Some new isocurvature directions

Daniel Grin (KICP Chicago)
Fermilab Particle Astrophysics Seminar
2/3/2014

Outline

✳ *Are the primordial fluctuations adiabatic?*

Isocurvature and CMB spectral distortions

Isocurvature and the axiverse

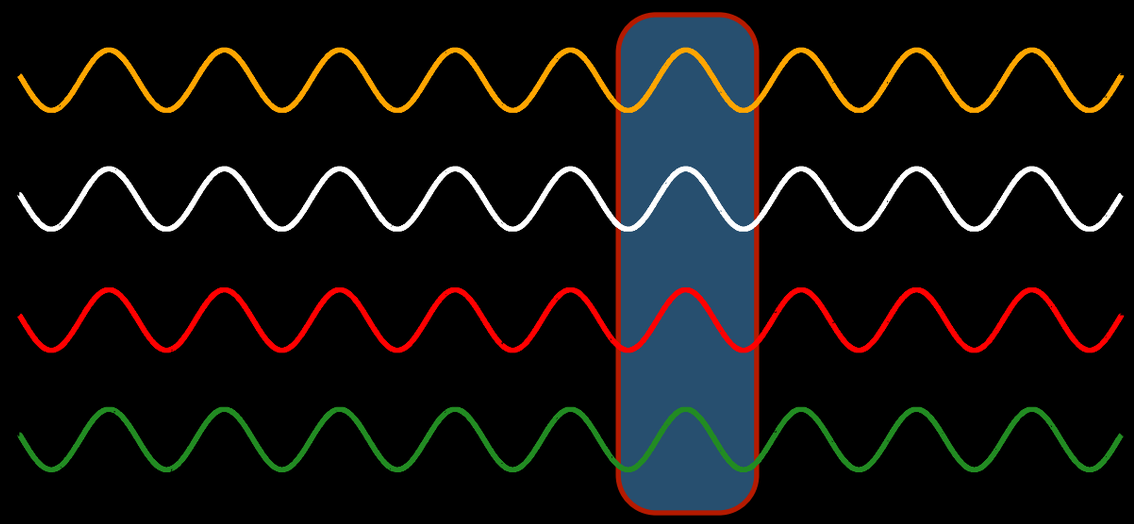
Baryon-DM isocurvature fluctuations and the CMB

CMB frequency spectrum distortions from isocurvature modes

with J.Chluba (CITA/JHU)
arXiv:1304.4596, *MNRAS 434, 1619*

Zoology of initial conditions

Adiabatic



Neutrinos
CDM
Photons
Baryons

$$S_i = 0$$

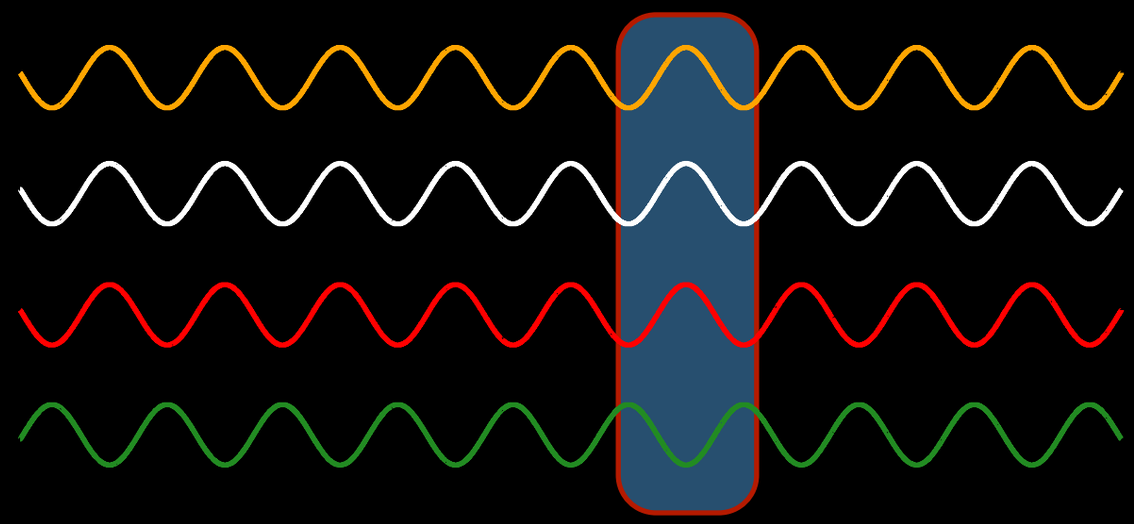
$$S_i = \frac{\delta n_i}{n_i} - \frac{\delta n_\gamma}{n_\gamma}$$

$$\nabla^2 \Phi = 4\pi G \delta\rho$$

$$ds^2 = a^2(\eta)\left\{-(1+2\Phi)\,d\eta^2 + (1-2\Phi)\,dx^i dx_j\right\}$$

Zoology of initial conditions

Baryon isocurvature



$$S_b \neq 0 \; \Delta\Phi = 0$$

$$S_i = \frac{\delta n_i}{n_i} - \frac{\delta n_\gamma}{n_\gamma}$$

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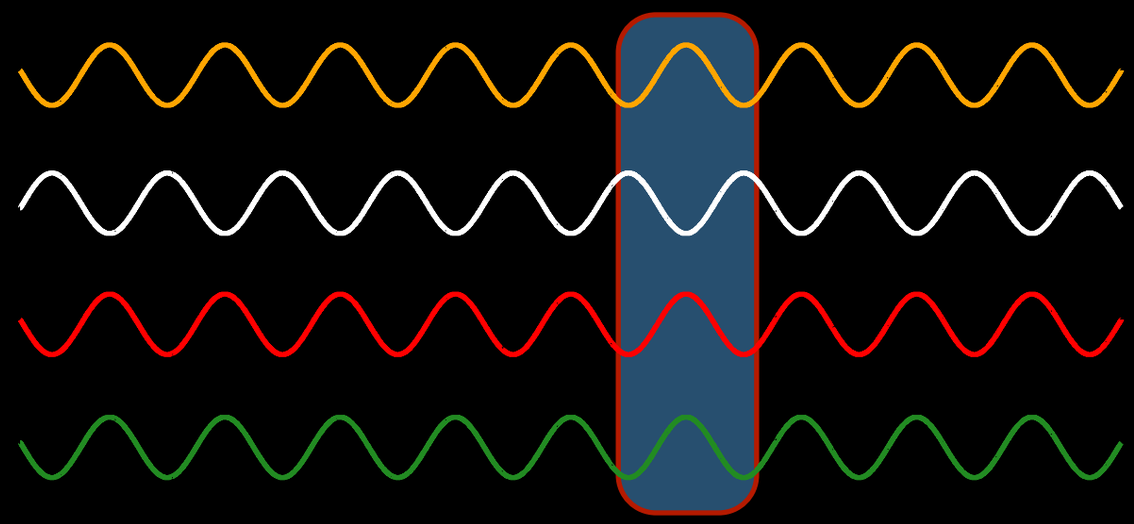
Zoology of initial conditions

CDM isocurvature



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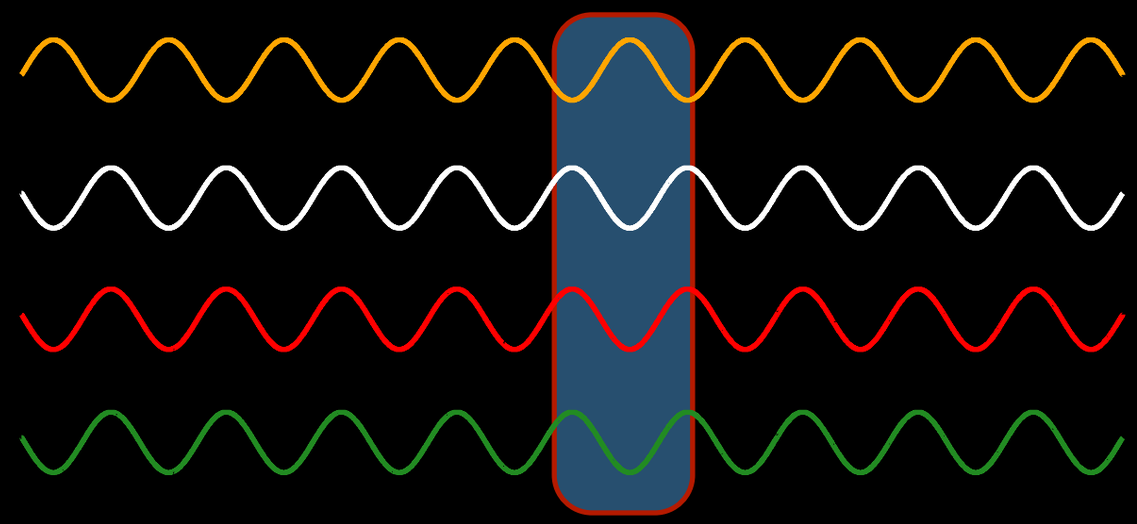
Zoology of initial conditions

ν isocurvature



Neutrinos
CDM
Photons
Baryons

$$S_\nu \neq 0 \quad \Delta\Phi = 0$$

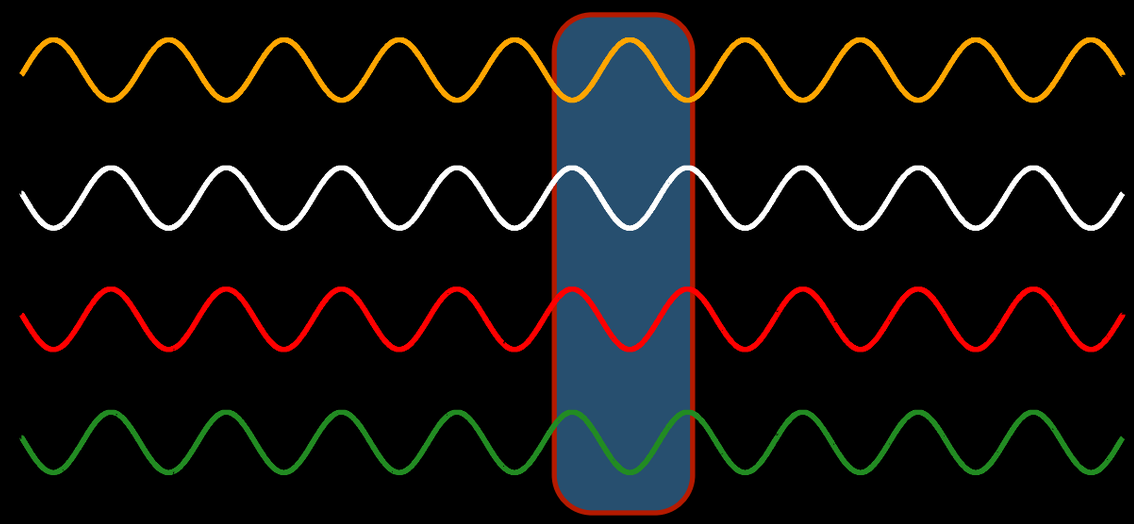
$$S_i = \frac{\delta n_i}{n_i} - \frac{\delta n_\gamma}{n_\gamma}$$

$$\nabla^2 \Phi = 4\pi G \delta\rho$$

$$ds^2 = a^2(\eta)\left\{-(1+2\Phi)\,d\eta^2 + (1-2\Phi)\,dx^i dx_j\right\}$$

Zoology of initial conditions

ν
isocurvature



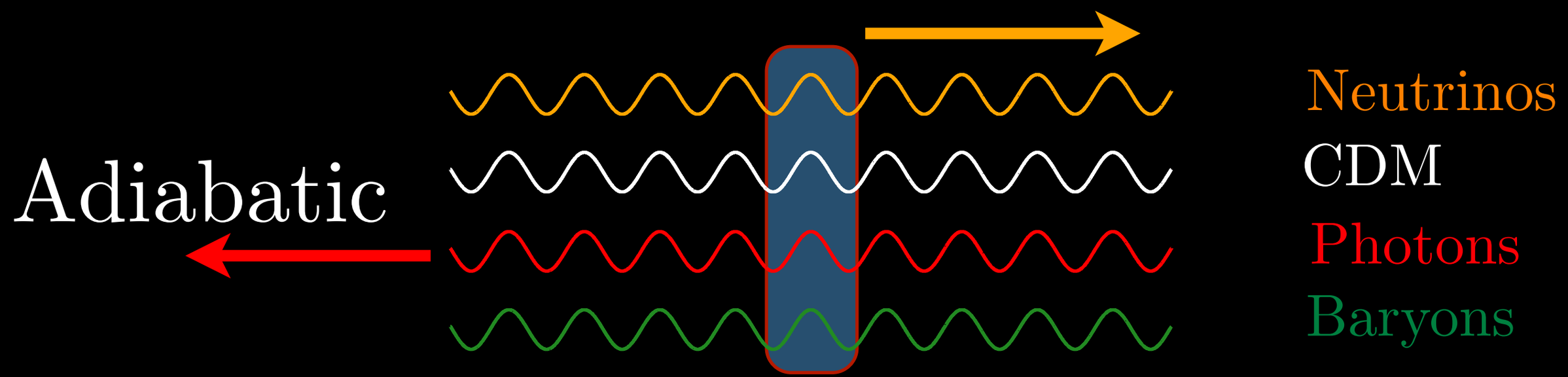
Neutrinos
CDM
Photons
Baryons

$$S_\nu \neq 0 \quad \Delta\Phi = 0$$

All density initial conditions can be expressed in terms of these!
These conditions are not conserved under fluid evolution

Velocity isocurvature modes

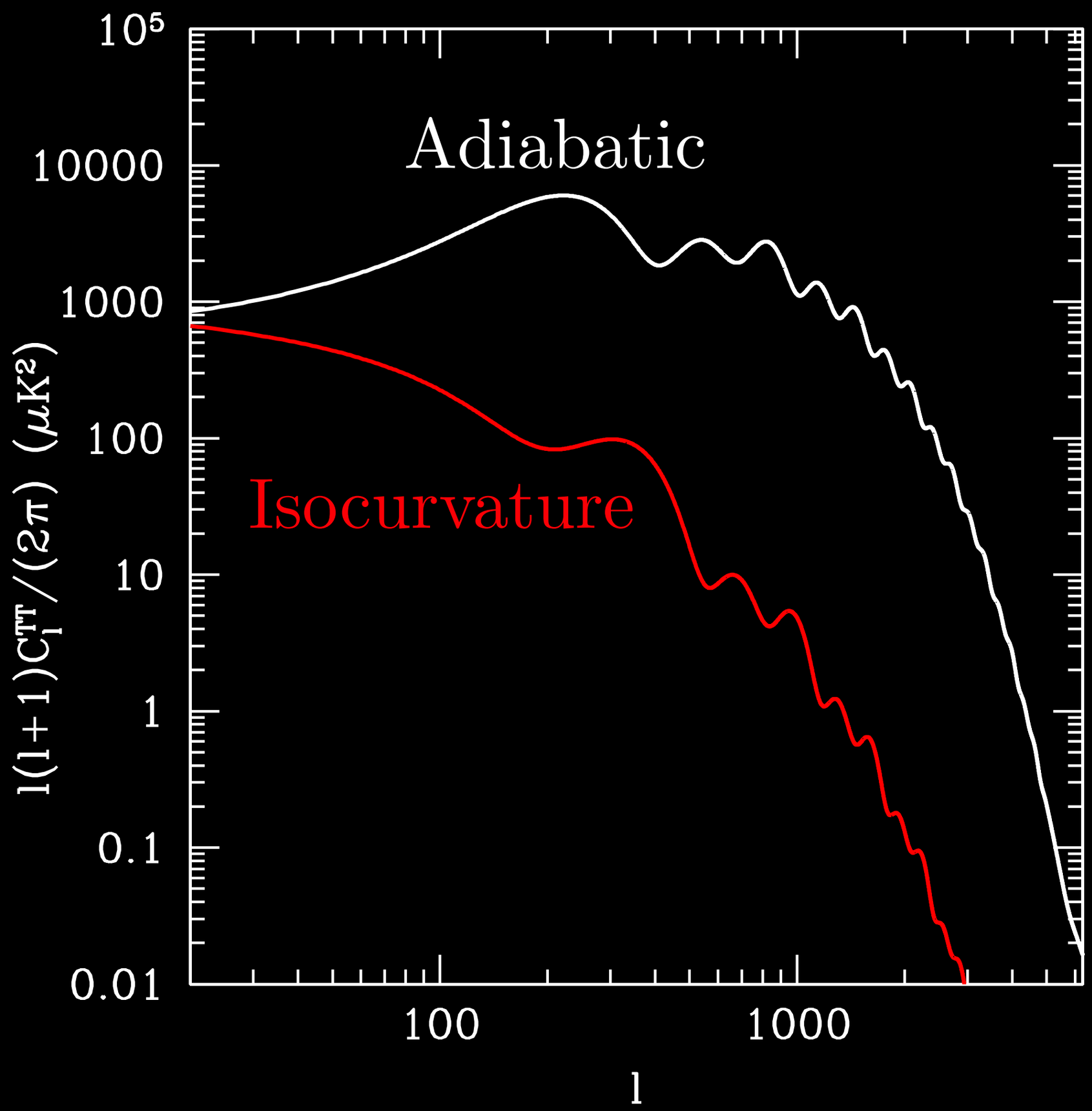
Example:



Momentum density also gravitates!

