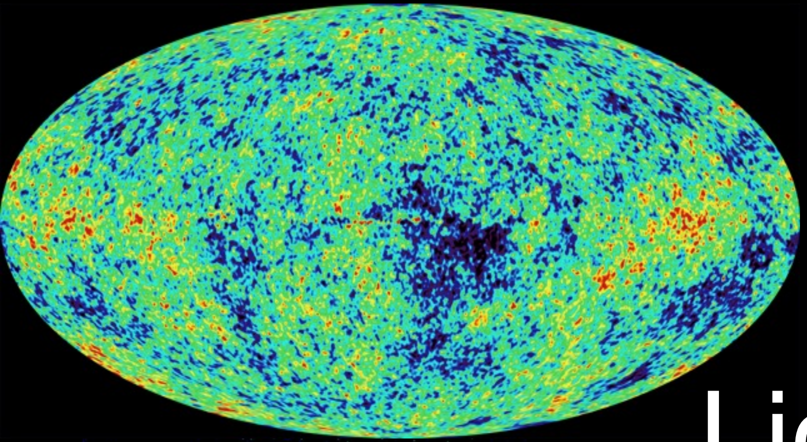
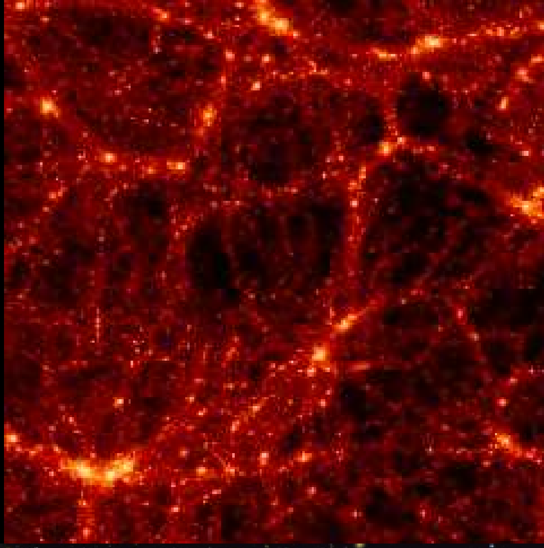
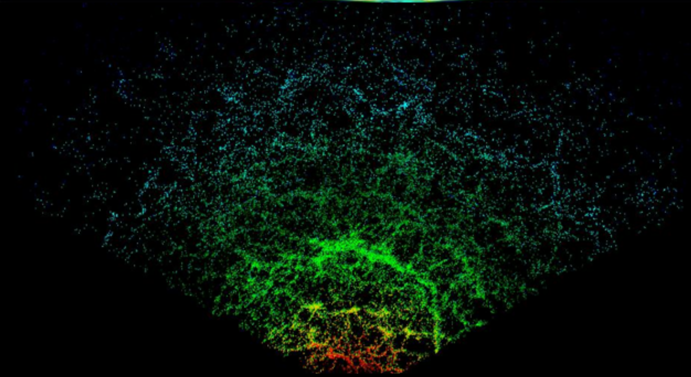


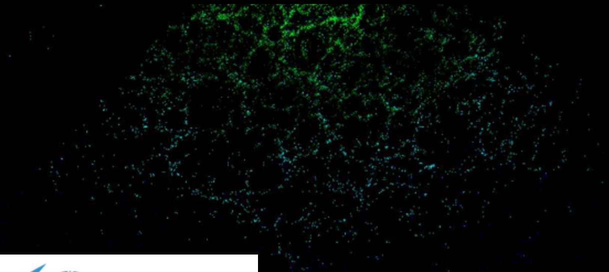


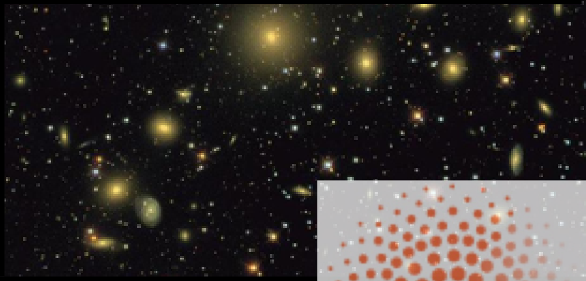
Licia Verde

ICREA & ICC-UB-IEEC
Barcelona, Spain



Neutrino properties from cosmology





icc.ub.edu.liciaverde

ICCUB Institute of Cosmos Sciences
EXCELENCIA MARÍA DE MAEZTU
ICREA
UNIVERSITAT DE BARCELONA
GOBIERNO DE ESPAÑA
MINISTERIO DE ECONOMÍA, INDUSTRIA Y COMPETITIVIDAD
erc

Other things we can talk about

- Cosmology in general
- arXiv
- Scientific publishing process
- Diversity equity inclusion in STEMS/Academia

A possible reference point

Particle data group, Neutrinos in Cosmology, Lesgourgues & Verde
Chapter 26
https://pdg.lbl.gov/2022/reviews/astro-cosmo.html
(fully updated every 2 years, revised every year*)

Cosmology is special

We can't make experiments, only observations

We have to use the entire Universe as a detector:
 the detector is given, we can't tinker with it. (Jim
Peebles)

This has driven a massive experimental effort

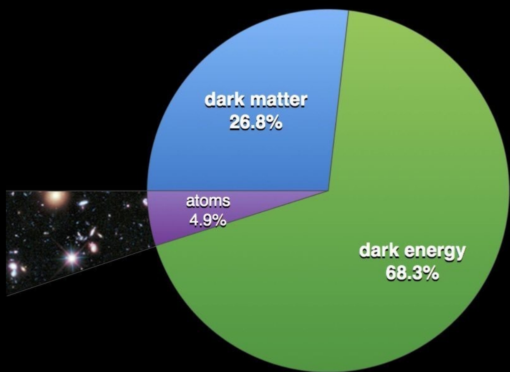
- Observe as much as possible of the Universe.

The standard model of cosmology

The ΛCDM model

few cosmological parameters: “Just 6 numbers”….

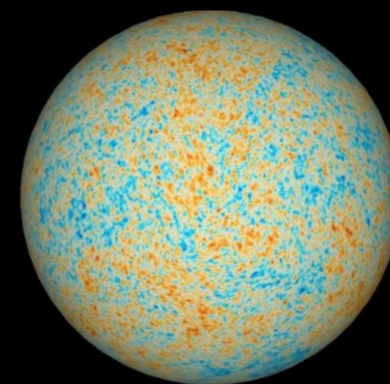
Composition,
background evolution



@AstroKatie/Planck13

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

perturbations



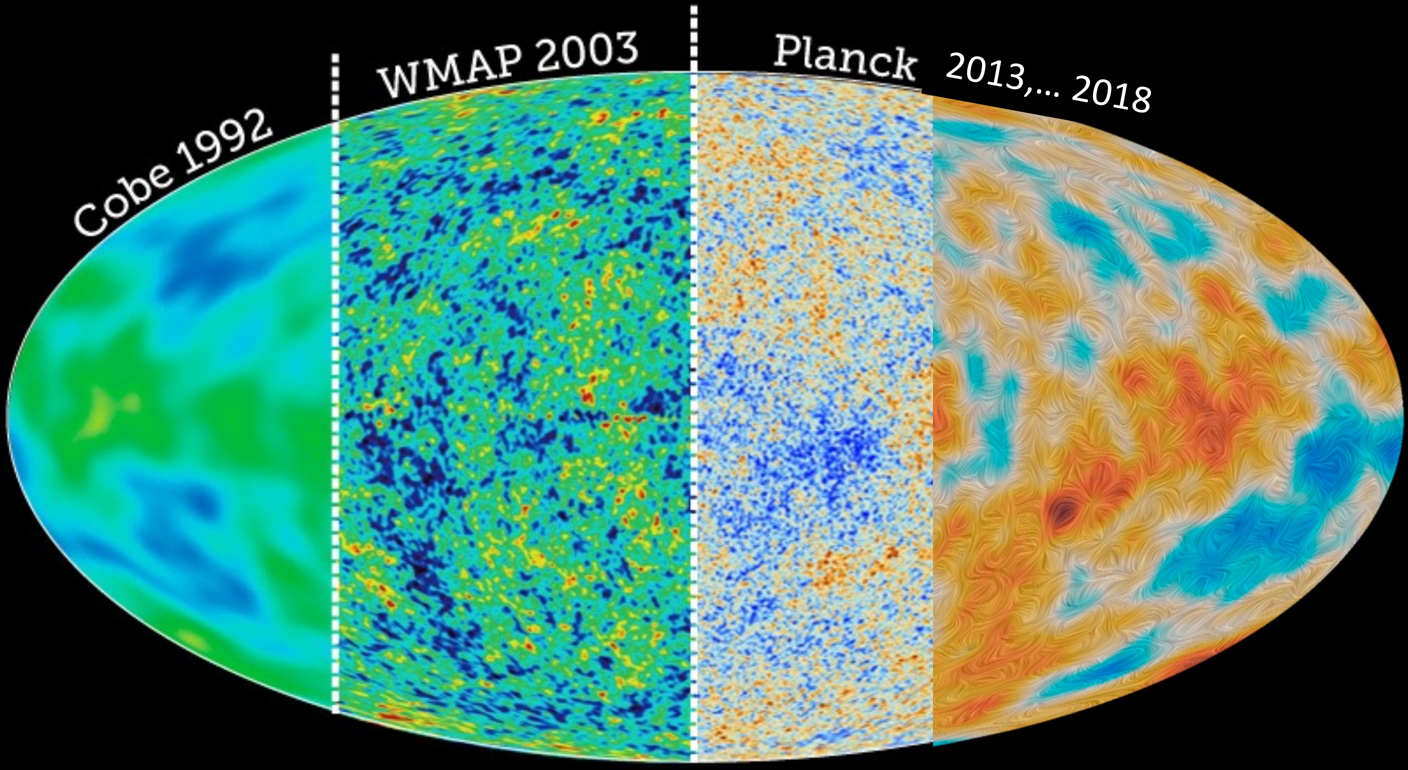
τ, As ns

….describe observations of the Universe
across some 14 billion years of evolution

The model’s parameters are now determined with % accuracy: Precision cosmology!

What happened in these last 2 decades?

The ΛCDM model has survived unscathed an avalanche of data



How's that useful?

The Universe back then was made of a very hot and dense "gas",
so it was emitting radiation

This is the radiation we see when we look at the CMB

Uniform , but with tiny (contrast x 100000) density (and temperature) ripples

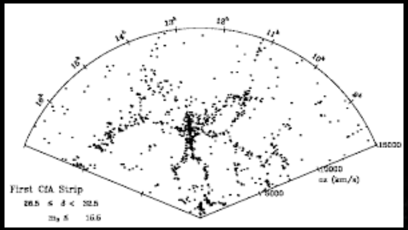
Ripples in a gas? SOUND WAVES!

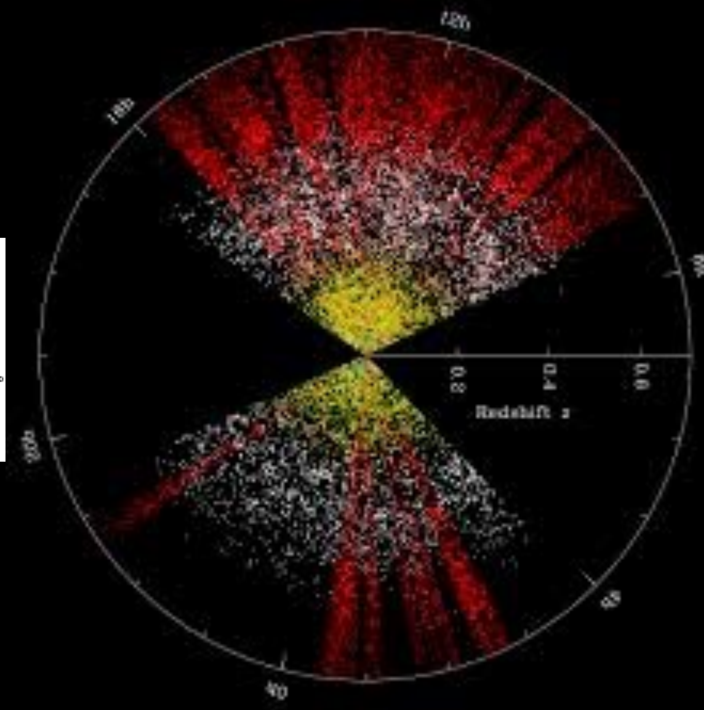
Truly a cosmic symphony… We are seeing sound!

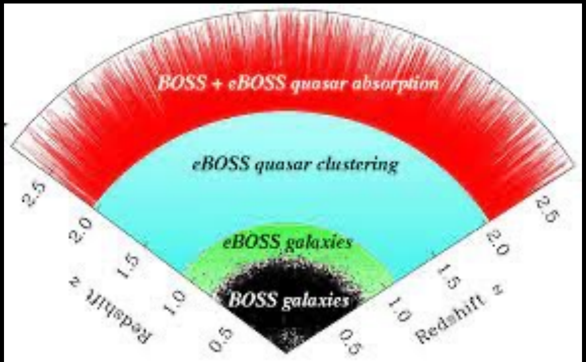
These tiny fluctuations, quantitatively, give rise galaxies

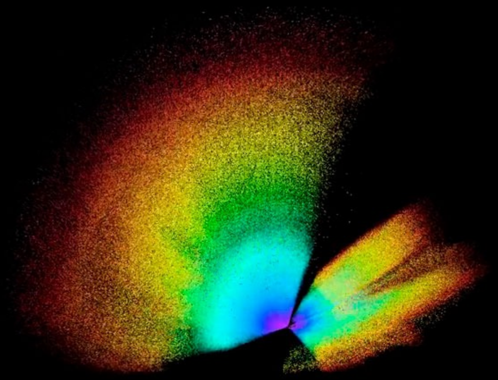
We try to listen to the sound and figure out how the instrument is made

