NAT-NET Meeting WP1

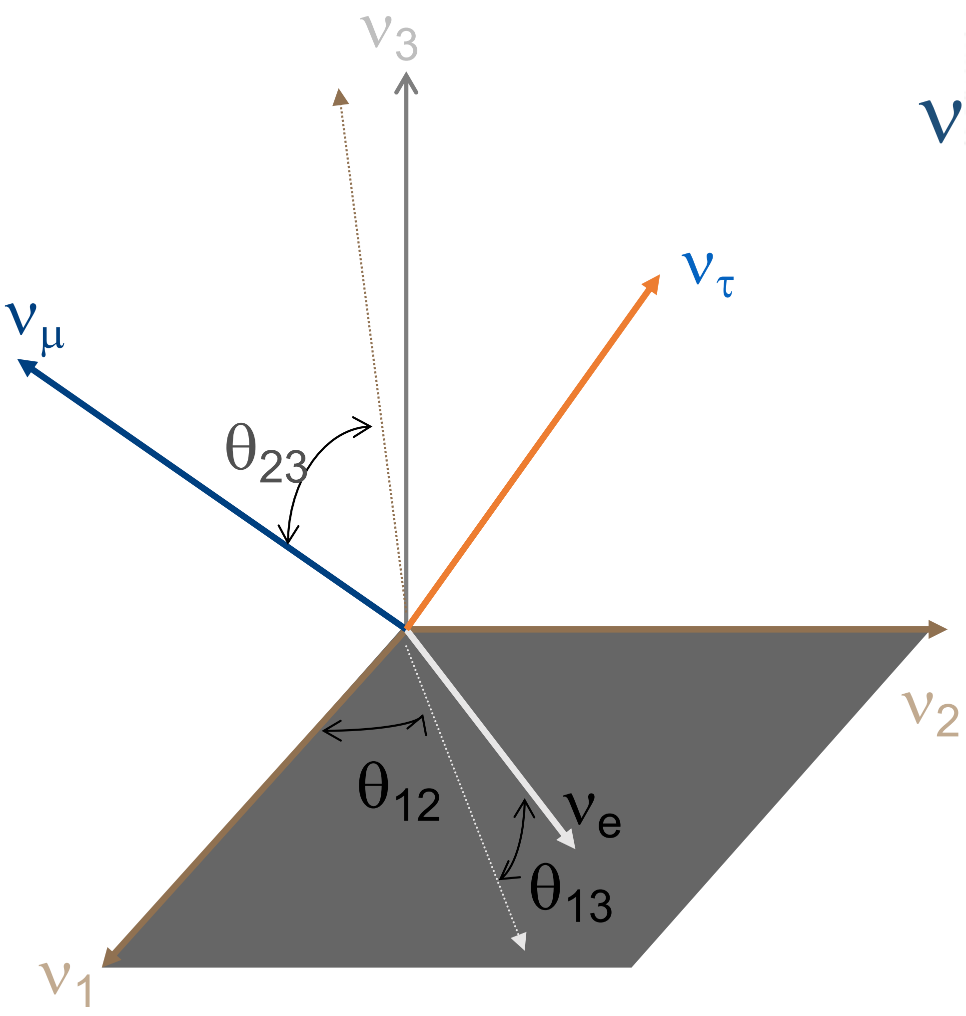
νapoli

january 27-28 2020

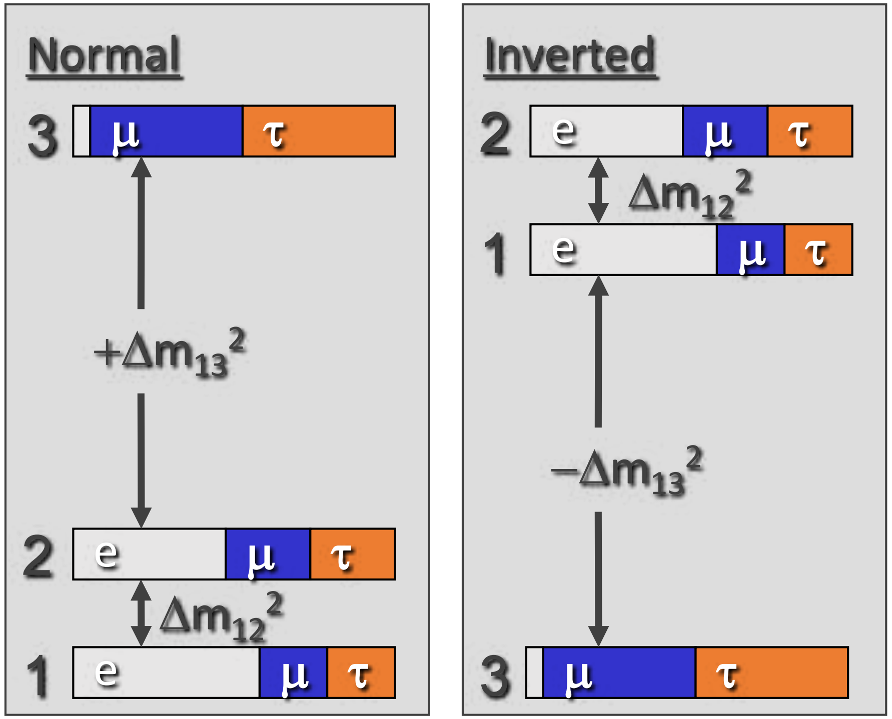
3ν flavor global analysis and standard framework

3ν mixing paradigm

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}=\begin{bmatrix}1 & & \\ & \cos\theta_{23} & -\sin\theta_{23}\\ & \sin\theta_{23} & \cos\theta_{23}\end{bmatrix}\cdot\begin{bmatrix}\cos\theta_{13} & & -e^{i\delta_{CP}}\sin\theta_{13}\\ & 1 & \\ e^{i\delta_{CP}}\sin\theta_{13} & & \cos\theta_{13}\end{bmatrix}\cdot\begin{bmatrix}\cos\theta_{12} & -\sin\theta_{12} & \\ \sin\theta_{12} & \cos\theta_{12} & \\ & & 1\end{bmatrix}\cdot\begin{bmatrix}e^{i\varphi_1} & & \\ & e^{i\varphi_2} & \\ & & 1\end{bmatrix}\cdot\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$



$\varphi_{1,2}$ are “physical” only if neutrinos are Maiorana particles. Anyway they are unobservable in oscillation experiments



Known and unknown in the 3ν paradigm

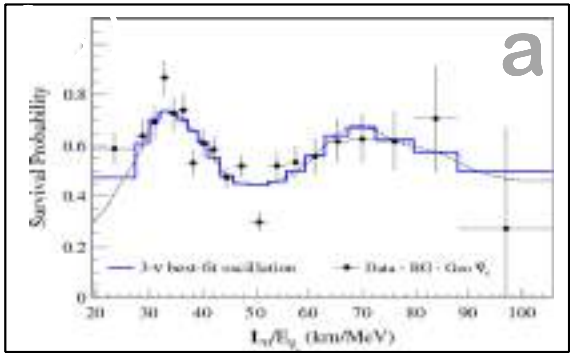
Known and unknown in the 3ν paradigm

- Known
  - Δm_{12}^2
  - Δm_{13}^2
  - θ_{12}
  - θ_{23} (more or less…)
  - θ_{13}

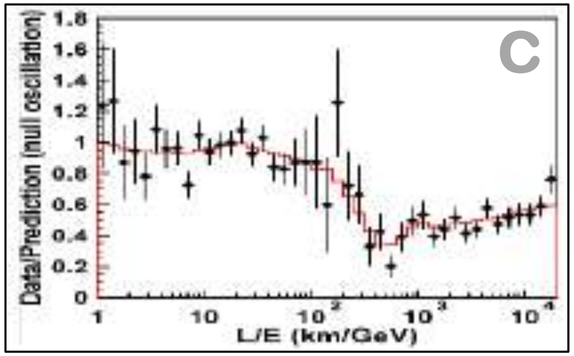
- Unknown
  - Mass Ordering (NH favourite @3σ)
  - θ_{23} octant
  - δ_{CP} (Hints for $\delta_{CP} \neq 0$)
  - Absolute mass scale
  - Dirac or Majorana nature of neutrinos
  - Majorana phases (if Majorana…)

Beautiful ν oscillation data have established this 3ν paradigm…

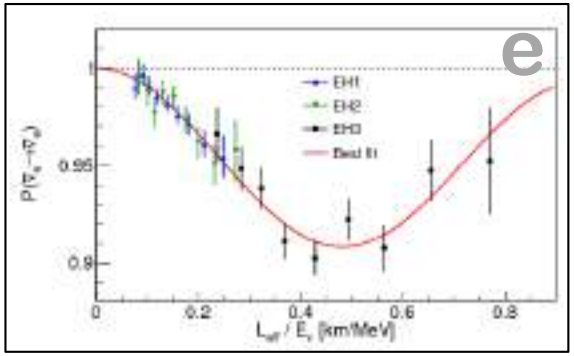
e→e (KamLAND, KL)



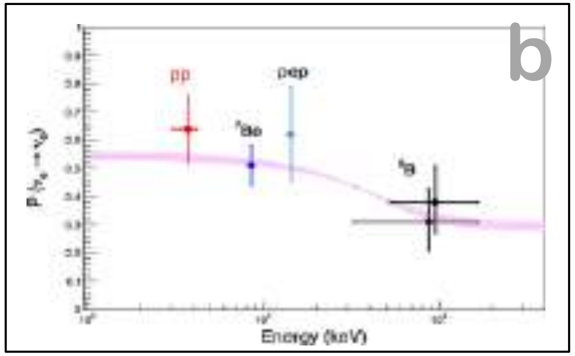
μ→μ (Atmospheric)



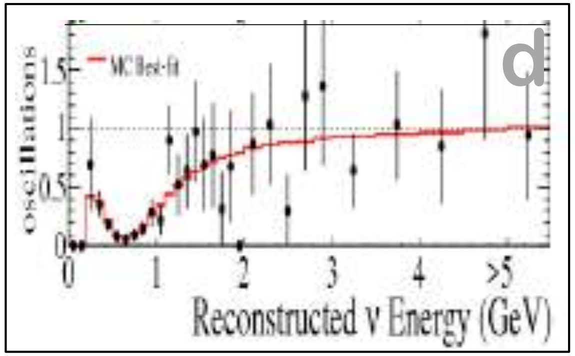
e→e (SBL Reac.)



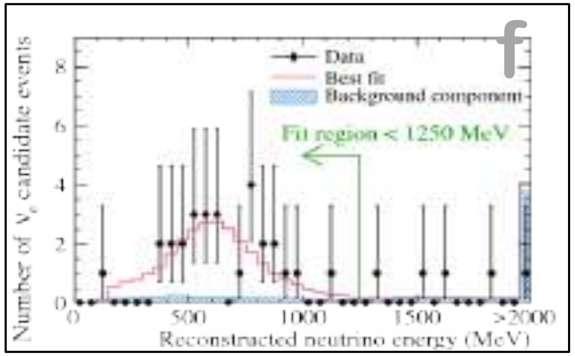
e→e (Solar)



μ→μ (LBL Accel)



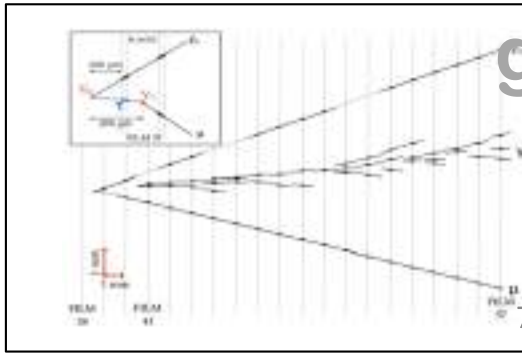
μ→e (LBL Accel)



Data from various types of neutrino experiments: (a) solar, (b) long-baseline reactor, (c) atmospheric, (d) long-baseline LBL accelerator, (e) short-baseline SBL reactor, (f,g) long baseline accelerator (and, in part, atmospheric).

(a) KamLAND [plot]; (b) Borexino [plot], Homestake, Super-K, SAGE, GALLEX/GNO, SNO; (c) Super-K atmosph. [plot], DeepCore, MACRO, MINOS etc.; (d) T2K (plot), NOvA, MINOS, K2K; (e) Daya Bay [plot], RENO, Double Chooz; (f) T2K [plot], MINOS, NOvA; (g) OPERA [plot], Super-K and IC-CD atmospheric.

μ→τ (OPERA, SK, DC)



Combined (global) 3ν analysis of world oscillation data, 2019

Our oscillation analysis includes increasingly rich data sets:

LBL Accel + Solar + KL (KamLand)
LBL Accel + Solar + KL + SBL Reactor
LBL Accel + Solar + KL + SBL Reactor + Atmosph.

