Title: Cosmic initial conditions and the CMB

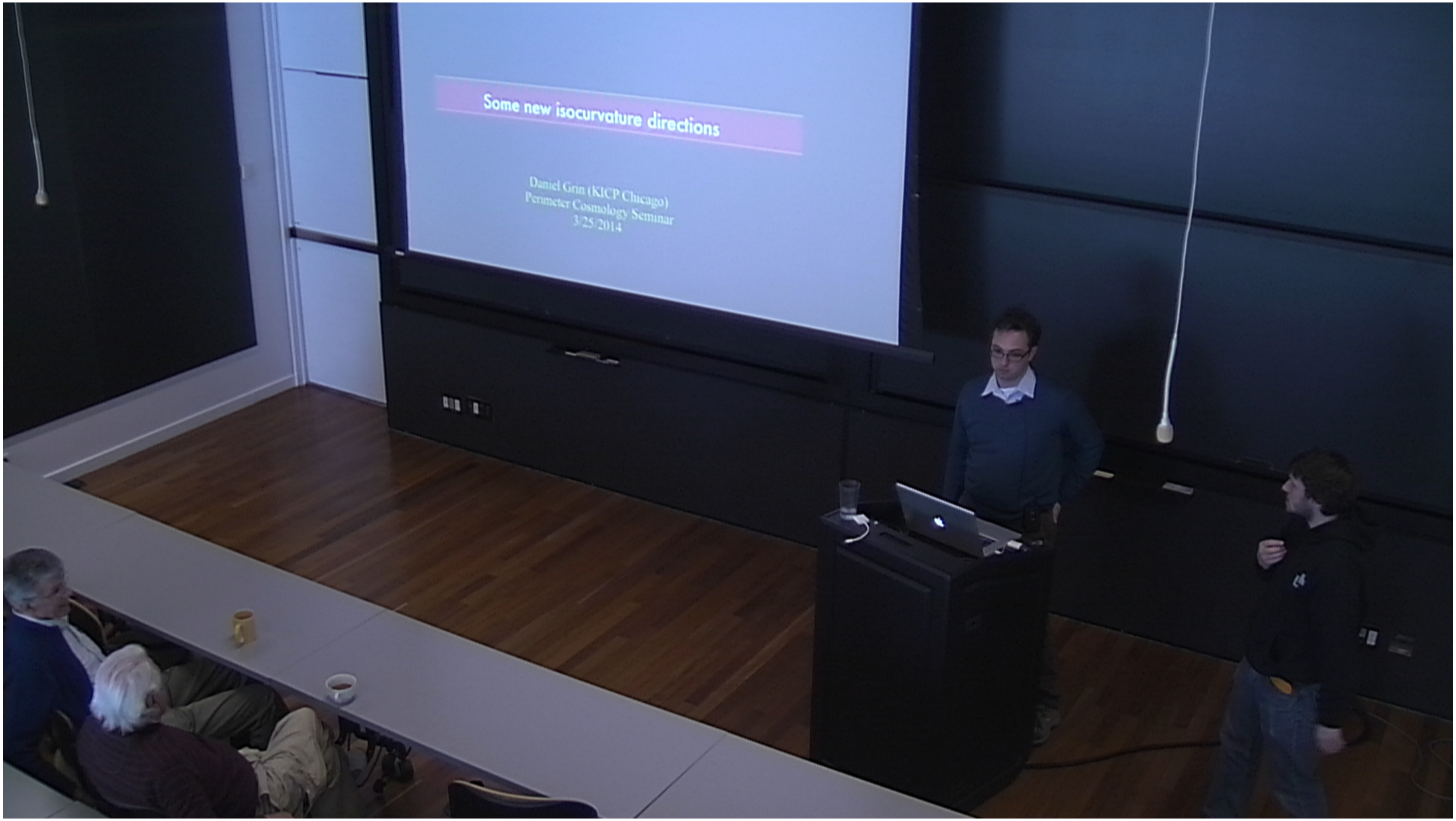
Date: Mar 25, 2014 11:00 AM

URL: http://pirsa.org/14030112

Abstract: <span>One new frontier in cosmology is the frequency spectrum of the CMB. Future instruments may be precise enough to measure deviations from the nearly-perfect blackbody, measuring a chemical potential and thus probing energy injection at extremely high redshift. I will discuss ($\mu$ and $y$-type) CMB spectral distortions from the dissipation of entropy (isocurvature)-sourced acoustic modes. I will then discuss how a high-energy phase transition could also source such distortions. I will then switch gears and talk about the possibility of measuring a spatial fluctuation in the baryon/DM ratio using the CMB, including recent observational results. I may also muse on the surprising possible connection between these compensated isocurvature modes and the anomalously low large-scale scalar power hinted at by Planck observations of the CMB temperature power spectrum and the recent claimed BICEP2 detection of primordial tensor modes</span>

# Some new isocurvature directions

Daniel Grin (KICP Chicago)
Perimeter Cosmology Seminar
3/25/2014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# Outline

*Are the primordial fluctuations adiabatic?*

Isocurvature and CMB spectral distortions

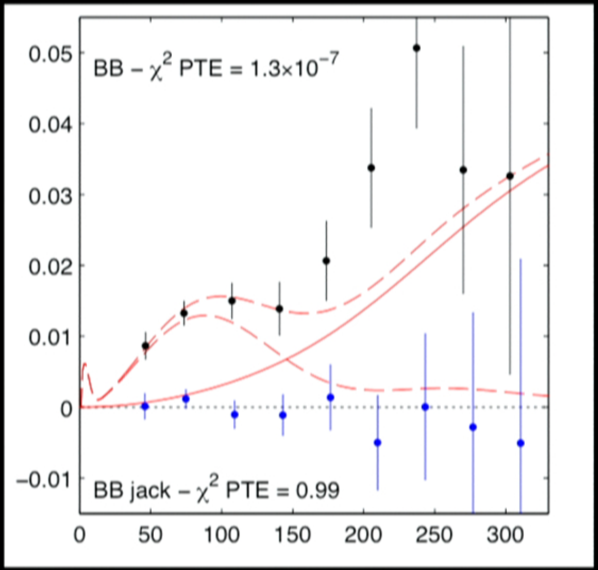
Baryon-DM isocurvature fluctuations and the CMB

2

# 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)*

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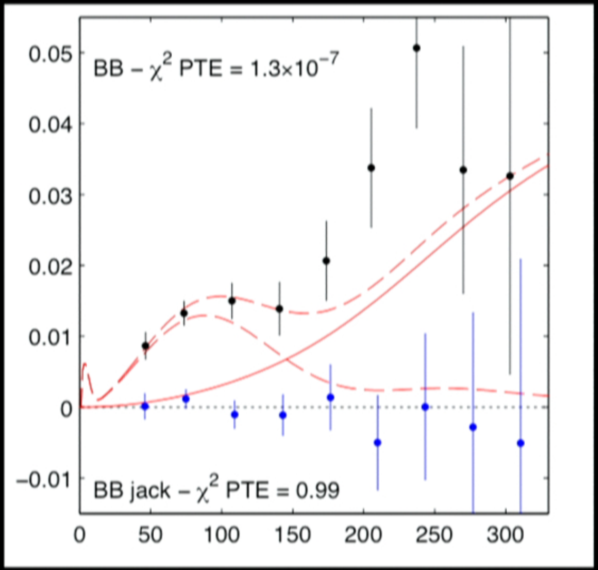
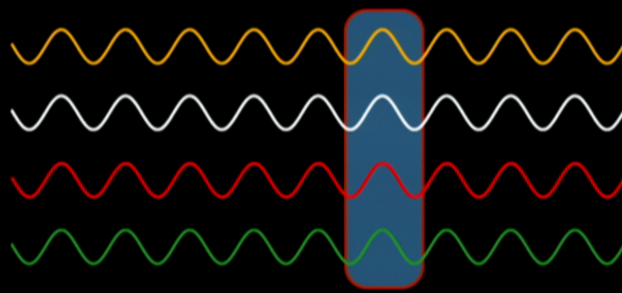


# ZOOLOGY OF INITIAL CONDITIONS

Adiabatic



Neutrinos
CDM
Photons
Baryons

$$S_i = 0$$

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

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

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

5

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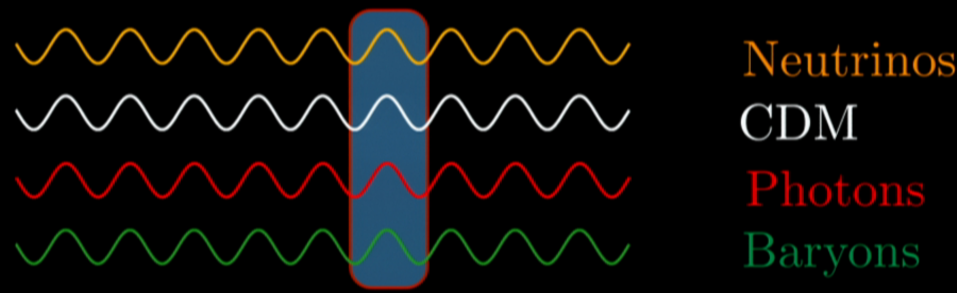


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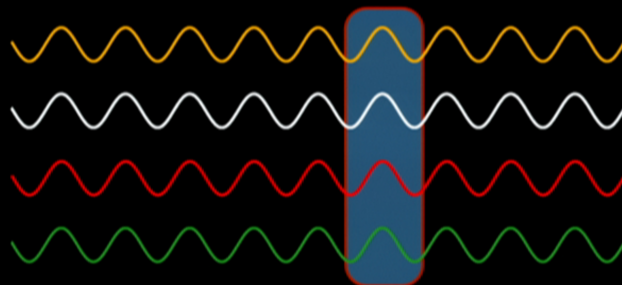

