Isocurvature bounds on ALP DM

Thomas Schwetz

based on Enander, Pargner, TS, 1708.04466
Feix, Frank, Pargner, Reischke, Schäfer, TS, 1903.06194
Feix, Hagstotz, Pargner, Reischke, Schäfer, TS, in prep.

LDMA'19 — Venice, Italy, 20-22 Nov 2019

Karlsruher Institut für Technologie

elusives
neutrinos, dark matter &

Axion-like particles (ALPs)

- pNBG boson:
  spontaneous U(1) breaking scale f_a („PQ-scale“)
  expl. U(1) breaking at Λ by exotic non-pert. effects

$$V(a) \approx \Lambda^4 \left[1 - \cos\left(\frac{a}{f_a}\right)\right], \qquad m_a^2 = \frac{\partial^2 V}{\partial a^2}\Big|_{\rm min} = \frac{\Lambda^4}{f_a^2}$$

- parametrize temperature dependence

$$m_a(T) = \min\left[\frac{\Lambda^2}{f_a},\, b\frac{\Lambda^2}{f_a}\left(\frac{\Lambda}{T}\right)^n\right]$$

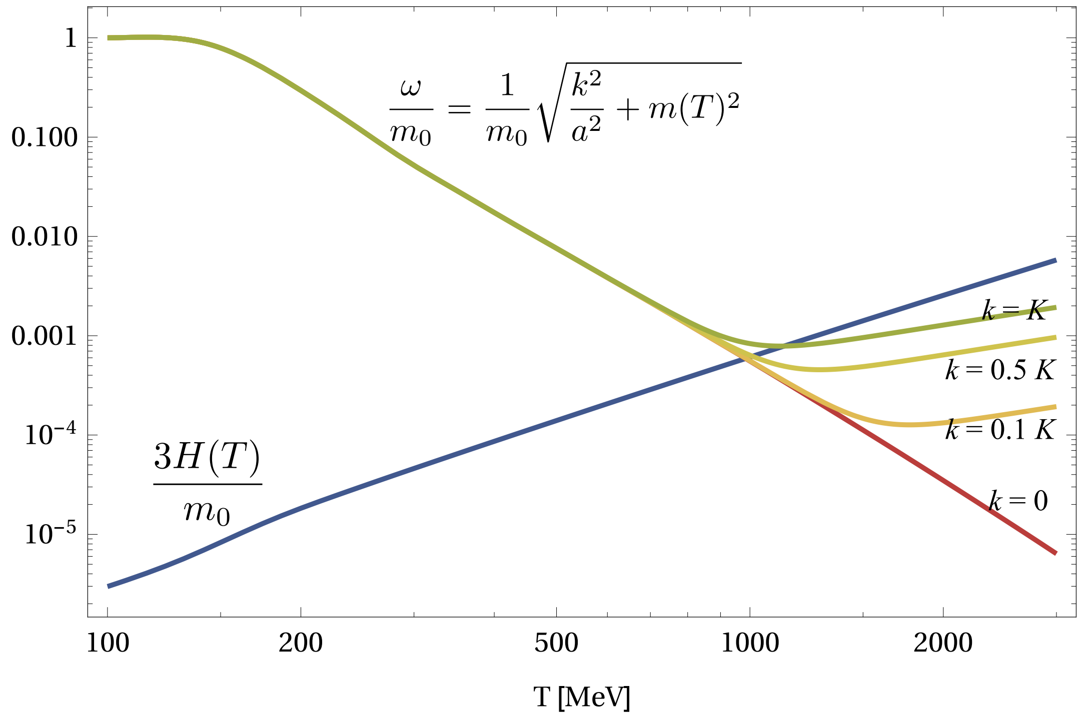
- QCD axion for: $\Lambda = 75.5~\mathrm{MeV},\ b = 10,\ n = 4$

Cosmological evolution

small field values → harmonic approx for potential: $V(\theta, T) \approx \frac{1}{2} m^2(T)\theta^2$

$$\ddot{\theta}_k + 3H(T)\dot{\theta}_k + \omega^2\theta_k = 0 \qquad \omega^2 = \frac{k^2}{a^2} + m(T)^2$$

- modes outside the horizon $3H(T) > \omega$:
  over-damped oscillator, field frozen: $\theta_k = const$
- modes inside the horizon $3H(T) < \omega$:
  oscillator with frequency ω, amplitude decays with expansion
  relativistic modes are red shifted relative to non-relativistic modes



- initial conditions depend crucially on PQ-symmetry breaking happening during or after inflation

Adiabatic vs isocurvature fluctuations

- density contrast in component i = DM, b, γ

$$\delta_i = \frac{\rho_i - \overline{\rho}_i}{\overline{\rho}_i}$$

- decompose DM fluctuations

$$\delta_{\rm DM} = \delta_{\rm DM}^{ad} + \delta_{\rm DM}^{iso}$$

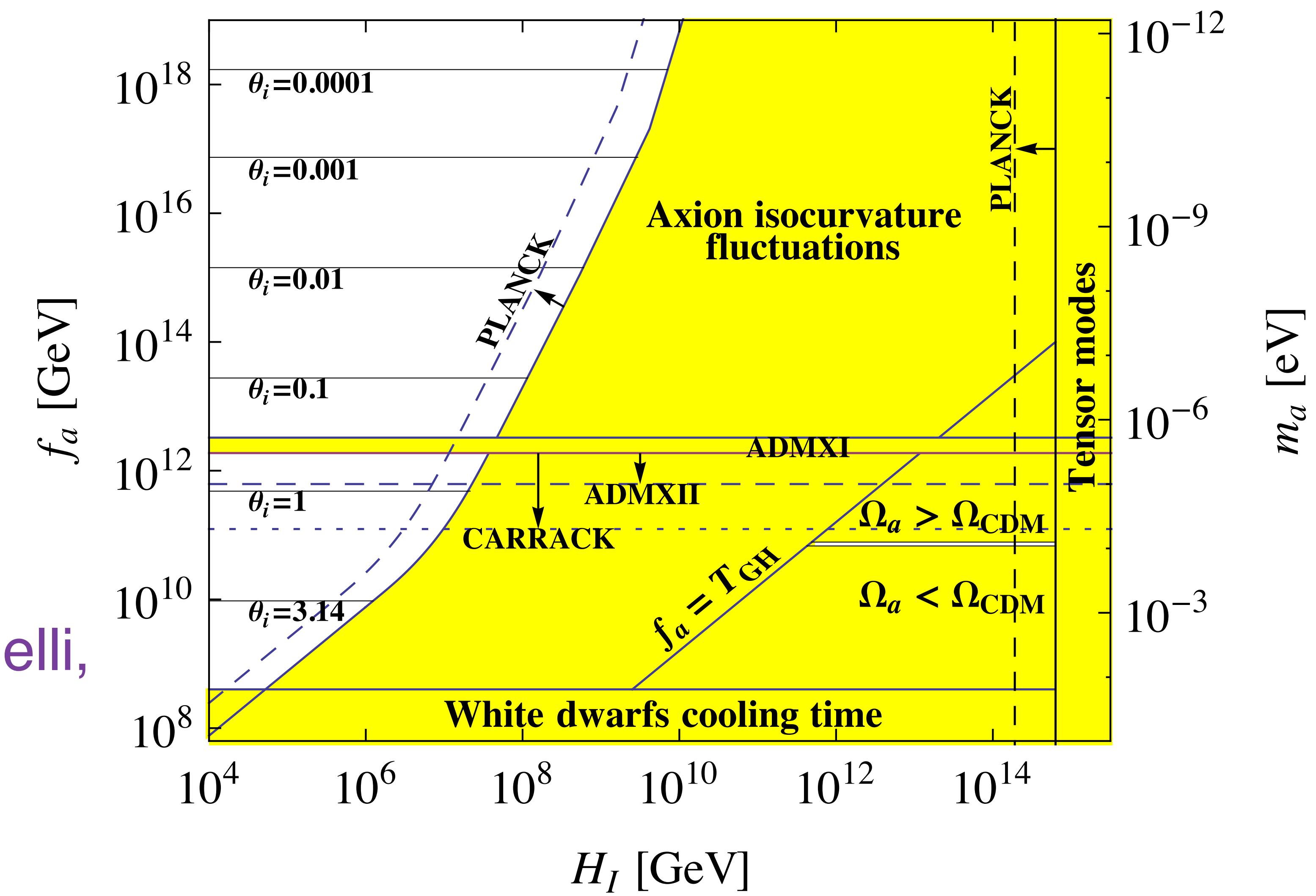
$$\delta_{\rm DM}^{ad} = \frac{3}{4}\delta_\gamma \quad , \qquad \delta_{\rm DM}^{iso} = \delta_{\rm DM} - \frac{3}{4}\delta_\gamma$$

