Cosmic initial conditions, dark matter, and the microwave background

Daniel Grin (IAS Princeton)
FermiLab seminar
12/3/2012

Smörgåsbord

A meal of axions, isocurvature fluctuations, non-Gaussian perturbations, and their estimators

Outline

- *Are the CMB fluctuations Gaussian?*

  Improving CMB estimators of local-type non Gaussianity

- *Are the primordial fluctuations adiabatic?*

  Baryon-DM isocurvature fluctuations and the CMB

  Isocurvature and the axiverse

- *Telescope searches for decaying relic axions*

  A new search in galaxy cluster RDCS 1252

Improved CMB estimator for primordial non-Gaussianity

with T. L. Smith and M. Kamionkowski

arXiv: 1211.3417, submitted to Phys. Rev. D

Gaussian fluctuations

- N-point fluctuation PDF is

$$P[\Phi(\hat{x}_1)\ldots\Phi(\hat{x}_N)] \sim e^{-\frac{\overline{\Phi}_i \overline{\overline{M}}_{ij}^{-1} \overline{\Phi}_j}{2}}$$

- All cumulants specified by 2-pt function (via Wick's theorem)

$$\langle\Phi_1\Phi_2\Phi_3\Phi_4\rangle = \langle\Phi_1\Phi_2\rangle\langle\Phi_3\Phi_4\rangle + \langle\Phi_1\Phi_3\rangle\langle\Phi_2\Phi_4\rangle + \langle\Phi_1\Phi_4\rangle\langle\Phi_2\Phi_2\rangle$$

- Massive scalar field has Gaussian wave function: higher order terms (non-Gaussian) probe interactions

Local-type non-Gaussianity

- Local model $$\Phi(\vec{x}) = \phi(\vec{x}) + f_{\rm NL}\left\{\phi^2(\vec{x}) - \langle\phi(\vec{x})\rangle^2\right\}$$

$$\frac{\Delta\Phi}{\Phi} \sim f_{\rm NL}\phi \sim 10^{-3}\left(\frac{f_{\rm NL}}{100}\right)$$ **Small parameter**

- Claimed WMAP detection (Yadav et al.) $f_{\rm NL} = 87 \pm 60$

vs $-4 \lesssim f_{\rm NL} \lesssim 80$ Smith et al. 2009

- Planck Sensitivity $f_{\rm NL} \gtrsim \mathcal{O}(10)$

Bispectrum

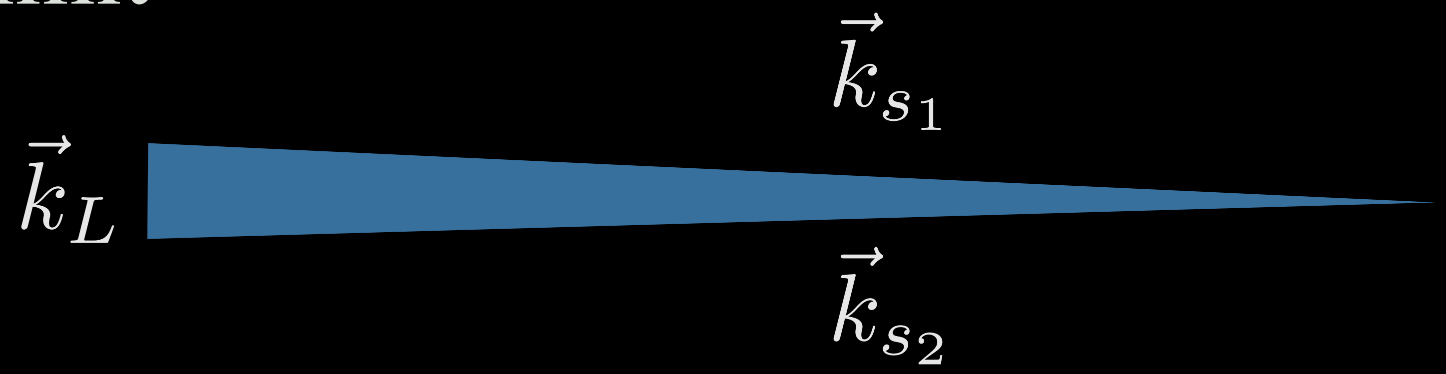
- Odd cumulants

$$\left\langle \Phi_{\vec{k}_1} \Phi_{\vec{k}_2} \Phi_{\vec{k}_3} \right\rangle = \delta^3(\vec{k}_1 + \vec{k}_2 + \vec{k}_3) B_{k_1 k_2 k_3}$$

- Mode correlations

$$\left\langle \Phi_{\vec{k}_{s_1}} \Phi_{\vec{k}_{s_2}} \right\rangle \propto \Phi_{\vec{k}_L}$$

- Squeezed limit



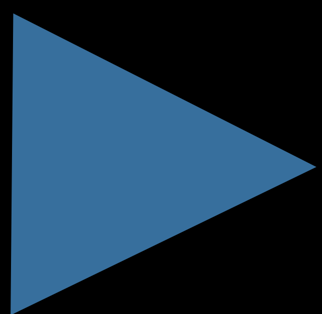
Bispectrum estimator

$$\hat{f}_{\rm NL} = \sigma_0^2 \sum_{\vec{l}_1+\vec{l}_2+\vec{l}_3=0} \frac{a_{\vec{l}_1} a_{\vec{l}_2} a_{\vec{l}_3} B_{l_1 l_2 l_3}}{6\Omega^2 C_{l_1} C_{l_2} C_{l_3}}$$

Non-gaussianity and fundamental physics

- Other shapes probe novel inflationary models

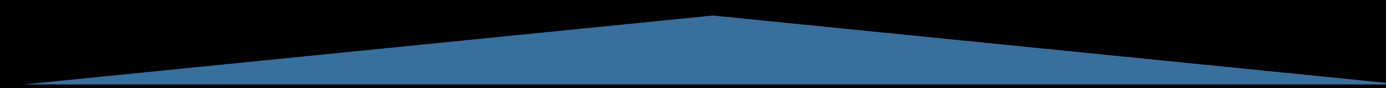
Equilateral



$$f_{\rm NL}^{\rm equil} \propto \frac{1}{c_\phi^2}$$

Non-canonical kinetic terms for inflaton

Folded

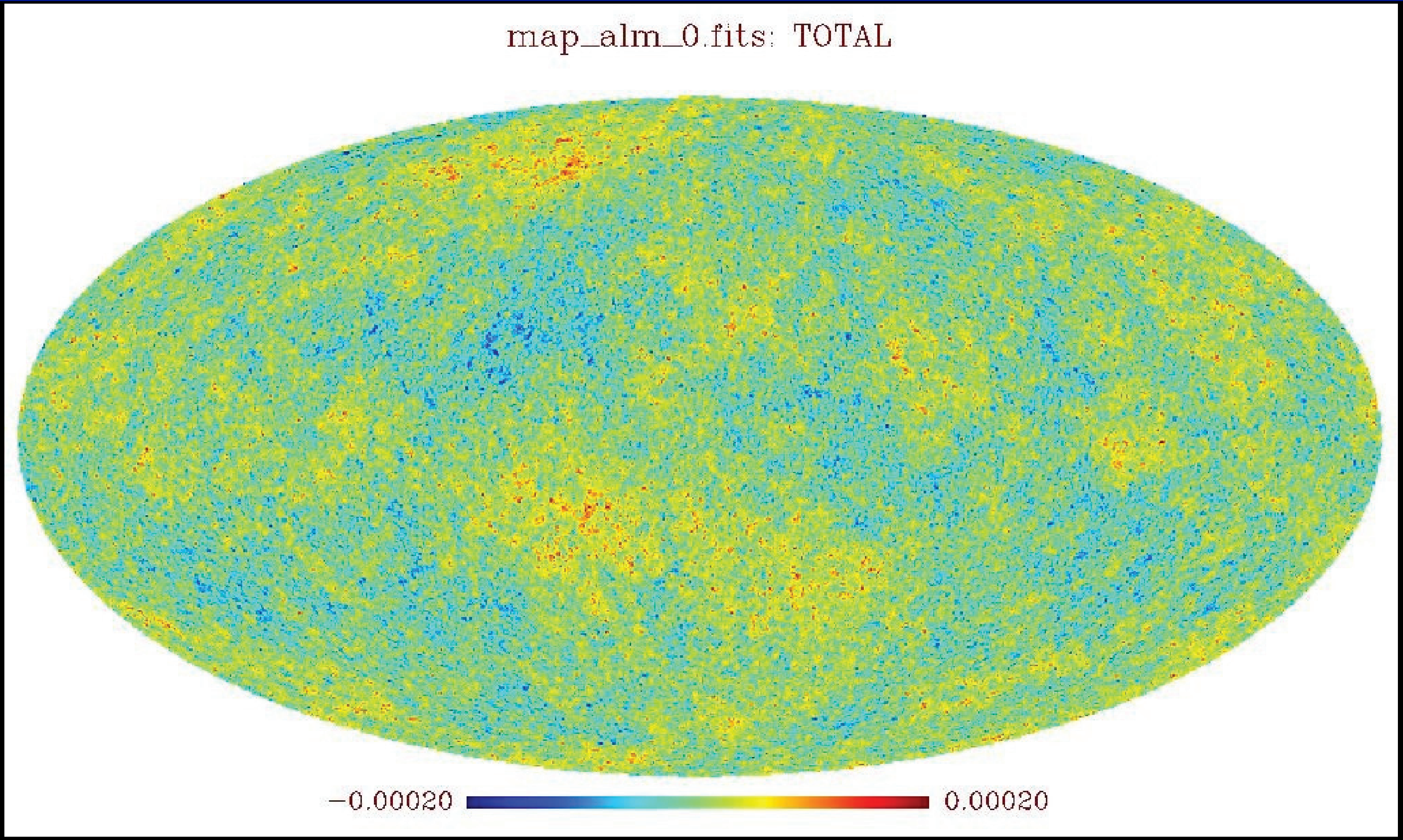


Non Bunch-Davies vacuum

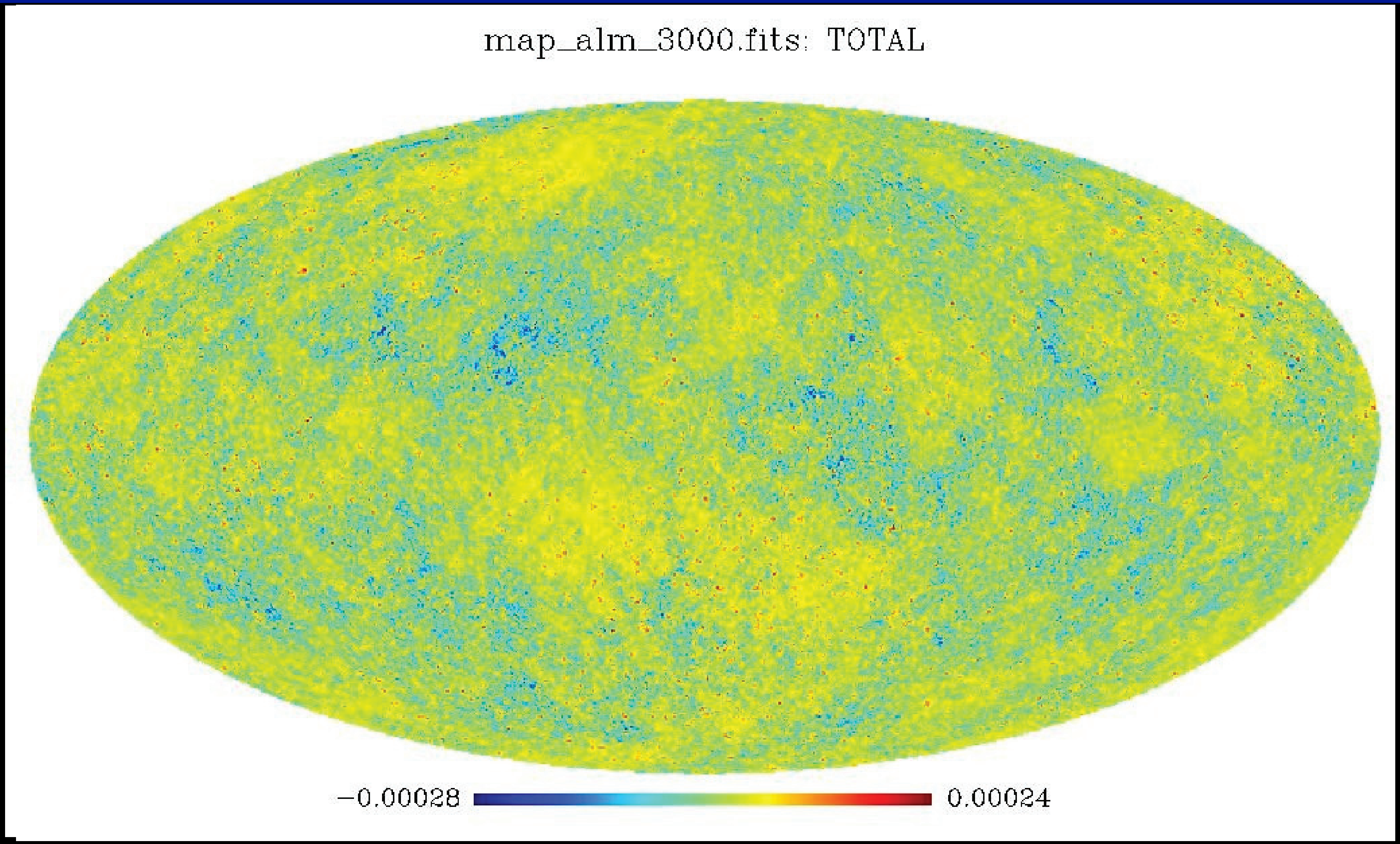
- Curvaton model predicts local-type non-Gaussianity
- Large local non-Gaussianity falsifies single-field inflationary models

$$f_{\rm NL}^{\rm local} = \frac{1 - n_s}{4}$$

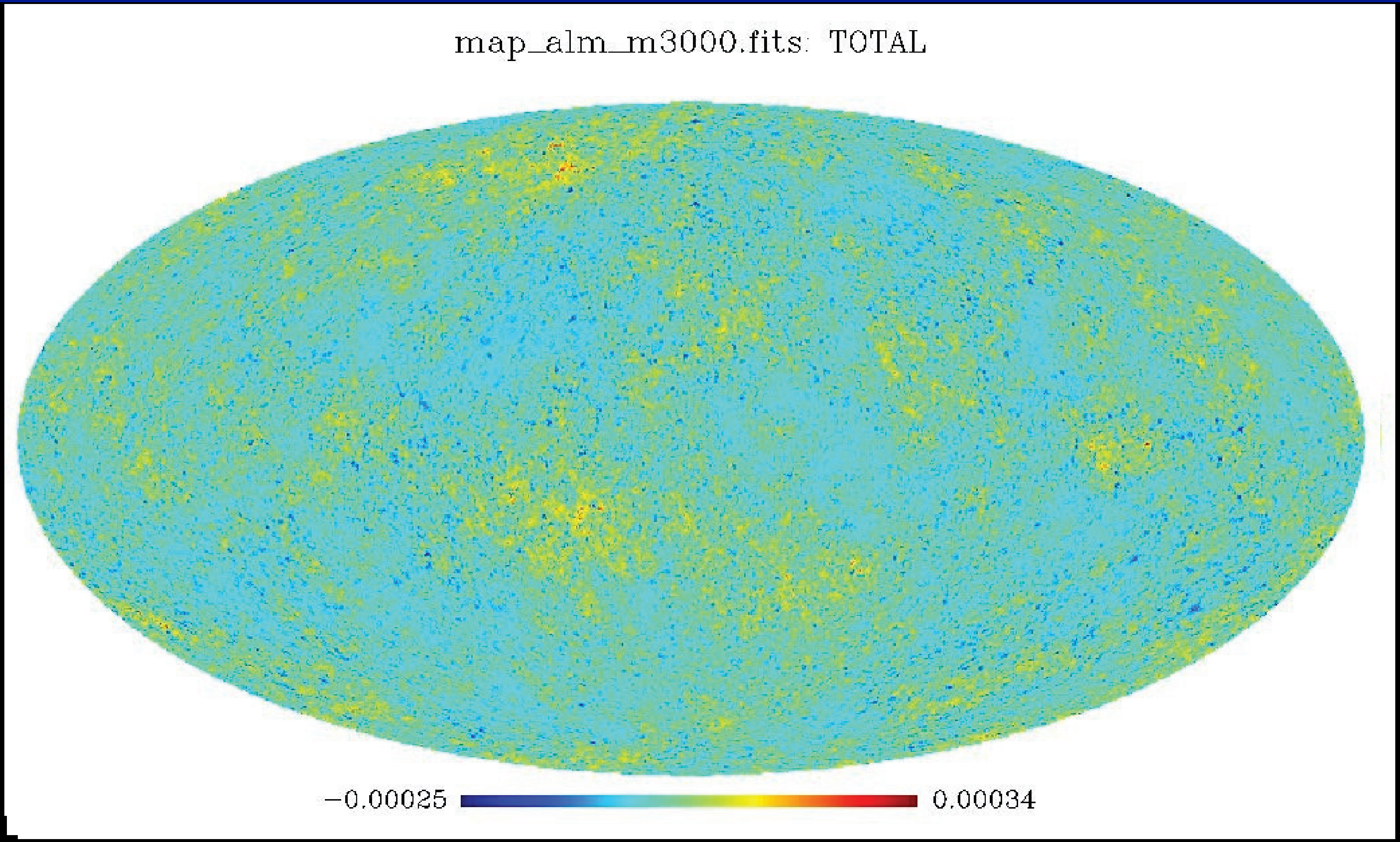
Visualizing non-Gaussianity



Visualizing non-Gaussianity



Visualizing non-Gaussianity



f_{NL}-dependent variance of NHMV

- Expand estimator in powers of f_{NL}

$$\hat{f}_{\rm NL} \propto \sum_{\vec{l}_1+\vec{l}_2+\vec{l}_3=0} \frac{B_{l_1 l_2 l_3} a_{l_1} a_{l_2} a_{l_3}}{C_{l_1} C_{l_2} C_{l_3}}$$

$$\sim \quad \mathcal{B}_0 \quad + f_{\rm NL} \sum_{\vec{l}_1+\vec{l}_2+\vec{l}_3=0, l_a+l_b=-l_1} \frac{B_{l_1 l_2 l_3} a^{\rm G}_{l_a} a^{\rm G}_{l_b} a^{\rm G}_{l_2} a^{\rm G}_{l_3}}{C_{l_1} C_{l_2} C_{l_3}}$$

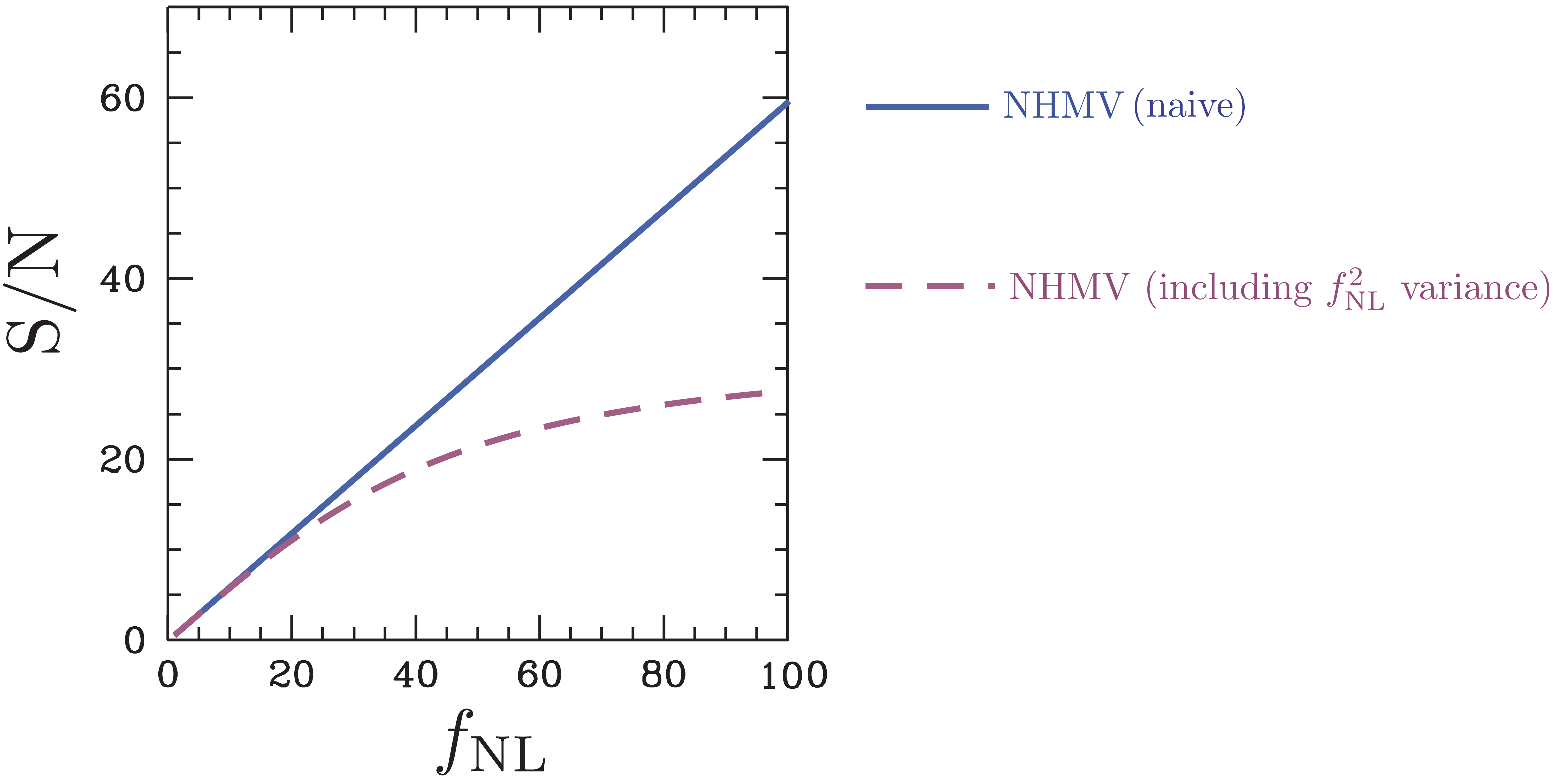
f_{NL}-dependent variance of NHMV

- Naively expect

$$\left\langle \left(\hat{f}_{\rm NL} - f_{\rm NL} \right)^2 \right\rangle = \sigma_0^2 \left\{ 1 + f_{\rm NL}^2 \frac{k^3 P_k}{2\pi^2} \right\}$$

Fractional correction of order 10^{-5} if f_{NL}~100!

f_{NL}-dependent variance of NHMV



What's going on? *Toy model*

- Let a_i be a Gaussian random variable with

$$\langle a_i \rangle = 0$$
$$\langle a_i a_j \rangle = \sigma^2 \delta_{ij}$$

- Choose an estimator

$$\hat{\sigma}^2 \equiv \frac{\sum_{ij} a_i a_j}{N}$$

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Sum over all pairs is unconventional

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Sum over all pairs is unconventional

- Audience exercise: Proof: there exist stupid estimators!

$$\langle S/N \rangle \equiv \frac{\sigma^2}{\sqrt{\left\langle \left(\hat{\sigma}^2 - \sigma^2\right)^2 \right\rangle}} = 1/\sqrt{2}$$

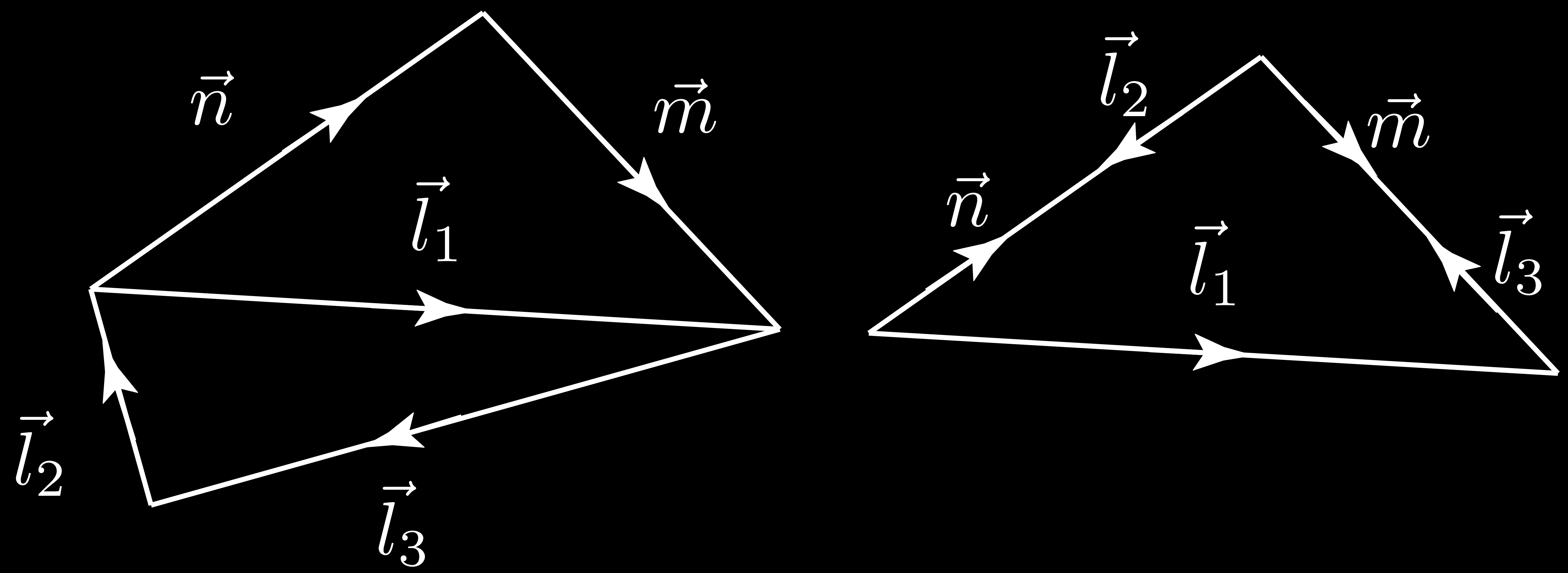
What's going on? *Local model*

- Schematically

$$\mathcal{B}_1 = \sum_{ij} W(i) A_i A_j$$

$$i = \left\{\vec{l}_1, \vec{l}_2, \vec{l}_3\right\} \;\; j = \left\{\vec{l}_1, \vec{m}, \vec{n}\right\}$$

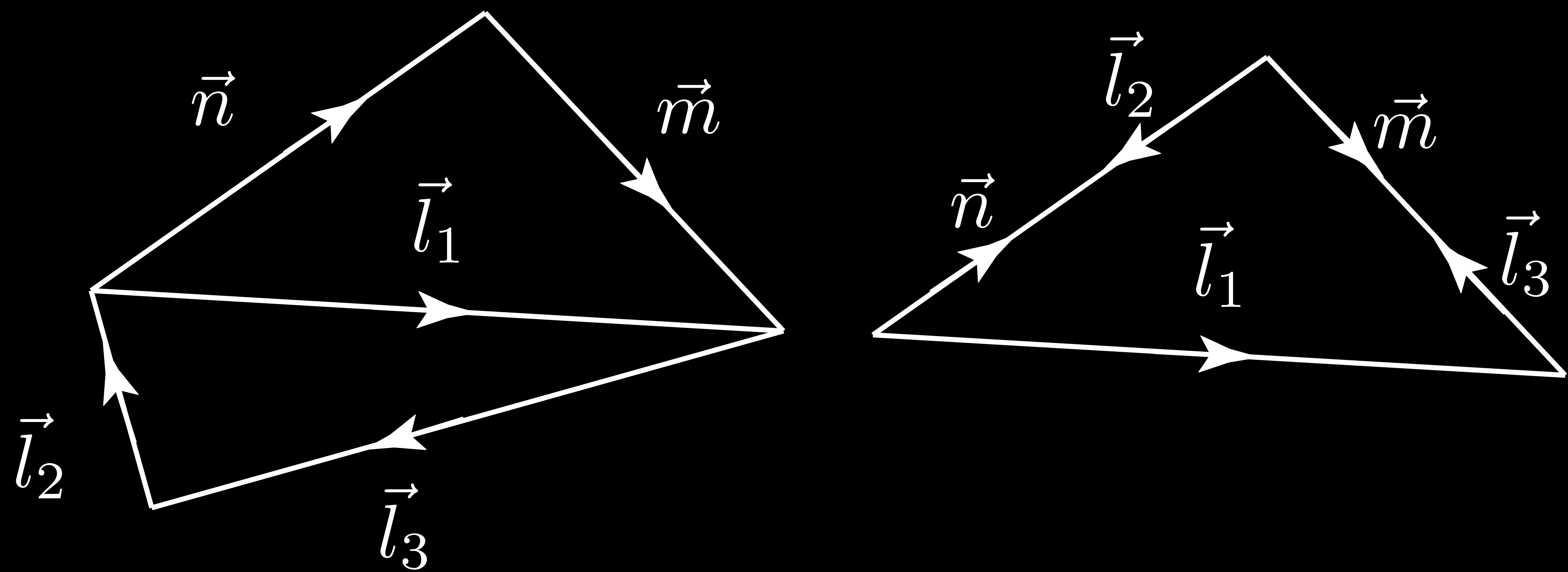
What's going on? *Local model*



$$\langle \mathcal{B}_1 \rangle = \sum_i W(i) \langle A_i^2 \rangle$$

schematically $\langle \Delta \mathcal{B}_1^2 \rangle = \sum_{ij} W(i) W(j) A_i^2 A_j^2$

What's going on? *Local model*



$$\langle \mathcal{B}_1 \rangle = \sum_i W(i) \langle A_i^2 \rangle$$ $l_{\max}^4$ terms!

schematically $\langle \Delta \mathcal{B}_1^2 \rangle = \sum_{ij} W(i) W(j) A_i^2 A_j^2$ $l_{\max}^6$ terms

What's going on? *Local model*

$$\langle \Delta \mathcal{B}_1^2 \rangle \propto \ln^{-2}(l_{\max})$$

$$\langle \mathcal{B}_1 \rangle = \sum_i W(i) \langle A_i^2 \rangle$$ $l_{\max}^4$ terms!

schematically $\langle \Delta \mathcal{B}_1^2 \rangle = \sum_{ij} W(i) W(j) A_i^2 A_j^2$ $l_{\max}^6$ terms

Realization-normalized estimator (RNE)

- Term with excess variance

$$\mathcal{B}_1 = \sigma_0^2 \sum_{\vec{l}_1+\vec{l}_2+\vec{l}_3=0} \frac{B_{l_1 l_2 l_3} a^{\rm NG}_{\vec{l}_1} a^{\rm G}_{\vec{l}_2} a^{\rm G}_{\vec{l}_3}}{2\Omega^2 C_{l_1} C_{l_2} C_{l_3}}$$

- Seek MV estimator of non-linear multipole
- `Divide out' extra stochasticity (Creminelli et al. 2006)

Realization-normalized estimator (RNE)

* Term with excess variance

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Realization-normalized estimator (RNE)

- Term with excess variance

$$\hat{\mathcal{B}}_1 = \sigma_0^2 \sum_{\vec{l}_1+\vec{l}_2+\vec{l}_3=0,\vec{l}_a+\vec{l}_b+\vec{l}_1=0} \frac{B_{l_1 l_2 l_3} B_{l_a l_b l_1} a_{\vec{l}_a} a_{\vec{l}_b} a_{\vec{l}_2} a_{\vec{l}_3}}{12\Omega^2 C_{l_1} C_{l_2} C_{l_3} C_{l_a} C_{l_b}}$$

- Seek MV estimator of non-linear multipole
- `Divide out' extra stochasticity (Creminelli et al. 2006)

Realization-normalized estimator (RNE)

$$\hat{f}_{\rm NL}^{\rm renorm} = \frac{\hat{f}_{\rm NL}}{\hat{\mathcal{B}}_1} \quad \left\langle \hat{f}_{\rm NL}^{\rm renorm} \right\rangle = f_{\rm NL}$$

$$\left\langle \left(\hat{f}_{\rm NL}^{\rm renorm} - f_{\rm NL} \right)^2 \right\rangle = \sigma_0^2$$

if $a_{lm} \simeq -\frac{\Phi_{lm}}{3}$

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Excess variance is removed in the Sachs-Wolfe limit!

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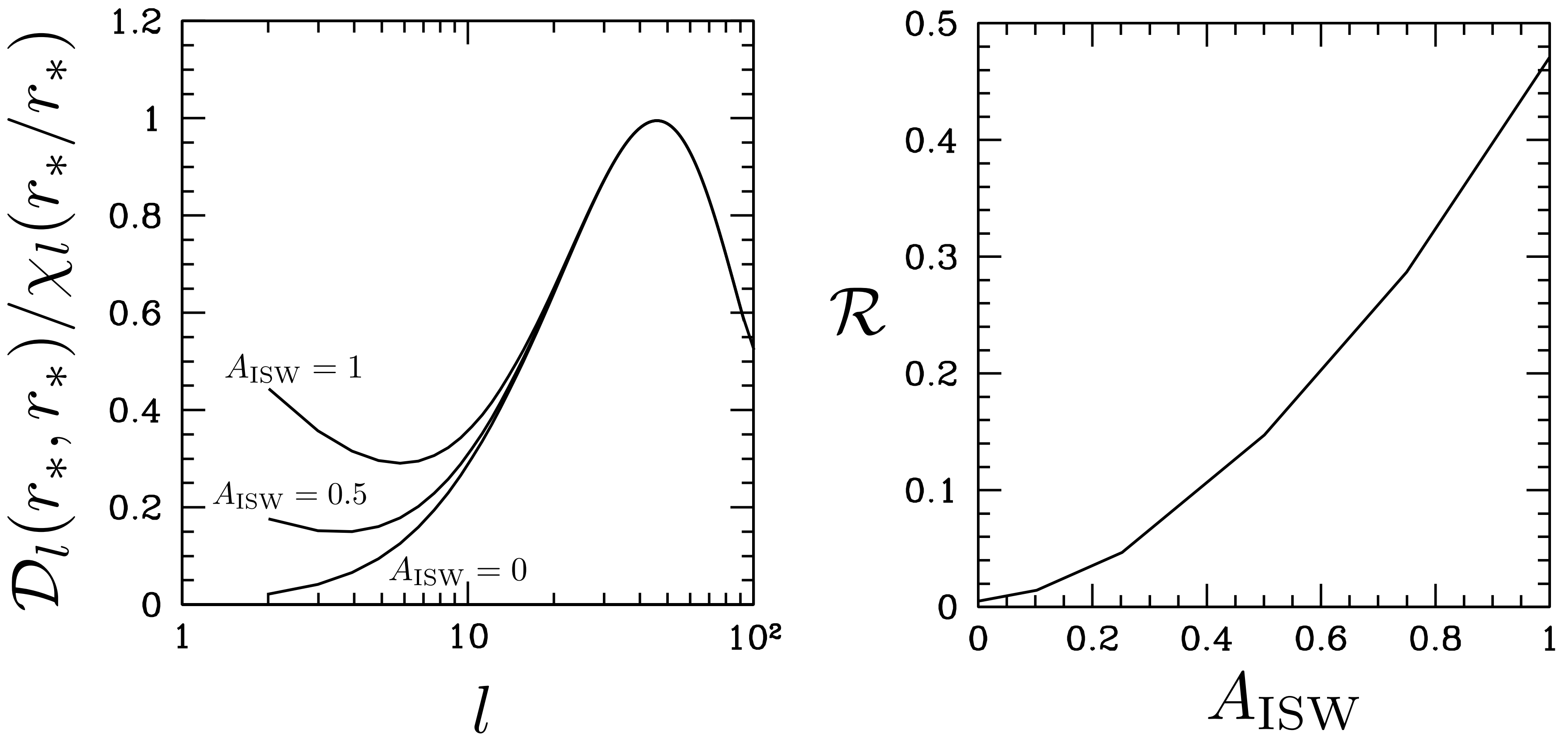
Goal:
How well does the RNE do for a realistic transfer function?

