

Licia Verde

**Neutrino properties and
cosmology (large-scale structure)**

Connecting Cosmology to Fundamental Physics: Example

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



Institut de Ciències
del Cosmos



Overview

Recent work on neutrino properties from cosmology

Neutrino masses

Number of families

Mass hierarchy

New developments: data

CMB damping tail (ACT, SPT)

Sloan Digital Sky Survey BOSS, WIGGLEZ

Baryon Acoustic Oscillations & clustering

Direct measurement of expansion history

NEWS: FUTURE DATA: Euclid, recycled spy satellite, WFIRST

New developments: theory

Better modeling of non-linearities via N-body simulations
(and perturbation theory)

Neutrino mass: Physical effects

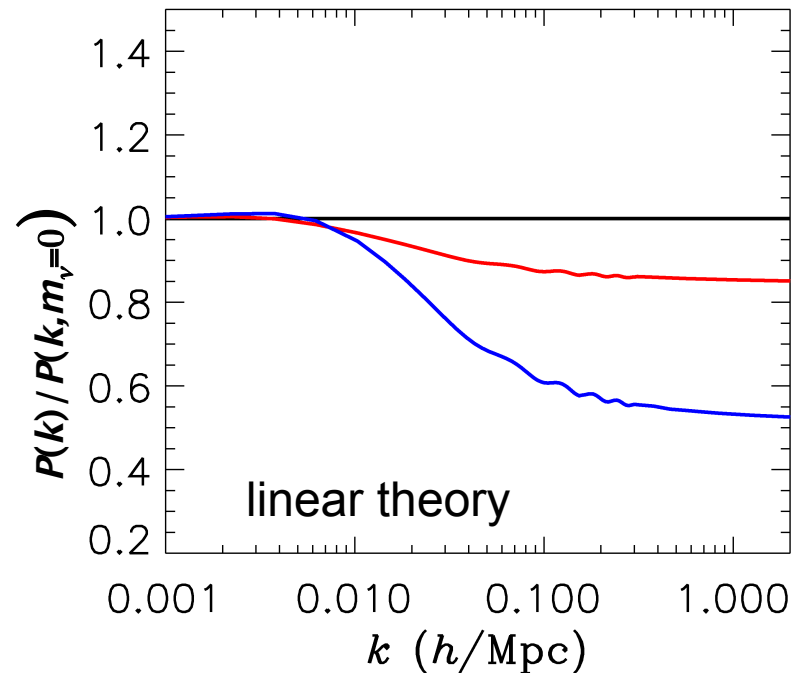
Total mass $> \sim 1$ eV become non relativistic before recombination CMB

Total mass $< \sim 1$ eV become non relativistic after recombination:
alters matter-radiation 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



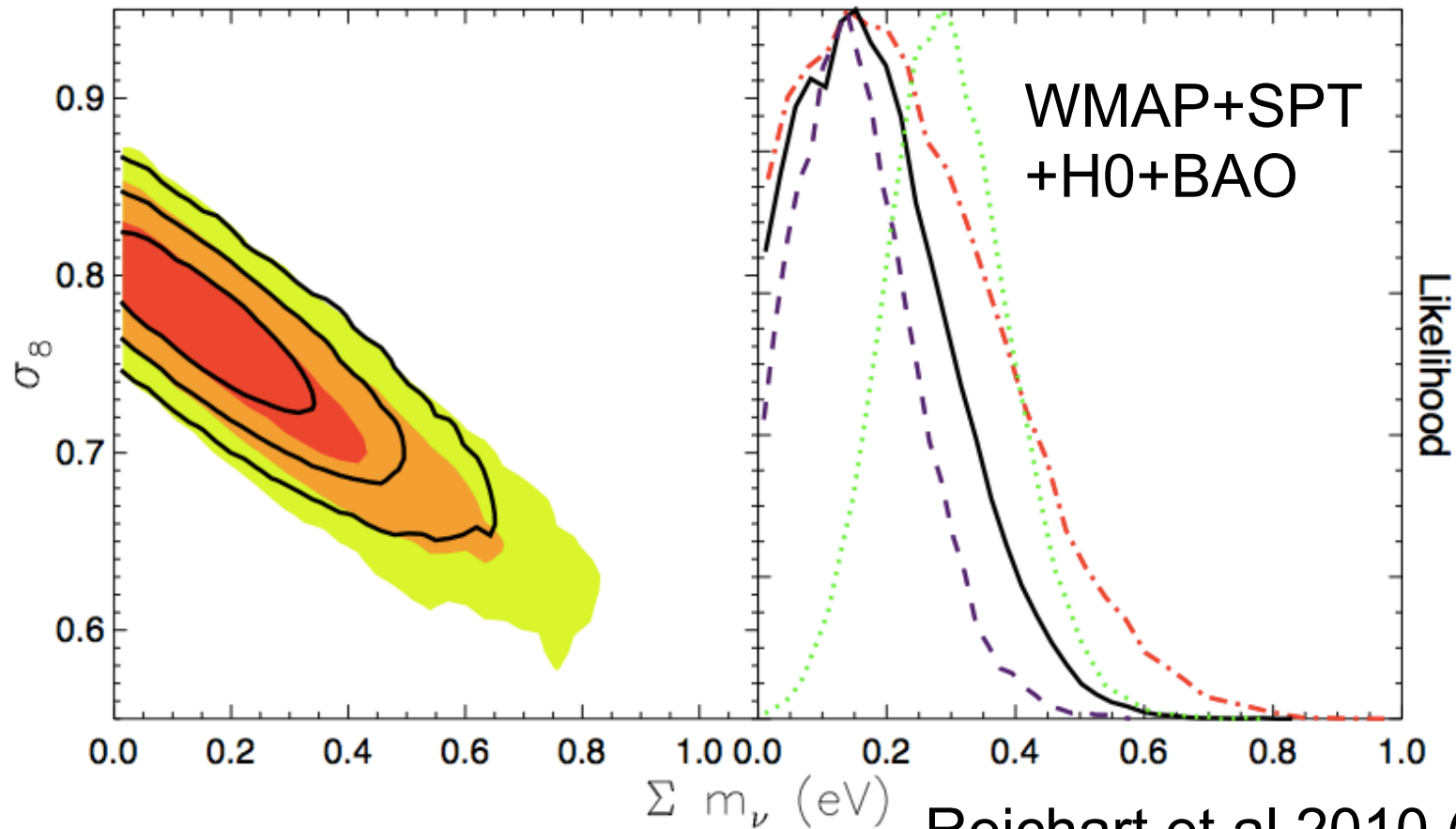
$\Sigma m = 0$ eV

$\Sigma m = 0.3$ eV

$\Sigma m = 1$ eV

WMAP: $\Sigma < 1.3$ eV (95% CL)

Adding measurements of the CMB damping tail to the primary signal (WMAP) does not help much (look into secondary effects)



Reichart et al 2010 (SPT)

Must add low redshift Universe information (σ_8 , clustering etc.)

Robust neutrino constraints on the total mass

Reid, et al 2010, WMAP+H0+MaxBCG, SDSS DR7 P(k)

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

model	Bayesian base dataset	upper 95% C.L. bound on $\sum m_\nu$			
		-	+maxBCG	+ H_0	+maxBCG+ H_0
Λ CDM	WMAP5	1.3	1.1	0.59	0.40
Λ CDM	WMAP5+BAO+SN	0.67	0.35	0.59	0.31
Λ CDM + α	WMAP5	1.34	1.25	0.54	0.39
Λ CDM + r	WMAP5	1.36	1.18	0.83	0.40
w CDM	WMAP5+BAO+SN	0.80	0.52	0.72	0.47

Also: Thomas et al. (2010), Gonzalez-Garcia et al (2010), Giusarma et al (2011), Riemer-Sørensen (2012, wigglez++) etc.

dePutter et al 2012 (SDSS DR9 BOSS)

95% CL $\sum m_\nu$ [eV]	prior only	prior+CMASS, $\ell_{\max} = 150$	prior+CMASS, $\ell_{\max} = 200$
WMAP7 prior	1.1	0.74 (0.92)	0.56 (0.90)
WMAP7 + HST prior	0.44	0.31 (0.40)	0.26 (0.36)

TABLE 1

THE 95% CONFIDENCE LEVEL UPPER LIMITS ON THE SUM OF THE NEUTRINO MASSES Σm_ν . THE TOP ROW INVESTIGATES THE EFFECT OF ADDING THE CMASS GALAXY POWER SPECTRA TO A WMAP PRIOR WHILE THE BOTTOM ROW USES WMAP AND THE H_0 CONSTRAINT FROM HST AS A PRIOR. IN PARENTHESES WE SHOW RESULTS FOR THE MORE CONSERVATIVE MODEL MARGINALIZING OVER THE SHOT NOISE-LIKE PARAMETERS a_i .

Robust neutrino constraints... on the total mass

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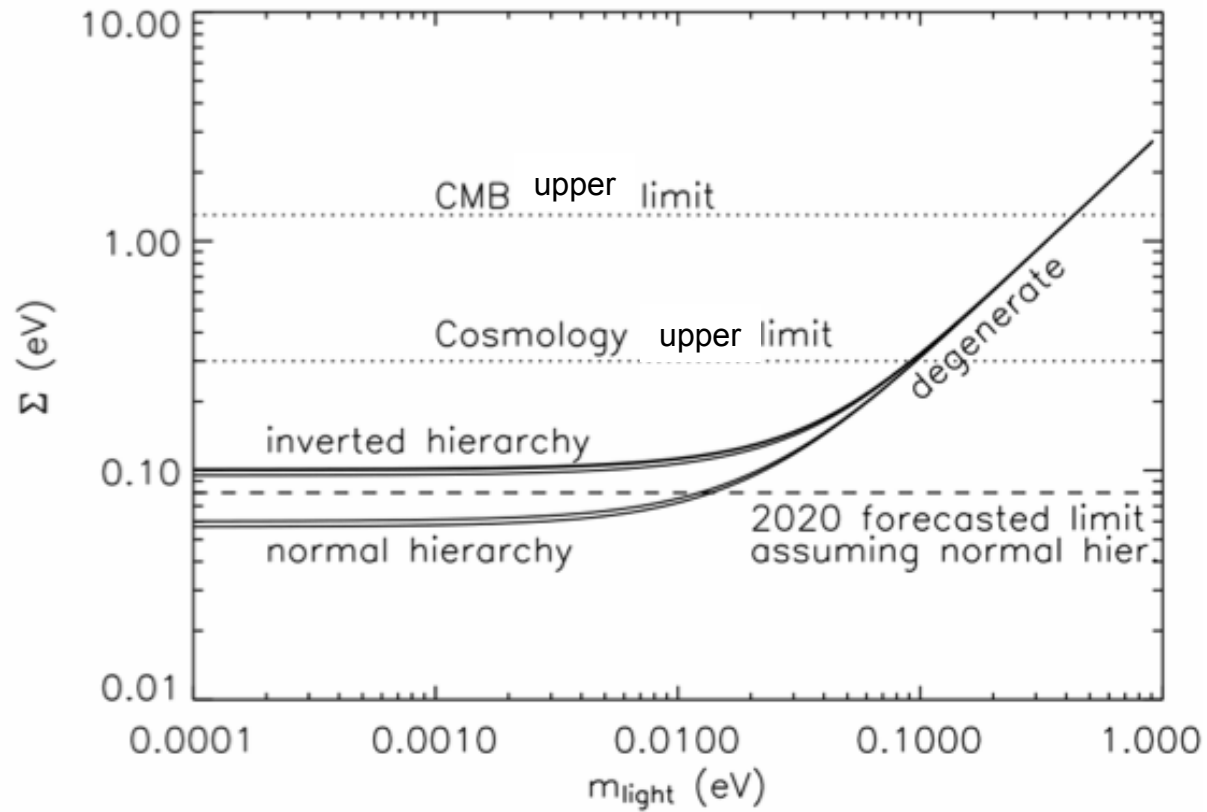
$\Sigma < 0.3$ (95% CL) in a minimal Λ CDM scenario

