Precision early universe cosmology from gravitational waves

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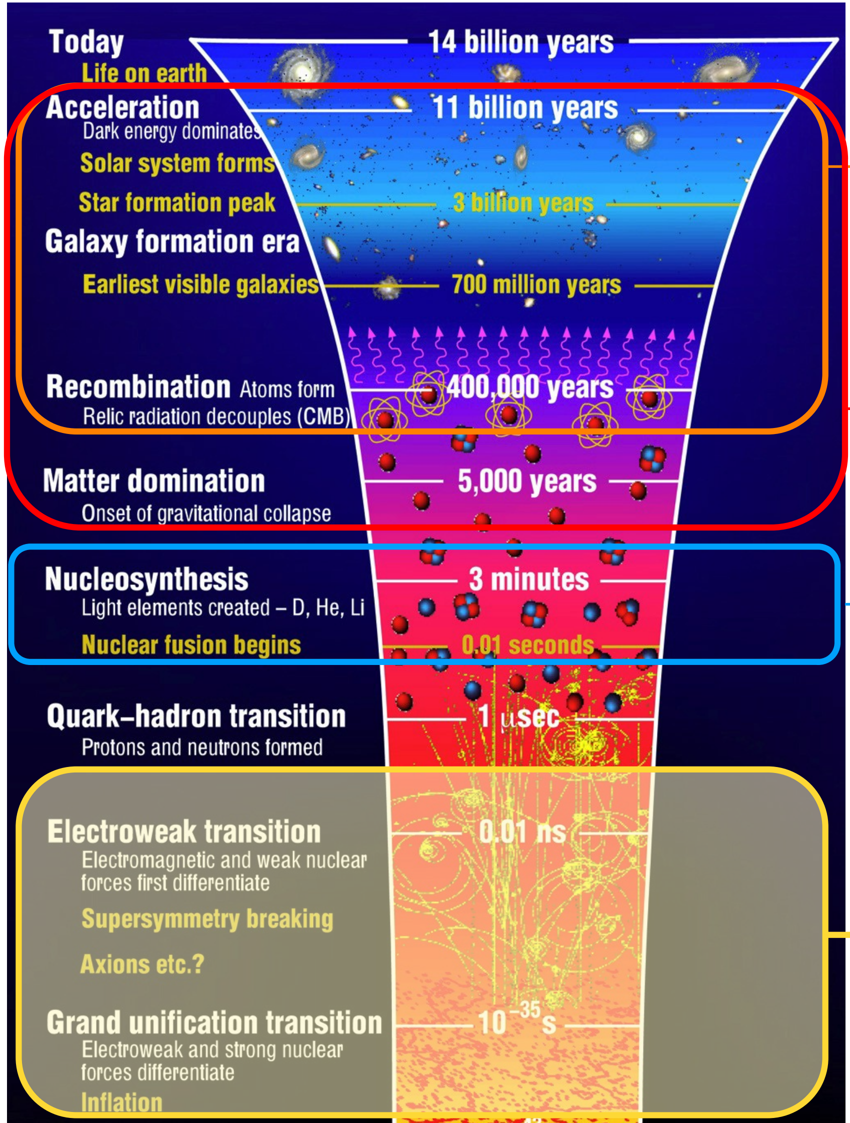
Based on work with D. Brzeminski, A. Hook and D. Racco
arxiv: 2010.03568 & 2203.13842

Particle physics from cosmology

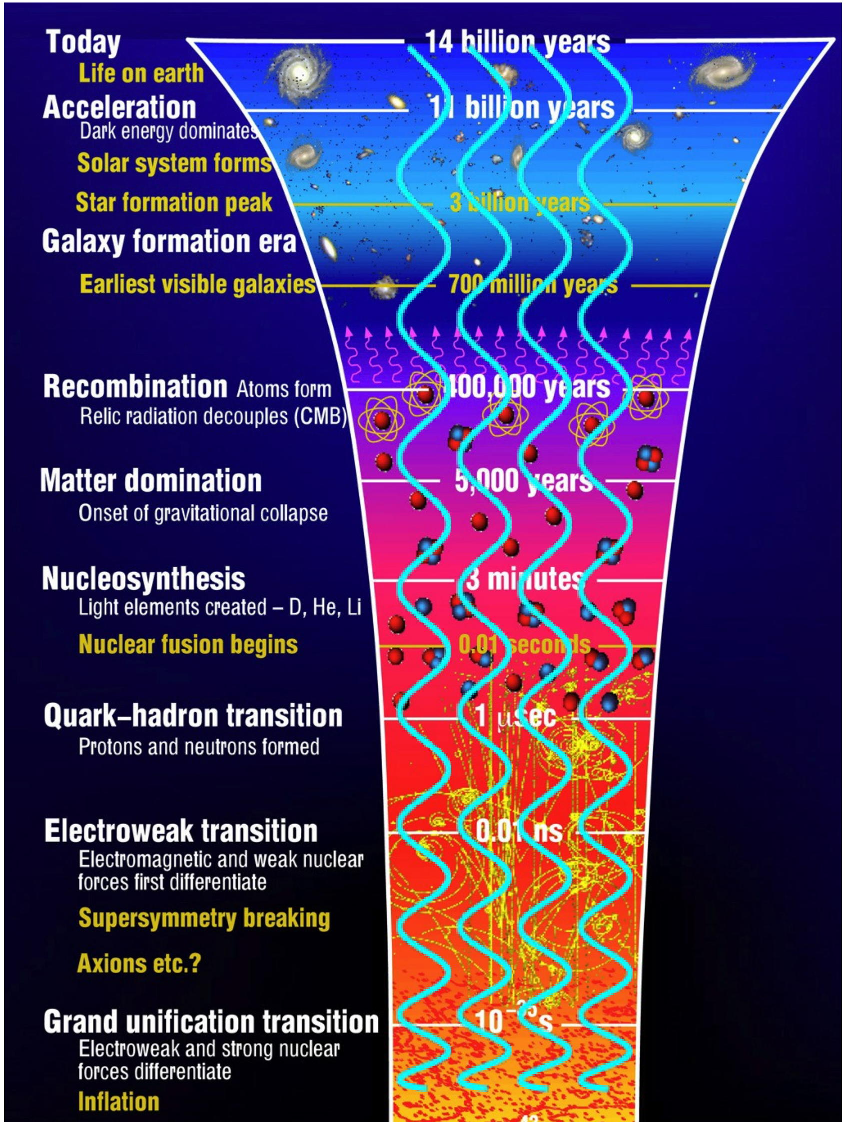


Very precise information about universe after temperature ~ eV

Matter power spectrum carries information from up to T ~ keV

Light elements (BBN) give us some information about T ~ MeV;
Detecting cosmic neutrinos could teach us even more up to MeV

How can we probe much earlier times when particles had higher energies than what we can achieve in the lab?



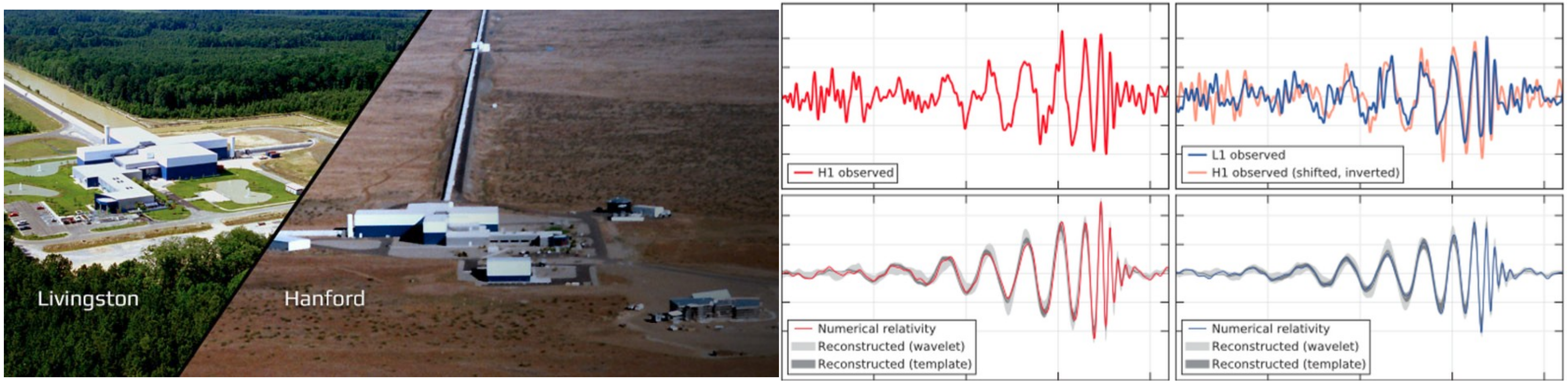
New window to the universe

- The detection of gravitational waves gave us a new window into the universe
- Gravitational interactions are so weak that the universe is always transparent
- Can carry information from the earliest times of the universe. Time to explore how to interpret that information

