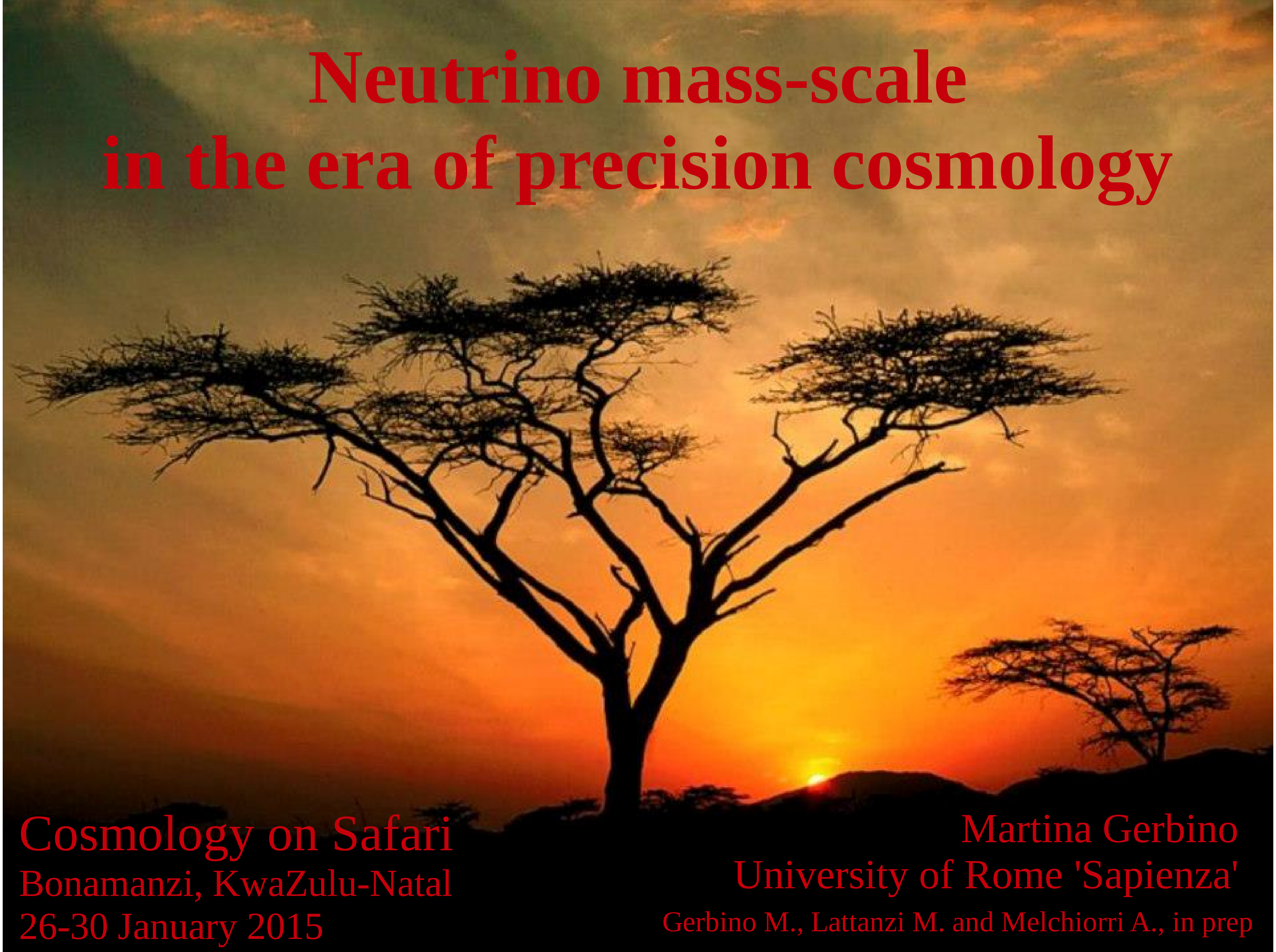


Neutrino mass-scale in the era of precision cosmology

Cosmology on Safari
Bonamanzi, KwaZulu-Natal
26-30 January 2015

Martina Gerbino
University of Rome 'Sapienza'

Gerbino M., Lattanzi M. and Melchiorri A., in prep

Roadmap

- Introduction
Neutrino physics: which parameters?
  What experiments?

- Data analysis: the likelihood

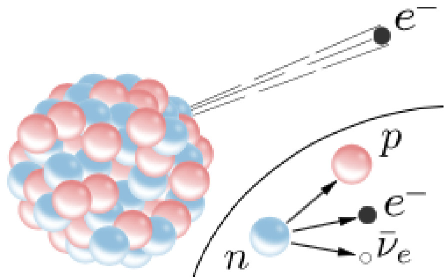
- Results

- Conclusions

A little bit of history

Neutrinos are weakly interacting and electrically neutral particles

Postulated by Pauli in 1930 to explain non-monochromatic beta decay
Accepted by Fermi's theory of beta decay in 1933
First detected by Cowan and Reines in 1956



More than one neutrino flavor exists:
Cowan and Reines detected electronic neutrinos
Muonic neutrino interactions observed by Lederman, Schwartz and Steinberger in 1962
Tauonic neutrino first detected in 2000

Neutrino nature still debated
- Dirac particles $\nu_j \neq \bar{\nu}_j$
- Majorana particles $\chi_j \equiv \bar{\chi}_j$

Oscillations

First suggested by Pontecorvo in 1957
Observed in solar, atmospheric and reactor neutrino experiments

Oscillations are transitions in flight between neutrino flavors
Due to non zero neutrino mass and neutrino mixing

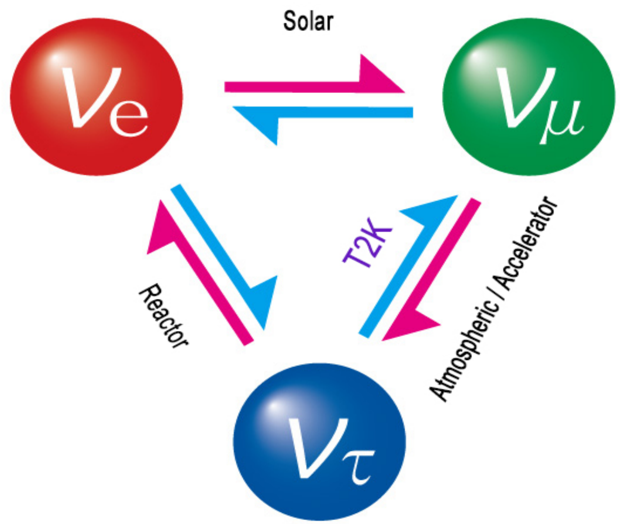
$$P(\nu_\mu \rightarrow \nu_\tau; E, L) \neq 0$$

The Infamous "Neutrino-burglar"

Parameterized with mixing angles θ_{ij} and phases (one δ if Dirac, two φ_2 and φ_3 if Majorana)

$$\nu_{l\mathrm{L}}(x) = \sum_j U_{lj}\, \nu_{j\mathrm{L}}(x), \quad l = e, \mu, \tau$$

Mass eigenstates



j=1,...,n
n=3 light neutrinos with different masses (<1eV) compatible with Z-decay
Additional one or two sterile neutrinos (~1eV)

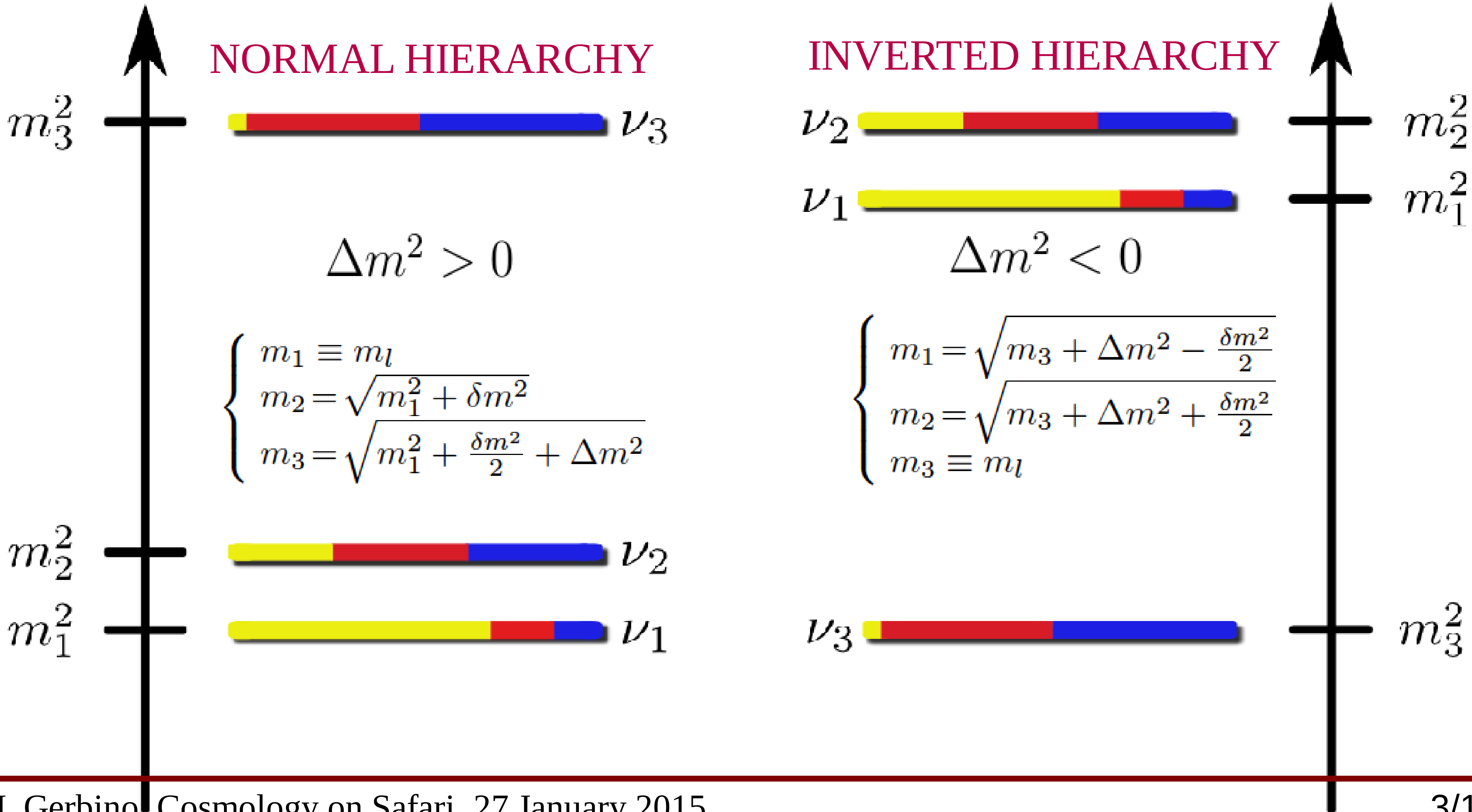
Oscillation parameters

Oscillation experiments are sensible to squared mass differences and mixing angles

$$\delta m^2 = m_2^2 - m_1^2$$

$$\Delta m^2 = m_3^2 - \frac{1}{2}(m_2^2 - m_1^2)$$

$$\sin^2\theta_{ij},\ i,j = 1,2,3$$



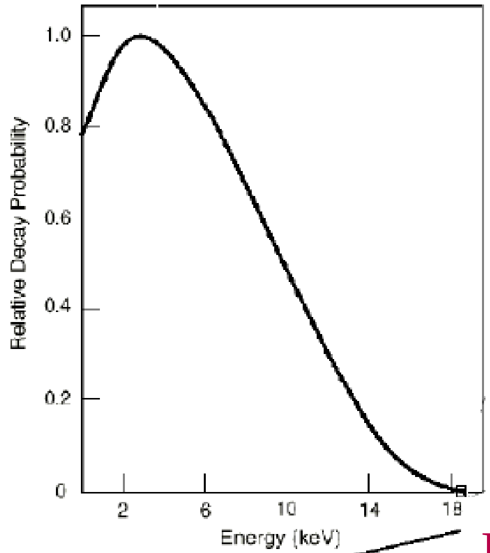
Tritium β decay spectrum

$$^{3}\mathrm{H} \longrightarrow {}^{3}\mathrm{He}^{+} + e^{-} + \bar{\nu}_{e} \ :$$