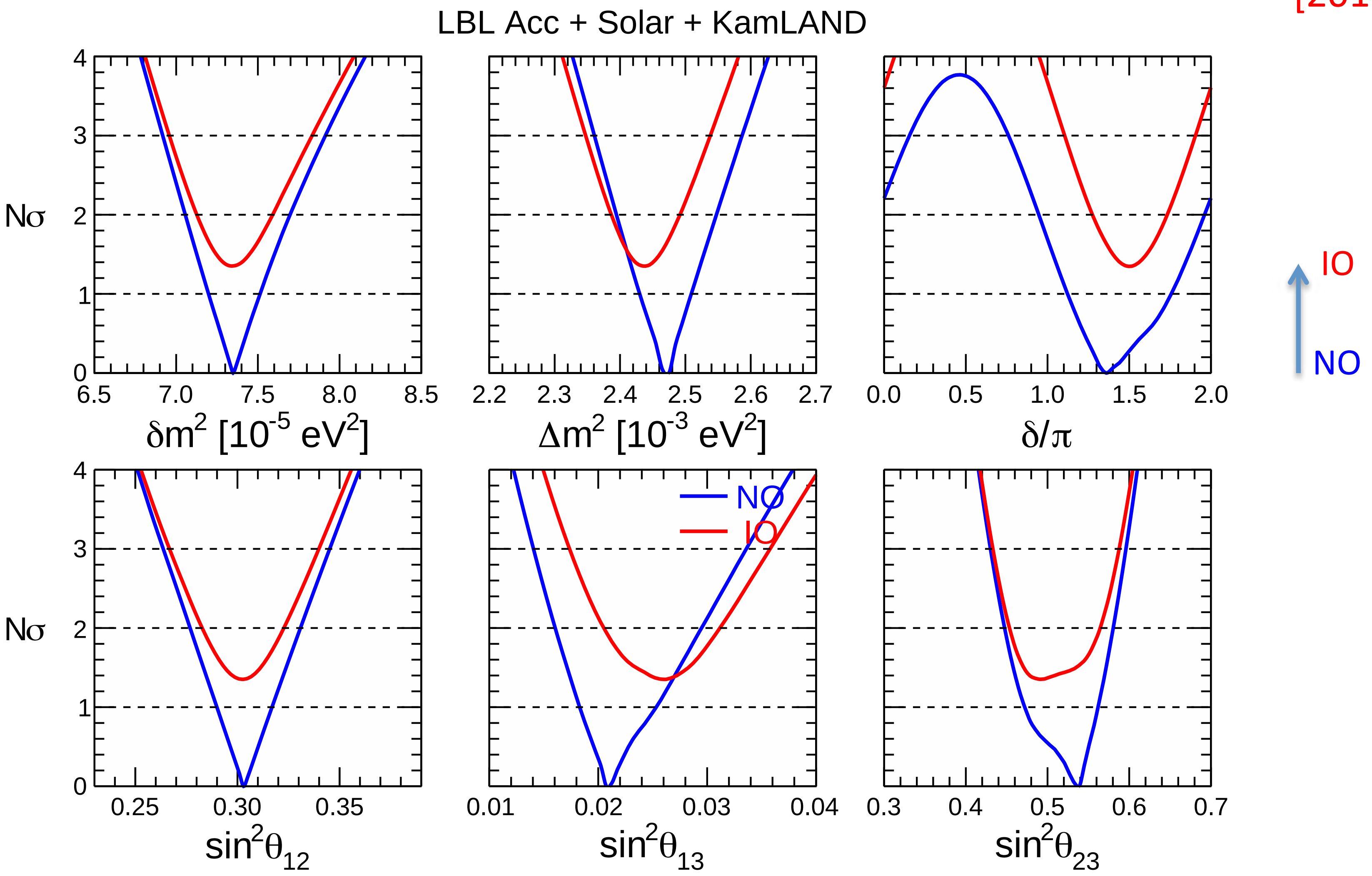
χ^2 metric adopted. Parameters not shown are marginalized away:

C.L.'s refer to $N\sigma = \sqrt{\Delta\chi^2} = 1, 2, 3, \ldots$

2018: 1804.09678 by F. Capozzi, E. Lisi, A. Marrone, A. Palazzo, PPNP 102, 48 (2018)

Courtesy of Eligio Lisi

[2019]



Five parameters (2 mass^2 gaps and 3 mixing angles) measured at $>4\sigma$.

IO slightly disfavored with respect to NO at $\sim 1.4\sigma$ level.

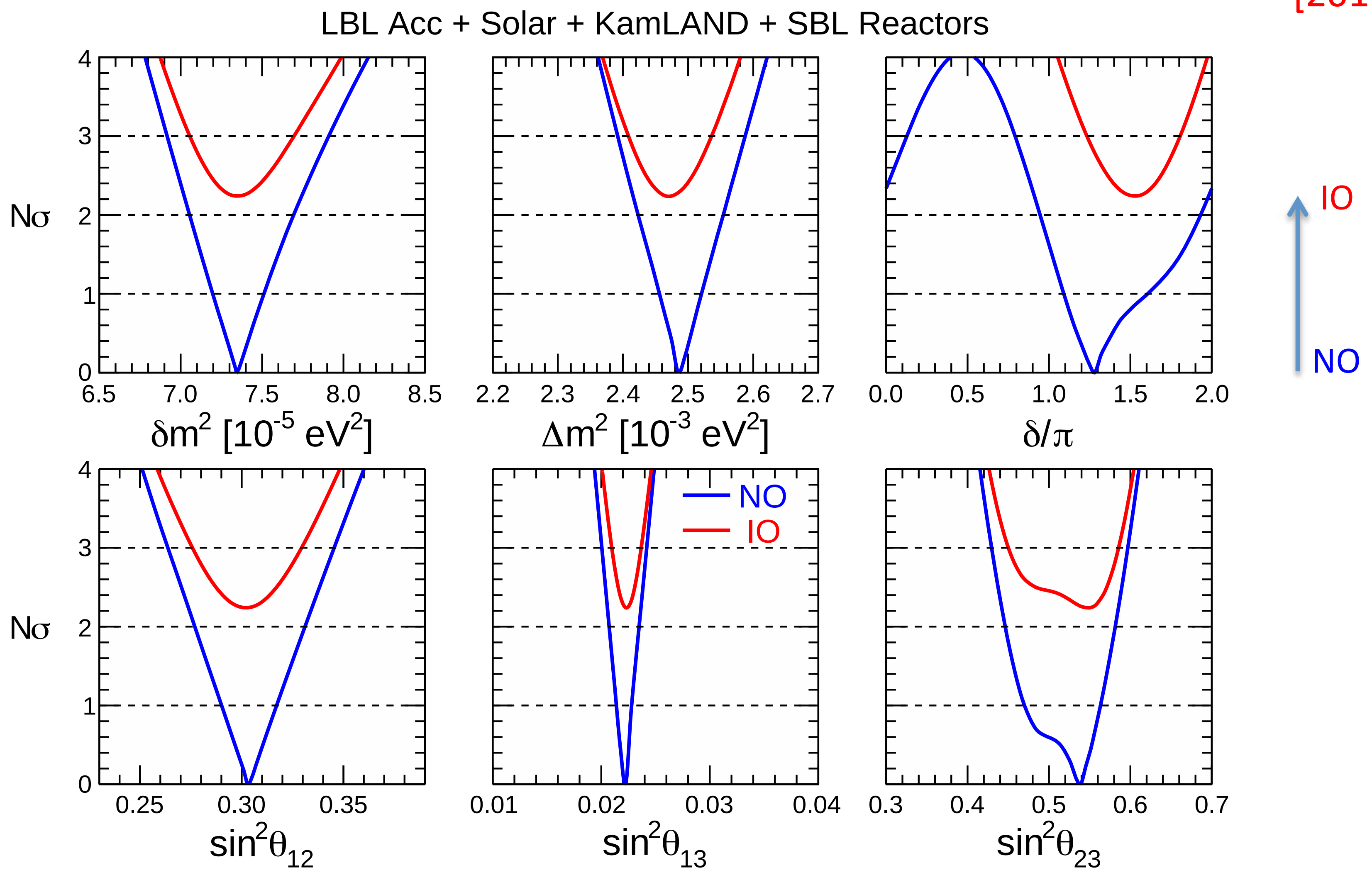
CP phase δ favored around $3\pi/2$ (max CPV with $\sin\delta \sim -1$).

Largest mixing angle θ_{23} slightly above $\pi/4$, but 1st octant allowed at 1σ.

Courtesy of Eligio Lisi

[2019]

LBL Acc + Solar + KamLAND + SBL Reactors



Direct impact of SBL reactors: range of θ_{13} strongly reduced; Δm^2 improved

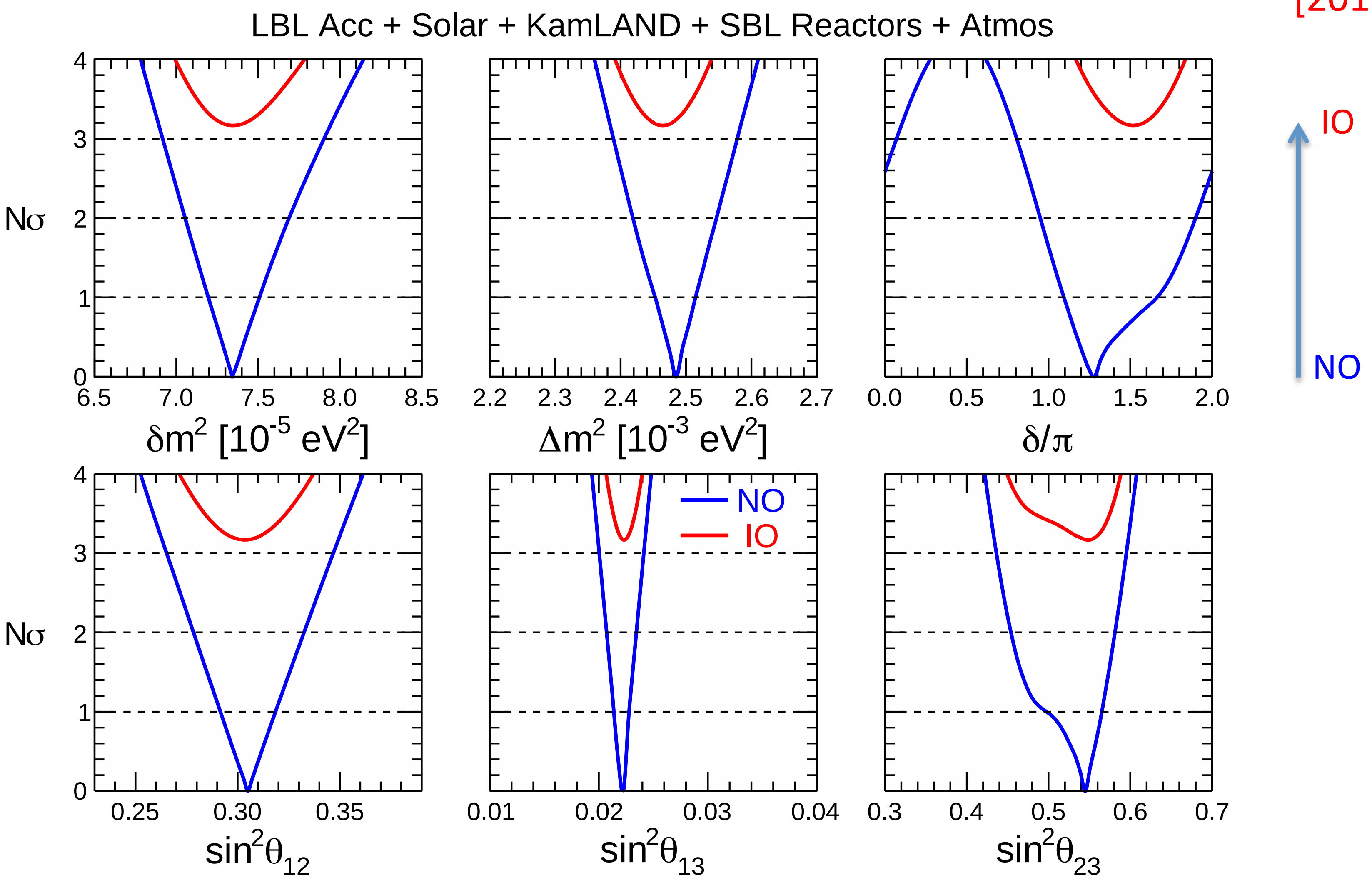
Indirect impact: IO more disfavored wrt NO, at $\sim 2.2\sigma$ level

indirect impact: indications on δ improved

Largest mixing angle θ_{23} slightly above $\pi/4$, but 1st octant allowed at 1σ.

Courtesy of Eligio Lisi

[2019]



Overall convergence of “measurements” and “hints”. Ranking hints by CL:

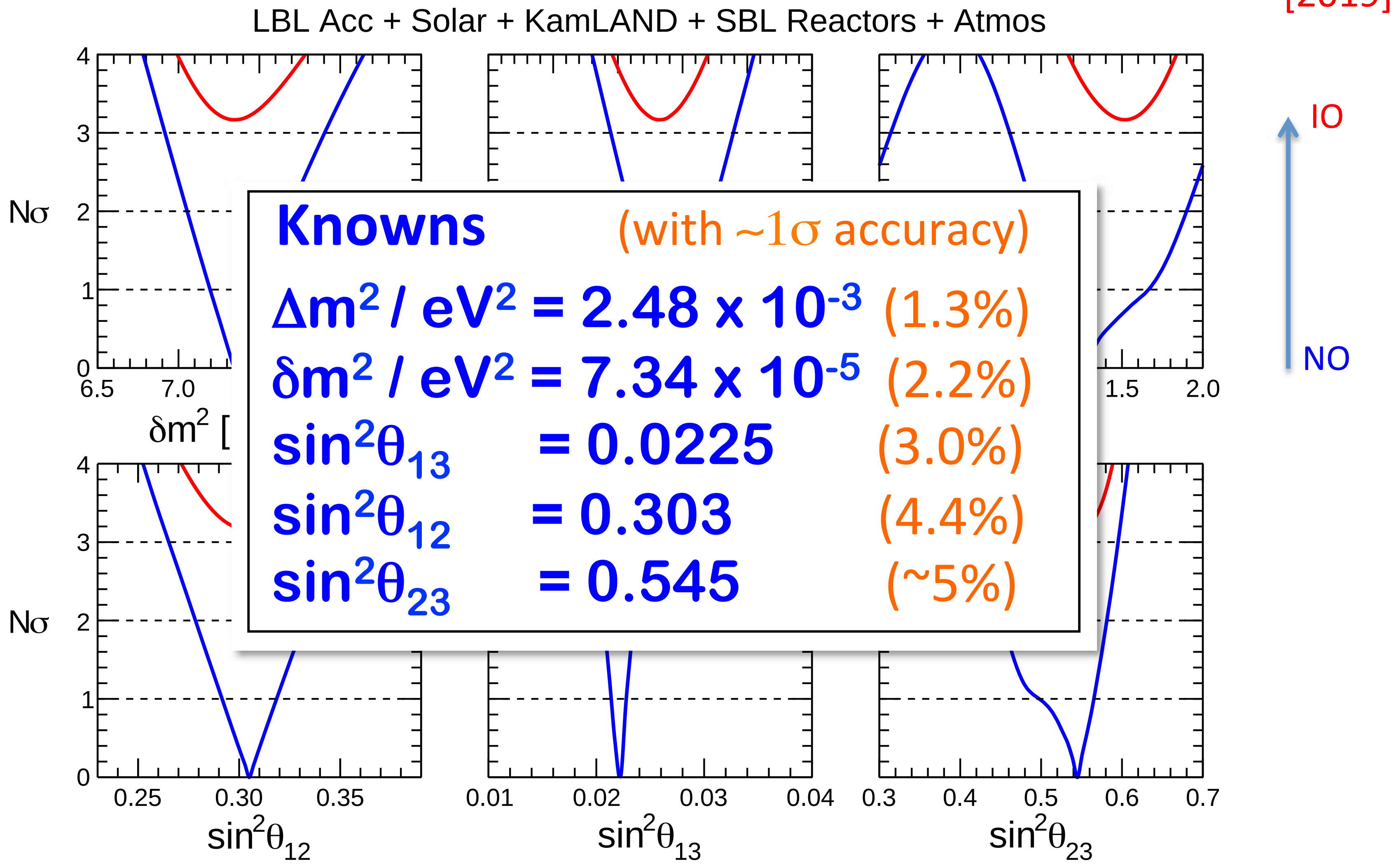
IO significantly disfavored with respect to NO, at ~3.2σ level

CPV favored (~max): $\delta = \pi$ disfavored at ~1.6σ; $\delta = 0, 2\pi$ disfavored at ~2.6σ

Slight preference for θ_{23} above $\pi/4$ at ~1σ (caution: fragile!)

