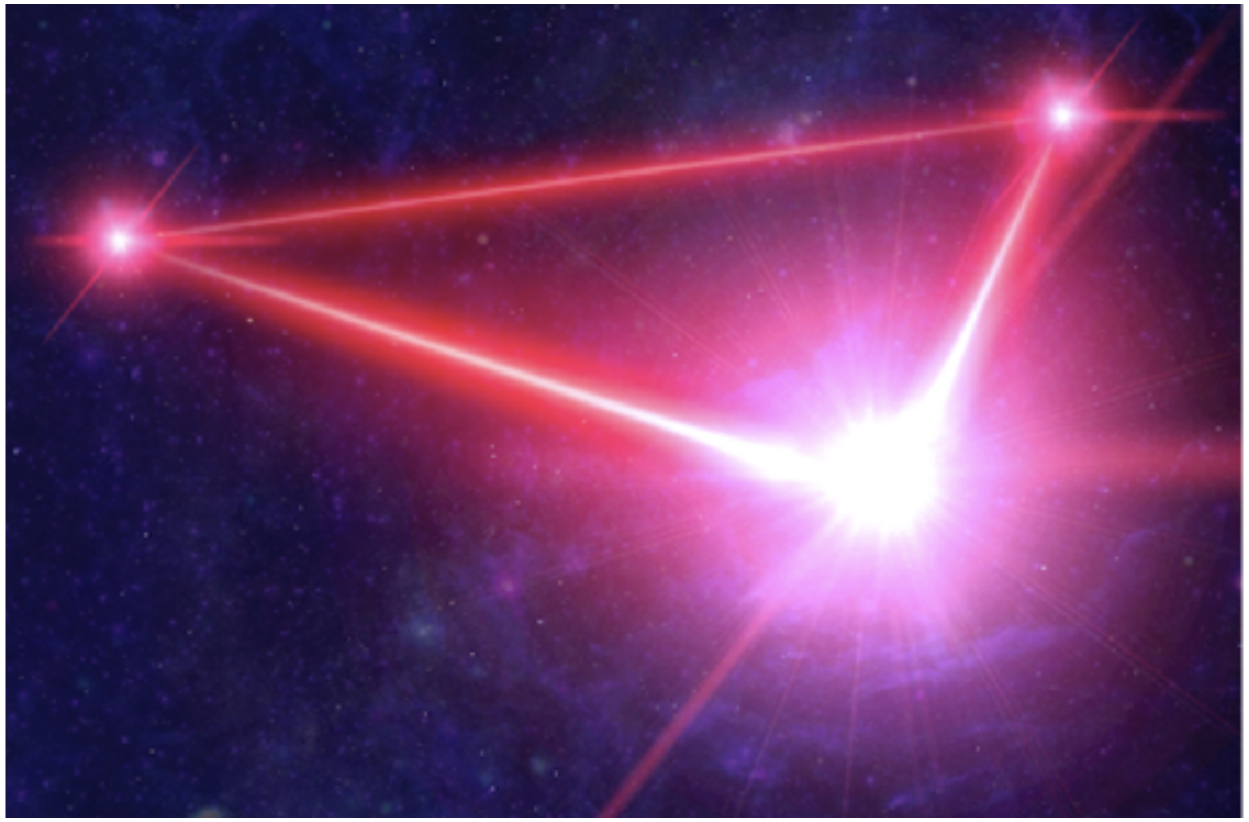
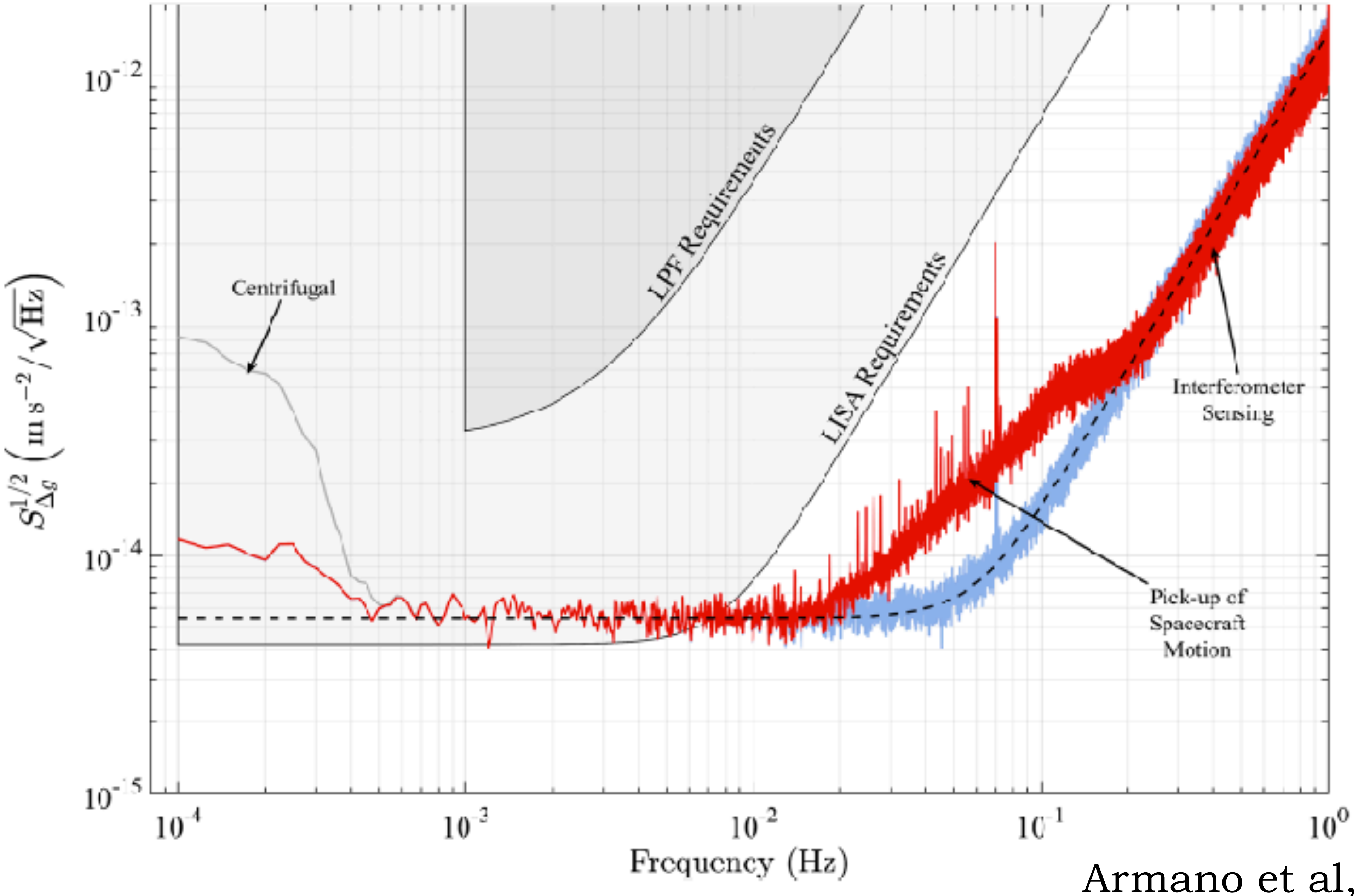
COSMOLOGY
WITH THE GRAVITATIONAL WAVE INTERFEROMETER LISA

Chiara Caprini
APC Paris



LISA
space-based interferometer performing direct GW detection

LISA Pathfinder launch Dec 2015, operations March 2016 -> now



one LISA arm reduced in one spaceship

<u>test the ability to put two masses in free fall</u>: measure the differential acceleration among them

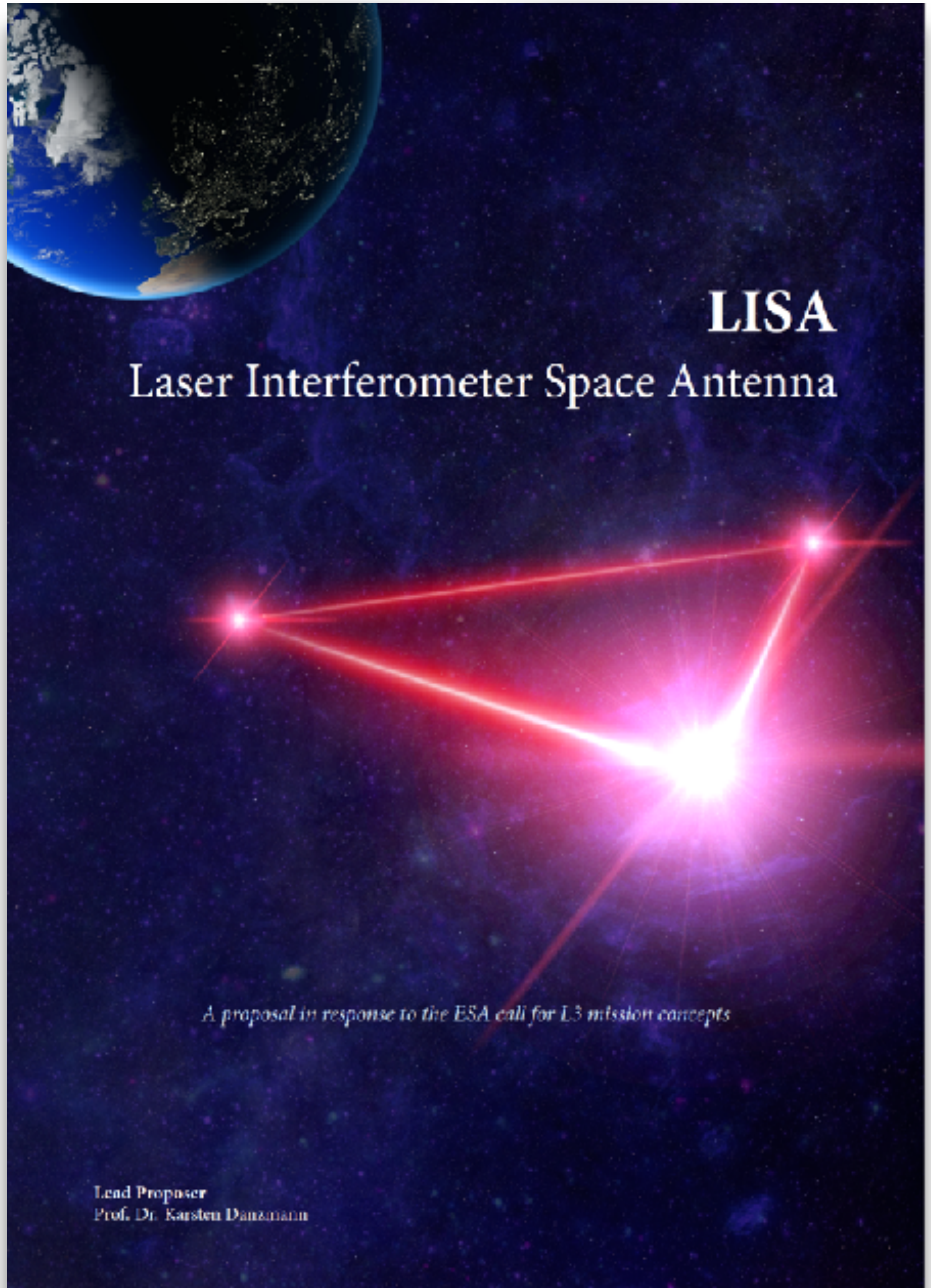
Armano et al, PRL 116, 231101 (2016)

LISA chronology

- 1980s - 2011: joint NASA/ESA proposal
- 2011: NASA withdraws, ESA continues with descoped mission NGO (two arms)
- 2012: ESA selects JUICE for L1
- 2013: ESA selects LISA scientific theme for L3: “the gravitational universe”
- 2013 - 2016: studies of different configurations and refinement of the scientific case
- 25/10/2016: ESA call for mission
- 13/01/2017: LISA Consortium submits the LISA proposal (3 arms), approved!
- 3/2017 - fall 2017: ESA Phase 0 study
- fall 2017 - 2019: ESA Phase A study
- 2019 - 2020: preparation of industrial implementation
- 2020 - 2021: ESA mission adoption
- 8.5 years: mission construction
- around 2030: launch (Ariane 6)
- nominal mission duration 4 years, tested extension up to 10 years
- cost: 1050 M€

LISA proposal

https://www.elisascience.org/files/publications/LISA_L3_20170120.pdf

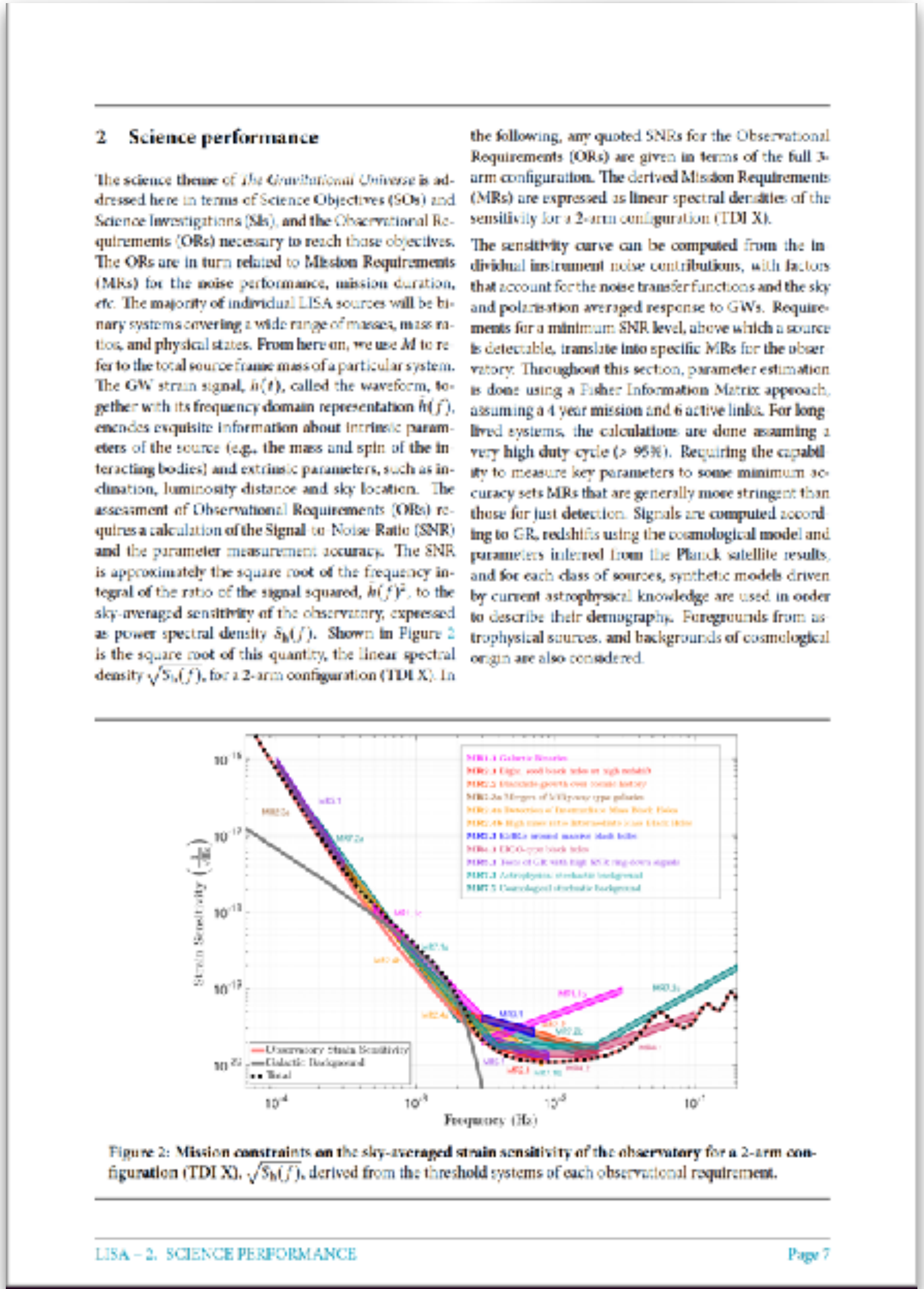


LISA

Laser Interferometer Space Antenna

A proposal in response to the ESA call for L3 mission concepts

Lead Proposer
Prof. Dr. Karsten Danzmann



2 Science performance

The science theme of *The Gravitational Universe* is addressed here in terms of Science Objectives (SOs) and Science Investigations (SIs), and the Observational Requirements (ORs) necessary to reach those objectives. The ORs are in turn related to Mission Requirements (MRs) for the noise performance, mission duration, *etc.* The majority of individual LISA sources will be binary systems covering a wide range of masses, mass ratios, and physical states. From here on, we use M to refer to the total source frame mass of a particular system. The GW strain signal, $h(t)$, called the waveform, together with its frequency domain representation $\tilde{h}(f)$, encodes exquisite information about intrinsic parameters of the source (e.g., the mass and spin of the interacting bodies) and extrinsic parameters, such as inclination, luminosity distance and sky location. The assessment of Observational Requirements (ORs) requires a calculation of the Signal to Noise Ratio (SNR) and the parameter measurement accuracy. The SNR is approximately the square root of the frequency integral of the ratio of the signal squared, $\tilde{h}(f)^2$, to the sky-averaged sensitivity of the observatory, expressed as power spectral density $S_h(f)$. Shown in Figure 2 is the square root of this quantity, the linear spectral density $\sqrt{S_h(f)}$, for a 2-arm configuration (TDI X). In the following, any quoted SNRs for the Observational Requirements (ORs) are given in terms of the full 3-arm configuration. The derived Mission Requirements (MRs) are expressed as linear spectral densities of the sensitivity for a 2-arm configuration (TDI X).