$l_{\rm max}^6$ computation steps **!**

RNE performance with a real transfer function



$$\langle \phi_{lm}(r)\, \phi_{l'm'}(r') \rangle = \delta_{ll'}\delta_{mm'}\chi_l(r,r')$$

$$D_l(r,r') = \chi_l(r,r') - \hat{\chi}_l(r,r')$$

Success is determined by fidelity of primordial potential reconstruction!

Integrated Sachs-Wolfe (ISW) effect

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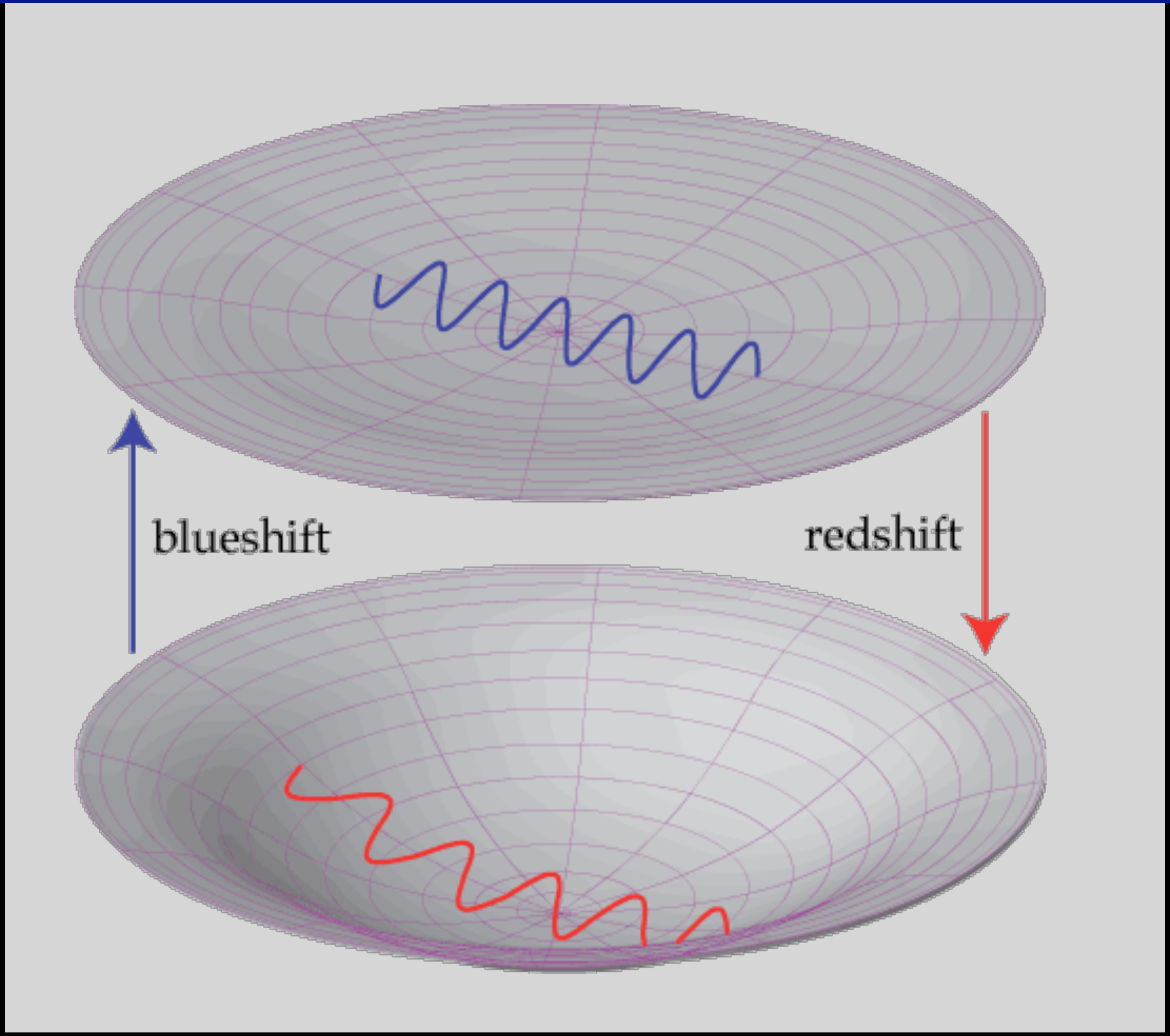
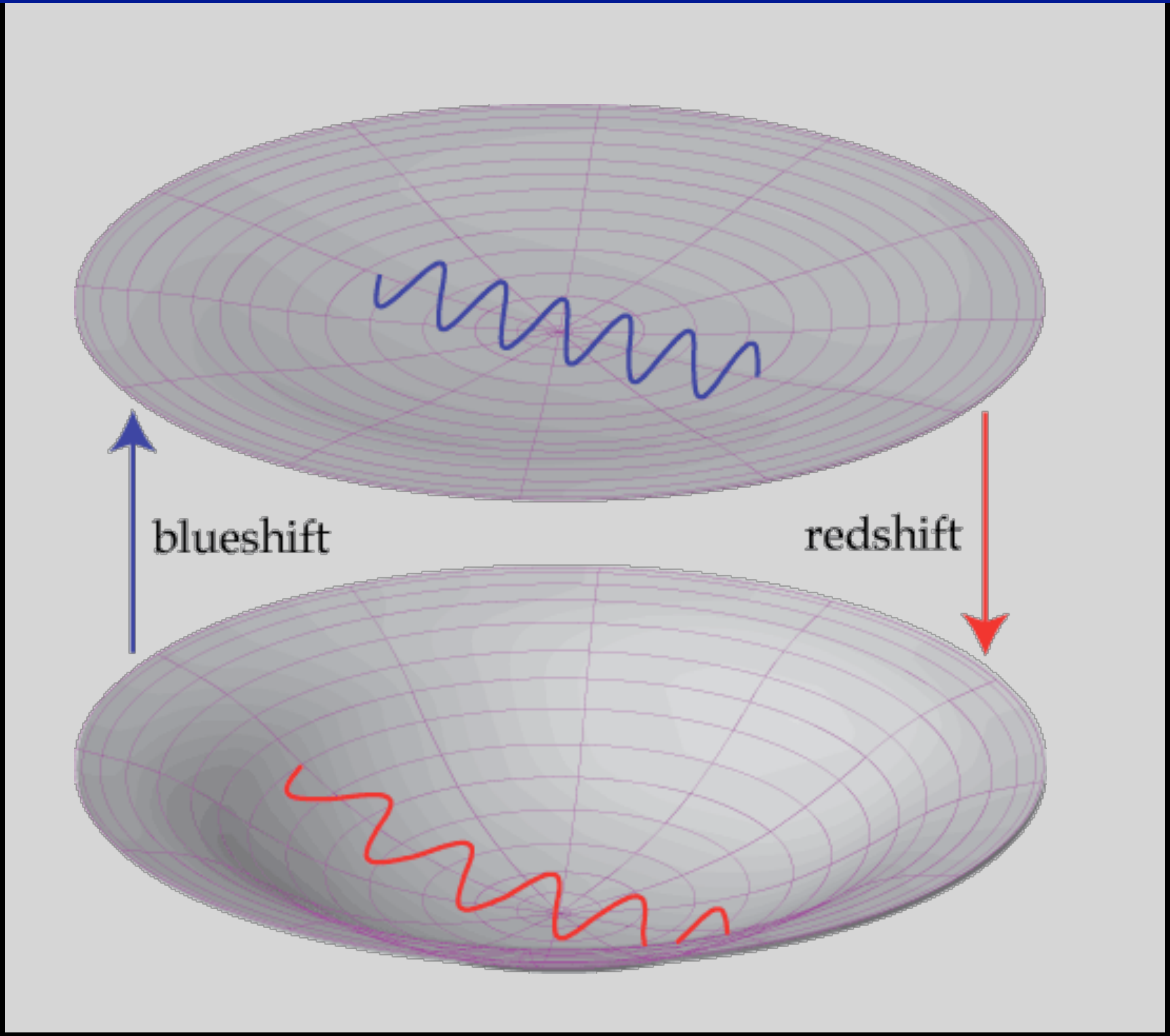
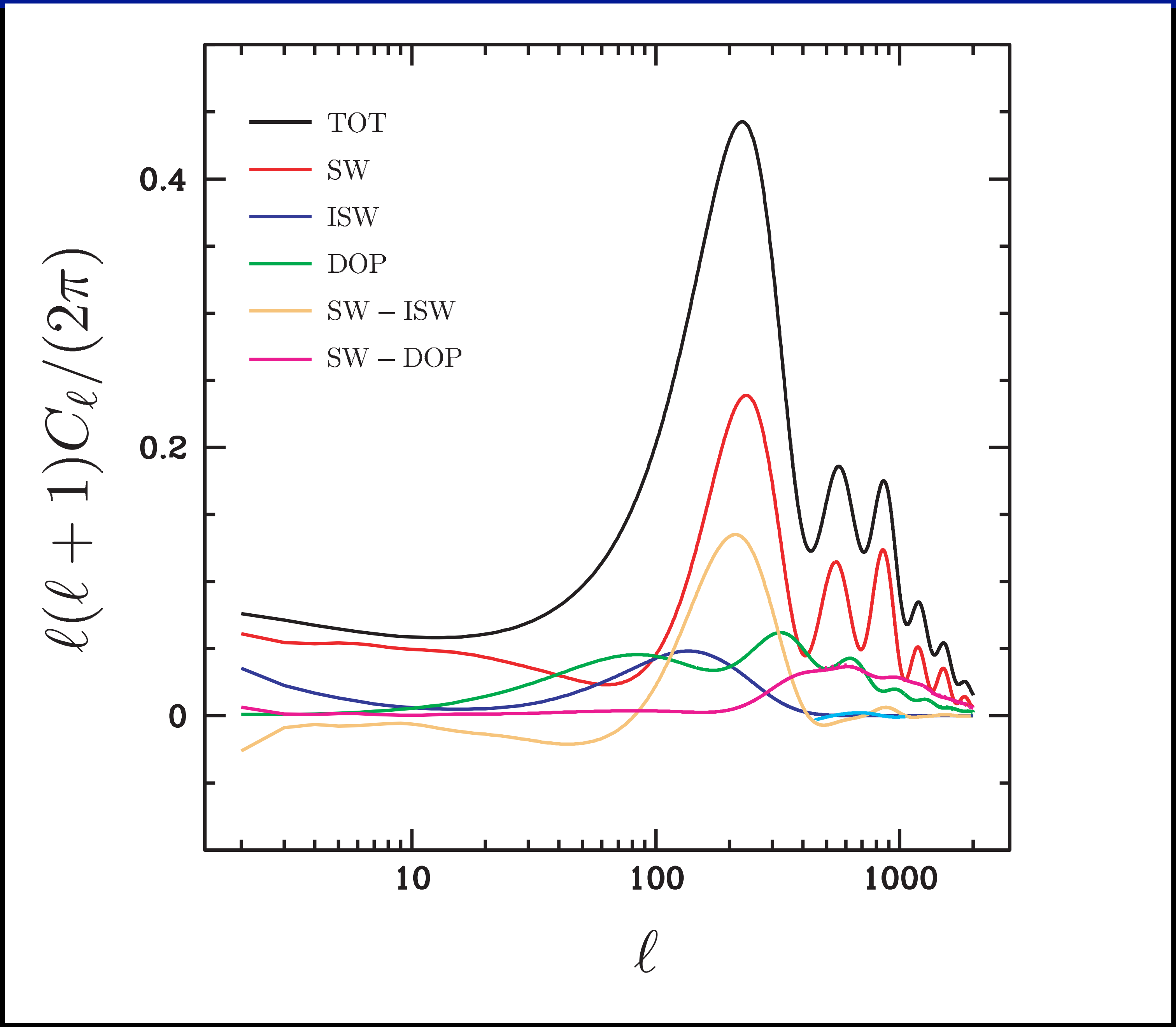


Integrated Sachs-Wolfe (ISW) effect



$$\left.\frac{\delta T(\hat{n})}{T}\right|_{\rm ISW} = 2\int d\eta \dot{\Phi}\left[\eta, \hat{n}(\eta_0 - \eta)\right]$$

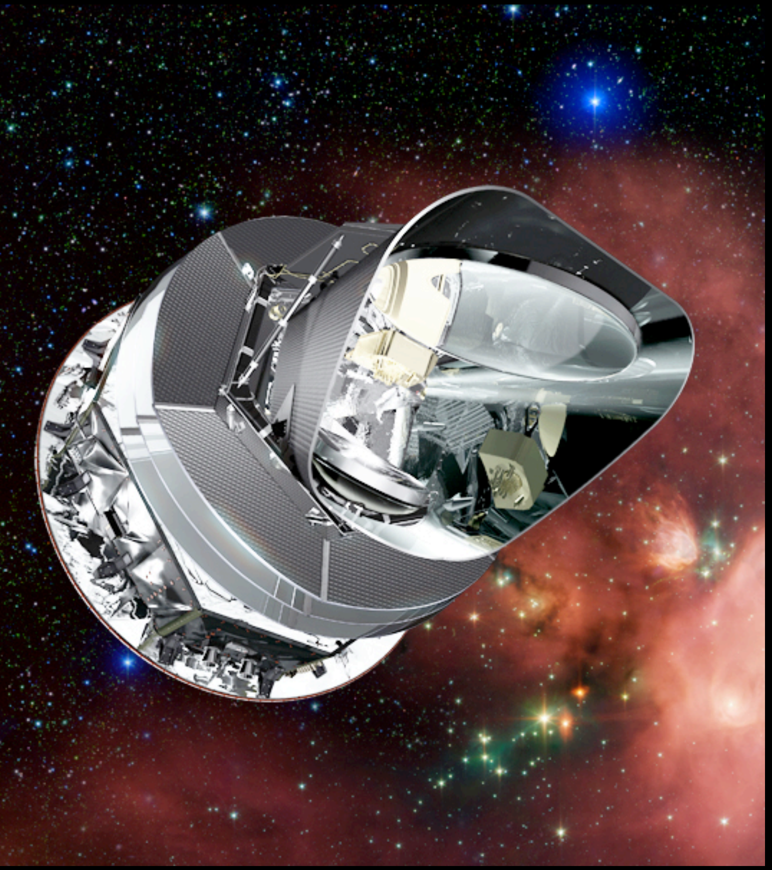
Integrated Sachs-Wolfe (ISW) effect



$$\left.\frac{\delta T(\hat{n})}{T}\right|_{\rm ISW} = 2\int d\eta\dot{\Phi}\left[\eta, \hat{n}(\eta_0-\eta)\right]$$

Integrated Sachs-Wolfe (ISW) effect

$$\left.\frac{\delta T(\hat{n})}{T}\right|_{\rm SW} = -\frac{\Phi}{3}$$



z~1

z~1100

$$\left.\frac{\delta T(\hat{n})}{T}\right|_{\rm ISW} = 2\int d\eta \dot{\Phi}\left[\eta, \hat{n}(\eta_0 - \eta)\right]$$

Integrated Sachs-Wolfe (ISW) effect

$$\mathcal{C} \equiv \frac{\left\langle \hat{a}_{\vec{l}}^{\mathrm{NG}} a_{\vec{l}}^{\mathrm{NG}} \right\rangle}{\sqrt{\left\langle a_{\vec{l}}^{\mathrm{NG}} a_{\vec{l}}^{\mathrm{NG}} \right\rangle} \sqrt{\left\langle \hat{a}_{\vec{l}}^{\mathrm{NG}} \hat{a}_{\vec{l}}^{\mathrm{NG}} \right\rangle}} \neq 1$$

Cleaned maps

- Clean map with a foreground tracer using theoretical tracer-ISW correlation

$$a_{lm}^{c} = a_{lm} - \frac{\langle a_{lm}^{\rm ISW} t_{lm}^{*} \rangle}{\langle t_{lm} t_{lm}^{*} \rangle} t_{lm}$$

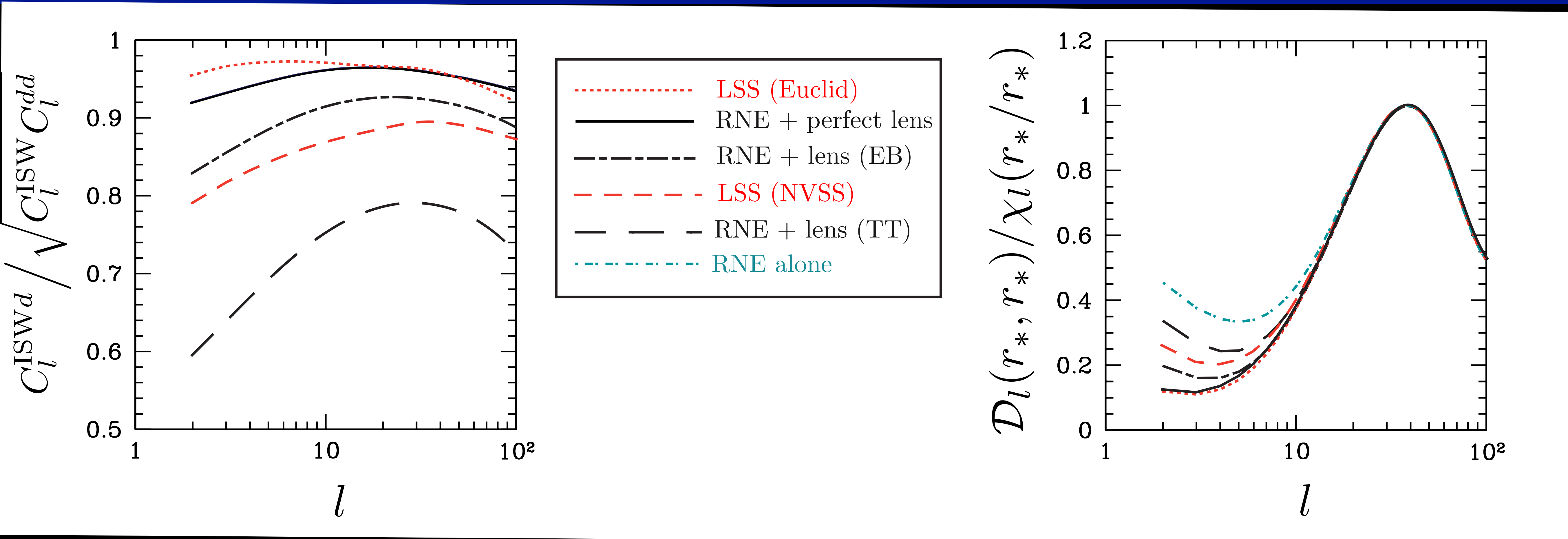
Cleaned maps

- Clean map with a foreground tracer using theoretical tracer-ISW correlation

$$a^c_{lm} = a_{lm} - \frac{\langle a^{\rm ISW}_{lm} t^*_{lm} \rangle}{\langle t_{lm} t^*_{lm} \rangle} t_{lm}$$

- Tracers of structure at z~1
  - High-z galaxy survey
  - CMB weak lensing

Cleaned maps



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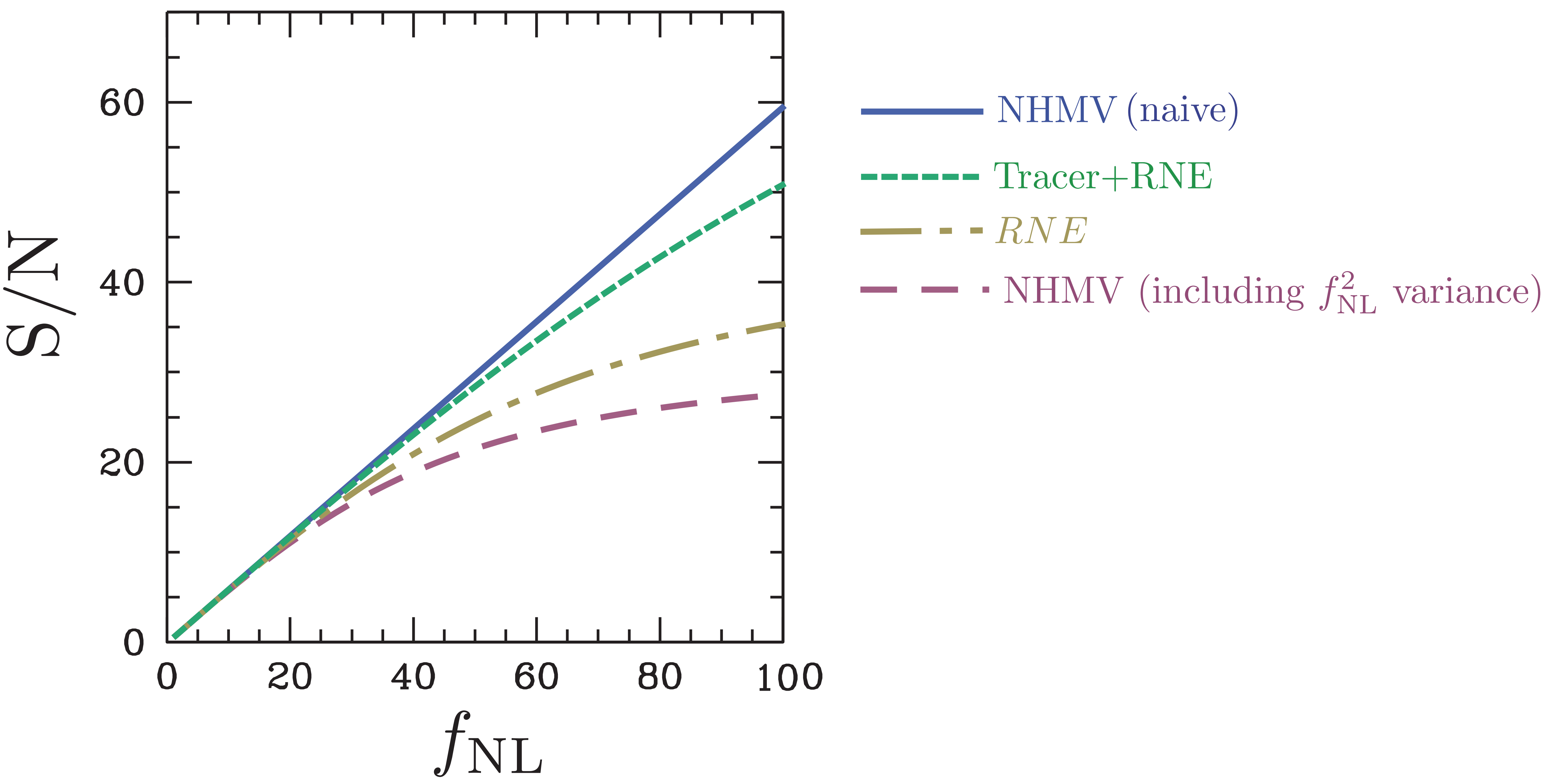

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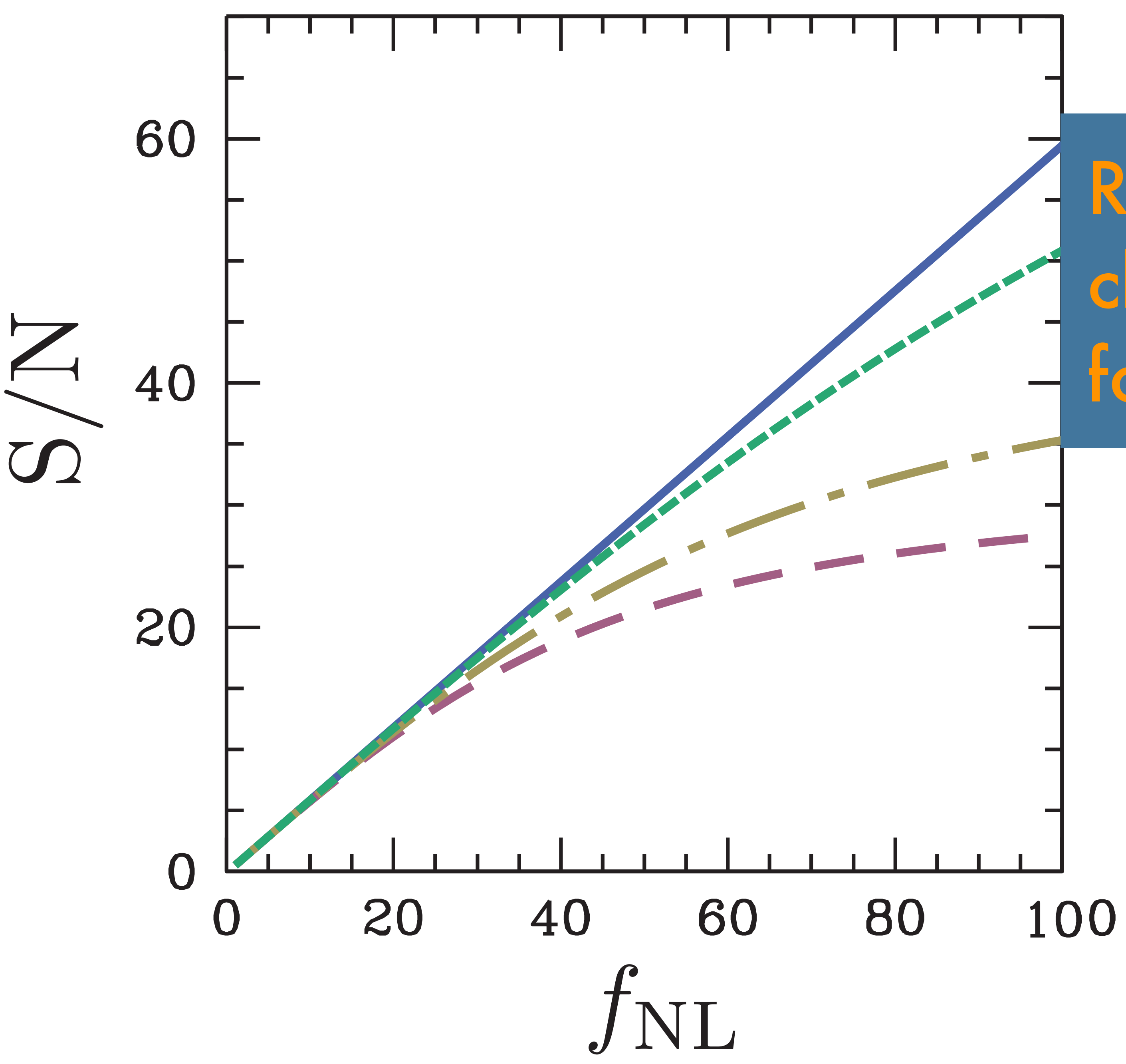
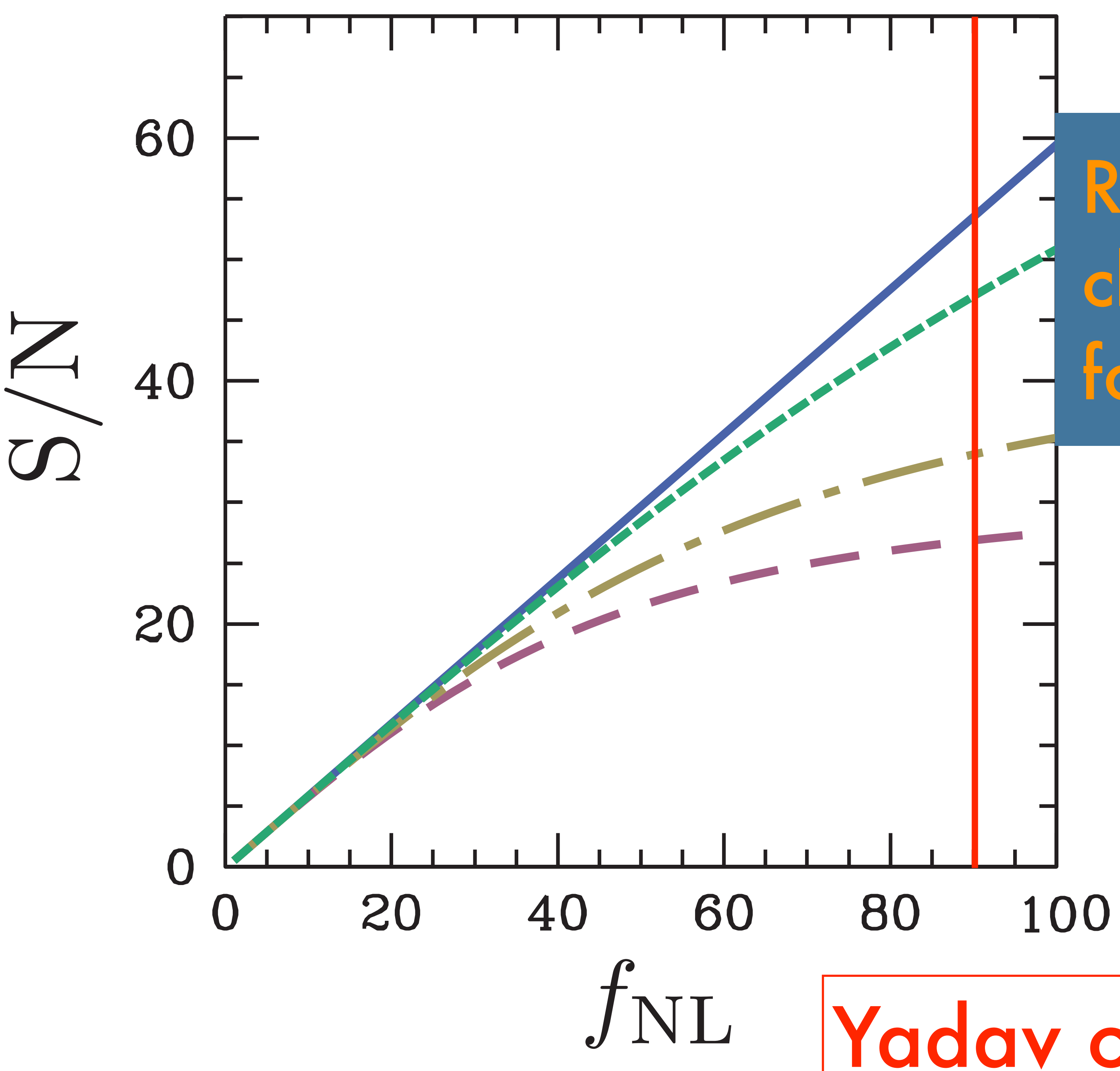


RNE works very well if map is cleaned of ISW effect using foreground tracer (Euclid params)

Cleaned maps



RNE works very well if map is cleaned of ISW effect using foreground tracer (Euclid params)

Yadav claim

Conclusions/Remaining questions

- The RNE can only remove 50% of the extra variance with realistic data
- The RNE can remove almost all of the extra variance if maps are cleaned of the late-time ISW effect
- Why do we have to reach outside primary data set?
- Simple arguments show CR bound is changed when late-time ISW is introduced? Compare with Bayesian methods (Elsner and Wandelt 2010)- Expensive but optimal?
- Polarization?

