Variation in the cosmic baryon fraction and the CMB

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

Daniel Grin (KICP/Chicago)

Presentation for CAP workshop

09/24/2013

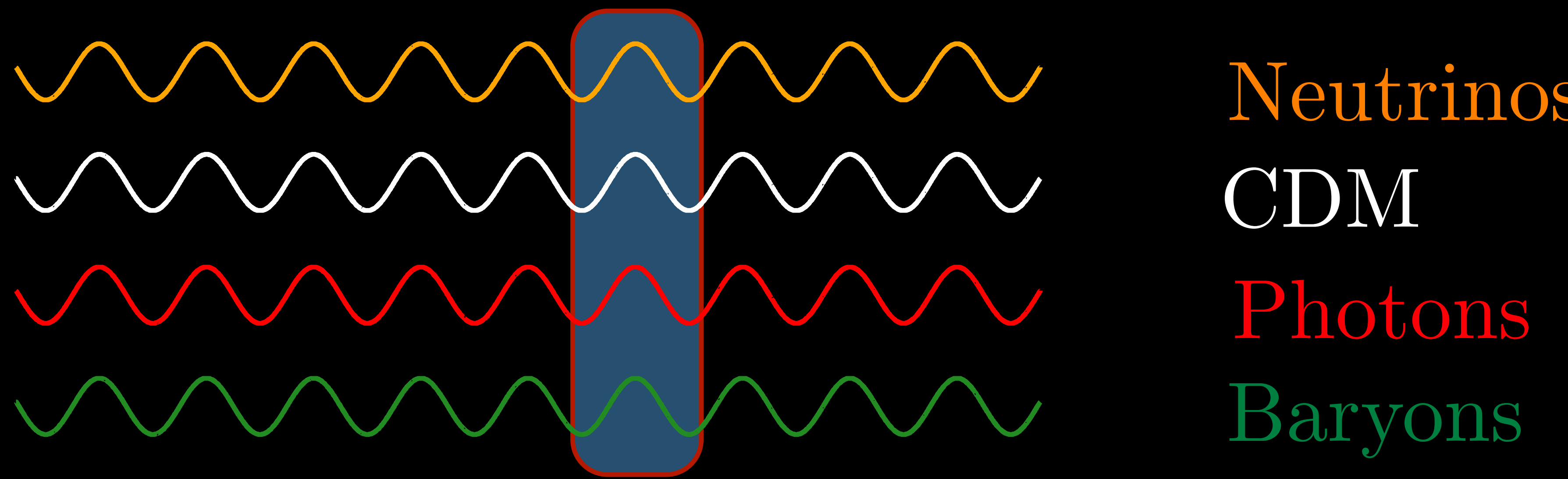
arXiv: 1107.1716 (DG, OD, and MK)- Phys. Rev. Lett. 107 261301

arXiv: 1107.5047 (DG, OD, and MK)- Phys. Rev. D. 84 123003

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

ZOOLOGY OF INITIAL CONDITIONS

Adiabatic



$$S_i = 0$$

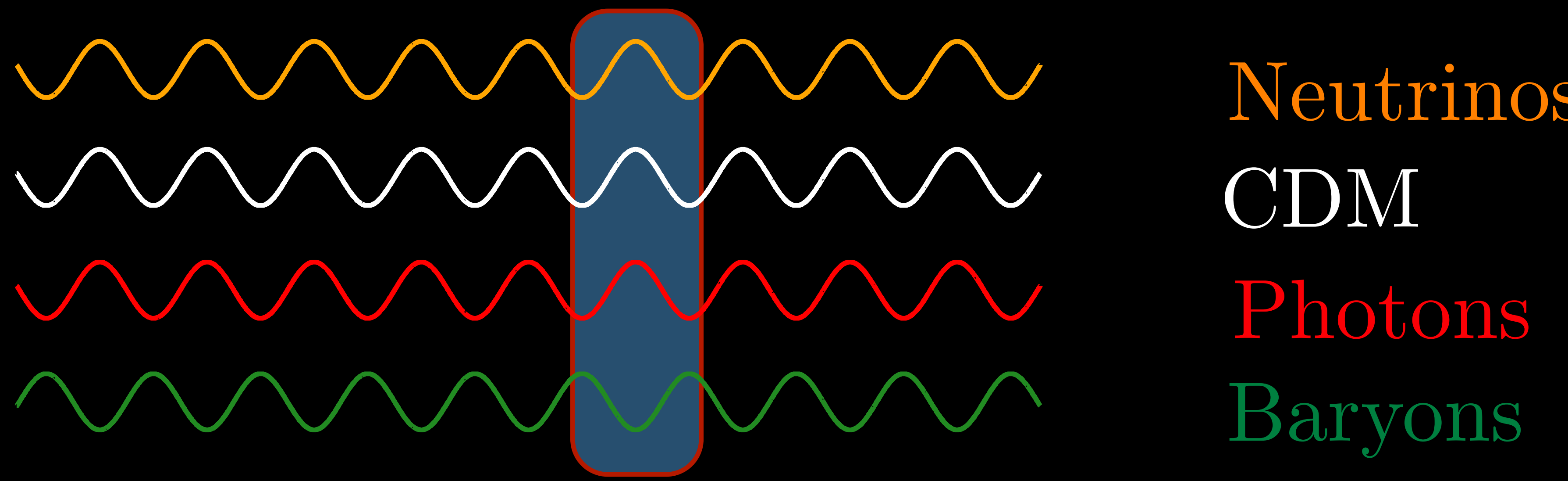
$$S_i = \frac{\delta n_i}{n_i} - \frac{\delta n_\gamma}{n_\gamma}$$

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

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

ZOOLOGY OF INITIAL CONDITIONS

Baryon isocurvature



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

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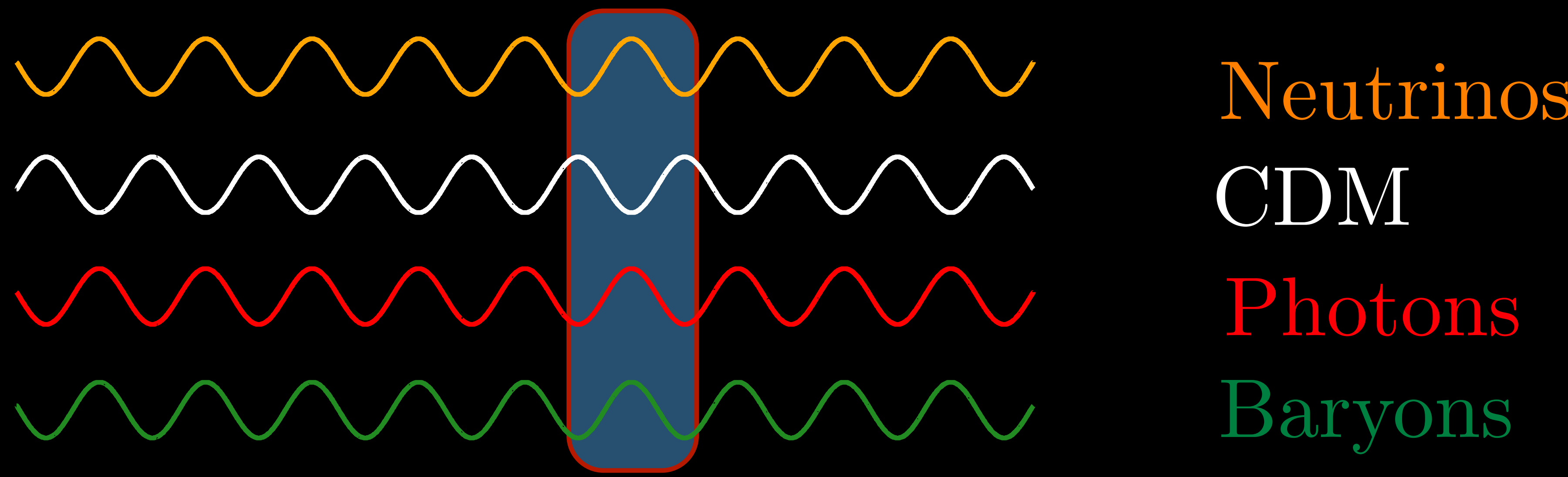
ZOOLOGY OF INITIAL CONDITIONS

CDM isocurvature



$$S_c \neq 0 \quad \Delta\Phi = 0$$

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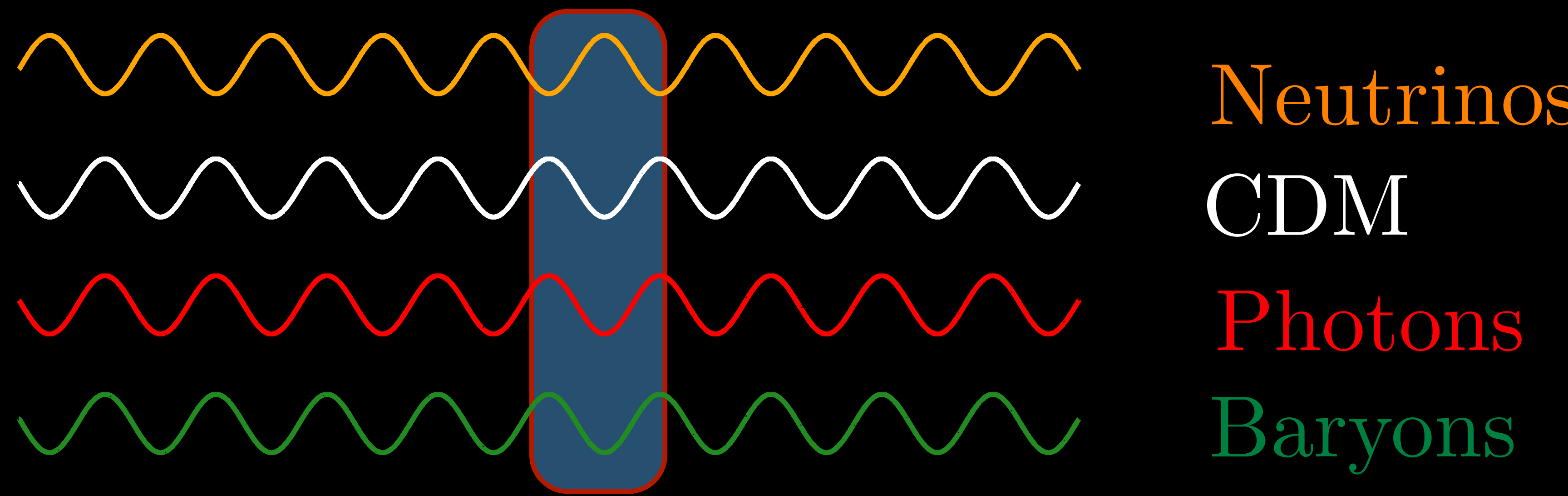
ZOOLOGY OF INITIAL CONDITIONS

ν
isocurvature



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

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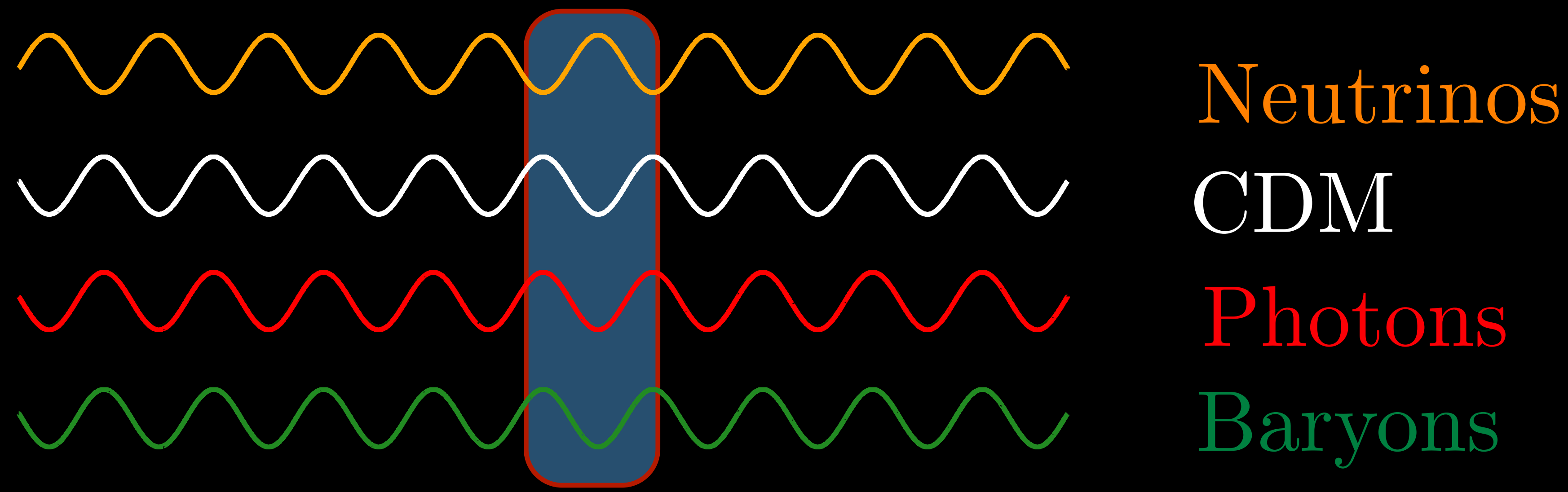
Zoology of initial conditions

ν
isocurvature



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

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

- **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
	$n_{adi} = n_{iso}$	$n_{adi} = n_{iso}$	$n_{adi} = n_{iso}$
r_{iso}	< 0.13	< 0.08	< 0.14

→

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

✳ 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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- “Nuisance” mode identified (Lewis 2002)

Compensated Isocurvature Perturbation (CIP)

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

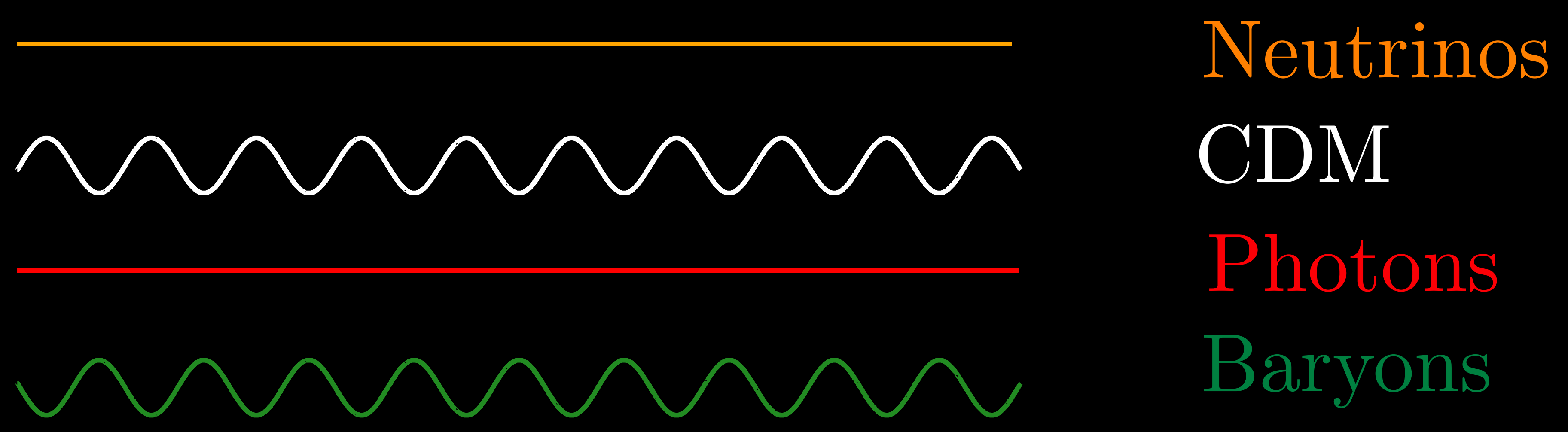
$$\mathcal{S}_{\rm bc} = \frac{\delta n_{\rm b}}{n_{\rm b}} - \frac{\delta n_{\rm c}}{n_{\rm c}} \neq 0$$

Baryon-dark matter entropy

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

BARYON-DM ISOCURVATURE

- “Nuisance” mode identified (Lewis 2002)



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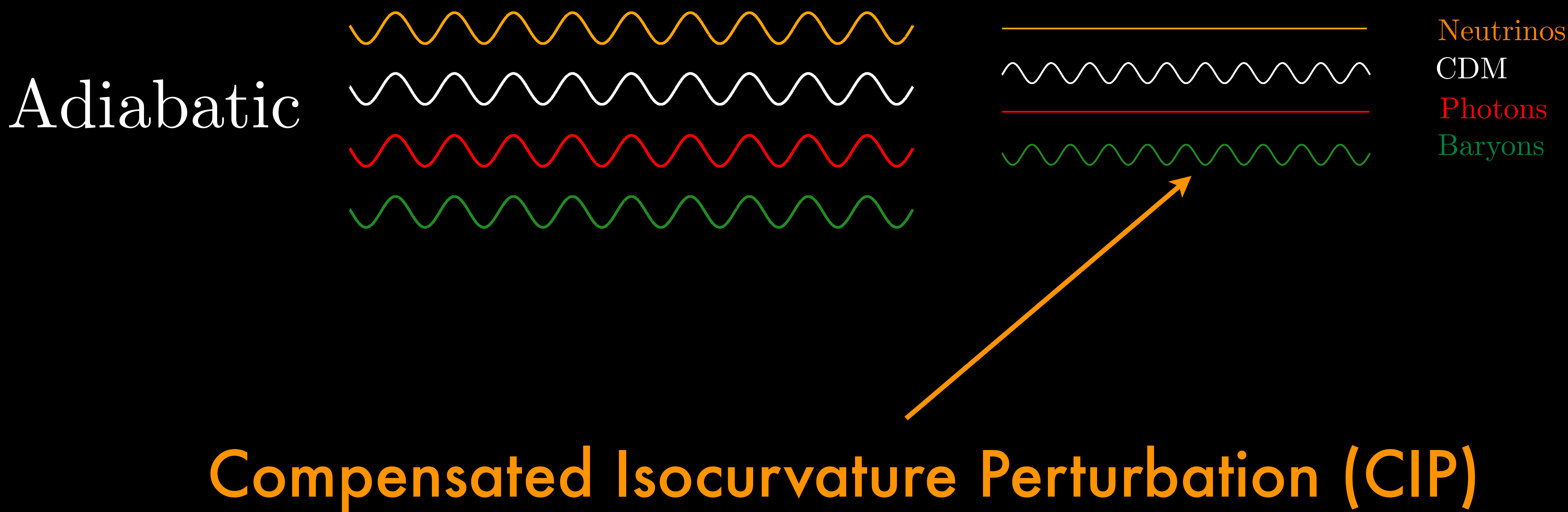

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CIPS AND THE SACHS-WOLFE EFFECT

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

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

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

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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?*

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

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

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

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

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

- *Run your favorite Boltzmann code (CAMB/CMBFAST) with a CIP*
  - *Fractional change in anisotropies of less than 0.00001 for angular scales l<10000*

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

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

$$l > 10^5$$

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

- *Run your favorite Boltzmann code (CAMB/CMBFAST) with a CIP*
  - *Fractional change in anisotropies of less than 0.00001 for angular scales $l<10000$*

There seems to be no affect on the CMB!