Courtesy of Eligio Lisi

[2019]



Knowns (with ~1σ accuracy)

$\Delta m^2 / \mathrm{eV}^2 = 2.48 \times 10^{-3}$ (1.3%)

$\delta m^2 / \mathrm{eV}^2 = 7.34 \times 10^{-5}$ (2.2%)

$\sin^2\theta_{13} = 0.0225$ (3.0%)

$\sin^2\theta_{12} = 0.303$ (4.4%)

$\sin^2\theta_{23} = 0.545$ (~5%)

Overall convergence of “measurements” and “hints”. Ranking hints by CL:

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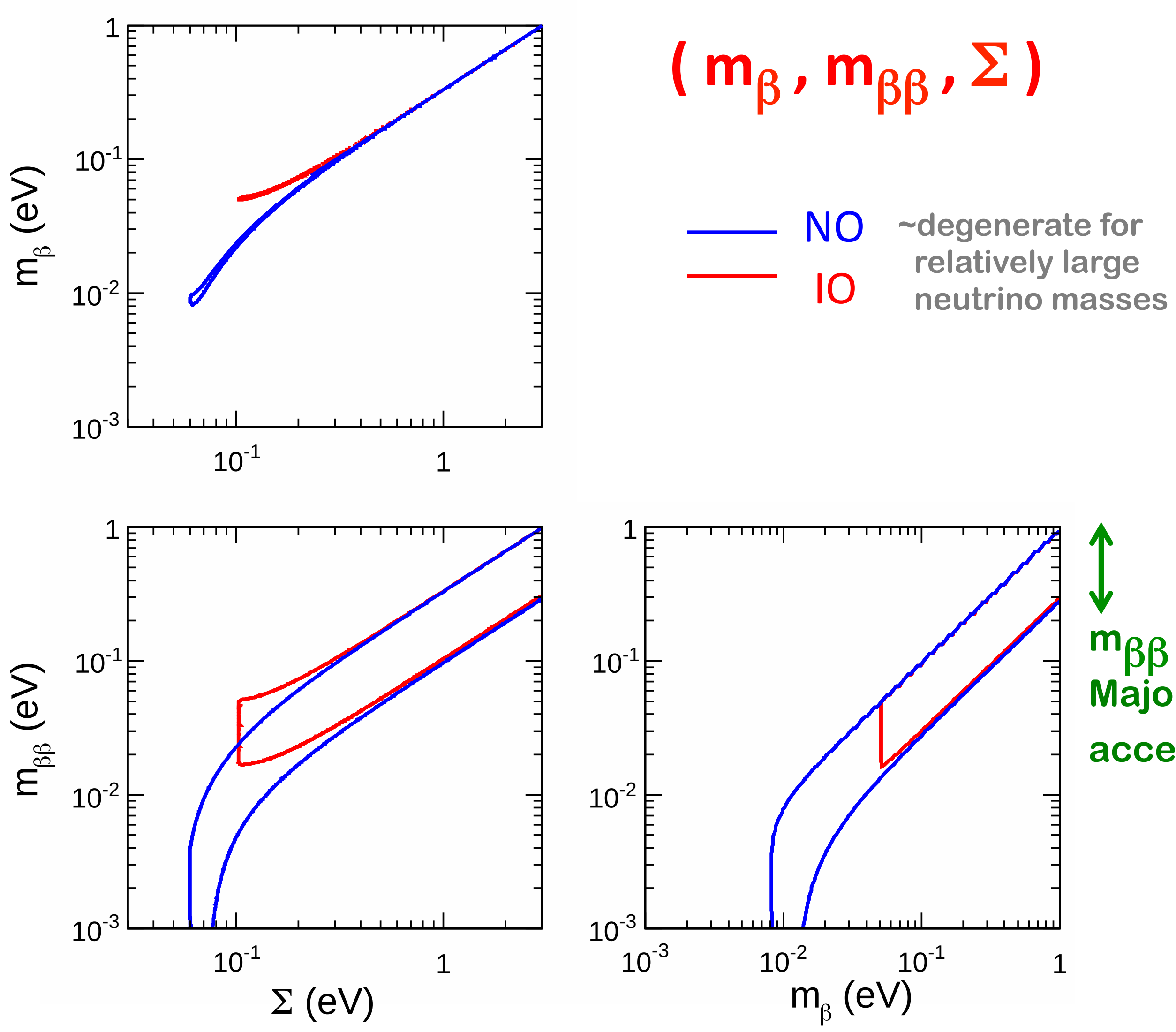
Slight preference for θ_{23} above $\pi/4$ at ~1σ (caution: fragile!)

Courtesy of Eligio Lisi

Oscillation constraints on nonoscillation observables

(m_β , $m_{\beta\beta}$, Σ)

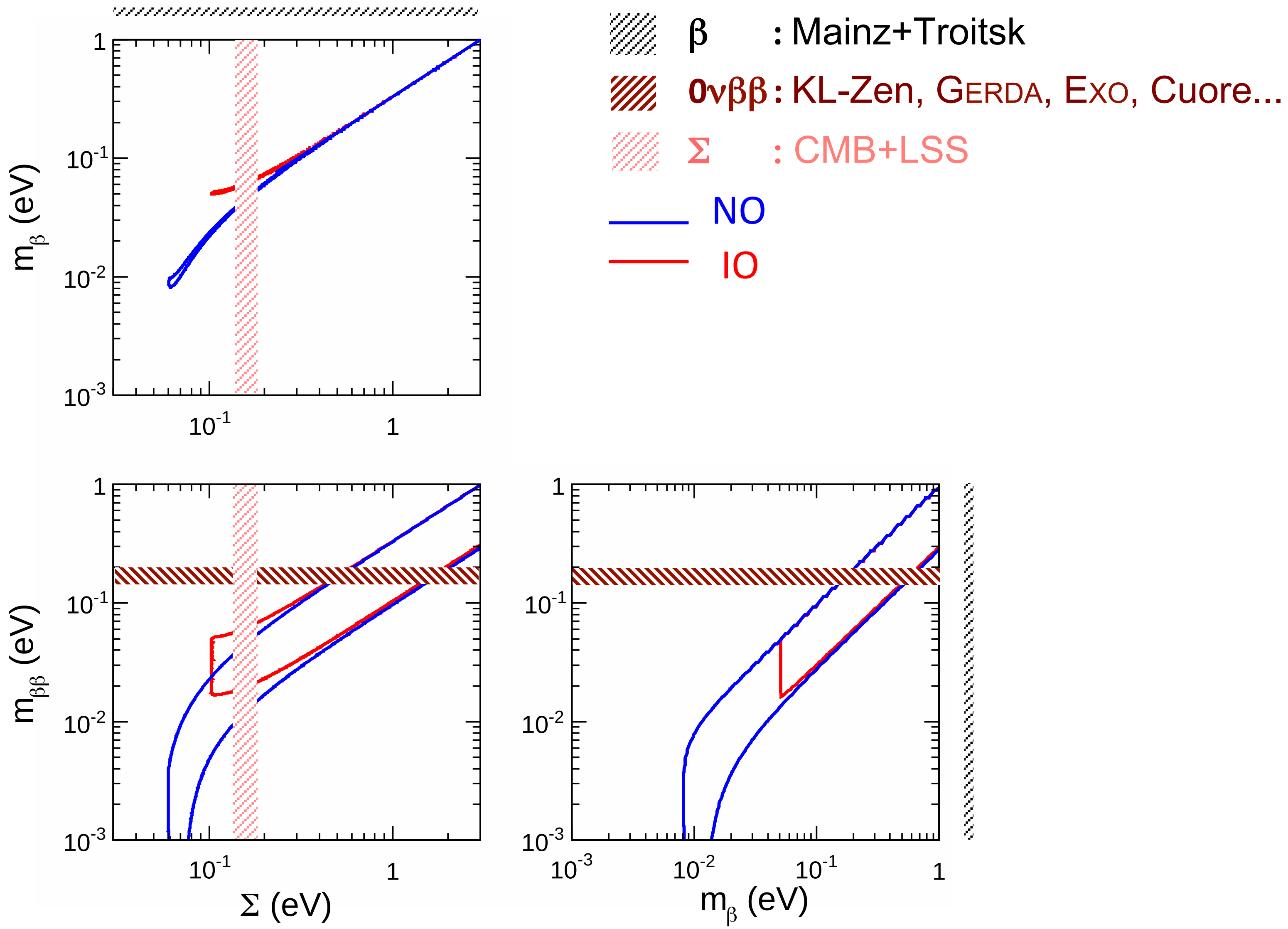


$m_{\beta\beta}$ spread due to Majorana CP phase(s): accessible in principle

m_β = effective neutrino mass in single beta decay
$m_{\beta\beta}$ = effective neutrino mass in neutrinoless double beta decay (if Majorana)
Σ = sum of neutrino masses in cosmology

Courtesy of Eligio Lisi

Current upper limits on m_β, $m_{\beta\beta}$, Σ (up to some syst.)

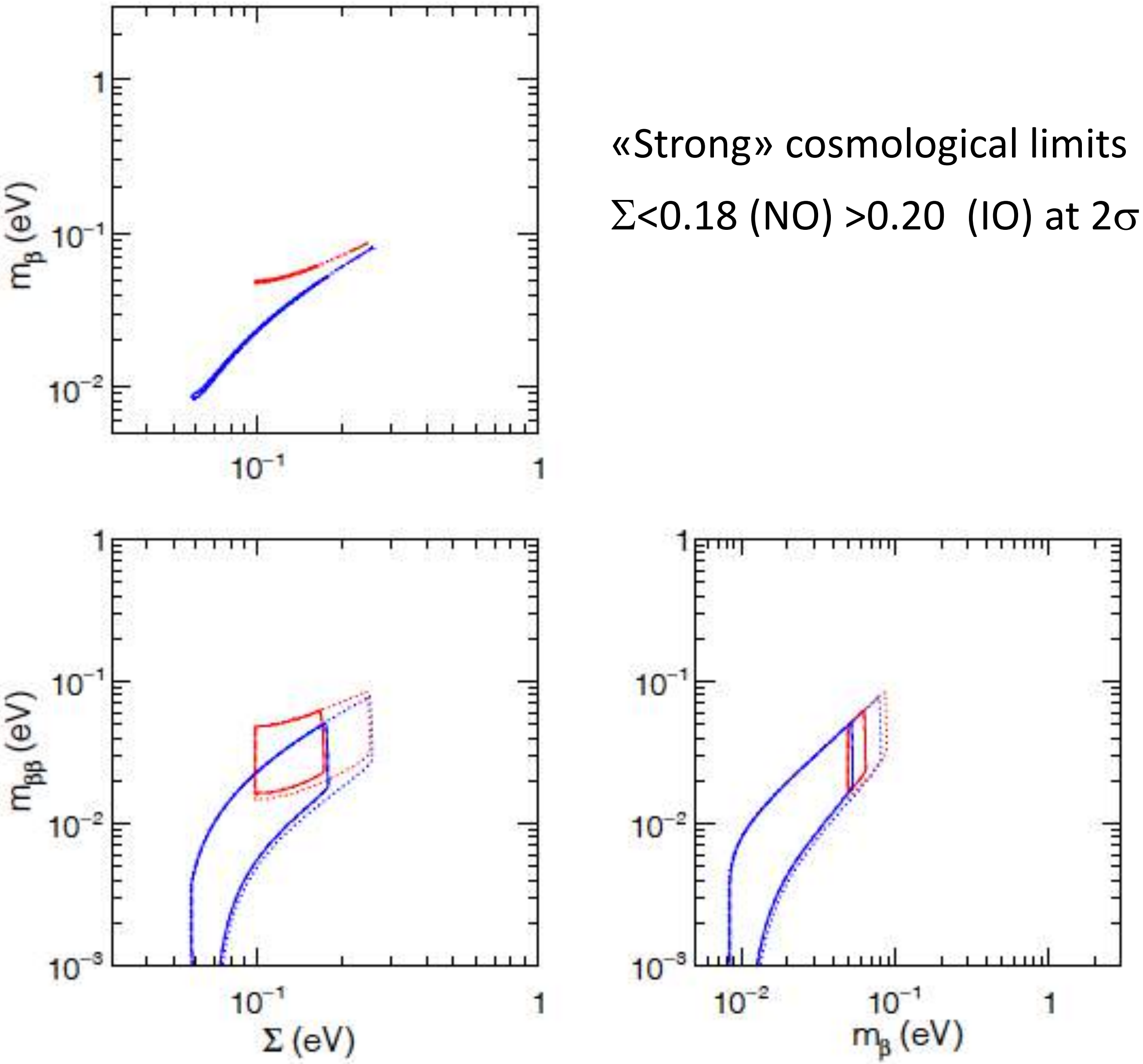


Neutrino mass scale: sub-eV from cosmo data (and from 0νββ if Majorana)