- adiabatic and isocurvature fluctuations evolve differently
- constraints from CMB on isocurvature component
  (< few % at CMB scales)

pre-inflationary case

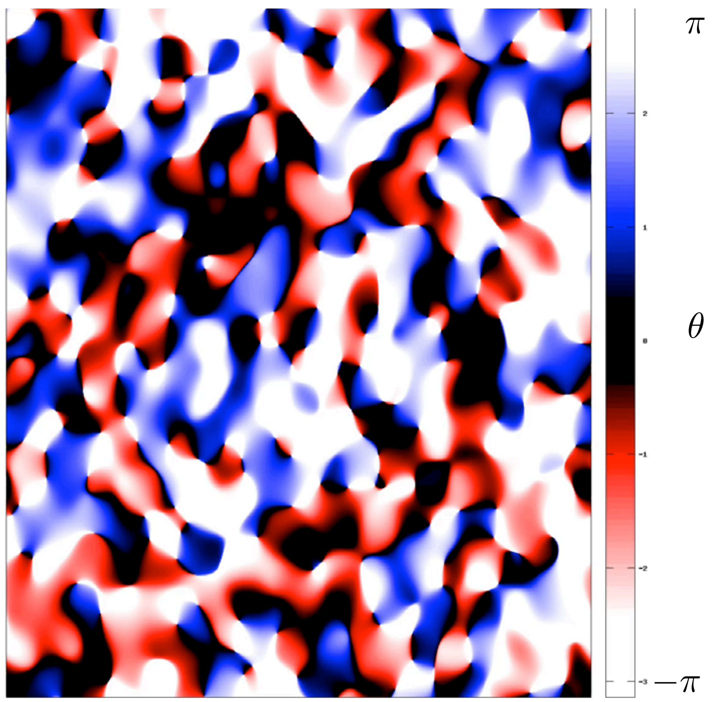
- PQ symmetry gets broken during inflation
- inflaton and axion are present simultaneously → generation of isocurvature fluctuations
  e.g. Turner Wilczek, 91; Lyth, 92

Gondolo, Visinelli, 0903.4377



This talk: post-inflationary scenario

- ALP field takes random values in causally disconnected regions
- random values of periodic field → cosmic strings
- Kibble mechanism:
  `scaling´ of string network: roughly one string per Hubble volume during expansion of Universe



J. Redondo

- Before onset of field oscillations remains
  ~ one string per Hubble volume and $\langle \theta(\vec{x})^2 \rangle = \pi^2/3$

Klaer, Moore, 1708.07521; Gorghetto, Hardy, Villadoro, 1806.04677

Initial condition

- axion field smooth on scales < horizon
  uncorrelated on scales > horizon
- assume power spectrum for axion field w Gaussian cut-off

$$\langle \theta_k \theta^*_{k'} \rangle = (2\pi)^3 \, \delta^3(\vec{k} - \vec{k}') P_\theta(k)$$

$$\boxed{P_\theta^{\rm G}(k) = \frac{8\pi^4}{3\sqrt{\pi}K^3} \exp\left(-\frac{k^2}{K^2}\right)}$$

- normalization: fixed by flat distribution $\langle \theta(\vec{x})^2 \rangle = \pi^2/3$
- cut-off: comoving horizon wave-number
  shortly before field starts oscillating: $K = a_i H_i$

Axion energy density

$$\rho(\vec{x}) = \frac{f_{\rm PQ}^2}{2}\left[\dot{\theta}^2 - \frac{1}{a^2}(\vec{\nabla}\theta)^2 + m^2\,(T)\,\theta^2\right]$$

$$\theta_k(a) = \theta_k\, f_k(a)$$

- go to Fourier space for field

$$\rho(\vec{x}) = \frac{1}{(2\pi)^6}\frac{f_{\rm PQ}^2}{2}\int d^3k d^3k'\,\theta_k\theta^*_{k'}F(k,k')e^{-i\vec{x}(\vec{k}-\vec{k}')}$$

$$F(k,k') = \dot{f}_k\dot{f}_{k'} + \left(\frac{\vec{k}\cdot\vec{k}'}{a^2} + m^2\,(T)\right) f_k f_{k'}$$

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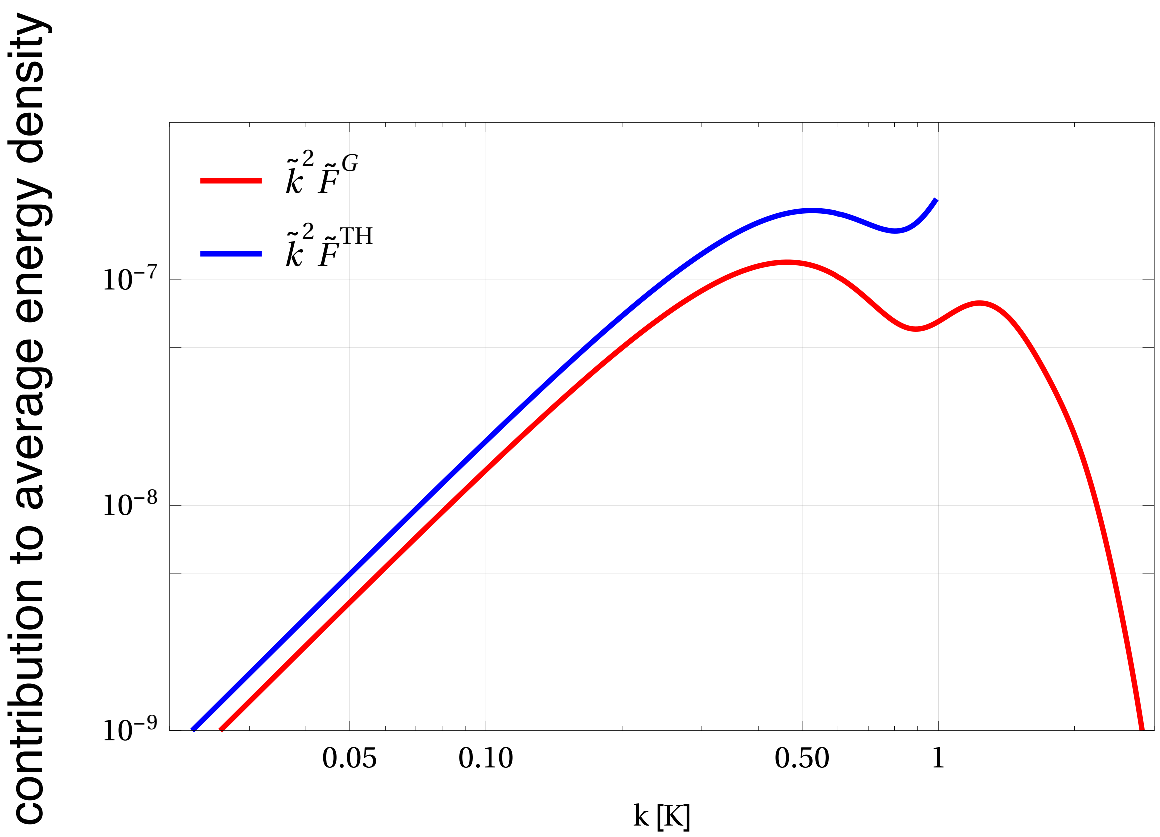
- average energy density (without string contribution):

$$\overline{\rho} \equiv \langle\rho(\vec{x})\rangle = \frac{1}{2\pi^2}\frac{f_{\rm PQ}^2}{2}\int_0^\infty dk\,k^2\,P_\theta(k)F(k,k)$$

$$F(k,k) = \dot{f}_k^2 + \omega_k^2 f_k^2$$

Axion energy density



generalizes usuall estimate:

$$\rho \sim f_a^2 m_0 m(T_{\rm osc}) \left(\frac{a_{\rm osc}}{a}\right)^3 \langle \theta^2 \rangle$$

- average energy density (without string contribution):

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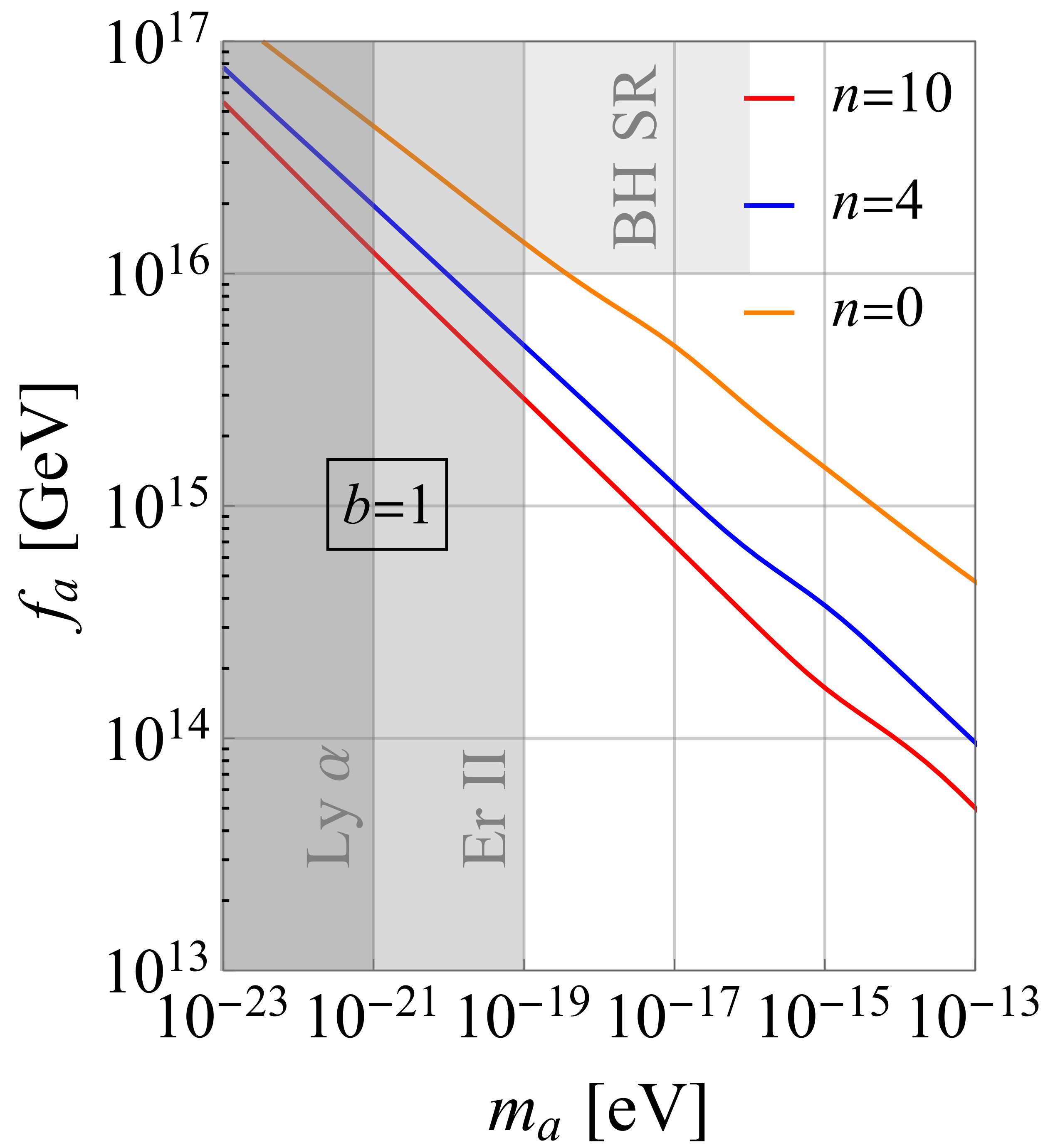
$$F(k,k) = \dot{f}_k^2 + \omega_k^2 f_k^2$$

