Impact of neutrinos on cosmology

μ-Collider and NF
Cosenor's House
October 22, 2007

Dave Wark
Imperial/RAL

Impact of cosmology on neutrinos

- This is a spectator's view.
- I will concentrate on those topics competitive or complementary to a NF.
- "Cosmology" will be loosely interpreted to mean any neutrino coming from outside the Earth's atmosphere.

Impact of cosmology on ν

- Neutrino oscillations were first observed with solar and atmospheric neutrinos.
- Can we get more information?
  - Solar Neutrinos
  - Atmospheric Neutrinos
  - Relic Neutrinos
  - Supernovae Neutrinos
  - TeV++ Neutrinos

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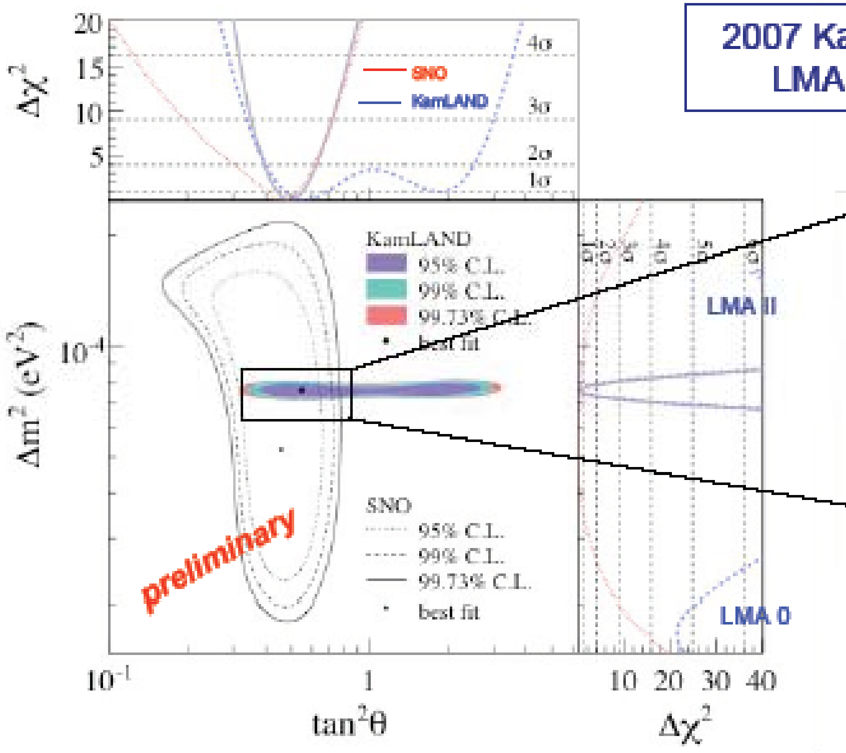
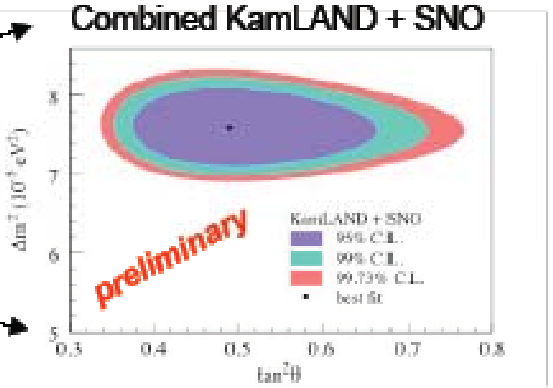
Oscillation Parameter Space

2007 KamLAND result excludes LMA 0 and LMA II at > 4σ



SNO ref: Phys Rev C 72, 055502(2005)

Combined KamLAND + SNO



Combined Best-Fit Parameters:

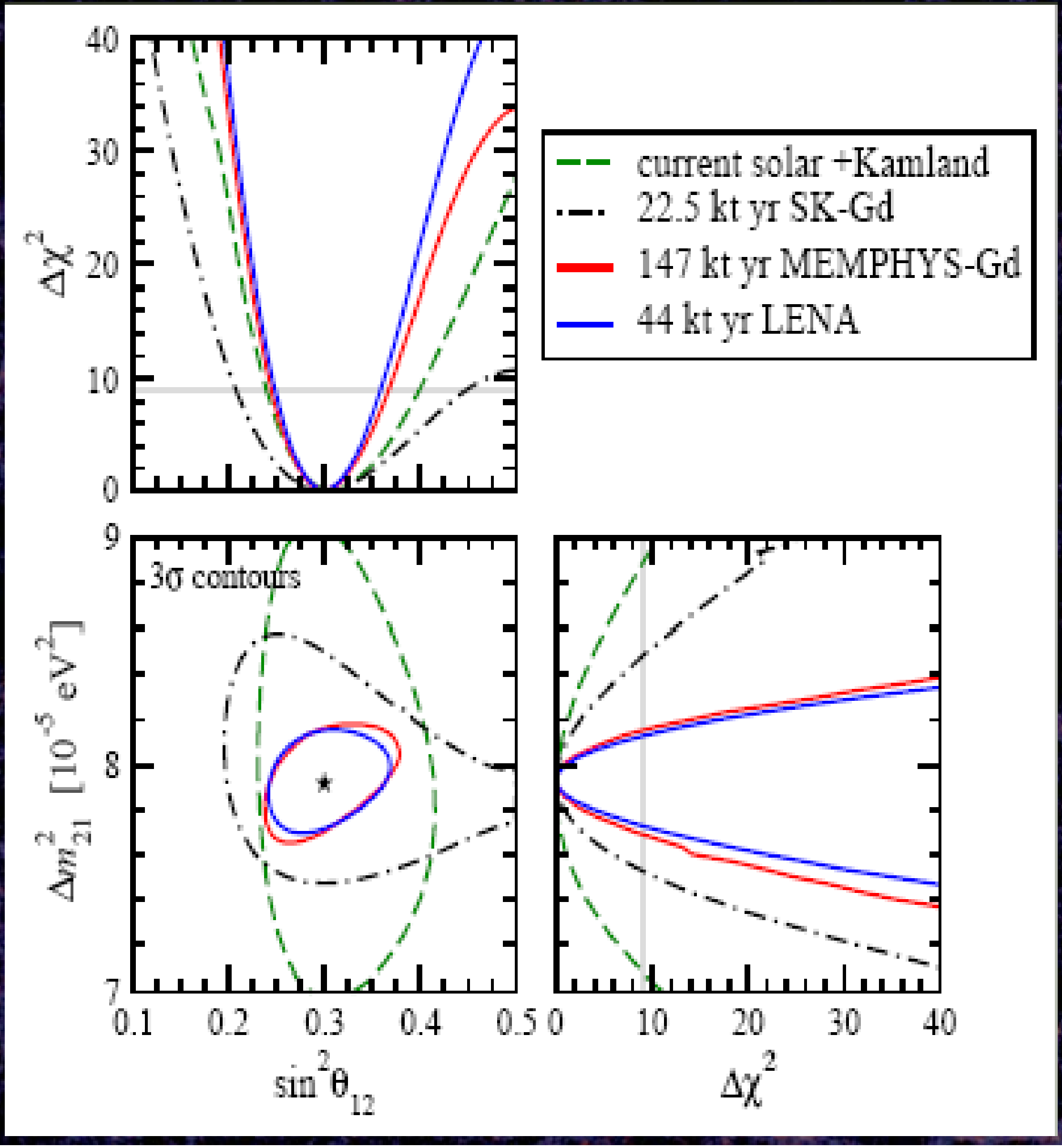
$$\Delta m^2 = 7.59^{+0.21}_{-0.20} \times 10^{-5}\ \text{eV}^2$$

$$\tan^2\theta = 0.49^{+0.07}_{-0.05}$$

(slide from Lauren Hsu)

Improvements from Future Large Facilities

I got the plot from Jose Valle, who got it from T. Schwetz.



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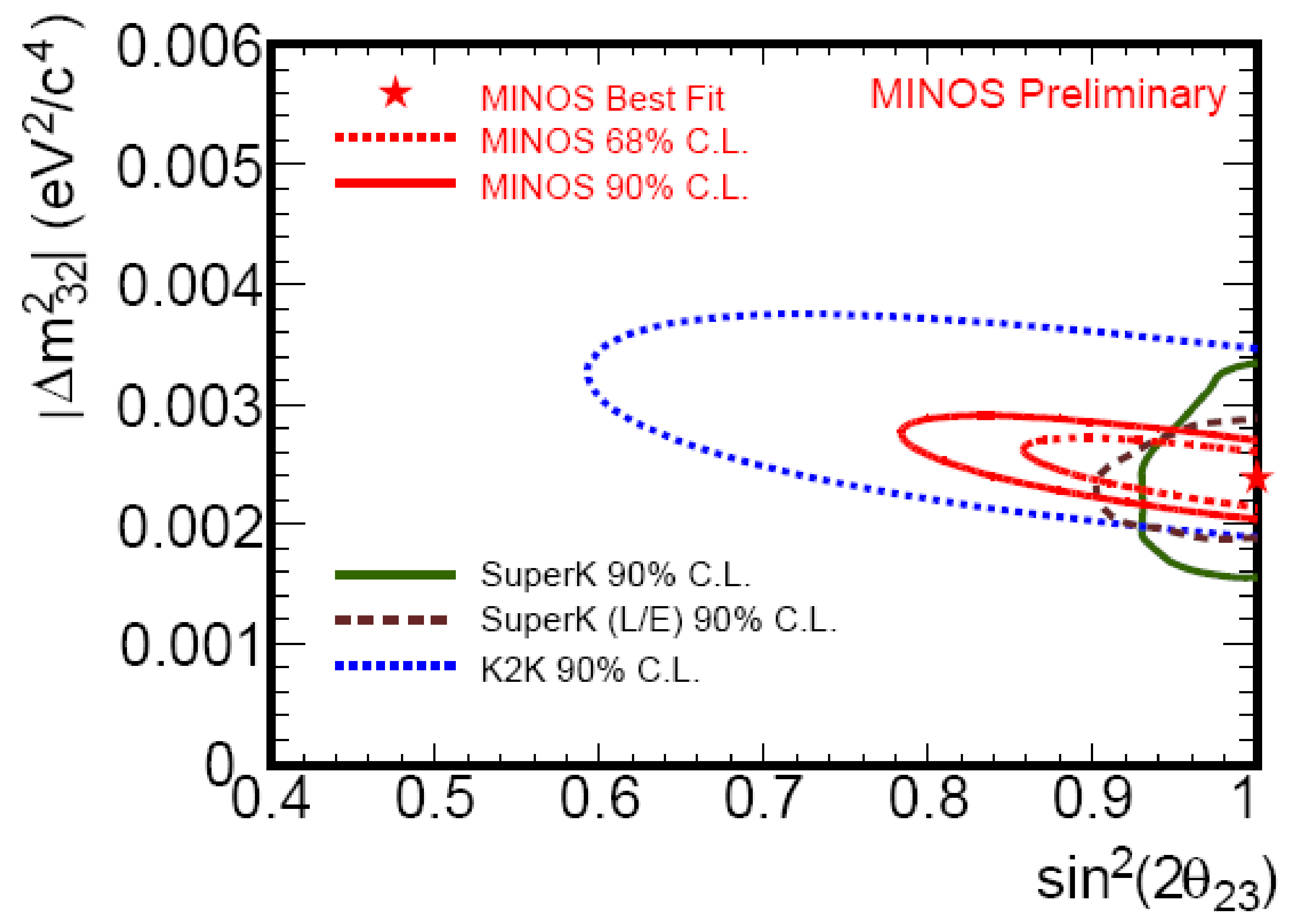
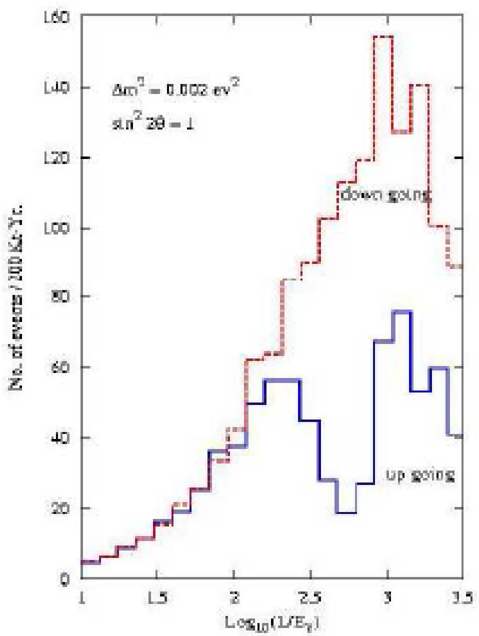
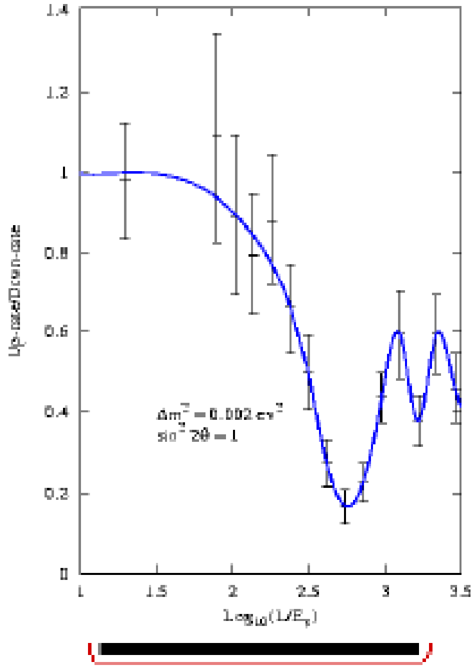
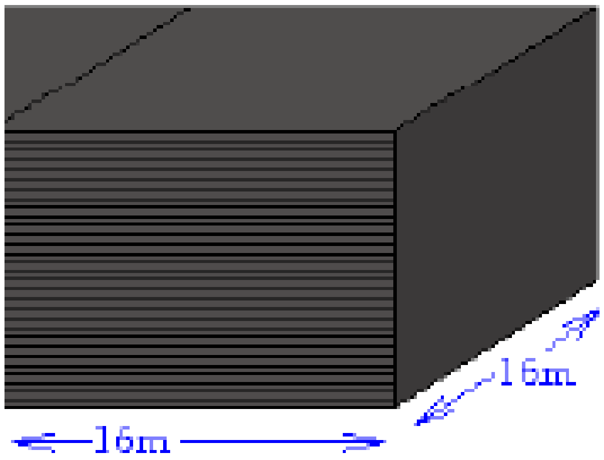
Existing θ_{23} Limits



A new player in town - INO







- Magnetized calorimeter.
- 140 horizontal iron plates each
  Glass RPC.
- Modular structure.

