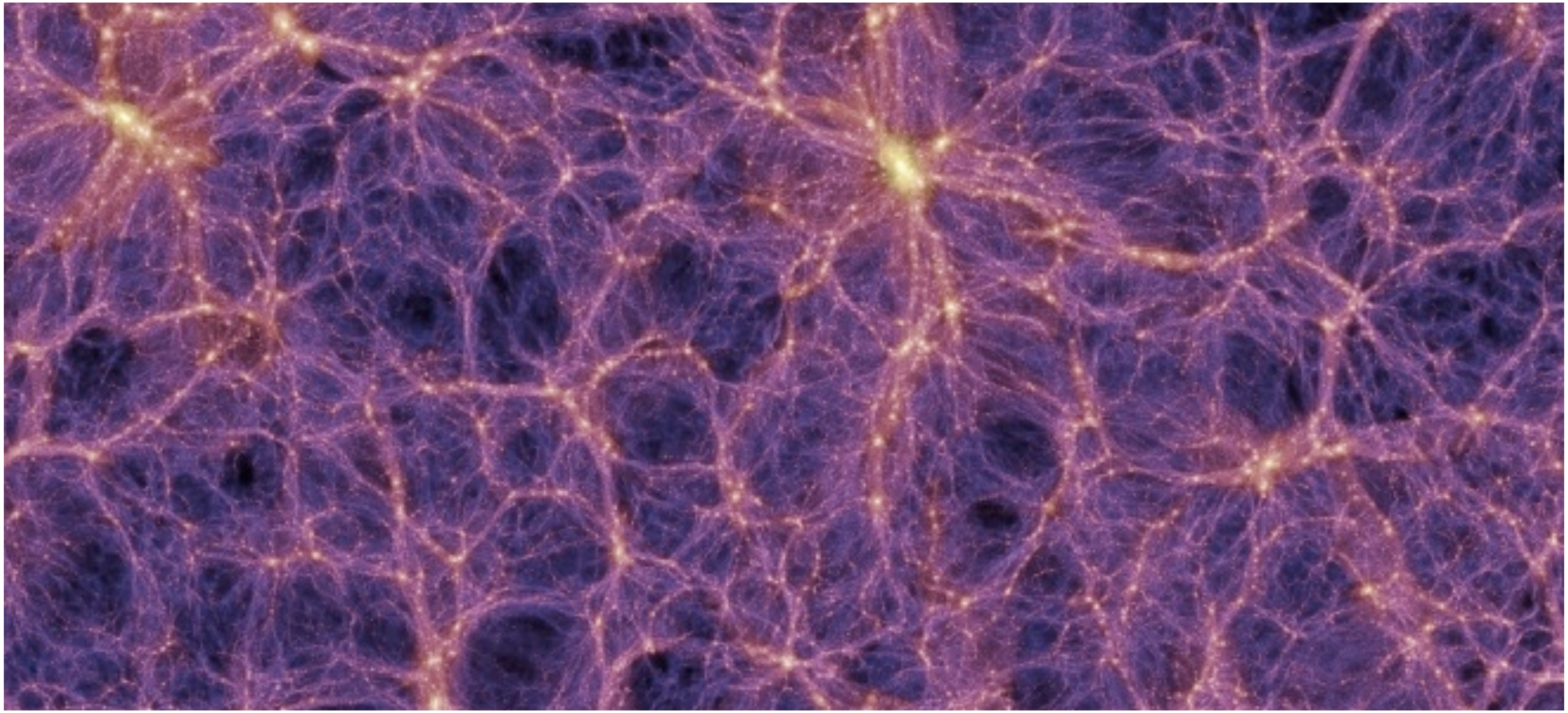
Dark Matter from cosmology/astrophysics



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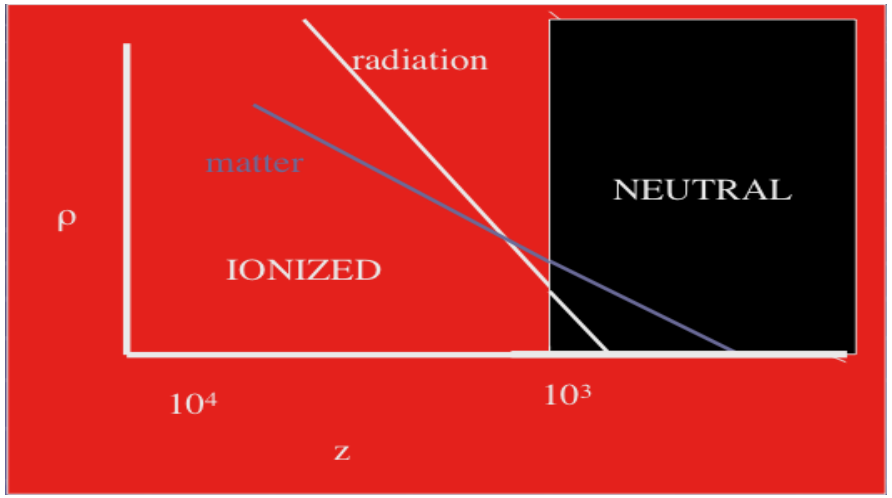
Summary

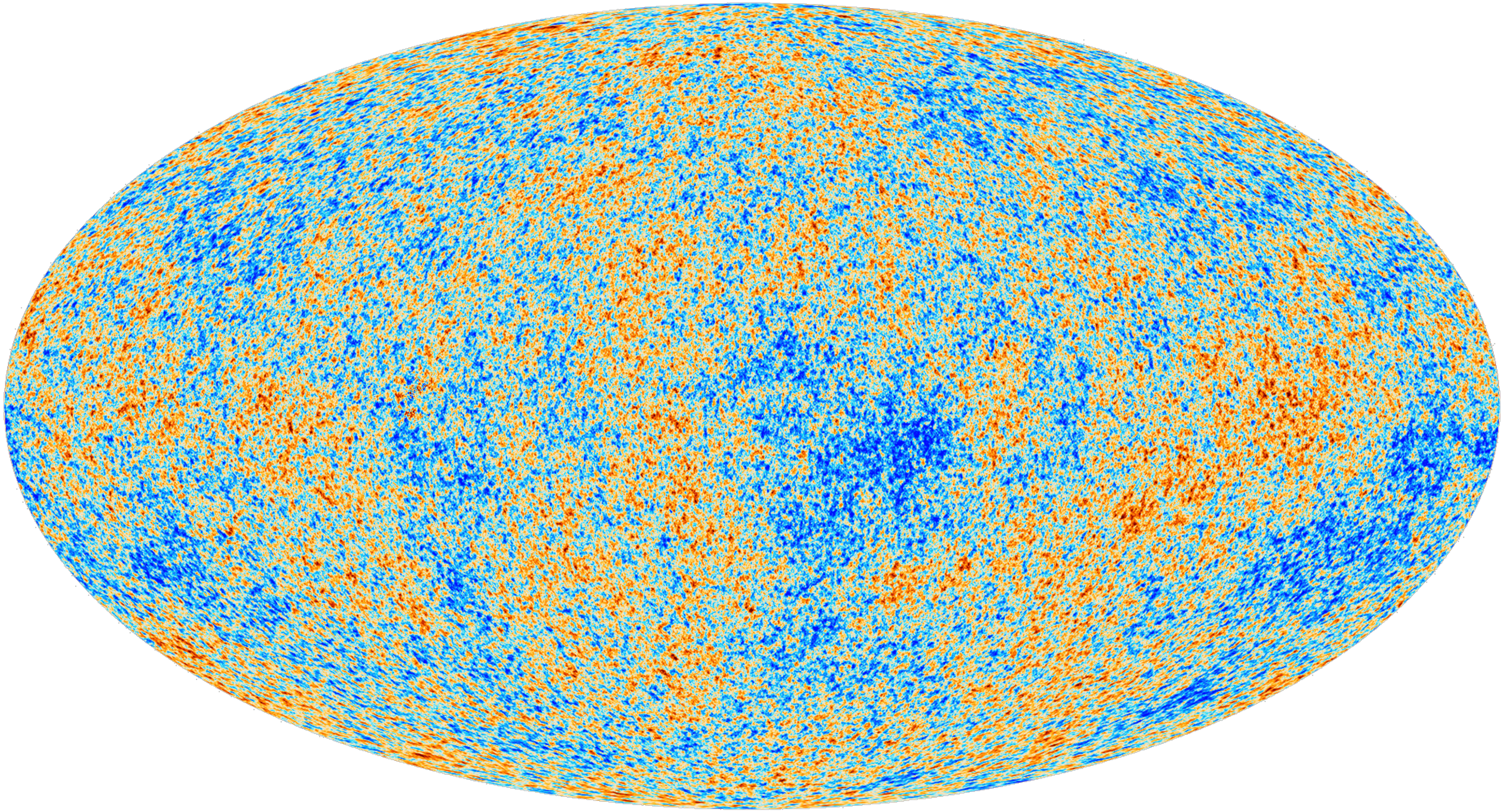
- Cosmological limits on cold dark matter (large scales)
  - CDM relic density
  - Could it be sterile neutrinos or axions?
  - Limits on DM annihilation
- Astrophysical concerns about cold dark matter (galactic scales)
  - simulations: cusp/core issues, missing satellites, mass of sub-halos
- Cosmological limits on neutrinos
- (Astrophysical indirect detection - not covered but extra slides)