SACHS WOLFE-EFFECT & POWER SPECTRA

SACHS WOLFE-EFFECT & POWER SPECTRA



ISOCURVATURE AND ACOUSTIC WAVE EVOLUTION

- Two independent sol'ns for acoustic wave eq:
  - *Adiabatic*

$$\frac{\Delta T}{T} \sim \cos\left(k c_{\rm s} \eta_{\rm dec}\right)$$

  - *Isocurvature*

$$\frac{\Delta T}{T} \sim \sin\left(k c_{\rm s} \eta_{\rm dec}\right)$$

- In coherent phase scenario see acoustic peaks (e.g. inflation)

TWO FLAVORS OF CDM ISOCURVATURE

- Axion-type isocurvature: S_c uncorrelated with ζ

  Axion exists, fluctuates, $\rho_{\rm axion} \ll \rho_{\rm inflaton}$

- Curvaton-type isocurvature: S_c correlated with ζ
  - Curvaton dominates after inflation, seeds adiabatic ζ
  - Baryons/CDM produced before ζ growth complete: isocurvature from mismatch

OBSERVATIONAL CONSTRAINTS TO ISOCURVATURE

✳ WMAP 7-year constraints (Komatsu/Larson et al 2010)

$$P_{\mathrm{S_c}}^{\mathrm{axion}}/P_\zeta \lesssim 0.13 \quad P_{\mathrm{S_c}}^{\mathrm{curvaton}}/P_\zeta \lesssim 0.01$$

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✳ Constraints relax if assumptions (scale-invariance, single isocurvature mode) relaxed: Bean et al. 2009

	CI	NID	NIV
r_{iso}	$n_{adi} = n_{iso}$	$n_{adi} = n_{iso}$	$n_{adi} = n_{iso}$
	< 0.13	< 0.08	< 0.14

CI+NID+NIV	No BBN/bias
0.44 ± 0.09	0.51 ± 0.09

OBSERVATIONAL CONSTRAINTS TO ISOCURVATURE

✳ Planck 1st-year temperature constraints (Et al *et al*..., 2013)

$$4.6 \times 10^{-3} \lesssim \frac{P_{\rm iso}}{P_{\rm tot}} \lesssim 1.6 \times 10^{-2}$$

✳ Constraints relax if assumptions (scale-invariance, single isocurvature mode) relaxed: Bean et al. 2009

	CI	NID	NIV
r_{iso}	$n_{adi} = n_{iso}$	$n_{adi} = n_{iso}$	$n_{adi} = n_{iso}$
	< 0.13	< 0.08	< 0.14

→

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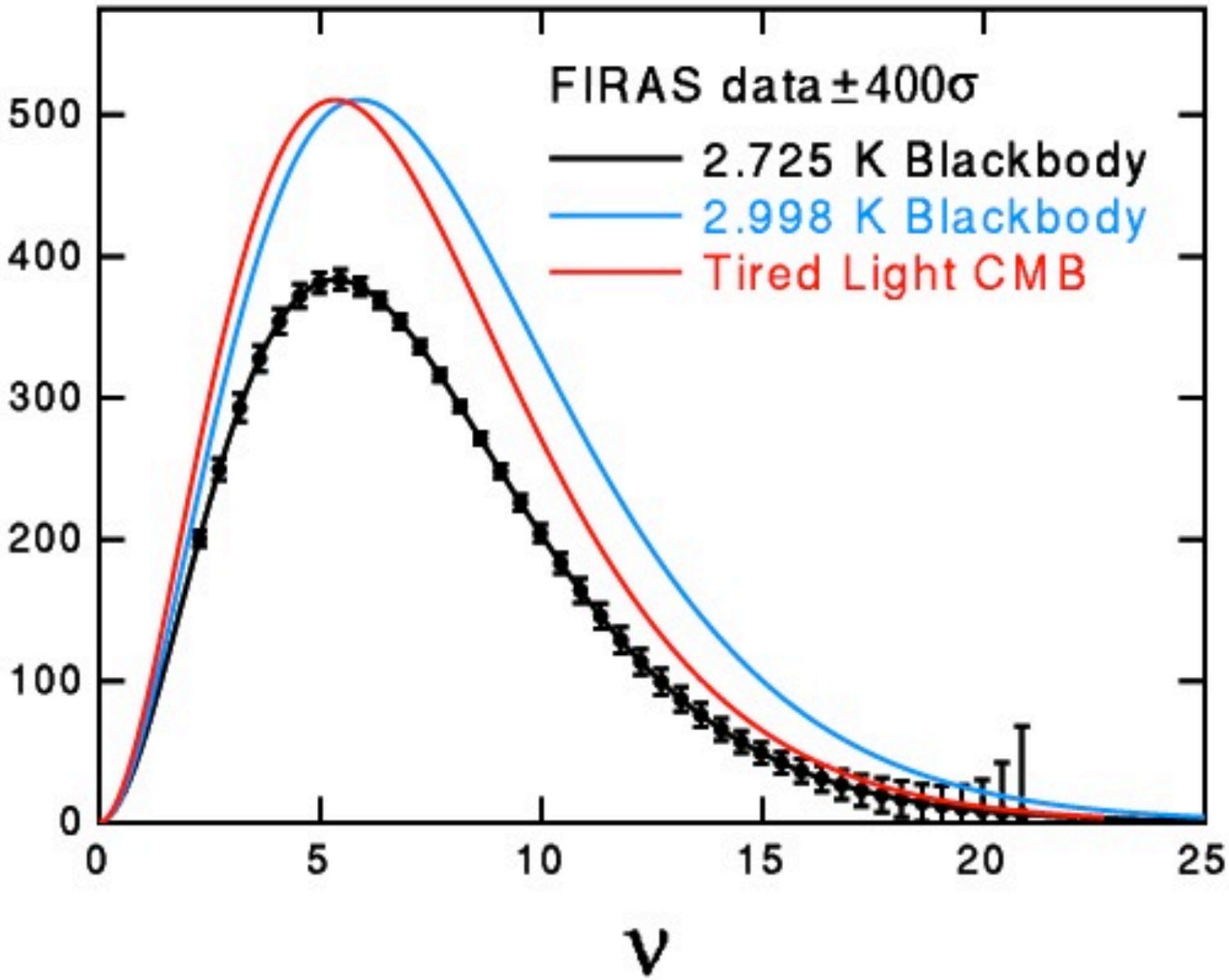
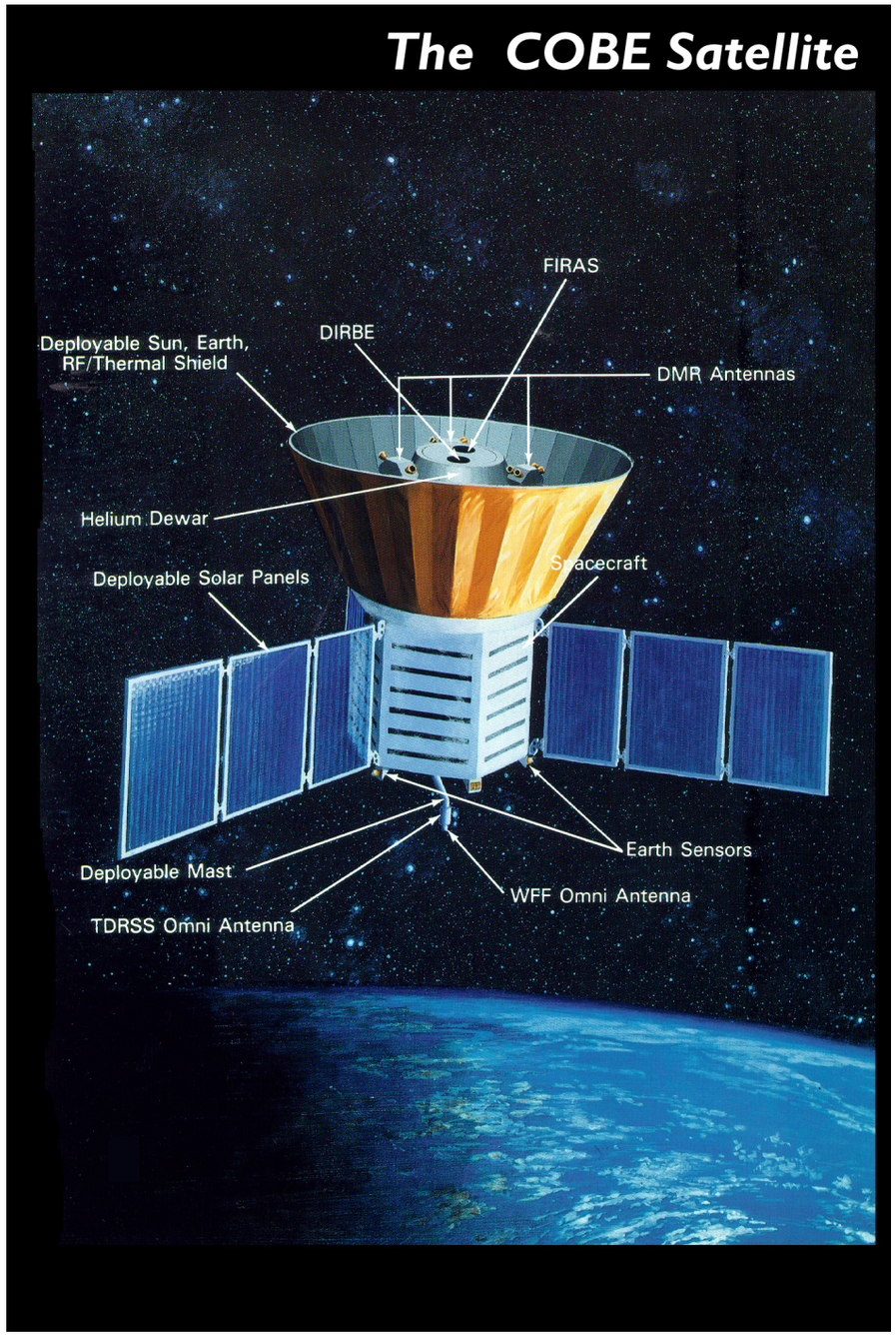
0.44 ± 0.09	0.51 ± 0.09

COBE BLACKBODY

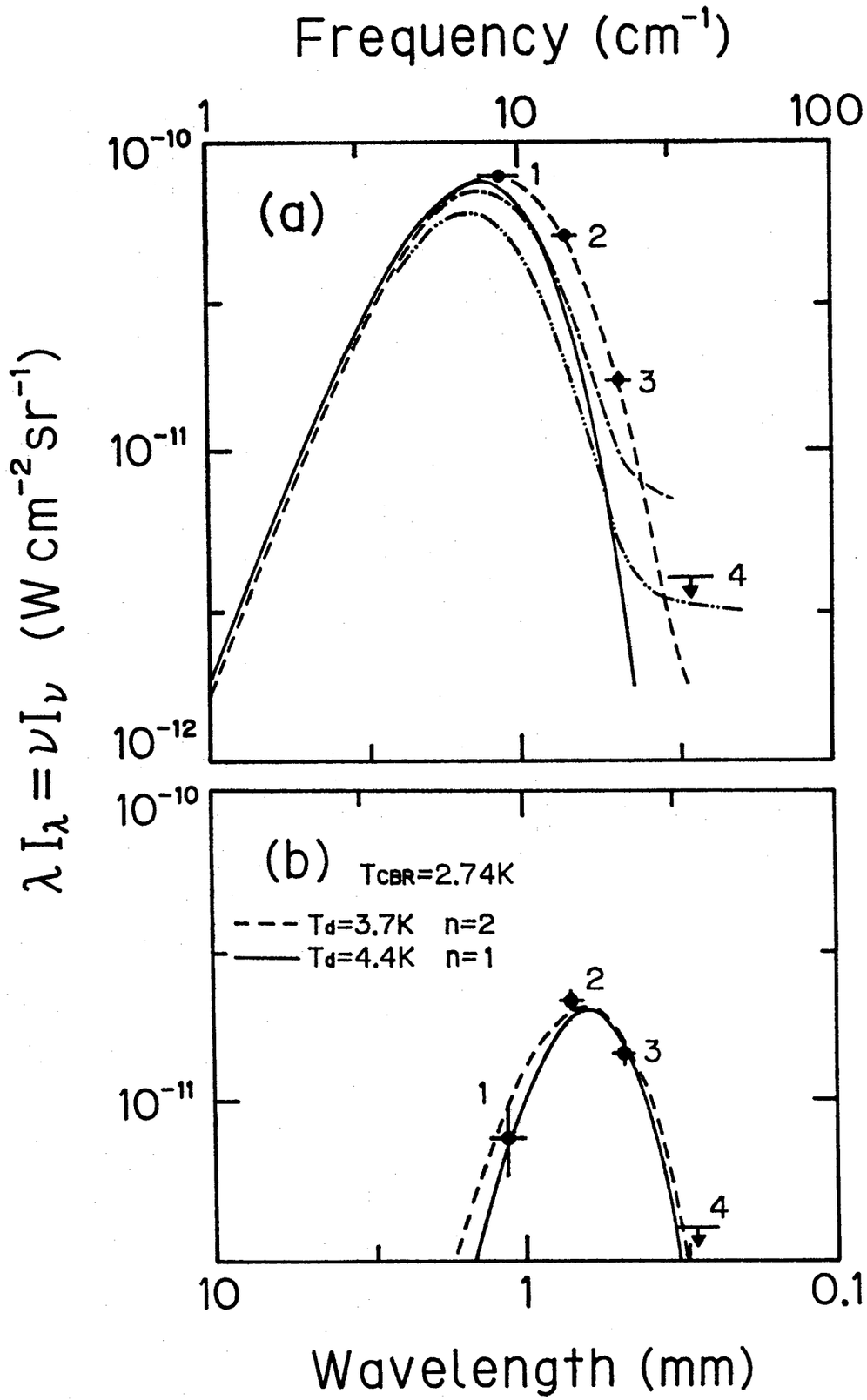




$$\mu \leq 9 \times 10^{-5}$$
$$y \leq 1.5 \times 10^{-5}$$

→ 3-4 orders of magnitude improvement now possible!!!

PHYSICS FROM 'DISTORTIONS'



Lange et al. 1987

PHYSICS FROM 'DISTORTIONS'

THE ASTROPHYSICAL JOURNAL, 344:24–34, 1989 September 1
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SPECTRAL DISTORTIONS OF THE COSMIC MICROWAVE BACKGROUND

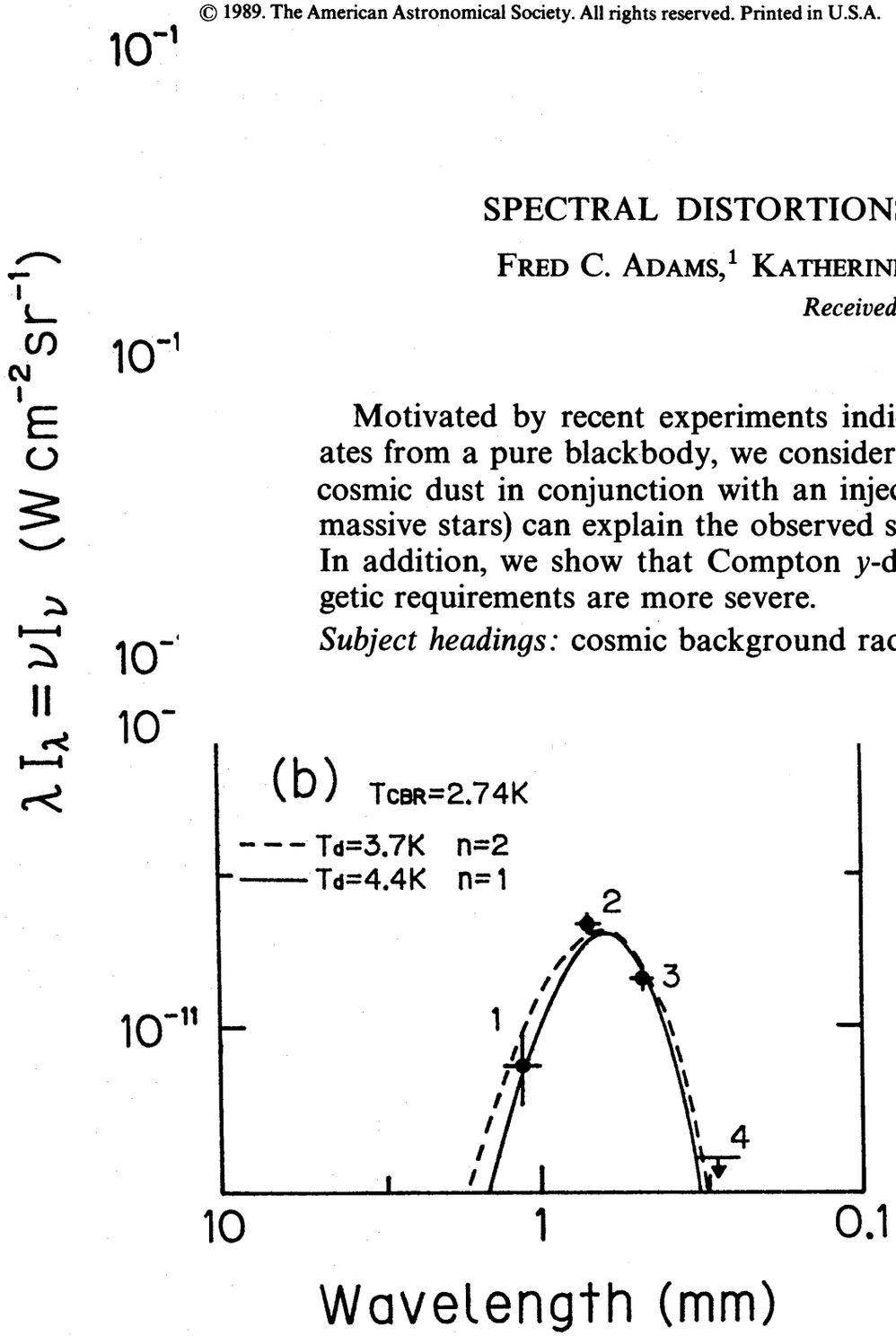
FRED C. ADAMS,[1] KATHERINE FREESE,[2] JANNA LEVIN,[2] AND JONATHAN C. MCDOWELL[1]

Received 1988 December 30; accepted 1989 February 22

ABSTRACT

Motivated by recent experiments indicating that the spectrum of the cosmic microwave background deviates from a pure blackbody, we consider spectral distortions produced by cosmic dust. Our main result is that cosmic dust in conjunction with an injected radiation field (perhaps produced by an early generation of very massive stars) can explain the observed spectral distortions without violating existing cosmological constraints. In addition, we show that Compton y-distortions can also explain the observed spectral *shape*, but the energetic requirements are more severe.

Subject headings: cosmic background radiation — cosmology — radiation mechanisms



Lange et al. 1987

EPOCHS AND EQUILIBRIA

* Chemical equilibrium epoch $z \gg 2 \times 10^6$

$$e^- + X \leftrightarrow e^- + X + \gamma \quad \text{Bremmstrahlung}$$

$$e^- + \gamma \leftrightarrow e^- + \gamma + \gamma \quad \text{Double Compton scattering}$$

* Comptonization (μ) epoch $4 \times 10^4 \ll z \ll 2 \times 10^6$

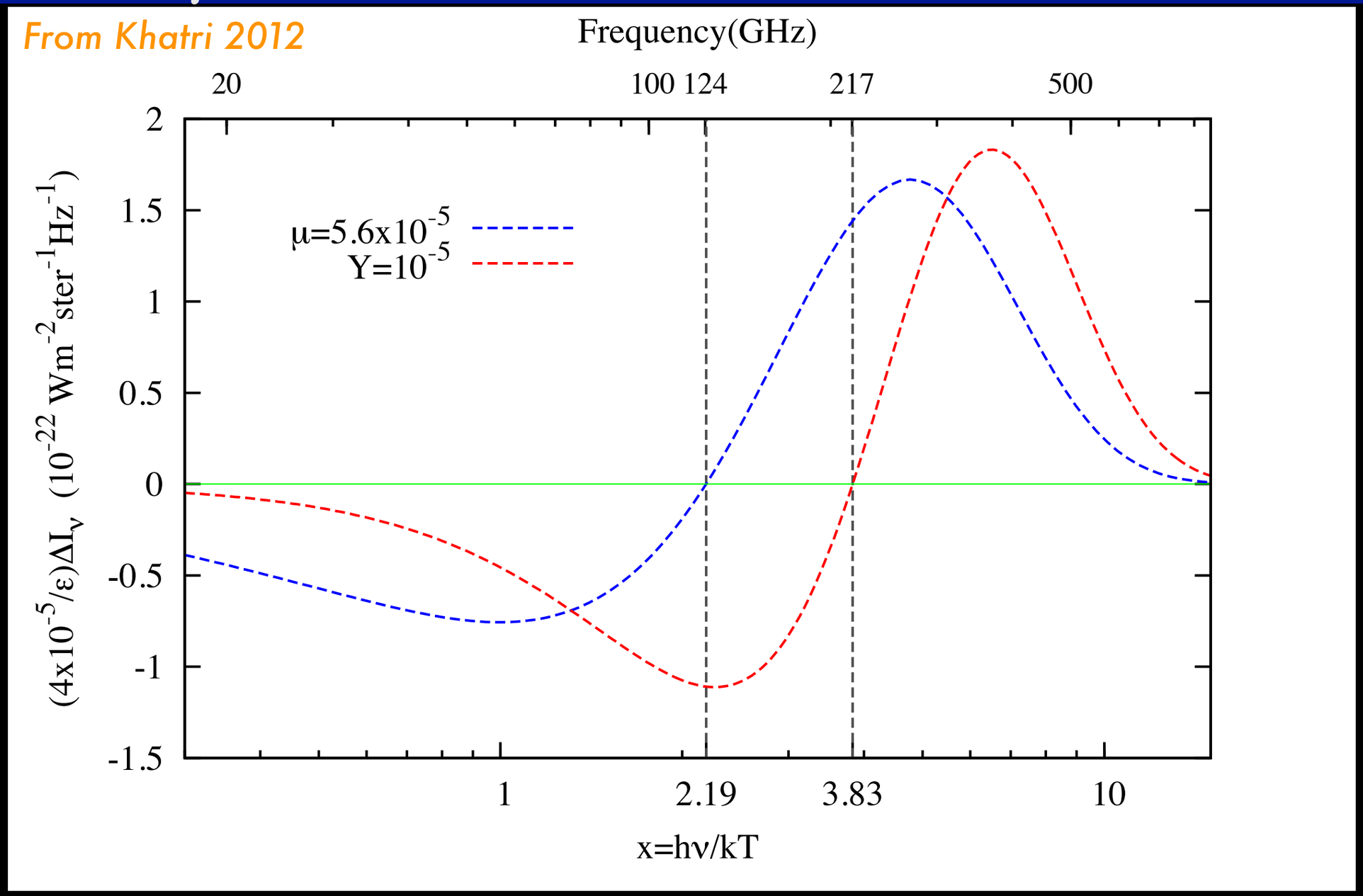
$$e^- + \gamma \leftrightarrow e^- + \gamma \quad \text{Energy-exchanging Compton scattering}$$