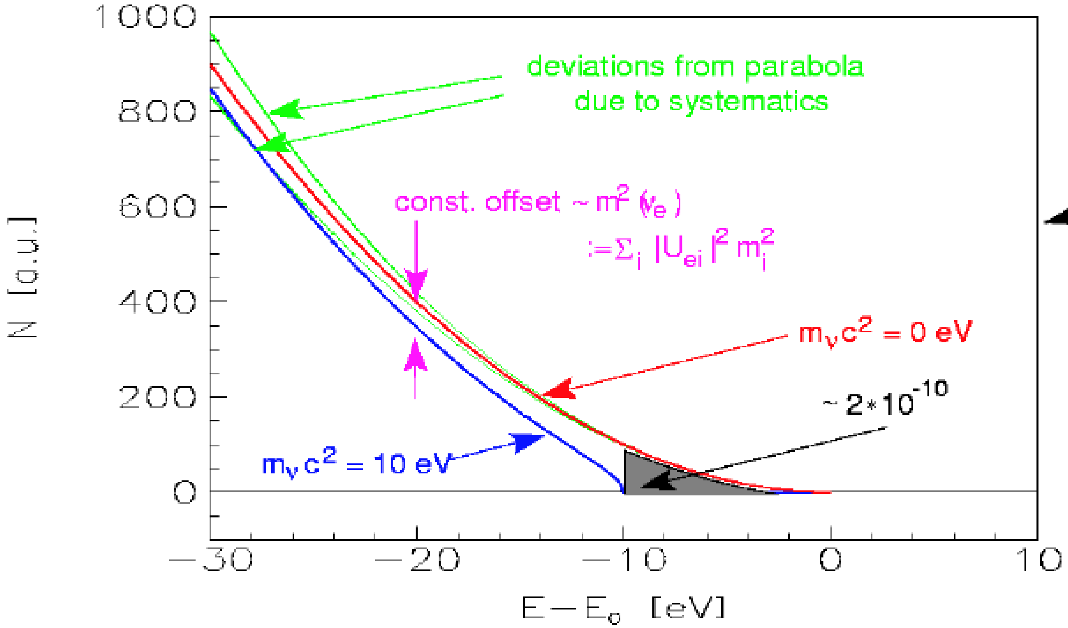
superallowed

$Q = 18.6$ keV

$t_{1/2}$: 12.3 y



The Mainz Neutrino Mass Experiment: http://www.physik.uni-mainz.de/exakt/neutrino/en_index.html



Direct measurement of electron antineutrino mass from the exact shape of the endpoint of beta-decay spectrum

$$m_\beta^2 = \sum_i U_{ei}^2 m_i^2$$

Pros: direct and model independent
Cons: less sensible than other methods

Current upper limits:

$$m_\beta < 2.12\,\mathrm{eV}\ (95\%\ \mathrm{CL})\ Troitsk$$

$$m_\beta < 2.20\,\mathrm{eV}\ (95\%\ \mathrm{CL})\ Mainz$$

Aseev V.N. et al, Phys. Rev. D 84, 112003, 2011
Weinheimer C. et al, Phys. Lett. B460 (1999) 219

Expected sensitivity from future experiments:

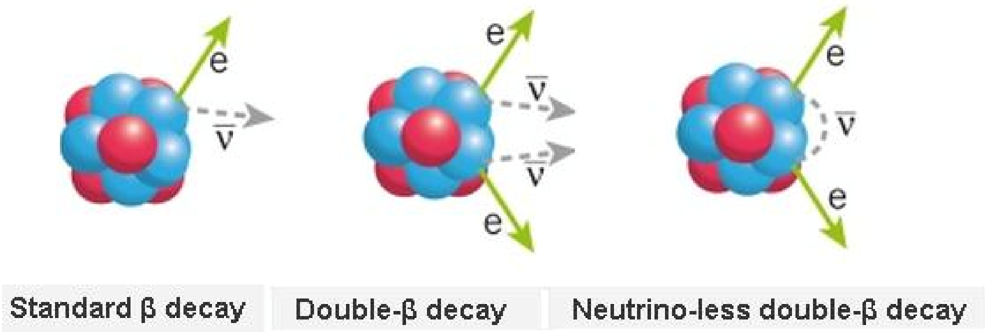
$$m_\beta < 0.2\,\mathrm{eV}\ (90\%\ \mathrm{CL})$$

$$m_\beta = 0.35\,\mathrm{eV}\ at\ 5\sigma$$

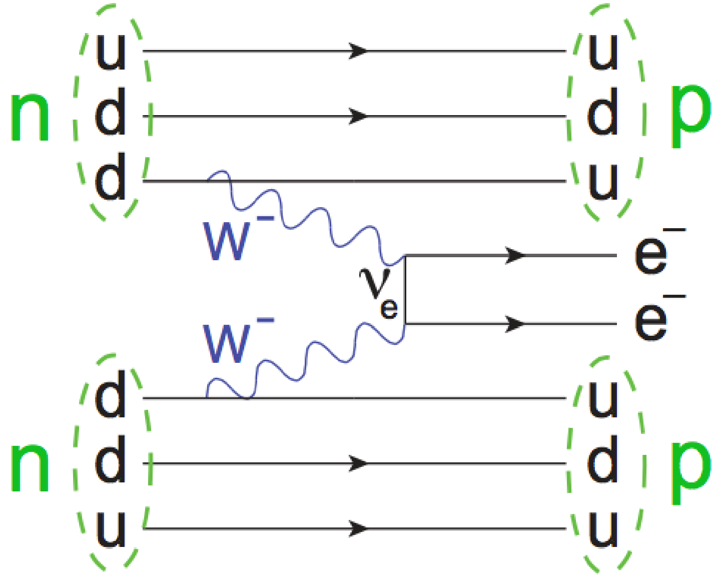
$$m_\beta = 0.30\,\mathrm{eV}\ at\ 3\sigma$$

KATRIN experiment: http://www.katrin.kit.edu

Neutrinoless double beta decay



Standard β decay   Double-β decay   Neutrino-less double-β decay



Nuclear Matrix Element
Hard to model

$$T_{1/2} = \frac{1}{G_{\nu}^{(0)}\mathcal{M}^{(0\nu)}}\frac{m_e^2}{m_{\beta\beta}^2}$$

Phase space factor

Majorana effective mass

$$m_{\beta\beta} = \left|\sum_i U_{ei}^2 m_i\right|$$

Pros: if observed, it will solve the dilemma about neutrino nature

Schechter J. and Valle J.W.F., Phys. Rev. D **25**, 2951

Cons: uncertainties from nuclear models

Experiment	$T_{1/2}(10^{25}\ \mathrm{yr})$
KamLAND-Zen	> 1.9
EXO-200	> 1.1
H-M	> 1.9
GERDA	> 2.1
CUORE	> 10
Majorana	> 70
NEXT	> 10

Current limits at 90% CL

$$m_{\beta\beta} < (0.2 - 0.4)\ \mathrm{eV}$$

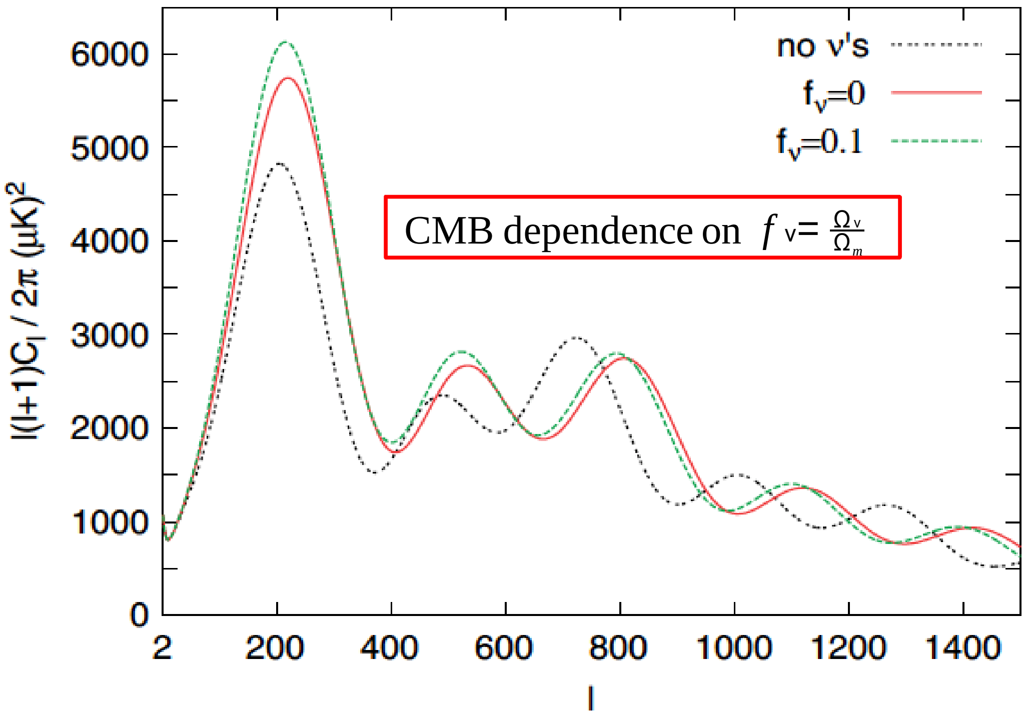
Expected limits

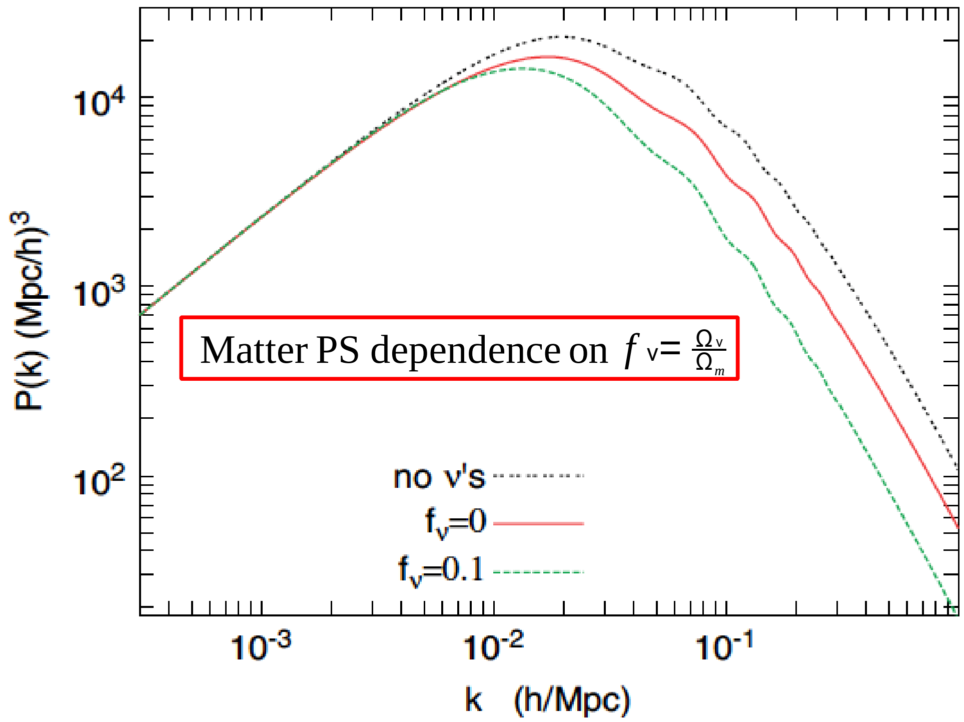
$$m_{\beta\beta} < 0.1\ \mathrm{eV}$$

Cosmology

$$\Omega_\nu = \frac{\rho_\nu}{\rho_c} = \frac{\sum_i m_i}{93.14 h^2 \text{ eV}}$$