Experiment	$\lvert\Delta m^2_{31}\rvert$	$\sin^2\theta_{23}$
Current	23%	33%
MINOS+CNGS	13%	38%
T2K (5 yrs)	6%	22%
NOνA (5 yrs)	13%	42%
Combination	4.5%	20%
SK20 (1.84 MTy)	17%	24%
INO (250 kTy)	10%	30%

Deviation from Maximal Mixing

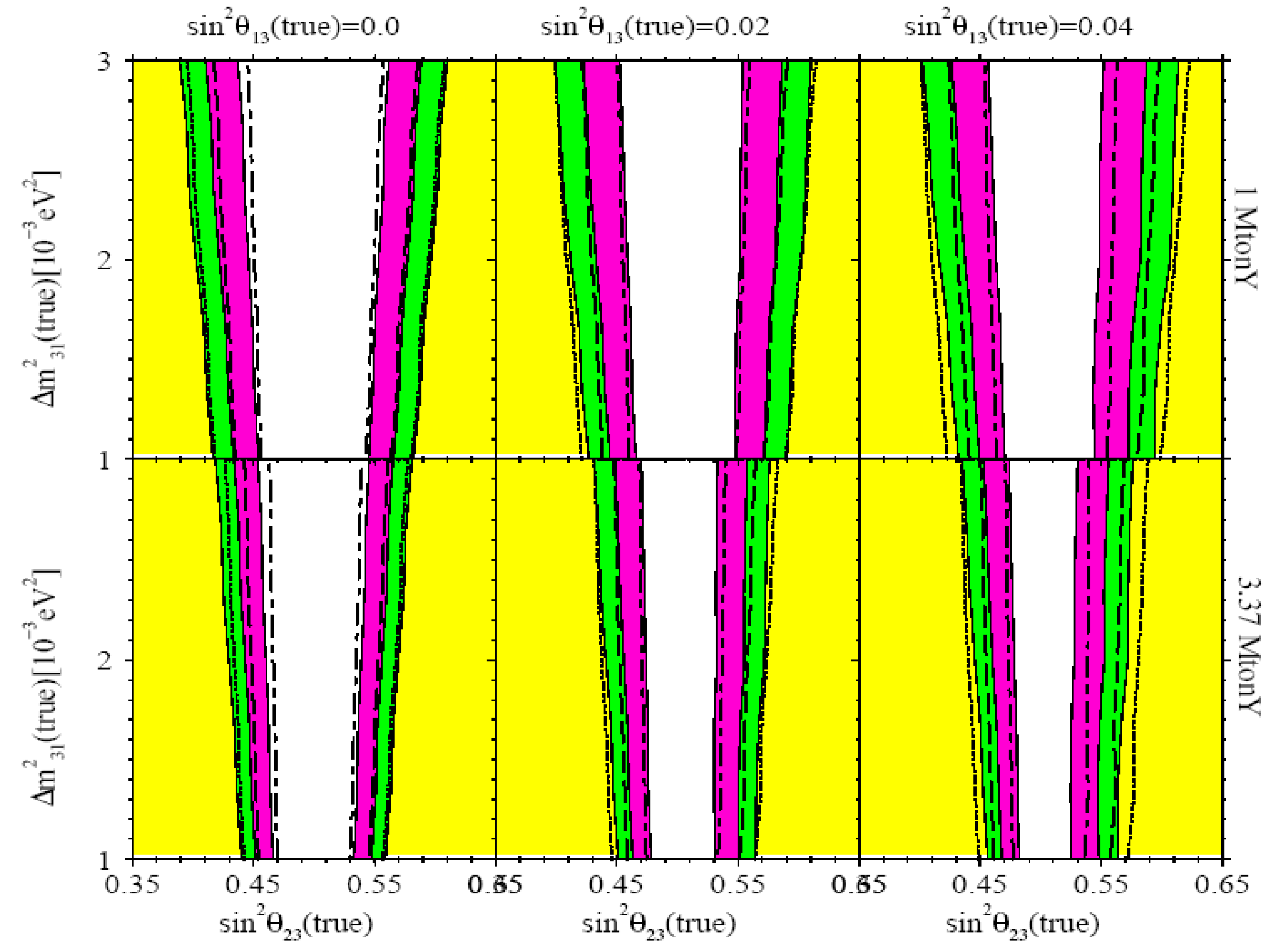
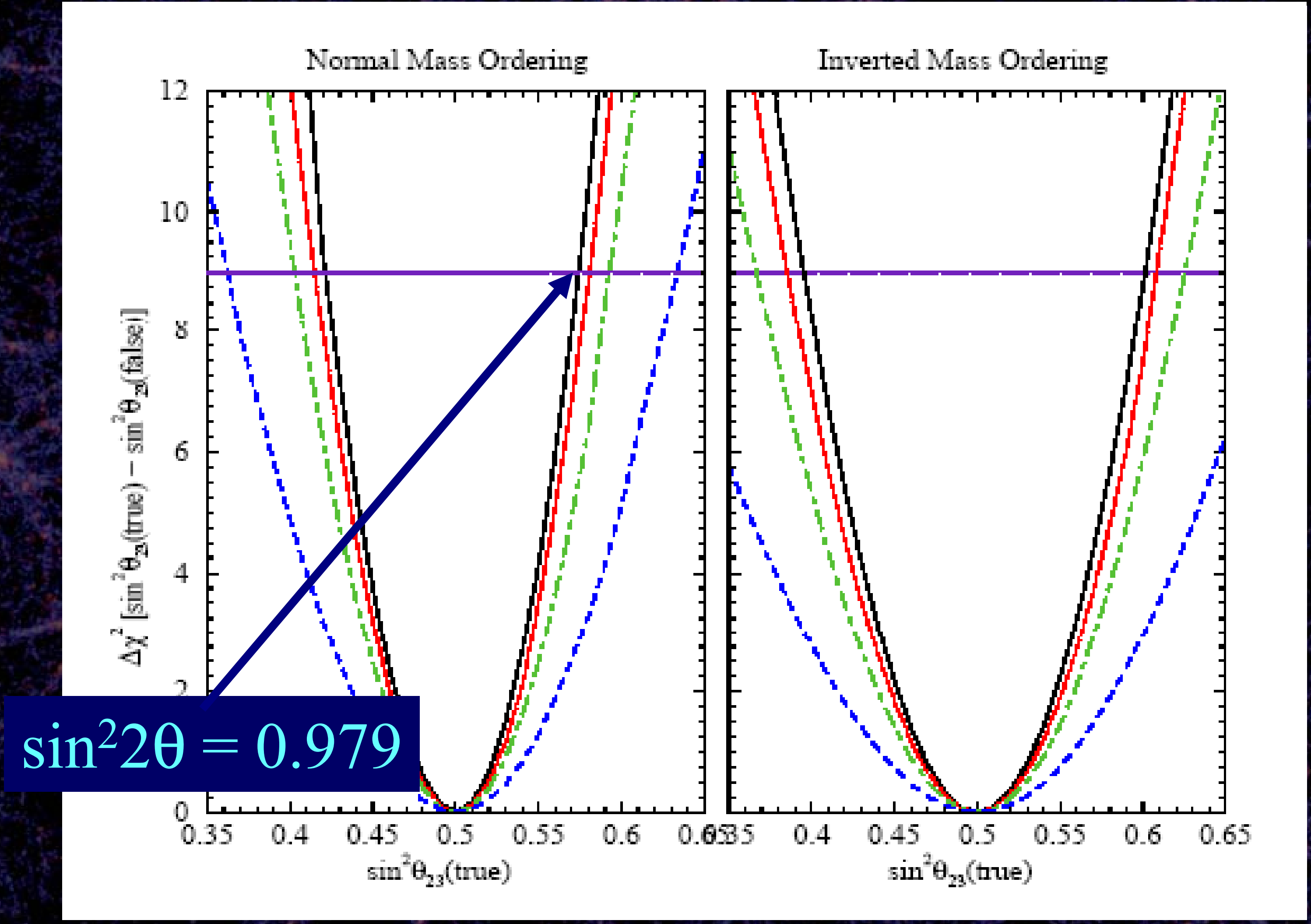


Figure 7: The regions of Δm^2_{31}(true) and $\sin^2\theta_{23}$(true) where maximal θ_{23} mixing can be rejected by using 1 MtonY (upper panels) and 3.37 MtonY (lower panels) atmospheric neutrino data in ICAL at 1σ (white band), 2σ (blue band) and 3σ (green band). The hollow dark lines show the corresponding bands for neutrinos travelling in pure vacuum. Benchmark parametric values of Table 2 have been assumed.

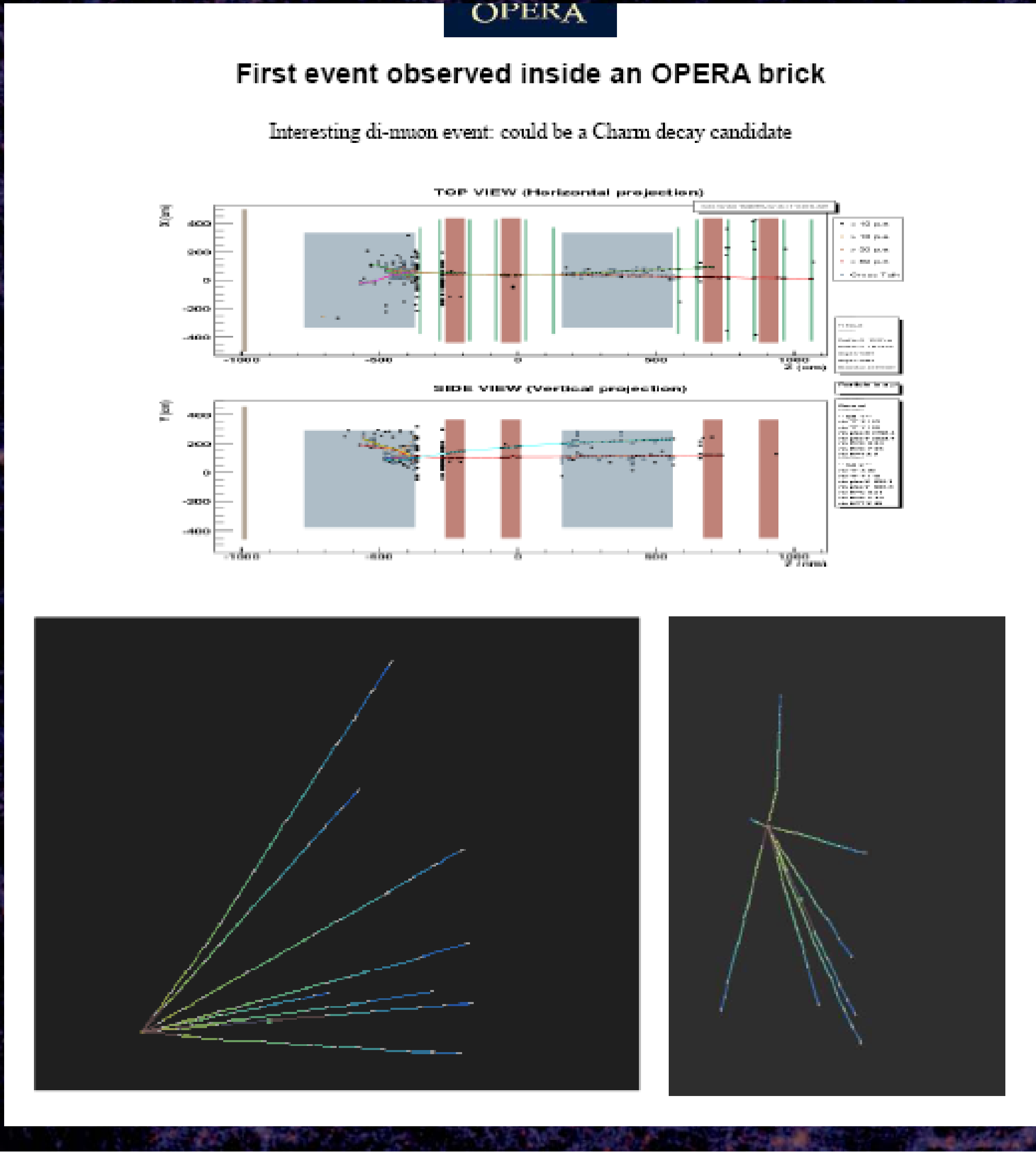
Sensitivity to octant of θ_{23}



$\sin^2 2\theta = 0.979$

Choubey and Roy

Figure 11: $\Delta\chi^2$ as a function of $\sin^2\theta_{23}$(true), showing the octant sensitivity of ICAL for the normal (left panel) and inverted (right panel) neutrino mass ordering. The blue short-dashed lines, green dot-dashed lines, red dotted lines and black solid lines are for $\sin^2\theta_{13}(\text{true}) = 0.01$, 0.02, 0.03 and 0.04 respectively.