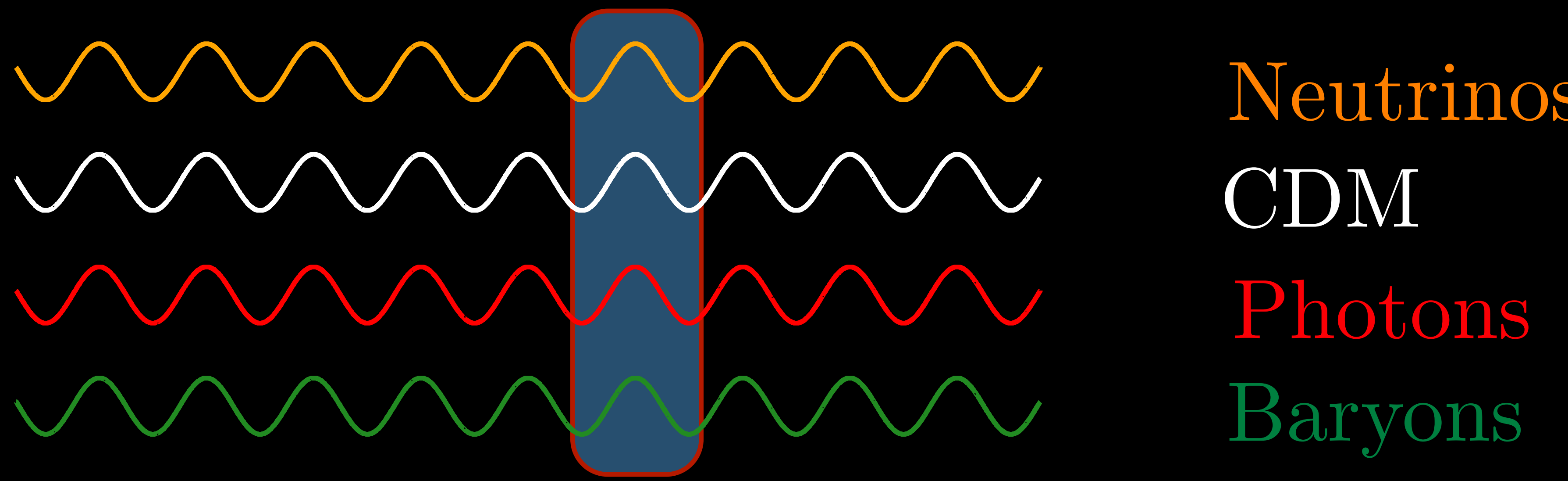
Compensated isocurvature perturbations (CIPs) between dark matter and baryons

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

arXiv: 1107.1716 (DG, OD, and MK)- Phys. Rev. Lett. 107 261301
arXiv: 1107.5047 (DG, OD, and MK)- Phys. Rev. D. 84 123003
DH, DG, and MK in prep

Zoology of Initial Conditions

Adiabatic



$$S_i = 0$$

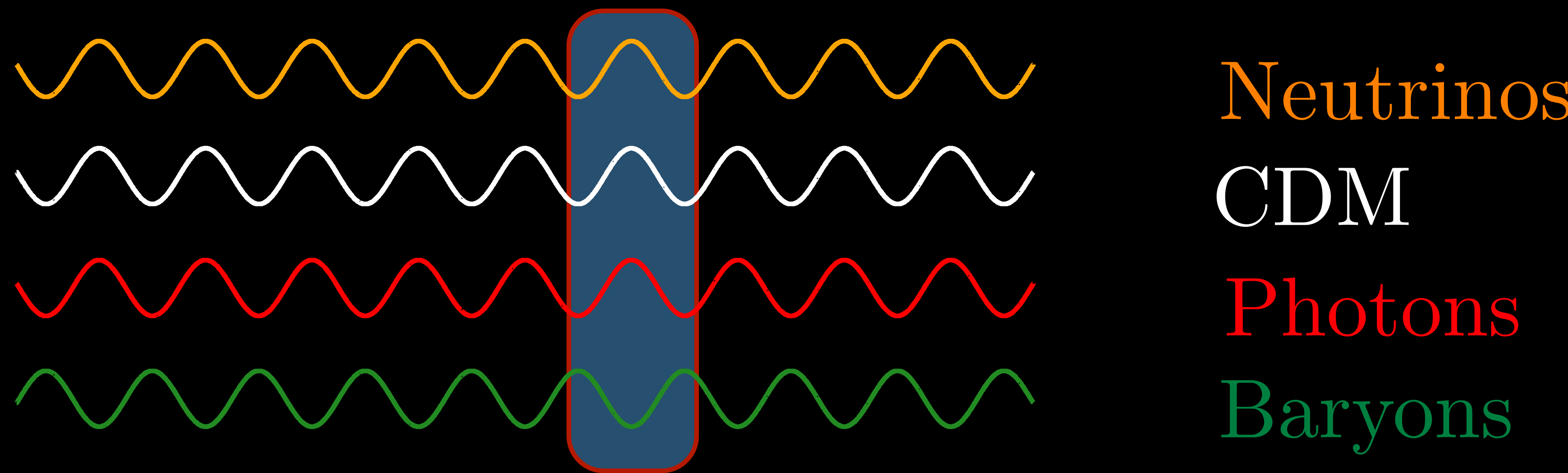
$$S_i = \frac{\delta n_i}{n_i} - \frac{\delta n_\gamma}{n_\gamma}$$

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

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

ZOOLOGY OF INITIAL CONDITIONS

Baryon isocurvature



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

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

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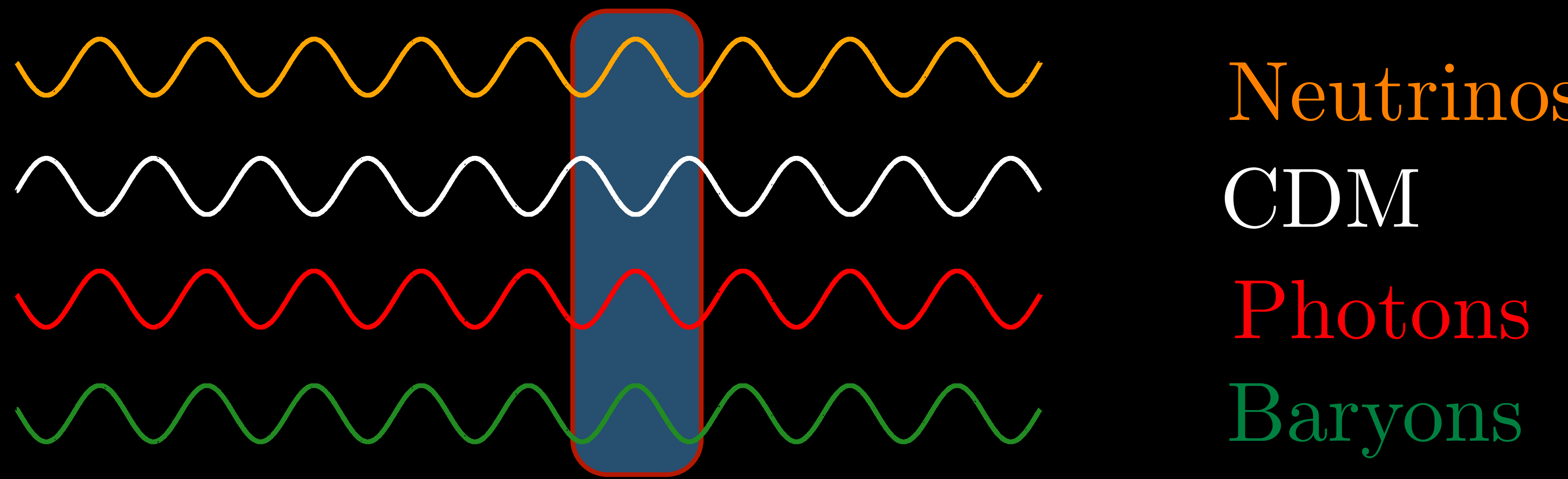
ZOOLOGY OF INITIAL CONDITIONS

CDM isocurvature



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

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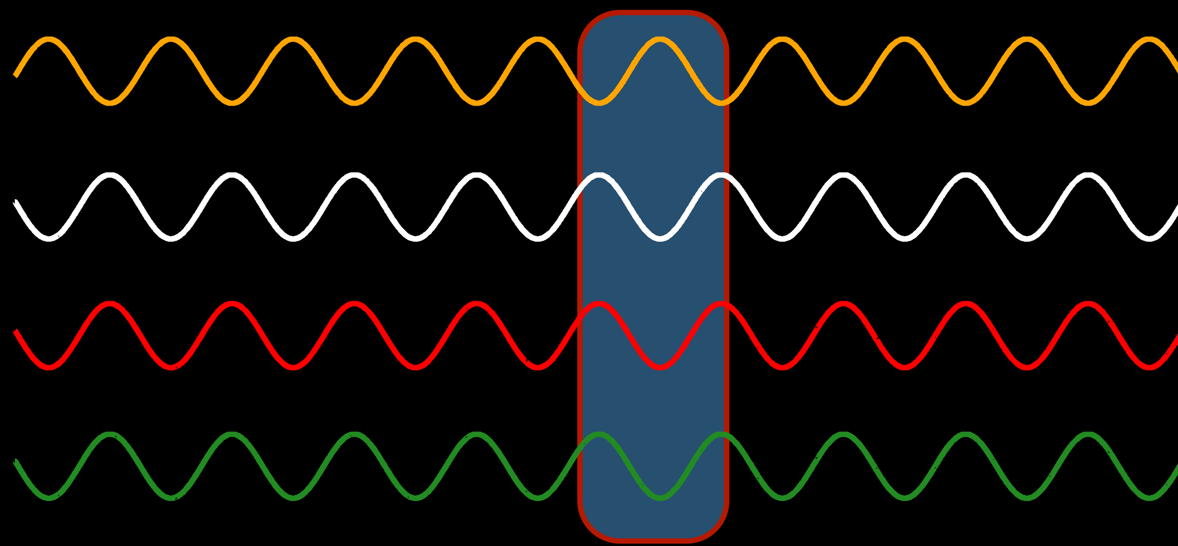
ZOOLOGY OF INITIAL CONDITIONS

ν isocurvature



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

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

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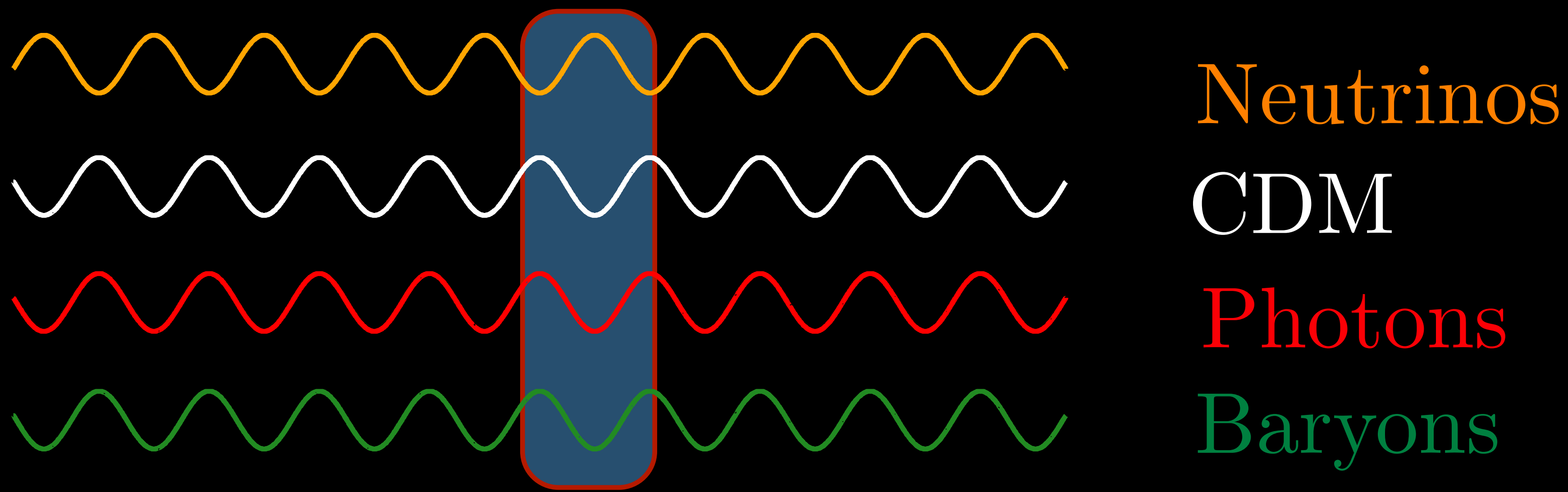
ZOOLOGY OF INITIAL CONDITIONS

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

SACHS WOLFE-EFFECT & POWER SPECTRA

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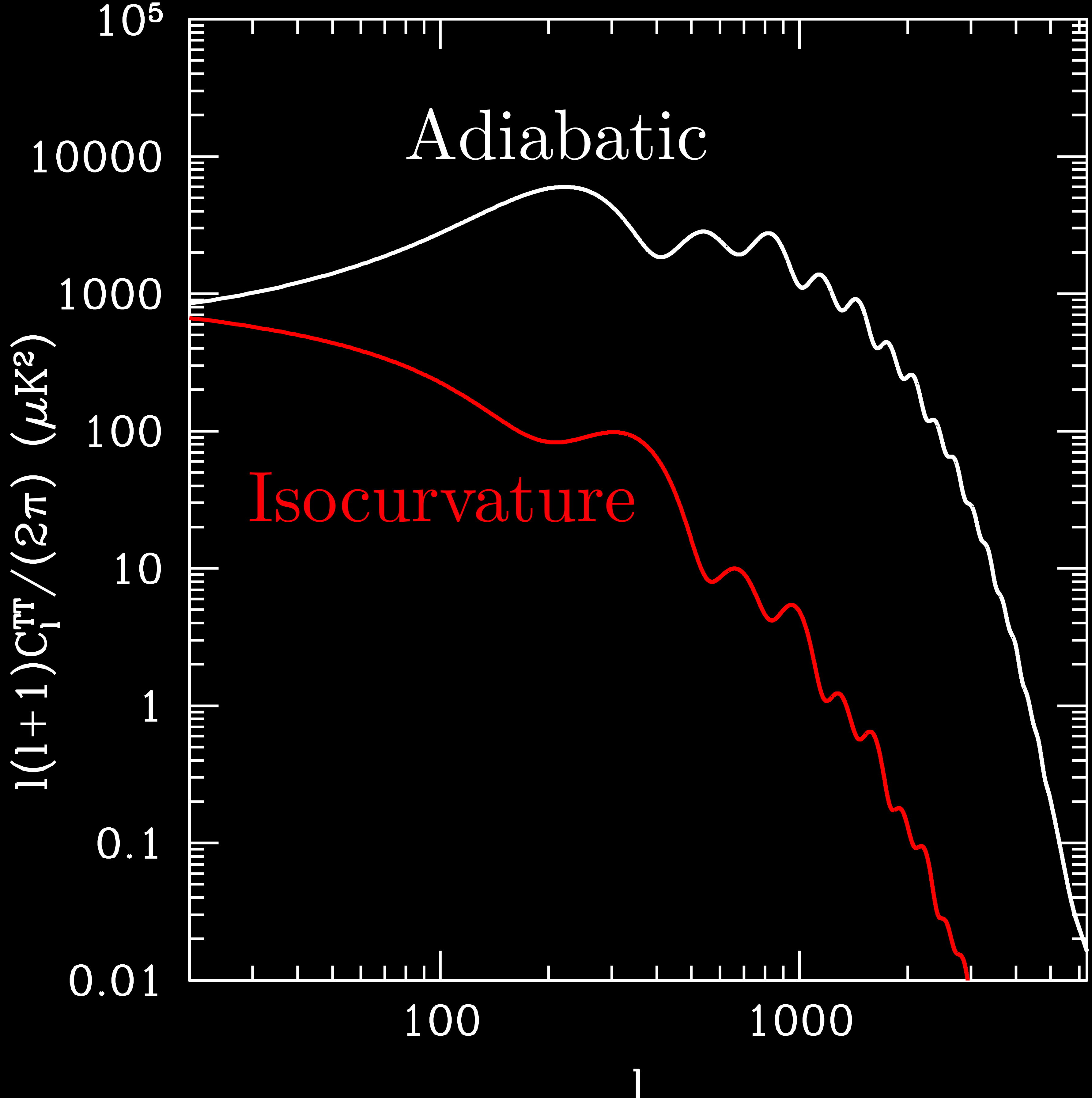


* WMAP 7-year constraints (Komatsu/Larson et al 2010)

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

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

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

✳ 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)

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

- “Nuisance” mode identified (Lewis 2002)

Compensated Isocurvature Perturbation (CIP)

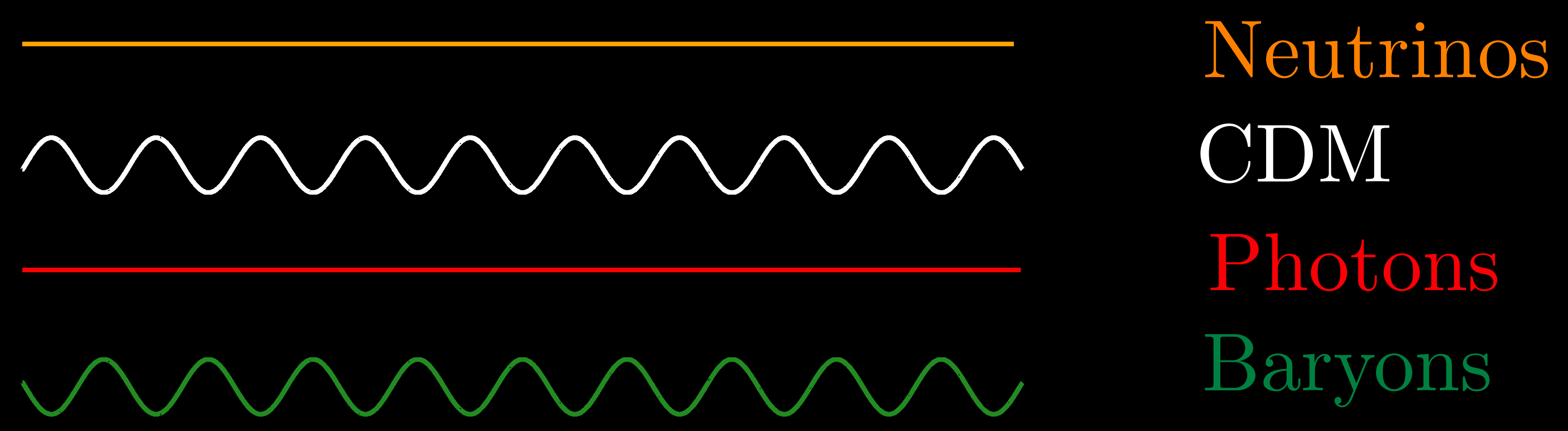
$$\delta\rho_{\rm b}^{\rm CIP} + \delta\rho_{\rm c}^{\rm CIP} = 0$$

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

Baryon-dark matter entropy

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

- “Nuisance” mode identified (Lewis 2002)



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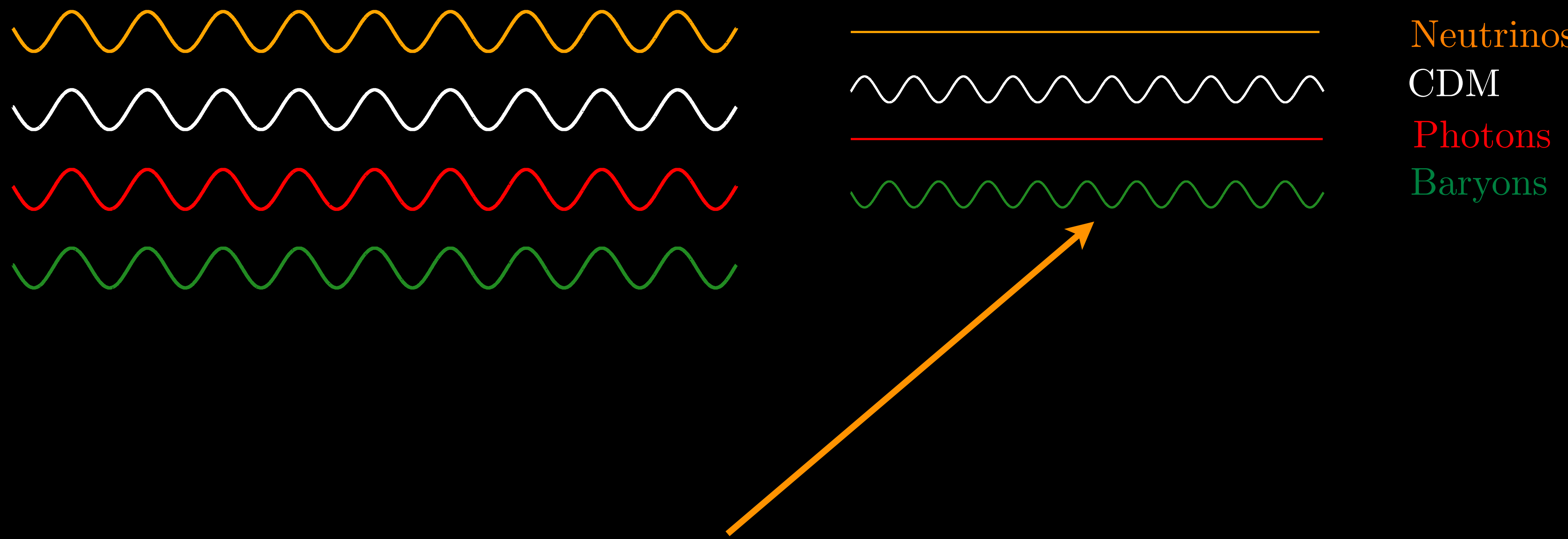
Adiabatic



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CIPS AND THE SACHS-WOLFE EFFECT

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

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

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

CIPS AND THE SACHS-WOLFE EFFECT

- *Observationally null in the CMB! (*surprising but true*)*
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$$\left(\frac{\Delta T}{T}\right)^{\rm SW} = \frac{\zeta}{5} - \frac{2}{5}\frac{\left(\rho_{\rm cdm}S_{{\rm cdm},\gamma} + \rho_{\rm b}S_{{\rm b},\gamma}\right)}{\rho_{\rm matter}}$$

Vanishes for all isocurvature modes

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

CIPS AND THE SACHS-WOLFE EFFECT

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

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?*

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

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

$$l > 10^5$$

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

- *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

Gordon and Pritchard, 2009

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

EXISTING MODELS FOR CIPS

Gordon and Pritchard, 2009

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

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

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

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

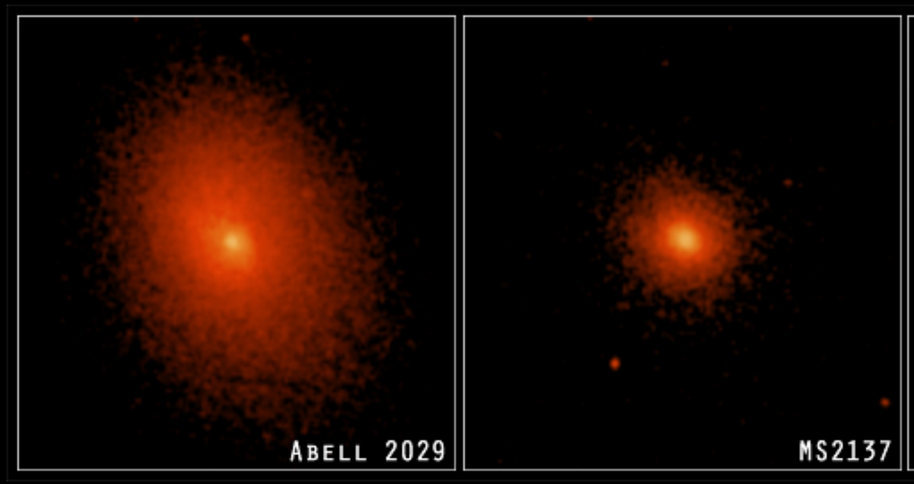
$$\Delta = S_{\rm bc} \sim 10^{-3}$$

EXISTING CONSTRAINTS TO CIPS- BBN

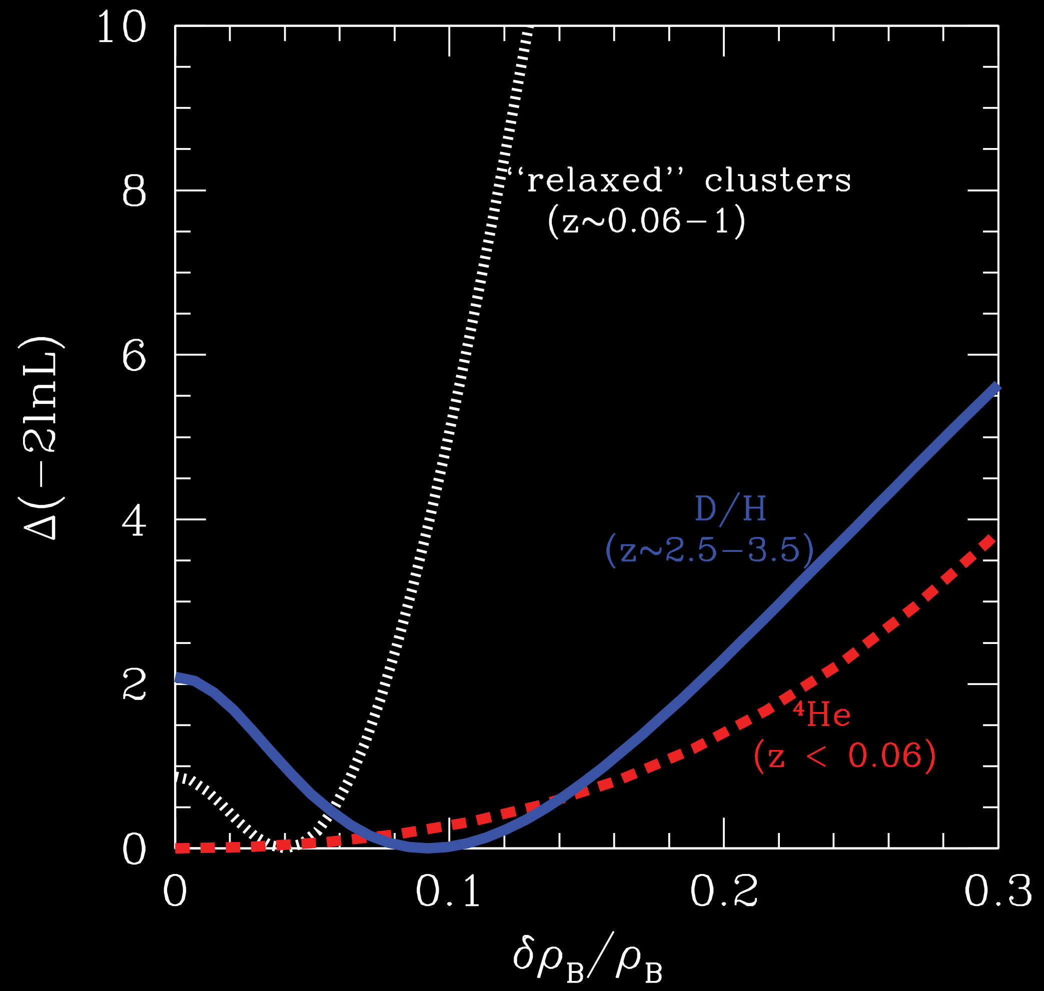
- Primordial abundances of De, ^{3}He, ^{4}He, ^{7}Li : Blue compact galaxies (He) and QSO Absorption systems (De)

- Baryon fraction measurements in galaxy clusters

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



EXISTING CONSTRAINTS TO CIPS- BBN

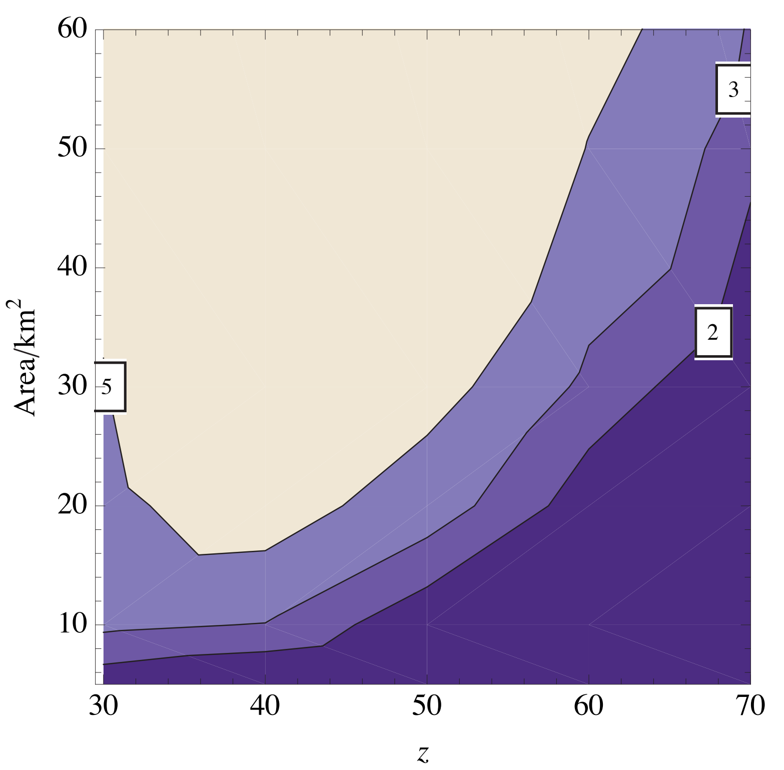


Fluctuations as high as **8%** are allowed by the data

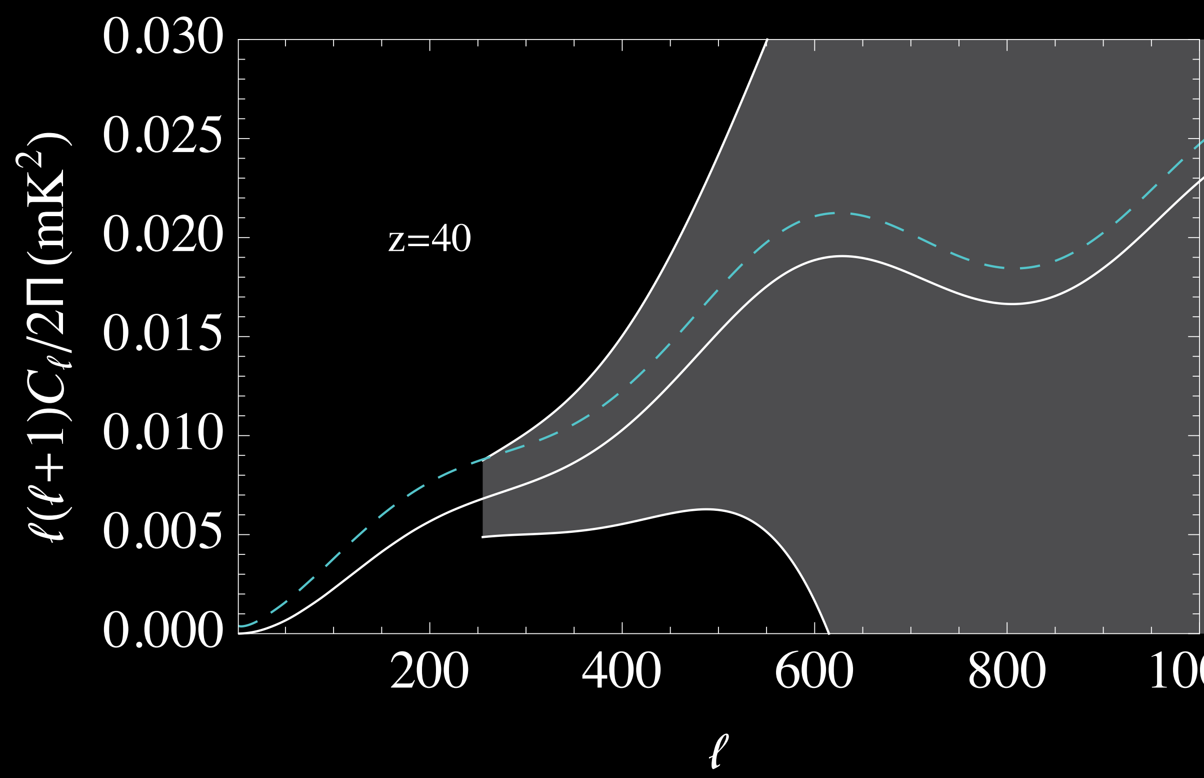
Can we empirically show, rather than simply assume, that baryon trace DM in the early universe?