ALP DM relic density

use DM abundance to fix f_a as a function of ALP mass

$$m_a(T) = \min\left[\frac{\Lambda^2}{f_a}, b\frac{\Lambda^2}{f_a}\left(\frac{\Lambda}{T}\right)^n\right]$$

$$m_0 = \frac{\Lambda^2}{f_a}$$



Density power spectrum

Fourier transform of the density:

$$\rho_q = \frac{1}{(2\pi)^3} \frac{f_{\rm PQ}^2}{2} \int d^3k \, \theta_k \theta^*_{k-q} F(k, k-q)$$

variance (use Wick's theorem):

$$\langle |\rho_q|^2 \rangle = \left[\frac{1}{(2\pi)^3} \frac{f_{\rm PQ}^2}{2} \right]^2 \int d^3k d^3k' \, \langle \theta_k \theta^*_{k-q} \theta^*_{k'} \theta_{k'-q} \rangle F(k, k-q) F^*(k', k'-q)$$

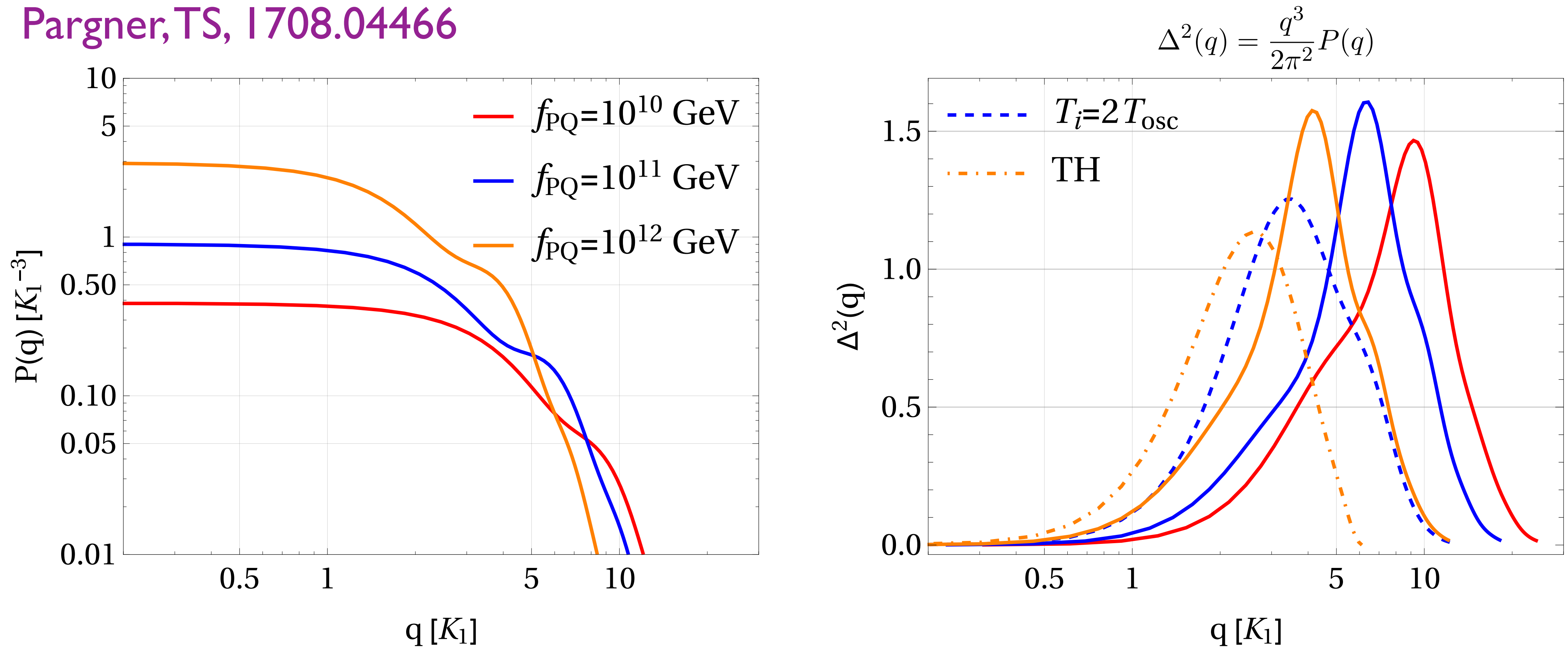
$$= 2 \frac{V}{(2\pi)^3} \left(\frac{f_{\rm PQ}^2}{2} \right)^2 \int d^3k \, P_\theta(|\vec{k}|) P_\theta(|\vec{k} - \vec{q}|) \, F(k, k-q)^2$$

this gives for the power spectrum

$$P(q) = \frac{1}{V} \frac{\langle |\rho_q|^2 \rangle}{\overline{\rho}^2} = 2(2\pi)^3 \frac{\int d^3k \, P_\theta(|\vec{k}|) P_\theta(|\vec{k} - \vec{q}|) \, F(k, k-q)^2}{\left[\int d^3k \, P_\theta(k) F(k, k) \right]^2}$$