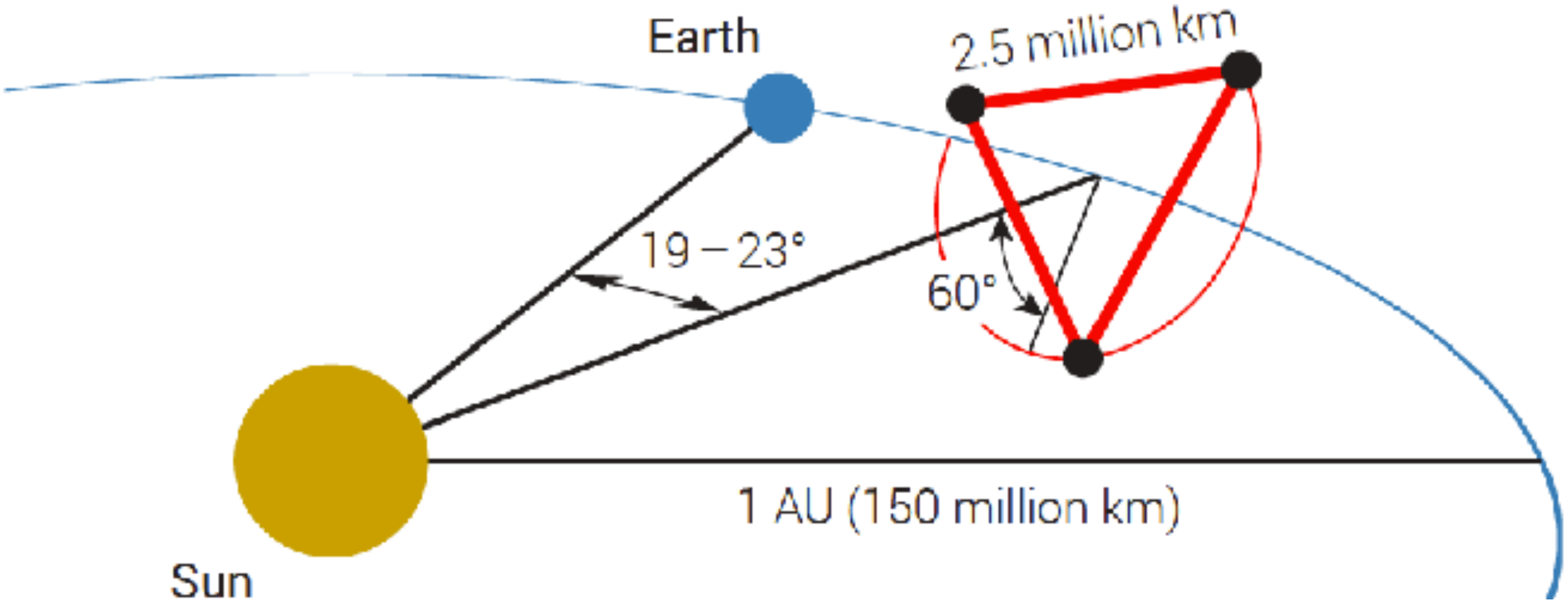
The sensitivity curve can be computed from the individual instrument noise contributions, with factors that account for the noise transfer functions and the sky and polarisation averaged response to GWs. Requirements for a minimum SNR level, above which a source is detectable, translate into specific MRs for the observatory. Throughout this section, parameter estimation is done using a Fisher Information Matrix approach, assuming a 4 year mission and 6 active links. For long lived systems, the calculations are done assuming a very high duty cycle (> 95%). Requiring the capability to measure key parameters to some minimum accuracy sets MRs that are generally more stringent than those for just detection. Signals are computed according to GR, redshifts using the cosmological model and parameters inferred from the Planck satellite results, and for each class of sources, synthetic models driven by current astrophysical knowledge are used in order to describe their demography. Foregrounds from astrophysical sources, and backgrounds of cosmological origin are also considered.

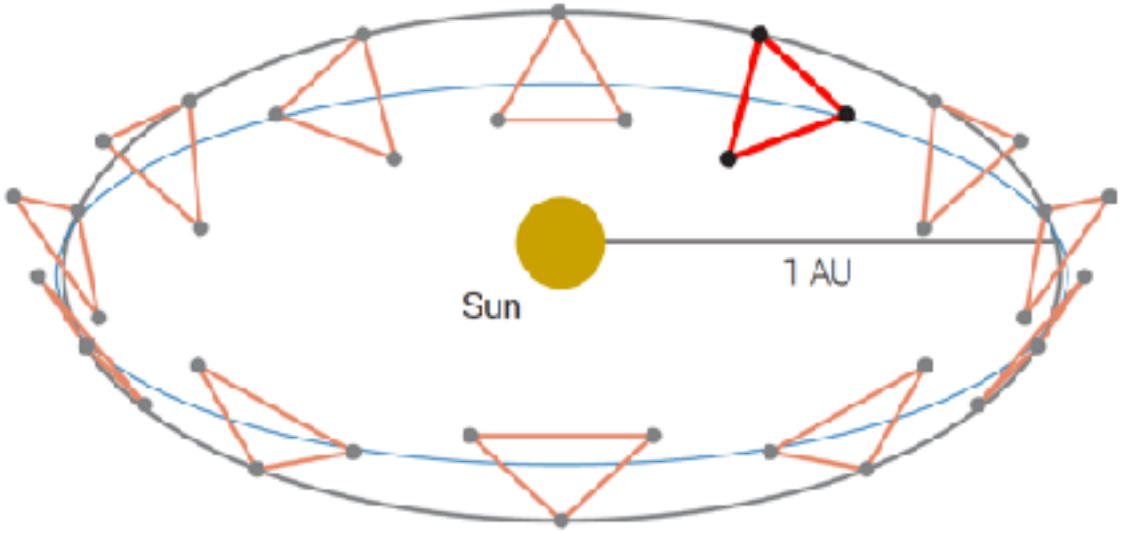
Figure 2: Mission constraints on the sky-averaged strain sensitivity of the observatory for a 2-arm configuration (TDI X), $\sqrt{S_h(f)}$, derived from the threshold systems of each observational requirement.

LISA – 2. SCIENCE PERFORMANCE Page 7

LISA configuration

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





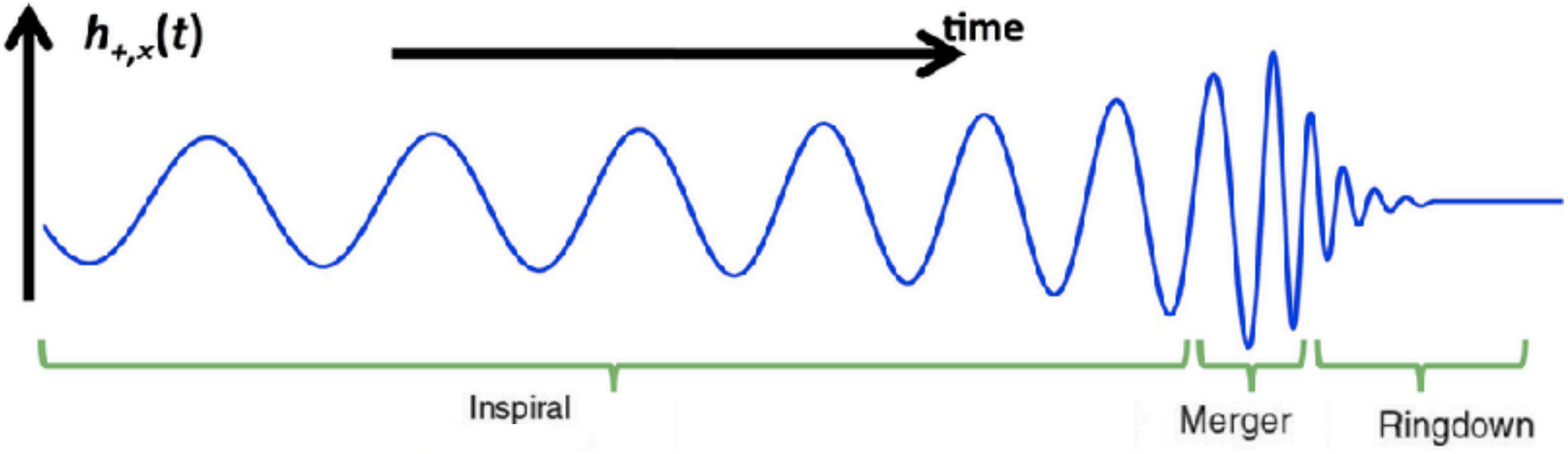
it is a survey instrument: no pointing
continuous sky observation
best angular resolution for high SNR sources: $1\mathrm{deg}^2$

What LISA measures

1. The gravitational wave strain from the inspiral and merger of compact binaries : it encodes information on the binary parameters

$$h(t) \sim 2\,\frac{\Delta L}{L} \qquad \mathcal{M}_c,\ d_L,\ t_c,\ \eta,\ \Phi_c,\ \phi$$

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

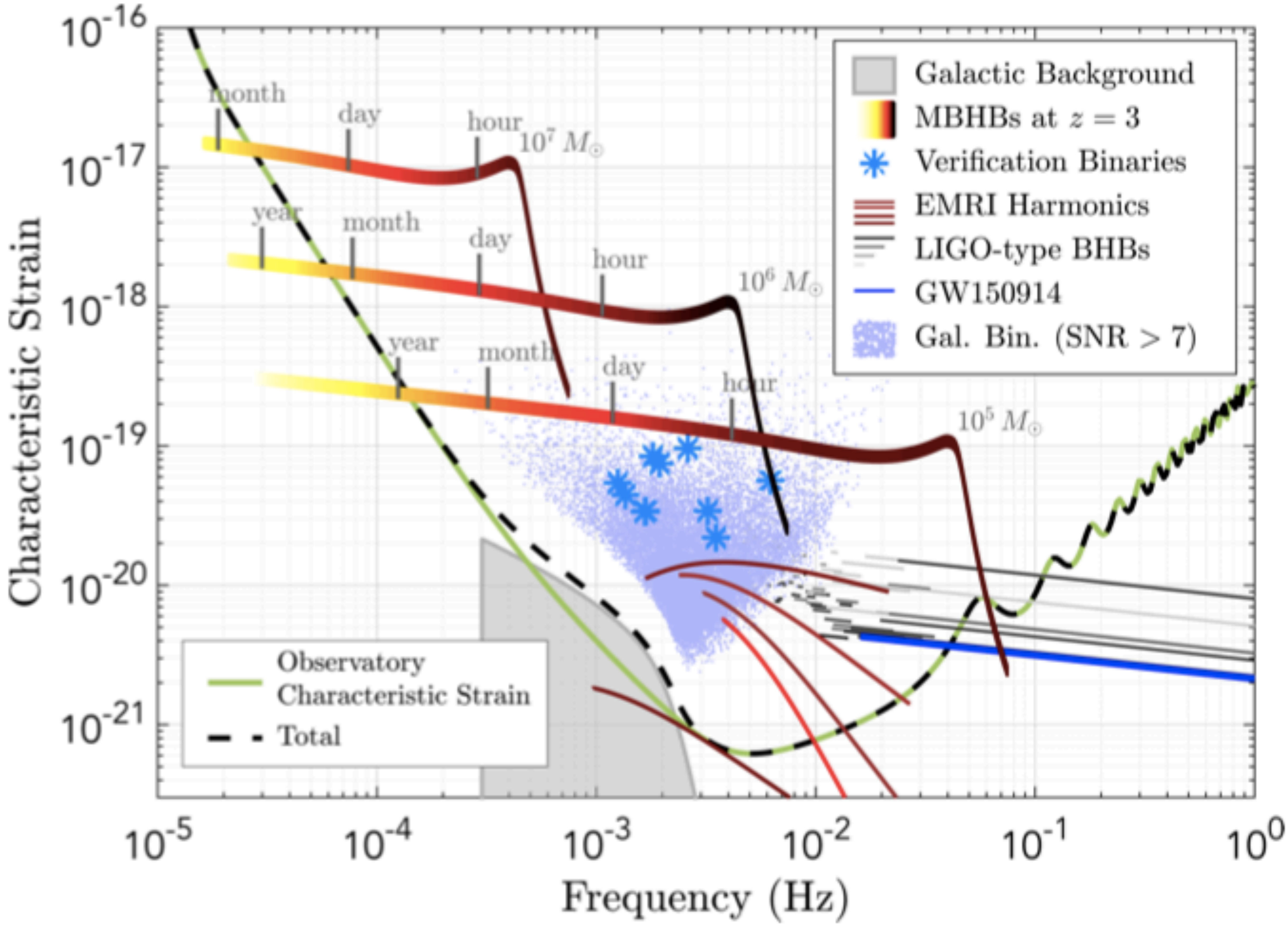
the superposition of sources that cannot be resolved individually

- binaries too numerous and with too low SNR to be identified
- signals from the early universe with too small correlation scale 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 AND COSMOLOGY:

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

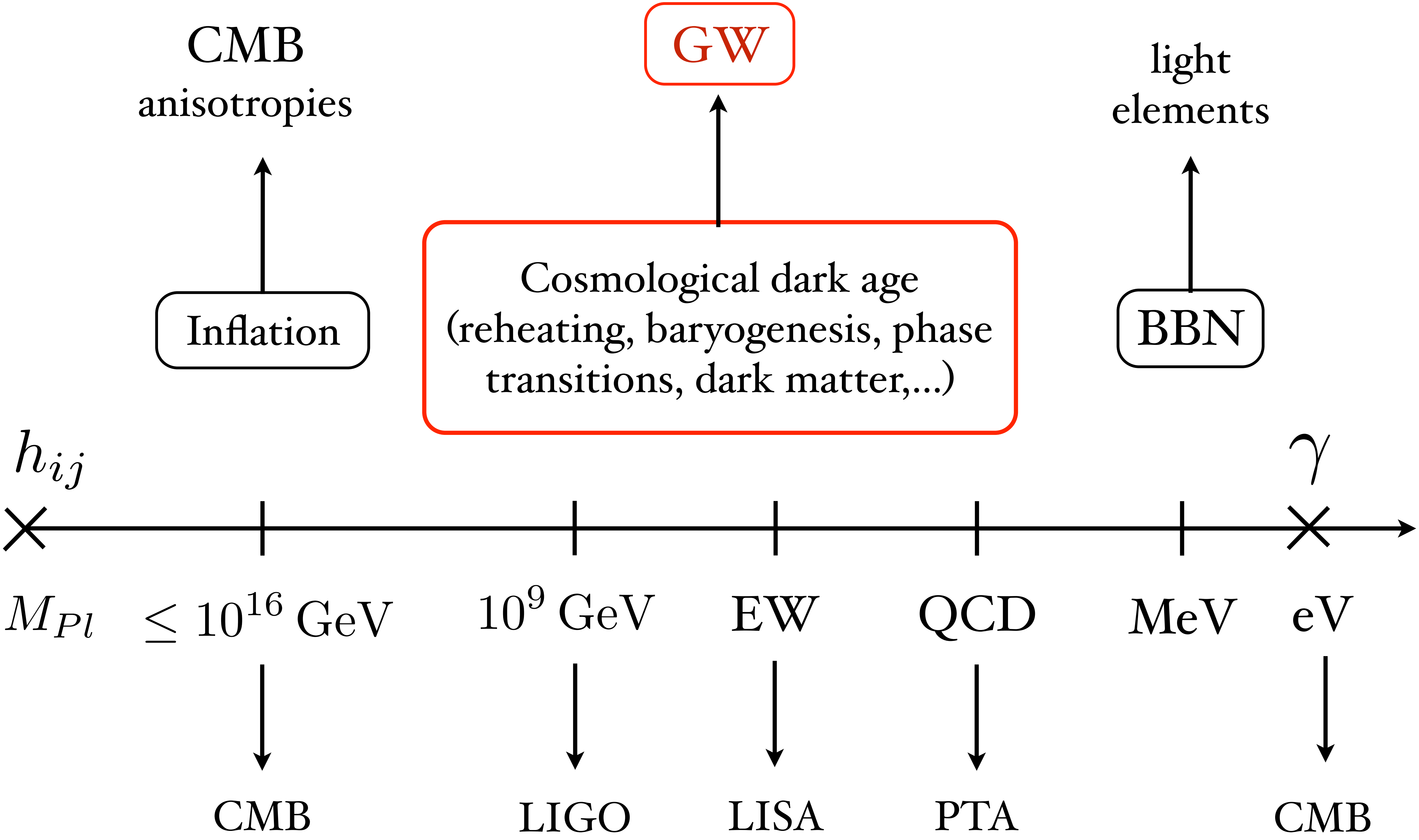
use of GW emission from binaries to probe the background expansion of the universe : test of acceleration

LISA AND COSMOLOGY:

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

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

because of the weakness of the gravitational interaction the universe is transparent to GW



CMB anisotropies

GW

light elements

Inflation

Cosmological dark age (reheating, baryogenesis, phase transitions, dark matter,...)

BBN

h_{ij}

γ

M_{Pl}

$\leq 10^{16}$ GeV

10^9 GeV

EW

QCD

MeV

eV

CMB

LIGO

LISA

PTA

CMB

Characteristic frequency for *causal sources*

$$f_* = \frac{H(T_*)}{\epsilon_*}$$

Hubble factor at GW production

parameter depending on the
dynamics of the source

$$\epsilon_* \leq 1$$

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assuming standard thermal history and radiation era:

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

characteristic frequency today

temperature (energy density) of the universe at the source time

Characteristic frequency for *causal sources*

$$f_* = \frac{H(T_*)}{\epsilon_*}$$

Hubble factor at GW production

parameter depending on the dynamics of the source

$$\epsilon_* \leq 1$$

assuming standard thermal history and radiation era:

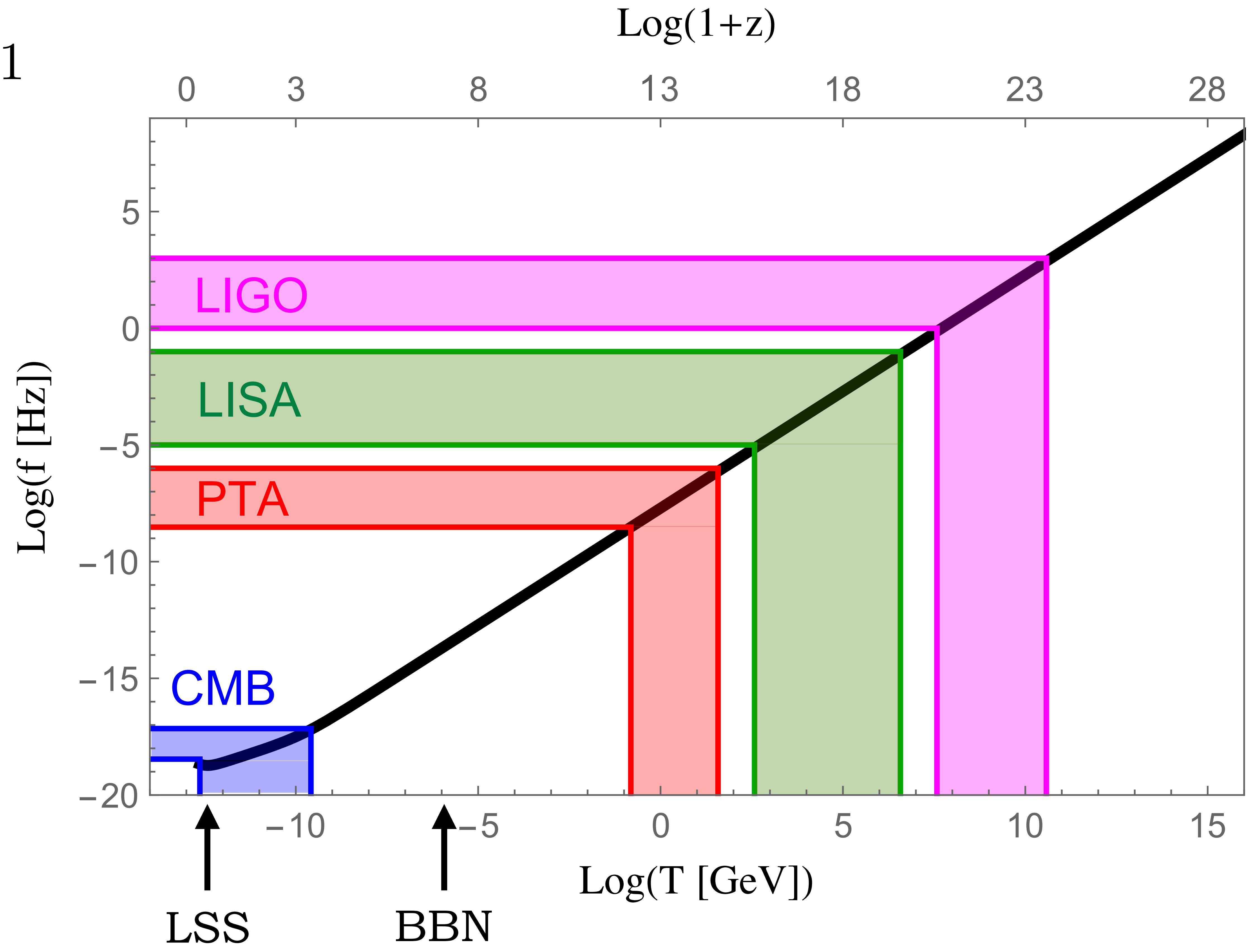
$$f_c = f_* \frac{a_*}{a_0} = \frac{2 \cdot 10^{-5}}{\epsilon_*} \frac{T_*}{1\,\mathrm{TeV}}\,\mathrm{Hz}$$

$$\epsilon_* \simeq 10^{-2} \qquad T_* \simeq 1\,\mathrm{TeV} \qquad \Rightarrow \qquad f_c \simeq \mathrm{mHz}$$

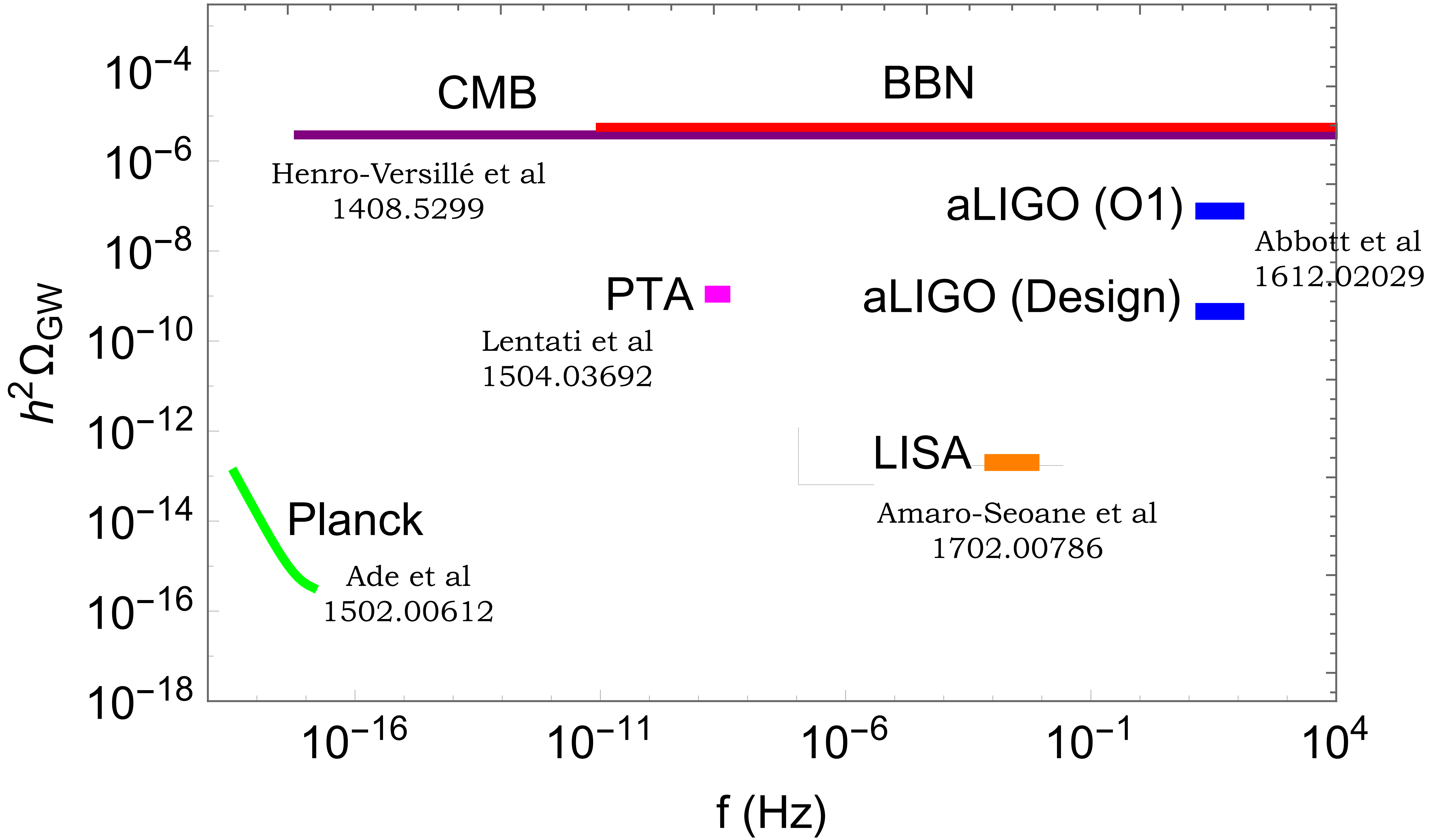
LISA!

Characteristic frequency for *causal sources*

$\epsilon_* = 1$



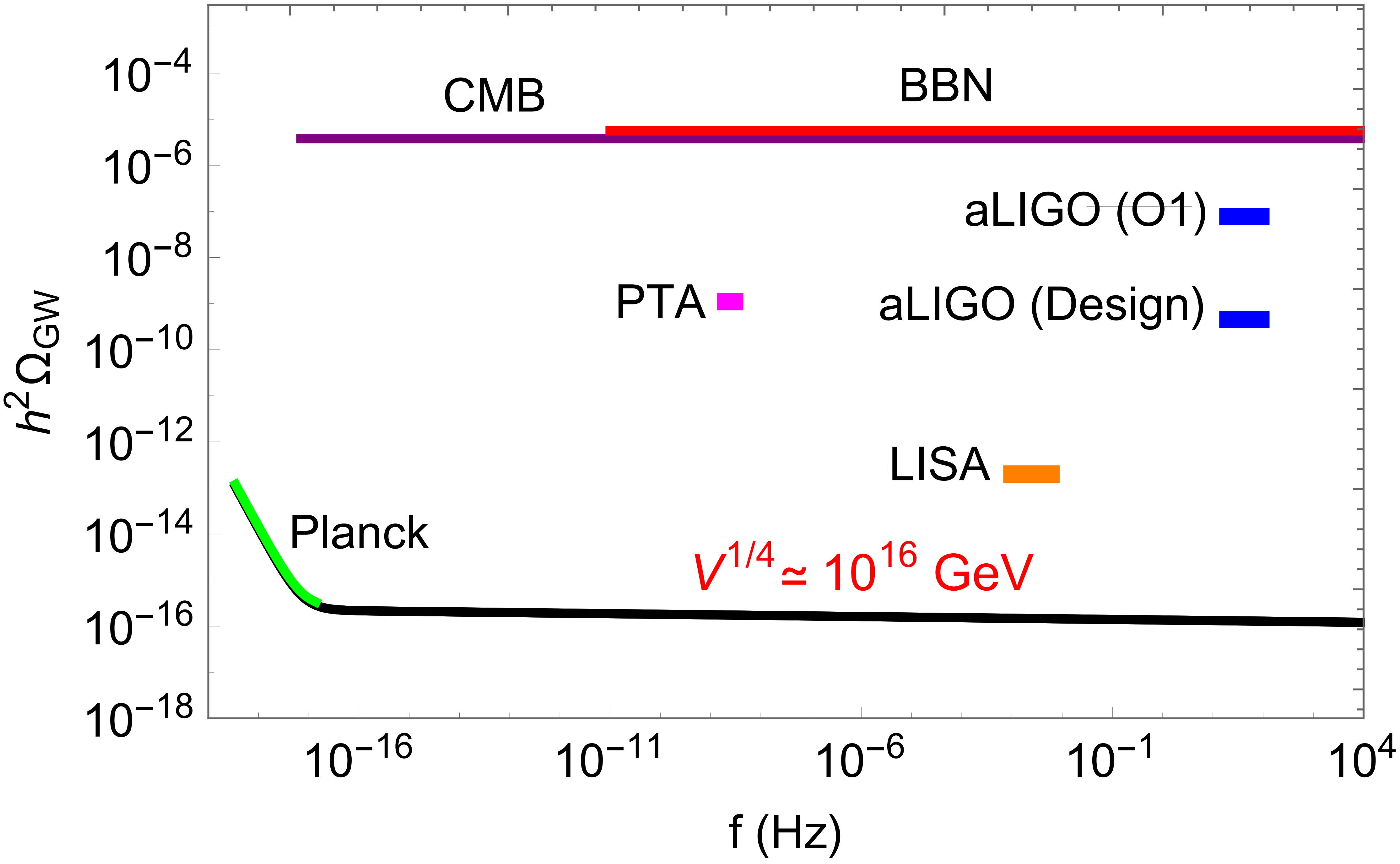
Observational bounds/sensitivities for SGWB



amplification of vacuum
fluctuations during inflation

$$\ddot{h}_{ij} + 3H\,\dot{h}_{ij} + k^2\,h_{ij} = 0$$

signal from a *simple slow roll inflation model* :
beyond the reach of direct detection



other possible sources of GW in the early universe more promising for direct detection (with future interferometers or PTA):

mechanisms that produce a non-zero tensor anisotropic stress

$$\ddot{h}_{ij} + 3H\,\dot{h}_{ij} + k^2\,h_{ij} = \boxed{16\pi G\,\Pi_{ij}^{TT}}$$

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$$\ddot{h}_{ij} + 3H\,\dot{h}_{ij} + k^2\,h_{ij} = \boxed{16\pi G\,\Pi_{ij}^{TT}}$$

but which amplitude is needed for detection ?