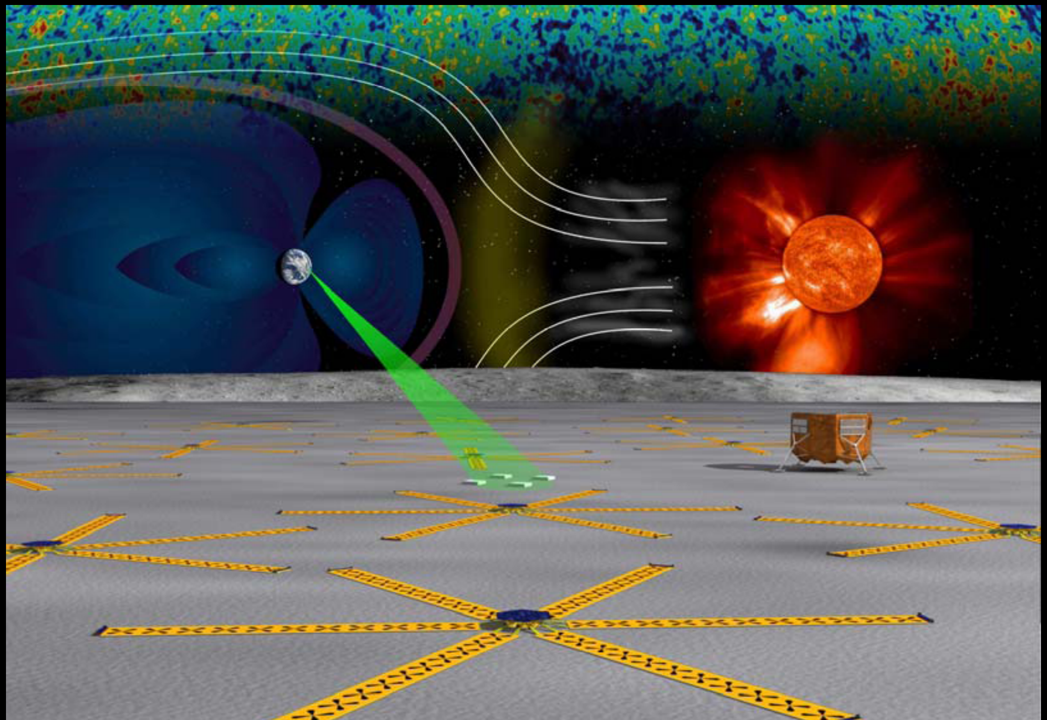
CIPS AND 21-CM FLUCTUATIONS

Gordon and Pritchard, 2009



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



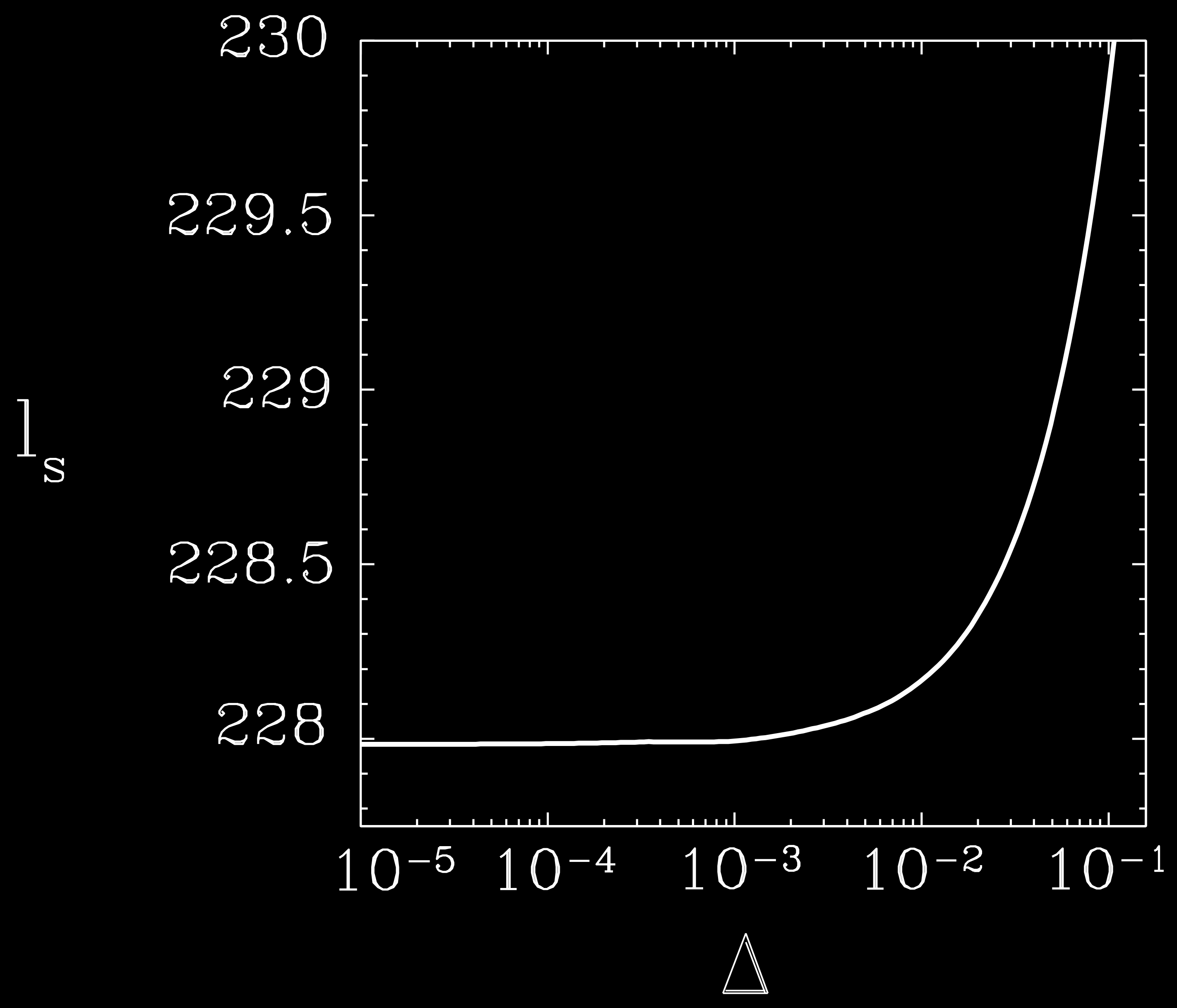


COMPENSATED ISOCURVATURE AND THE CMB:
z~1100 EFFECTS

- Acoustic scale modulated by CIP

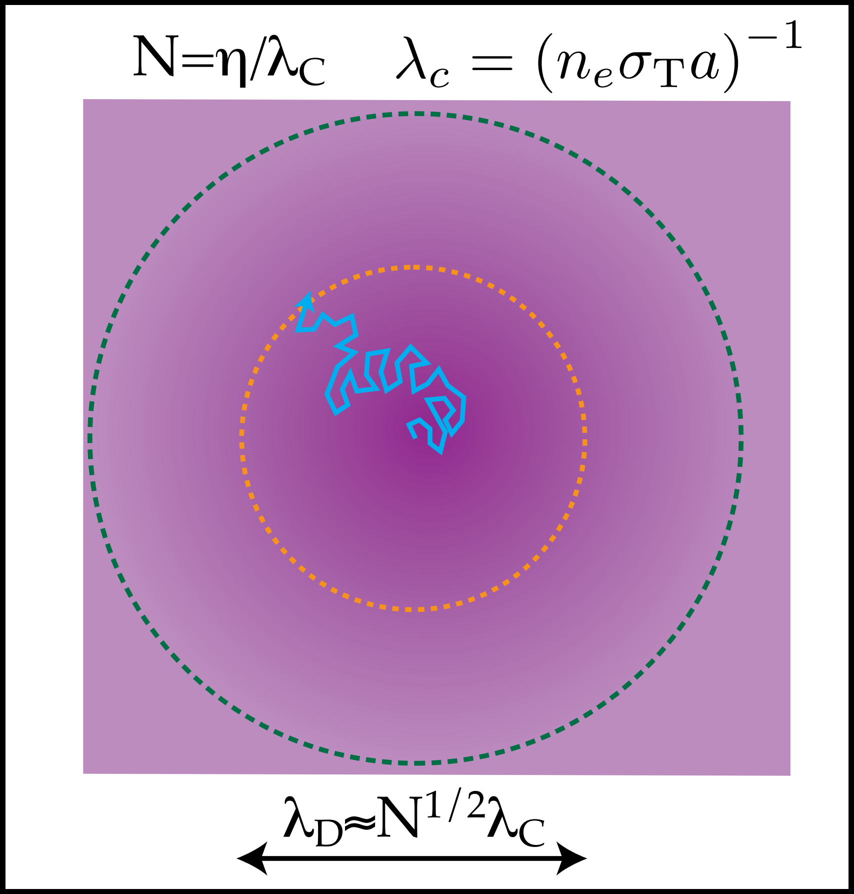
COMPENSATED ISOCURVATURE AND THE CMB: *z~1100 EFFECTS*

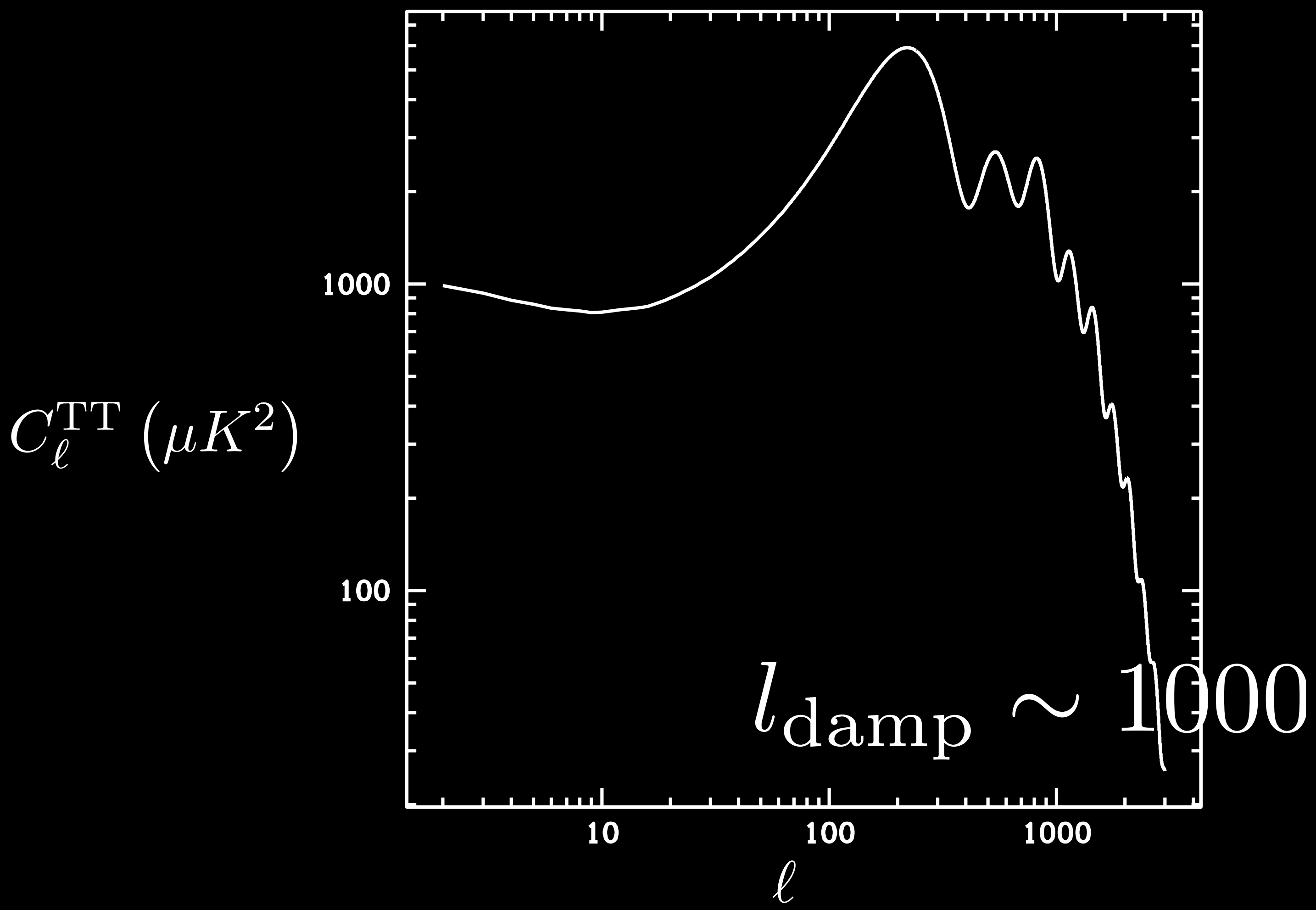
- Acoustic scale modulated by CIP



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

- Damping scale modulated by CIPs





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

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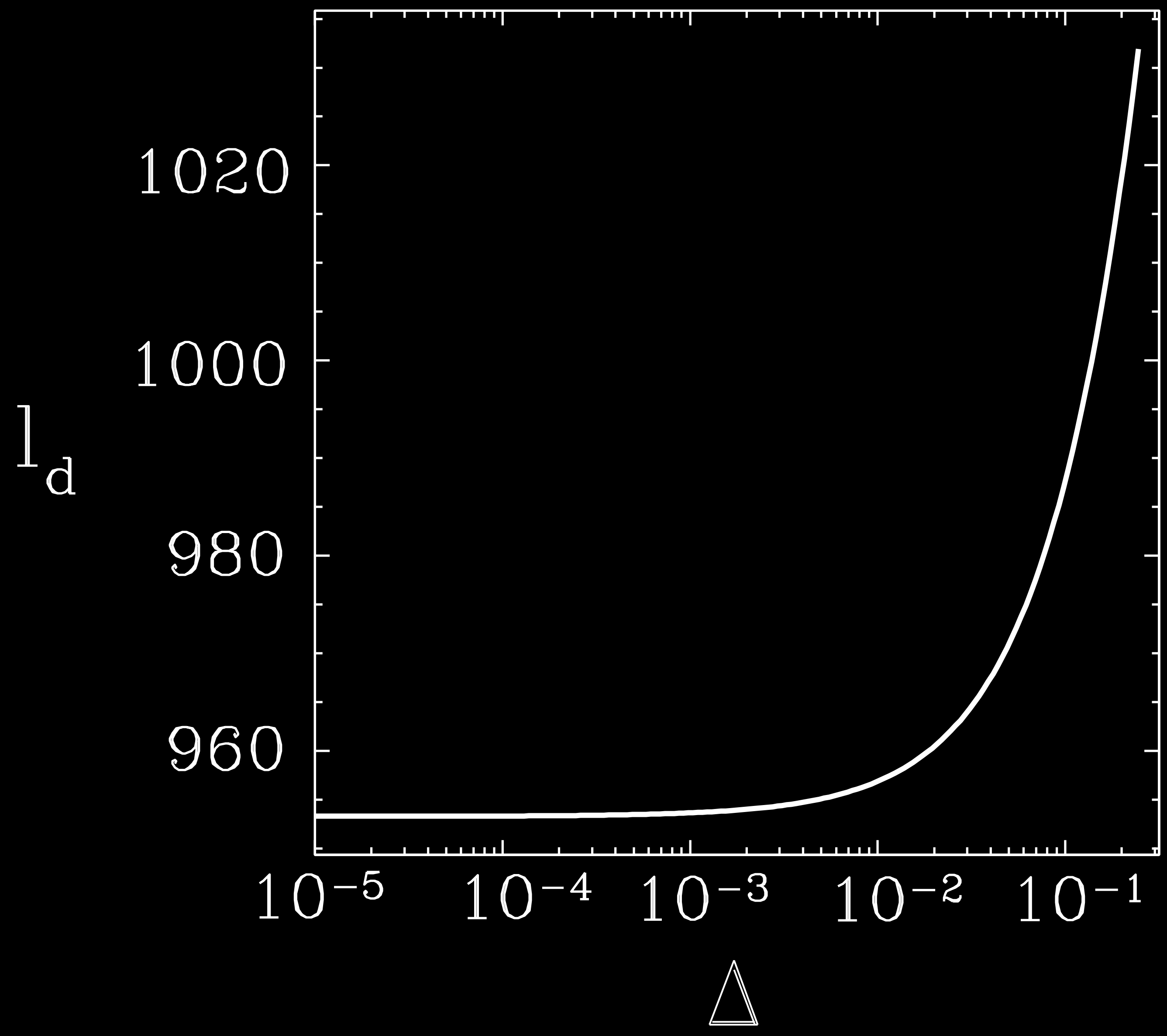
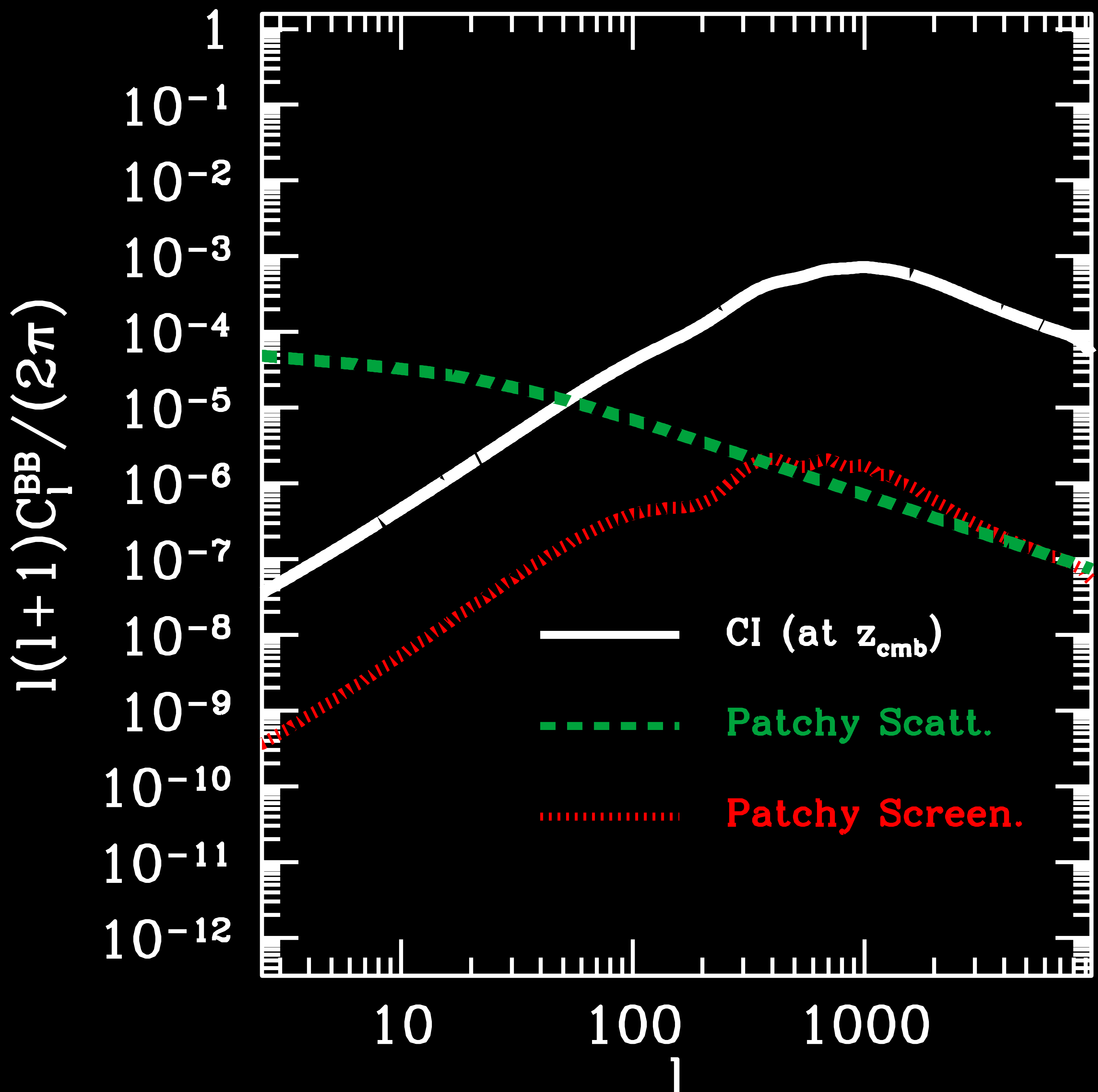


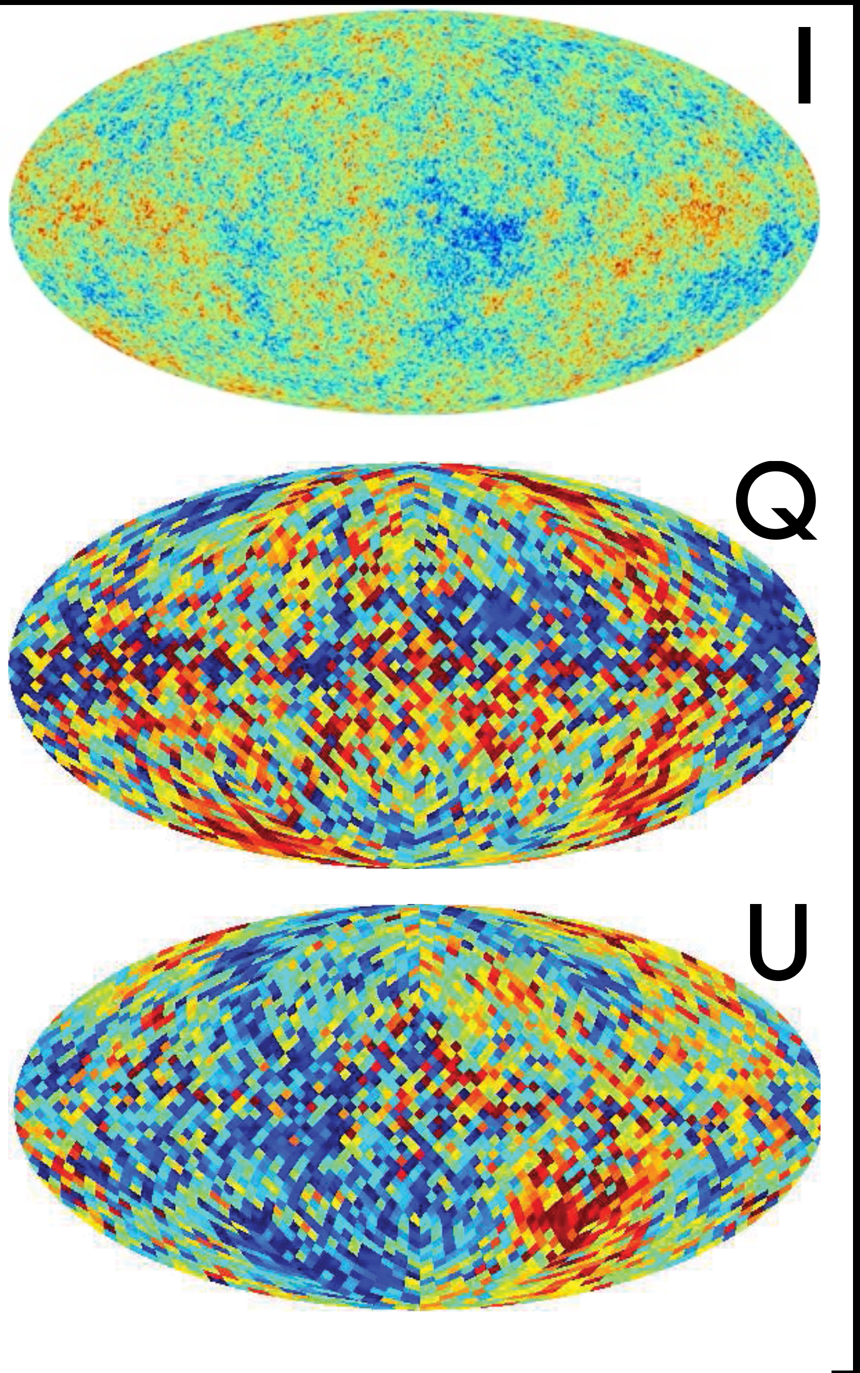
COMPENSATED ISOCURVATURE AND THE CMB:

RECOMBINATION B-MODES



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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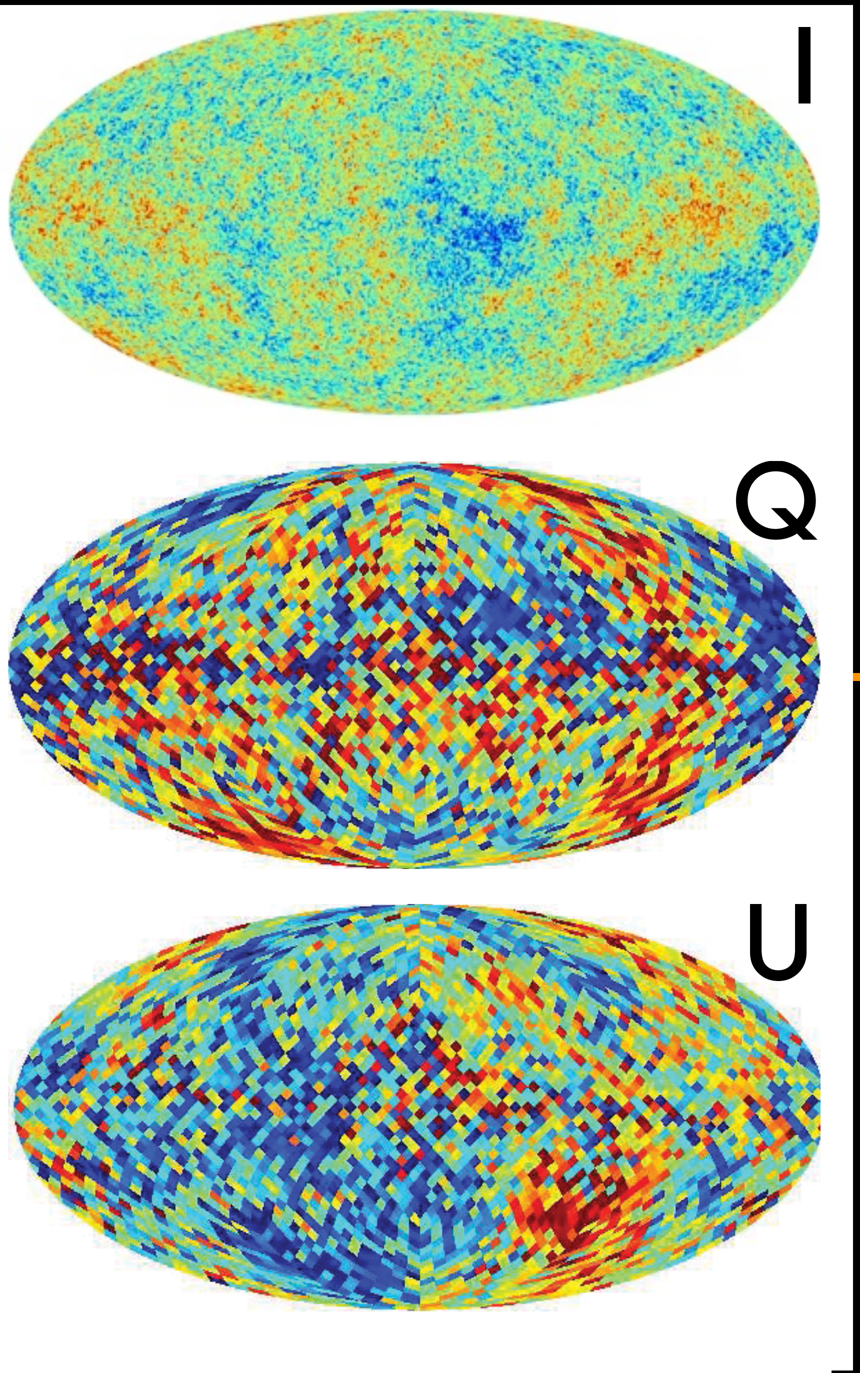

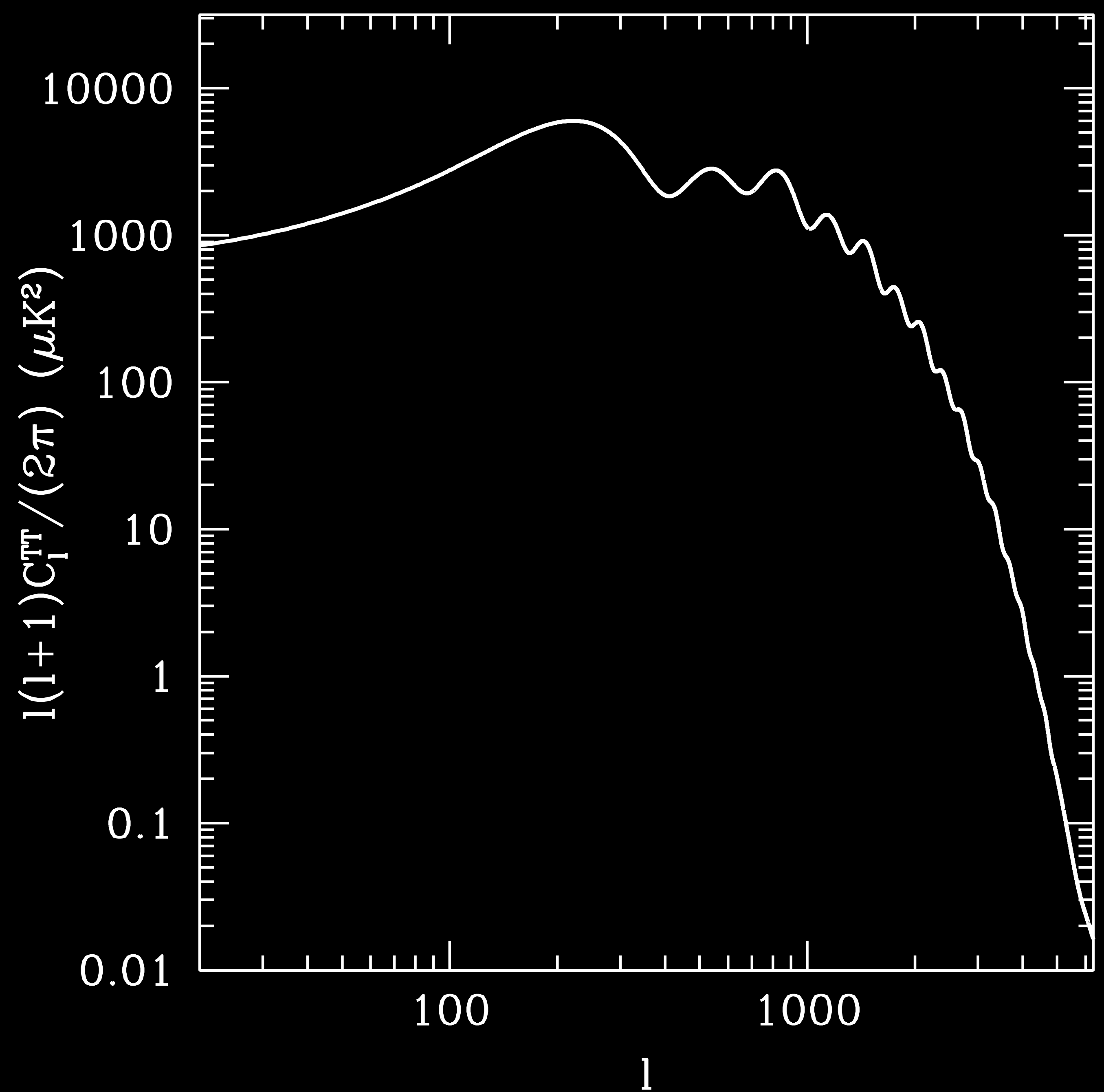

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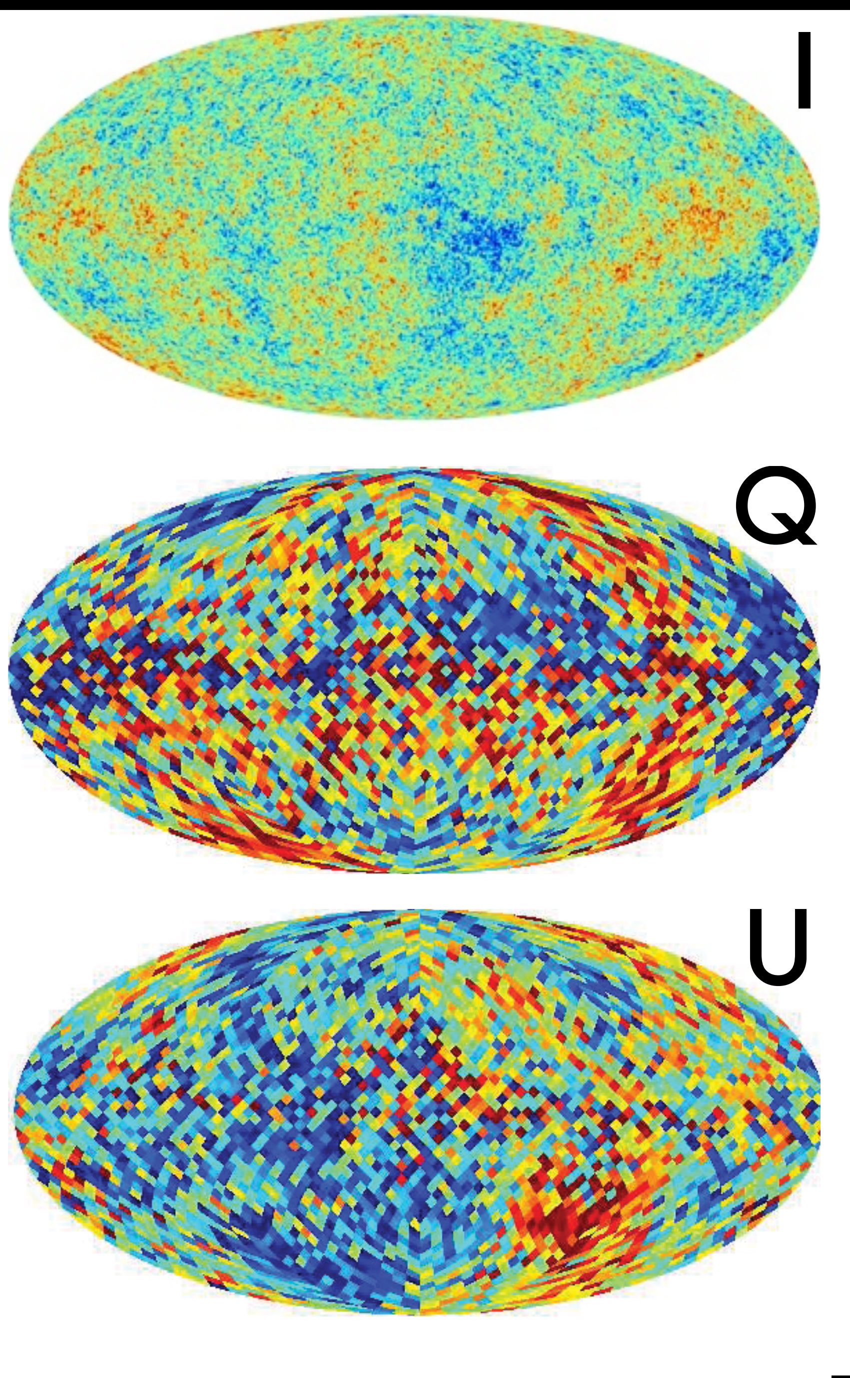

