Cosmology with CMB and Large-scale Structure of the Universe

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Cosmology: Next Decade?

- Astro2010: Astronomy & Astrophysics Decadal Survey
  - Report from *Cosmology and Fundamental Physics* Panel (Panel Report, Page T-3):

TABLE I Summary of Science Frontiers Panels' Findings

Panel		Science Questions
Cosmology and Fundamental Physics	CFP 1	How Did the Universe Begin?
	CFP 2	Why Is the Universe Accelerating?
	CFP 3	What Is Dark Matter?
	CFP 4	What Are the Properties of Neutrinos?

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TABLE I Summary of Science Frontiers Panels' Findings

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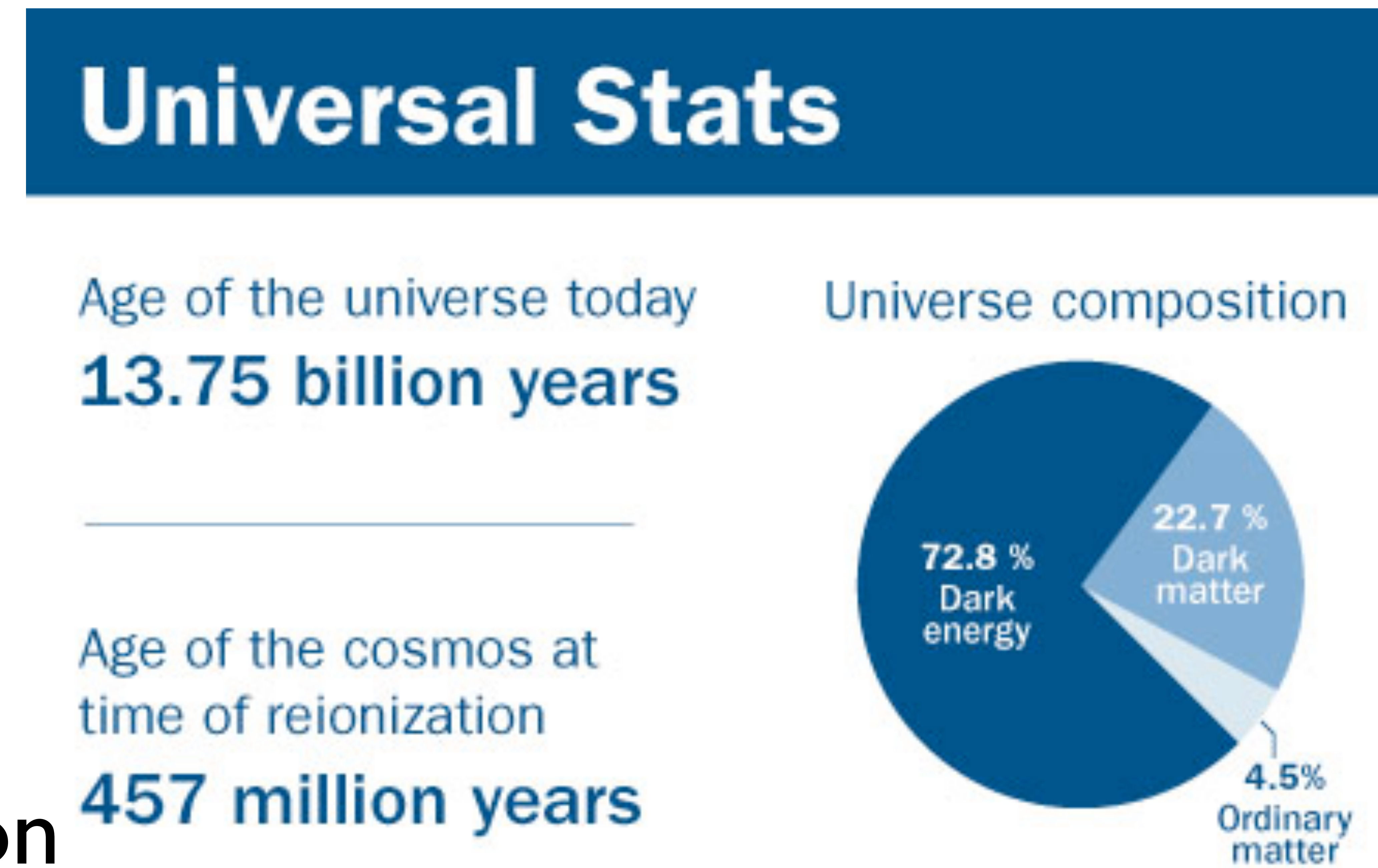
	CFP 2	Why Is the Universe Acceler	*Dark Energy*
	CFP 3	What Is Dark Matter?	*Dark Matter*
	CFP 4	What Are the Properties of N	*Neutrino Mass*

Cosmology Update: WMAP 7-year+

- **Standard Model**
  - H&He = 4.58% (±0.16%)
  - Dark Matter = 22.9% (±1.5%)
  - Dark Energy = 72.5% (±1.6%)
  - H_0=70.2±1.4 km/s/Mpc
  - Age of the Universe = 13.76 billion years (±0.11 billion years)



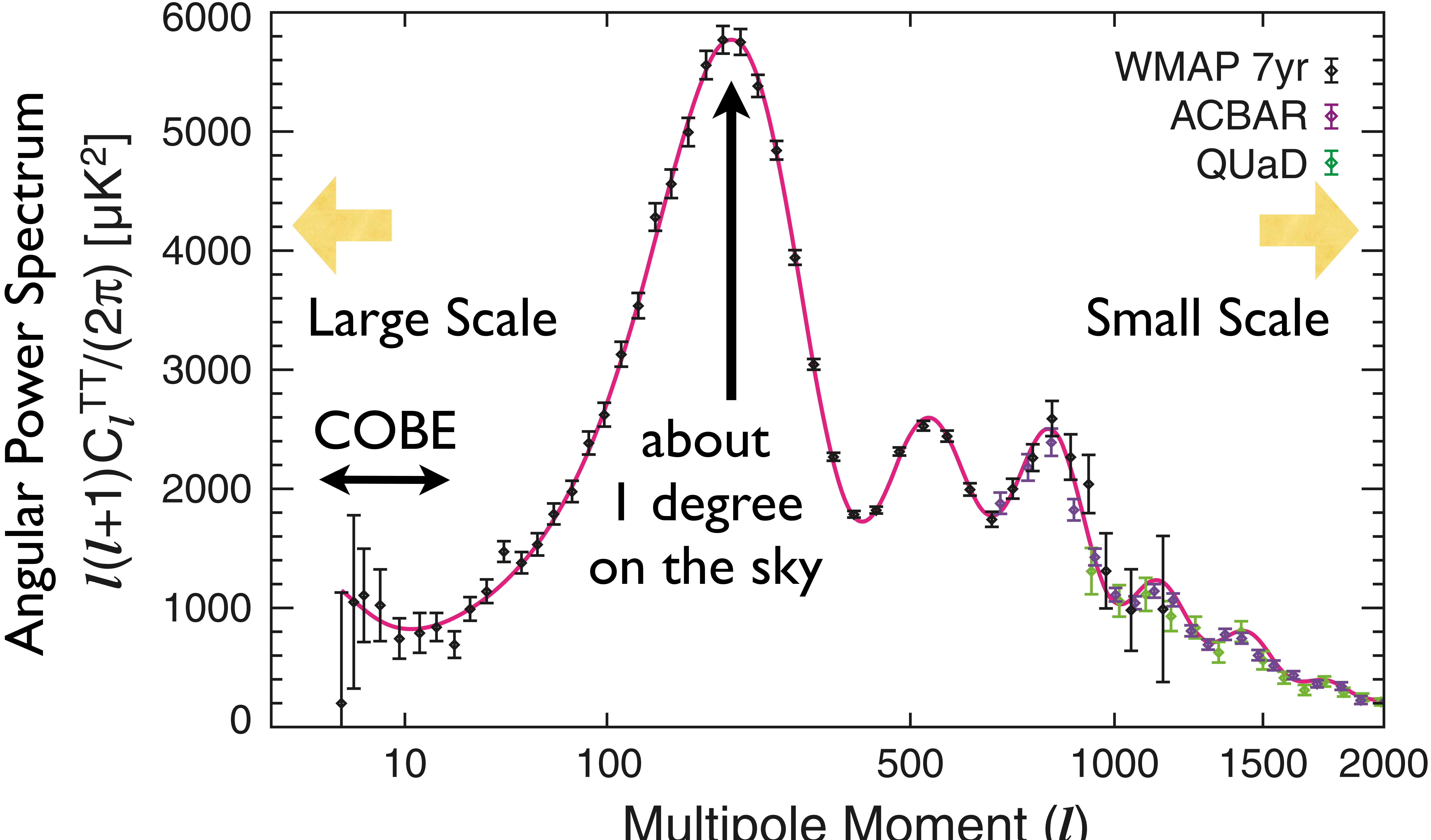
"ScienceNews" article on the WMAP 7-year results

What is new from WMAP7?

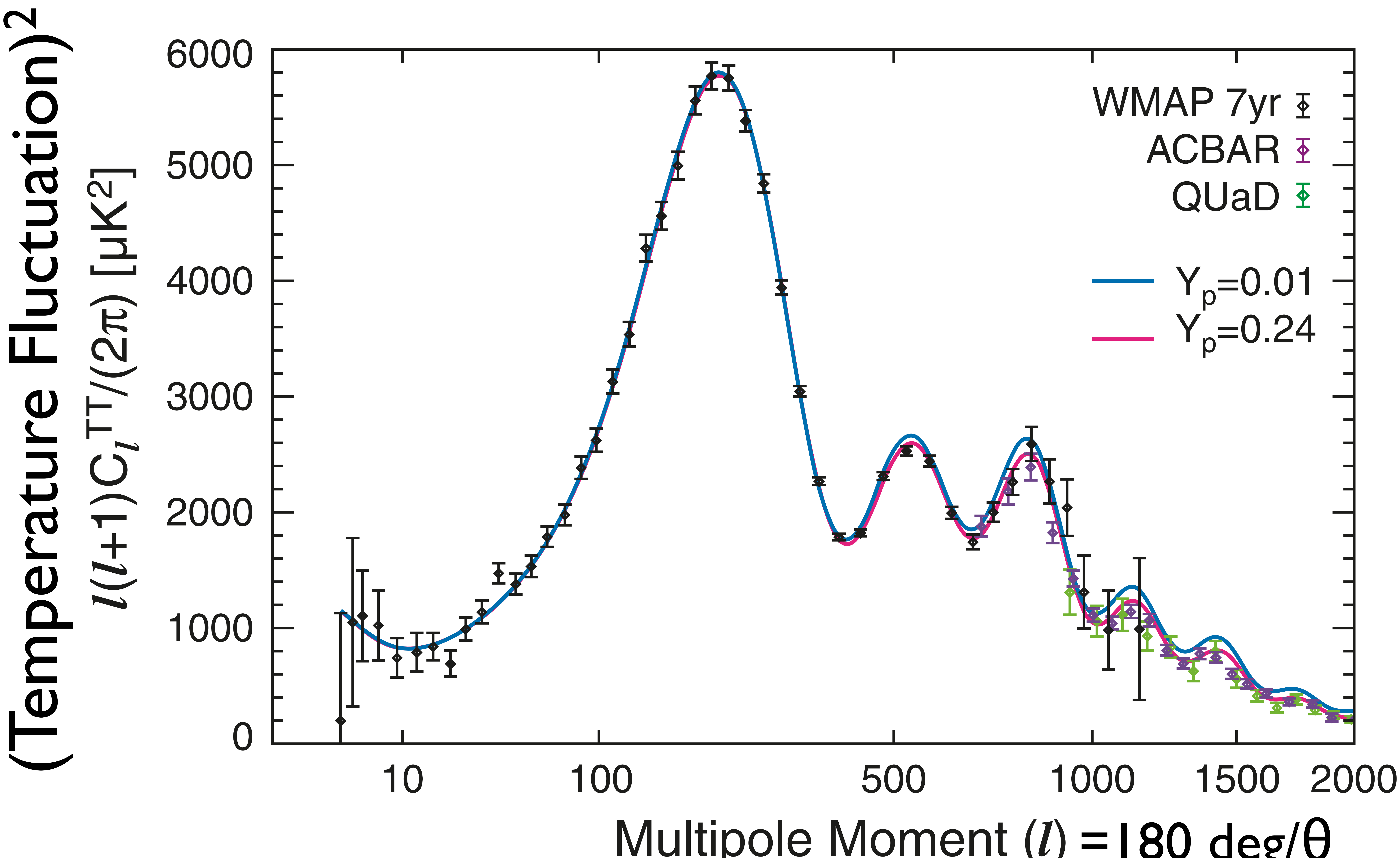
- First detection of the effect of primordial helium on the CMB power spectrum
- An extra neutrino (or something else)?
    - Not statistically significant, but an interesting thing to keep eyes on.
- First direct images of CMB polarization
- New limits on inflation from the tilting of the power spectrum; tensor modes (gravitational waves); and non-Gaussianity

Larson et al (2010); Komatsu et al. (2010)

7-Year Power Spectrum



Detection of Primordial Helium



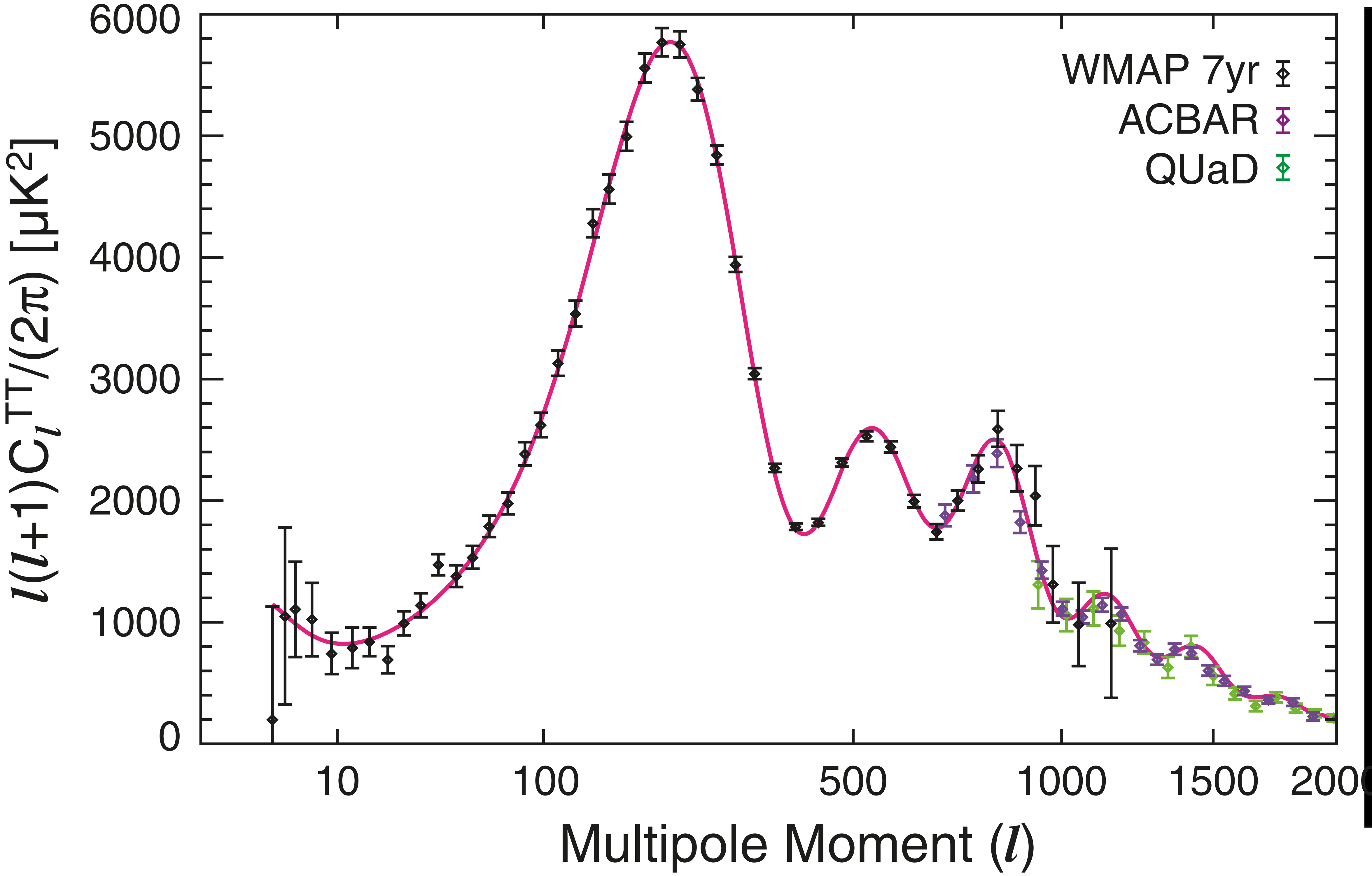
Effect of helium on C_l^{TT}

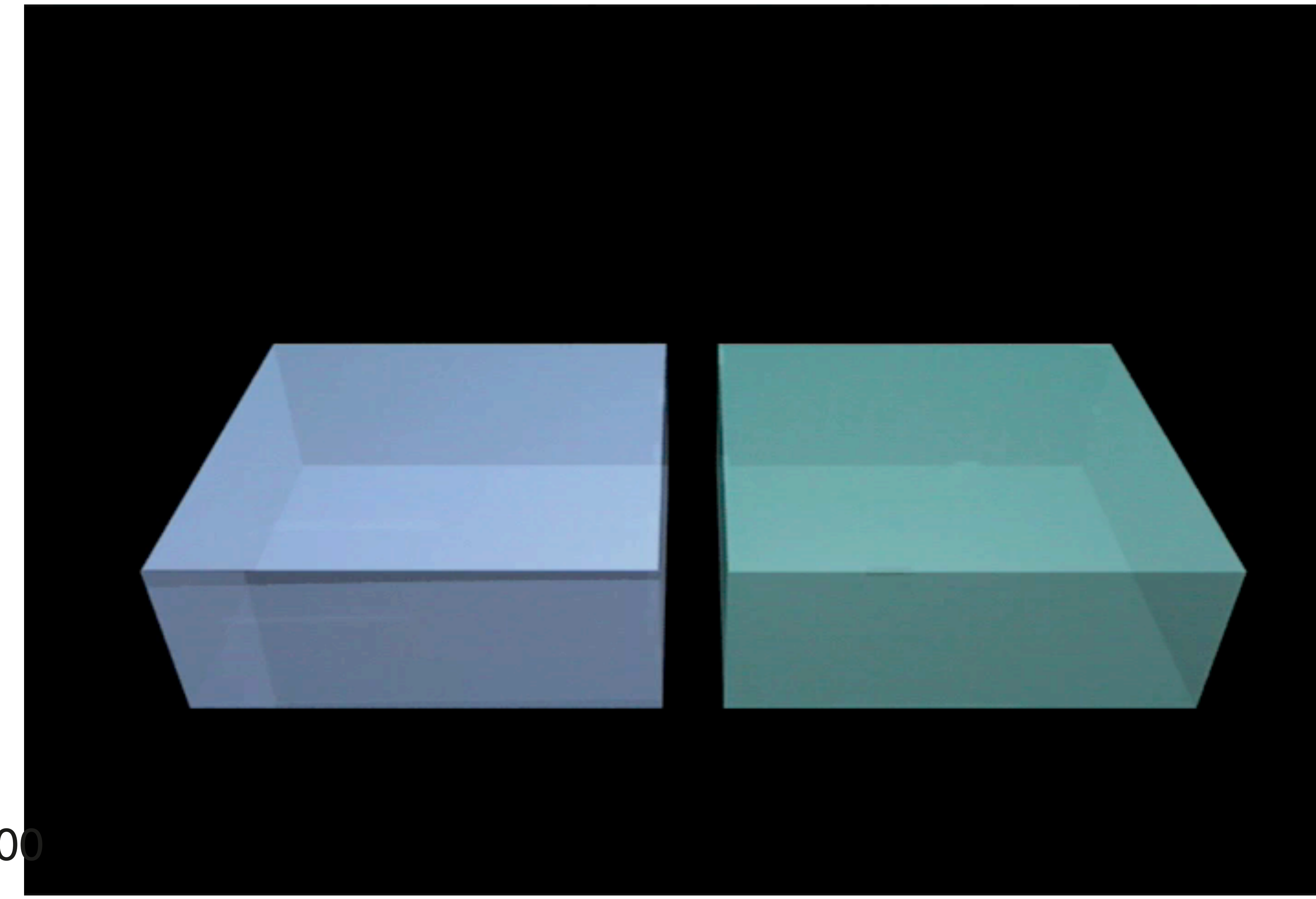
- We measure the baryon number density, n_b, from the 1st-to-2nd peak ratio.
- As helium recombined at z~1800, there were fewer electrons at the decoupling epoch (z=1090): $n_e=(1-Y_p)n_b$.
- **More helium** = Fewer electrons = Longer photon mean free path $1/(\sigma_T n_e)$ = **Enhanced damping**
- **Y_p = 0.33 ± 0.08** (68%CL)
  - Consistent with the standard value from the Big Bang nucleosynthesis theory: Y_P=0.24.

Neutrinos?

(Or anything that was relativistic at z~1100)

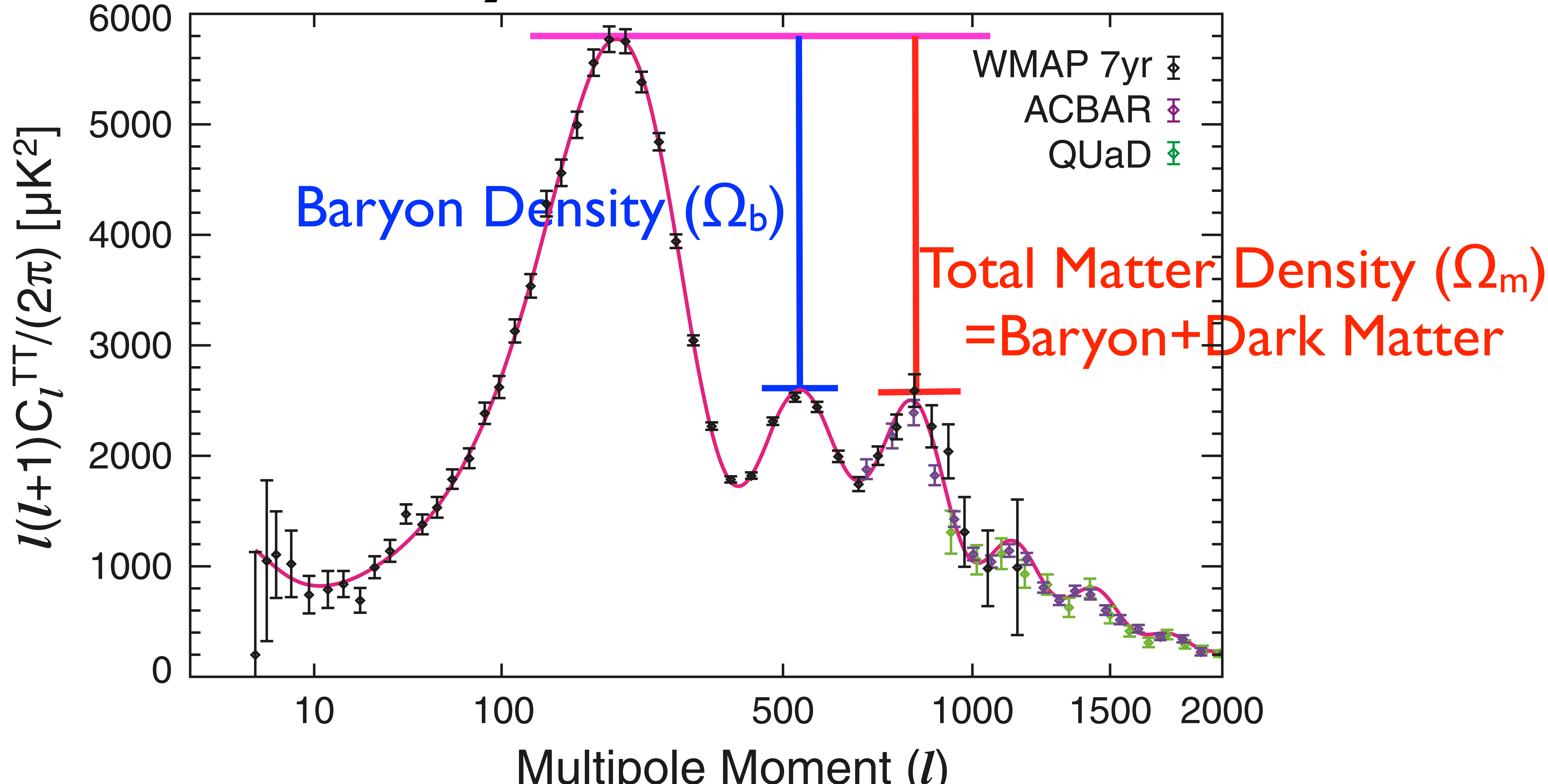
The Cosmic Sound Wave





- *"The Universe as a Miso soup"*
  - *Main Ingredients: protons, helium nuclei, electrons, photons*
- We measure the composition of the Universe by analyzing the wave form of the cosmic sound waves.

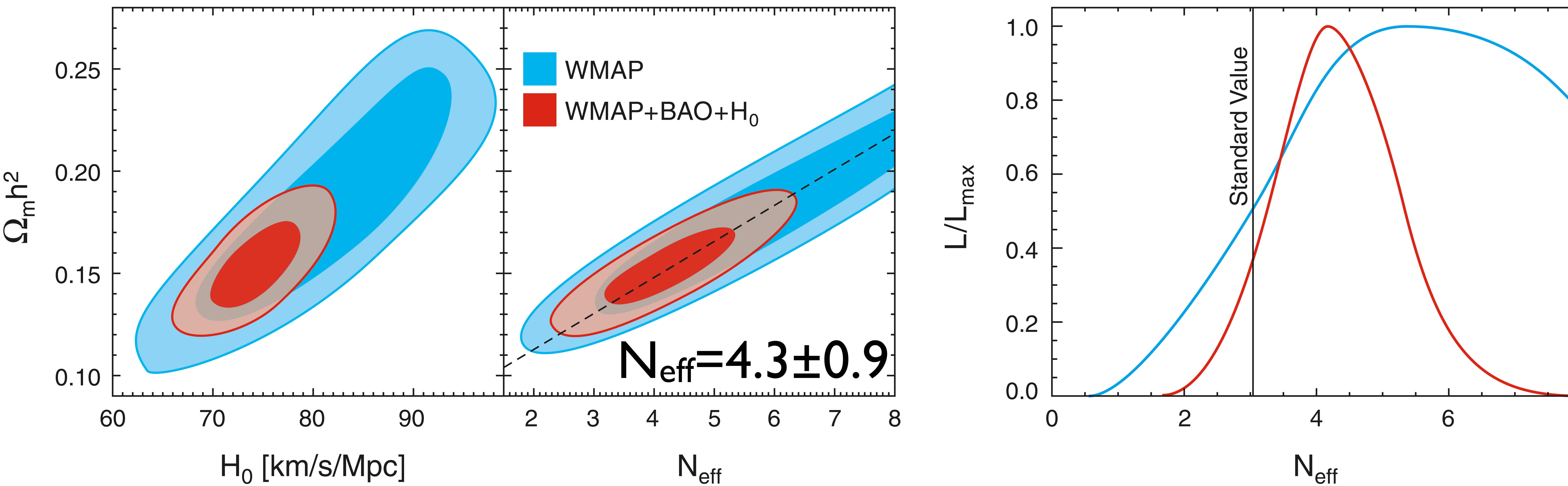
CMB to Baryon & Dark Matter



- 1-to-2: baryon-to-photon ratio
- 1-to-3: matter-to-radiation ratio (z_{EQ}: equality redshift)

"3rd peak science": Number of Relativistic Species

Komatsu et al. (2010)



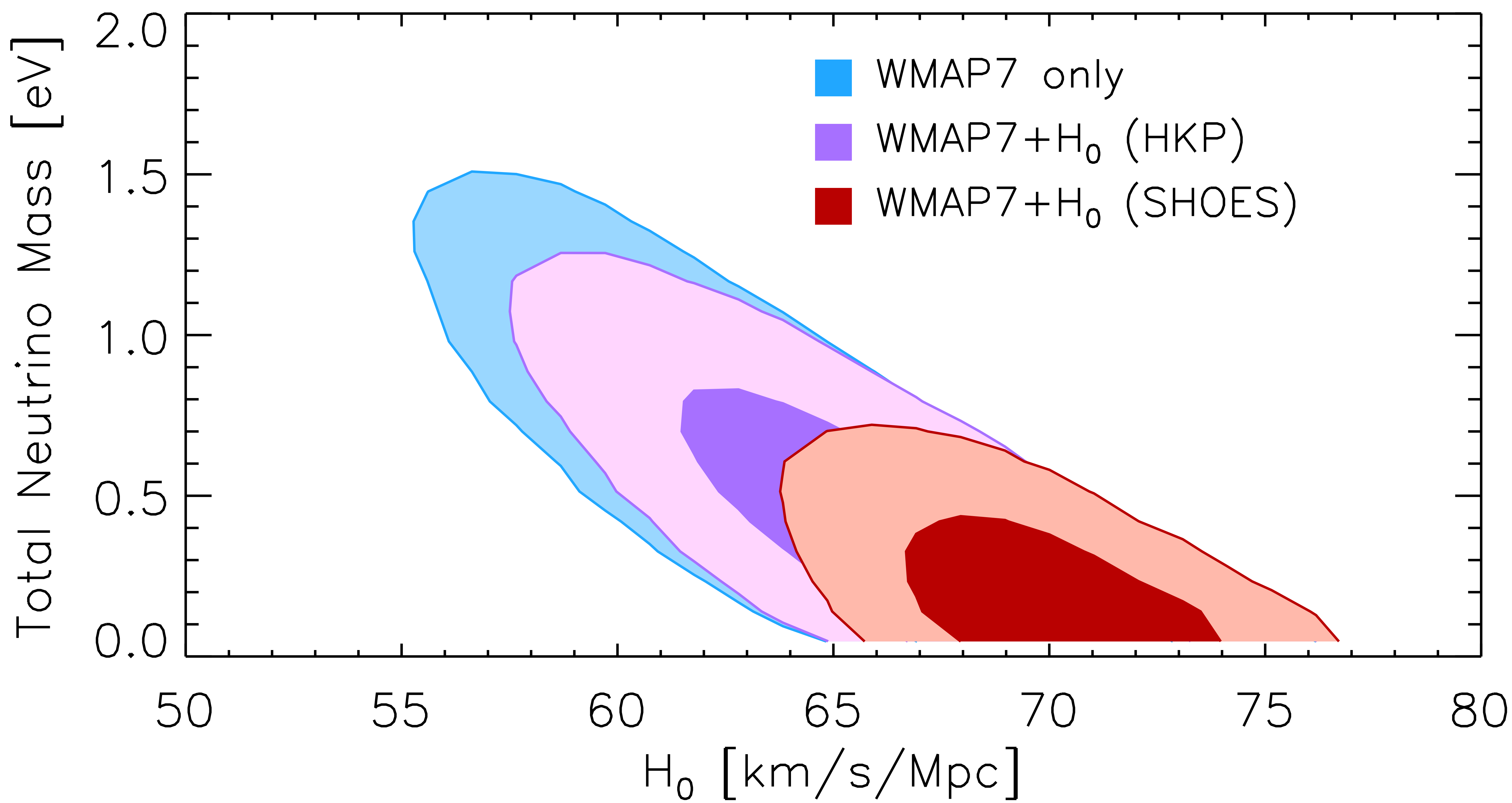
from external data

$$N_{\rm eff} = 3.04 + 7.44\left(\frac{\Omega_m h^2}{0.1308}\frac{3139}{1+z_{\rm eq}} - 1\right)$$

from 3rd peak

Komatsu et al. (2010)

