What can we learn from the low-frequency spectrum of causal gravitational waves?

arXiV:2203.13842

Dawid Brzeminski (UMD)

with Anson Hook (UMD) and Gustavo Marques-Tavares (UMD)

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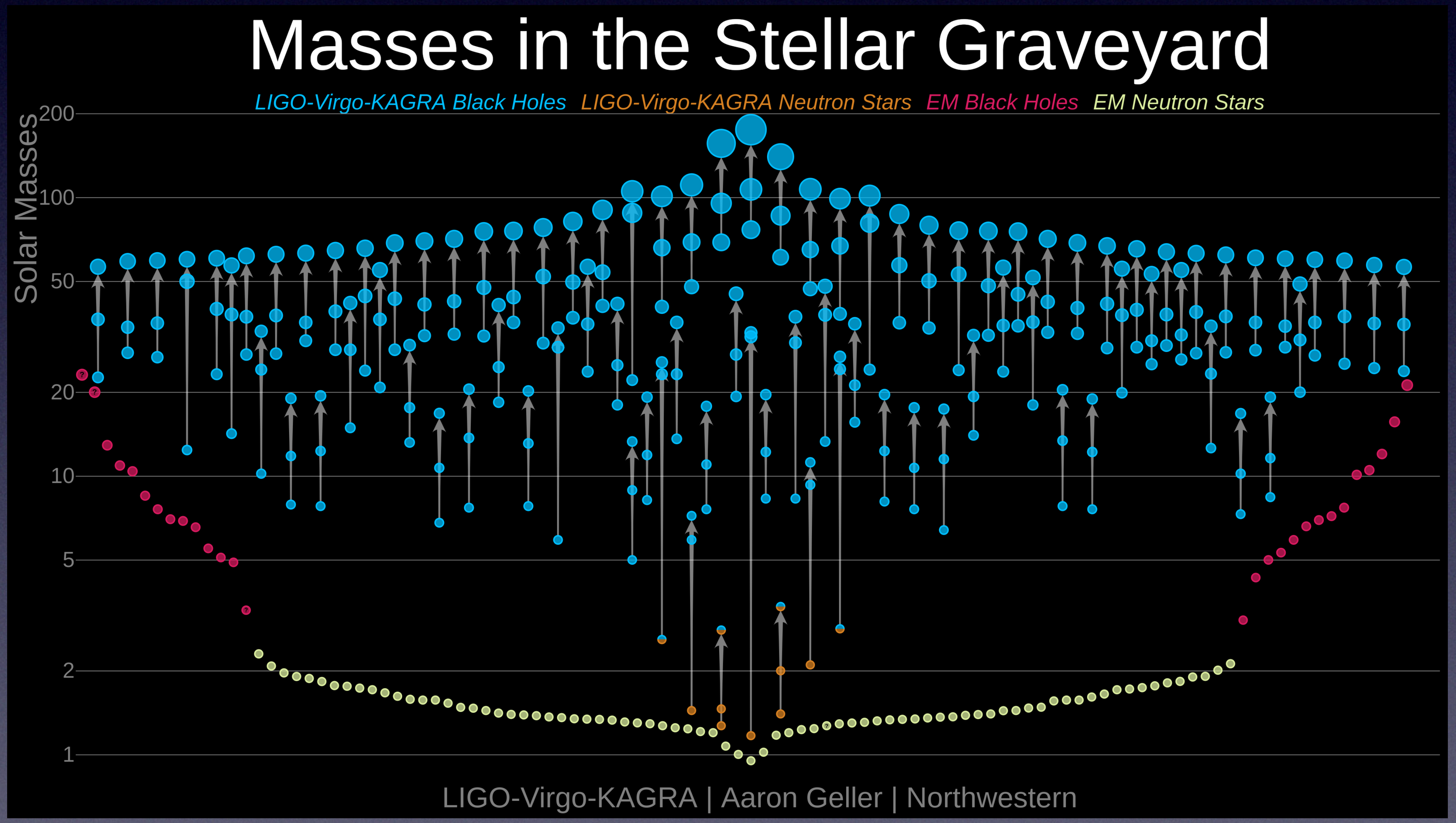
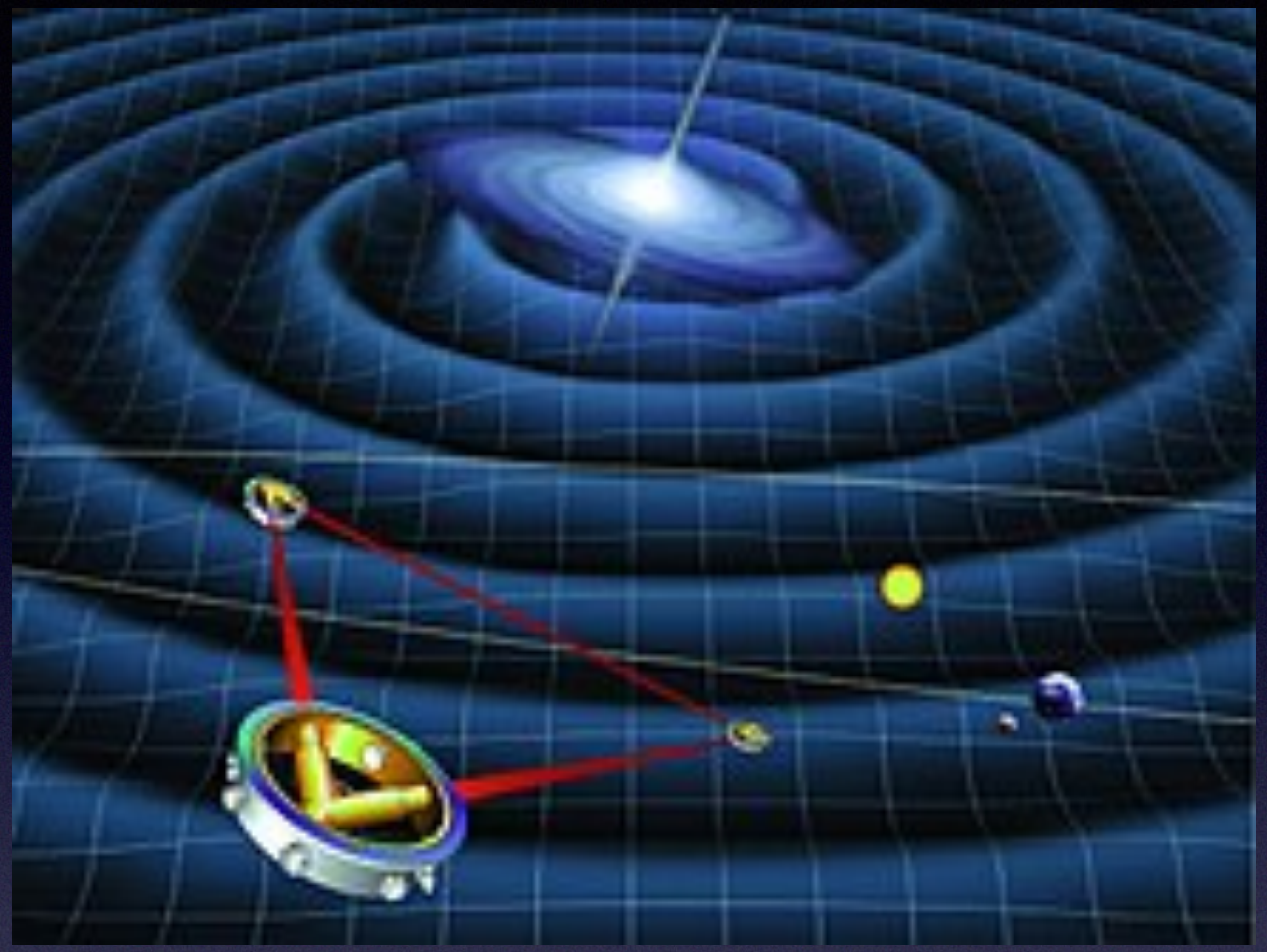
Plan

