Neutrino mass hierarchy

from JUNO to the Universe

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(IHEP, Beijing)

OUTLINE

★ **Flavor issues**

★ **Neutrino mass spectrum**

★ **Terrestrial matter effects at JUNO**

@ JUNO 中微子天文和天体物理学研讨会，南京大学，17/4/16

Flavor issues

♣ Dirac or Majorana?

Most theorists love Majorana neutrinos
You know why….

♣ Mass spectrum

Non-oscillation experimentalists frown at the normal ordering
You will see why….

See next page

♣ Flavor mixing

Oscillation experimentalists prefer large mixing angles
You have known why….

♣ CP violation

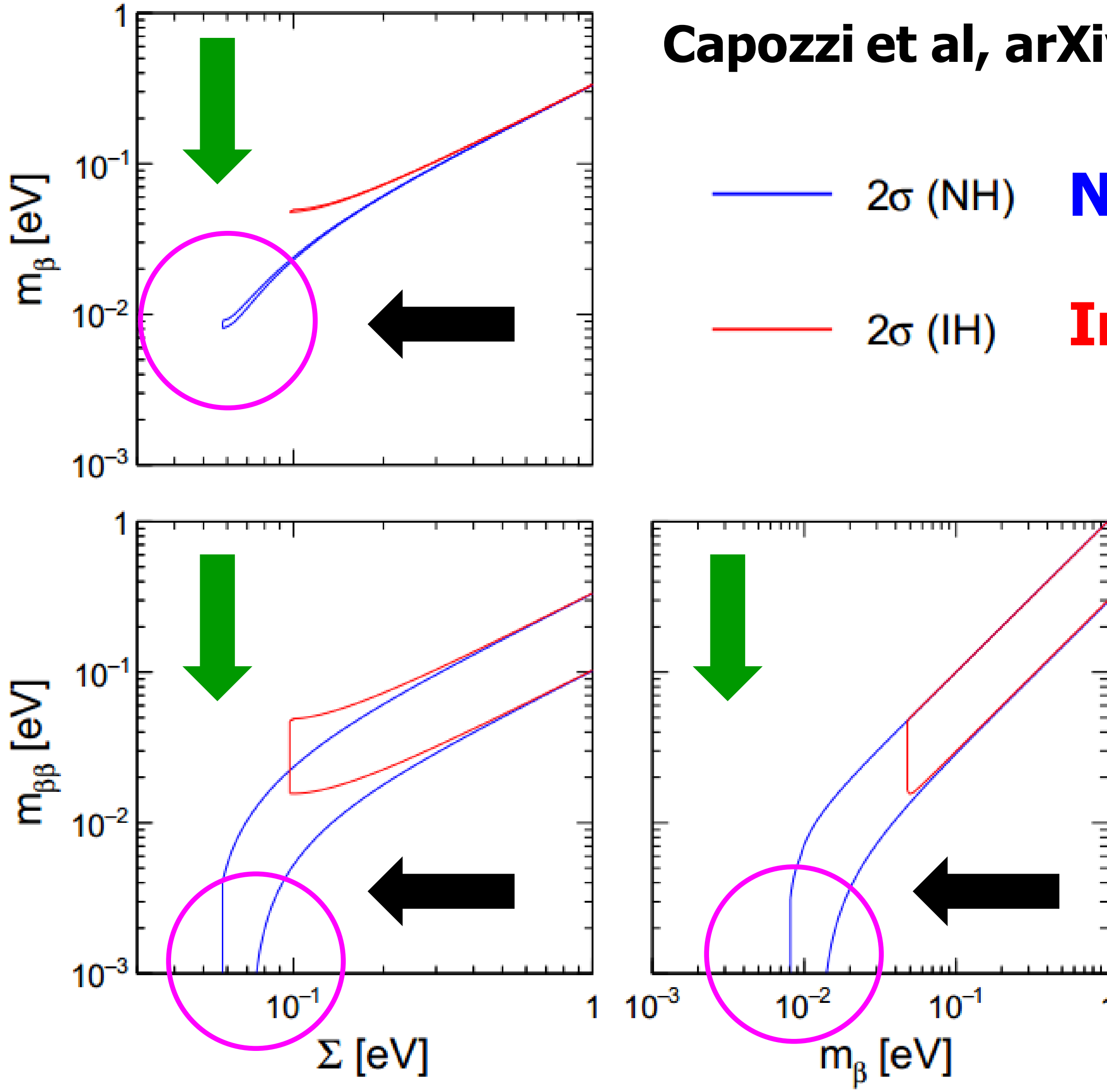
Minkowski once told me: "Asymmetry is a sister of symmetry"
So they are equally important….

♣ New species

Sterile neutrinos may be one of our mothers
Cosmological matter-antimatter asymmetry + dark matter + ….

Very normal hierarchy?

Capozzi et al, arXiv:1601.07777



Normal

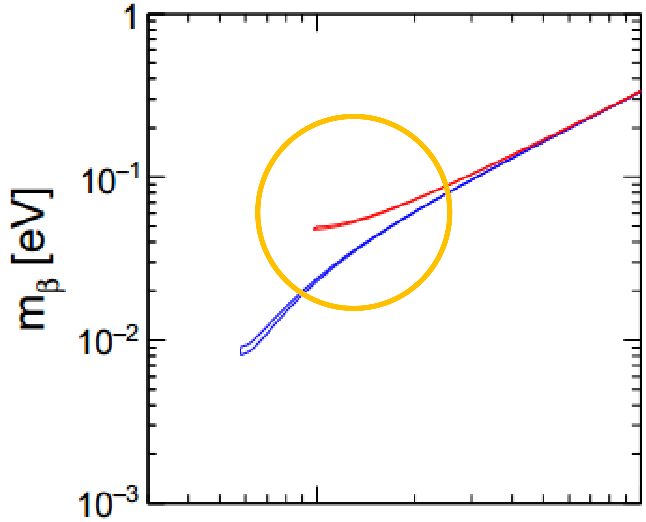
Inverted

cosmology

unlucky region

As normal as charged fermions

Intelligent design?

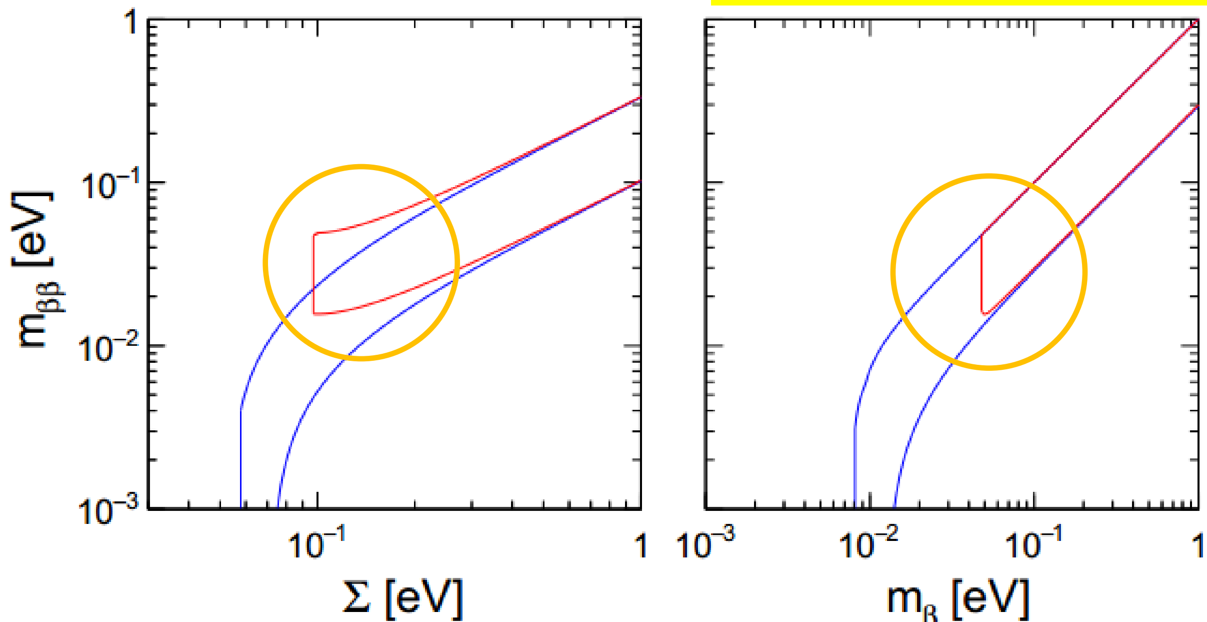


Capozzi et al, arXiv:1601.07777

2σ (NH) **Normal**

2σ (IH) **Inverted**

Einstein: Subtle is the Lord, but malicious He is not (1921).

