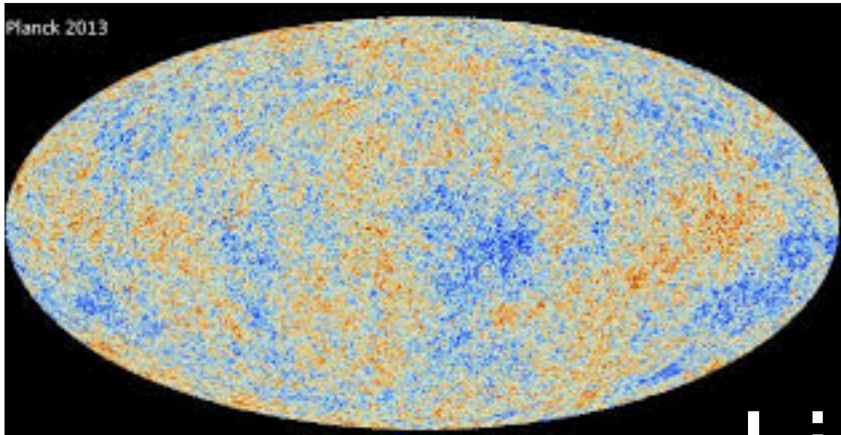
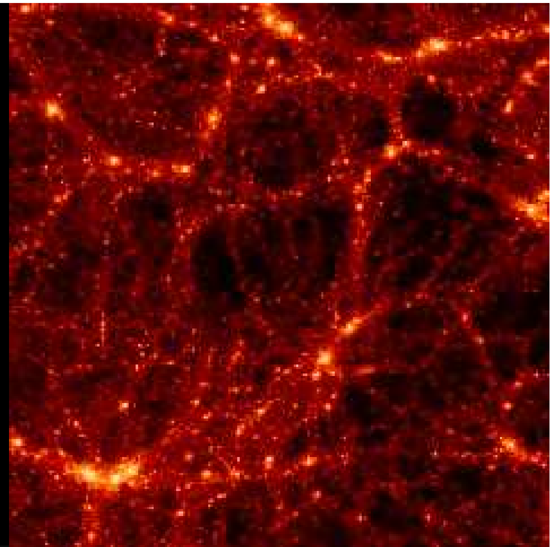




Licia Verde

ICREA & ICC-UB-IEEC (Barcelona)
OiU (Oslo)

Precision cosmology

Why should you care?

(only highlights)

http://icc.ub.edu/~liciaverde

icrea Institució Catalana de Recerca i Estudis Avançats
ICCUB Institut de Ciències del Cosmos
UNIVERSITAT DE BARCELONA
IEEC
UNIVERSITAS OSLOENSIS MDCCCXI

First decade of 2000: Precision cosmology

(WMAP, Boomerang, Acbar, …SDSS**,** 2dF, **Supernovae** etc..)

ΛCDM: The standard cosmological model

Just 6 numbers…..

describe the Universe composition and evolution

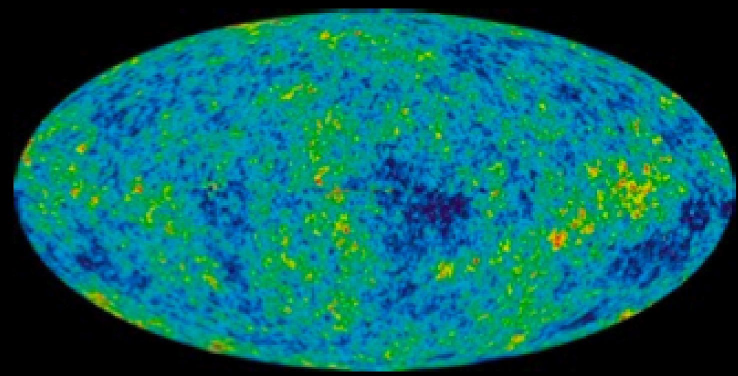
Homogenous background

$$\Omega_b, \Omega_c, \Omega_\Lambda, H_0, \tau$$

- atoms 4%
- cold dark matter 23%
- dark energy 73%

Λ? CDM?

Perturbations

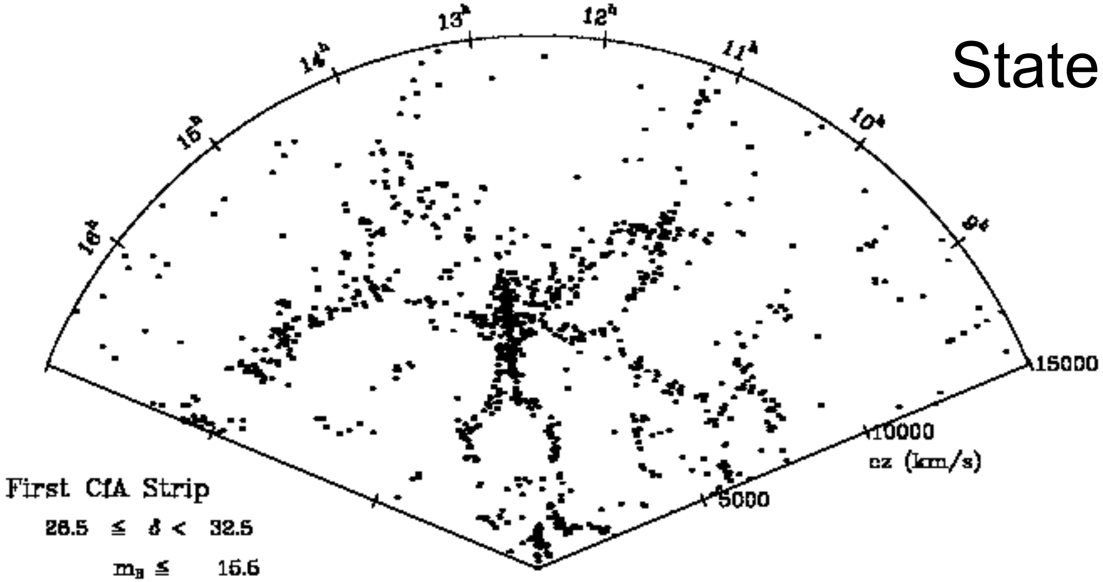


$$A_s, n_s, r$$

- nearly scale-invariant
- adiabatic
- Gaussian

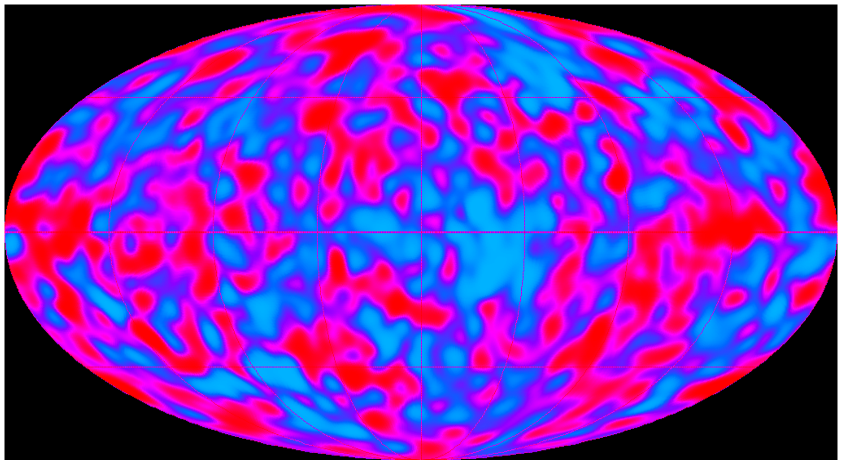
ORIGIN??

Extremely successful standard model for cosmology



State of the art of data then…

~14 Gyr
(a posteriori information)

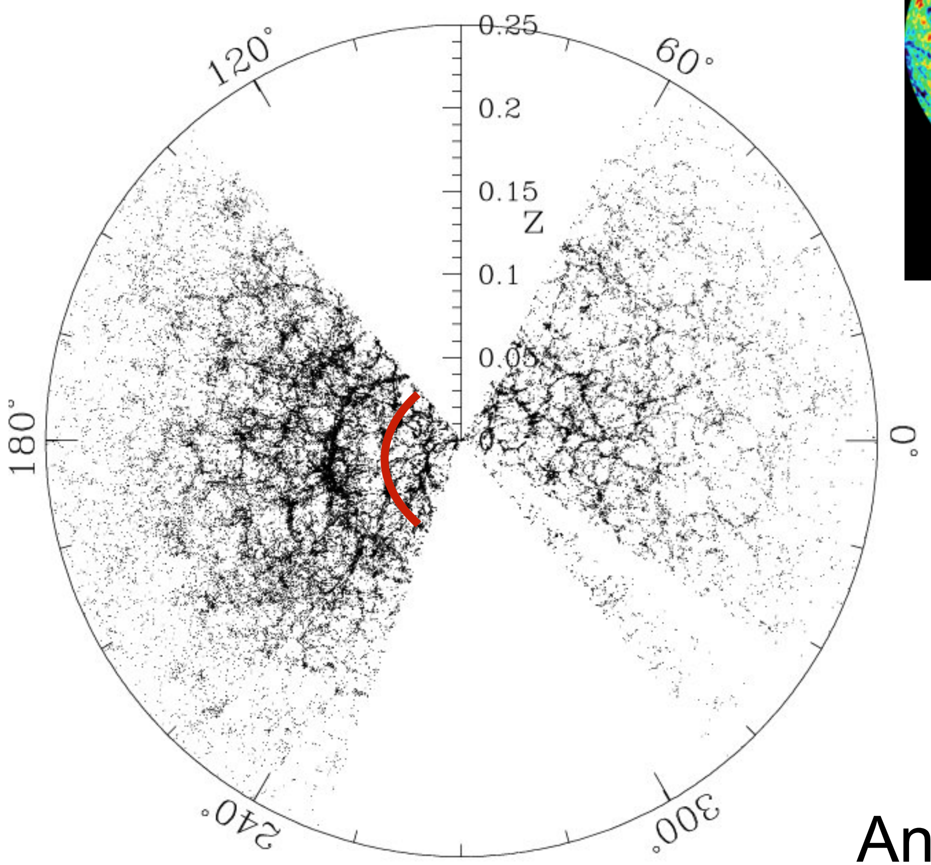


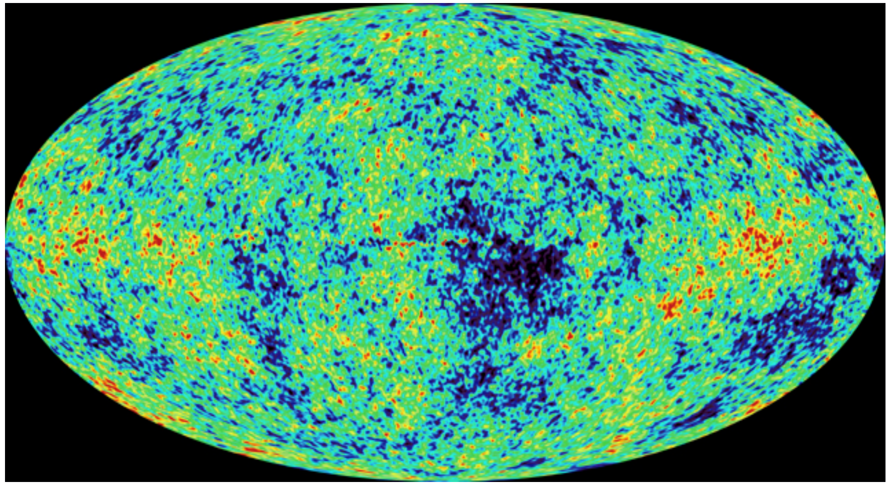
(DMR)COBE

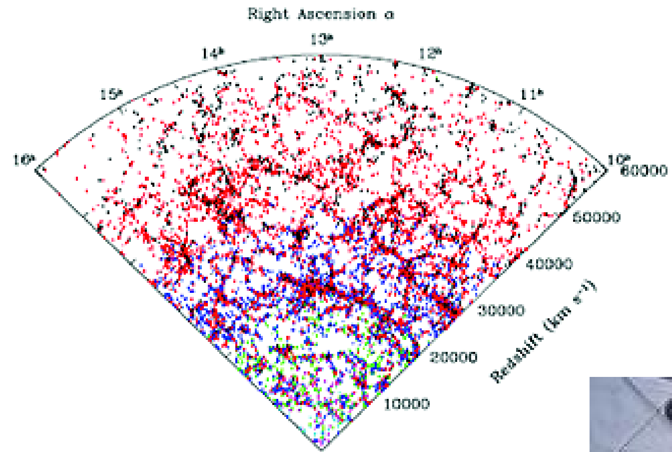
CMB

380000 yr
(a posteriori information)

Avalanche of data







And it still holds!

Context and overview

- Cosmology over the past 20 years has made the transition to *precision cosmology*
- Cosmology has moved from a *data-starved science* to a *data-driven science*
- Cosmology has now a *standard model.* The *standard cosmological model* only needs few parameters to describe origin composition and evolution of the Universe
- Big difference between modeling and understanding

Cosmology is special

We can't make experiments, only observations

The curse of cosmology

We only have one observable universe

We can only make observations (and only of the observable Universe) not experiments: we fit models (i.e. constrain numerical values of parameters) to the observations: <u>Any statement is model dependent</u>

Gastrophysics and non-linearities get in the way :
Different observations are more or less "trustable", it is however somewhat a question of personal taste (think about Standard & Poor's credit rating for countries)

Results will depend on the data you (are willing to) consider. (robustness?)

….And the Blessing

We can observe all there is to see

….And the Blessing

We can observe all there is to see

And almost do

Ultimate survey

challenges

Big data….

Precision cosmology, accurate cosmology!

challenges

As the statistical errors shrink.....

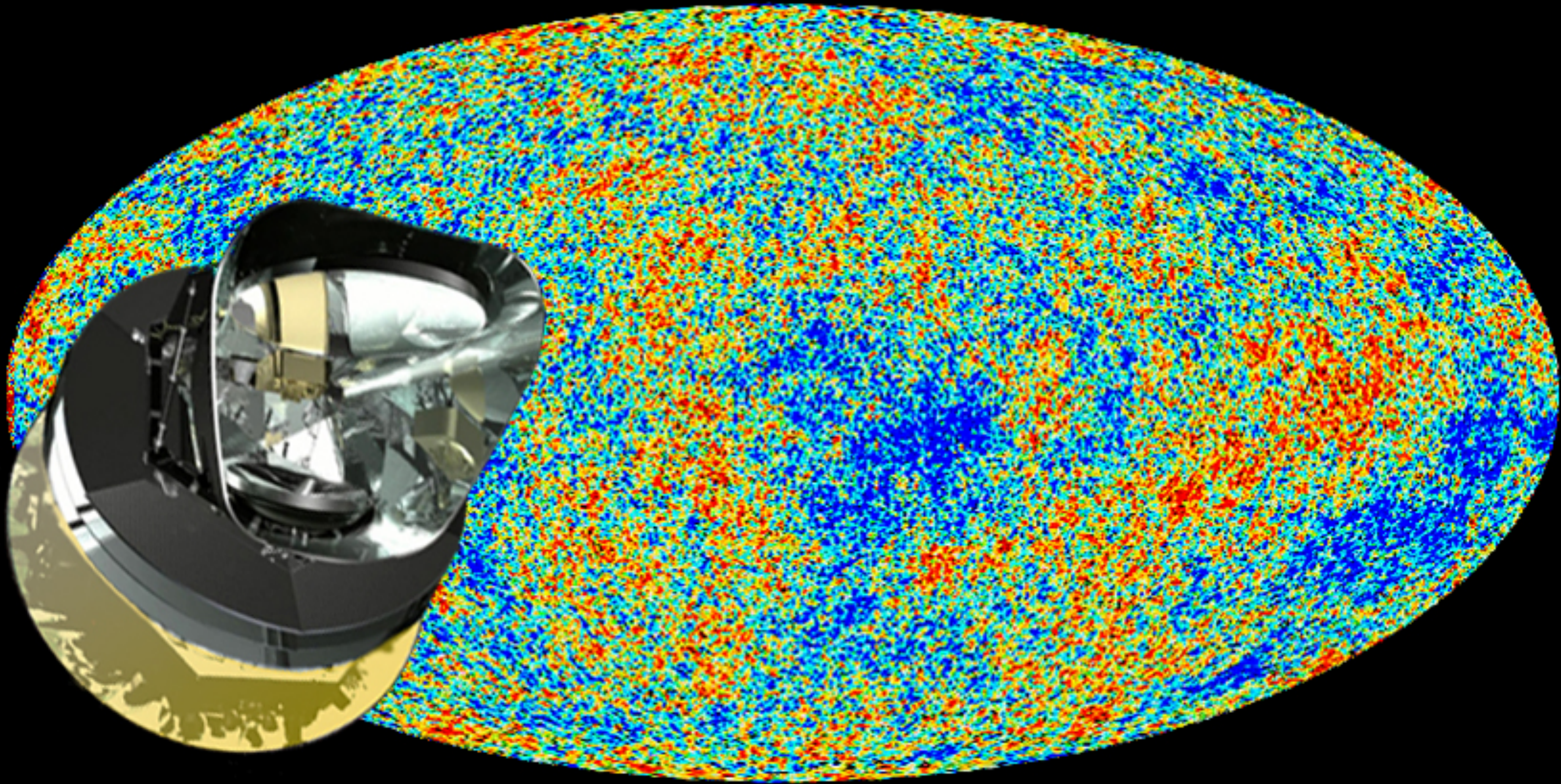
Systematic errors must be kept under exquisite control!

