Understanding the Universe: what will be the next disruption?

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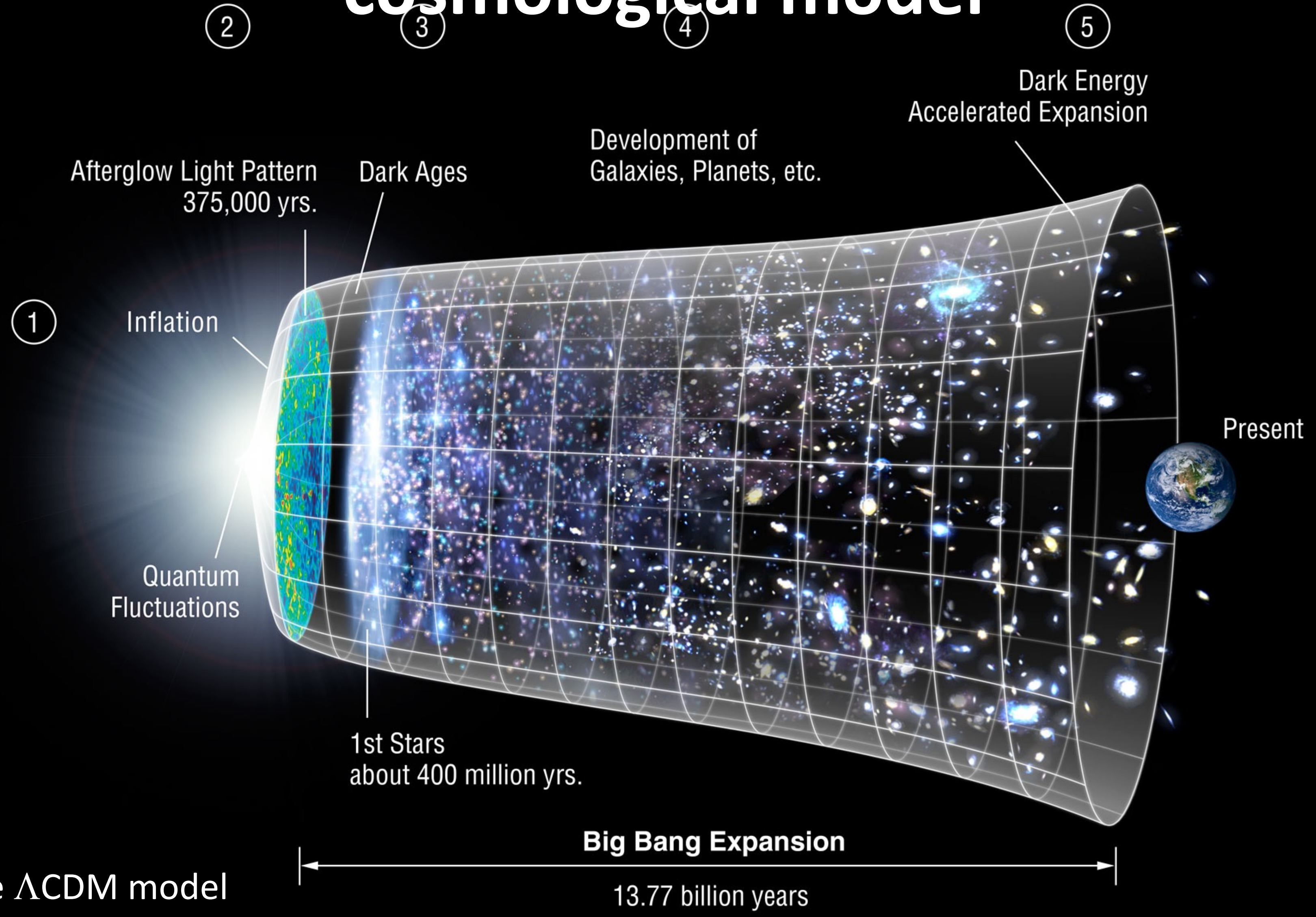
The coordinated effort of large collaborations

Too long to report all authors names and all the references for all the relevant collaborations.

But please take a look at the cosmology-related chapters of Review of particle physics book by Particle data group: all key references and latest results are/will be there.

NEW in the past year or so: KiDS , DES yr3, eBOSS
CMB: Planck, ACTpol, SPTpol

The extremely successful standard cosmological model



the ΛCDM model

Precision cosmology

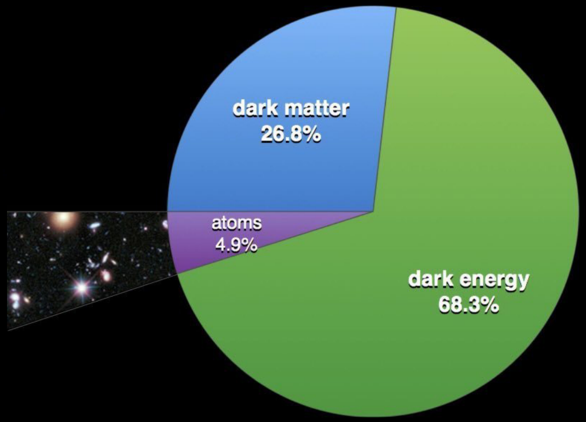
Early 2000s'

ΛCDM: The standard cosmological **model**

Just 6 numbers…..

describe the Universe composition and evolution

Homogenous background



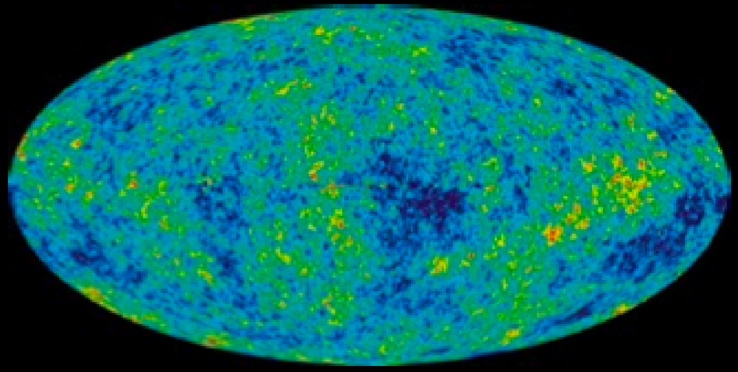
@AstroKatie/Planck13

- atoms 4%
- cold dark matter 23%

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

Λ? CDM?

Perturbations



$$A_s, n_s$$

- nearly scale-invariant
- adiabatic
- Gaussian

ORIGIN??

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.

A mixed blessing

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: (Almost) any statement is model dependent

*"Gastrophysics"** and non-linearities get in the way

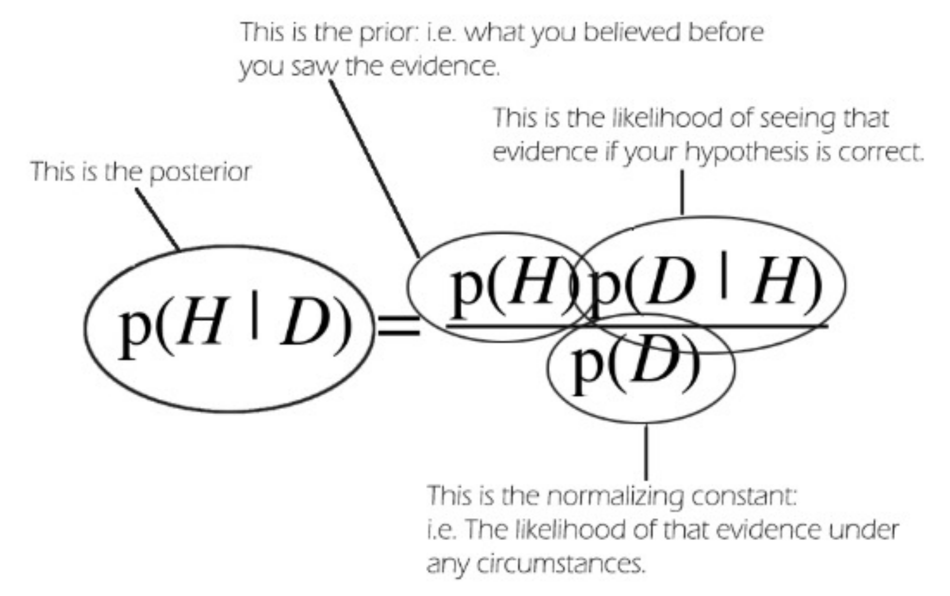
….And the Blessing

We can observe all there is to see

** Not a typo, means complex astrophysics that is poorly understood/hard to model*

challenges

Big data; Cosmology is special we only observe one sky; we only fit models



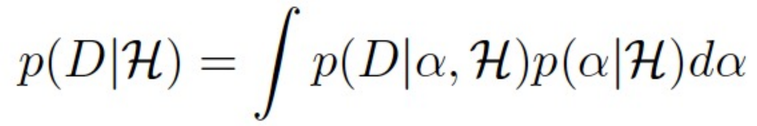
This is the prior: i.e. what you believed before you saw the evidence.

This is the likelihood of seeing that evidence if your hypothesis is correct.

This is the posterior

$$p(H \mid D) = \frac{p(H)\,p(D \mid H)}{p(D)}$$

This is the normalizing constant: i.e. The likelihood of that evidence under any circumstances.



$$p(D|\mathcal{H}) = \int p(D|\alpha,\mathcal{H})p(\alpha|\mathcal{H})d\alpha$$

Evidence Likelihood prior

What is a prior? What to use?

Exp(accuracy-complexity)

Model selection question: Bayesian Evidence

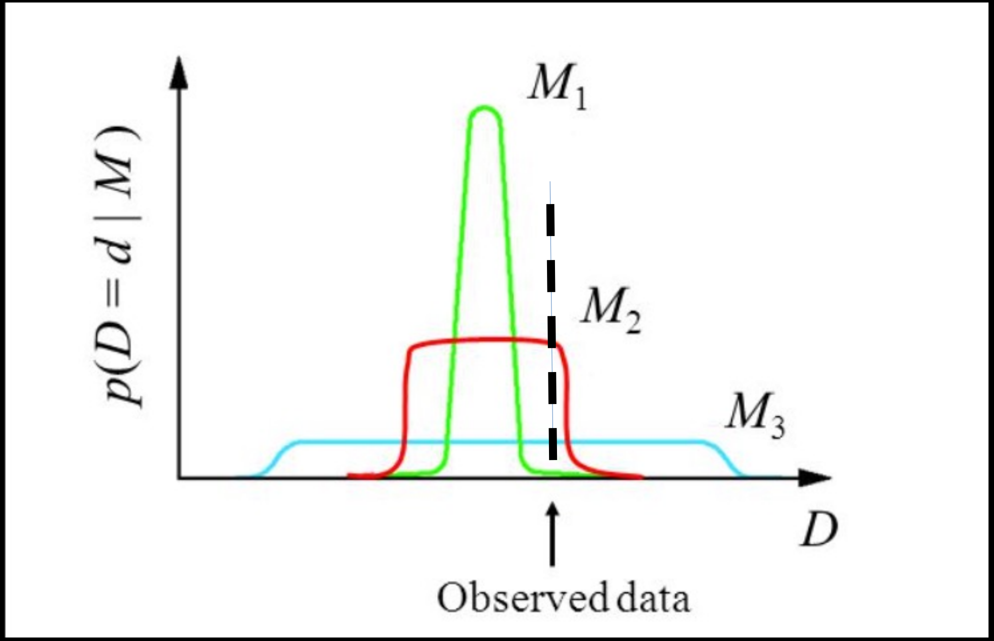
Simpson et al ‘17

When comparing two models or hypotheses use the Bayesian evidence and the Bayes factor

$$p(D|\mathcal{H}) = \int p(D|\alpha,\mathcal{H})p(\alpha|\mathcal{H})d\alpha$$

Evidence Likelihood prior

Exp(accuracy-complexity)



M1: too simple,
unlikely to generate the data

M3: too complex,
can generate many other cases,
why this one?

Prior choice: unconscious bias

There is a lot of noise out there, must be clarified.

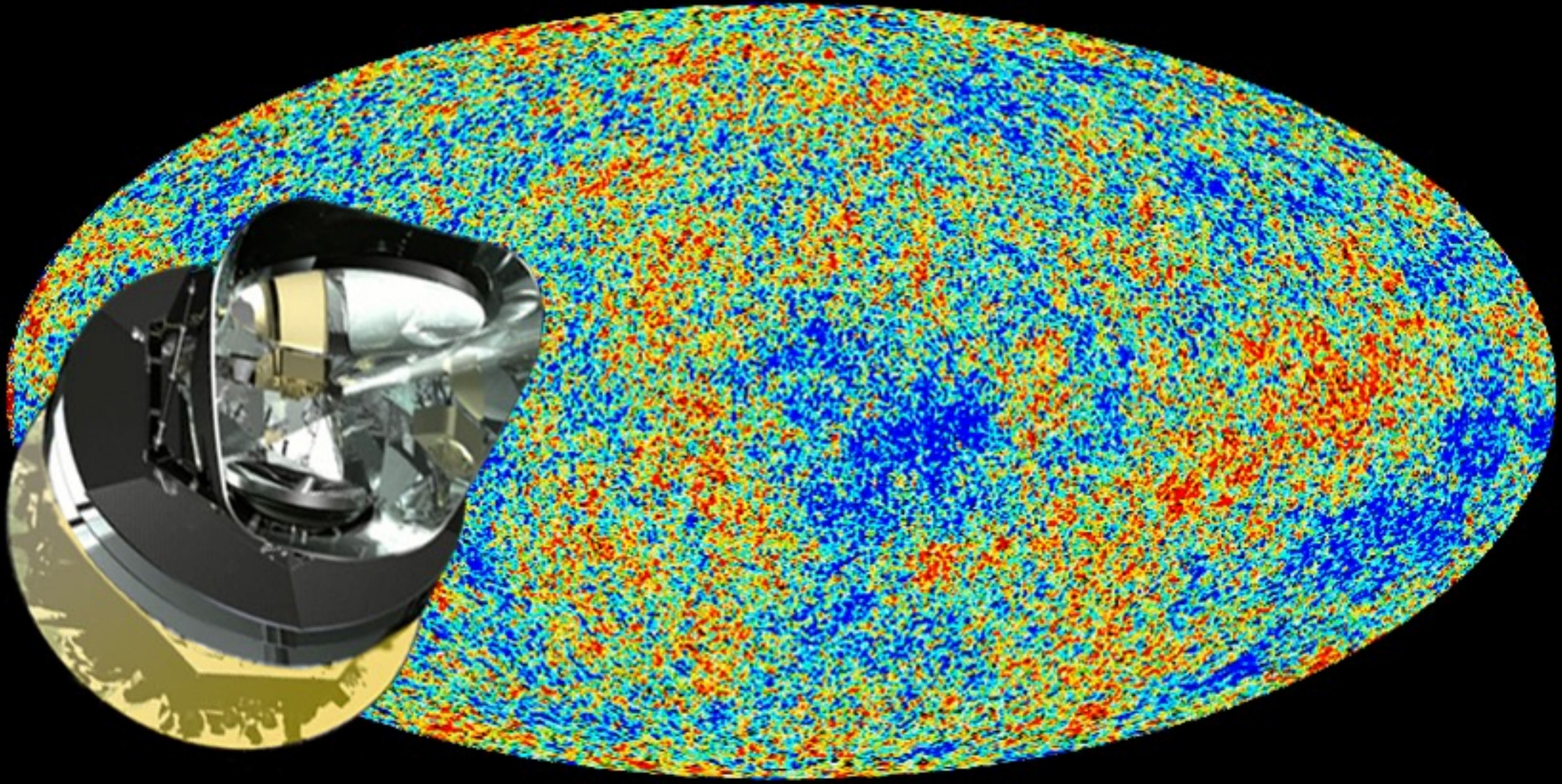
Gist: what is a prior?

- Information that “reflects our state of belief before the data arrived.”
    - use some information about the underlying physical theory/mechanism
    - scientist’s a priori choice to (not) have a personal preference
- Information coming from previous experiments (e.g., “CMB prior”)
- The prior that is most easily overwritten by the data for a given experiment (“Objective Bayesian”)

This choice matters **a lot** especially for model comparison!!!

Coincidences (as told to me by Fergus Simpson)

Example of an ultimate experiment



Planck

But also ACT, SPT, and in the near future S4 and SO.

CMB to study cosmology

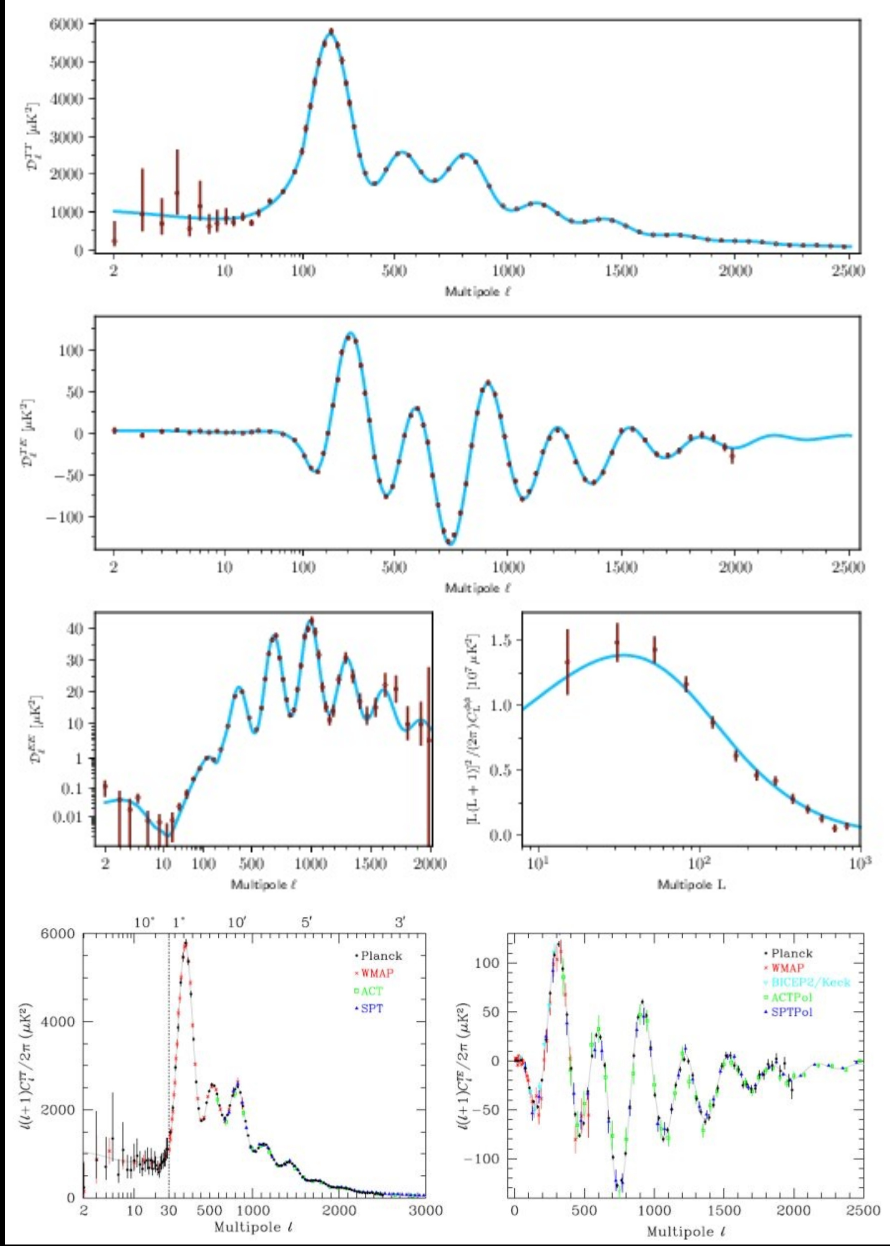
A snapshot of the photon baryon fluid at recombination (last scattering surface) ~300,0000 years after the big bang

A unique window into the early Universe

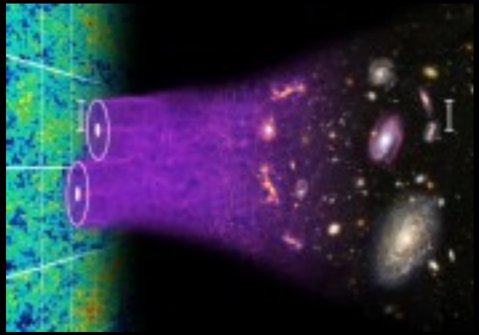
Temperature and polarization anisotropies

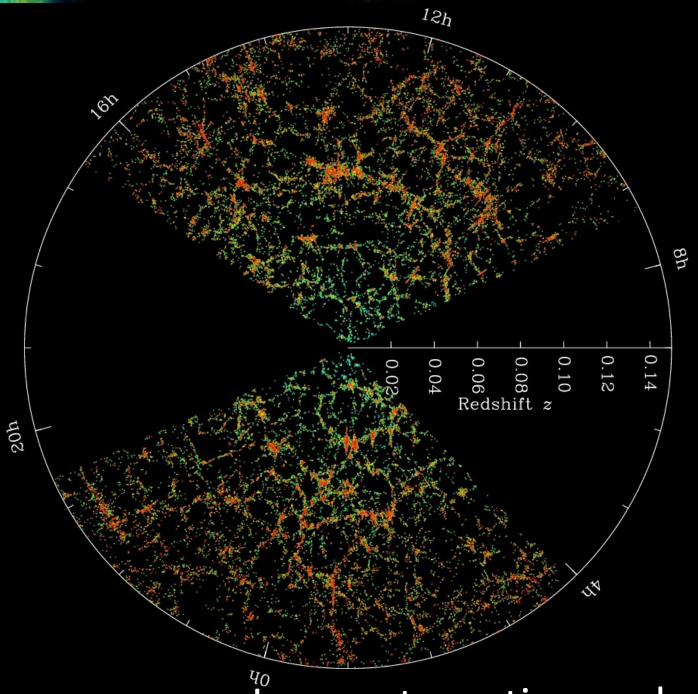
Secondary ainsotropies: especially ISW, and weak gravitational lensing.

