Adventures in the CMB Damping Tail

La Fièvre Neutrino et Comment Je Me Suis Soigné

Lloyd Knox (UC Davis)

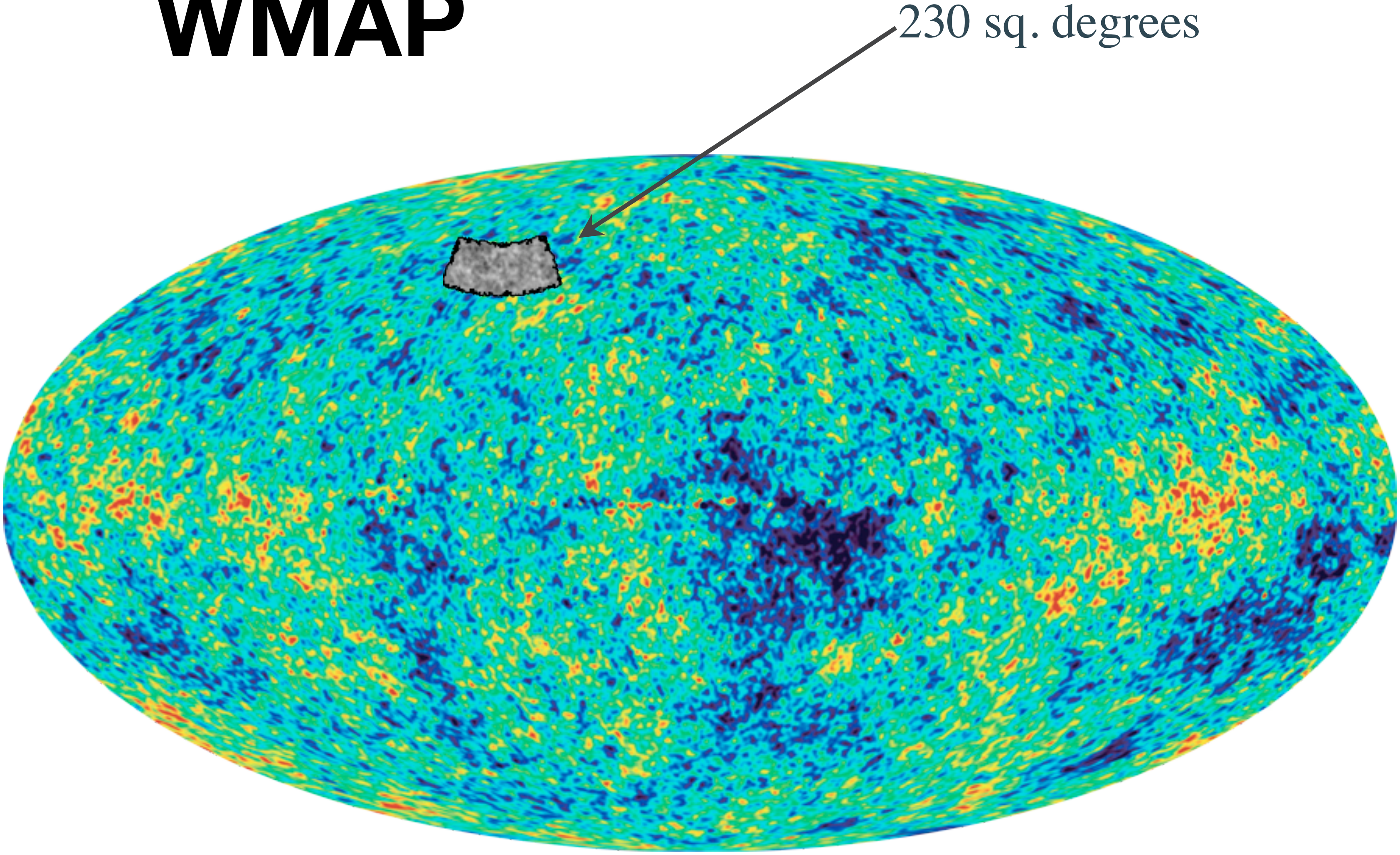
Zhen Hou & Marius Millea (UCD)

Ryan Keisler* (UC), Christian Reichardt (UCB)

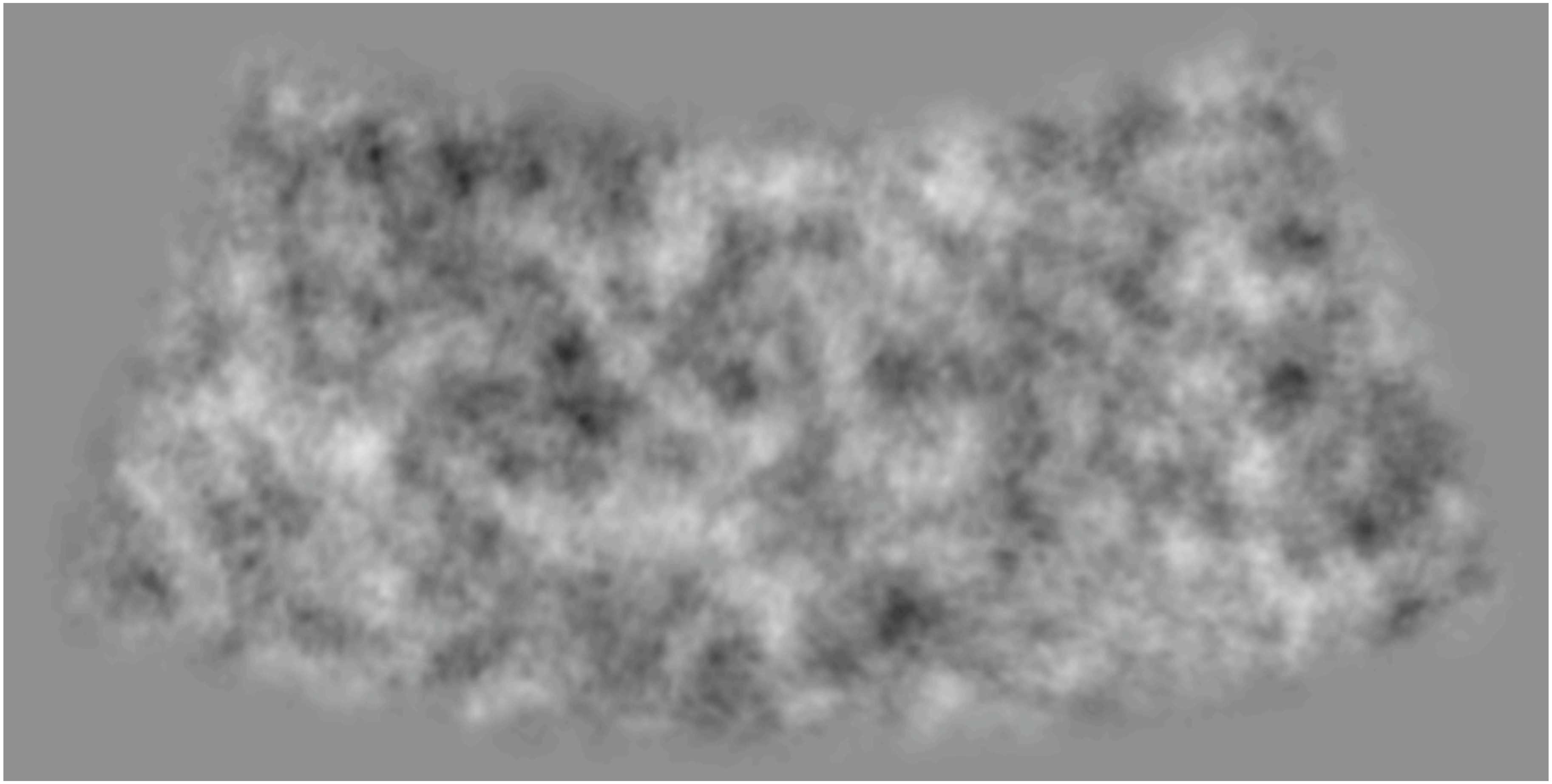
SPT collaboration

Hou et al. (2011), Keisler + SPT Collaboration (2011)

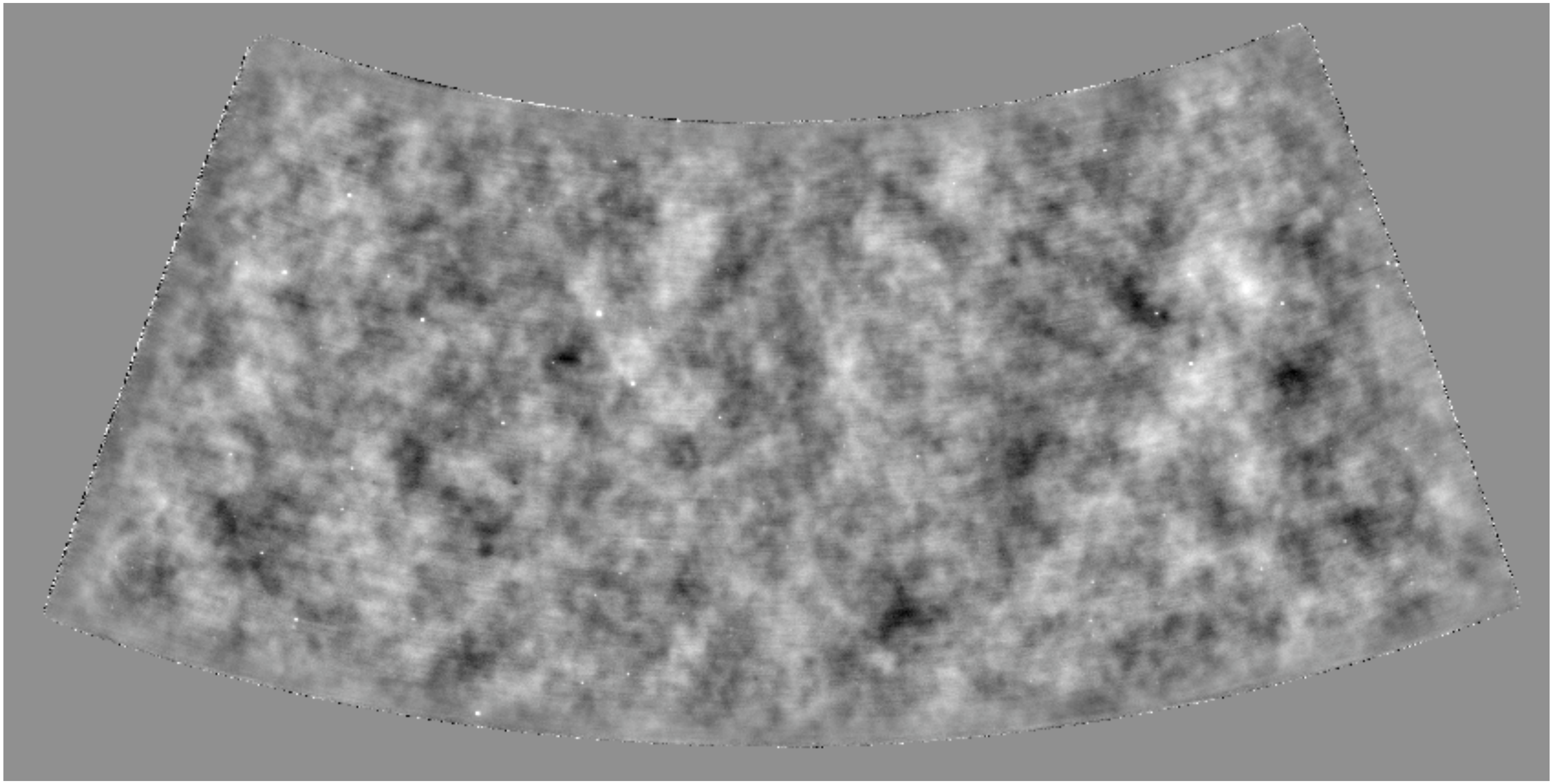
WMAP



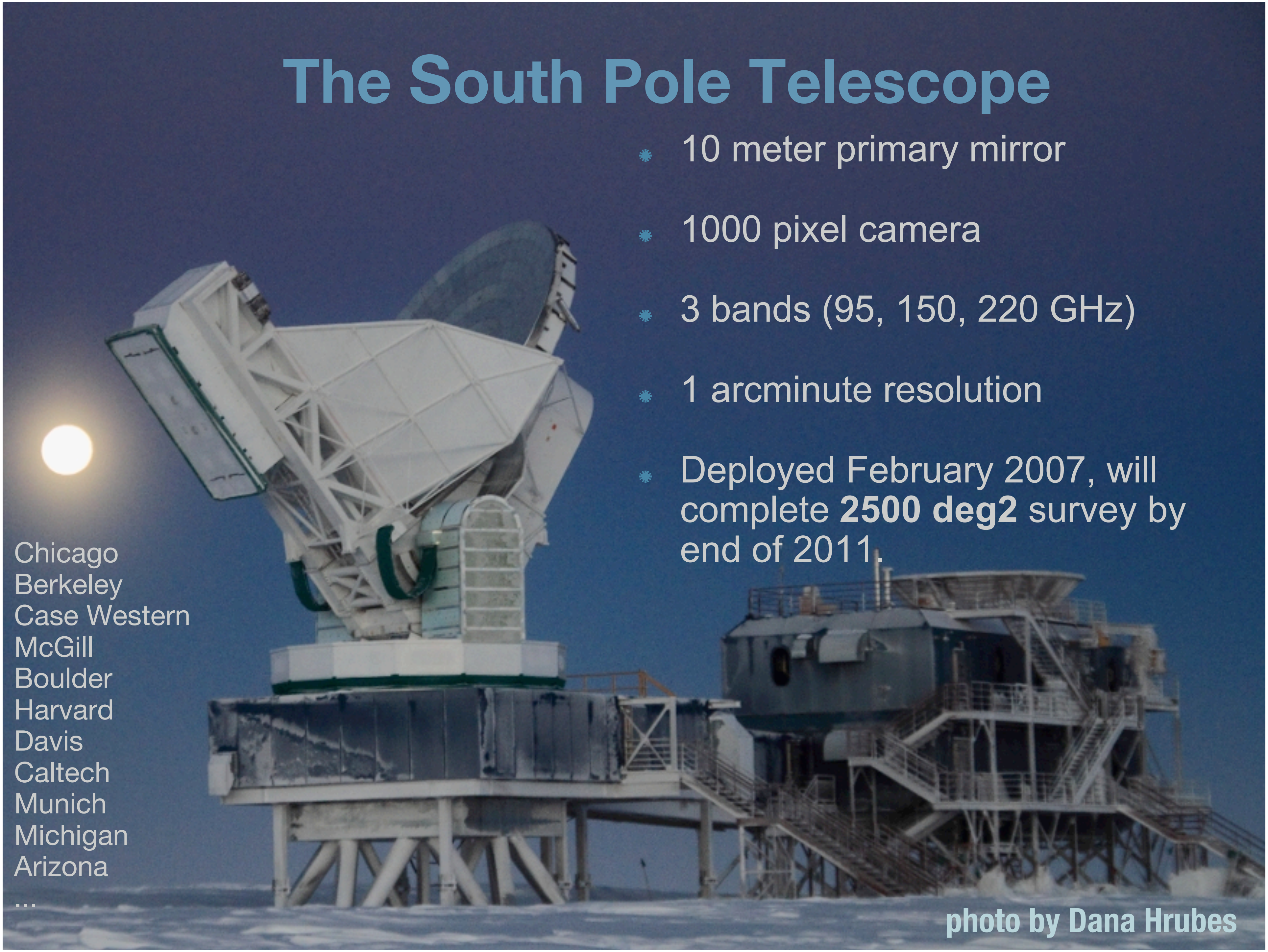
WMAP



SPT

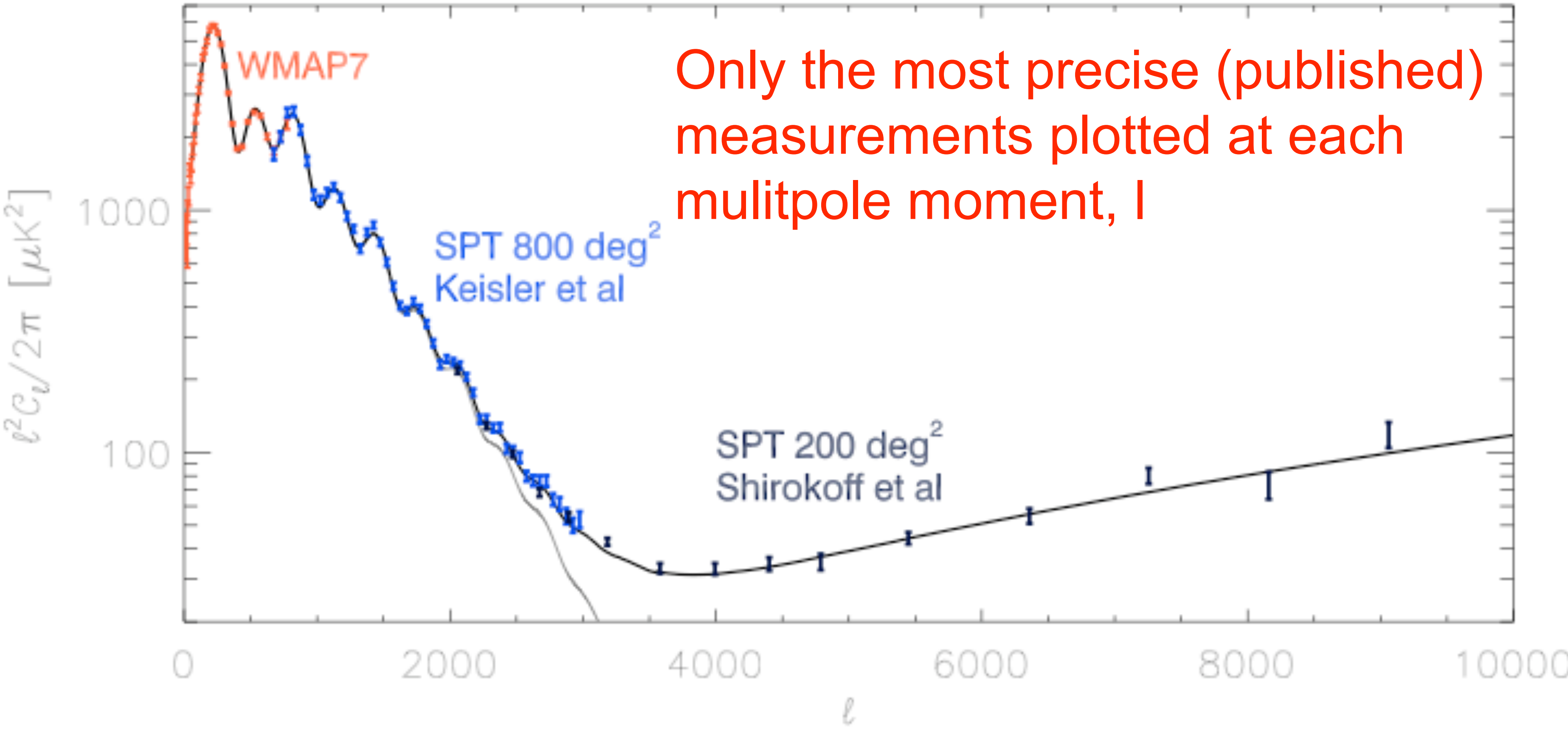


One of five fields observed in 2009, totaling 800 sq. deg.


