Primordial gravitational waves

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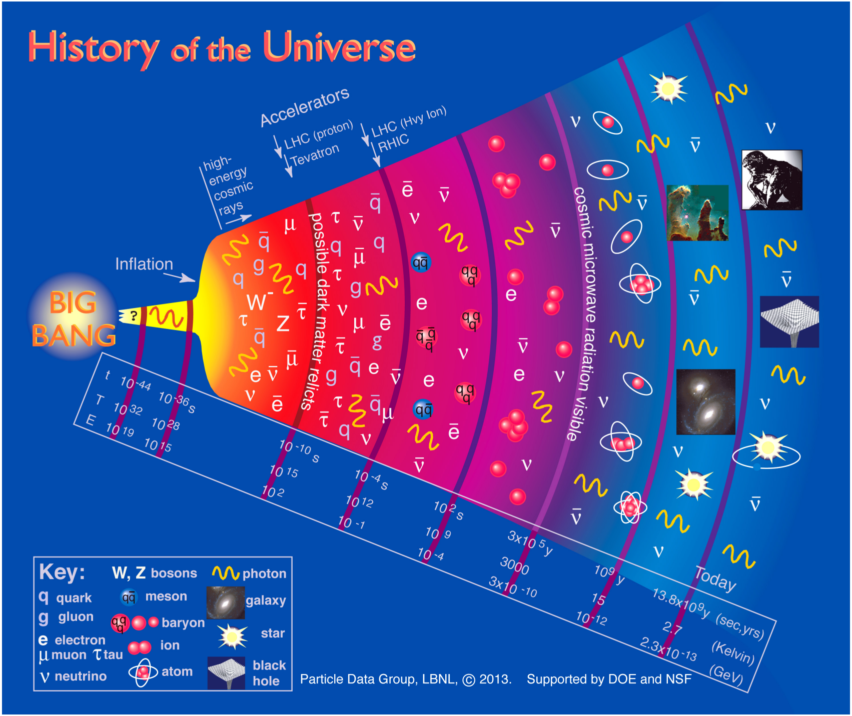
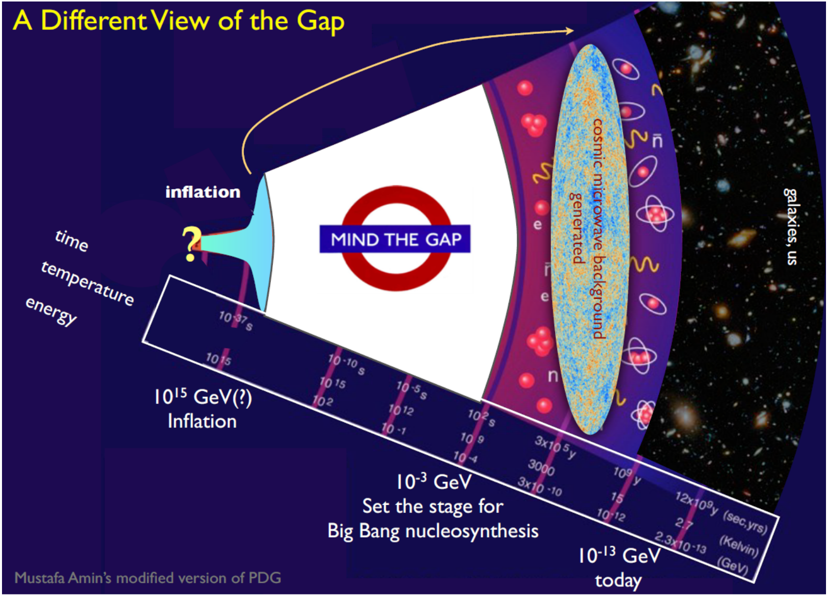
AION Workshop, Imperial College London, 26 March 2019

Based on:
J. Ellis, ML, J. M. No, V Vaskonen arXiv:1903.09642
J. Ellis, ML, J. M. No arXiv:1809.08242
Y. Cui, D. Morrissey, ML and J. D. Wells. arXiv:1711.03104, arXiv:1808.08968