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

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)

EXISTING MODELS FOR CIPS

Gordon and Pritchard, 2009

- Curvaton sources entropy fluctuation in CDM
- After curvaton dominates, adiabatic flucts generated

Existing models for CIPs

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- After curvaton dominates, adiabatic flucts generated

$$S_{\rm b}=3\frac{\rho_{\rm c}}{\rho_{\rm b}}\zeta$$

$$S_{\rm c}=-3\zeta$$

EXISTING MODELS FOR CIPS

Gordon and Pritchard, 2009

- Curvaton sources entropy fluctuation in CDM
- After curvaton dominates, adiabatic flucts generated

$$S_{\rm bc} = 3\left(1+\frac{\rho_{\rm c}}{\rho_{\rm b}}\right)\zeta$$

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

Existing models for CIPs

Gordon and Pritchard, 2009

- ✳ Curvaton sources entropy fluctuation in CDM
- ✳ After curvaton dominates, adiabatic flucts generated

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

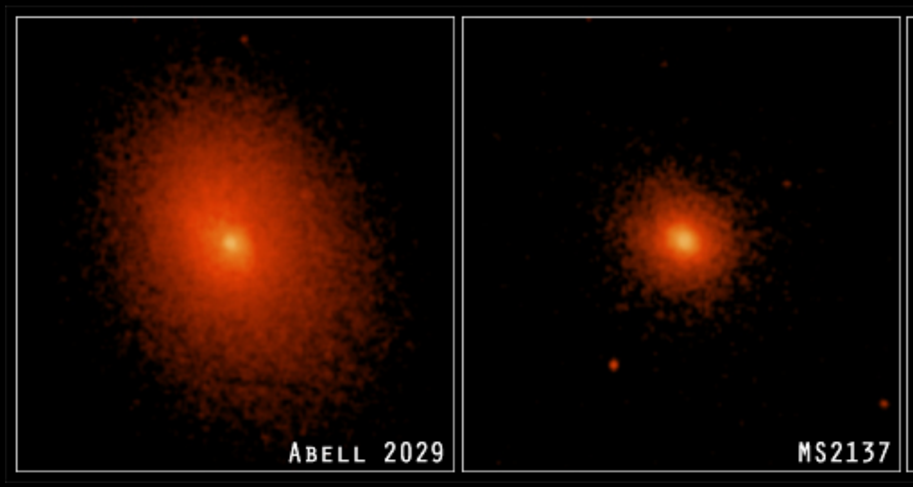
Fluctuations as high as 8% are allowed by the data

Existing constraints to CIPS- BBN

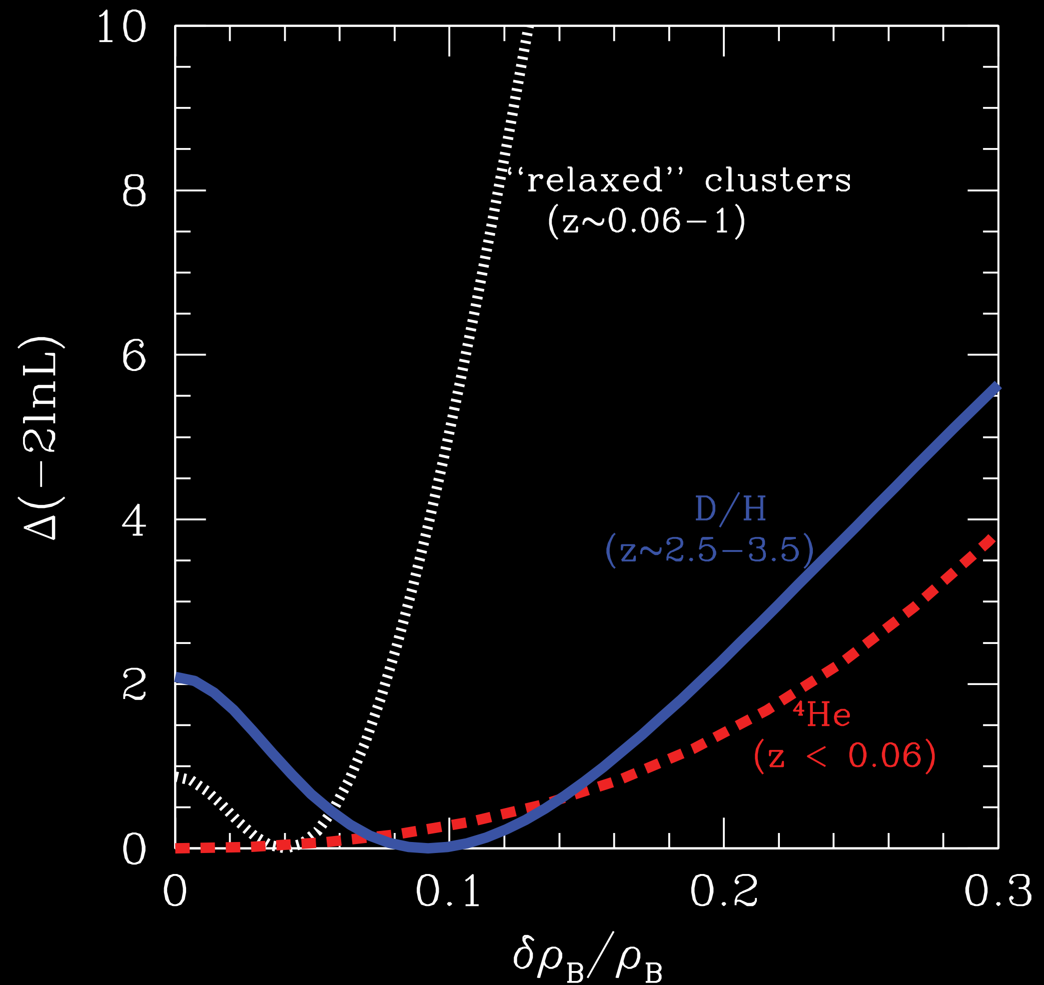
- Primordial abundances of De, ^{3}He, ^{4}He, ^{7}Li : Blue compact galaxies (He) and QSO Absorption systems (De)

- Baryon fraction measurements in galaxy clusters

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



EXISTING CONSTRAINTS TO CIPS- BBN

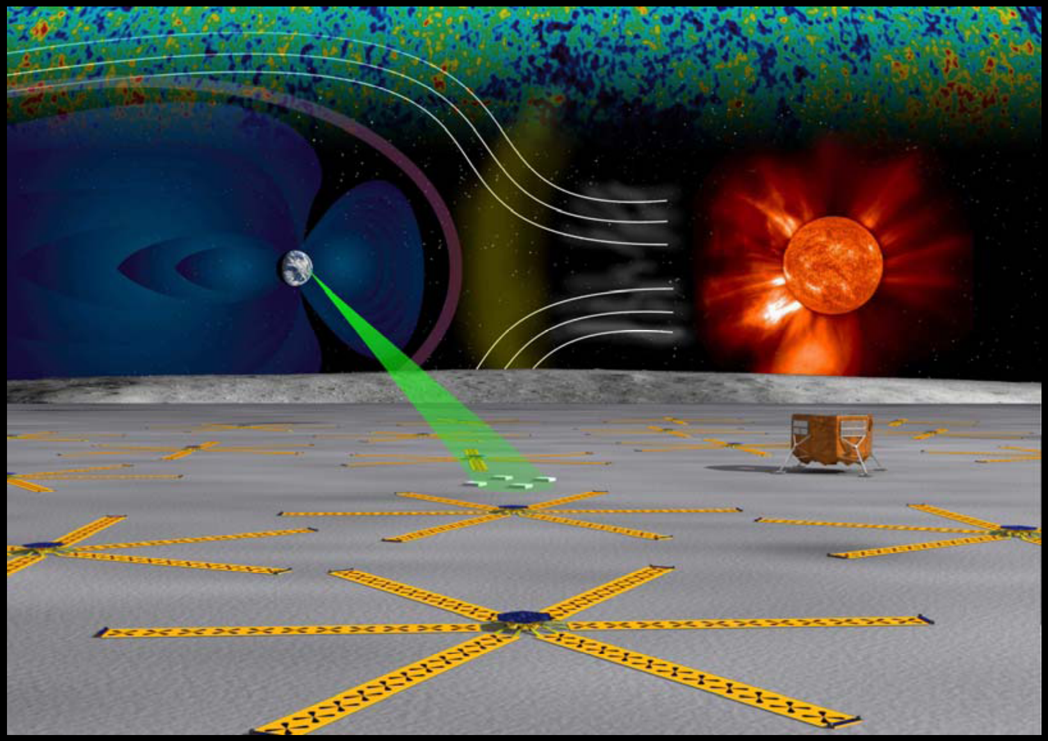


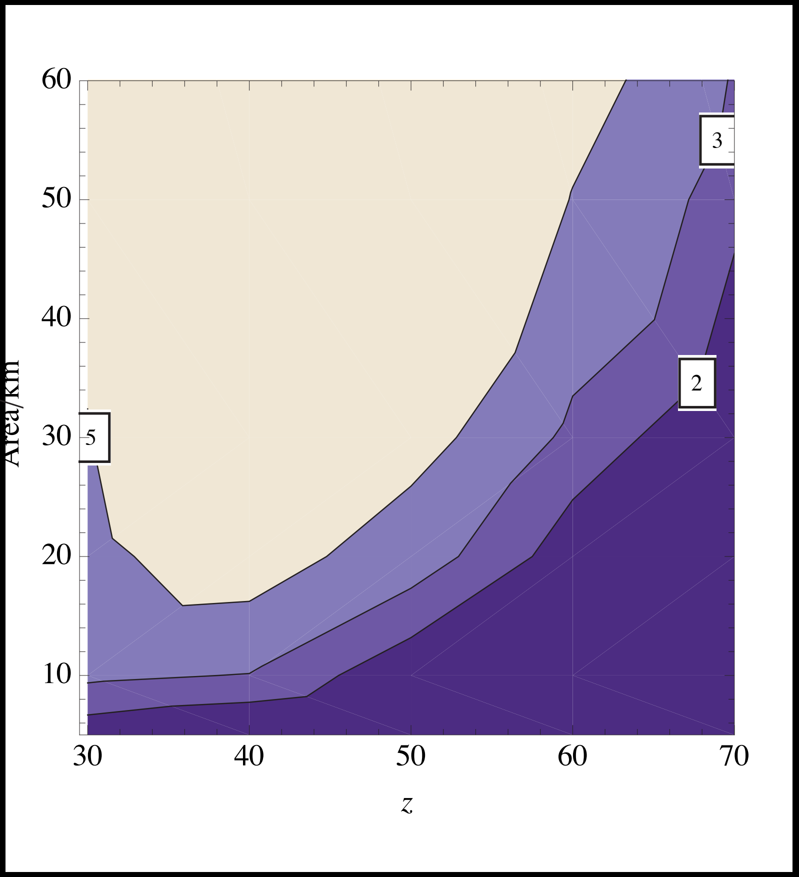
Fluctuations as high as **8%** are allowed by the data

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

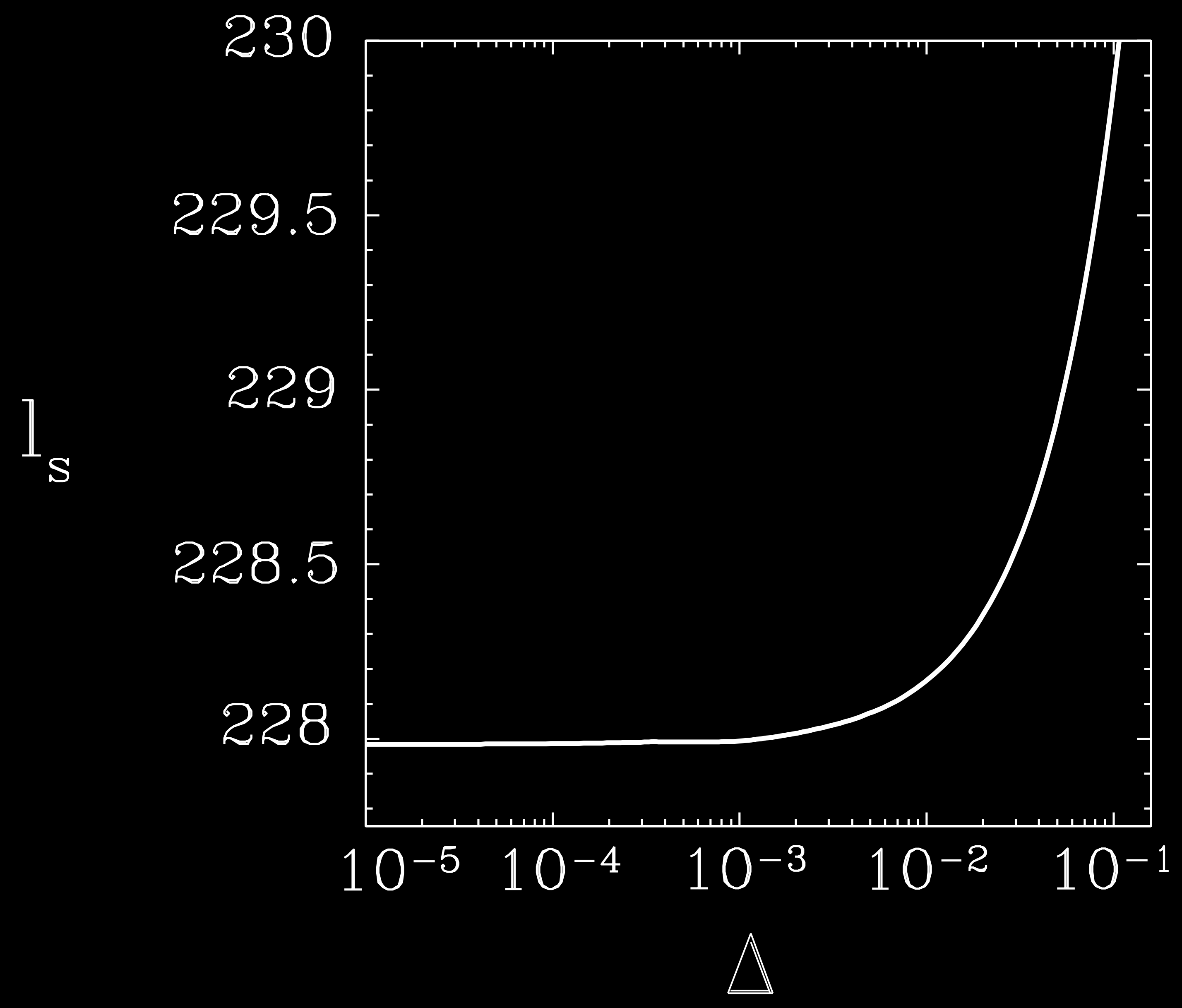




Significance of a 21-cm detection of amplitude 10^{-3} CIPs

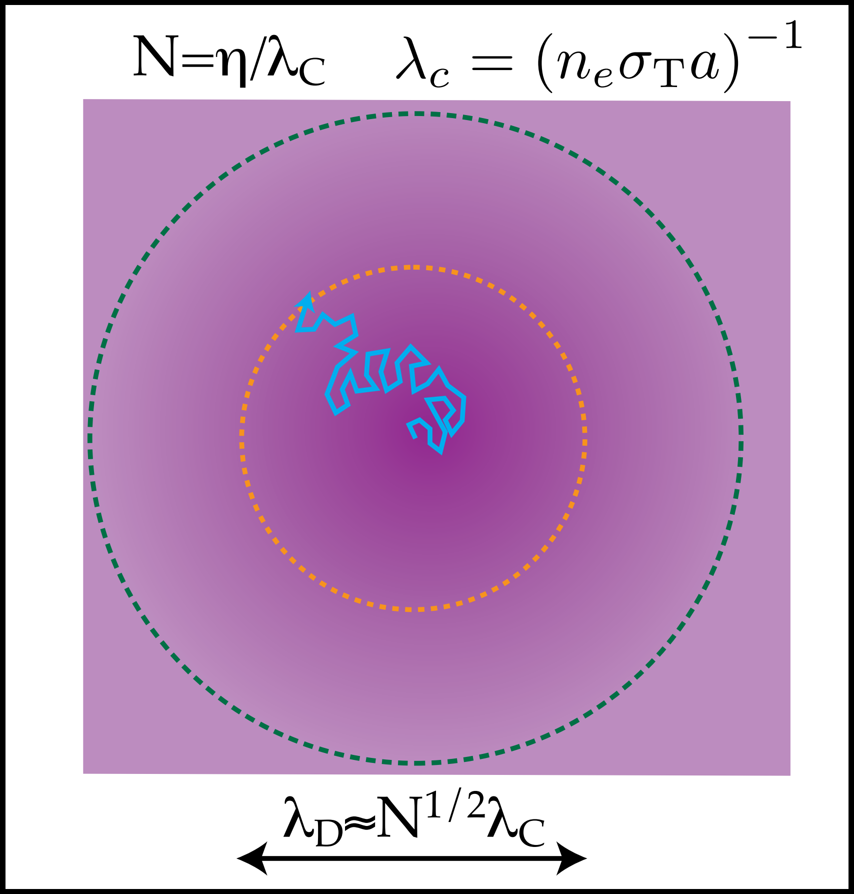
COMPENSATED ISOCURVATURE AND THE CMB: *z~1100 EFFECTS*

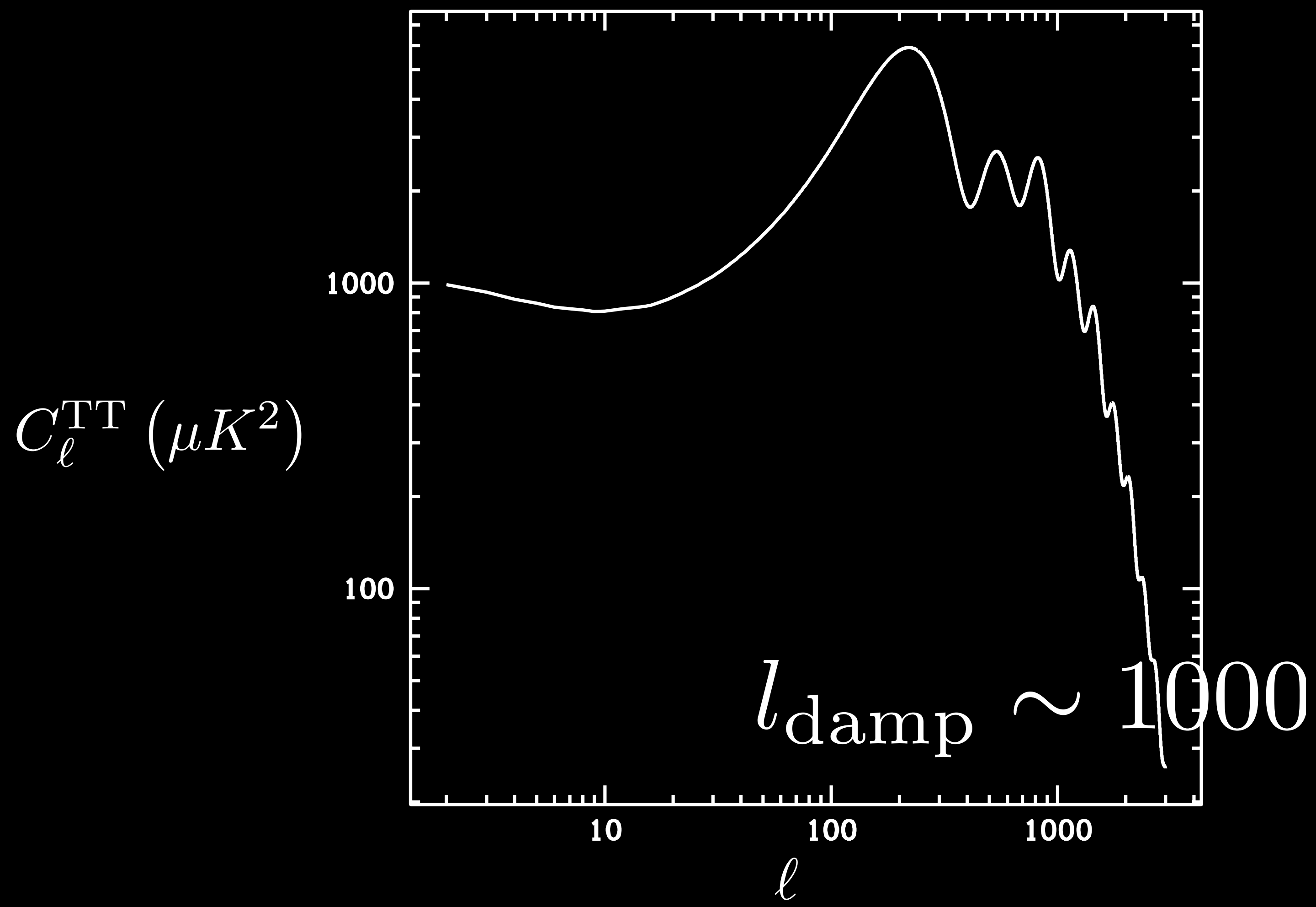
COMPENSATED ISOCURVATURE AND THE CMB:
z~1100 EFFECTS