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Outlook towards the future

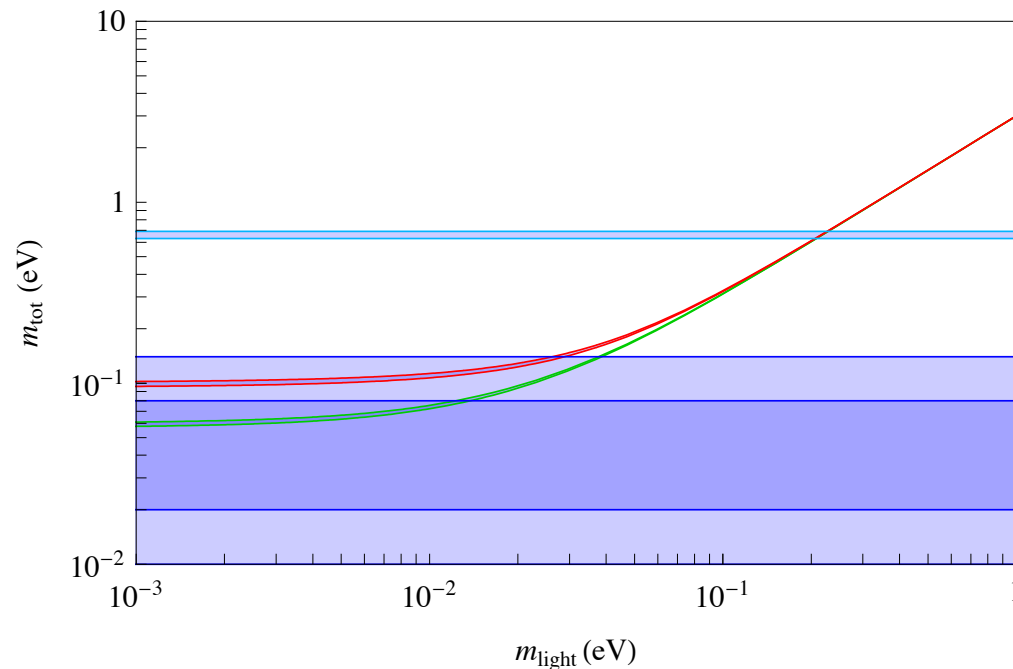


The future is bright: forecasts

Detailed errors depend on what assumptions about underlying cosmology one is willing to make

Example:

LSST (lensing)
+Planck primary



Look how errors depend on fiducial model

More forecasts: space-based

Carbone, LV et al (2012)

Two surveys strategies

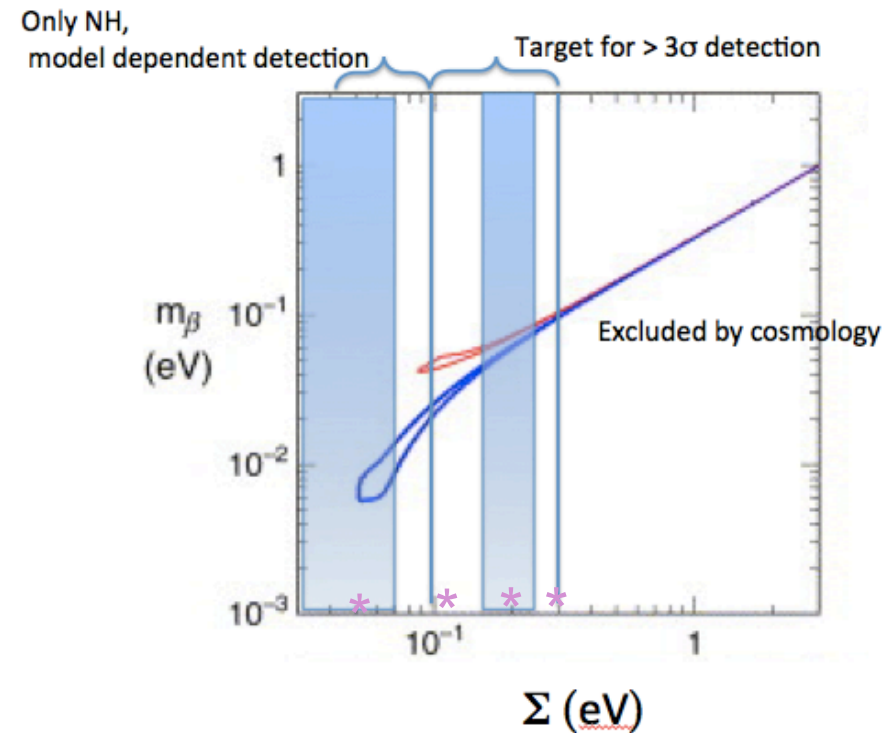
A EUCLID like survey (slitless spectroscopy of $H\alpha$ emission lines)

H-band magnitude limited survey , multislit spectroscopy (WFIRST)

Include redshift space distortions,
signal from growth,
different baseline models, etc.

Several fiducial models *

Study parameters degeneracies and
Survey set up and performance



Errors depend on fiducial model

More forecasts: space-based

Carbone, LV et al (2012)

Two surveys strategies

A EUCLID like survey (slitless spectroscopy of $H\alpha$ emission lines)

H-band magnitude limited survey , multislit spectroscopy (WFIRST)

Table 5: $\sigma(M_\nu)$ marginalised errors from LSS+CMB

General cosmology					
fiducial→	$M_\nu=0.3 \text{ eV}^a$	$M_\nu=0.2 \text{ eV}^a$	$M_\nu=0.125 \text{ eV}^b$	$M_\nu=0.125 \text{ eV}^c$	$M_\nu=0.05 \text{ eV}^b$
slitless+BOSS+Planck	0.035	0.043	0.031	0.044	0.053
multi-slit+Planck	0.030	0.038	0.027	0.039	0.046
Λ CDM cosmology					
slitless+BOSS+Planck	0.017	0.019	0.017	0.021	0.021
multi-slit+Planck	0.015	0.016	0.014	0.018	0.018

^afor degenerate spectrum: $m_1 \approx m_2 \approx m_3$; ^bfor normal hierarchy: $m_3 \neq 0, m_1 \approx m_2 \approx 0$

^cfor inverted hierarchy: $m_1 \approx m_2, m_3 \approx 0$;

Beware of systematics!!!!

It would be of great value to have an internal consistency check
(more later)

What about non-linearities?

Approaches: Analytic i.e. Perturbation theory e.g., Saito et al.
N-body Simulations Bandbye, Hannestad et al.
Viel, Springel et al.
Intermediate: Agarwal & Feldman

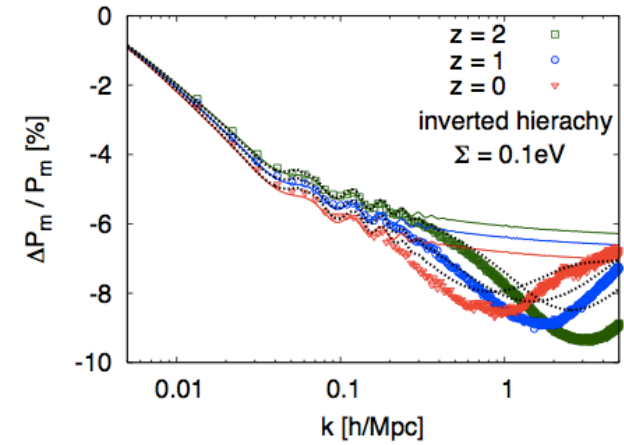
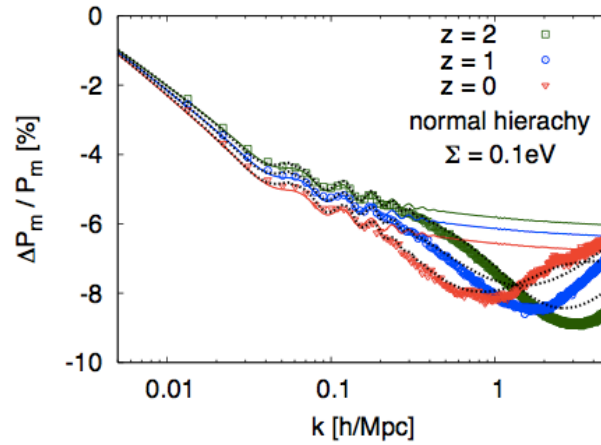
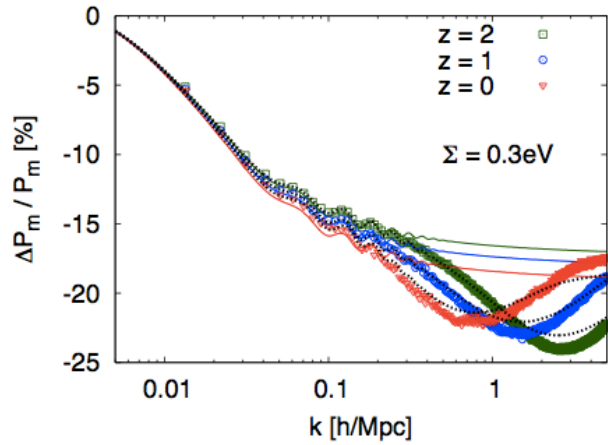
Options:

Simulate just neutrino masses

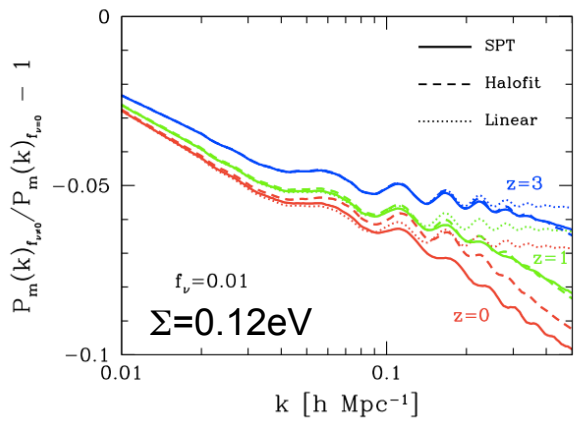
- Use particles
- Use grids
- Use hybrid

Simulate also hierarchy

Effect of Σ (total mass)



Wagner Verde Jimenez 2012



Saito et al 09

This is for MATTER
in real space

Enhancement of the effect on interesting scales!

N_{eff} : number of effective species

$$H^2(t) \simeq \frac{8\pi G}{3} (\rho_\gamma + \rho_\nu) \quad \rho_\nu \propto T^4 N_{\text{eff}} \quad \text{Standard: } N_{\text{eff}}=3.045$$

Any thermal background of light particles, anything affecting expansion rate

Look at BBN

N_{eff} around 3 to 4

Systematics!

Nollett, Holder 2011: Y_p difficult, better use CMB $(\Omega_b h^2) + D/H$

Pettini, Cooke 2012 $N_\nu = 3.0 \pm 0.5$

N_ν : number of effective species

$$H^2(t) \simeq \frac{8\pi G}{3} (\rho_\gamma + \rho_\nu) \quad \rho_\nu \propto T^4 N_{\text{eff}} \quad \text{Standard: } N_{\text{eff}}=3.045$$

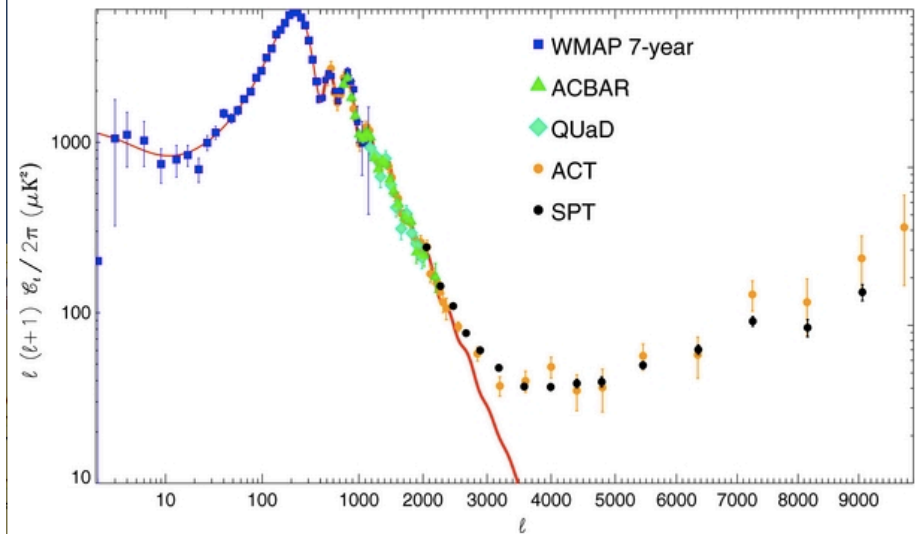
Any thermal background of light particles, anything affecting expansion rate

Look at BBN $N_{\text{eff}}= 3$ to 4

Systematics!