There is no systematic way to address systematic errors

The future is bright!

Ultimate surveys!

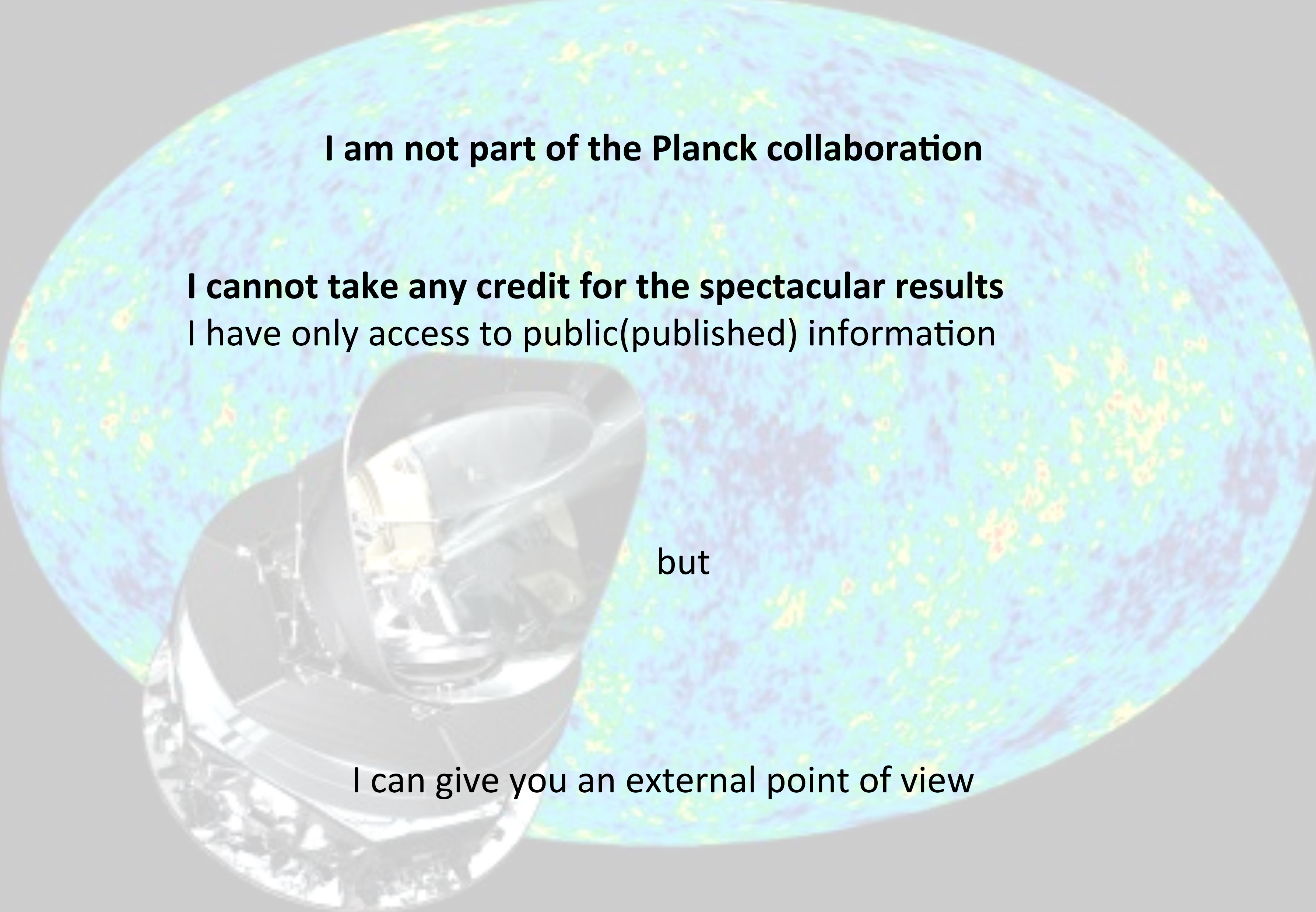
The future is here!



Planck 2015

See Matarrese talk for more details

DISCLAIMER



I am not part of the Planck collaboration

I cannot take any credit for the spectacular results
I have only access to public(published) information

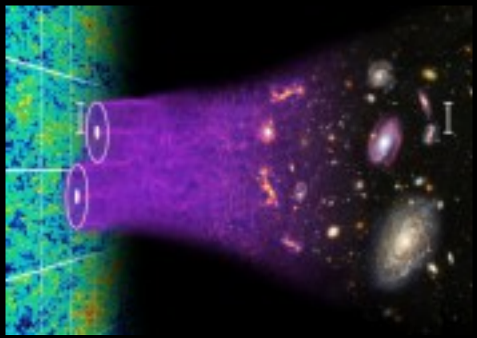
but

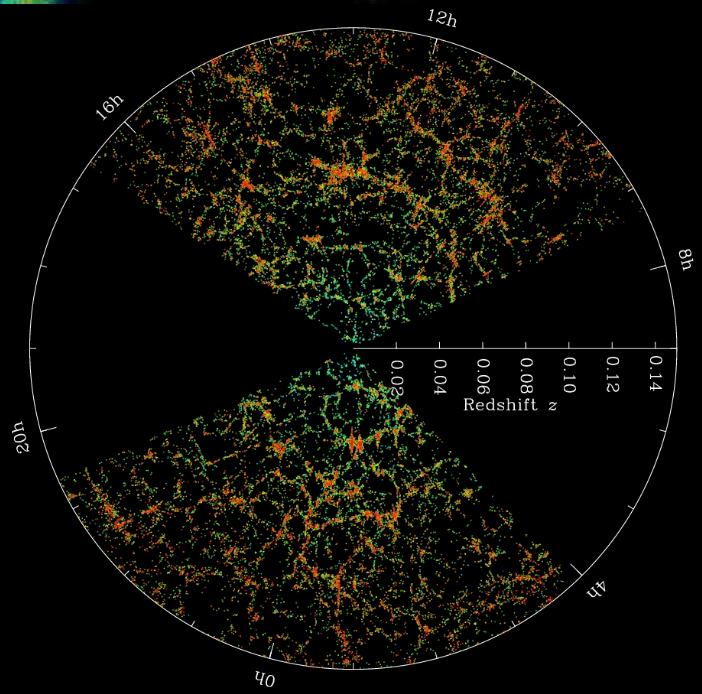
I can give you an external point of view

Wonderful agreement of new data with the ΛCDM model

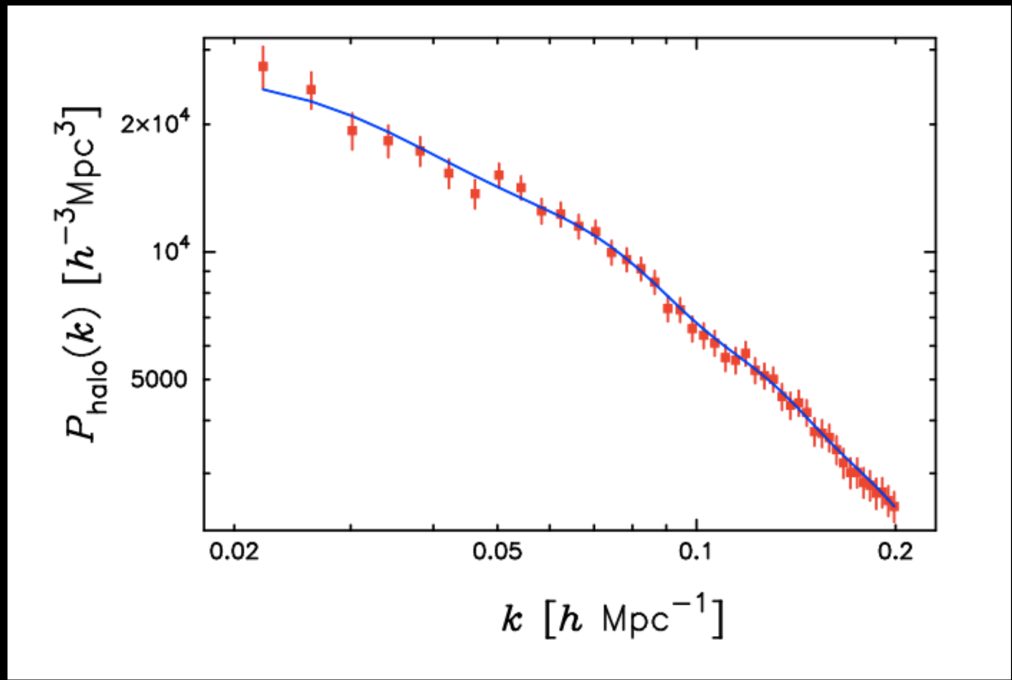
See Matarrese talk for more details

CMB temperature information content has been saturated
The near future IS large-scale structure



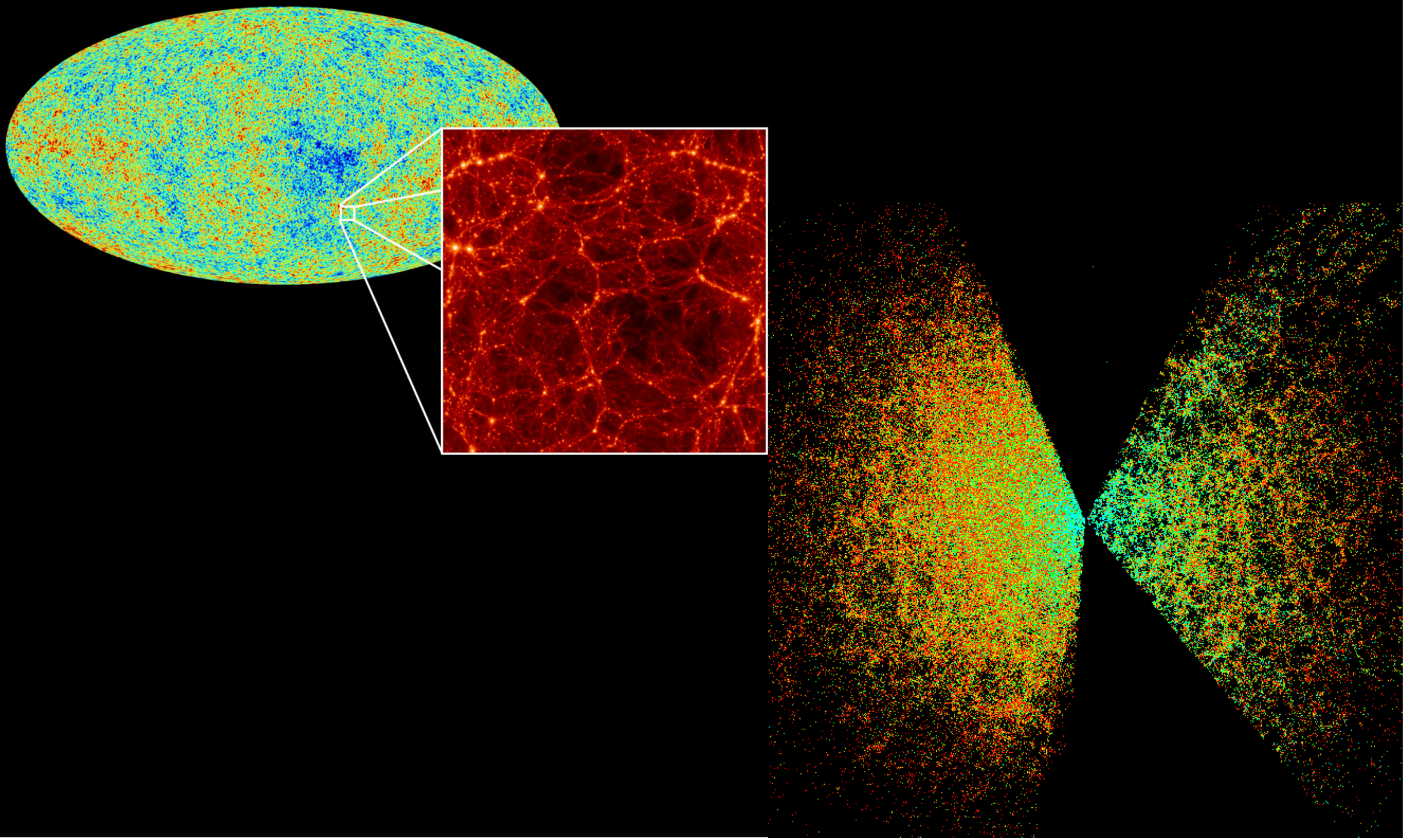


SDSS LRG galaxies power spectrum (Reid et al. 2010)



13 billion years of gravitational evolution

NEXT: Explore low(er)-redshift Universe

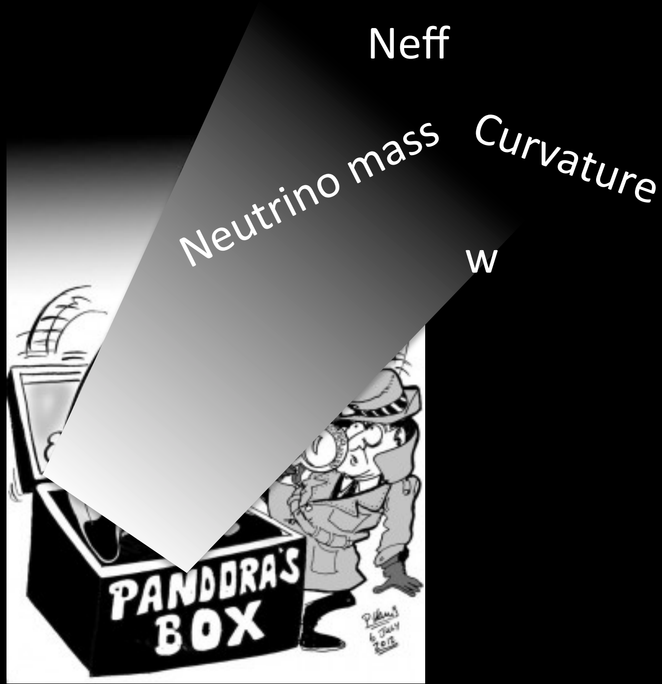


STILL….