* Thomson (y) epoch $z \ll 4 \times 10^4$

$$e^- + \gamma \leftrightarrow e^- + \gamma \quad \text{Elastic Compton scattering}$$

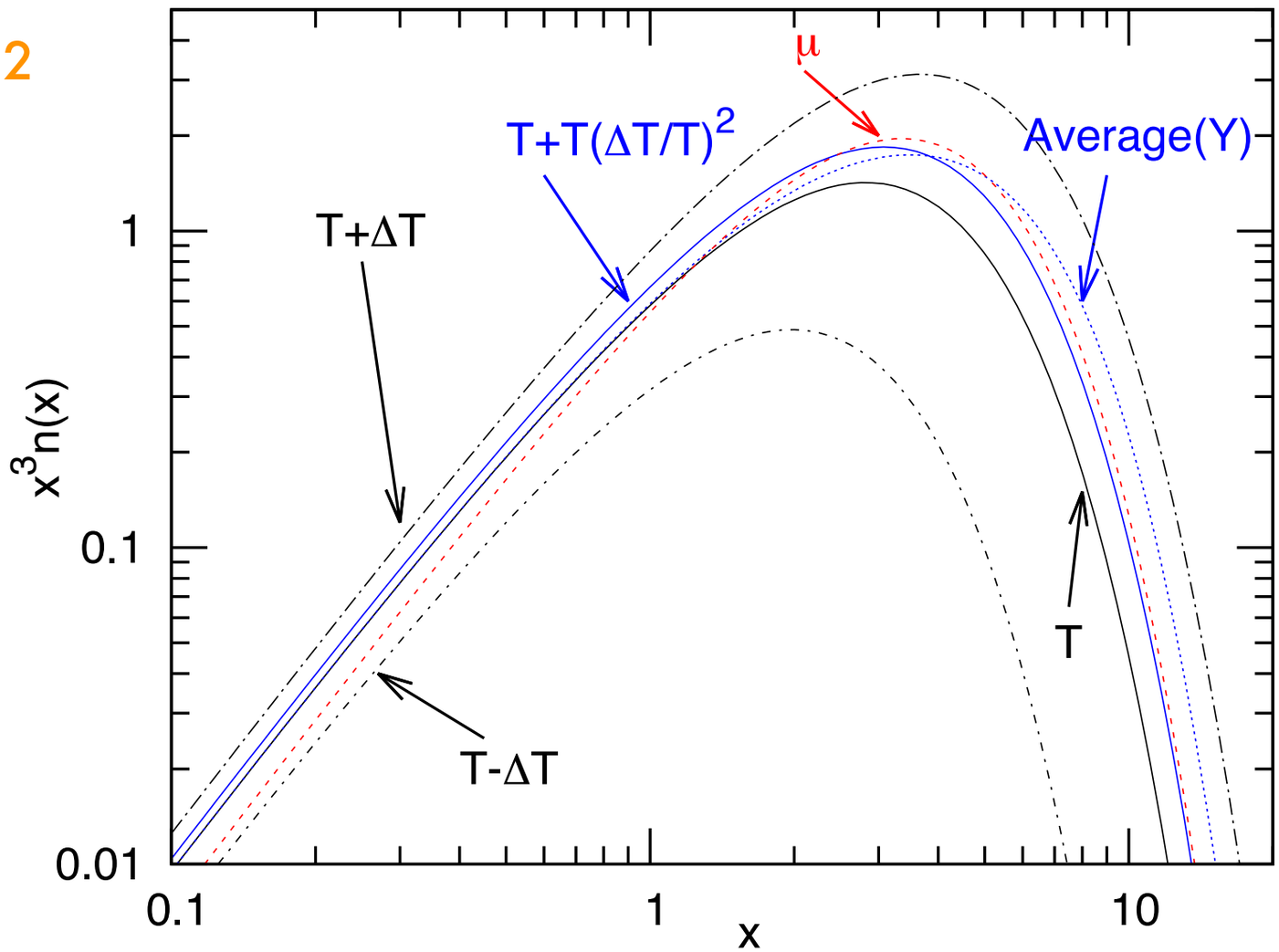
Seminal work by Zel'dovich and Sunyaev, revived by Chluba, Khatri, Sunyaev.....

μ AND Y-TYPE DISTORTION



SUPERPOSITION OF BLACKBODIES

From Khatri 2012

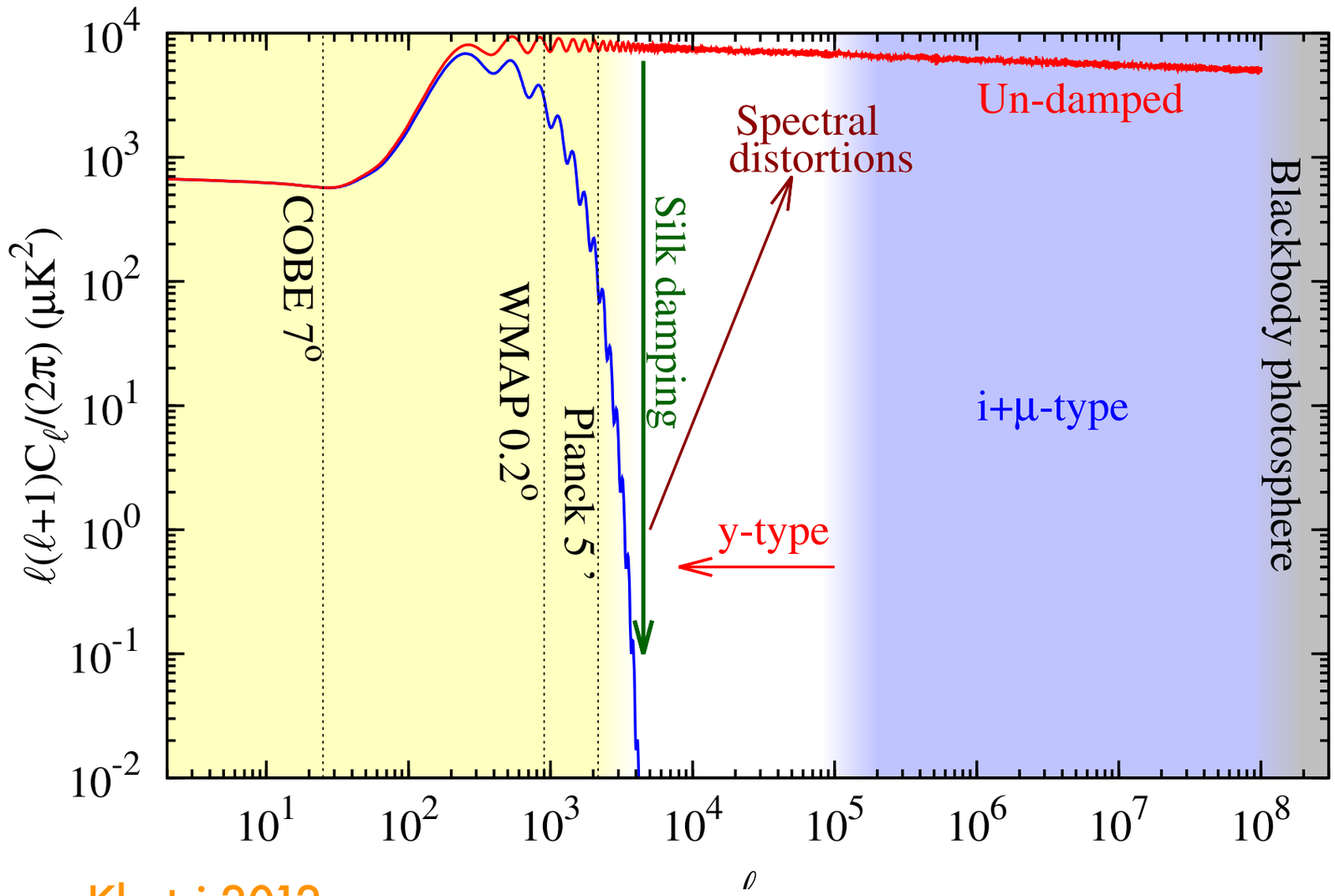


- 2/3 of energy goes to driving up plasma temp
- 1/3 of energy goes to distorting spectrum

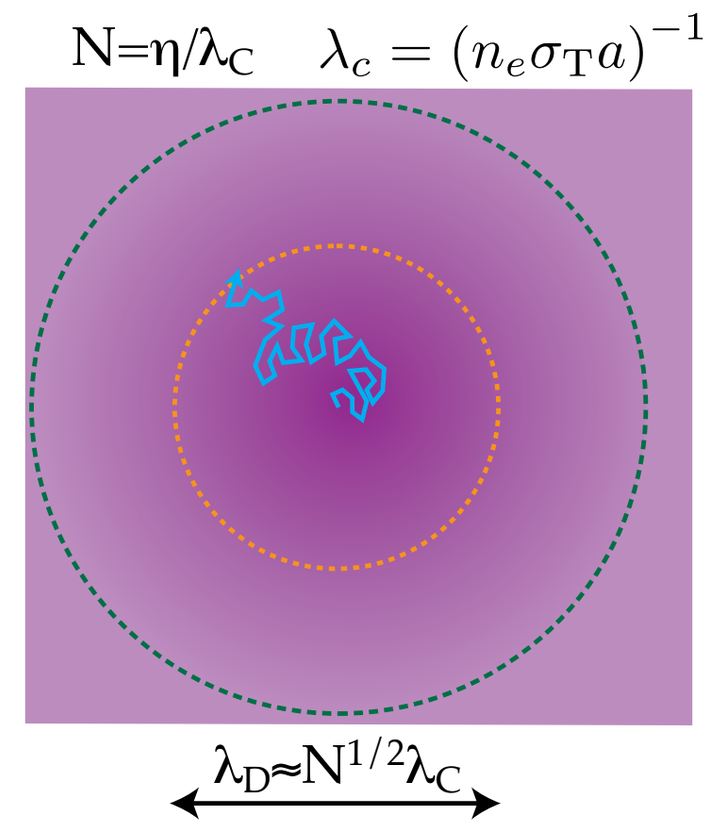
ENERGY INJECTION

- Dark matter annihilation (photons produced directly or through cascades)
- Dark matter decay
- Damping of acoustic modes
- Gauge boson production from cosmic strings

SILK DAMPING AND DISTORTION FROM ADIABATIC MODES



From Khatri 2012



Mode dissipation mixes black bodies – these distortions begin their life as y distortions, the epoch determines the rest

Scale-invariant LCDM cosmology → $\mu \sim 10^{-9}$

NEW PROBE OF SMALL-SCALE PERTURBATIONS

- Galaxy power spectrum $0.01\ \mathrm{Mpc}^{-1} \ll k \ll 0.3\ \mathrm{Mpc}^{-1}$
- CMB $0.001\ \mathrm{Mpc}^{-1} \ll k \ll 0.2\ \mathrm{Mpc}^{-1}$
- Lyman-α forest $0.1\ \mathrm{Mpc}^{-1} \ll k \ll 10\ \mathrm{Mpc}^{-1}$
- 21-cm cosmology $0.01\ \mathrm{Mpc}^{-1} \ll k \ll 100\ \mathrm{Mpc}^{-1}$
- Y-distortions [but confusion from reionization!]

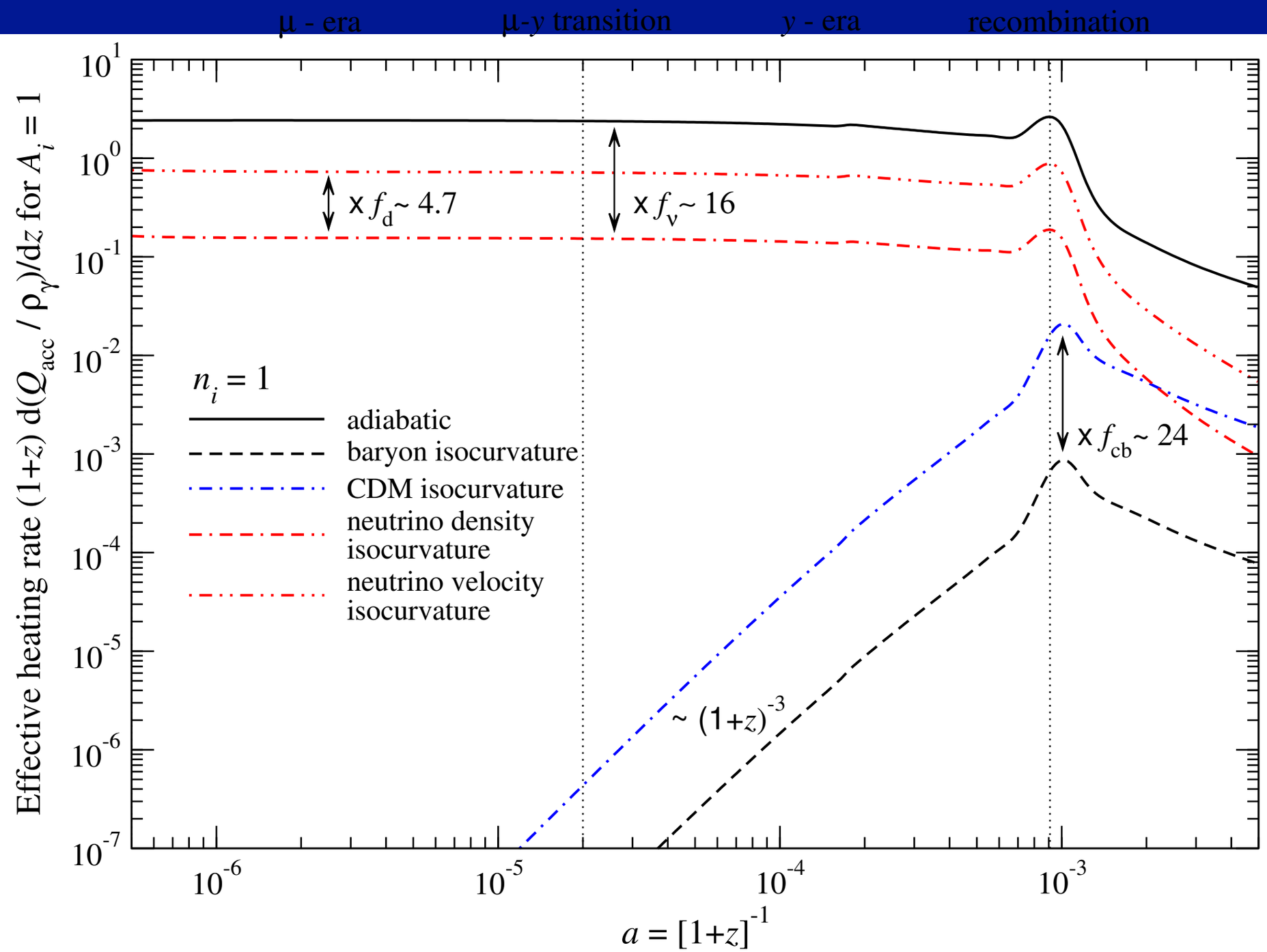
  $1\ \mathrm{Mpc}^{-1} \ll k \ll 50\ \mathrm{Mpc}^{-1}$
- μ-distortions $50\ \mathrm{Mpc}^{-1} \ll k \ll 10^4\ \mathrm{Mpc}^{-1}$

HEATING FROM ACOUSTIC MODE DISSIPATION

- Energy lost to Silk damping: $$\frac{d}{dt}\frac{\Delta E_\gamma}{E_\gamma} = 4 n_e \sigma_T \int \frac{k^2 dk}{2\pi^2} P_i(k) \left\{ \frac{(3\Theta_1 - v)^2}{3} + \frac{9}{2}\Theta_2^2 - \frac{1}{2}\Theta_2(\Theta_2^{\rm P} + \Theta_0^{\rm P}) + \sum_{l\geq 3}(2l+1)\,\Theta_l^2 \right\}$$

- COSMOTHERM (Chluba 2013) -- follows 80 moments, all relevant reactions
- Analytic CN gauge solutions needed for all isocurvature modes