<u>considerable amount of energy (in some anisotropic form) is needed to generate a detectable signal</u>

Possible GW sources in the early universe

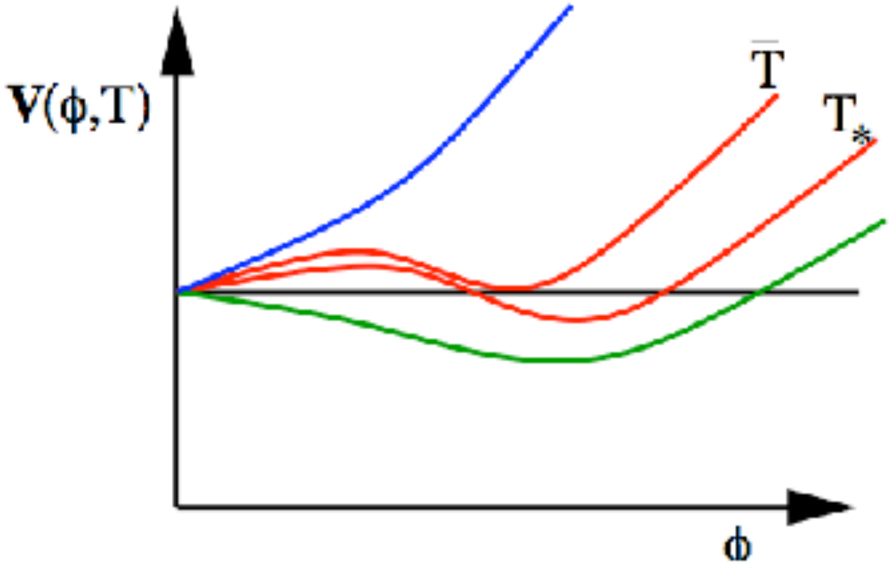
- "non-standard" inflation
  - particle production during inflation
  - fluid stiffer than radiation after inflation
  - preheating after inflation
  - phase transitions at the end or during inflation
  - …
- first order phase transitions
- cosmic strings
- other topological defects e.g. domain walls
- primordial black holes
- scalar field self-ordering
- …

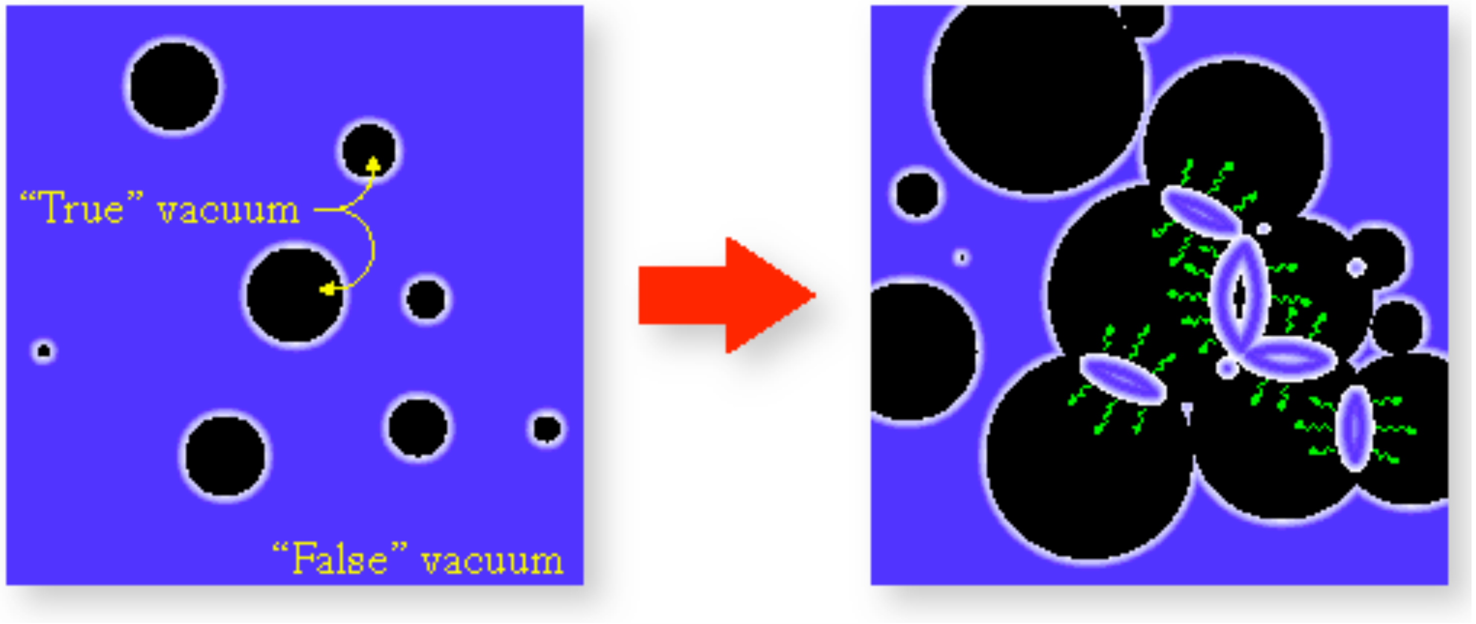
First order phase transitions

universe expands and temperature decreases : PTs, if first order lead to GW

potential barrier separates
true and false vacua

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

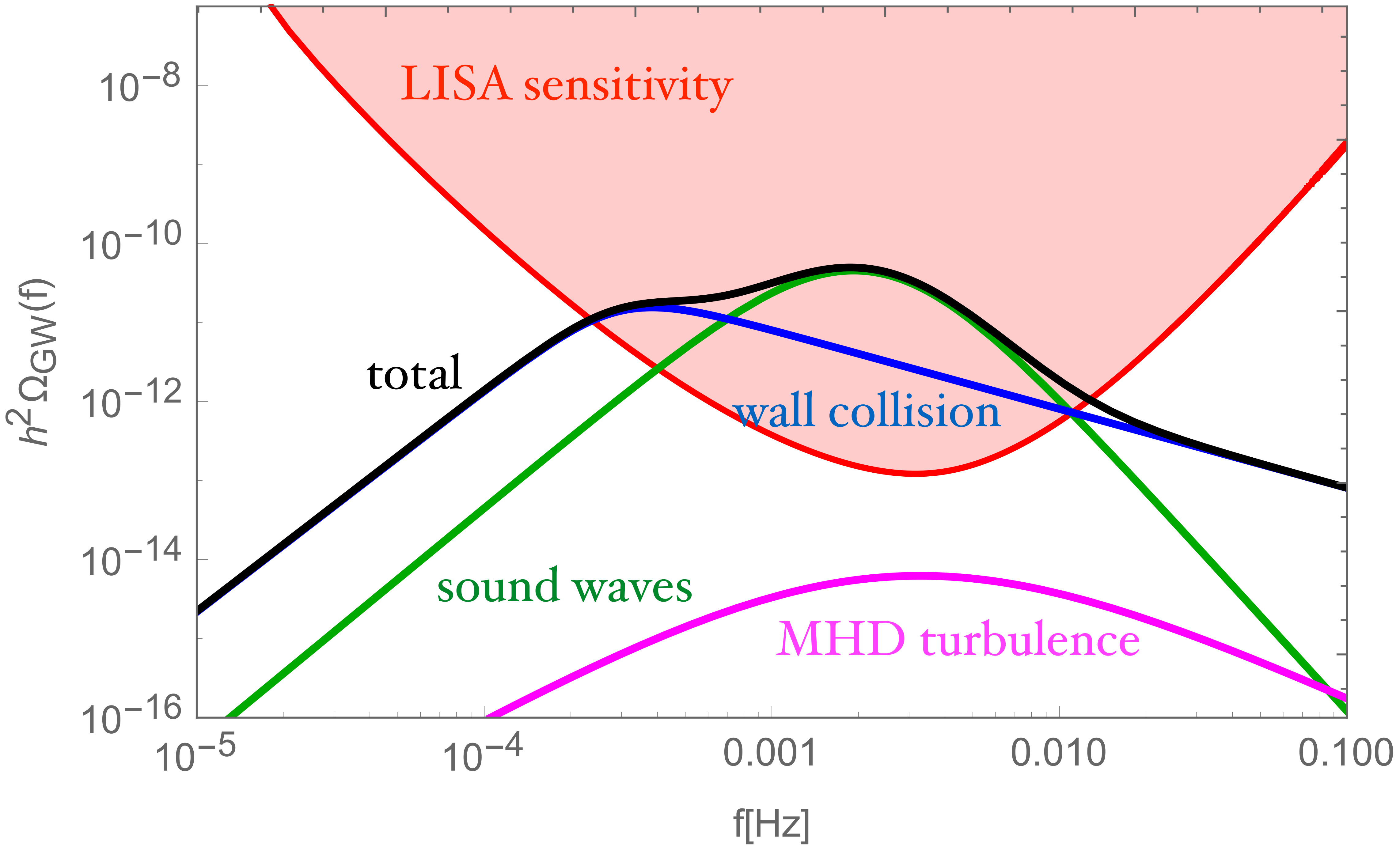




source: Π_{ij} tensor
anisotropic stress

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

Example of signal



temperature of the PT : 100 GeV

duration of the PT : 0.01 1/H

strength of the PT : $\rho_{\text{vac}} = \rho_{\text{rad}}$

CC et al, arXiv:1512.06239

Detection prospects for LISA

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

- LISA can probe the EWPT in BSM models …
  - singlet extensions of MSSM (Huber et al 2015)
  - direct coupling of Higgs sector with scalars (Kozackuz et al 2013)
  - SM plus dimension six operator (Grojean et al 2004)

- … and beyond the EWPT
  - Dark Matter sector : provides DM candidate and confining PT (Schwaller 2015)
  - Warped extra dimensions : PT from the dilaton/radion stabilisation in RS-like models (Randall and Servant 2015)

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

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Example of detection prospects for LISA

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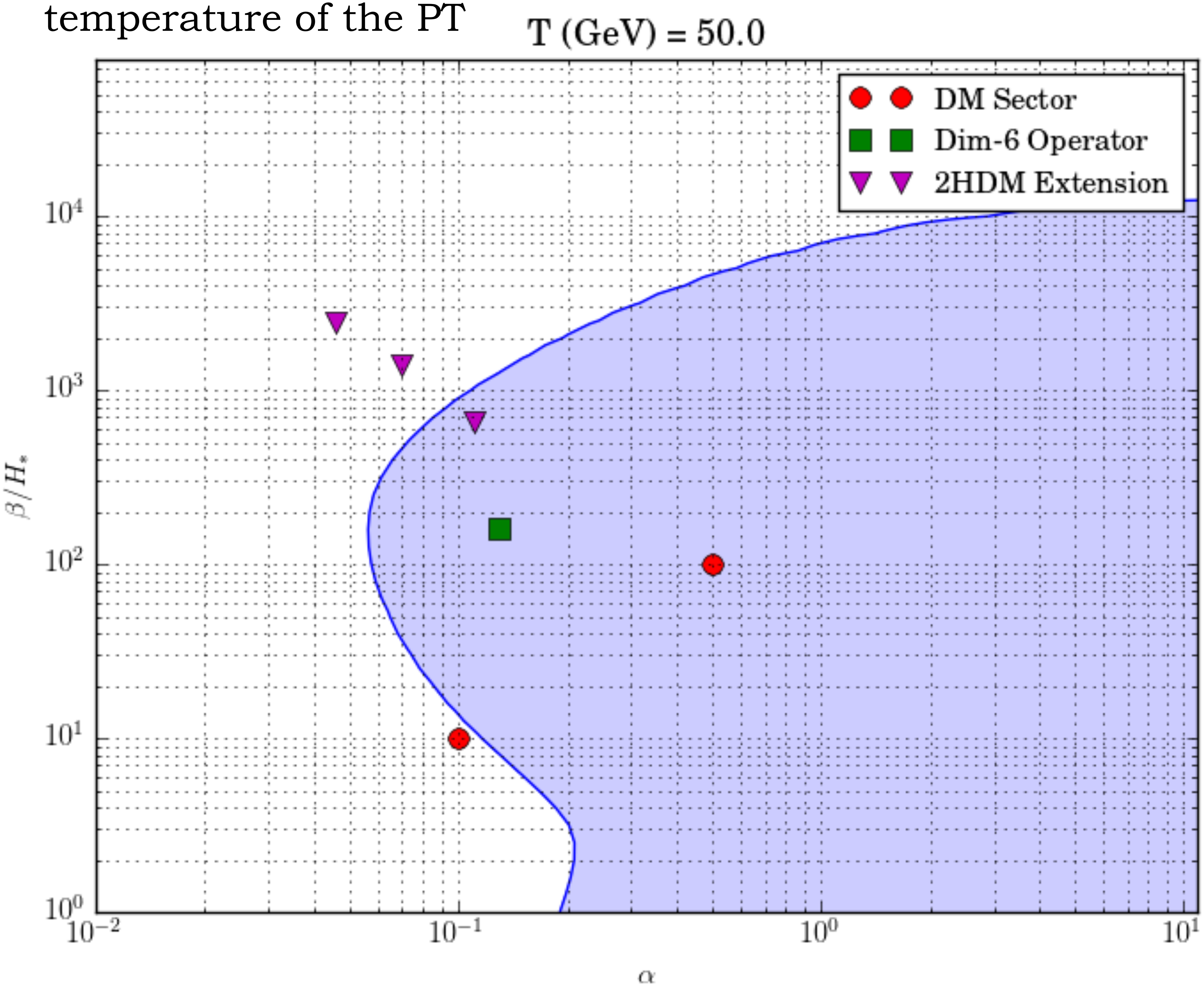
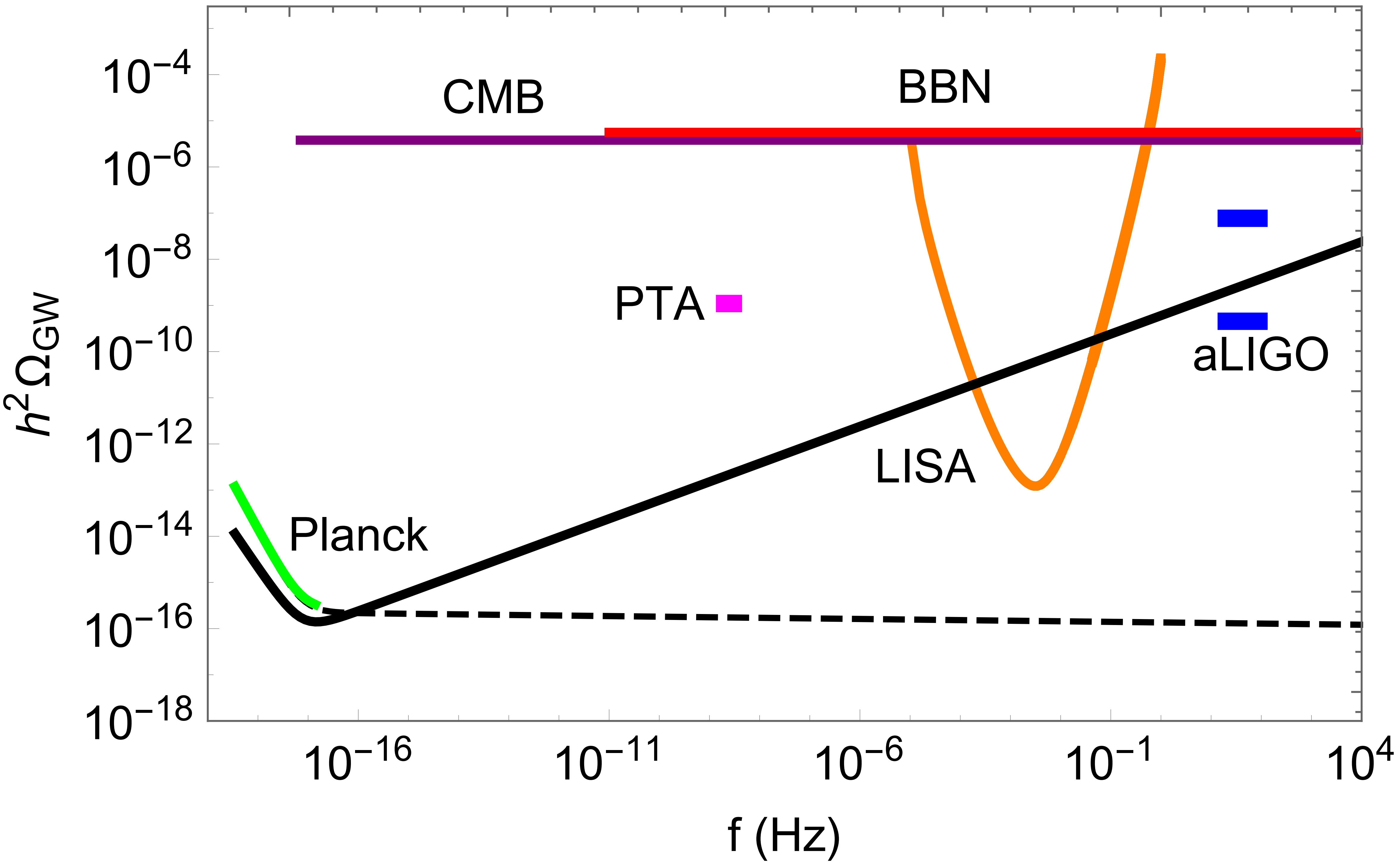