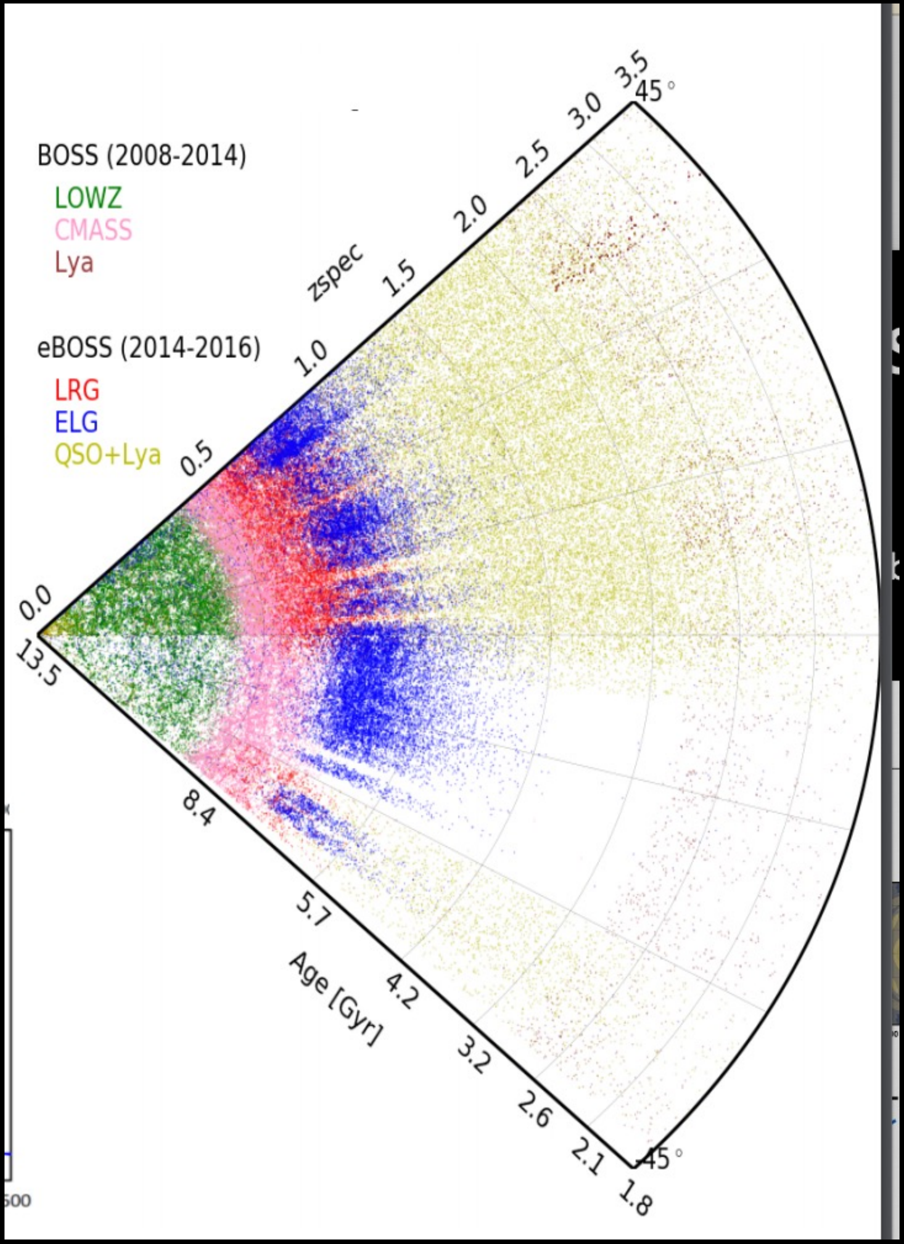
The ΛCDM model has survived unscathed an avalanche of data



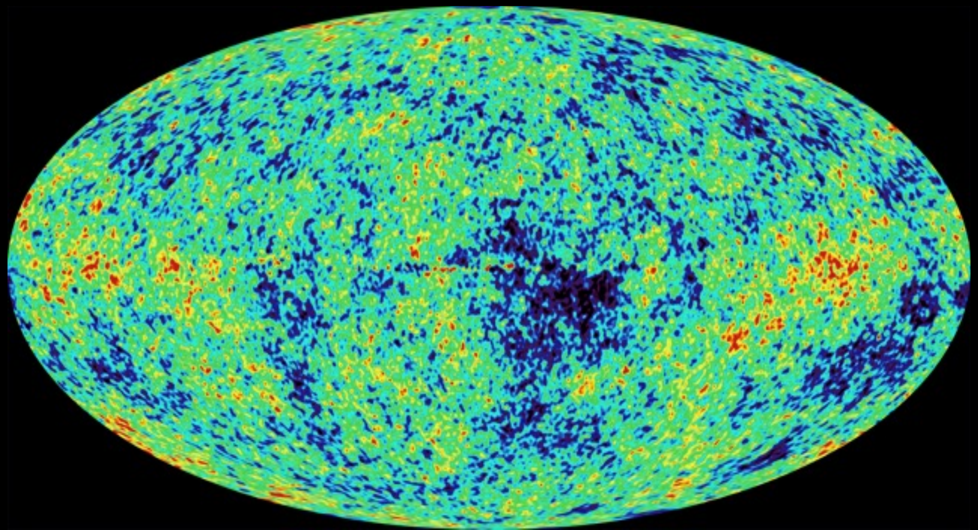


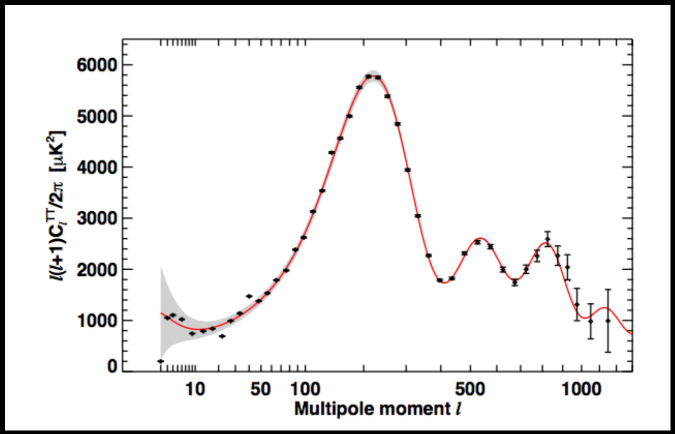


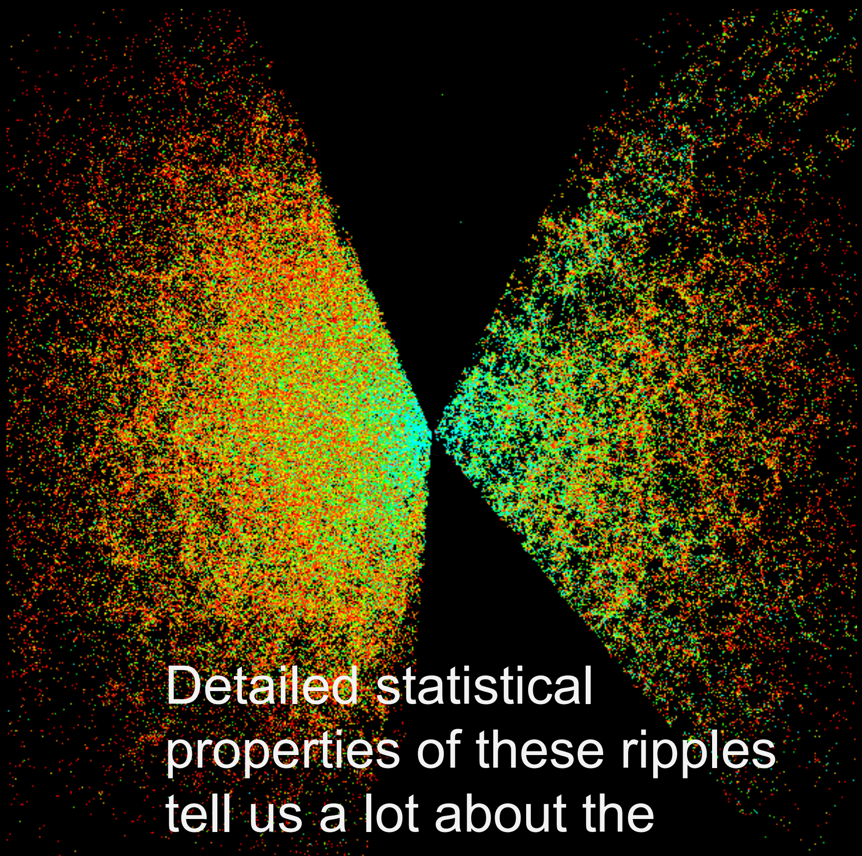



BOSS (2008-2014)
LOWZ
CMASS
Lya
eBOSS (2014-2016)
LRG
ELG
QSO+Lya
zspec
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
45°
-45°
13.5
8.4
5.7
4.2
3.2
2.6
2.1
1.8
Age [Gyr]

Avalanche of data over the last ~10 yr

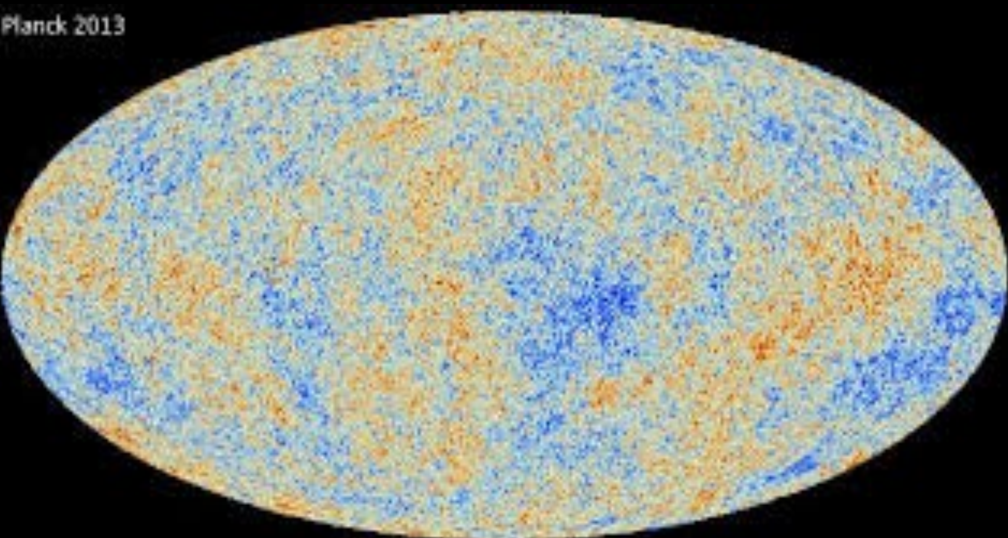


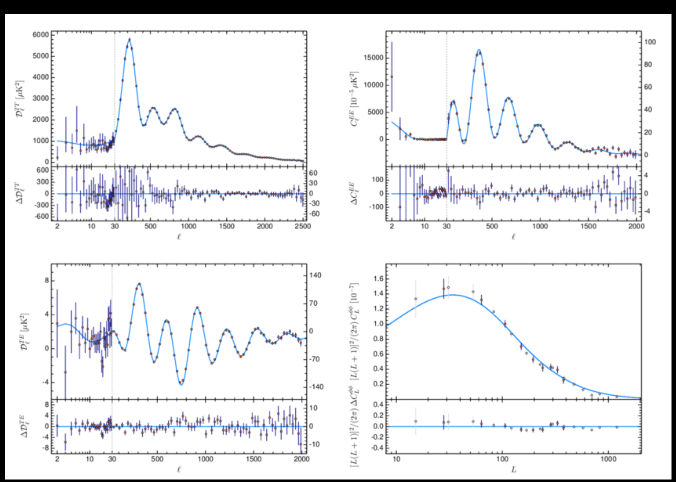


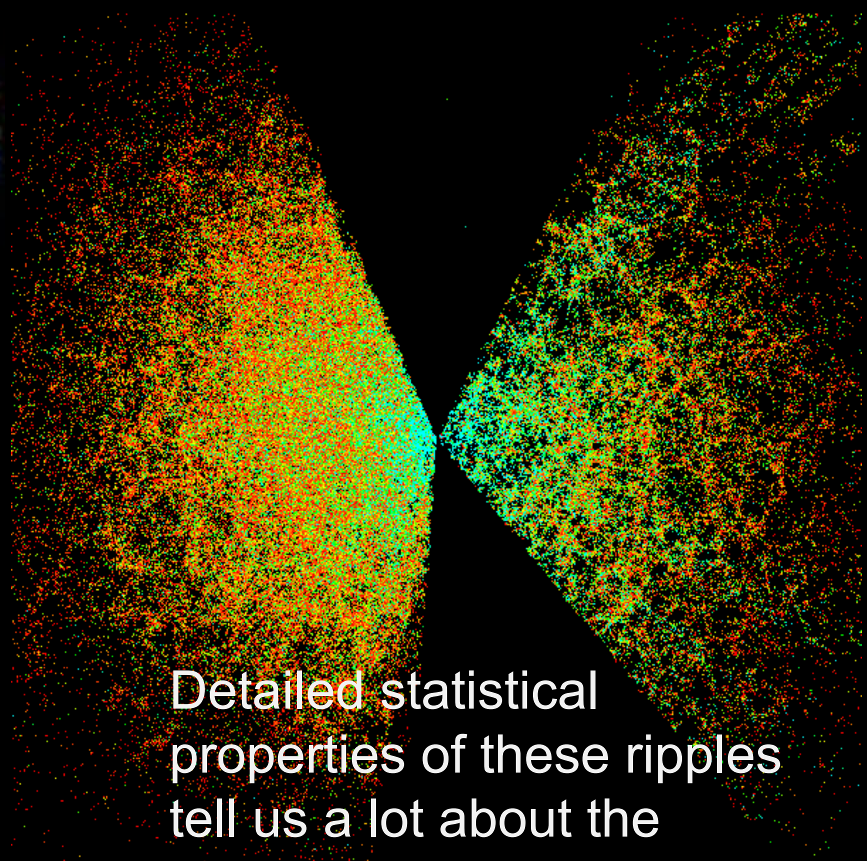


Detailed statistical properties of these ripples tell us a lot about the Universe

Avalanche of data over the last ~10 yr

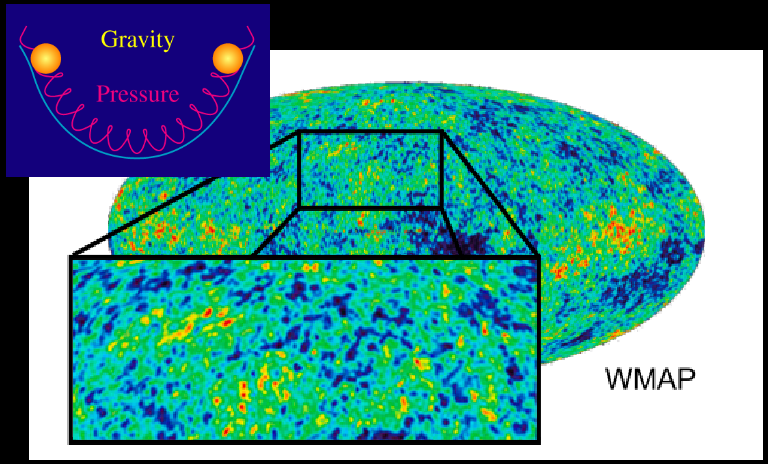


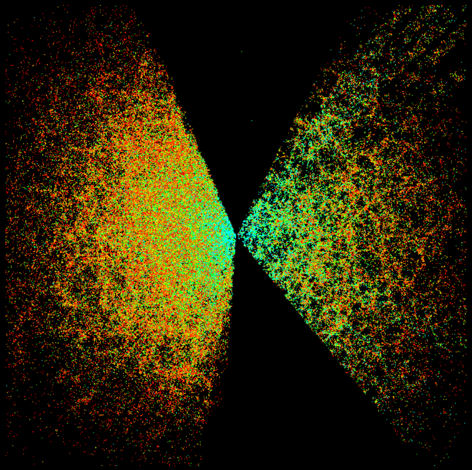


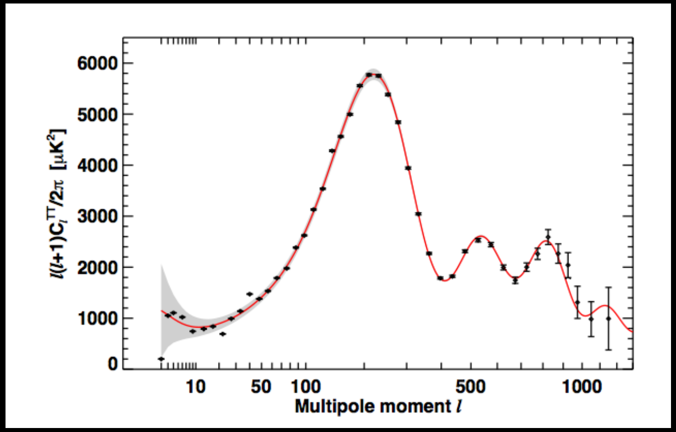


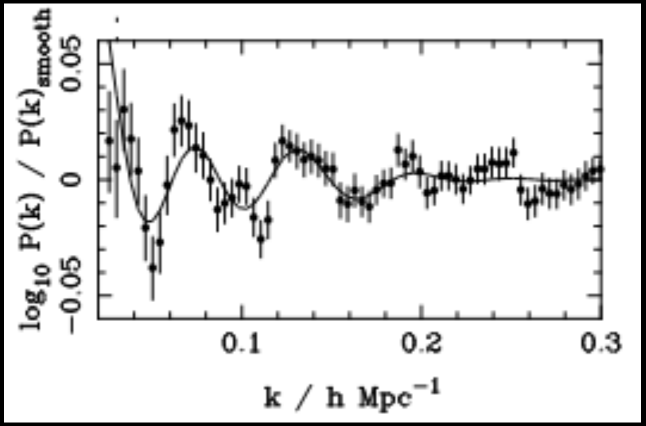
Detailed statistical properties of these ripples tell us a lot about the Universe