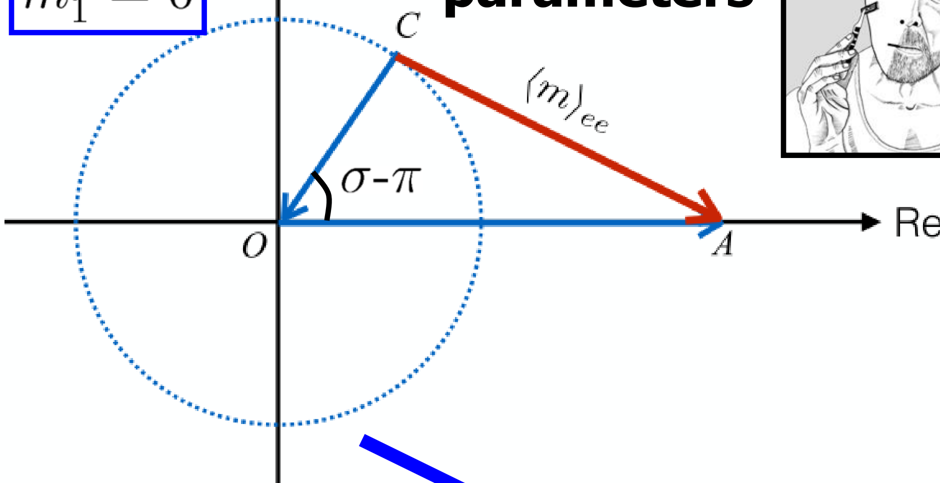


cosmology

lucky region

Maury Goodman

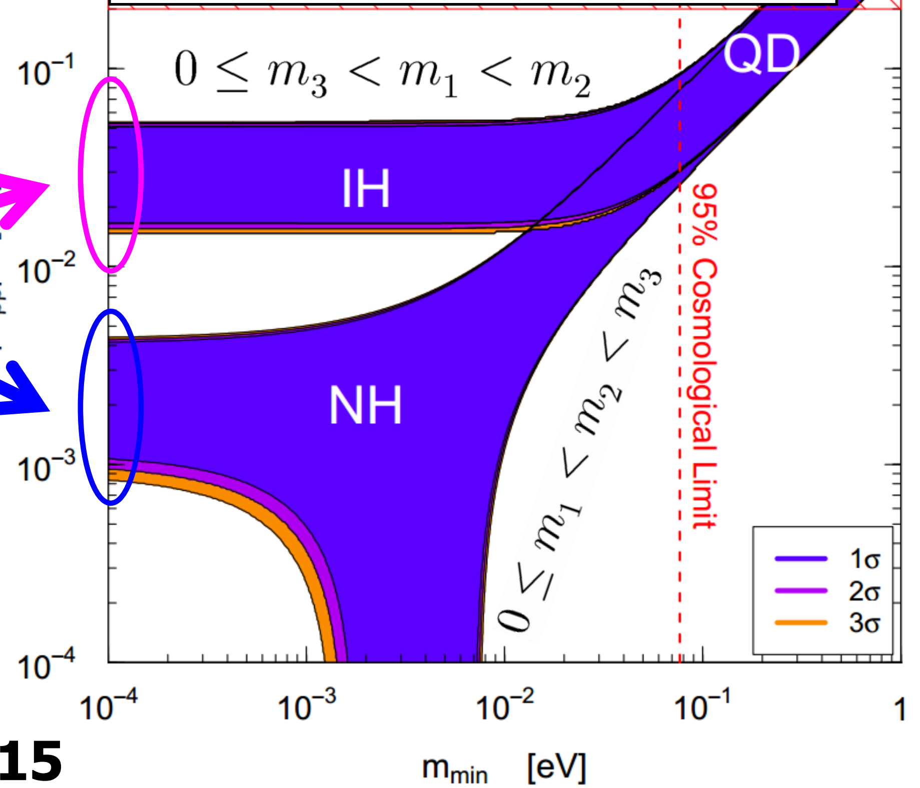
Occam's razor: 0ν2β

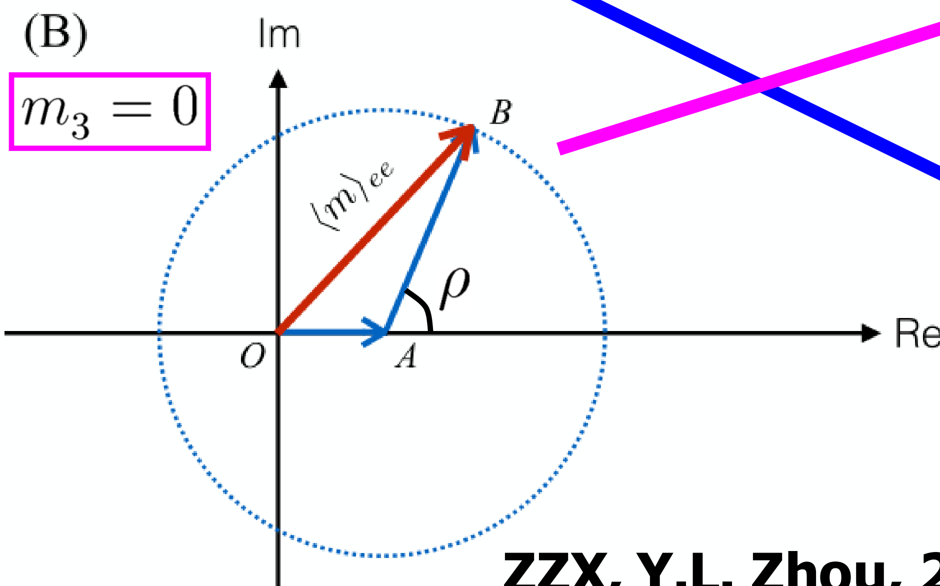


Fewer facial parameters

Entities must not be multiplied beyond necessity.

$$\overrightarrow{OA} \equiv m_2 U_{e2}^2 = m_2 |U_{e2}|^2 \,,$$
$$\overrightarrow{AB} \equiv m_1 U_{e1}^2 = m_1 |U_{e1}|^2 e^{i\rho}$$
$$\overrightarrow{CO} \equiv m_3 U_{e3}^2 = m_3 |U_{e3}|^2 e^{i\sigma}$$