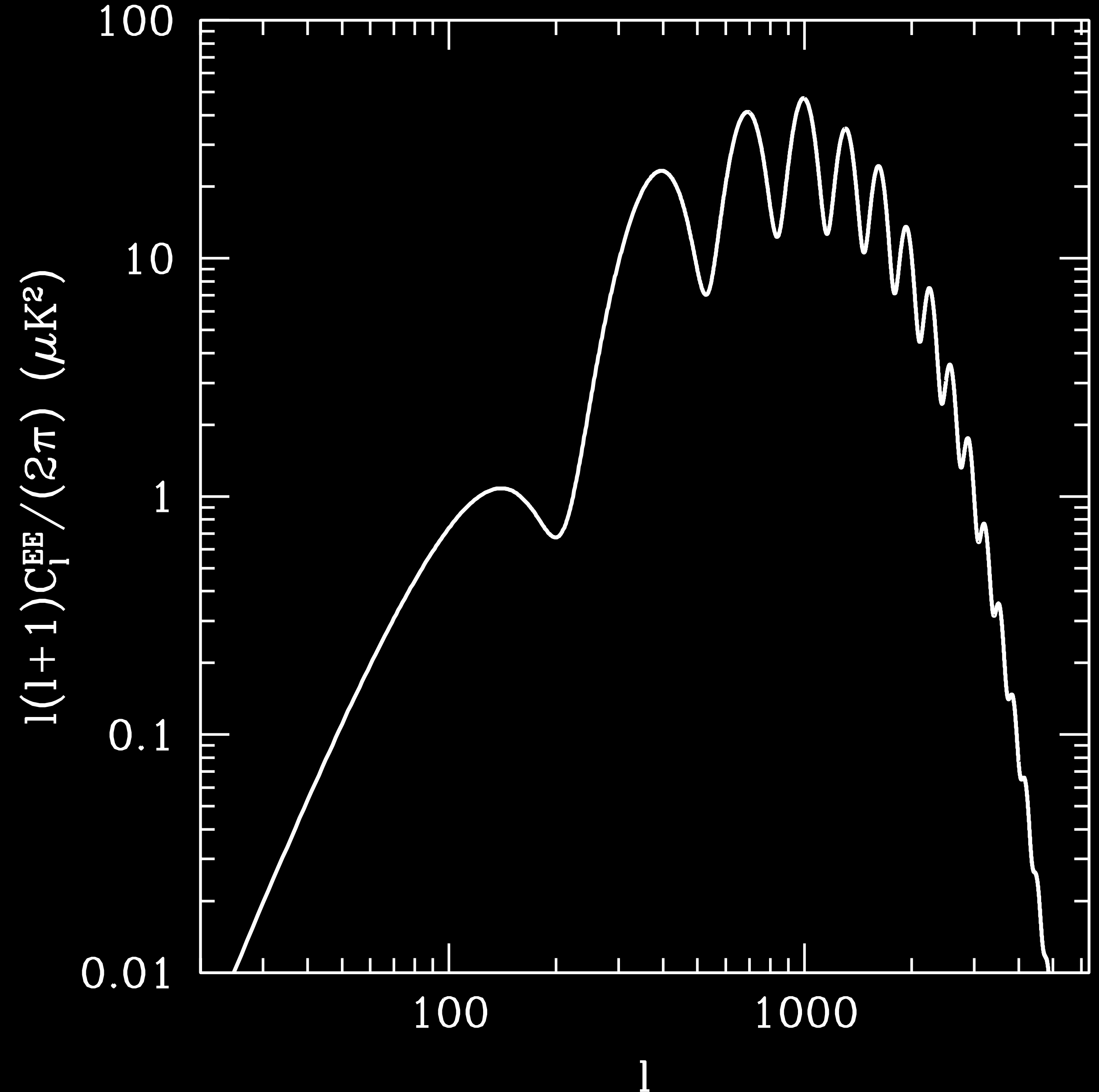

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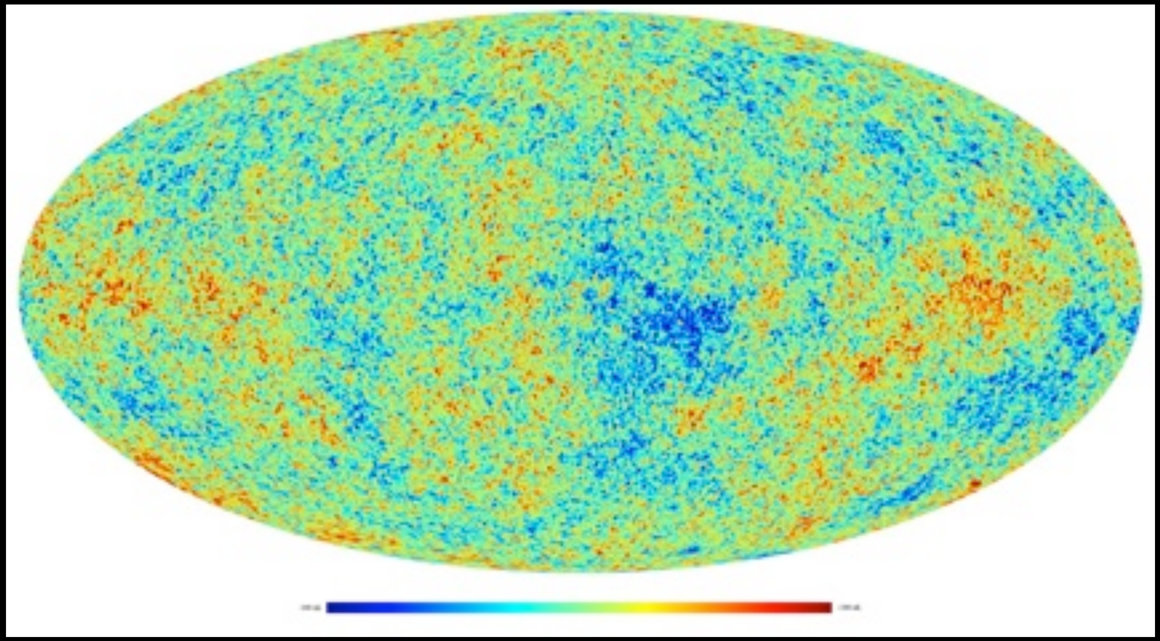
- Power spec. results were true, averaging over realizations of primordial $\Phi(\hat{n})$ and CIP amplitude $\Delta(\hat{n})$
- In single realization of CIP spec., a long wavelength CIP w/ amp Δ_{LM} modulates the power spectrum across the sky



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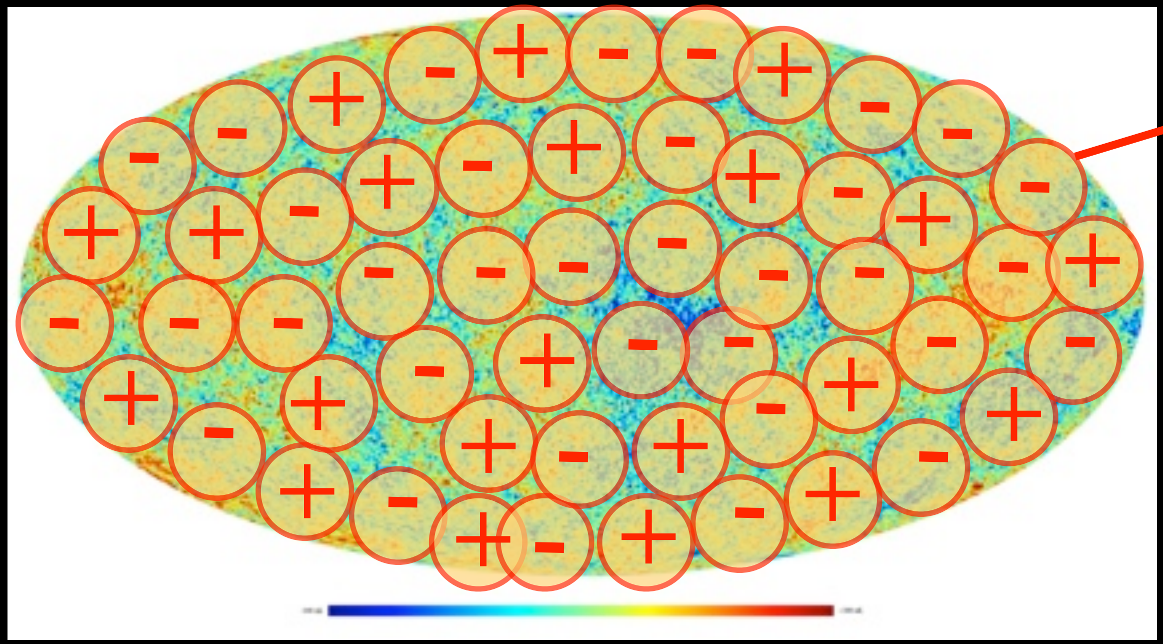
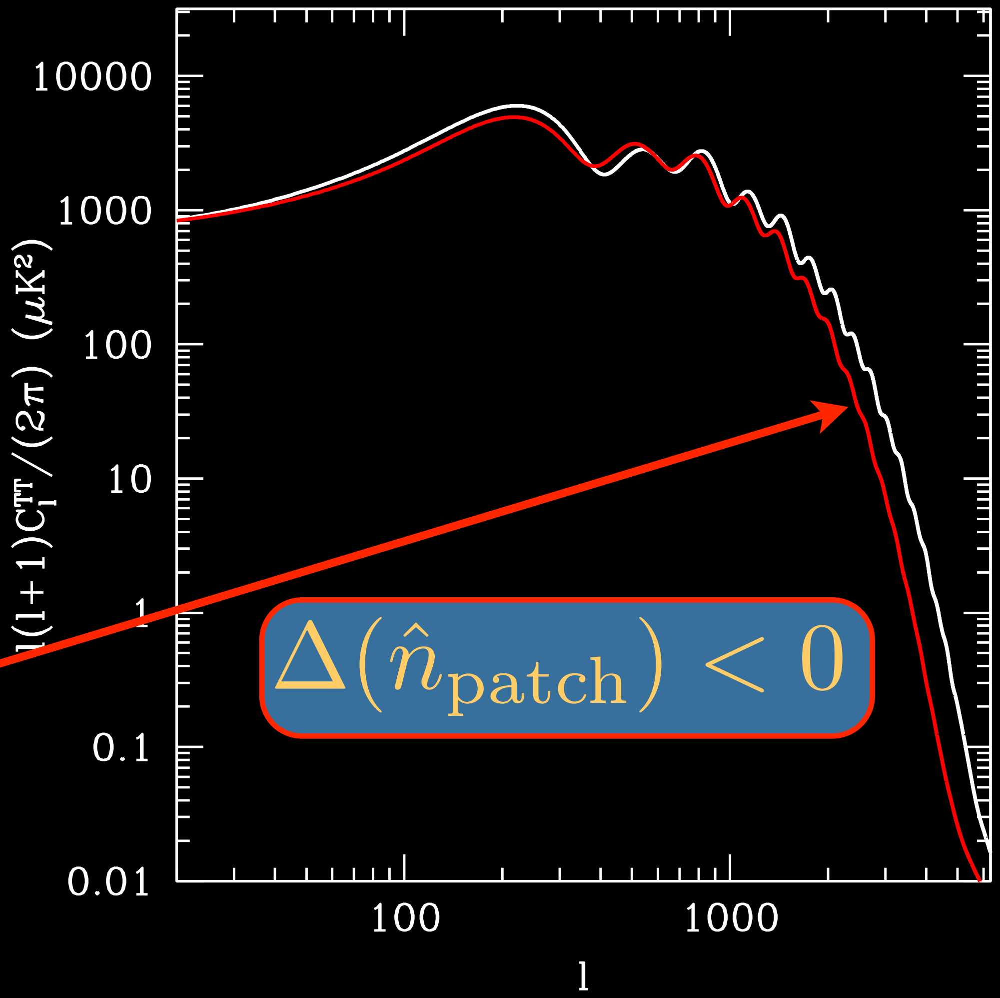
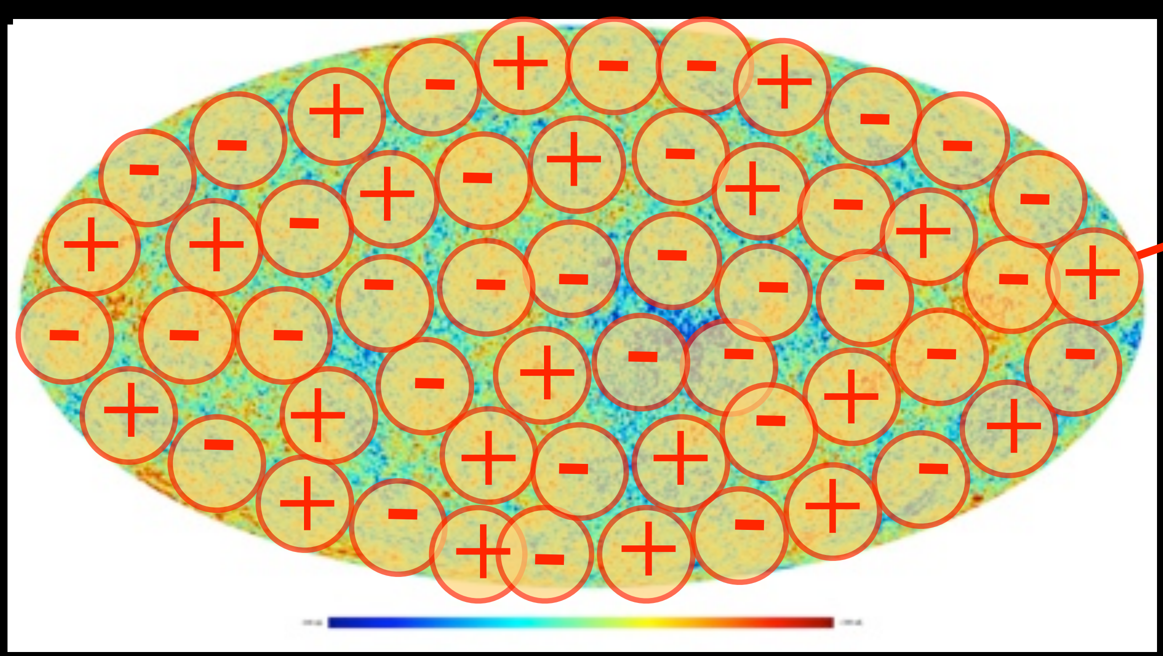
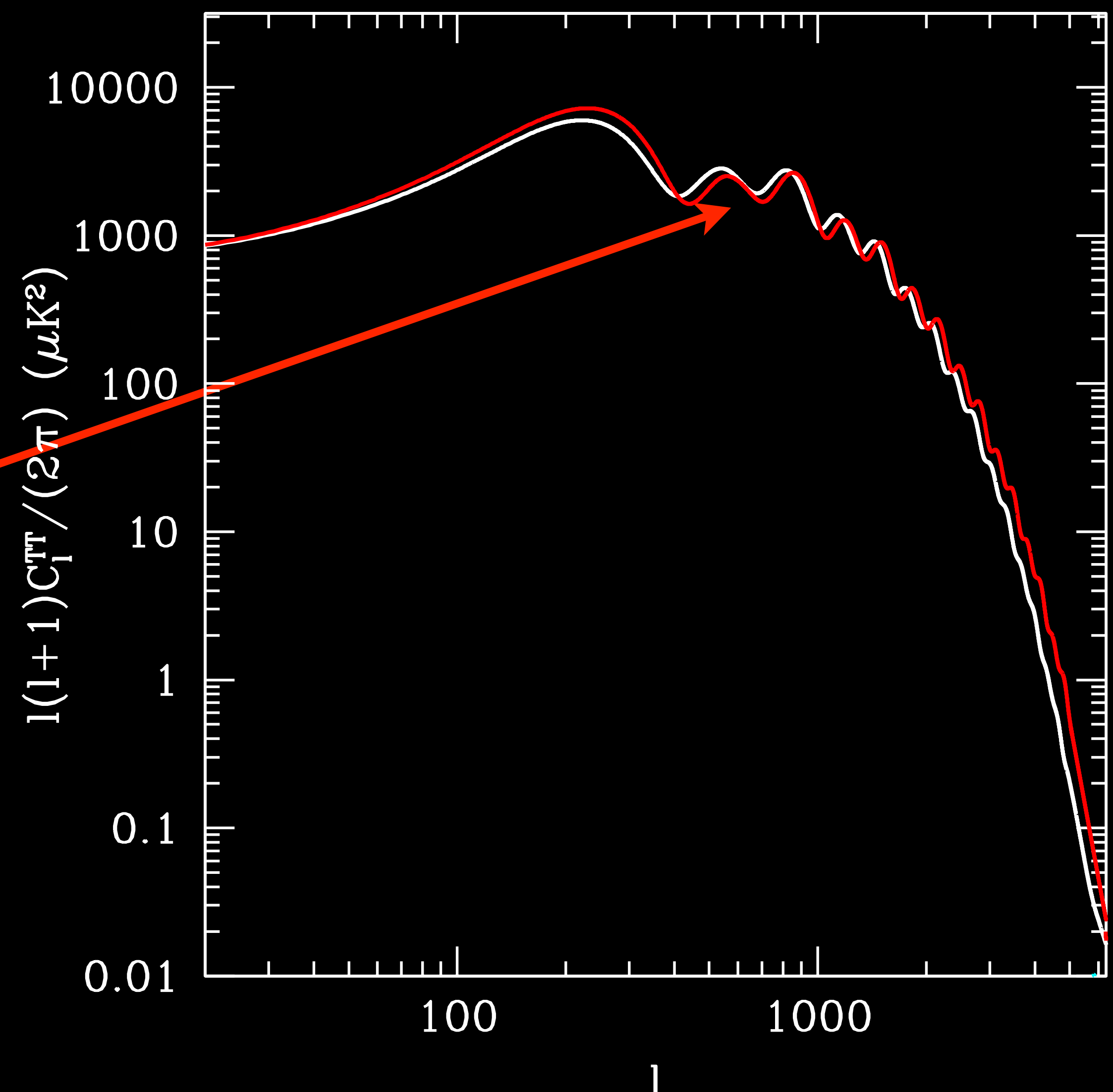




COMPENSATED ISOCURVATURE AND THE CMB: *RECOVERING THE REALIZATION*

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





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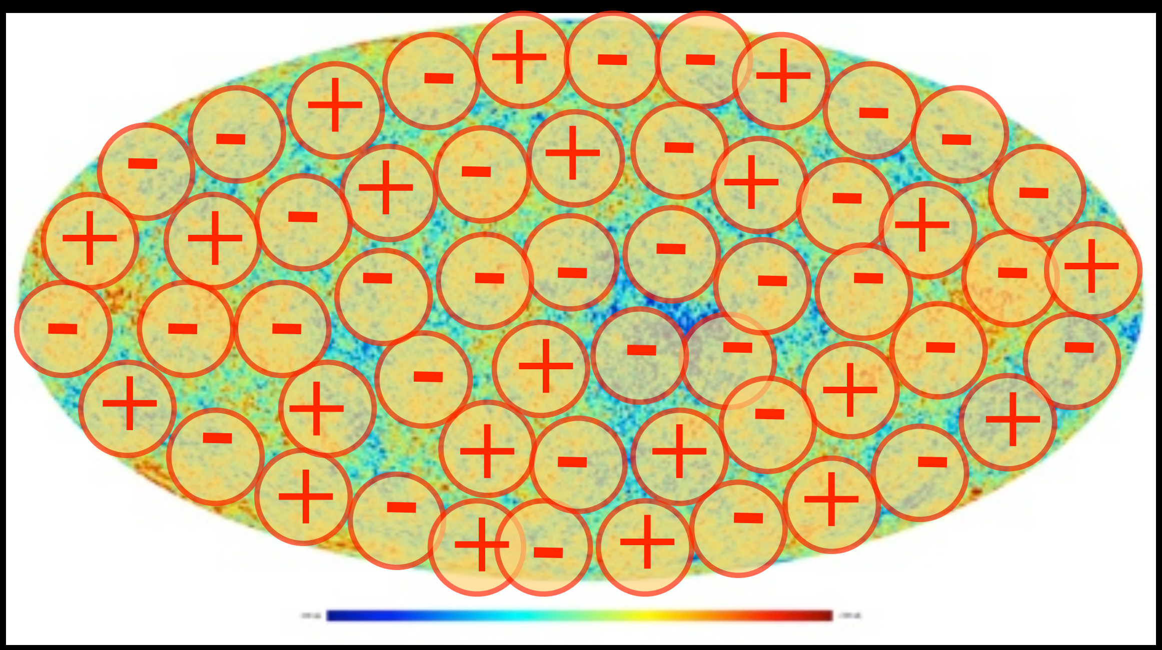

✳Heuristically:

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

COMPENSATED ISOCURVATURE AND THE CMB: *PROSPECTS*

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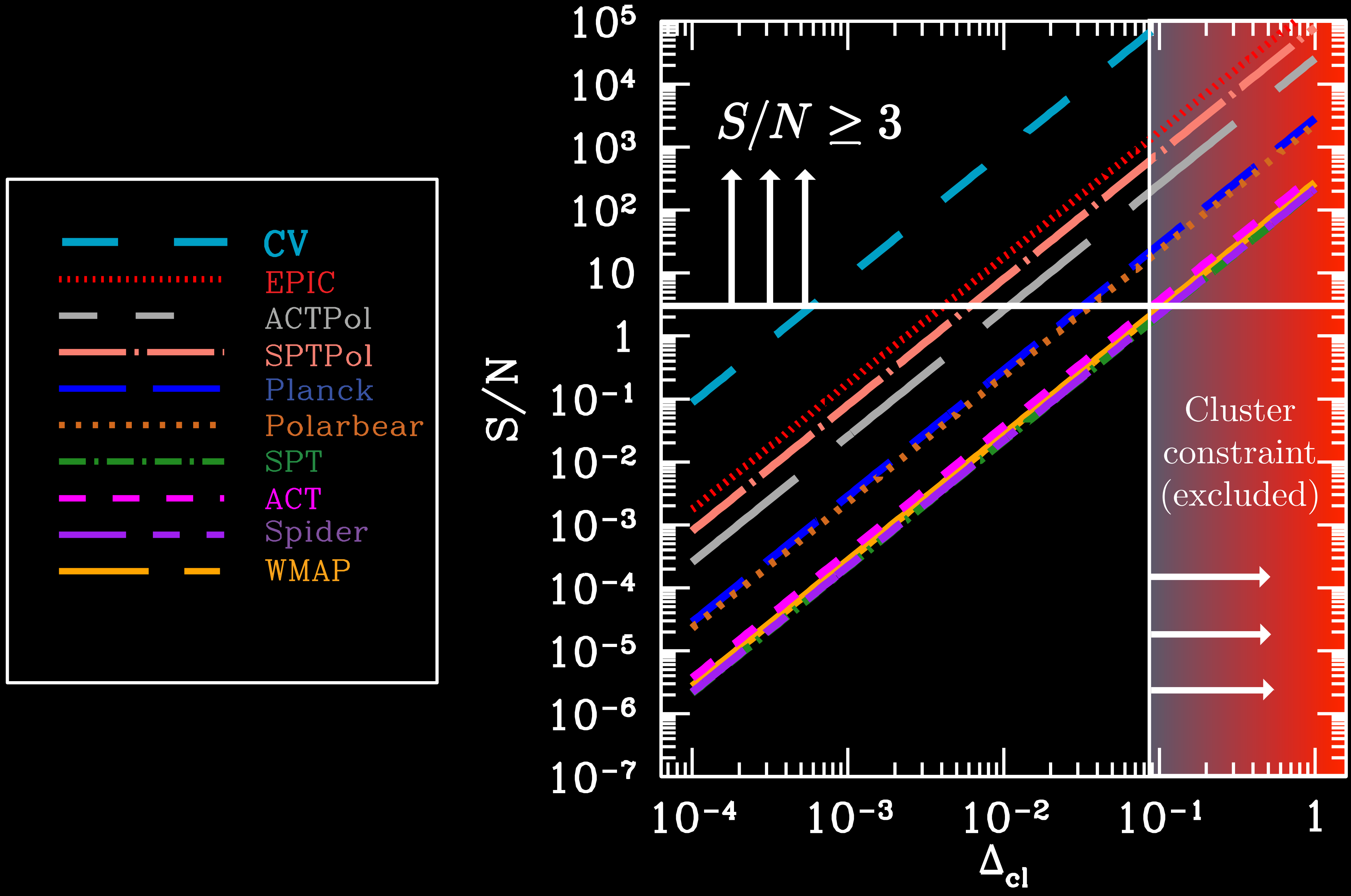
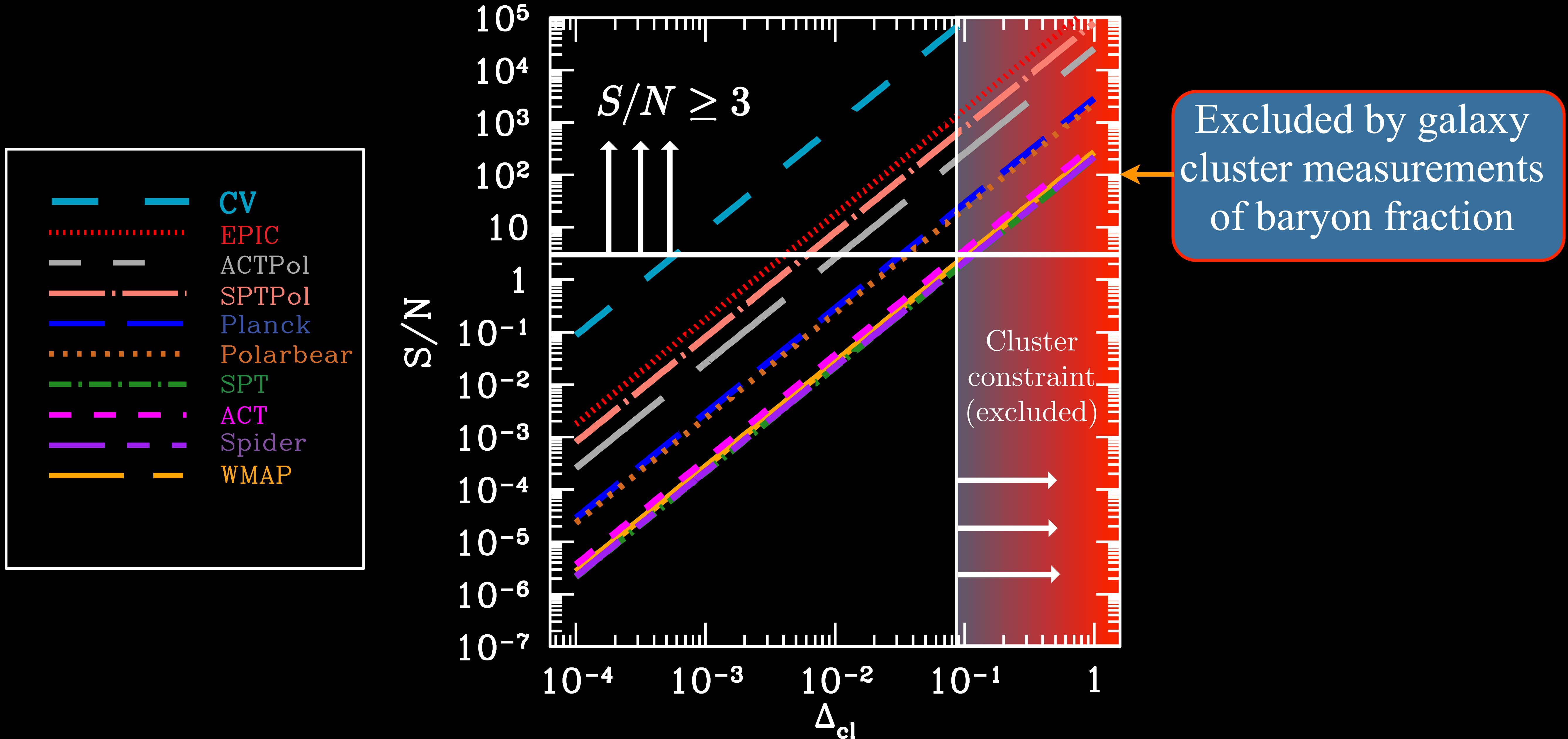
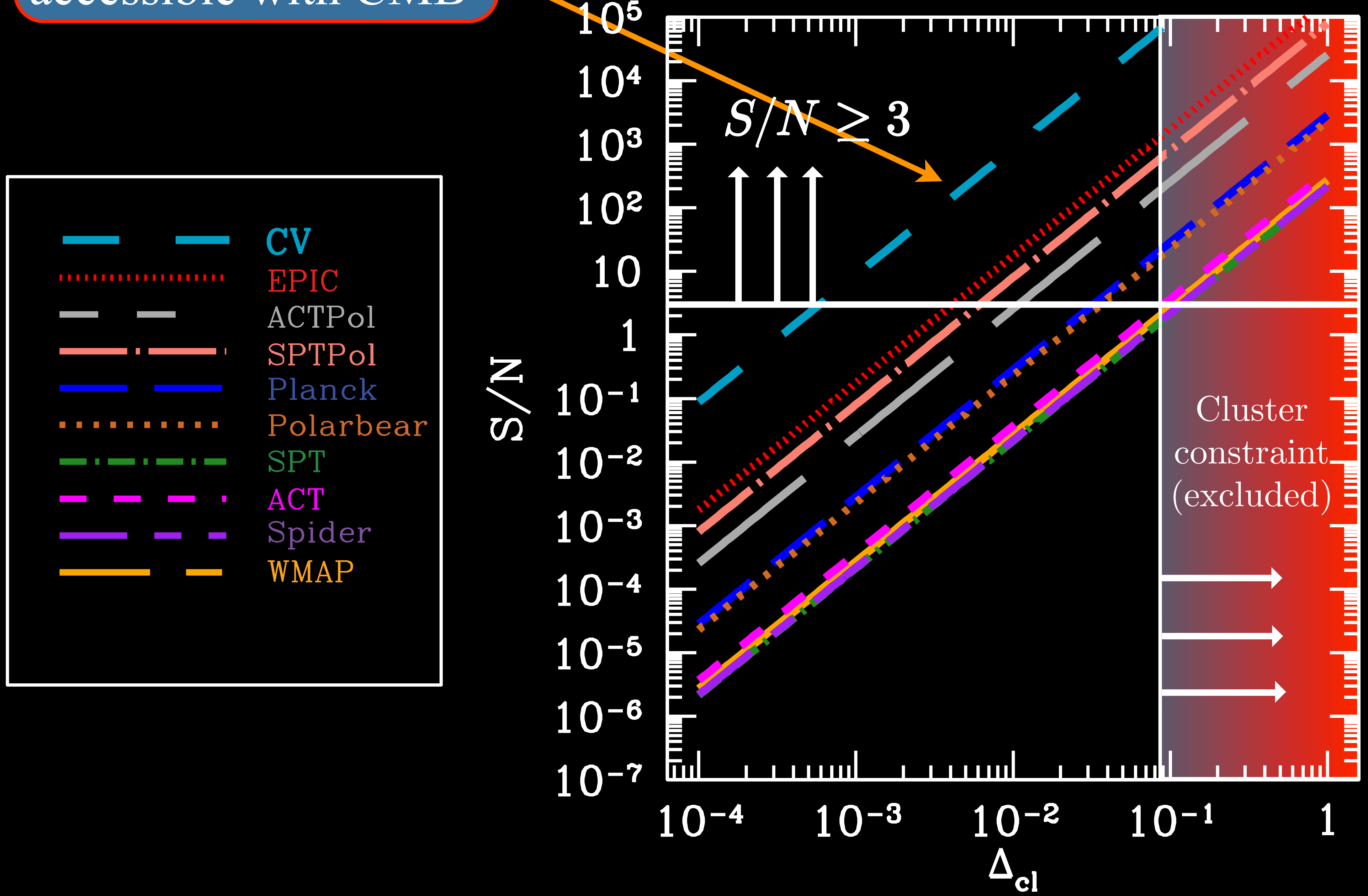


COMPENSATED ISOCURVATURE AND THE CMB: *PROSPECTS*



COMPENSATED ISOCURVATURE AND THE CMB: *PROSPECTS*

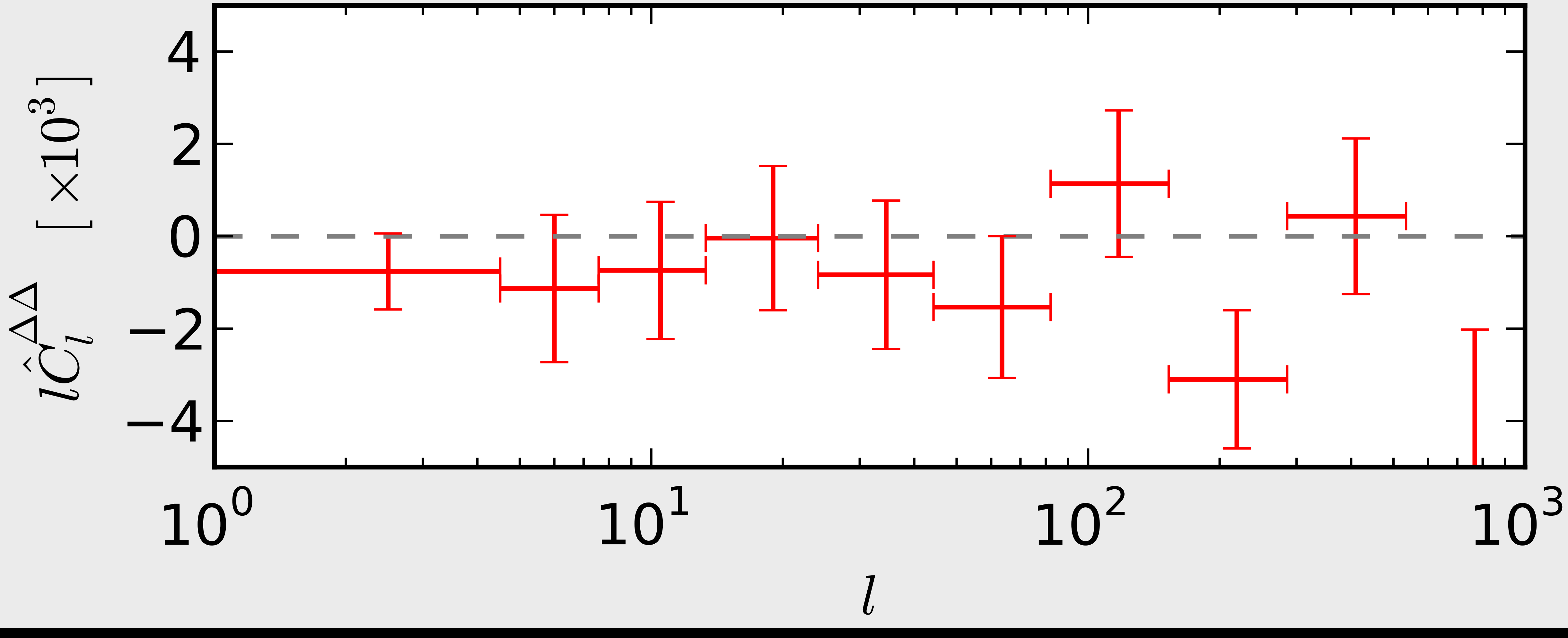
Parameter space accessible with CMB



Two orders of magnitude improvement: conservatively

First search for CIPs with WMAP

WORK IN PROGRESS



A cosmological search for ultra-light axions

with D. J.E. Marsh and R. Hlozek

Axions solve the strong CP problem

- Strong interaction violates CP through θ -vacuum term

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

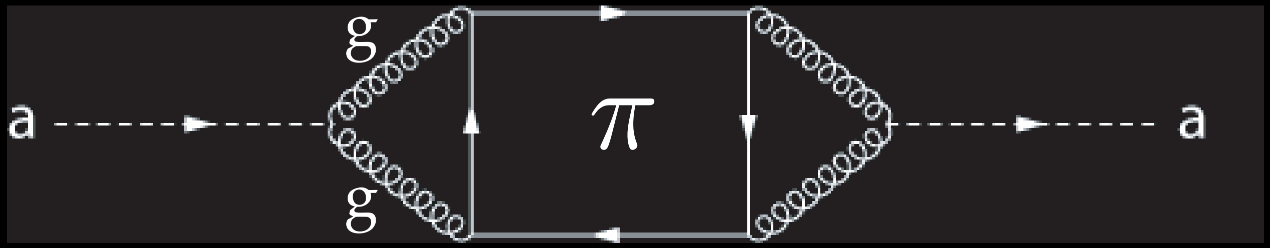
- Limits on the neutron electric dipole moment are strong. Fine tuning?

