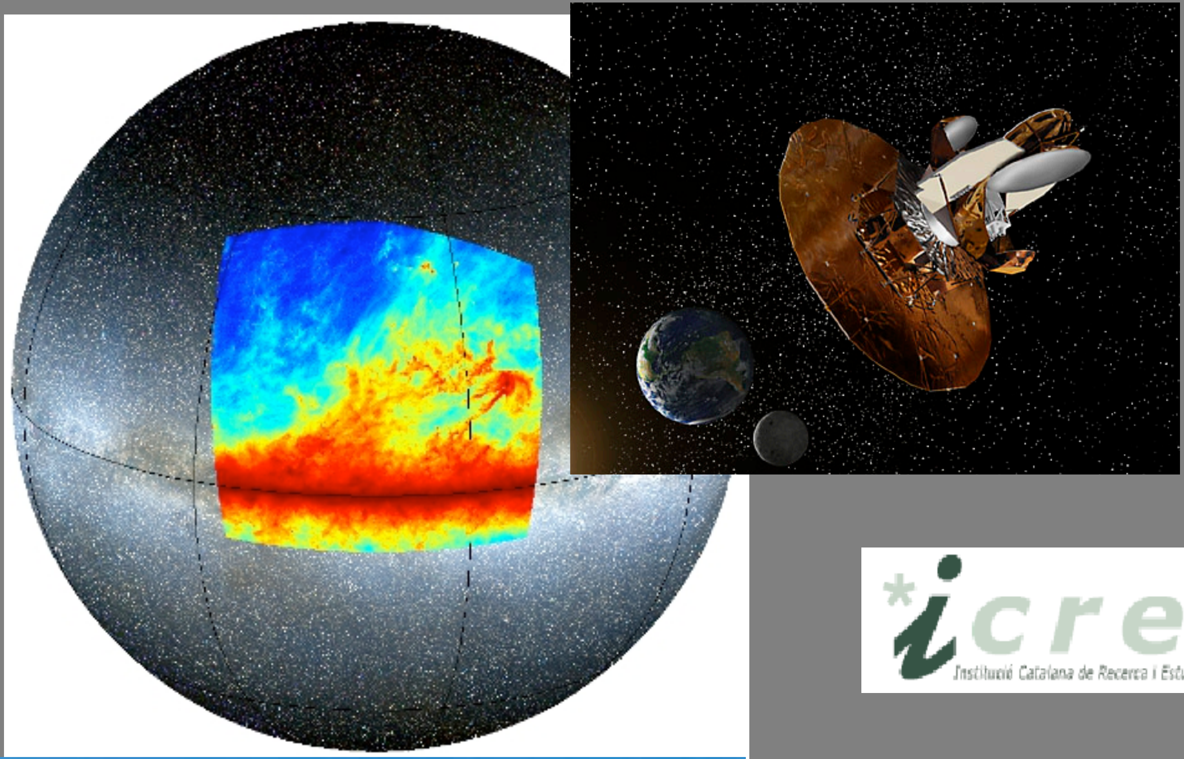
Fundamental physics from astronomical observations



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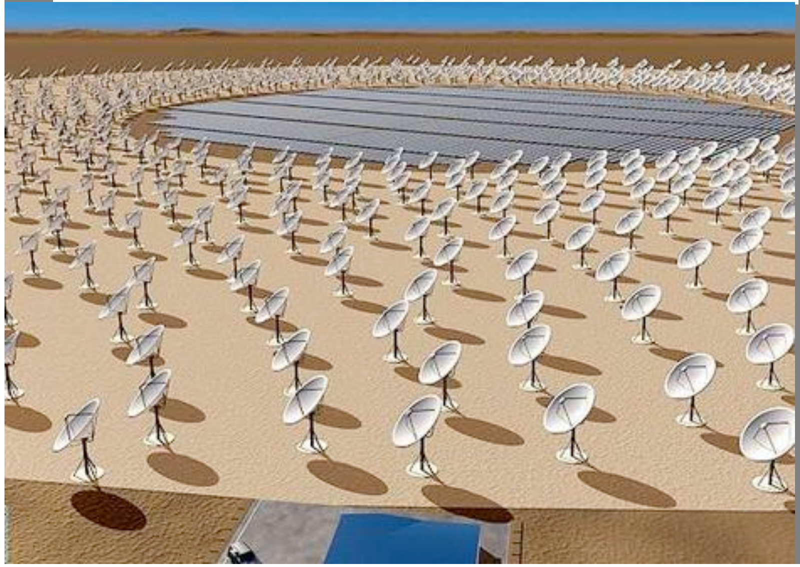
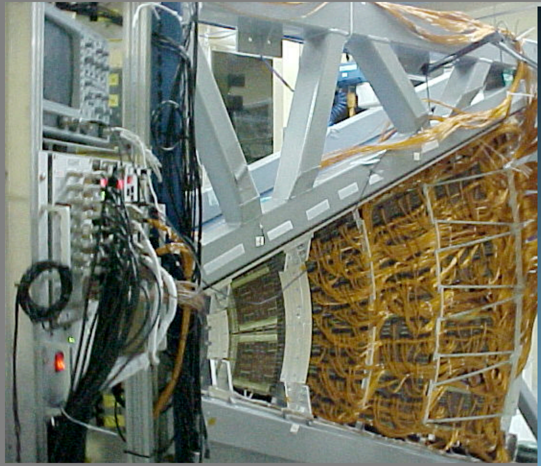




COSMOLÉ

OUR NEXT MEETING WILL TAKE PLACE ON 27-JAN-2010 in VALENCIA

Cosmole is one of the leading cosmology groups in Spain, includes members from three different institutions from the three major cities in Spain: The ICCUB in Barcelona, the IFIC in Valencia and the IFT/UAM in Madrid. We have tight links withthe CERN in Geneva. The group carries out research in cosmology and fundamental physics, ranging from the very early universe, the CMB, the large scale structure of the universe to the formation and evolution of galaxies. While physically located in different cities, we function as a single group, sharing students, postdocs and staff members. We meet monthly to discuss science in one of the cities.

Our mission is to foster the interplay between theory and observations, form students with both solid theoretical background and confidence in interpreting real data, investigate subjects in cosmology that are at the forefront of current knowledge and attract the leading researchers in the field offering them a congenial intellectual environment to carry on research at their best. While we have a very strong theoretical component to our research, some of us are also involved in large international collaborations in observational cosmology: SDSSIII, LSST, BPol, Euclid.

Courtesy of Planck and SKA teams

Ultimate Experiments

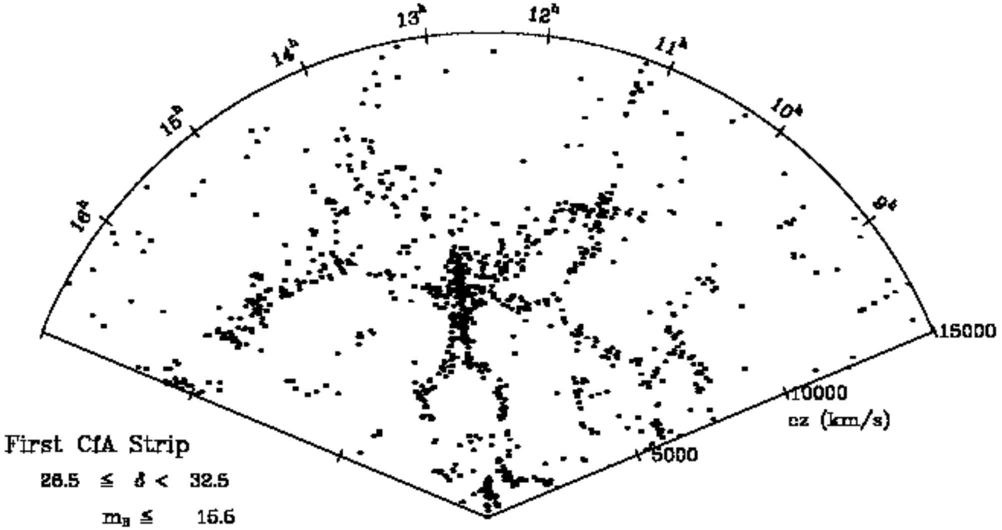
In cosmology one can actually perform **ultimate** experiments, i.e. those which contain ALL information available for measurement in the sky. The first one of its kind is be Planck (in Temperature) and in this decade we will also have such experiments mapping the galaxy field. Question is: how much can we learn about fundamental physics, if any, from such experiments?

My talk will cover a few examples:

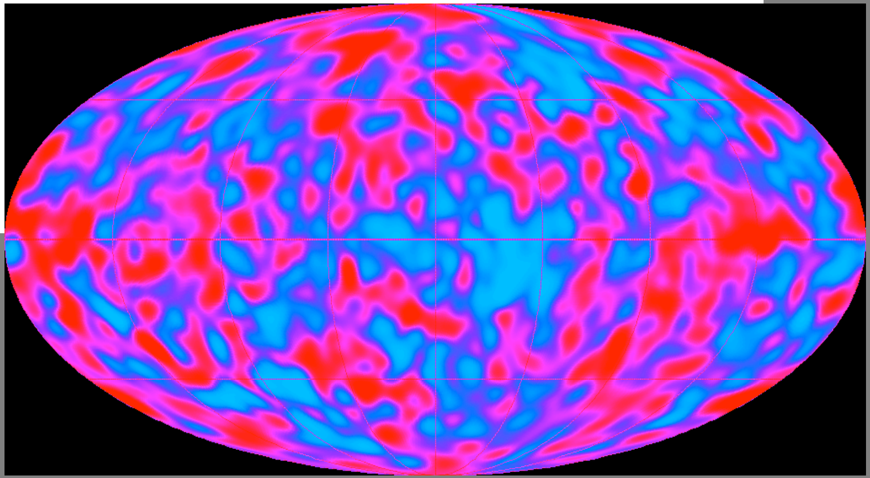
1. Neutrinos
2. Nature of the initial conditions and perturbations
3. Dark Energy
4. Beyond the Standard Model Physics

Extremely successful model

State of the art of data then…



~14 Gyr

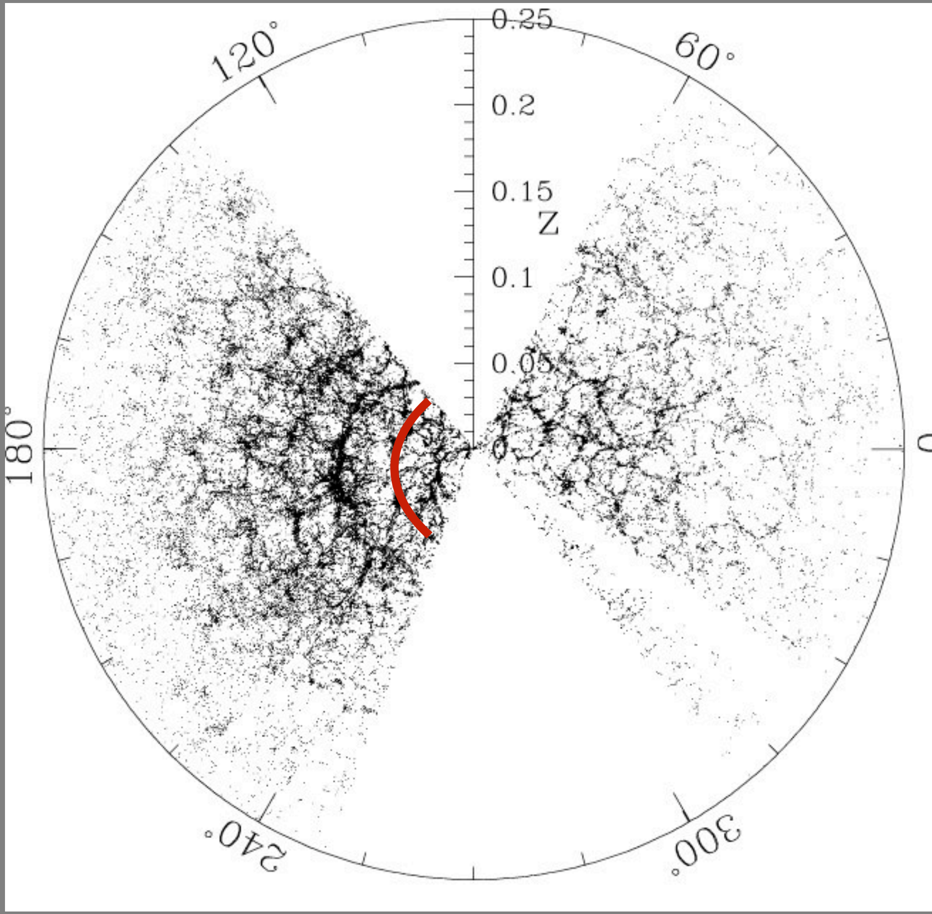


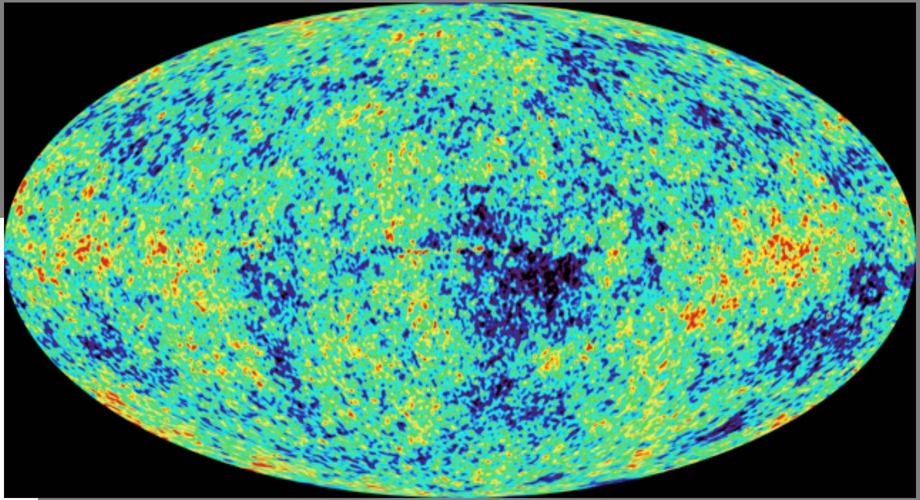
(DMR)COBE

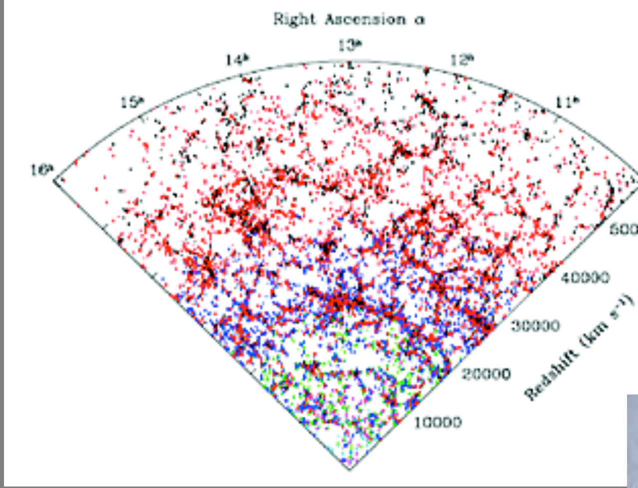
CMB

380000 yr
(a posteriori information)

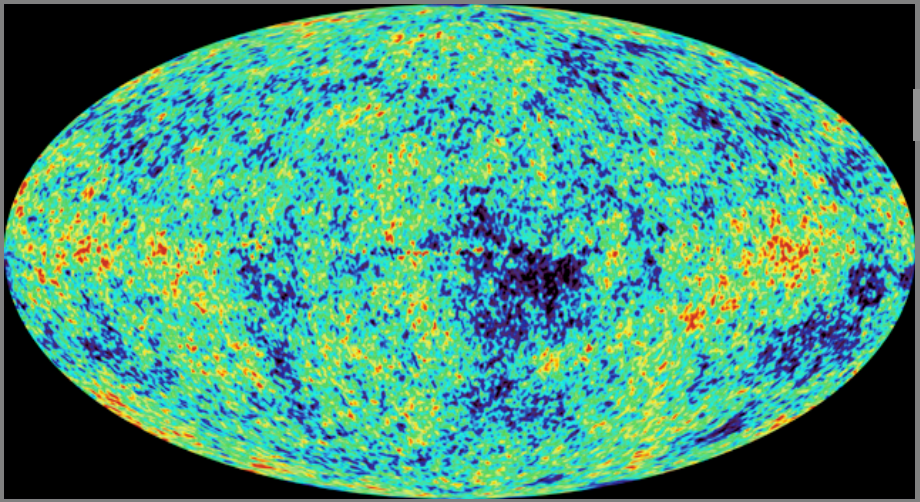
Avalanche of data





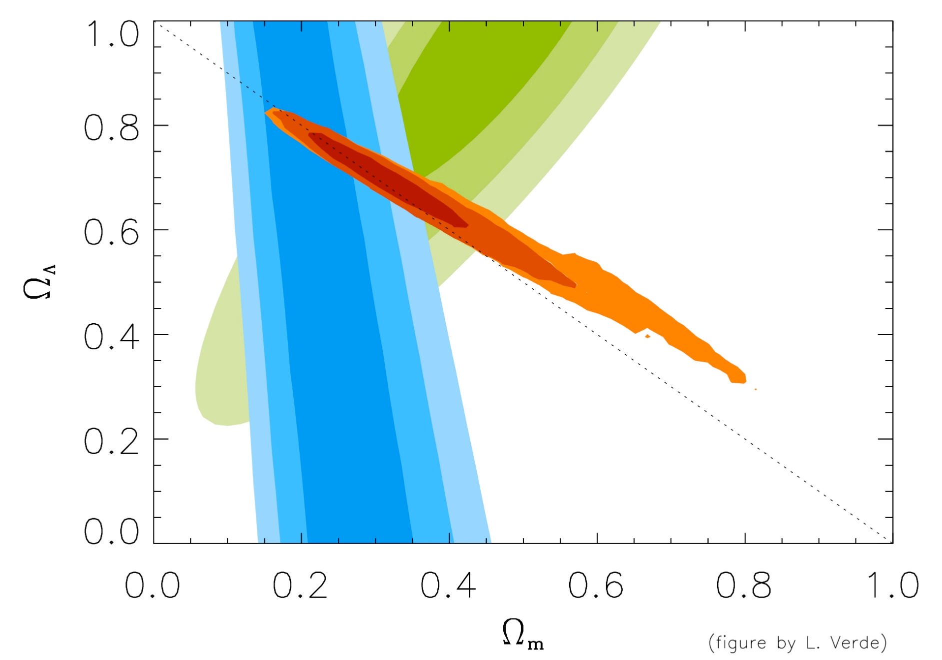


it still holds!

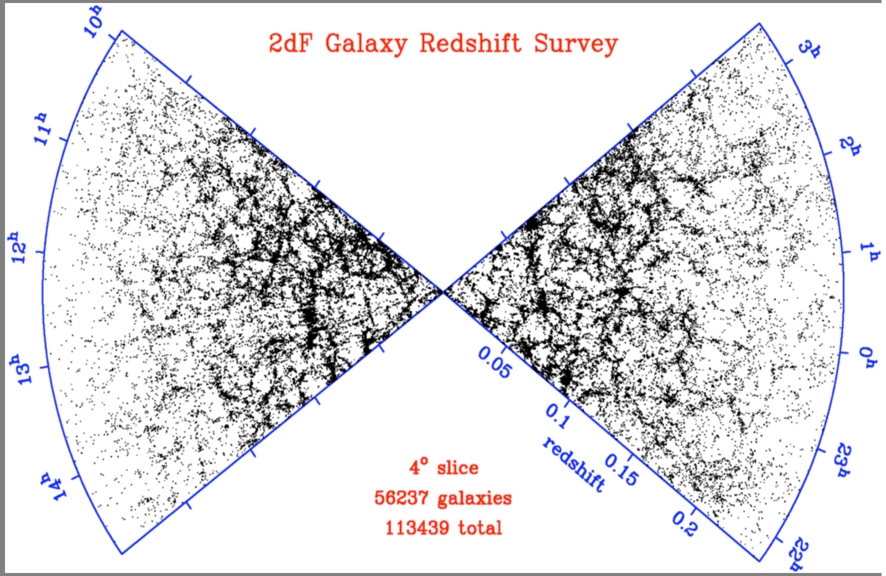


Horizon problem

Flatness problem



(figure by L. Verde)



Structure Problem

Most fundamental question in ν

Are neutrinos Dirac or Majorana?

