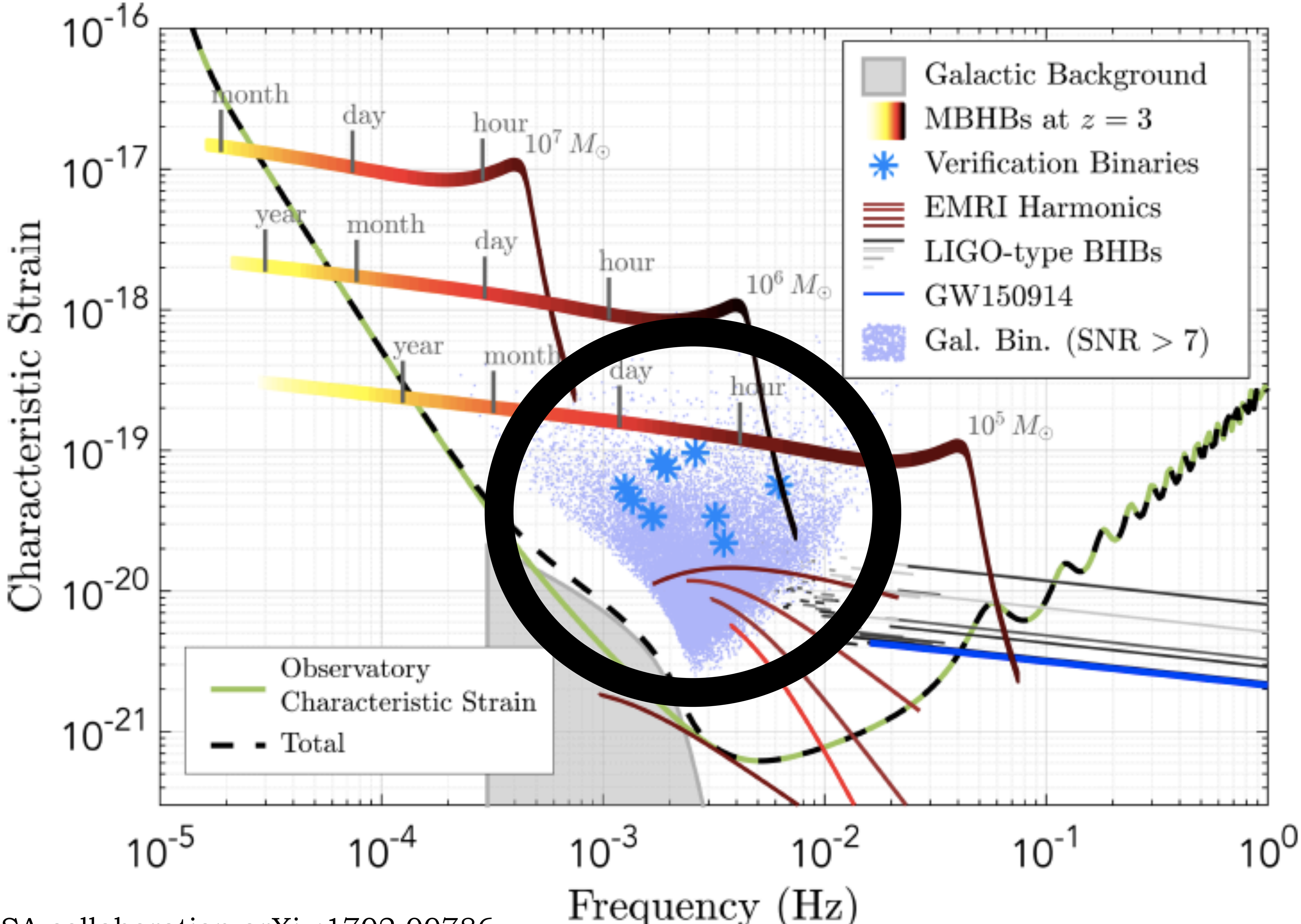
energy density power spectrum

What LISA measures



LISA collaboration arXiv:1702.00786

Compact binaries in the galaxy



LISA collaboration arXiv:1702.00786

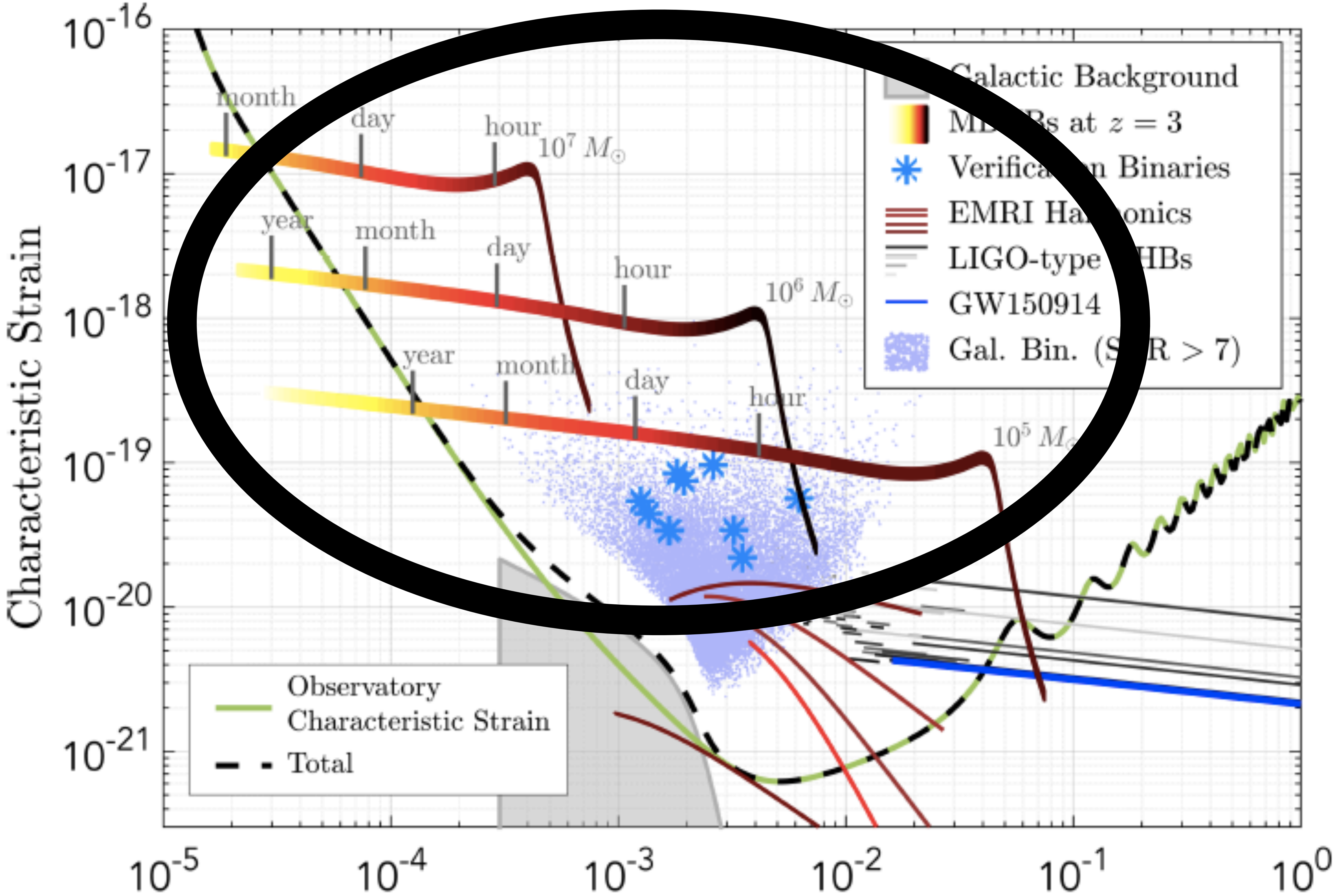
Compact binaries in the galaxy

- Neutron Star, White Dwarf and stellar origin Black Hole binaries
- most are in the inspiral phase: $M > 0.2\,M_\odot$ $d < 15\,\mathrm{kpc}$

$$M_c = 1\,\mathrm{M}_\odot \qquad \tau = 10^5\,\mathrm{years} \qquad \longrightarrow \qquad f = 3\,\mathrm{mHz}$$

- practically monochromatic, permanent signal
- several known systems: guaranteed LISA sources (verification)
- 25000 detected sources with SNR 7-1000
- SGWB from too low SNR sources, yearly modulated
- important to get good sky localisation to find em counterparts

