COSMOLOGY WITH GRAVITATIONAL WAVES

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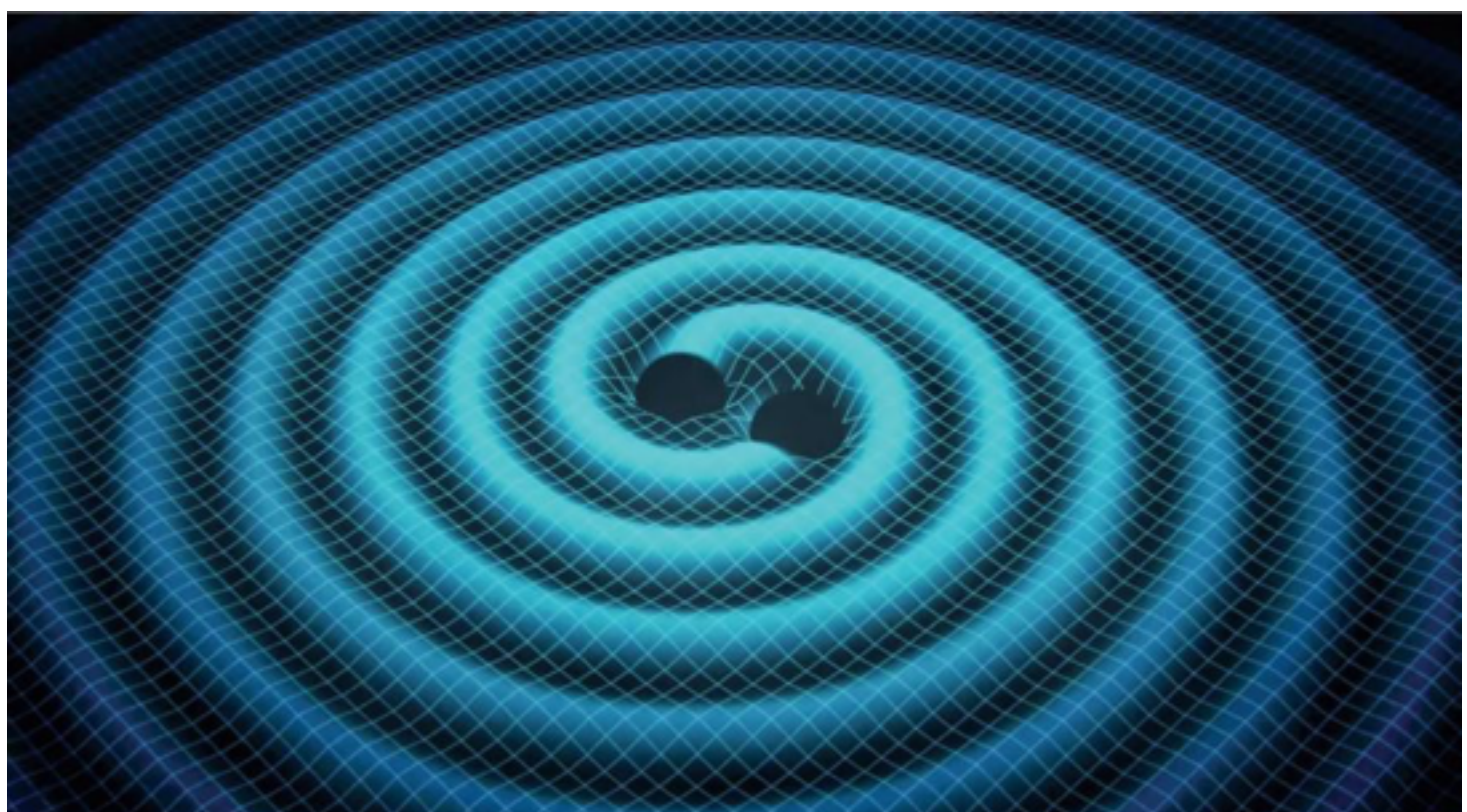


Outline

- overview of the current situation concerning GW detection
- focus on cosmology with GW : stochastic background from cosmological sources and standard sirens to probe the background expansion of the universe
- new results for eLISA : stochastic background of GW from first order phase transitions
- new results for eLISA : standard sirens from massive black hole binaries

Current situation for GW detection

- terrestrial interferometers : advanced LIGO/Virgo (direct, operating)

  - aLIGO : detection after two days of operation
  - Observation run **O1**: 4 months, wait for further data release
  - 2016-2017 **O2**: 6 months aLIGO and aVirgo
  - 2017-2018 **O3**: 9 months aLIGO, aVirgo and KAGRA
  - 2019+ : reach full sensitivity
  - 2022+ : LIGO India

  - targeted detection : BHBH, NSBH, NSNS coalescing binaries (masses of order of one to tents of solar masses)
  - supernovae explosion?
  - stochastic background?

frequency range of detection:

$$1\,\mathrm{Hz} < f < 1\,\mathrm{kHz}$$

Current situation for GW detection

- pulsar timing arrays (indirect, operating)
  - IPTA (EPTA, NanoGrav, PPTA)
  - PPTA, EPTA : interesting upper bounds on stochastic background from inspiralling SMBH binaries (masses of order 10^9 solar masses)

frequency range of detection:

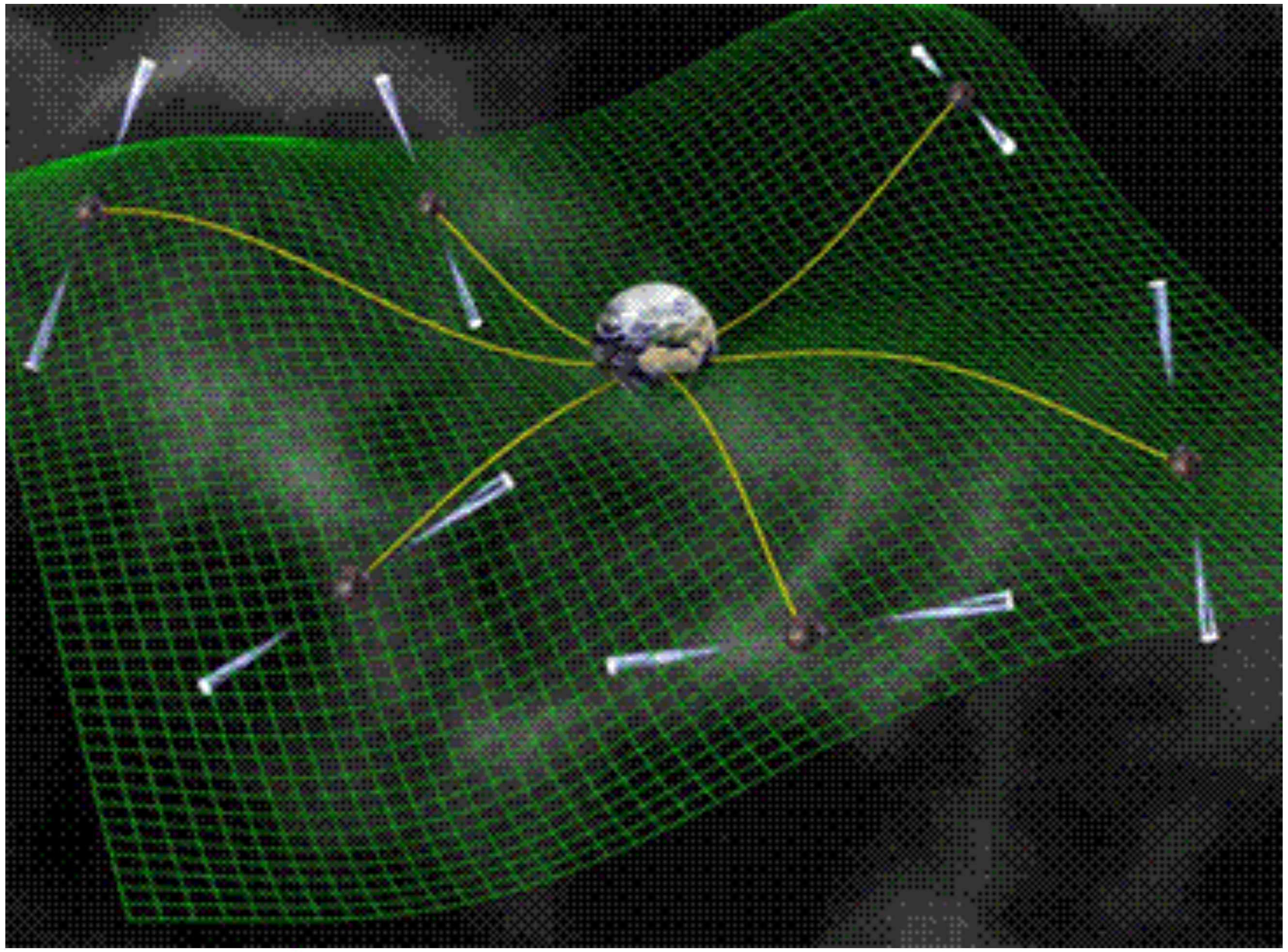
$$10^{-9}\,\mathrm{Hz} < f < 10^{-7}\,\mathrm{Hz}$$

upper bound on stochastic background:

$$\Omega_{\mathrm{GW}} < 1.1 \cdot 10^{-9}$$

$$f \simeq 2.8\,\mathrm{nHz}$$

Lentati et al 1504.03692



Current situation for GW detection

- cosmic microwave background (indirect, operating)

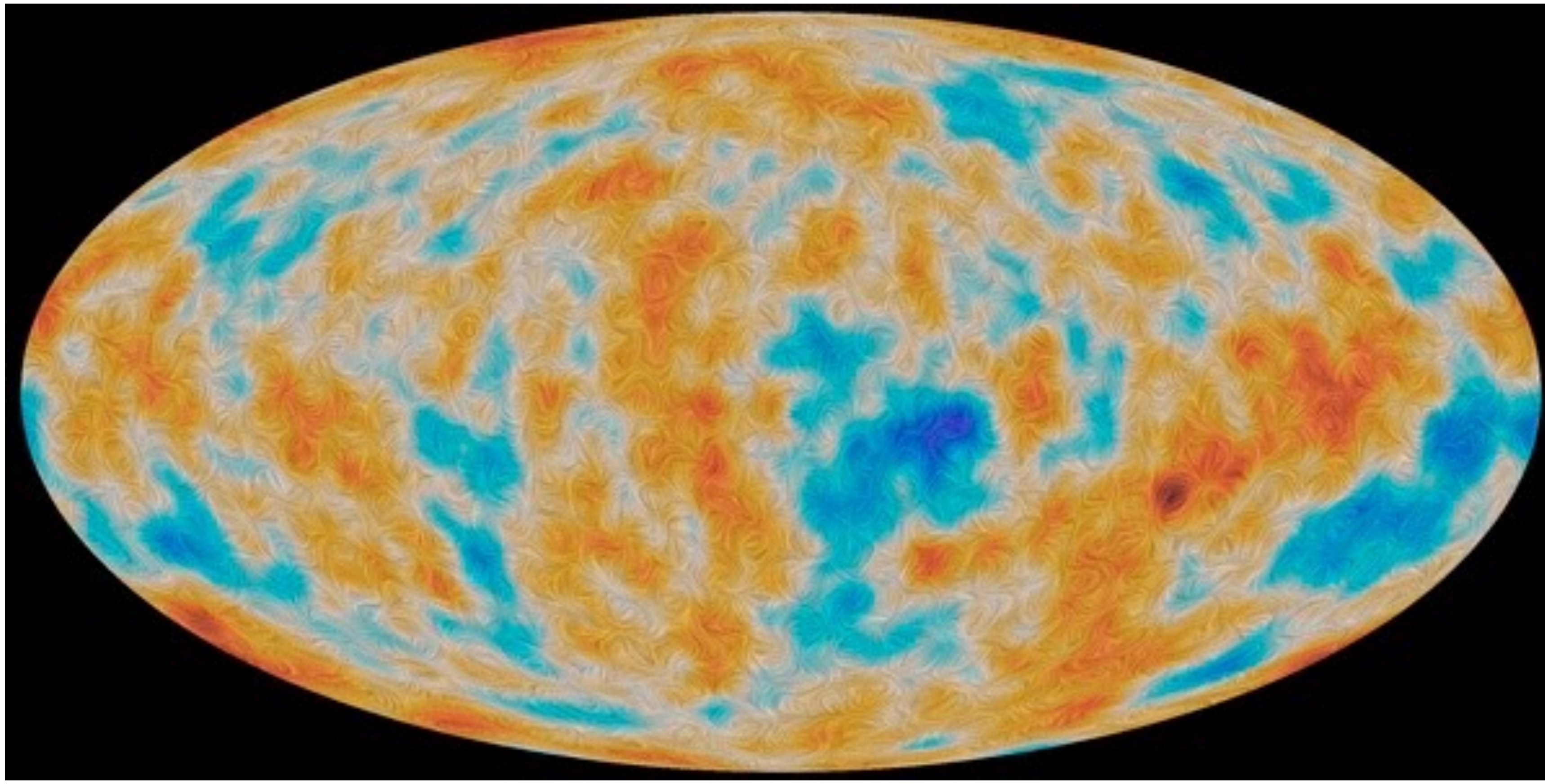
  - from temperature fluctuations (old) and B polarisation
  - upper bound on the signal from inflation from Planck and BICEP
  - new experiments from ground or a new satellite are expected in the time scale from here to 2030

frequency range of detection: $10^{-18}\,\mathrm{Hz} < f < 10^{-16}\,\mathrm{Hz}$

upper bound on stochastic background:

$$h^2\Omega_{\rm GW} \lesssim 10^{-11}\left(\frac{H_0}{f}\right)^2$$

Lasky et al 1511.05994



Current situation for GW detection

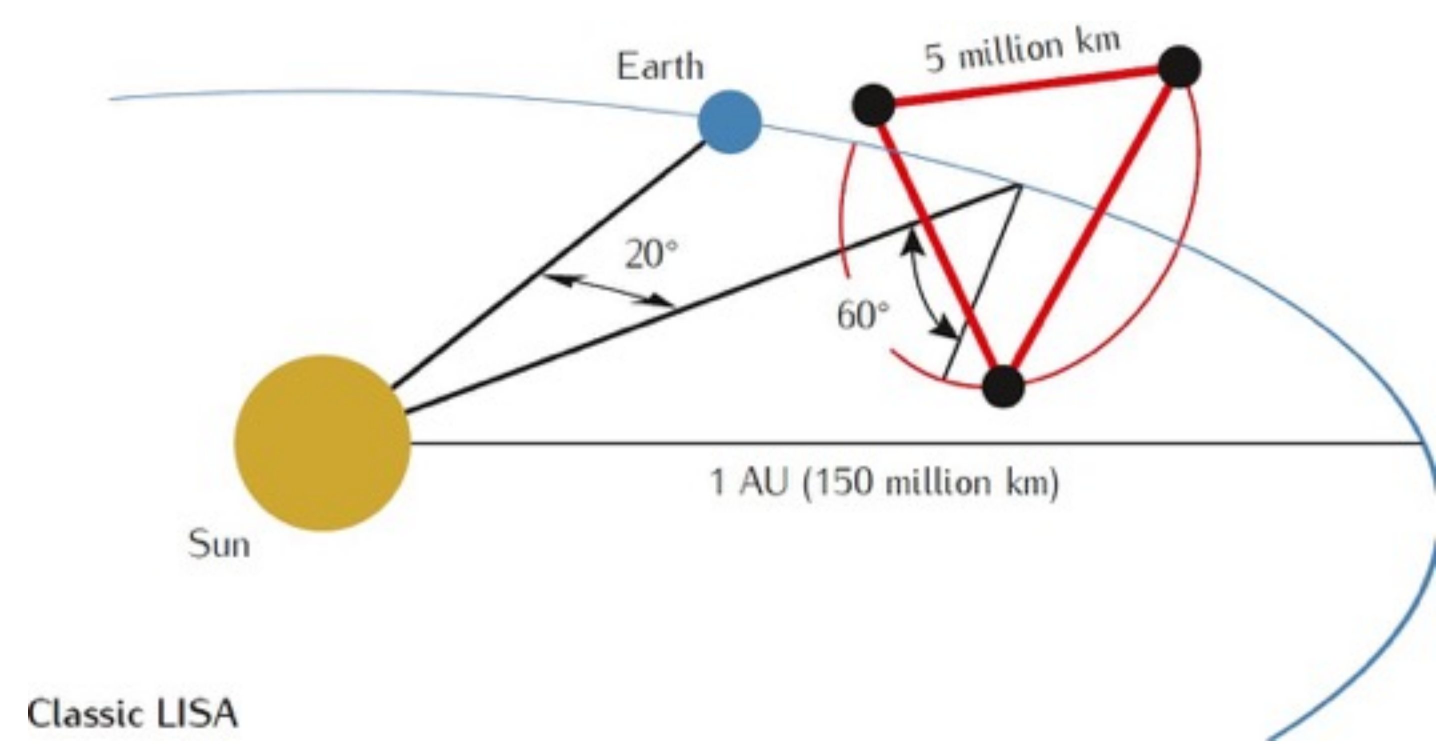
- space based interferometers (direct, future)

