Early Universe Cosmology from Stochastic Gravitational Waves

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LIGO

Exciting time for gravity waves

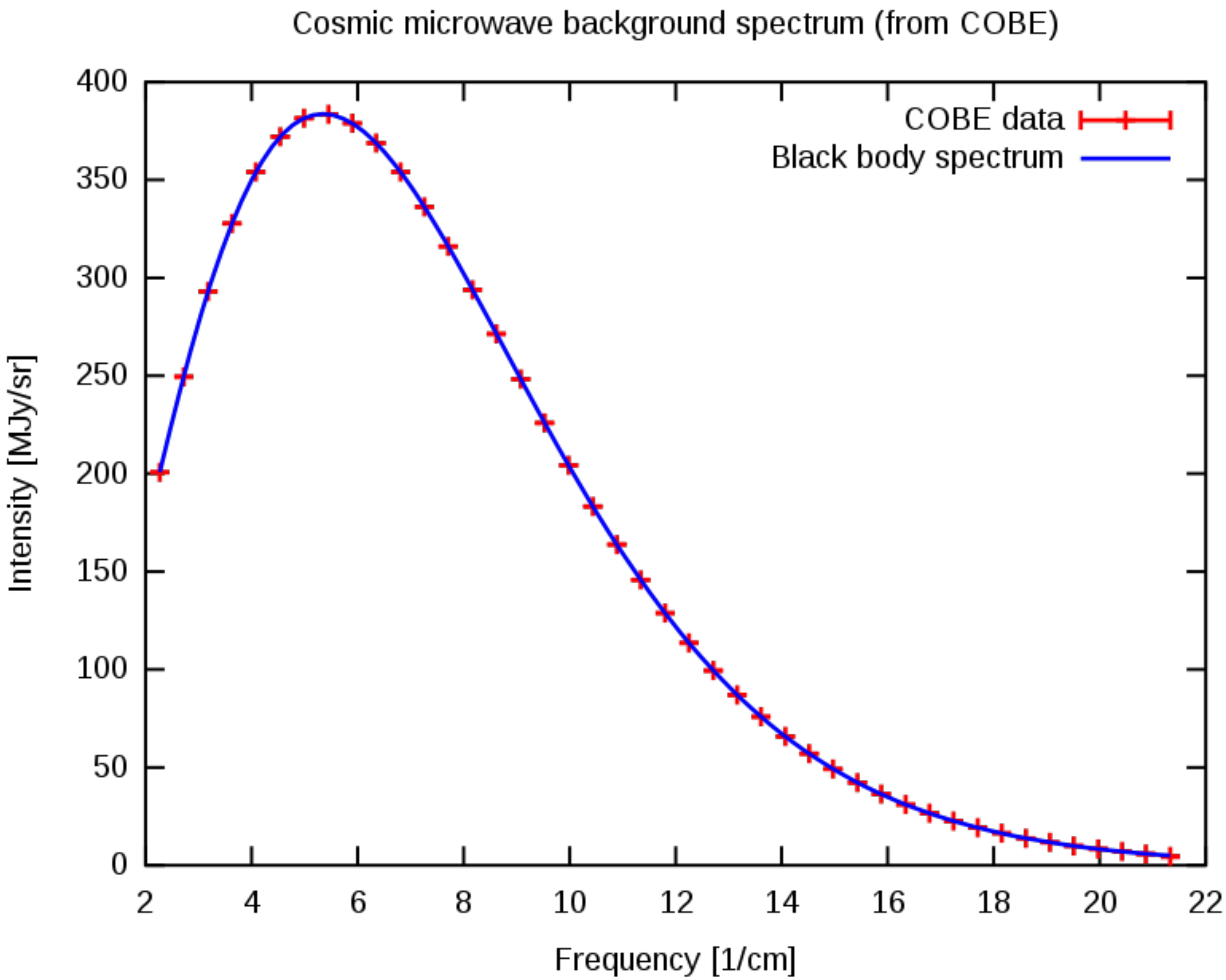
Stochastic Gravitational Waves

CMB of Gravitational Waves

Produced in the early universe and free streamed to us

Anything the CMB taught us, GWs can teach us too

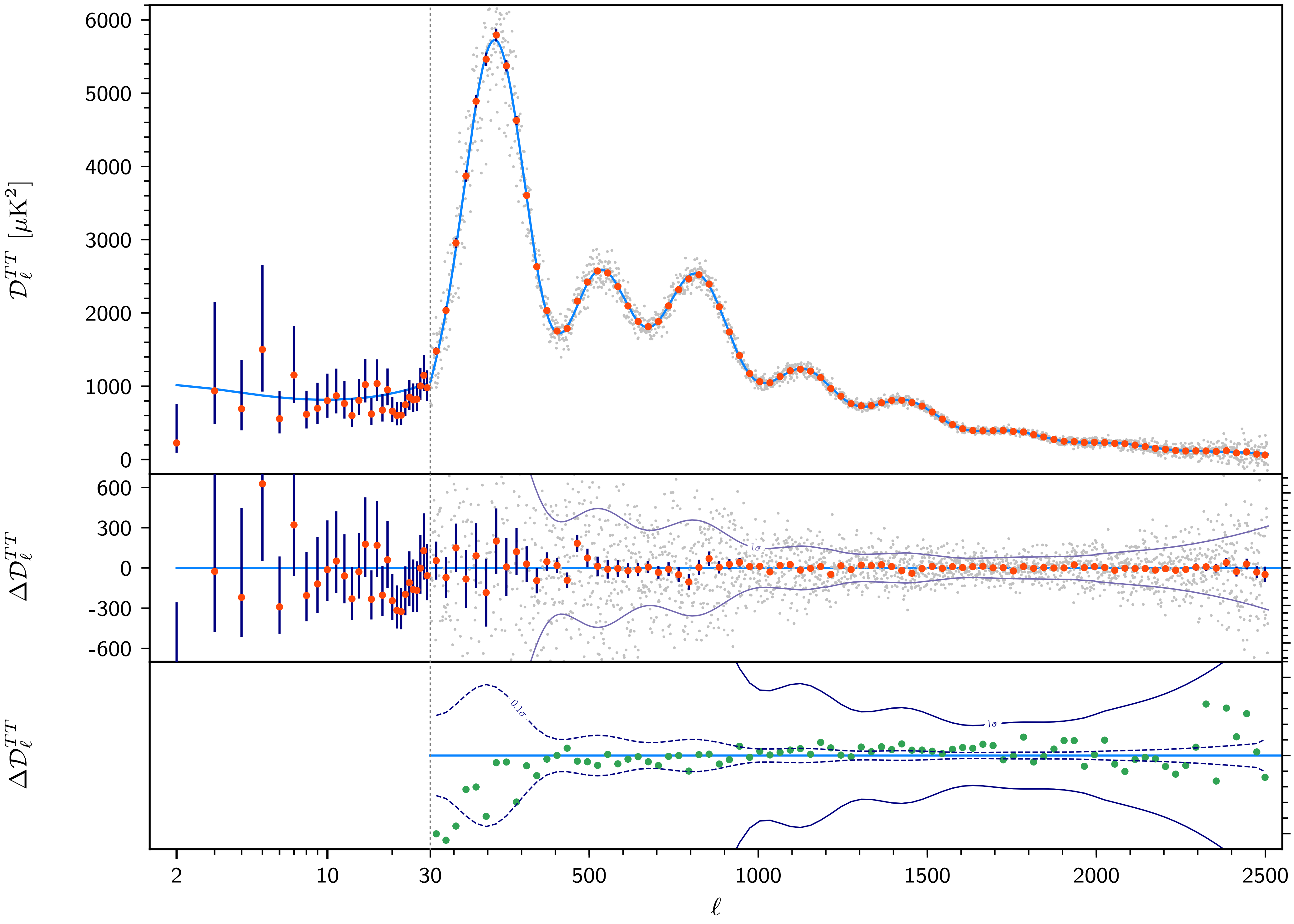
CMB : Frequency spectrum



CMB : Frequency spectrum

1. Black body radiation with a temperature of 2.7 K
   - Universe was in thermal equilibrium
   - CMB emitted as black body radiation
2. Small distortions, e.g. 21 cm
   - Propagation effects
   - Tells us about the universe between surface of last scattering and now

CMB : Angular dependences



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CMB : Angular dependences

1. Uniform temperature
   - Acausal physics, e.g. Inflation
2. Scale invariance and small deviations
   - Inflationary parameters
   - Propagation effects