inverse duration of the PT with respect to Hubble time

(ϵ_*)

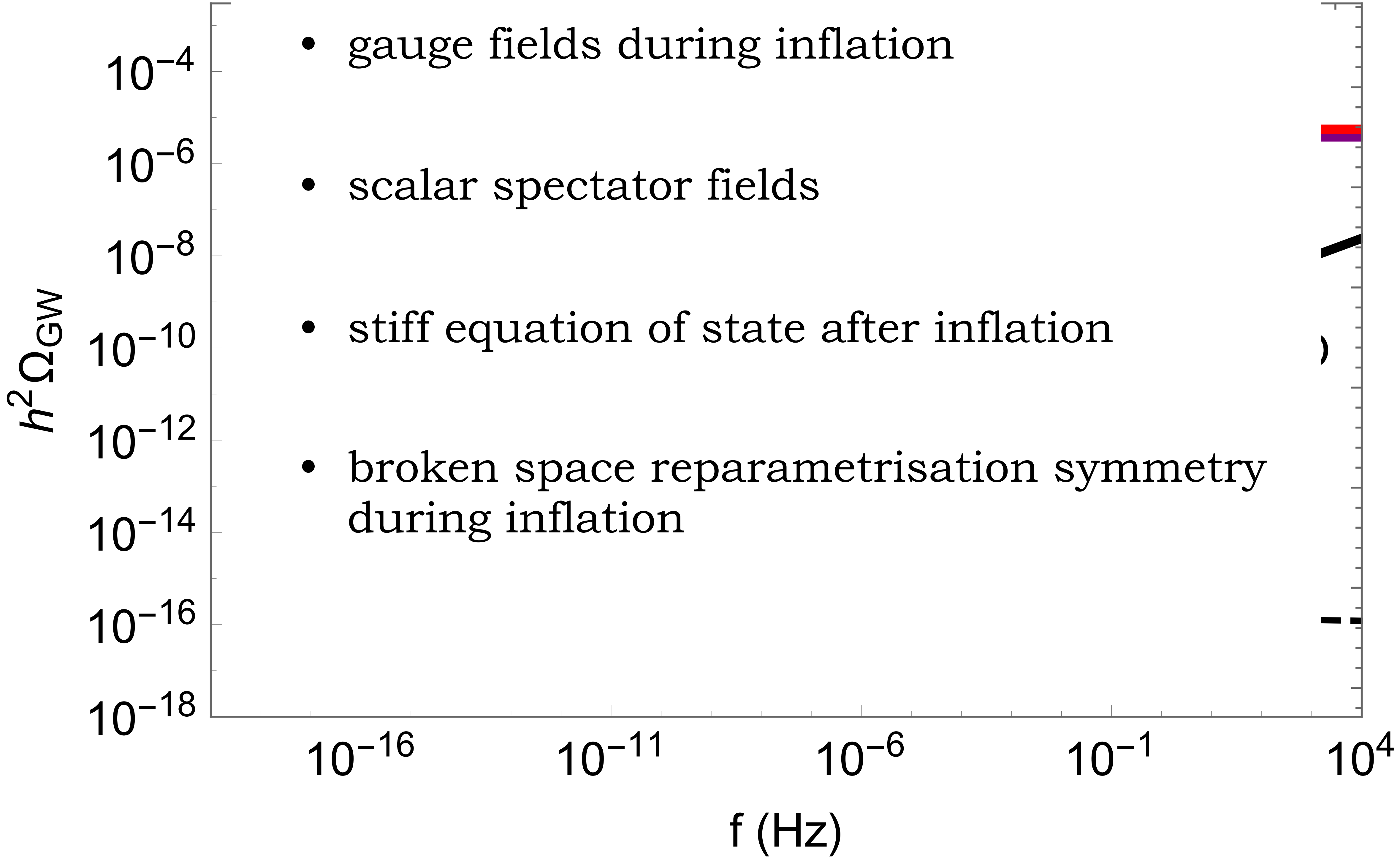
strength of the PT

“Non-standard inflation”



“Non-standard inflation”

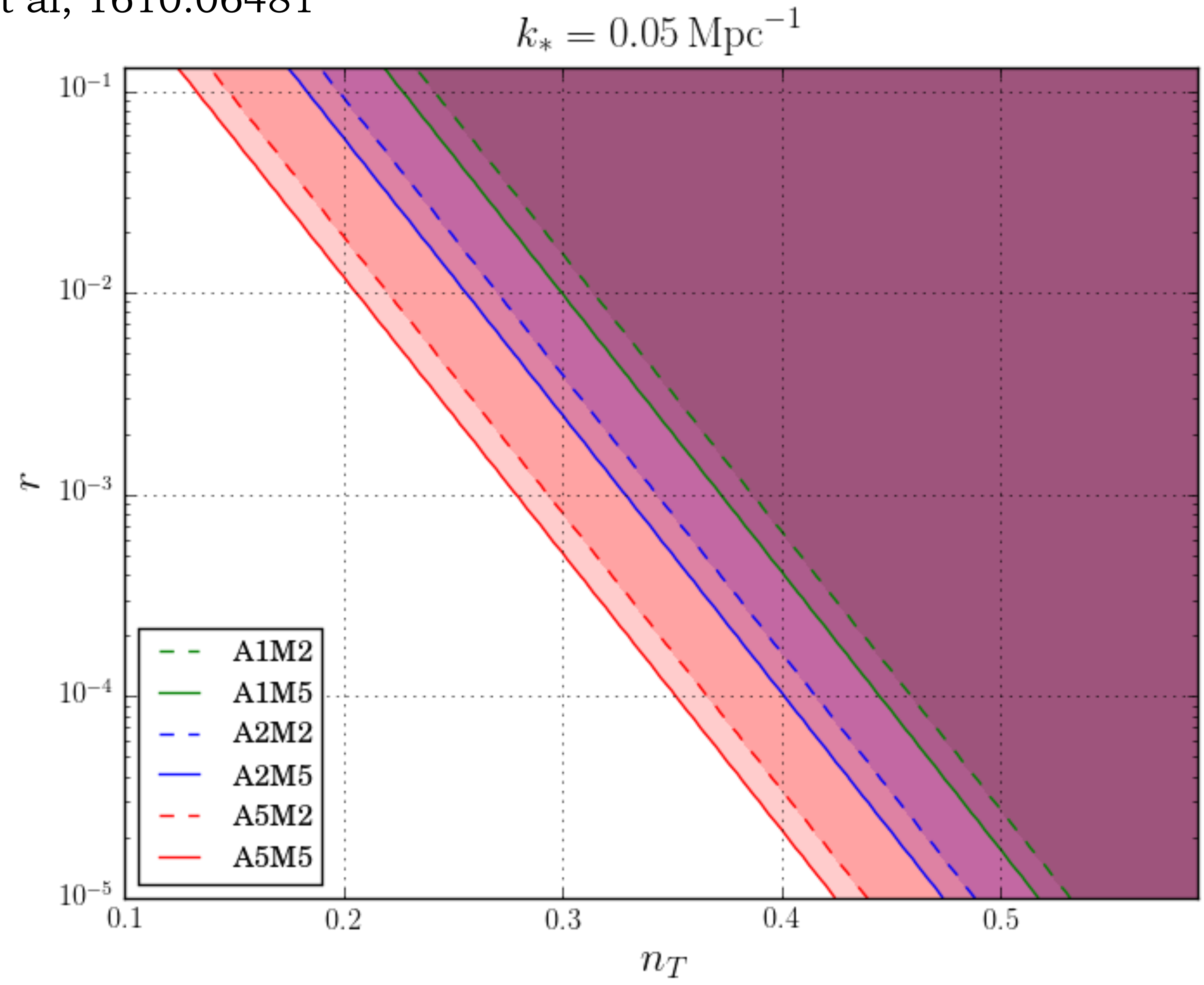
N. Bartolo et al, 1610.06481



- gauge fields during inflation
- scalar spectator fields
- stiff equation of state after inflation
- broken space reparametrisation symmetry during inflation

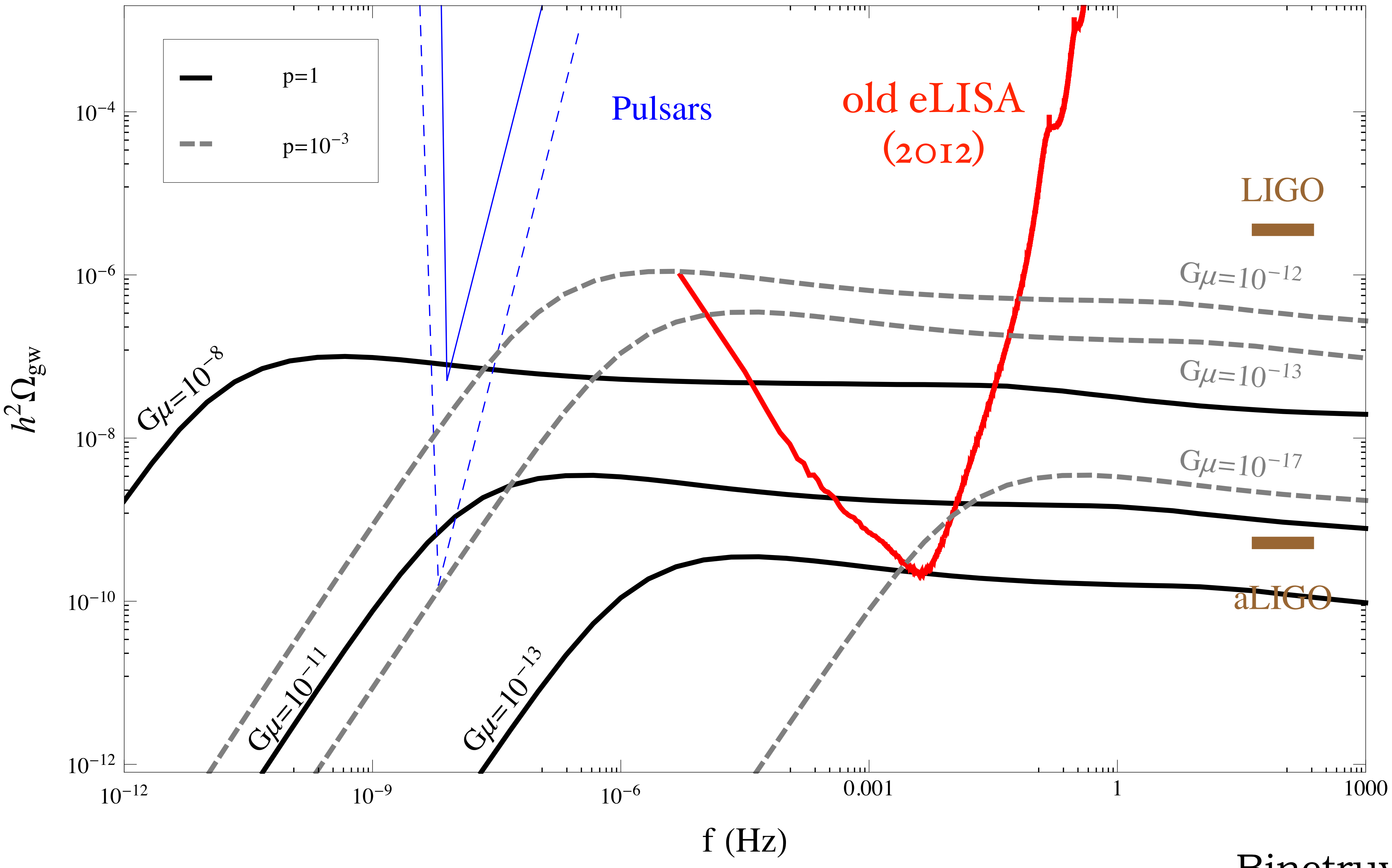
“Non-standard inflation”

