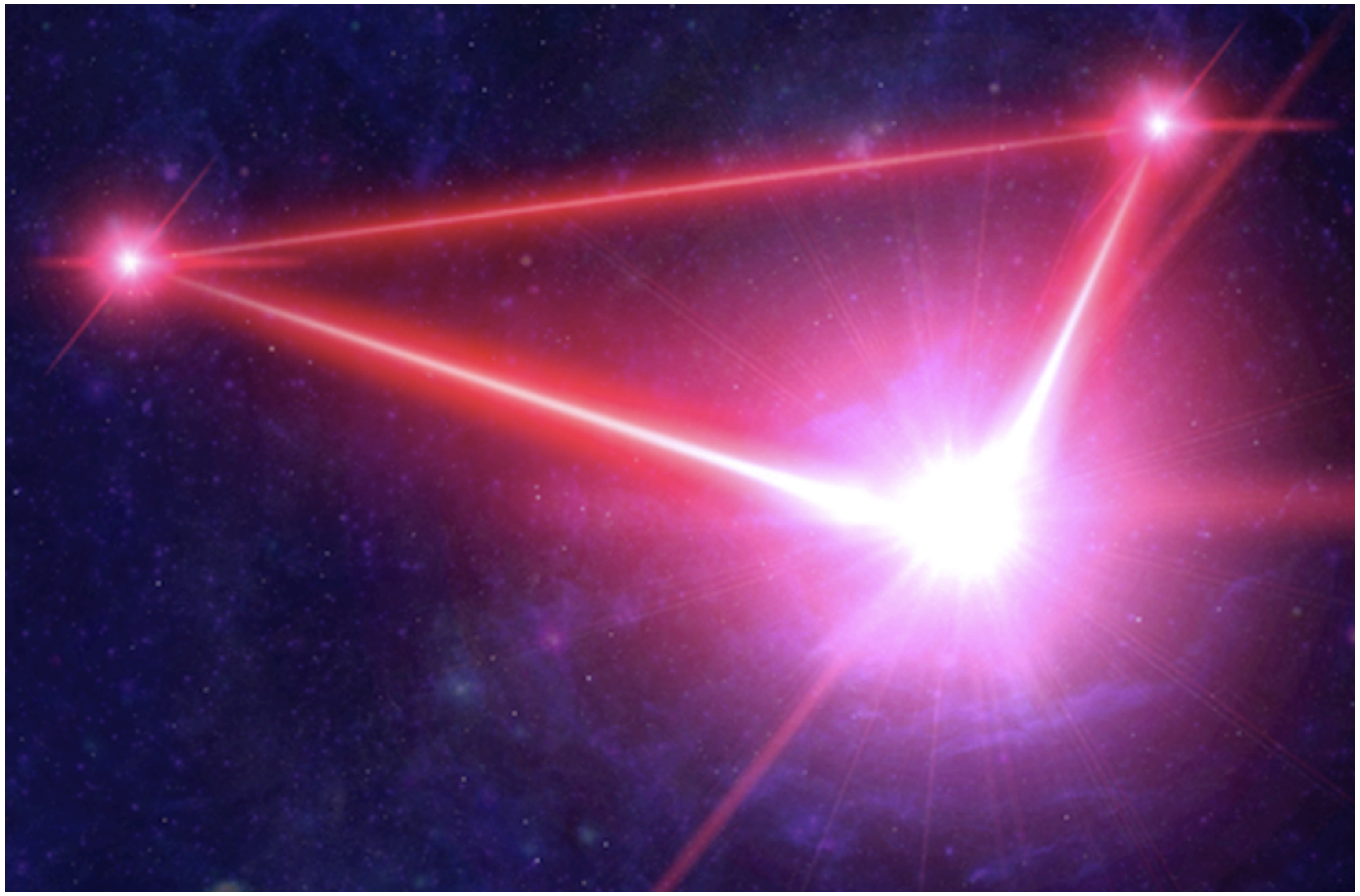
Gravitational waves and cosmology: the potential of the LISA observatory

Chiara Caprini
CNRS (APC Paris)



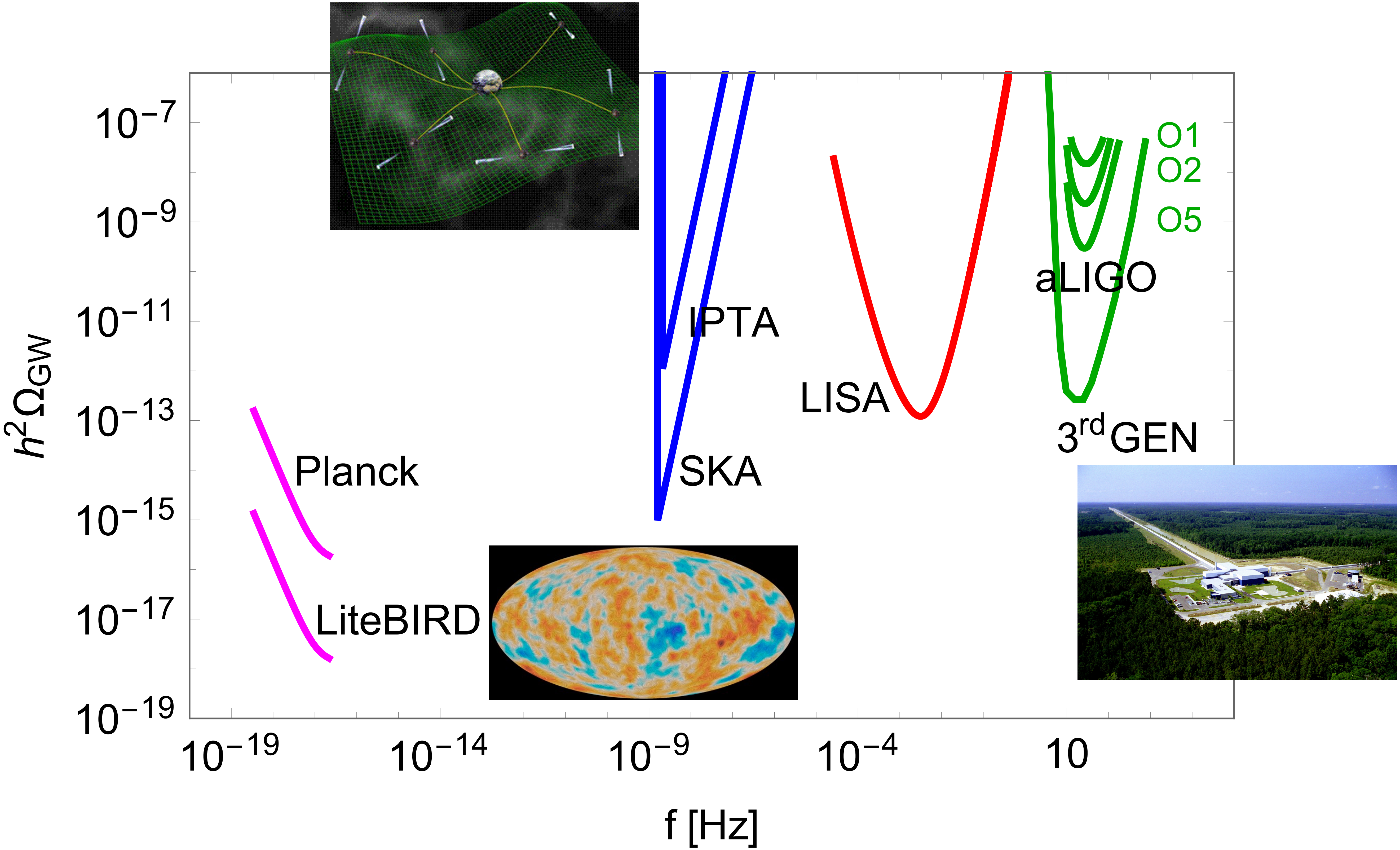
GW and cosmology: observational scientific context

- Several direct GW detections by the Earth-based interferometer network LIGO/Virgo since 2015
  we have a new observable to probe the universe

- GW170817 NS binary merger: first coincident detection of GW and EM signals, measure of Hubble factor, constrains on modified gravity theories
  GW have the potential to constrain cosmology

- ESA space mission LISA is on the path to launch in 2032
  a new frequency range will be accessible, between Pulsar Timing Array and Earth-based interferometers, with great potential for cosmology

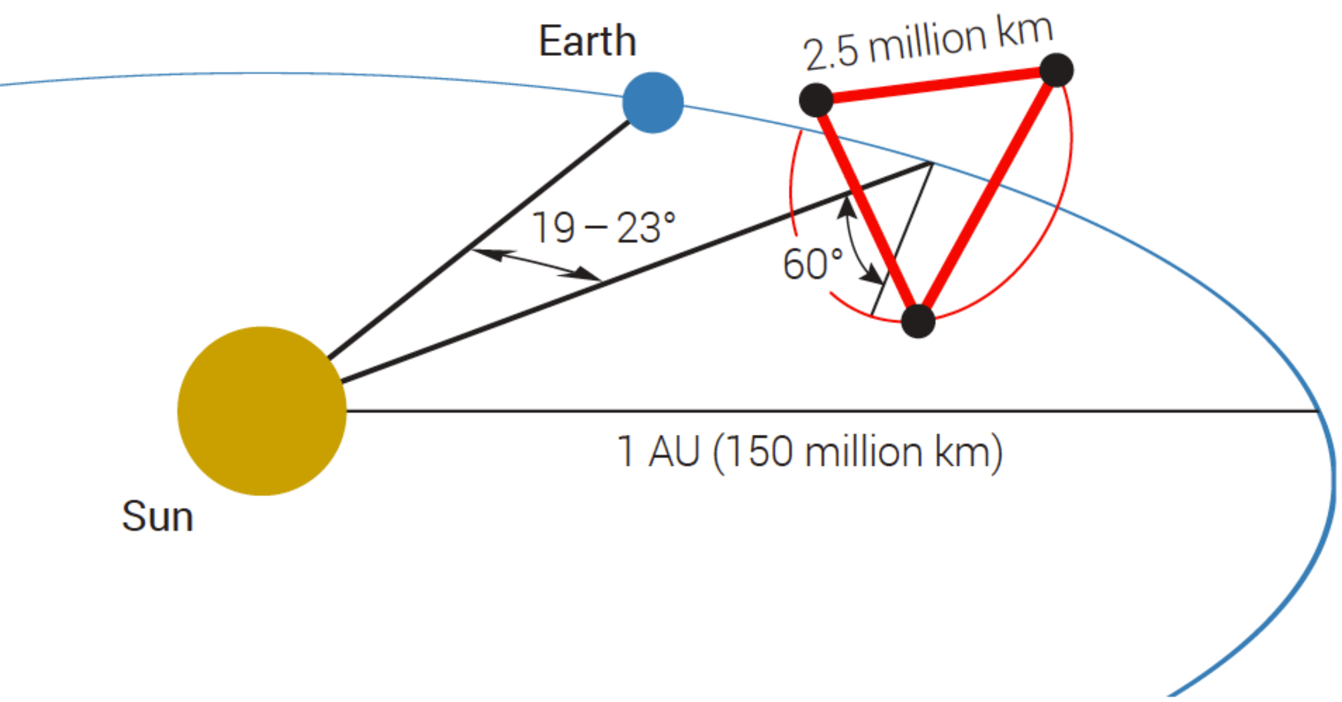
GW and cosmology: detectors



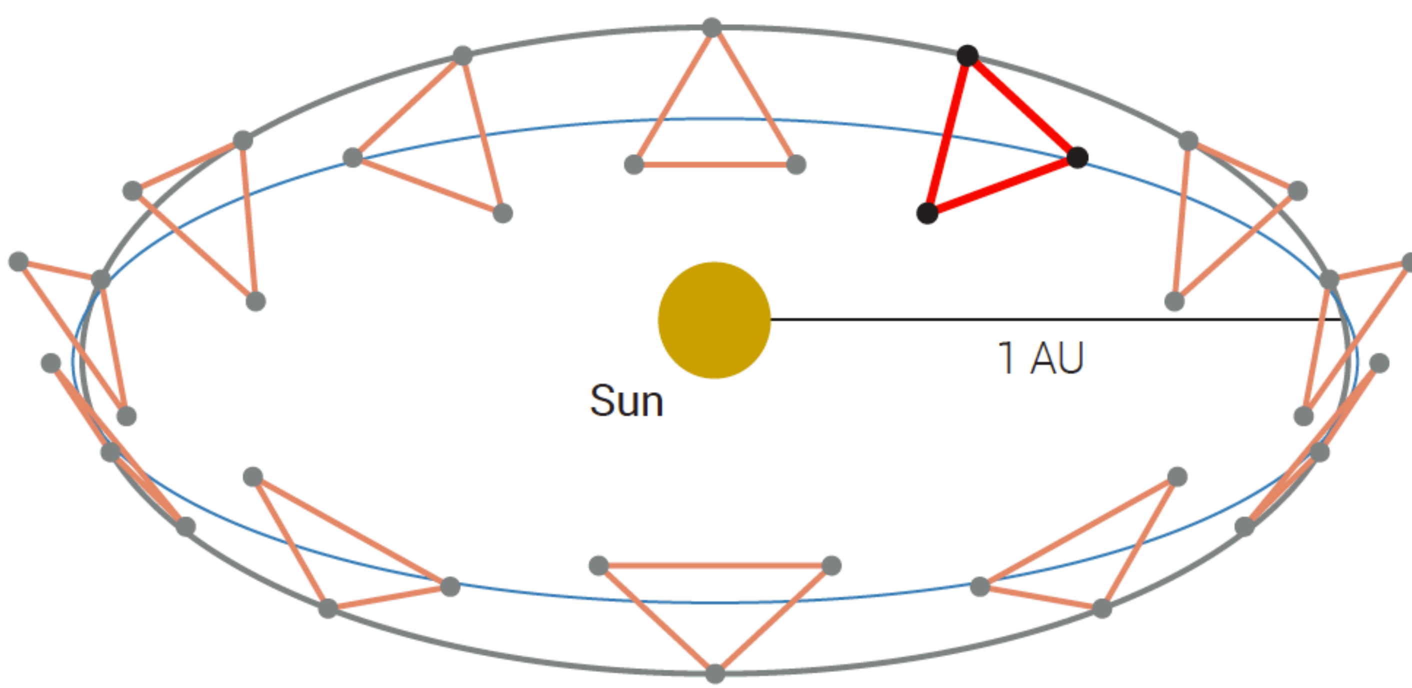
LISA: Laser Interferometer Space Antenna

- no seismic noise
- much longer arms than on Earth

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



- Launch in ~2032
- two masses in free fall per spacecraft
- 2.5 million km arms
- picometer displacement of masses



LISA collaboration arXiv:1702.00786

LISA mission chronology

- 2013: ESA selects LISA scientific theme for L3: “the gravitational universe”
- LISA Pathfinder : 2016-2017, it demonstrates the feasibility of LISA
- 1/2017: LISA Consortium submits the LISA proposal, approved by ESA
- 3/2017 - 3/2018 : ESA Phase 0 study,
- 3/2018 - ~2020 : ESA Phase A study (with industries)
- Reboot of the Consortium: ~1000 membres
- ~2022: ESA mission adoption
- ~8.5 years: mission construction
- ~2034: launch (Ariane 6)

