constraints on neutrinos from WMAP9, SPT and ACT

- WMAP9 : arXiv:1212.5225 & 1212.5226v2
- SPT : arXiv:1210.7231 & 1212.6267
- ACT : arXiv:1301.0816 & 1301.0824
- Lesgourgues & Pastor 2006, Phys. Rep. 429, 307
- Lesgourgues & Pastor 2012 : arXiv:1212.6154

Jean-Marc Le Goff

cosmo-club, feb 2013

WMAP, SPT, ACT

- WMAP satellite full sky
  23, 33, 41, 61 and 94 GHz
  13 arc min -> l < 800
- South Pole Telescope 10m
  1 arcmin, 2540 deg^2 650<l<3000
  95, 150, 220 GHz
- Atacama Cosmology Telescope 6m
  Atacama desert (Chile) 5200 m 500<l<3000
  148 218 277 GHz

model

ΛCDM with 6 parameters (flat) :

- baryon density $\omega_b=\Omega_b h^2$ (H_0=100*h km/s/Mpc)
- cold dark matter density $\omega_c=\Omega_c h^2$
- dark energy density Ω_Λ (eq. of state w=-1)
- amplitude of inhomogeneities $\Delta_R{}^2$
- spectral index n_s $\Delta_R{}^2(k) \sim k^{(n\_s\ -1)}$
- optical depth to reionization τ

Big bang nucleosynthesis (BBN) : $Y_{He}=\rho_{He}/\rho_b= f(\omega_b,N_{eff})$

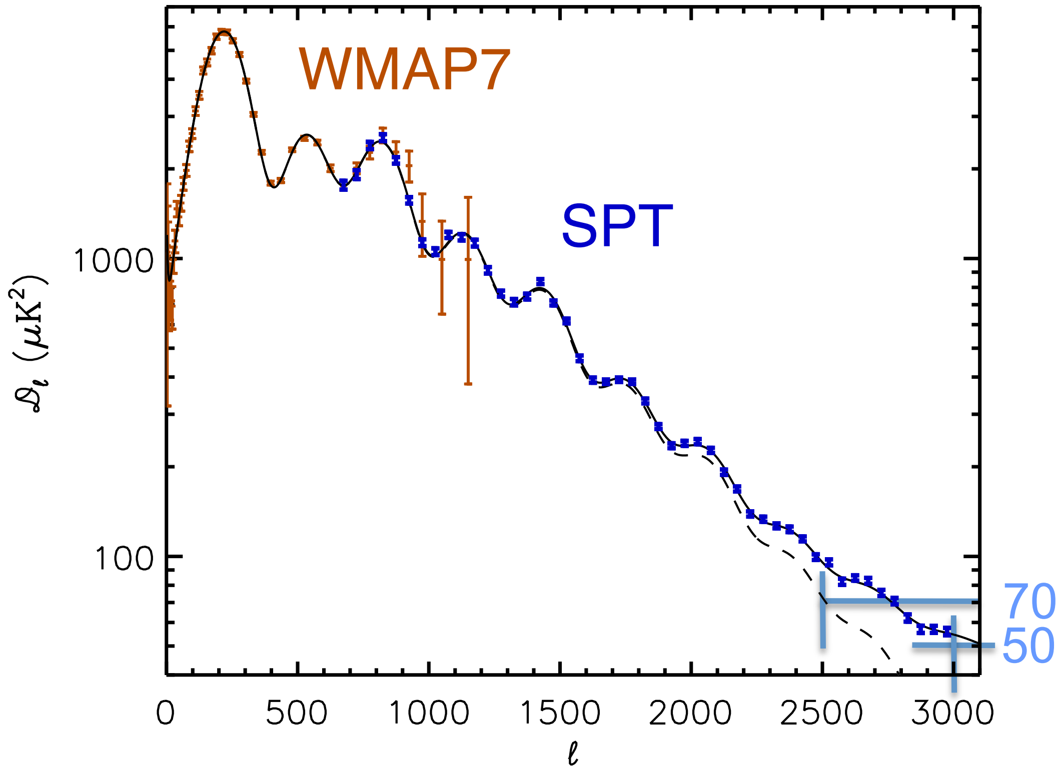
Possible additional parameters :

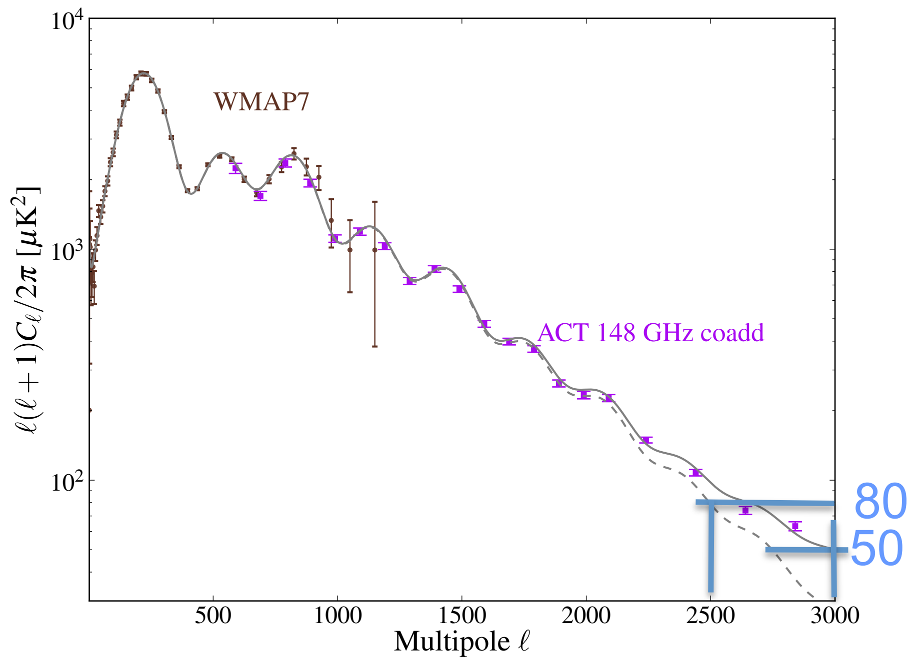
N_{eff} $\Sigma\, m_\nu$ Y_{he} $d\, n_s / d \ln k$ Ω_k w

datasets

- WMAP7/9: 9 year minor improvement,
  mostly due to better estimator
- SPT11/12, ACT11/12: 2012 errors reduced by ~ 2
- BAO
- H_0
- LRG galaxy power spectrum
- SPT_{cl} : SZ selected clusters
- SN1a : used only for DE studies