Massive black hole binaries

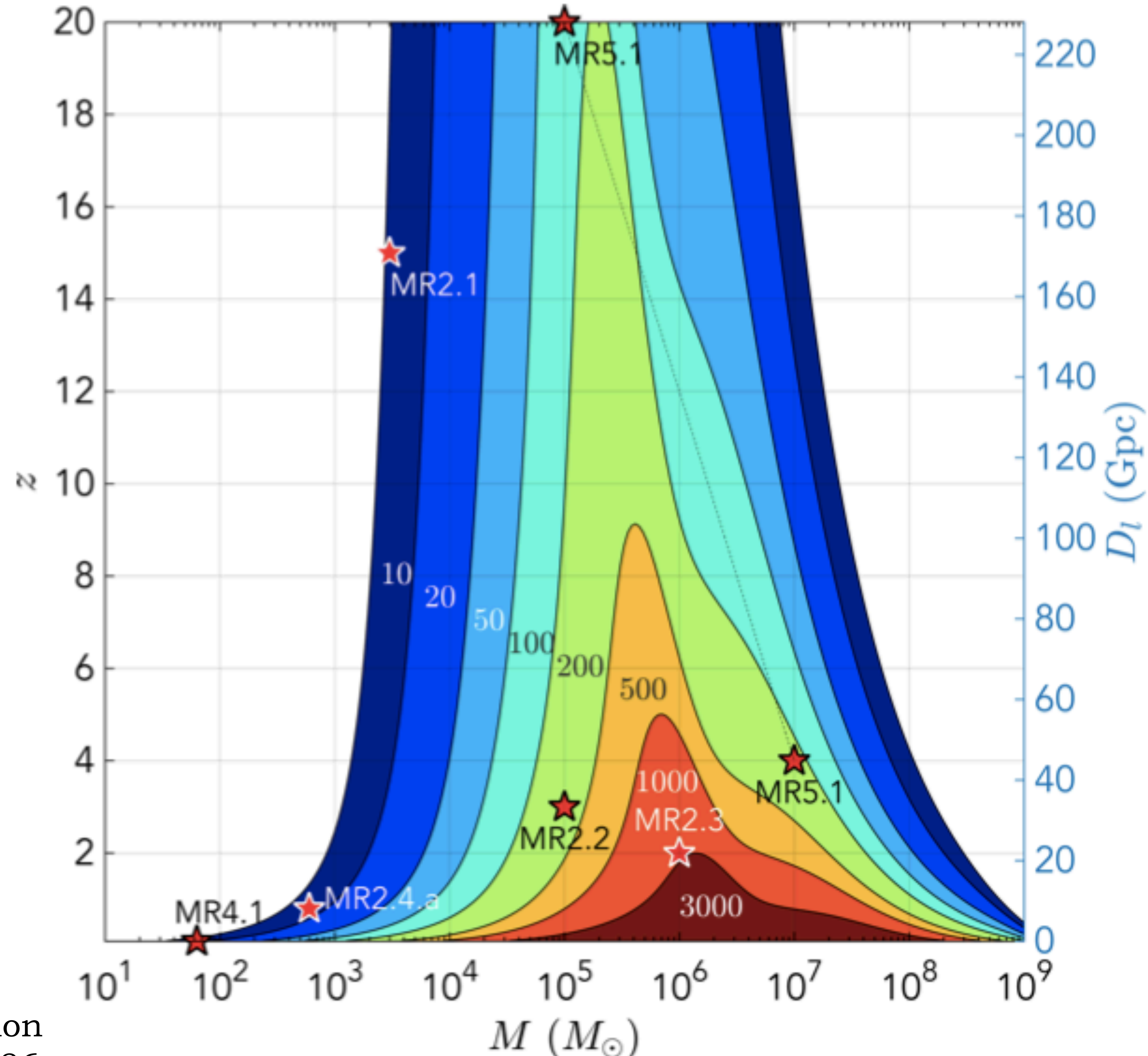


LISA collaboration arXiv:1702.00786

Massive black hole binaries

- MBH “indirectly” observed in the centre of many galaxies
- galaxies merge, leading to MBH binaries
- the best LISA sources! (other than the unexpected)
- expected rate in LISA: few to few hundreds per year
- signal duration: several months to few hours before merger
- LISA measures inspiral, merger, ring-down
- can have very high SNR
- seeds: $10^3 < M < 10^5\, M_\odot \qquad 10 < z < 15$
- accretion and mergers brings them to $M \geq 10^8\, M_\odot$
- electromagnetic counterpart?

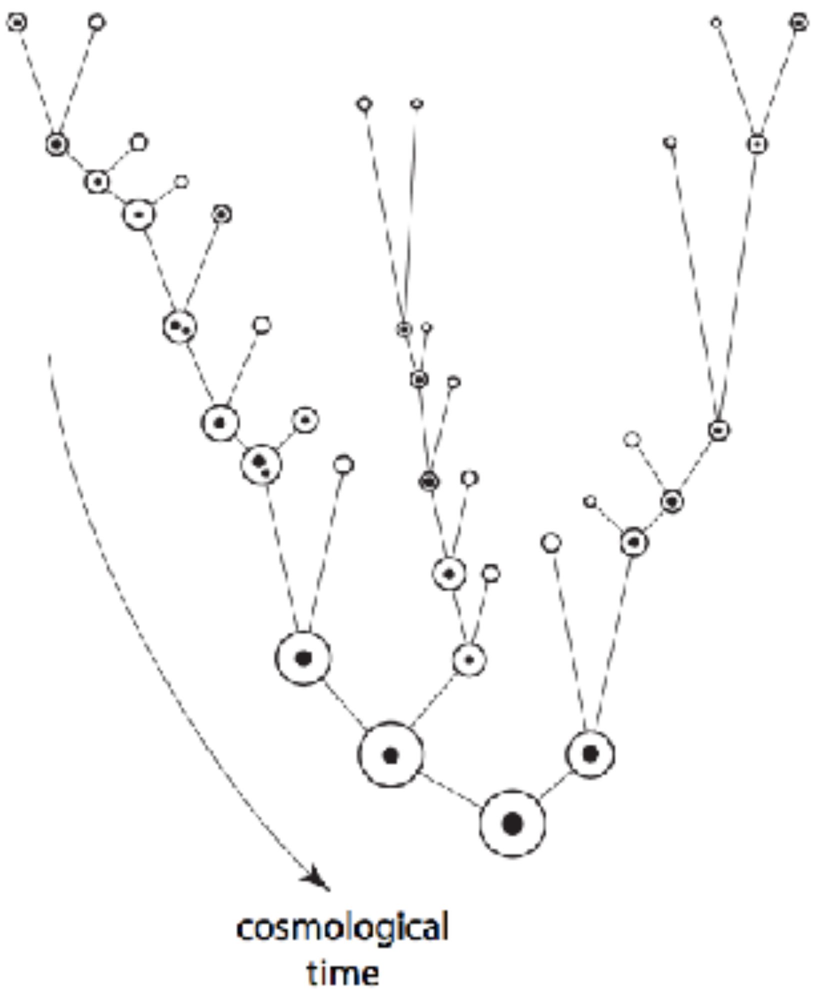
Massive black hole binaries



LISA collaboration
arXiv:1702.00786

Massive black hole binaries

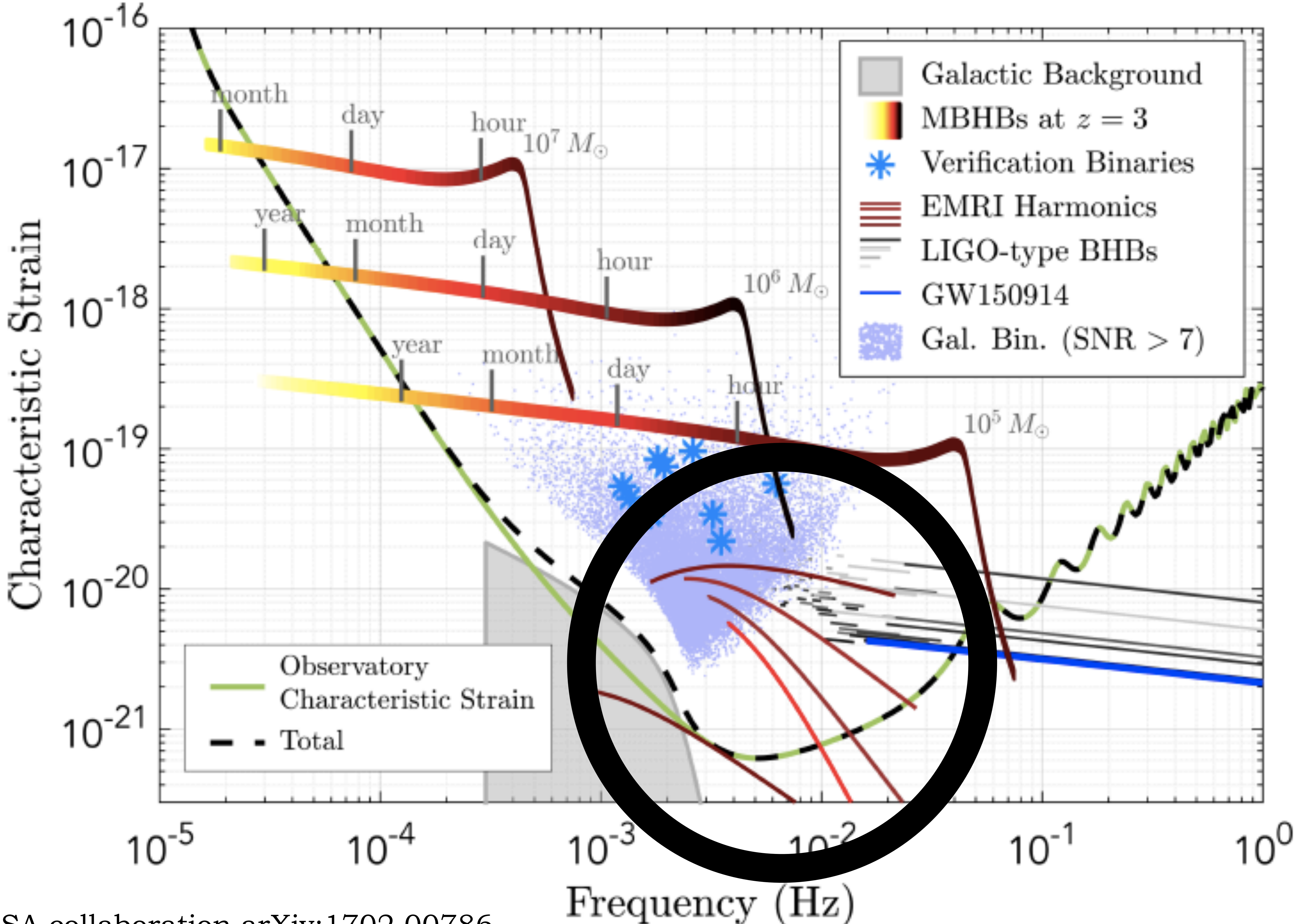
- study the MBH merger tree: what are their seeds?
- they participate in the clustering of cosmic structure: how did they grow?
- probe the existence of intermediate mass BH
- electromagnetic counterparts: probe the environment of the MBHB
- tests of General Relativity in the strong field regime:



- GW emission properties: scalar and dipole radiation
- use the ring-down phase to test the post-merger object
- GW propagation properties: dispertion relation, mass of the graviton, Lorentz invariance…
- test the presence of scalar fields around the BH

image:
M. Volonteri

Extreme mass ratio inspirals

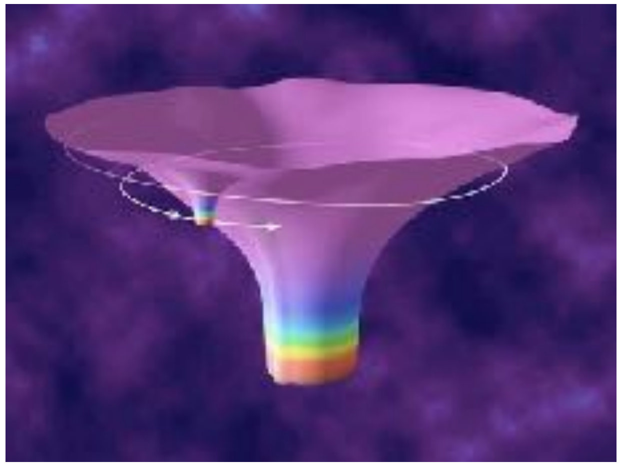


LISA collaboration arXiv:1702.00786

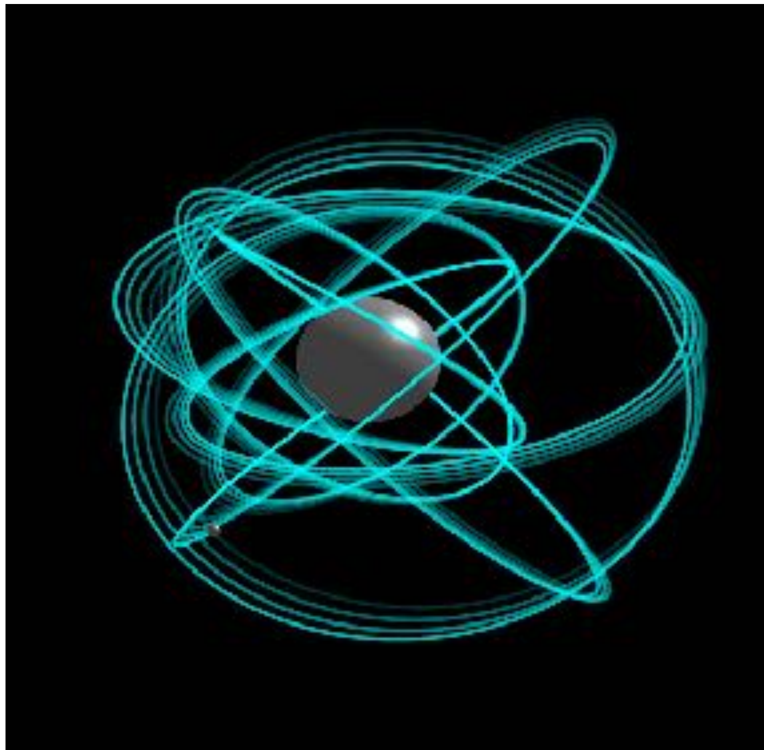
Extreme mass ratio inspirals

- the masses of the two objects are very different
- inspiral and merger of a stellar mass BH into massive BHs