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

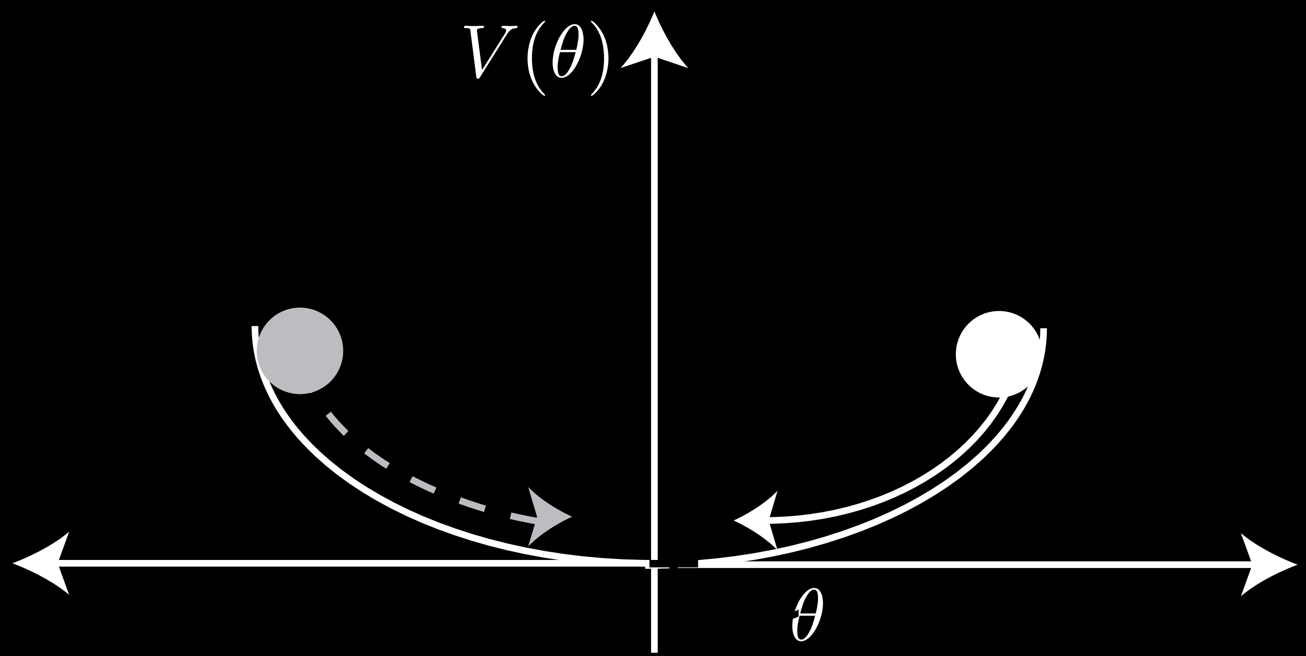
- New field (axion) and U(1) symmetry dynamically drive net CP-violating term to 0

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

- Through coupling to pions, axions pick up a mass

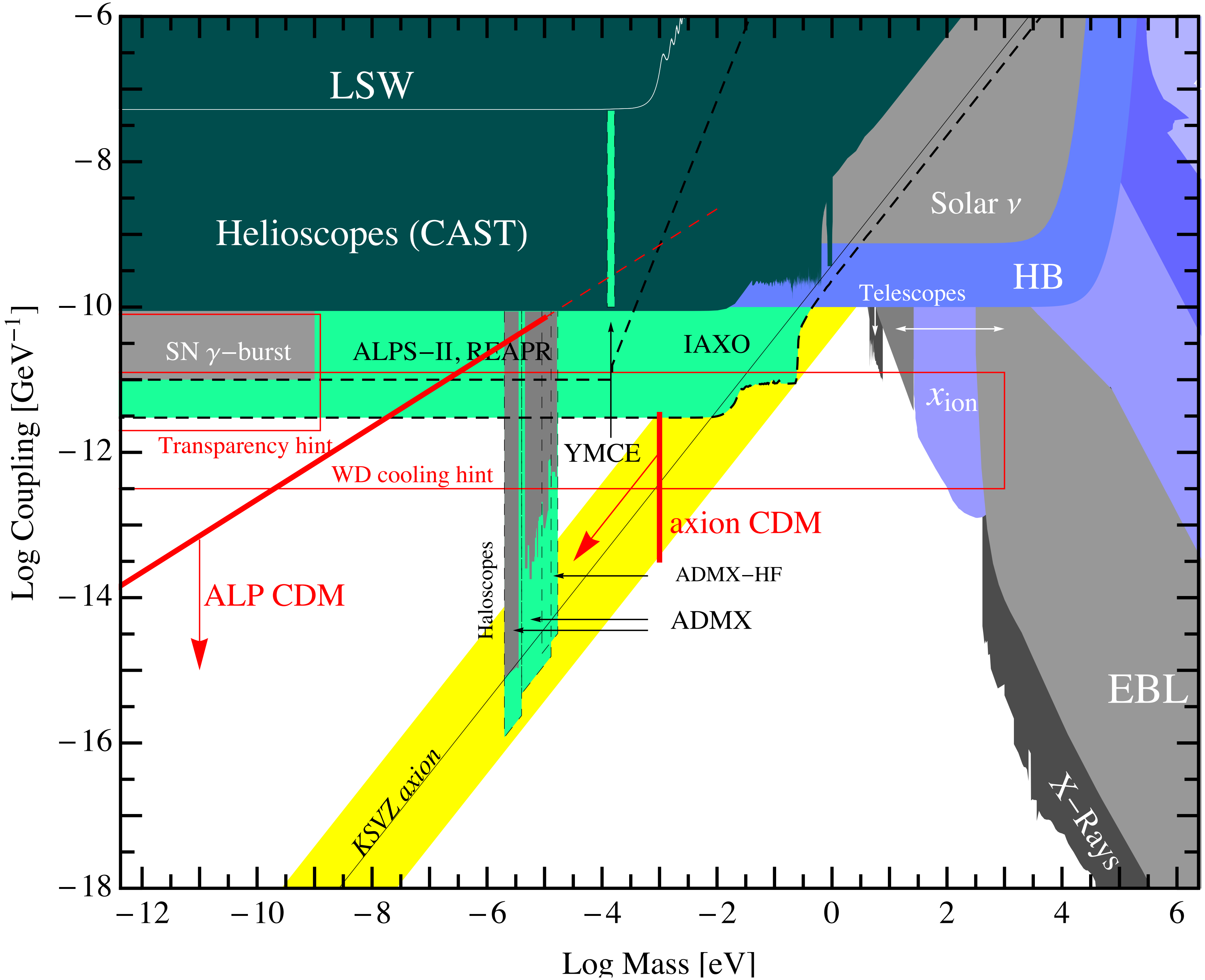


2 axion populations: Cold axions



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

Lay of the land



A new scale for perturbed scalars

- *Perturbations obey*

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

- *Structure suppressed when*

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

- *Scales are very small for QCD axion*

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

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

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

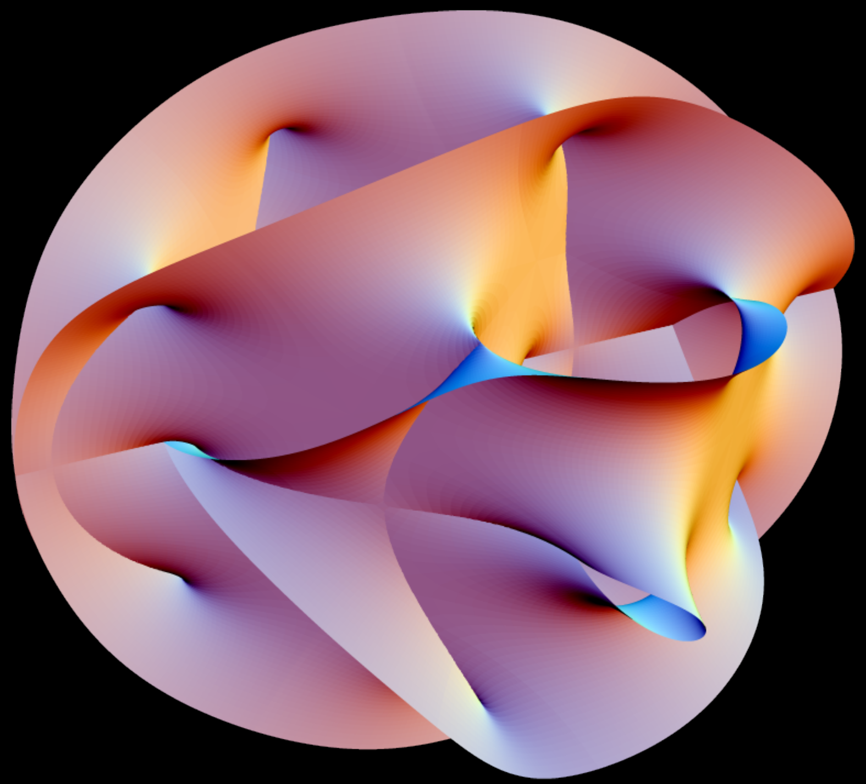
$$S_{a\gamma} = \frac{\delta n_a}{n_a} - \frac{\delta n_\gamma}{n_\gamma} = \frac{\delta\rho_a}{\rho_a} - \frac{3}{4}\frac{\delta\rho_\gamma}{\rho_\gamma} \sim 10^{-5}$$

Axiverse! (Arvanitaki et al. 2009)

- Calabi-Yau manifolds

Many 2-cycles → Many axions

Hundreds!

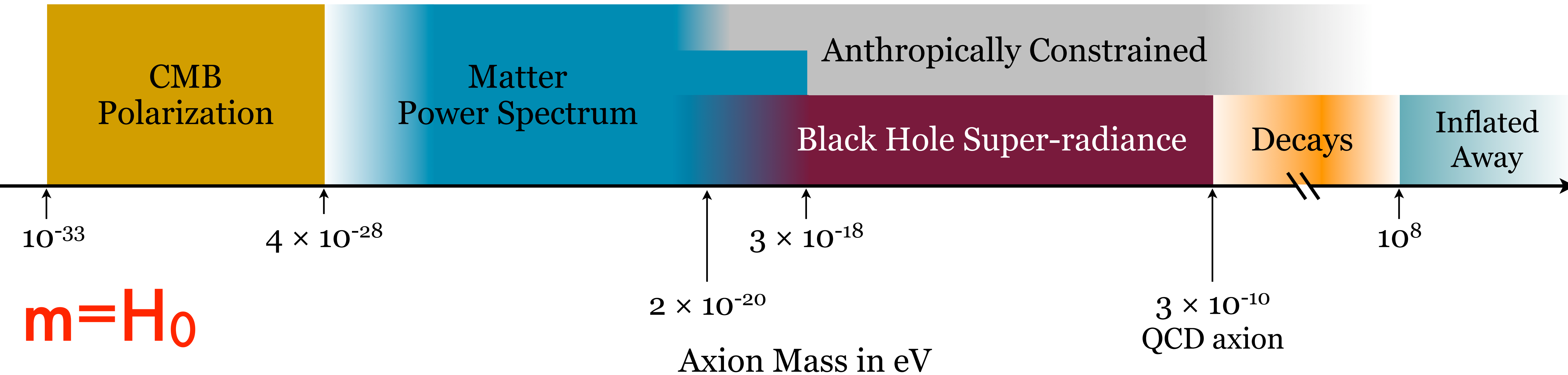


- Mass from non-perturbative physics (instantons, D-branes)

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

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***

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

Effective fluid approximation

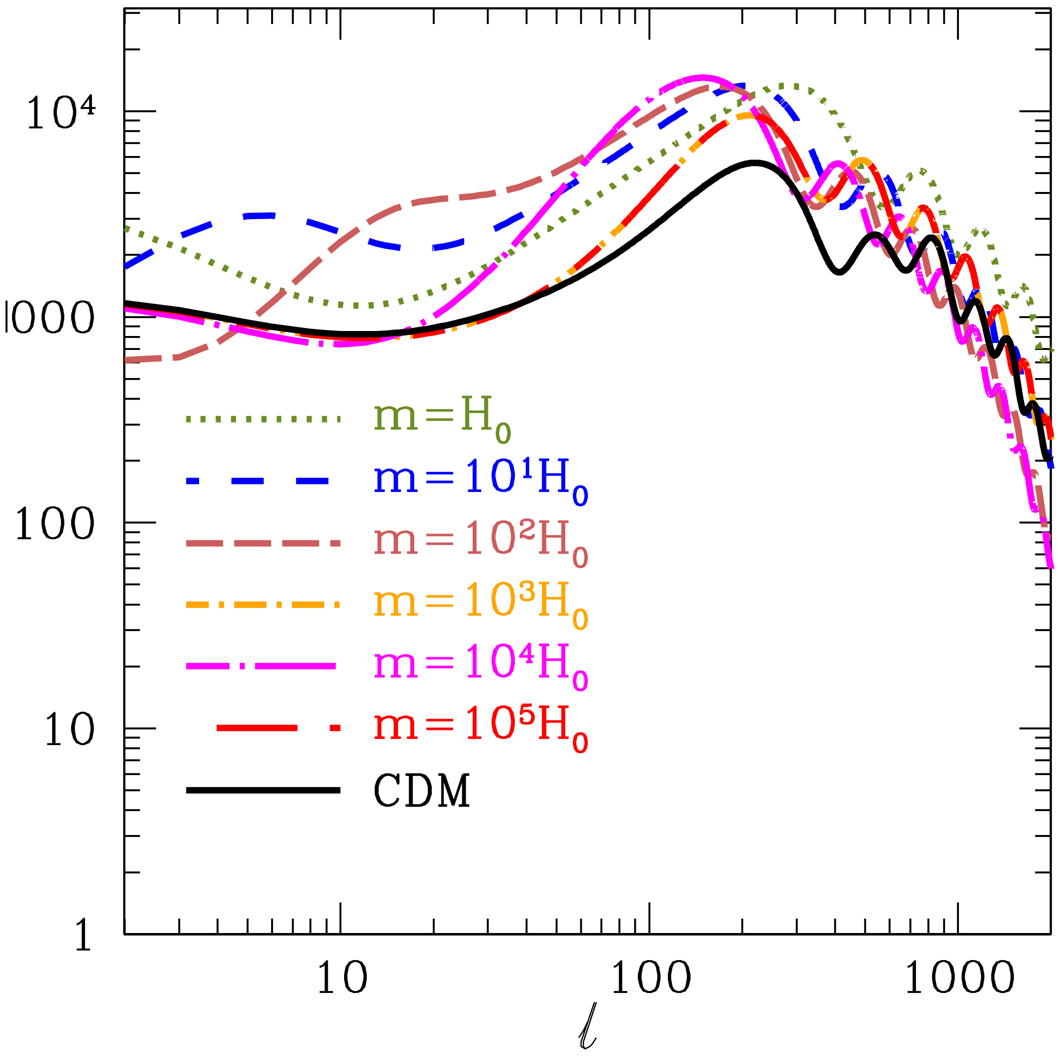
- Computing observables is expensive for $m \gg H_0$:
  - Coherent oscillation time scale

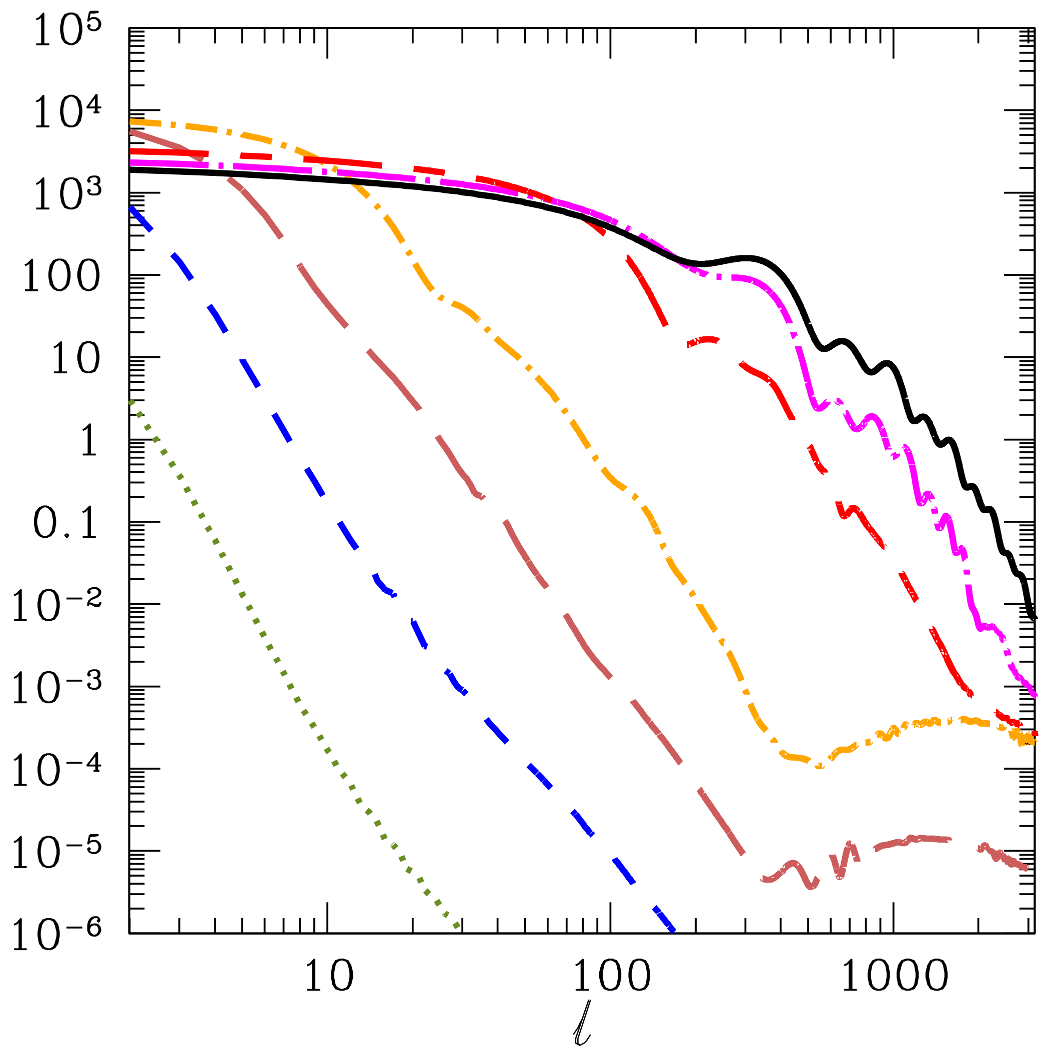
$$\Delta\eta \sim (ma)^{-1} \ll \Delta\eta_{\rm CAMB}$$

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

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

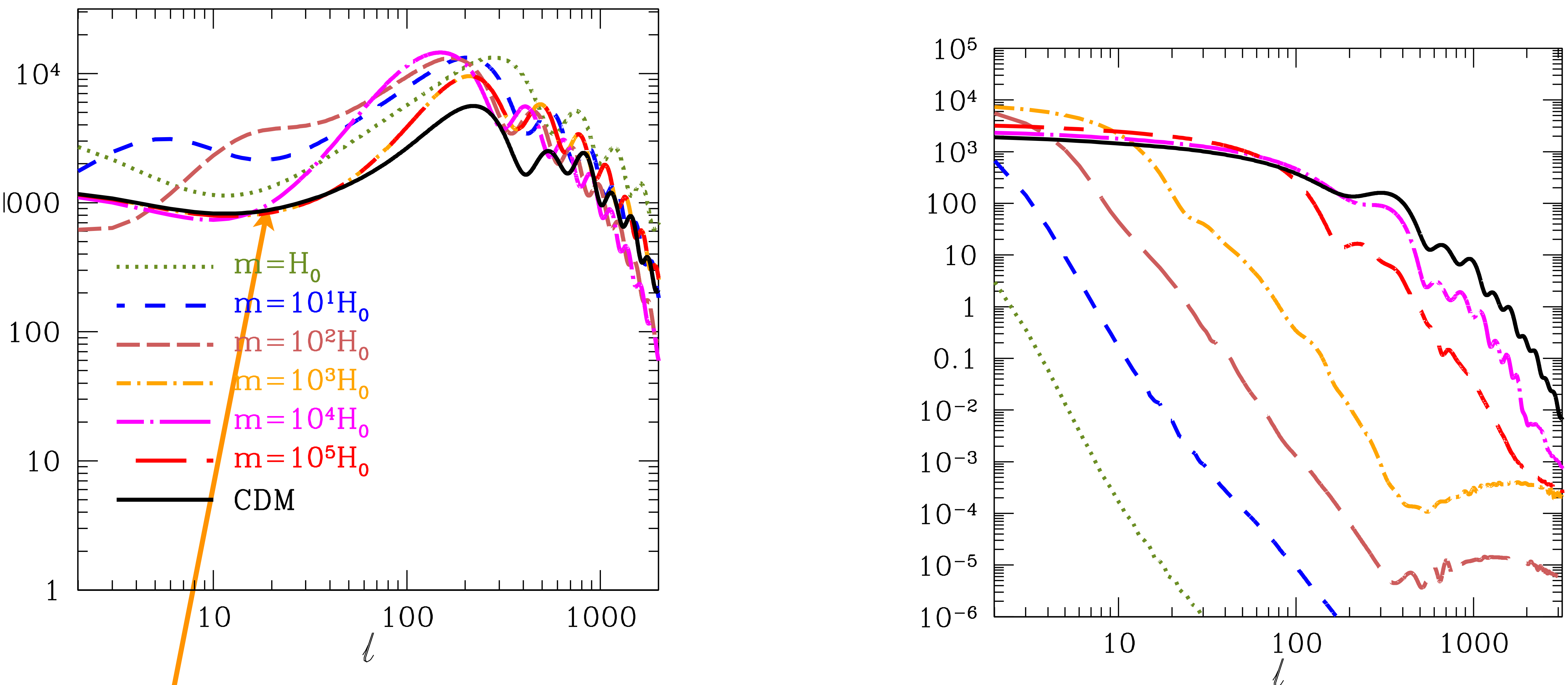
CMB anisotropy power spectra





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

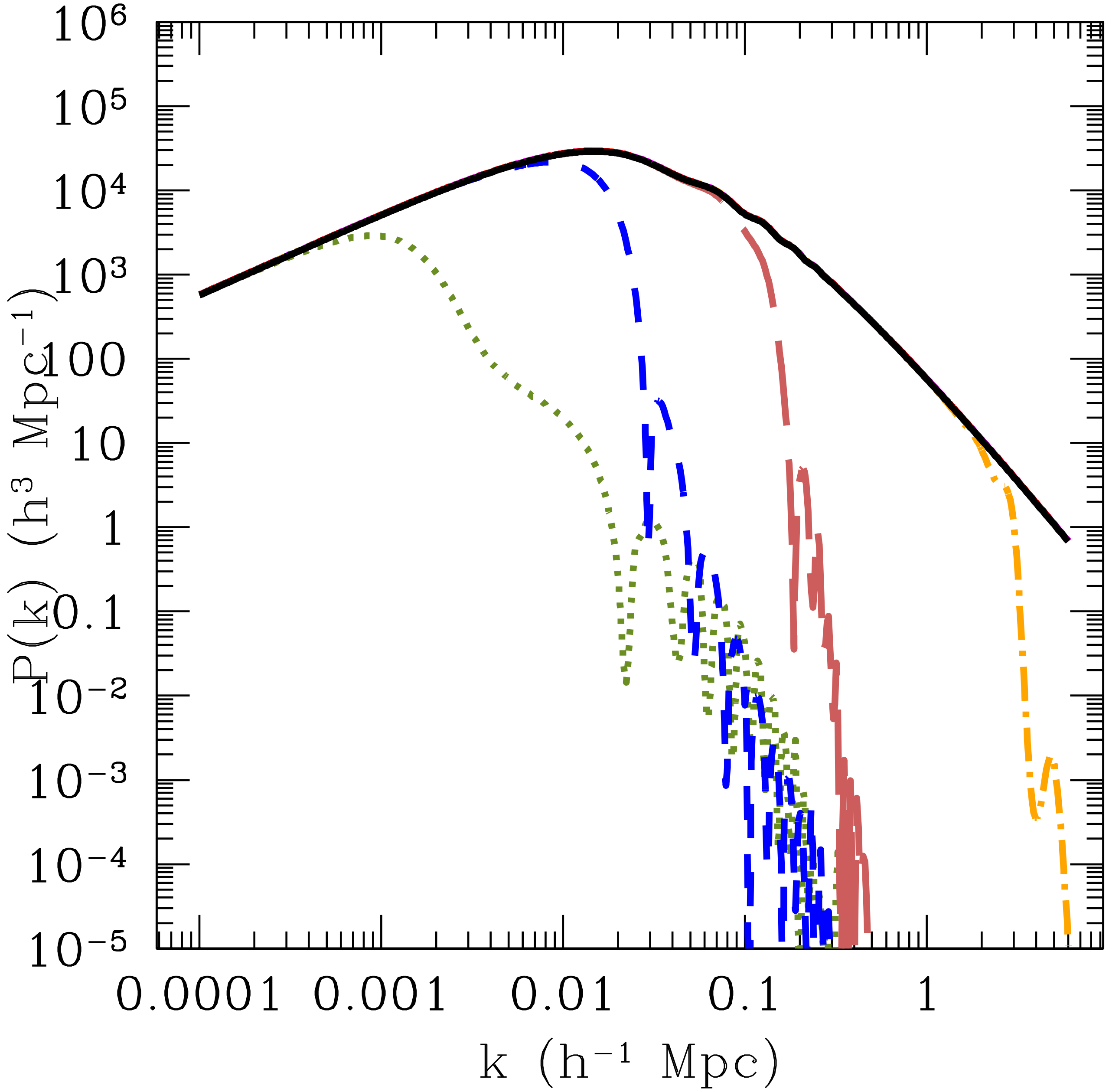
CMB anisotropy power spectra



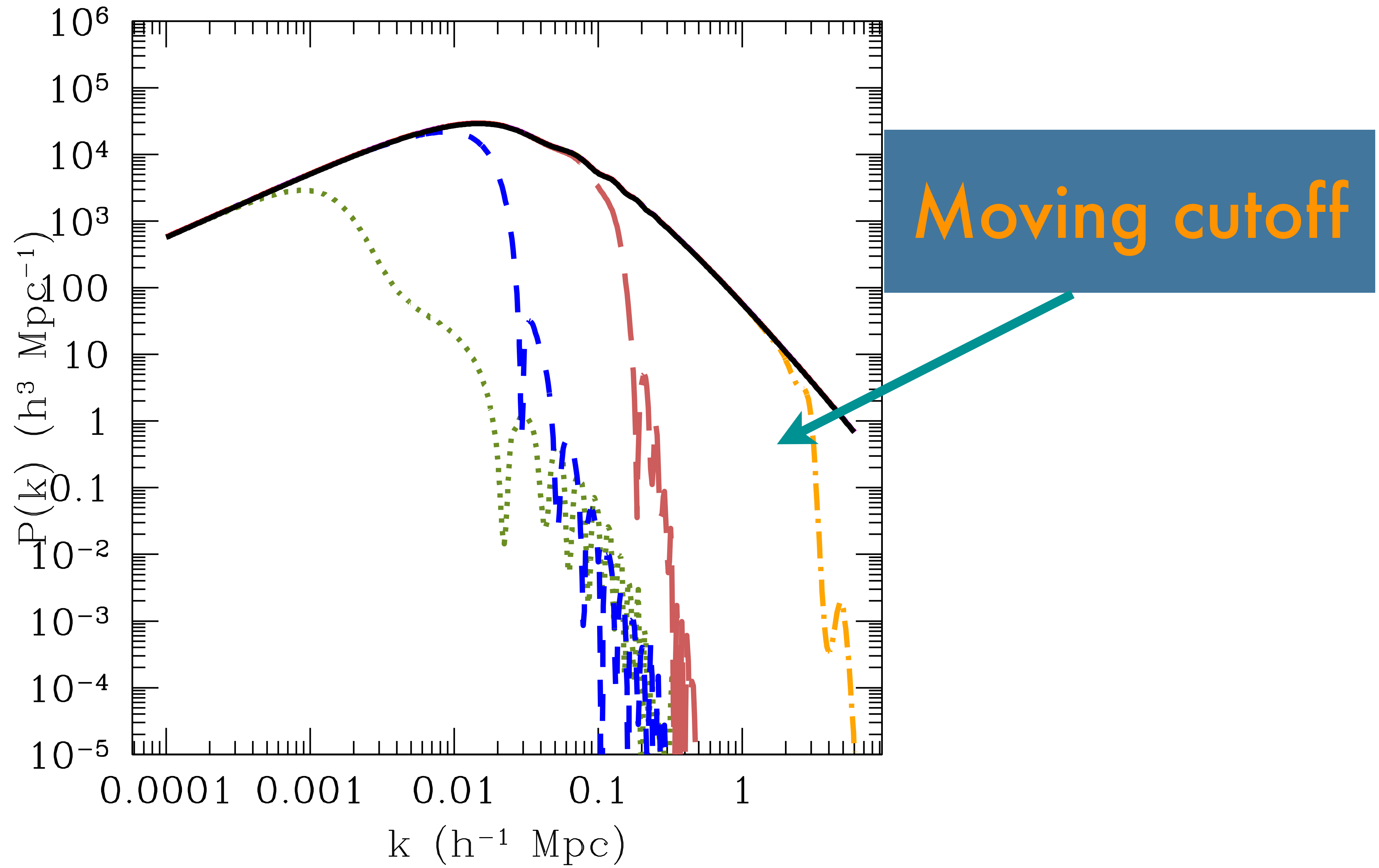
Enhanced ISW

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

Matter power spectrum



Matter power spectrum



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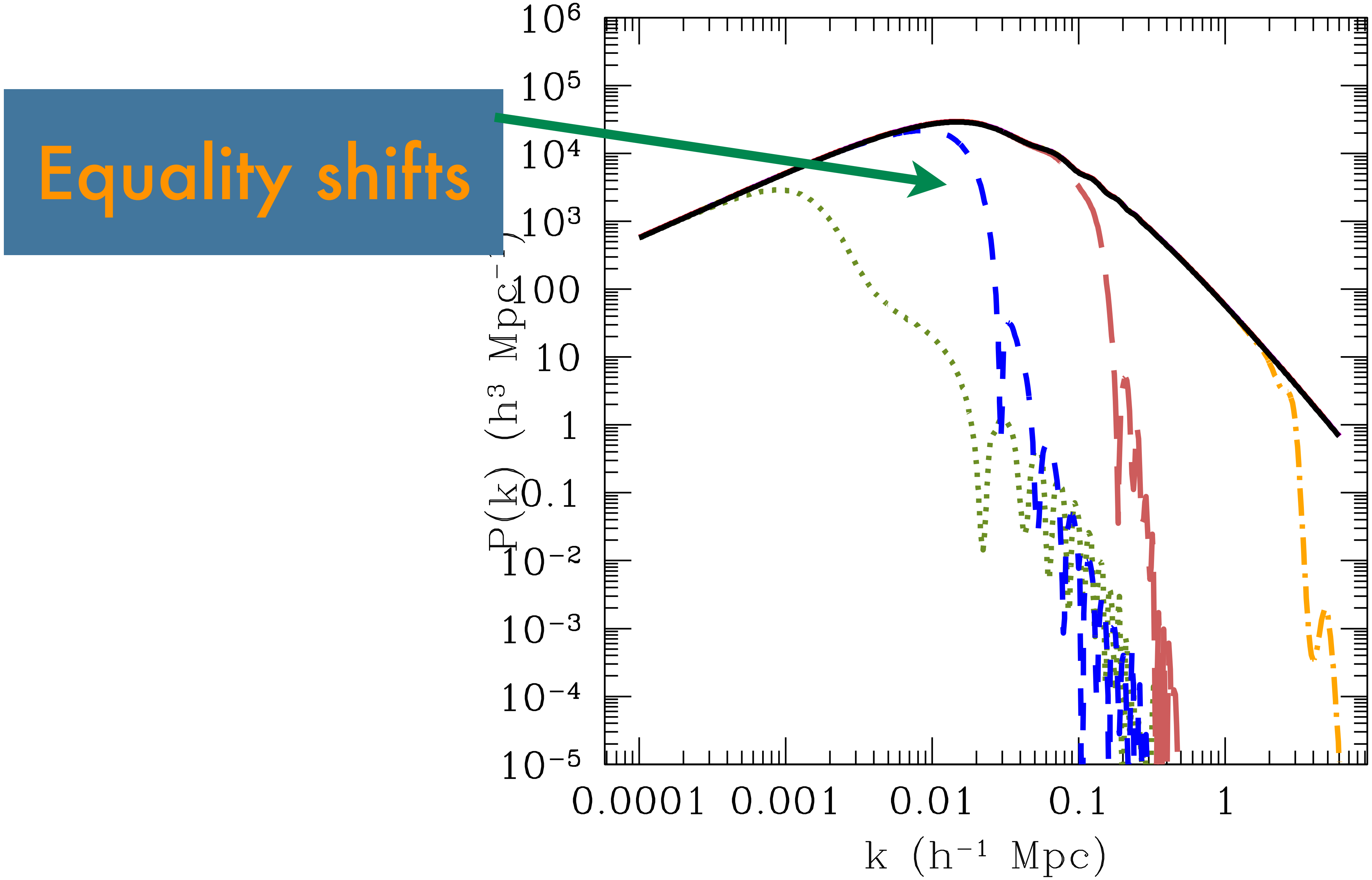

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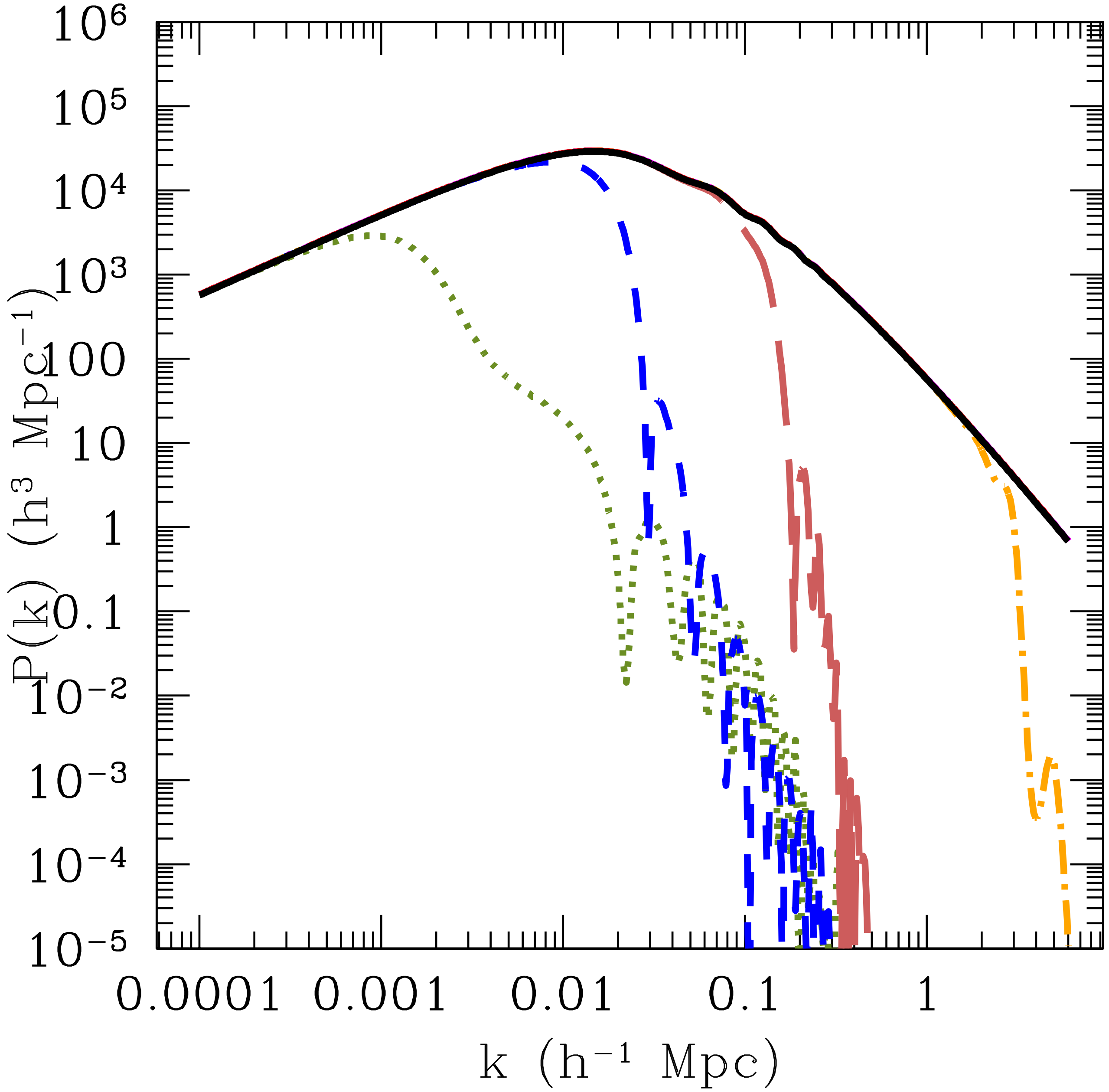

We may now probe ultra-light axions and the axiverse with an MCMC covering 15 orders of magnitude in axion mass

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

Komatsu al. 2008/2011 find

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

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

Stay tuned for MCMC constraints to the axiverse!