SPT versus ACT





CMB + foregrounds
SPT fit (3000) ~ 55
ACT fit (3000) ~ 50

CMB alone ACT > SPT (10%)
SPT fit (2500) ~ 70
ACT fit (2500) ~ 80

cosmic neutrino background

- high T : ν in equilibrium
- T ~ 1.1 MeV : ν decouple -> $n_\nu^{comobile}$ = cst
- T ~ 0.2 MeV e^+e^- annihilations heat up the γ
- $T_\gamma / T_\nu = (11/4)^{1/3} = 1.40$ $\quad$ $n_\nu = (3/11)\, n_\gamma = 113\ /cm^3$
- $$\rho_R = \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{eff}\right]\rho_\gamma$$
- some e^+e^- -> $\nu\,\bar{\nu}$ so $N_{eff} = 3.046$
- $$f_\nu = \frac{\Omega_\nu}{\Omega_m} = \frac{\sum m_i}{\Omega_m h^2 \times 94.1 eV} \approx \frac{\sum m_i}{13.3 eV}$$

N_{eff} radiative species

4 Effects on N_{eff} on CMB

1) N_{eff} ↗ $H^2 = (8\pi G/3)(\rho_m+\rho_R)$ ↗ r_s = 150 Mpc ↘
all peak positions ↗

2) N_{eff} ↗ t_{eq} ↗ early ISW ↗
amplitude of peaks 1 and 2 ↗

3) N_{eff} ↗ anisotropic stress ↗
power for l>130 ↗

All above effects can be compensated by other param
-> WMAP7 alone very little constrain on N_{eff}