The South Pole Telescope
10 meter primary mirror
1000 pixel camera
3 bands (95, 150, 220 GHz)
1 arcminute resolution
Deployed February 2007, will complete **2500 deg2** survey by end of 2011.
Chicago
Berkeley
Case Western
McGill
Boulder
Harvard
Davis
Caltech
Munich
Michigan
Arizona
...
photo by Dana Hrubes

The Angular Power Spectrum at 150 GHz

WMAP7
Extrapolated from
94 GHz



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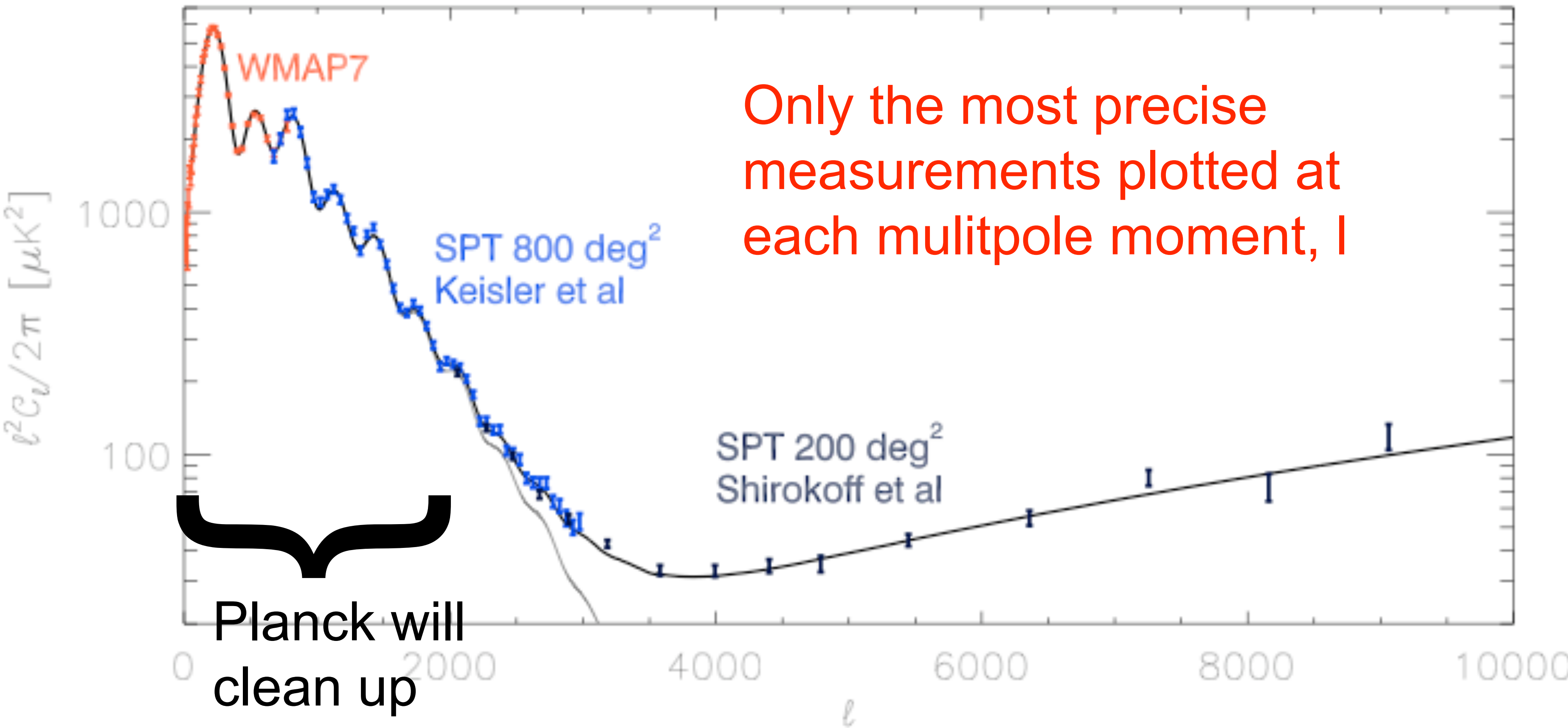
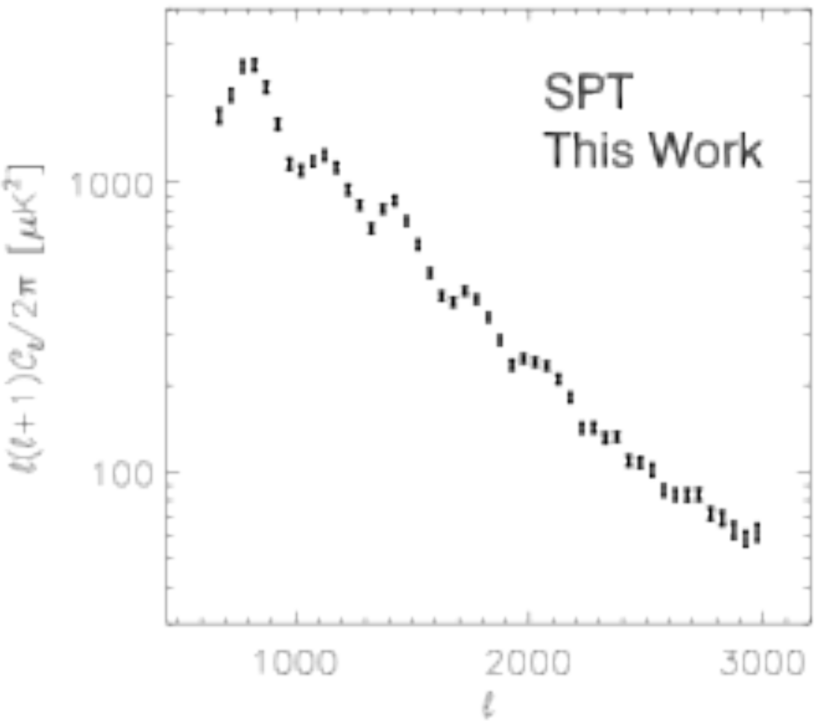
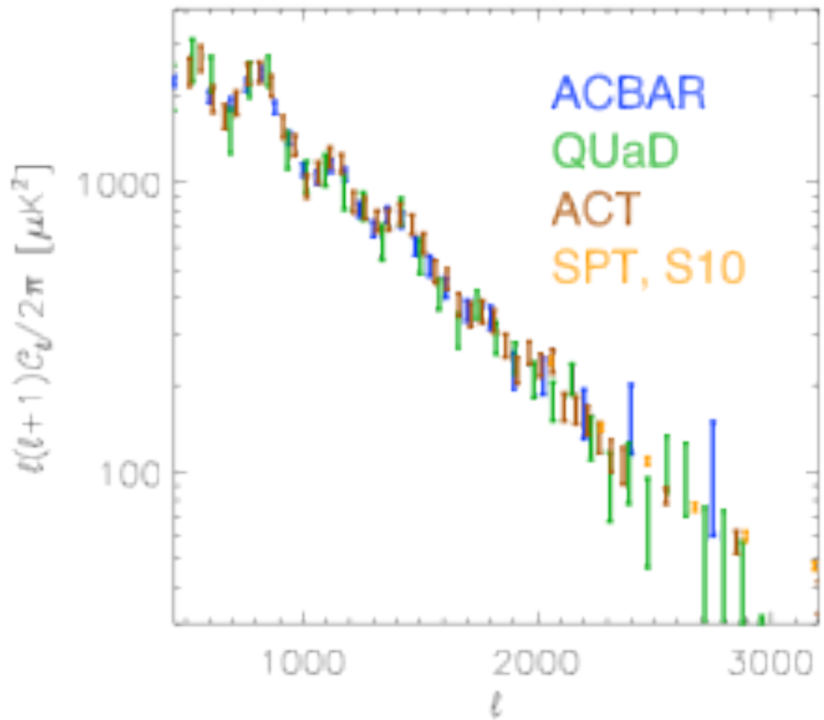


Keisler et al. (2011) provides a significant improvement in our knowledge of the damping tail





Prior state of the art

With this advance, and with much more to come soon from Planck, it's perhaps timely to review the physical interpretation.

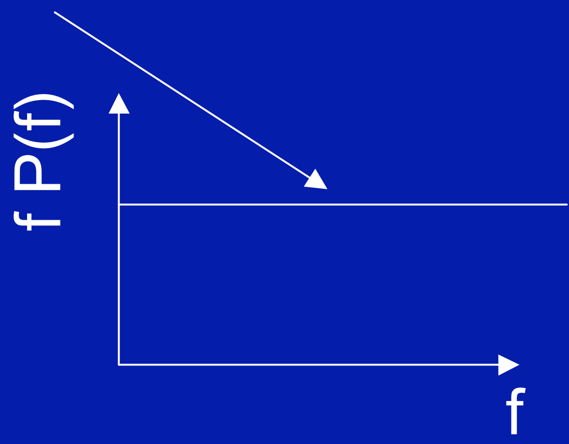
Outline

- CMB Theory for CMB Experimentalists
  - A Transfer Function Controlled by Three Angular Scales
- What can we learn from the damping tail
- Non-CMB evidence for extra neutrinos
- Conclusions

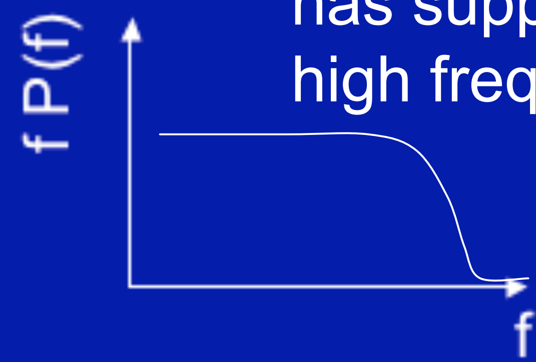
The CMB is Like a Detector of Some Noise Source

1/f noise

detector



Transfer function has suppressed high frequencies

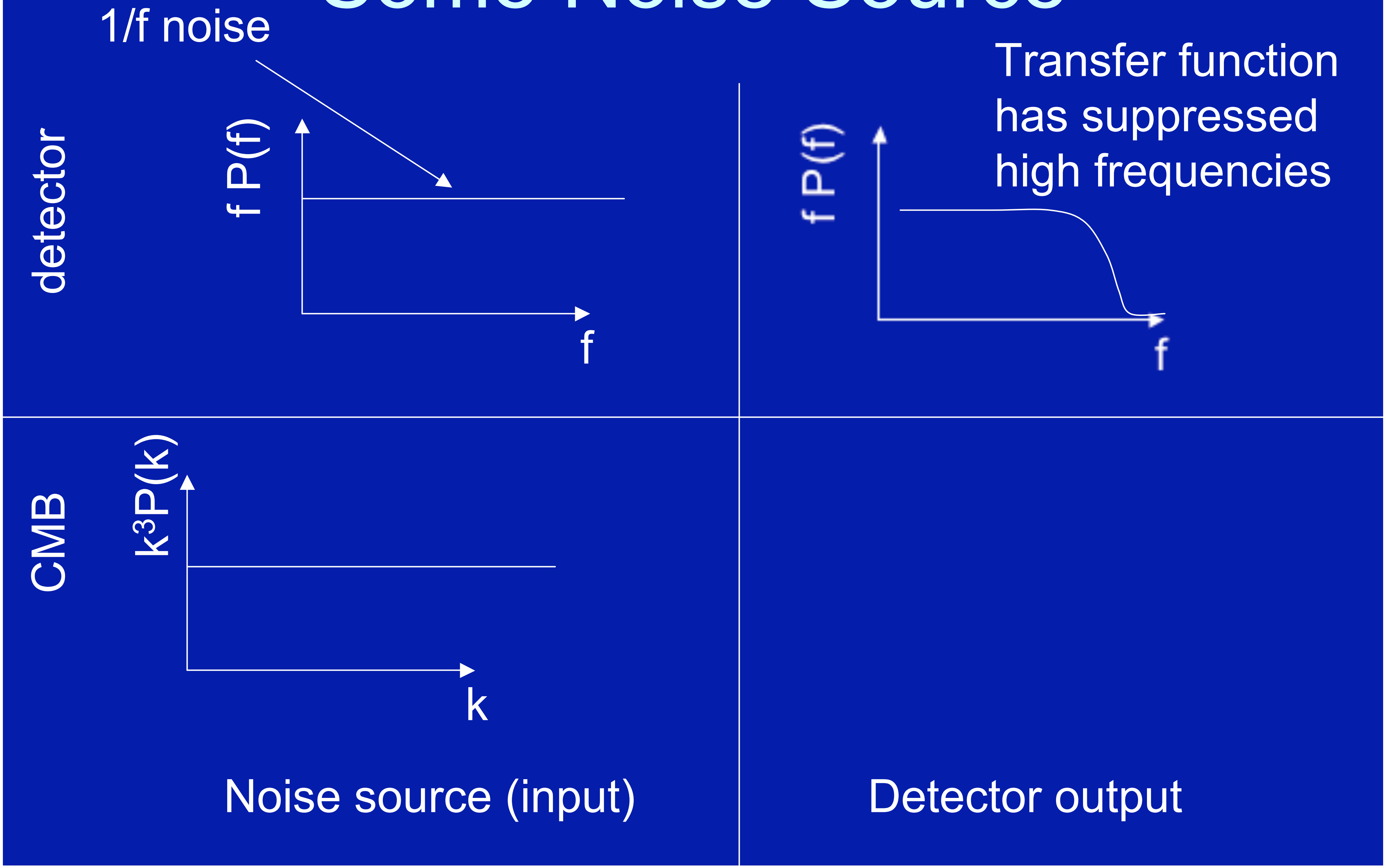


CMB

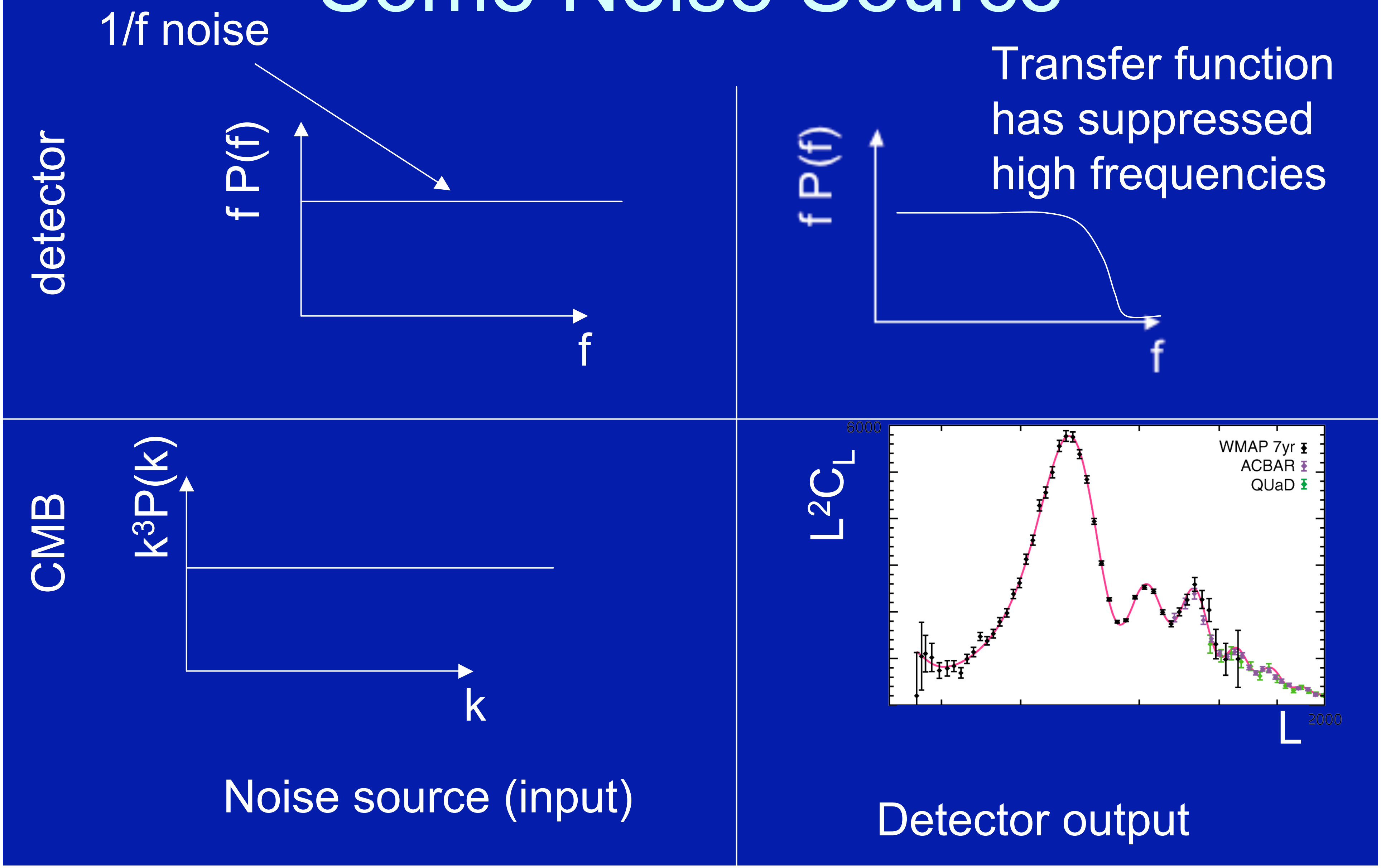
Noise source (input)

Detector output

The CMB is Like a Detector of Some Noise Source



The CMB is Like a Detector of Some Noise Source



CMB as a Detector

Noise Source

Primordial fluctuation generator (inflation works well)

Transfer Function

Depends on matter content

CMB as a Detector

Noise Source

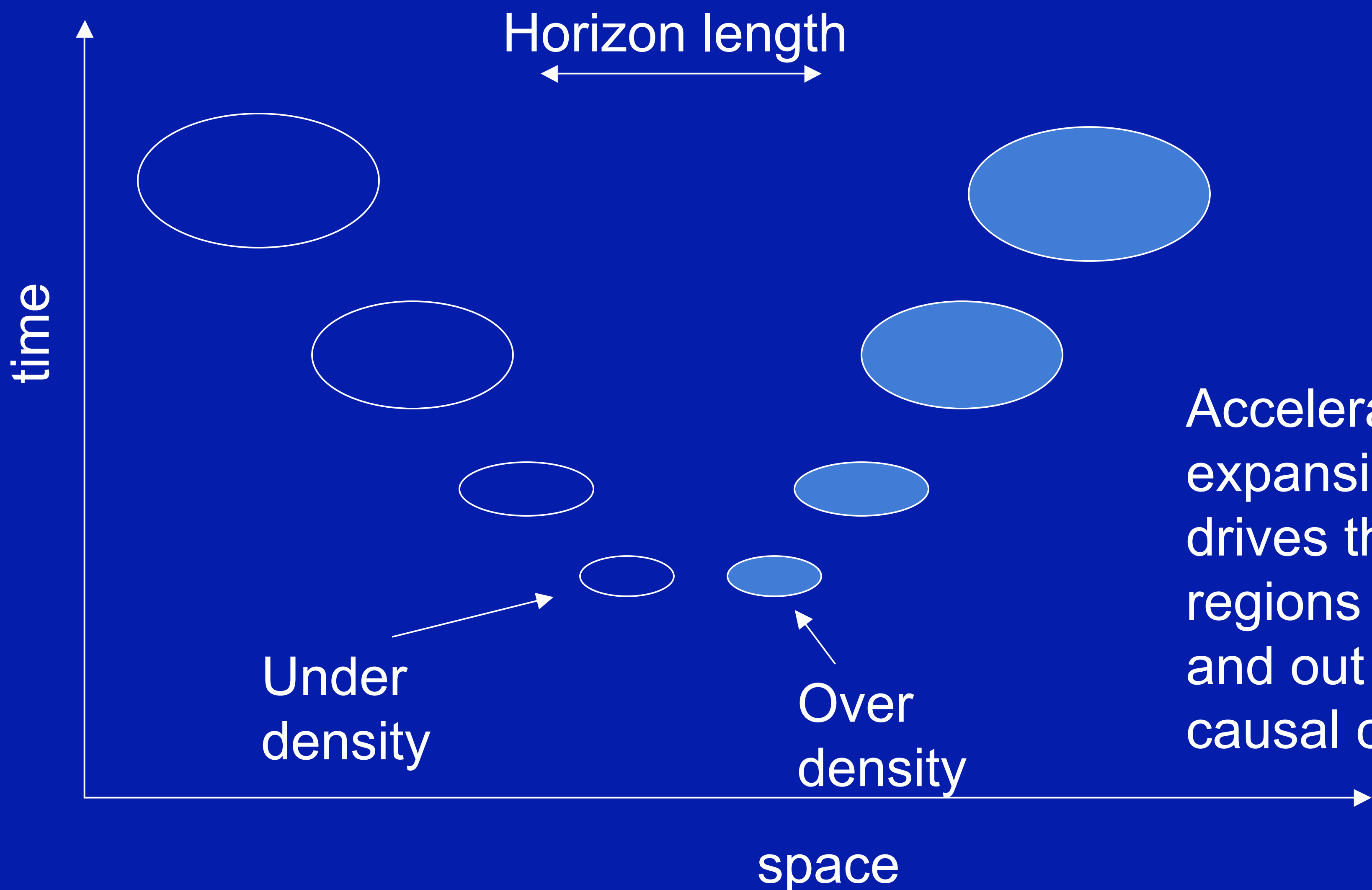
Primordial fluctuation generator (inflation works well)

Transfer Function

Depends on matter content

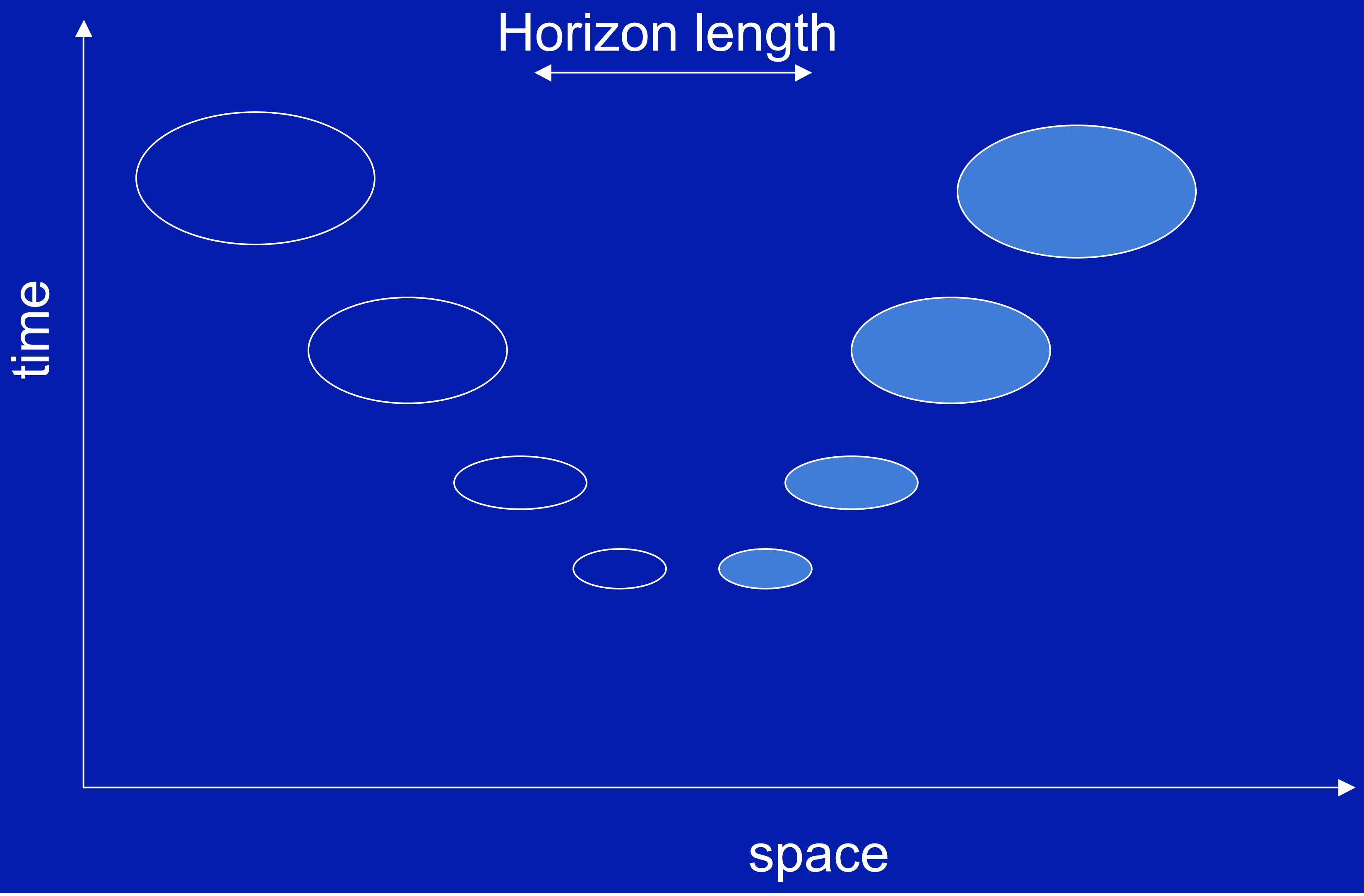
Inflation is a period of accelerating expansion rate