  - launch of LISA Pathfinder on Dec 3, science begun in March
  - ESA L3 mission will be a GW observer (launch 2030-2034)
  - **eLISA** : committee appointed by ESA to study the mission design, results provided last March
  - detailed design and member state contributions to be defined in the next months for a call in autumn
  - targeted detection : MBH binaries (masses of order $10^{3\text{-}7}$ solar masses)

frequency range of detection:

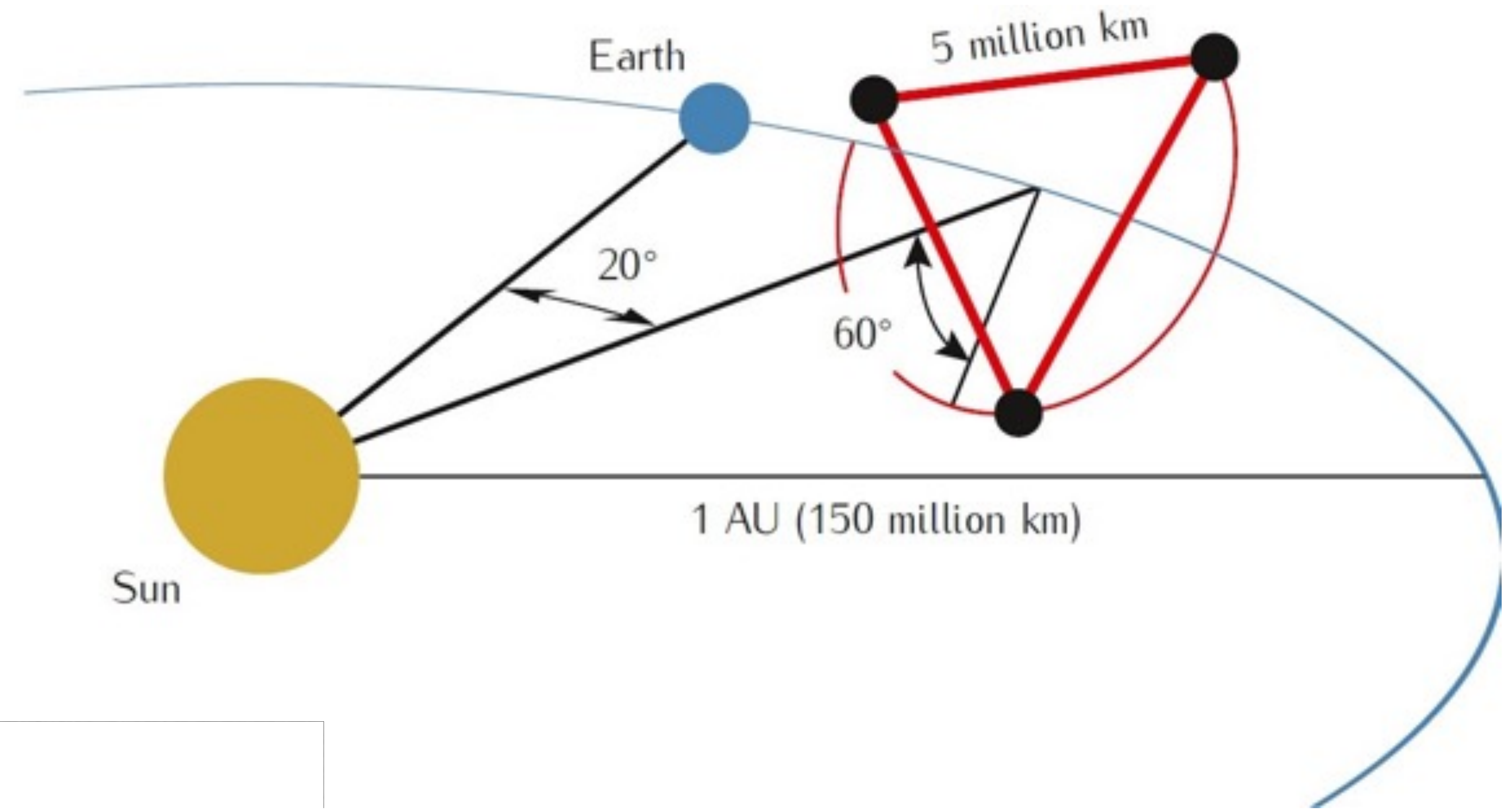
$$10^{-4}\,\mathrm{Hz} < f < 1\,\mathrm{Hz}$$

GW AND COSMOLOGY :
some results from the *eLISA cosmology working group*



eLISA observatory

www.elisascience.org

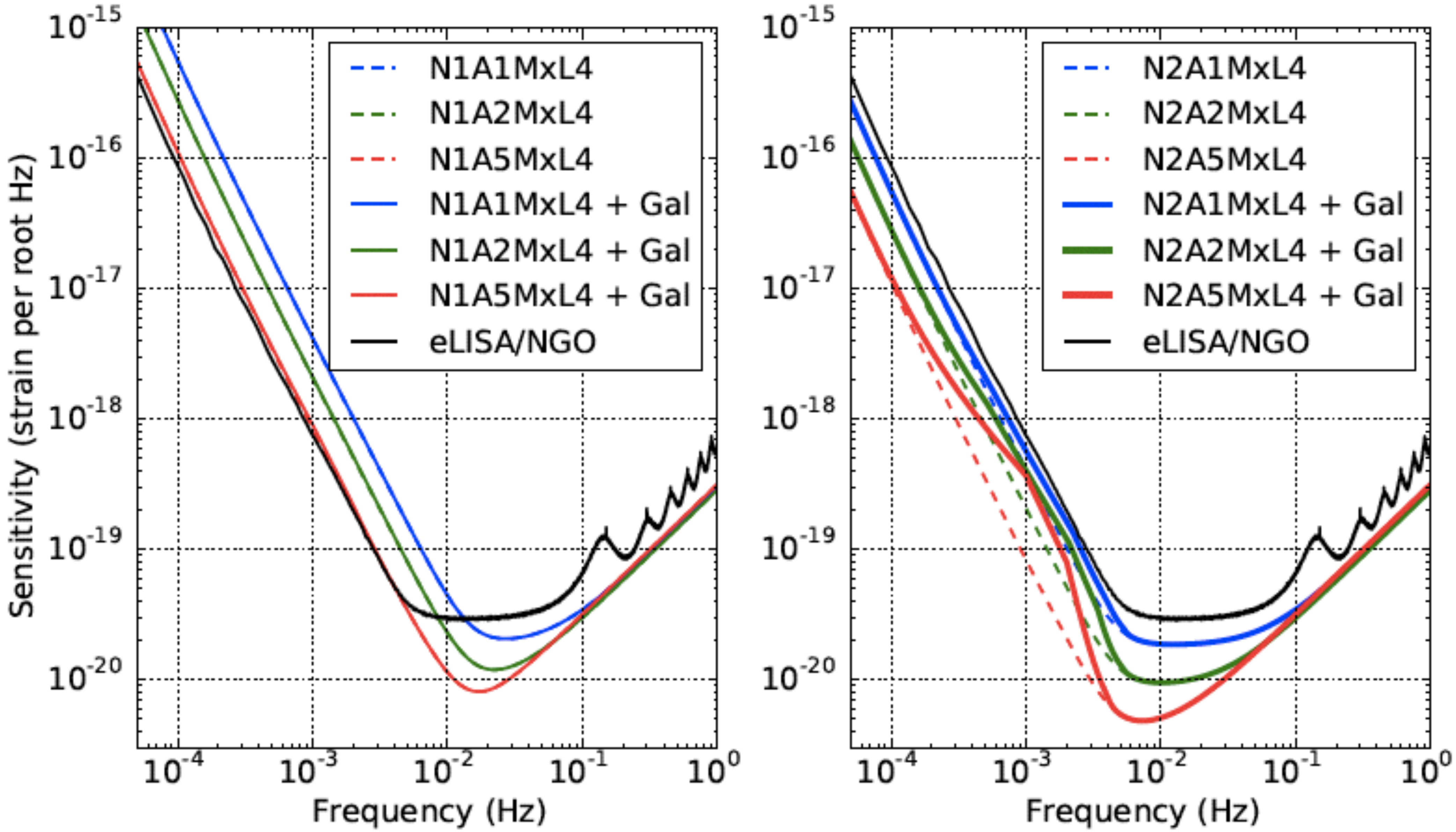


eLISA mission design study for ESA

- number of laser links : 4 or 6?
- length of the arms : 1, 2, 5 million km?
- noise level : pathfinder required (worst) or pathfinder expected (better)?
- duration : two or five years ?

working groups studied the science return of different designs

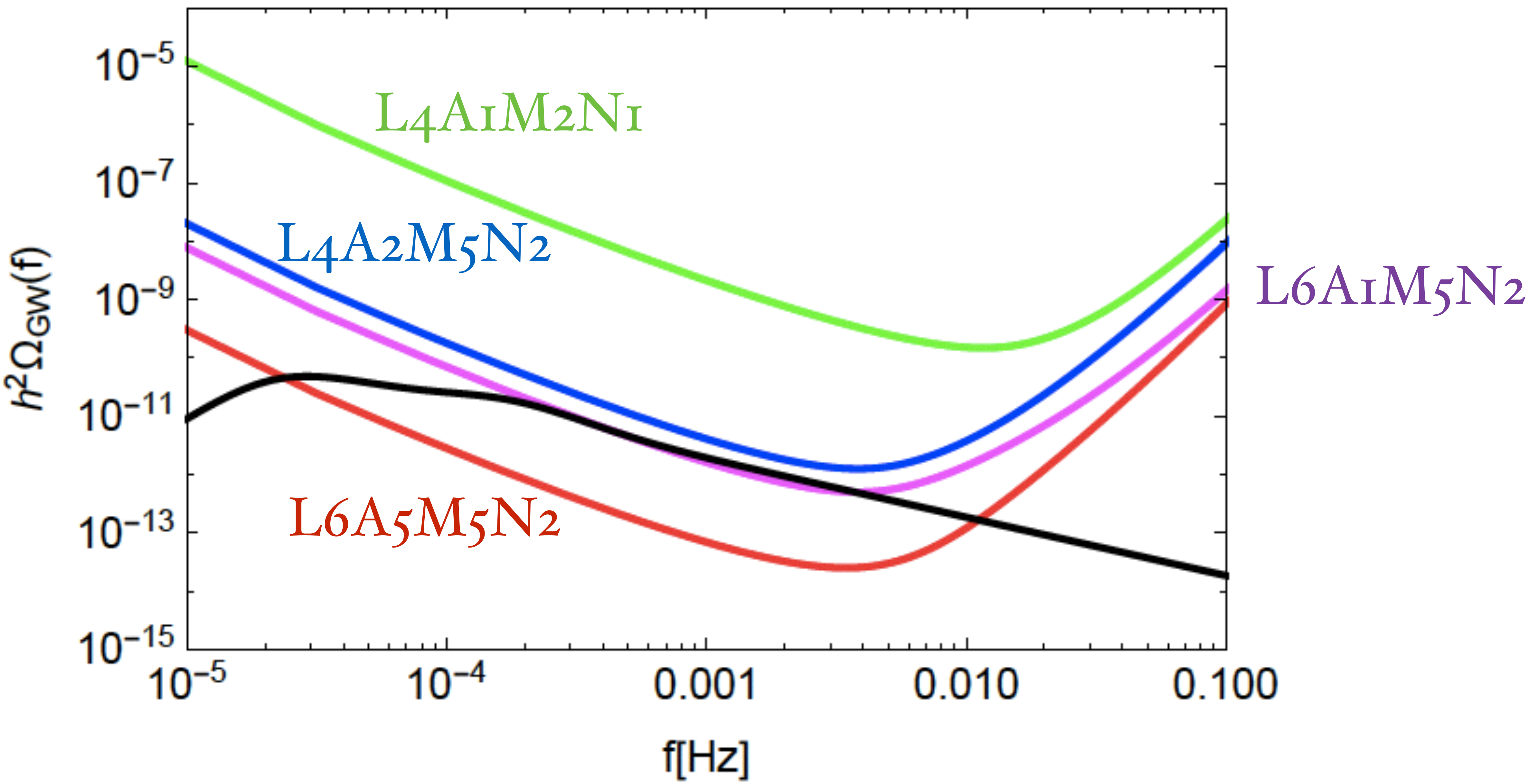
eLISA observatory



papers on the science return of different designs

A. Klein et al, arXiv1511.05581 : MBH binaries
CC et al, arXiv1512.06239 : primordial phase transitions
N. Tamanini et al, arXiv1601.07112 : standard sirens

eLISA observatory



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the stochastic background from cosmological sources

GW from cosmological 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 cosmological sources

tensor perturbations of FRW metric:

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

WAVE EQUATION

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

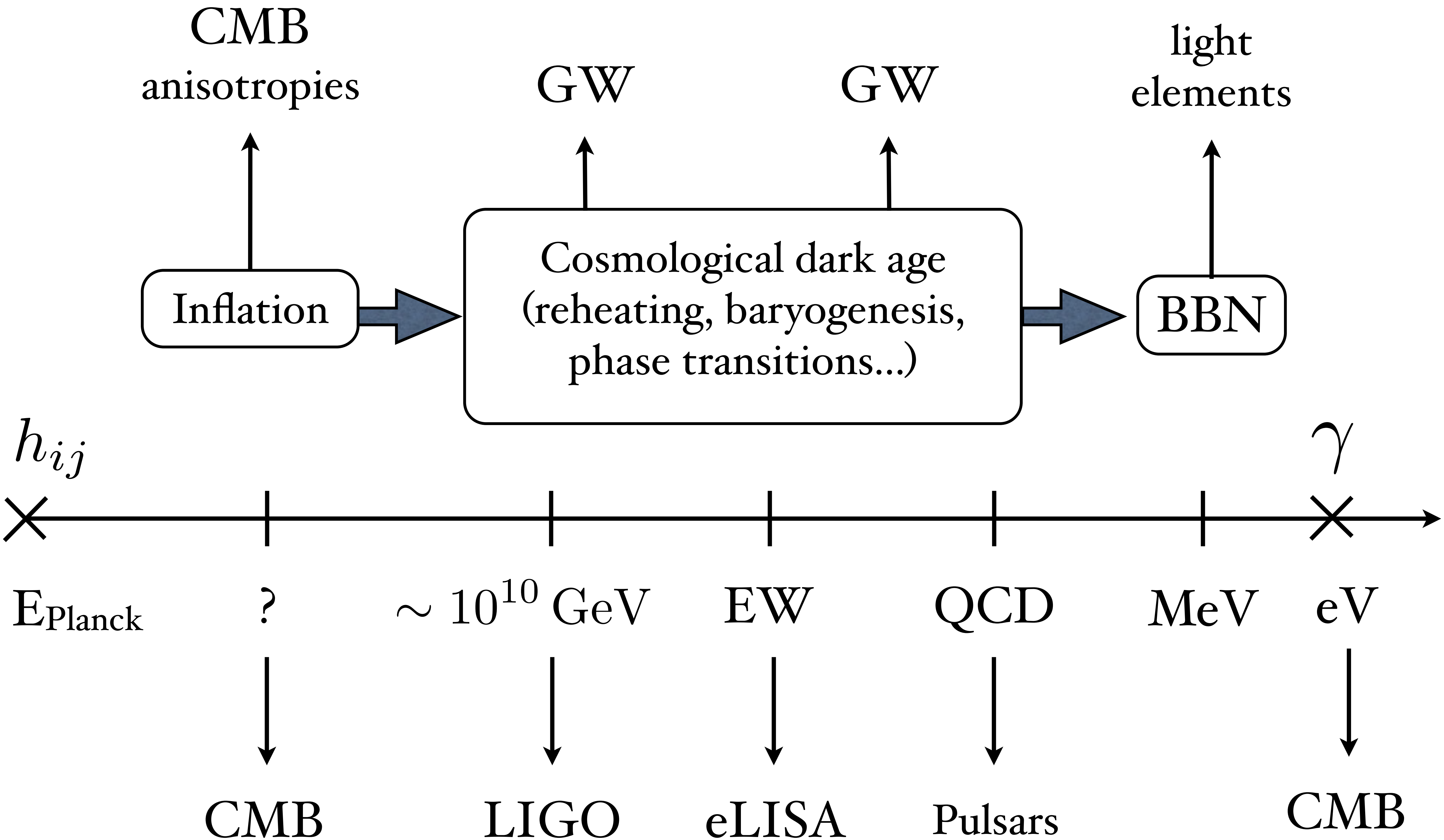
source: Π_{ij}^{TT} tensor anisotropic stress

- fluid $\quad \Pi_{ij} \sim \gamma^2(\rho + p)\,v_i v_j$
- electromagnetic field $\quad \Pi_{ij} \sim \frac{(E^2 + B^2)}{3} - E^i E^j - B^i B^j$
- scalar field $\quad \Pi_{ij} \sim \partial_i\phi\,\partial_j\phi$

GW from cosmological sources

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

$$\frac{\Gamma(T)}{H(T)} \sim \frac{G^2\, T^5}{T^2/M_{Pl}} \sim \left(\frac{T}{M_{Pl}}\right)^3 < 1$$



CMB
anisotropies
GW
GW
light
elements
Inflation
Cosmological dark age
(reheating, baryogenesis,
phase transitions...)
BBN
h_{ij}
γ
E_{Planck}
?
$\sim 10^{10}$ GeV
EW
QCD
MeV
eV
CMB
LIGO
eLISA
Pulsars
CMB

GW from cosmological sources

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

$$\frac{\Gamma(T)}{H(T)} \sim \frac{G^2 T^5}{T^2/M_{Pl}} \sim \left(\frac{T}{M_{Pl}}\right)^3 < 1$$

- sources from the early universe: stochastic background of GW statistically homogenous, isotropic and Gaussian

$$\langle \dot{h}_{ij}(\mathbf{k}) \dot{h}^*_{ij}(\mathbf{q}) \rangle = (2\pi)^3 \delta(\mathbf{k}-\mathbf{q}) |\dot{h}(k)|^2$$

  - GW generated by anisotropic stresses: causal source many independent horizon volumes visible today

  - inflation: intrinsic, quantum fluctuations that become classical (stochastic) outside the horizon

GW from cosmological sources

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

$$\frac{\Gamma(T)}{H(T)} \sim \frac{G^2\, T^5}{T^2/M_{Pl}} \sim \left(\frac{T}{M_{Pl}}\right)^3 < 1$$

- sources from the early universe: stochastic background of GW statistically homogenous, isotropic and Gaussian

$$\langle \dot{h}_{ij}(\mathbf{k}) \dot{h}^*_{ij}(\mathbf{q}) \rangle = (2\pi)^3 \delta(\mathbf{k}-\mathbf{q}) |\dot{h}(k)|^2$$

GW energy density power spectrum

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

GW frequency : $f = f_* \dfrac{a_*}{a_0}$

Characteristic frequency for *causal sources*

(not inflation, GW generated by anisotropic stresses)
causal source of GW cannot operate beyond the horizon (Hubble scale):

$$f_* = \frac{H(T_*)}{\epsilon_*} \qquad \epsilon_* \leq 1$$

parameter depending on the dynamics of the source

Hubble rate is related to temperature in the universe :
assuming standard thermal history

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

characteristic frequency today

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

Characteristic frequency for *causal sources*

(not inflation, GW generated by anisotropic stresses)
causal source of GW cannot operate beyond the horizon (Hubble scale):

$$f_* = \frac{H(T_*)}{\epsilon_*} \qquad \epsilon_* \leq 1$$

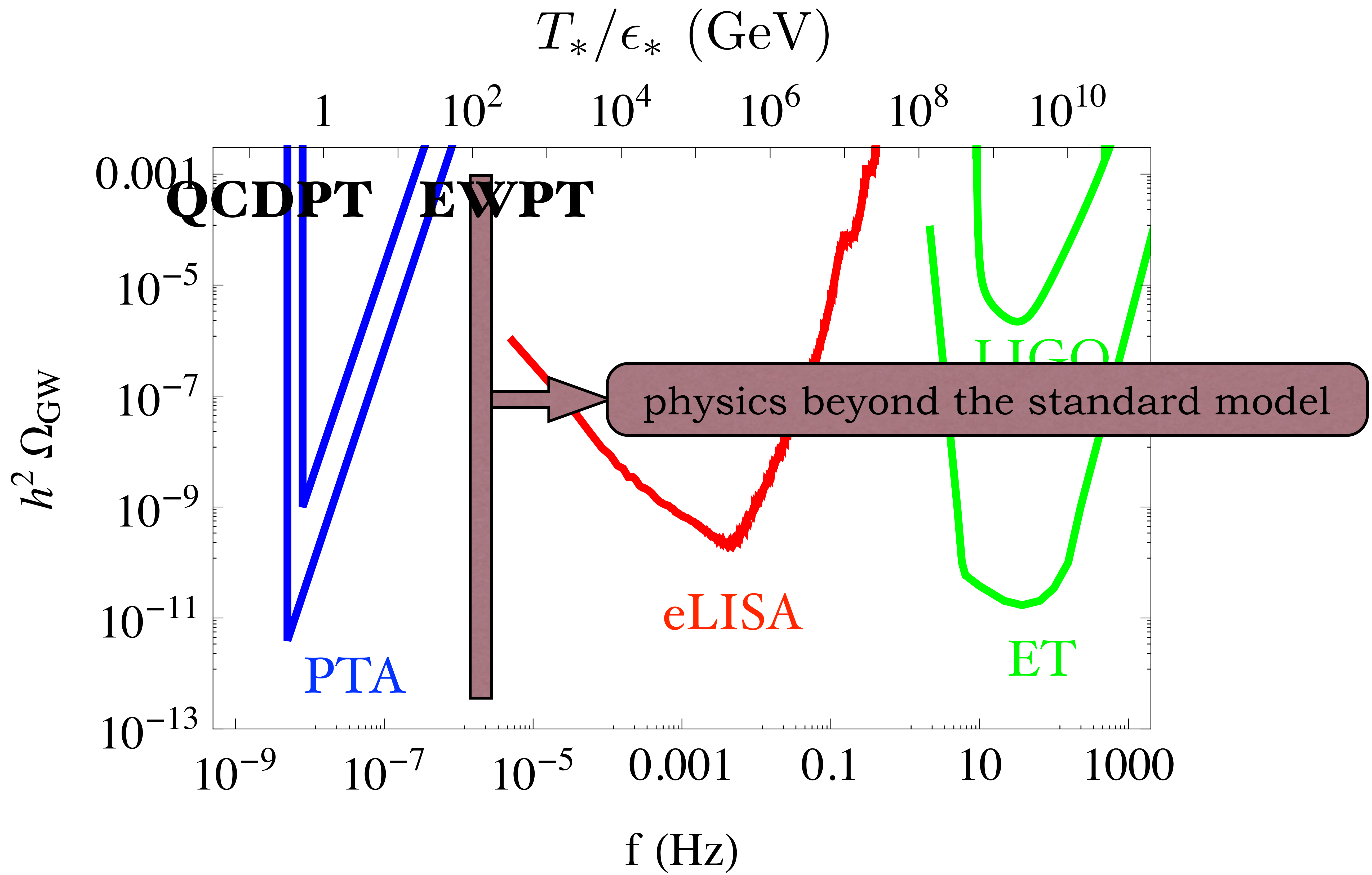
parameter depending on the dynamics of the source

Hubble rate is related to temperature in the universe :
assuming standard thermal history

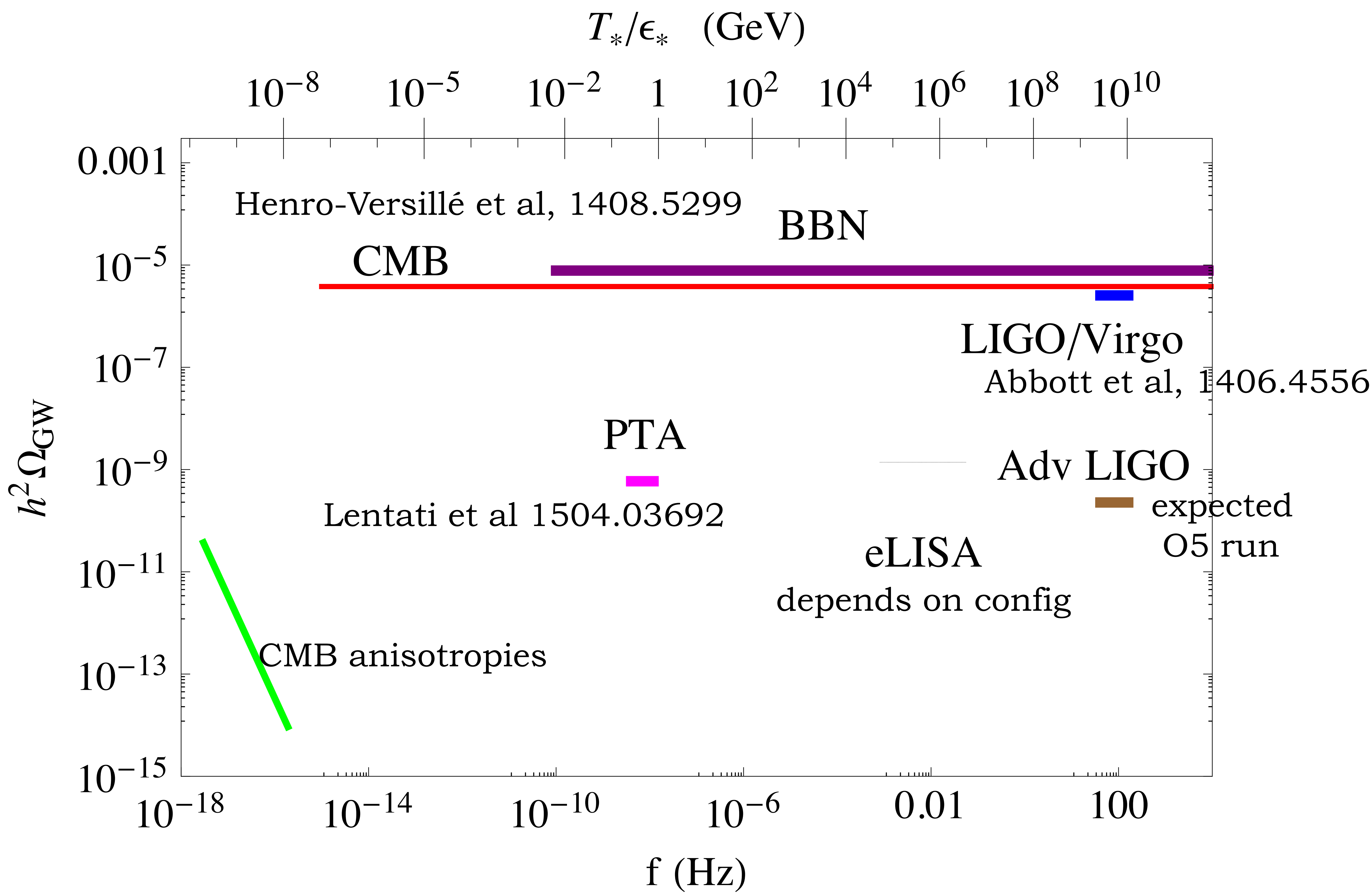
$$f_c = f_* \frac{a_*}{a_0} = \frac{2 \cdot 10^{-5}}{\epsilon_*} \frac{T_*}{1\,\mathrm{TeV}}\,\mathrm{Hz} \quad \simeq \mathrm{mHz}$$

for $\epsilon_* \simeq 10^{-2}$ $\quad T_* \simeq 1\,\mathrm{TeV}$

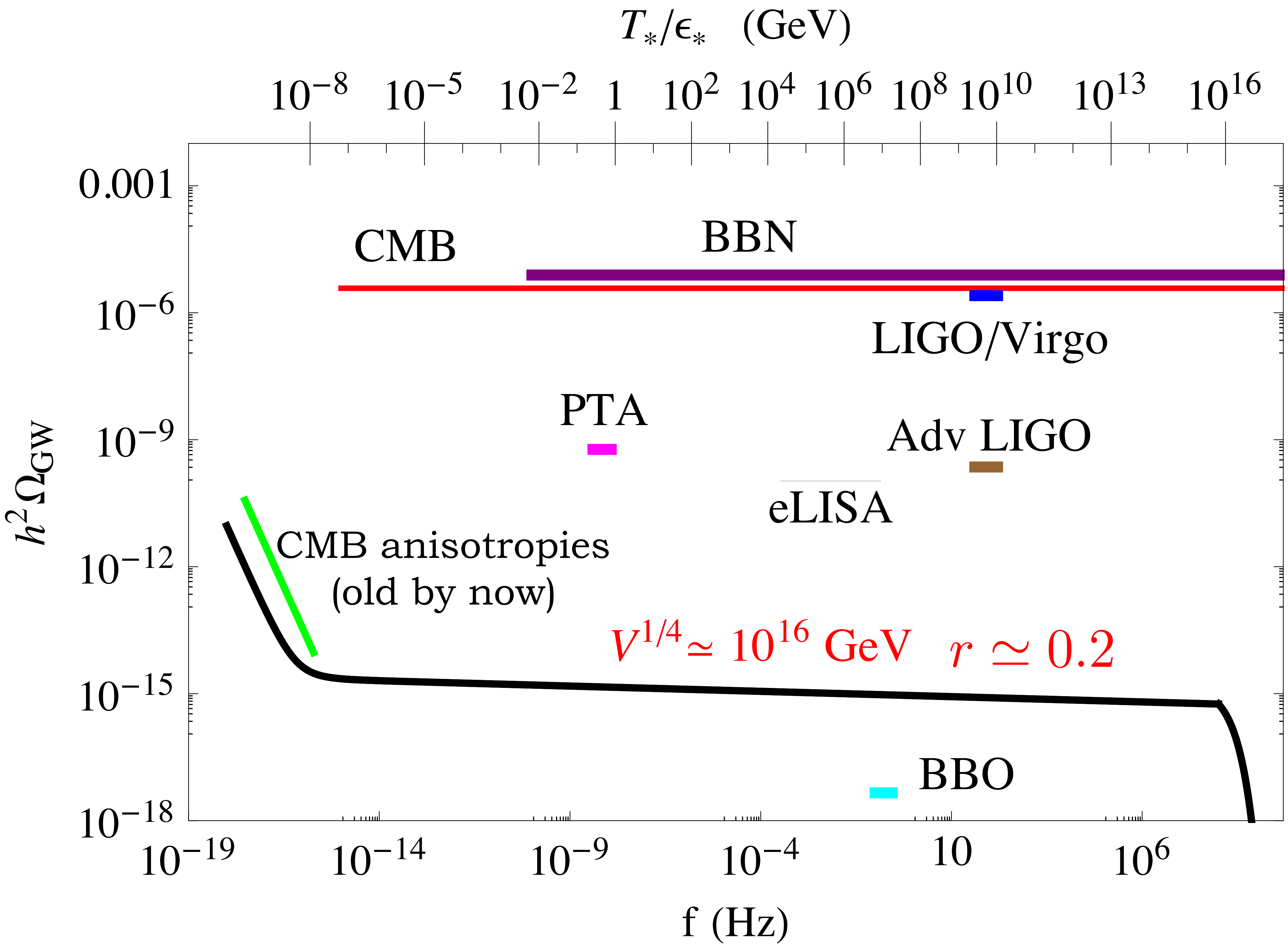
Characteristic frequency for *causal sources*



Observational bounds/sensitivities for GWSB



Observational bounds/sensitivities for GWSB



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

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

but which amplitude is needed for detection ?