Outline

- Introduction
- Causality and gravitational waves spectrum
  - Effects of modified expansion history
  - Free streaming particles
- Forecast sensitivity to motivated BSM scenarios
  - Axions
  - Supersymmetry

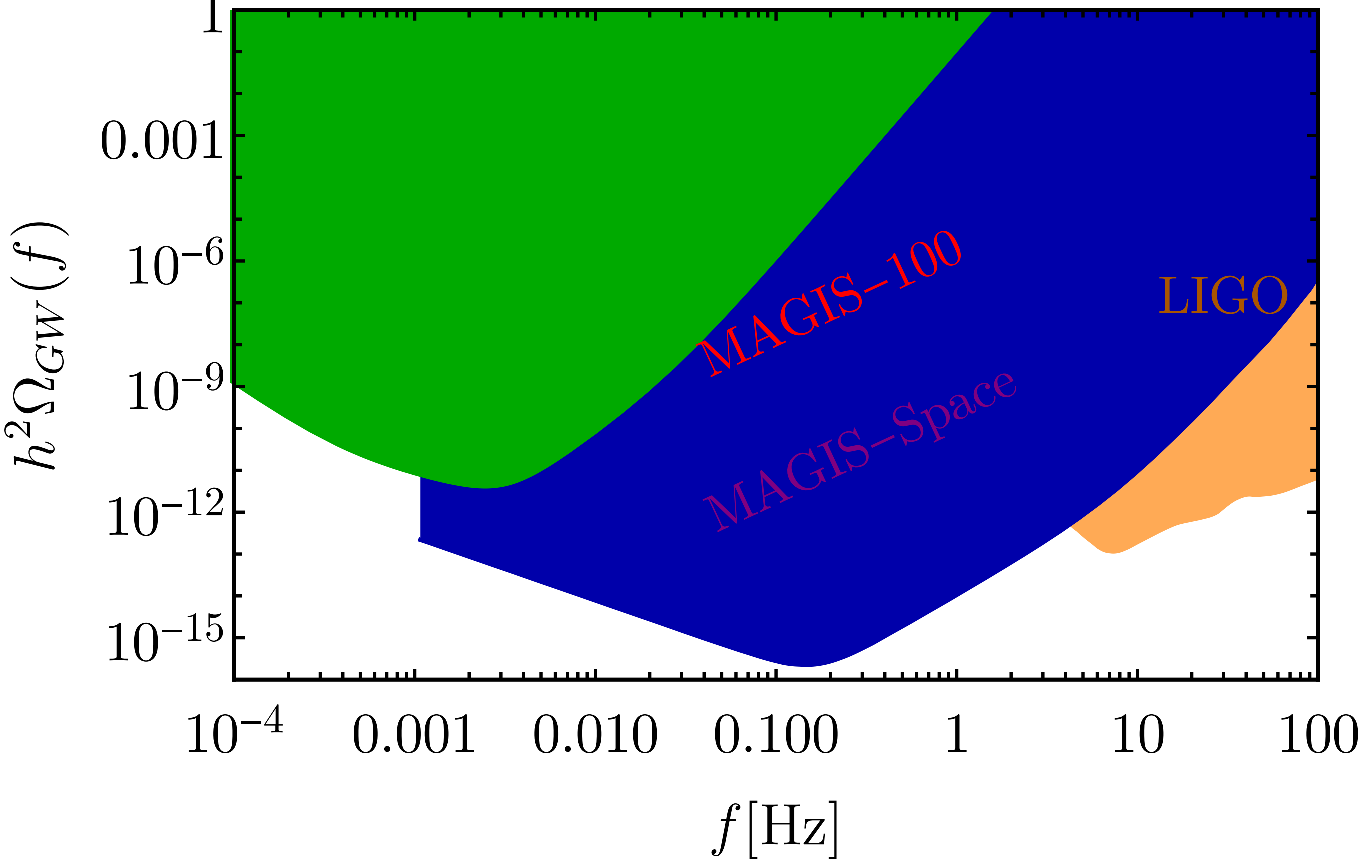
Gravitational wave astronomy



- In 2015 LIGO had the first detection of gravitational waves
- LIGO/Virgo have observed 90 merger events (transient signals)
- Next target: stochastic gravitational wave signal

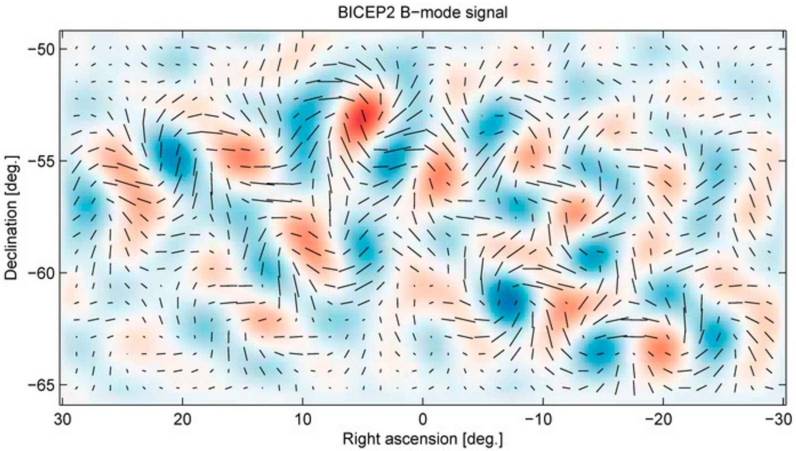
Experimental landscape

$$\Omega_{\rm GW}(f) = \frac{1}{\rho_c}\frac{d\rho_{\rm GW}}{d\log f}$$

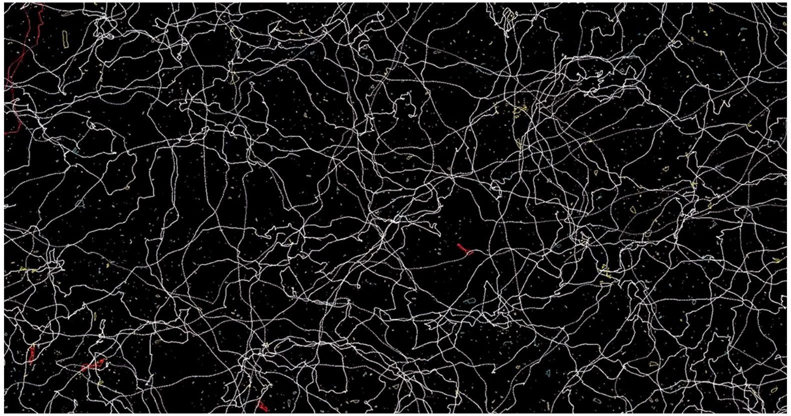


Cosmological sources

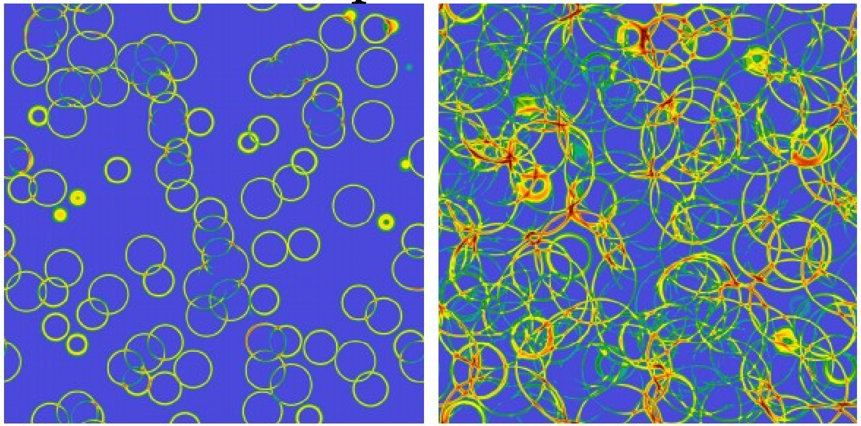
Inflation



Cosmic strings

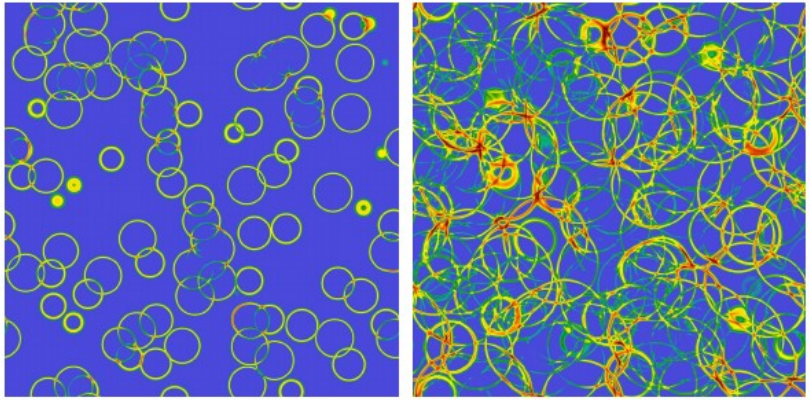


1st order phase transition

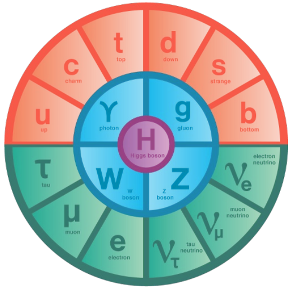


Short duration sources

1st order phase transition



- Common expectation in gauge theories
- Bubble nucleations of true vacuum and subsequent expansion generates GW
- Transition usually completes quickly compared to expansion rate