Conclusions

- Fast algorithm for Realization-normalized estimator of local non-Gaussianity.
    - Late time ISW degrades it!
    - Secondary tracers to the rescue
- Baryons ***DO*** trace DM at surface of last-scattering. Soon we will know how well!
- New fast code to compute cosmo consequences of ultra-light axion
- Tight constraint to axion EM coupling for 8 eV<m<14 eV

A new telescope search for decaying relic axions

with K.Z. Khor, M. Kamionkowski, E.Jullo, G.Covone, J.P-Kneib

Axion decay line

- Monochromatic emission line:

$$\lambda = \frac{c}{m_a c^2/2h} = 24800\mathring{A}\,\frac{(1+z_c)}{m_a/\text{ eV}}$$

- Resolvable $\delta\lambda = 195\sigma_{1000} m_{a,\text{eV}}^{-1} \mathring{A}$

- Axions decay:

$$\tau = 6.8\times 10^{24}\xi^{-2} m_{a,\text{eV}}^{-5}\text{ s}$$

- Axion thermal abundance

$$\Omega_{\text{ax}} h^2 \simeq \frac{m_a}{130\text{ eV}}$$

Axion decay line

- Monochromatic emission line:

$$\lambda = \frac{c}{m_a c^2/2h} = 24800\mathring{A}\,\frac{(1+z_c)}{m_a/\text{ eV}}$$

Visible

- Resolvable $\delta\lambda = 195\sigma_{1000} m_{a,\text{eV}}^{-1}\mathring{A}$

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$$\tau = 6.8\times 10^{24}\xi^{-2} m_{a,\text{eV}}^{-5}\text{ s}$$

- Axion thermal abundance

$$\Omega_{\text{ax}} h^2 \simeq \frac{m_a}{130\text{ eV}}$$

Axion decay line

- Monochromatic emission line:

Visible

$$\lambda = \frac{c}{m_a c^2/2h} = 24800\mathring{A}\ \frac{(1+z_c)}{m_a/\ \mathrm{eV}}$$

- Resolvable $\delta\lambda = 195\sigma_{1000} m_{a,\mathrm{eV}}^{-1} \mathring{A}$

- Axions decay:

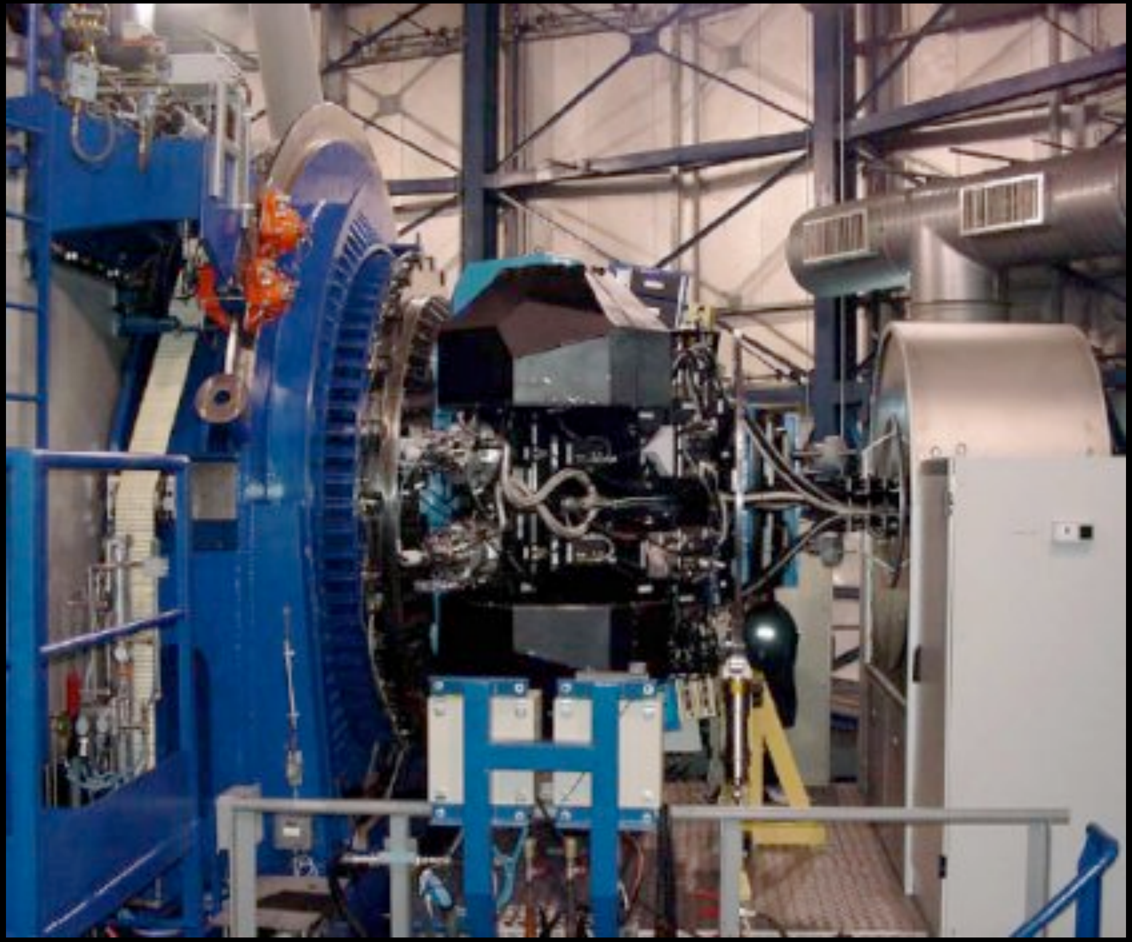
$$\tau = 6.8 \times 10^{24} \xi^{-2} m_{a,\mathrm{eV}}^{-5}\ \mathrm{s}$$

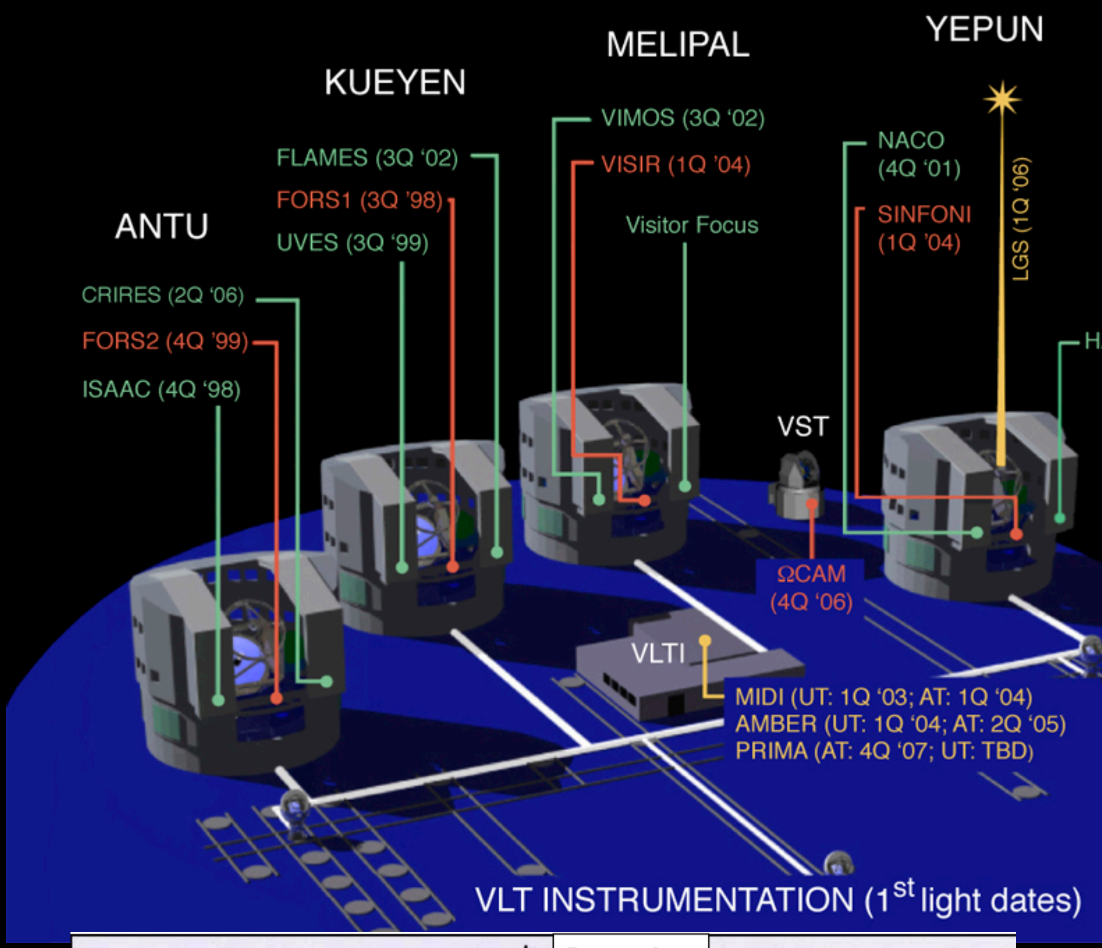
Following in the footsteps of Ressell, Bershady, Turner 1991

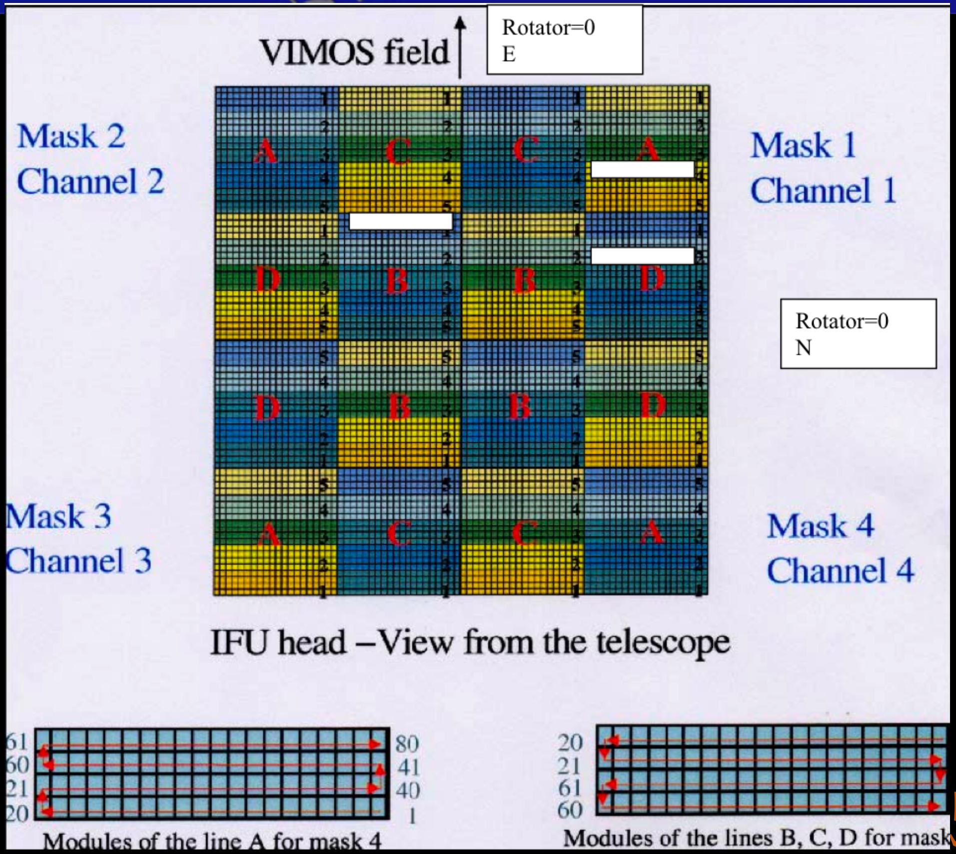
VIMOS IFU

- At VLT (Very Large Telescope) array of ~8 m instruments at Paranal, Chilé

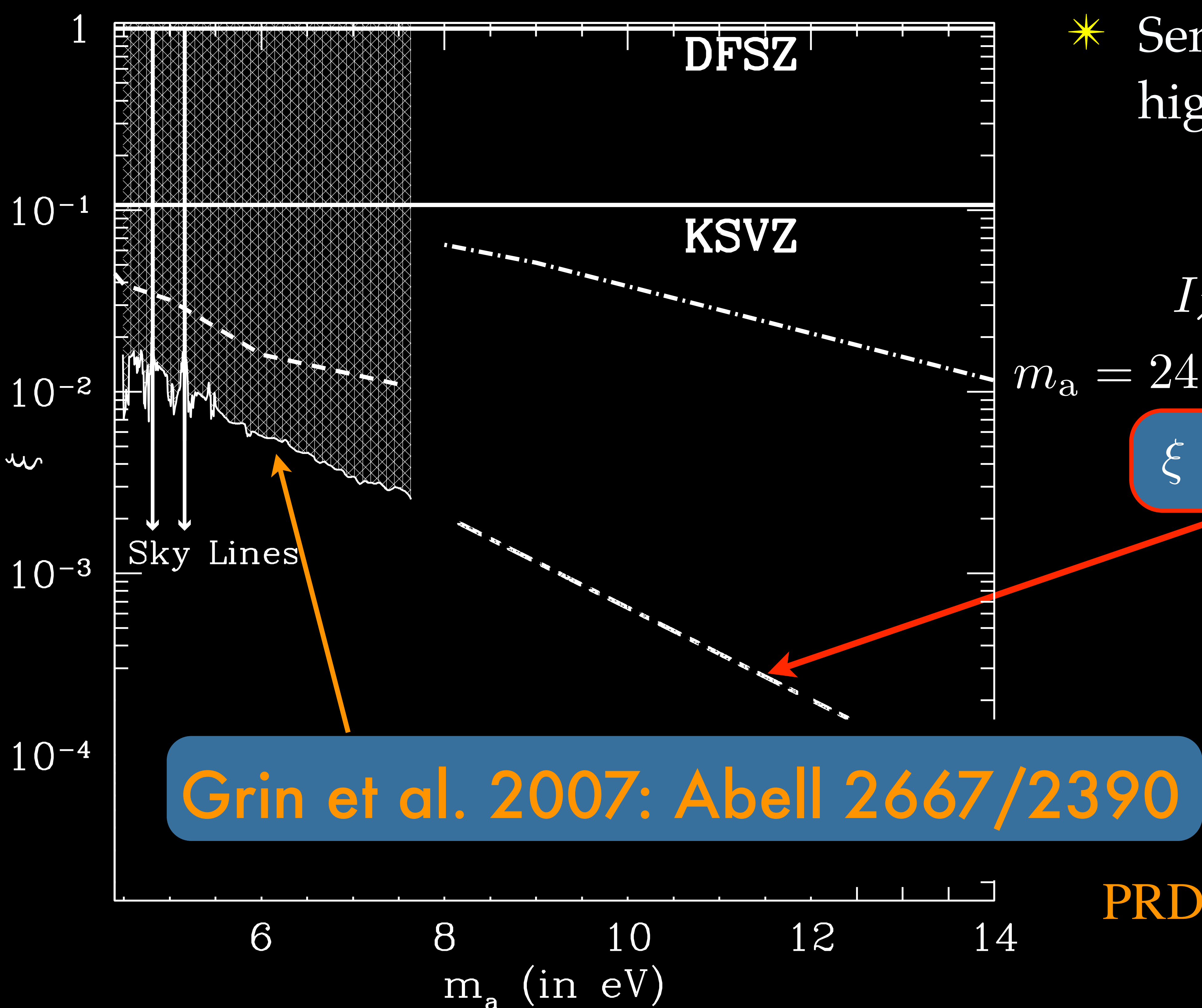
- VIMOS IFU yields spatially resolved spectroscopy (6400 fibers in 1 arcmin^{2})







Extending the optical axion window



- Sensitivity improves at higher redshift!

$$I_{\lambda_o} \propto m_a^7 (1 + z_{cl})^{-4}$$

$$m_a = 24,800 \text{ Å} (1 + z_{cl}) / \lambda_a$$

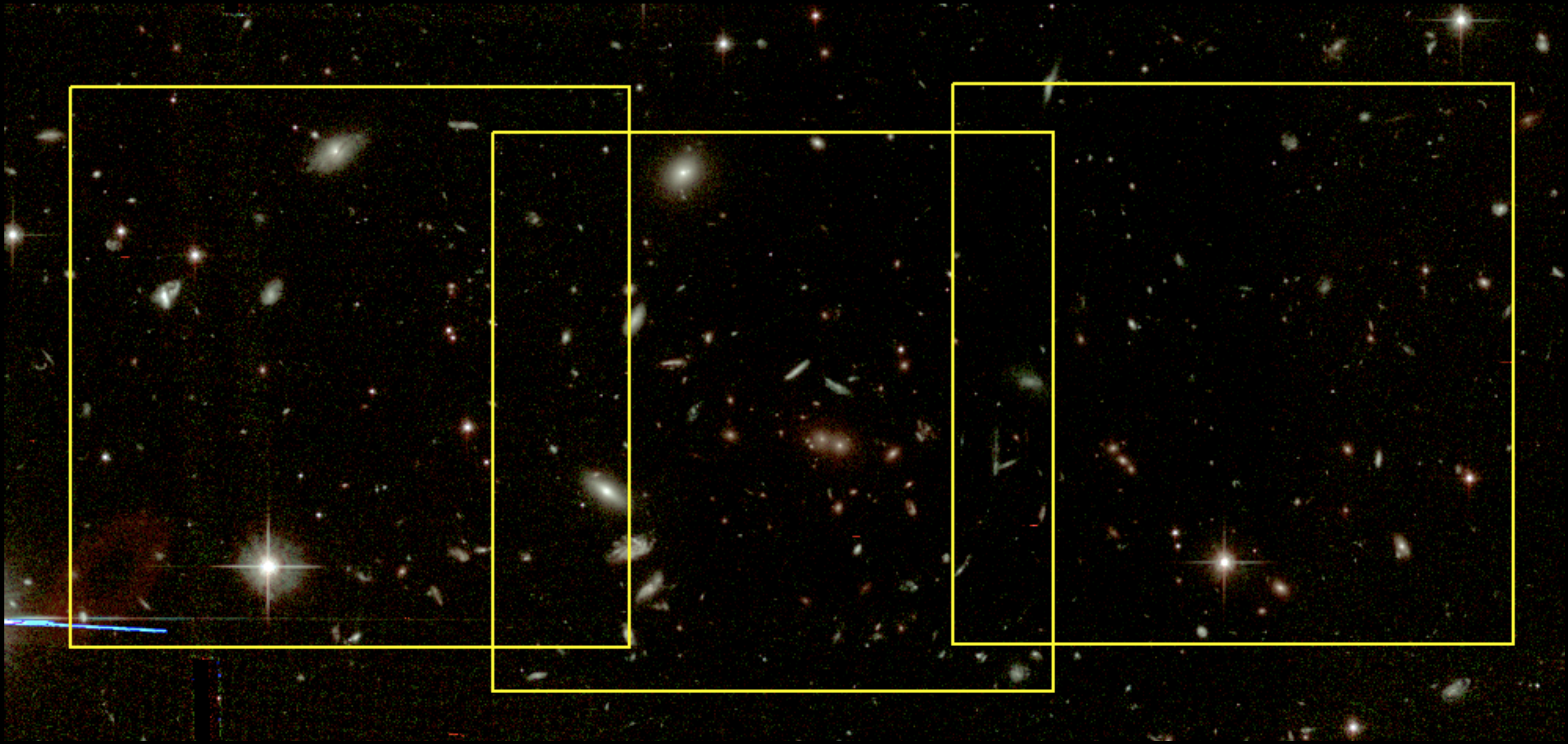
$$\xi \propto I_{\lambda_o}^{1/2} (1 + z_{cl})^{-3/2}$$

PRD, astro-ph/0611502

RDCS 1252

- RDCS 1252 is a $8 \times 10^{14} M_{\odot}$ cluster at $z = 1.237$
- Obtained 17 hrs of time for VIMOS IFU spectra using LR-Blue grism
- Publicly available weak-lensing mass maps (Lombardi et al. 2005) + single confirmed SL arc

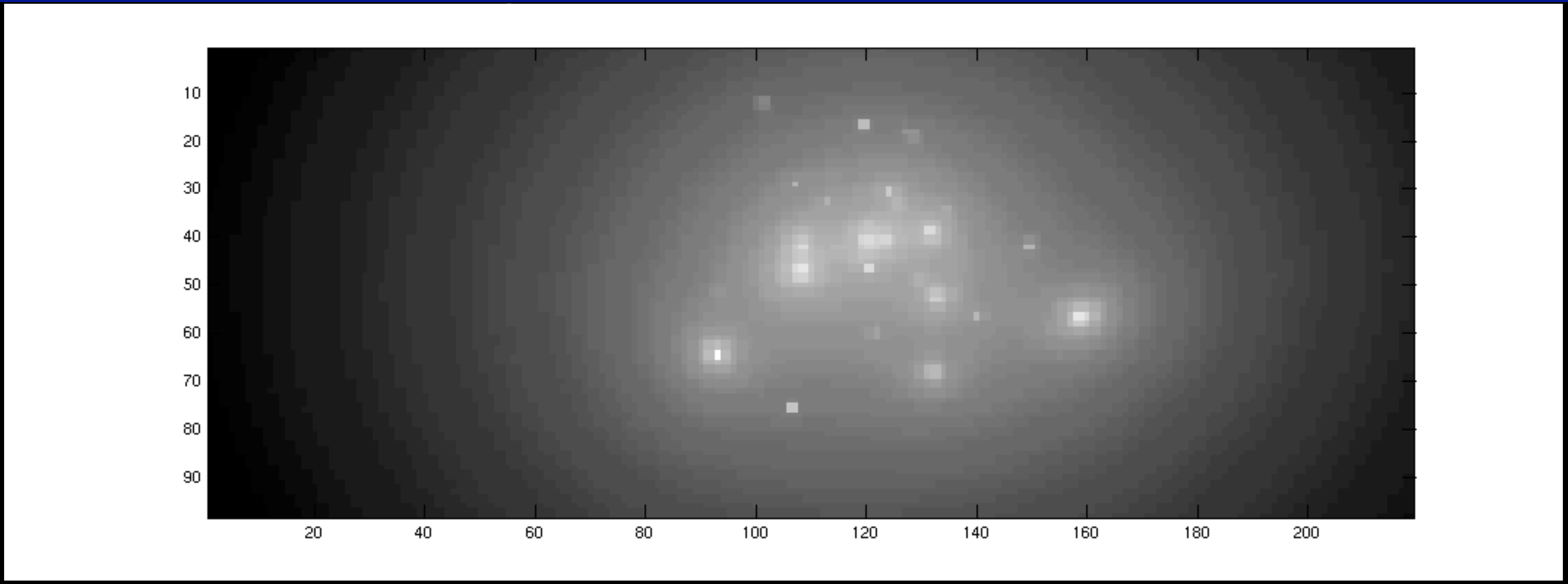
RDCS 1252



RDCS 1252

K.Z. Khor (Princeton Class of 2014)

Cluster mass maps and masking



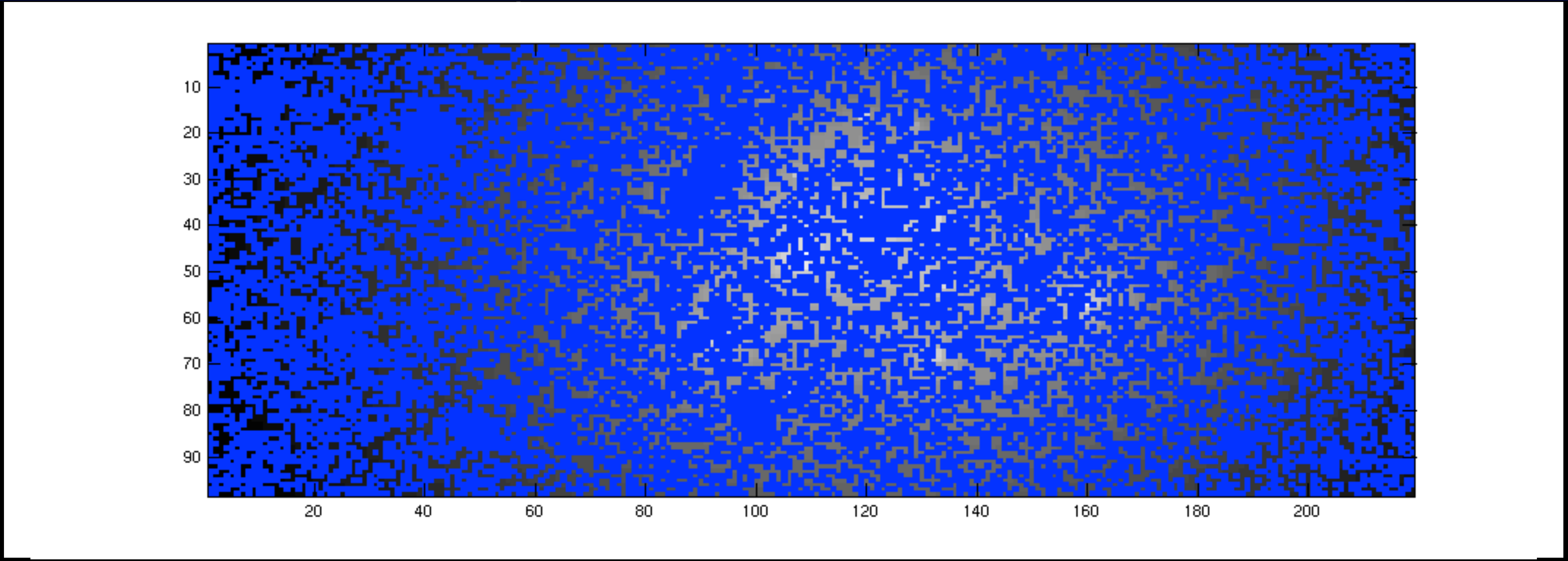
$\Sigma(10^{12} M_\odot \text{ pix}^{-2})$

- Cluster galaxies selected by redshift
- BCG, galaxies near arcs, cluster-scale mass component modeled individually

$$\Sigma(R) = \frac{\Sigma_0 r_0}{1 - r_0/r_t} \left(\frac{1}{\sqrt{r_0^2 + R^2}} - \frac{1}{\sqrt{r_t^2 + R^2}} \right)$$

- HST Shear map (Rosati et al.) and arc locations fit

Cluster mass maps and masking



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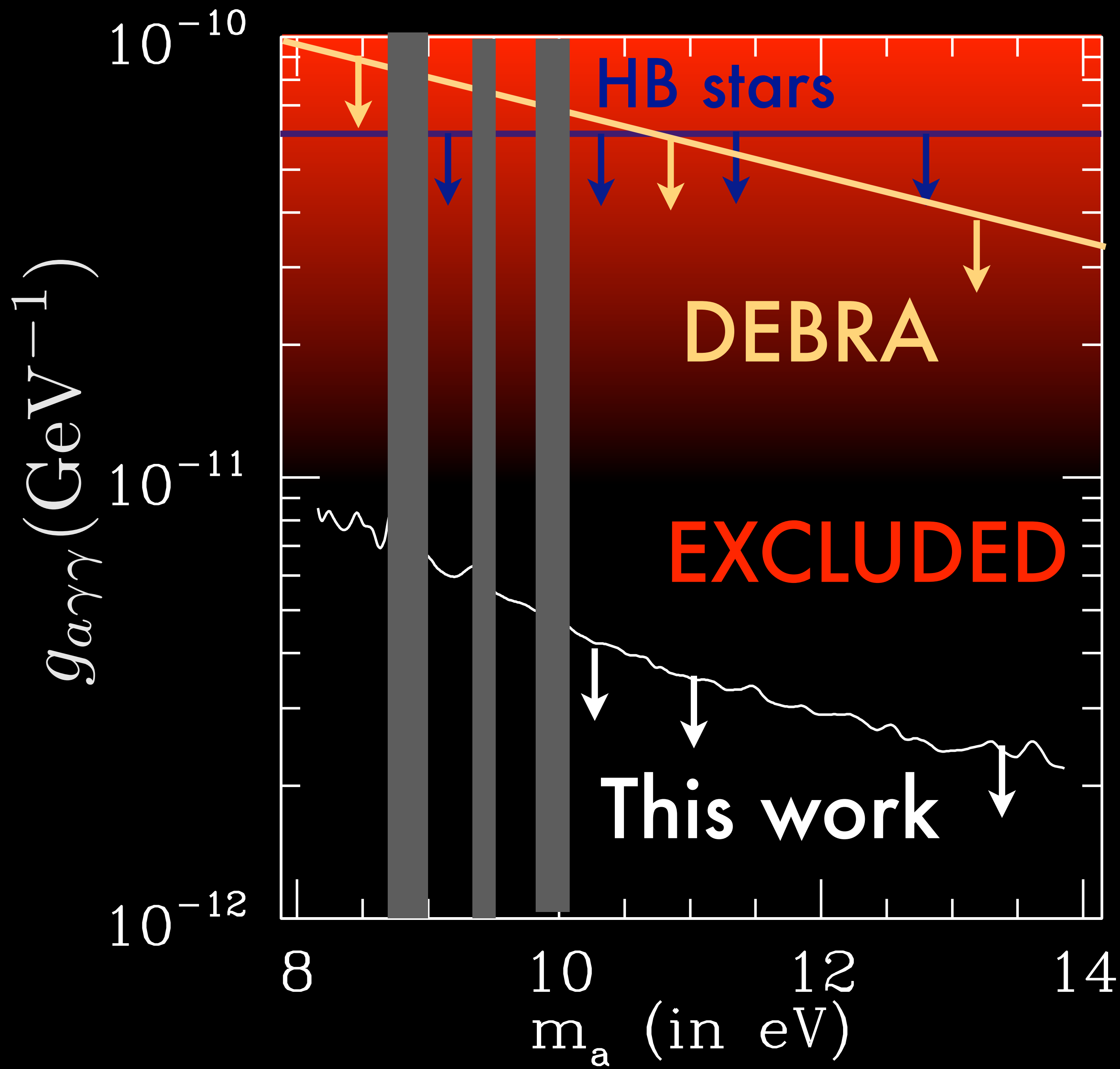
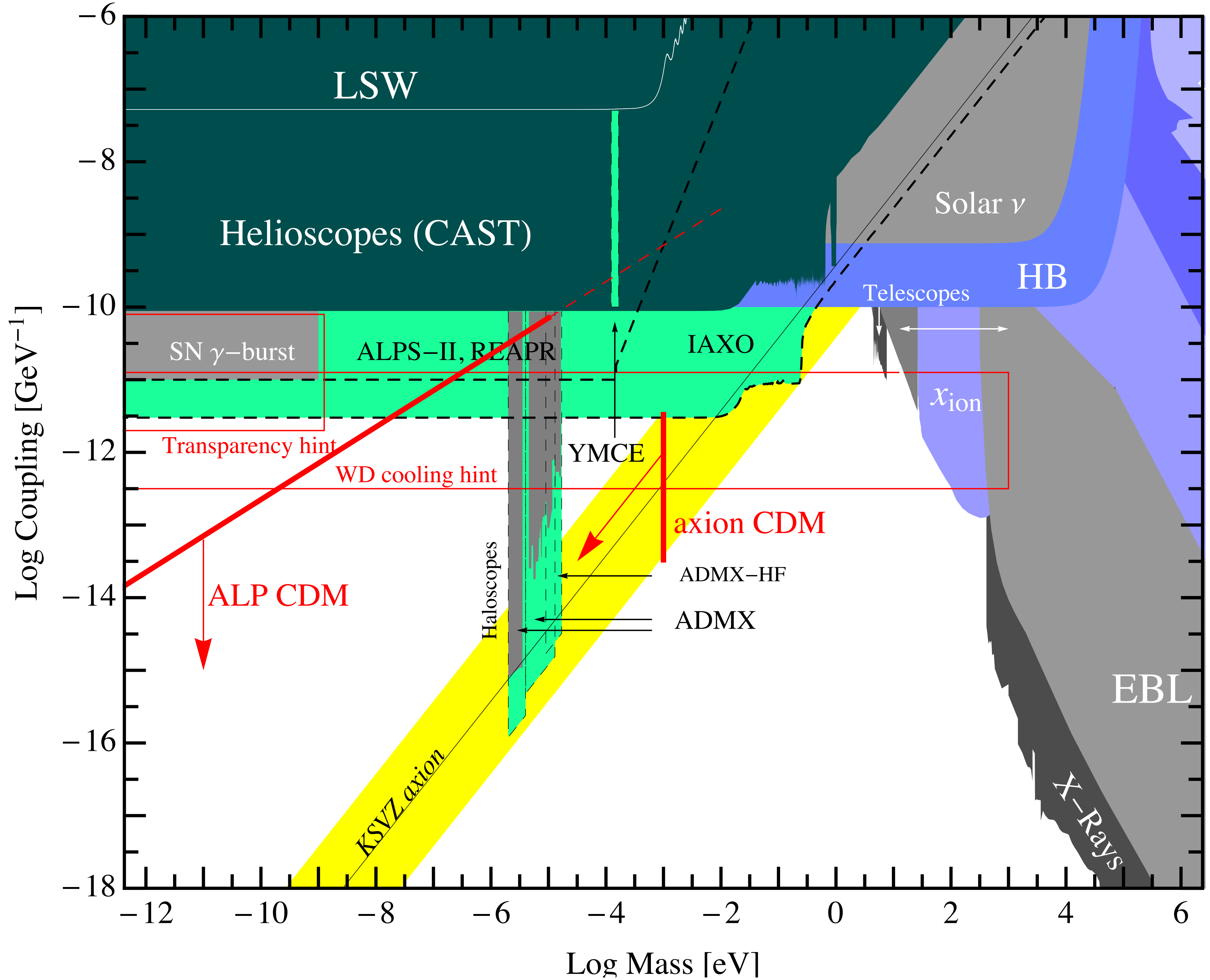
✳HST Shear map (Rosati et al.) and arc locations fit