Example: amplitude for detection with eLISA

frequency :

$$f_c = \frac{2 \cdot 10^{-5}}{\epsilon_*} \frac{T_*}{1\,\mathrm{TeV}}\,\mathrm{Hz} \simeq \;\mathrm{mHz}$$

for

$$\epsilon_* \simeq 10^{-2}$$

$$T_* \simeq 1\,\mathrm{TeV}$$

amplitude :

$$\Omega_{\rm GW} \sim \Omega_{\rm rad}\, \epsilon_*^2 \left(\frac{\rho_{\rm s}^*}{\rho_{\rm tot}^*} \right)^2$$

radiation parameter

DURATION/SIZE of the source with respect to Hubble parameter

RELATIVE ENERGY DENSITY available in the source for the GW generation

Example: amplitude for detection with eLISA

frequency :

$$f_c = \frac{2 \cdot 10^{-5}}{\epsilon_*} \frac{T_*}{1\,\mathrm{TeV}}\,\mathrm{Hz} \simeq \;\mathrm{mHz}$$

for

$$\epsilon_* \simeq 10^{-2}$$

$$T_* \simeq 1\,\mathrm{TeV}$$

amplitude :

$$\Omega_{\mathrm{GW}} \sim \Omega_{\mathrm{rad}}\,\epsilon_*^2 \left(\frac{\rho_{\mathrm{s}}^*}{\rho_{\mathrm{tot}}^*}\right)^2 \sim 10^{-11}$$

$$10^{-5} \qquad 10^{-4} \qquad 10^{-2}$$

$$\rho_{\mathrm{s}}^* \simeq 0.1\,\rho_{\mathrm{tot}}^*$$

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

Possible GW sources in the early universe

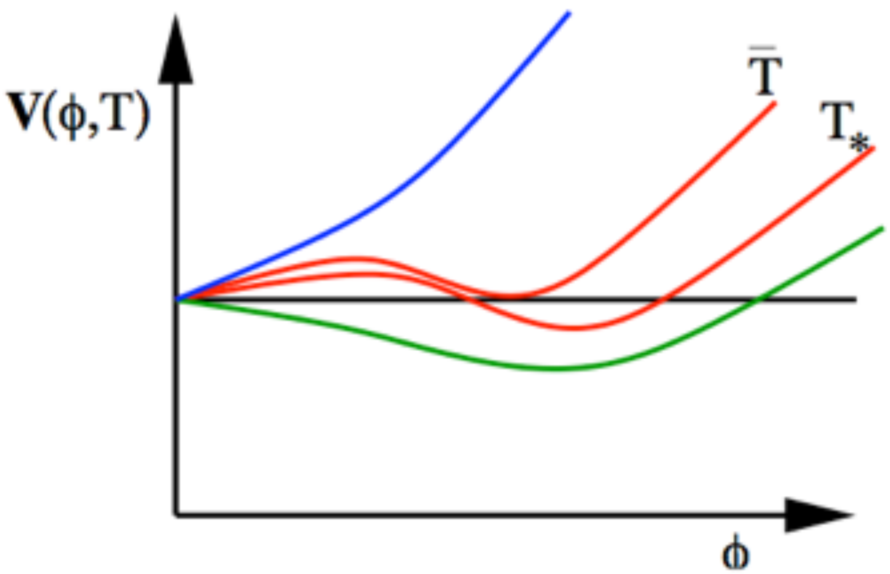
- "non-standard" inflation
  - particle production during inflation
  - fluid stiffer than radiation after inflation
  - preheating after inflation
  - phase transitions at the end or during inflation
  - ...
- first order phase transitions
- cosmic strings
- other topological defects e.g. domain walls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

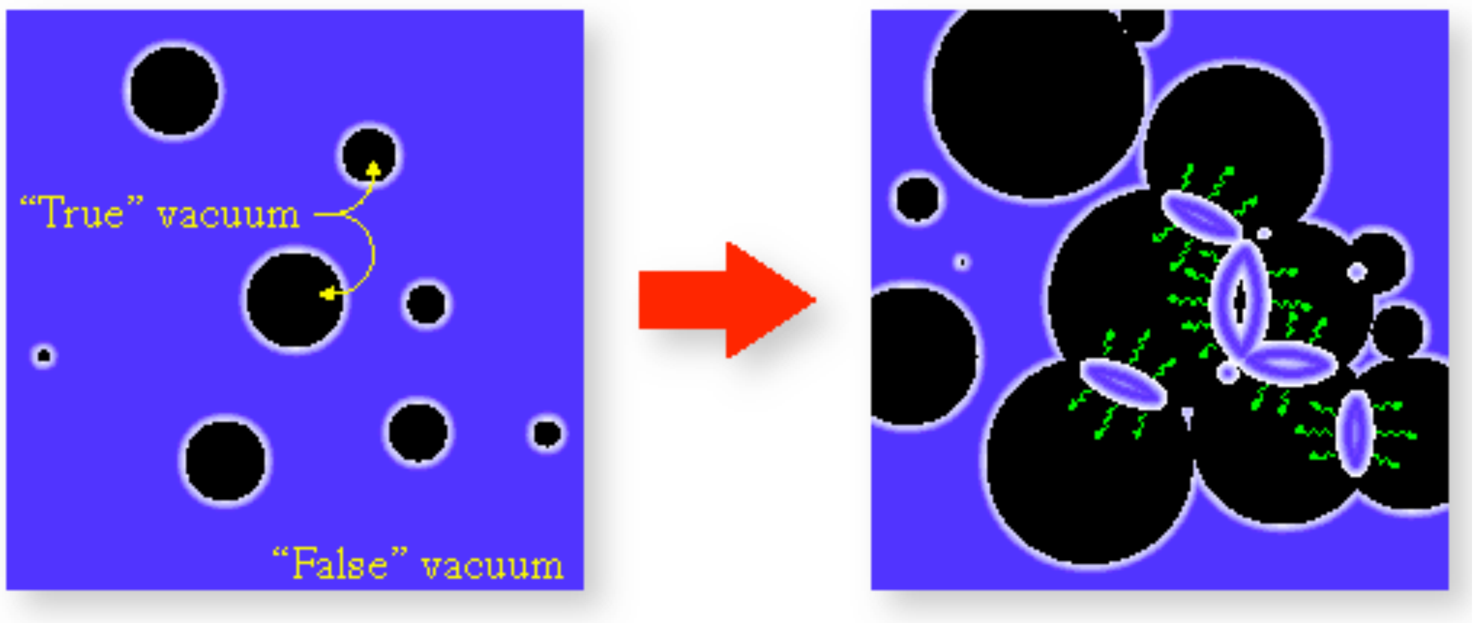
GW background from first order phase transitions

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





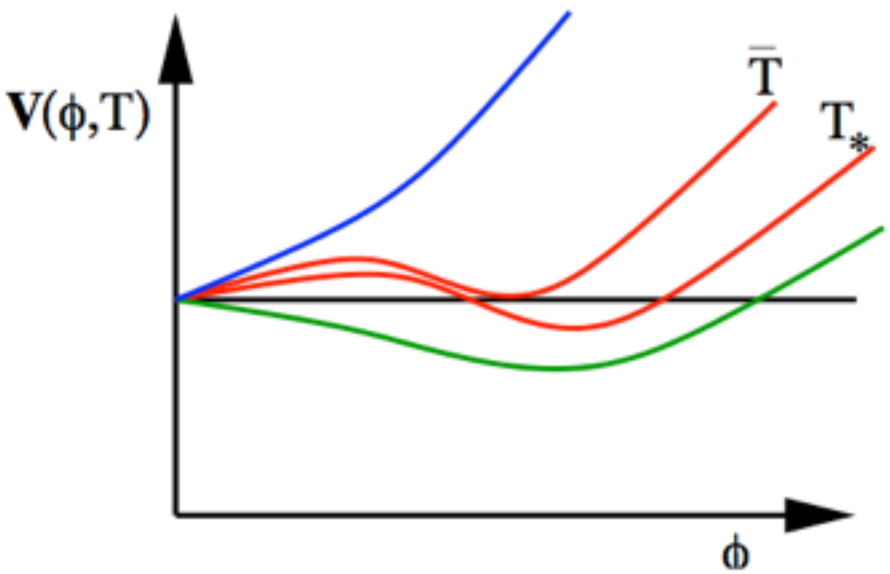
source: Π_{ij} tensor anisotropic stress

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

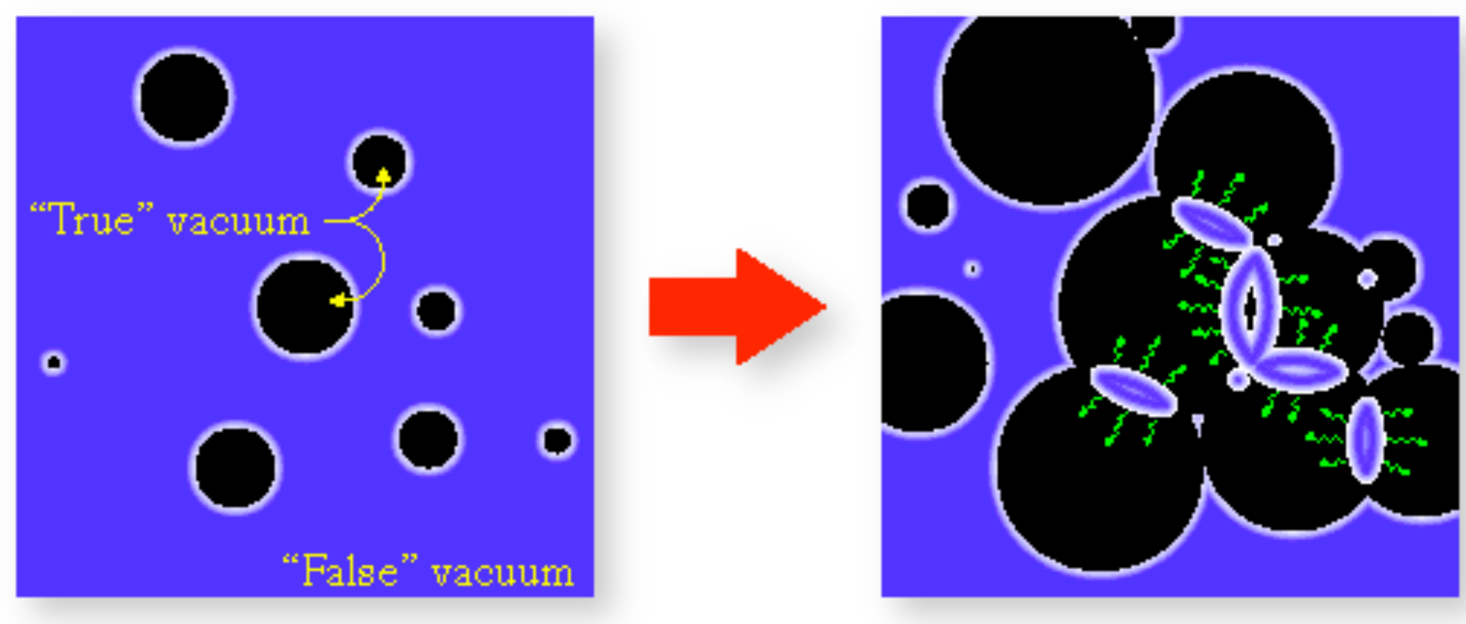
GW background from first order phase transitions

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



$$\Pi_{ij} \sim \partial_i \phi \, \partial_j \phi$$

source: Π_{ij} tensor anisotropic stress

$$\Pi_{ij} \sim \gamma^2 (\rho + p) \, v_i v_j$$

$$\Pi_{ij} \sim \frac{(E^2 + B^2)}{3} - E^i E^j - B^i B^j$$

GW background from first order phase transitions

- Very interesting for eLISA, since it is sensitive to energy scale
  10 GeV - 100 TeV

- eLISA 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)