Effects on the expansion rate of the Universe
Effects on growth of cosmological structures





Lesgourgues J., Pastor S., Physics Reports 429 (2006) 307 – 379

CMB is only sensitive to the sum of neutrino masses
Pros: Tightest constraints on the total mass come from cosmology
Cons: model dependent

P. A. R. Ade et al, A&A 571 A16 2014

$$\sum_i m_i < 0.66\,\text{eV} \quad (\text{Planck} + \text{WP} + \text{highl})$$

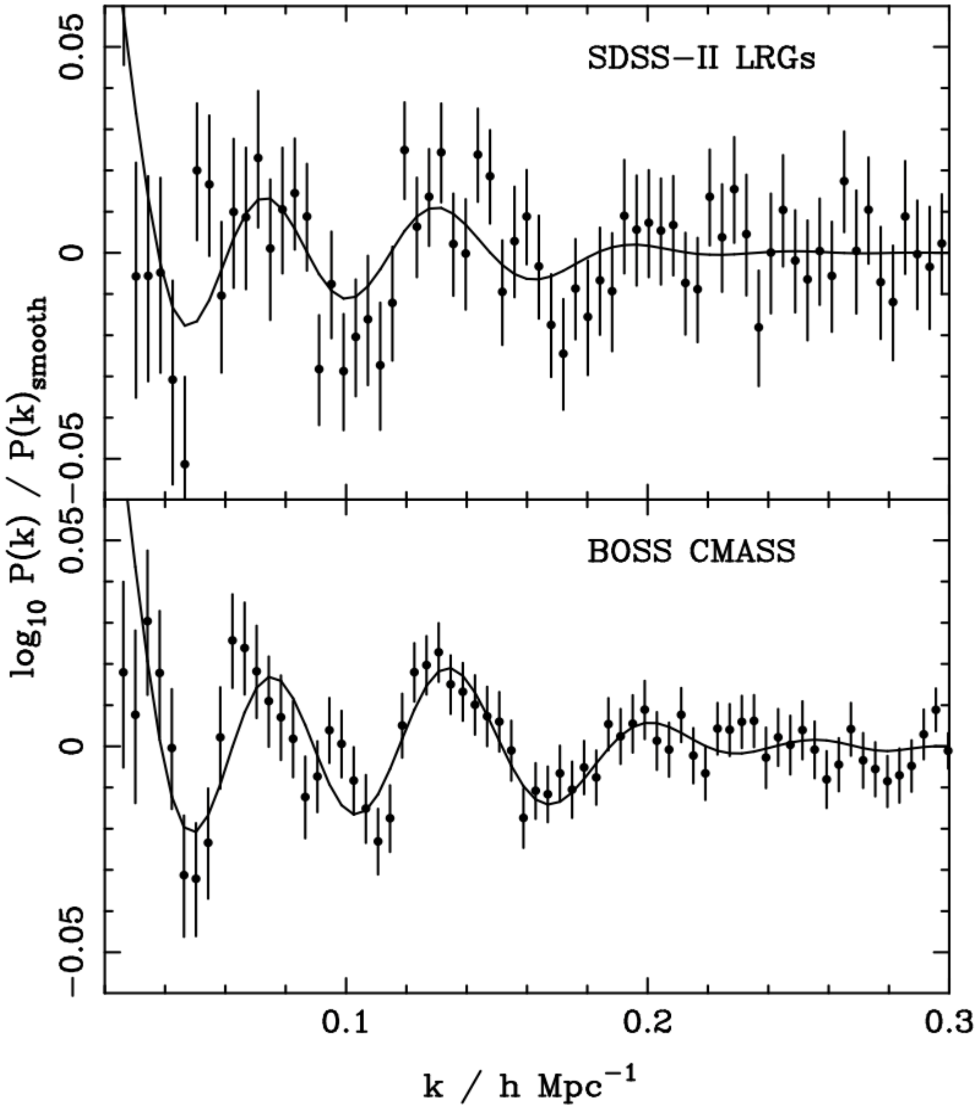
$$\sum_i m_i < 0.23\,\text{eV} \quad (\text{Planck} + \text{WP} + \text{highl} + \text{BAO})$$

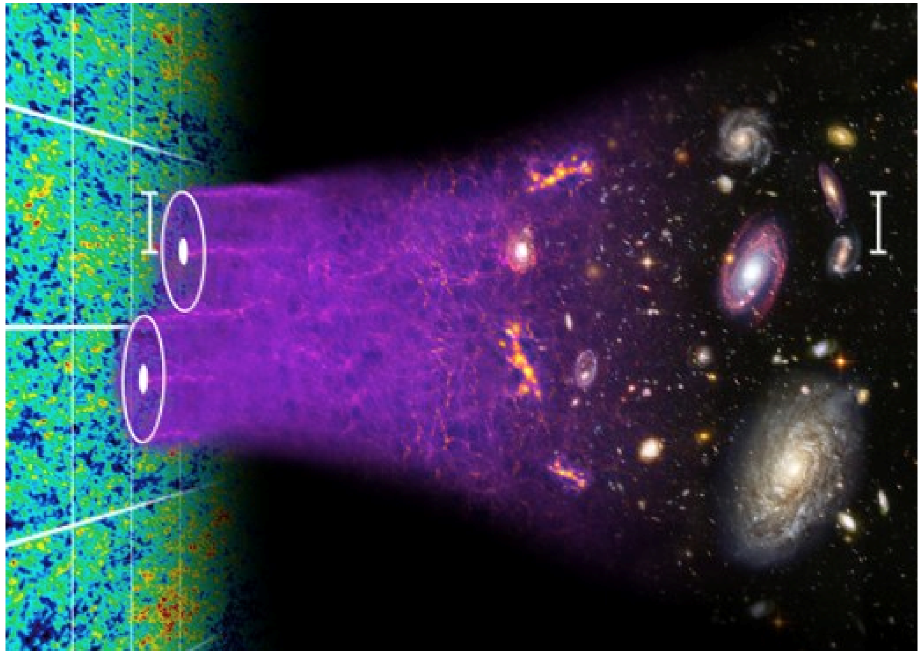
Baryon Acoustic Oscillations

Counteraction of gravitational attraction and radiation pressure produces acoustic oscillations

Acoustic peaks in the CMB spectrum (see previous slide)

Overdensity of galaxies separated by a characteristic scale (sound horizon)





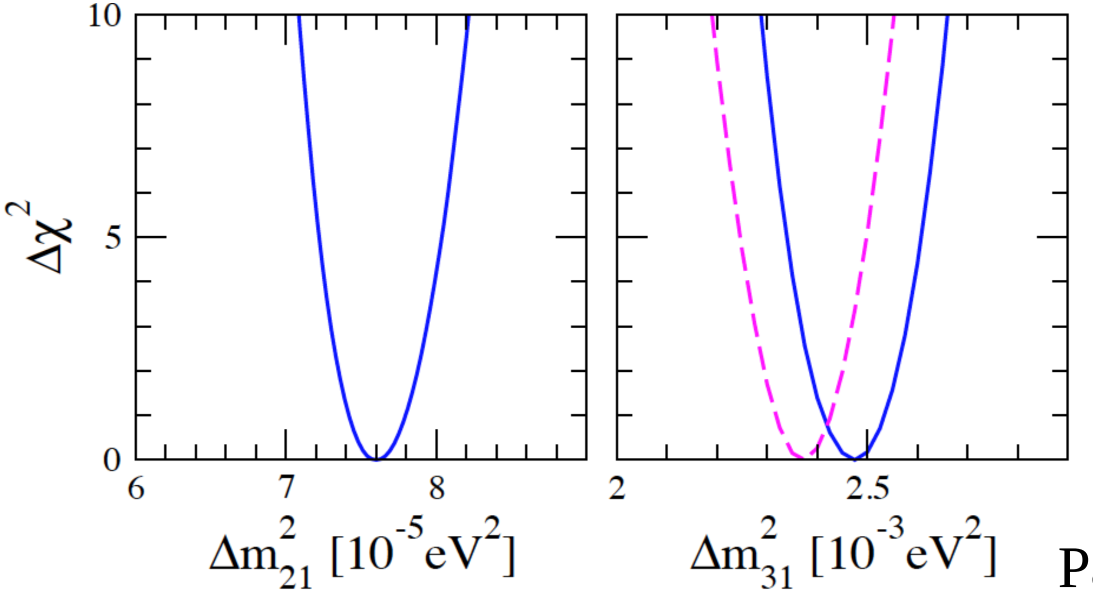
Courtesy of Chris Blake and Sam Moorfield

Several galaxy surveys observed BAO (SDSS, WiggleZ, 6dFGS,...)

Anderson et al, MNRAS 427 4, 2014

Building the likelihood

Baseline: oscillation parameters



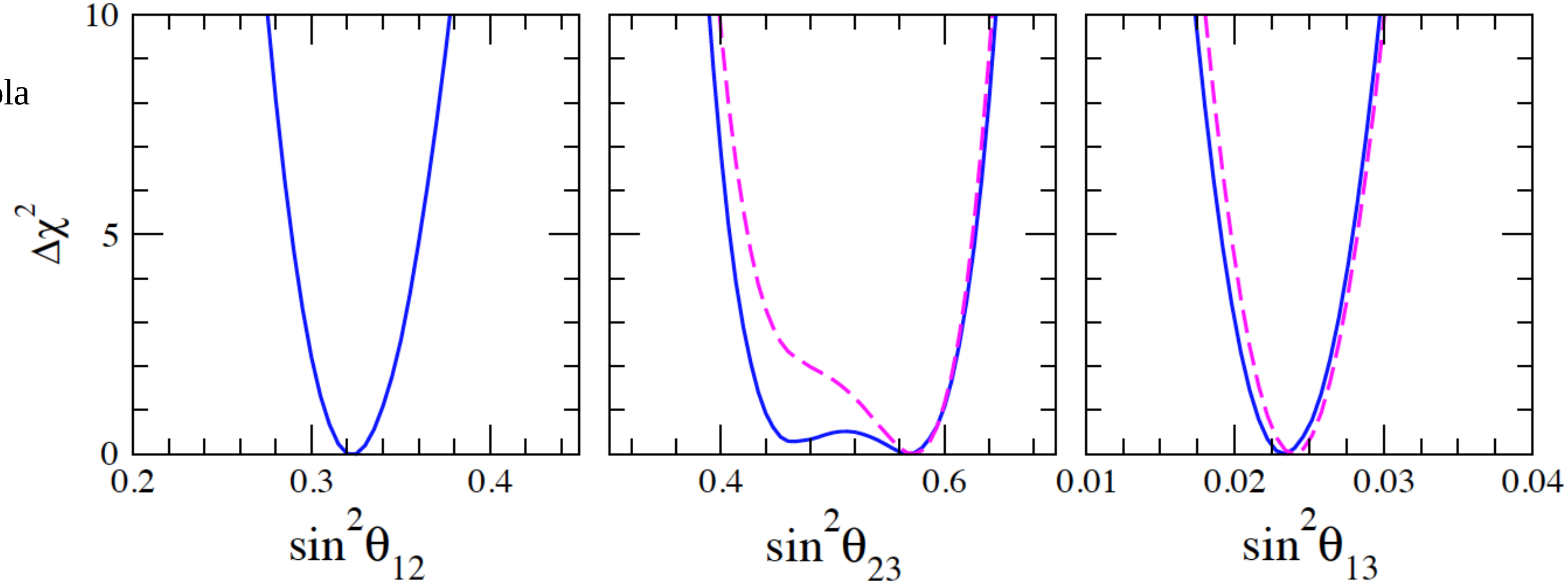
Parameter	68% CL
$\delta m^2\,[10^{-5}]\,\mathrm{eV}^2$	7.600 ± 0.185
$\lvert\Delta m^2\rvert\,[10^{-3}]\,\mathrm{eV}^2$	$2.48 \pm 0.06\,(2.380 \pm 0.055)$
s^2_{12}	0.323 ± 0.016
s^2_{13}	$0.0234 \pm 0.0020\,(0.0240 \pm 0.0019)$

$$\mathcal{L}_{osc} = \prod_i \mathcal{L}(x_i)$$

Gaussian likelihood and MCMC analysis

Parameters: $\boxed{s^2_{12},\ s^2_{13},\ \delta m^2,\ \Delta m^2,\ \phi_2,\ \phi_3,\ \Sigma m_\nu}$

