Some new isocurvature directions

Daniel Grin (KICP Chicago)
Dartmouth Physics/Astronomy Seminar
3/27/2014

Outline

✴ *Are the primordial fluctuations adiabatic?*

Isocurvature and CMB spectral distortions

QCD axions, ultralight axions, and isocurvature

CMB frequency spectrum distortions from isocurvature modes

with J.Chluba (CITA/JHU)

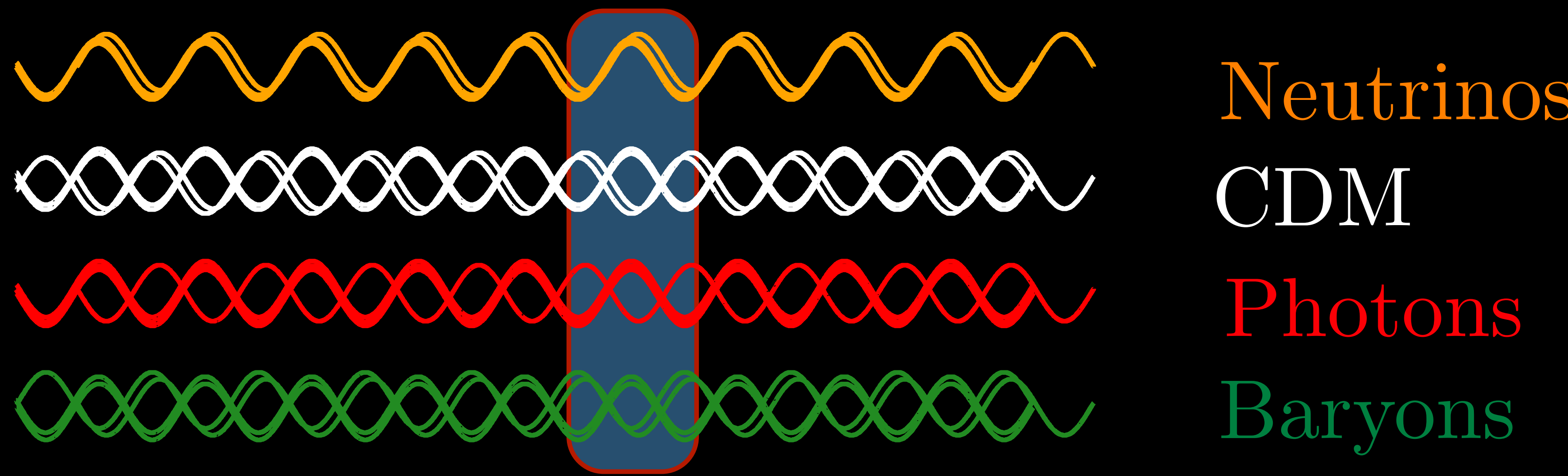
arXiv:1304.4596, *MNRAS 434, 1619*

Baryon isocurvature

CDM isocurvature

ν isocurvature

Adiabatic



$S_b \neq 0$

$S_c \neq 0$

$S_\nu \neq 0$

$S_i = 0$

$\Delta\Phi = 0$

All density initial conditions can be expressed in terms of these!

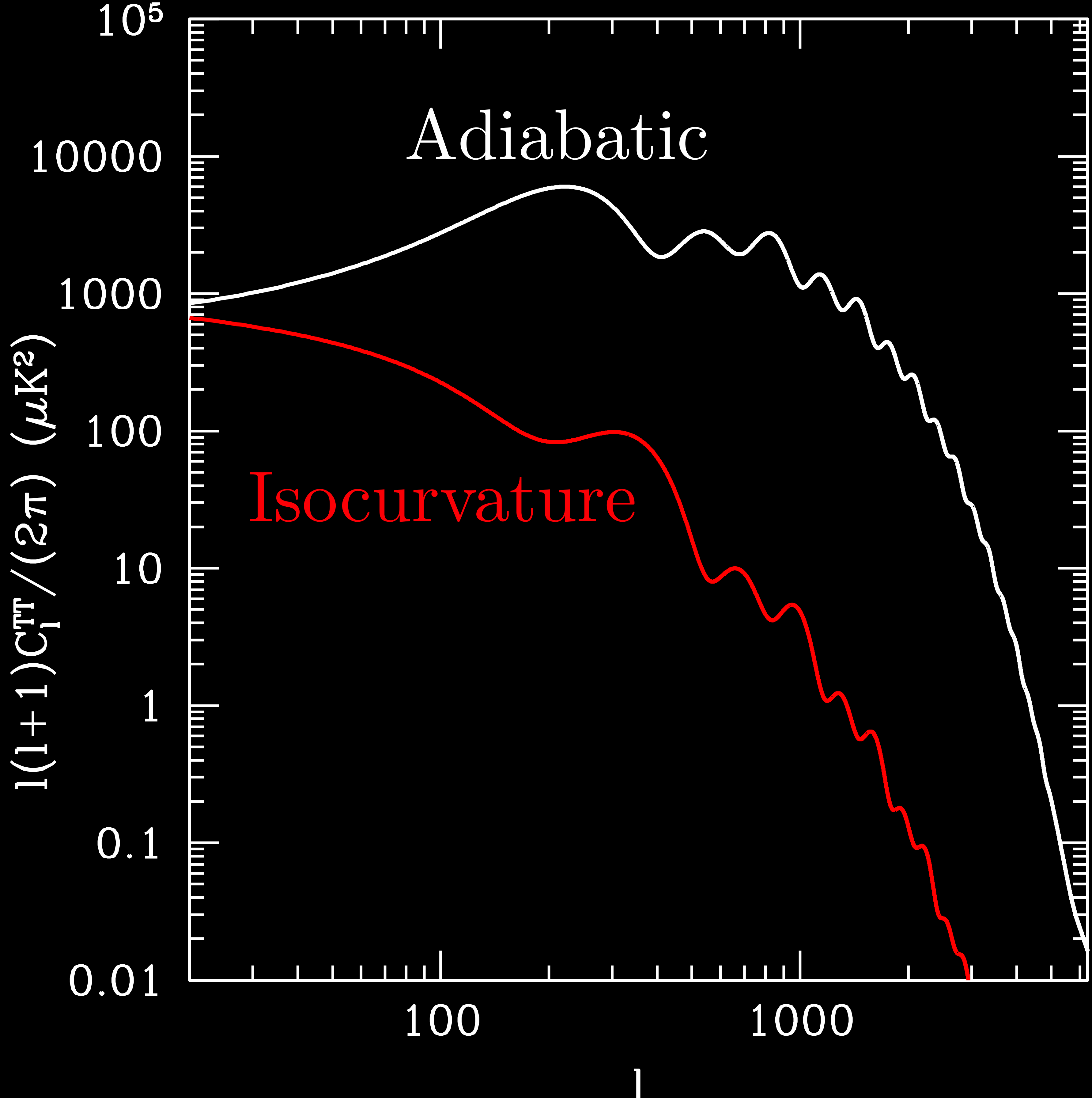
These conditions are not conserved under fluid evolution

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

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

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

SACHS WOLFE-EFFECT & POWER SPECTRA



ISOCURVATURE AND ACOUSTIC WAVE EVOLUTION

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

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

  - *Isocurvature*

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

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

Two flavors of CDM isocurvature

- Axion-type isocurvature: $\boxed{S_{\rm c} \text{ uncorrelated with } \zeta}$

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

- Curvaton-type isocurvature: $\boxed{S_{\rm c} \text{ correlated with } \zeta}$
  - Curvaton dominates after inflation, seeds adiabatic ζ
  - Baryons/CDM produced before ζ growth complete: isocurvature from mismatch

CURVATON MODELS AND ISOCURVATURE

- Hard for an inflationary model to do everything you want

$$\frac{k^3 P_{\mathcal{R}}(k)}{2\pi^2} = \frac{H_k^2}{8\pi^2 M_{\rm pl}^2 \epsilon} \qquad \epsilon = \frac{M_{\rm pl}^2}{2}\left(\frac{V'}{V}\right)^2$$

- Instead, have a spectator σ (curvaton) that briefly dominates after inflation
- Sources entropy fluctuation in species that are generated before curvaton dom.

$$S_{\rm c} = \delta_{\rm c} - \frac{3}{4}\delta_{\rm rad} = -\frac{3}{4}\delta_{\rm rad}$$

- Curvaton dominates, decays, adiabatic (correlated with isocurvature) results

$$\zeta = \frac{\rho_\sigma}{3\rho_{\rm tot}}\delta_\sigma$$

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

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

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

OBSERVATIONAL CONSTRAINTS TO ISOCURVATURE

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

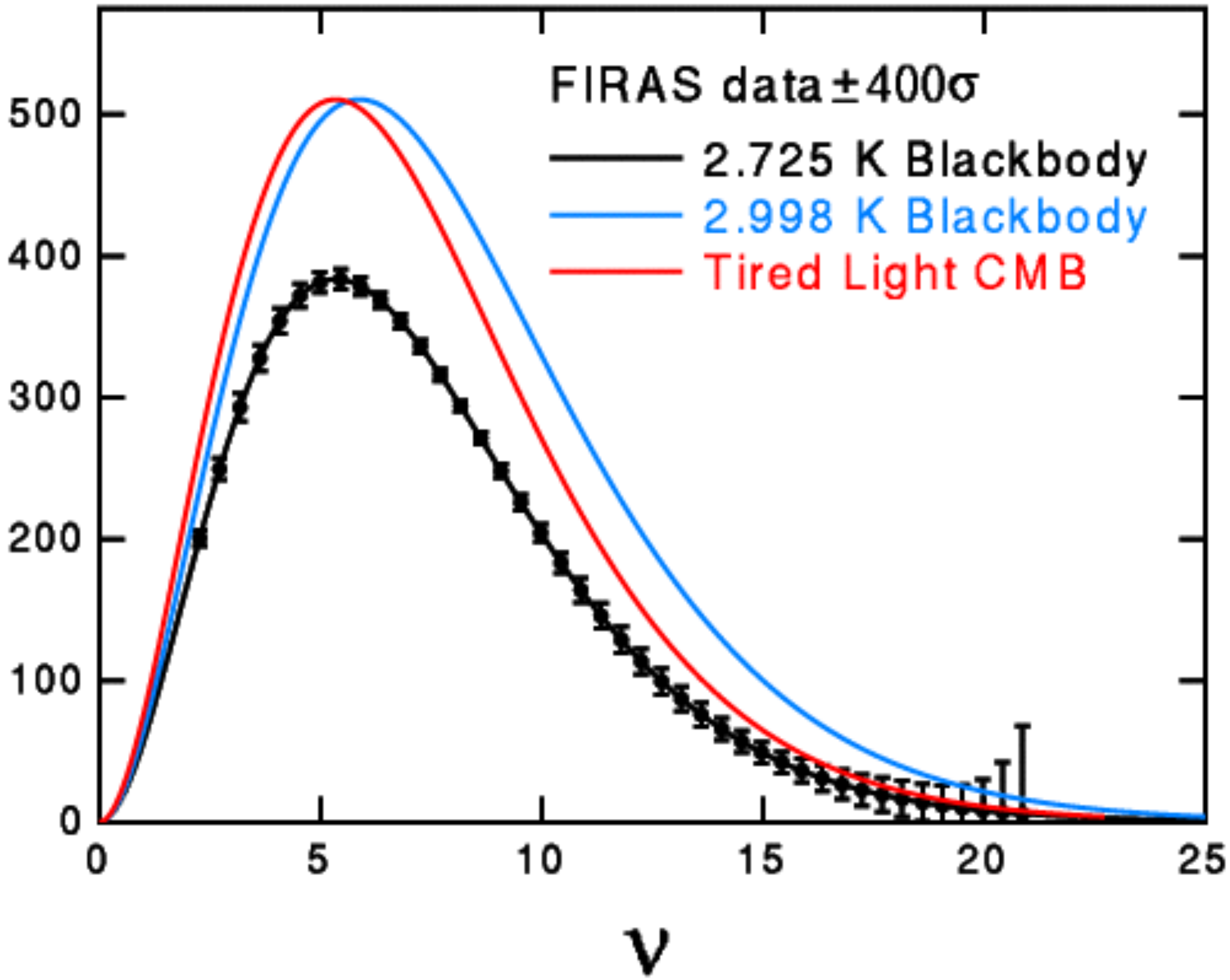
$$P_{\mathrm{S_c}}^{\mathrm{axion}}/P_\zeta \lesssim 0.13 \qquad P_{\mathrm{S_c}}^{\mathrm{curvaton}}/P_\zeta \lesssim 0.01$$

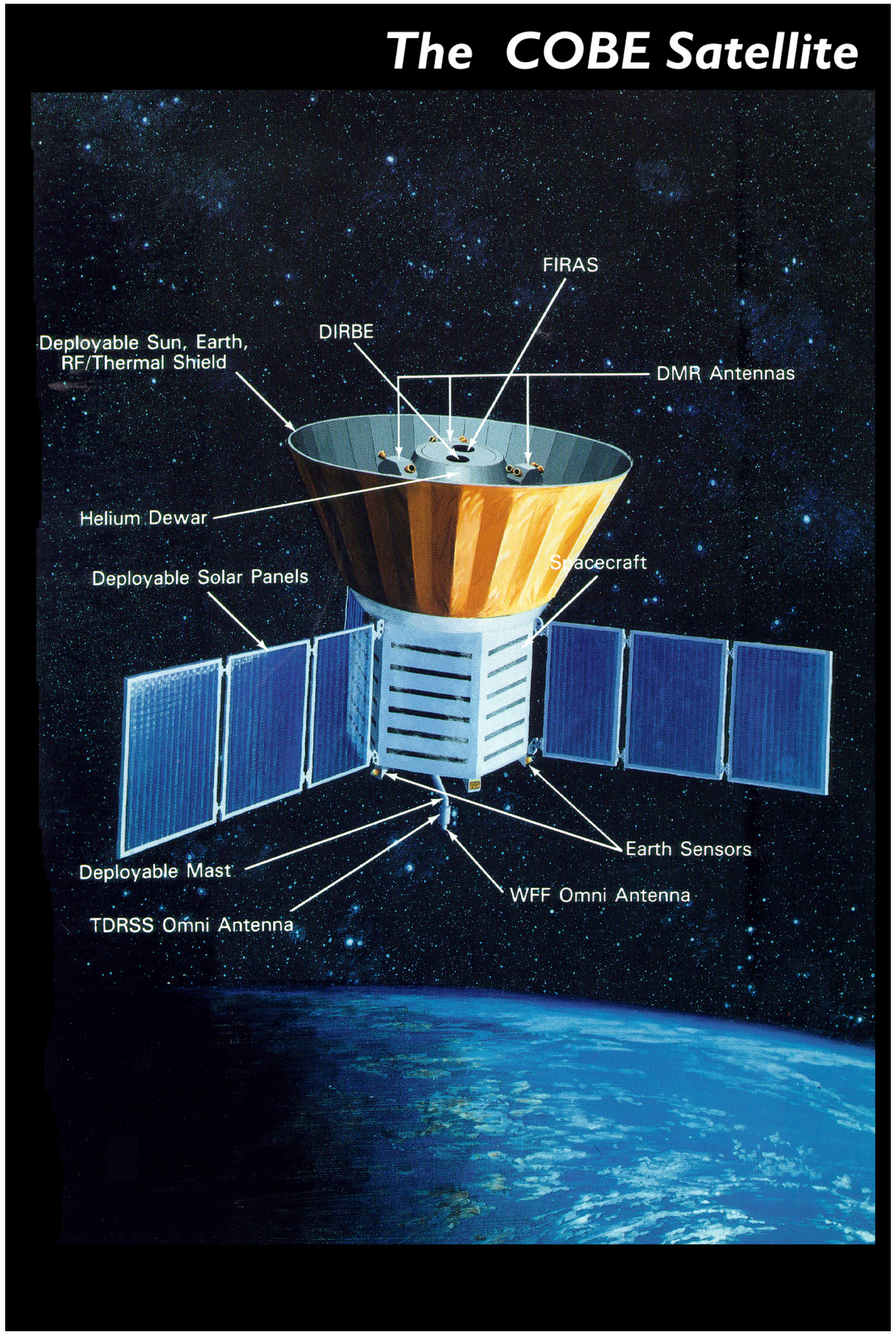
$$4.6 \times 10^{-3} \lesssim \frac{P_{\mathrm{iso}}}{P_{\mathrm{tot}}} \lesssim 1.6 \times 10^{-2}$$

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

- Planck 1st-year temperature constraints (Et al *et al*

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’

THE ASTROPHYSICAL JOURNAL, **344**:24–34, 1989 September 1

SPECTRAL DISTORTIONS OF THE COSMIC MICROWAVE BACKGROUND

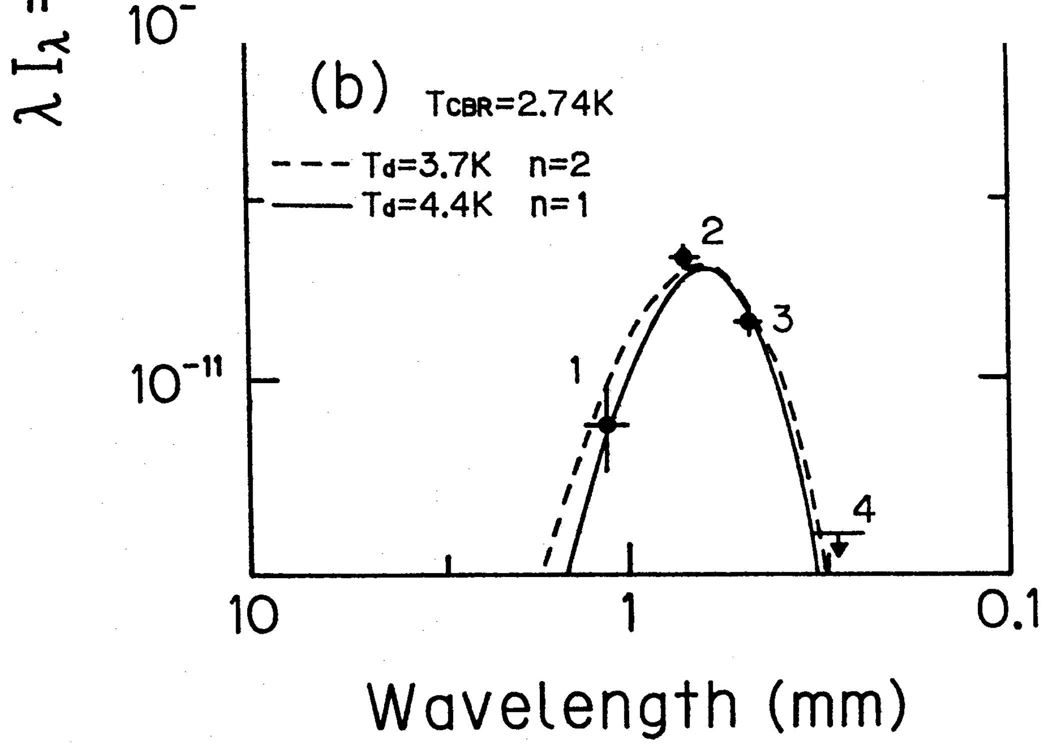
FRED C. ADAMS,[1] KATHERINE FREESE,[2] JANNA LEVIN,[2] AND JONATHAN C. MCDOWELL[1]

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.

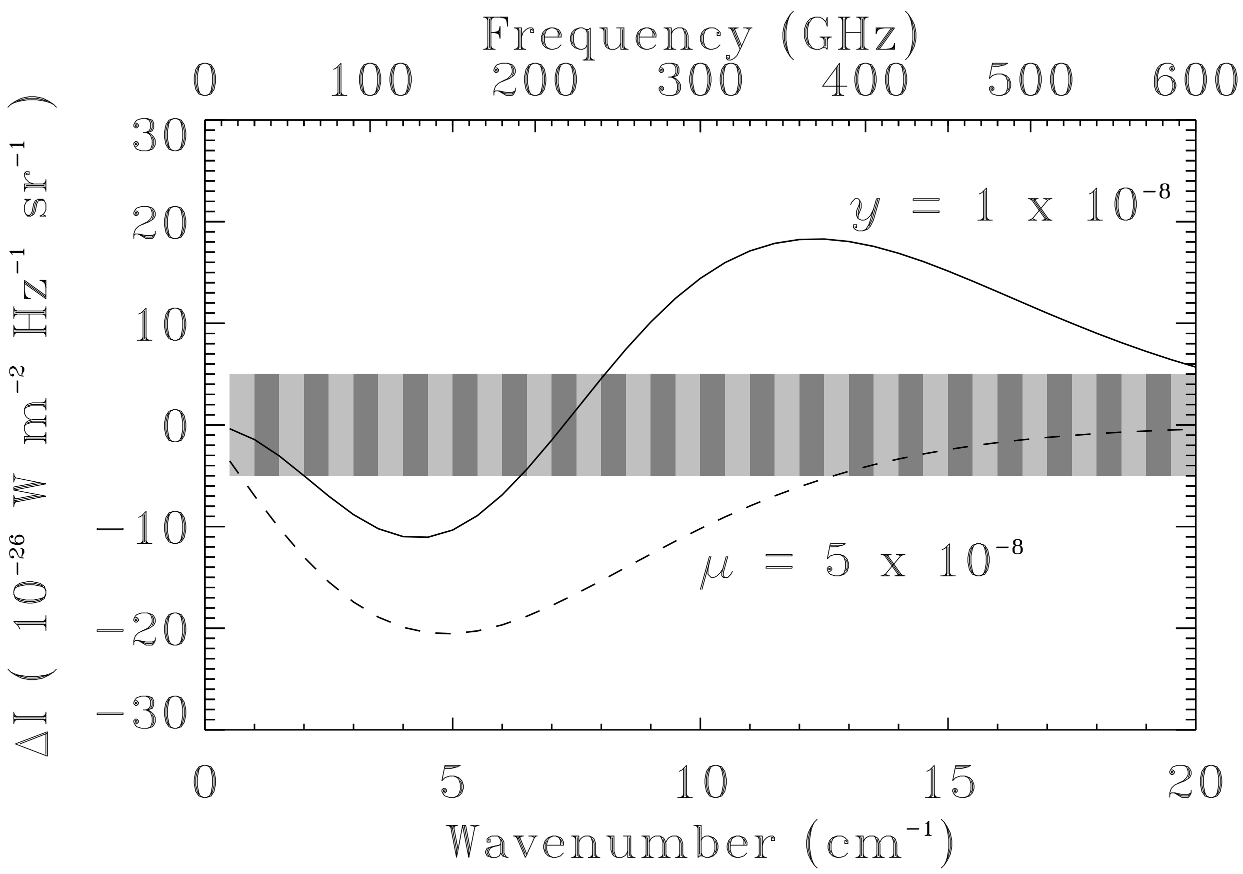
Subject headings: cosmic background radiation — cosmology — radiation mechanisms

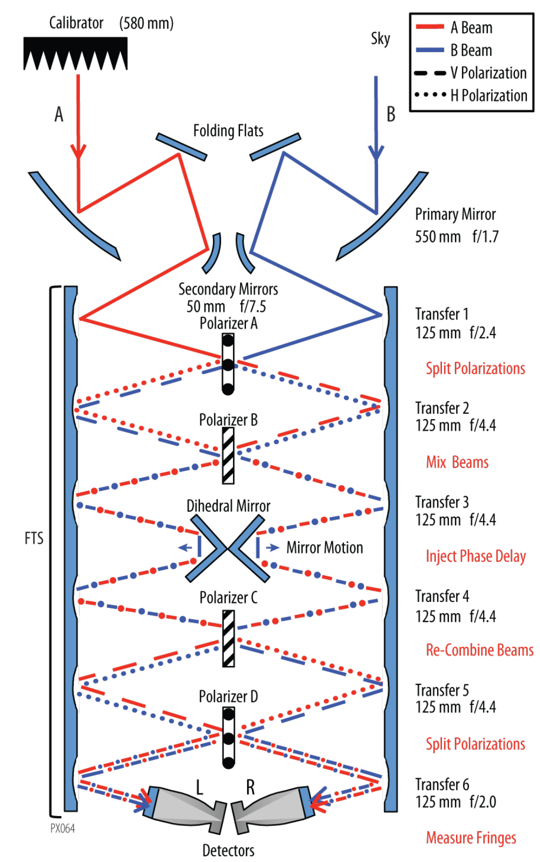


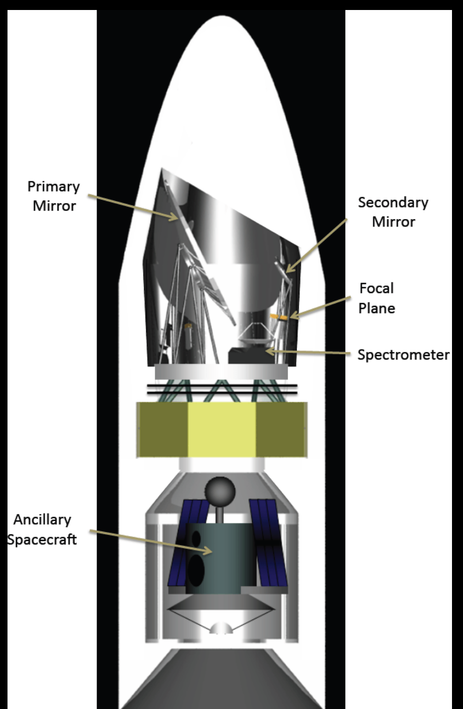
Lange et al. 1987

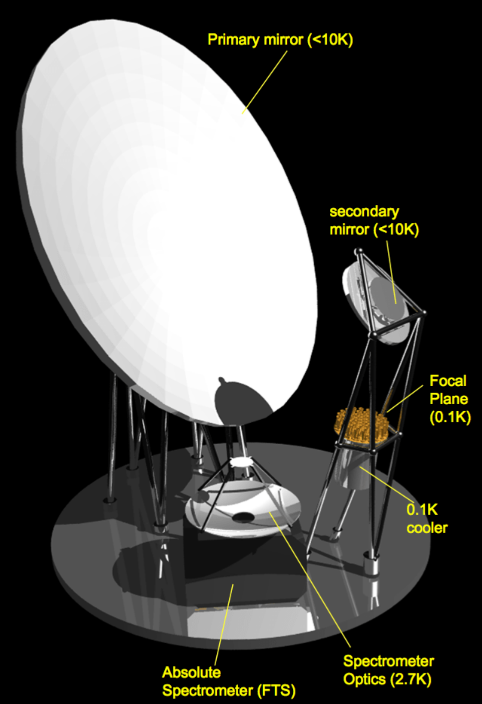
EXPERIMENTAL HORIZON

PIXIE (Explorer proposal, $200M)









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

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 $4 \times 10^4 \ll z \ll 2 \times 10^6$

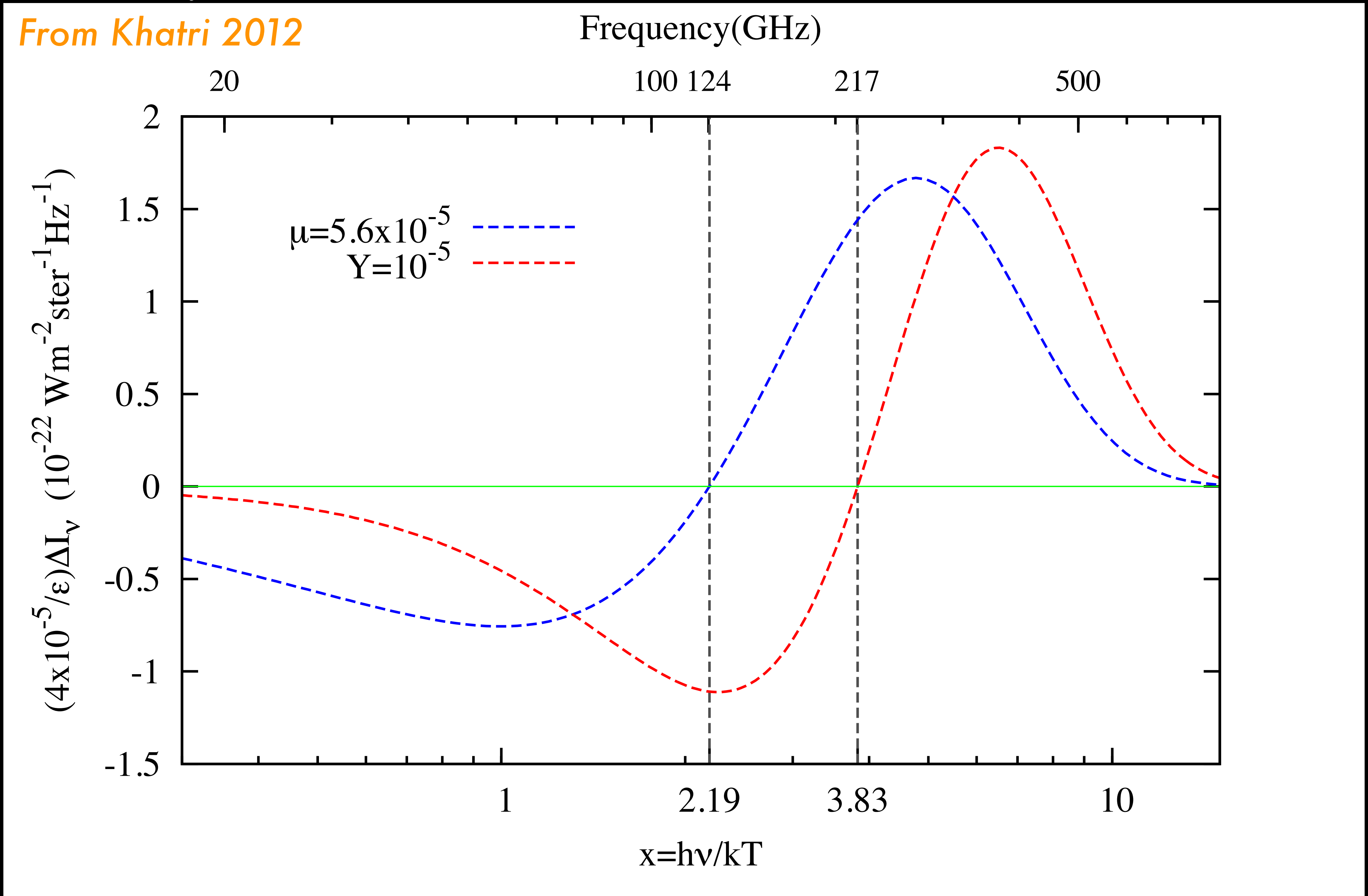
$$e^- + \gamma \leftrightarrow e^- + \gamma \quad \text{Energy-exchanging Compton scattering}$$

✳ 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.....