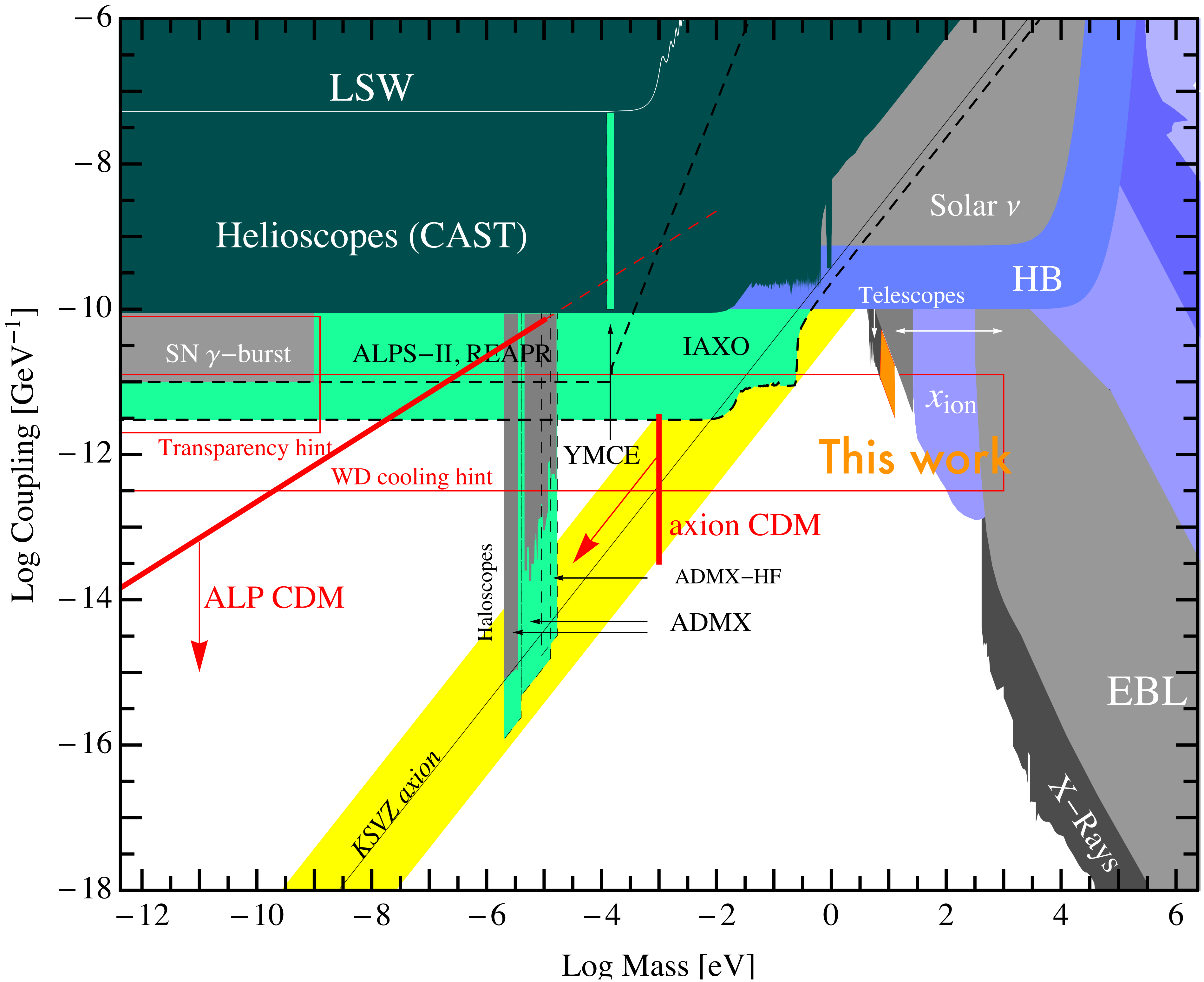
Axion constraints



Parameter space in context



Parameter space in context



Conclusions

- Fast algorithm for Realization-normalized estimator of local non-Gaussianity.
  - Late time ISW degrades it!
  - Secondary tracers to the rescue
- Baryons ***DO*** trace DM at surface of last-scattering. Soon we will know how well!
- New fast code to compute cosmo consequences of ultra-light axion
- Tight constraint to axion EM coupling for 8 eV<m<14 eV

Fast algorithm

$$B(\hat{n}, r) = \sum_{lm} \beta_l(r) Y_{lm}(\hat{n}) a_{lm}$$

$$\hat{\mathcal{B}}_1 = 9\sigma_0^{-2} \sum_{lm} \mathcal{V}_{lm} \mathcal{V}^*_{lm}$$

$$\mathcal{V}_{lm} = \int dr r^2 \alpha_l(r) B^{(2)}_{lm}(r)$$

$$B^{(2)}_{lm}(r) = \int d\hat{n} Y^*_{lm}(\hat{n}) B^2(r, \hat{n})$$

$l_{\mathrm{max}}^{5/2} \log\left(l_{\mathrm{max}}\right) N_{\mathrm{int}}$ vs l_{max}^{10}

FFTs can be used to dramatically accelerate the RNE!
(in spirit of Komatsu, Spergel, Wandelt 2003)

CURVATON

- 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.

$$S_c = \delta_c - \frac{3}{4}\delta_{\rm rad} = -\frac{3}{4}\delta_{\rho_\sigma}$$

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

$$\Phi \propto \zeta = \frac{\rho_\sigma}{3\rho_{\rm tot}}\delta_{\rho_\sigma} = \frac{\rho_\sigma}{3\rho_{\rm tot}}\left[2\frac{\delta\sigma}{\sigma} + \left(\frac{\delta\sigma}{\sigma}\right)^2\right]$$

CURVATON

- 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

$$f_{\rm NL} = \frac{5\rho_{\rm tot}}{4\rho_\sigma}$$

Non-Gaussianity of local type!

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

$$\Phi \propto \zeta = \frac{\rho_\sigma}{3\rho_{\rm tot}}\delta_{\rho_\sigma} = \frac{\rho_\sigma}{3\rho_{\rm tot}}\left[2\frac{\delta\sigma}{\sigma} + \left(\frac{\delta\sigma}{\sigma}\right)^2\right]$$

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

$$\delta\,\{\rm T,\ E,\ B\} \propto \zeta\Delta \propto \zeta^2$$

$$\{\rm T,\ E,\ B\}_0 \propto \zeta$$

$$\langle XYZ \rangle \propto \zeta^4$$

COMPENSATED ISOCURVATURE AND THE CMB: *RECOVERING THE REALIZATION*

✴ Realization of CIPs breaks usual statistical isotropy

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

$$X \in \{\mathrm{T}, \mathrm{E}, \mathrm{B}\}\,, \quad D_{ll'}^{LM,XX'} = \Delta_{LM}\; S_{ll'}^{L,XX'}$$

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

COMPENSATED ISOCURVATURE AND THE CMB: *RECOVERING THE REALIZATION*

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Usual term

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

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

COMPENSATED ISOCURVATURE AND THE CMB: *RECOVERING THE REALIZATION*

- Realization of CIPs breaks usual statistical isotropy

Anisotropic generalization of C_l

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

$$X \in \{\mathrm{T}, \mathrm{E}, \mathrm{B}\}, \quad D_{ll'}^{LM,XX'} = \Delta_{LM} \; S_{ll'}^{L,XX'}$$

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

COMPENSATED ISOCURVATURE AND THE CMB: *RECOVERING THE REALIZATION*

- Realization of CIPs breaks usual statistical isotropy

Geometric function of multipoles

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

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$$X \in \{\mathrm{T},\mathrm{E},\mathrm{B}\}, \quad D_{ll'}^{LM,XX'} = \Delta_{LM} \, S_{ll'}^{L,XX'}$$

Response power spectra

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

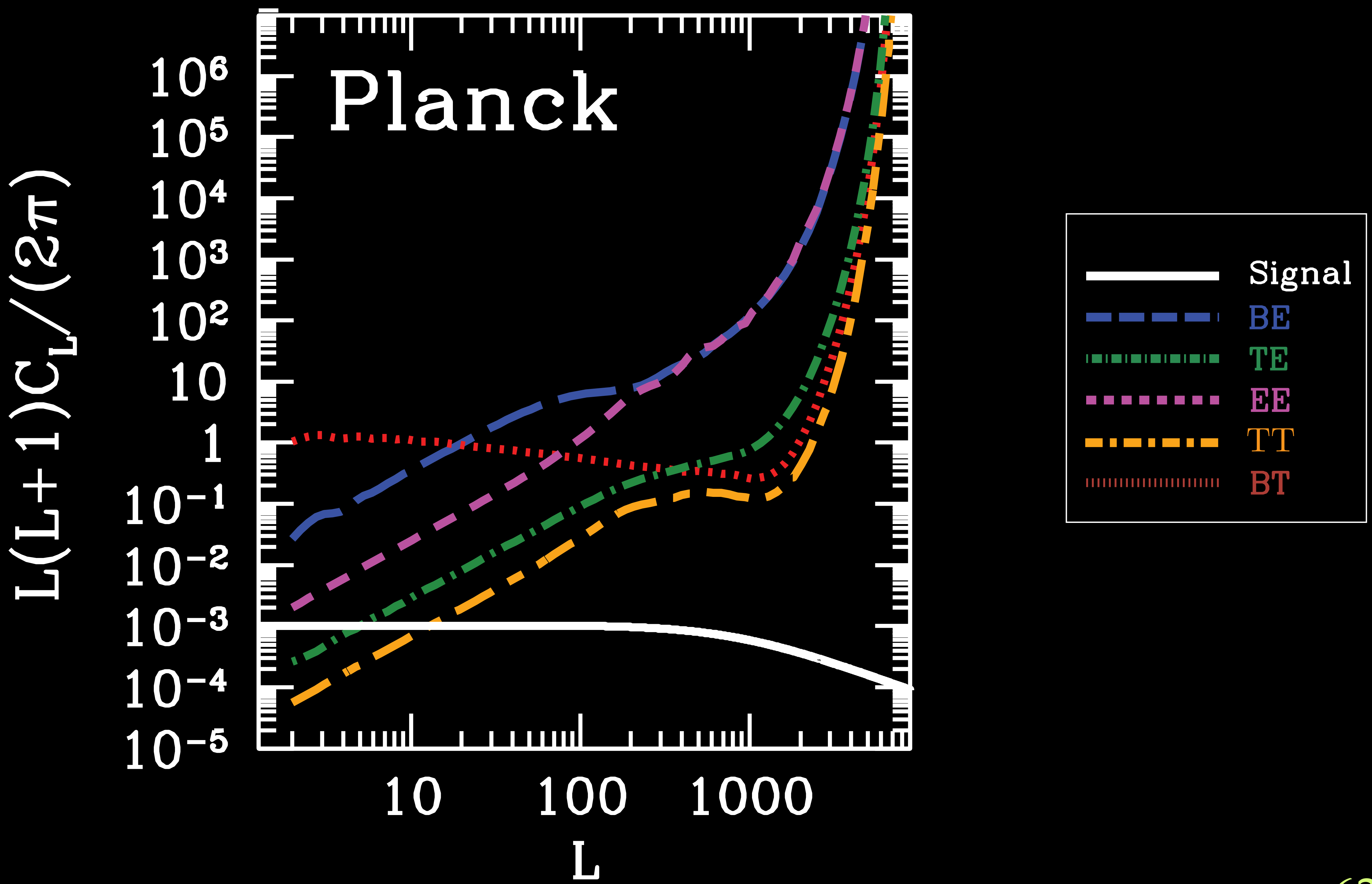
COMPENSATED ISOCURVATURE AND THE CMB: *NOISE CURVES*

- Special case: TB estimator

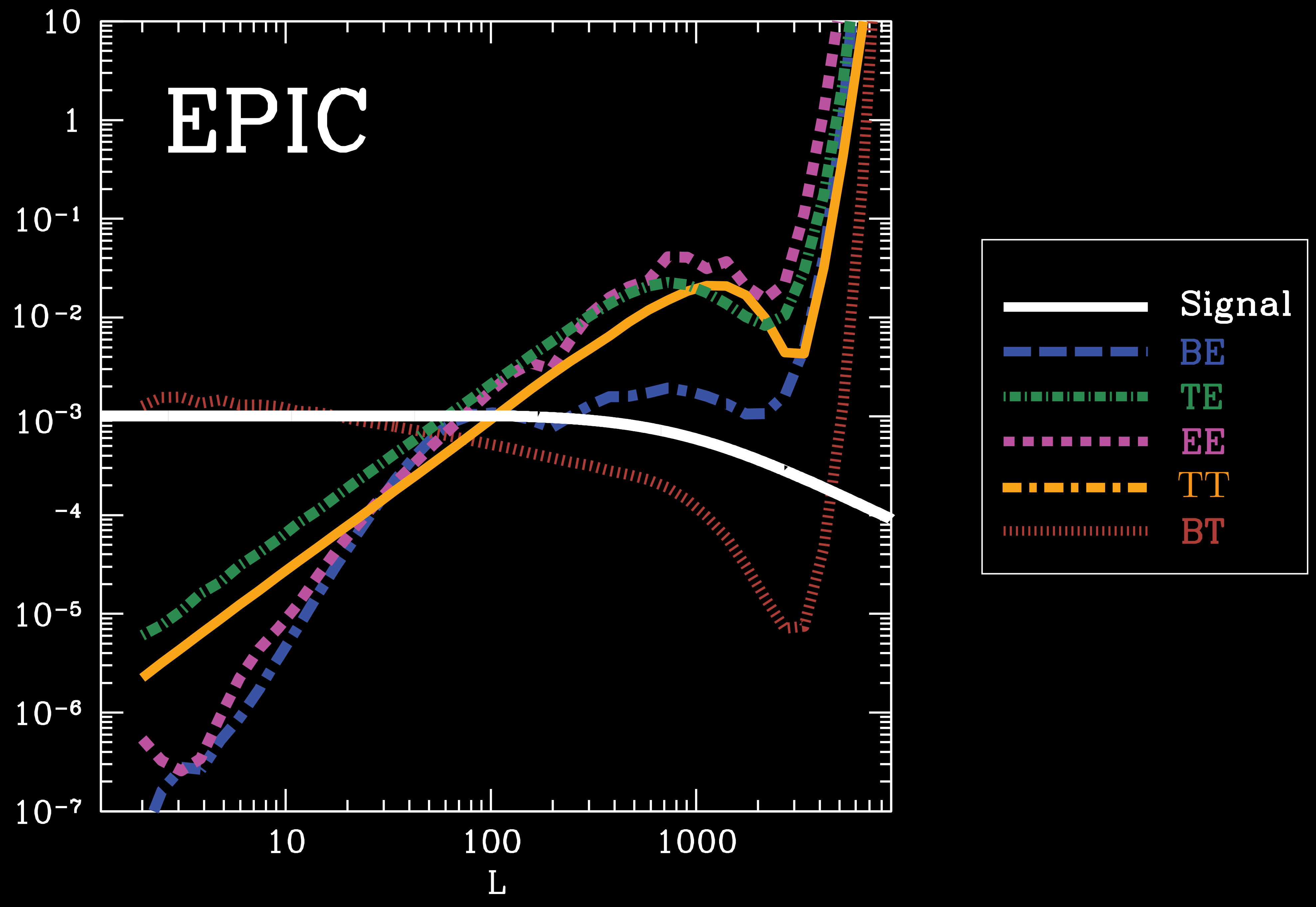
$$\widehat{\Delta}_{LM} = \sigma^2_{\Delta_{LM}} \sum_{l' \geq l}^{l+l'+L \text{ odd}} \frac{G_{ll'} \mathcal{S}_{ll'}^{LM,\mathrm{A}'} W_l W_{l'} \widehat{D}_{ll'}^{LM,\mathrm{A,map}}}{C_l^{\mathrm{BB,\ map}} C_{l'}^{\mathrm{TT,\ map}}},$$

$$\sigma^{-2}_{\Delta_L} = \sum_{l' \geq l}^{l+l'+L \text{ odd}} G_{ll'} \frac{\left(S_{ll'}^{LM,\mathrm{TB}} W_l W_{l'}\right)^2}{C_l^{\mathrm{BB,map}} C_{l'}^{\mathrm{TT,map}}} + \{\mathrm{T} \leftrightarrow \mathrm{B}\}.$$

COMPENSATED ISOCURVATURE AND THE CMB: *NOISE CURVES*

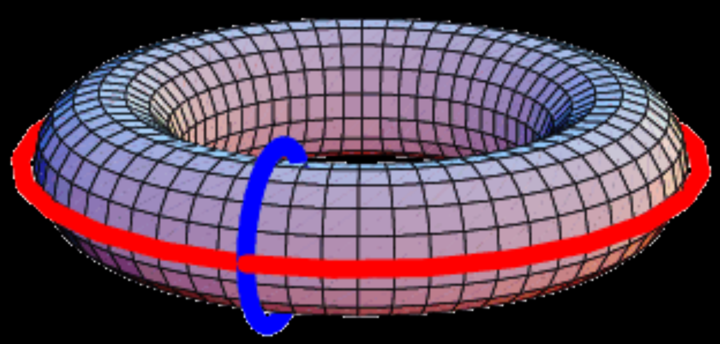


COMPENSATED ISOCURVATURE AND THE CMB: *NOISE CURVES*



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



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

CORRELATED CIPs AND THE CURVATON MODEL

- Induced (reduced) temperature bispectrum is

$$\langle a_{lm} a_{l'm'} a_{l''m''} \rangle = \sqrt{\frac{(2l+1)(2l'+1)(2l''+1)}{4\pi}} \begin{pmatrix} l & l' & l'' \\ 0 & 0 & 0 \end{pmatrix} b_{ll'l''} \begin{pmatrix} l & l' & l'' \\ m & m' & m'' \end{pmatrix}$$

$$b_{ll'l''} = \frac{A}{2} \int r^2 dr \frac{d\alpha_l}{d\Delta}(r)\beta_{l'}(r)\beta_{l''}(r) + \text{permutations}$$

$$\Delta = A\Phi$$

WORK IN PROGRESS

Perhaps a more sensitive probe is possible!

CORRELATED CIPs AND THE CURVATON MODEL

Compare with local-model bispectrum

$$b_{ll'l''} = 2f_{\rm NL}\int r^2 dr \alpha_l(r)\beta_{l'}(r)\beta_{l''}(r) + \text{permutations}$$

$$\Phi(\vec{x}) = \Phi_{\rm G} + f_{nl}\left(\Phi_G^2(\vec{x}) - \left\langle \Phi_{\rm G}^2(\vec{x})\right\rangle\right)$$

$$b_{ll'l''} = \frac{A}{2}\int r^2 dr \frac{d\alpha_l}{d\Delta}(r)\beta_{l'}(r)\beta_{l''}(r) + \text{permutations}$$

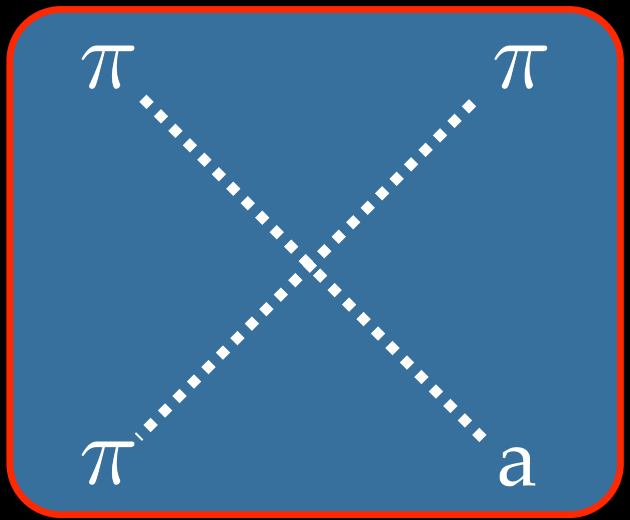
$$\Delta = A\Phi$$

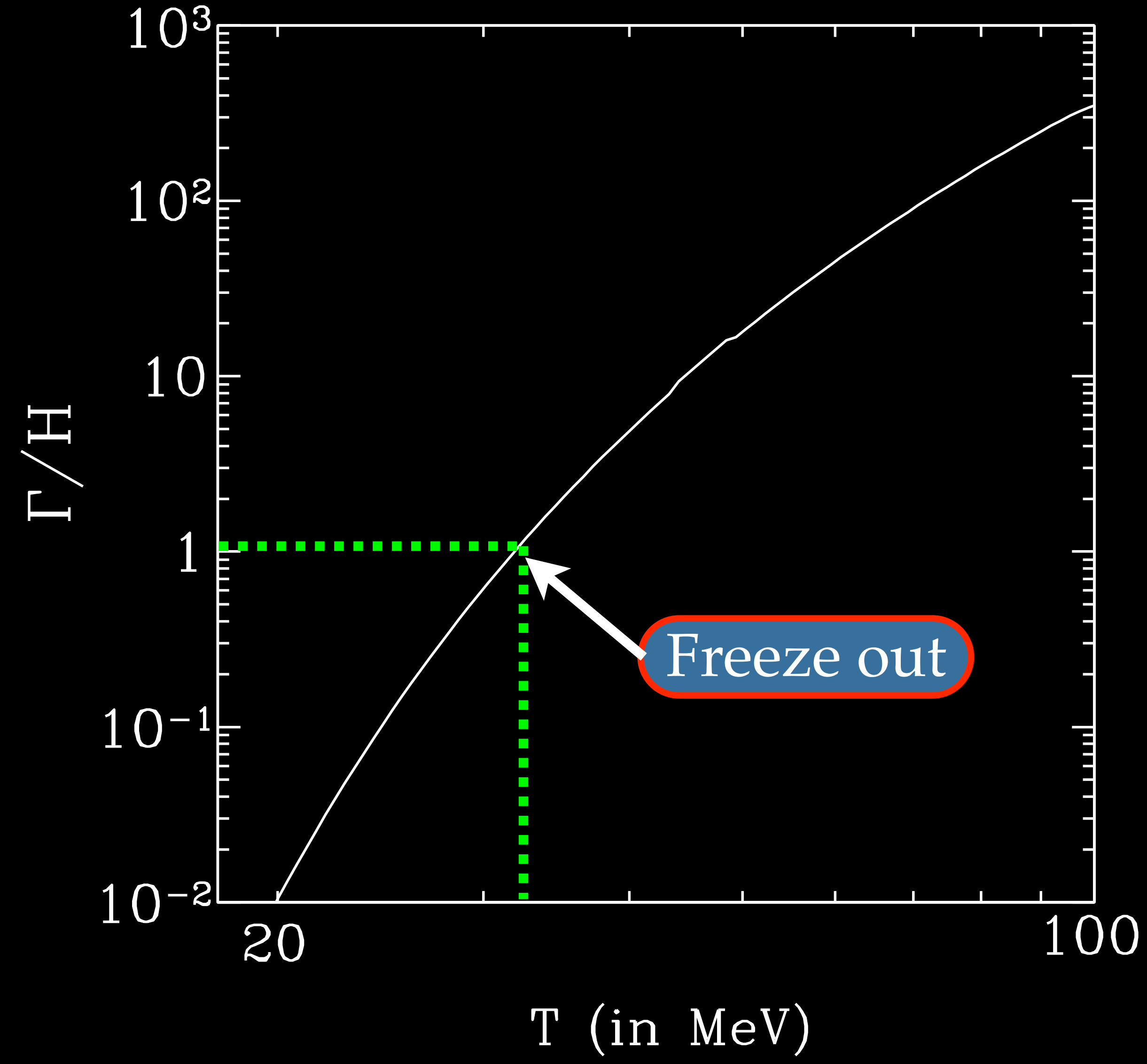
WORK IN PROGRESS

Perhaps a more sensitive probe is possible!

Hot axion production at early times

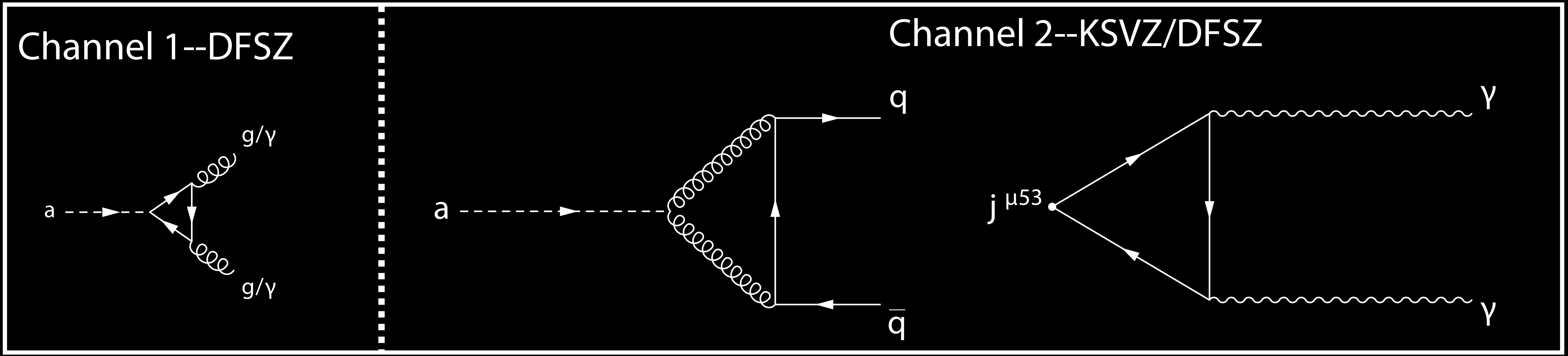
Axion Production:





- Axions produced through interactions between non-relativistic pions in chemical equilibrium with rate

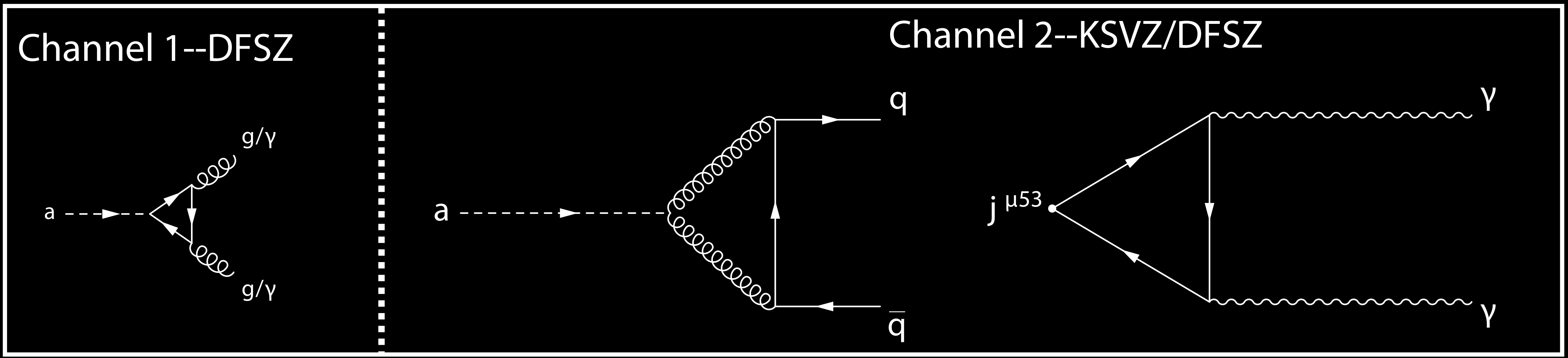
Axion decay



- Axions interact weakly with SM particles $\Gamma, \sigma \propto \alpha^2$
- Axions have a two-photon coupling $g_{a\gamma\gamma} = -\frac{3\alpha}{8\pi f_a}\xi$

$$\xi \equiv \frac{4}{3}\left\{E/N - \frac{2\,(4 + m_u/m_d)}{3\,(1 + m_U/m_d)}\right\}$$

Axion decay



- Axions interact weakly with SM particles $\Gamma, \sigma \propto \alpha^2$
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QCD

$$\xi \equiv \frac{4}{3}\left\{E/N - \frac{2\,(4 + m_u/m_d)}{3\,(1 + m_U/m_d)}\right\}$$

Galaxy clusters and axions

- Galaxy clusters are huge axion reservoirs

$$N_{\rm ax} = 10^{80} m_{a,{\rm eV}}^{-1} \ !$$

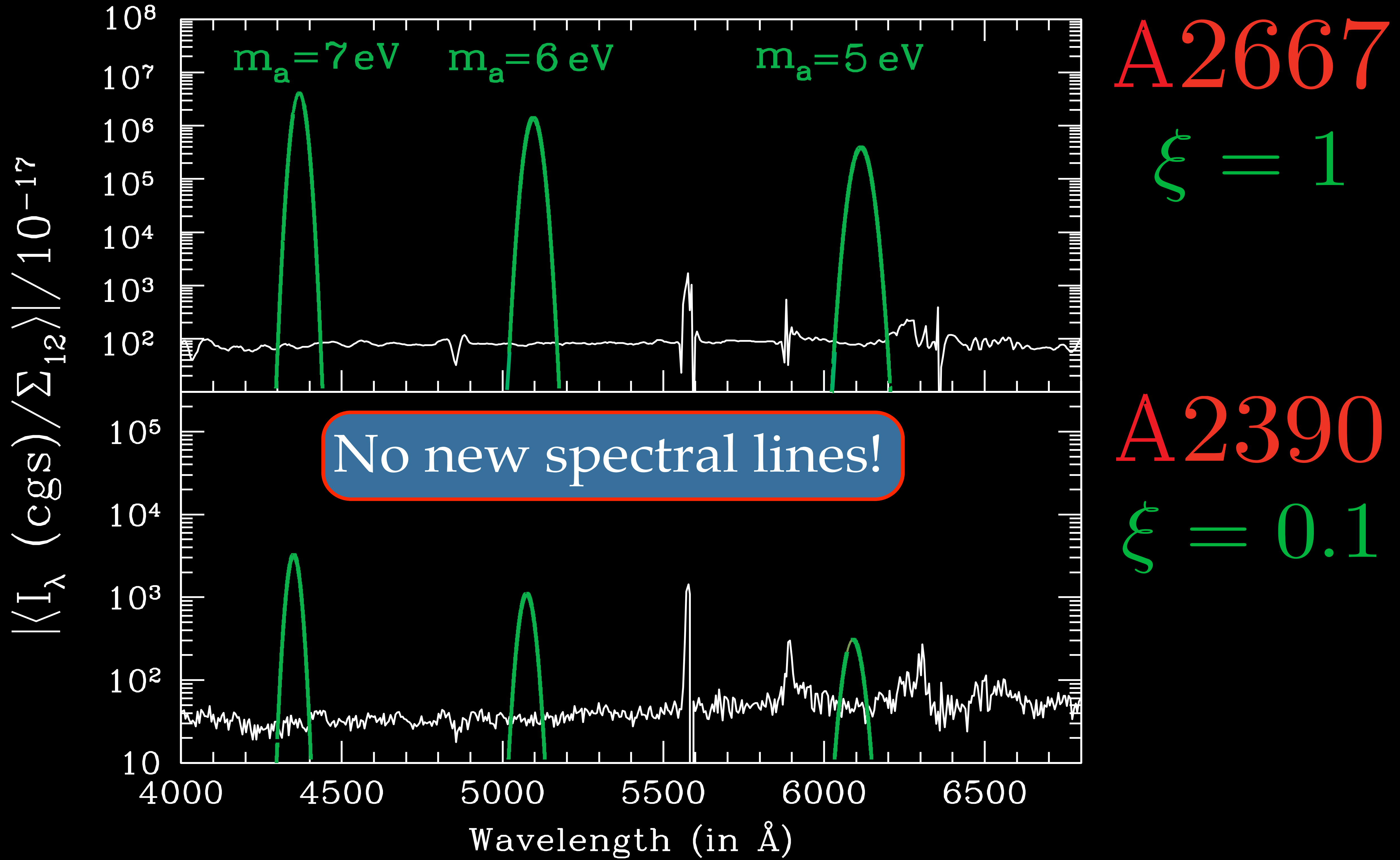
- Reasonably wide line $\sigma_{1000} \sim 1$

- Strong/weak gravitational lensing mass maps available

- Comparable to sky brightness

$$I_\lambda \simeq 10^{-18} \ {\rm cgs} \frac{{\rm m}_{\rm a,eV}^7 \xi^2}{(1+{\rm z_c})^4} \frac{\Sigma}{10^{12} {\rm M}_\odot {\rm pix}^{-2}}$$

Past optical telescope axion searches



Data

- Noise model: shot noise, dark current, fiber flux leakage between fibers, lensing fit errors
- Fiber flux normalized using continuum lamp exposure
- Reduced spectrum convolved against Gaussian line shape