BAOs
Baryon acoustic oscillations

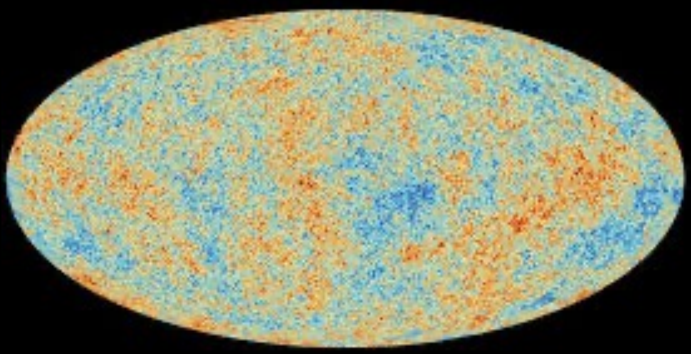


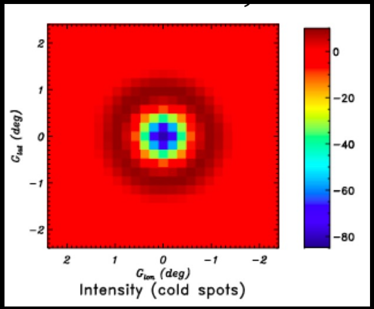


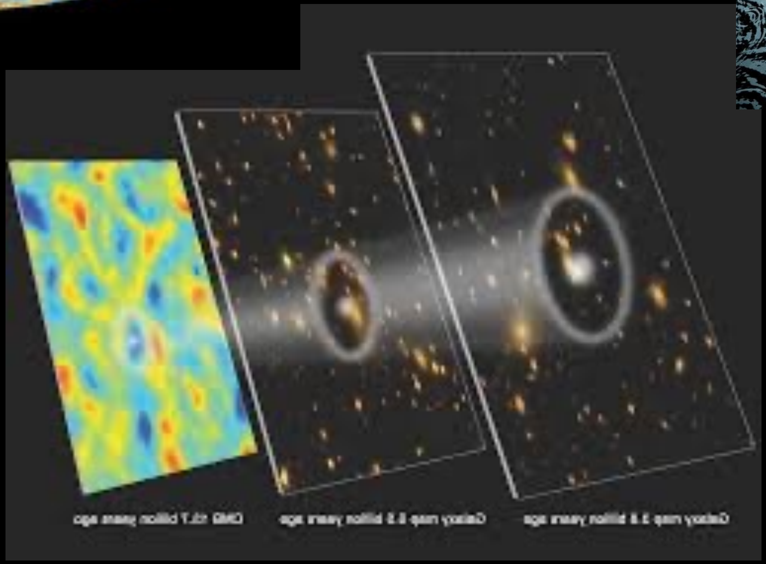




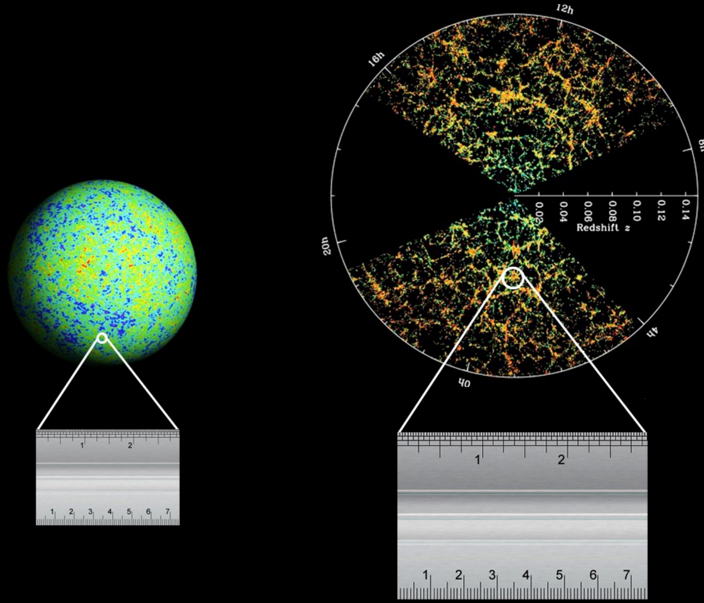
Seeds of galaxies…..Like throwing stones in a pond, or rain…







A standard ruler
(well… in 3d a standard bubble.. But ok)

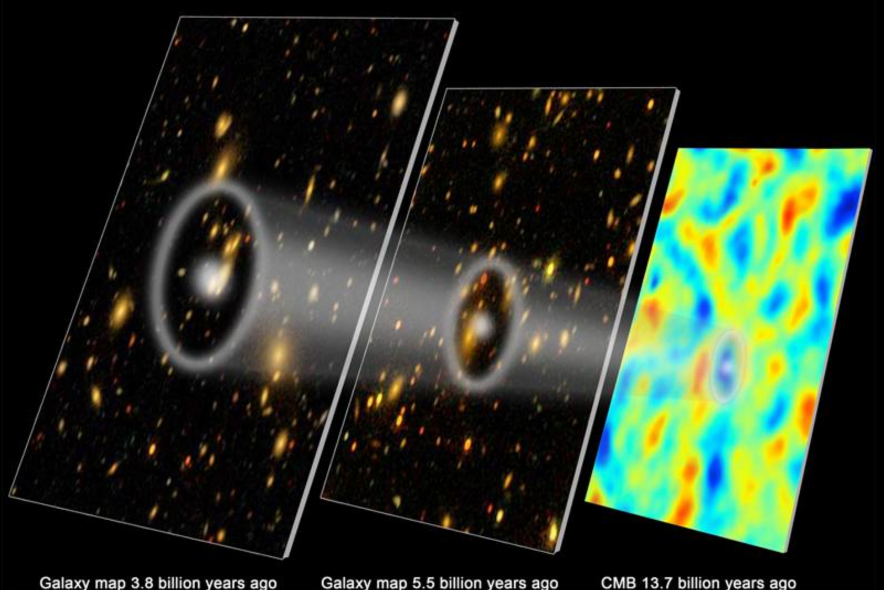


Effect is a "classic" AP

The ruler is the sound horizon at recombination (CMB), at radiation drag (LSS) but it is the same ruler. Symbols: r_s or r_d

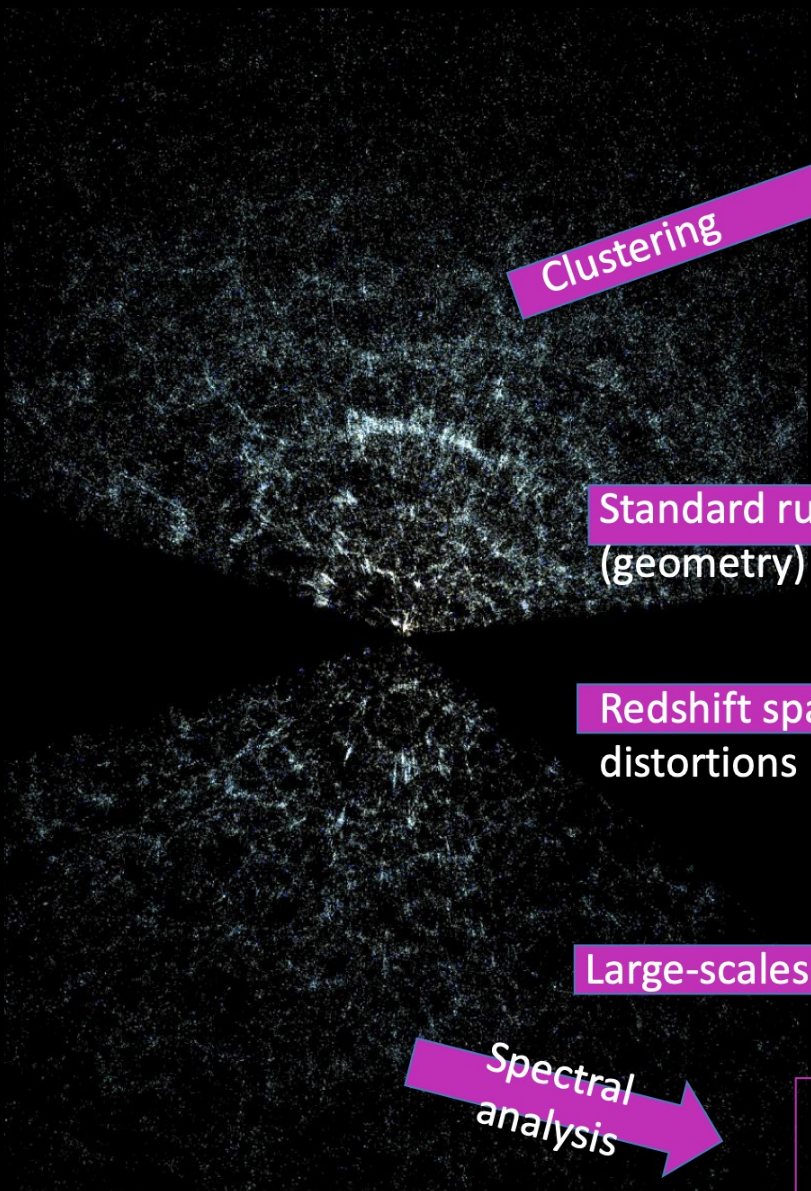
Baryon acoustic oscillations (BAO)
as a Standard ruler

- Physics: sound waves in early Universe propagate until radiation and matter decouple
- Imprints a scale - standard ruler
- Key Observable. (sound horizon)
- Useful for:
  - geometry of Universe (Dark Energy equation of state, or modifications to GR)
  - early Universe physics (well known) sets it



CMB and early universe physics in LCDM constrain the standard ruler length to 0.2%

Physical information from large-scale structure



Clustering → What are the constituents of matter? What is the physics of inflation? e.g. Neutrino masses, Primordial P(k), Nature of dark matter, growth of perturbations

Standard ruler (geometry) → What is the expansion history of the Universe? e.g. Dark energy

Redshift space distortions → How does structure form within this background? e.g. modified gravity, GR

Understanding cosmic acceleration

Large-scales → Homogenetiy, non-gaussianity

Spectral analysis → other non-cosmological info e.g. Galaxy formation

May be Key to ensure robustness

Fig. adapted from W. Percival

Extremely successful standard cosmological model
Look for deviations from the standard model

Test physics on which it is based and beyond it

- Dark energy
- Nature of initial conditions: Adiabaticity, Gaussianity
- <u>Neutrino properties</u>
- Inflation properties
- Beyond the standard model physics…

We only have one observable universe

The curse of cosmology

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: Almost <u>Any statement is model dependent</u>

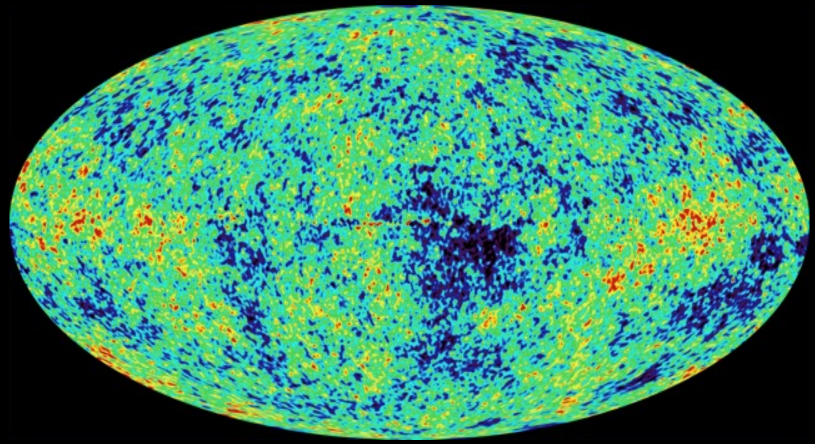
Gastrophysics and non-linearities get in the way :
Different observations are more or less "trustable", it is however somewhat a question of personal taste (think about Standard & Poor's credit rating for countries): <u>Any statement depends on the data-set chosen and to some extent the analysis methodology</u>

Results will depend on the data you (are willing to) consider.
I try to use > A rating ;)

….And the Blessing

We can observe all there is to see

Cosmic Neutrino Background

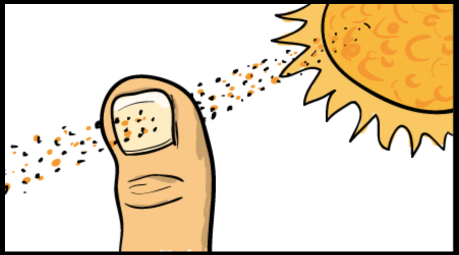


A relict of the big bang, similar to the CMB except that the CνB decouples from matter after 2s (~ MeV) not 380,000 years

At decoupling they are still relativistic ($m_\nu \ll T_\nu$) → large velocity dispersions (1eV ~ 100 Km/s)

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

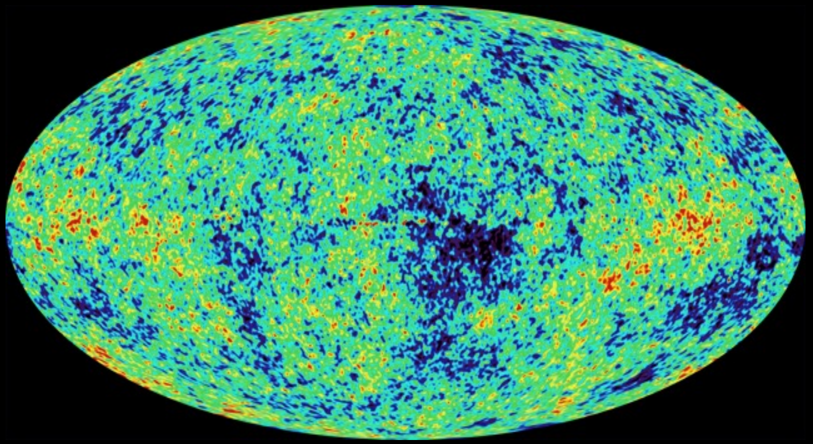
60Billion nu/s/cm^2 from the sun
~300nu/cm^3 from CνB



*

Cosmic Neutrino Background

60Billion nu/s/cm^2 from the sun
~100nu/cm^3 from CvB



Compare that with 1.d-7 baryons

Is generic prediction of the standard hot big bang model.
indirectly confirmed by the accurate **agreement of predictions and observations** of
a) the primordial abundance of light elements
b) the power spectra of CMB anisotropies
c) the large scale clustering of cosmological structures.

such good agreement would fail dramatically
without a CvB & the standard neutrino decoupling model.

*

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”)

Neutrinos

The **only** known **particle** behaving
as **radiation** at early time (during the CMB acoustic oscillations)
and as **dark matter (not cold**) at late time (during structure formation)
This has consequences for <u>the background evolution</u> and the <u>structure growth</u>.