Look at CMB:
effects matter-radiation equality
and so sound horizon at decoupling
→ degeneracy with ω_m and H

Anisotropic stress,
 z_{eq} on diffusion damping



Literature review

Cosmological analyses consistently give best fit values >3.04 .
 “dark radiation”
 But analyses are NOT independent
 (WMAP is always in common, H_0 many times in common)

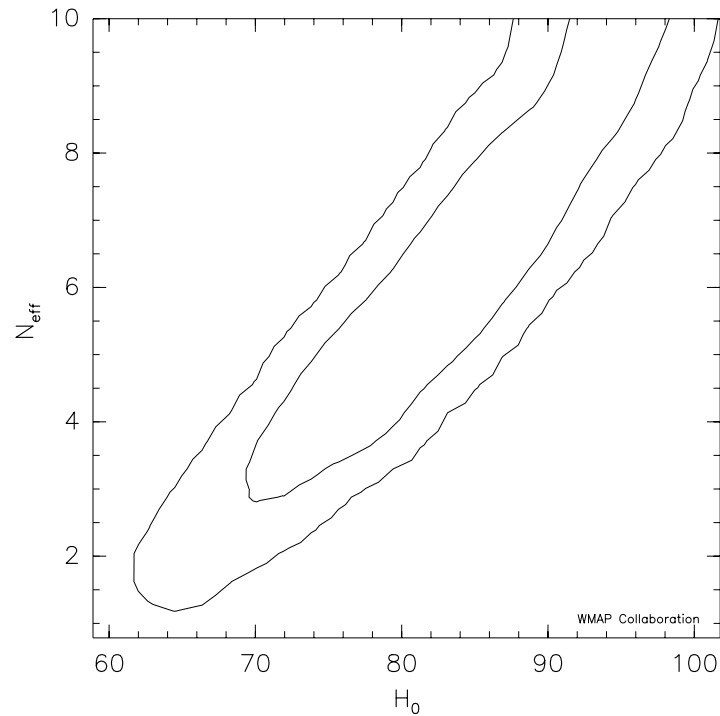
It's barely 2 sigmas
 (except for one data set: ACT)

Also,
 beware of degeneracies

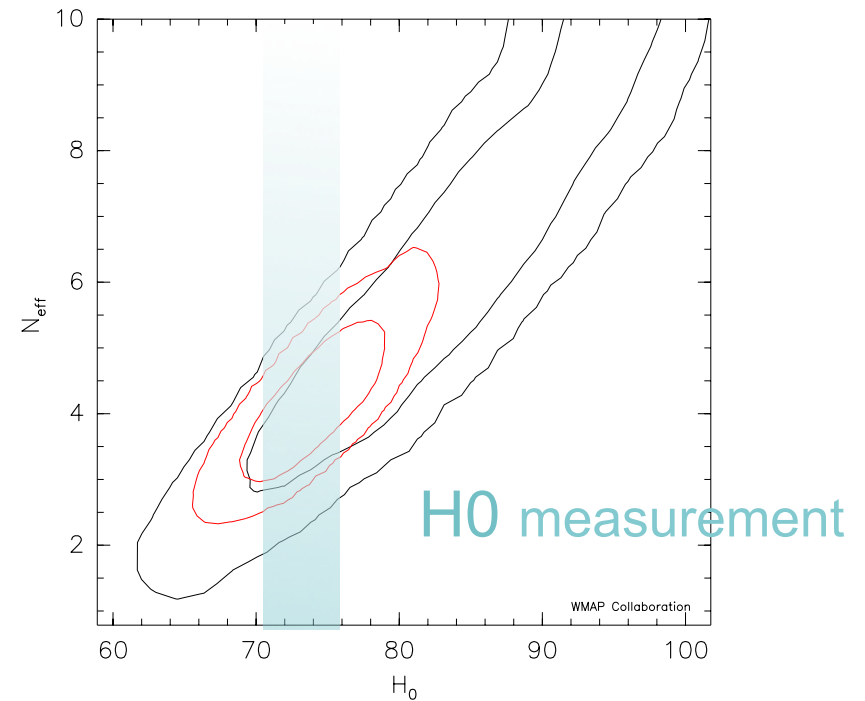
Tab 3 white paper
 1204.5379

Model	Data	N_{eff}	Ref.
N_{eff}	W-5+BAO+SN+ H_0	$4.13^{+0.87(+1.76)}_{-0.85(-1.63)}$	[346] Reid et al '10
	W-5+LRG+ H_0	$4.16^{+0.76(+1.60)}_{-0.77(-1.43)}$	[346] Mantz et al 10
	W-5+CMB+BAO+XLF+ $f_{gas}+H_0$	$3.4^{+0.6}_{-0.5}$	[349] Reid et al '10
	W-5+LRG+maxBCG+ H_0	$3.77^{+0.67(+1.37)}_{-0.67(-1.24)}$	[346] Komatsu et al 11
	W-7+BAO+ H_0	$4.34^{+0.86}_{-0.88}$	[338] (WMAP7)
	W-7+LRG+ H_0	$4.25^{+0.76}_{-0.80}$	[338] Dunkley et al 10
	W-7+ACT	5.3 ± 1.3	[343] (ACT)
	W-7+ACT+BAO+ H_0	4.56 ± 0.75	[343] Keisler et al 11
	W-7+SPT	3.85 ± 0.62	[344] (SPT)
	W-7+SPT+BAO+ H_0	3.85 ± 0.42	[344] Archidiacono et al 20
	W-7+ACT+SPT+LRG+ H_0	$4.08^{(+0.71)}_{(-0.68)}$	[350]
	W-7+ACT+SPT+BAO+ H_0	3.89 ± 0.41	[351]
$N_{eff}+f_v$	W-7+CMB+BAO+ H_0	$4.47^{(+1.82)}_{(-1.74)}$	[352] Hamann et al 2010
	W-7+CMB+LRG+ H_0	$4.87^{(+1.86)}_{(-1.75)}$	[352]
$N_{eff}+\Omega_k$	W-7+BAO+ H_0	4.61 ± 0.96	[351] Smith et al 2011
	W-7+ACT+SPT+BAO+ H_0	4.03 ± 0.45	[352] Hamann et al 2010
$N_{eff}+\Omega_k+f_v$	W-7+ACT+SPT+BAO+ H_0	4.00 ± 0.43	[351] Smith et al 2011
$N_{eff}+f_v+w$	W-7+CMB+BAO+ H_0	$3.68^{(+1.90)}_{(-1.84)}$	[352] Hamann et al 2010
	W-7+CMB+LRG+ H_0	$4.87^{(+2.02)}_{(-2.02)}$	[352]
$N_{eff}+\Omega_k+f_v+w$	W-7+CMB+BAO+SN+ H_0	$4.2^{+1.10(+2.00)}_{-0.61(-1.14)}$	[353] Gonzalez-Garcia et al. 2010
	W-7+CMB+LRG+SN+ H_0	$4.3^{+1.40(+2.30)}_{-0.54(-1.09)}$	[353]

What may be going on?



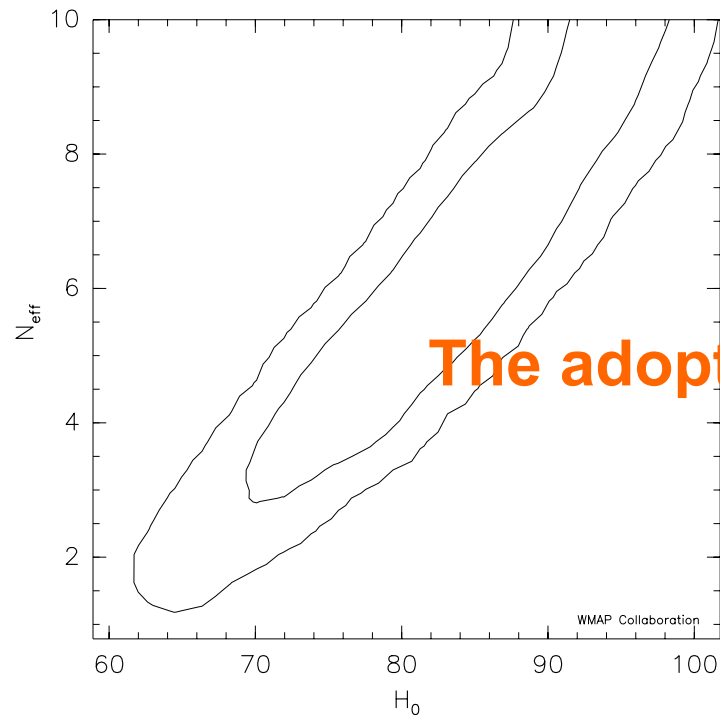
WMAP only



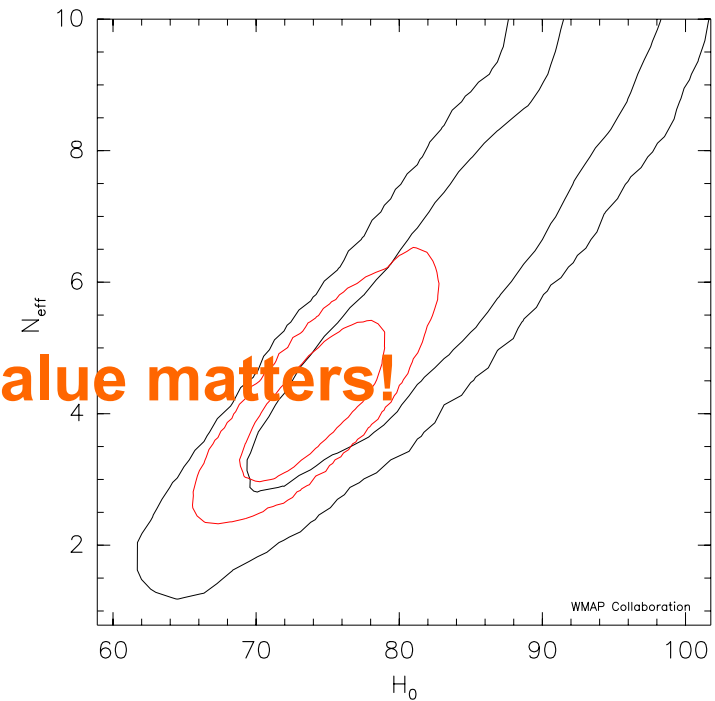
WMAP+H0+BAO

Straight from the on-line LAMBDA cosmological parameters plotter

What may be going on?



WMAP only

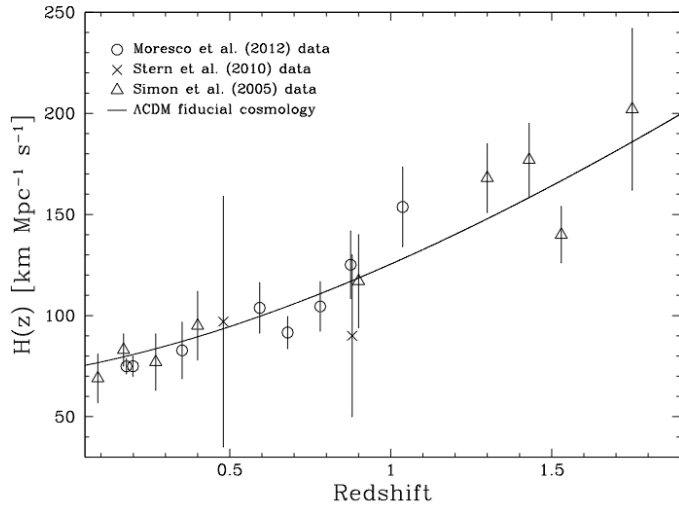


WMAP+H0+BAO

The adopted H_0 value matters!