History of early universe

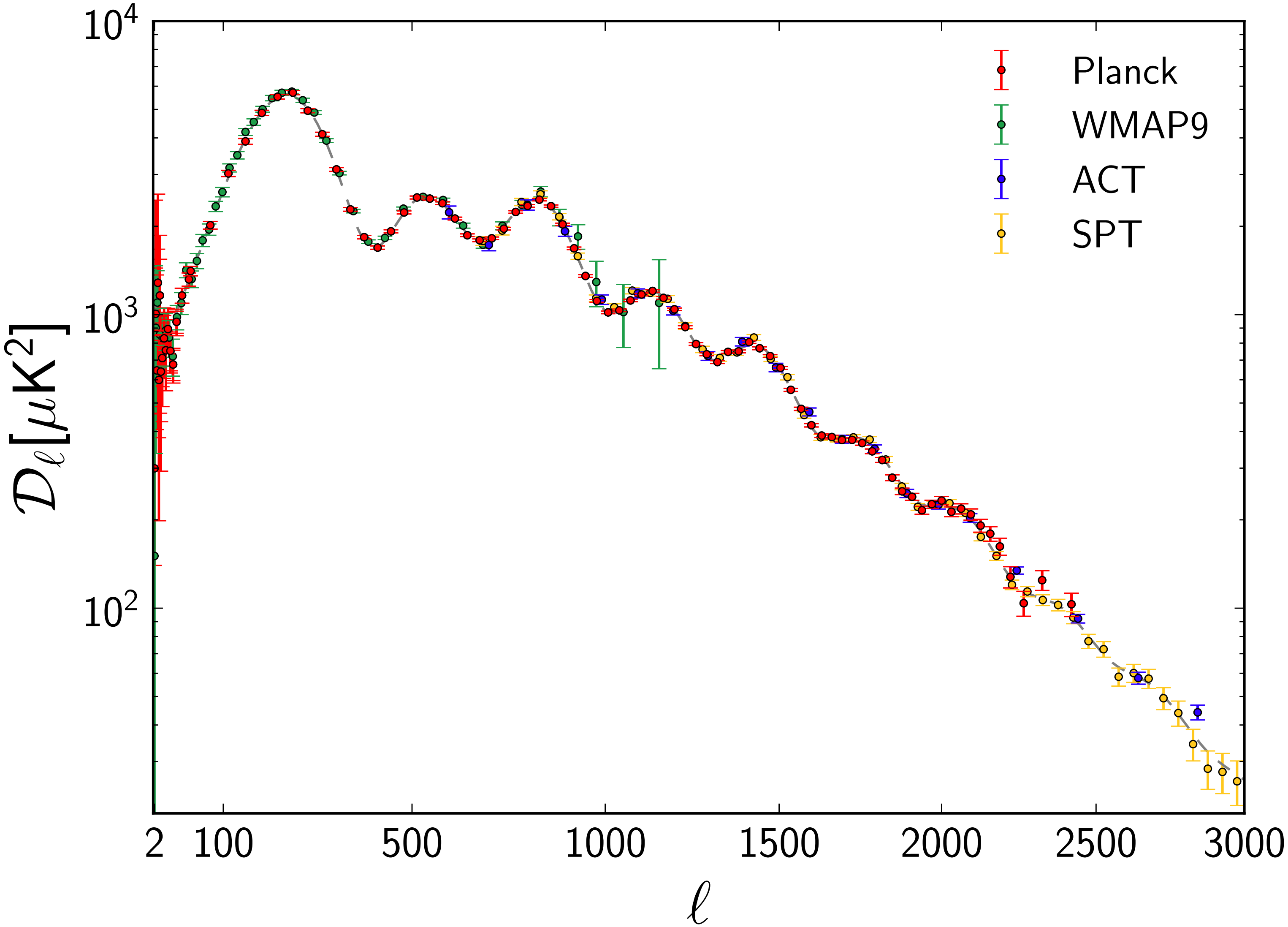
Inflation?	$T \sim 10^{15}$ GeV	$t \sim 10^{-35}$ s
CDM decoupling?	$T \sim 10$ GeV?	$t \sim 10^{-8}$ s
Quark-hadron transition	$T \sim$ GeV	$t \sim 10^{-6}$ s
Neutrino Decoupling	$T \sim 1$MeV	$t \sim 1$s
Big Bang Nucleosynthesis	$T \sim 100$ keV	$t \sim 10$ min
Matter-Radiation Equality	$T \sim 0.8$eV	$t \sim 60000$ yr
Recombination	$T \sim 0.3$eV	$t \sim 380000$ yr



The CMB temperature sky

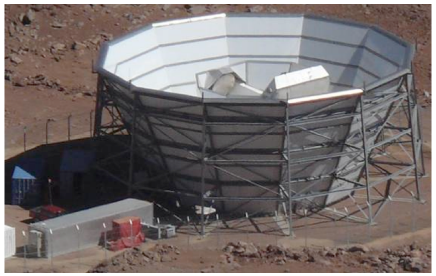


Planck Collaboration 2013



10^4
10^3
10^2
$\mathcal{D}_\ell [\mu K^2]$
Planck
WMAP9
ACT
SPT
2 100 500 1000 1500 2000 2500 3000
ℓ

planck



ΛCDM: constraint on relic density

Planck +WP (2013)