effect of N_{eff} on CMB

WMAP7 alone very little constrain on N_{eff}

4) diffusion (Silk) damping of CMB small scales ~ r_d / r_s

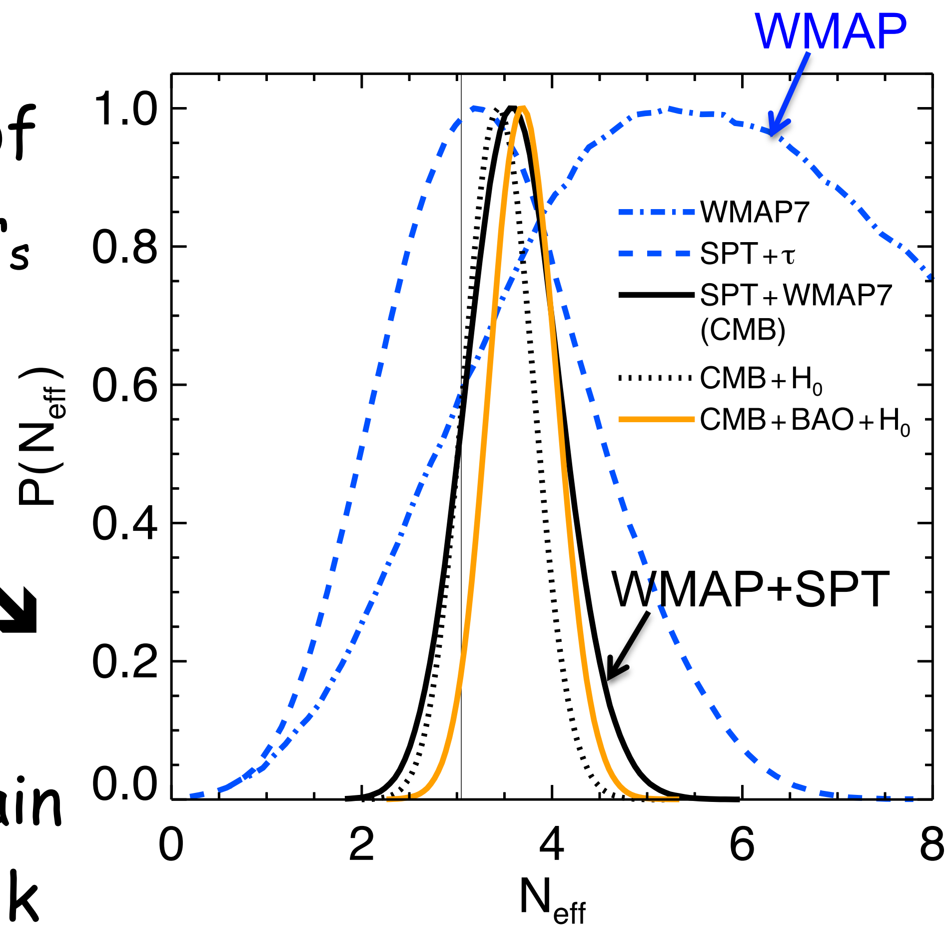
N_{eff} ↗ H ↗

$r_s \sim 1/H$ $r_d \sim 1/\sqrt{H}$

so $r_d/r_s \sim \sqrt{H}$ ↗

low scale (large l) power ↘

- WMAP + SPT: good constrain
- degenerate with $d\, n_s / d \ln k$



CMB alone

- WMAP9 + SPT11 + ACT11

  N_{eff}=3.89 ± 0.67

- SPT12 + WMAP7

  N_{eff}=3.55 ± 0.49

- ACT12 + WMAP7

  N_{eff}=2.78 ± 0.55

ACT > SPT
so less damping
smaller N_{eff}

CMB + BAO + H_0

- WMAP9 + SPT11 + ACT11

  $N_{eff}=3.26 \pm 0.35$ 1212.5226v1

  analytic formula for r_s was assuming $N_{eff}=3$

  $N_{eff}=3.84 \pm 0.40$ 1212.5226v2

2 σ

- SPT12 + WMAP7

  $N_{eff}=3.71 \pm 0.35$

- ACT12 + WMAP7

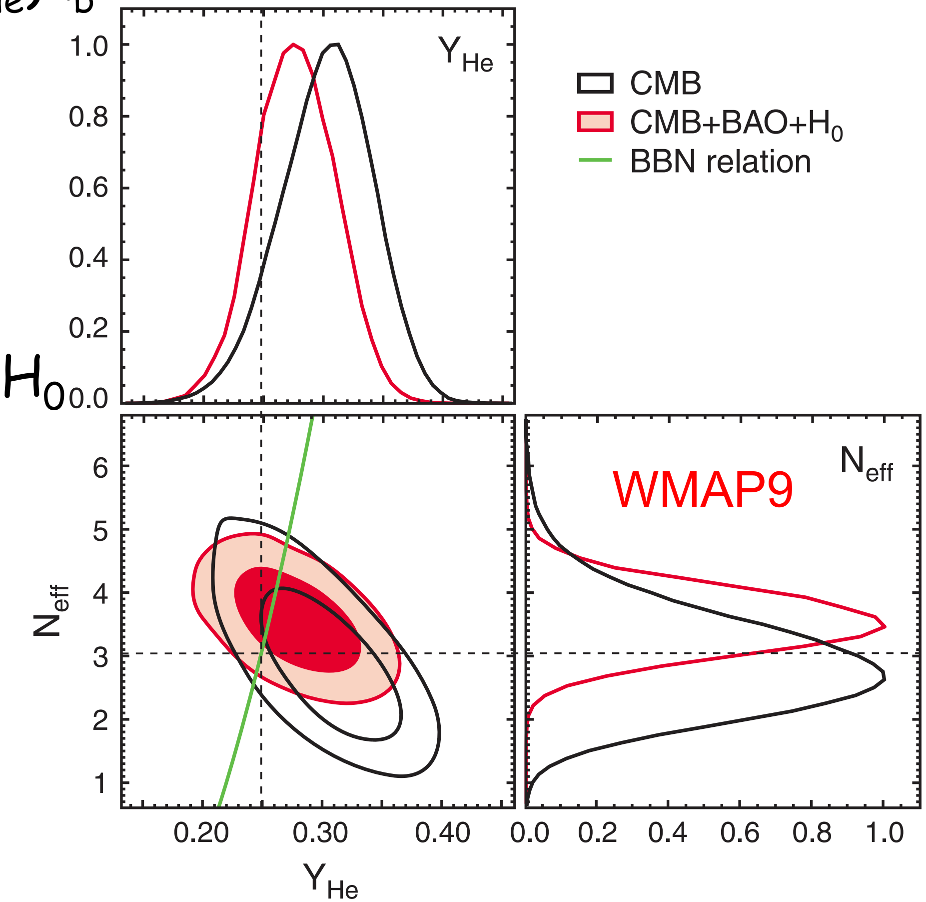
  $N_{eff}=3.52 \pm 0.39$

releasing $Y_{He}=f(\omega_b, N_{eff})$

- $r_d/r_s \sim (H/n_e)^{1/2}$ and $n_e = (1-Y_{He})n_b$
  so Y_{He} ↗ -> r_d/r_s ↗
  and N_{eff} Y_{He} anticorrelated
  so effect decreases

- WMAP9 + SPT11 +ACT11 + BAO +H_0
  $N_{eff}=3.55 \pm 0.49$ 1.1 σ
  $Y_{He}=0.278 \pm 0.033$

- WMAP7 +SPT12 + BAO + H_0
  $N_{eff}=3.32 \pm 0.45$ < 1 σ
  $Y_{He}=0.294 \pm 0.030$

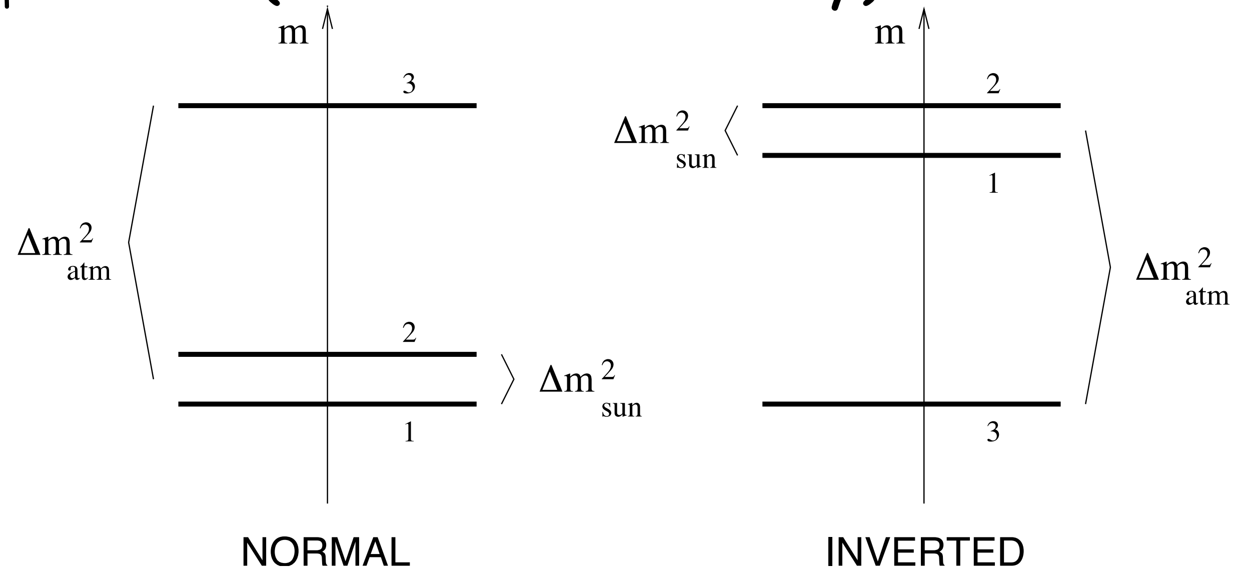


- BBN: $Y_{He}=0.257 \pm 0.001 \pm 0.005$ -> $N_{eff} \sim 2.5^{+1.1}_{-0.9}$

neutrino mass

direct constrains on neutrino masses

- ν oscillations :
  - Δm_{12}^2=7.58 10^{-5} eV^2 (solar)
  - Δm_{23}^2=2.43 10^{-3} eV^2 (atmospheric)
- tritium β decay $m(\nu_e) < 2$ eV (95% CL)
- 0.056 eV < $\Sigma\, m_i$ < 6 eV (normal hierarchy)
- 0.095 eV < $\Sigma\, m_i$ < 6 eV (inverted hierarchy)