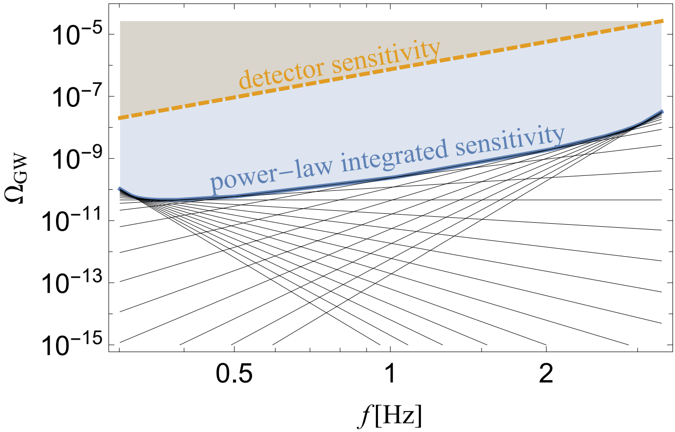


History of the Universe
Accelerators
LHC (proton)
Tevatron
LHC (Hvy Ion)
RHIC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
t 10-44 10-36 s
T 10 32 10 28
E 10 19 10 15
10 -10 s
10 15
10 2
10 -4 s
10 12
10 -1
10 2 s
10 9
10 -4
3x10 5 y
3000
3x10 -10
10 9 y
15
10-12
Today
13.8x10⁹y (sec,yrs)
2.7 (Kelvin)
2.3x10 -13 (GeV)
Key:
W, Z bosons
photon
q quark
meson
galaxy
g gluon
baryon
e electron
ion
star
μ muon τ tau
ν neutrino
atom
black hole
Particle Data Group, LBNL, © 2013. Supported by DOE and NSF

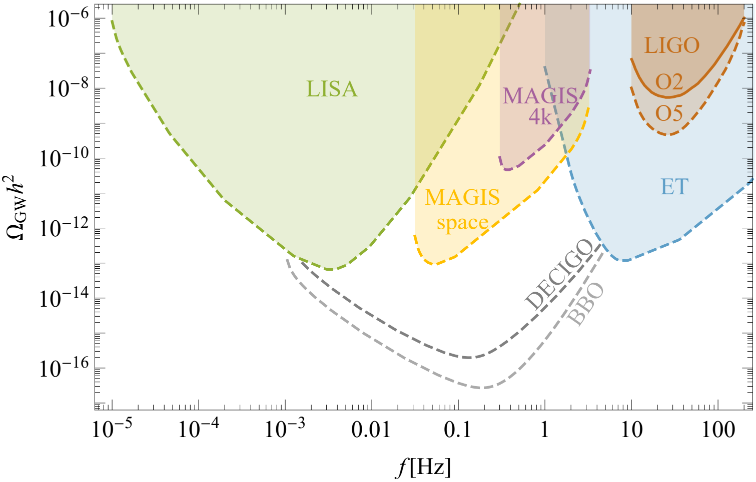

A Different View of the Gap
inflation
?
time
temperature
energy
MIND THE GAP
cosmic microwave background generated
galaxies, us
e
e
n
n̄
10-37 s
1015
10-10 s
1015
102
10-5 s
1012
10-1
102 s
109
10-4
3x105 y
3000
3x10-10
109 y
15
10-12
12x109 y (sec,yrs)
2.7 (Kelvin)
2.3x10-13 (GeV)
1015 GeV(?)
Inflation
10-3 GeV
Set the stage for
Big Bang nucleosynthesis
10-13 GeV
today
Mustafa Amin's modified version of PDG

Power-law integrated sensitivity

$$\Omega_{\rm GW} = \frac{2\pi}{3}\frac{f^3 S_h^2}{H_0^2}, \qquad \mathrm{SNR} = \sqrt{\mathcal{T}\int df \left(\frac{\Omega_{\rm GW}^{\rm signal}}{\Omega_{\rm GW}^{\rm noise}}\right)^2}$$



Thrane, Romano '13


LISA
MAGIS
space
MAGIS
4k
LIGO
O2
O5
ET
DECIGO
BBO
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{-16}
$\Omega_{\rm GW} h^2$
10^{-5}
10^{-4}
10^{-3}
0.01
0.1
1
10
100
f[Hz]

phase transition dynamics

Bubble: static field configuration passing the barrier (excited through thermal fluctuations)