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

- Damping scale modulated by CIPs





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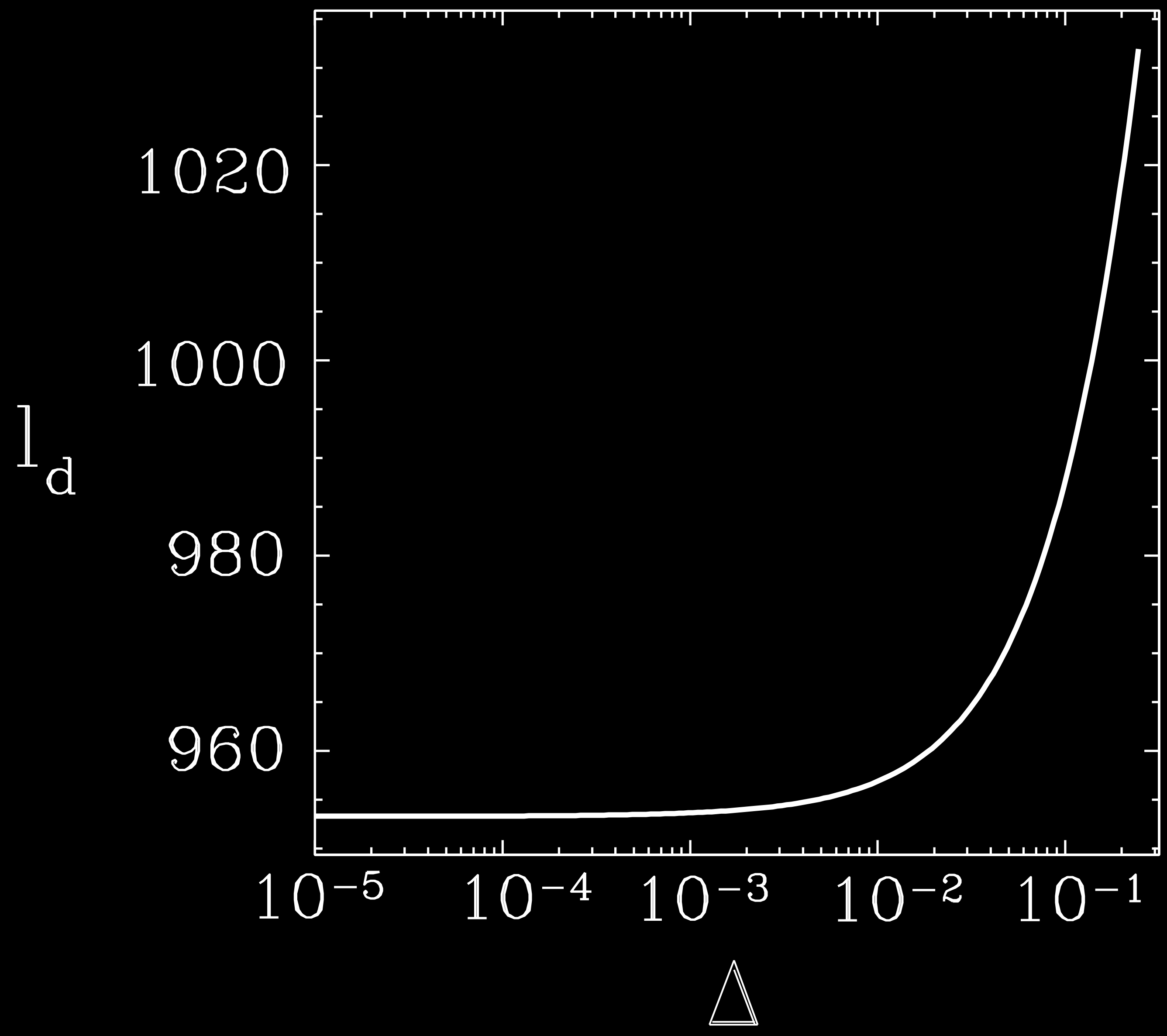
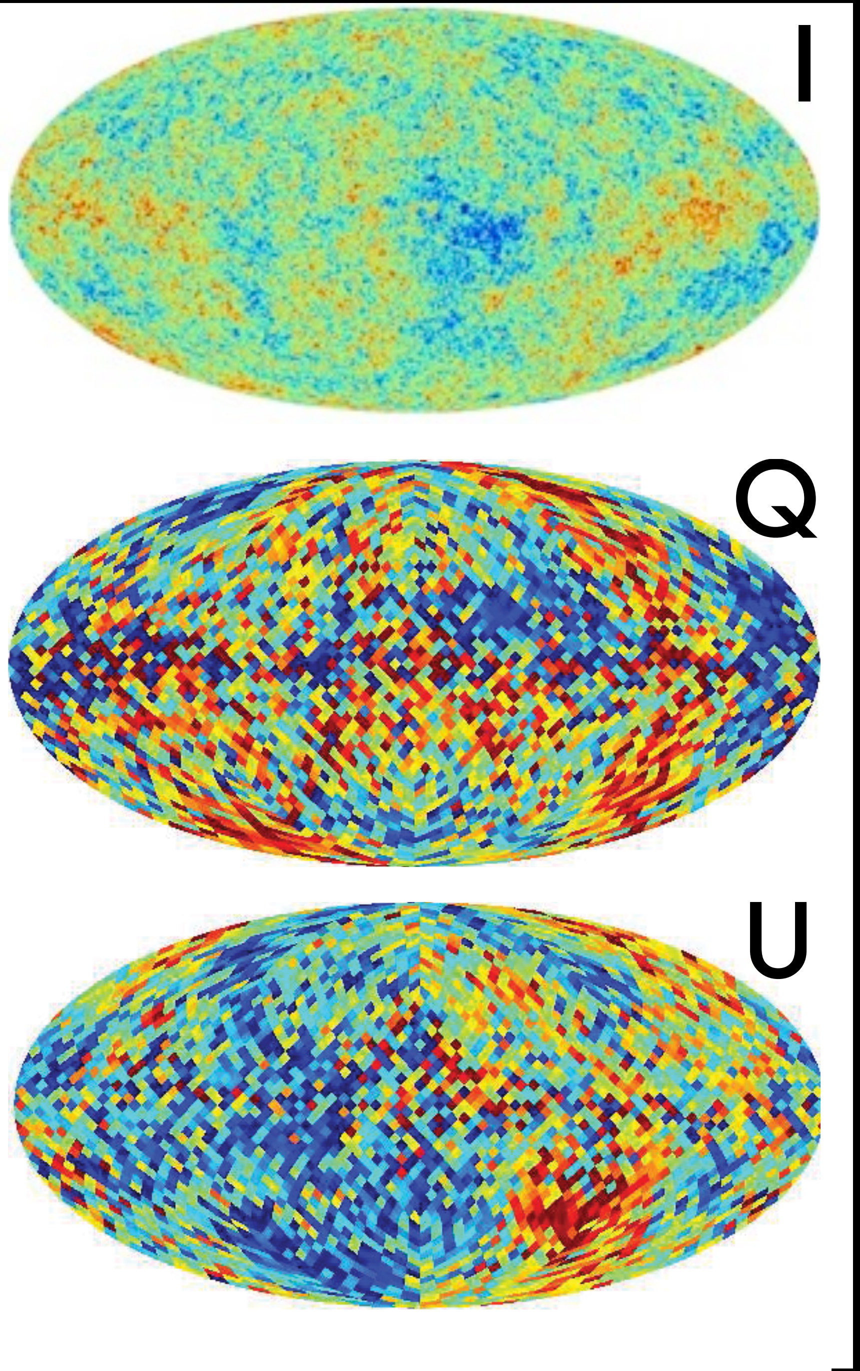


COMPENSATED ISOCURVATURE AND THE CMB: *RECOVERING THE REALIZATION*

- Power spec. results were true, averaging over realizations of primordial $\Phi(\hat{n})$ and CIP amplitude $\Delta(\hat{n})$



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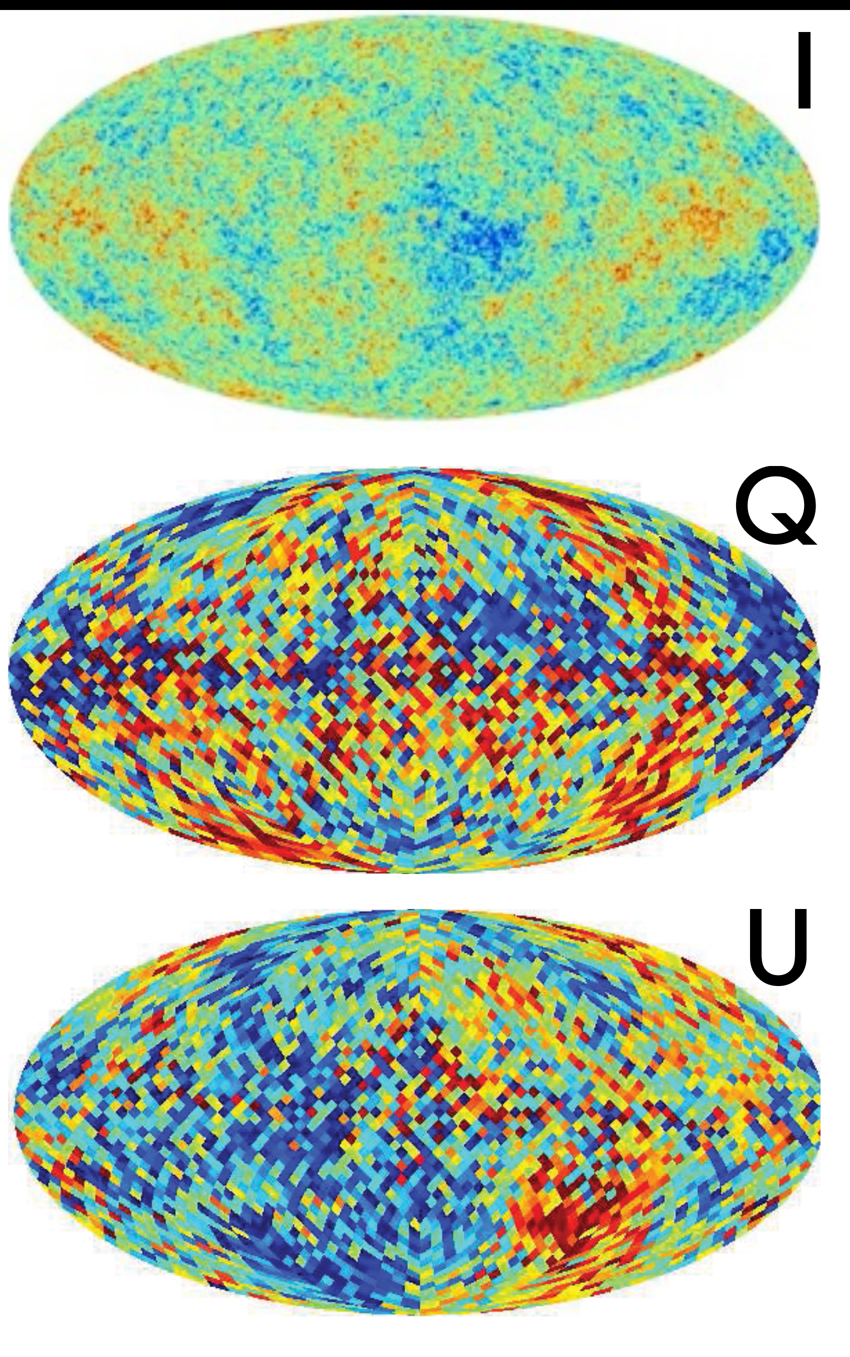

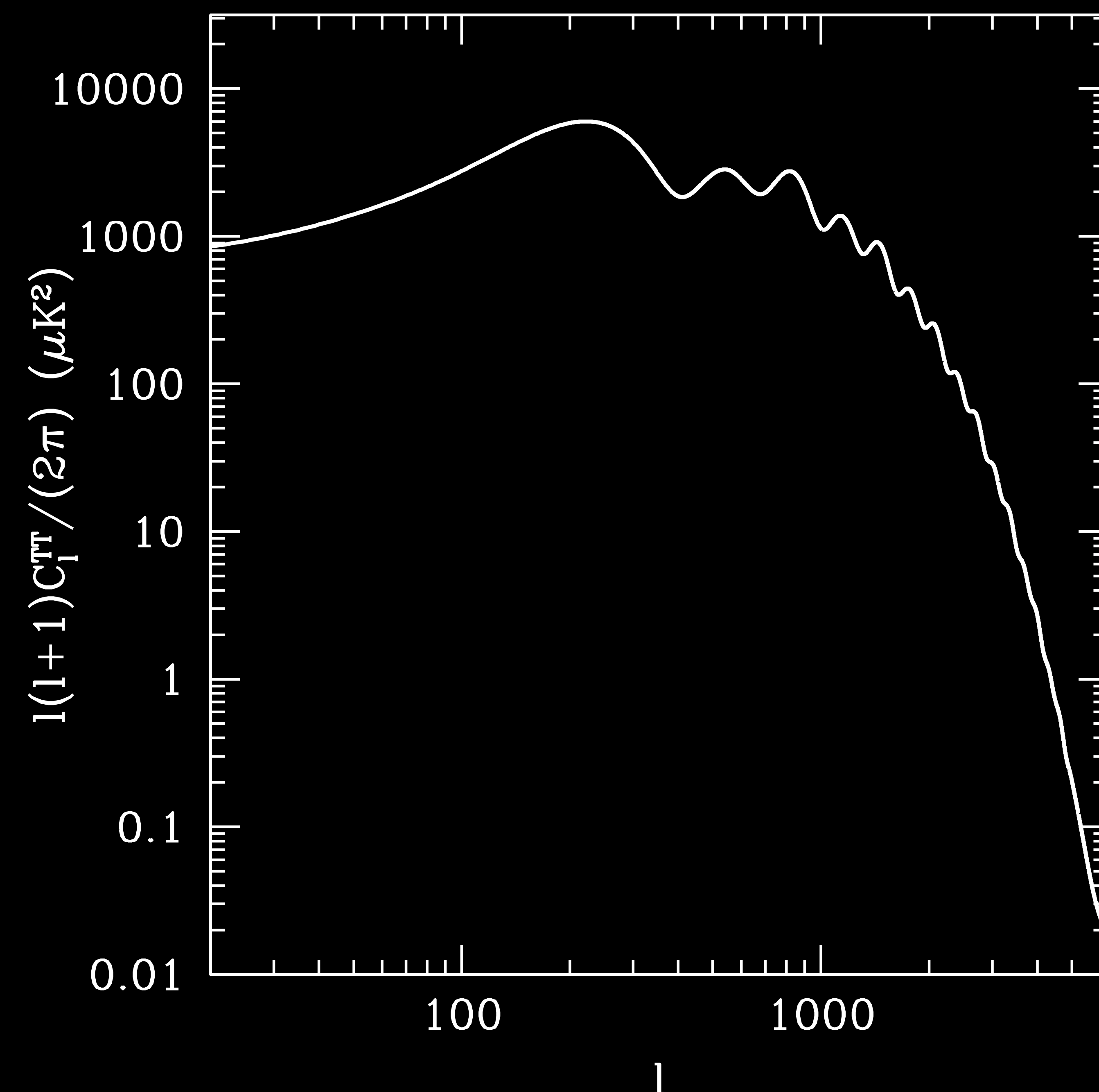

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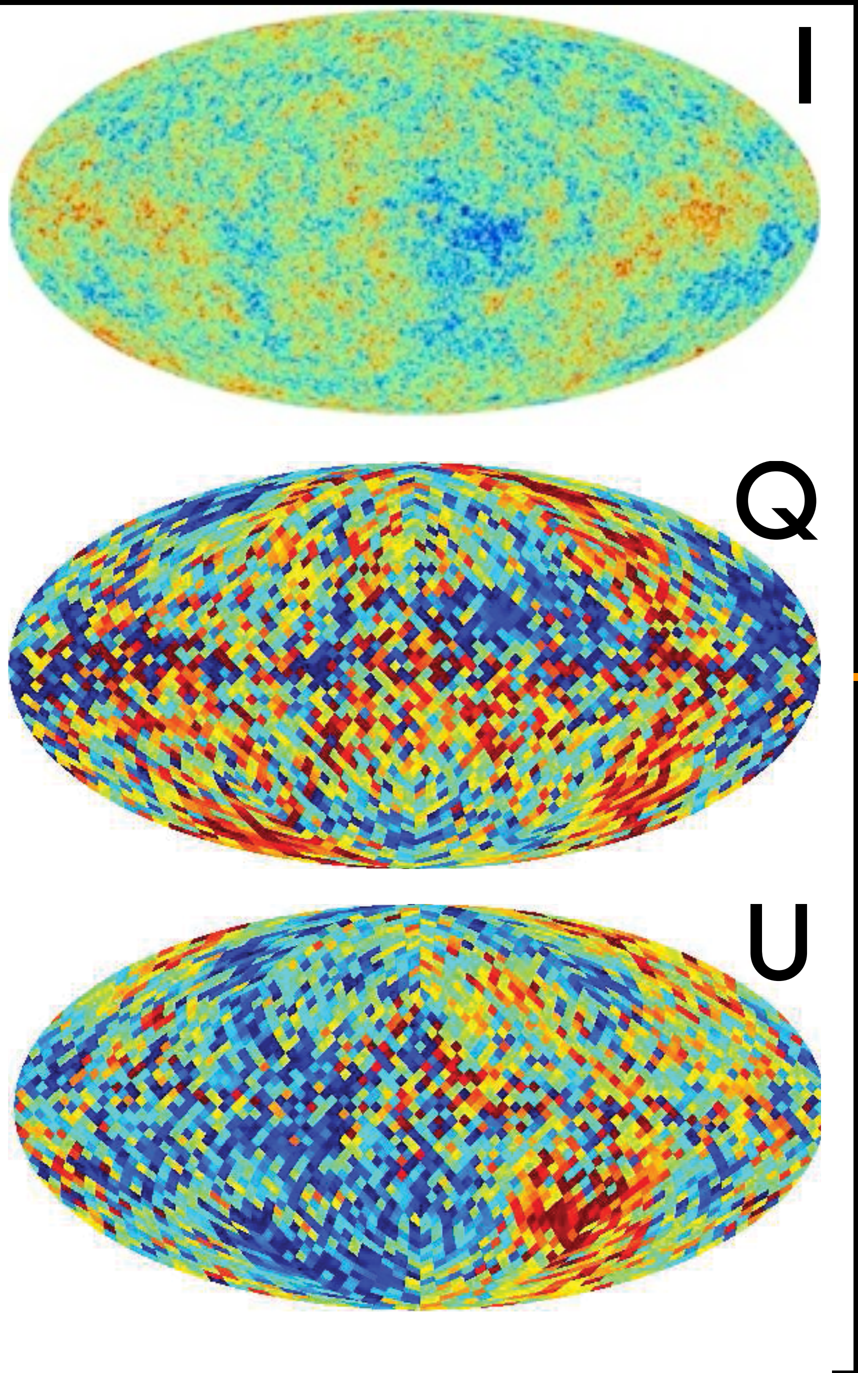