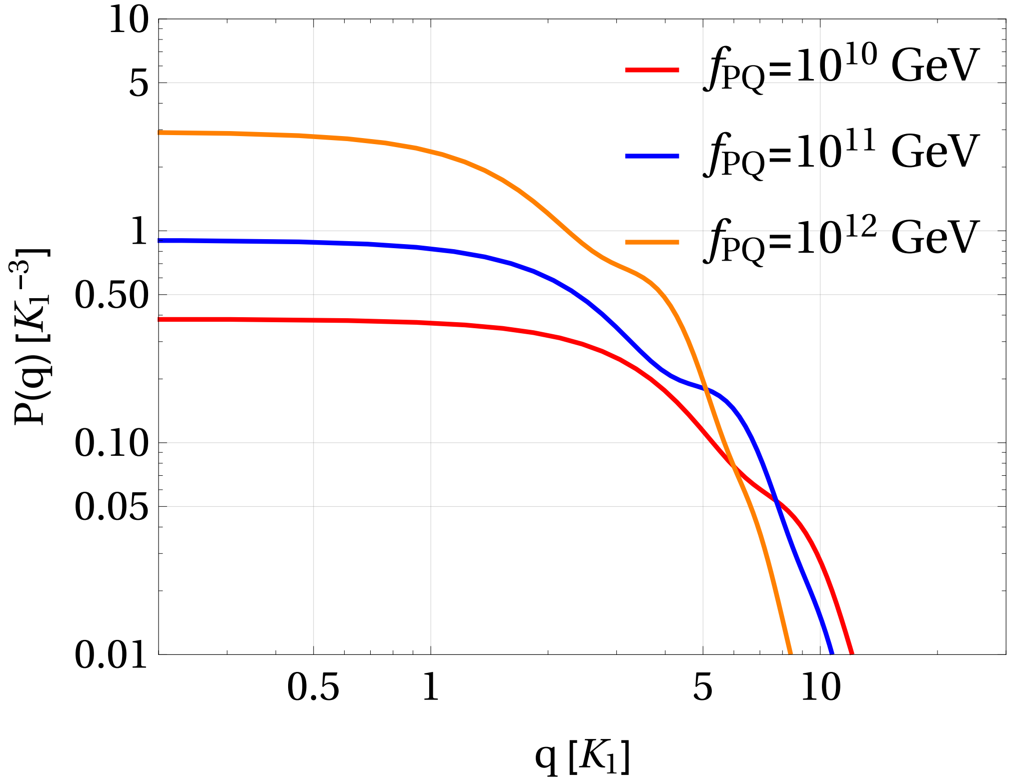
Density power spectrum

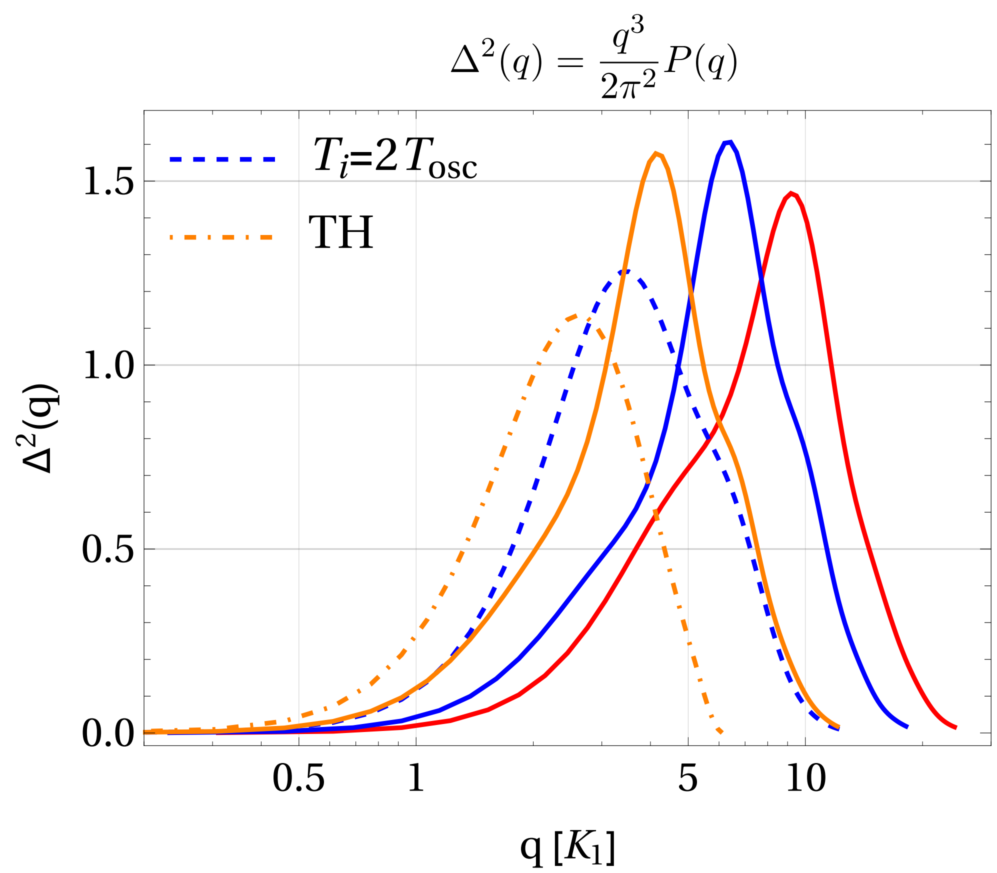
Enander, Pargner, TS, 1708.04466



- density fluctuations of order one
- charact. size a few times smaller than horizon @ T_{osc}
- formation of grav. bound objects (mini cluster) Hogan, Rees, 1988

Density power spectrum





$$K \equiv a_{osc} H(T_{osc})$$

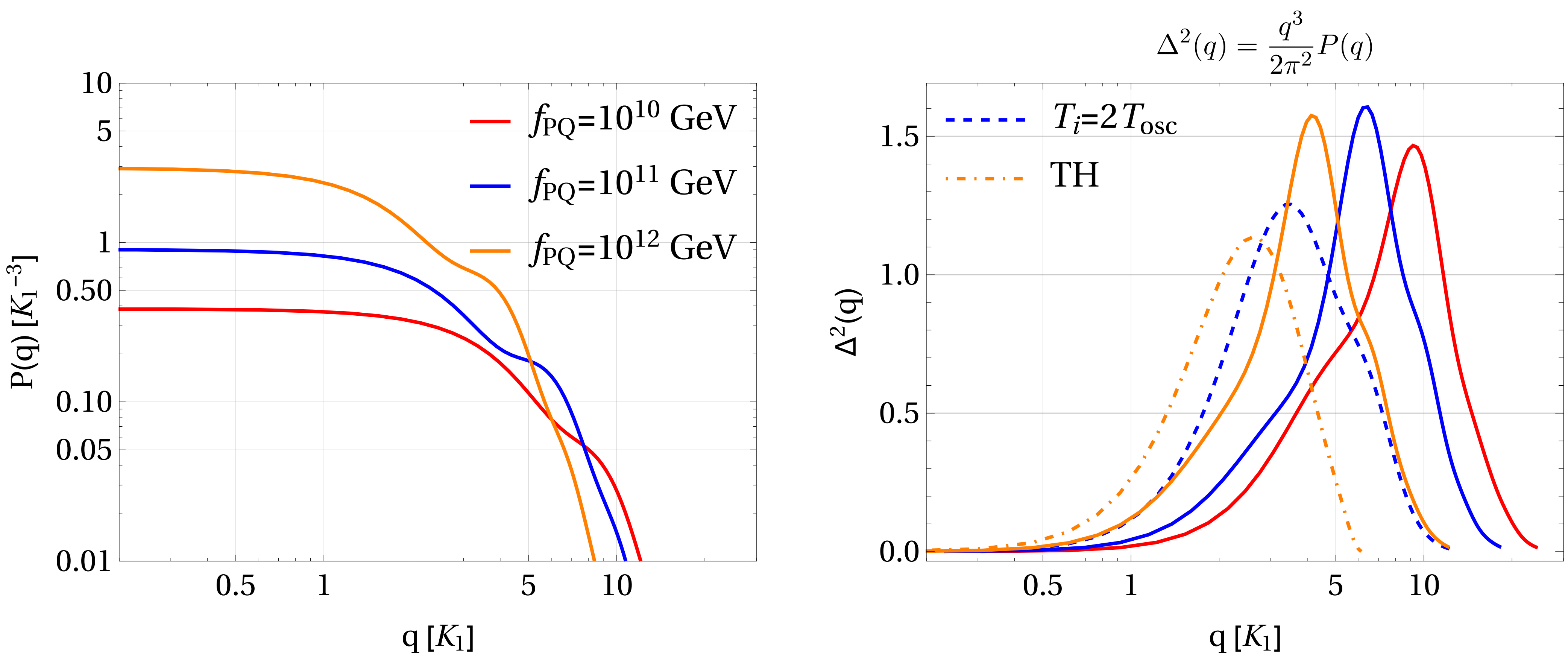
$$\Delta^2(k) \approx C \left(\frac{k}{K}\right)^3$$

$$P(k) \approx \frac{2\pi^2 C}{K^3}$$

$$k \ll K$$

- white noise power spectrum for small k
- fluctuations linear for $k << K$
- coeff. C ≈ 0.04 - 0.3 obtained by fitting to numerical results for P(k)

Density power spectrum



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$$\Delta^2(k) \approx C \left(\frac{k}{K}\right)^3 \qquad k \ll K$$

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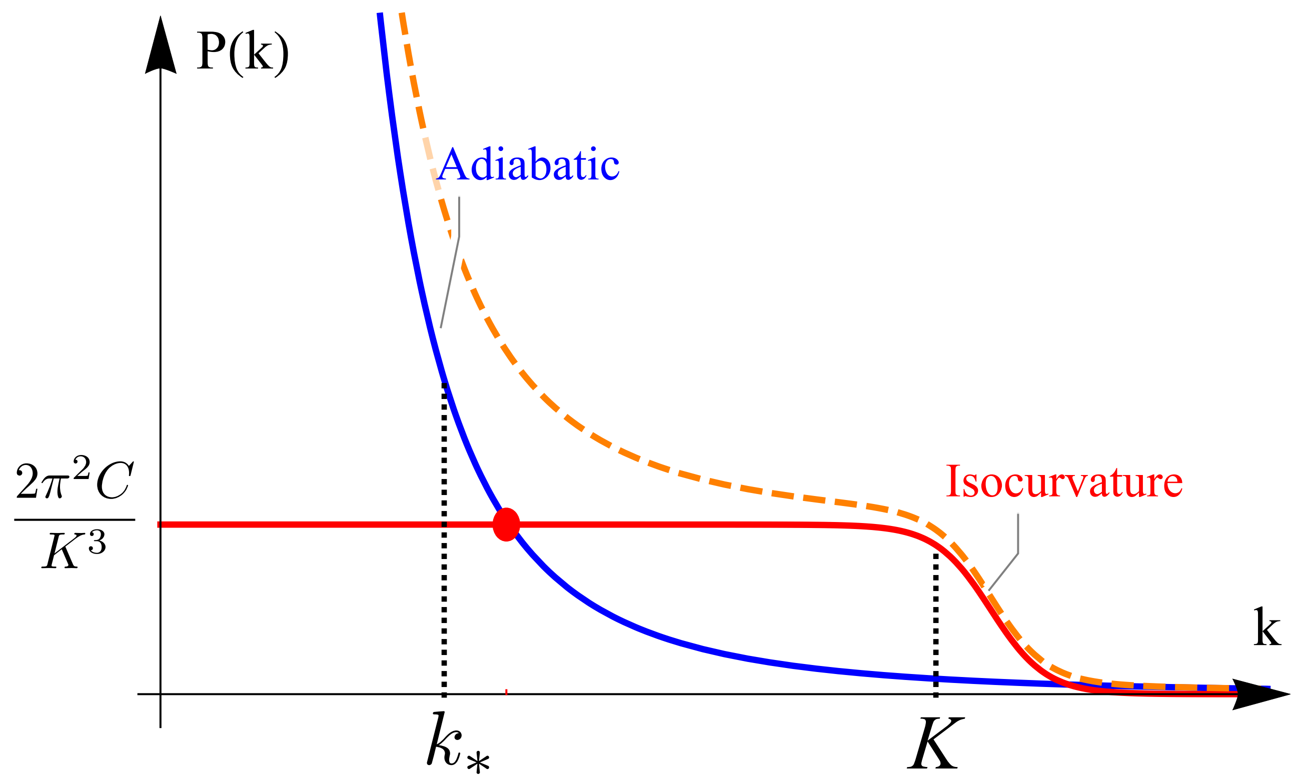
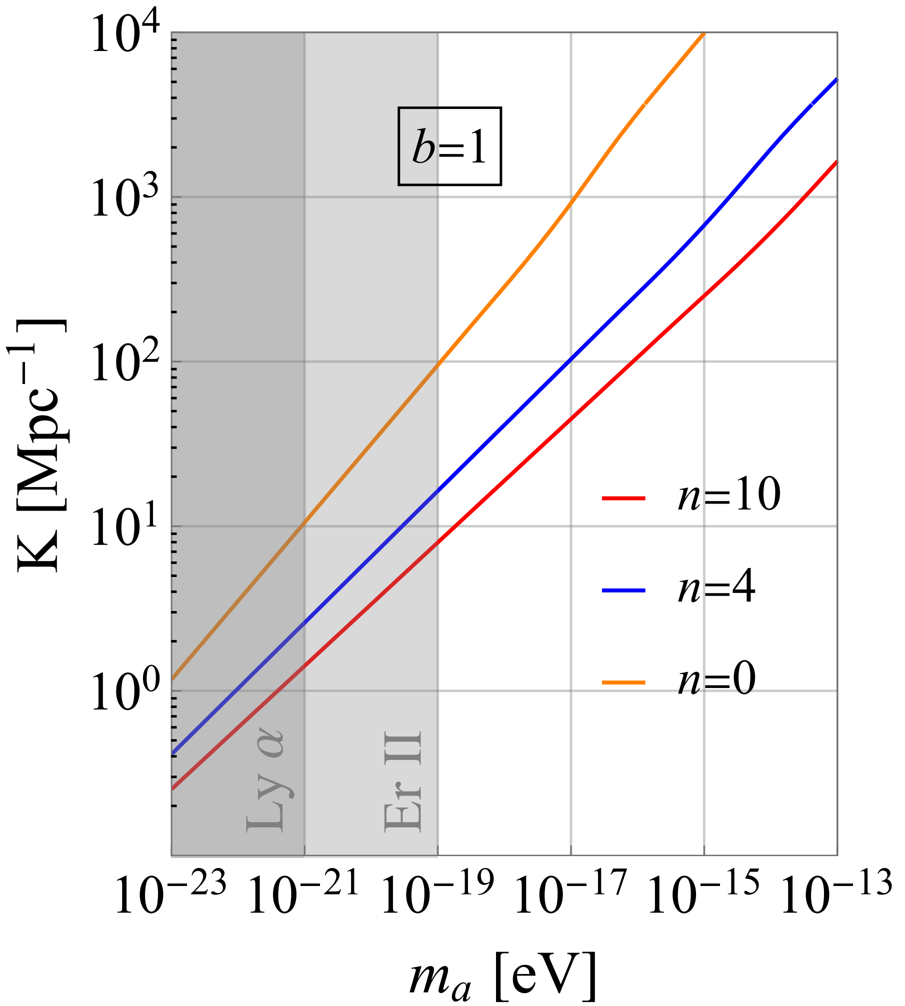
- expect qualitative similar result including topological defects and the periodic potential
- allow for factor 5 uncertainty from comparison with simulations (incl. strings) Vaquero, Redondo, Stadler, 1809.09241