Mass ordering: cosmo data contribute to put IO "under pressure"

Courtesy of Eligio Lisi

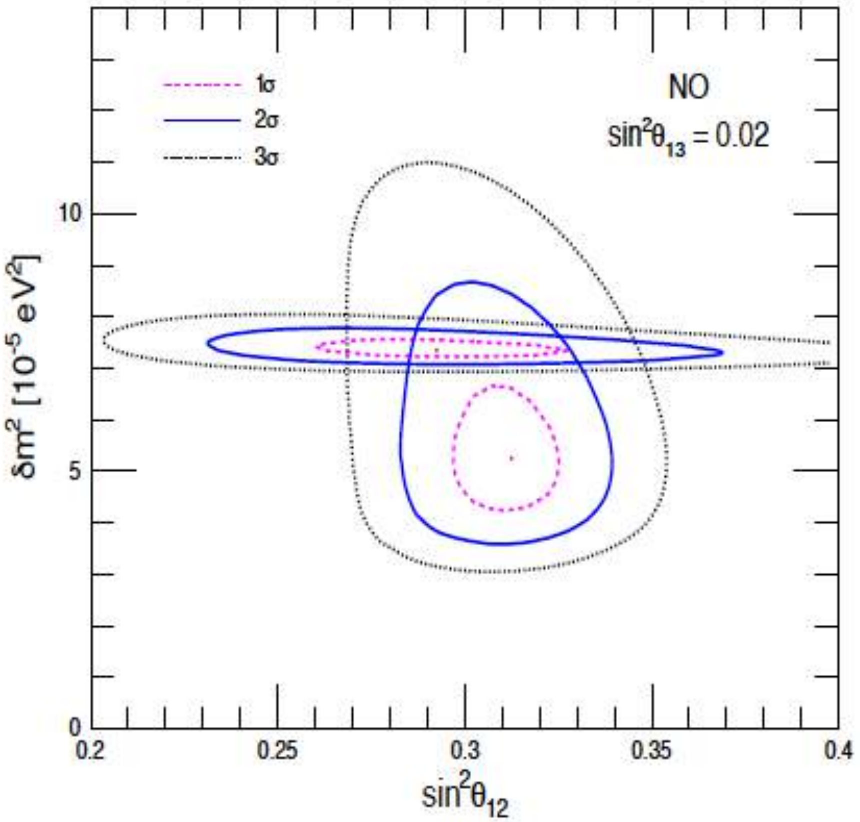
Capozzi, Lisi, Marrone and Palazzo, Prog. Part. Nucl. Phys. **102**, 48 (2018)

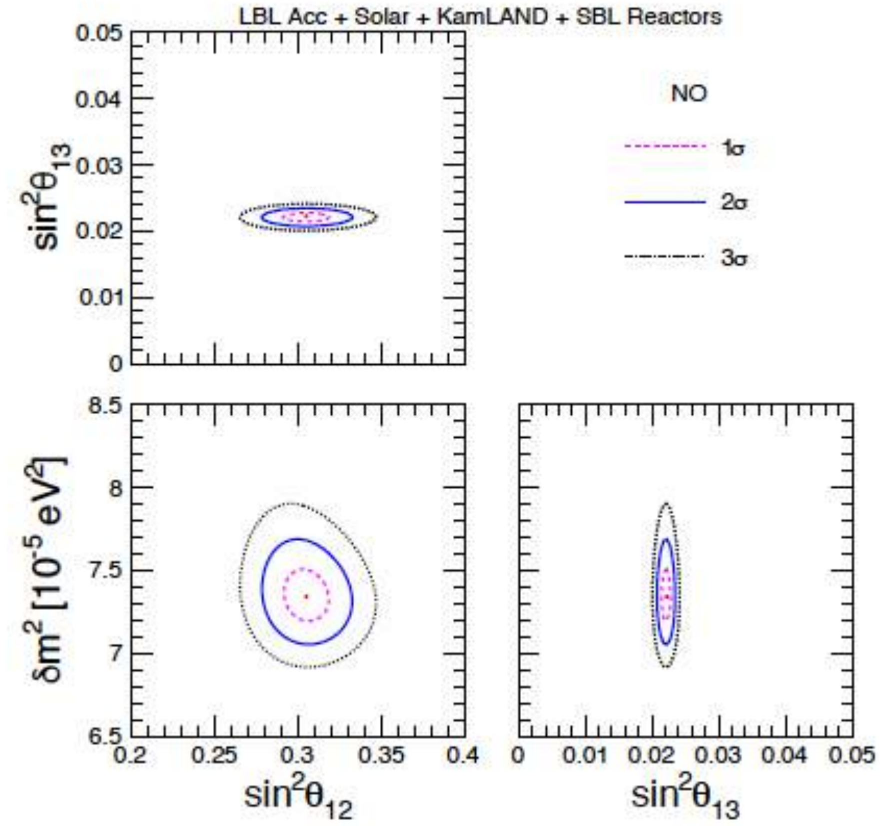


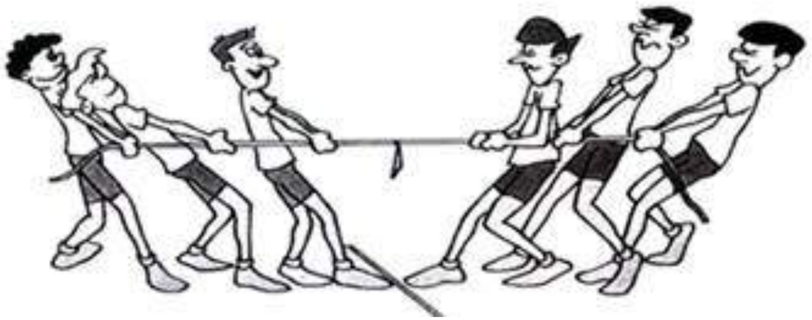
«Strong» cosmological limits

Σ<0.18 (NO) >0.20 (IO) at 2σ

“Solar” oscillation parameters (2018)







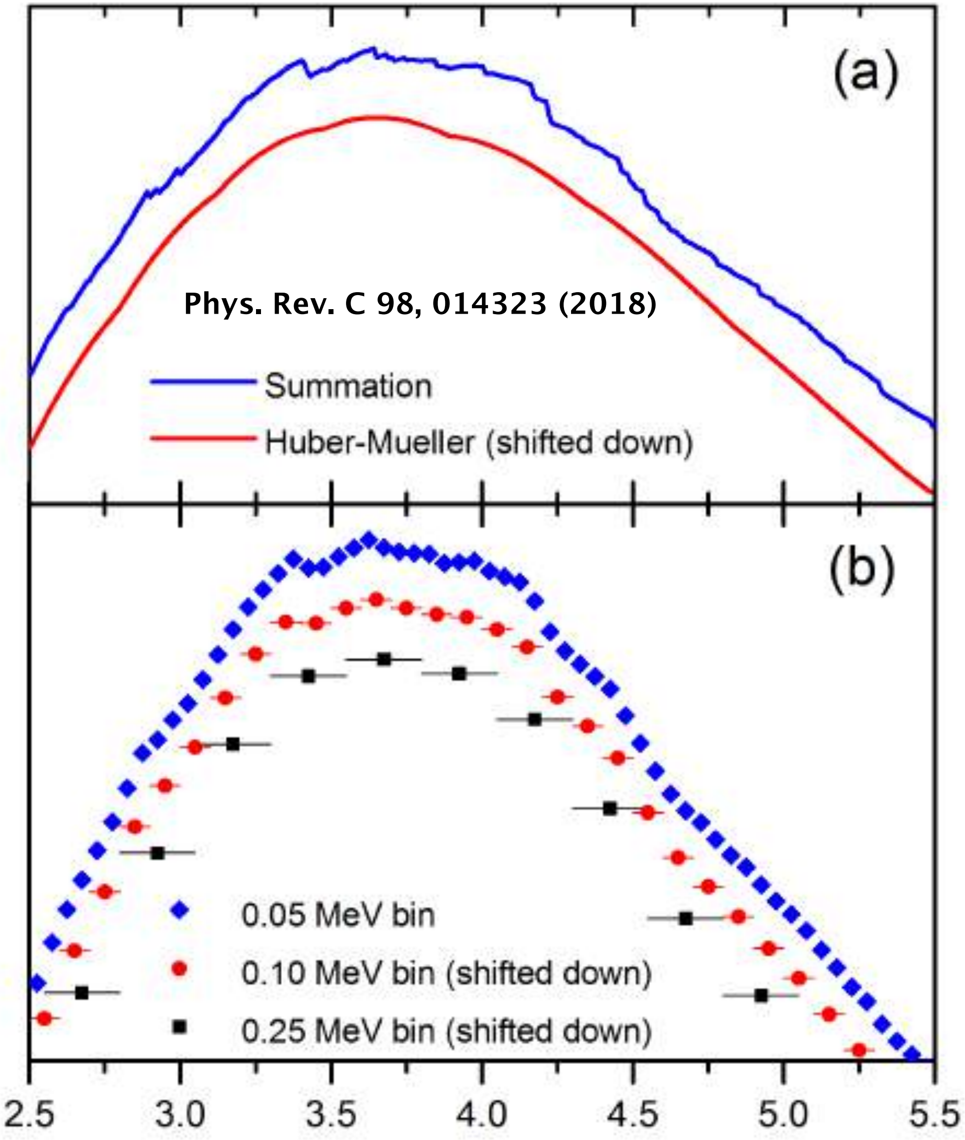
Still unresolved «tension»
between solar and Kamland Data

Courtesy of Eligio Lisi

Study of JUNO Performance

- The Jiangmen Underground Neutrino Observatory (JUNO) is a multipurpose neutrino experiment designed to determine neutrino mass hierarchy and precisely measure oscillation parameters by detecting reactor neutrinos at distance of ~50km far from source
- Many issue regard the uncertainties on the initial neutrino spectrum recently arose
- A close detector (named JUNO-TAO) has been proposed to determine with high precision the initial spectrum

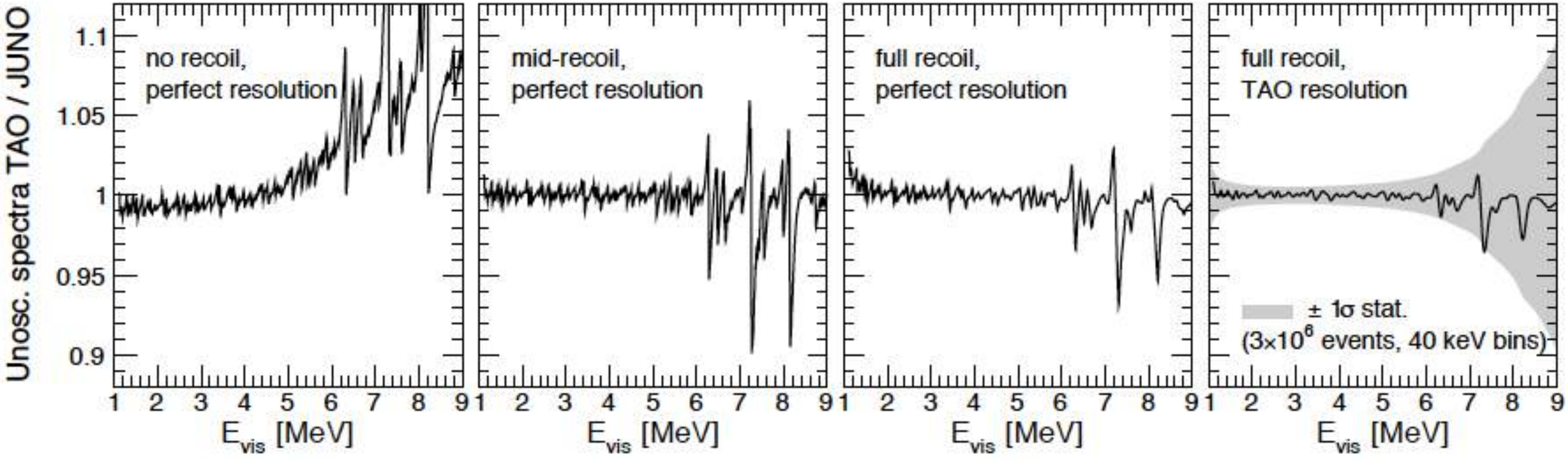
Sawtooth shape of ν reactor spectrum



Phys. Rev. C 98, 014323 (2018)

- Coulomb field of nuclei slows down electrons in β decay giving rise to abrupt «cut-off» in the ν spectra
- ν spectrum shows a sawtooth shape due the decays at different Q-values
- This sawtooth shape can potentially ruin the sensitivity of Juno to mass ordering (based on shift of few oscillations peak)
- A high-resolution near detector (JUNO-TAO) can measure the spectrum with high-precision

Spectrum in JUNO-TAO detector (with recoil and resolution)