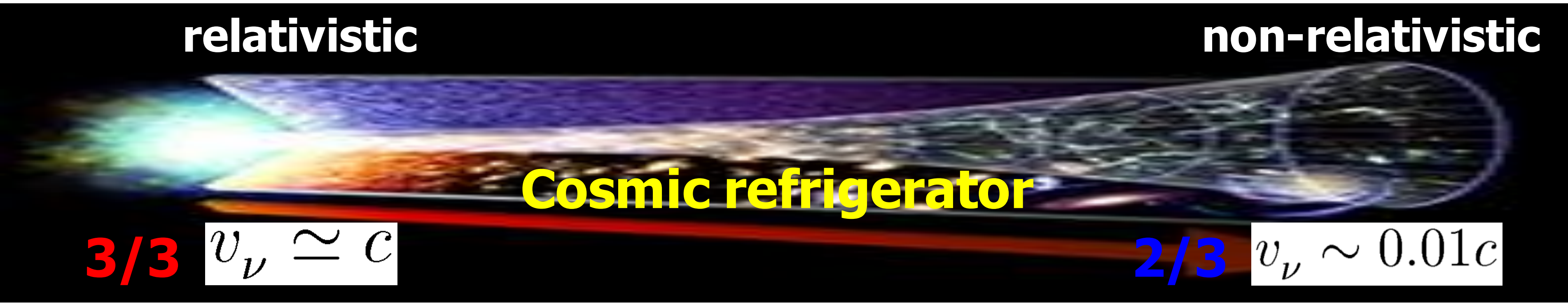




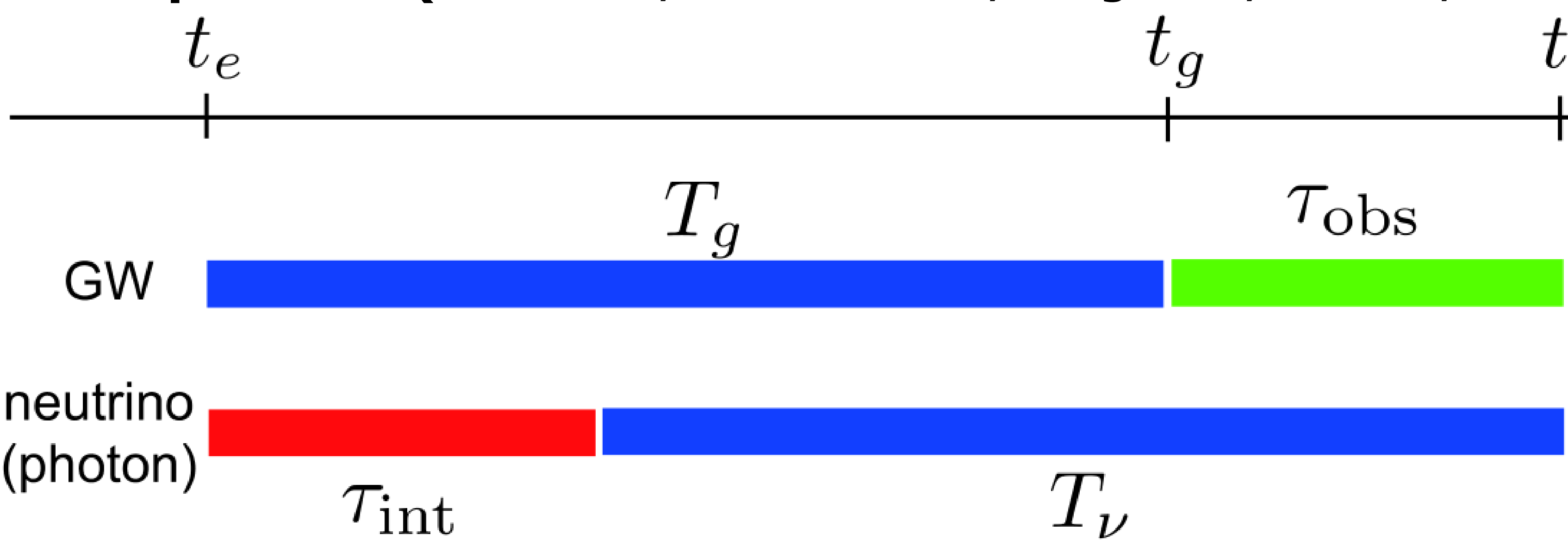
ZZX, Y.L. Zhou, 2015

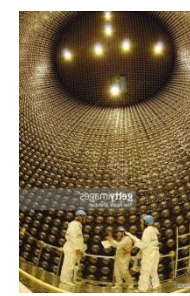
Occam's razor: CνB + …

Let's consider: in today's Universe, 2/3 of relic ν's become cold but 1/3 of them are Weyl particles and remain hot.



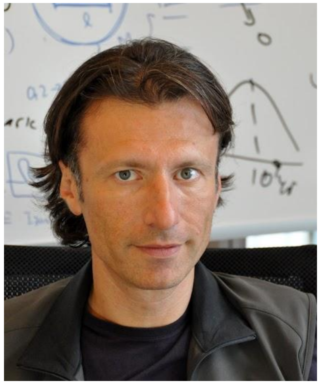
Gravitational waves, neutrinos, photons from compact binary mergers and supernovae (Nishizawa, Nakamura 14; Langaeble, Meroni, Sannino 16)





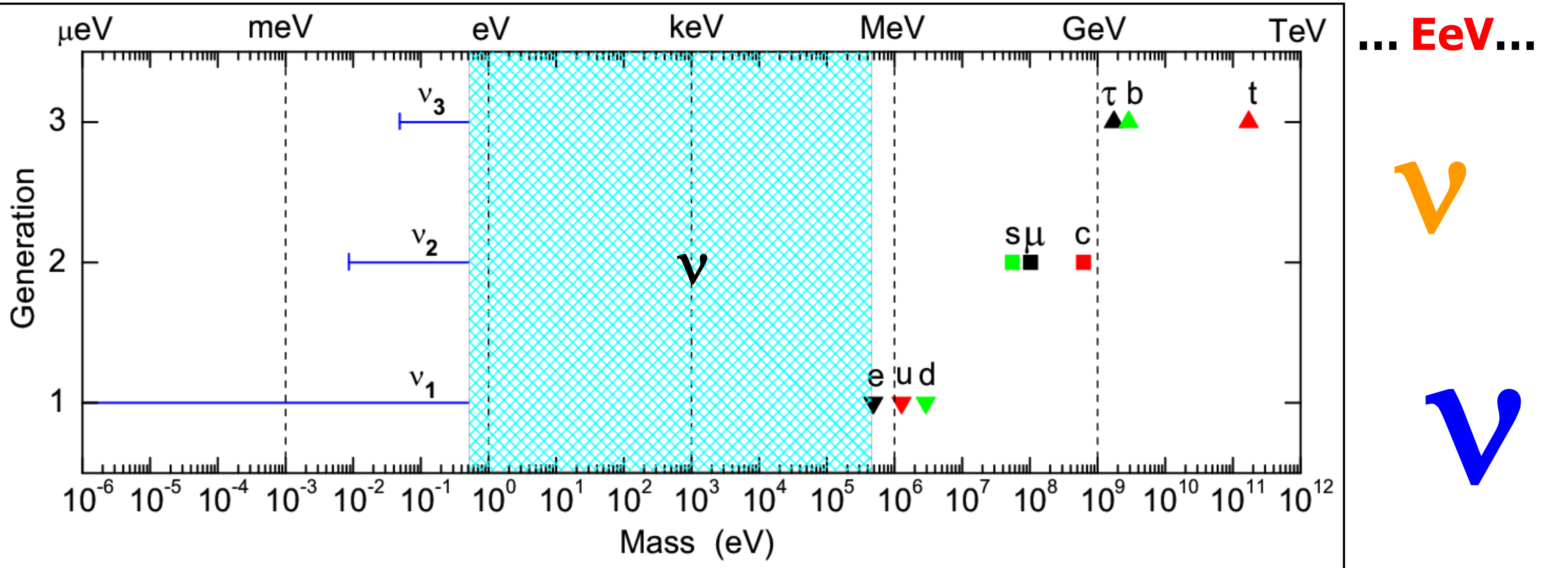
Anthropic sterile species

The split seesaw: 2 heavy right-handed neutrinos + 1 keV right-handed neutrino (Kusenko, Yanagida 2010, 2016).