- decay rate

$$\Gamma(T) \approx T^4 \exp\left(-\frac{S_3(T)}{T}\right),$$

- $\mathcal{O}(3)$ symmetric action

$$S_3(T) = 4\pi \int dr r^2 \left[\frac{1}{2}\left(\frac{d\phi}{dr}\right)^2 + V(\phi, T)\right].$$

- EOM $\rightarrow$ bubble profile

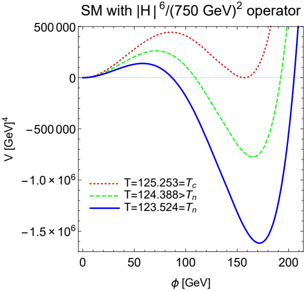
$$\frac{d^2\phi}{dr^2} + \frac{2}{r}\frac{d\phi}{dr} - \frac{\partial V(\phi,T)}{\partial\phi} = 0,$$

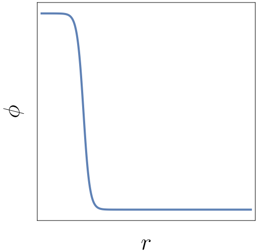
$$\phi(r \rightarrow \infty) = 0 \quad \text{and} \quad \dot{\phi}(r = 0) = 0.$$

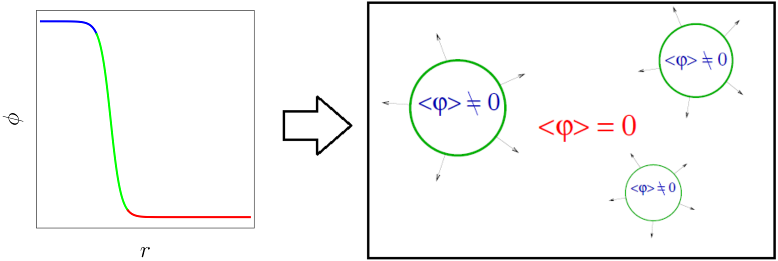
- nucleation temperature

$$N(T_n) = \int_{t_c}^{t_n} dt \frac{\Gamma(t)}{H(t)^3} = \int_{T_n}^{T_c} \frac{dT}{T}\frac{\Gamma(T)}{H(T)^4} = 1$$

Linde '81 '83







Morrissey ’12

Gravitational waves from a PT

- Strength of the transition

$$\alpha \approx \left.\frac{\Delta V}{\rho_R}\right|_{T=T_*}, \quad \Delta V = V_f - V_t$$

- Characteristic scale

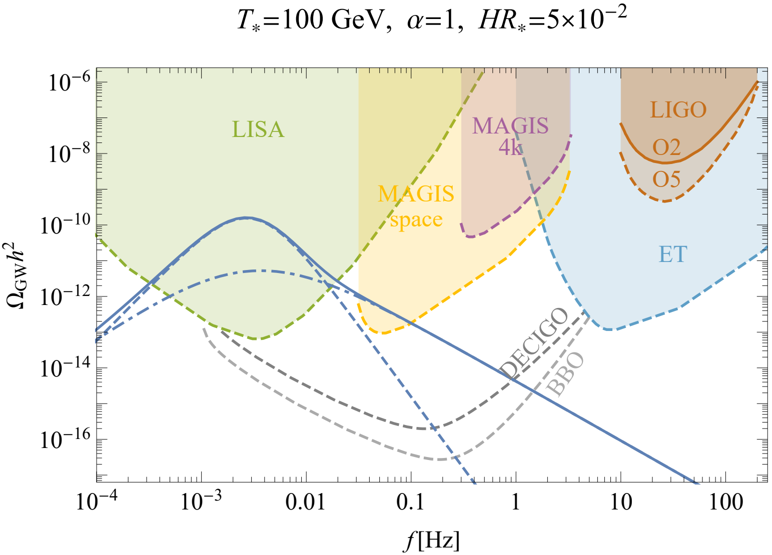
$$HR_* = H_* N_b^{-\frac{1}{3}} = H_* \left(\int dt' \left(\frac{a(t')}{a(t)} \right)^3 \Gamma(t') P(t') \right)^{-\frac{1}{3}}$$