Sawtooth-like structures perfectly well resolved

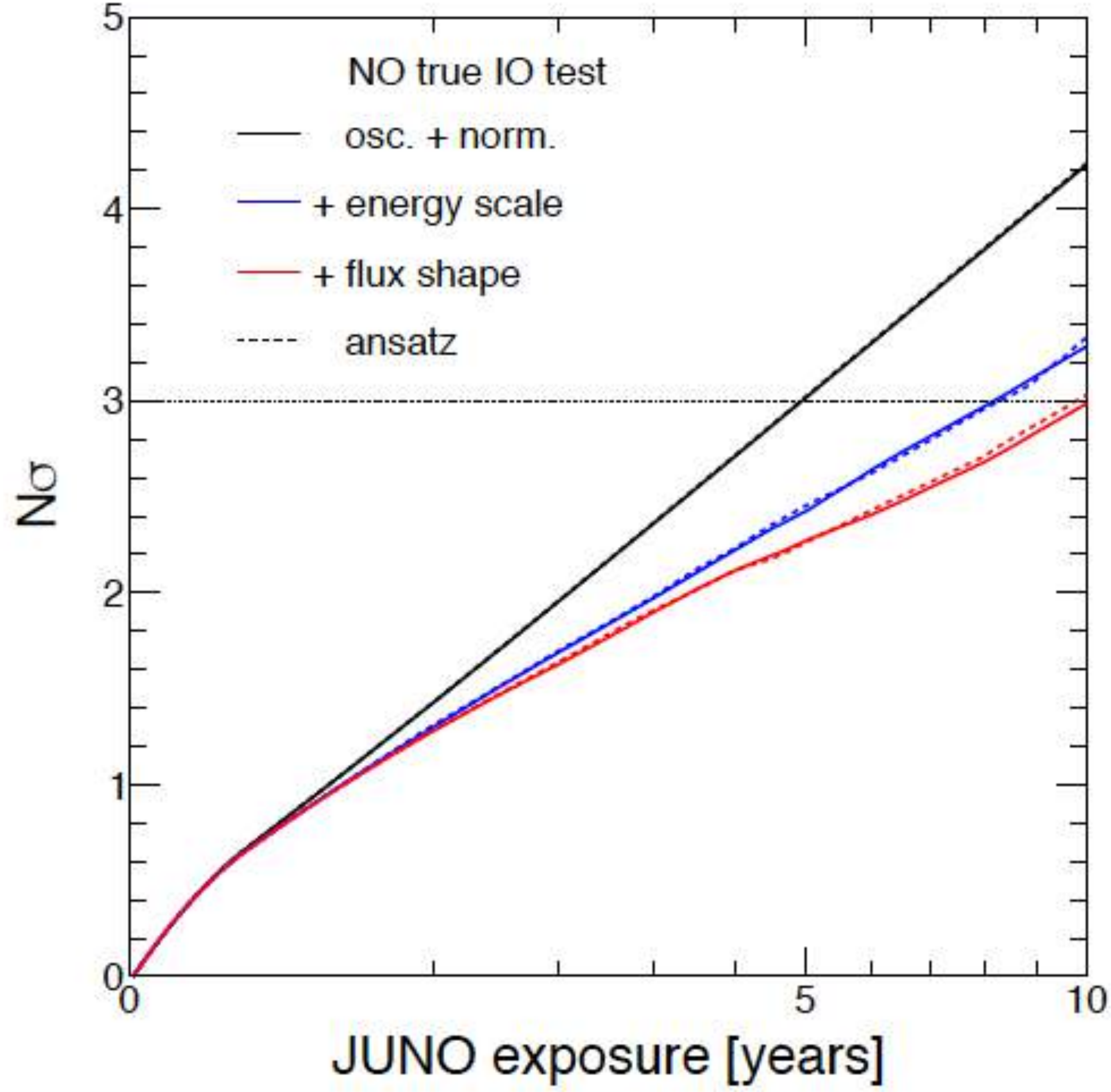
In this case $E_e = (E_1+E_2)/2$

Fine structures partially suppressed

Fine structures suppressed but still visible

Courtesy of Antonio Marrone

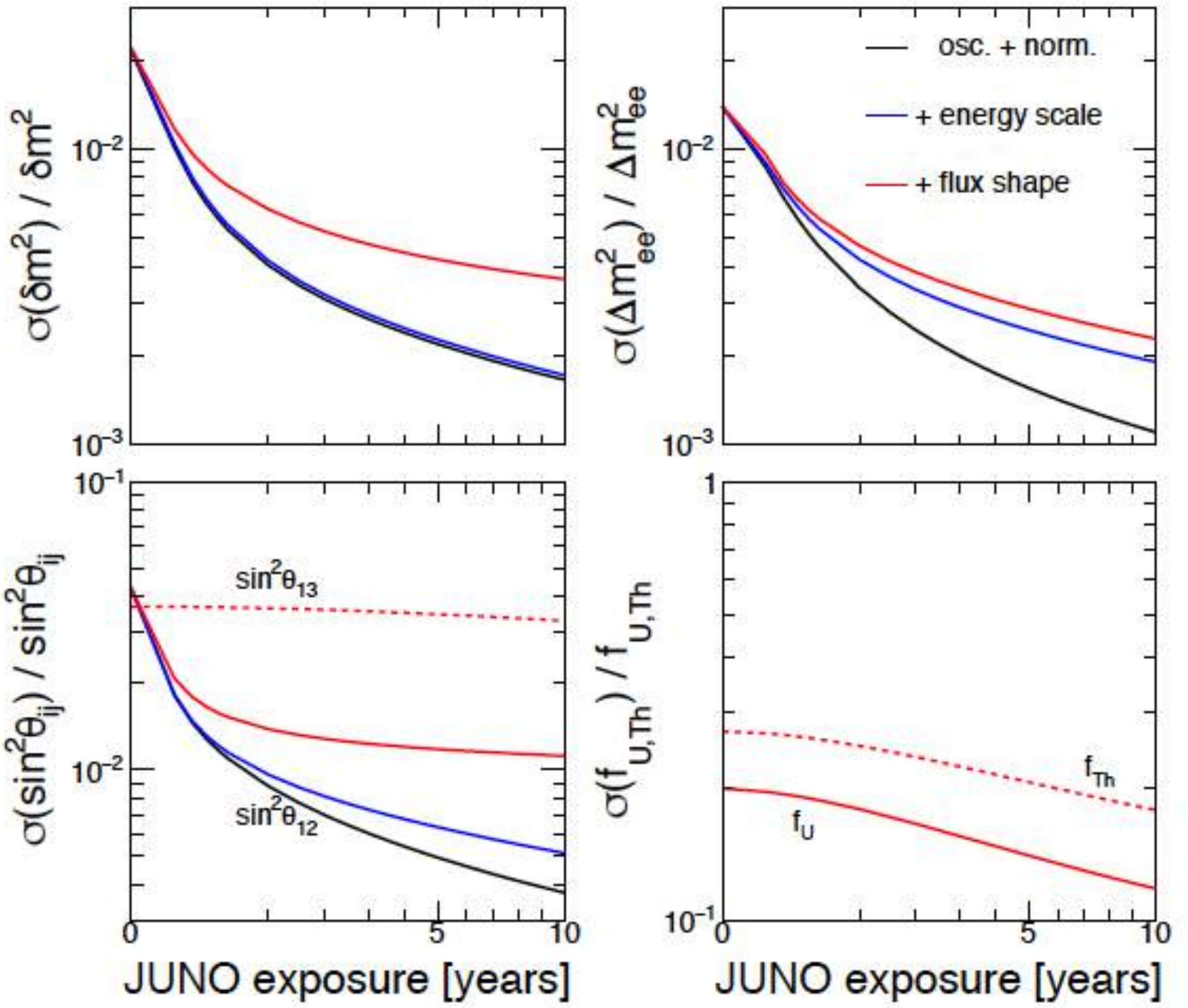
Statistical significance of IO rejection if NO is true (following Phys. Rev. D92, 093011)



Ansatz: use the unoscillated NEAR measured spectrum to calculated the FAR oscillated spectrum. This approximation works with a precision of ~‰

Courtesy of Antonio Marrone

Precision measure of oscillation parameters



Interdisciplinary aspects of neutrinos

V-A and ν elicity	(SM)
Other particle and interactions	(SM,BSM)
Leptonic flavor transformation	(BSM)
Neutrino masses	(BSM)
Matter stability	(BSM, nuc)
Nuclear reactions in the Sun	(nuc, astro)
Gravitational Collapses	(nuc, astro)
Cosmic ray sources	(part, astro)

Neutrinos and Nuclear Physics

Some relevant aspects of nuclear physics

- Uncertainties on nuclear matrix elements β, EC e ββ
- Reactor antineutrino spectrum
- Quenching of form factors (in particular, g_A)
- Contribution of excited states for cross sections (ex. ν_e – Ga)
- S-factors for solar neutrinos and BBN

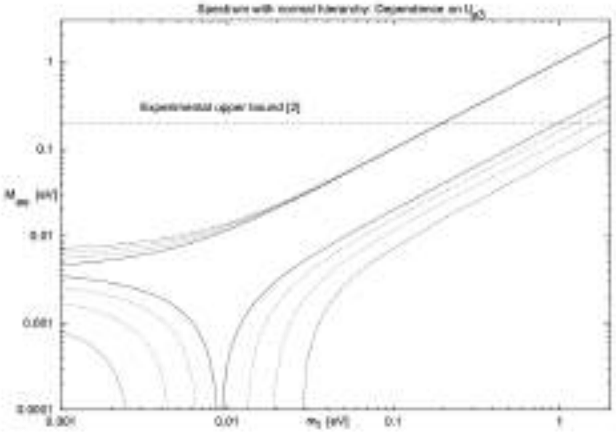
Open question: quenching of g_A in Nuclear Matrix Element

- No serious reason to assume g_A=1
- g_A and g_V can be constrained by the study of spectral shape of the 1st forbidden β decays or equivalently through the spectral moments (half-life, average energy, variance)
- NME calculation important both for neutrinoless-2β decay and for reactor neutrino spectra
- Work in progress by the Bari Group

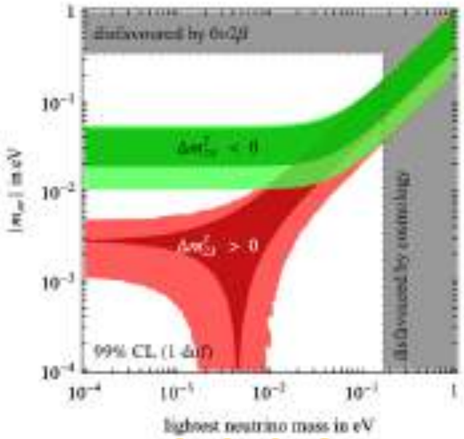
“neutrinoless etc”: a misnamer?

- it is funny to define a process in terms of something absent (i.e., neutrinos) - hippo is not a trunkless elephant
- the name “creation of electrons” is much neater and reminds us that **B-L** is broken
- the term β comes from Rutherford times, when the β was used for “nuclear electrons” – i.e., a wrong model!!
- this name reminds us one theoretical belief: that BSM physics is at ultra-high scale, and therefore, mechanism of (virtual) light Majorana neutrino exchange drives $0\nu2\beta$

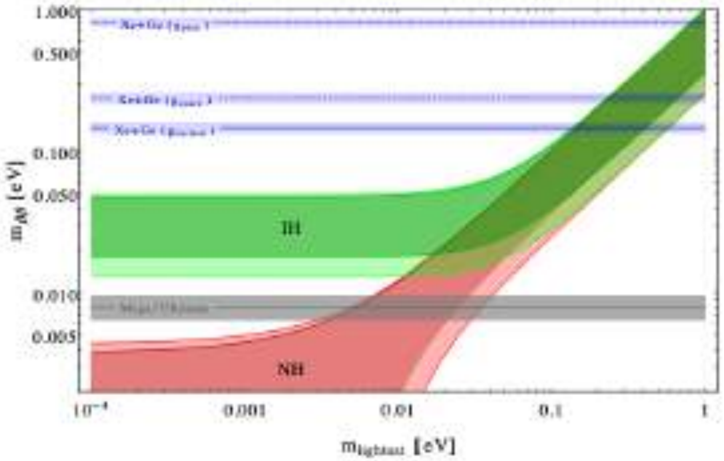
Observations and the $m_{\beta\beta}$ parameter