Existence of life **requires: a) primordial antimatter disappeared; b) dark matter mattered.**

Split seesaw + thermal leptogenesis + warm dark matter + ...



Ordering or reordering

All charged fermions: normal mass hierarchies. How about neutrinos?

$$-\mathcal{L}_{\rm cc} = \frac{g}{\sqrt{2}} \left[\overline{\begin{pmatrix} e & \mu & \tau \end{pmatrix}_{\rm L}} \gamma^\mu \, U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}_{\rm L} W^-_\mu + \overline{\begin{pmatrix} u & c & t \end{pmatrix}_{\rm L}} \gamma^\mu \, V \begin{pmatrix} d \\ s \\ b \end{pmatrix}_{\rm L} W^+_\mu \right] + {\rm h.c.}$$

PMNS (U) **CKM** (V)

Normal: $m_1 < m_2 < m_3$

Inverted: $m_3 < m_1 < m_2$

Given a weak basis, the mass ordering is fixed. A basis change is possible.

For instance: $(\nu_1, \nu_2, \nu_3) \to (\nu_2^\prime, \nu_3^\prime, \nu_1^\prime)$

Reorder: $m_1^\prime < m_2^\prime < m_3^\prime$

$$|U| = \begin{pmatrix} 0.795 \to 0.846 & 0.513 \to 0.585 & 0.126 \to 0.178 \\ 0.205 \to 0.543 & 0.416 \to 0.730 & 0.579 \to 0.808 \\ 0.215 \to 0.548 & 0.409 \to 0.725 & 0.567 \to 0.800 \end{pmatrix}$$

$$|U^\prime| = \begin{pmatrix} 0.126 \to 0.178 & 0.795 \to 0.846 & 0.513 \to 0.585 \\ 0.579 \to 0.808 & 0.205 \to 0.543 & 0.416 \to 0.730 \\ 0.567 \to 0.800 & 0.215 \to 0.548 & 0.409 \to 0.725 \end{pmatrix}$$

SK + T2K hint

Summary

SK + T2K fit prefers normal hierarchy at $\chi^2_{IH} - \chi^2_{NH} = 3.2$

SK+T2K fit prefers $\delta_{cp}\sim240°$

- both SK and T2K separately prefer $\delta_{cp}\sim240°$, combination strengthens this preference
- sin $\delta_{cp}=0$ is still allowed at 68% confidence

Improvements in mind

Improving Hierarchy Sensitivity

More Data

SK continues to run

T2K $\bar{\nu}$

NOνA

Reduce/Constrain Backgrounds

improve ν_e-ν_μ separation with better MutliGeV PID

constrain ν_τ background with neural net techniques from ν_τ appearance analysis

Improve ν-$\bar{\nu}$ Separation

n-H capture

n-Gd capture (with future addition of Gadolinium)

C. Kachulis

Boston U.
EPS 2015

NOvA hint

Summary

- NOvA has analyzed its first data set for both ν_μ disappearance and ν_e appearance
  - Made 6.5% measurement of Δm^2_{32}; θ_{23} is consistent with maximal mixing
  - Two methods for searching for ν_e events were used, the primary selector finds a signal at 3.3σ while the secondary sees one at 5.5σ
  - Both methods hint at a preference for the normal ordering with $\pi < \delta < 2\pi$
- Data set will be doubled by next summer - stay tuned!

Brian Rebel

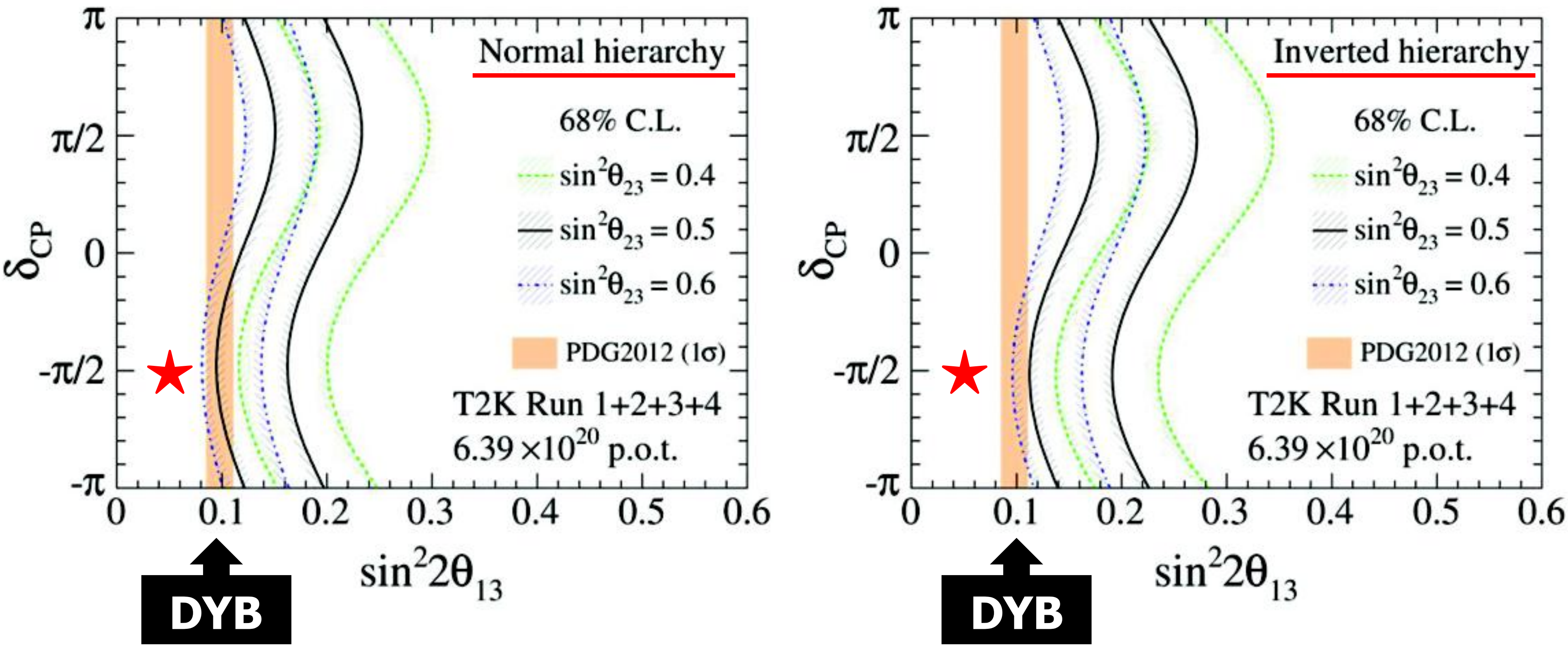
Fermilab

TAUP 2015

www-nova.fnal.gov

T2K + DYB hint

The **T2K** observation of a relatively strong $\nu_\mu \to \nu_e$ appearance plays a crucial role in the global fit to make θ_{13} consistent with the **Daya Bay** result and drive a slight but intriguing preference for $\delta \sim -\pi/2$.



DYB's good news: θ_{13} **unsuppressed**
T2K's good news: δ **unsuppressed**

Life is easier for probing CP violation, ν mass hierarchy ....