(in other words, origin of neutrino mass: Higgs mechanism or beyond the SM mechanism?)

ν mass in cosmology

Influence in background and growth of structure
Many works in how neutrinos modify cosmology and
Astrophysics and in nonstandard neutrino physics.
Not discussed today.

Today we use standard physics and try to answer:
What cosmology can do for fundamental neutrino
physics?

Previous works: Pastor, Slosar, de Bernardis, Komatsu,….

Physical effects

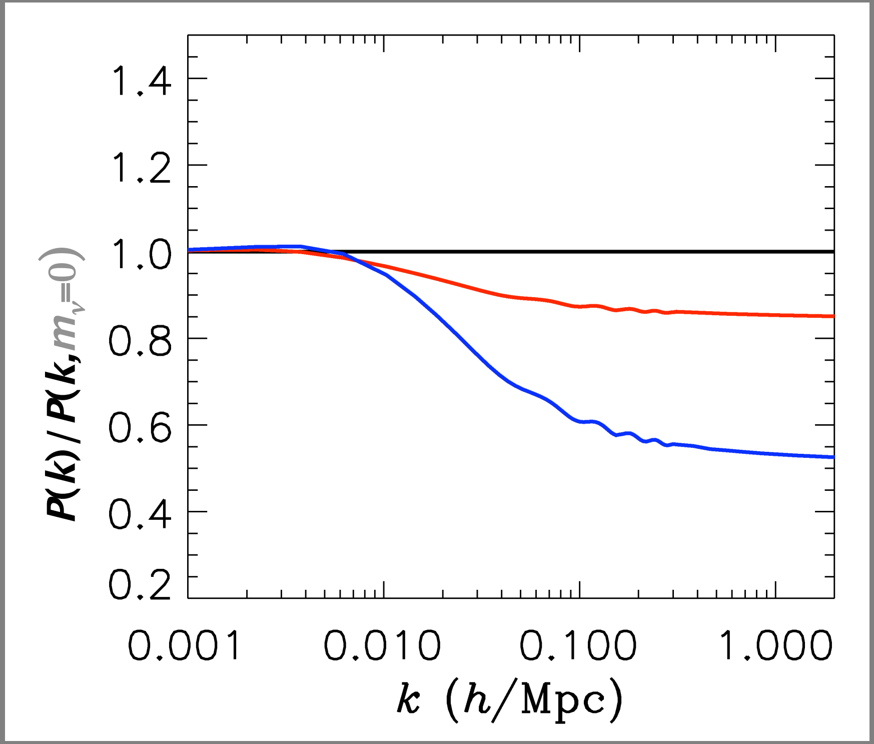
Total mass >~1 eV become non relativistic before recombination CMB

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

Degeneracy

After recombination

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



Σm = 0 eV

Σm = 0.3 eV

Σm = 1 eV

Mass scale searches:

beta decay $m_{\nu_e} = \left(\sum_i |U_{ei}|^2 m_i^2 \right)^{1/2} \leq 2.3\ eV$

$$[c_{13}^2 c_{12}^2 m_1^2 + c_{13}^2 s_{12}^2 m_2^2 + s_{13}^2 m_3^2]^{1/2}$$

0νββ decay $m_{ee} = \left| \sum_i U_{ei}^2 m_i \right|$ **If Majorana neutrinos**

$$|c_{13}^2 c_{12}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi_3}|$$

cosmology $\sum_i m_i \leq 0.3\ eV$ Reid et al (cosmole) 2010

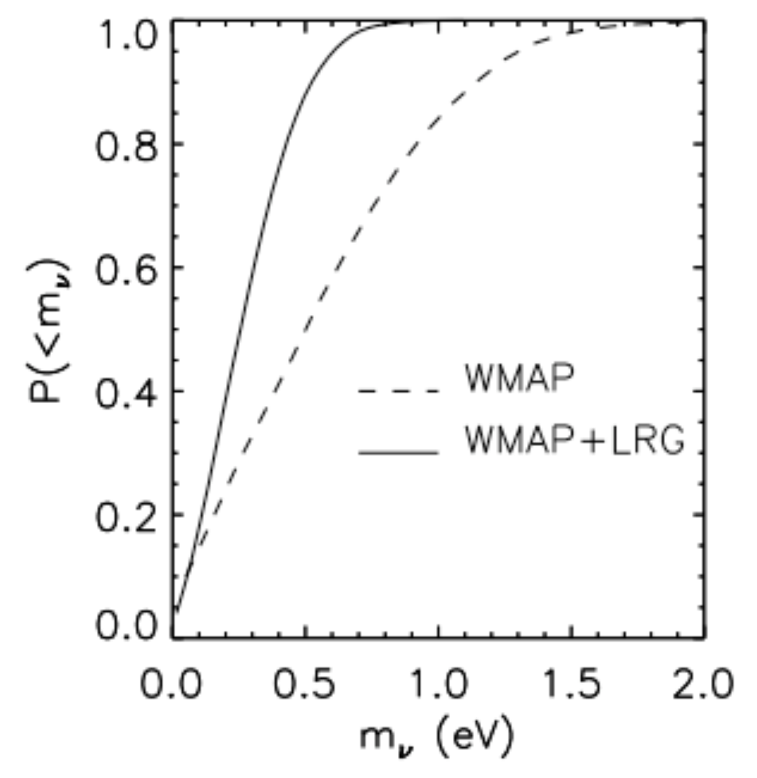
Cosmic Neutrino Background

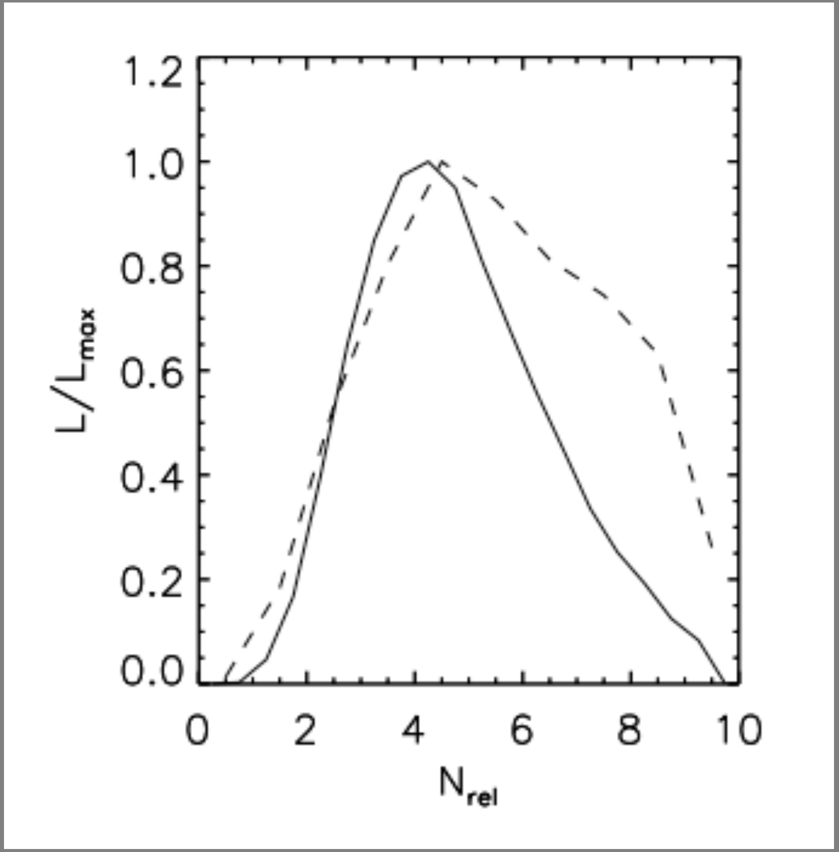
56 cm^{-3} at 1.95 K (0.17 meV)

Possible mechanical effect : torque of order G_F if target and neutrino background are polarized (Stodolsky effect) and net neutrino-antineutrino asymmetry

Still far from observability, awaiting for future technology

Neutrinos....





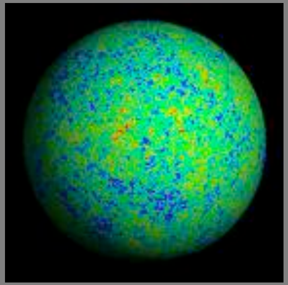
Reid et al. arXiv:0907.1659

Robust neutrino constraints…

Beth Reid, LV, R. Jimenez, Olga Mena,(JCAP 2010) arXiv:0910.0008

DATA:

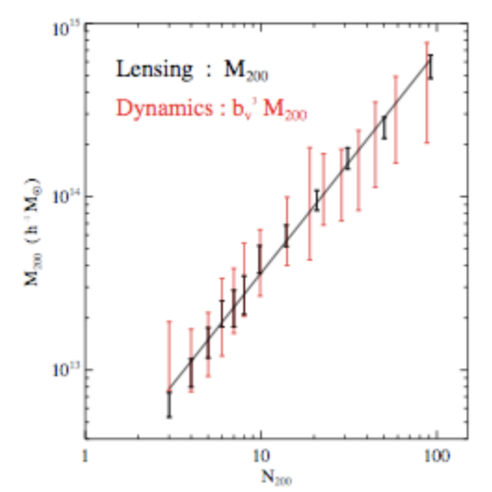
WMAP5



H0 from Riess et al 2009 h=0.74+-0.036

MaxBCG $\sigma_8(\Omega_m/0.25)^{0.41} = 0.832 \pm 0.033.$

Rozo et al 09, Koester et al 07, Johnston et al 07

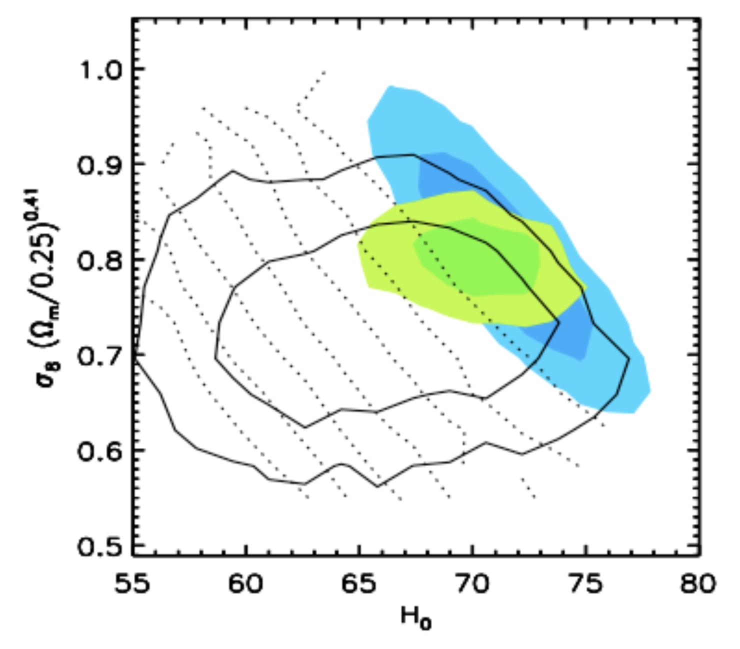


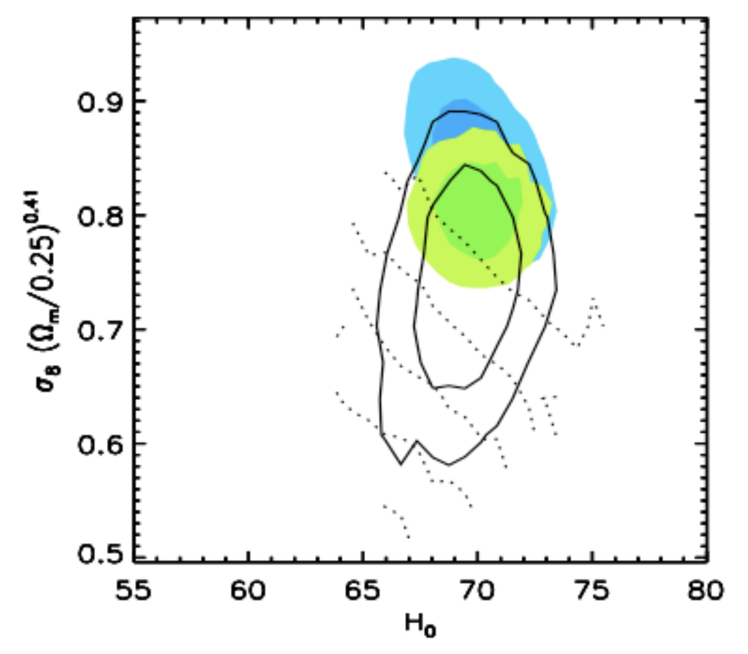
SDSS DR7 halo P(k)

Physical effects cnt'

Beth Reid, LV, R. Jimenez, Olga Mena, arXiv:0910.0008

LCDM+ $m\nu$





WMAP $M\nu=0$

WMAP

.... Constant $\Sigma m\nu$

WMAP+maxBCG+H_0

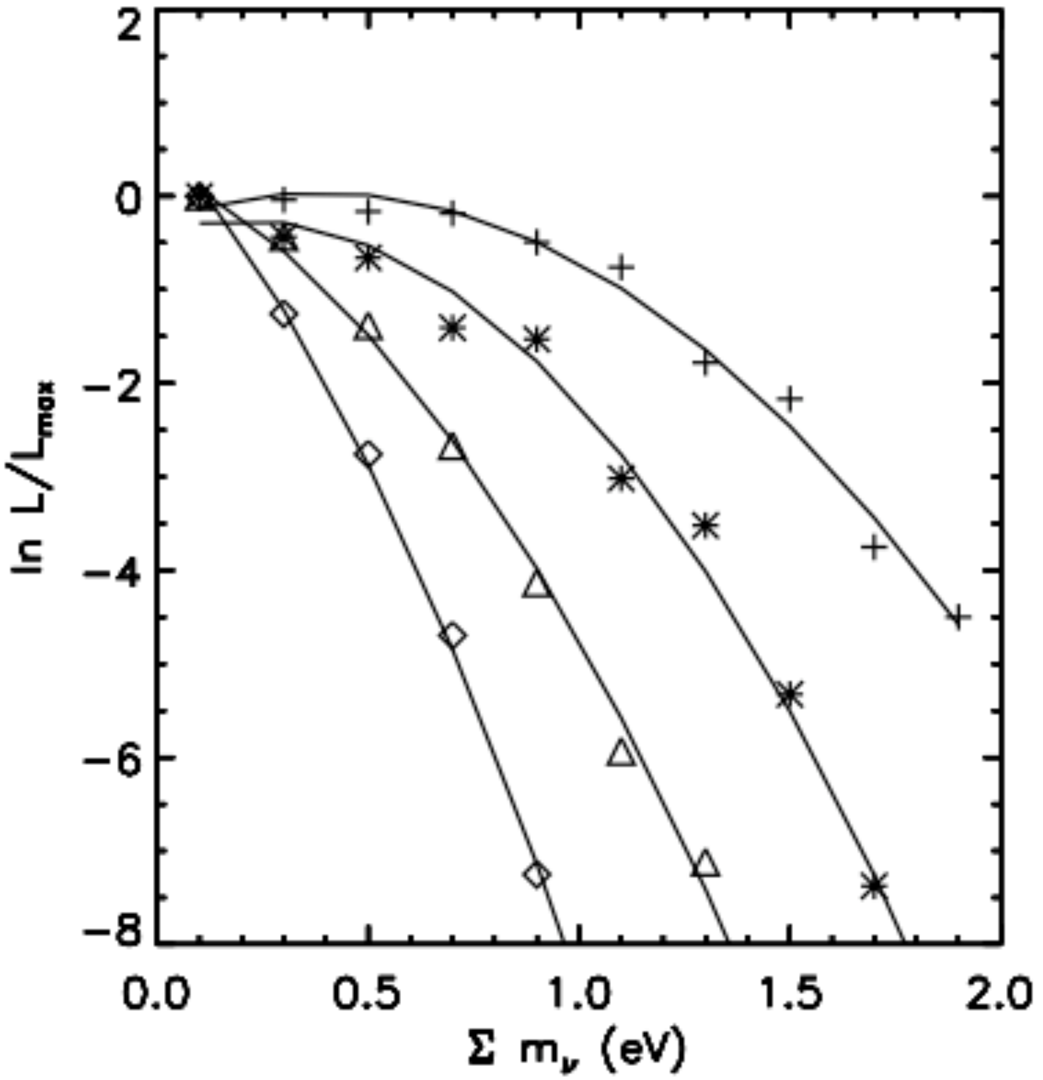
WMAP+BAO+SNe $M\nu=0$

WMAP+BAO+SNe

.... Constant $\Sigma m\nu$

+maxBCG+H_0

Profile likelihood ratio



\+ WMAP

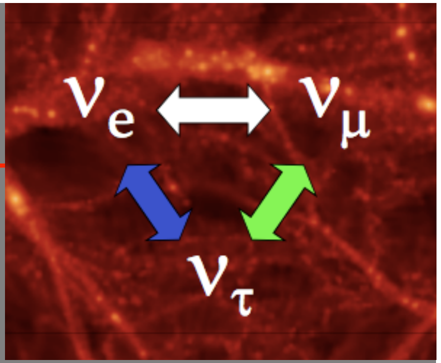
* WMAP+maxBCG

△ WMAP +H0

◇ WMAP+H0+maxBCG

Beth Reid, LV, R. Jimenez, Olga Mena, arXiv:0910.0008

Neutrino properties



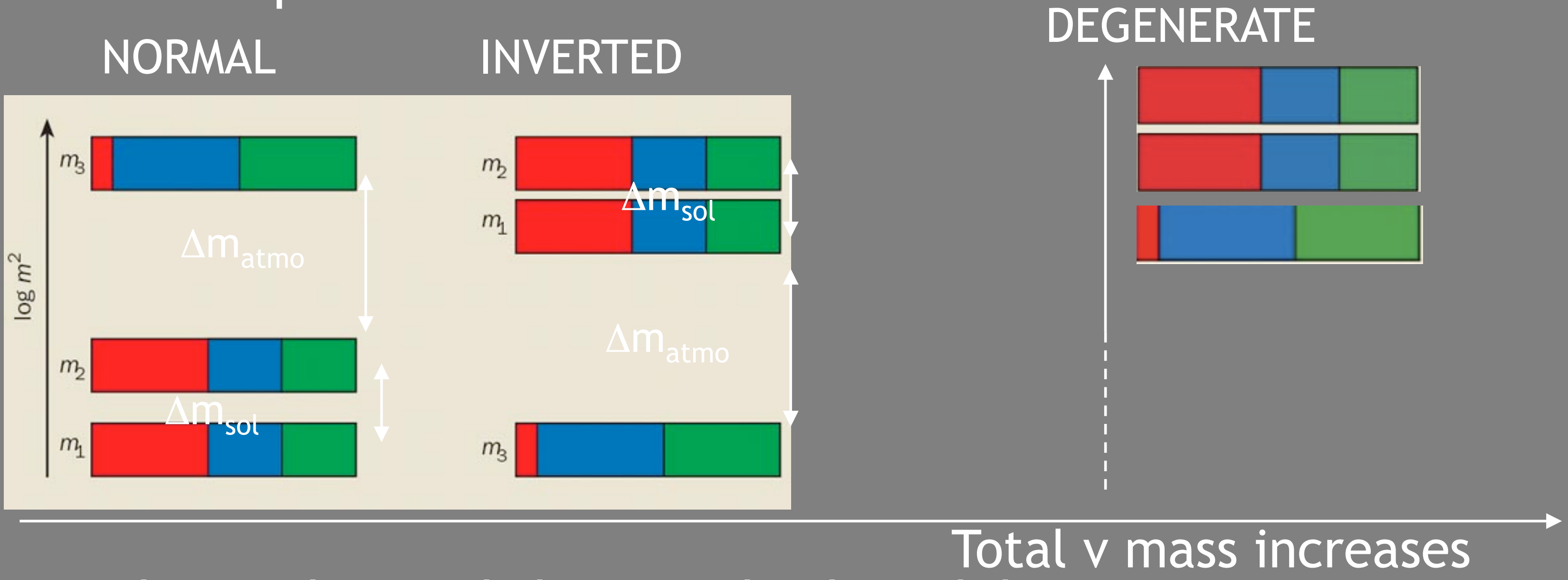
Neutrino mass eigenstates are not the same as flavor