CC et al, arXiv:1512.06239

GW background from first order phase transitions

- Very interesting for eLISA, since it is sensitive to energy scale 10

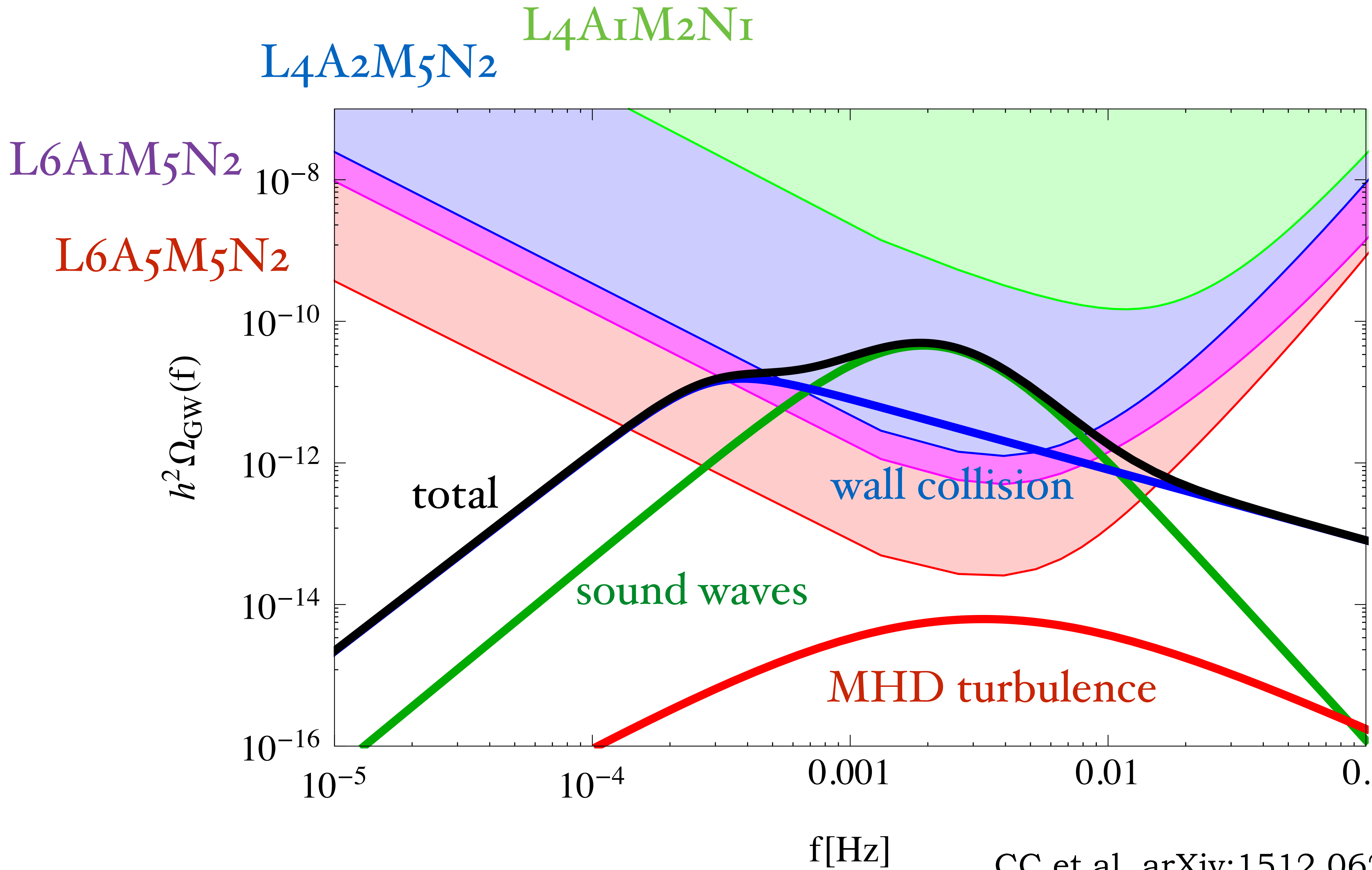
interesting models from the point of view of both cosmology and particle physics: connections with baryon asymmetry, dark matter

- eLIS
  - direct coupling of Higgs sector with scalars (Kozackuz et al 2013)
  - SM plus dimension six operator (Grojean et al 2004)

eLISA as a new probe of BSM physics complementary to future colliders

- … a
  - PT (Schwaller 2015)
  - Warped extra dimensions : PT from the dilaton/radion stabilisation in RS-like models (Randall and Servant 2015)

Example of signal (runaway bubble walls)



CC et al, arXiv:1512.06239

Detection prospects for eLISA

Relevant parameters:

$$\alpha = \frac{\rho_{\rm vac}}{\rho^*_{\rm rad}}$$

strength
of the PT

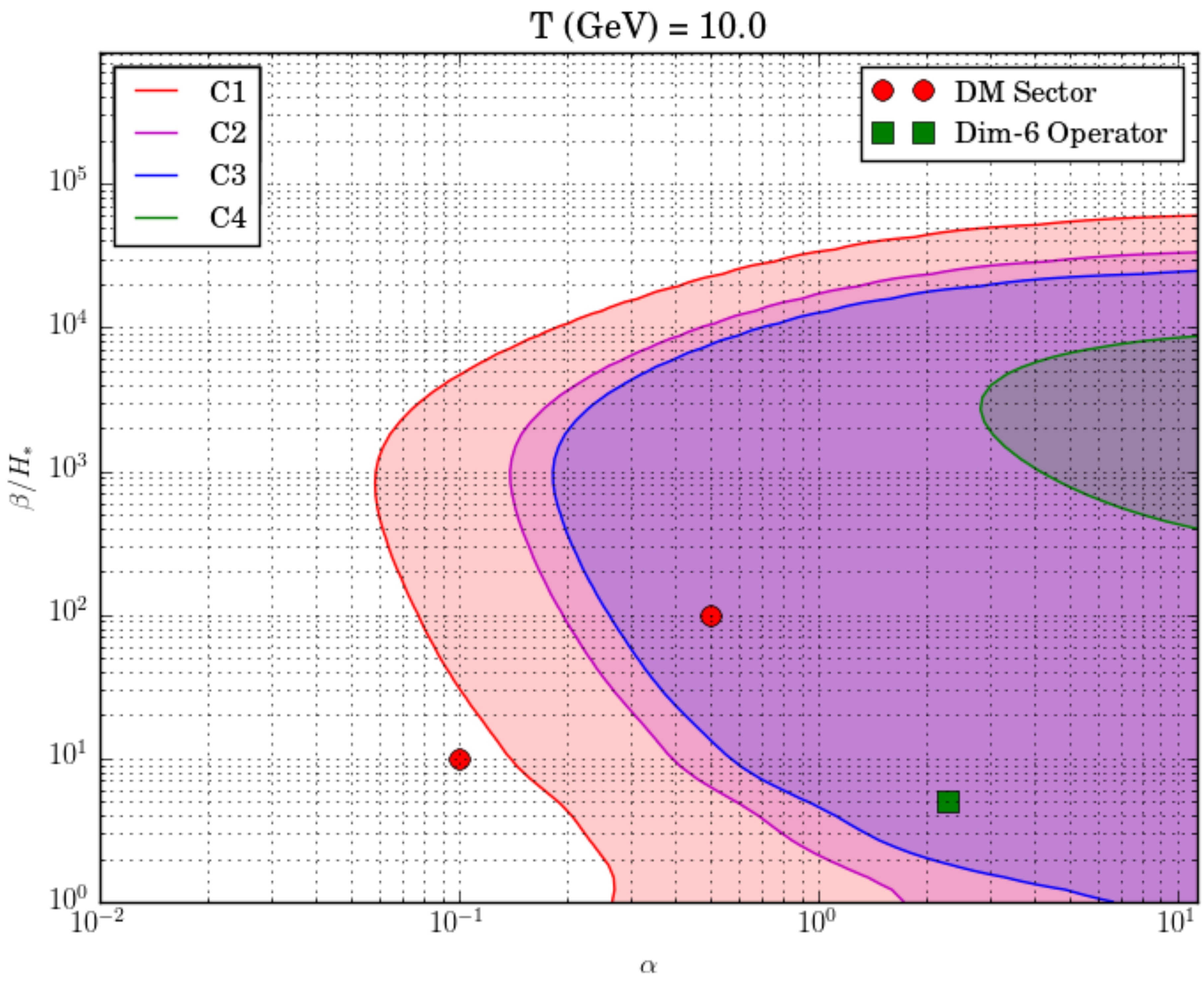
$$\frac{\beta}{H_*}$$

inverse duration
of the PT with respect
to Hubble time

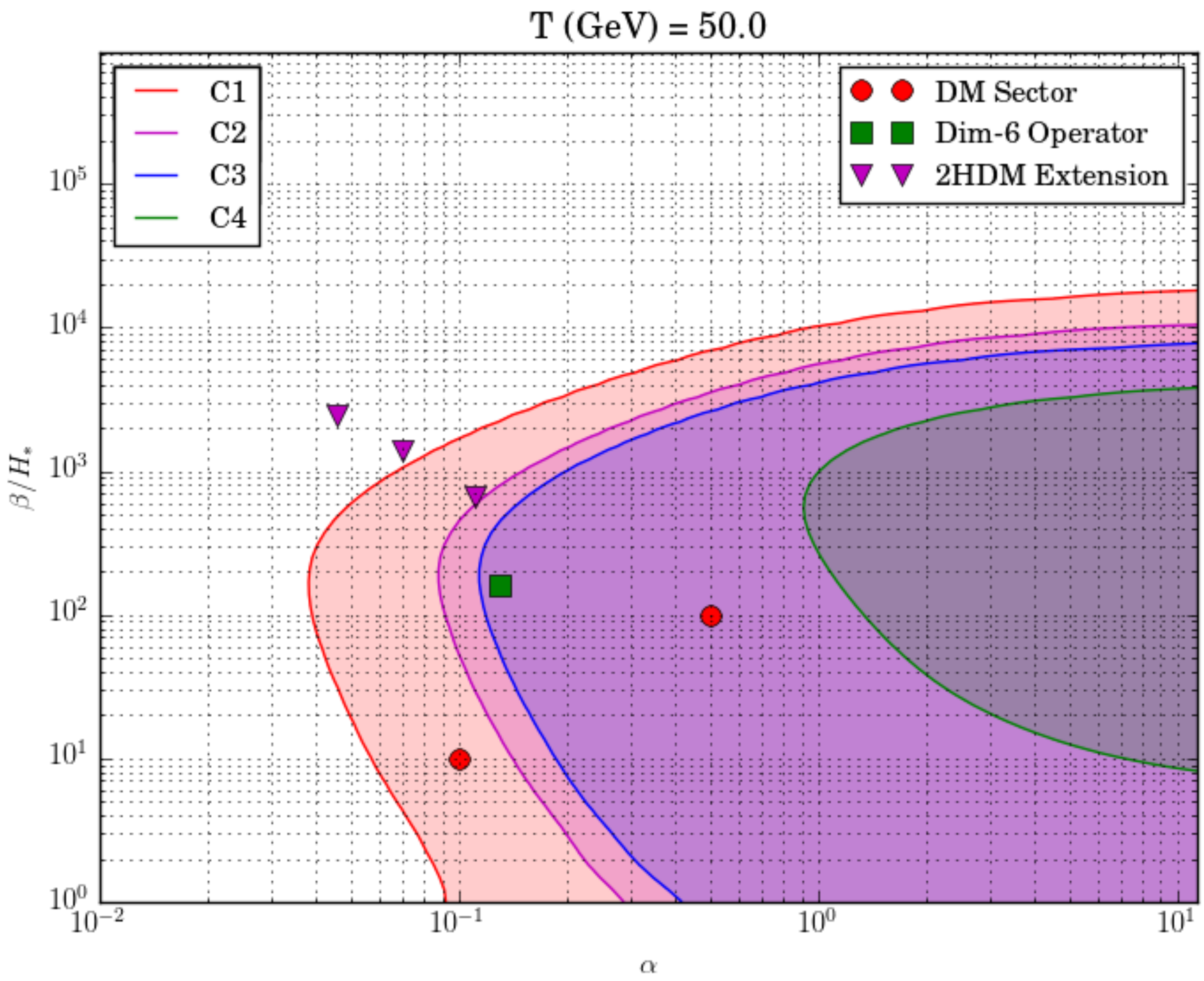
$$T_*$$

temperature
of the PT

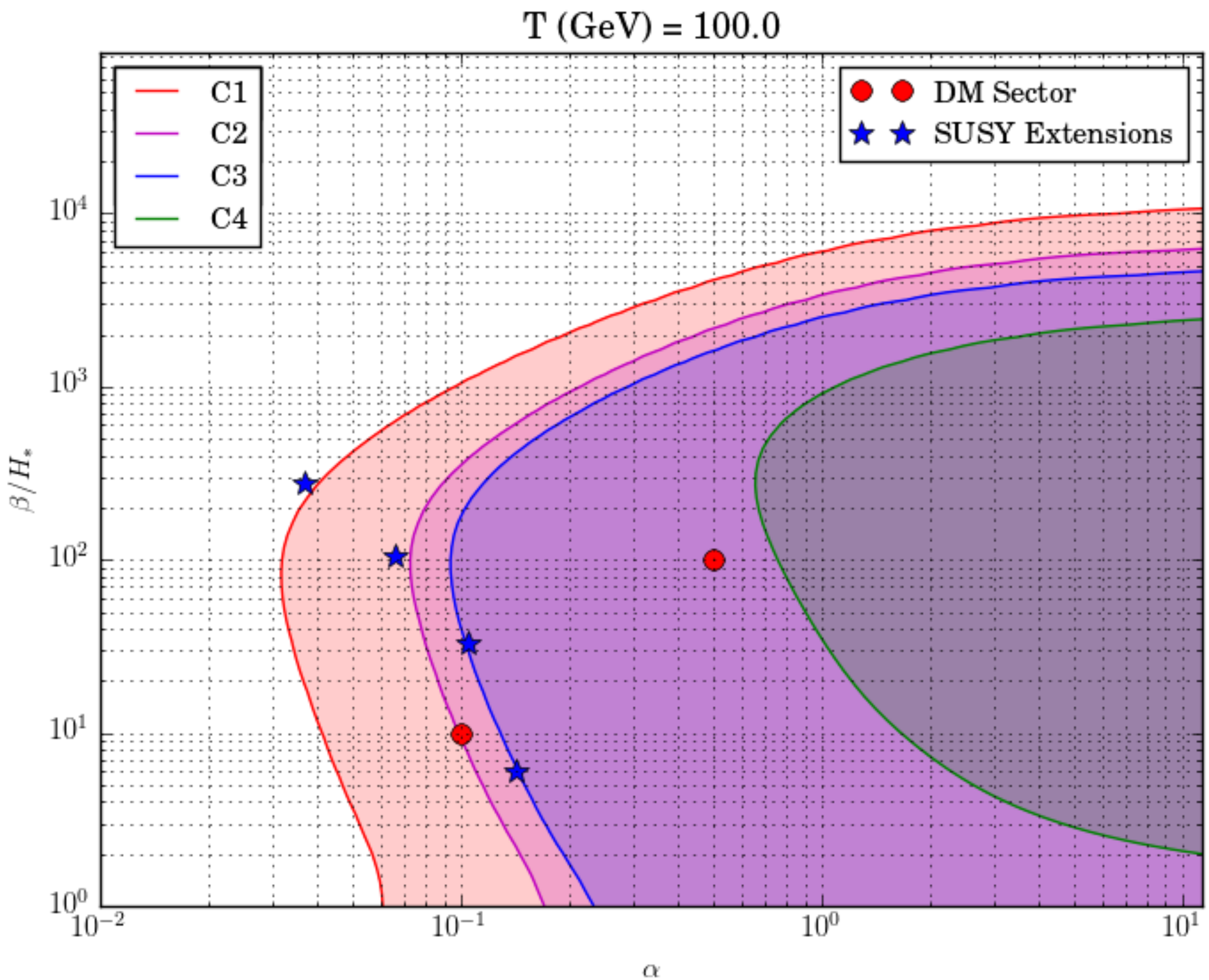
Detection prospects for eLISA : no runaway