Forero D.V., Tortola M., Valle J.W.F., arXiv:1405.7540 [hep-ph]



Additional datasets

Name	Data (68%CL)	Dataset combination
GERDA	$T_{1/2} > 2.1 \cdot 10^{25}$ yr	Gerda experiment, phase 1 [16]. Mean value from different NME calculations and marginalization over NME uncertainty [17, 22].
$\mathrm{P} + \mathrm{WP} + \mathrm{high}\ell$	$\Sigma m_\nu < 0.33$	Planck[2], ACT[4] and SPT[5] TT power spectra in combination with WMAP9 lowl polarization. We refer to the Planck+WMAP9 combination as P+WP hereafter.
CMB + LSS1a	$\Sigma m_\nu = 0.36 \pm 0.10$	P+WP[2] marginalized over the weak lensing amplitude parameter A_L[3], CMASS measurements from (Beutler,2013), CFHTlens (Kilibinger,2013), GGlensing (Mandelbaum,2013) and BAO (6dFGS from Beutler,2011 and LOWZ from Anderson,2013b, Tojeiro,2014).
CMB + LSS2	$\Sigma m_\nu = 0.38 \pm 0.11$	P+WP[2] marginalized over the weak lensing amplitude parameter A_L[3], CMASS measurements from (Chuang,2013), CFHTlens (Kilibinger,2013), GGlensing (Mandelbaum,2013) and BAO (6dFGS from Beutler,2011 and LOWZ from Anderson,2013b, Tojeiro,2014).
CMB + LSS3	$\Sigma m_\nu = 0.324 \pm 0.099$	P+WP[2] marginalized over the weak lensing amplitude parameter A_L[3], CMASS measurements from (Samushia,2013), CFHTlens (Kilibinger,2013), GGlensing (Mandelbaum,2013) and BAO (6dFGS from Beutler,2011 and LOWZ from Anderson,2013b, Tojeiro,2014).
CMB + LSS4	$\Sigma m_\nu = 0.27 \pm 0.11$	P+WP[2] marginalized over the weak lensing amplitude parameter A_L[3], CMASS measurements from (Anderson,2013b), CFHTlens (Kilibinger,2013), GGlensing (Mandelbaum,2013) and BAO (6dFGS from Beutler,2011 and LOWZ from Anderson,2013b, Tojeiro,2014).
CMB + LSS1b	$\Sigma m_\nu = 0.35 \pm 0.10$	WMAP9[6], CMASS measurements from (Beutler,2013), CFHTlens (Kilibinger,2013), GGlensing (Mandelbaum,2013) and BAO (6dFGS from Beutler,2011 and LOWZ from Anderson,2013b, Tojeiro,2014).
CMB + LSS1c	$\Sigma m_\nu = 0.27 \pm 0.12$	P+WP, CMASS measurements from (Beutler,2013), CFHTlens (Kilibinger,2013), GGlensing (Mandelbaum,2013) and BAO (6dFGS from Beutler,2011 and LOWZ from Anderson,2013b, Tojeiro,2014).

Agostini M. et al, PRL 111, 122503; P. A. R. Ade et al, A&A 571 A16 2014; Beutler F. et al, MNRAS 444, 3501 2014

Great uncertainty from nuclei models

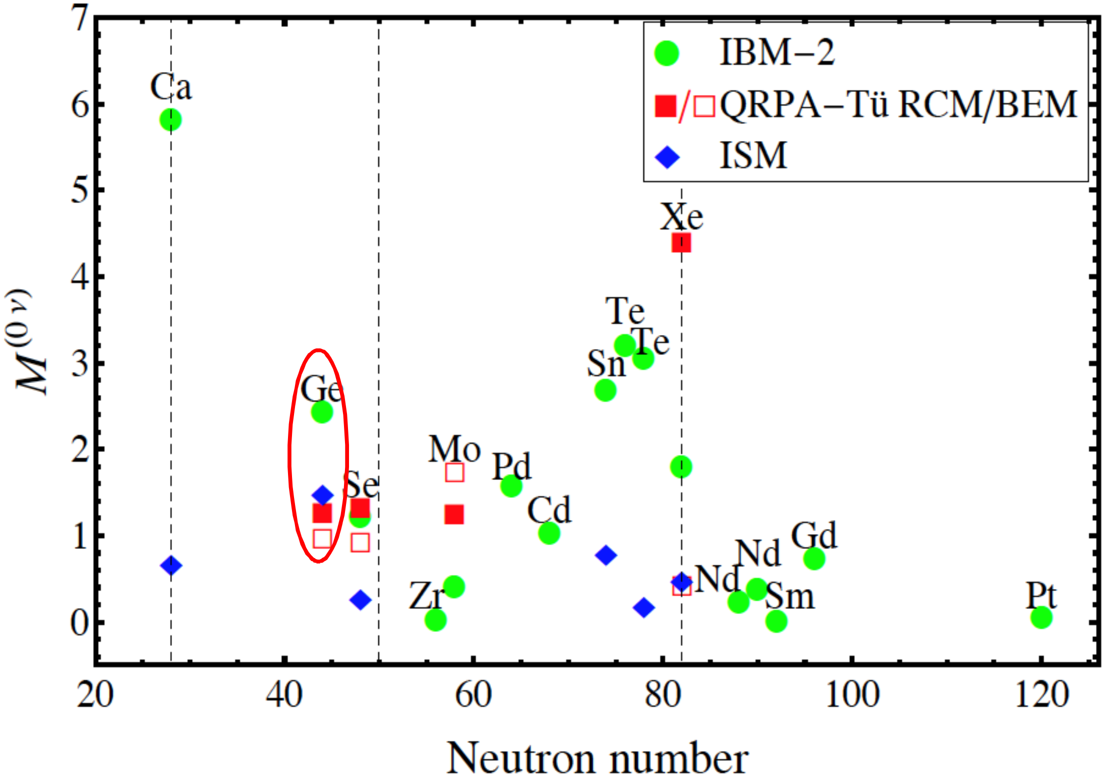
Trick: introduce ξ as a nuisance parameter
and marginalize over it

Minakata H., Nunokawa H., Quiroga A.A., arXiv:1402.6014

$$\xi = \frac{\mathcal{M}_0^{(0\nu)}}{\mathcal{M}^{(0\nu)}}$$

Reference value

Unknown exact value



Barea J., Kotila J. Iachello F., Phys.Rev. C87 (2013) 014315

$$T_{1/2} = \frac{1}{G_\nu^{(0)} \mathcal{M}^{(0\nu)}} \frac{m_e^2}{m_{\beta\beta}^2} = \frac{\xi^2}{G_\nu^{(0)} \mathcal{M}_0^{(0\nu)}} \frac{m_e^2}{m_{\beta\beta}^2}$$

$$\mathcal{L}(T_{1/2}|m_{\beta\beta},\xi) = \exp\left[-\frac{(\sqrt{1/T_{1/2}})^2}{2\sigma_{Ge}^2}\right]\mathcal{P}(\xi)$$

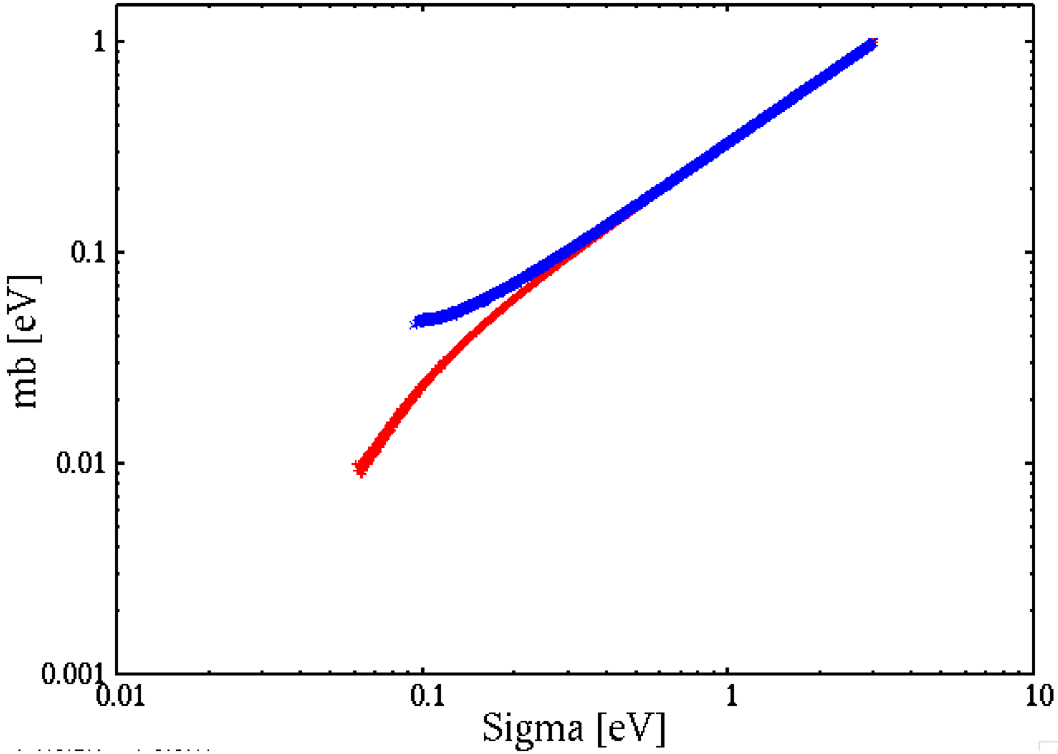
Flat prior on ξ within [0.5; 2] range

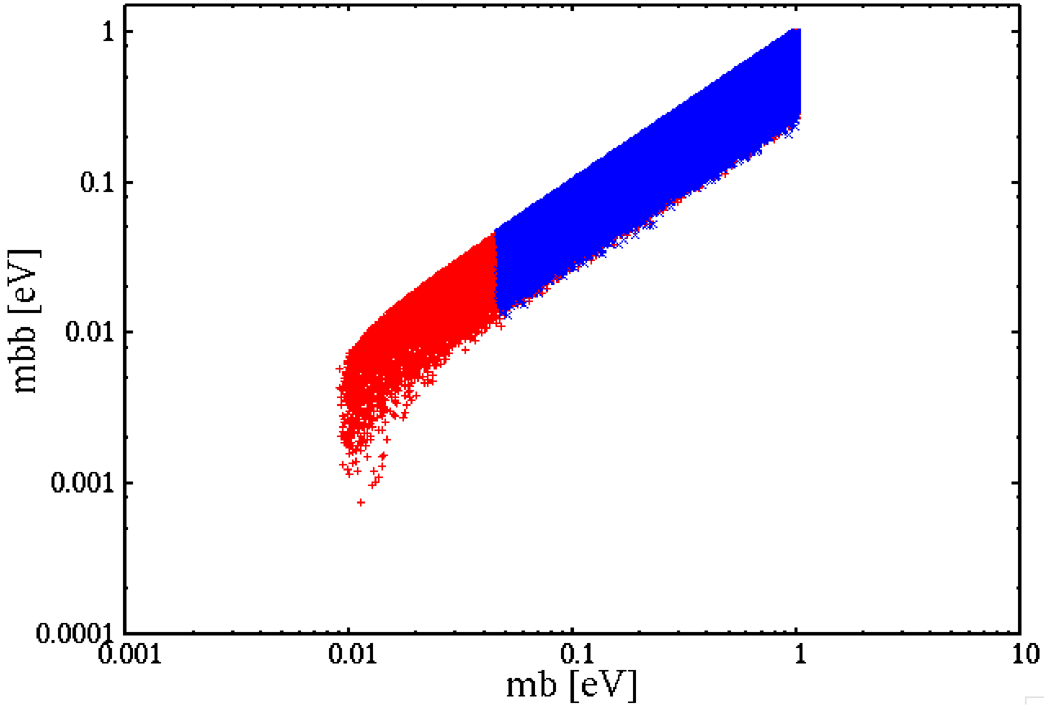
From GERDA lower limit on the Ge half life