The model IS incomplete… Neutrinos have mass

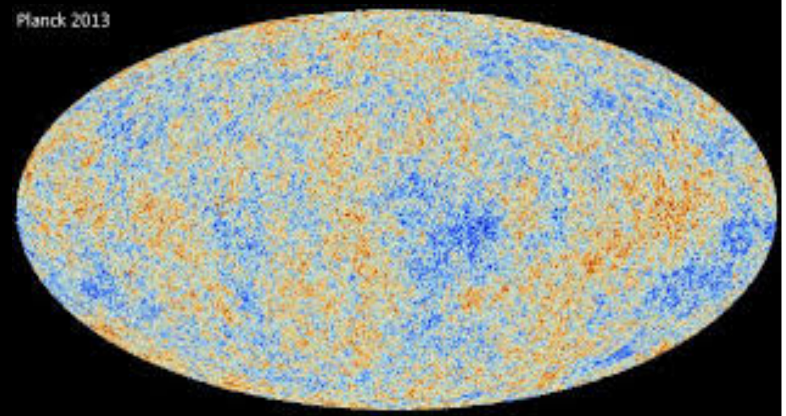
The model is unsatisfactory

The cosmological constant problem
Inflation is more than n_s



This drives a massive experimental effort

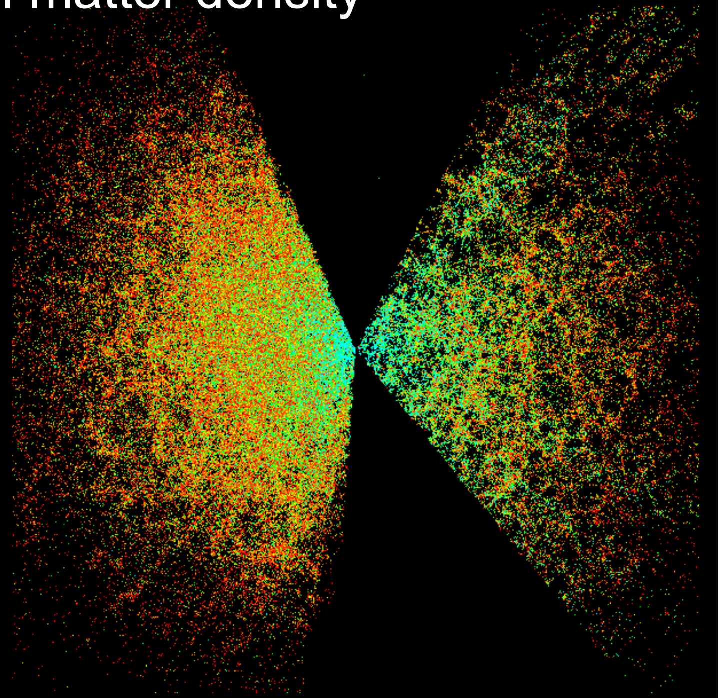
WHY SHOULD YOU CARE?



Forthcoming new avalanche of data enables

PRECISION tests beyond the standard model

Neutrinos contribute at least to ~0.5% of the total matter density



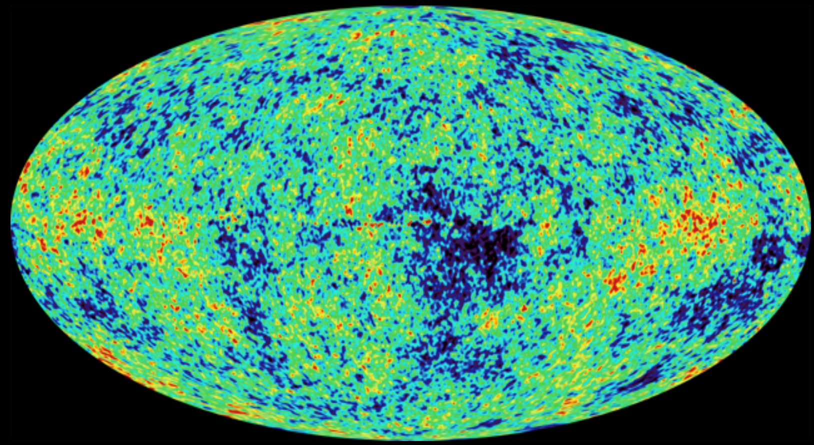
Use the entire Universe as “detector”!

What is a neutrino? (for cosmology)

- Behaves like radiation at T~ eV (recombination/decoupling)
- Eventually (possibly) becomes non-relativistic, behaves like matter
- Small interactions (not perfect fluid)
- Has a high velocity dispersion (is “HOT”)

Cosmic Neutrino Background

A relict of the big bang, similar to the CMB except that the CvB decouples from matter after 2s (~ MeV) not 380,000 years



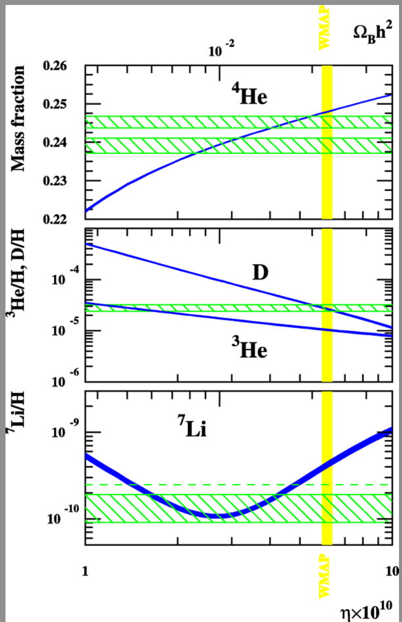
At decoupling they are still relativistic ($m\nu << T\nu$) ➔ large velocity dispersions (1eV ~ 100 Km/s)

Recall:
T~1eV Matter-radiation equality, T=0.26eV at recombination

600Billion nu/s/cm^3 from the sun
~100nu/cm^3 from CvB

Relict neutrinos influence in cosmology

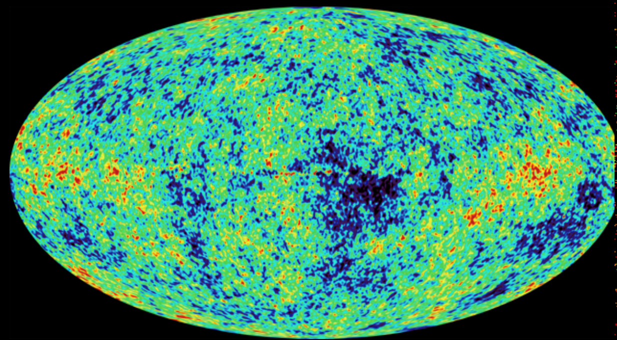
Primordial nucleosynthesis



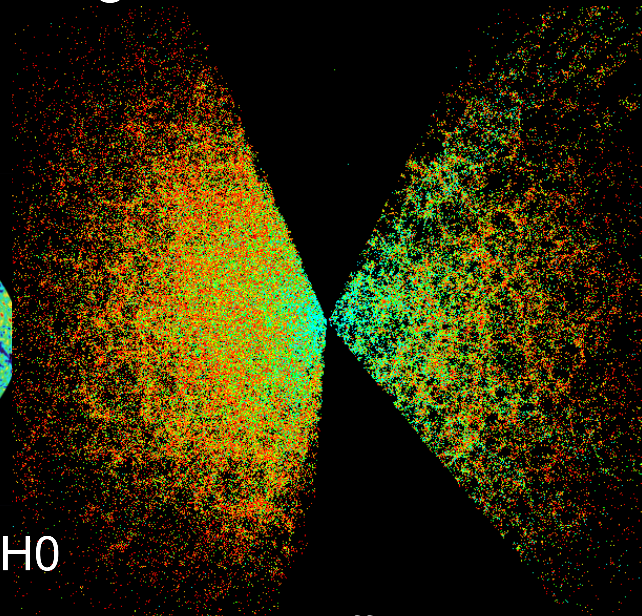
T~ MeV

N_{eff} *changes neutron freezeout and hence Y_{He} & Y_D*

CMB



Large-scale structure



& H0

T<eV

N_{eff}

mass

Neutrinos affect the growth of cosmic clustering (below the free streaming scale) and expansion rate so they can leave key imprints on the cosmological observables

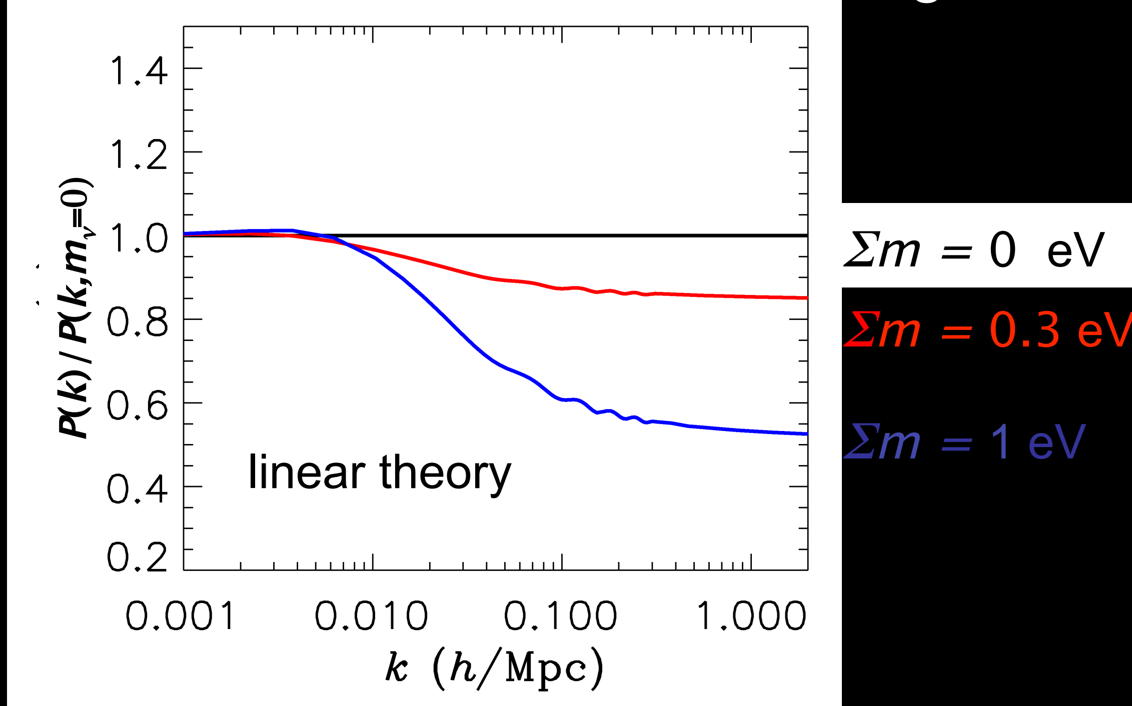
Neutrino mass: Physical effects

Total mass >~1 eV become non relativistic before recombination — CMB

Total mass <~1 eV become non relativistic after recombination: alters matter-radn equality but effect can be "cancelled" by other parameters — CMB Degeneracy

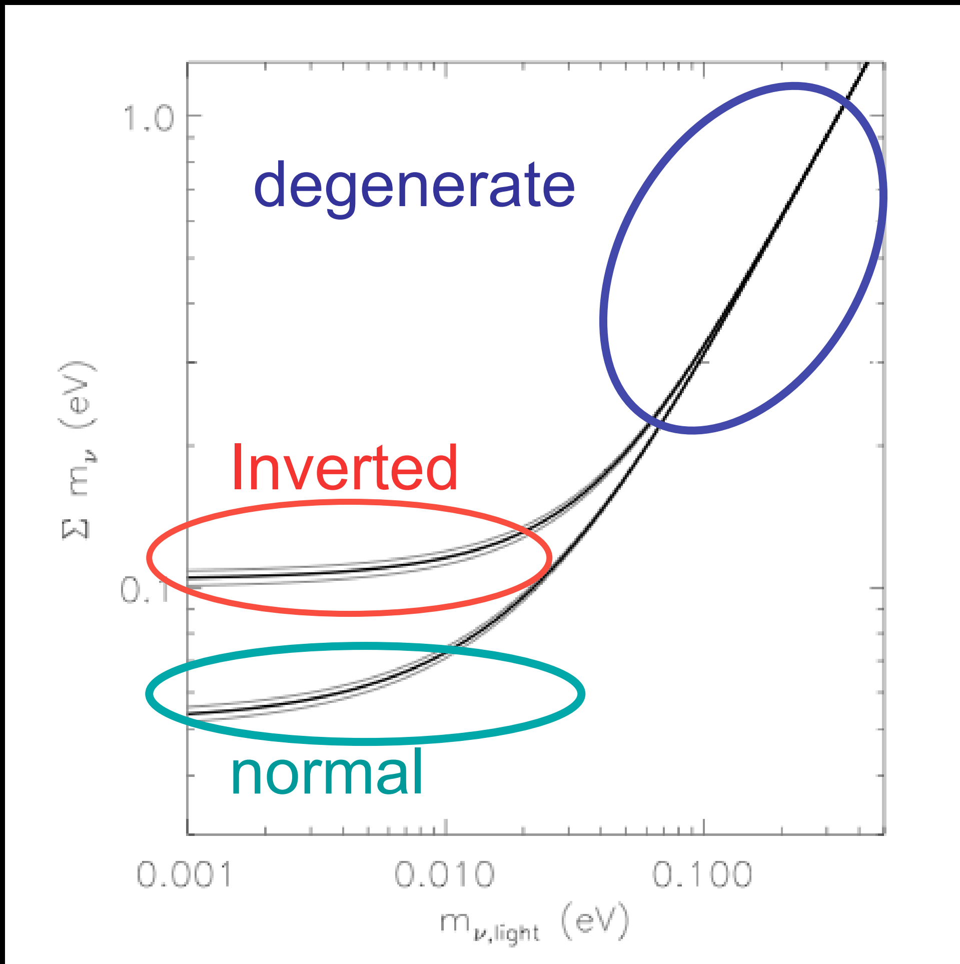
After recombination

FINITE NEUTRINO MASSES SUPPRESS THE MATTER POWER SPECTRUM ON SCALES SMALLER THAN THE FREE-STREAMING LENGTH



Different masses become non-relativistic a slightly different times
Cosmology can yield information about neutrino mass hierarchy

Cosmology is key in determining the absolute mass scale

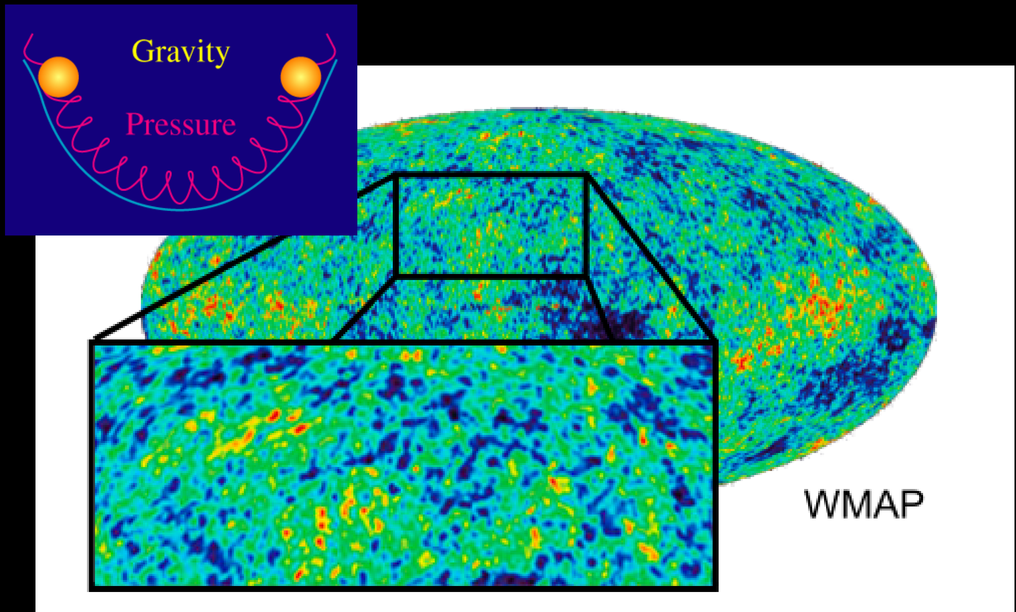


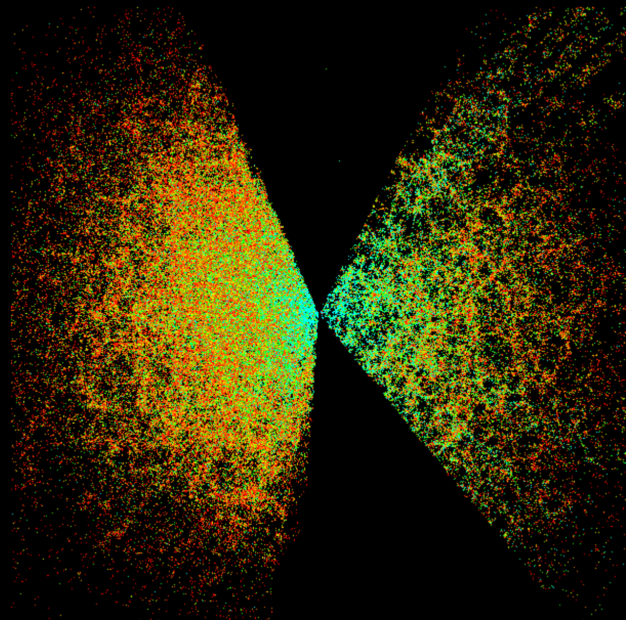
The problem is systematic errors

This means that neutrinos contribute at least to ~0.5% of the total matter density