$\Omega_b h^2 = 0.0221 \pm 0.0003$

$\boxed{\Omega_c h^2 = 0.120 \pm 0.003}$

$n_s = 0.960 \pm 0.007$

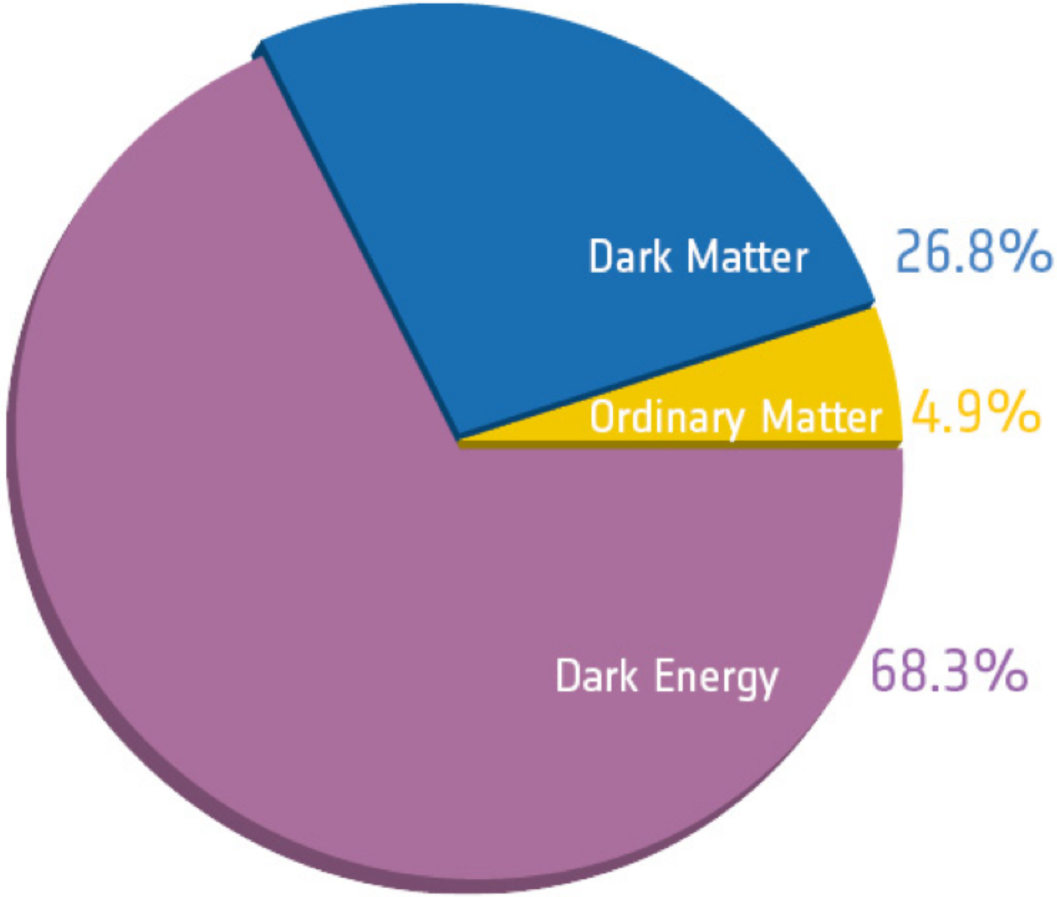
$10^9 A_s = 2.20 \pm 0.06$

$\tau = 0.089 \pm 0.014$

$\Omega_\Lambda = 0.685 \pm 0.017$

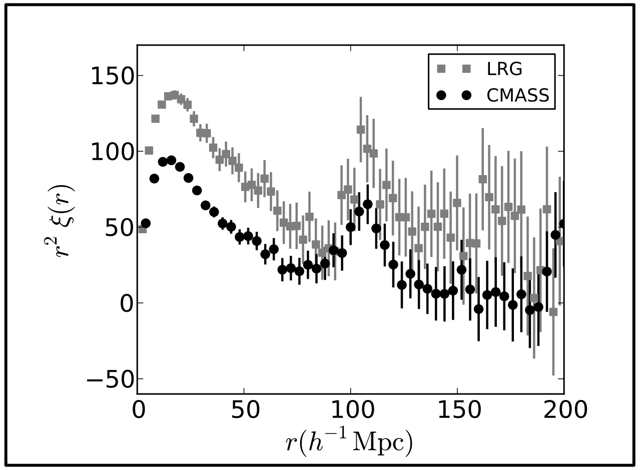
$H_0 = 67.3 \pm 1.2$

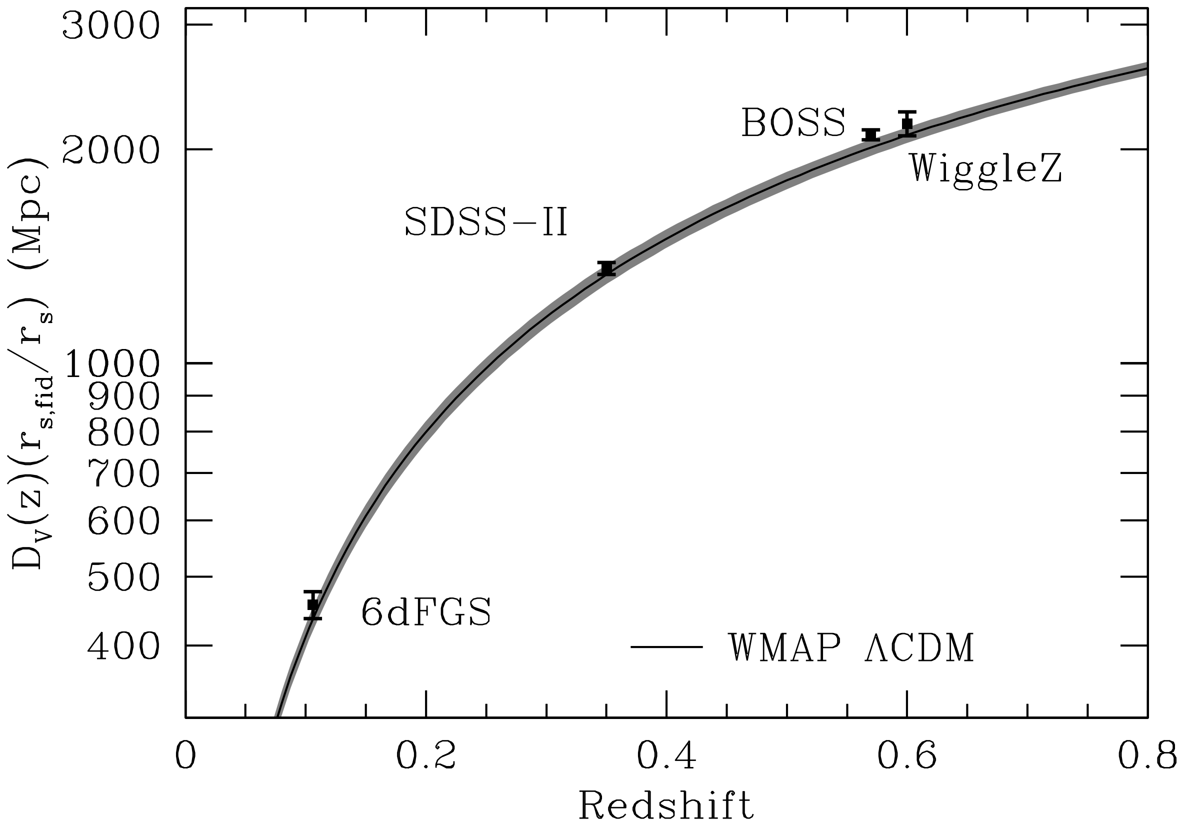
$\sigma_8 = 0.83 \pm 0.01$



High mass → low cross section → high relic density
Assume a collisionless non-relativistic particle

Baryon Acoustic Oscillations





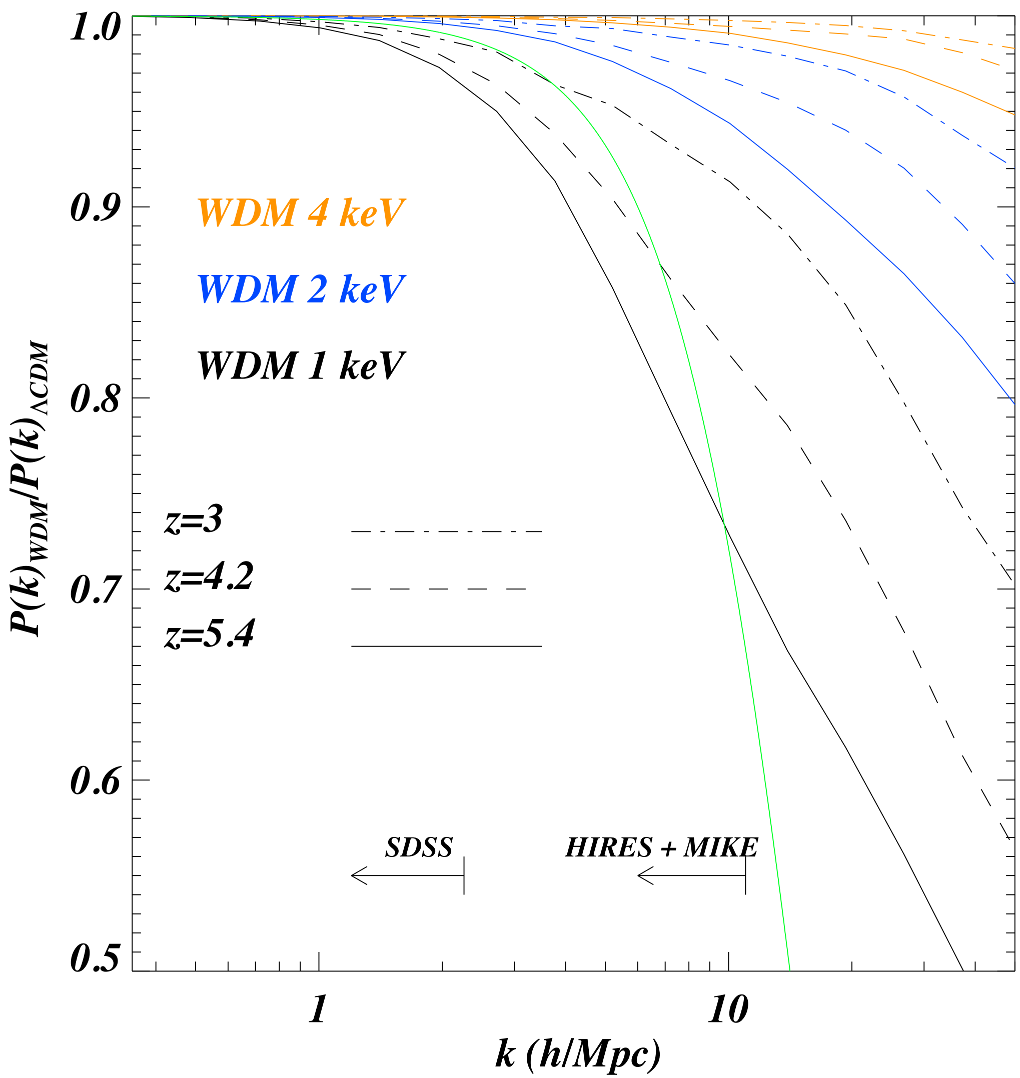
BOSS,
Anderson et al 2012

$$D_V(z) = \left[(1+z)^2 D_A^2(z)\frac{cz}{H(z)}\right]^{1/3}.$$

r_s is the comoving sound horizon at the baryon drag epoch

D_V combines the angular diameter distance and the Hubble parameter

Could it be warm dark matter?

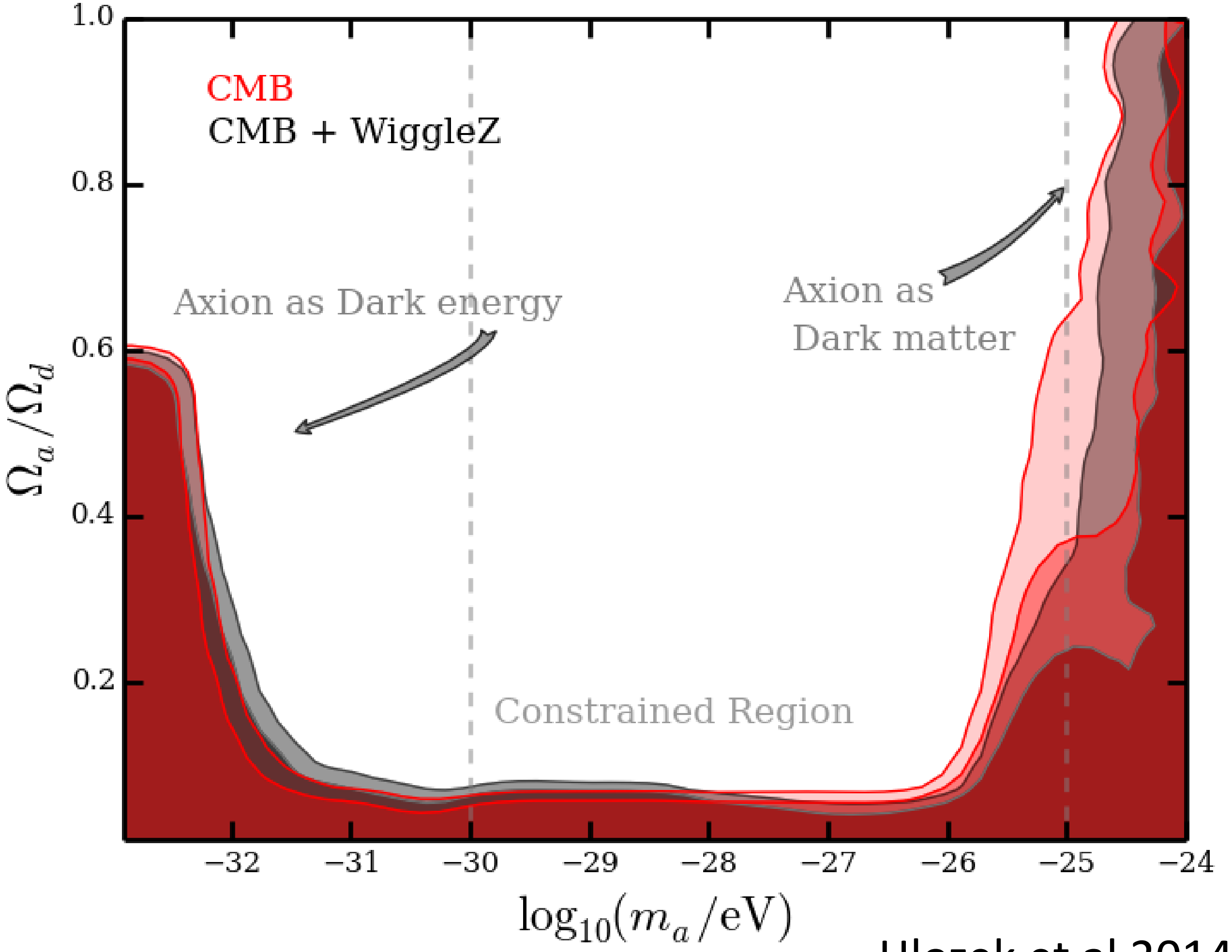


- Viel et al 2013, analyse clustering of hydrogen via the Lyman-alpha forest from high-redshift quasars.