- Oscillations indicate neutrinos have mass:

$$\Delta m^2_{21} \equiv \Delta m^2_{\mathrm{sol}} = 8.0^{+0.6}_{-0.4} \cdot 10^{-5}\mathrm{eV}^2$$

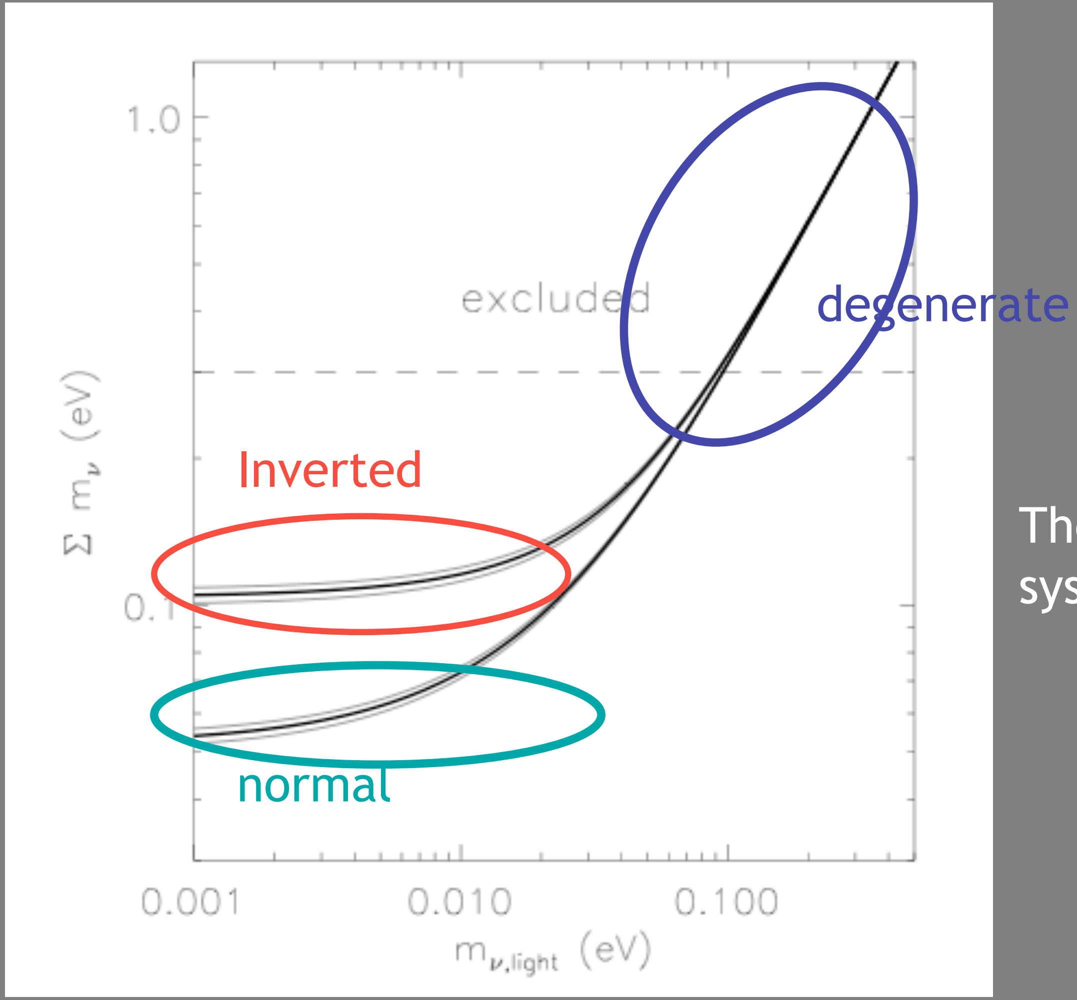
$$|\Delta m^2_{31}| \approx |\Delta m^2_{32}| \equiv \Delta m^2_{\mathrm{atm}} = 2.4^{+0.6}_{-0.5} \cdot 10^{-3}\mathrm{eV}^2$$

- Three possible hierarchies



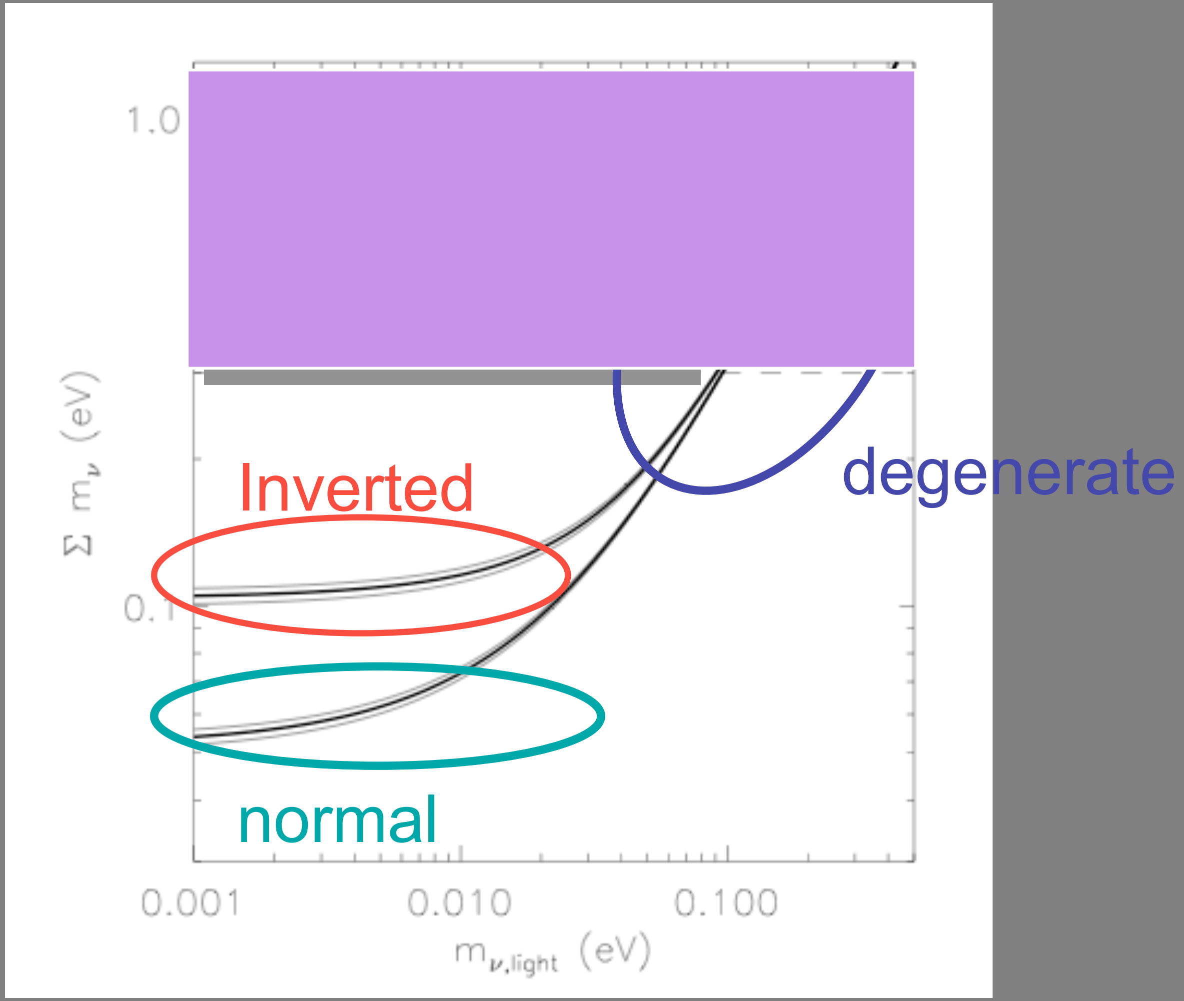
- Physics beyond the standard model!
- The standard model has 3 neutrino species, but…

Cosmology is key in determining the absolute mass scale



The problem is systematic errors

Cosmology is key in determining the absolute mass scale



Beth Reid, LV, R. Jimenez, Olga Mena, arXiv:0910.0008 JCAP (2010)

Dirac or Majorana? ↔ hierarchy

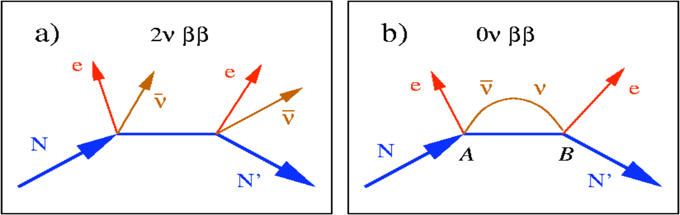
Are neutrinos their own anti-particle?(are they Majorana or Dirac?)

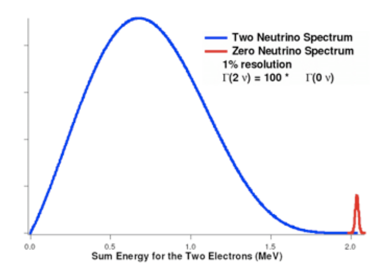
$0\nu\beta\beta$ (next generation)

Yes

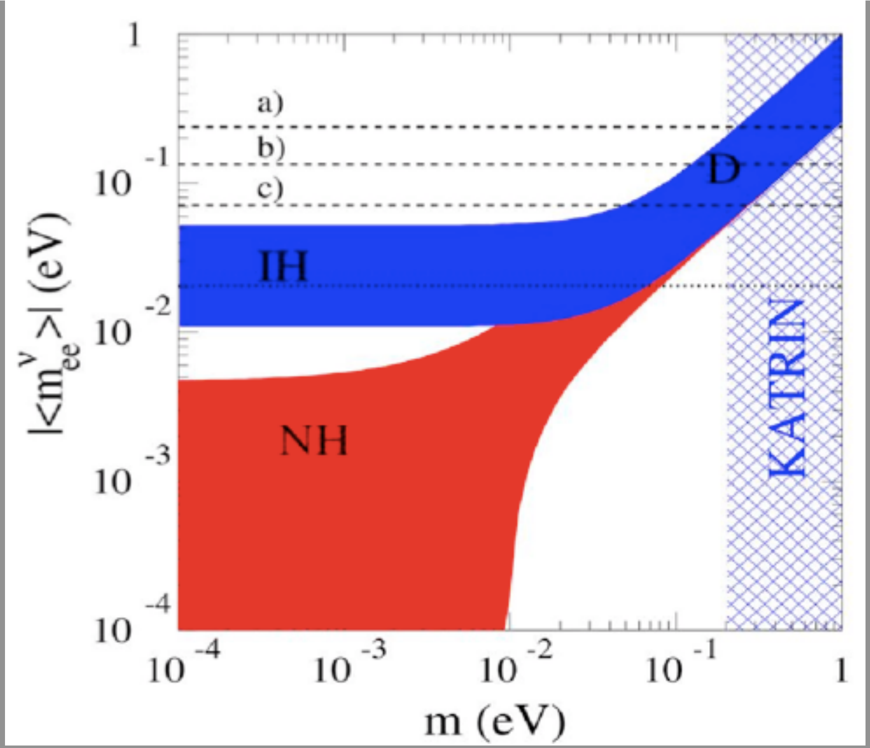
No

Because Dirac OR
because below threshold (still unknown)?





Majorana



Jimenez, Kitching, Penya-Garay, Verde, arXiv:1003:5918

Parameterization: Σ, Δ, sgn(Δ)

$$\mathrm{NH}: \quad \Sigma = 2m + M \quad \Delta = (M - m)/\Sigma$$
$$\mathrm{IH}: \quad \Sigma = m + 2M \quad \Delta = (m - M)/\Sigma$$

Examples:

(0.0, 0.009, 0.05) eV min NH
(0.0, 0.049, 0.05) eV min IH

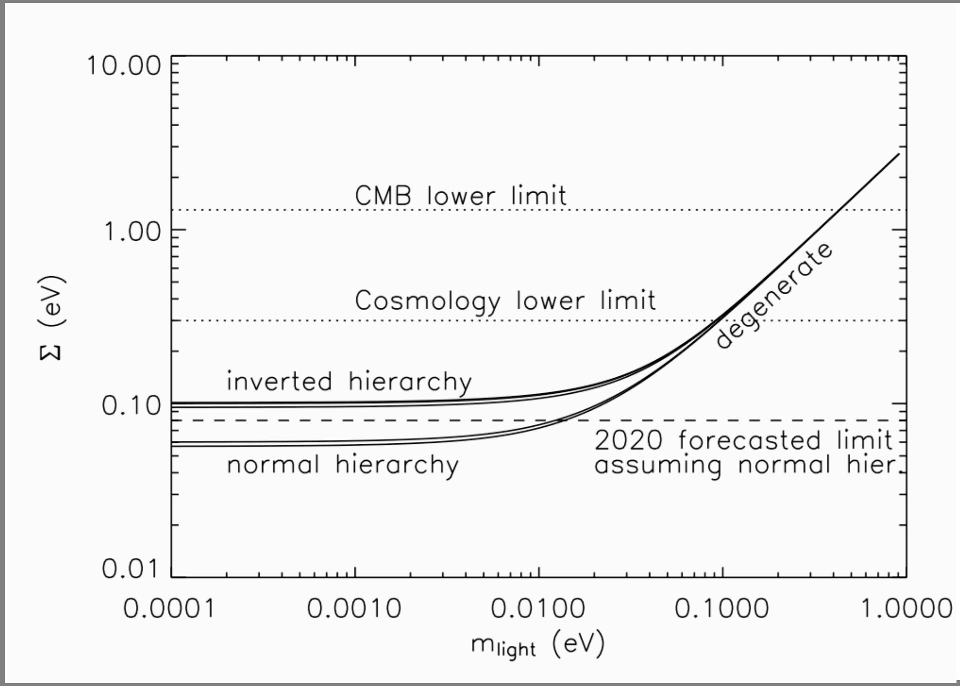
(0.032, 0.033, 0.06) eV NH
(0.02, 0.054, 0.055) eV IH

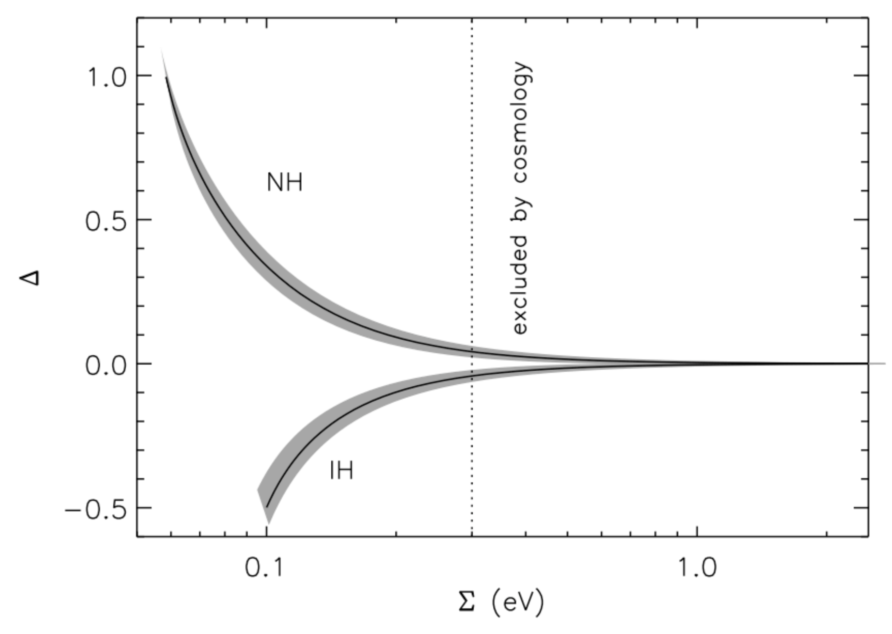
Neglect solar splitting is a good approx.

Parameterization: Σ, Δ, sgn(Δ)

$$\mathrm{NH}: \quad \Sigma = 2m + M \quad \Delta = (M - m)/\Sigma$$

$$\mathrm{IH}: \quad \Sigma = m + 2M \quad \Delta = (m - M)/\Sigma$$





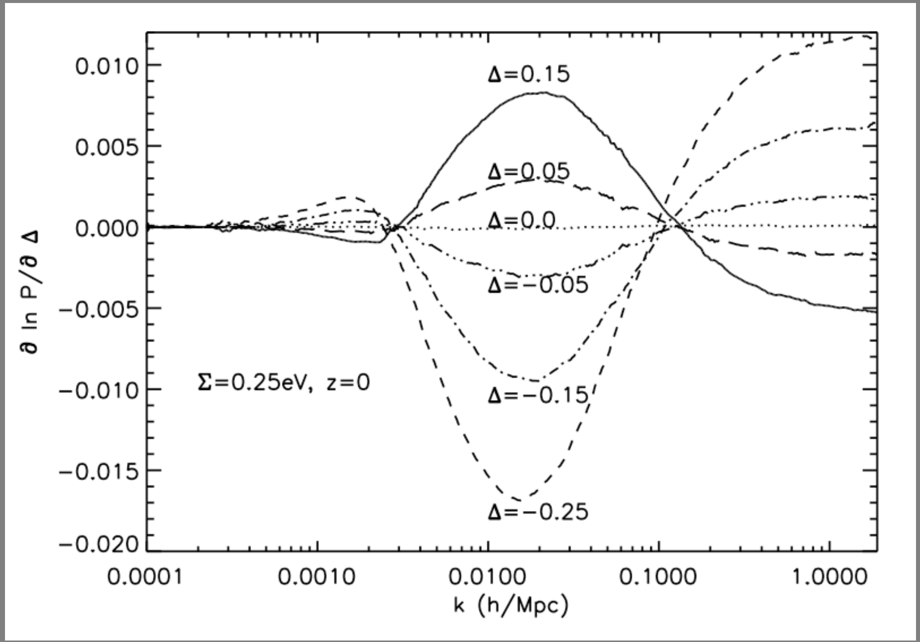
Jimenez-Kitching-Pena-Garay-Verde JCAP (2010)