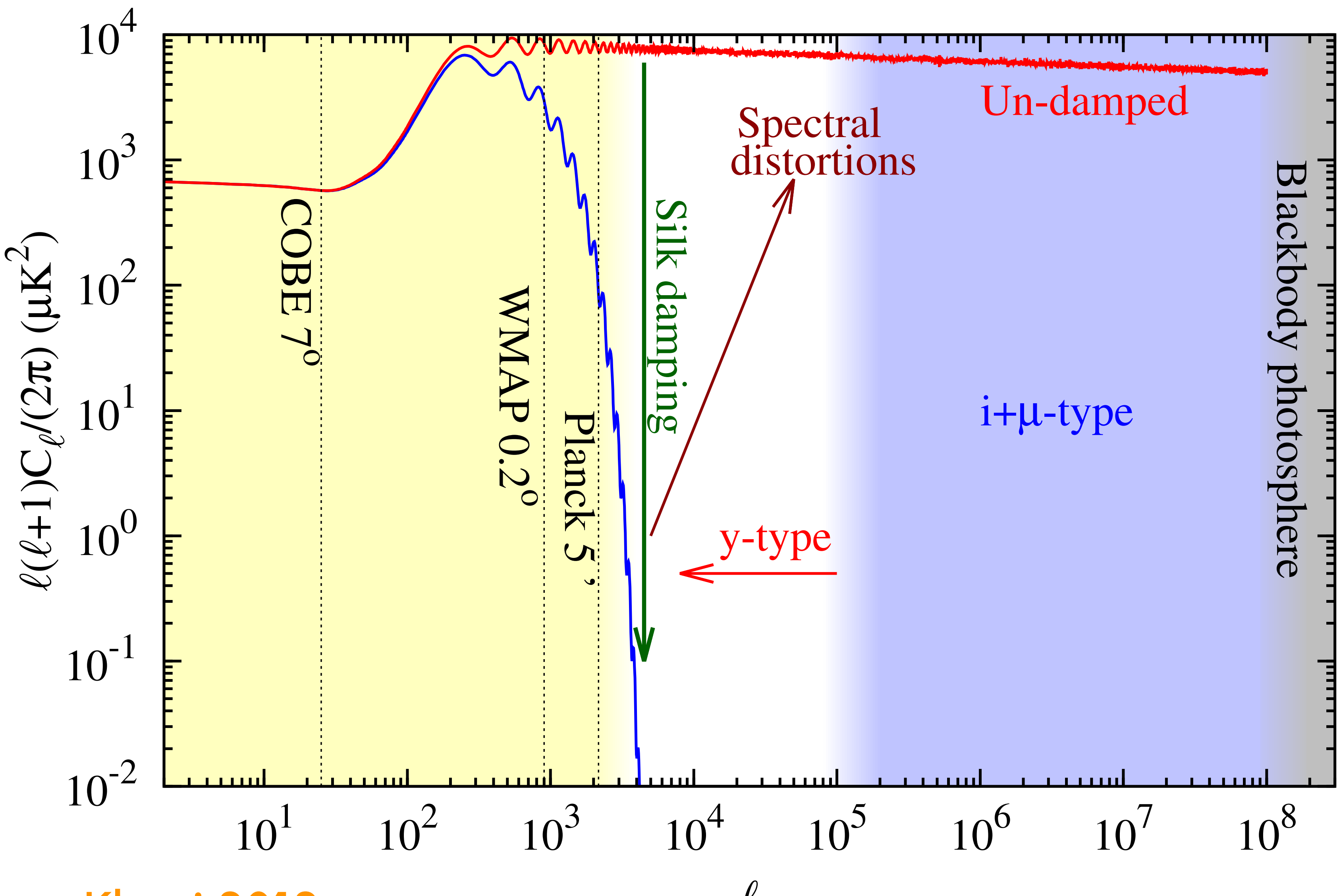
μ AND Y-TYPE DISTORTION



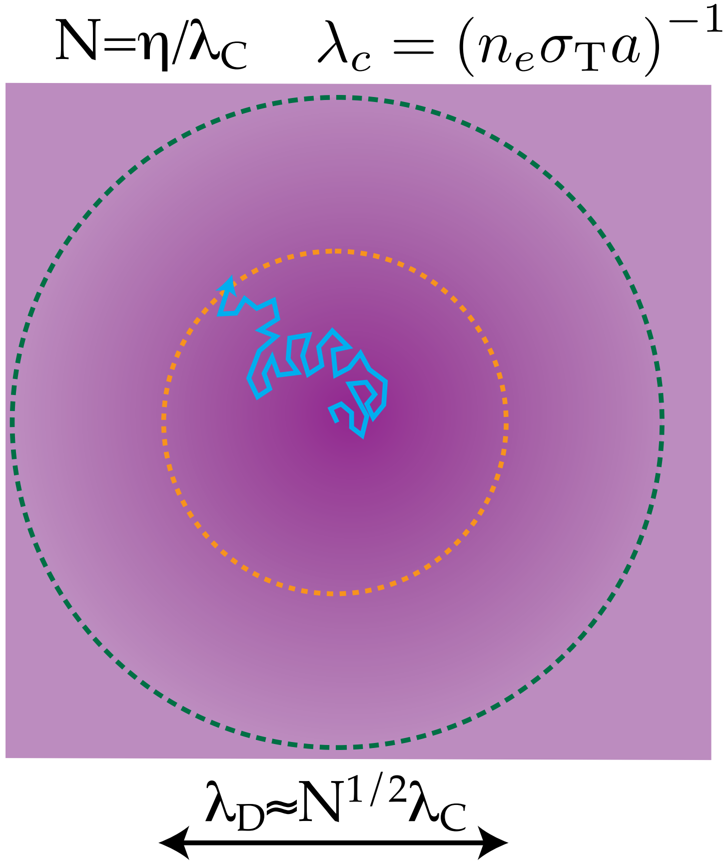
ENERGY INJECTION

- Dark matter annihilation (photons produced directly or through cascades)
  Chluba 2009
- Dark matter decay
- Damping of acoustic modes — Chluba/Erickcek/Ben-Dayan 2012
  - Steps in primordial power spectrum
  - Bumps in primordial power spectrum
  - Features from inflationary particle production
  - Running mass inflaton
- Gauge boson production from cosmic strings — Tashiro and Vachaspati 2012
- Primordial magnetic field damping — Marsh/Silk/Tashiro 2013

SILK DAMPING AND DISTORTION FROM ADIABATIC MODES



From Khatri 2012



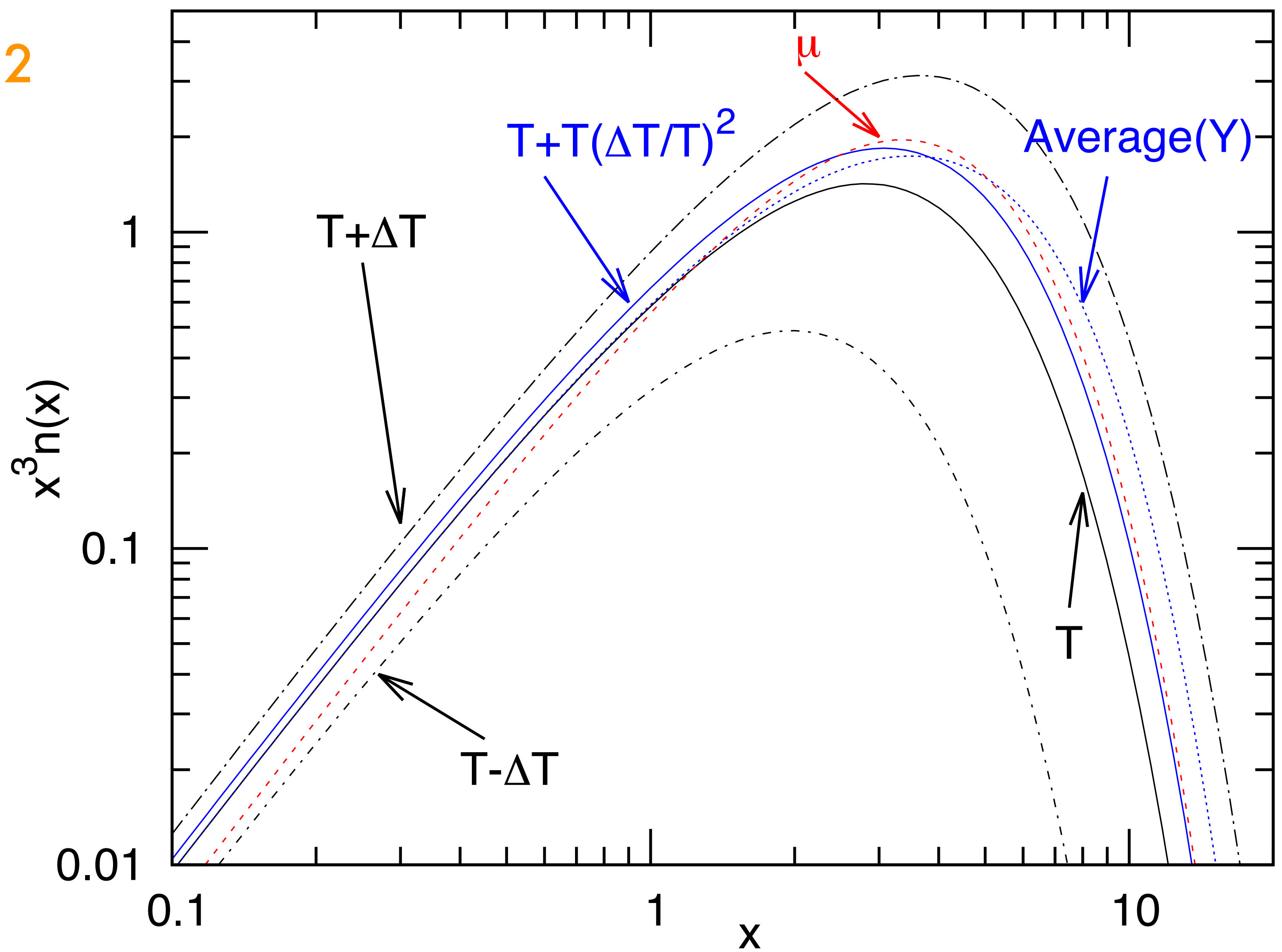
Mode dissipation mixes black bodies – these distortions begin their life as y distortions, the epoch determines the rest

NEARLY Scale-invariant LCDM cosmology

$$\mu \sim 2 \times 10^{-8}$$
$$y \sim 4 \times 10^{-9}$$

SUPERPOSITION OF BLACKBODIES

From Khatri 2012



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

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!]

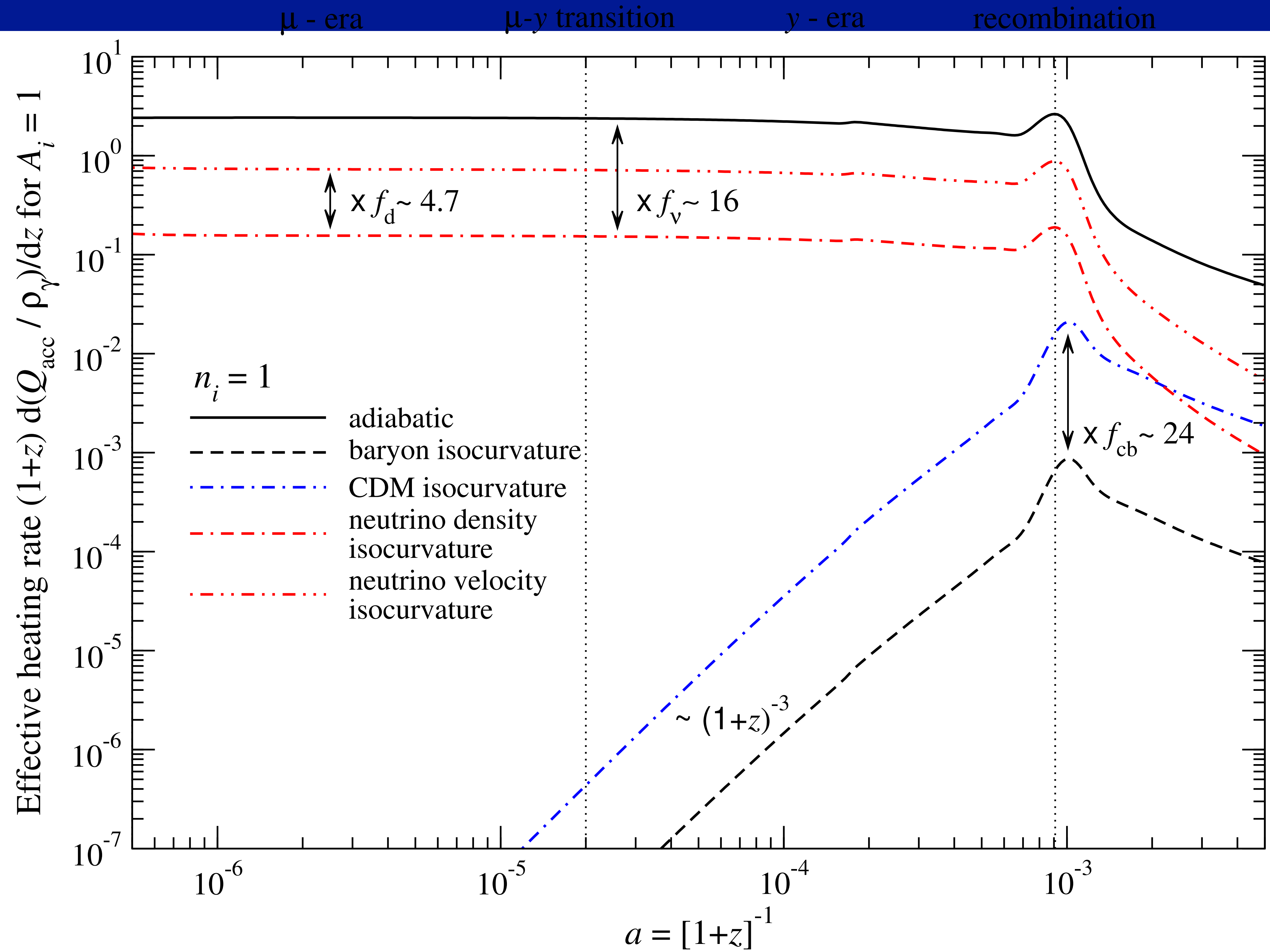
  $1\ \mathrm{Mpc}^{-1} \ll k \ll 50\ \mathrm{Mpc}^{-1}$
- μ-distortions $50\ \mathrm{Mpc}^{-1} \ll k \ll 10^4\ \mathrm{Mpc}^{-1}$

- Energy lost to Silk damping: $\frac{d}{dt}\frac{\Delta E_\gamma}{E_\gamma} = 4n_e\sigma_T \int \frac{k^2 dk}{2\pi^2} P_i(k)$

$$\left\{ \frac{(3\Theta_1 - v)^2}{3} + \frac{9}{2}\Theta_2^2 - \frac{1}{2}\Theta_2(\Theta_2^{\mathrm{P}} + \Theta_0^{\mathrm{P}}) + \sum_{l\geq 3} (2l+1)\,\Theta_l^2 \right\}$$

- 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

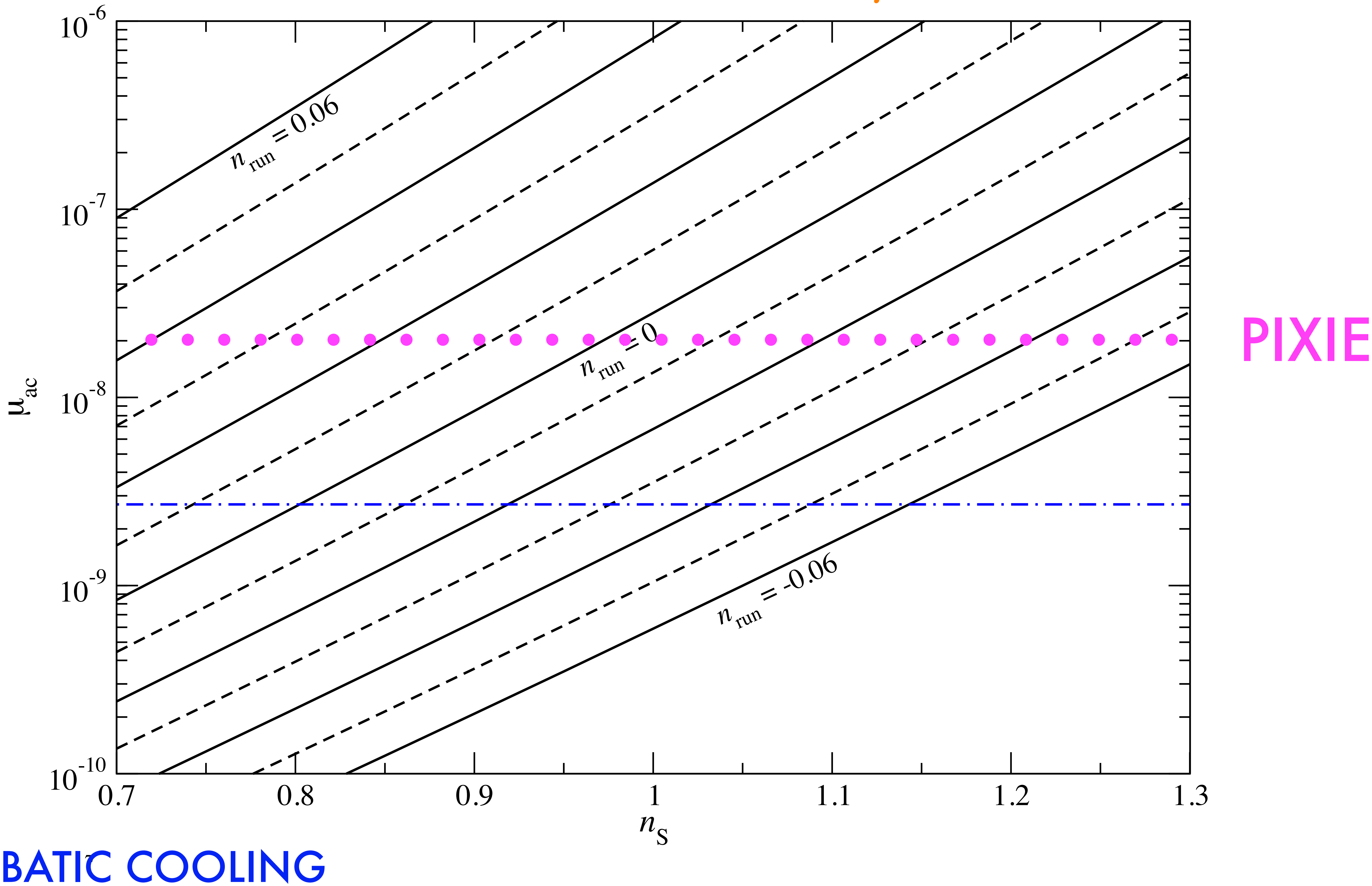


Isocurvature in relativistic species yields more energy injection during μ-era

Isocurvature in non-relativistic species less suppressed during matter domination

Silk damping and distortion from adiabatic modes

Nearly scale-invariant LCDM cosmology → $\mu \sim 2 \times 10^{-8}$



From Chluba 2012

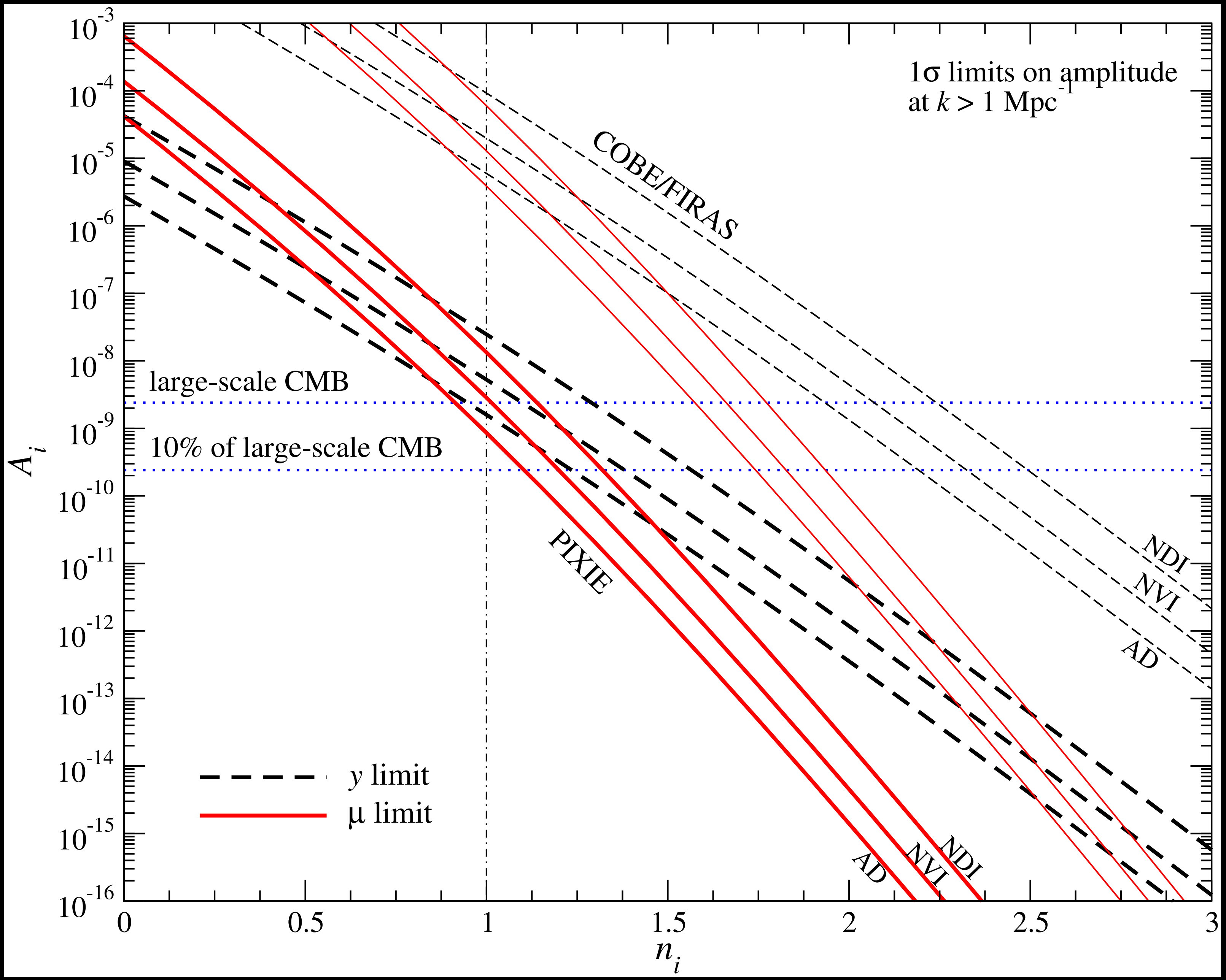
Curvaton

- Tested correlated isocurvature with amplitudes allowed by Planck CMB local-type non-G constraints

- All 18 scenarios allowed by *Planck* limits are ~2 orders of magnitude away from PIXIE detectability

Simple curvaton models are not a promising target for SD experiments!

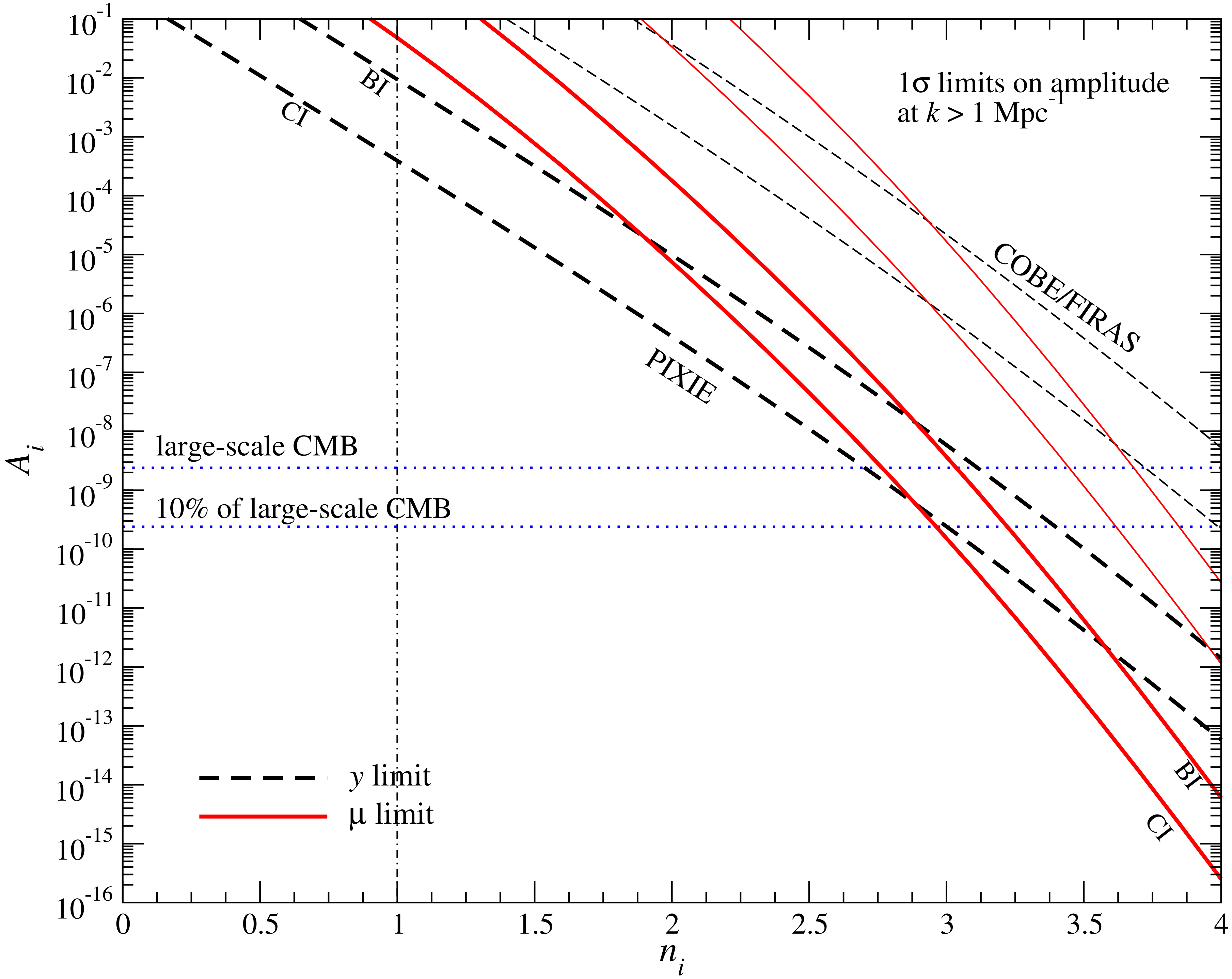
Distortions probe spectral slope and/or initial conditions of primordial fluctuations