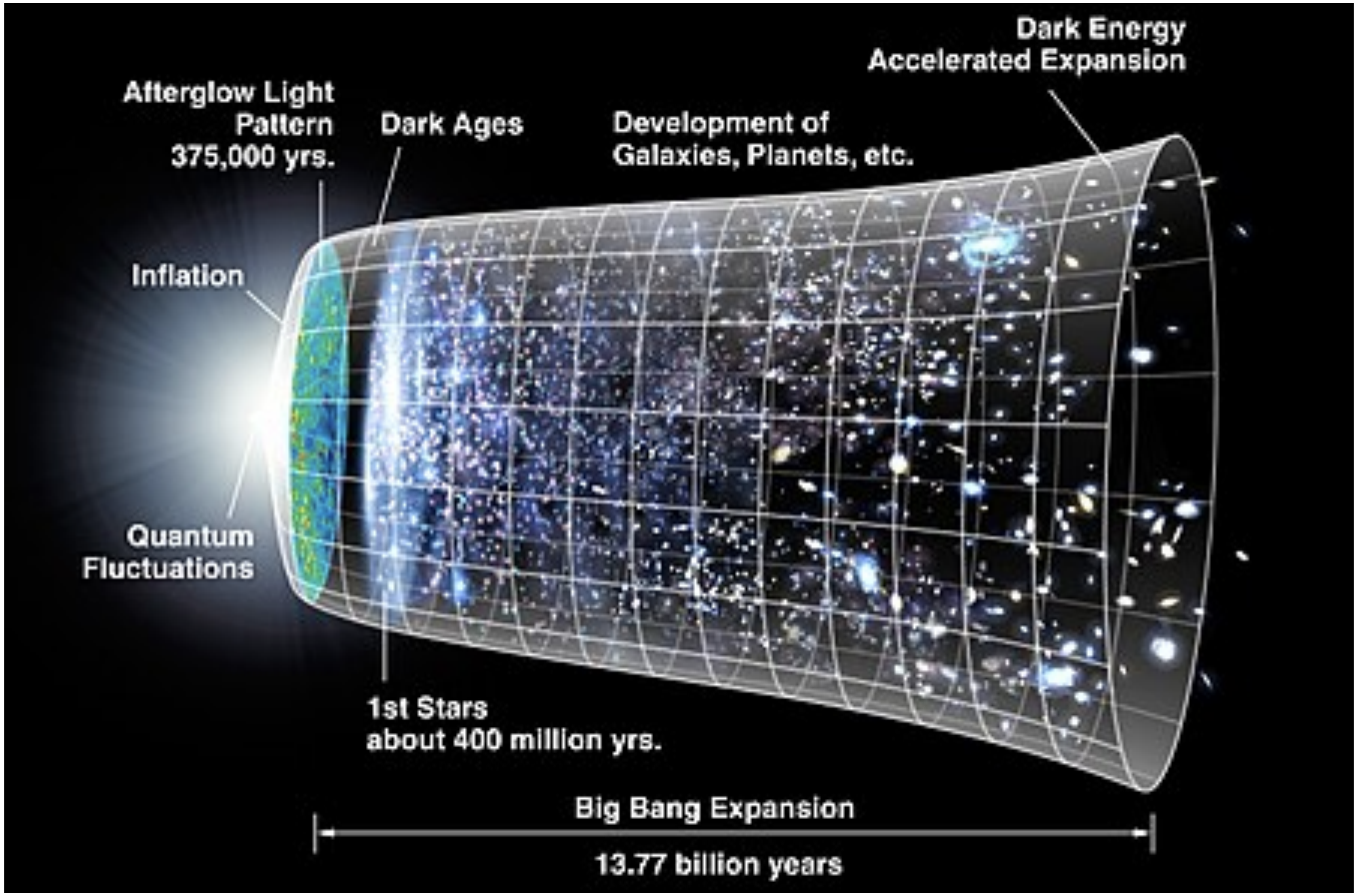
- nominal mission duration 4 years, tested extension up to 10 years, cost: 1050 M€

LISA Cosmology Working Group

The goal of the CosWG is to investigate the scientific return of LISA in relation to cosmology

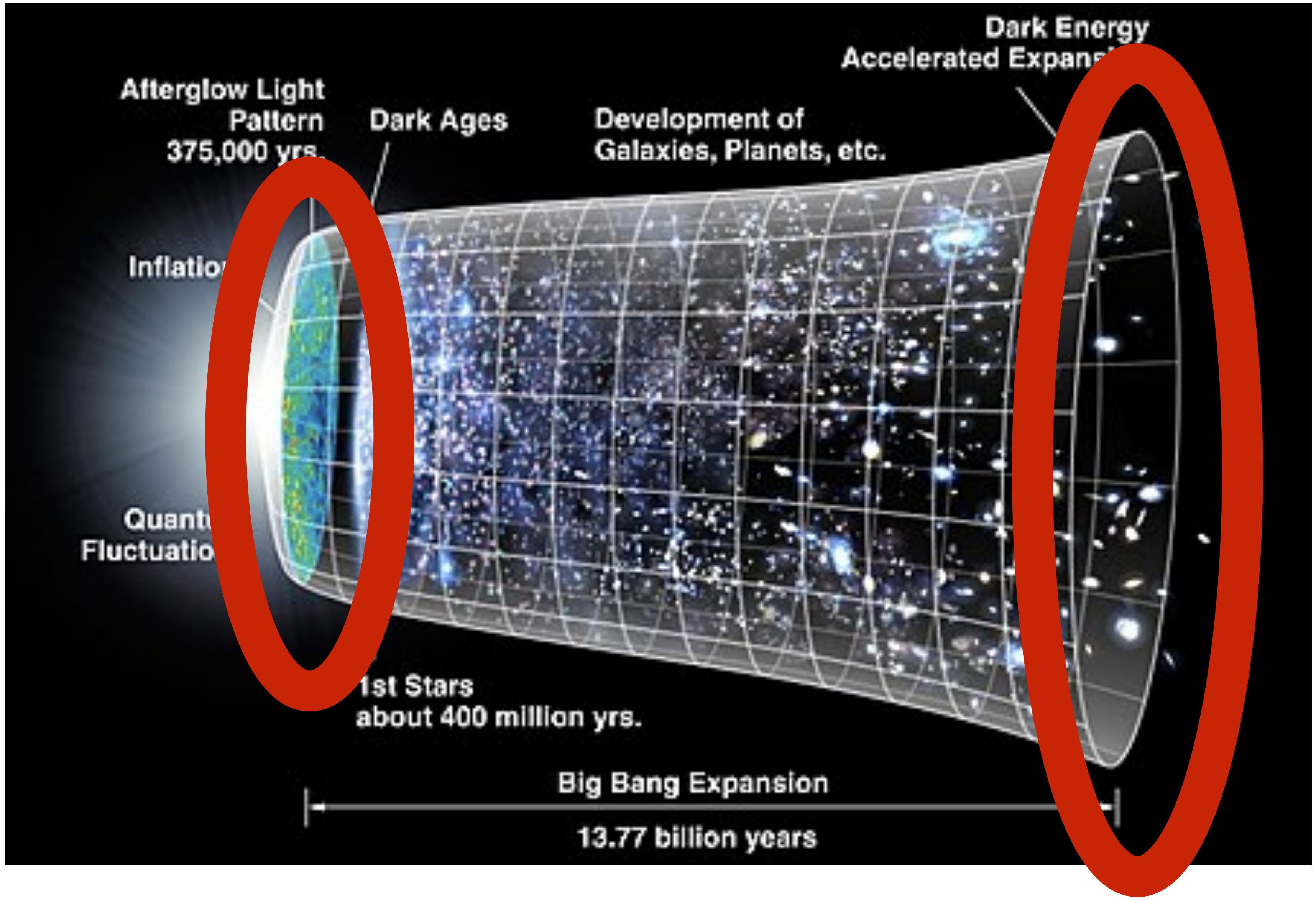
- operational since 2015, ~230 members
- coordinators: R. Caldwell, CC, G. Nardini
- eight meetings, one school
- several scientific results, presented in the following

GW AND COSMOLOGY



LISA has a great potential to probe cosmology

GW AND COSMOLOGY

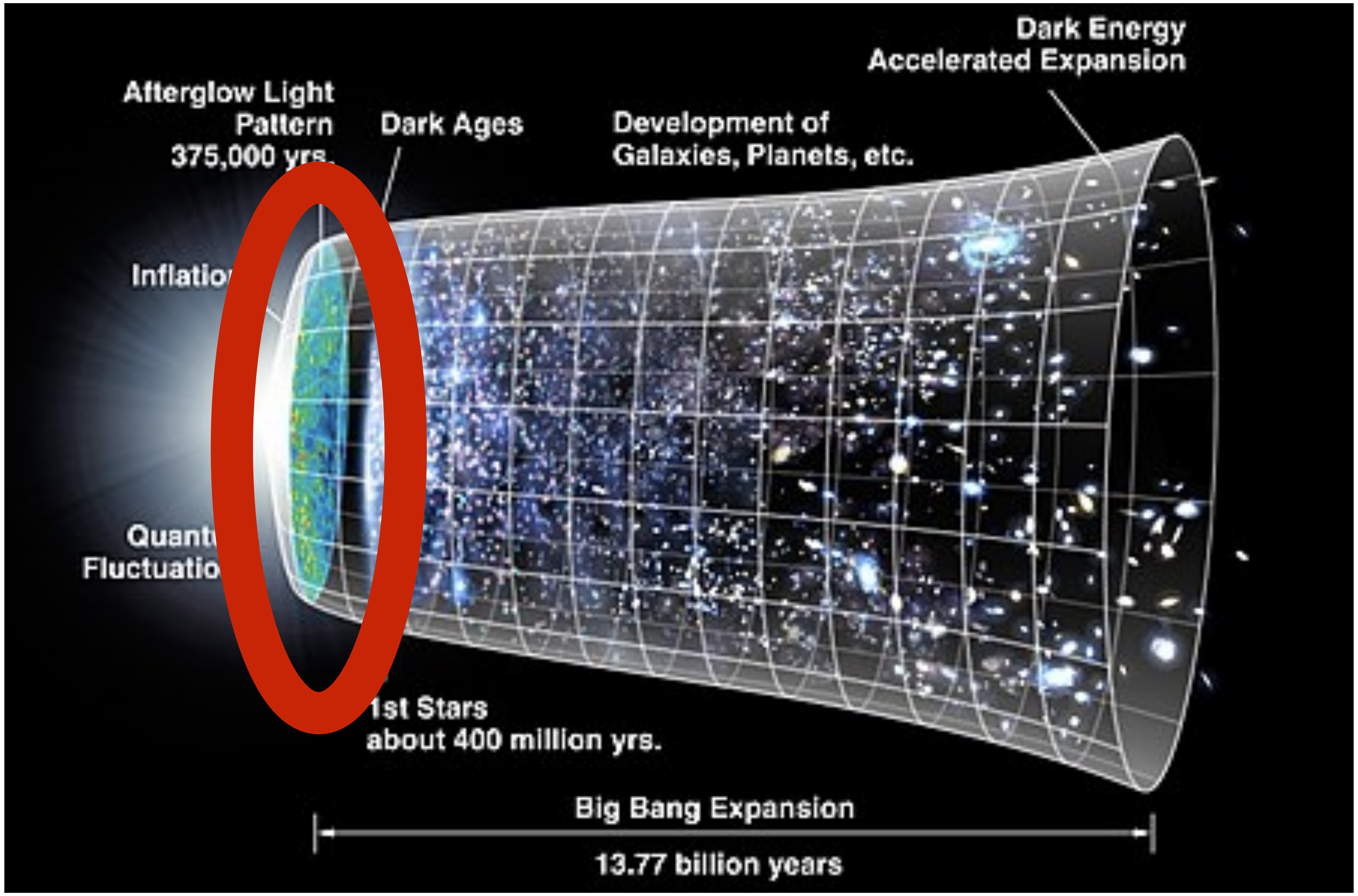


the stochastic GW background from primordial sources: test of early universe and high energy phenomena

LISA has a great potential to probe cosmology

use of GW emission from binaries to probe late-time dynamics and content of the universe

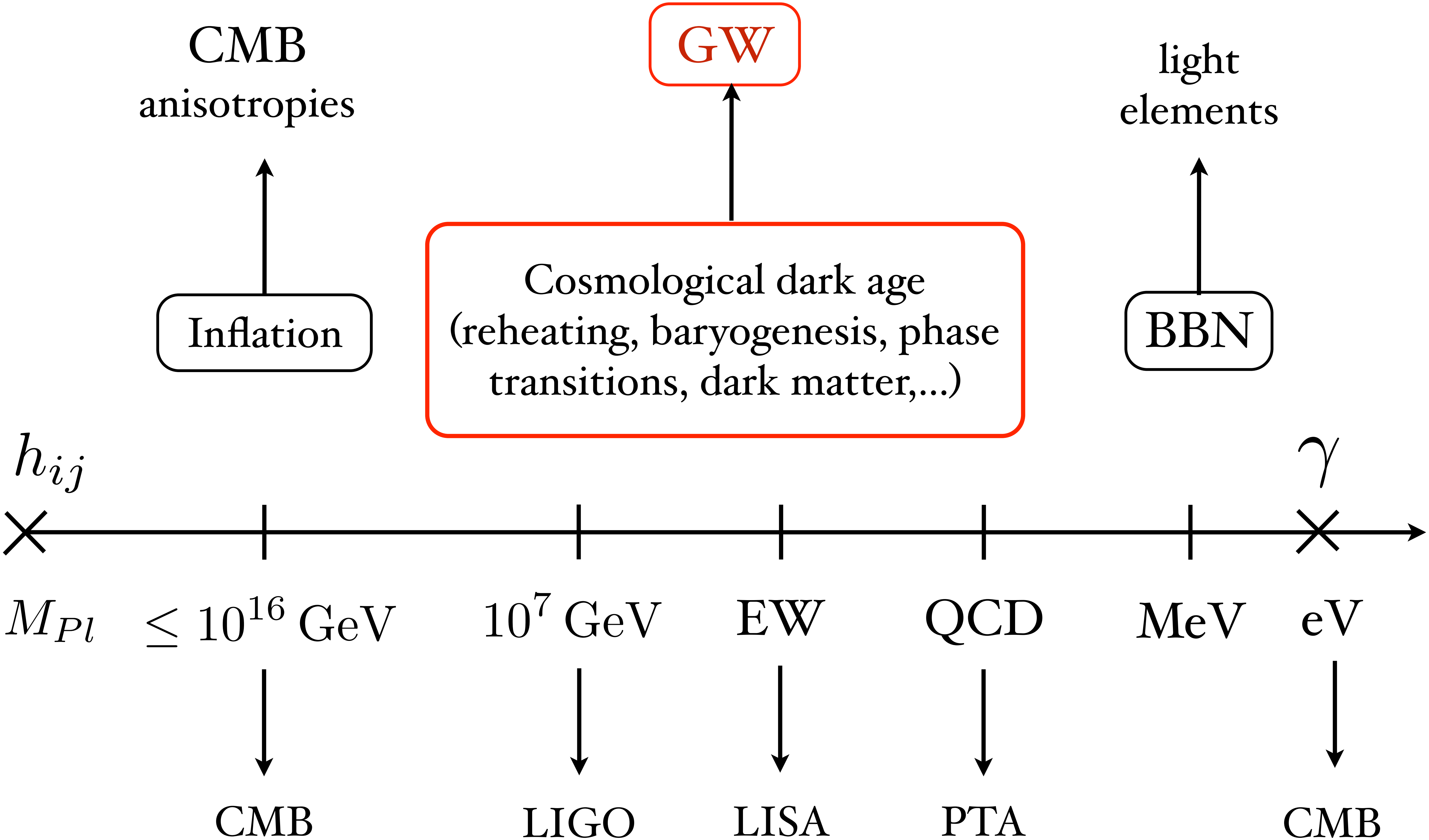
GW AND COSMOLOGY: early universe



- prediction of the SGWB signal from early universe sources: inflation-related, phase transition-related…

- develop SGWB detection techniques: parameter estimation, foreground analysis…

GW from early universe sources



GW from early universe sources

- Since gravity is weak, GW propagate freely through the universe
  the GW signal from the early universe can be used as a probe of high energy physics

- The potential of GW to improve our knowledge of the universe is comparable to the one of the CMB at its dawn

- but do we expect primordial sources providing a GW signal high enough to be detectable?