And, the mass of neutrinos



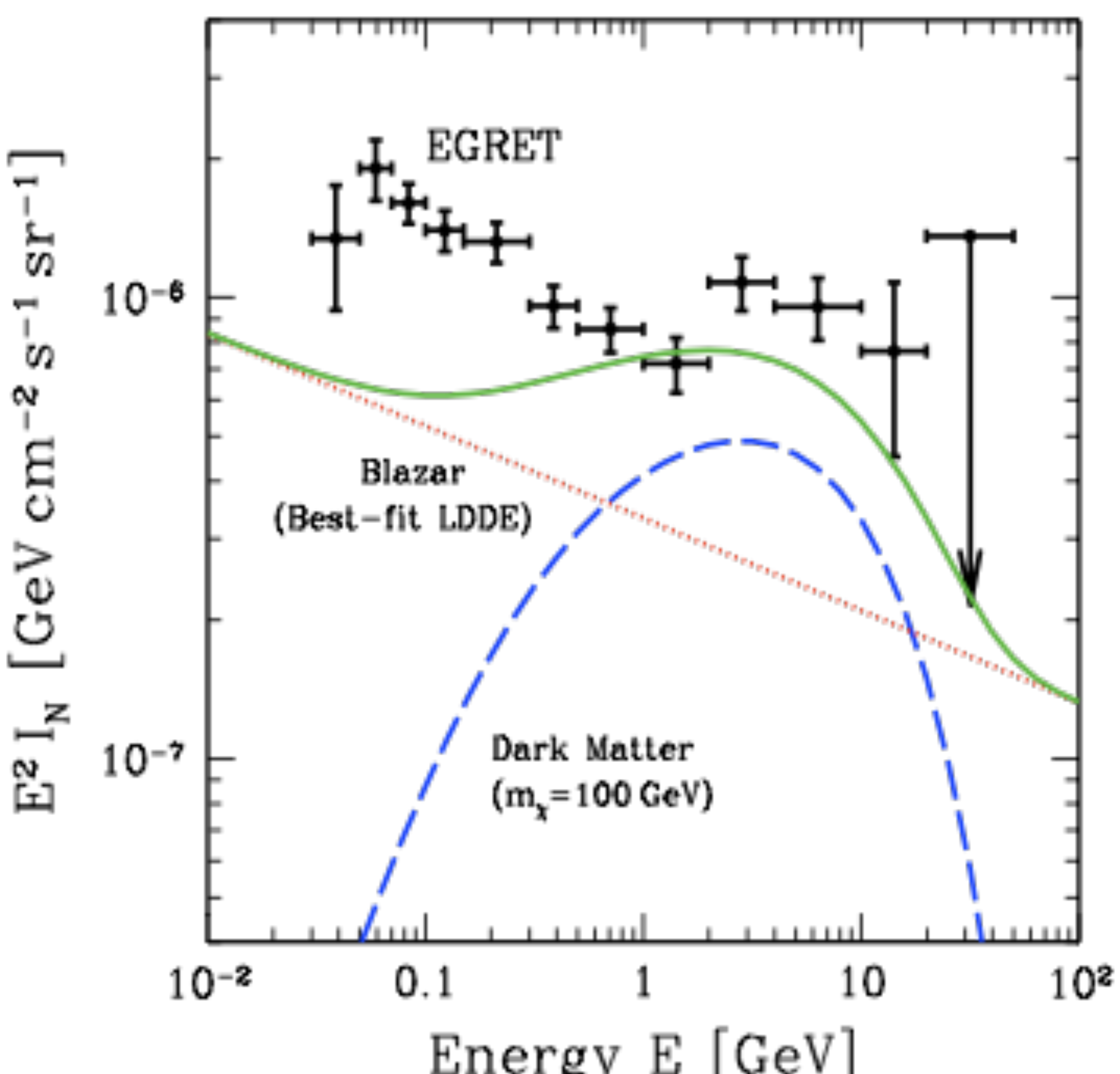
- WMAP data combined with the local measurement of the expansion rate (H_0), we get $\sum m_\nu < 0.6$ eV (95%CL)

Leave WMAP for a moment:

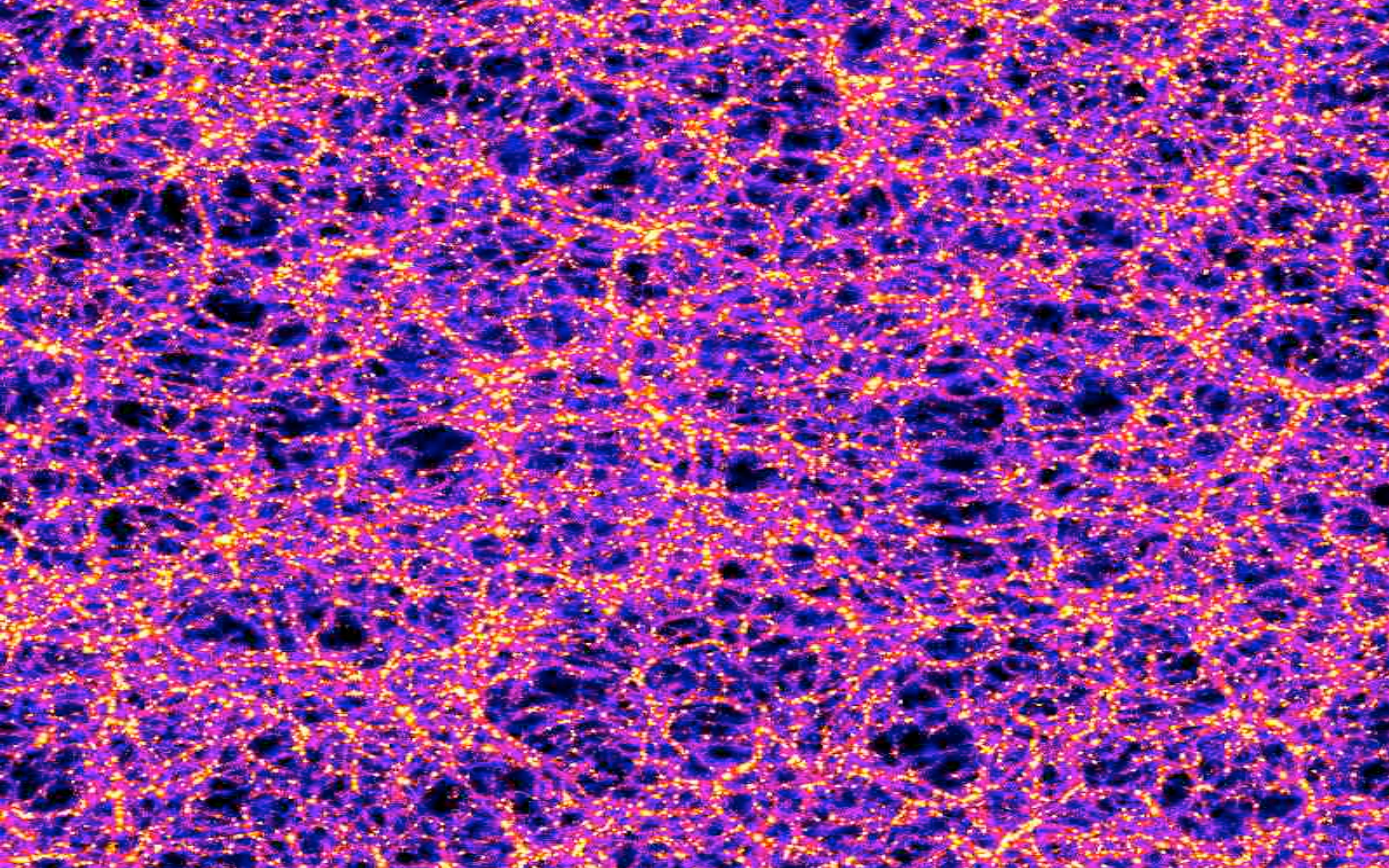
Hunting for Dark Matter in the Gamma-ray Sky

- *Direct* detections of dark matter particles may be possible using metals (Ge), noble gas (Ar), etc.
- ***Indirect detections*** may also be possible using astrophysical observations, e.g., gamma-rays from annihilation of dark matter particles.
  - But, what could be a smoking-gun?

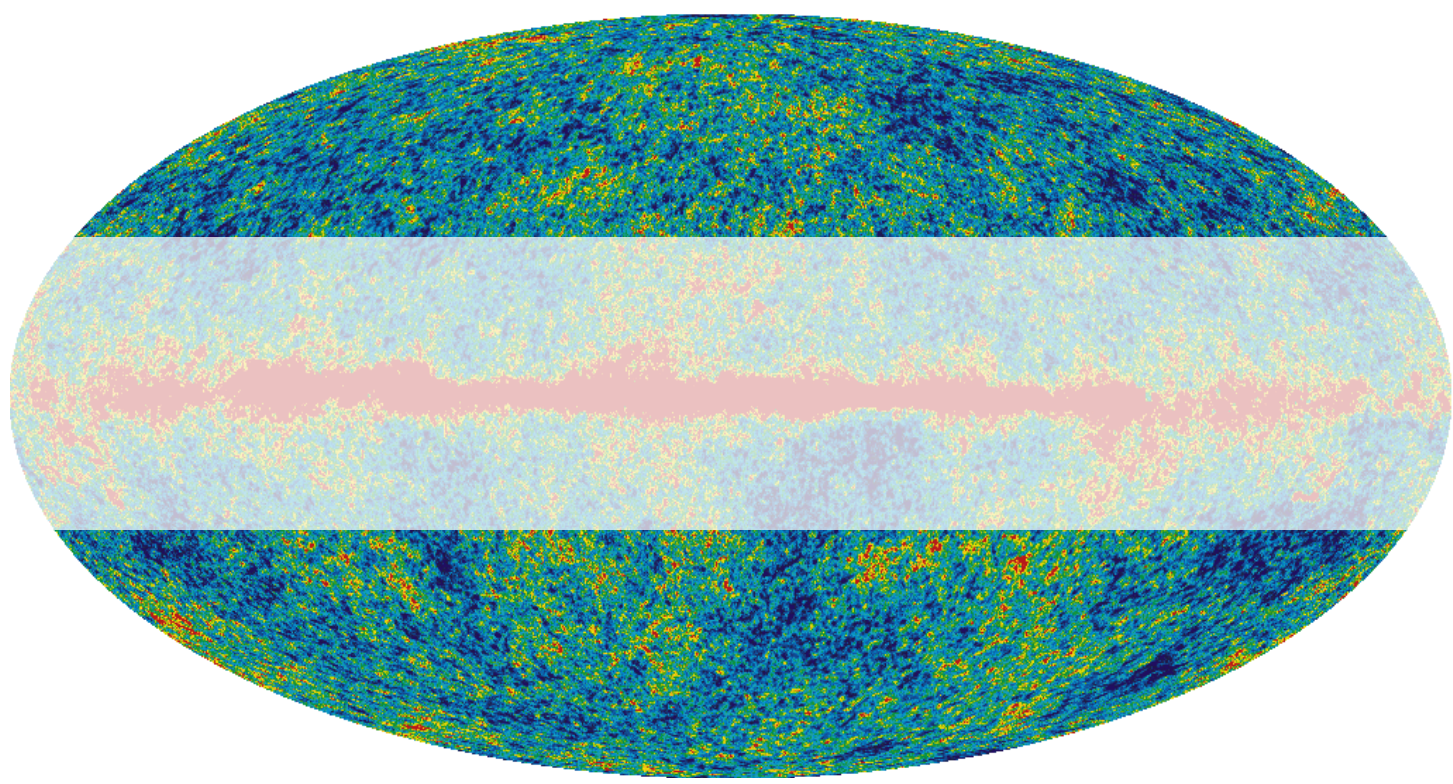
Energy Spectrum? Not Convincing...



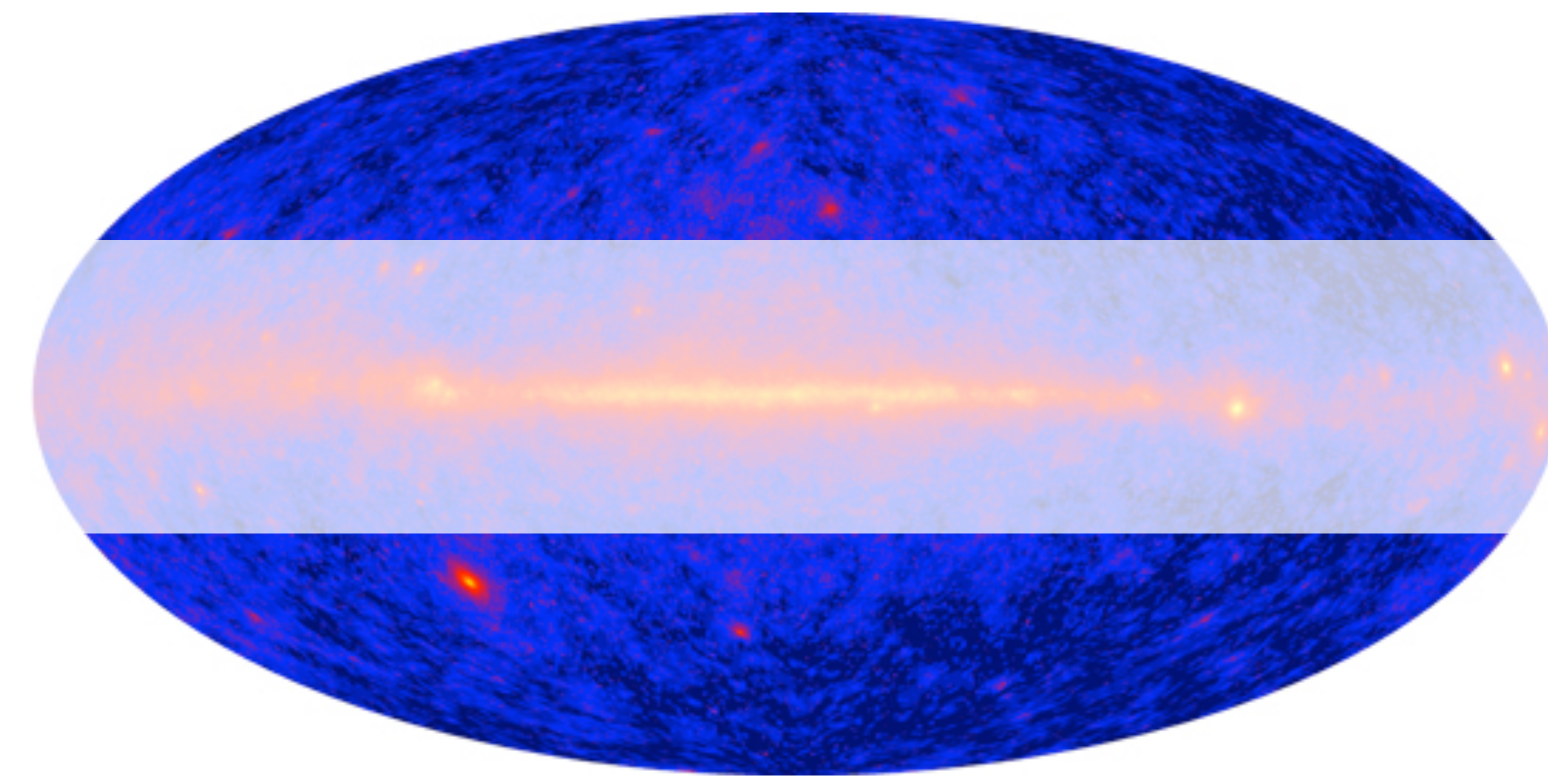
- Conventionally, people were focused on the spectrum of the diffuse gamma-ray background (after removing point sources).
- However, the dark matter spectrum is not so distinct – this cannot be a smoking gun. What else?



Gamma-ray Background Must Be Anisotropic

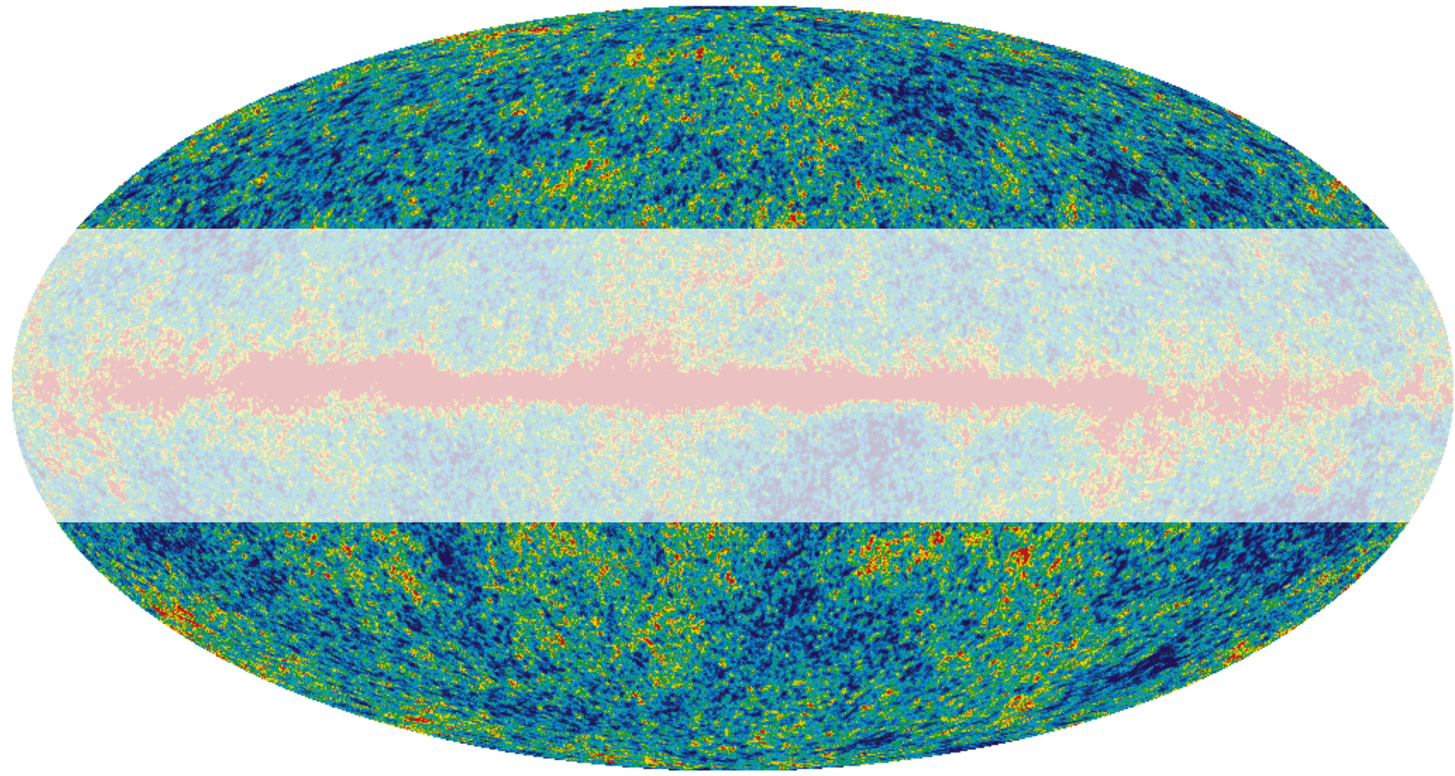


WMAP Data

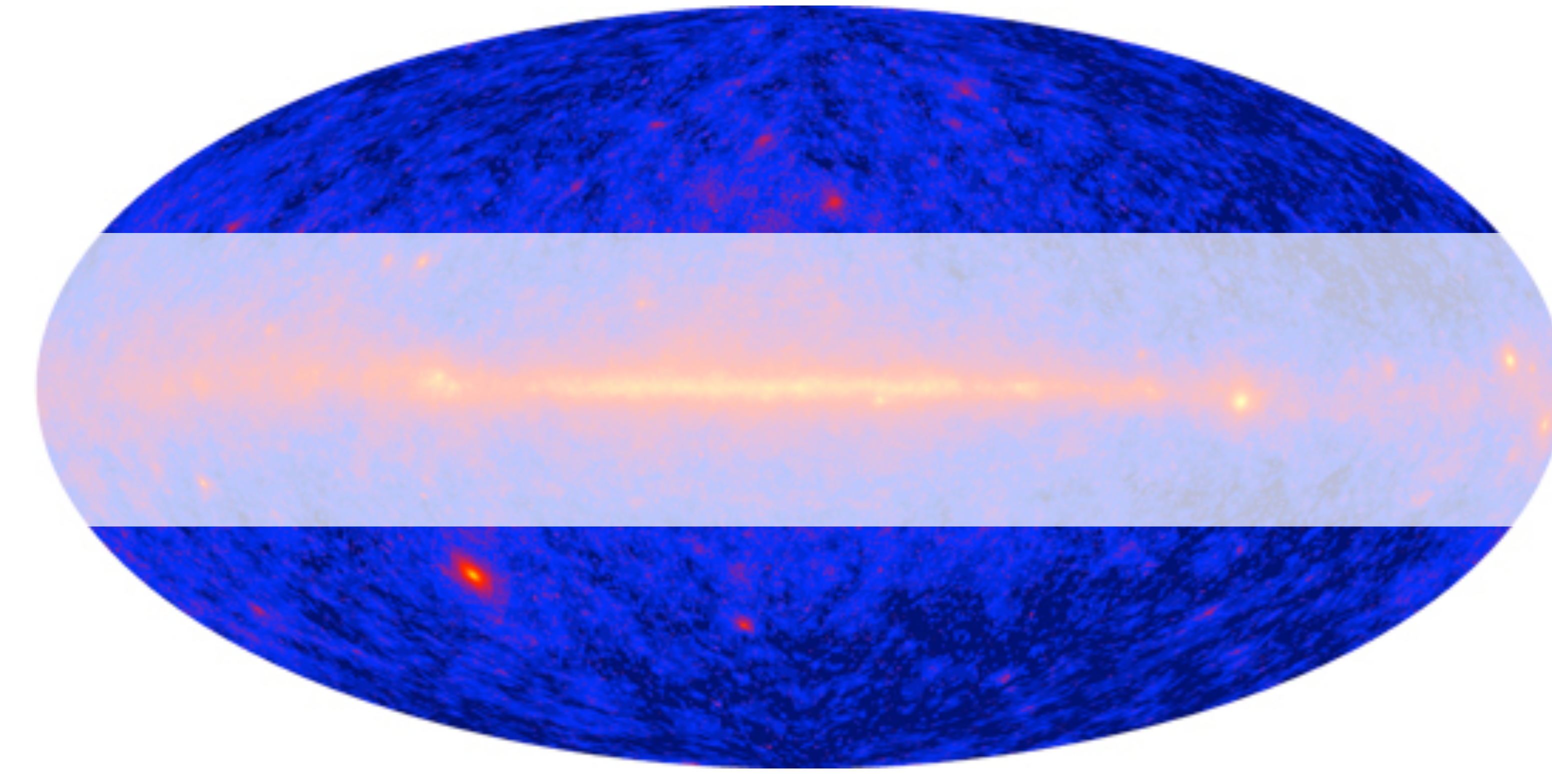


Fermi Data

- Use the Fermi data, just like the WMAP data, and measure the power spectrum!



WMAP Data



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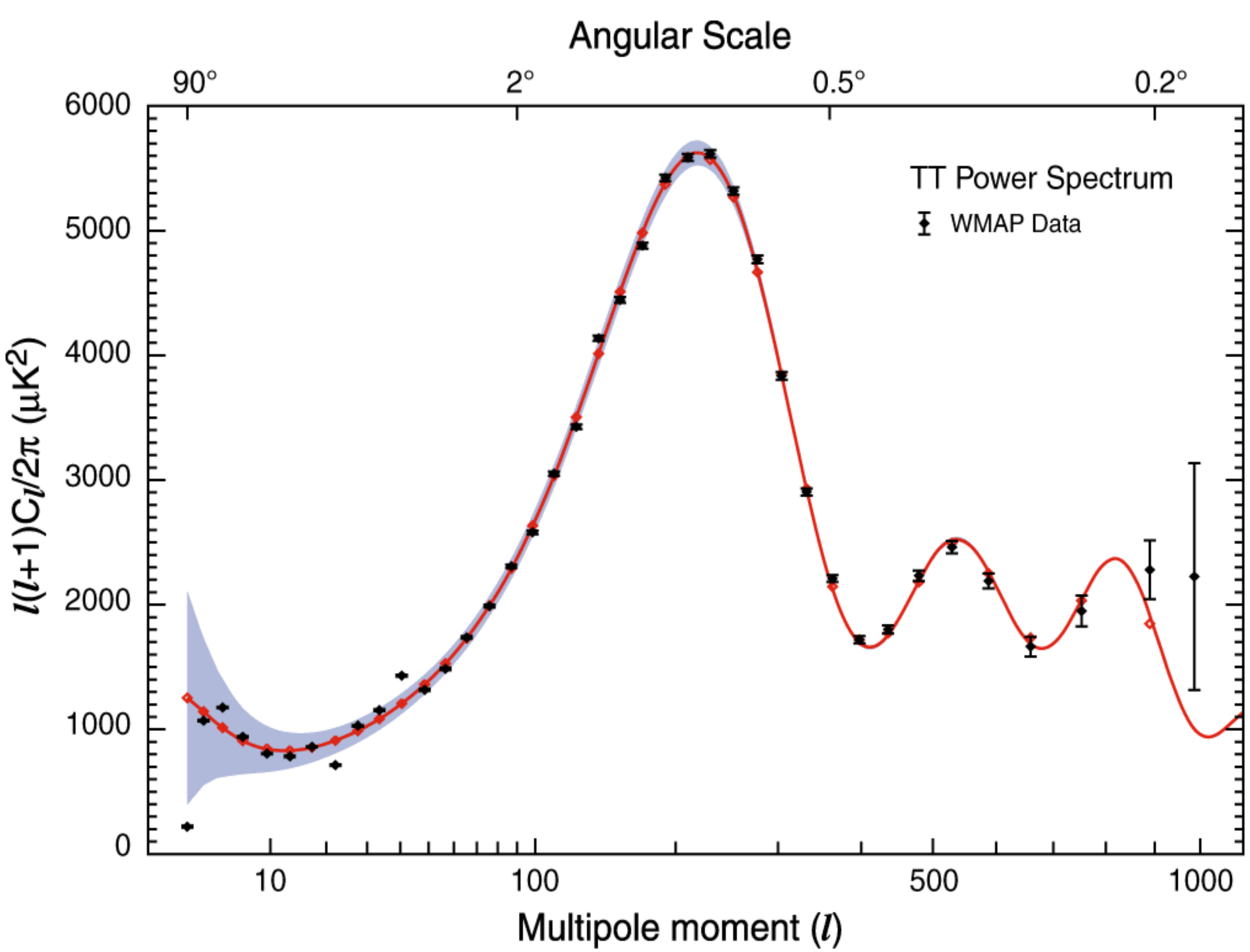
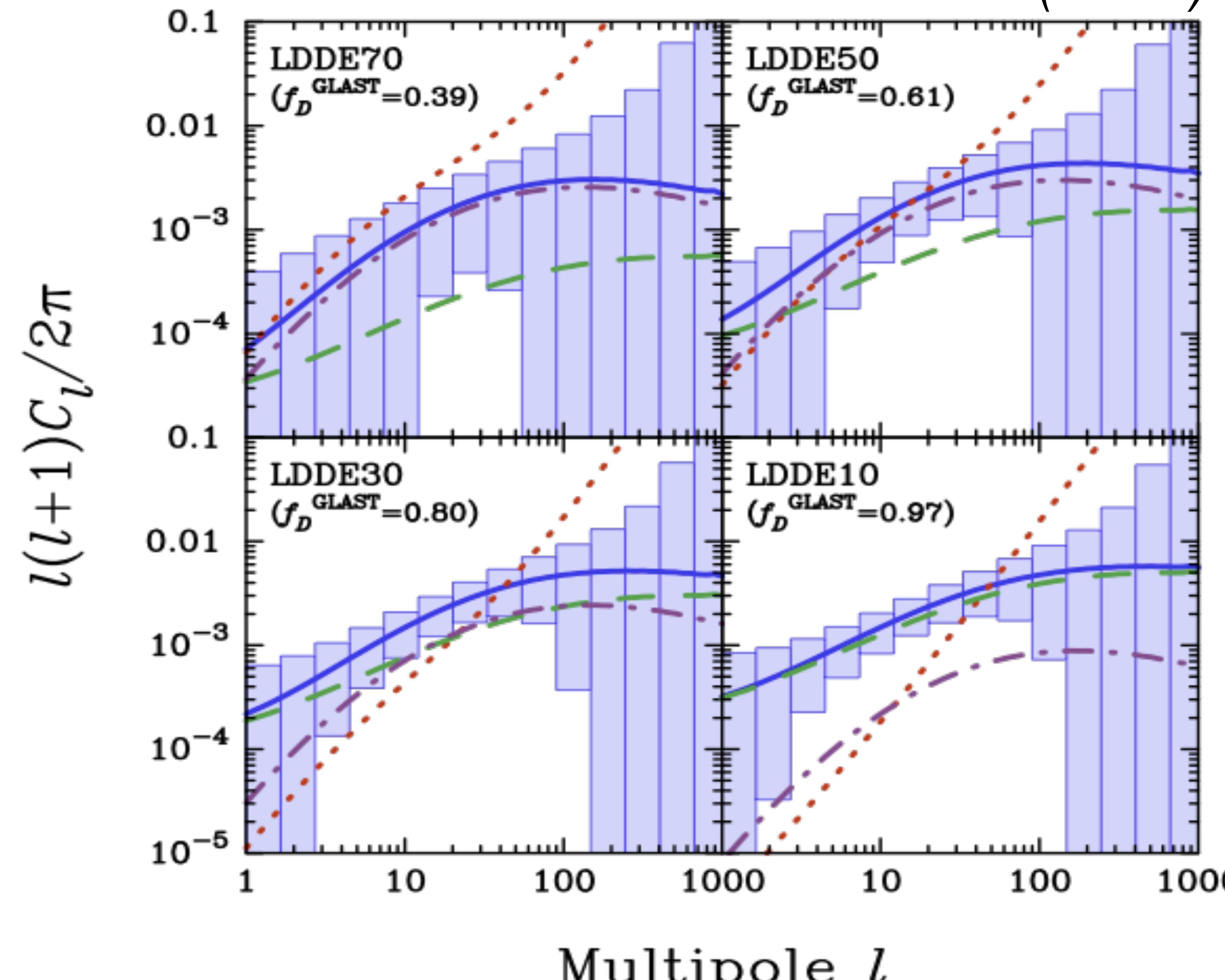
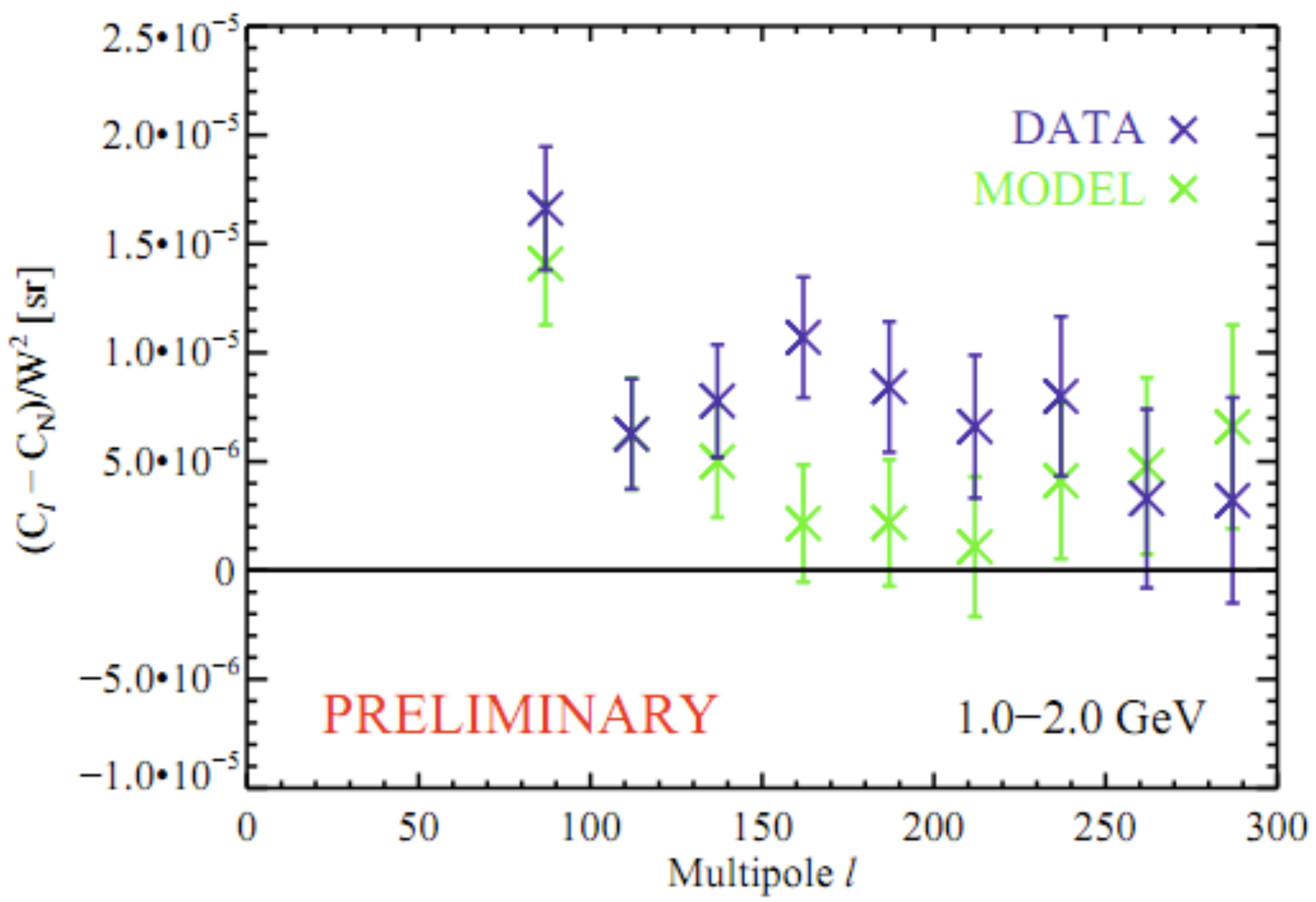