CMB

1. Frequency
   - Black Body - Production mechanism
   - Deviation From Black Body - Propagation

2. Anisotropies
   - Scale Invariance - Inflation
   - Deviation From Scale Invariance - Propagation

Stochastic Gravitational Waves

1. Frequency
   - Spectrum - Production mechanism
   - Deviation From Spectrum - Propagation

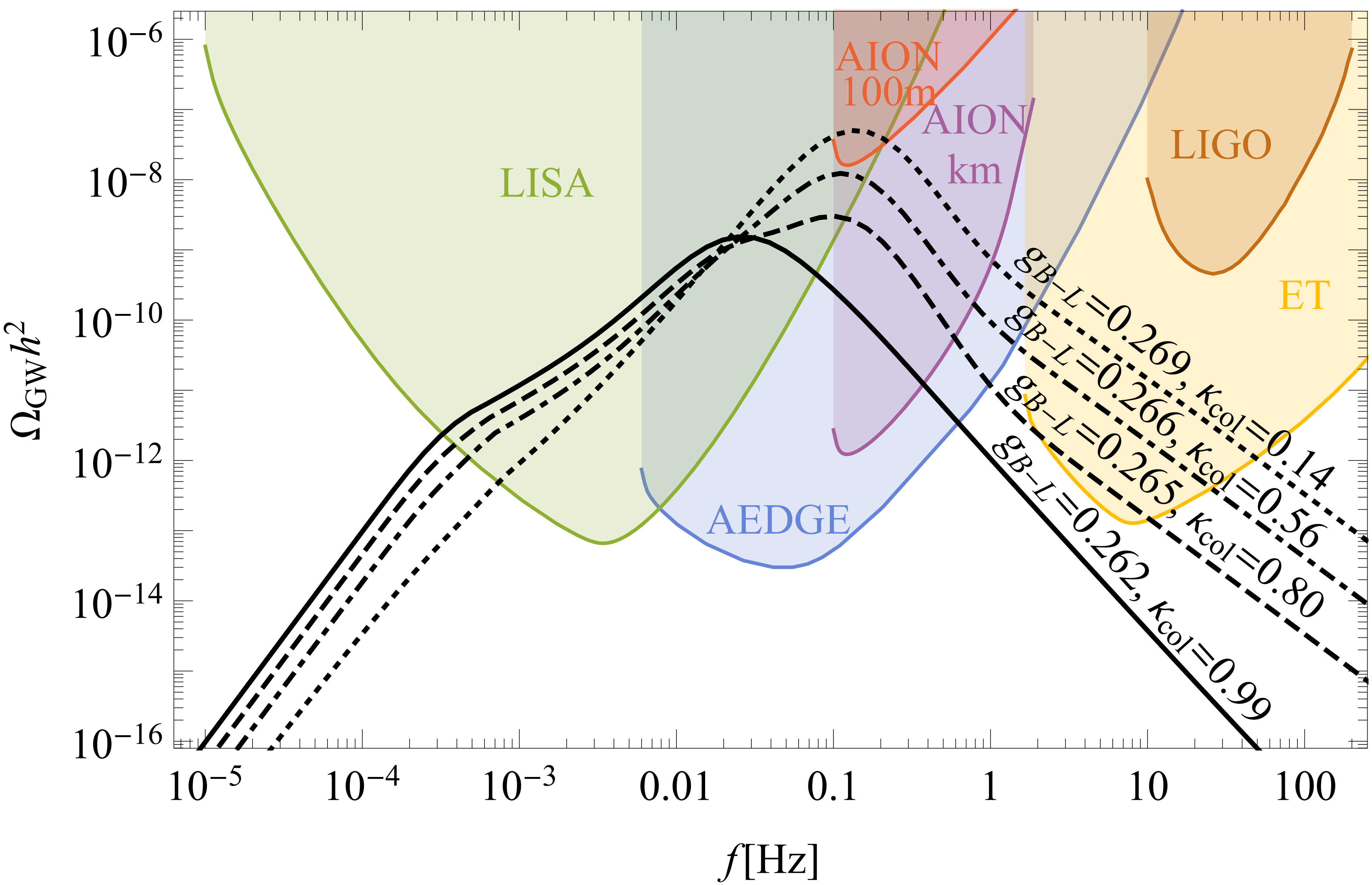
2. Anisotropies
   - Scale Invariance - Inflation
   - Deviation From Scale Invariance - Propagation

Stochastic Gravitational Waves

1. Frequency
   - Spectrum - Production mechanism
   - Deviation From Spectrum - Propagation
2. Anisotropies
   - Scale Invariance - Inflation
   - Deviation From Scale Invariance - Propagation

To Study Deviations…

We need to know the spectrum very very accurately



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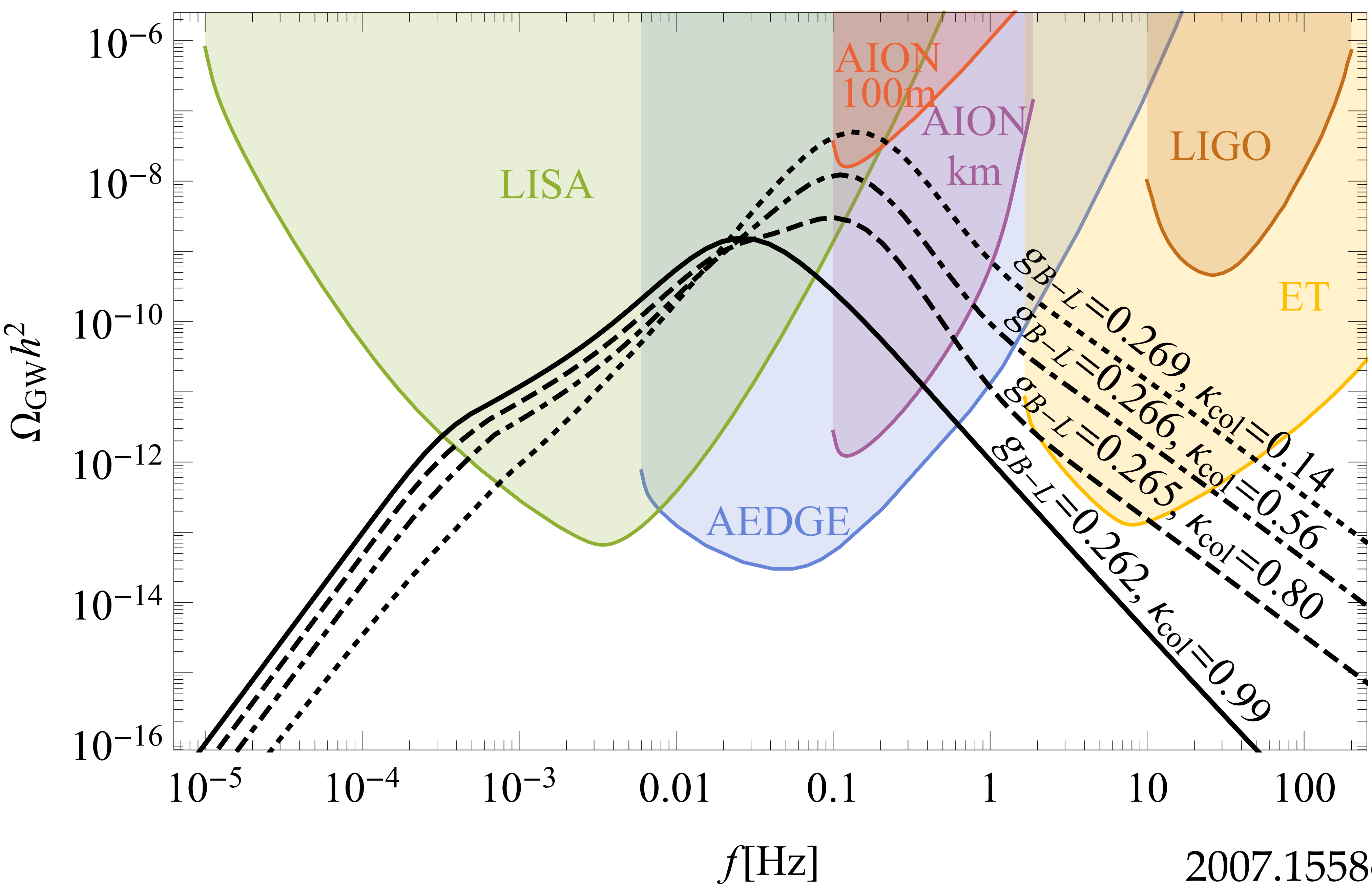
GW Signal