P(k) dependence on Δ

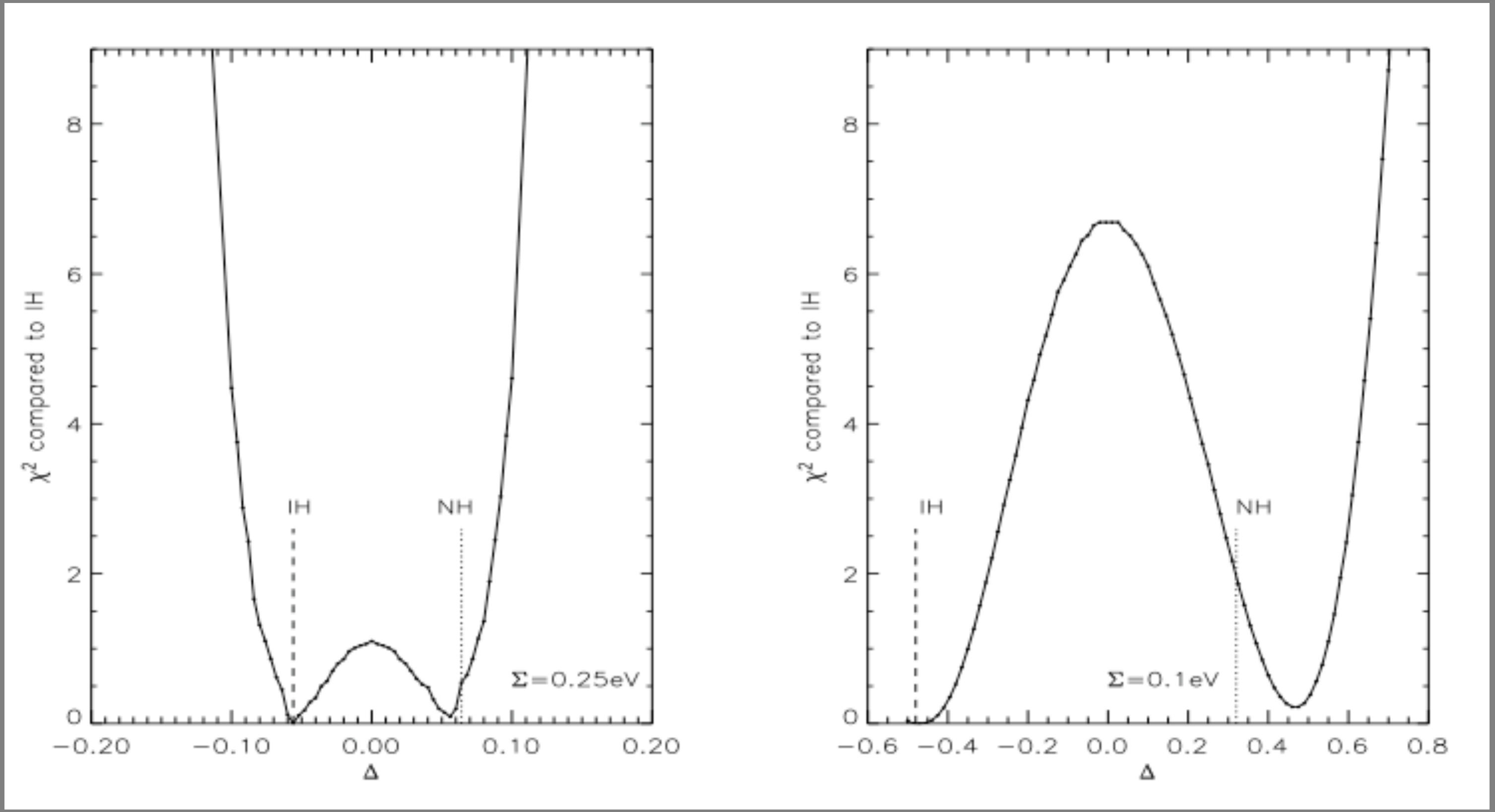
$$k_{\mathrm{fs},i} = 0.113 \left(\frac{m_{\nu_i}}{1\mathrm{eV}}\right)^{1/2} \left(\frac{\Omega_m h^2}{0.14}\frac{5}{1+z}\right)^{1/2} \mathrm{Mpc}^{-1}$$

$$\begin{array}{ll} D_\nu(k,z) = D(k,z) & k < k_{\mathrm{fs},m} \\ D_\nu(k,z) = (1-f_{\nu,m})D(z)^{(1-p_m)} & k_{\mathrm{fs},m} < k < k_{\mathrm{fs},\Sigma} \\ D_\nu(k,z) = (1-f_{\nu,\Sigma})D(z)^{(1-p_\Sigma)} & k > k_{\mathrm{fs},\Sigma}\,, \end{array}$$

Numerical with CAMB (and care)



Hierarchy effect on the shape of the power spectrum



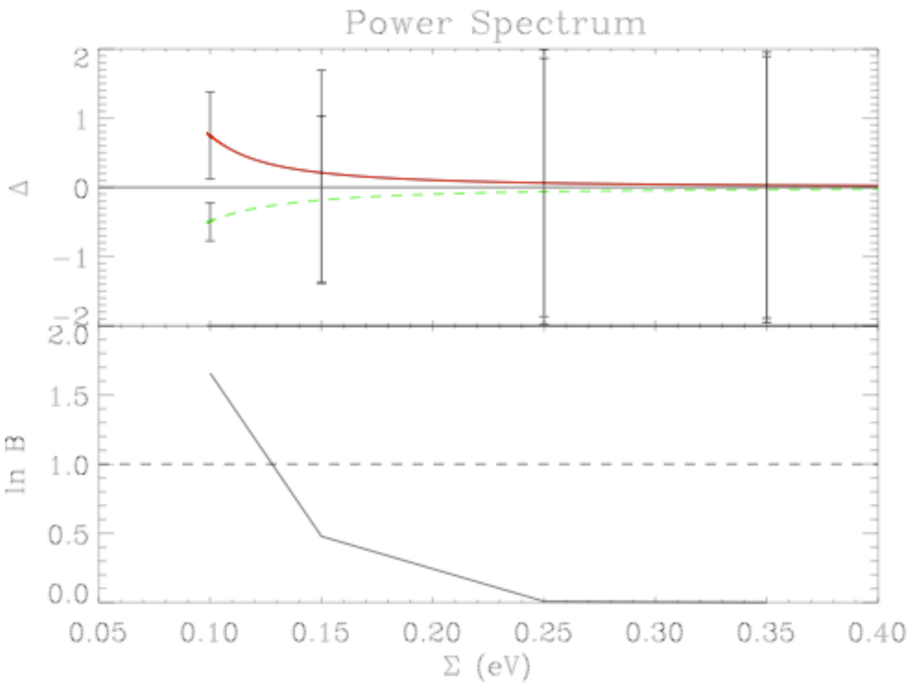
Jimenez, Kitching, Penya-Garay, Verde, arXiv:1003:5918 (JCAP 2010)

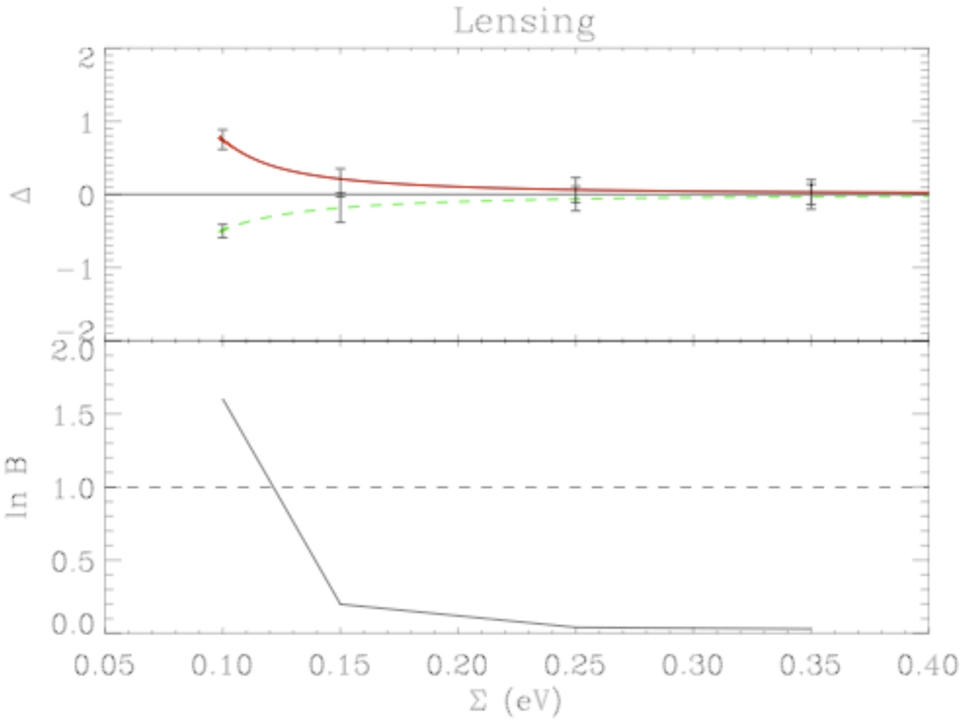
A word of warning!

Can we see ν-hierarchy in the sky?

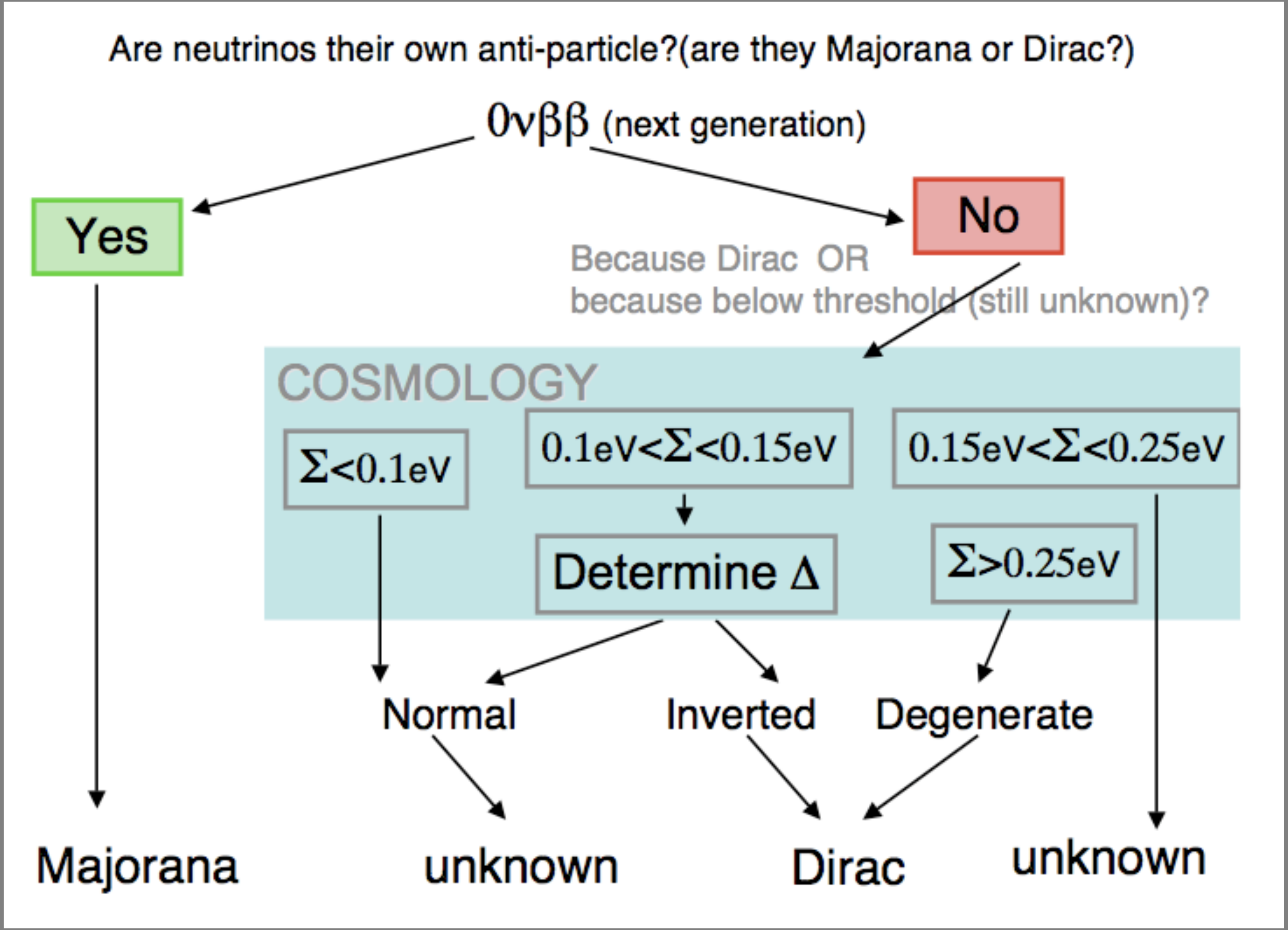
$n_s, \alpha_s, \Omega_\nu h^2, \Delta, Z, \Omega_b h^2, \Omega_c h^2, h, A_s$

Full sky, variance-dominated
Gal survey, 600 Gpc^3 (z<2) **WL survey (<z> < 3)**
21cm HI, 2000 Gpc^3 (z<5) **50 gal / sq-arcmin**





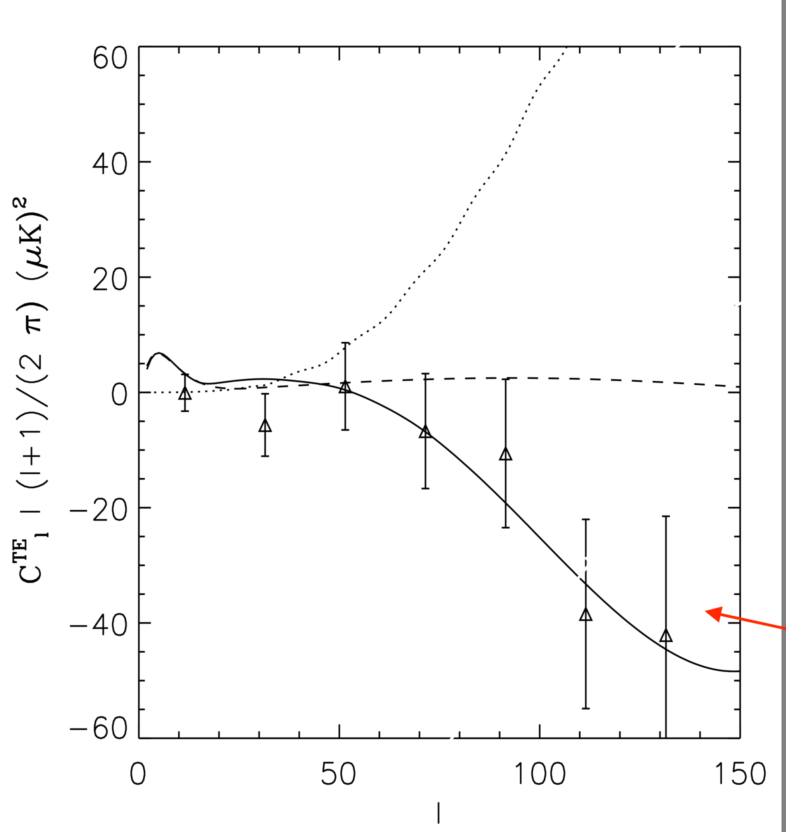
Future surveys can help!



Jimenez, Kitching, Penya-Garay, Verde, arXiv:1003:5918 (JCAP 2010)

WMAP Consistent with Simplest Inflationary Models

- Flat universe: $\Omega_{tot} = 1.02 \pm 0.02$
- Gaussianity: $-58 < f_{NL} < 134$
- Power Spectrum spectral index nearly scale-invariant:
  $n_s = 0.96 \pm 0.04$ (*WMAP* only)
- Adiabatic initial conditions
- Superhorizon fluctuations
  (TE anticorrelations)



Causal
Seed model
(Durrer et
al. 2002)

Primordial
Isocurvature
i.c.

WMAP TE
data in
bins of
Δl=10

Primordial Adiabatic i.c.

Hu & Sujiyama 1995
Zaldarriaga & Harari 1995
Spergel & Zaldarriaga 1997

Gaussian but:

Simplest inflationary models predict SMALL deviations from Gaussian initial conditions

How small is small? In some models “small” can be “detectable”

Many write:

$$\Phi = \phi + \boxed{f_{\rm NL}}\left(\phi^2 - \langle\phi^2\rangle\right)$$

Gaussian

Salopek Bond 1990; Gangui et al 1994;
Verde et al 2000 (VWHK);
Komatsu Spergel 2001

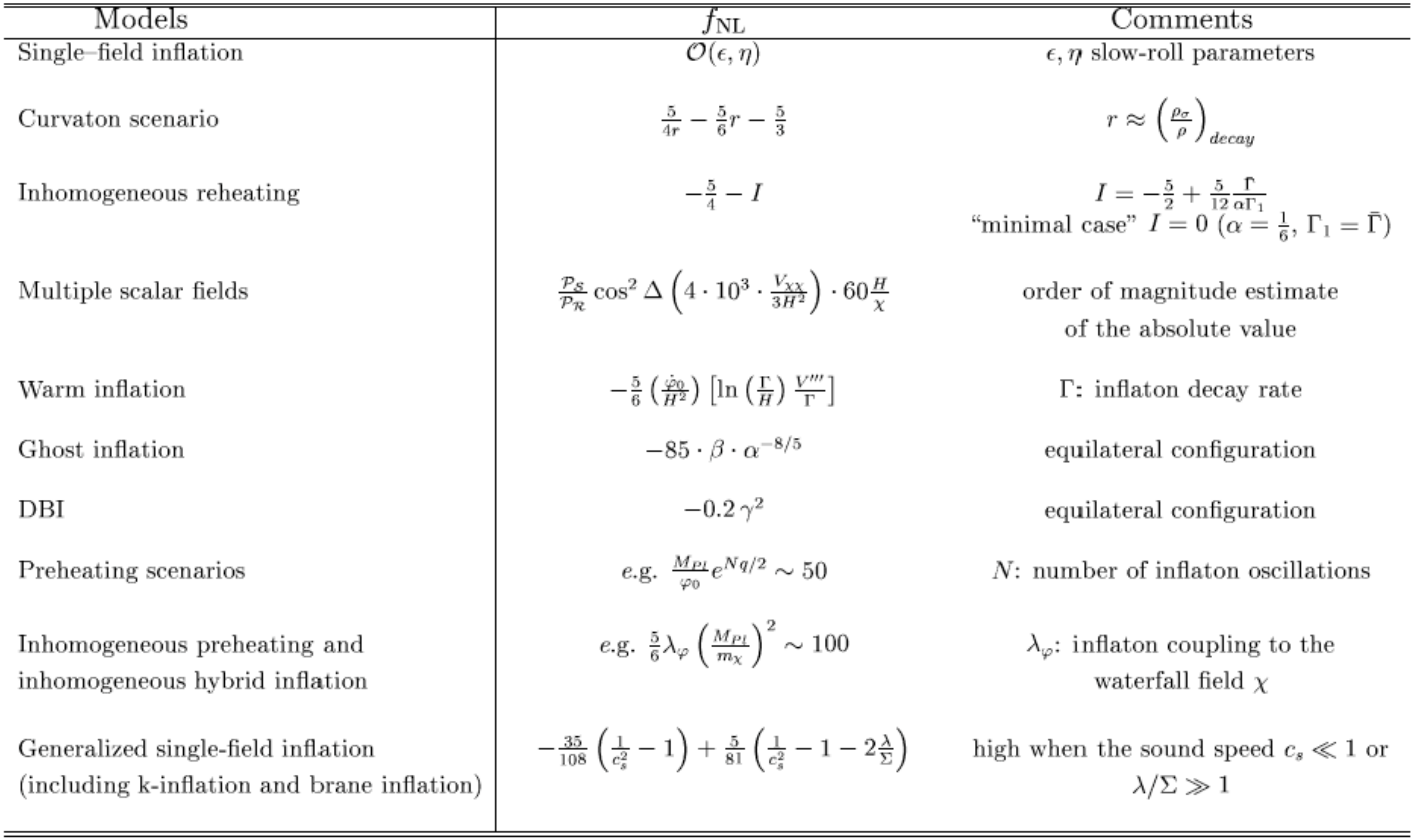
Defined on Gravitational potential
(actually Bardeen potential, important for sign)
This evolves in a LCDM universe... more later

And then say: “fNL” constant

And call it “local” form

BUT

Inflationary predictions for f_{NL}



Models	$f_{\rm NL}$	Comments
Single–field inflation	$\mathcal{O}(\epsilon, \eta)$	ϵ, η slow-roll parameters
Curvaton scenario	$\frac{5}{4r} - \frac{5}{6}r - \frac{5}{3}$	$r \approx \left(\frac{\rho_\sigma}{\rho}\right)_{decay}$
Inhomogeneous reheating	$-\frac{5}{4} - I$	$I = -\frac{5}{2} + \frac{5}{12}\frac{\bar\Gamma}{\alpha\Gamma_1}$ "minimal case" $I = 0$ $(\alpha = \frac{1}{6}, \Gamma_1 = \bar\Gamma)$
Multiple scalar fields	$\frac{\mathcal{P}_\mathcal{S}}{\mathcal{P}_\mathcal{R}} \cos^2\Delta \left(4 \cdot 10^3 \cdot \frac{V_{\chi\chi}}{3H^2}\right) \cdot 60\frac{H}{\chi}$	order of magnitude estimate of the absolute value
Warm inflation	$-\frac{5}{6}\left(\frac{\dot\varphi_0}{H^2}\right)\left[\ln\left(\frac{\Gamma}{H}\right)\frac{V'''}{\Gamma}\right]$	Γ: inflaton decay rate
Ghost inflation	$-85 \cdot \beta \cdot \alpha^{-8/5}$	equilateral configuration
DBI	$-0.2\,\gamma^2$	equilateral configuration
Preheating scenarios	$e.$g. $\frac{M_{Pl}}{\varphi_0}e^{Nq/2} \sim 50$	N: number of inflaton oscillations
Inhomogeneous preheating and inhomogeneous hybrid inflation	$e.$g. $\frac{5}{6}\lambda_\varphi\left(\frac{M_{Pl}}{m_\chi}\right)^2 \sim 100$	λ_φ: inflaton coupling to the waterfall field χ
Generalized single-field inflation (including k-inflation and brane inflation)	$-\frac{35}{108}\left(\frac{1}{c_s^2} - 1\right) + \frac{5}{81}\left(\frac{1}{c_s^2} - 1 - 2\frac{\lambda}{\Sigma}\right)$	high when the sound speed $c_s \ll 1$ or $\lambda/\Sigma \gg 1$

Measuring fNL allows us to constraint inflationary models

Remember slow-roll parameters

$$\epsilon_* = \frac{m_{\rm Pl}^2}{16\pi}\left(\frac{V'}{V}\right)^2, \quad \text{and} \quad \eta_* = \frac{m_{\rm Pl}^2}{8\pi}\left[\frac{V''}{V} - \frac{1}{2}\left(\frac{V'}{V}\right)^2\right]$$

The skewness is

$$S_{3,\Phi} = \langle \Phi_{\rm B}^3 \rangle / \langle \Phi_{\rm B}^2 \rangle^2$$

$$S_{3,\Phi} = 2\epsilon_{\rm B} \times 3[1 + \gamma(n)]$$

Verde, RJ, Kamionkowski, Matarrese MNRAS (2001)

Measuring fNL allows us to determine the shape of the inflaton potential

Relating the skewnness to the slow-roll parameters

fNL = $\epsilon_{\mathrm{B}} = (5/2)\epsilon_* - (5/3)\eta_*$

But the primordial slope is

$$n = 2\epsilon_* - 6\eta_* + 1$$

So a measurement of fNL and n gives you a measurement of the slow-roll parameters

Searching for non-Gaussianity with rare events

- Besides using standard statistical estimators, like bispectrum, trispectrum, three and four-point function, skewness , etc. …, one can look at the tails of the distribution, i.e. at rare events.