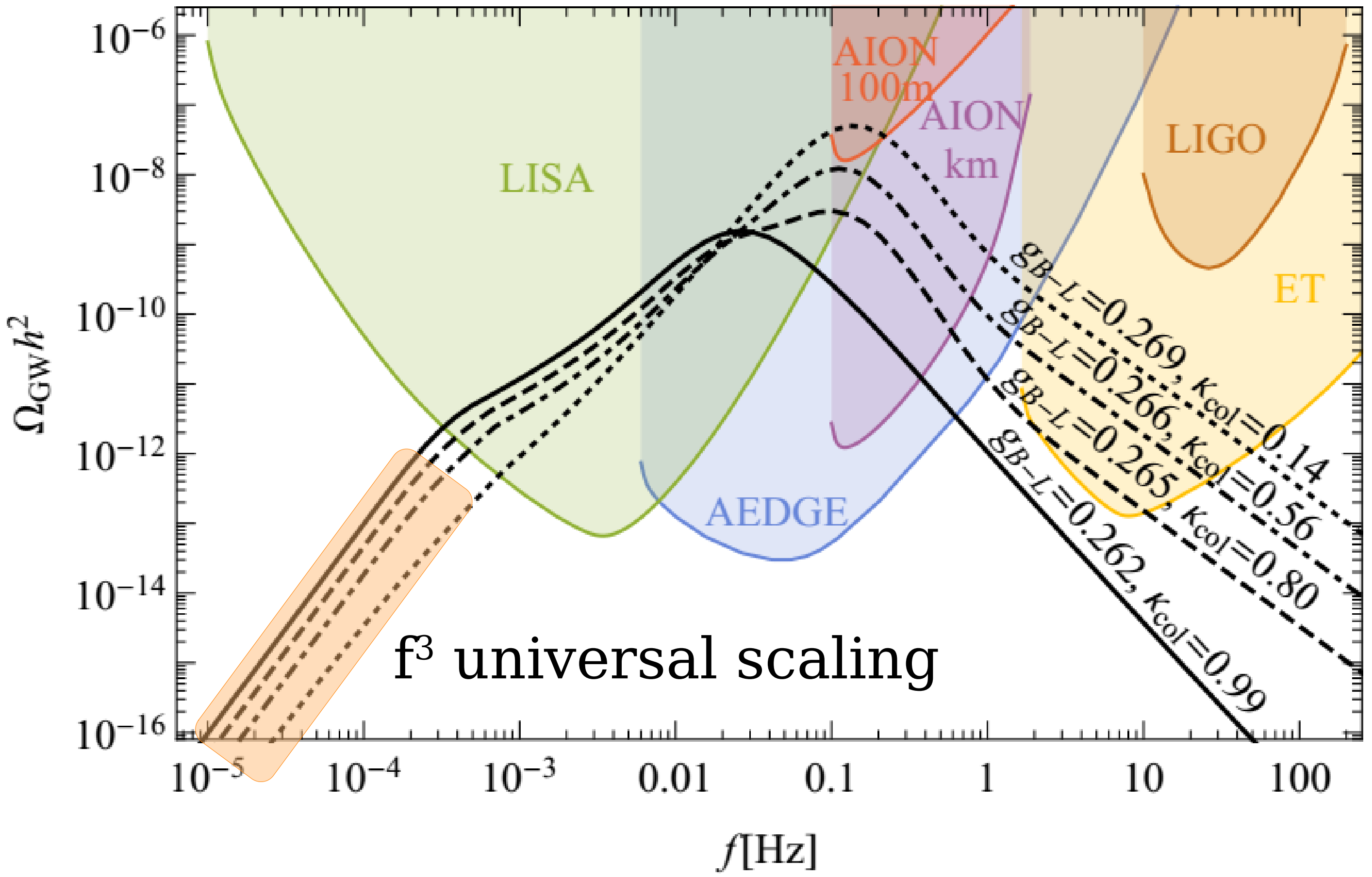


→ QCD if $m_s << \Lambda_{QCD}$ ✗

→ Electroweak if $m_h < 80$ GeV ✗

Possible in many BSM scenarios

Example signal



*Ellis, Lewicki and Vaskonen, JCAP 11 (2020)

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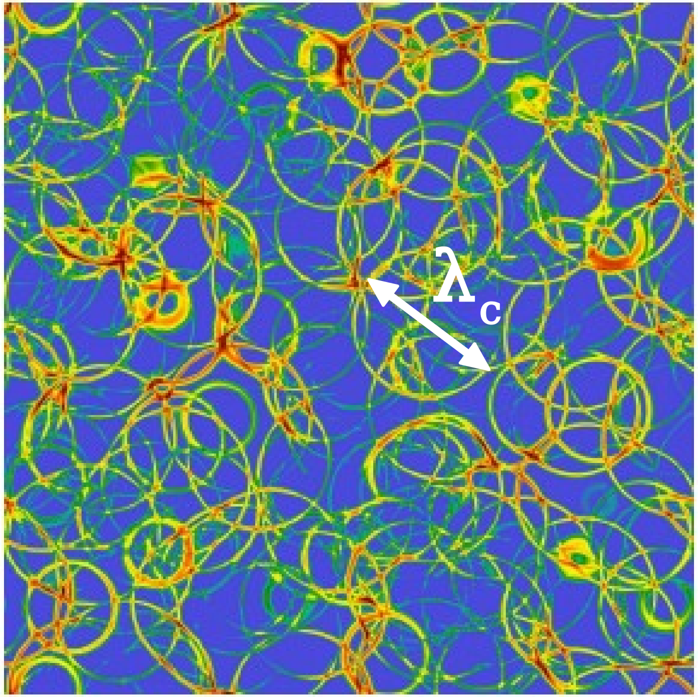
Causal source

$\Pi(k)$



$\lambda_c \ll \mathcal{H}_{\rm PT}^{-1}$

$$h'' + 2\mathcal{H}h' + k^2 h = \frac{32\pi G a^2 \rho}{3}\Pi$$

$$\Omega_{\rm GW}(k) \propto \langle \Pi(k)\Pi(-k)\rangle'$$

➔ There is a maximum correlation length, λ_c, because source duration is finite.

$$\langle \Pi(k)\Pi(-k)\rangle' \xrightarrow[k \ll \lambda_c^{-1}]{} \text{const}$$

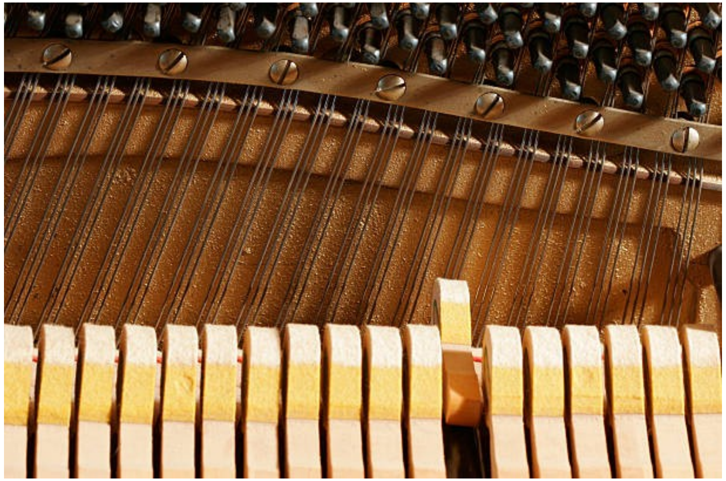
Low wavelength modes are "independent" of source dynamics