Ando & Komatsu (2006)

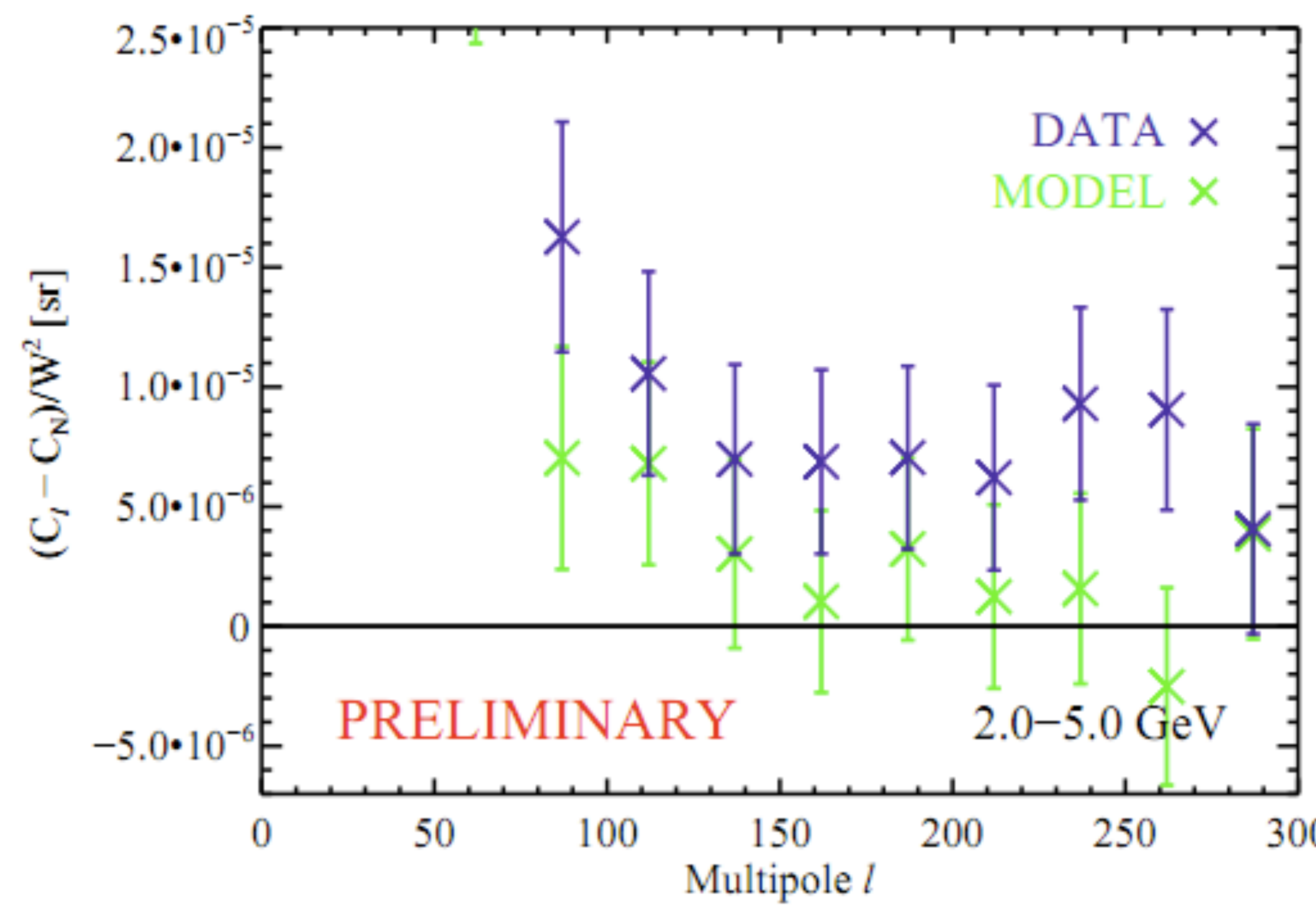


The First Results from Fermi 22mo Data

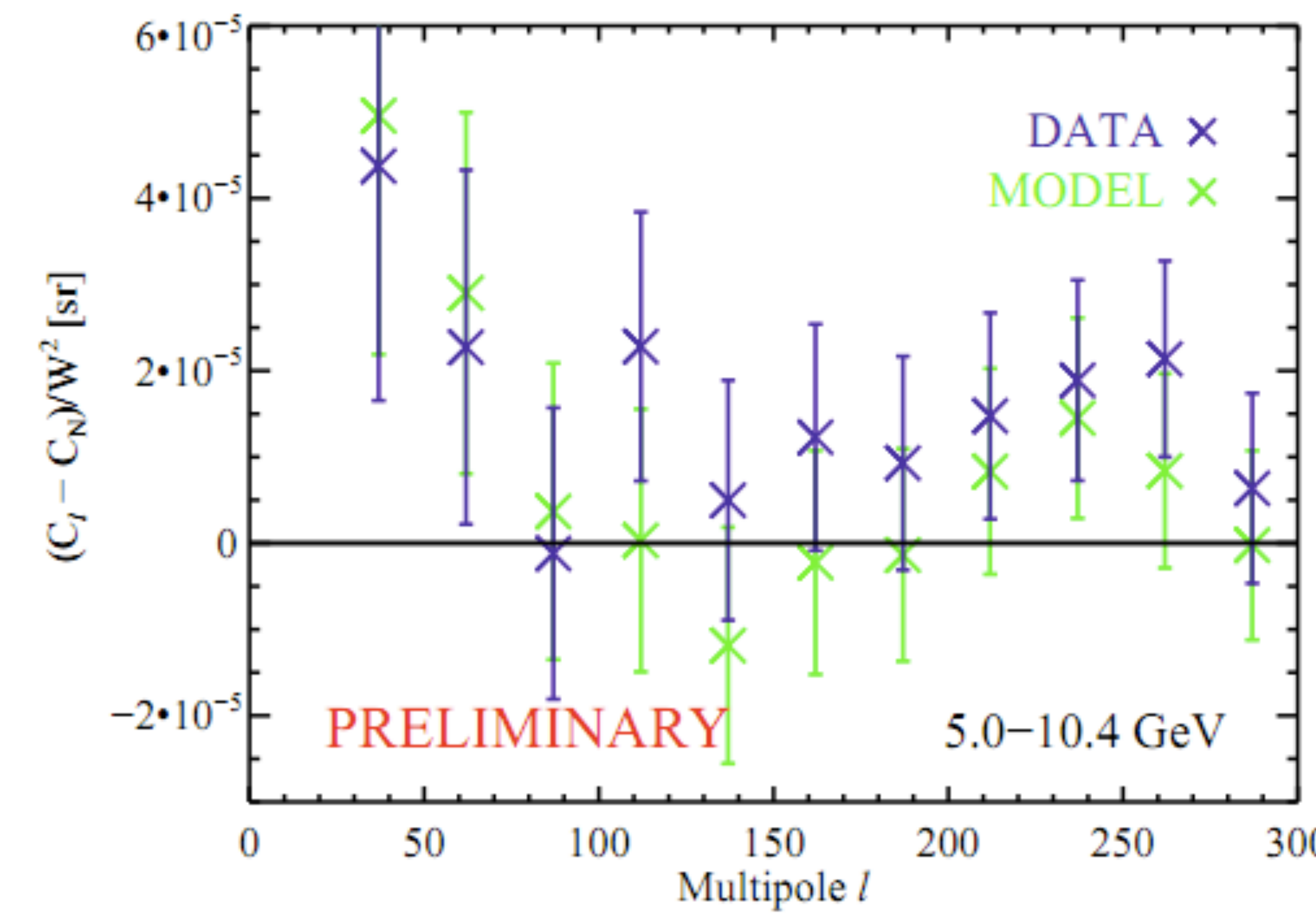
Siegal-Gaskins et al. (Fermi Collaboration + EK) arXiv:1012.1206



1–2 GeV



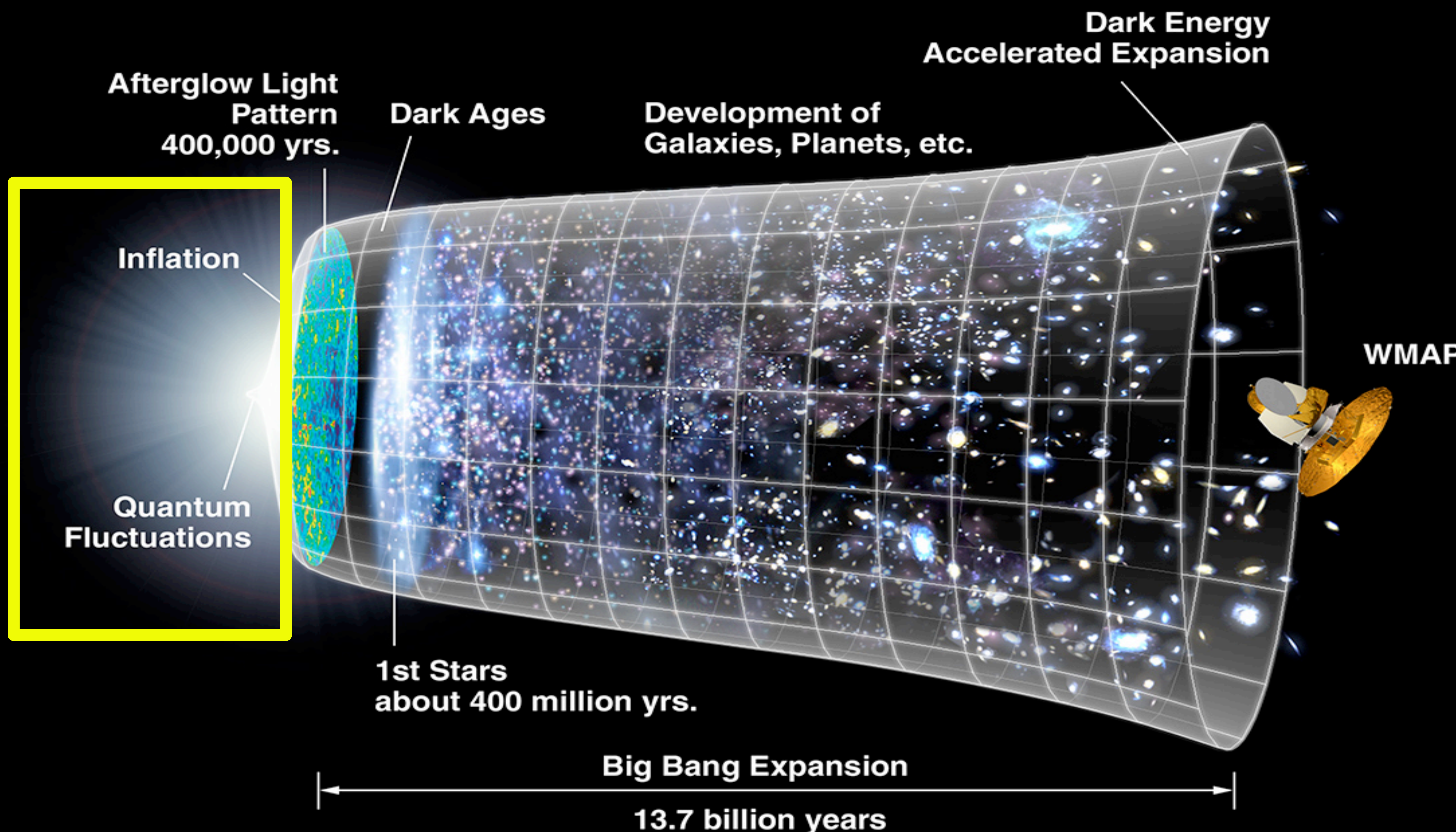
2–5 GeV



5–10 GeV

- We are seeing the excess power spectrum at l>50, likely coming from **unresolved** blazars.
  - "Model" has the Galactic diffuse emission.
  - Detected point sources have been removed.

Cosmic Inflation = Very Early Dark Energy



NASA/WMAP Science Team

Theory Says...

- The leading theoretical idea about the primordial Universe, called "***Cosmic Inflation***," predicts:
  - The expansion of our Universe ***accelerated*** in a tiny fraction of a second after its birth.
  - the primordial ripples were created by ***quantum fluctuations*** during inflation, and
  - how the power is distributed over the scales is determined by the **expansion history during cosmic inflation**.
- Detailed observations give us **this** remarkable information!

We have learned a lot about inflation from WMAP

Peiris, Komatsu et al. (2003)
Komatsu et al. (2009; 2010)

- Spatial geometry of the observable universe is flat, with a deviation less than ~1%.
- Initial fluctuations were "adiabatic," meaning the photon fluctuations and matter fluctuations were perturbed in a similar way such that the entropy per matter was unperturbed. Non-adiabaticity is less than ~10%.
- Initial fluctuations were close to, but not exactly, *scale invariant*, with $P(k) \sim k^{n_s-1}$ with $n_s = 0.97 \pm 0.01$
- Initial fluctuations were Gaussian, with deviation less than 0.1%. [*BUT*... I will come back to this later.]

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- Spatial geometry of the observable universe is flat, with a deviation less than ~1%.

Current Situation:
The simplest model of inflation (say, driven by a single scalar field with a quadratic potential, $V \sim m^2\varphi^2$) fits everything we have so far.

- ...on ... in ... unperturbed. Non-adiabaticity is less than ~10%.
- Initial fluctuations were close to, but not exactly, *scale invariant*, with $P(k) \sim k^{ns-1}$ with $n_s = 0.97 \pm 0.01$
- Initial fluctuations were Gaussian, with deviation less than 0.1%. [*BUT*... I will come back to this later.]

Mukhanov & Chibisov (1981); Guth & Pi (1982); Starobinsky (1982); Hawking (1982); Bardeen, Turner & Steinhardt (1983)

(Scalar) Quantum Fluctuations

$\delta\varphi$ = (Expansion Rate)/(2π) [in natural units]

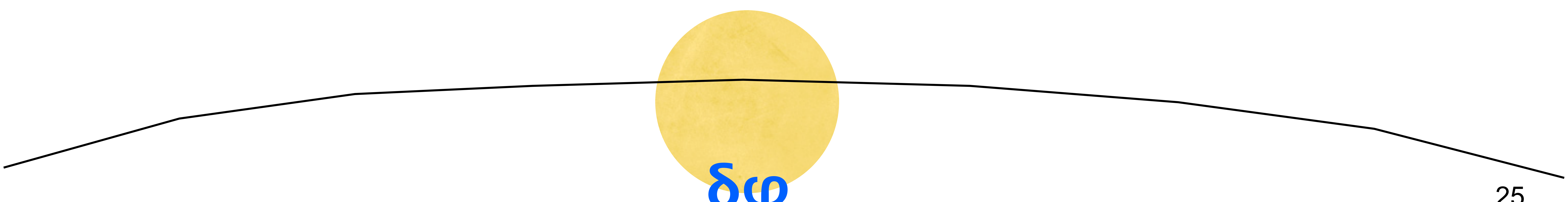
- Why is this relevant?
- The cosmic inflation (probably) happened when the Universe was a tiny fraction of second old.
  - Something like 10^{-36} second old
  - (Expansion Rate) ~ 1/(Time)
    - which is a big number! (~10^{12}GeV)
  - *Quantum fluctuations were important during inflation!*

Stretching Micro to Macro

Macroscopic size at which gravity becomes important

Quantum fluctuations on microscopic scales

INFLATION!



Quantum fluctuations cease to be quantum, and become observable!

Starobinsky (1979)

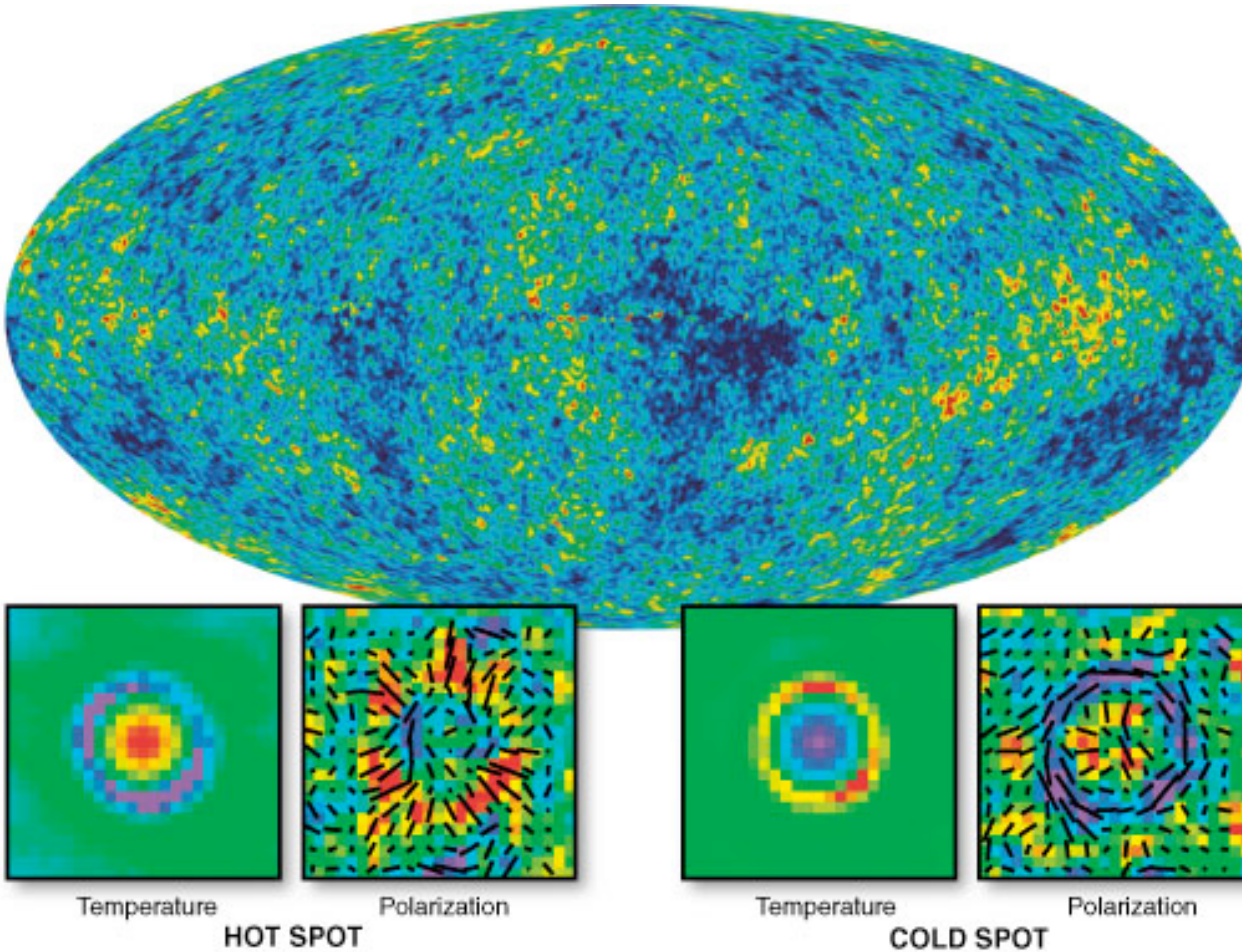
(Tensor) Quantum Fluctuations, a.k.a. Gravitational Waves

h = (Expansion Rate)/($2^{1/2}\pi M_{planck}$) [in natural units]

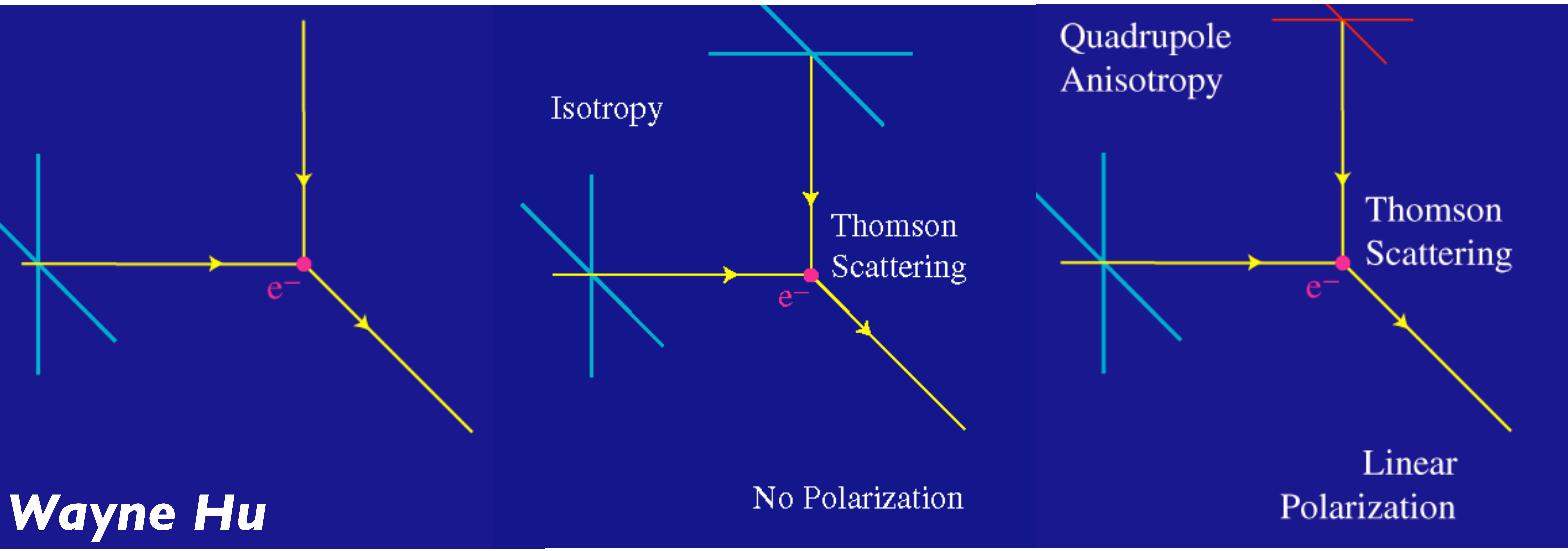
[h = "strain"]

- Quantum fluctuations also generate ripples in space-time, i.e., gravitational waves, by the same mechanism.
- Primordial gravitational waves generate temperature anisotropy in CMB, as well as polarization in CMB with a distinct pattern called "**B-mode polarization**."

CMB is Polarized!

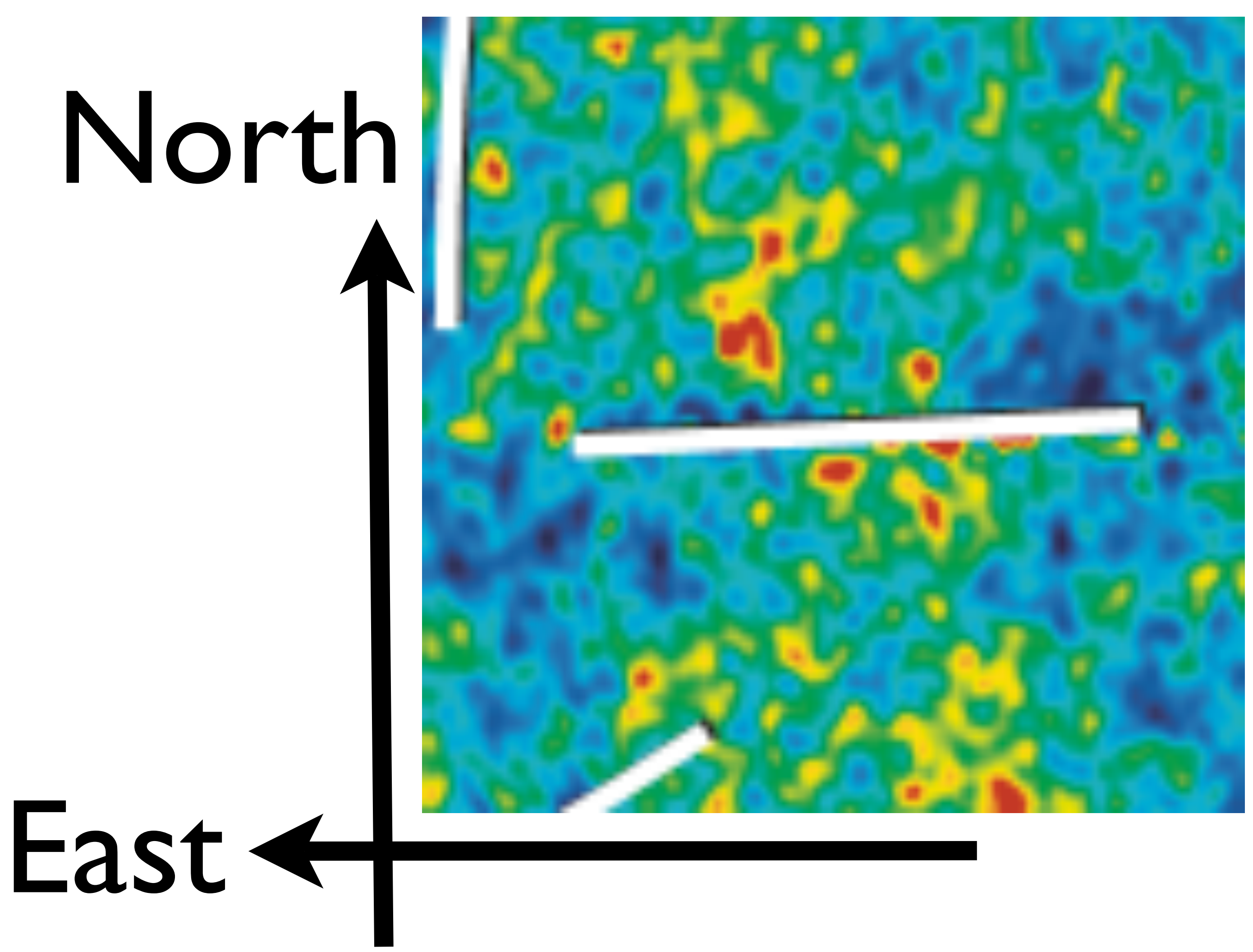


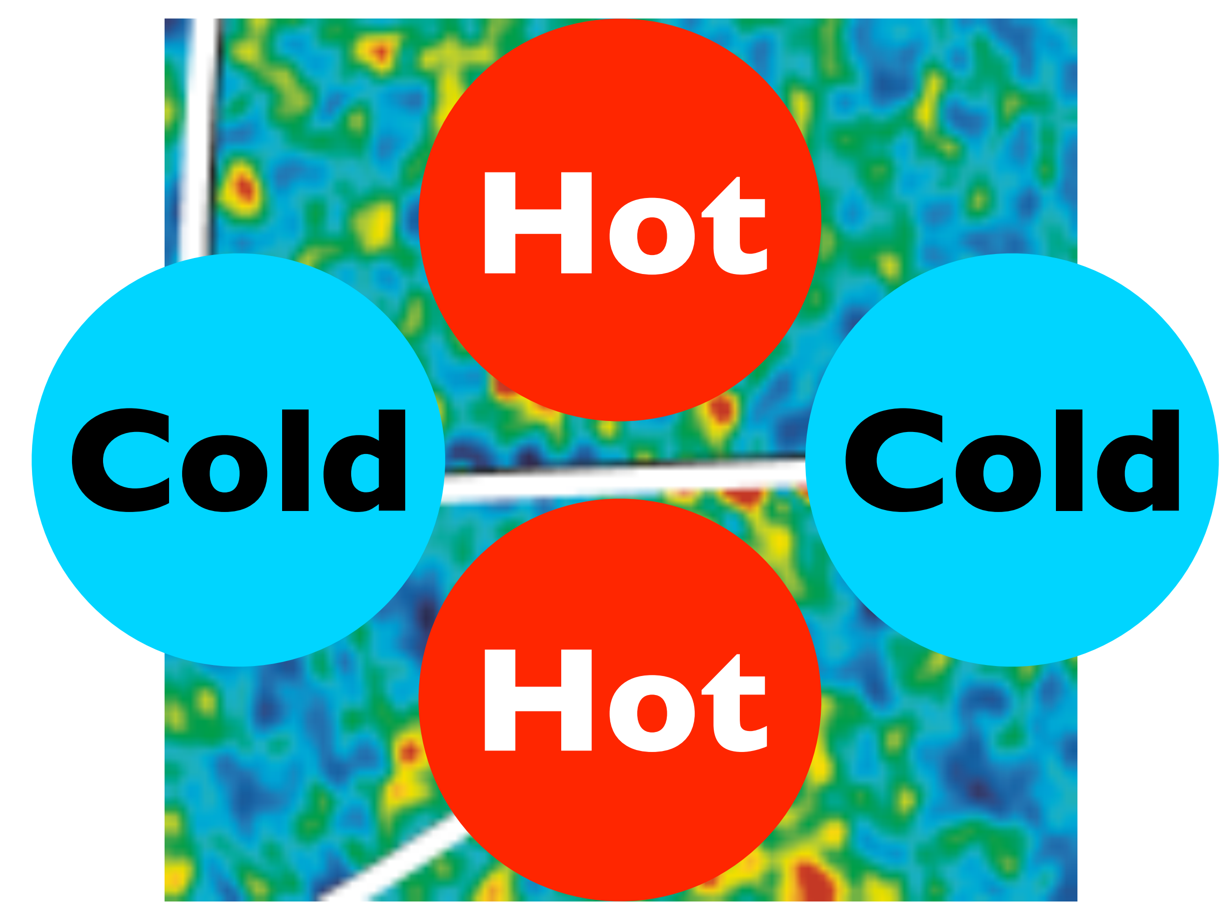
Physics of CMB Polarization



- CMB Polarization is created by a local temperature **quadrupole** anisotropy.