Straight from the on-line LAMBDA cosmological parameters plotter

H(z) estimates

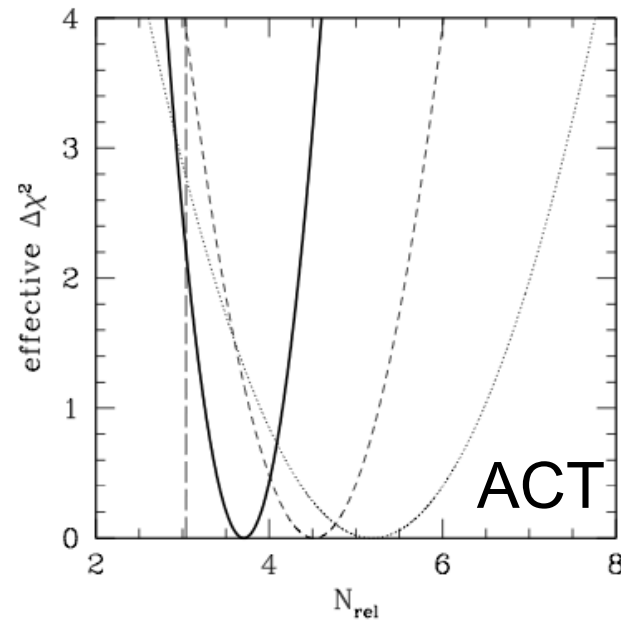
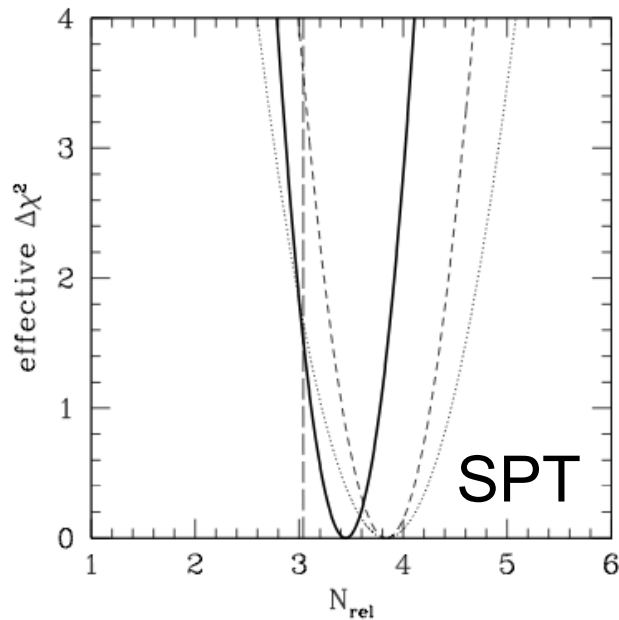


$$N_\nu = 3.59 \pm 0.48 (\pm 0.94) \quad \text{WMAP} + \text{ACT} + \text{H}(z)$$

$$N_\nu = 3.37 \pm 0.34 (\pm 0.67) \quad \text{WMAP} + \text{SPT} + \text{H}(z)$$

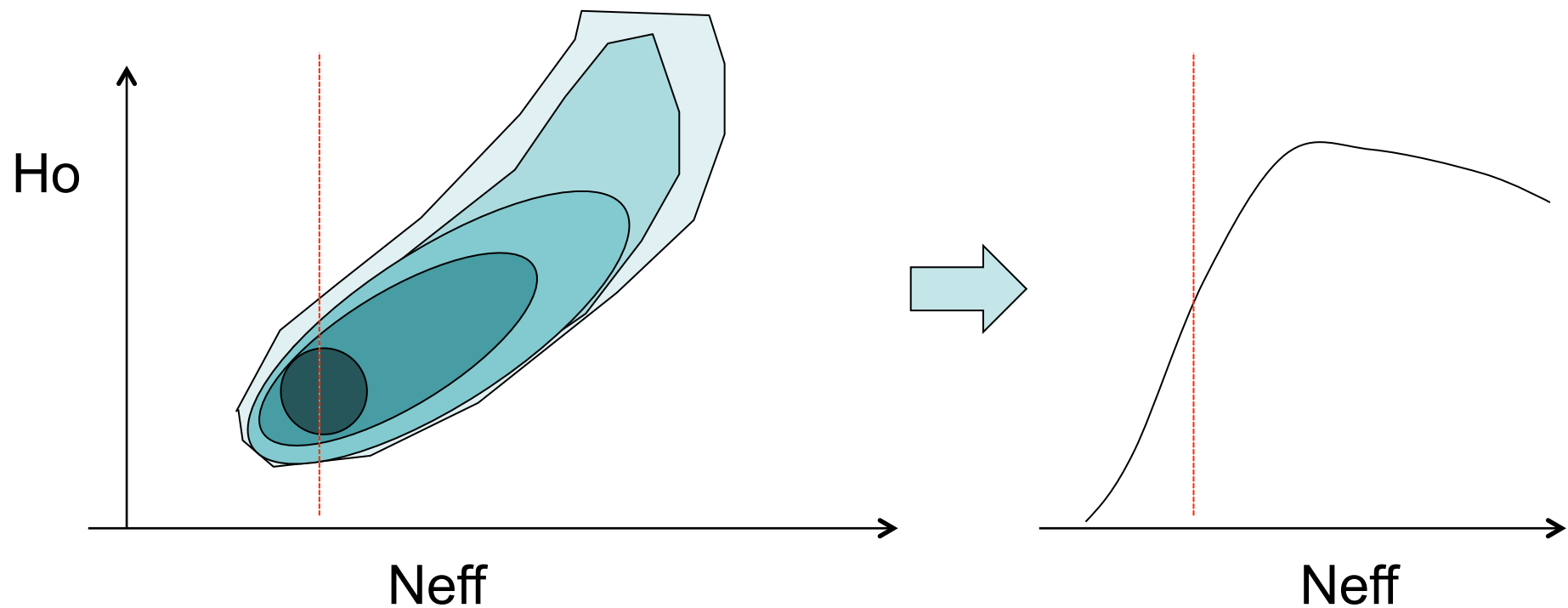
$$N_\nu = 3.38 \pm 0.50 (\pm 1) \quad \text{WMAP} + \text{H}(z)$$

$$N_\nu < 4 \text{ at } 95\% (74\%) \text{ C.L.}$$

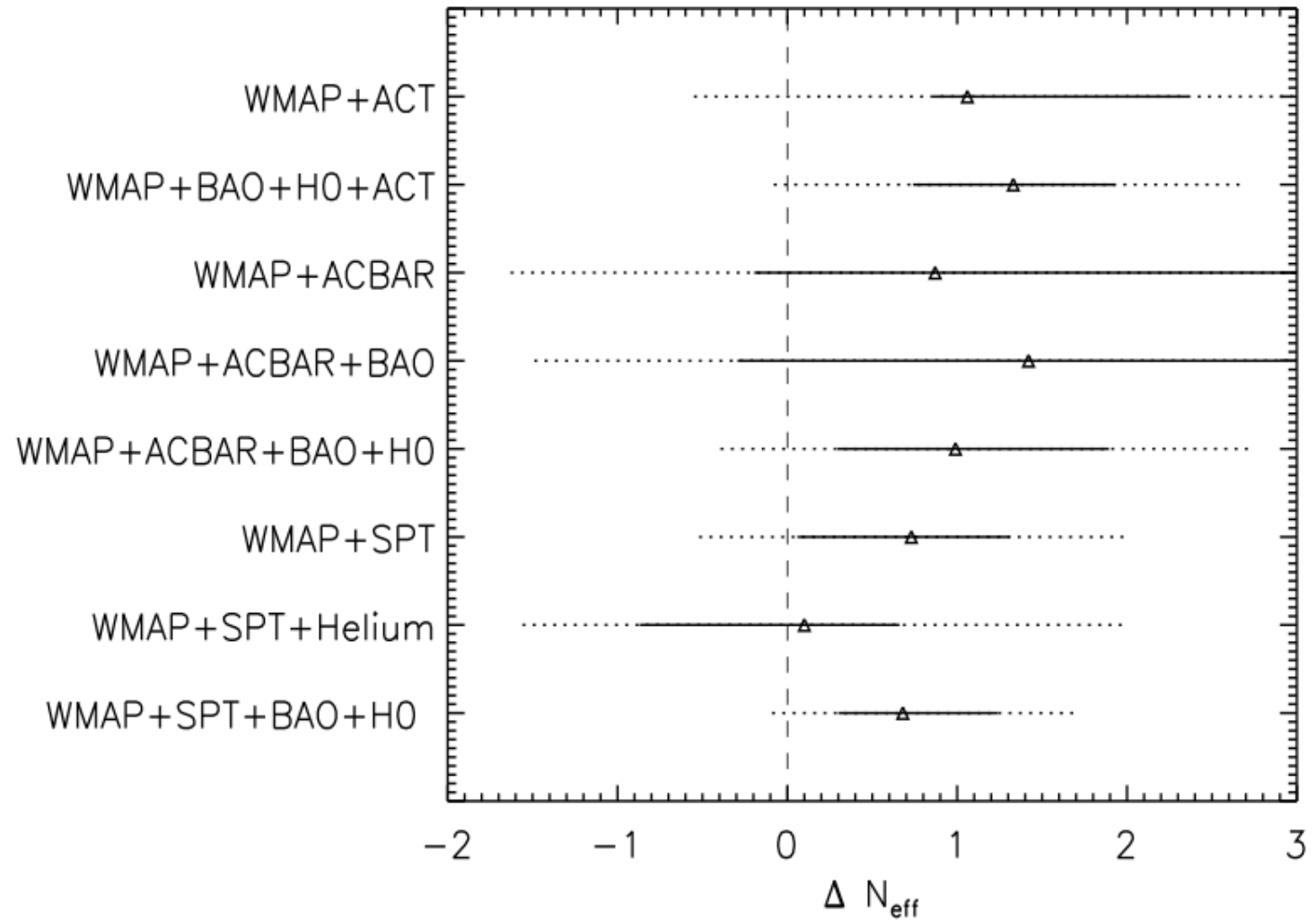


Effect of priors?

“This is not interpreted as a statistically significant departure from the concordance value; the best-fit χ^2 is only 1.3 less than for $N_{\text{eff}}=3.04$.”
(from the ACT paper Dunkley et al '10)



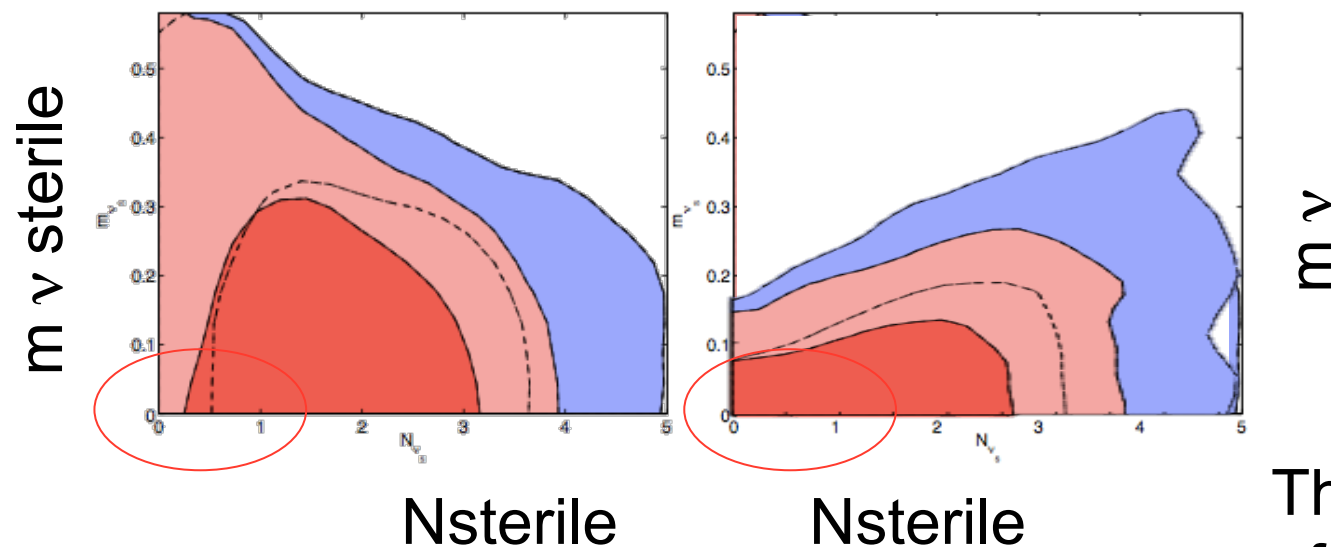
Look at the likelihood



Gonzalez-Morales et al. 2011(12)?

