High-resolution CMB Temperature Anisotropies as a Particle Detector: Are We Detecting (Sterile) Neutrinos?

Lloyd Knox (UC Davis)

Zhen Hou & Marius Millea (UCD)

Ryan Keisler (UC), Christian Reichardt (UCB)

SPT collaboration

Planck collaboration

Review of This Session

- Neal Weiner: Direct Detection

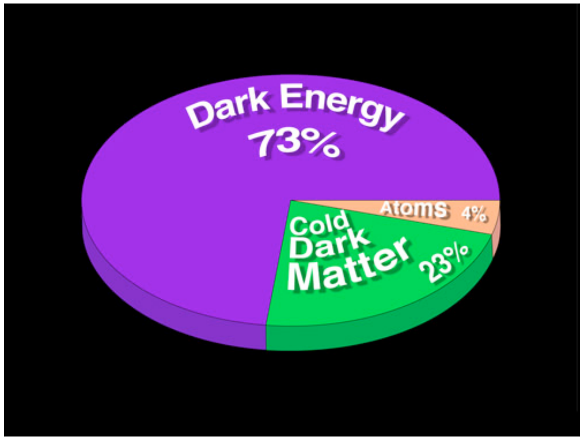
Review of This Session

- Neal Weiner: Direct Detection
- Nicole Bell: Indirect Detection

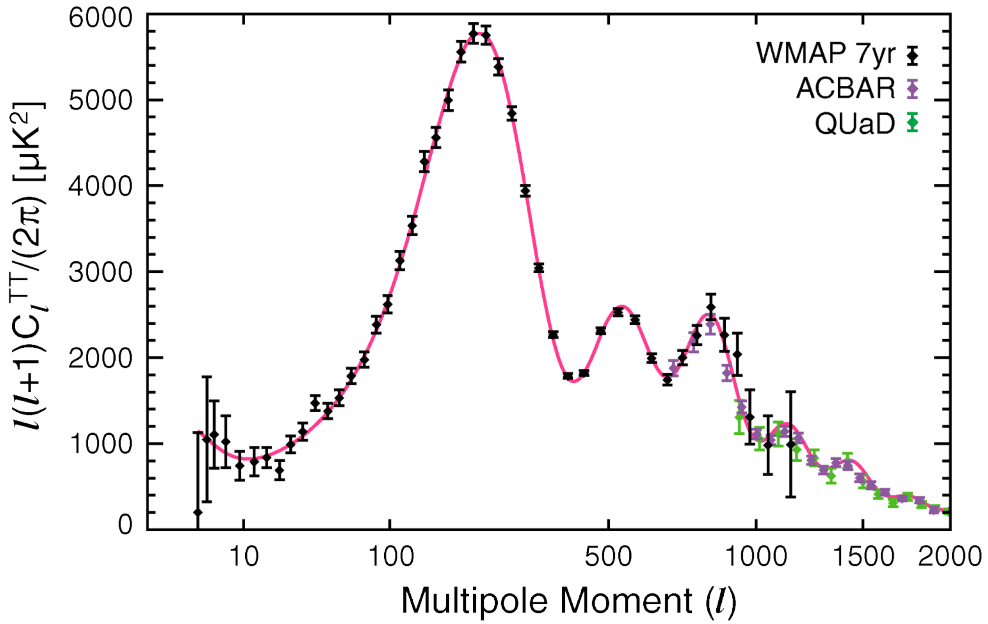
Review of This Session

- Neal Weiner: Direct Detection
- Nicole Bell: Indirect Detection
- Lloyd Knox: Really Indirect Detection (of dark stuff)

CMB is a well-calibrated detector



Contents of Universe*



Theory-observation agreement quite striking.

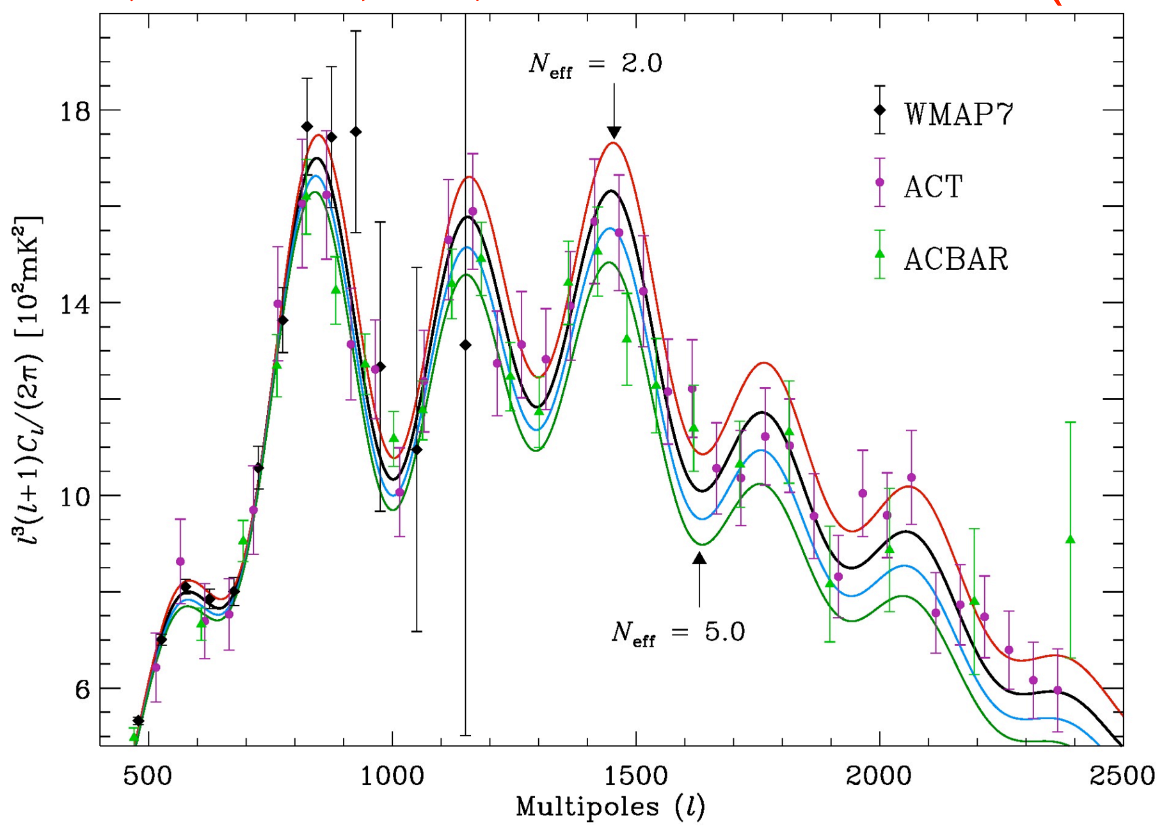
Confirmation and increased precision, but no surprises.

*contains trace amounts of nuts

Surprises may come at higher resolution

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

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



Extra neutrino species?

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

New results soon from SPT and ACT shrinking errors by ~3.

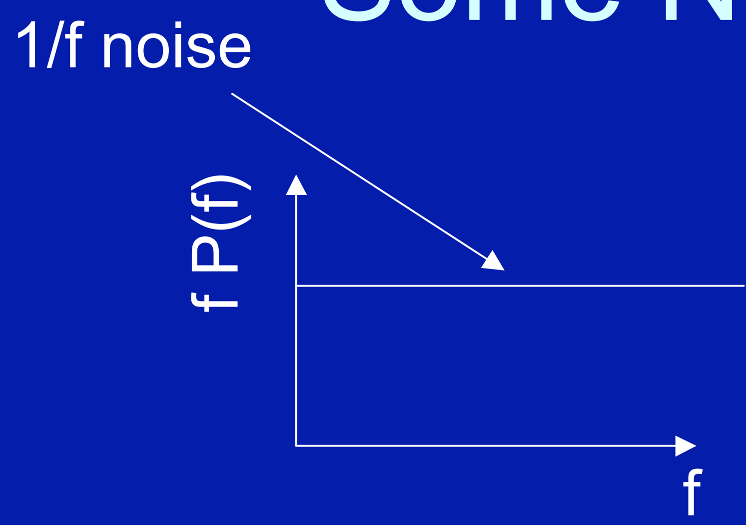
Planck in ~Jan 2013 will shrink errors by a further factor of ~5.

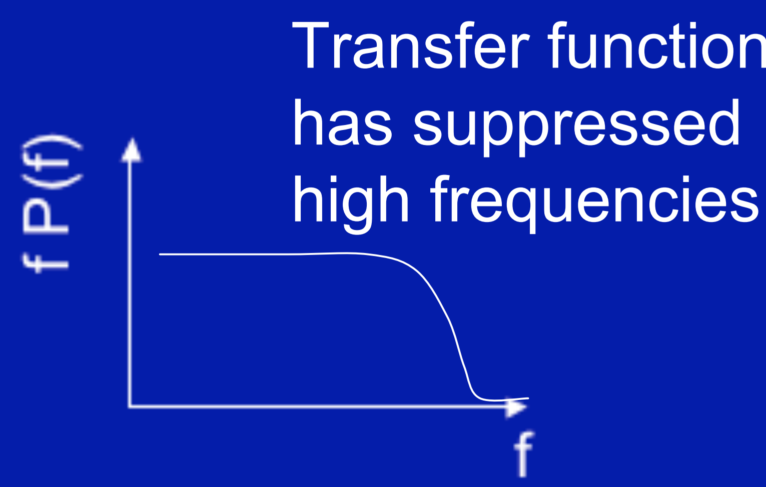
Outline

- CMB as a detector of a stochastic process
- The stochastic process (inflation)
- Review of BBN and neutrinos
- Impact of extra neutrinos on the detector's (CMB's) transfer function
- Relation to other evidence for extra (sterile) neutrinos
- Discriminating changes to the stochastic process, from changes to the transfer function