For aficionados

- Neutrinos are in equilibrium with the primeval plasma through weak interaction reactions. They decouple from the plasma at a temperature 1MeV
- We then have today a Cosmological Neutrino Background at a temperature

$$T_\nu = \left(\frac{4}{11}\right)^{1/3} T_\gamma \approx 1.945K \rightarrow kT_\nu \approx 1.68 \cdot 10^{-4} eV$$

at least two neutrino mass eigenstates are non-relativistic today

With a density of:

$$n_f = \frac{3}{4}\frac{\varsigma(3)}{\pi^2} g_f T_f^3 \rightarrow n_{\nu_k,\bar{\nu}_k} \approx 0.1827 \cdot T_\nu^3 \approx 112 cm^{-3}$$

That, for a massive neutrino translates in:

$$\Omega_\nu h^2 = \frac{\sum_\nu m_\nu}{93.14 eV}$$

Neutrinos affect the growth of cosmic clustering and (indirectly) the expansion history so they can leave key imprints on the cosmological observables

CνB

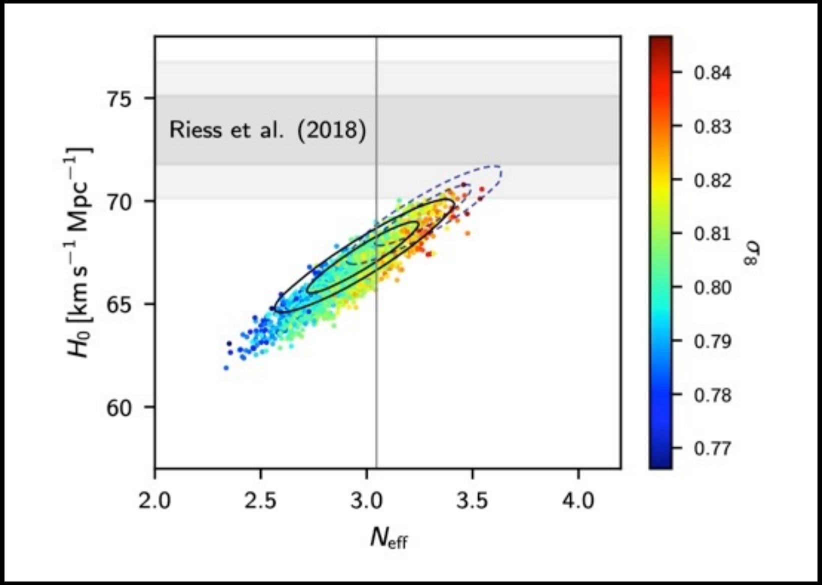
PHYSICAL REVIEW VOLUME 92, NUMBER 6 DECEMBER 15, 1953

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)

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

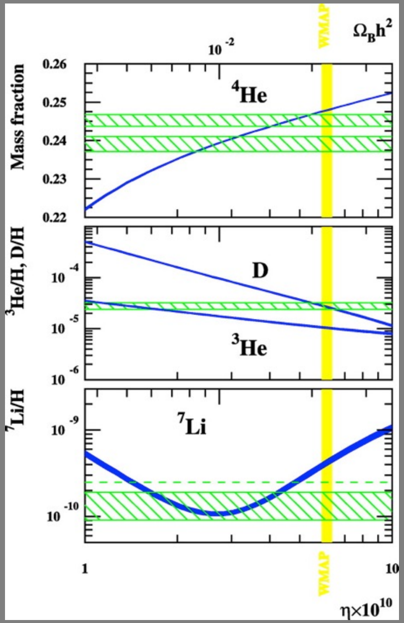
N_{eff} should be 3.046 (if they are neutrinos)



Planck 2018 (cosmology)

Relict neutrinos influence in cosmology

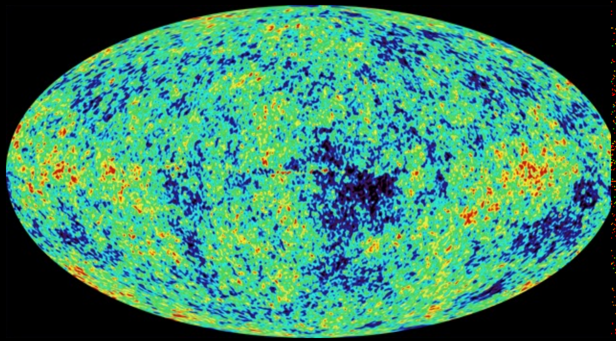
Primordial nucleosynthesis



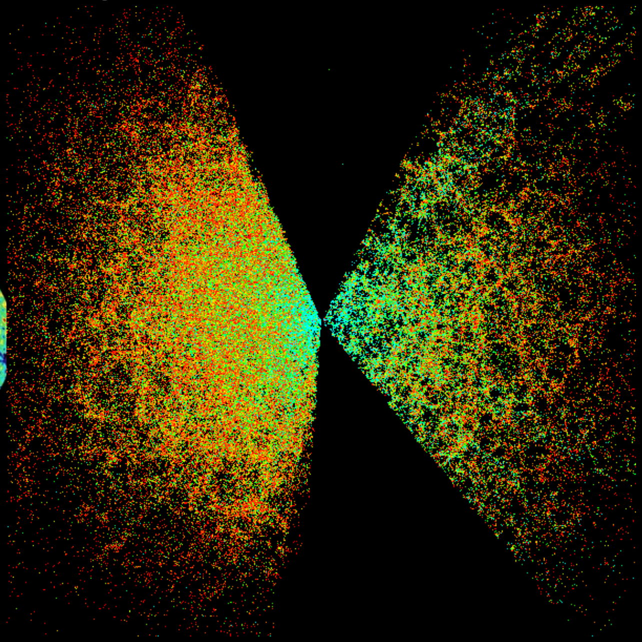
T~ MeV

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

CMB



Large-scale structure



T<eV

N_{eff} mass

What do we know and what would we like to know?

How many “neutrinos”? (dark radiation)

Have we really seen the cosmic neutrino background?
(i.e. Are we really sure it’s neutrinos?)

Their total mass $M\nu$ or Σ
(and are we really sure??)

The individual masses (hierarchy)

Mostly model-dependent statements: measuring cosmological parameters values**

Neutrino mass: Physical effects

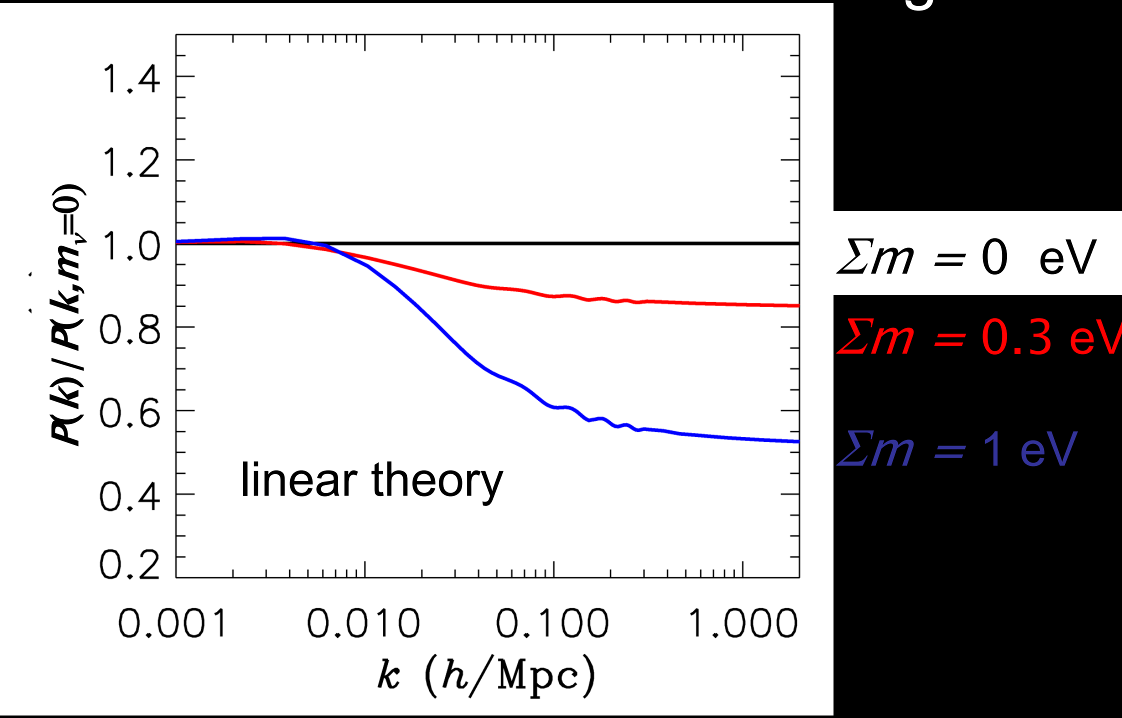
Total mass >~0.6 eV become non relativistic before recombination CMB*

Total mass <~0.6 eV become non relativistic after recombination:
alters matter-radn equality but effect can be "cancelled"
by other parameters

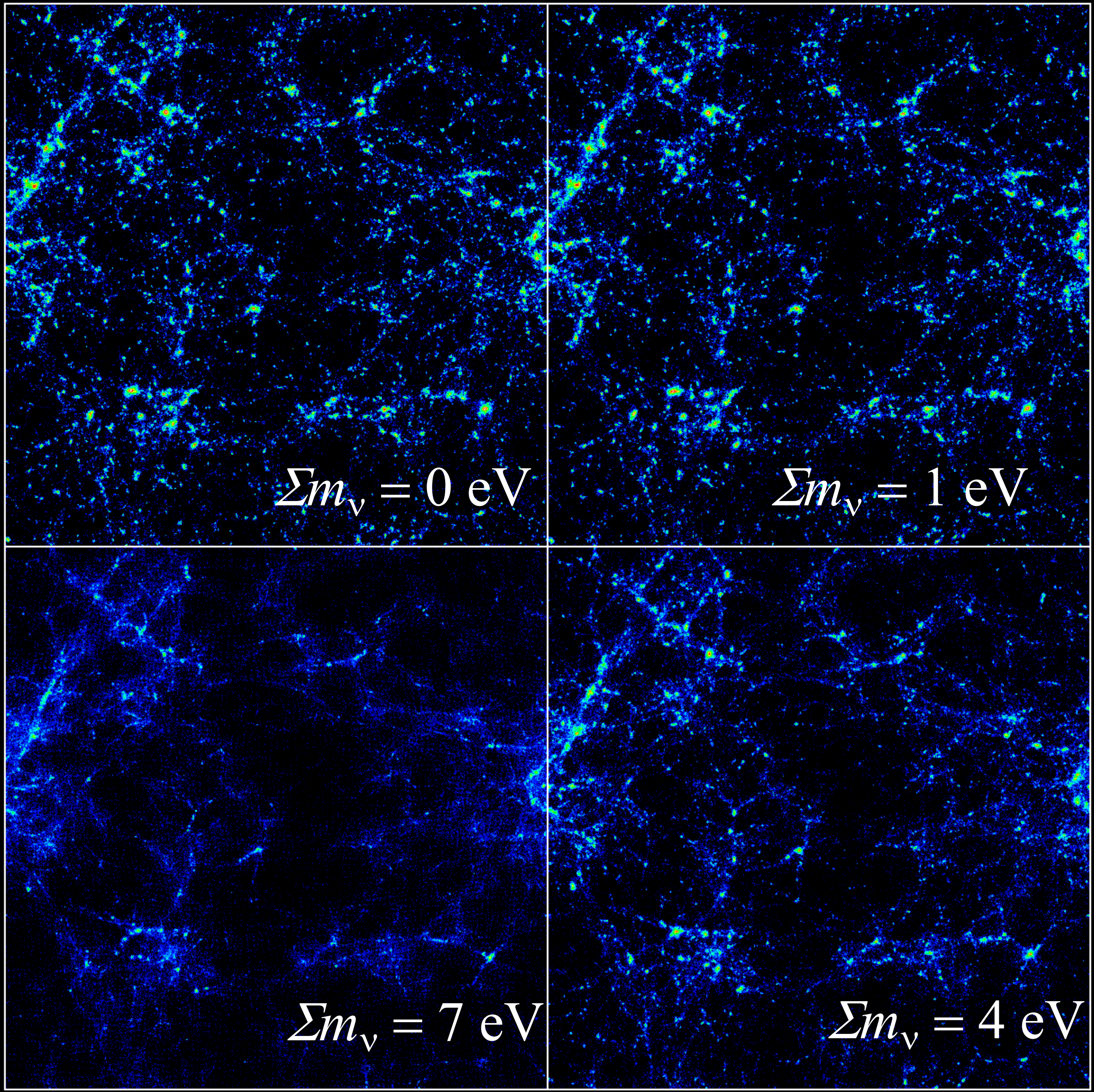
CMB
Degeneracy

After recombination

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

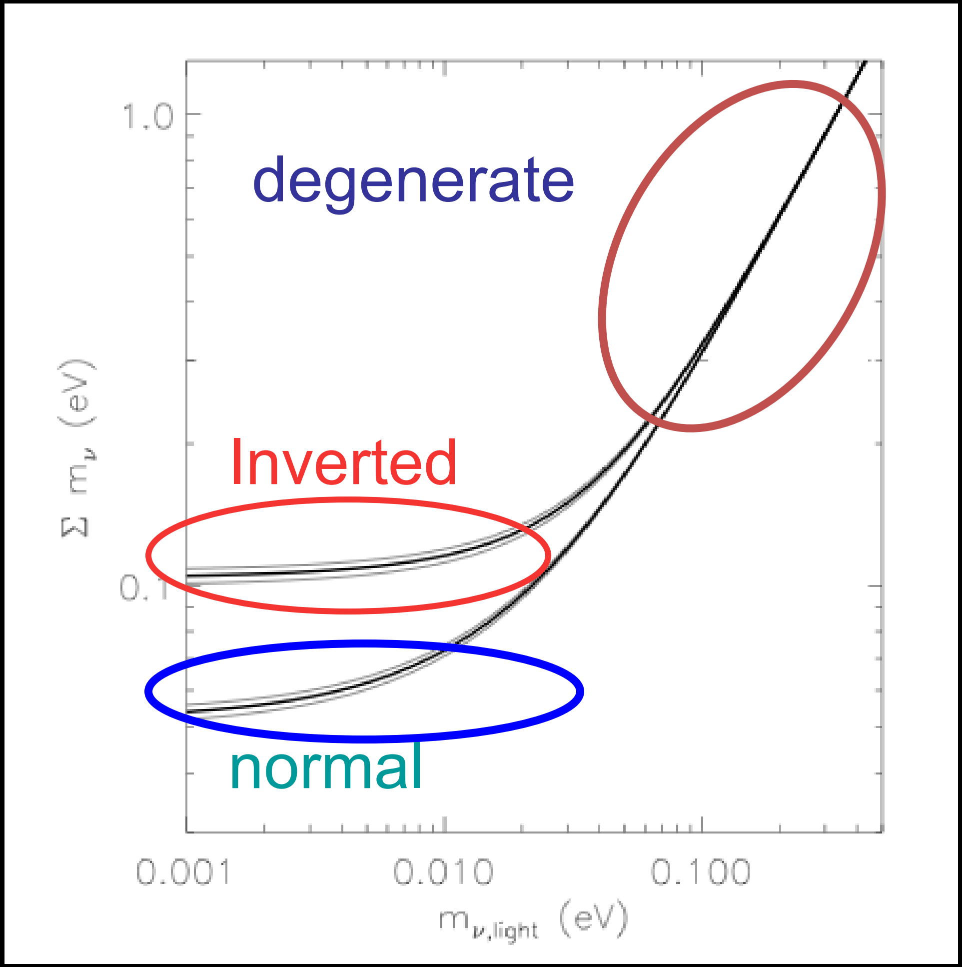


Different masses become non-relativistic a slightly different times
Cosmology can yield information about neutrino mass hierarchy