Accelerating Expansion prevents quantum fluctuation from becoming undone

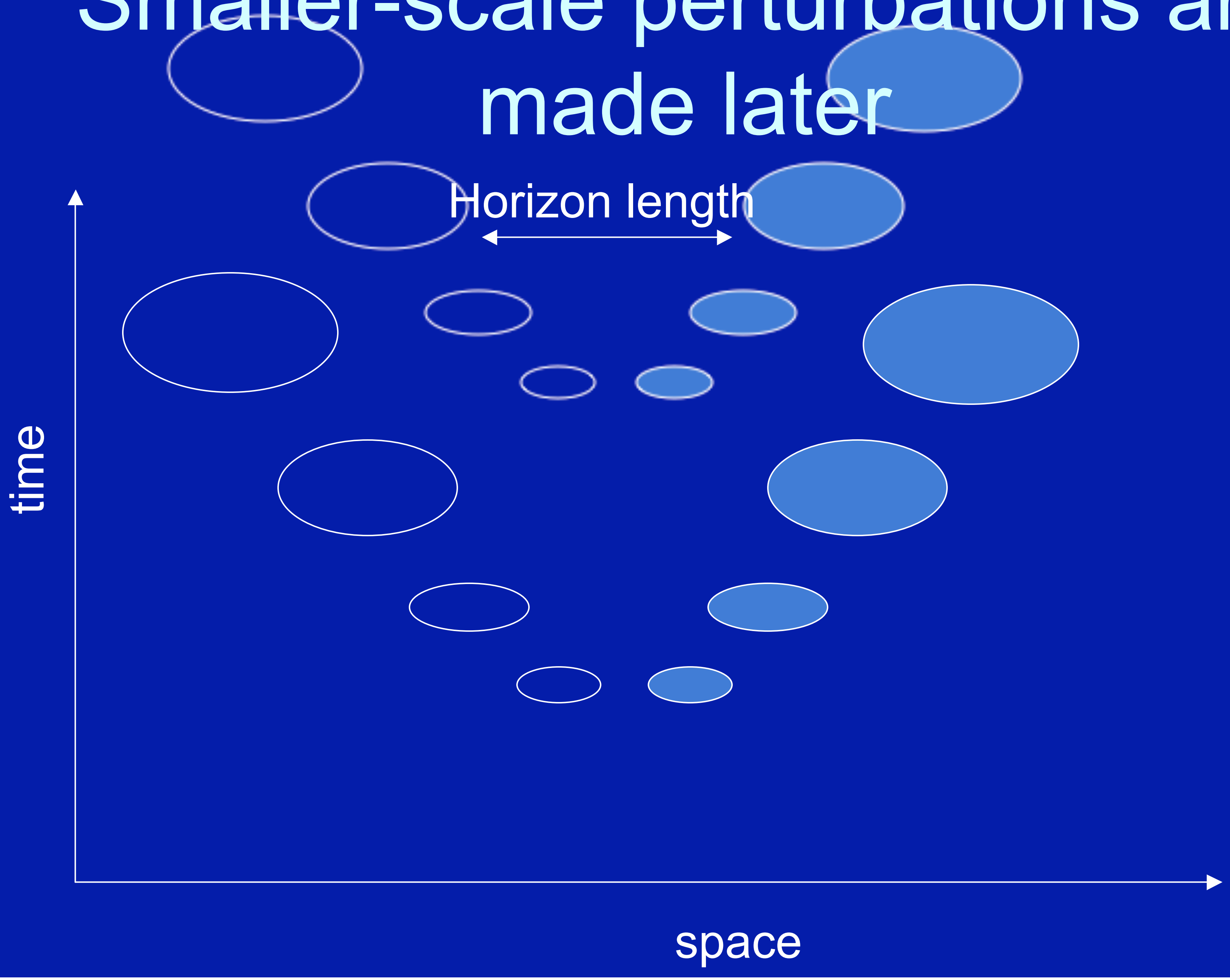


Accelerating expansion drives the regions apart and out of causal contact.

Smaller-scale perturbations are made later



Smaller-scale perturbations are made later



CMB as a Detector

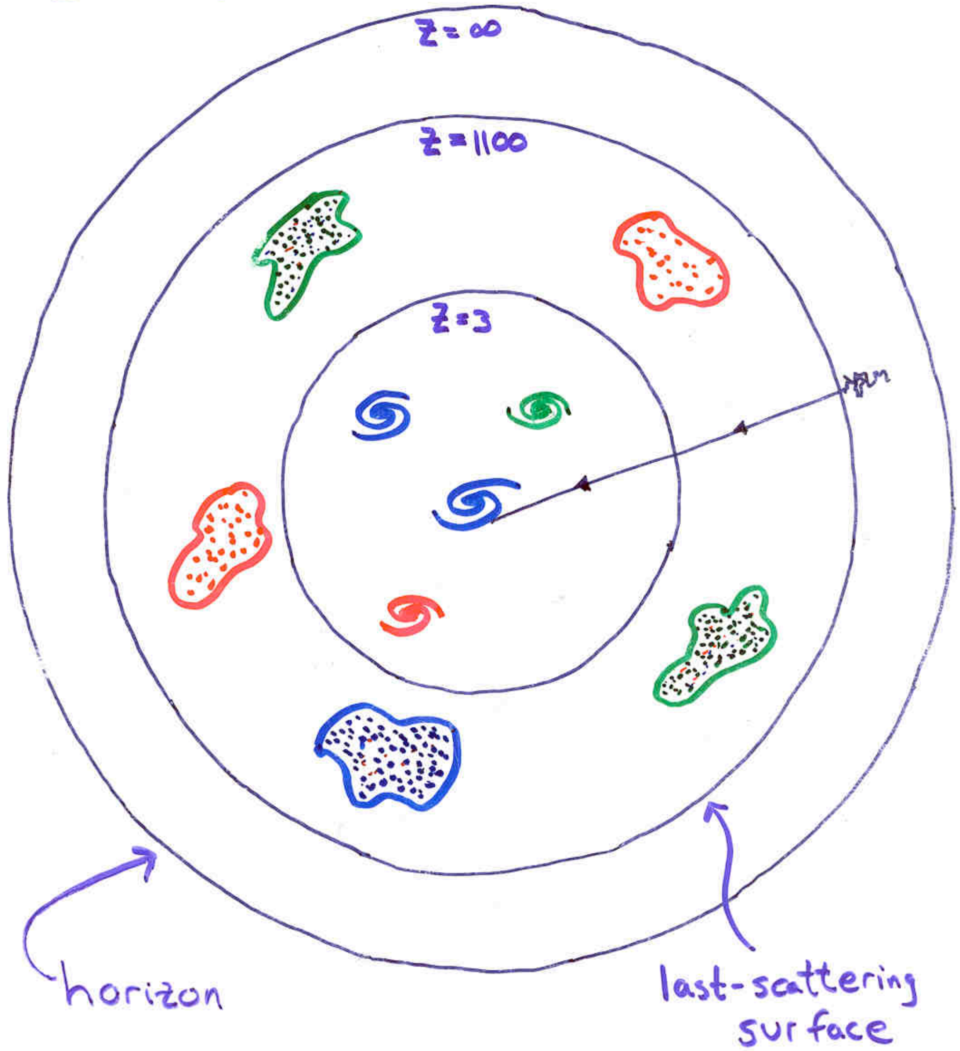
Noise Source

Primordial fluctuation generator (inflation works well)

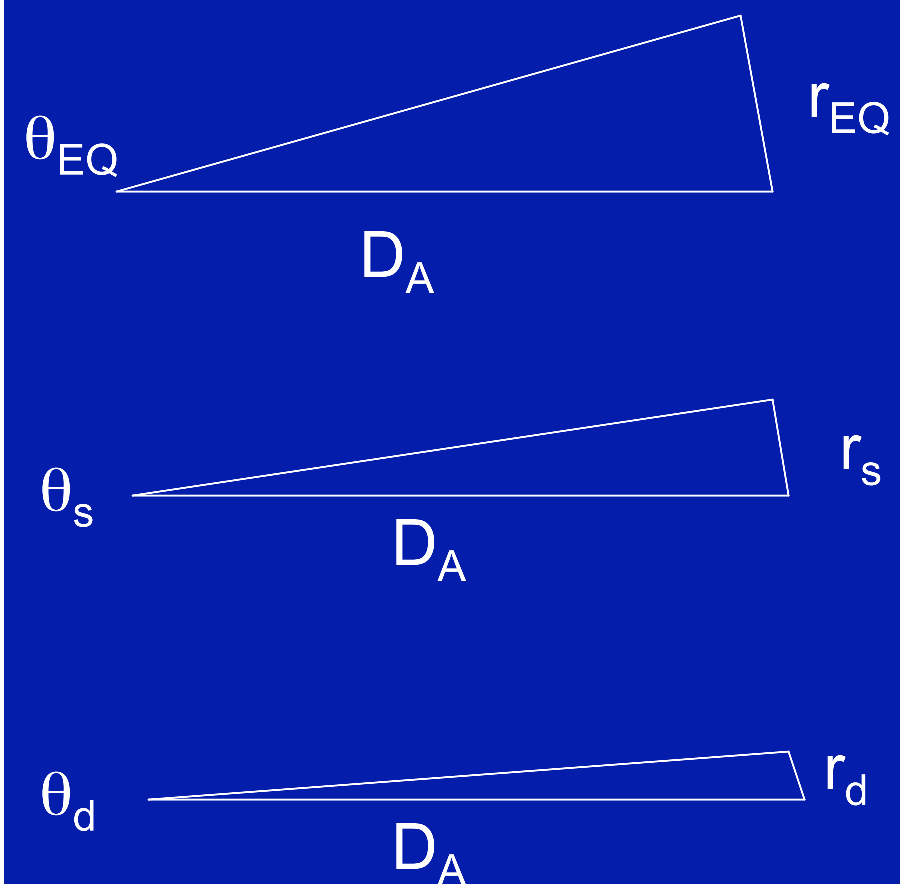
Transfer Function

Depends on matter content

THE HISTORY OF A SINGLE PHOTON



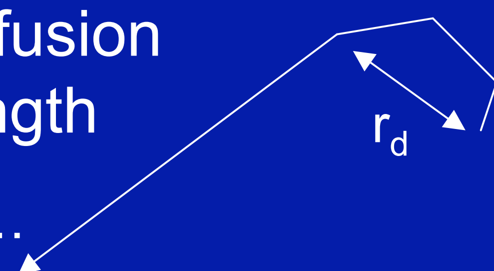
Three Scales in the CMB Transfer Function



r_{EQ} is the comoving size of the Hubble radius at EQuality.

sound horizon: distance sound could travel by the time of last scattering. θ_s controls peak locations.

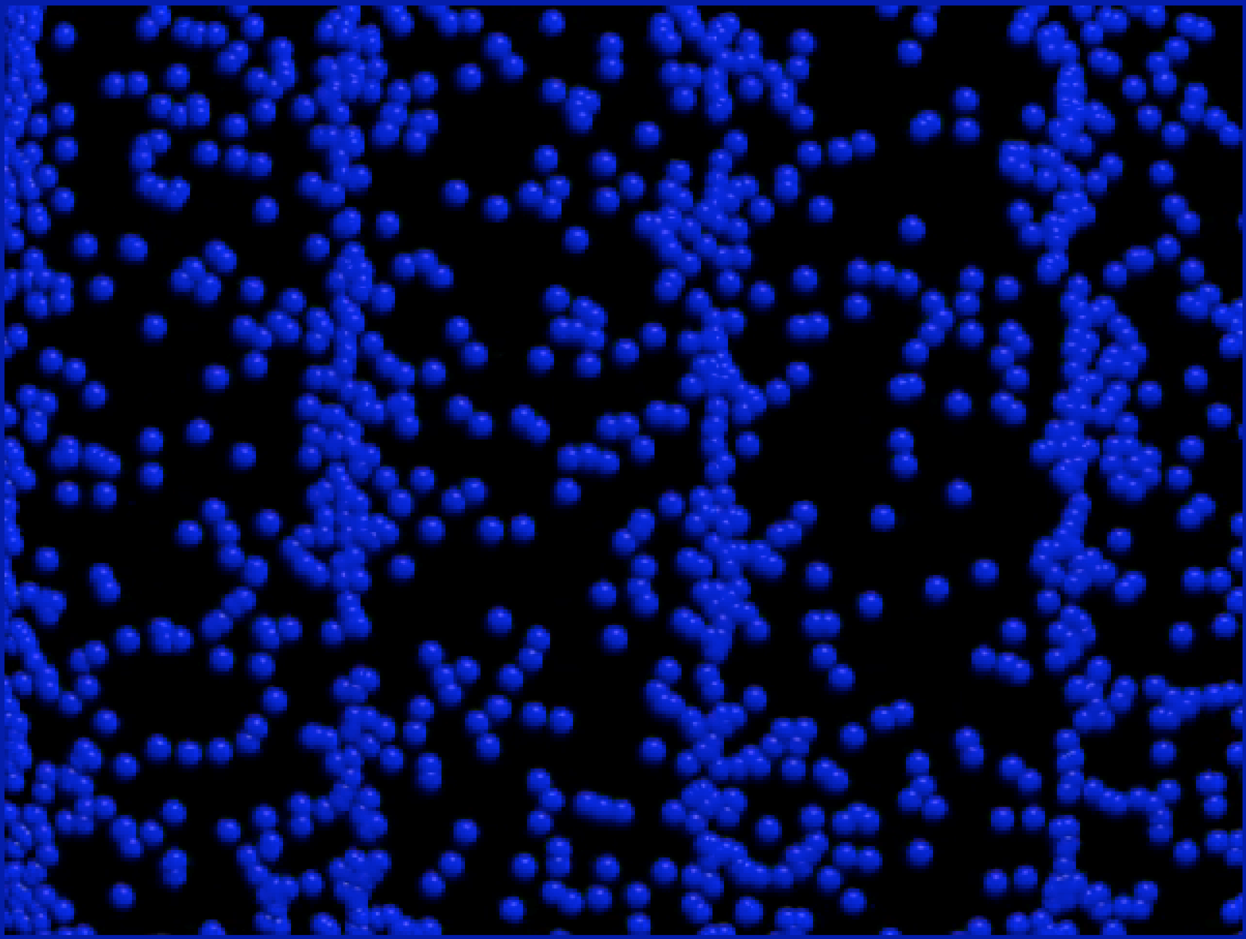
diffusion length



Silk, Kaiser, Hu, White, Bashinsky, Seljak, …

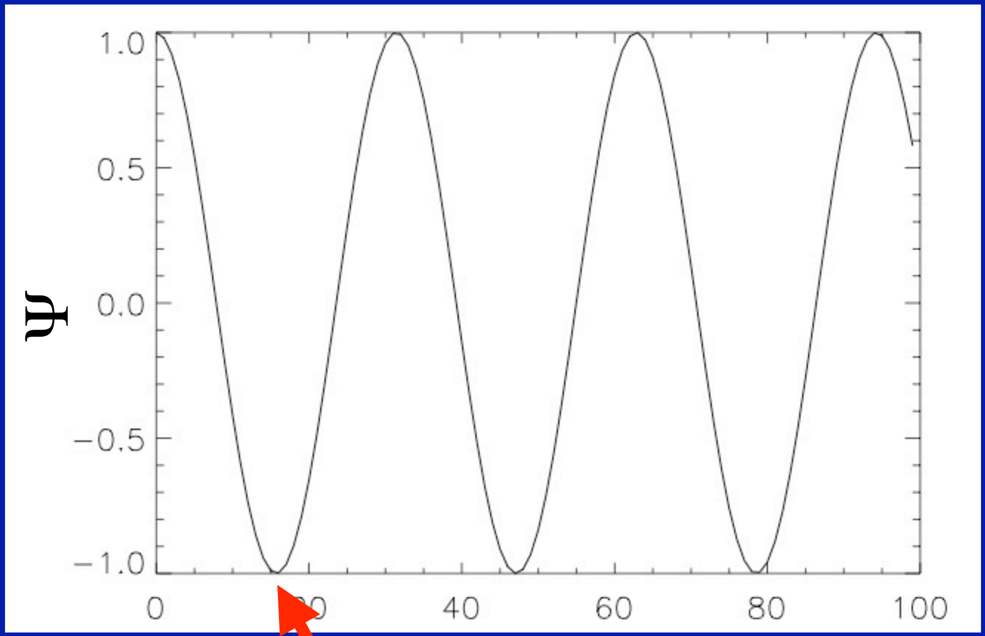
Animation credit: Damien Martin (UCD)

Evolution of Single Fourier Mode



Potential Well Potential Hill

A Single Fourier Mode



space

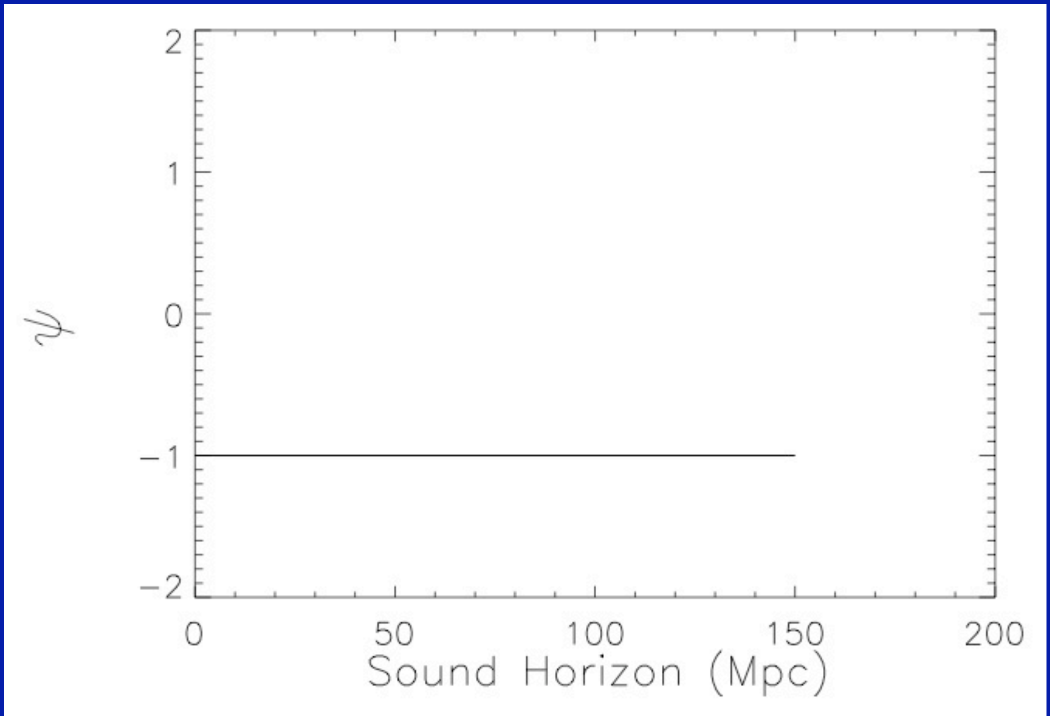
We will be considering how this single Fourier mode evolves with time.

For specificity, we will be tracking the amplitude of temperature and Ψ at this point in space.