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

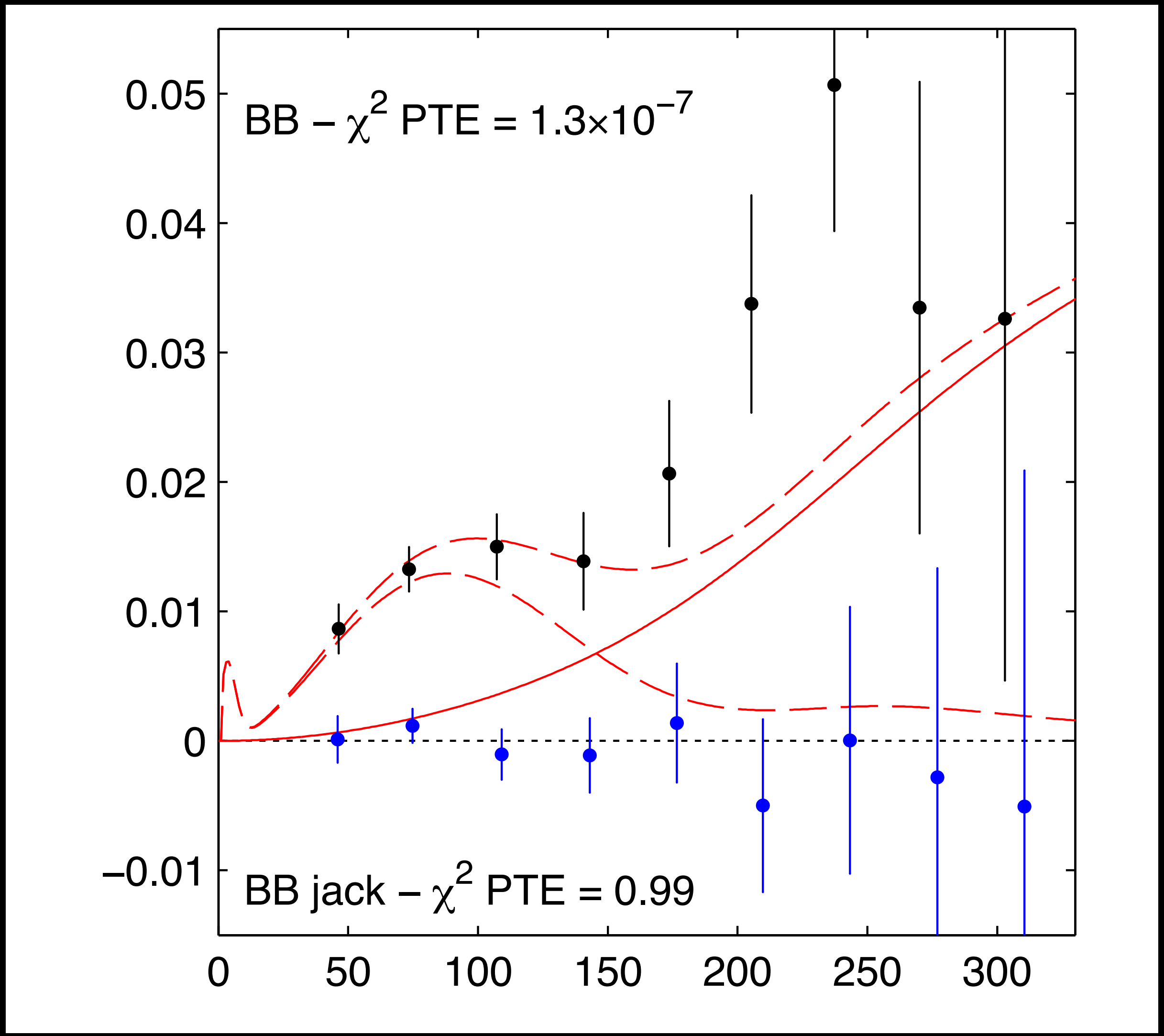
PIXIE SENSITIVITY

Distortions probe spectral slope and/or initial conditions of primordial fluctuations

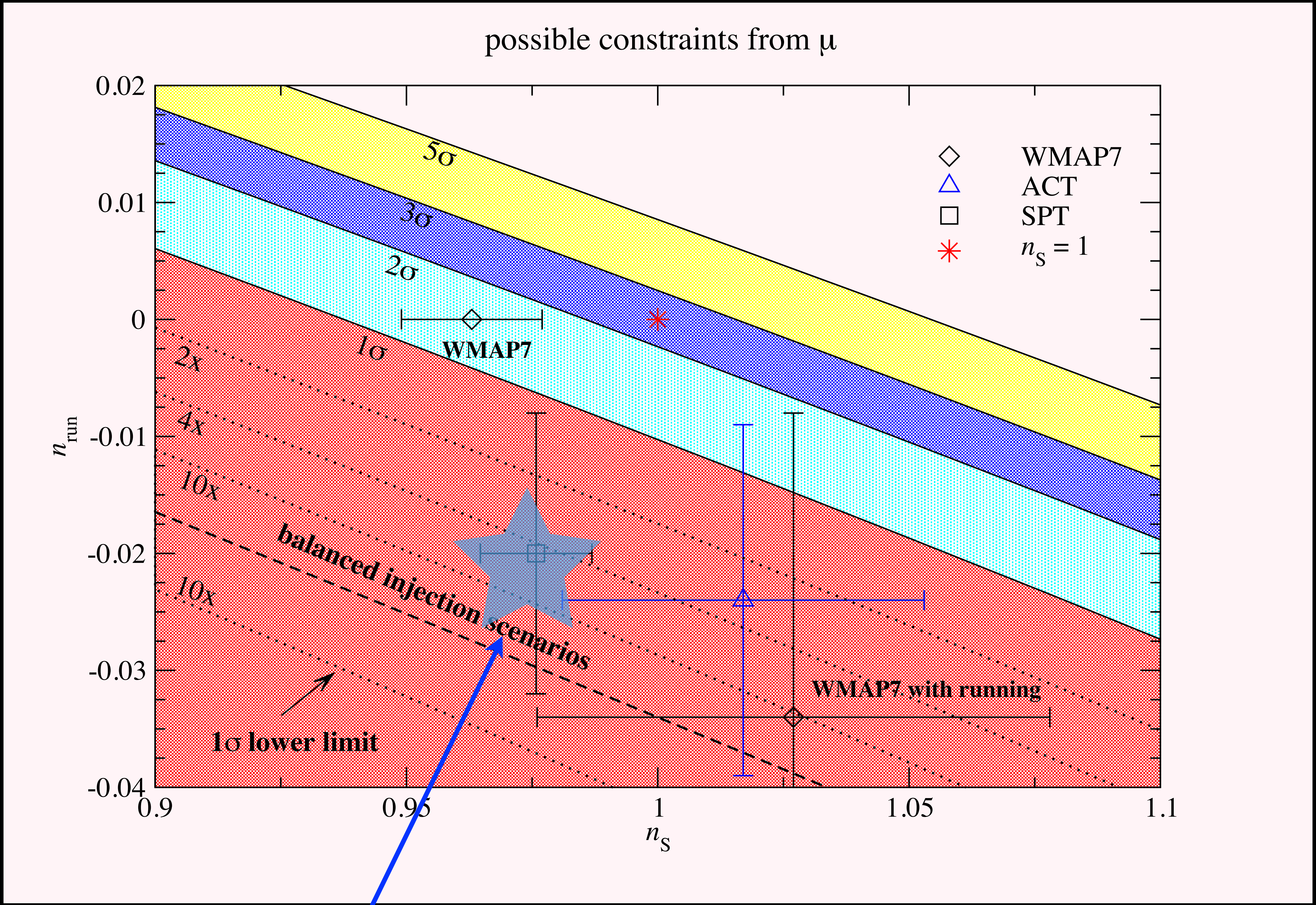


SHAMELESS PANDERING

- *The CMB is still rich with opportunity, don't be a mode-counting snob!*
- *WOW! BICEP2! (if confirmed, r=0.16-0.2)*



Details of spectrum matter!



BICEP+PLANCK?

Small field models

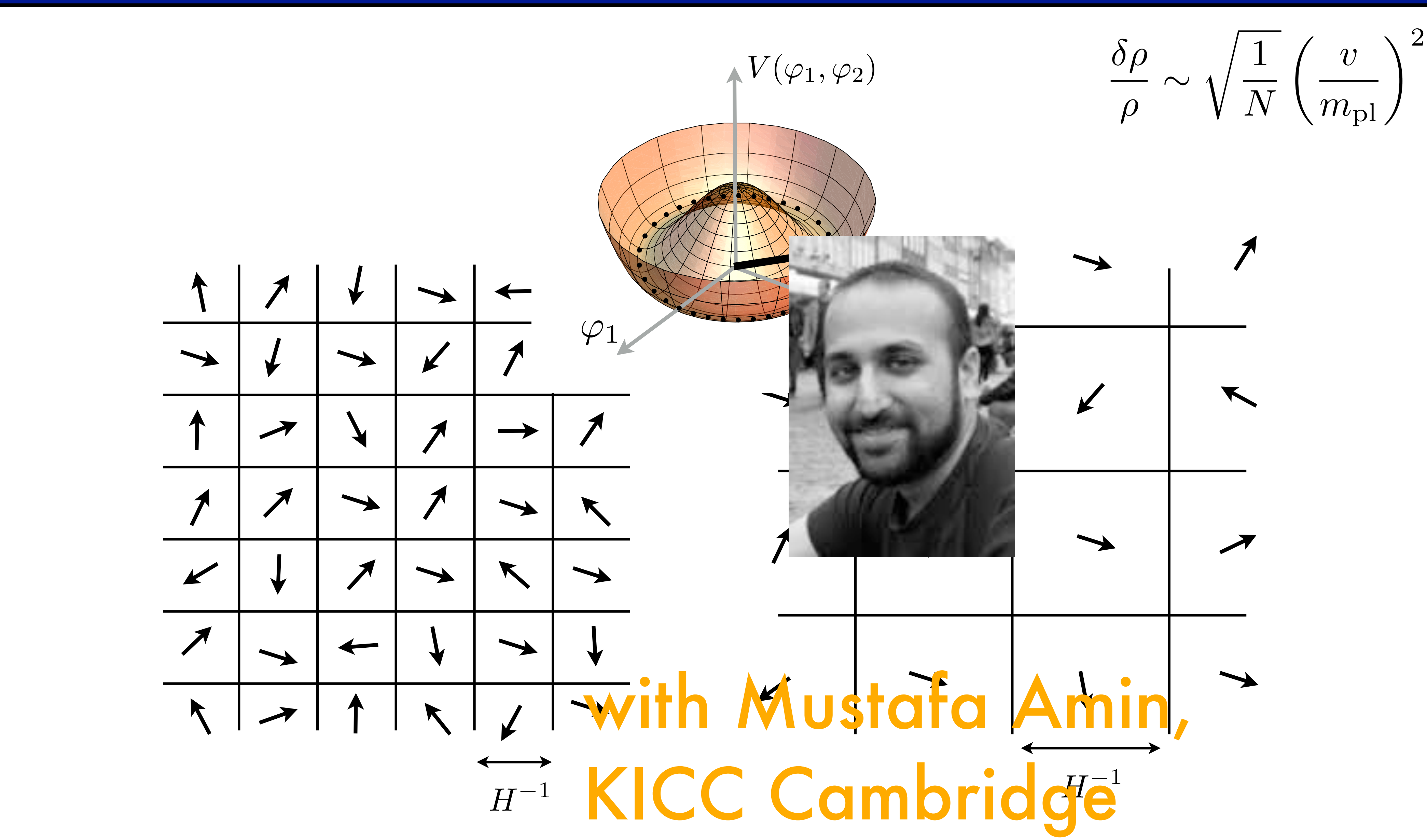
* Small-field inflationary models with non-monotonic $\left(\frac{V'}{V}\right)^2$ (Ben-Dayan/Brustein 2010) can evade Lyth Bound

$$\Delta\phi \geq m_{\rm pl}\sqrt{\frac{r}{4\pi}}$$

Experimentally relevant!

* Model predicts $\mu \sim 10^{-6}$ (Chluba/Erickcek/Ben-Dayan 2012)

Phase transitions and spectral distortions

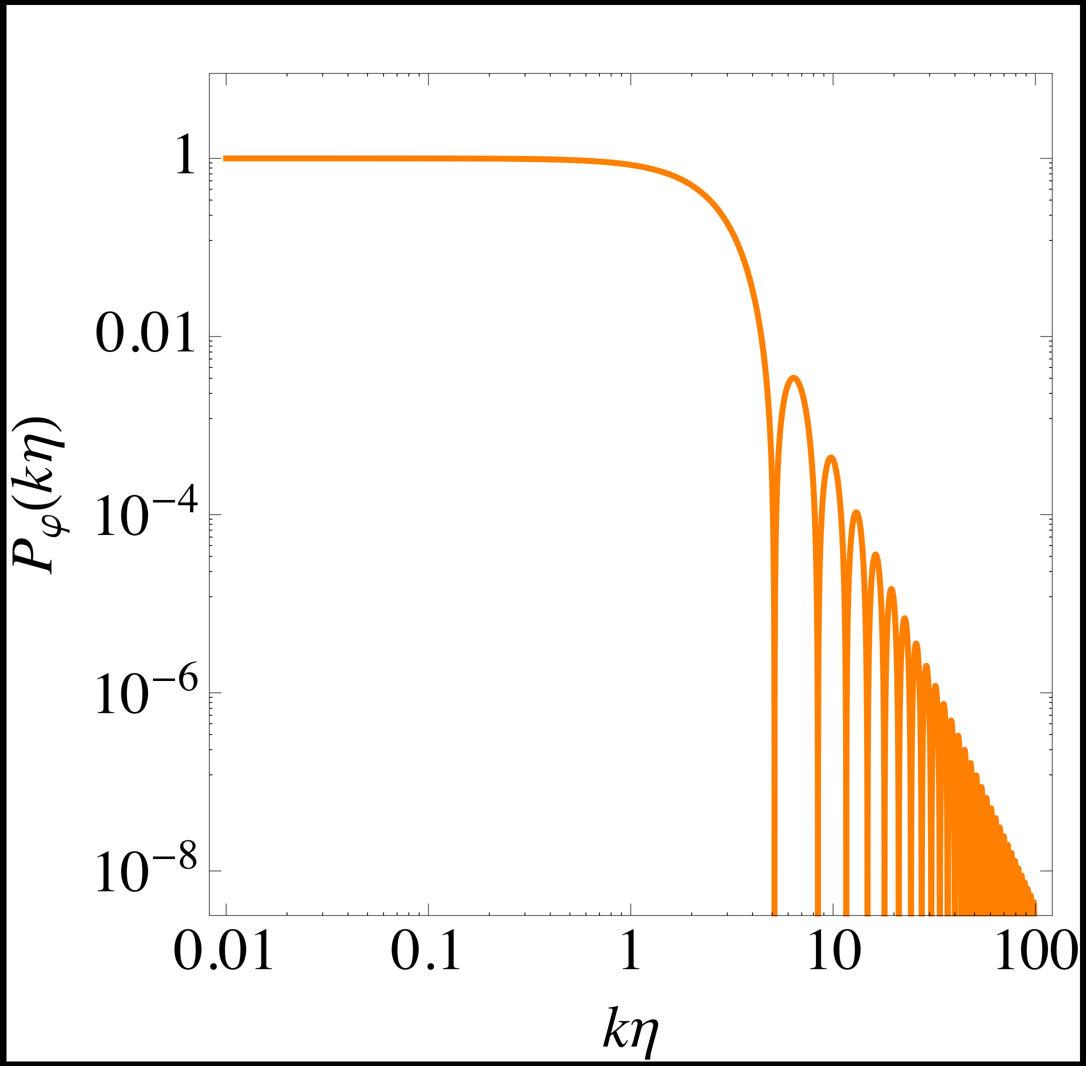


with Mustafa Amin,
KICC Cambridge

Break a global O(N) symmetry

Compute gravitational potential fluctuations

Scaling seeds are self-similar



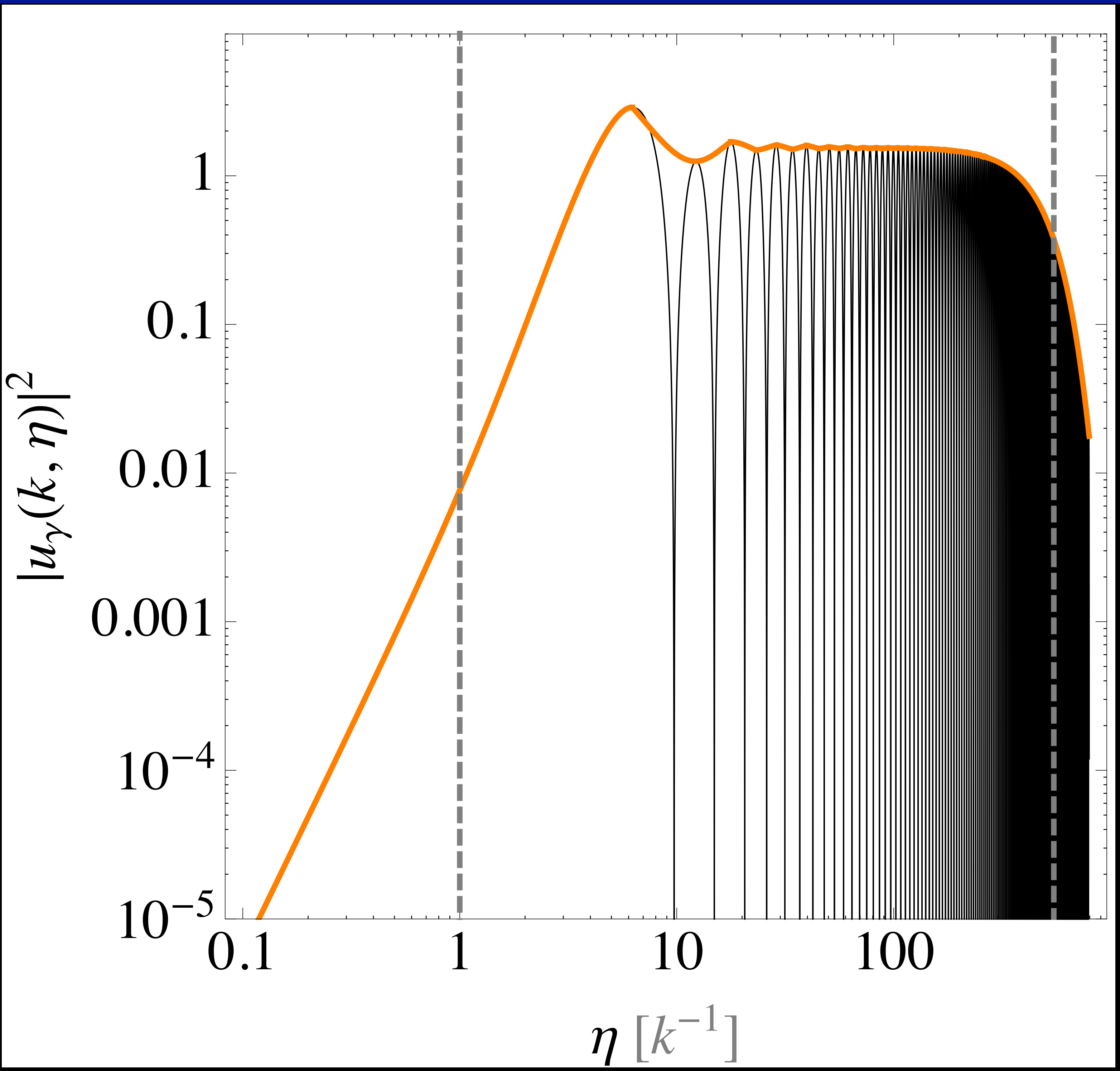
- ✳ Maximal (and conserved) power on the horizon!
- ✳ Even as horizon evolves

Write CMB-verySLOW

- Mathematica notebook solving tight-coupling equations
  - Fluid equations
  - Einstein equations
  - First 10 moments of Neutrino Boltzmann hierarchy
  - Heating rate for acoustic mode dissipation and distortions

- Tensors/vectors appear to be relevant only for y distortion

Seeds drive baryon-photon plasma sound waves



with Mustafa Amin, KICC Cambridge

$\mu \sim 3 \times 10^{-9}$

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)

arXiv: 1403.4216

Axions solve the strong CP problem

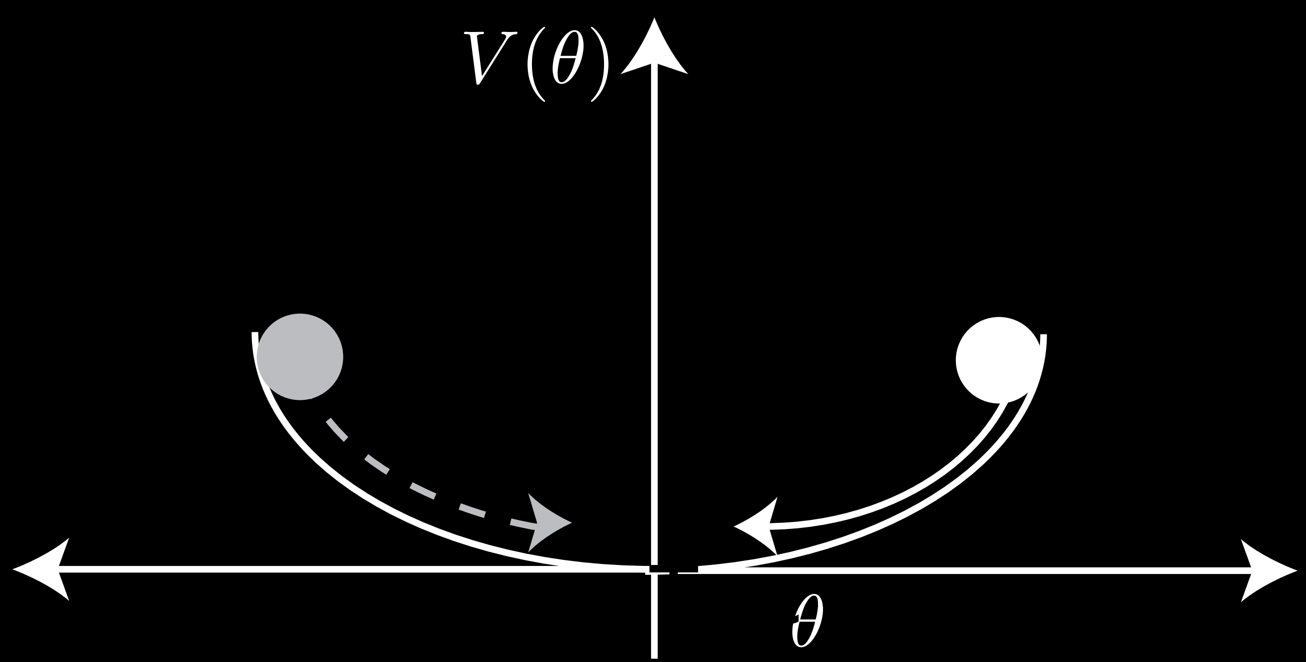
- Limits on the neutron electric dipole moment are strong. Fine tuning?

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

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

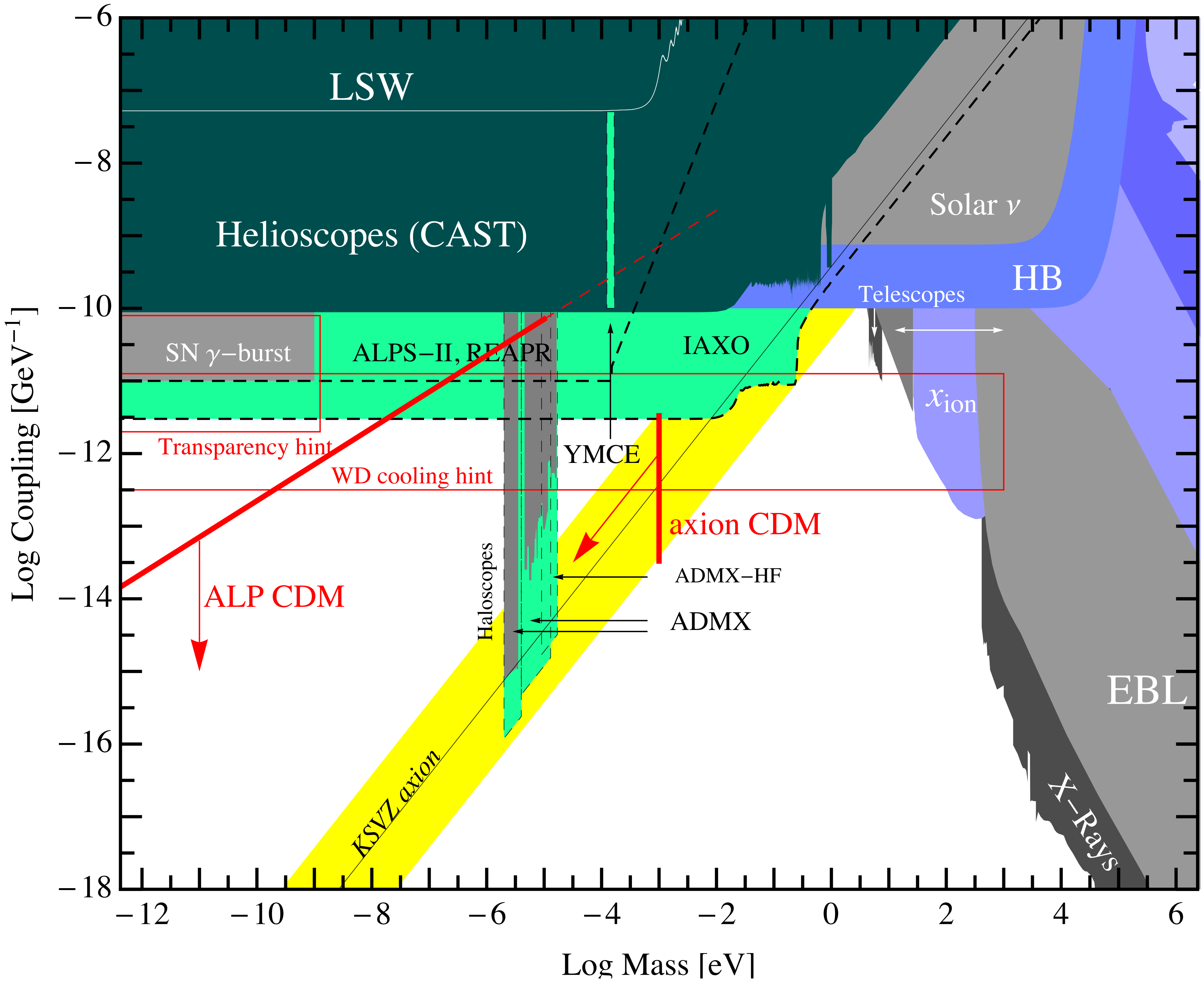
$$\mathcal{L}_{\mathrm{CPV}} = \frac{\theta g^2}{32\pi^2} G\tilde{G} - \frac{a}{f_{\mathrm{a}}} g^2 G\tilde{G}$$

2 axion populations: Cold axions



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

Lay of the land



A new scale for perturbed scalars

- *Perturbations obey*

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

- *Structure suppressed when*

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

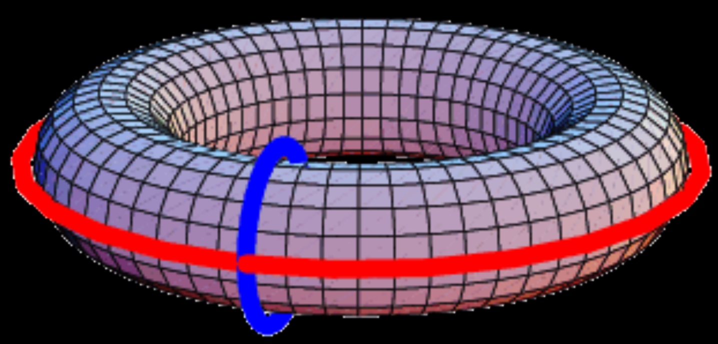
- *Scales are very small for QCD axion*

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

What about lighter axions?