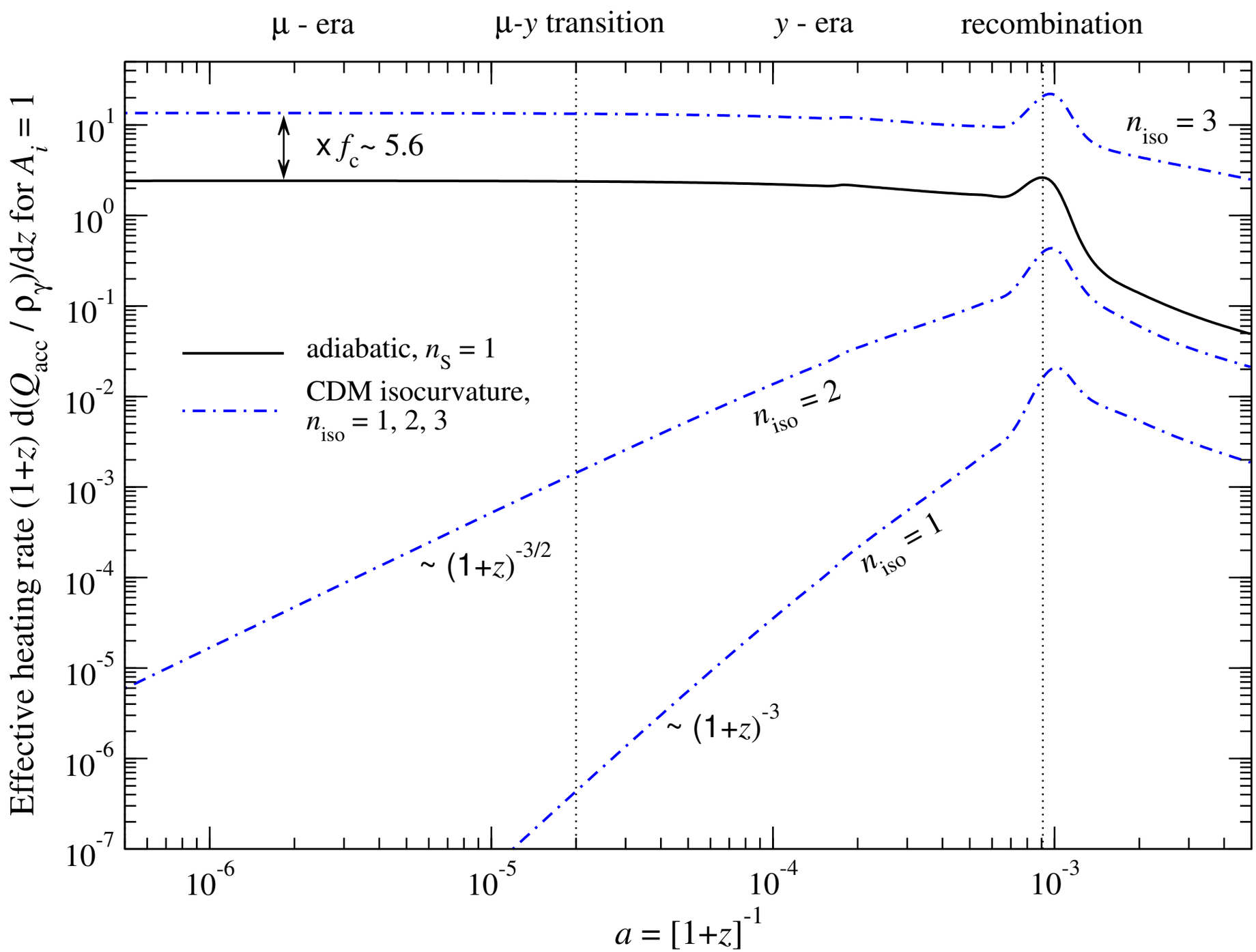
HEATING AND DISTORTION FROM ALTERNATE INITIAL CONDITIONS



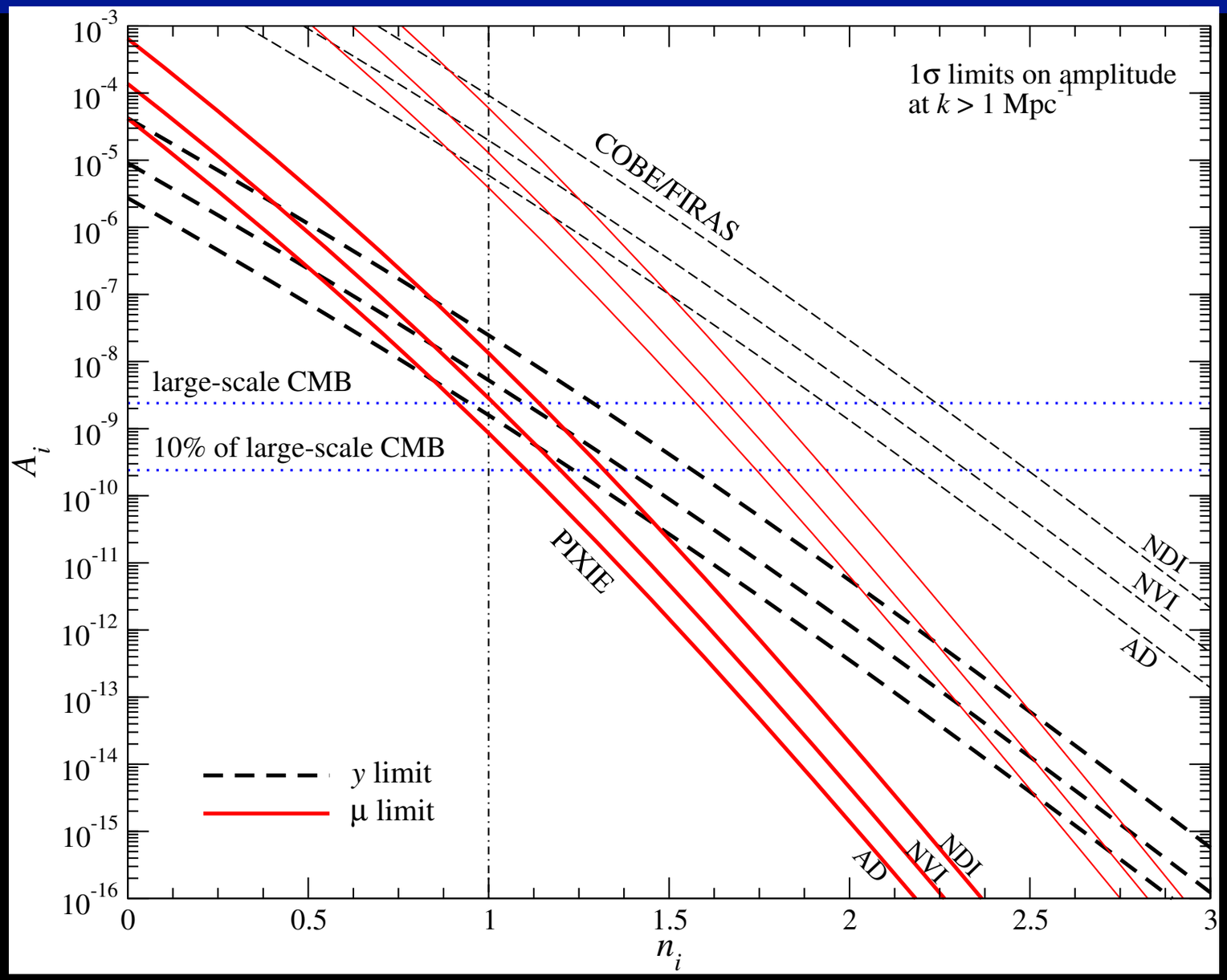
Isocurvature in relativistic species yields more energy injection during μ-era

Isocurvature in non-relativistic species less suppressed during matter domination

RESULTS DEPEND ON POWER SPECTRUM OF ISOCURVATURE MODES



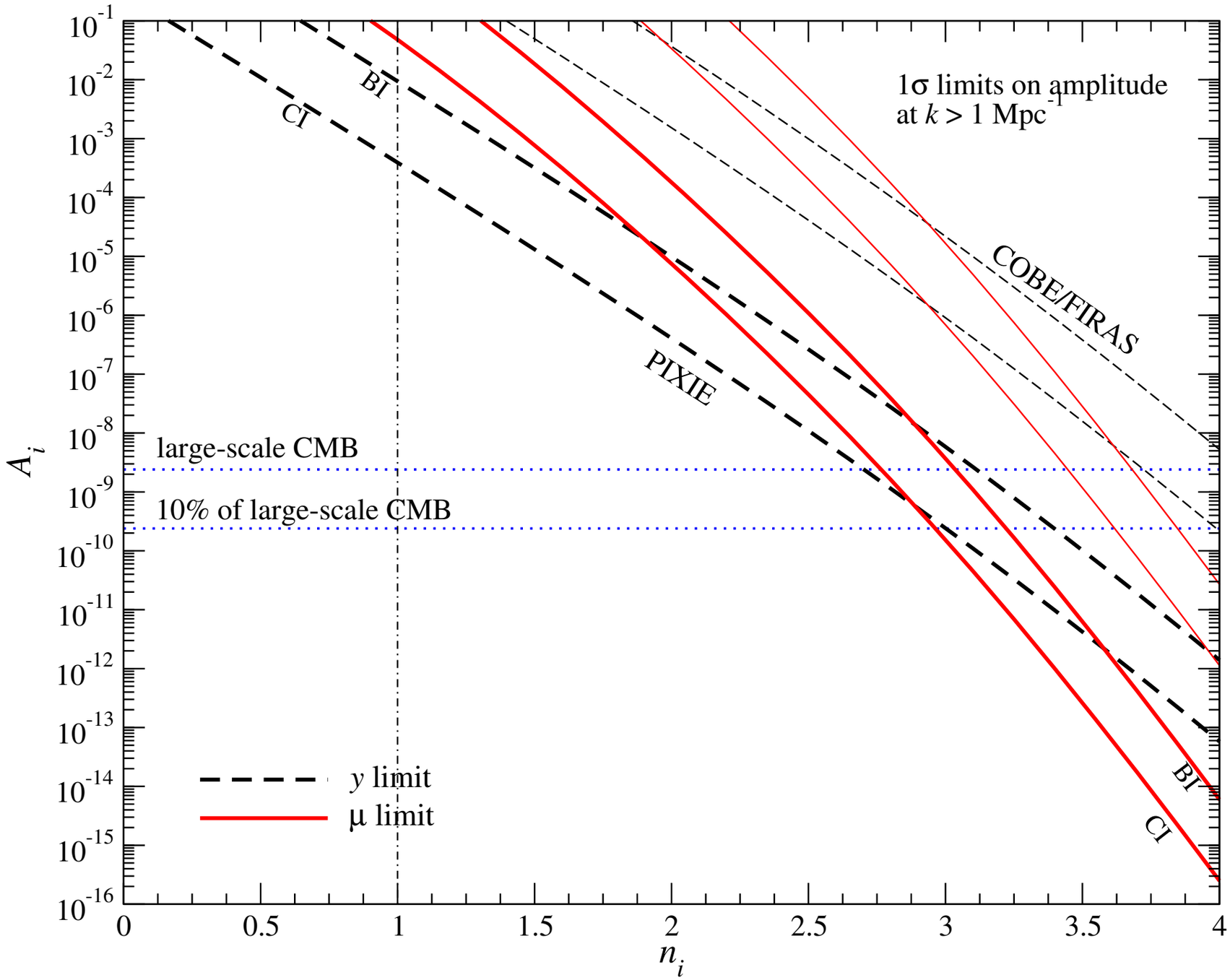
DISTORTIONS PROBE SPECTRAL SLOPE AND/OR INITIAL CONDITIONS OF PRIMORDIAL FLUCTUATIONS



$$\mu \leq 10^{-8}$$
$$y \leq 2 \times 10^{-9}$$

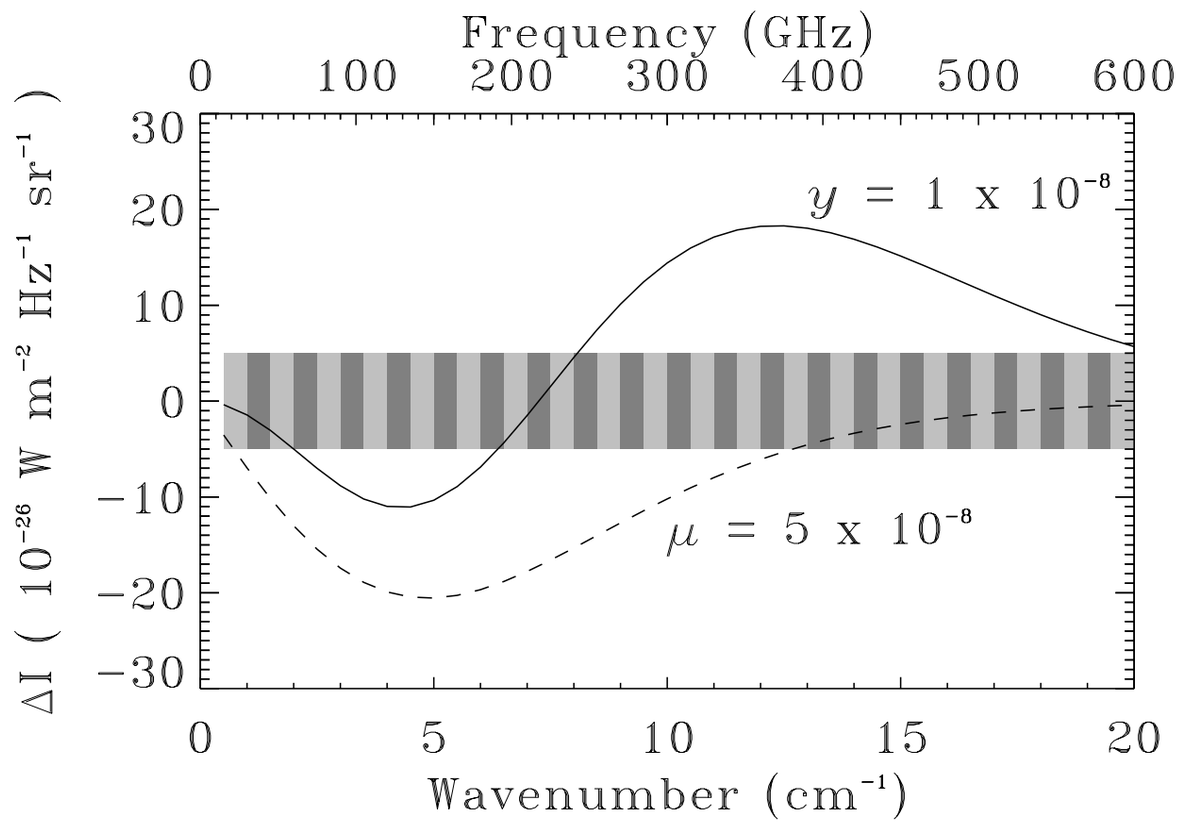
→ PIXIE SENSITIVITY

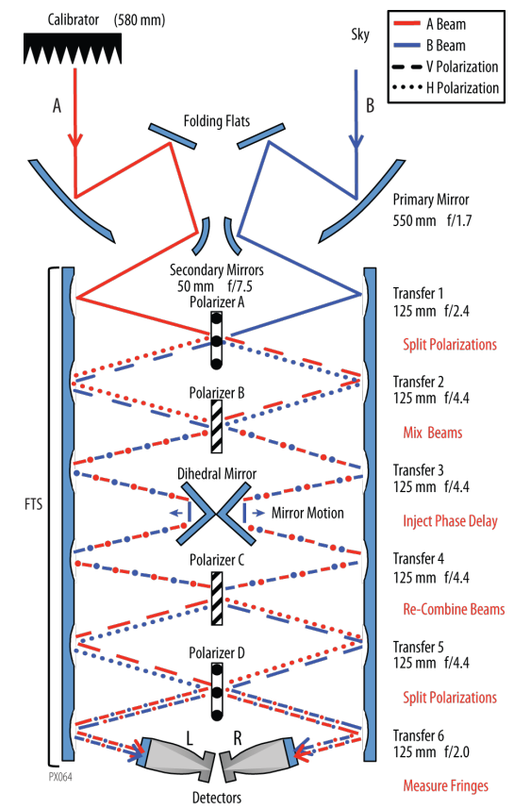
DISTORTIONS PROBE SPECTRAL SLOPE AND/OR INITIAL CONDITIONS OF PRIMORDIAL FLUCTUATIONS

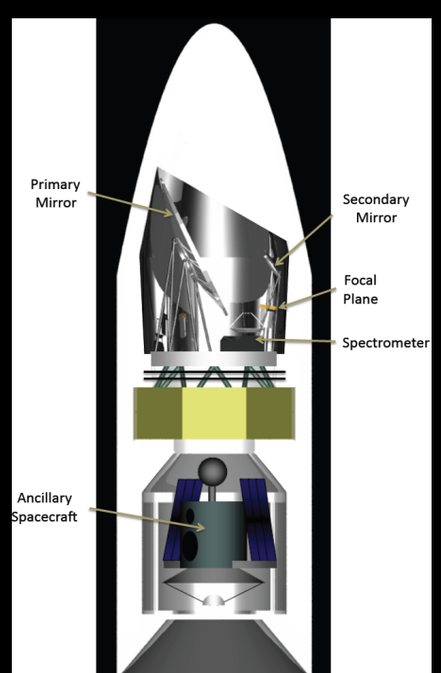


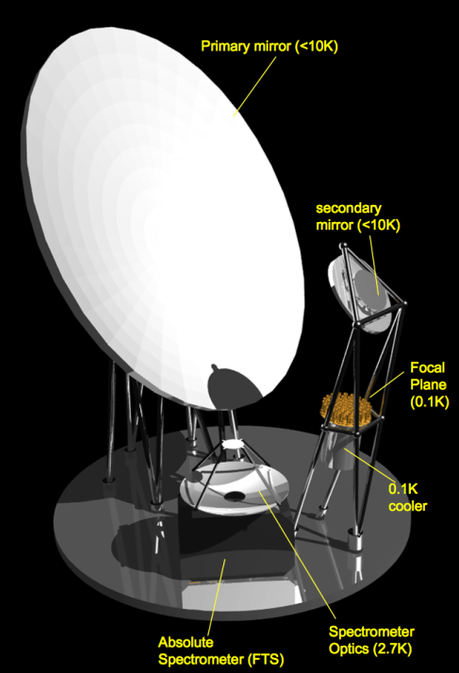
EXPERIMENTAL HORIZON

PIXIE (Explorer proposal, $200M)









PRISM [50 cm spectrophotometer +imager: 4m telescope, 7600 bolometers, ~30 frequency bands] (billions and billions....)

A cosmological search for ultra-light axions

with D. J.E. Marsh, R. Hlozek and P. Ferreira

arXiv:1303.3008, *Phys. Rev. D 87, 121701(R) (2013)*
(with MCMC results and methods paper forthcoming)

Axions solve the strong CP problem

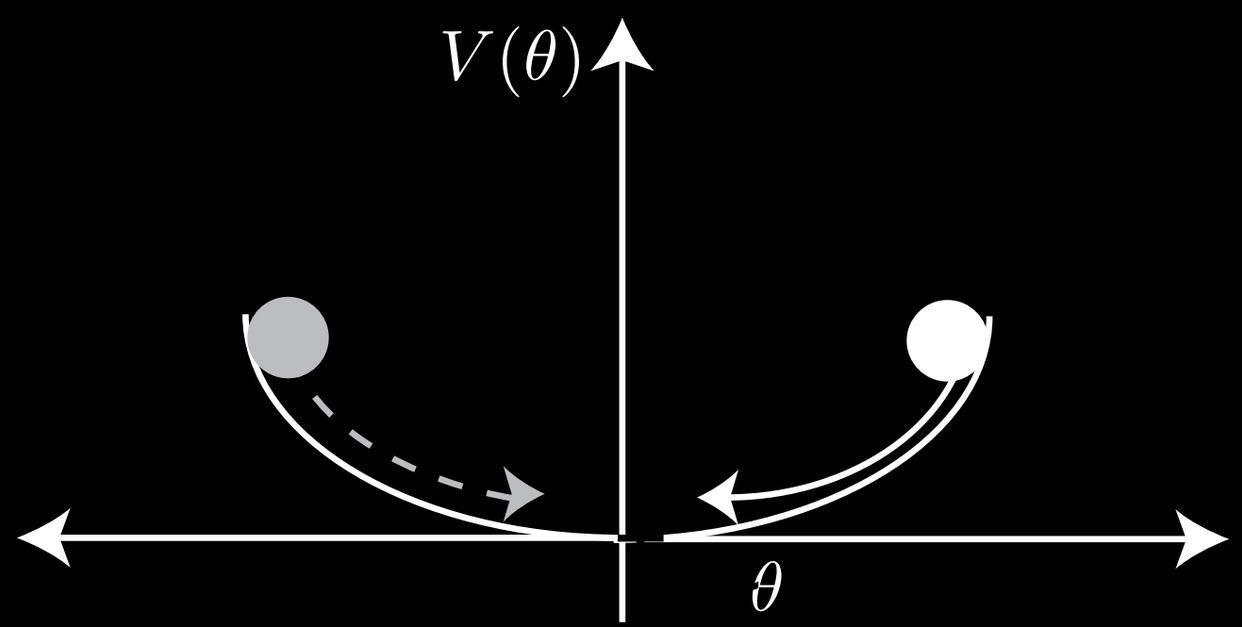
- Limits on the neutron electric dipole moment are strong. Fine tuning?

$$d_n \simeq 10^{-16}\ \theta \text{ e cm}$$
$$\theta \lesssim 10^{-10}$$

- New field (axion) and U(1) symmetry dynamically drive net CP-violating term to 0

$$\mathcal{L}_{\rm CPV} = \frac{\theta g^2}{32\pi^2} G\tilde{G} - \frac{a}{f_{\rm a}} g^2 G\tilde{G}$$

2 axion populations: Cold axions



- Prior to $m \sim 3H$, θ is generically displaced from vacuum value
- EOM: $\ddot{\bar{\theta}} + 3H\bar{\theta} + m_{\rm a}^2(T)\,\bar{\theta} = 0$ $\quad m_{\rm a}(T) \simeq 0.1 m_{\rm a}(T=0)\,(\Lambda_{\rm QCD}/T)^{3.7}$
- After $m_{\rm a}(T) \gtrsim 3H(T)$, coherent oscillations begin, leading to $n_{\rm a} \propto a^{-3}$
- Relic abundance $\Omega_{\rm a} h^2 \simeq 0.13 \times g(\theta_0)\,(m_{\rm a}/10^{-5}{\rm eV})^{-1.18}$
- Particles are cold

A new scale for perturbed scalars

✳*Perturbations obey*

$$\delta\ddot{\phi} + 2\mathcal{H}\delta\dot{\phi} + \left(k^2 + m^2a^2\right)\delta\phi = -\dot{\phi}_0\dot{h}/2$$

✳*Structure suppressed when*

$$k \gg k_{\rm J} \sim \sqrt{m\mathcal{H}}$$

✳*Scales are very small for QCD axion*

$$\lambda \sim 10^{10}\ {\rm cm}$$

What about lighter axions?