Long wavelength modes

Source turns off much faster than mode frequency:

$$h'' + 2\mathcal{H}h' + k^2 h = J\delta(\tau - \tau_{PT})$$

Shortly after source turns off: $\begin{cases} h = 0 \\ h' \approx J \end{cases}$

h  $\frac{J}{\mathcal{H}_{PT}}$

Super-horizon modes

After production: super-horizon modes remain frozen until horizon entry

$$h \approx \frac{J}{\mathcal{H}_{PT}} \,, \quad k < \mathcal{H}$$

Once they enter the horizon: oscillate with an amplitude that decays as a^{-1}

$$|h| \approx \frac{J}{\mathcal{H}_{PT}} \frac{a_k}{a}$$

➡ Amplitude sensitive to how long a mode wavelength stays larger than horizon size (expansion history)

In a radiation dominated universe

$$|h| \approx \frac{J}{\mathcal{H}_{PT}} \frac{a_k}{a_{PT}} \frac{a_{PT}}{a} \xrightarrow{\mathcal{H} \propto a^{-1}} |h| \approx \frac{J}{k} \frac{a_{PT}}{a}$$

$$\Omega_{GW}(k) \propto \underbrace{\boxed{k^3}}_{\text{phase space}} \times \underbrace{\boxed{k^2}}_{\omega = k} \times \left(\frac{J}{k} \frac{a_{PT}}{a} \right)^2 \propto k^3$$

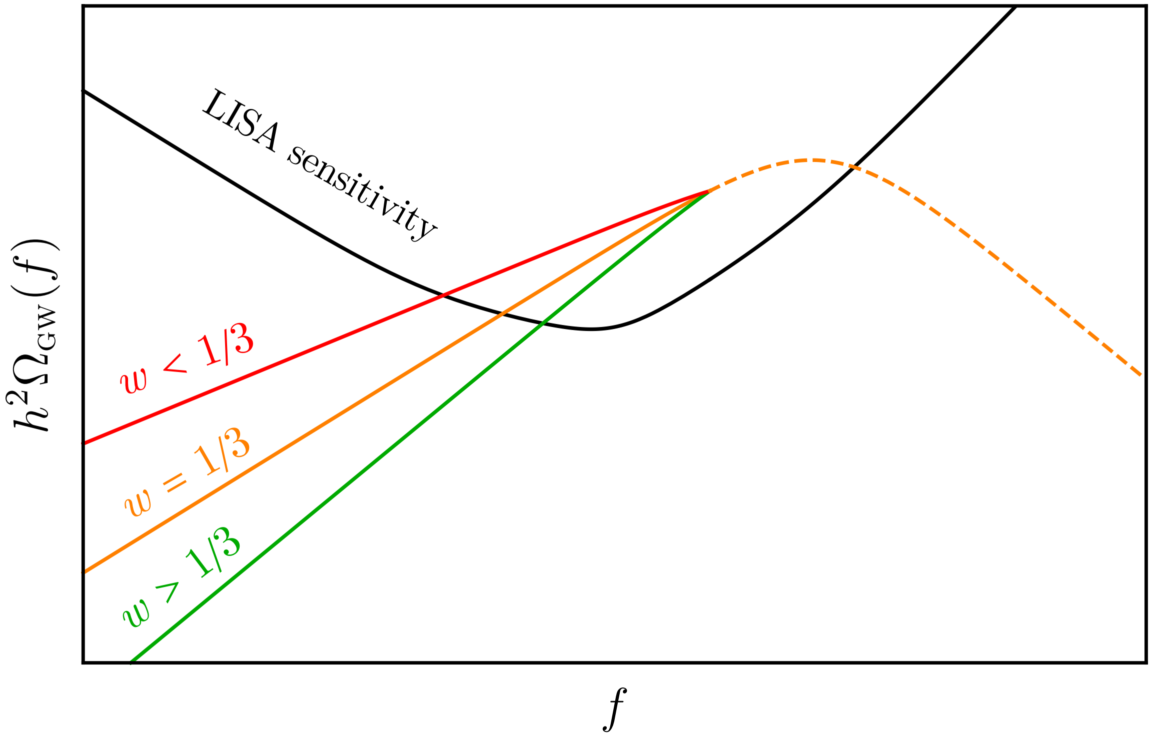
f^3 universal scaling only if universe was radiation dominated

For general equation of state

$p = w\rho$

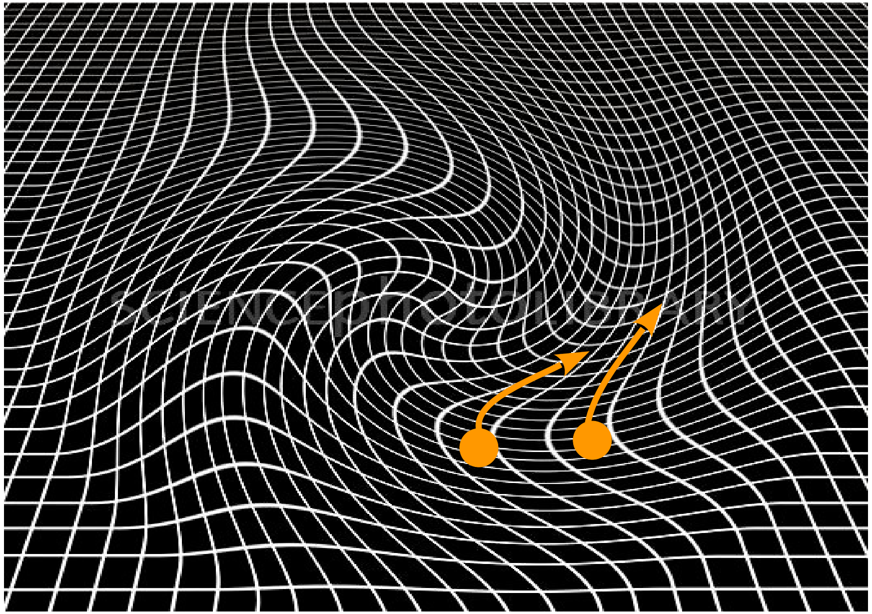
equation of state

$$\Omega_{GW}(k) \propto k^{3-2\left(\frac{1-3w}{1+3w}\right)}$$



Free streaming relativistic particles

- We have shown equation of state affects spectrum by changing expansion
- Can something feedback into gravitational waves? → Free streaming particles

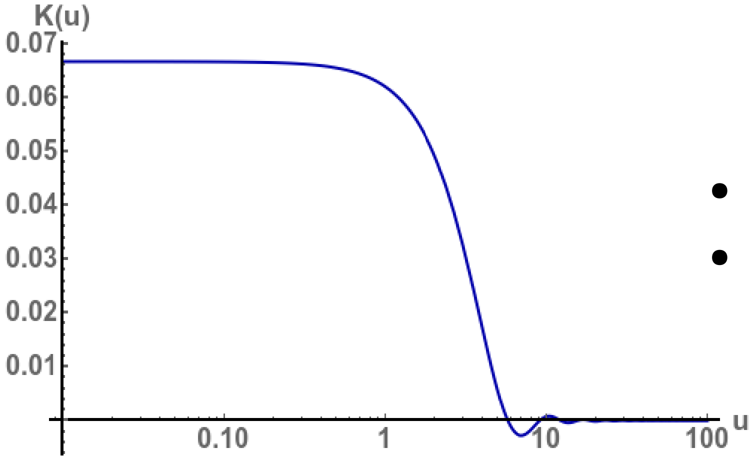


- Free streaming particles follow geodesics
- Tensor perturbations induce anisotropic stress, which affects gravitational waves
- First studied by Weinberg in the context of inflationary gravitational waves (free streaming particles not present at generation)

Impact of free streaming particles

➔ Time dependence of h leads affects free streaming geodesics

$$\Pi(\tau) = -4\rho_{\rm fs}(\tau)\int^{\tau} dy K(k\tau - ky)h'(y)$$



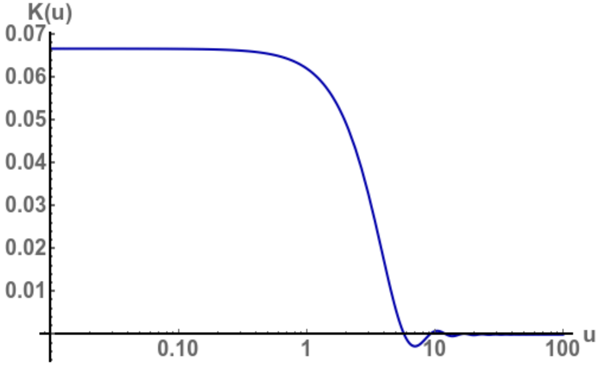
- Inflationary case has h' = 0 until kτ ~ 1
- Leads to a universal suppression in power