GW from early universe sources

tensor perturbations of FRW metric:

$$ds^2 = -dt^2 + a^2(t)[(\delta_{ij} + h_{ij})dx^i dx^j]$$

$$|h_{ij}| \ll 1$$

$$h_i^i = \partial_j h_i^j = 0$$

superimposed on the homogeneous and isotropic background

GW from early universe sources

tensor perturbations of FRW metric:

$$ds^2 = -dt^2 + a^2(t)[(\delta_{ij} + h_{ij})dx^i dx^j]$$

WAVE EQUATION

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

source: amplification of vacuum fluctuations during inflation

GW from early universe sources

tensor perturbations of FRW metric:

$$ds^2 = -dt^2 + a^2(t)[(\delta_{ij} + h_{ij})dx^i dx^j]$$

WAVE EQUATION

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

source: Π_{ij}^{TT} tensor anisotropic stress

- fluid $\quad \Pi_{ij} \sim \gamma^2(\rho + p)\,v_i v_j$
- electromagnetic field $\quad \Pi_{ij} \sim (E^2 + B^2)\dfrac{\delta_{ij}}{3} - E_i E_j - B_i B_j$
- scalar field $\quad \Pi_{ij} \sim \partial_i\phi\,\partial_j\phi$

GW from active sources in the early universe: inflation-related

- SGWB from inflation by second order scalar perturbations
- beyond the irreducible SGWB from inflation
  - particle production during inflation (scalar, gauge fields… coupled to the inflaton)
  - spectator fields
  - breaking symmetries (space-dependent inflaton, massive graviton…)
  - modified gravity during inflation (massive GWs with $c \neq 1$)
  - primordial black holes
- preheating and non-perturbative phenomena
  - parametric amplification of bosons/fermions
  - symmetry breaking in hybrid inflation
  - decay of flat directions
  - oscillons

CC and Figueroa arXiv:1801.04268

GW from active sources in the early universe: phase transition-related

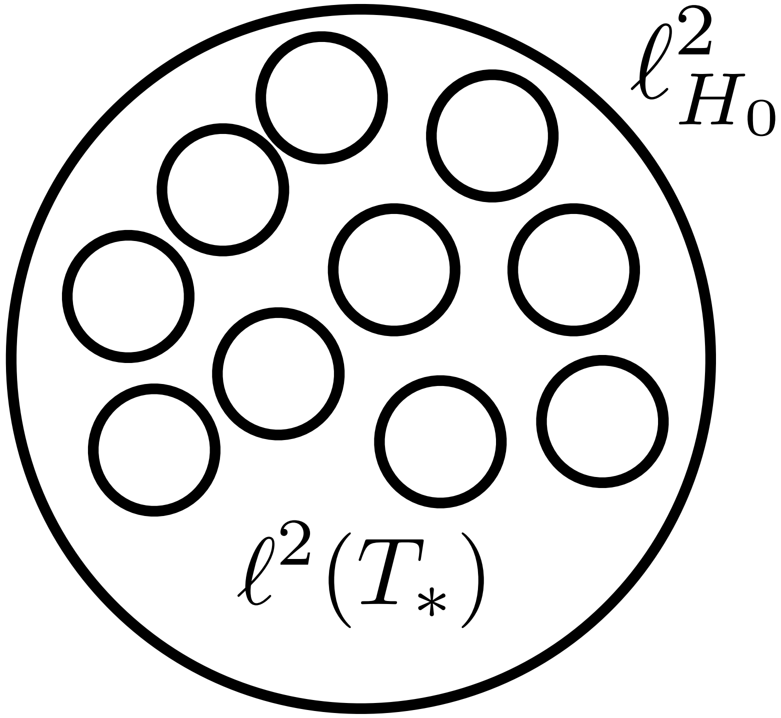
- first order phase transition
    - true vacuum bubble collision
    - sound waves
    - turbulence

- cosmic topological defects
    - irreducible SGWB from topological defect networks
    - decay of cosmic string loops

CC and Figueroa arXiv:1801.04268

Stochastic GW background

active causal source of GW cannot operate beyond the horizon (Hubble scale)



Characteristic frequency for causal sources

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

→ parameter depending on the dynamics of the source

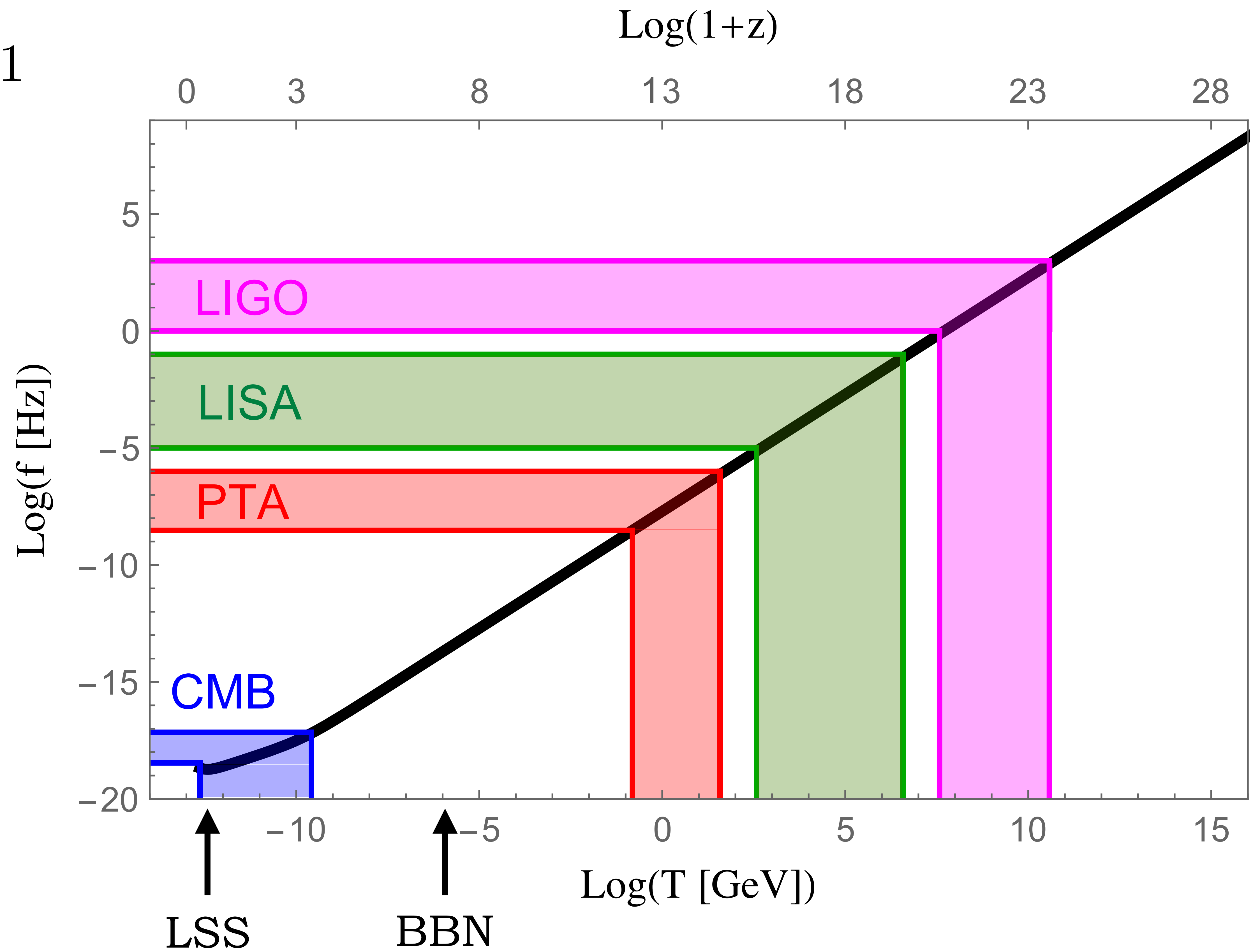
$$\epsilon_* = L_* H_*$$

↑ characteristic scale of tensor stresses

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

Characteristic frequency for causal sources

$\epsilon_* = 1$

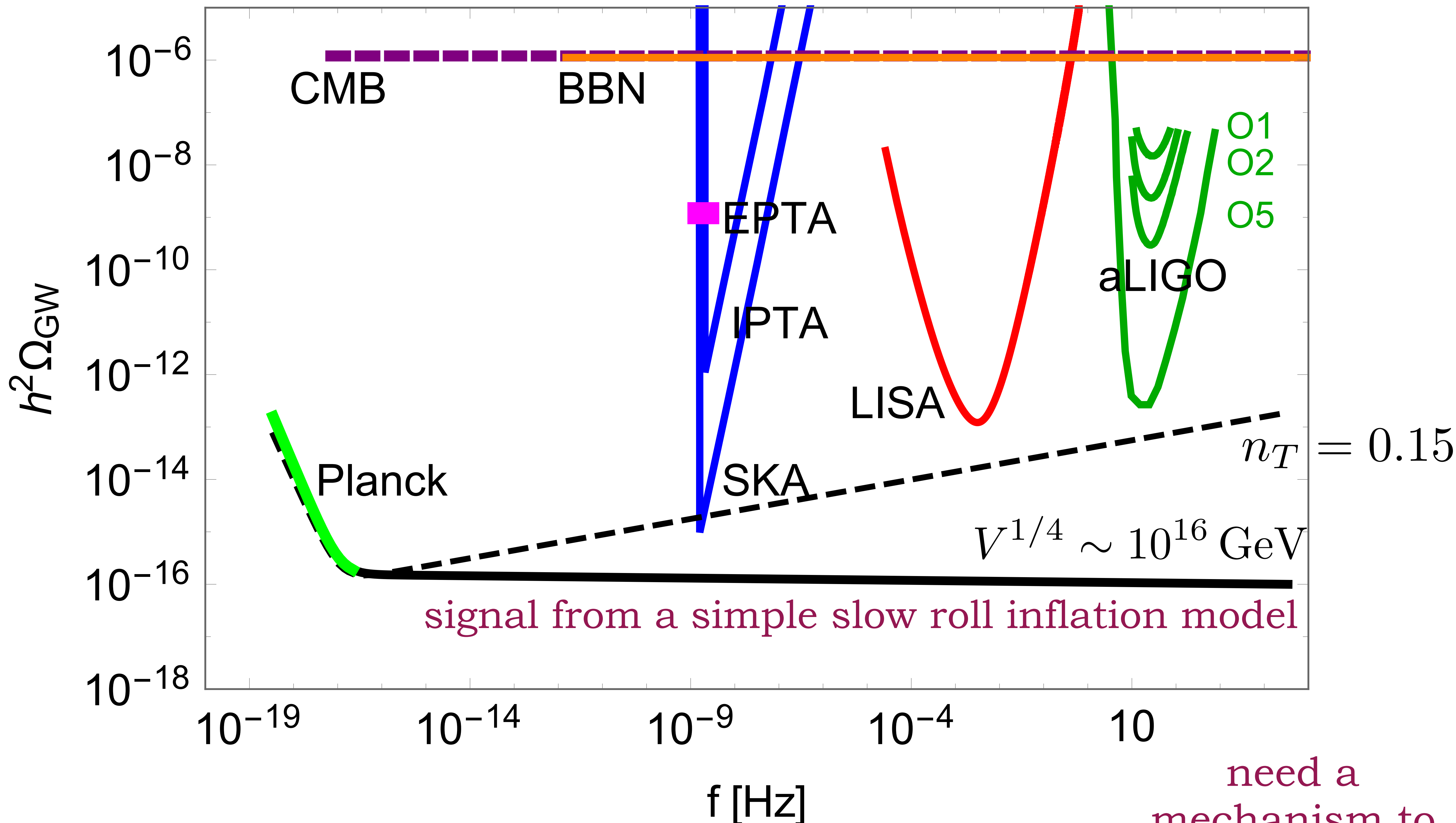


SGWB from slow roll inflation

$$\Omega_{\rm GW}(f) = \frac{3}{128}\,\Omega_{\rm rad}\, r\, \mathcal{P}_{\mathcal{R}}^{*} \left(\frac{f}{f_*}\right)^{n_T} \left[\frac{1}{2}\left(\frac{f_{\rm eq}}{f}\right)^2 + \frac{16}{9}\right]$$

- tensor to scalar ratio $\quad r = \mathcal{P}_h/\mathcal{P}_{\mathcal{R}} \quad\quad r_* \leq 0.07$
- scalar amplitude at CMB pivot scale $\quad \mathcal{P}_{\mathcal{R}}^{*} \simeq 2\cdot 10^{-9} \quad\quad k_* = \frac{0.05}{\rm Mpc}$
- tensor spectrum $\quad \mathcal{P}_h = \frac{2}{\pi}\frac{H^2}{m_{Pl}^2}\left(\frac{k}{aH}\right)^{-2\epsilon} \quad\quad n_T \simeq -2\epsilon$
- transfer function from inflation to today

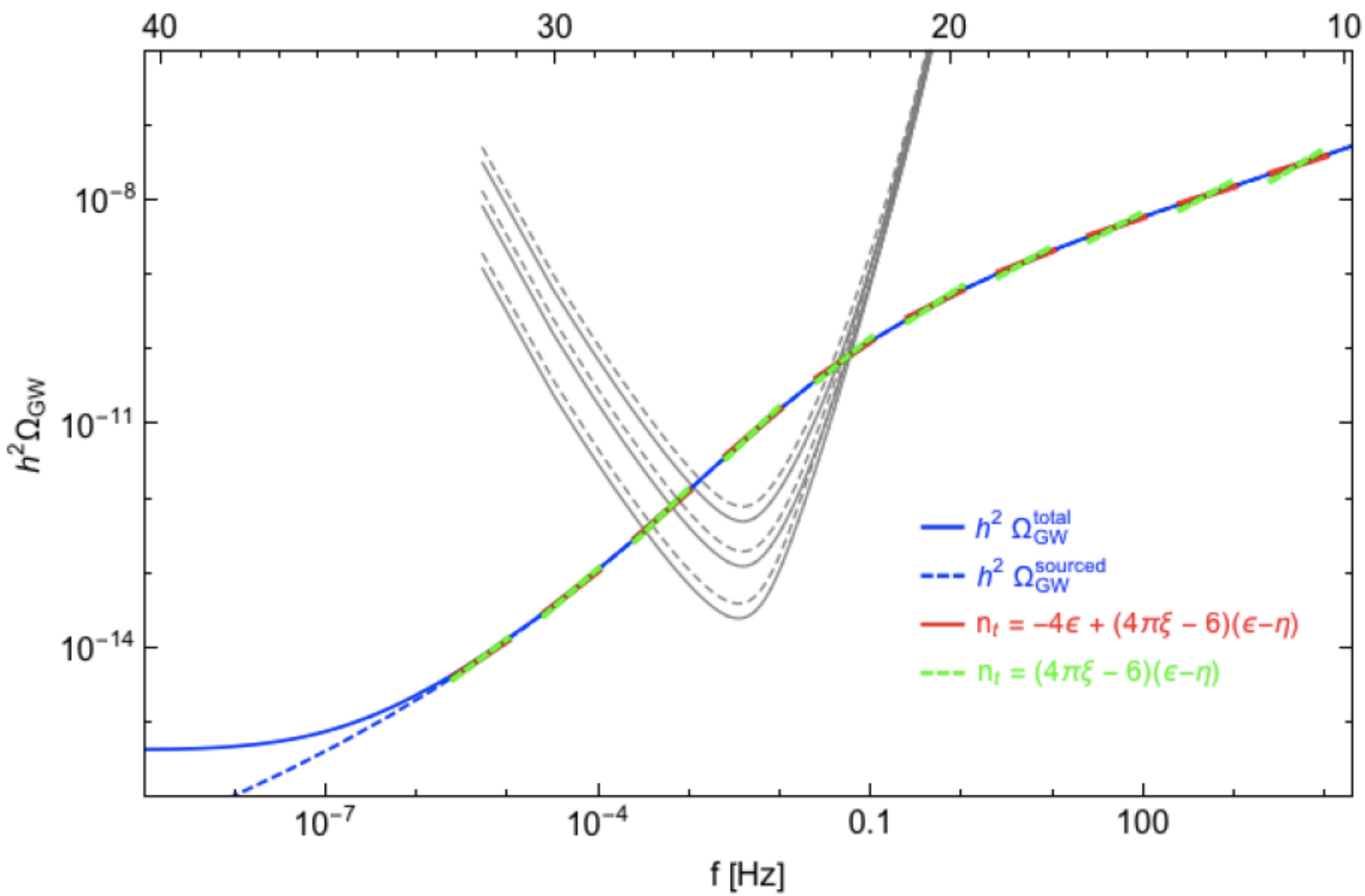
SGWB from slow roll inflation



need a mechanism to enhance it!