Very model dependent shape

Turbulence

Collision of bubbles

Sound waves



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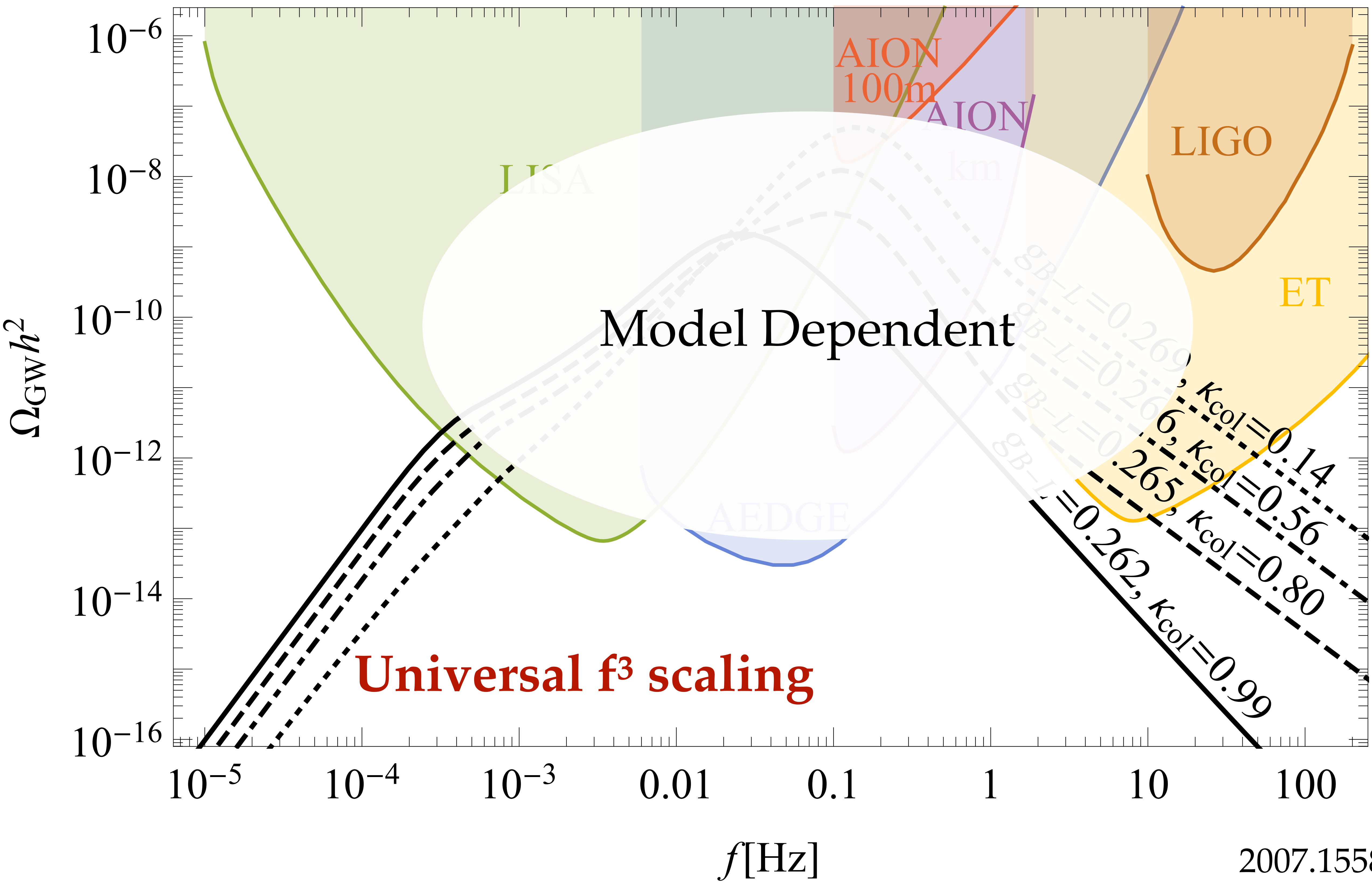
Signal at LISA



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Low frequency signatures

f^3 behavior is model independent so we know the "background", which means we can look for a "signal"

Only things that change the propagation of gravity waves can create a signal

Equation of state of the universe

Free streaming particles

Today

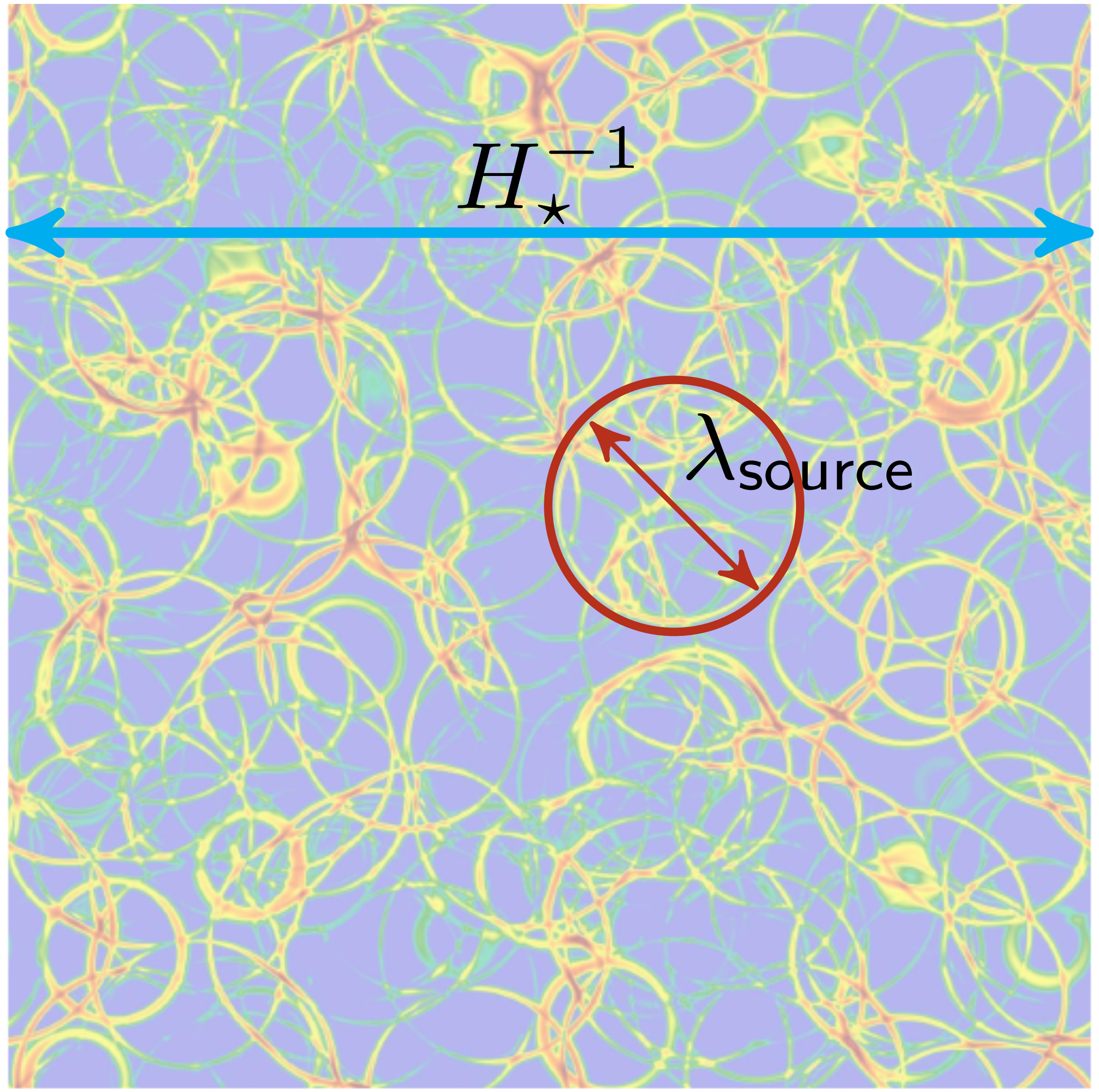
- What is the physical reason behind the low frequency behavior?