N. Bartolo et al, 1610.06481



GW background from cosmic strings

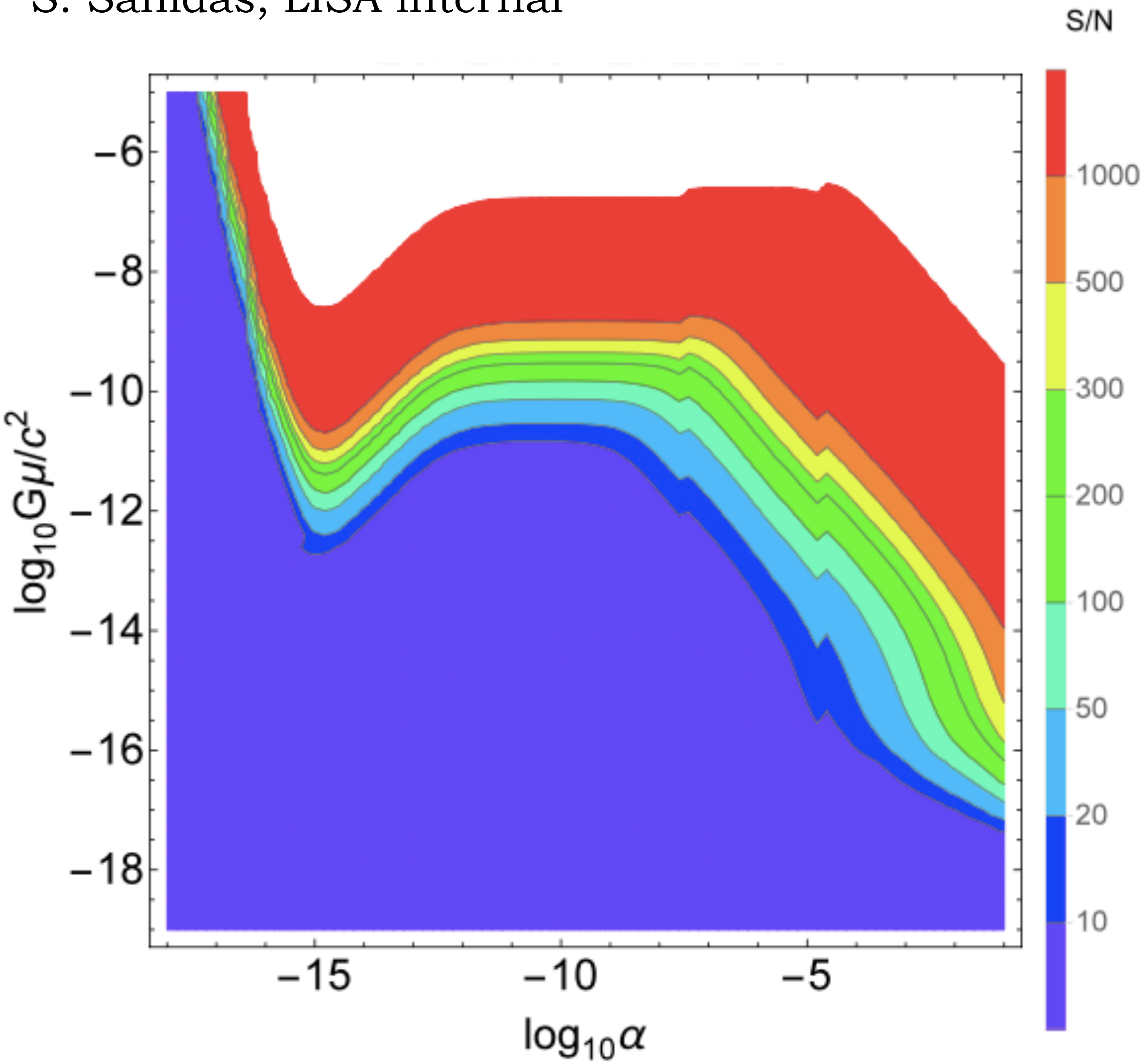
- model dependent GW signal : here Nambu Goto with large loops
- spectral shape extended in frequency because of continuous production



Binetruy et al 2012

LISA bounds on Nambu-Goto strings, loop size

S. Sanidas, LISA internal



Current
NanoGRAV

$G\mu < 1.3 \cdot 10^{-10}$

future
CMB B-modes

$G\mu < 10^{-9}$

Future SKA

$G\mu < 10^{-13}$

Janssen et al 2015

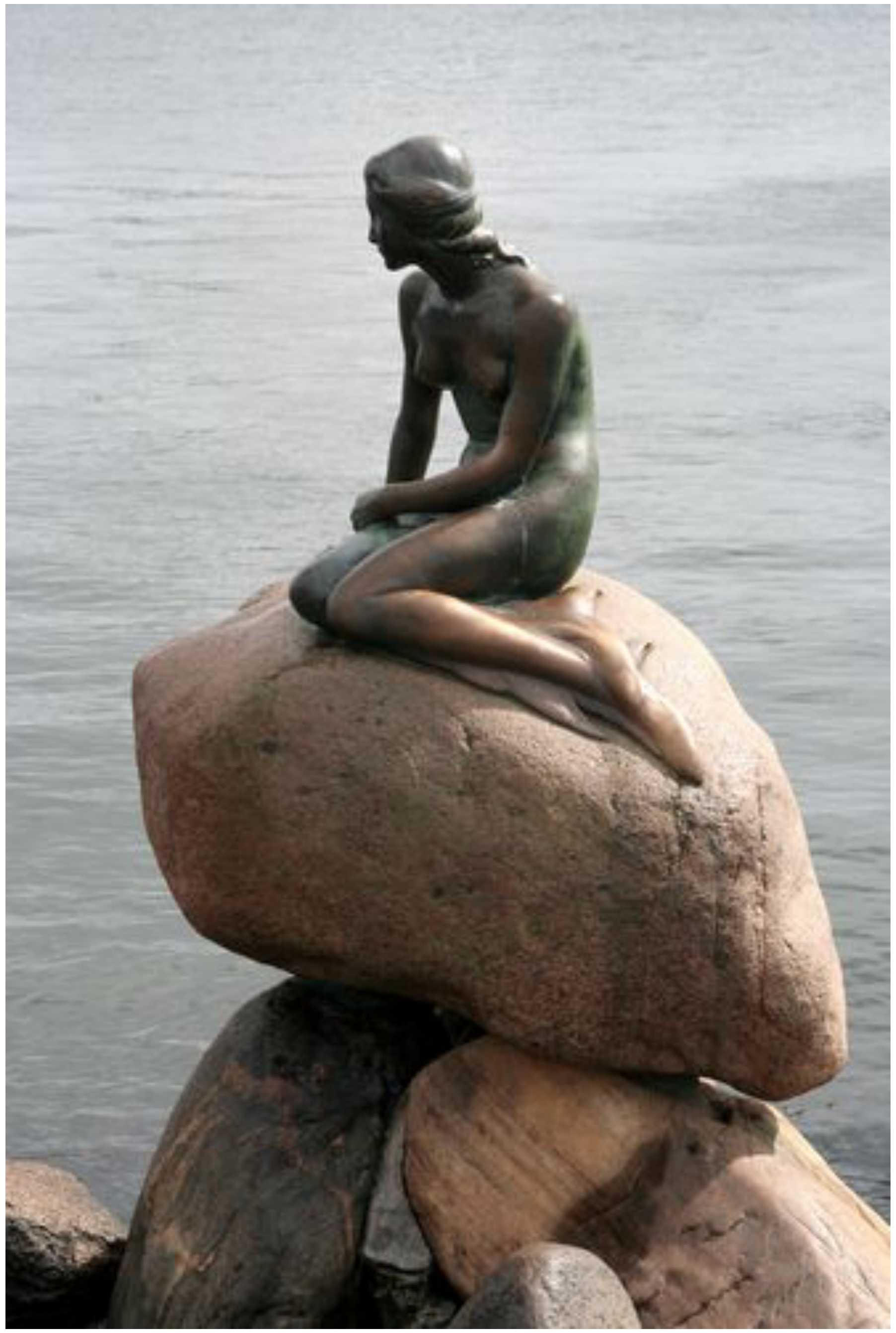
LISA AND COSMOLOGY:

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

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

Standard sirens

GW emission by massive black hole binaries can be used as SuperNovae Ia (standard candles) to test the content 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

$$d_L(H_0, \Omega_\Lambda, \Omega_M, w_0, w_a)$$

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no distance ladder

c

ass

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

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no distance ladder

c

but no redshift either!

ass

$$d_L(H_0, \Omega_\Lambda, \Omega_M, w_0, w_a)$$

Standard sirens

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

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

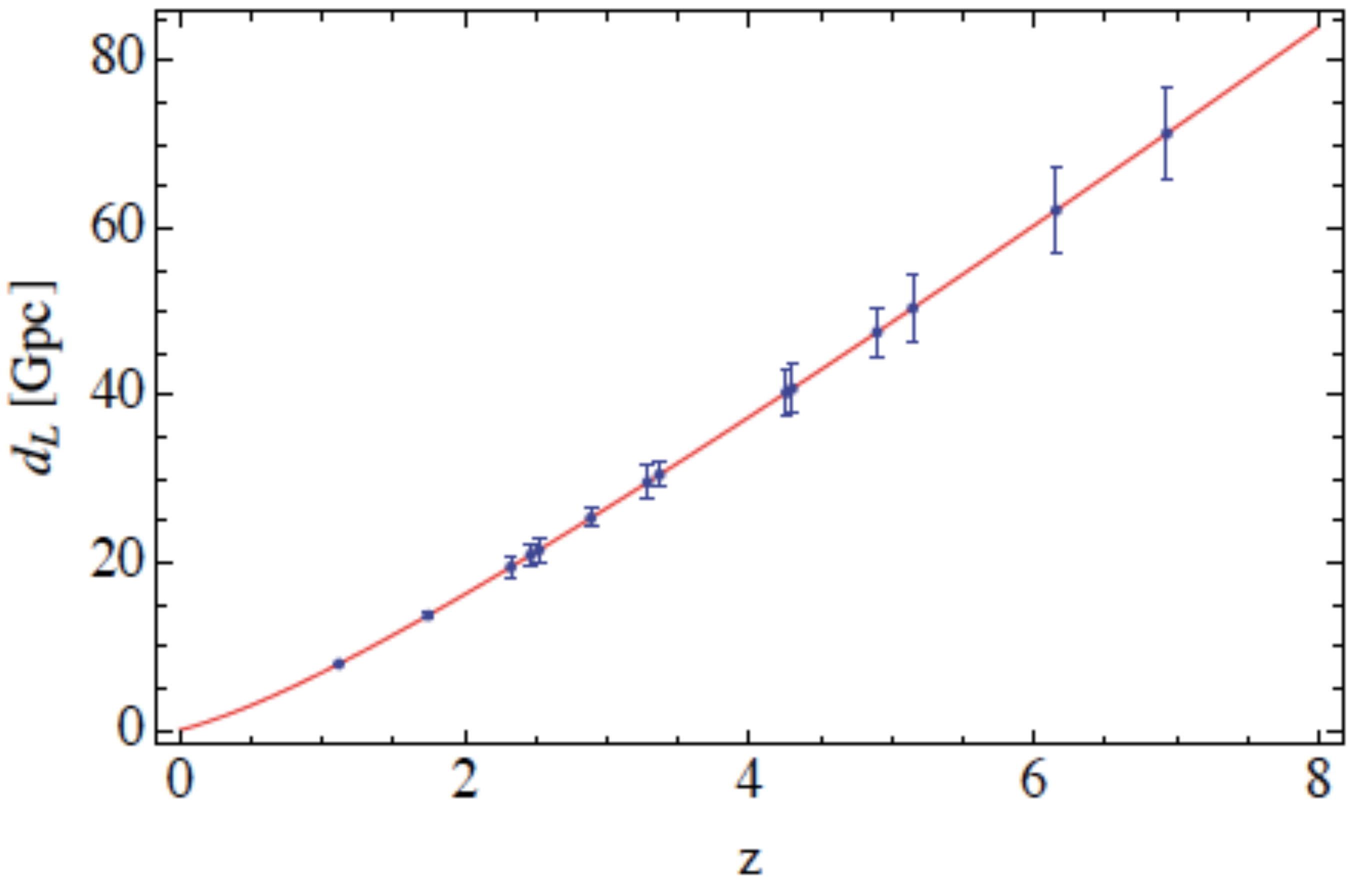
redshifted chirp mass

Analogous to SNIa, but :

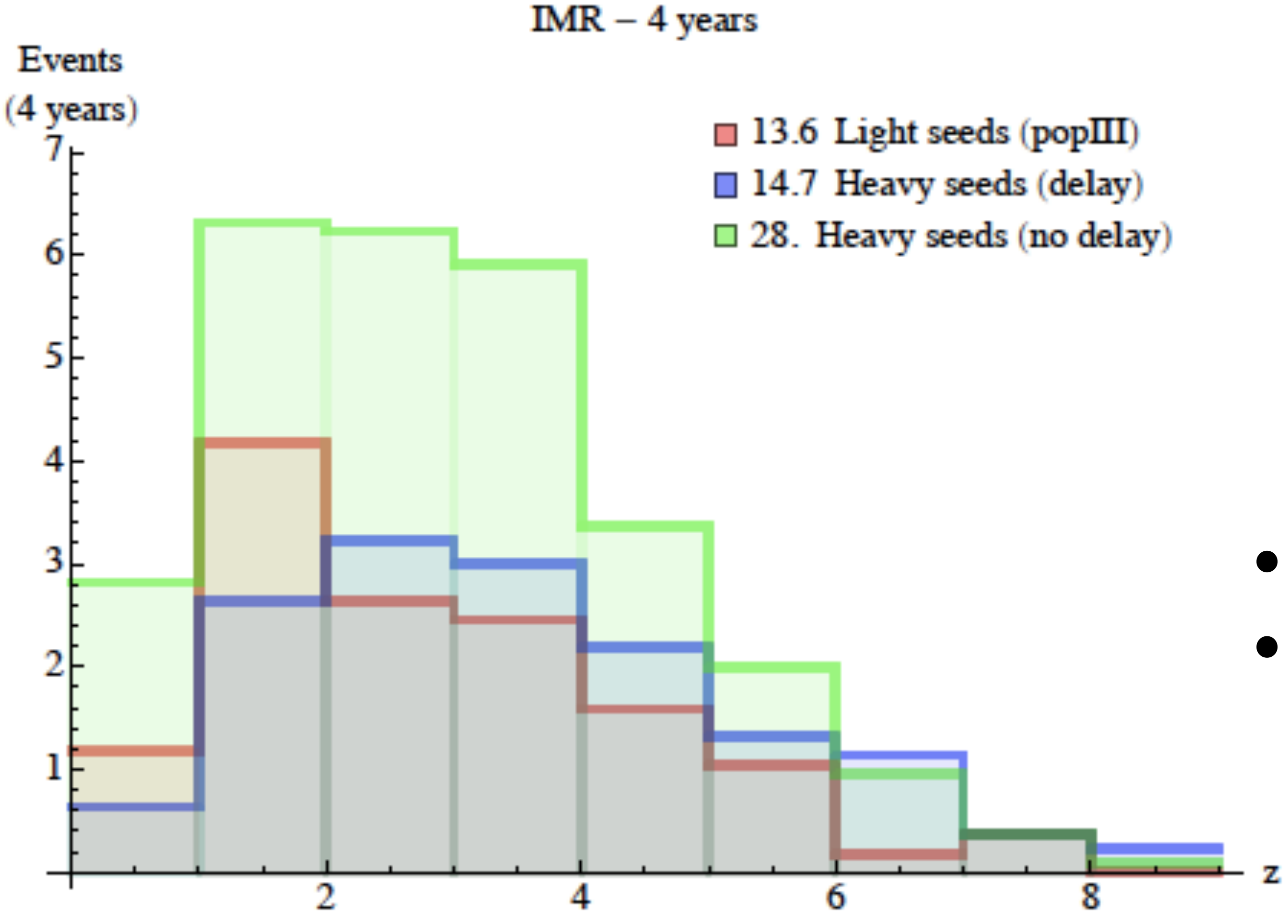
- direct measurement of d_L up to large redshift with GW - good
- needs an independent (optical) measurement of the redshift - bad

standard sirens with LISA: MBHB coalescence

N. Tamanini et al arXiv:1601.07112



example of simulated data
with counterparts
(SKA+EELT)
and weak lensing errors



VERY FEW EVENTS AT
LOW REDSHIFT !