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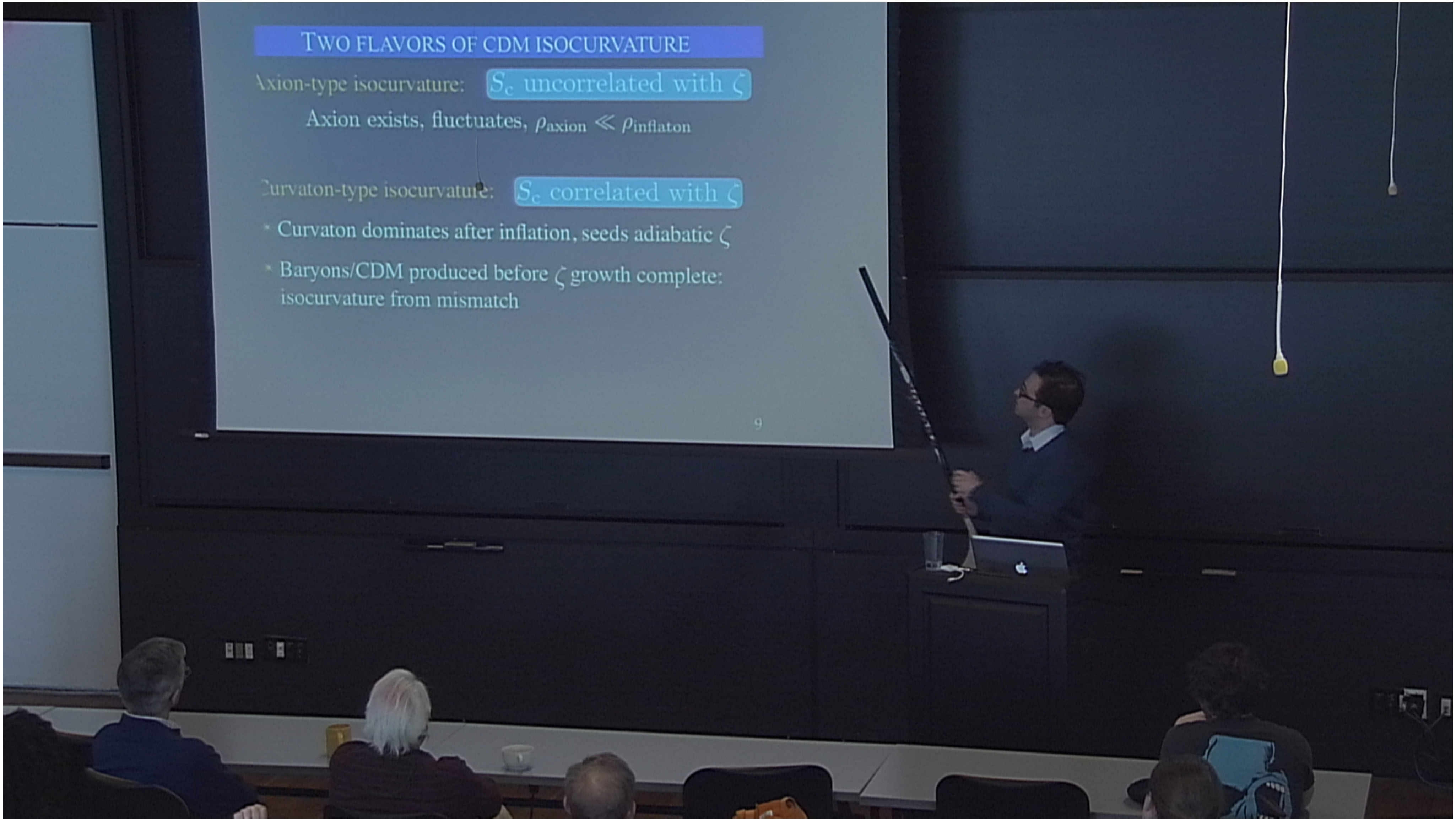
# TWO FLAVORS OF CDM ISOCURVATURE

Axion-type isocurvature: $S_c$ uncorrelated with $\zeta$

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

Curvaton-type isocurvature: $S_c$ correlated with $\zeta$

- Curvaton dominates after inflation, seeds adiabatic $\zeta$
- Baryons/CDM produced before $\zeta$ growth complete: isocurvature from mismatch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## 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 $\sigma$ (curvaton) that briefly dominates after inflation

Sources entropy fluctuation in species that are generated before curvaton dom.

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

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

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# 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

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

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

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## OBSERVATIONAL CONSTRAINTS TO ISOCURVATURE

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

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

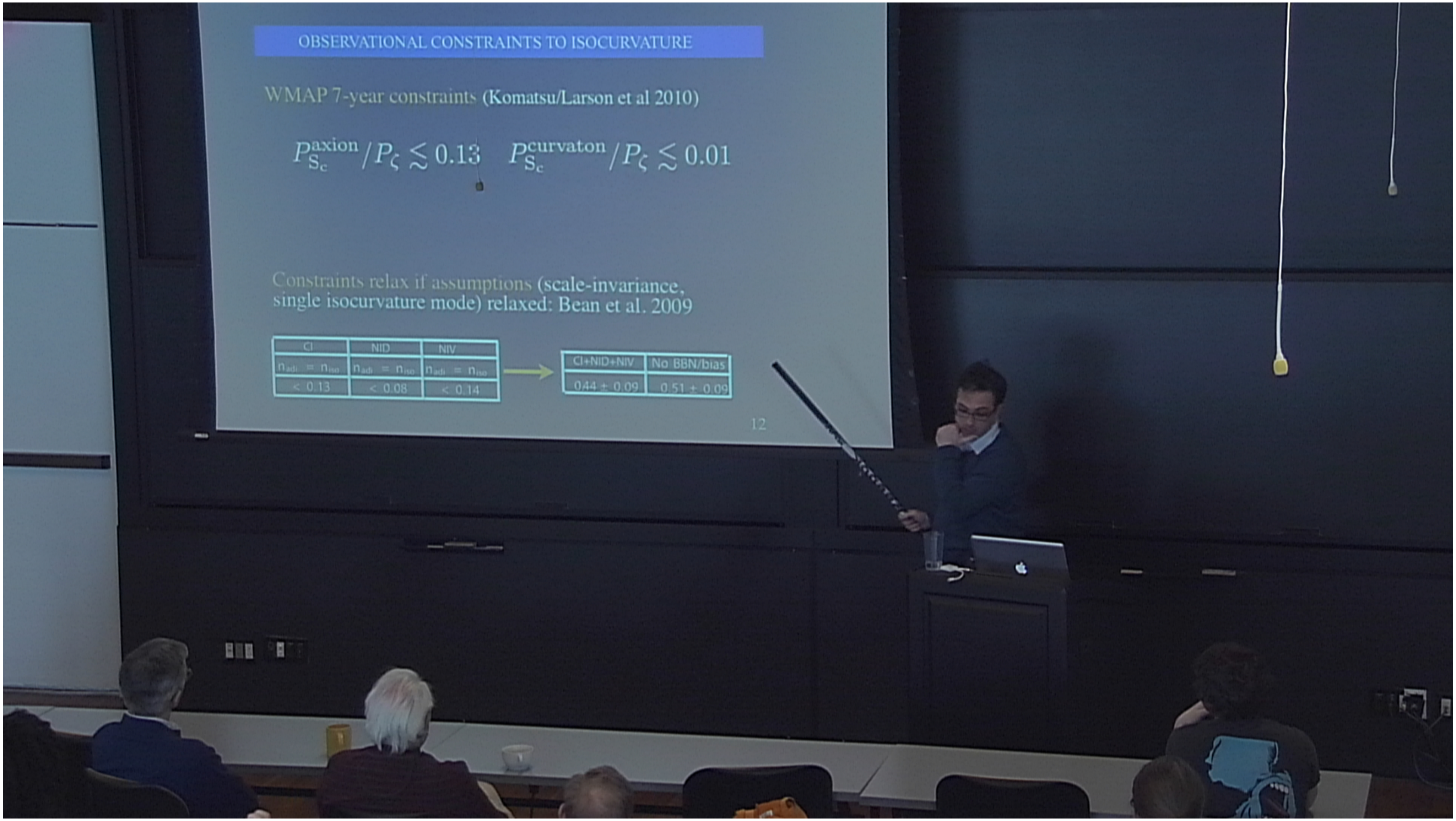
- Constraints relax if assumptions (scale-invariance, single isocurvature mode) relaxed: Bean et al. 2009