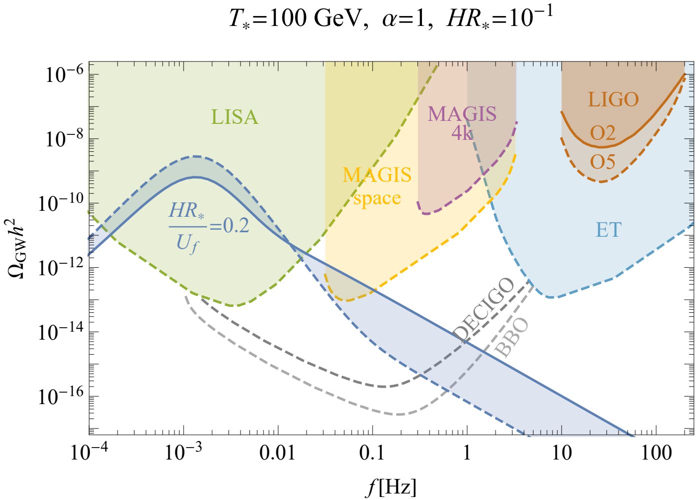
- Signals are produced by three main mechanisms:
  - collisions of bubble walls: $\Omega_{\rm col} \propto \left(\frac{\kappa_{\rm col}\alpha}{\alpha+1} \right)^2 (HR_*)^2$

    Kamionkowski ‘93, Huber ‘08, Hindmarsh ‘18,
  - sound waves: $\Omega_{\rm sw} \propto \left(\frac{\kappa_{\rm sw}\alpha}{\alpha+1} \right)^2 HR_* \frac{HR_*}{U_f}$

    Hindmarsh ‘13 ‘15 ‘17 Ellis ’18
  - turbulence $\Omega_{\rm turb} \propto \left(\frac{\kappa_{\rm turb}\alpha}{\alpha+1} \right)^{\frac{3}{2}} HR_*$

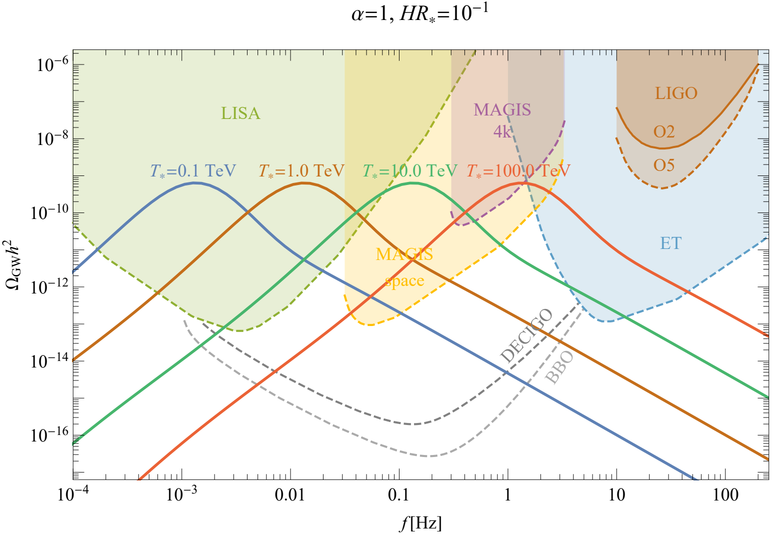
    Caprini ‘09
- The frequency of the signal changes as $f \propto \frac{T_*}{HR_*}$


$T_* = 100$ GeV, $\alpha = 1$, $HR_* = 5\times10^{-2}$
LISA
MAGIS space
MAGIS 4k
LIGO
O2
O5
ET
DECIGO
BBO
$\Omega_{GW}h^2$
f[Hz]
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{-16}
10^{-4}
10^{-3}
0.01
0.1
1
10
100