OPERA

First event observed inside an OPERA brick

Interesting di-muon event: could be a Charm decay candidate

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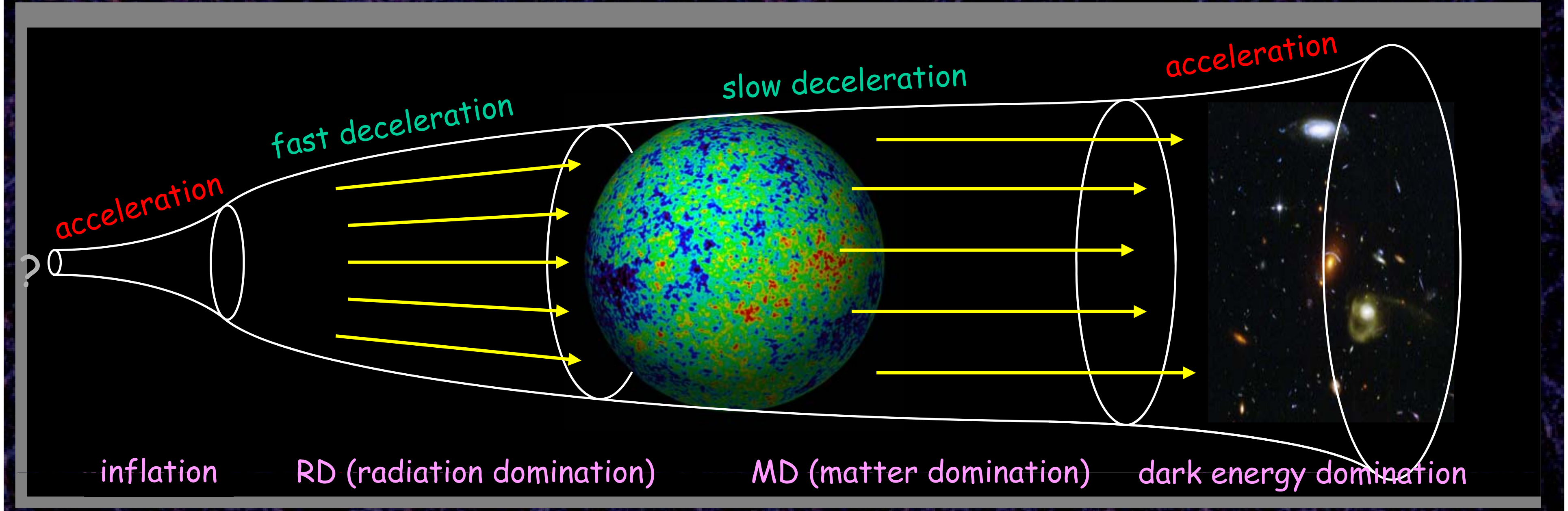
Evolution of the Universe

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3p)$$

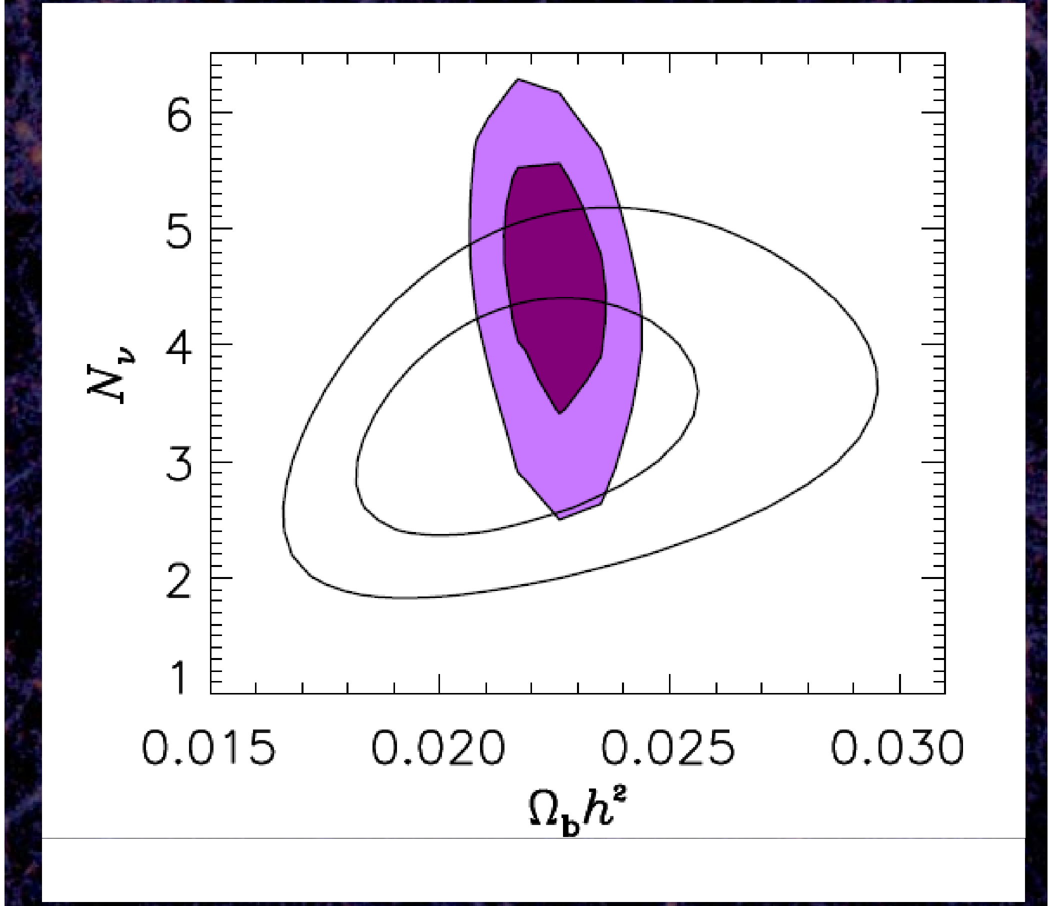


$a(t) \sim e^{Ht}$

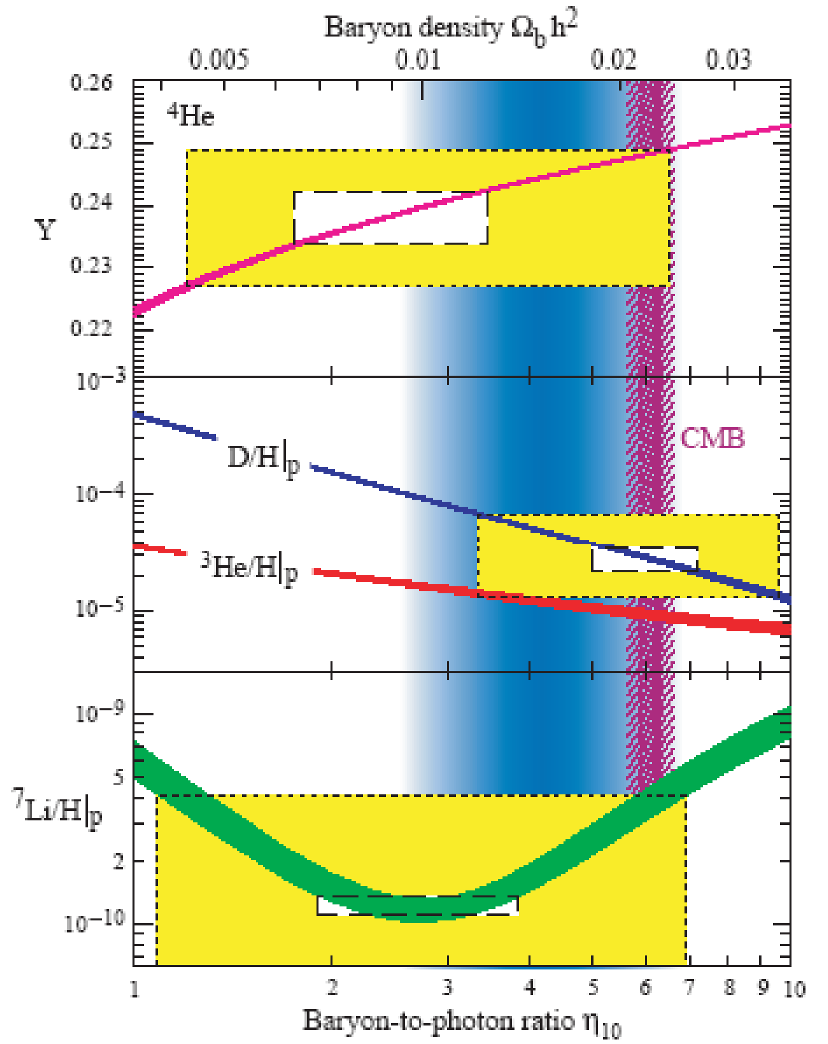
$a(t) \sim t^{1/2}$

$a(t) \sim t^{2/3}$

BBN and N_ν



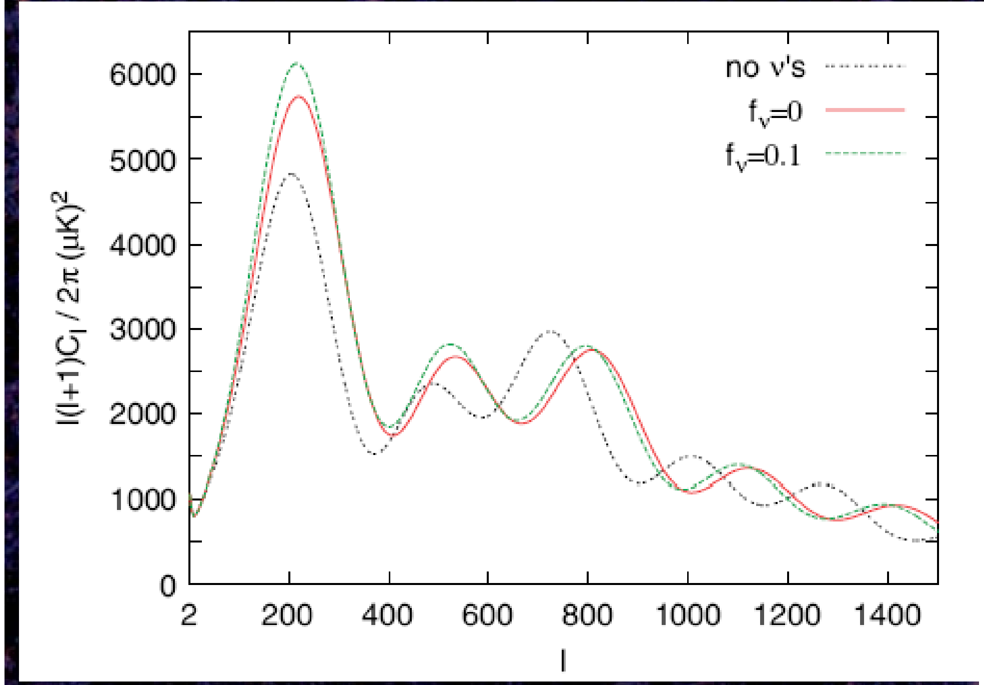
S. Hannestad, arXiv:astro-ph/0510582

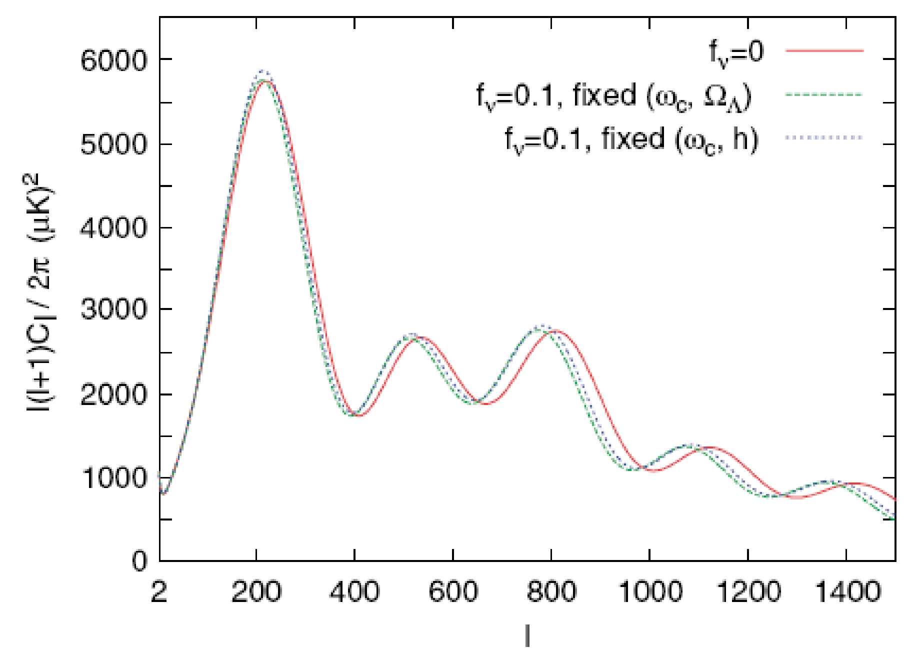


Fields and Sarkar, PDG 2004

$N_\nu > 0 \Rightarrow$ Relic ν detected!

Effects of $m_\nu \neq 0$ on the CMBR





No degeneracies…

…but what about covariances

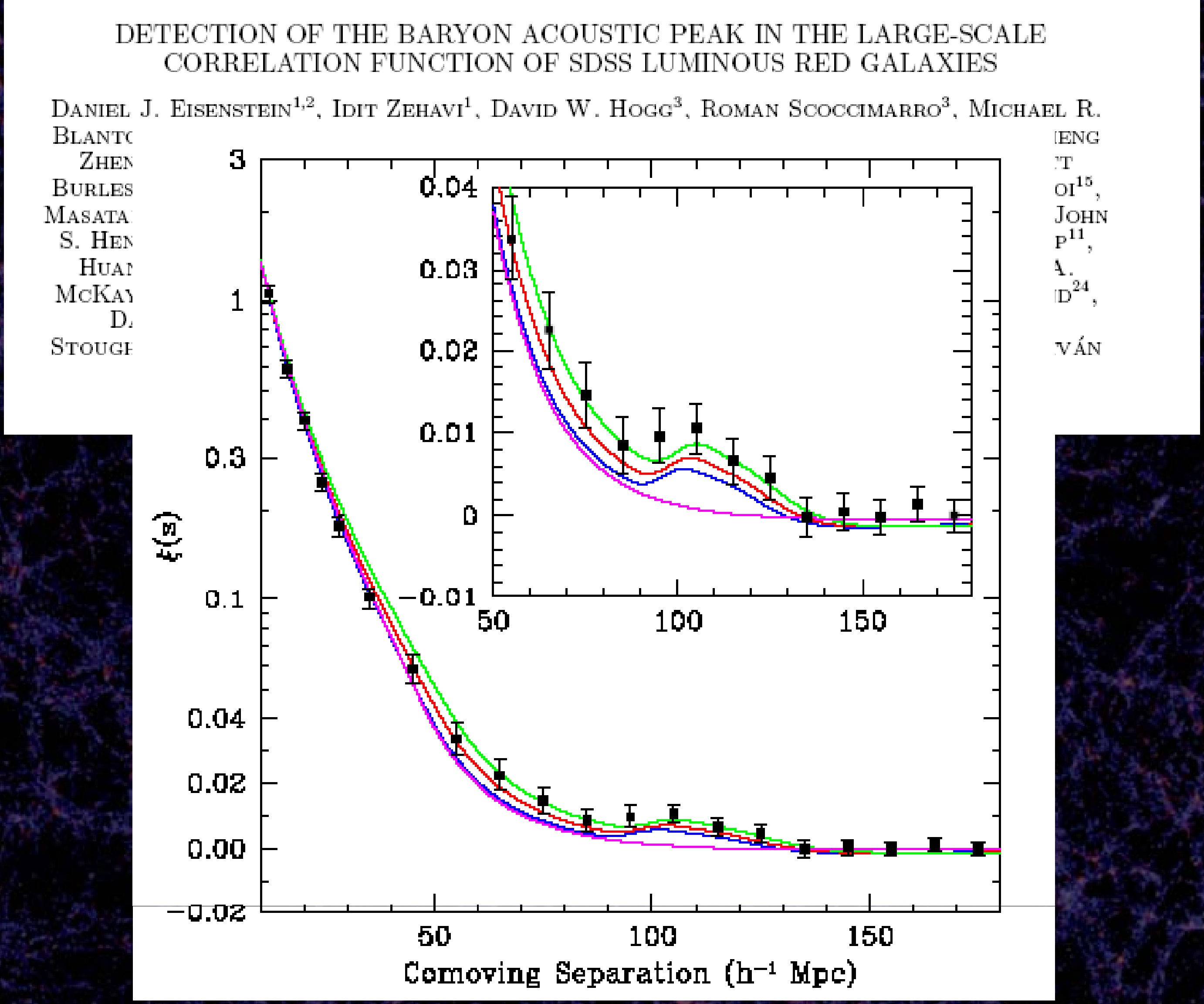
Massive neutrinos and cosmology

Julien Lesgourgues[a,*], Sergio Pastor[b]

