Spectral Distortions from Dark Turbulence

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ArXiv: 2209.14313

Recontres de Blois, 2023

מכון ויצמן למדע

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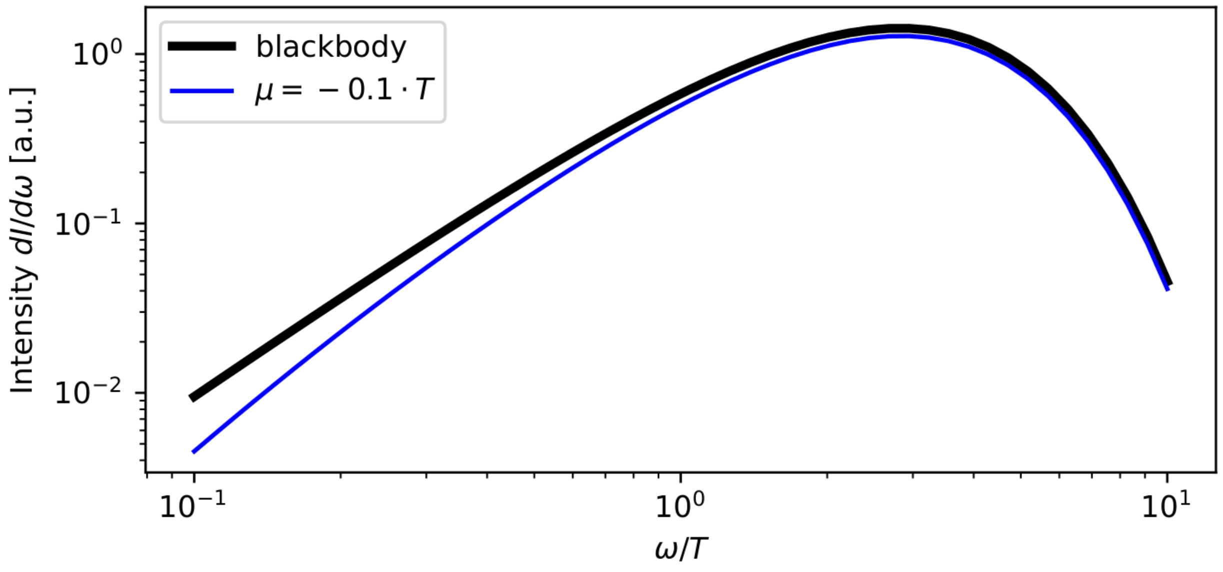
What is a spectral distortion?

CMB has blackbody spectrum with T~2K

Spectral distortion: Any deviation

μ-distortion:

$$\frac{dI}{d\omega} \propto \omega^3 \frac{1}{\exp((\omega - \mu)/T) - 1}$$



What is a spectral distortion?

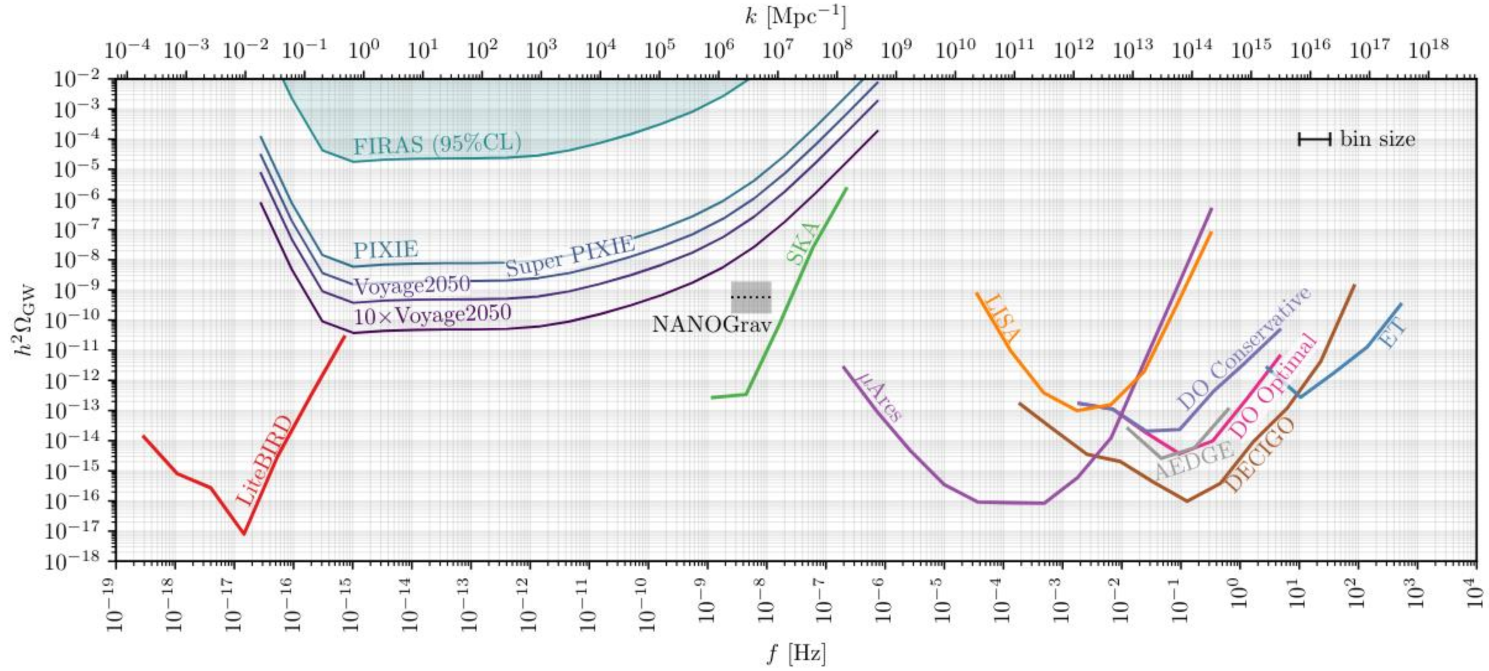
- T<100eV: no thermalization -> need to go case by case

μ- distortion gets created if energy is injected

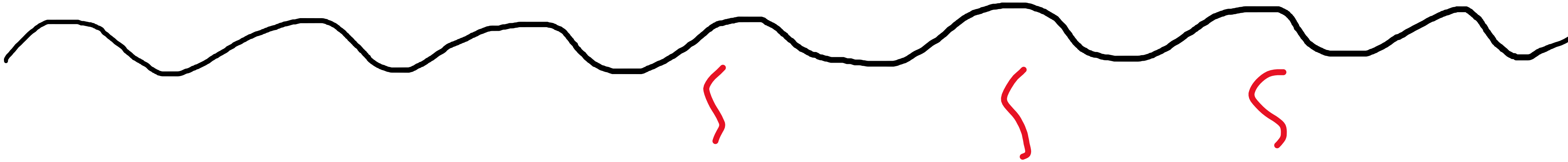
- T<1keV: no more Bremsstrahlung, double Compton scattering
  - Photon number conserved -> chemical potential
  - $\mu \approx \rho_{in}/\rho_\gamma \lesssim 10^{-4}$ from COBE/FIRAS
  - Future: $\mu \lesssim 10^{-8} - 10^{-9}$ PIXIE/Voyage2050

Motivation:

2010.00040 **Bridging the gap: spectral distortions meet gravitational waves**



Grav. Wave: h

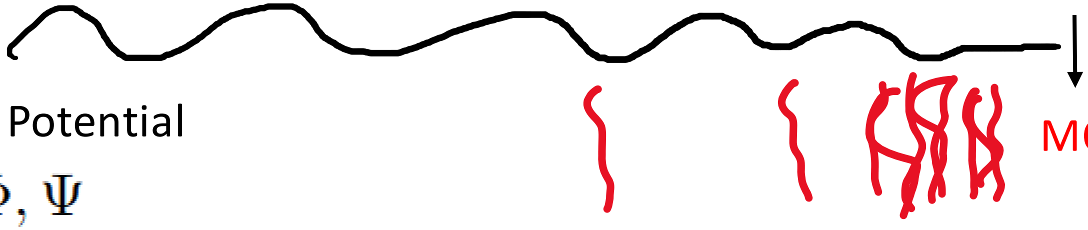


Deformation of plasma-> heat: $\mu \approx \rho_{in}/\rho_\gamma \approx 10^{-5}\ \Omega_{GW}$

Idea:

Acoustic Wave in baryon-photon fluid δ_γ

diffusion damping



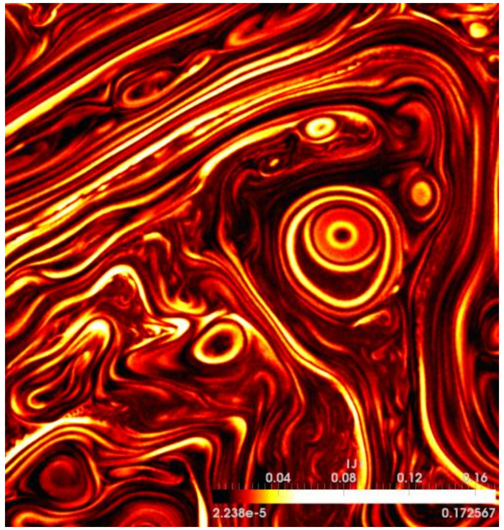
MORE heat

Grav. Potential

Φ, Ψ

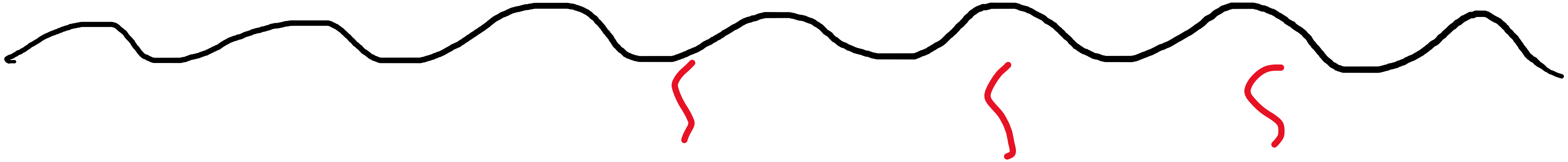
$$\mu \approx \rho_{in}/\rho_\gamma = \rho_{ac}/\rho_\gamma$$