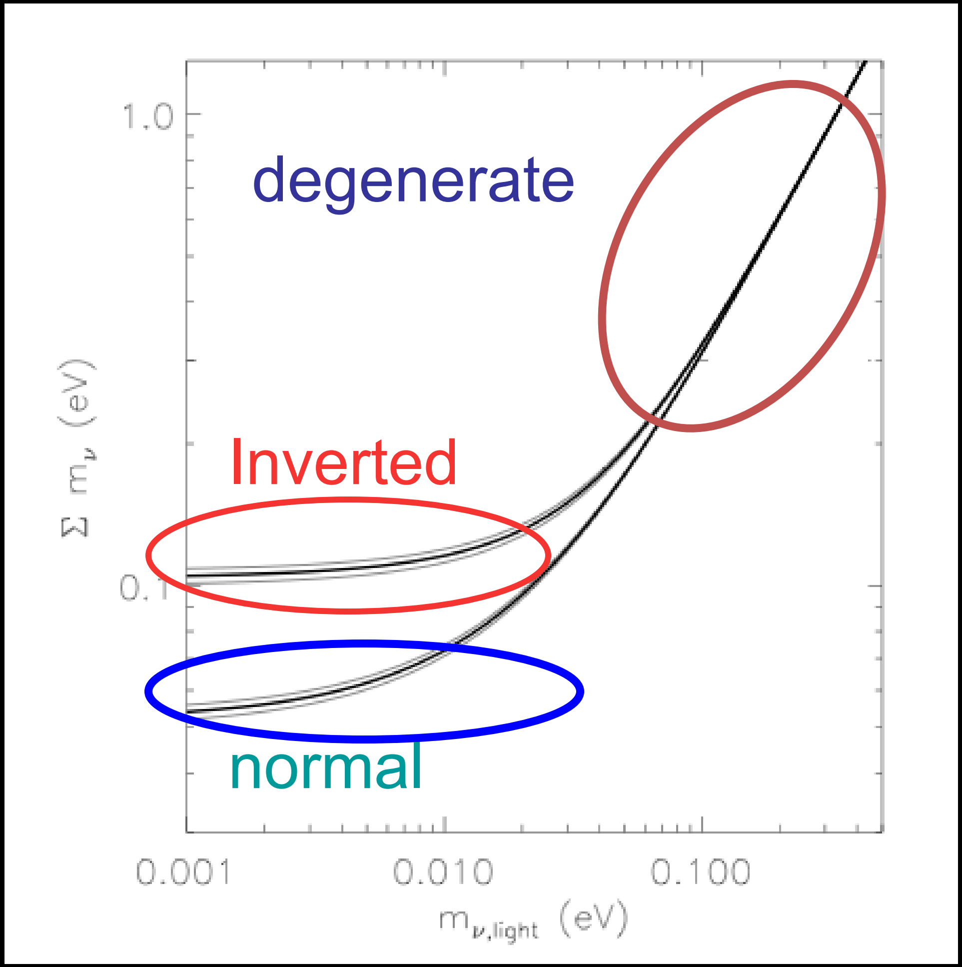
Ma '96

Cosmology is key in determining the absolute mass scale



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

Cosmology is key in determining the absolute mass scale



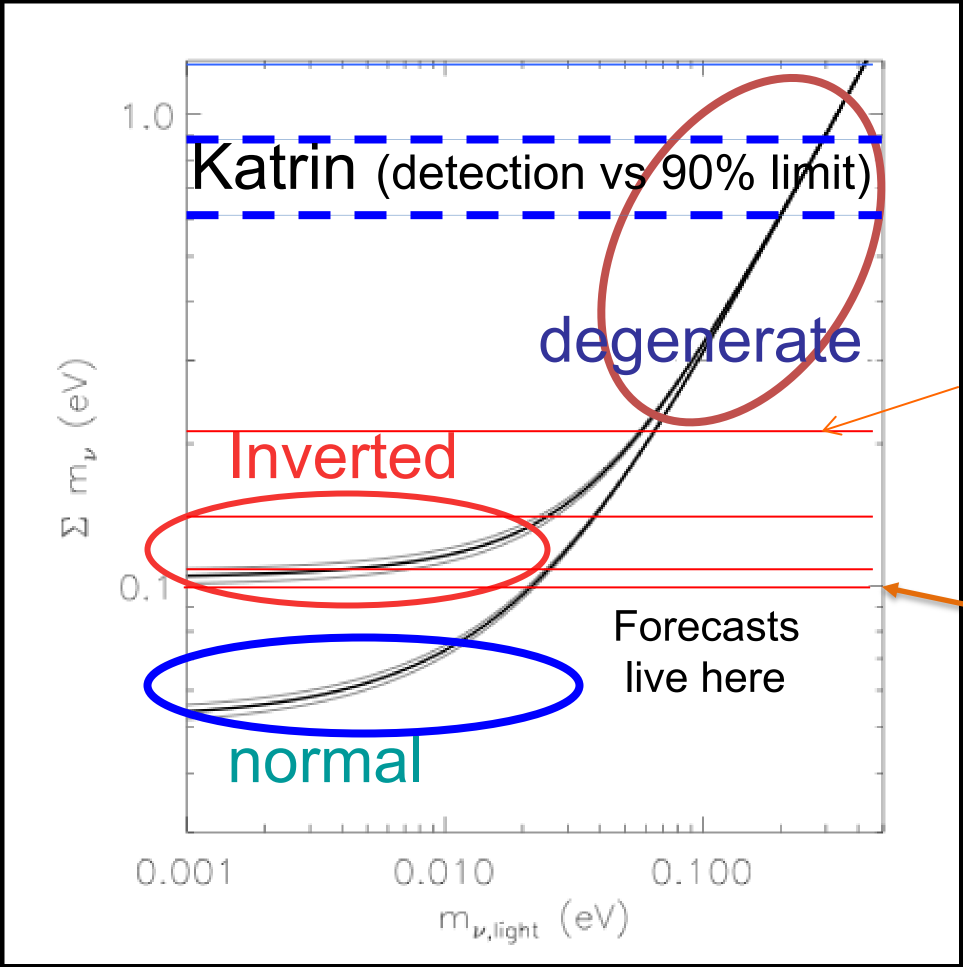
These are tiny effects

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

The KATRIN Experiment

Ambitious terrestrial experiment

Cosmology is key in determining the absolute mass scale



Katrin limit (Aker et al. 2.4eV)

forecasted

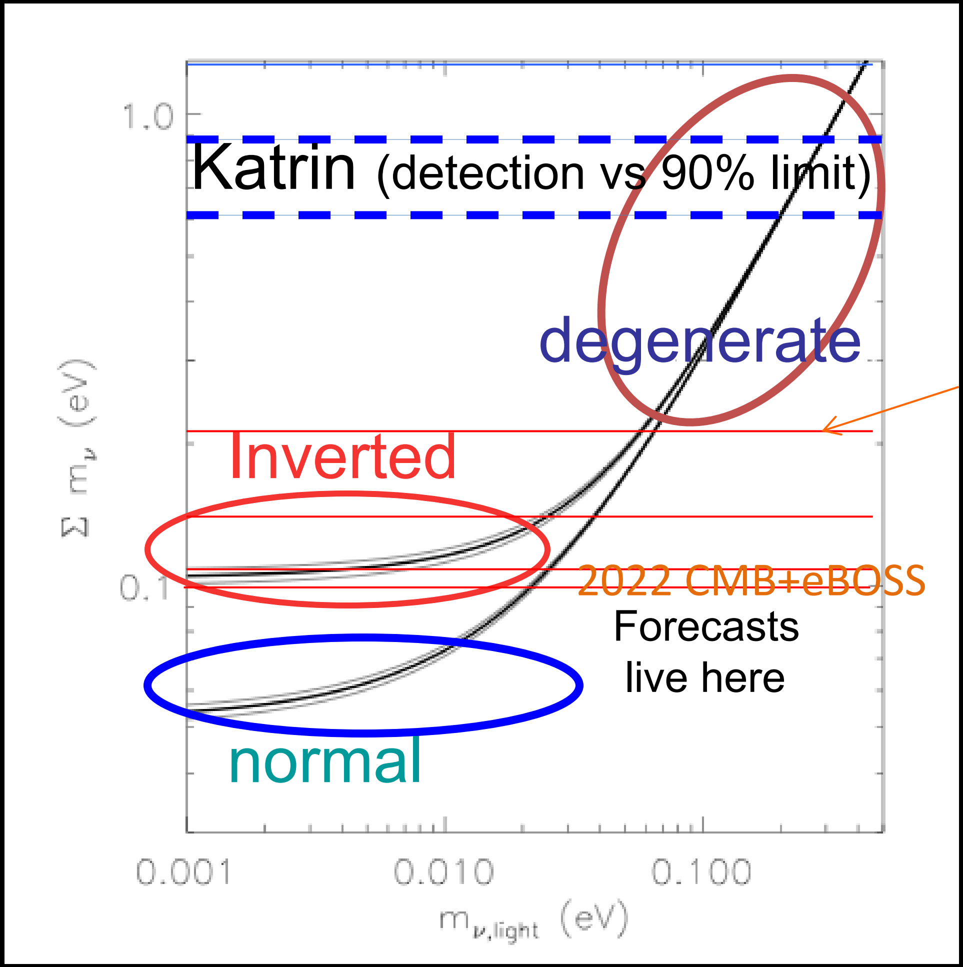
CMB(Planck) +BAO 2018
95% limit

2018+ lensing +BAO+pol

2022 CMB+eBOSS

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

Cosmology is key in determining the absolute mass scale



Katrin limit (Aker et al. 2.4 eV)

forecasted

CMB(Planck) +BAO
95% limit

2018+ lensing +BAO+pol

The challenge is
systematic errors

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

Neutrino mass: Physical effects

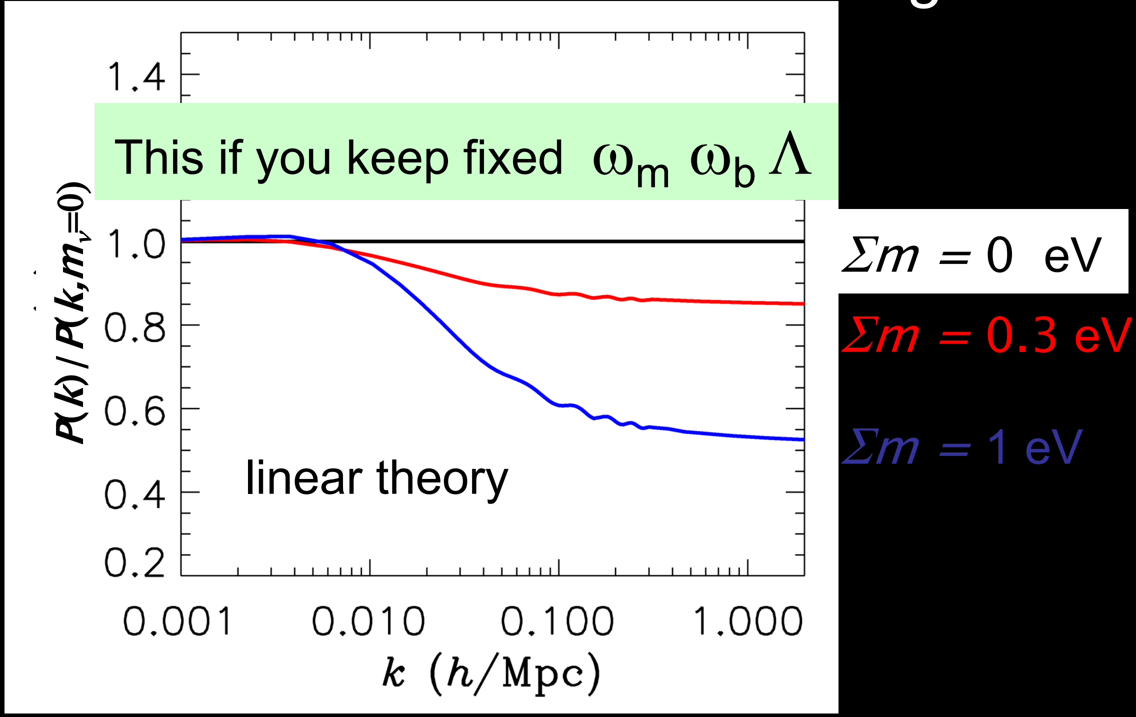
Total mass >~0.6 eV become non relativistic before recombination CMB*

Total mass <~0.6 eV become non relativistic after recombination: alters matter-radn equality, da, 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

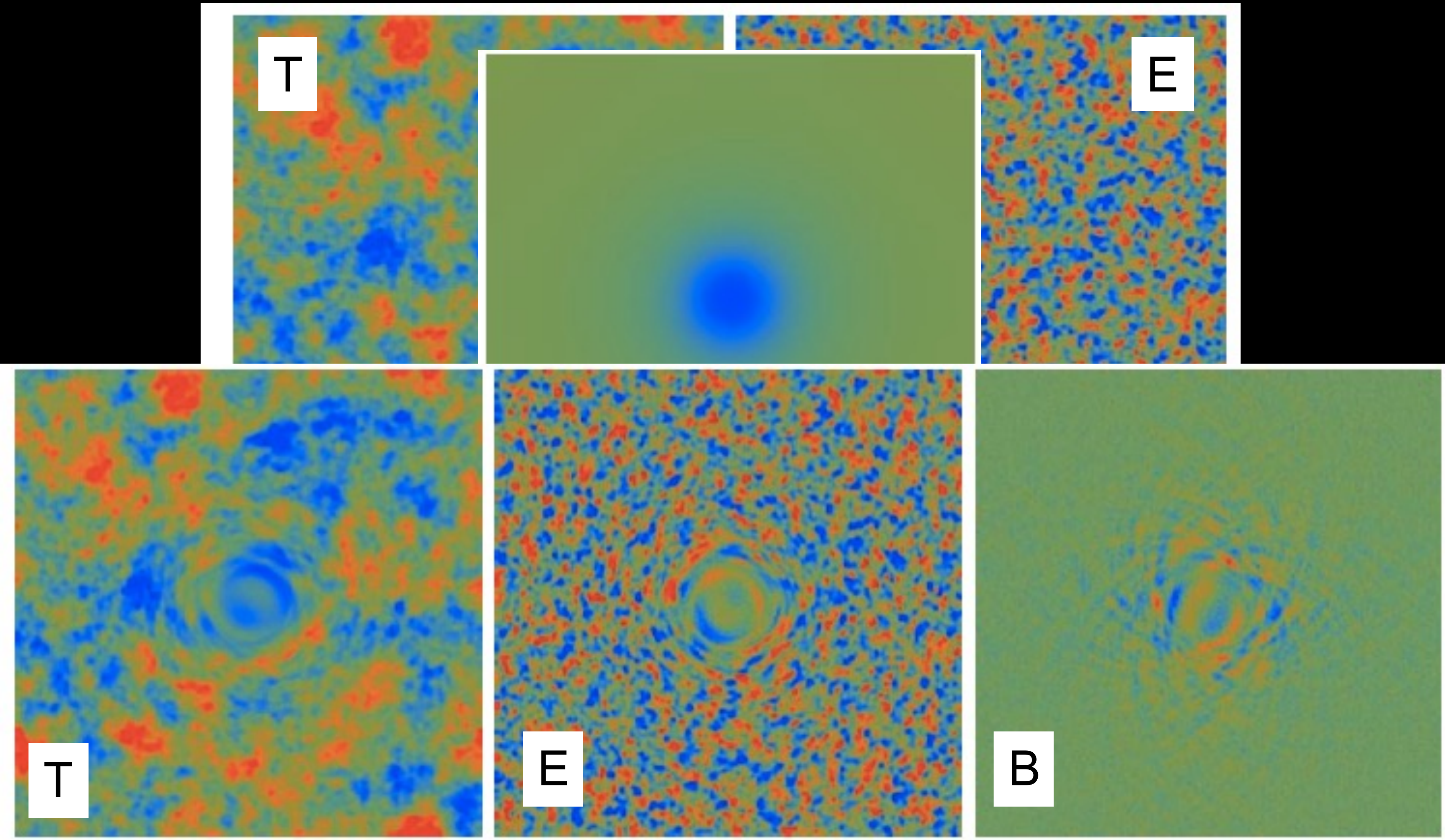


Different masses become non-relativistic a slightly different times
Cosmology can yield information about neutrino mass hierarchy**