- Rare events have the advantage that they often maximize deviations from what predicted by a Gaussian distribution, but have the obvious disadvantage of being … rare!

- Matarrese LV & Jimenez (2000) and Verde, Jimenez, Kamionkowski & Matarrese showed that clusters at high redshift ($z>1$) can probe NG down to $f_{NL} \sim 10^2$ which is, however, not competitive with future CMB (Planck) constraints.
- For other type of non-gaussianity rare events may be competitive.

Improved formula obtained by LoVerde et al. 2007

DM halo mass-function in NG models

M. Grossi, K. Dolag, E. Branchini, S. Matarrese & L. Moscardini 2007

Deviations from the Gaussian mass-function in excellent agreement with the theoretical predictions by Matarrese, Verde & Jimenez (2000):

$$F_{NG}(M, z, f_{\rm NL}) \simeq \frac{1}{6}\frac{\delta_c^2(z_c)}{\delta_*(z_c)}\frac{dS_{3,M}}{d\ln\sigma_M} + \frac{\delta_*(z_c)}{\delta_c(z_c)}$$

where F_{NG} represents the NG/G mass-function ratio

$$n(M, z, f_{\rm NL}) = n_G(M, z)\, F_{NG}(M, z, f_{\rm NL})$$

and

$$\delta_*(z_c) = \delta_c(z_c)\sqrt{1 - S_{3,M}\,\delta_c(z_c)/3},$$

with $S_{3,M}$ the skewness of the mass-density field on scale M

$$S_{3,M} \equiv \frac{\langle\delta_M^3\rangle}{\sigma_M^4} \propto -f_{\rm NL}$$

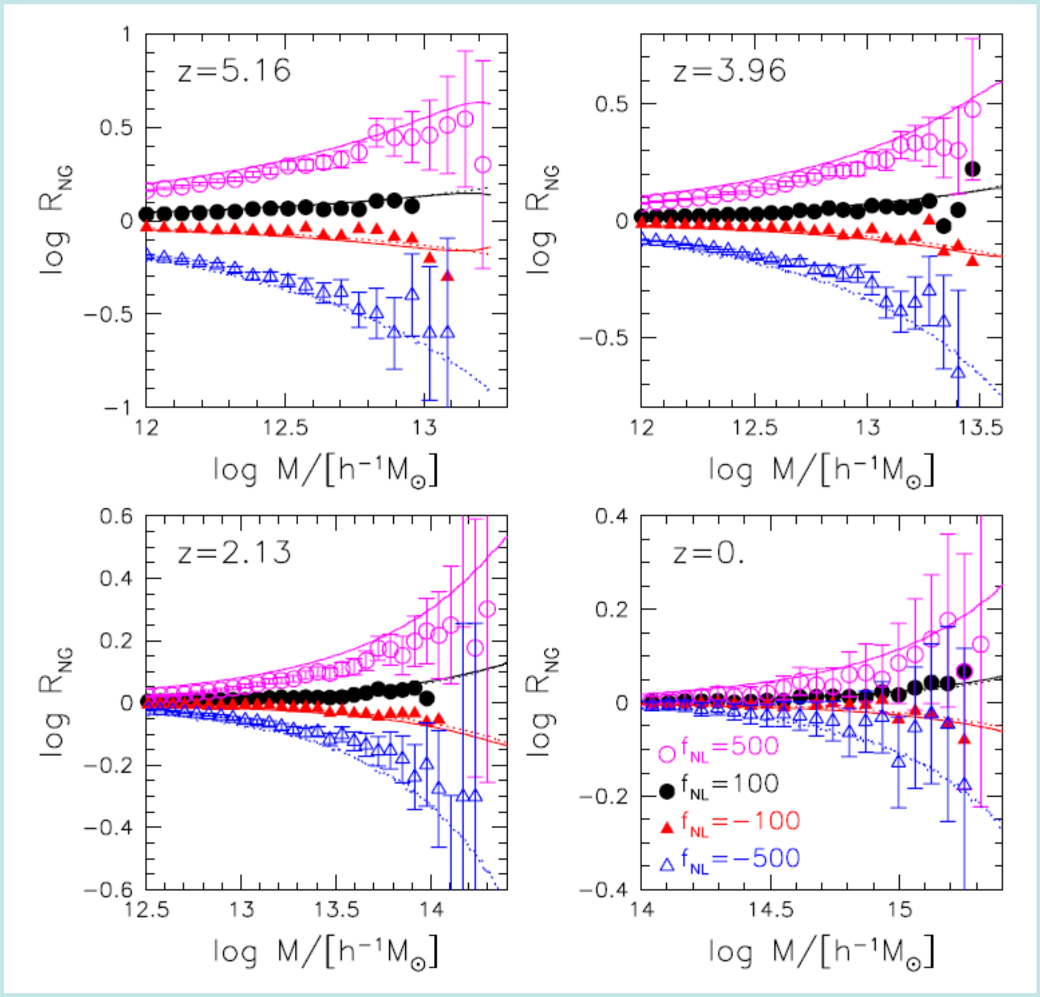


Figure 3. Logarithm of the ratio of the halo cumulative mass functions R_{NG} as a function of the mass is shown in the different panels at the same redshifts as in Fig. 1. Circles and triangles refer to positive and negative values for $f_{\rm NL}$; open and filled symbols refer to $f_{\rm NL} = \pm 500$ and $f_{\rm NL} = \pm 100$, respectively. Theoretical predictions obtained starting from eqs. (3) and (4) are shown by dotted and solid lines, respectively. Poisson errors are shown for clarity only for the cases $f_{\rm NL} = \pm 500$.

Tantalizing hints
(this year only)

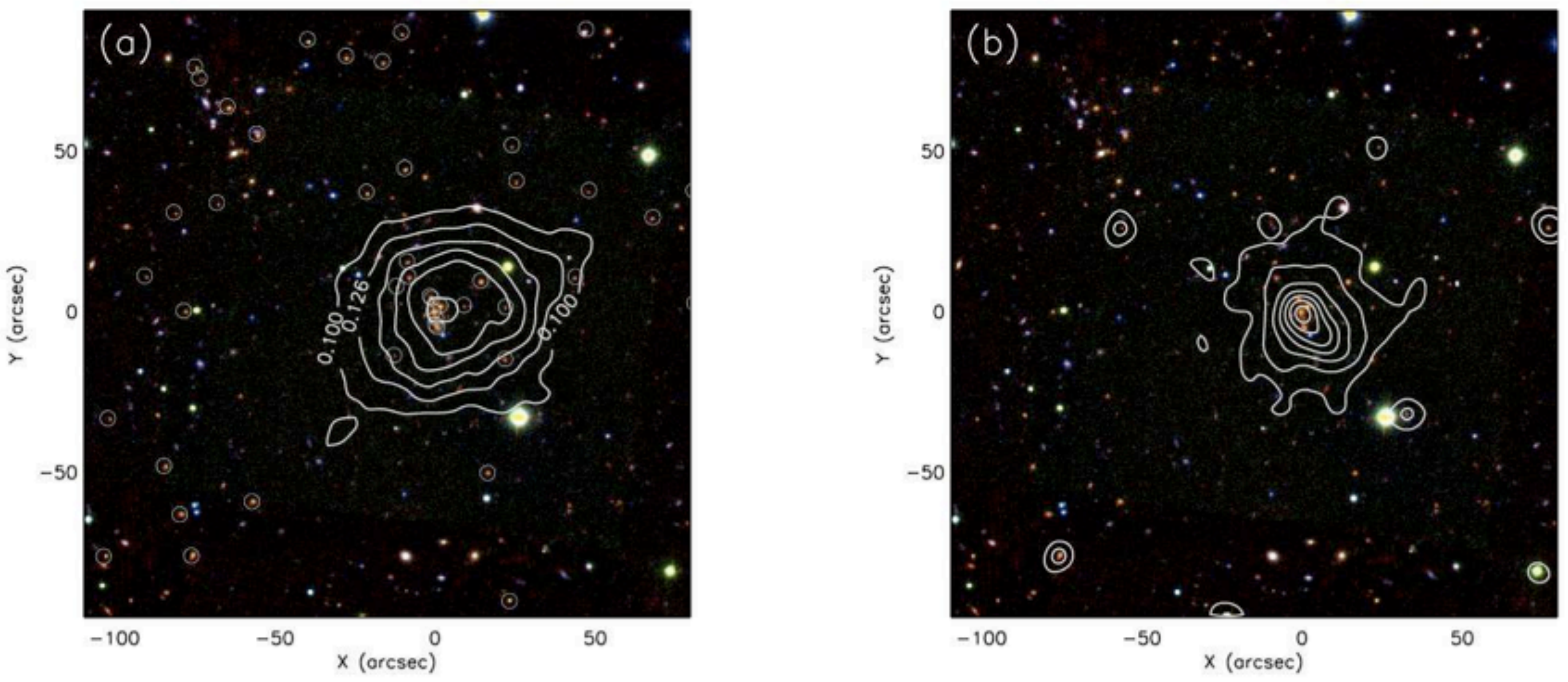
XMMUJ2235.3-2557

$(8.5 \pm 1.7) \times 10^{14} M_\odot$

z=1.4

Lensing + optical

X-ray + optical



Declared survey area: 11 sq deg

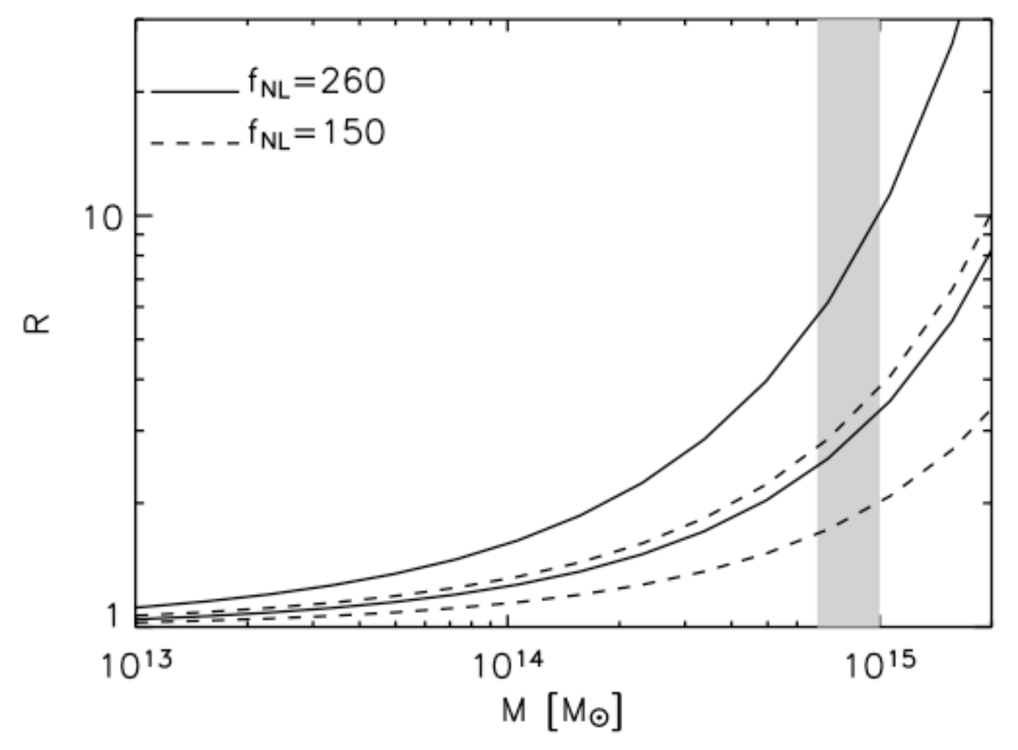
Jee, et al., 2009, ApJ, 704, 672, arXiv:0908.3897

XMMUJ2235.3-2557

$(8.5 \pm 1.7) \times 10^{14} M_\odot$ z=1.4

M> central estimate
expect ZERO in the 4π

M> lower estimate
expect 7 in the 4π



NON-GAUSSIAN ENHANCEMENT

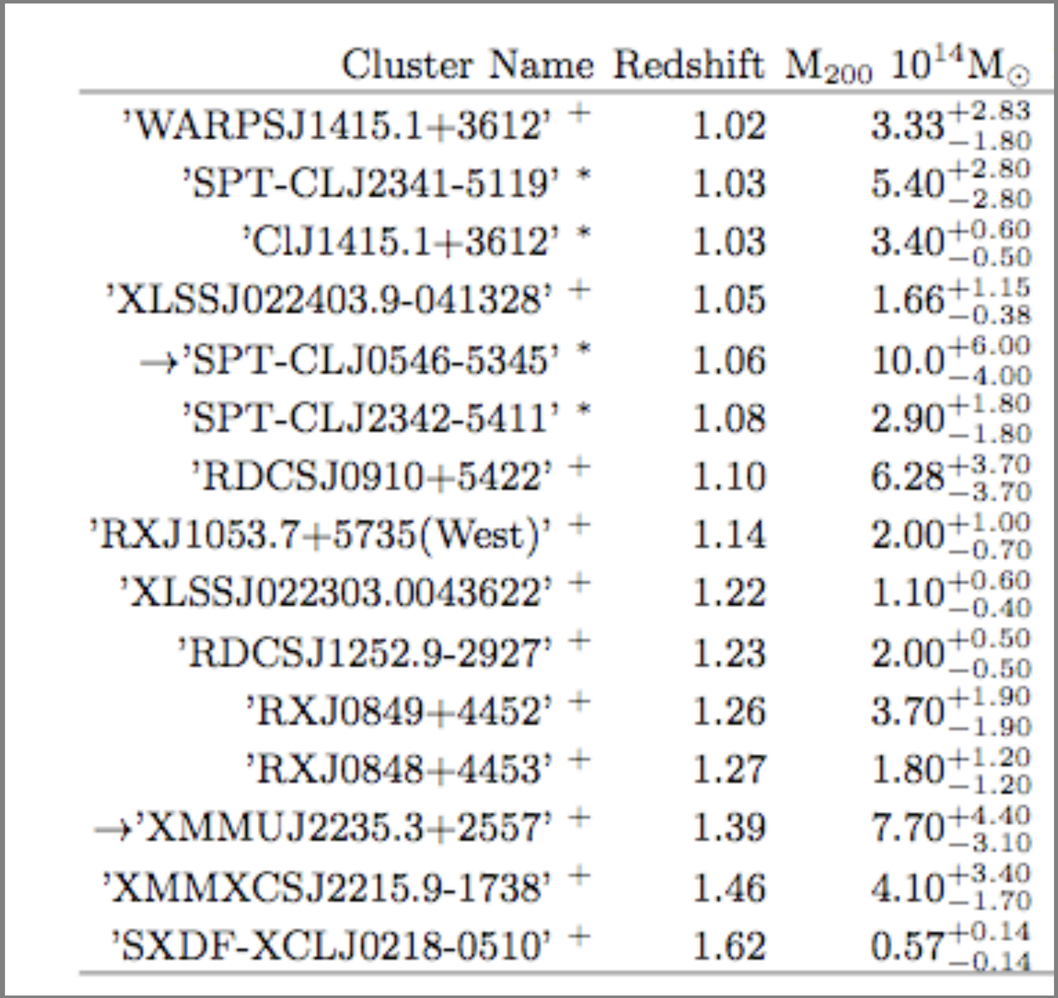
Jimenez, Verde, 2010 arXiv:0909.0
Sartoris et al. arXiv:1003.0841
Holz, Perlmutter, arXiv:1004.5349
Cayon et al arXiv:1006.1950

Weak lensing area 11 sq deg → P=0.005
XMM serendipitous survey area
in 2006: 165 sq deg → P=0.07
Now : 400 sq deg → P=0.17

Too big, too early?

XMMUJ2235.3-2557 is not alone

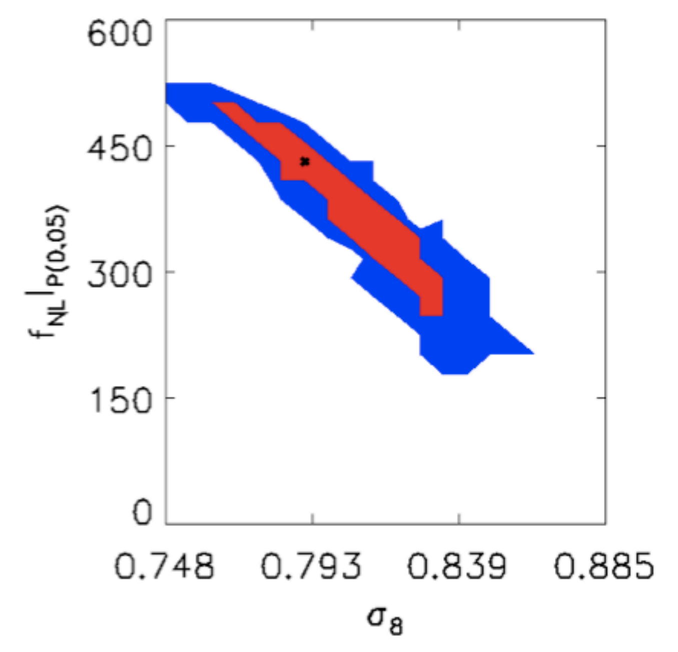
B. Hoyle, R. Jimenez, LV, arXiv: 1009:3884



Cluster Name	Redshift	M_{200} $10^{14} M_\odot$
'WARPSJ1415.1+3612' +	1.02	$3.33^{+2.83}_{-1.80}$
'SPT-CLJ2341-5119' *	1.03	$5.40^{+2.80}_{-2.80}$
'ClJ1415.1+3612' *	1.03	$3.40^{+0.60}_{-0.50}$
'XLSSJ022403.9-041328' +	1.05	$1.66^{+1.15}_{-0.38}$
→'SPT-CLJ0546-5345' *	1.06	$10.0^{+6.00}_{-4.00}$
'SPT-CLJ2342-5411' *	1.08	$2.90^{+1.80}_{-1.80}$
'RDCSJ0910+5422' +	1.10	$6.28^{+3.70}_{-3.70}$
'RXJ1053.7+5735(West)' +	1.14	$2.00^{+1.00}_{-0.70}$
'XLSSJ022303.0043622' +	1.22	$1.10^{+0.60}_{-0.40}$
'RDCSJ1252.9-2927' +	1.23	$2.00^{+0.50}_{-0.50}$
'RXJ0849+4452' +	1.26	$3.70^{+1.90}_{-1.90}$
'RXJ0848+4453' +	1.27	$1.80^{+1.20}_{-1.20}$
→'XMMUJ2235.3+2557' +	1.39	$7.70^{+4.40}_{-3.10}$
'XMMXCSJ2215.9-1738' +	1.46	$4.10^{+3.40}_{-1.70}$
'SXDF-XCLJ0218-0510' +	1.62	$0.57^{+0.14}_{-0.14}$

These 15 objects
should NOT be there

What would one have to do to make f_{NL} go away?