➔ Long wavelength modes and short duration sources: $\begin{cases} h = 0 \\ h' \approx J \end{cases}$

Free streaming and fast sources

Note that for super-horizon modes ($k\tau \ll 1$) :

$$\Pi(\tau) = -4\rho_{\rm fs}(\tau)\int^{\tau} dy K(k\tau - ky)h'(y) \approx -\frac{4}{15}\rho_{\rm fs}h(\tau)$$

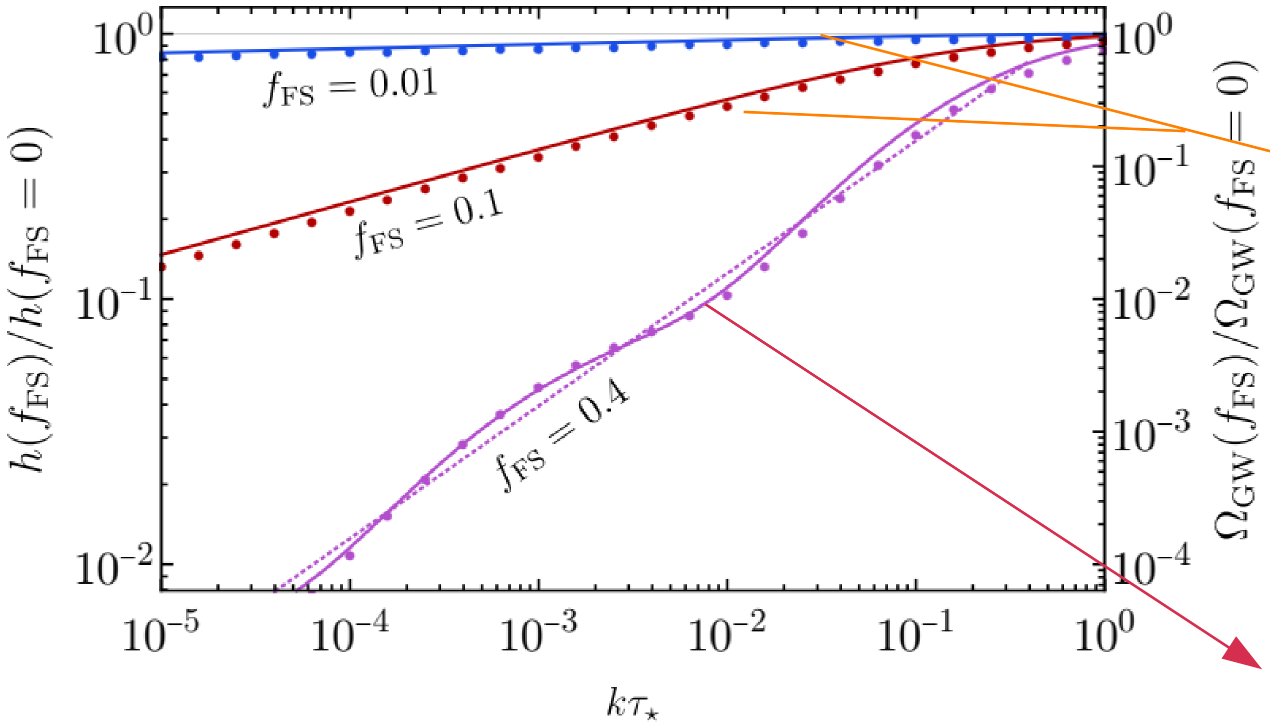


$$h'' + \frac{2}{\tau}h' + \left(k^2 + \frac{8\rho_{\rm fs}}{5\rho_{\rm total}\tau^2}\right)h = 0$$

Time dependent frequency changes super-horizon evolution

Impact of free streaming particles

$$f_{\mathrm{fs}} = \rho_{\mathrm{fs}}/\rho_{\mathrm{total}}$$



Small f_{fs}

$$\frac{\Omega_{\mathrm{GW}}^{f_{\mathrm{fs}}}}{\Omega_{\mathrm{GW}}} = (k\tau_*)^{\frac{16 f_{\mathrm{fs}}}{5}}$$

$$f_{fs} > 5/32$$

$$\frac{\Omega_{\mathrm{GW}}^{f_{\mathrm{fs}}}}{\Omega_{\mathrm{GW}}} = (k\tau_*)\left[A_1 + A_2 \sin\left(\sqrt{\frac{32 f_{\mathrm{fs}}}{5} - 1}\,\log(k\tau_*) + A_3\right)\right]$$

Summary of effects

- Low frequency spectral shape of GW generated by phase transitions is independent of details of the phase transition.
- Wavelengths longer than horizon size at PT are sensitive to the eq of state of the universe and also to free streaming radiation:

eq. of state: $$\Omega_{GW}(k) \propto k^{3-2\left(\frac{1-3w}{1+3w}\right)}$$

free stream: $$\Omega_{GW}(k) \propto k^{3-\frac{16}{5}f_{\rm fs}}$$

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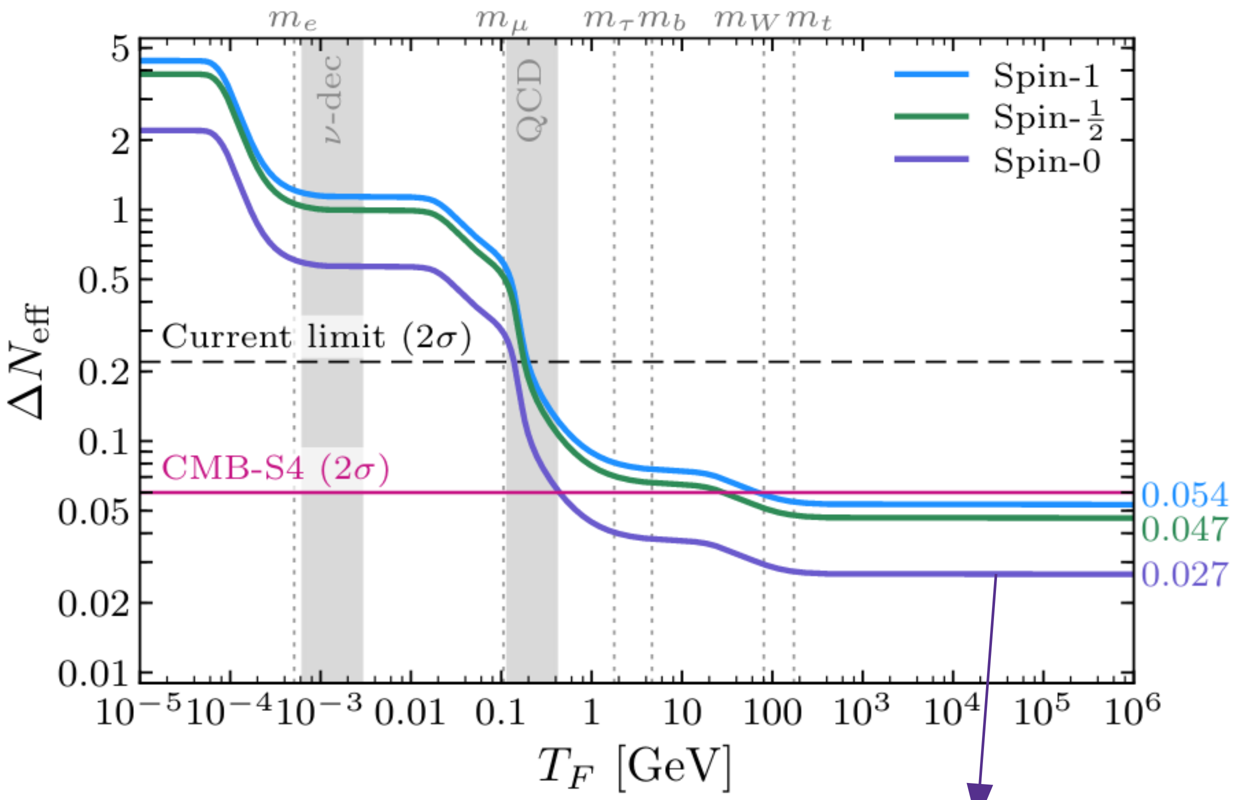
BSM targets: free streaming



$f_{fs} \approx 10^{-2}$

- New types of relativistic particles in cosmology
- Searching for their effects at much earlier times than $N_{\rm eff}$ constraints (BBN & CMB)
- Effect present for free streaming particles