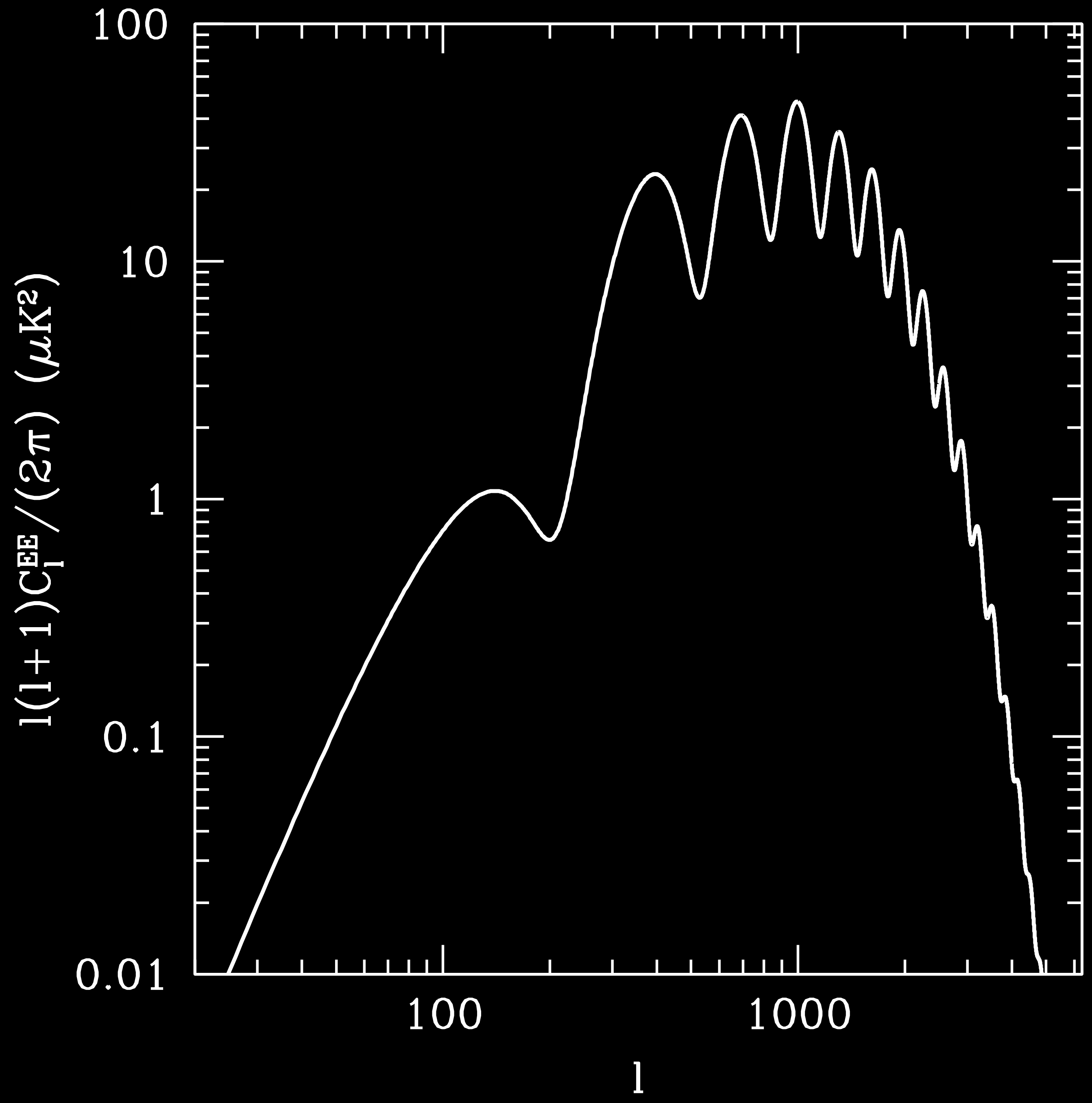

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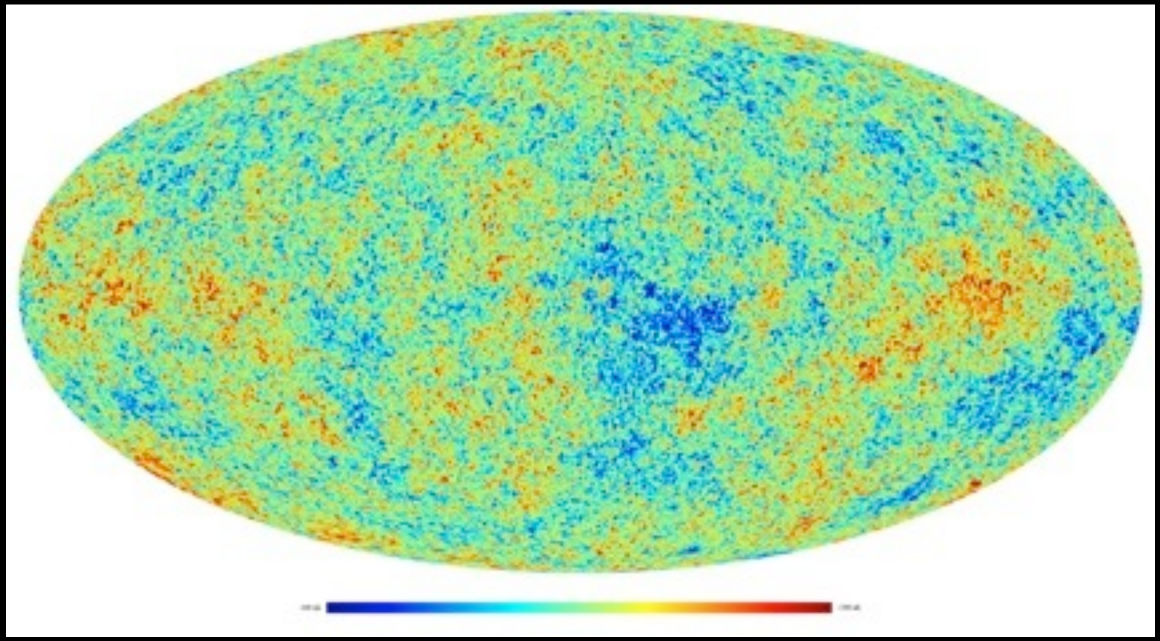
- In single realization of CIP spec., a long wavelength CIP w/ amp Δ_{LM} modulates the power spectrum across the sky



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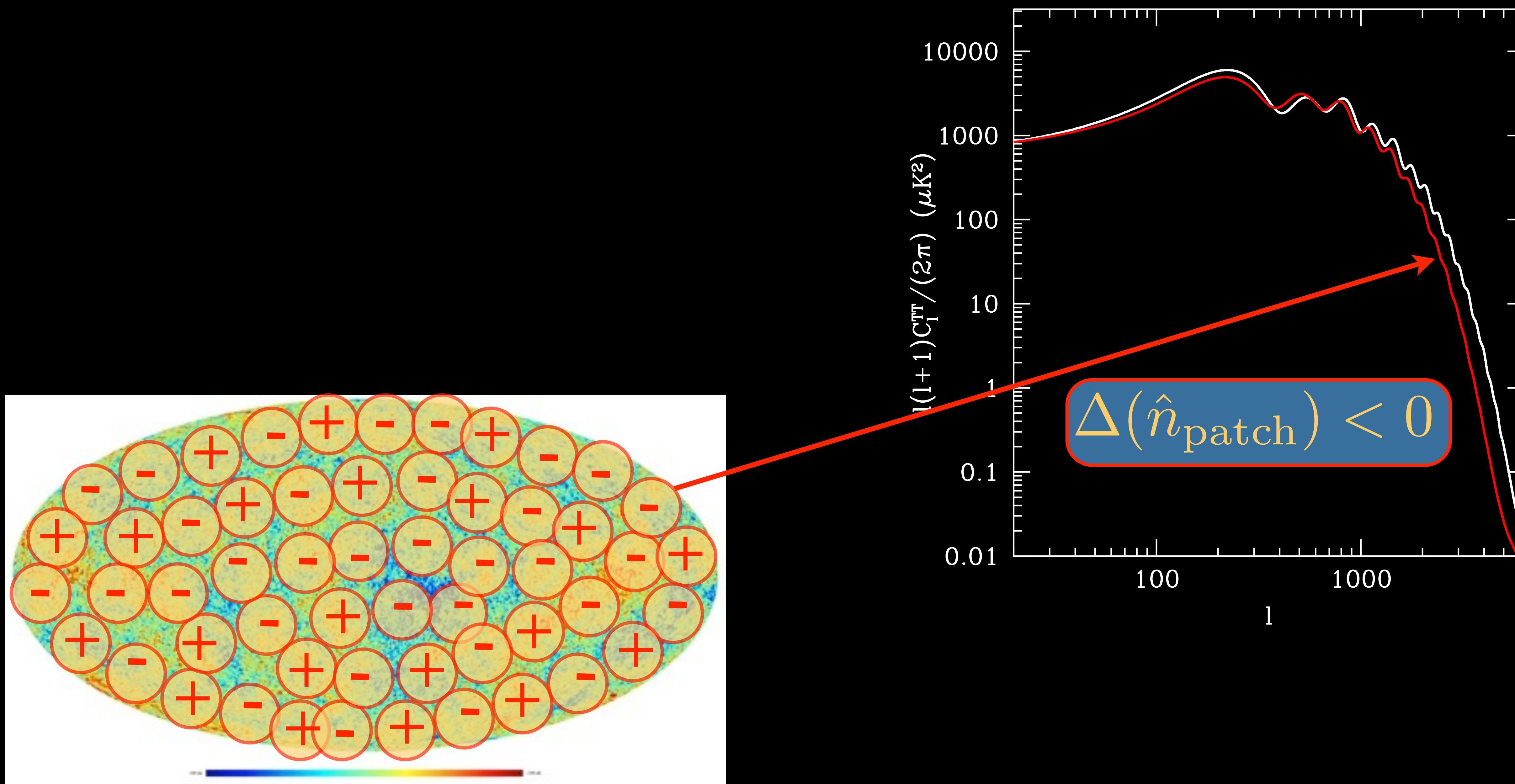
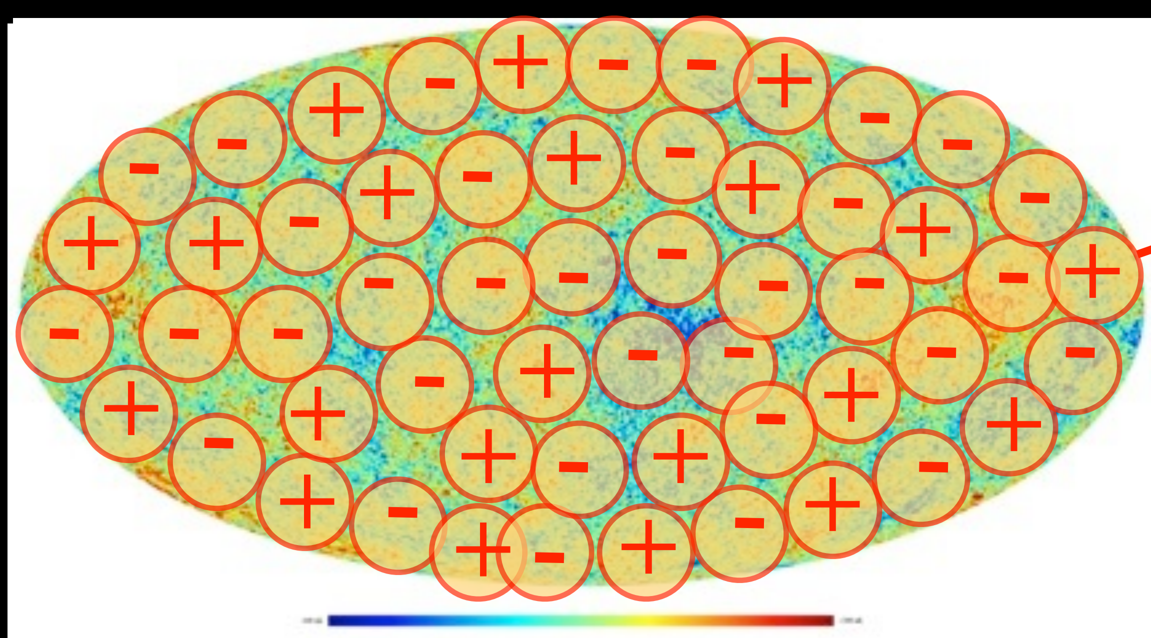
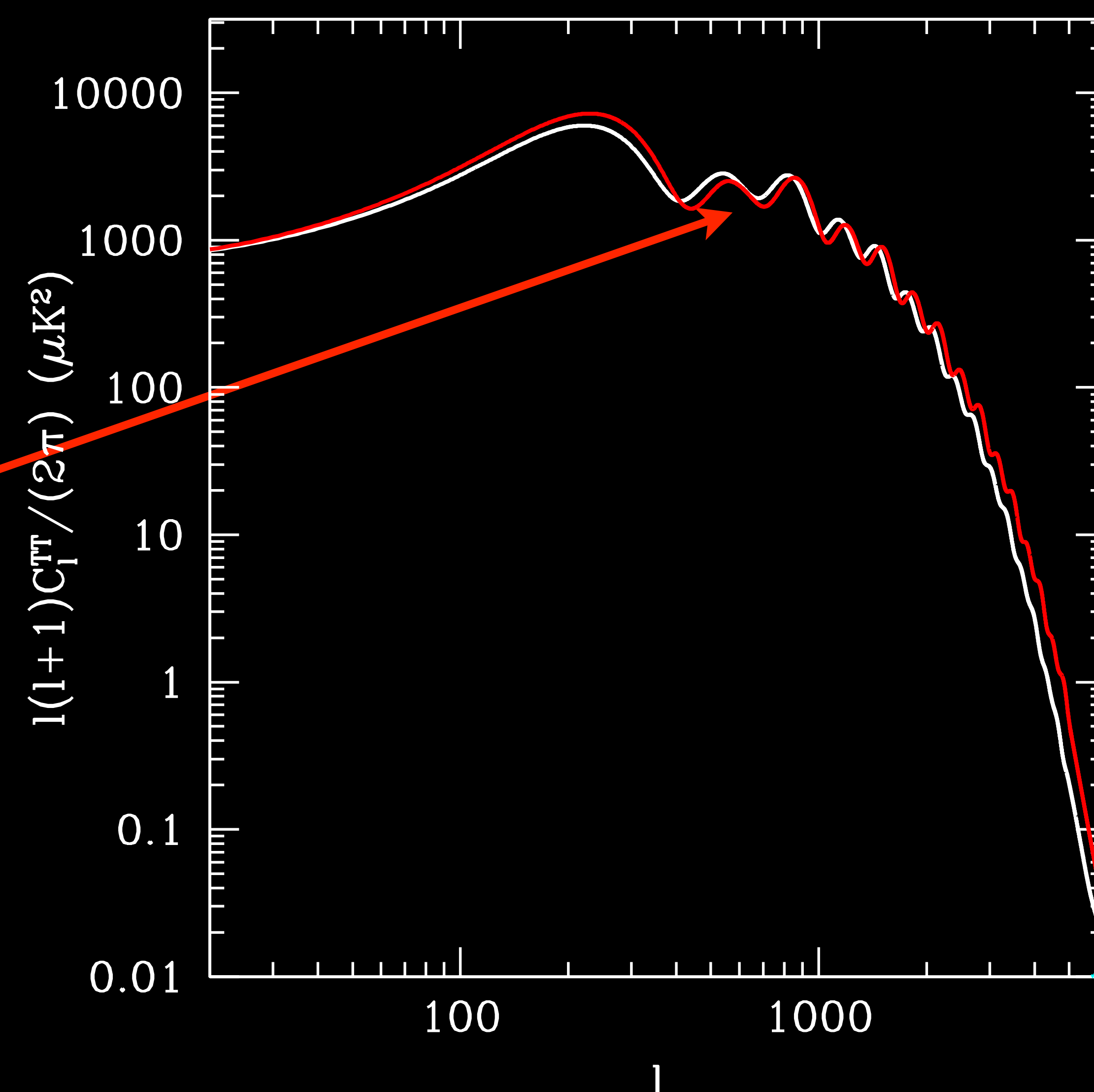


COMPENSATED ISOCURVATURE AND THE CMB: *RECOVERING THE REALIZATION*

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





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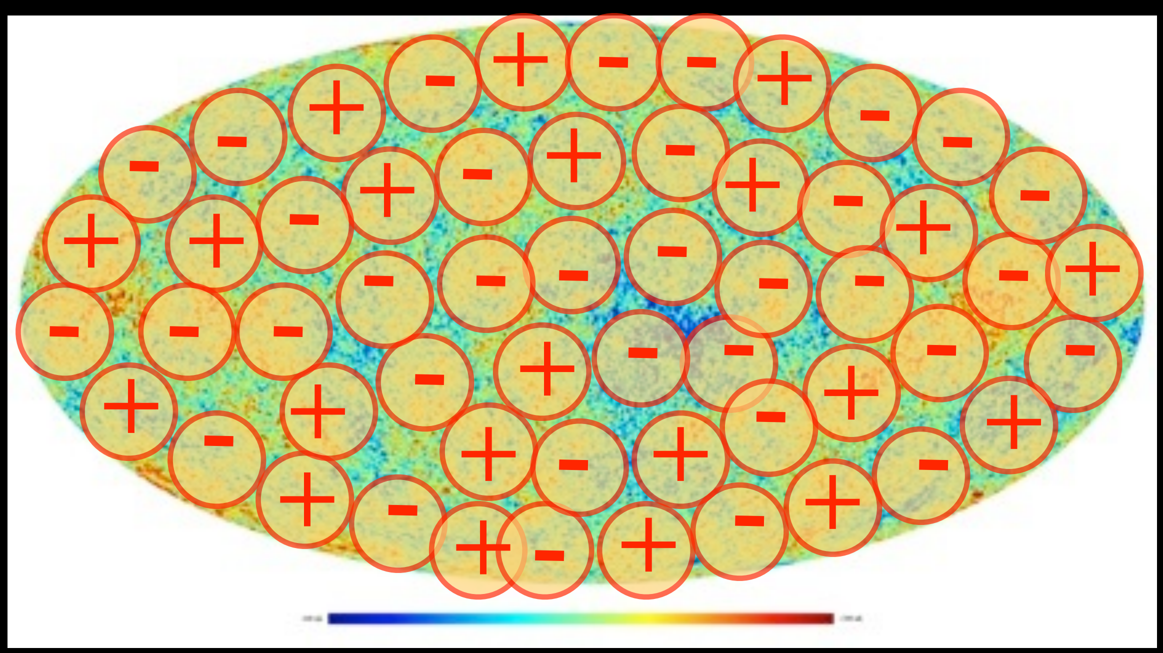