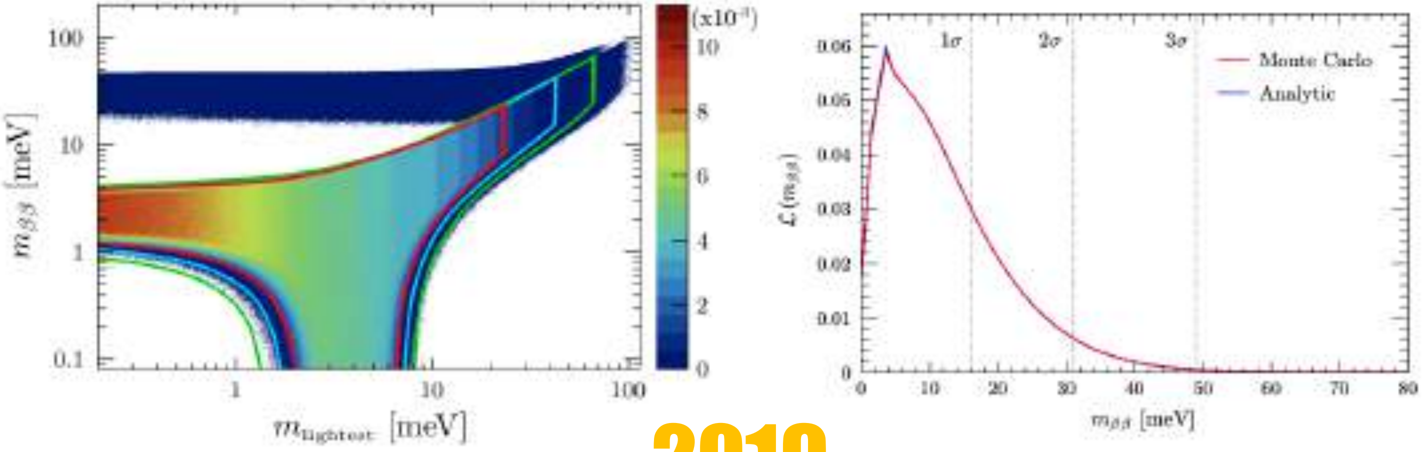
1999



2006



2014



2019

Francesco Vissani

Neutrinos and the Sun

Neutrinos and the Sun

- Solar models
  - ✓APJ714:2,2010 (linear perturbation of Standard Solar Model)
  - ✓APJ835:202,2017 (updated solar models)
- Inference of solar properties and solar composition from solar neutrino fluxes and helioseismology
  - ✓Astrophys.J.724:98-110,2010 (opacity profile)
  - ✓MNRAS477:1397,2018 (reconstruction of solar properties)
  - ✓APJ787:13,2014 (chemical composition of Sun)
  - ✓MNRAS463:2,2016 (chemical composition of Sun from solar wind)
- Precise measurement of solar neutrino fluxes (in particular *pp* and CNO)
  - ✓Nature **562**, 505 (2018) (Borexino *pp*-chain measure)
  - ✓PLB701:336,2011 (scintillator detectors for CNO)
  - ✓PLB742:297,2015 (ecCNO: a gigantic scintillator detector for CNO)

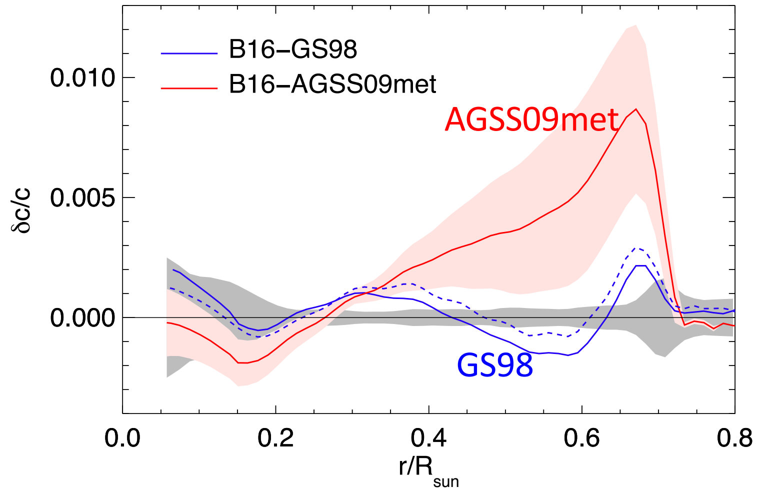
The solar composition problem

The **downward revision** of heavy elements photospheric abundances …

Element	GS98	AGSS09met	δz_i
C	8.52 ± 0.06	8.43 ± 0.05	0.23
N	7.92 ± 0.06	7.83 ± 0.05	0.23
O	8.83 ± 0.06	8.69 ± 0.05	0.38
Ne	8.08 ± 0.06	7.93 ± 0.10	0.41
Mg	7.58 ± 0.01	7.53 ± 0.01	0.12
Si	7.56 ± 0.01	7.51 ± 0.01	0.12
S	7.20 ± 0.06	7.15 ± 0.02	0.12
Fe	7.50 ± 0.01	7.45 ± 0.01	0.12
$(Z/X)_\odot$	0.02292	0.01780	0.29

$$[I/H] \equiv \log\left(N_I/N_H\right) + 12$$

Vinyoles et al, ApJ 835 (2017) no.2, 202



… leads to SSMs which **do not correctly reproduce helioseismic observables**

Flux	B16-GS98	B16-AGSS09met	Solar
Y_S	0.2426 ± 0.0059	0.2317 ± 0.0059	0.2485 ± 0.0035
$R_{cz}/R_\odot$	0.7116 ± 0.0048	0.7223 ± 0.0053	0.713 ± 0.001
Φ_{pp}	$5.98(1 \pm 0.006)$	$6.03(1 \pm 0.005)$	$5.97^{(1+0.006)}_{(1-0.005)}$
Φ_{Be}	$4.93(1 \pm 0.06)$	$4.50(1 \pm 0.06)$	$4.80^{(1+0.050)}_{(1-0.046)}$
Φ_B	$5.46(1 \pm 0.12)$	$4.50(1 \pm 0.12)$	$5.16^{(1+0.025)}_{(1-0.017)}$
Φ_N	$2.78(1 \pm 0.15)$	$2.04(1 \pm 0.14)$	≤ 13.7
Φ_O	$2.05(1 \pm 0.17)$	$1.44(1 \pm 0.16)$	≤ 2.8

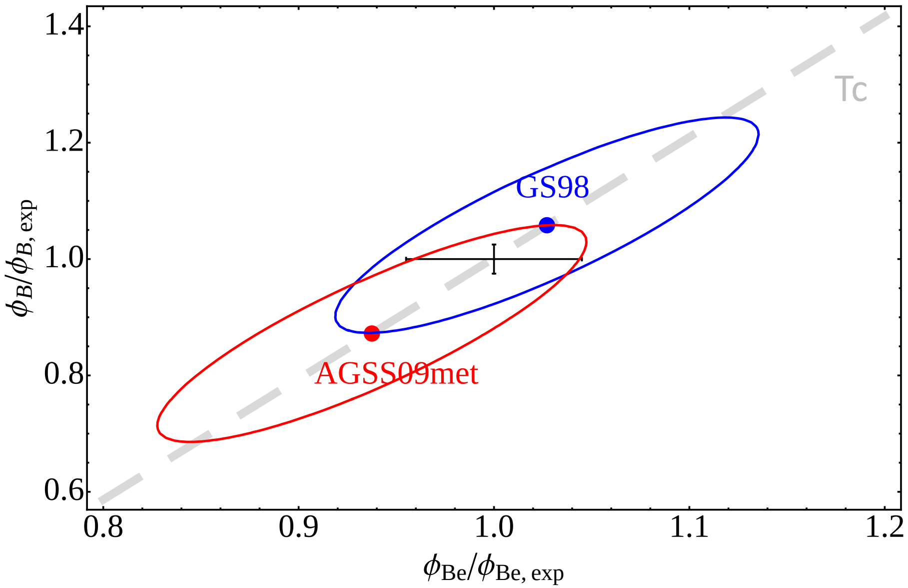
(≈ 2-3σ discrepancies)

Units:
pp: 10^{10} cm ^{2} s^{-1};
Be: 10^{9} cm ^{2} s^{-1};
pep, N, O: 10^{8} cm ^{2} s^{-1};
B, F: 10^{6} cm ^{2} s^{-1};
hep: 10^{3} cm ^{2} s^{-1}

Courtesy of Francesco Villante

The ^{7}Be and ^{8}B neutrino fluxes

N.Vinyoles et al. ApJ 2017 [arXiv:1611.09867v1]



$$\phi_{\rm B} \propto T_{\rm c}^{20} \quad \rightarrow \quad (\delta T_{\rm c})^{\rm GS98}_{\rm AGSS09} \leq 1\%$$

Solar neutrino data are sufficiently accurate to discriminate GS98-AGSS09met central values. Unfortunately, **theoretical uncertainties dominate the error budget**. These are due to:

- Surface composition
- Environmental parameters: opacity (few %), diffusion coeff. (15%), etc
- Nuclear cross section: S_{17}(4.7%), S_{33}(5.2%), S_{34}(5.4%) dominant error sources

At the moment, **^{7}Be and ^{8}B neutrinos do not determine composition with suff. accuracy**

Courtesy of Francesco Villante

The solar composition problem

The **solar composition problem** indicates that there is something **wrong** or **unaccounted** in solar models

- Are the new abundances (i.e. the atmospheric model) **wrong**?
- Are properties of the solar matter (e.g. **opacity**) correctly described?
- Is the **chemical evolution** not understood (extra mixing?) or peculiar (accretion?) with respect to other stars?

Note that:
*The Sun provide the **benchmark** for stellar evolution. If there is something wrong in solar models, then this is wrong for all the stars ...*

The interpretation is complicated by the **opacity-composition** degeneracy, i.e.:

*A change of **composition** produces the same effects on the helioseismic observables and neutrino fluxes (except CNO) of a **suitable change of the solar opacity profile $\delta\kappa(r)$***

Courtesy of Francesco Villante

The importance of CNO neutrinos

- Probe the dominant H-burning mechanism in massive and/or evolved stars
- Permit to break the opacity-composition degeneracy and provide a direct determination of the C+N abundance in the **solar core**:

Indeed, the (strong) dependence on solar environmental parameter (e.g. opacity) can be eliminated by using **B-neutrinos as solar thermometer**. E.g:

$$\delta\phi_{\mathrm{O}} - 0.785\,\delta\phi_{\mathrm{B}} = \delta X_{\mathrm{CN}}^{\mathrm{core}} \;\pm 0.4\%(\mathrm{env})\; \pm 2.6\%(\mathrm{diff})\; \pm 10\%(\mathrm{nuc})$$

Serenelli et al., PRD 2013

<u>High-Z .vs. Low-Z</u>

$$\delta\phi_{\mathrm{O}} = \frac{\phi_{\mathrm{O}}^{\mathrm{HZ}} - \phi_{\mathrm{O}}^{\mathrm{LZ}}}{\phi_{\mathrm{O}}^{\mathrm{LZ}}} \simeq 40\%$$

Beyond solar composition problem (10%):

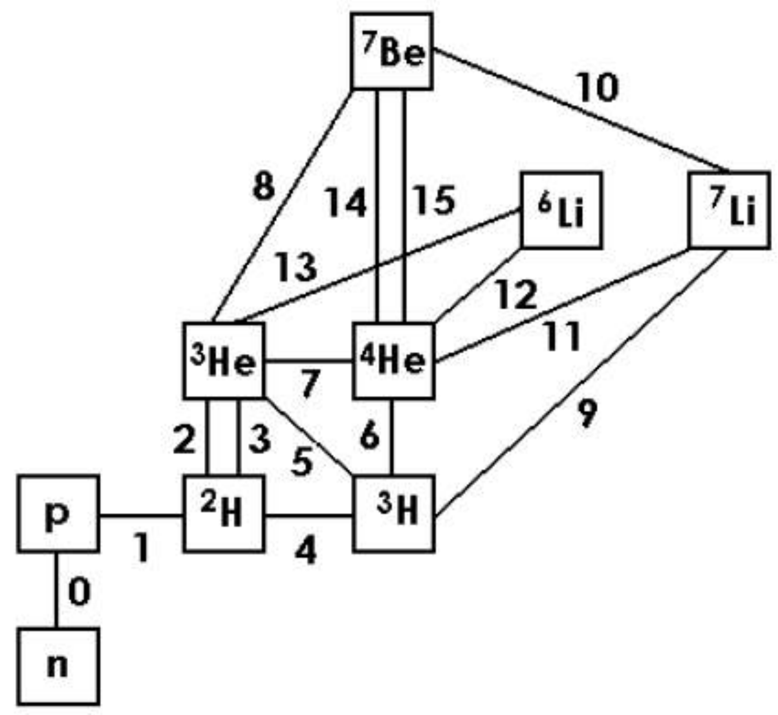
Using CNO neutrinos to probe for mixing processes in the Sun (and other stars)

$$\delta X_{\mathrm{CN}} = \frac{X_{\mathrm{CN}}^{\mathrm{core}} - X_{\mathrm{CN}}^{\mathrm{surf}}}{X_{\mathrm{CN,ini}}} \simeq 15\%$$

Courtesy of Francesco Villante

Big Bang Nucleosynthesis

Deuterium synthesis



Symbol	Reaction	Symbol	Reaction
R_0	τ_n	R_8	$^3\mathrm{He}(\alpha,\gamma)^7\mathrm{Be}$
R_1	$p(n,\gamma)d$	R_9	$^3\mathrm{H}(\alpha,\gamma)^7\mathrm{Li}$
R_2	$^2\mathrm{H}(p,\gamma)^3\mathrm{He}$	R_{10}	$^7\mathrm{Be}(n,p)^7\mathrm{Li}$
R_3	$^2\mathrm{H}(d,n)^3\mathrm{He}$	R_{11}	$^7\mathrm{Li}(p,\alpha)^4\mathrm{He}$
R_4	$^2\mathrm{H}(d,p)^3\mathrm{H}$	R_{12}	$^4\mathrm{He}(d,\gamma)^6\mathrm{Li}$
R_5	$^3\mathrm{He}(n,p)^3\mathrm{H}$	R_{13}	$^6\mathrm{Li}(p,\alpha)^3\mathrm{He}$
R_6	$^3\mathrm{H}(d,n)^4\mathrm{He}$	R_{14}	$^7\mathrm{Be}(n,\alpha)^4\mathrm{He}$
R_7	$^3\mathrm{He}(d,p)^4\mathrm{He}$	R_{15}	$^7\mathrm{Be}(d,p)2\,^4\mathrm{He}$