The CMB is Like a Detector of Some Noise Source

detector



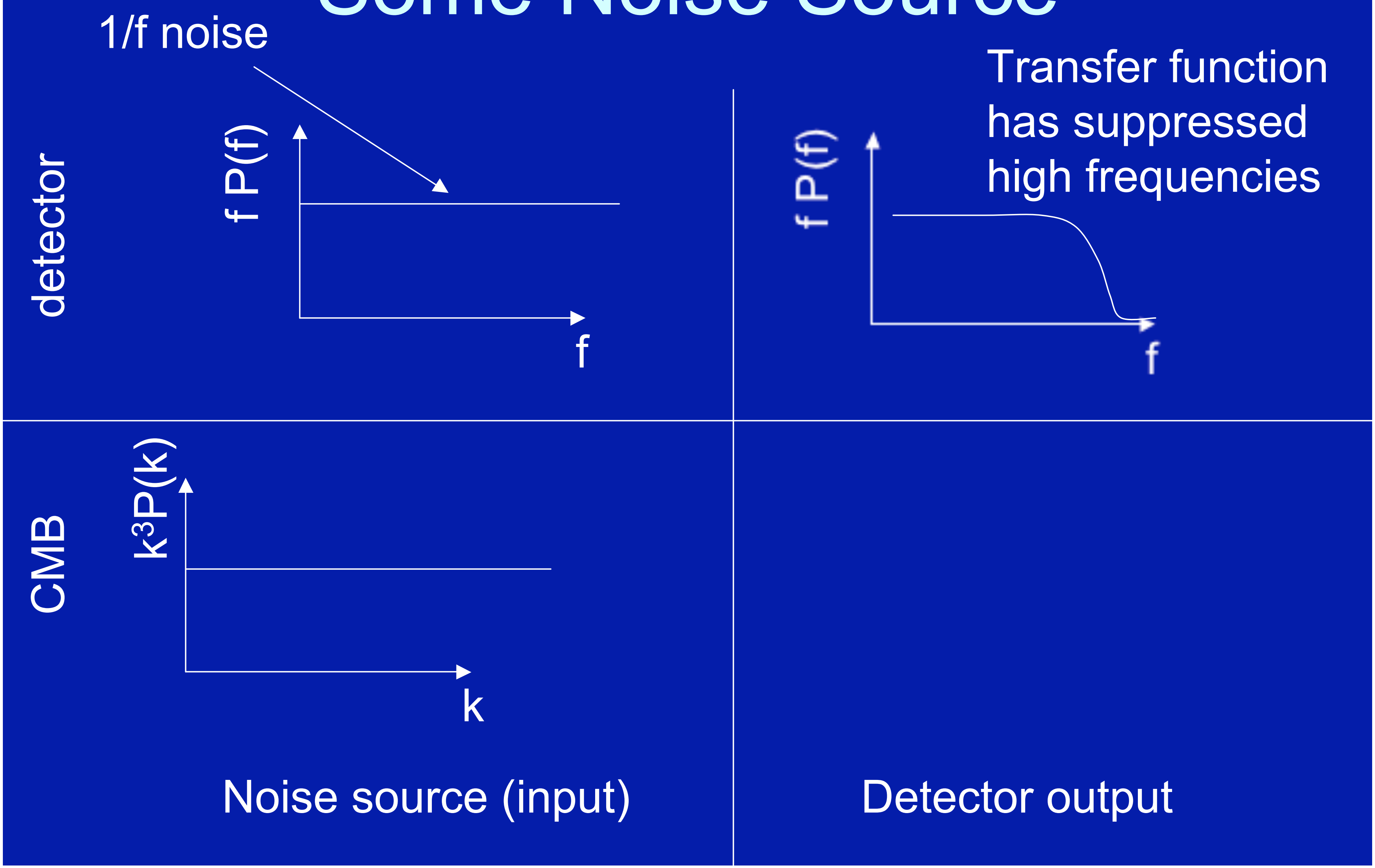


CMB

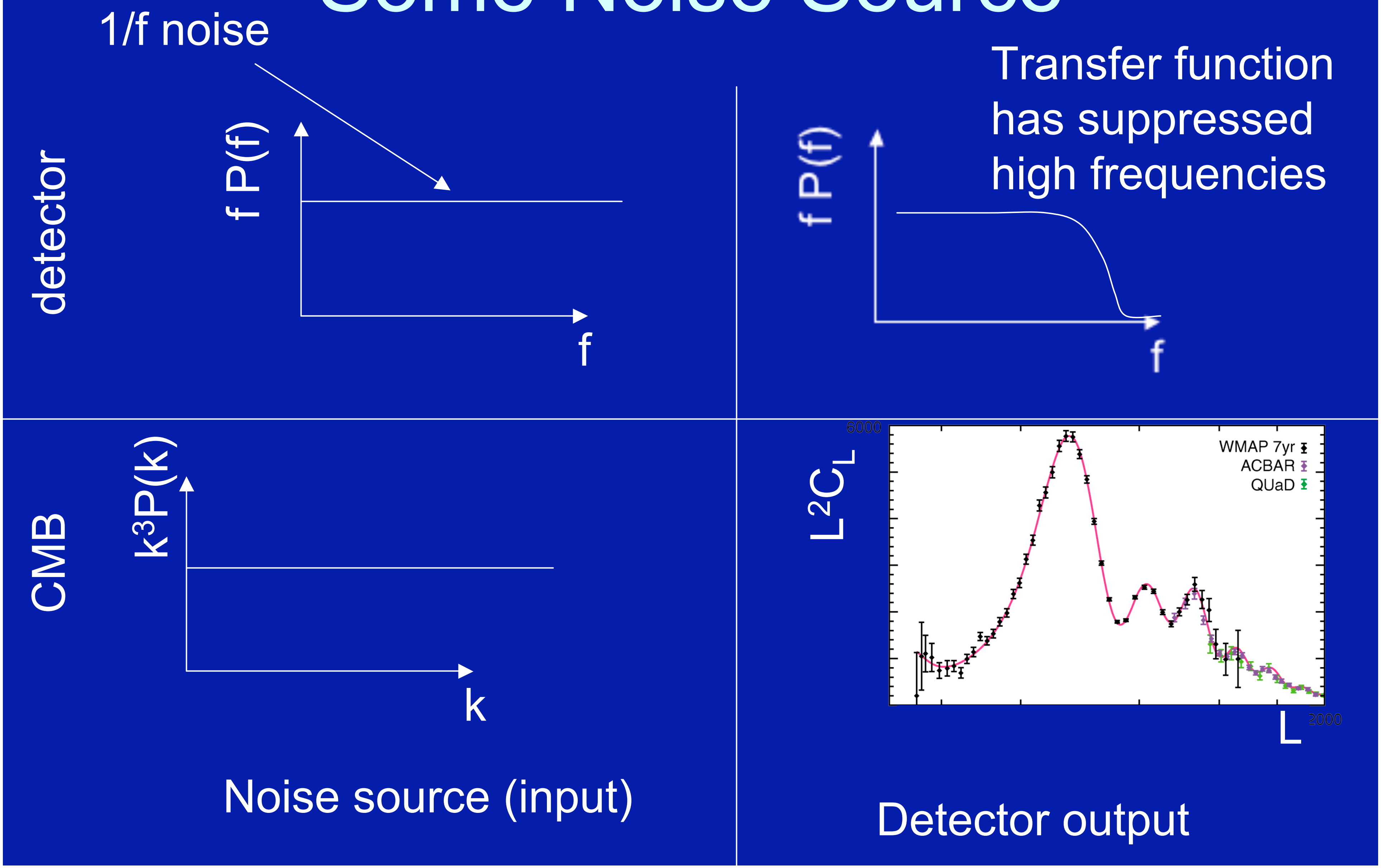
Noise source (input)