$$T_{1/2} > 2.1 \cdot 10^{25}\,\mathrm{yr}\ (90\%\ \mathrm{CL})$$

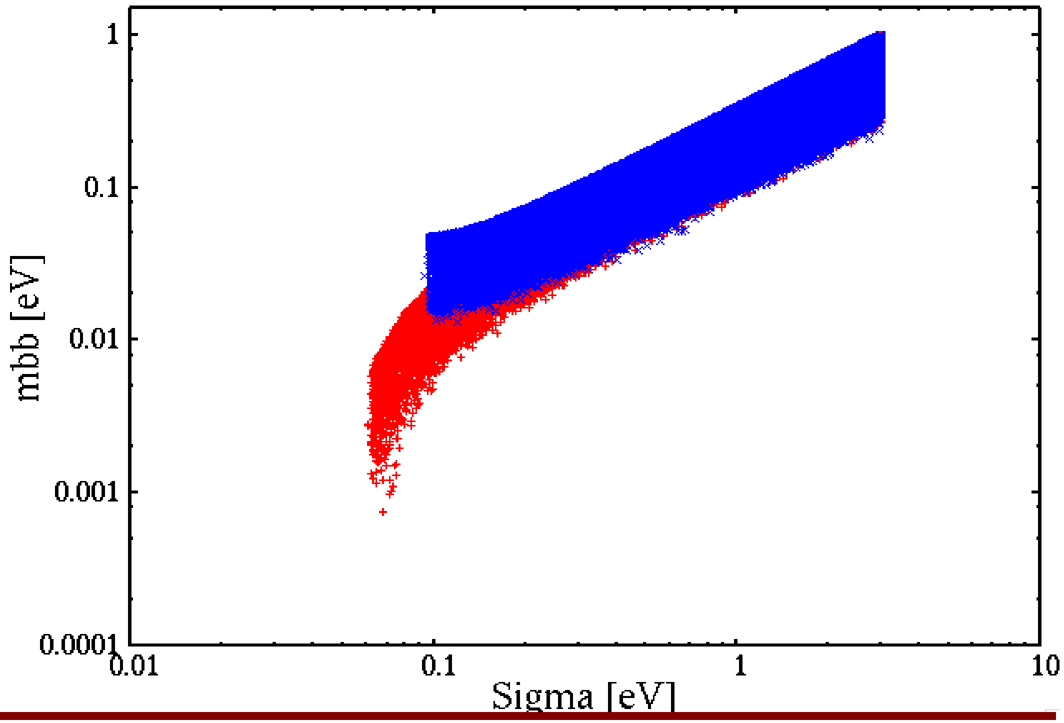
Agostini M. et al, Phys. Rev. Lett. 111, 122503

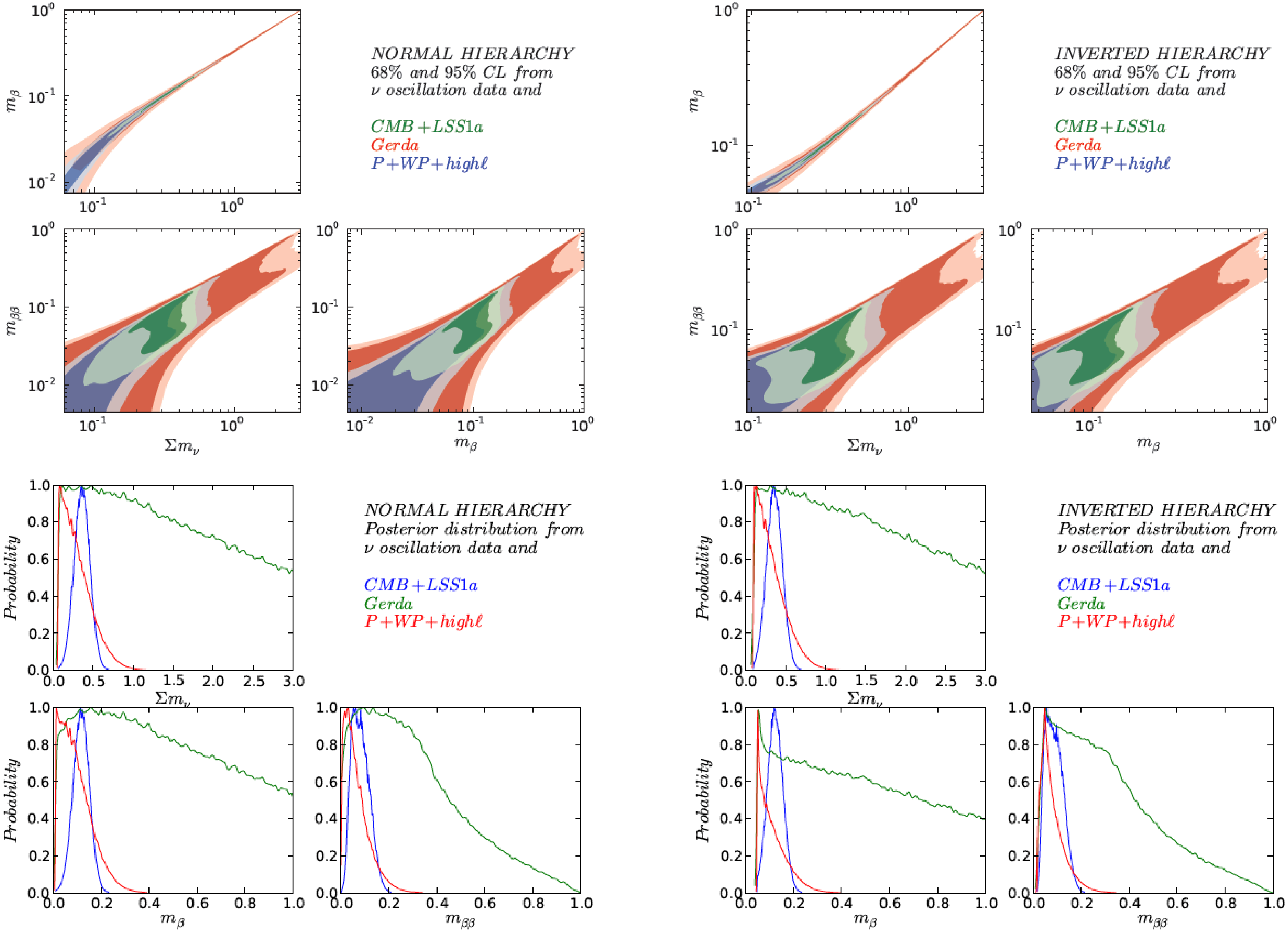
Parameter constraints from oscillation data