Gravitational Potential, Ψ, as a function of time in a Matter-Dominated Universe

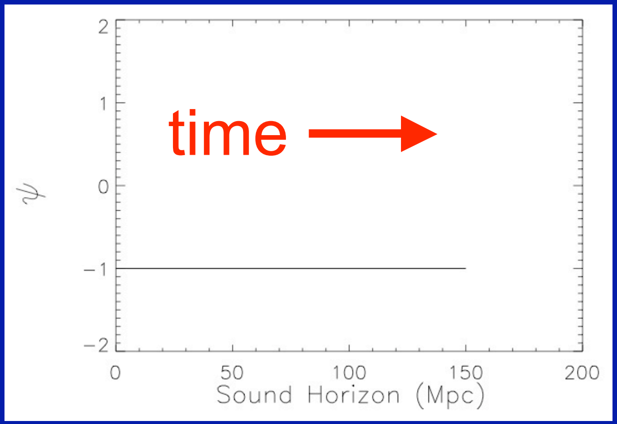
(We will be using the comoving size of the sound horizon as our time-like variable)

Gravitational Potential, Ψ, as a function of time in a Matter-Dominated Universe

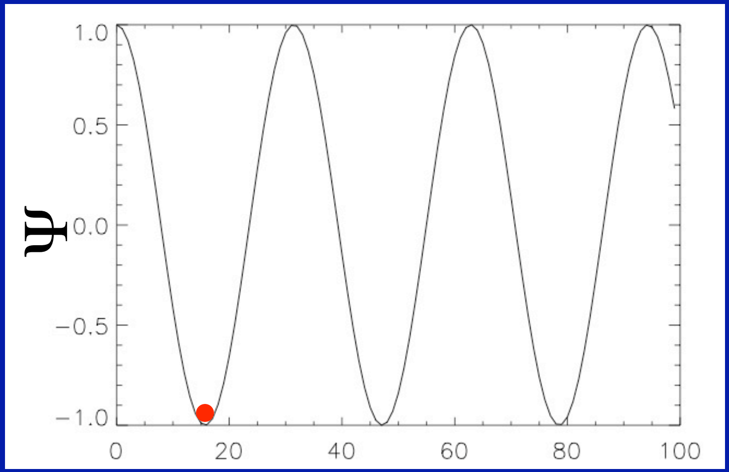


(We will be using the comoving size of the sound horizon as our time-like variable)

Evolution Assuming Matter Domination

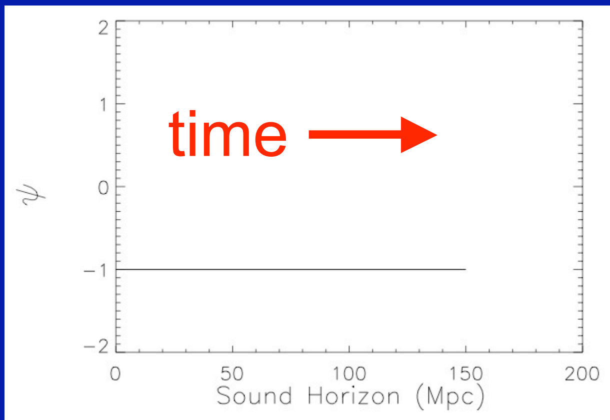


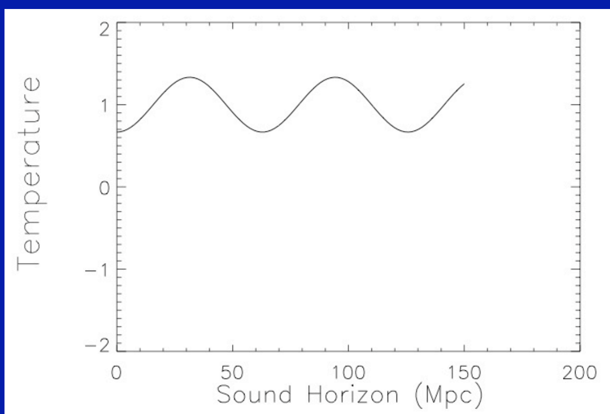
Initial spatial dependence



space

Evolution Assuming Matter Domination





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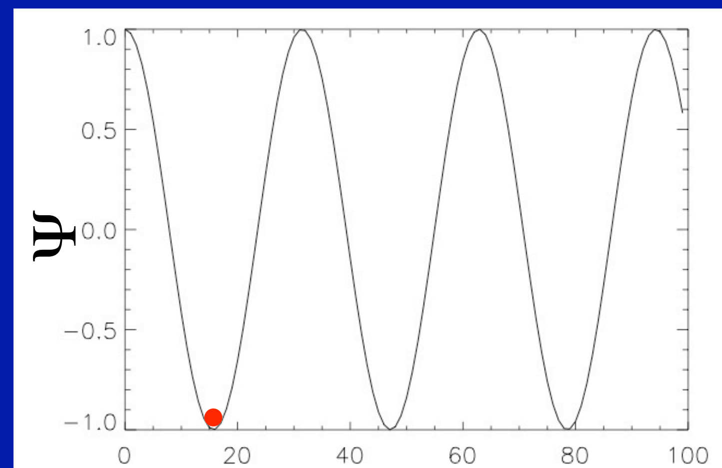
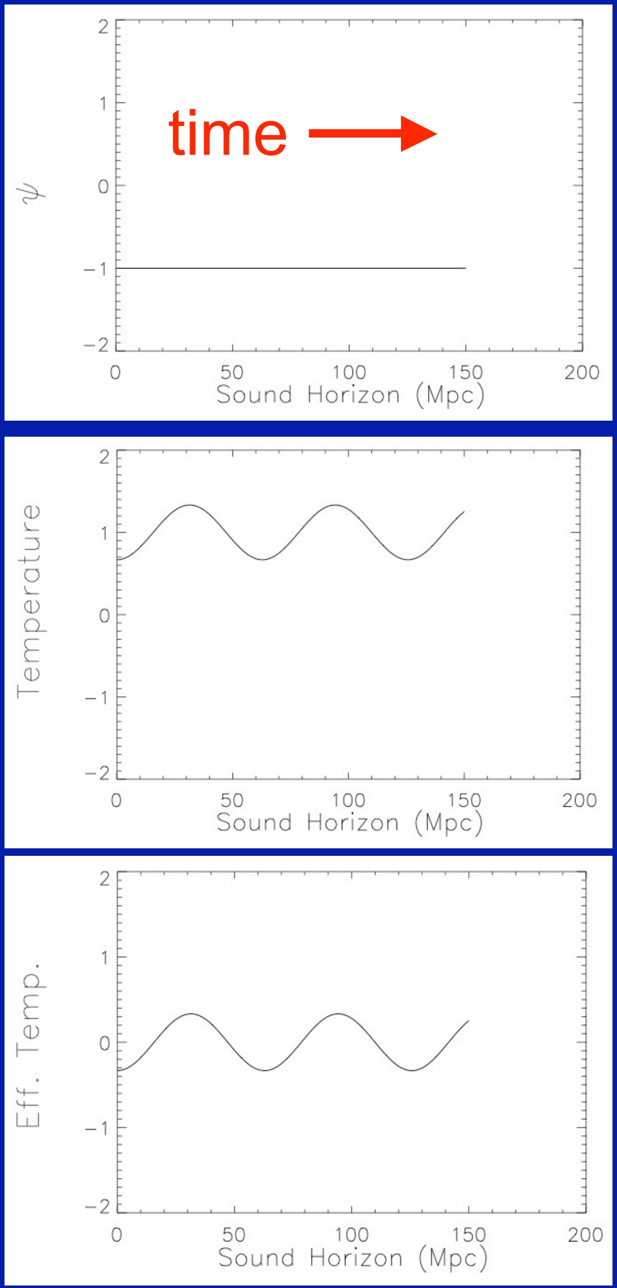


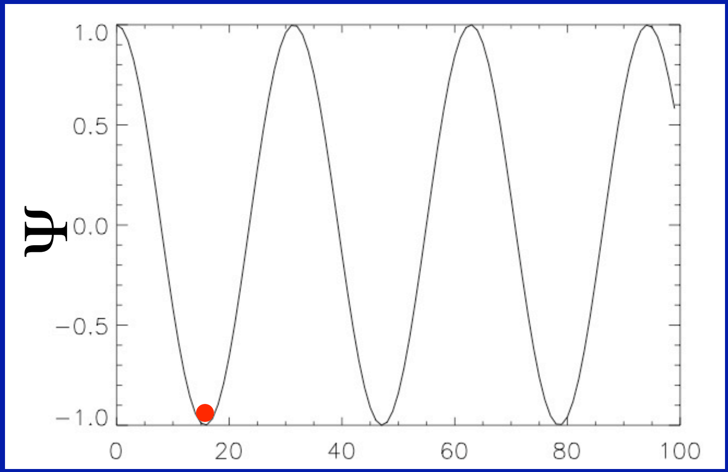
space

"Temperature" = $\Theta_0 = \delta T/T$

Evolution Assuming Matter Domination



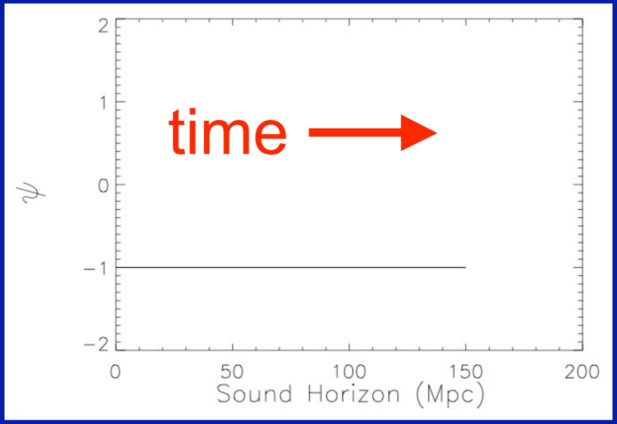
Initial spatial dependence

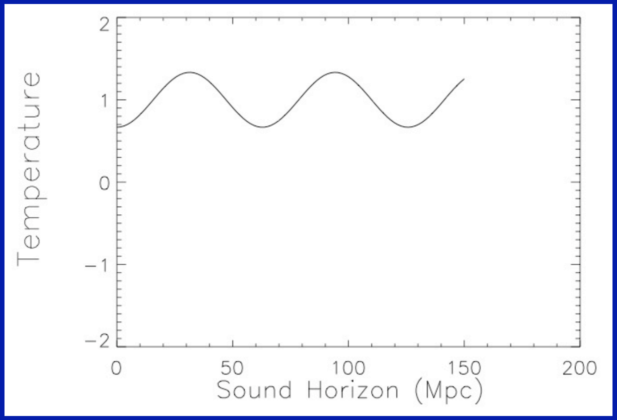


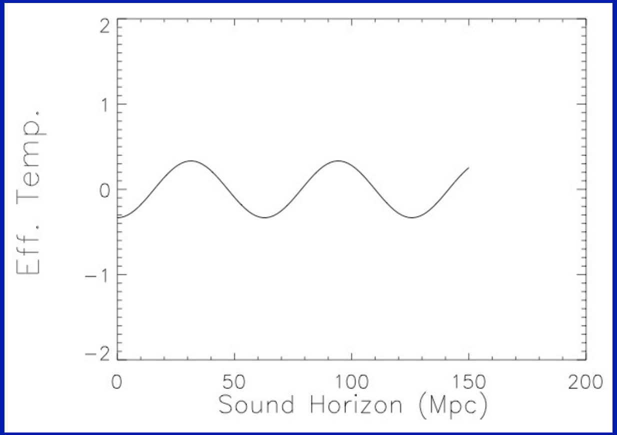
space

"Effective Temperature" = $\Theta_0 + \Psi$

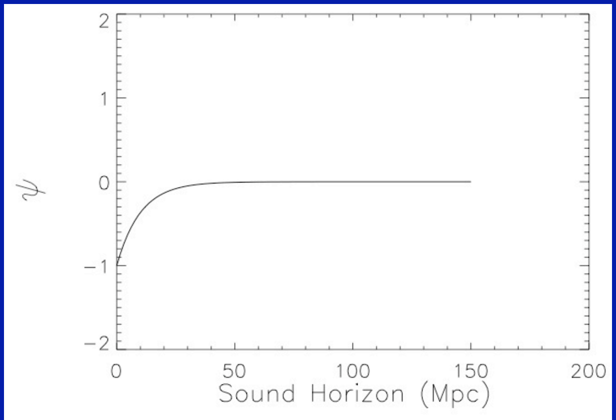
Evolution Assuming Matter Domination



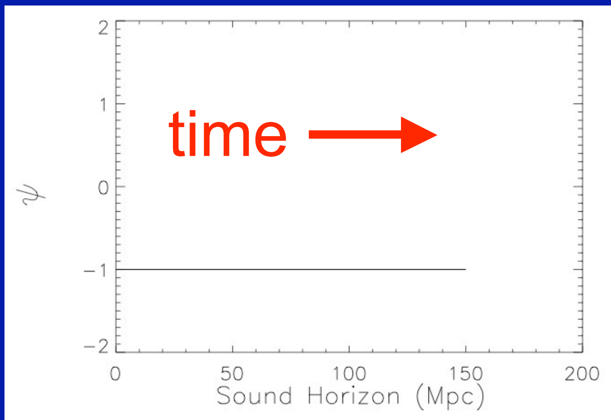


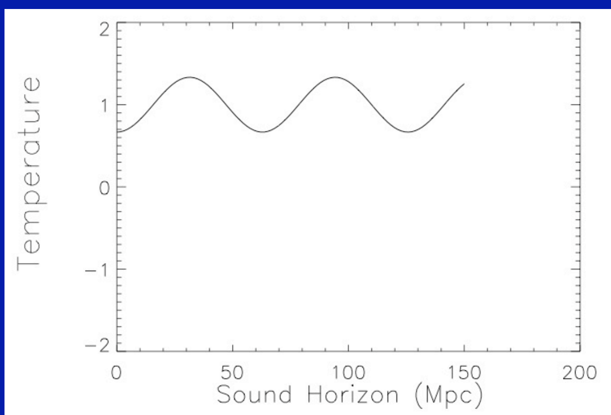


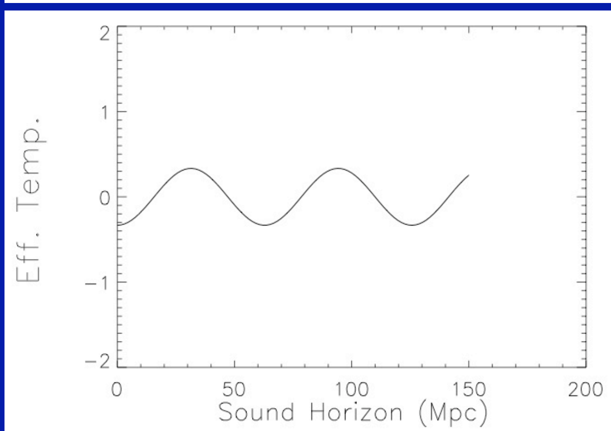
Evolution Assuming Radiation Domination



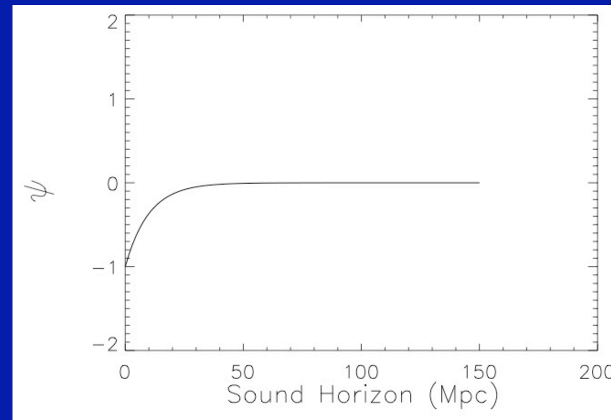
Evolution Assuming Matter Domination

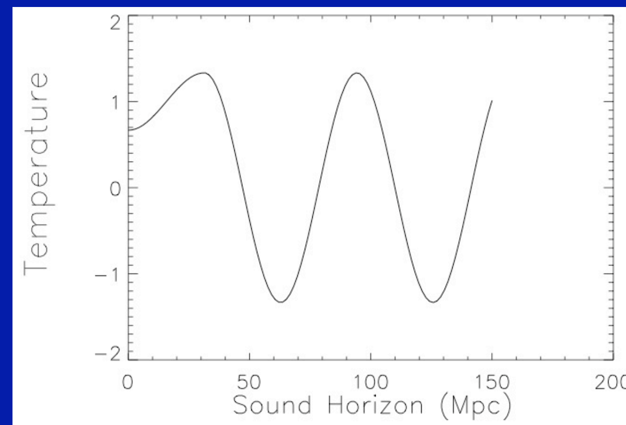




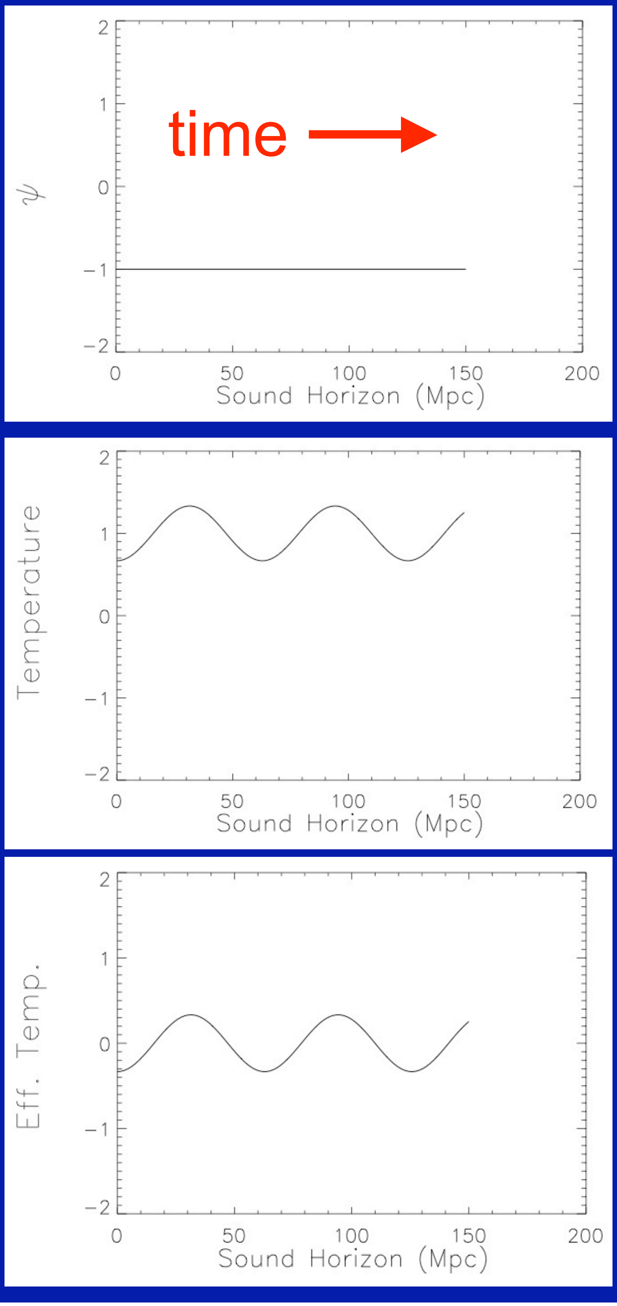


Evolution Assuming Radiation Domination

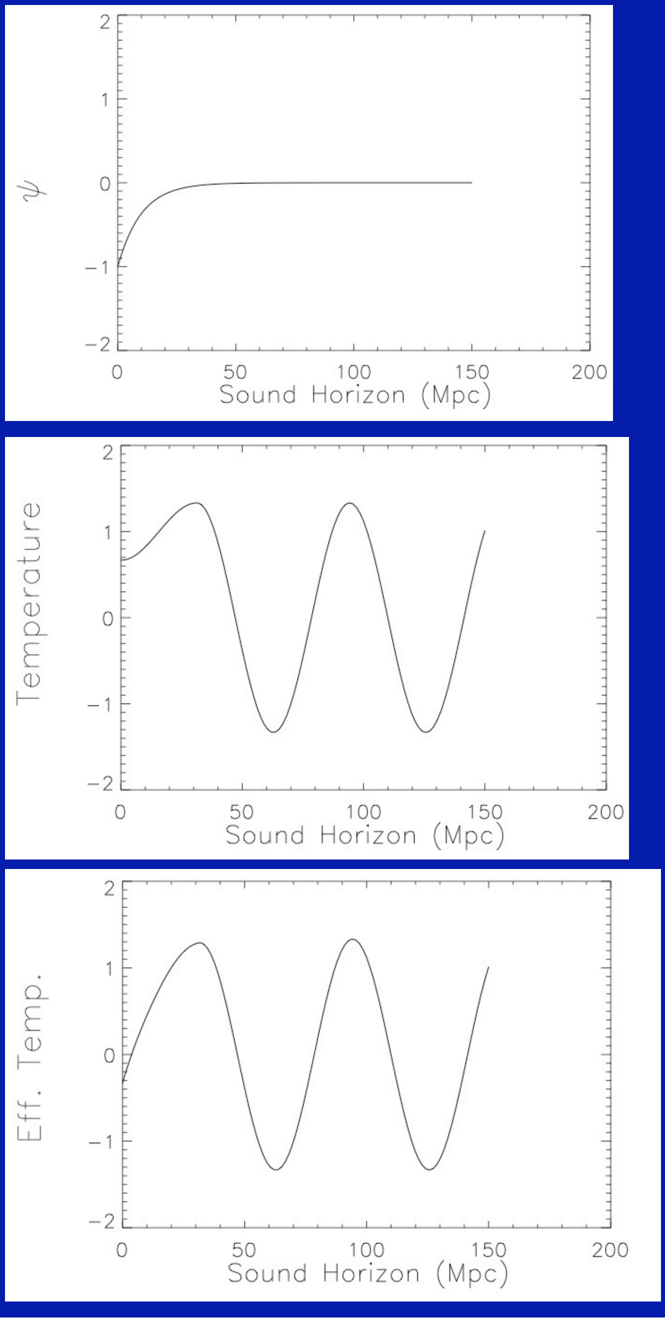




Evolution Assuming Matter Domination

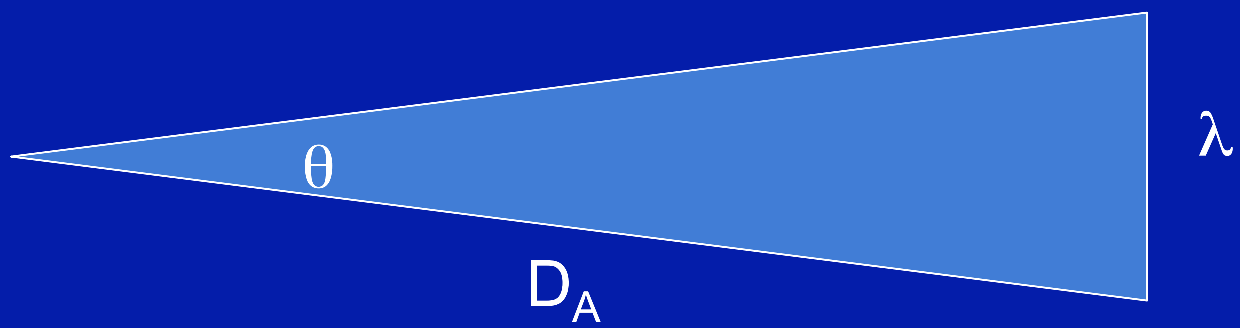


Evolution Assuming Radiation Domination



$r_{EQ} = H^{-1}_{EQ}/a_{EQ}$ is an important length scale

The amplitude of the “radiation driving” effect is controlled by the ratio of matter to radiation when oscillations begin (when $\lambda = H^{-1}/a$) and therefore by $\theta/\theta_{EQ} = \lambda/r_{EQ}$.