Physics Reports 429 (2006) 307–379

Another observable – the BAO

arXiv:astro-ph/0501171v1 10 Jan 2005

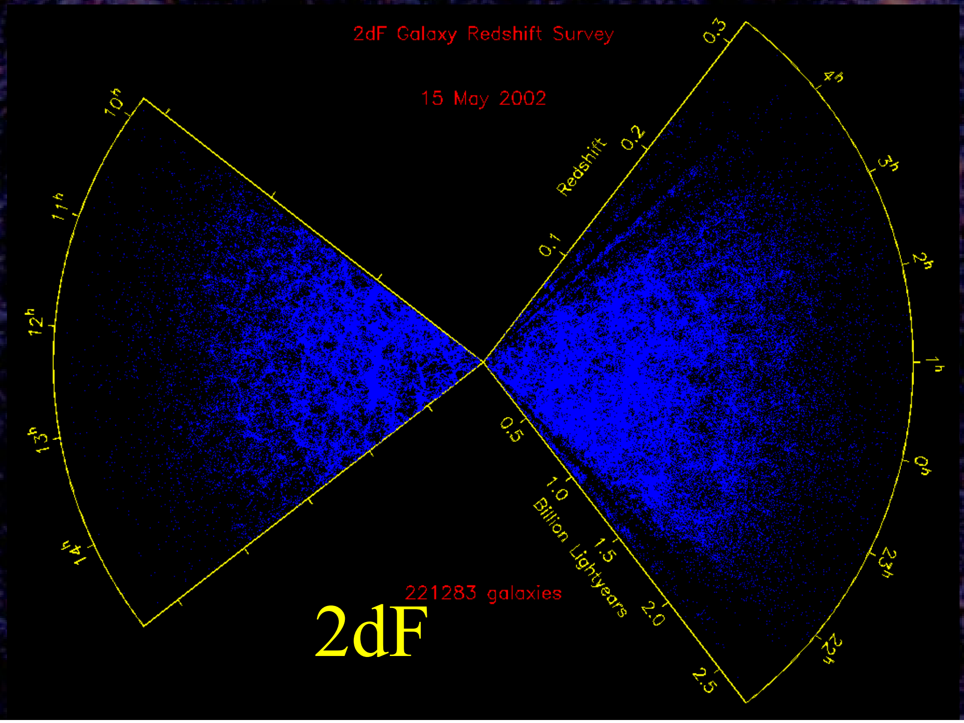


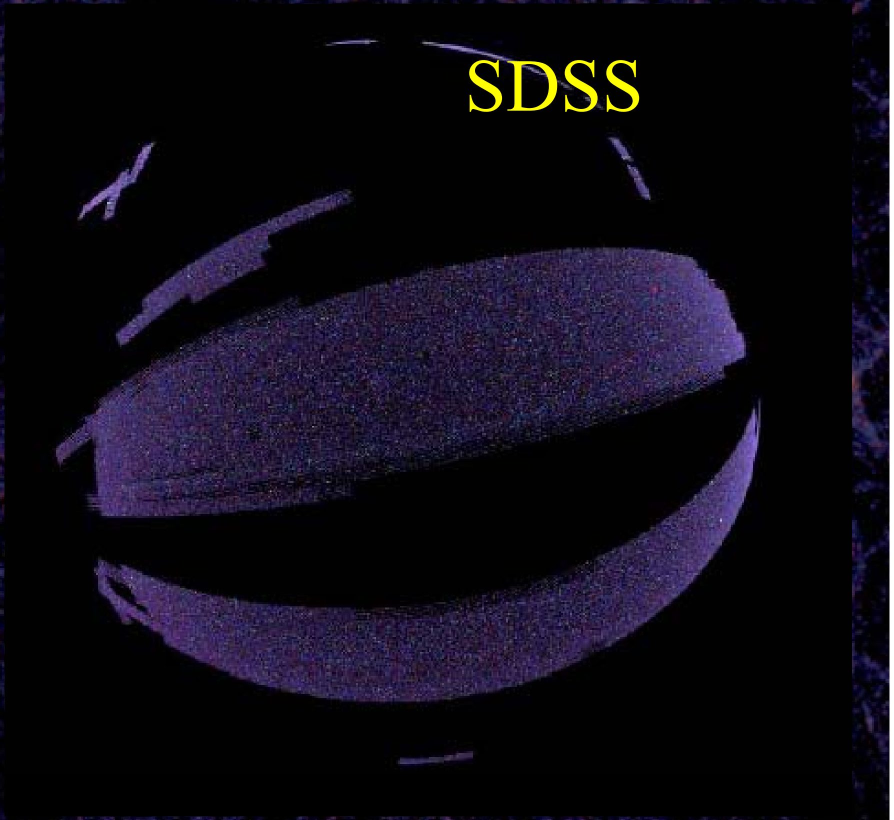
DETECTION OF THE BARYON ACOUSTIC PEAK IN THE LARGE-SCALE
CORRELATION FUNCTION OF SDSS LUMINOUS RED GALAXIES

DANIEL J. EISENSTEIN[1,2], IDIT ZEHAVI[1], DAVID W. HOGG[3], ROMAN SCOCCIMARRO[3], MICHAEL R.
BLANTC … IENG
ZHEN … T
BURLES … OI[15],
MASATA … JOHN
S. HEN … P[11],
HUAN … A.
MCKAY … ID[24],
D…
STOUGH … VÁN

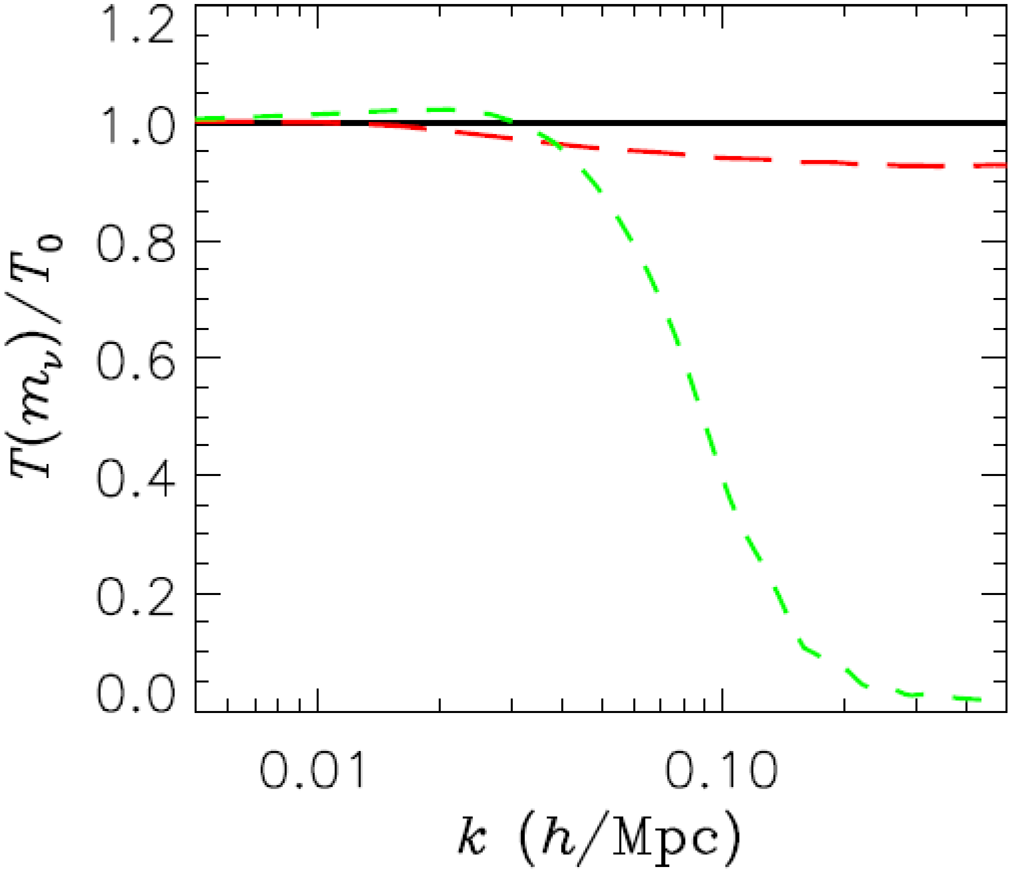
LSS from Galaxy Surveys

With independent data sets from….