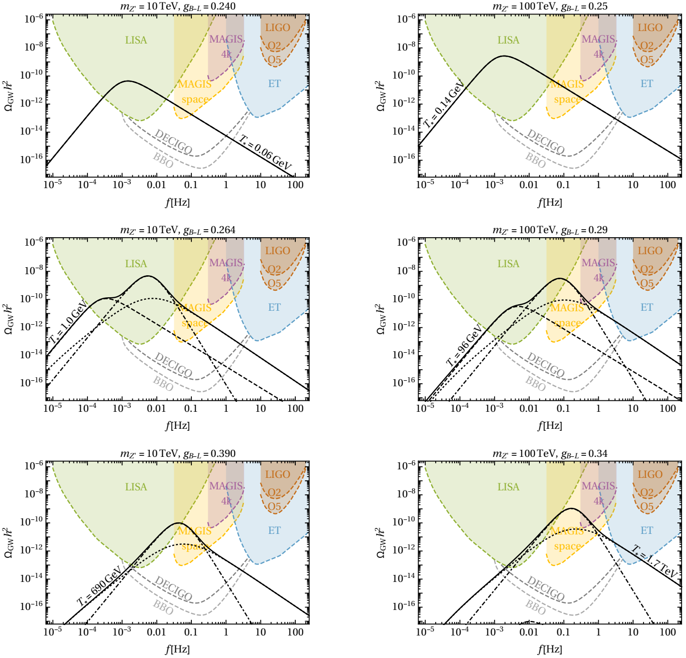


- Root-mean-square four-velocity of the plasma

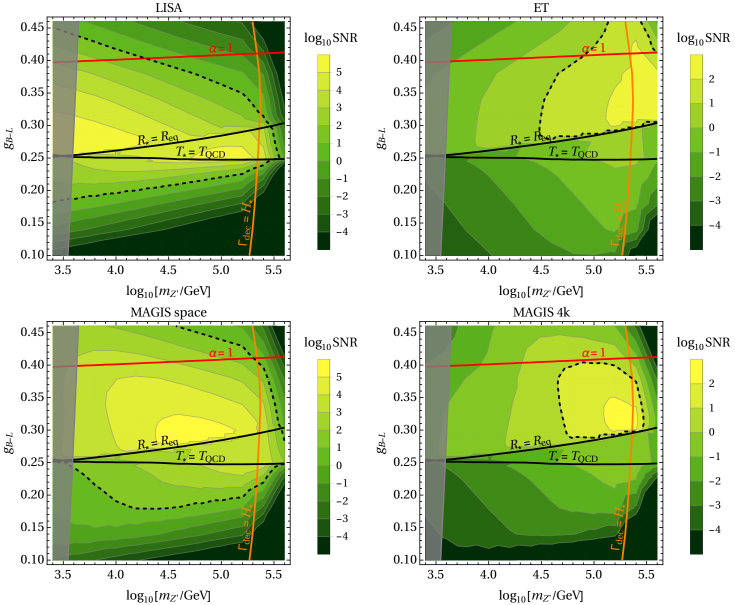
$$\bar{U}_f \approx \sqrt{\frac{3}{4}\frac{\kappa_{\rm sw}\alpha}{1+\alpha}} \xRightarrow{v_w \approx 1} \frac{\sqrt{3}\alpha}{2(1+\alpha)\sqrt{0.73+0.083\sqrt{\alpha}+\alpha}}\,.$$



α=1, HR∗=10^−1
LISA
MAGIS
4k
LIGO
O2
O5
T∗=0.1 TeV
T∗=1.0 TeV
T∗=10.0 TeV
T∗=100.0 TeV
MAGIS
space
ET
DECIGO
BBO
Ω_GW h^2
f [Hz]
10^−6
10^−8
10^−10
10^−12
10^−14
10^−16
10^−4
10^−3
0.01
0.1
1
10
100



$m_{Z'} = 10\,\mathrm{TeV}$, $g_{B-L} = 0.240$
$m_{Z'} = 100\,\mathrm{TeV}$, $g_{B-L} = 0.25$
$m_{Z'} = 10\,\mathrm{TeV}$, $g_{B-L} = 0.264$
$m_{Z'} = 100\,\mathrm{TeV}$, $g_{B-L} = 0.29$
$m_{Z'} = 10\,\mathrm{TeV}$, $g_{B-L} = 0.390$
$m_{Z'} = 100\,\mathrm{TeV}$, $g_{B-L} = 0.34$
$\Omega_{\mathrm{GW}} h^2$
f[Hz]
LISA
MAGIS 4k
MAGIS space
LIGO
O2
O5
ET
DECIGO
BBO
$T_* = 0.06\,\mathrm{GeV}$
$T_* = 0.14\,\mathrm{GeV}$
$T_* = 1.0\,\mathrm{GeV}$
$T_* = 96\,\mathrm{GeV}$
$T_* = 690\,\mathrm{GeV}$
$T_* = 1.7\,\mathrm{TeV}$