Principle





- **Polarization direction is parallel to "hot."**

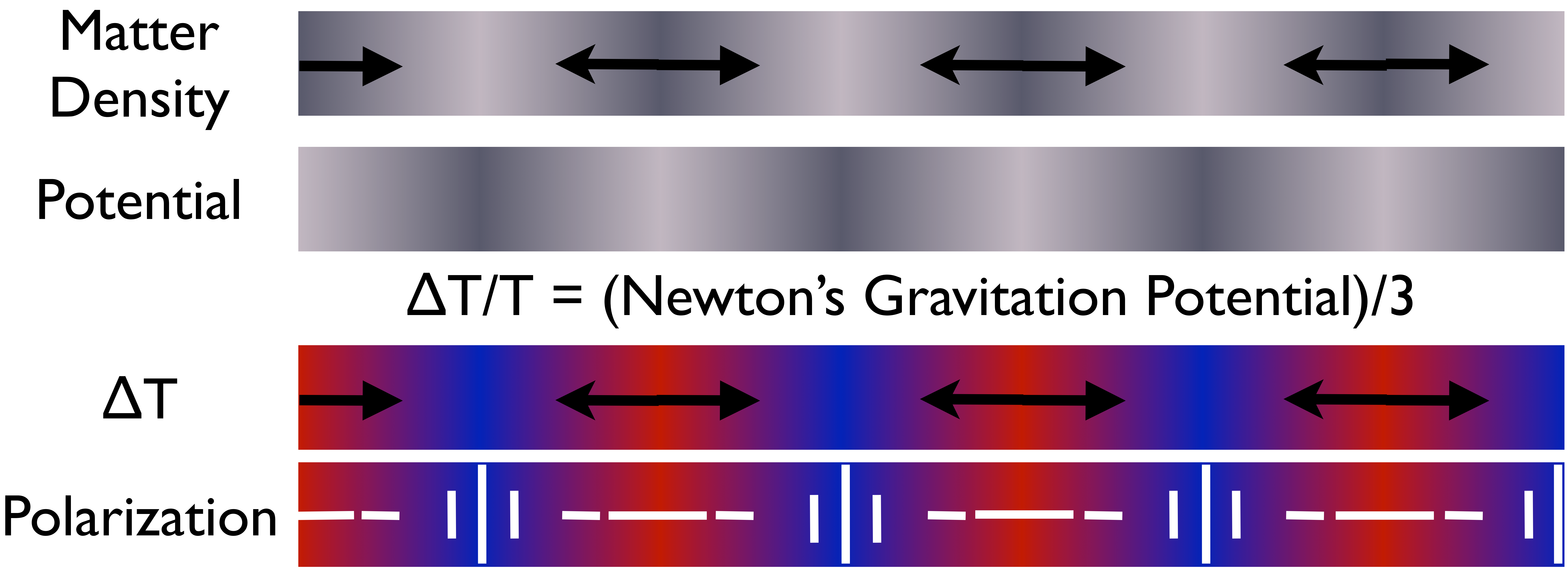
CMB Polarization on Large Angular Scales (>2 deg)

ΔT/T = (Newton's Gravitation Potential)/3

- How does the photon-baryon plasma move?

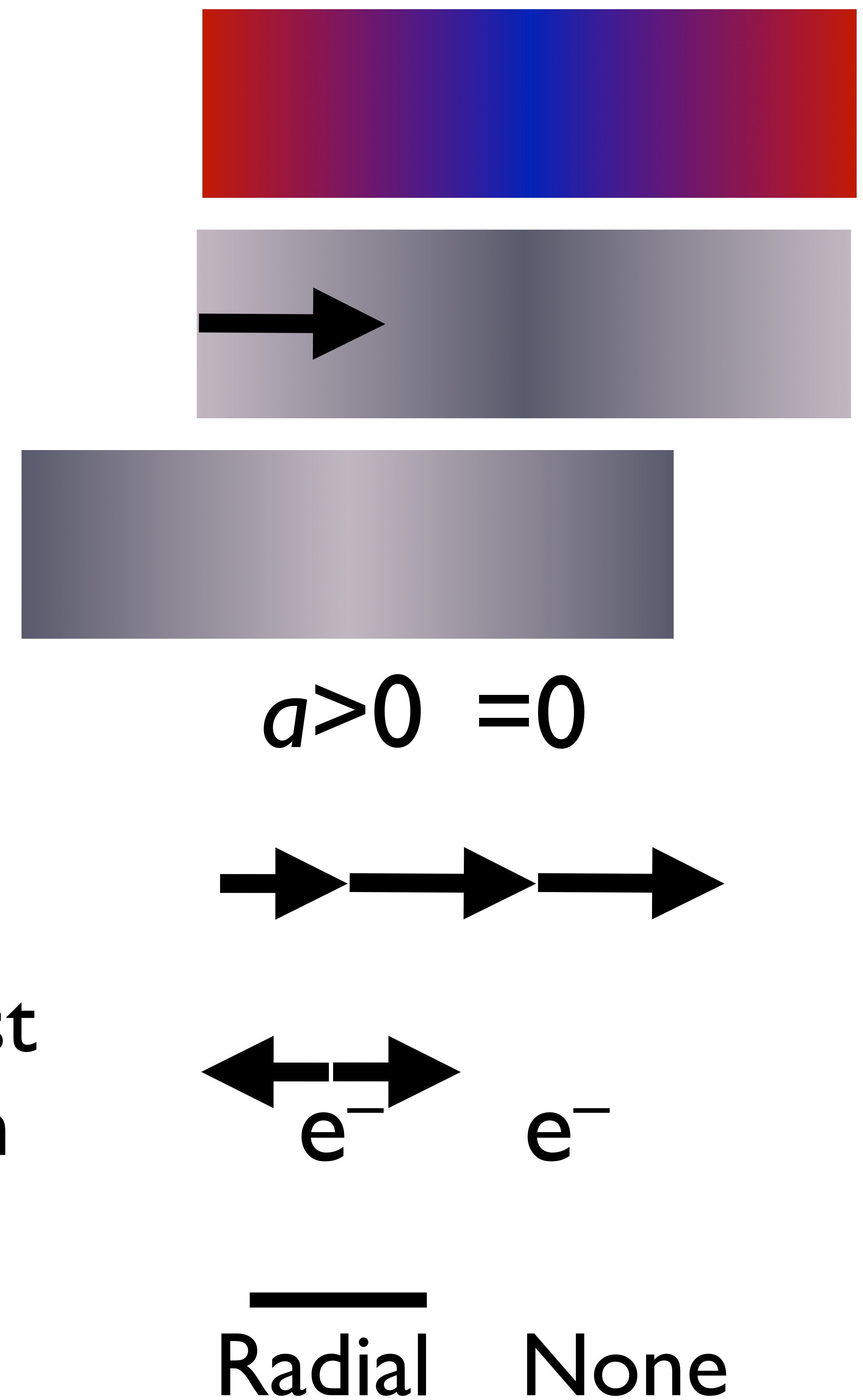
CMB Polarization Tells Us How Plasma Moves at z=1090

Zaldarriaga & Harari (1995)



- Plasma **falling into** the gravitational potential well = **Radial** polarization pattern

Quadrupole From Velocity Gradient (Large Scale)



ΔT	Sachs-Wolfe: ΔT/T=Φ/3
Potential Φ	Stuff flowing *in*
Acceleration $a=-\partial\Phi$	
Velocity	Velocity gradient
Velocity in the rest frame of electron	The left electron sees colder photons along the plane wave
Polarization	

Quadrupole From Velocity Gradient (Small Scale)

ΔT — Compression increases temperature

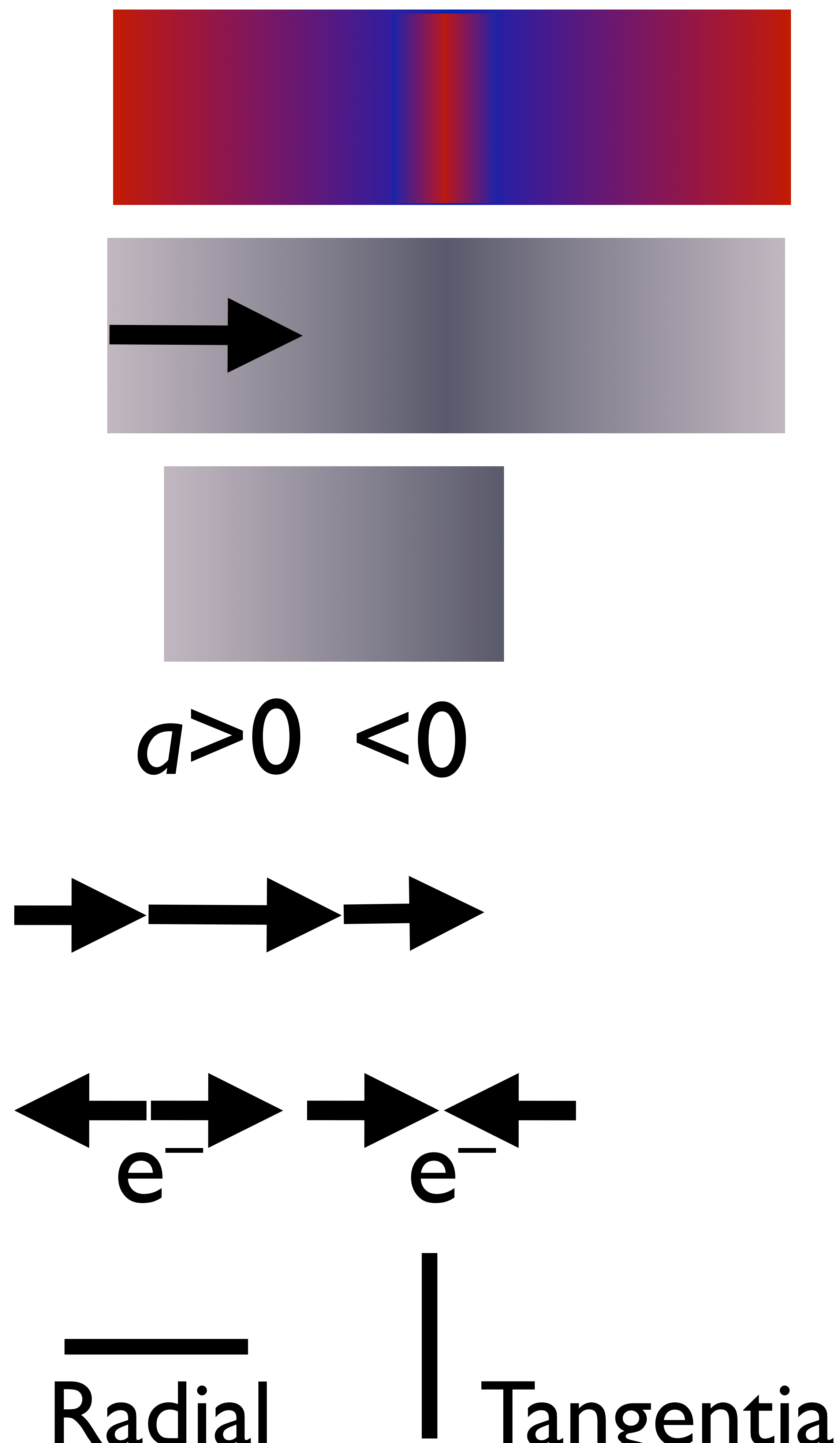
Potential Φ — Stuff flowing *in*

Acceleration $a = -\partial\Phi - \partial P$ — Pressure gradient slows down the flow

Velocity — Velocity gradient

Velocity in the rest frame of electron

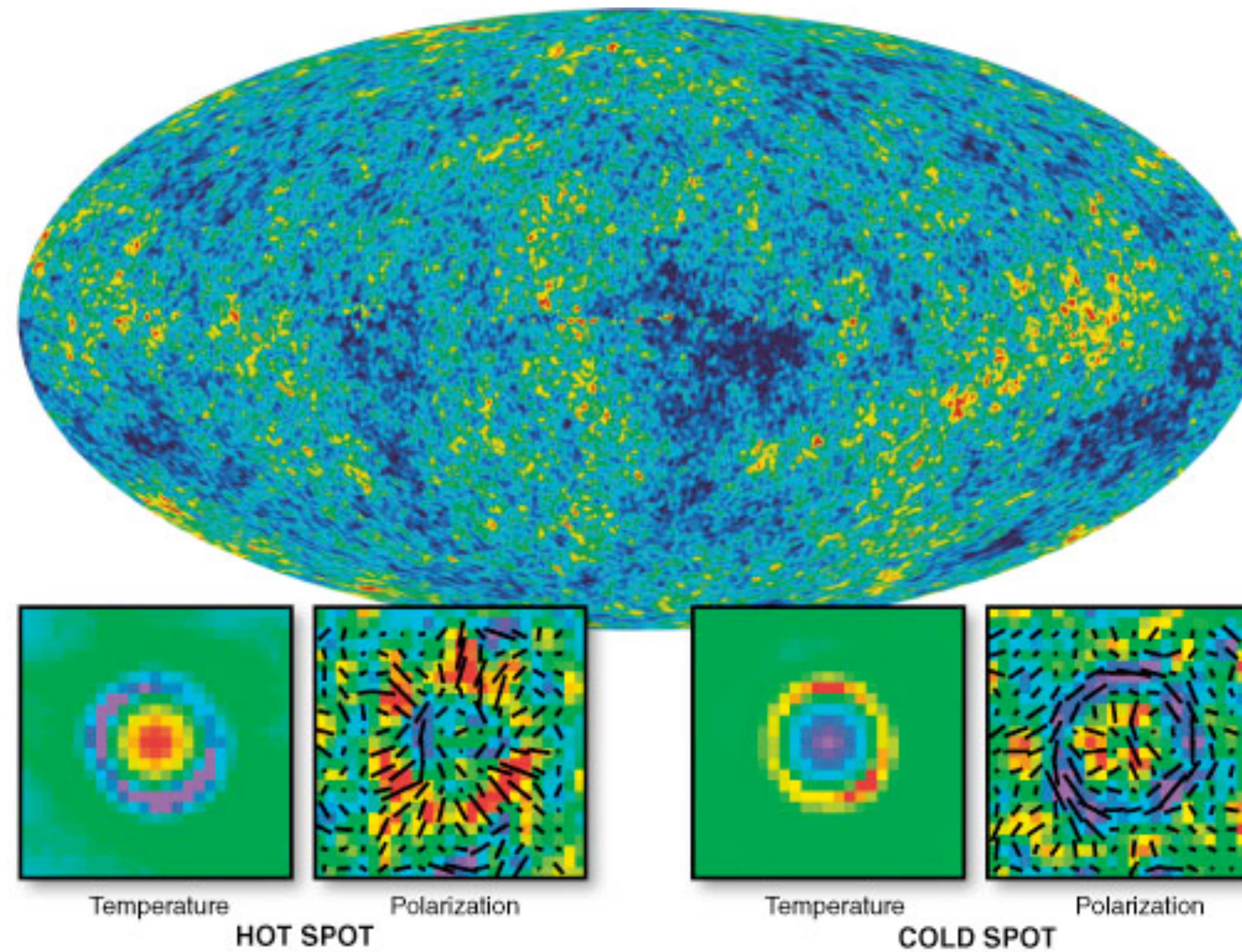
Polarization

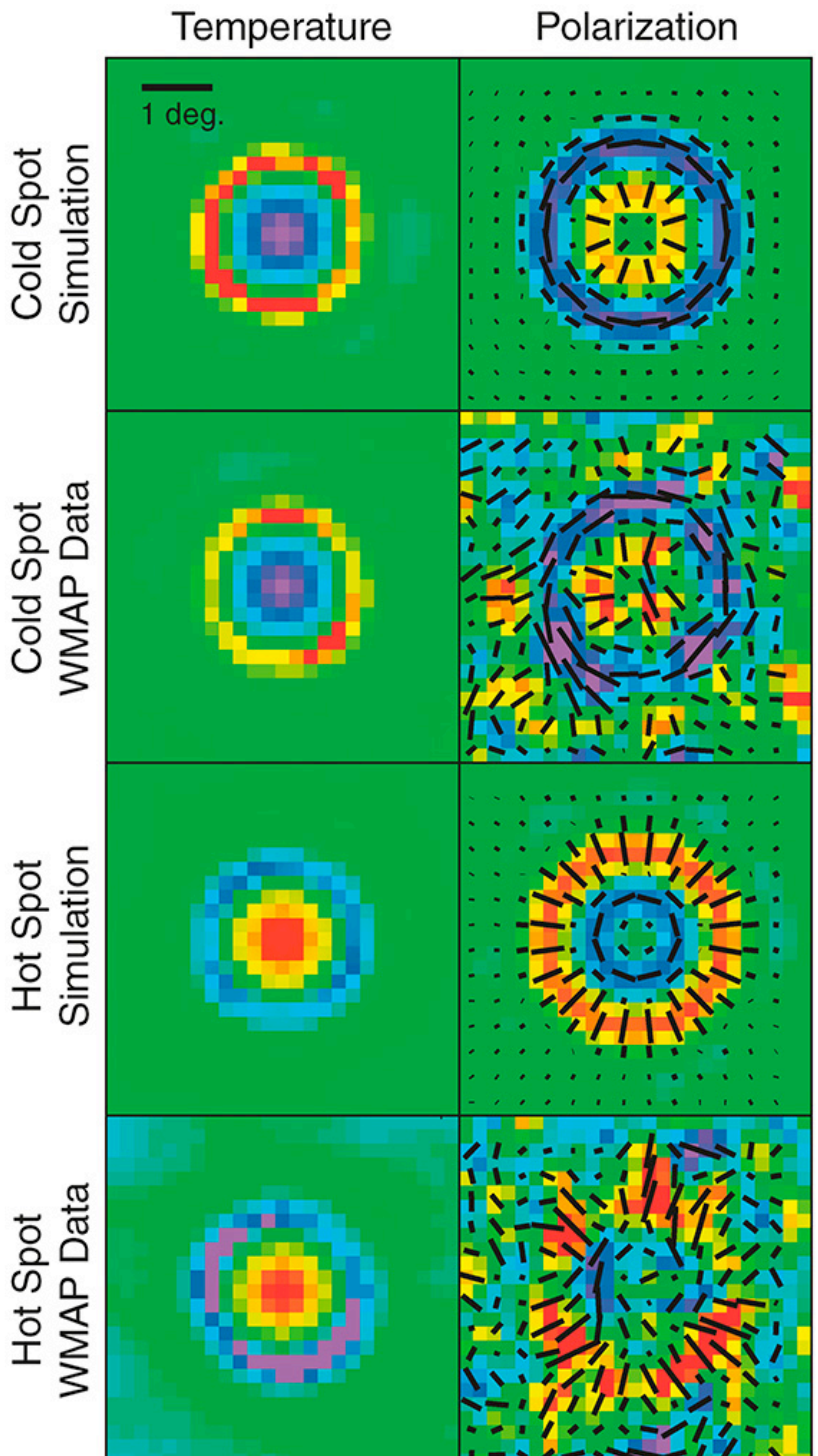


Komatsu et al. (2010)

Stacking Analysis

- Stack polarization images around temperature hot and cold spots.
- Outside of the Galaxy mask (not shown), there are **12387 hot spots** and **12628 cold spots**.



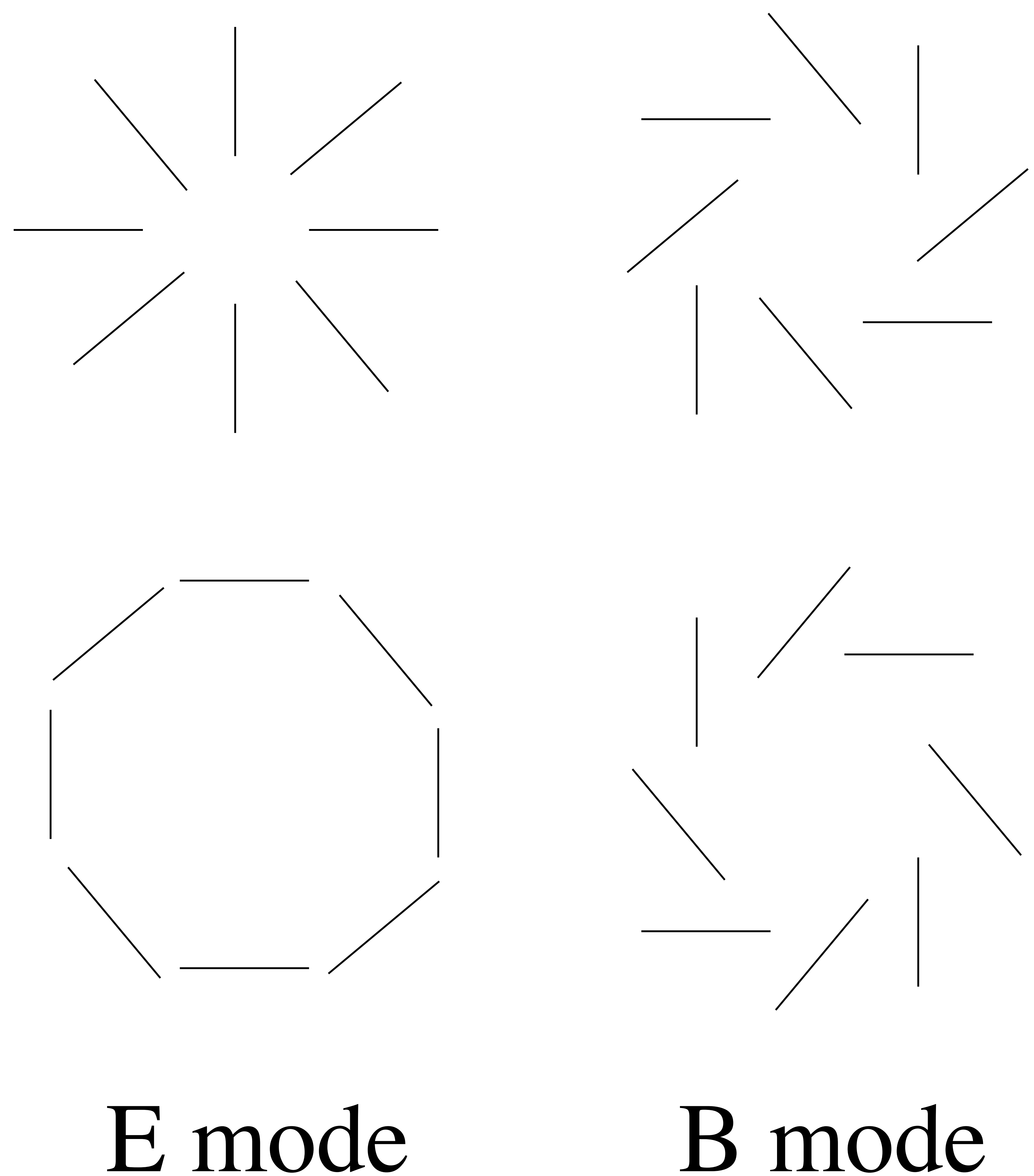


Komatsu et al. (2010)

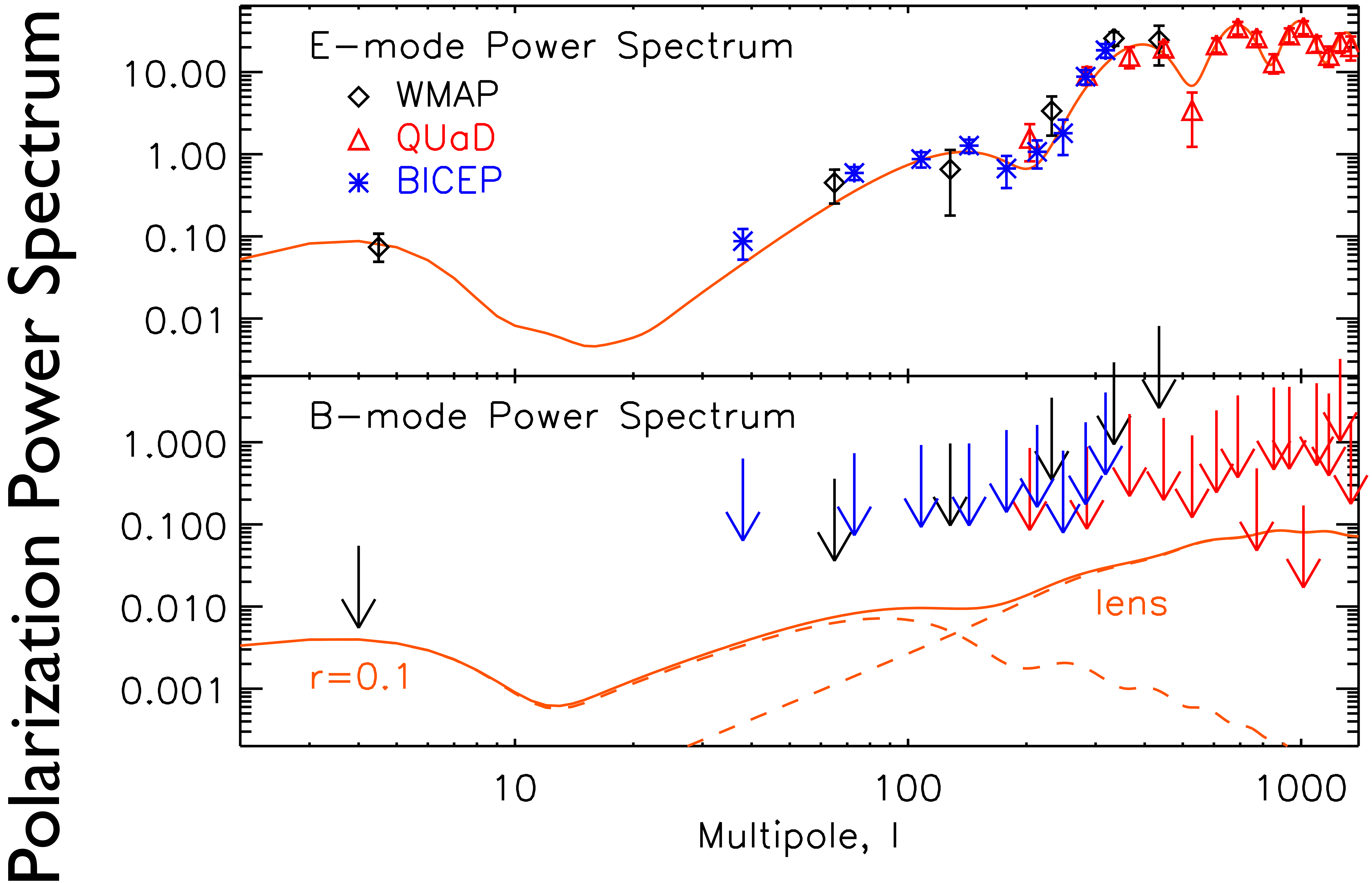
Two-dimensional View

- All hot and cold spots are stacked (the threshold peak height, $\Delta T/\sigma$, is zero)
- "Compression phase" at θ=1.2 deg and "slow-down phase" at θ=0.6 deg are predicted to be there and we observe them!
  - The overall significance level: 8σ

E-mode and B-mode



- Gravitational potential can generate the E-mode polarization, but not B-modes.
- **Gravitational waves** can generate both E- and B-modes!

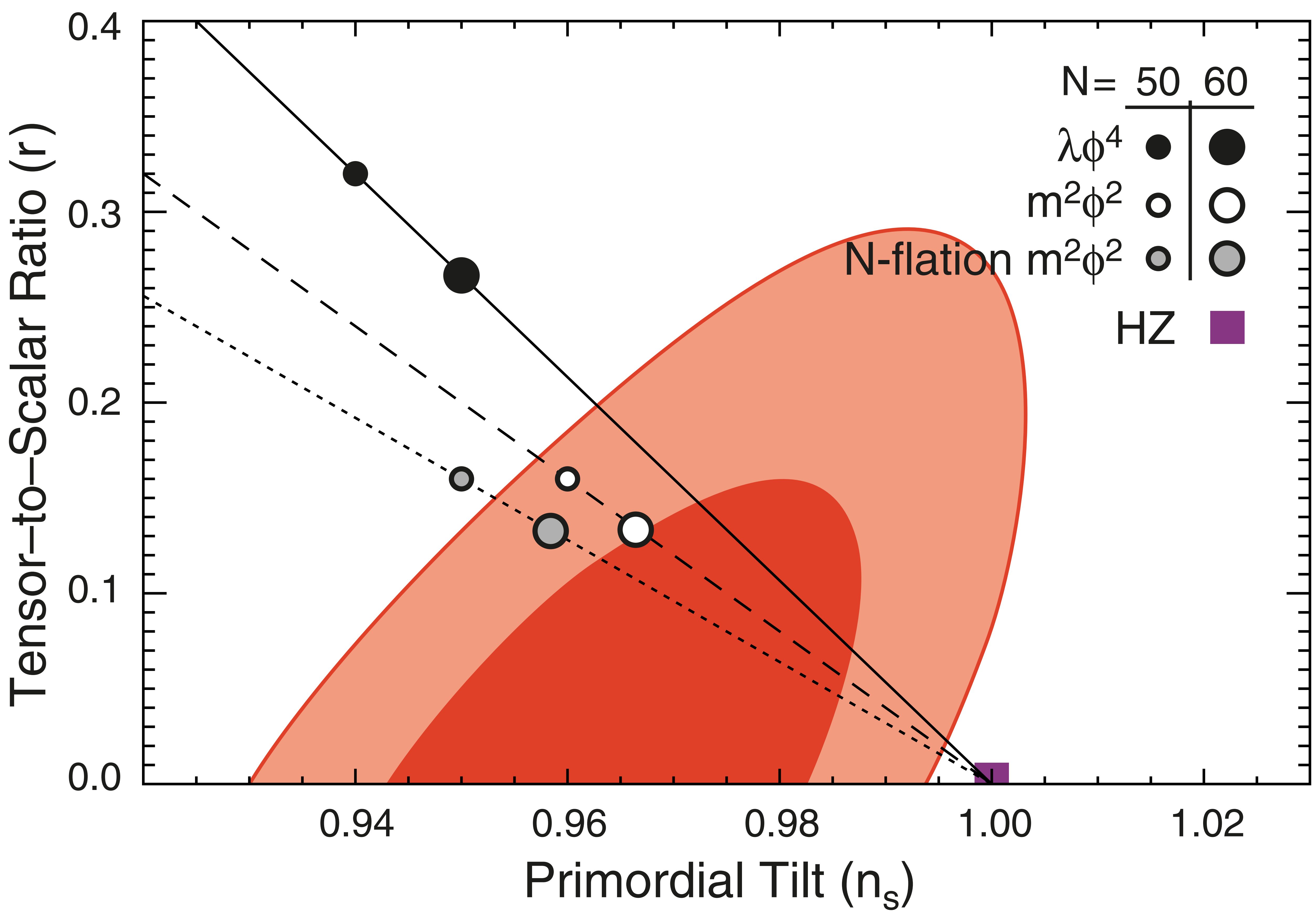


- No detection of B-mode polarization yet.
  B-mode is the next holy grail.