$$m_{\rm WDM} \gtrsim 3.3\ \ {\rm keV}\ (2\sigma)$$

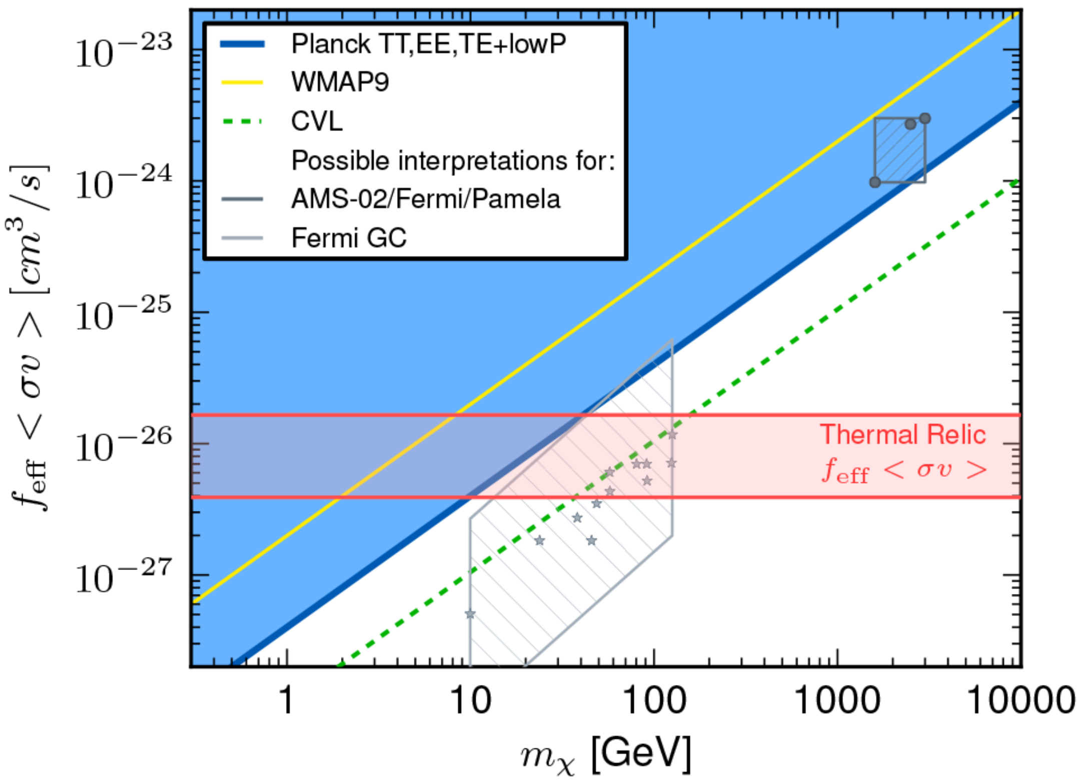
- Constrain mass for particles as early decoupled thermal relics
- Could be sterile right-handed neutrino
- This is a difficult measurement

Could it all be (ultra-light) axions?



Hlozek et al 2014

Can we put limits on DM annihilation?



Planck 2014 in prep - French press

$$\frac{dE}{dt}(z) = 2\, g\, \rho_c^2 c^2 \Omega_c^2 (1+z)^6 p_{\rm ann}(z),$$

$$p_{\rm ann}(z) \equiv f(z) \frac{\langle \sigma v \rangle}{m_\chi}$$

- If DM annihilates, energy injection changes recombination
- Suppression of peaks due to increased recombination duration
- Boost of large-scale polarisation

CDM on galaxy scales

Large numerical simulations, now increasingly with baryons but largest still CDM

Astrophysical concerns:

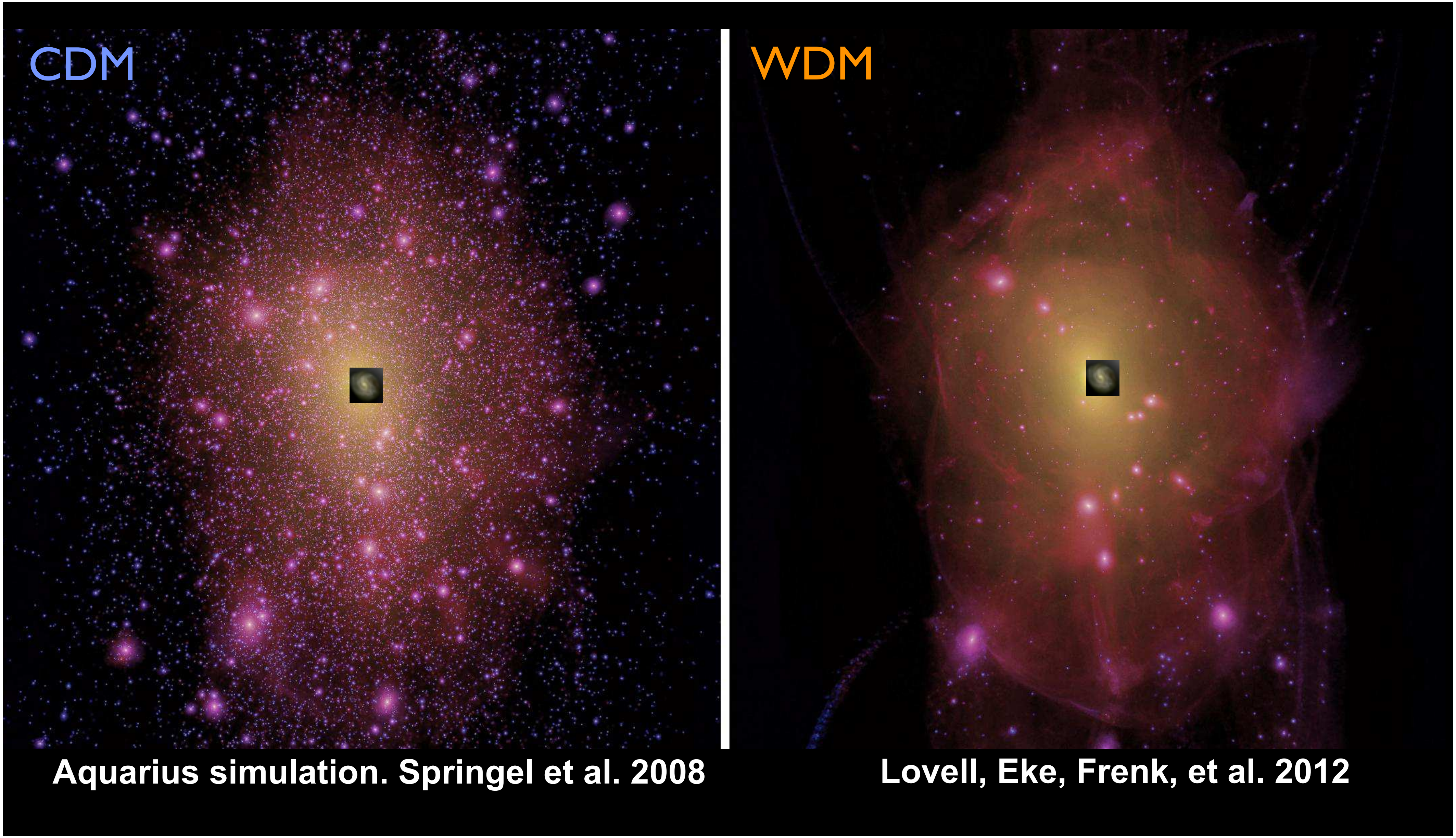
- cusp/core problem: simulations mostly predicted cuspy behavior, but observed halos have flat core. But may be effect of baryons in simulations

- ‘Missing satellite problem’ - thought to be missing satellites, but perhaps not after all.

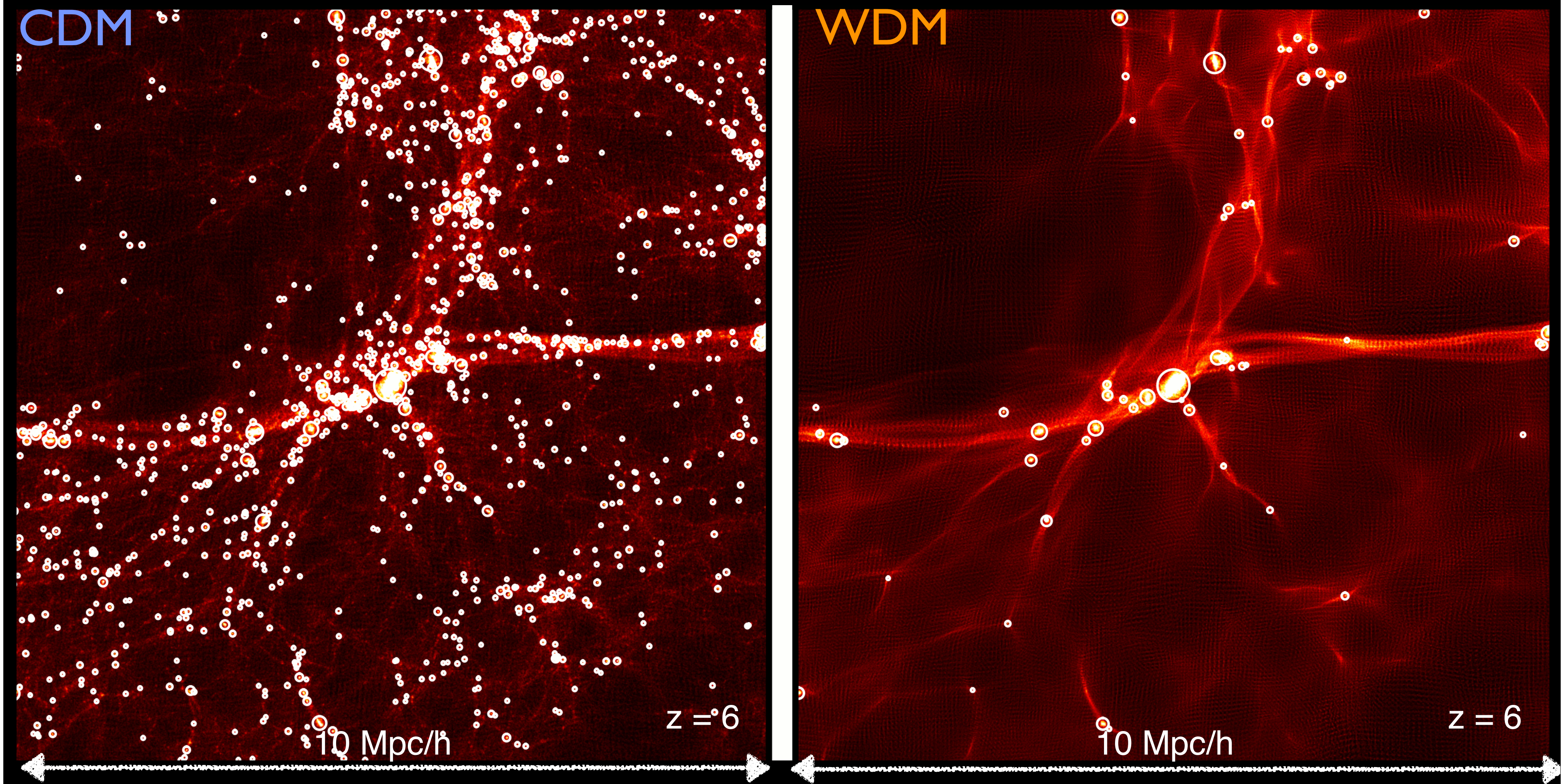
- ‘Too Big to Fail’ - simulations predict larger sub-halos than we see. But may just be simulation limitations.