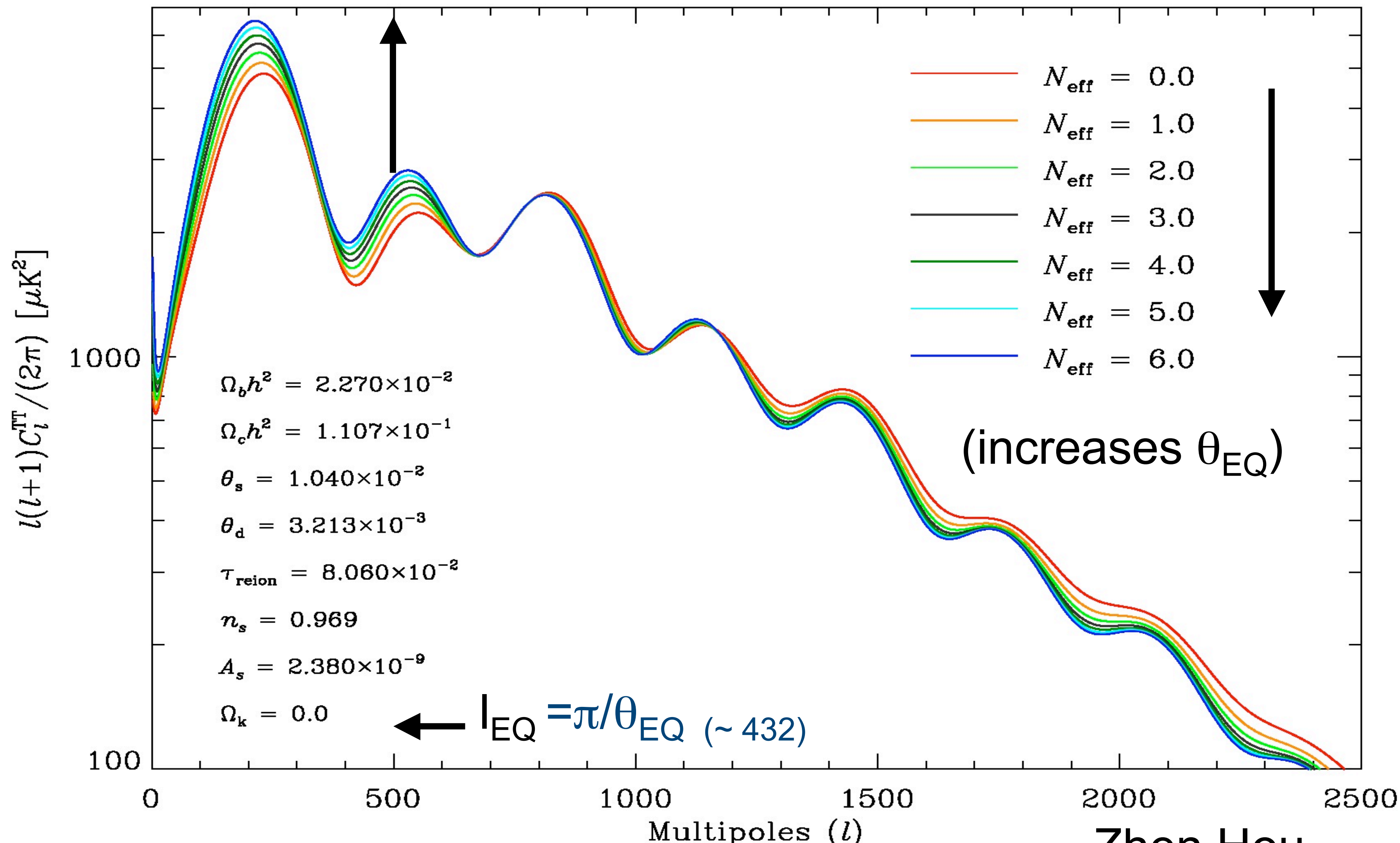


$\theta_{EQ} = r_{EQ}/D_A$

$l = \pi/\theta$

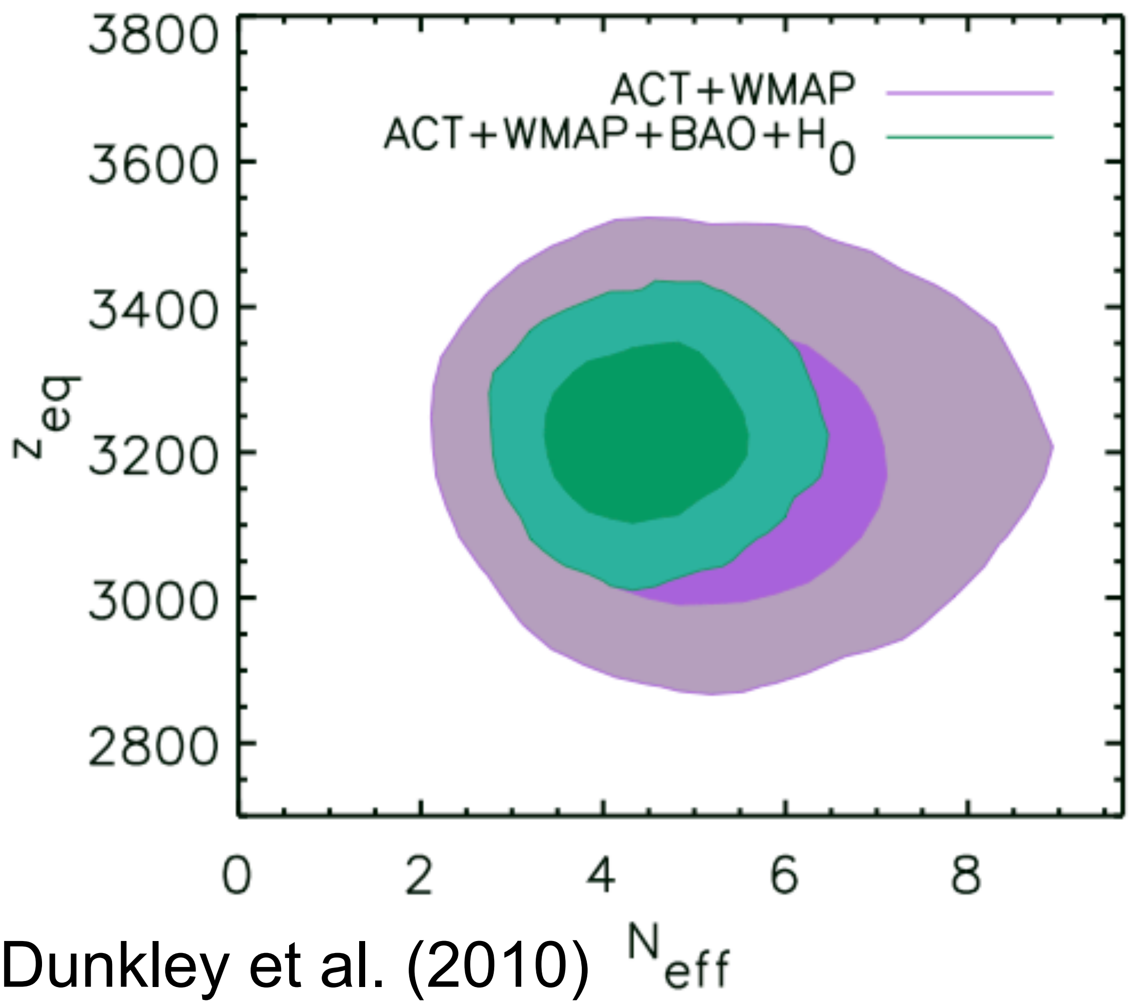
$l_{EQ} = \pi/\theta_{EQ}$

Changing θ_{EQ} at fixed θ_s and θ_d



Zhen Hou

$\theta_{\rm EQ} = I(\Omega_m)/\sqrt{1+z_{\rm EQ}}$ where $I(\Omega_m)$ is a very slowly-varying function of Ω_m



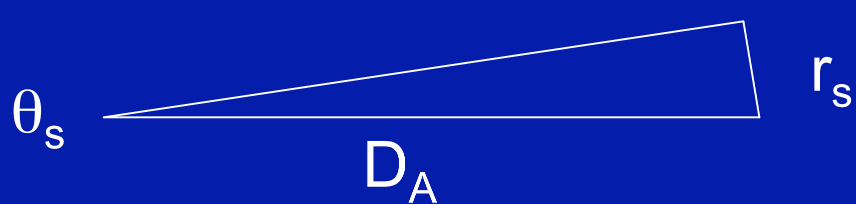
Dunkley et al. (2010)

As Neff is varied, ρ_m is increased to keep z_{EQ} (and therefore θ_{EQ}) fixed, because θ_{EQ} is robustly determined by the data.

Komatsu et al. (2010)

The Sound Horizon

sound horizon: distance sound could travel by the time of last scattering.



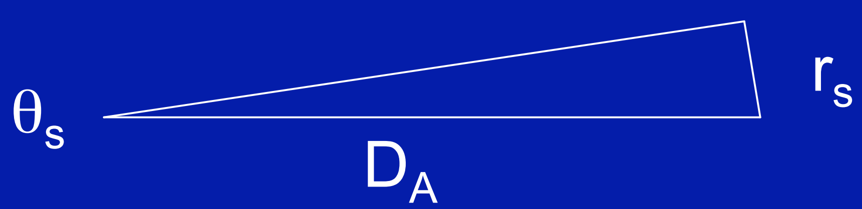
$\Theta_0 + \Psi \sim \cos(kr_s(\eta))$ so $kr_s(\eta_*) = kr_s$ controls oscillation phase at last scattering and therefore whether k corresponds to a peak or a trough. Or if you want to swap l for k:

$kr_s = kD_A\,(r_s/D_A) = l\theta_s$ $l\theta_s$ controls oscillation phase of mode that projects to multipole moment l.

Effect of extra ν on r_s

$100\ \theta_s = 1.04 +/- 0.0016$

Keisler et al. (2011)



sound horizon: distance sound could travel by the time of last scattering. θ_s controls peak locations.

$r_s = \int_0^{a^*} c_s\, da/(a^2 H)$

Extra ν ==> higher ρ ==> higher H ==> takes less time to cool to T_{rec} ==> r_s is smaller

$H^2 = 8\pi G\rho/3$

If we knew D_A we could find $r_s = \theta_s D_A$ and determine H

Effect of extra ν on r_d

Random-walk so goes as sq. root of time ==> $r_d \sim 1/H^{0.5}$

(Remember $r_s \sim 1/H$)

$\theta_d/\theta_s = r_d/r_s \sim H^{0.5}$

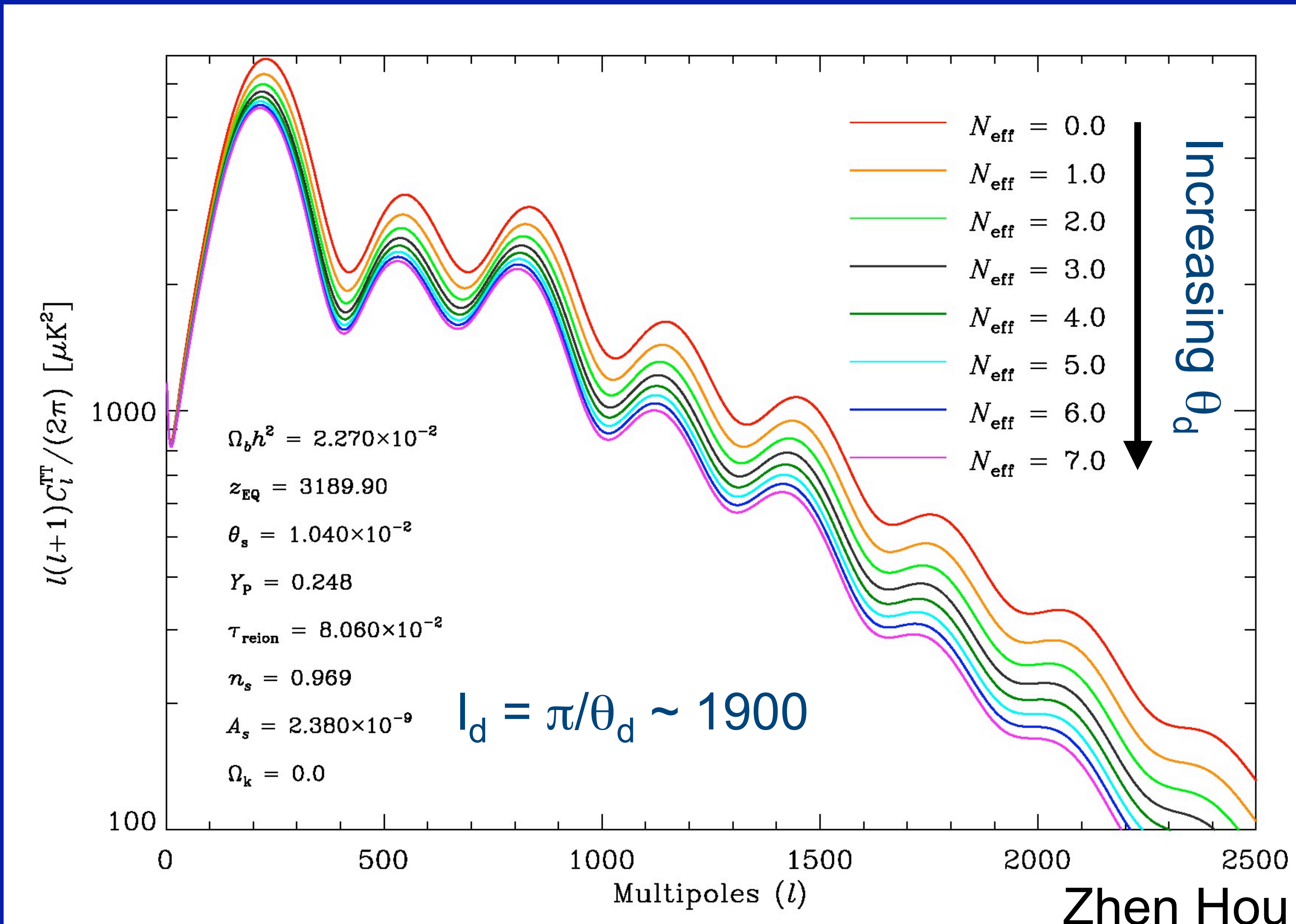
Dependence on D_A has dropped out!

diffusion length

Modes with $\lambda < r_d$ are suppressed

Silk damping

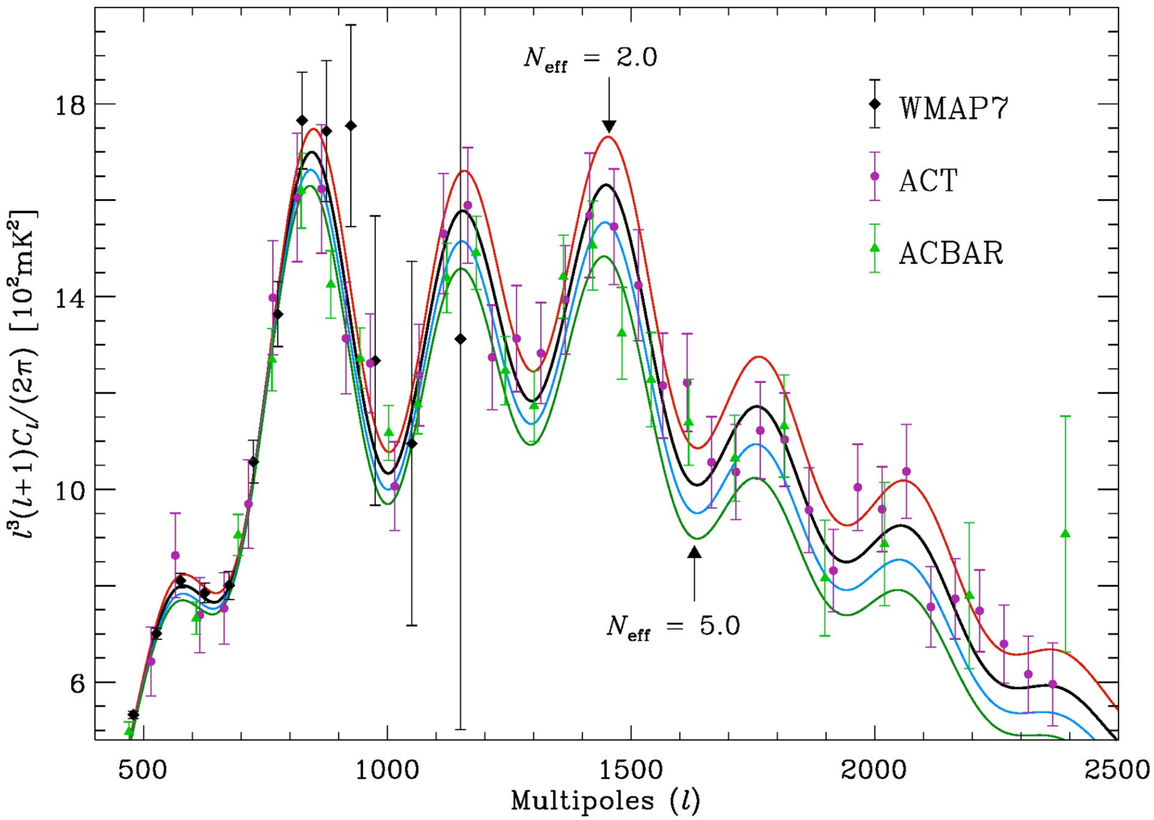
Changing θ_d at fixed θ_{EQ} and θ_s



Increasing N_{eff} increases θ_d, reducing small-scale power

Hou, Keisler, LK, Millea & Reichardt (2011)

$l^4C_l/(2\pi)$

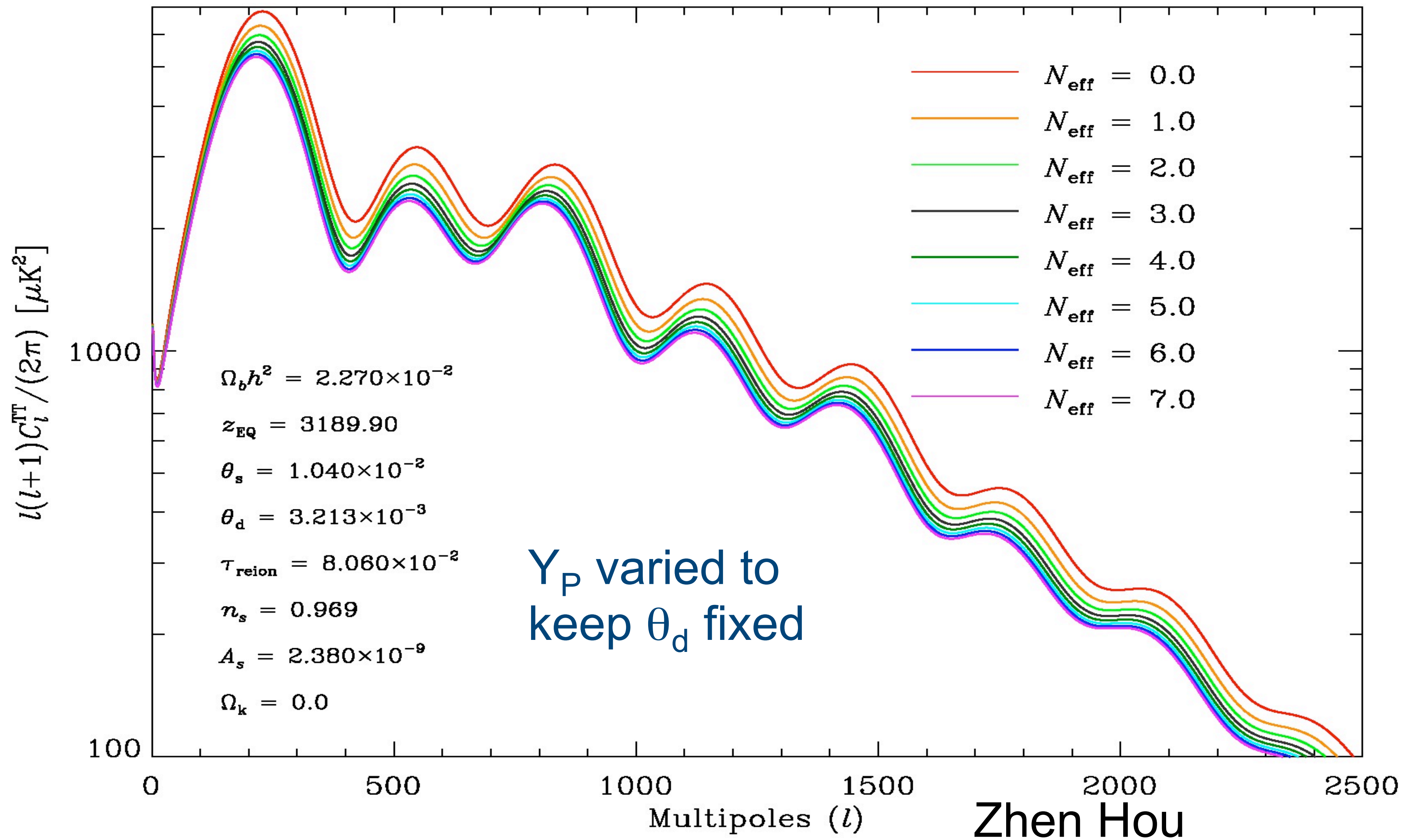


98.4% confidence that N_{eff} > standard model value (Hou et al. 2011)