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

→

| CI+NID+NIV | No BBN/bias |
|---|---|
| $0.44 \pm 0.09$ | $0.51 \pm 0.09$ |

12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0.51 ± 0.09
12

## 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

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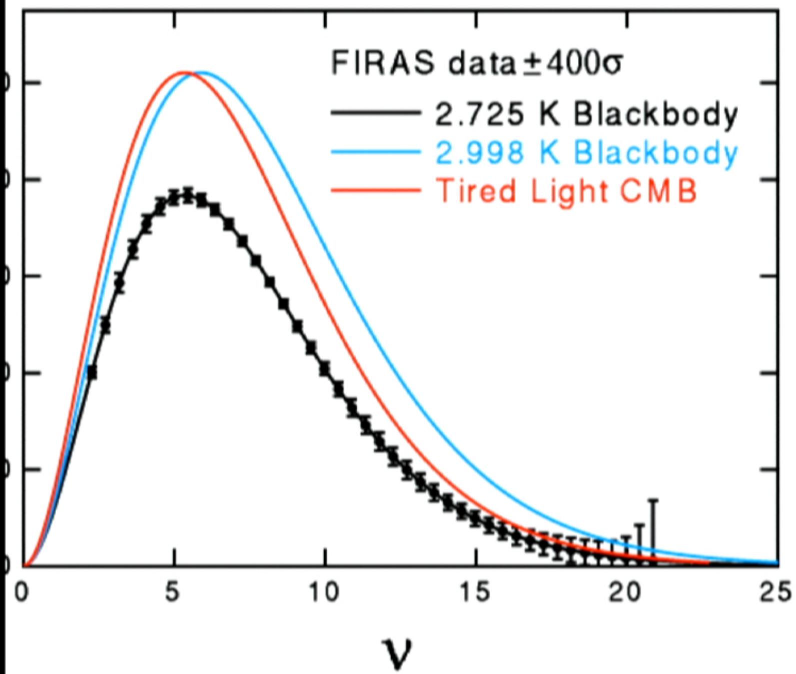
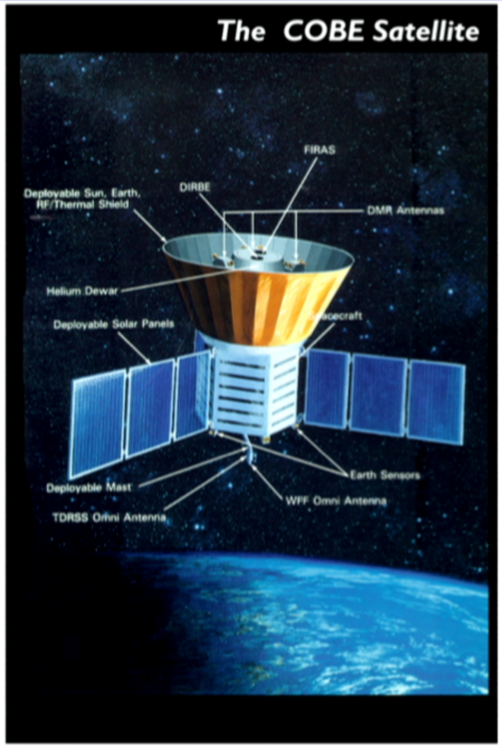
# COBE BLACKBODY




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

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

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

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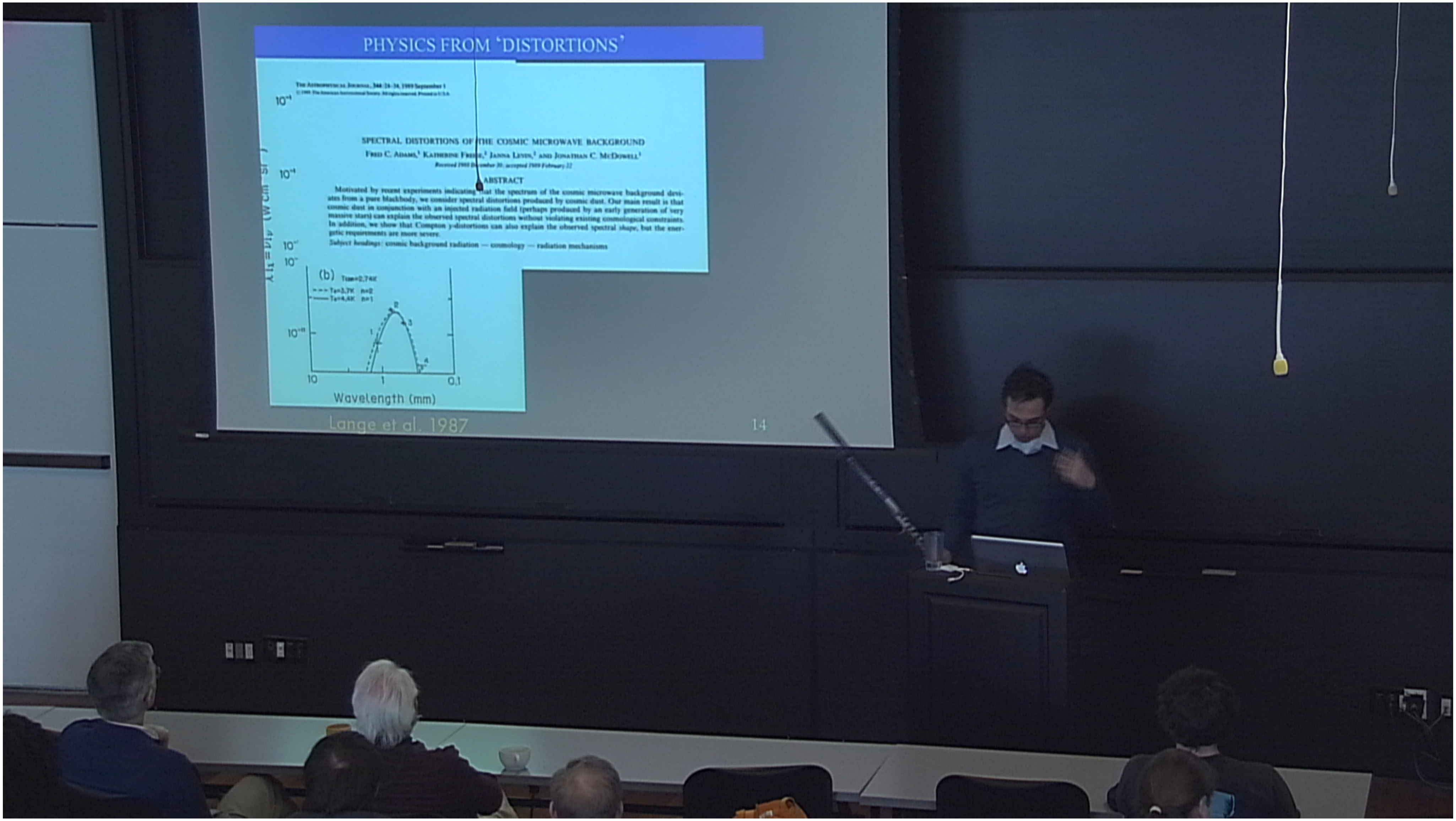

PHYSICS FROM 'DISTORTIONS'
SPECTRAL DISTORTIONS OF THE COSMIC MICROWAVE BACKGROUND
ABSTRACT
Wavelength (mm)
Lange et al. 1987
14

# PHYSICS FROM 'DISTORTIONS'

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


## SPECTRAL DISTORTIONS OF THE COSMIC MICROWAVE BACKGROUND

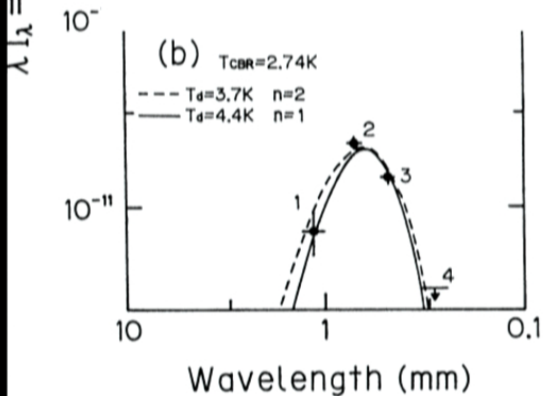
FRED C. ADAMS,[1] KATHERINE FREESE,[2] JANNA LEVIN,[2] AND JONATHAN C. MCDOWELL[1]

*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

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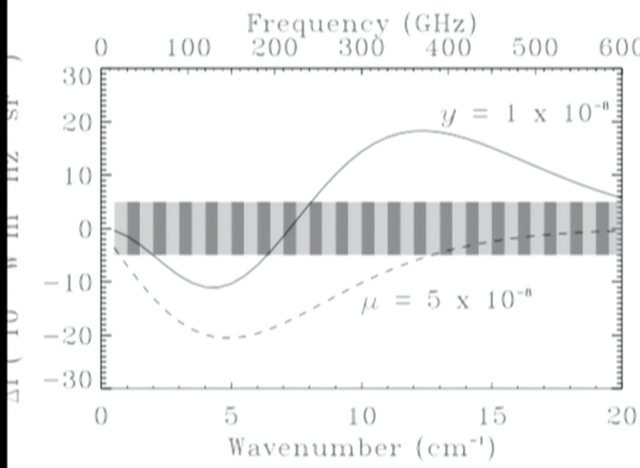
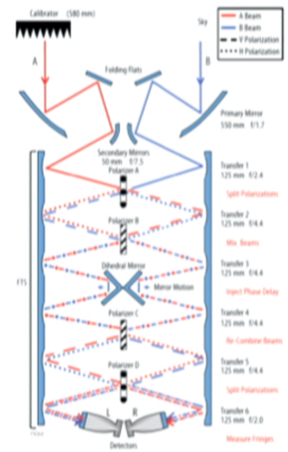
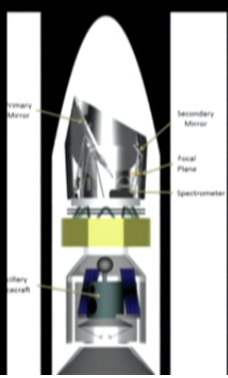
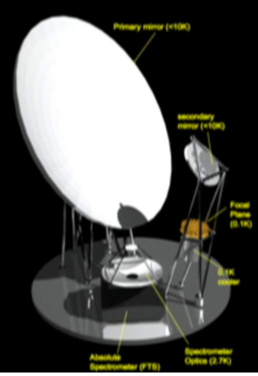
# EXPERIMENTAL HORIZON