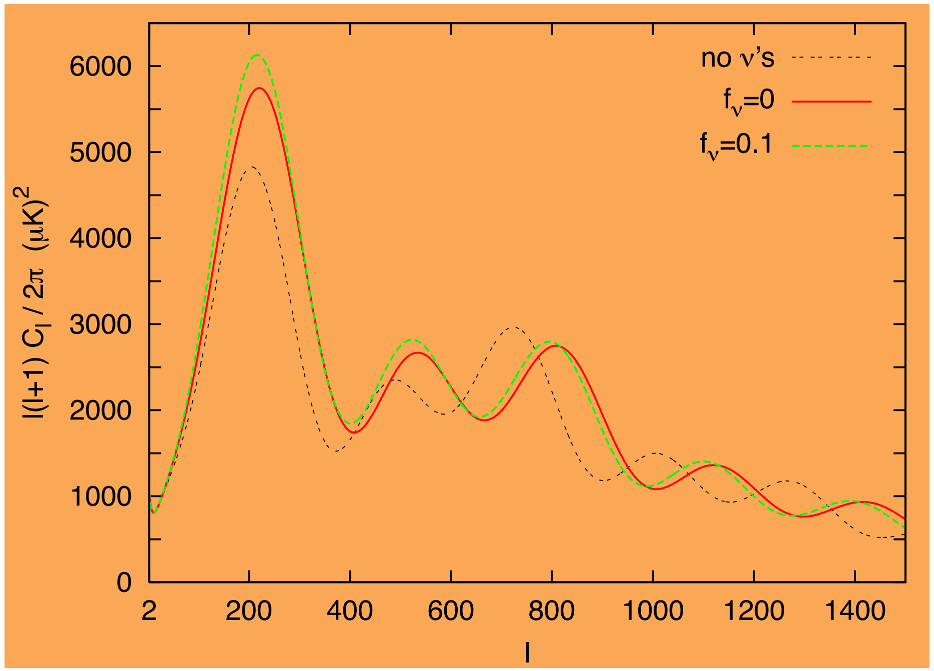


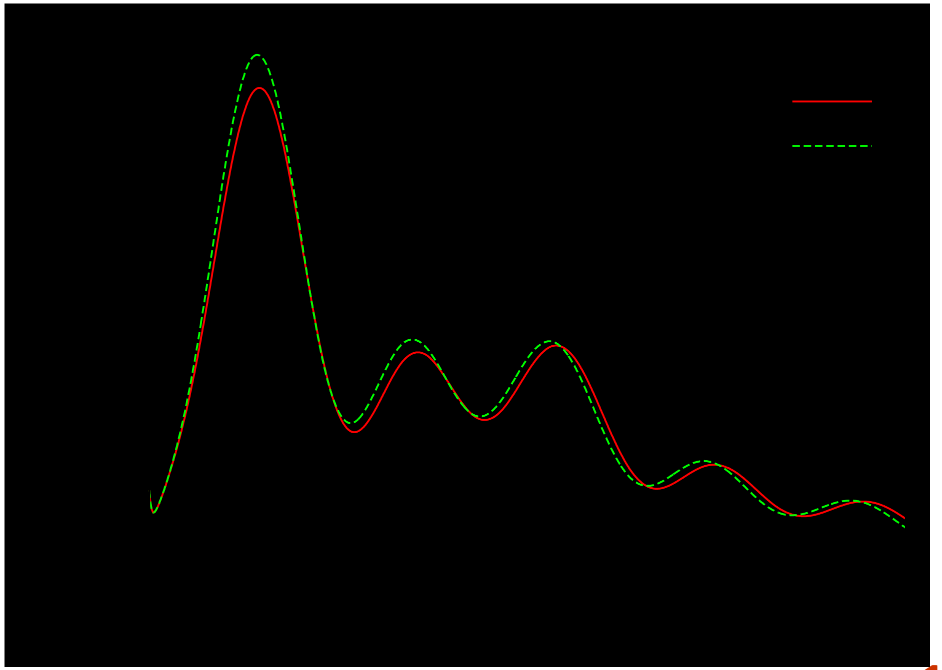
Effect on CMB

- if $f_\nu < 0.1$ ($\Sigma m_i < 1.3$ eV) :

  ν NR after decoupling -> no big effet

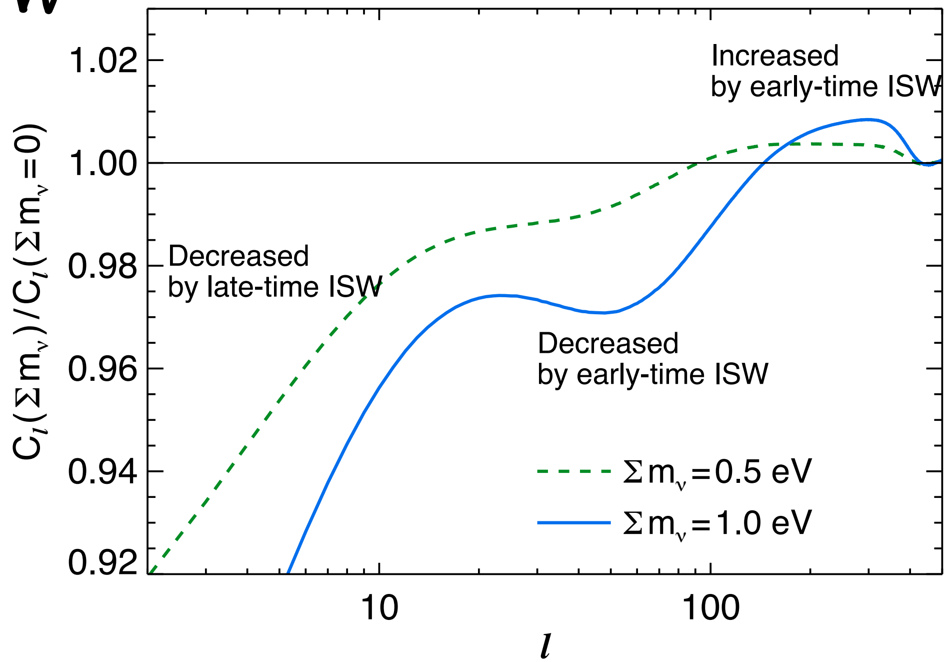
- for cst Ω_Λ Ω_b: $m_\nu > 0$ reduces Ω_{cdm} and postpones t_{eq}