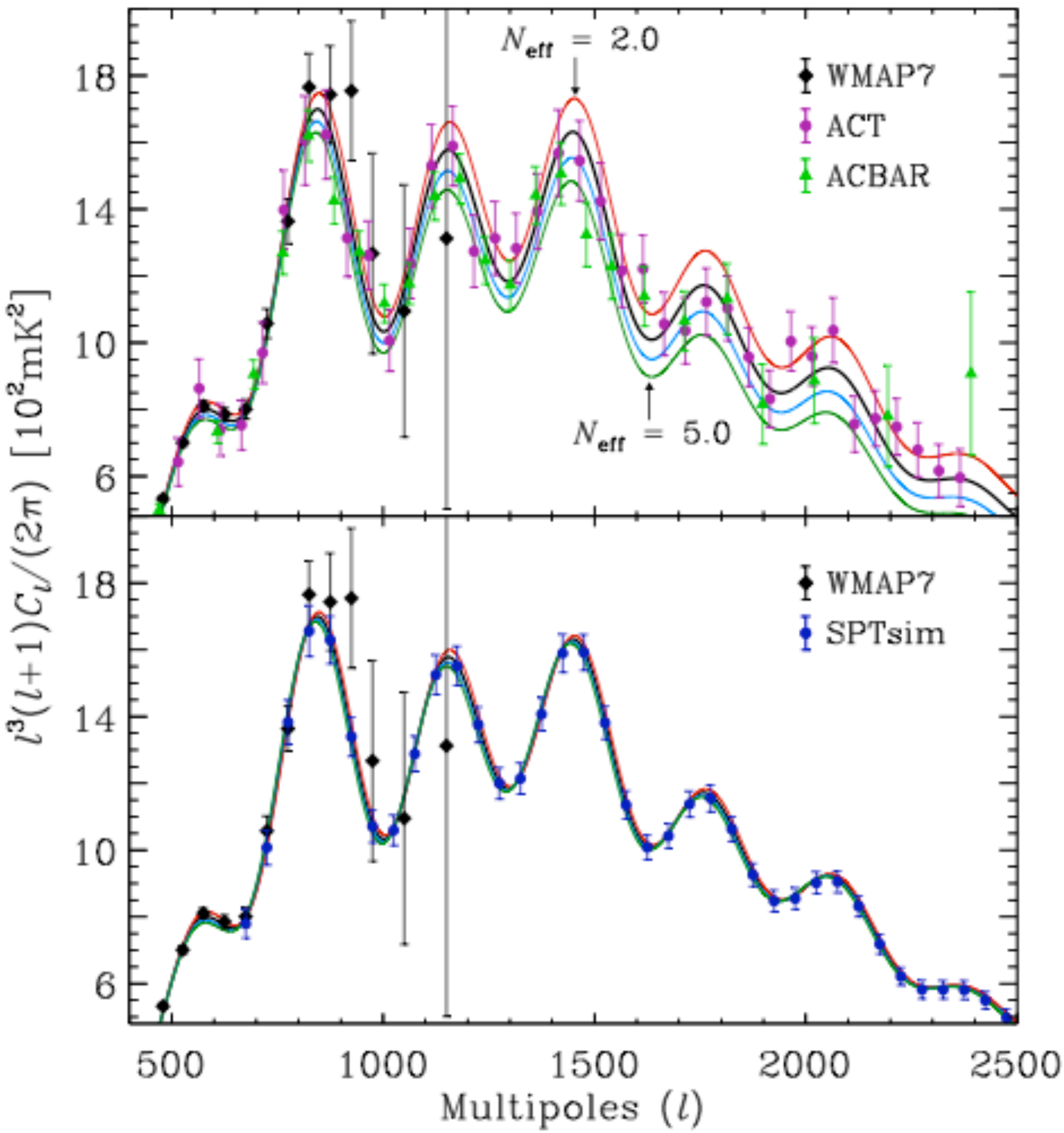
Neff is increased here from 2 to 5 with fixed θ_{EQ} and θ_s.

To fix θ_{EQ} we increase ρ_{cdm}. To fix θ_s we adjust ρ_Λ to change D_A.

Changing N_{eff} at fixed θ_d ,θ_{EQ} and θ_s



Zhen Hou

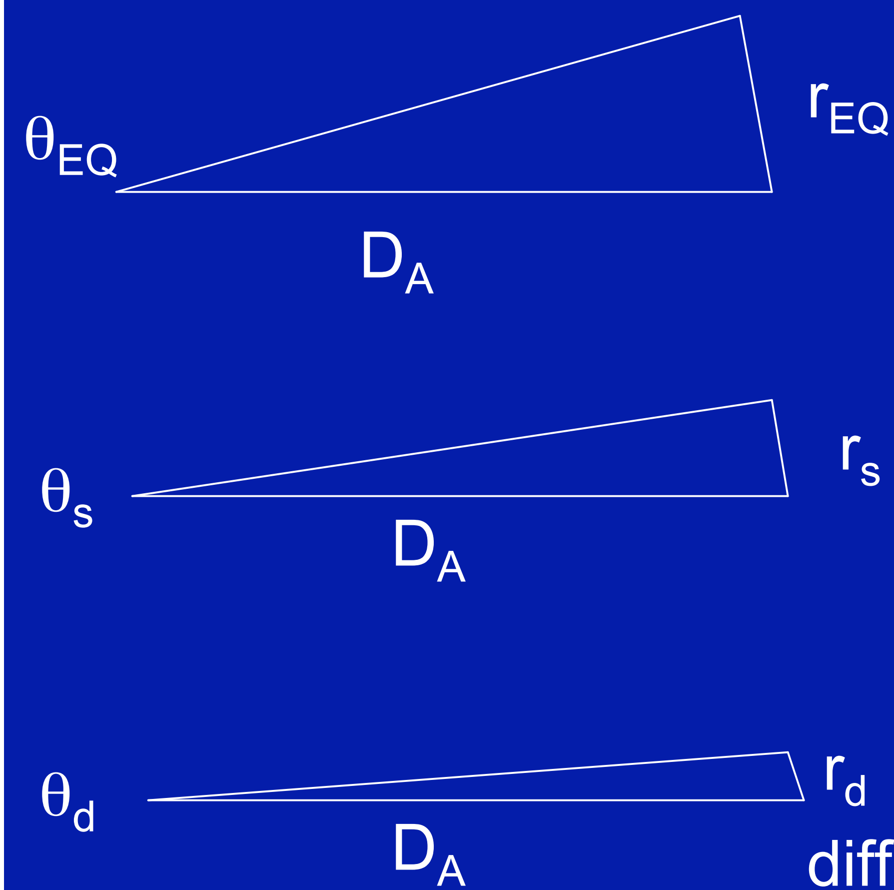


Same models but with θ_d fixed as well (by varying the Helium fraction).

The effect is indeed due to change to θ_d

Bashinsky & Seljak (2004)

Summary of Three Scales



diffusion length

r_{EQ} controls radiation driving

sound horizon: distance sound could travel by the time of last scattering. θ/θ_s controls oscillation phase at last scattering.

Modes with $\lambda < r_d$ are suppressed

Silk damping

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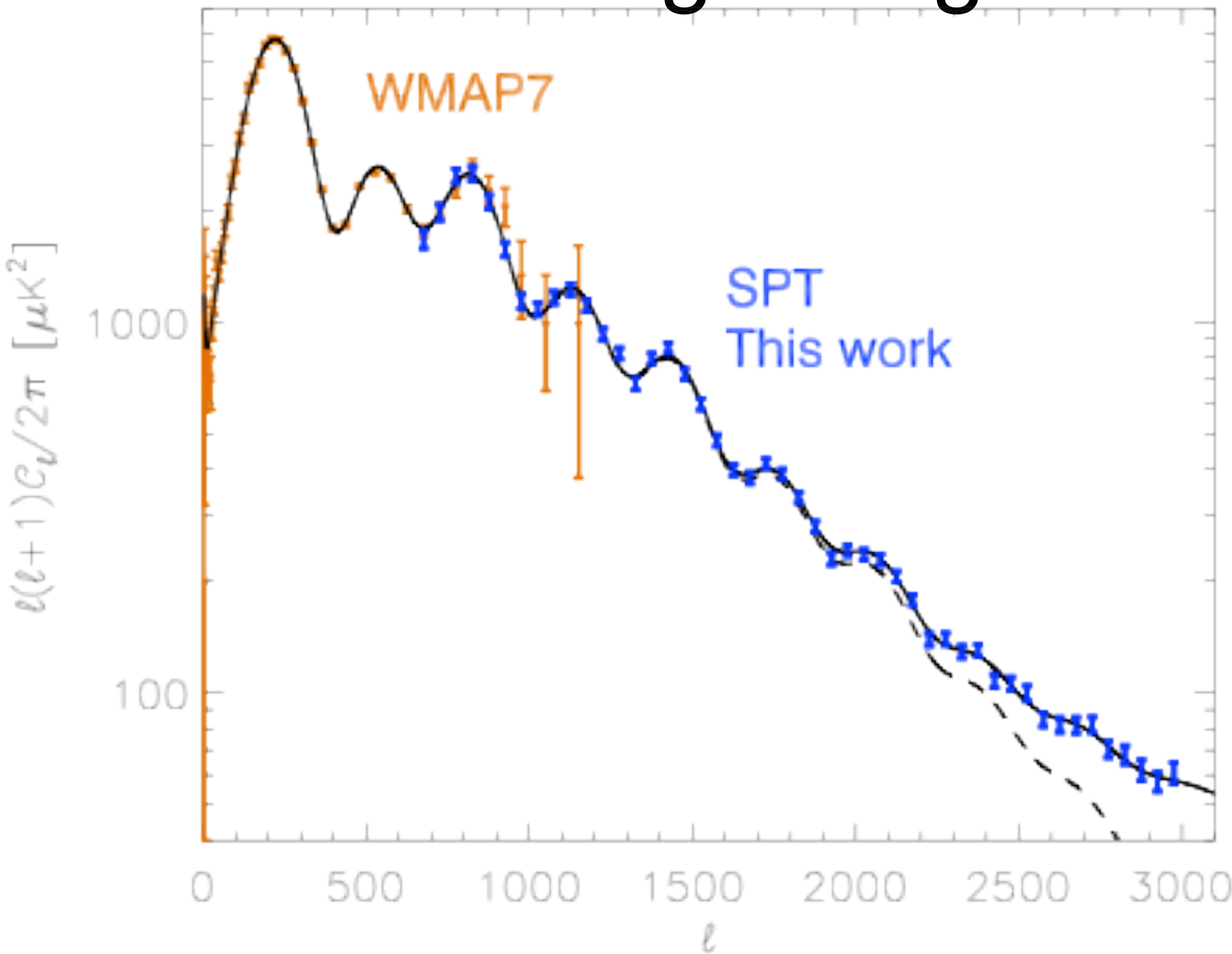
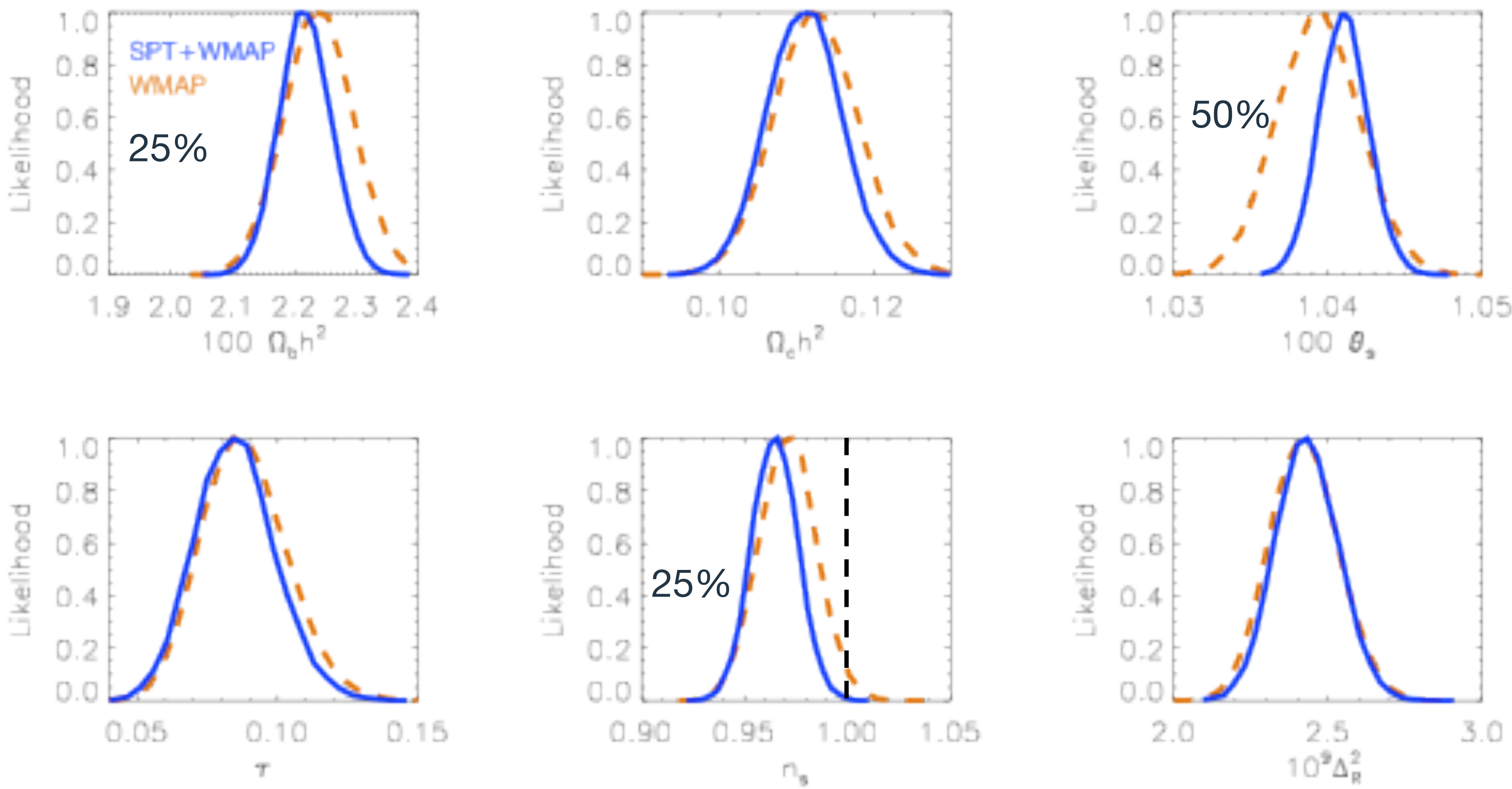
SPT error bars are small and over large range in ell



SPT provides modest improvement on 6 “vanilla” cosmo parameters



Six-parameter Model

Input spectrum parameters

A

n_s

Transfer function parameters

τ

ρ_b

ρ_m

ρ_Λ

Assumptions

1) Standard radiation content (T_γ from FIRAS, 3 SM neutrinos)
2) $Y_P = f(N_{eff}, \rho_b)$
3) $dn_s/d\ln k = 0$
4) Dark energy = Λ and $\Omega_k = 0$

Six-parameter Model

Input spectrum parameters

A

n_s

Transfer function parameters

τ

ρ_b

ρ_m (θ_{EQ})

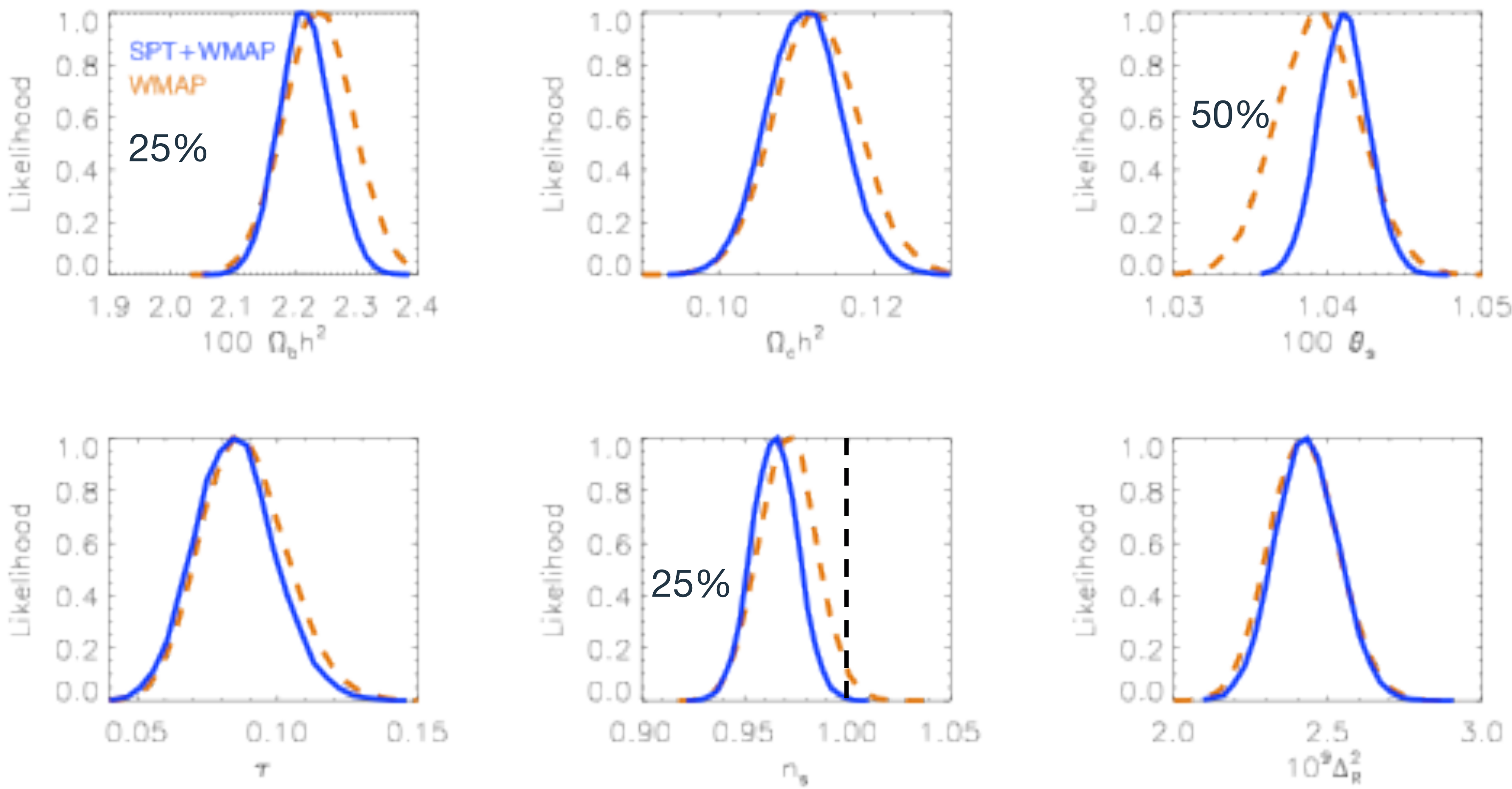
ρ_Λ (θ_s)

Assumptions

1) Standard radiation content (T_γ from FIRAS, 3 SM neutrinos)
2) $Y_P = f(N_{eff}, \rho_b)$
3) $dn_s/d\ln k = 0$
4) Dark energy = Λ and $\Omega_k = 0$

For WMAP7, effects that lead to constraints on τ, ρ_b and ρ_m are gone at higher ell.

SPT provides modest improvement on 6 “vanilla” cosmo parameters



Six-parameter Model

Input spectrum parameters

A

n_s

Transfer function parameters

τ

ρ_b

ρ_m (θ_{EQ})

ρ_Λ (θ_s)

Assumptions

1) Standard radiation content (T_γ from FIRAS, 3 SM neutrinos)
2) $Y_P = 0.24$
3) $dn_s/d\ln k = 0$
4) Dark energy = Λ and $\Omega_k = 0$

High ell data ==> sensitive to θ_d, which can be predicted from ρ_b, ρ_m, ρ_Λ which are already determined from low ell.

SPT provides a strong test of the 6-parameter model rather than great refinement of the parameter values

θ_d predicted

How does the prediction compare with measurement?