just one example: inflaton-gauge field coupling

$$\Delta\mathcal{L} = -\frac{1}{4\Lambda}\phi F_{\mu\nu}\tilde{F}^{\mu\nu}$$



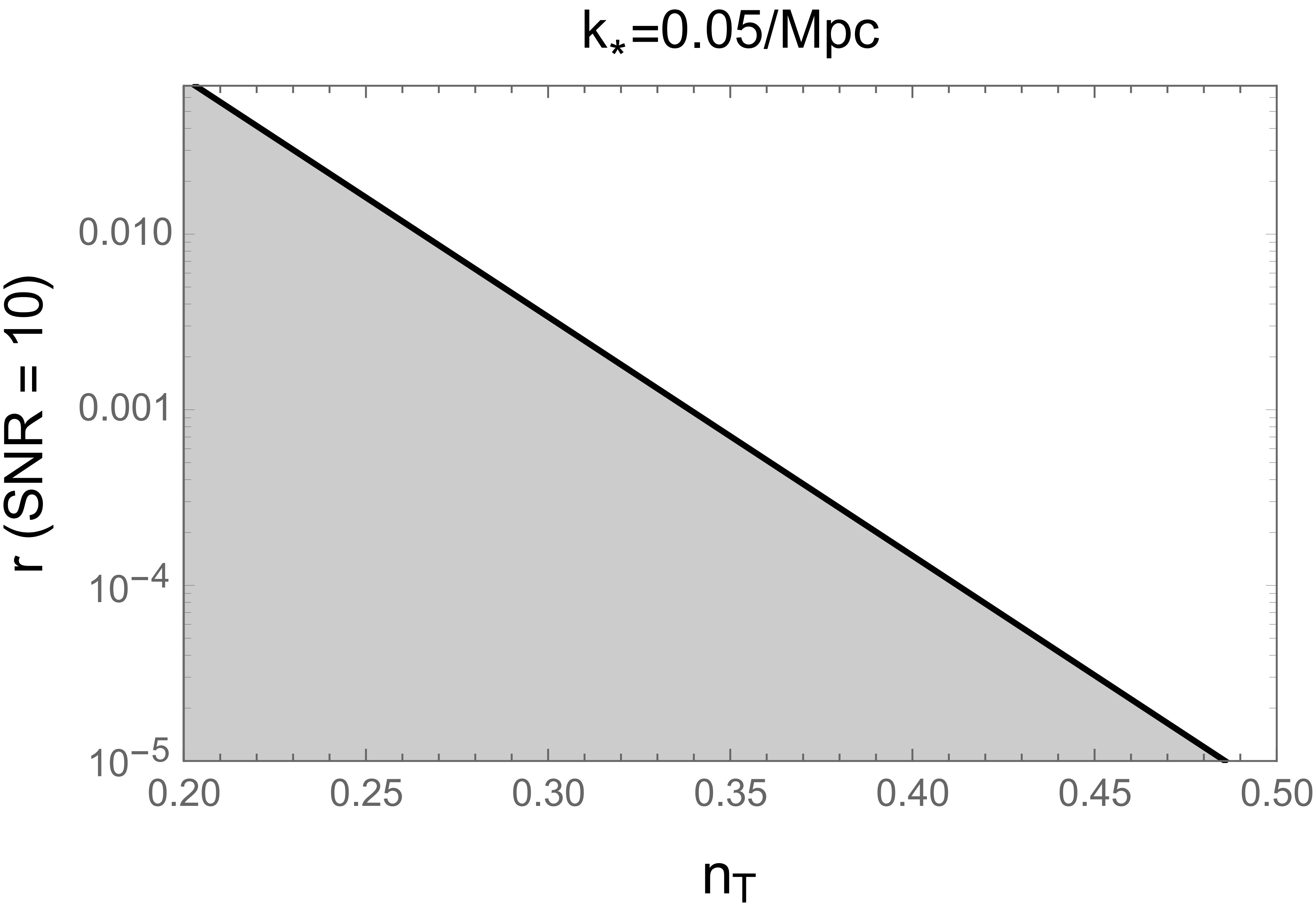
$$\Lambda = \frac{M_{Pl}}{35}$$

quadratic inflaton potential

OTHER SIGNATURES:
non-gaussianity, chirality

N. Bartolo et al, arXiv:1610.06481
N. Bartolo et al, arXiv:1806.02819

general constraints on (r,n_T) from LISA

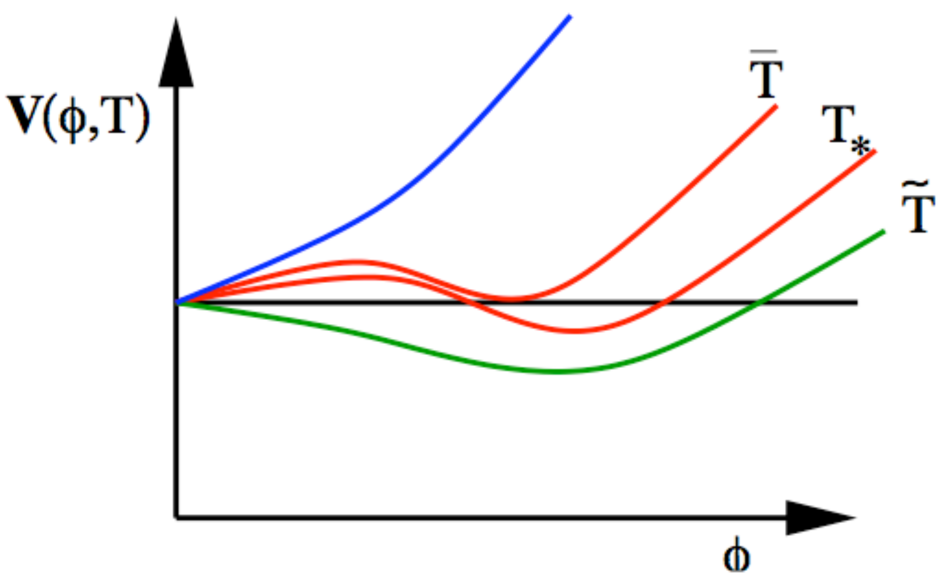


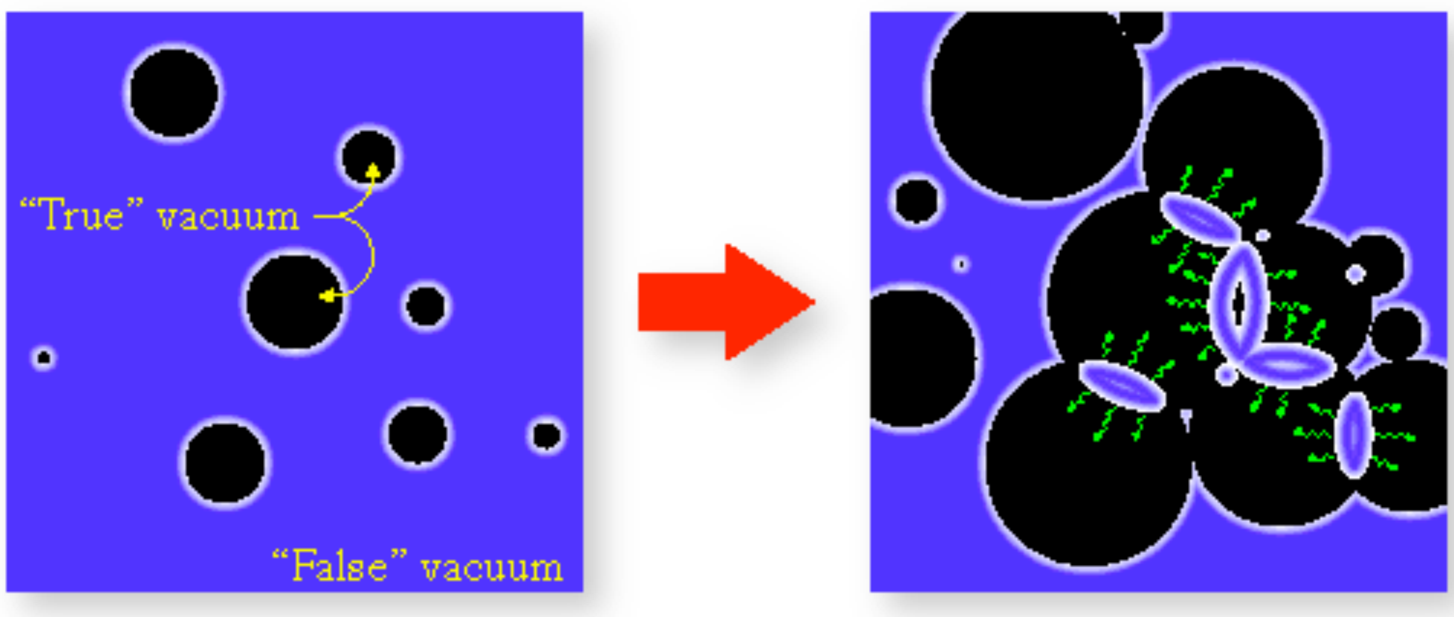
SGWB from first order phase transitions

in the course of its adiabatic expansion, the universe might have undergone several PTs, maybe of first order

potential barrier separates true and false vacua

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





- QCD and EWPT (beyond the standard paradigm)
- higher temperature PTs (extra dimensions, dark matter models...)

SGWB from first order phase transitions

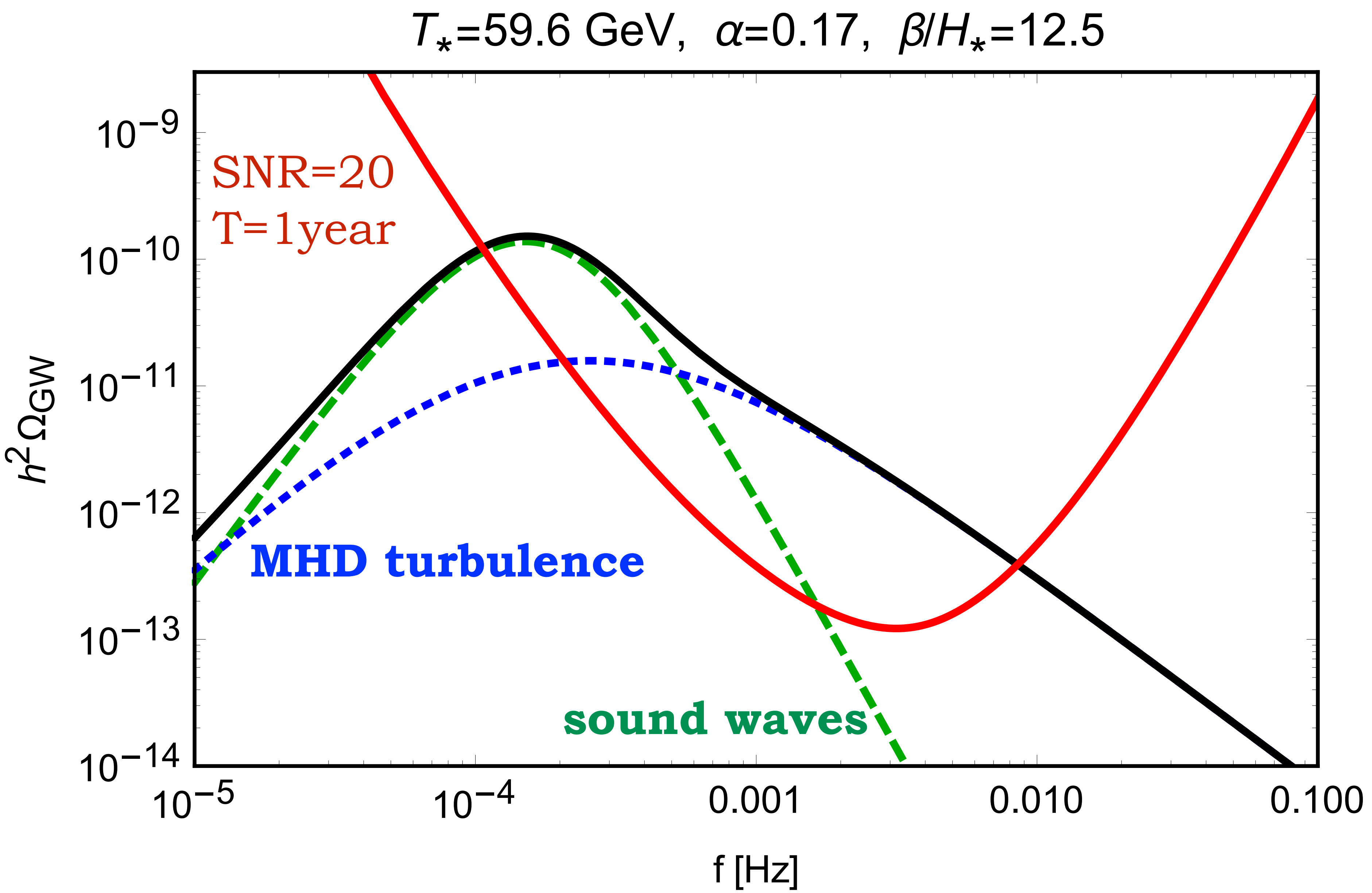
$$\ddot{h}_{ij} + 3H\,\dot{h}_{ij} + k^2\,h_{ij} = 16\pi G\,\Pi_{ij}^{TT}$$

- collisions of bubble walls $\quad \Pi_{ij} \sim \partial_i\phi\,\partial_j\phi$
- sound waves and turbulence in the fluid $\quad \Pi_{ij} \sim \gamma^2(\rho + p)\,v_i v_j$
- primordial magnetic fields (MHD turbulence)

$$\Pi_{ij} \sim (E^2 + B^2)\frac{\delta_{ij}}{3} - E_iE_j - B_iB_j$$

LISA (mHz) is sensitive to energy scales around the **TeV scale**, so it can can probe the EWPT in BSM models and more exotic PTs beyond the EWPT