Axions carry isocurvature

- If PQ symmetry broken during/before inflation

$$\sqrt{\langle a^2 \rangle} = \frac{H_{\rm I}}{2\pi}$$

Quantum zero-point fluctuations!

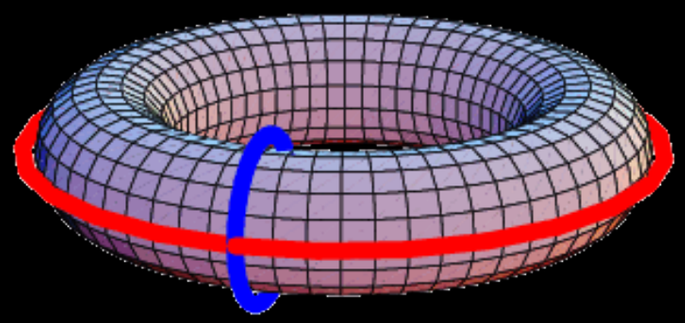
- Subdominant species seed isocurvature fluctuations

$$\zeta \propto \frac{\rho_a}{\rho_{\rm tot}} \frac{\delta\rho_a}{\rho_a} \ll 10^{-5}$$

$$S_{a\gamma} = \frac{\delta n_a}{n_a} - \frac{\delta n_\gamma}{n_\gamma} = \frac{\delta\rho_a}{\rho_a} - \frac{3}{4}\frac{\delta\rho_\gamma}{\rho_\gamma} \sim 10^{-5}$$

Light axions and string theory

- String theory has extra dimensions: *compactify (6)!*
- Form fields and gauge fields: `Axion' is KK zero-mode of form field



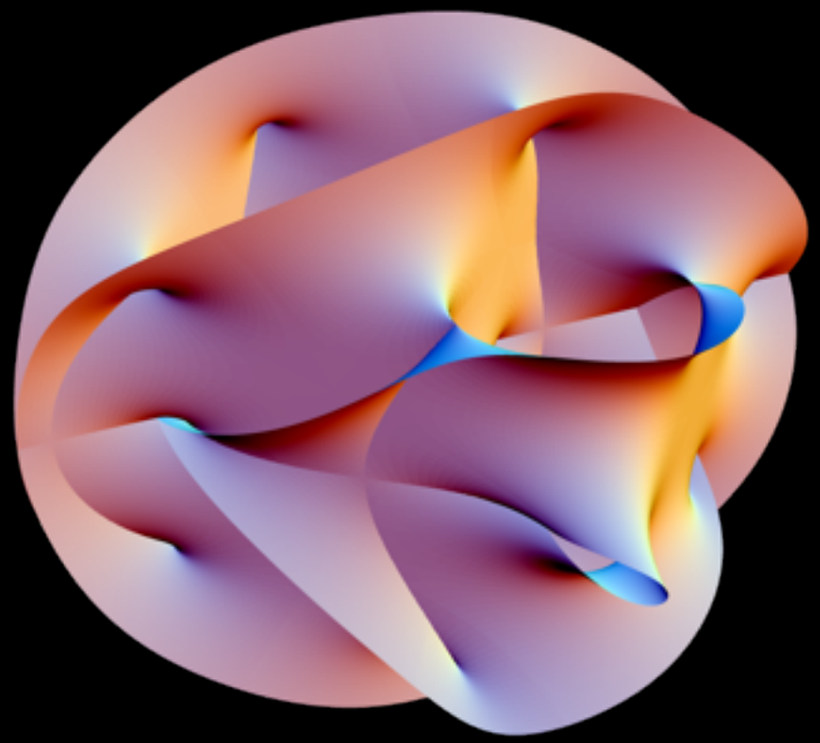
$$\mathcal{L} \propto \frac{a\tilde{G}G}{f_{\mathrm{a}}}$$

Axiverse! (Arvanitaki et al. 2009)

- Calabi-Yau manifolds

  Many 2-cycles ⟶ Many axions

  Hundreds!

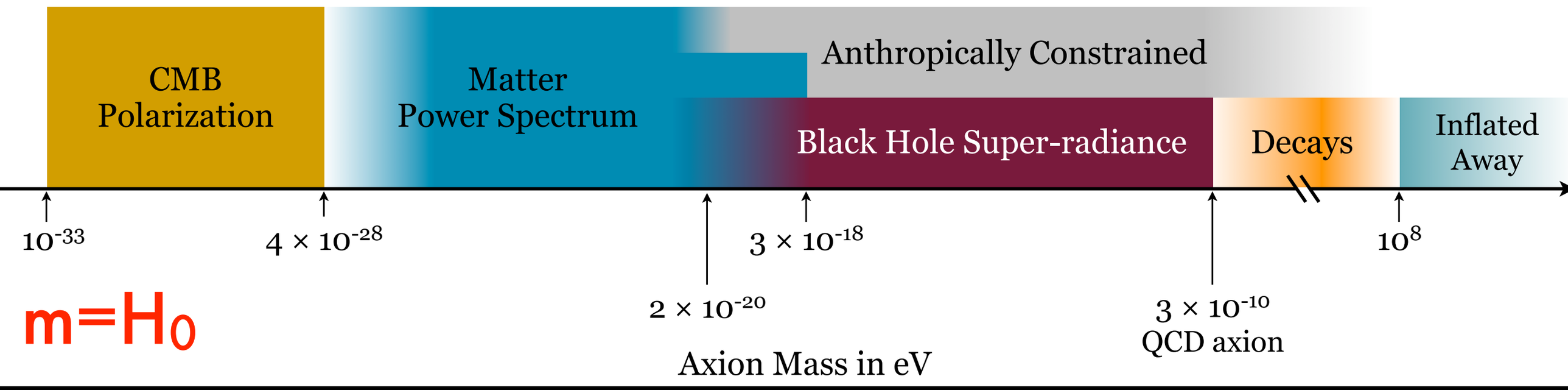


- Mass from non-perturbative physics (instantons, D-branes)

$$m_a^2 = \frac{\mu^4}{f_a^2} e^{-S} \quad f_a \propto \frac{M_{\rm pl}}{S}$$

Many decades in mass covered!

Axiverse! (Phenomena)



$m = H_0$

✳ ***Birefringence (Faraday rotation), model dependent:***

$$\mathcal{L} \propto \frac{a\vec{E}\cdot\vec{B}}{f_a}$$

✳ ***Decrement in matter power spectrum for***

$$k \gg k_{\rm J} \sim \sqrt{m\mathcal{H}}$$

Effective fluid approximation

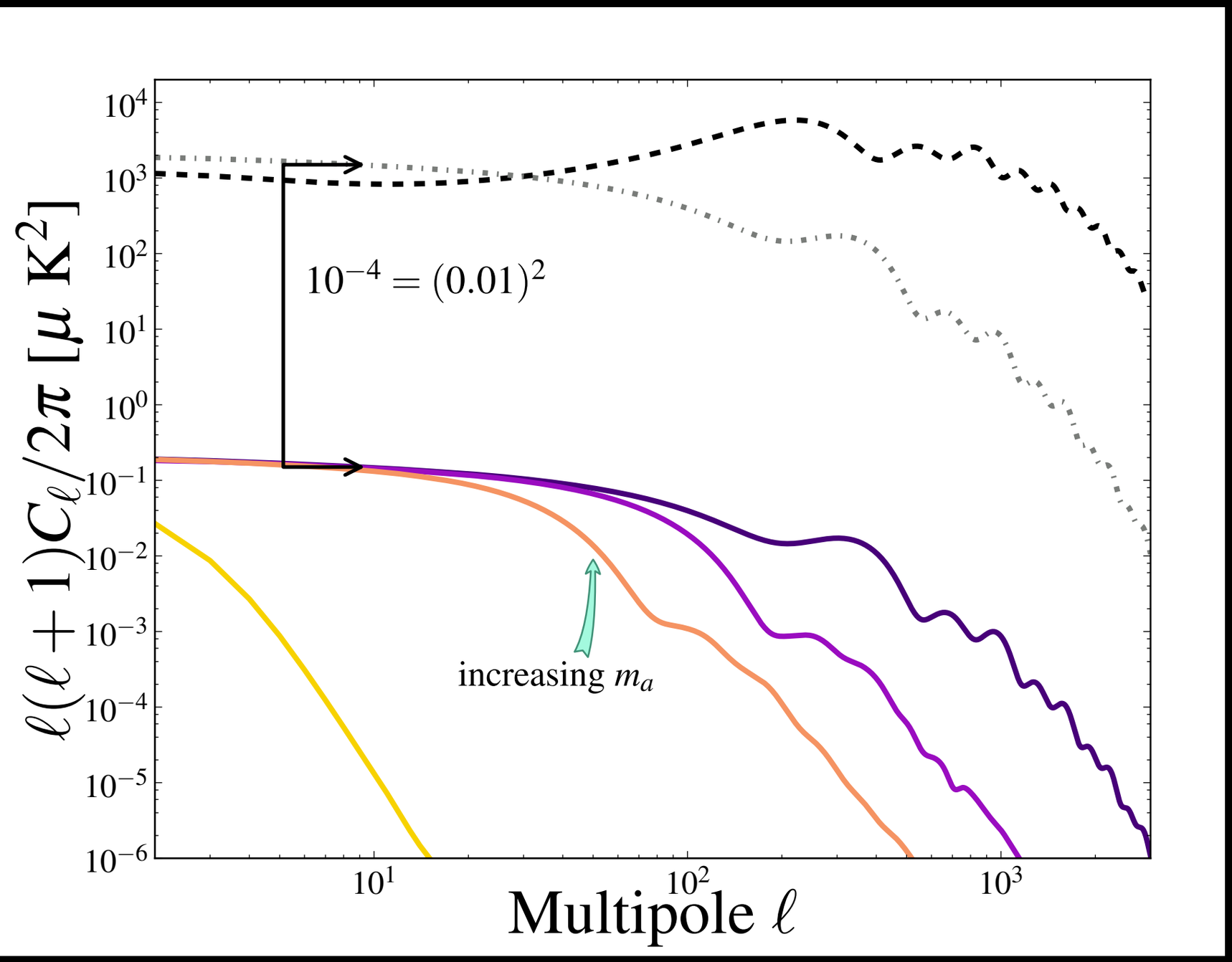
- Computing observables is expensive for $m \gg H_0$:
  - Coherent oscillation time scale

$$\Delta\eta \sim (ma)^{-1} \ll \Delta\eta_{\rm CAMB}$$

  - Ansatz $\delta\phi = A_c \Delta_c(k,\eta)\cos(m\eta) + A_s \Delta(k,\eta)\sin(m\eta)$

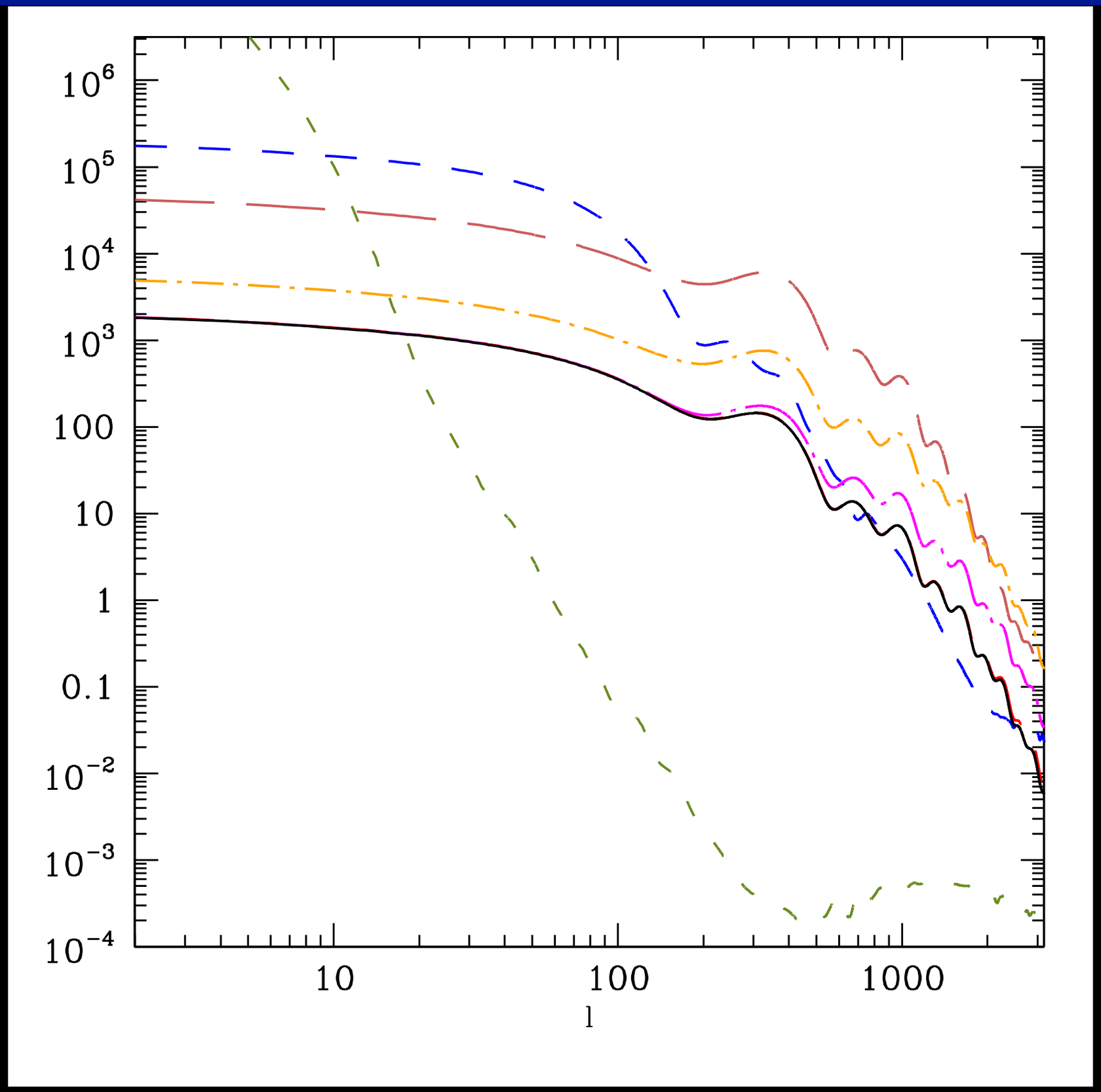
$$c_a^2 = \frac{\delta P}{\delta\rho} = \frac{k^2/(4m^2a^2)}{1 + k^2/(4m^2a^2)}$$

CMB anisotropy power spectra



Power spectra may now be quickly computed for 15 orders of magnitude in axion mass!

Getting under the hood: The need for numerical care



Getting under the hood: The need for numerical care

$$\dot{\delta}_a = 3\mathcal{H}\left[w_a - 1\right]\delta_a - \left(1 + w_a\right)\left(kv_a + \dot{h}\right)$$

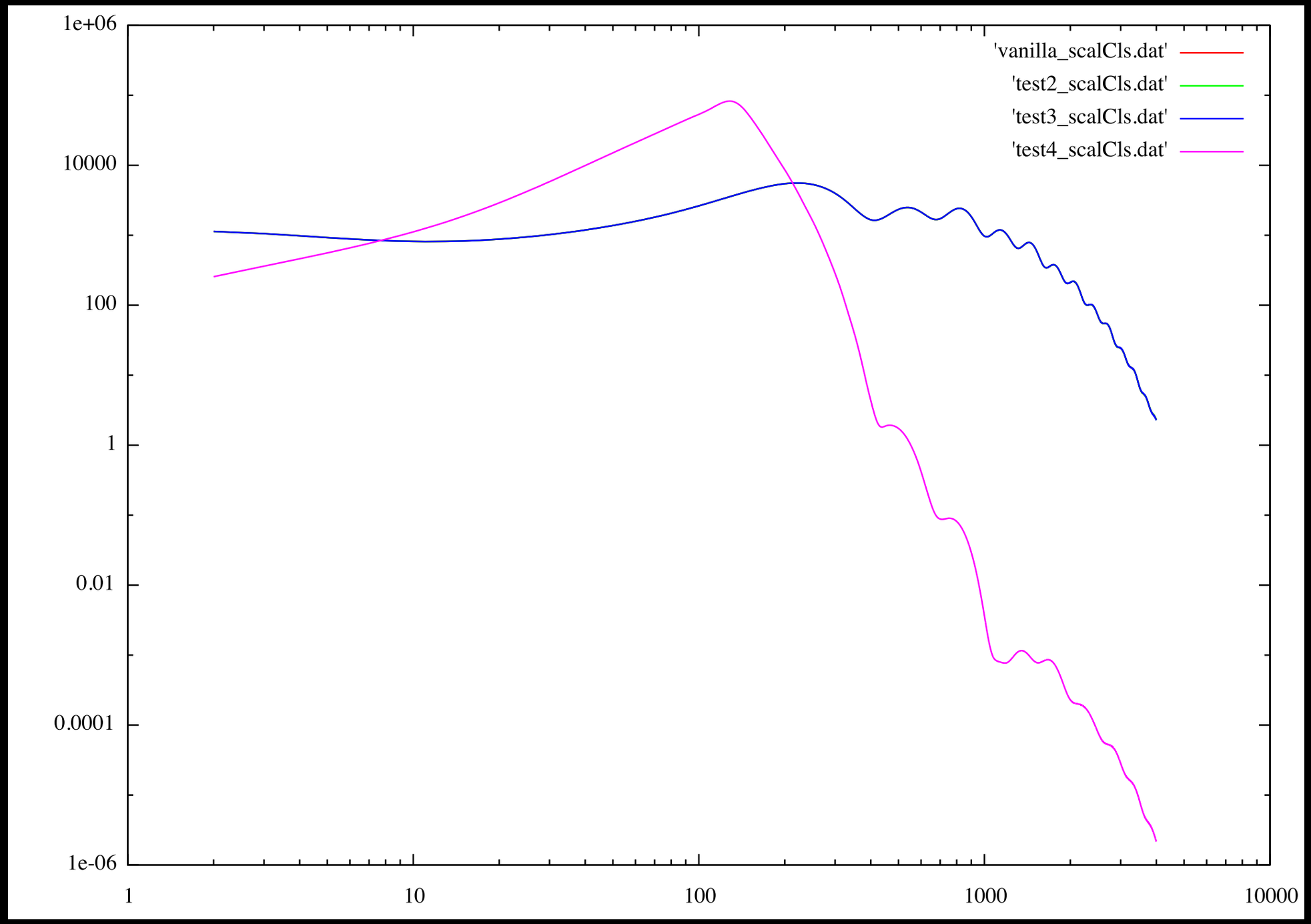
$$\dot{v}_a = -3\mathcal{H}\left[1 - 3w_a\right]v_a - \frac{\dot{w}_a}{(1 + w_w)}v_a + \frac{k\delta_a}{(1 + w_a)}$$

$$\dot{w}_a = -3\mathcal{H}\left(1 + w_a\right)\left[c_{\mathrm{ad}}^2 - w_a\right]$$

$$c_{\mathrm{ad}}^2 = \frac{\dot{P}_a}{\dot{\rho}_a} = -1 + \frac{2m_a a}{\mathcal{H}}\sqrt{\frac{(1 - w_a)}{(1 + w_a)}}$$

$$\dot{\rho}_a = -3\mathcal{H}\rho_a\left(1 + w_a\right)$$

Getting under the hood: The need for correct (super-horizon) initial conditions



Getting under the hood: The need for correct (super-horizon) initial conditions

Synchronous gauge 00-Einstein

$$\dot{h} \propto \eta \left[\frac{3\delta_{\mathrm{R}}}{a^2} + 3a^2 \mathcal{A} \delta_a \right]$$

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Perrotta and Baccigalupi, astro-ph/9811156

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NOT KOSHER!