CMB back to the rescue

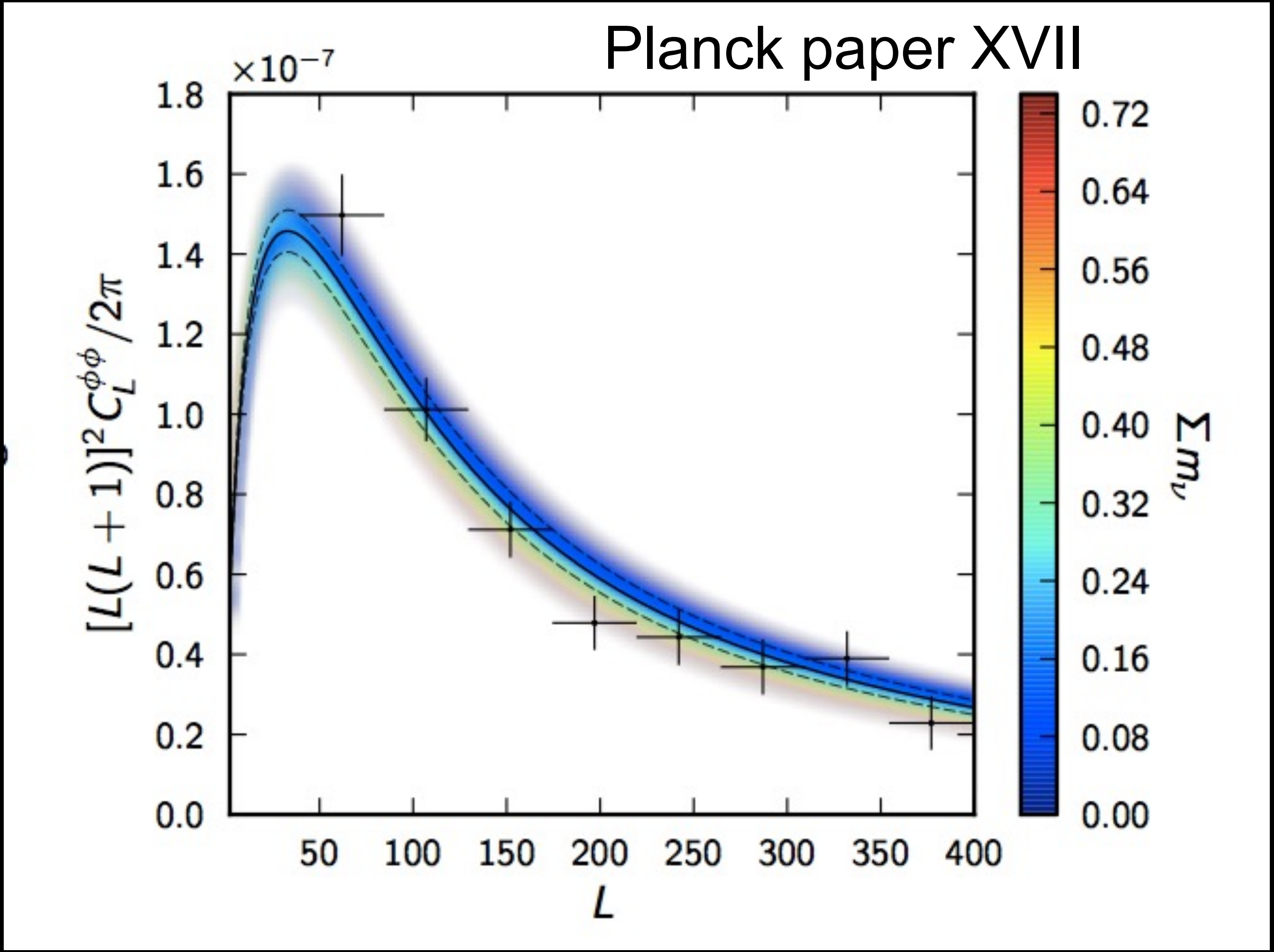
Lensing

From Hu Okamoto 2001



CMB back to the rescue

Lensing



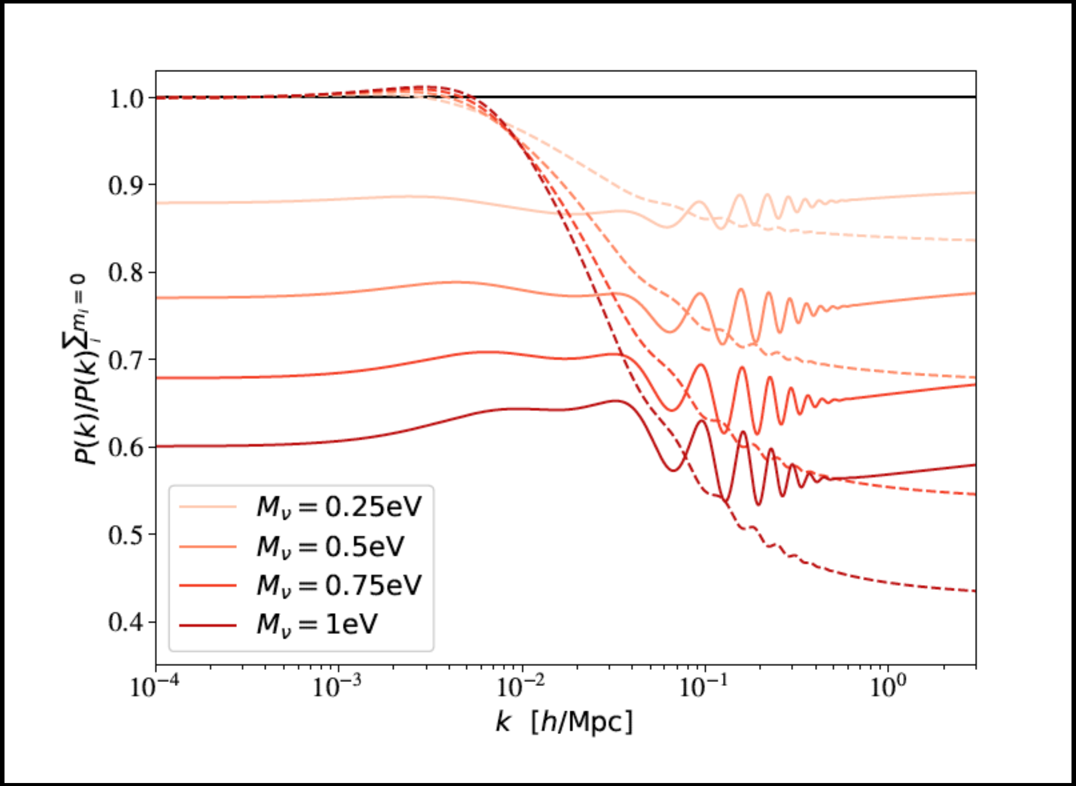
Neutrino mass: Physical effects

Move along CMB parameters degeneracy

keep fixed ω_c ω_b, θ_s

i.e. play with h …

H0 is everywhere!



Suppression

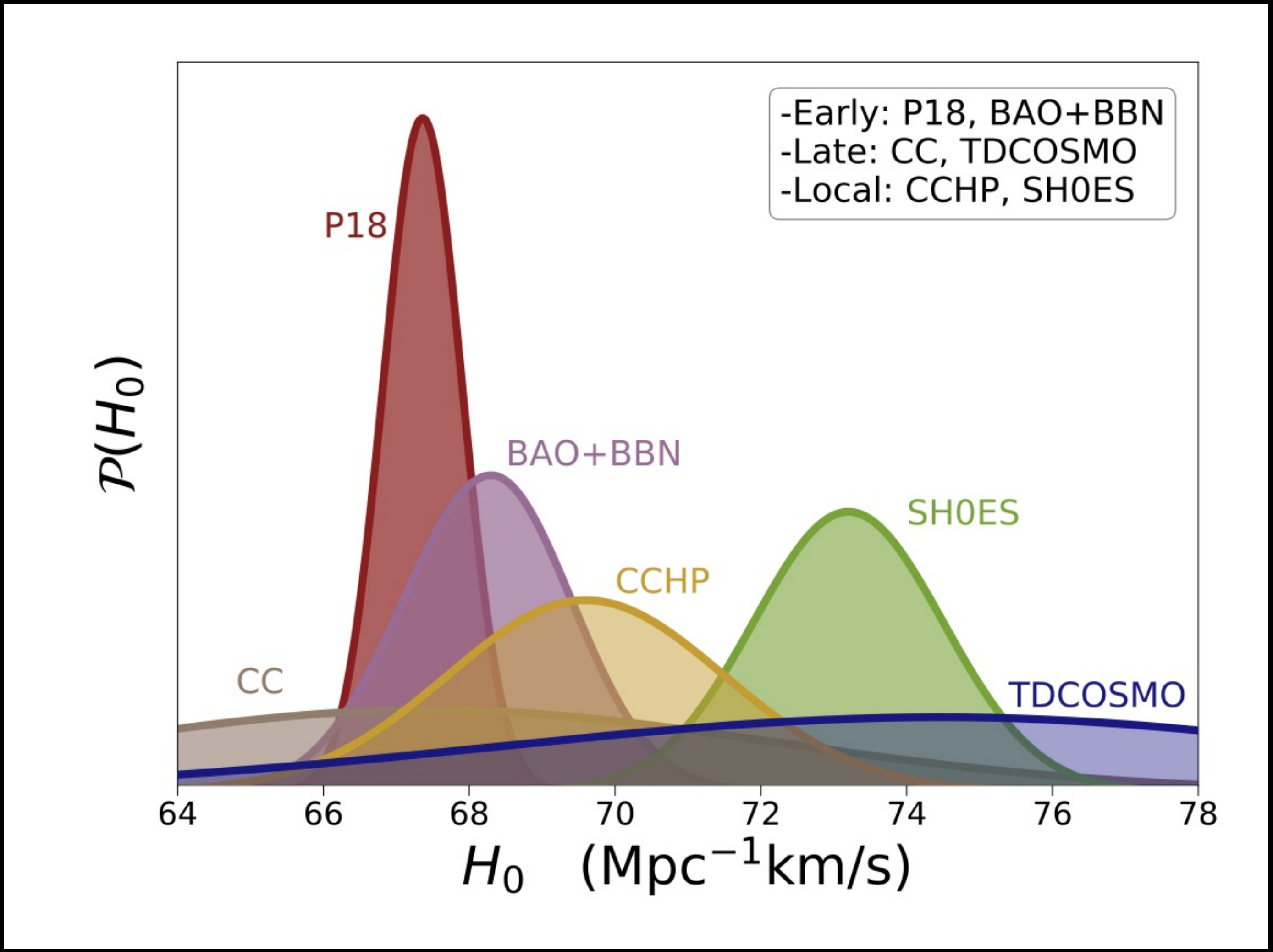
BAO

(exp.history)

There are many H_0

Not all measurements measure directly the current expansion rate

Model dependent vs model independent



This type of plot change by week soo… just illustrative

Bernal et al. 2102.05066

Including large-scale structure clustering

Pros: see the “signature” scale-dependent clustering suppression

Cons: astrophysics, bias,non-linearities

Possible approach & useful exercise: use completely different tracers and see if there is agreement

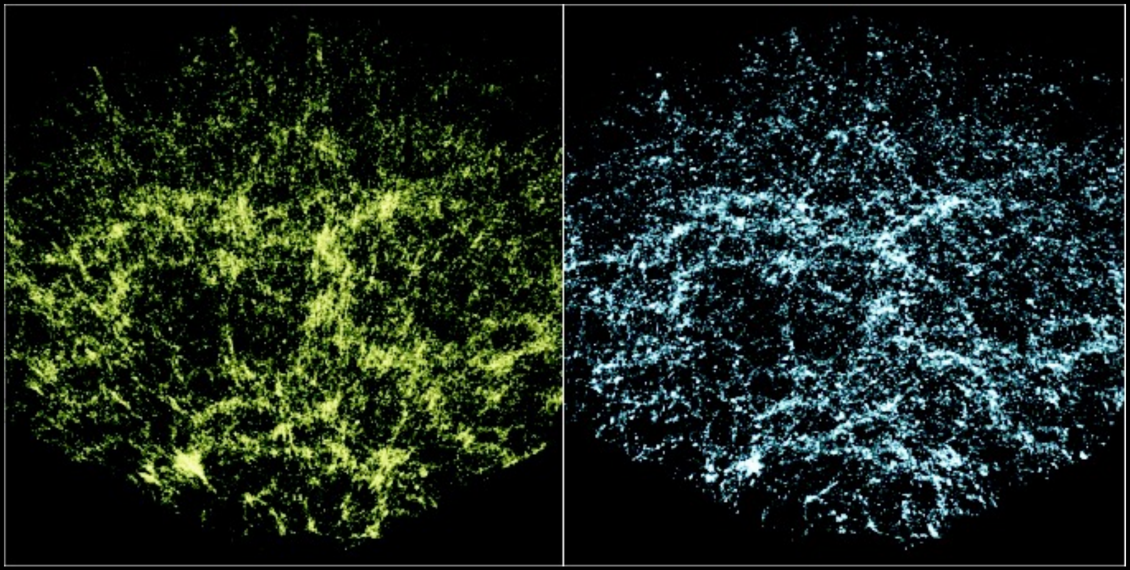
Limits on the sum of the masses

	Model	95% CL (eV)
CMB alone		P18
Pl18[TT+lowE]	ΛCDM+$\sum m_\nu$	< 0.54
Pl18[TT,TE,EE+lowE]	ΛCDM+$\sum m_\nu$	< 0.26
CMB + probes of background evolution		
Pl18[TT+lowE] + BAO	ΛCDM+$\sum m_\nu$	< 0.16
Pl18[TT,TE,EE+lowE] + BAO	ΛCDM+$\sum m_\nu$	< 0.13
		DiValentino et al 19
Pl18[TT,TE,EE+lowE]+BAO	ΛCDM+$\sum m_\nu$+5 params.	< 0.515
CMB + LSS		
Pl18[TT+lowE+lensing]	ΛCDM+$\sum m_\nu$	< 0.44
Pl18[TT,TE,EE+lowE+lensing]	ΛCDM+$\sum m_\nu$	< 0.24
CMB + probes of background evolution + LSS		
Pl18[TT+lowE+lensing] + BAO	ΛCDM+$\sum m_\nu$	< 0.13
Pl18[TT,TE,EE+lowE+lensing] + BAO	ΛCDM+$\sum m_\nu$	< 0.12
Pl18[TT,TE,EE+lowE+lensing] + BAO+Pantheon	ΛCDM+$\sum m_\nu$	< 0.11

eBOSS CMB+BAO+RSD	eBOSS (Alam et al 2021)	<0.102
eBOSS CMB+BAO+RSD+Sne (*)		<0.099
eBOSS CMB+BAO+RSD+Sne+Lya	Palanque delabrouille et al 2020	<0.089

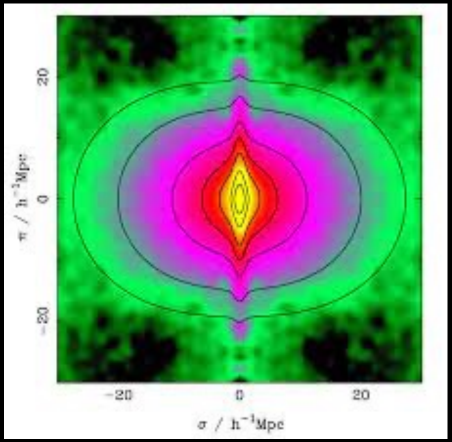
What’s RSD?