Cosmological hint (1)

Cosmological limits on neutrino unknowns versus low redshift priors

Eleonora Di Valentino,[1] Elena Giusarma,[2] Olga Mena,[3] Alessandro Melchiorri,[2] and Joseph Silk[1,4,5]

arXiv:1511.00975v1 [astro-ph.CO] 3 Nov 2015

Recent Cosmic Microwave Background (CMB) temperature and polarization anisotropy measurements from the Planck mission have significantly improved previous constraints on the neutrino masses as well as the bounds on extended models with massless or massive sterile neutrino states. However, due to parameter degeneracies, additional low redshift priors are mandatory in order to sharpen the CMB neutrino bounds. We explore here the role of different priors on low redshift quantities, such as the Hubble constant, the cluster mass bias, and the reionization optical depth τ. Concerning current priors on the Hubble constant and the cluster mass bias, the bounds on the neutrino parameters may differ appreciably depending on the choices adopted in the analyses. With regard to future improvements in the priors on the reionization optical depth, a value of $\tau = 0.05 \pm 0.01$, motivated by astrophysical estimates of the reionization redshift, would lead to $\sum m_\nu < 0.0993$ eV at 95% CL, thereby opening the window to unravel the neutrino mass hierarchy with existing cosmological probes.

	Planck pol +BAO+SZ+tau6	Planck pol +BAO+SZ+tau5	Planck pol H073p0+SZ+tau6	Planck pol H073p0+SZ+tau5	Planck pol+BAO +H073p0+SZ+tau6	Planck pol +BAO +H073p0+SZ+tau5
$\Omega_c h^2$	$0.1194^{+0.0021}_{-0.0021}$	$0.1195^{+0.0021}_{-0.0021}$	$0.1190^{+0.0026}_{-0.0025}$	$0.1192^{+0.0026}_{-0.0025}$	$0.1190^{+0.0020}_{-0.0020}$	$0.1192^{+0.0020}_{-0.0021}$
Σm_ν [eV]	< 0.122	< 0.116	< 0.112	< 0.107	< 0.104	< 0.0993
H_0 [km s^{-1} Mpc^{-1}]	$67.7^{+1.0}_{-1.0}$	$67.6^{+1.0}_{-1.0}$	$67.9^{+1.3}_{-1.4}$	$67.8^{+1.2}_{-1.4}$	$67.88^{+0.96}_{-0.98}$	$67.83^{+0.99}_{-0.98}$
σ_8	$0.823^{+0.022}_{-0.024}$	$0.818^{+0.022}_{-0.023}$	$0.824^{+0.022}_{-0.023}$	$0.819^{+0.021}_{-0.022}$	$0.824^{+0.021}_{-0.022}$	$0.819^{+0.021}_{-0.022}$
Ω_m	$0.311^{+0.013}_{-0.013}$	$0.311^{+0.014}_{-0.013}$	$0.307^{+0.018}_{-0.017}$	$0.309^{+0.018}_{-0.017}$	$0.308^{+0.013}_{-0.012}$	$0.308^{+0.013}_{-0.013}$
τ	$0.066^{+0.017}_{-0.017}$	$0.059^{+0.017}_{-0.017}$	$0.067^{+0.017}_{-0.017}$	$0.060^{+0.017}_{-0.017}$	$0.067^{+0.017}_{-0.017}$	$0.059^{+0.017}_{-0.017}$

Cosmological hint (2)

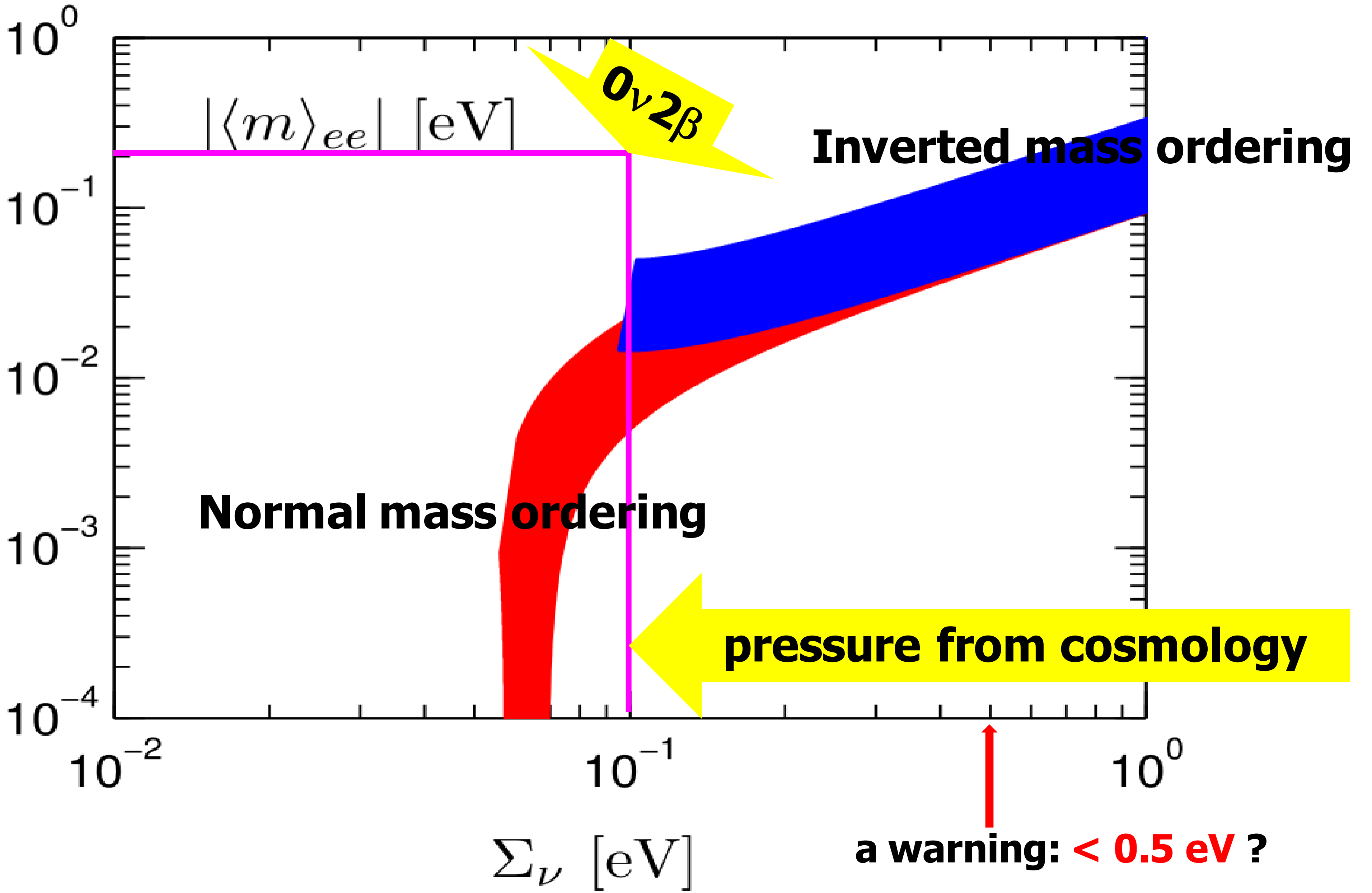
Neutrino mass limits: robust information from the power spectrum of galaxy surveys

Antonio J. Cuesta[a*], Viviana Niro[b†], Licia Verde[acde‡]