$$m_1 = 10 - 60\, M_\odot$$
$$m_2 = 10^5 - 10^6\, M_\odot$$

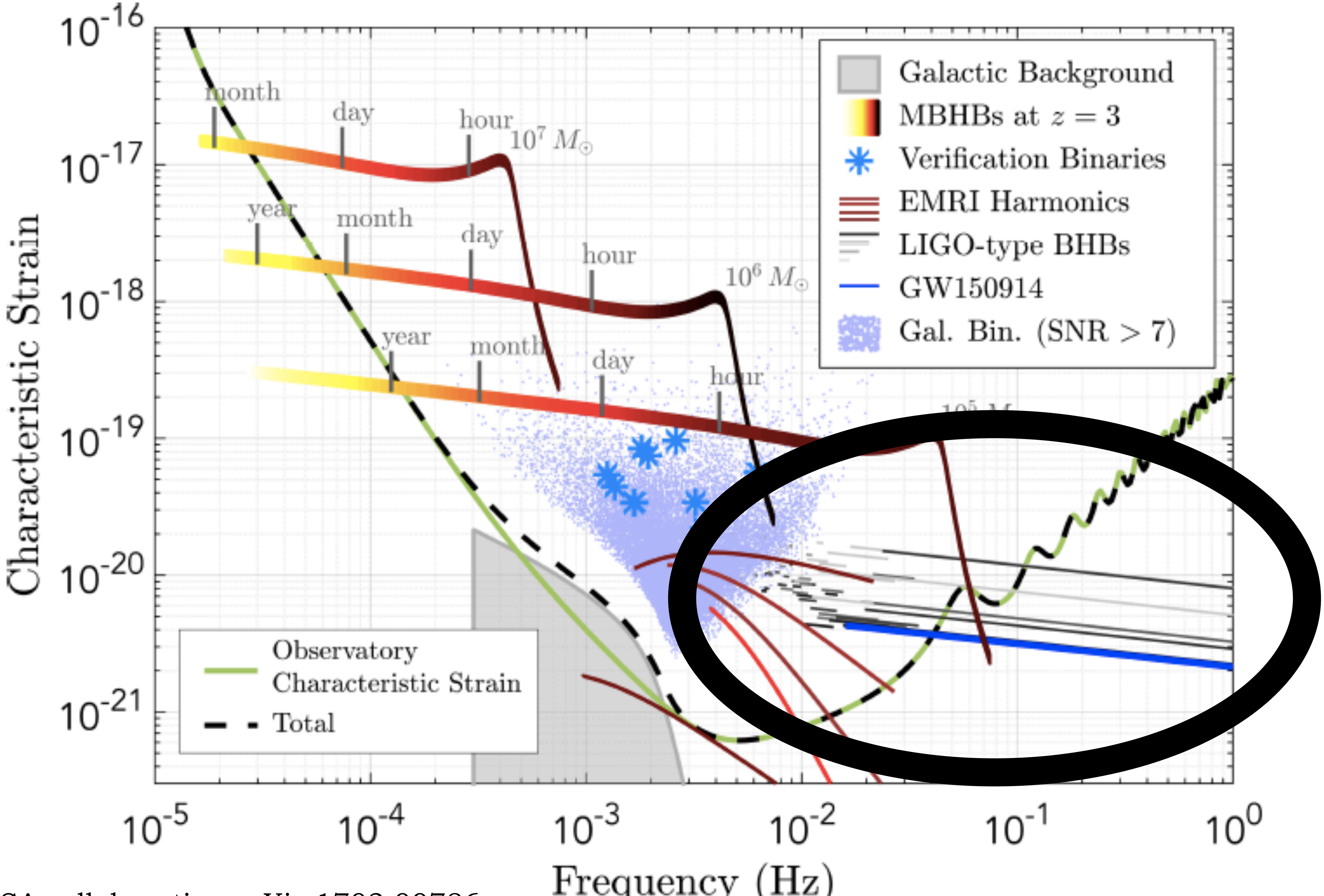


- the signal lasts months to years: 10^3 - 10^5 orbits, very precise determination of the binary parameters



- the orbits are highly relativistic, very complicated: precise mapping of spacetime around the MBH - tests of General Relativity
- test of the environment of dense nuclear clusters around milky-way like BH

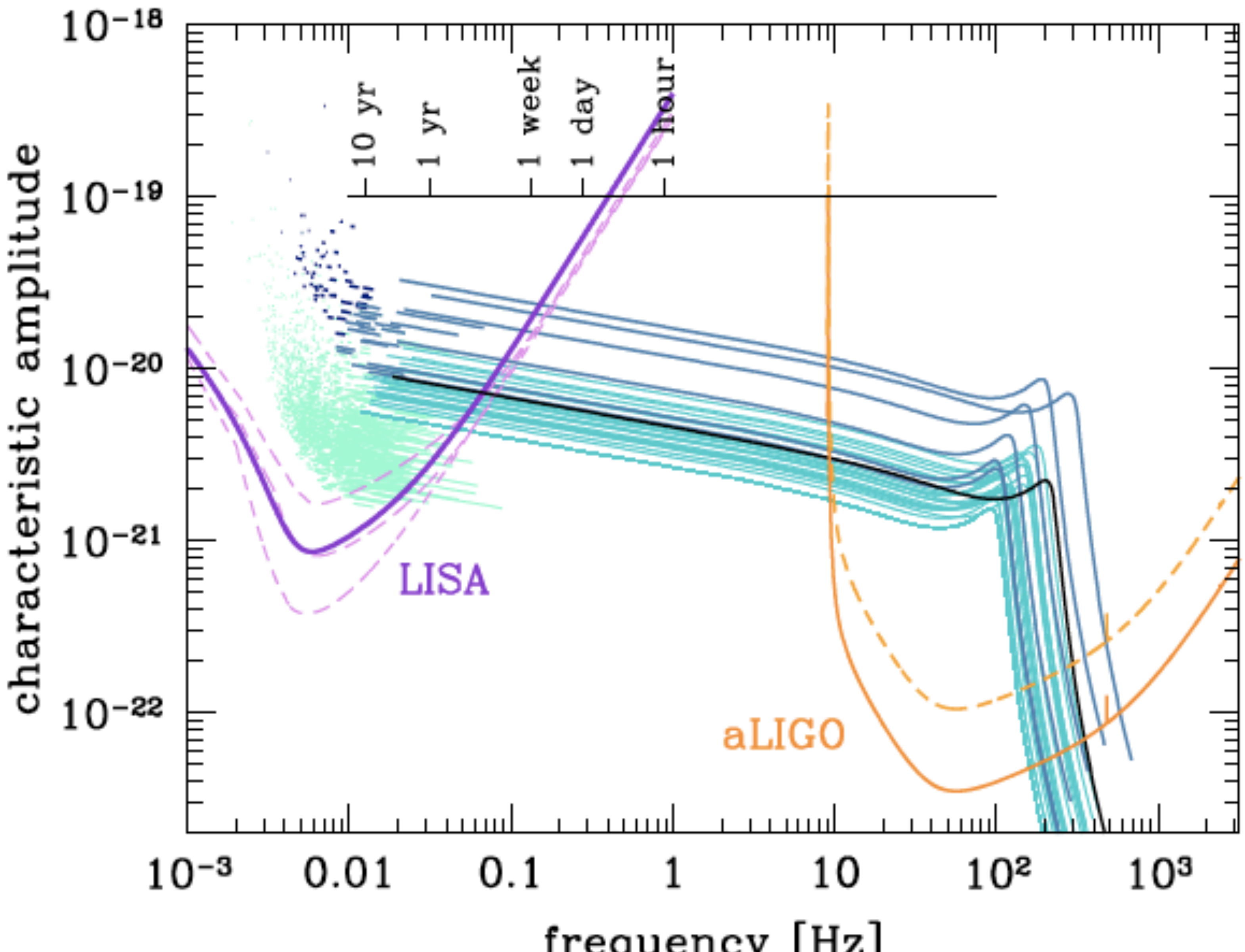
Black hole binaries of tents of solar masses



LISA collaboration arXiv:1702.00786

Black hole binaries of tents of solar masses

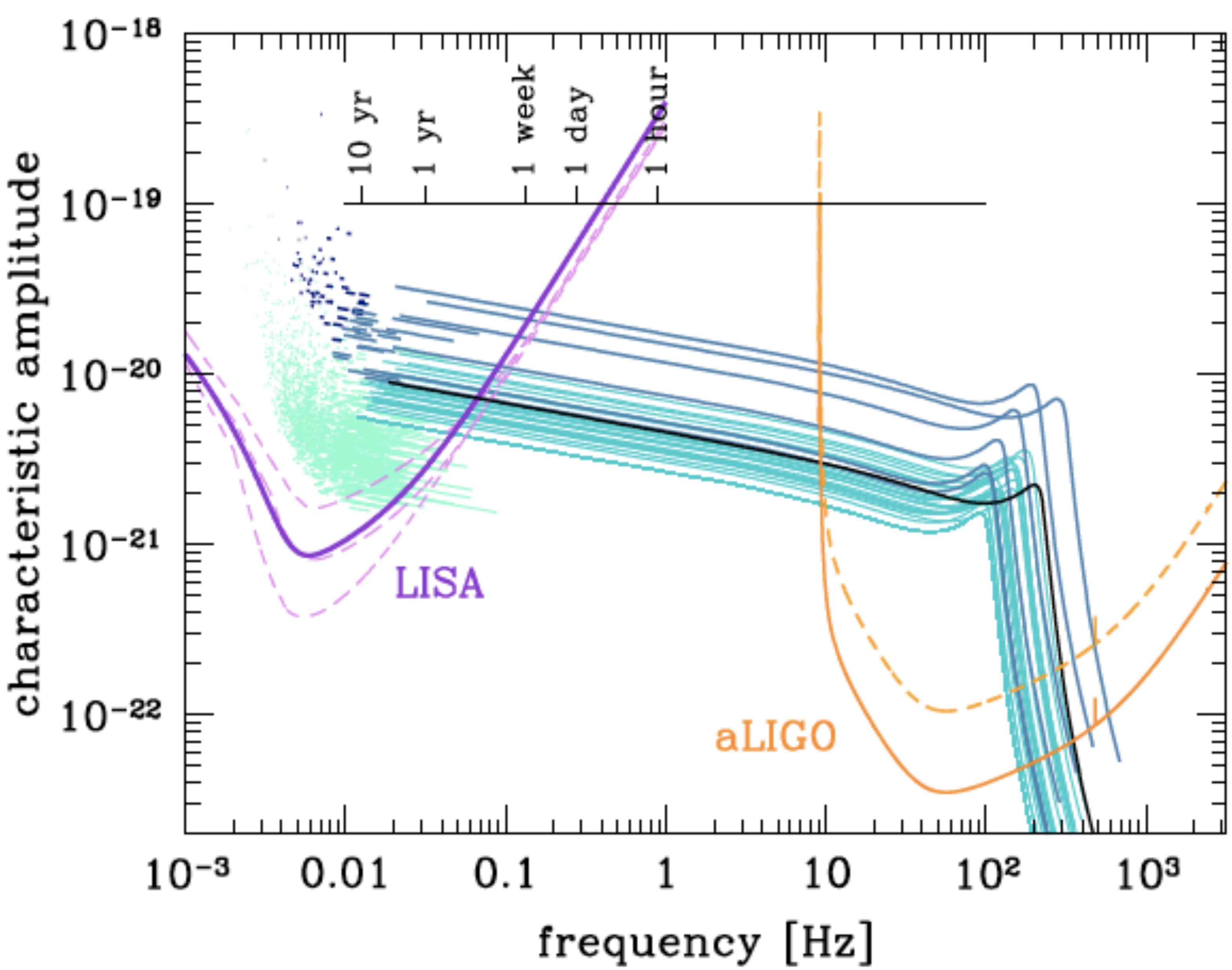
about 100 binaries based on LIGO rates
some will cross LIGO band when close to merger