- Introduction
- Propagation Effects
- Conclusions

GW: Present and the future

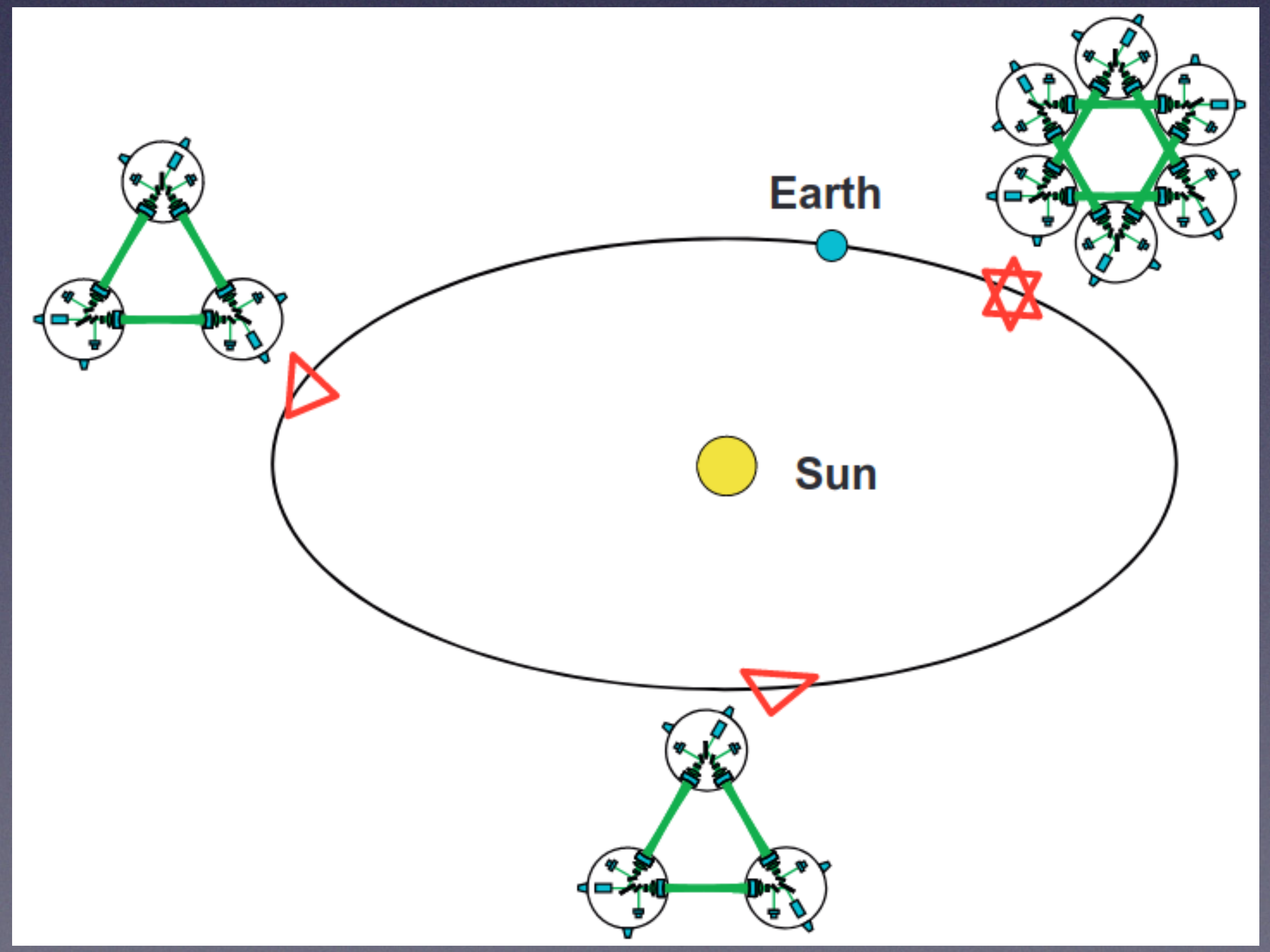


LISA:



[NASA/ESA]

DECIGO/BBO:



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[Kawamura et al. '20]

Our goal

- We want to learn about free streaming particles and equation of state in the early universe from propagation effects
- Need an **old** source that lasted a finite time
- Astrophysical sources are **too young**
- Inflation spectrum is **too weak**
- What we need are GW of **cosmological origin**