✳Heuristically:

1. Tile all-sky map with patches
2. Measure power spec in each patch
3. Reconstruct $\Delta(\hat{n})$

Filtering the map

- Reconstruct CIP map

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

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

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

Estimating CIP power spectrum from data

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

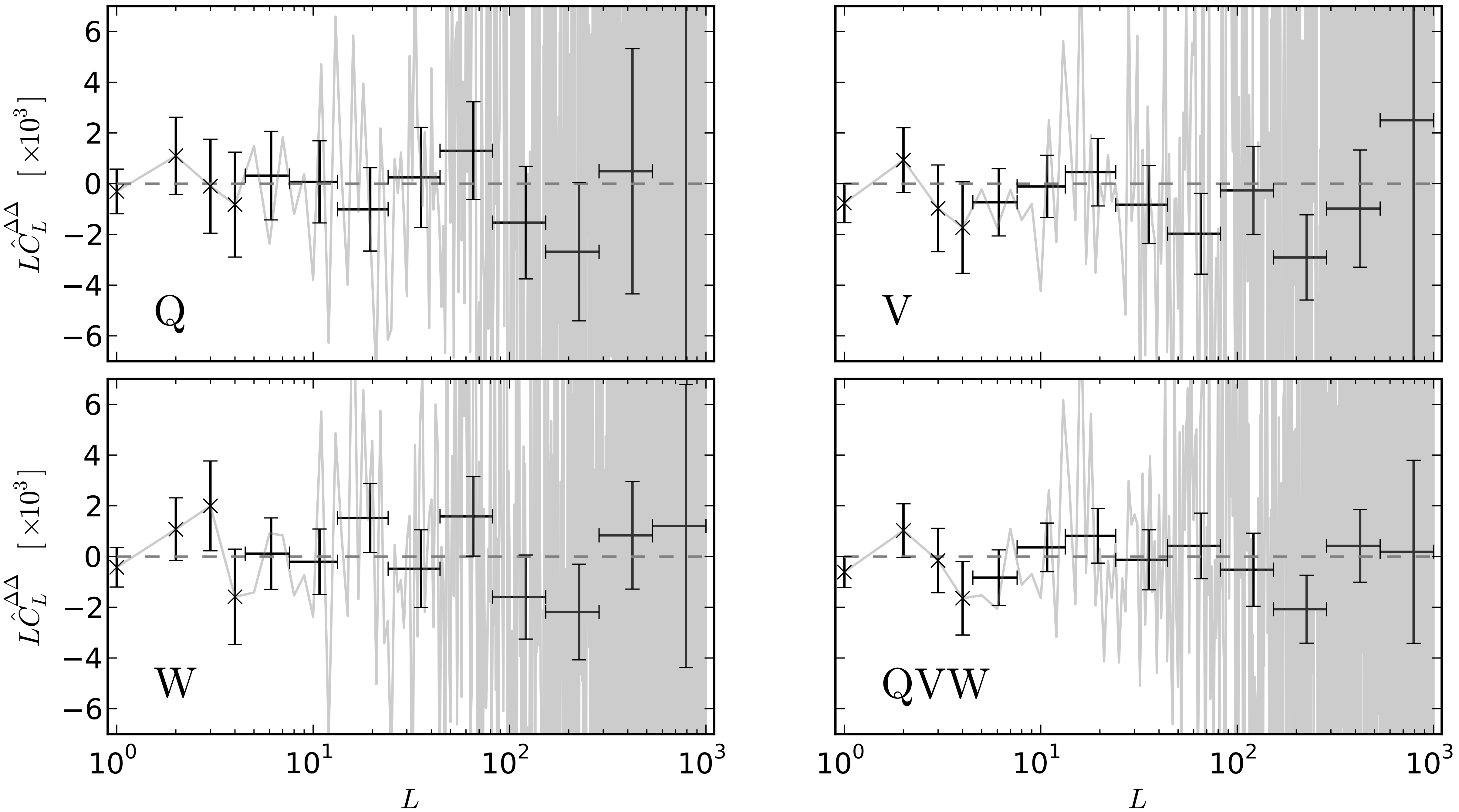
Non-Gaussianity at 4-pt function (trispectrum) level

$$\left\langle T_{\vec{l_1}} T_{\vec{l_2}} T_{\vec{l_3}} T_{\vec{l_4}} \right\rangle_{\text{connected}} \propto C_L^{\Delta\Delta} \quad \text{X} \quad \mathcal{O}\left(\frac{dC_l}{dn_b}\right)\Bigg|_{\Omega_{\rm m}}^2 \quad \text{X} \quad \text{Spherical geometry}$$

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

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

Reconstructed power spectrum from WMAP 9-year data



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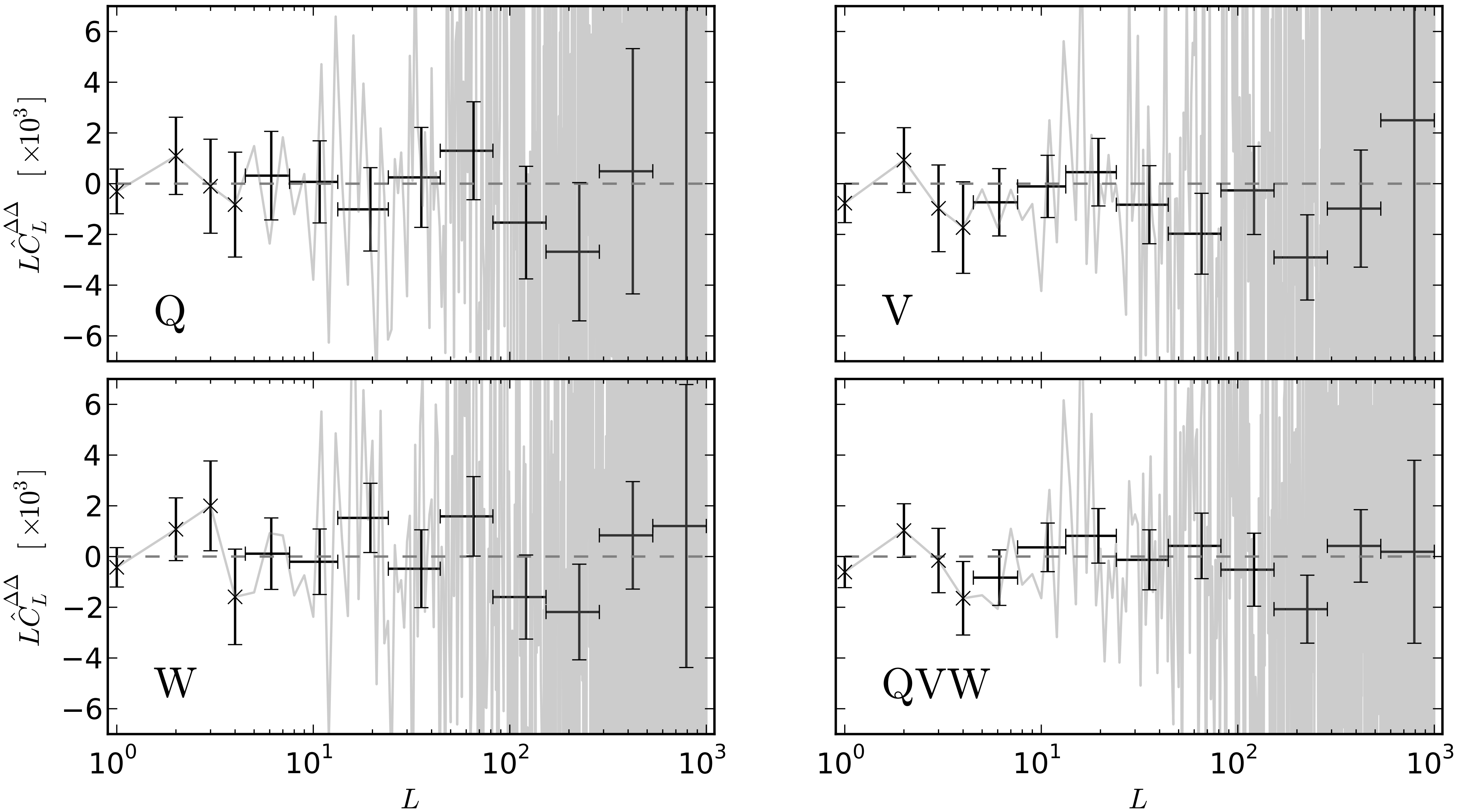
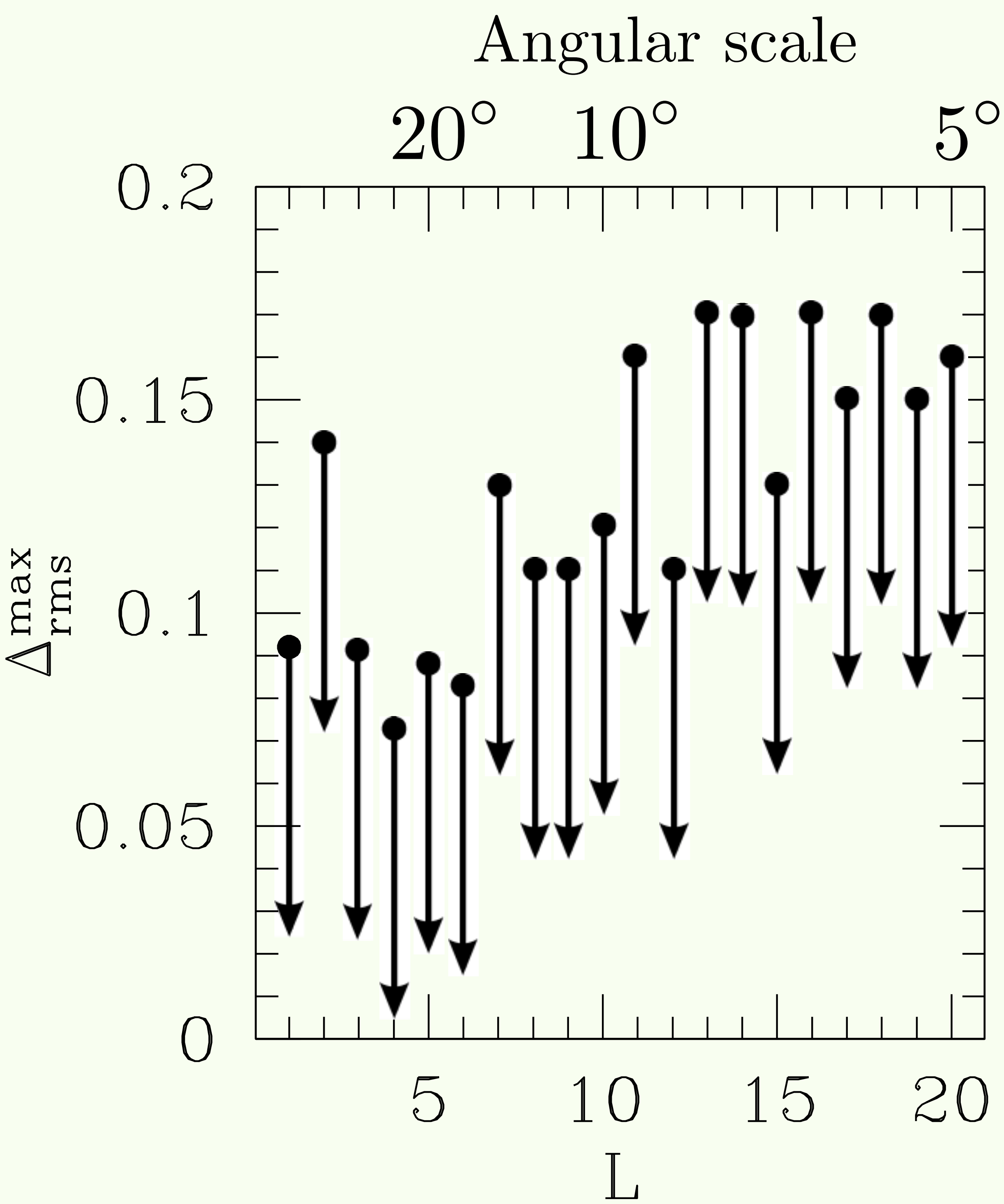


No evidence for CIPs! Cosmic baryon fraction is homogeneous

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

Upper limit to CIP spectrum at a variety of scales



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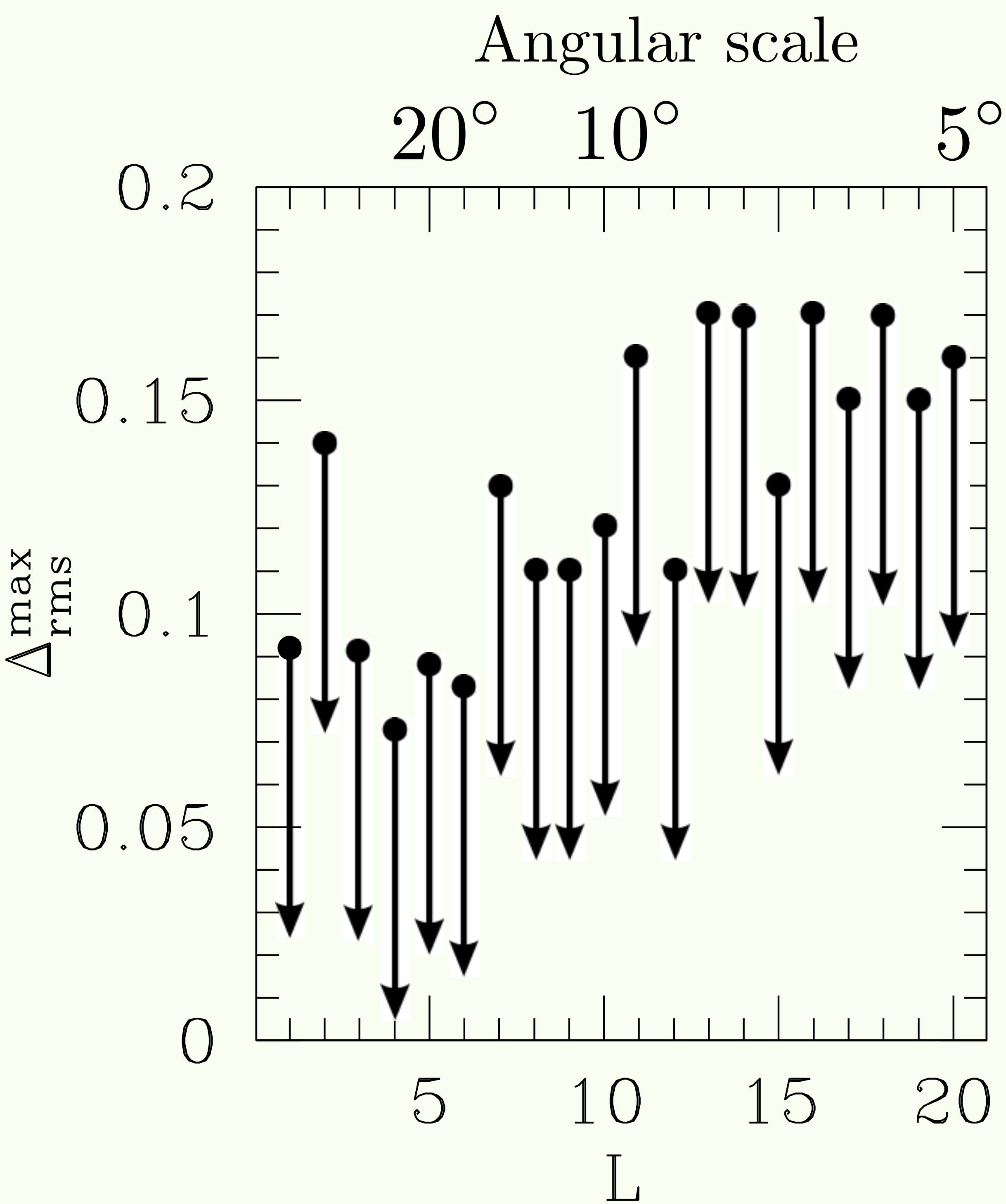
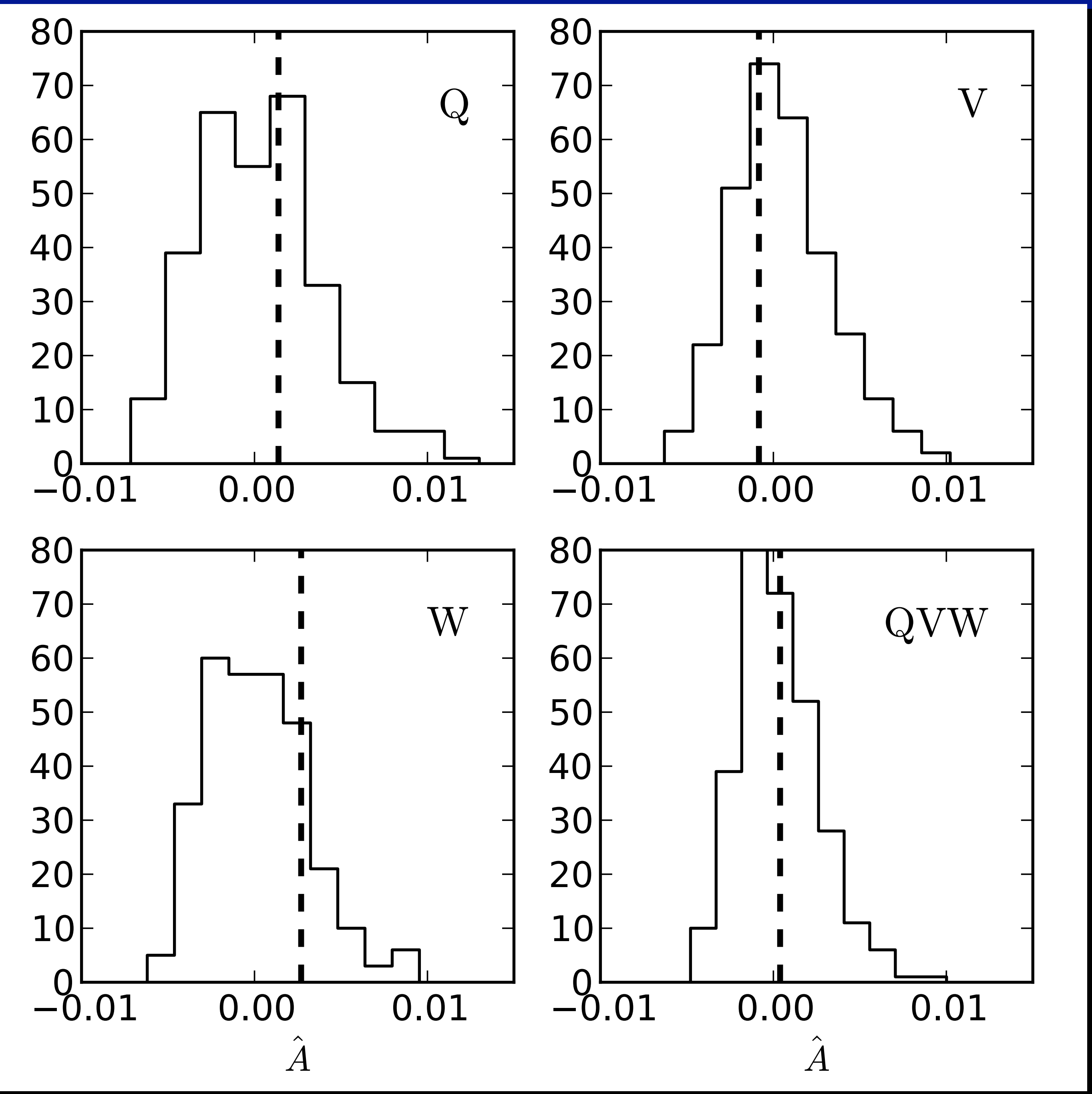