- Propagation effects
  - Equation of state of the universe
  - Free streaming particles

- LISA Sensitivity to Propagation effects
  - Equation of state of the universe
  - Free streaming particles

Low frequency behavior

White noise behavior induced by causality



Wavelengths longer than the correlation length, source becomes independent of frequency

Low frequency behavior

$$\Omega_{GW} = \frac{1}{\rho_c}\frac{d\rho_{GW}}{d\log k} \propto \frac{k}{dk} < \dot{h}_{ij}(x)\dot{h}_{ij}(x) >$$

$$\sim \frac{k}{dk} d^3k\, k^2 < h_{ij}(k)h^*_{ij}(k) >$$

Phase space

Derivatives

Low frequency behavior

$$\Omega_{GW} \sim k^5 < h_{ij}(k) h^*_{ij}(k) >$$

Low frequency behavior

$$\Omega_{GW} \sim k^5 < h_{ij}(k) h^*_{ij}(k) >$$

Propagation

$$h_{ij}(k) \sim G(t, t_0, k)\, \Pi(t_0, k)$$

Source

Low frequency behavior

$$\Omega_{GW} \sim k^5 \, G^2(t, t_0, k) \; < \Pi(k) \, \Pi^*(k) >$$

2 point function of the source in
momentum space

How does the graviton propagate to us

Low frequency behavior

$$P_\Pi(x) = \langle \Pi(x)\Pi(0)\rangle = 0 \qquad\qquad x \gtrsim \lambda$$

Regions are uncorrelated beyond correlation length

$$P_\Pi(k) = \int d^3\mathbf{x} e^{i\mathbf{k}\cdot\mathbf{x}} P_\Pi(x) = \int_0^\lambda dx\, 4\pi x\, \frac{\sin(kx)}{k} P_\Pi(x)$$

$$\approx \int_0^\lambda dx\, 4\pi x^2\, P_\Pi(x)$$

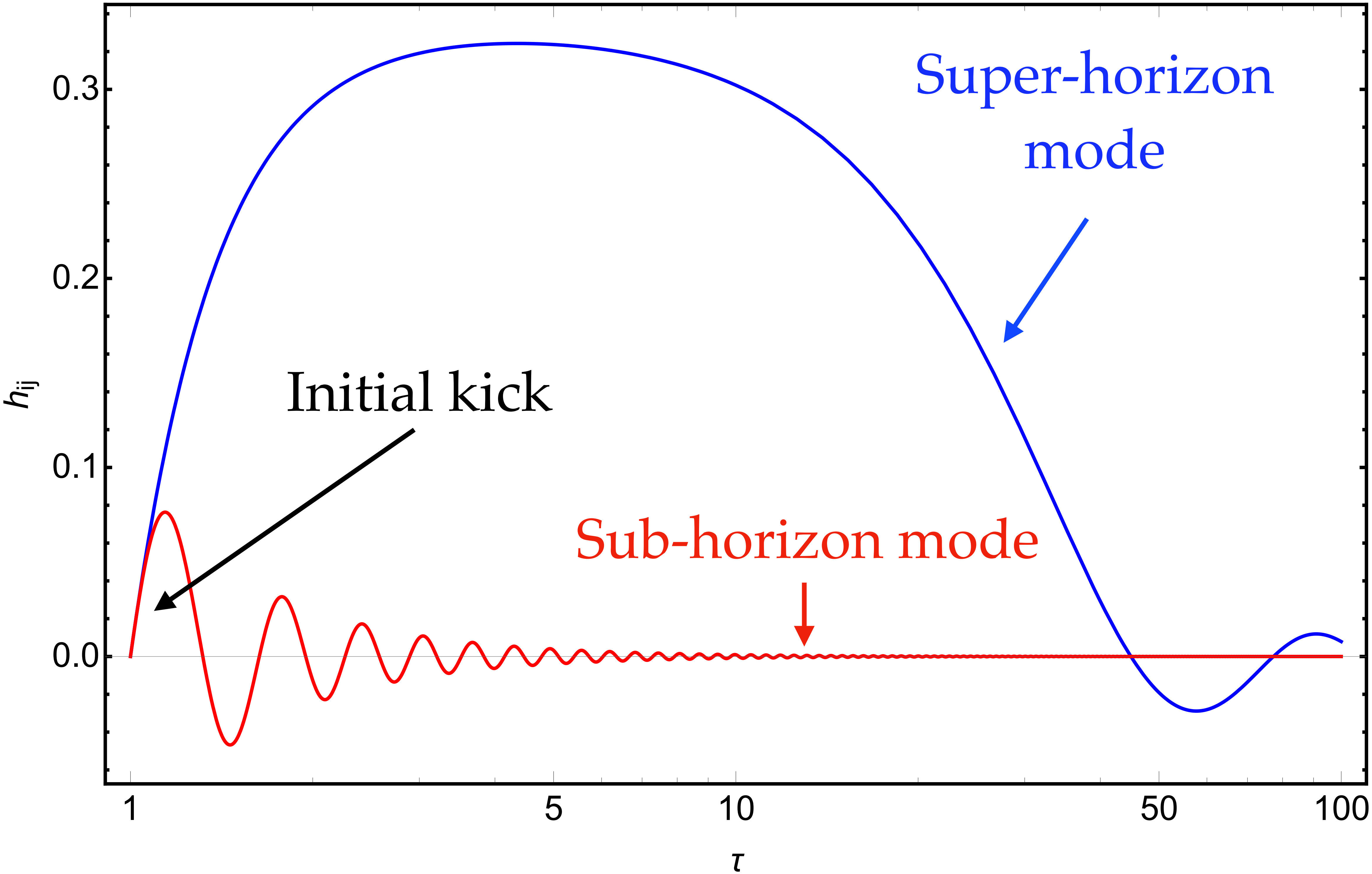
Source is frequency independent at low frequencies

Low frequency behavior

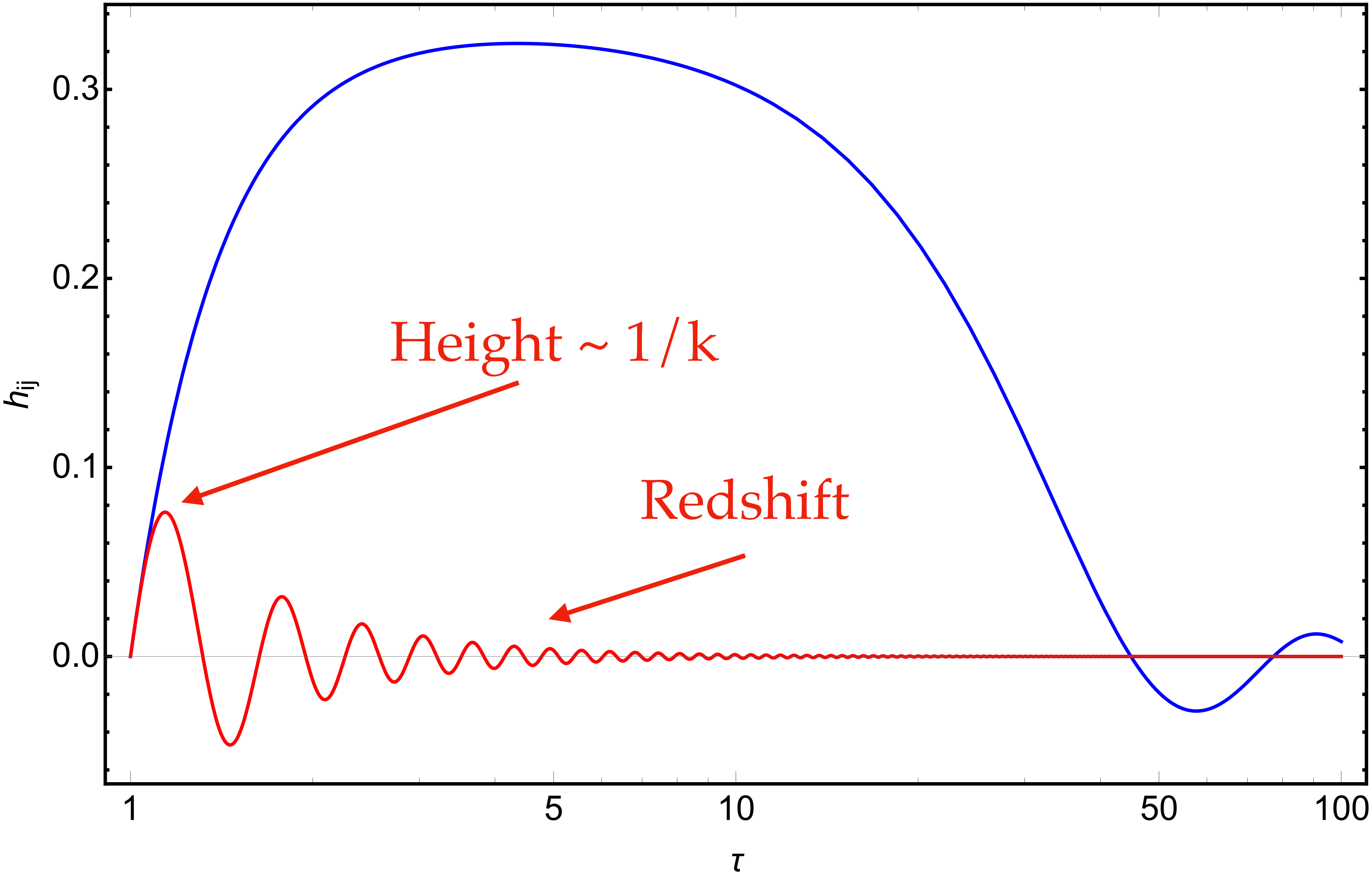
$$\Omega_{GW} \sim k^5 \, G^2(t, t_0, k)$$