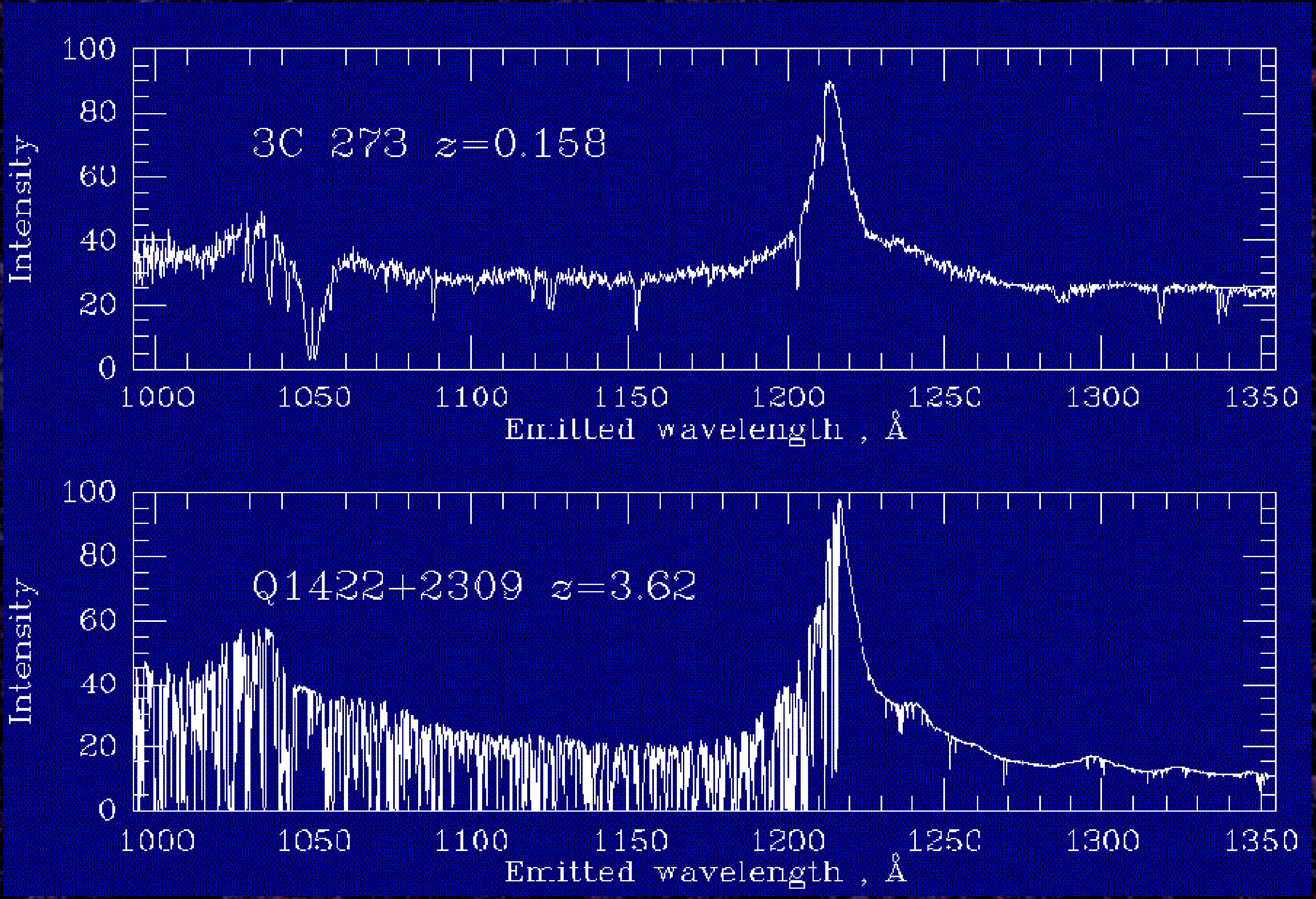




LSS from Galaxy Surveys

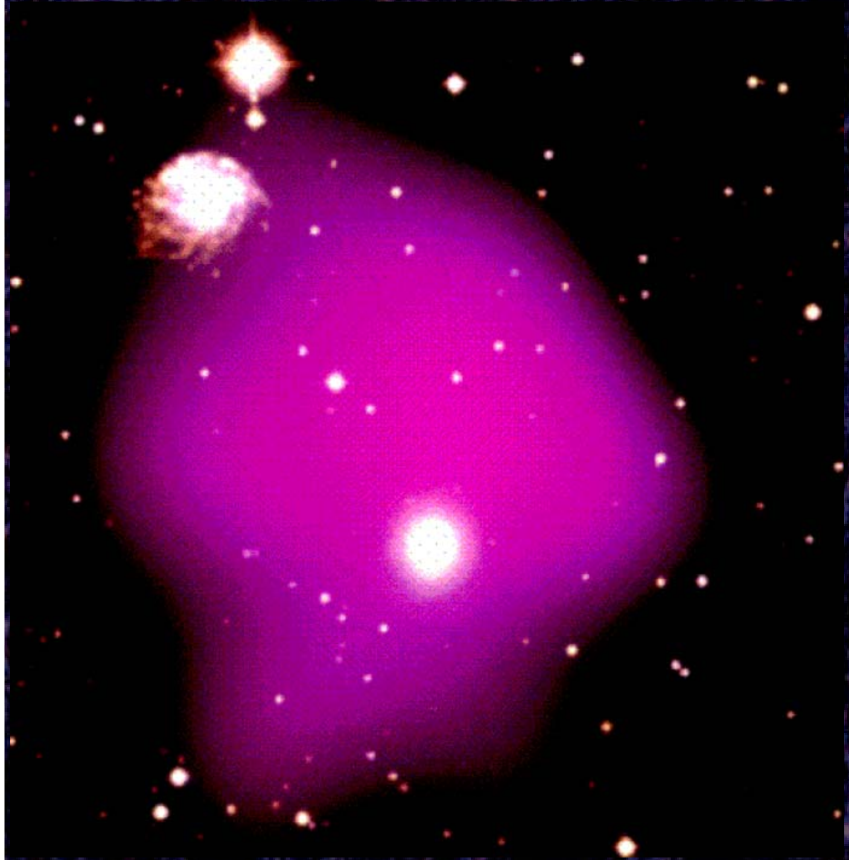


Another observable – the Lyman-α Forest

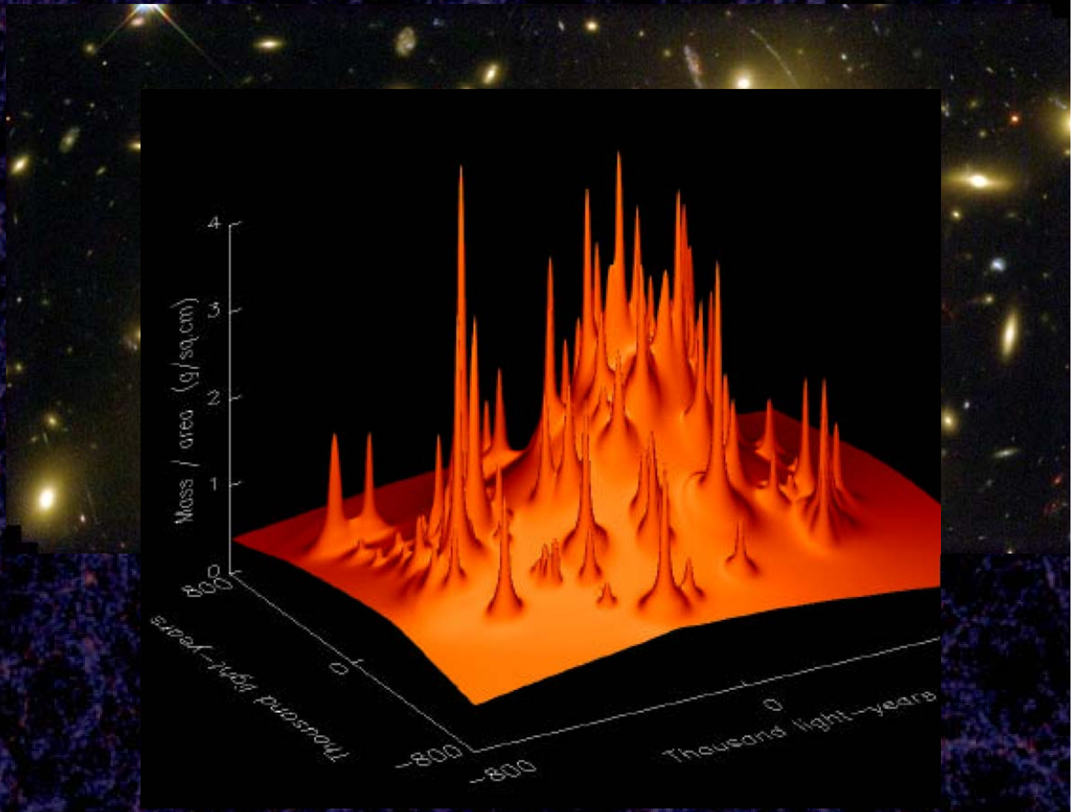


But there is more…

Hot gas in clusters…



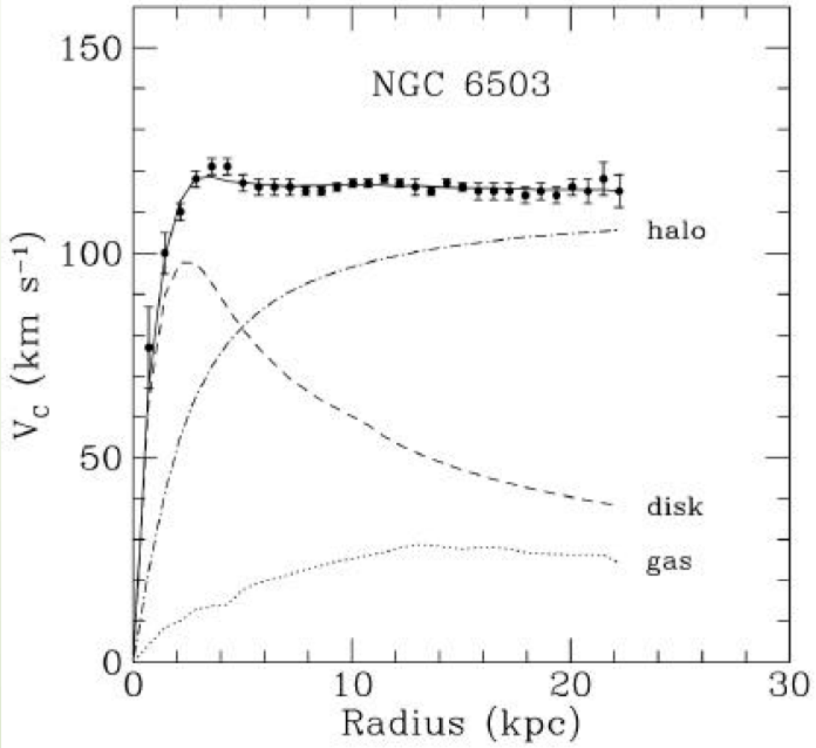
Gravitational lensing…

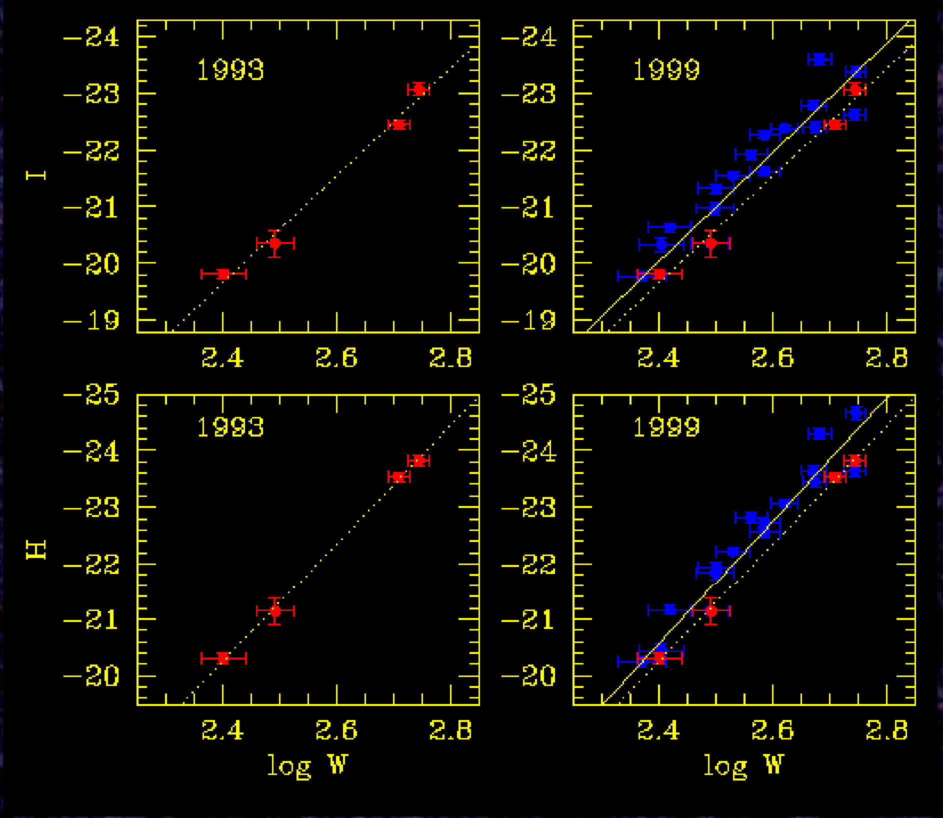


But there is more…

With independent data sets from….

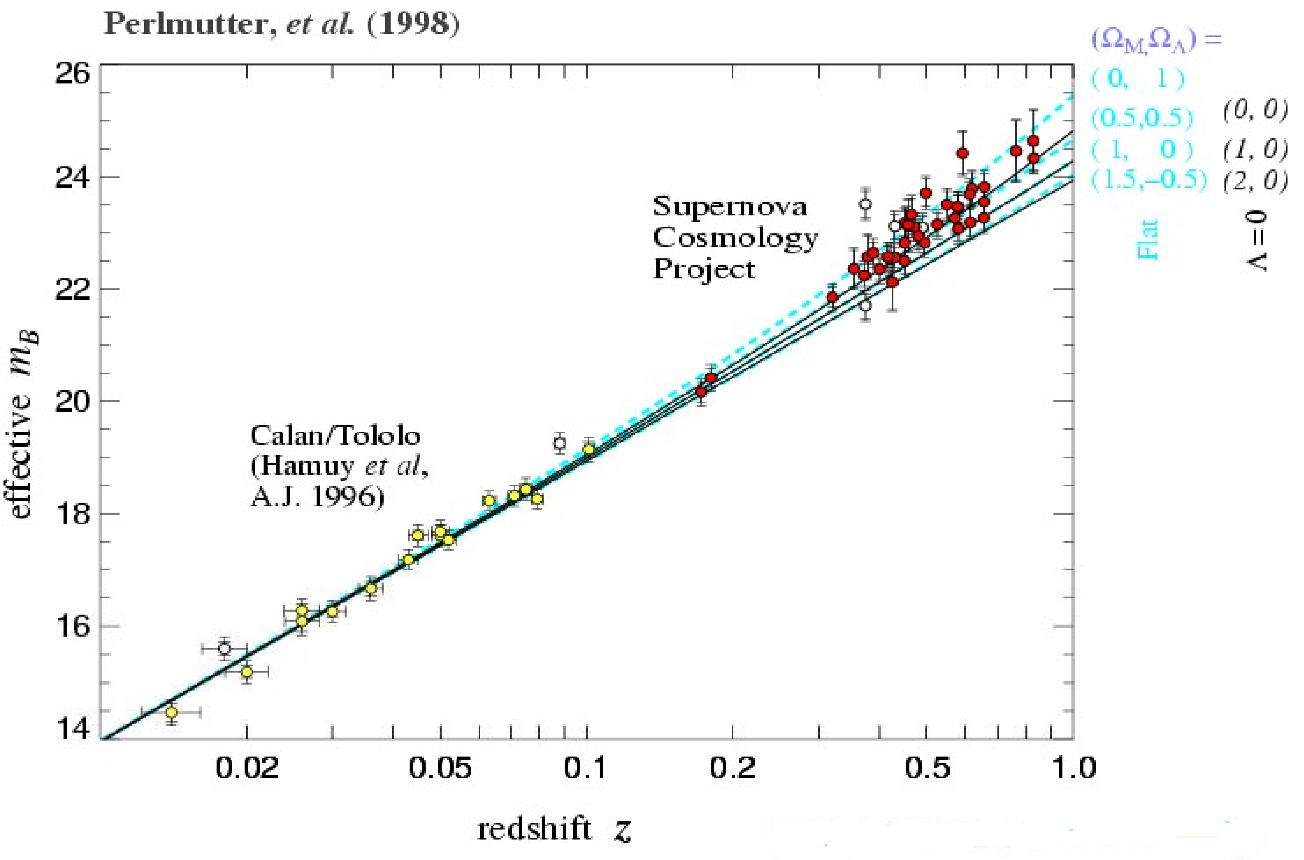
Galaxy rotation curves… HST Key Determination of H_0…