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



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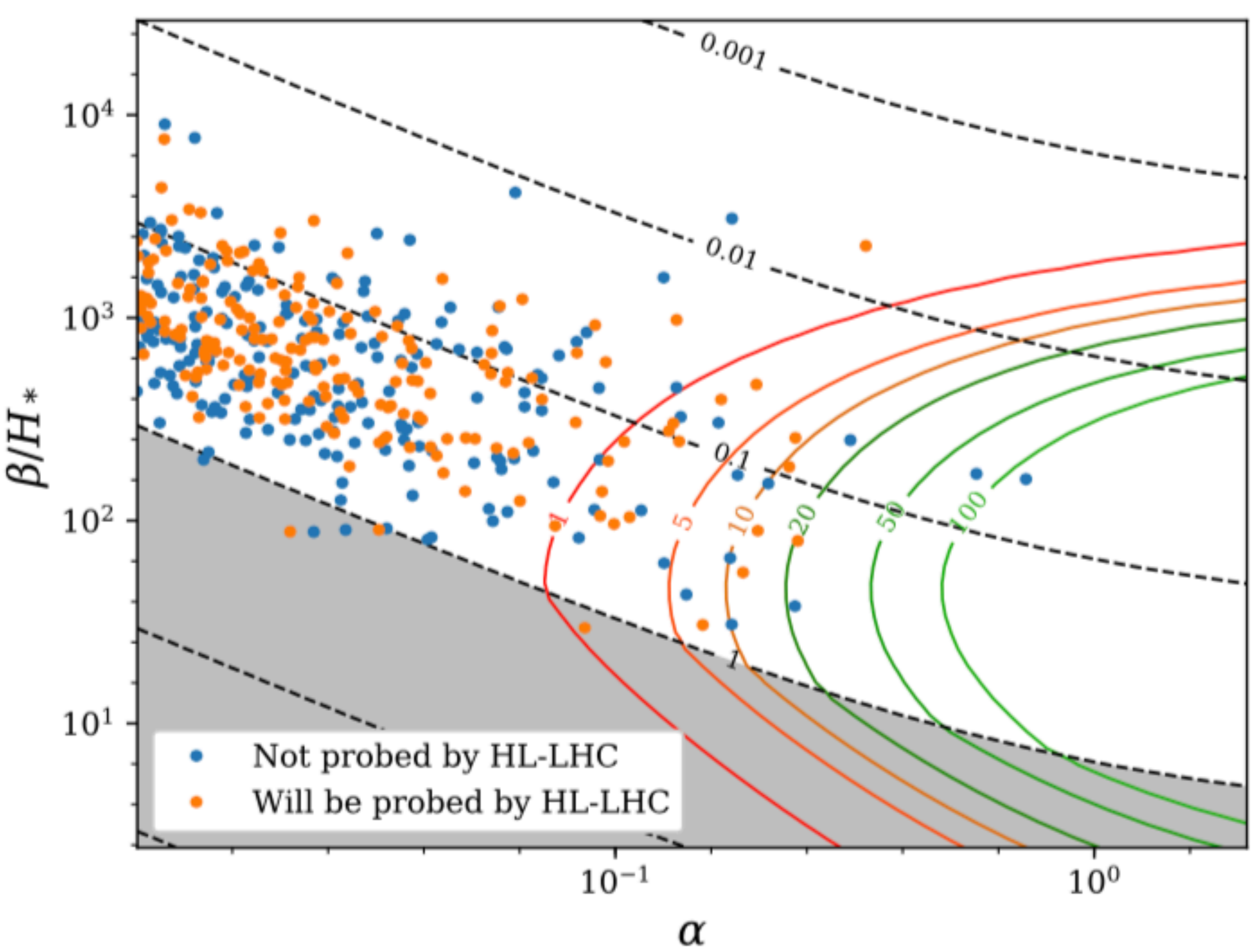
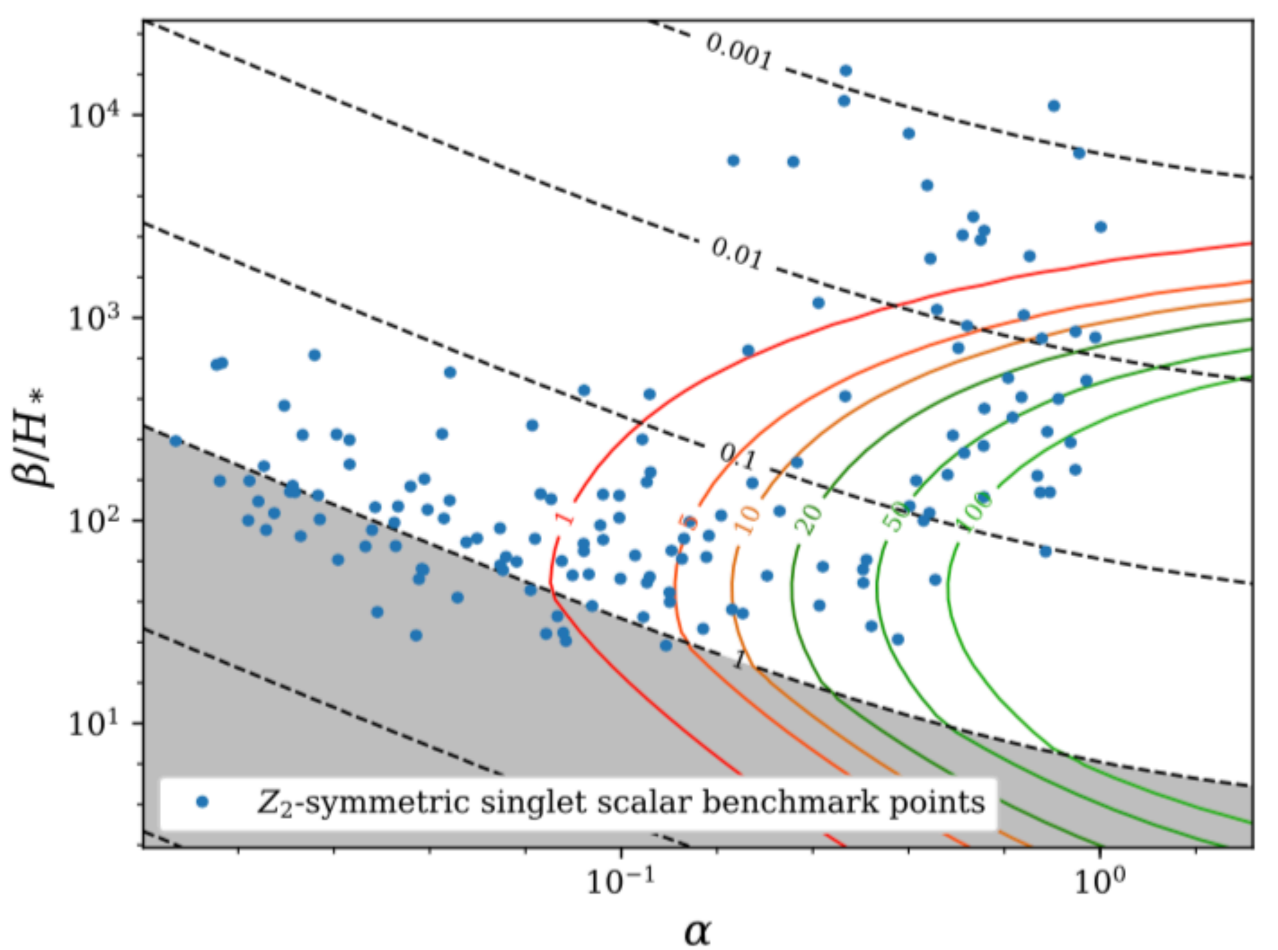
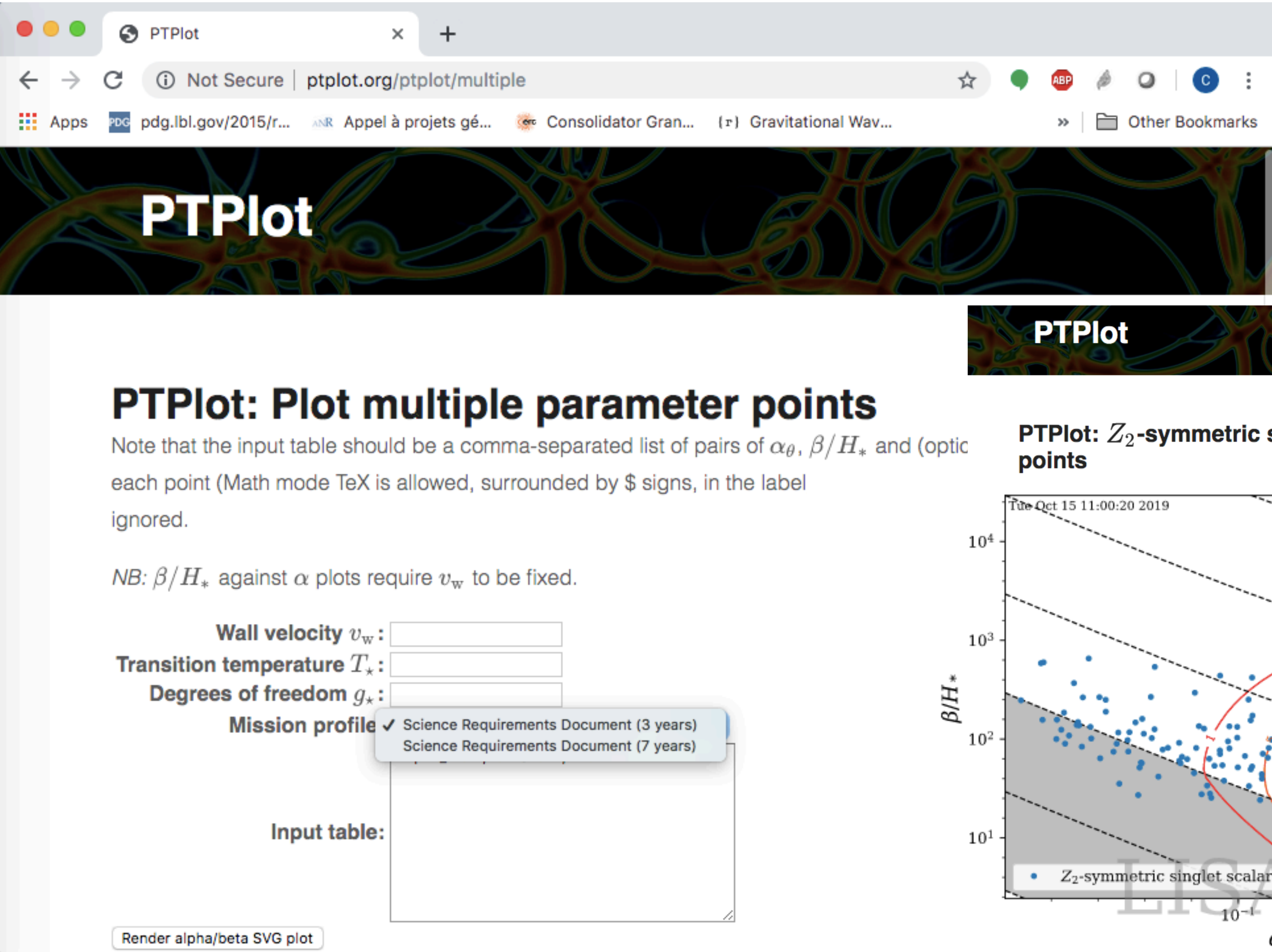
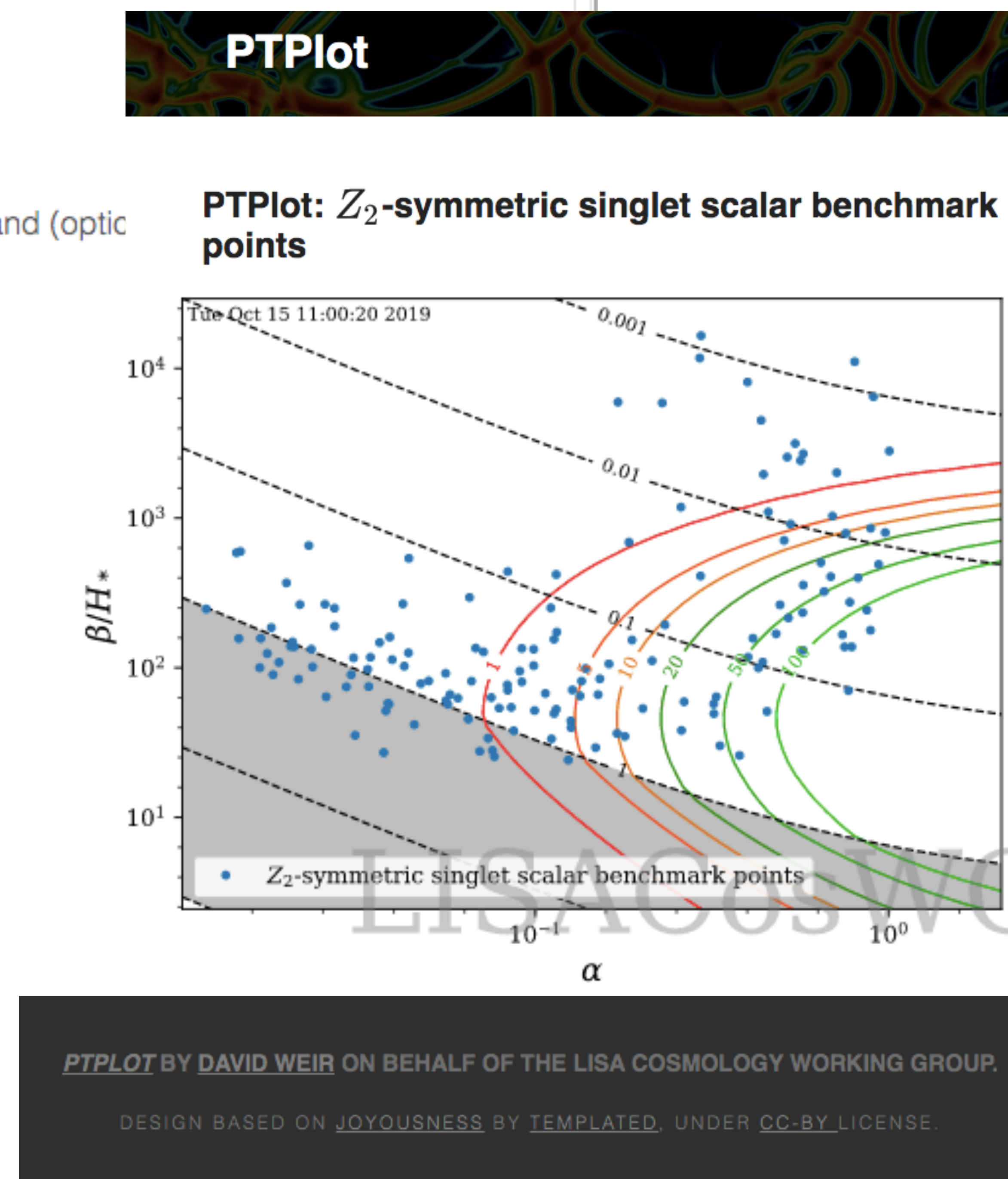




CC et al, arXiv:1910.13125

http://www.ptplot.org/ptplot/





SGWB from cosmic strings

Cosmic strings are topological defects that can be left over after a phase transition in the early universe

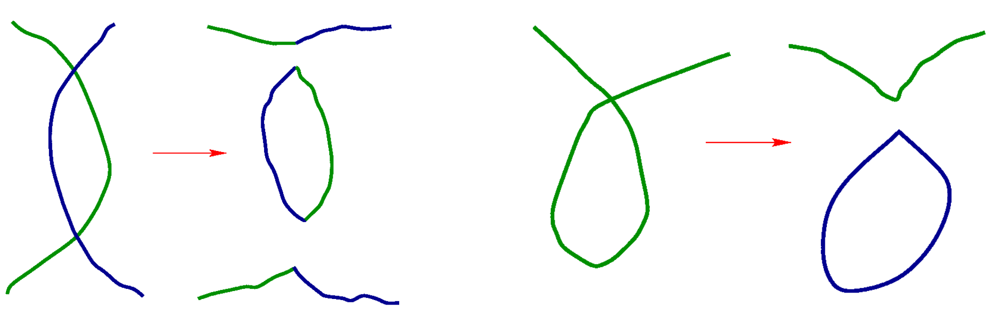
A network of cosmic strings emits a GW background

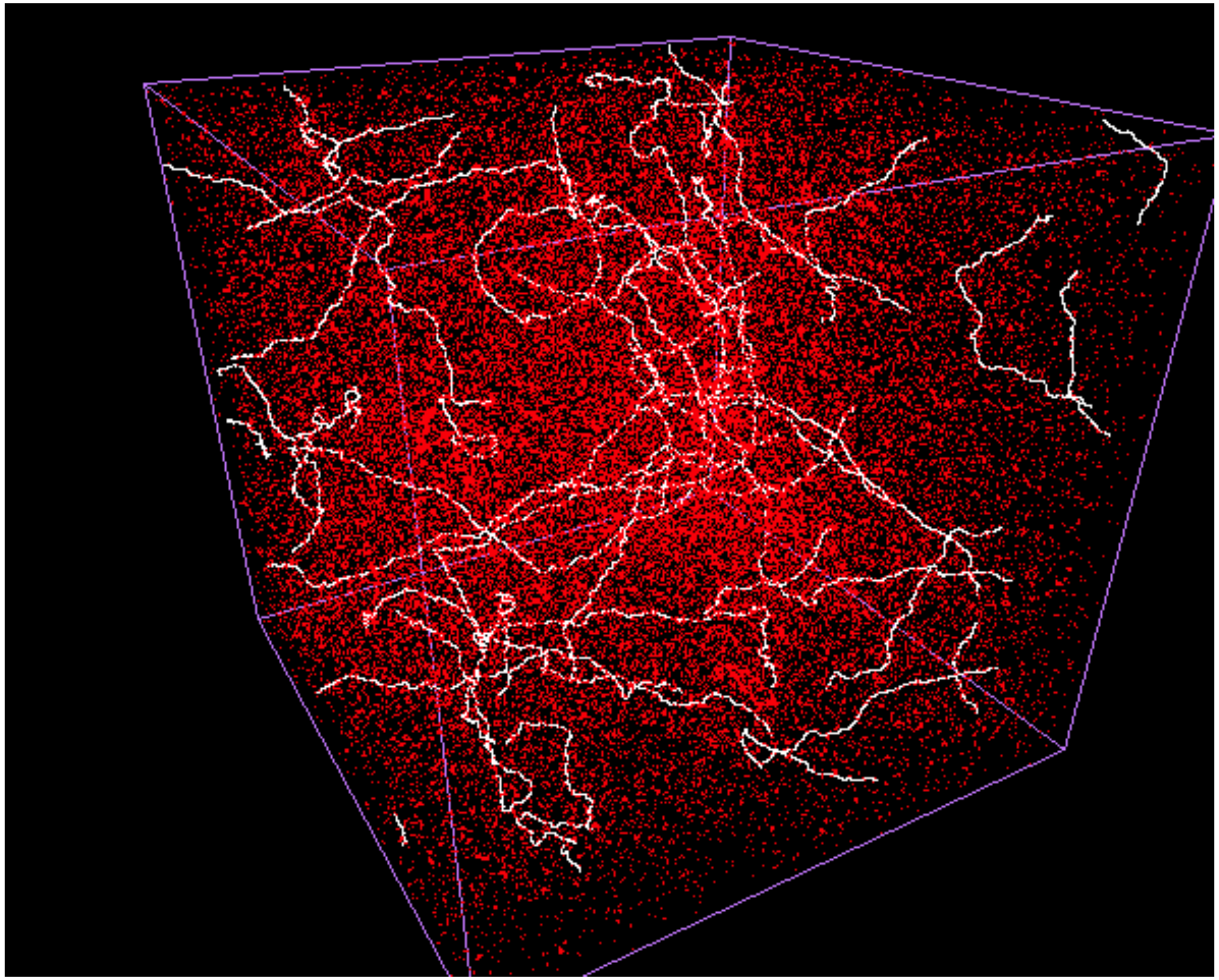
(though the results are very model dependent)