Isocurvature fluctuations from post-inflationary ALP DM





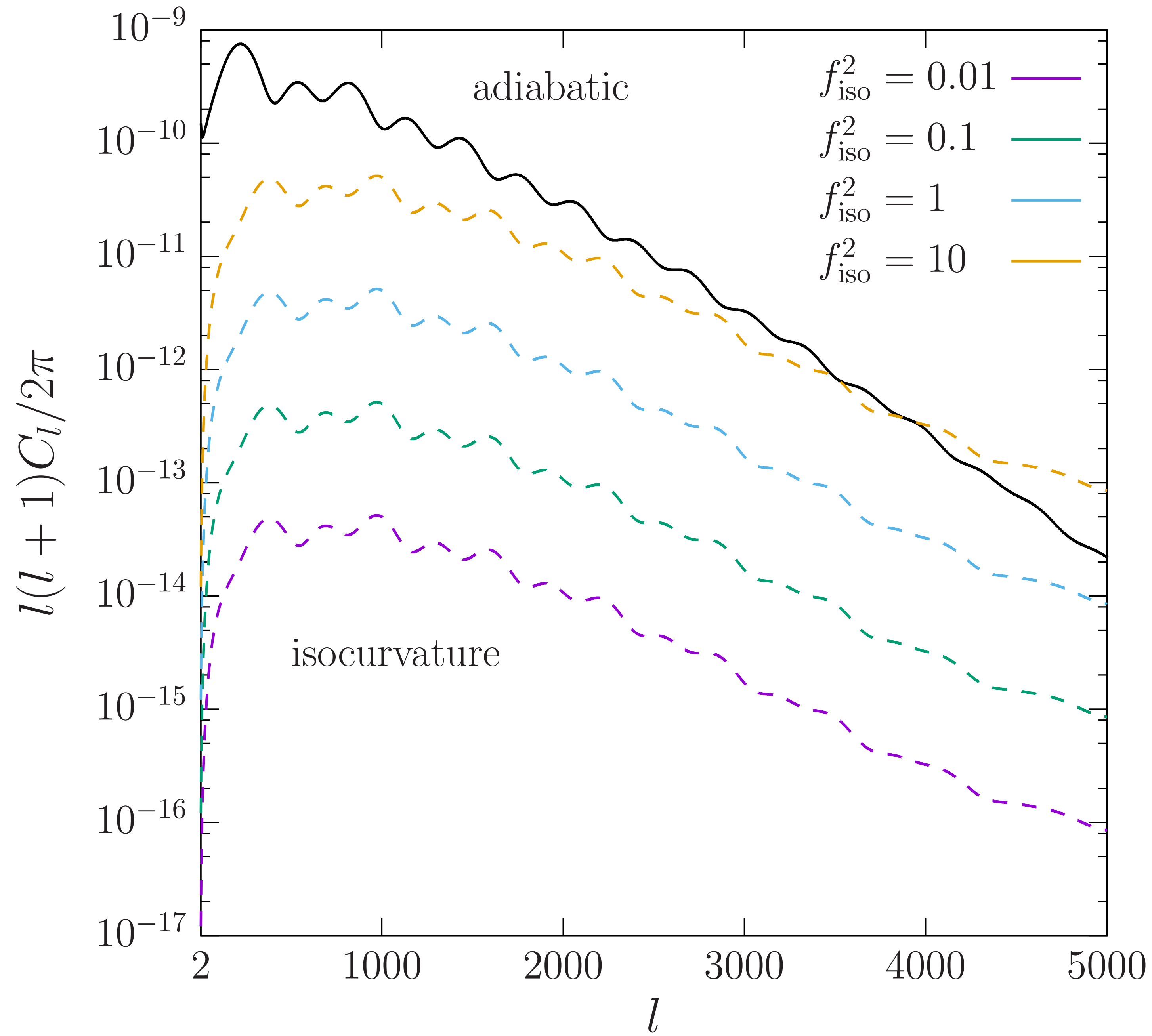
$$f_{\rm iso}^2 \equiv \left.\frac{P_{\rm iso}(k)}{P_{\rm ad}(k)}\right|_{k_*} \quad , \qquad \Delta^2_{\rm ad}(k) = \frac{k^3}{2\pi^2} P_{\rm ad}(k) = A_s \left(\frac{k}{k_*}\right)^{n_s - 1}$$