Komatsu et al. (2010)

Probing Inflation (2-point Function)

r = (gravitational waves)^2 / (gravitational potential)^2



- Joint constraint on the primordial tilt, n_s, and the tensor-to-scalar ratio, r.
  - Not so different from the 5-year limit.
  - $r < 0.24$ (95%CL)
- Limit on the tilt of the power spectrum: $n_s=0.968\pm0.012$ (68%CL)

Komatsu et al. (2010)

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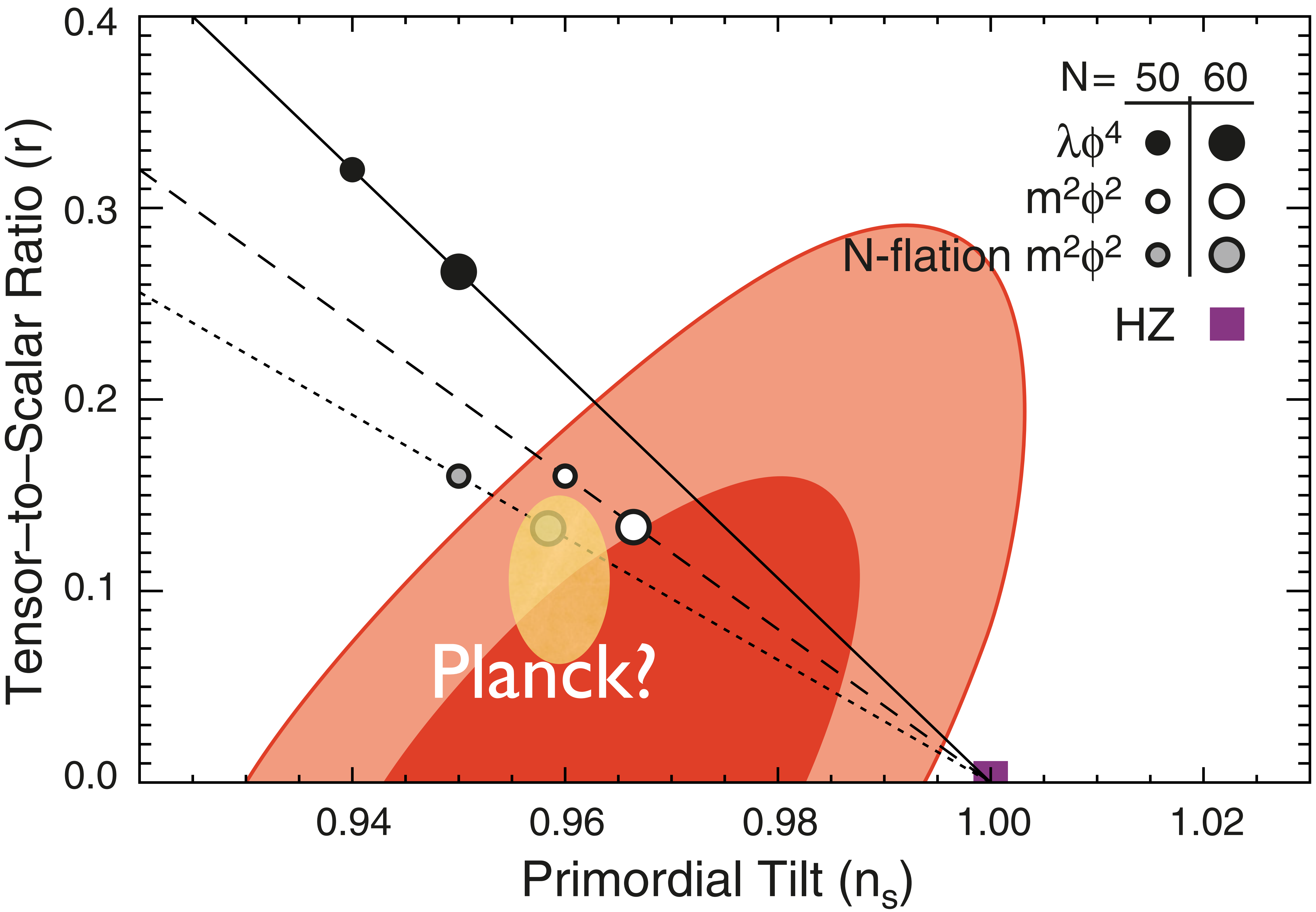

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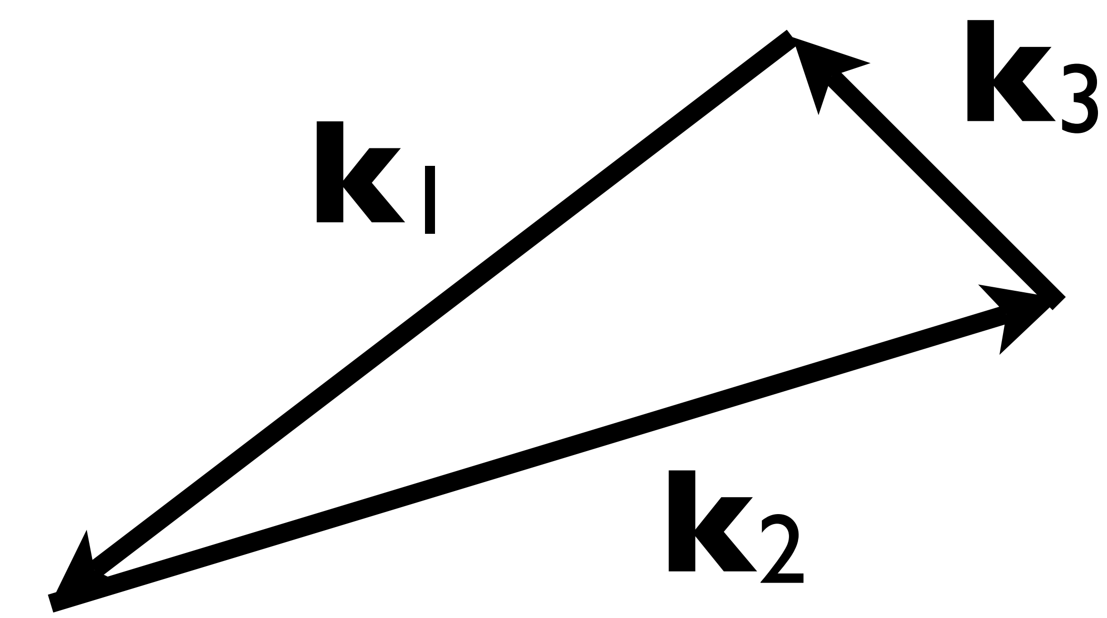
Probing Inflation (3-point Function)

Can We Rule Out Inflation?

- Inflation models predict that primordial fluctuations are very close to Gaussian.
  - In fact, ALL SINGLE-FIELD models predict a particular form of **3-point function** to have the amplitude of $f_{NL}=0.02$.
  - Detection of $f_{NL}>1$ would rule out ALL single-field models!

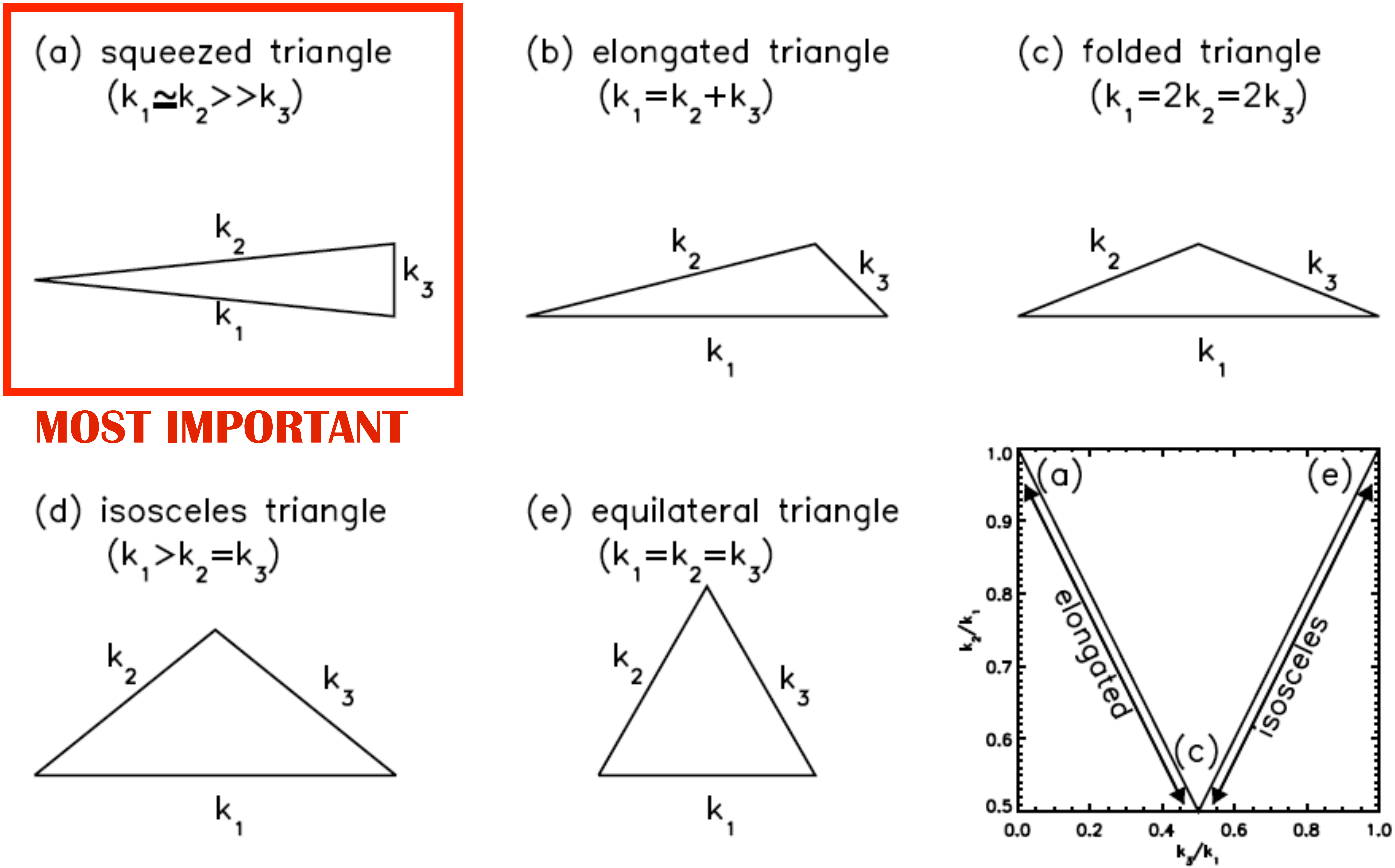
Bispectrum



- Three-point function!
- $B_\zeta(\mathbf{k}_1,\mathbf{k}_2,\mathbf{k}_3)$
  $= \langle \zeta_{\mathbf{k}_1}\zeta_{\mathbf{k}_2}\zeta_{\mathbf{k}_3} \rangle$ = (amplitude) x $(2\pi)^3\delta(\mathbf{k}_1+\mathbf{k}_2+\mathbf{k}_3)F(k_1,k_2,k_3)$

  model-dependent function

Primordial fluctuation


(a) squeezed triangle
(k1≃k2>>k3)
k2
k3
k1
MOST IMPORTANT
(b) elongated triangle
(k1=k2+k3)
k2
k3
k1
(c) folded triangle
(k1=2k2=2k3)
k2
k3
k1
(d) isosceles triangle
(k1>k2=k3)
k2
k3
k1
(e) equilateral triangle
(k1=k2=k3)
k2
k3
k1
(a)
(e)
(c)
elongated
isosceles
k2/k1
k3/k1
1.0
0.9
0.8
0.7
0.6
0.5
0.0
0.2
0.4
0.6
0.8
1.0

Maldacena (2003); Seery & Lidsey (2005); Creminelli & Zaldarriaga (2004)

Single-field Theorem (Consistency Relation)

- For **ANY** single-field models*, the bispectrum in the squeezed limit is given by
  - $B_\zeta(\mathbf{k}_1,\mathbf{k}_2,\mathbf{k}_3) \approx (1-n_s) \times (2\pi)^3\delta(\mathbf{k}_1+\mathbf{k}_2+\mathbf{k}_3) \times P_\zeta(k_1)P_\zeta(k_3)$
  - Therefore, all single-field models predict $f_{NL} \approx (5/12)(1-n_s)$.
  - With the current limit $n_s=0.963$, f_{NL} is predicted to be 0.015.

* for which the single field is solely responsible for driving inflation and generating observed fluctuations.

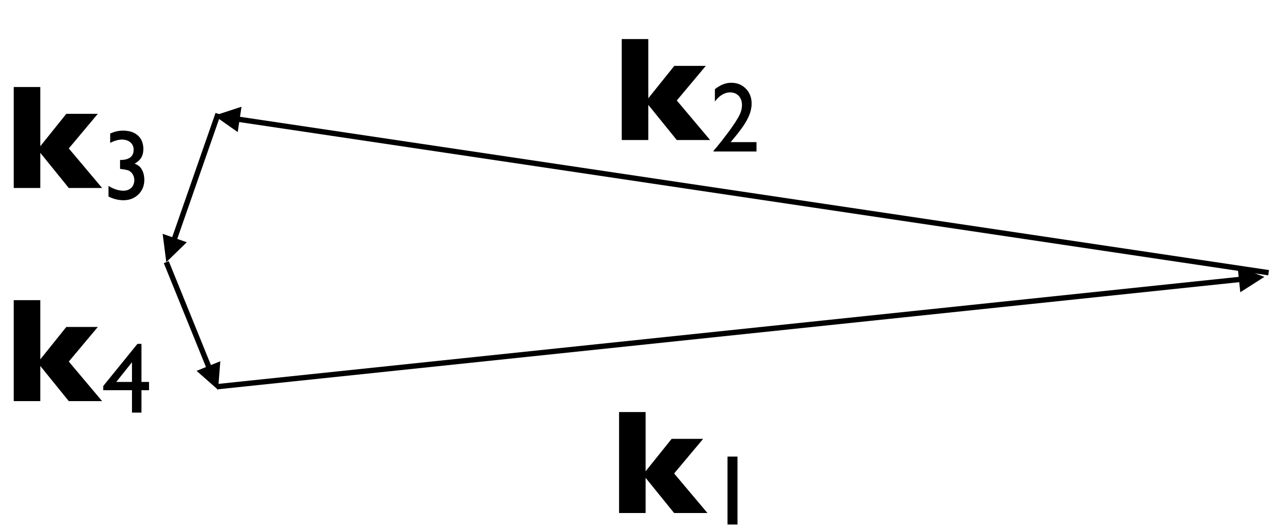
Komatsu et al. (2010)

Probing Inflation (3-point Function)

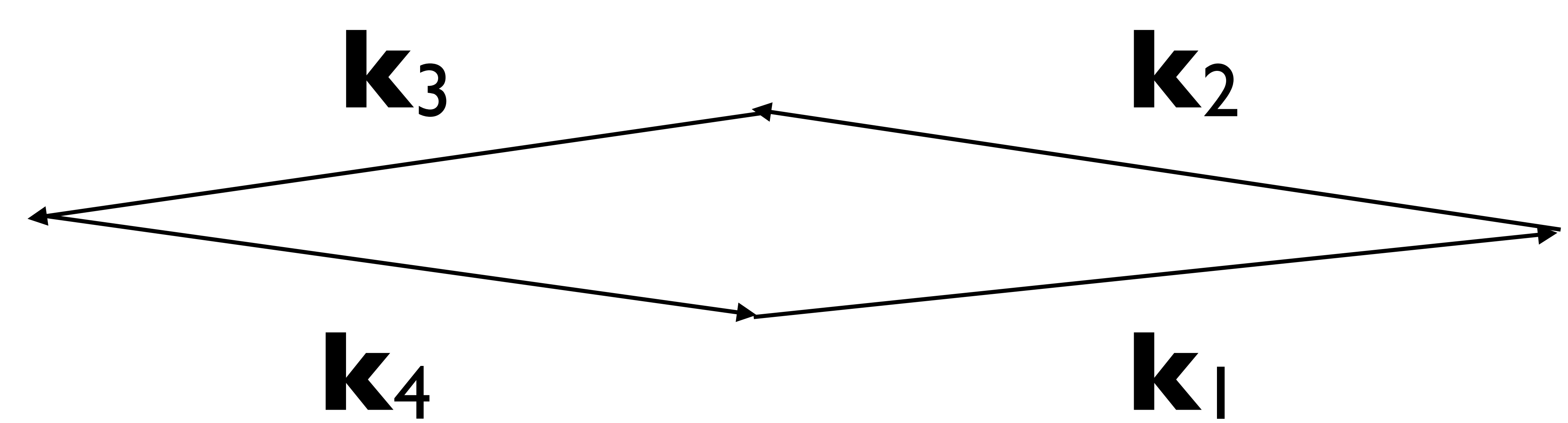
- No detection of 3-point functions of primordial curvature perturbations. The 95% CL limit is:
  - $-10 < f_{NL} < 74$
- The 68% CL limit: $f_{NL} = 32 \pm 21$
  - The WMAP data are consistent with the prediction of **simple single-field inflation** models: $1-n_s \approx r \approx f_{NL}$
- The Planck's expected 68% CL uncertainty: $\Delta f_{NL} = 5$

Trispectrum

- $T_\zeta(\mathbf{k}_1,\mathbf{k}_2,\mathbf{k}_3,\mathbf{k}_4)=(2\pi)^3\delta(\mathbf{k}_1+\mathbf{k}_2+\mathbf{k}_3+\mathbf{k}_4)\ \{g_{NL}[(54/25)P_\zeta(k_1)P_\zeta(k_2)P_\zeta(k_3)+\mathrm{cyc.}]+\tau_{NL}[P_\zeta(k_1)P_\zeta(k_2)(P_\zeta(|\mathbf{k}_1+\mathbf{k}_3|)+P_\zeta(|\mathbf{k}_1+\mathbf{k}_4|))+\mathrm{cyc.}]\}$

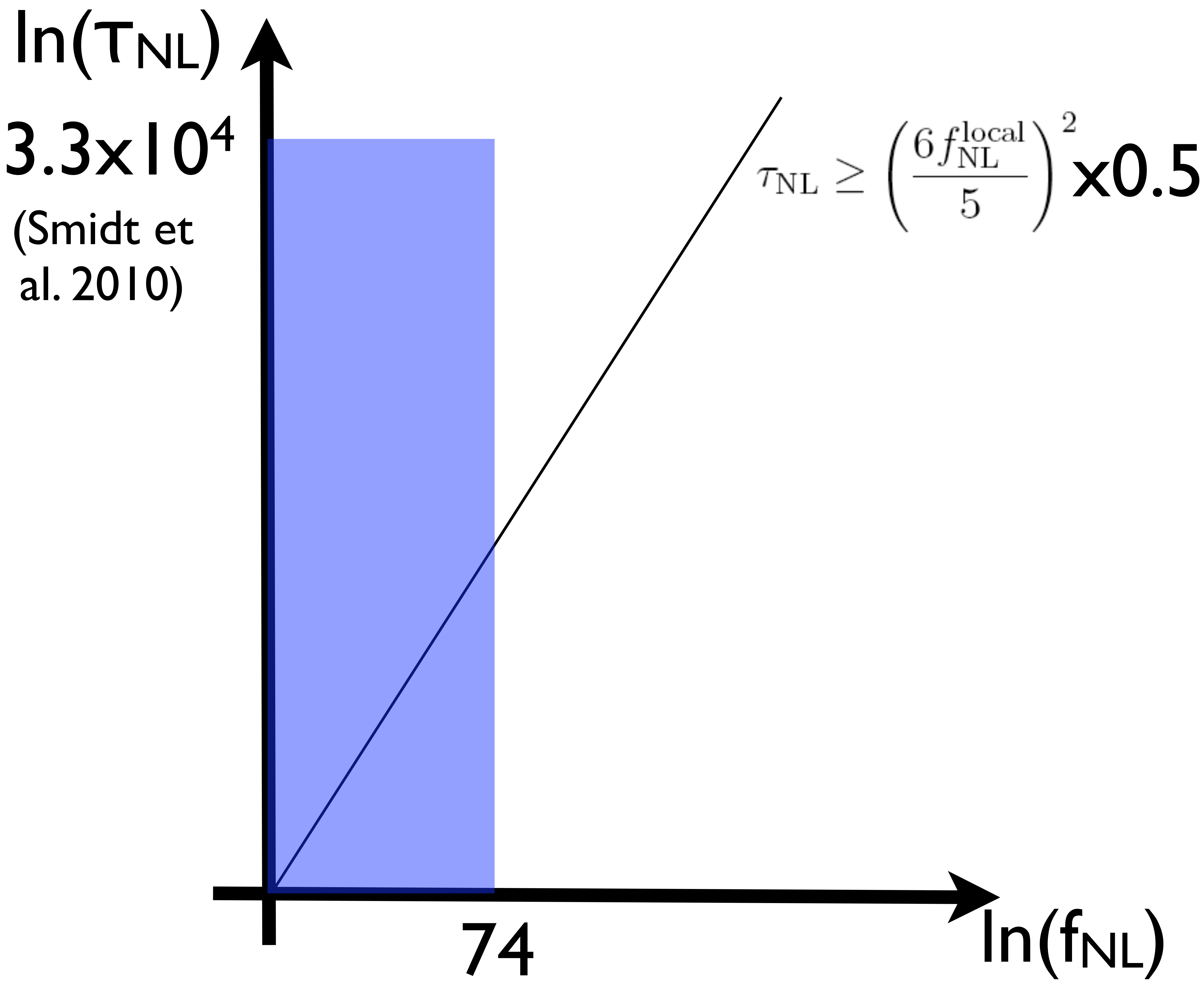


g_{NL}



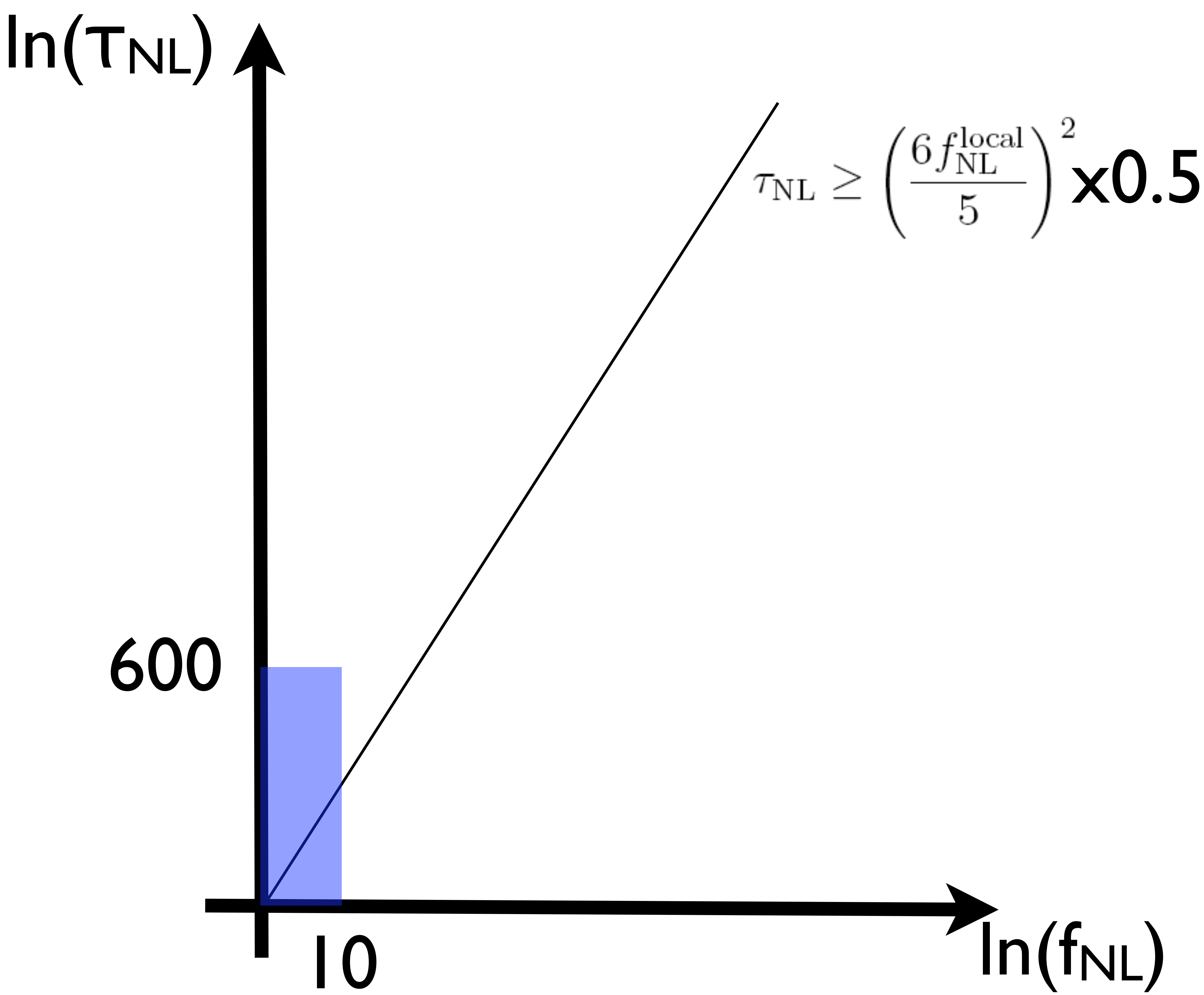
τ_{NL}

The diagram that you should take away from this talk.



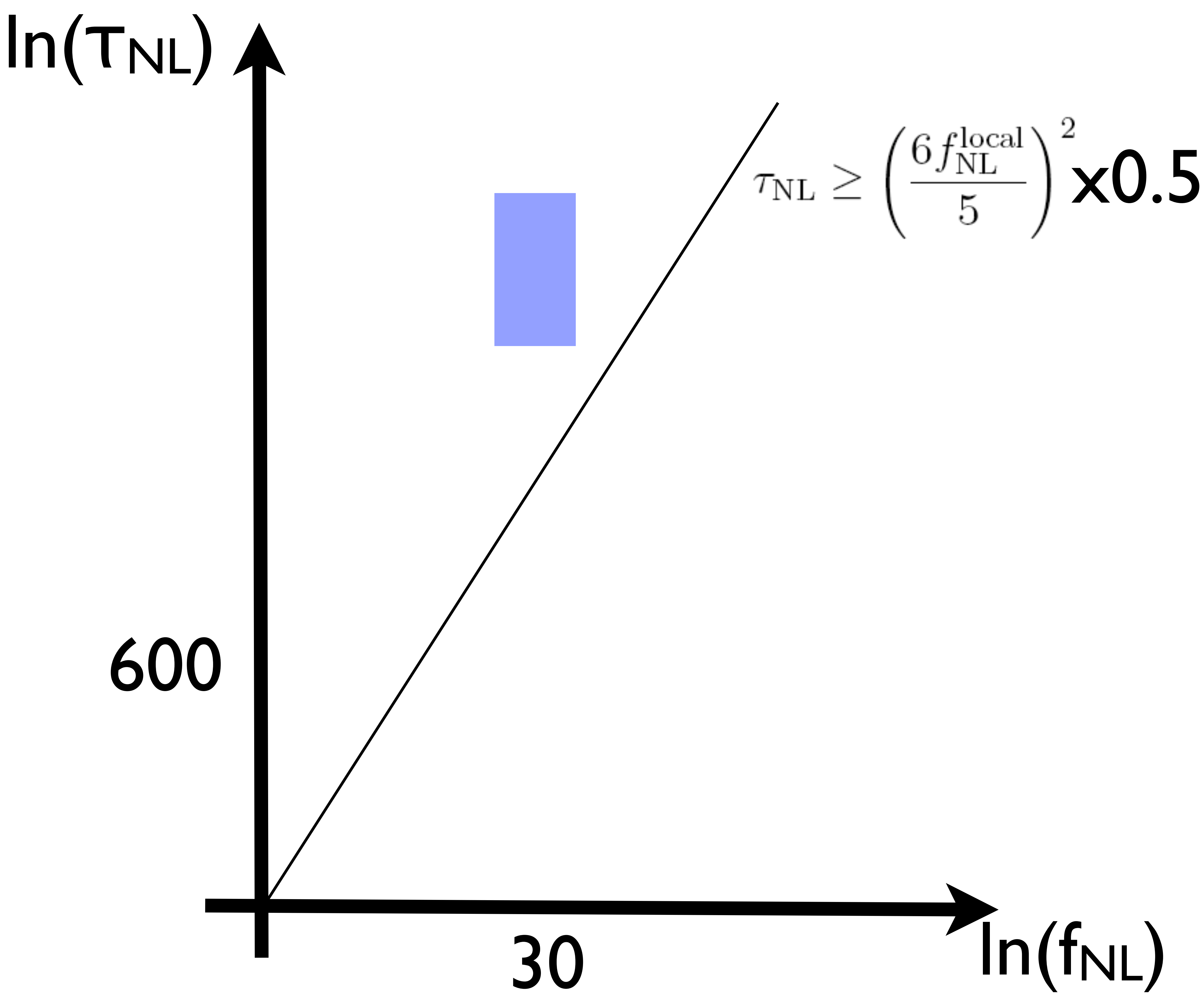
- The current limits from WMAP 7-year are consistent with single-field or multi-field models.
- So, let's play around with the future.