Detector output

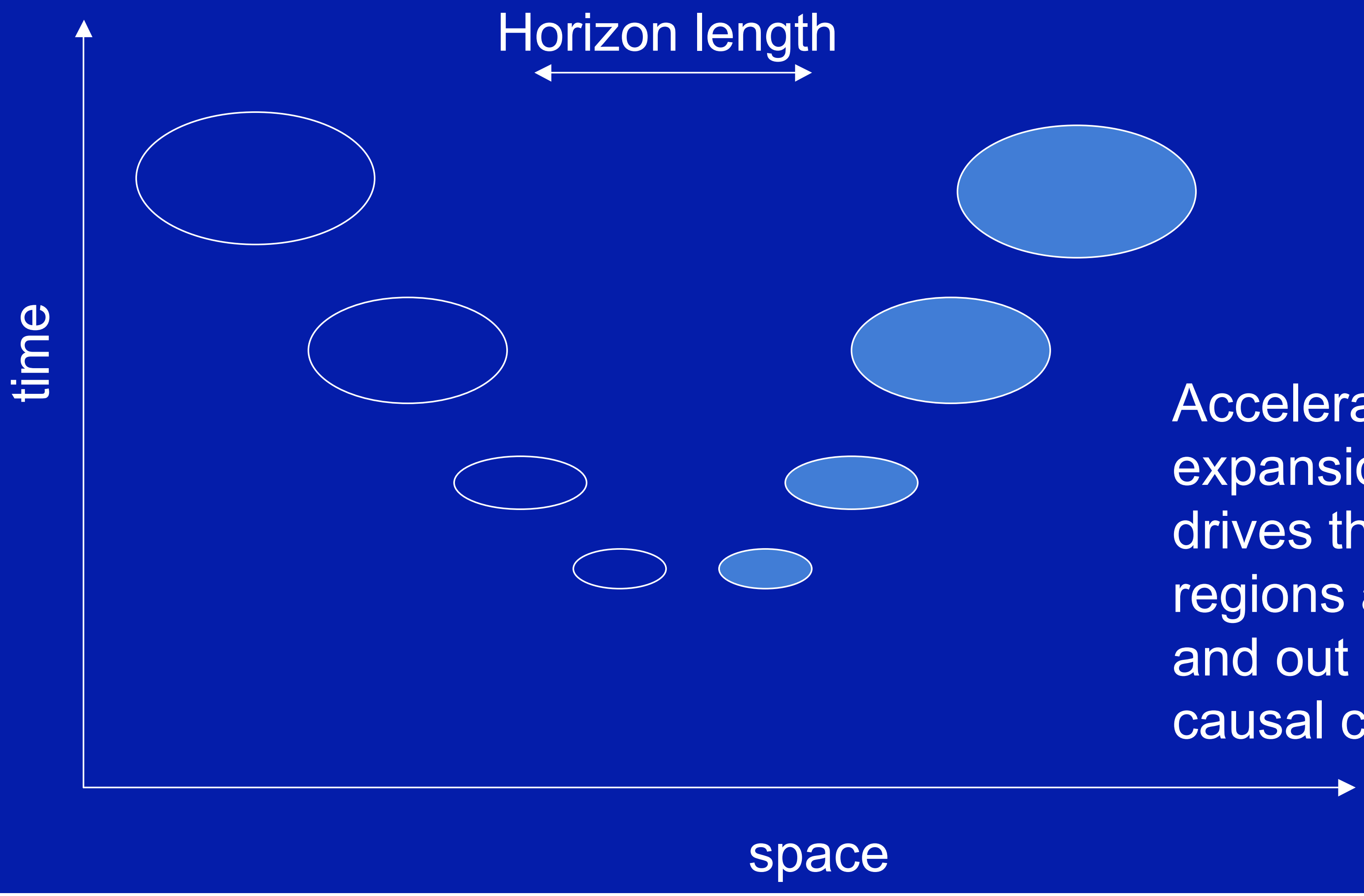
The CMB is Like a Detector of Some Noise Source