BAOs

Baryon acoustic oscillations





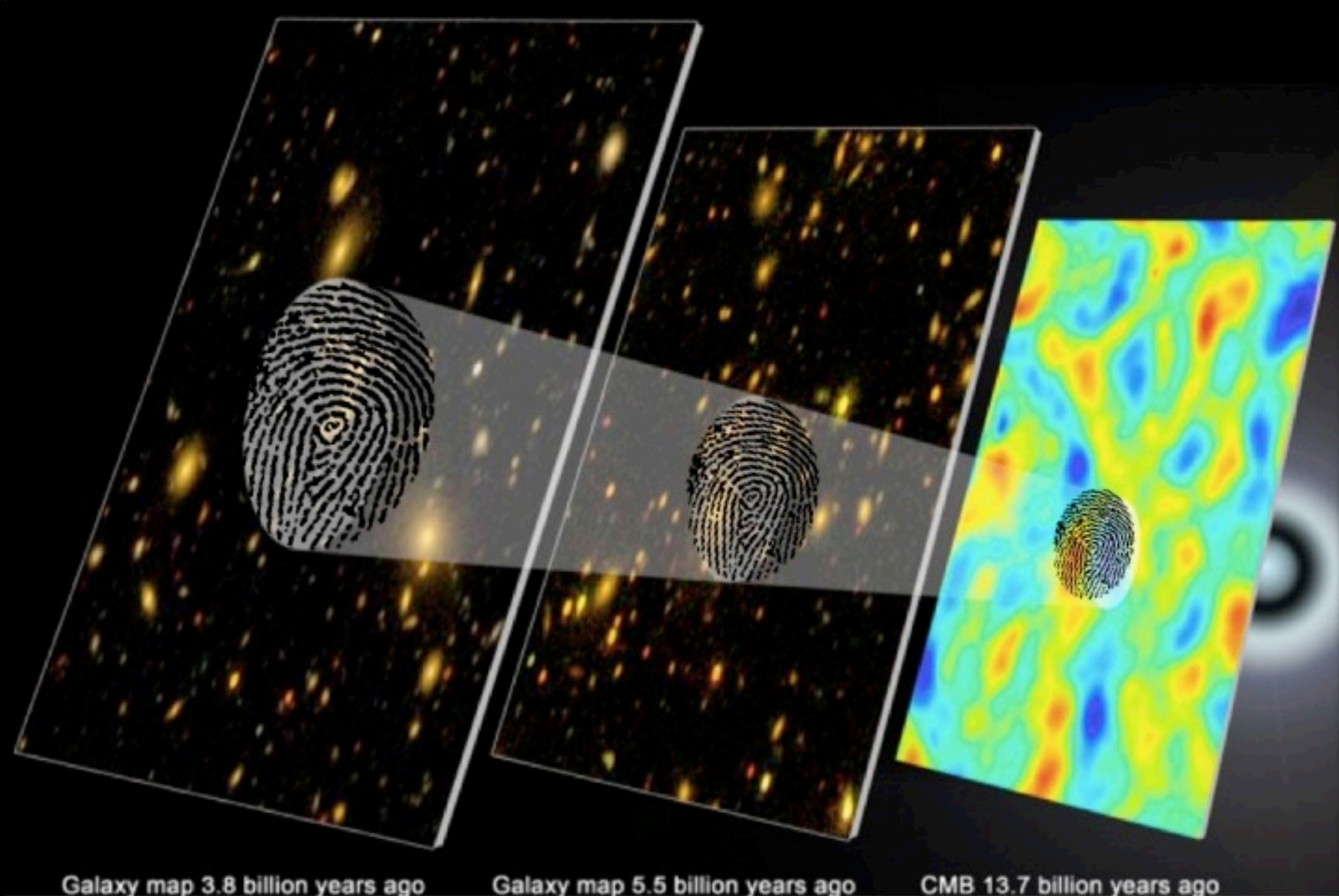
Observe photons

Photons coupled to baryons

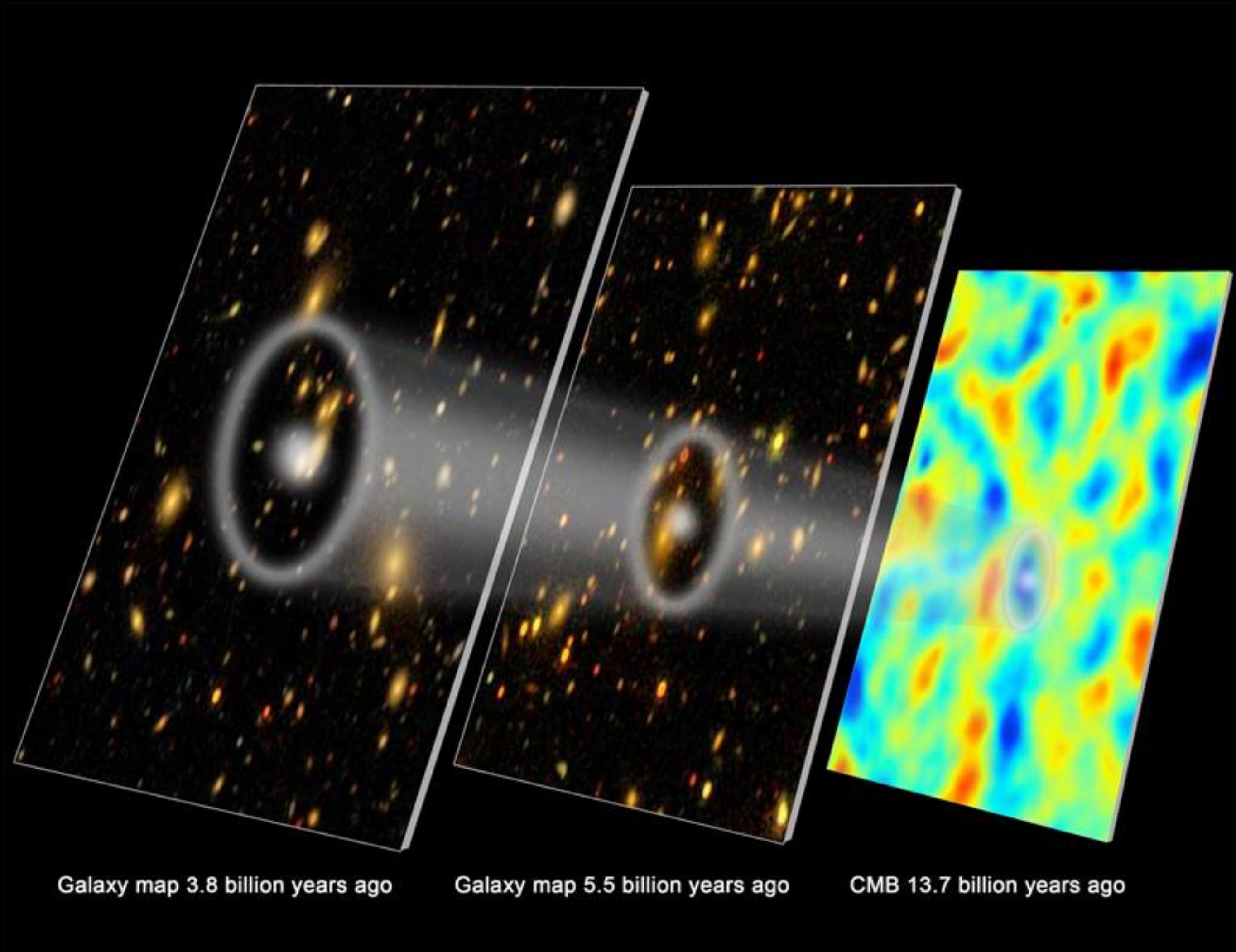
"See" dark matter

AS baryons are ~1/6 of the dark matter these baryonic oscillations leave some imprint in the dark matter distribution (gravity is the coupling)

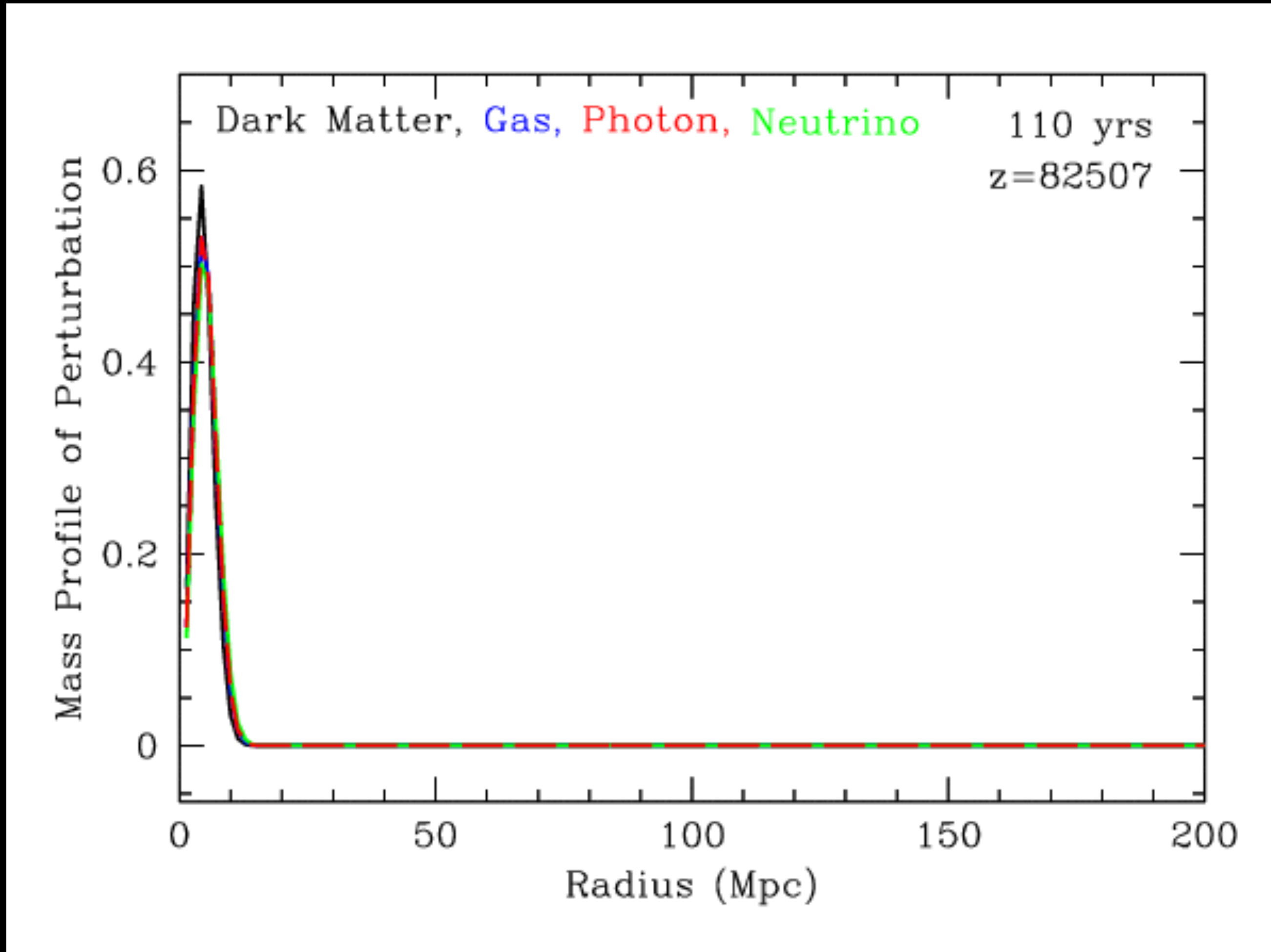
Baryon acoustic oscillations (BAO)



Baryon acoustic oscillations (BAO)



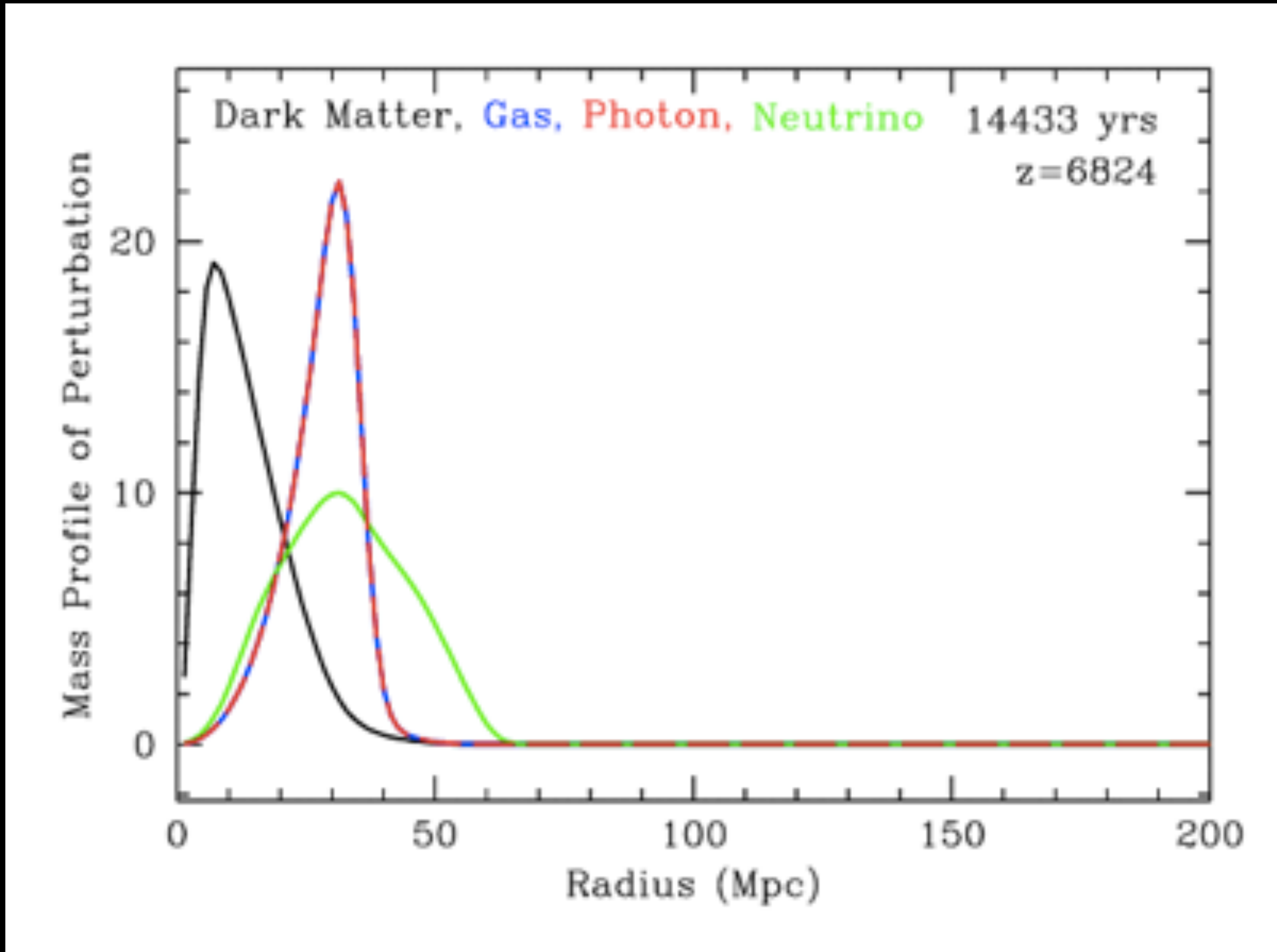
Baryon acoustic oscillations (BAO)



History of a single perturbation: imagine a superposition!