Warm dark matter doesn’t solve all problems, and not evidence yet that there is a problem that definitively can’t be solved with CDM.

Dark matter halo substructure is interesting path for distinguishing DM models.



From J. Primack



WDM simulation at right has no "too big to fail" subhalos, but it is inconsistent at >10σ with Ultra Deep Field galaxy counts.

From J. Primack

Neutrinos: cosmological effects

- Neutrinos thermally decouple when weak interaction rate < expansion rate of universe ~ 1 MeV.

- If massive, become non-relativistic (z=6000 for 3eV; z=30 for 0.05eV)

$$\Omega_\nu h^2 = \frac{\sum m_\nu}{94 eV}$$

$$T_\nu = T_\gamma \left(\frac{4}{11}\right)^{1/3} \qquad \rho_\nu = \left[\frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{eff}\right]\rho_\gamma$$

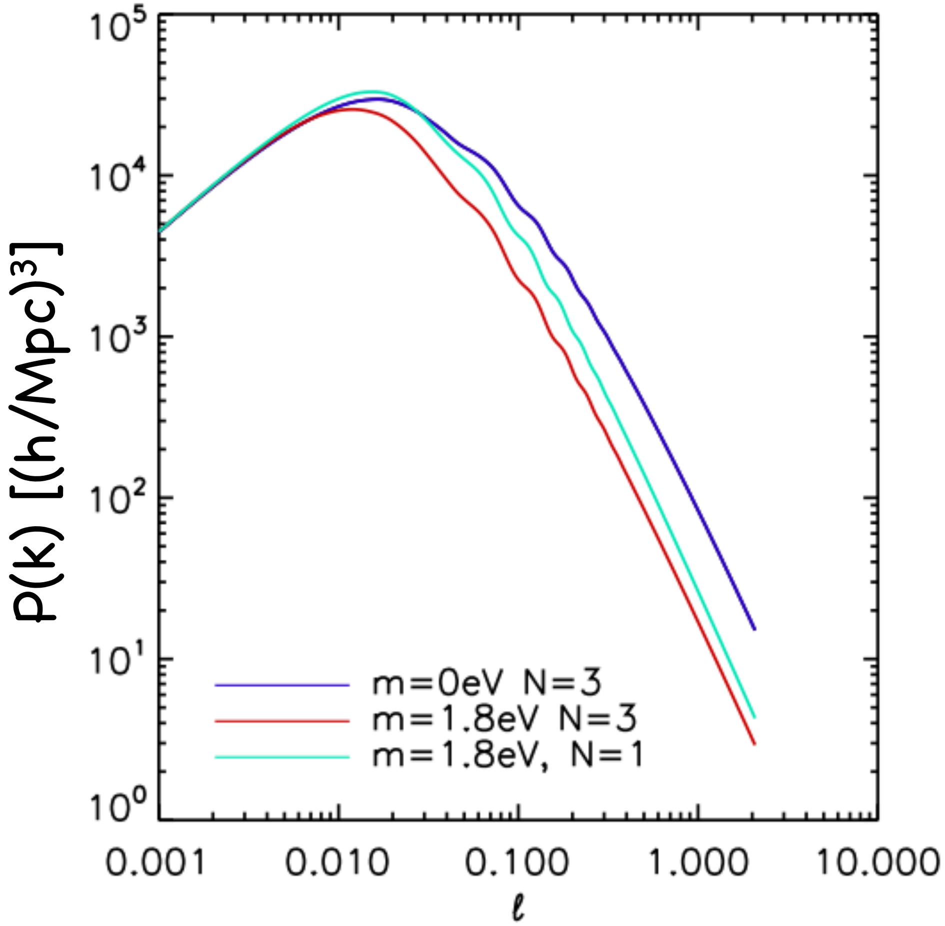
Standard model: N=3.046
Effect of electron-positron annihilation (0.034)
Finite temperature QED (0.01)

Neutrinos: measuring mass

1. **Background:** Neutrinos act like radiation while relativistic.

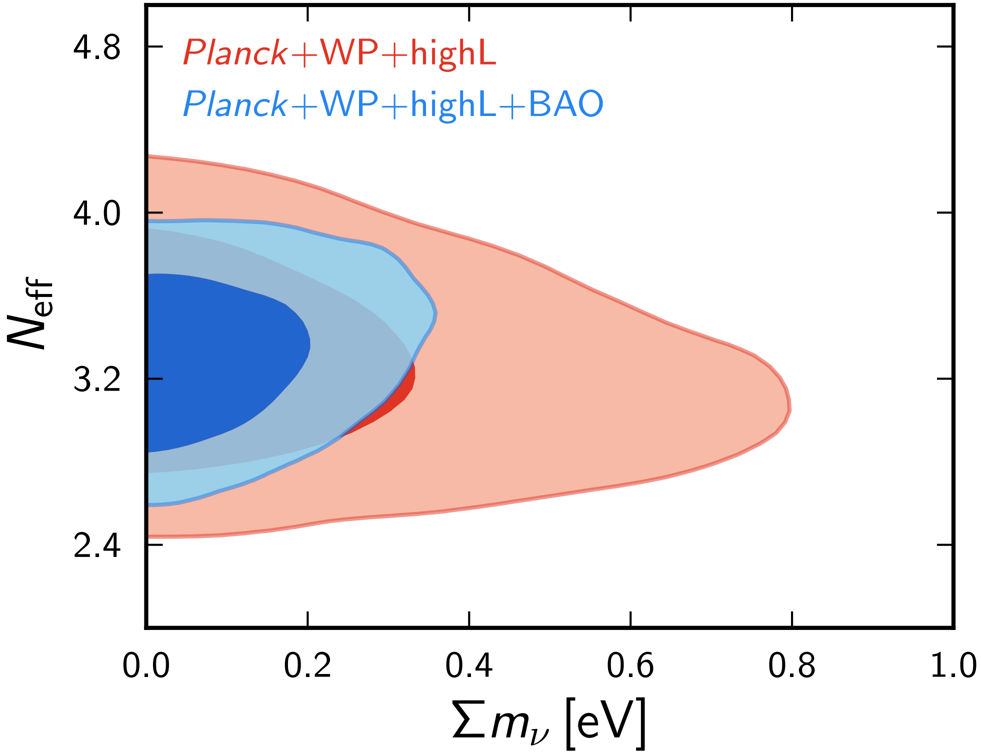
2. **Perturbations:**
   – Neutrinos free-stream when relativistic, and reduce damping of photon-baryon oscillations.
   – 1.5eV total mass ~ time of CMB
   – smears out matter clustering on scales where relativistic.
   – if N_mass<3, each neutrino becomes non-relativistic sooner.

$$k_{nr} = 0.026\left(\frac{m_\nu}{1eV}\right)^{1/2}\Omega_m{}^{1/2}h\mathrm{Mpc}^{-1}$$



k (h/Mpc)