Low frequency scaling determined entirely due to propagation from production to now

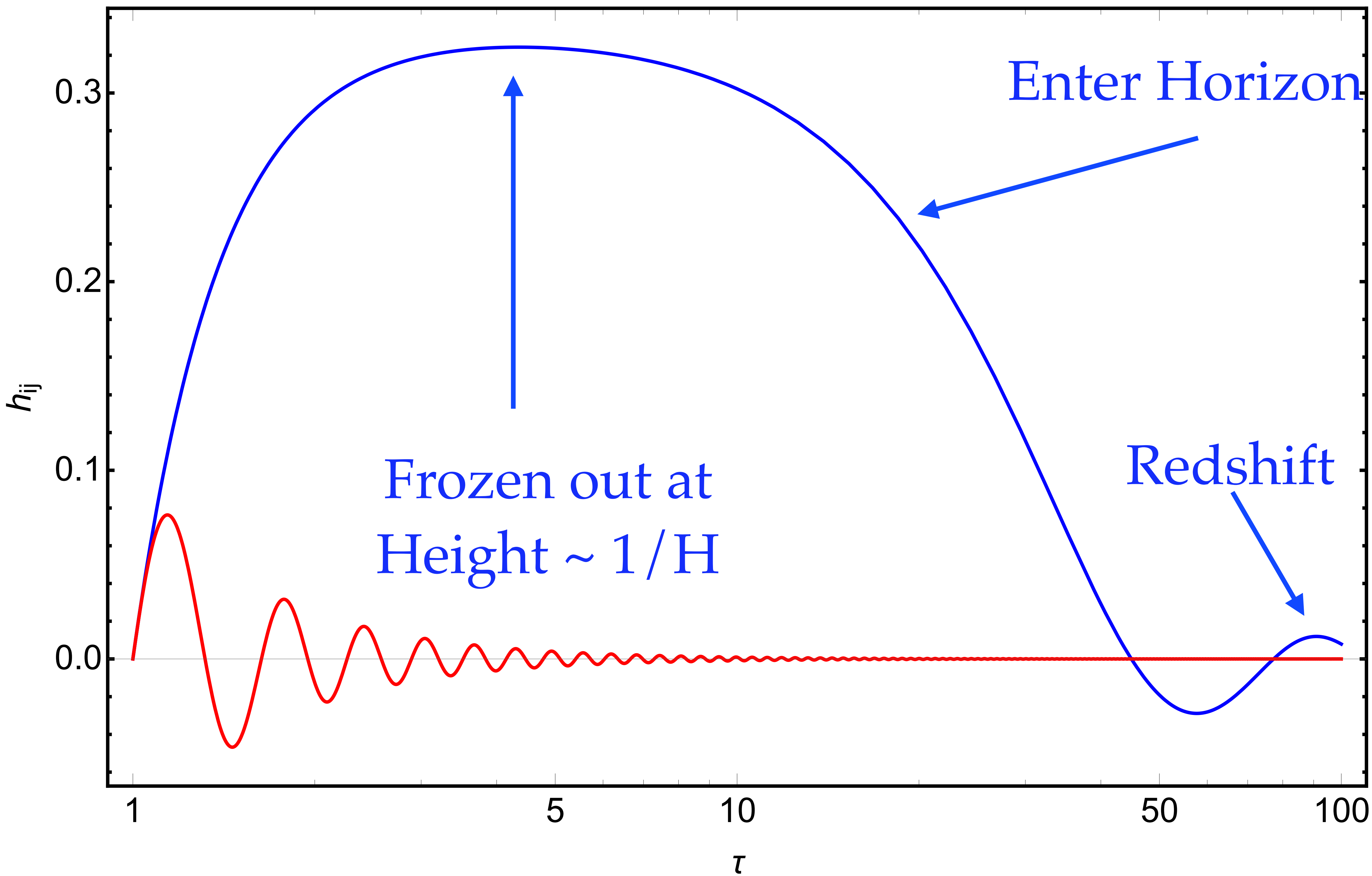
Low frequency behavior



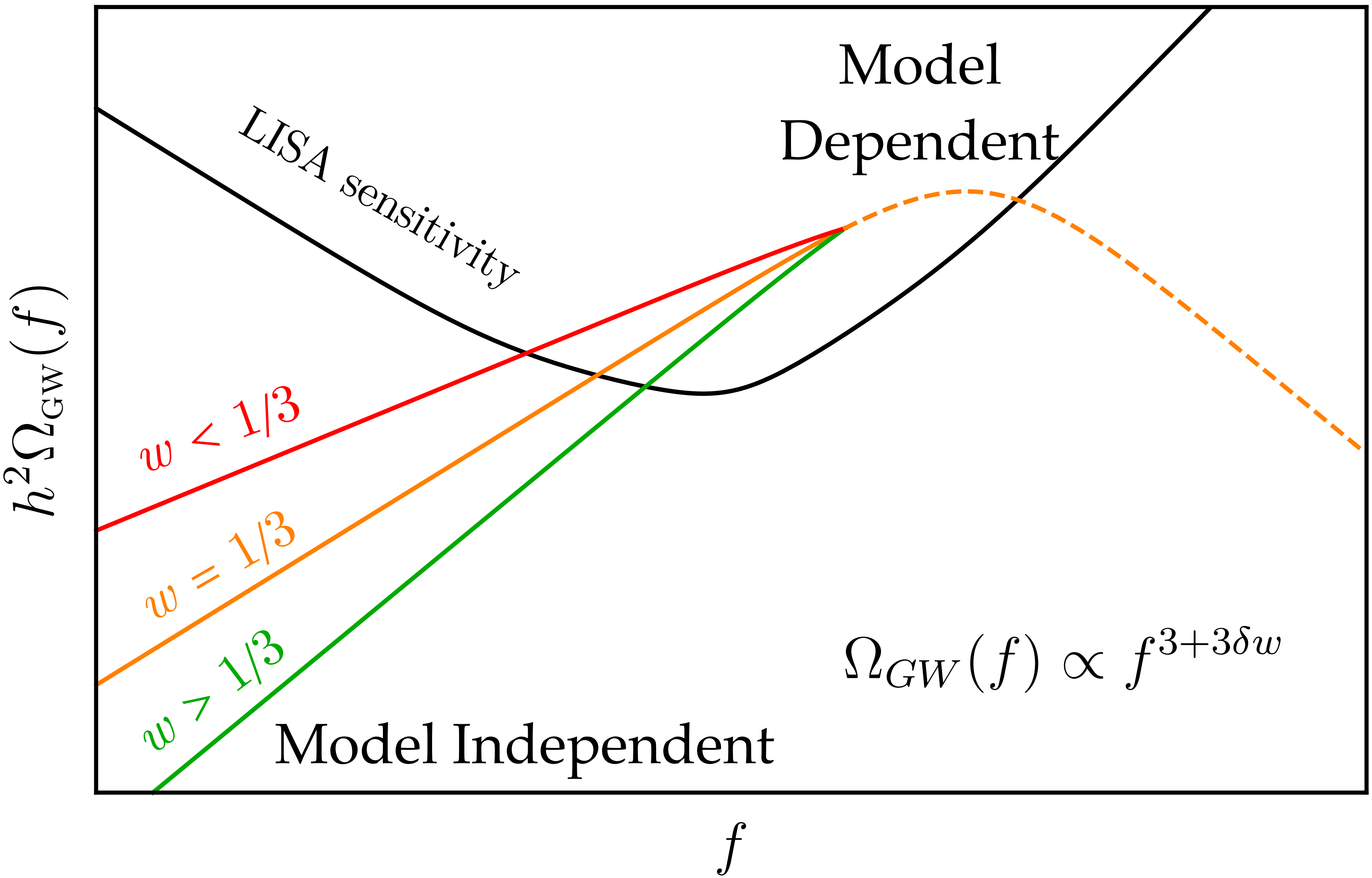
Low frequency behavior



Low frequency behavior



Frequency spectrum



Free-streaming particles

Thermal equilibrium	Free streaming
Constant scattering	No scattering
Random walk	Follow geodesics

Free-streaming particles

Thermal equilibrium	Free streaming
Constant scattering	No scattering
Random walk	Follow geodesics

Cares about gravity waves!