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

$^- + \gamma \leftrightarrow e^- + \gamma$ Energy-exchanging Compton scattering

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

$e^- + \gamma \leftrightarrow e^- + \gamma$ Elastic Compton scattering

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

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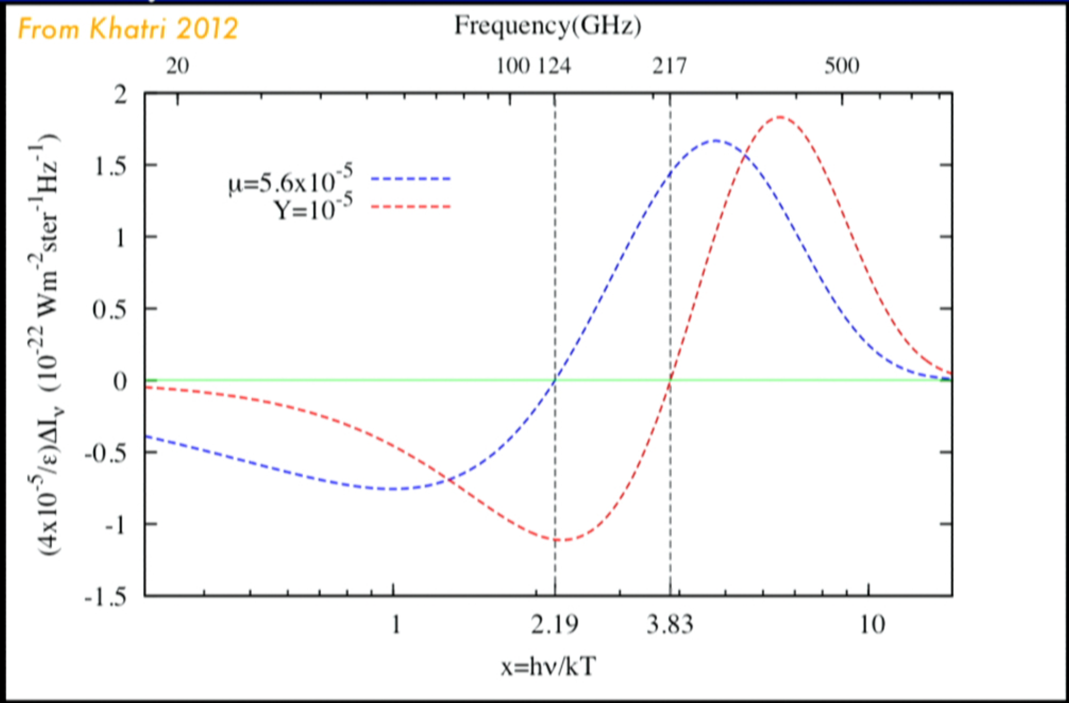
# $\mu$ AND Y-TYPE DISTORTION

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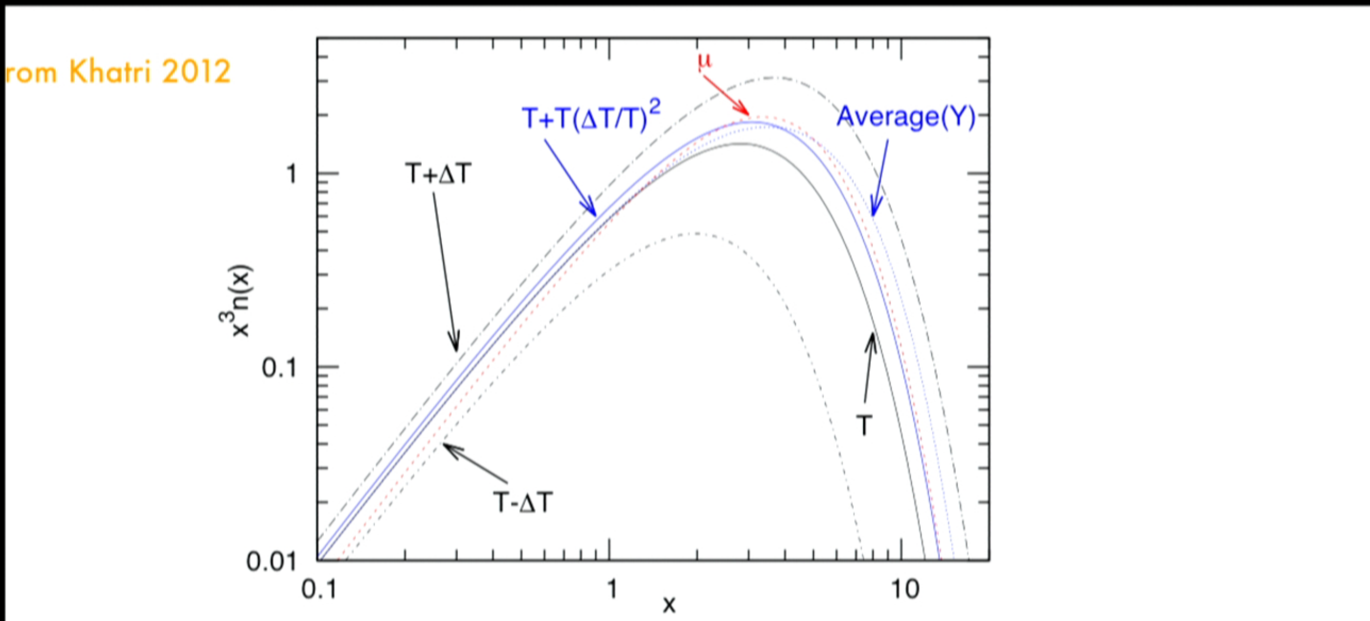
# SUPERPOSITION OF BLACKBODIES




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

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# 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

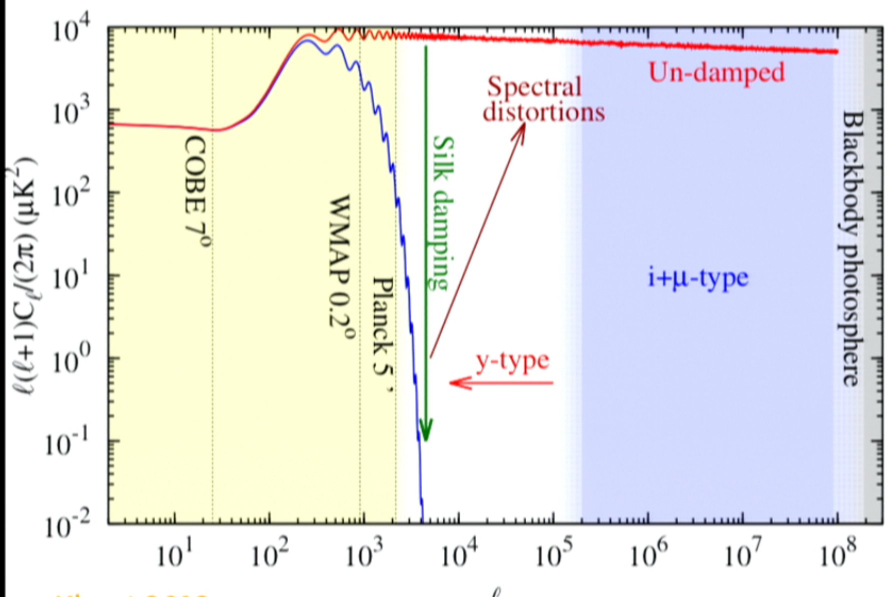
Gauge boson production from cosmic strings

Tashiro and Vachaspati 2012

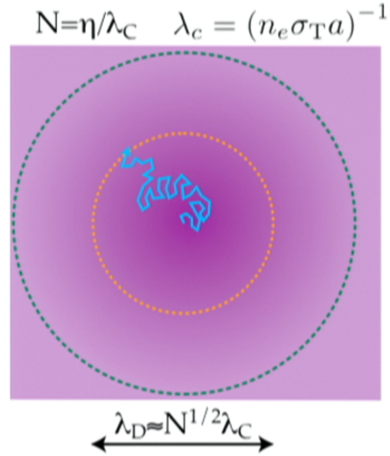
Primordial magnetic field damping

Marsh/Silk/Tashiro 2013

# SILK DAMPING AND DISTORTION FROM ADIABATIC MODES




om 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 →

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

20

## SILK DAMPING AND DISTORTION FROM ADIABATIC MODES

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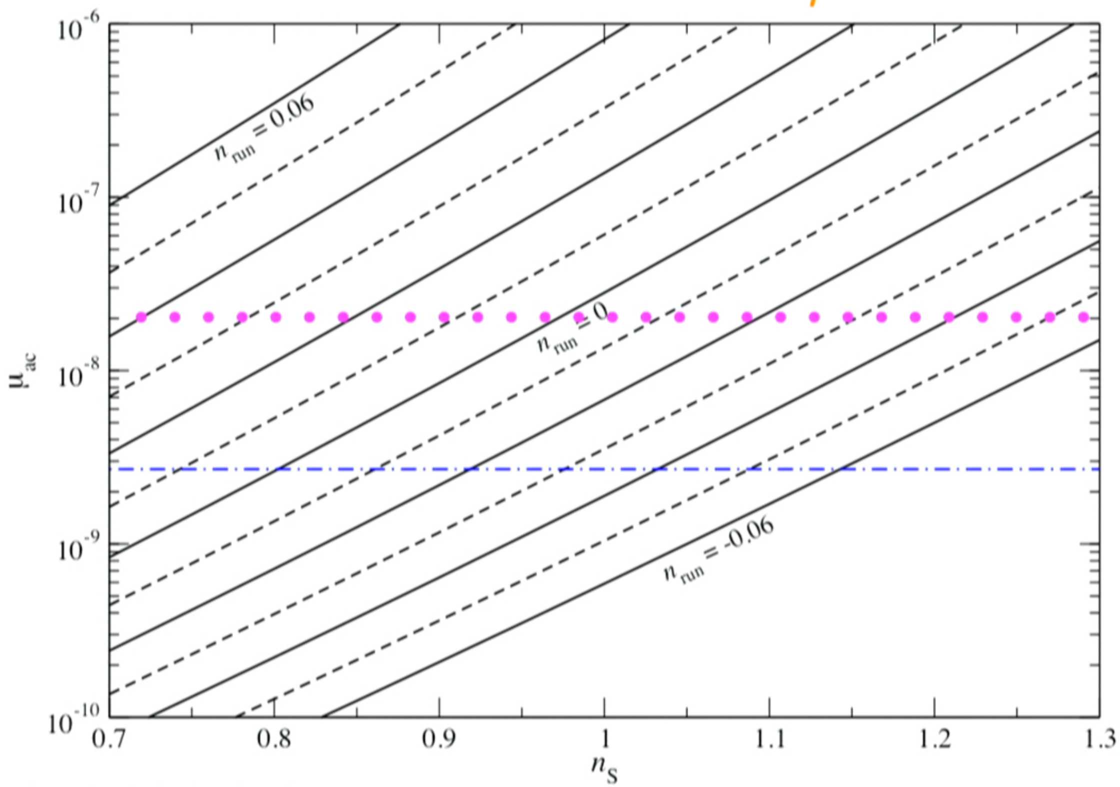