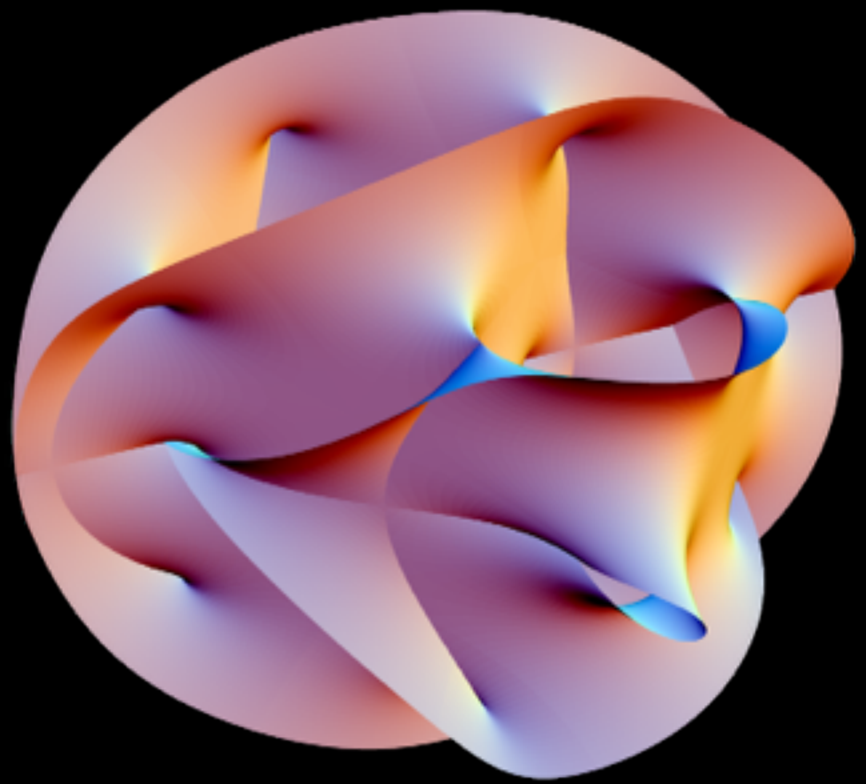
Light axions and string theory

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



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

Axiverse! (Arvanitaki et al. 2009)



- Calabi-Yau manifolds

Many 2-cycles ⟶ Many axions

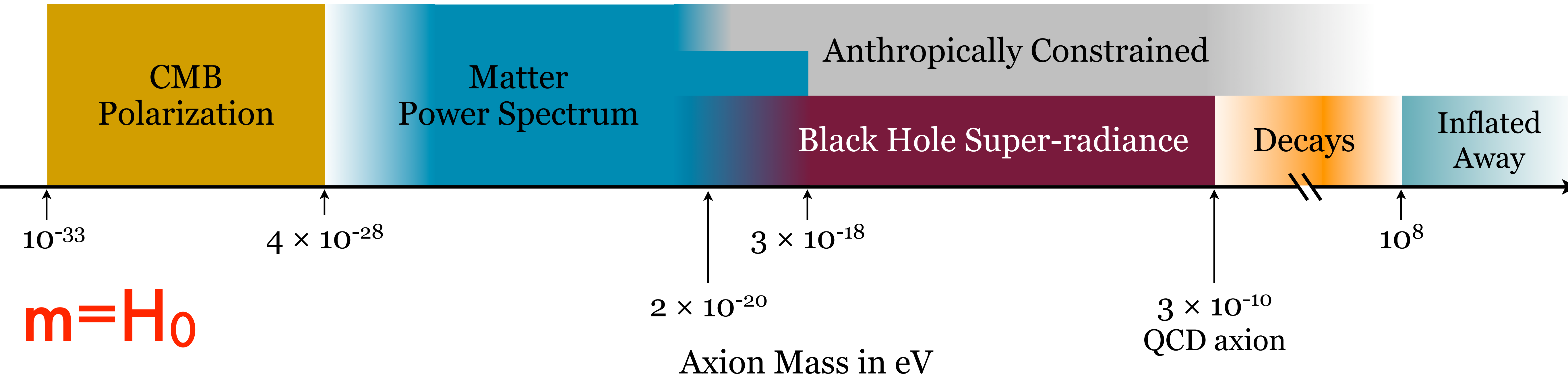
Hundreds!

- 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)



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

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

- ***Decrement in matter power spectrum for***

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

Effective fluid approximation

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

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

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

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

Axions carry isocurvature

- If PQ symmetry broken during/before inflation

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

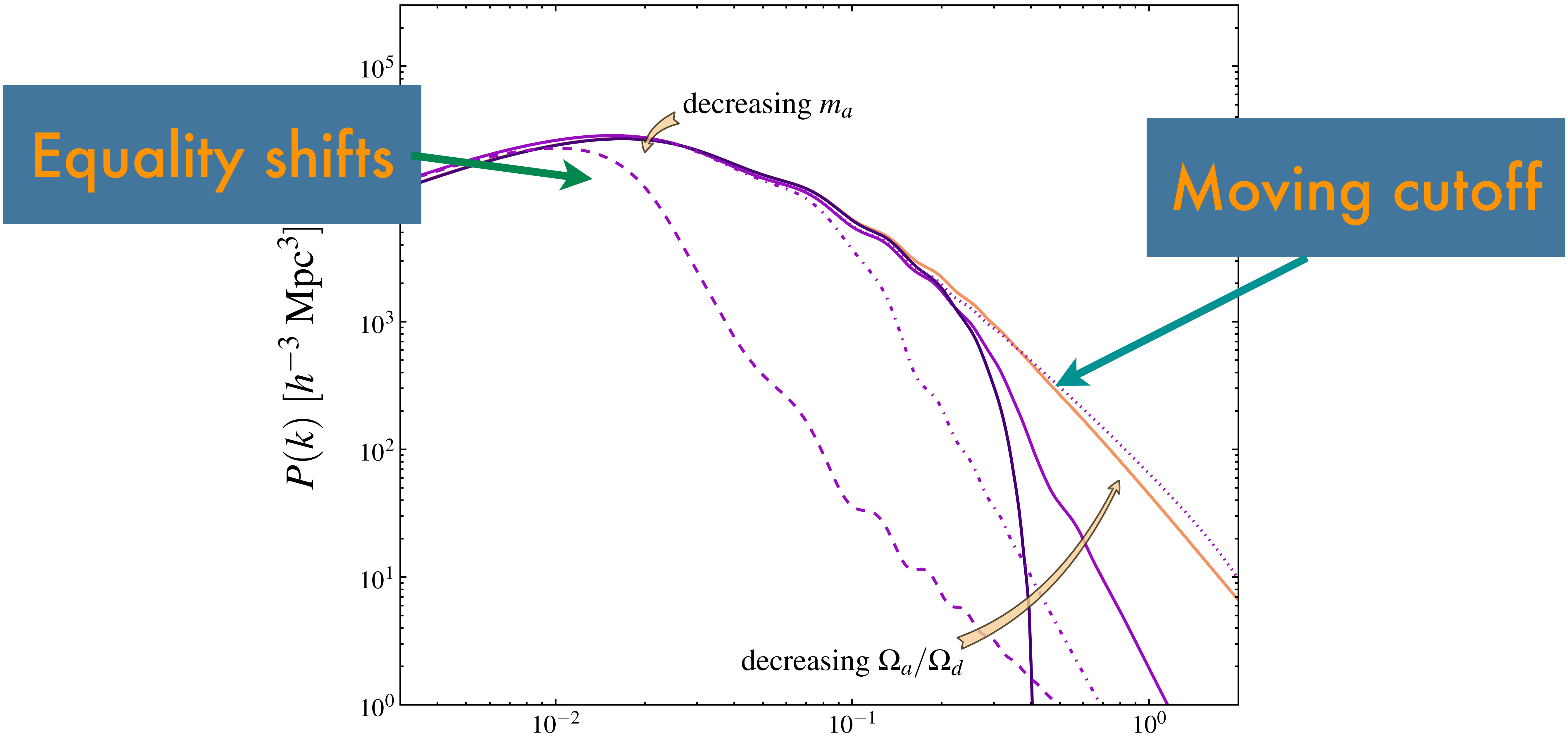
Quantum zero-point fluctuations!

- Subdominant species seed isocurvature fluctuations

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

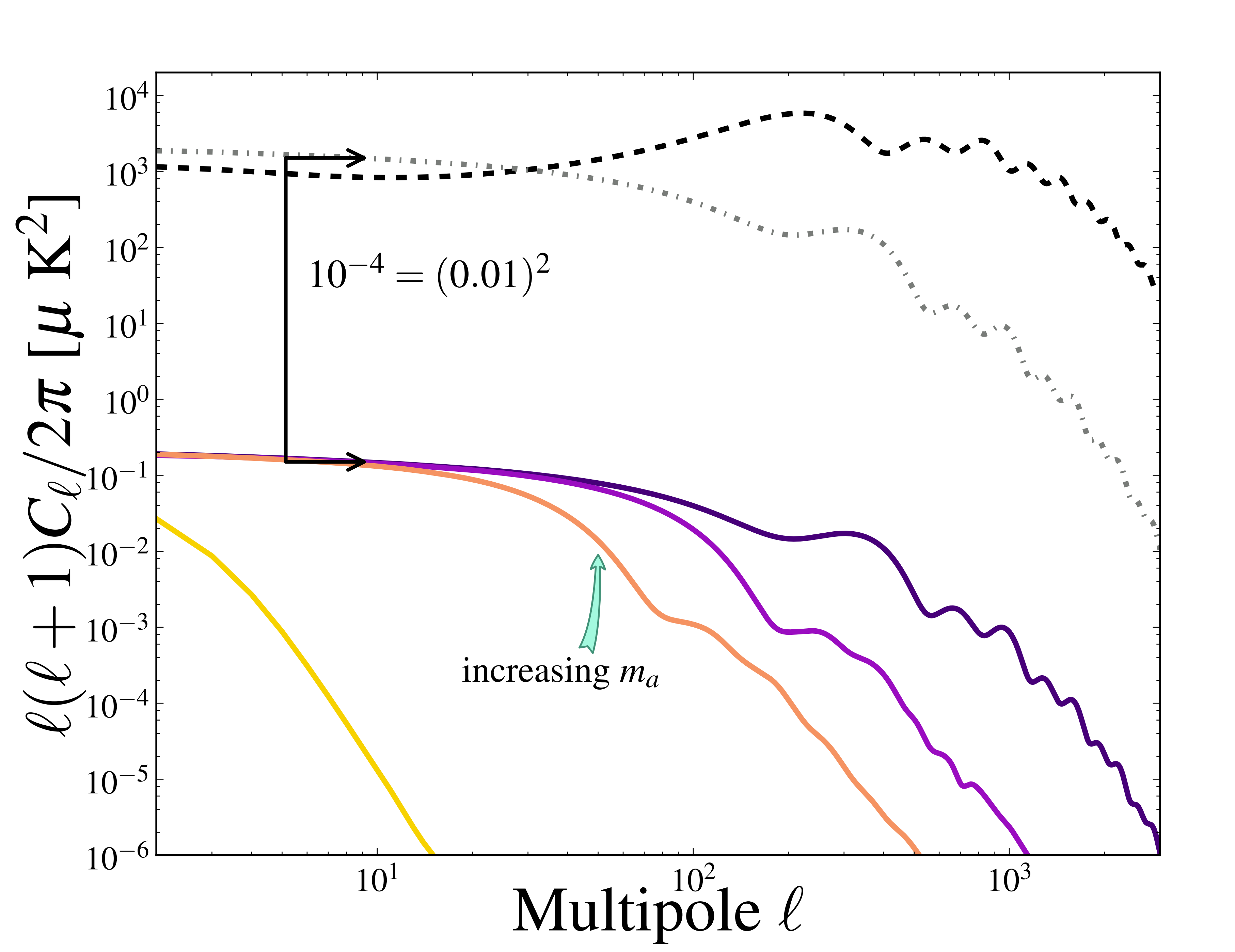
$$S_{a\gamma} = \frac{\delta n_a}{n_a} - \frac{\delta n_\gamma}{n_\gamma} = \frac{\delta \rho_a}{\rho_a} - \frac{3}{4} \frac{\delta \rho_\gamma}{\rho_\gamma} \sim 10^{-5}$$

Matter power spectrum



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

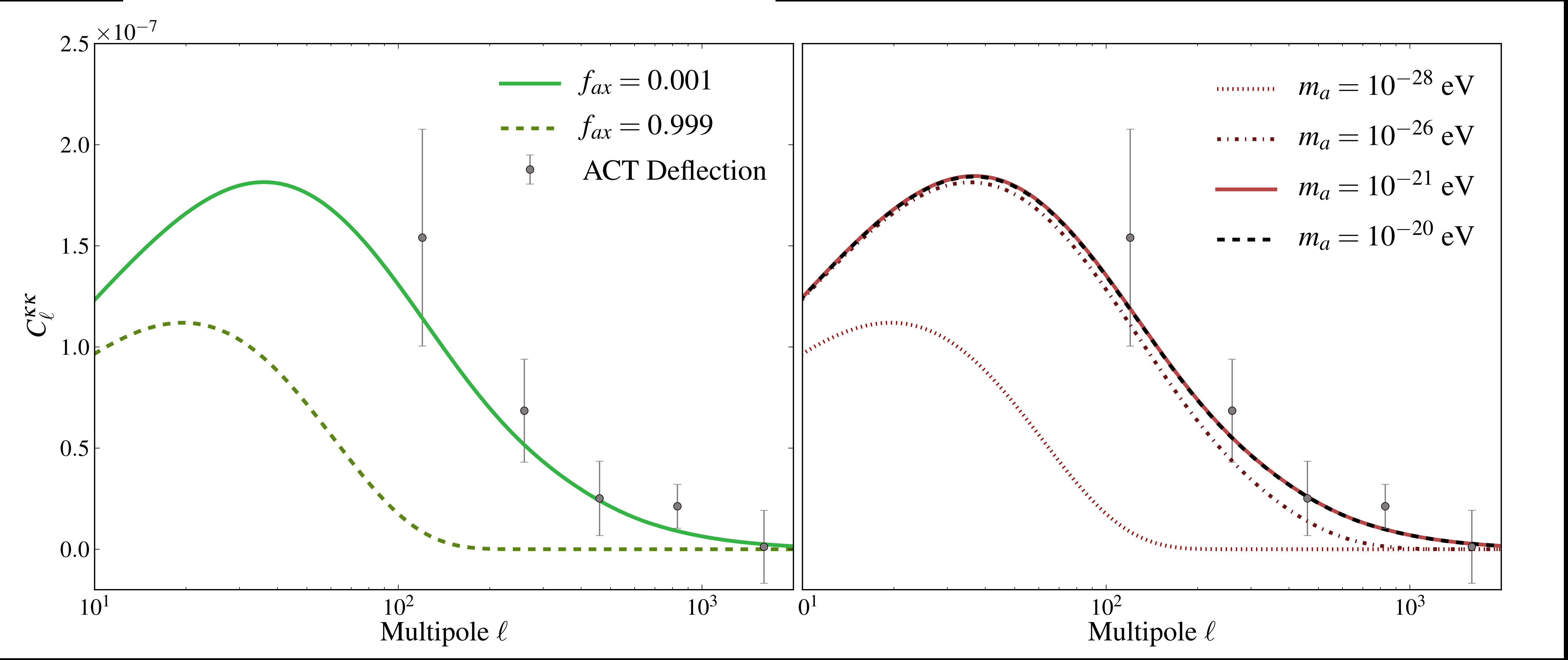
CMB anisotropy power spectra



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

CMB lensing [a probe of axions]

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



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

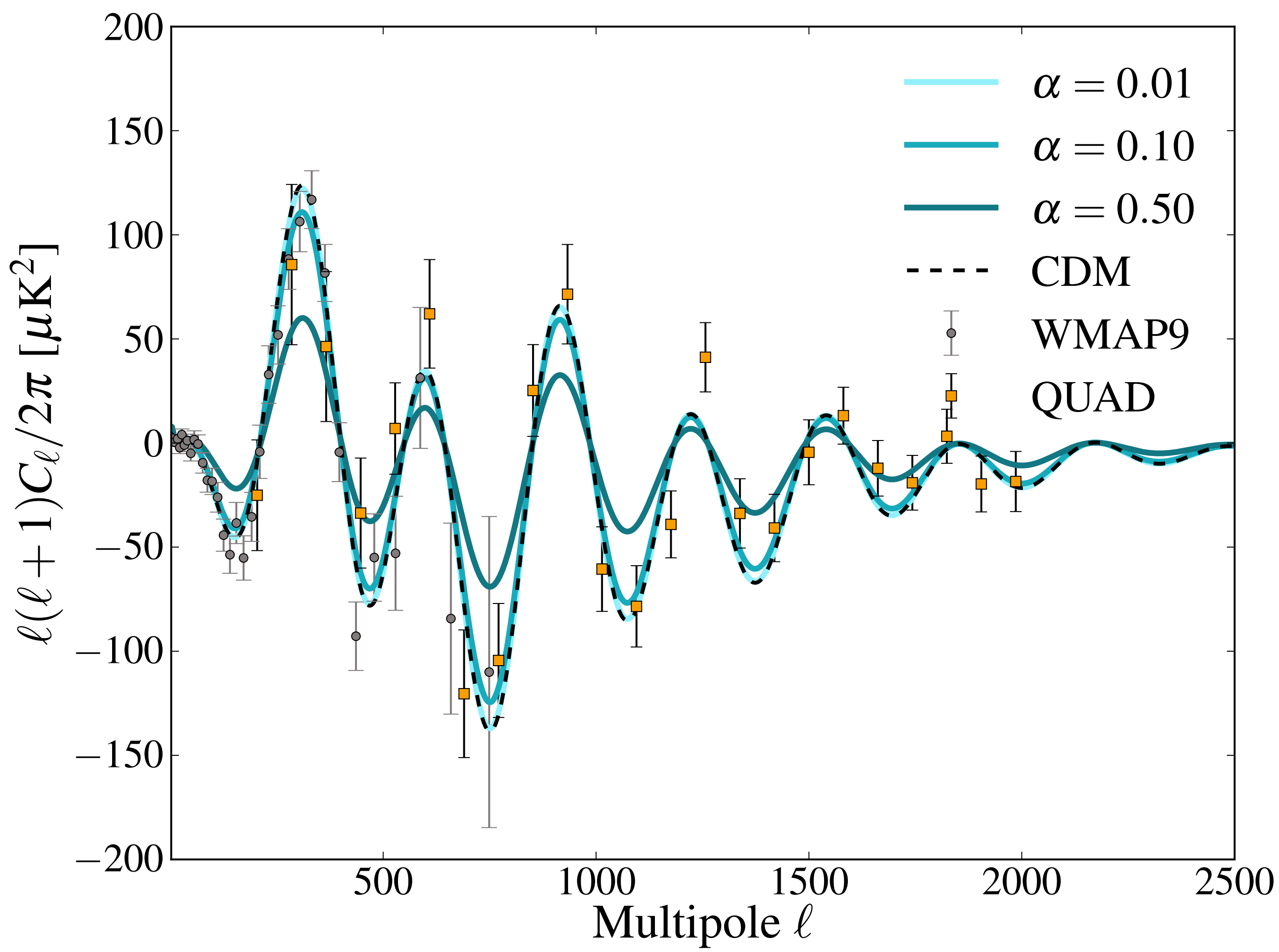


FIG. 5: CMB adiabatic and isocurvature TE polarization power spectra, varying the isocurvature amplitude from $\alpha = 0.01, 0.1, 0.5$ for fixed axion mass, with axions making up nearly all of the DM, $f_{\rm ax} = 0.9999$. The spectra are are a sum of $(1-\alpha)C_\ell^{ad} + \alpha C_\ell^{iso}$, 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

Planck 2013 limits

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

$$\boxed{\alpha_{ax} \lesssim 0.04}$$

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

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

The axiverse and the scale of inflation

Taking BICEP r=0.2 at face value

$$\frac{\Omega_{\rm a}}{\Omega_{\rm d}} \lesssim 2 \times 10^{-1} \left(\frac{10^{-26}\ {\rm eV}}{m_{\rm a}} \right)^{1/2}$$

The QCD axion and the scale of inflation

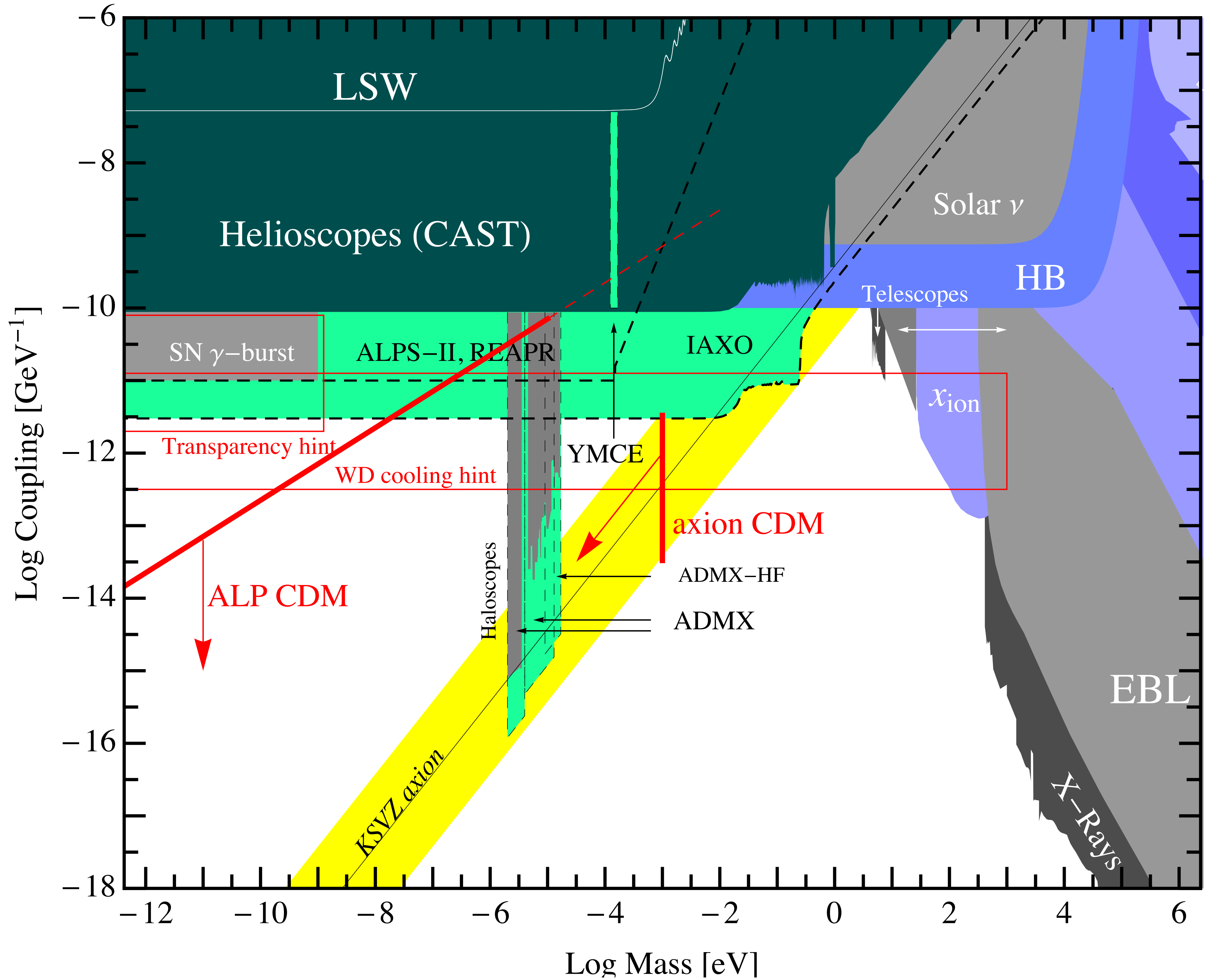
- Including temperature dependence of QCD mass

$$\frac{\Omega_{\mathrm{a,QCD}}}{\Omega_{\mathrm{D}}} \lesssim \frac{9\times 10^{-12}}{\gamma}\left(\frac{f_{\mathrm{a}}}{10^{16}\ \mathrm{GeV}}\right)^{5/6}\left(\frac{0.2}{r}\right)$$

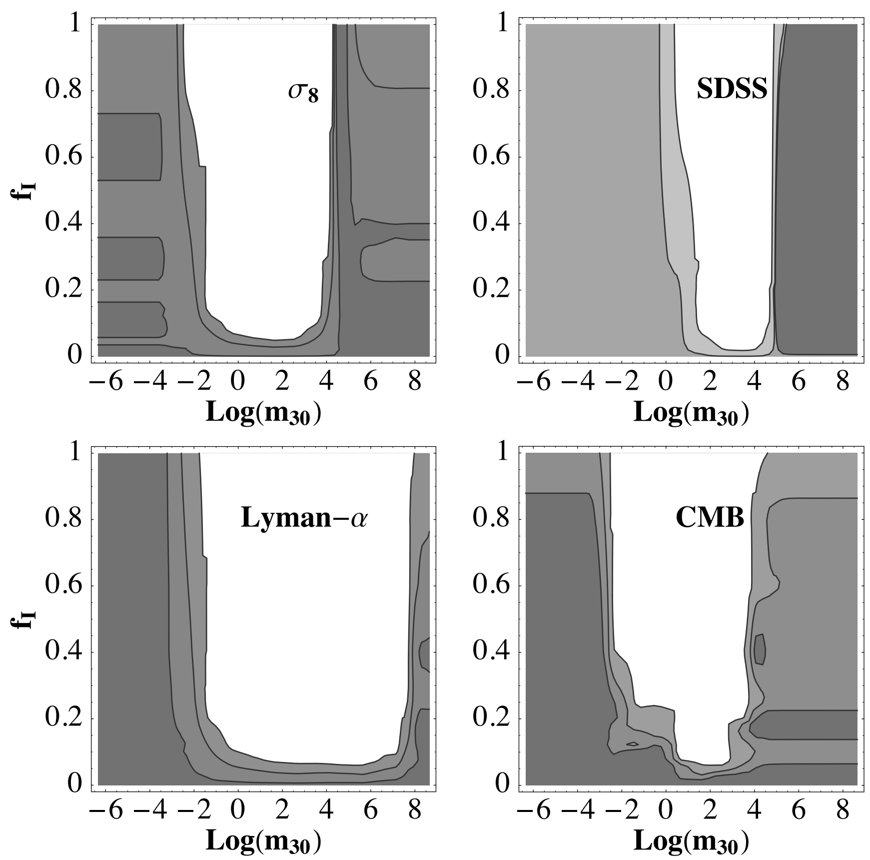
- Only afflicts $m \lesssim 60\mu\mathrm{eV}$: Axion direct search experiments still well motivated, though late PQ transition poses defects challenge

- Outs: Entropy generation, massive axion during inflation

Lay of the land



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

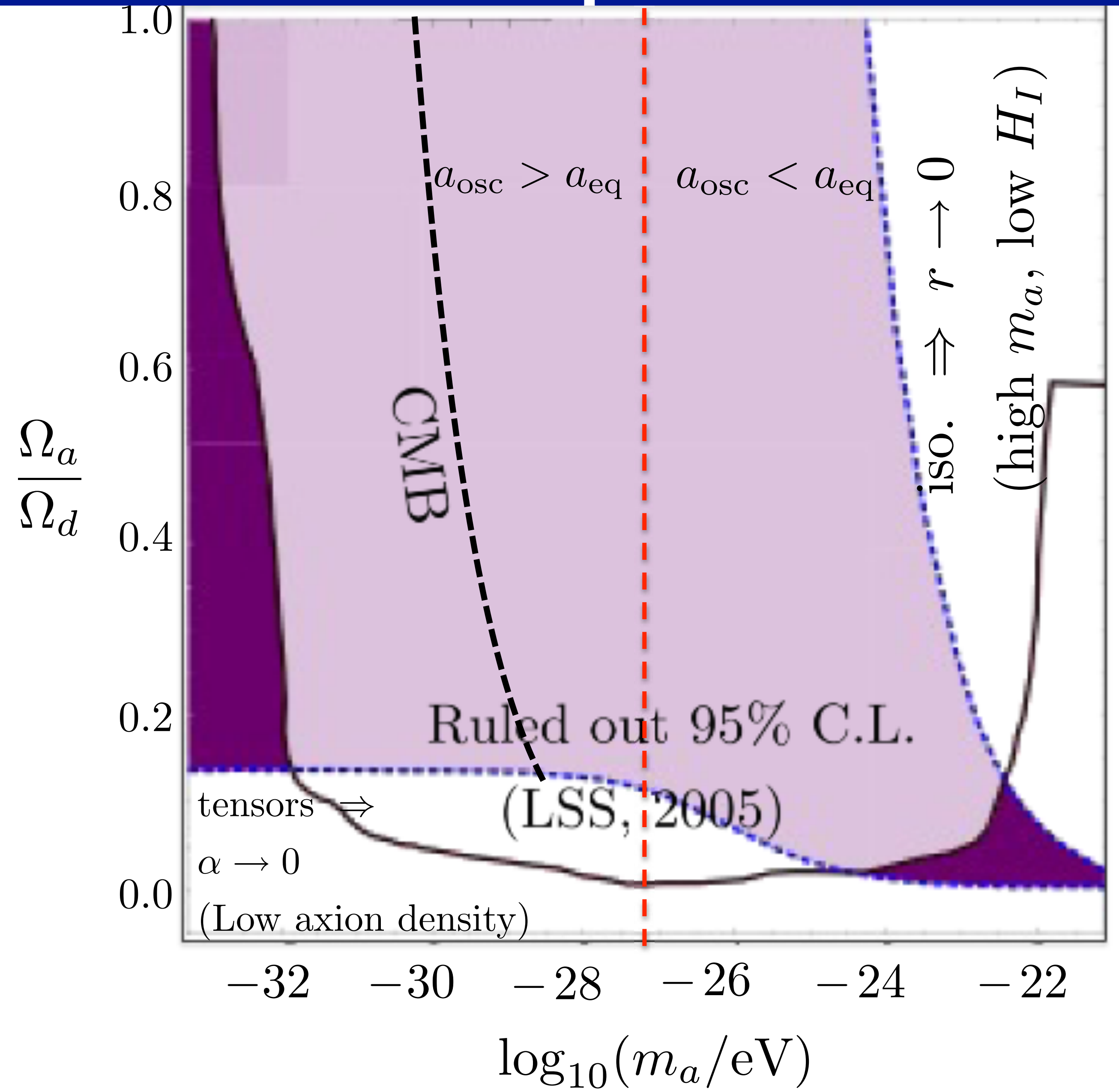
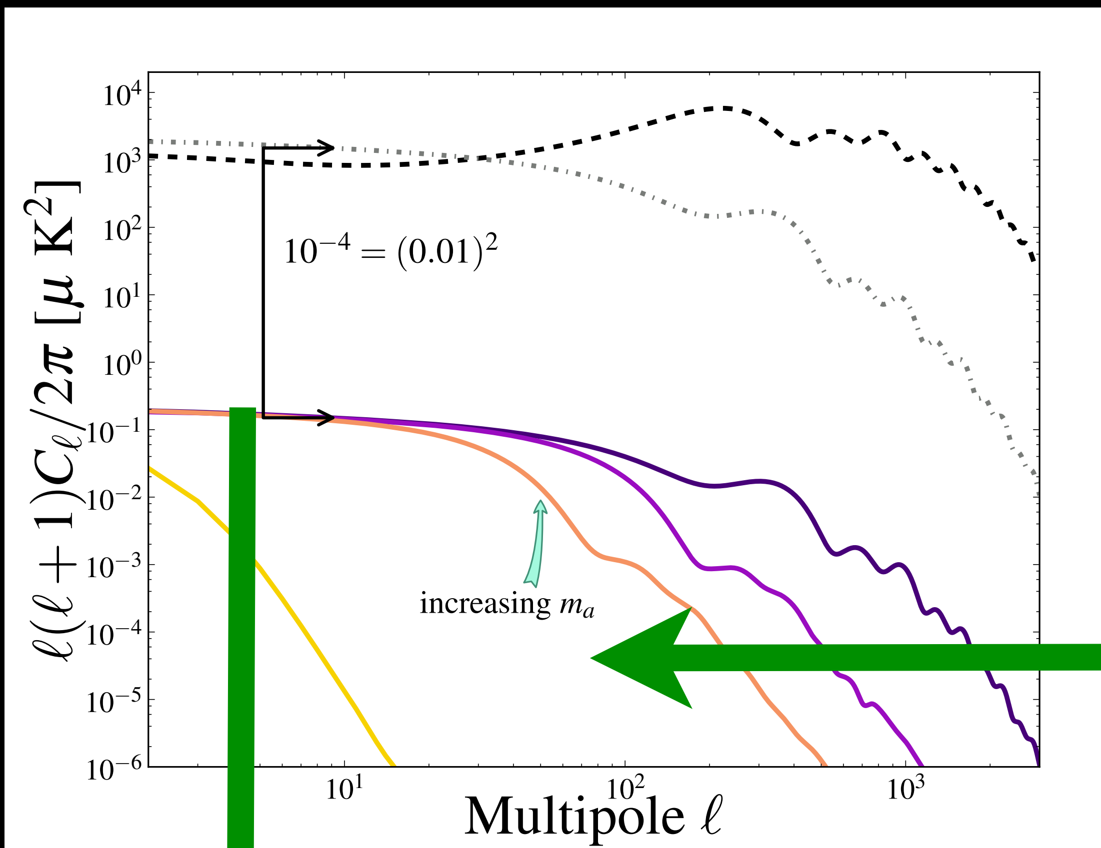


FIG. 2 (color online). Phenomenology in the $\{m_a, \Omega_a/\Omega_d\}$ plane. The shaded regions lie between the dashed contours and satisfy $\{0.01 < r < 0.1, 0.01 < \alpha_{\rm CDM} < 0.047\}$, evading current constraints, while being potentially observable with future data.