In summary:

- N_{eff} consistent with 3 (but also with 4) at 2σ
- These are “light” neutrinos (<0.5 eV)
- more wiggle room: go beyond the minimal LCDM (errors gets slightly larger, but... epicycles)
- Avoid thermalization (some v. radical options)



More forecasts

Carbone LV et al (2012)

Two surveys strategies

A EUCLID like survey (slitless spectroscopy of H α emission lines)

H-band magnitude limited survey , multislit spectroscopy (WFIRST)

Table 5: $\sigma(M_\nu)$ and $\sigma(N_{\text{eff}})$ marginalised errors from LSS+CMB

General cosmology						
fiducial→	$M_\nu=0.3$ eV ^a	$M_\nu=0.2$ eV ^a	$M_\nu=0.125$ eV ^b	$M_\nu=0.125$ eV ^c	$M_\nu=0.05$ eV ^b	$N_{\text{eff}}=3.04$ ^d
slitless+BOSS+Planck	0.035	0.043	0.031	0.044	0.053	0.086
multi-slit+Planck	0.030	0.038	0.027	0.039	0.046	0.082
Λ CDM cosmology						
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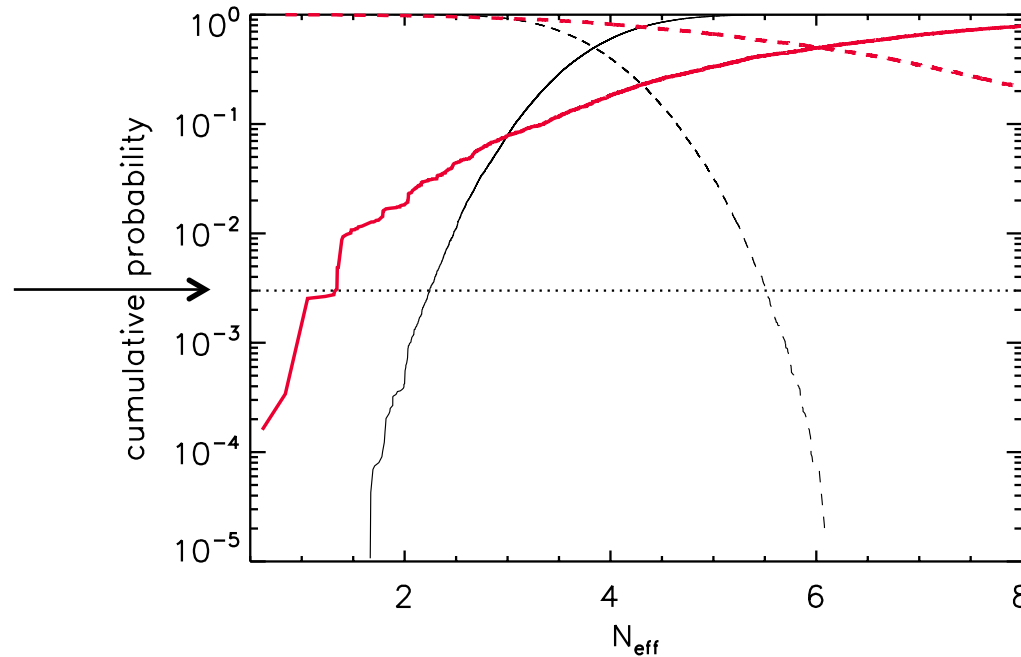
^afor degenerate spectrum: $m_1 \approx m_2 \approx m_3$; ^bfor normal hierarchy: $m_3 \neq 0, m_1 \approx m_2 \approx 0$

^cfor inverted hierarchy: $m_1 \approx m_2, m_3 \approx 0$; ^dfiducial cosmology with massless neutrinos

On the other hand...

the cosmic neutrino background
has been detected at $\gg 4\sigma$

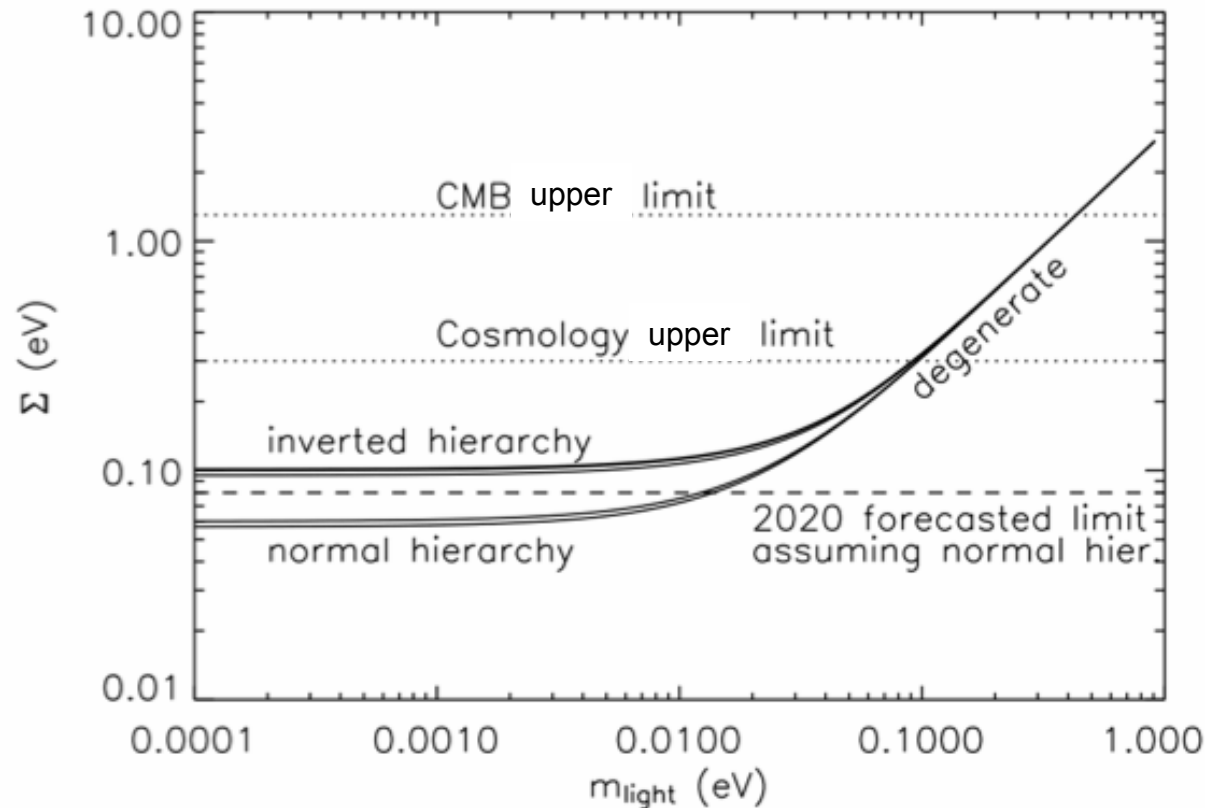
99.7%
or 0.003



WMAP

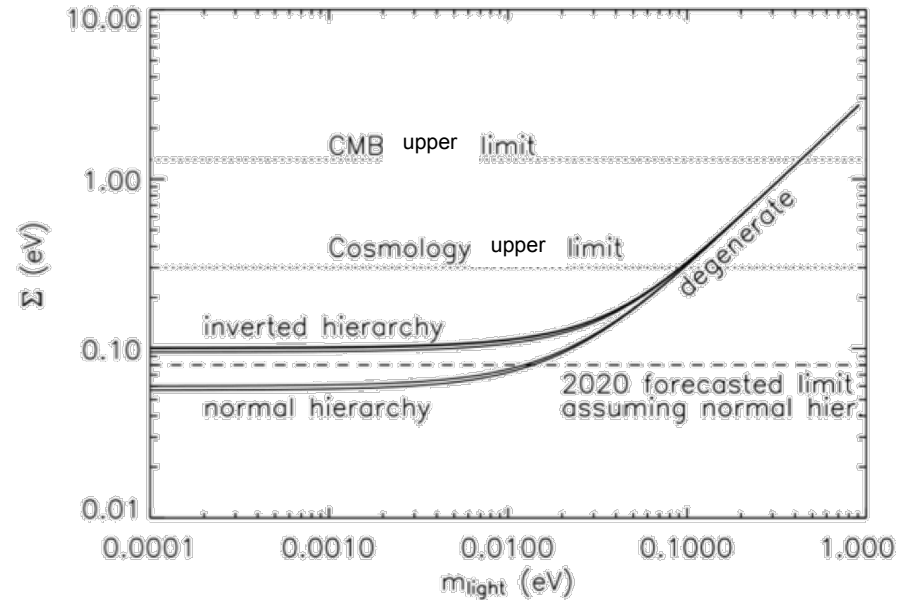
SPT

Outlook towards the future



Can the hierarchy be determined?
Are neutrino Majorana or Dirac?

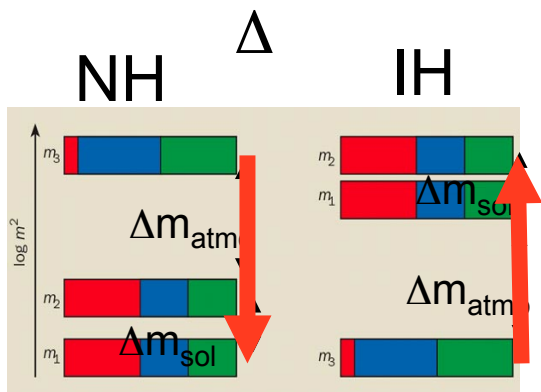
Can the hierarchy be determined?



Is there enough information in the sky? (ultimate experiment)

Can this be done with a specific survey?

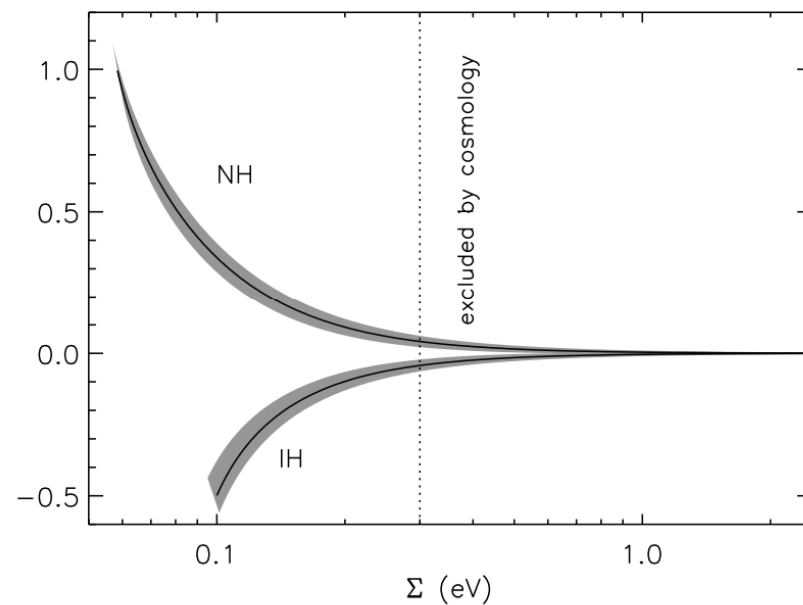
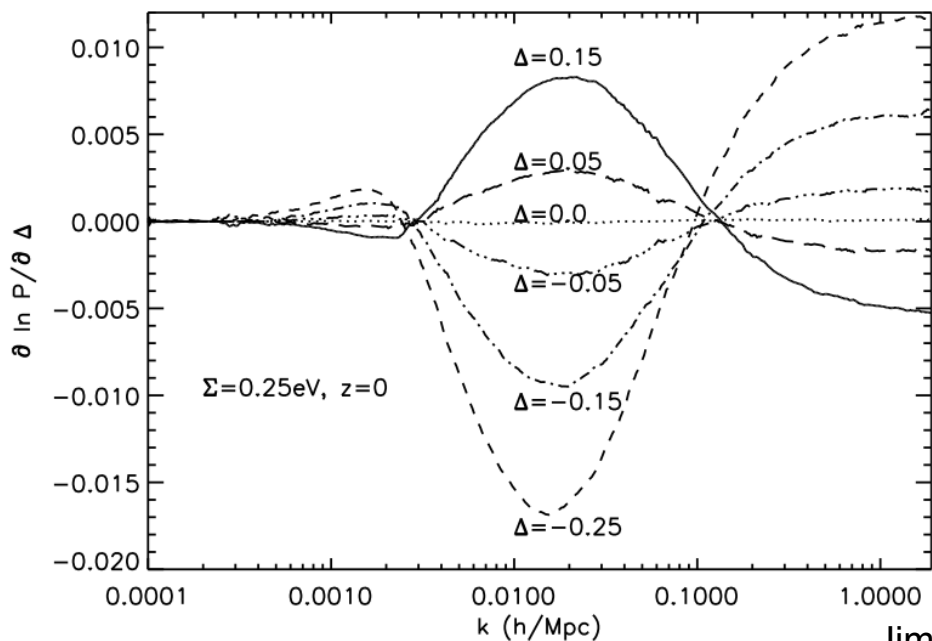
Hierarchy effect on the shape of the linear matter power spectrum



Neutrinos of different masses have different transition redshifts from relativistic to non-relativistic behavior, and their individual masses and their mass splitting change the details of the radiation-domination to matter- domination regime.