PIXIE

DIABATIC COOLING

From Chluba 2012

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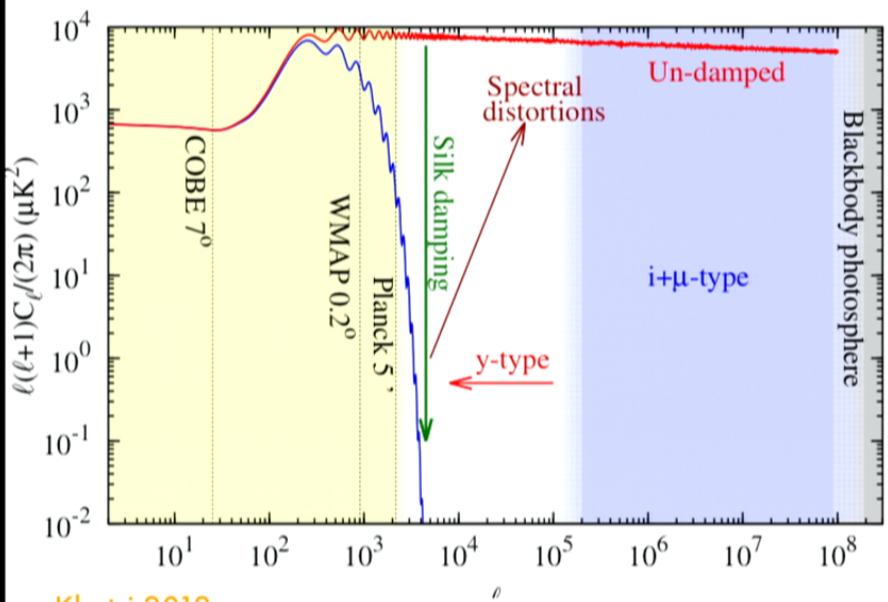


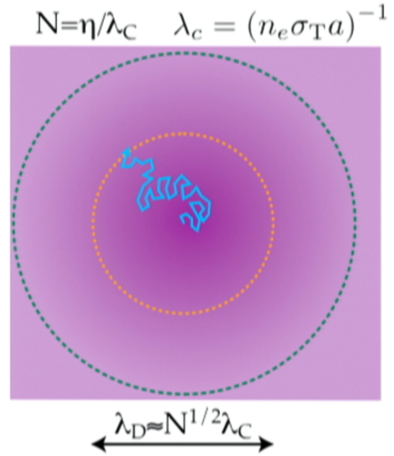


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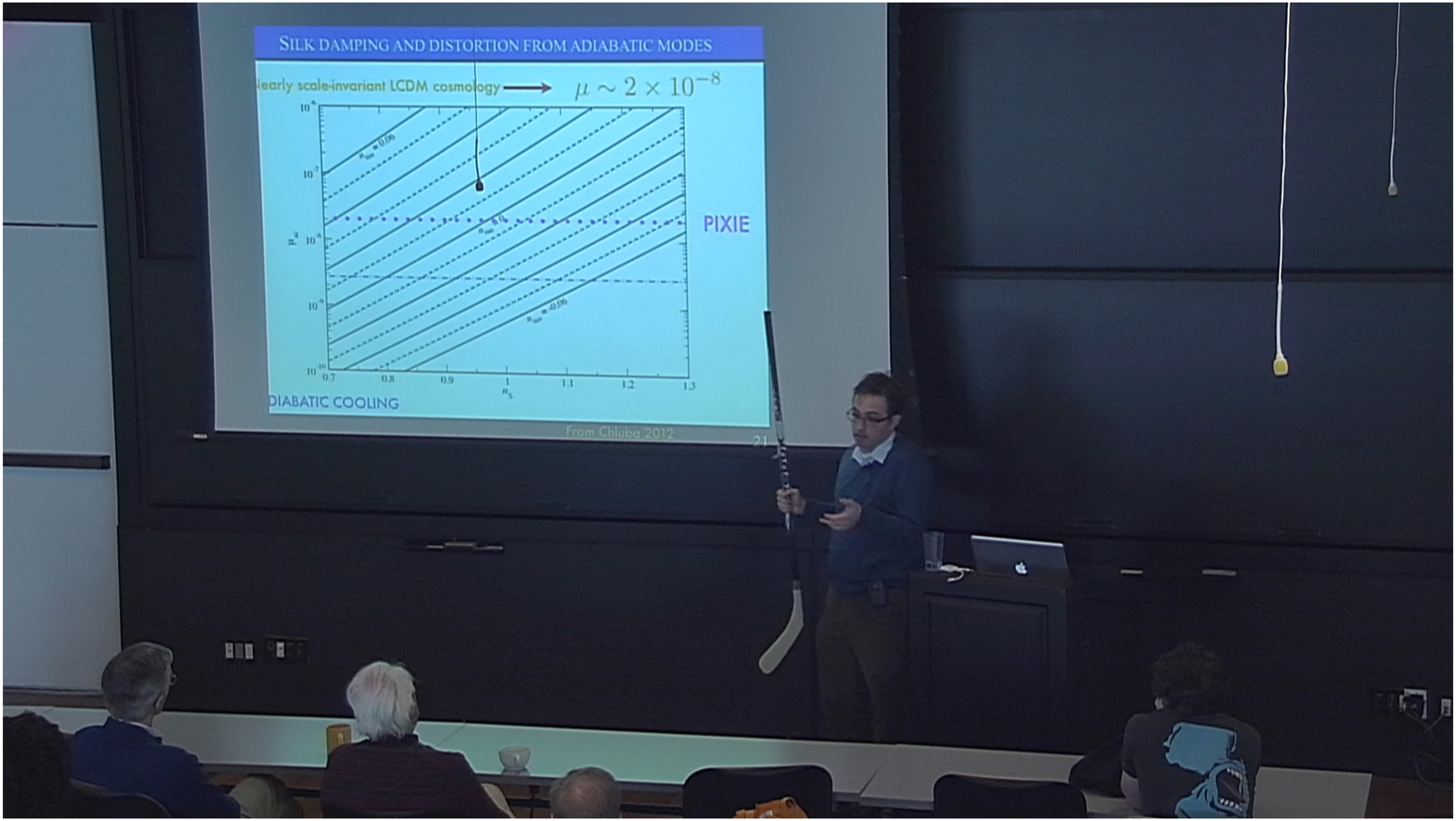
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## NEW PROBE OF SMALL-SCALE PERTURBATIONS

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

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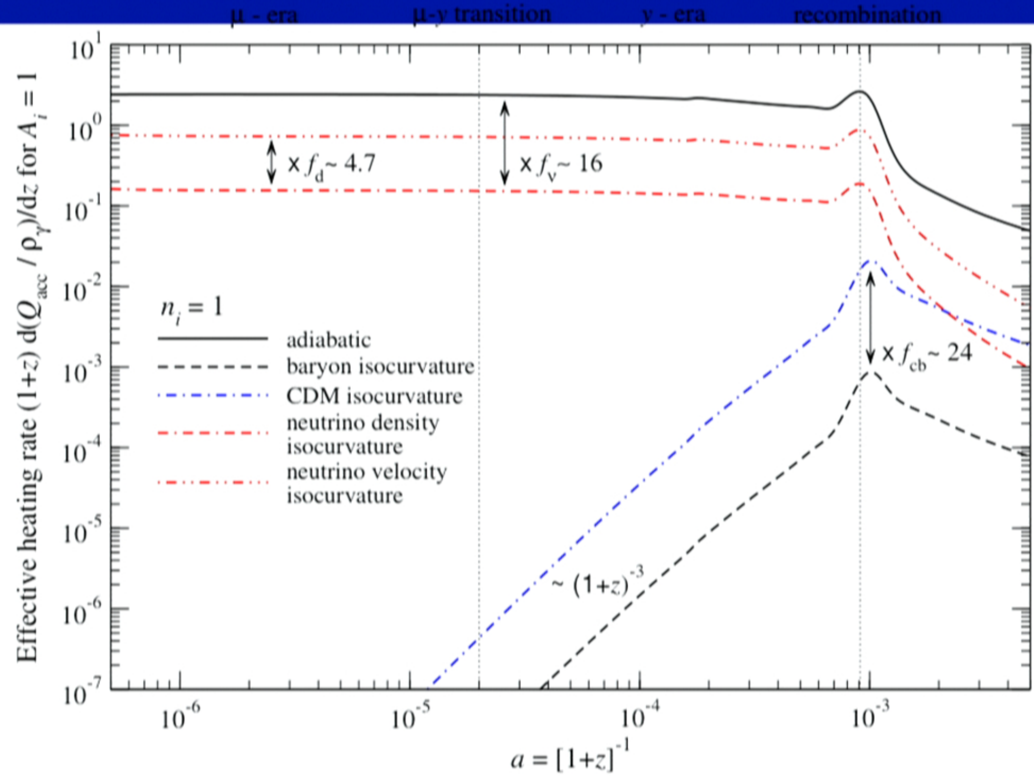
22