We present cosmological upper limits on the sum of active neutrino masses using large-scale power spectrum data from the WiggleZ Dark Energy Survey and from the Sloan Digital Sky Survey -Data Release 7 (SDSS-DR7) sample of Luminous Red Galaxies (LRG). Combining measurements on the Cosmic Microwave Background temperature and polarisation anisotropies by the Planck satellite together with WiggleZ power spectrum results in a neutrino mass bound of 0.43 eV at 95% C.L., while replacing WiggleZ by the SDSS-DR7 LRG power spectrum, the 95% C.L. bound on the sum of neutrino masses improves to 0.17 eV. Adding Baryon Acoustic Oscillation (BAO) distance scale measurements, the neutrino mass upper limits greatly improve, since BAO data break degeneracies in parameter space. Within a ΛCDM model, we find an upper limit of 0.11eV (0.15 eV) at 95% C.L., when using SDSS-DR7 LRG (WiggleZ) together with BAO and Planck. The addition of BAO data makes the neutrino mass upper limit robust, showing only a weak dependence on the power spectrum used. We also quantify the dependence of neutrino mass limit reported here on the CMB lensing information. The tighter upper limit (0.11 eV) obtained with SDSS-DR7 LRG is very close to that recently obtained using Lyman-alpha clustering data, yet uses a completely different probe and redshift range, further supporting the robustness of the constraint. This constraint puts under some pressure the inverted mass hierarchy and favours the normal hierarchy.

arXiv:1511.05983v1 [astro-ph.CO] 18 Nov 2015

Strongest bound?



a warning: < 0.5 eV ?

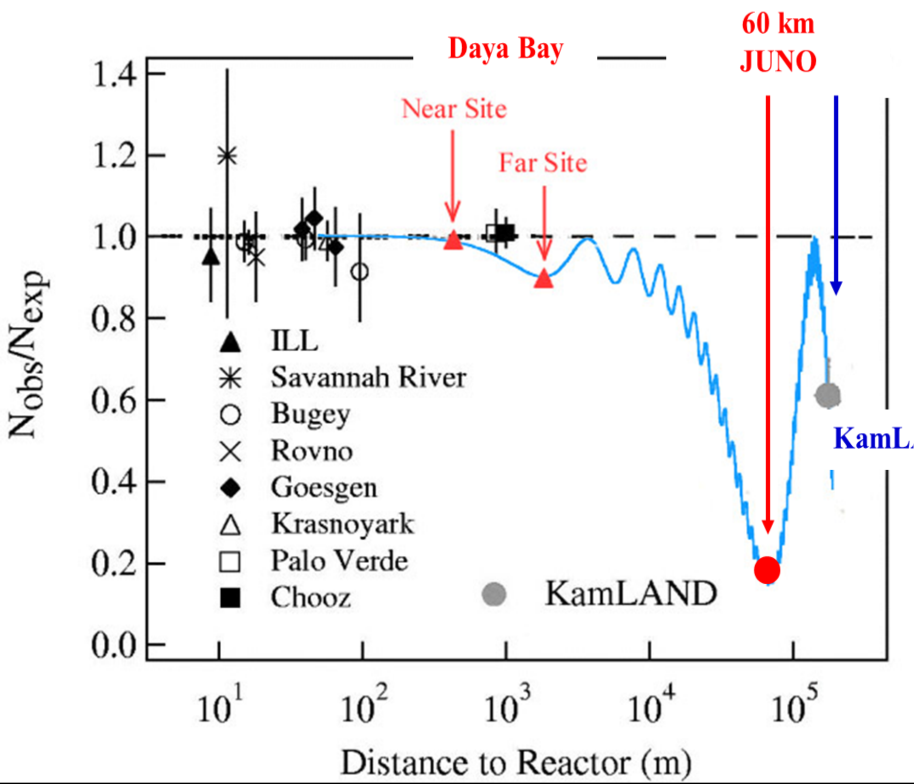
Oscillation experiments

Accelerator/atmospheric: terrestrial matter effects play crucial roles.

$$\Delta m^2_{31} \mp 2\sqrt{2} G_F N_e E$$

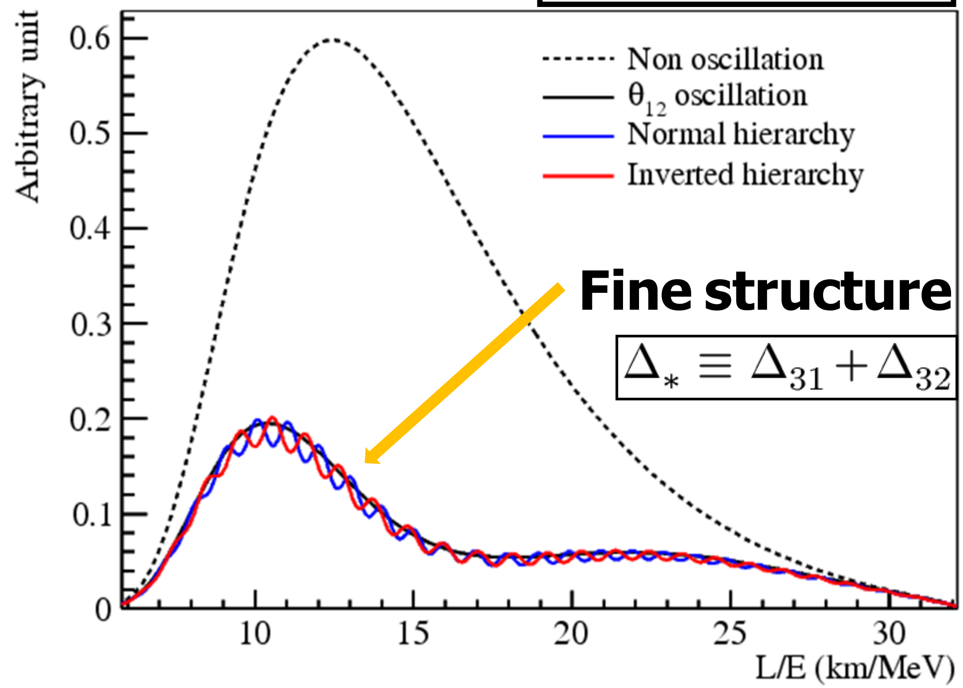
T2K, NOνA, SK, PINGU, INO, …

Reactor (JUNO): Optimum baseline at the valley of Δm^2_{21} oscillations, corrected by the fine structure of Δm^2_{31} oscillations.



JUNO's idea

$$F_{ji} \equiv \Delta_{ji} L / (4E)$$



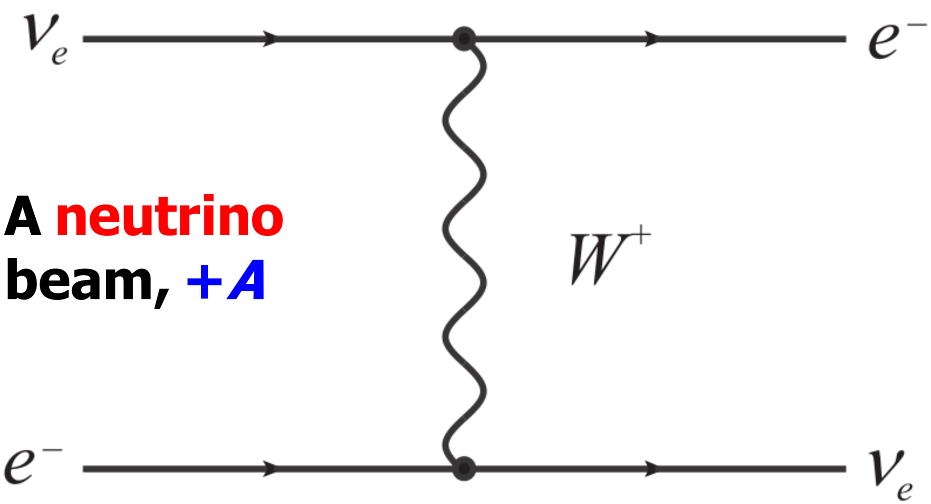
$$\Delta_* \equiv \Delta_{31} + \Delta_{32}$$

$$P(\overline{\nu}_e \to \overline{\nu}_e) = 1 - \sin^2 2\theta_{12} \cos^4 \theta_{13} \sin^2 F_{21} - \frac{1}{2} \sin^2 2\theta_{13} \left[1 - \cos F_* \cos F_{21} + \cos 2\theta_{12} \sin F_* \sin F_{21}\right]$$