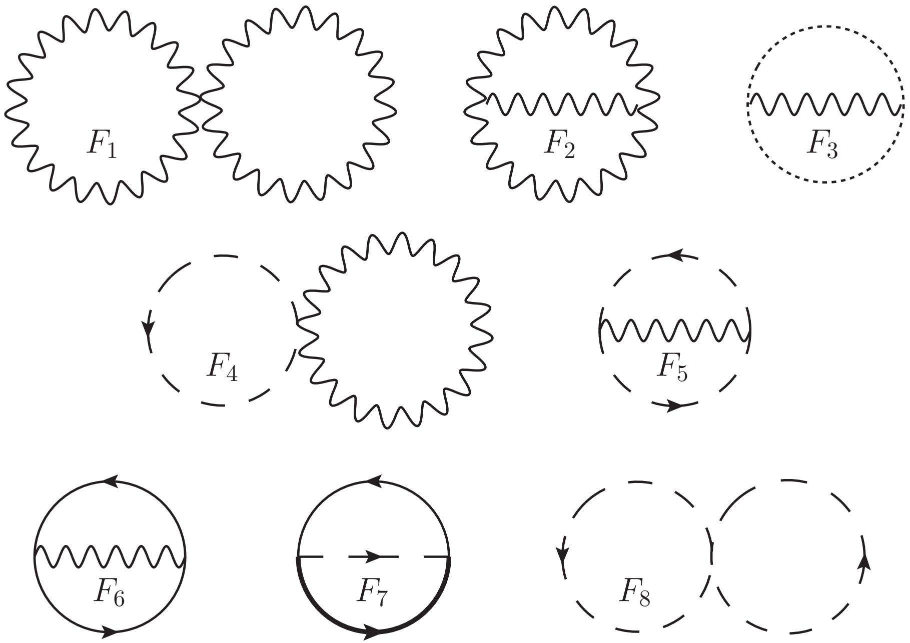
What about interacting particles?

Equation of state

Even when the universe is radiation dominated we expect: $w \neq \frac{1}{3}$

$$T^\mu_\mu = \rho - 3p \sim \beta$$

conformal anomaly



$$\delta w = \frac{T^4}{\rho}\left(\frac{55}{1728}\beta_{g'^2} + \frac{43}{576}\beta_{g^2} + \frac{7}{36}\beta_{g_s^2} + \frac{5}{288}\beta_{y_t^2} + \frac{1}{72}\beta_\lambda\right) \approx -3\times 10^{-4}\left(\frac{100}{g_\star}\right)$$

New particles set sensitivity target

$$\Omega_{GW}(k) \propto k^{3+\delta}$$

Particles that were initially in thermal equilibrium and decouple are easier:

$$\delta \approx 10^{-2} \times N_{dof}$$

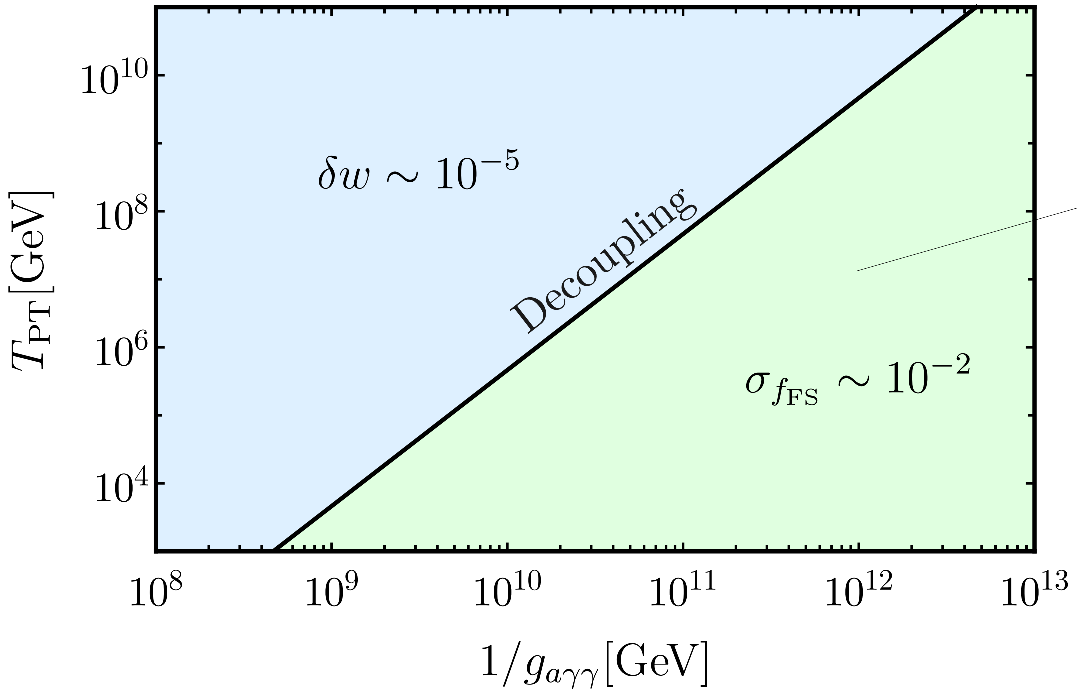
Particles that remain in equilibrium with Standard Model:

$$\delta \approx 3 \times 10^{-4} \left(\frac{N_{dof}}{g_\star} + \frac{\delta \beta_{\rm QCD}}{\beta_{\rm QCD}^{SM}} \right) \sim 10^{-5}$$

Axions

One new degree of freedom. Out of reach for traditional N_{eff} searches if it decouples before temperature reaches weak scale.

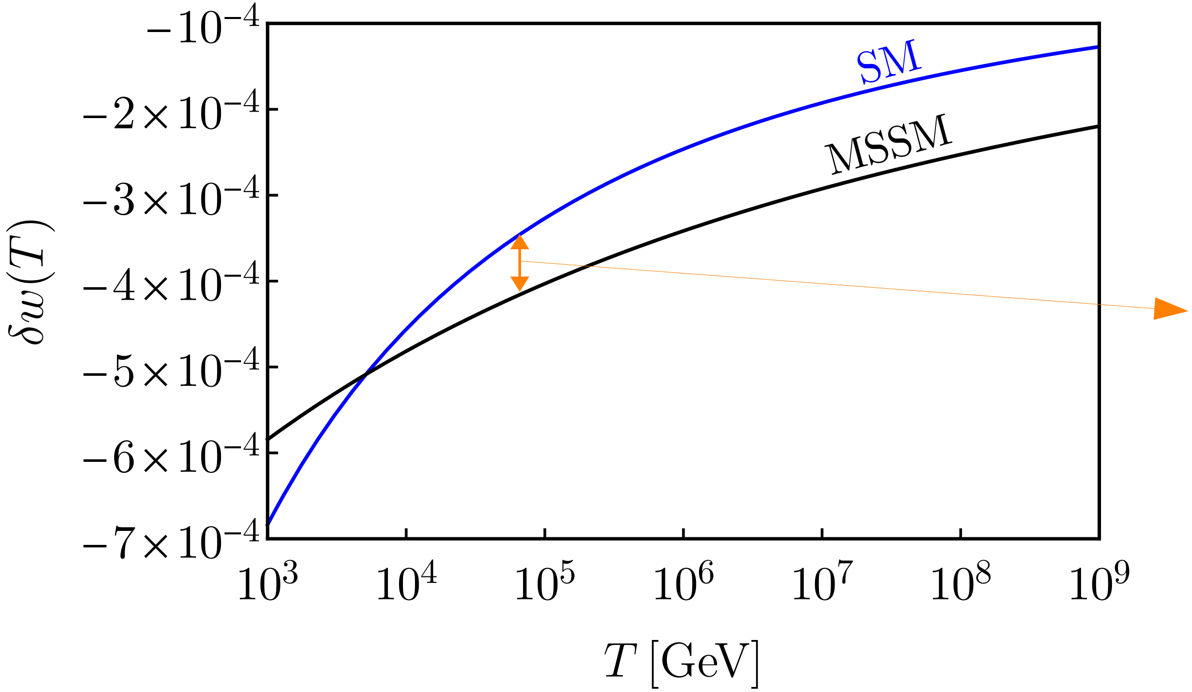
$$\frac{g_{a\gamma\gamma}}{4} aF\tilde{F}$$



assuming T_{reheat} is larger than decoupling T

Supersymmetry

If supersymmetry solves the Higgs hierarchy problem: order 1 change in the number of particles and beta functions somewhere above TeV scale



$$\delta w \approx 10^{-4}$$

Can we actually reach this sensitivities?