Say that $\sigma_8 \simeq 0.90.$

And accept lower p-values

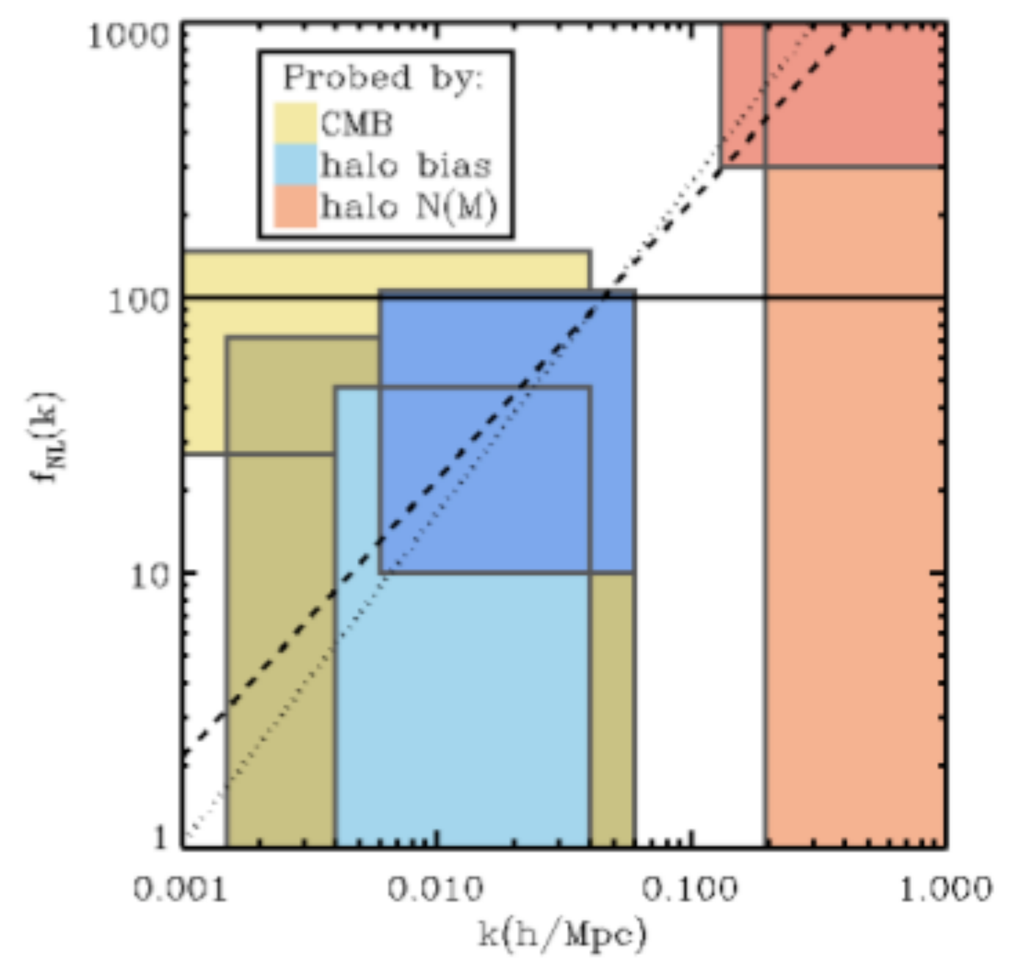
Such σ_8 is 4 σ higher than other cosmological probes measures

All cluster masses should have been systematically overestimated by 1.5 σ

RELIABLE GRAVITATIONAL LENSES MASSES ARE NEEDED!

Scale dependent F_{NL} ?

Hoyle, Jimenez, Verde 1009.3884



The basics

Action describing the dynamics of the universe is:

$$S = \int dt d^3x \sqrt{-g} \left\{ -\frac{m_p^2}{16\pi} R + \frac{g^{\mu\nu}}{2} \partial_\mu q \partial_\nu q - V(q) + S_{matter} \right\}$$

Consider quintessence a perfect fluid:

$$\rho_Q = \frac{1}{2}\dot{q}^2 + V(q)$$

$$p_Q = \frac{1}{2}\dot{q}^2 - V(q)$$

Which has conservation law:

$$\dot{\rho}_q + 3H(\rho_q + p_q) = 0$$

All left now is use Einstein eq:

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi}{3m_p^2}(\rho_m + \rho_q)$$

All left now is use Einstein eq:

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi}{3m_p^2}\left(\rho_m + \rho_q\right)$$

And Klein-Gordon equation:

$$\ddot{q} + 3H\dot{q} + V' = 0$$

What I want to know is shape of potential V

$$\varepsilon_1 = -\frac{\dot{H}}{H^2};\ \varepsilon_2 = \frac{\dot{\varepsilon}_1}{H\varepsilon_1}$$

$$V(z) = (3-\varepsilon_1)\frac{H^2}{m_p} - \frac{1}{2}\sum_i (1-w_i)\rho_i - \frac{1}{2}(\rho_f - p_f)$$

But what I really need is V(q)

$$K(q) = \varepsilon_1 \frac{H^2}{m_p} - \frac{1}{2}(\rho_T + p_T)$$

We can “measure” dark energy because of its effects on the expansion history of the universe: a(t)

$$\frac{\dot{a}(t)}{a(t)} = H(z) = -\frac{1}{(1+z)}\frac{dz}{dt}$$

$$H^2 = H^2{}_0[\rho(z)/\rho(0)]$$

$$\dot{\rho}_Q = -3H(z)(1+w(z))\rho_Q$$

$$d_L = (1+z)\int_z^0 (1+z')\frac{dt}{dz'}dz'$$

SN: measure dL
CMB: θ_A and ISW → a(t)
LSS or LENSING: g(z) or r(z) → a(t)

AGES: H(z) → a(t)

$$H_0^{-1}\frac{dz}{dt} = -(1+z)^{5/2}\{\Omega_m(0)+\Omega_Q(0)\exp[3\int_0^z \frac{dz'}{(1+z')}w_Q]\}^{1/2}$$

2b:Reconstruct w(z): use dz/dt

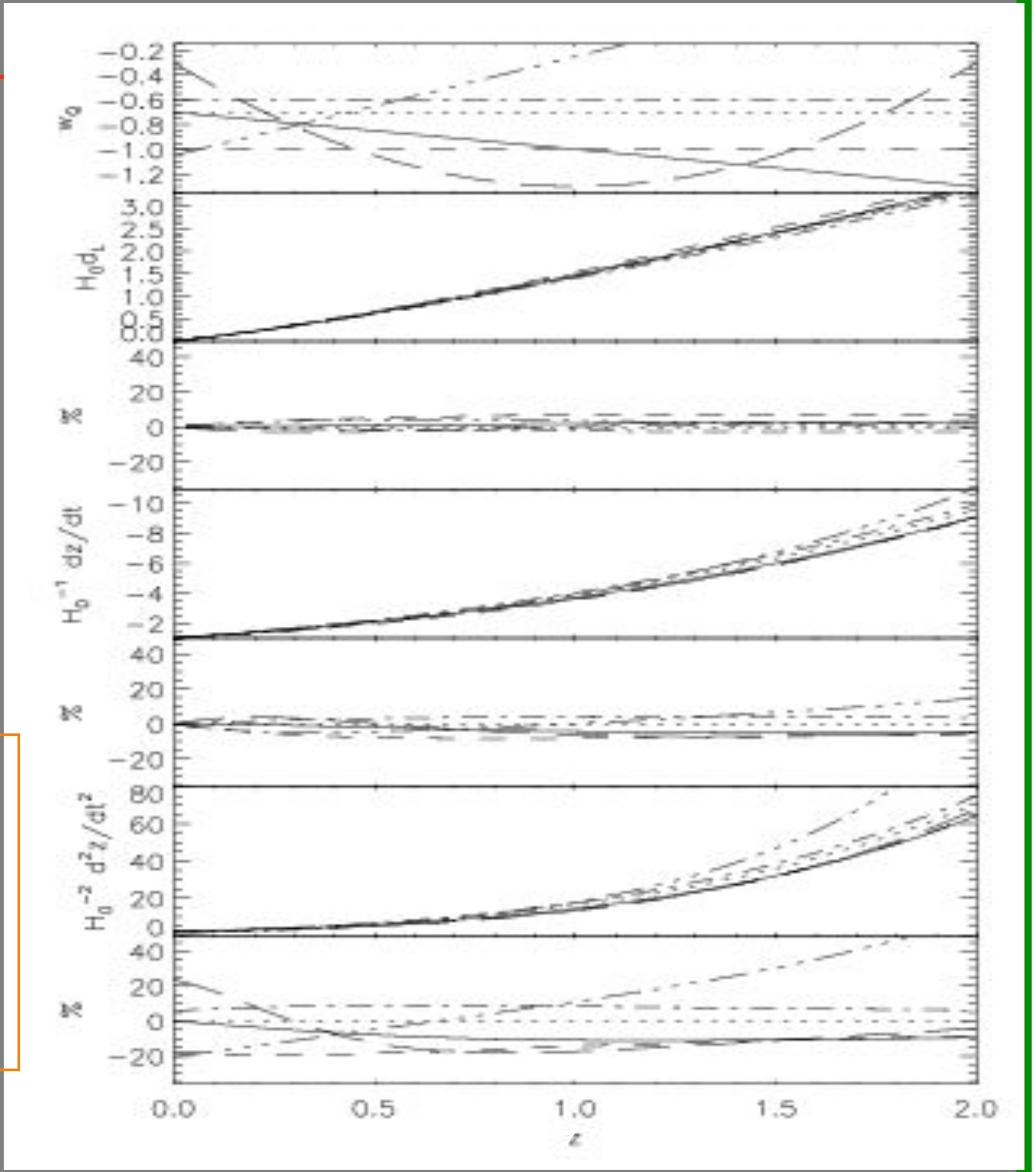
Non-parametric!

Note:
$$d_L = (1+z)\int_z^0 (1+z')\boxed{\frac{dt}{dz'}}dz'$$

$$H(z) = -\frac{1}{(1+z)}\boxed{\frac{dz}{dt}}$$

w(z) in here

$$\boxed{\begin{aligned}\frac{d^2z}{dt^2} &= \left(\frac{dz}{dt}\right)^2 (1+z)^{-1}\left(\frac{5}{2}+\frac{3}{2}w(z)\right)\\ &-\frac{3}{2}\Omega_m(1+z)^4 w(z)\end{aligned}}$$



(from Jimenez & Loeb 2002)

Experimental concerns

How well can gE's be approximated as passively evolving, old systems?

- mergers; early-type galaxies still assembling at $z<1$?
- on-going star formation ("frosting")

How can we best model the stellar ages?

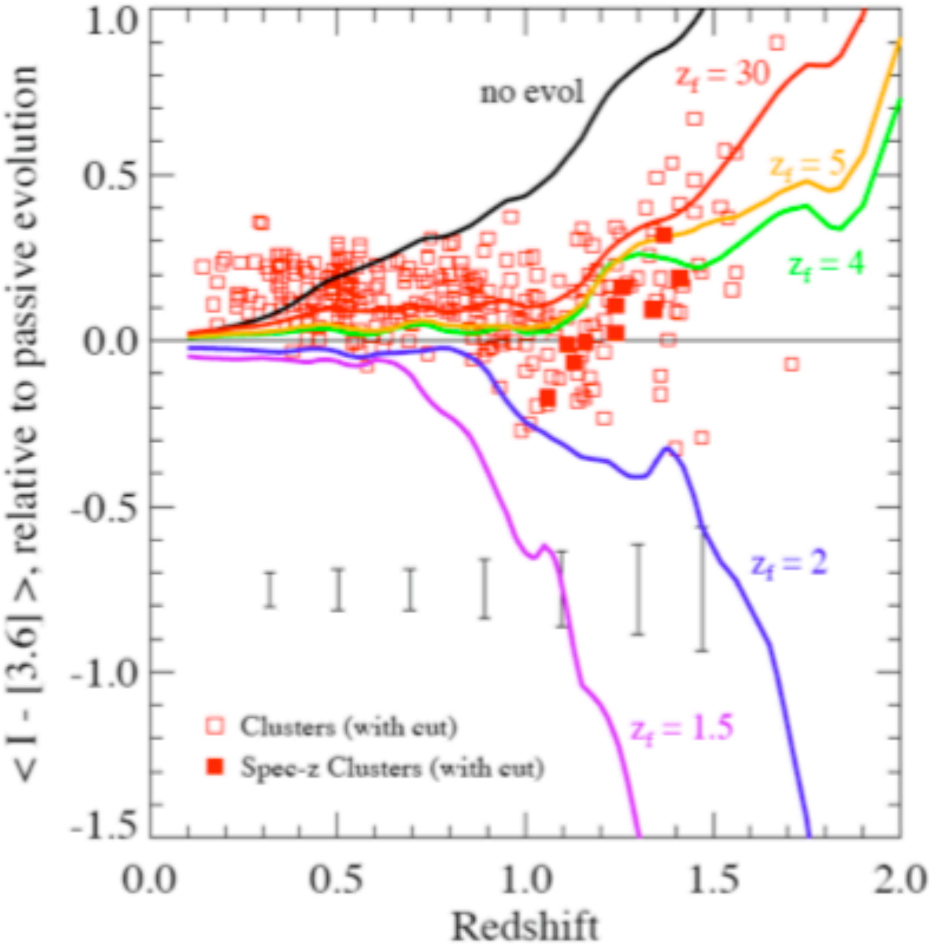
- systematics between stellar synthesis models

How can we best measure the stellar ages?

- ability to measure accurate stellar ages
- efficiency at obtaining spectra

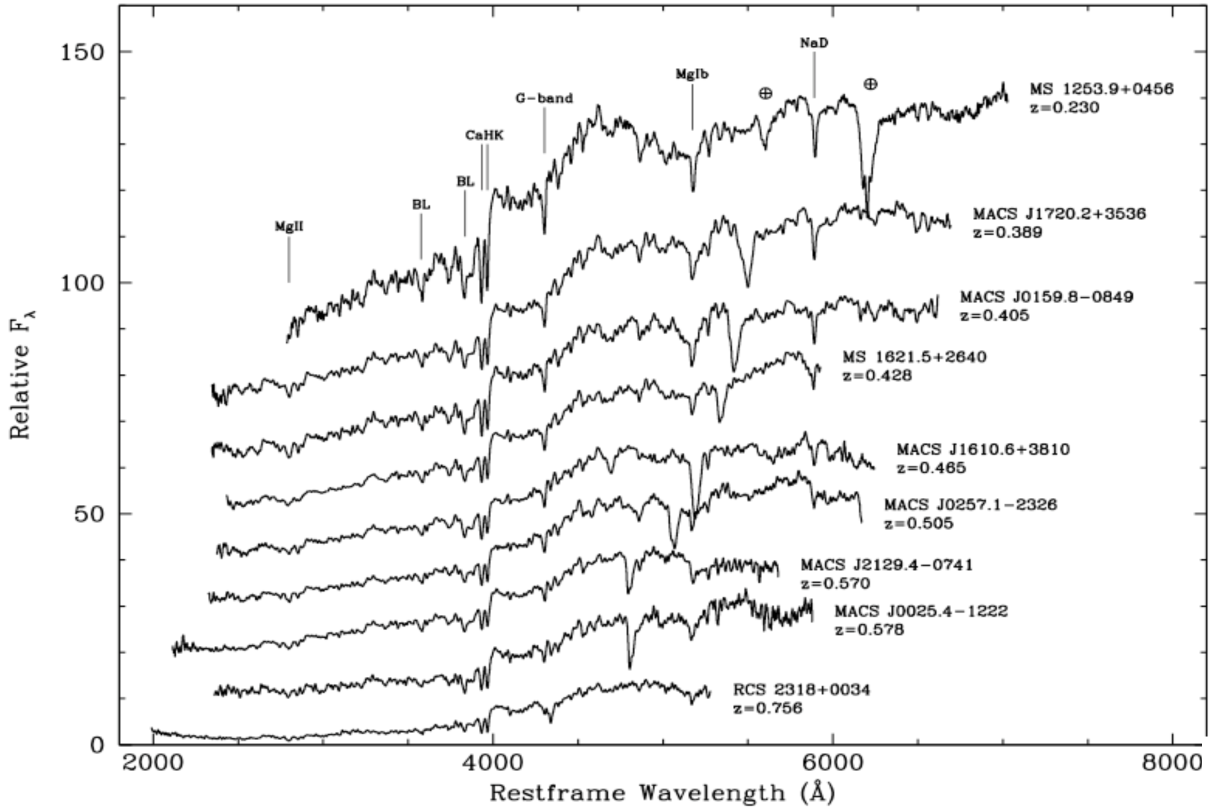
gE’s as passively evolving, old systems

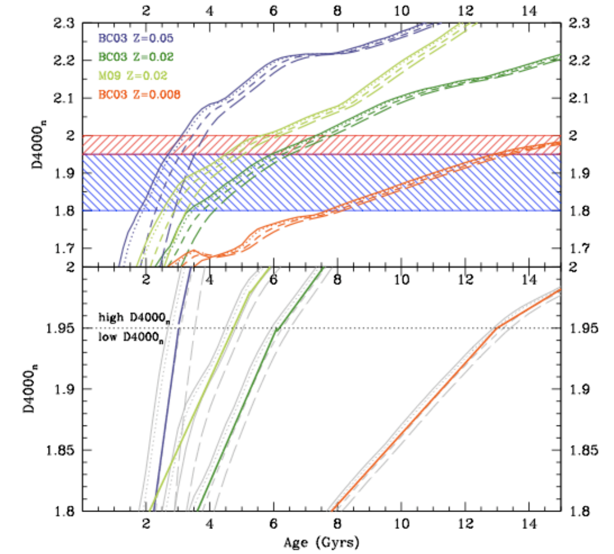
colors indicate a high formation redshift (for cluster gE’s)



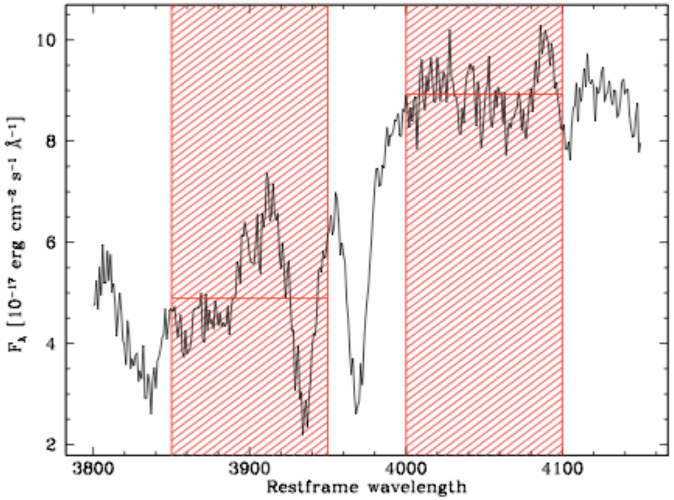
Eisenhardt et al. (ApJ, submitted)