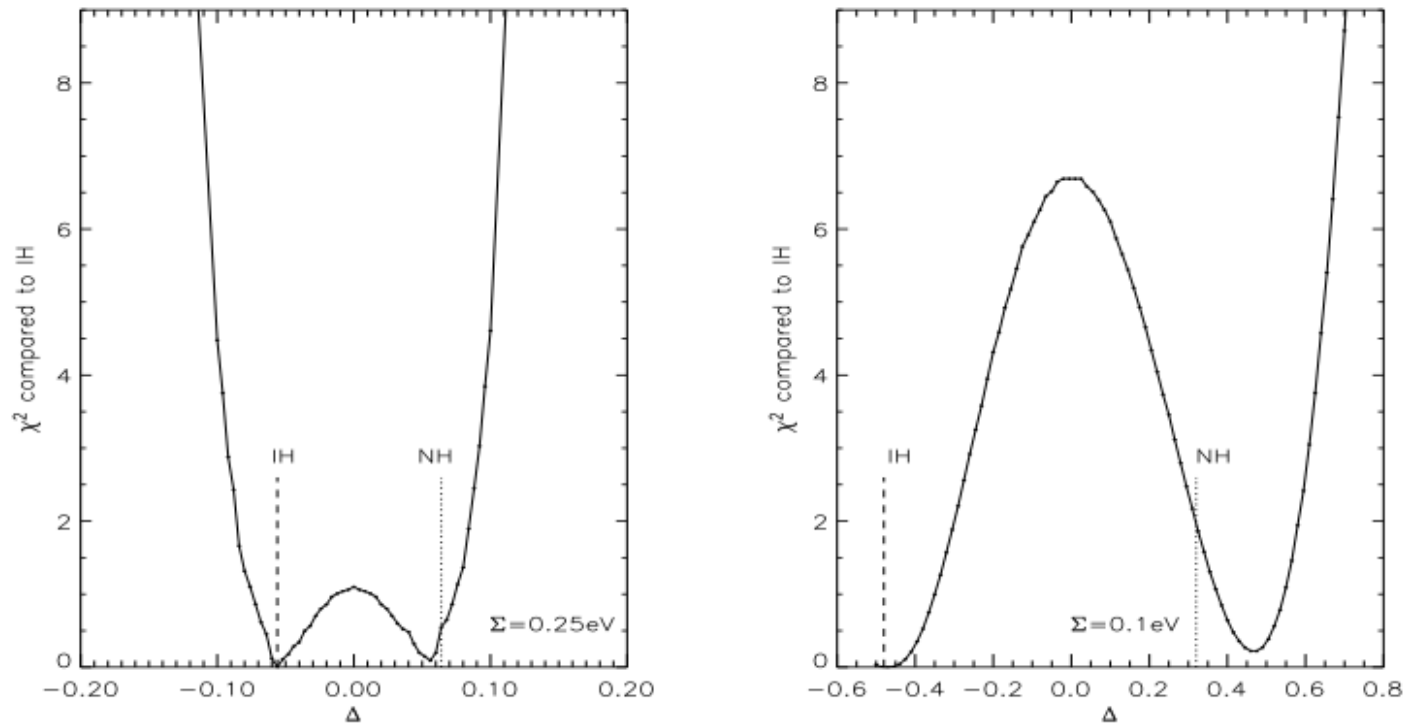
$$\text{NH : } \Sigma = 2m + M \quad \Delta = (M - m)/\Sigma$$

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



Jimenez, Kitching, Penya-Garay, Verde, JACP2010

Hierarchy effect on the overall likelihood function



Jimenez, Kitching, Peña-Garay, Verde, JCAP 2010

A word of warning!

Lessons so far:

Should be careful about parameterization choice

Use information from oscillations

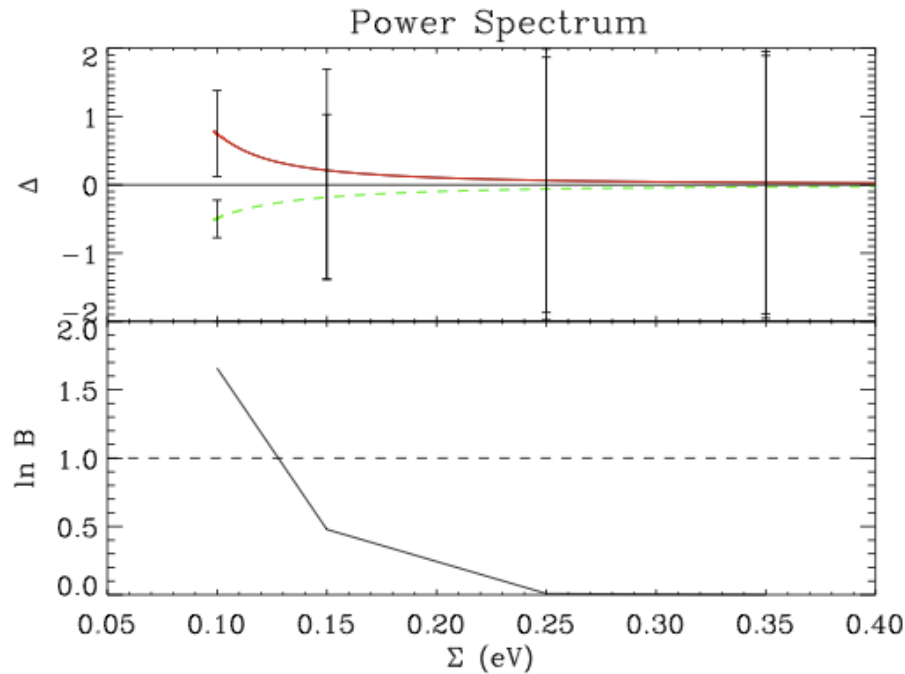
Cosmology is (mostly) sensitive to $|\Delta|$

Fisher estimates are great but have limitations!

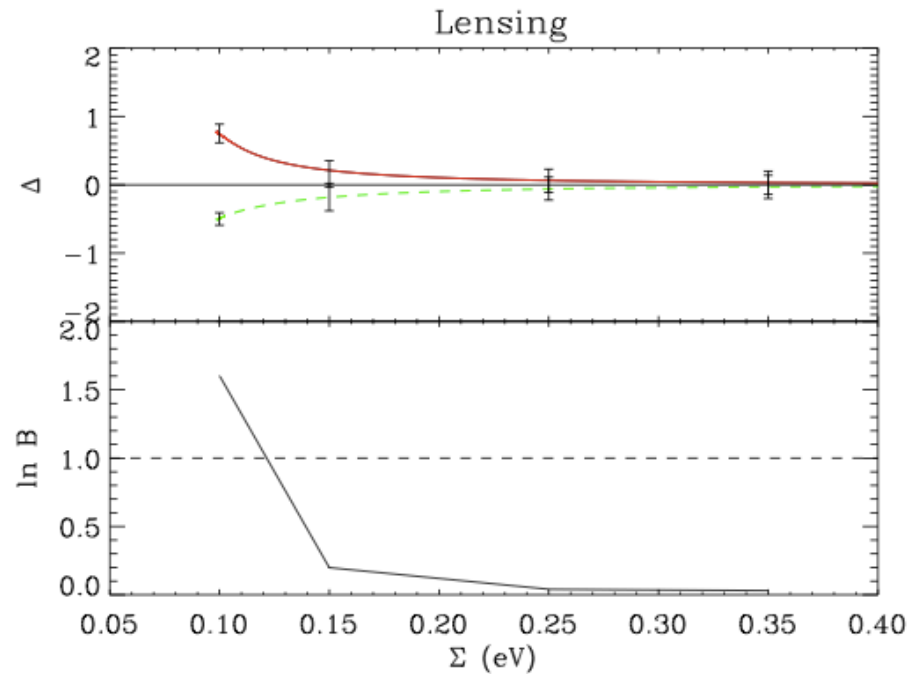
Natural question to ask:

What would it take to measure Δ ?

Basically, the ultimate experiment



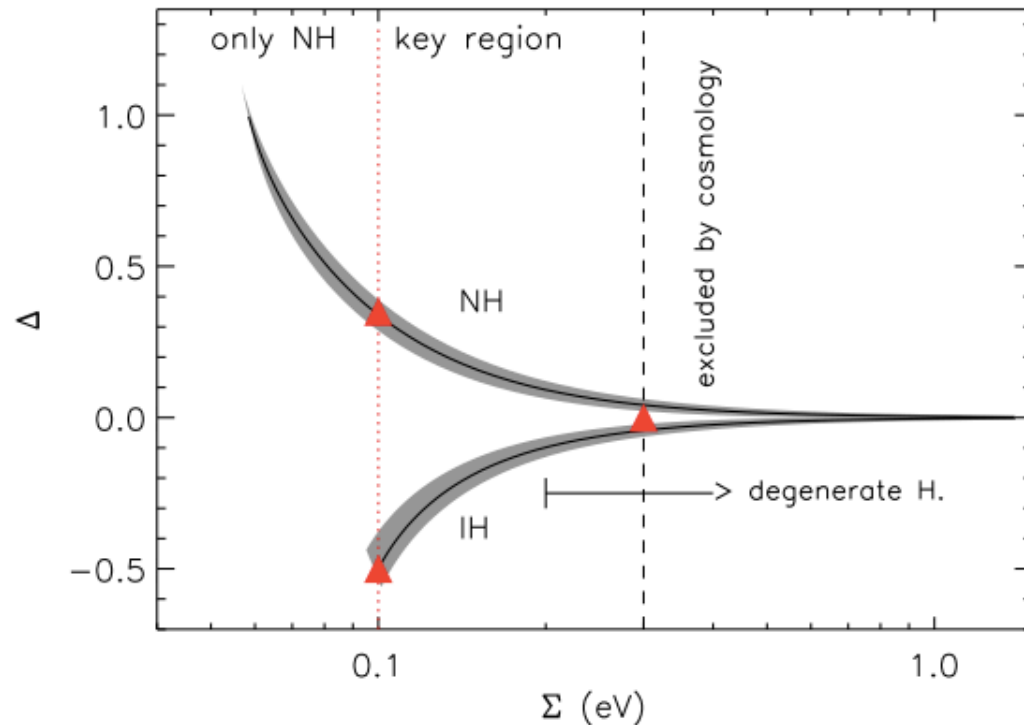
600 Gpc³ at $z = 2$ and 2000 Gpc³ at $z = 5$.



40,000 sq. deg. median redshift of 3.0
number density of 150 galaxies per \square'