Animation courtesy of D. Eisenstein

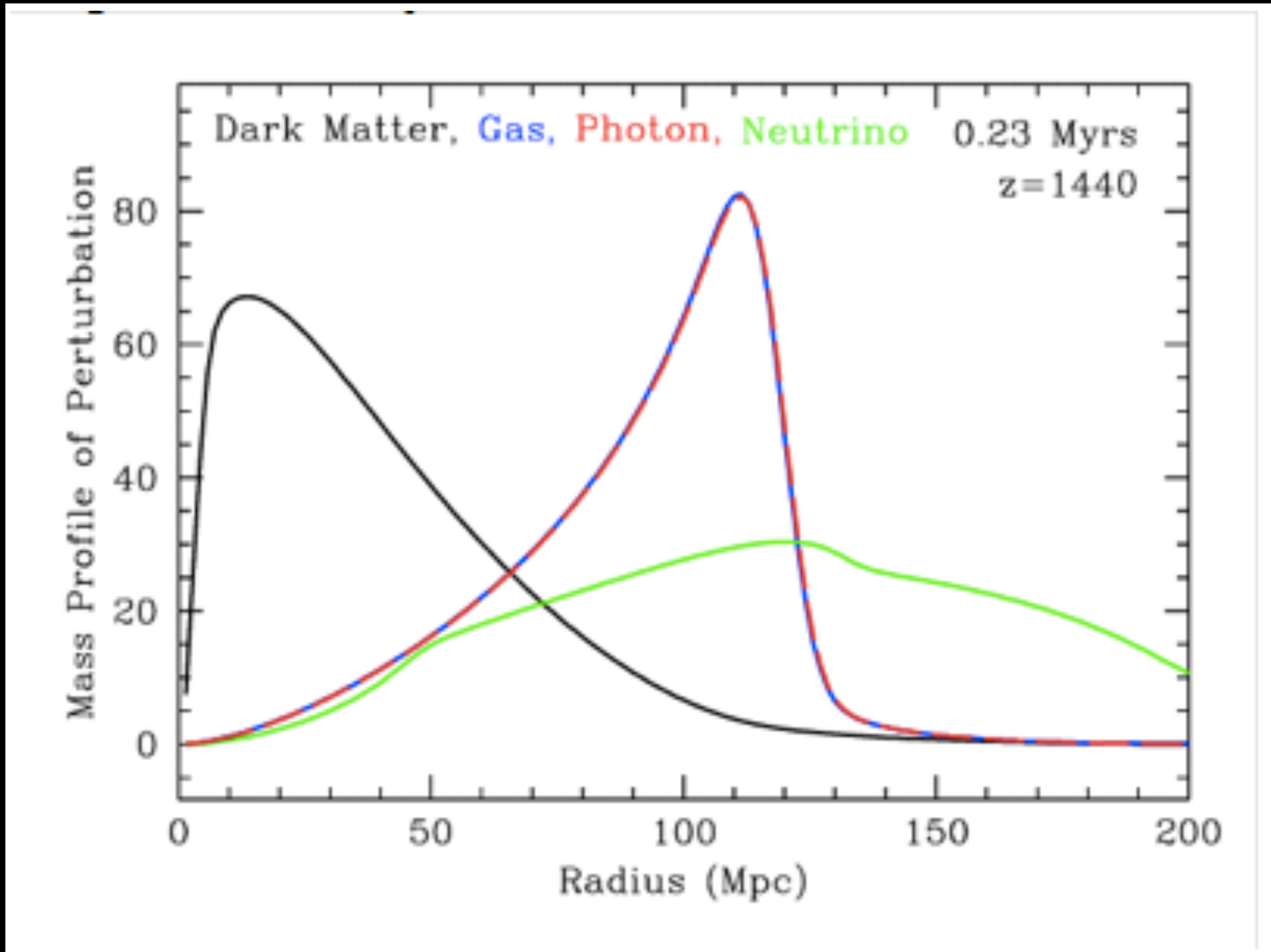
Baryon acoustic oscillations (BAO)



History of a single perturbation: imagine a superposition!

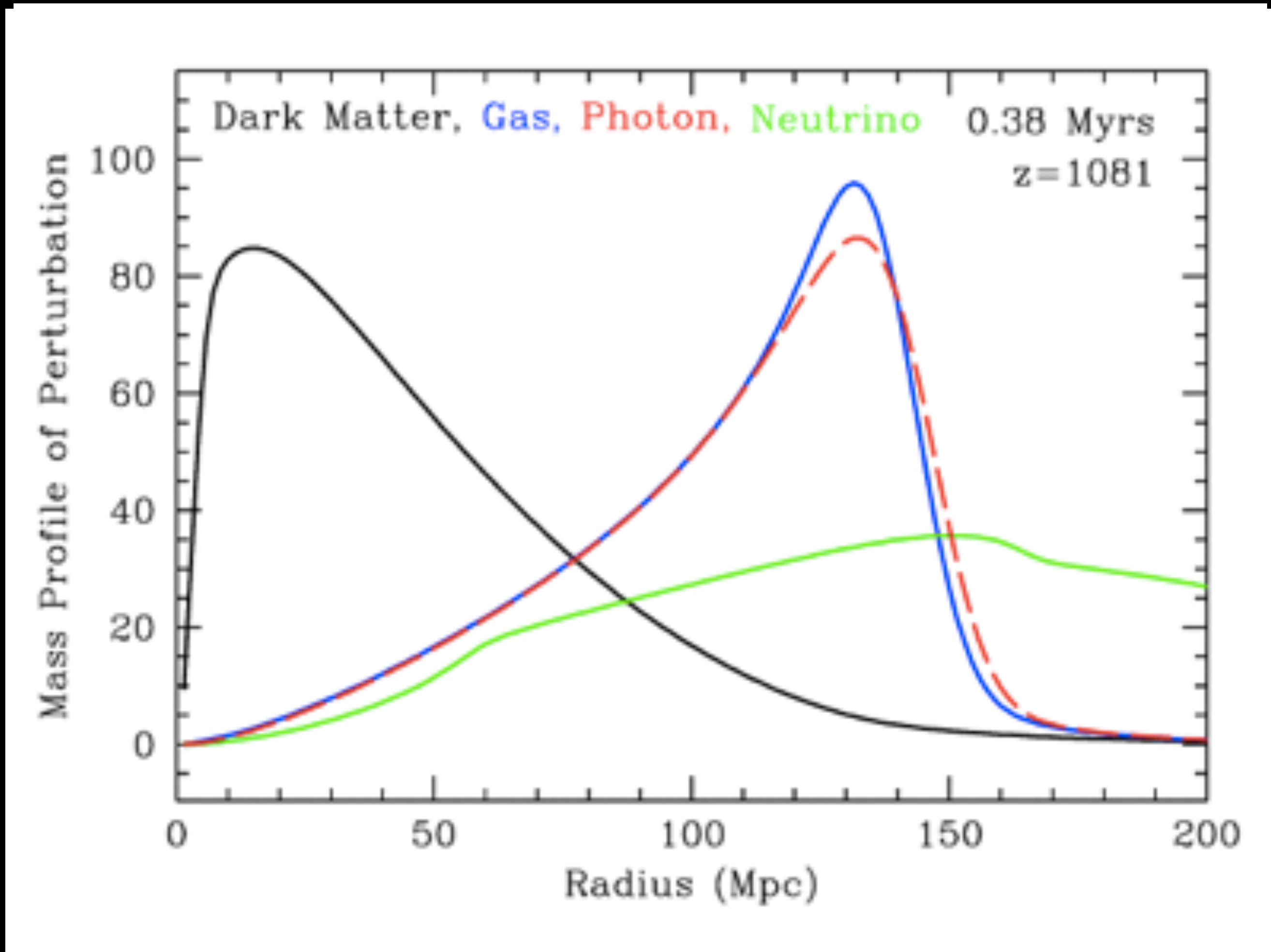
Animation courtesy of D. Eisenstein

Baryon acoustic oscillations (BAO)



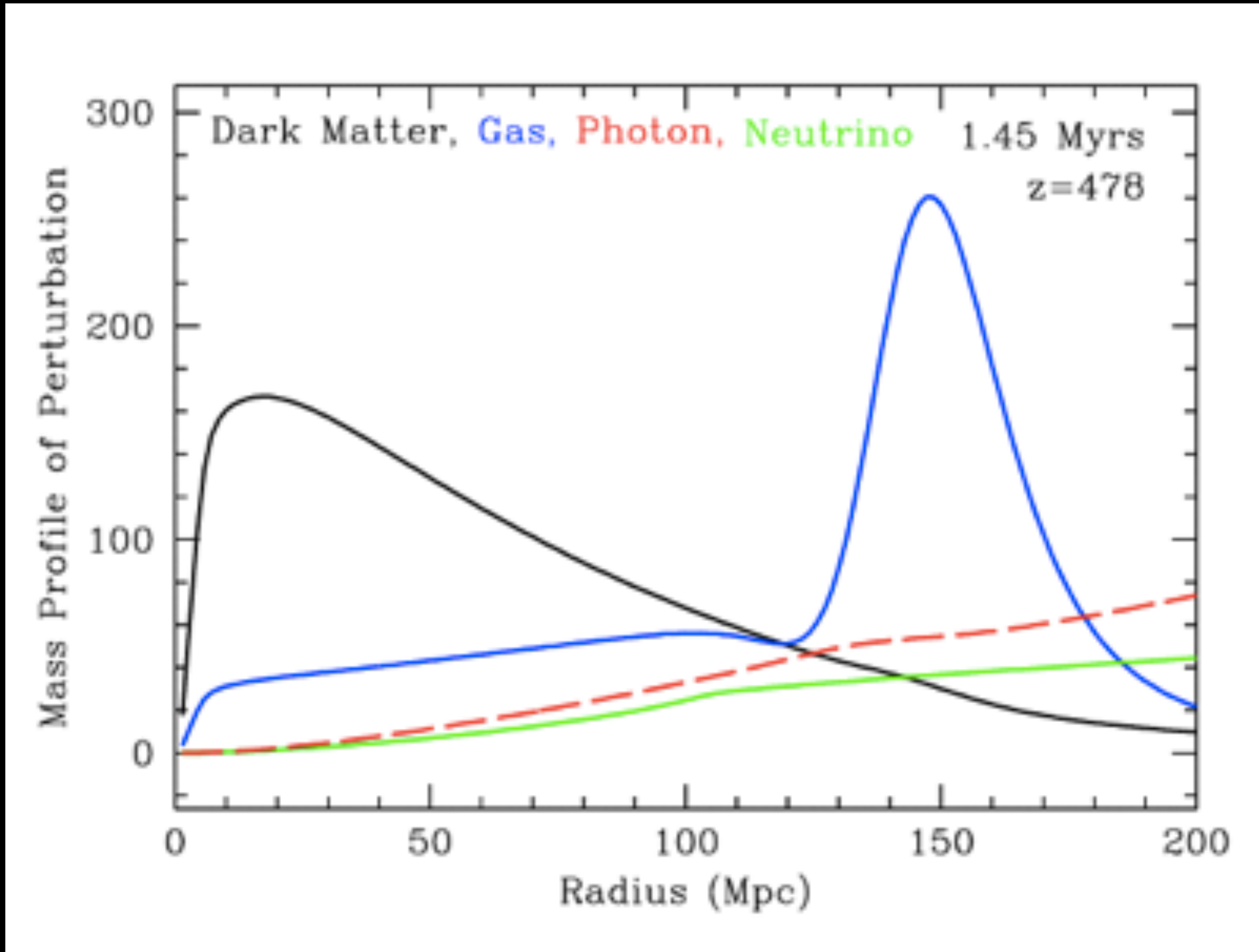
Animation courtesy of D. Eisenstein

Baryon acoustic oscillations (BAO)



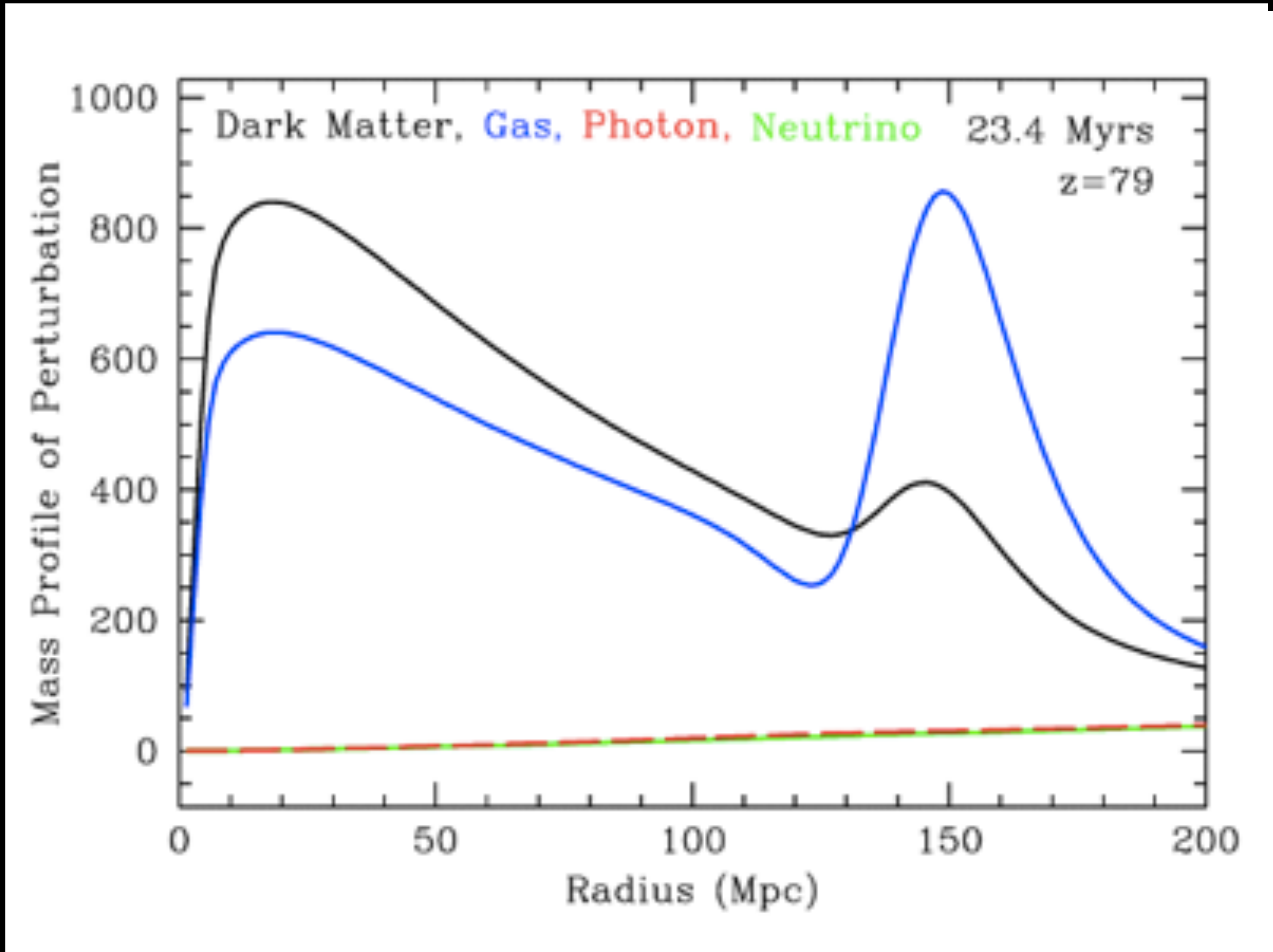
Animation courtesy of D. Eisenstein

Baryon acoustic oscillations (BAO)