A Sesana
arXiv:1702.04356

Black hole binaries of tents of solar masses

- new phase term in the waveform from the centre of mass acceleration
- infer the formation environment of the binary (nearby a SMBH?)
- tests of General Relativity



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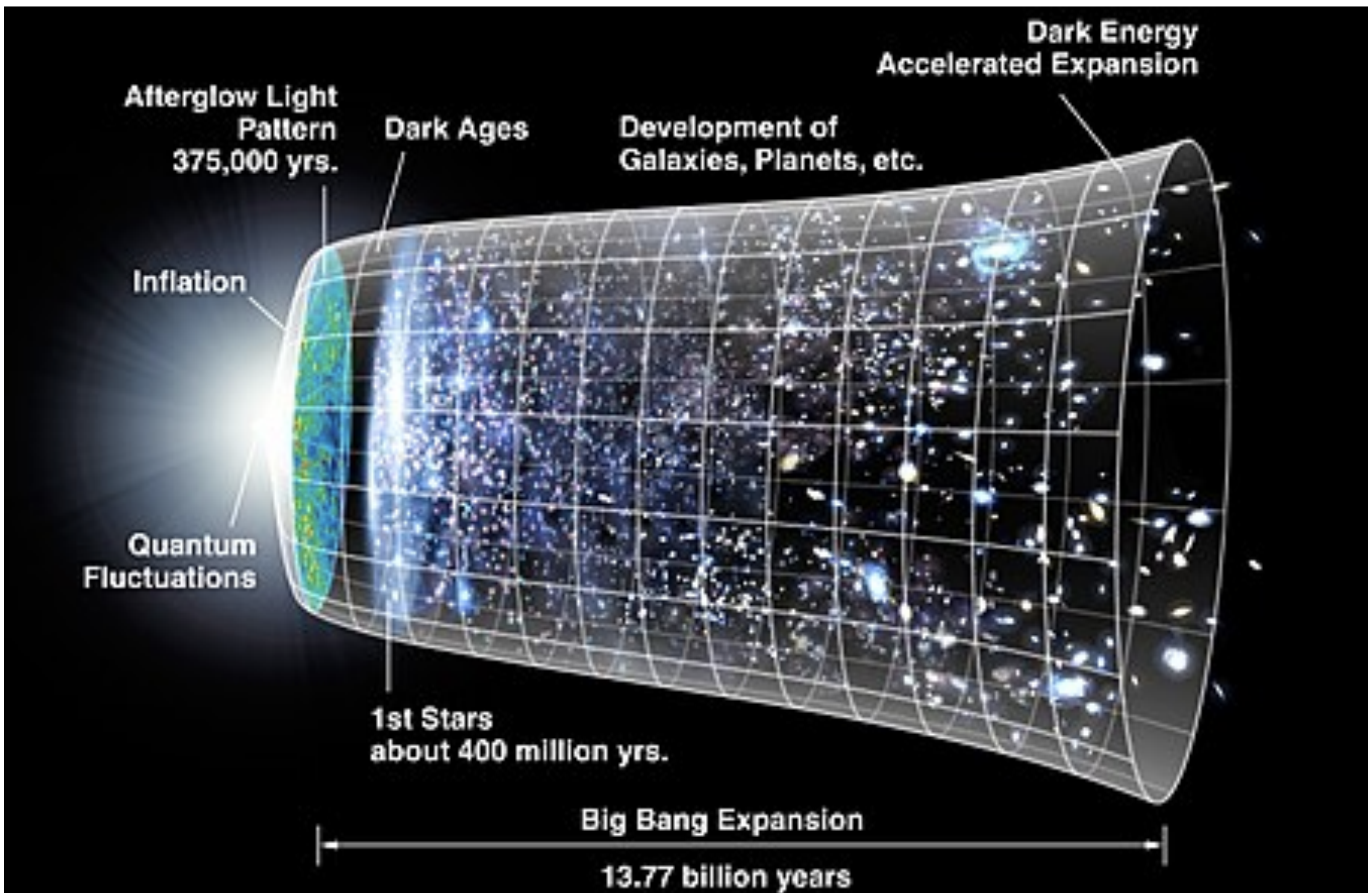
arXiv:1702.04356

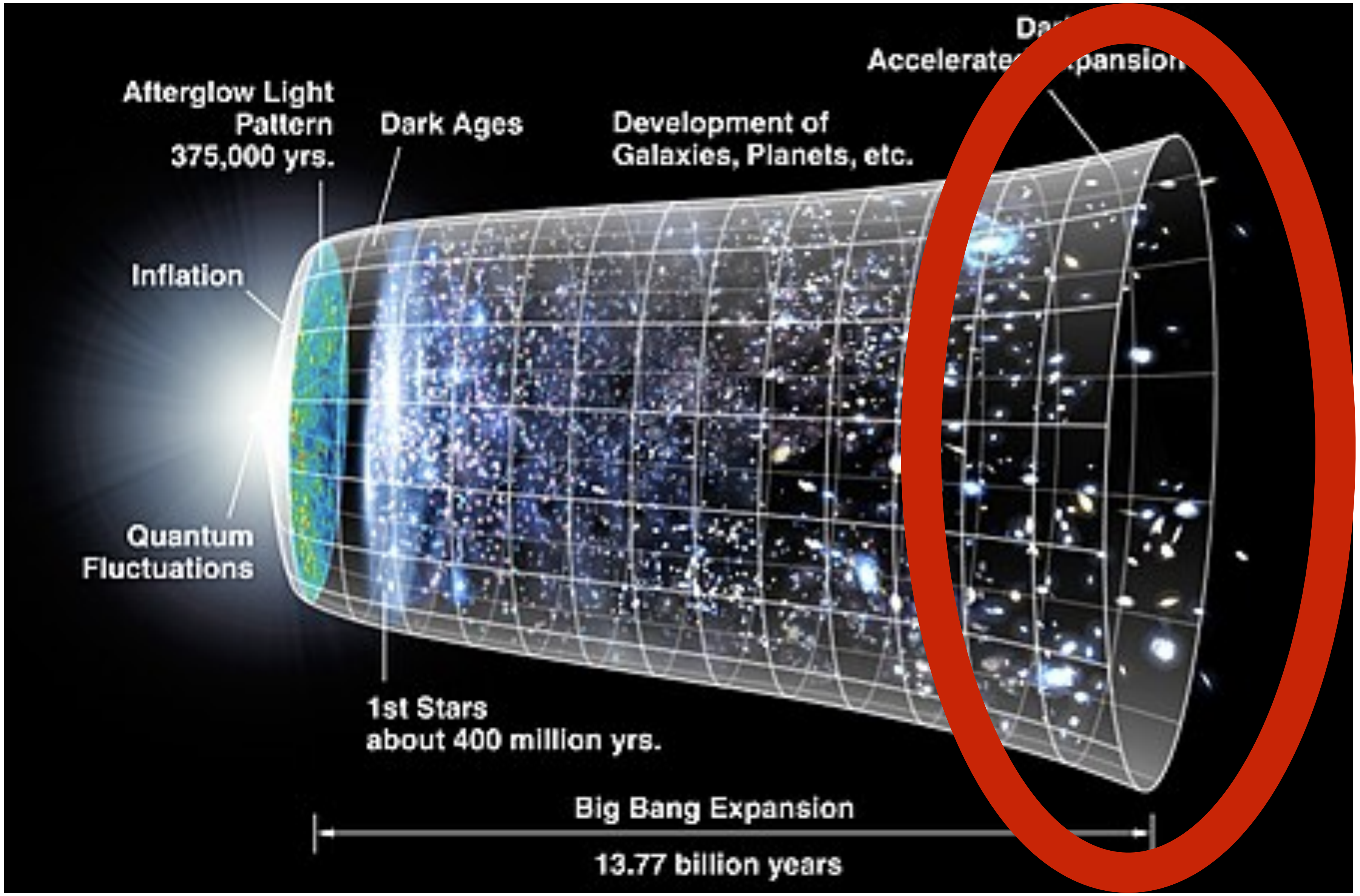
LISA AND COSMOLOGY:

two results of the *LISA cosmology working group*



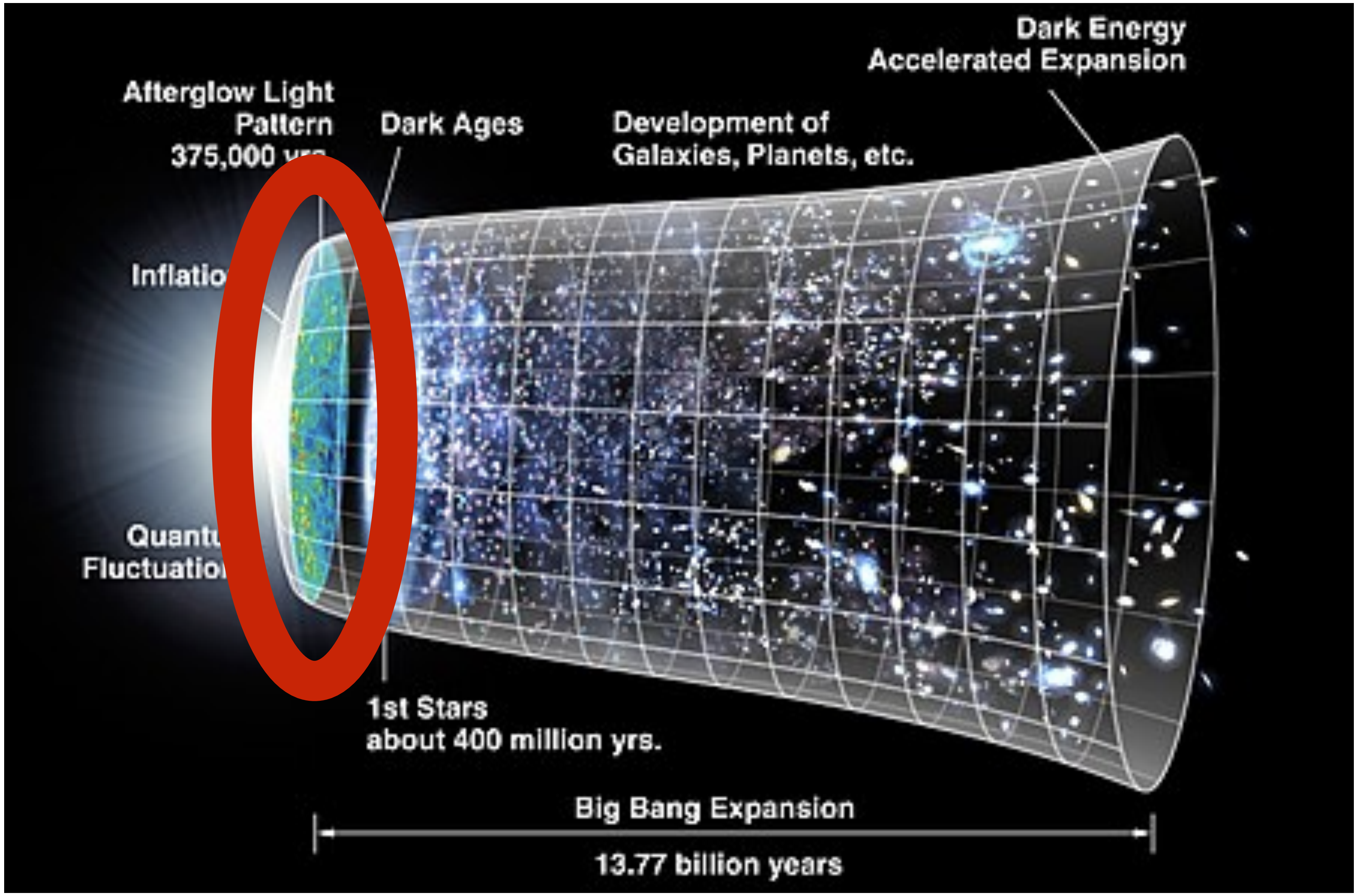
LISA AND COSMOLOGY:

use of GW emission from binaries to probe the background expansion of the universe: tests of acceleration



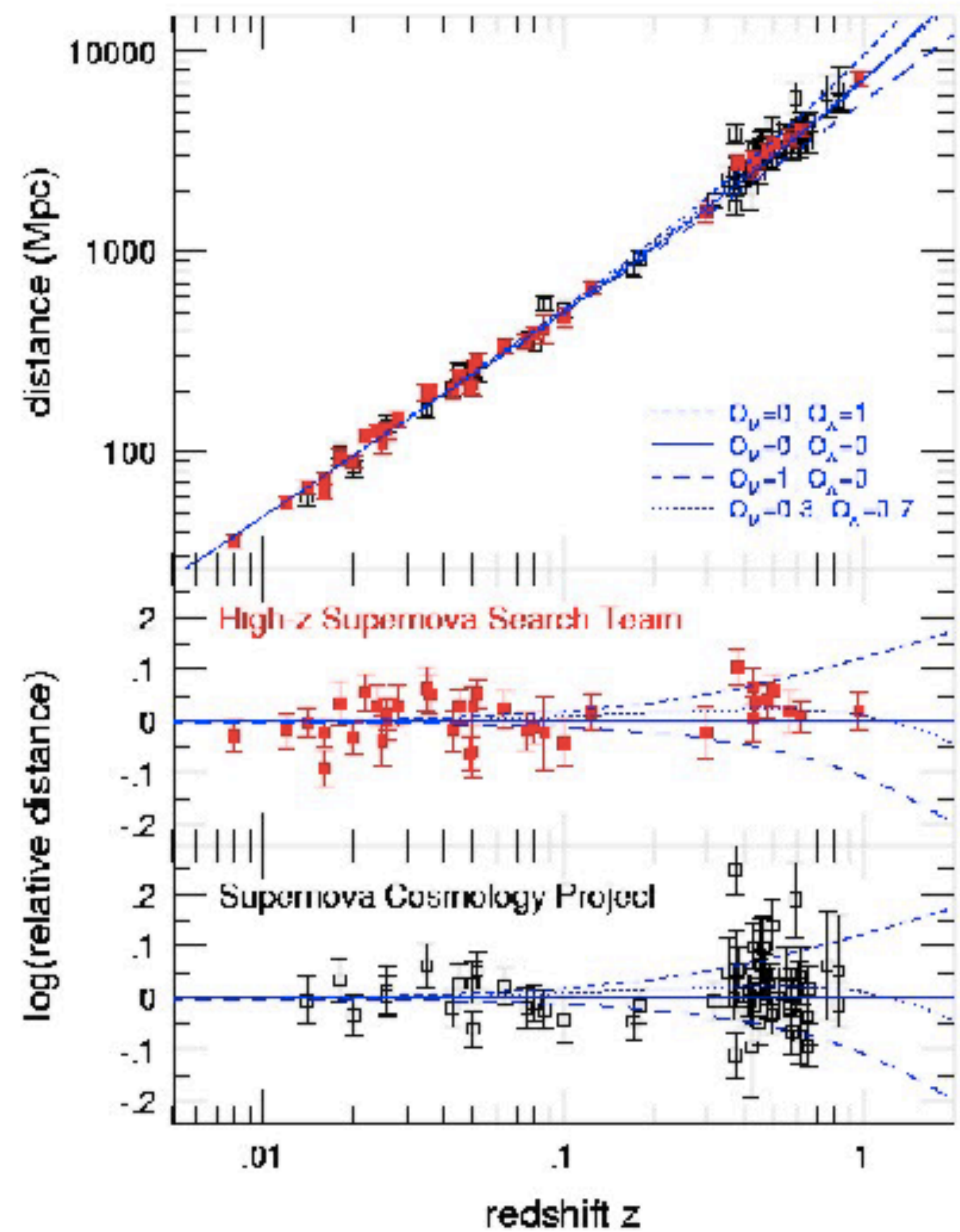
LISA AND COSMOLOGY:

the stochastic GW background from primordial sources:
test of early universe and high energy phenomena



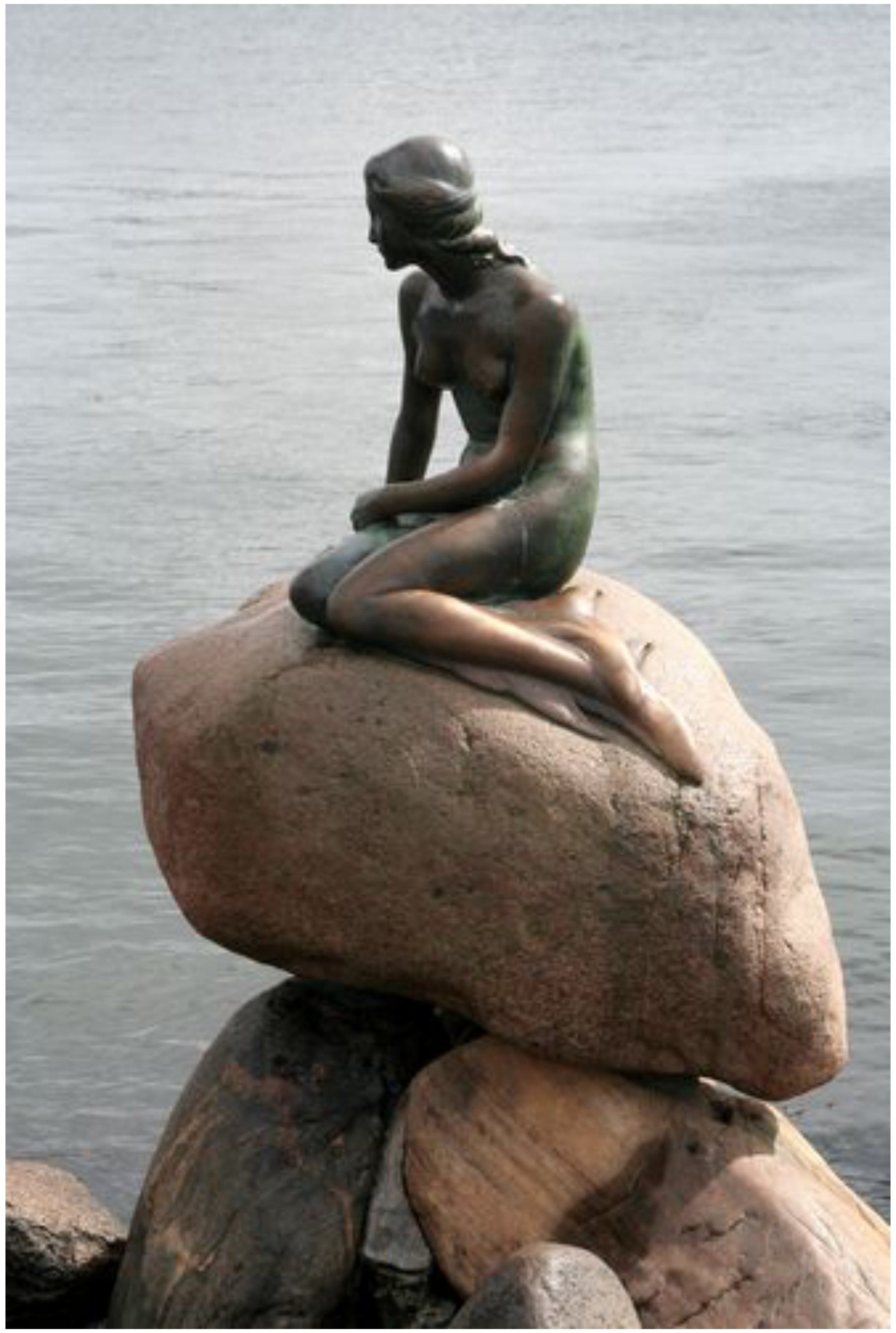
Standard candles

Nobel prize in physics 2011:
discovery of the late-time acceleration of the universe



Standard sirens

GW emission by compact binaries
can be used as SuperNovae Ia
to test the expansion of the universe