Cosmic baryon fraction is homogeneous at 10-20% level at 5-100˚ scales

Limit to amplitude of scale-invariant spectrum



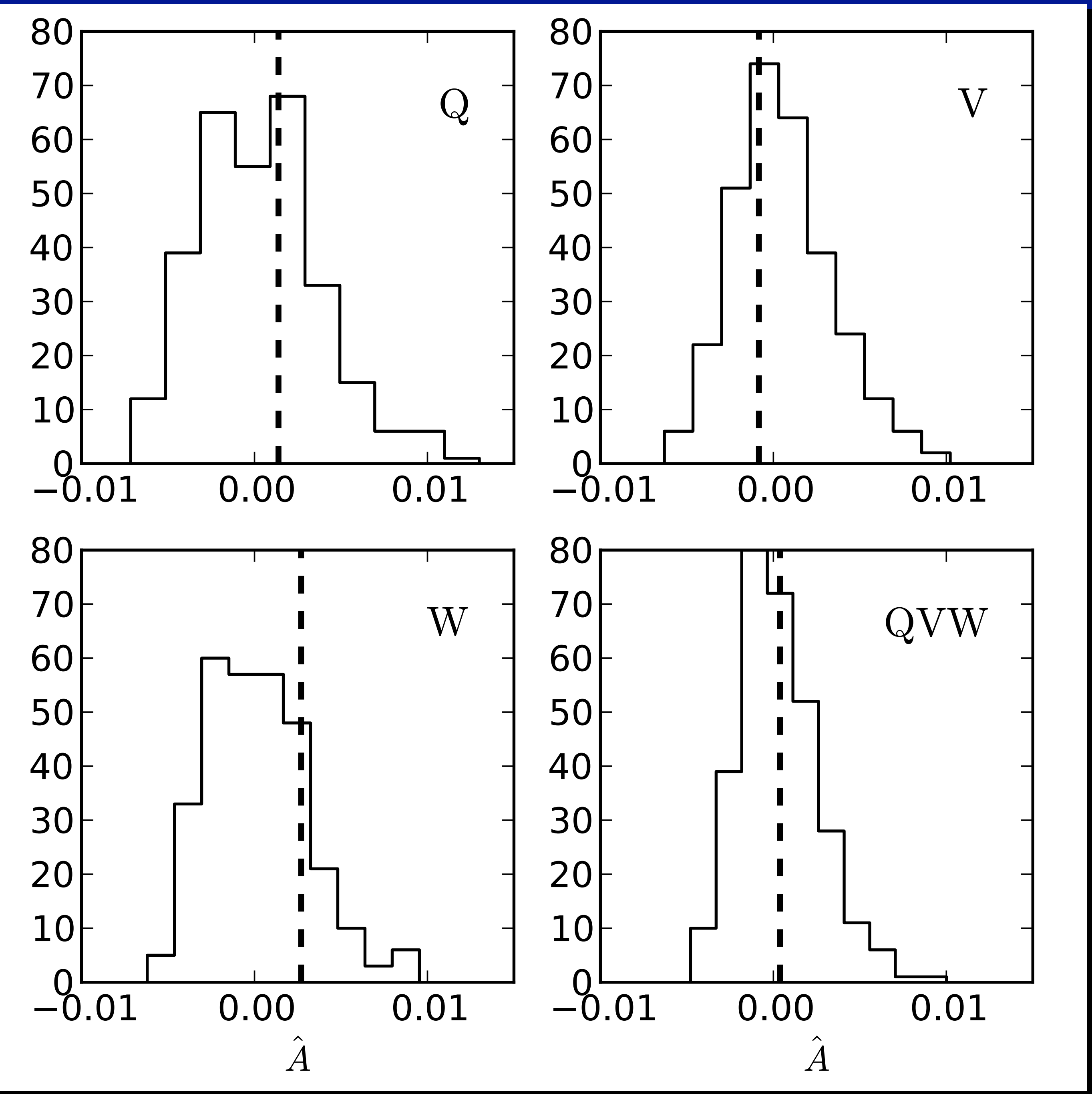
- Combine scales to probe models
- Scale-invariant CIP spectrum

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

- Monte Carlo null hypothesis

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

Limit to amplitude of scale-invariant spectrum



- Combine scales to probe models
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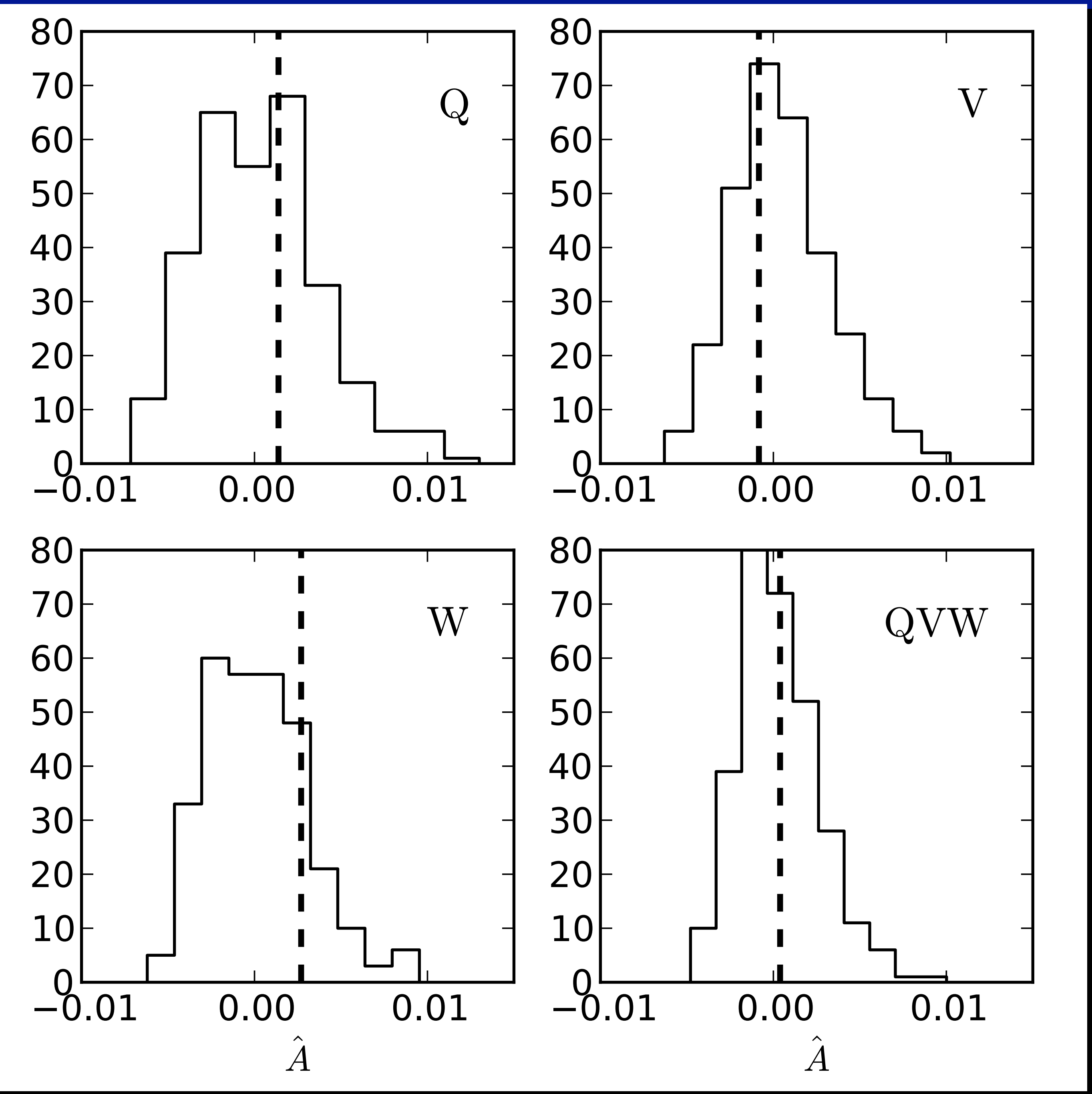
- Monte Carlo null hypothesis
- Observations consistent with null hypothesis

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

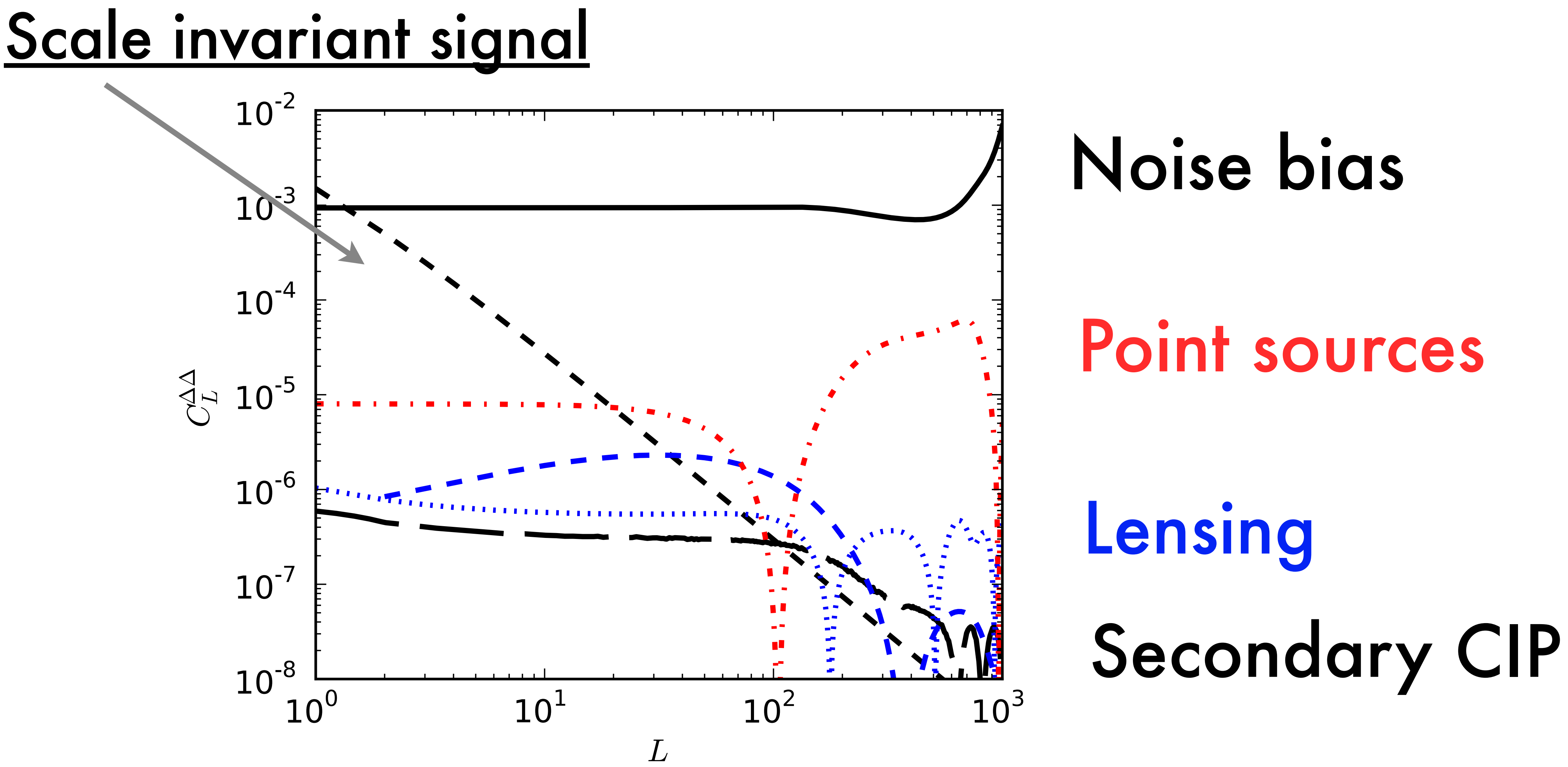
Limit to amplitude of scale-invariant spectrum



- Proof of technique
- First purely primordial test
- Great improvement with coming experiments

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

Possible sources of bias



All secondary biases can be neglected for WMAP-9 analysis

COMPENSATED ISOCURVATURE AND THE CMB: *PROSPECTS*

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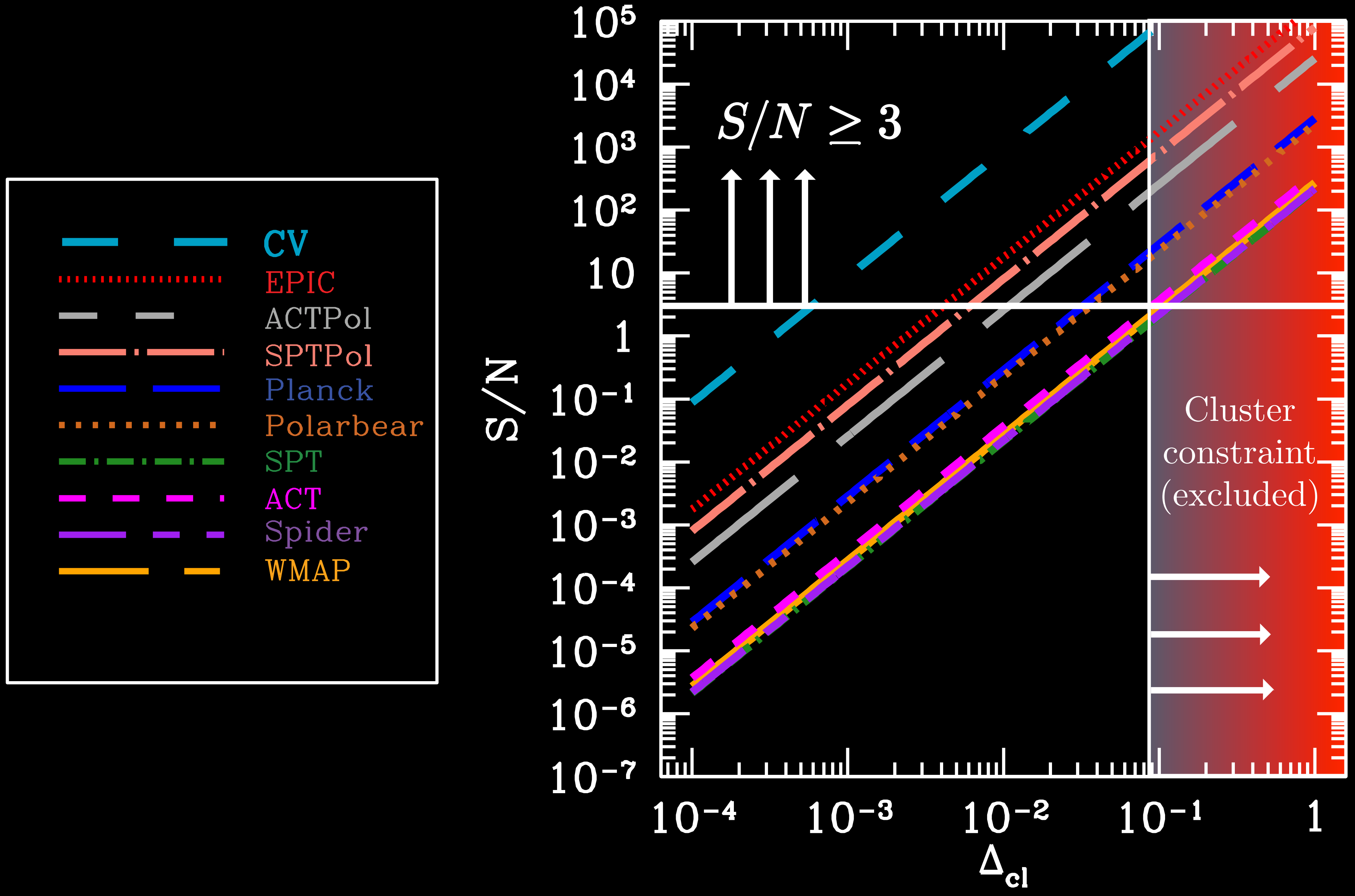
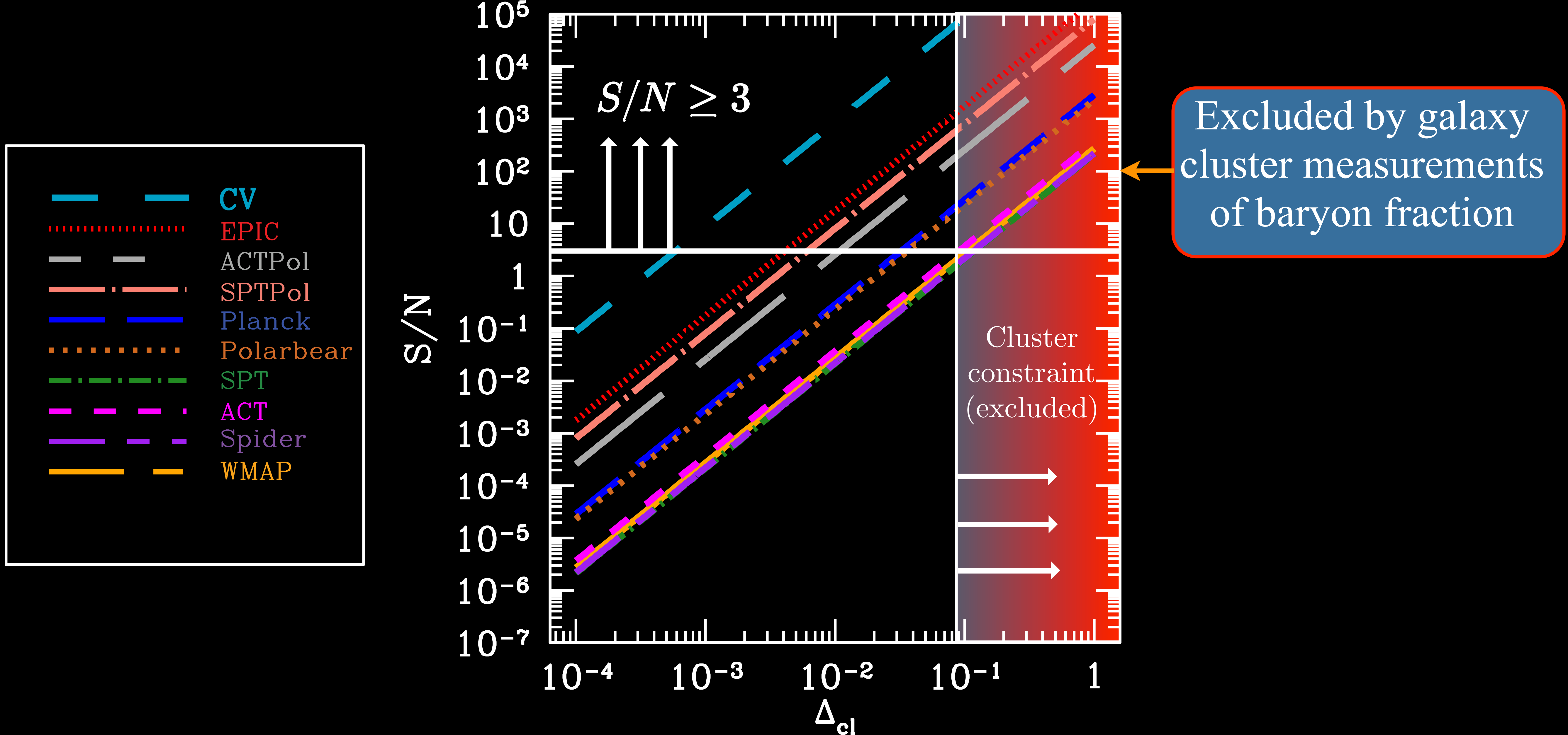
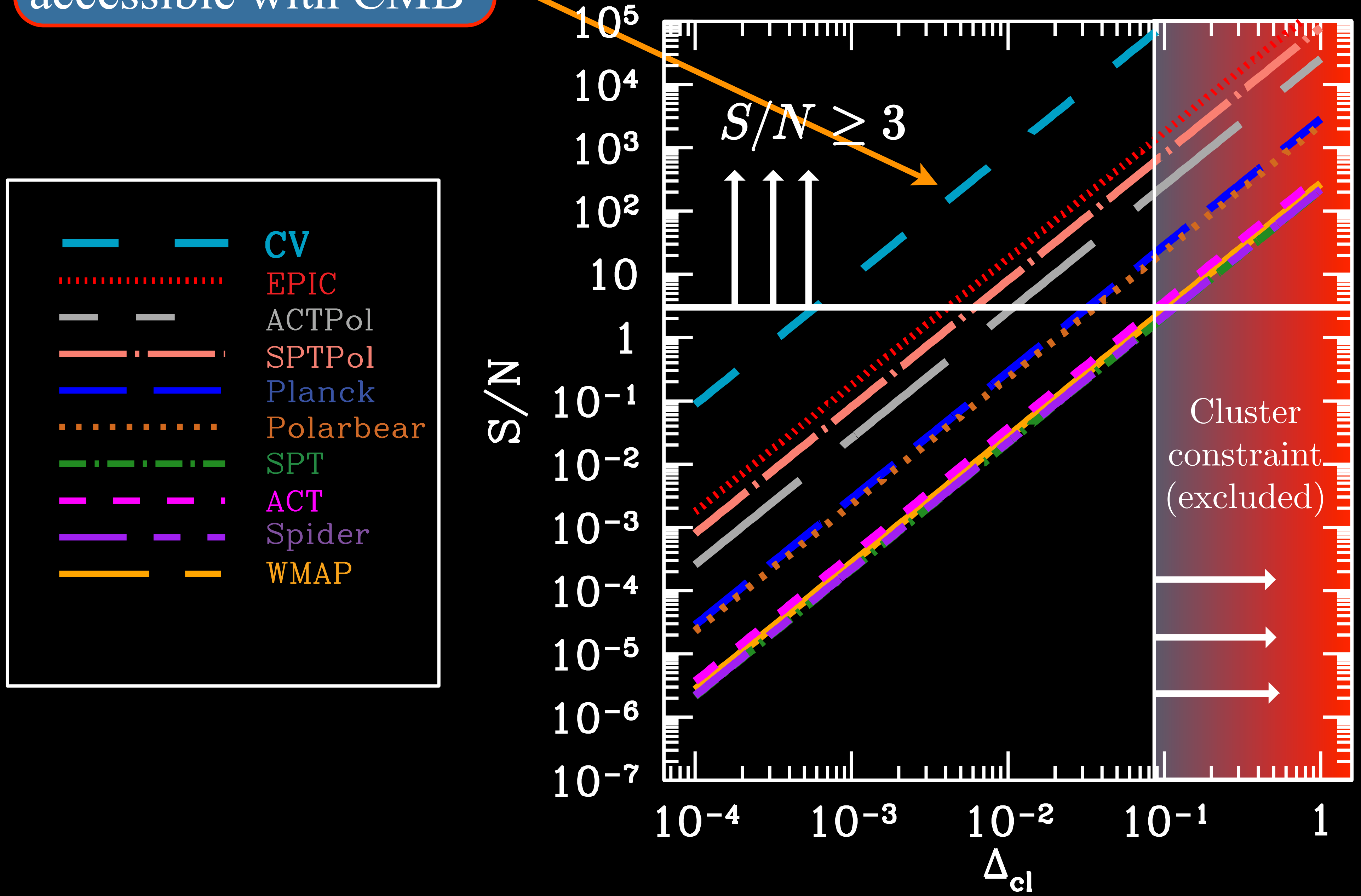