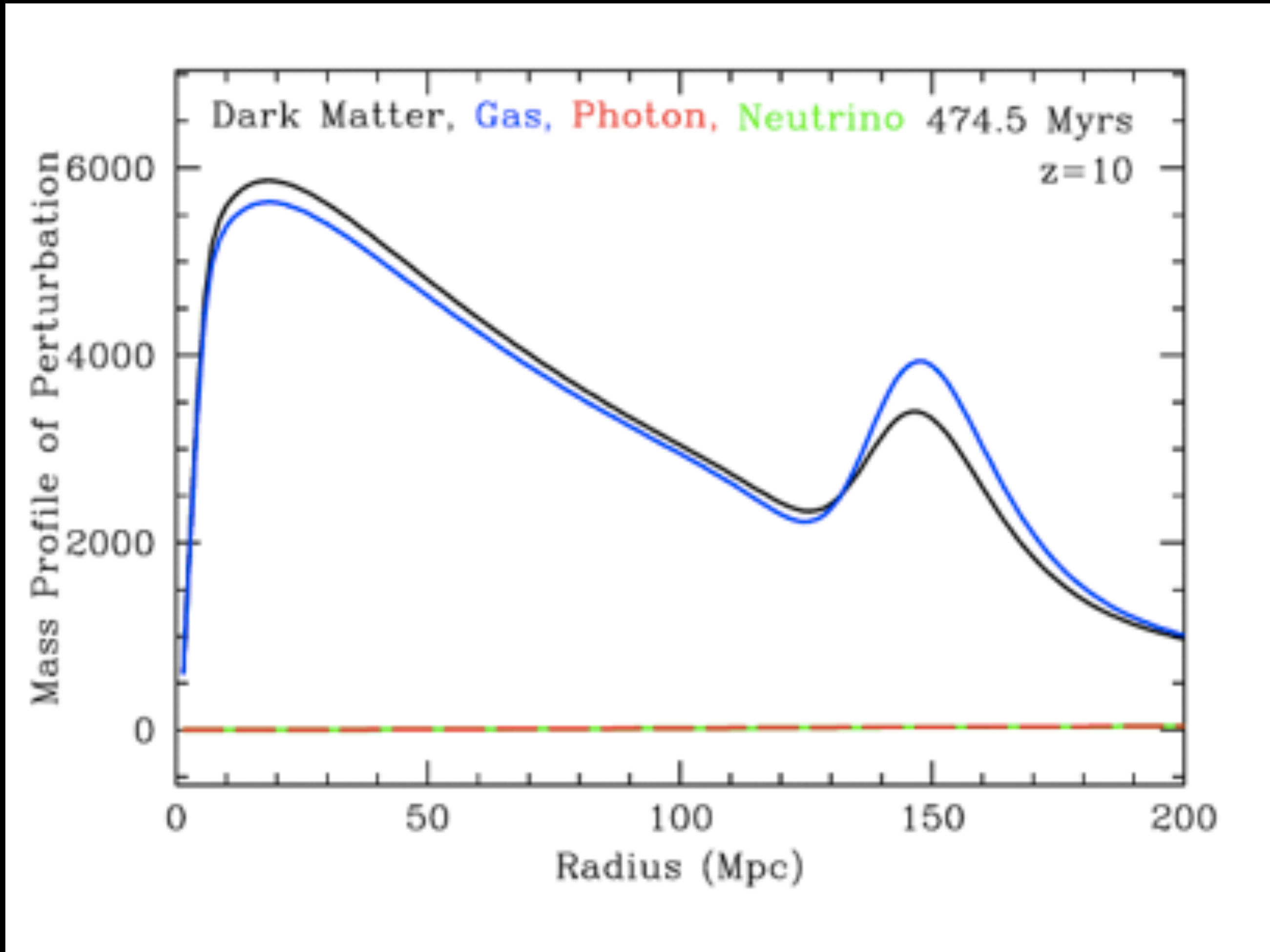
Animation courtesy of D. Eisenstein

Baryon acoustic oscillations (BAO)



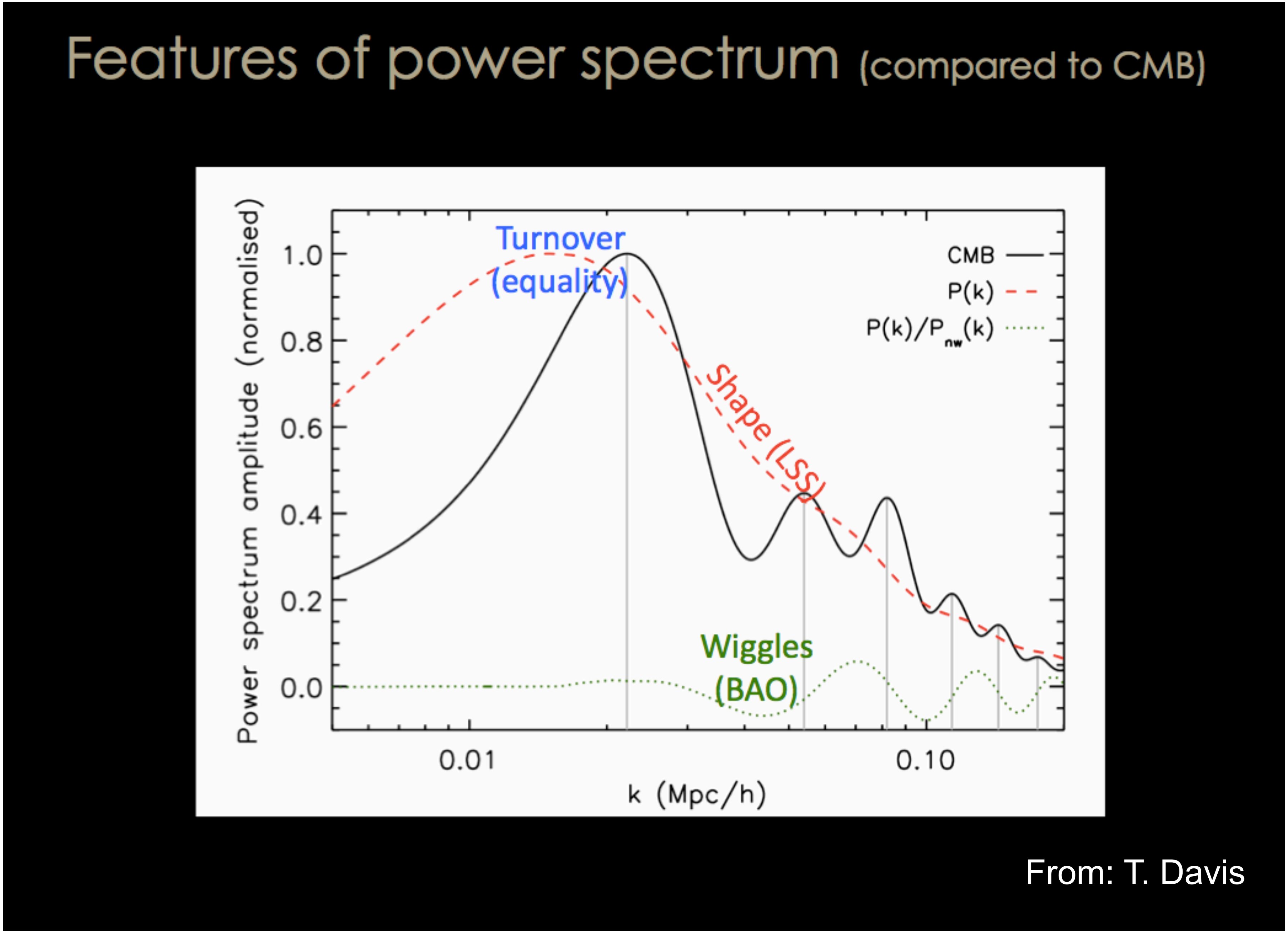
Animation courtesy of D. Eisenstein

Baryon acoustic oscillations (BAO)

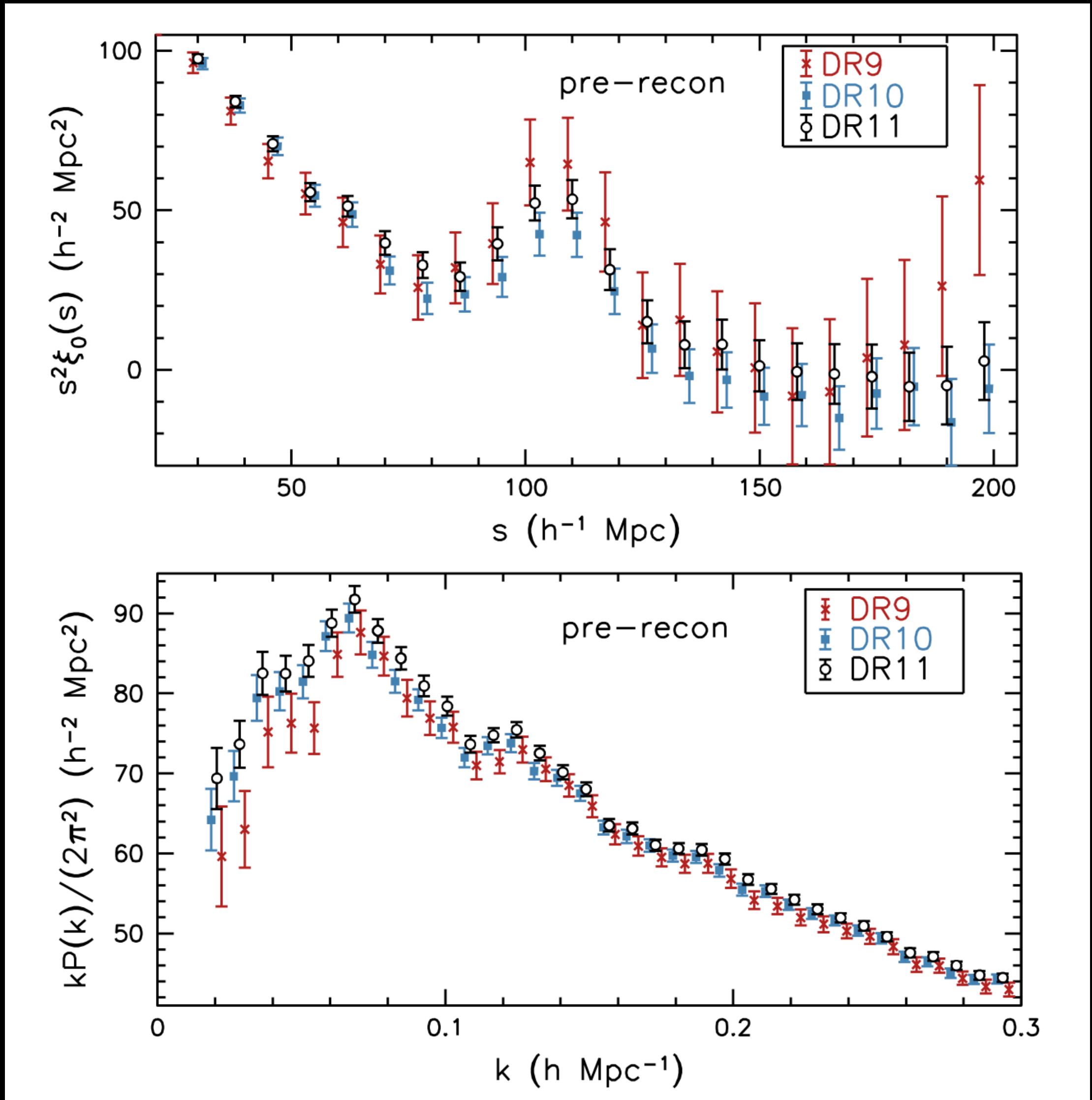


Animation courtesy of D. Eisenstein

Another way to see this:



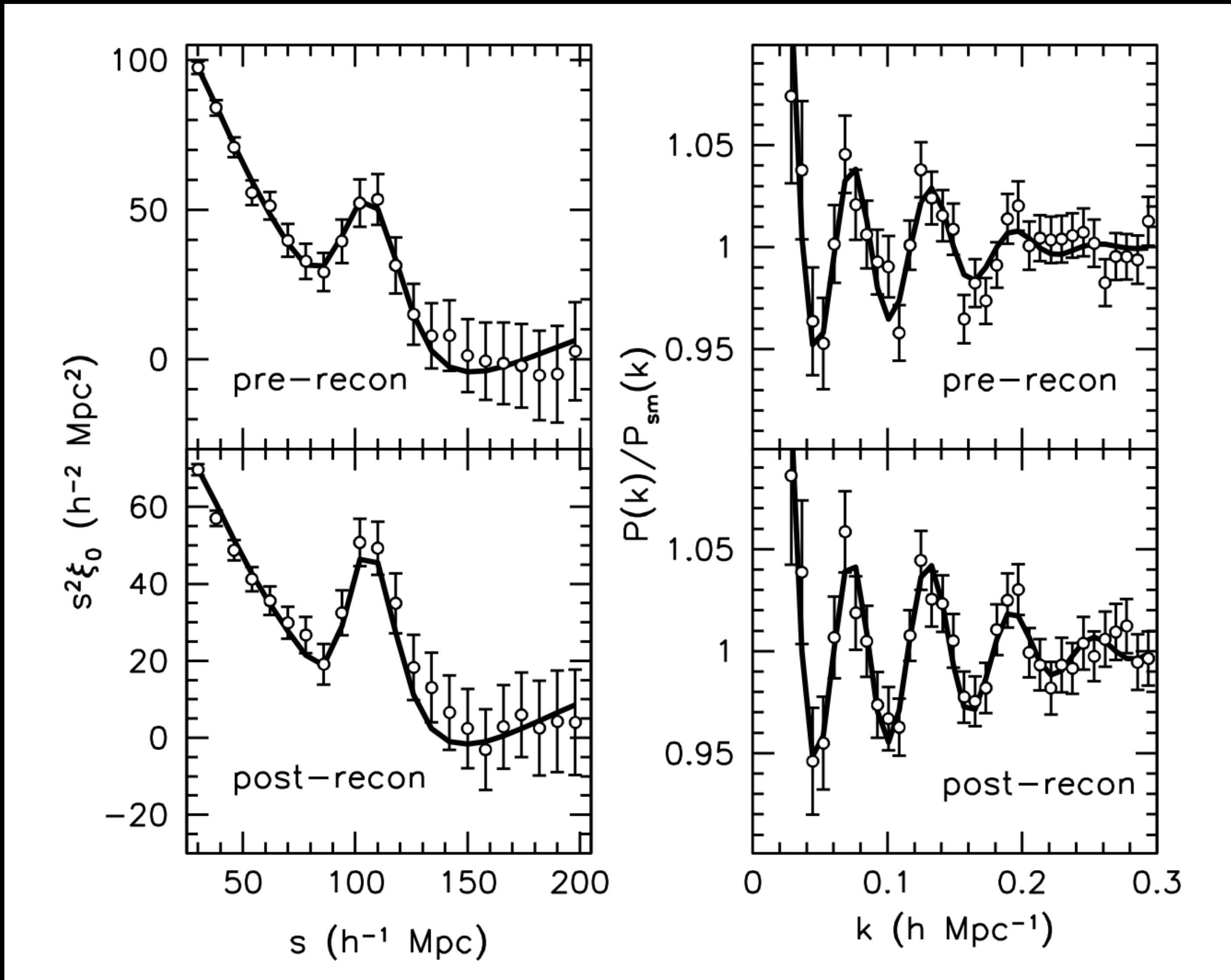
Baryon acoustic oscillations (BAO) in the new decade



Here it is!