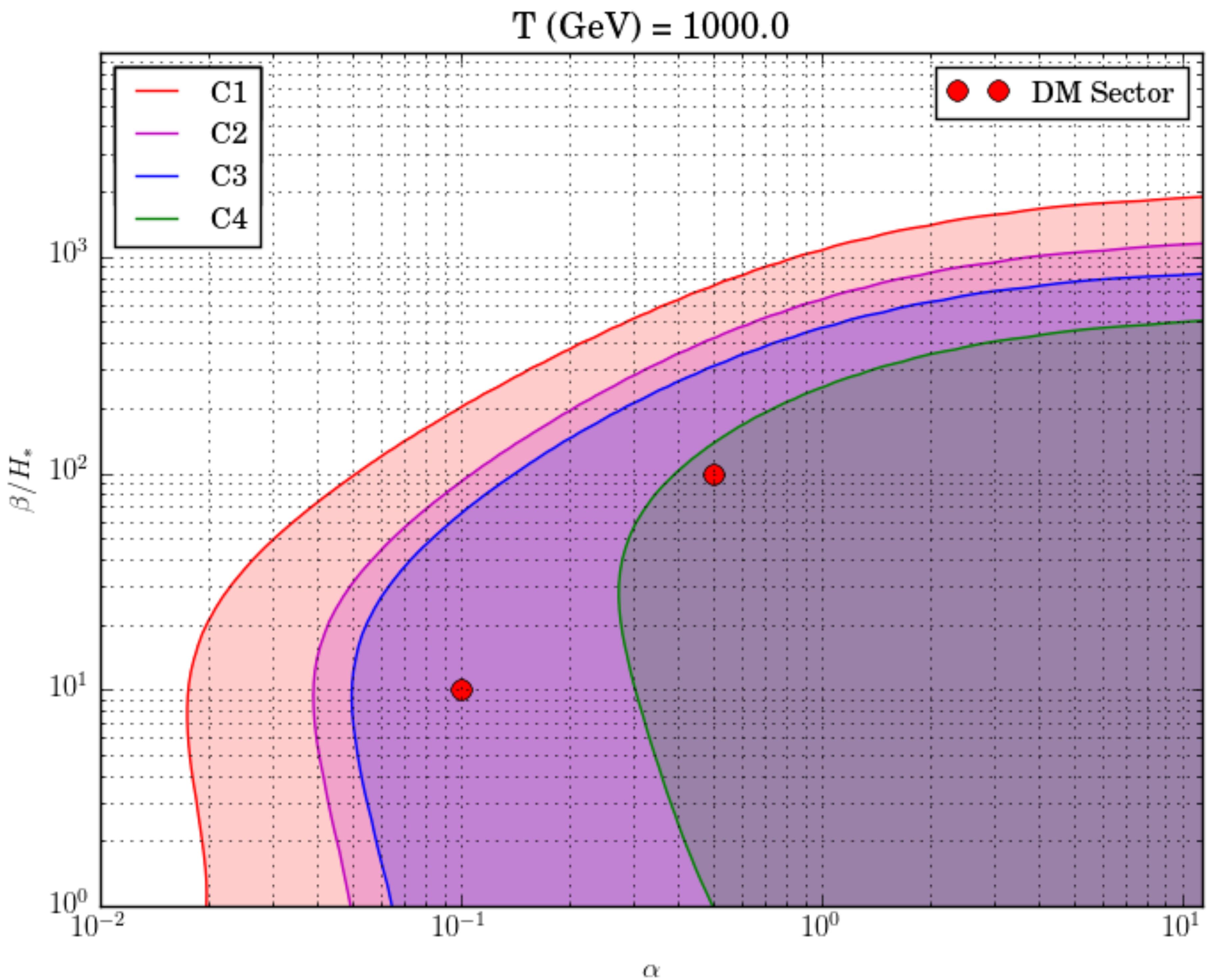
Detection prospects for eLISA : no runaway



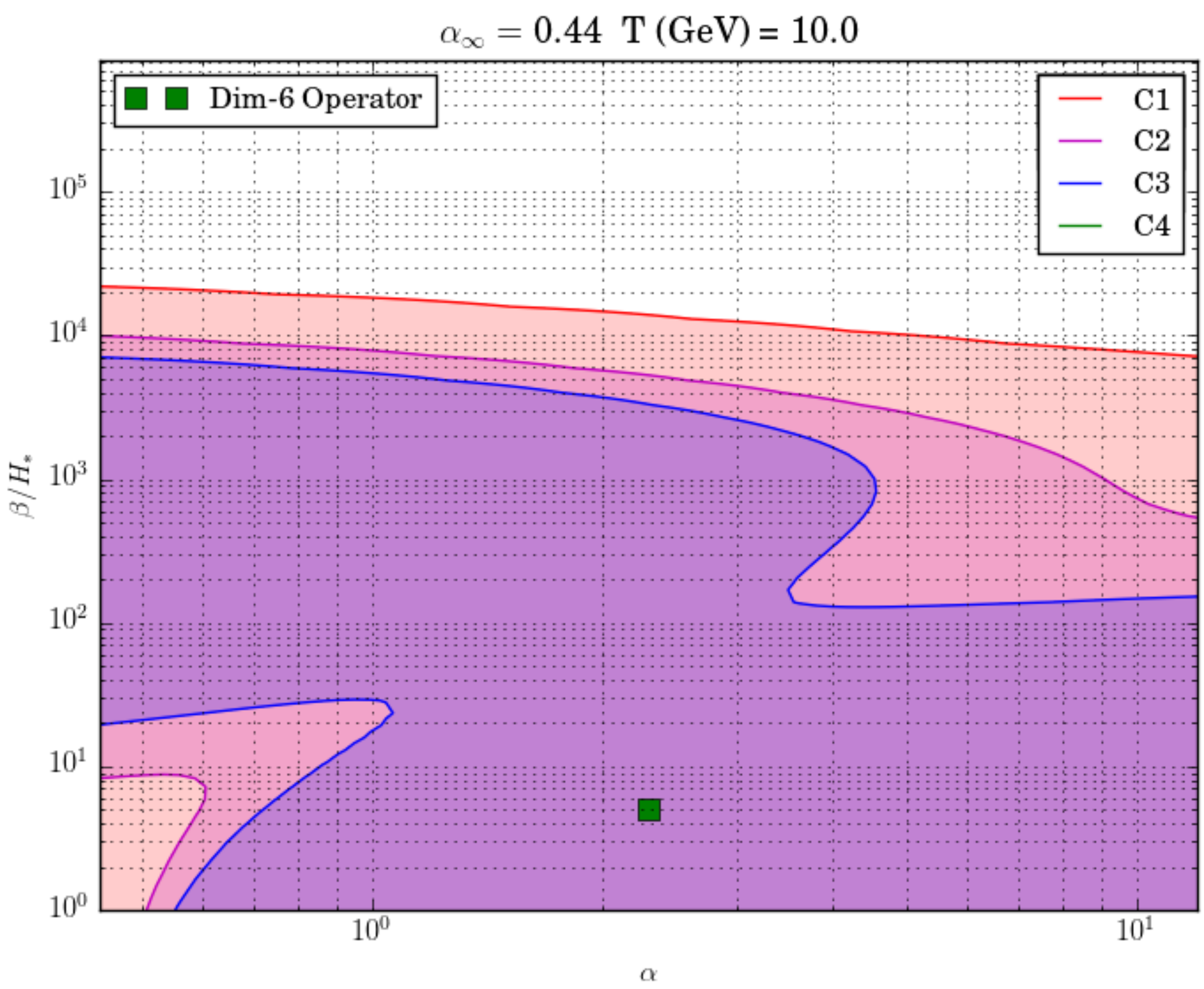
Detection prospects for eLISA : no runaway



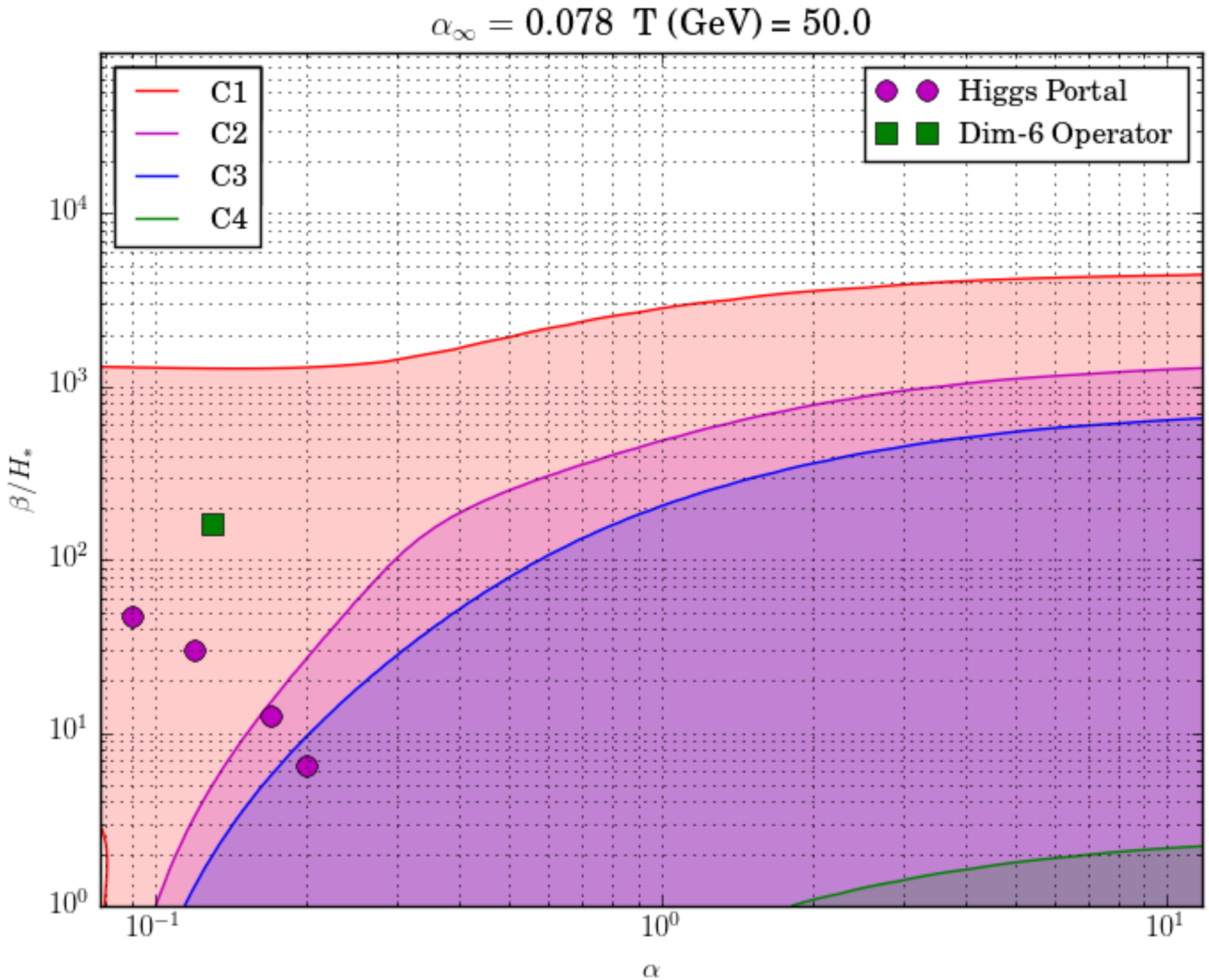
Detection prospects for eLISA : no runaway



Detection prospects for eLISA : runaway in plasma



Detection prospects for eLISA : runaway in plasma



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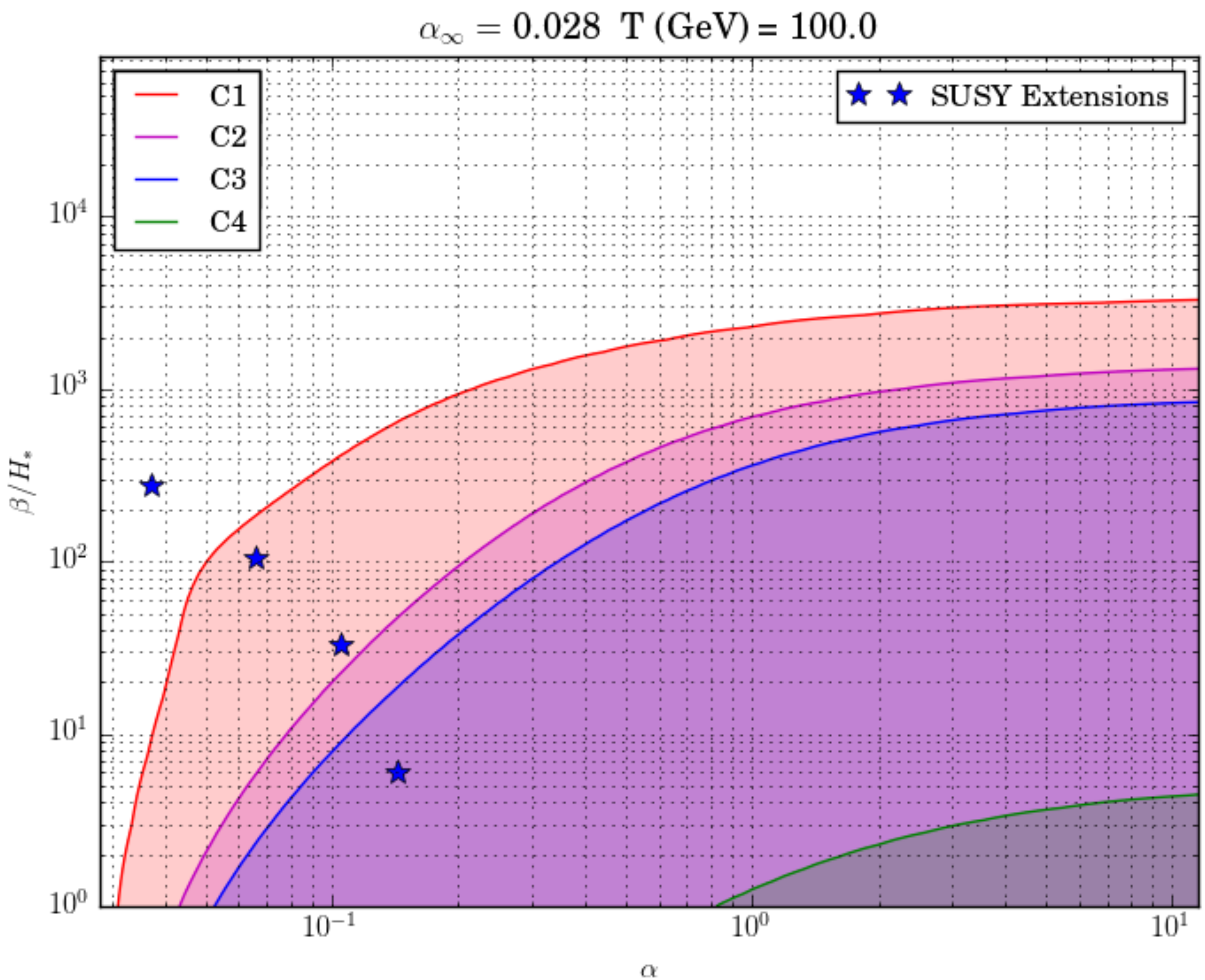