Standard sirens

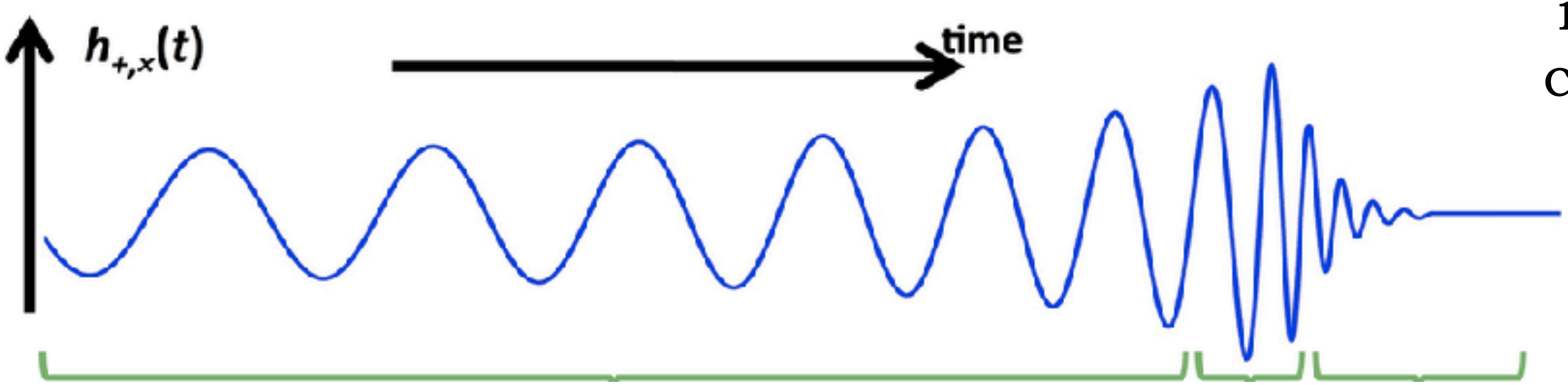
GW emission by compact binaries + redshift by an EM counterpart can be used to probe the distance-redshift relation

$$h_+(t) = \frac{4}{d_L(z)} \left(\frac{G\mathcal{M}_c}{c^2}\right)^{\frac{5}{3}} \left(\frac{\pi f}{c}\right)^{\frac{2}{3}} \frac{1+\cos^2\imath}{2} \cos[\Phi(t)]$$

$$h_\times(t) = \frac{4}{d_L(z)} \left(\frac{G\mathcal{M}_c}{c^2}\right)^{\frac{5}{3}} \left(\frac{\pi f}{c}\right)^{\frac{2}{3}} \cos\imath \, \sin[\Phi(t)]$$

$$\mathcal{M}_c = (1+z)M_c$$

redshifted chirp mass



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$$d_L(z, H_0, \Omega_M, \Omega_\Lambda, \dots)$$

- direct measurement of d_L up to large redshift with GW
- it needs an independent measurement of the redshift

Standard sirens

GW emission by compact binaries + redshift by an EM counterpart
can be used to probe the distance-redshift relation

A GRAVITATIONAL-WAVE STANDARD SIREN MEASUREMENT OF THE HUBBLE CONSTANT

THE LIGO SCIENTIFIC COLLABORATION AND THE VIRGO COLLABORATION, THE 1M2H COLLABORATION,
THE DARK ENERGY CAMERA GW-EM COLLABORATION AND THE DES COLLABORATION,
THE DLT40 COLLABORATION, THE LAS CUMBRES OBSERVATORY COLLABORATION,
THE VINROUGE COLLABORATION, THE MASTER COLLABORATION, et al.

$$H_0 = 70^{+12}_{-8}\ \mathrm{km\,sec^{-1}Mpc^{-1}}$$

Standard sirens

LISA alone :

$$\Omega_M = 0.3 \pm [0.05,\ 0.03]$$
$$h = 0.67 \pm [0.02,\ 0.01]$$

LISA fixing Ω_M :

$$h = 0.67 \pm [0.006,\ 0.004]$$

0.6% in best case

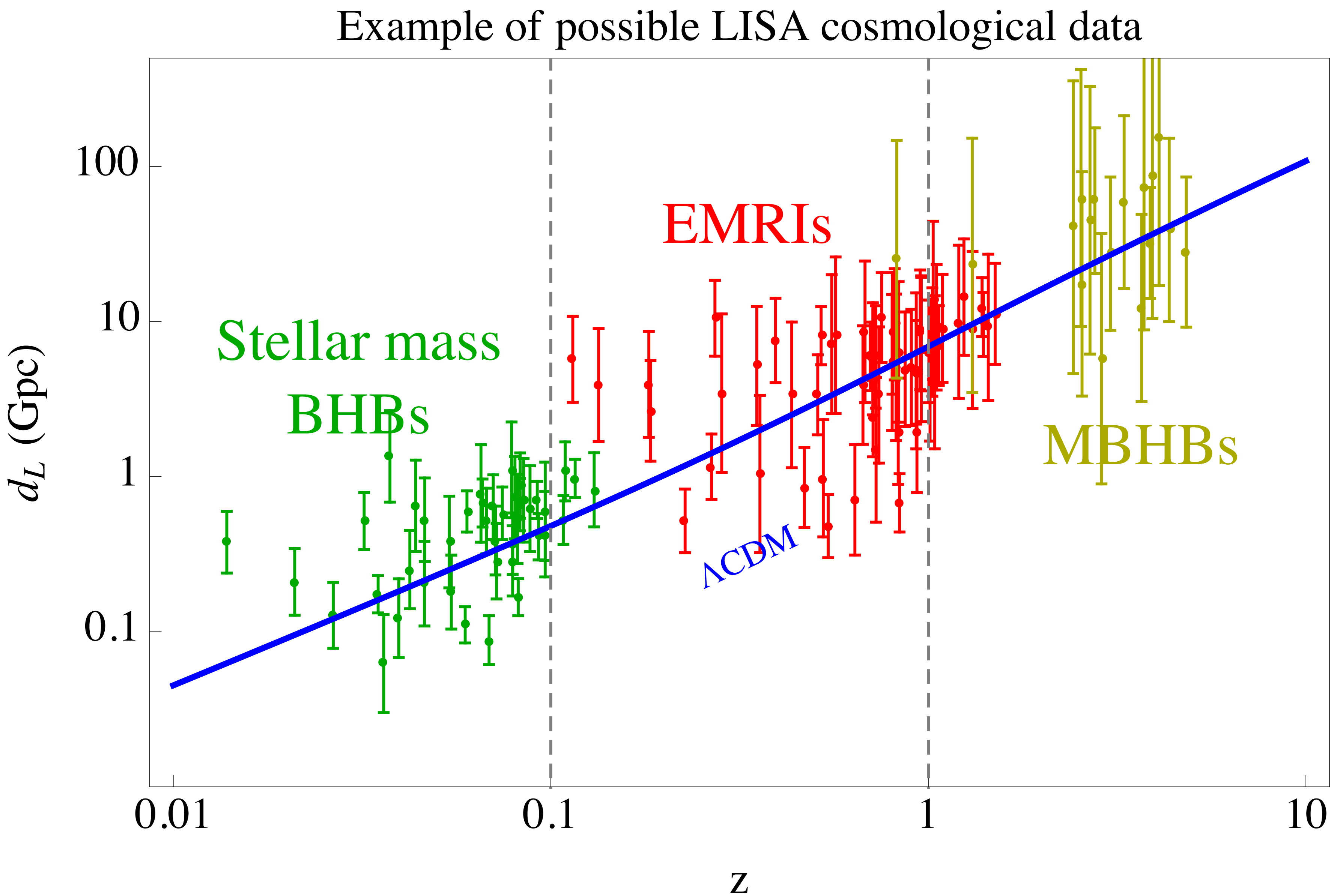
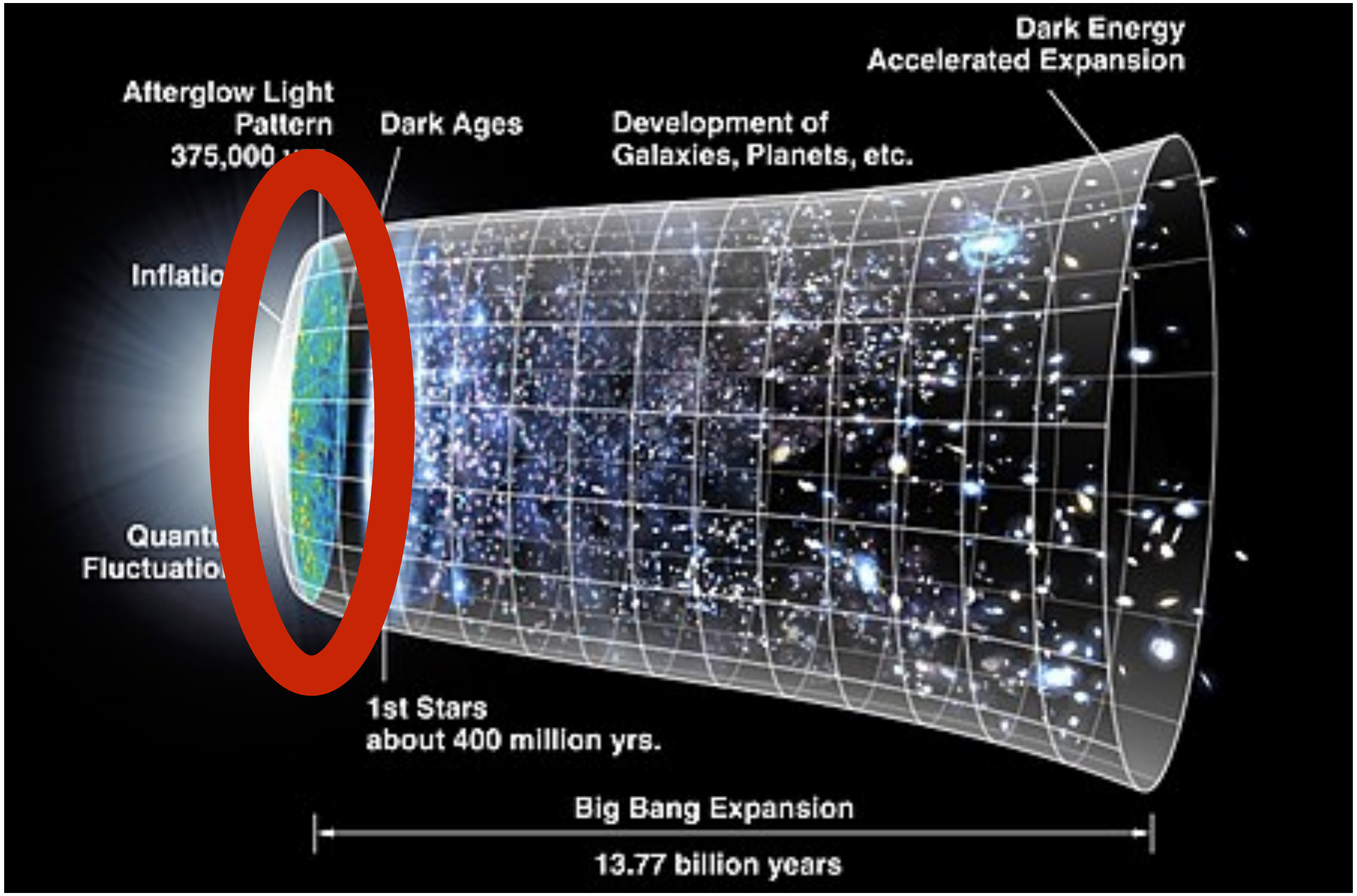