The CMB is Like a Detector of Some Noise Source

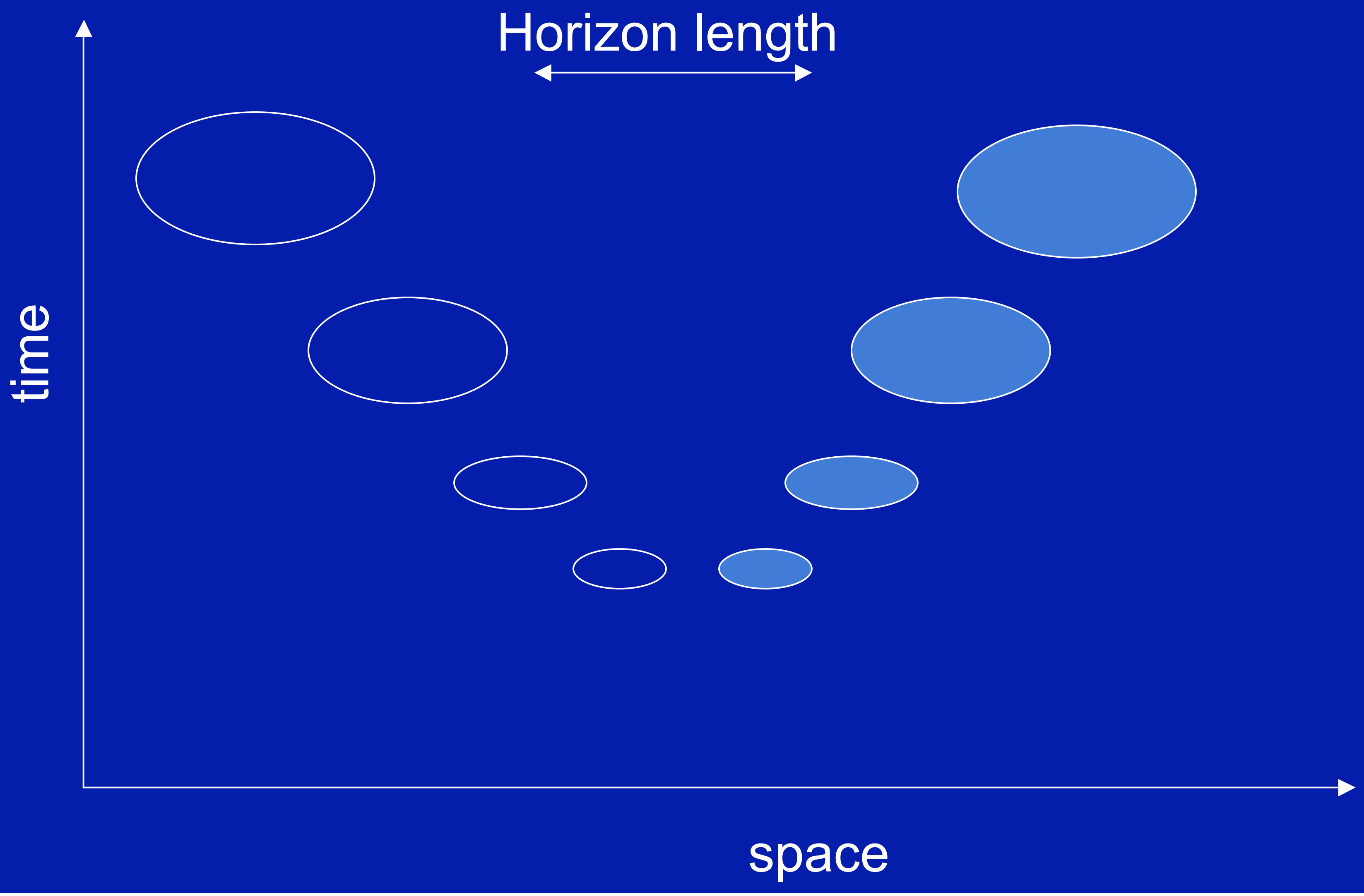


Expansion prevents quantum fluctuation from becoming undone



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

Smaller-scale perturbations are made later

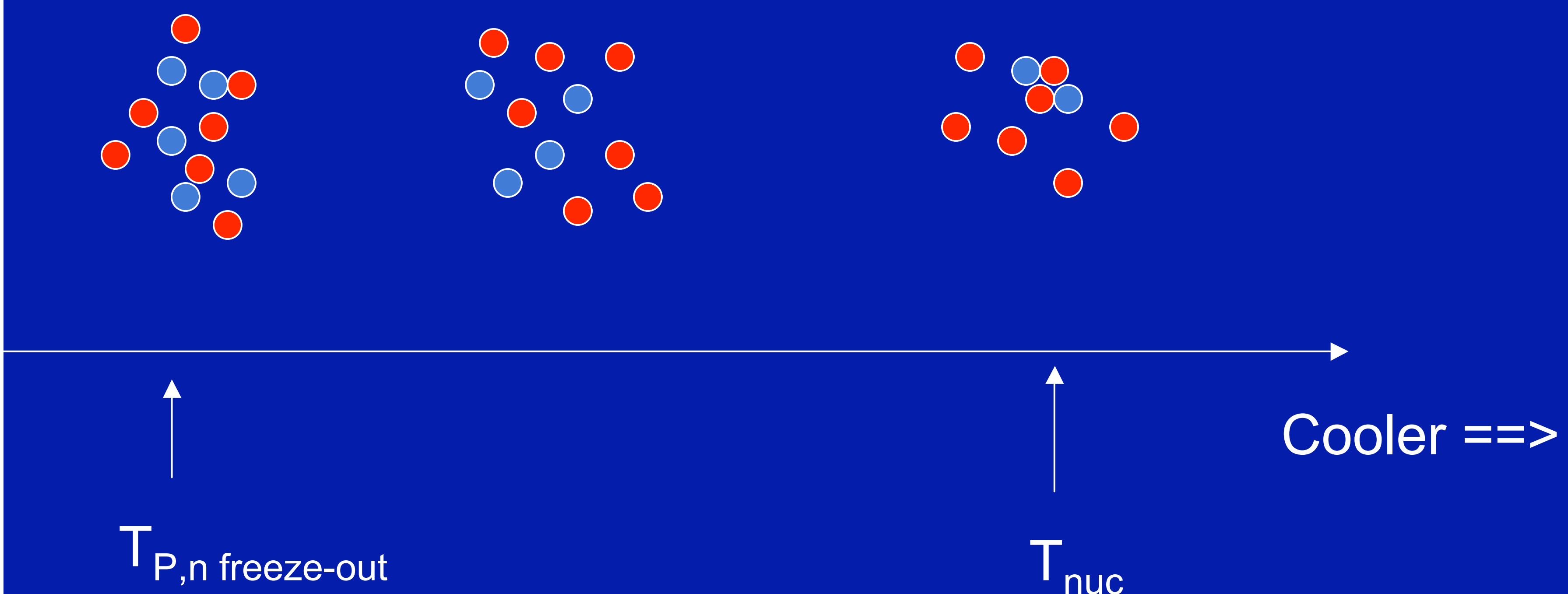


Smaller-scale perturbations are made later

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

● p
● n

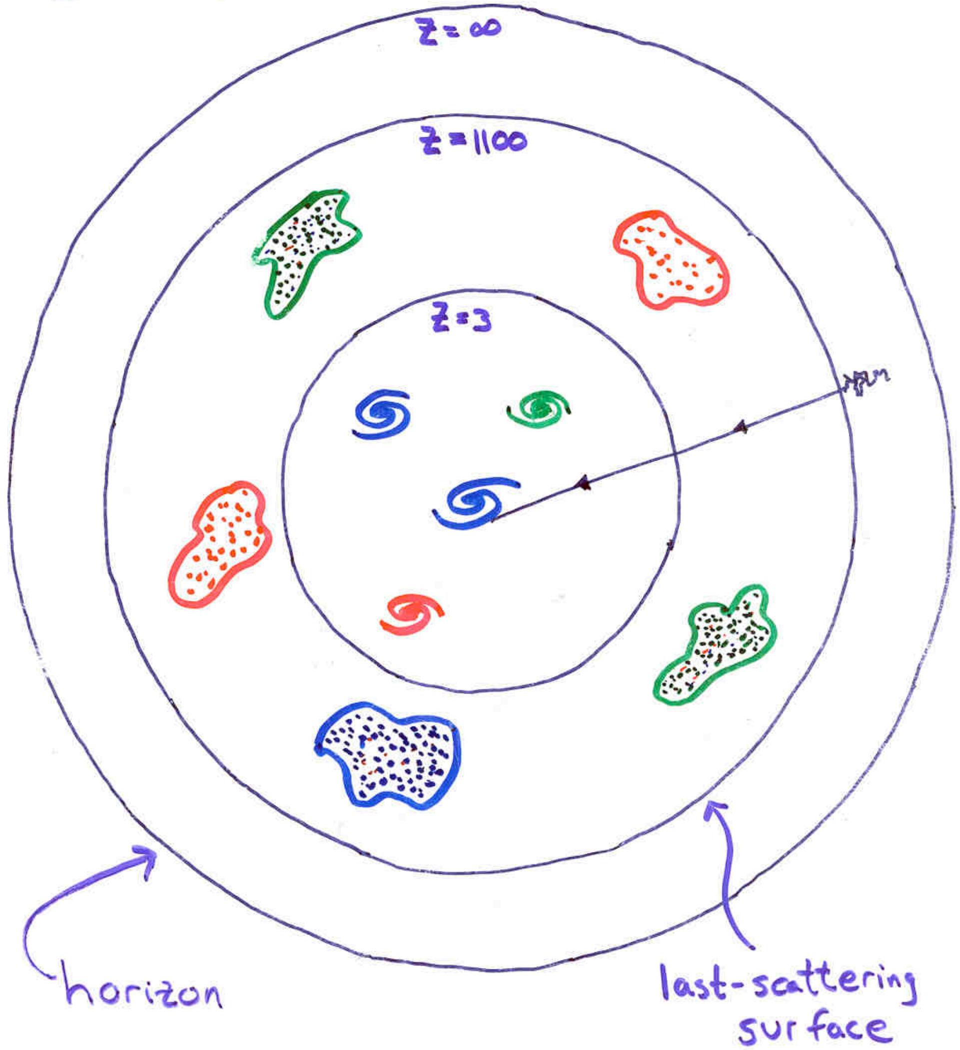
BBN and Y^*_P Review



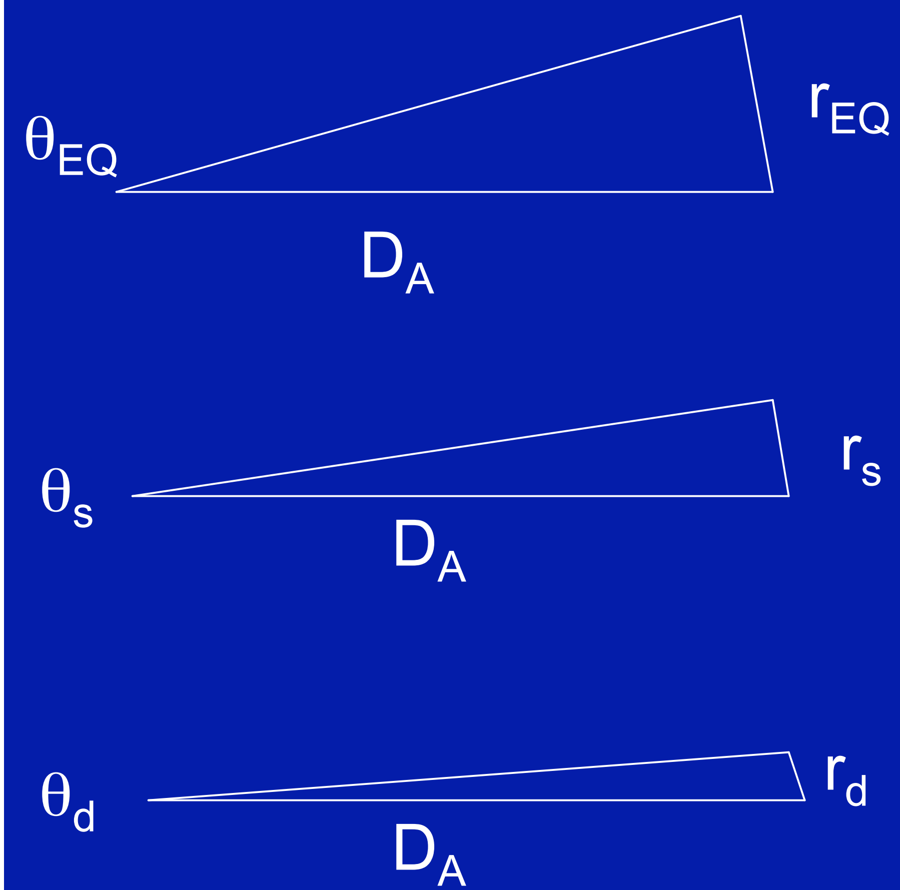
More ν species ==> higher H (at given T) ==> less time to cool to T_{nuc} ==> fewer decays ==> more Helium (also freeze-out n/p ratio increases with H)

*Fraction of baryonic mass in Helium

THE HISTORY OF A SINGLE PHOTON



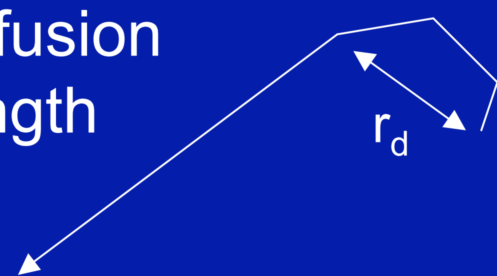
Three Scales in the CMB Transfer Function



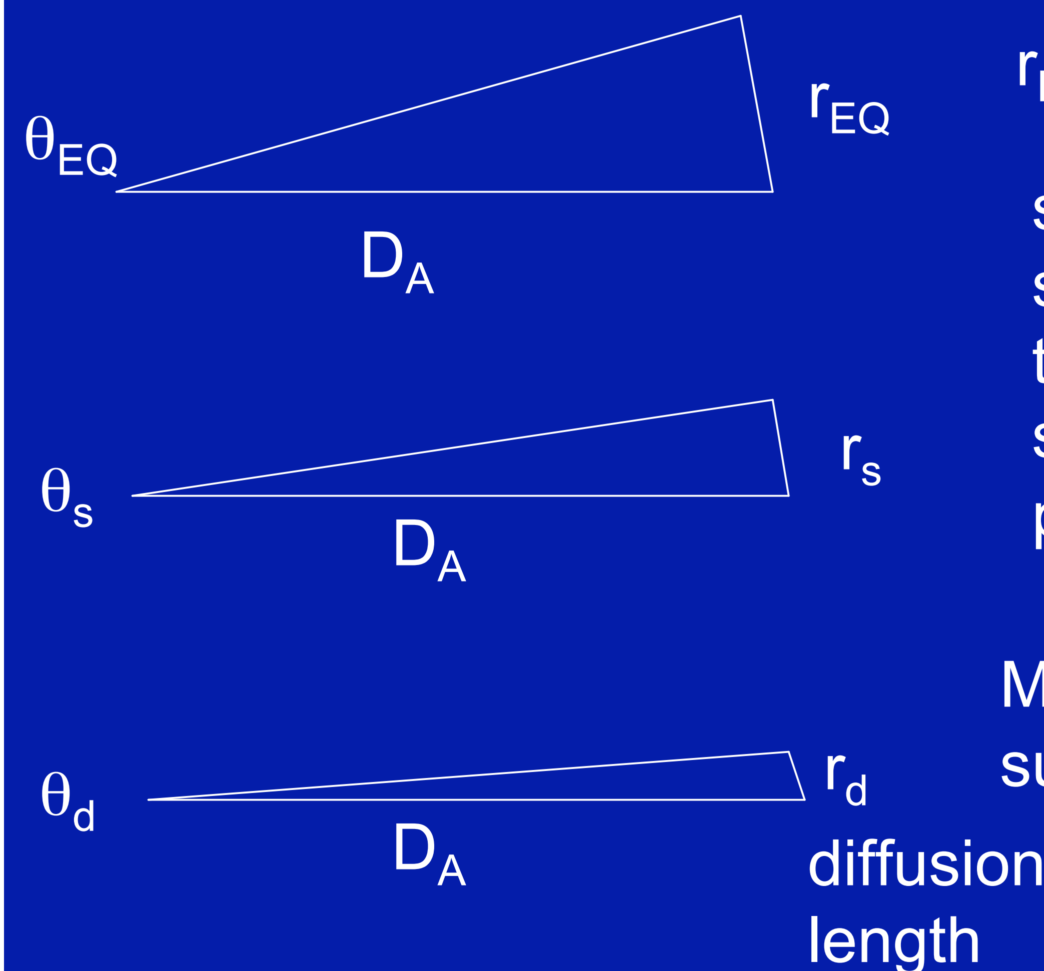
r_{EQ} included for completeness

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

diffusion length



Three Scales in the CMB Transfer Function



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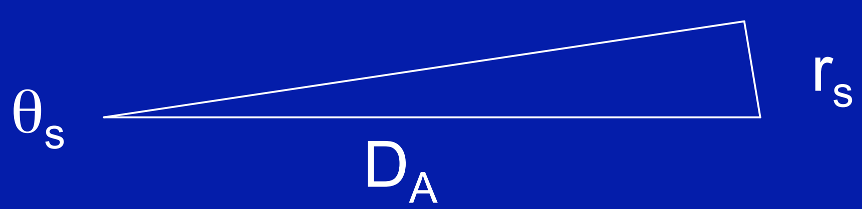
sound horizon: distance sound could travel by the time of last scattering. θ_s controls peak locations.