- where needed to probe DE (bad)
- can test expansion at high redshift (good)

standard sirens with LISA: MBHB coalescence

ΛCDM

most optimistic scenario for BBH formation gives an independent measurement of the Hubble parameter to 1%

LISA alone :

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

Planck alone :

$$\Omega_M = 0.308 \pm 0.0012$$
$$h = 0.678 \pm 0.009$$

LISA fixing Ω_M :

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

- fully independent constraint
- 0.6% in best case

standard sirens with LISA: MBHB coalescence

Dynamical Dark Energy

too few events at low redshift to get a good measurement

$$w_0 = -1 \pm [0.3,\ 0.1]$$
$$w_a = 0 \pm [1.5,\ 0.8]$$

Euclid forecast :

$$\Delta w_0 = 0.02$$
$$\Delta w_a = 0.1$$

standard sirens with LISA: MBHB coalescence

Dynamical Dark Energy

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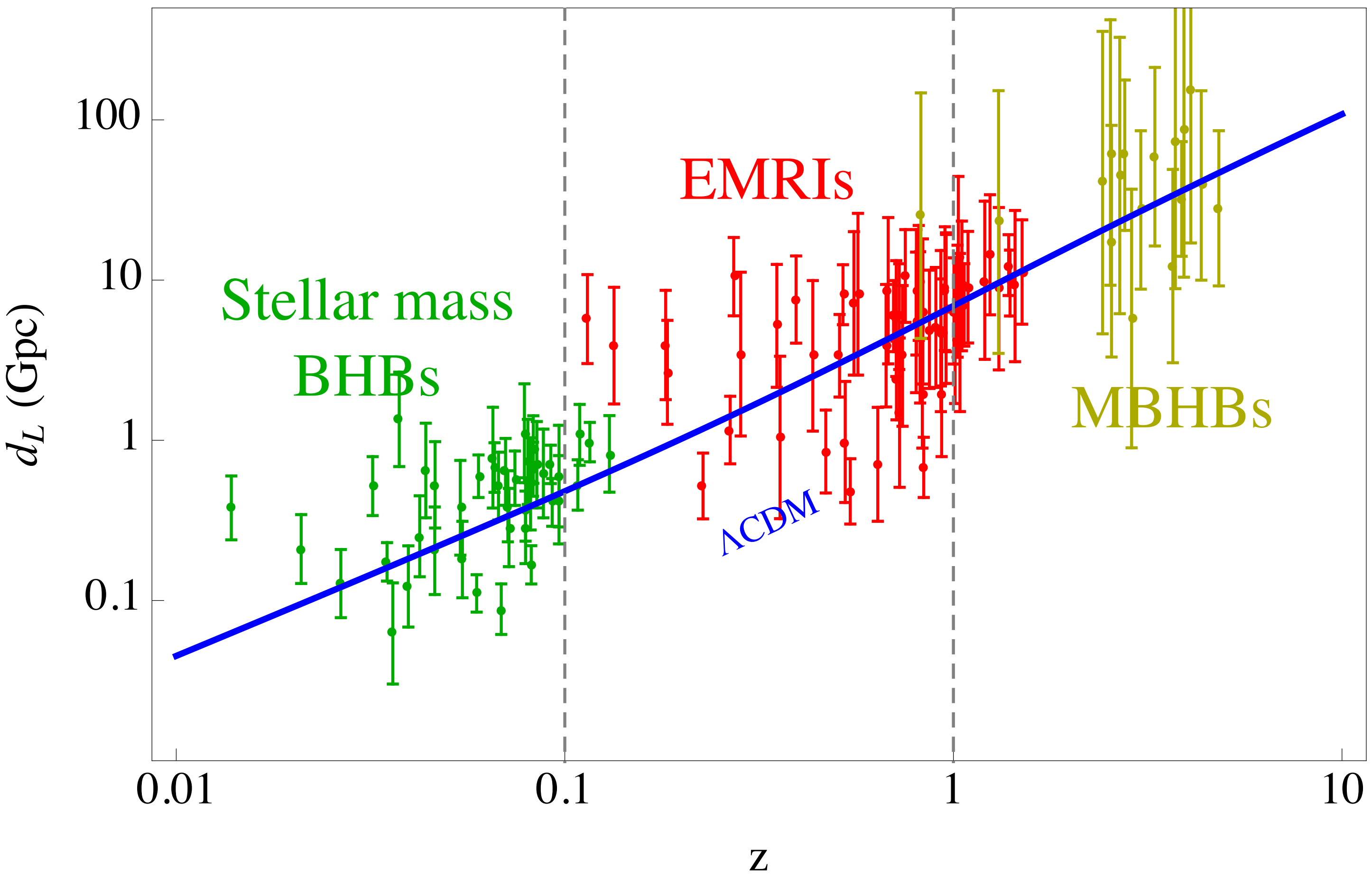
$$w_a = 0 \pm [1.5,\, 0.8]$$

Euclid forecast : $\Delta w_0 = 0.02$ $\Delta w_a = 0.1$

can be improved using other sources at low redshift besides MBHB

Example of possible LISA cosmological data



credits: N. Tamanini

standard sirens with LISA: MBHB coalescence

Dynamical Dark Energy

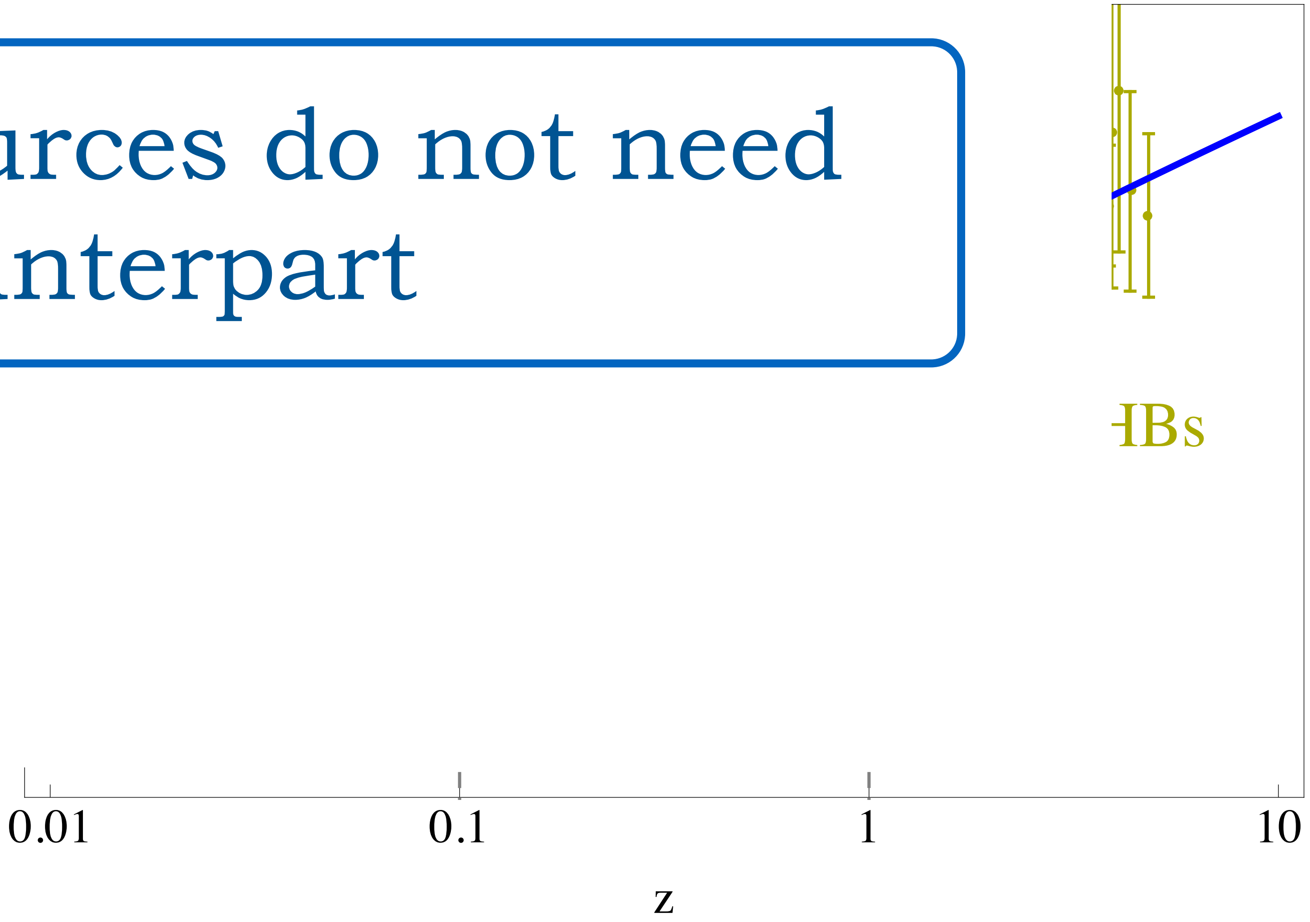
too few events at low redshift to get a good measurement

w ... $\Delta w_0 = 0.02$

w ... $.1$

low-redshift sources do not need em counterpart

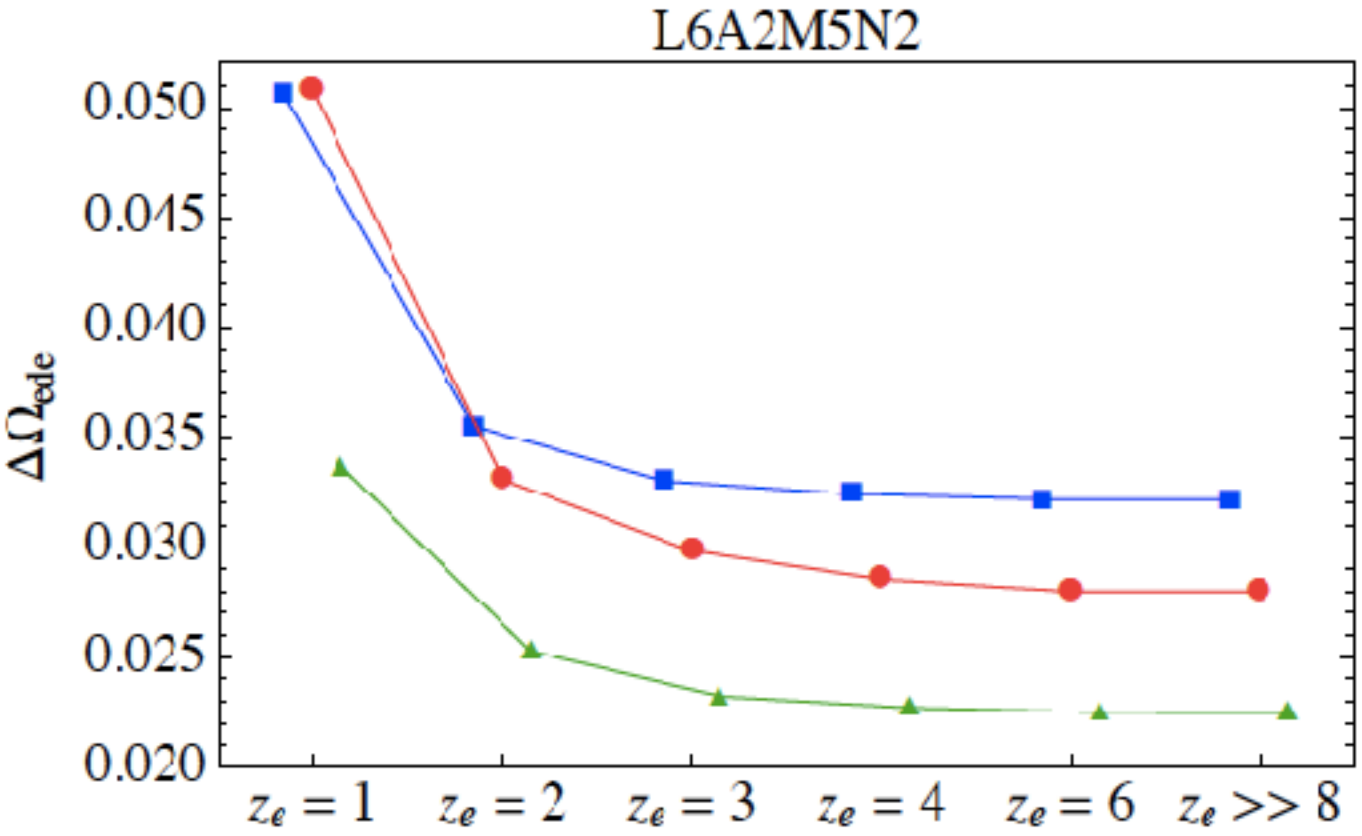
can b
sou



credits: N. Tamanini

LISA can provide competitive constrains on models where dark energy starts to contribute at early times

Early Dark Energy



Ω_{de} fraction of dark energy at early times

z_e redshift up to which dark energy contributes

Planck alone : $\Delta\Omega_{de} = 0.0036$

but only if it contributes up to decoupling, otherwise the measurement quickly degrades