B is the Bayesian evidence ratio

What about non-linearities? simulations



Gadget 2

Small test runs to optimize
time steps, varying initial z
and number of tracers

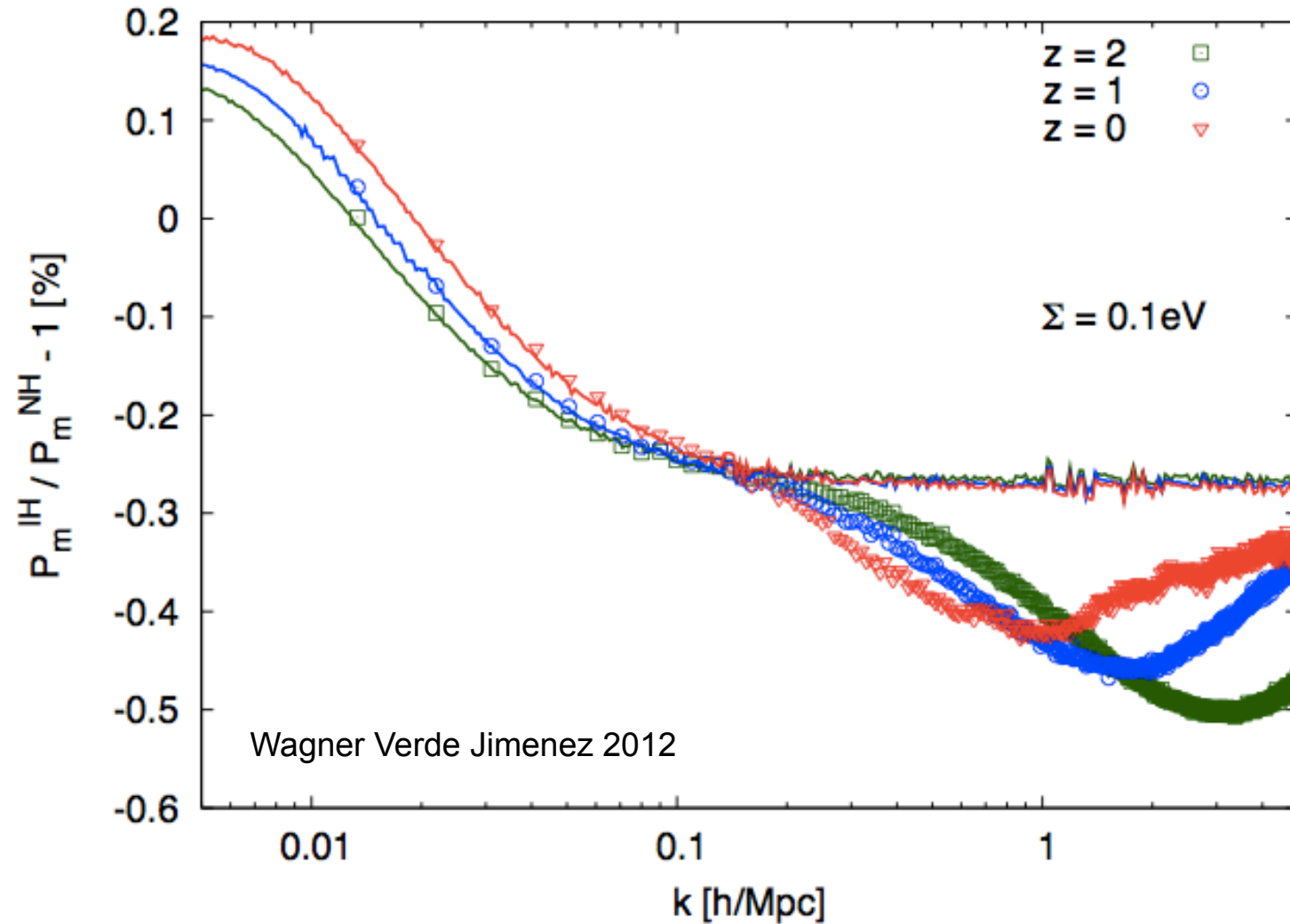
Wagner LV Jimenez 2012

$$V=(600h/\text{Mpc})^3$$

1 billion CDM particles and 2 billion ν 's

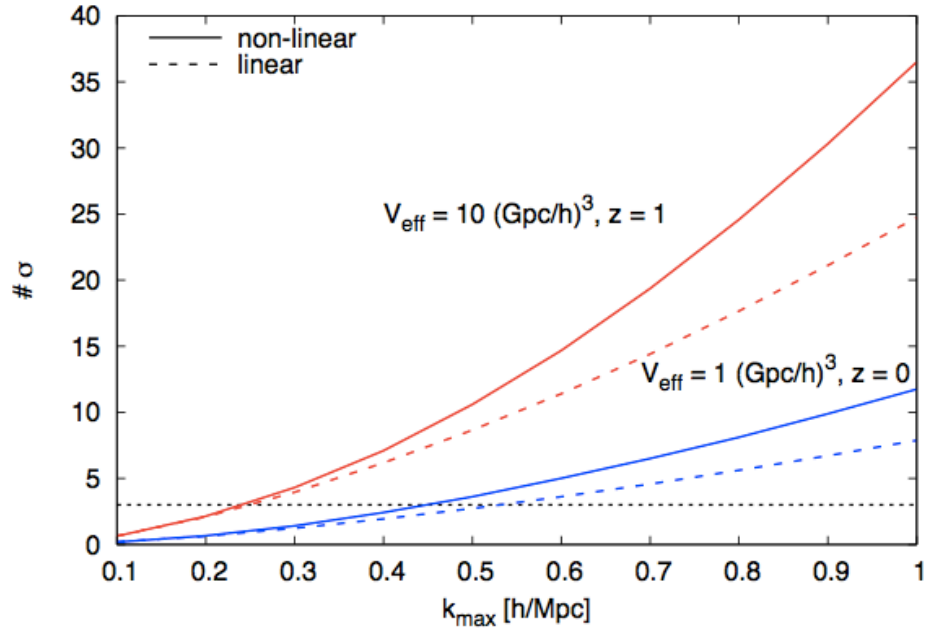
LDCM cosmology

Effect of Δ



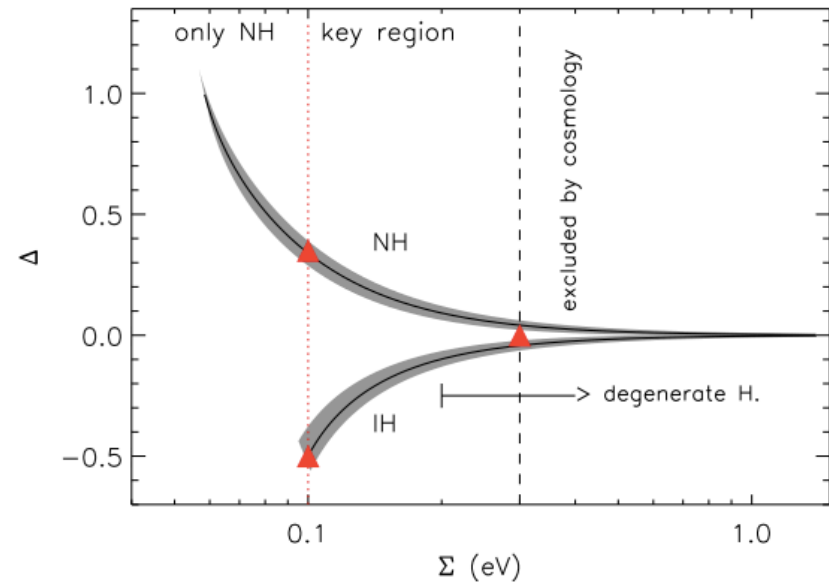
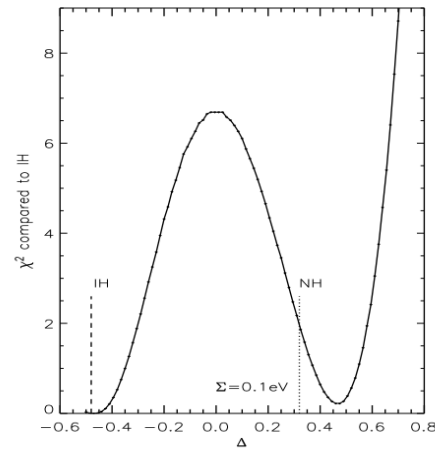
Non-linearities enhance the effect!

Detectability



NH vs IH

Keeping all other parameters fixed!



There's more parameter space!

Food for thoughts

This is a sub % effect!

Different linear Einstein-Boltzmann codes (e.g. CAMB (Lewis et al. 2000) and CLASS (Blas et al. 2011)) still do not agree to 0.1% precision on the relevant scales.
(this is a much easier problem!)

We have quantified the effect on the RELATIVE quantity: much more robust against numerical errors.

Even without massive neutrinos, it is challenging to compute the non-linear power spectrum to sub-percent precision.

At small scales baryonic effects dominate!

Effect of degeneracy with cosmology (de Putter et al, in preparation)

Will soon be possible to constrain $|\Delta|$, powerful consistency check!!!

Conclusions

- Precision cosmology means that we can start (or prepare for) constraining interesting physical quantities.
- Neutrino properties: absolute mass scale, number of families, maybe hierarchy
- $\Sigma m\nu < 0.3$ eV (95%)
- N_{eff} consistent with 3.04 (error of ~ 1 , 95%)
- The cosmic neutrino background is there!
- Large future surveys means that sub % effects become detectable, which brings in a whole new set of challenges and opportunities (e.g., mass hierarchy)

END

Bayesian Evidence

$$E = \int \mathcal{L}(\theta) \text{Pr}(\theta) d\theta.$$

it does not focus on the best-fitting parameters of the model, but rather asks “of all the parameter values you thought were viable before the data came along, how well on average did they fit the data?”

$$P(H|D) = \frac{P(D|H)P(H)}{P(D)} \quad \text{Bayes}$$

$$P(\theta|D, H) = \frac{P(D|\theta, H)P(\theta|H)}{P(D|H)} \quad \text{Bayes for parameter estimation}$$

$$\mathcal{E} \equiv P(D|H) = \int d^n \theta P(D|\theta, H)P(\theta|H) \quad \text{Bayes for model itself}$$

Computationally expensive! (there are packages to help out there e.g. cosmonest)

In the Laplace approximation can be computed with the same framework as the Fisher matrix

A “frequentist” approach

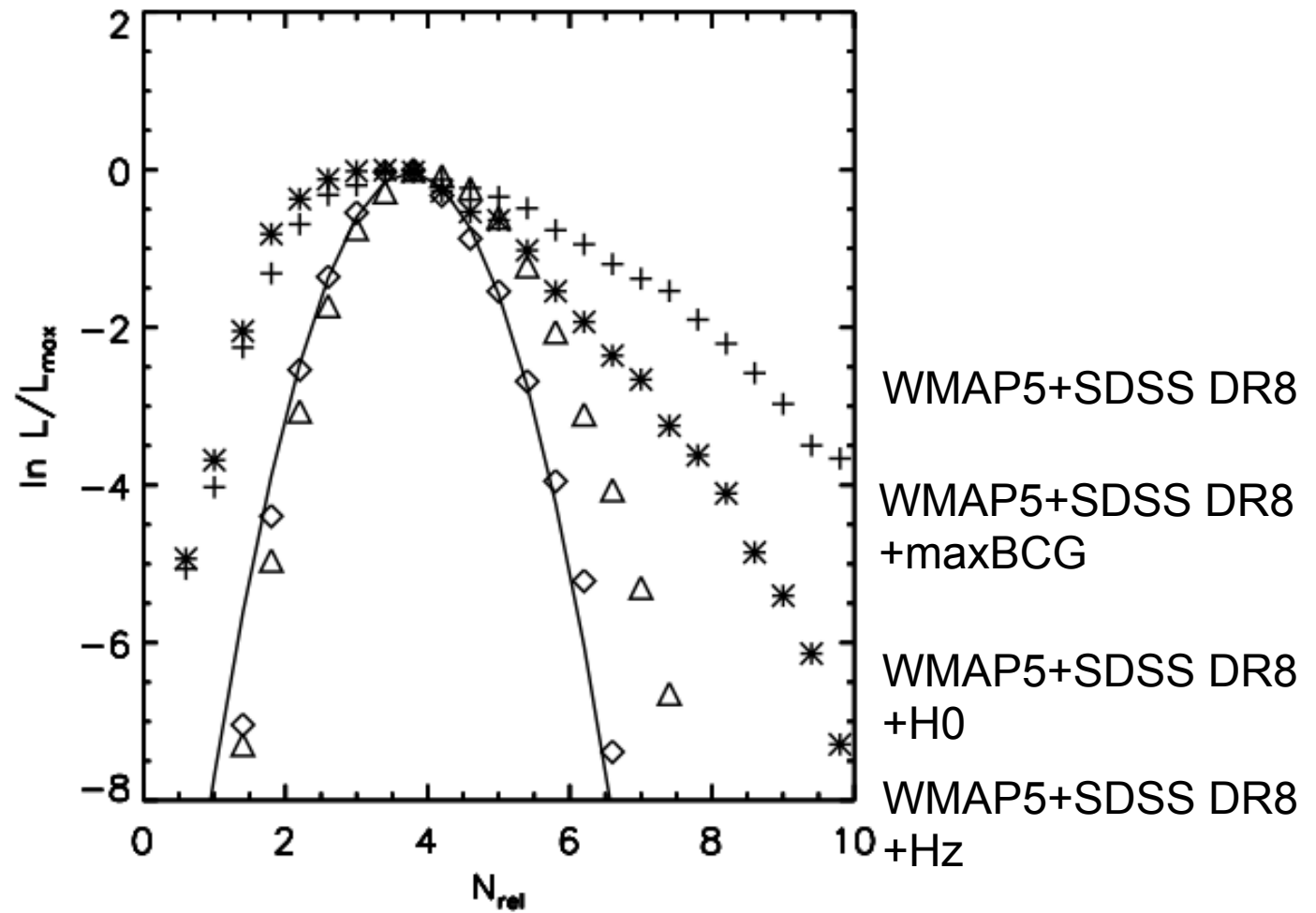
Profile likelihood ratio

Say you have n uninteresting parameters and one, θ that you are interested in e.g. $m\nu$ or N_{eff} . For each value of θ find the maximum likelihood L_m regardless of the values assumed by the other parameters (max of the conditional likelihood). Then consider L_m/L_{max} as a function of θ .

Pros: there's no prior in here

Cons: interpretation of confidence levels is more complex.

How does it look like



Reid et al 2010

Neutrino properties

Robust neutrino constraints...