Fig. Planck collab.

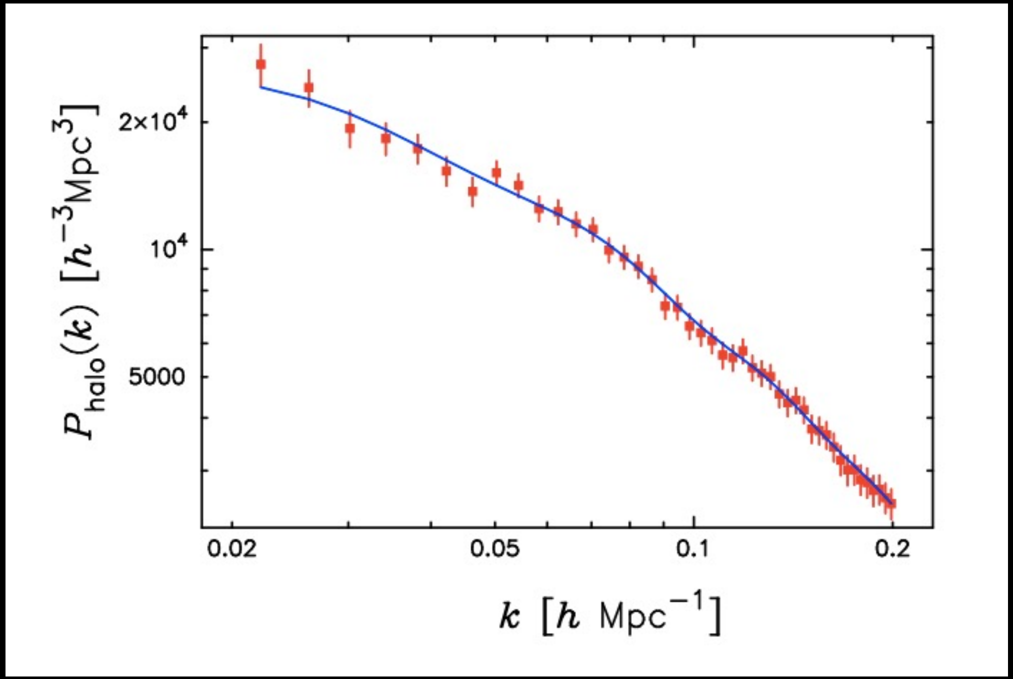


Primary CMB temperature information content has been saturated. The near future is large-scale structure.





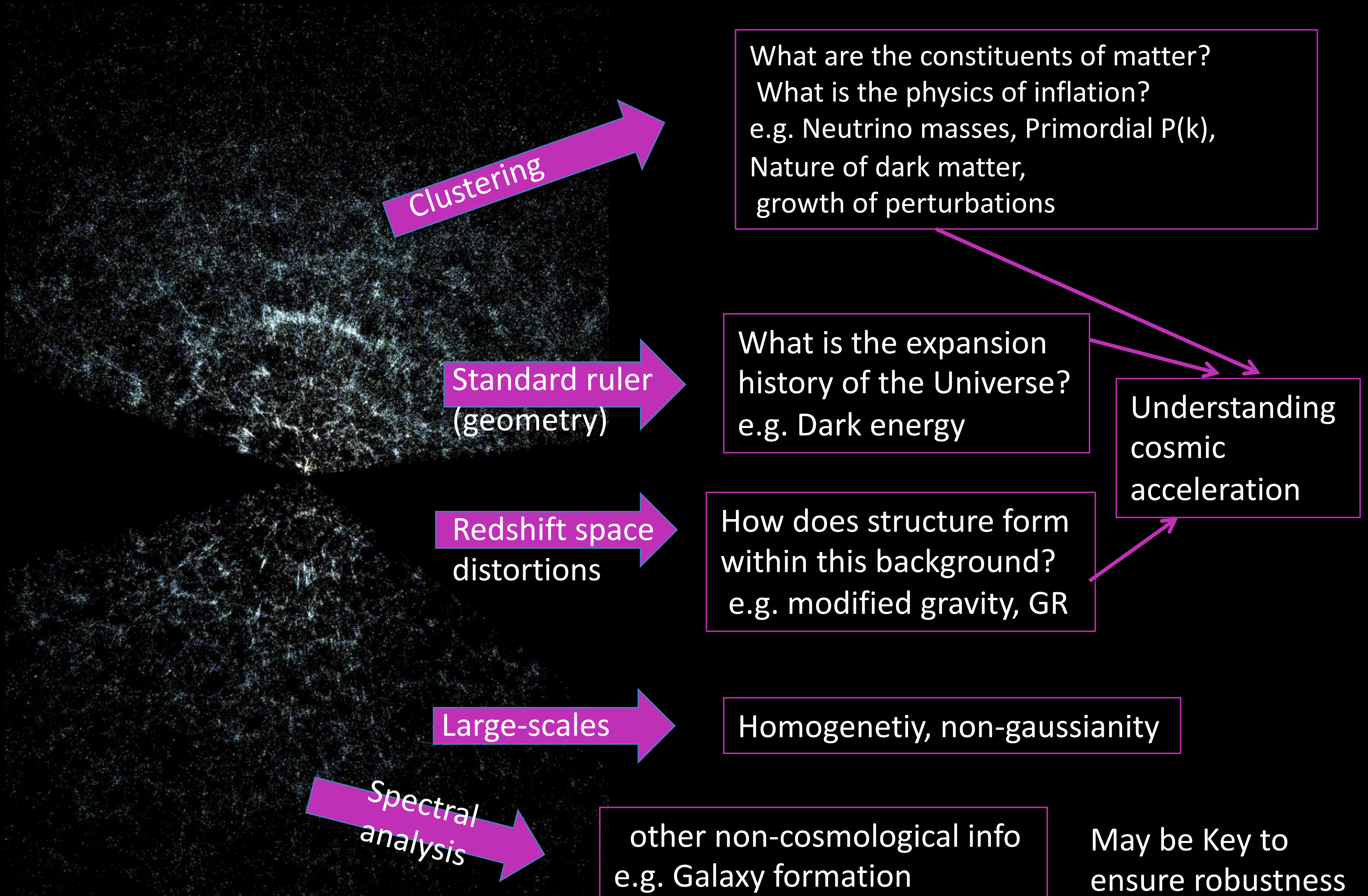
SDSS LRG galaxies power spectrum (Reid et al. 2010)



13 billion years of gravitational evolution

Longer-term timescale: CMB polarization

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

Understanding
cosmic
acceleration

Redshift space
distortions

How does structure form
within this background?
e.g. modified gravity, GR

Large-scales

Homogenetiy, non-gaussianity

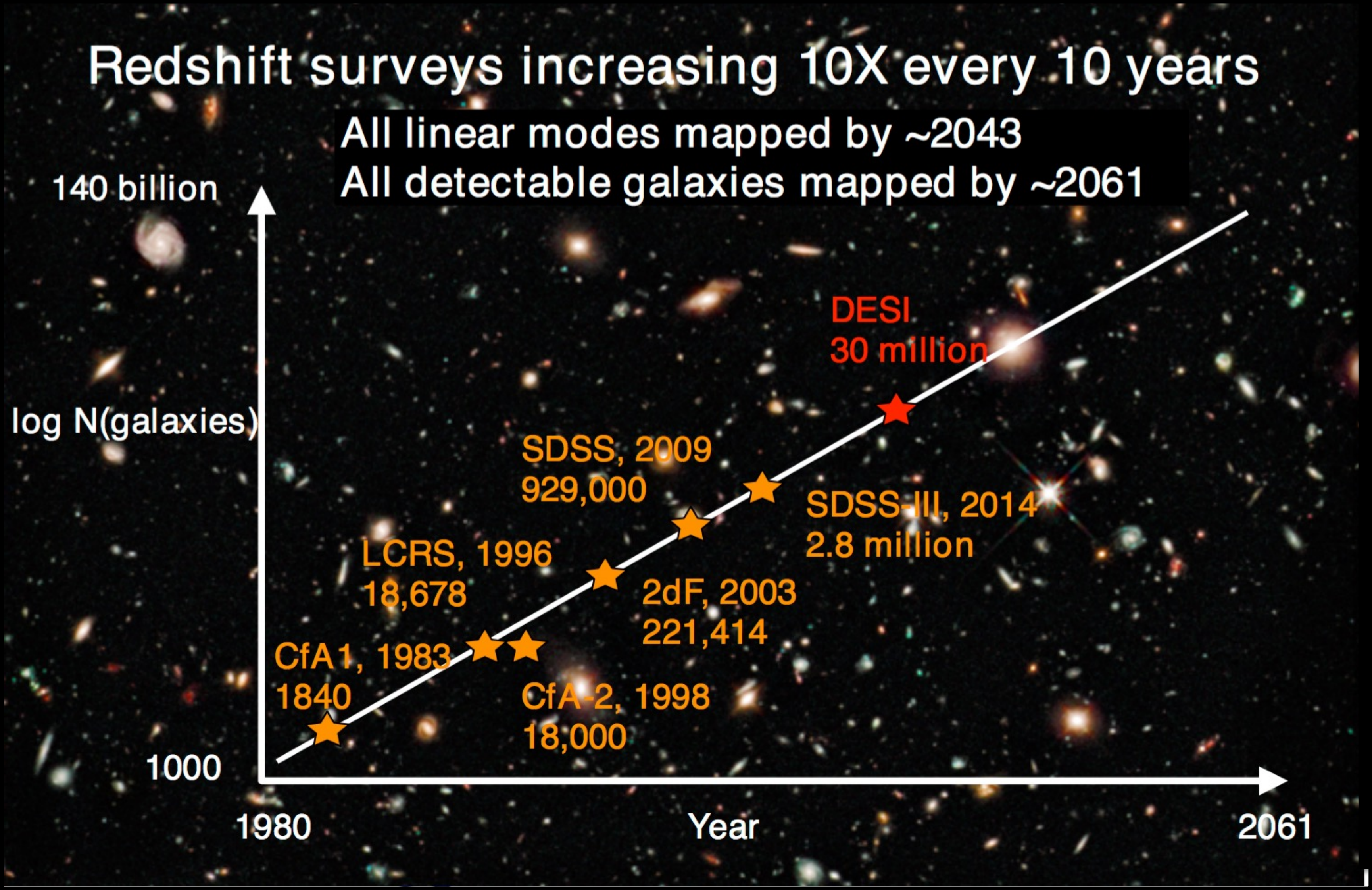
Spectral
analysis

other non-cosmological info
e.g. Galaxy formation

May be Key to
ensure robustness

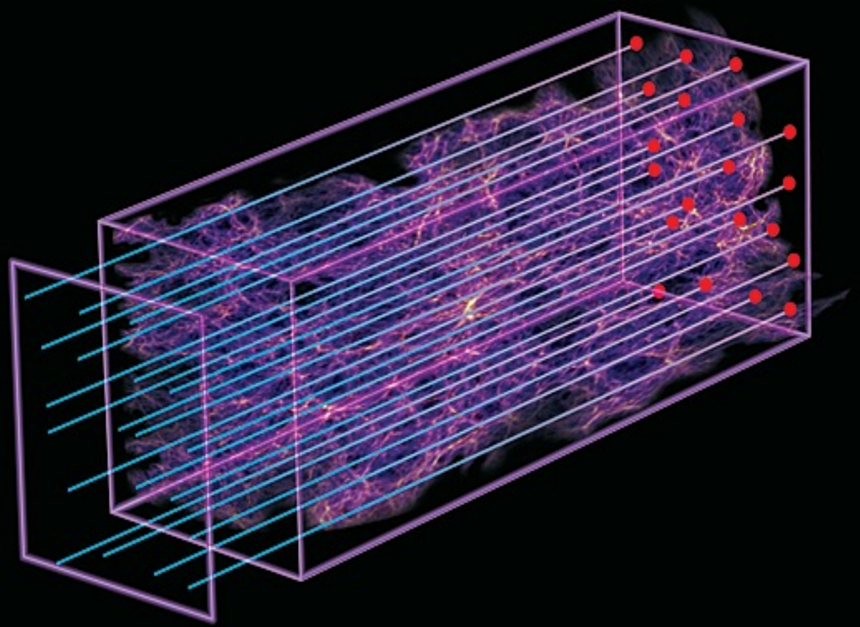
Fig. adapted from W. Percival

Golden age or Gold rush?



Courtesy of D. Schlegel

The Lymanalpha forest



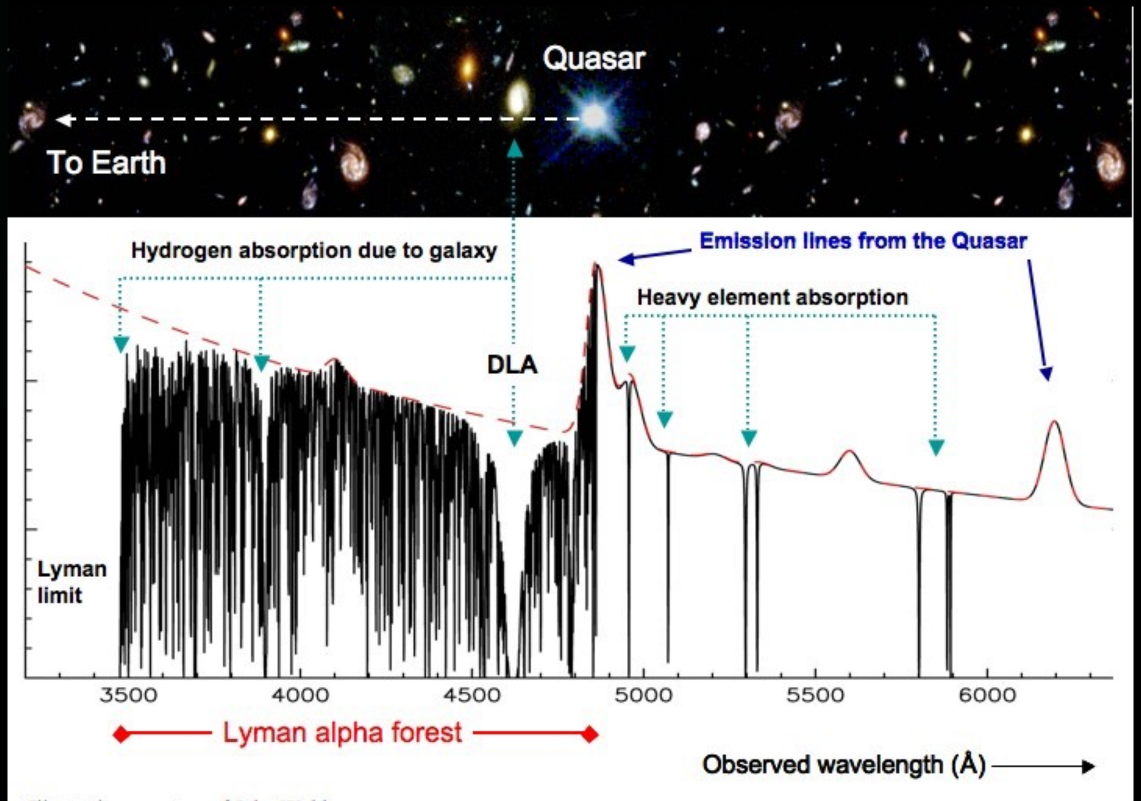
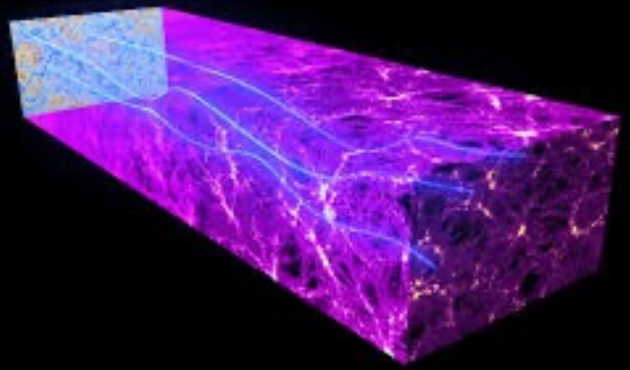
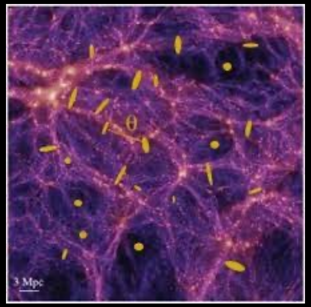
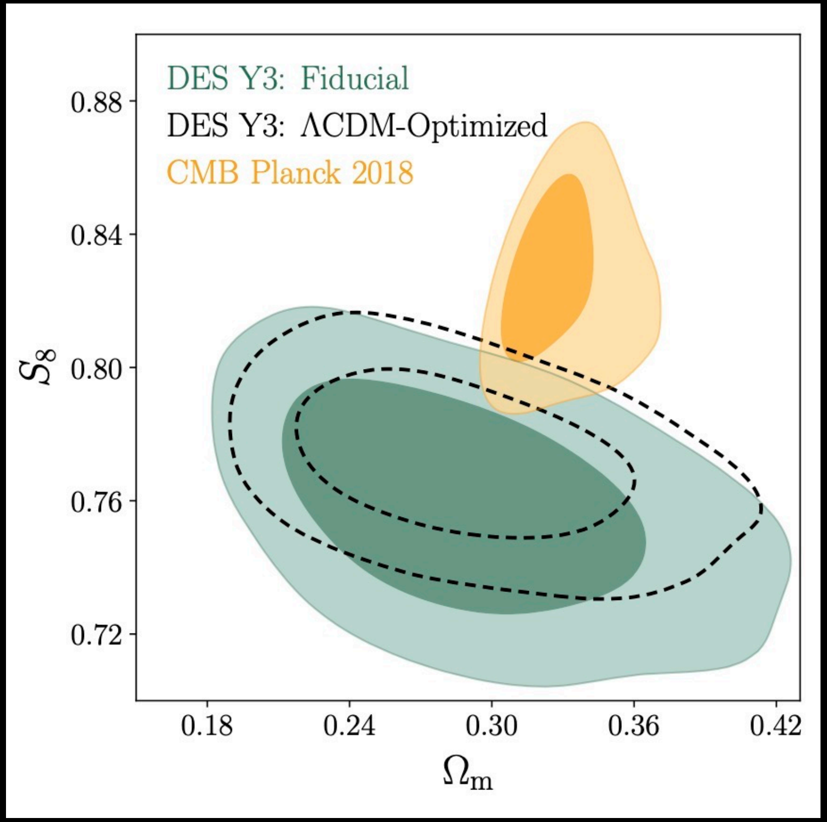