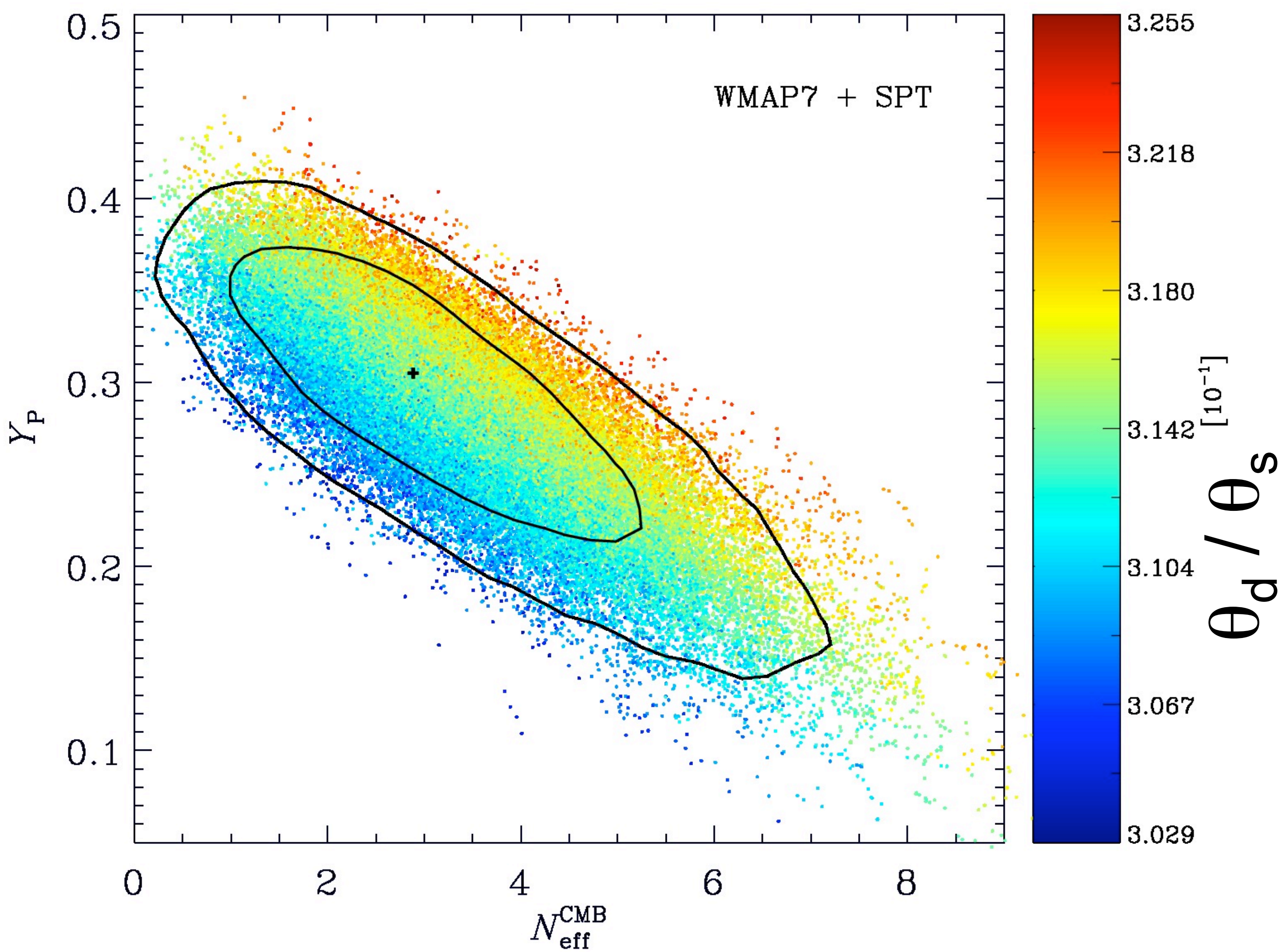
Mild preference (~ 1.7σ) for models with less power in damping tail than for the best-fit 6-parameter model

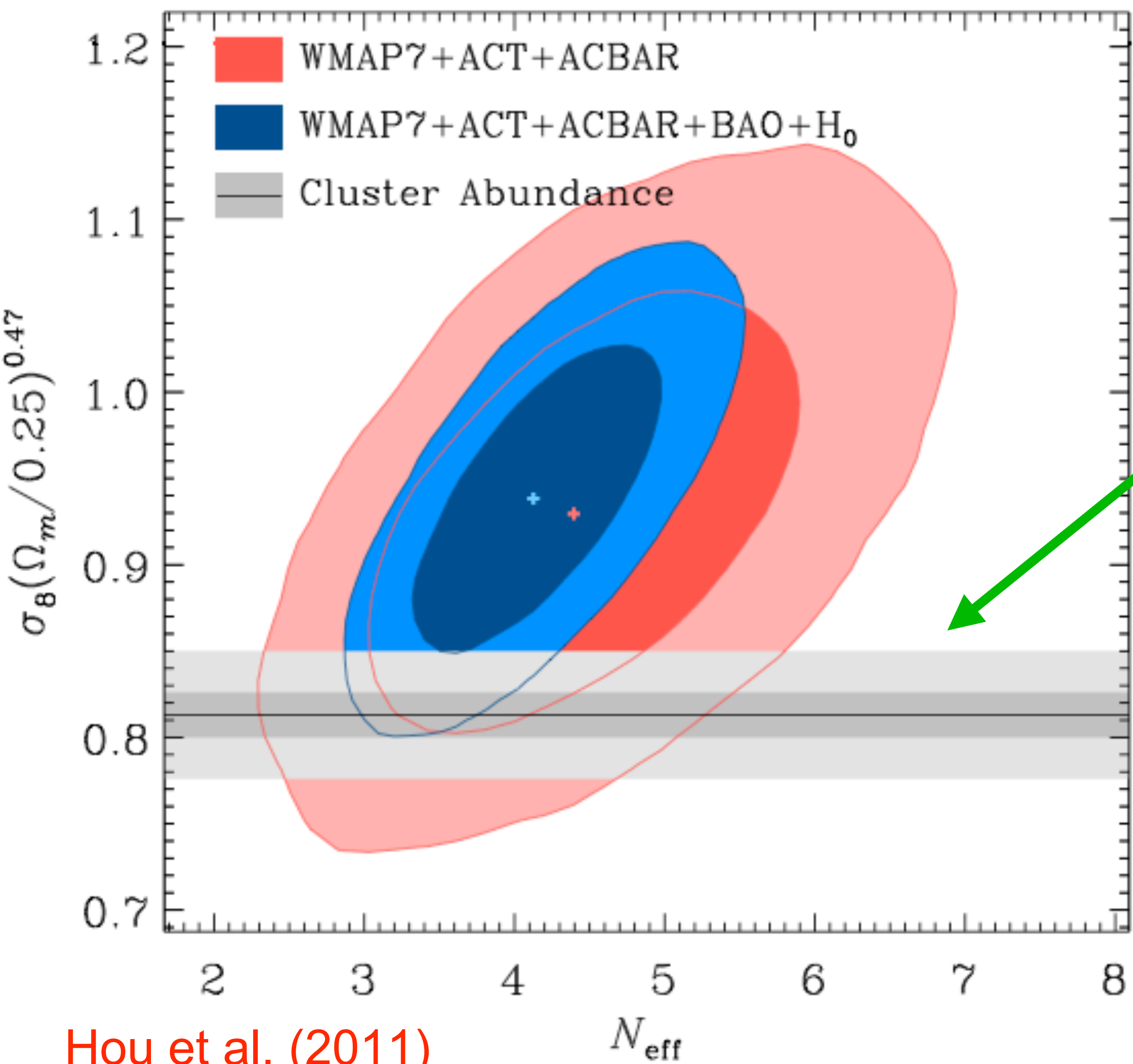
Constraints on Extensions

	WMAP7+SPT	WMAP7+SPT +BAO+H_0
N_{eff} (3.046)	3.85 +/-0.62	3.86 +/-0.42
Y_P (0.24)	0.296 +/-0.030	0.30 +/- 0.030
$dn_s/dlnk$ $((1-n_s)^2 = 0)$	-0.024 +/- 0.013	-0.020 +/- 0.012
r	< 0.21 @ 95% confidence	< 0.17 @ 95% confidence

θ_d { (N_{eff}, Y_P)

N_{eff} vs Y_P


WMAP7 + SPT
0.5
0.4
0.3
0.2
0.1
Y_P
0
2
4
6
8
N_{eff}^{CMB}
3.255
3.218
3.180
3.142
3.104
3.067
3.029
θ_d / θ_s $[10^{-1}]$



Hou et al. (2011)

Vikhlinin et al. (2009) constraint from X-ray cluster abundanc es

Low z cluster abundances break degeneracies

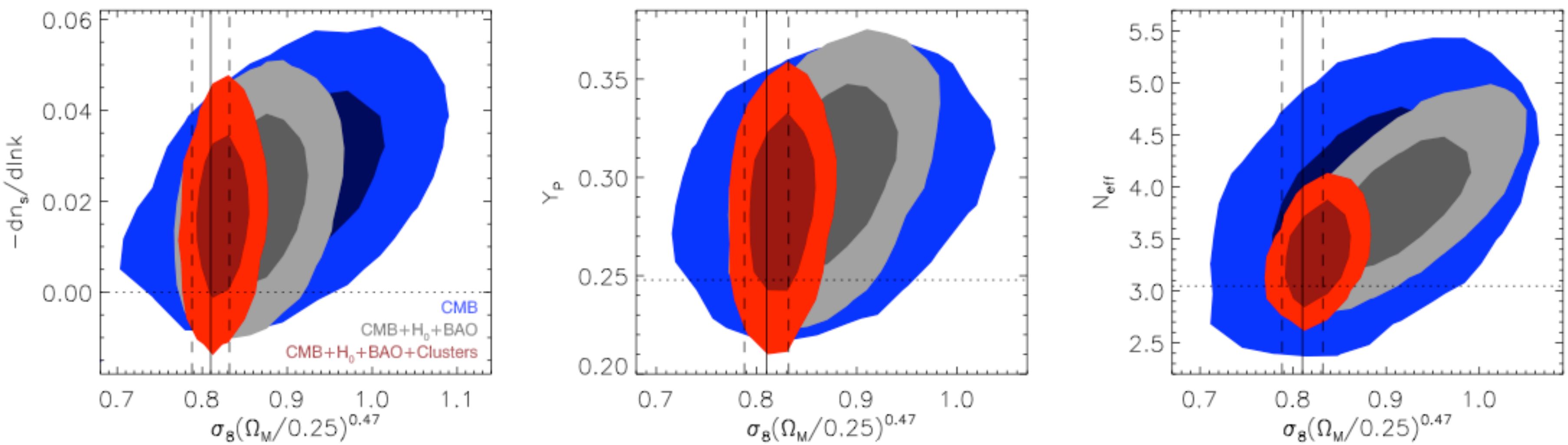


FIG. 14.— The two-dimensional marginalized constraint on spectral running, primordial helium, or the effective number of relativistic species versus the combination $\sigma_8(\Omega_M/0.25)^{0.47}$, which is well constrained by the cluster abundance measurement of Vikhlinin et al. (2009). "CMB" corresponds to SPT+WMAP7. The constraint on $\sigma_8(\Omega_M/0.25)^{0.47}$ from the clusters and the corresponding 1σ uncertainties are shown by the vertical lines. The standard values of the spectral running, primordial helium, and the effective number of relativistic species are shown by the dotted horizontal lines. Adding the cluster abundance information moves the constraints on these parameters closer to their standard values.

Keisler et al. (2011)

Outline

- CMB Theory for CMB Experimentalists
  - A Transfer Function Controlled by Three Angular Scales
- Why do "standard" constraints improve so little?
- What we can learn from the damping tail
- Non-CMB evidence for extra neutrinos

Strigari story

Neutrino Fever

Neutrino Fever

6. arXiv:1006.5276 [pdf, ps, other]

Cosmology seeking friendship with sterile neutrinos

Jan Hamann, Steen Hannestad, Georg G. Raffelt, Irene Tamborra, Yvonne Y.Y. Wong

Comments: 4 pages, 1 figure, matches version published in PRL

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Cosmology Favoring Extra Radiation and Sub-eV Mass Sterile Neutrinos as an Option

Abstract | References | Citing Articles (10)

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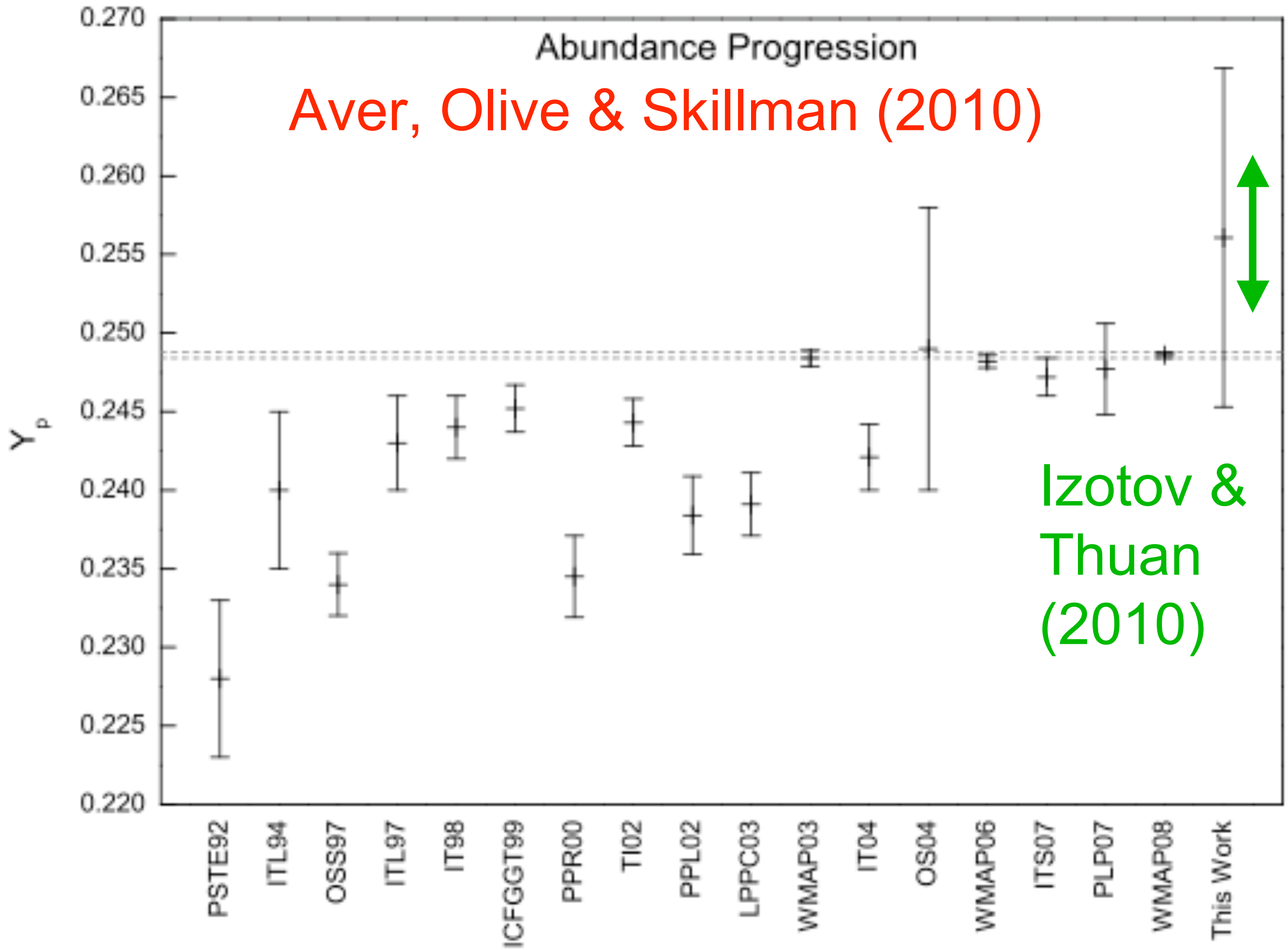
Jan Hamann[1], Steen Hannestad[1], Georg G. Raffelt[2], Irene Tamborra[2,3,4], and Yvonne Y. Y. Wong[5]

Extra Cosmological Neutrinos? Arguments For

- Mild preference for lower damping tail power than in standard cosmological model.
- Measurements of Y have increased in magnitude and uncertainty allowing Neff = 4 to be consistent with BBN and perhaps preferred (Izotov & Thuan 2010, Aver, Olive & Skillman 2010, 2011)
- Oscillation evidence for sterile neutrinos from mini-Boone / LSND / Minos
- Oscillation to sterile neutrinos can explain reactor anomalies too.

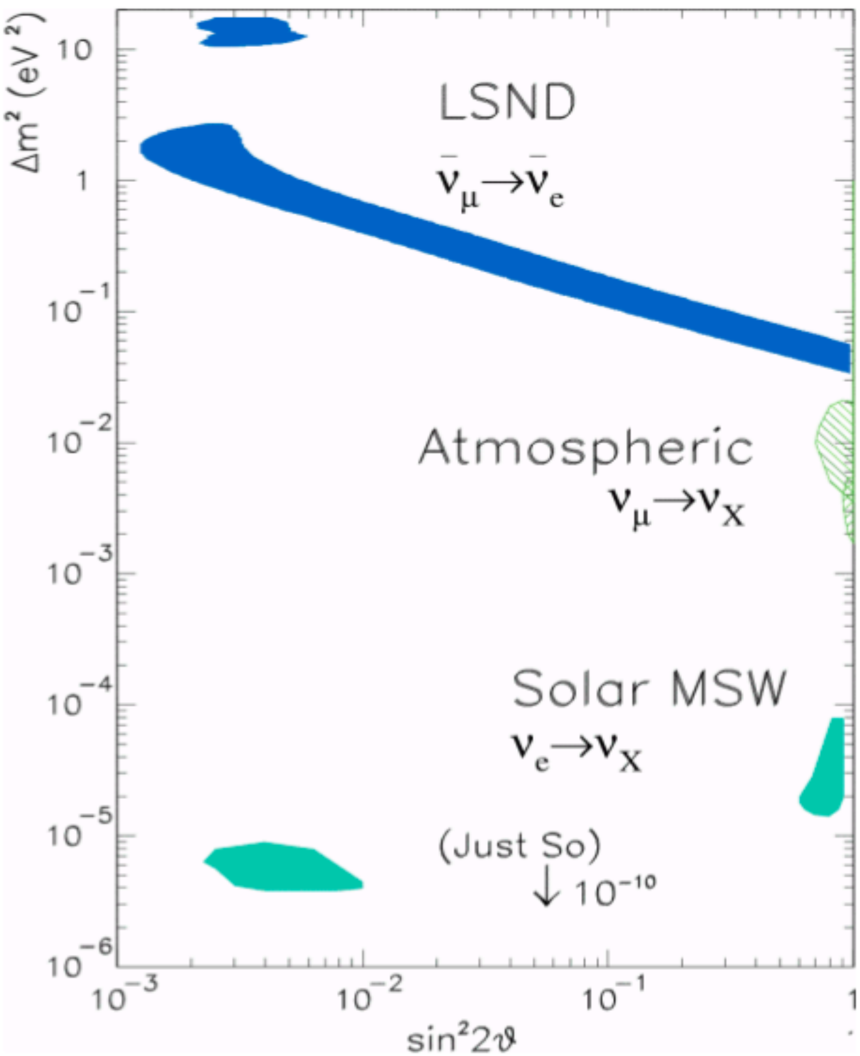
Y_P Measurements



From extragalactic regions of ionized low-metallicity gas

(except for WMAP points)

Decade-old evidence for an m ~ eV sterile neutrino



LEP proved that there are only three light neutrinos coupling to the Z^0.

Therefore there can be at most two neutrino mass difference scales.

But the oscillation results from atmospheric and solar neutrinos are well established.

If LSND is right it implies new physics such as a fourth neutrino that is sterile.

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$< 2\sigma$, tension with σ_8

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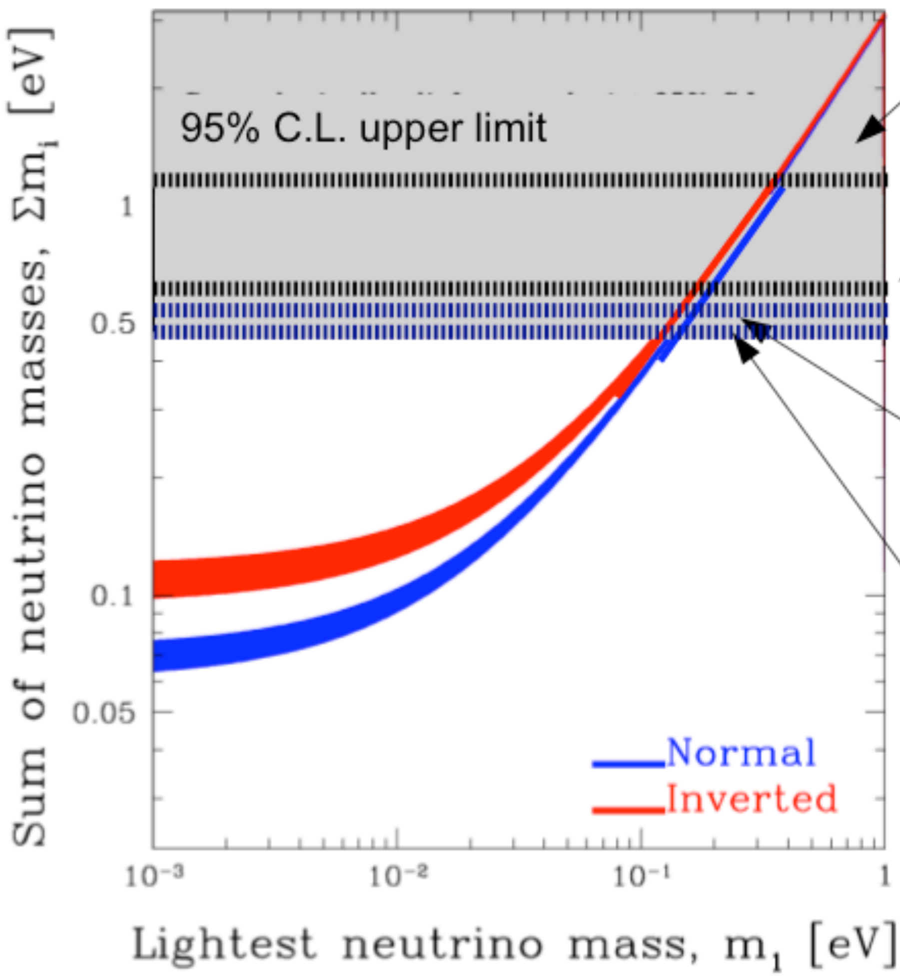
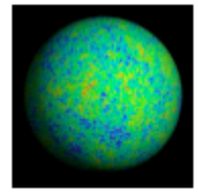
  only 2σ

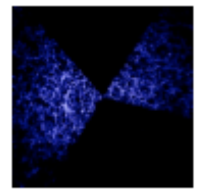
Plus: we don't want a thermal background of 1eV mass sterile neutrinos!