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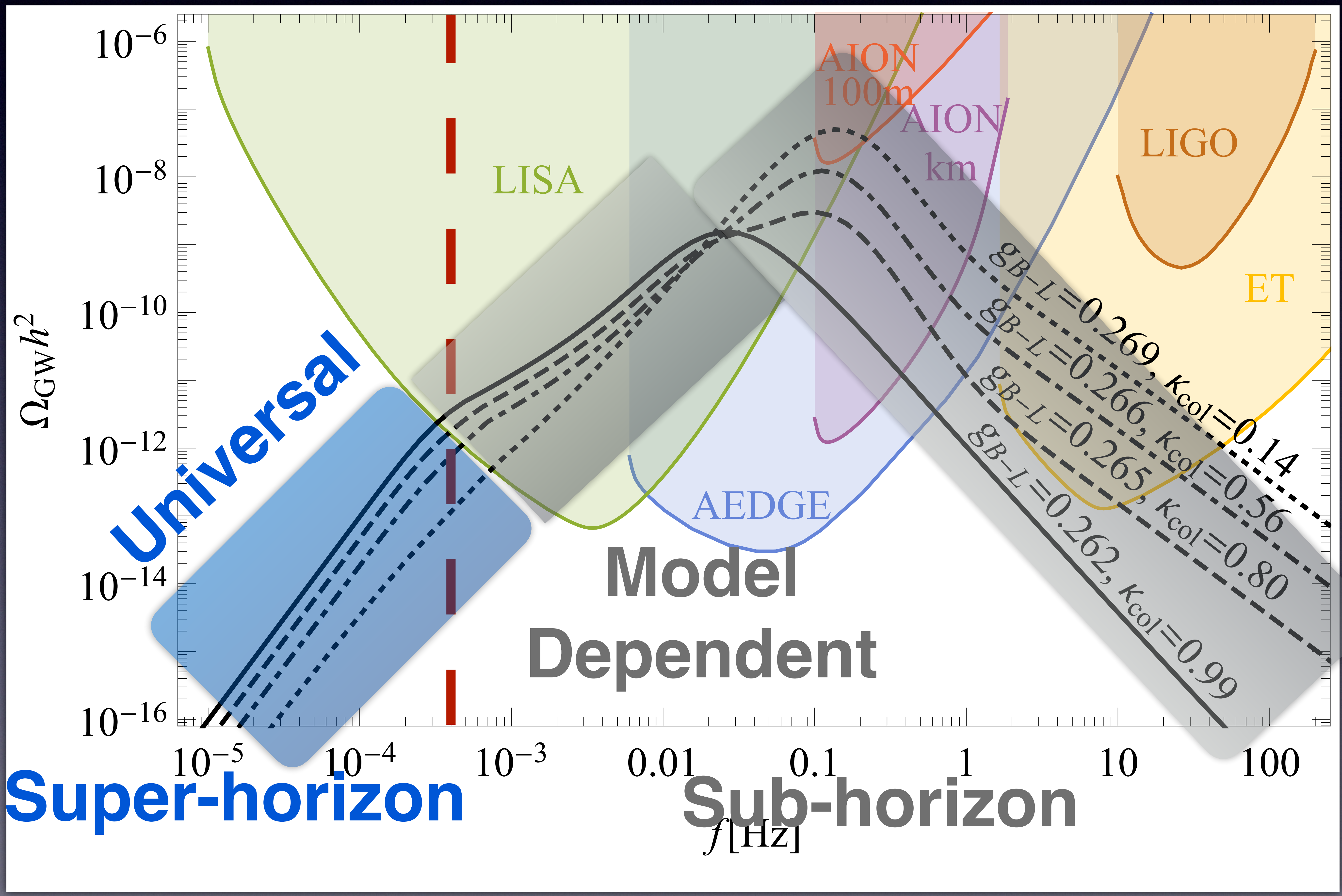
GWB of cosmological origin

- Typically, the shape of GWB from cosmological source is **model dependent**
- However, causally produced GW have a **universal** feature of k^3 scaling during RD for low frequency modes [Caprini et al., '09]
- This **universal** part of the spectrum depends only on the **propagation effects**
- **First-order phase transition** is an example causality respecting process.