Turbulent Dark Sector:



e.g: 1st Order PT,
Defect Network

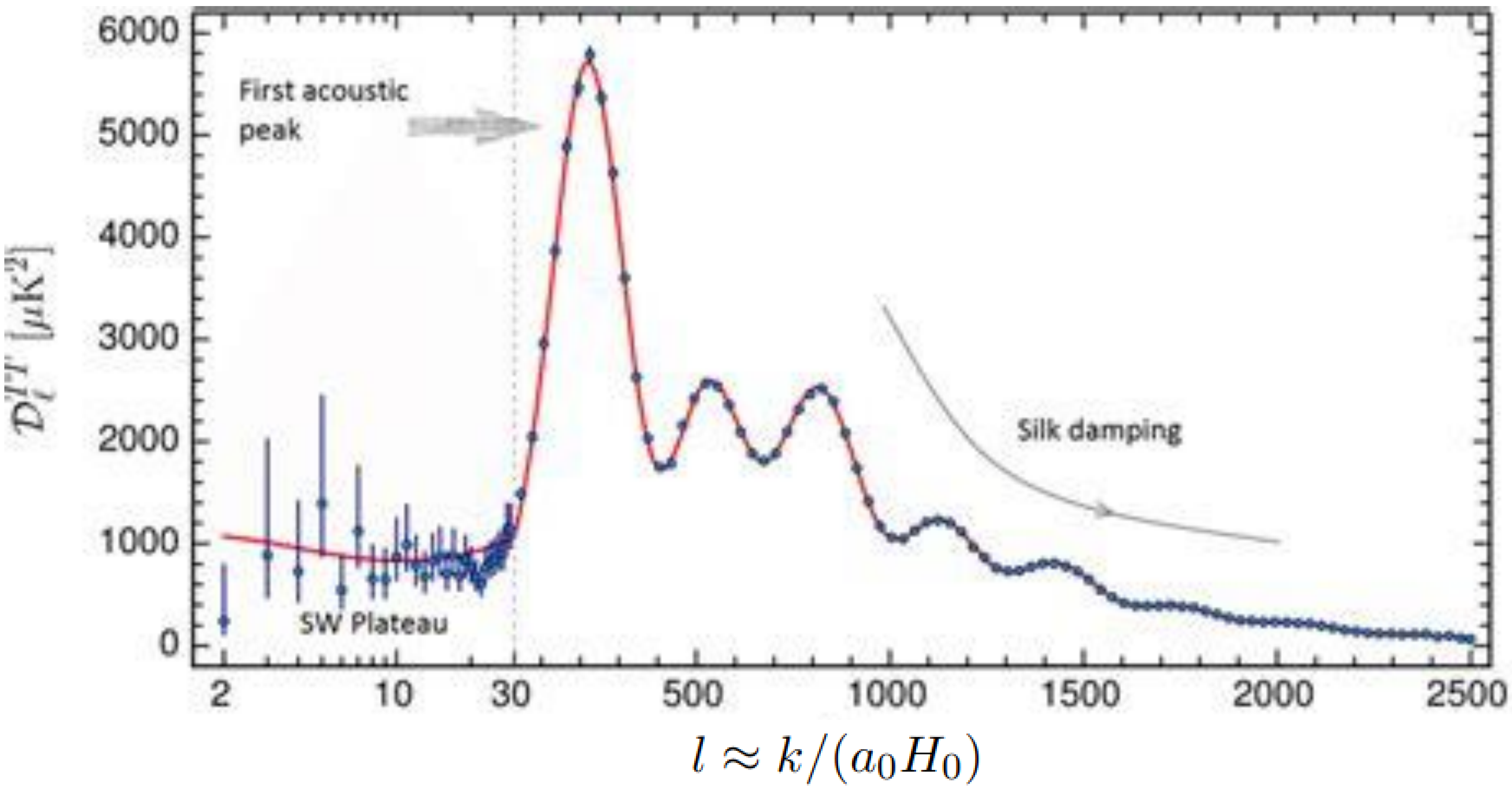
Grav. Wave: h



$$\mu \approx \rho_{in}/\rho_\gamma \approx 10^{-5}\ \Omega_{GW}$$

Reminder Diffusion/Silk Damping

CMB angular power spectrum:

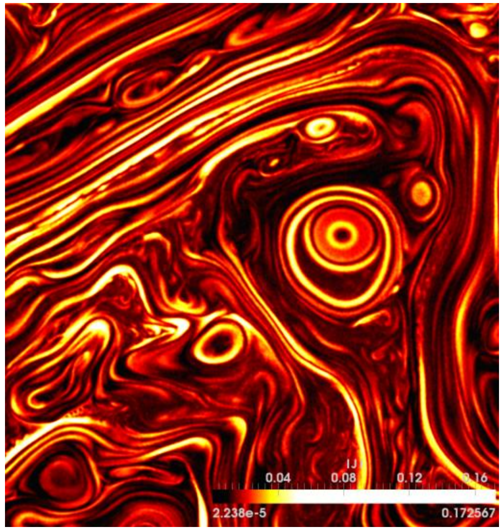


For SD higher k relevant:

Complete Damping

Idea:

Turbulent Dark Sector:



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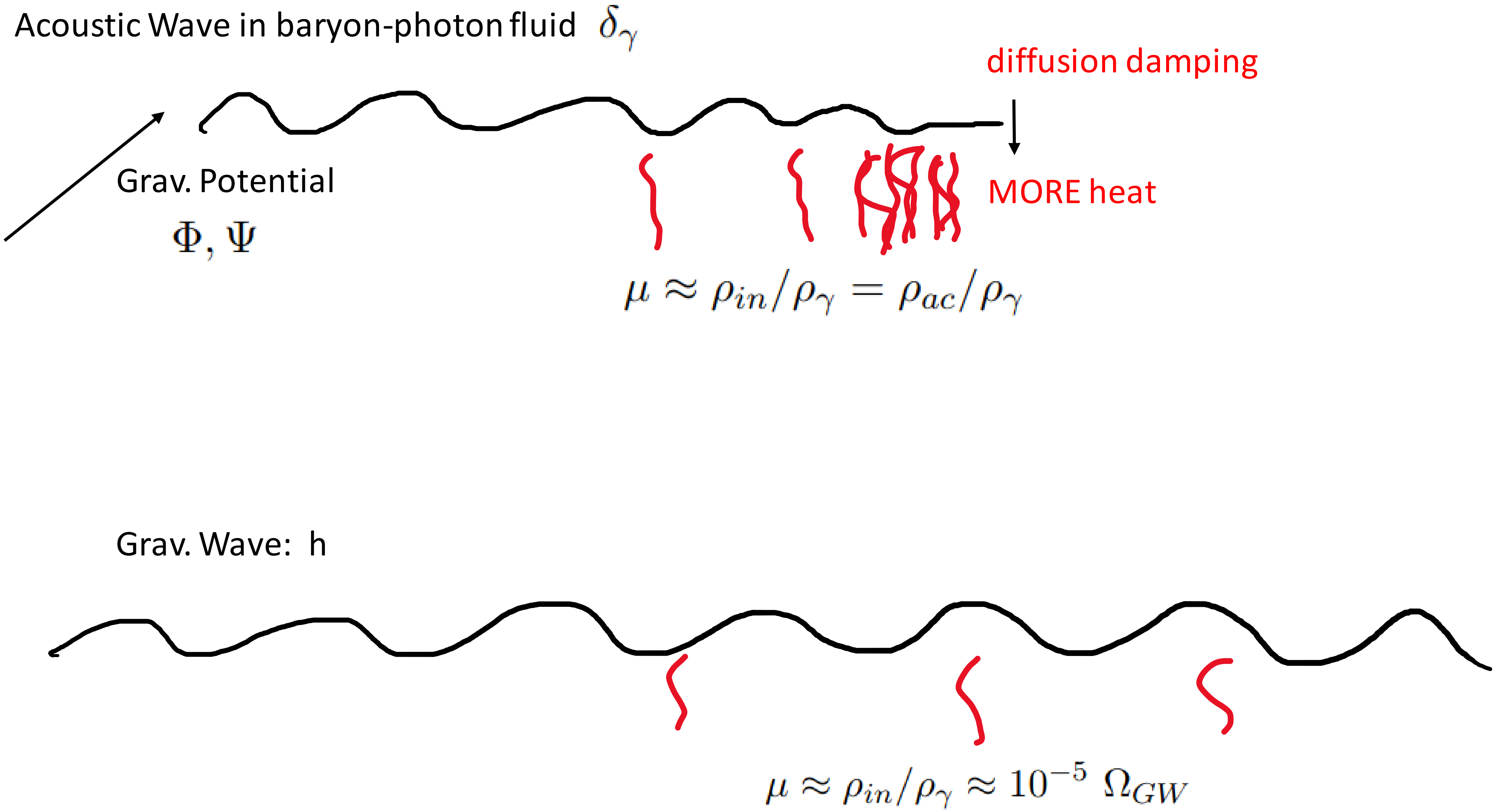
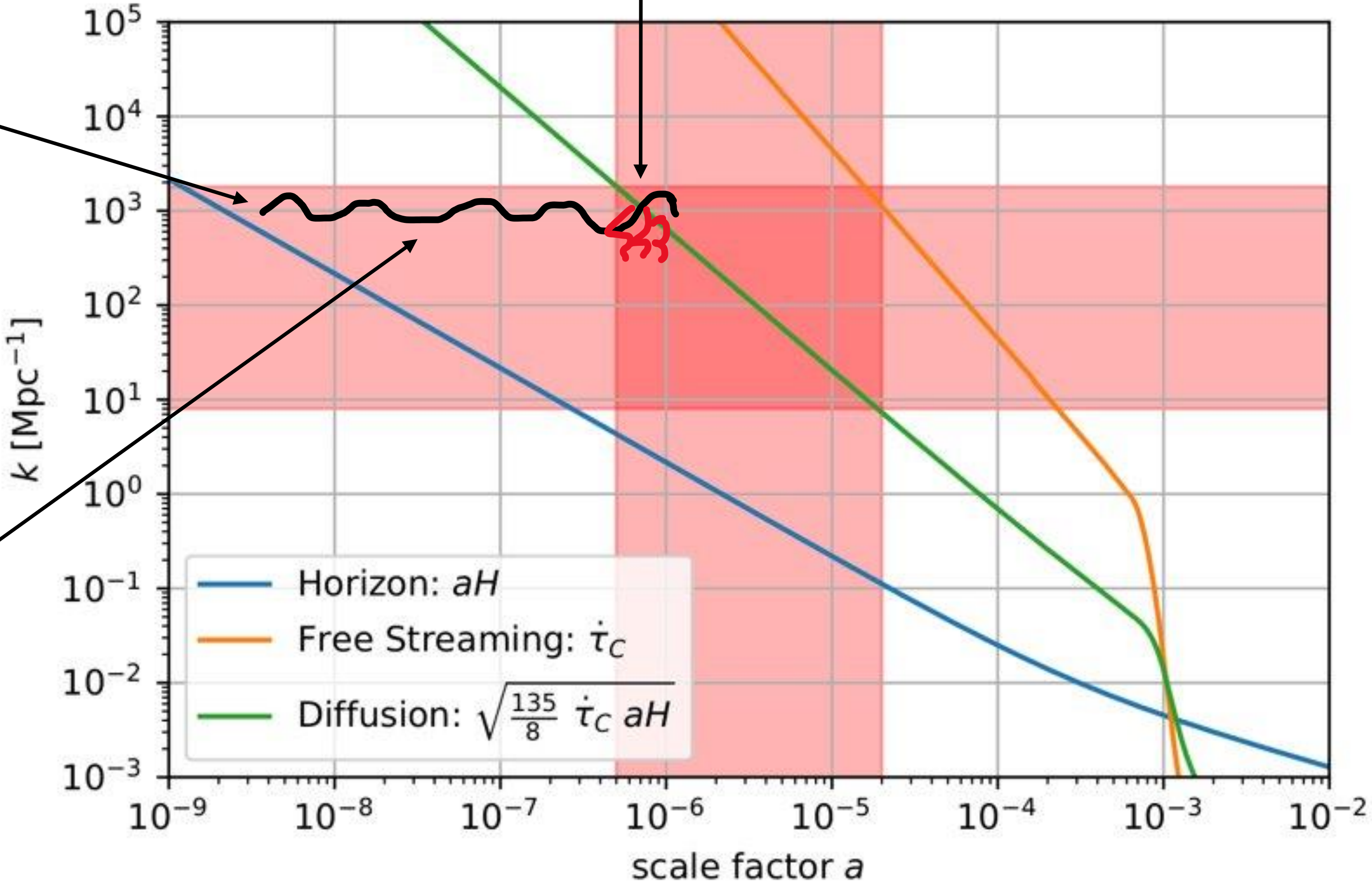