Relative aging of galaxies



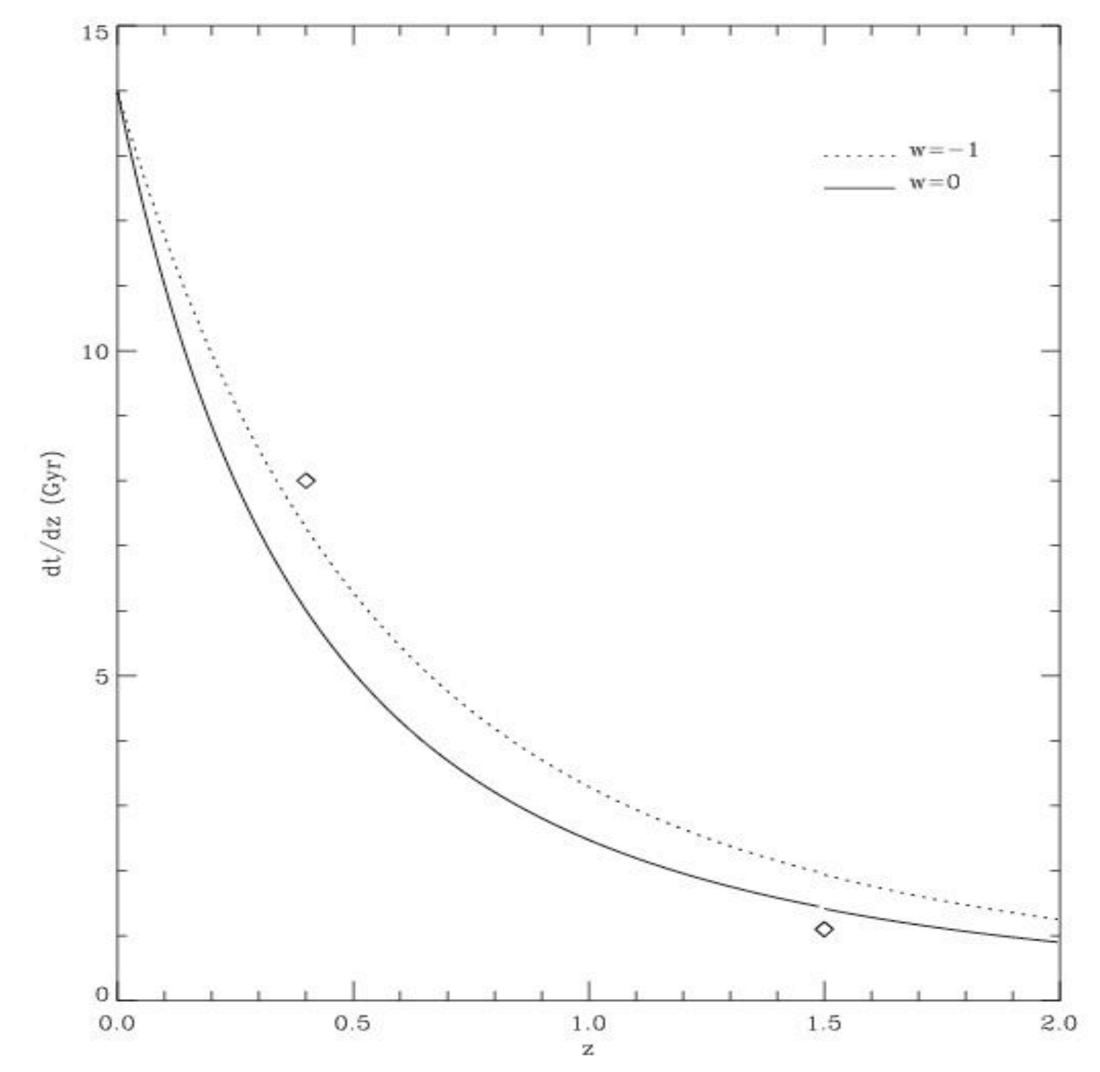


$$H(z) = -\frac{A}{1+z}\frac{dz}{dD4000_n}$$



Moresco, RJ, Cimatti, Pozzetti JCAP (2010)

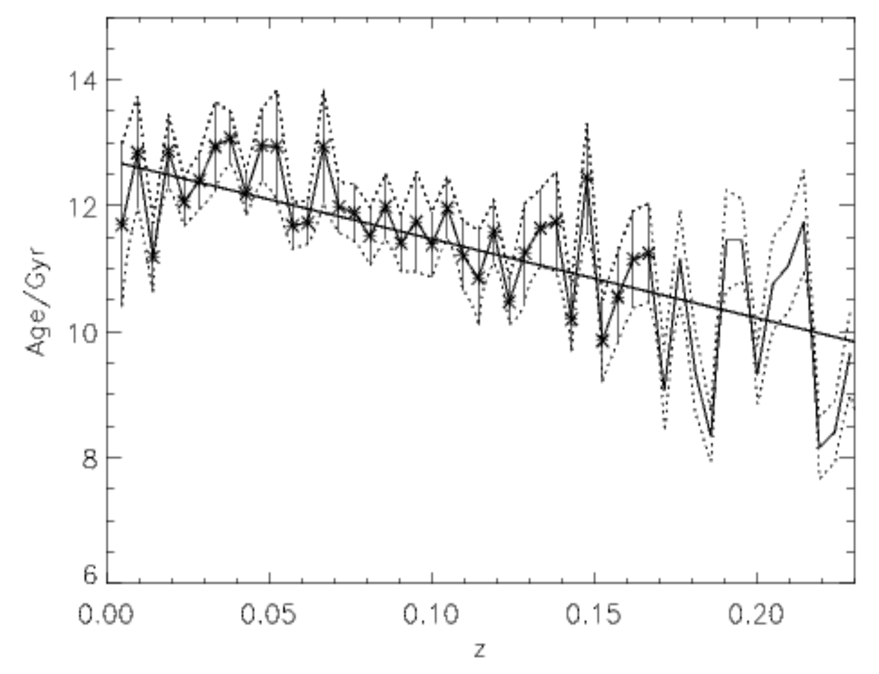
Variations in the observed evolution of w



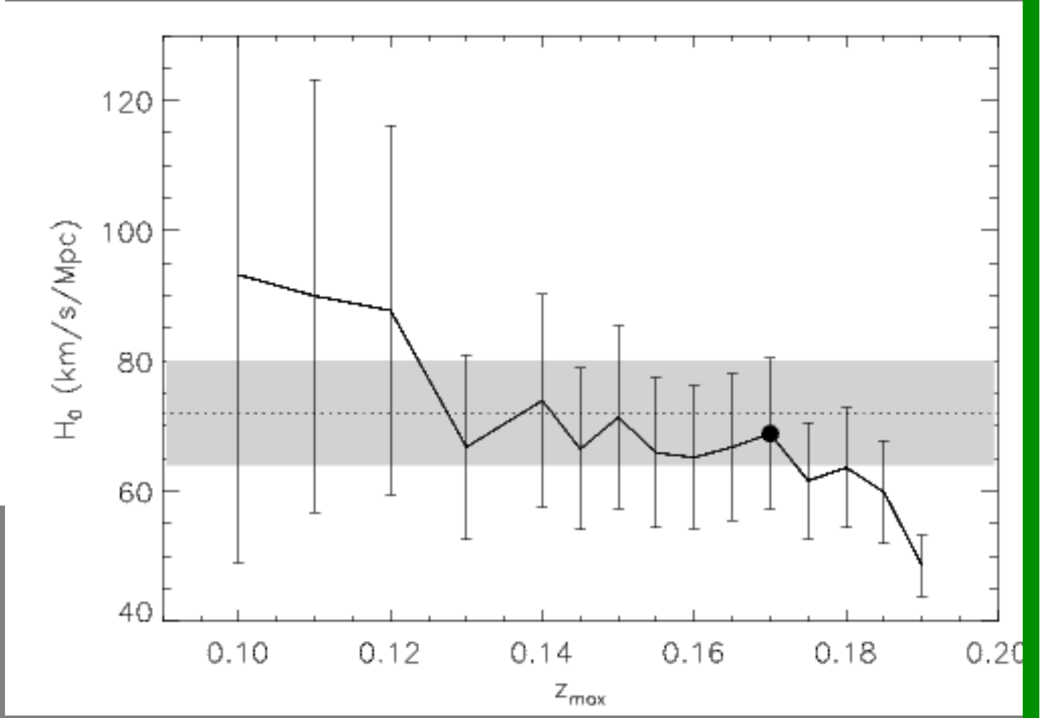
2b:Reconstruct w(z): CAN IT work?

At z=0 dz/dt gives Ho and we have SDSS galaxies:

$$H(z) = -\frac{1}{(1+z)}\frac{dz}{dt}$$

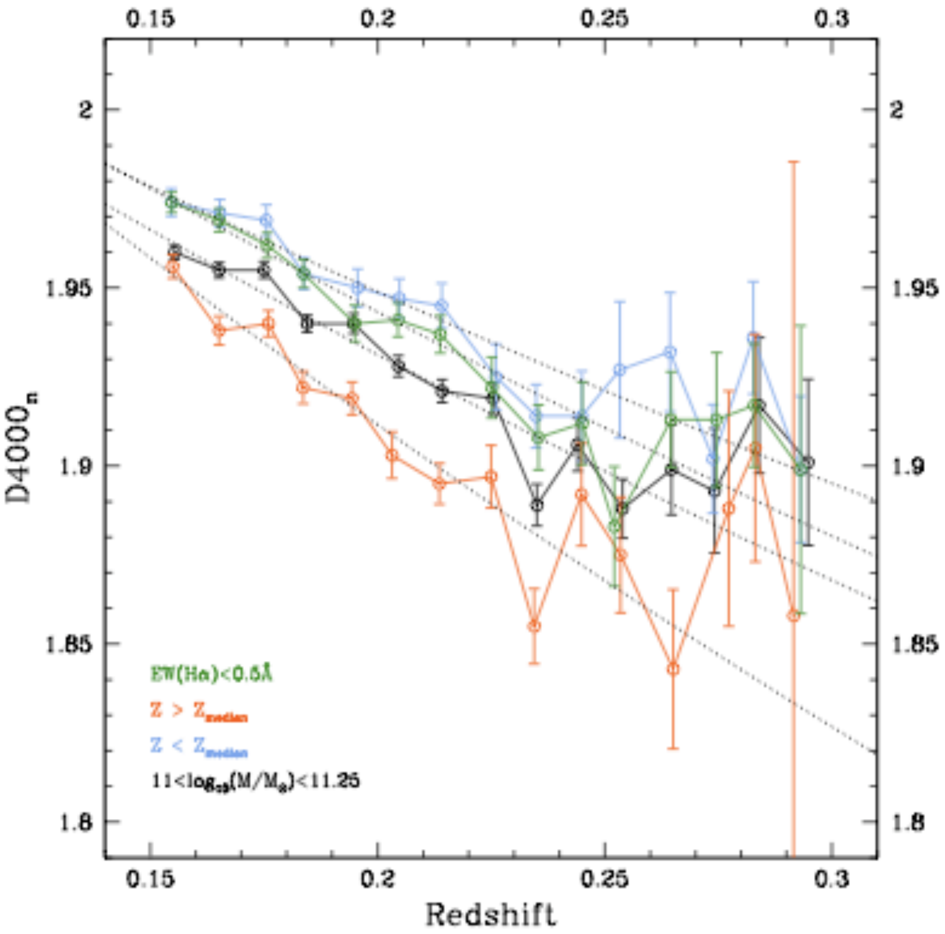


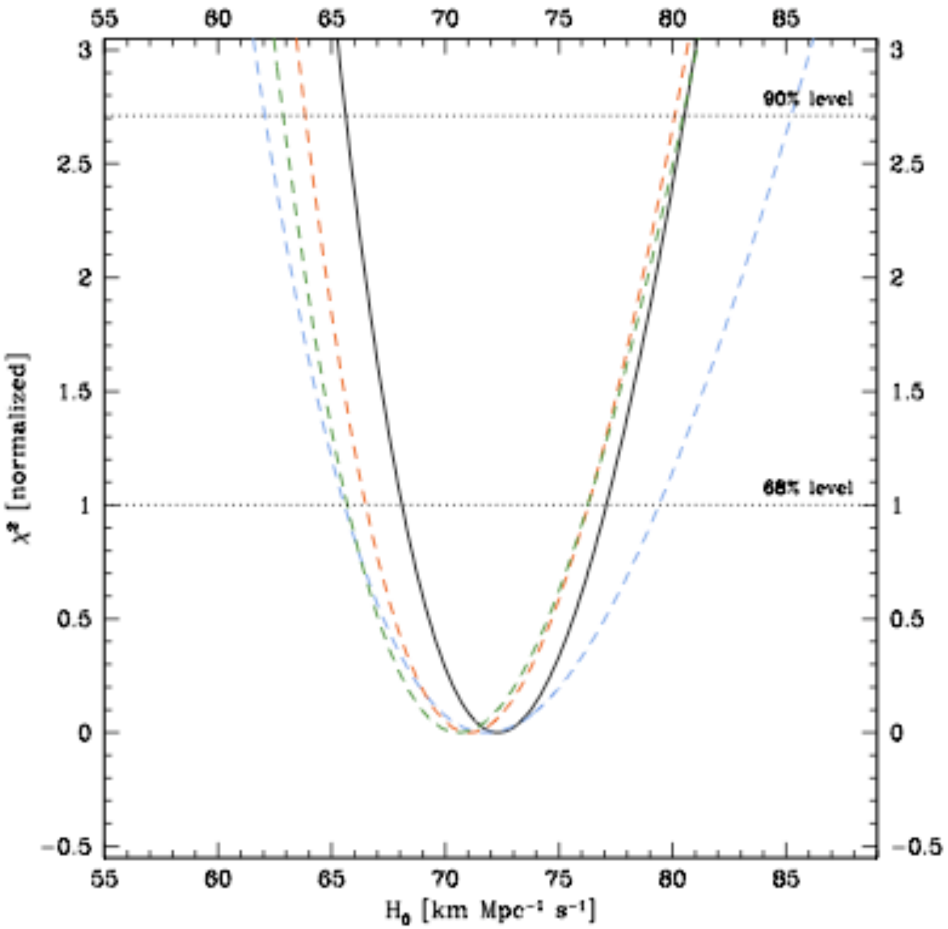
The edge for z<0.2



The value of H0

A good test, to determine H(z=0)

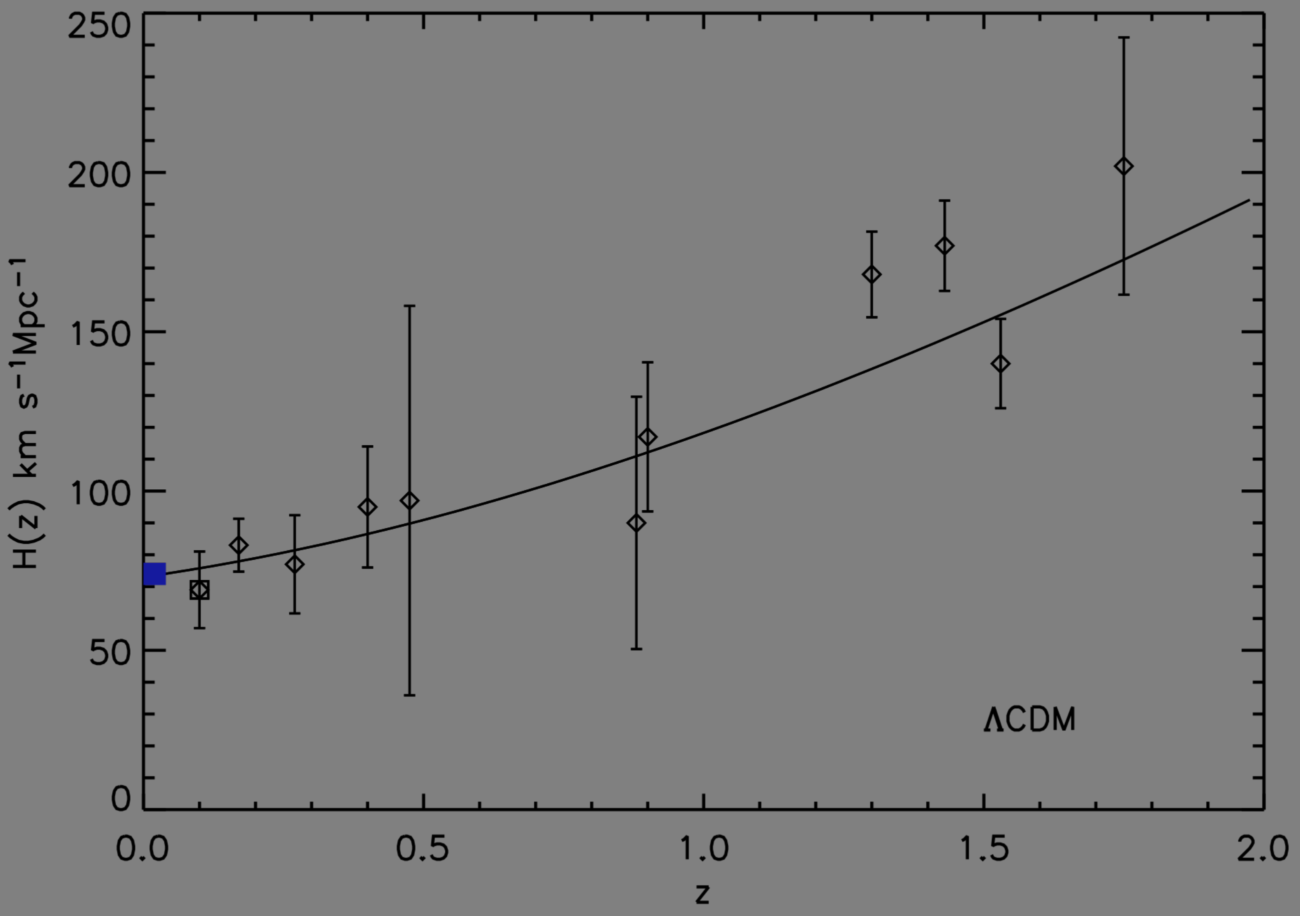




Moresco, RJ, Cimatti, Pozzetti JCAP (2010)

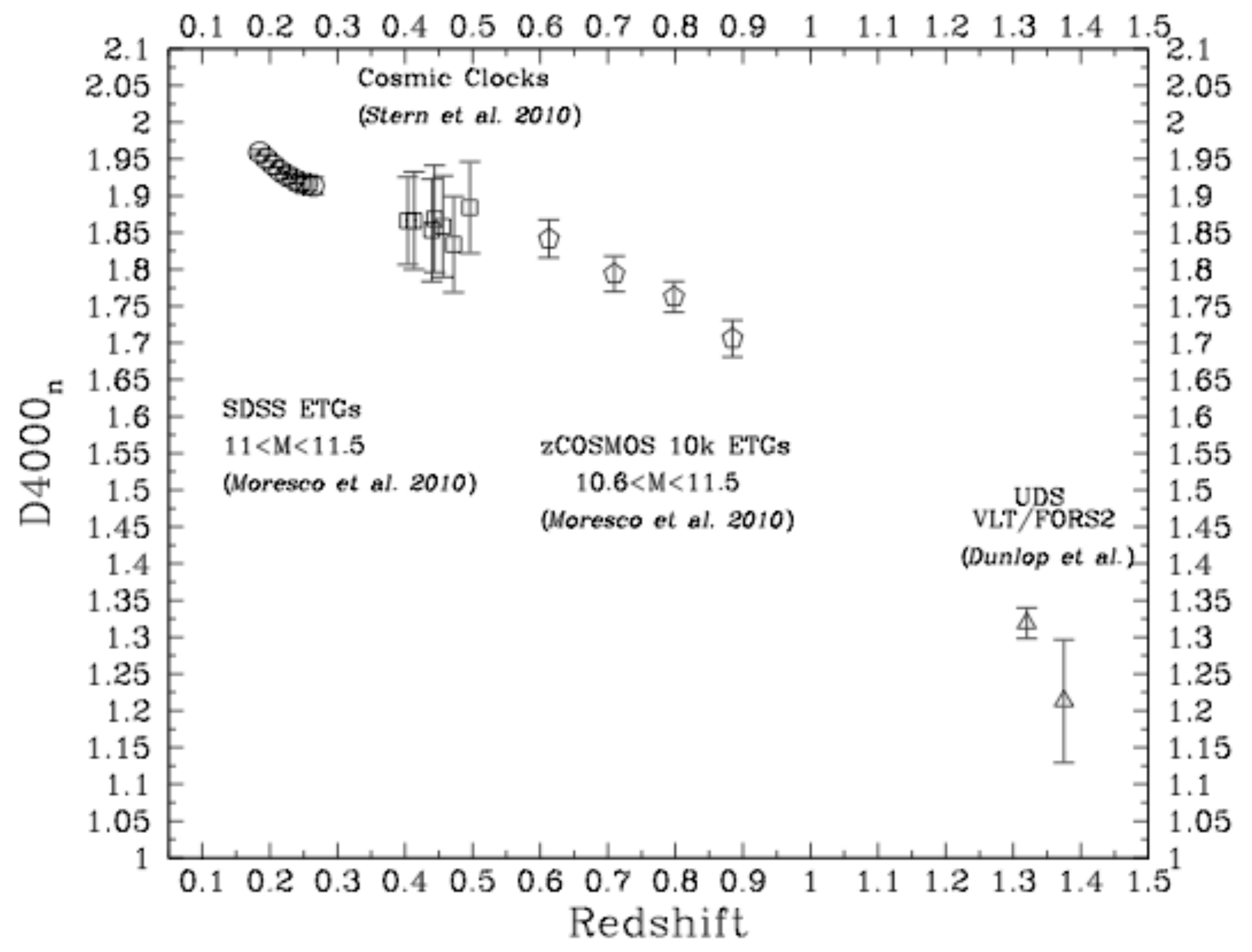
H(0) = 72.3 ± 2.8

CURRENT STATUS



From Stern, RJ, Verde, Kamionkowski, Stamford JCAP (2010)