Anderson et al 2015 (BOSS)

Baryon acoustic oscillations (BAO) in the new decade

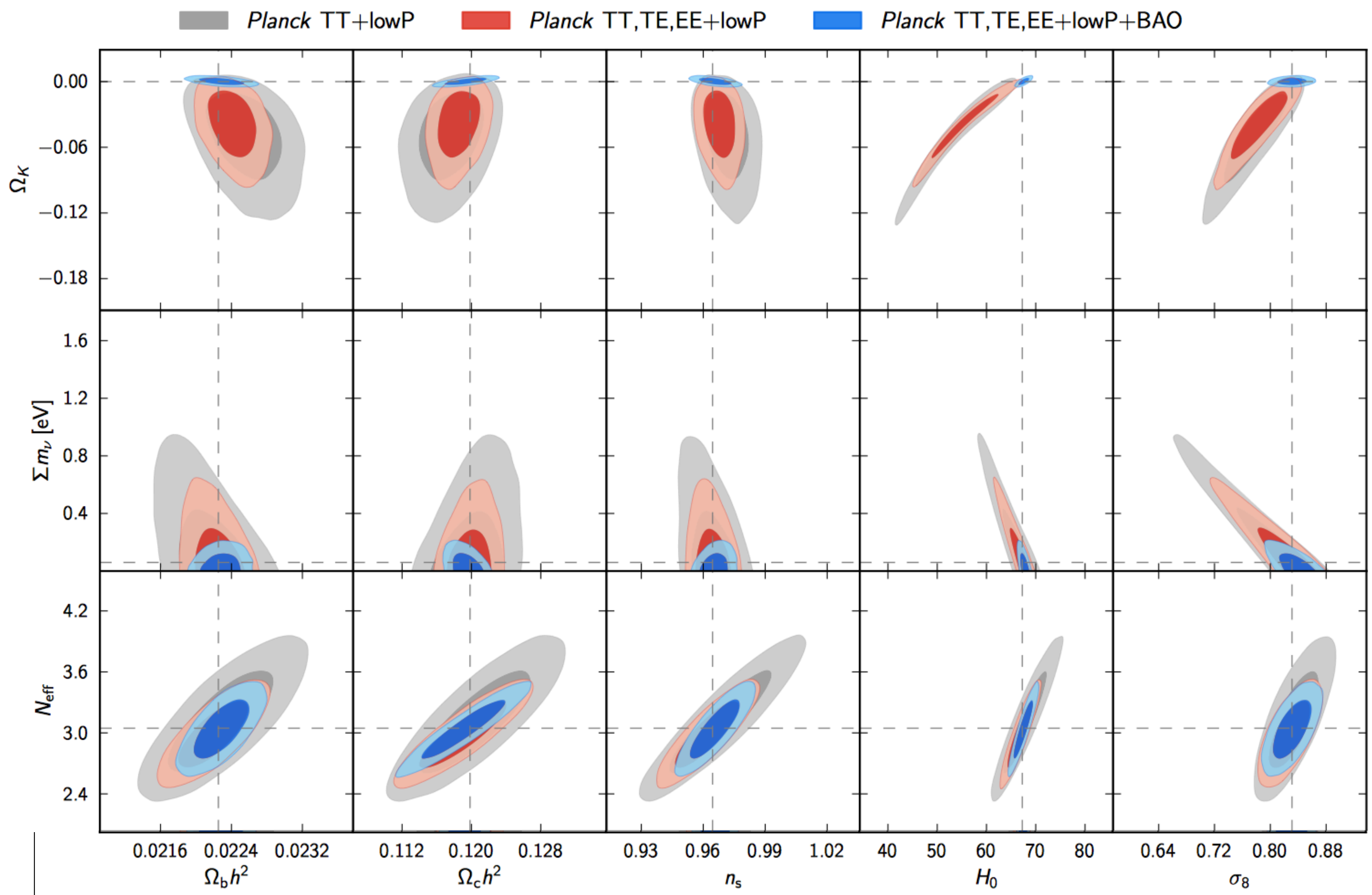


Here it is!

Anderson et al 2015 (BOSS)

The power of BAO

Planck collaboration 2015



Planck Constraints on Neutrinos

$$\sum m_\nu < 0.72\ \text{eV} \quad \textit{Planck}\ \text{TT+lowP}\,;$$
$$\sum m_\nu < 0.21\ \text{eV} \quad \textit{Planck}\ \text{TT+lowP+BAO}\,;$$
$$\sum m_\nu < 0.49\ \text{eV} \quad \textit{Planck}\ \text{TT,TE,EE+lowP}\,;$$
$$\sum m_\nu < 0.17\ \text{eV} \quad \textit{Planck}\ \text{TT,TE,EE+lowP+BAO}\,.$$

95% CL

$$N_{\text{eff}} = 3.13 \pm 0.32 \quad \textit{Planck}\ \text{TT+lowP}\,;$$
$$N_{\text{eff}} = 3.15 \pm 0.23 \quad \textit{Planck}\ \text{TT+lowP+BAO}\,;$$
$$N_{\text{eff}} = 2.99 \pm 0.20 \quad \textit{Planck}\ \text{TT,TE,EE+lowP}\,;$$
$$N_{\text{eff}} = 3.04 \pm 0.18 \quad \textit{Planck}\ \text{TT,TE,EE+lowP+BAO}\,.$$

68% CL

Planck collaboration 2015

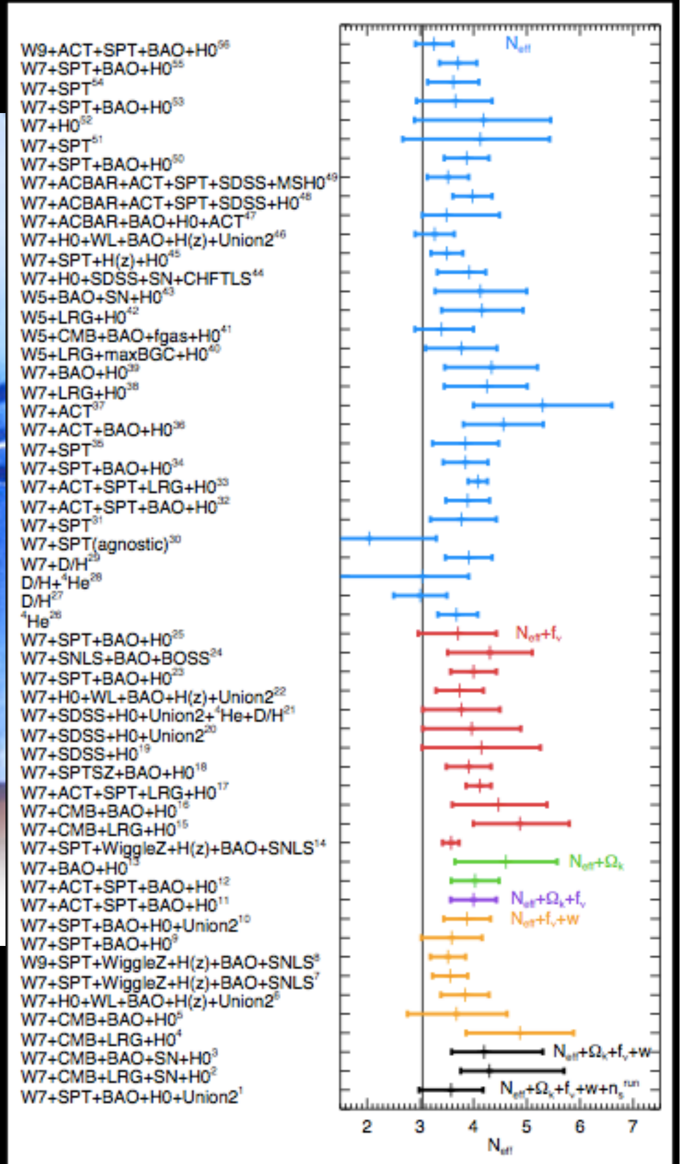
Neutrinos beyond the Standard Model?

Until 2013 or so cosmological analyses consistently used to give best fit values >3.04.

“dark radiation”

But analyses are NOT independent

(WMAP is always in common, H0 many times in common)

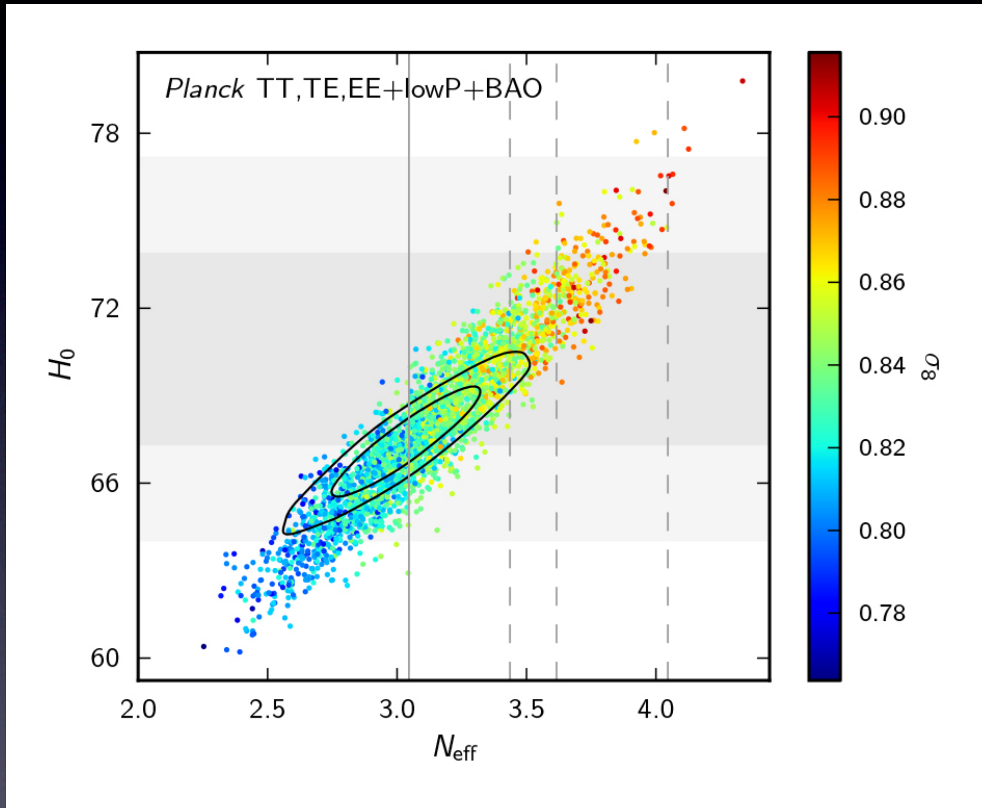


See also the white paper Abazajian et al. arXiv:1204.5379

Riemer-Sørensen et al. [2013]

The CνB has been detected to extremely high statistical significance

Results from Planck 2015



N_{eff}=0 excluded at 17sigma

Also, the possibility of a 4th neutrino is fading away (dashed lines)

How robust is the detection of the cosmic neutrino background?

Predicted in 1953 with correct temperature (Tν = (4/11)4/3 Tγ) by *Alpher, Follin & Herman*:

PHYSICAL REVIEW VOLUME 92, NUMBER 6 DECEMBER 15, 1953

Physical Conditions in the Initial Stages of the Expanding Universe*,†

RALPH A. ALPHER, JAMES W. FOLLIN, JR., AND ROBERT C. HERMAN
Applied Physics Laboratory, The Johns Hopkins University, Silver Spring, Maryland
(Received September 10, 1953)

$$\omega_R = \omega_\gamma \left(1 + N_{eff} \times 7/8\, (4/11)^{4/3}\right) \quad \text{with } N_{eff} = 3.046$$

62 years later we ask… …are we sure it exists?

B. Audren, **E. Bellini, A. Cuesta**, S. Gontcho A Gontcho, J. Lesgourgues, V. Niro, M. Pellejero-Ibanez, I. Pérez-Ràfols, V. Poulin, T. Tram, D. Tramonte, L. Verde

arXiv:1412.5948 (JCAP 2015)

http://icc.ub.edu/~liciaverde/ERCtraining.html

Could be anything behaving like radiation

other light decoupled relics (axions, gravitinos, etc.)

scalar field oscillating in quartic potential

background of gravitational waves

standard neutrinos

neutrinos with exotic interactions (self-inter., or with dark sector)

other light relics with interactions (self-inter., or with dark sector)

effects from modified gravity, extra dimensions...

Fig adapted from J. Lesgourgues

Can we probe the nature of the perturbations?

Neutrinos density/pressure perturbations, energy flux and anisotropic pressure/shear act as sources in Einstein equations: *gravitational interactions with photons, baryons*.

Affects the amount of gravitational boost of CMB acoustic oscillations just after Hubble crossing.

Controls *amplitude and phase of CMB acoustic oscillations*.

Can we see these free-streaming effects?

approach

Define two phenomenological parameters changing the perturbation equations:

1) Effective *sound speed* : $\delta p = c_{eff}^2 \, \delta\rho$
2) Effective *viscosity speed* cvis controlling the amount of anisotropic pressure / shear