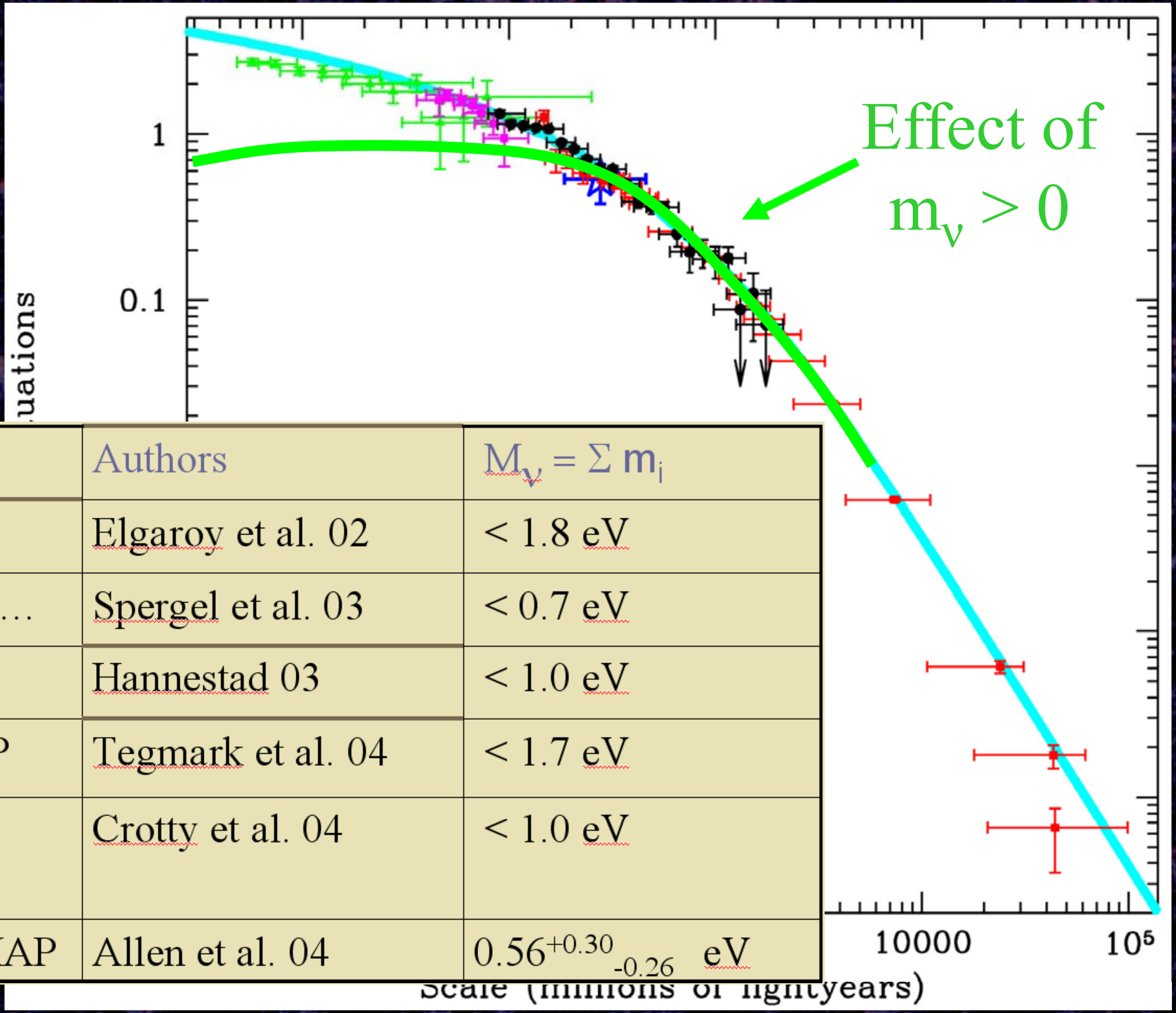


But there is more…

Type 1a supernovae…



Cosmic ν - mass



Effect of $m_\nu > 0$

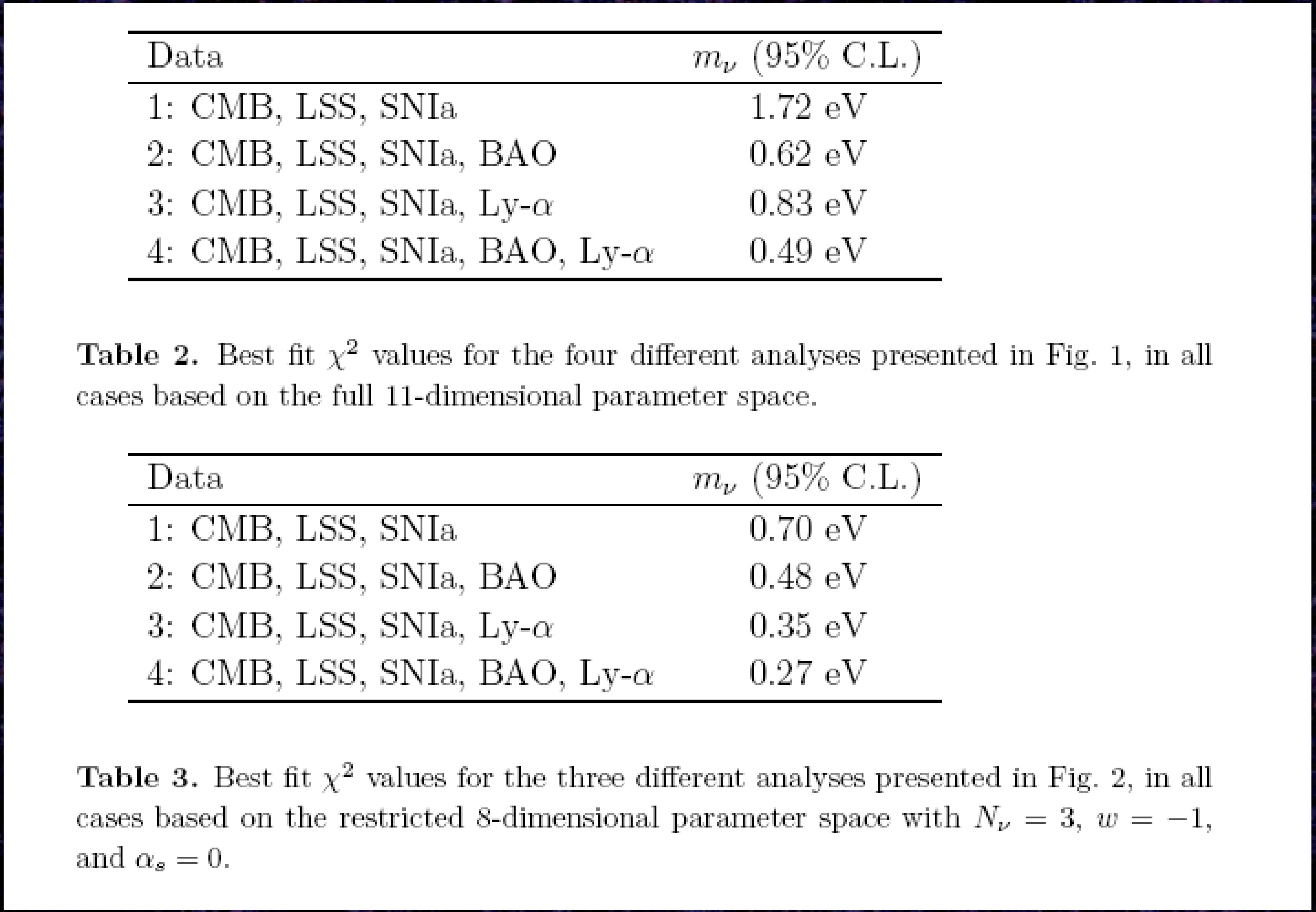
Data	Authors	$M_\nu = \Sigma m_i$
2dFGRS	Elgaroy et al. 02	< 1.8 eV
WMAP+2dF+…	Spergel et al. 03	< 0.7 eV
WMAP+2dF	Hannestad 03	< 1.0 eV
SDSS+WMAP	Tegmark et al. 04	< 1.7 eV
WMAP+2dF+ SDSS	Crotty et al. 04	< 1.0 eV
Clusters +WMAP	Allen et al. 04	$0.56^{+0.30}_{-0.26}$ eV

Potential sensitivity is very high $\Sigma m_\nu < 0.1$

Plot from Max Tegmark's website, table from Ofer Lahav

More Recent Analysis

arXiv:astro-ph/0602155 v2 29 May 2006



Data	m_ν (95% C.L.)
1: CMB, LSS, SNIa	1.72 eV
2: CMB, LSS, SNIa, BAO	0.62 eV
3: CMB, LSS, SNIa, Ly-α	0.83 eV
4: CMB, LSS, SNIa, BAO, Ly-α	0.49 eV

Table 2. Best fit χ^2 values for the four different analyses presented in Fig. 1, in all cases based on the full 11-dimensional parameter space.

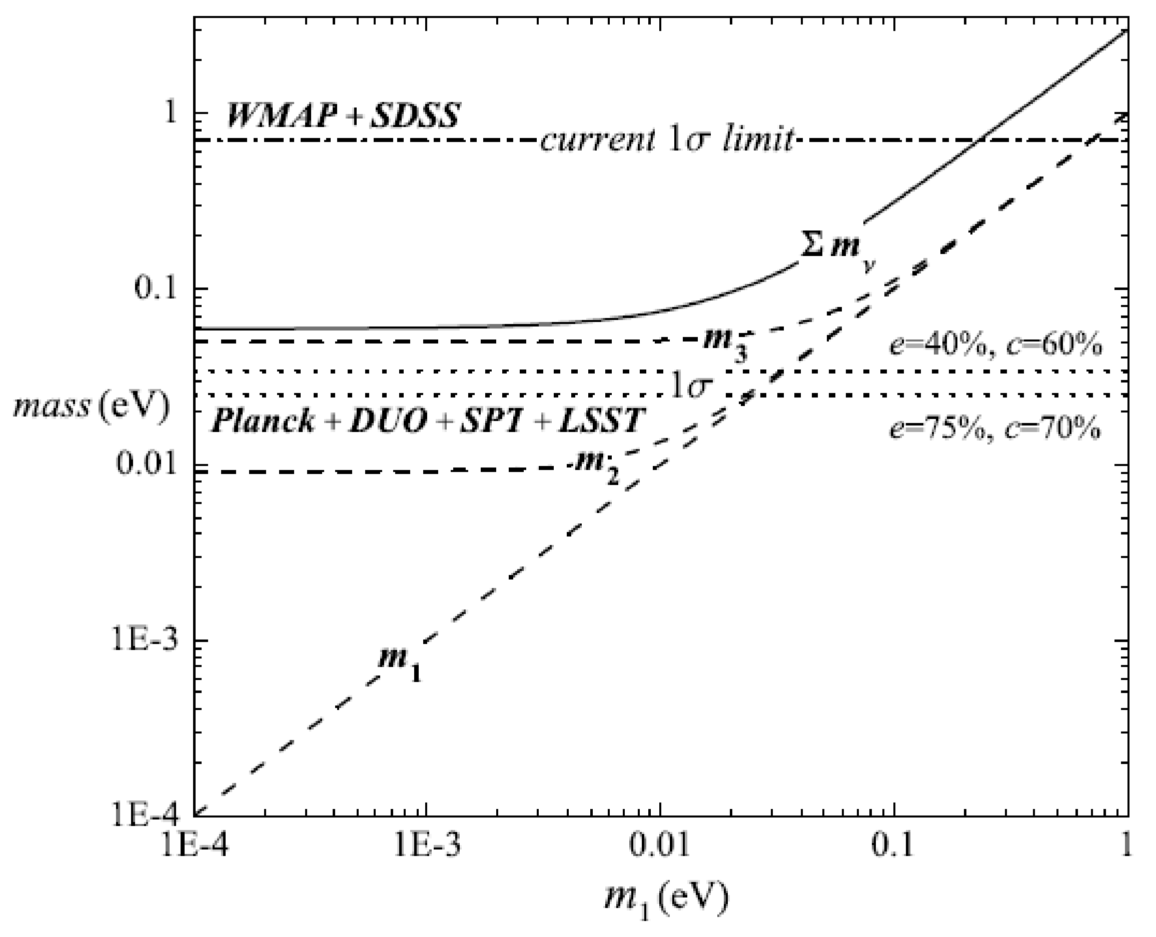
Data	m_ν (95% C.L.)
1: CMB, LSS, SNIa	0.70 eV
2: CMB, LSS, SNIa, BAO	0.48 eV
3: CMB, LSS, SNIa, Ly-α	0.35 eV
4: CMB, LSS, SNIa, BAO, Ly-α	0.27 eV

Table 3. Best fit χ^2 values for the three different analyses presented in Fig. 2, in all cases based on the restricted 8-dimensional parameter space with $N_\nu = 3$, $w = -1$, and $\alpha_s = 0$.

arXiv:hep-ph/0602058v1 7 Feb 2006

How well could you do?