D4000 up to z ~ 1.5



Constraints on sub-eV physics beyond the SM from cosmological distance measurements

Based on:

Arxiv:1004.2053 (JCAP)

Arxiv:0902.2006 (JCAP)

with A. Avgoustidis, C. Burrage, J. Redondo & L. Verde

The QCD Axion

QCD allows for a CP-violating term:

$$\mathcal{L}_{\not{C}\not{P}} = \frac{\alpha_s}{4\pi}\,\theta\,\mathrm{tr}G_{\mu\nu}\tilde{G}^{\mu\nu}$$

Parameter θ constrained experimentally:

$$\boxed{|\bar{\theta}| \lesssim 10^{-10}}$$

unnaturally small

Peccei-Quinn: Promote θ to a dynamical field, the axion a, with shift symmetry $a \to a + \mathrm{const}:$

$$\mathcal{L}_a = \frac{1}{2}\partial_\mu a \partial^\mu a + \frac{\alpha_s}{4\pi f_a} a\,\mathrm{tr}G_{\mu\nu}\tilde{G}^{\mu\nu} + \frac{\alpha}{8\pi f_a} a\,F_{\mu\nu}\tilde{F}^{\mu\nu} + \mathcal{L}_{\mathrm{int}}[\partial_\mu a/f_a, \psi]$$

coupling to EM

Non-trivial potential around $\langle a \rangle = 0$, axion is a PNG boson with parametrically small mass:

$$m_a \simeq 0.6\,\mathrm{meV} \times \left(\frac{10^{10}\mathrm{GeV}}{f_a}\right)$$

Axions in String Theory

Axion-Like Particles (ALPs) arise in String Theory as 0-modes of antisymmetric tensor fields

- *Type II*: bosonic action for a D*p*-brane has two contributions:

$$S_p = -T_p\left(\int d^{p+1}\underbrace{\xi\, e^{-\phi}\sqrt{\det(g+B+2\pi\alpha' F)}}_{\textit{DBI piece: includes } F_{\mu\nu}F^{\mu\nu}} + i\int \sum_q \underbrace{\overset{\text{RR q-form}}{C_q}\wedge e^{B+2\pi\alpha' F}}_{\textit{WZ piece: includes } aF_{\mu\nu}\tilde{F}^{\mu\nu}}\right)$$

Axion decay const set by the string scale: $f_a \sim \frac{M_s}{g_s} \sim 10^{4-17}\,\mathrm{GeV}$

Light particles suggested to solve puzzling experimental results, but are also a generic feature of fundamental theory

Distance Measures in Cosmology

- *Luminosity distance*:

$$d_L(z) = (1+z)\frac{c}{H_0}\int_0^z dz' \left[\Omega_m(1+z)^3 + \Omega_V(1+z)^{3(1+w)}\right]^{-1/2}$$

Inferred from *standard candles*, notably Ia SNae

- *Ang. diameter distance* related through Etherington relation:

(from *standard rulers*)

$$d_L(z) \overset{?}{=} (1+z)^2 d_A(z)$$

If photon number conservation is violated, there will be a mismatch in the above due to a non-trivial τ "opacity" :

$$d_{L,obs}(z) = d_{L,true}(z)\, e^{\tau(z)}$$

This can happen if photons are converted to ALPs along line of sight

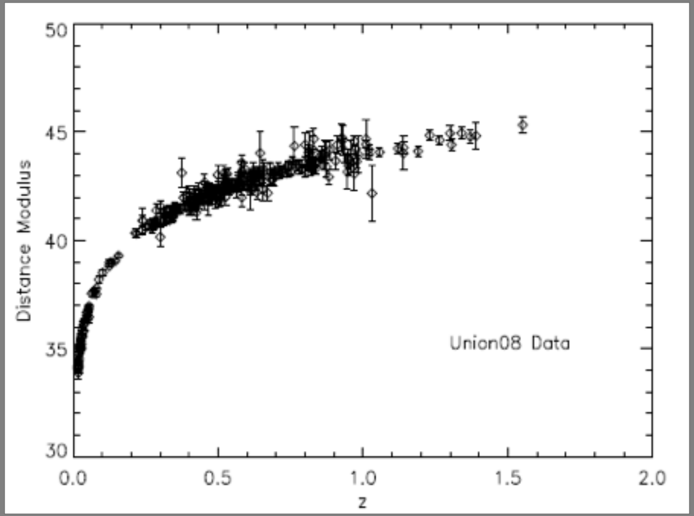
Constraining opacity & ALPs

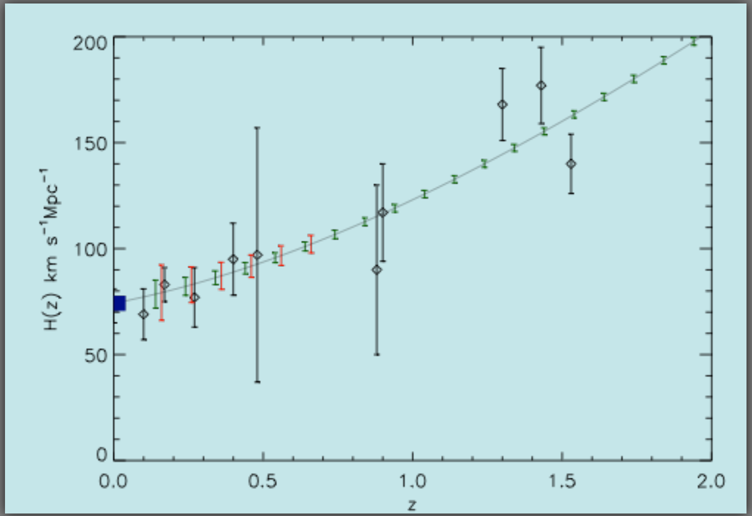
$$d_{L,obs}(z) = (1+z)^2 e^{\tau} d_A(z)$$

constrain

Measure from SN observations

Predict from H(z) data





Any ALP coupling to photons via $\frac{1}{4M} F_{\mu\nu} F^{\mu\nu} \phi$ or $\frac{1}{8M} \epsilon_{\mu\nu\kappa\lambda} F^{\mu\nu} F^{\kappa\lambda} \phi$ will produce non-trivial opacity.

Can constrain jointly ALP coupling and cosmological parameters by using SN and H(z) (or BAO) data.

Method

Run likelihood analysis for flat ΛCDM models in (τ, Ω_m, H_0)

Constrain opacity parameter(s) by marginalising over cosmologies:

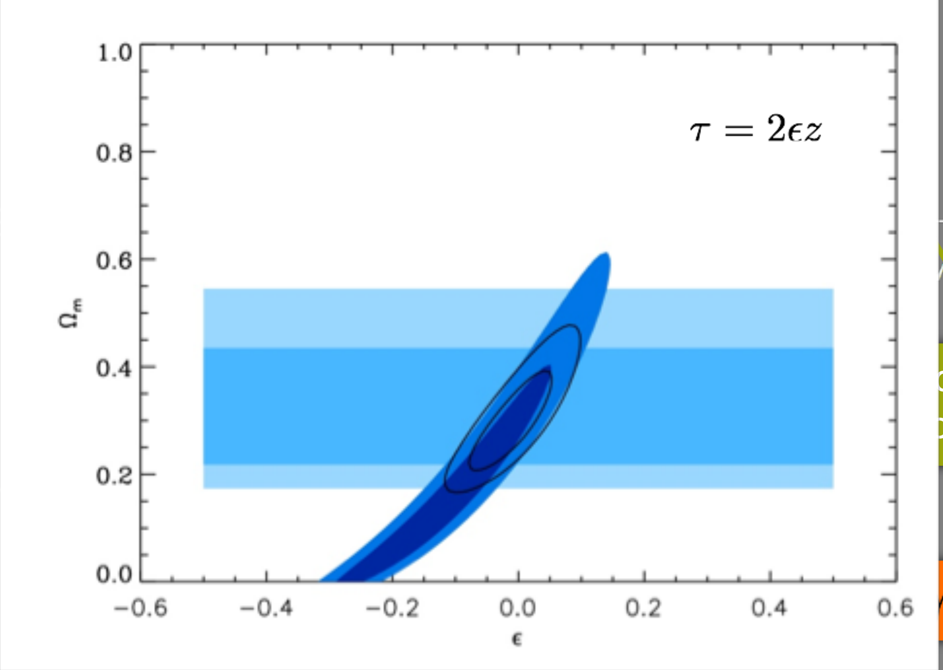
$$P(\tau|S,E) = \int_{\Omega_m}\int_{H_0} P(\tau,\Omega_m,H_0|S)\,P(\Omega_m,H_0|E)\,\mathrm{d}\Omega_m\mathrm{d}H_0$$

$$d_{L,obs}(z) = (1+z)^2 e^{\tau} d_A(z)$$

- For ALPs: $e^{-\tau} =$ … $\frac{H(z)-H_0}{\Omega_m H_0}\Big)$

oton-axion conversion
obability

- For MCPs: $e^{-\tau}$ … $\to \psi\bar{\psi}$

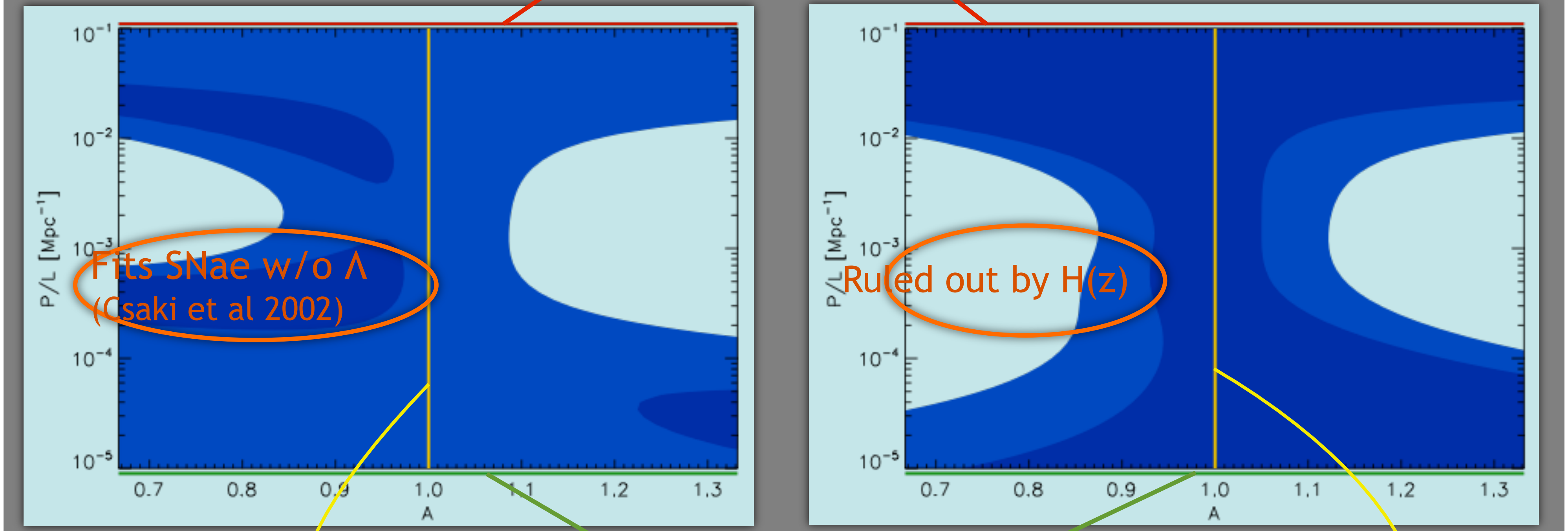


Axion-Like Particles (incl. Chameleons)

SN only

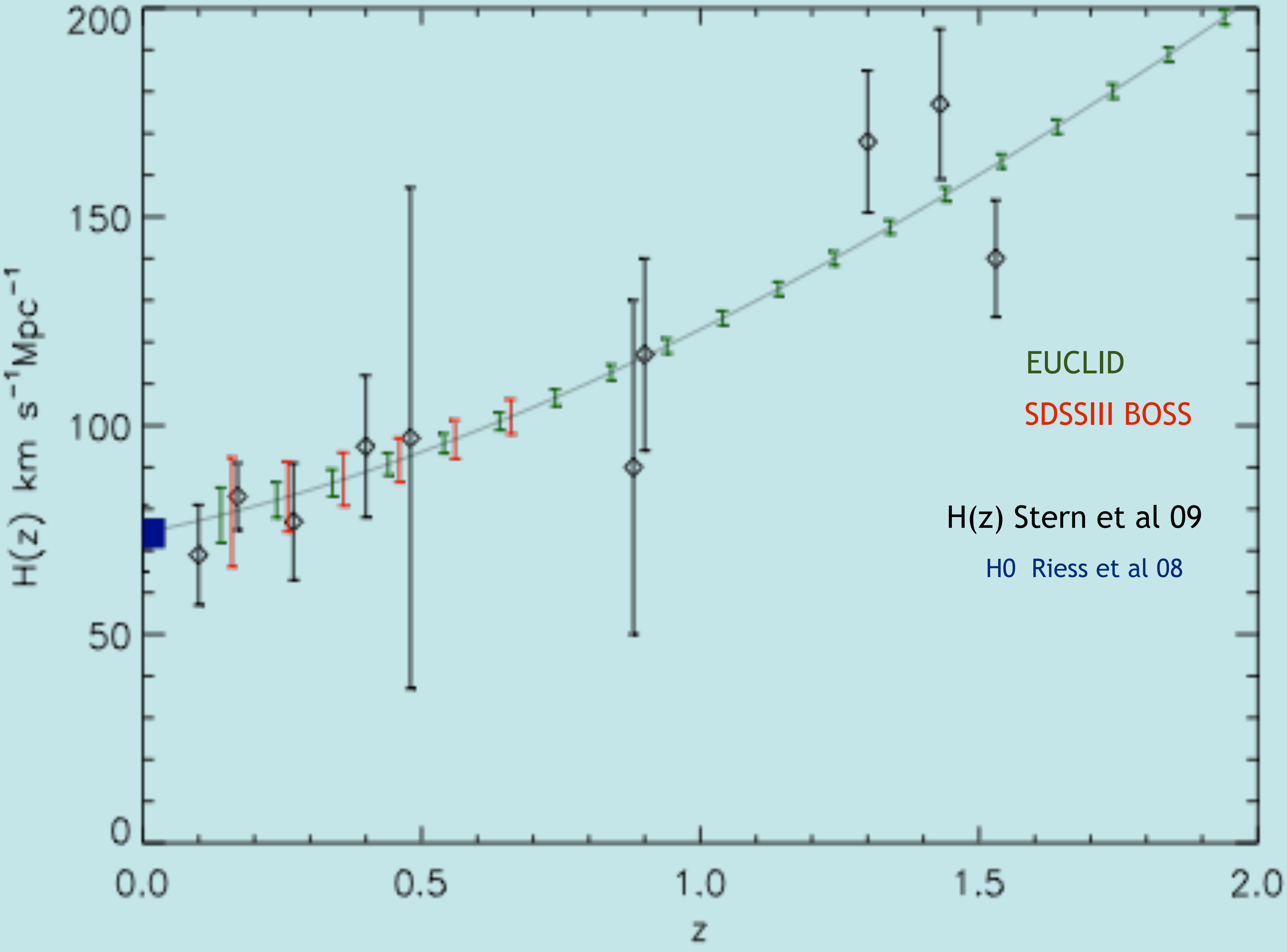
Rapid photon-axion thermalization

SN + H(z)



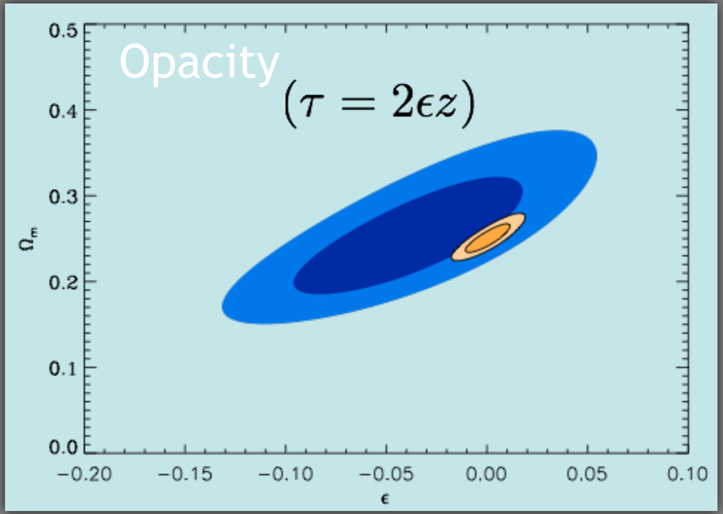
No photon-axion mixing

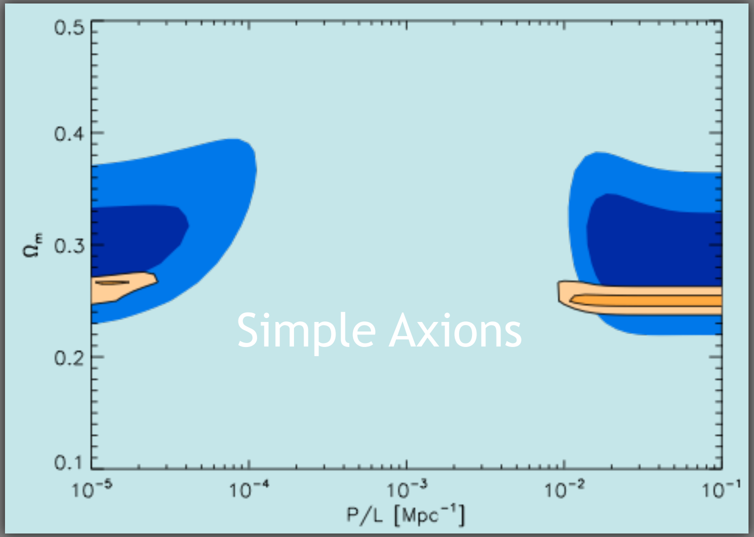
Flux thermalised at SN:
no propagation effect

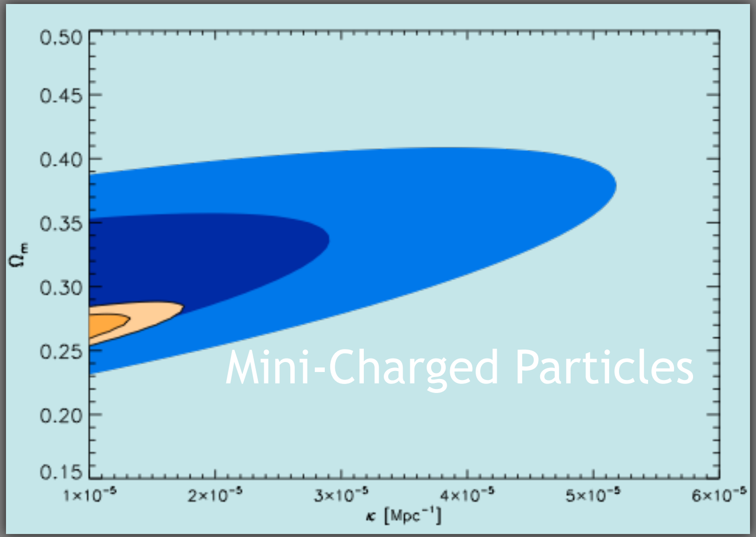

EUCLID
SDSSIII BOSS
H(z) Stern et al 09
H0 Riess et al 08
$H(z)\ \mathrm{km\ s^{-1}Mpc^{-1}}$
z
0
50
100
150
200
0.0
0.5
1.0
1.5
2.0

Forecasts (BAO & SN)

Dramatic improvement on these constraints expected with future BAO (notably EUCLID) and SN (SNAP) missions







Summary

- Vast quantity of high quality cosmo data fast approaching: CMB, BAOs, Gravitational waves, 21cm,...
- Fruitful interplay between HEP/cosmo theory and cosmological observation (cf compactification scales from inflation!)
- New physics at sub-eV scales (notably ALPs & MCPs) generic in fundamental theory
- A good chance to measure neutrino mass and hierrachy
- Dramatic improvement expected as new data arrives and astrophysics better understood