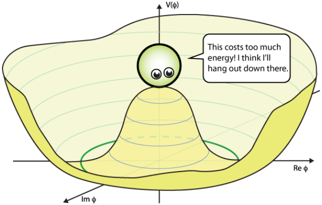


LISA
ET
MAGIS space
MAGIS 4k
g_{B-L}
$\log_{10}[m_{Z'}/\mathrm{GeV}]$
$\log_{10}\mathrm{SNR}$
$\alpha = 1$
$R_* = R_{\mathrm{eq}}$
$T_* = T_{\mathrm{QCD}}$
$\Gamma_{\mathrm{dec}} = H_*$

Cosmic String formation (Kibble mechanism)

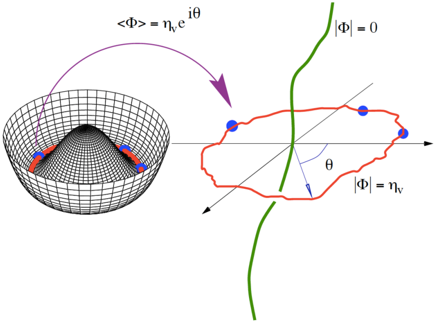
- Charged complex scalar field

$$V = \lambda \left(\Phi^\dagger \Phi - \frac{v^2}{2} \right)^2$$



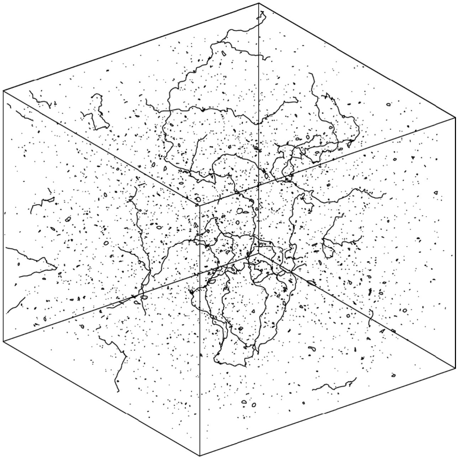
- Horizon size at early time (high temperature) $d_H \propto M_p / T^2$
- we need a solution:

$$\Phi \xrightarrow{r \to \infty} \frac{v}{\sqrt{2}} e^{i\theta}$$



Christophe Ringeval (Adv.Astron. 2010)