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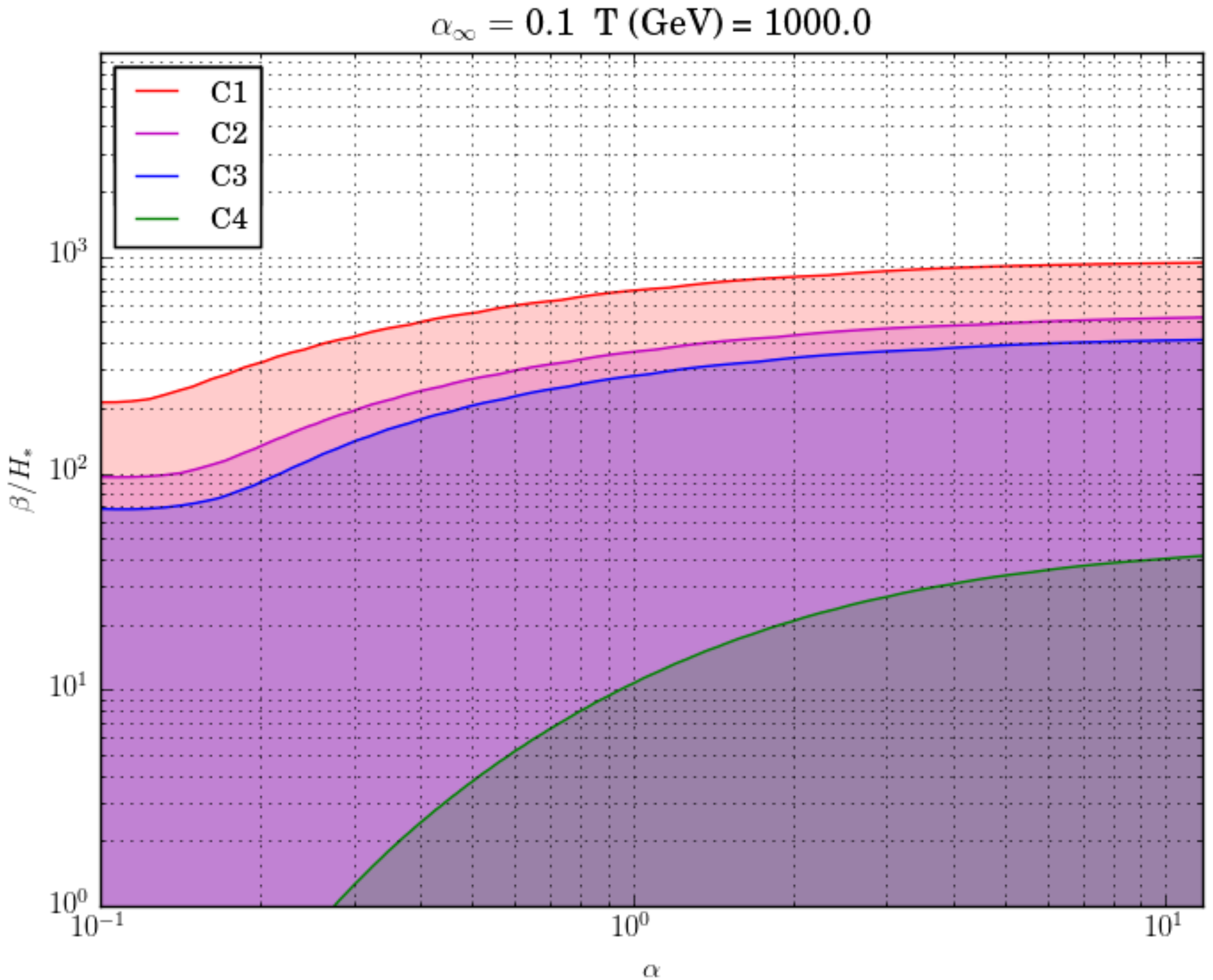
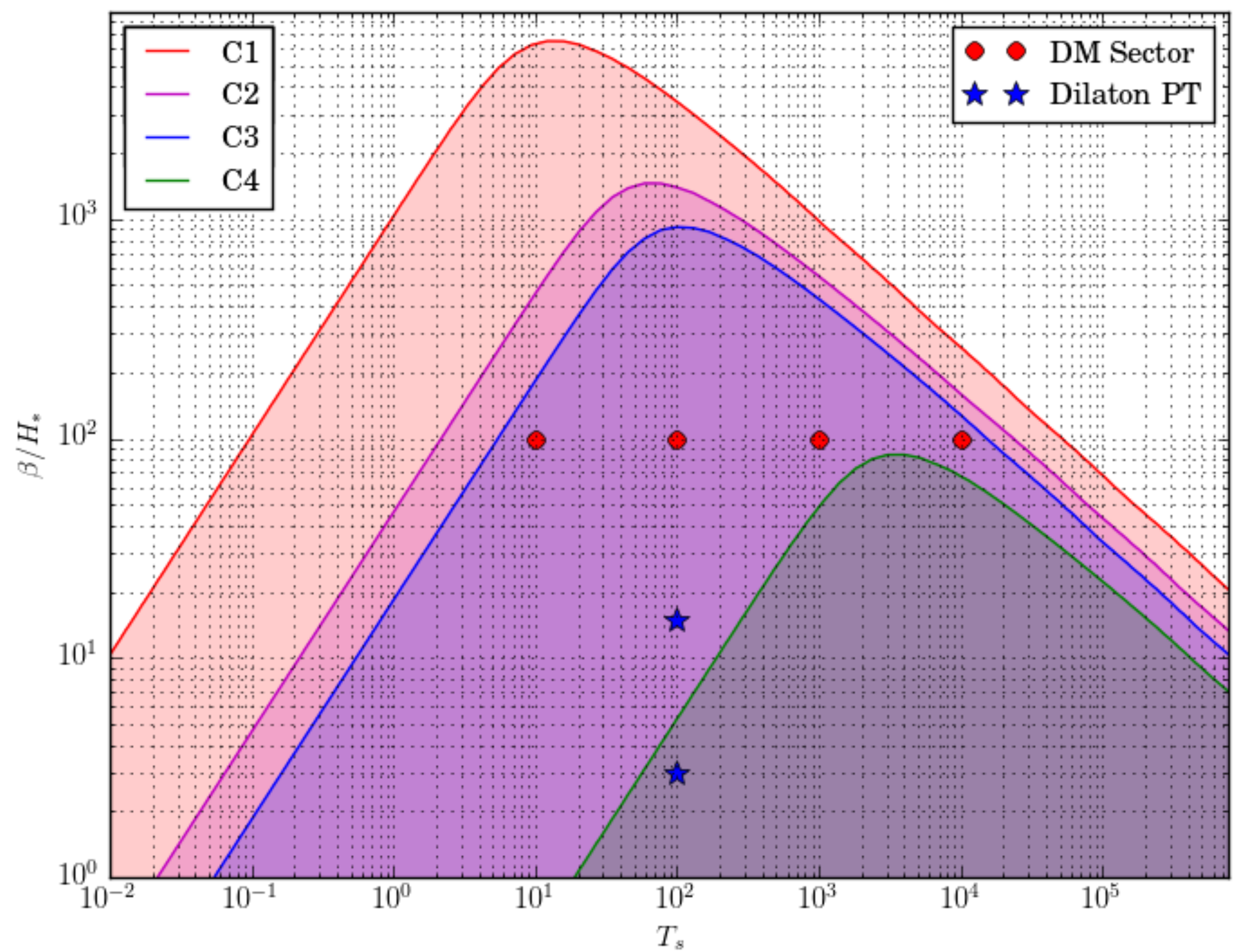


Detection prospects for eLISA : runaway in vacuum



Detection prospects for eLISA : conclusions

- there is a large range of viable new physics scenarios which can predict an observable signal of GW at eLISA

- eLISA has the potential to probe BSM physics

- L6AXM5N2 provides the biggest access to the EWPT parameter space, the arm length improves the detectable region

- L4A2M5N2 cannot (or barely) probe the simplest BSM models of EWPT, but can constraint other kinds of PT

  (provided we know very well the noise)

Using compact binaries to probe cosmology : eLISA and standard sirens

N. Tamanini, CC, E. Barausse, A. Sesana, A. Klein, A. Petiteau
arXiv:1601.07112

standard sirens

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

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

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

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

<u>Analogous to SNIa, but :</u>

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

standard sirens with eLISA

- the rate and redshift distribution of MBH binary events are obtained from numerical simulations
  (three different models - PopIII, heavy seeds with delay, heavy seeds without delay)

- Fisher matrix code to calculate SNR, the error on d_L and on sky localisation from inspiral (conservative) or inspiral+merger and ringdown (optimistic) for every eLISA configuration

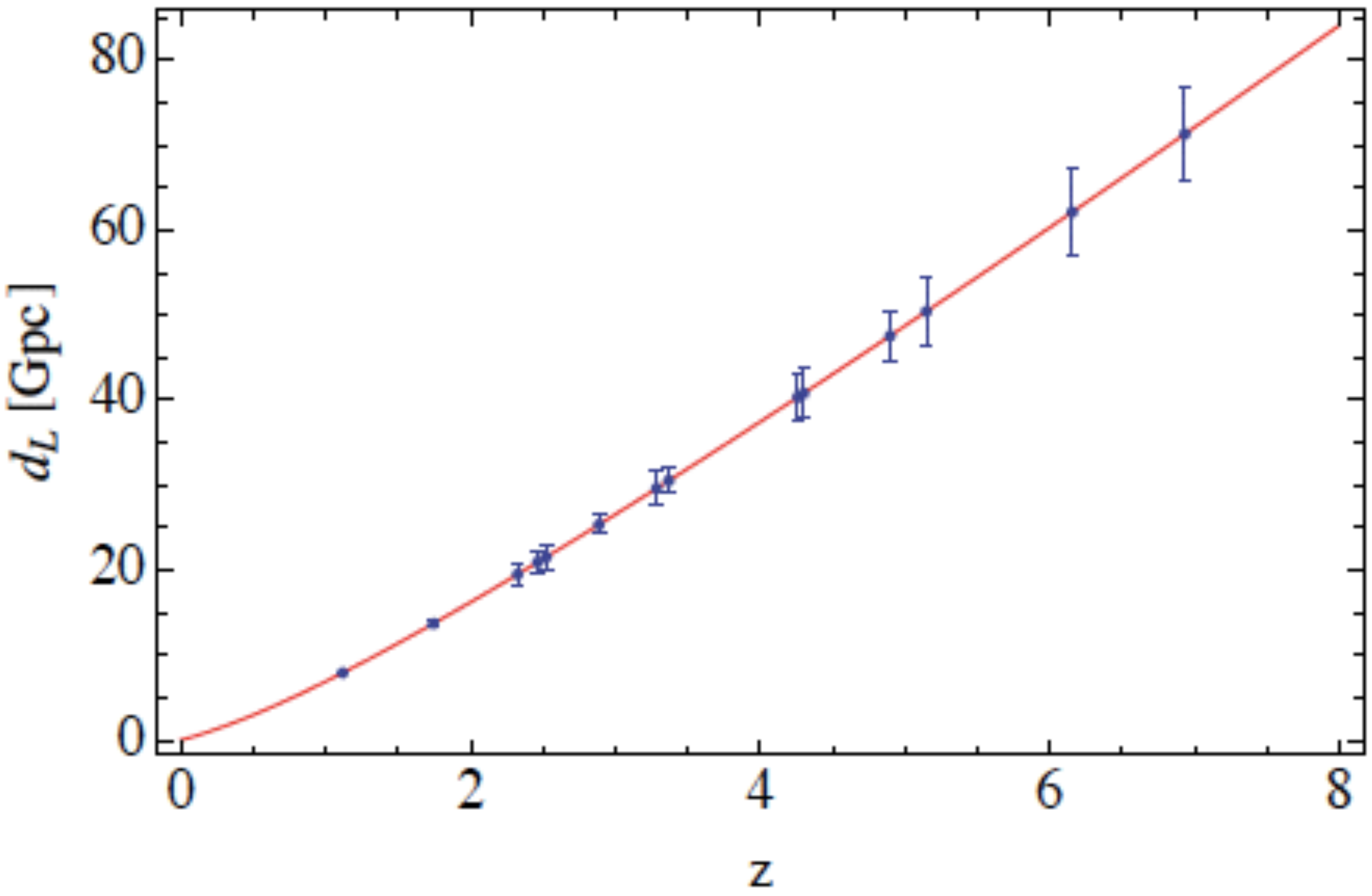
- Select events with SNR>8 and sky localisation < 10 deg^2

- Add weak lensing and peculiar velocities errors to d_L

- model of the counterparts :
  - detected directly in the optical by LSST
  - detected first in the radio by SKA and then in the optical by E-ELT
  - add extra redshift error if photometric

standard sirens with eLISA

example of simulated data <u>with counterparts</u> (weak lensing and peculiar velocity errors)



VERY FEW EVENTS AT LOW REDSHIFT !

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

standard sirens with eLISA

- eLISA cannot constrain simultaneously the five parameters $(\Omega_M,\ \Omega_\Lambda,\ h,\ w_0,\ w_a)$

Cosmological constant + curvature

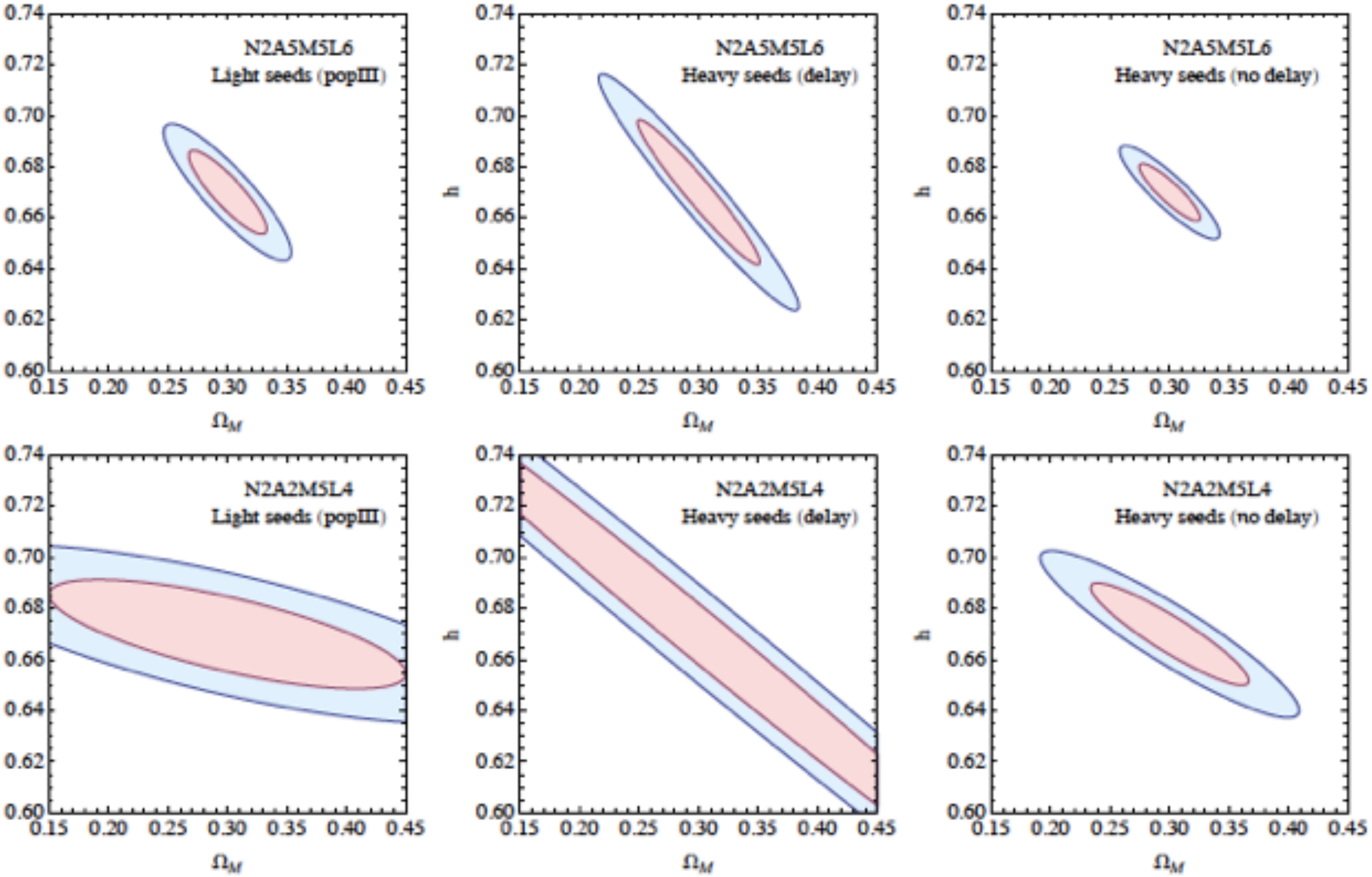
$$\Omega_M = 0.3 \pm [0.22,\ 0.026]$$
$$\Omega_\Lambda = 0.7 \pm [0.54,\ 0.09]$$
$$h = 0.67 \pm [0.13,\ 0.016]$$

most optimistic scenario gives a 2% fully independent measurement of the Hubble parameter