energy scale

$$G\mu \sim 10^{-6} \left(\frac{\eta}{10^{16}\,\mathrm{GeV}} \right)^2$$

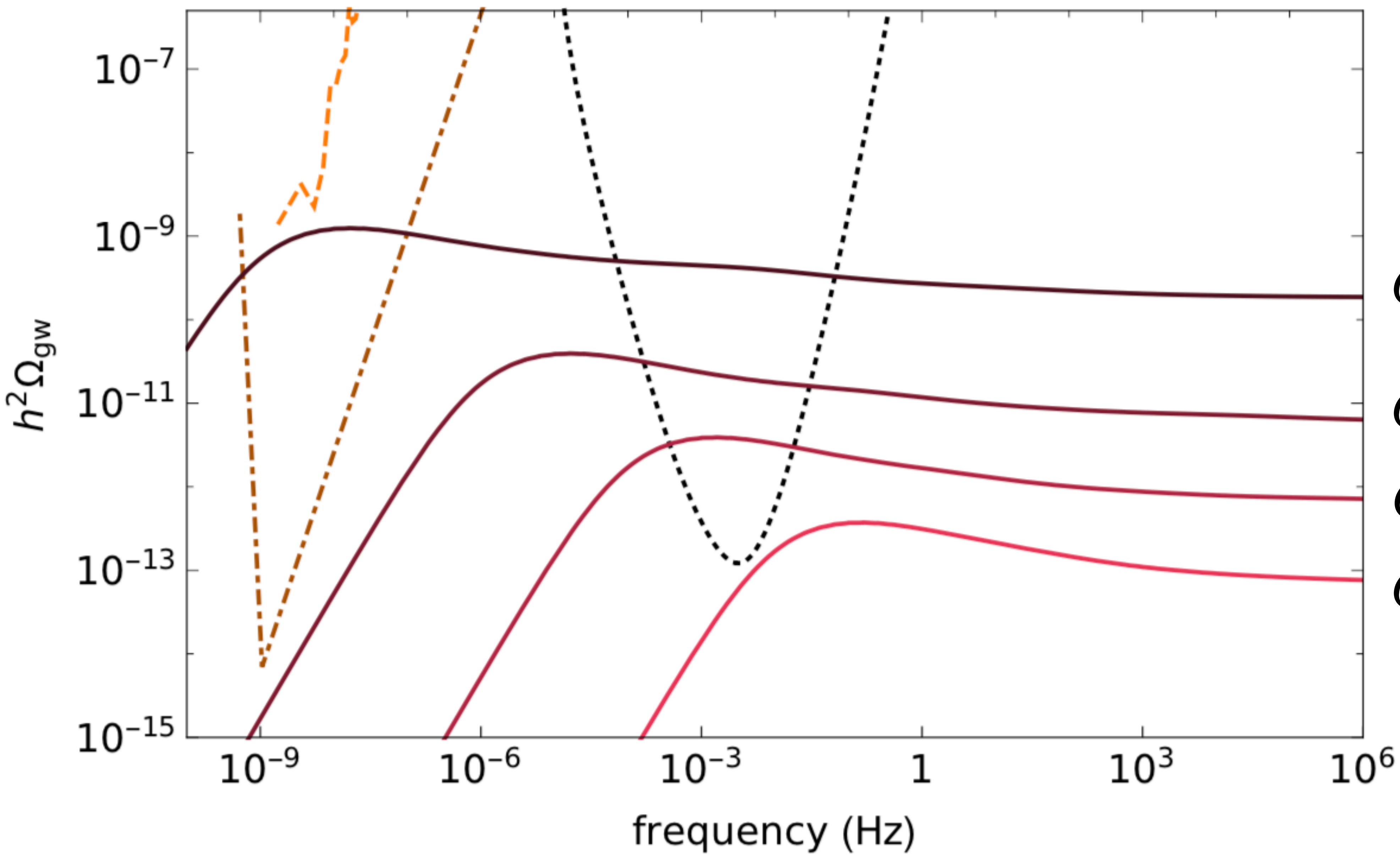
tension





https://curl.irmp.ucl.ac.be/~chris/strings.html

One model of Nambu Goto local strings



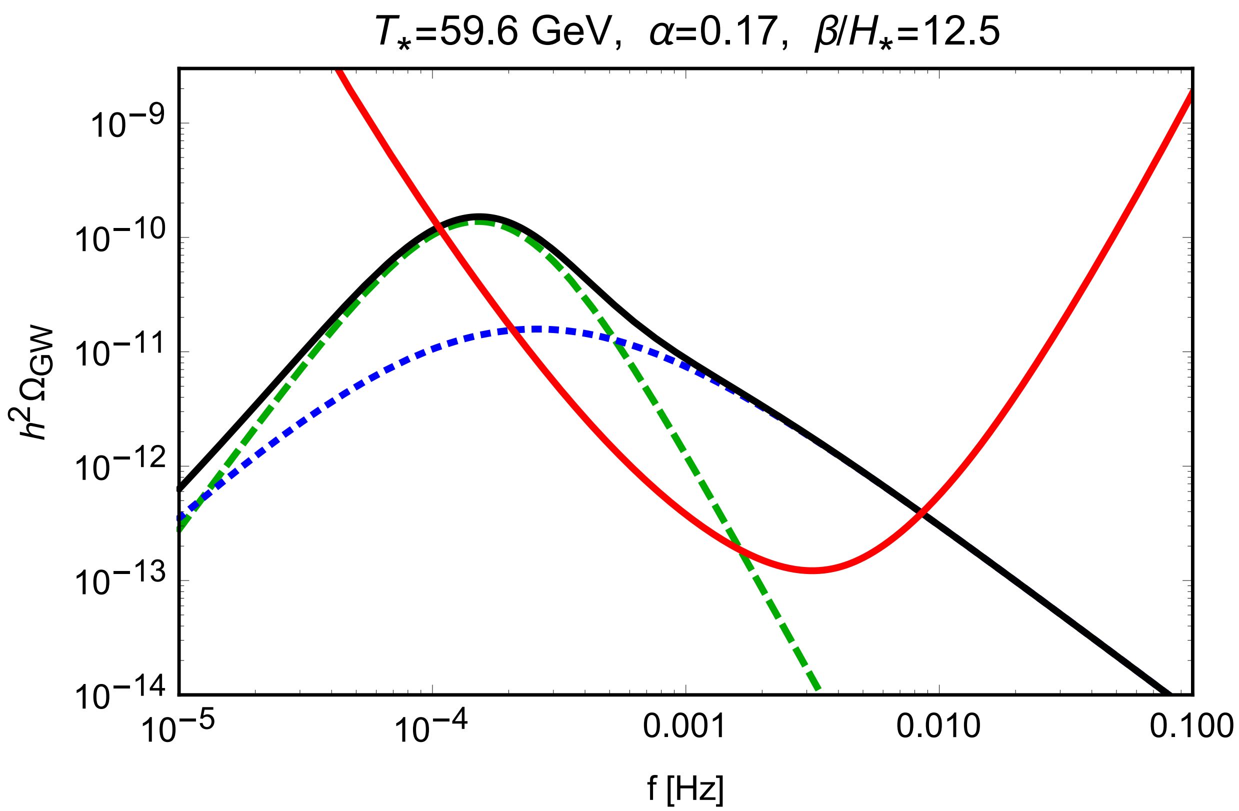
LISA $G\mu < \mathcal{O}(10^{-17})$

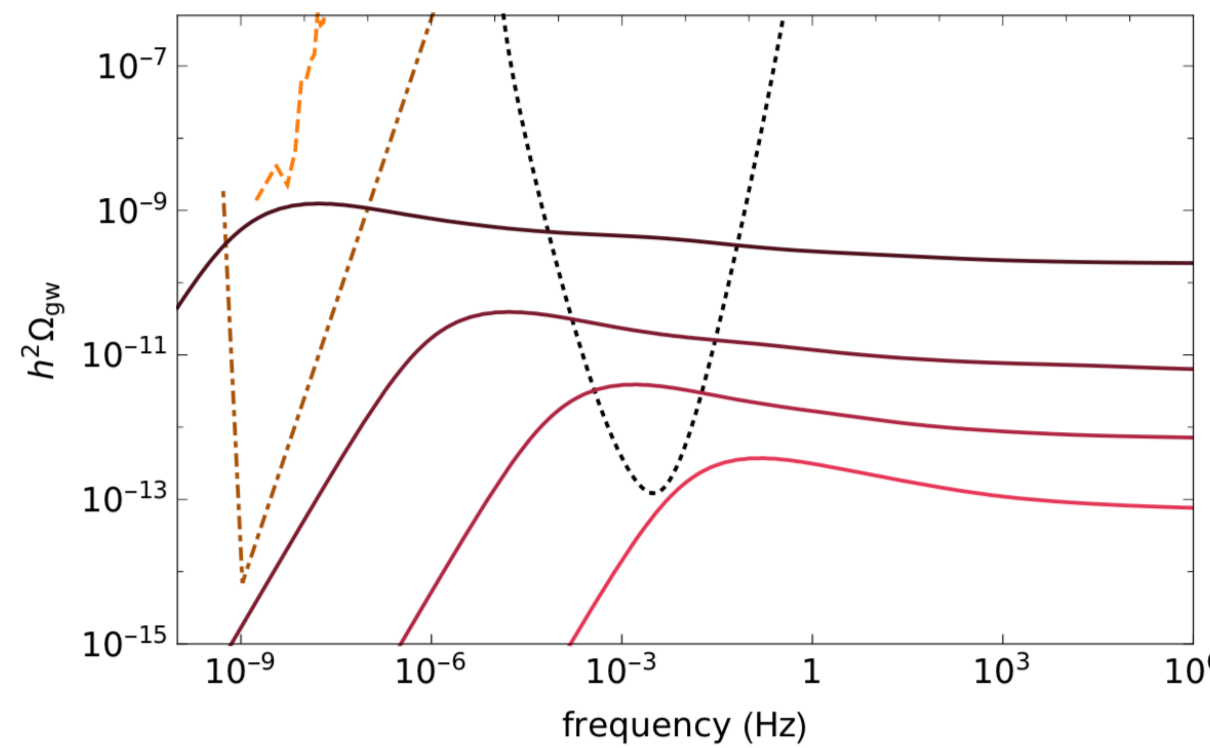
future CMB B-modes $G\mu < 10^{-9}$

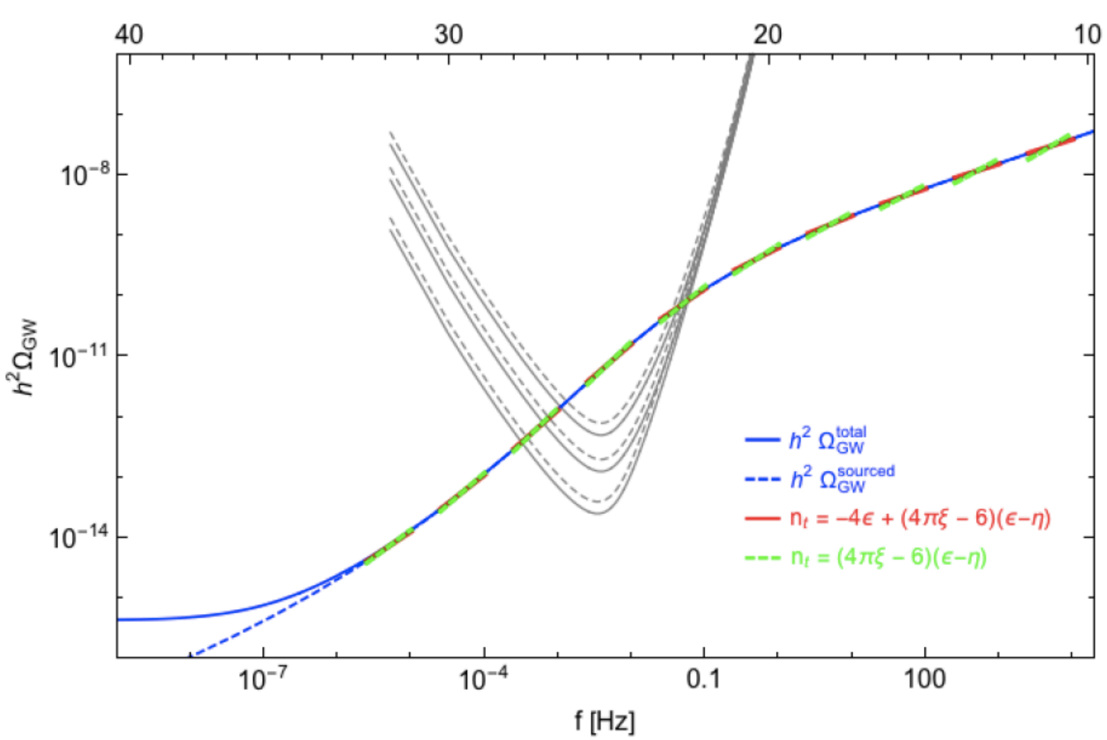
Future SKA $G\mu < 10^{-13}$

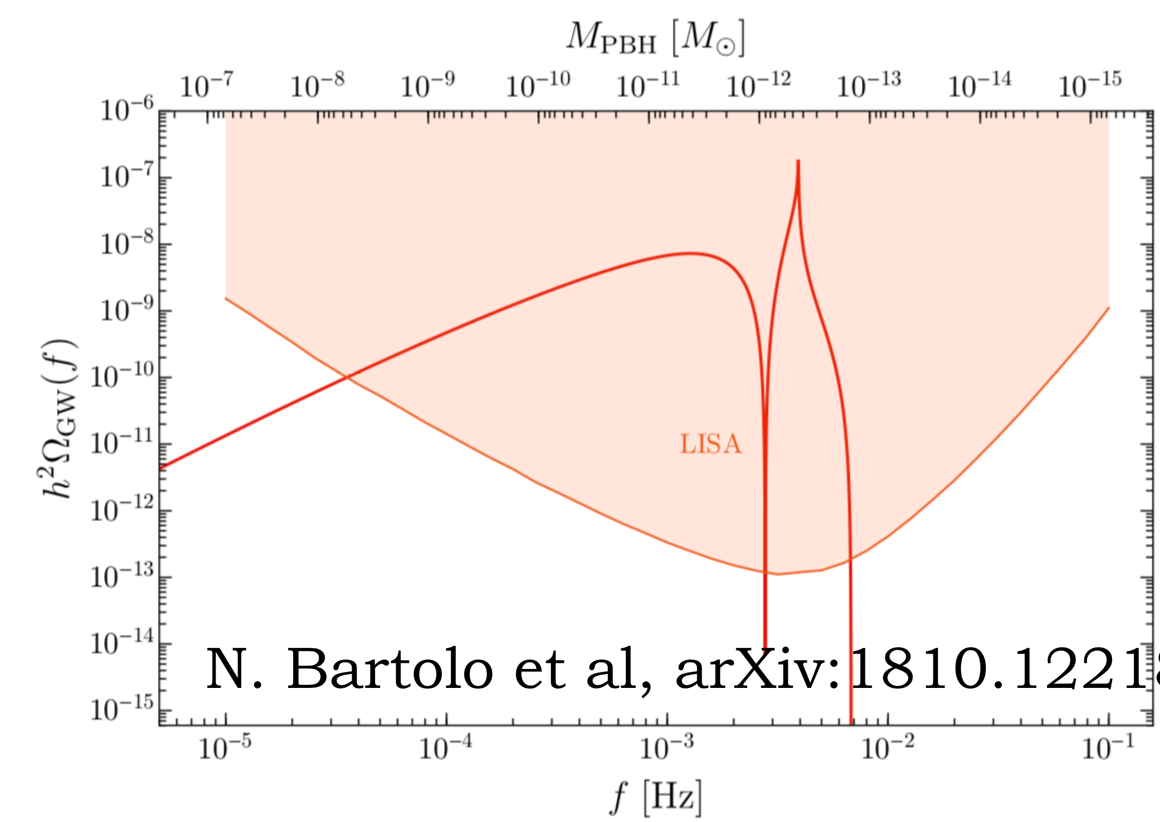
Auclair et al, arXiv:1909.00819

Suppose we detect a SGWB: is it primordial or astrophysical? Which source generated it?