Has the potential for back reaction

Free-streaming particles

Effect on gravity waves in equation form

$$u^2\partial_u^2 h(u) + 2u\partial_u h(u) + u^2 h(u) =$$

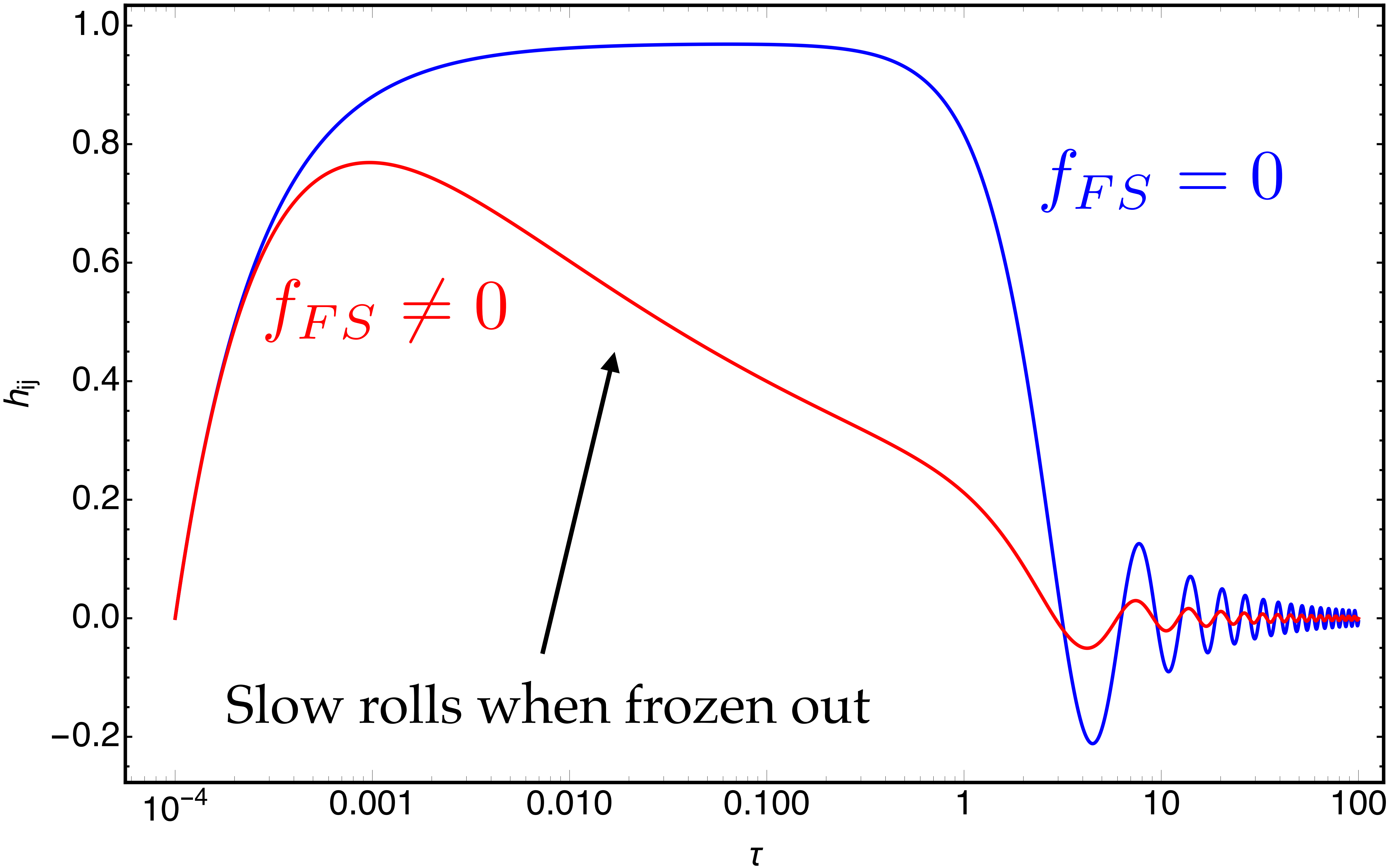
$$-24 f_{\rm FS}\int_{u_\star}^{u} {\rm d}x \left(-\frac{\sin(u-x)}{(u-x)^3} - 3\frac{\cos(u-x)}{(u-x)^4} + 3\frac{\sin(u-x)}{(u-x)^5}\right)\partial_x h(x)$$

where

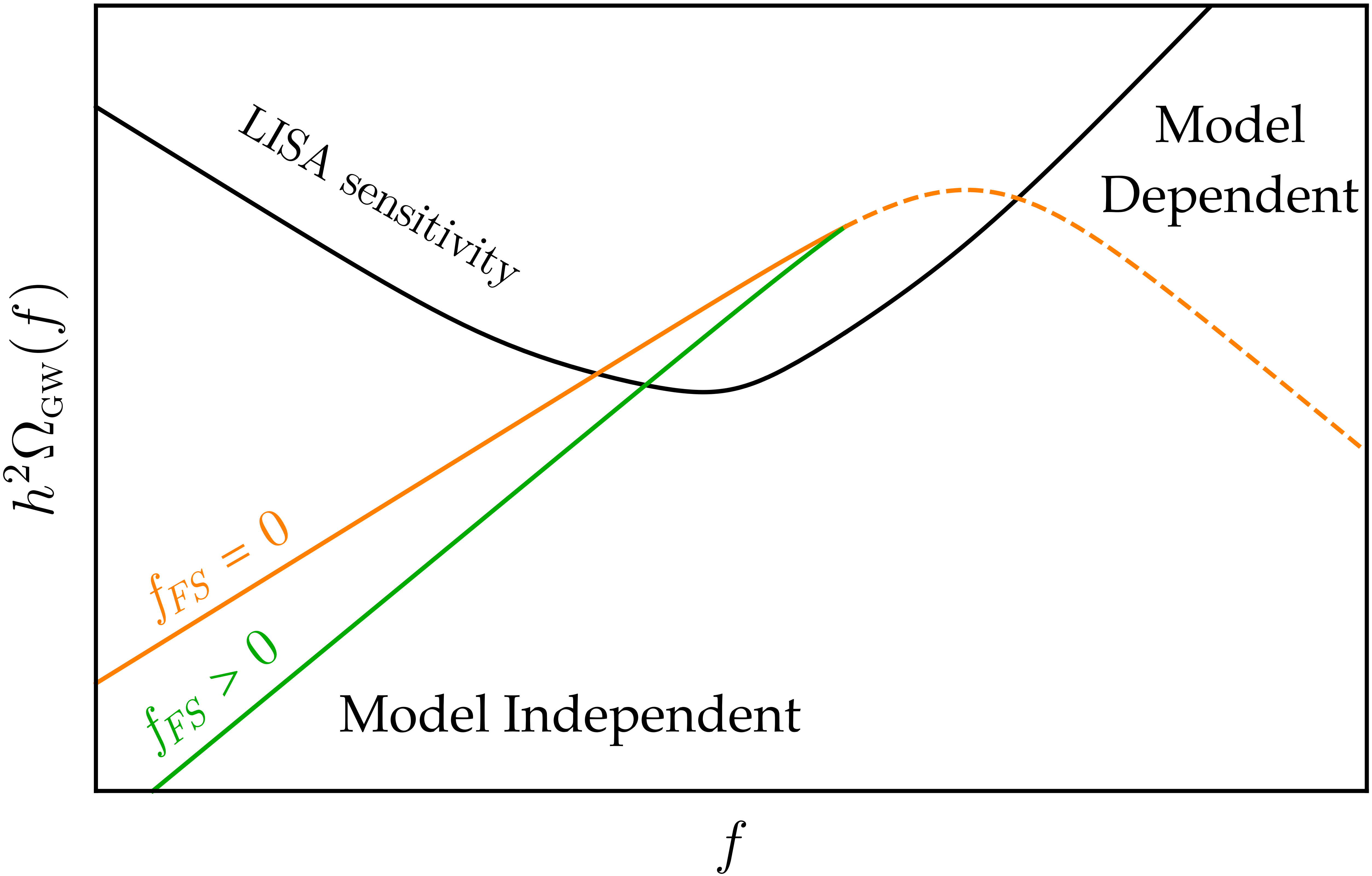
$$f_{\rm FS} = \rho_{\rm FS}/\rho_{\rm total}$$

$$u = k\tau$$

Free-streaming particles



Frequency spectrum



LISA Sensitivity

Estimate how accurately LISA can measure the free streaming fraction of the universe and its equation of state using Fisher Information Matrix