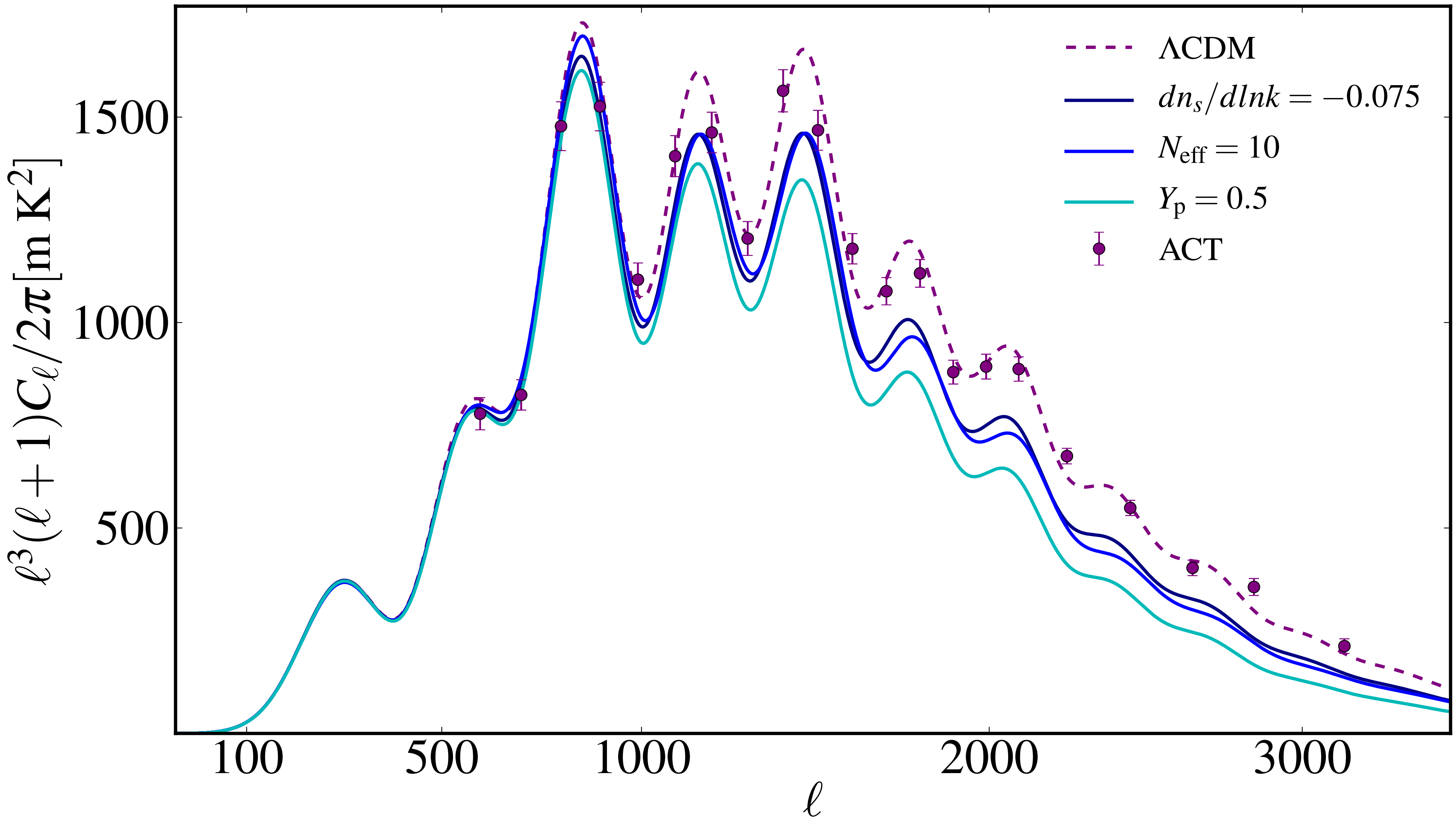
Planck constraints



Σm_ν < 0.66 eV (95%, Planck+WP+highL)
Σm_ν < 0.23 eV (+BAO)

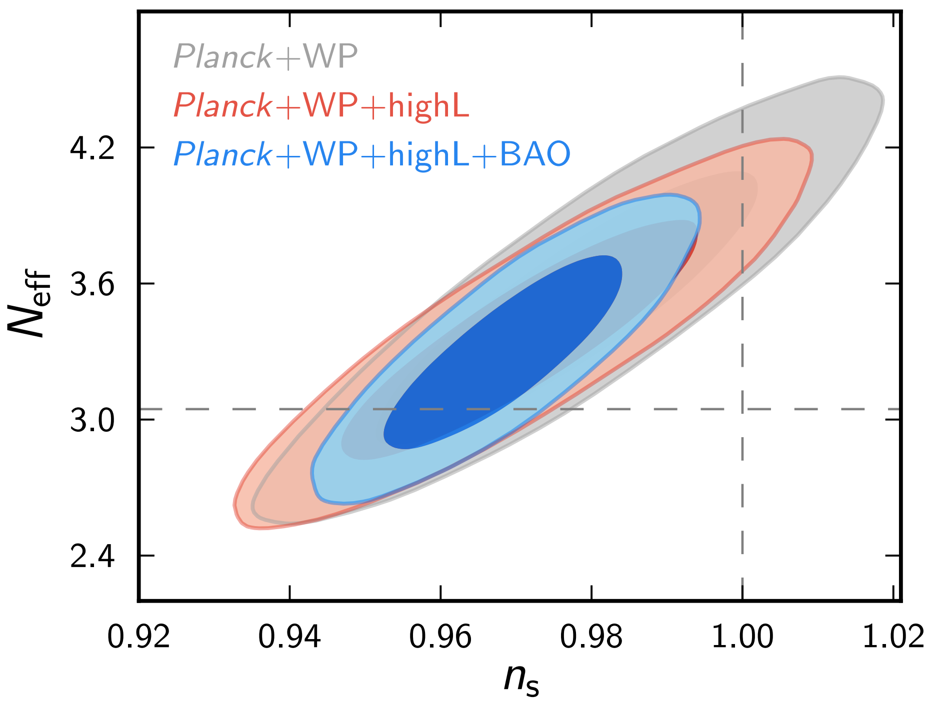
- Still relativistic at recombination
- Improved limit also driven by lensing effect in power spectrum
- More mass; more suppression of lensing
- Some hints of 'tensions' with cluster counts - no evidence yet that this is not just astrophysics