Examples of GWs from first-order PT



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[Ellis et al. 2007.15586]

Universal scaling

$$-\frac{1}{2}h_{ij;\nu}^{;\nu} = 8\pi G\Pi_{ij}$$

Super-horizon modes

$$\lambda \gg H_{PT}^{-1} \Rightarrow \langle \Pi(0)\Pi(\lambda)\rangle = 0$$

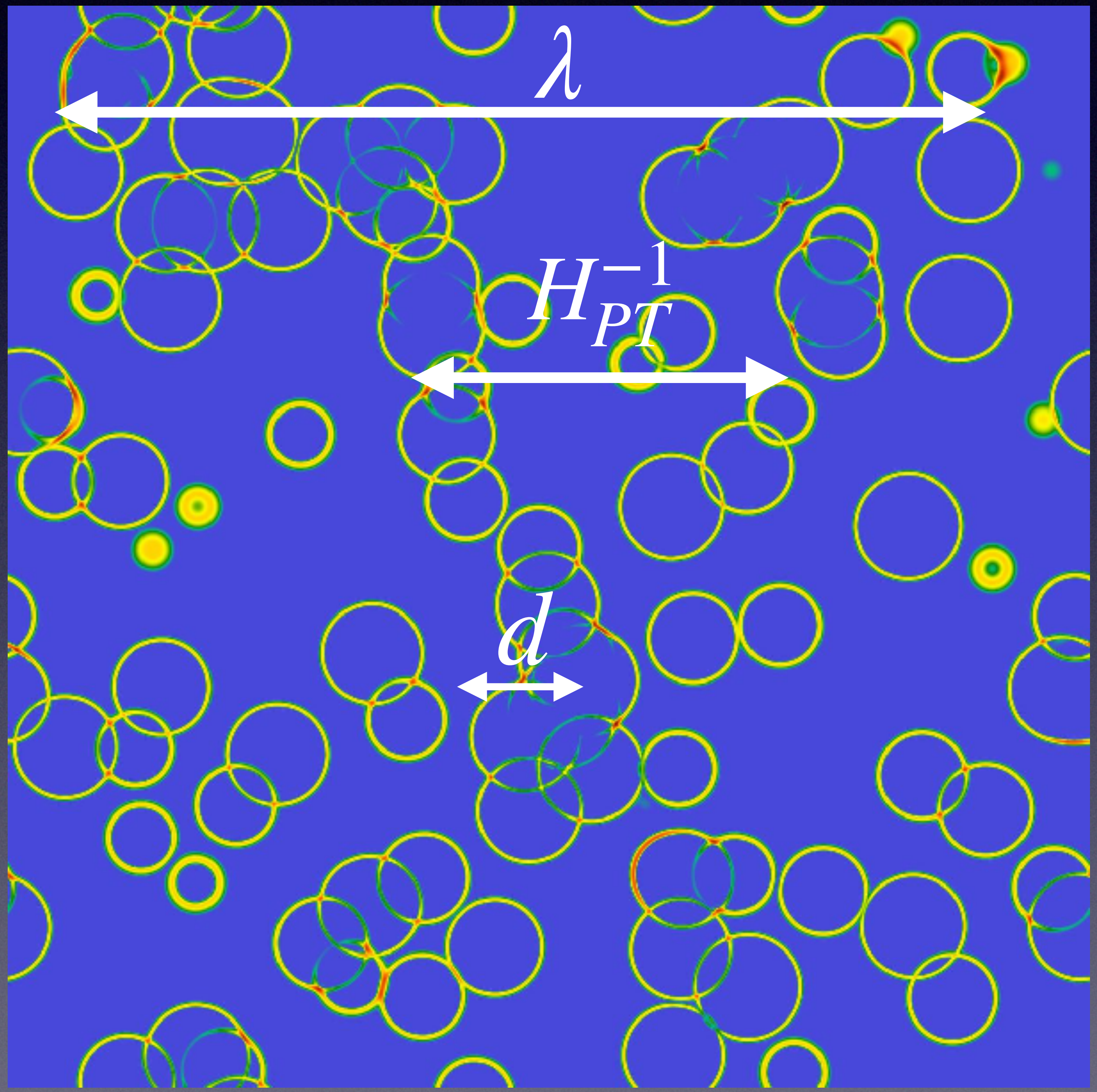
$$\langle \tilde{\Pi}(-k)\tilde{\Pi}(k)\rangle = \text{const} \Rightarrow h'(k,\tau_{PT}) = \text{const}$$

$$\Omega_{GW}(k) = \frac{1}{\rho_c}\frac{d\rho_{GW}}{d\log k} \propto k^3(h')^2 \propto k^3\frac{k^2}{k^2} = k^3$$

Time der.