Effect on CMB

- when increasing m_ν :
  decrease Ω_Λ to keep θ_s constant
  => small effect
- dominant effect due to ISW
- for l < 20
  large cosmic variance



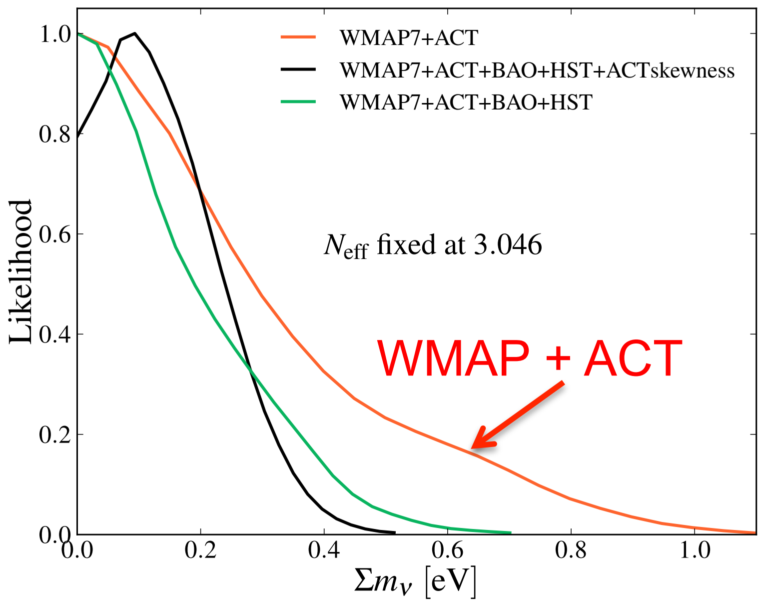
ISW: photons get energy
going down in a potential well
- the gravitational potential decreases
due to dark energy (late time)
or radiation (early time)
-the photons loose less energy going out
=> photons have gained energy

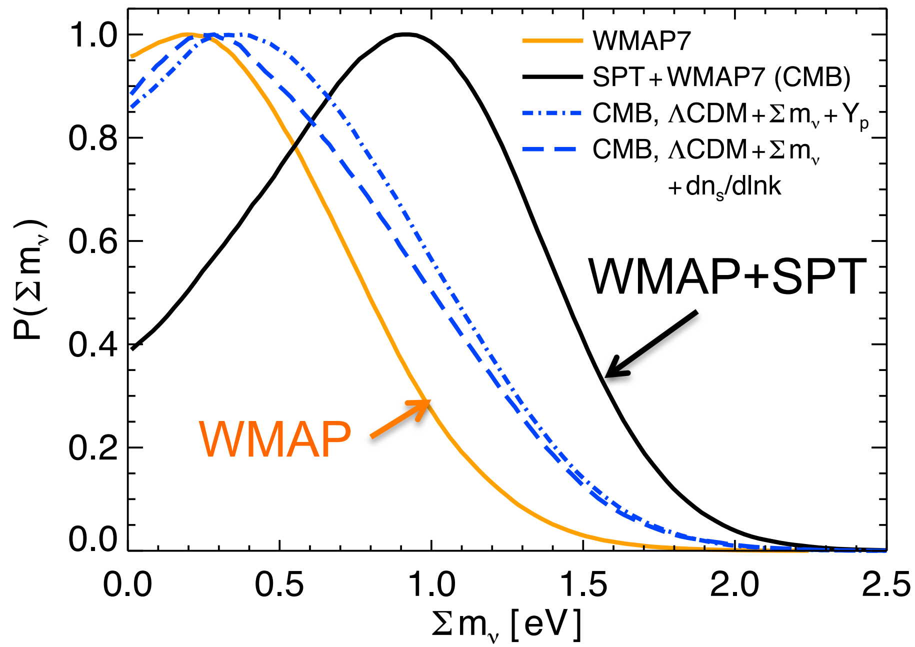
CMB alone

- WMAP9: $\sum m_\nu < 1.3$ eV

$\sum m_\nu$ anticorrelated with n_s so high l help :