Modes with $\lambda < r_d$ are suppressed

Silk damping

Three Scales in the CMB Transfer Function

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



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

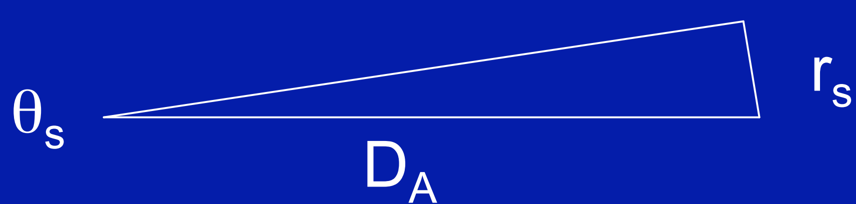
$r_s \ \alpha \ 1/H$

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

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

Effect of extra ν on r_s

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



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

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

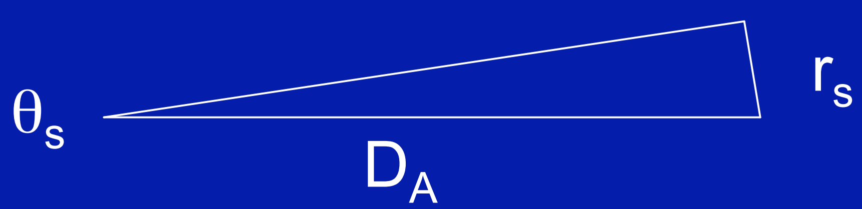
If we knew D_A we could find $r_s = \theta_s D_A$ and determine H

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

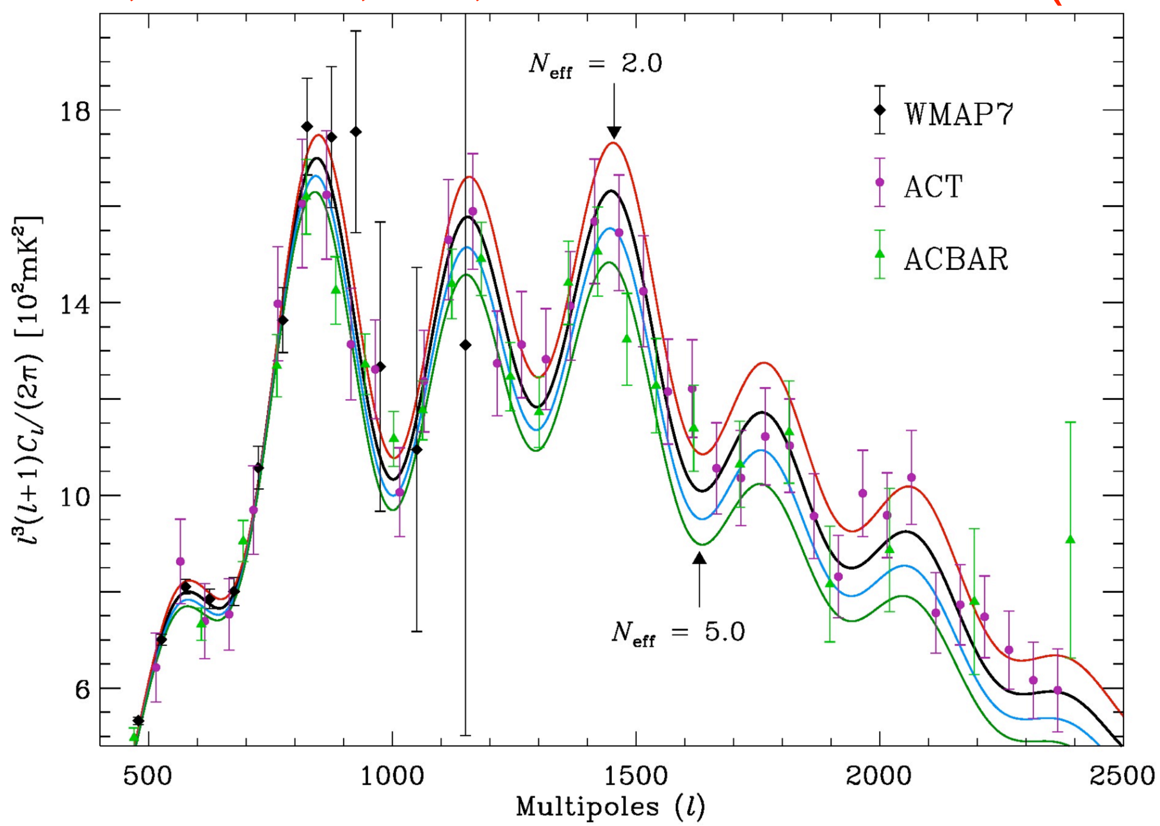
Modes with $\lambda < r_d$ are suppressed

Silk damping

Surprises may come at higher resolution

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

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

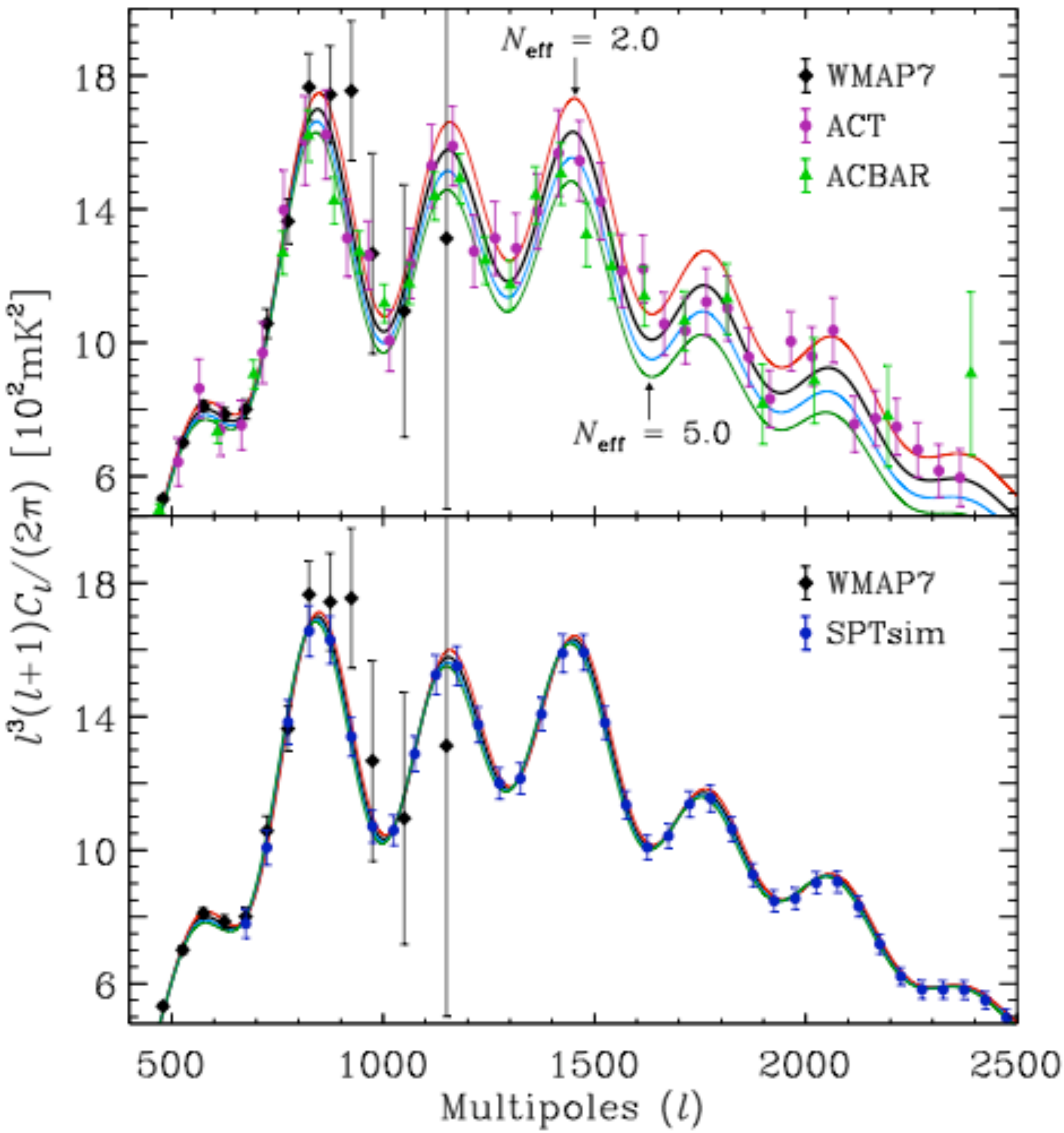


Extra neutrino species?

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.



Same models but with θ_d fixed as well.