SNIa + Planck + BAO
(Betoule et al 2014)

$$\Omega_M = 0.305 \pm 0.01$$
$$\Omega_\Lambda = 0.693 \pm 0.01$$
$$h = 0.683 \pm 0.01$$

ΛCDM



$$\Omega_M = 0.3 \pm [0.09,\ 0.018]$$

$$h = 0.67 \pm [0.048,\ 0.008]$$

Planck alone :

$$\Omega_M = 0.308 \pm 0.0012$$

$$h = 0.678 \pm 0.009$$

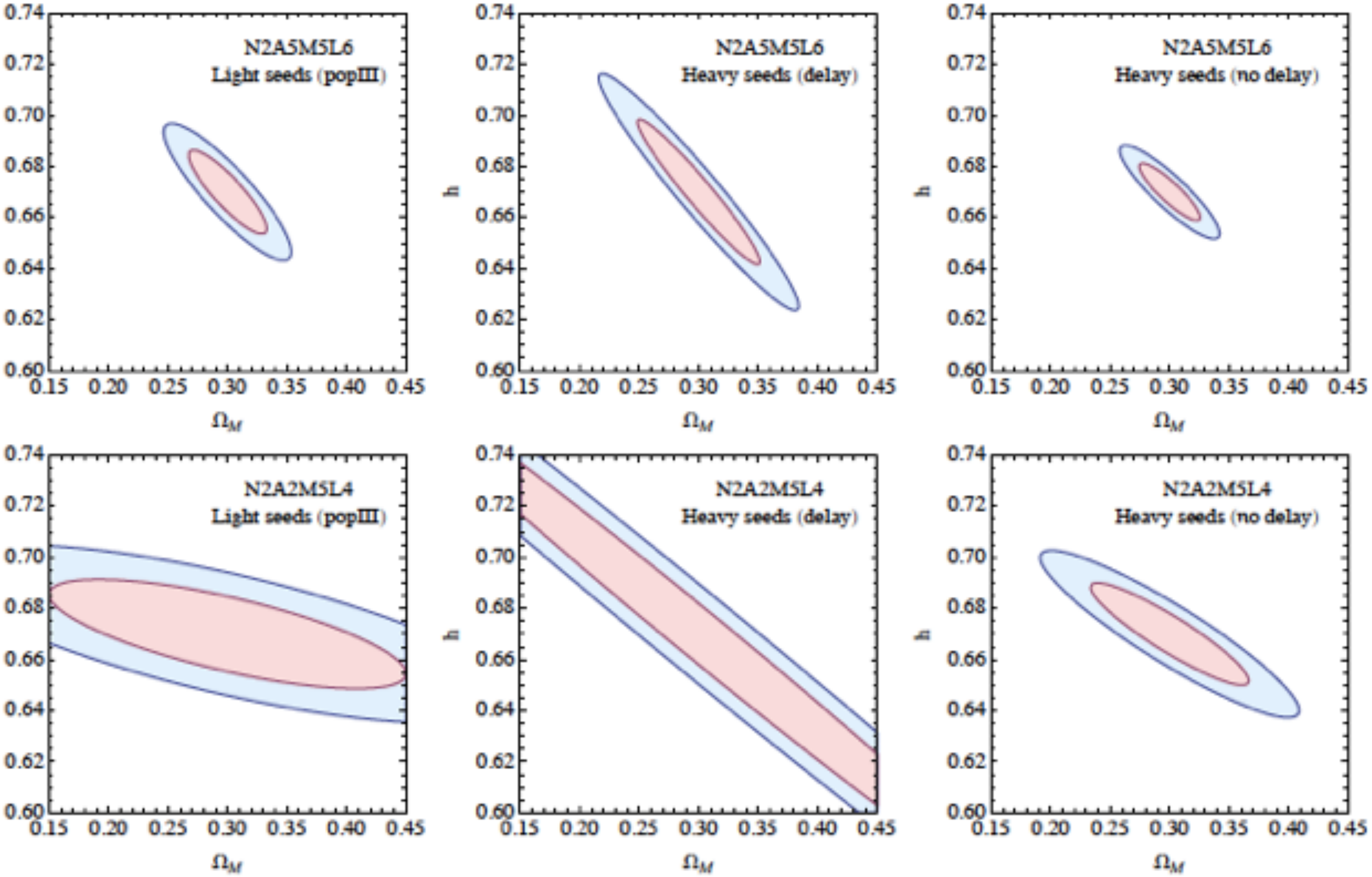
eLISA fixing H_0 :

$$\Omega_M = 0.3 \pm [0.024\,,\, 0.0078]$$

SNIa alone : (Betoule et al 2014)

$$\Omega_M = 0.294 \pm 0.034$$

ΛCDM



$$\Omega_M = 0.3 \pm [0.09,\ 0.018]$$

$$h = 0.67 \pm [0.048,\ 0.008]$$

Planck alone :

$$\Omega_M = 0.308 \pm 0.0012$$

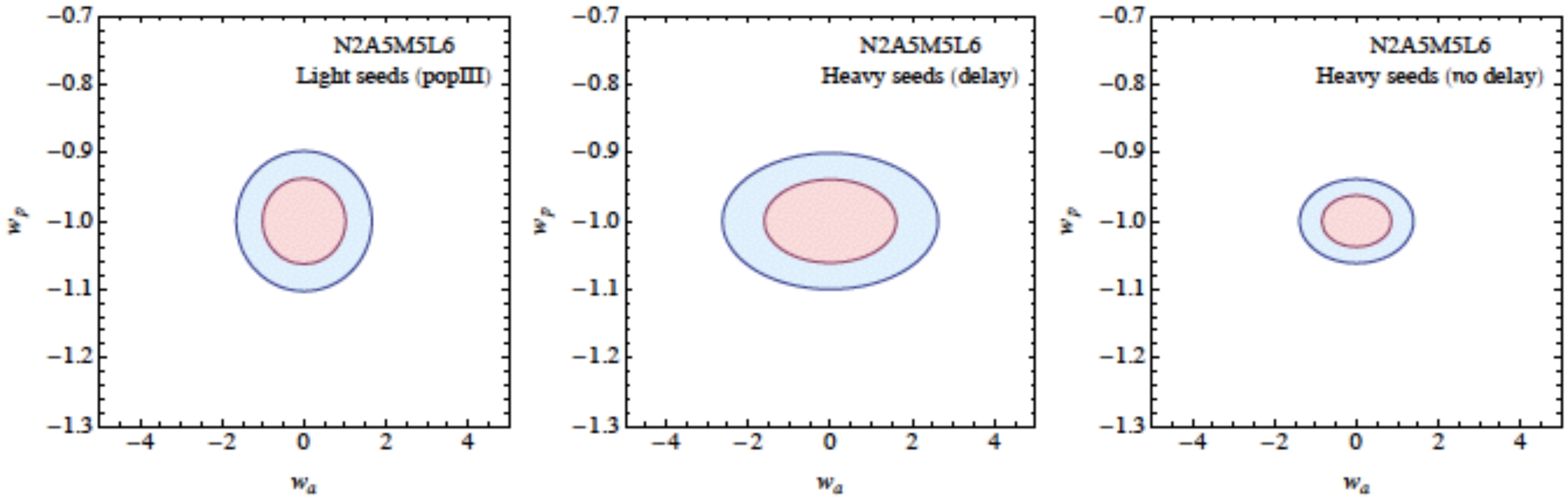
$$h = 0.678 \pm 0.009$$

eLISA fixing Ω_M :

$$h = 0.67 \pm [0.0099\,,\, 0.003]$$

- fully independent constraint
- comparable with Planck in worst case
- 0.4% in best case

Dynamical Dark Energy



too few events at low redshift to get a good measurement

N2A5M5L6			N2A2M5L4		
z_p	Δw_p	Δw_a	z_p	Δw_p	Δw_a
0.244	0.0413	0.665	0.193	0.0626	3.34
0.264	0.0401	1.06	0.239	0.0830	3.30
0.228	0.0248	0.559	0.194	0.0455	1.14

$$w_0 = -1 \pm [0.58,\ 0.1]$$
$$w_a = 0 \pm [2.78,\ 0.56]$$

SNIa + Planck + BAO :
(Betoule et al 2014)

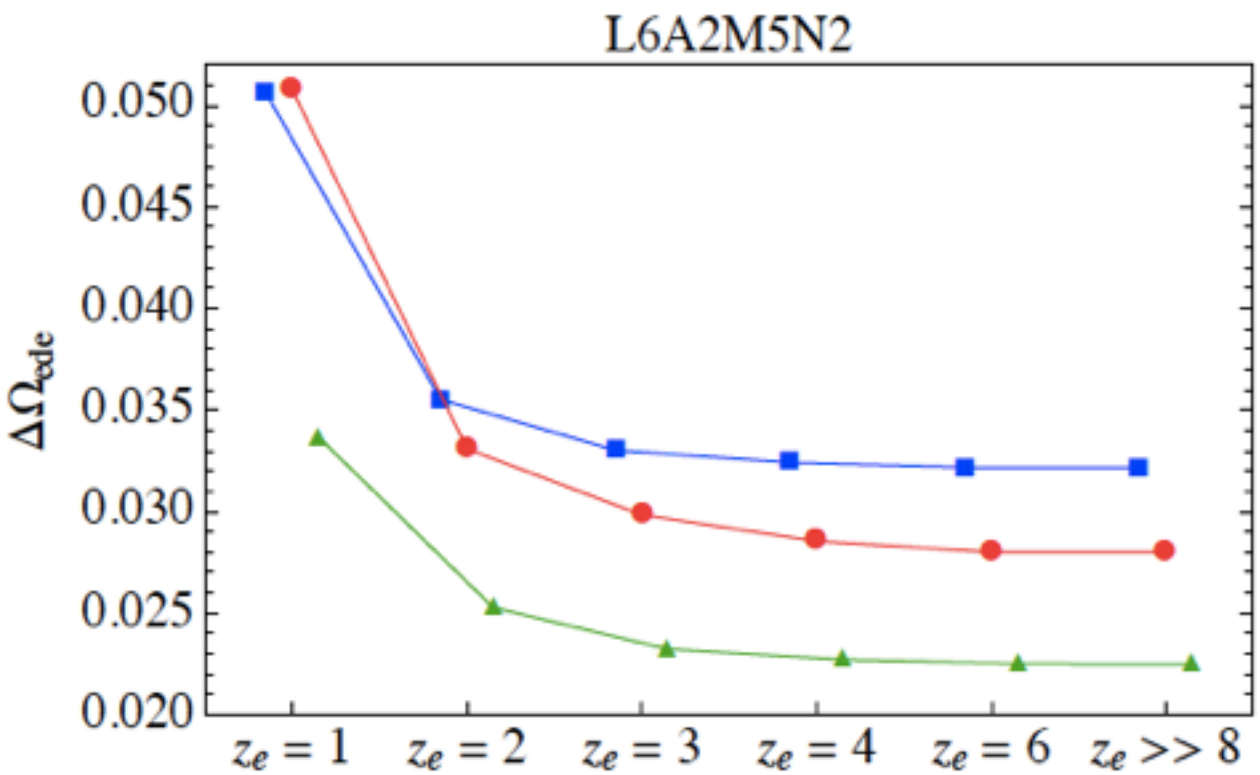
Euclid forecast :

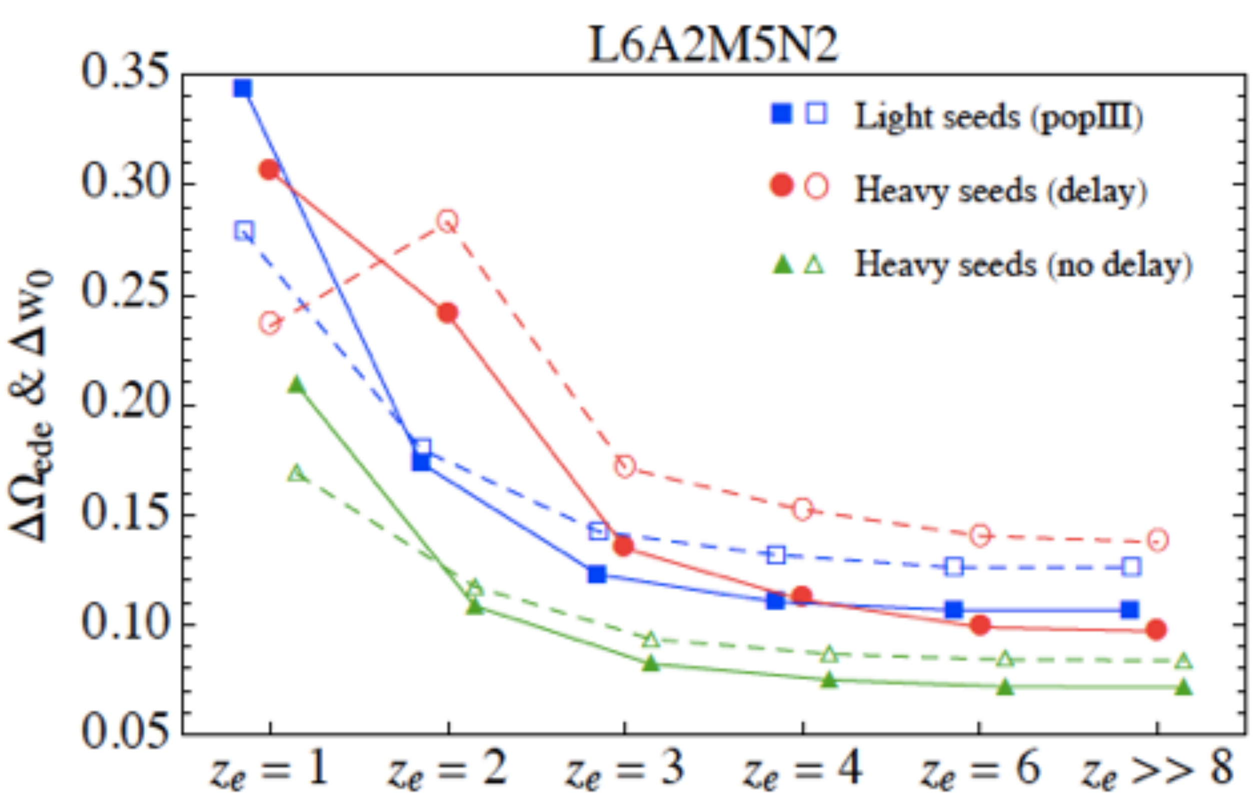
$$\Delta w_0 = 0.02$$
$$\Delta w_a = 0.1$$

$$w_0 = -0.957 \pm 0.124$$
$$w_a = -0.336 \pm 0.552$$

Early Dark Energy

model in which dark energy can contribute also at high redshift





Ω_{de} fraction of dark energy at early times

w_0 present equation of state

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

Conclusions

we have assisted to a historical event, the aLIGO/Virgo detection, which (so far) confirms GR

this will open the era of GW astronomy and cosmology : we have a new, independent "messenger"

GW could be a powerful mean to probe the early universe (and consequently high energy physics) but also the cosmological expansion: detection is difficult but great payoff