Relevant Scales

Wave damped by diffusion:
-> ac. energy released as heat

Ac. wave sourced by gravitational interaction

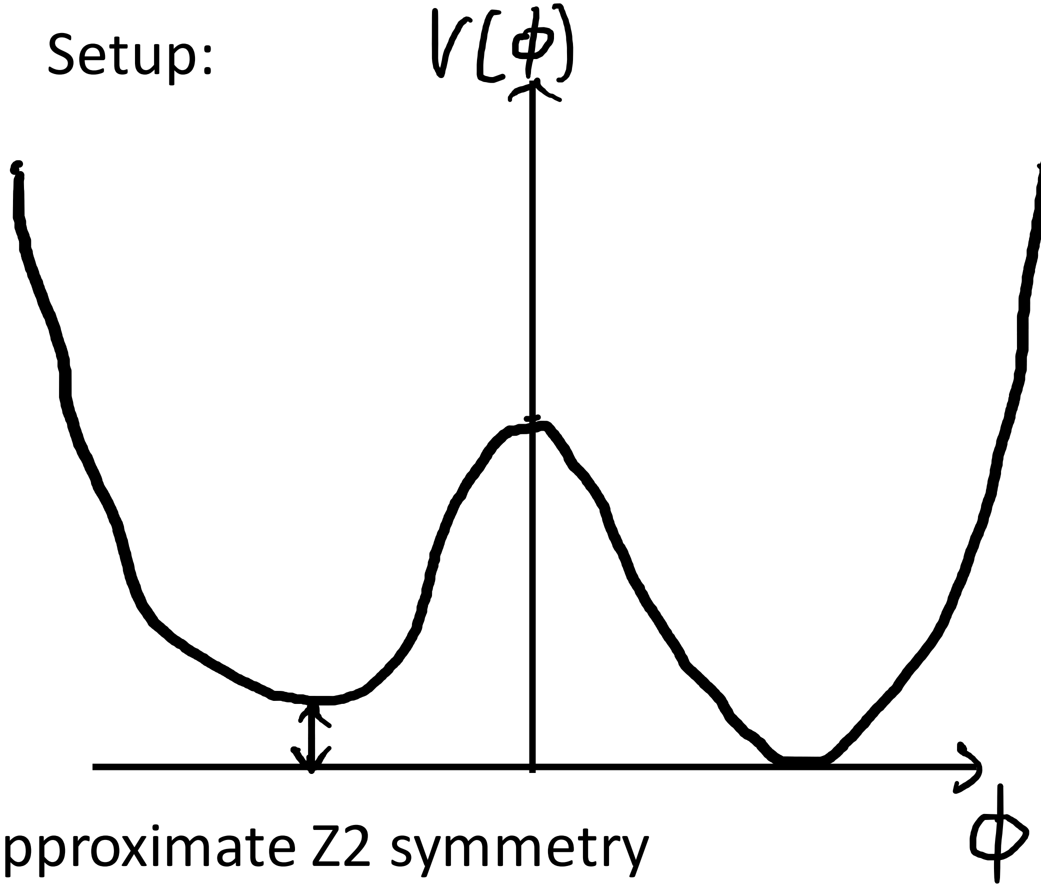
Propagation with const. amplitude:
-> const. ac. energy
$\epsilon_{\rm ac} = \rho_{\rm ac}/\rho_\gamma$



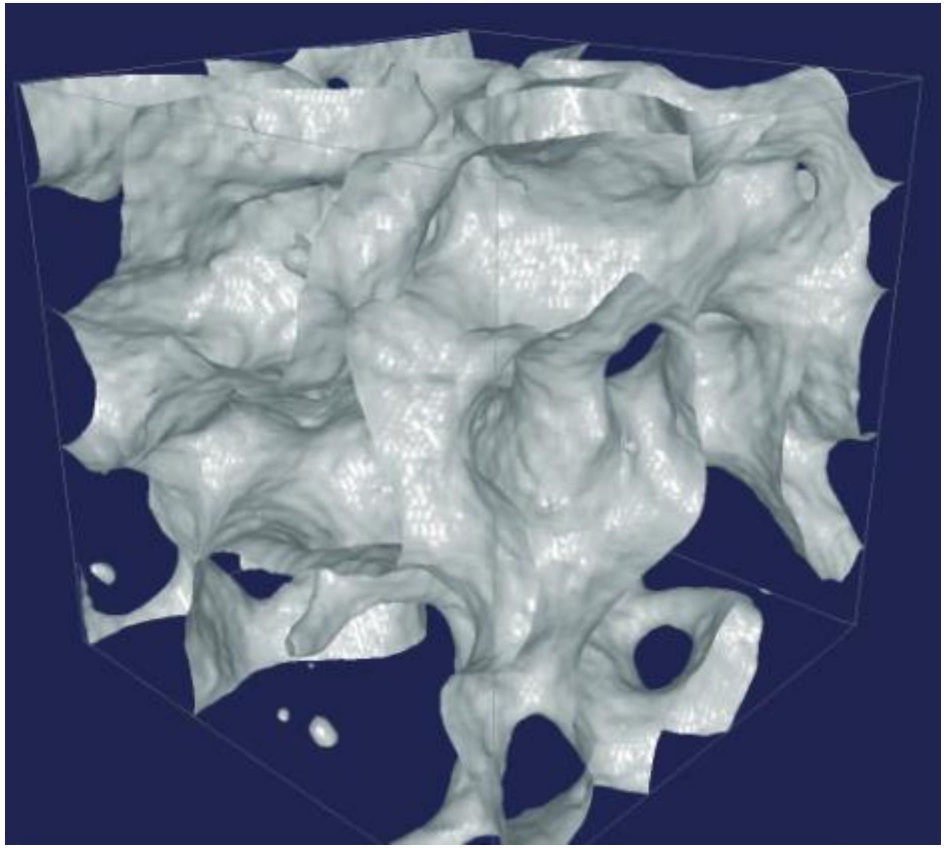
Example: Annihilating Domain Walls

based on T. Hiramatsu, et al. '14

Setup:



Approximate Z2 symmetry
-> network decays



Example: Annihilating Domain Walls

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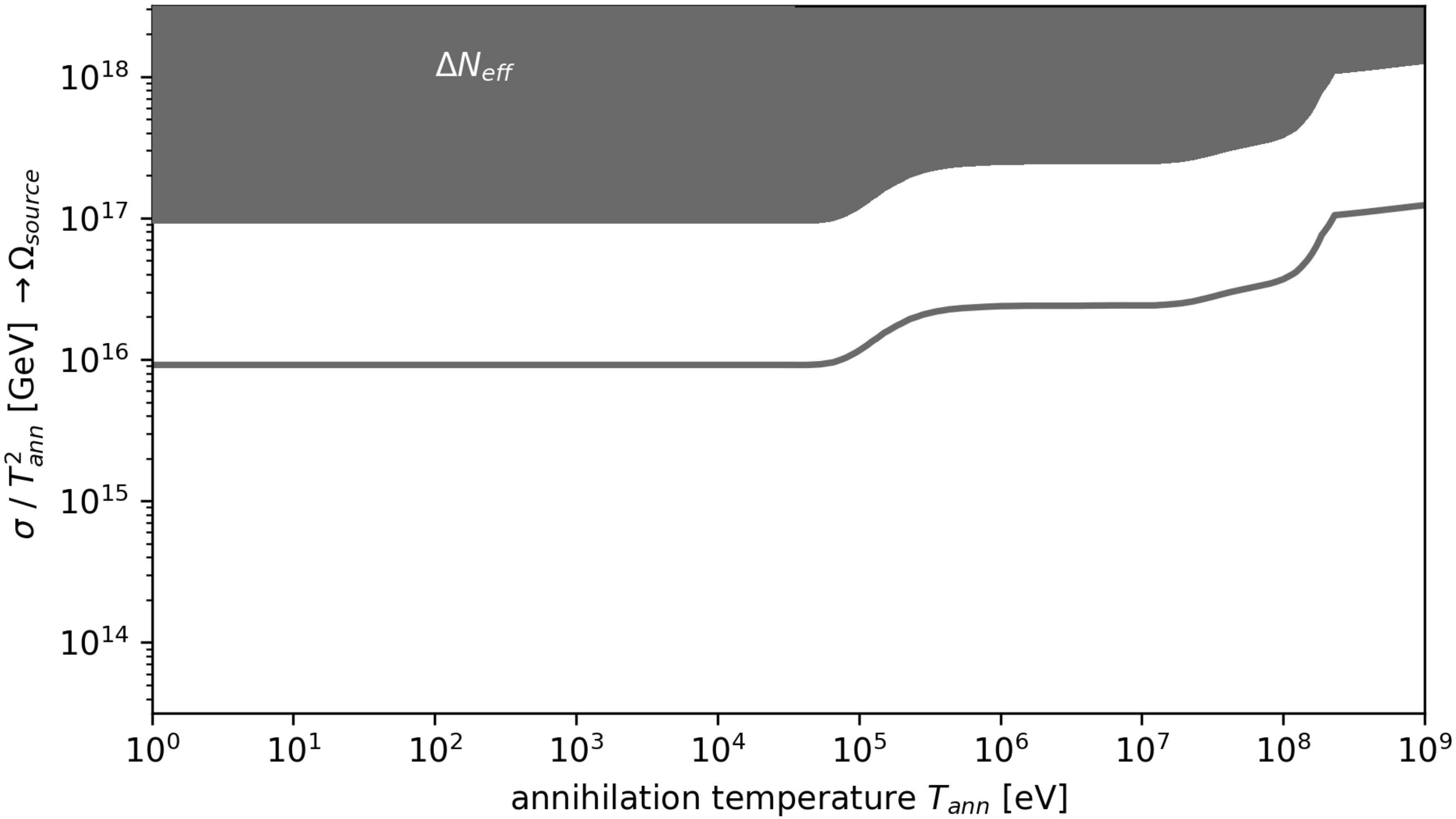
Constraints



Example: Annihilating Domain Walls

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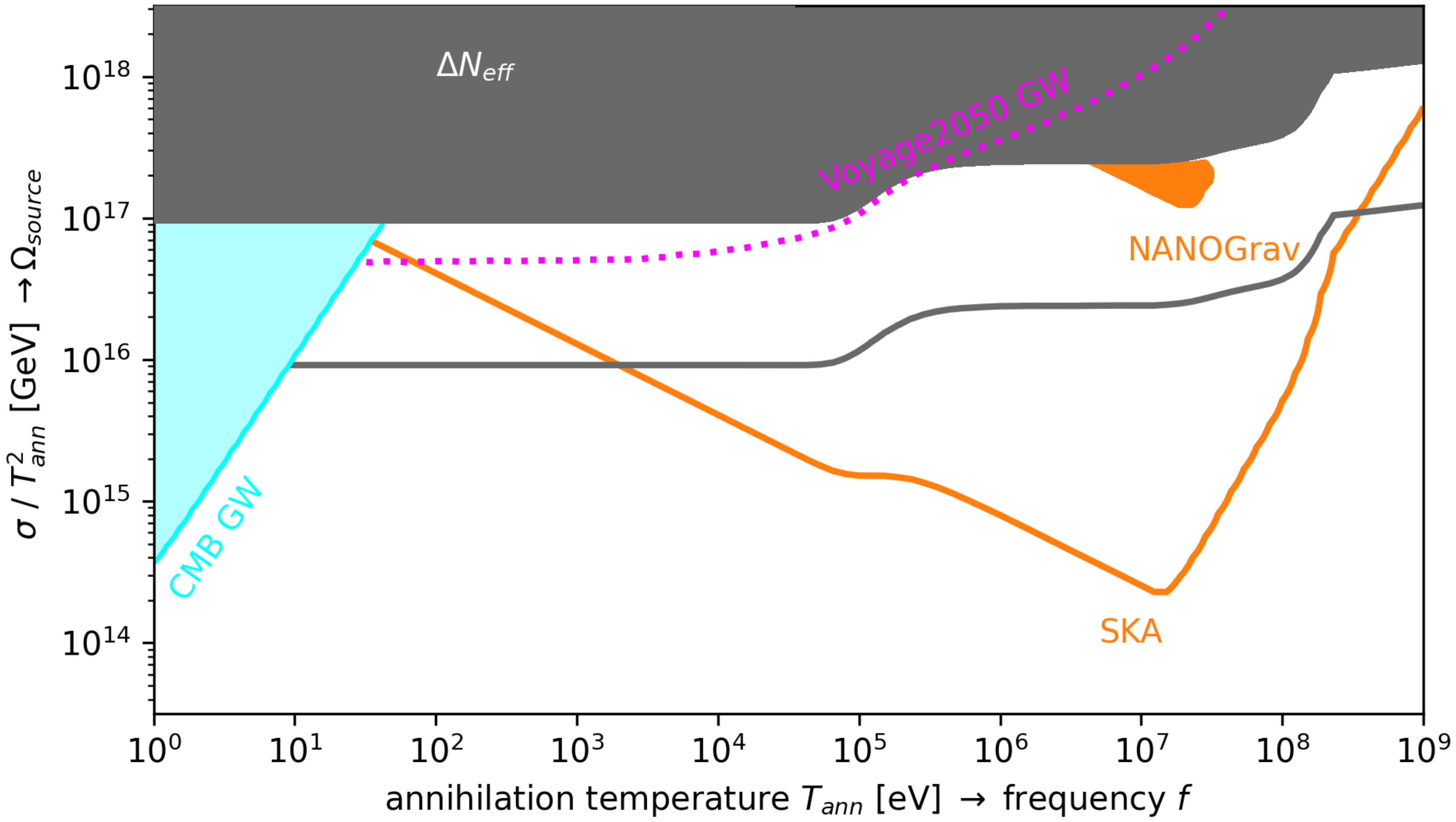
Constraints+
GWs