The effect is indeed due to change to θ_d

Bashinsky & Seljak (2004)

Extra Cosmological Neutrinos? Arguments For

- 98.4% confidence that Neff > standard model value of 3.046
- Oscillation evidence for sterile neutrinos from mini-Boone / LSND
- Oscillation to sterile neutrinos can explain reactor anomalies too.
- 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)

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

Journal-ref: Phys.Rev.Lett.105:181301,2010

Subjects: **High Energy Physics - Phenomenology (hep-ph)**; Cosmology and Extragalactic Astrophysics (astro-ph.CO)

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Phys. Rev. Lett. 105, 181301 (2010) [4 pages]

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

Abstract	References	Citing Articles (10)

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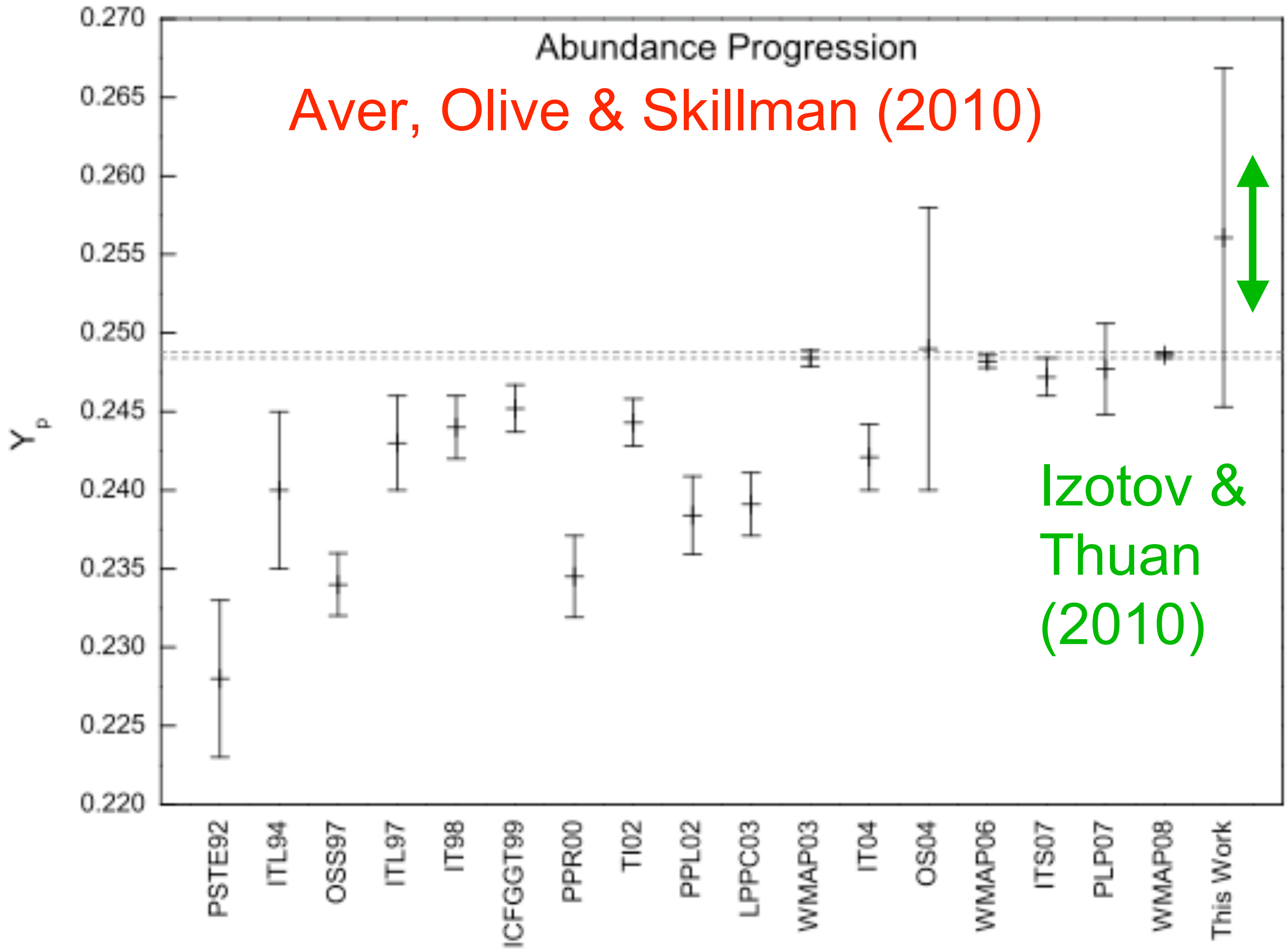
Jan Hamann[1], Steen Hannestad[1], Georg G. Raffelt[2], Irene Tamborra[2,3,4], and Yvonne Y. Y. Wong[5]

Y_P Measurements



From extragalactic regions of ionized low-metallicity gas

(except for WMAP points)

Extra Neutrinos ? Arguments against

1) There are other solutions to the damping tail power deficit

- Statistical fluke
- Increasing Y_P (btw, that's how we kept θ_d fixed)
- Primordial power spectrum ($dn_s/d\ln k$ non-zero)

Extra Neutrinos ?
Arguments against

1) There are other solutions to the damping tail power deficit
   - Statistical fluke
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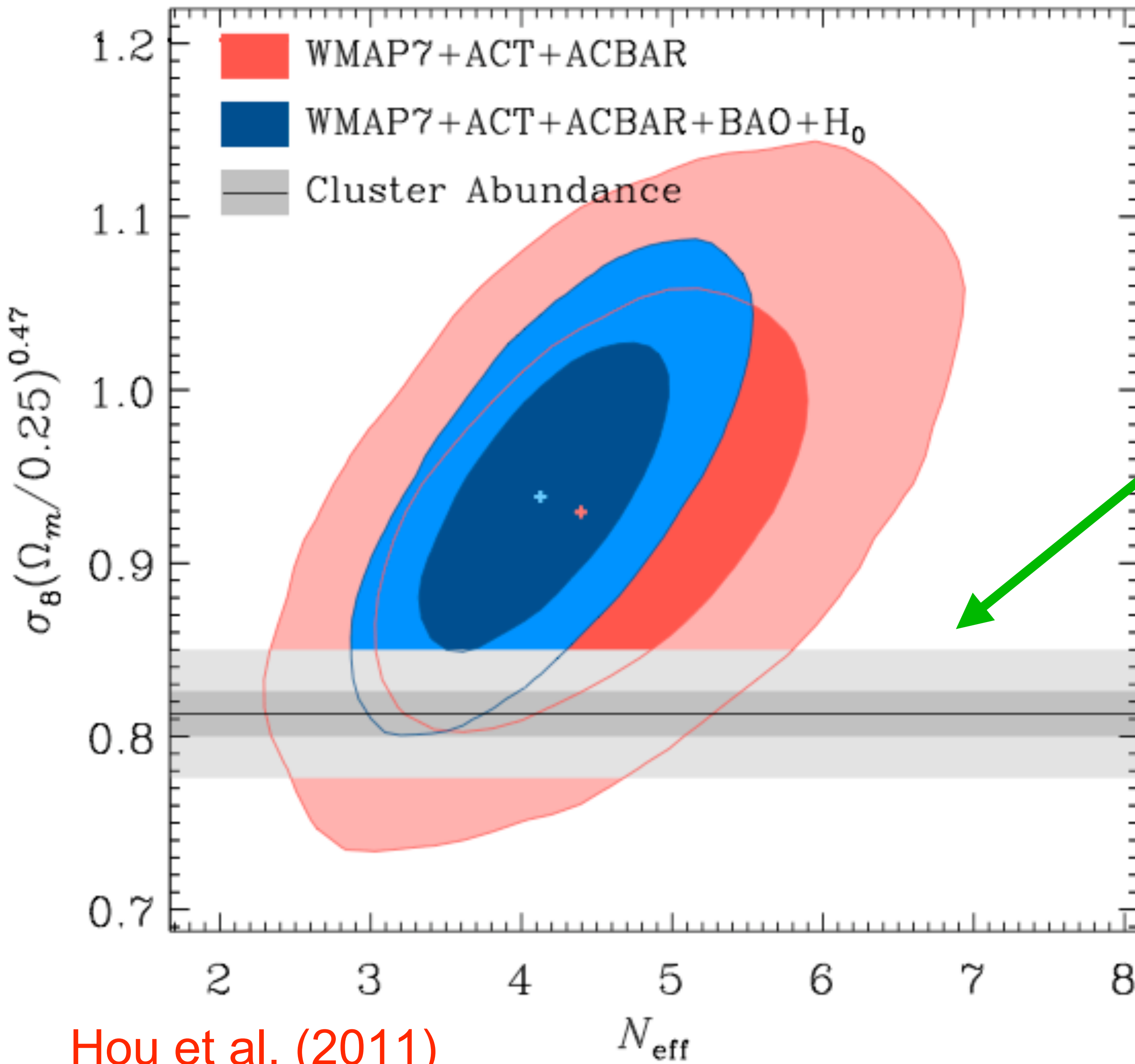
   - Primordial power spectrum ($dn_s/d\ln k$ non-zero)

2) They lead to too many galaxy clusters.