arXiv:astro-ph/0505390 v1 19 May 2005

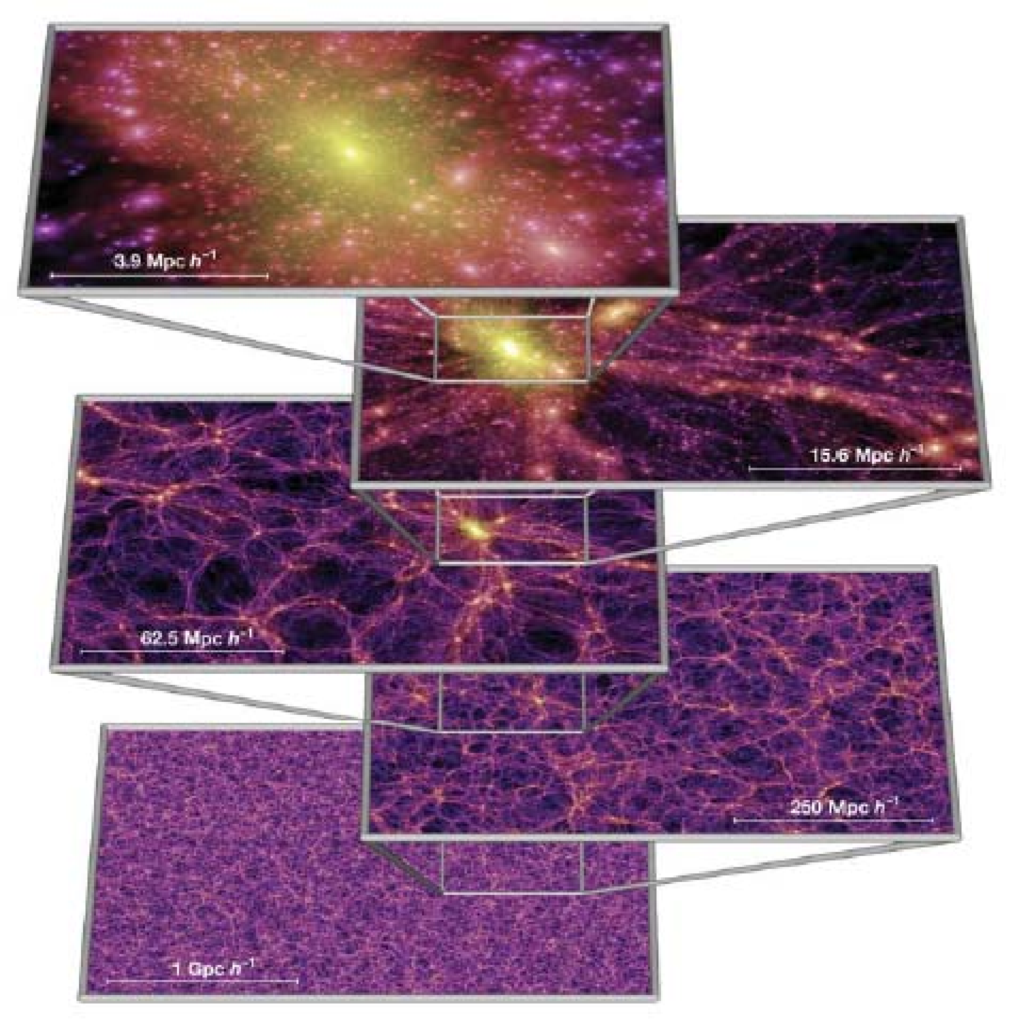


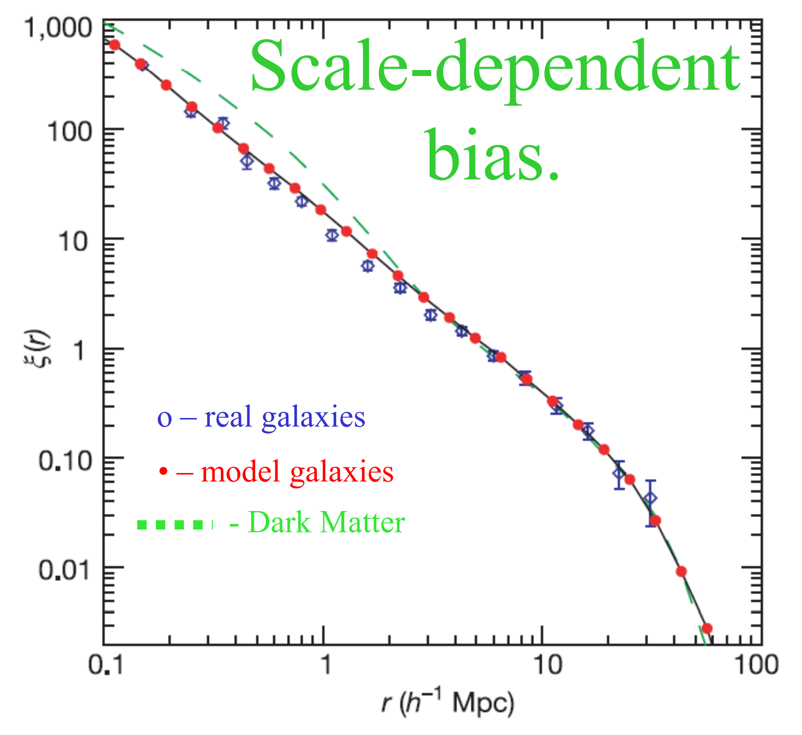
This would determine the mass hierarchy…

…if you believed it.

And what do we compare all this to?

Virgo consortium has published
the Millenium Run



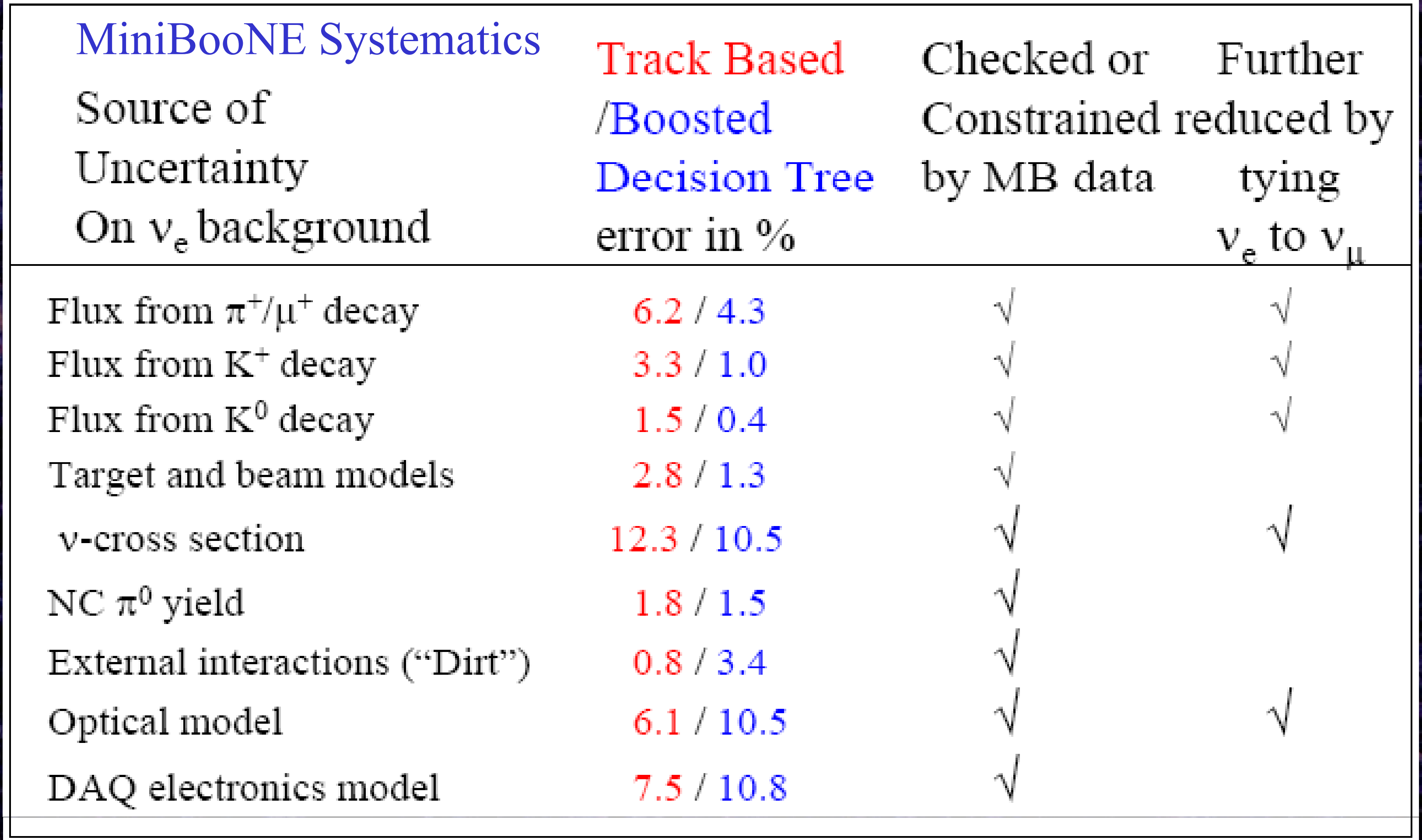


Scale-dependent bias.

Uncertainties and model dependencies
in other parameters also
induce systematic bias

2 June 2005 Nature

If you are measuring a mass, you must QUANTIFY the systematics!



MiniBooNE Systematics

Source of Uncertainty On ν_e background	Track Based /Boosted Decision Tree error in %	Checked or Constrained by MB data	Further reduced by tying ν_e to ν_μ
Flux from π^+/μ^+ decay	6.2 / 4.3	√	√
Flux from K^+ decay	3.3 / 1.0	√	√
Flux from K^0 decay	1.5 / 0.4	√	√
Target and beam models	2.8 / 1.3	√	
ν-cross section	12.3 / 10.5	√	√
NC π^0 yield	1.8 / 1.5	√	
External interactions ("Dirt")	0.8 / 3.4	√	
Optical model	6.1 / 10.5	√	√
DAQ electronics model	7.5 / 10.8	√	

If you are measuring a mass, you must

VOLUME 67, NUMBER

Limit

R. G. H.

P

TABLE II. Contri
1 standard deviation.

Analysis (thr	
Statistics	
Beta monit	
Energy loss:	
18% in theo	
5% uncertai	
Resolution:	
Variance of response function	5
Tail	15
Final States:	
Differences between theories	8
Limited configuration space	10
Sudden approximation	2
Apparatus efficiency:	
Linear vs quadratic	32
Total	79

VOLUME 67, NUMBER 17 PHYSICAL REVIEW LETTERS 21 OCTOBER 1991

Correspondence of Electron Spectra from Photoionization and Nuclear Internal Conversion

D. L. Wark,[a] R. Bartlett, T. J. Bowles, R. G. H. Robertson, D. S. Sivia, W. Trela, and J. F. Wilkerson
Los Alamos National Laboratory, Los Alamos, New Mexico 87545

G. S. Brown
Stanford Synchrotron Radiation Laboratory, P.O. Box 4349, Bin 69, Stanford, California 94305

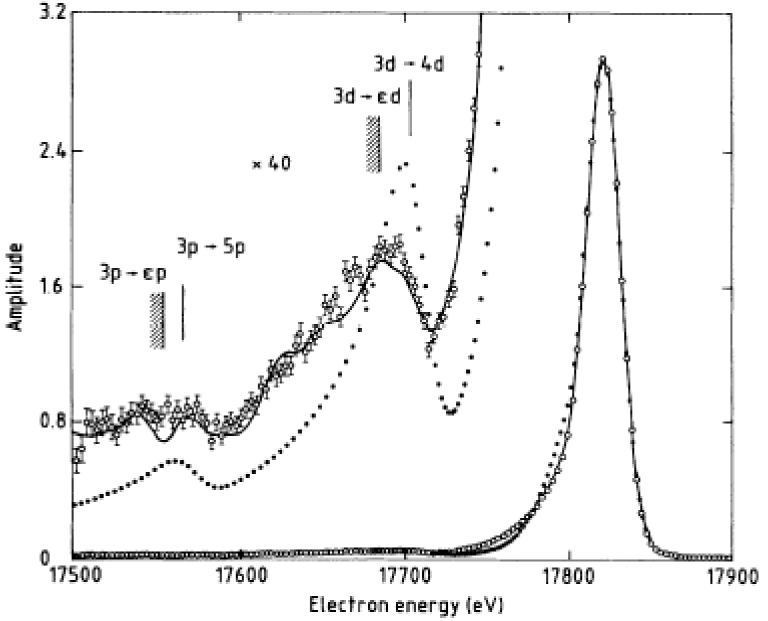
B. Crasemann, S. L. Sorensen,[b] and S. J. Schaphorst
Physics Department, University of Oregon, Eugene, Oregon 97403

D. A. Knapp and J. Henderson
Lawrence Livermore National Laboratory, P.O. Box 808, Livermore, California 94550

J. Tulkki and T. Åberg
Laboratory of Physics, Helsinki University of Technology, 02150 Espoo, Finland

Electron energy spectra have been
mechanisms: (1) photoionization and
It is demonstrated experimentally th
primary 1*s*-electron peak, are identi
given. The spectra agree well with a
tributed to excitation and ionization c

PACS numbers: 32.80.Fb, 23.20.Nx



SNO Systematic Flux Uncertainties

Error Source	CC error (%)	ES error (%)
Energy scale	-5.2, +6.1	-3.5, +5.4
Energy resolution	±0.5	±0.3
Non-linearity	±0.5	±0.4
Vertex shift	±3.1	±3.3
Vertex resolution	±0.7	±0.4
Angular resolution	±0.5	±2.2
High Energy γ's		
Low energy backgro		
Instrumental backgr		
Trigger efficiency		
Live time		
Cut acceptance		
Earth orbit eccentric		
^{17}O, ^{18}O		
Experimental uncertainty	**-6.2, +7.0**	**-5.7, +6.8**
Cross-section	3.0	0.5
Solar Model	-16, +20	-16, +20

Unless a real error analysis is done for astrophysical mass “limits” they cannot really be compared with laboratory limits… but that doesn’t mean they won’t be!

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  - Supernovae Neutrinos ←Bob Bingham
  - TeV++ Neutrinos

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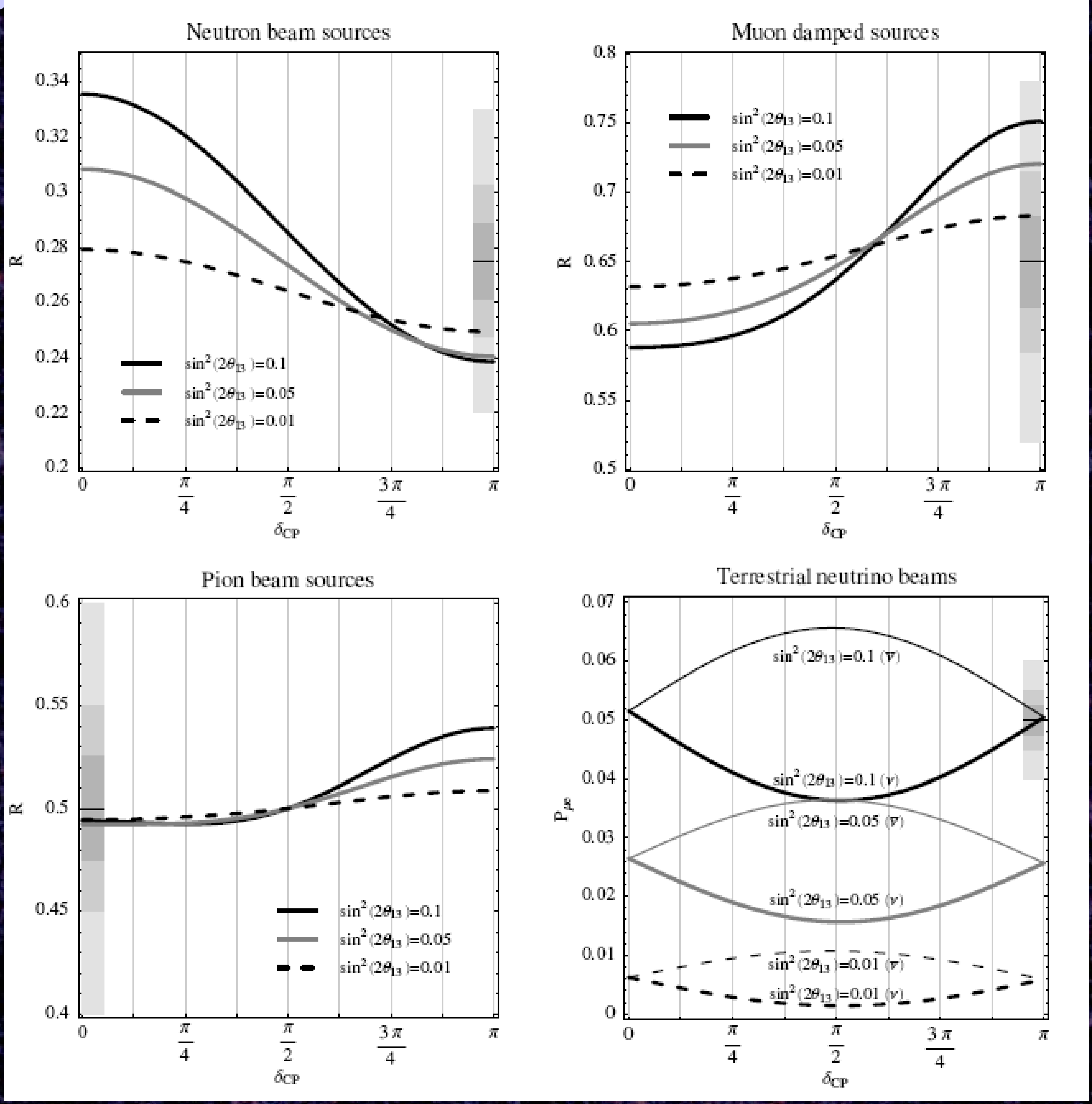
Help from outer space?