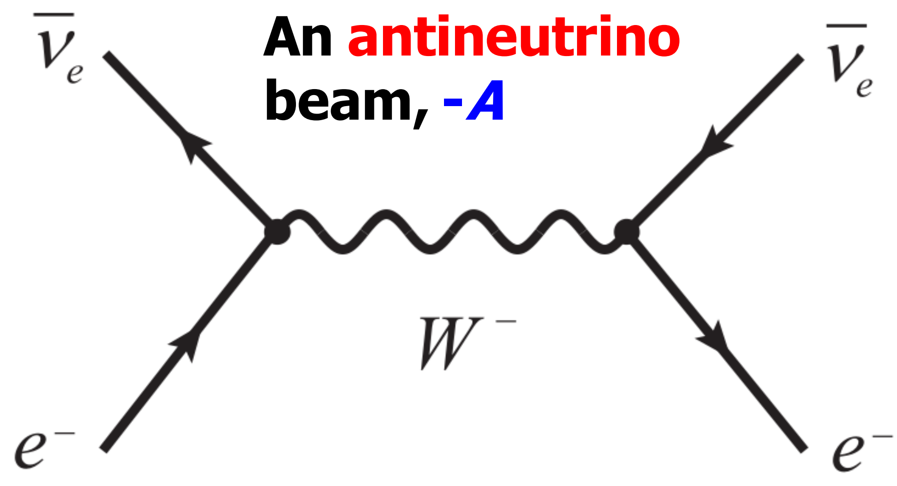
Matter effects

Matter effects in reactor antineutrino oscillations must be very small, but how small is small? —— it makes sense to fix its fine effects.

A neutrino beam, $+A$



An antineutrino beam, $-A$



Coherent forward scattering from weak charged-current interactions. The effective Hamiltonian for neutrino propagation in matter:

$$\widetilde{\mathcal{H}}_{\rm eff} = \frac{1}{2E}\left[\widetilde{U}\begin{pmatrix}\widetilde{m}_1^2 & 0 & 0\\ 0 & \widetilde{m}_2^2 & 0\\ 0 & 0 & \widetilde{m}_3^2\end{pmatrix}\widetilde{U}^\dagger\right] = \frac{1}{2E}\left[U\begin{pmatrix}m_1^2 & 0 & 0\\ 0 & m_2^2 & 0\\ 0 & 0 & m_3^2\end{pmatrix}U^\dagger + \begin{pmatrix}A & 0 & 0\\ 0 & 0 & 0\\ 0 & 0 & 0\end{pmatrix}\right]$$

in matter **in vacuum** **correction**

One may establish the relations between the effective & fundamental parameters.

$$A = 2\sqrt{2}\, G_{\rm F} N_e E$$

Analytical approximations

The effective probability of reactor antineutrino oscillations in matter:

$$\widetilde{P}(\overline{\nu}_e \to \overline{\nu}_e) = 1 - \sin^2 2\widetilde{\theta}_{12} \cos^4 \widetilde{\theta}_{13} \sin^2 \widetilde{F}_{21} - \frac{1}{2} \sin^2 2\widetilde{\theta}_{13} \left[1 - \cos \widetilde{F}_* \cos \widetilde{F}_{21} + \cos 2\widetilde{\theta}_{12} \sin \widetilde{F}_* \sin \widetilde{F}_{21}\right]$$

$$\sin^2 2\widetilde{\theta}_{12} \simeq \sin^2 2\theta_{12} \left(1 - 2\frac{A}{\Delta_{21}} \cos 2\theta_{12}\right)$$

$$\cos 2\widetilde{\theta}_{12} \simeq \cos 2\theta_{12} + \frac{A}{\Delta_{21}} \sin^2 \theta_{12}$$

$$\frac{A}{\Delta_{21}} \simeq 1.2 \times 10^{-2} \times \frac{E}{4\ \text{MeV}} \times \frac{7.5 \times 10^{-5}\ \text{eV}^2}{\Delta_{21}}$$

About 1% correction!

$$\widetilde{\Delta}_{21} \simeq \Delta_{21} + A \cos 2\theta_{12}$$

$$\widetilde{\Delta}_* \simeq \Delta_* + A$$

Close to 1% correction!

Close to 0.02% correction, negligible?

$$\Delta_{21} \simeq 7.5 \times 10^{-5}\ \text{eV}^2$$

$$\Delta_* \simeq \pm 4.8 \times 10^{-3}\ \text{eV}^2$$

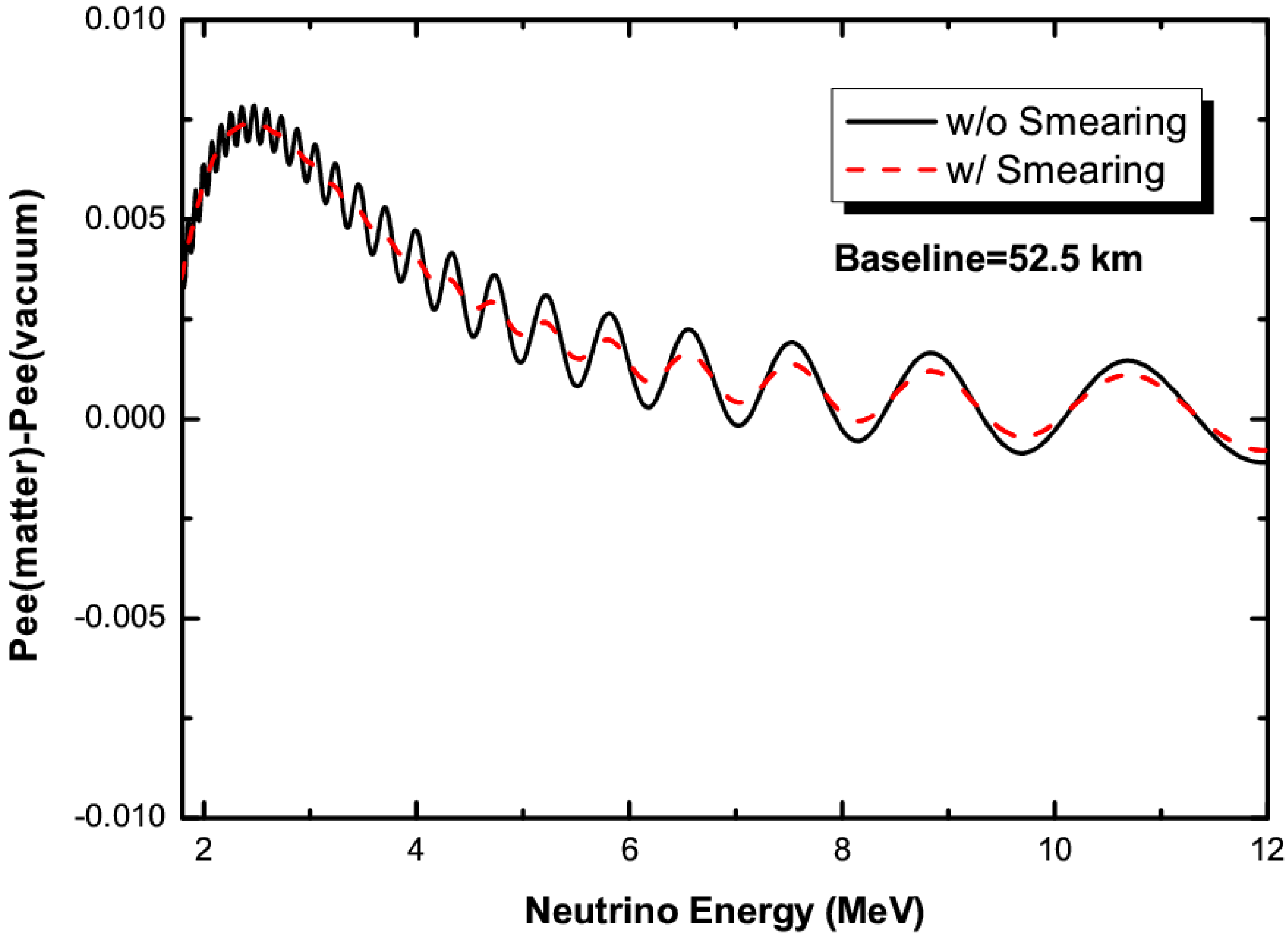
$$A \simeq 9.12 \times 10^{-7}\ \text{eV}^2 (E/4\ \text{MeV})$$