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NOT KOSHER!

Solve Eigensystem and expand systematically

$$\frac{d\vec{U}_{\vec{k}}}{d\ln x} = (\underline{A}_0 + \underline{A}_1 x + \ldots \underline{A}_n x^n)\, \vec{U}_{\vec{k}}$$

Bucher, Moodley, and Turok, PRD62, 083508, sol'ns can be obtained using this technique, outlined in Doran et al. , astro-ph/0304212

Matter power spectrum

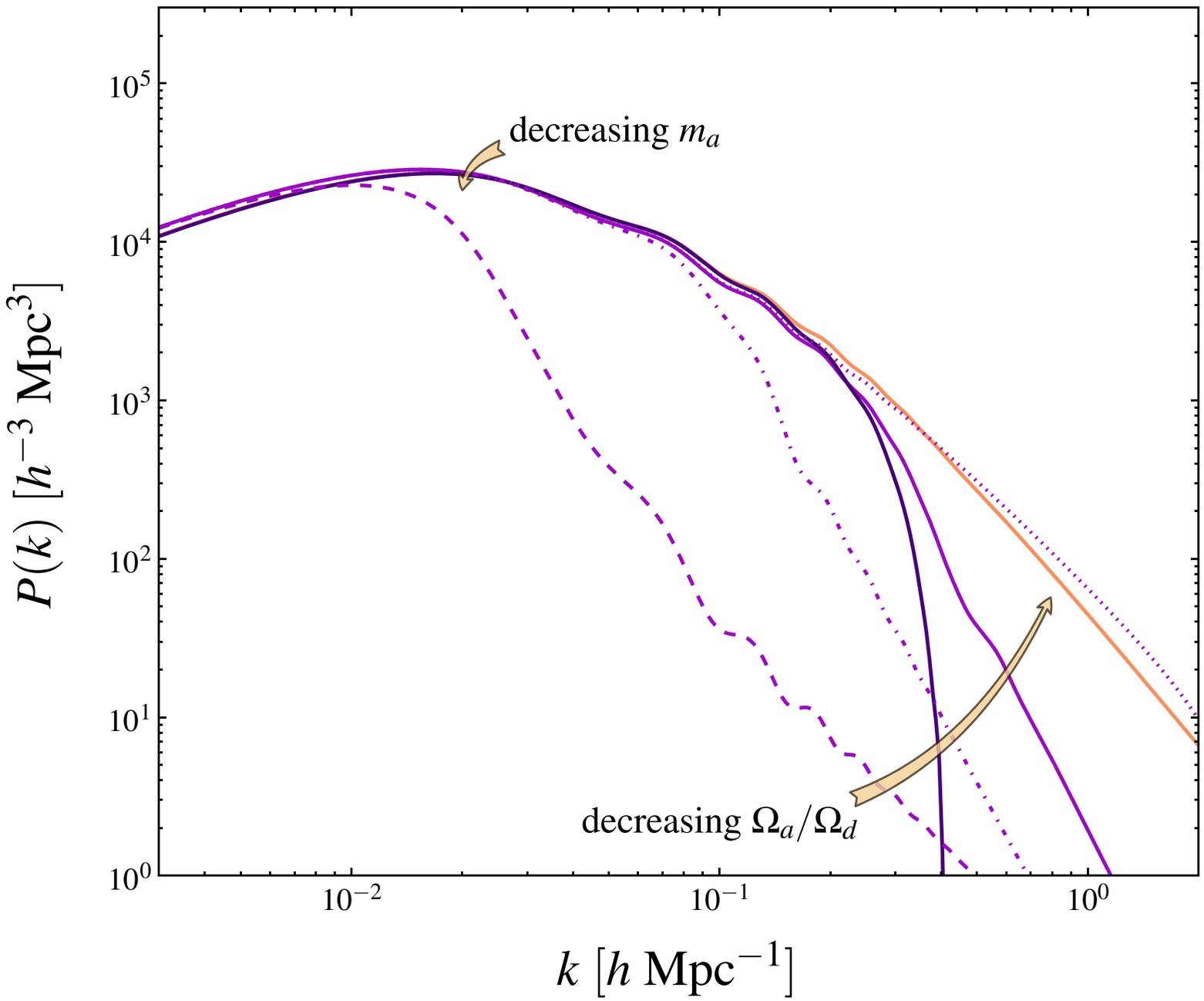
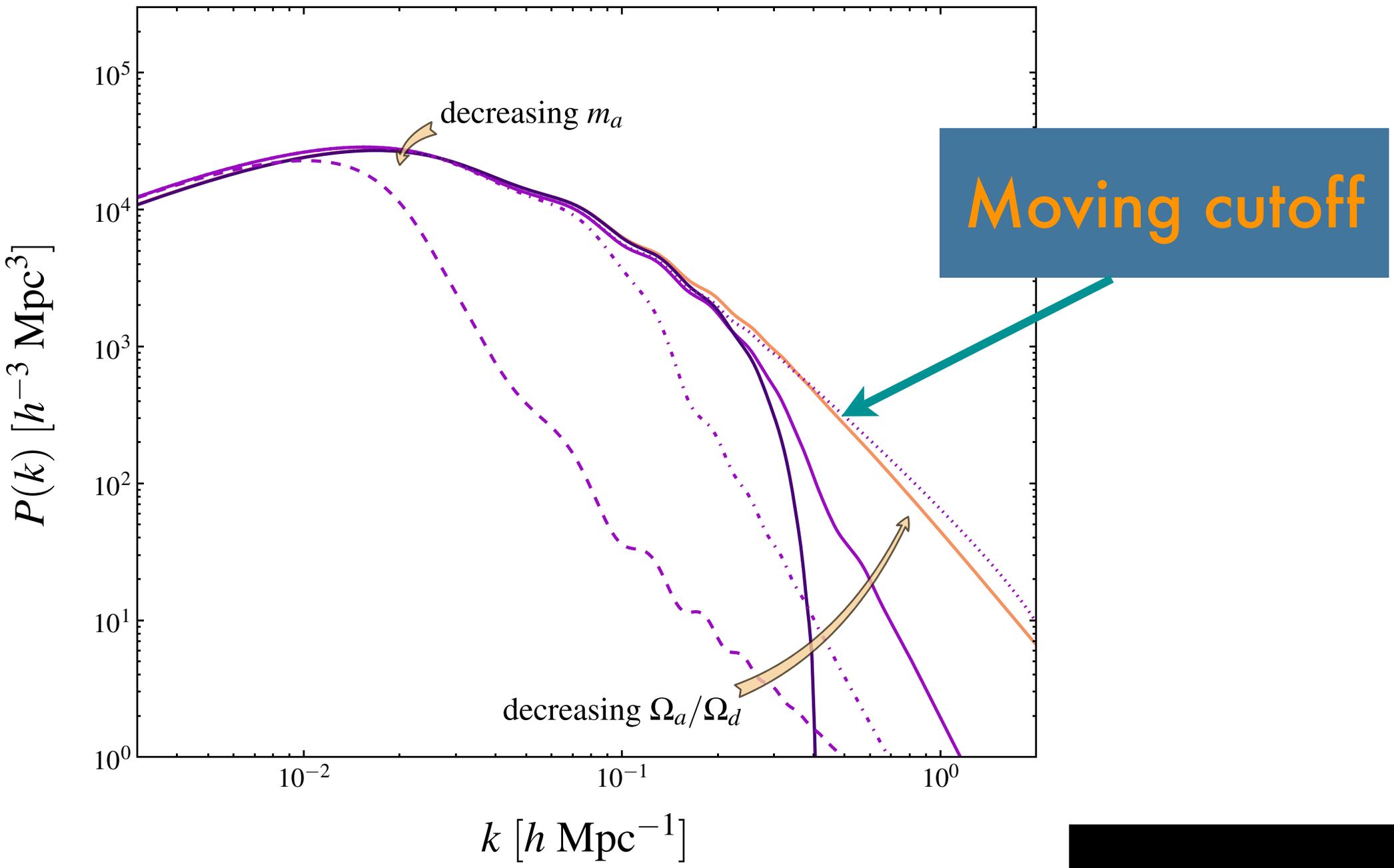


FIG. 1 (color online). Adiabatic matter power spectra, with varying axion mass $m_a = 10^{-28}$, 10^{-26}, 10^{-25}, 10^{-23} eV at fixed density fraction $\Omega_a/\Omega_d = 0.5$ (dashed) and varying $\Omega_a/\Omega_d = 0.1$, 0.5, 1 at fixed $m_a = 10^{-25}$ eV (solid). Spectra

Matter power spectrum



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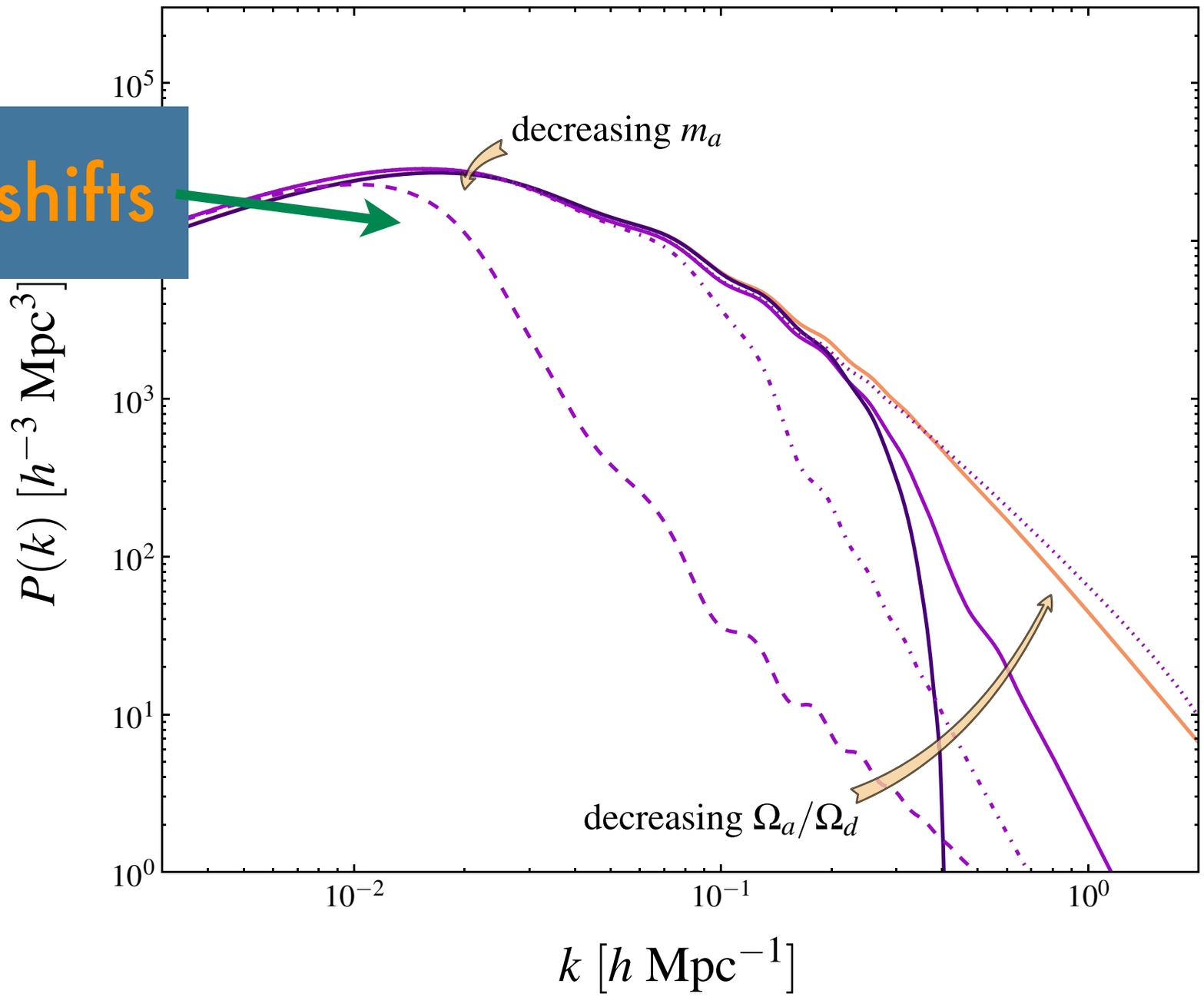
Matter power spectrum

Equality shifts



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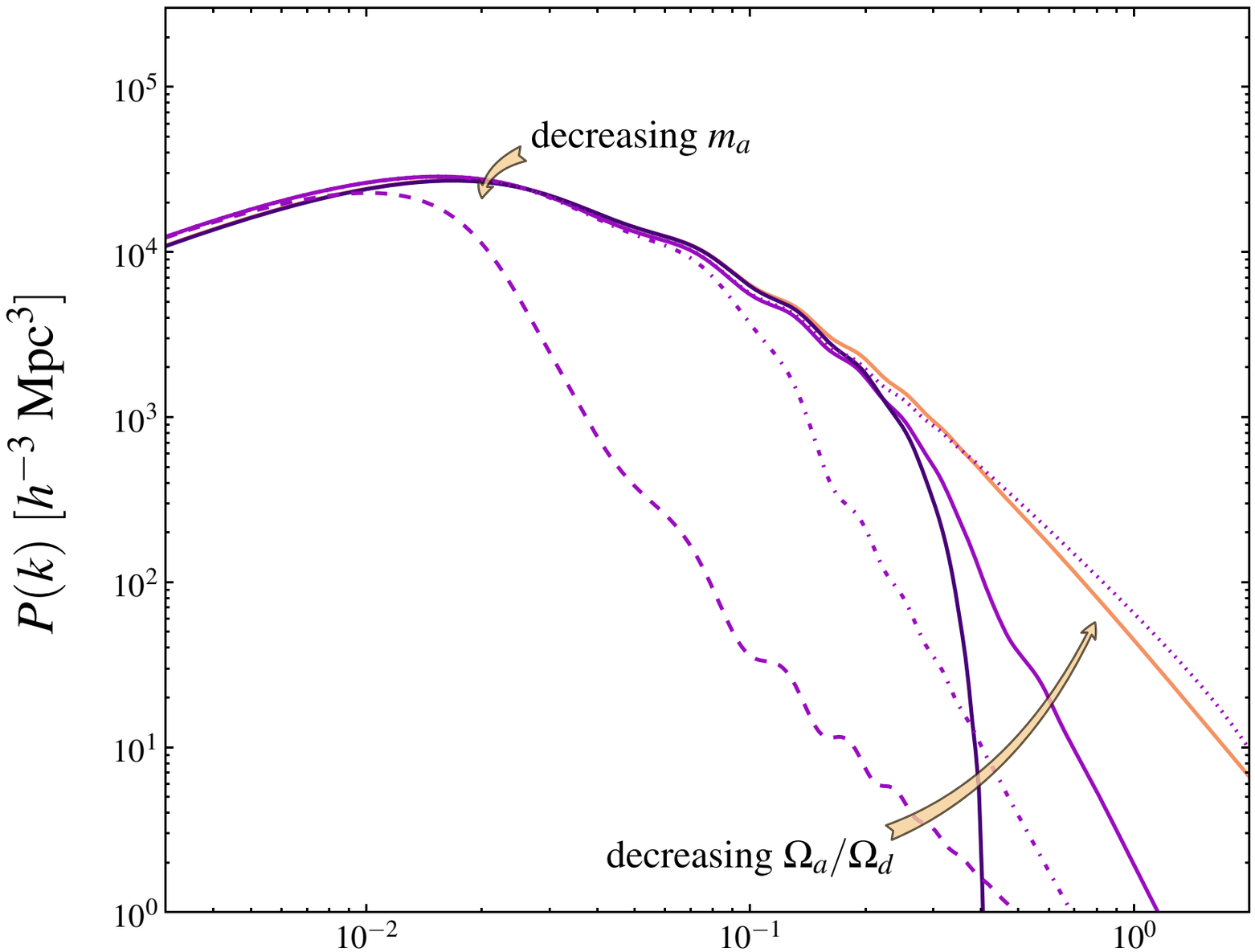
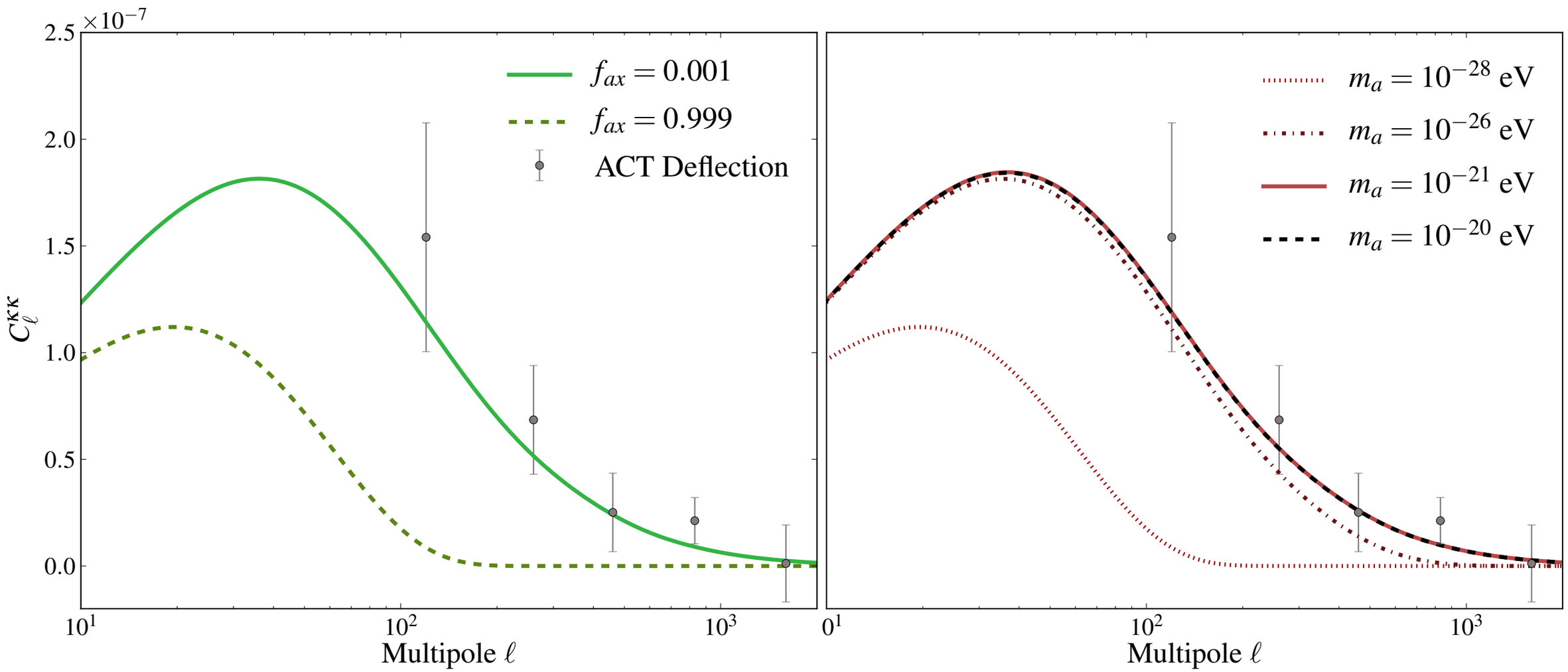


We may now probe ultra-light axions and the axiverse with an MCMC covering 15 orders of magnitude in axion mass

CMB lensing [a probe of matter power spectrum]

$$m_a \sim 10^{-28}\ \mathrm{eV}$$



A new isocurvature signature [e.g. TE polarization]