Case A: Single-field Happiness



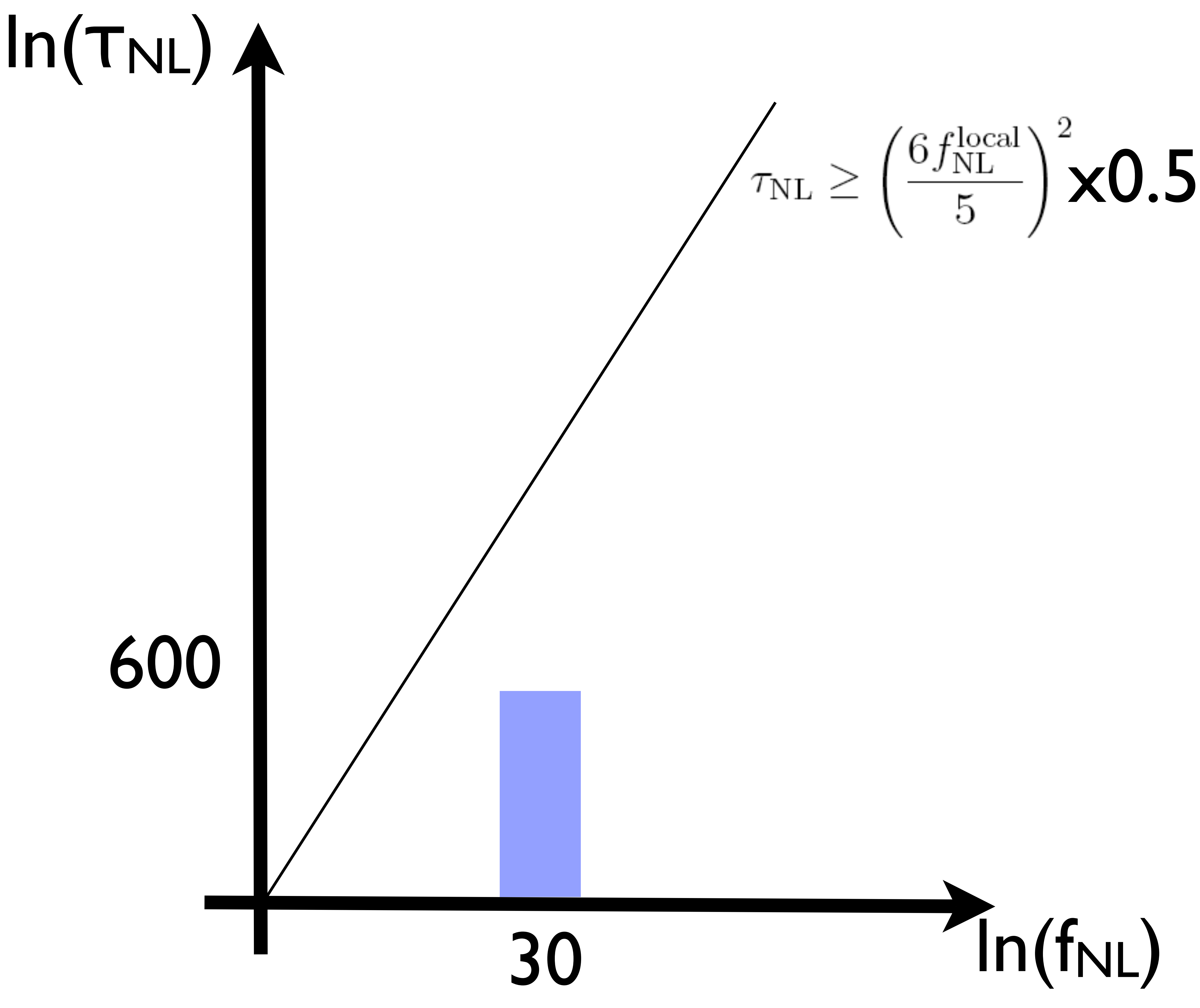
- No detection of anything after Planck. Single-field survived the test (for the moment: the future galaxy surveys can improve the limits by a factor of ten).

Case B: Multi-field Happiness



- f_{NL} is detected. Single-field is dead.
- But, τ_{NL} is also detected, in accordance with multi-field models: $\tau_{NL}>0.5 (6f_{NL}/5)^2$ [Sugiyama, Komatsu & Futamase, to appear]

Case C: Madness



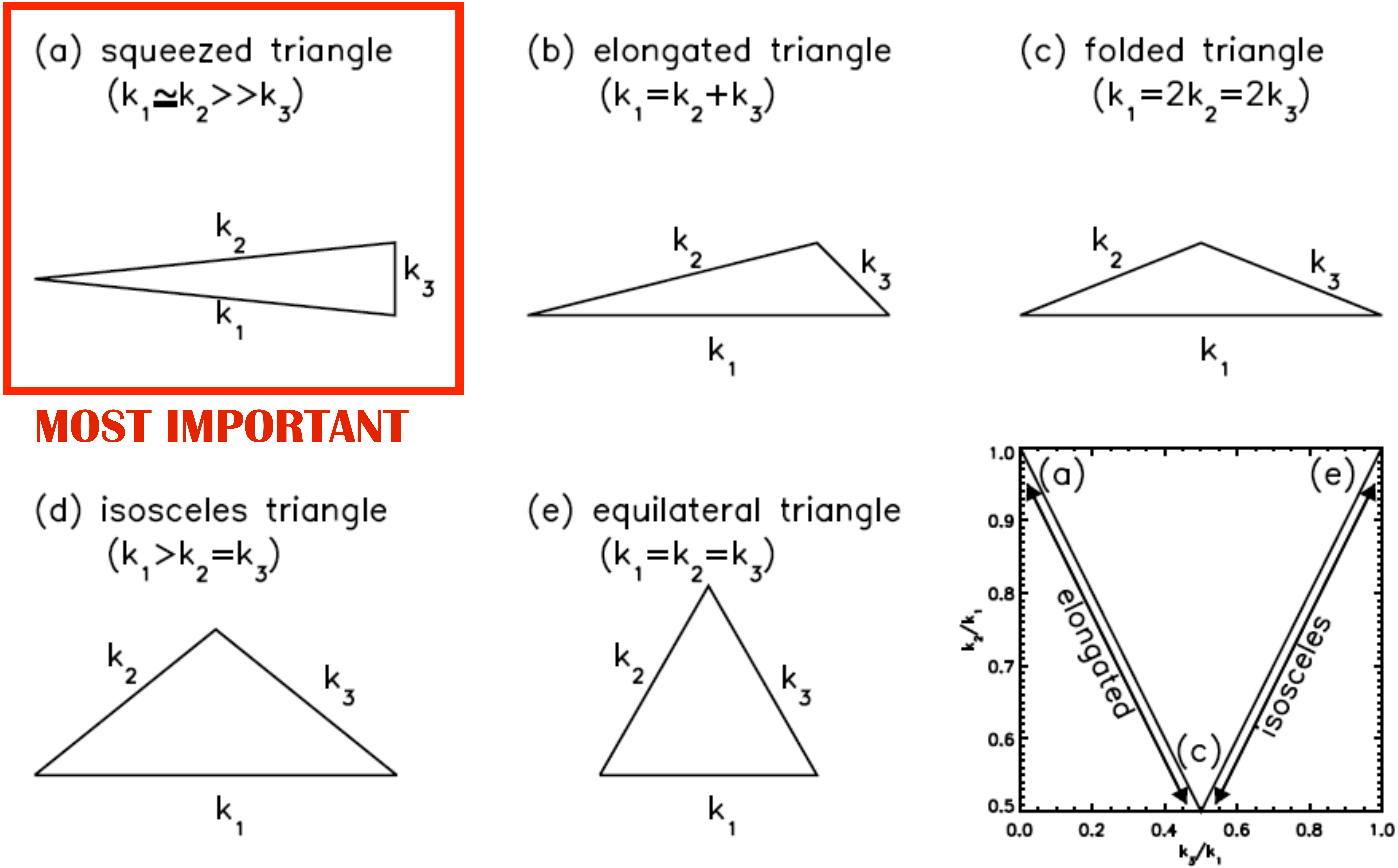
- f_{NL} is detected. Single-field is dead.
- But, τ_{NL} is **not** detected, inconsistent with the multi-field bound.
- (With the caveat that this bound may not be completely general) BOTH the single-field and multi-field are gone.

Beyond CMB: Large-scale Structure!

- In principle, the large-scale structure of the universe offers a lot more statistical power, because we can get 3D information. (CMB is 2D, so the number of Fourier modes is limited.)

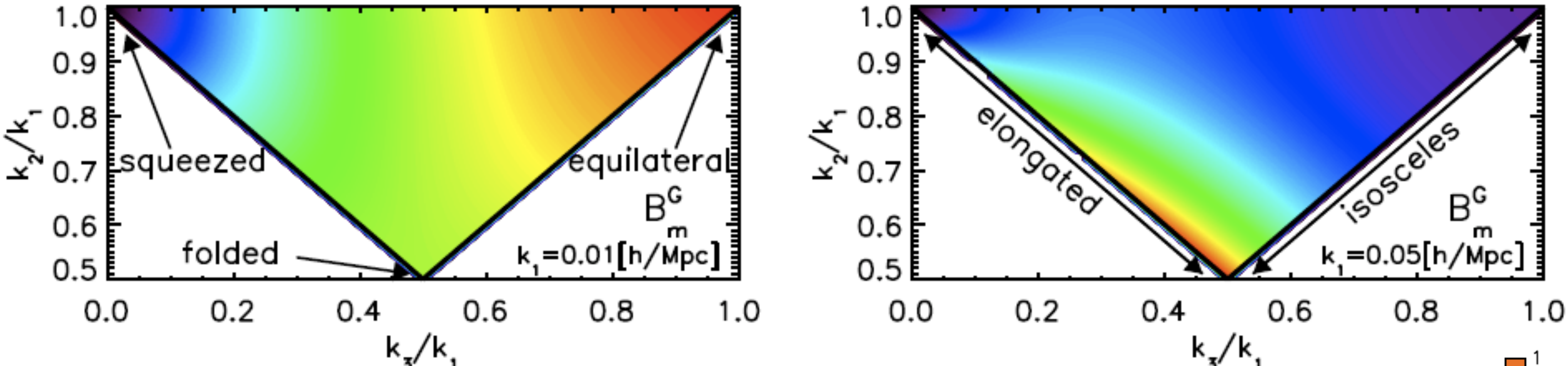
Beyond CMB: Large-scale Structure?

- Statistics is great, but the large-scale structure is non-linear, so perhaps it is less clean?
  - Not necessarily.

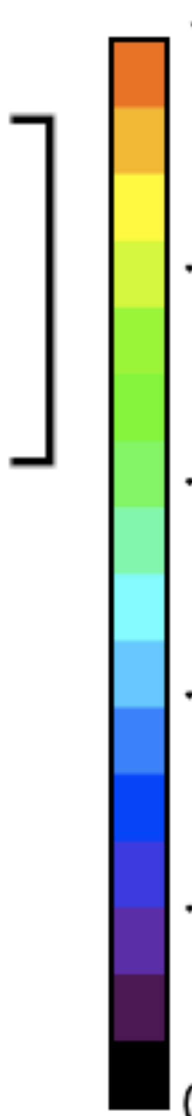


(a) squeezed triangle
($k_1 \simeq k_2 >> k_3$)
k_2
k_3
k_1
MOST IMPORTANT
(b) elongated triangle
($k_1 = k_2 + k_3$)
k_2
k_3
k_1
(c) folded triangle
($k_1 = 2k_2 = 2k_3$)
k_2
k_3
k_1
(d) isosceles triangle
($k_1 > k_2 = k_3$)
k_2
k_3
k_1
(e) equilateral triangle
($k_1 = k_2 = k_3$)
k_2
k_3
k_1
(a)
(e)
(c)
elongated
isosceles
k_2/k_1
k_3/k_1
1.0
0.9
0.8
0.7
0.6
0.5
0.0
0.2
0.4
0.6
0.8
1.0

Non-linear Gravity

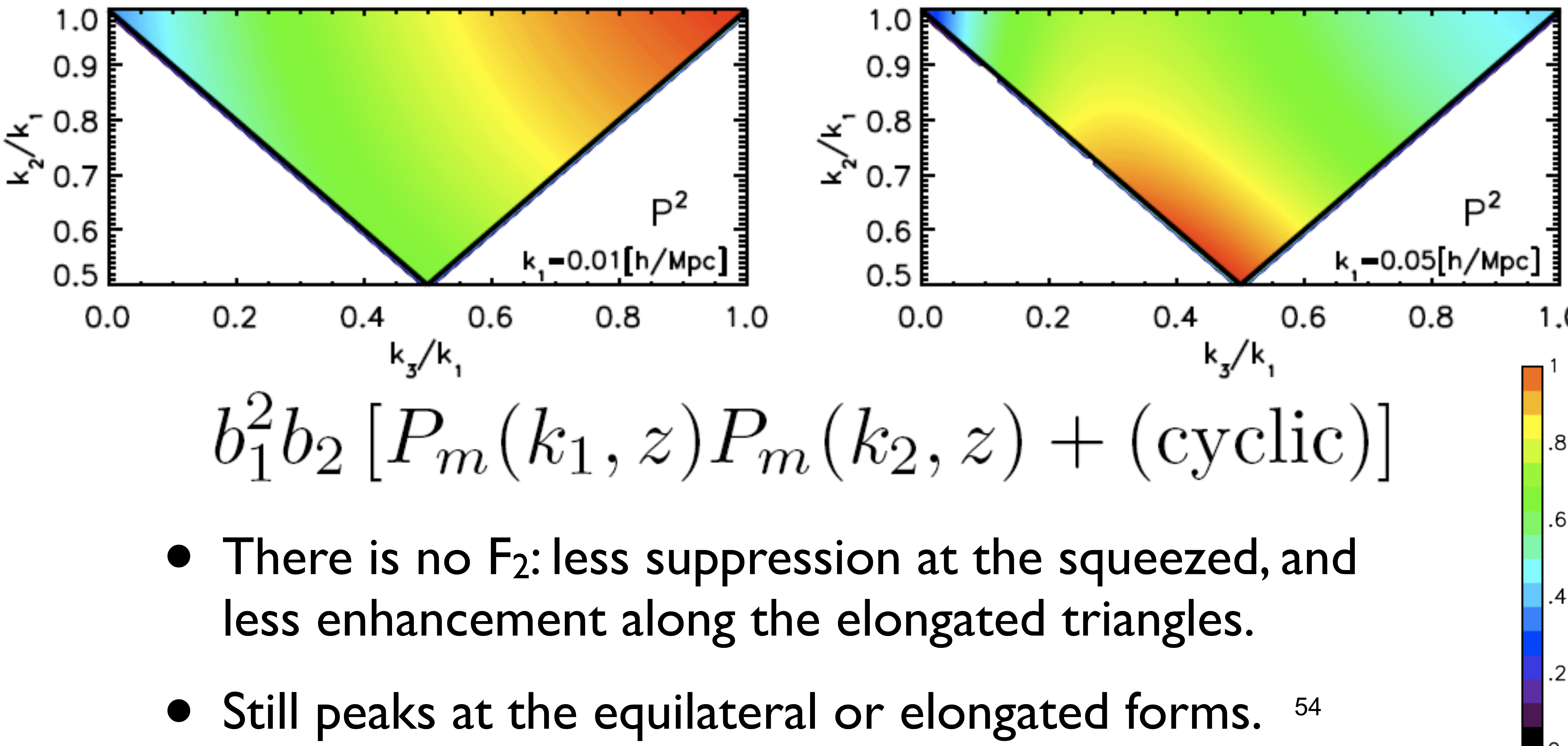


$$2b_1^3\left[F_2^{(s)}(\boldsymbol{k}_1,\boldsymbol{k}_2)P_m(k_1,z)P_m(k_2,z)+(\text{cyclic})\right]$$



- For a given k_1, vary k_2 and k_3, with $k_3 \leq k_2 \leq k_1$
- $F_2(k_2,k_3)$ vanishes in the squeezed limit, and peaks at the elongated triangles.

Non-linear Galaxy Bias

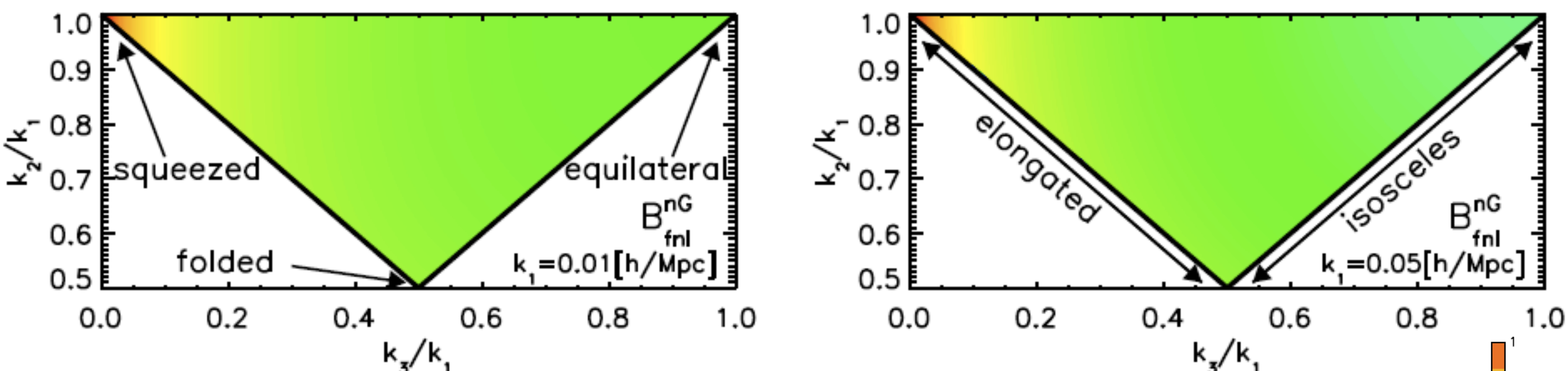


$$b_1^2 b_2 \left[P_m(k_1, z) P_m(k_2, z) + (\mathrm{cyclic})\right]$$

- There is no F_2: less suppression at the squeezed, and less enhancement along the elongated triangles.
- Still peaks at the equilateral or elongated forms.

Sefusatti & Komatsu (2007); Jeong & Komatsu (2010)

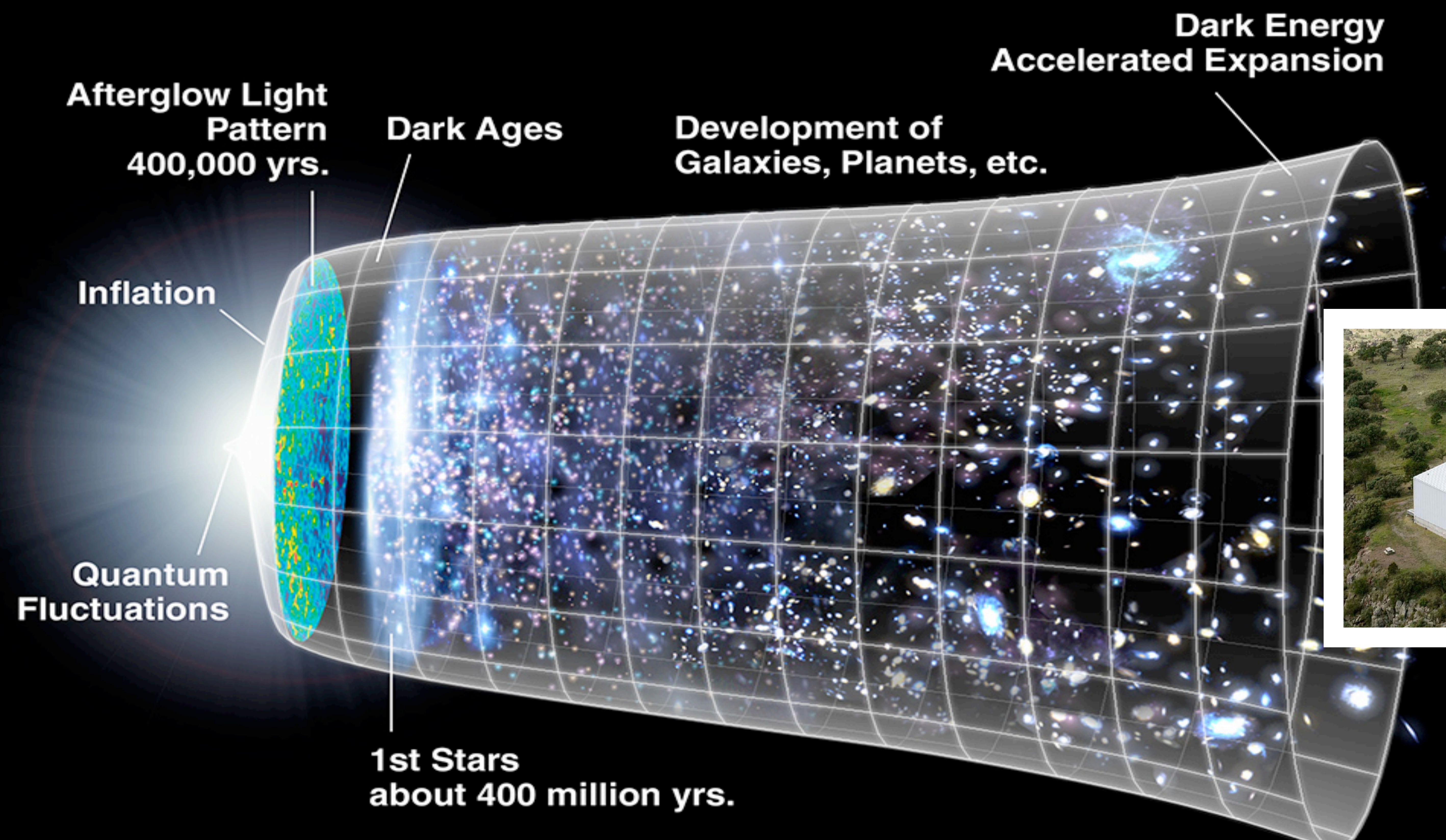
Primordial Non-Gaussianity



$$3b_1^3 f_{\rm NL}\Omega_m H_0^2\left[\frac{P_m(k_1,z)}{k_1^2T(k_1)}\frac{P_m(k_2,z)}{k_2^2T(k_2)}\frac{k_3^2T(k_3)}{D(z)}+(\text{cyclic})\right]$$

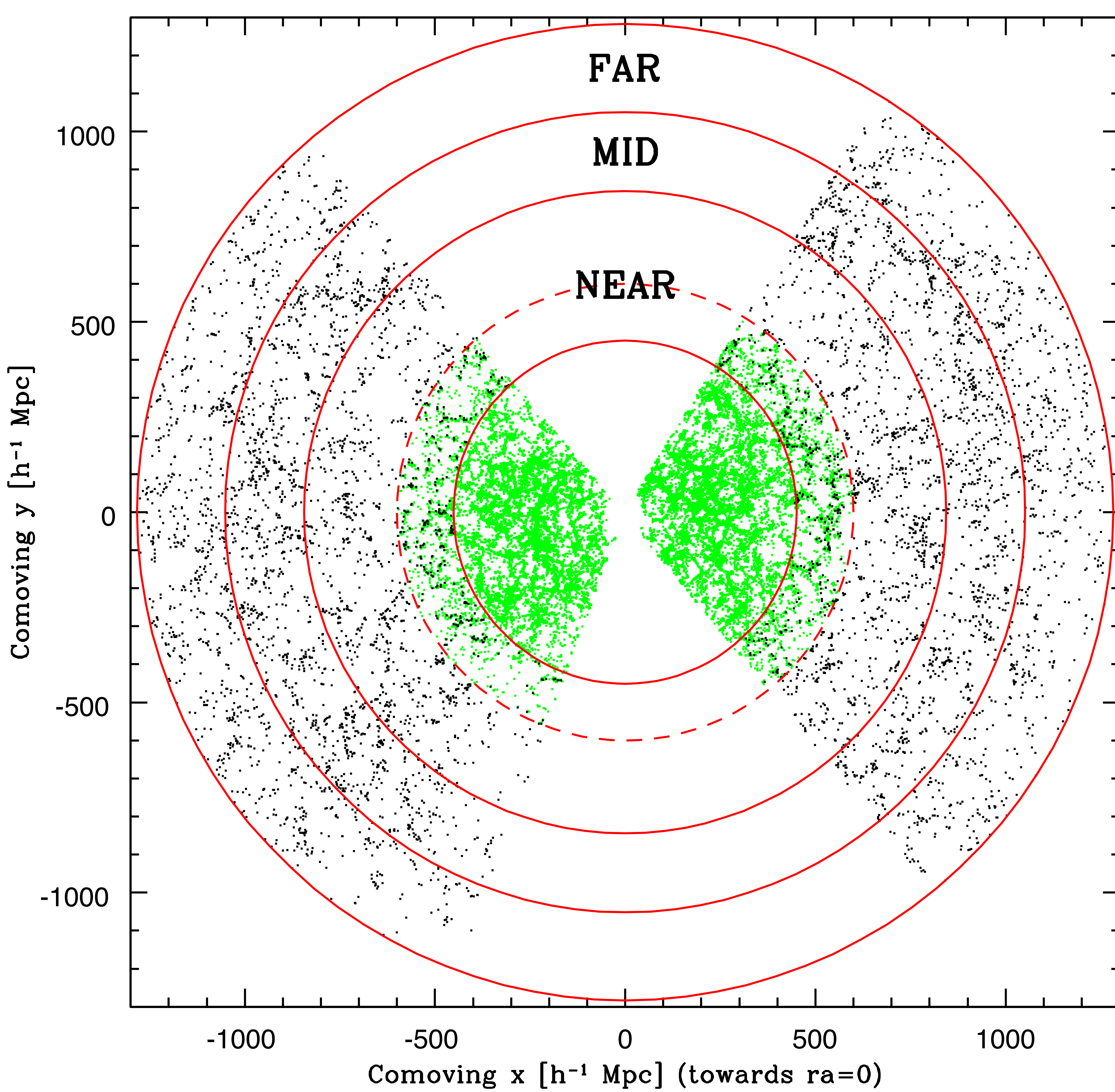
- This gives the peaks at the squeezed configurations, clearly distinguishable from other non-linear/astrophysical effects.

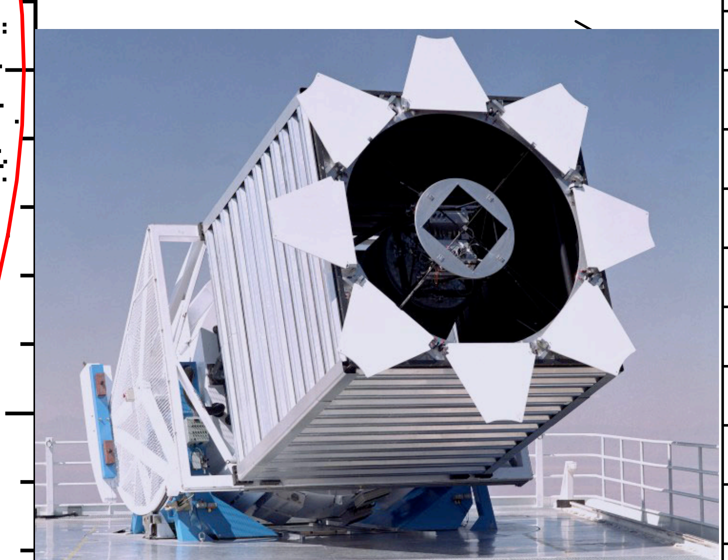
Hobby-Eberly Telescope Dark Energy Experiment (HETDEX)



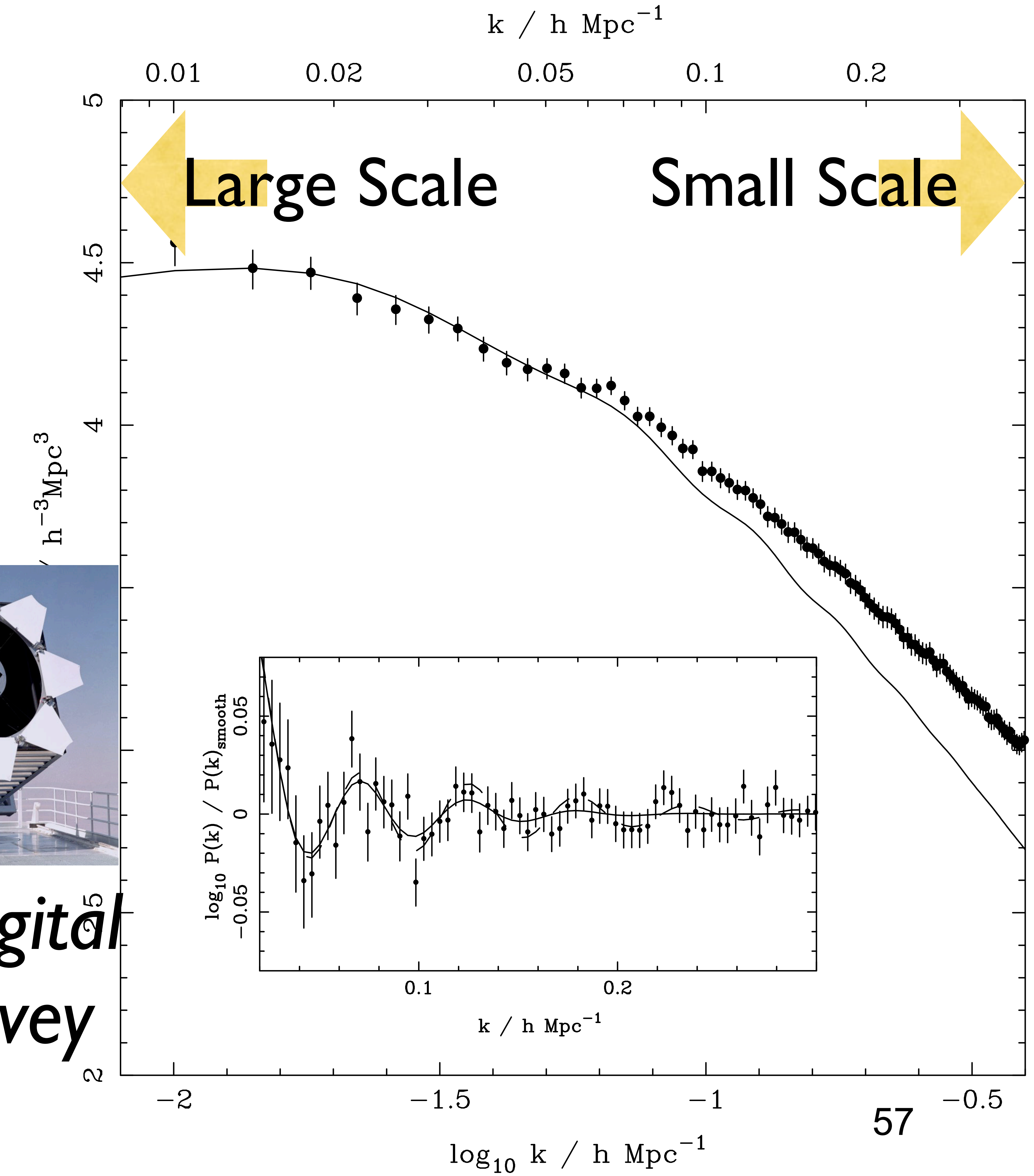
Use 9.2-m HET to map the universe using 0.8M Lyman-alpha emitting galaxies in z=1.9–3.5