- WMAP7 + ACT12 : $\sum m_\nu < 0.72$ eV
- WMAP7 + SPT12 : $\sum m_\nu < 1.6$ eV

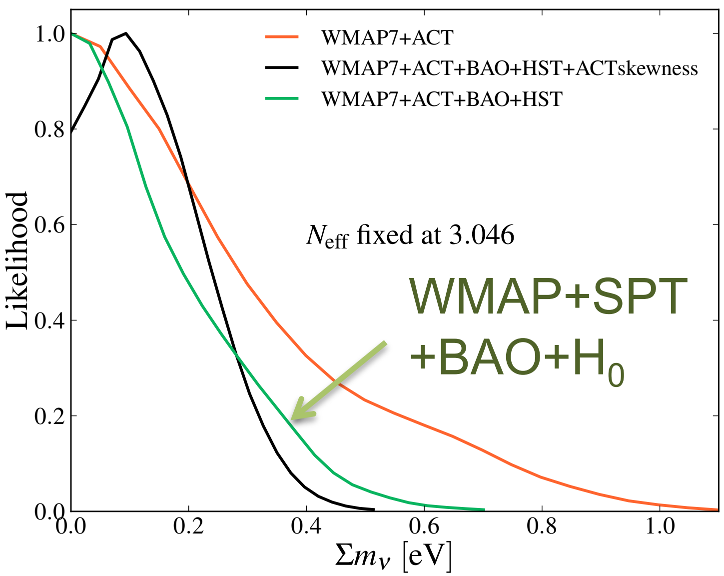


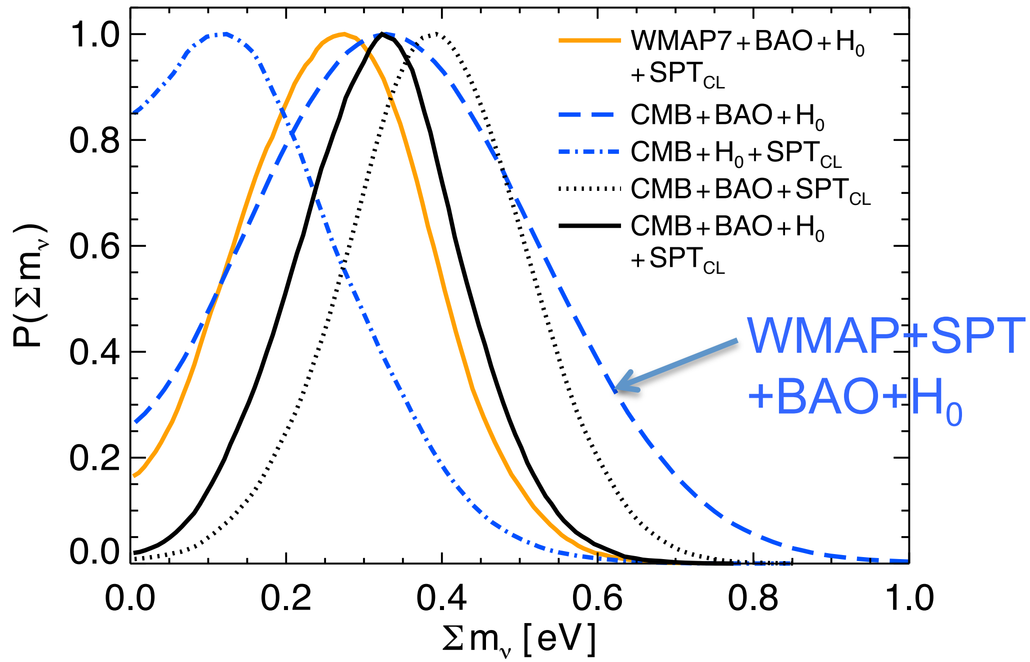


CMB + BAO + H_0

- WMAP9 + ACT11 + SPT11 + BAO + H_0 : $\Sigma m_\nu < 0.44$ eV
- WMAP7 + ACT12 + BAO + H_0 : $\Sigma m_\nu < 0.39$ eV
- WMAP7 + SPT12 + BAO + H_0 : $\Sigma m_\nu < 0.66$ eV

  but close to a 2 σ measurement : $\Sigma m_\nu = 0.34 \pm 0.18$





CMB + BAO + H_0 + SPT_{cl}

- SPT # clusters : σ_8 = 0.739 +- 0.027 (rather low)

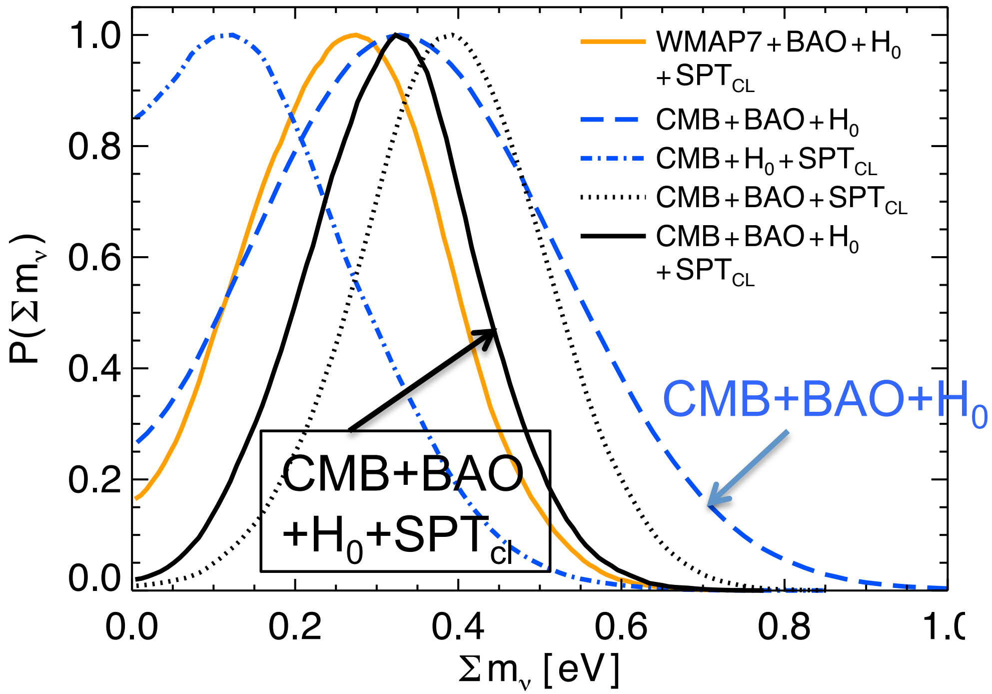
WMAP7 + SPT12 + BAO + H_0 + SPT_{cl}: $\Sigma m_\nu = 0.32 \pm 0.11$

doubling the uncertainty on cluster mass calibration -> 0.34 ± 0.12

- removing H_0

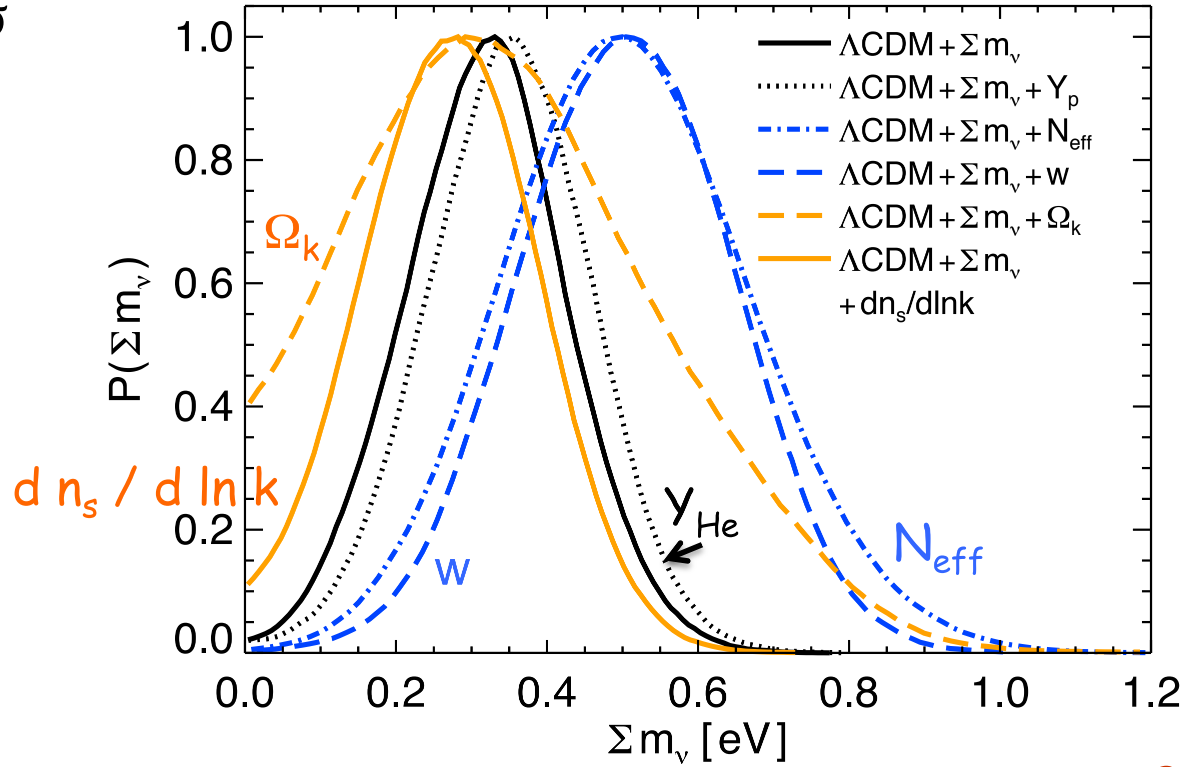
WMAP7 + SPT12 + BAO :