Illustration courtesy of John Webb

Weak gravitational lensing





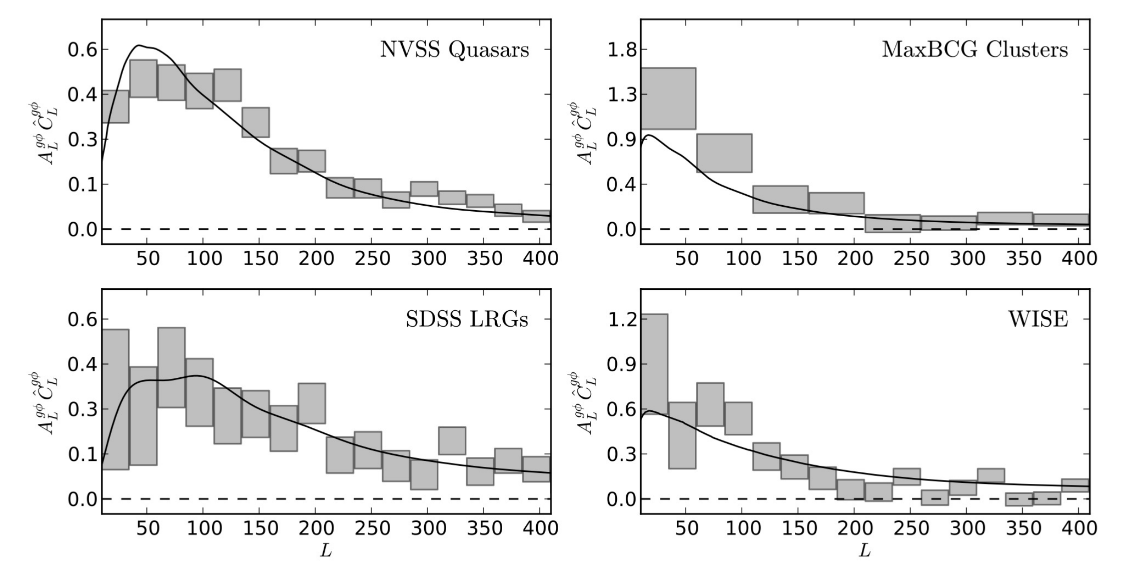


The dark energy survey Yr3 results
https://www.darkenergysurvey.org/

KiDS 1000

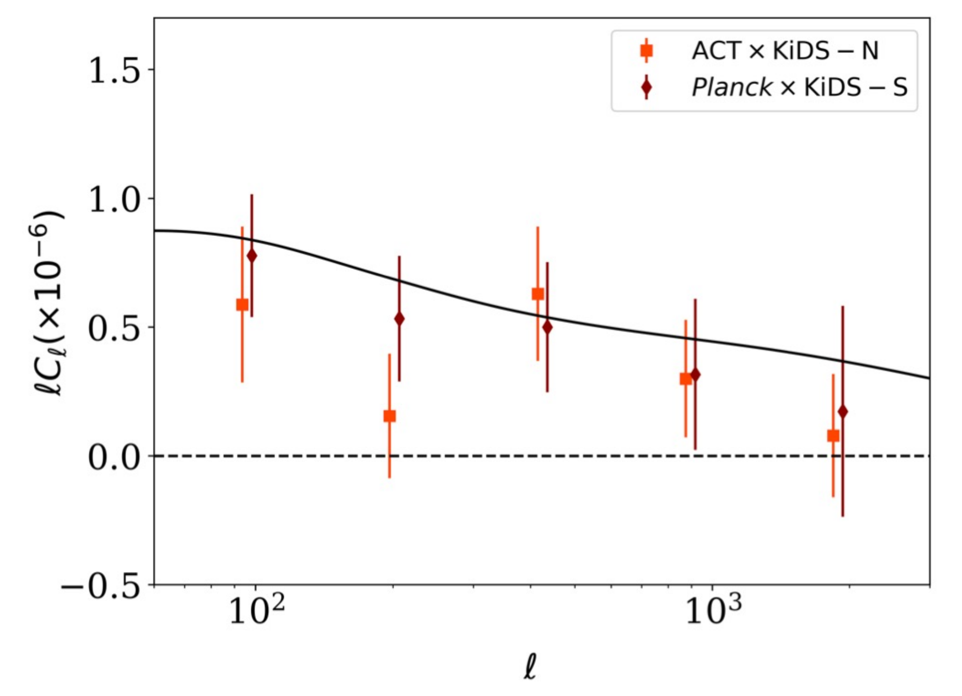
Cross-correlations

CMB lensing with galaxy tracers

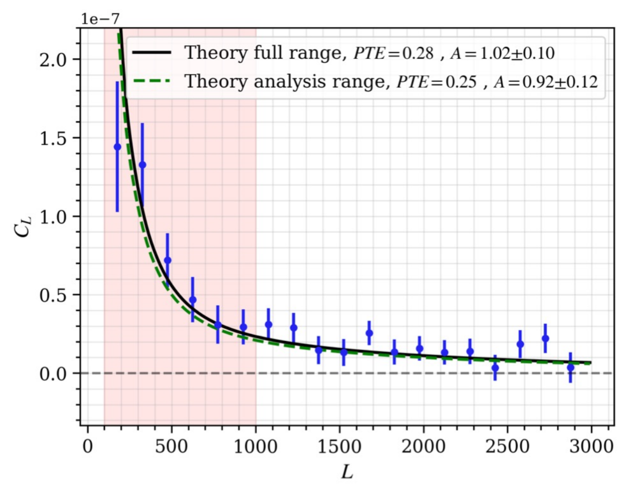


Planck collab 2013

CMB lensing x LSS lensing

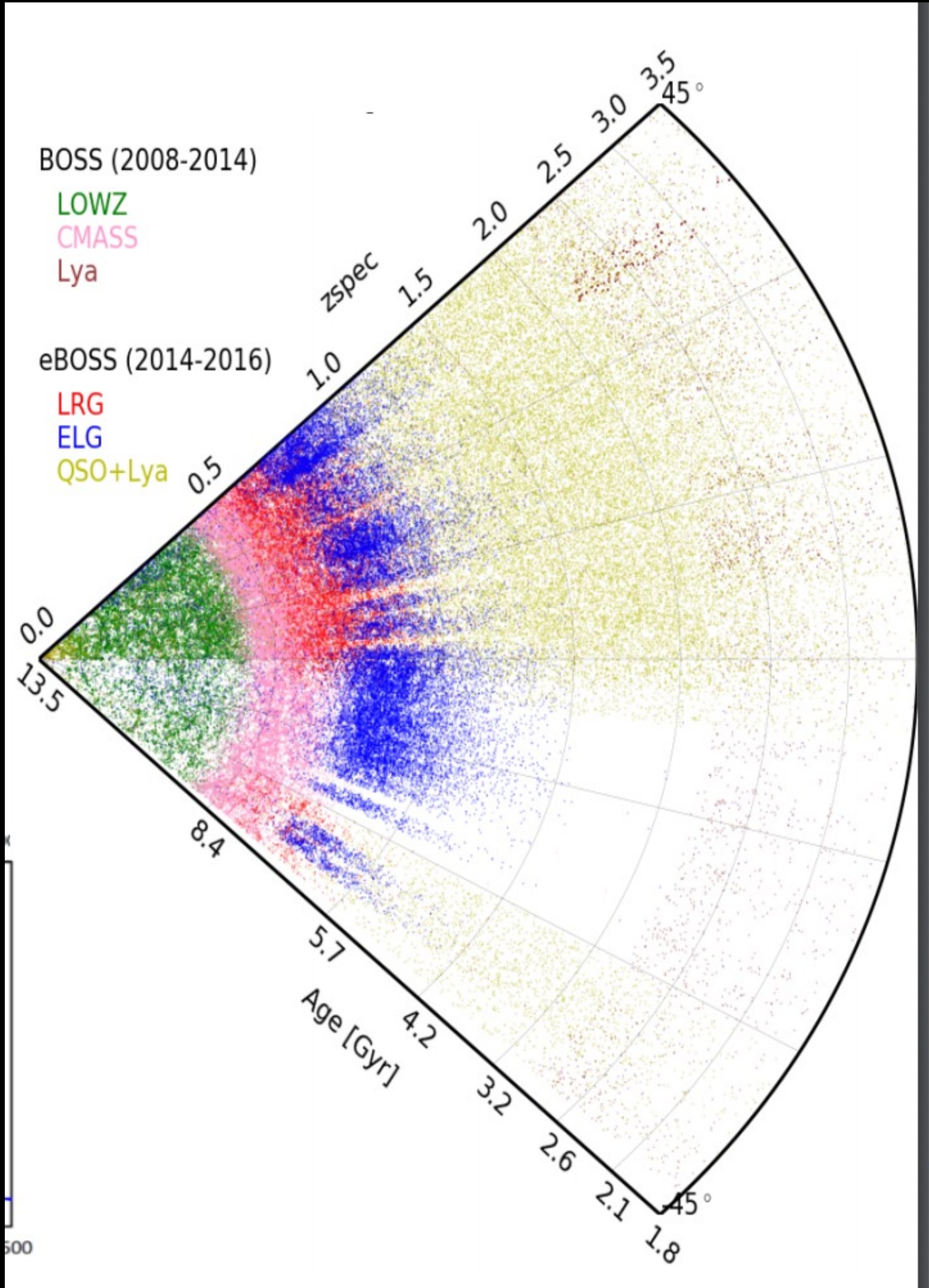


NEW:Robertson et al. (KiDS1000 +ACT+Planck)



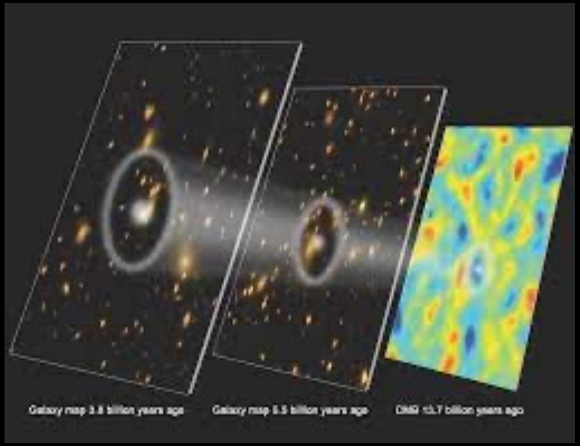
ACT collab.
Planck+ACT X SDSS BOSS

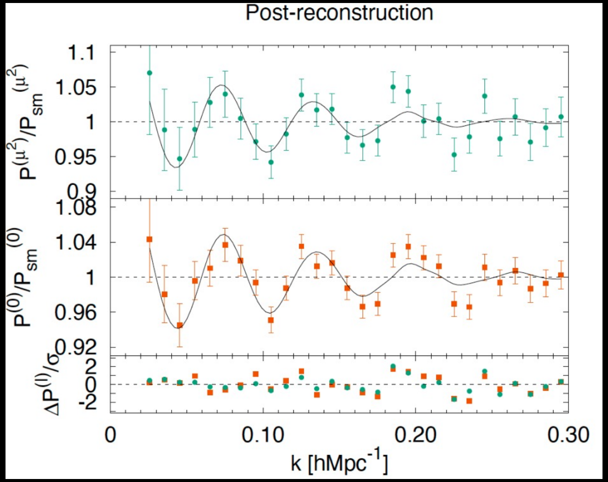
Spectroscopic Galaxy surveys

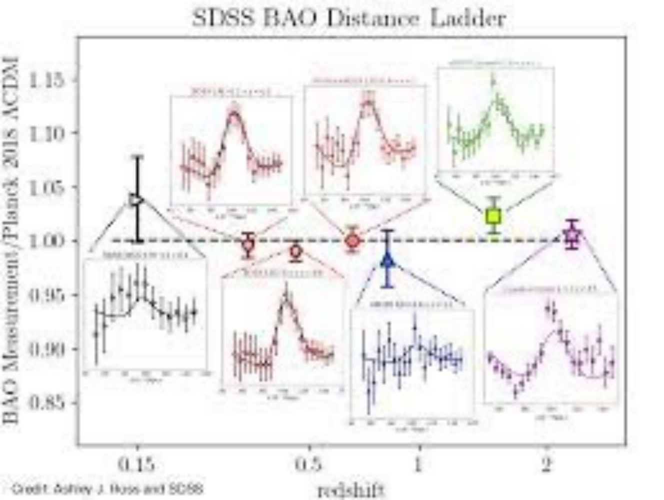


Latest results are from the e-BOSS collaboration
before BOSS DR12, next DESI

Two philosophies to constrain cosmology:
1: BAO; BAO +RSD (compression)





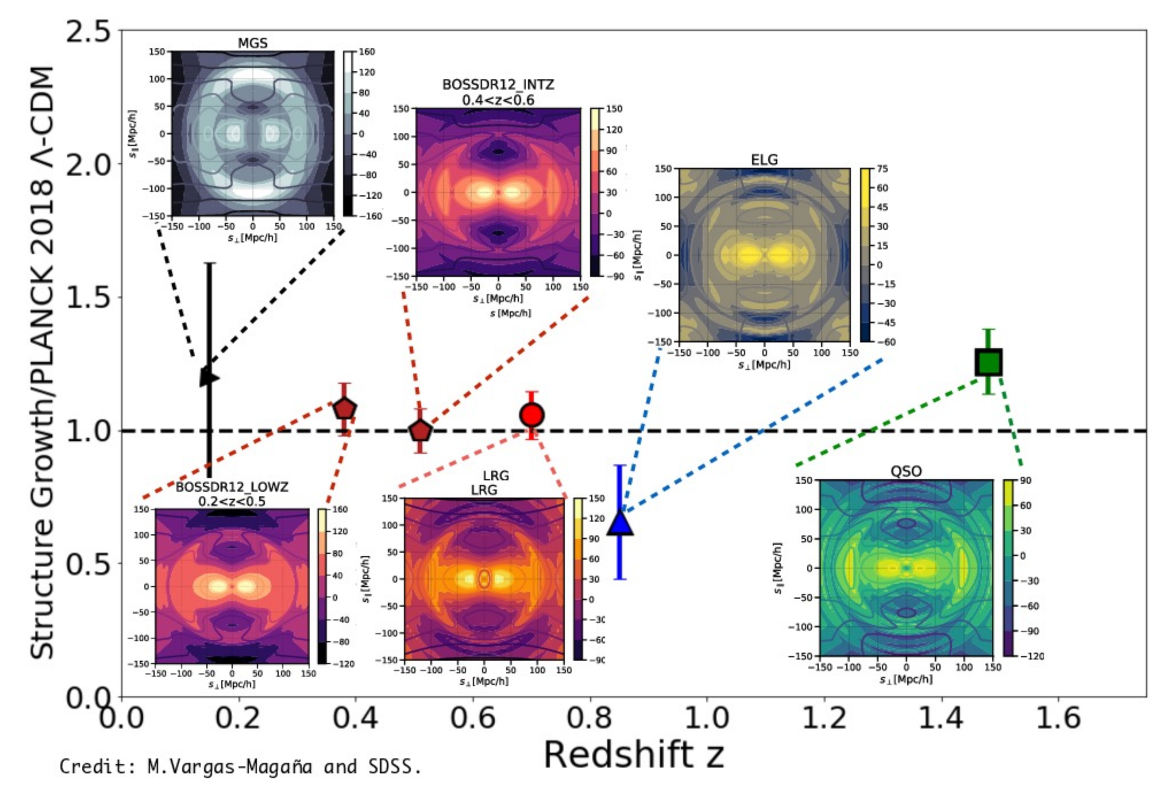


BAO is a standard ruler: early time physics sets it "rs"; galaxy clustering then measures rs Da(z) and rs/H(z)
Signal is the angular "location" of the BAO (not its amplitude)

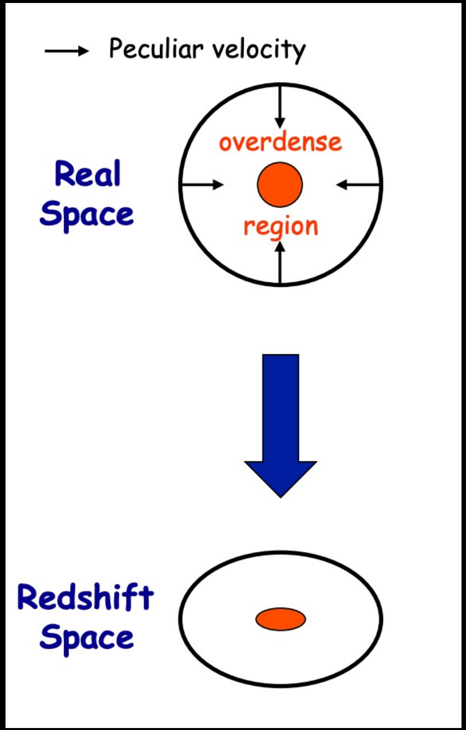
- → Expansion history, but not its normalization (i.e. not H0 b/c measuring angles!).
- → Only early-time physics information (and data) give the length of the standard ruler

Two philosophies to constrain cosmology:
1: BAO; BAO +RSD (compression)

Redshift space distortions: peculiar velocities are sourced by gravitational pull of the inhomogeneities measure growth of structure i.e. f σ8



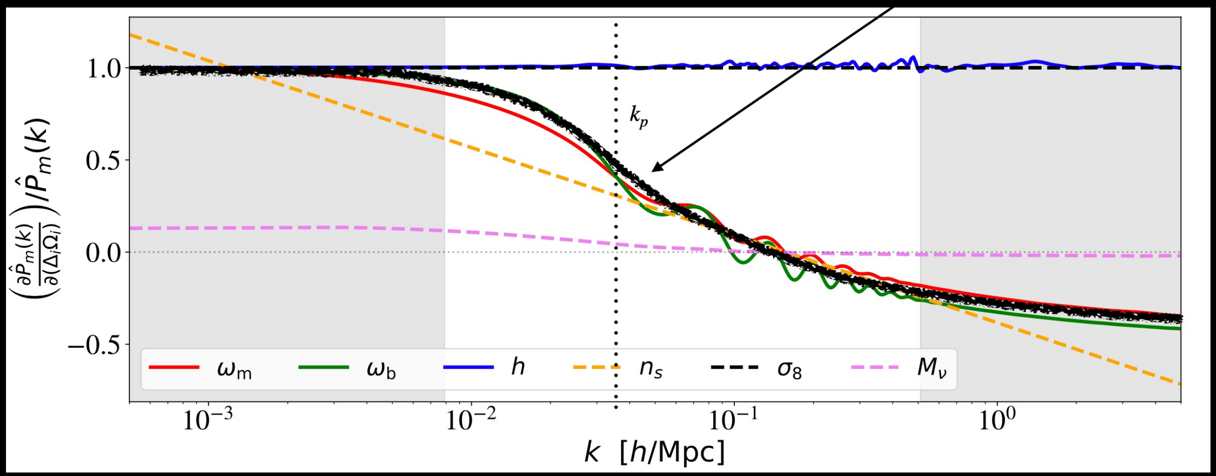
Credit: M.Vargas-Magaña and SDSS.