COMPENSATED ISOCURVATURE AND THE CMB: *PROSPECTS*



COMPENSATED ISOCURVATURE AND THE CMB: *PROSPECTS*

Parameter space accessible with CMB



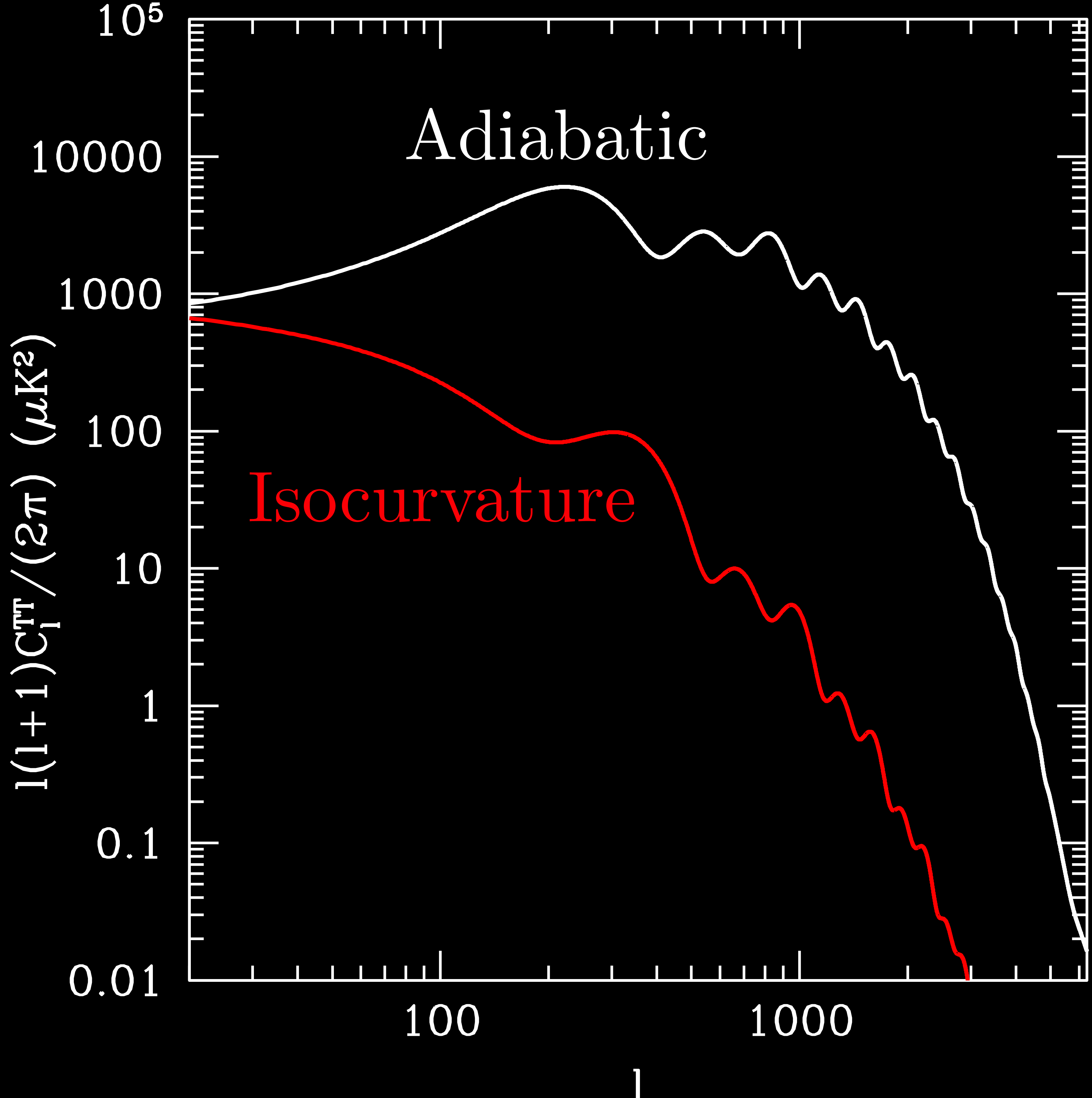
Two orders of magnitude improvement: conservatively

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
- Future work: (use SPT/Planck data)

SACHS WOLFE-EFFECT & POWER SPECTRA

SACHS WOLFE-EFFECT & POWER SPECTRA



CIPS AND GALAXIES (IN REALITY)

WORK IN PROGRESS

- 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

FUTURE WORK: CORRELATED CIPS AND THE CURVATON MODEL

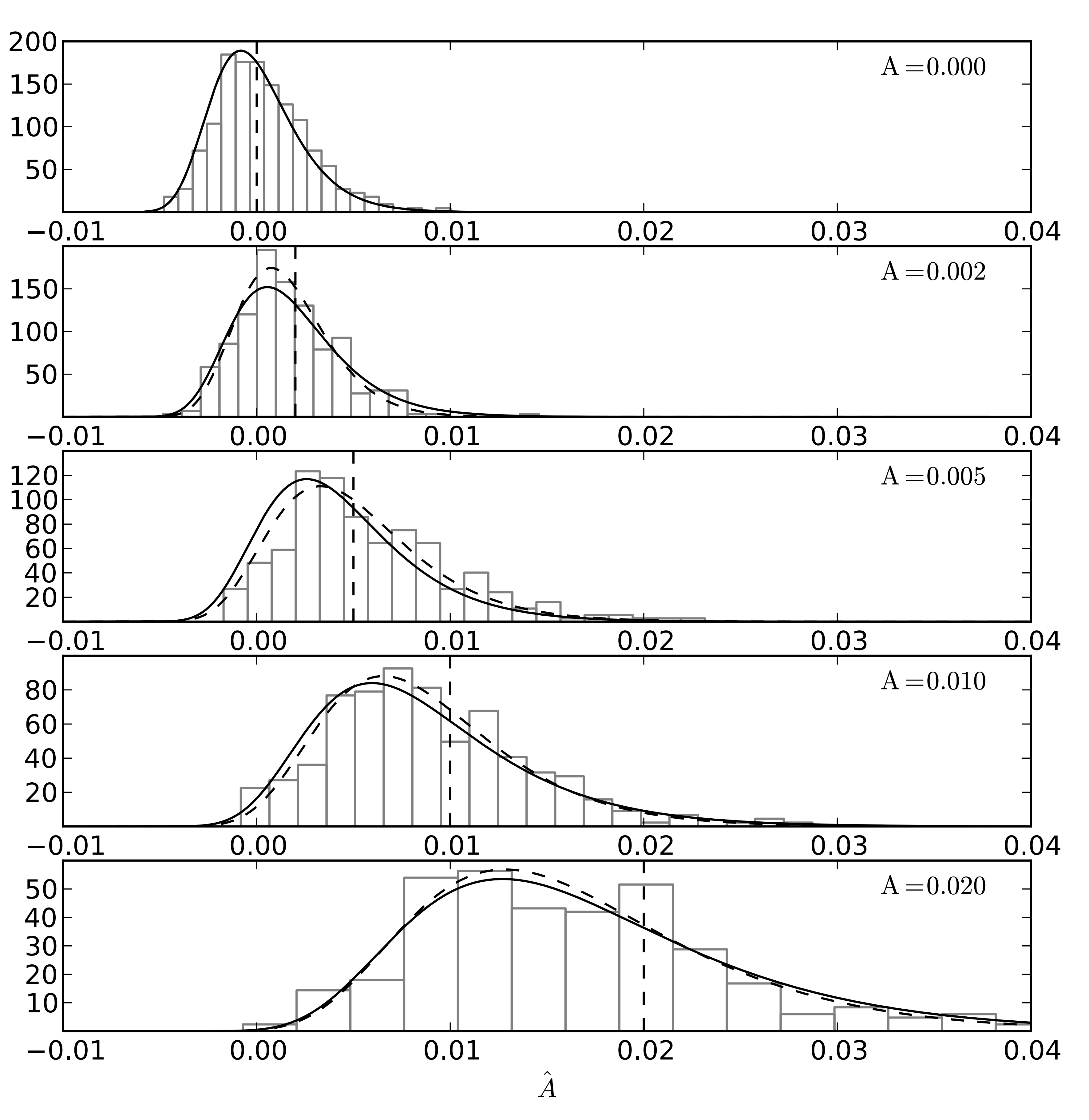
- All perturbations $(\zeta, \ S_{\rm c}, \ S_{\rm b})$ seeded by curvaton
- CIPs are correlated with adiabatic flucts

$$\Delta \propto S_{\rm bc} \simeq 16\zeta$$

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

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

Errors are strongly signal-dependent



ISOCURVATURE AND SACHS-WOLFE EFFECT

- From gravitational redshifting

$$\left(\frac{\Delta T}{T}\right)_{\rm CMB} = \Delta\Phi^{\rm SLS} + \frac{\delta_\gamma^{\rm SLS}}{4}$$

- For adiabatic initial condition

$$\left(\frac{\Delta T}{T}\right)_{\rm CMB} = \frac{\Delta\Phi^{\rm SLS}}{3}$$

- For density isocurvature

$$\left(\frac{\Delta T}{T}\right)_{\rm CMB} = 2\Delta\Phi^{\rm SLS}$$

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

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

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

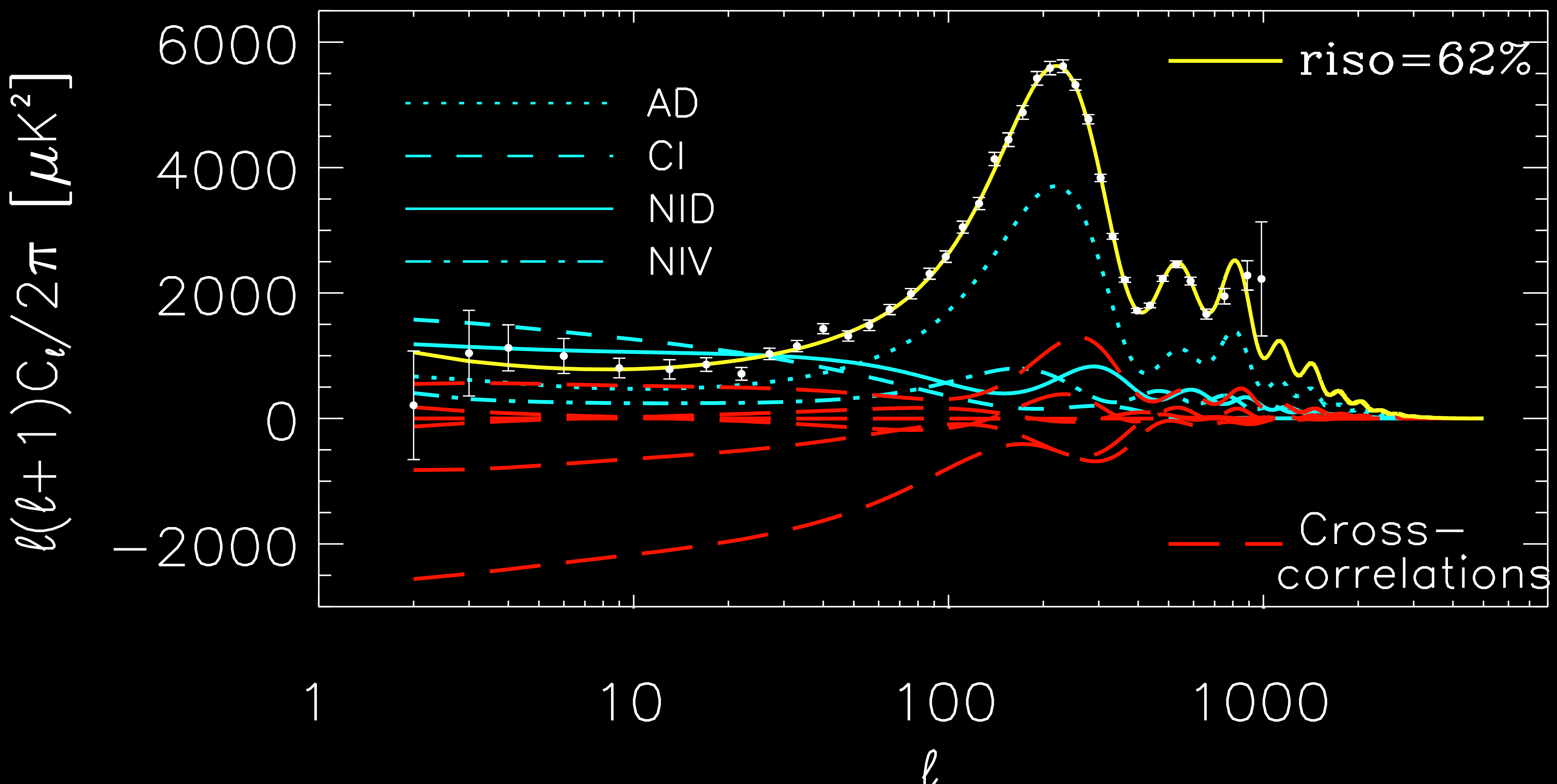
	CI	NID	NIV
r_{iso}	$n_{adi} = n_{iso}$	$n_{adi} = n_{iso}$	$n_{adi} = n_{iso}$
	< 0.13	< 0.08	< 0.14