$\Sigma m_\nu = 0.49 \pm 0.20$



adding more parameters

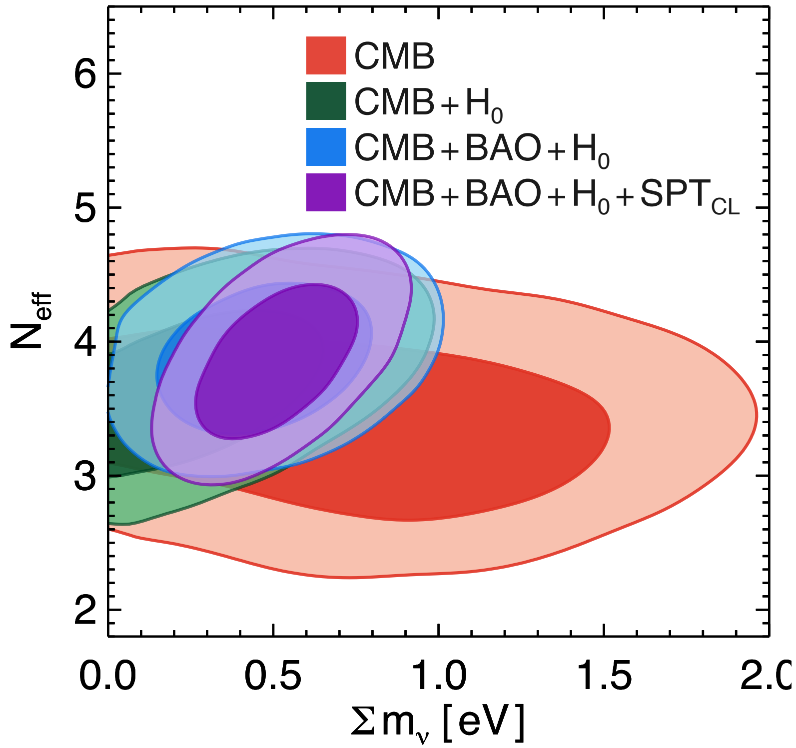
- WMAP7 + SPT12 + BAO + H_0 + SPT_{cl}:
  $\Sigma m_\nu = 0.32 \pm 0.11$
- significance maintained with N_{eff}, Y_{He} and w
- $d\, n_s / d \ln k$: 2.4 σ
- Ω_k : 1.7 σ

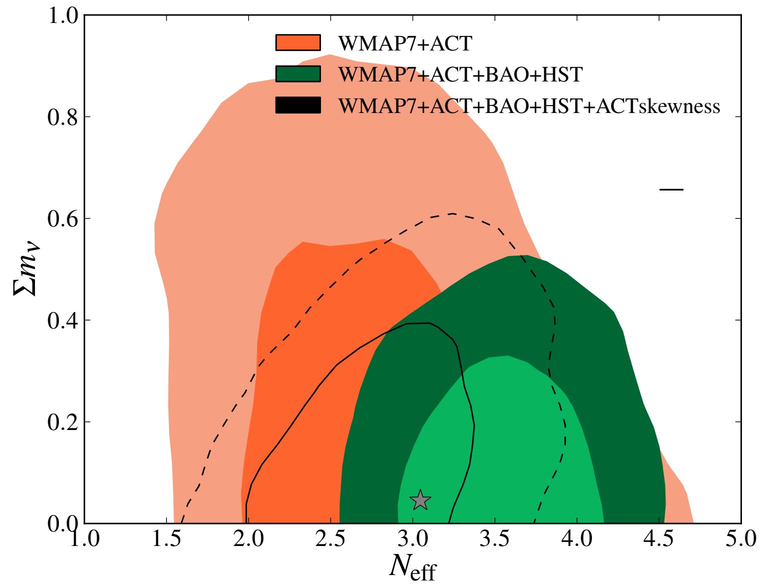


N_{eff} + $\sum m_\nu$ (SPT)

- with CMB only, N_{eff} and $\sum m_\nu$ not correlated
- W9 + SPT12 + BAO +H_0 correlated -> effects increase

  $\sum m_\nu = 0.48 \pm 0.21$ $N_{eff}=3.89 \pm 0.37$
- idem + SPT_{cl} $\sum m_\nu = 0.51 \pm 0.15$ $N_{eff}=3.86 \pm 0.37$





sterile neutrino ?