Example: Annihilating Domain Walls

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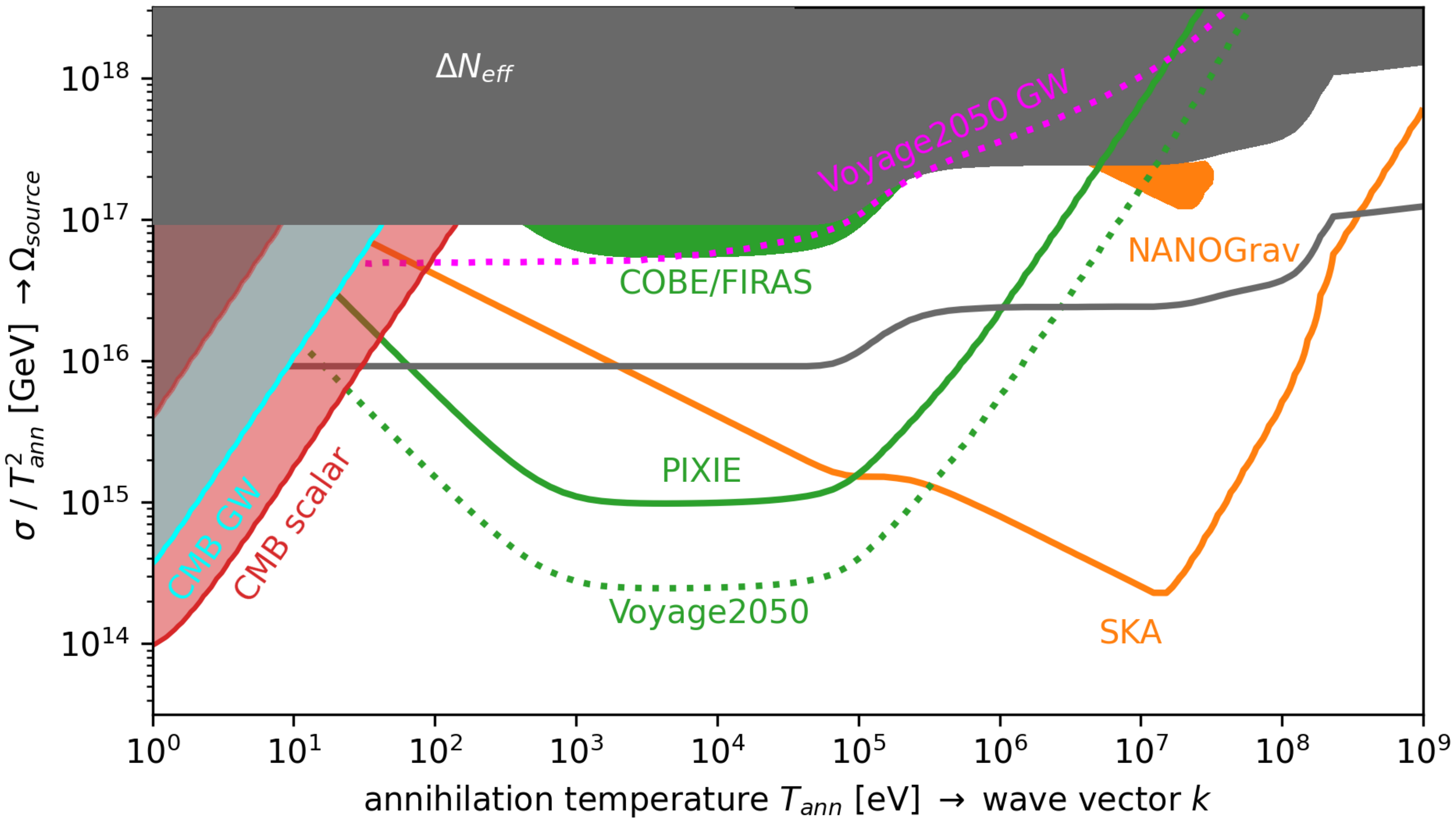
Constraints+
GWs+
Ac. Waves



Example: Annihilating Domain Walls

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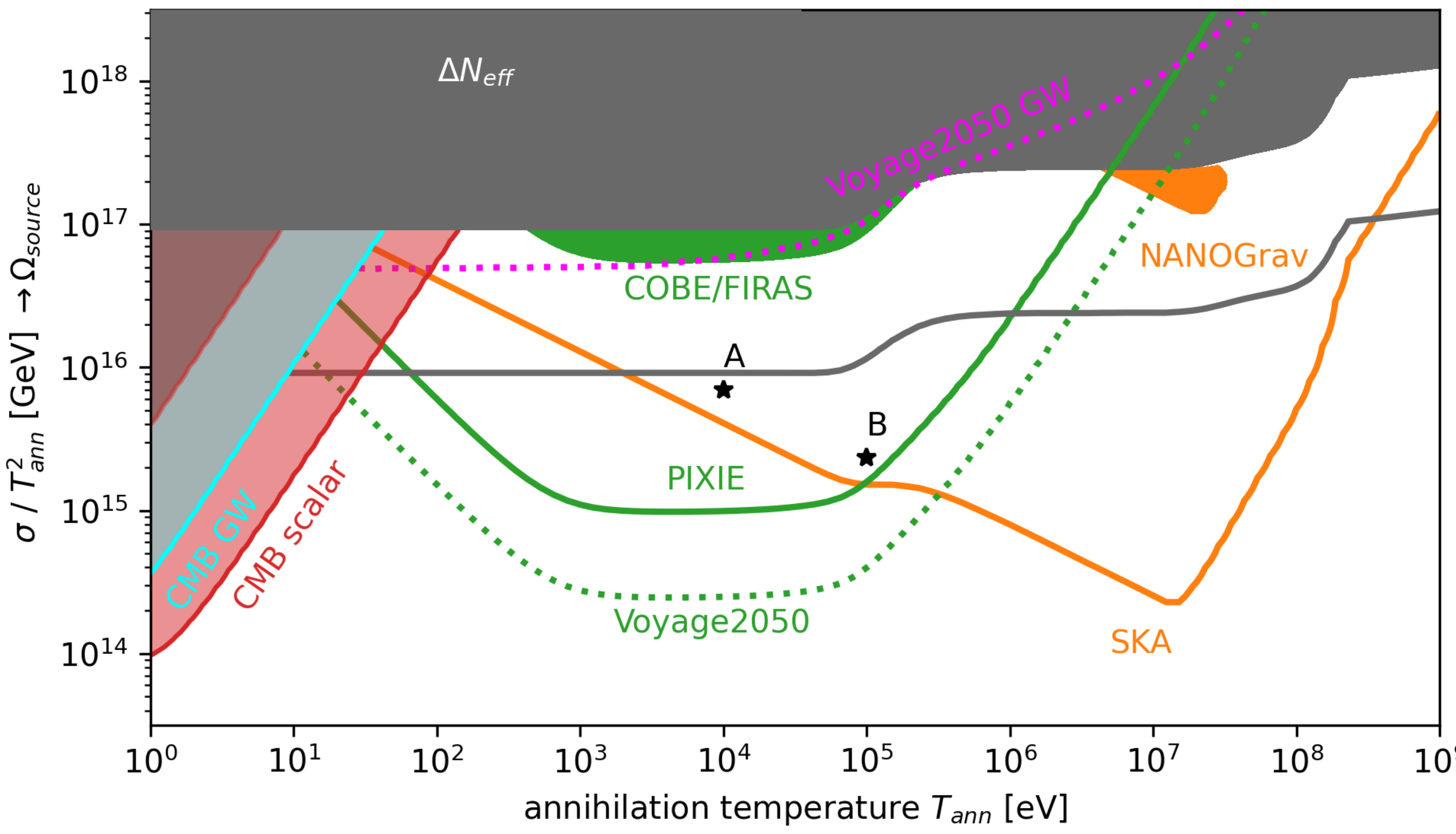
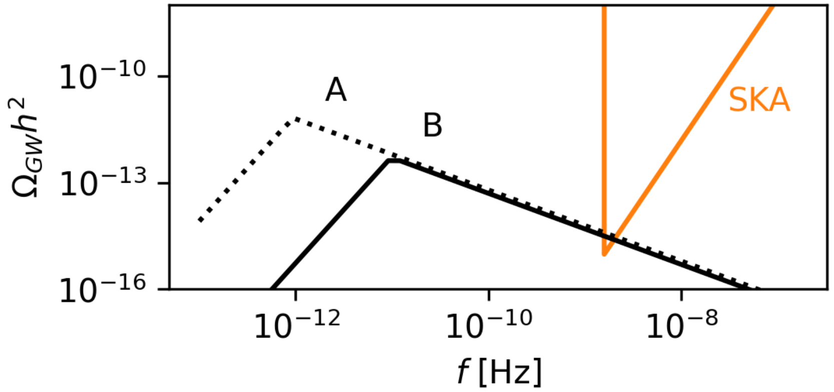
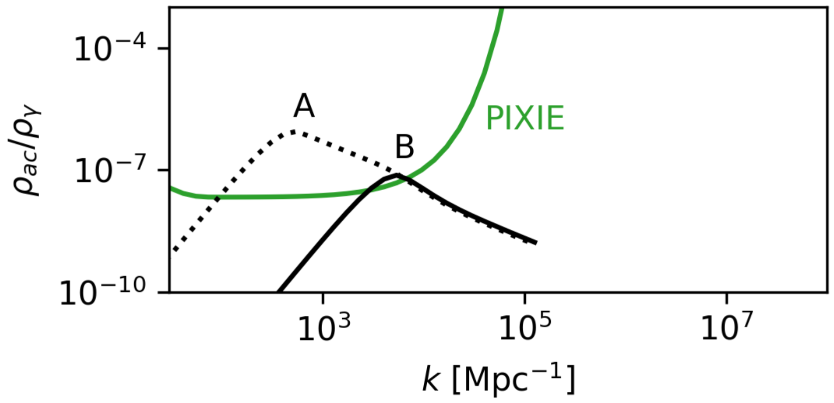






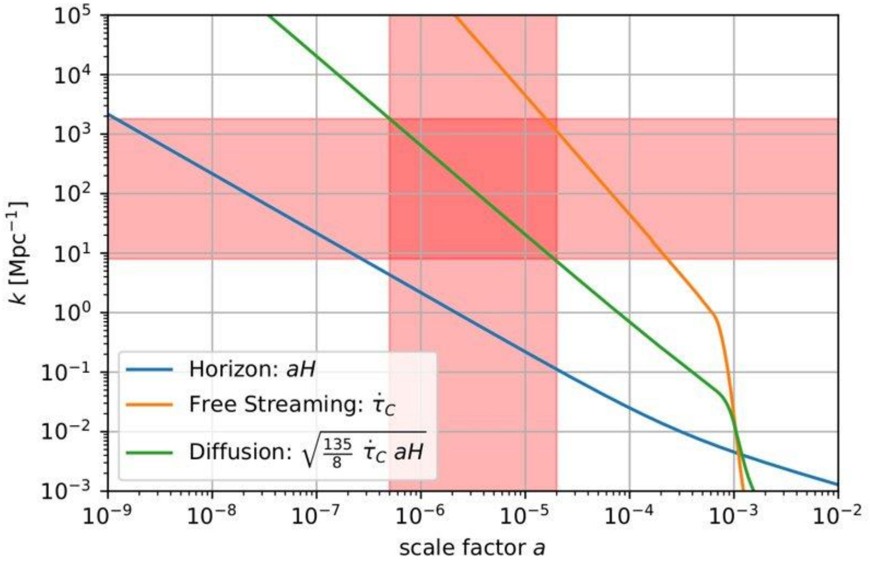
Conclusion

- Spectral Distortions powerful new probe of grav. coupled sectors
  - Interesting interplay with GW searches
- Easy + Reliable estimate available
  - Comparison with full numerical study for toy model
  - Also looked at cosmic strings, 1st order PT

Thanks!