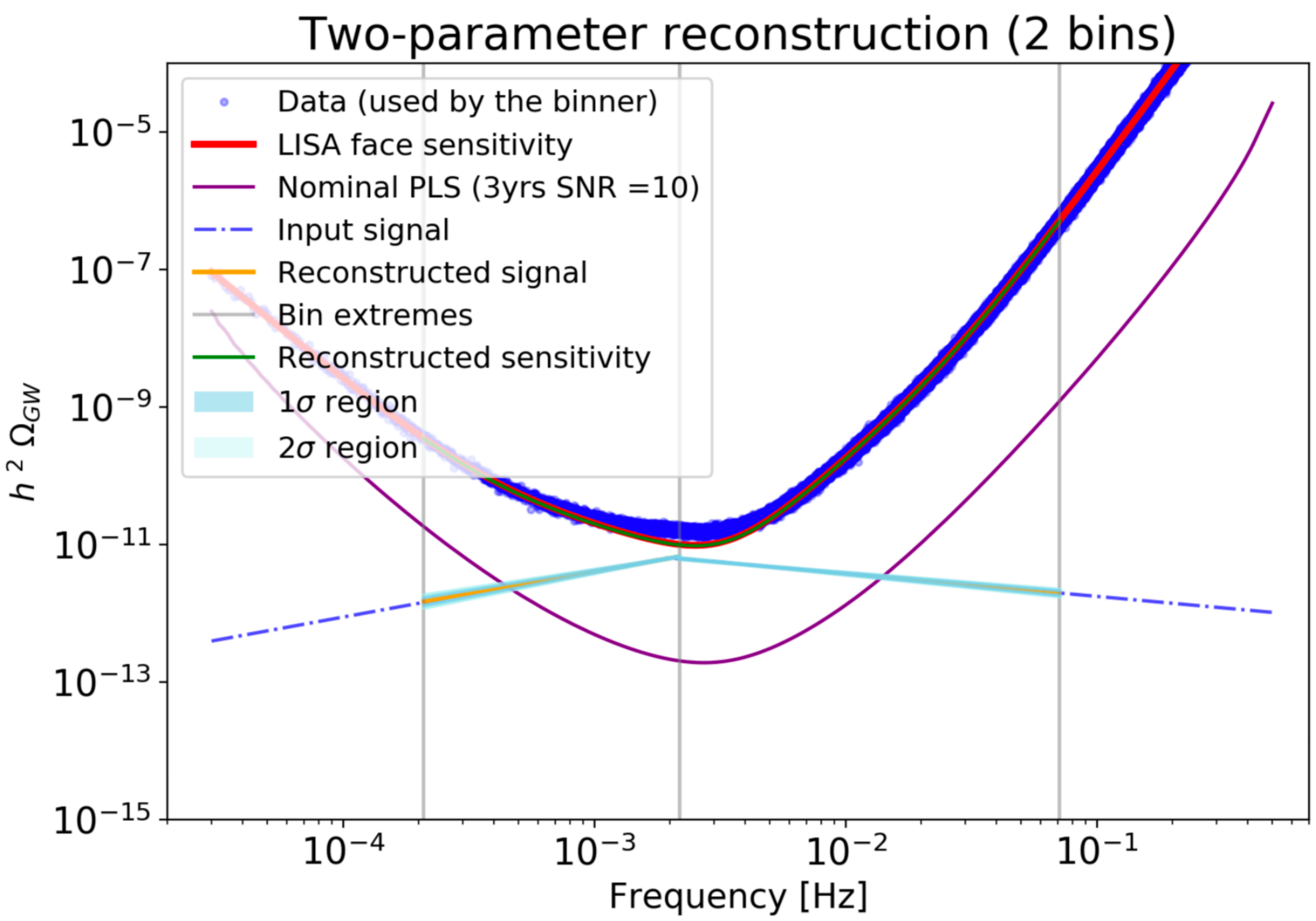


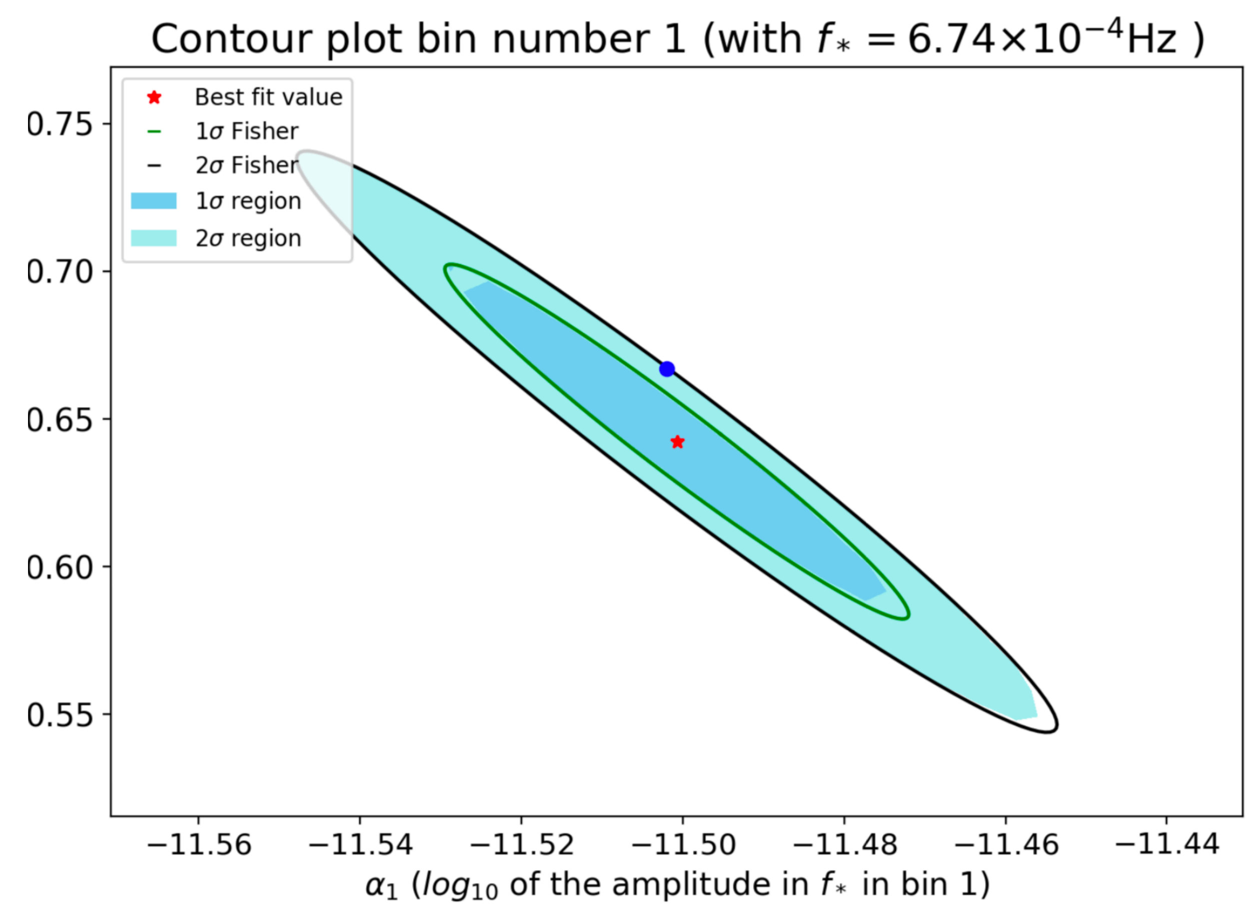


N. Bartolo et al, arXiv:1810.12218

The SGWBinner code proposes a method to reconstruct the SGWB shape

- Simulates data with noise
- Divides LISA sensitivity band in bins, and fits for noise and signal within each bin assuming a simple power law for the signal
- Merges nearby bins if the likelihood improves





CC et al, arXiv:1906.09244

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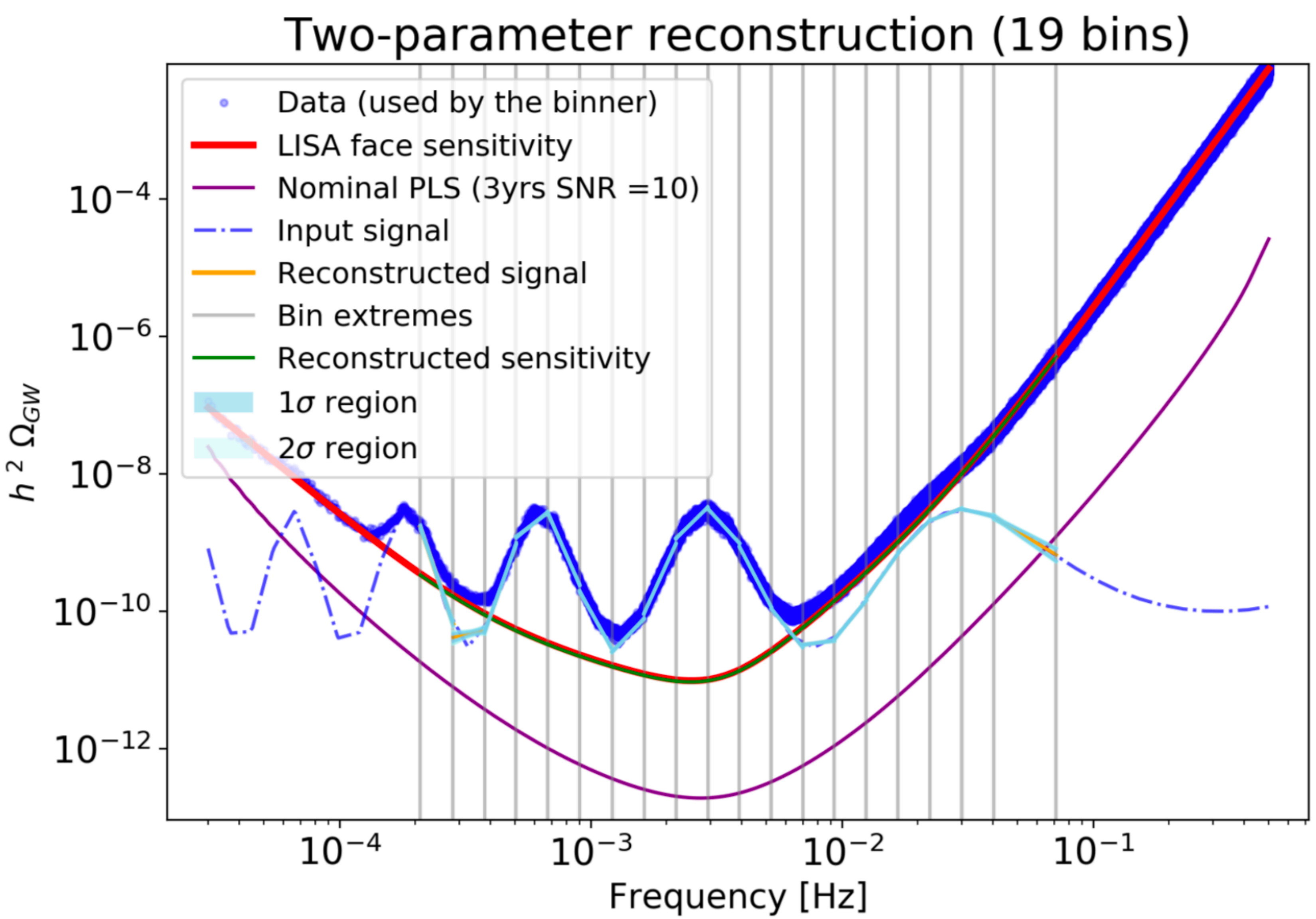
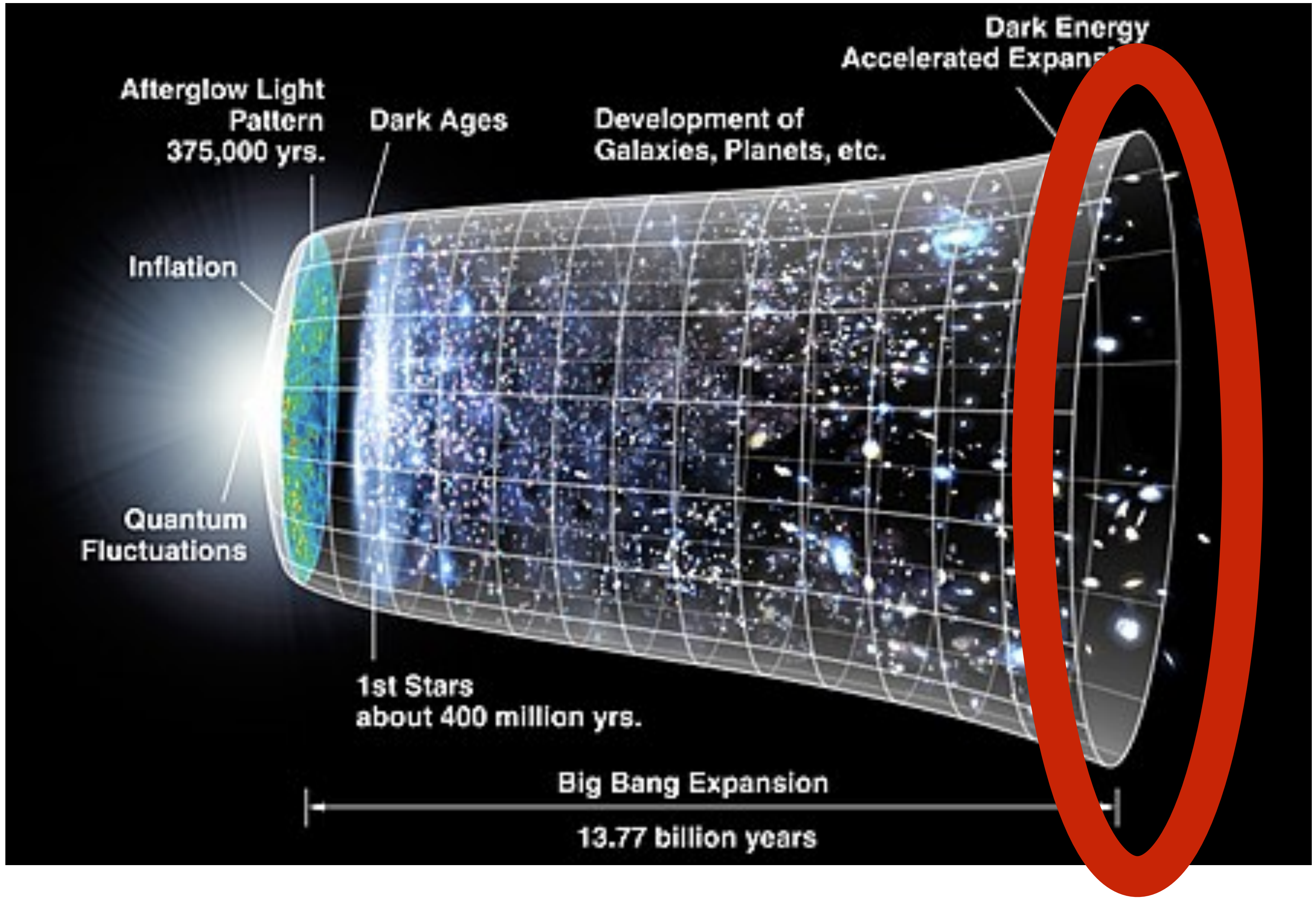