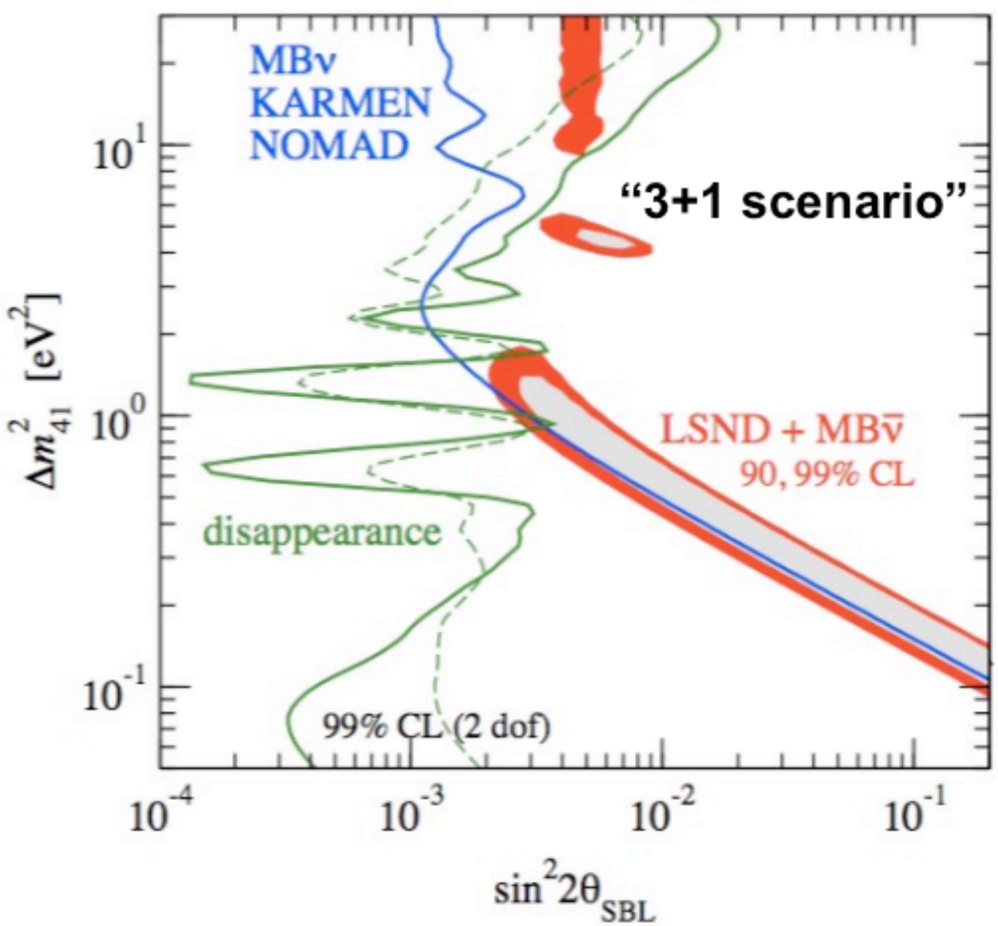
Hou et al. (2011)

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

Extra Neutrinos ? Arguments against

1) There are other solutions to the damping tail power deficit
   - Statistical fluke
   - Increasing Y_P (btw, that's how we kept θ_d fixed)
   - Primordial power spectrum ($dn_s/d\ln k$ non-zero)
2) They lead to too many galaxy clusters.
3) Laboratory and Reactor neutrino oscillation solutions require ~ 1 eV masses. Too massive. They would cluster on large scales, altering shape of matter power spectrum.

From Yvette Wong's Avignon presentation



Kopp, Maltoni & Schwetz 1103.4570

New reactor fluxes

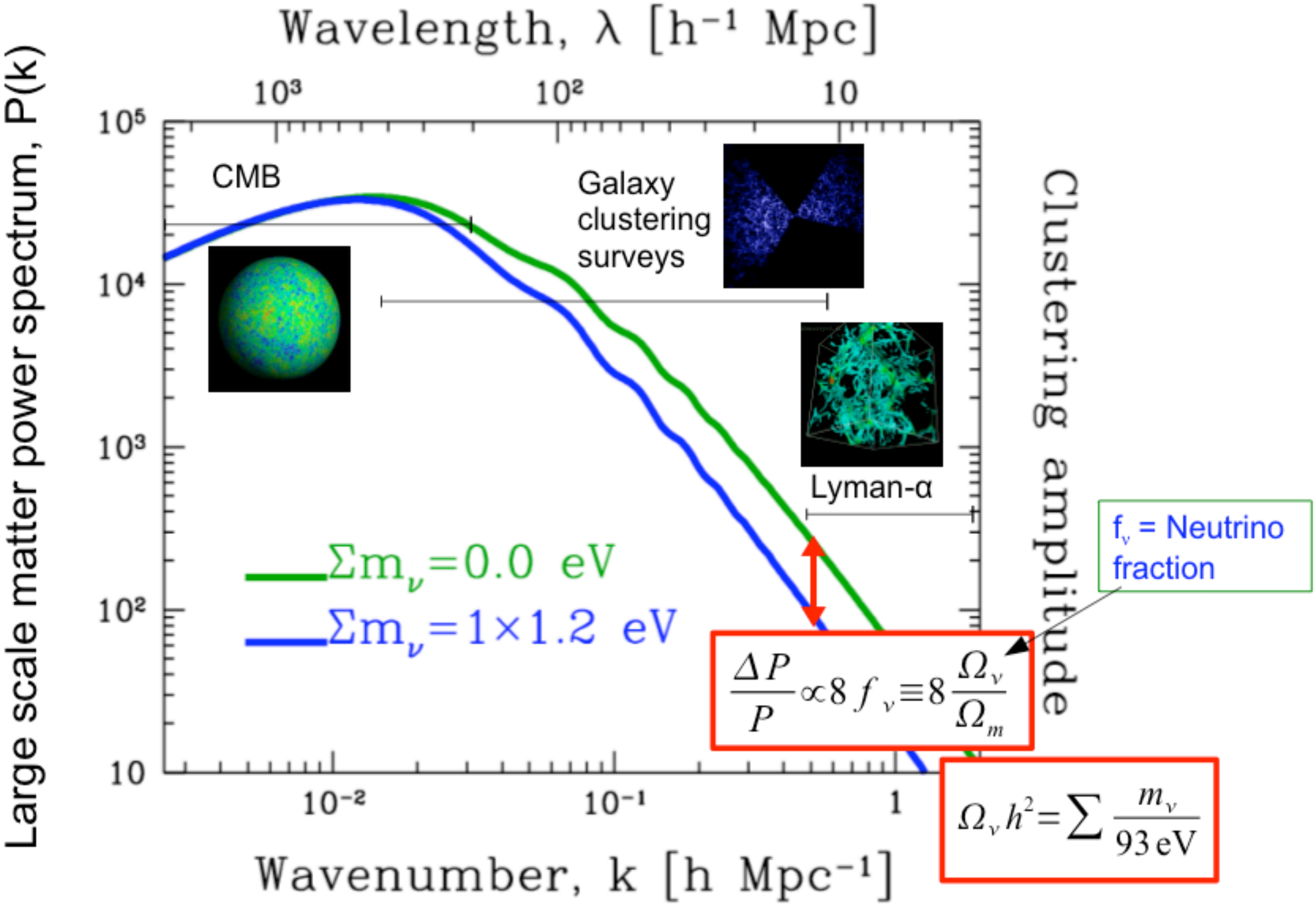
Old reactor fluxes

- Tension between LSND/ MiniBooNE and reactor disappearance experiments.
- New analysis of reactor fluxes finds 3% higher mean flux.
  → disappearance @98.6% confidence (old: 68% CL).
  Mention et al. 1101.2755
- "3+1" best-fit: $\Delta m^2_{41} \sim 1 \ \text{eV}^2$

→ $m_s \sim 1 \ \text{eV}$

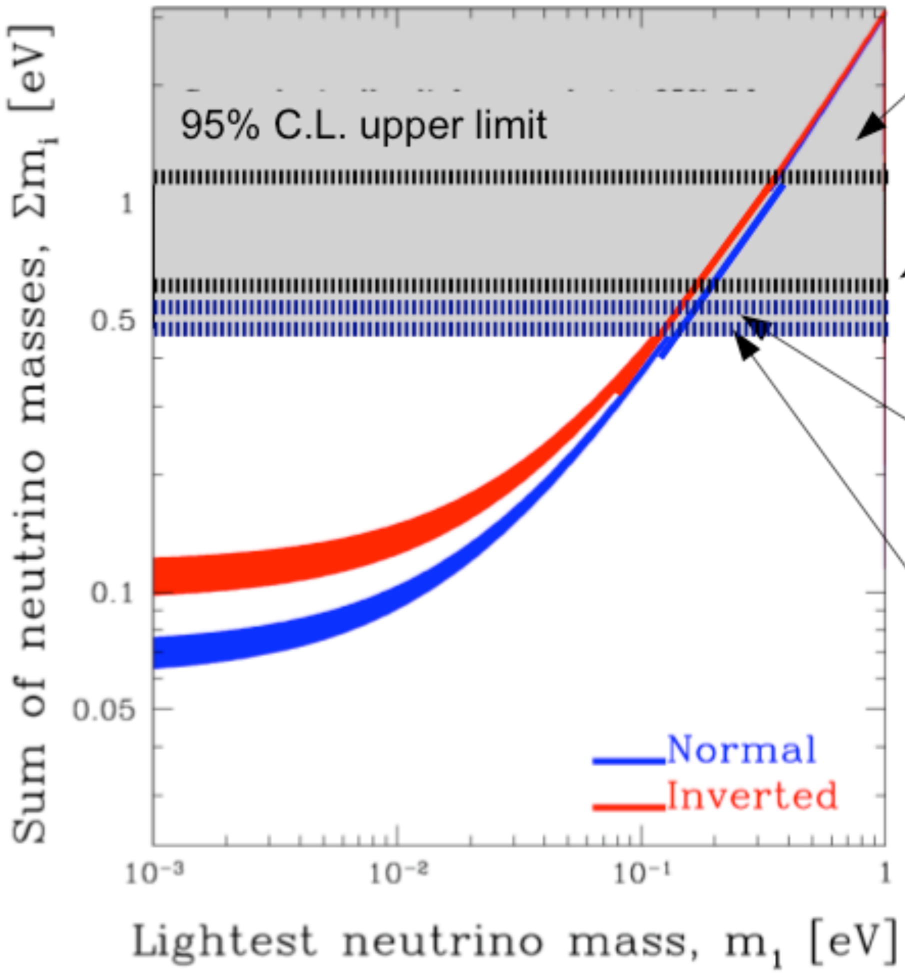
If lightest neutrino mass ~ 0 eV

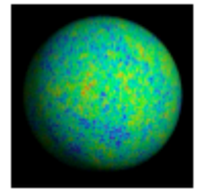
From Yvette Wong’s Avignon presentation



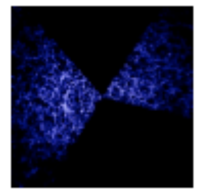
From Yvette Wong's Avignon presentation

Present status...