Phase space

RD



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Plan

- ~~Introduction~~
- **Propagation effects**
- Conclusions

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Propagation Effects

This talk

Free streaming particles

Equation of state

$$\Omega_{GW} \propto k^{3+\frac{16 f_{FS}}{5}} \qquad f_{FS} = \frac{\rho_{FS}}{\rho_{tot}}$$

$$\Omega_{GW} \propto k^{3+3\delta w} \qquad \text{RD: } w = 1/3 + \delta w$$

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Free streaming particles

$$-\frac{1}{2}h^{;\nu}_{ij;\nu} = 8\pi G \Pi_{ij} \quad + \quad \frac{dF}{d\tau} = \frac{\partial F}{\partial \tau} + \frac{dx^i}{d\tau}\frac{\partial F}{\partial x^i} + \frac{dq}{d\tau}\frac{\partial F}{\partial q} + \frac{d\gamma^i}{d\tau}\frac{\partial F}{\partial \gamma^i} \quad =$$

$$= \quad h'' + 2Hh' + k^2 h = -24 f_{FS} H^2 \int_{\tau_0}^{\tau} d\tau' \frac{j_2\left(k(\tau-\tau')\right)}{(\tau-\tau')^2} h'(\tau')$$

[Weinberg, 2004]

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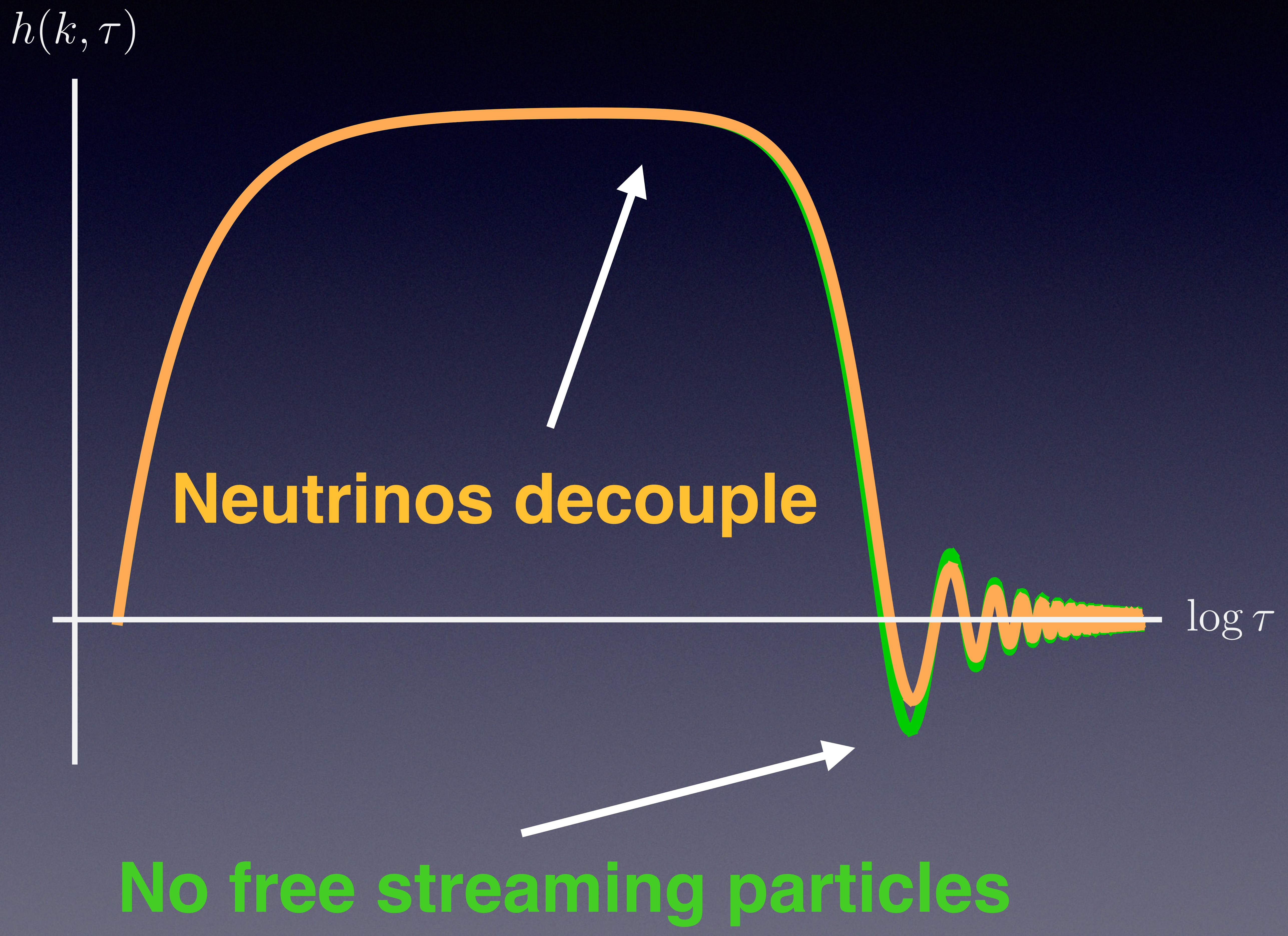
Free streaming particles

The effect of neutrino decoupling on the inflationary GW spectrum was first studied by Weinberg in 2004 and is known as Weinberg damping.