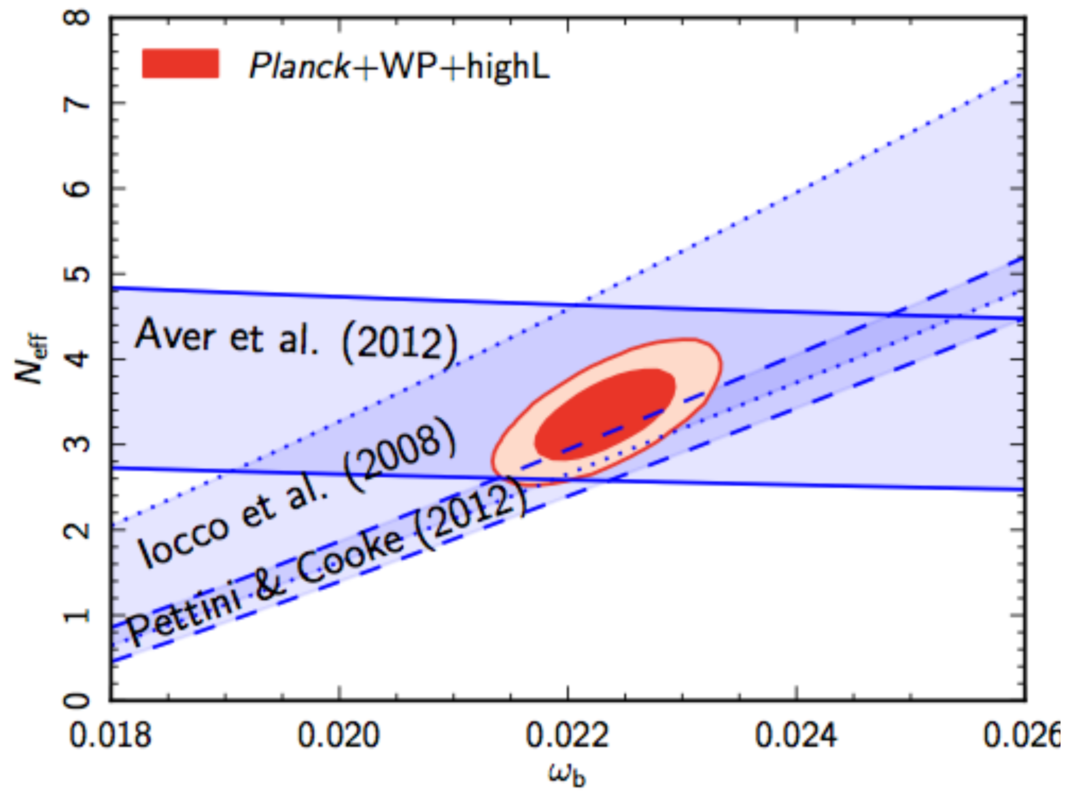
Neutrino number: effect on small scales



From E. Calabrese, for ACT

Relativistic species

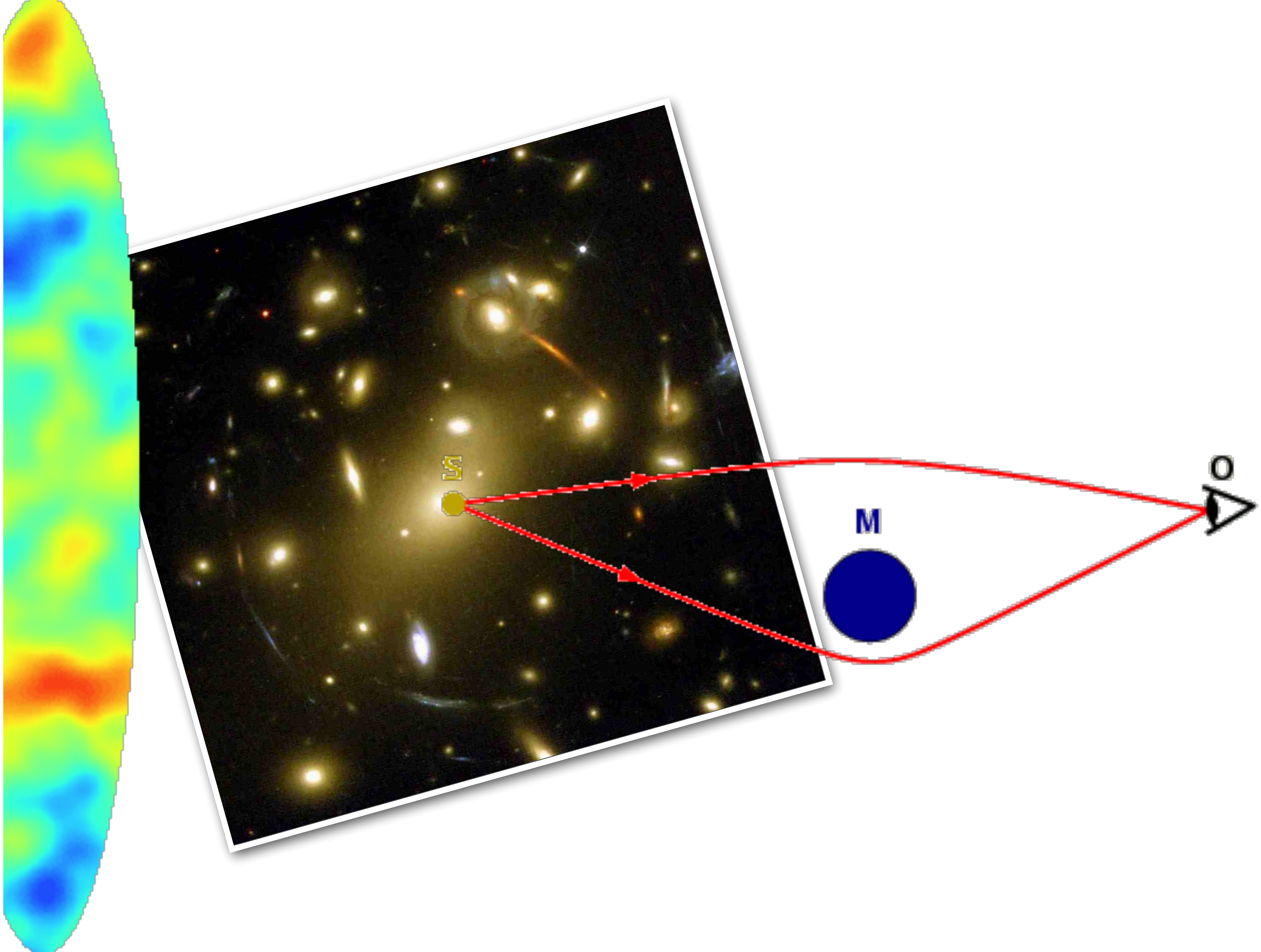


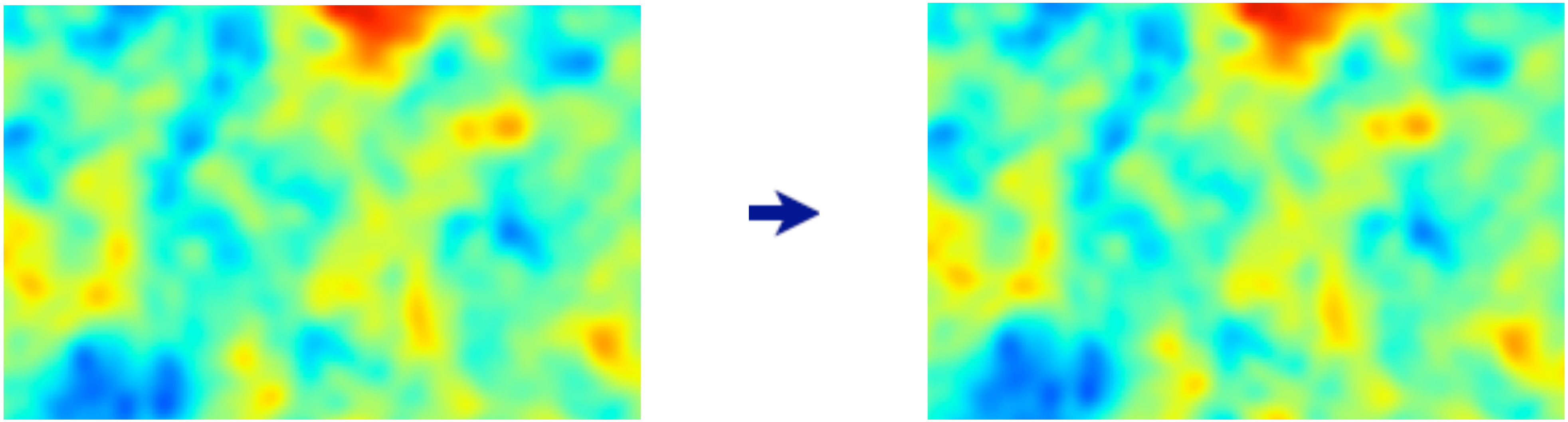


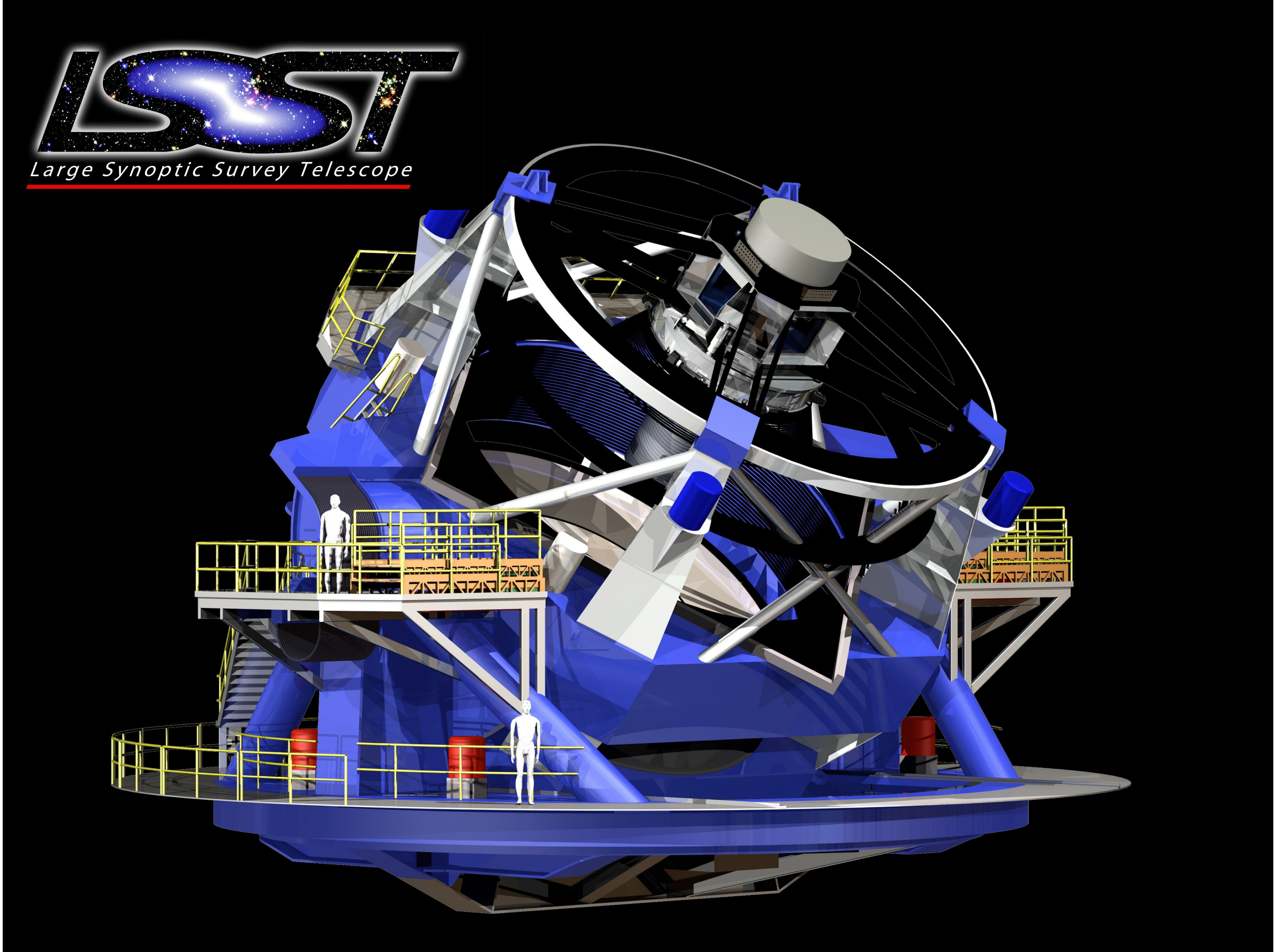
Planck Collab XVI 2013

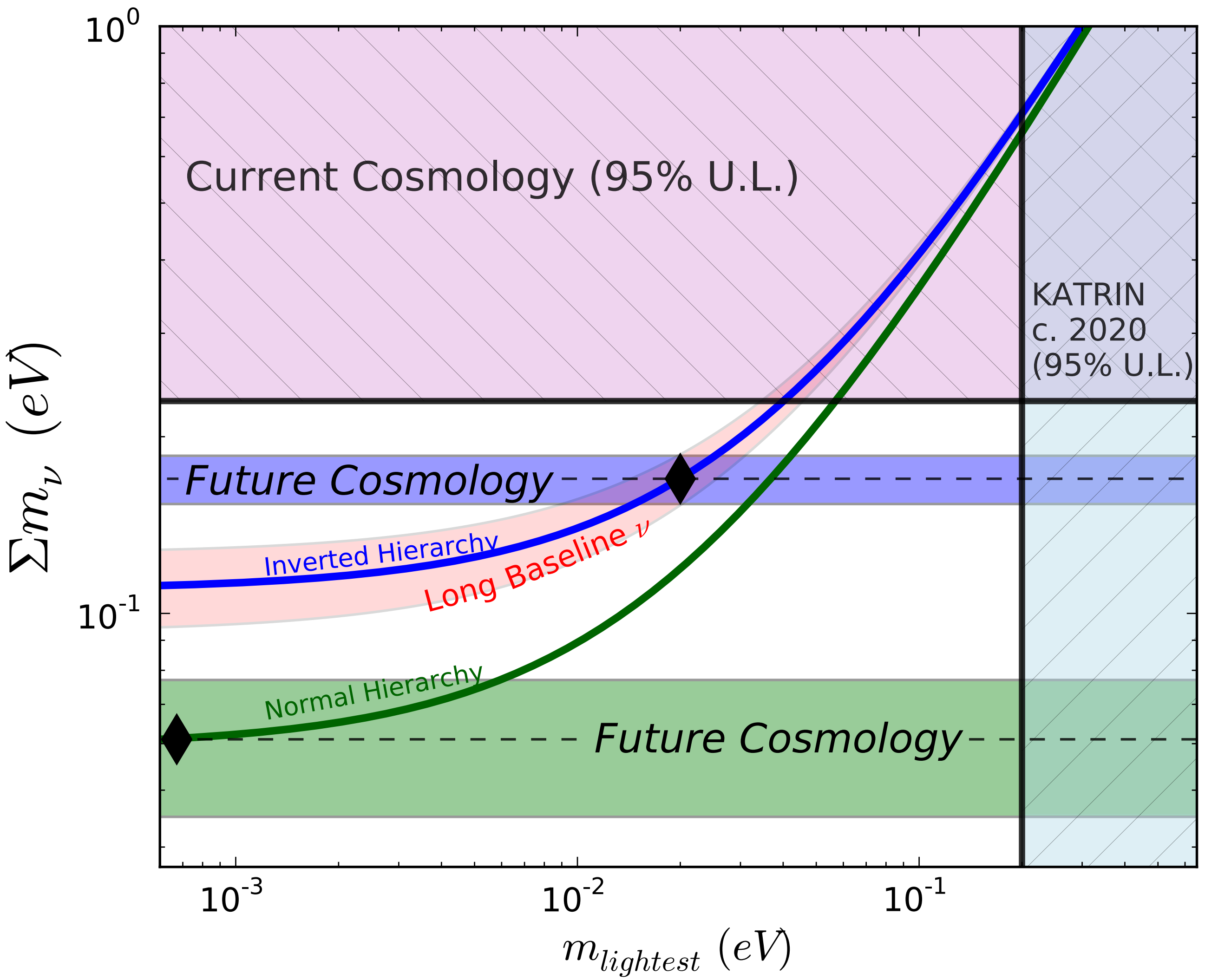
More species, longer radiation domination; suppress early acoustic oscillations in primary CMB; have anisotropic stress

N_{eff} = 3.36 ± 0.34 (68%, Planck+WP+highL)
N_{eff} = 3.30 ± 0.27 (+BAO)


S
M
O




LSST
Large Synoptic Survey Telescope



Gravitational lensing and galaxy clustering promises to detect a 0.05eV neutrino mass sum in the next decade (sigma = 16meV) - some close work needed between astro and particle to make sure we trust any result.