Backup

Damping and Generation of SD

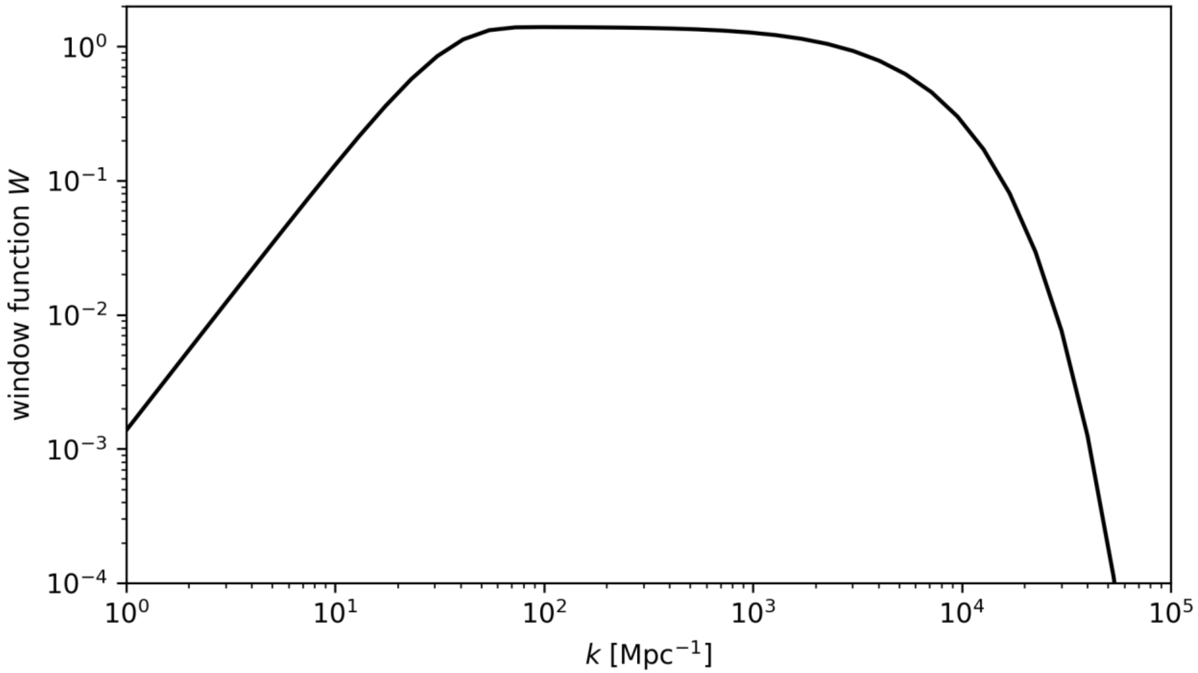


-Independent of generation of acoustic wave

-> No knowledge about dark sector required

-Summed up in window function W(k):

$$\mu = \int d\log k\ \epsilon_{ac}(k)\mathcal{W}(k)$$



Induced Accoustic Waves: Analytic estimate -The Dark Sector

Dark Sector subdominant: $\Omega_d = \frac{\rho_d}{\rho_{tot}} \ll 1$

Turbulence created at time: $\tau_* \to a_*,\ H_*$

Characteristic Length Scale: $L_* \approx 1/k_* < 1/(a_* H_*)$

Amplitude of fluctuations: $\langle \delta_d^2 \rangle = A_{\delta_d}$

Ansatz for temporal structure:

$$\delta_d(\tau, k) = \frac{\delta\rho_d}{\overline{\rho_d}} \propto \theta(\tau - \tau_*) \sin(c_d k(\tau - \tau_*)); \qquad c_d \lesssim 1$$

Induced Accoustic Waves: Analytic estimate -Gravity

Conformal Newtonian Gauge:

$$ds^2 = a^2(\tau)\left[(1+2\Psi(\mathbf{x},\tau))d\tau^2 - (1+2\Phi(\mathbf{x},\tau))d\mathbf{x}^2\right]$$

Evolution in Fourier space (x->k):

$$3aH\left(\dot{\Phi} - aH\Psi\right) + \underline{k^2\Phi} = \frac{3a^2H^2}{2}\left(\Omega_\gamma\delta_\gamma + \Omega_n\delta_n + \underline{\Omega_d\delta_d}\right)\ ,$$

$$\Phi + \Psi = -\frac{6a^2H^2}{k^2}\left(\Omega_\gamma\sigma_\gamma + \Omega_n\sigma_n + \frac{3}{4}(1+w_d)\Omega_d\sigma_d\right)$$

In Super-Horizon limit k>>aH:

$$\Phi = -\Psi = \frac{3}{2}\frac{a^2H^2}{k^2}\Omega_d\delta_d$$

Or more familar:

$$\frac{\nabla^2}{a^2}\Phi = 4\pi G\delta\rho_d$$

Induced Accoustic Waves: Analytic estimate -Baryon Photon Fluid

Evoltution of sound waves:

$$\ddot{\delta}_\gamma + \frac{1}{3}k^2\delta_\gamma = -4\ddot{\Phi} - \frac{4}{3}k^2\Psi$$

$$\approx a_*^2 H_*^2 \Omega_{d,*} \sin(c_d k(\tau - \tau_*)) \quad \text{while} \quad \tau_* < \tau < \tau_* + 1/(a_* H_*)$$

-> Harmonic oscillator driven for one Hubble time:

$$\epsilon_{ac} \propto \langle \delta_\gamma^2 \rangle \approx \Omega_{d,*}^2 \left(\frac{a_* H_*}{k}\right)^4 \begin{cases} N_{osc}^2 & \text{resonant } c_d = 1/\sqrt{3} \\ 1 & \text{off resonant } c_D \neq 1/\sqrt{3} \\ N_{osc} & \text{stochastic} \end{cases} \quad \text{with} \quad N_{osc} = \frac{k}{a_* H_*}$$

Induced Accoustic Waves: Analytic estimate

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Amplitude of fluctuations: $\langle \delta_d^2 \rangle = A_{\delta_d}$

Result:

$$\epsilon_{ac}(k) \approx \Omega_{d,*}^2 \; A_{\delta_d} \; \left(\frac{k}{k_*}\right)^3 \exp\left(-\frac{k^2}{2k_*^2}\right) \left(\frac{a_* H_*}{k}\right)^n \quad \text{with} \quad \begin{cases} n = 2 & \text{resonant } c_d = 1/\sqrt{3} \\ n = 4 & \text{off resonant } c_D \neq 1/\sqrt{3} \\ n = 3 & \text{stochastic} \end{cases}$$

Application to Domain Walls

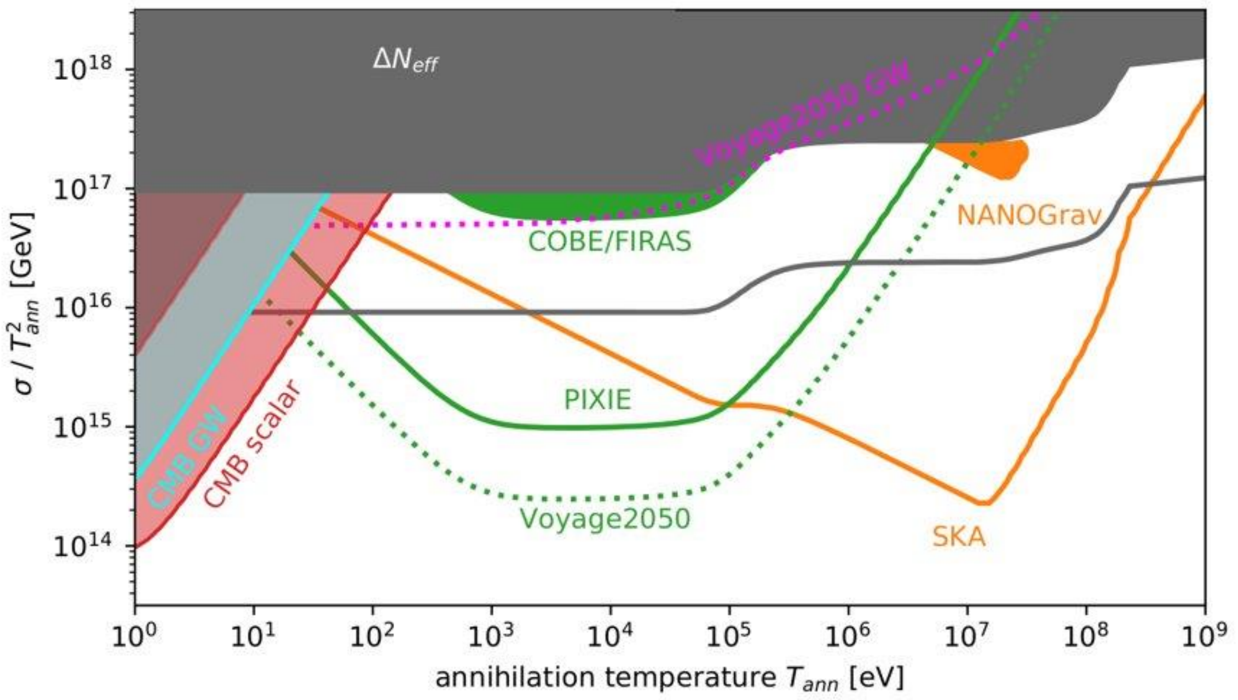
Dark Sector subdominant: $\Omega_{d,ann} \propto \sigma / T_{ann}^2$