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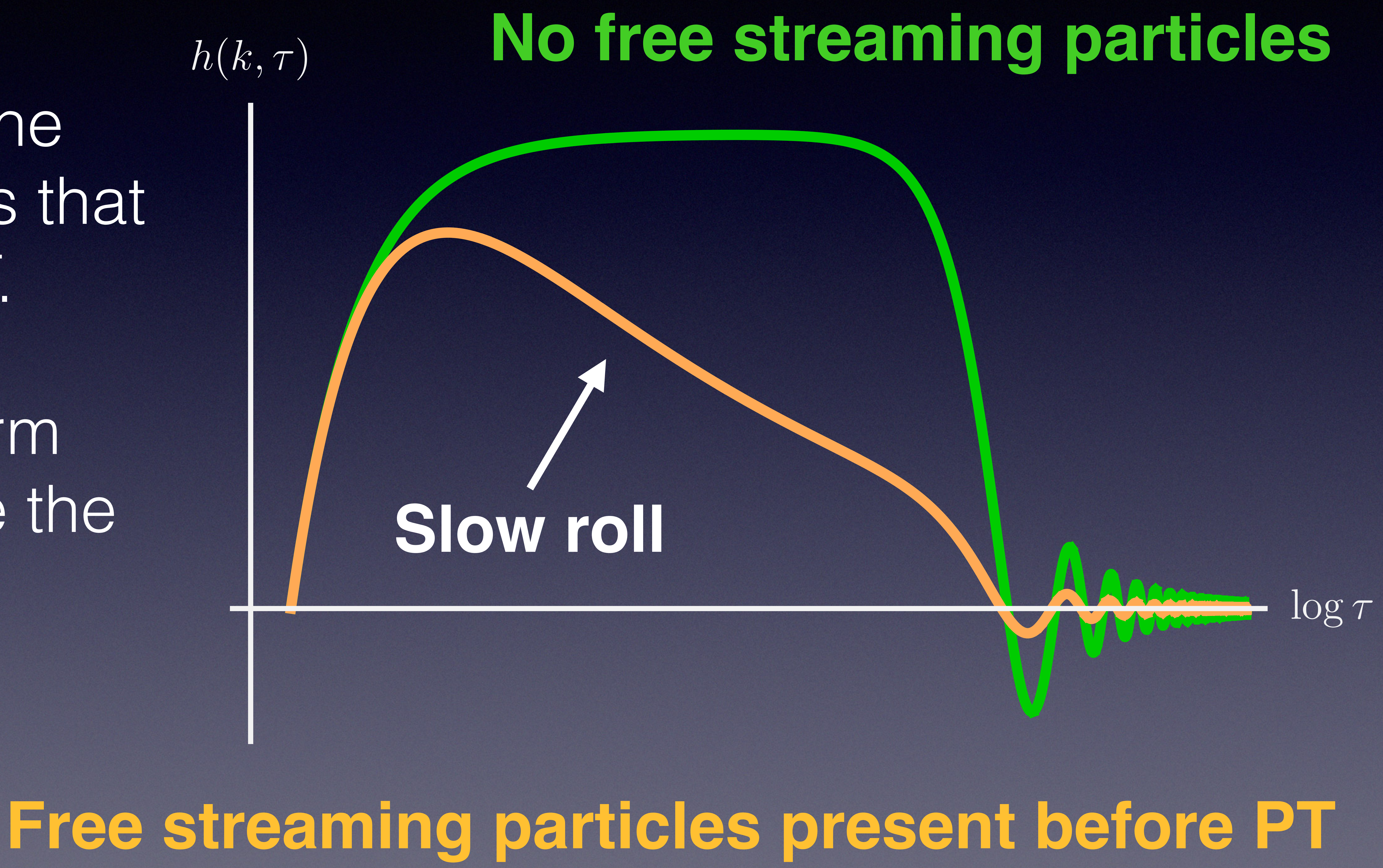
Free streaming particles

- In our work, we are looking for the effect of free streaming particles that were already present **before** PT.
- Their presence adds a mass term that results in a **slow roll** before the mode enters the horizon.