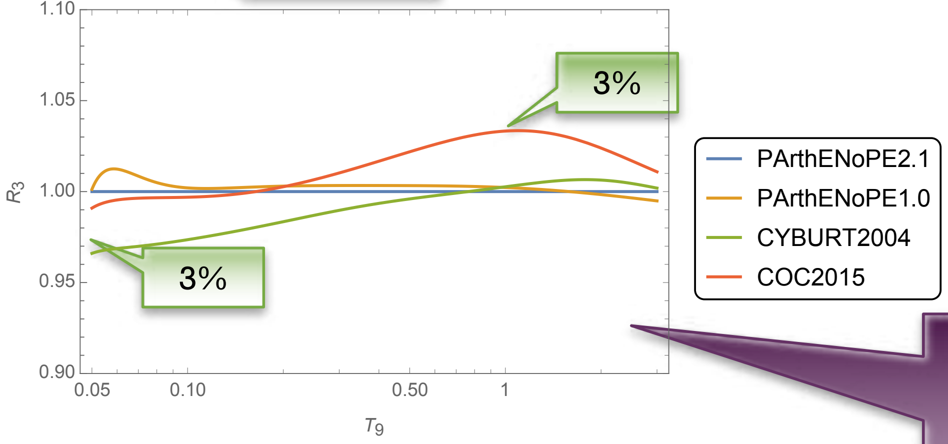
Reaction	Rate symbol	$\sigma_{^2\mathrm{H/H}} \times 10^5$
$p(n,\gamma)^2\mathrm{H}$	R_1	± 0.002
$d(p,\gamma)^3\mathrm{He}$	R_2	± 0.062
$d(d,n)^3\mathrm{He}$	R_3	± 0.020
$d(d,p)^3\mathrm{H}$	R_4	± 0.013

0.1%
87%
9%
3.8%

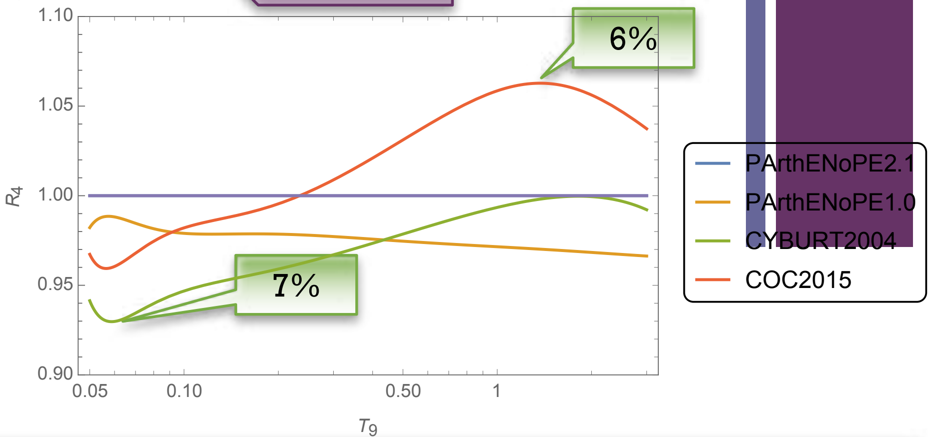
Di Valentino et al, **Phys.Rev. D90 (2014) no.2, 023543**

+ Rate comparison (1)

ddn

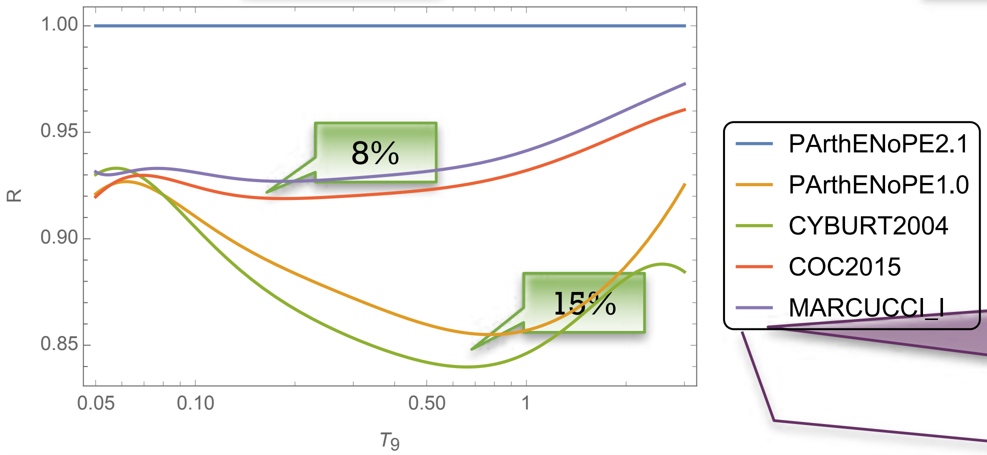


ddp



Update of PArthENoPE (TH data), difference with CYBURT2004/COC2015 is due to different data selection/analysis

dpγ



Update of PArthENoPE (MARCII versus AD2011), difference with CYBURT2004/COC2015 is MARCII versus AD2011/MARCI

MARCI: Marcucci et al., **Phys.Rev. C72 (2005) 014001**
MARCII: Marcucci et al., **Phys.Rev.Lett. 116 (2016) no.10, 102501**

Results on Deuterium

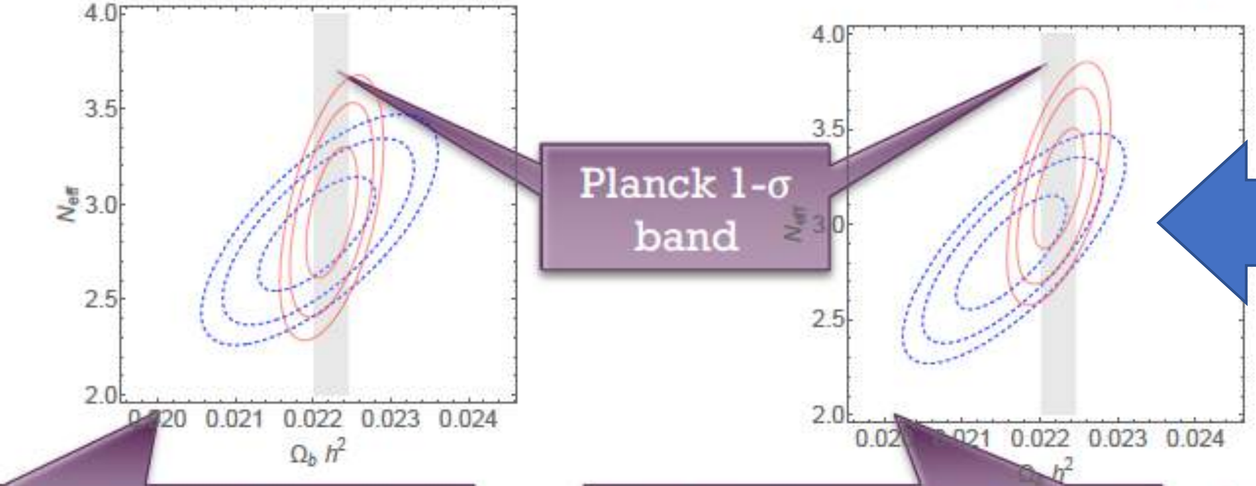
Adopted values are τ_n=879.5 s, $\Omega_B h^2$ = 0.02225±0.00016, ΔN_{eff}=0.

$D/H \times 10^{-5}$	PArthENoPE2.1	Coc2018	Cyburt2016
dpγ MARCI	2.52±0.07	2.459±0.036	
dpγ AD2011	2.58±0.07		2.579*
dpγ MARCII	2.45±0.07		

- Exp. value (Cooke et al, 2018): (2.527±0.030)×10^{-5}
- Different nuclear data selection in ddn and ddp and analysis method are responsible for +2.4% difference in D/H between present work (PArthENoPE with dpγ MARCI) and Coc2018.
- Good agreement between D/H of present work (PArthENoPE with AD2011) and Cyburt2016 (*Table II of the paper)

BBN/CMB analysis

- Exp. values:
  - $\Omega_B h^2 = 0.02242 \pm 0.00014$ (Planck 2018)
  - $D/H = (2.527 \pm 0.030)$ (Cooke et al., 2018)
  - $Y_p = 0.2446 \pm 0.0029$ (Peimbert et al., 2016)
- ddn+ddp = PArthENoPE2.1, dpγ = MARCI or MARCII
- D+Planck prior (red) and D+He (only BBN, blue) analyses



Planck 1-σ band

MARCI: $N_{eff} = 2.95 \pm 0.22$

MARCII: $N_{eff} = 3.18 \pm 0.21$

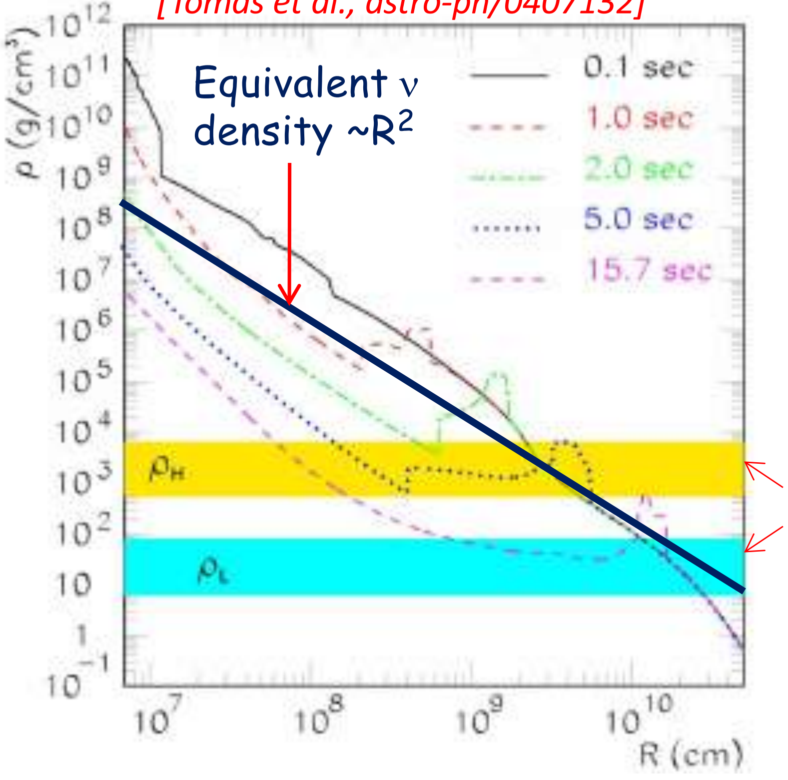
D+Planck

- Neff≃3
- MARCII: slight tension between “D+Planck” and “Only BBN”

Supernova neutrinos

SNAPSHOT OF SN DENSITIES

[Tomas et al., astro-ph/0407132]



Equivalent ν density ~R^2

- Matter bkg potential

$$\lambda = \sqrt{2} G_F N_e \quad \sim R^{-3}$$

- ν–ν interaction

$$\mu = \sqrt{2} G_F n_\nu \quad \sim R^{-2}$$

- Vacuum oscillation frequencies

$$\omega = \frac{\Delta m^2}{2E}$$

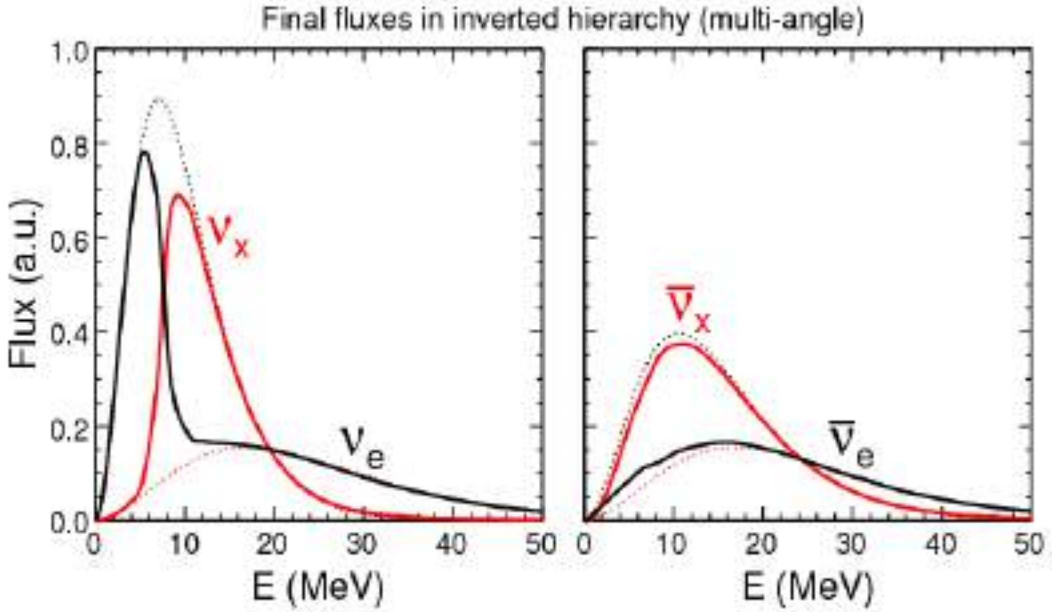
When $\mu >> \lambda$, SN ν oscillations dominated by ν-ν interactions

Collective flavor transitions at low-radii [O (10^2 – 10^3 km)]

Courtesy of Alessandro Mirizzi

SELF-INDUCED SPECTRAL SPLITS

[Fogli, Lisi, Marrone, A.M. , arXiV: 0707.1998 [hep-ph], Duan, Carlson, Fuller, Qian, astro-ph/0703776, Raffelt and Smirnov, 0705.1830 [hep-ph], Dasgupta, Dighe, Raffelt & Smirnov, arXiv:0904.3542 [hep-ph], Duan & Friedland, arXiv: 1006.2359, A.M. & Tomas, arXiv:1012.1339, Choubey, Dasgupta, Dighe, A.M., 1008.0308....]