$$k_* = 0.05 \ {\rm Mpc}^{-1}$$

$$\Rightarrow \qquad f_{\rm iso} \approx \sqrt{\frac{C k_*^3}{A_s K^3}}$$

White noise isocurvature fluctuations in the CMB

isocurvature component with white noise spectrum implemented in CLASS



Feix, Frank, Pargner, Reischke, Schäfer, TS, 1903.06194

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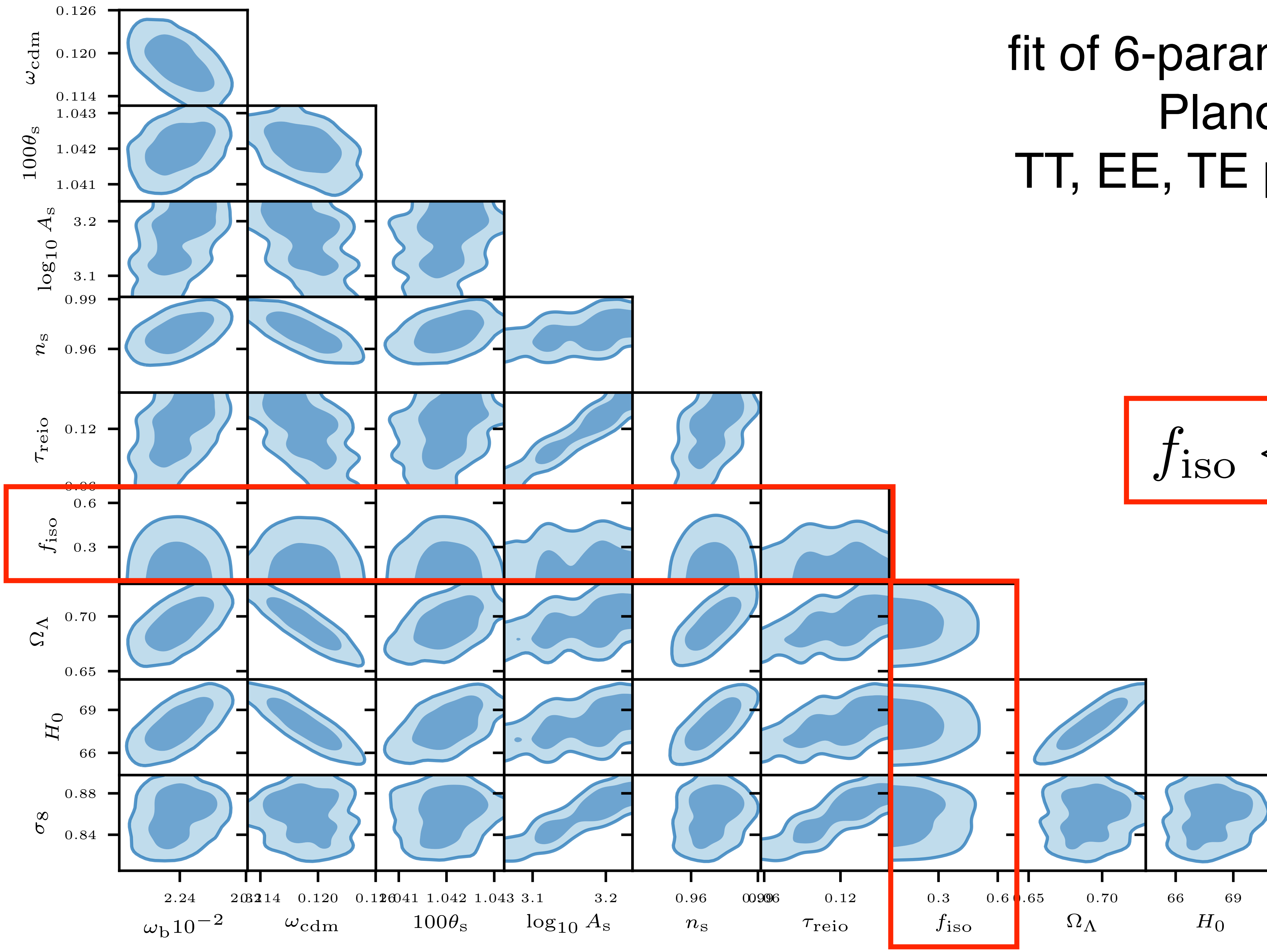
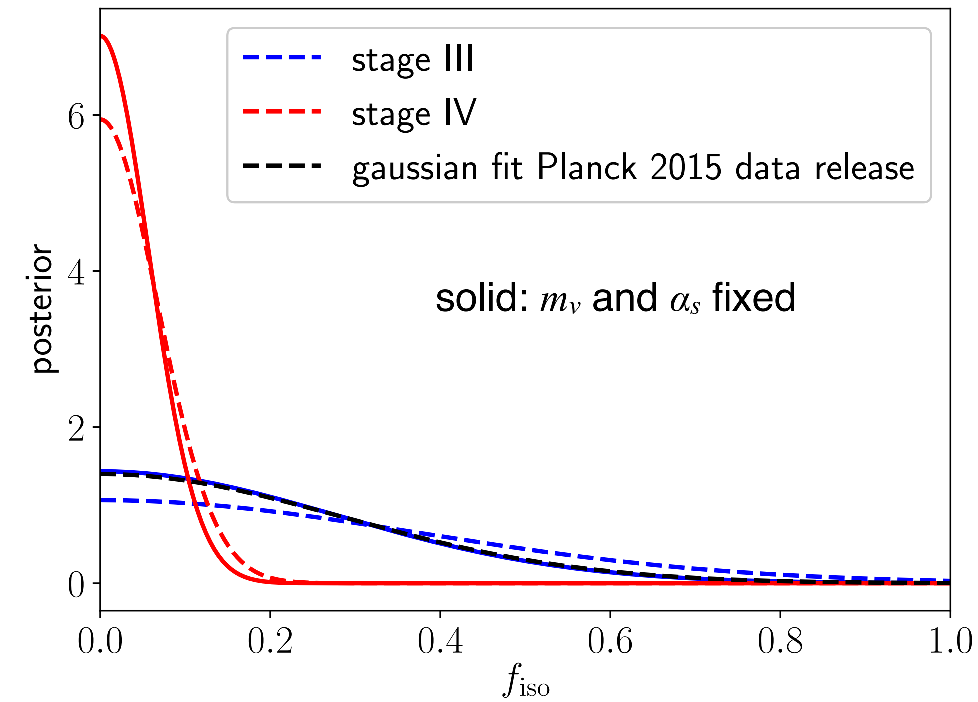


fit of 6-param LCDM + fiso
Planck 2015
TT, EE, TE power spectra

$$f_{\rm iso} < 0.31\,(2\sigma)$$

Sensitivity forecasts

- Planck-like CMB experiment (s3)
  $l = 30 - 2500$
- Stage IV CMB experiment (s4)
  $l < 5000$ (temperature & polarization)
- 21cm observations with SKA:
  900 antenas (SKA1), 3600 antenas (SKA2)
  optimistic assumptions on foregrounds
- LCDM + f_{iso} + α_s + m_ν + H_0 + x_H

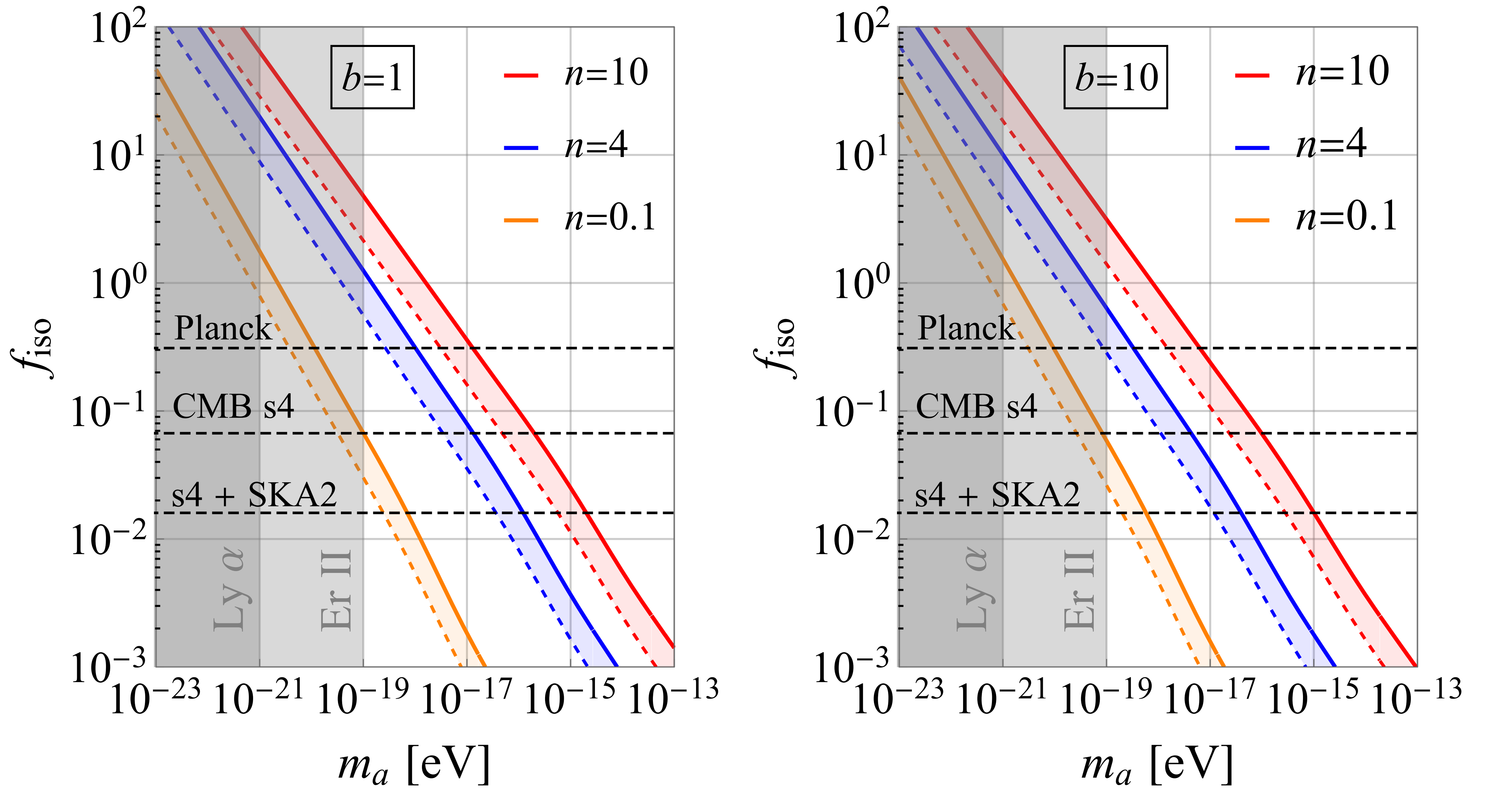


Experiment	f_{iso}	α_{s}	$\sum m_\nu$ [eV]	n_{s}	A_{s}	Ω_{b}	τ	h	Ω_{m}	$\bar{x}_H$
s3	0.38	0.0052	0.34	0.0034	0.021	0.0045	0.0045	0.032	0.038	-
s3+SKA1	0.20	0.0044	0.28	0.0031	0.021	0.0037	0.0043	0.027	0.031	0.082
s4	0.067	0.0018	0.050	0.0016	0.0080	0.00064	0.0017	0.0045	0.0053	-
s4 +SKA2	0.016	0.0017	0.042	0.0016	0.0080	0.00051	0.0017	0.0034	0.0040	0.012

1σ sens.