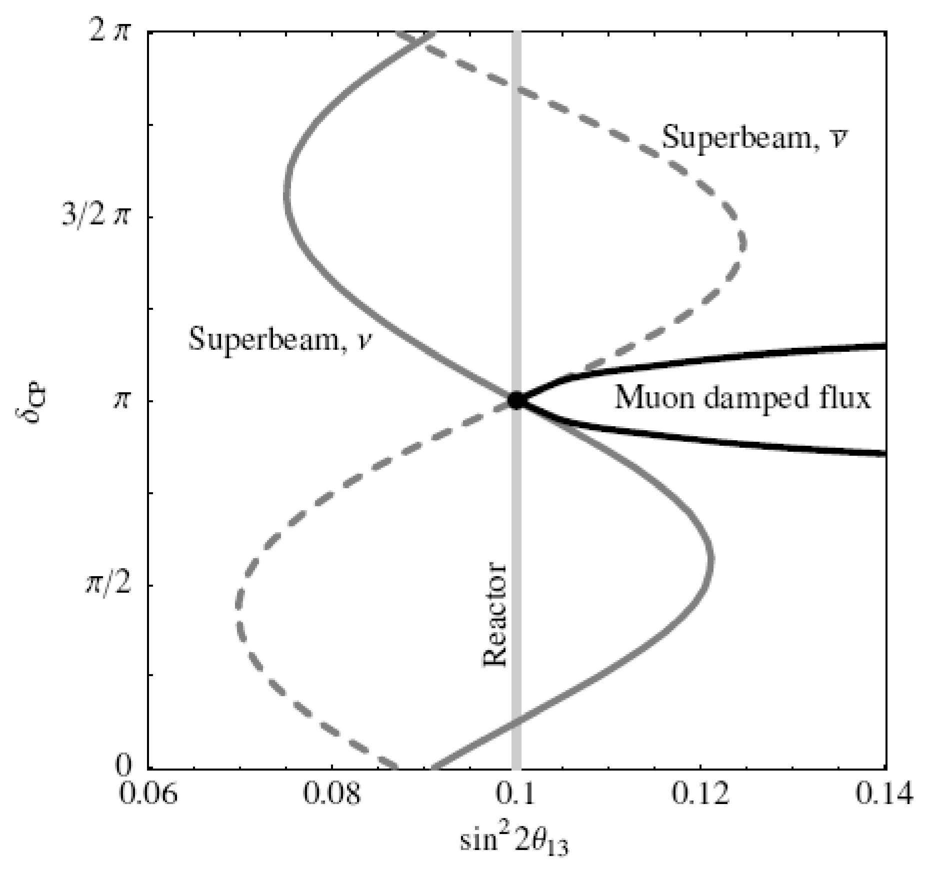
- Astrophysical neutrino sources produce certain flavor ratios of neutrinos (ν_e:ν_μ:ν_τ):
  Neutron decays: (1:0:0)
  Muon damped sources: (0:1:0)
  Pion decays: (1:2:0)
- These ratios are changed at Earth through averaged neutrino oscillations: $P_{\alpha\beta} = \sum_{i=1}^{3} |U_{\alpha i}|^2 |U_{\beta i}|^2$

~ cosδ

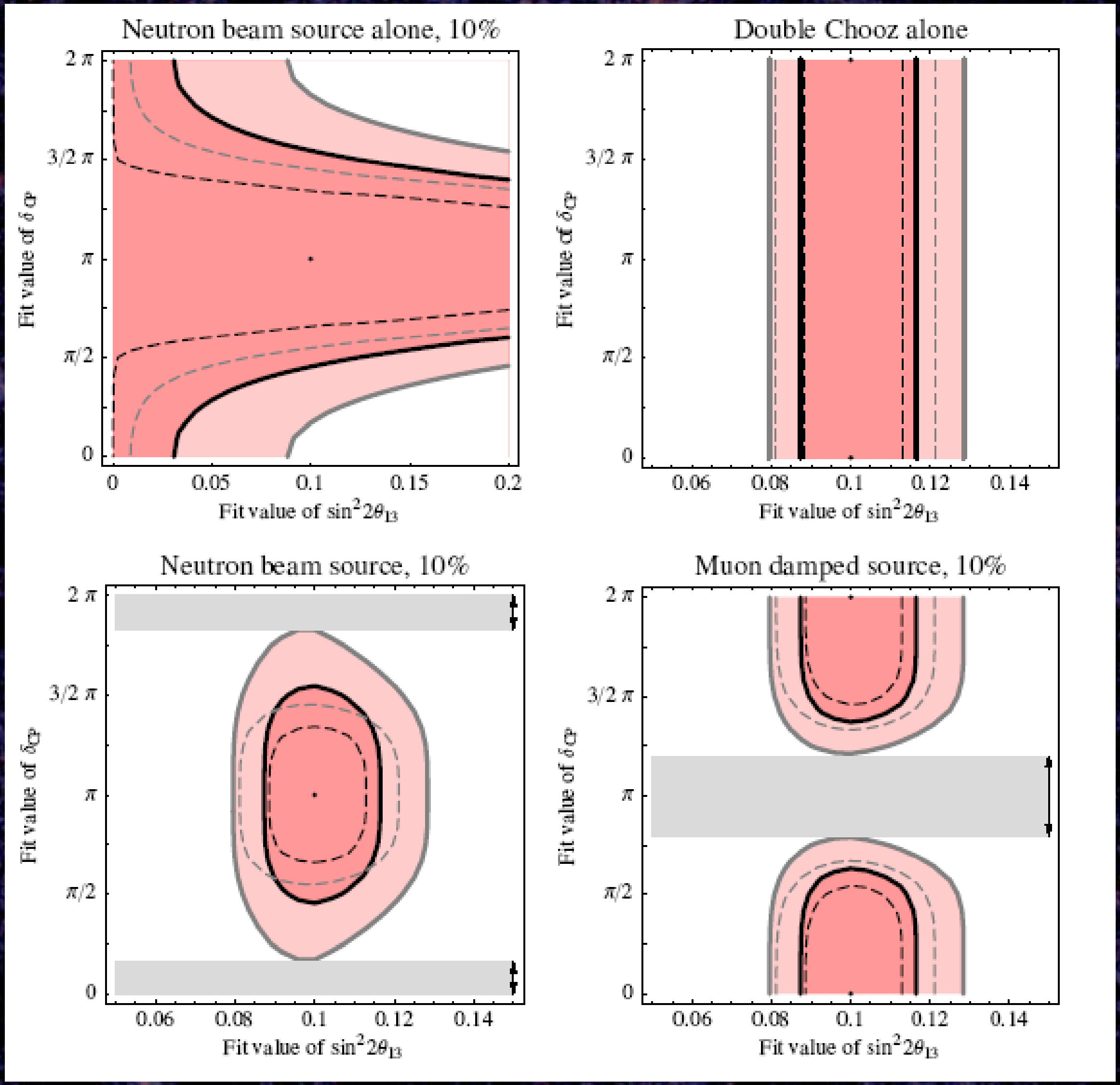
- Measure muon track to shower ratio at neutrino telescope: R = $\phi_\mu/(\phi_e+\phi_\tau)$

(From Walter Winter)

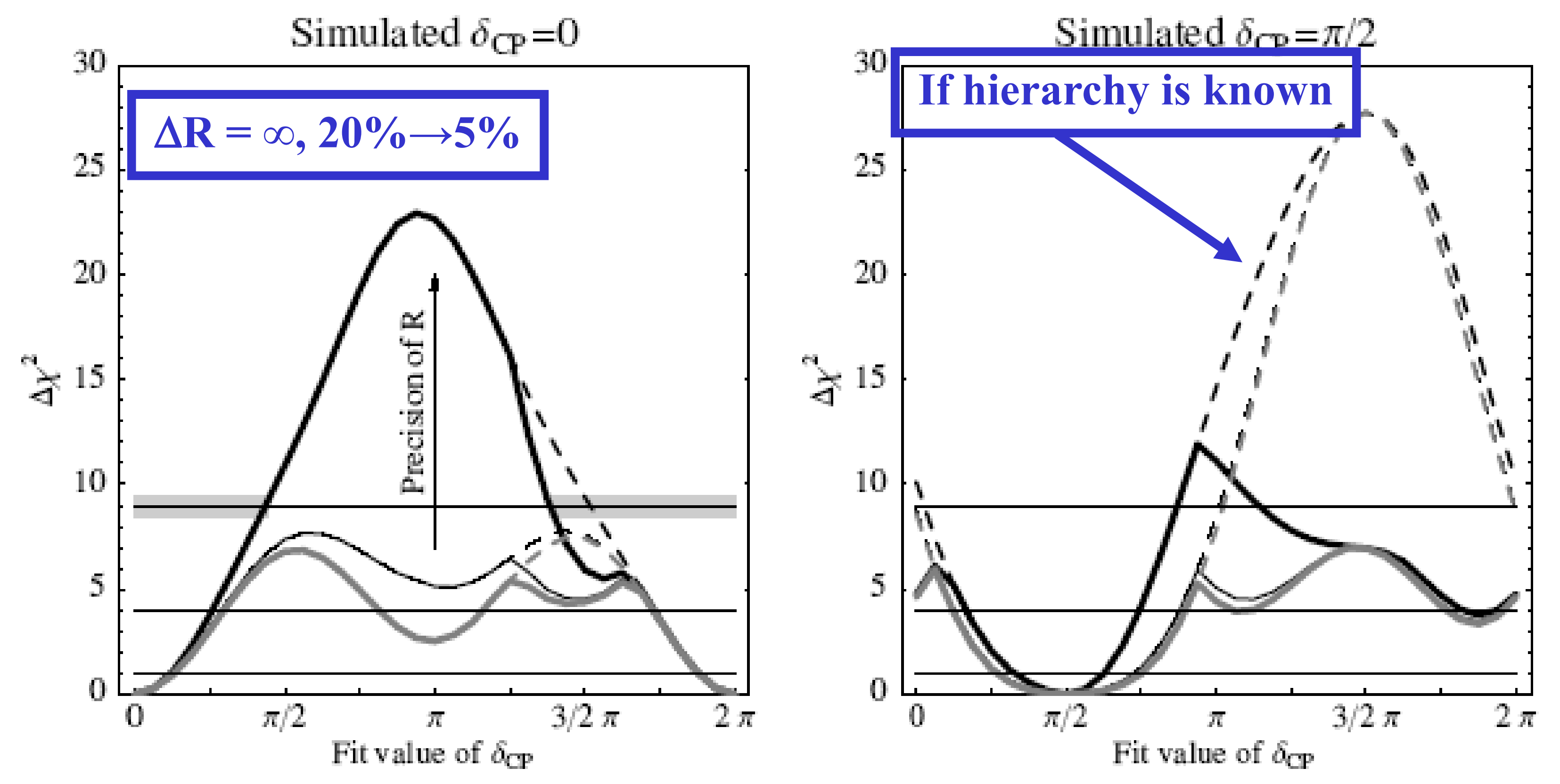

Neutron beam sources
R
0.34
0.32
0.3
0.28
0.26
0.24
0.22
0.2
0
π/4
π/2
3π/4
π
δ_CP
sin²(2θ13)=0.1
sin²(2θ13)=0.05
sin²(2θ13)=0.01
Muon damped sources
0.8
0.75
0.7
0.65
0.6
0.55
0.5
Pion beam sources
0.6
0.55
0.5
0.45
0.4
Terrestrial neutrino beams
P_μe
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
sin²(2θ13)=0.1 (ν̄)
sin²(2θ13)=0.1 (ν)
sin²(2θ13)=0.05 (ν̄)
sin²(2θ13)=0.05 (ν)
sin²(2θ13)=0.01 (ν̄)
sin²(2θ13)=0.01 (ν)


2 π
3/2 π
π
π/2
0
δ_{CP}
0.06
0.08
0.1
0.12
0.14
$\sin^2 2\theta_{13}$
Superbeam, $\bar{\nu}$
Superbeam, ν
Muon damped flux
Reactor

Cosenor's μ-collider



Combination with LBL Data



$\Delta R = \infty$, 20%→5%

If hierarchy is known

Assume MINOS, Double Chooz, T2K, and NOvA
What would a determination of R (muon damped) add?

Conclusions

- "Cosmological" neutrinos started the modern exploration of neutrino properties.
- For the study of oscillations further progress will depend primarily on neutrinos from terrestrial sources, although there may be some additional sensitivity from cosmological neutrinos.
- A wide range of cosmological data has considerable inherent sensitivity to the currently interesting range of absolute neutrino masses.
- Fluxes from distant high-energy neutrino sources are also modified by neutrino oscillations.
- However all cosmological neutrinos are seen in observations, not experiments, and therefore suffer from model uncertainties and hard-to-quantify systematics.
- We can produce controlled neutrino sources on earth – it is rather harder to produce supernovae, AGN, Big Bangs, etc.
- It seems a terrible waste of precious cosmological data to use it to determine particle properties measurable on earth, rather than use it to constrain models of new cosmic phenomena.
- This is a challenge to the neutrino physics community to produce terrestrial experiments of higher sensitivity to allow cosmological data to be used for cosmology!