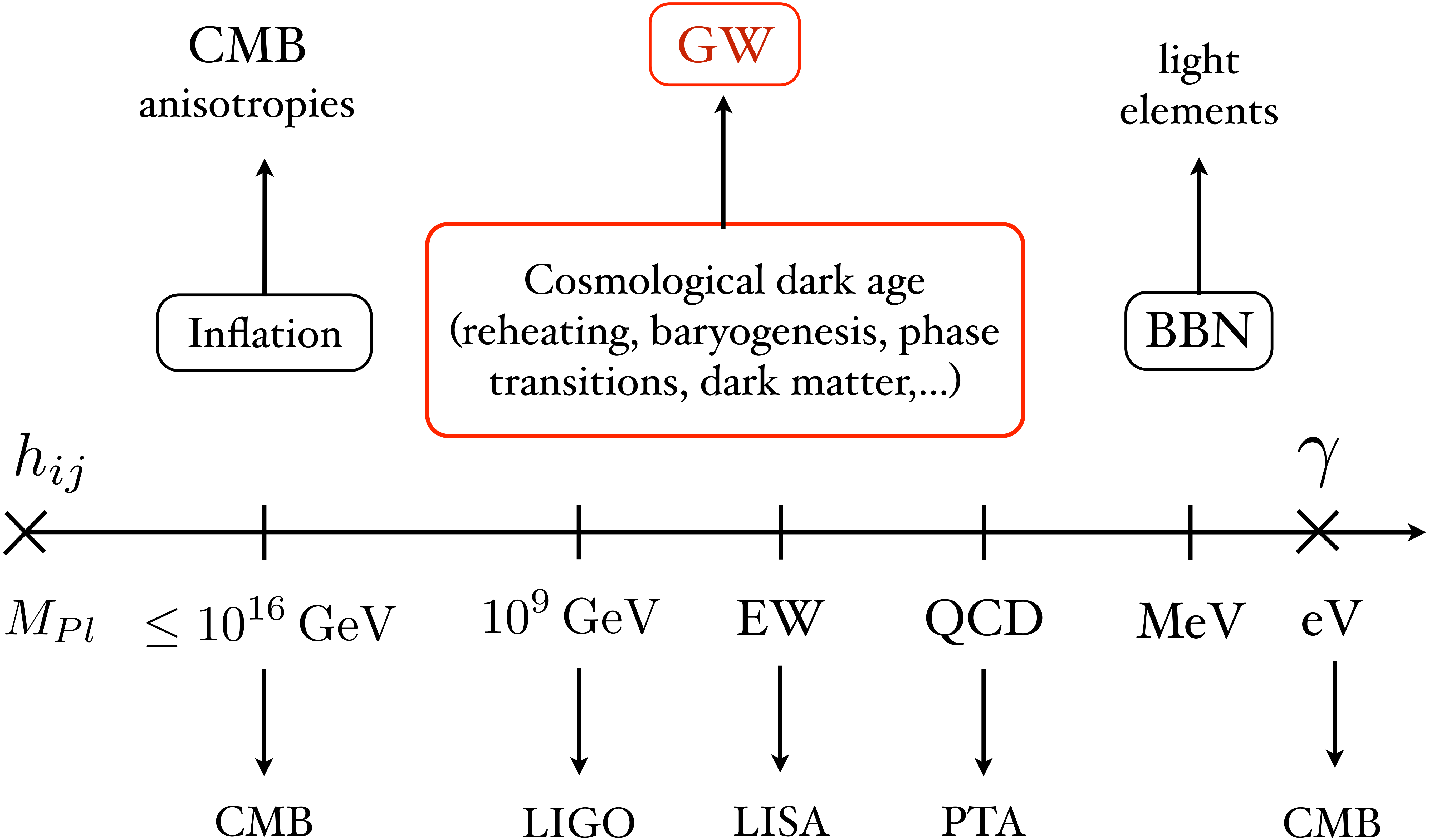
image:
N. Tamanini

LISA AND COSMOLOGY:

the stochastic GW background from primordial sources:
test of early universe and high energy phenomena

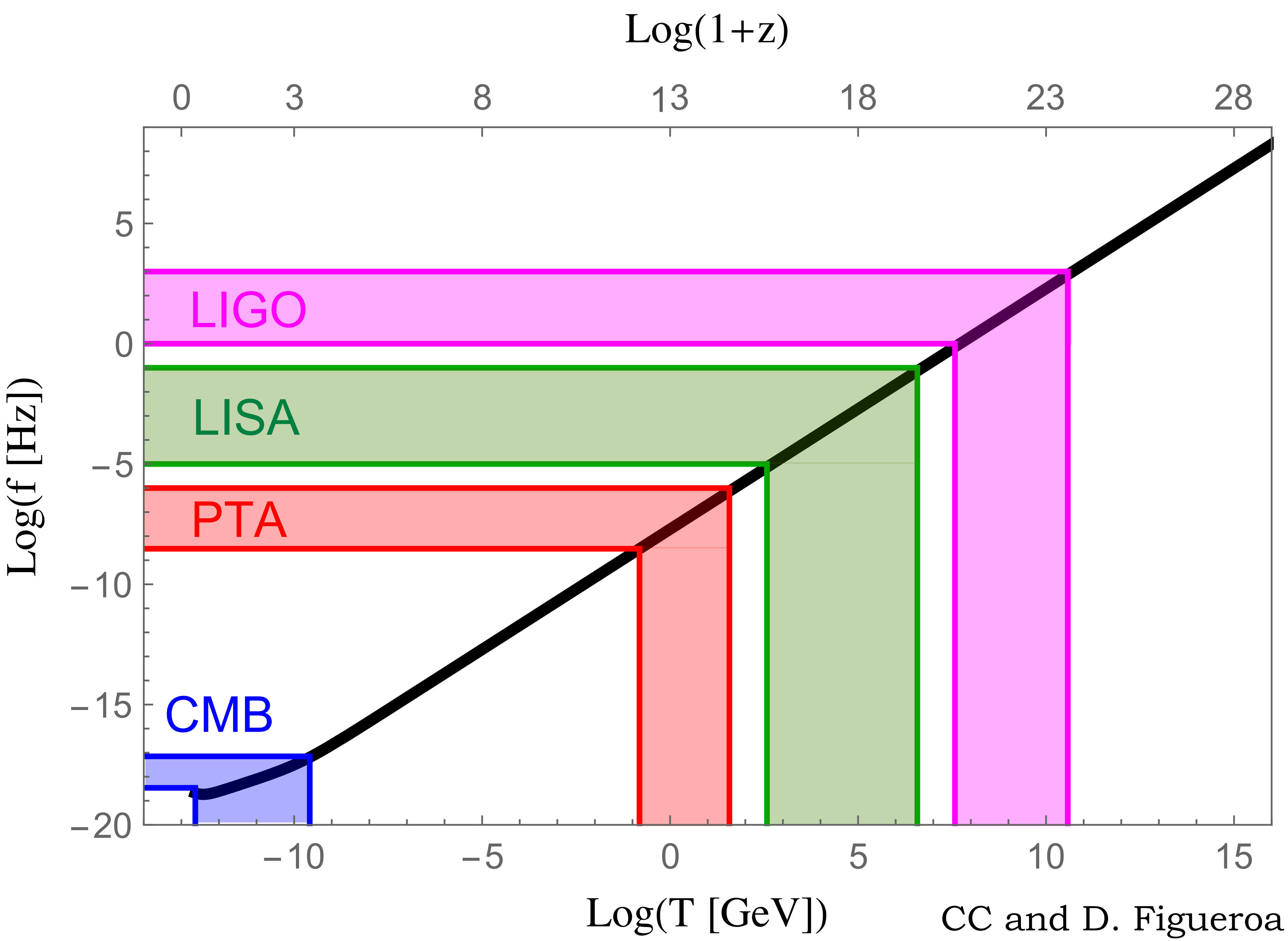


the stochastic GW background from primordial sources



the stochastic GW background from primordial sources

$$f_c = f_* \frac{a_*}{a_0} = \frac{2 \cdot 10^{-5}}{\epsilon_*} \frac{T_*}{1\,\text{TeV}}\,\text{Hz} \qquad \epsilon_* = L_* H_*$$



CC and D. Figueroa arXiv:1801.04268

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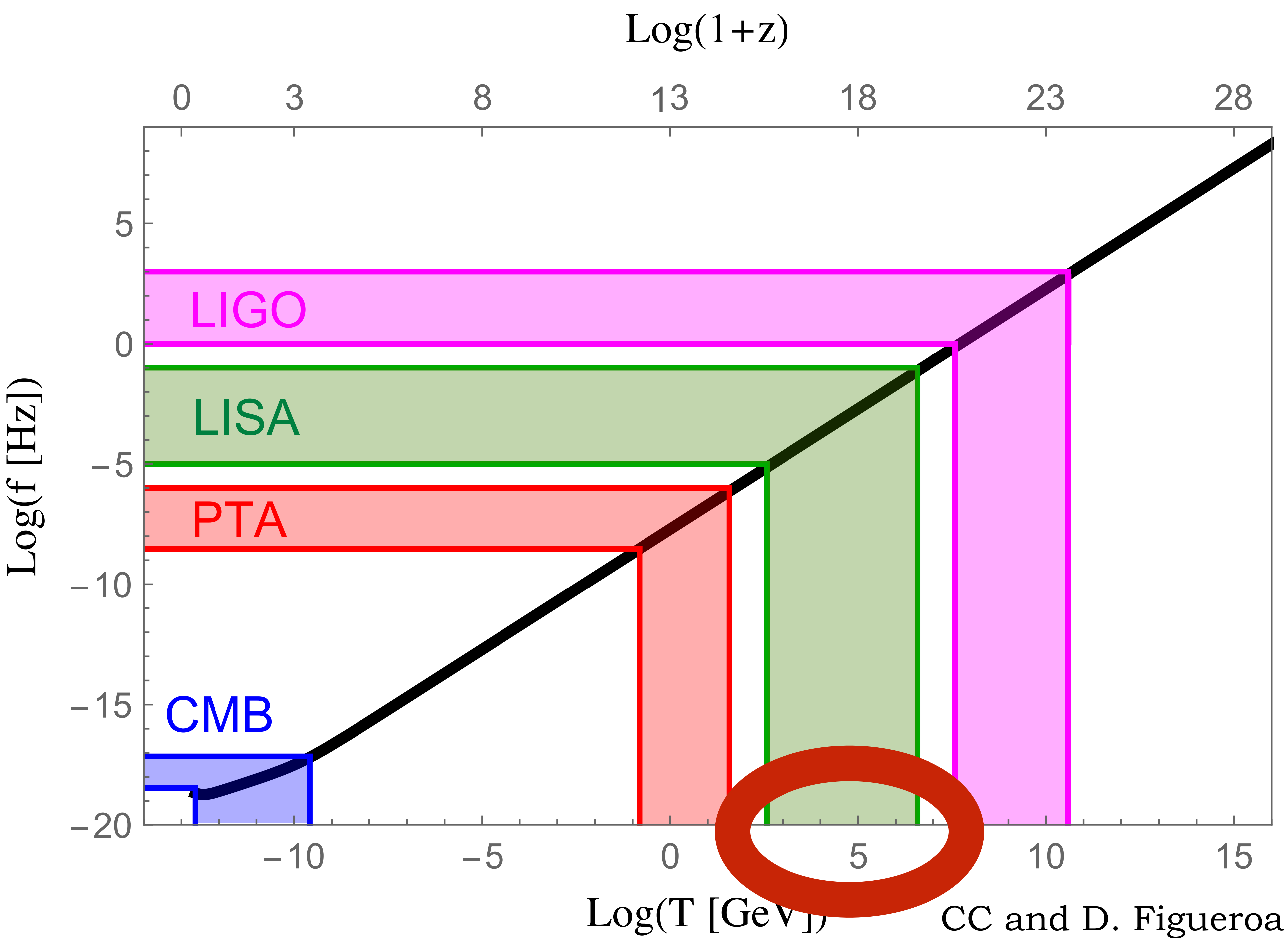
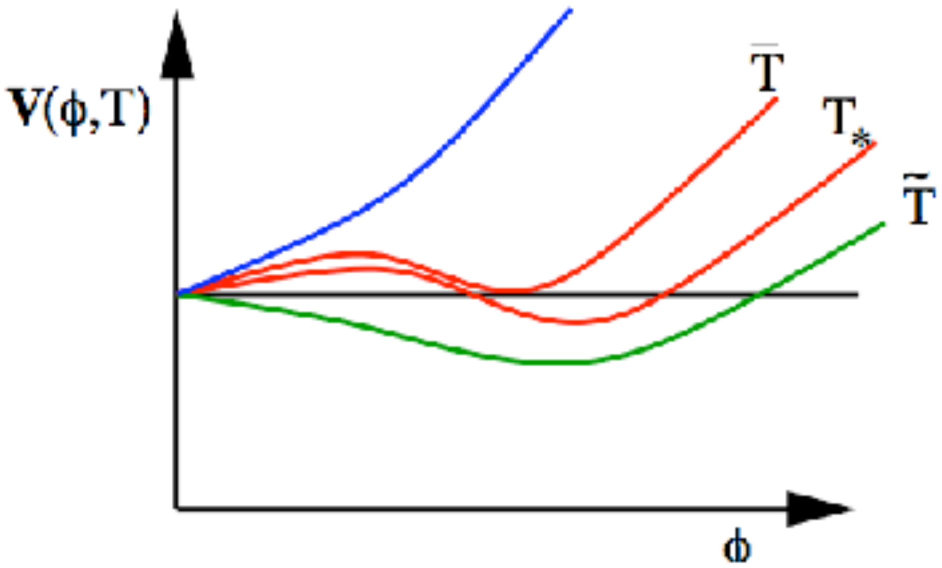