Turbulence created at time: $\tau_{ann} \leftrightarrow T_{ann}$

Characteristic Length Scale: $k_* \approx a_{ann} H_{ann}$

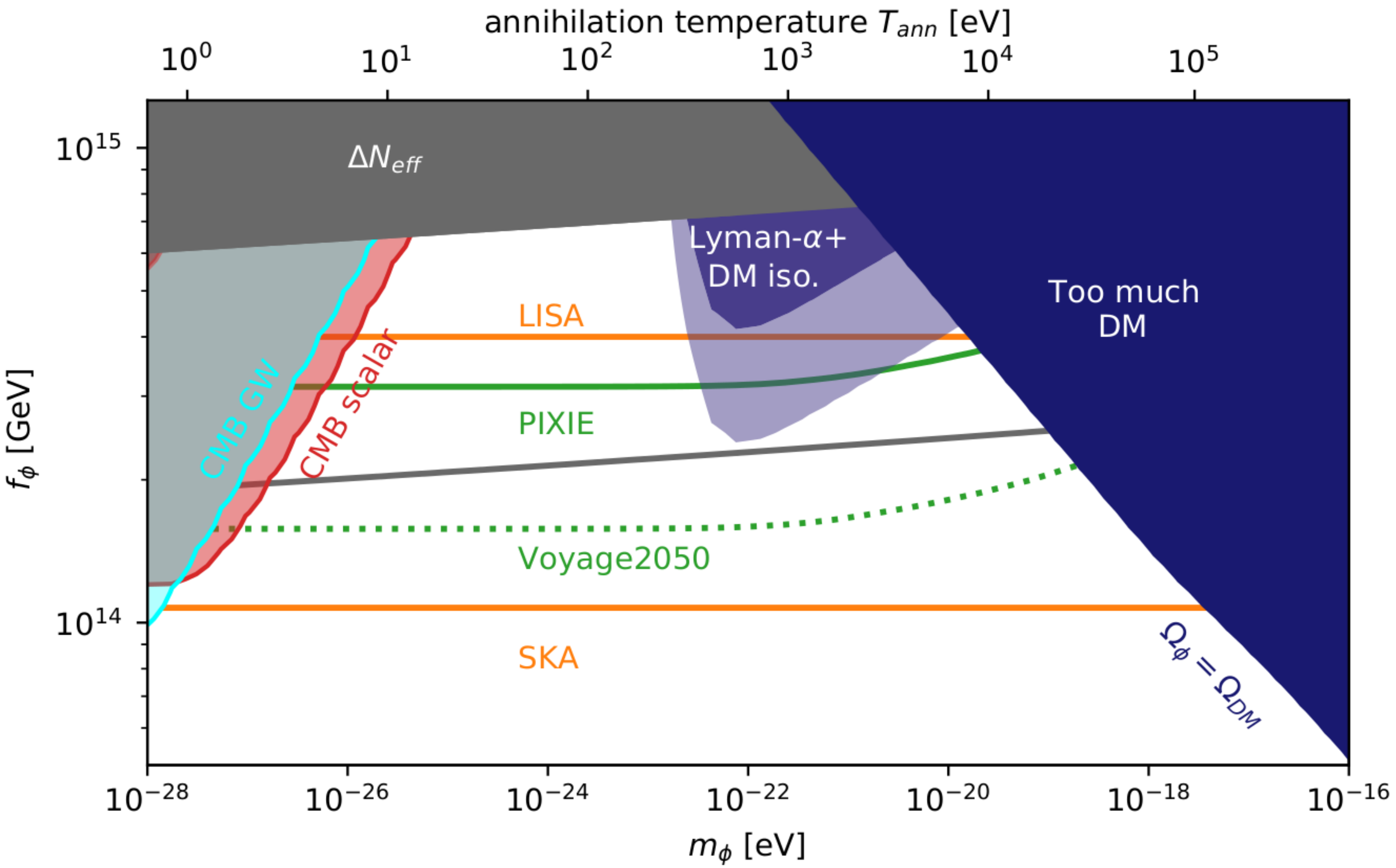
Amplitude of fluctuations: $A_{\delta_d} \approx 1$

Temporal Behavior: stochastic



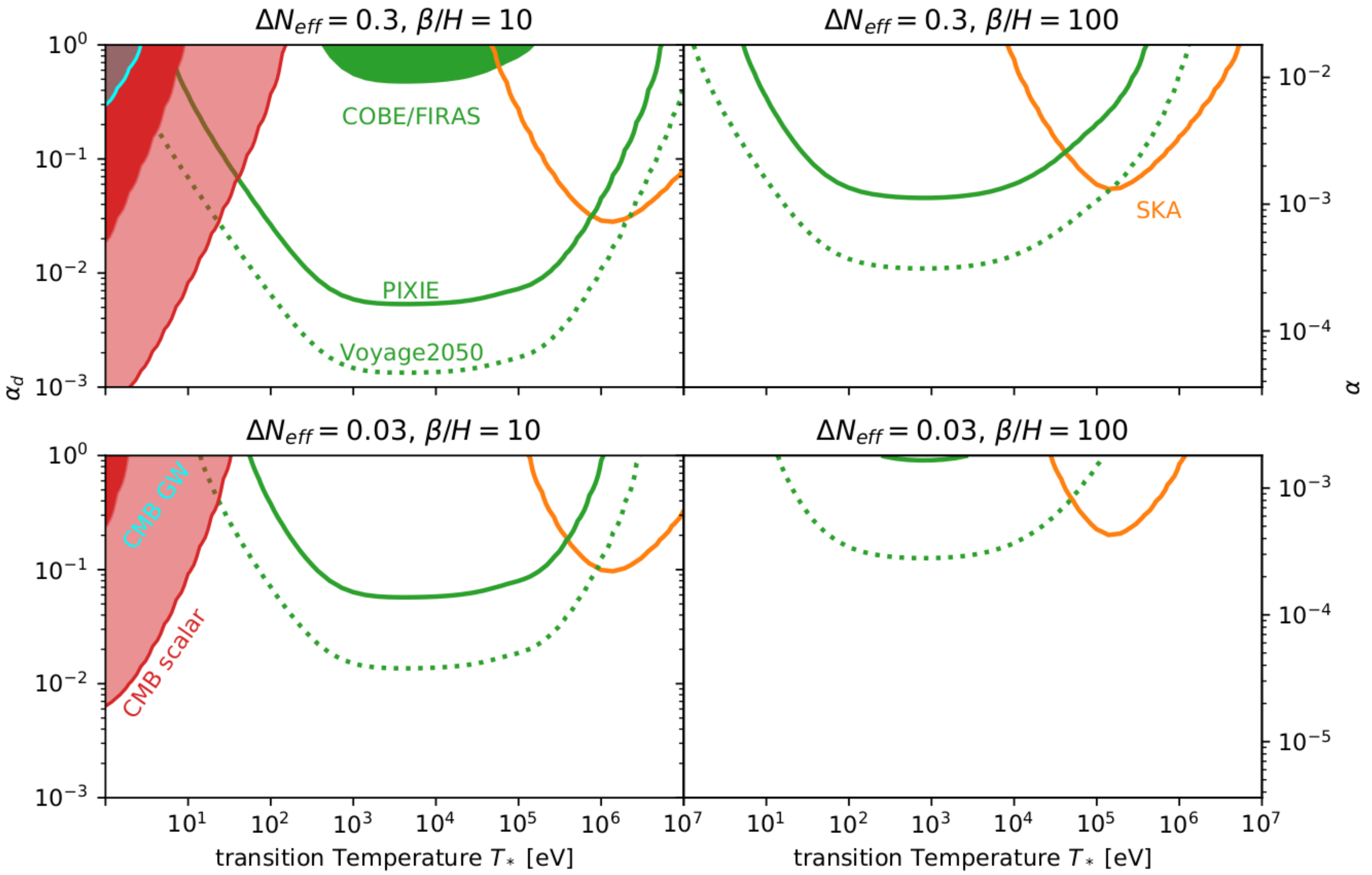
Strings from global U(1)

based on Hardy, Gorghetto et al.



1st order PT, dark acoustic waves

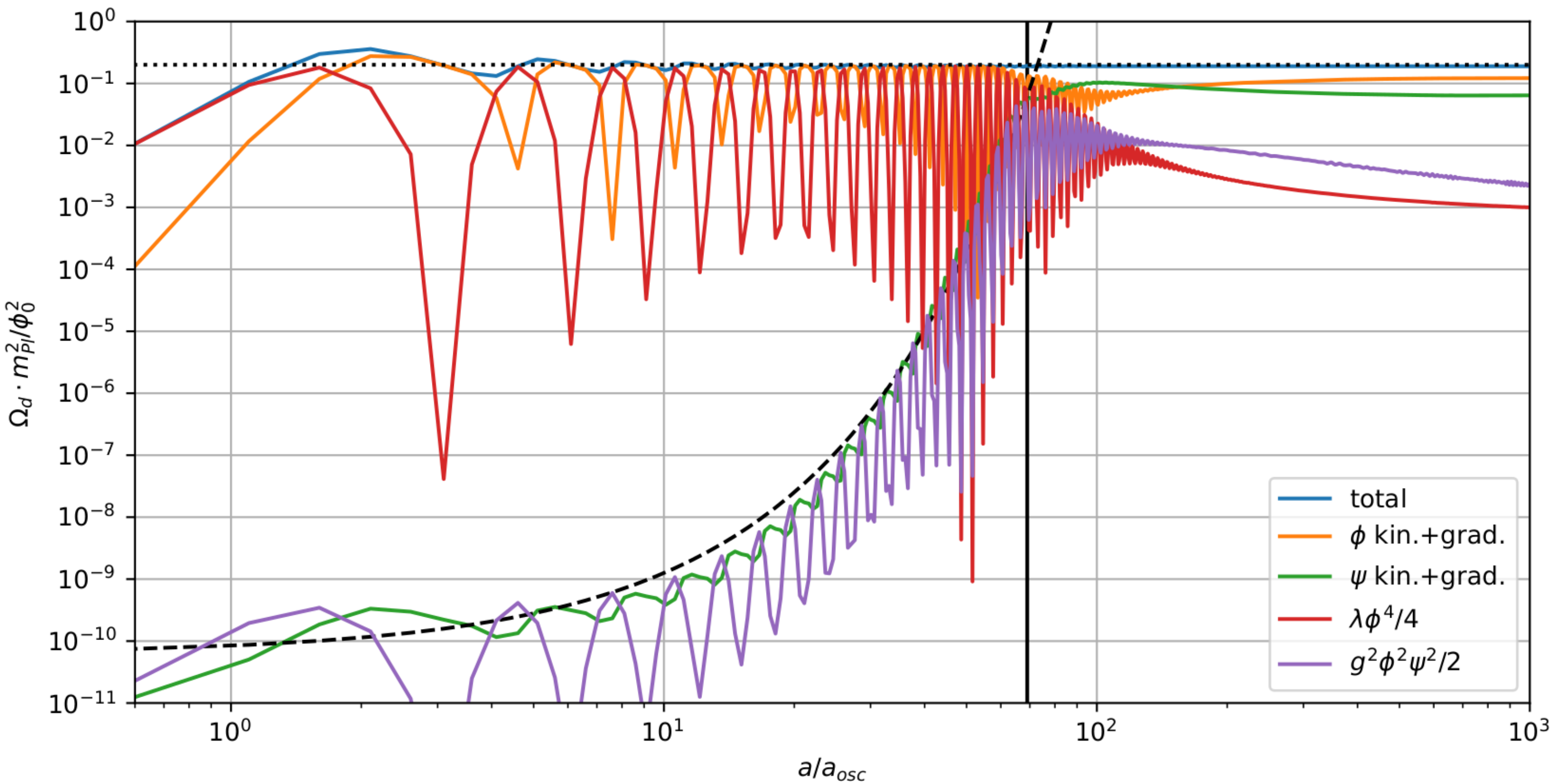
Resonant Case
-> Strong Distortion Bounds!



How good is the estimate?
Full numerical study on lattice for toy model

Two scalar fields with potential (similar to preheating) $V(\phi, \psi) = \frac{1}{4}\lambda\phi^4 + \frac{1}{2}g^2\phi^2\psi^2$

$$H_{osc} = \omega_* = \sqrt{\lambda\phi_i}, \qquad \Omega_{d,osc} \approx 0.2\frac{\phi_i^2}{m_{\rm Pl}^2}$$