HETDEX: Sound Waves in the Distribution of Galaxies

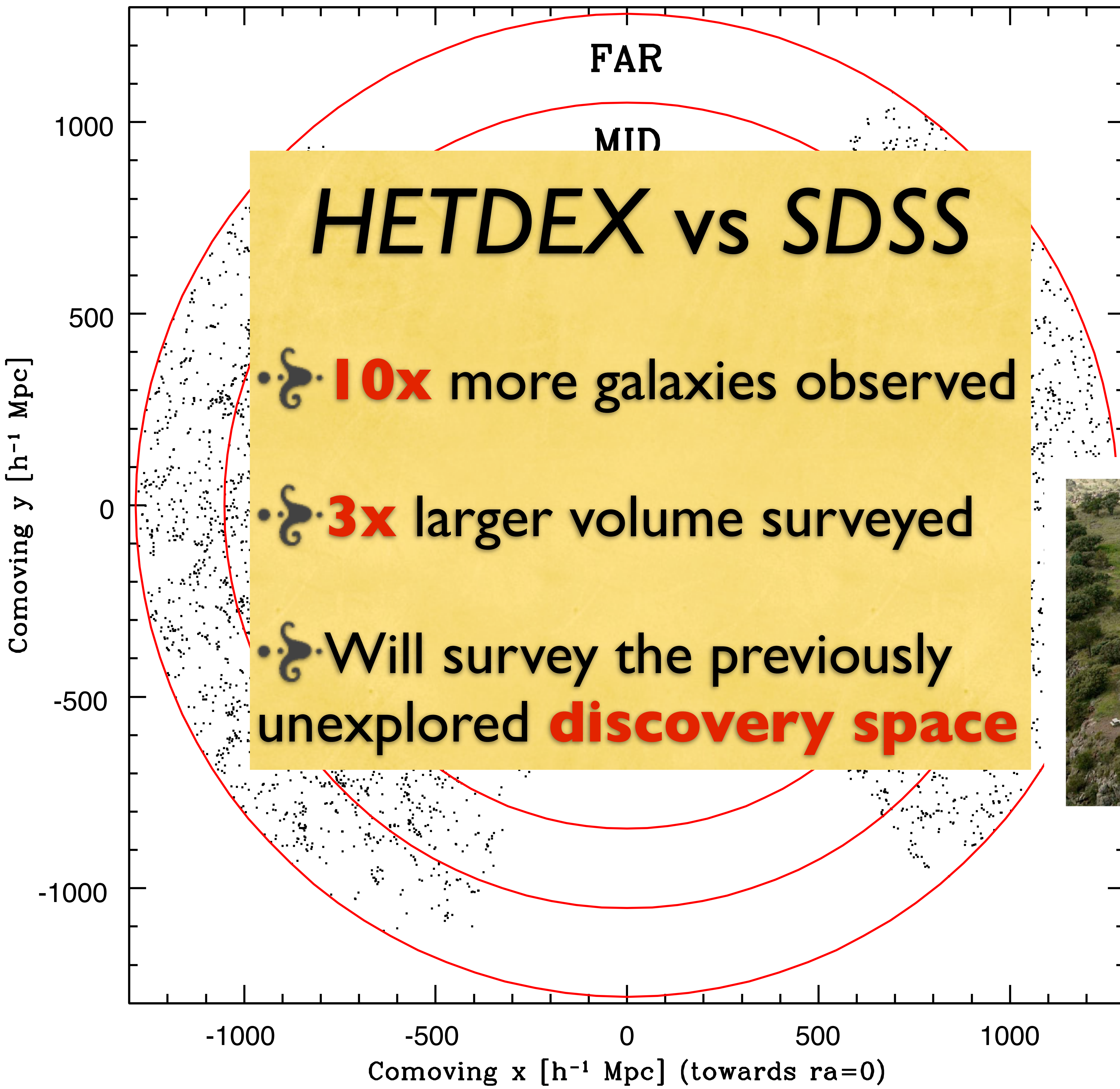




Sloan Digital Sky Survey



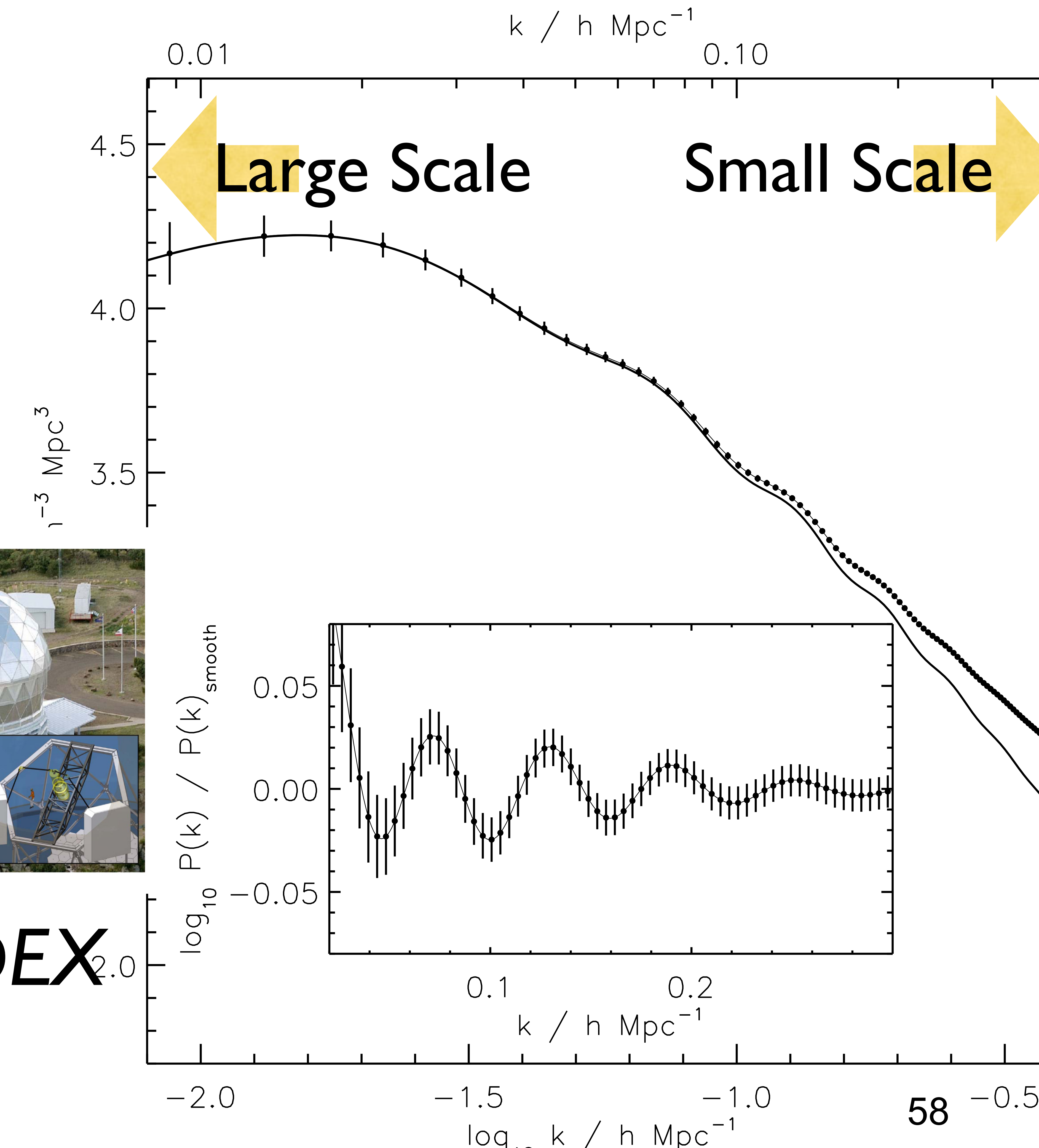
HETDEX: Sound Waves in the Distribution of Galaxies



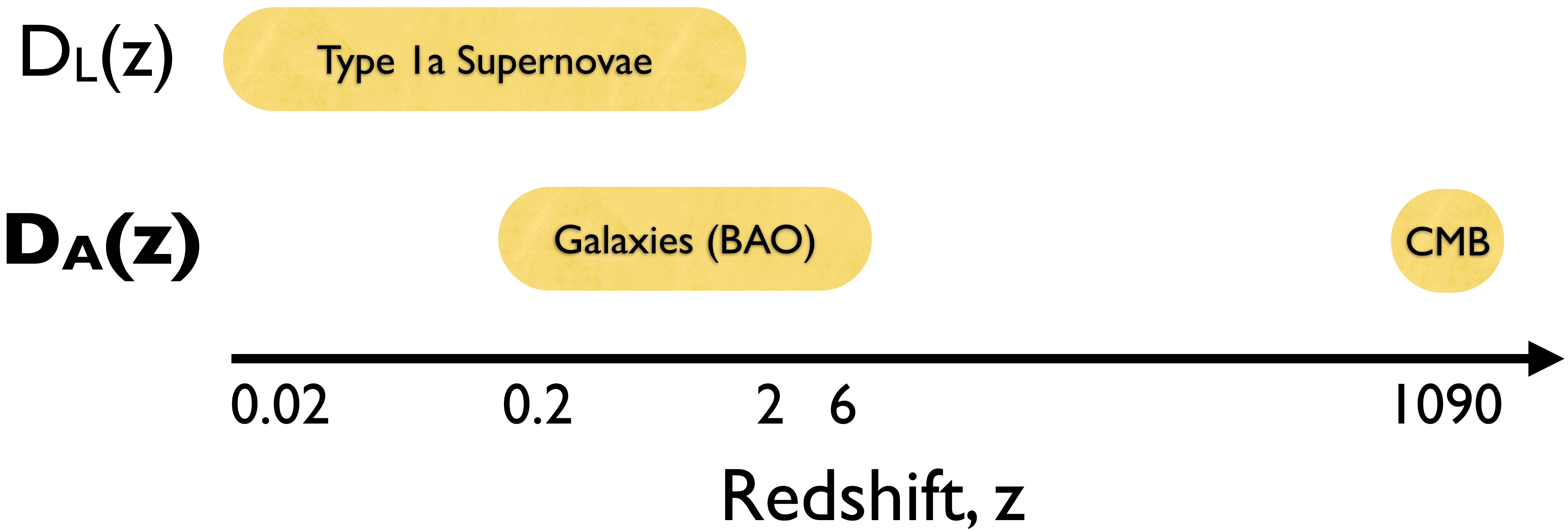
HETDEX vs SDSS

- **10x** more galaxies observed
- **3x** larger volume surveyed
- Will survey the previously unexplored **discovery space**

HETDEX

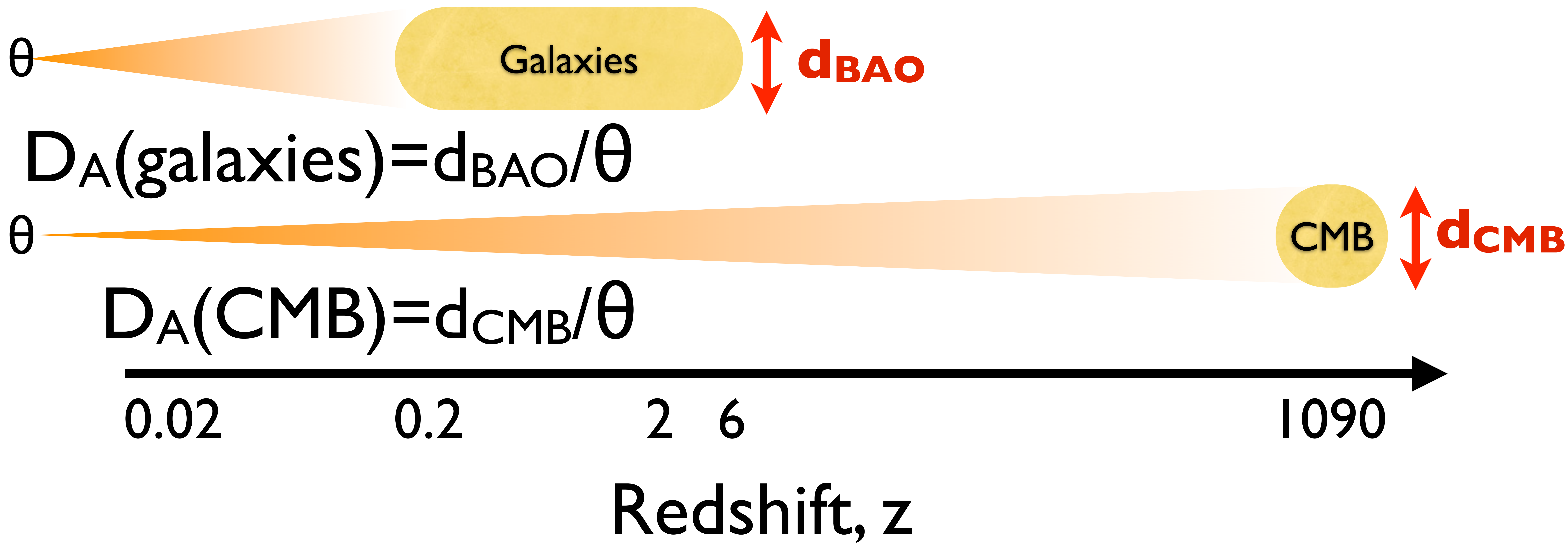


$$D_A(z) = (1+z)^{-2}\, D_L(z)$$



- To measure $D_A(z)$, we need to know the intrinsic size.
- What can we use as the *standard ruler*?

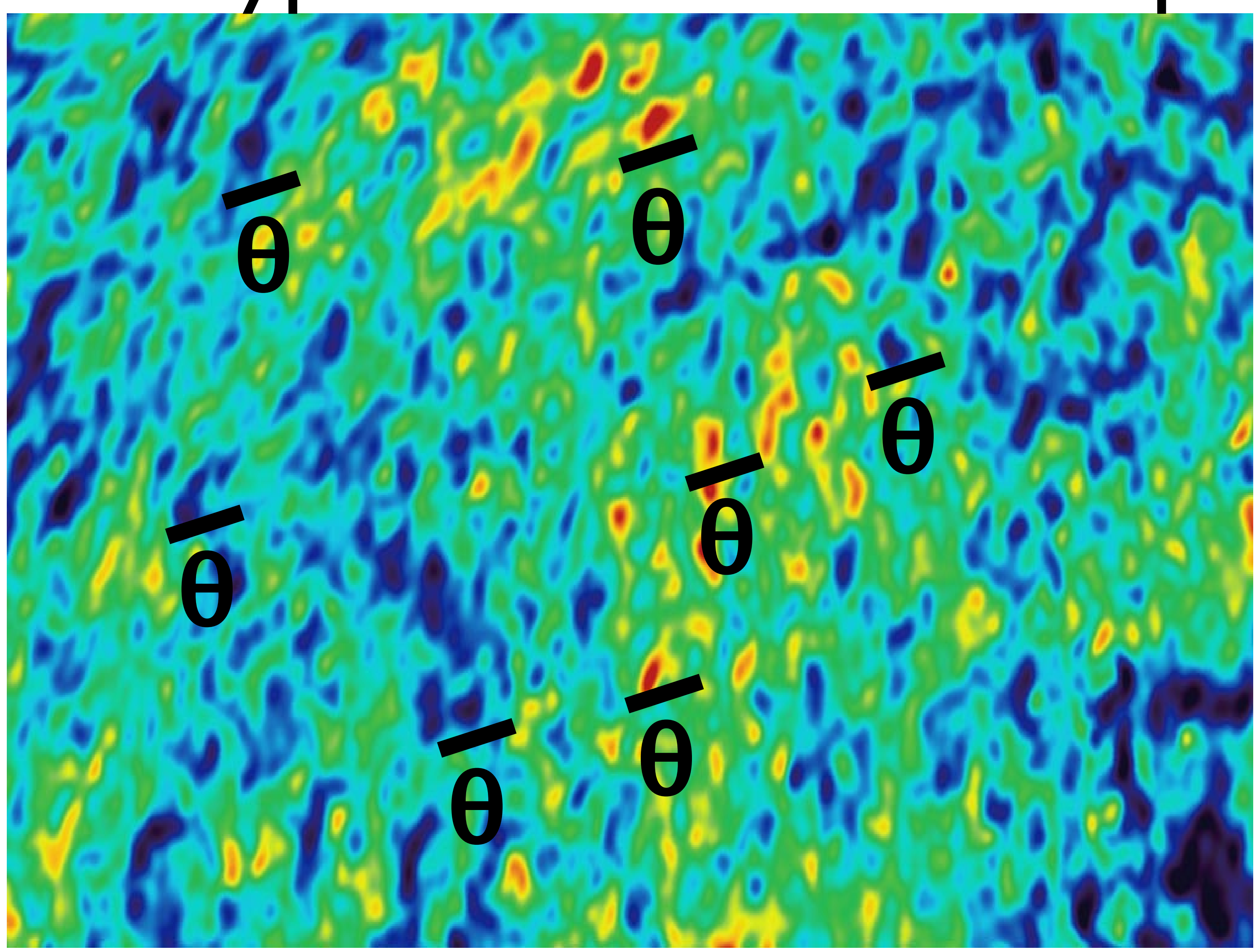
How Do We Measure $D_A(z)$?

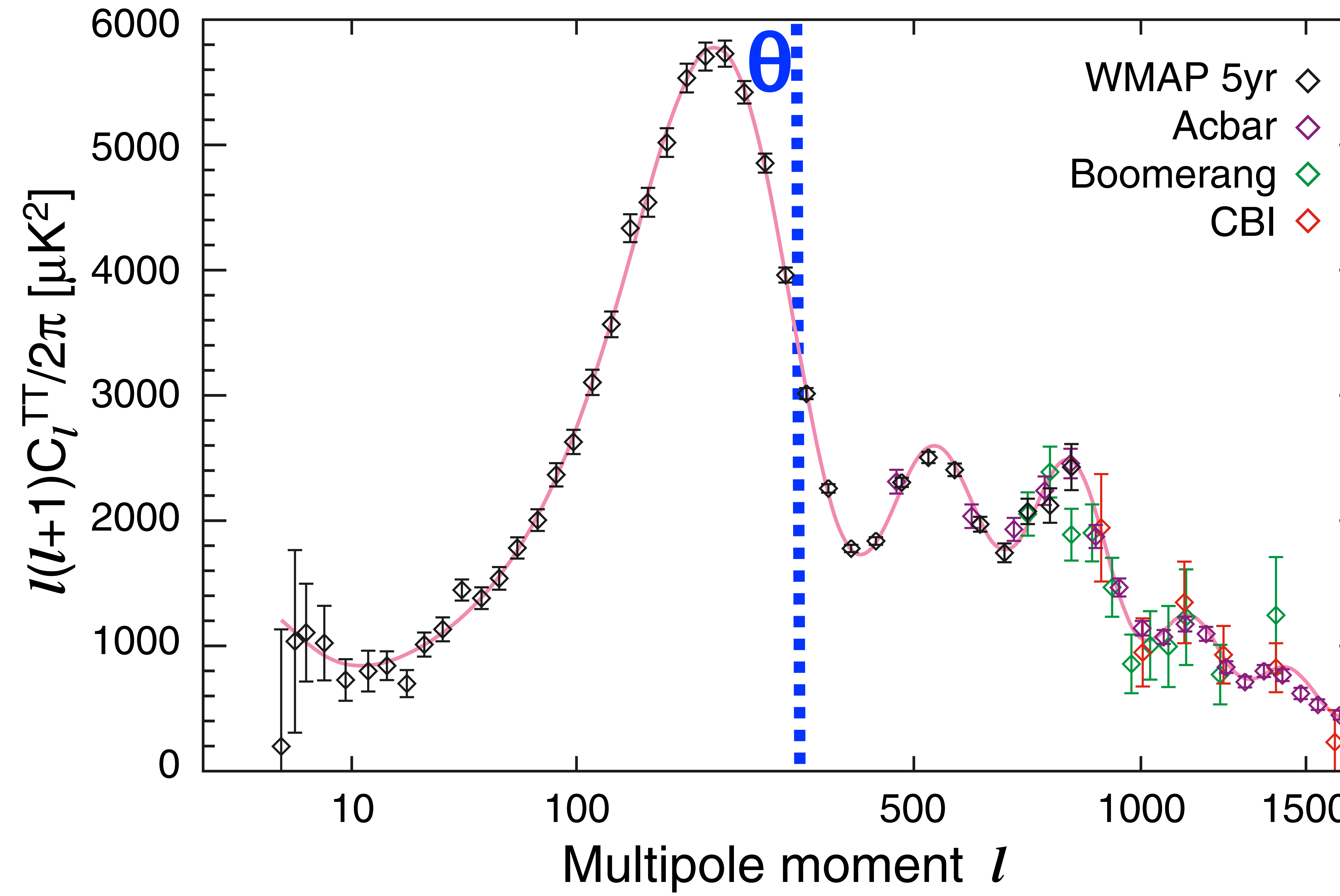


- If we know the intrinsic physical sizes, d, we can measure D_A. What determines d?

CMB as a Standard Ruler

θ~the typical size of hot/cold spots

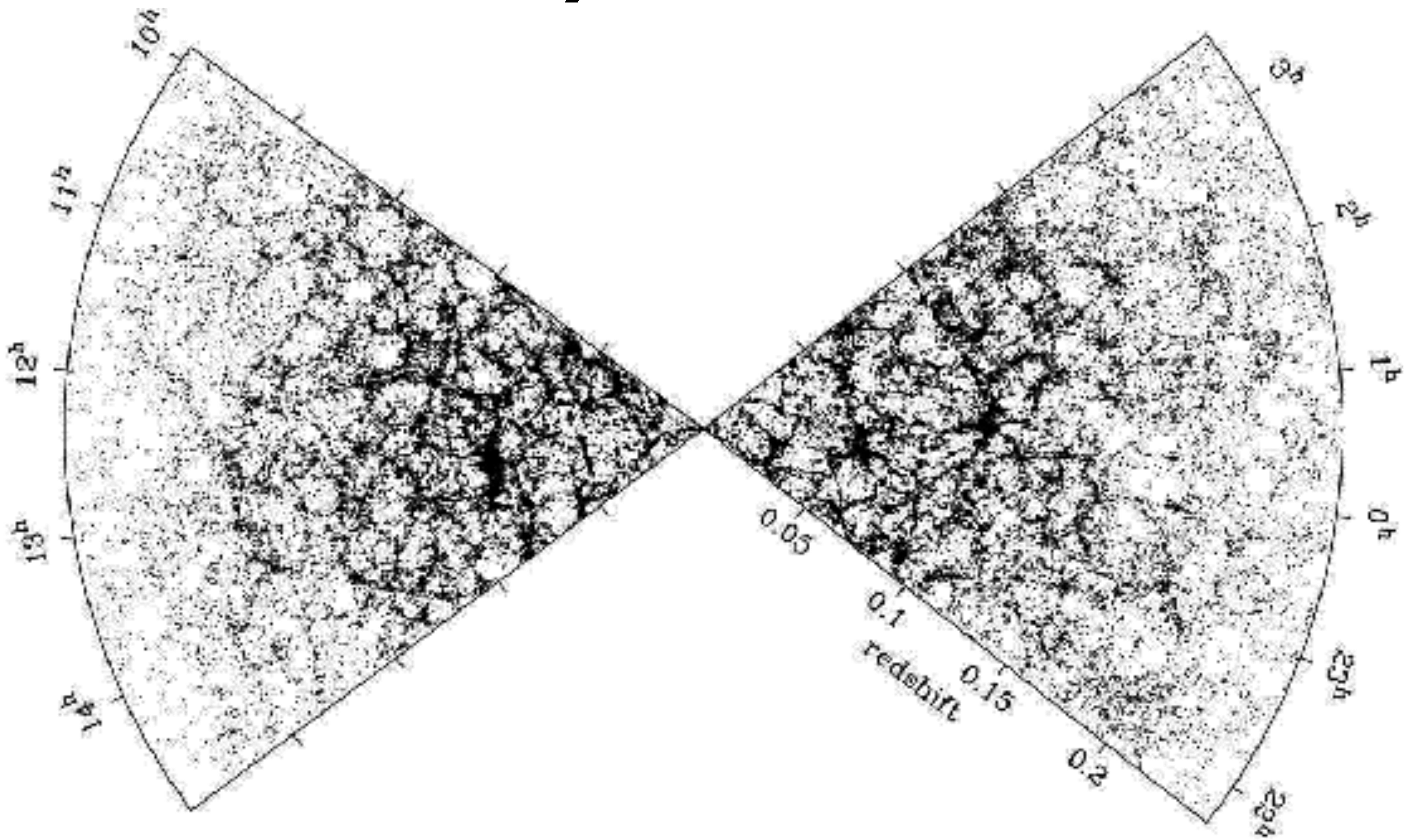




- The existence of typical spot size in image space yields oscillations in harmonic (Fourier) space.

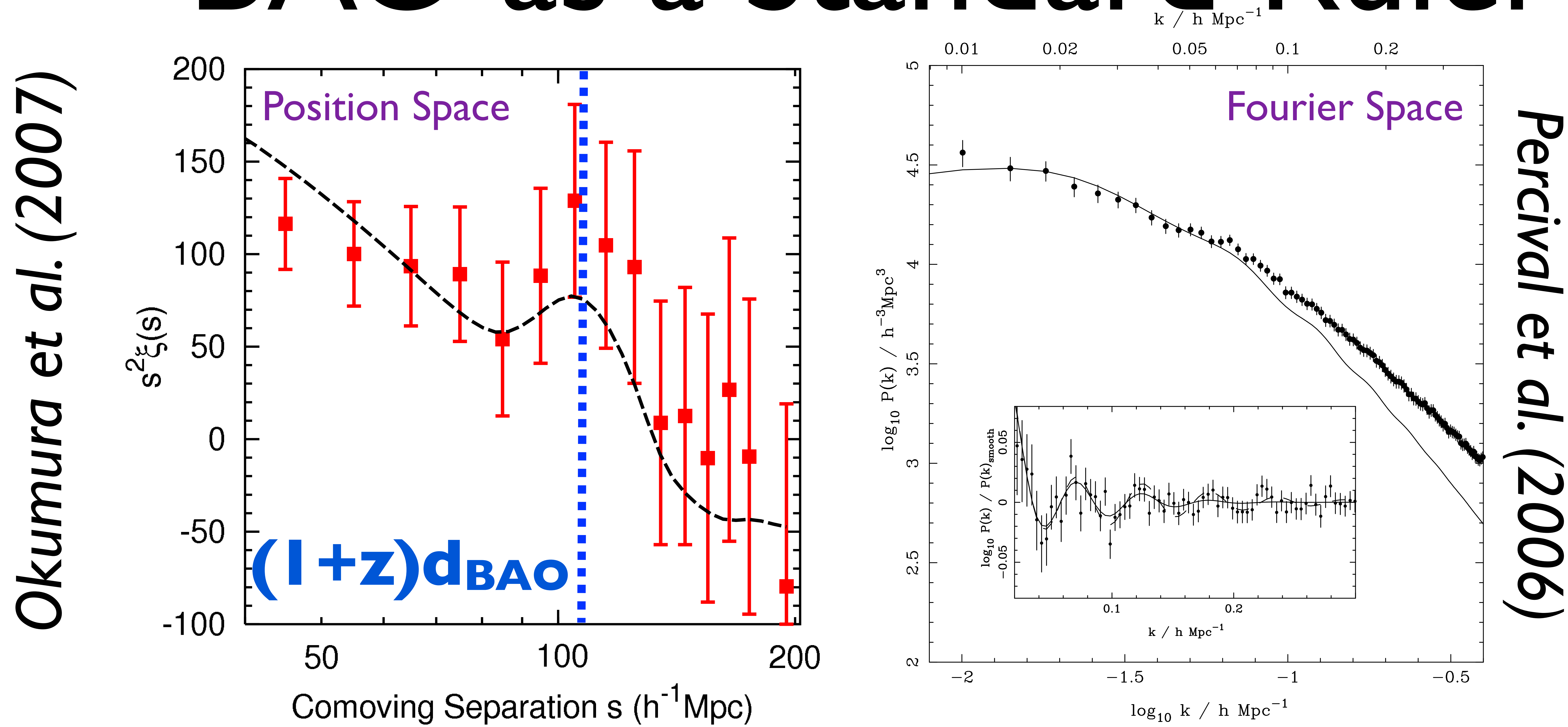
BAO in Galaxy Distribution

2dFGRS



- The same acoustic oscillations should be hidden in this galaxy distribution...

BAO as a Standard Ruler



- The existence of a localized clustering scale in the 2-point function yields oscillations in Fourier space.

Not Just $D_A(z)$...