Two philosophies to constrain cosmology:
2: do like for CMB

Pick a model and fit the anisotropic power spectrum

Approach 1 is said to be more model-independent; constrain physical quantities not parameters of a model
Approach 2 is more computationally expensive and obviosuly more model dependent but gives better constraints



Turns out (Brieden, Gil-Marin, Verde 2021) that the difference in information content between 1 and 2 is
* mostly the behaviour of the matter transfer function “turn around”
  i.e. details of expansion history around matter-radiation equality
* to a smaller extent the amplitude of the BAO

Recent constraints: update

Neutrino mass

dark energy

$\sigma 8$

H0

Of interest to this audience

I will be qualitative

Neutrino mass: Physical effects

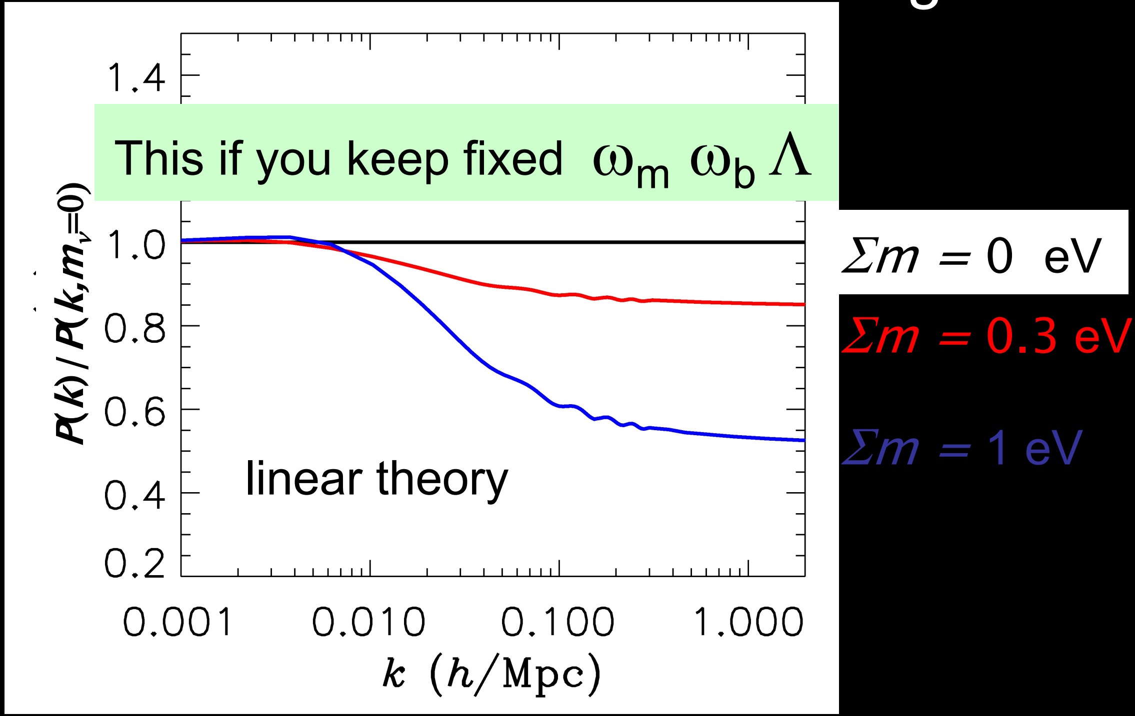
Total mass >~1 eV become non relativistic before recombination CMB

Total mass <~1 eV become non relativistic after recombination:
alters matter-radn equality, 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


This if you keep fixed ω_m ω_b Λ

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

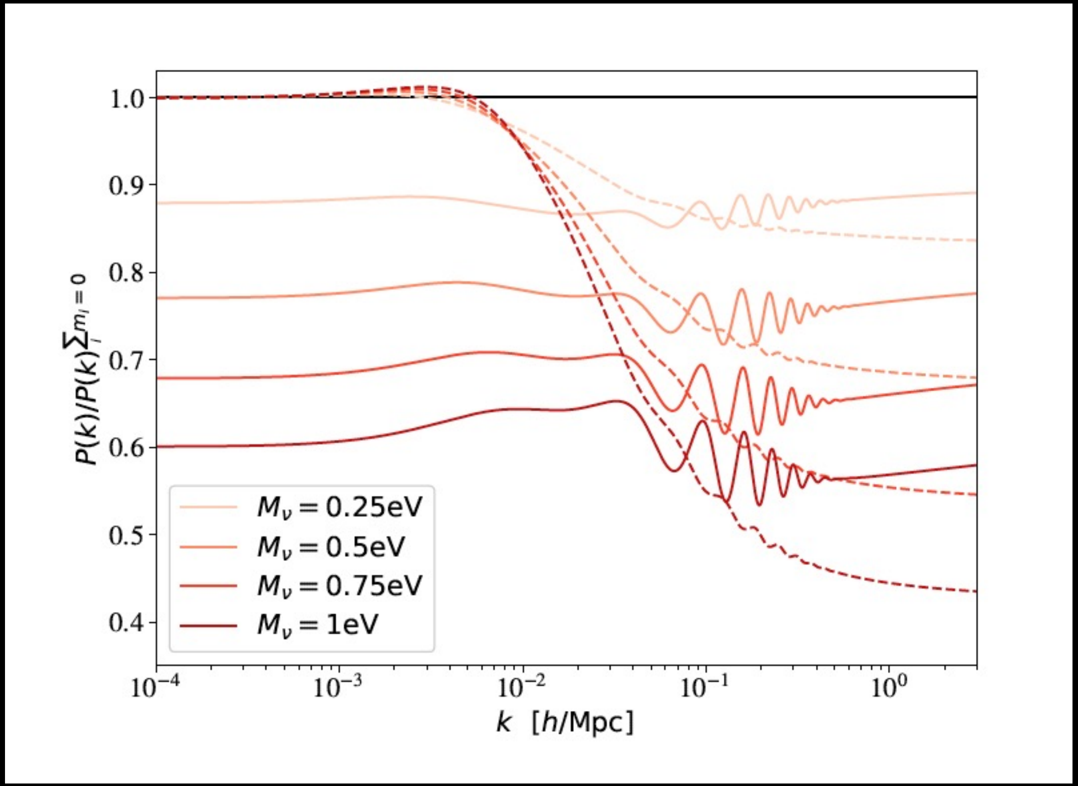
Neutrino mass: Physical effects

Move along CMB parameters degeneracy

H0 is everywhere!

keep fixed ω_c ω_b, θ_s

i.e. play with h …



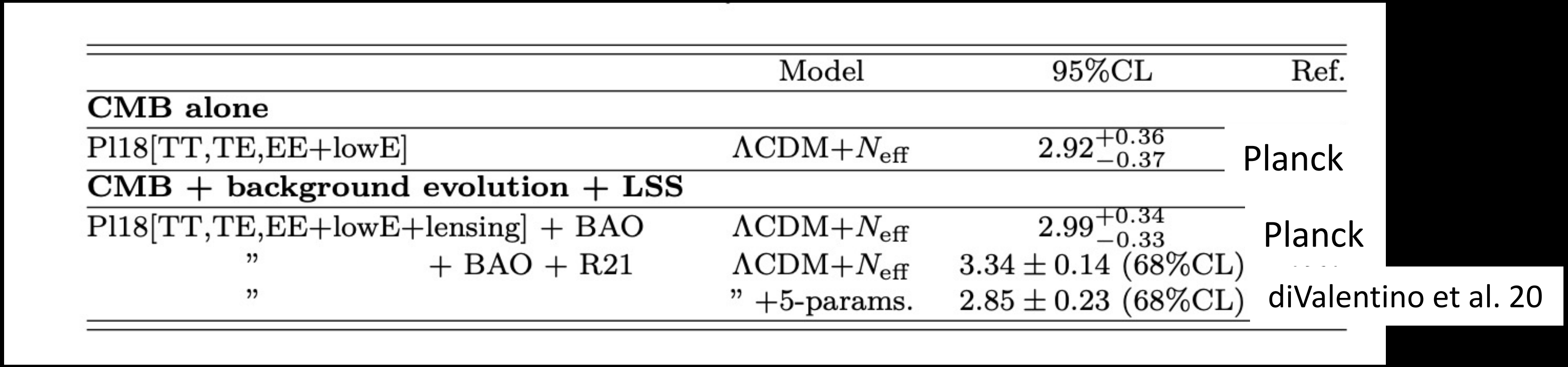
Suppression
BAO

From Lesgourgues, LV
Particle physics
data group

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

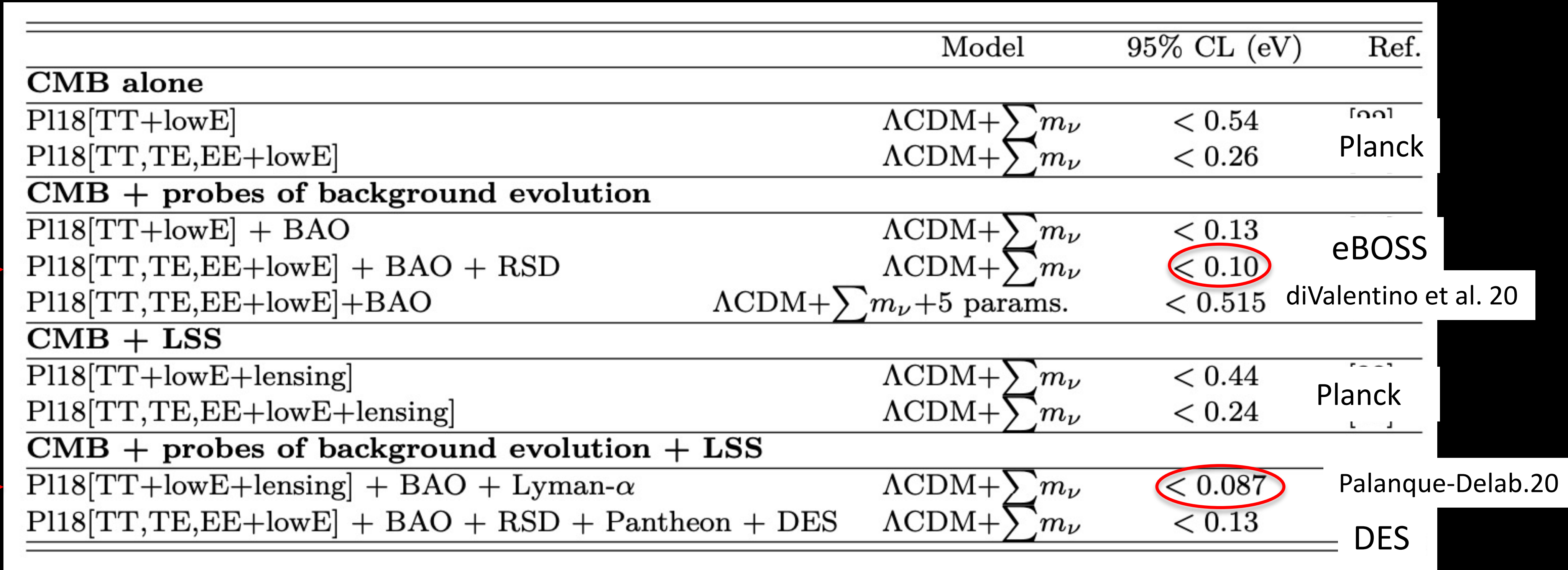
Latest constraints: 3 and light

Neff



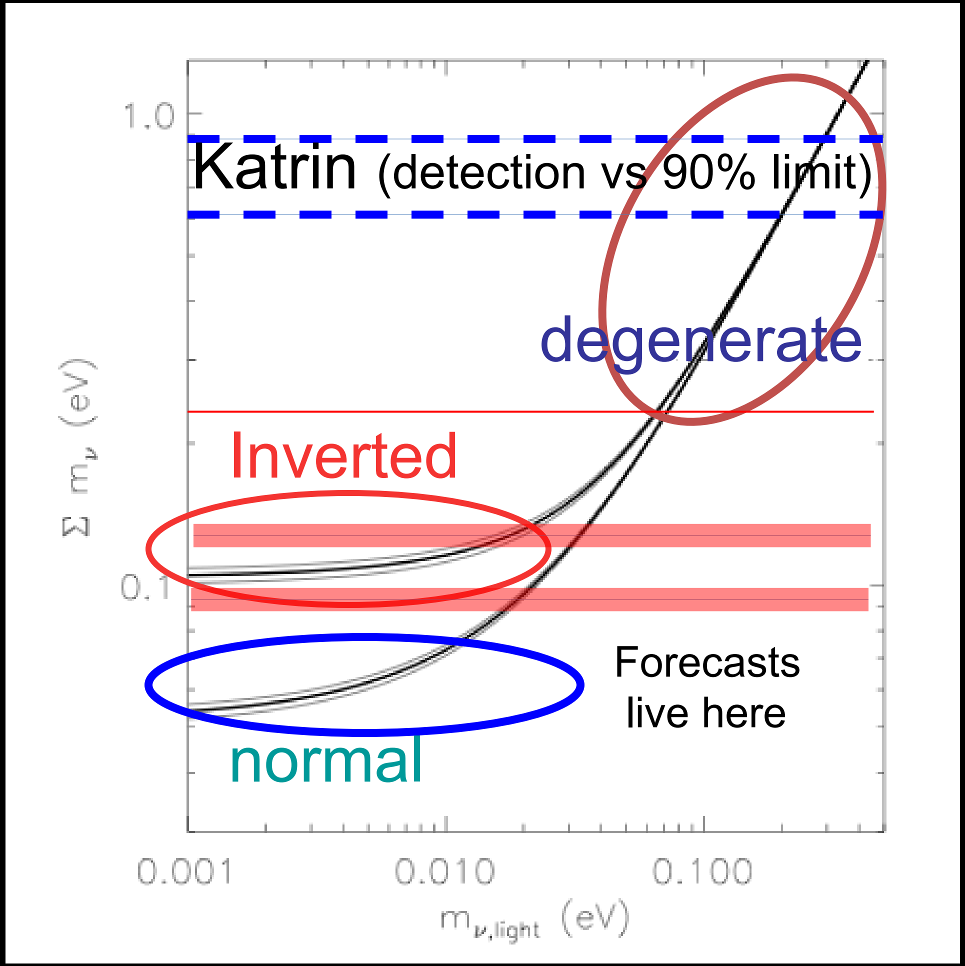
	Model	95%CL	Ref.
CMB alone			
Pl18[TT,TE,EE+lowE]	ΛCDM+$N_{\rm eff}$	$2.92^{+0.36}_{-0.37}$	Planck
CMB + background evolution + LSS			
Pl18[TT,TE,EE+lowE+lensing] + BAO	ΛCDM+$N_{\rm eff}$	$2.99^{+0.34}_{-0.33}$	Planck
" + BAO + R21	ΛCDM+$N_{\rm eff}$	3.34 ± 0.14 (68%CL)	
"	" +5-params.	2.85 ± 0.23 (68%CL)	diValentino et al. 20

Sum of the masses



	Model	95% CL (eV)	Ref.
CMB alone			
Pl18[TT+lowE]	ΛCDM+$\sum m_\nu$	< 0.54	Planck
Pl18[TT,TE,EE+lowE]	ΛCDM+$\sum m_\nu$	< 0.26	
CMB + probes of background evolution			
Pl18[TT+lowE] + BAO	ΛCDM+$\sum m_\nu$	< 0.13	eBOSS
Pl18[TT,TE,EE+lowE] + BAO + RSD	ΛCDM+$\sum m_\nu$	< 0.10	
Pl18[TT,TE,EE+lowE]+BAO	ΛCDM+$\sum m_\nu$+5 params.	< 0.515	diValentino et al. 20
CMB + LSS			
Pl18[TT+lowE+lensing]	ΛCDM+$\sum m_\nu$	< 0.44	Planck
Pl18[TT,TE,EE+lowE+lensing]	ΛCDM+$\sum m_\nu$	< 0.24	
CMB + probes of background evolution + LSS			
Pl18[TT+lowE+lensing] + BAO + Lyman-α	ΛCDM+$\sum m_\nu$	< 0.087	Palanque-Delab.20
Pl18[TT,TE,EE+lowE] + BAO + RSD + Pantheon + DES	ΛCDM+$\sum m_\nu$	< 0.13	DES

Neutrino mass limits



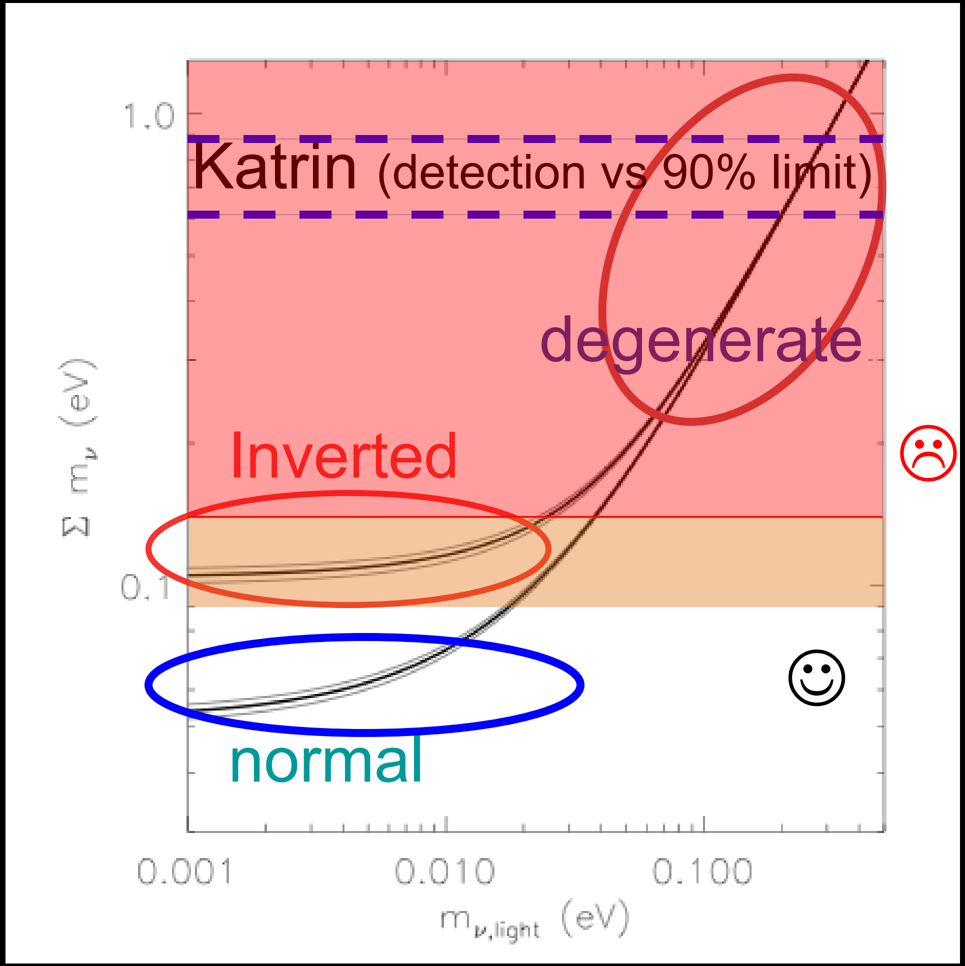
CMB(Planck)