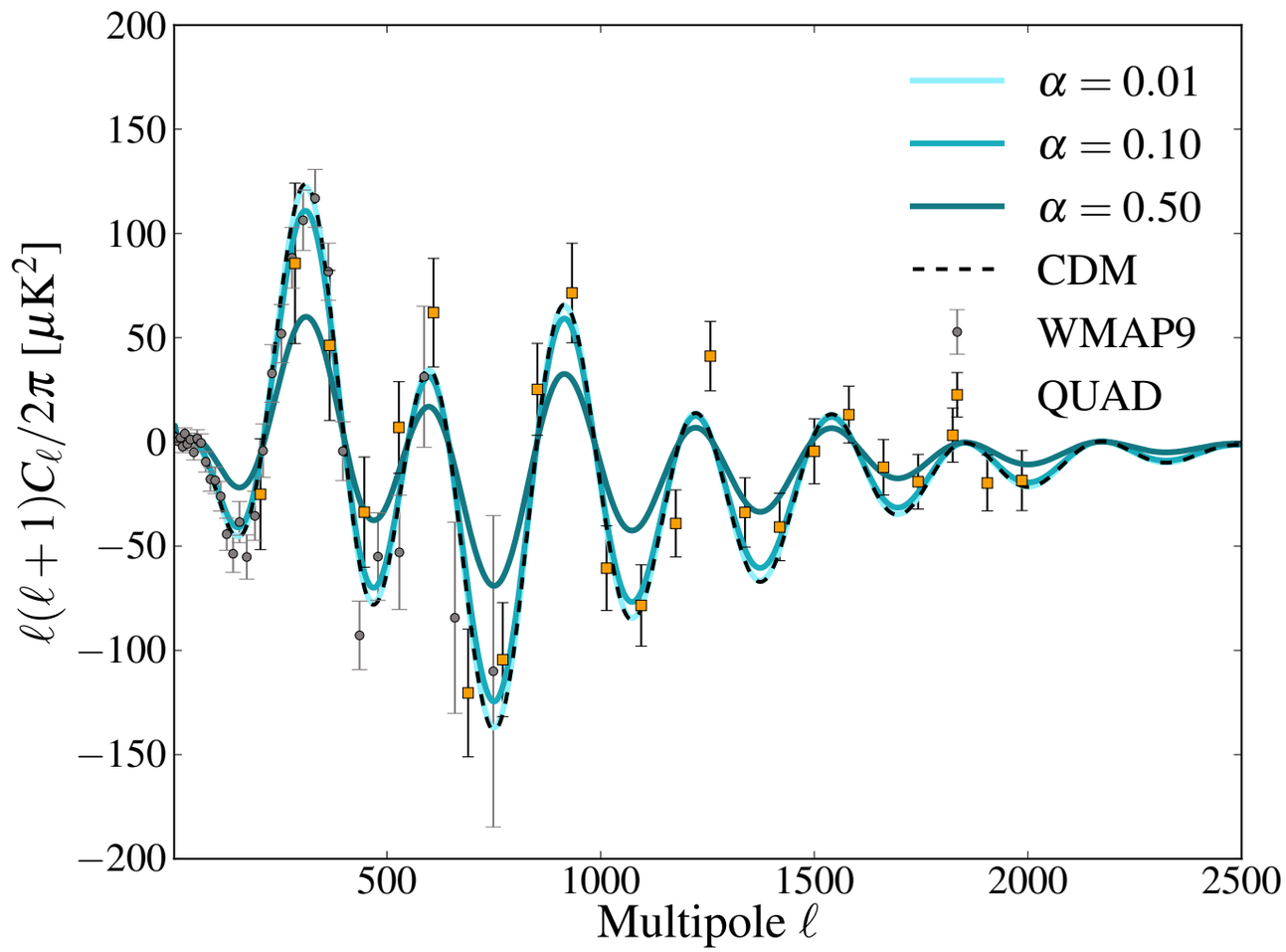


FIG. 5: CMB adiabatic and isocurvature TE polarization power spectra, varying the isocurvature amplitude from $\alpha = 0.01, 0.1, 0.5$ for fixed axion mass, with axions making up nearly all of the DM, $f_{\rm ax} = 0.9999$. The spectra are are a sum of $(1-\alpha)C_\ell^{ad} + \alpha C_\ell^{iso}$, hence adding in isocurvature removes adiabatic power, as can be seen by comparing the combined spectra to the adiabatic CDM-only spectrum, shown by the dashed curve.

The axiverse and the scale of inflation

- Tensor mode amplitude set by inflationary energy scale

$$\frac{k^3 P_h}{2\pi^2} = 8\left(\frac{H_{\rm I}/M_{\rm pl}}{2\pi}\right)^2 \qquad \frac{k^3 P_{\rm R}}{2\pi^2} = \frac{1}{2\epsilon}\left(\frac{H_{\rm I}/M_{\rm pl}}{2\pi}\right)^2\left(\frac{k}{k_0}\right)^{n_s-1}$$

$$\frac{k^3 P_S}{2\pi^2} = 4\left(\frac{H_{\rm I}}{2\pi\phi}\right)^2 \qquad \left(\frac{\phi}{M_{\rm pl}}\right)^2 = \frac{6H_0^2\Omega_a}{m_a^2 a_{\rm osc}^3}$$

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$$r = 2.3\Omega_d h^2\left(\frac{z_{\rm eq}}{\Omega_m}\right)^{3/4}\left(\frac{\Omega_d}{\Omega_a}\right)\left(\frac{10^{-33}{\rm eV}}{m_a}\right)^{1/2}\left(\frac{\alpha}{1-\alpha}\right)$$

The axiverse and the scale of inflation

Komatsu al. 2008/2011 find

$$\alpha_{\rm ax} \lesssim 0.1$$

The axiverse and the scale of inflation

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$$\alpha_{\rm ax} \lesssim 0.1$$

$$r = 0.3 \left(\frac{\Omega_d/\Omega_a}{100} \right) \left(\frac{10^{-33}\mathrm{eV}}{m_a} \right)^{1/2}$$

Stay tuned for MCMC constraints to the axiverse!

New window on inflationary energy scale

$$H_I = 2.4 \times 10^{13}\ \mathrm{GeV} \left(\frac{\alpha_{\mathrm{CDM}}}{0.047}\right)^{1/2} \left(\frac{\Omega_a}{0.233}\right)^{-1/2}$$

$$\times \begin{cases} \left(\frac{m_{\mathrm{a}}}{3\times 10^{-28}\ \mathrm{eV}}\right)^{-1/4} & \text{if } a_{\mathrm{osc}} < a_{\mathrm{eq}} \\ 1 & \text{if } a_{\mathrm{osc}} \geq a_{\mathrm{eq}} \end{cases}$$

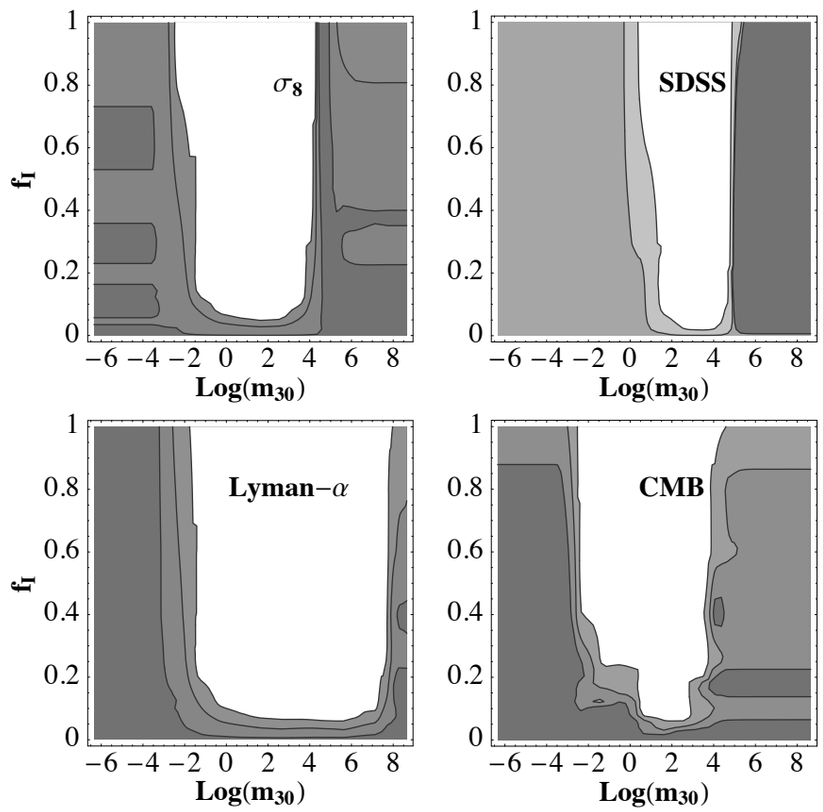
The axiverse and the scale of inflation

✳ Compare with (in usual scenario)

$$r \sim 5 \times 10^{-12} \left(\frac{\Omega_{\rm c}}{\Omega_{\rm a}} \right)^{2/7}$$

Komatsu al. 2008/2011

Amendola and Barbieri



Old power spectrum constraints from Amendola and Barbieri, arXiv:hep-ph/0509257

1) Grid search
2) No isocurvature
3) No marginalization over foregrounds
4) No lensing, no polarization
5) No real Boltzmann code [step in power spectrum, or unclustered DE at low m]

Motivation/anticipated contours

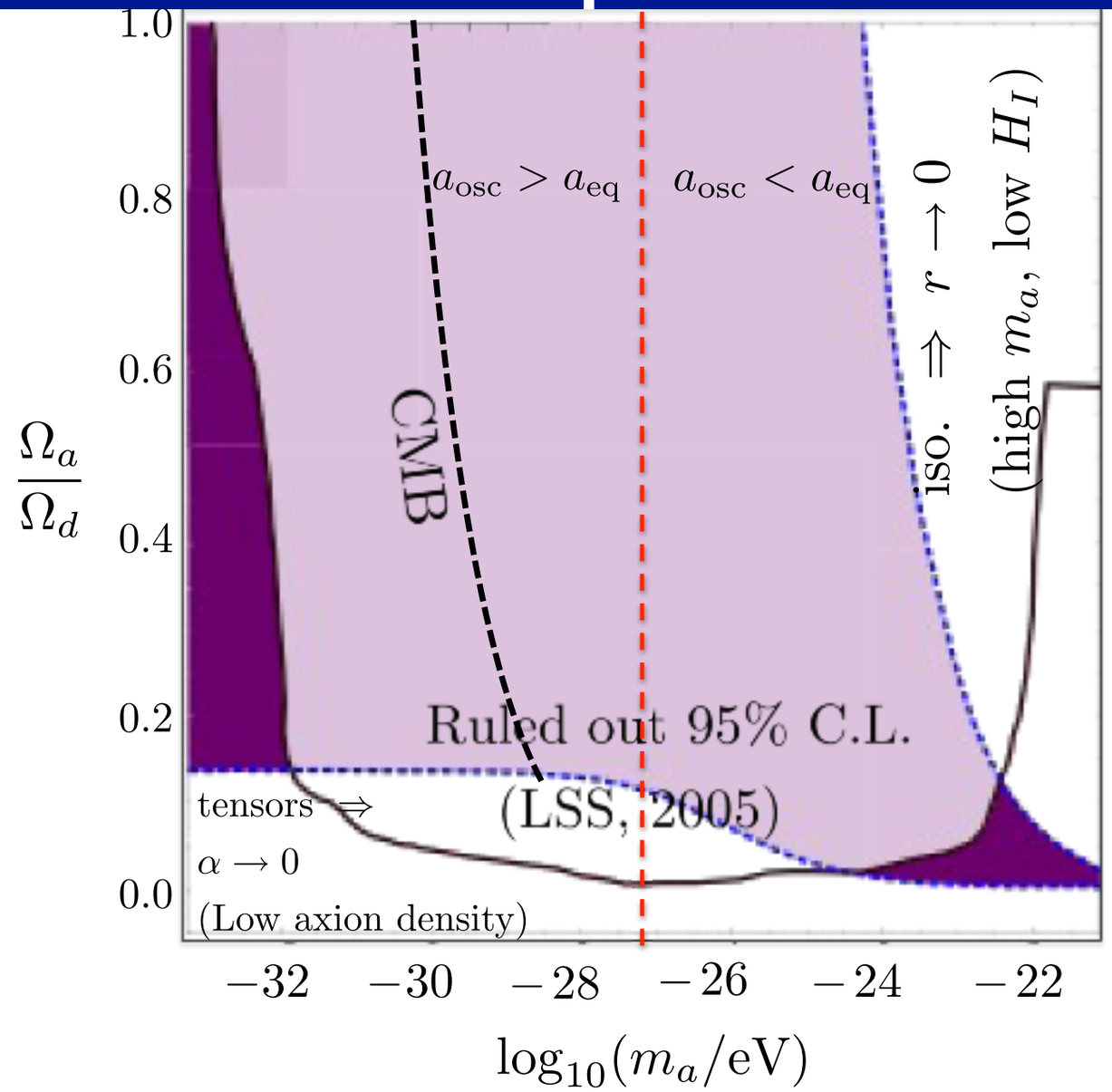
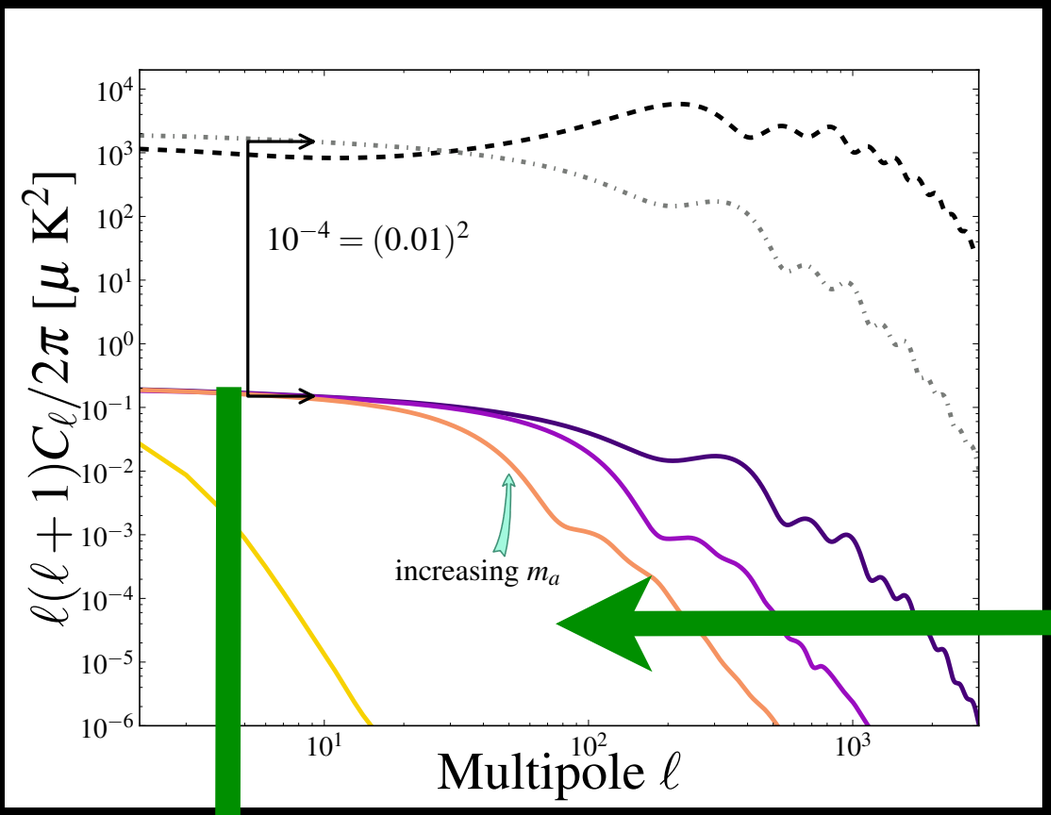
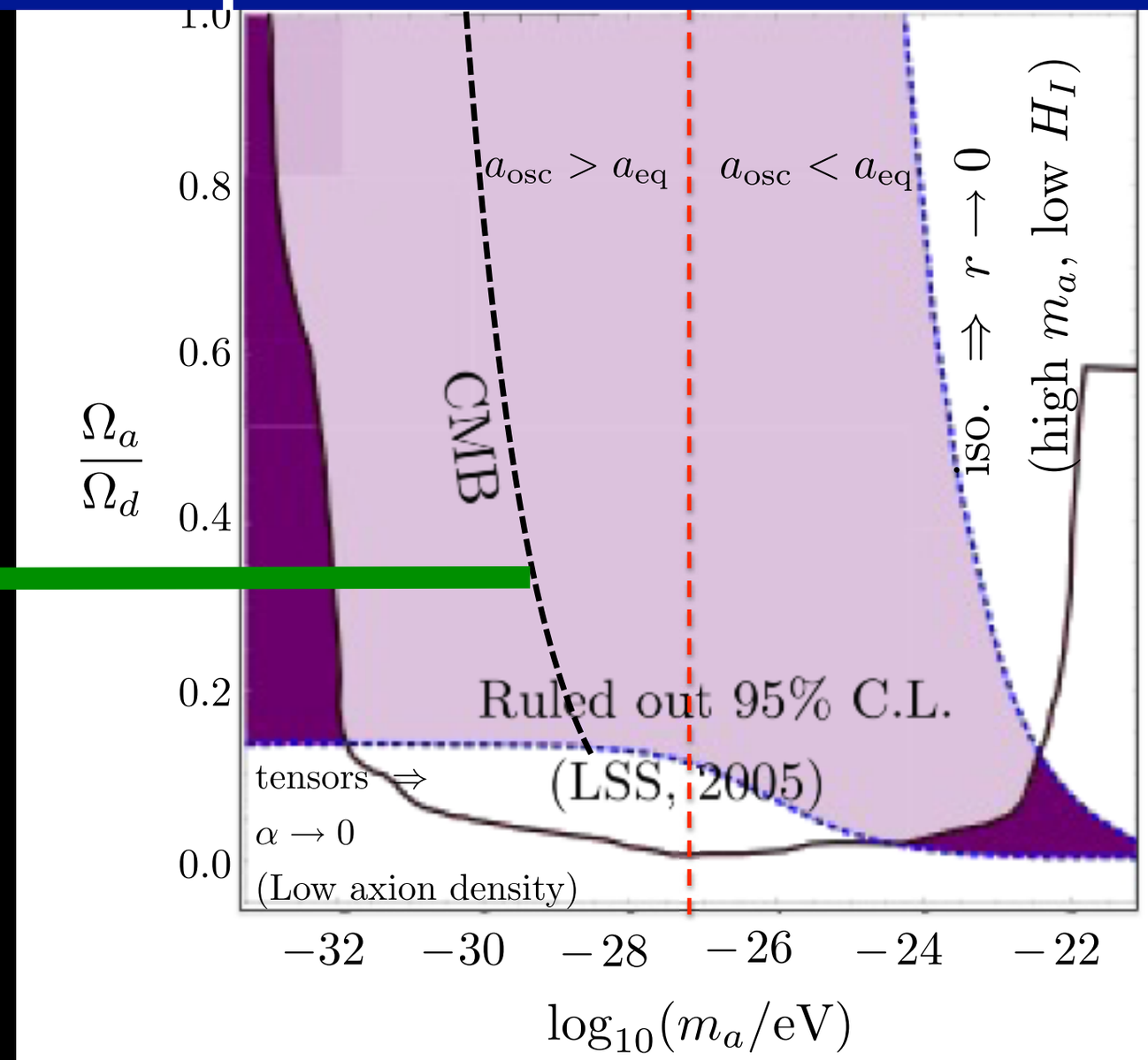


FIG. 2 (color online). Phenomenology in the $\{m_a, \Omega_a/\Omega_d\}$ plane. The shaded regions lie between the dashed contours and satisfy $\{0.01 < r < 0.1, 0.01 < \alpha_{\rm CDM} < 0.047\}$, evading current constraints, while being potentially observable with future data.