# HEATING AND DISTORTION FROM ALTERNATE INITIAL CONDITIONS




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

socurvature in non-relativistic species less suppressed during matter domination

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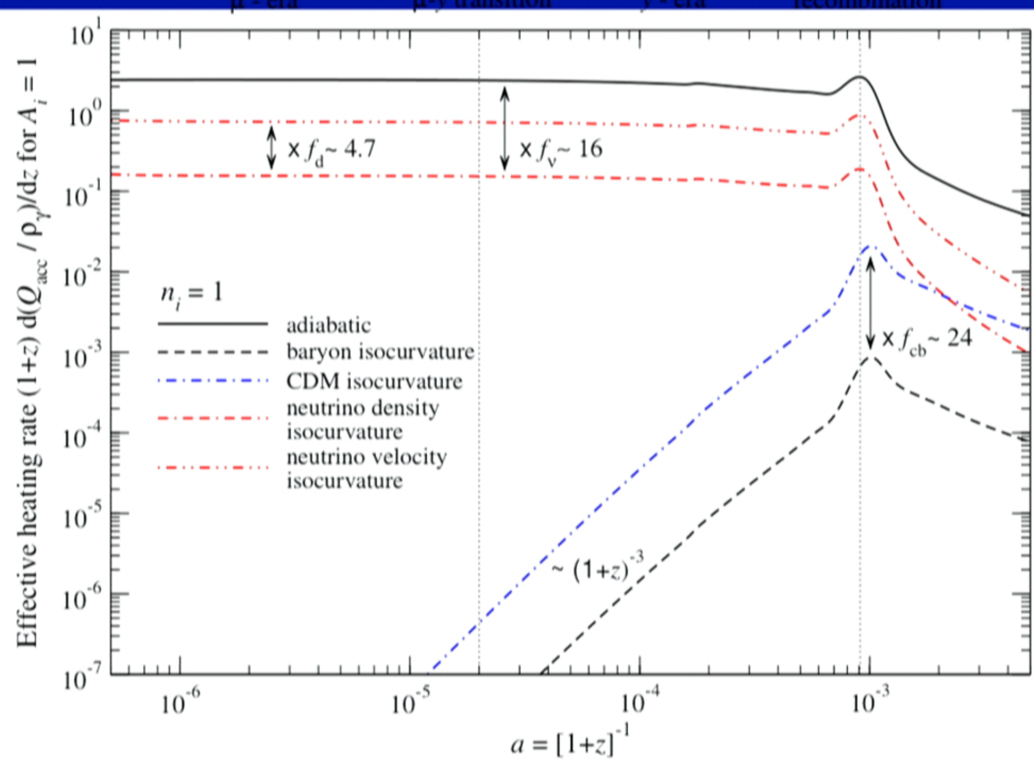


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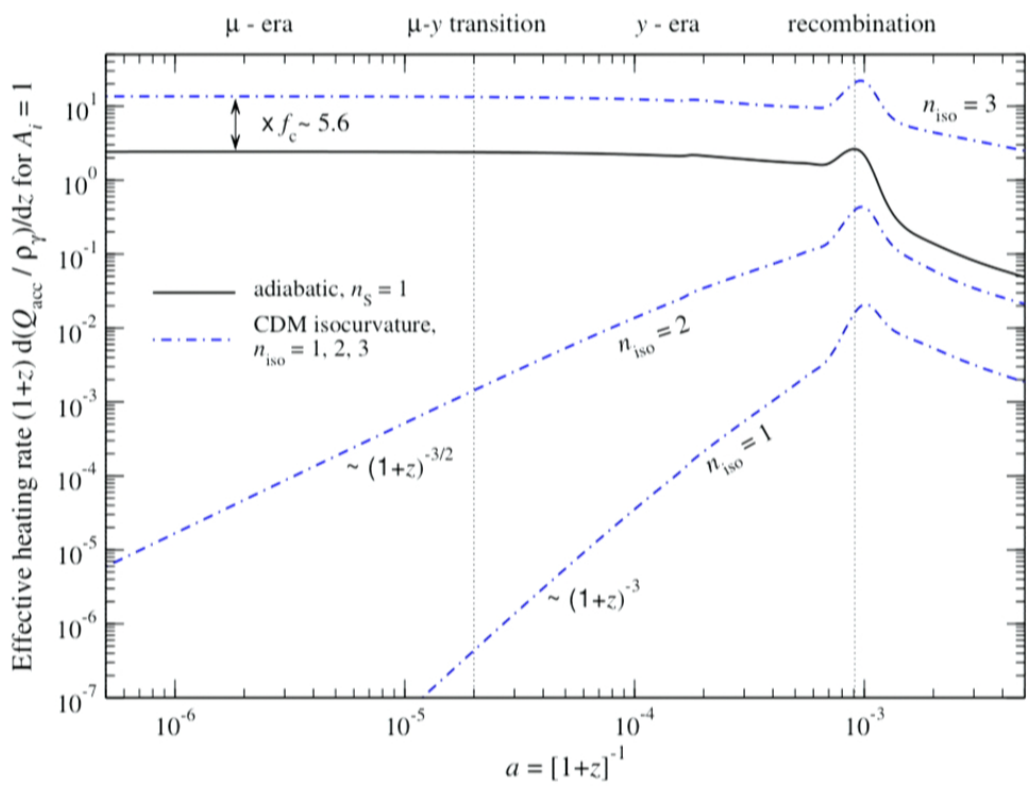
# RESULTS DEPEND ON POWER SPECTRUM OF ISOCURVATURE MODES

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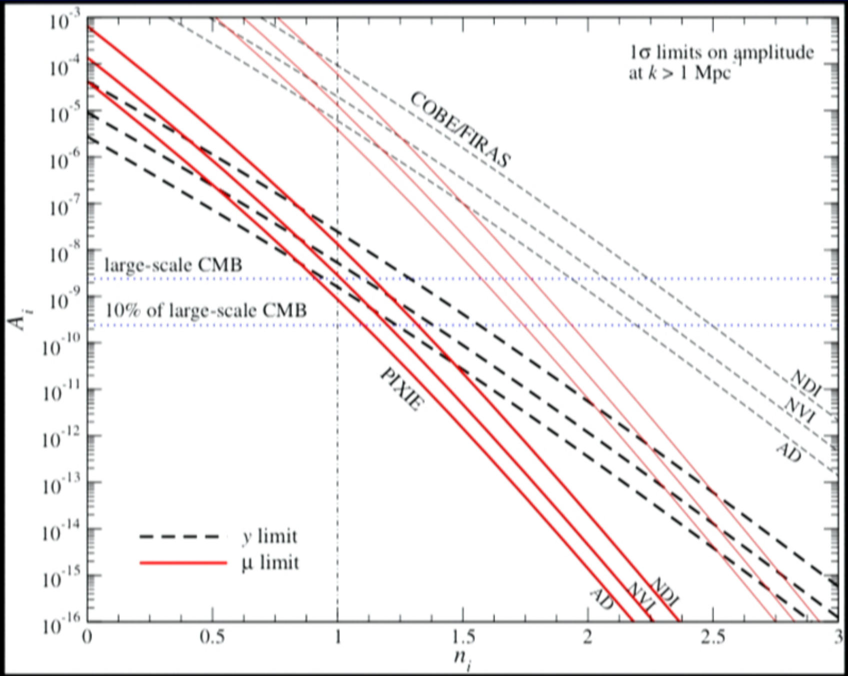
# Curvaton

- 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

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




$\mu \leq 10^{-8}$

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

→ PIXIE SENSITIVITY

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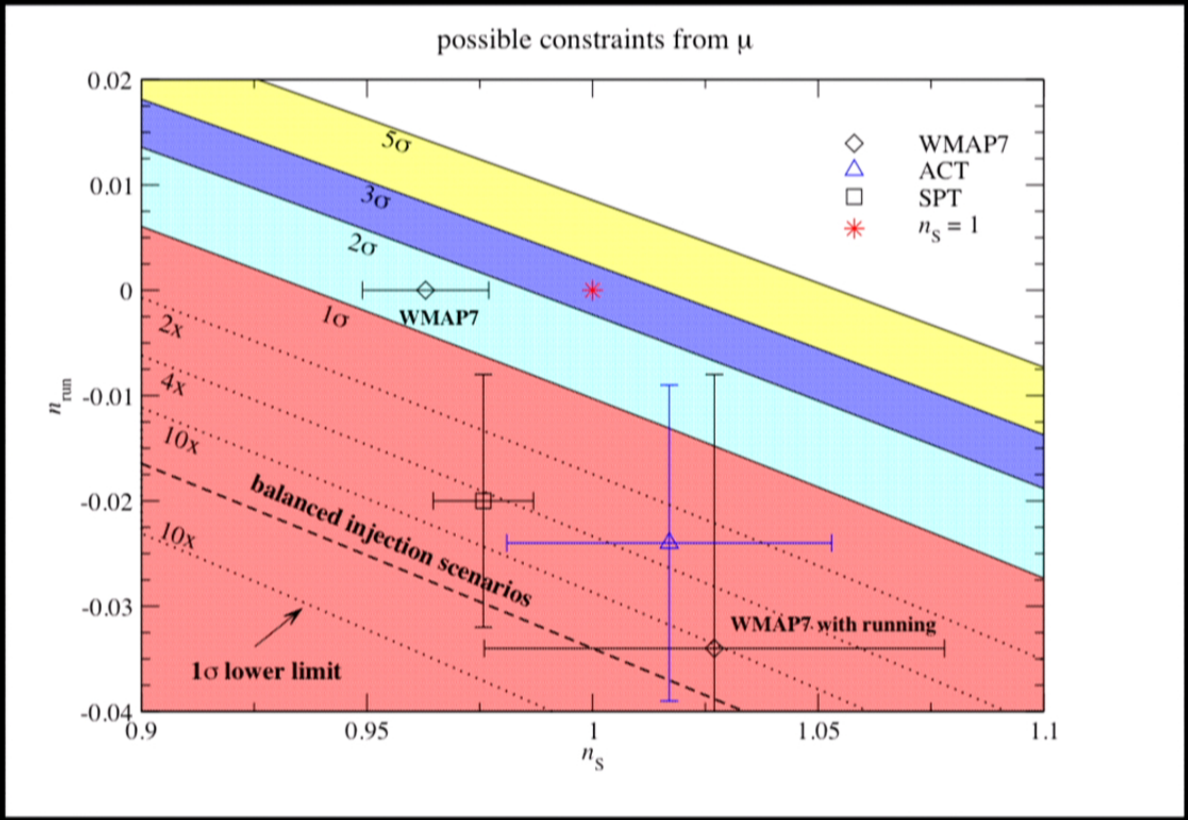
# Details of spectrum matter!