Present status...

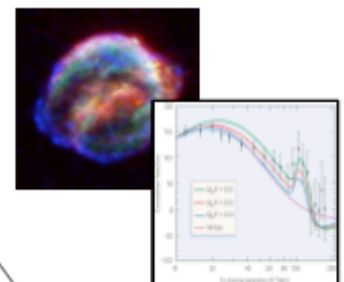




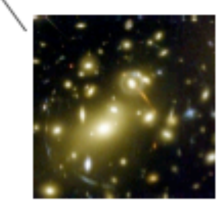
WMAP7 only*
Komatsu et al. 2010



WMAP7+SDSS-HPS *
Hannestad, Mirizzi, Raffelt & Y^{3}W 2010



WMAP5+SDSS-HPS +SN+HST
Reid et al. 2009
(extended models)



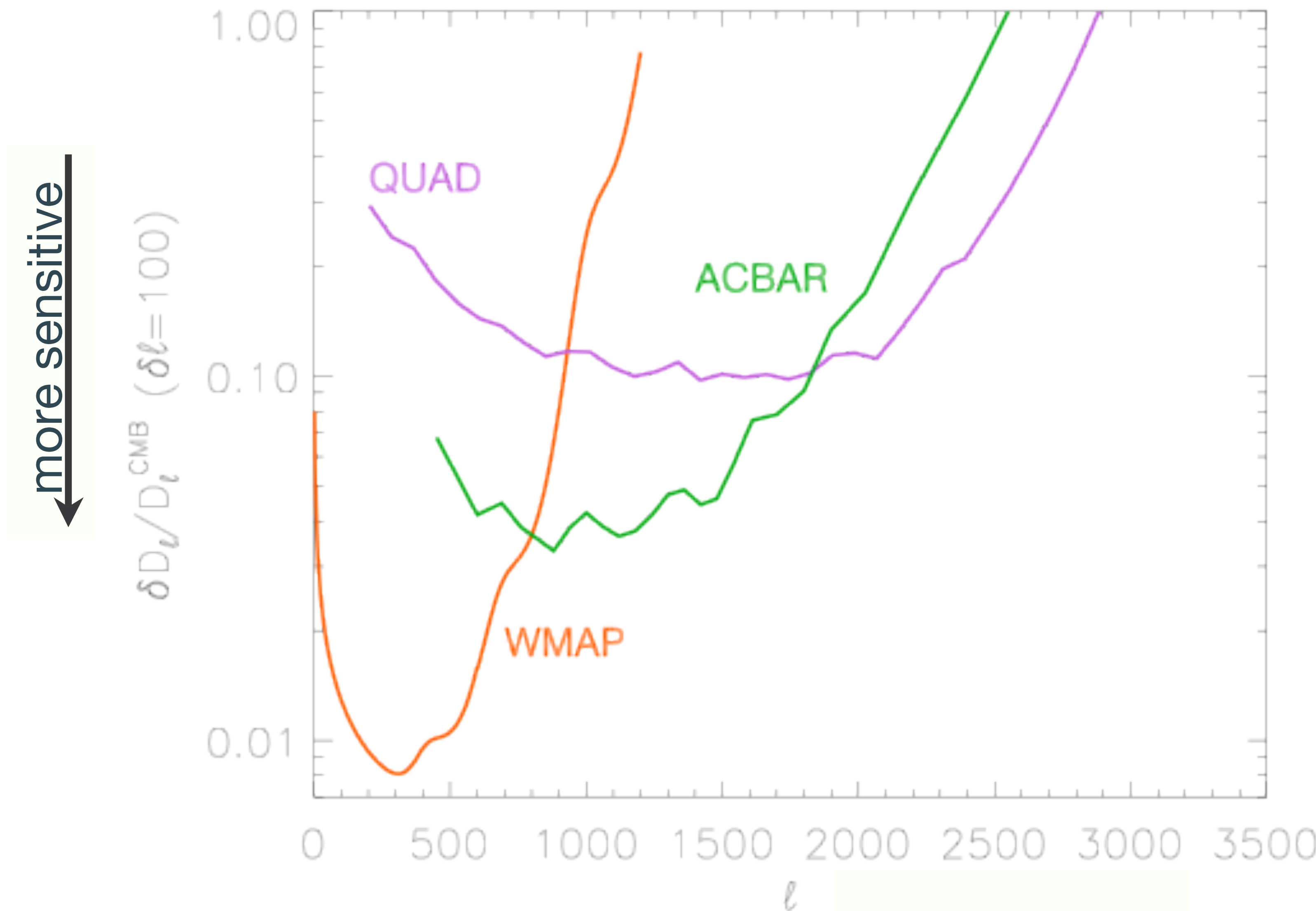
WMAP5+Weak lensing*
Tereno et al. 2008
Ichiki et al. 2008

* ΛCDM+m_ν

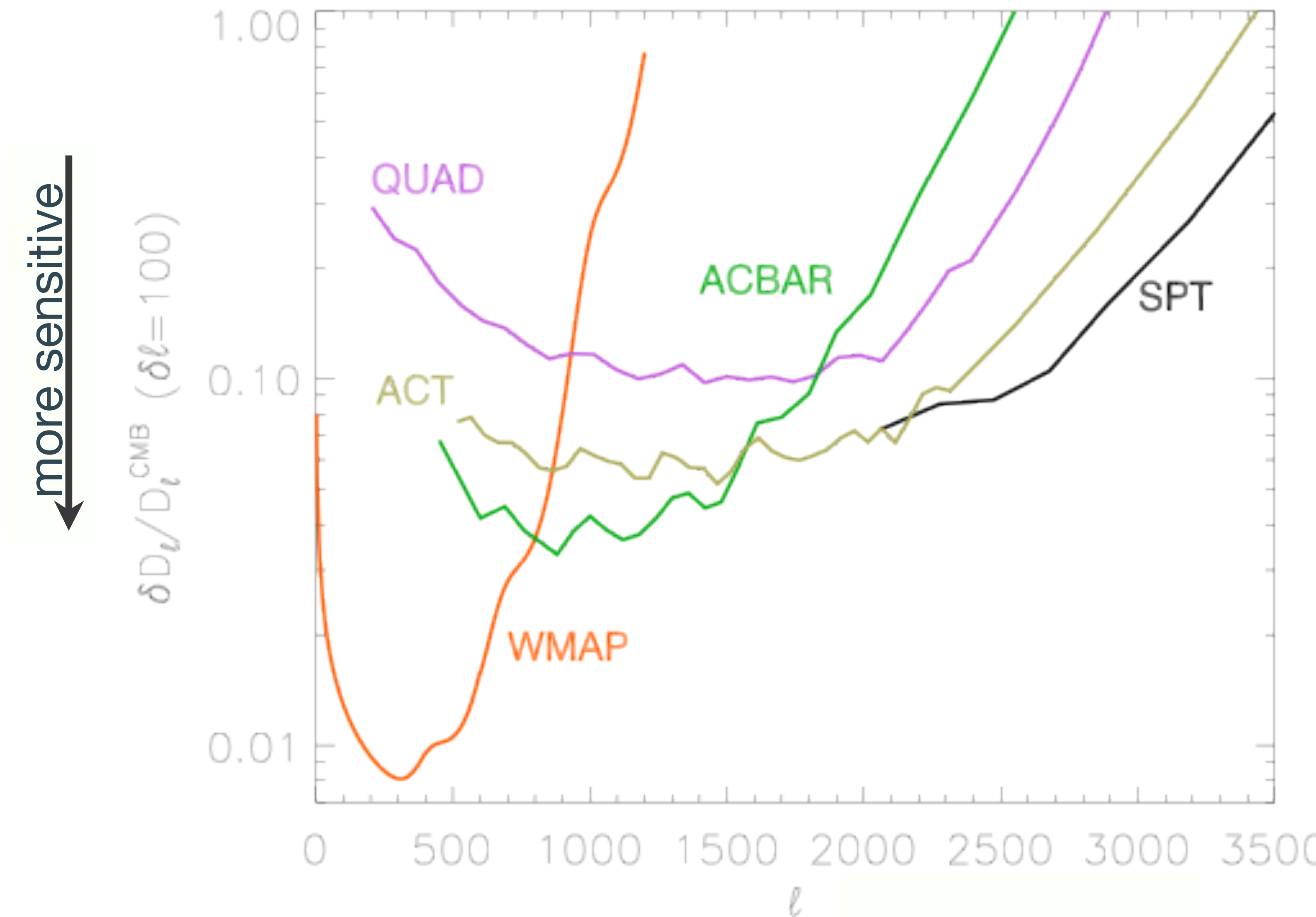
From Yvette Wong's Avignon presentation

The Future

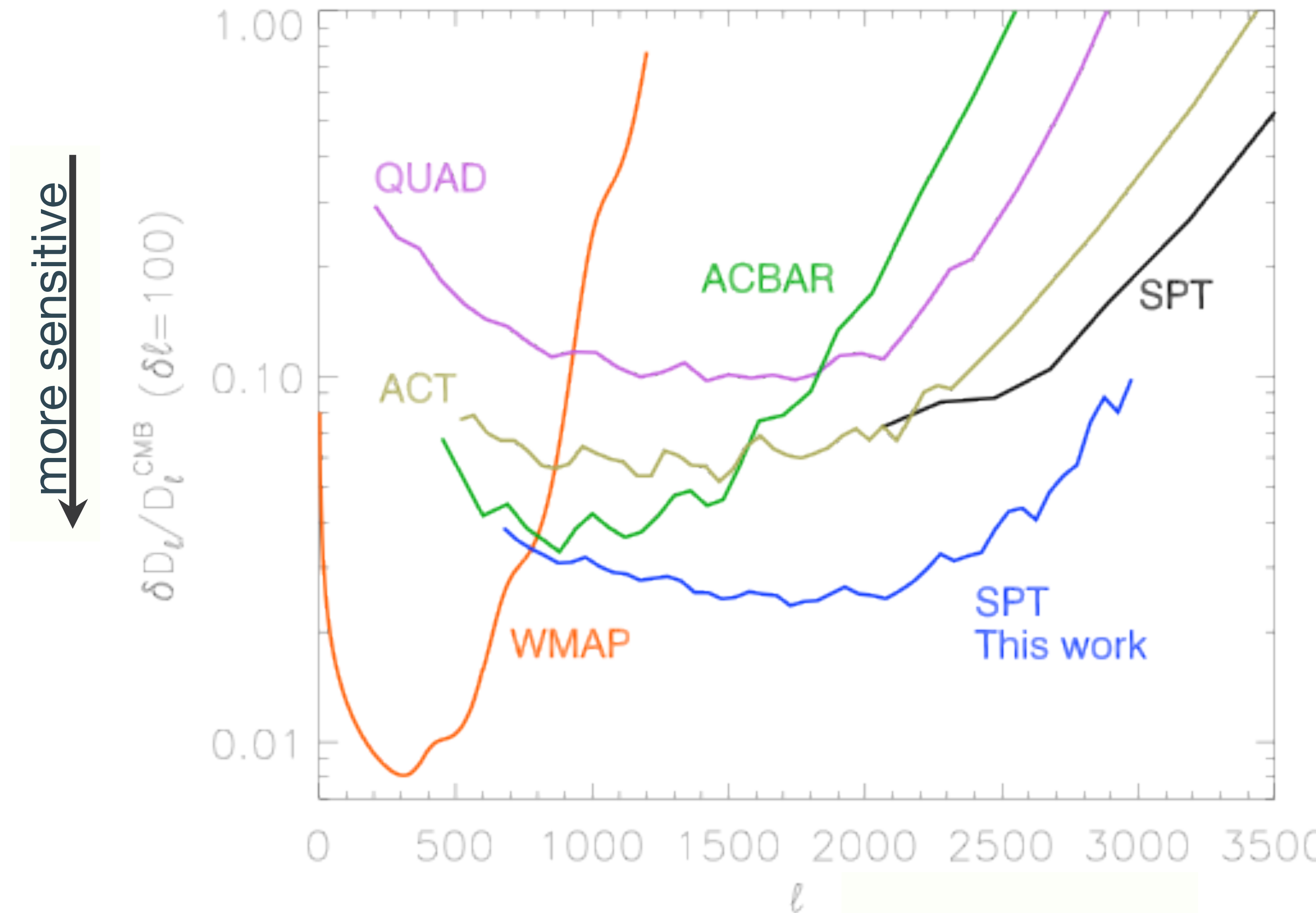
lay of the land



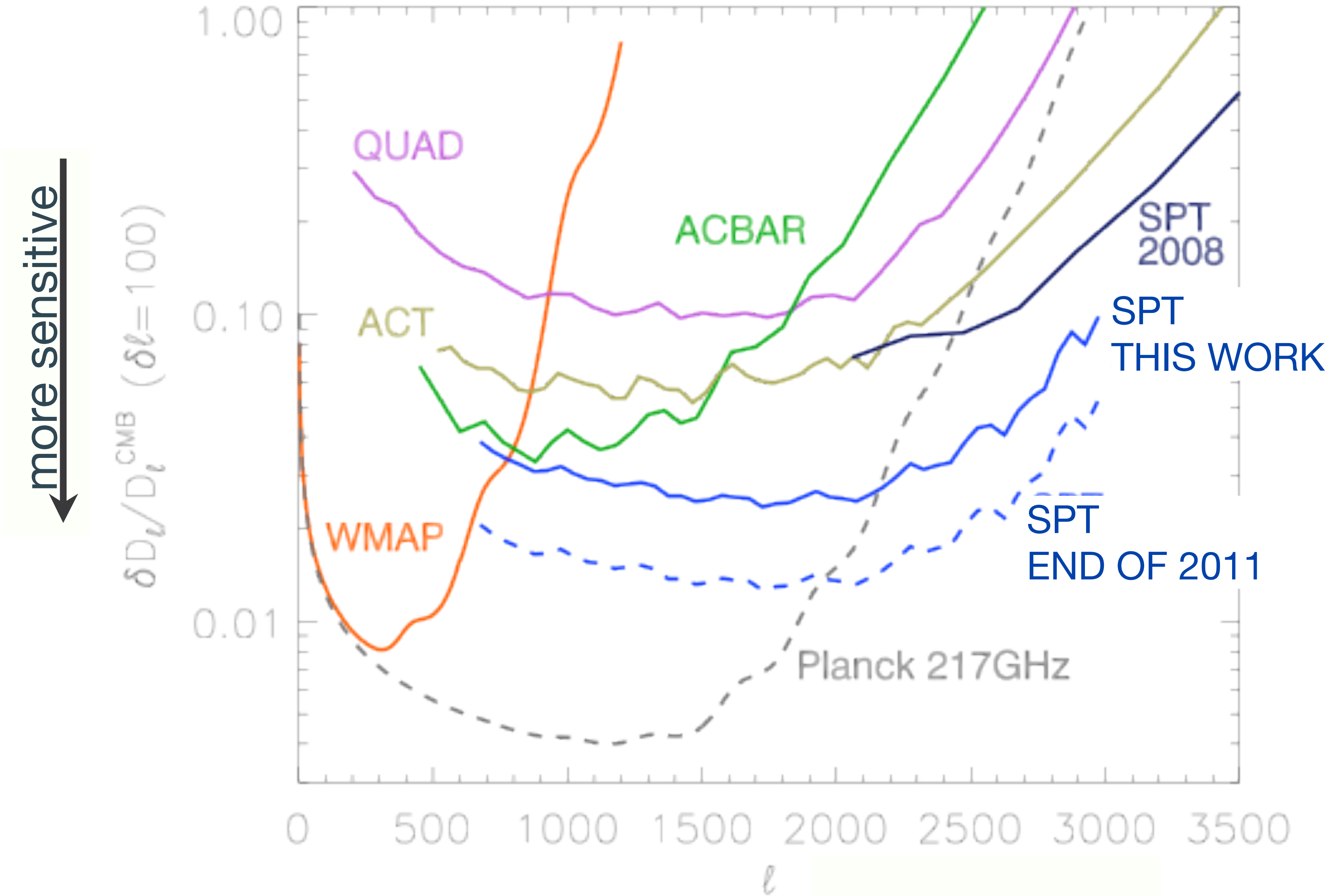
lay of the land



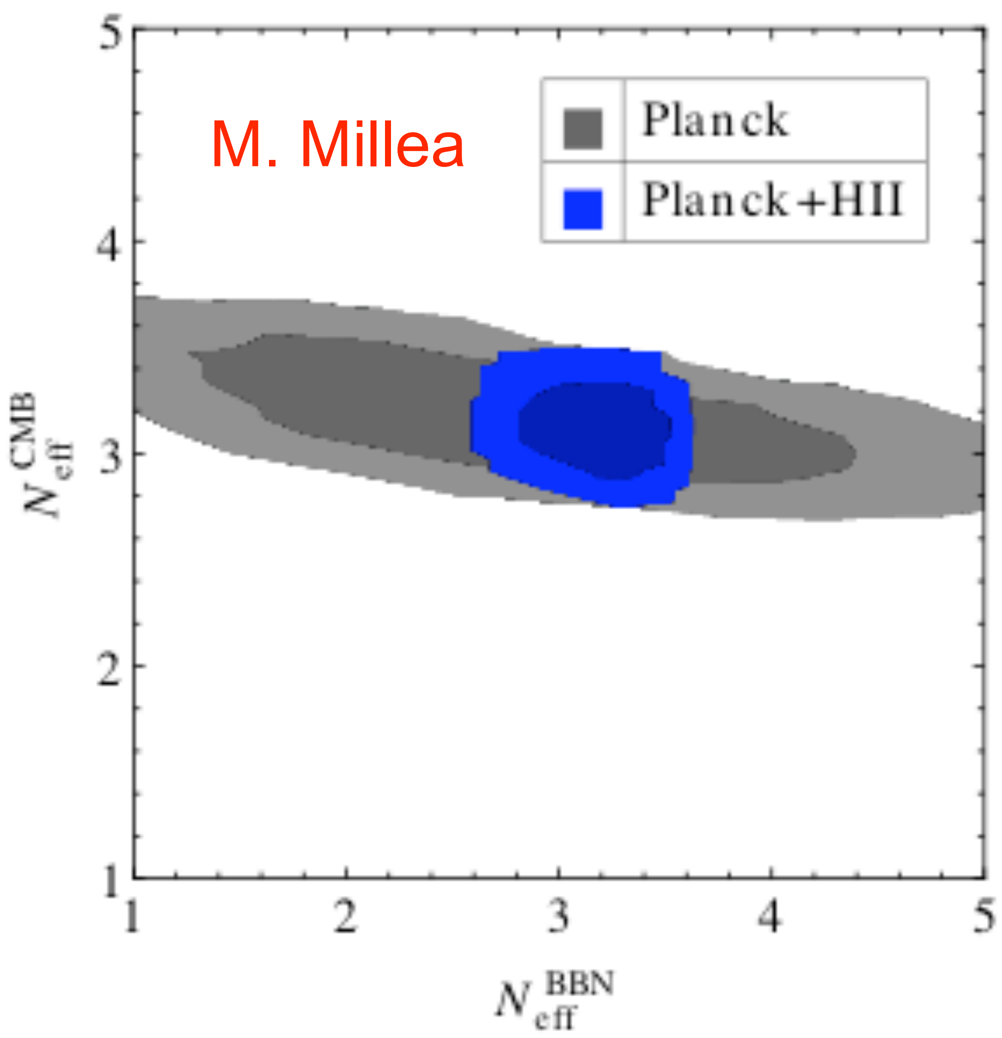
lay of the land



lay of the land



The Future



With better data we can relax assumption that NeffBBN = NeffCMB (so far assumed implicitly throughout this talk).

Forecast for Planck

Forecast for Planck + Y_P measurement with error same size as reported by Izotov & Thuan (2010).

With luck, these will disagree! (e.g. Fischler & Myers (2010)

Summary and Conclusions

- SPT collaboration has measured CMB power spectrum at high resolution from 800 sq. deg.
- Results are consistent with the (very tight) predictions of the standard cosmological model.
- High-resolution observations allow us to probe the third angular scale in the CMB transfer function, which gives us sensitivity to the expansion rate leading up to recombination,as well as Y_P.
- Current data (including lab and reactor) do not paint a compelling picture for additional neutrinos.
- We are hopeful for surprises from Planck.