CC et al, arXiv:1906.09244

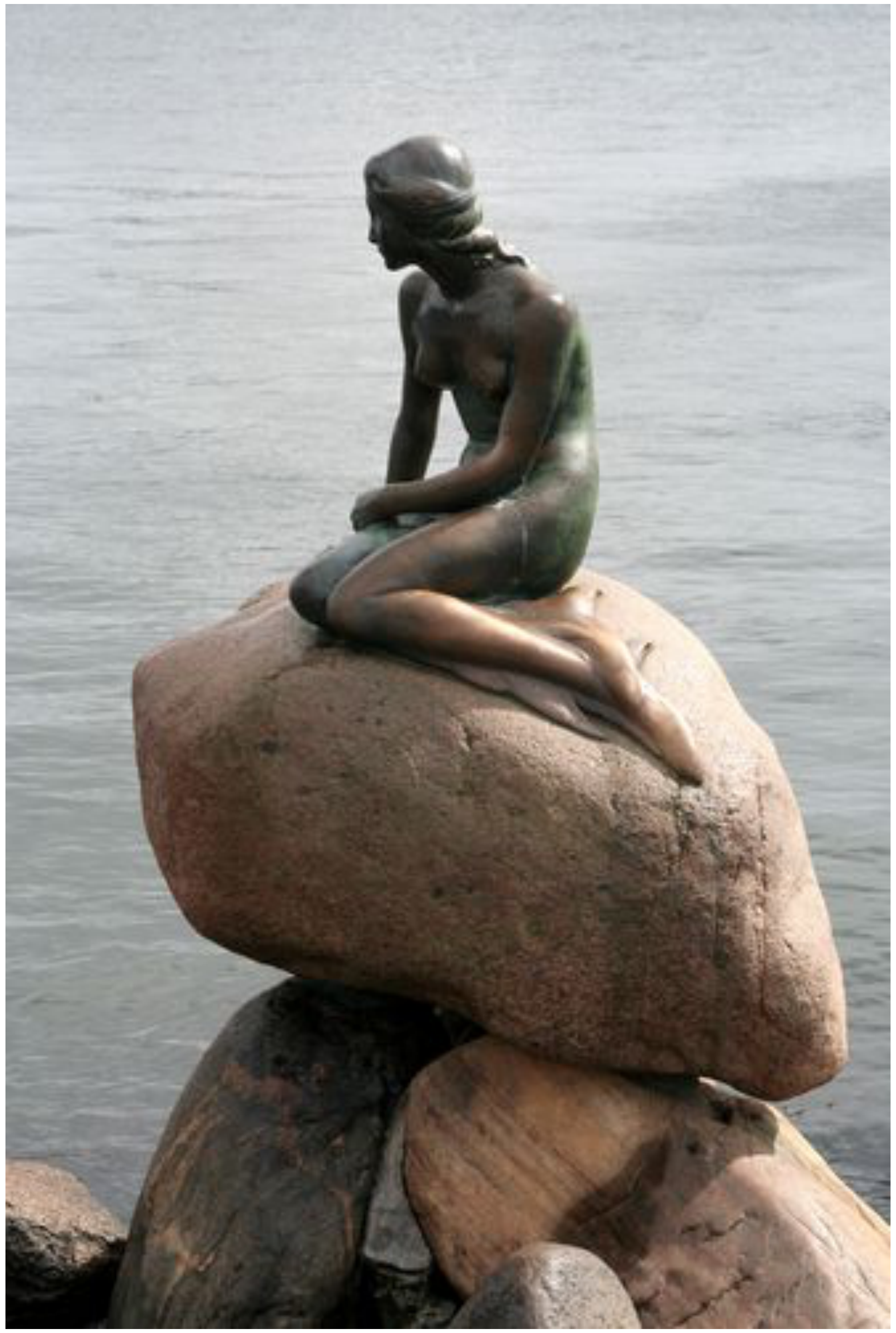
GW AND COSMOLOGY: late time universe



- forecasts of LISA standard sirens: type of sources, counterparts, new methods (GW propagation, clustering…)
- analysis of models and their observables: cosmological constant, (dynamical) dark energy, modified gravity theories, PBH…

Late-time 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

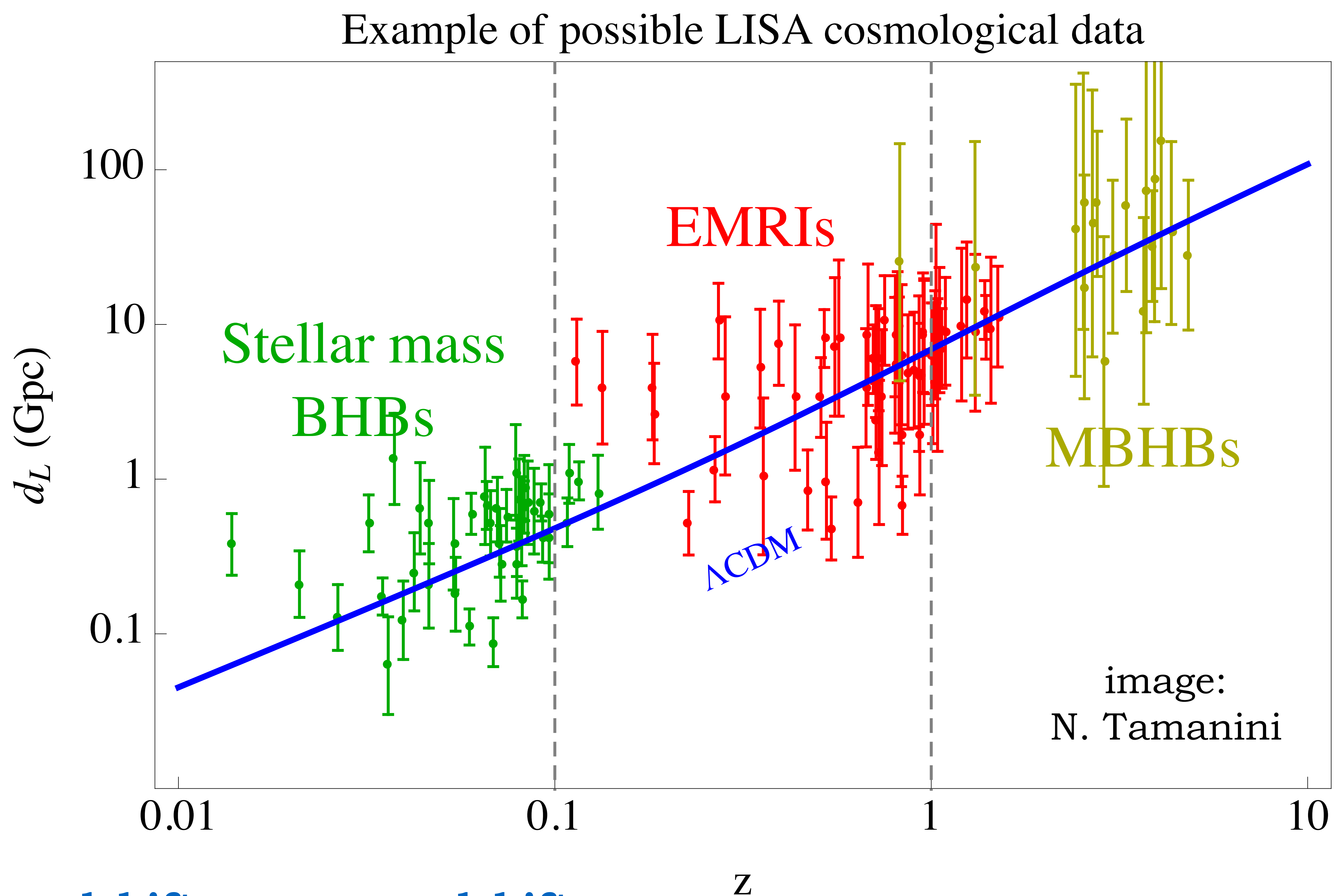
$$h_+(t) = \frac{4}{d_L(z)} \left(\frac{G\mathcal{M}_c}{c^2}\right)^{\frac{5}{3}} \left(\frac{\pi f}{c}\right)^{\frac{2}{3}} \frac{1+\cos^2 \imath}{2} \cos[\Phi(t)]$$

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

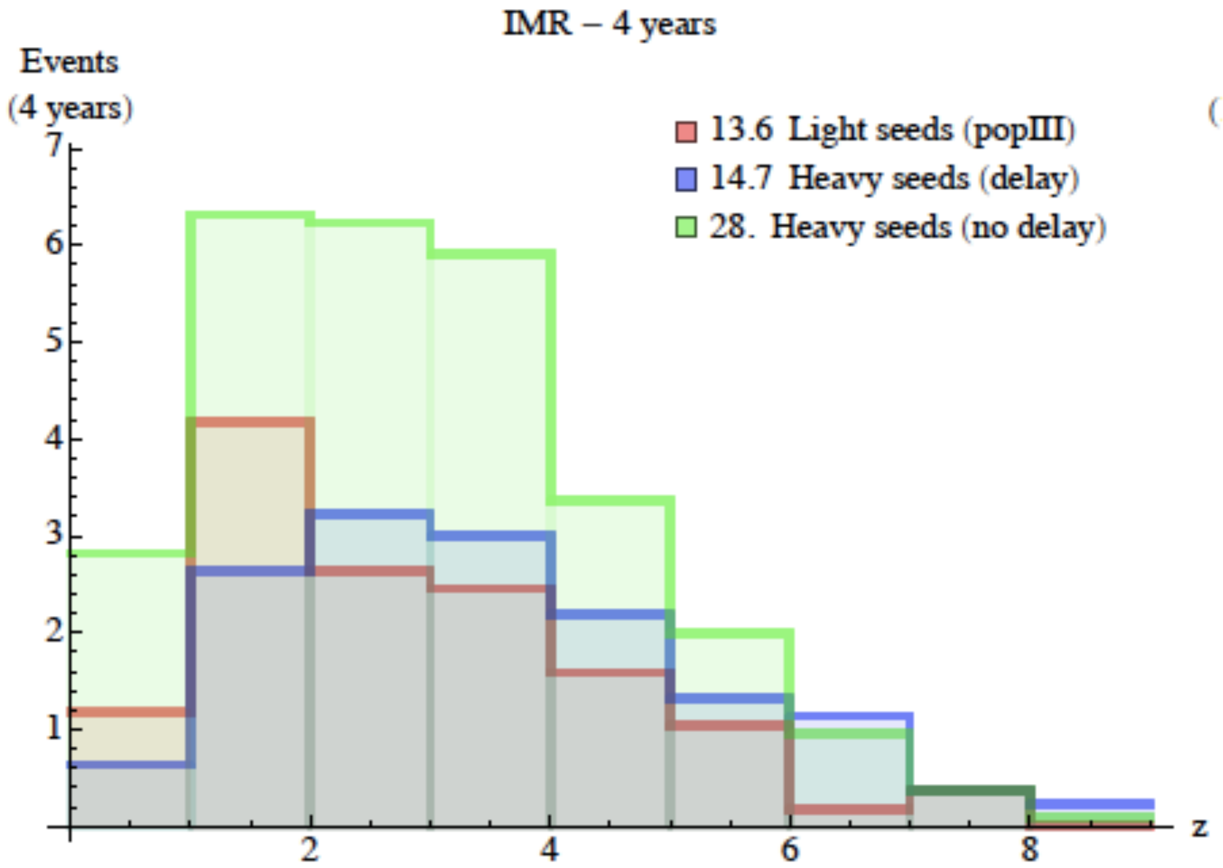
$$d_L(z, H_0, \Omega_M, \Omega_\Lambda, \dots)$$

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

Standard sirens with LISA



low redshift sources: redshift identification without counterpart



Massive black hole binaries catalogues used to test modified gravity theories

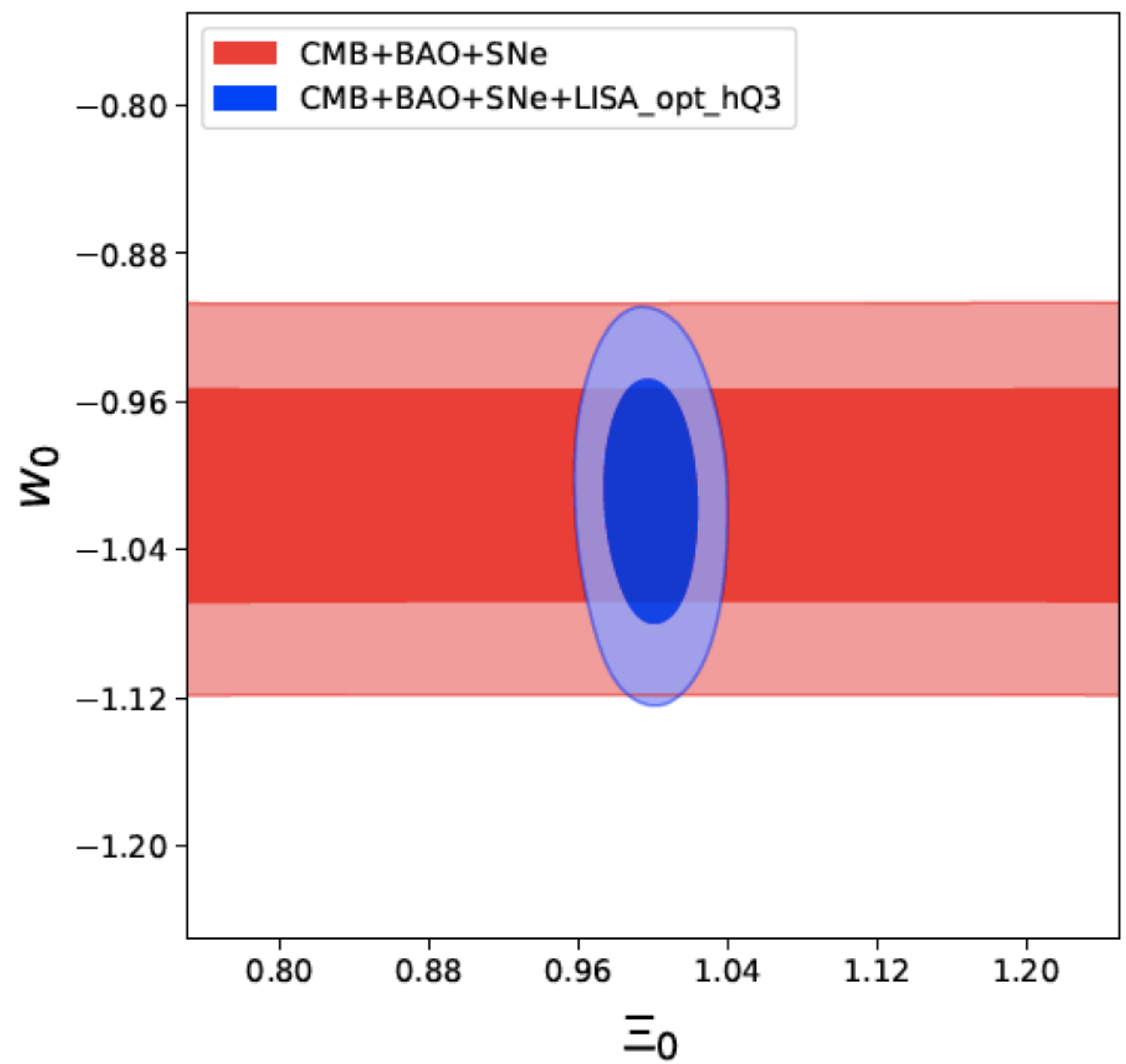
$$\frac{\Delta H_0}{H_0} = 3.8\%$$

Belgacem et al, arXiv:1906.01593

$$\tilde{h}''_A + 2\mathcal{H}[1-\delta(\eta)]\tilde{h}'_A + k^2\tilde{h}_A = 0$$

general parametrisation:

$$\frac{d_L^{\rm gw}(z)}{d_L^{\rm em}(z)} = \Xi_0 + \frac{1-\Xi_0}{(1+z)^n}$$



Conclusions

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

LISA is on the path to launch in 2034 and it has the potential to probe the early universe and late-time cosmology

there can be a cosmic relic SGWB which, if detected, will bring information on the very early universe and high energy physics (complementary to particle colliders)

LISA can test non-standard inflationary models, the EW symmetry breaking and beyond, cosmic strings...

GW emission from compact binaries with or without em counterpart can be used to probe the cosmological parameters and modified gravity theories