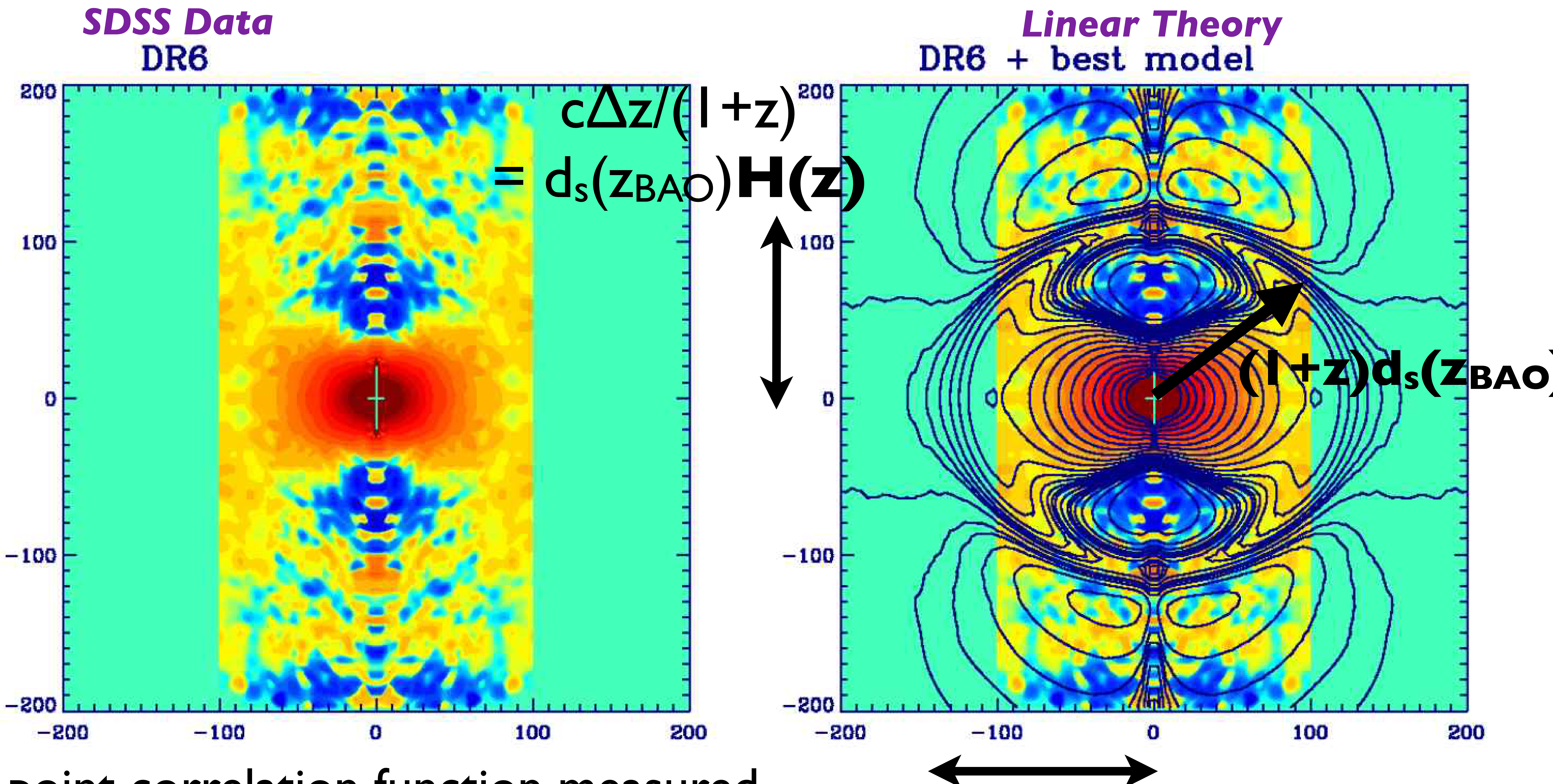
- A really nice thing about BAO at a given redshift is that it can be used to measure not only $D_A(z)$, but also the expansion rate, $H(z)$, directly, at **that** redshift.
  - BAO perpendicular to l.o.s

    $$=> D_A(z) = d_s(z_{BAO})/\theta$$

  - BAO parallel to l.o.s

    $$=> \mathbf{H(z) = c\Delta z/[(1+z)d_s(z_{BAO})]}$$

Transverse=$D_A(z)$; Radial=$H(z)$



$\theta = d_s(z_{BAO})/\mathbf{D_A(z)}$

Two-point correlation function measured from the SDSS Luminous Red Galaxies (Gaztanaga, Cabre & Hui 2008)

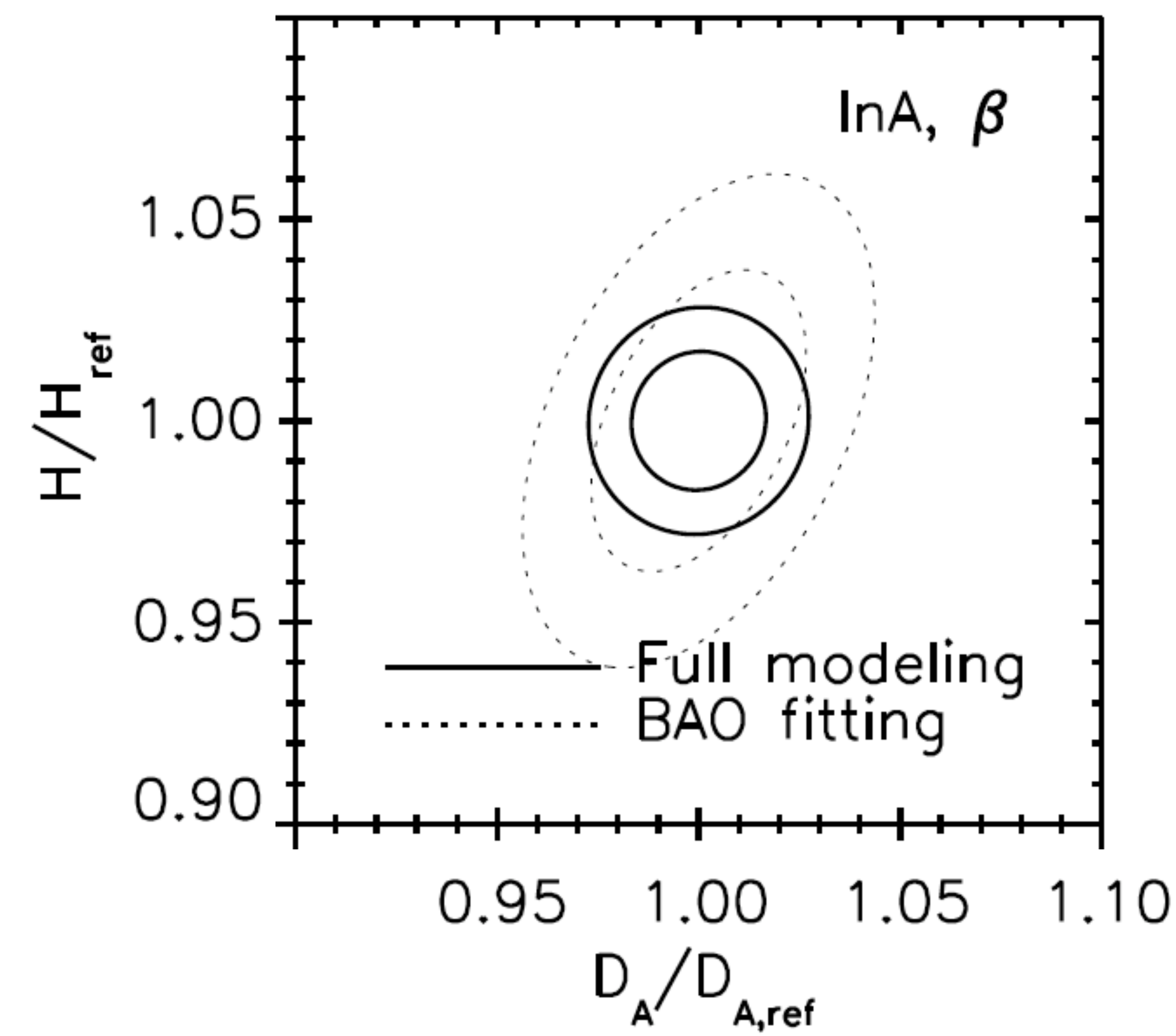
Beyond BAO

- BAOs capture only a **fraction** of the information contained in the galaxy power spectrum!
- The full usage of the 2-dimensional power spectrum leads to a *substantial* improvement in the precision of distance and expansion rate measurements.

Shoji, Jeong & Komatsu (2008)

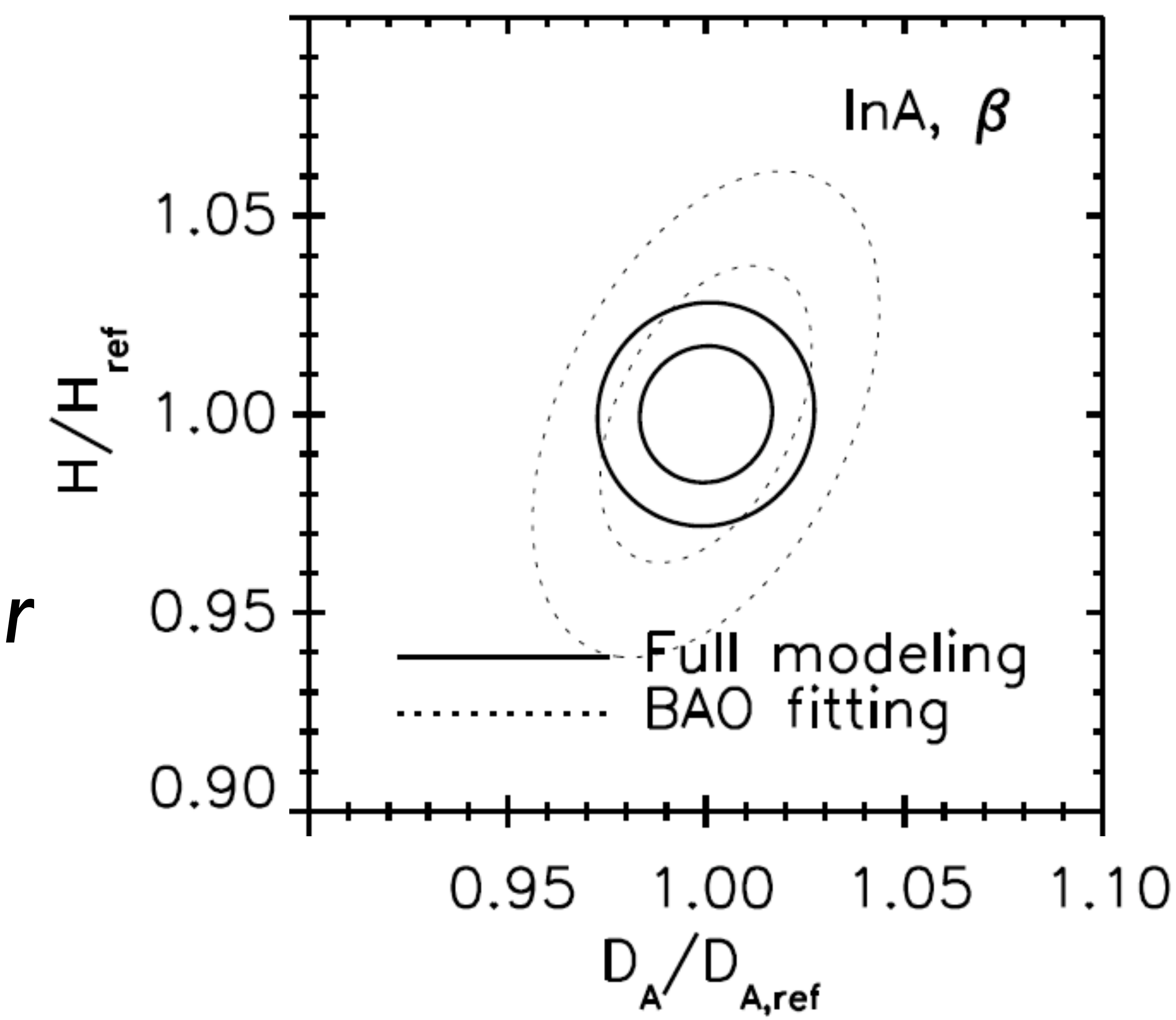
BAO vs Full Modeling

- Full modeling improves upon the determinations of D_A & H by more than a factor of two.
- On the D_A-H plane, the size of the ellipse shrinks by more than a factor of four.



Alcock-Paczynski: The Most Important Thing For HETDEX

- **Where does the improvement come from?**
  - The Alcock-Paczynski test is the key. *This is the most important component for the success of the HETDEX survey.*



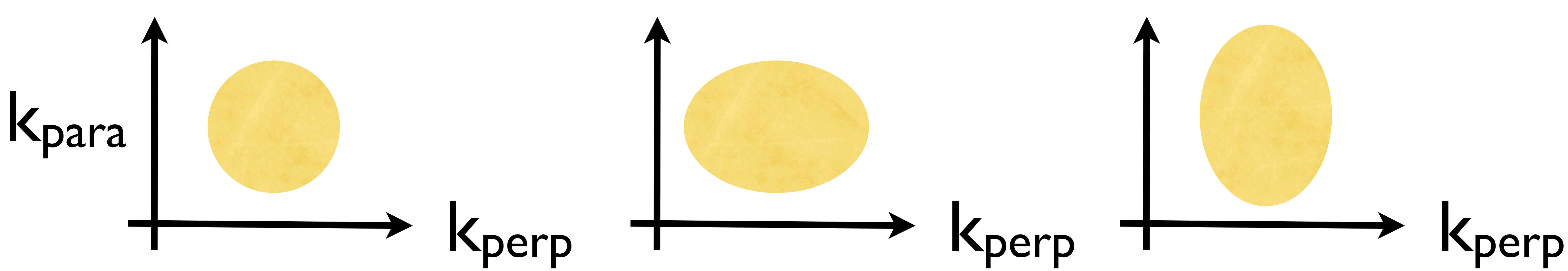
The AP Test: How That Works

- The key idea: (*in the absence of the redshift-space distortion - we will include this for the full analysis; we ignore it here for simplicity*), the distribution of the power should be **isotropic** in Fourier space.

The AP Test: How That Works

- **D_A**: (RA,Dec) to the transverse separation, r_{perp}, to the transverse wavenumber
    - $k_{perp} = (2\pi)/r_{perp} = (2\pi)$[Angle on the sky]/$\mathbf{D_A}$
- **H**: redshifts to the parallel separation, r_{para}, to the parallel wavenumber
    - $k_{para} = (2\pi)/r_{para} = (2\pi)\mathbf{H}/(c\Delta z)$

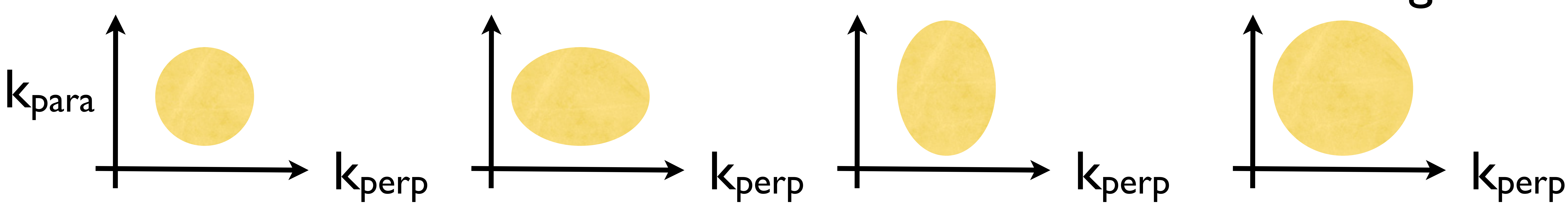
If D_A and H are correct: | If D_A is wrong: | If H is wrong:



The AP Test: How That Works

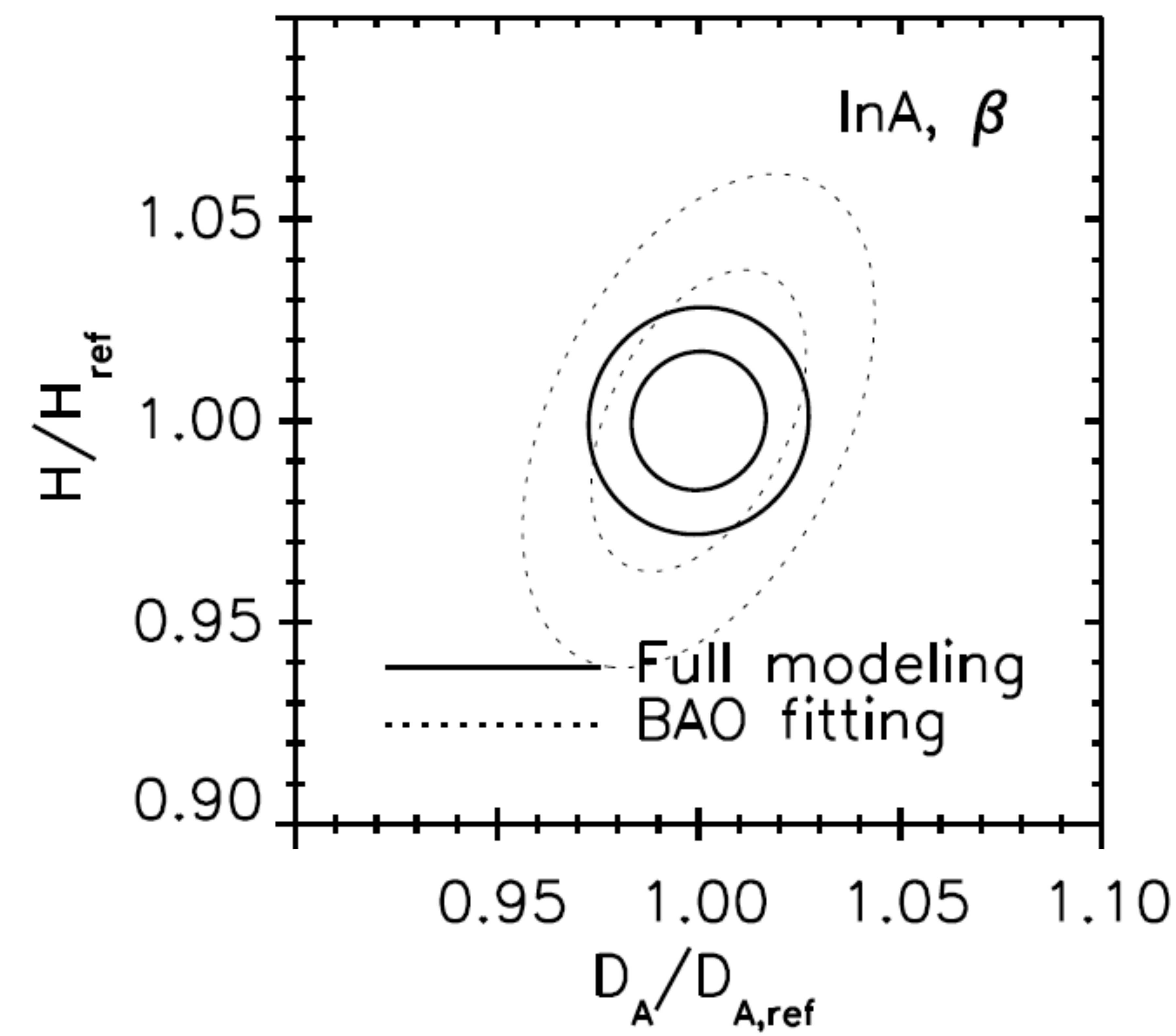
- **D_A**: (RA,Dec) to the transverse separation, r_{perp}, to the transverse wavenumber
    - $k_{perp} = (2\pi)/r_{perp} = (2\pi)[\text{Angle on the sky}]/D_A$
- **H**: redshifts to the parallel separation, r_{para}, to the parallel wavenumber
    - $k_{para} = (2\pi)/r_{para} = (2\pi)H/(c\Delta z)$

If D_A and H are correct: | If D_A is wrong: | If H is wrong: | If D_A and H are wrong:

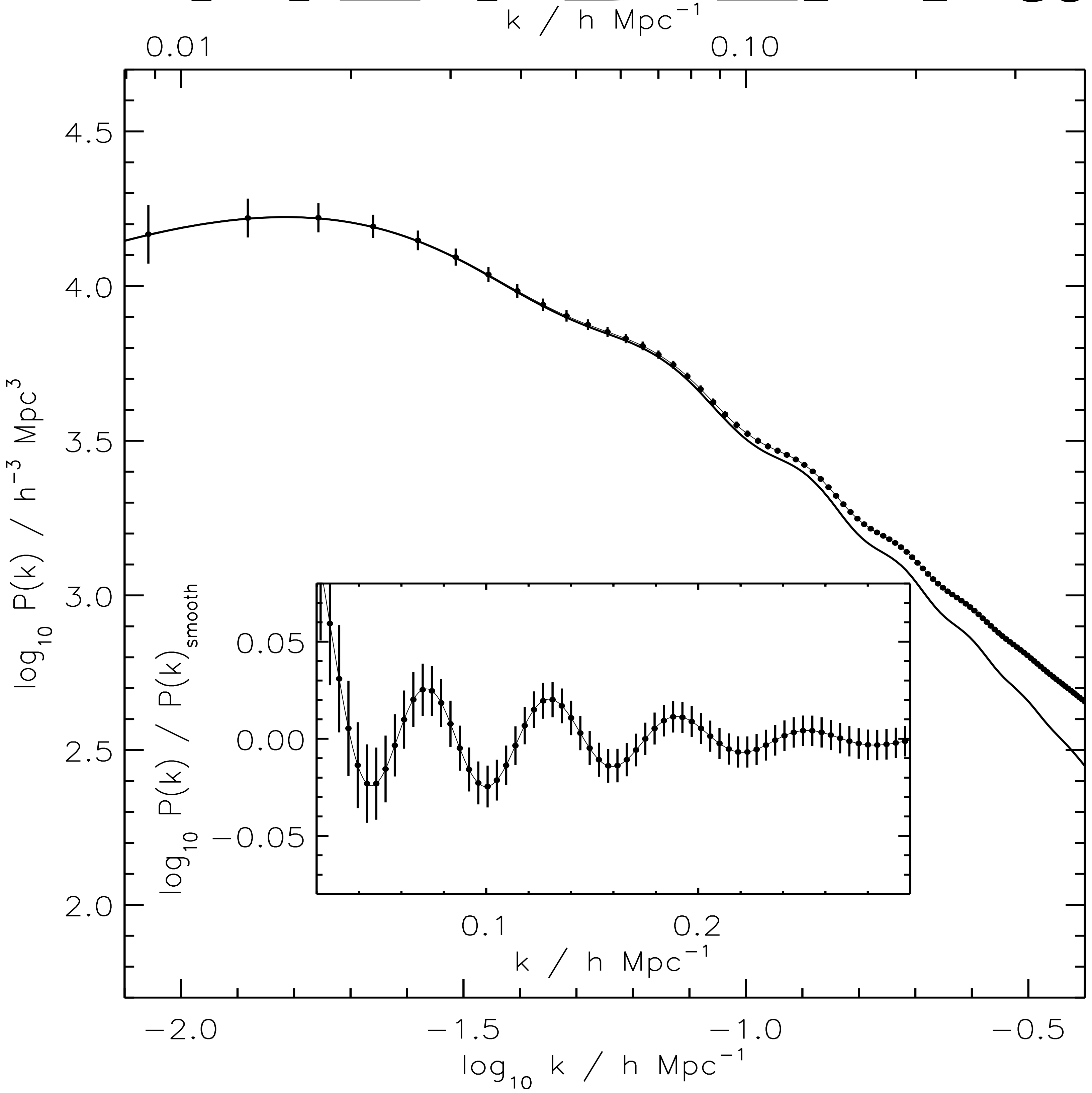


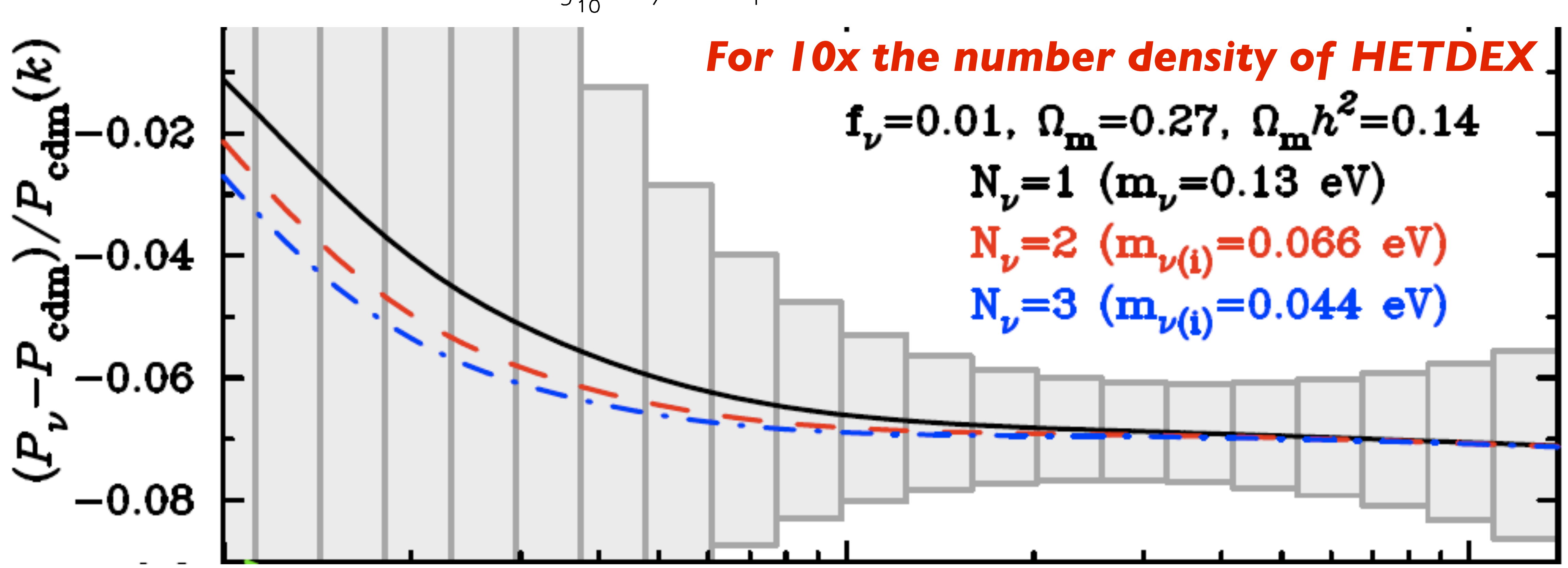
$D_A H$ from the AP test

- So, the AP test can't be used to determine D_A and H separately; however, it gives a measurement of **$D_A H$**.
- Combining this with the BAO information, and marginalizing over the redshift space distortion, we get the solid contours in the figure.



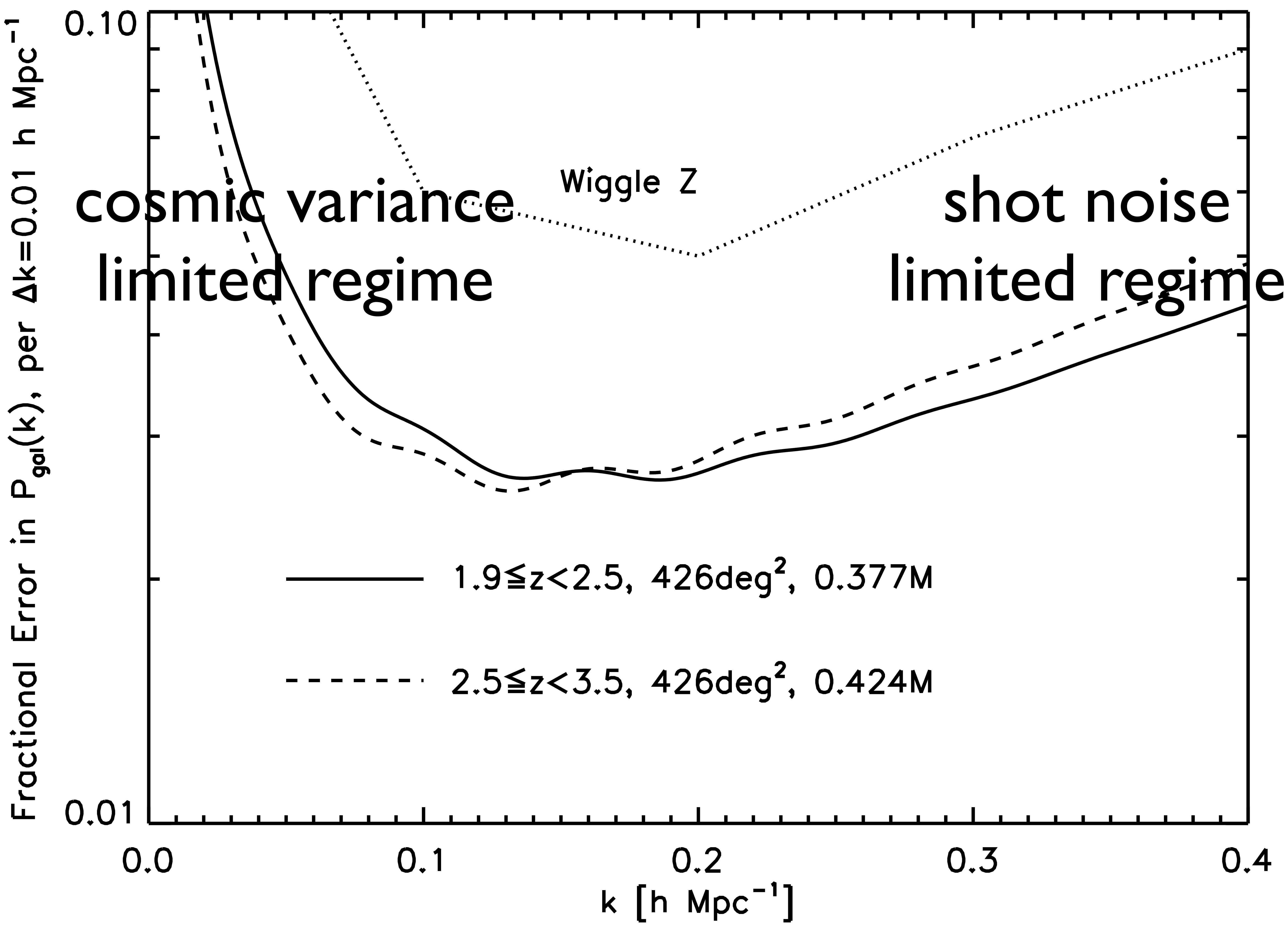
HETDEX and Neutrino Mass





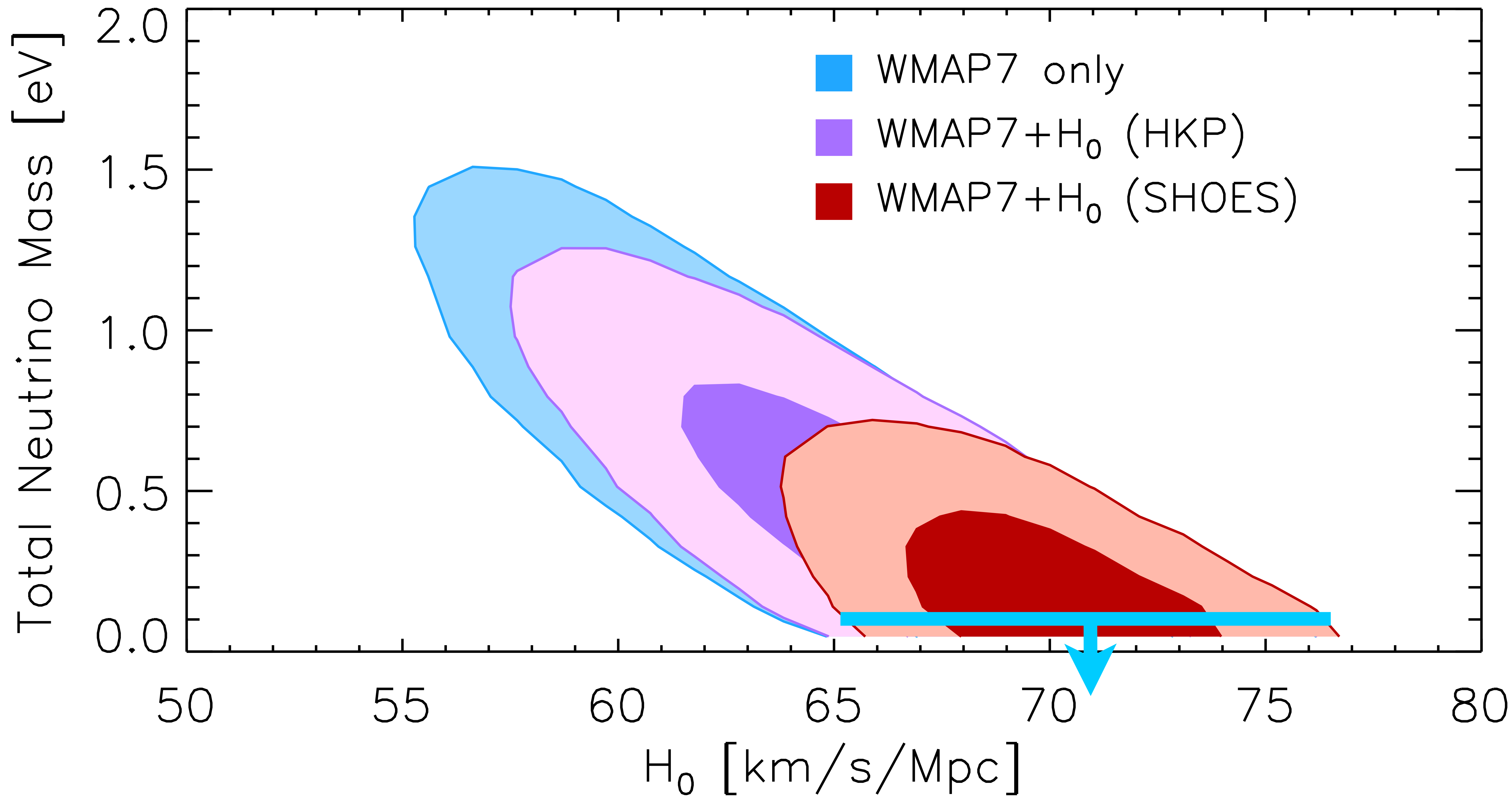
- Neutrinos suppress the matter power spectrum on small scales (k>0.1 h Mpc^{-1}).
- A useful number to remember:
  - For $\sum m_\nu$=0.1 eV, the power spectrum at k>0.1 h Mpc^{-1} is suppressed by **~7%**.
  - We can measure this easily!

Expectation for HETDEX



- CV limited: error goes as 1/sqrt(volume)
- SN limited: error goes as 1/(number density)/sqrt(volume)

Expected HETDEX Limit



- ~6x better than WMAP 7-year+H_0

Summary

- Four questions:
  - What is the physics of inflation?
  - What is the nature of dark matter
  - What is the nature of dark energy?
  - What are the number and mass of neutrinos?
- CMB, large-scale structure, and gamma-ray observations can lead to major breakthroughs in any of the above questions.
  - Things I did not have time to talk about but are also important for this endeavor: gravitational lensing and clusters of galaxies.

Redshift Space Distortion

- Both the AP test and the redshift space distortion make the distribution of the power anisotropic. Would it spoil the utility of this method?
  - Some, but not all!