Beyond BAO: Redshift space distortions (RSD)

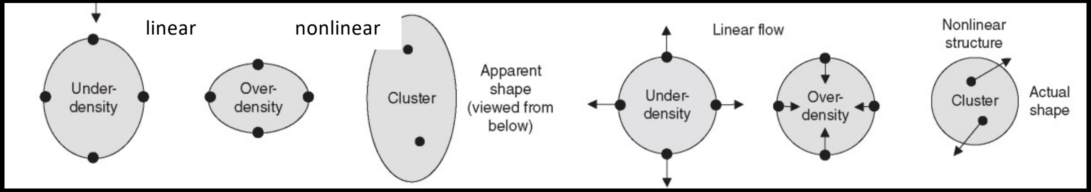


But we don't, use redshifts If we could measure distances…

Mock (simulated) survey

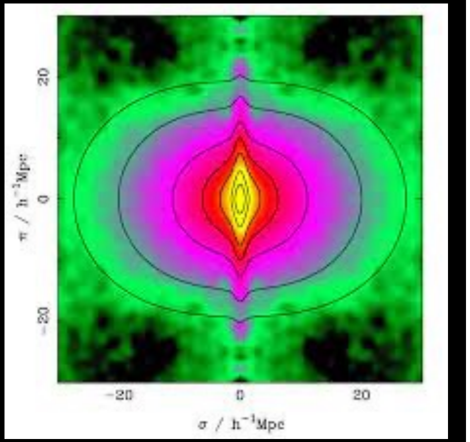


Correlation function…

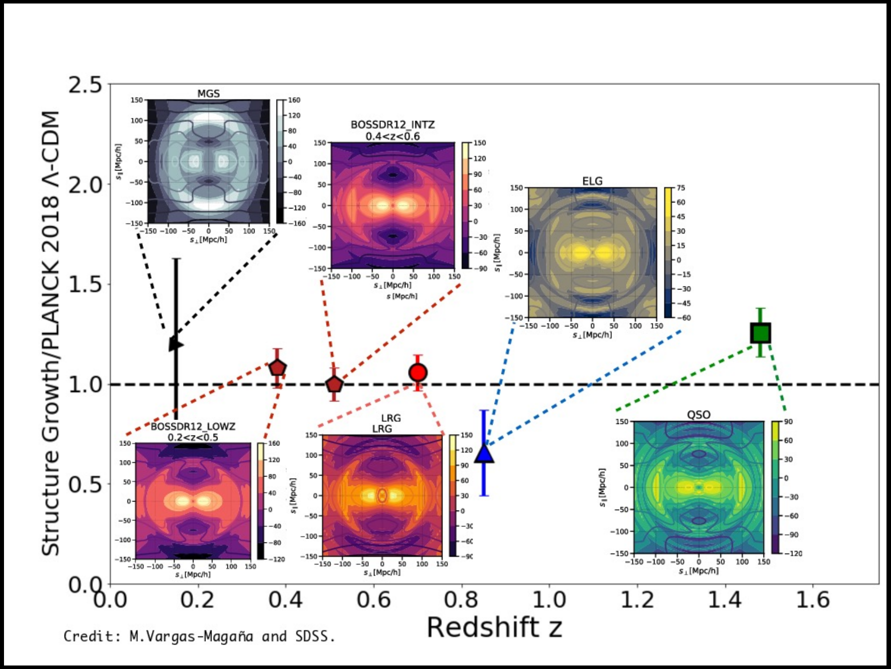


Beyond BAO: Redshift space distortions (RSD)

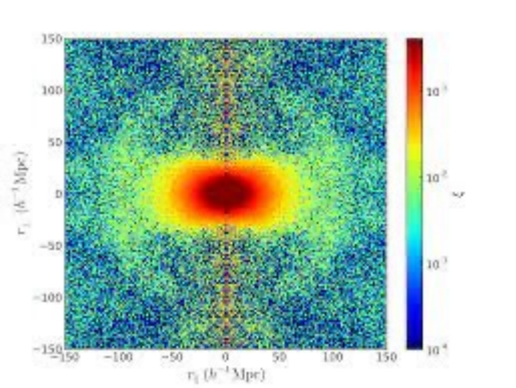
Redshift space distortions: peculiar velocities are sourced by gravitational pull of the inhomogeneities measure growth of structure i.e. f $\sigma 8$



2001 2dFGRS, Peacock et al.

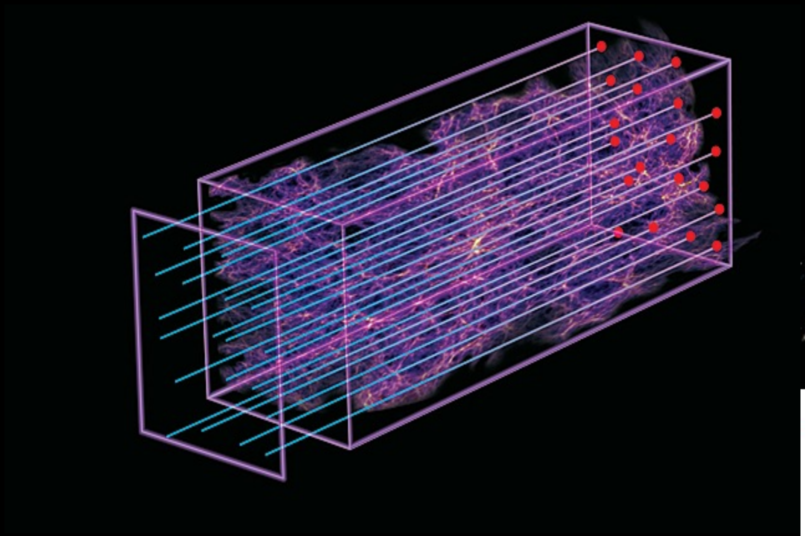


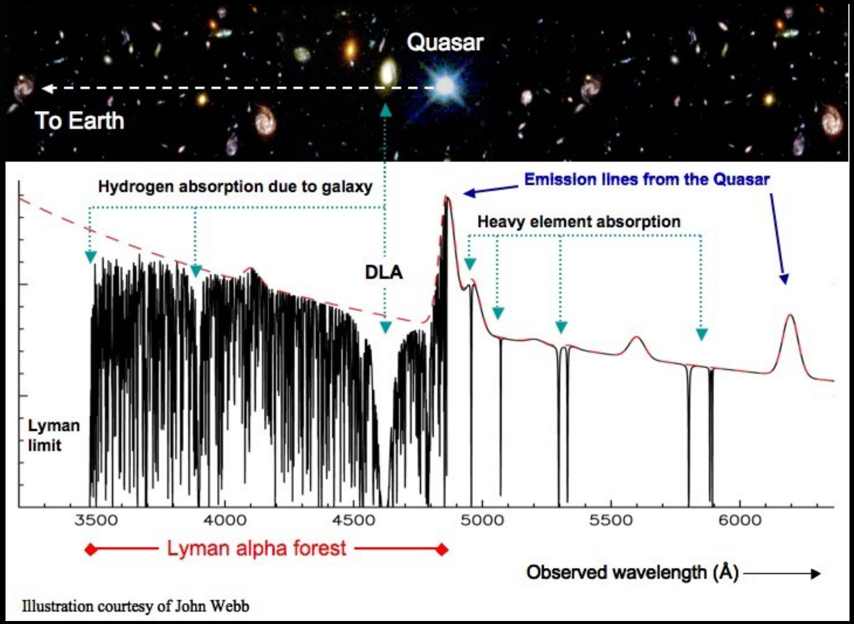
2021 e-BOSS



2013 BOSS collab,

The Lymanalpha forest





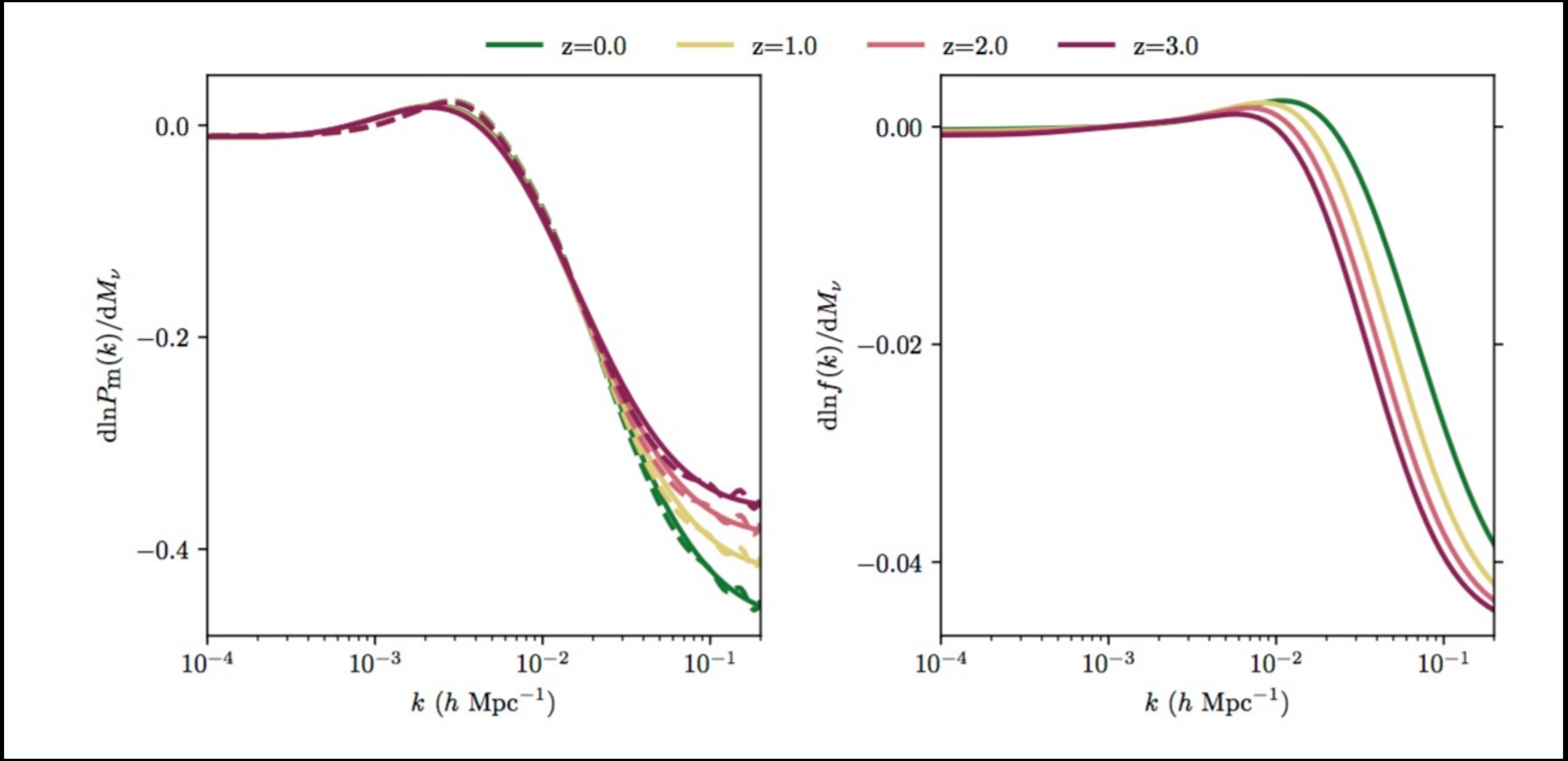
Limits on the sum of the masses

		95%CL
eBOSS CMB+BAO+RSD	eBOSS (Alam et al 2021)	<0.102
eBOSS CMB+BAO+RSD+Sne (*)		<0.099
eBOSS CMB+BAO+RSD+Sne+Lya	Palanque Delabrouille et al 2020	<0.089