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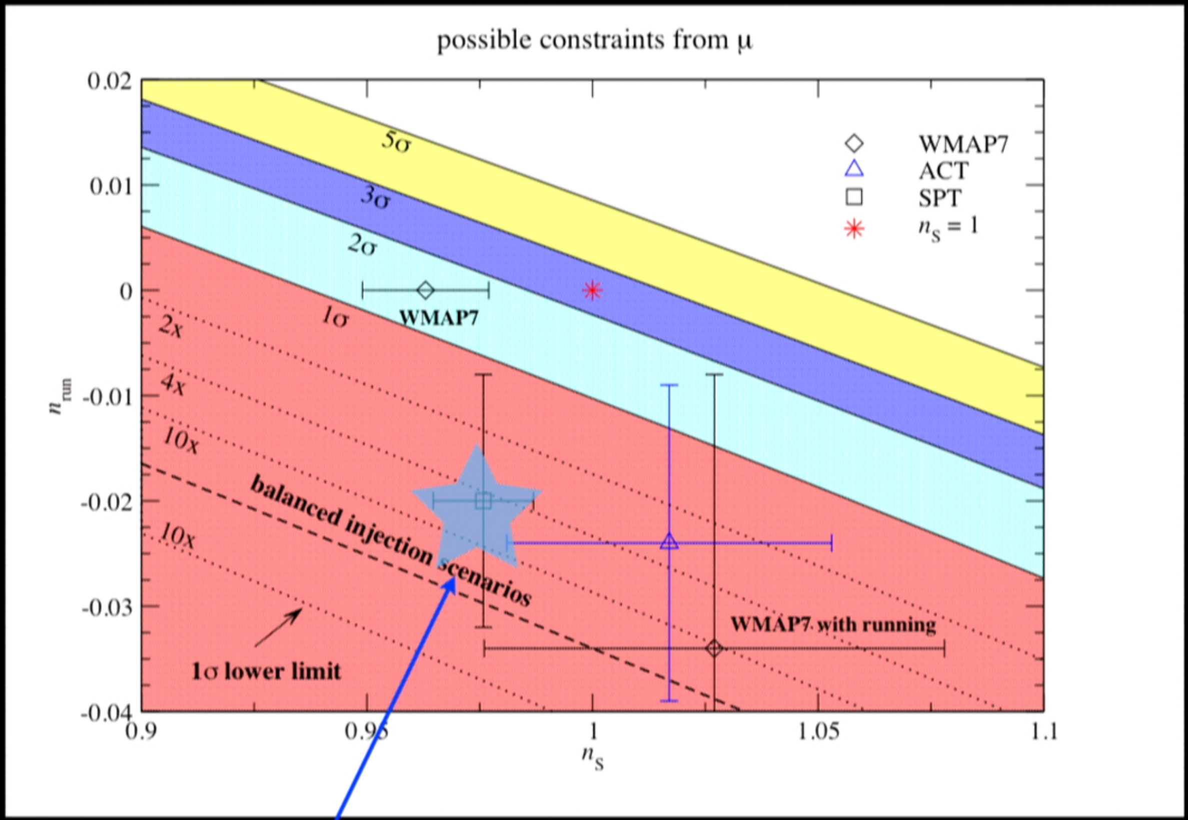



BICEP+PLANCK?

# Small field models

Small-field inflationary models with non-monotonic $\left(\frac{V'}{V}\right)^2$

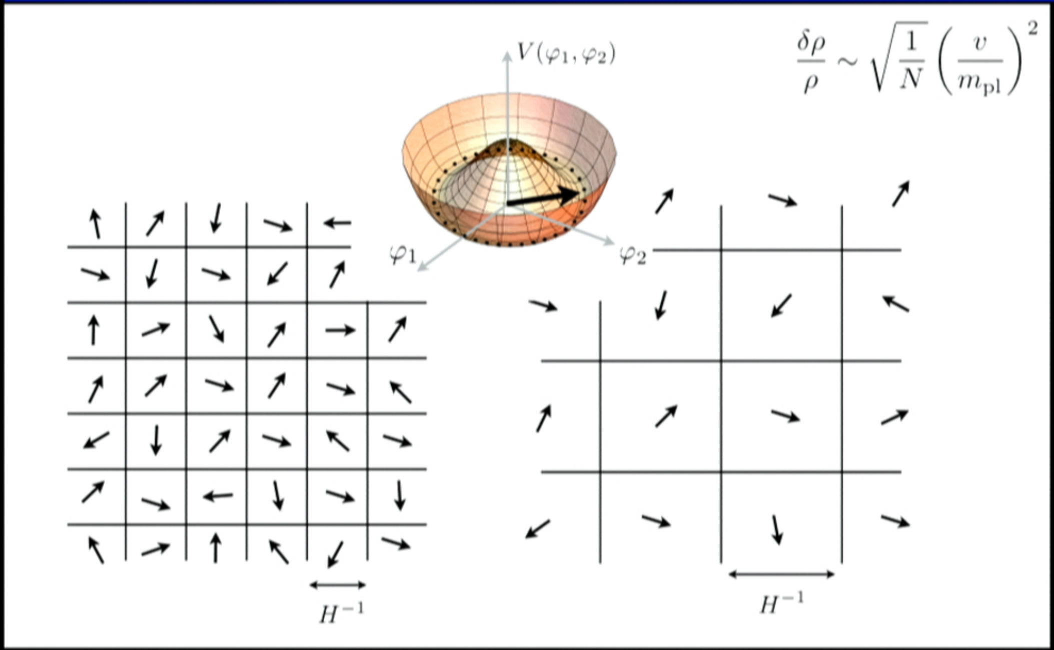
(Ben-Dayan/Brustein 2010) can evade Lyth Bound

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

Experimentally relevant!

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

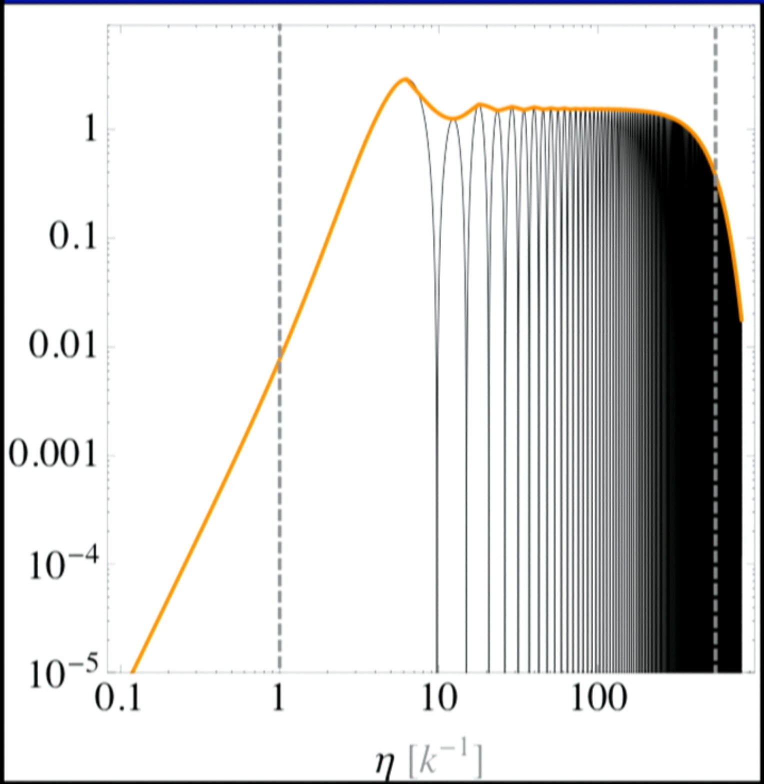
# Phase transitions and spectral distortions