→

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

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

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

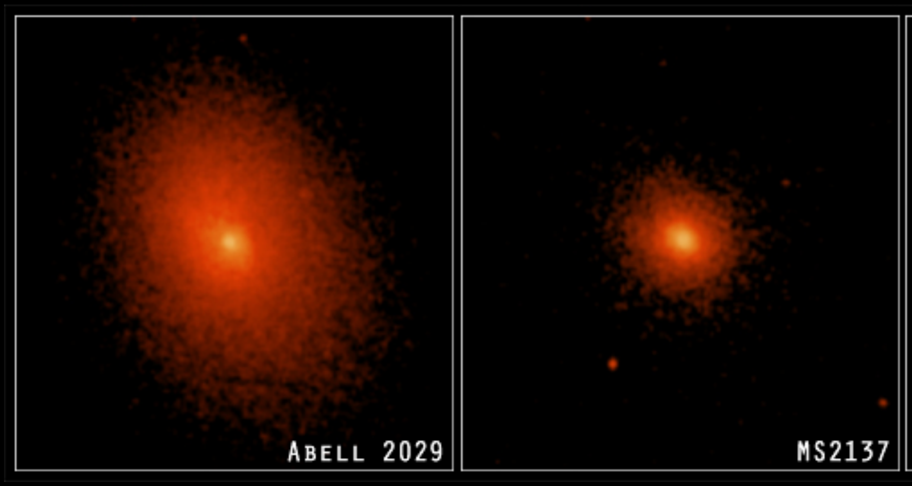


EXISTING CONSTRAINTS TO CIPS- BBN

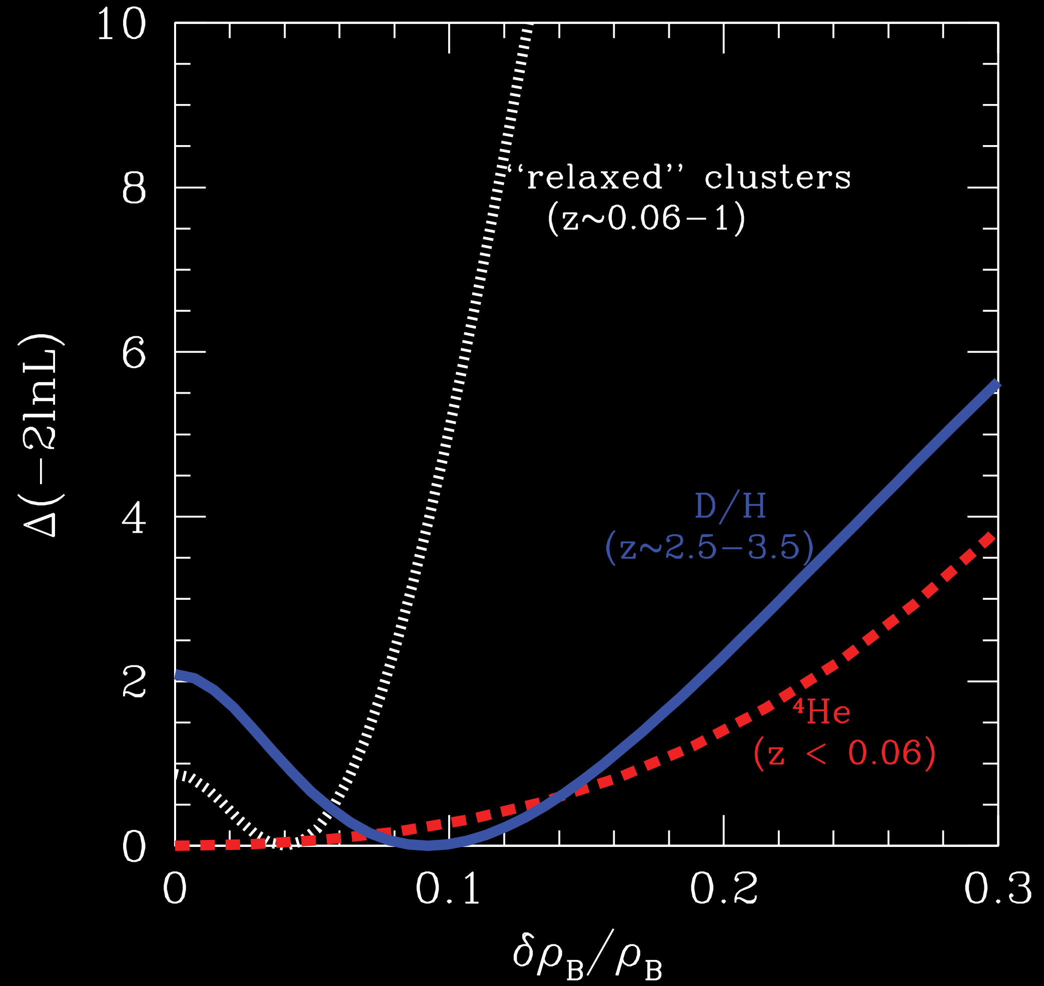
- Primordial abundances of De, ^{3}He, ^{4}He, ^{7}Li : Blue compact galaxies (He) and QSO Absorption systems (De)

- Baryon fraction measurements in galaxy clusters

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



EXISTING CONSTRAINTS TO CIPS- BBN



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?

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!!!

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

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

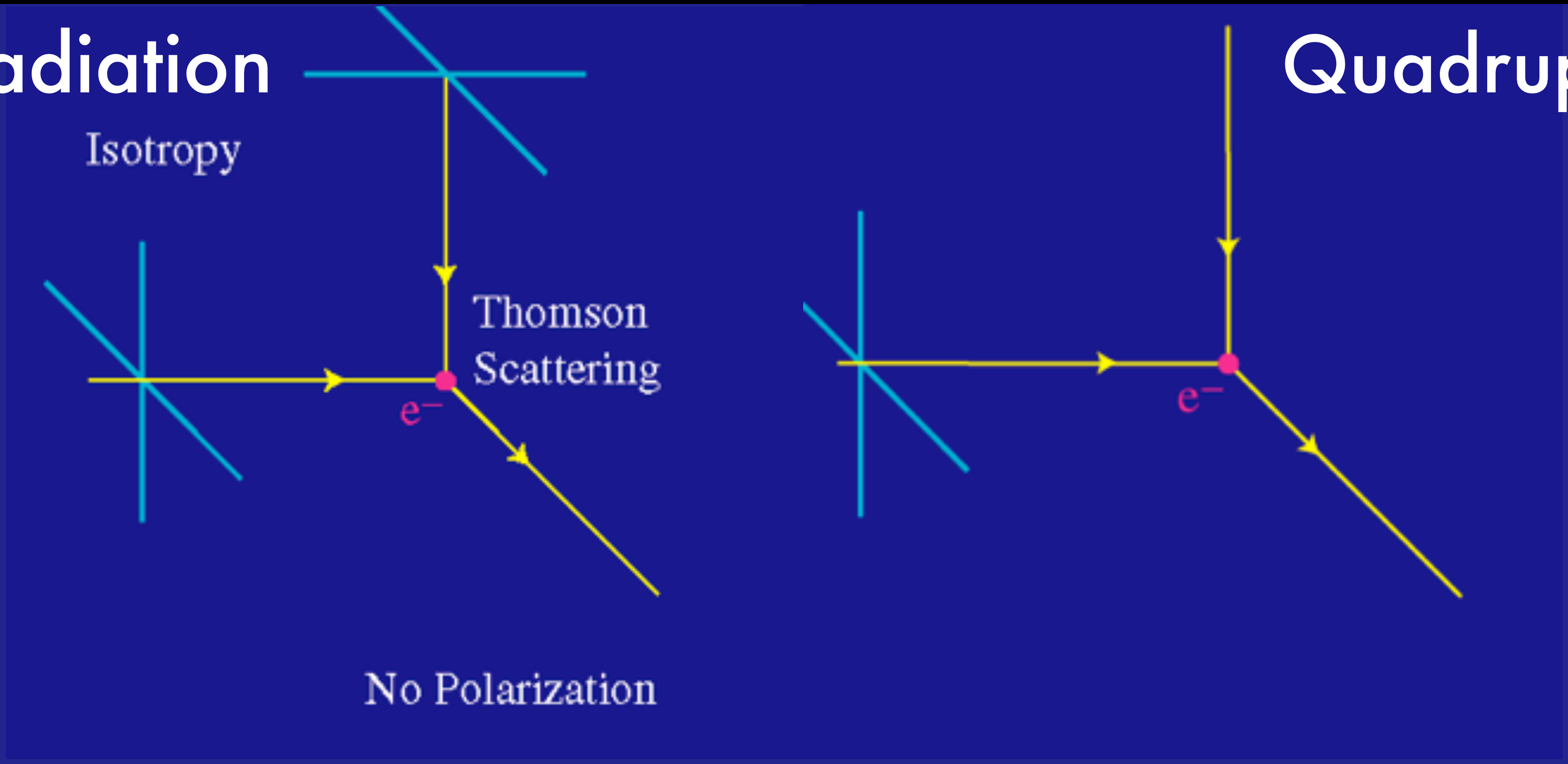
$$Q, U \propto \int n_e(\eta)\left[1 + \Delta\left(\hat{n}\right)\right] T_{2i}\left(\eta, \hat{n}\right) d\eta$$

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

- Efficiency of polarization generation is modulated

Isotropic radiation

Quadrupole moment



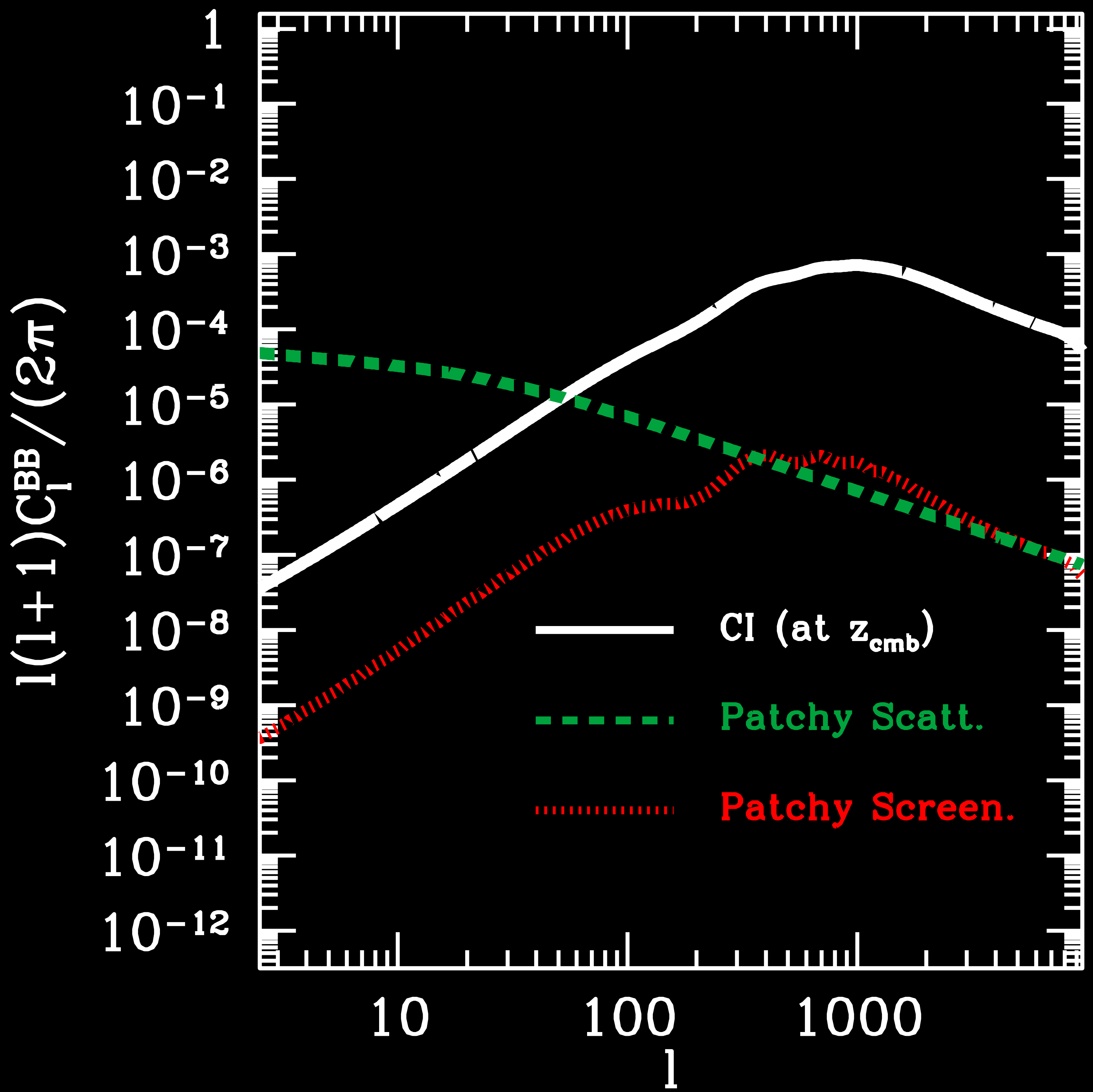
From Wayne Hu's website

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

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

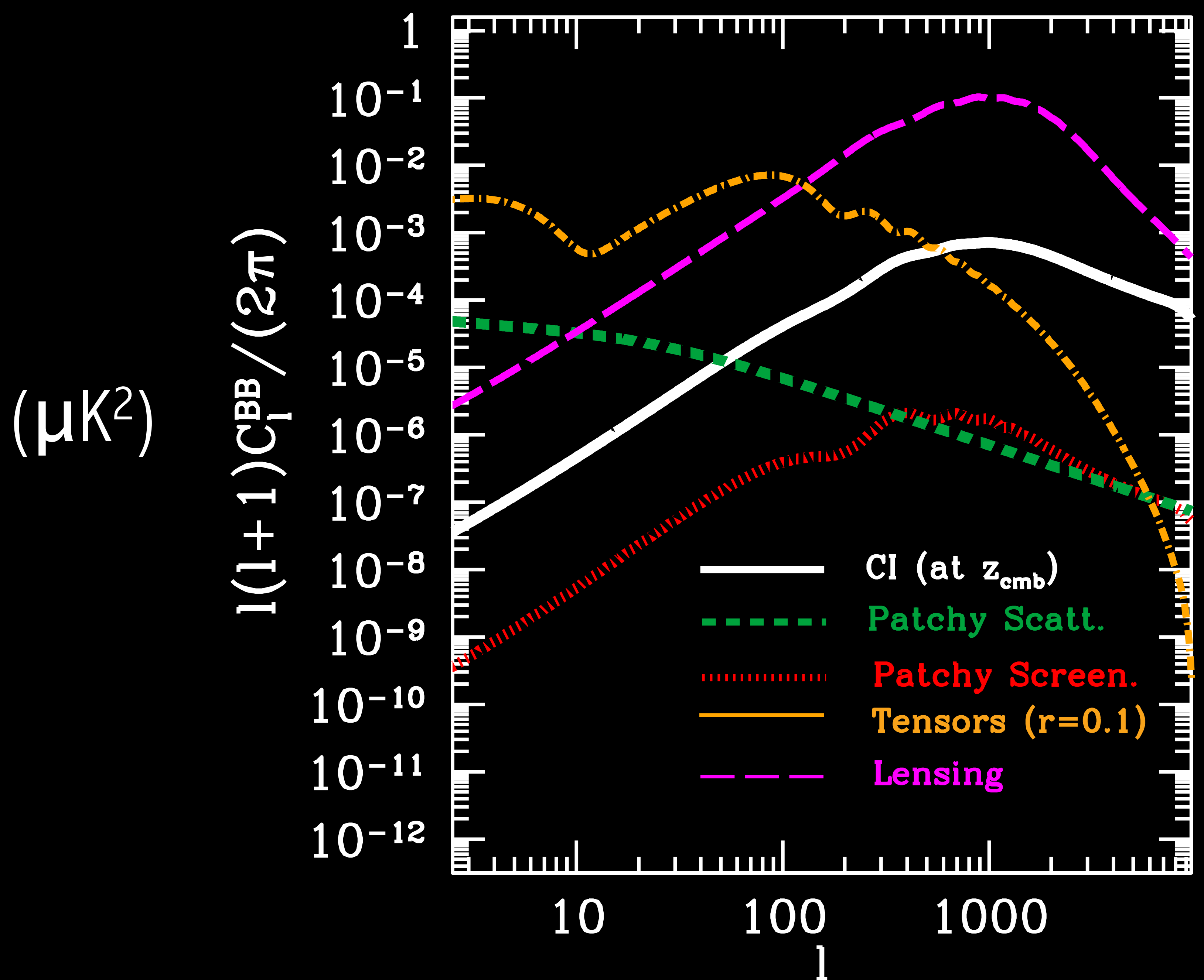
$$Q, U \propto \int n_e(\eta)\left[1 + \Delta\left(\hat{n}\right)\right] T_{2i}\left(\eta, \hat{n}\right) d\eta$$

COMPENSATED ISOCURVATURE AND THE CMB:
RECOMBINATION B-MODES



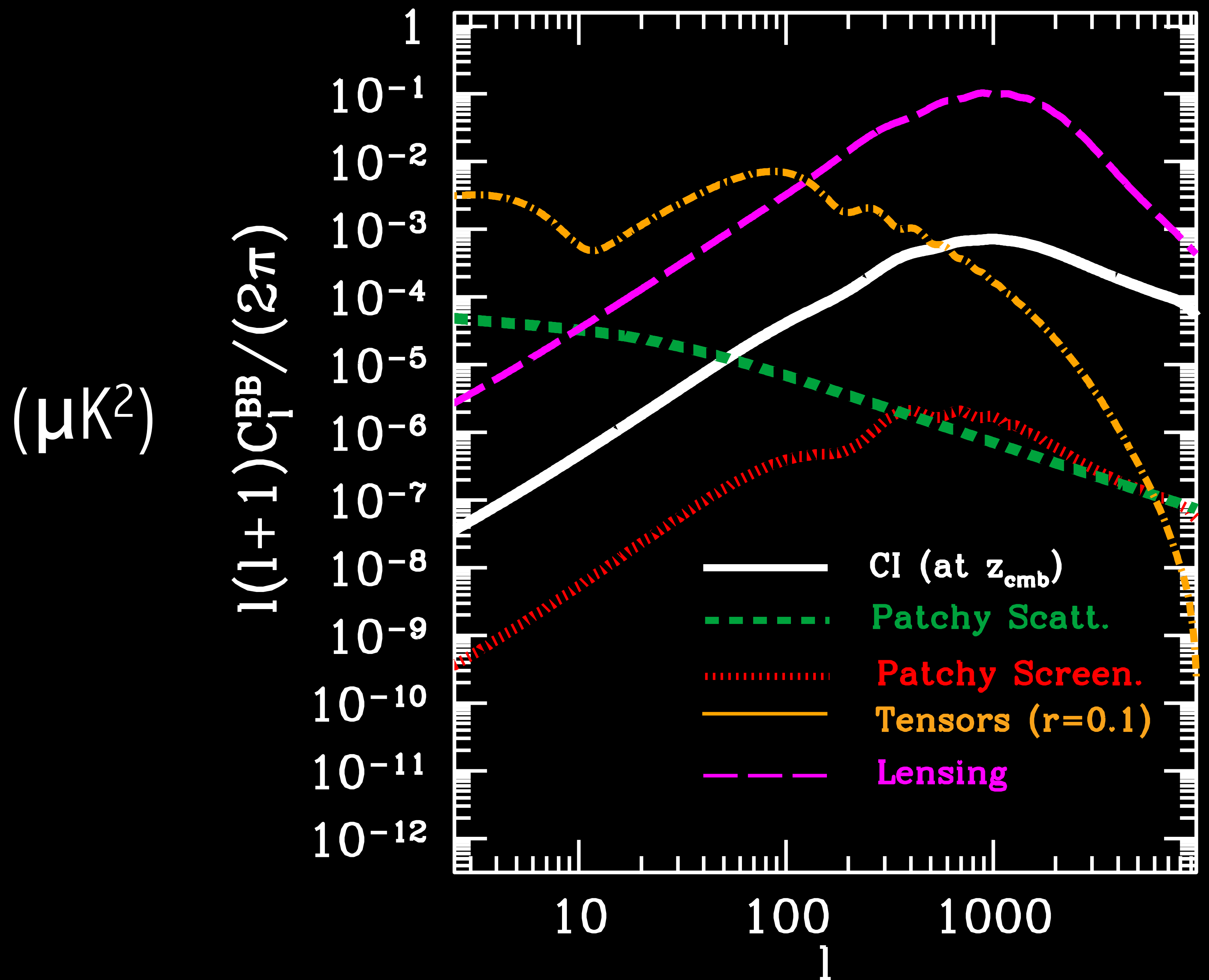
COMPENSATED ISOCURVATURE AND THE CMB: *CIPS VS LENSING*

- ... but at power spectrum level for l>100, all are swamped by lensing!



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!



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