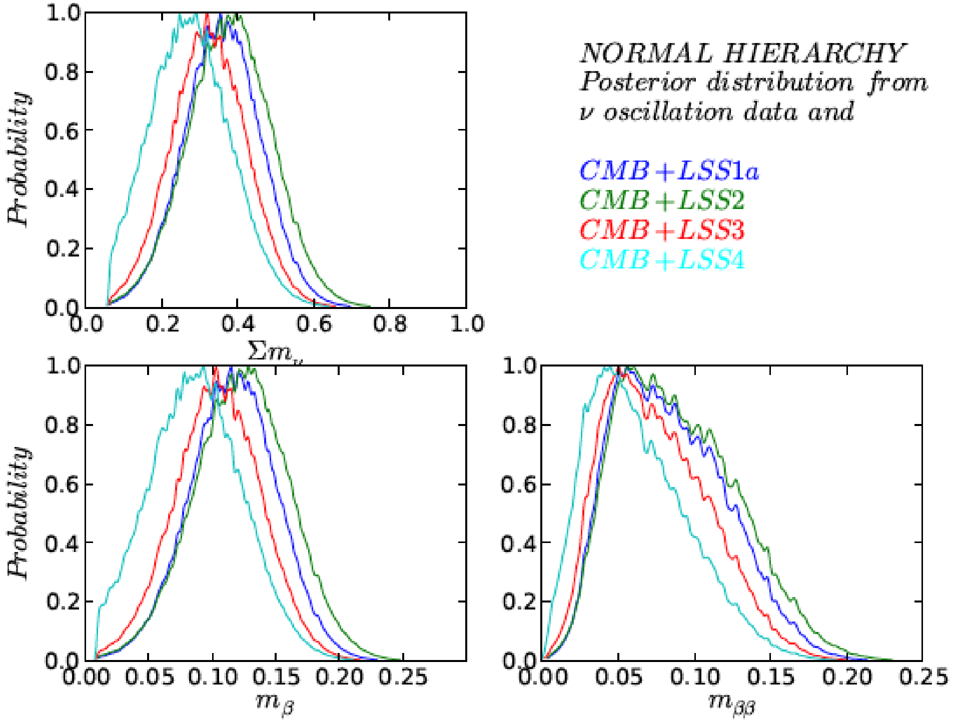




NORMAL HIERARCHY
INVERTED HIERARCHY




NORMAL HIERARCHY
68% and 95% CL from
ν oscillation data and
CMB+LSS1a
Gerda
P+WP+highℓ
INVERTED HIERARCHY
68% and 95% CL from
ν oscillation data and
CMB+LSS1a
Gerda
P+WP+highℓ
m_β
$m_{\beta\beta}$
Σm_ν
NORMAL HIERARCHY
Posterior distribution from
ν oscillation data and
CMB+LSS1a
Gerda
P+WP+highℓ
INVERTED HIERARCHY
Posterior distribution from
ν oscillation data and
CMB+LSS1a
Gerda
P+WP+highℓ
Probability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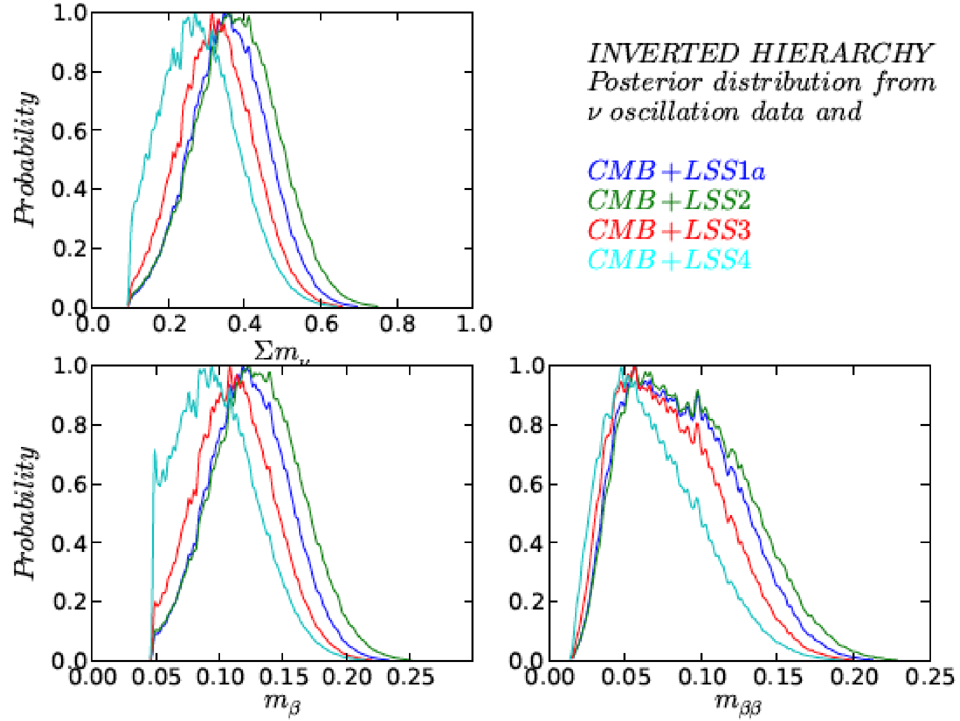
CMB+LSS2
CMB+LSS3
CMB+LSS4
Probability
Σm_ν
m_β
m_ββ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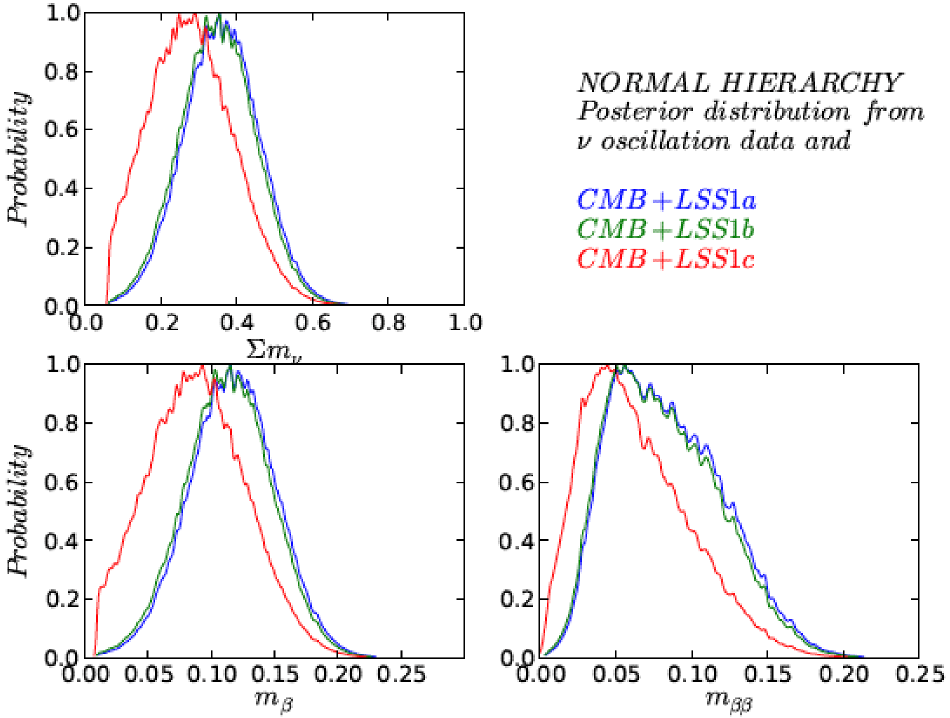
CMB+LSS4
Probability
Σm_ν
m_β
m_ββ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Probability
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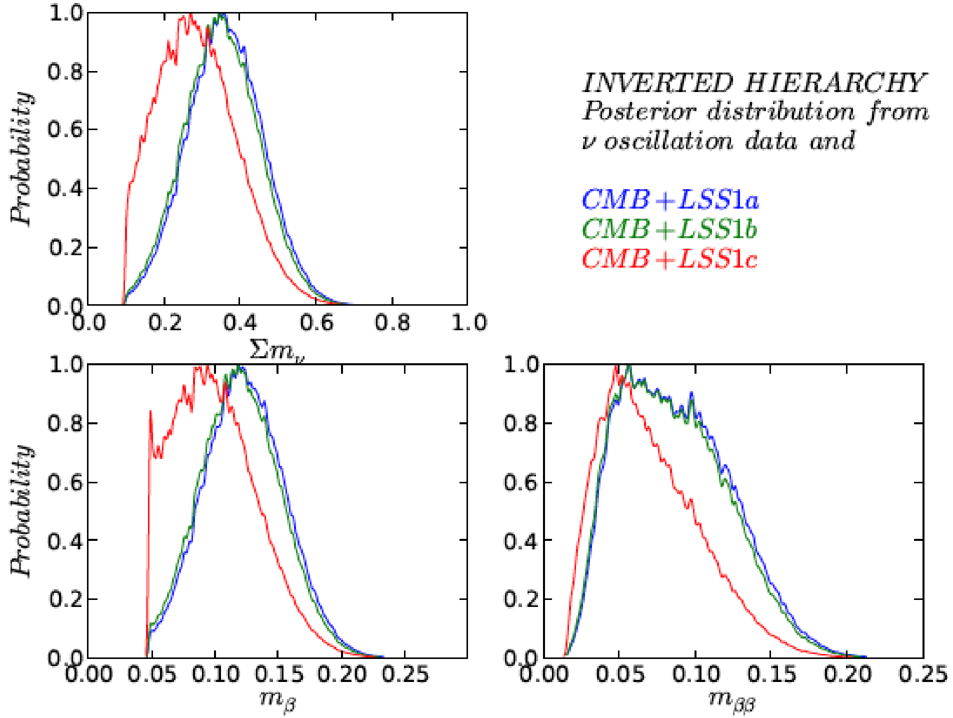
m_β
m_ββ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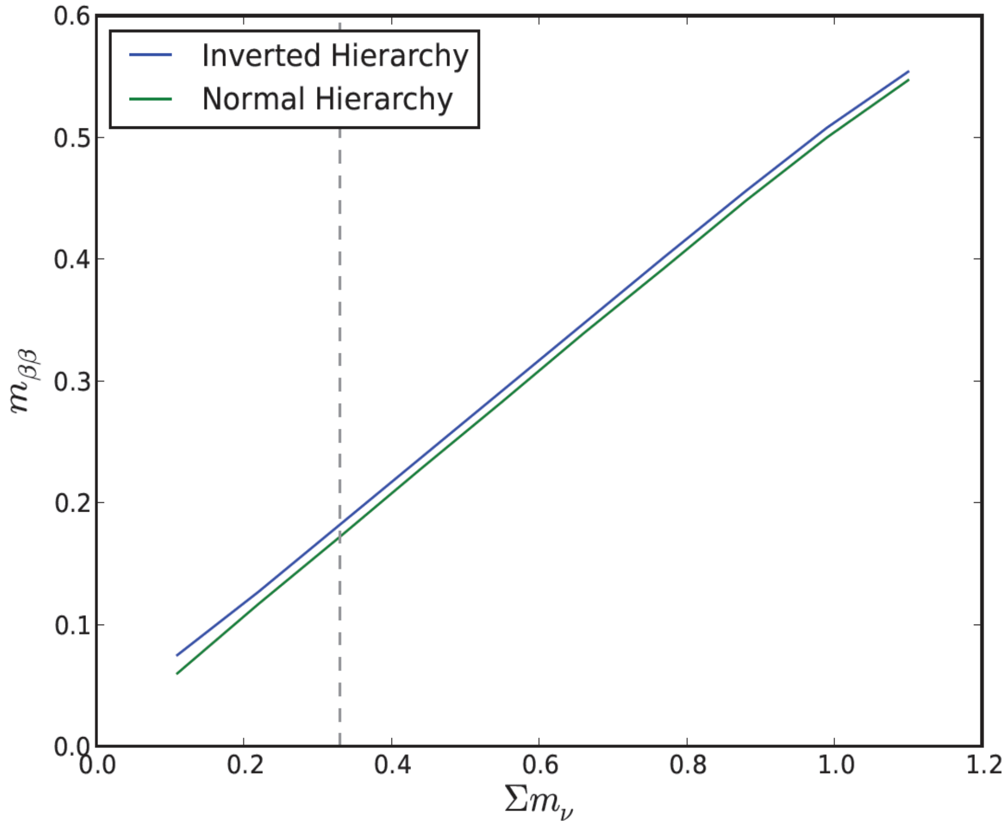
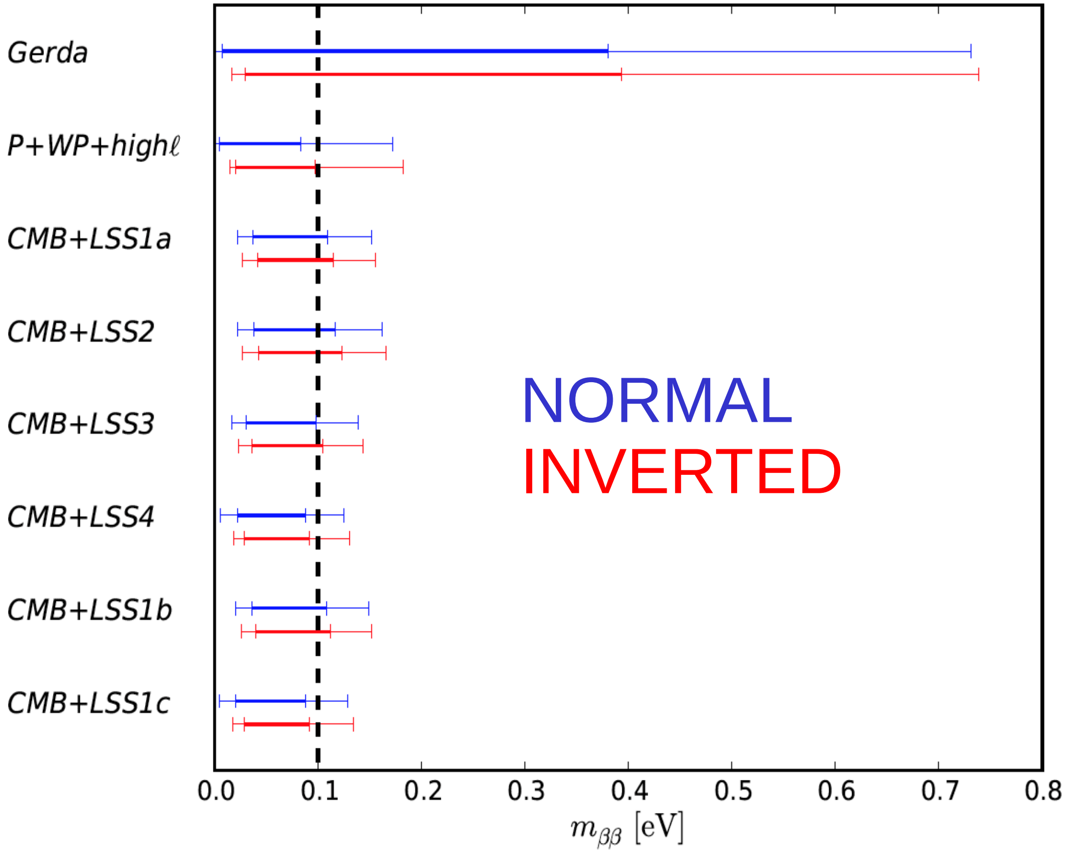
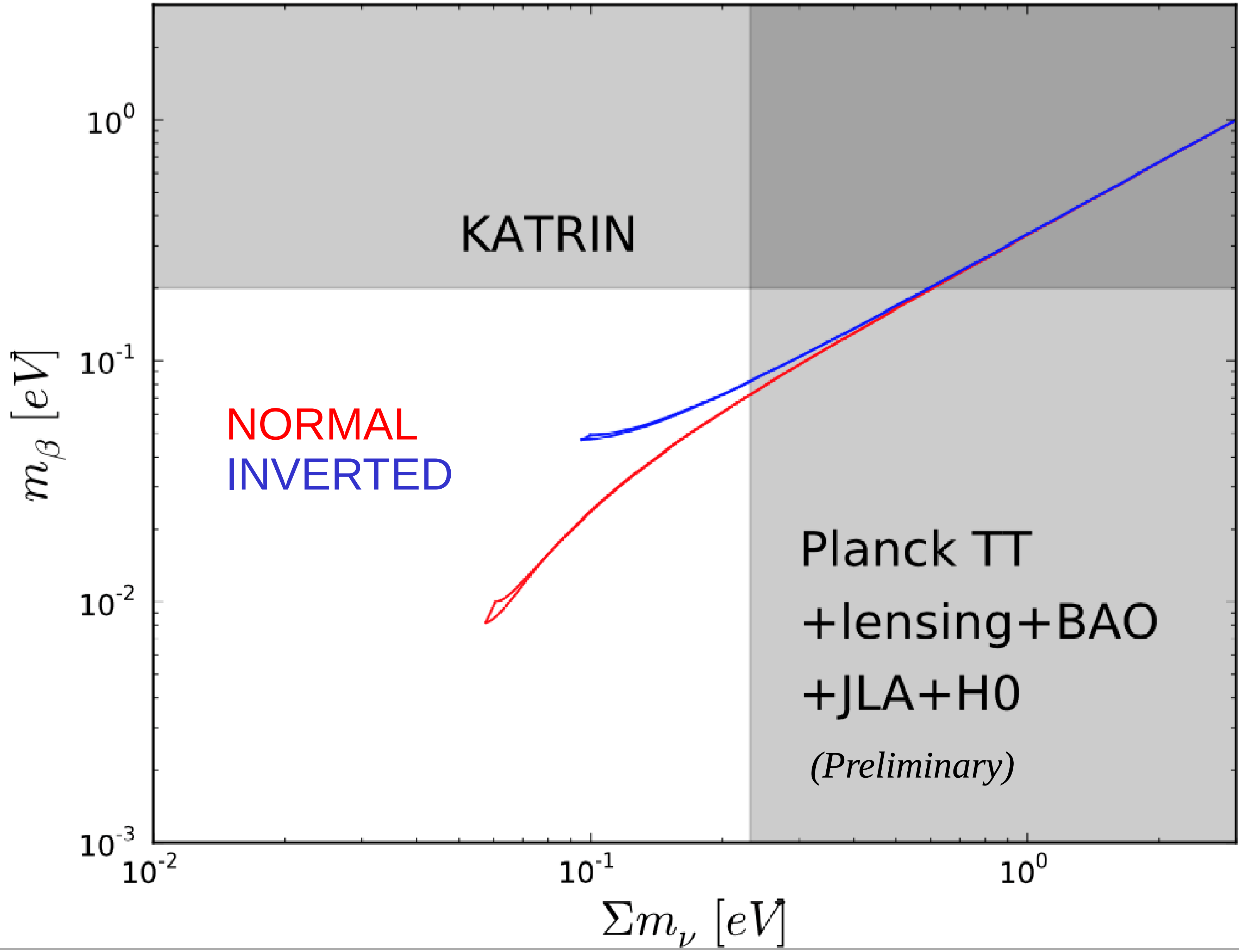
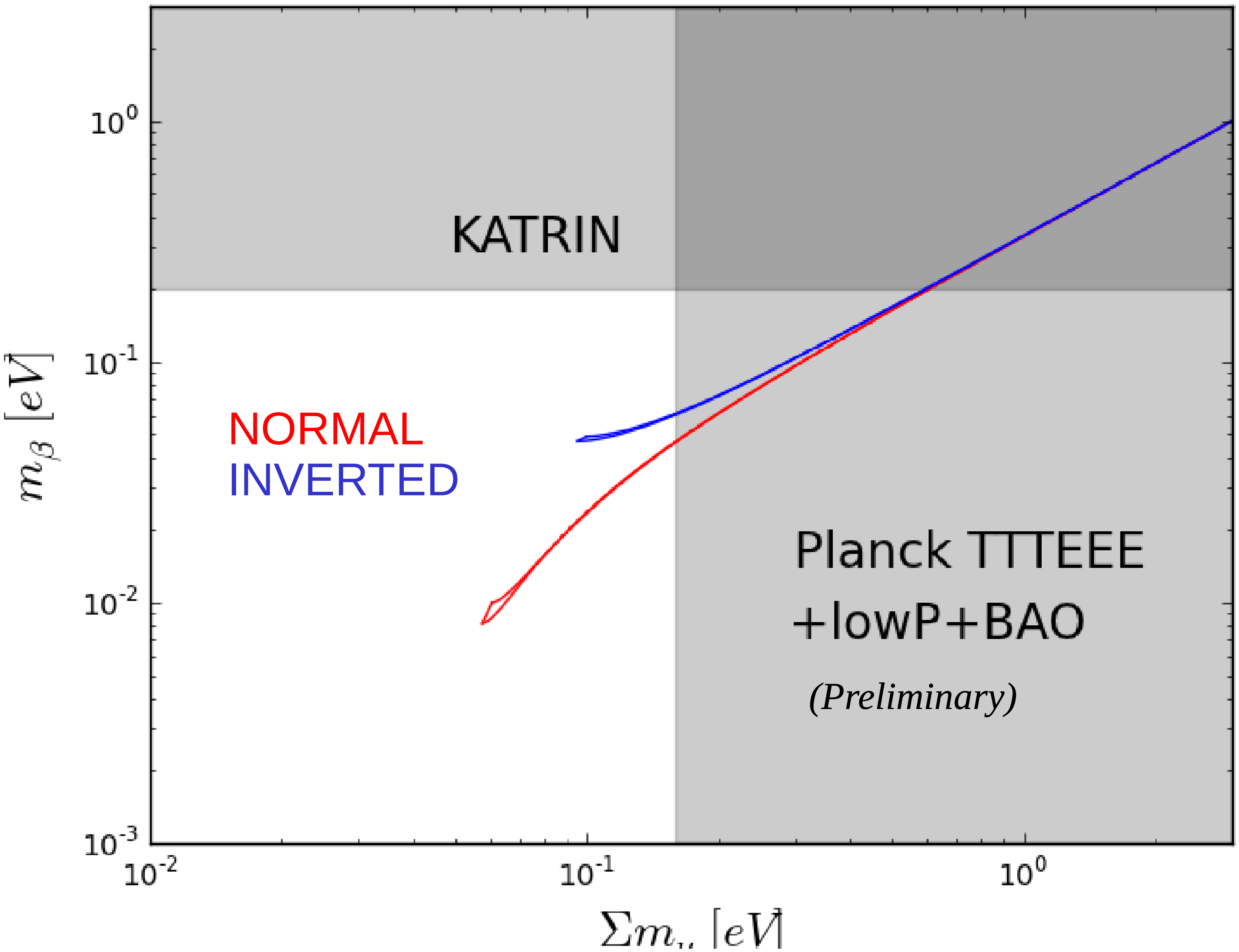