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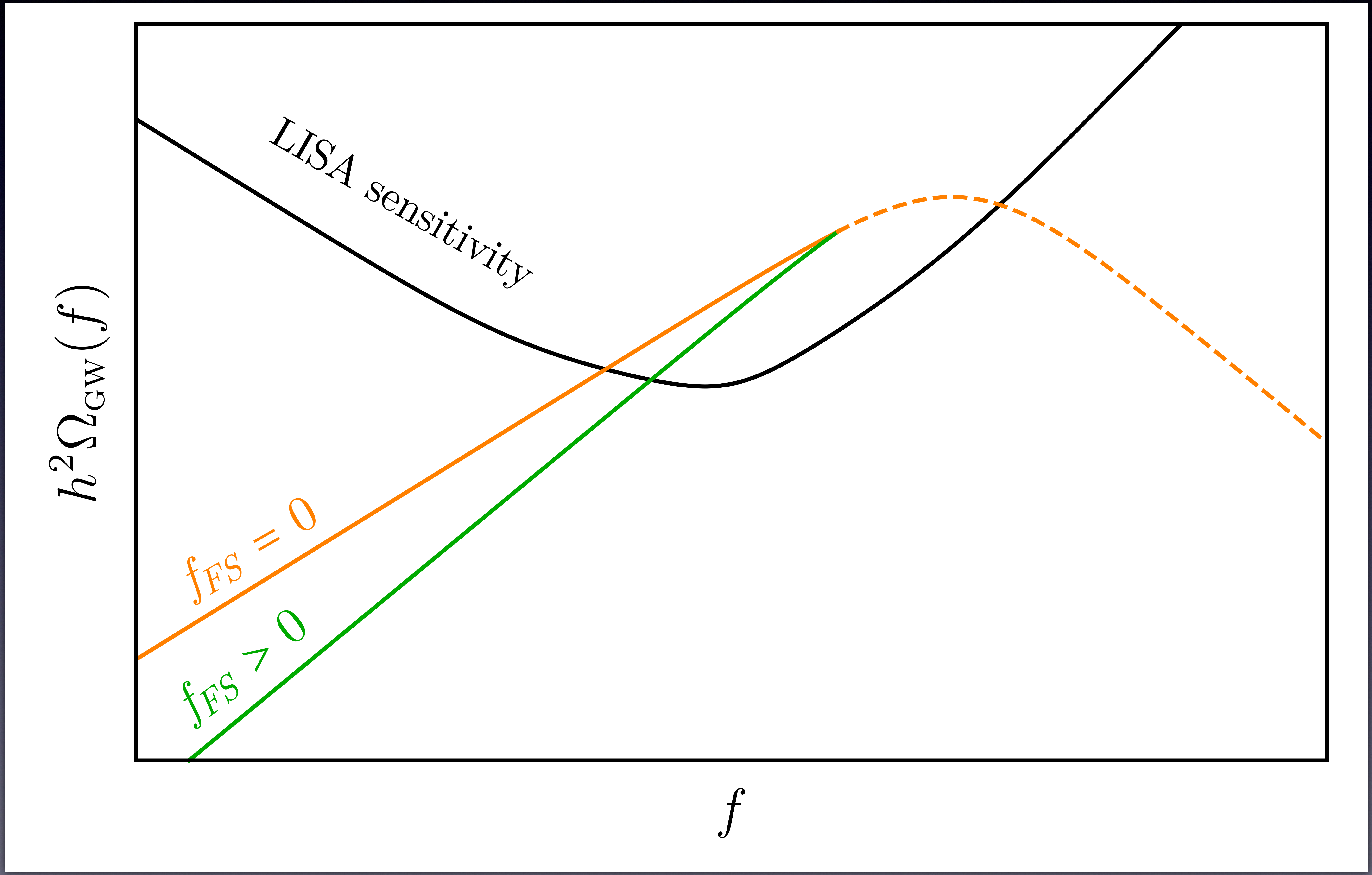
Free streaming particles

- Lower frequency modes spend more time in the slow roll phase before entering the horizon, leading to the steeper slope

- For small values of f_{FS}, the GW spectrum scales as $\Omega_{GW} \propto k^{3+\frac{16 f_{FS}}{5}}$ [Hook et al., 2020]



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Analysis

- We estimate sensitivity to f_{FS} using Fisher information matrix and vary 3 different parameters of the PT:
  - Ratio of the energy released during PT to the radiation bath energy $\alpha = \rho_{vac}/\rho_{rad}$
  - Time scale of the phase transition β^{-1}
  - Temperature of the phase transition T_{PT}