+BAO

+LSS Lyman alpha

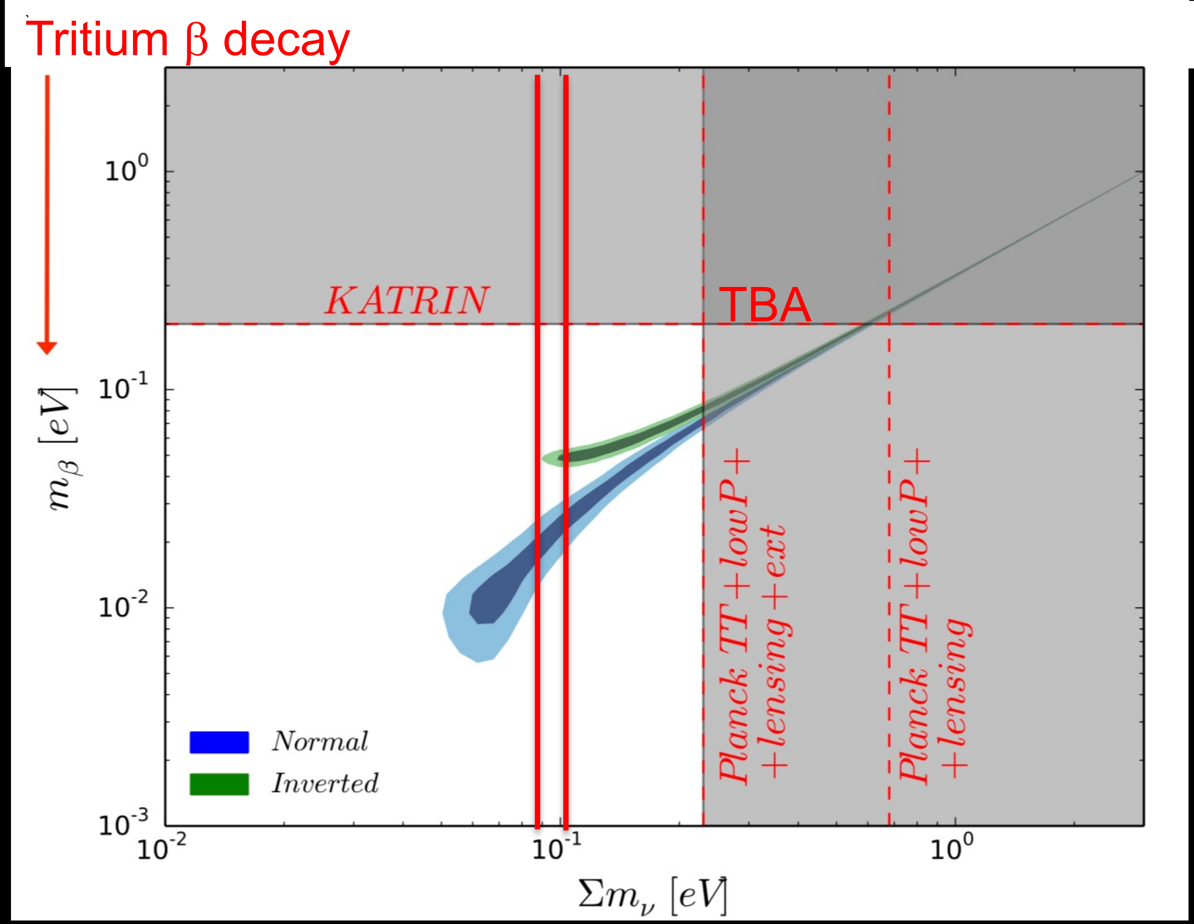
5% or less effects on P(k)

Implications



Implications II

CMB+BAO+LSS limit 0.10 or 0.09 eV



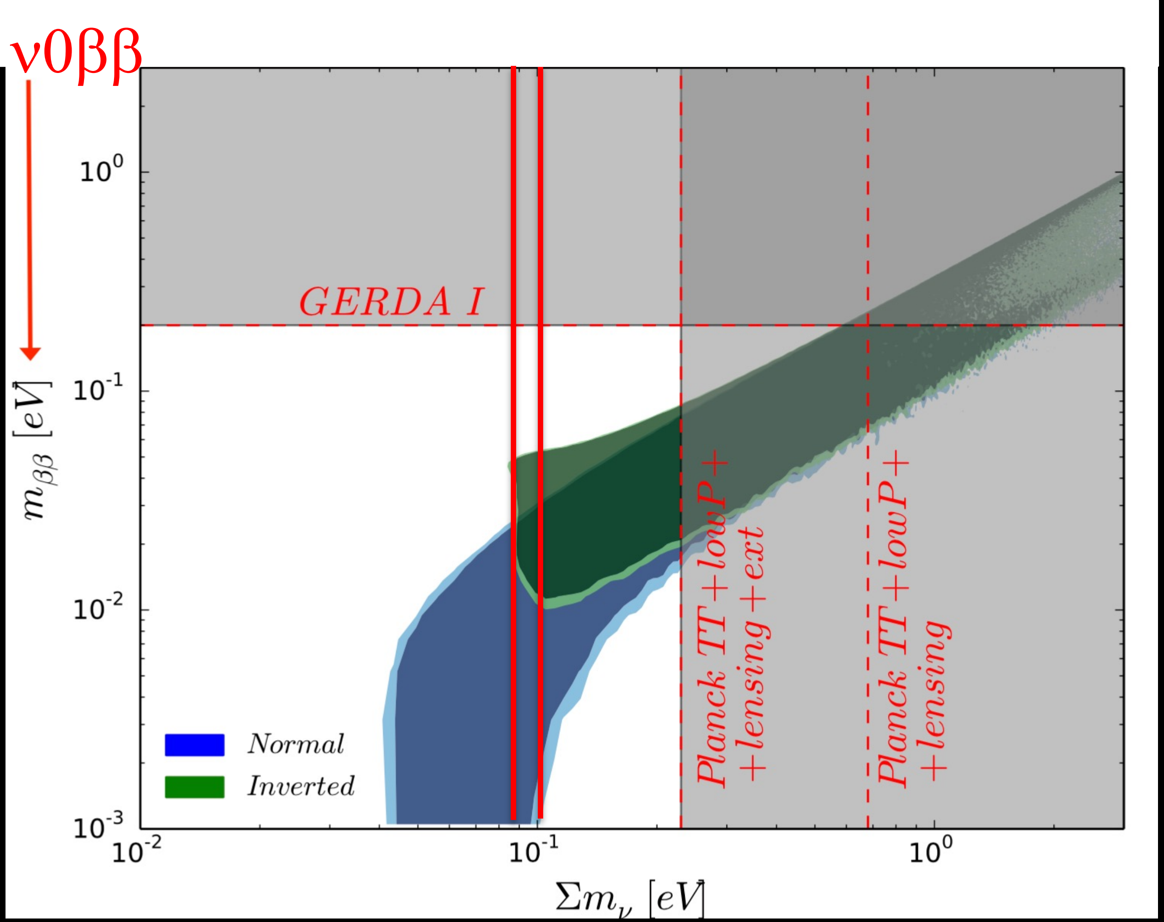


Fig. adapted*
from M. Lattanzi

* Taken from google

Current LSS surveys already tell us that the neutrino hierarchy is the **NORMAL** one (Simpson et al. JCAP 2018). BUT this statement depends on the choice of prior, as any Bayesian model selection will

NB: in late 2018 T2K using nu from accelerators and atmospheric favors NORMAL hierarchy at ~ 2.5 sigma

Table 2. The same as Table 1, but now for the scenario where $p(D_\Sigma|\Sigma)$, the evidence for Σ from cosmological data, peaks at 0.05 eV.

Σ (eV) 95%	< 0.1	< 0.15	< 0.17	< 0.2	< 0.25	< 0.5	< 6.9
Odds (NH/IH)	225:1	33:1	24:1	18:1	13:1	6.3:1	2.6:1
log K	5.4	3.5	3.2	2.9	2.5	1.8	1.0
Classification	Very Strong	Strong	Strong	Positive	Positive	Positive	Weak

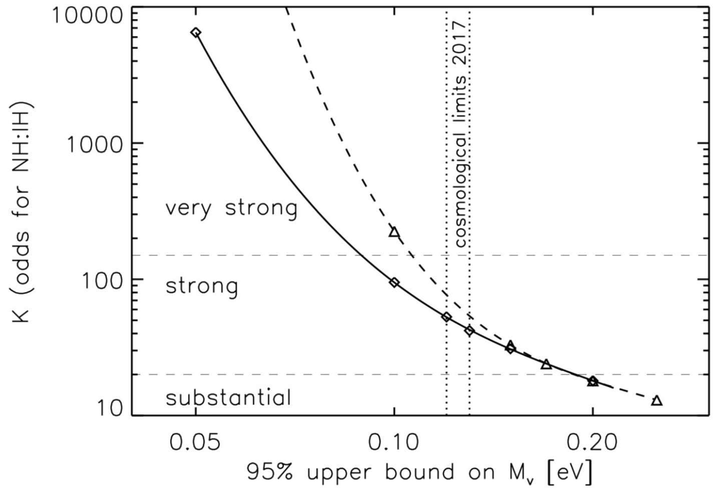


Figure 6. Odds as a function of cosmological upper limits on the sum of neutrino masses Σ. The solid line corresponds to the (actual) case where the maximum of the Σ distribution is indistinguishable from zero. The dashed line correspond to a case where maximum of the Σ distribution is at 0.05 eV. The symbols correspond to the values reported in Tab. 1 and 2. Also indicated (vertical dotted lines) are the current limits from CMB and clustering of galaxies [2] or Lyman α forest [6]. Jeffreys' interpretation of the Bayes factor values are also reported.

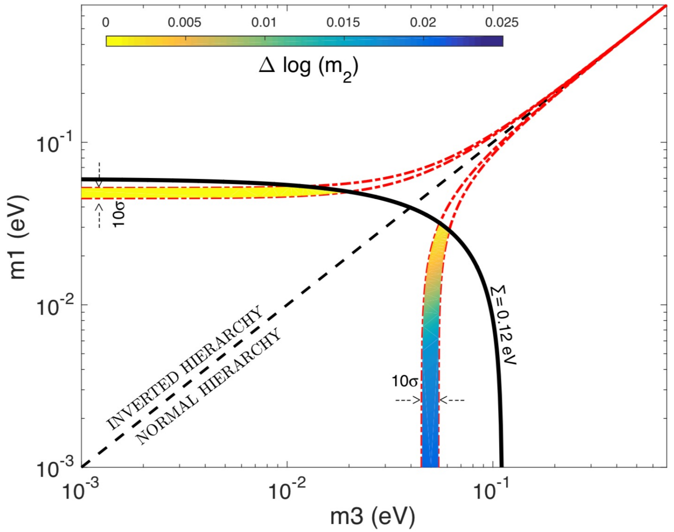


Figure 1. A visualisation of the heavily reduced parameter space available in the case of the inverted neutrino mass hierarchy, relative to the normal case. The red dash-dot contours illustrate constraints on the mass splittings, as imposed by neutrino oscillation experiments (broadened to show 10σ uncertainties for visualisation purposes). The solid black line corresponds to the combination of a cosmological upper bound on the sum of the neutrino masses $\Sigma < 0.12$ eV with the measurement of Δm^2_{12}. The diagonal dashed line demarcates the two hierarchies. The colouring of the shaded areas represents the amount of parameter space available in the third dimension, $\Delta(\log m_2)$.

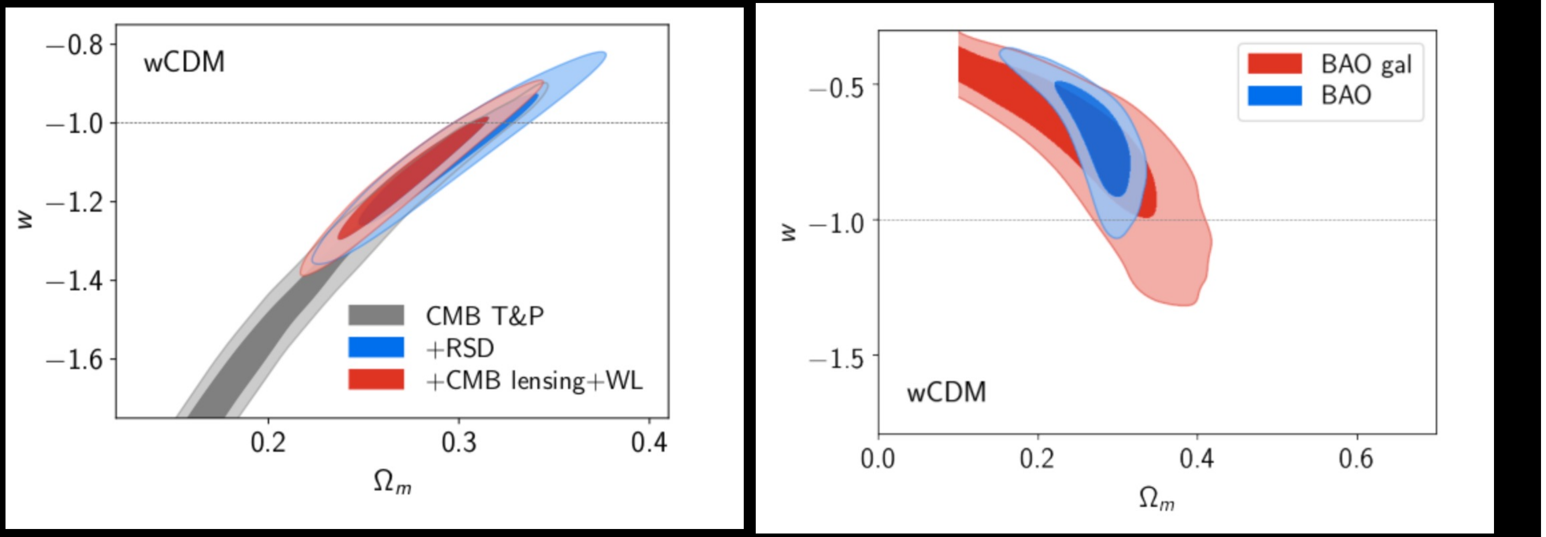
Dark energy is not going away

Effects on expansion history (e.g., supernovae) and growth of structure

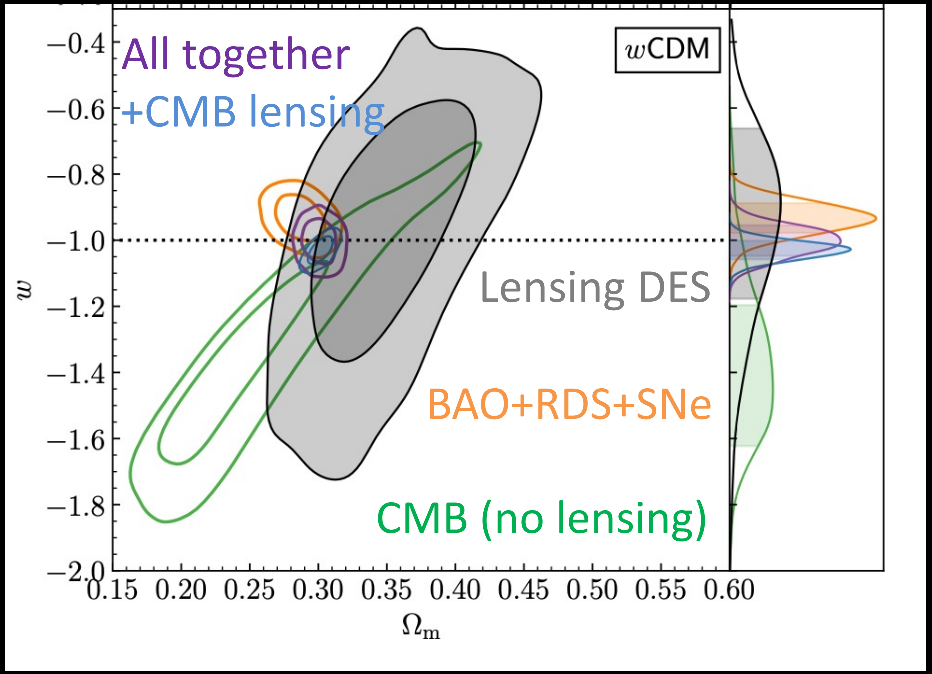
CMB: geometry, integrated expansion history, growth via lensing

Gravitational lensing: both

BAO: expansion history; RSD growth



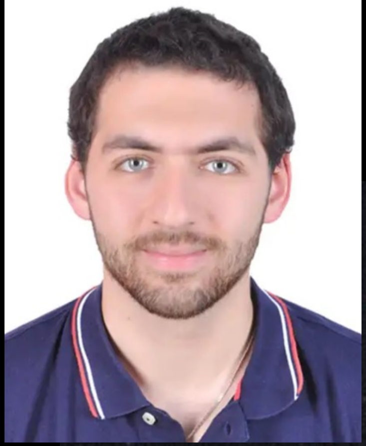
eBOSS



DES

News: KiDS , DES yr3, eBOSS

Hard to get rid of dark matter also



Ali Rida Khalifeh & Jimenez MNRAS (2021)

NGC 1052-DF2

Dwarfs galaxies without dark matter

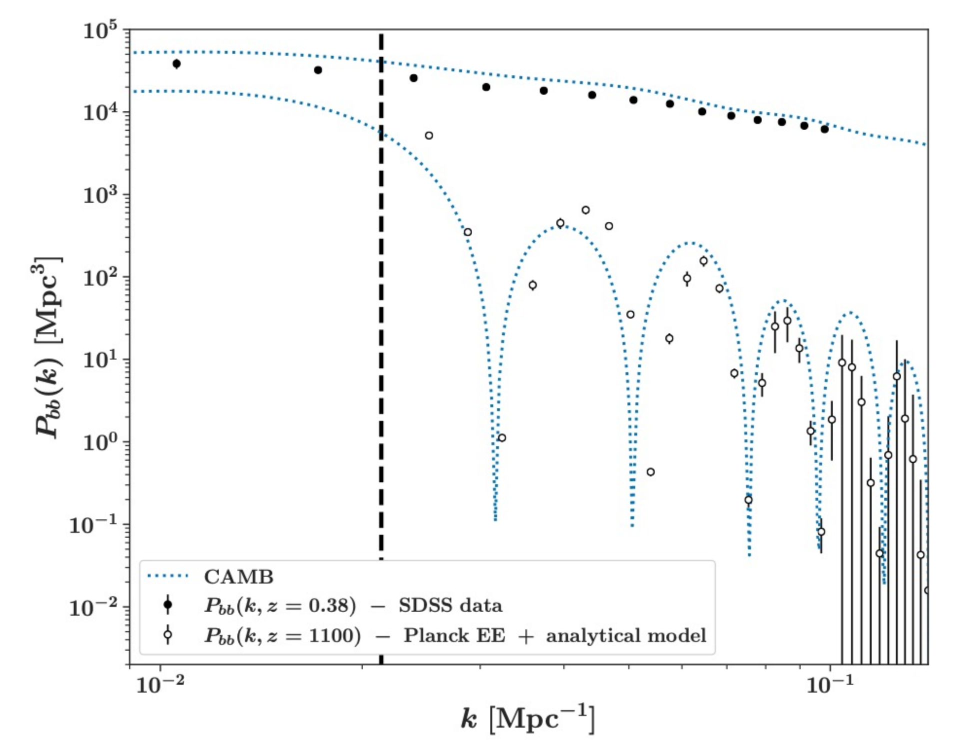
sculptor

Dwarf galaxies dark matter dominated

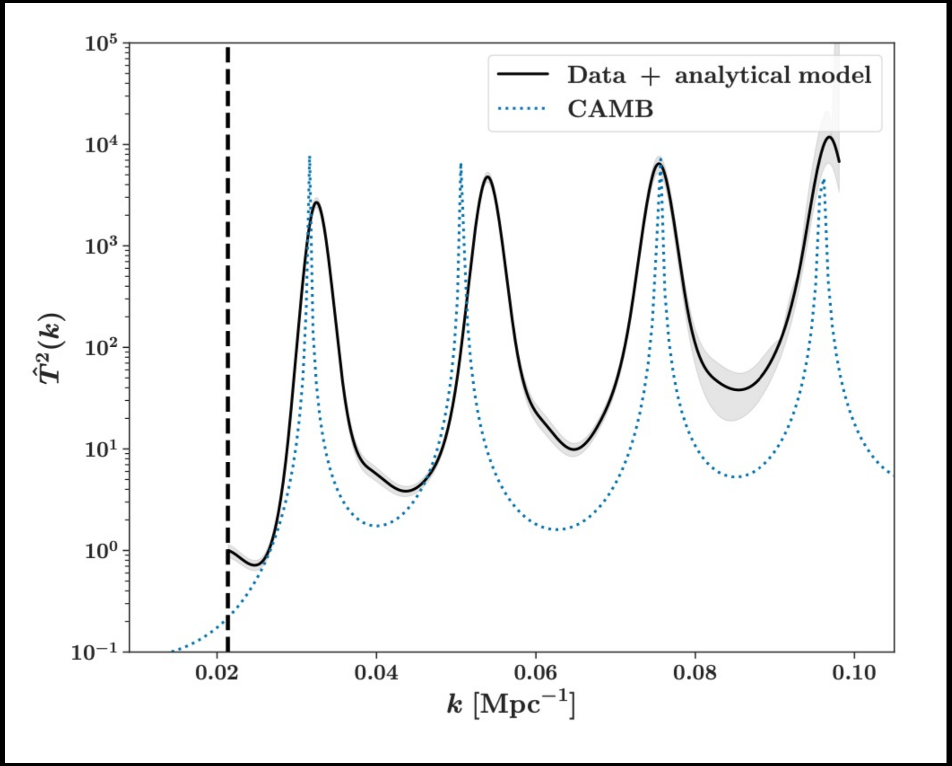
Altrnative thory of gravity must explain both (no correlarion with size/mass)