Improving constraints on Σm
would increase the evidence for mbb

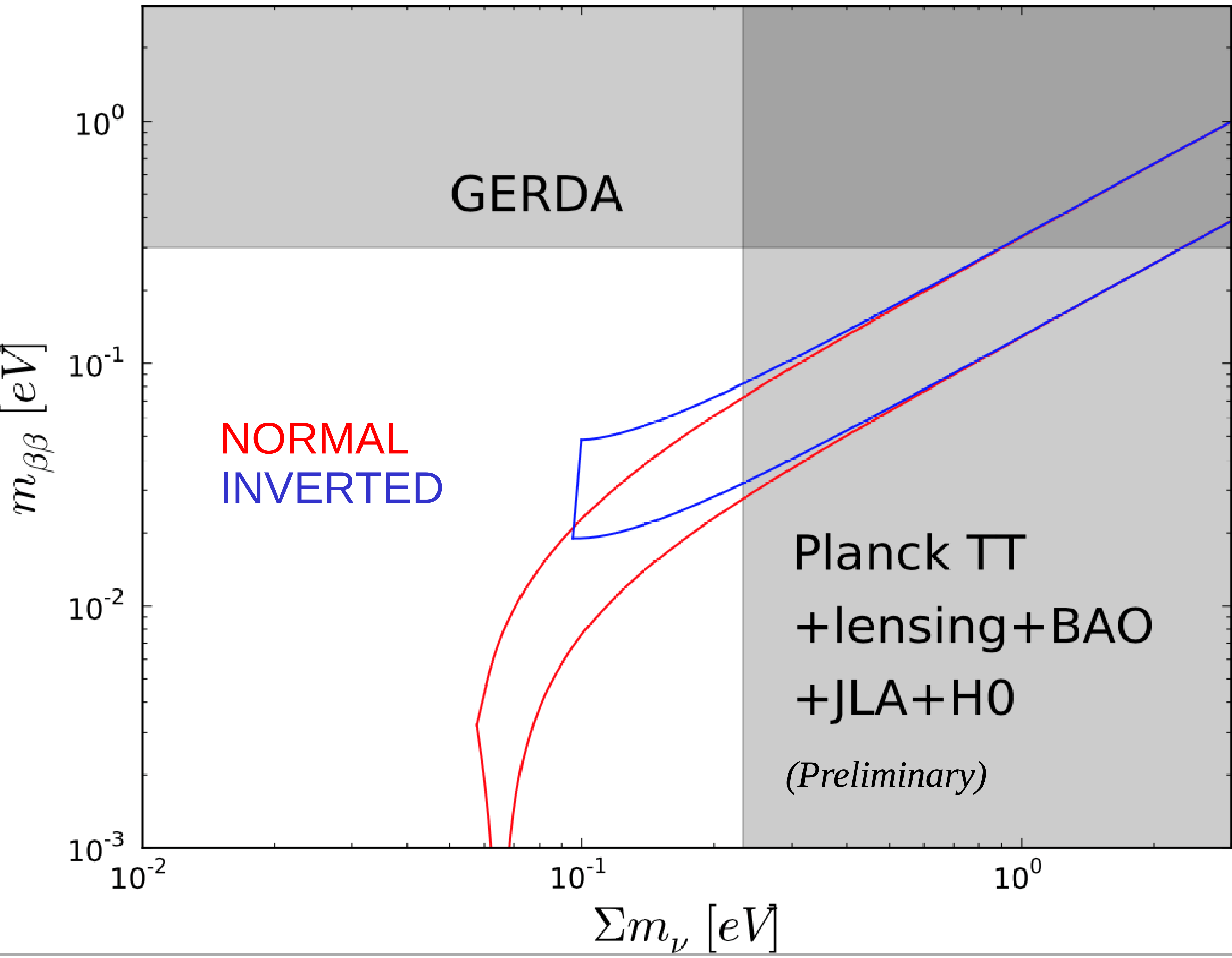


Need for reaching the region
far below mbb=0.1 eV
in order to discriminate
between hierarchies


KATRIN
NORMAL
INVERTED
Planck TT
+lensing+BAO
+JLA+H0
(Preliminary)
m_β [eV]
Σm_ν [eV]
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-2}
10^{-1}
10^0