曹俊：

JUNO sensitivity to mass hierarchy 3%

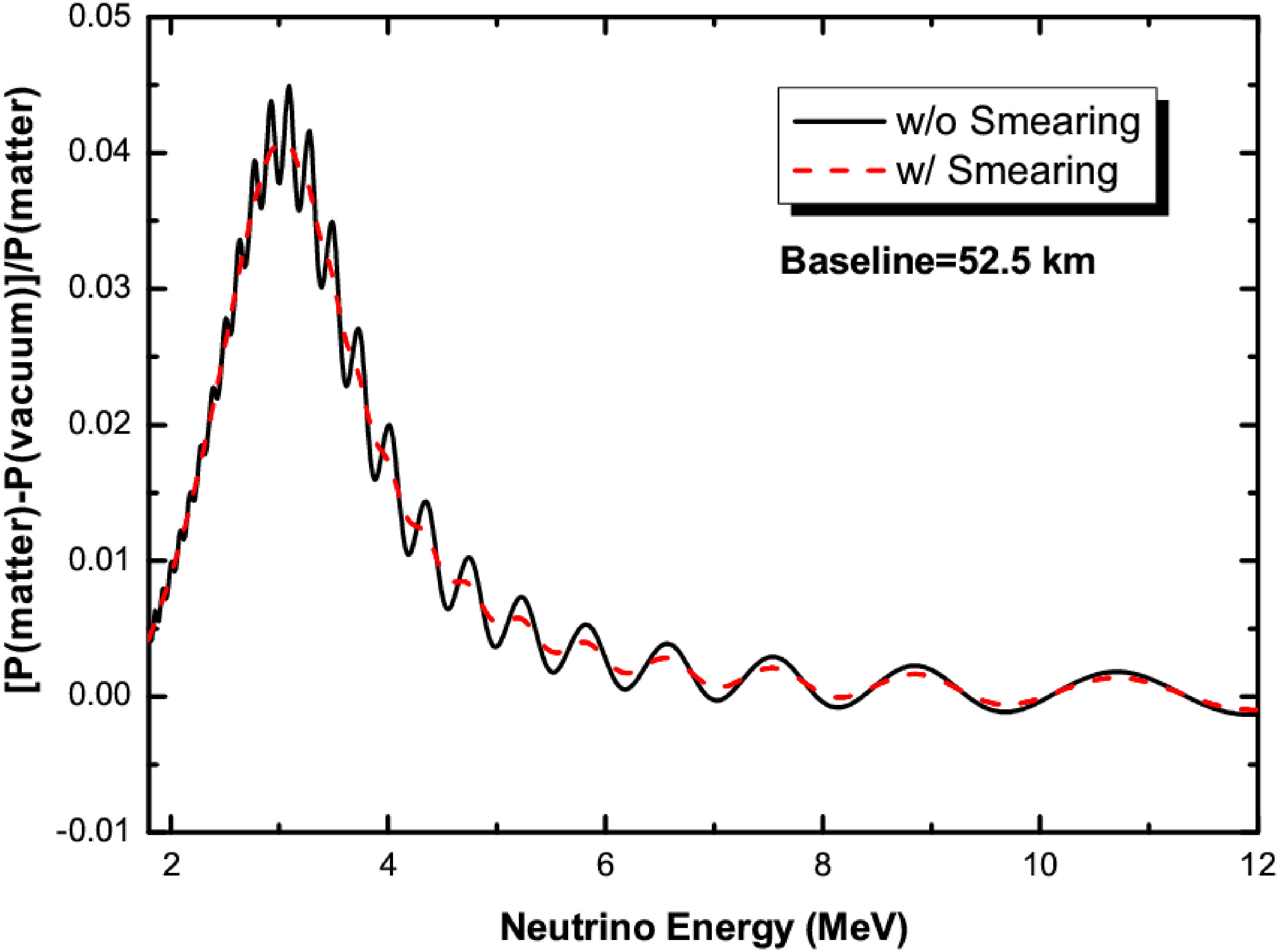
Numerical illustration

Let's take a look at the difference of oscillation probabilities between matter and vacuum (absolute difference):



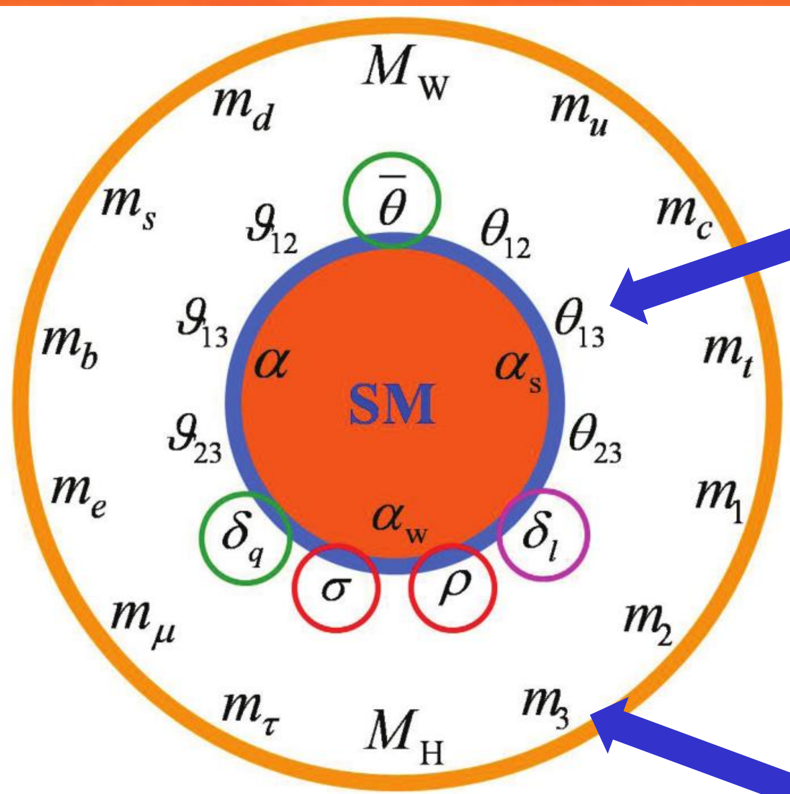
Numerical illustration

Let's take a look at the difference of oscillation probabilities between matter and vacuum (relative difference):



SM + ν's

Martinus Veltman:
we go on until we go wrong!



究竟有多小?
大亚湾2012
5.2 σ

最大或最小?
江门2025 ?
~4 σ ?

Thank you for your attention