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

Motivation/anticipated contours



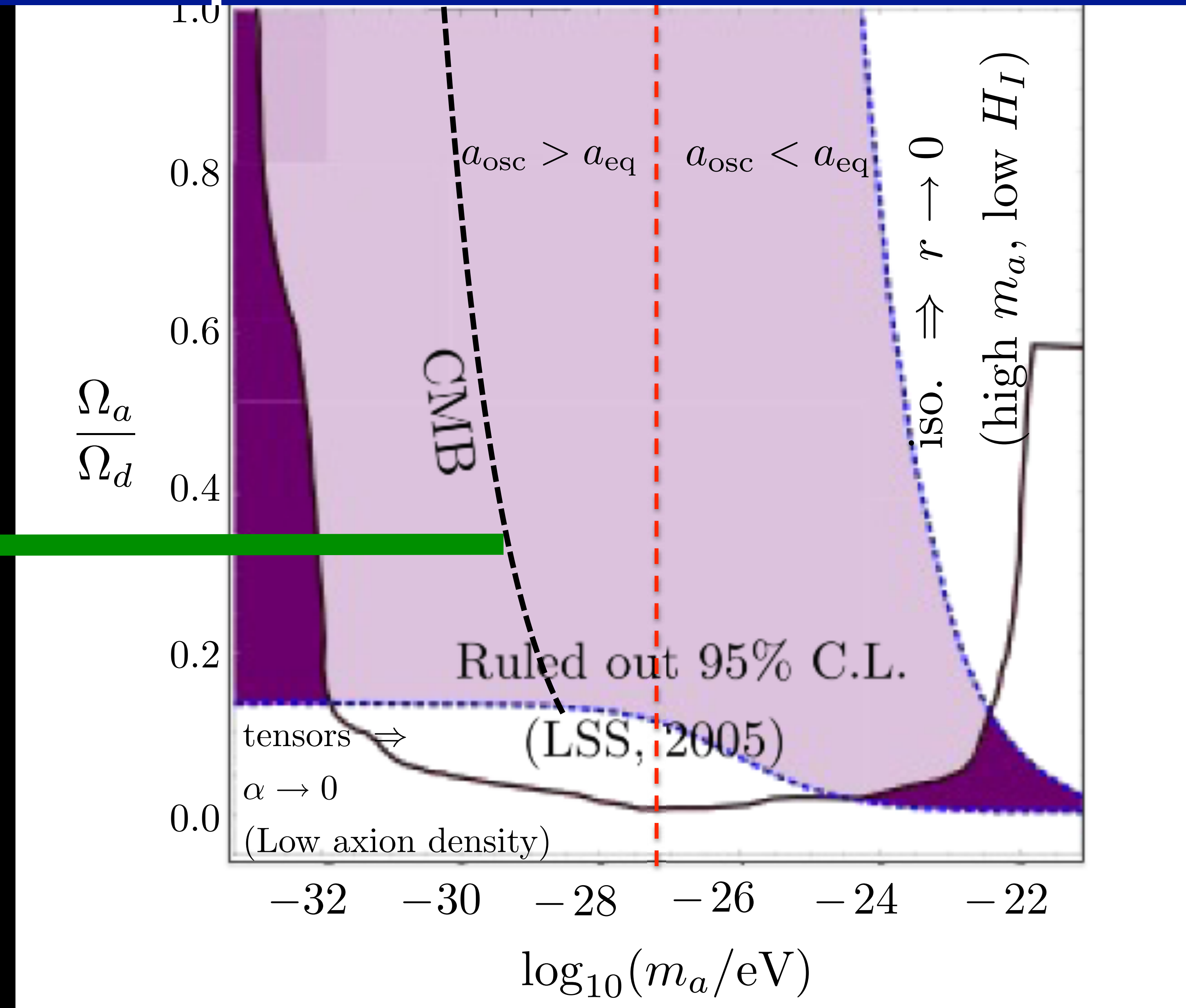
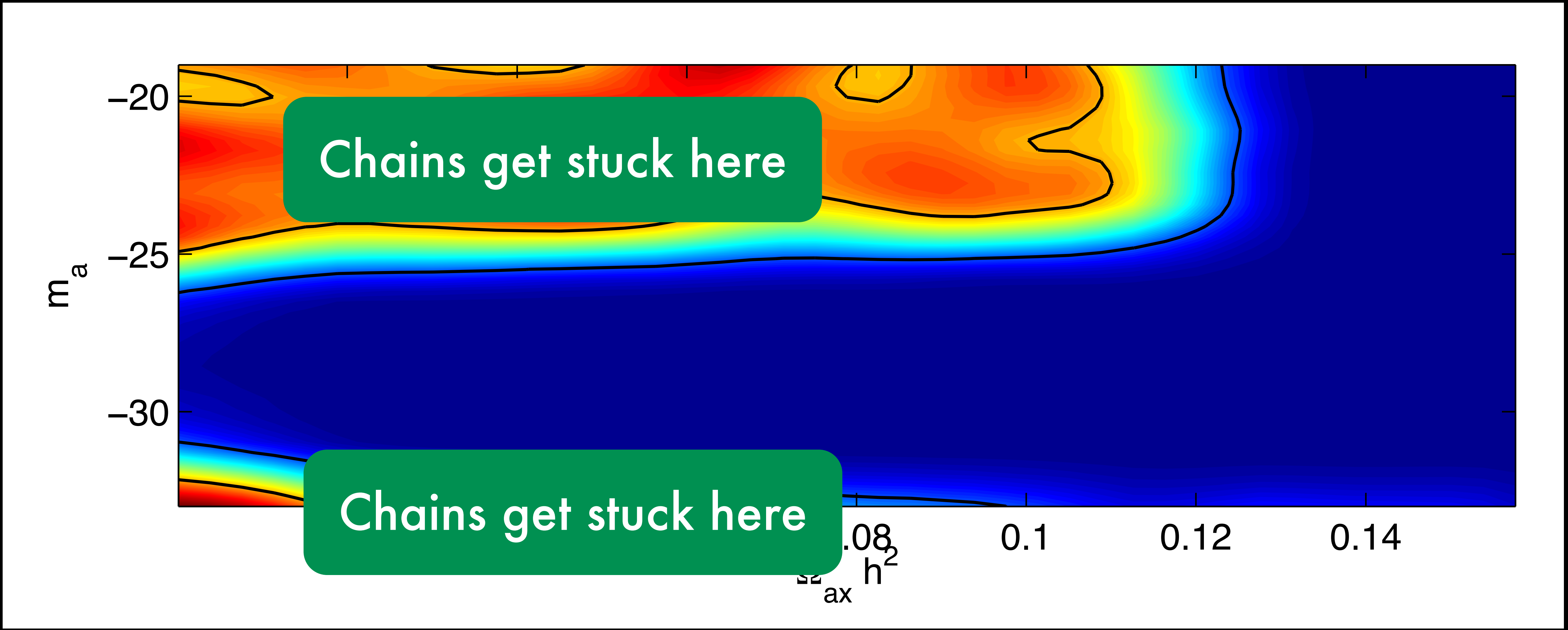


FIG. 2 (color online). Phenomenology in the $\{m_a, \Omega_a/\Omega_d\}$ plane. The shaded regions lie between the dashed contours and satisfy $\{0.01 < r < 0.1, 0.01 < \alpha_{\rm CDM} < 0.047\}$, evading current constraints, while being potentially observable with future data.

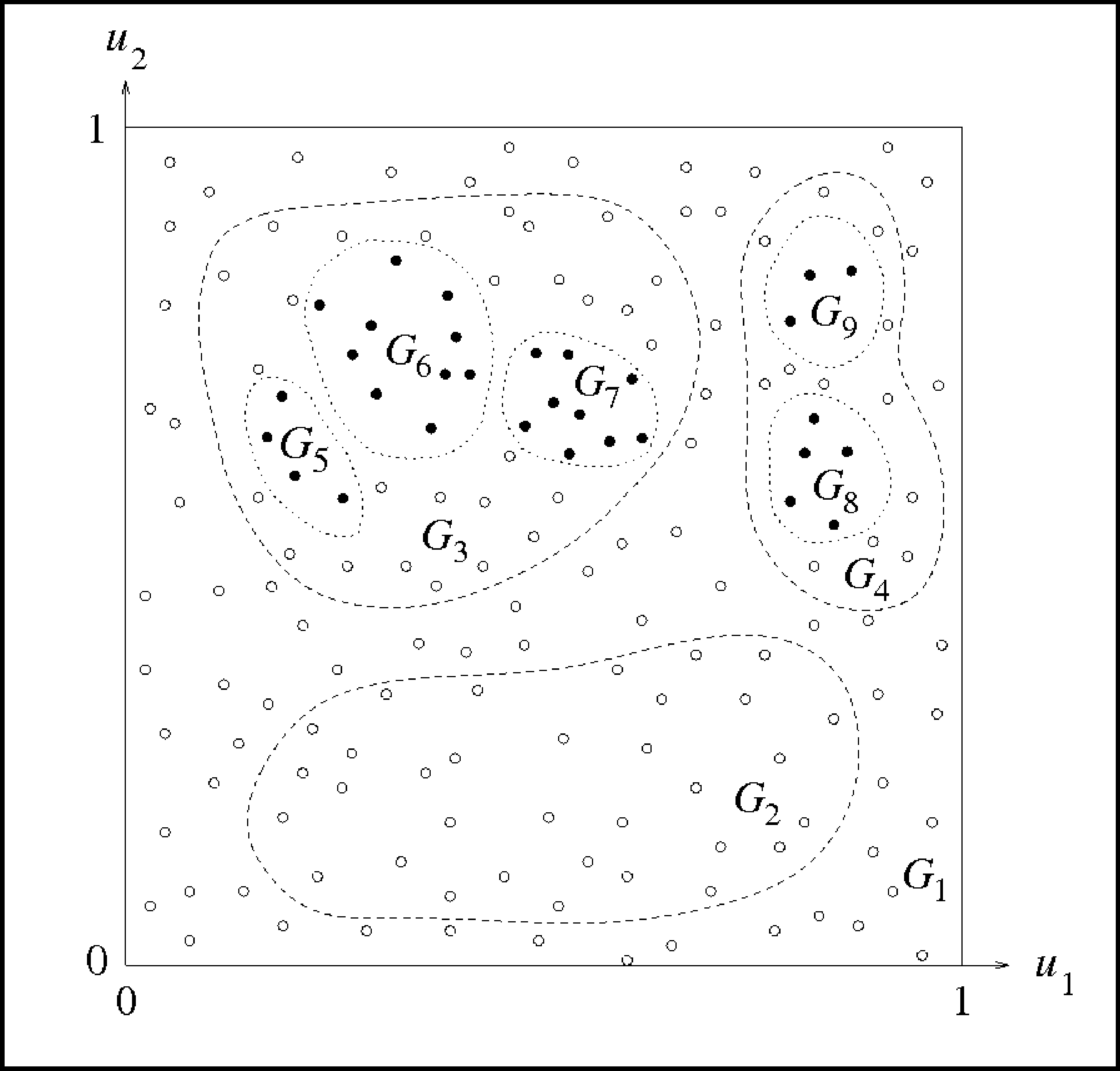
Loss of low-l modes in SW plateau when axion mass is low: analytic estimate

Preliminary adiabatic results



Metropolis-Hastings algorithm is not good for multimodal distributions!

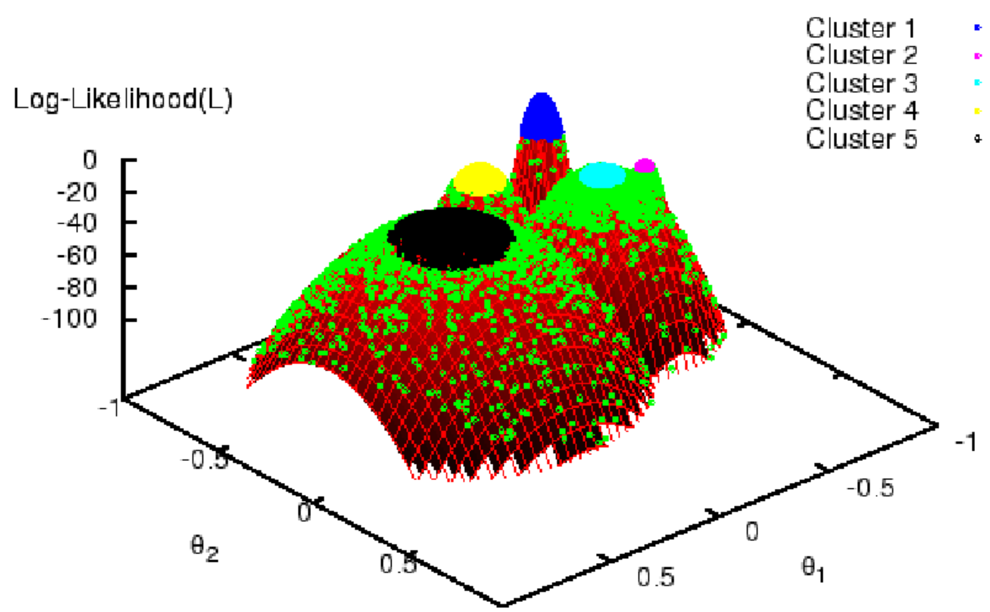
We use nested sampling instead



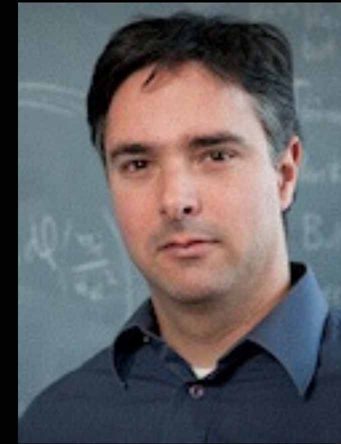
We use nested sampling instead

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



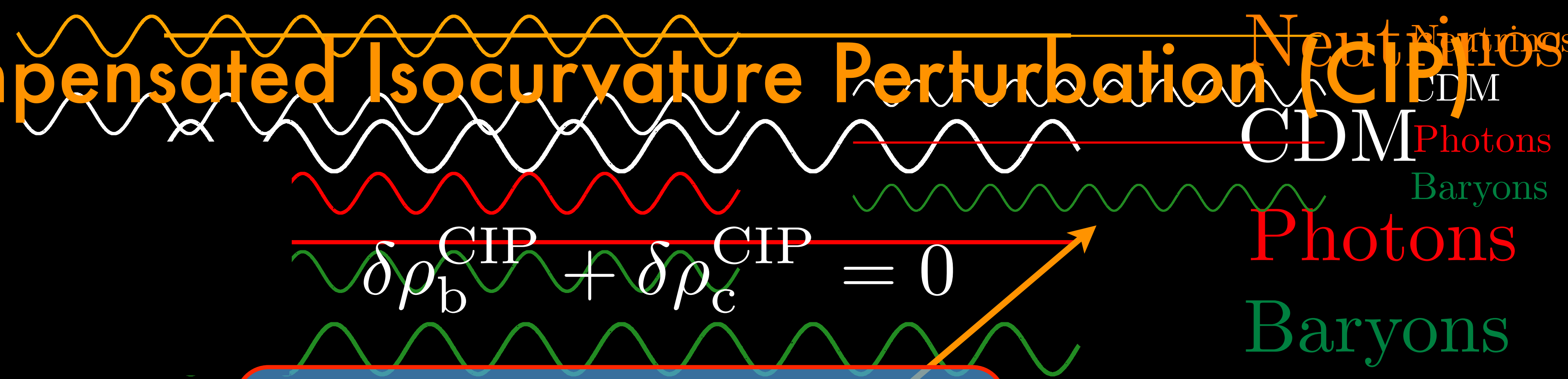
Variation in the cosmic baryon fraction and the CMB

with D. Hanson, G. Holder, O. Doré, and M. Kamionkowski

arXiv: 1107.1716- Phys. Rev. Lett. 107 261301
arXiv: 1107.5047- Phys. Rev. D. 84 123003
arXiv: 1306.4319- Phys. Rev. D.89 023006

- “Nuisance” mode identified (Lewis 2002)

Compensated Isocurvature Perturbation (CIP)



$$\delta\rho_{\rm b}^{\rm CIP} + \delta\rho_{\rm c}^{\rm CIP} = 0$$

$$\mathcal{S}_{\rm bc} = \frac{\delta n_{\rm b}}{n_{\rm b}} - \frac{\delta n_{\rm c}}{n_{\rm c}} \neq 0$$

Compensated Isocurvature Perturbation (CIP)

Baryon-dark matter entropy

- Subdominant fluctuations: Adiabatic modes dominate, but do the relative number densities of DM and baryons fluctuate?

- *Observationally null in the CMB! (*surprising but true*)*
  - Vanishing Sachs-Wolfe effect from CIPs

$$\left(\frac{\Delta T}{T}\right)^{\mathrm{SW}} = \boxed{\cancel{\frac{\zeta}{5}}} - \boxed{\cancel{\frac{2}{5}\frac{\left(\rho_{\mathrm{cdm}}S_{\mathrm{cdm},\gamma} + \rho_{\mathrm{b}}S_{\mathrm{b},\gamma}\right)}{\rho_{\mathrm{matter}}}}}$$

$$\zeta = -\frac{5}{3}\Phi$$

Vanishes for all isocurvature modes

Also Vanishes for compensated modes

✳ *Run your favorite Boltzmann code (CAMB/CMBFAST) with a CIP*

✳*Fractional change in anisotropies of less than 0.00001 for angular scales l<10000*

✳ *Why?*

✳*For CIPs, CMB is only affected on scales where baryonic pressure matters*

$$\theta = \nabla \dot{v}$$ Definition

$$\dot{\delta}_{\rm b} = -\theta_{\rm b} + 3(\Delta\Phi)$$ Baryon conservation

$$\dot{\theta}_{\rm b} = -\frac{\dot{a}}{a}\theta_{\rm b} + c_{\rm s}^2 k^2 \delta_{\rm b} + \frac{4\bar{\rho}_\gamma}{3\bar{\rho}_{\rm b}} a n_{\rm e}\sigma_T(\theta_\gamma - \theta_{\rm b}) + k^2\Delta\Phi$$ Gravity, pressure, Thomson scattering

$$\dot{\delta}_{\rm c} = -\theta_{\rm c} + 3(\Delta\Phi)$$ DM conservation

$$\dot{\theta}_{\rm c} = -\frac{\dot{a}}{a}\theta_{\rm c} + k^2\Delta\Phi$$ Gravity

There seems to be no affect on the CMB!

Solution only affected if $k^2 c_{\rm s}^2 \gg H^2$, here $c_{\rm s}^2 \sim k_{\rm B}T/m_{\rm p}$

$$l > 10^5$$

No way to observationally disentangle (using CMB) CDM and baryon isocurvature models!

$\delta_{\rm c} - \delta_{\rm b}$ frozen on large scales

EXISTING MODELS FOR CIPS

- If heavy CDM produced before curvaton domination
  - Direct branching from inflaton
  - Gravitational particle production during inflation

$$10^{10}\ \mathrm{GeV} \lesssim M_{\mathrm{dm}} \lesssim 10^{15}\ \mathrm{GeV}$$

WIMPzilla (Kolb et al. 1998)

- Curvatons dominate, decay to baryons (Lyth et al. 2002)

- Curvaton sources entropy fluctuation in CDM

$$S_{\rm c} = \delta_{\rm c} - \frac{3}{4}\delta_{\rm rad} = -\frac{3}{4}\delta_{\rm rad}$$

- After curvaton dominates, adiabatic flucts generated

$$\delta_{\rm rad} = 4\zeta \qquad \delta_{\rm b} = \delta_\sigma$$

$$S_{\rm tot} = \frac{\rho_{\rm b}}{\rho_{\rm tot}}S_{\rm b} + \frac{\rho_{\rm c}}{\rho_{\rm tot}}S_{\rm c} = 0$$

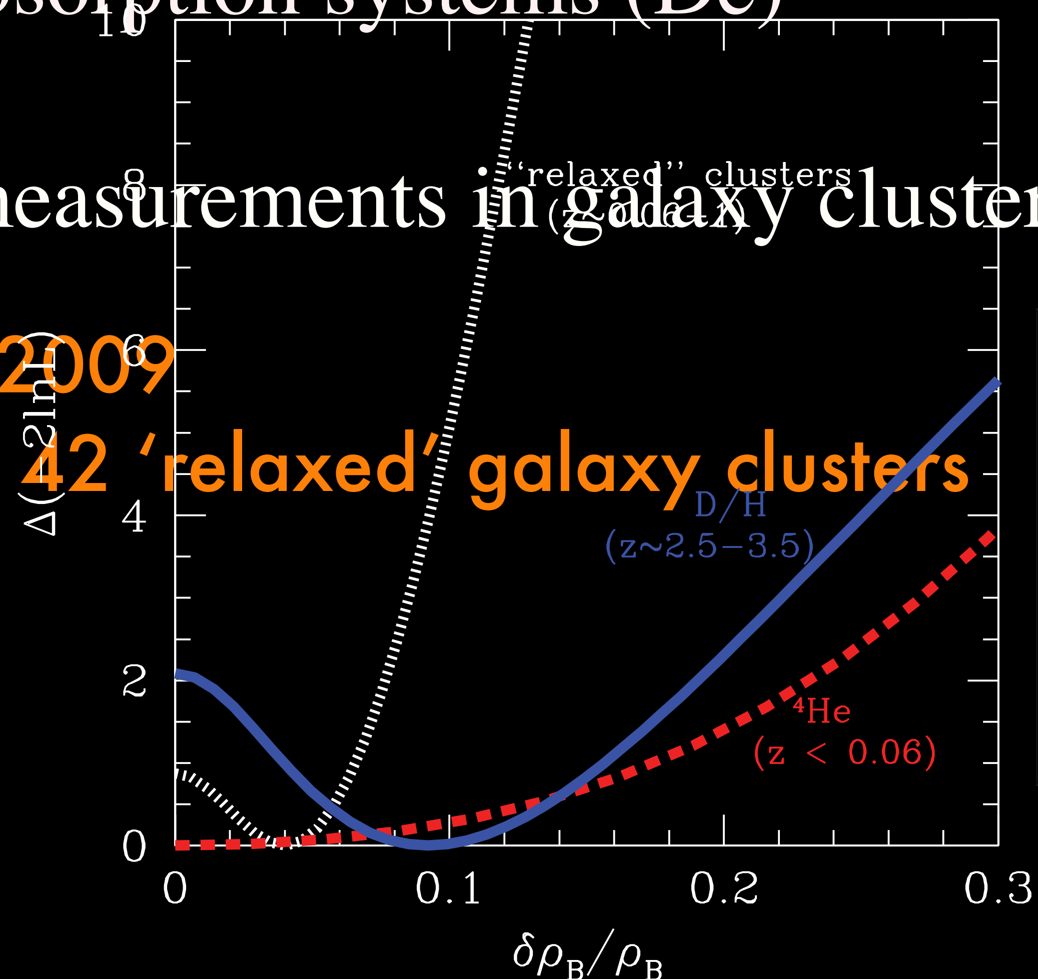
$$\Delta \equiv S_{\rm bc} \sim 10^{-3}$$

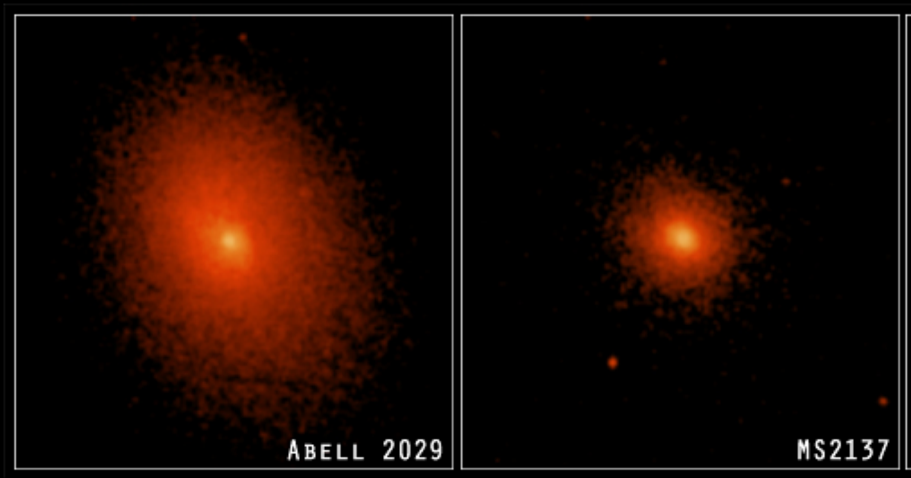
EXISTING CONSTRAINTS TO CIPS- BBN

- Primordial abundances of $De, \ ^3He, \ ^4He, \ ^7Li$: Blue compact galaxies (He) and QSO Absorption systems (De)

- Baryon fraction measurements in galaxy clusters

from Holder et al. 2009
(from Allen 2008)- 42 'relaxed' galaxy clusters



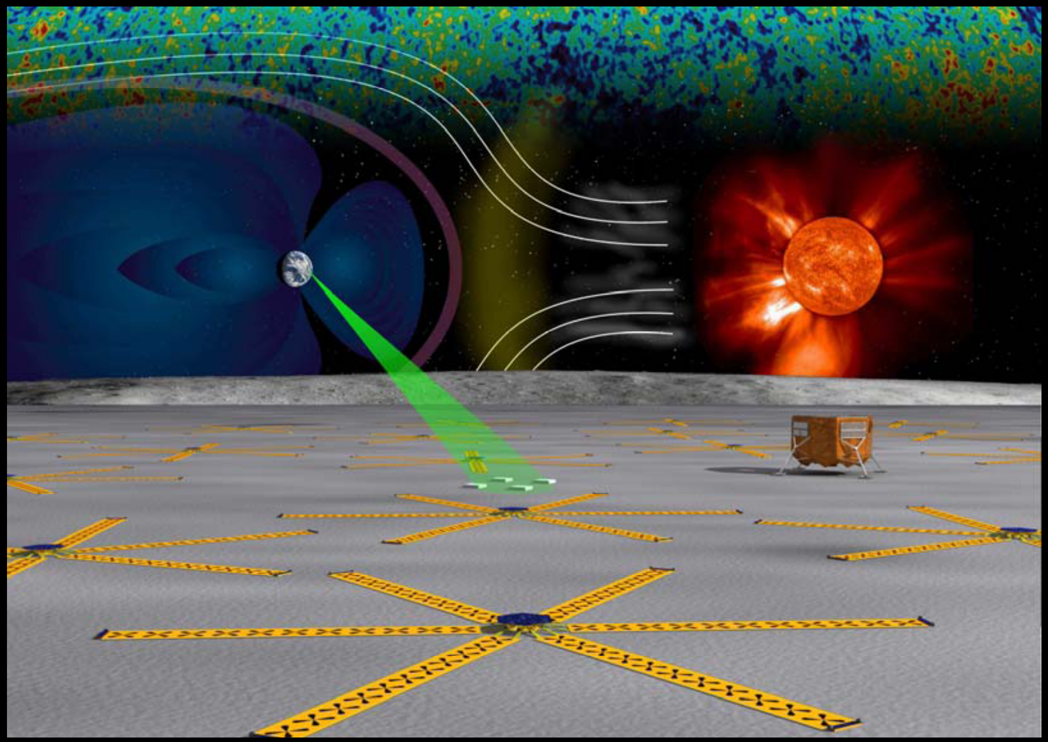


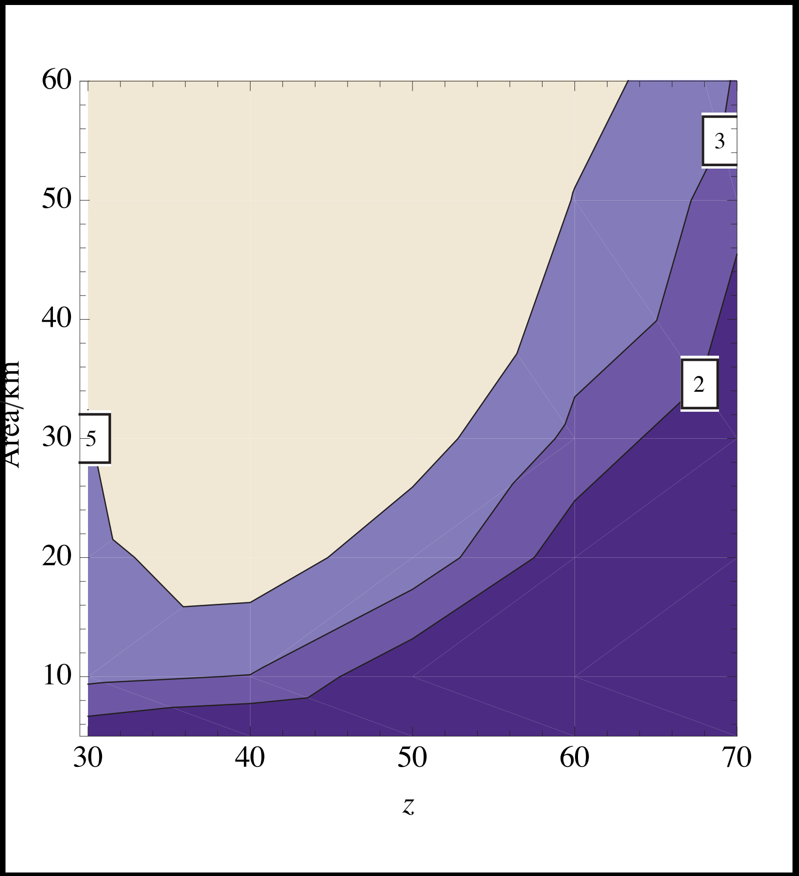
Fluctuations as high as **8%** are allowed by the data

Can we empirically show, rather than simply assume, that baryon trace DM in the early universe?