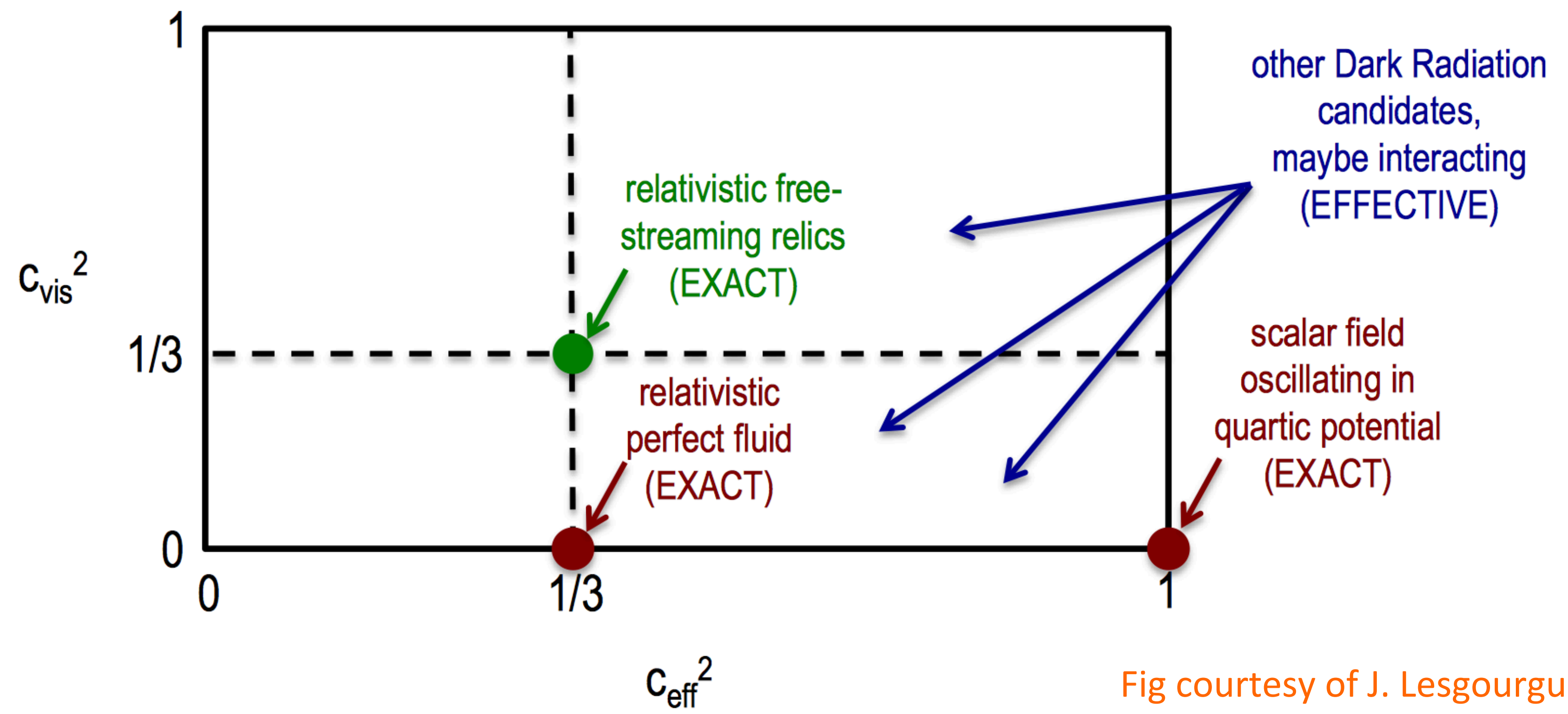


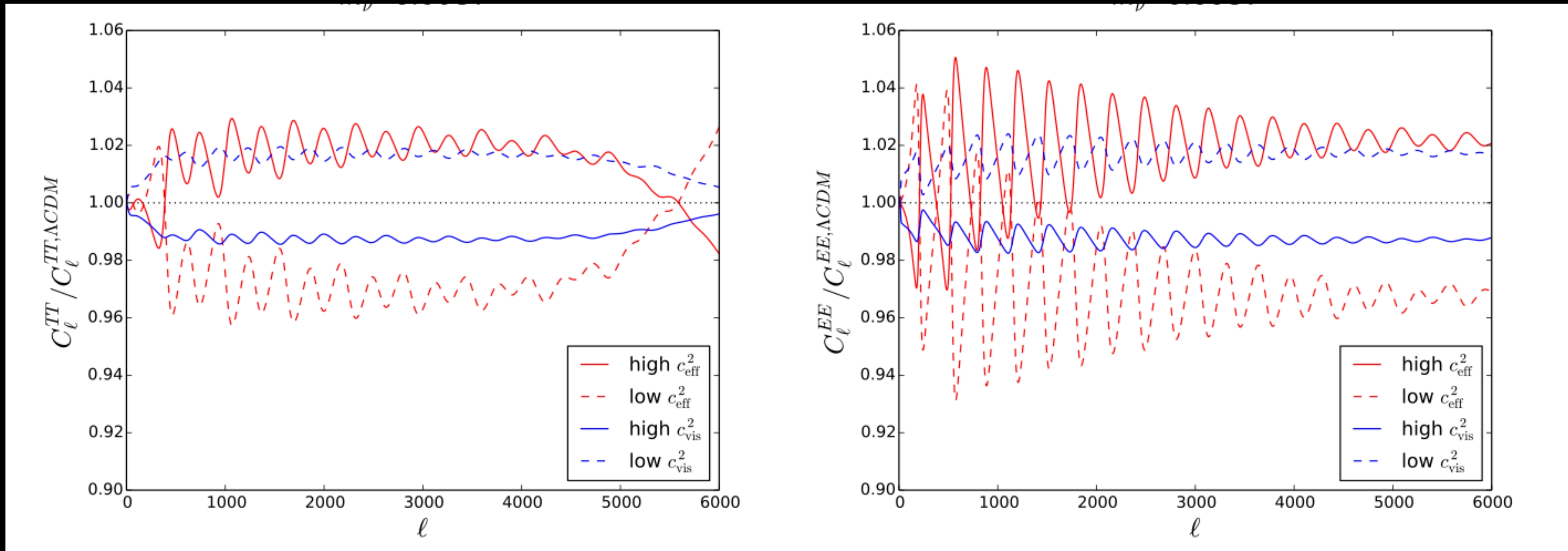
Fig courtesy of J. Lesgourgues

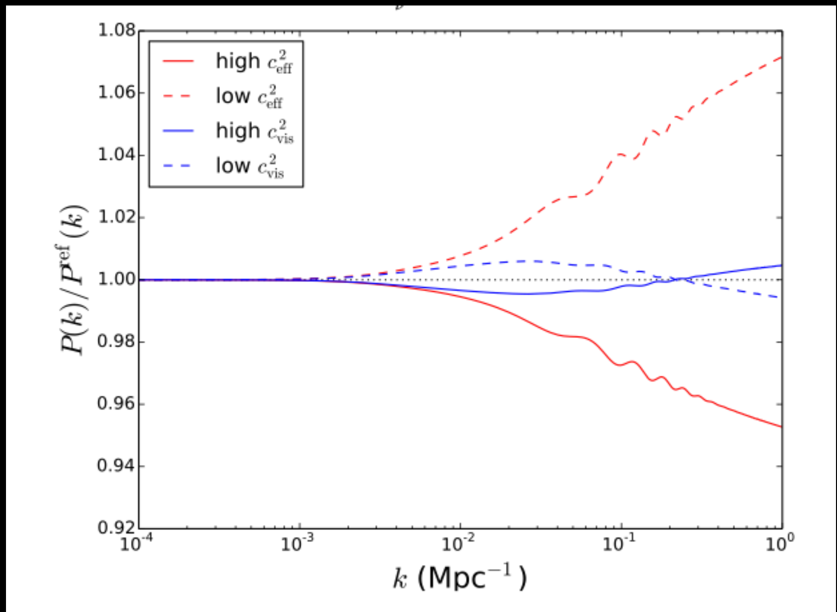
For a model LCDM+c_{eff}+c_{vis} from Planck data we have learned that there is no compelling avidence for deviations from standard values

BUT… how robust is this statement?

Our approach: brute force, really…

But it was an exercise…





Polarization data help!

$\Delta c_{\rm eff}^2=0.03$

Large scale structure
can potentially help even more

Our approach: brute force, really…

Consider a minimal collection of state-of-the art data (CMB Planck, BAO) and explore whether c_{eff} and c_{vis} are degenerate with neutrino mass, effective number of species, dark energy …etc.

We conclude: not to worry about degeneracies

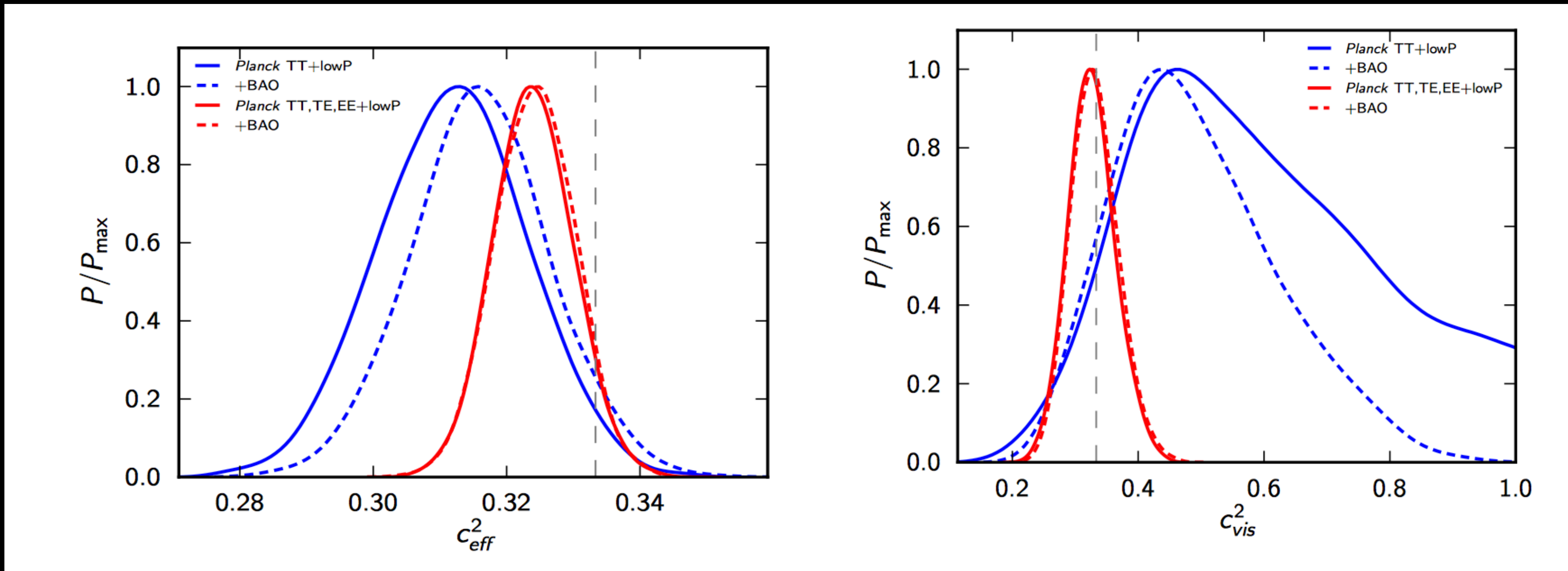
With Mv, Neff or both : very little if at all

With running of spectra index: some anti-correlation, but small

With w: no

Upshot: you can take the Planck 2015 results and be sure they hold also for more general cosmologies

Back to Planck 2015 results



$$\left.\begin{aligned} c^2_{\rm eff} &= 0.3242 \pm 0.0059 \\ c^2_{\rm vis} &= 0.331 \pm 0.037 \end{aligned}\right\} \textit{Planck}\ \text{TT,TE,EE+lowP+BAO.} \tag{69d}$$

Everything else here is LCDM
But we show this will hold for LCDM++

Can we observe these free-streaming effects?

YES!

other light decoupled relics
(axions, gravitinos, etc.)

~~scalar field oscillating in quartic potential~~

~~background of gravitational waves~~

standard neutrinos

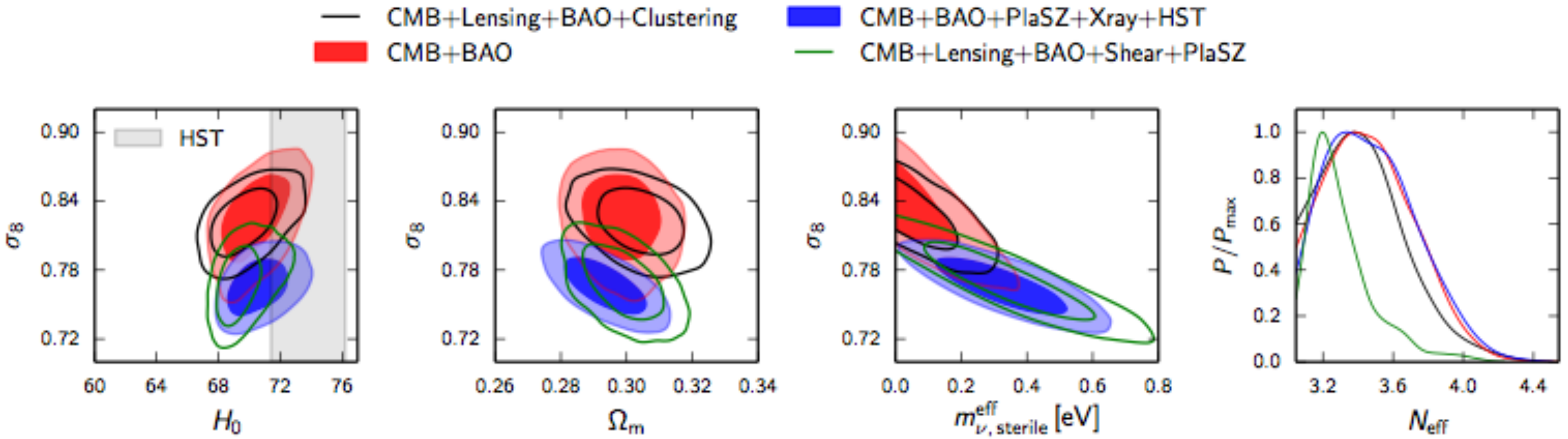
~~neutrinos with exotic interactions (self-inter., or with dark sector)~~

~~other light relics with interactions (self-inter., or with dark sector)~~

~~effects from modified gravity, extra dimensions...~~

Disfavored!

Cosmic Concordance?

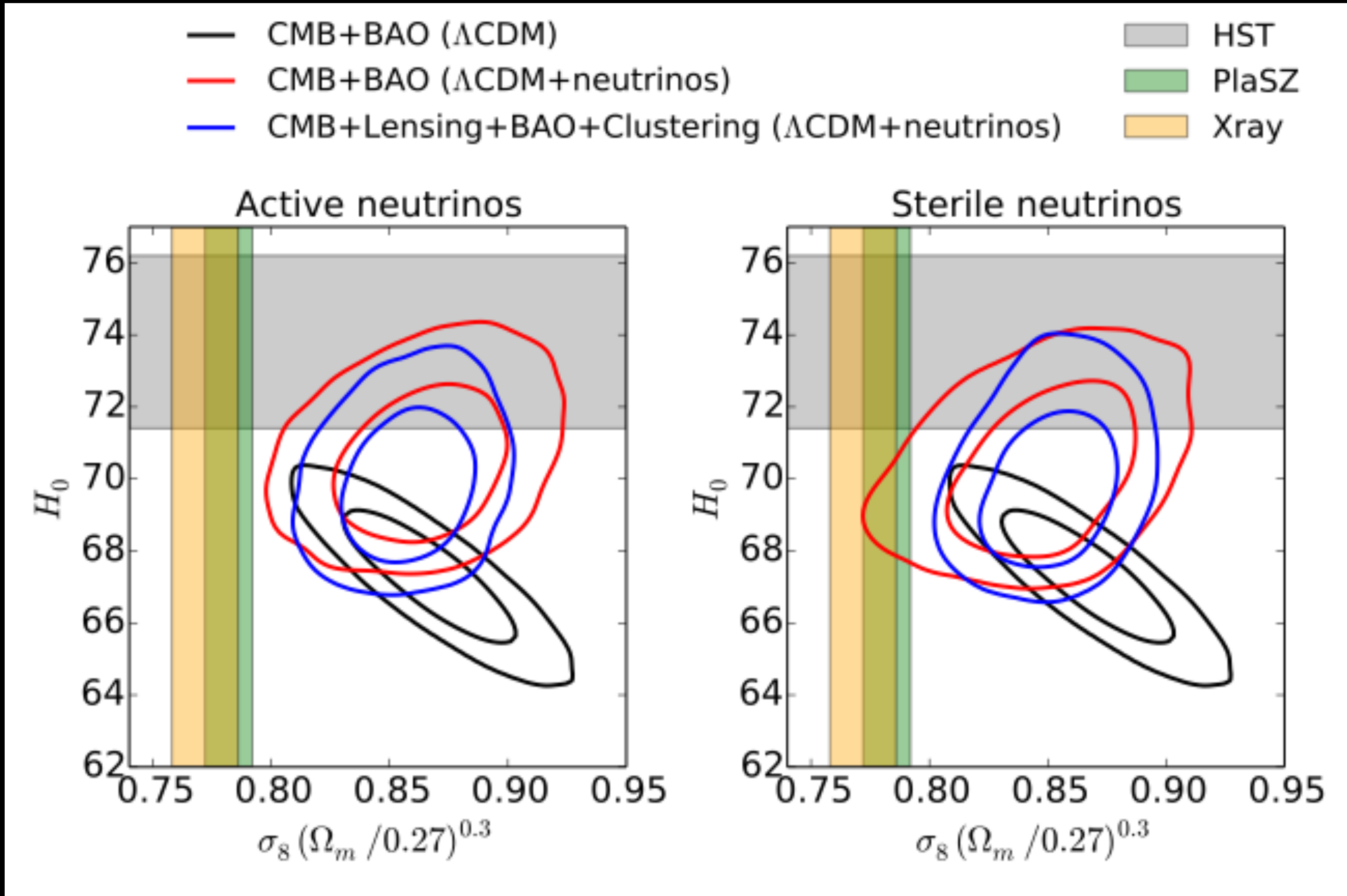


Non-zero sterile neutrino mass only favoured due to:

tension between CMB and clusters (Planck SZ, X-ray) in σ8–Ω_m plane

degeneracy between σ_8 & neutrino mass.

Leistedt, Peiris, Verde, 2014



Conclusion premature; datasets remain in tension

Leistedt, Peiris, Verde, 2014

Conclusions: glass half empty

… the maximally boring universe…

The standard cosmological model has survived ever more stringent tests

Deviations from it are even more constrained

Eventually something will have to give, the model IS incomplete
(and the cosmological constant IS ugly..
And we have extrapolated the law of gravity some 13 orders of magnitude!!)

The point is how much smaller would the observational error bars have to be

Conclusions (glass half full)

- Precision cosmology means that we can start (or prepare for) constraining interesting physical quantities
- Neutrino properties: absolute mass scale, number of families, possibly hierarchy
- My "bet": $\Sigma m_\nu <\sim 0.2$ eV (95%) (once the dust has settled)
- Large future surveys means that sub % effects become detectable, which brings in a whole new set of challenges and opportunities (e.g., mass, hierarchy)
- The (indirect) detection of neutrino masses is within the reach of forthcoming experiments (even for the minimum mass allowed by oscillations)
- Systematic and real-world effects are the challenge, need for in-build consistency checks!
- COMPLEMENTARITY is key

END