CC and D. Figueroa arXiv:1801.04268

The stochastic GW background from a first order phase transition

potential barrier separates true and false vacua



quantum tunneling across the barrier : nucleation of bubbles of true vacuum

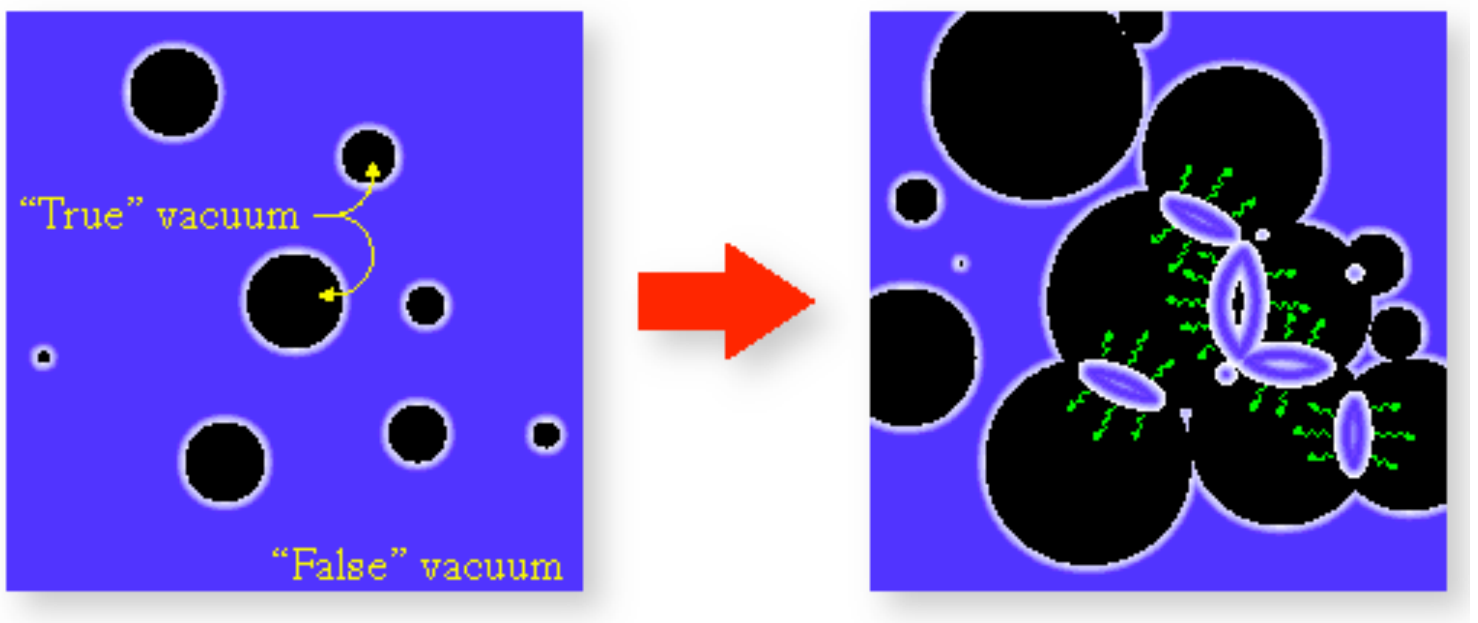


image: P. Binetruy

source: Π_{ij} tensor anisotropic stress

- collisions of bubble walls
- sound waves and turbulence in the fluid
- primordial magnetic fields (MHD turbulence)

The stochastic GW background from a first order phase transition

- LISA is sensitive to energy scales 10 GeV - 100 TeV

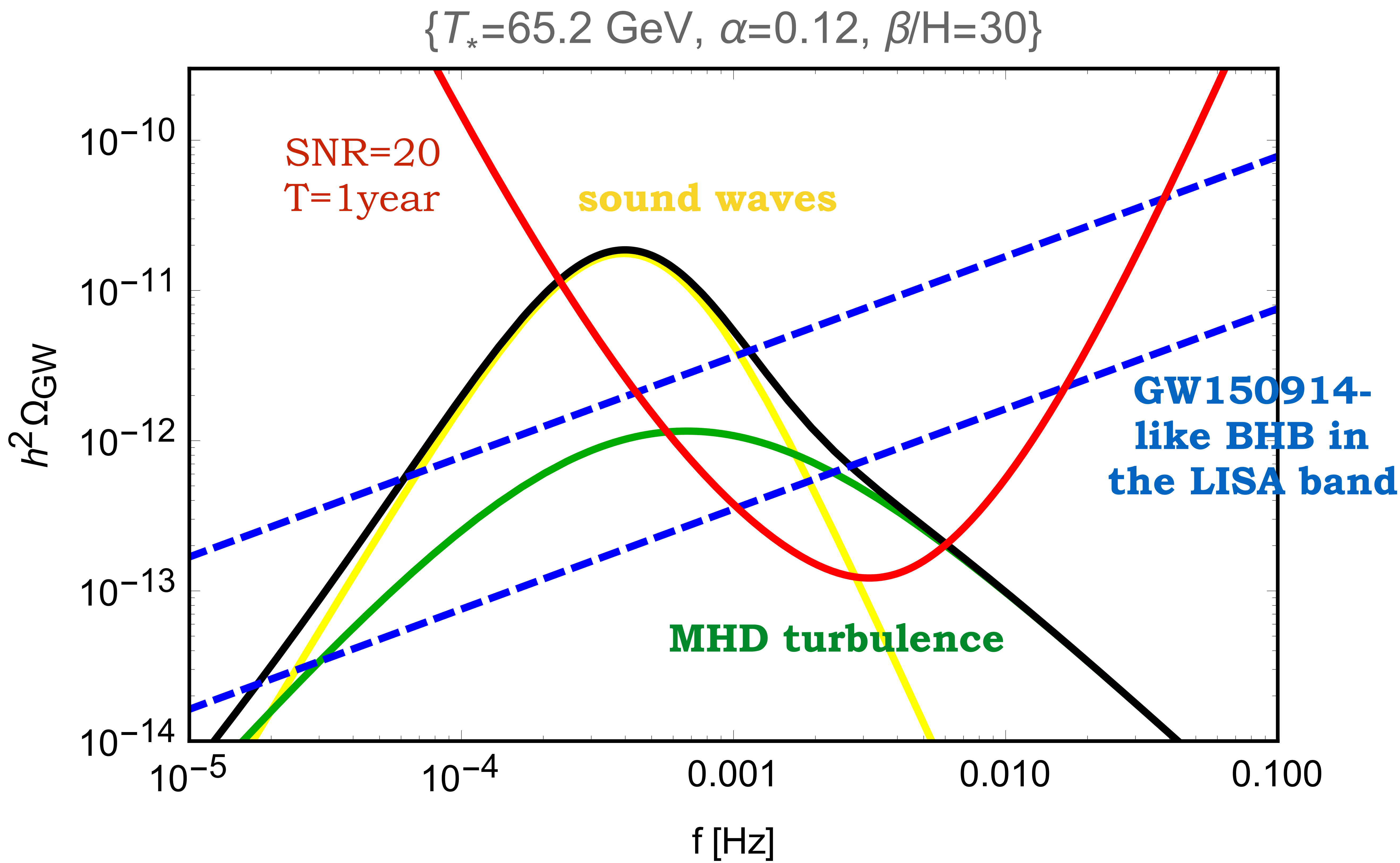
- LISA can probe the Electroweak Phase Transition in Beyond Standard Model scenarios …
  - singlet extensions of MSSM
  - direct coupling of Higgs sector with scalars
  - SM plus dimension six operator

- … and beyond the Electroweak Phase Transition
  - Dark Matter sector
  - Warped extra dimensions

connections with baryon asymmetry, dark matter : LISA as a probe of BSM physics, complementary to colliders

CC et al, arXiv:1512.06239

Example of signal from + foreground



SUMMARY

- LIGO/Virgo direct GW detections have opened the era of GW astronomy and cosmology (tests of GR, measurement of H_0...)

- LISA is on the path to launch in 2032

- LISA is a discovery mission that will enlarge our knowledge of the Universe, from galactic to Hubble scales, from the present time to the very early universe

- it has the ability to test fundamental physics:

  - tests of GR and of the universe late-time acceleration
  - constrain models of the very early universe
  - test the electroweak symmetry breaking and beyond