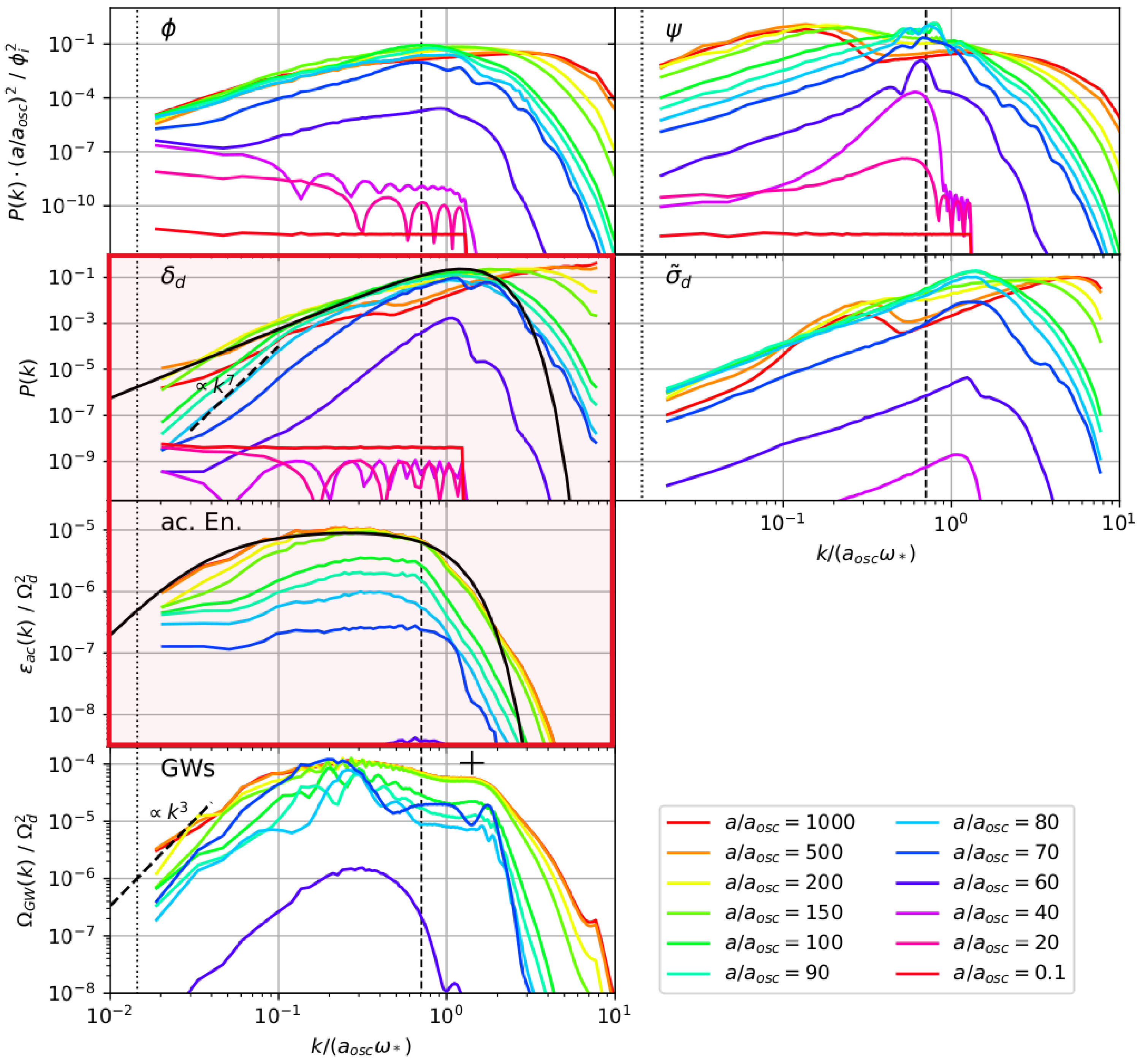


Fluctuations in fields:

Energy fluctuations + shear:

Accoustic energy:

Gravity Waves:



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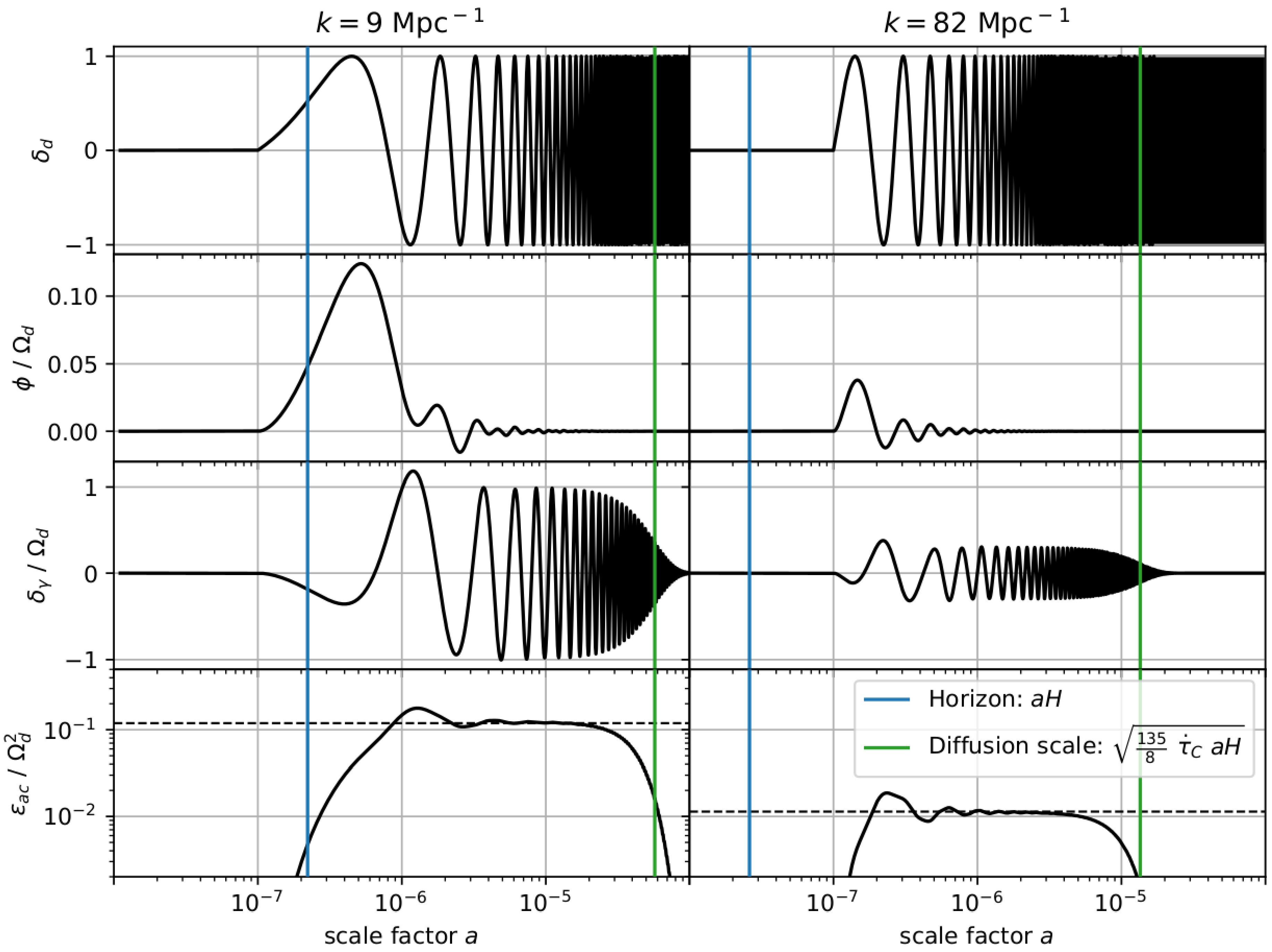
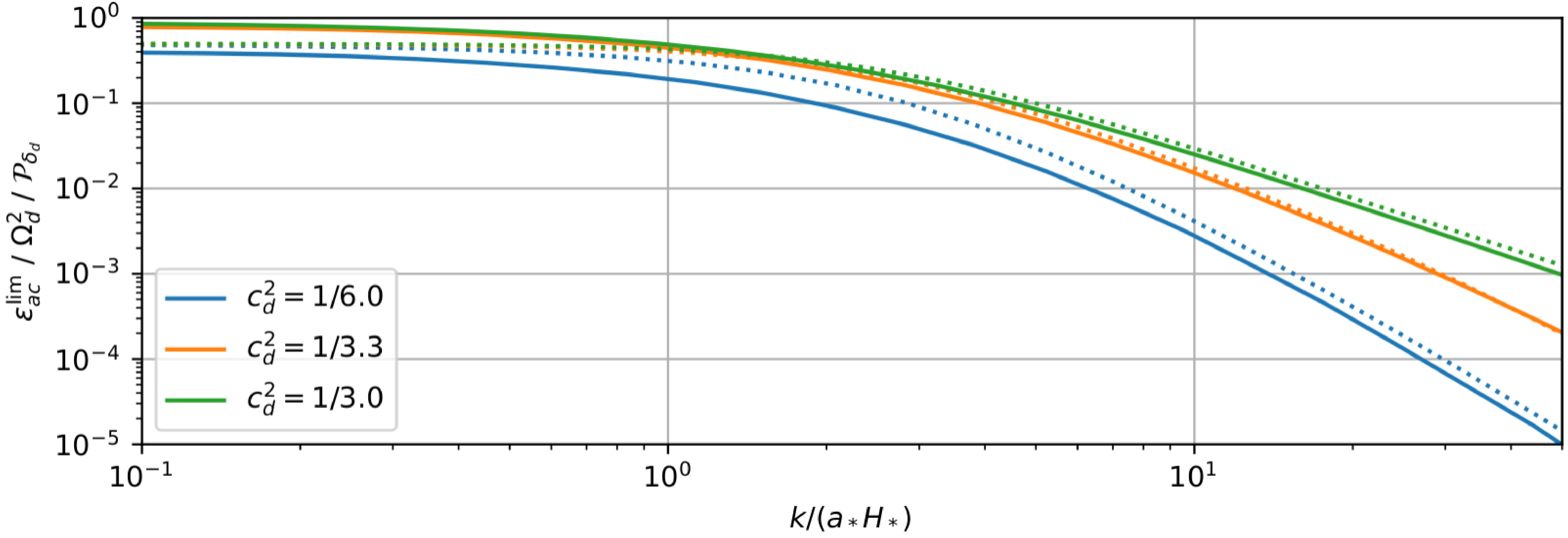
Amplitude of fluctuations: $\langle \delta_d^2 \rangle = A_{\delta_d}$

Ansatz for spatial structure:

$$\langle \delta_d(\mathbf{x}) \delta_d(\mathbf{y}) \rangle = A_{\delta_d} \exp\left(-\frac{|\mathbf{x}-\mathbf{y}|^2 k_*^2}{2} \right) \quad \Longrightarrow \quad \mathcal{P}_{\delta_d}(k) = A_{\delta_d} \sqrt{\frac{2}{\pi}} \frac{k^3}{k_*^3} \exp\left(-\frac{k^2}{2k_*^2} \right)$$

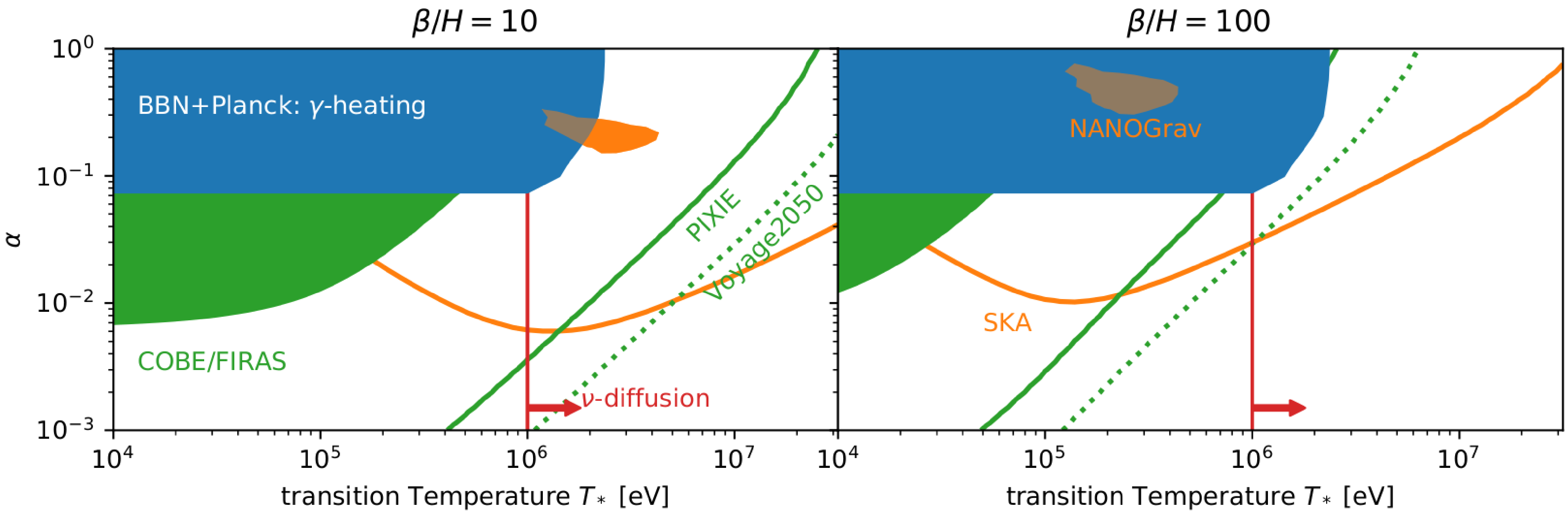


$k = 9$ Mpc^{-1}
$k = 82$ Mpc^{-1}
δ_d
ϕ / Ω_d
δ_γ / Ω_d
ε_{ac} / Ω_d^2
1
0
−1
0.10
0.05
0.00
10^{-1}
10^{-2}
10^{-7}
10^{-6}
10^{-5}
scale factor a
Horizon: aH
Diffusion scale: $\sqrt{\frac{135}{8}\ \dot{\tau}_C\ aH}$