Feix, Frank, Pargner, Reischke, Schäfer, TS, 1903.06194

Isocurvature component for DM ALPs



Feix et al., 1903.06194

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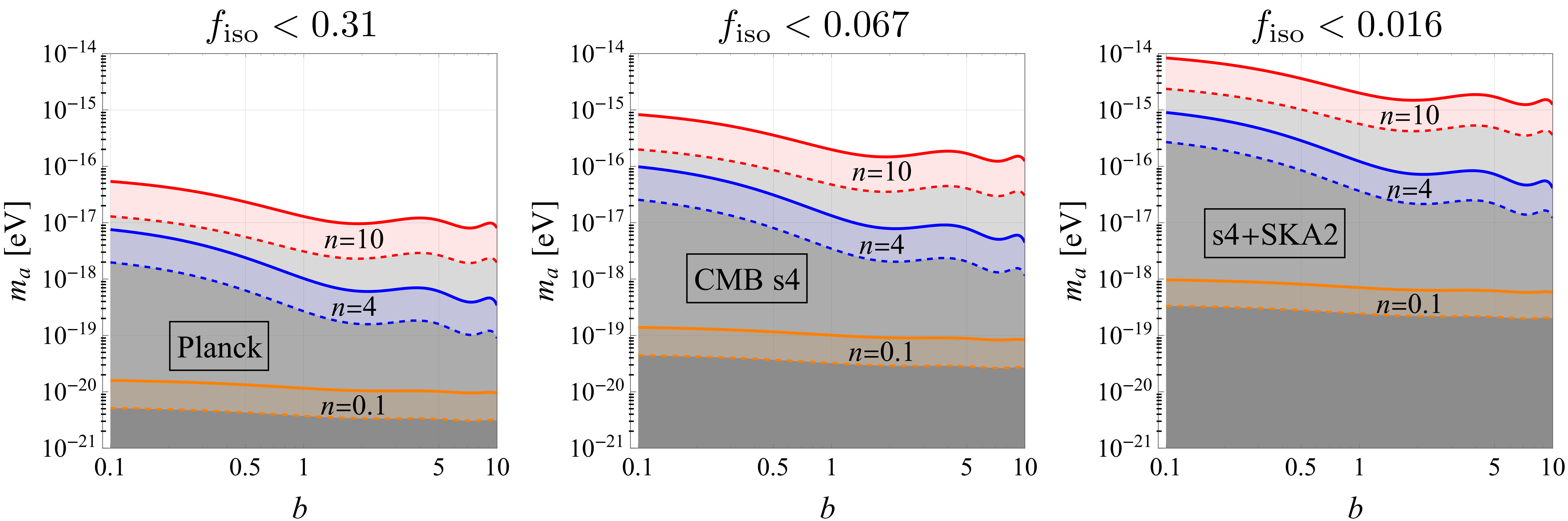
$$m_a(T) = \min\left[\frac{\Lambda^2}{f_a},\, b\frac{\Lambda^2}{f_a}\left(\frac{\Lambda}{T}\right)^n\right]$$

Lower limits on ALP mass

Planck 2015 | sensitivity forecasts



$$m_a(T) = \min\left[\frac{\Lambda^2}{f_a},\, b\frac{\Lambda^2}{f_a}\left(\frac{\Lambda}{T}\right)^n\right]$$

Feix et al., 1903.06194

Crucial assumption: post-inflationary scenario

- PQ symmetry is broken only after end of inflation or it gets restored after inflation:

$$f_a < \max\left[\frac{H_I}{2\pi}, \epsilon_{\rm eff} E_I\right] \qquad H_I^2 = \frac{8\pi}{3}\frac{E_I^4}{M_{Pl}^2}$$

e.g., Hertzberg, Tegmark, Wilczek, 0807.1726

- upper bound from non-observation of CMB tensor modes (in simple inflation models):

$$E_I < 1.7 \times 10^{16}\ \text{GeV}\ \ (95\%\ \text{CL})$$

$$\frac{H_I}{2\pi} < 10^{13}\,\text{GeV}$$

Planck, 1807.06211

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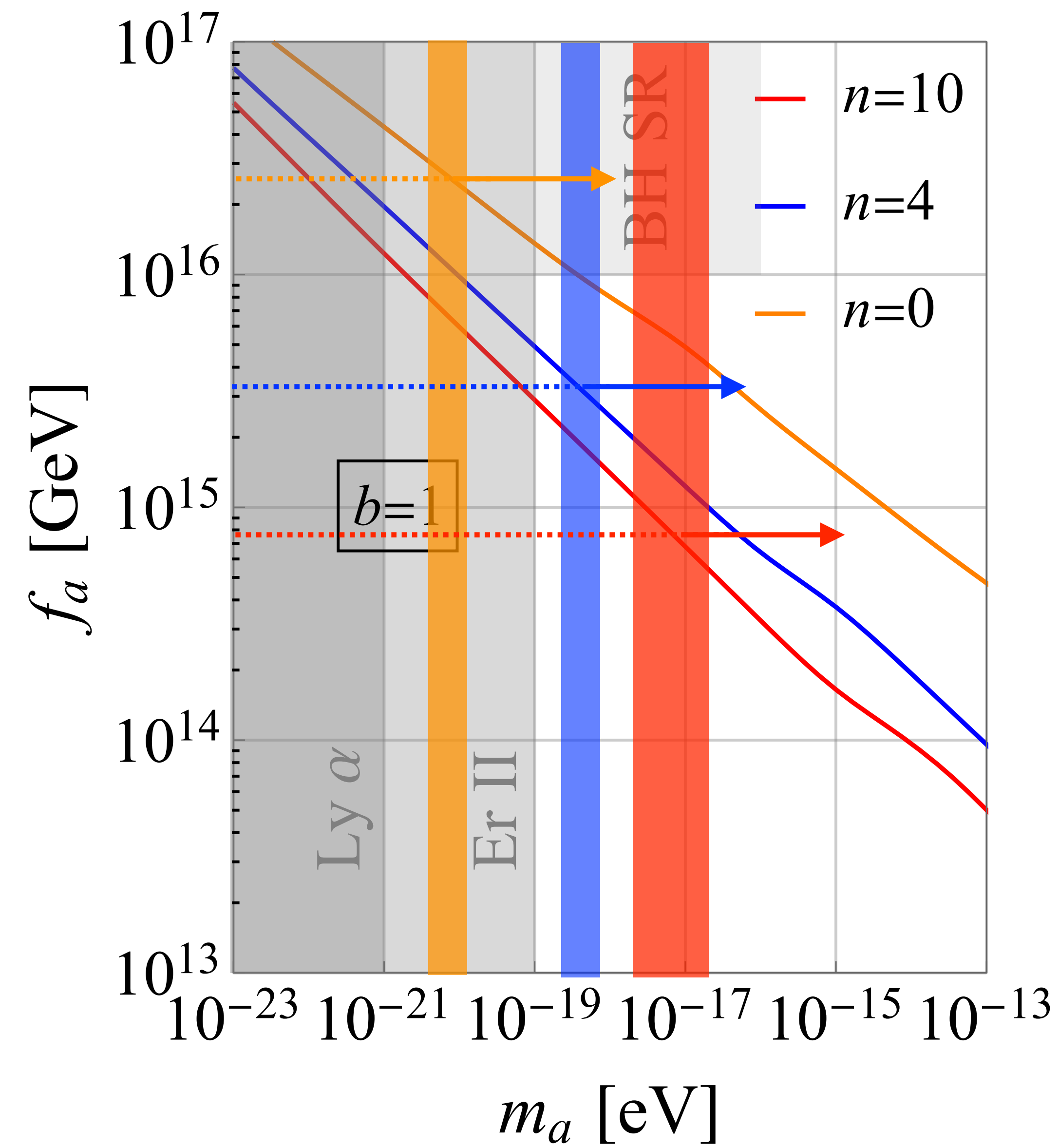
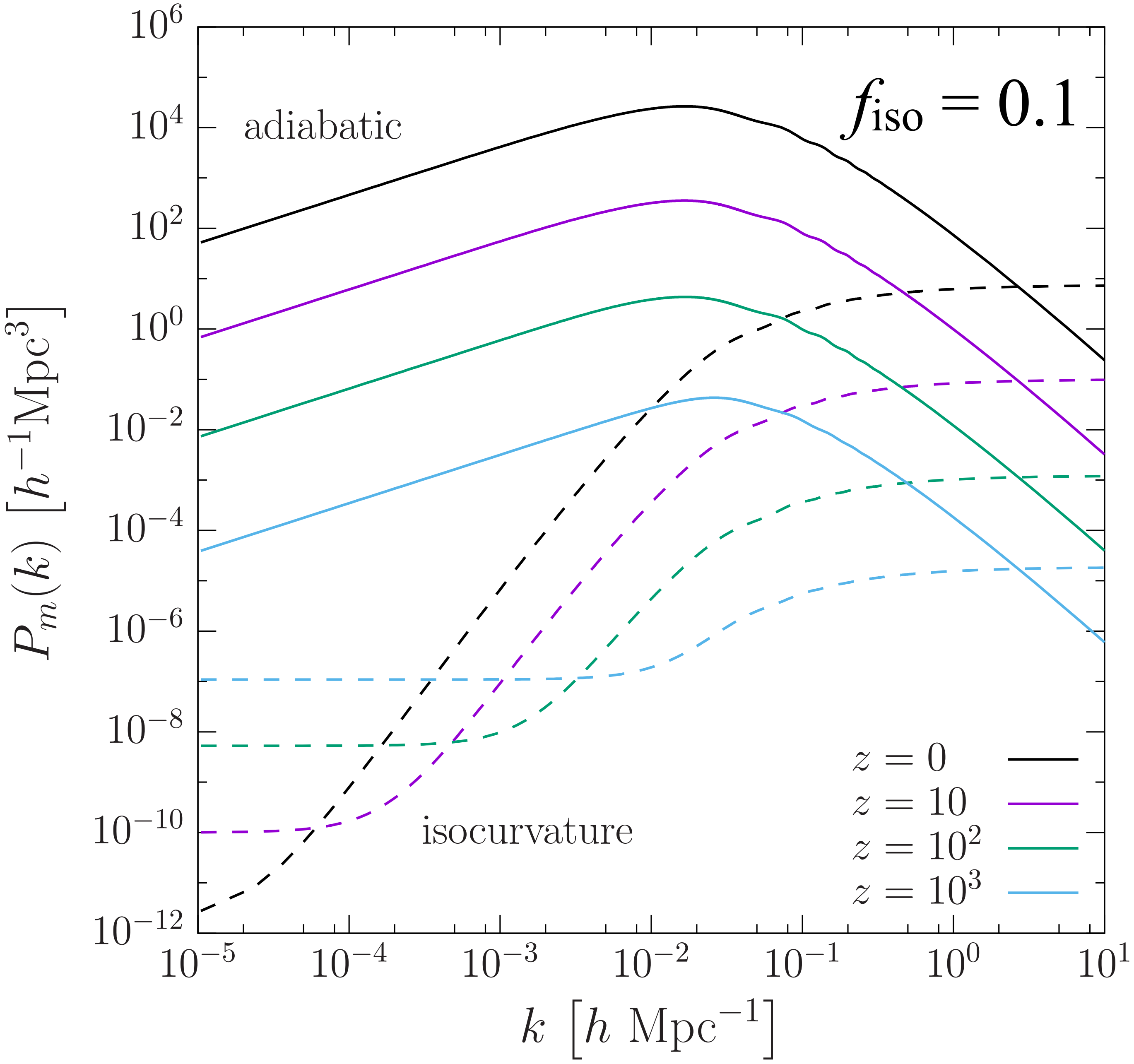