Assume GW source are the sound waves from a phase transition

Intuition for Sensitivity

If you make N measurements, sensitive to $1/\sqrt{N}$ effects

$$N \approx f\,T$$

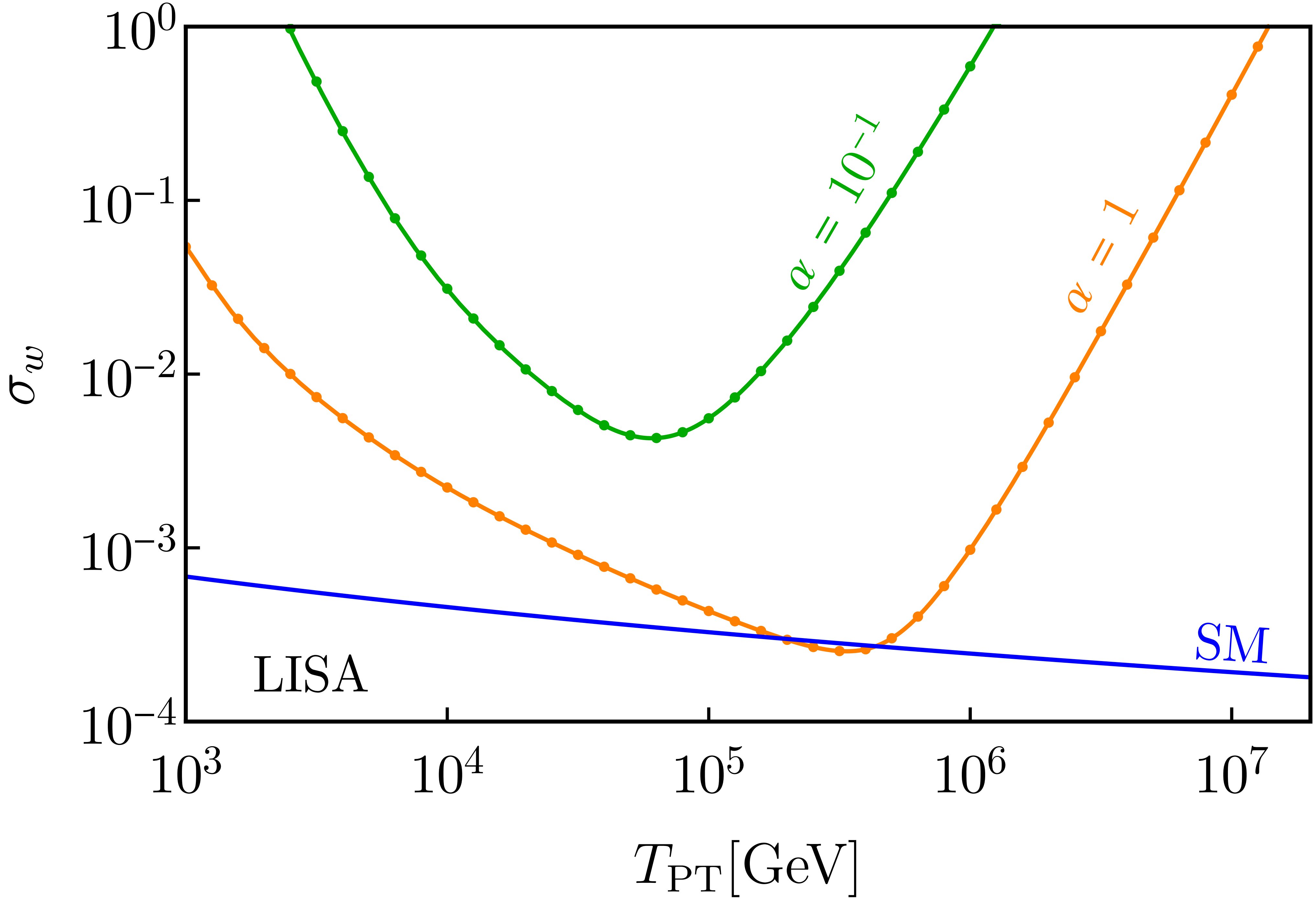
N measurements given a frequency f and time T

$$1/\sqrt{\mathrm{mHz\,year}} \sim 10^{-3}$$

Expect 10^{-3} level sensitivity

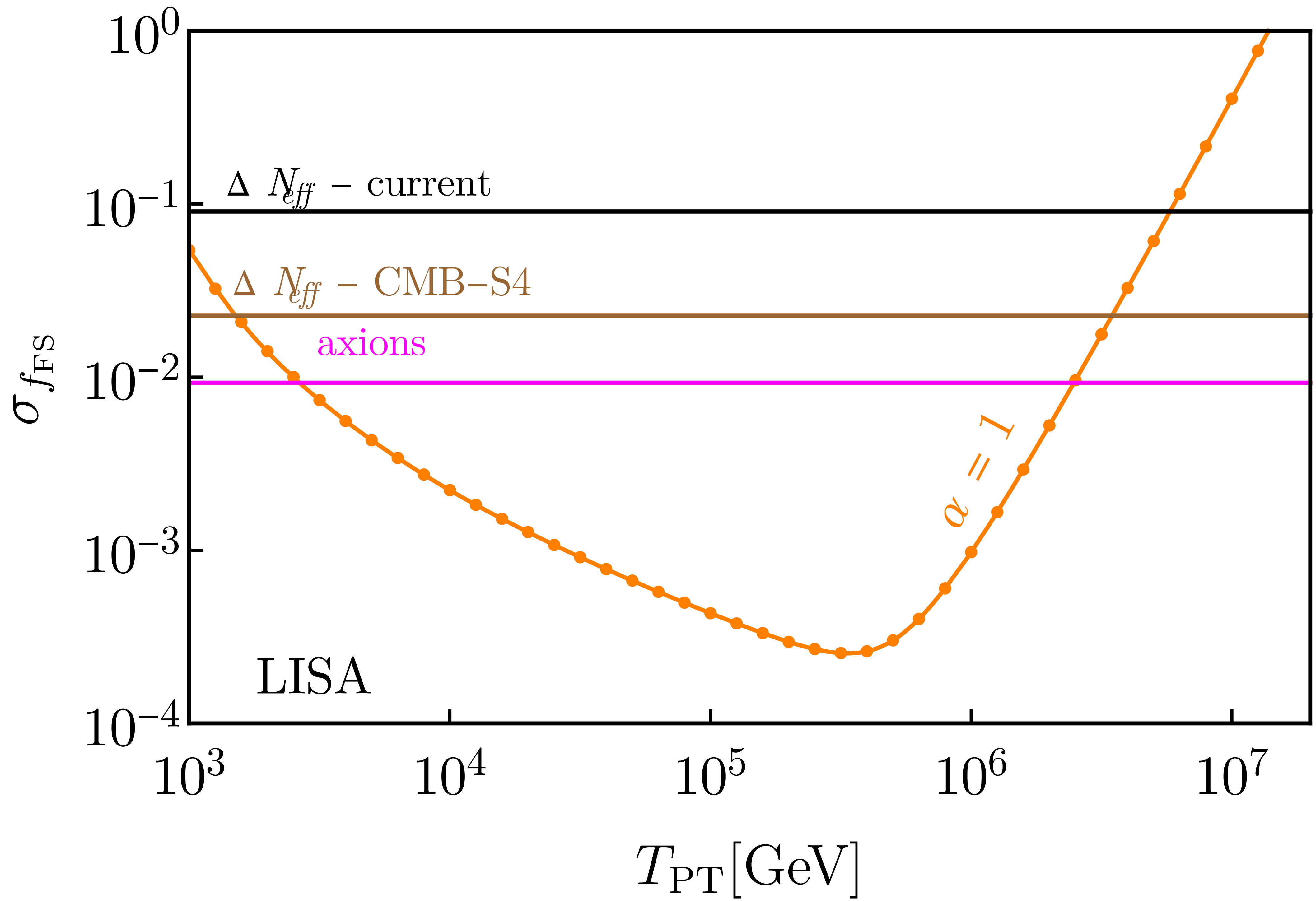
LISA Sensitivity

Can measure equation of state to an accuracy of 10^{-3}



LISA Sensitivity

Can measure free streaming fraction to 10^{-3}



Implications

Can measure free streaming fraction 10^2 - 10^3 times better than current constraints at T ~ 10^3 - 10^6 GeV