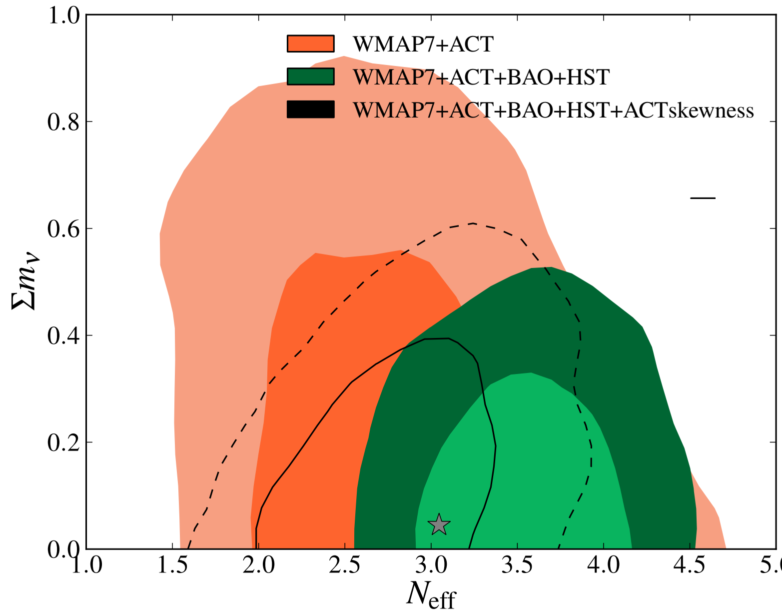
- oscillation experiments suggest: sterile ν ~ 1eV

- 1 eV excluded by SPT (2.5σ) and ACT (many σ)

- but this assumes sterile ν in thermal equilibrium before ν decoupling

- initial lepton asym (~1%) can break this

(Hannestad et al. 2012)



Gravitationnal lensing

Di Valentino et al., arXiv: 1301.7343 :

- Gravitat. lensing increases power in the damping tail
- parameter A_L : A_L= 0 no lensing, A_L= 1 nominal (i.e. GR)

SPT12+WMAP9 : A_L= 0.85±0.13 N_{eff} = 3.72 ± 0.46 $\Sigma m_\nu < 0.77$

ACT12+WMAP9 : A_L= 1.64±0.36 N_{eff} = 2.85 ± 0.56 $\Sigma m_\nu < 0.55$

- SPT12+WMAP7 : A_L= 0.86±0.13
- ACT12+WMAP7 : A_L= 1.7±0.38 2 σ violation of GR !

- A_L can also be measured directly through 4pt function

  SPT12 : A_L= 0.90 ± 0.19

  ACT12 : A_L= 1.16 ± 0.29

Bayesian Evidence

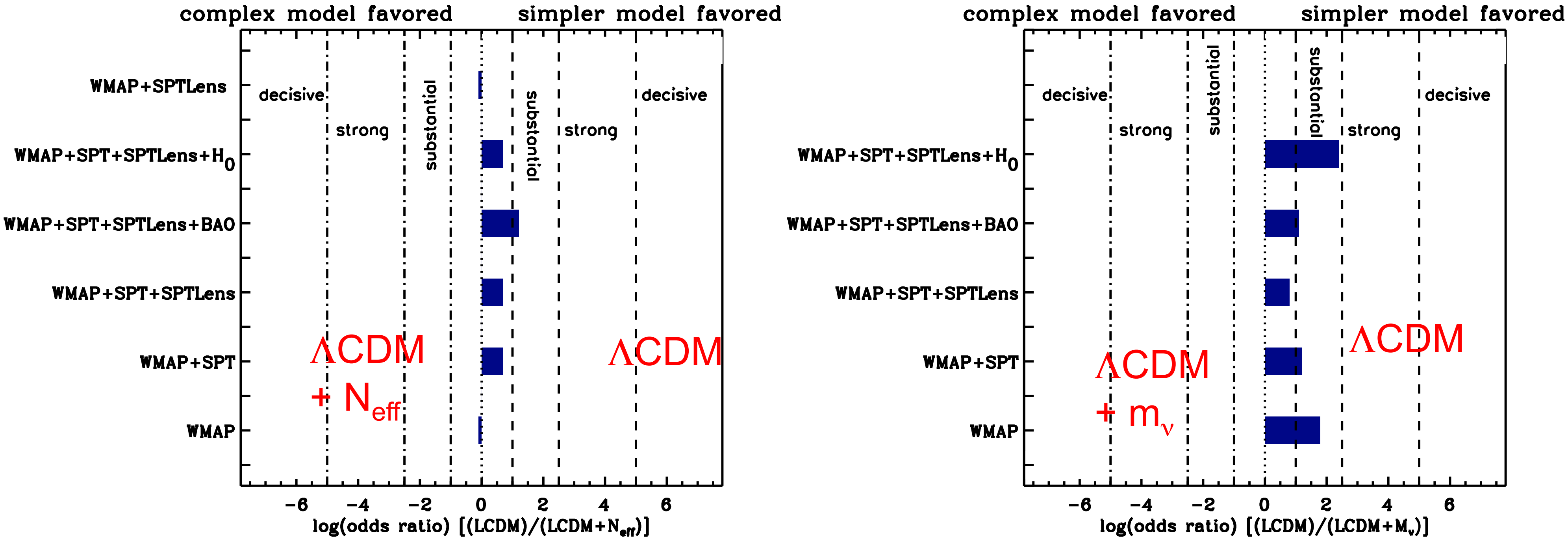
S Feenay, H Peiris, L verde arXiv:1302.0014

- N_{eff} is an issue of model selection and not param fit
  indeed when we release N_{eff}=3.046 we remove 1 dof
- "marginalizing over N_{eff} Ω_c, which extends to large values of N_{eff}, will bias N_{eff} to large values"
- when adding more and more data N_{eff} remains 1.5 σ above 3

- Bayesian Evidence $E = \int d\alpha P(\mathbf{d}|\alpha, M)P(\alpha|M)$

- consider $\ln\left[\frac{E(\Lambda CDM)}{E(\Lambda CDM + N_{eff})}\right]$

Bayesian Evidence



- but they use WMAP7, SPT11, Wiggle Z

because SPT12 and BOSS create some tensions !!!

Conclusions

- ACT+… compatible with standard model
- SPT+… mild preference for $N_{eff} > 3$

  disappears when $dn_s/d \ln k$ or Y_{He} are freed

  $\Sigma\, m_i = 0.32 \pm 0.11$, disappears if A_L is freed
- Bayesian Evidence ?
- constraints from LSS (galaxies and Lyman α)

  => Waiting for Planck
- Planck should reach $\delta N_{eff} = 0.20 - 0.25$

  and $\Sigma\, m_i < 0.15$ (CMB lensing)
- Planck + COrE : $\delta N_{eff} = 0.05$
- LSST + Planck $\Sigma\, m_i < 0.05$