KATRIN
NORMAL
INVERTED
Planck TTTEEE
+lowP+BAO
(Preliminary)
m_β [eV]
Σm_ν [eV]
10^0
10^{-1}
10^{-2}
10^{-3}


GERDA
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+JLA+H0
(Preliminary)
$m_{\beta\beta}$ [eV]
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10^0
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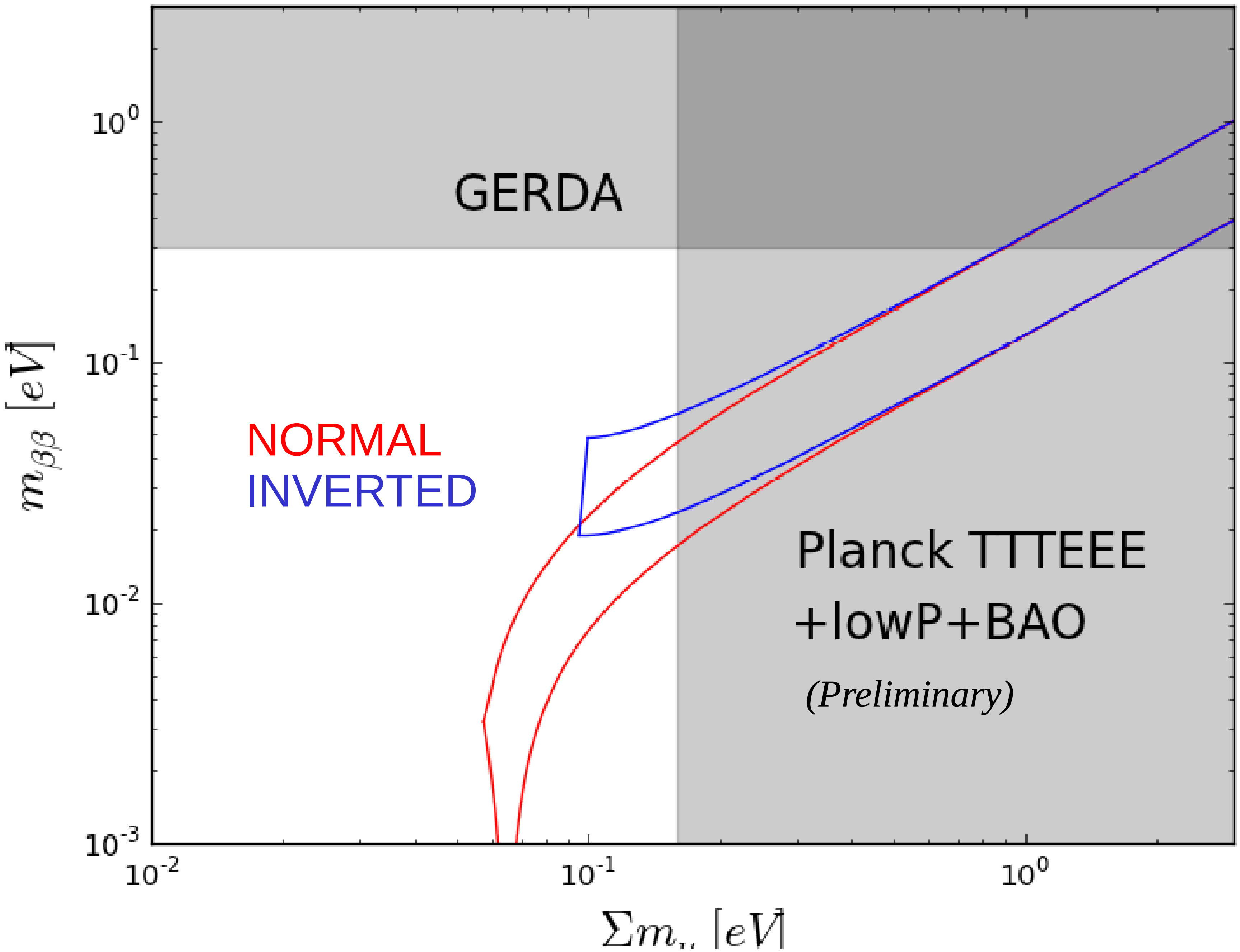
10^{-2}
10^{-3}
10^{-2}
10^{-1}
10^0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Σm_ν $[eV]$
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-2}
10^{-1}
10^0

Conclusions

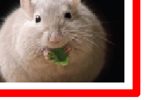
- Combinations of CMB and LSS
give the tightest constraints on the scale-mass parameters

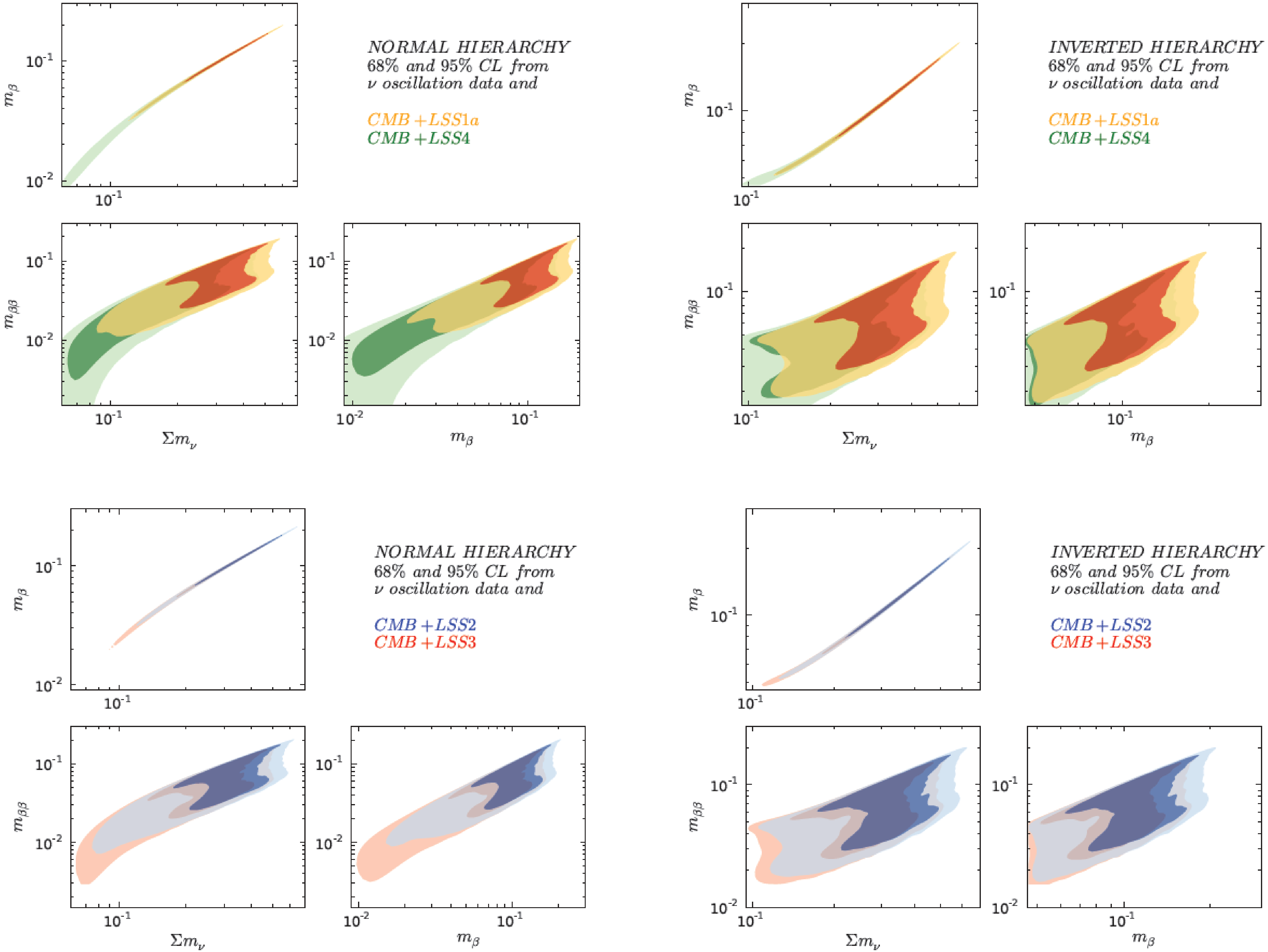
- CMB+LSS hints for m_{bb} and m_b to be within the region [0-0.2] eV

- Better constraints on Σm_{nu} will result in stronger evidence for $m_{bb} \neq 0$

- Discrimination between hierarchies
possible if future achieved sensibility is << 0.1 eV

For further questions:
martina.gerbino@uniroma1.it





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CMB+LSS2
CMB+LSS3
INVERTED HIERARCHY
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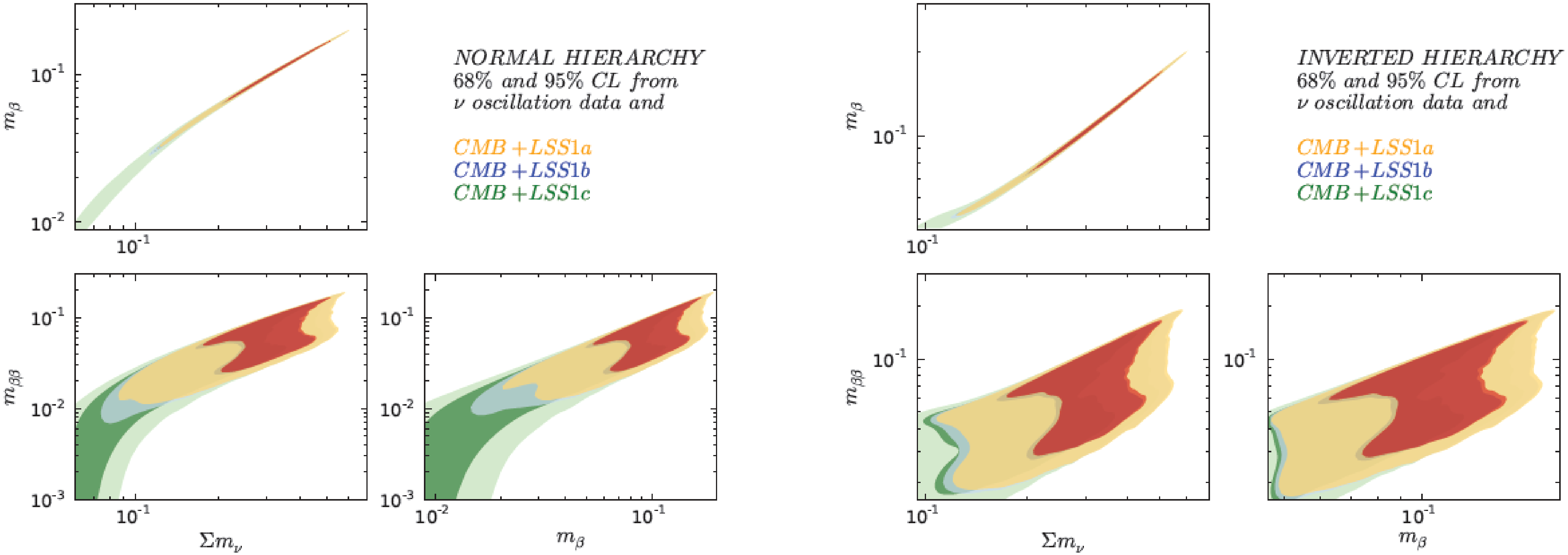
CMB+LSS2
CMB+LSS3
m_β
$m_{\beta\beta}$
Σm_ν



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CMB+LSS1b
CMB+LSS1c
INVERTED HIERARCHY
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ν oscillation data and
CMB+LSS1a
CMB+LSS1b
CMB+LSS1c
m_β
$m_{\beta\beta}$
Σm_ν
m_β
10^{-1}
10^{-2}
10^{-3}