Reaches some interesting benchmarks such as free streaming axions

Can measure equation of state to an accuracy of 10^{-3} at T ~ 10^5 - 10^6 GeV

$\delta w \sim 10^{-3} - 10^{-4}$ **Is a Game Changer**

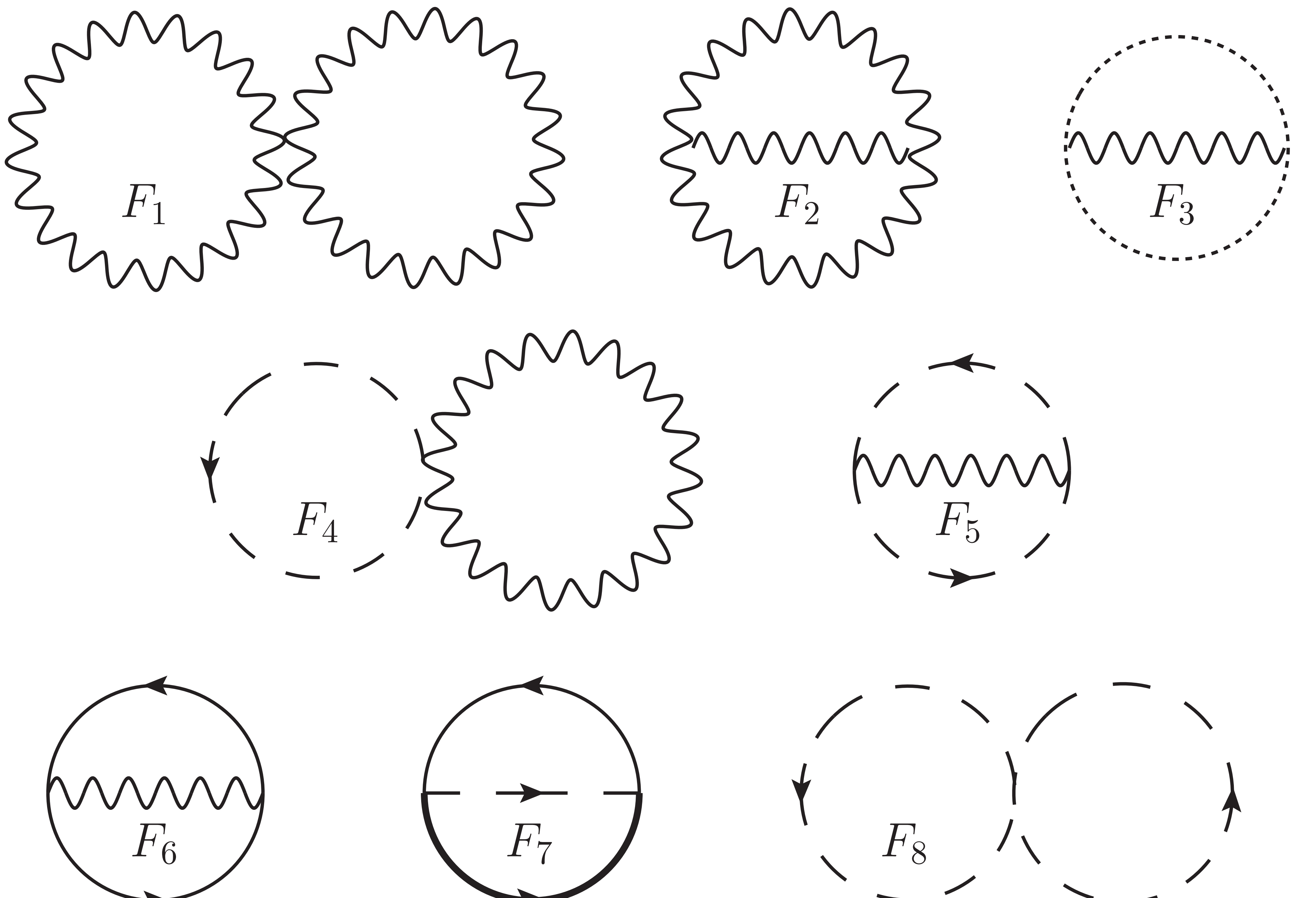
Implications

What is the equation of state of the early universe?

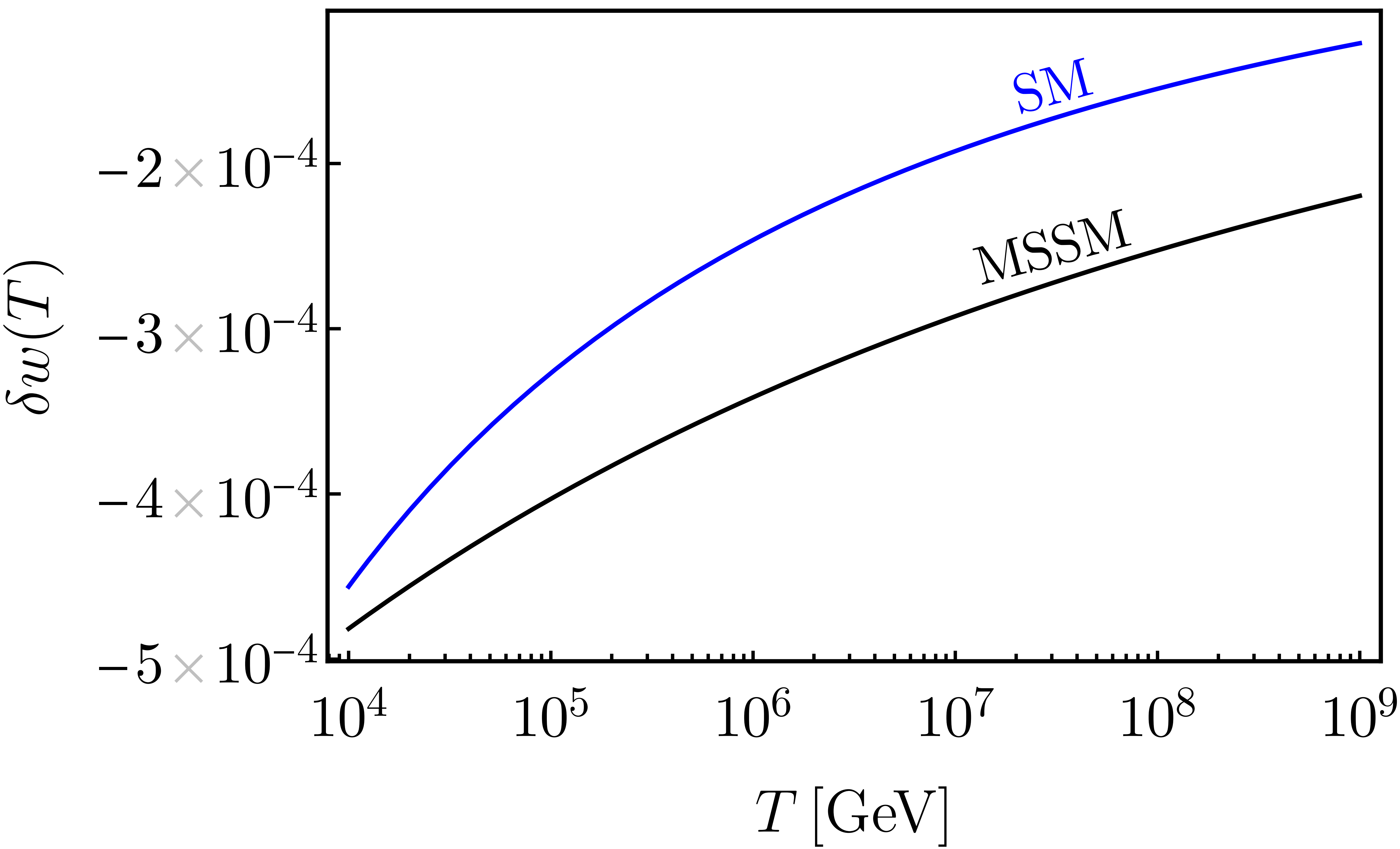
$$T^{\mu}_{\mu} \sim \rho - 3p \sim (1-3w)g_{\star} \sim \beta_{QCD}$$

Deviations from w = 1/3 give us information about beta functions and number of degrees of freedom

Implications



Implications



Implications

$$\delta w \sim 10^{-3} - 10^{-4}$$

You are O(1) sensitive to changes in the SM values of the QCD beta function and $g_\star$

Many BSM models predict changes at this order

Any future detector only does better

Conclusion

Low frequency part of a stochastic GW spectrum is model independent and sensitive to free streaming particles and EOS

LISA can measure

$$\delta w \, , \, \delta f_{FS} \sim 10^{-3} - 10^{-4}$$

$$T \sim 10^{5 \pm 1} \, \mathrm{GeV}$$

Most interesting case may be seeing a radiation dominated universe!