Hard to get rid of dark matter also

Spergel and Pardo 21



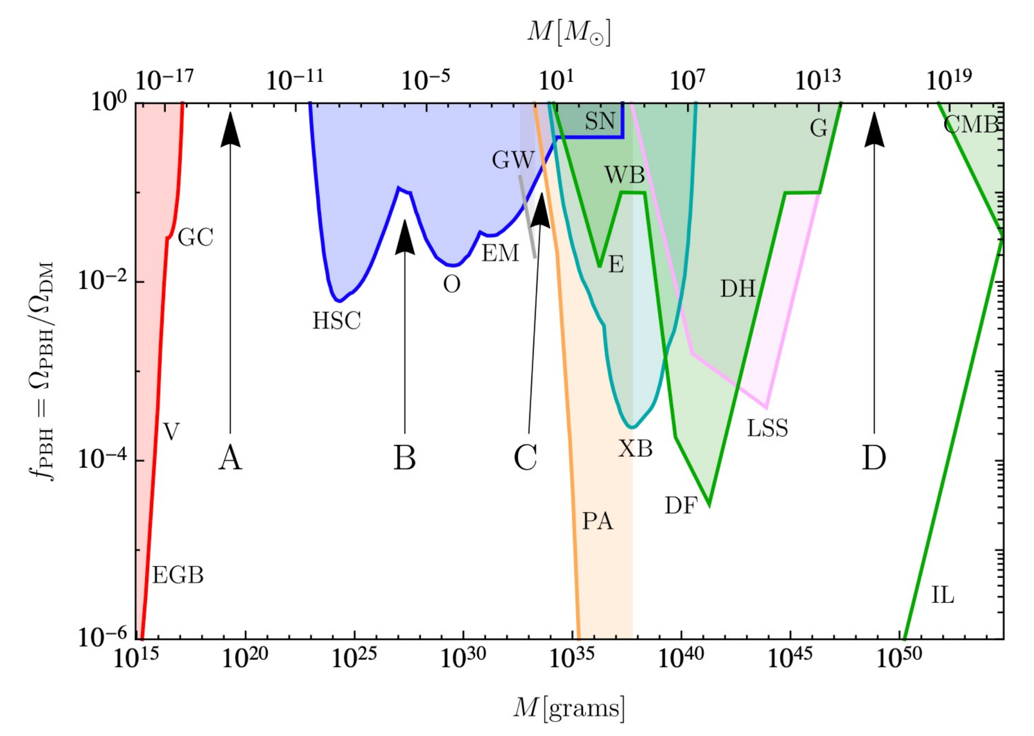
Baryon power spectra



Baryon transfer function

Altrnative thory of gravity must provide the oscillations which are an effect of dark matter

Primordial black holes?



Evaporation , GW, Dynamical, accretion, CMB, LSS

Carr, Kuhnel 2020

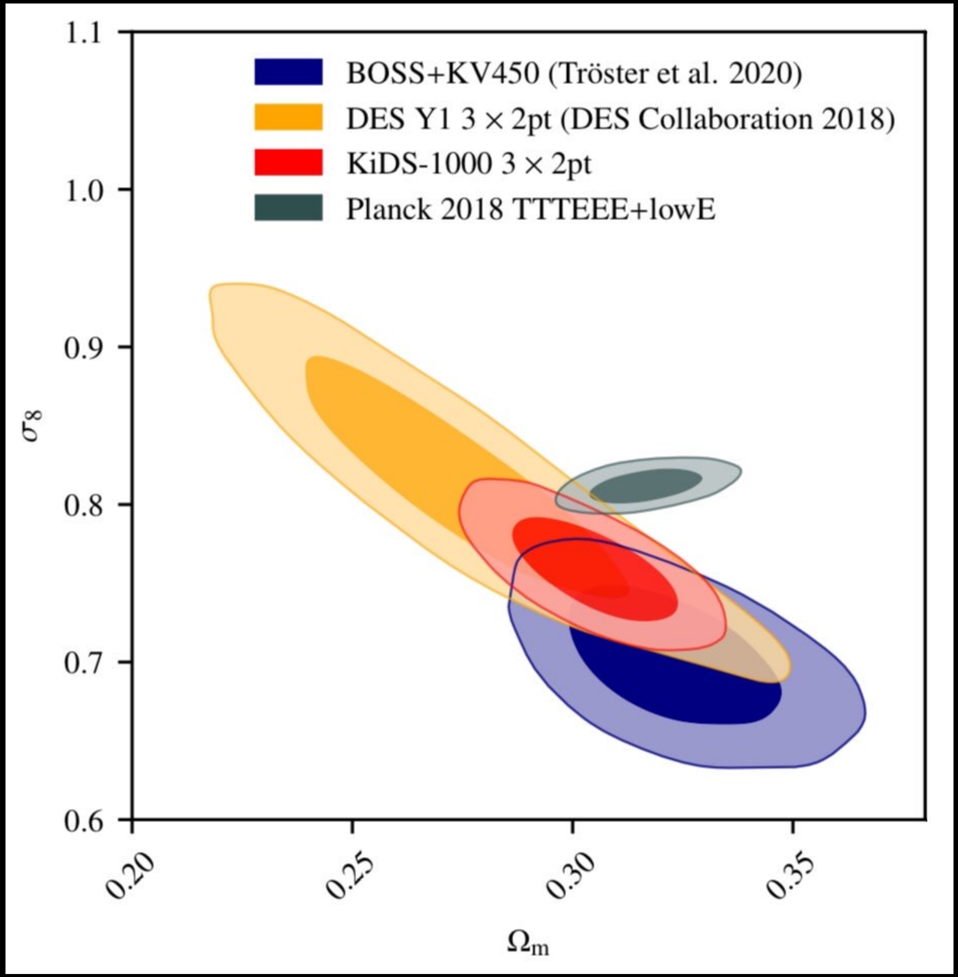
We can talk about the "windows"

A asteriod to moon size

C relevant for LIGO-Virgo (but not 100% of DM)

D extremely massives… hard to make it work.

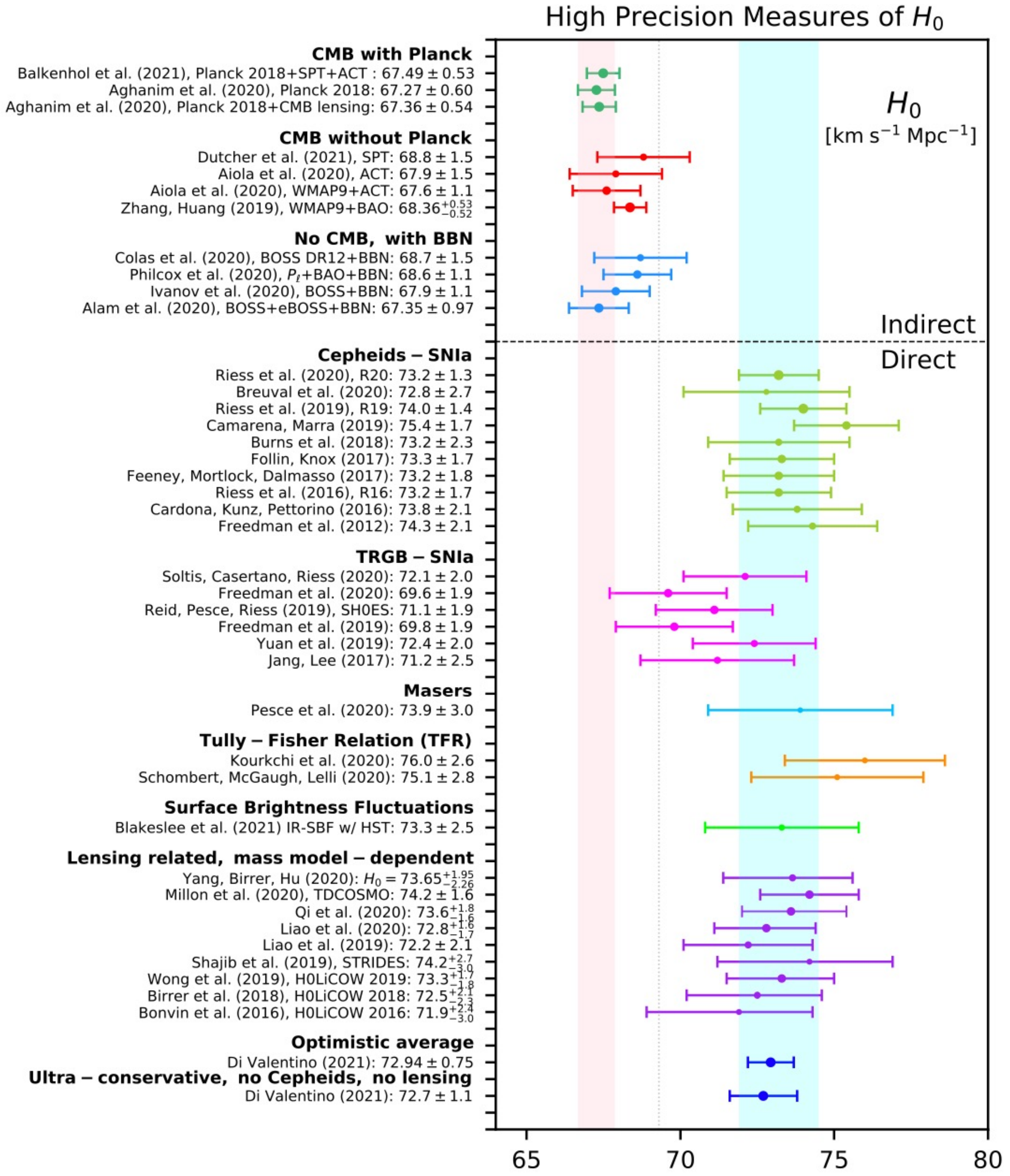
What’s up with σ8?



It has been acting up lately: In a LCDM model
the low z Universe seems to prefer a lower σ8 than CMB

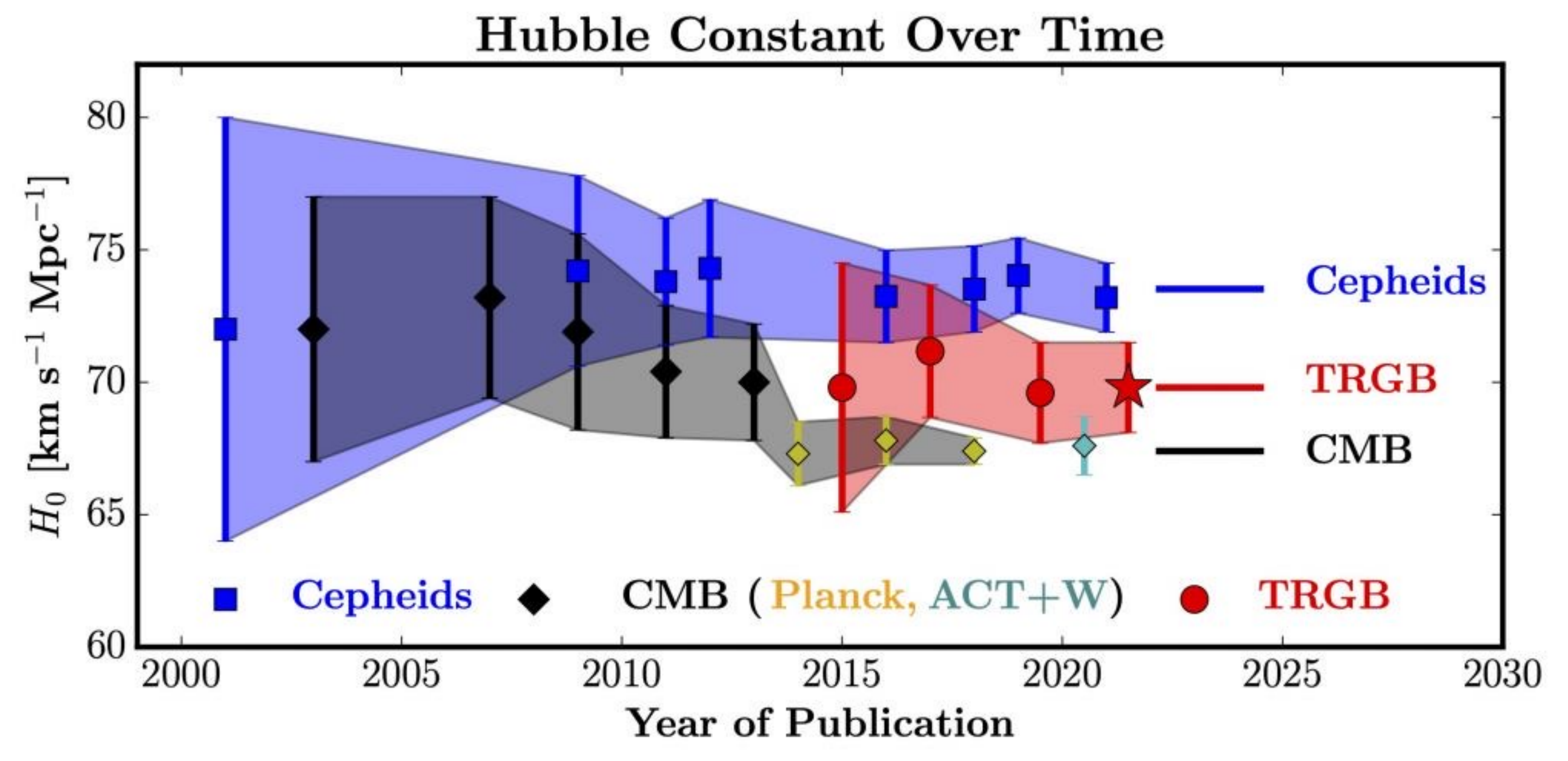
Precision and accuracy in the measurements has increased
The tension has remained the same… 2 σ (but different surveys)

….. What’s up with H_0?



diValentino et al 21

…and… What's up with H_0?



However, extensions to LCDM are not favored (see Heavens et al. 2017)

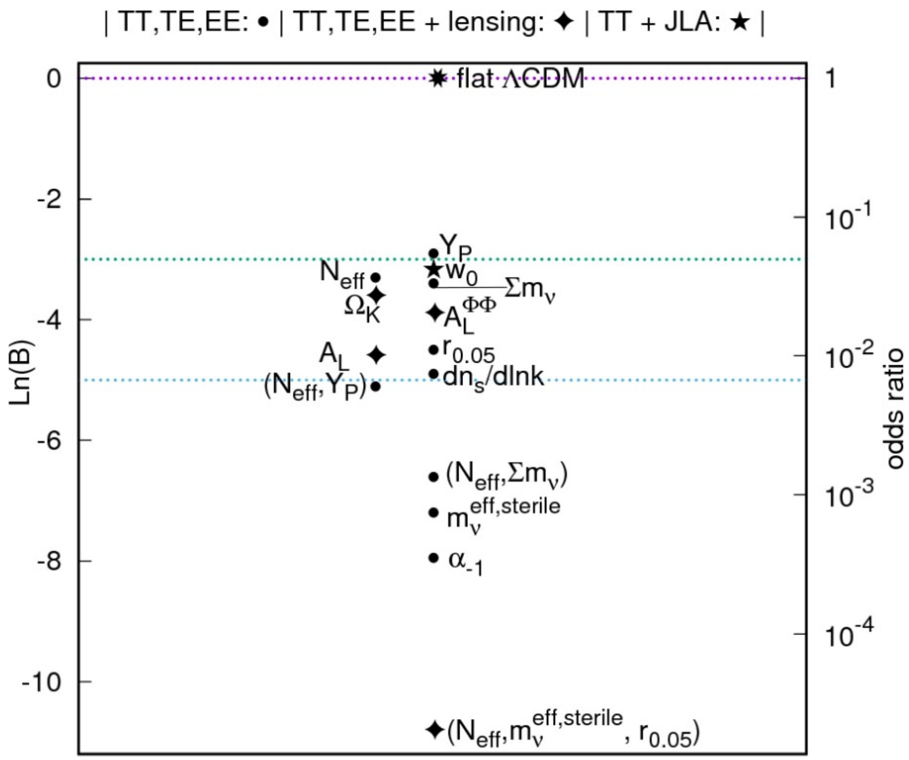
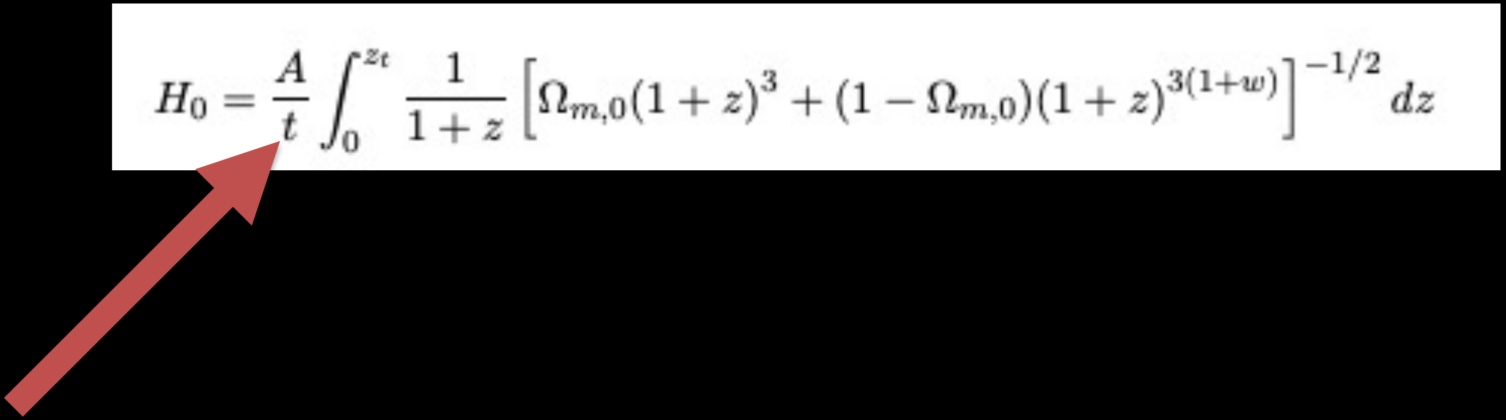


FIG. 1. Bayes factors ln$B$ w.r.t. the highest evidence model (base: flat ΛCDM). Most constraining dataset is indicated by the symbol: filled circles refer to TTTEEE_lowTEB; diamonds to TTTEEE_lowTEB_lensing, and the star to TT_lowTEB_post_JLA. Horizontal lines mark the boundaries corresponding to strong (ln$B < -3$) and very strong (ln$B < -5$) evidence in the Kass & Raftery (1995) scale.