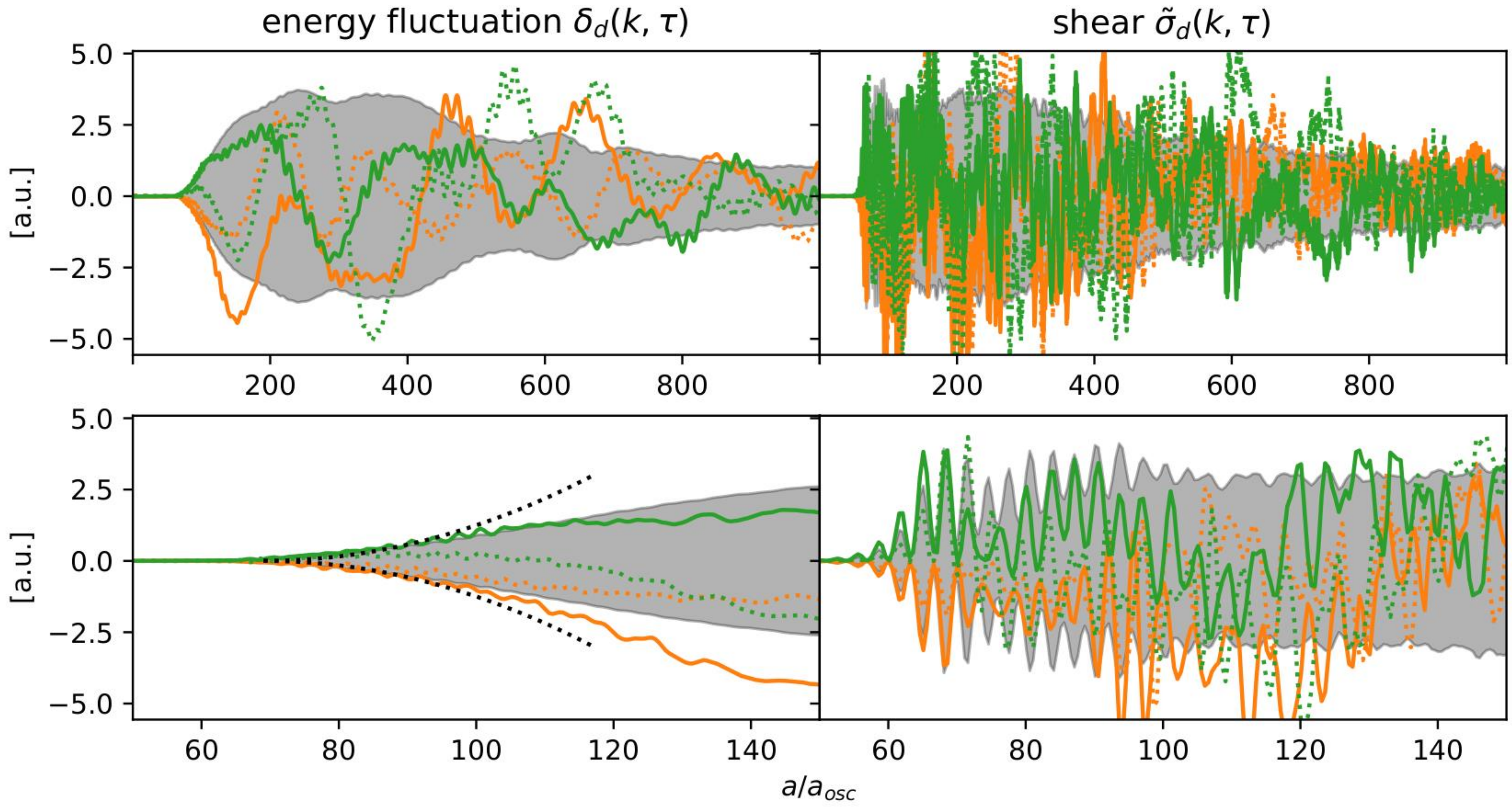


$\varepsilon_{ac}^{\lim}$ / Ω_d^2 / $\mathcal{P}_{\delta_d}$
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-1}
10^0
10^1
$k/(a_* H_*)$
$c_d^2 = 1/6.0$
$c_d^2 = 1/3.3$
$c_d^2 = 1/3.0$

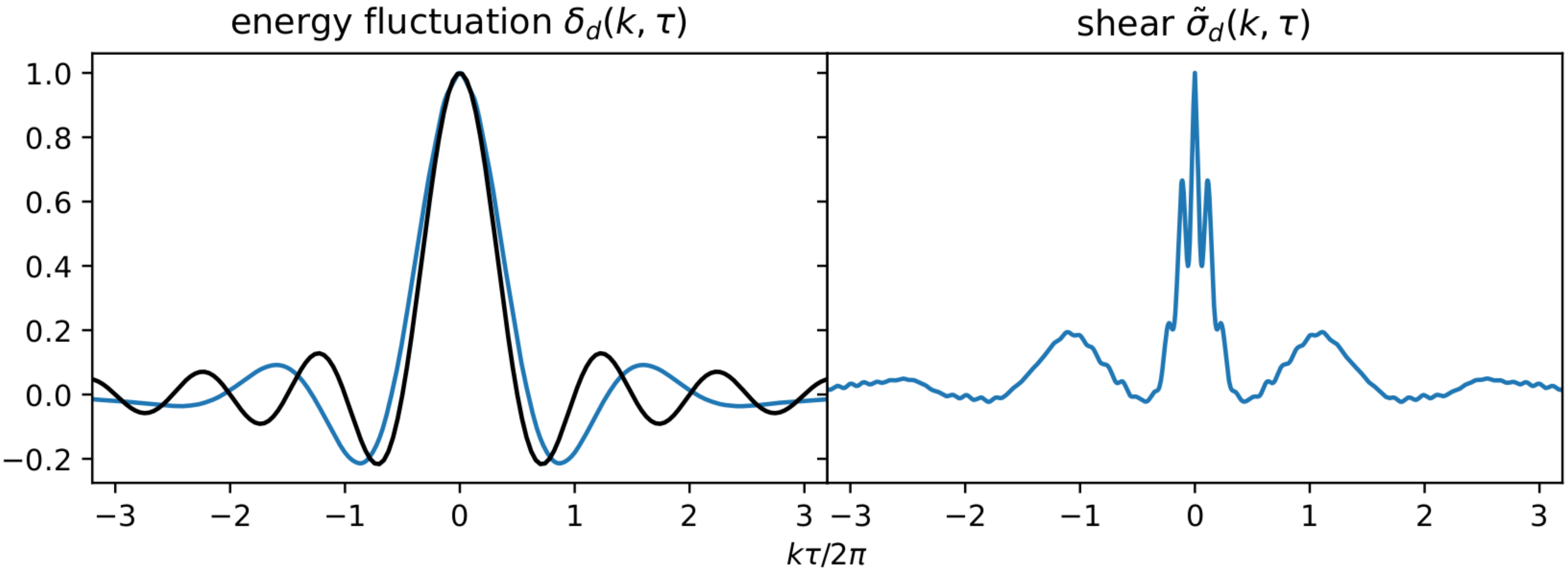
1st order PT, direct acoustic waves



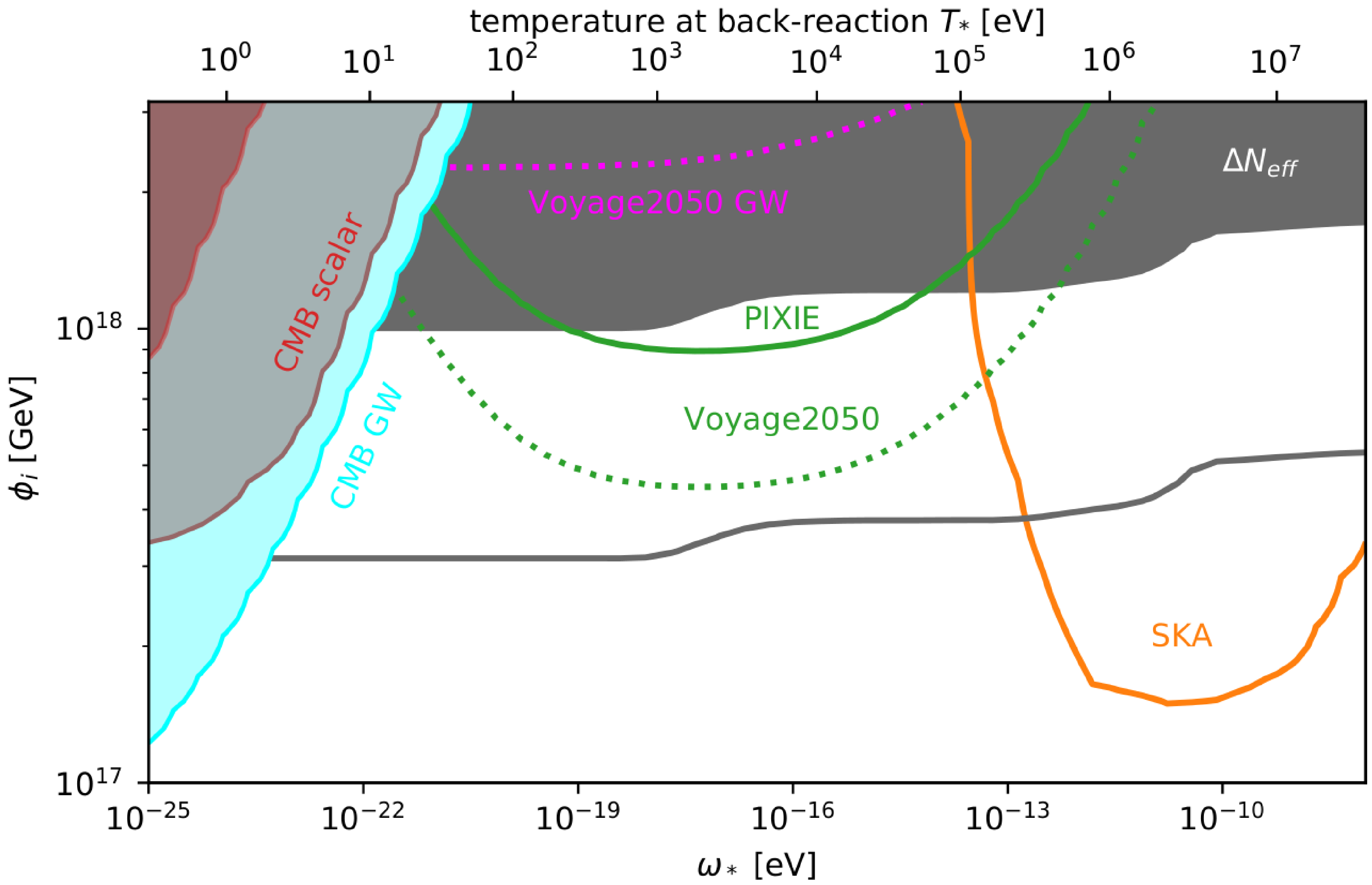
Evolution of fluctuations



Autocorrelation of fluctuations



Phi^4


temperature at back-reaction T_* [eV]
10^0
10^1
10^2
10^3
10^4
10^5
10^6
10^7
ΔN_{eff}
Voyage2050 GW
CMB scalar
PIXIE
Voyage2050
CMB GW
SKA
ϕ_i [GeV]
10^{18}
10^{17}
10^{-25}
10^{-22}
10^{-19}
10^{-16}
10^{-13}
10^{-10}
ω_* [eV]