How well could we do?

- We will assume only instrumental noise (optimistic)
- Use fisher information matrix to determine optimal sensitivity

$$\sigma_\theta^{-2} = T \int df \left(\frac{\partial \Omega_{GW}}{\partial \theta} \right)^2 \frac{4\Omega_{GW}^2 + 2\Omega_{GW}\Omega_{\rm noise} + \Omega_{\rm noise}^2}{(2\Omega_{GW}^2 + 2\Omega_{GW}\Omega_{\rm noise} + \Omega_{\rm noise}^2)^2}$$

observation time

signal dependence on parameter of interest

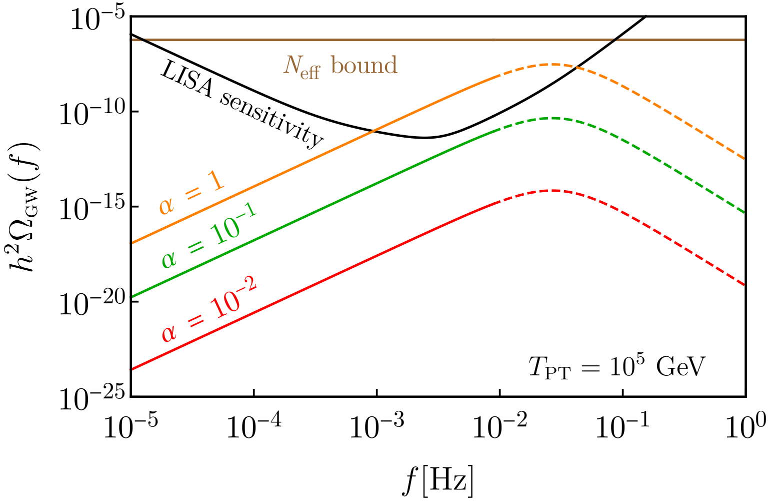
noise power spectrum

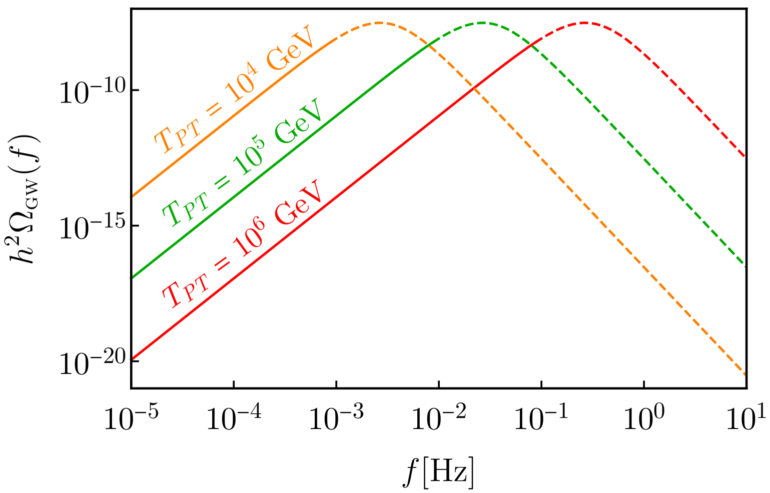
Ω template

There are 3 main contributions to GW from phase transitions:

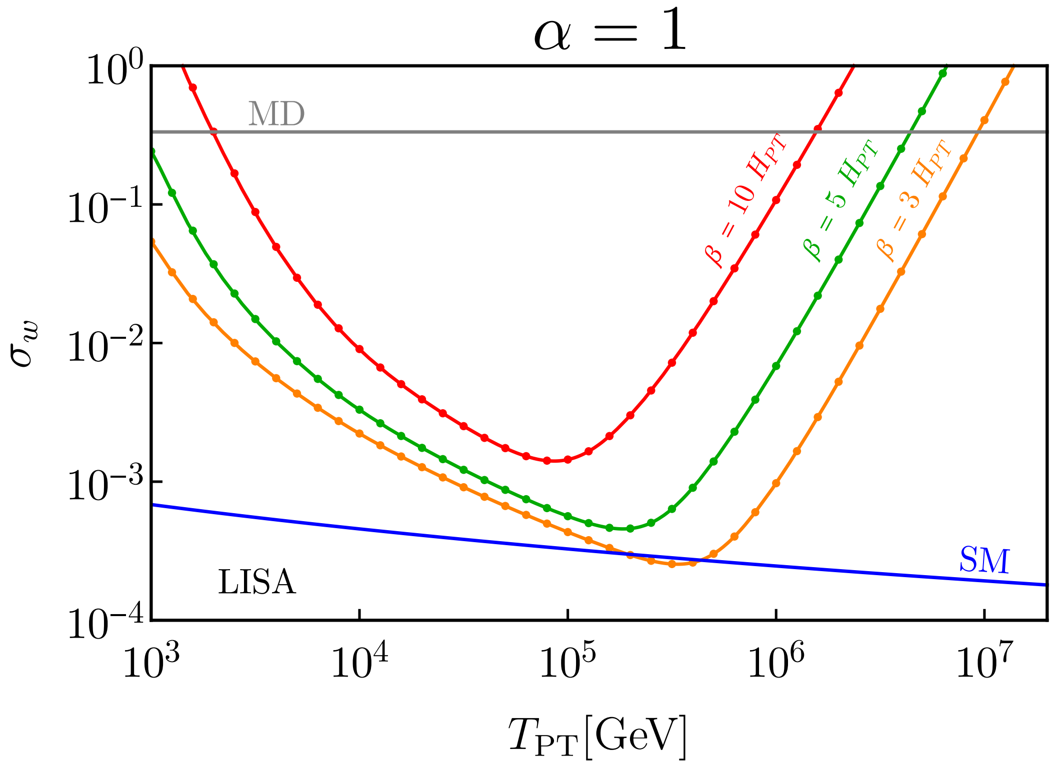
- Bubble wall collisions
- Sound waves
- Turbulence

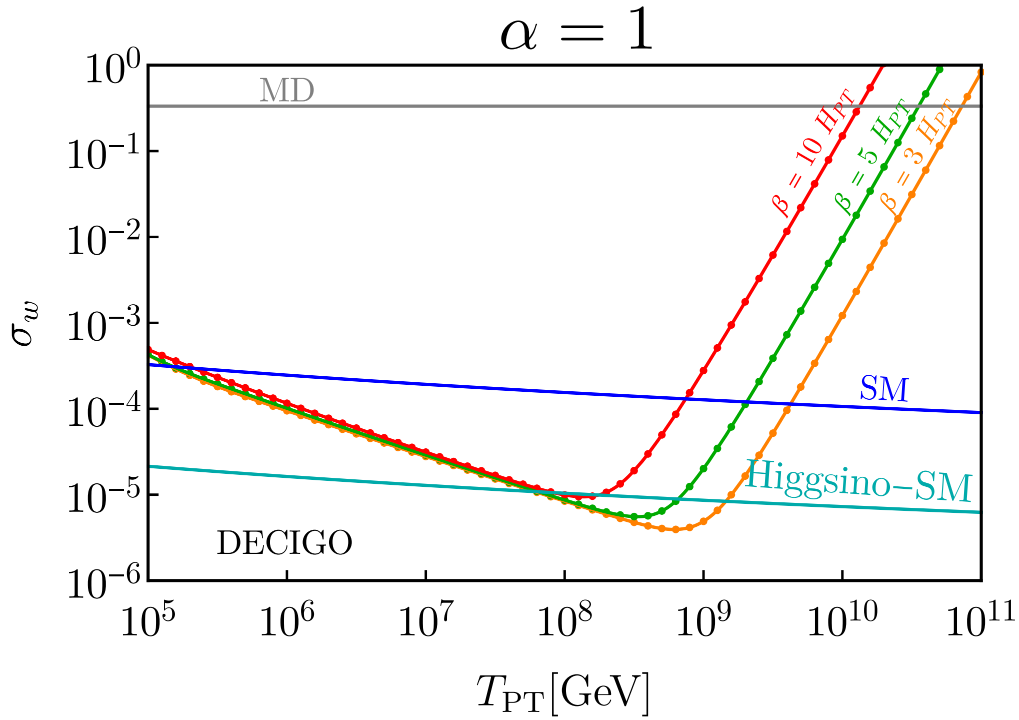
$$h^2\Omega^0_{GW} = 1.19\times 10^{-6}\left(\frac{H_{PT}}{\beta}\right)\left(\frac{\kappa_v\alpha}{1+\alpha}\right)^2\left(\frac{100}{g_\star}\right)^{1/3}\left(\frac{f}{f_\star}\right)^3\left(\frac{7}{4+3\,(f/f_\star)^2}\right)^{7/2}$$