Stellar ages: a tool to measure the expansion rate



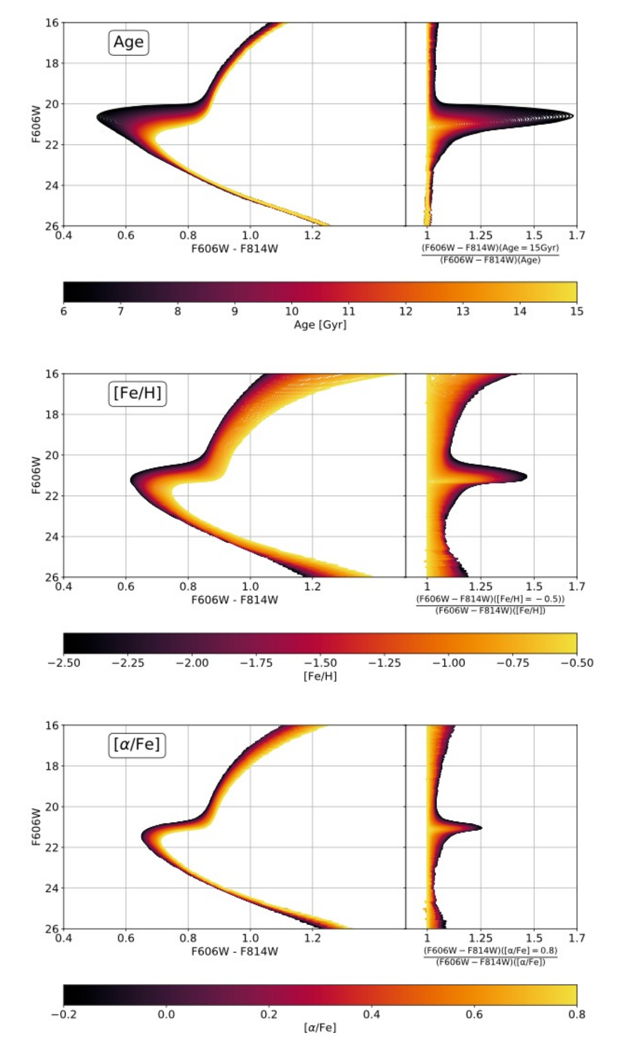
$$H_0 = \frac{A}{t}\int_0^{z_t} \frac{1}{1+z}\left[\Omega_{m,0}(1+z)^3 + (1-\Omega_{m,0})(1+z)^{3(1+w)}\right]^{-1/2} dz$$

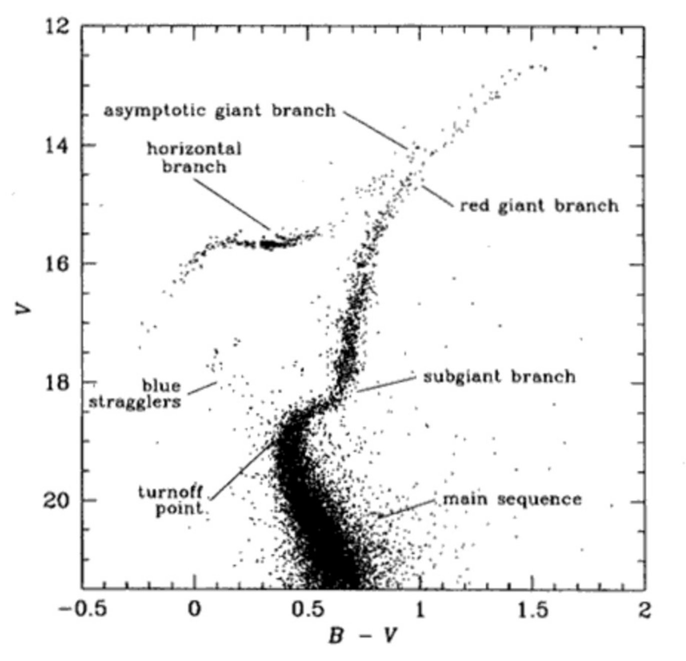
Stellar ages: a tool to measure the expansion rate

- Relative stellar ages at z provide an estimate of the current acceleration rate at z H(z)

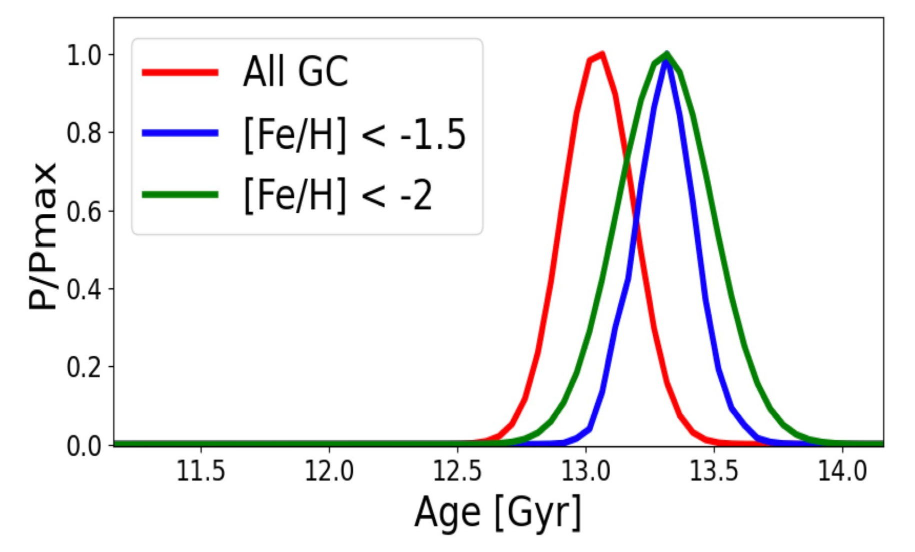
$$\delta t(z) \simeq \frac{\delta z}{H(z)(1+z)}$$

Globular Clusters have been for decades excellent places to estimate the age of the oldest stars

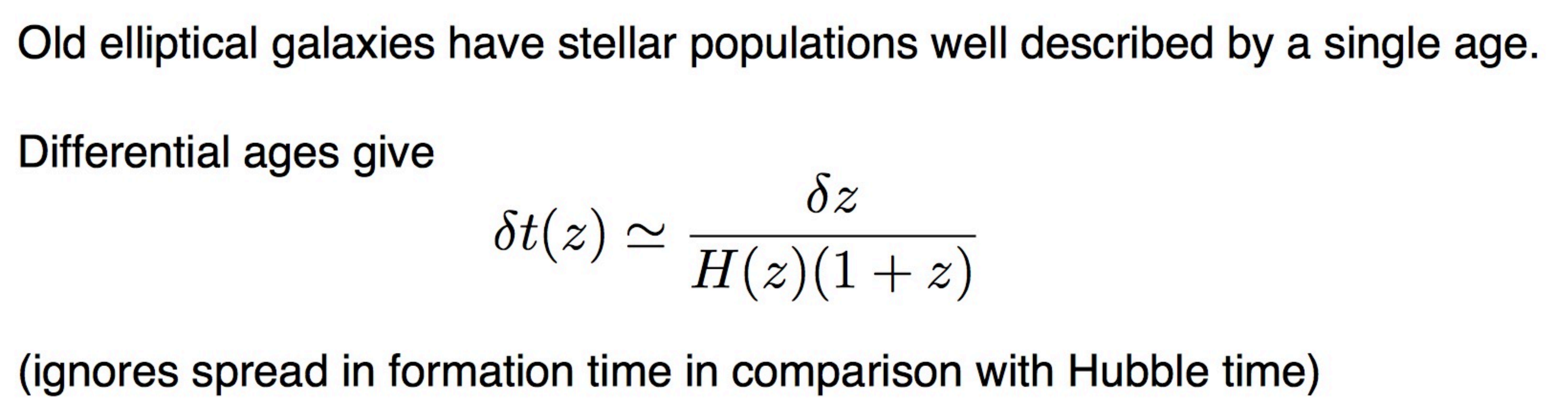




From Valcin et al JCAP (2021)



Probes of the expansion history



Old elliptical galaxies have stellar populations well described by a single age.

Differential ages give

$$\delta t(z) \simeq \frac{\delta z}{H(z)(1+z)}$$

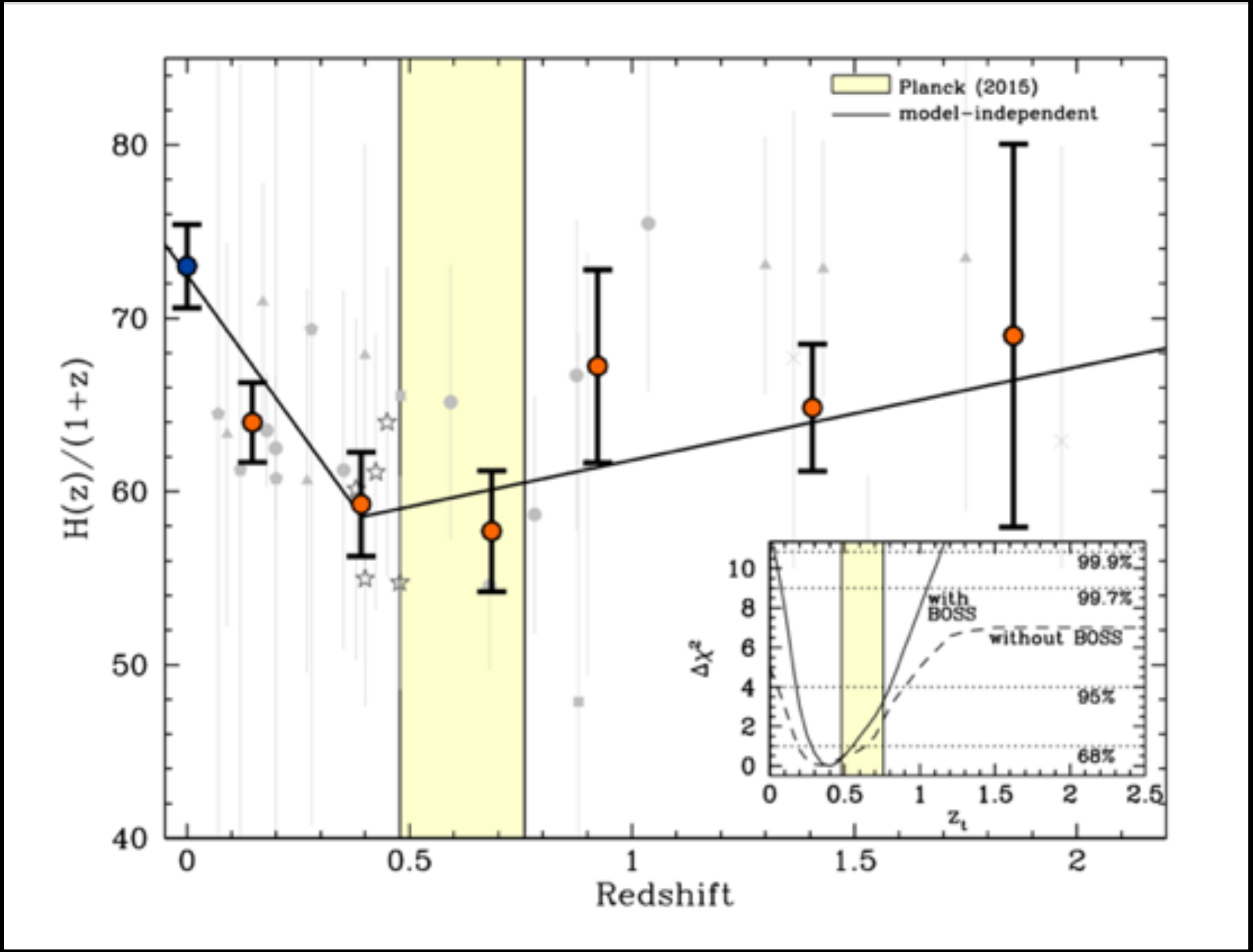
(ignores spread in formation time in comparison with Hubble time)

Simon et al. 2005, Stern et al. 2010, Moresco et al. 2012, 2015, 2016

Wonderful agreement of new data with the ΛCDM model*

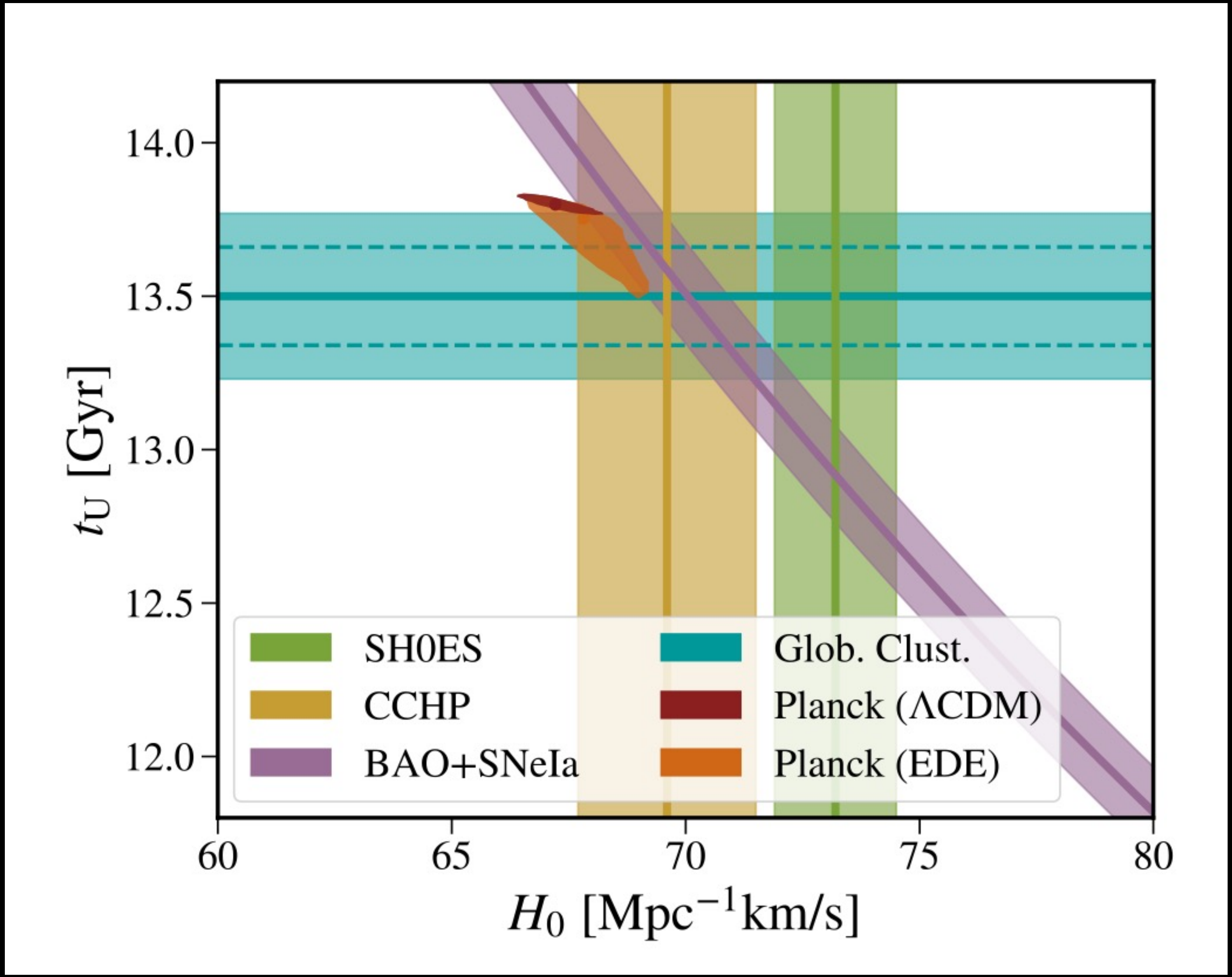
“the maximally boring Universe”

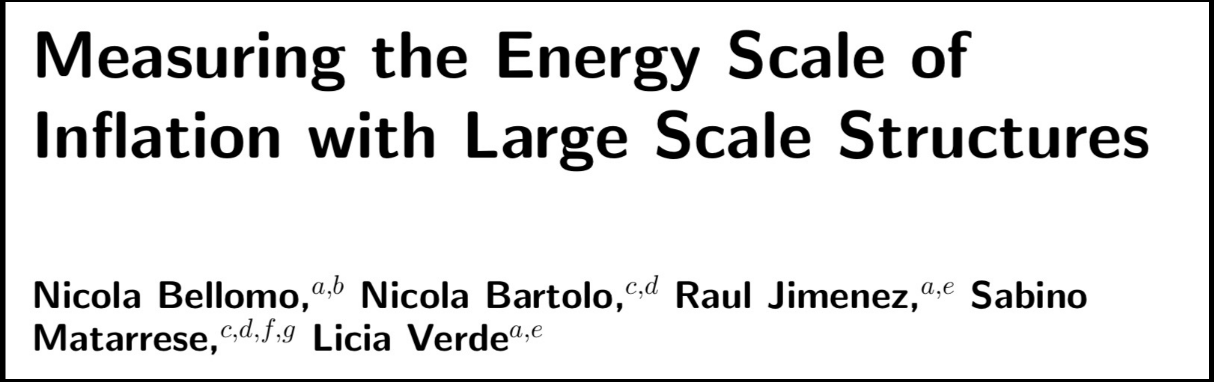
Jimenez et al. JCAP 2017



* With some notable exceptions which are still up for discussion.

From Bernal et al PRD (2021)





Measuring the Energy Scale of Inflation with Large Scale Structures

Nicola Bellomo,^{a,b} **Nicola Bartolo,**^{c,d} **Raul Jimenez,**^{a,e} **Sabino Matarrese,**^{c,d,f,g} **Licia Verde**^{a,e}

Exploiting Graviton Exchange

JCAP 2018

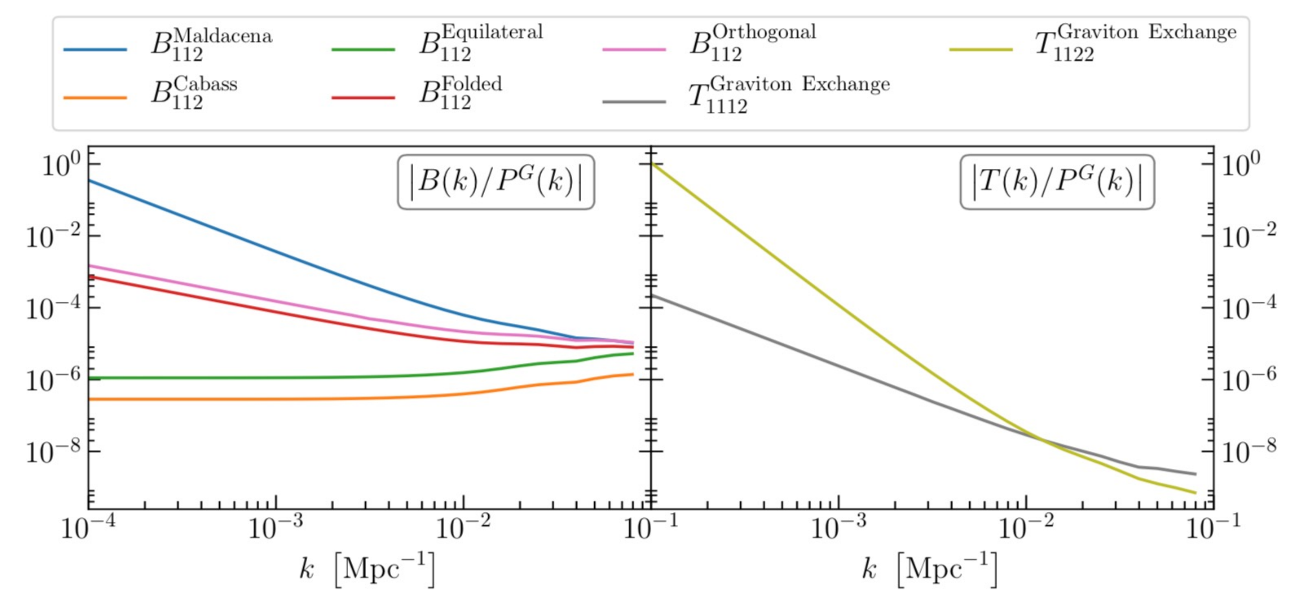


Figure 2: *Left Panel:* ratio between different bispectra and the Gaussian halo power spectrum. For Maldacena and Cabass we used a slow-roll parameter value $\epsilon = 10^{-2}$, while for the Equilateral, Folded and Orthogonal we set $f_{\rm NL} = 0.04$. *Right Panel:* ratio between the graviton exchange contributions and the Gaussian halo power spectrum for $\epsilon = 10^{-2}$ and $k_{\rm hor} = 10^{-6}$ Mpc^{-1}. In this context different values of ϵ just rescale vertically the contrib
tion.