CIPS AND 21-CM FLUCTUATIONS

Gordon and Pritchard, 2009





Significance of a 21-cm detection of amplitude 10^{-3} CIPs

COMPENSATED ISOCURVATURE AND THE CMB: *PATCHY REIONIZATION*

✳ *Patchy Screening:* (Smith/Dvorkin 2008/2009)

Angular dependence of $\tau(\hat{n})$ modulates $e^{-\tau}\left\{\delta T(\hat{n}), E(\hat{n}), B(\hat{n})\right\}$

✳ *Patchy scattering*

Polarization : $\boxed{\Delta(\hat{n})}$ affects T_{2i} generation and n_e

$$Q, U \propto \int \boxed{n_e}(\eta)\left[1+\boxed{\Delta\left(\hat{n}\right)\right] T_{2i}\left(\eta, \hat{n}\right)} d\eta$$

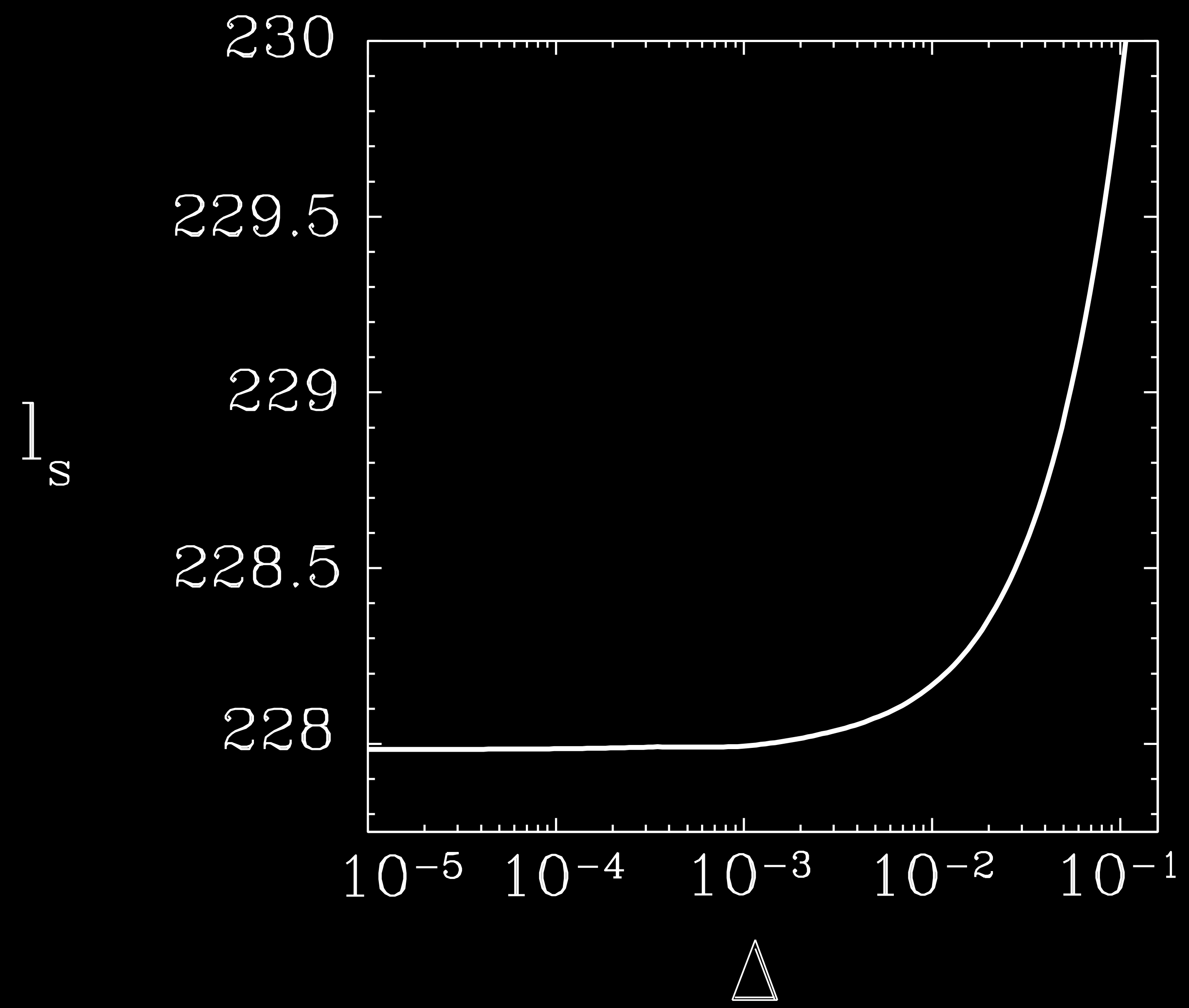
COMPENSATED ISOCURVATURE AND THE CMB: *z~1100 EFFECTS*

- 90% of CMB photons last scatter at *decoupling* (z~1100)
- CIPs are primordial: induced anisotropies at z~1100 >> reionization terms
- Prior work neglected effects at z~1100

Vastly exceeds reionization signal!!!

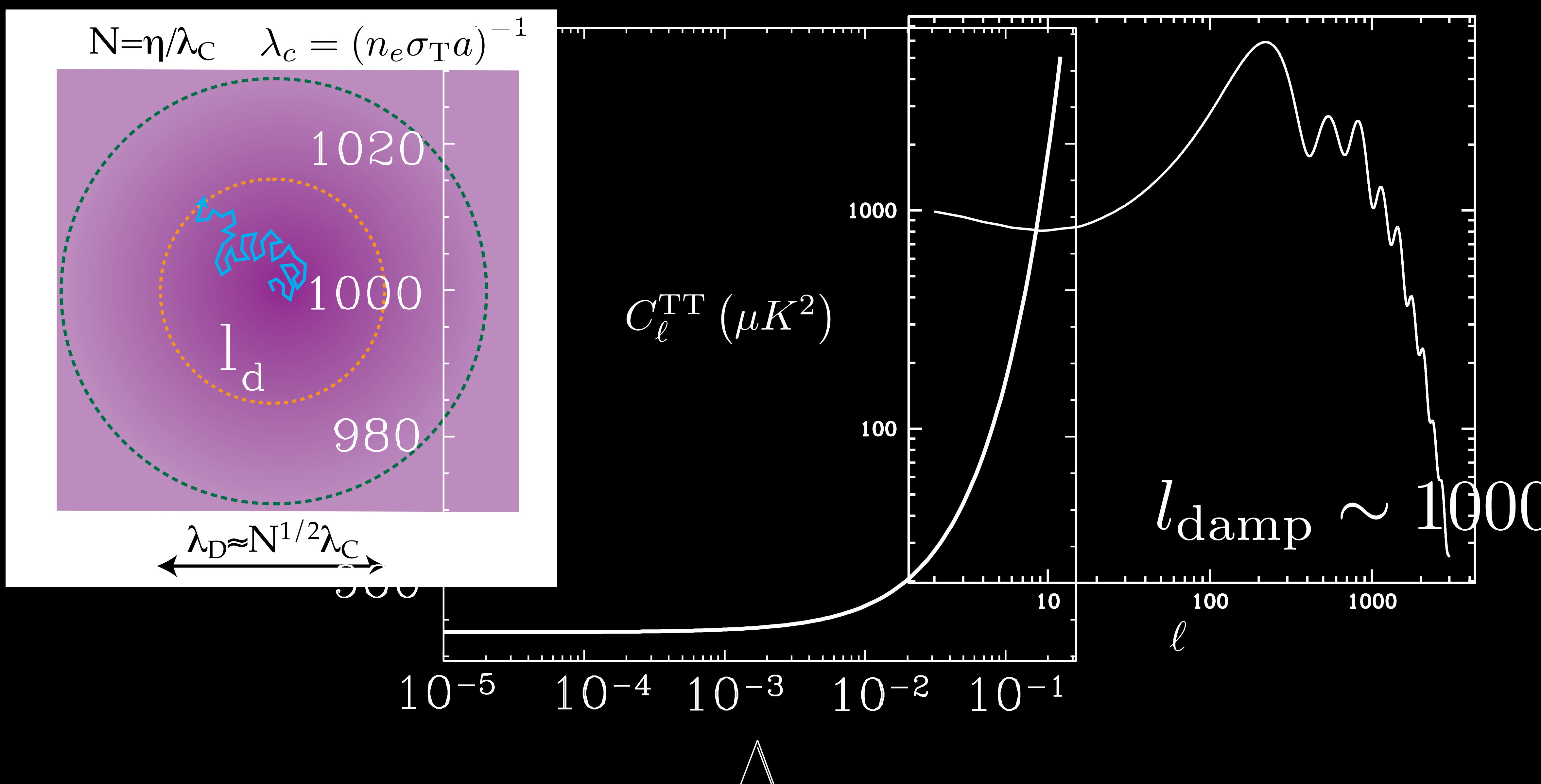
$\text{Thompson scattering rate} \propto \ \dot{\tau}\,(1+\Delta)\,\nabla\cdot\delta_i$ Second order!

COMPENSATED ISOCURVATURE AND THE CMB: *z~1100 EFFECTS*



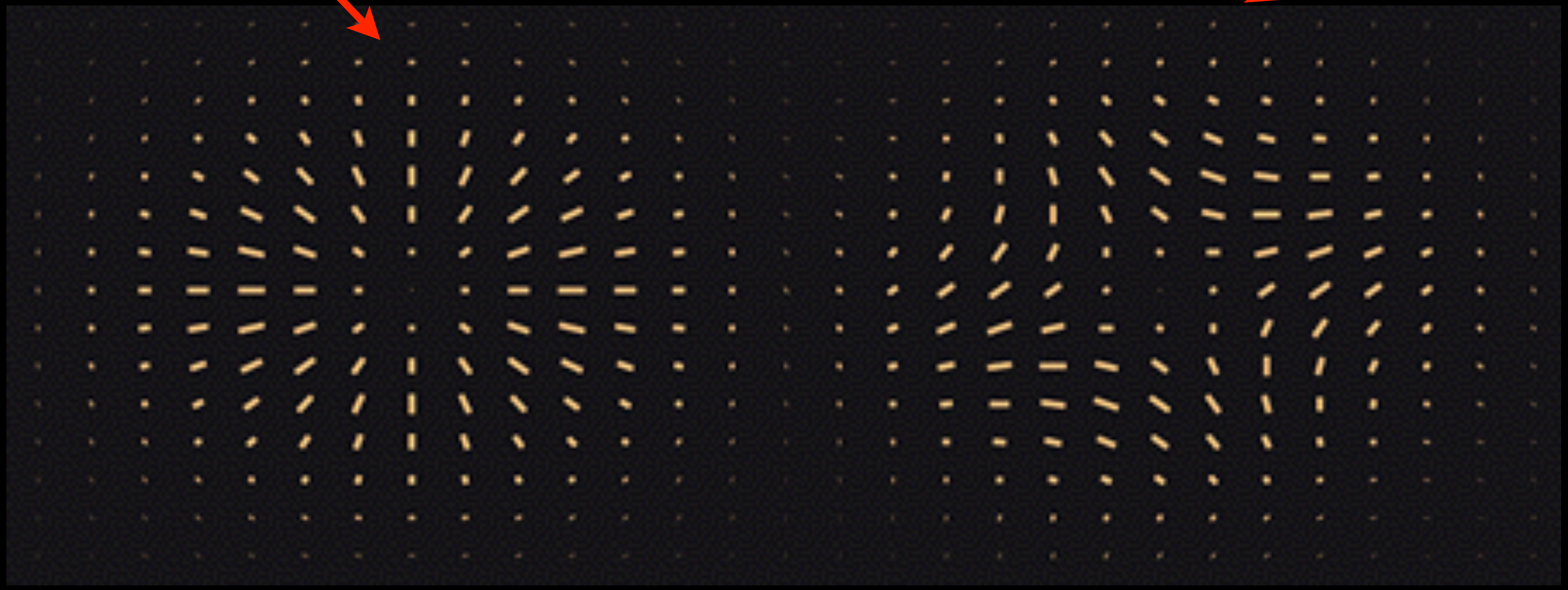
COMPENSATED ISOCURVATURE AND THE CMB: *z~1100 EFFECTS*

- Damping scale modulated by CIPs



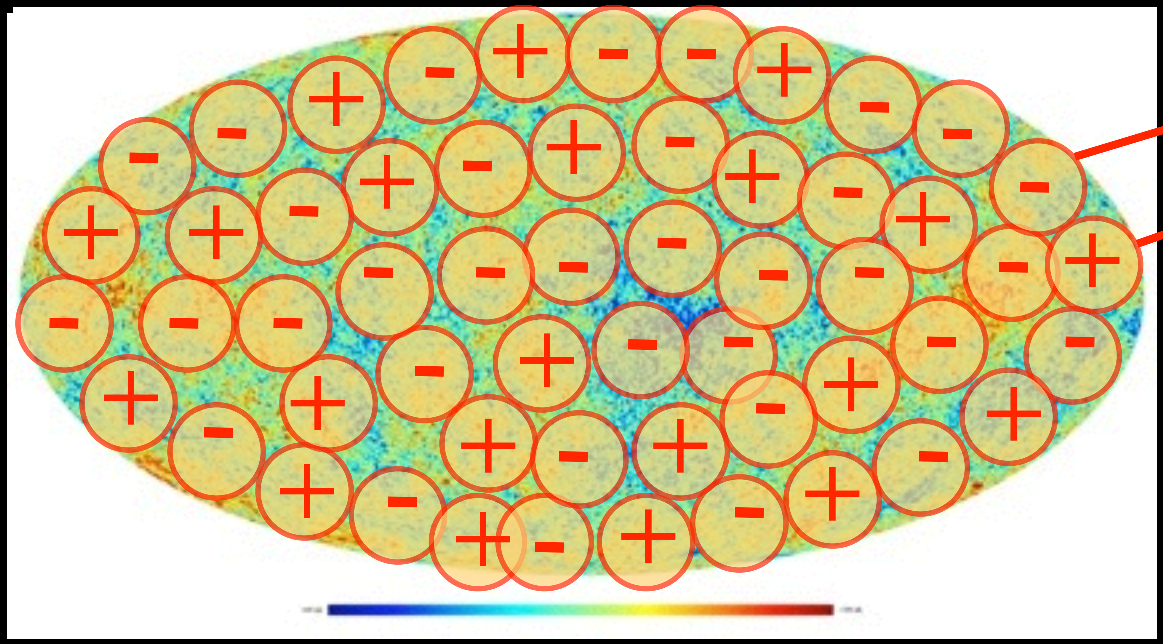
COMPENSATED ISOCURVATURE AND THE CMB:
PATCHY REIONIZATION B-MODES

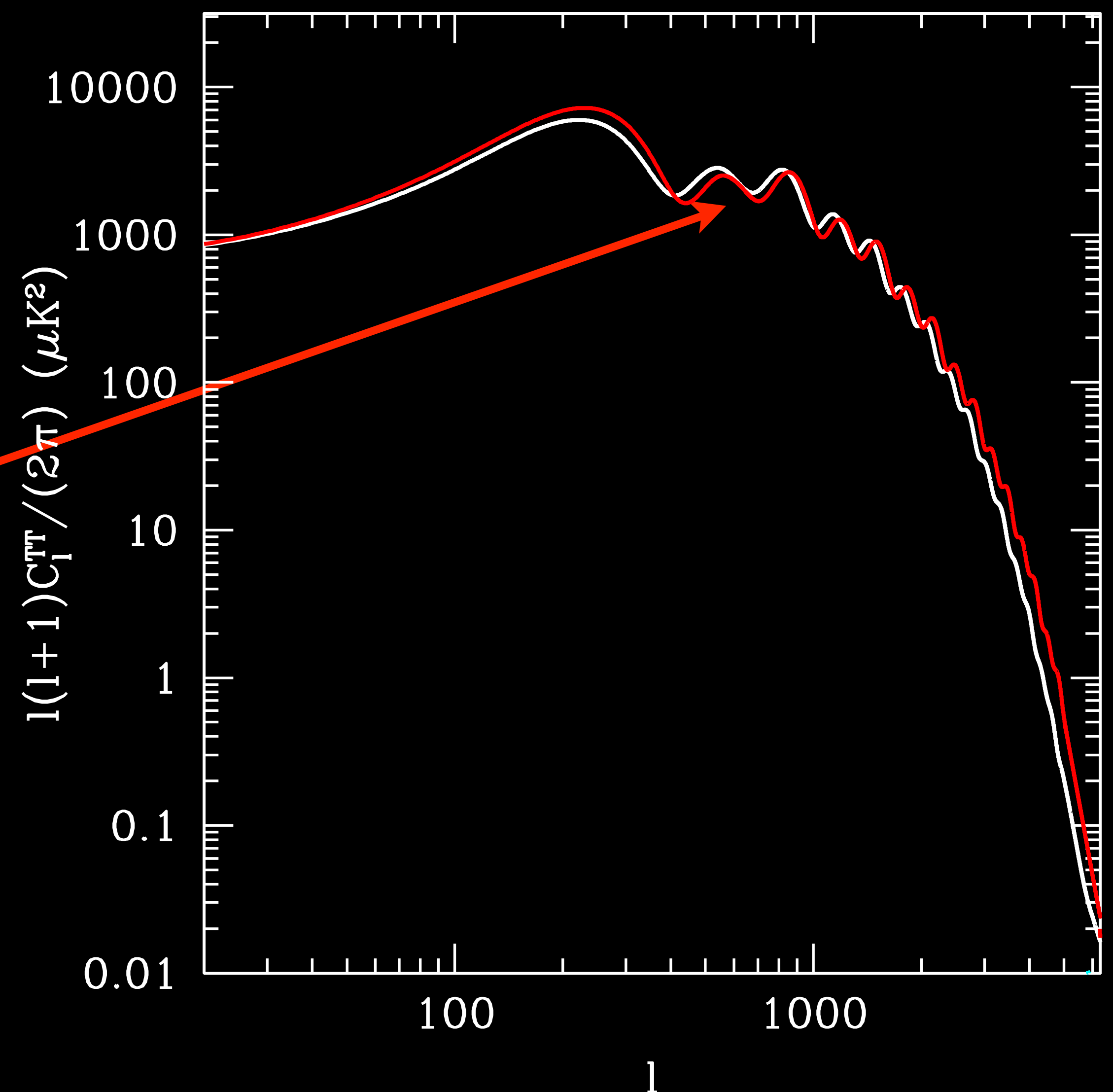
- Funnels E modes to B modes



COMPENSATED ISOCURVATURE AND THE CMB:
RECOVERING THE REALIZATION

$\Delta(\hat{n}_{\rm patch}) > 0$





Filtering the map

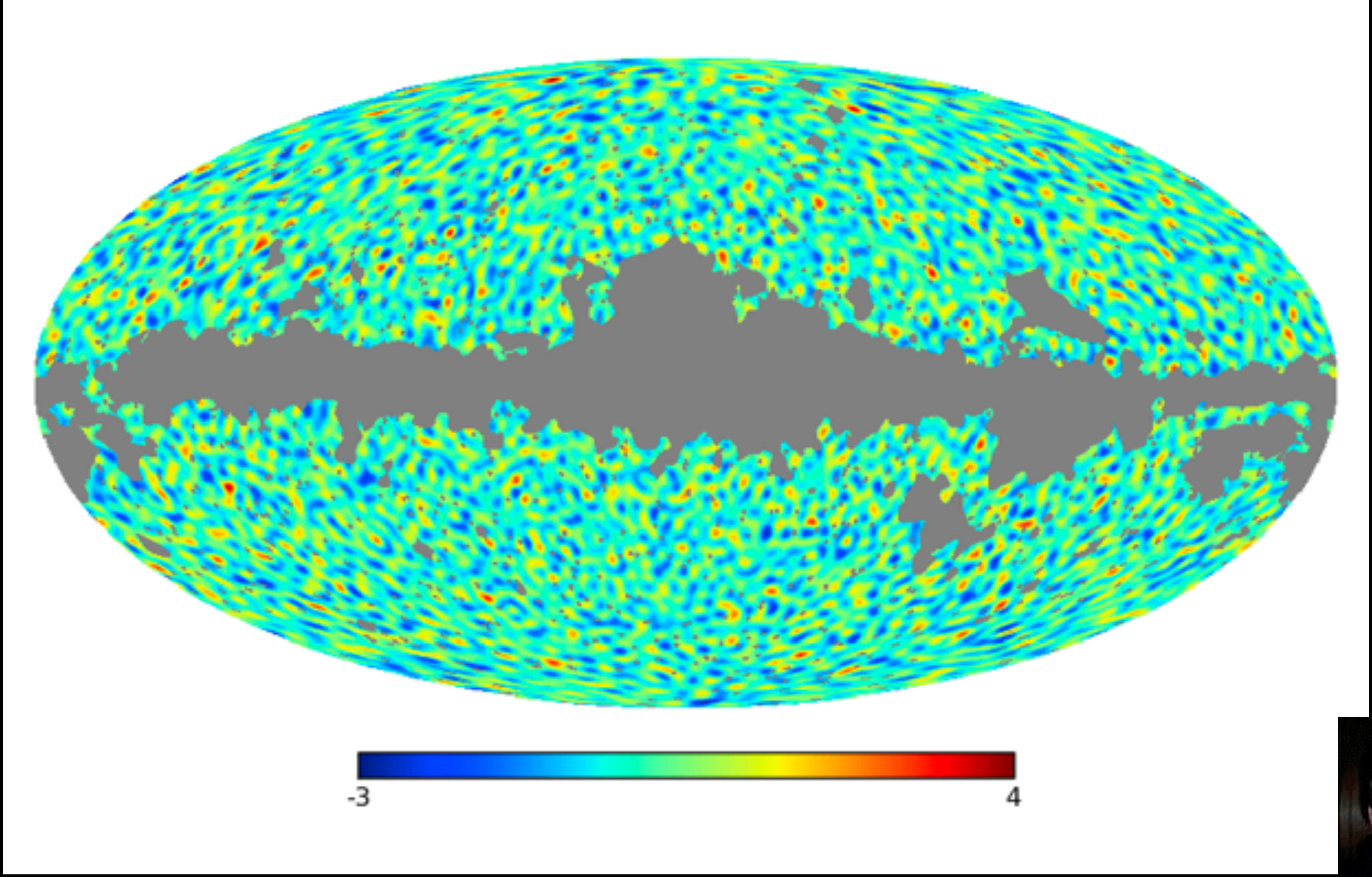
- Reconstruct CIP map

$$\bar{\Delta}_{LM} = \int d\hat{n} Y^*_{LM}(\hat{n}) \bar{T}(\hat{n}) S(\hat{n})$$

$$\bar{T}(\hat{n}) = \sum_{lm} Y_{lm}(\hat{n}) \bar{T}^{(a)}_{lm},$$

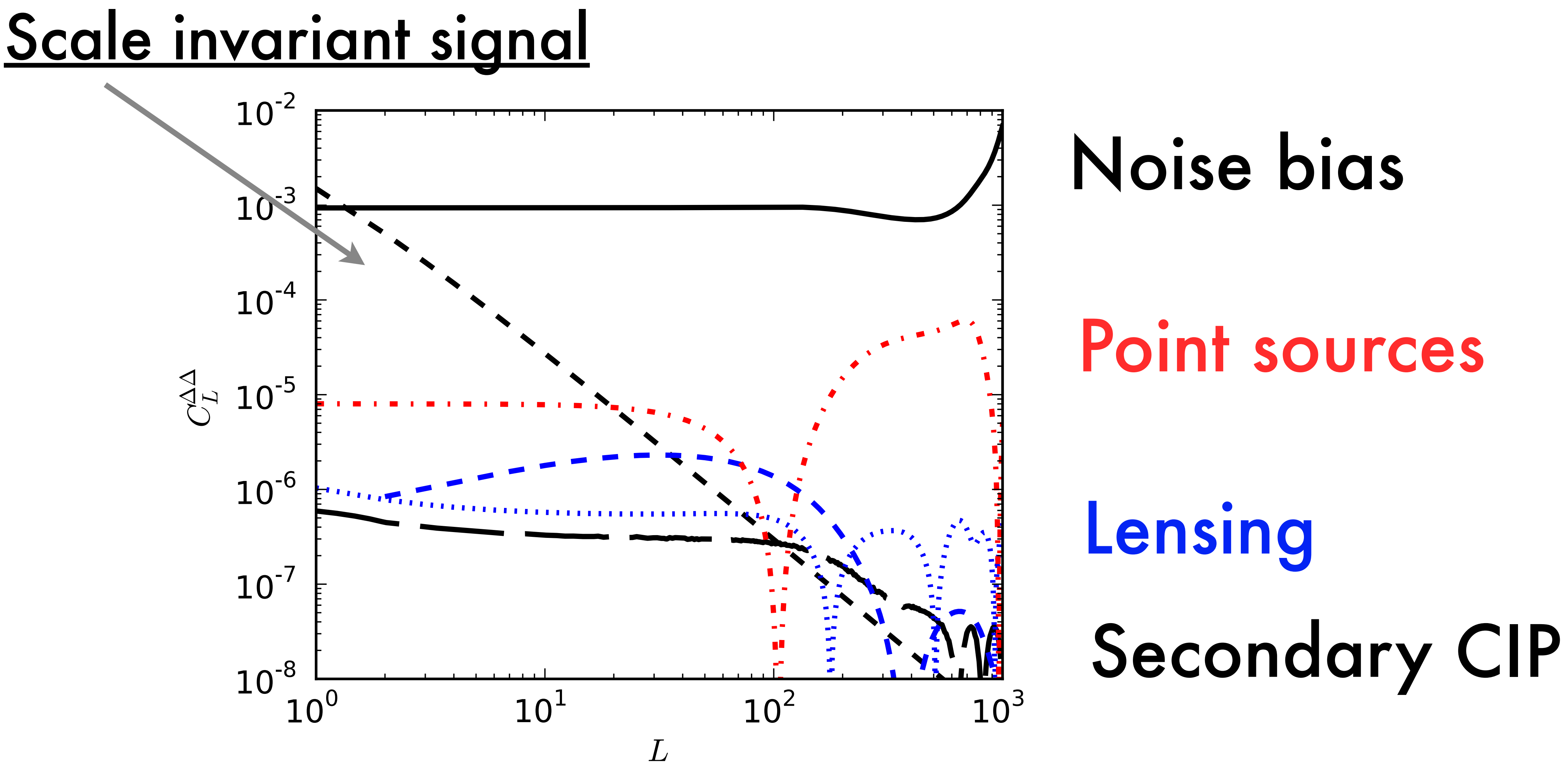
$$S(\hat{n}) = \sum_{lm} Y_{lm}(\hat{n}) C_l^{\mathrm{T,dT}} \bar{T}_{lm},$$