Use (almost) everything we’ve got…

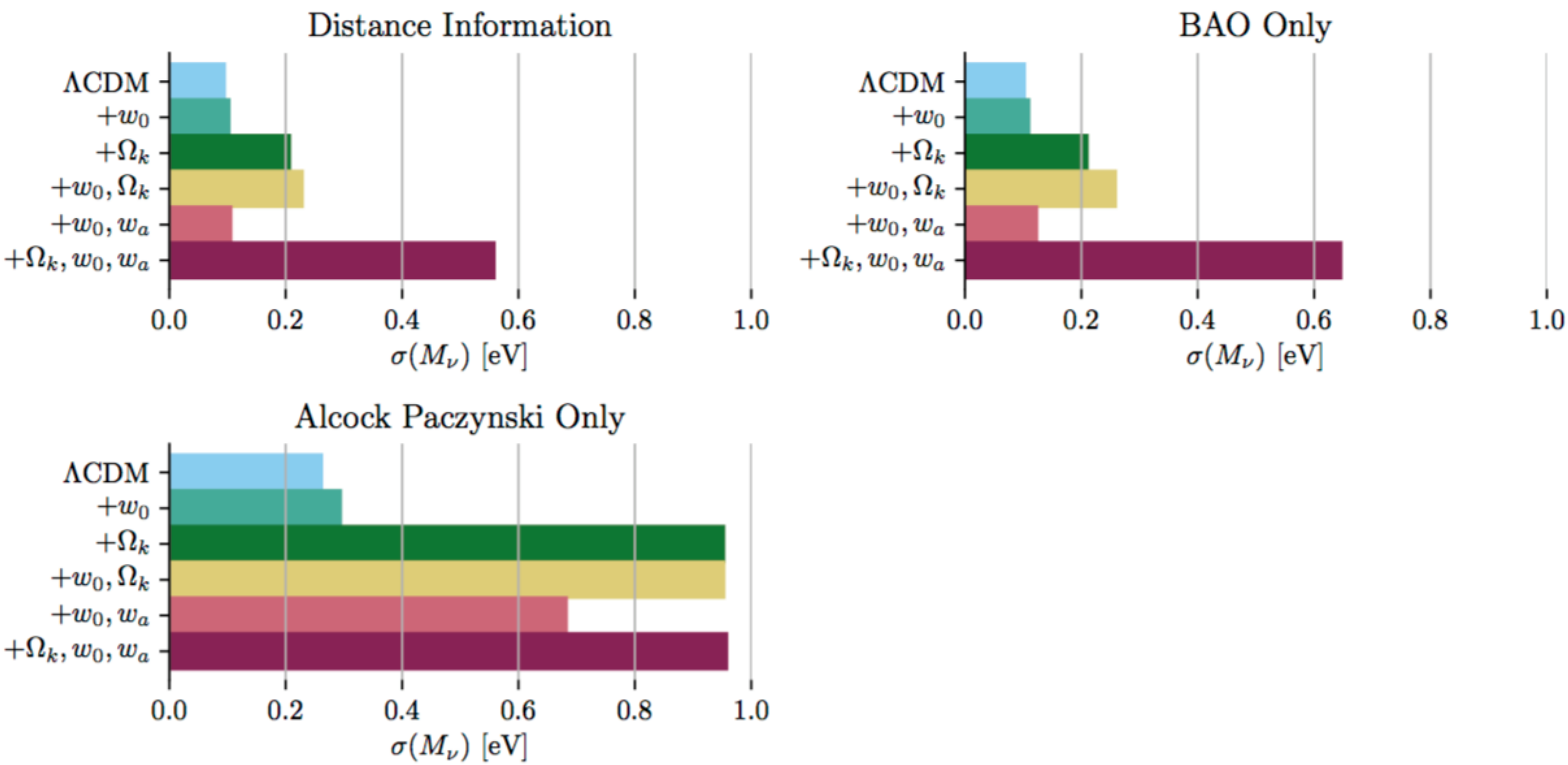
OK or not OK we can discuss

Expansion history vs growth



Boyle & Komatsu 2019

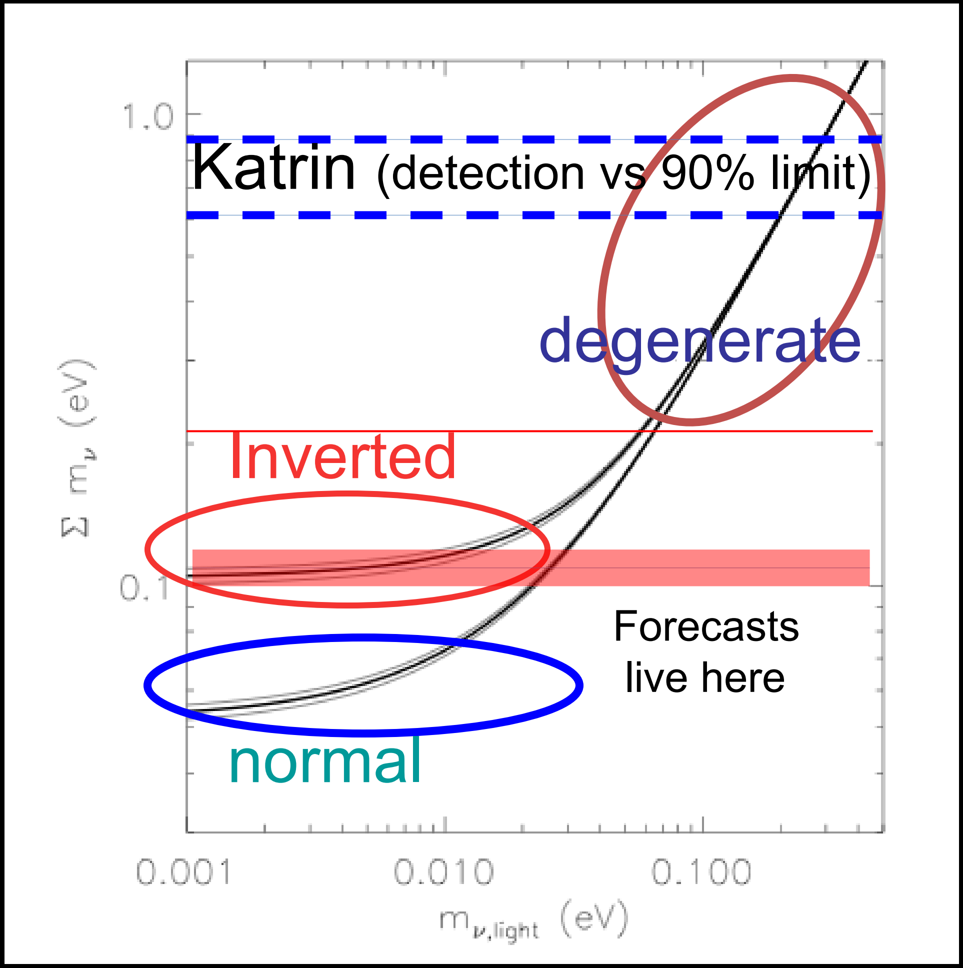
Expansion history vs growth



Forecast for Euclid

Boyle & Komatsu 2019

Neutrino mass limits

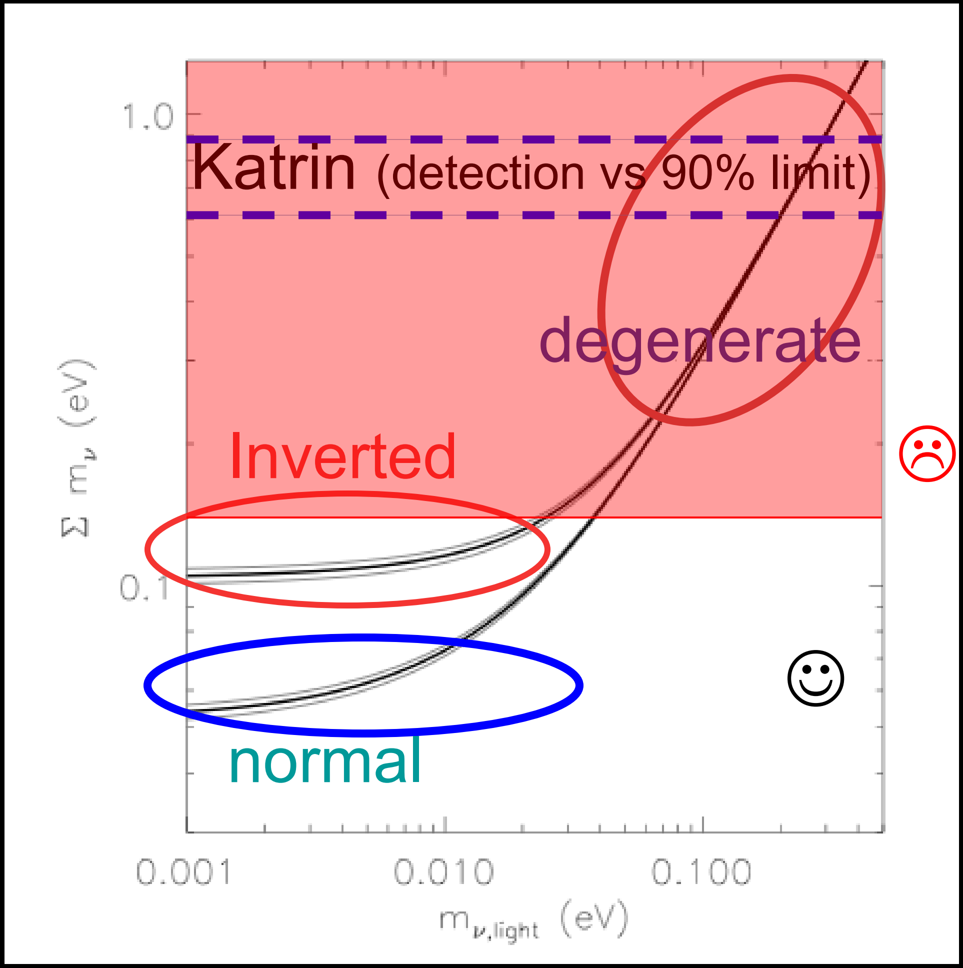


CMB(Planck) +BAO

+LSS

5% or less effects on P(k)

Implications I



If we add eBOSS then HI ☹ $\Sigma<0.099$eV @95%

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

Implications II

CMB+BAO+LSS limit   0.099- 0.11 eV

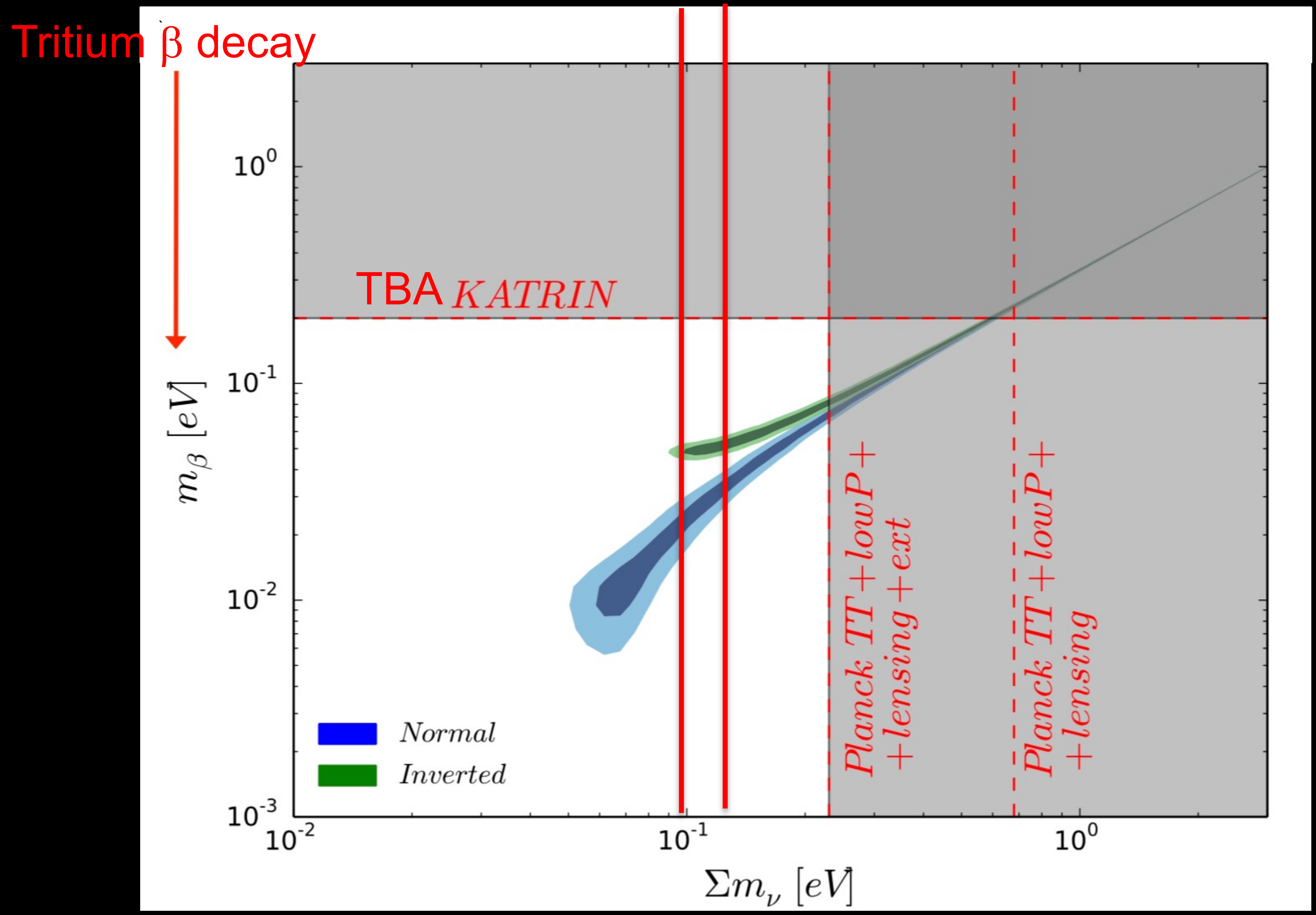


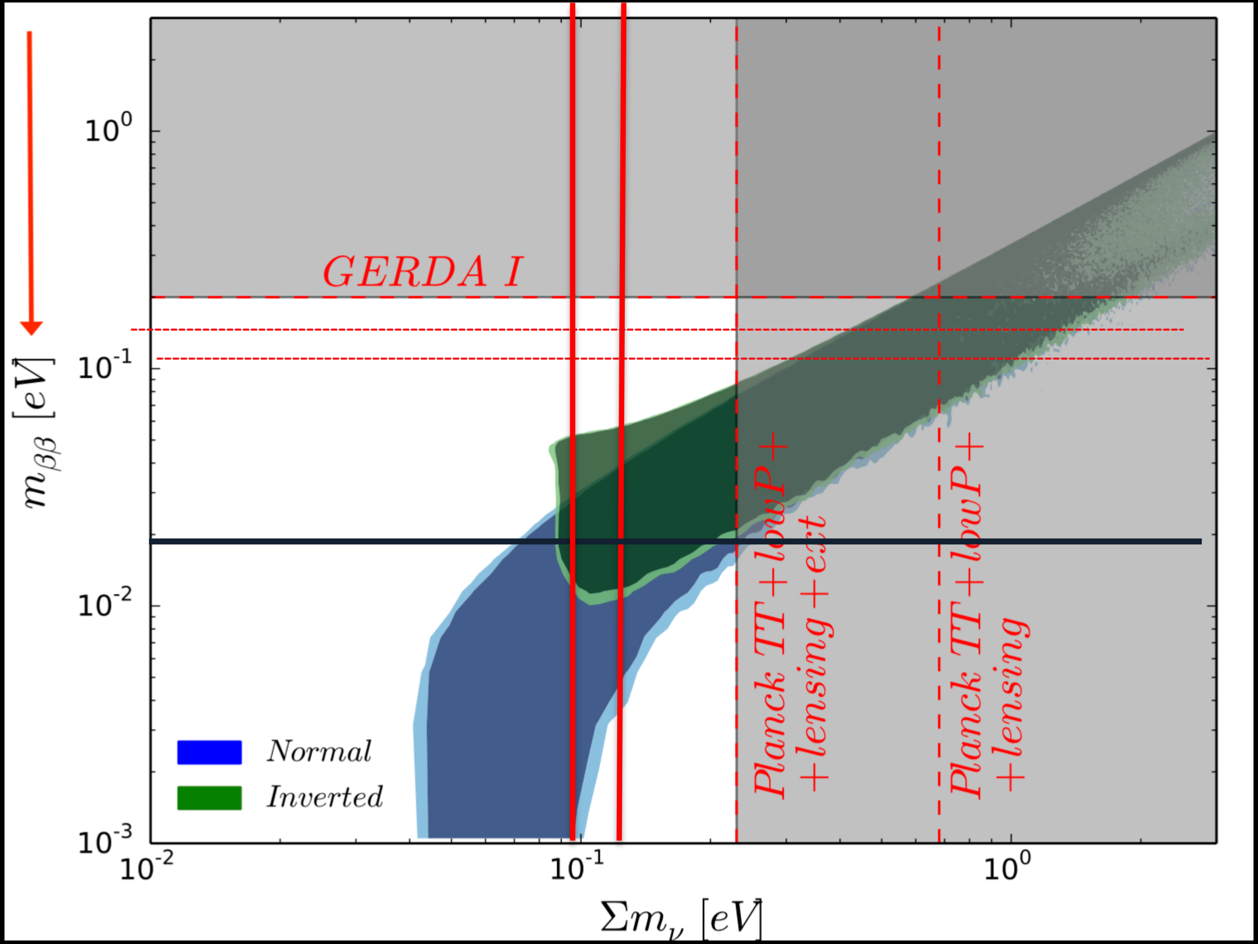
Fig. adapted* from M. Lattanzi

* Taken from google

Implications III

ν0ββ

0.099- 0.11 eV



GERDAII

Kamland-Zen

Ton-scale experiment

Fig. adapted* from M. Lattanzi

Of course <T ν0ββ experiments could see something, that would be interesting

Implications: tldnr

Cosmology is key to determine neutrino masses

The pessimist: The inverted hierarchy is under pressure

The optimist: If IH then a measurement of $M\nu$ is just around the corner!

recap

- There is a CνB
- Cosmology places stringent limits on Σm_ν
- If IH then a measurement is around the corner
- However, IH is disfavoured from a Bayesian perspective
- This has important implications
- What is KATRIN measures something?

END