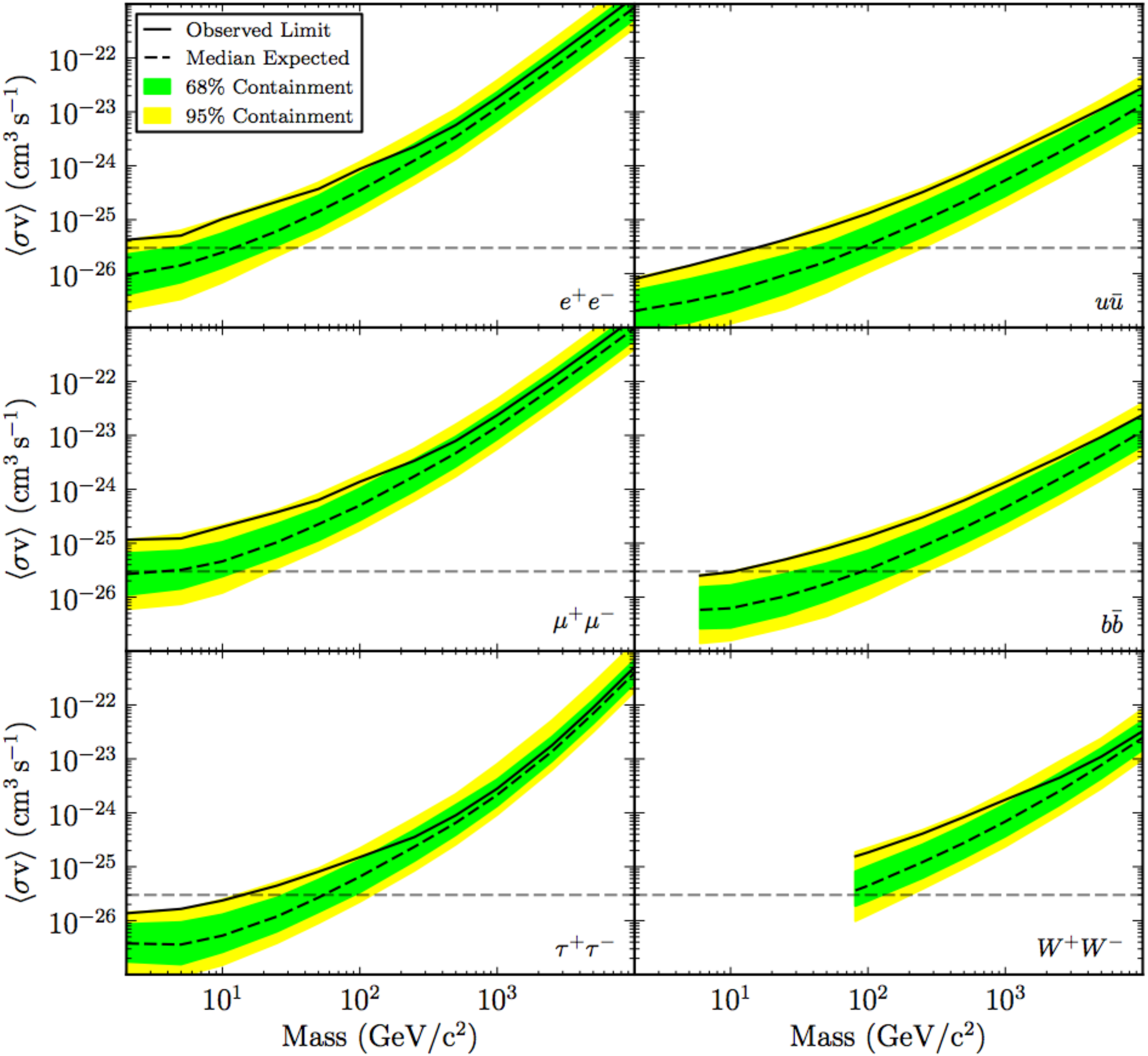
Summary

- CMB tightly constrains the relic density of CDM. Within that there is room for it to be WIMP, sterile neutrino, or axion etc.

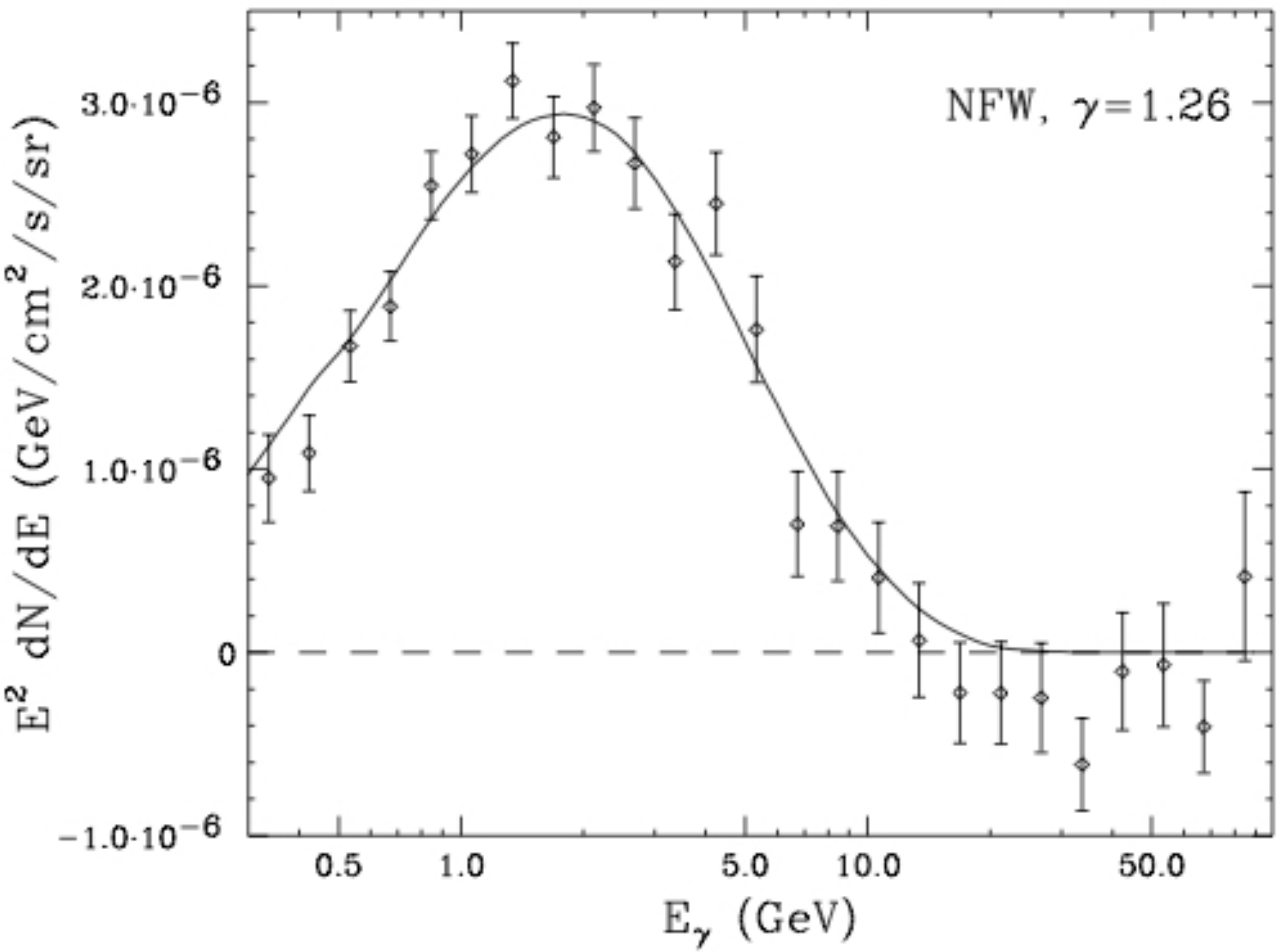
- On galactic scales there are questions about whether CDM really works, zooming in on halo substructure. But effects are very hard to simulate correctly.

- From cosmology we limit the sum of neutrino masses to be <0.23eV, and limit any excess relativistic density to be Delta Neff=0.3+-0.3

- Numerical simulations will continue to improve, and we will map out the CDM with gravitational lensing. Projected to reach a neutrino mass detection in next decade.



Observed Limit
Median Expected
68% Containment
95% Containment
$\langle \sigma v \rangle$ (cm^3 s^{-1})
10^{-22}
10^{-23}
10^{-24}
10^{-25}
10^{-26}
e^+e^-
$u\bar{u}$
$\mu^+\mu^-$
$b\bar{b}$
$\tau^+\tau^-$
W^+W^-
10^1
10^2
10^3
Mass (GeV/c^2)



NFW, γ=1.26
3.0·10⁻⁶
2.0·10⁻⁶
1.0·10⁻⁶
0
−1.0·10⁻⁶
E² dN/dE (GeV/cm²/s/sr)
0.5
1.0
5.0
10.0
50.0
Eγ (GeV)