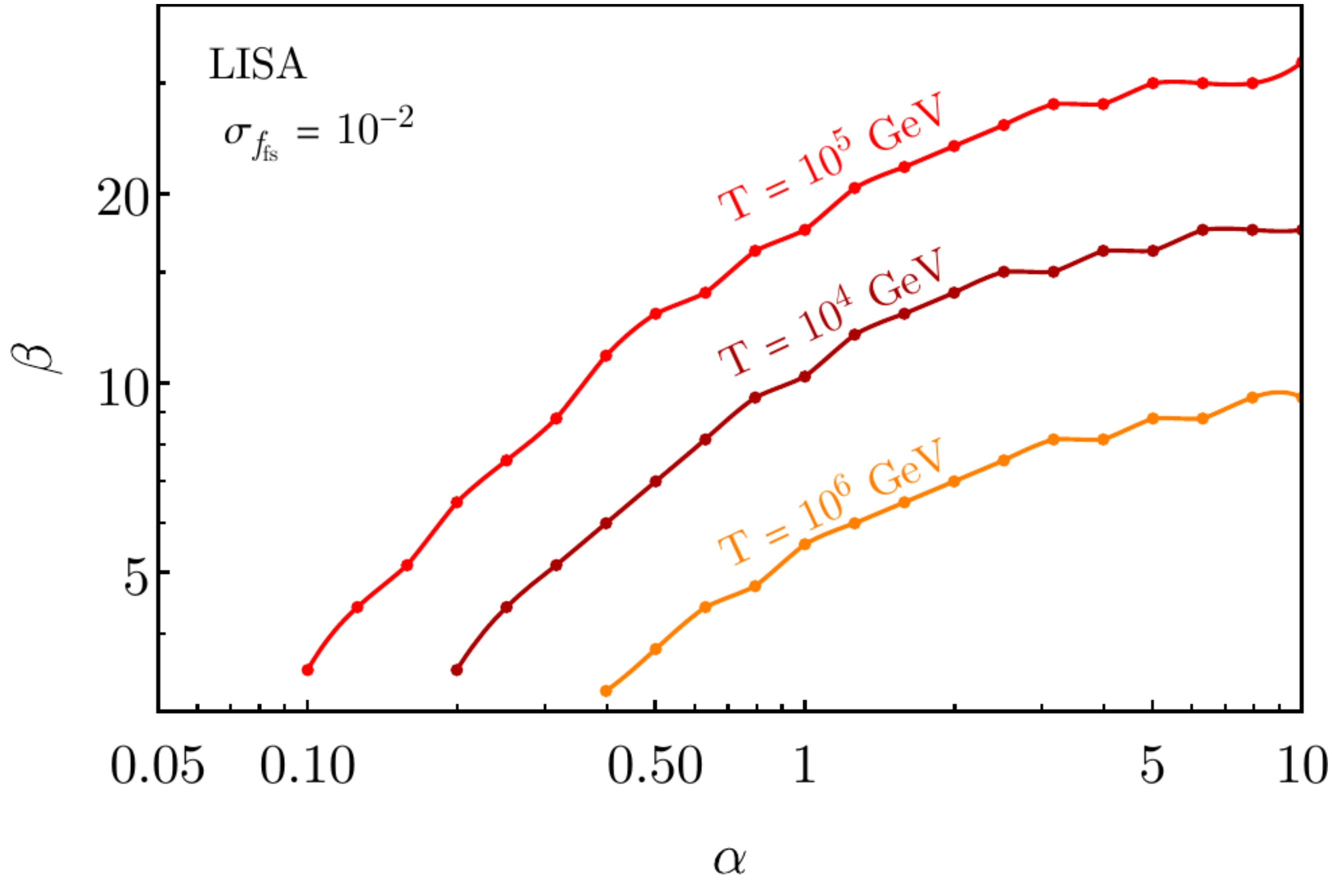


Sensitivity will depend on PT



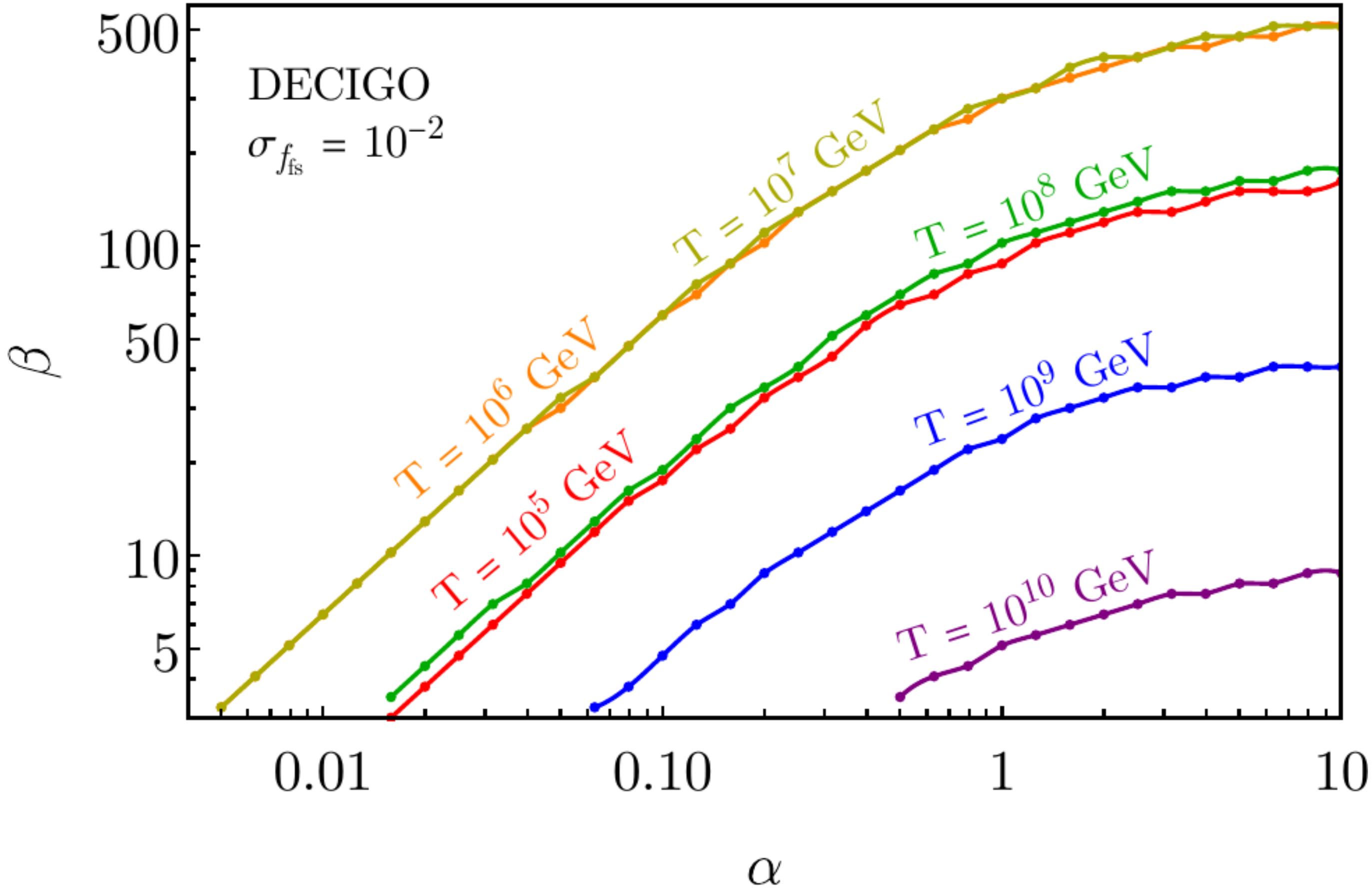


Axions LISA



LISA
$\sigma_{f_{\rm fs}} = 10^{-2}$
T = 10^5 GeV
T = 10^4 GeV
T = 10^6 GeV
20
10
5
β
0.05
0.10
0.50
1
5
10
α

Axions DECIGO



Conclusions & Outlook

- Gravitational waves are a window into the earliest stages of the universe
- GW from short lived cosmological sources expected to have universal spectral shape at low frequencies: prime target to study cosmology
- Taking only instrumental noise into account, one could be able to discover supersymmetry (or other symmetry solutions to naturalness)
- Probe presence of new radiation at very early universe. For strong signals can beat sensitivity of CMB and BBN searches
- Motivates understanding whether we will be able to control other sources of uncertainties to the required level