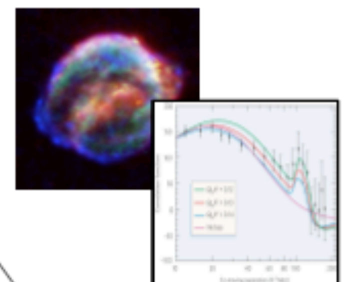




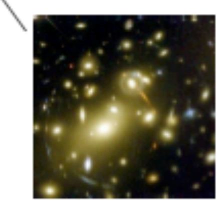
WMAP7 only*
Komatsu et al. 2010



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

So what's going on?

- If there are extra sterile neutrinos (as lab and nuclear experiments indicate), they better not get thermally produced in the early Universe because their masses are too large.
- Lab and nuclear experiments indicate two extra species. Could their be a third sterile neutrino, produced in early U that is massive enough to be the dark matter?

So what's going on?

- If there are extra sterile neutrinos (as lab and nuclear experiments indicate), they better not get thermally produced in the early Universe because their masses are too large.
- Lab and nuclear experiments indicate two extra species. Could their be a third sterile neutrino, produced in early U that is massive enough to be the dark matter?

16. arXiv:0812.3256 [pdf, ps, other]

Realistic sterile neutrino dark matter with keV mass does not contradict cosmological bounds

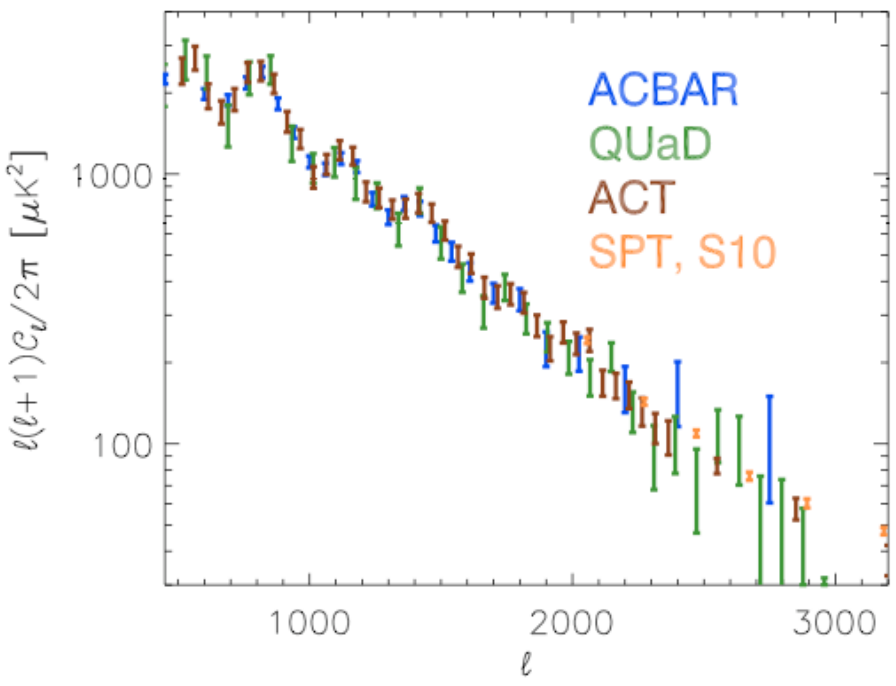
Alexey Boyarsky, Julien Lesgourgues, Oleg Ruchayskiy, Matteo Viel

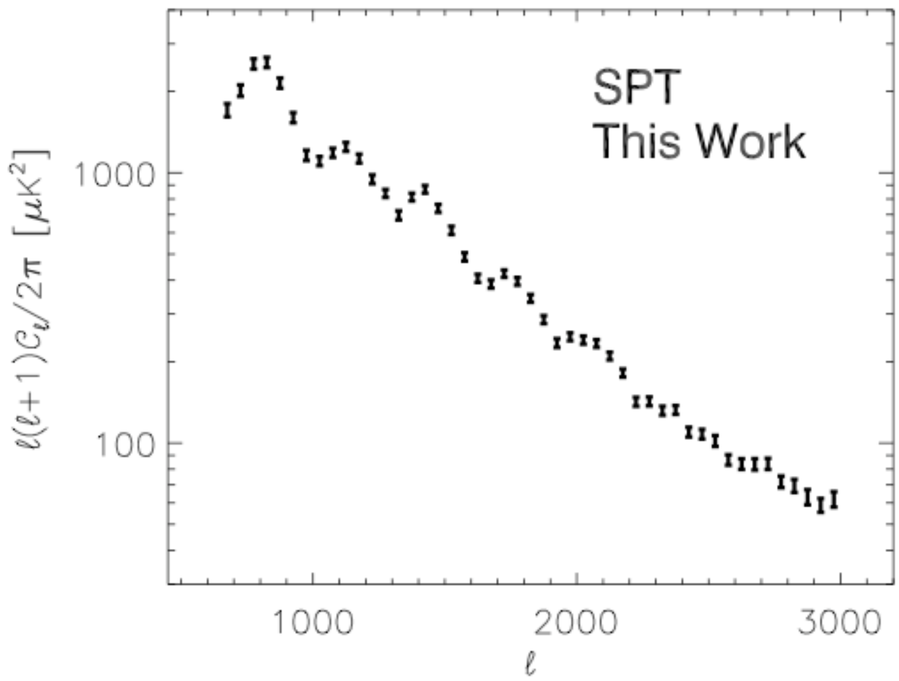
Comments: 4 pages, 4 figures

Journal-ref: Phys.Rev.Lett.102:201304,2009

Subjects: **High Energy Physics - Phenomenology (hep-ph)**; Astrophysics (astro-ph)

Advertisement for Keisler et al. (SPT, in prep)

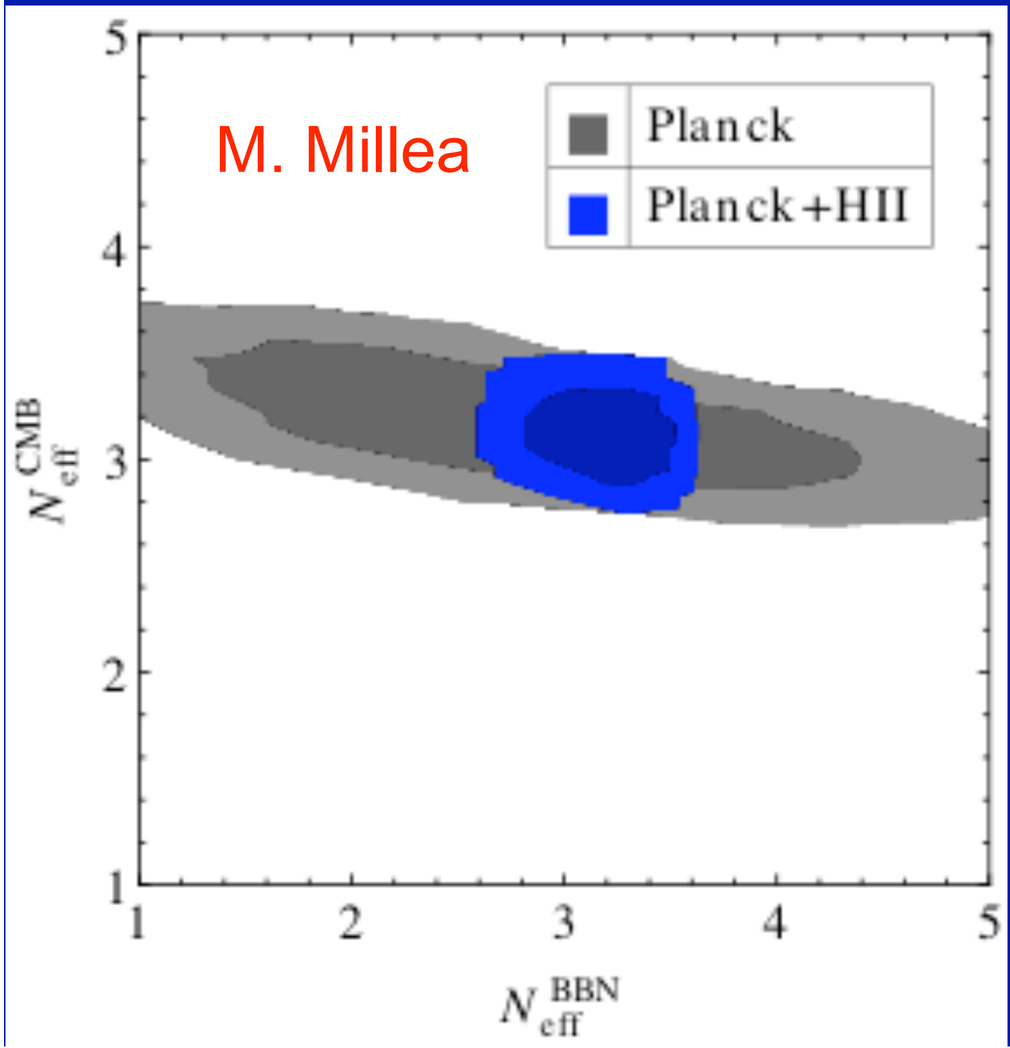




Data available now

Data available soon

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)

High-resolution CMB Temperature Anisotropies as a Particle Physics Detector

- High-resolution CMB data, by being sensitive to the diffusion scale, allow us to determine expansion rate up to recombination -- similar to Helum abundance sensitivity to expansion rate during BBN.
- There are interesting things happening now regarding BBN, high-res CMB, and lab and reactor neutrino data.
- It is not obvious how this all fits together.
- New damping tail measurements will be out very soon, and dramatically improved ones will be out from Planck in ~ Jan 2013.
- Planck measurements will provide tight constraints on (or detections of) hot relics.