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

DATA: WMAP5 H0 from Riess et al 2009 $h=0.74\pm 0.036$

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)

Bayesian and Frequentist upper **95% C.L.** bound on $\sum m_\nu$

model	base dataset	-	+maxBCG	+ H_0	+maxBCG+ H_0
Λ CDM	WMAP5	1.3	1.1	0.59	0.40
Λ CDM	WMAP5+BAO+SN	0.67	0.35	0.59	0.31
Λ CDM + α	WMAP5	1.34	1.25	0.54	0.39
Λ CDM + r	WMAP5	1.36	1.18	0.83	0.40
w CDM	WMAP5+BAO+SN	0.80	0.52	0.72	0.47
dark coupling	WMAP5+ $\hat{P}_{halo}(k)$ +SN	-	-	0.51	-
Λ CDM	WMAP5	1.3	1.0	0.57	0.41
Λ CDM	WMAP5+BAO+SN	0.71	0.41	0.61	0.30
Λ CDM + α	WMAP5	1.28	1.17	0.63	0.43
Λ CDM + r	WMAP5	1.23	0.86	0.72	0.30
w CDM	WMAP5+BAO+SN	0.82	0.46	0.74	0.44
dark coupling	WMAP5+ $\hat{P}_{halo}(k)$ +SN	-	-	0.56	-

Bayesian

Frequentist

Dirac or Majorana? \longleftrightarrow hierarchy

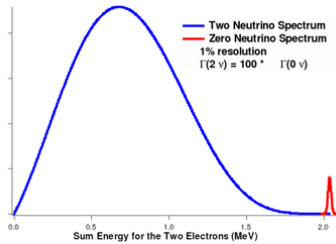
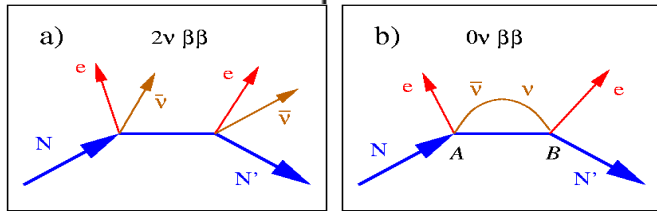
Are neutrinos their own anti-particle?(are they Majorana or Dirac?)

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

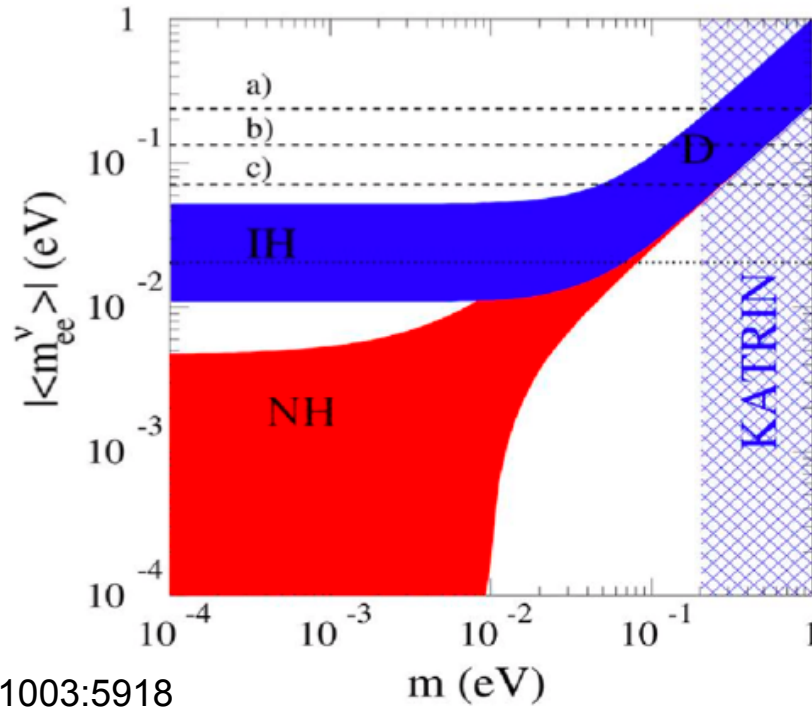
Yes

No

Because Dirac OR because below threshold (still unknown)?

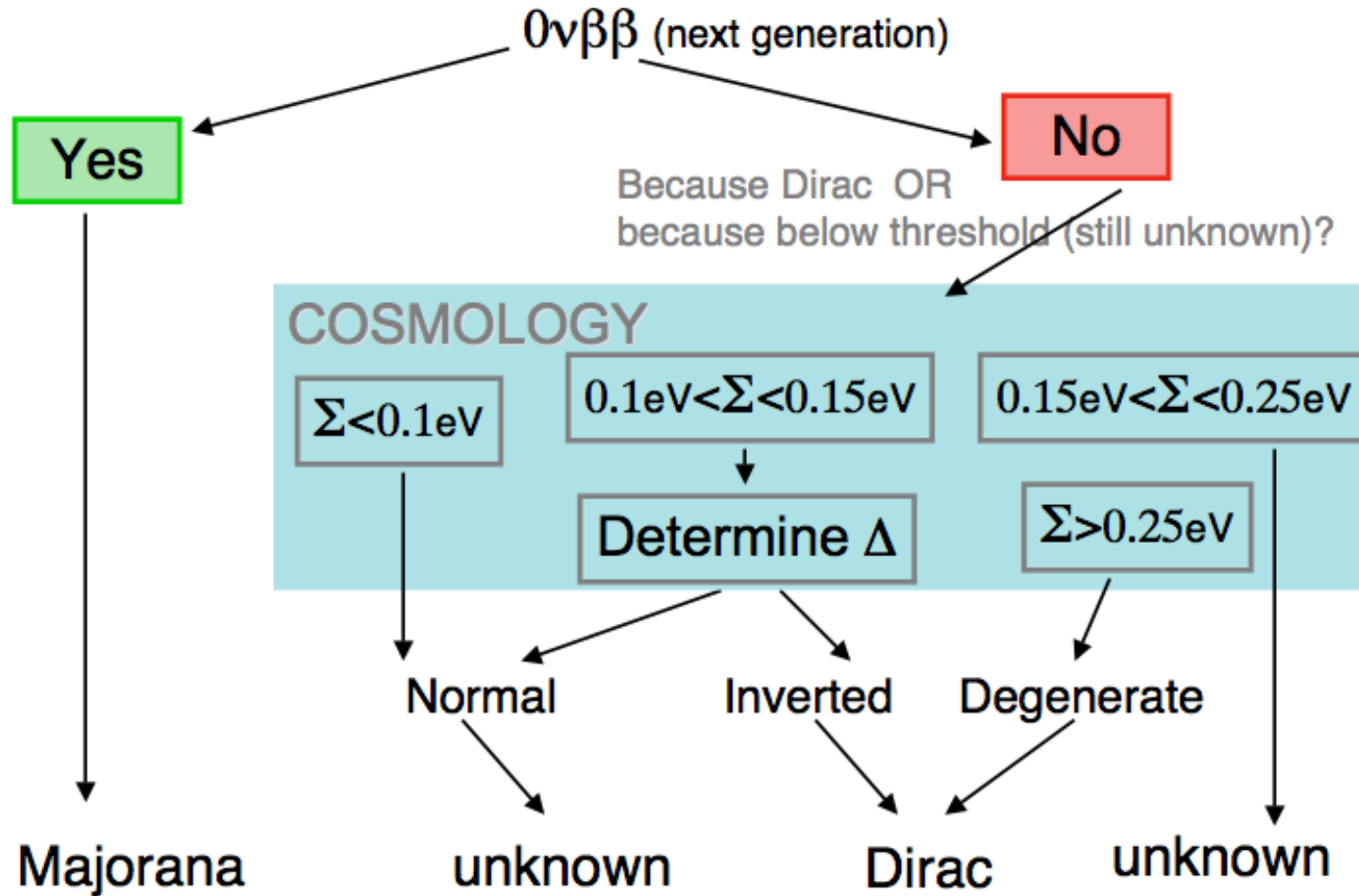


Majorana



Future surveys can help!

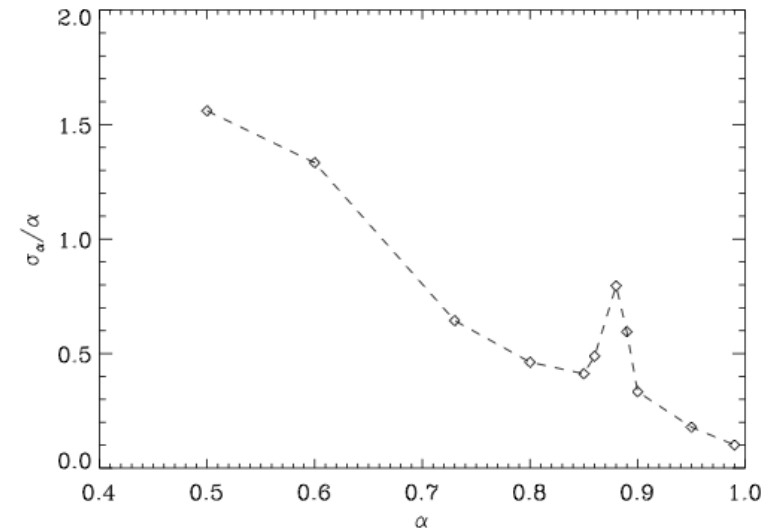
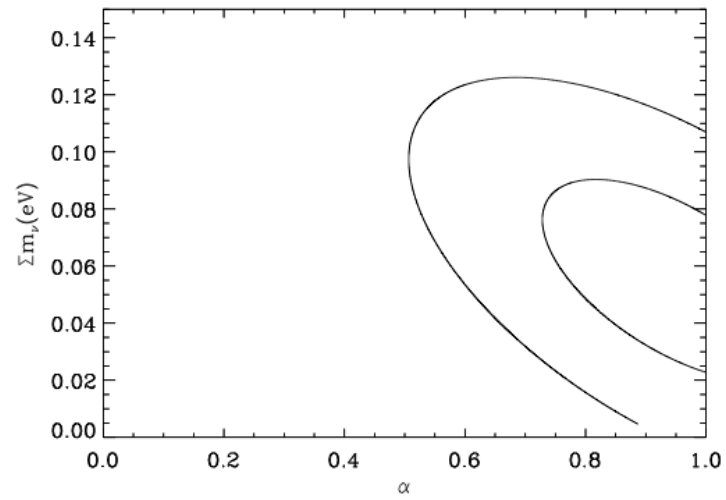
Are neutrinos their own anti-particle?(are they Majorana or Dirac?)



aside

$$m_3 = \alpha \sum m_\nu. \quad m_1 = m_2$$

De Bernardis et al. 09,
Slosar 06



In details....

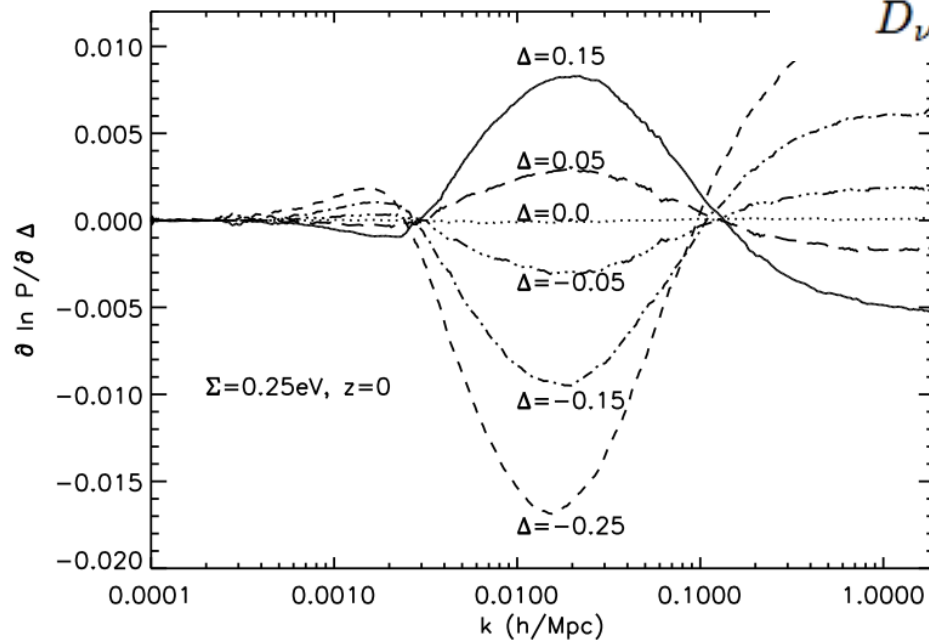
$$\frac{k^3 P(k; z)}{2\pi^2} = \Delta_R^2 \frac{2k^2}{5H_0^2 \Omega_m^2} D_\nu^2(k, z) T^2(k) \left(\frac{k}{k_0}\right)^{(n_s-1)}$$

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

$$D_\nu(k, z) = D(k, z) \quad k < k_{\text{fs},m}$$

$$D_\nu(k, z) = (1 - f_{\nu,m}) D(z)^{(1-p_m)} \quad k_{\text{fs},m} < k < k_{\text{fs},\Sigma}$$

$$D_\nu(k, z) = (1 - f_{\nu,\Sigma}) D(z)^{(1-p_\Sigma)} \quad k > k_{\text{fs},\Sigma}$$



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

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