Outlook

explore signatures in the matter power spectrum



Feix et al. 1903.06194

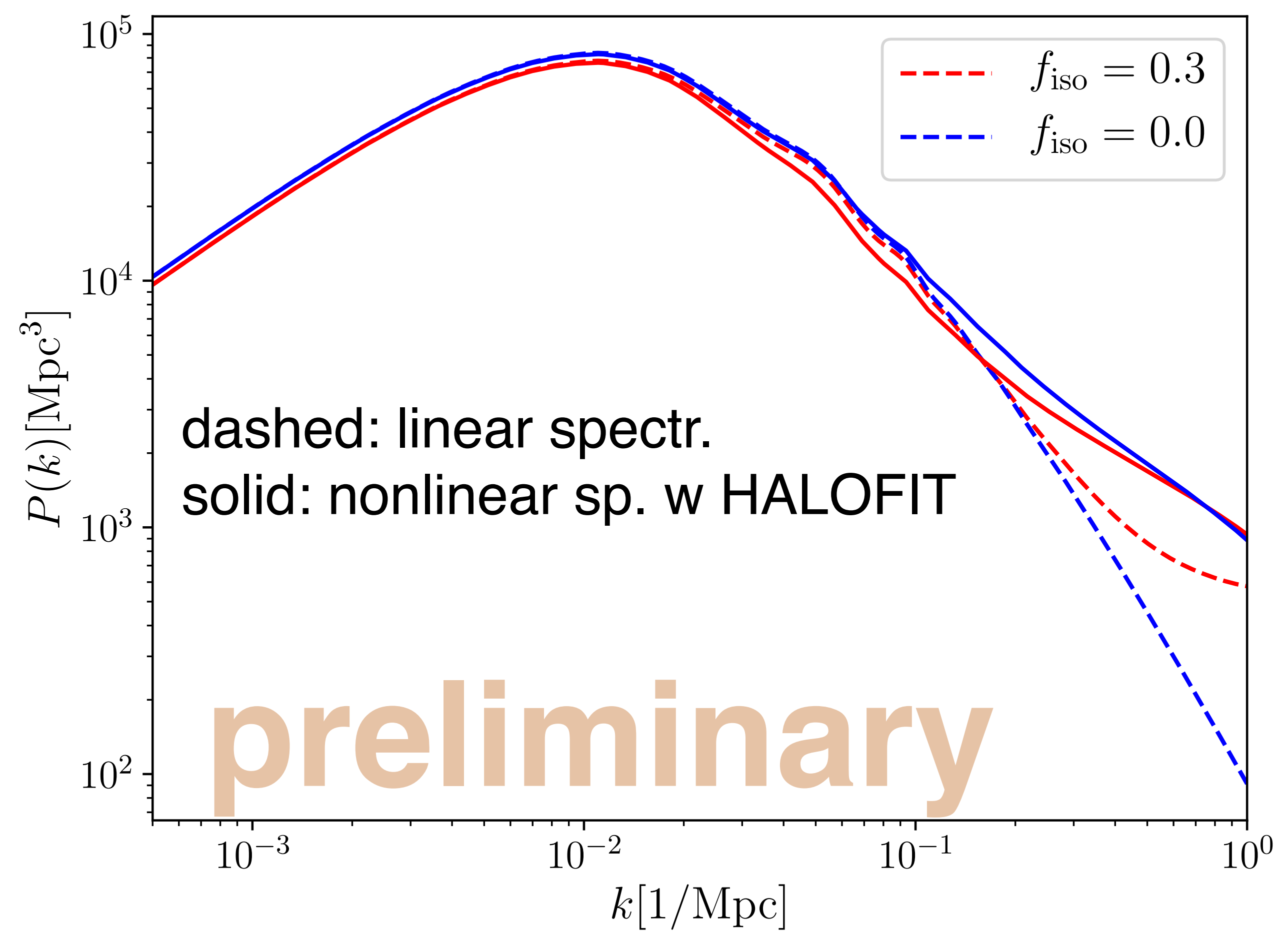
Outlook

explore signatures in the matter power spectrum

Feix, Hagstotz, Pargner, Reischke, Schäfer, TS, in prep.

- cosmic shear
- CMB lensing
- galaxy clustering
- galaxy counts

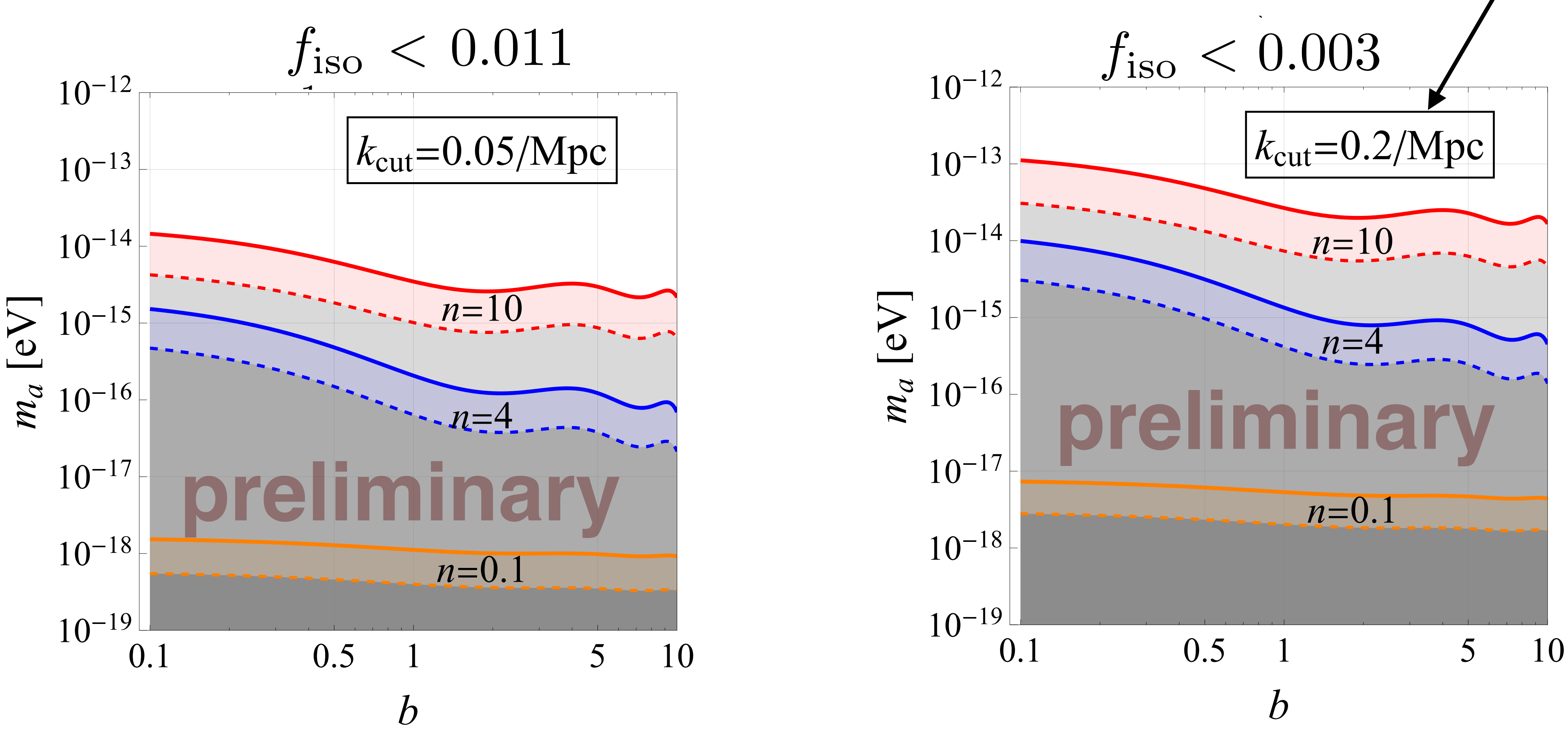
- crucial: how far can we trust linear predictions?



CMB lensing, galaxy clustering, cosmic shear

Feix, Hagstotz, Pargner, Reischke, Schäfer, TS, in prep.

optimistic assumption on non-linearities



combined sens. at 1σ from CMB lensing (S4 experiment) +
galaxy clustering & cosmic shear (EUCLID)
sensitivity dominated by **cosmic shear**

Summary

- isocurvature fluctuations are generated in post-inflationary ALP DM scenario
- white noise power spectrum with cut-off due to uncorrelated field values per Hubble patch
- lower limit on ALP mass in range 10^{-19}—10^{-16} eV from Planck CMB data (weaker limits for temp.-indep. ALP mass)
- purely gravitational effect
- significant improvement expected from S4 CMB, 21cm maps, EUCLID LSS (cosmic shear)

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Thank you for your attention!