Old power spectrum constraints from Amendola and Barbieri, rough forecast of what we should see

Motivation/anticipated contours





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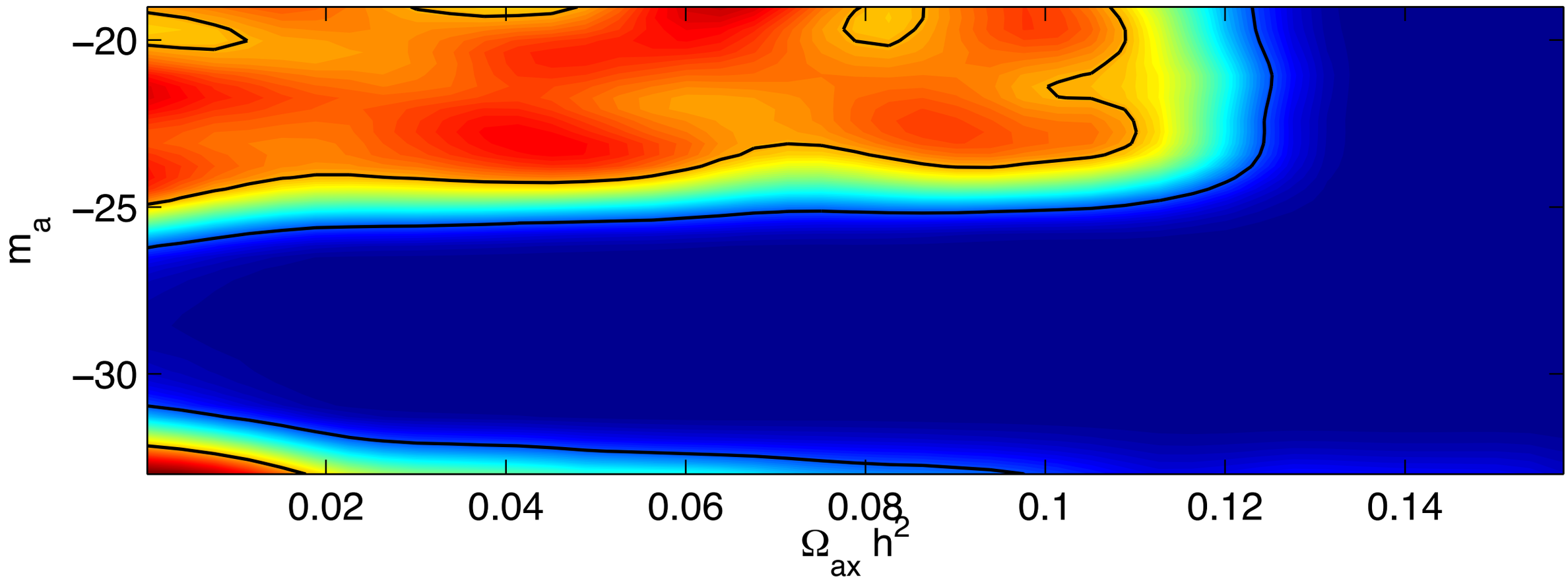
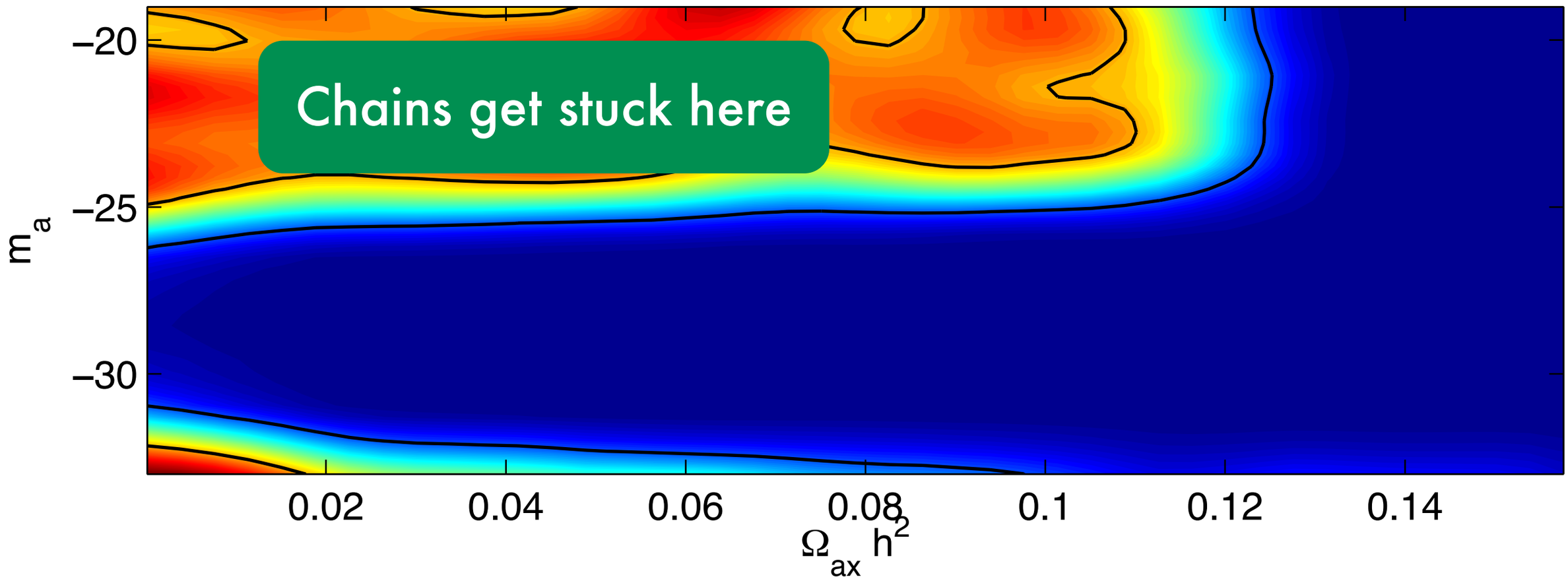
Loss of low-l modes in SW plateau when axion mass is low: analytic estimate

Preliminary adiabatic results



Metropolis-Hastings algorithm is not good for multimodal distributions!

Preliminary adiabatic results



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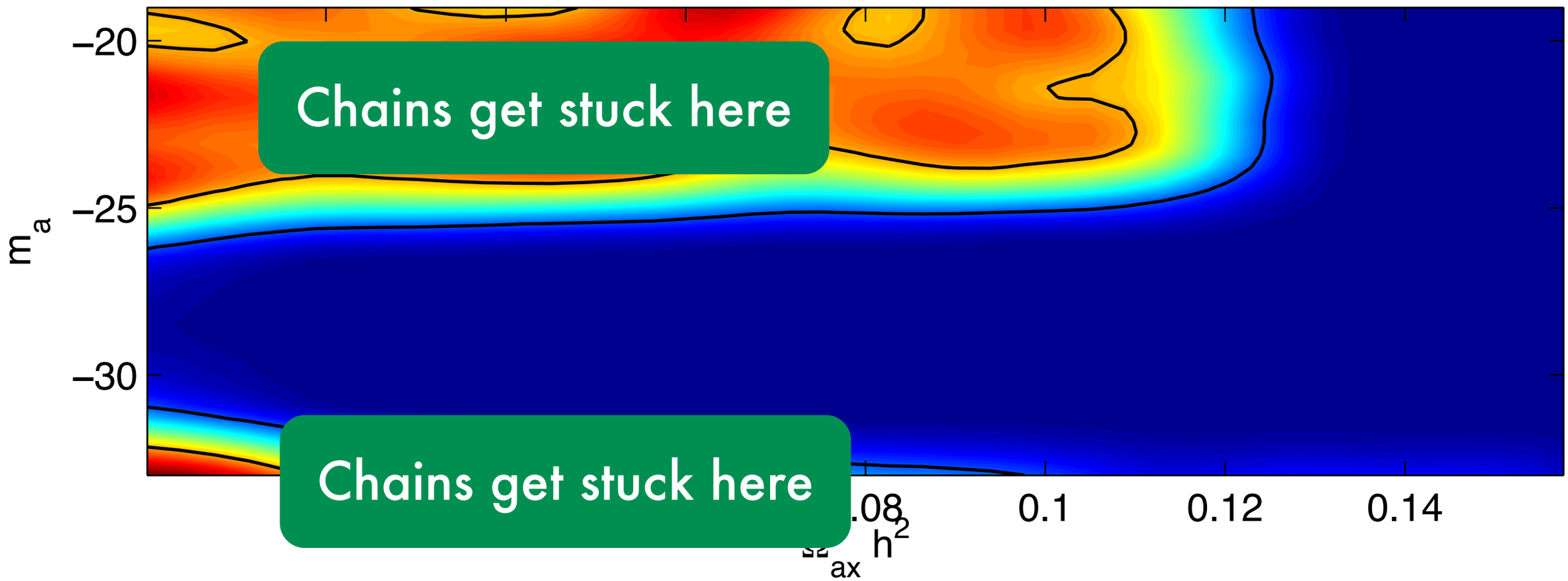
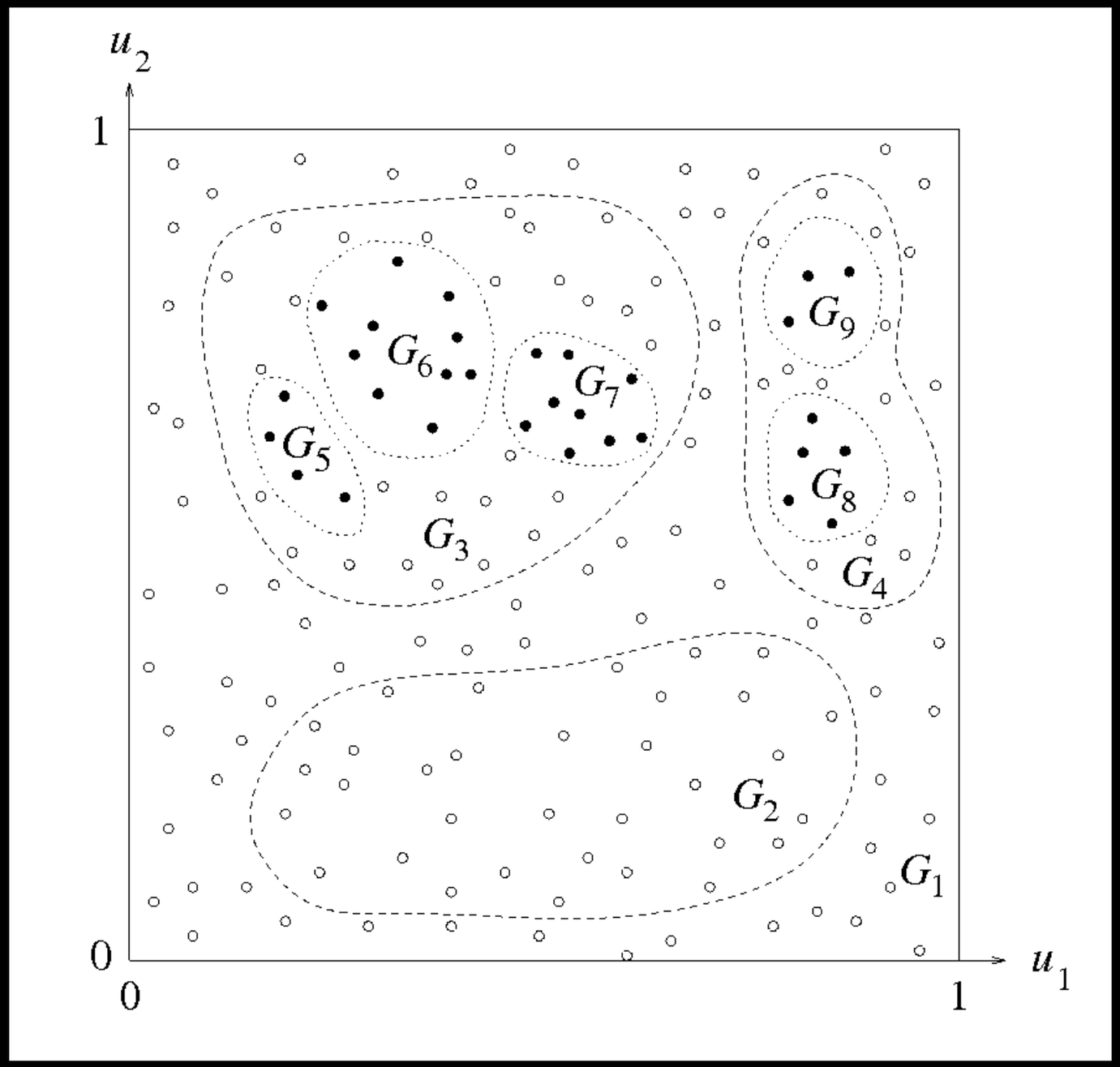


Metropolis-Hastings algorithm is not good for multimodal distributions!

We use nested sampling instead



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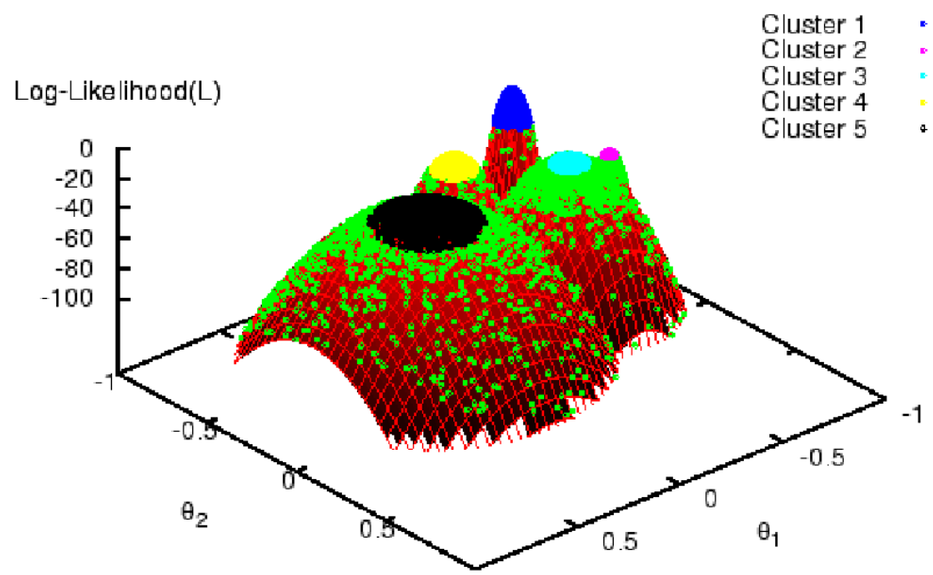
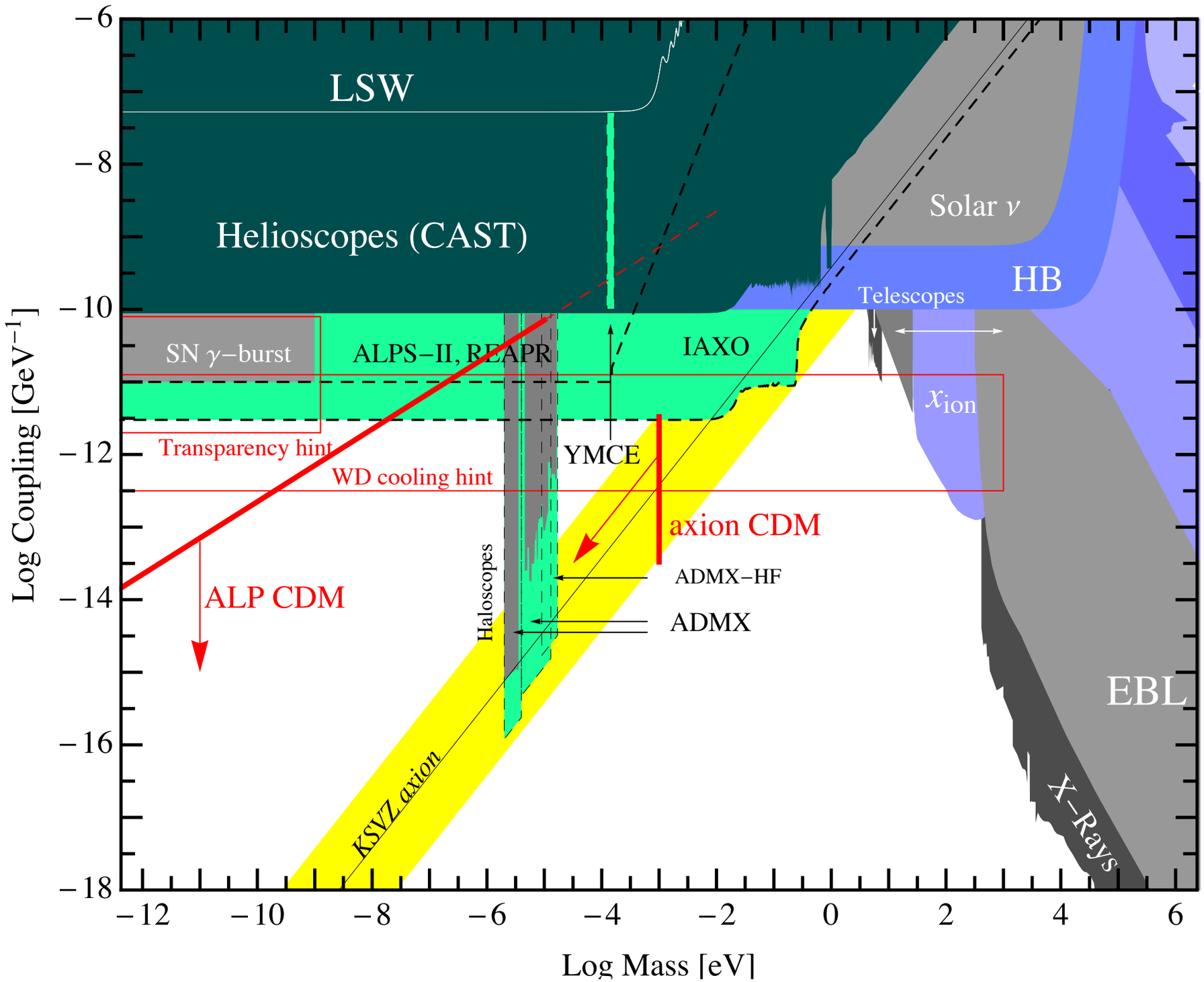
From Hobson 2012

TOY PROBLEM: MULTIPLE GAUSSIAN LIKELIHOOD



- Likelihood = five 2-D Gaussians of varying widths and amplitudes; prior = uniform
- Analytic evidence integral $\log E = -5.27$
- MULTINEST: $\log E = -5.33 \pm 0.11$, $N_{\text{like}} \approx 10^4$
- Thermodynamic integration (+ error): $\log E = -5.24 \pm 0.12$, $N_{\text{like}} \approx 4 \times 10^6$
- Typical of real applications (see later): $\sim 500\times$ efficiency of standard MCMC

Lay of the land



PREVIOUSLY KNOWN CONSTRAINTS/PROBES

✳ ***Solutions:*** non-Gaussianity? (Lyth, Ungarelli, Wands 2008)

- ✳In curvaton models, $\rho_\sigma = m^2\sigma^2/2$
- ✳Non-linearity in σ induces local type non-Gaussianity

$$f_{\rm nl} = \frac{5}{4}\left(\frac{\rho_{\rm tot}}{\rho_{\rm curvaton}}\right)_{\rm decay}$$

$$1 \lesssim f_{\rm nl} \lesssim 10$$

Very challenging to detect!

- ✳Not a unique probe of CIPs: true for curvaton model in general
- ✳Would fail to detect a non-curvaton CIP!