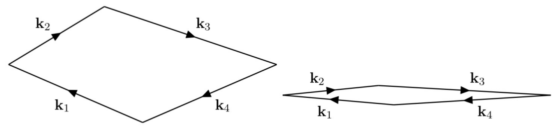
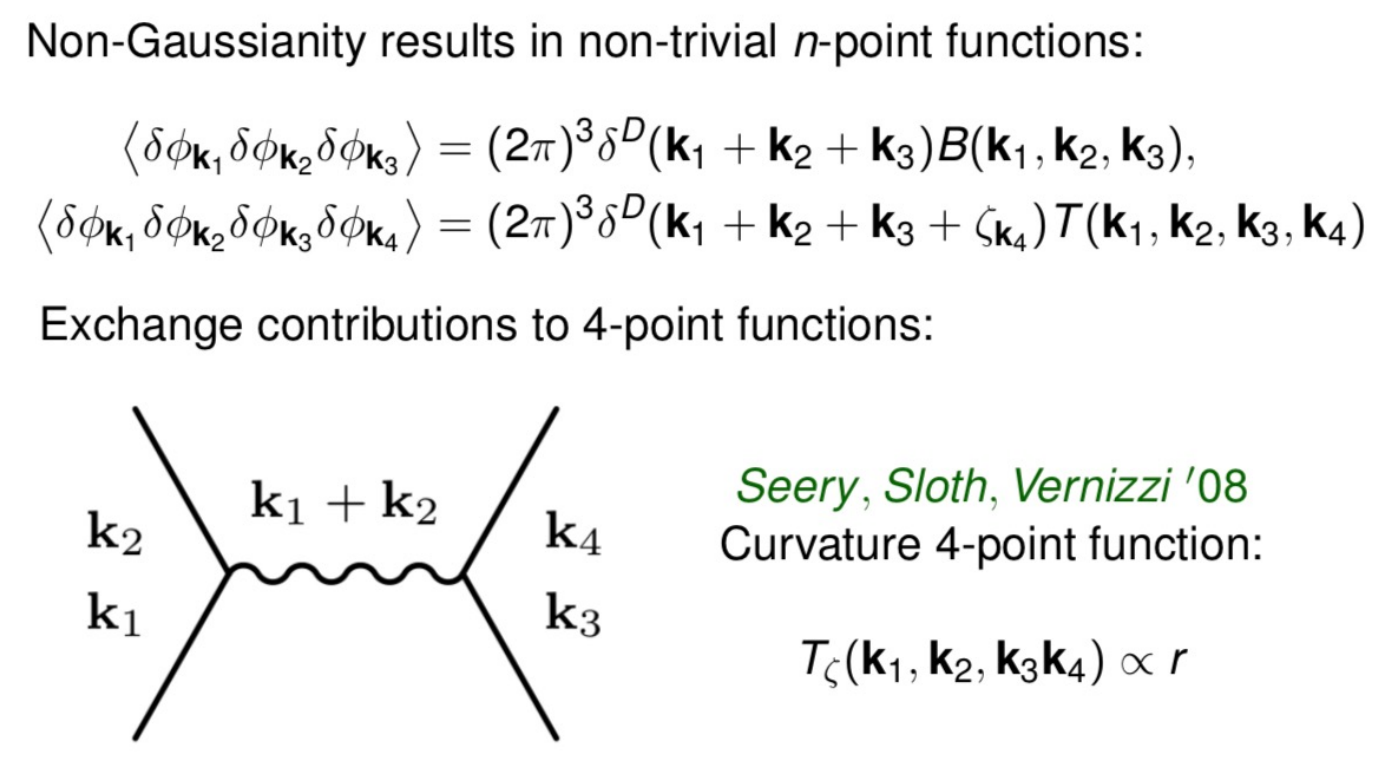


Figure 1: Kite (*left panel*) and folded kite (*right panel*) diagrams. In the left diagram we $k_{13} \ll k_1 \sim k_3, k_2 \sim k_4$, while in the right one we have $k_{12} \ll k_1 \sim k_2, k_3 \sim k_4$. Feynman diagrams have been drawn with Ti*k*Z-Feynman [73].

Look at Trispectrum



Non-Gaussianity results in non-trivial n-point functions:

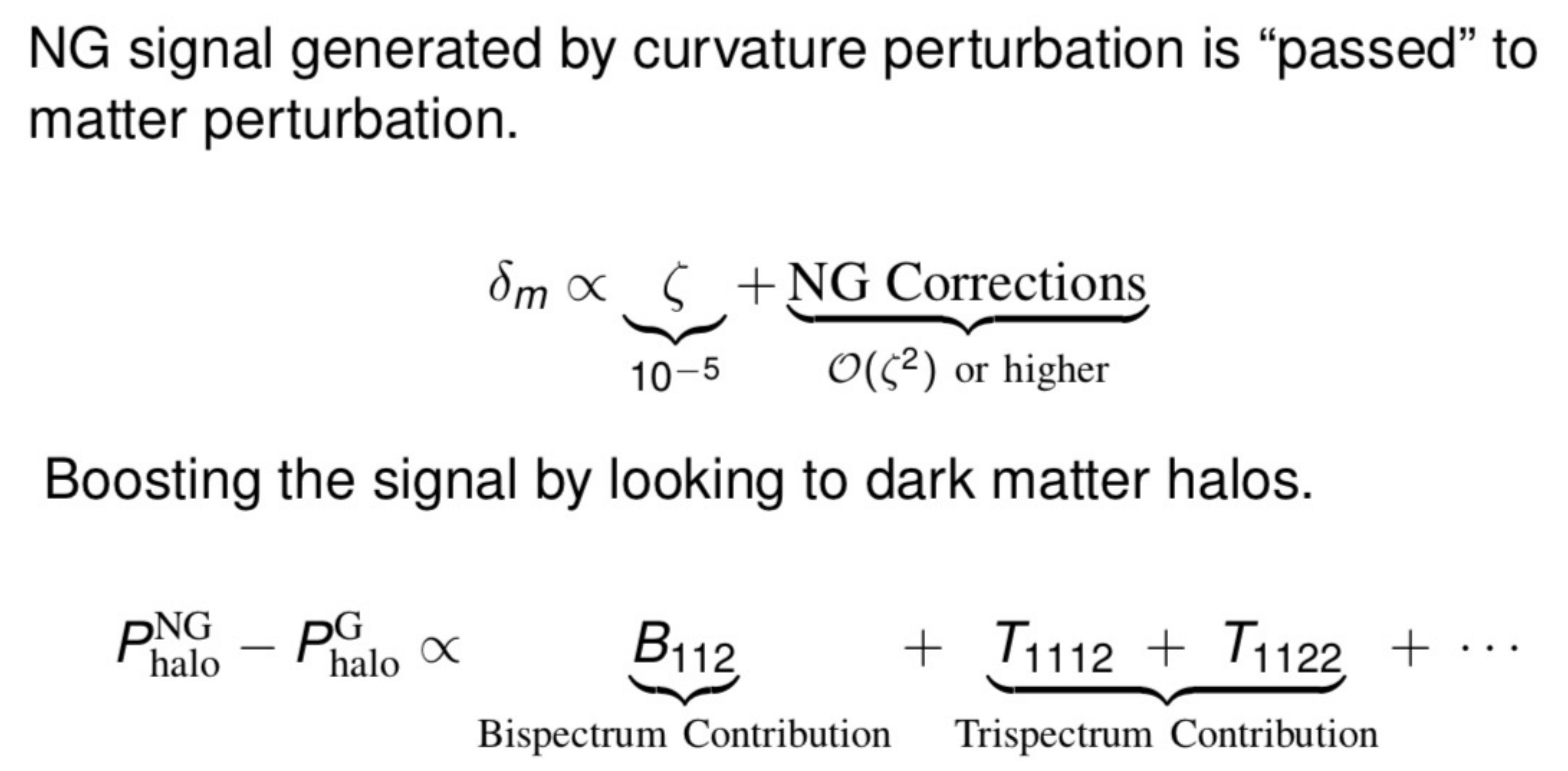
$$\langle \delta\phi_{\mathbf{k}_1}\delta\phi_{\mathbf{k}_2}\delta\phi_{\mathbf{k}_3}\rangle = (2\pi)^3\delta^D(\mathbf{k}_1+\mathbf{k}_2+\mathbf{k}_3)B(\mathbf{k}_1,\mathbf{k}_2,\mathbf{k}_3),$$
$$\langle \delta\phi_{\mathbf{k}_1}\delta\phi_{\mathbf{k}_2}\delta\phi_{\mathbf{k}_3}\delta\phi_{\mathbf{k}_4}\rangle = (2\pi)^3\delta^D(\mathbf{k}_1+\mathbf{k}_2+\mathbf{k}_3+\zeta_{\mathbf{k}_4})T(\mathbf{k}_1,\mathbf{k}_2,\mathbf{k}_3,\mathbf{k}_4)$$

Exchange contributions to 4-point functions:

Seery, *Sloth*, *Vernizzi* '08
Curvature 4-point function:

$$T_\zeta(\mathbf{k}_1,\mathbf{k}_2,\mathbf{k}_3\mathbf{k}_4) \propto r$$

This signal arises from correlations between inflaton fluctuations **mediated by a graviton and enters in the four-point function of scalar curvature perturbations**. The magnitude of this non-Gaussian effect is directly proportional to the tensor-to-scalar ratio r, therefore by isolating this contribution we can extract a direct information (or a stronger upper bound) on the energy scale of inflation. Moreover, this GE contribution contains much more information about inflationary dynamics, in particular on whether inflation is a strong isotropic attractor



NG signal generated by curvature perturbation is “passed” to matter perturbation.

$$\delta_m \propto \underbrace{\zeta}_{10^{-5}} + \underbrace{\text{NG Corrections}}_{\mathcal{O}(\zeta^2)\ \text{or higher}}$$

Boosting the signal by looking to dark matter halos.

$$P^{\text{NG}}_{\text{halo}} - P^{\text{G}}_{\text{halo}} \propto \underbrace{B_{112}}_{\text{Bispectrum Contribution}} + \underbrace{T_{1112} + T_{1122}}_{\text{Trispectrum Contribution}} + \cdots$$

Since curvature perturbations are small (typically ζ ∼ O(10−5) at cosmological scales), t is naively believed that the (n + 1)-point function is just a small correction to the the n-point function, however this statement does not take into account the numerous possible mechanisms that can generate a non-Gaussian signal. Moreover, existing

Look at the correlation of high excursion regions

Remember the **gist** behind this **NG bias**…

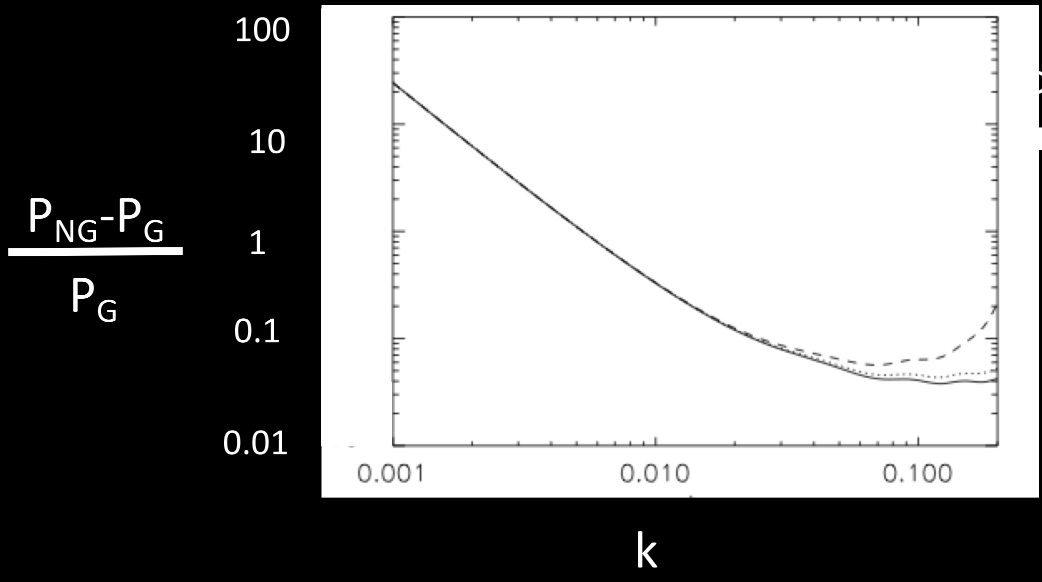
Local case

$$P_h(k,z) = \frac{\delta_c^2(z) P_{\delta\delta}(k,z)}{\sigma_R^4 D^2(z)} \left[1 + 4 f_{\rm NL} \delta_c(z) \frac{\mathcal{F}_R(k)}{\mathcal{M}_R(k)} \right]$$

Gaussian bias (squared)
-can be improved…-

In general

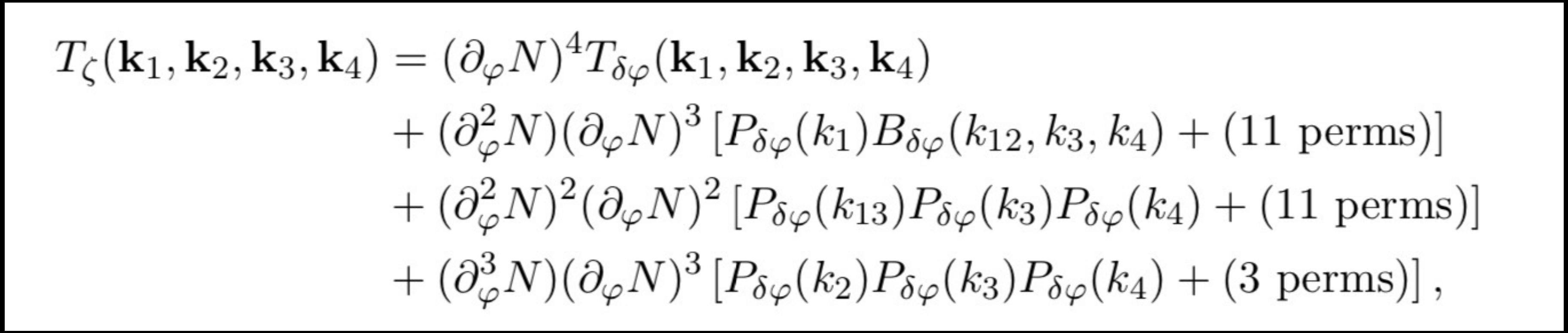
$$\frac{\delta_c}{8\pi^2\sigma_R^2} \int dk_1 k_1^2 \mathcal{M}_R(k_1) \times \int_{-1}^{1} d\mu \mathcal{M}_R\left(\sqrt{\alpha}\right) \frac{B_\phi(k_1, \sqrt{\alpha}, k)}{P_\phi(k)}.$$



cts as a scale dependent
nd z dependent) bias!

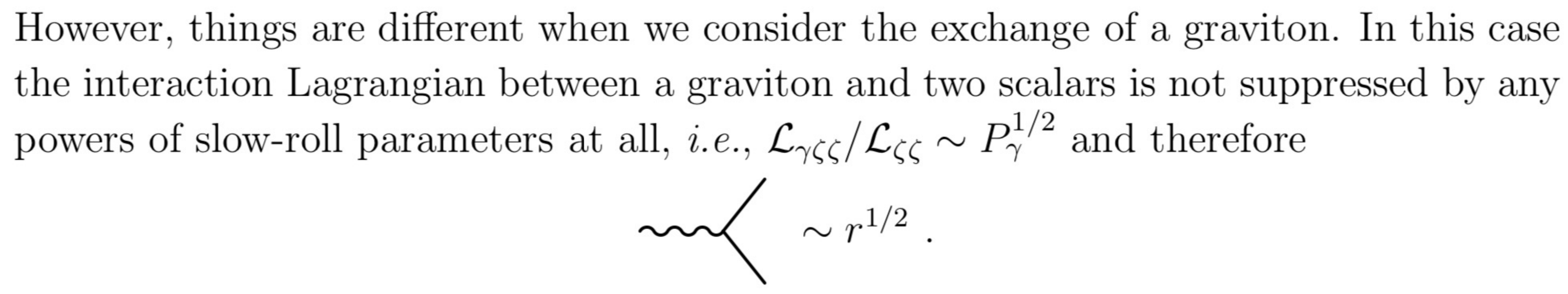
Important on large scales!

In this work we are mainly interested in the four-point function or trispectrum, in particular its connected part (the disconnected part is always present even in the purely Gaussian case). The complete form of the curvature perturbation trispectrum in single-field inflation, up to second order in slow-roll parameters is:



$$\begin{aligned}T_\zeta(\mathbf{k}_1,\mathbf{k}_2,\mathbf{k}_3,\mathbf{k}_4) &= (\partial_\varphi N)^4 T_{\delta\varphi}(\mathbf{k}_1,\mathbf{k}_2,\mathbf{k}_3,\mathbf{k}_4)\\ &+ (\partial^2_\varphi N)(\partial_\varphi N)^3\left[P_{\delta\varphi}(k_1)B_{\delta\varphi}(k_{12},k_3,k_4)+(11\text{ perms})\right]\\ &+ (\partial^2_\varphi N)^2(\partial_\varphi N)^2\left[P_{\delta\varphi}(k_{13})P_{\delta\varphi}(k_3)P_{\delta\varphi}(k_4)+(11\text{ perms})\right]\\ &+ (\partial^3_\varphi N)(\partial_\varphi N)^3\left[P_{\delta\varphi}(k_2)P_{\delta\varphi}(k_3)P_{\delta\varphi}(k_4)+(3\text{ perms})\right],\end{aligned}$$

Graviton exchange is NOT suppressed by high-orders of slow-roll parameters



However, things are different when we consider the exchange of a graviton. In this case the interaction Lagrangian between a graviton and two scalars is not suppressed by any powers of slow-roll parameters at all, *i.e.*, $\mathcal{L}_{\gamma\zeta\zeta}/\mathcal{L}_{\zeta\zeta} \sim P_\gamma^{1/2}$ and therefore

$$\sim r^{1/2}\,.$$

Questions and some answers

Is it a problem?	YES
Where is the problem? Systematics? A specific data set?	Systematics increasingly unlikey, not in the CMB data.
If not in the data..then in the model?	Pre recombination? Or post recombination?
Early vs late?	TRGB agrees with CMB but cepheid-based method yield high H0

Need next data release of GAIA: Watch this space

Conclusions

Concordance, vanilla ΛCDM still rules

Some puzzles remain (H0, σ8)

Coordinated effort to move from precision cosmology to accurate cosmology

The field has moved well beyond “spherical cows” and “pie in the sky”.

CMB initially was simple: now the game has changed.