CC and N. Tamanini arXiv:1607.08755

Interacting Dark Energy

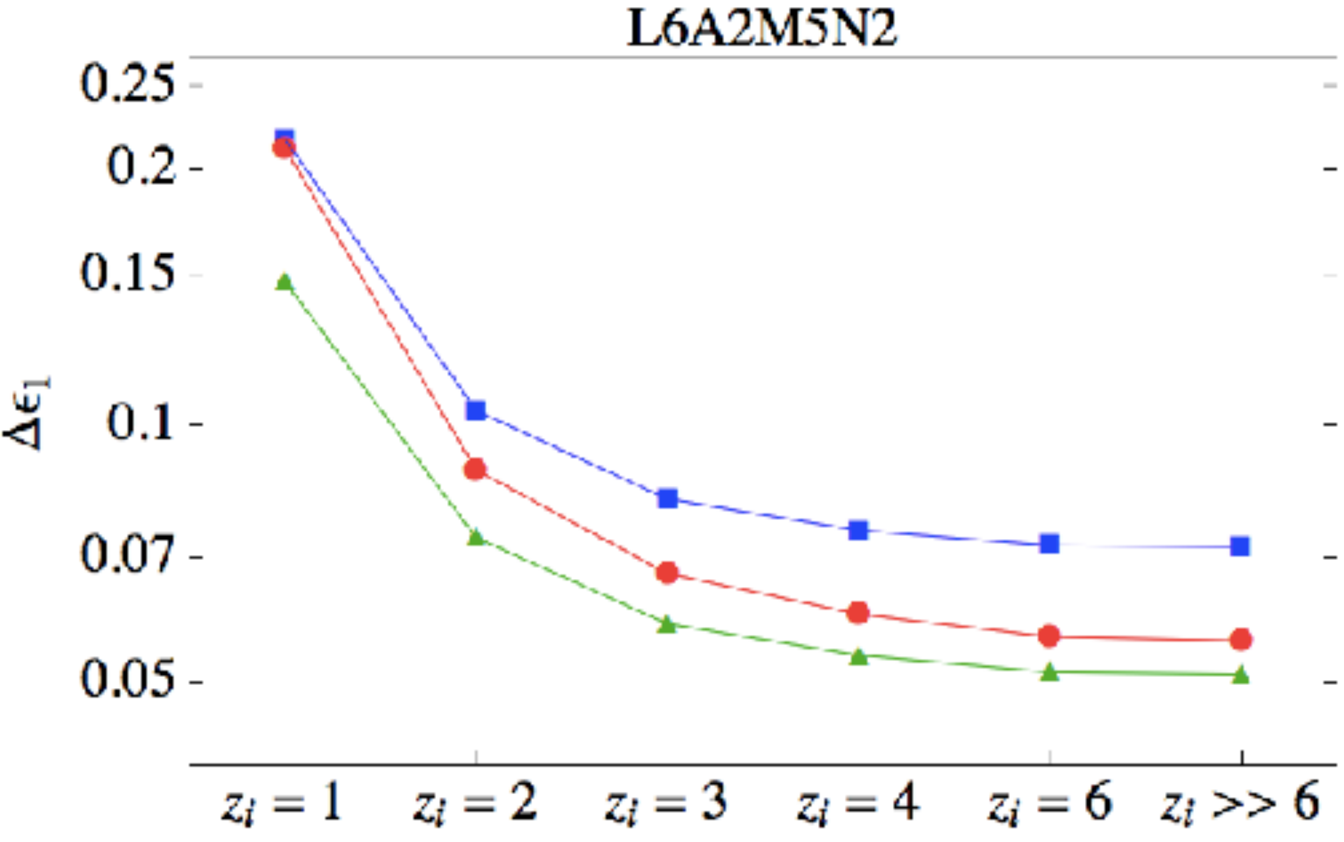
$$\dot{\rho}_{dm} + 3H\rho_{dm} = Q$$

$$\dot{\rho}_{de} + 3H(1+w_0)\rho_{de} = -Q$$

two models for the interaction

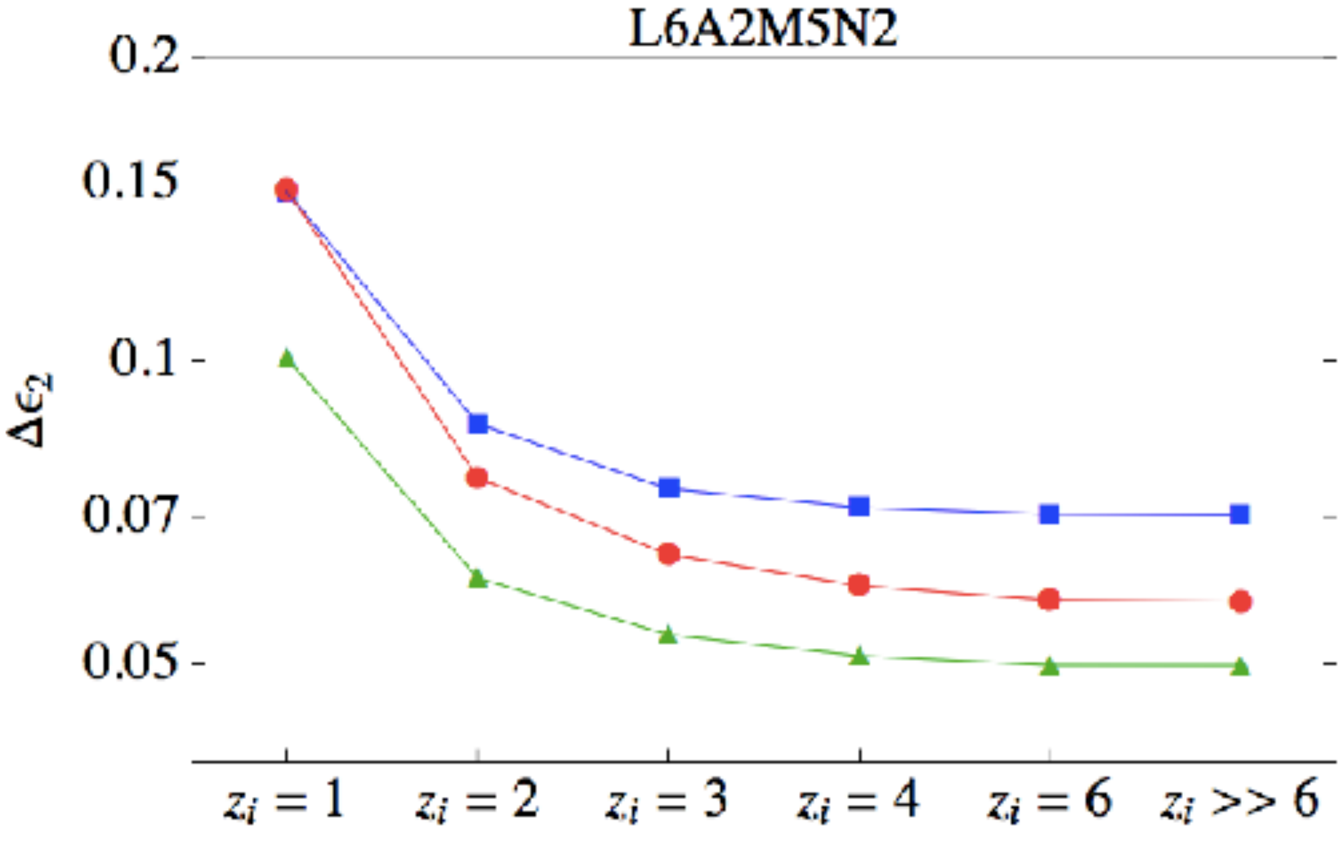
$Q = \epsilon_1 H \rho_{dm}$ and $Q = \epsilon_2 H \rho_{de}$

redshift when the interaction turns on : z_i



$$\epsilon_1 = 0.00199^{+0.00024}_{-0.00177}$$

Costa et al 2016



$$\epsilon_2 = 0.159^{+0.146}_{-0.154}$$

Murgia et al 2016

Binary at cosmological distance

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

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

redshifted chirp mass

if the redshift is constant during the time of observation of the GW signal

Binary at cosmological distance

time variation of the redshift changes the evolution of the frequency with time as the binary chirps:

1. the background expansion of the universe varies during the time of observation of the binary

2. the redshift perturbations due to the distribution of matter between the GW source and the observer vary in time during the time of observation of the binary

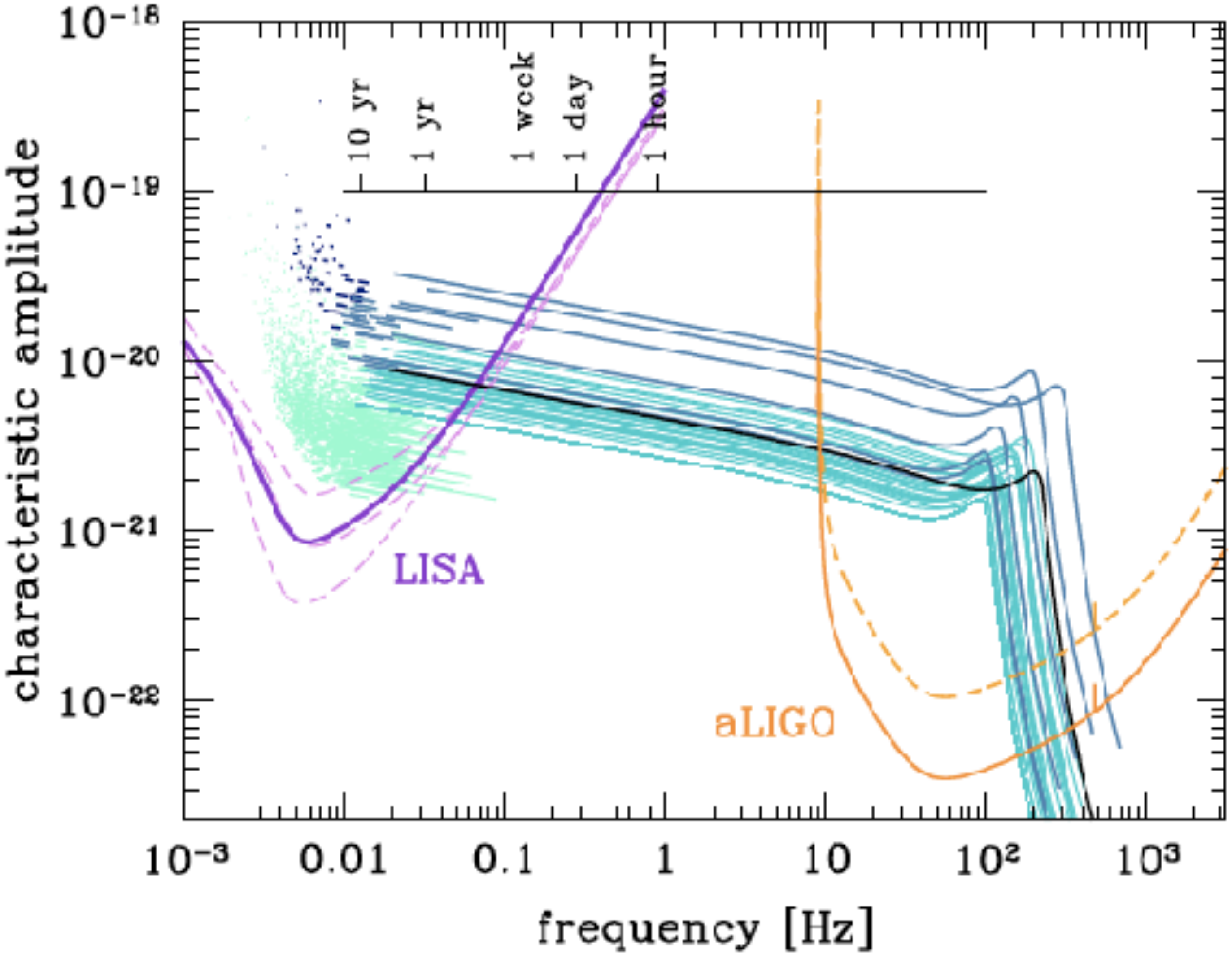
main effect: peculiar acceleration of the binary centre of mass

C Bonvin et al arXiv:1609.08093

Extra term in the waveform phase

- Earth based interferometers are not sensitive to this effect: they do not follow the GW source for enough time

- but this effect is <u>relevant for LISA</u>: binaries which stay in band for enough time, with *low chirp-mass, that enter the detector around ten mHz* and go to the LIGO band after ~5 years



A Sesana
arXiv:1702.04356

Extra term in the waveform phase

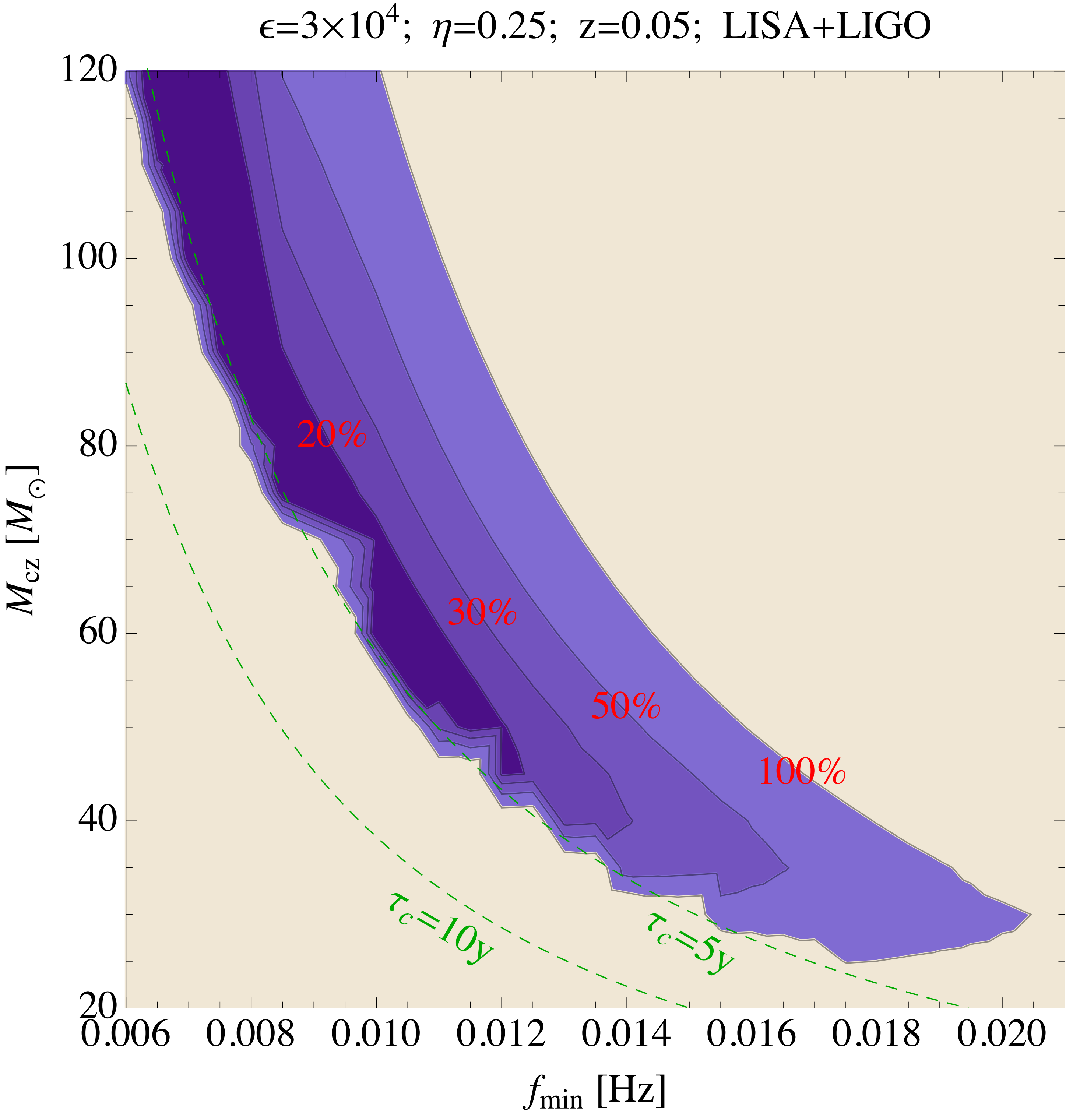
- the effect can be measured for binaries with high enough acceleration

$$v \sim 200\,\frac{\mathrm{km}}{\mathrm{sec}}$$

$$r \sim 1\ \mathrm{pc}$$

- knowing the acceleration can provide information on the formation of the binary (nearby a SMBH?)

Inayoshi et al 1702.06529



Conclusions

we have assisted to a historical event, the aLIGO/Virgo detection
which (so far) confirms GR
and opens the era of GW astronomy and cosmology

LISA has been fully approved by ESA
and it is on the path to launch in 2030

GW could be a powerful mean to probe the early universe
(and consequently high energy physics)
and the late-time cosmology:
detection is difficult but great payoff