Cosmic Strings



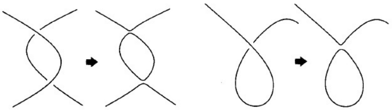
Vilenkin and Shellard ’94

Cosmic String network

- Static string network would red-shift as

$$\rho_\infty \propto a^{-2}$$

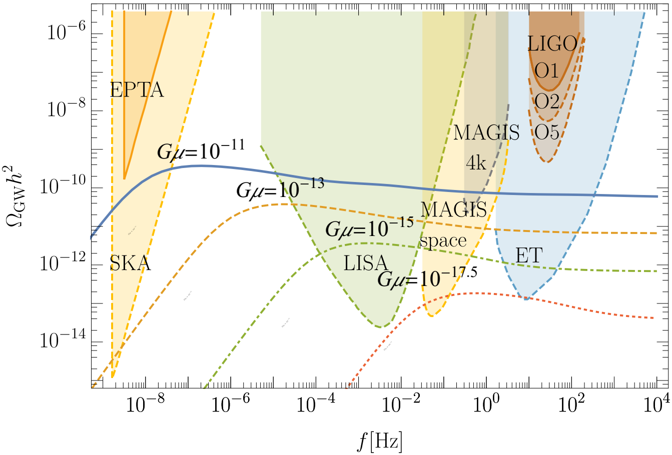
- strings intercommute on collision



- overall energy density of the network scales with total energy density

$$\frac{\rho_\infty}{\rho_{\rm tot}} \propto G\mu$$

Stochastic GW background from Cosmic Strings

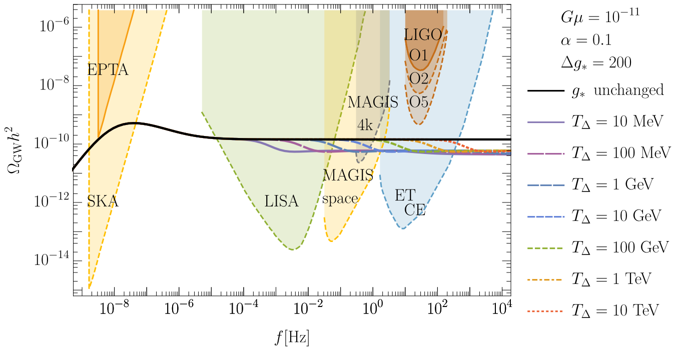


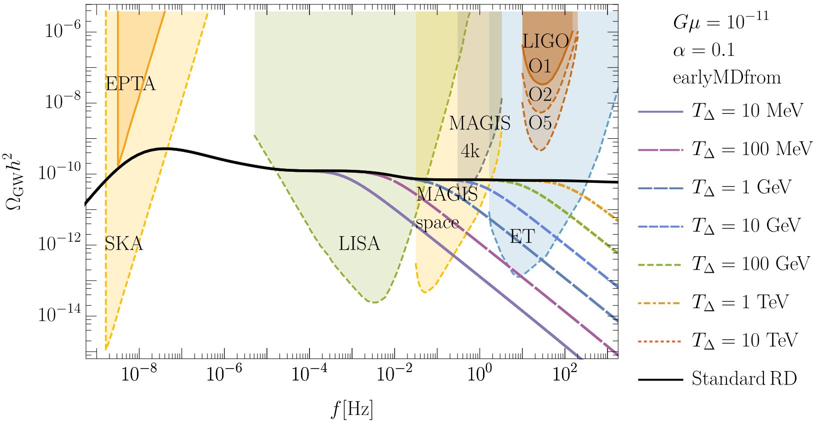
Extra DOF

- We add Δg_* new degrees of freedom at T_Δ

$$g_*(T) = \begin{cases} g_*^{\mathrm{SM}}(T) & \text{for} \quad T < {\color{red}T_\Delta} \\ g_*^{\mathrm{SM}}(T) + \Delta g_* & \text{for} \quad T > {\color{red}T_\Delta} \end{cases}$$

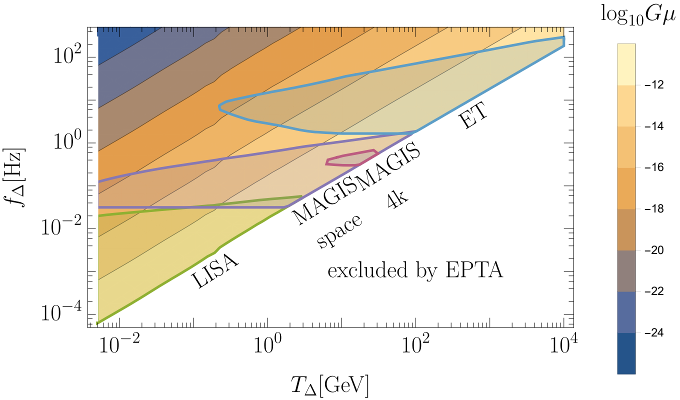
- An example with $\Delta g_* = 200$





$G\mu = 10^{-11}$
$\alpha = 0.1$
earlyMDfrom
$T_\Delta = 10$ MeV
$T_\Delta = 100$ MeV
$T_\Delta = 1$ GeV
$T_\Delta = 10$ GeV
$T_\Delta = 100$ GeV
$T_\Delta = 1$ TeV
$T_\Delta = 10$ TeV
Standard RD
EPTA
SKA
LISA
MAGIS space
MAGIS 4k
ET
LIGO
O1
O2
O5
$\Omega_{\rm GW} h^2$
$f\,[\rm Hz]$

Detection capabilities



- slightly better numerical result

$$f_\Delta = (8.67 \times 10^{-9}\,\text{Hz}) \frac{T_\Delta/\text{GeV}}{\sqrt{\alpha\, G\mu}} \left(\frac{g_*(T_\Delta)}{g_*(T_0)}\right)^{\frac{8}{6}} \left(\frac{g_S(T_0)}{g_S(T_\Delta)}\right)^{-\frac{7}{6}}$$