Break a global O(N) symmetry

Compute gravitational potential fluctuations

# Seeds drive baryon-photon plasma sounds waves




with Mustafa Amin,
KICC Cambridge

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

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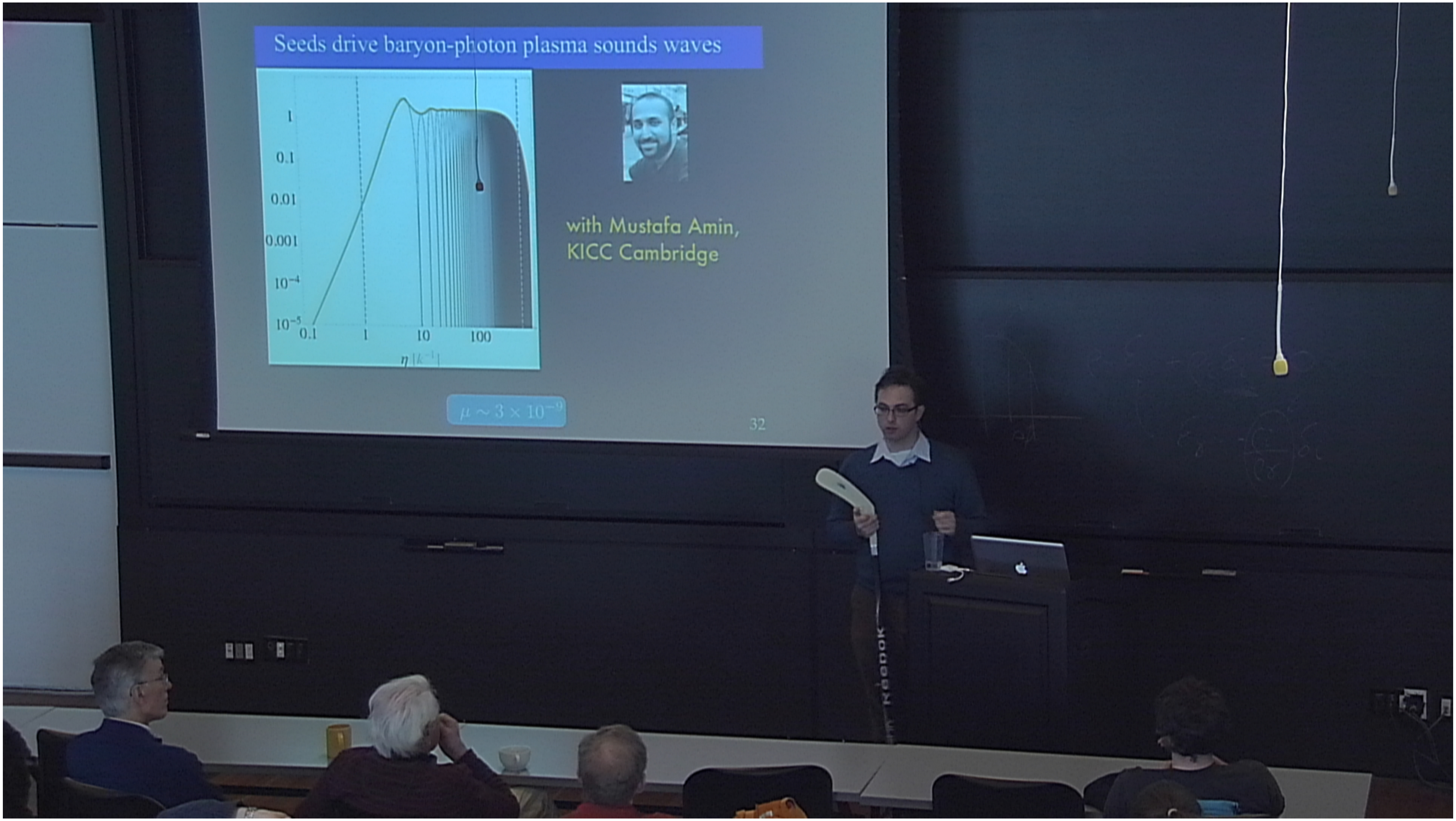
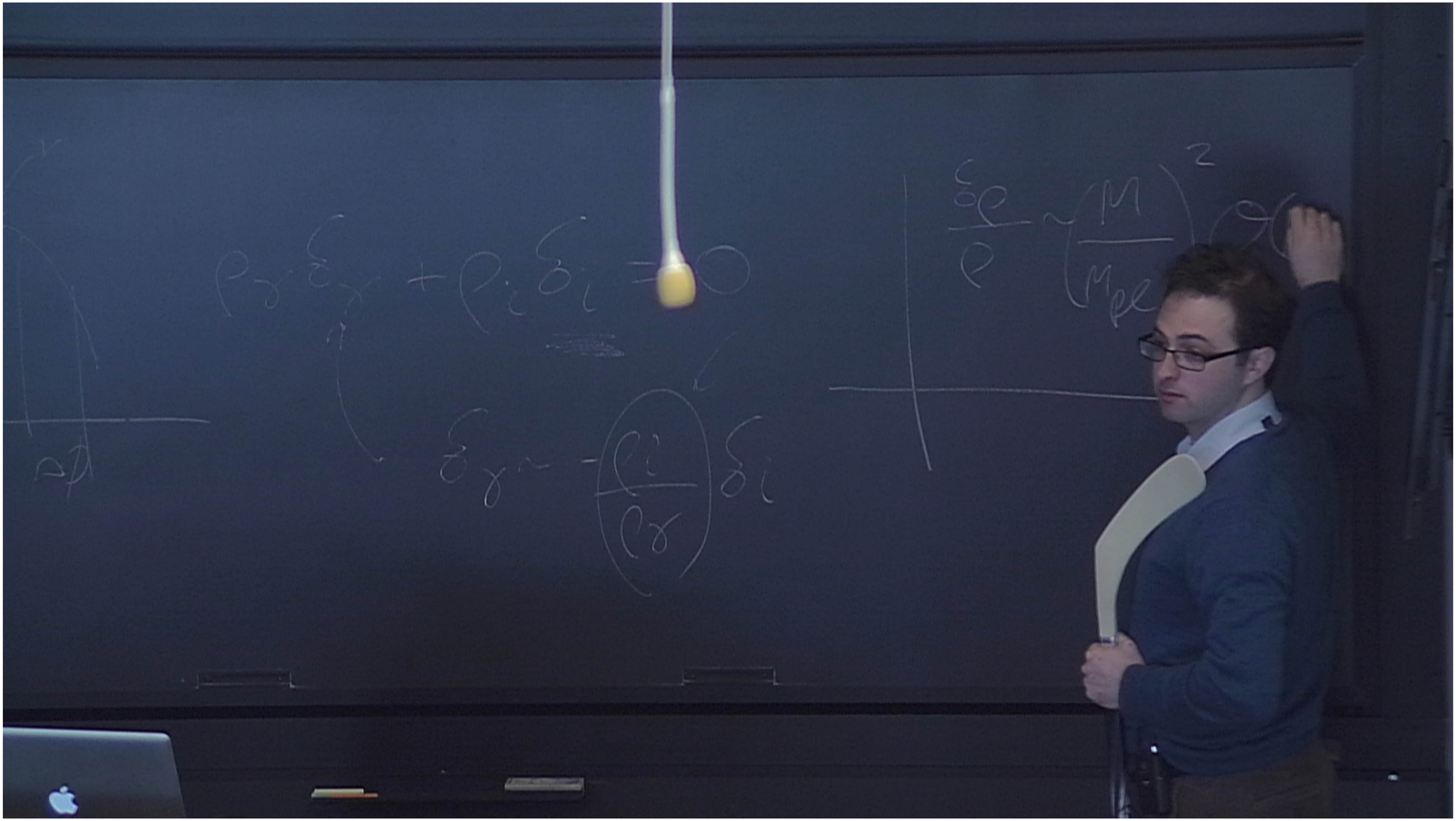
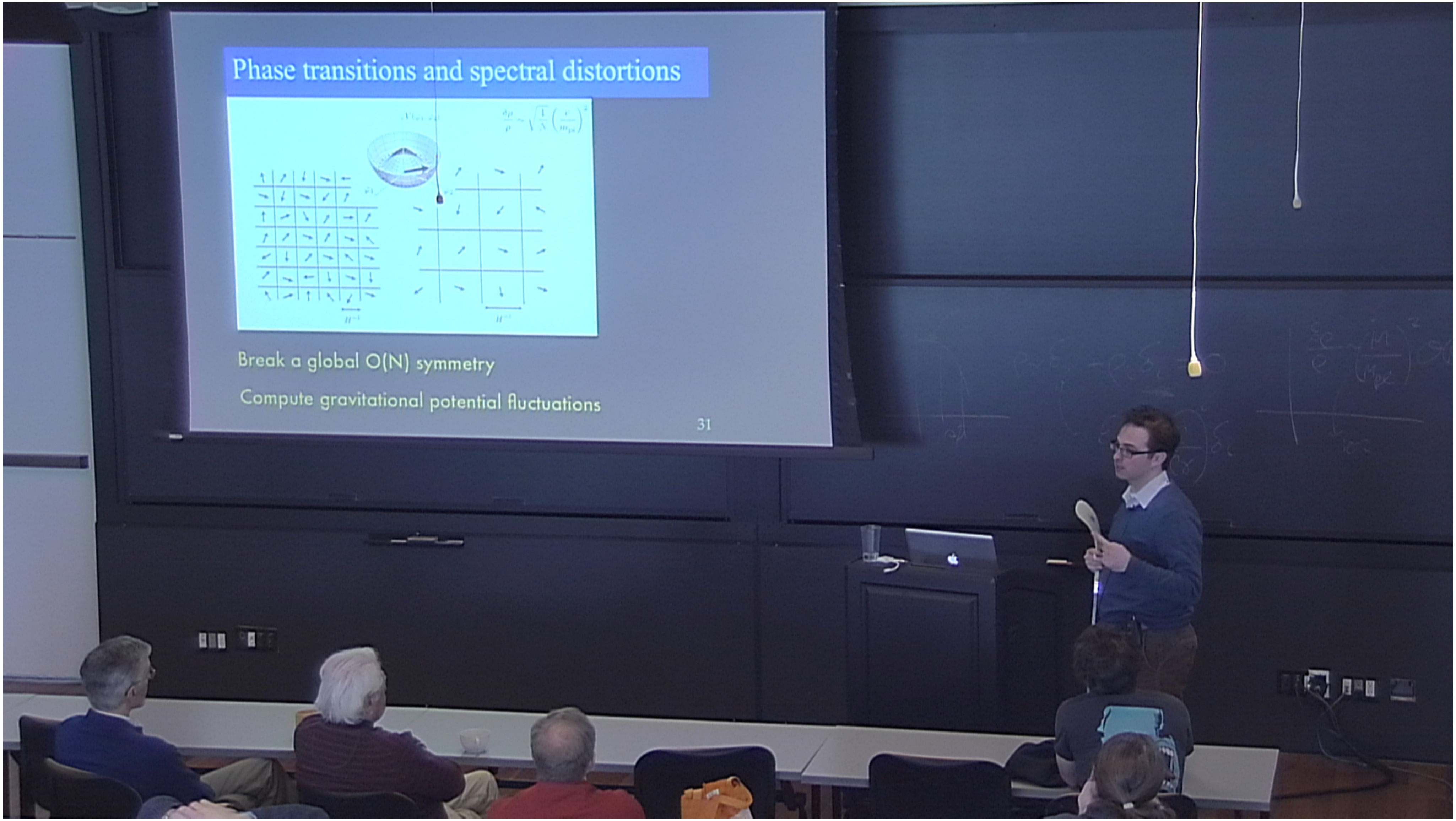


Seeds drive baryon-photon plasma sounds waves
1
0.1
0.01
0.001
$10^{-4}$
$10^{-5}$
0.1
1
10
100
with Mustafa Amin,
KICC Cambridge
$\mu \sim 3 \times 10^{-9}$
32


ρ_γ δ_γ + ρ_i δ_i = 0
δ_γ ~ − (ρ_i / ρ_γ) δ_i
δρ/ρ ~ (M/M_pl)^2


Phase transitions and spectral distortions
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