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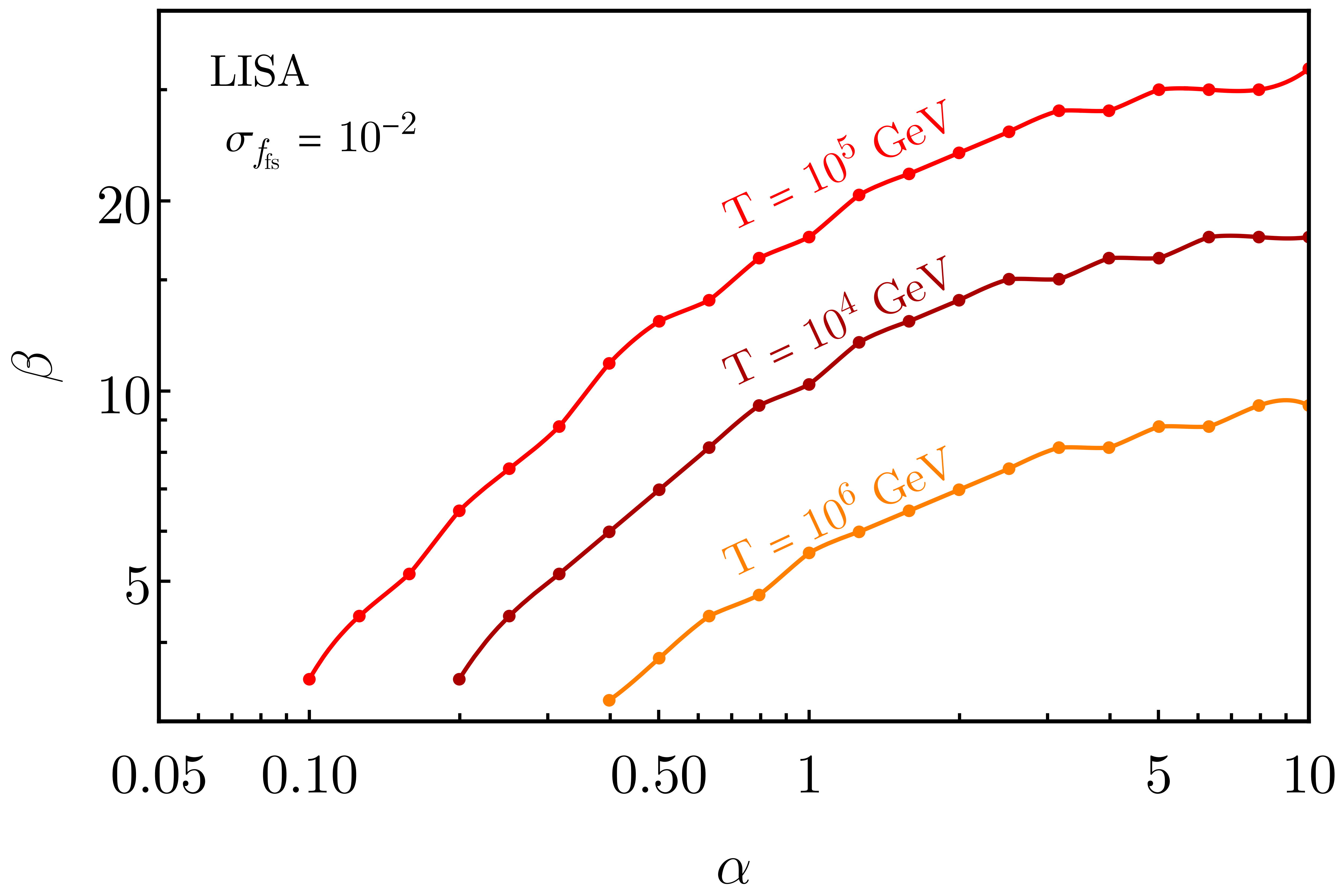
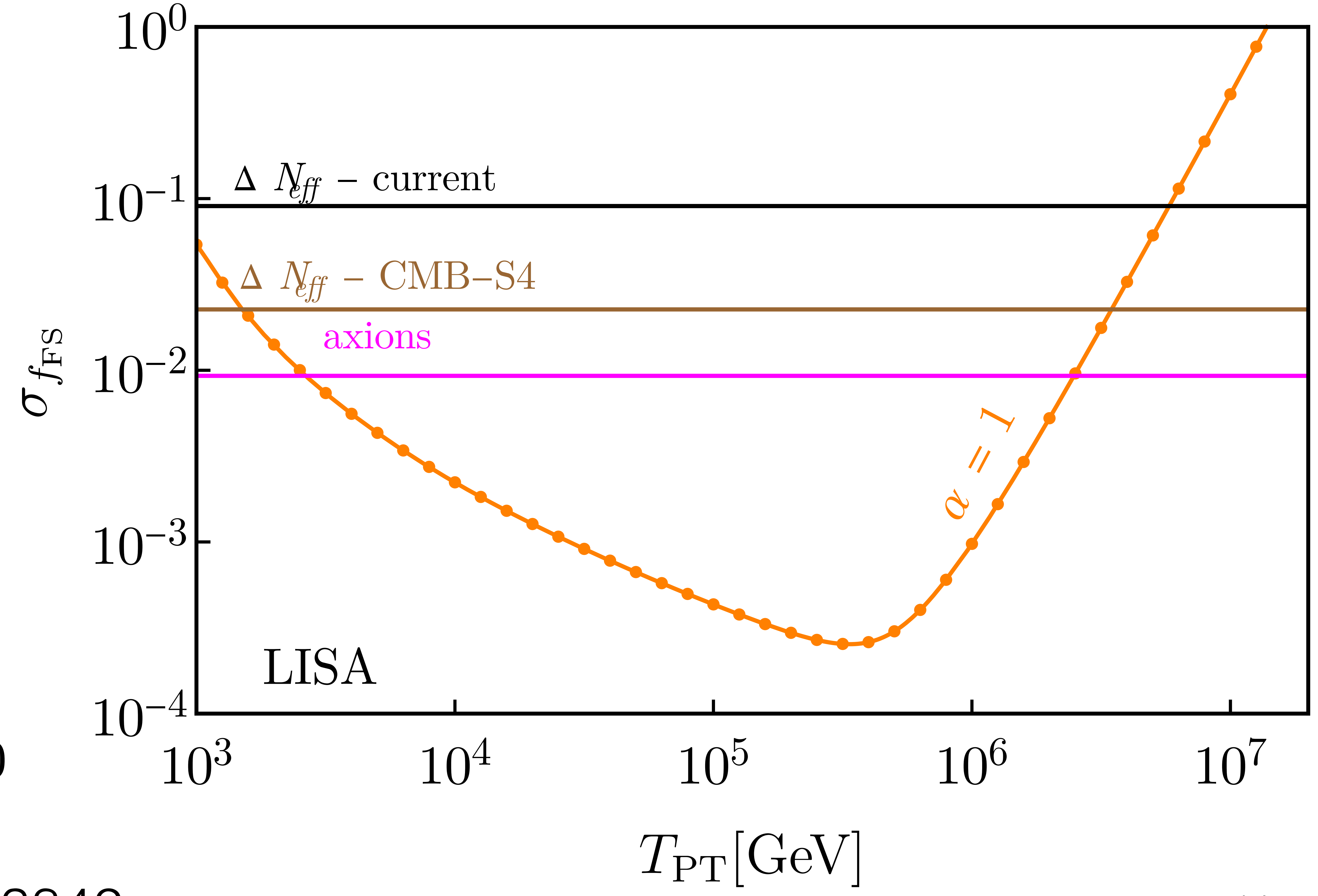
Sensitivity to free streaming axions





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Conclusions

- Low frequency tail of causally produced GW encodes information about the EOS of the and the free streaming content of the universe
- LISA will launch durning the next decade and can improve bounds set by CMB-S4 by up two orders of magnitude.
- LISA will also be sensitive to free streaming axions over wide range of parameters if phase transition happened at 10^4 GeV $\lesssim T_{PT} \lesssim 10^6$ GeV

Thank you

Backup slides

Sensitivity to free streaming axions

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Sensitivity to equation of state

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