Filtering the map



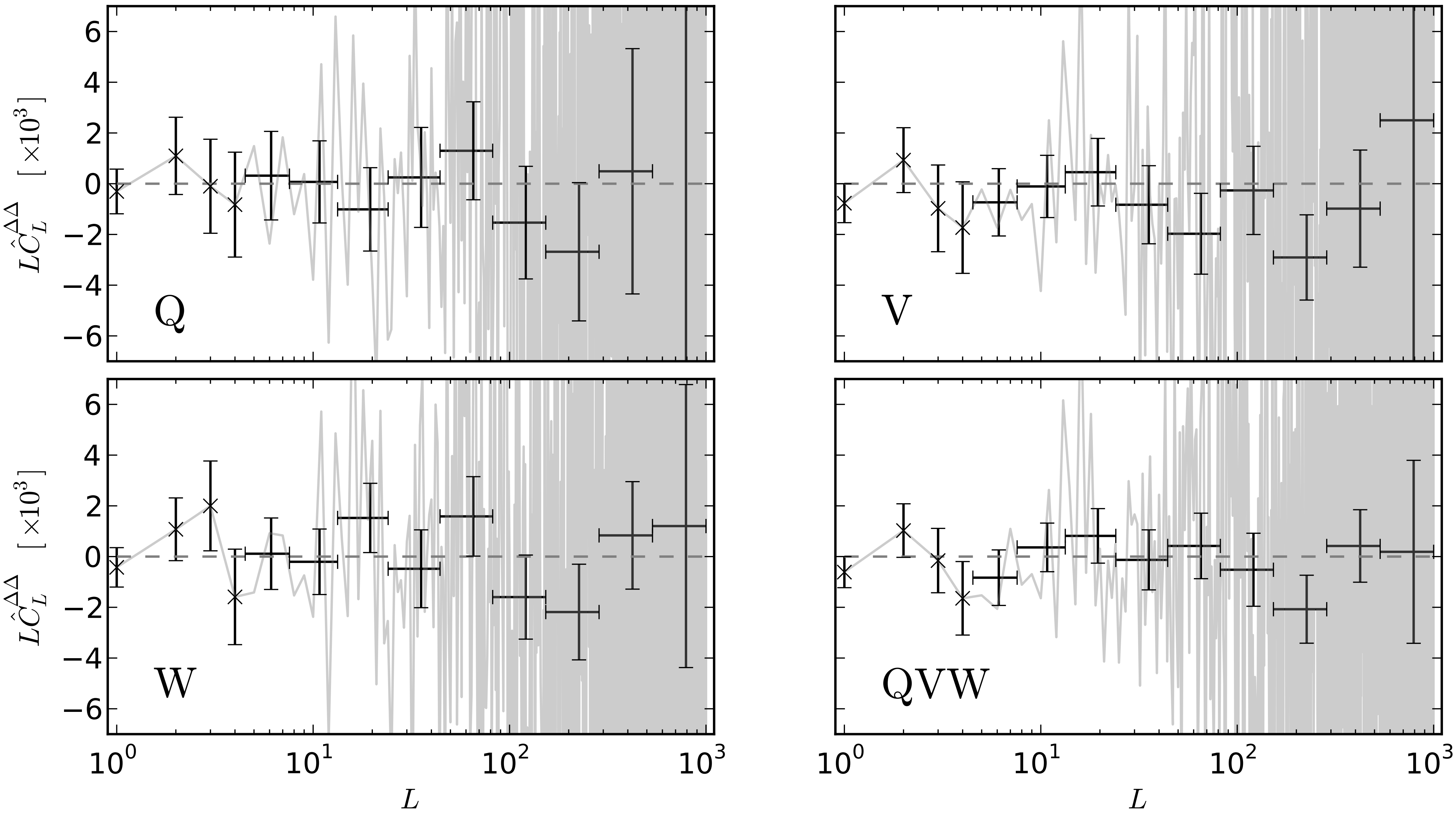
in collaboration with Duncan Hanson

Possible sources of bias



All secondary biases can be neglected for WMAP-9 analysis

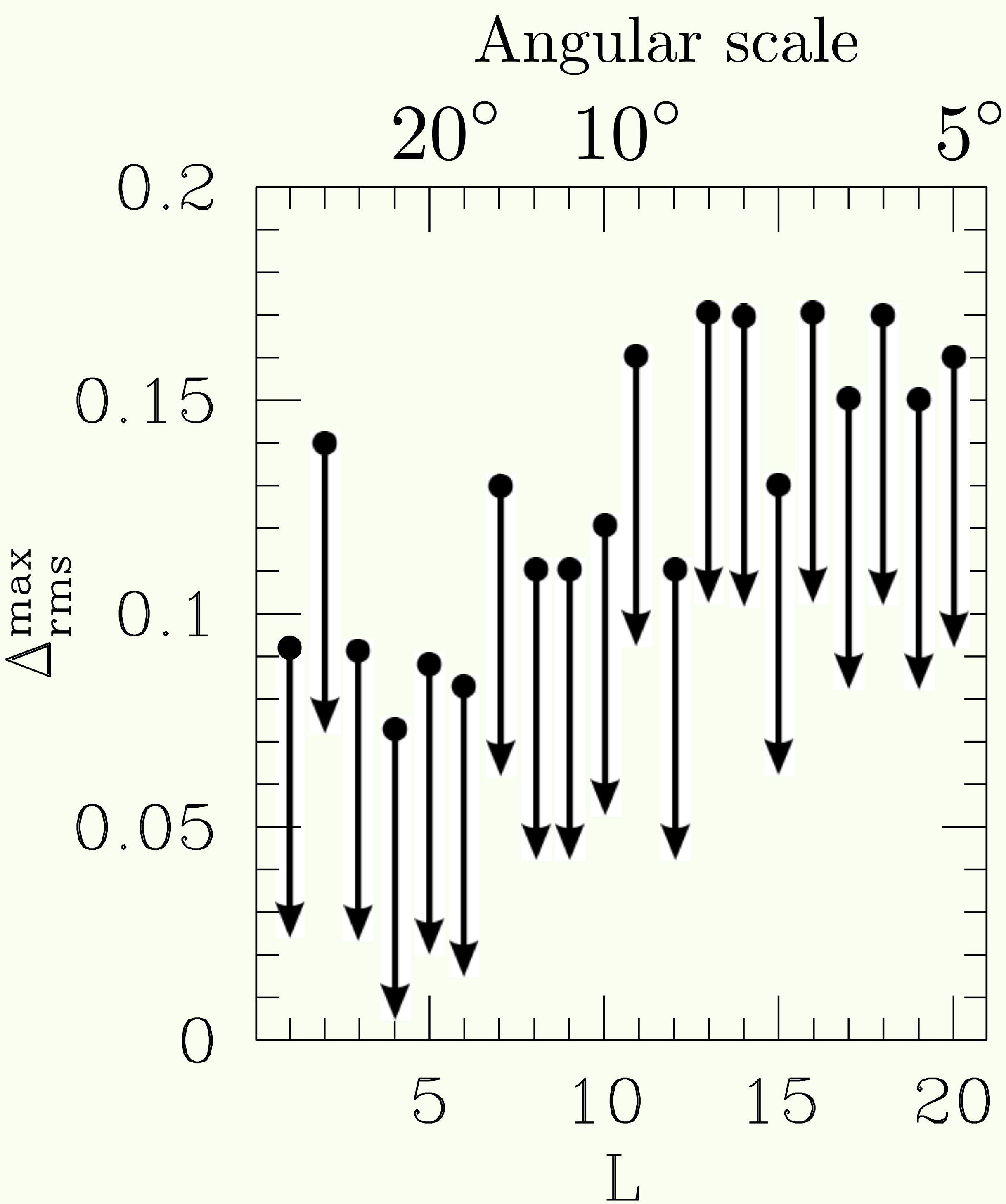
Reconstructed power spectrum from WMAP 9-year data



No evidence for CIPs! Cosmic baryon fraction is homogeneous

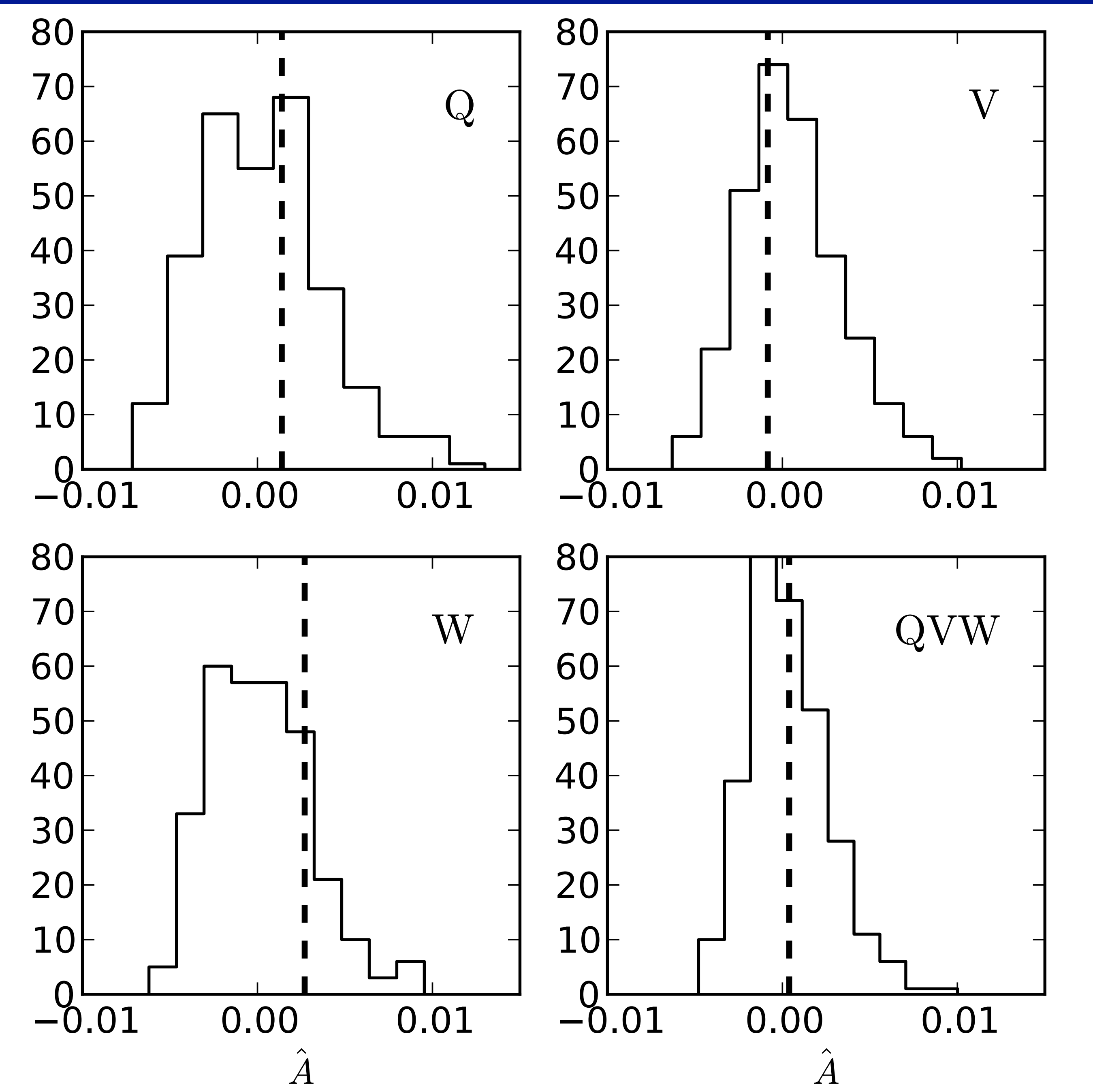
arXiv: 1306.4319 (DG, DH, GH, OD, and MK)- Phys. Rev. D published

Upper limit to CIP spectrum at a variety of scales



Cosmic baryon fraction is homogeneous at 10-20% level at 5-100° scales

Limit to amplitude of scale-invariant spectrum



- Combine scales to probe models
- Scale-invariant CIP spectrum

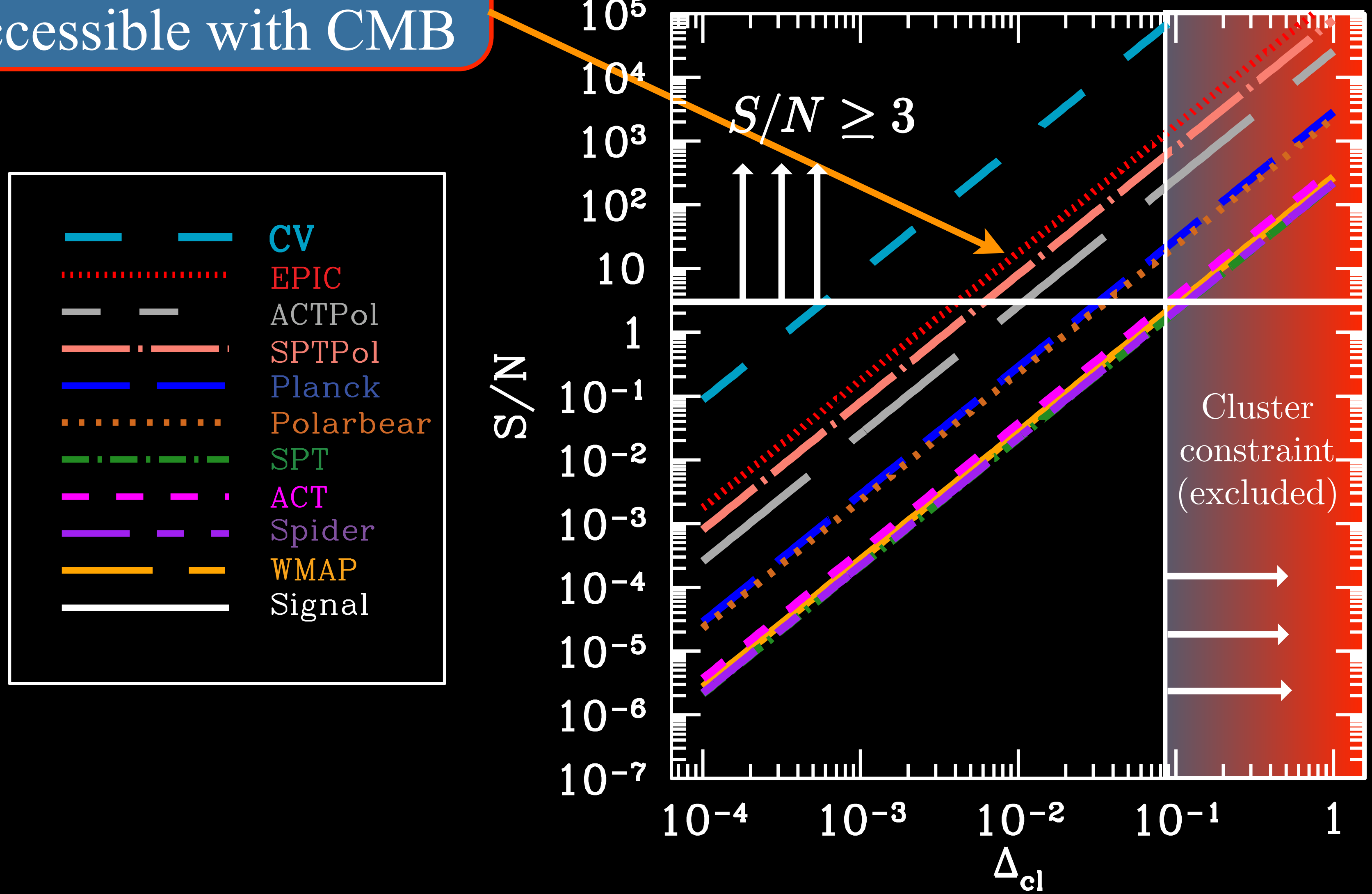
$$C_L = \frac{A}{L(L+1)}$$

- Proof of technique
- First purely primordial test
- Great improvement with coming experiments
- Monte Carlo null hypothesis
- Observations consistent with null hypothesis

$$A \lesssim 1.1 \times 10^{-2}$$

COMPENSATED ISOCURVATURE AND THE CMB: *PROSPECTS*

Parameter space accessible with CMB



Excluded by galaxy cluster measurements of baryon fraction

Two orders of magnitude improvement: conservatively

Forecasts need to be revised: sample variance from primordial B-modes!

Future work: correlated CIPs and the curvaton model

- All perturbations $(\zeta,\ S_{\rm c},\ S_{\rm b})$ seeded by curvaton
- CIPs are correlated with adiabatic flucts

$$\boxed{3\zeta \lesssim \Delta \lesssim 18\zeta}$$

- Non-vanishing 3 pt-functions in specific curvaton implementation

$$\delta\left\{\mathrm{T},\ \mathrm{E},\ \mathrm{B}\right\} \propto \zeta\Delta \propto \zeta^2$$
$$\left\{\mathrm{T},\ \mathrm{E},\ \mathrm{B}\right\}_0 \propto \zeta$$
$$\langle XYZ\rangle \propto \zeta^4$$

FUTURE WORK: CORRELATED CIPS AND THE CURVATON MODEL



- Free parameter: Strength of cross-correlation A

$$\Delta \simeq A\zeta$$

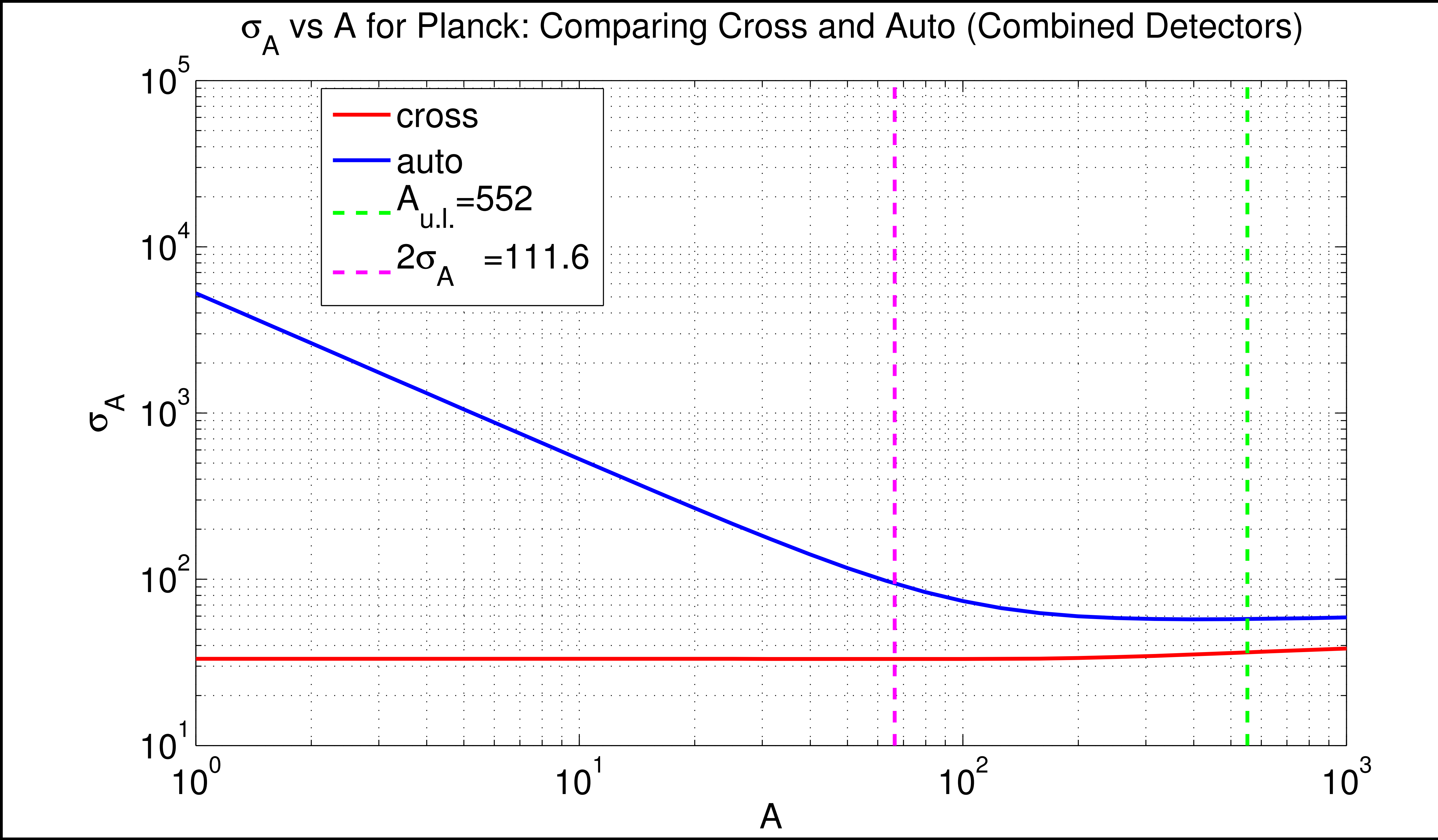
- `Maps' already exist

$$\hat{A} = \mathcal{N} \sum_{LM} \frac{-T^{*}_{LM}\hat{\Delta}_{LM}}{5(2L+1)C_{L}^{TT}c^{2}_{LM}}$$

$$c^{2}_{LM} \simeq \sigma^{2}_{L}$$

- Forecast and analysis underway (KICP collabs): Chen He, Wayne Hu, Duncan Hanson

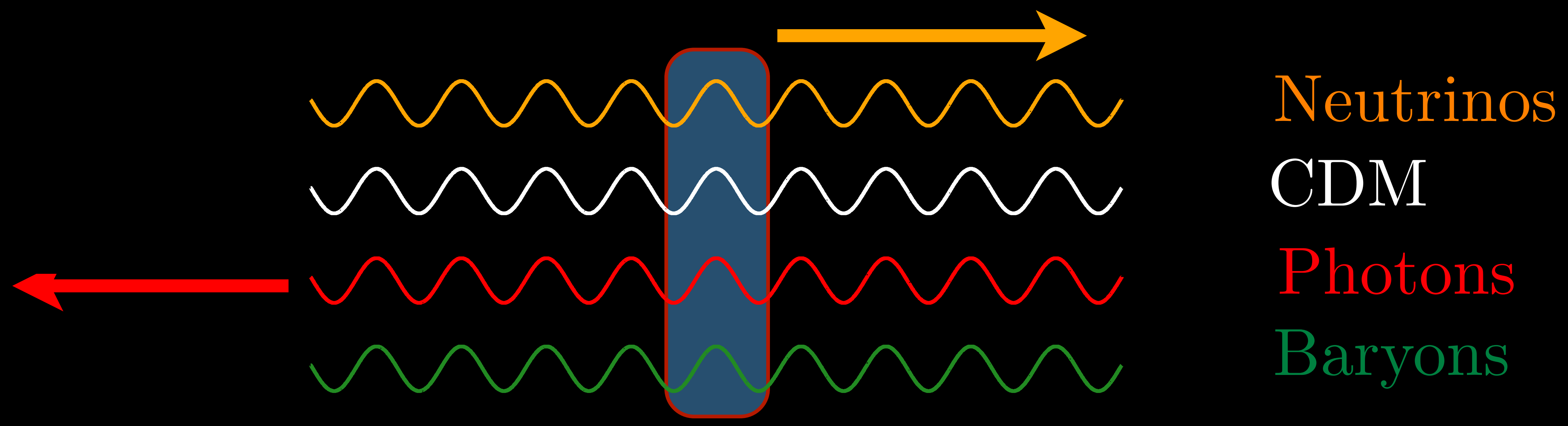
FORECAST: CORRELATED CIPS AND THE CURVATON MODEL



CONCLUSIONS

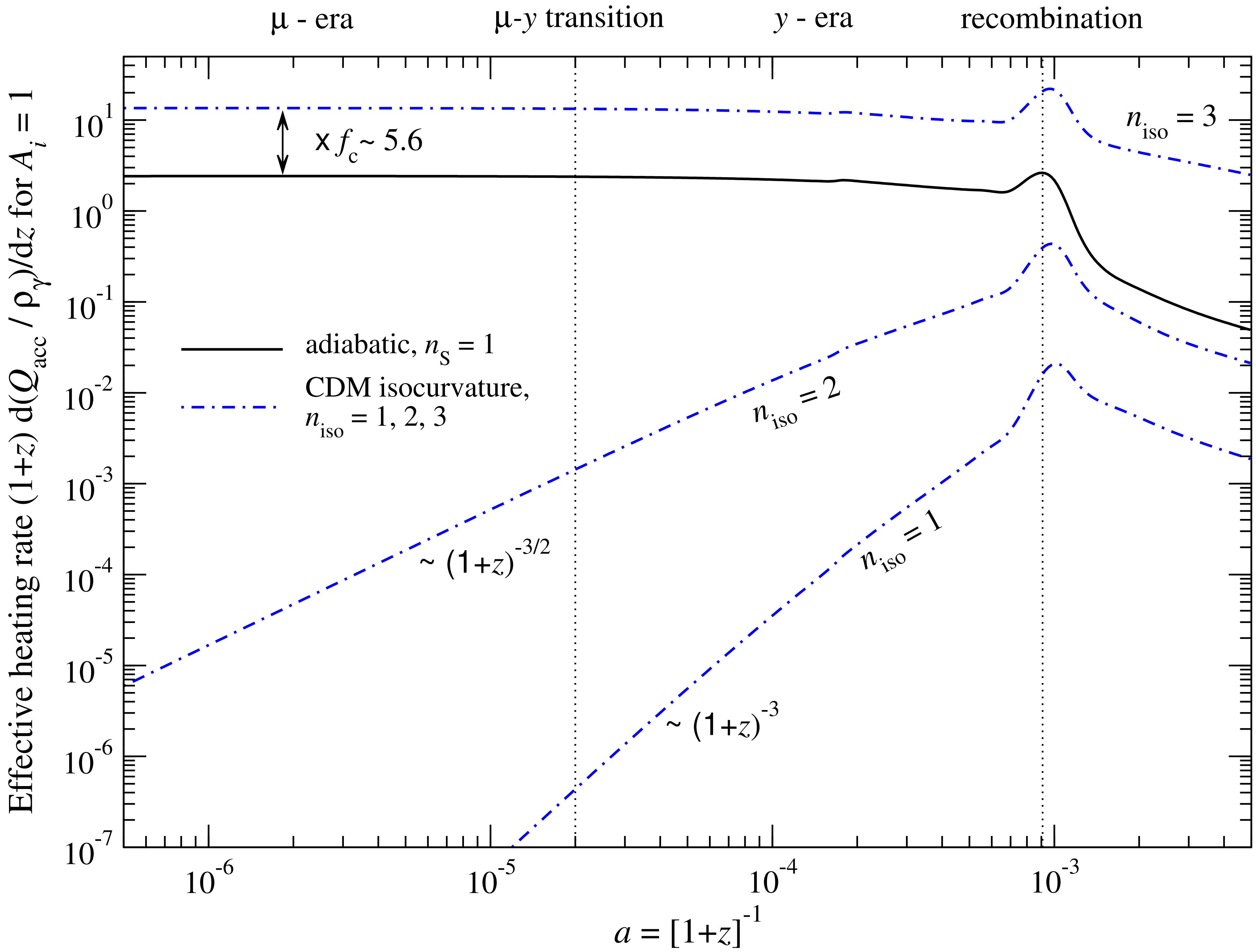
- Primordial, baryons trace DM at ~10-20% level
- A new test of curvaton models is at hand
- Degeneracy between baryon and CDM isocurvature can be broken with CMB data
- In progress: Correlated case, effect on galaxies, small scale CIPs
- Future work: (use SPT/Planck polarization+ T data)

Example:

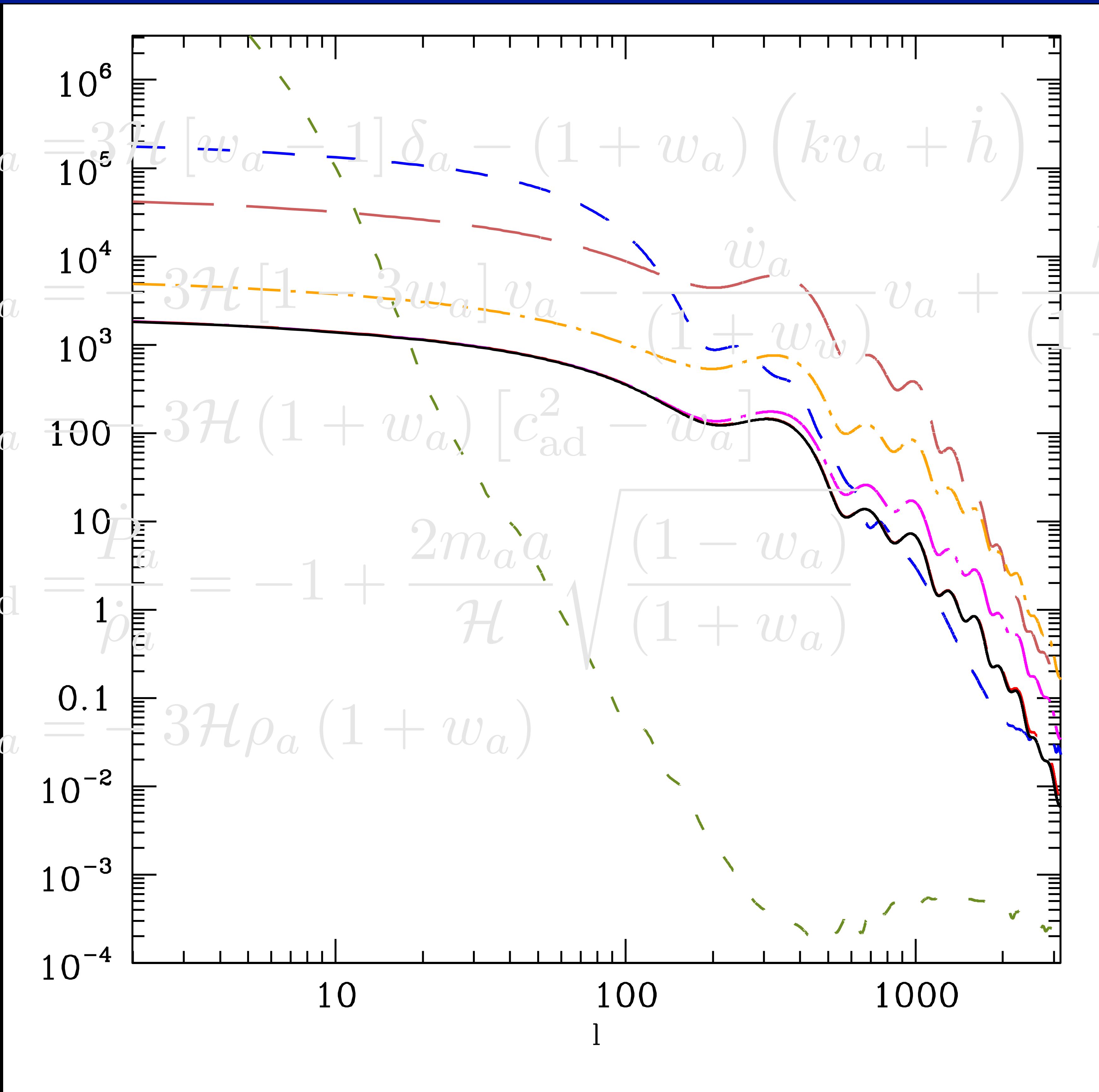


Momentum density also gravitates!

RESULTS DEPEND ON POWER SPECTRUM OF ISOCURVATURE MODES



Getting under the hood: The need for numerical care



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

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

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

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

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

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

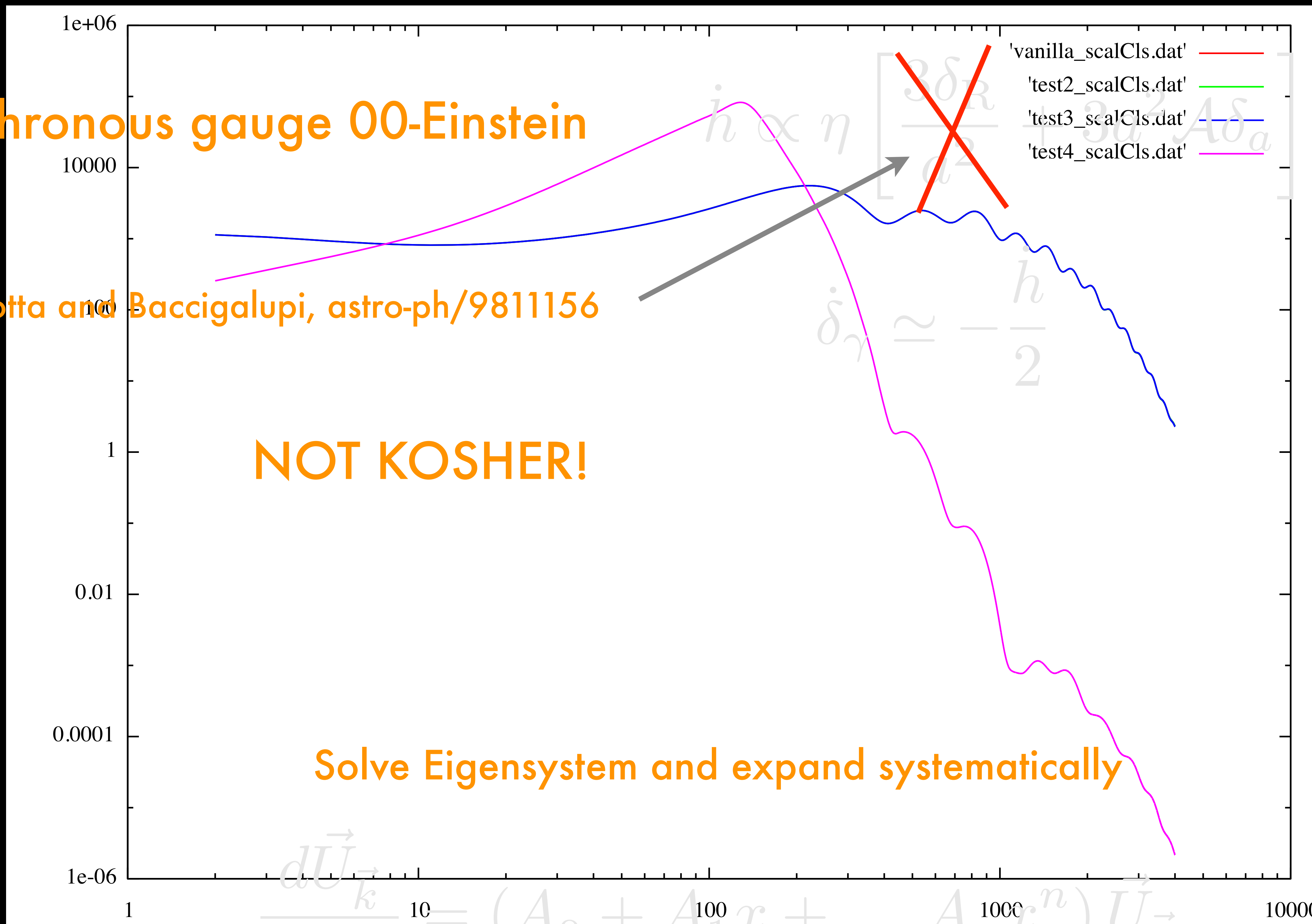
Synchronous gauge 00-Einstein

$$\dot{h} \propto \eta \left[\cancel{\frac{3\delta_R}{a^2}} + 3a^2 A\delta_a \right]$$

$$\dot{\delta}_\gamma \simeq -\frac{\dot{h}}{2}$$

Perrotta and Baccigalupi, astro-ph/9811156

NOT KOSHER!



Solve Eigensystem and expand systematically

$$\frac{d\vec{U}_{\vec{k}}}{d\ln x} = (A_0 + A_1 x + \dots A_n x^n)\,\vec{U}_{\vec{k}}$$

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

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

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

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

Very challenging to detect!

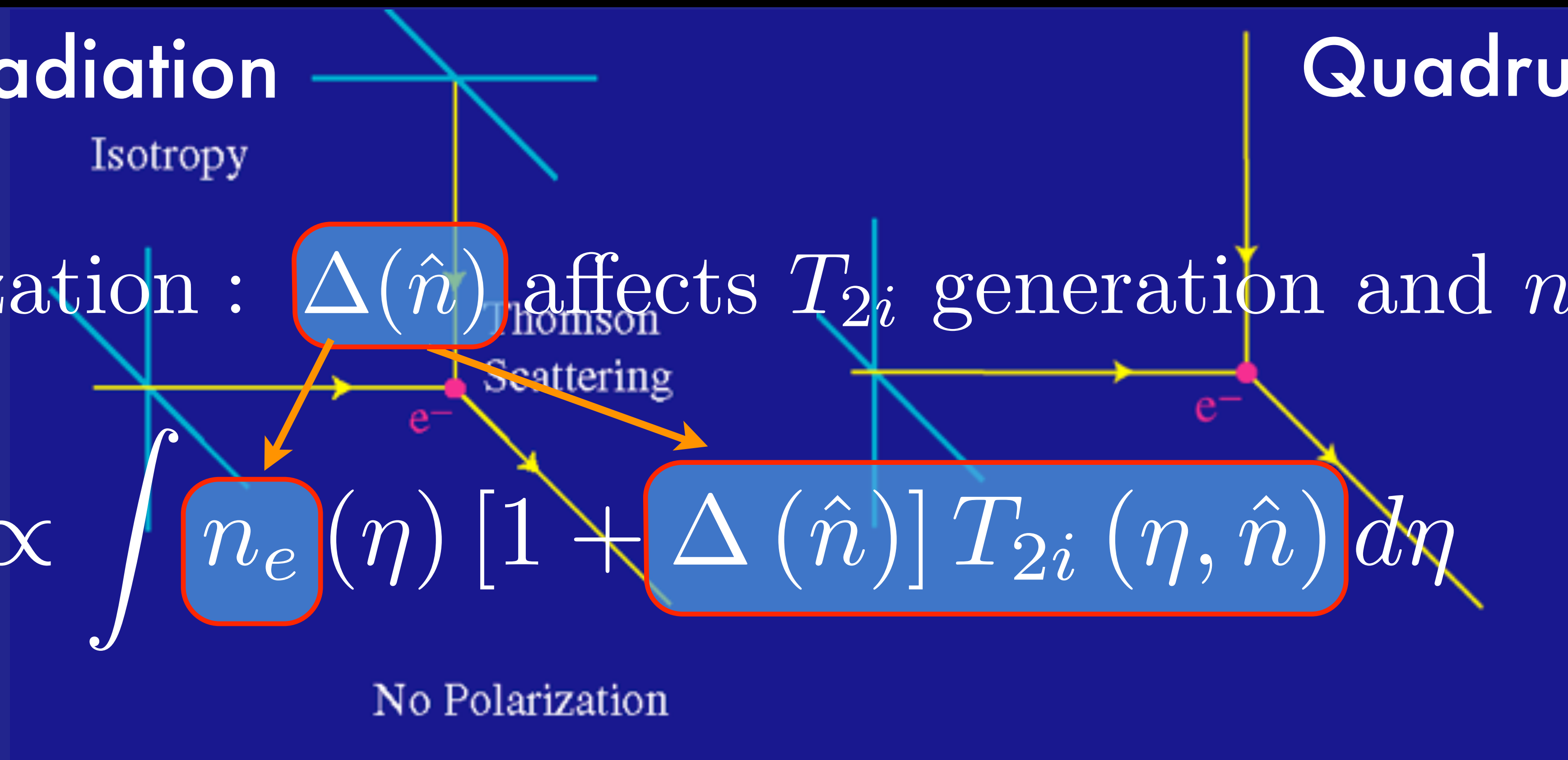
- ✳Not a unique probe of CIPs: true for curvaton model in general
- ✳Would fail to detect a non-curvaton CIP!

COMPENSATED ISOCURVATURE AND THE CMB: *z~1100 EFFECTS*

- Efficiency of polarization generation is modulated

Isotropic radiation

Quadrupole moment



- Polarization : $\Delta(\hat{n})$ affects T_{2i} generation and n_e

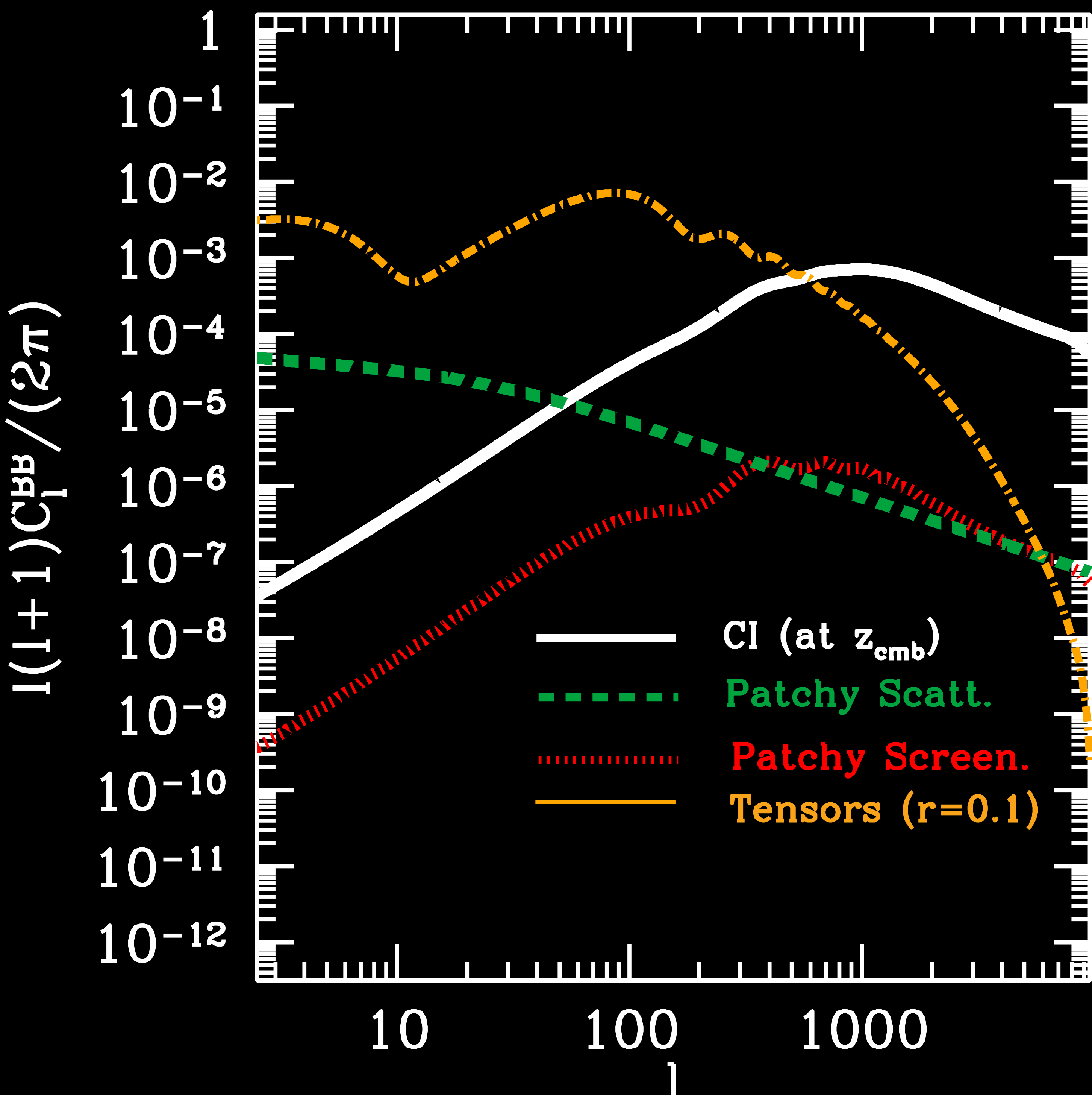
$$Q, U \propto \int \boxed{n_e}(\eta)\left[1+\boxed{\Delta\left(\hat{n}\right)\right] T_{2i}\left(\eta,\hat{n}\right)}\, d\eta$$

From Wayne Hu's website

COMPENSATED ISOCURVATURE AND THE CMB:
OTHER EFFECTS

* ....and that from r=0.1 tensor modes for l>300.

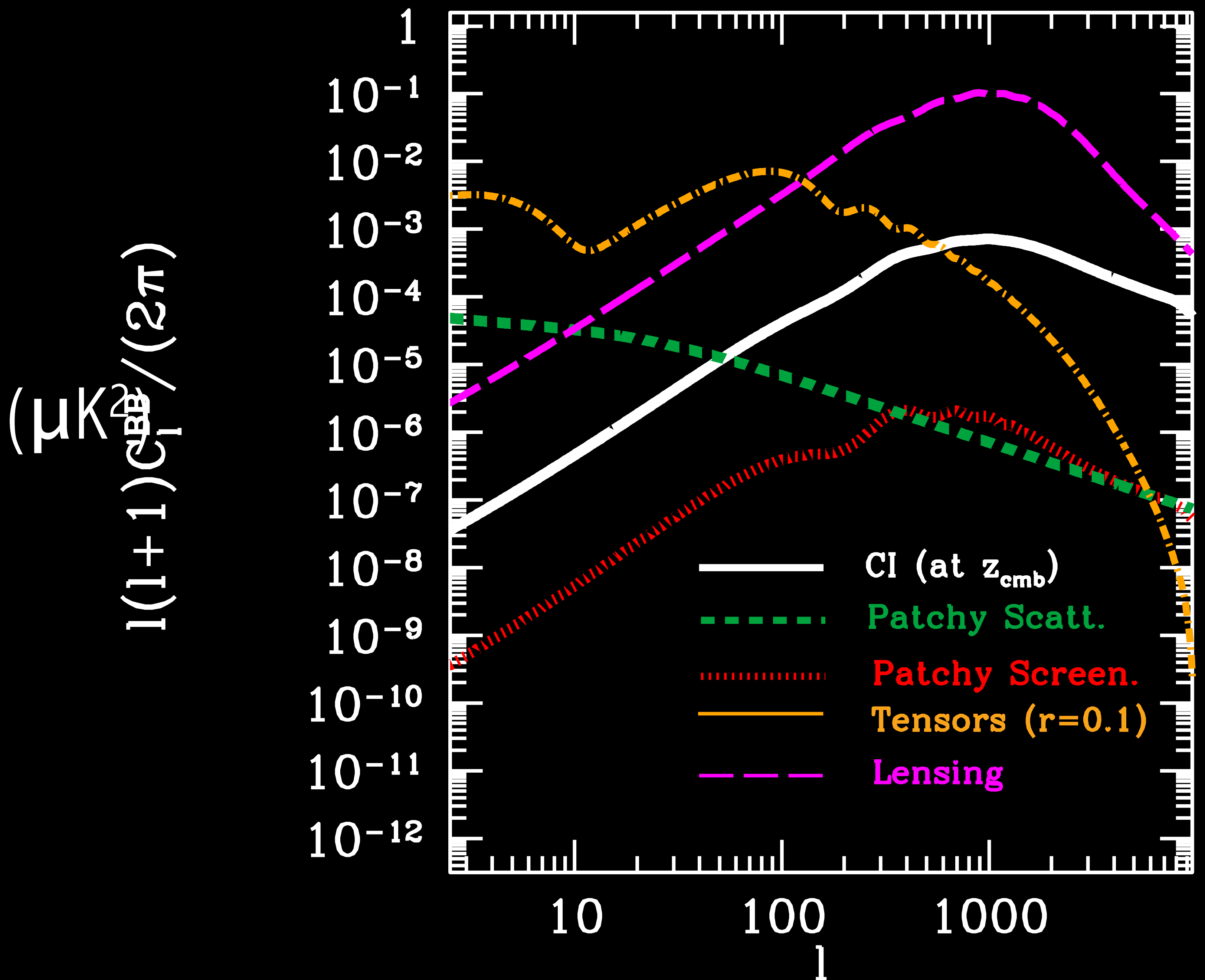
(μK²)



Can't fake BICEPs!
Need to exercise harder!

COMPENSATED ISOCURVATURE AND THE CMB: *CIPS VS LENSING*

- ... but at power spectrum level for l>100, all are swamped by lensing!
- ...fortunately, there is life beyond the power spectrum!



COMPENSATED ISOCURVATURE AND THE CMB:
RECOVERING THE REALIZATION

- Realization of CIPs breaks usual statistical isotropy

Usual term

Anisotropic generalization of C_l

Geometric function of multipoles

$$\langle X^*_{l'm'} X_{lm}\rangle = \boxed{C_l^{XX'}\delta_{ll'}\delta_{mm'}} + \sum_{LM} \boxed{D^{LM,XX'}_{ll'}}\, \boxed{\xi^{LM}_{lml'm'}}$$

$$X \in \{\mathrm{T}, \mathrm{E}, \mathrm{B}\}, \quad D^{LM,XX'}_{ll'} = \boxed{\Delta_{LM}}\, \boxed{S^{L,XX'}_{ll'}}$$

$$\langle T^*_{l'm'} T_{lm}\rangle = \left(C_l^{\mathrm{T,dT}} + C_{l'}^{\mathrm{T,dT}}\right) K^L_{ll'}$$

$$H^L_{ll'} = \begin{pmatrix} l & L & l' \\ 2 & 0 & -2 \end{pmatrix}$$

$$K^L_{ll'} = \begin{pmatrix} l & L & l' \\ 0 & 0 & 0 \end{pmatrix}$$

Signal: reconstruction of CIP amplitude

Response power spectra

$\mathrm{XX'}$	$S^{L,\mathrm{XX'}}_{ll'}$
TT	$\left(C_l^{\mathrm{T,dT}} + C_{l'}^{\mathrm{T,dT}}\right) K^L_{ll'}$
EE	$\left(C_l^{\mathrm{E,dE}} + C_{l'}^{\mathrm{E,dE}}\right) H^L_{ll'}$
EB	$-iC_{l'}^{\mathrm{E,dE}} H^L_{ll'}$
TB	$-iC_{l'}^{\mathrm{T,dE}} H^L_{ll'}$
TE	$\left(C_{l'}^{\mathrm{T,dE}} H^L_{ll'} + C_l^{\mathrm{E,dT}} K^L_{ll'}\right)$

$$\xi^{LM}_{lml_1m_1} = (-1)^m \sqrt{\frac{(2L+1)(2l+1)(2l_1+1)}{4\pi}} \begin{pmatrix} l & L & l' \\ -m & M & m' \end{pmatrix}$$

Estimating CIP power spectrum from data

- Universe gives us CIP amplitudes as random variables: nonlinear modulation of linear theory CMB

Non-Gaussianity at 4-pt function (trispectrum) level

$$\left\langle T_{\vec{l}_1} T_{\vec{l}_2} T_{\vec{l}_3} T_{\vec{l}_4} \right\rangle_{\rm connected} \propto C_L^{\Delta\Delta} \quad \text{X} \quad \mathcal{O}\left(\frac{dC_l}{dn_b}\right)\Bigg|_{\Omega_{\rm m}}^2 \quad \text{X} \quad \text{Spherical geometry}$$

- CIP power spectrum estimate from Monte Carlos and filtered CMB map

$$\hat{C}_L^{\bar{\Delta}\bar{\Delta}} \propto \sum_M \frac{1}{(2L+1)} \left(\bar{\Delta}_{LM} - \bar{\Delta}_{LM}^{\rm null}\right)^* \times \left(\bar{\Delta}_{LM} - \bar{\Delta}_{LM}^{\rm null}\right)$$

LENSING BIAS

- Our estimator is unbiased under assumption that lensing is only contributor to off-diagonal correlations

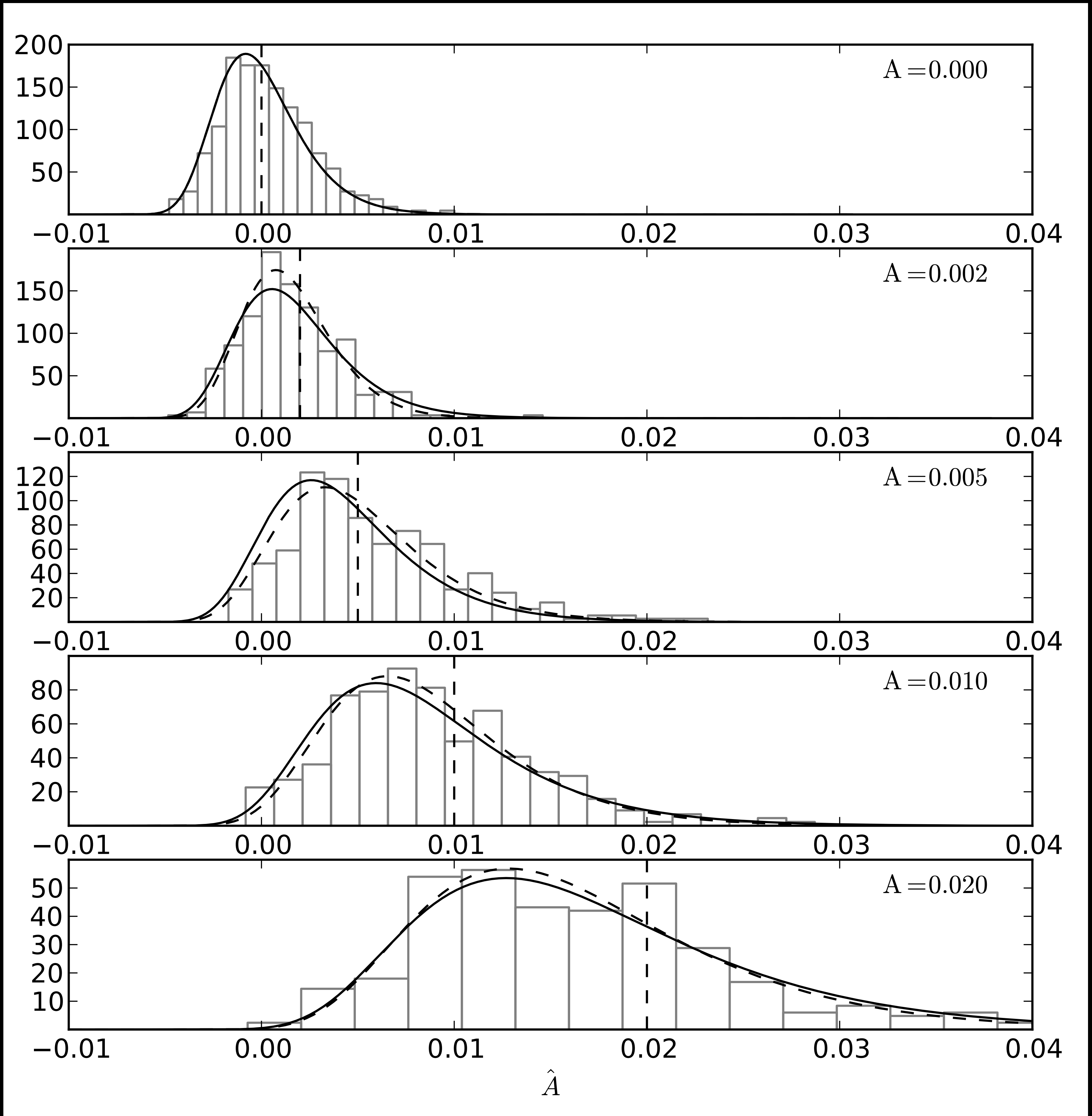
$$\langle X^*_{l'm'} X_{lm} \rangle = C_l^{XX'} \delta_{ll'} \delta_{mm'} + \sum_{LM} D_{ll'}^{LM,XX'} \xi^{LM}_{lm,l'm'},$$

$$D_{ll'}^{LM,XX'} = \Delta_{LM}\ S_{ll'}^{L,XX',\,\mathrm{CIP}} + \boxed{\phi_{LM}\ S_{ll'}^{L,XX',\,\mathrm{lens}}}$$

- Estimator will thus detect 'fake CIP' due to lensing

$$\widehat{\Delta}_{LM} = \sigma^2_{\Delta_{LM}} \sum_{l' \geq l} G_{ll'} \sum_{\mathrm{AA'}} S_{ll'}^{LM,\mathrm{A'}} W_l W_{l'} \boxed{\widehat{D}_{ll'}^{LM,\mathrm{A,map}}} [\mathcal{C}_{ll'}^{-1}]_{\mathrm{AA'}}$$

Errors are strongly signal-dependent



CIPS AND GALAXIES (IN REALITY)

FUTURE WORK

- CIPs would change baryon fraction of halos: affect properties of galaxies in different patches of sky (detectable in SDSS? vs. astrophysical confusion)
- Baryonic part of halo collapses late
- CIPs would change transfer function for LSS power spectrum, induce couplings between scales

$$P_{\rm gal} = b^2 T^2_{\rm matter}\left(k\right) P_{\Phi}\left(k\right)$$

Might be detectably modulated by CIPs

Possible sources of bias

- Chance correlations (noise bias)
- Weak lensing of CMB
  - Trispectrum (statistical)
  - Off-diagonal correlations (in a realization of lensing potential)
- Unresolved point sources
  - Bispectrum detected in *Planck 2013* temp data
- Secondary CIP/lensing contractions