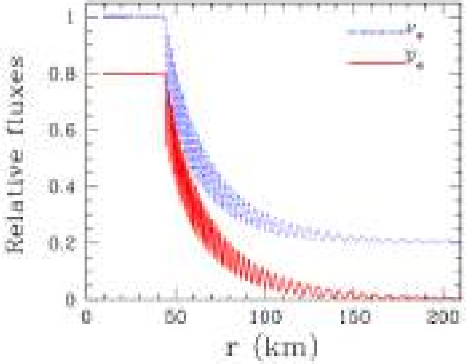
Swap of the original SN ν spectra in inverted mass hierarchy

Strong dependence of collective oscillations on mass hierarchy and on the energy ("splits")

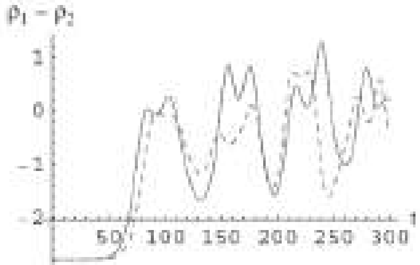
Splits possible in both normal and inverted hierarchy, for ν & $\bar{\nu}$!!

Courtesy of Alessandro Mirizzi

FLAVOR CONVERSIONS NEAR SN CORE?



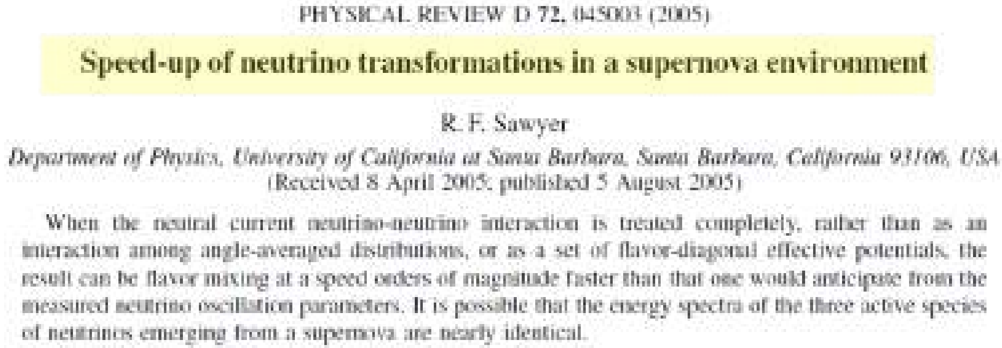
- Most of the studies assume no flavor conversion at $r < 50$ km (only synchronized oscillations). After self-induced conversions develop with a rate $\sim \sqrt{\omega\mu}$ *[see, e.g., Hannestad et al, astro-ph/0608695]*



- However, since more than a decade Ray Sawyer is pointing out that close to nu-sphere nu angular distributions of different species are rather different. This would lead to a new flavor instability (absent assuming equal angular distributions). The outcome would be a possible complete flavor mixing of the outgoing stream just above the nu-sphere. Fast rate $\sim\mu$

Courtesy of Alessandro Mirizzi

FAST FLAVOR CONVERSIONS NEAR SN CORE



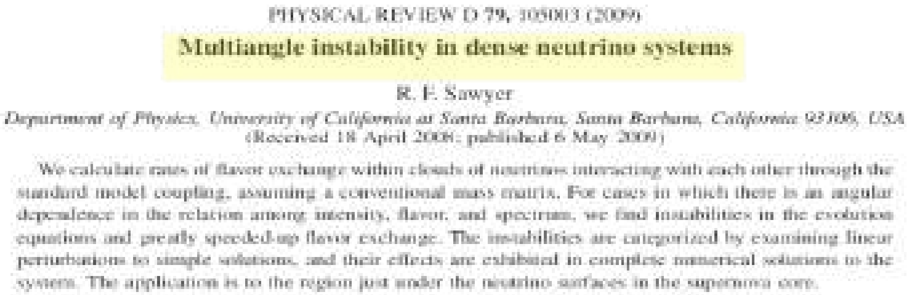
PHYSICAL REVIEW D **72**, 045003 (2005)

Speed-up of neutrino transformations in a supernova environment

R. F. Sawyer
Department of Physics, University of California at Santa Barbara, Santa Barbara, California 93106, USA

(Received 8 April 2005; published 5 August 2005)

When the neutral current neutrino-neutrino interaction is treated completely, rather than as an interaction among angle-averaged distributions, or as a set of flavor-diagonal effective potentials, the result can be flavor mixing at a speed orders of magnitude faster than that one would anticipate from the measured neutrino oscillation parameters. It is possible that the energy spectra of the three active species of neutrinos emerging from a supernova are nearly identical.



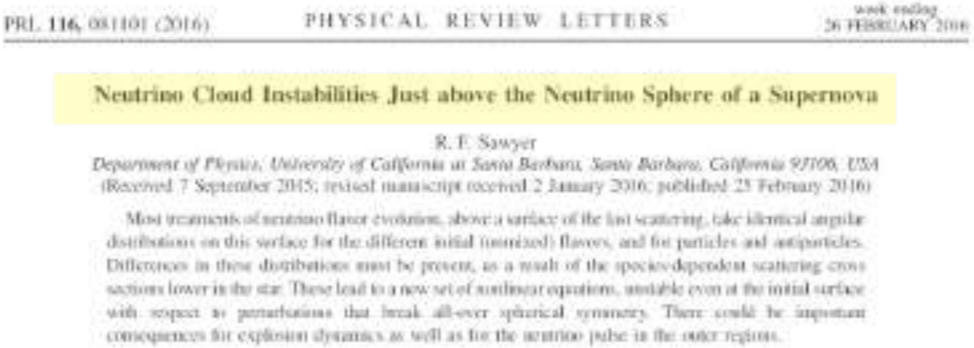
PHYSICAL REVIEW D **79**, 105003 (2009)

Multiangle instability in dense neutrino systems

R. F. Sawyer
Department of Physics, University of California at Santa Barbara, Santa Barbara, California 93106, USA

(Received 18 April 2008; published 6 May 2009)

We calculate rates of flavor exchange within clouds of neutrinos interacting with each other through the standard model coupling, assuming a conventional mass matrix. For cases in which there is an angular dependence in the relation among intensity, flavor, and spectrum, we find instabilities in the evolution equations and greatly speeded-up flavor exchange. The instabilities are categorized by examining linear perturbations to simple solutions, and their effects are exhibited in complete numerical solutions to the system. The application is to the region just under the neutrino surfaces in the supernova core.



PRL **116**, 081101 (2016) PHYSICAL REVIEW LETTERS week ending 26 FEBRUARY 2016

Neutrino Cloud Instabilities Just above the Neutrino Sphere of a Supernova

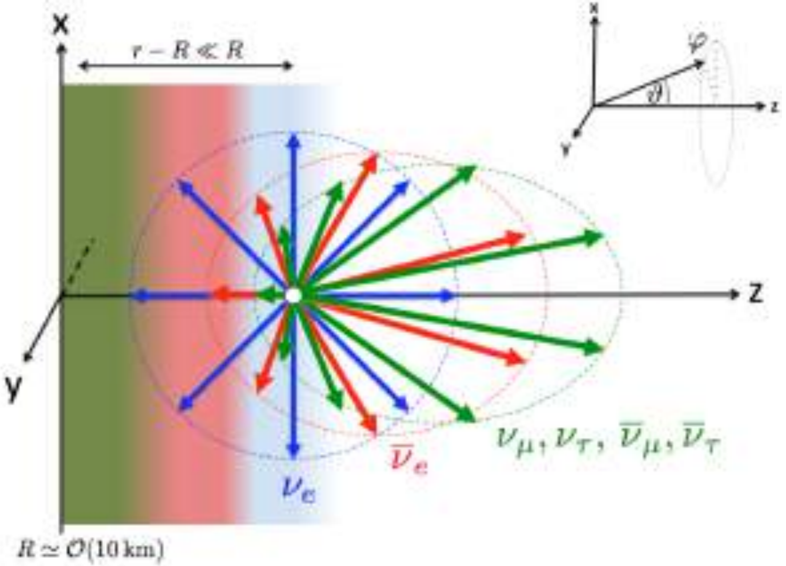
R. F. Sawyer
Department of Physics, University of California at Santa Barbara, Santa Barbara, California 93106, USA

(Received 7 September 2015; revised manuscript received 2 January 2016; published 23 February 2016)

Most treatments of neutrino flavor evolution, above a surface of the last scattering, take identical angular distributions on this surface for the different initial (unmixed) flavors, and for particles and antiparticles. Differences in these distributions must be present, as a result of the species-dependent scattering cross sections lower in the star. These lead to a new set of nonlinear equations, unstable even at the initial surface with respect to perturbations that break all-over spherical symmetry. There could be important consequences for explosion dynamics as well as for the neutrino pulse in the outer regions.

Courtesy of Alessandro Mirizzi

NEUTRINO ANGULAR DISTRIBUTIONS AT DECOUPLING

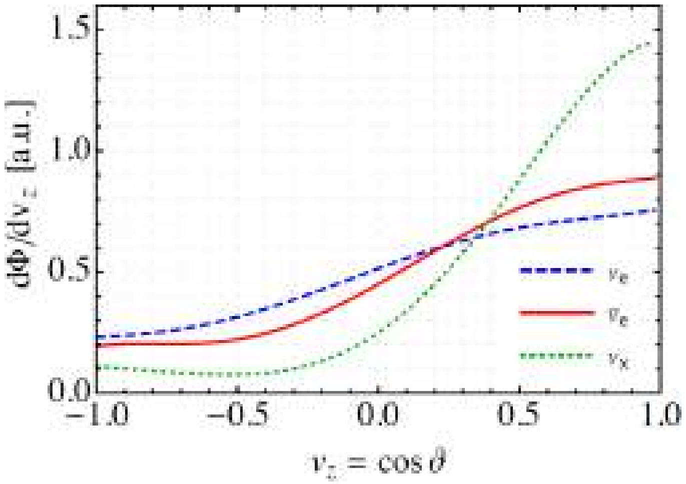


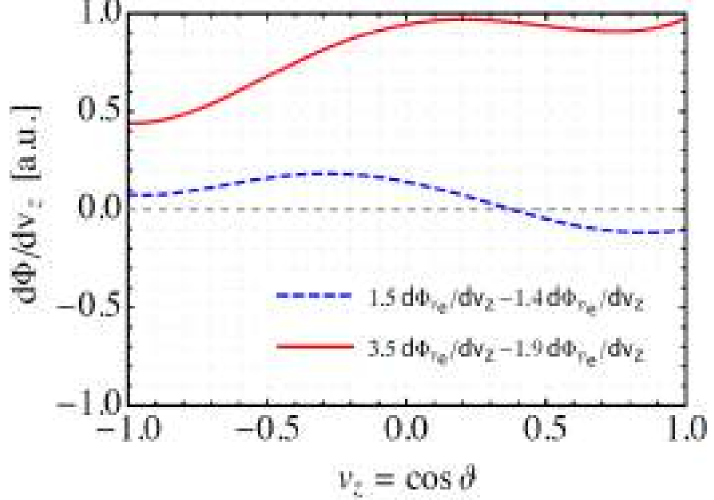
- Electron flavors remain in equilibrium with matter for a longer period than the non-electron flavors, due to the largest cross-sections of CC interactions
- Non-electron flavors decouple deeper in the star (more fwd-peaked distributions)
- Neutron-richness enhances CC interactions for ν_e keeping them more coupled to matter (more isotropic distribution) than $\bar{\nu}_e$.

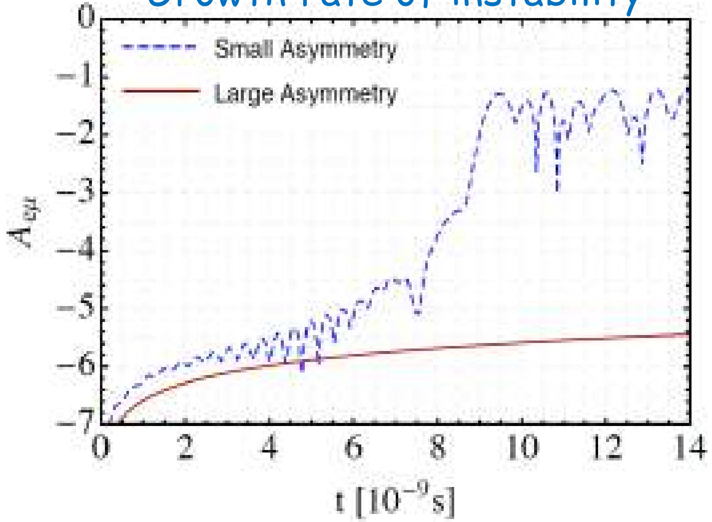
[Dasgupta, Mirizzi, Sen, arXiV:1609.00528]

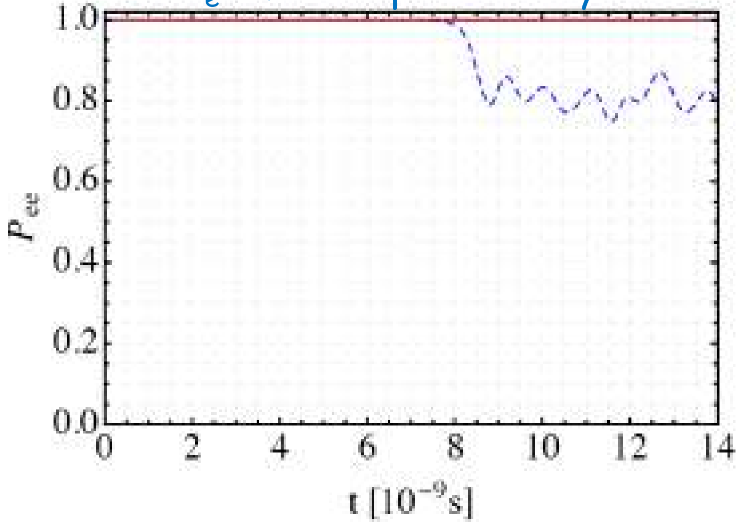
Courtesy of Alessandro Mirizzi

FAST FLAVOR CONVERSIONS


Nu angular distributions


$\nu_e - \bar{\nu}_e$ difference


Growth rate of instability


$\bar{\nu}_e$ survival probability

Courtesy of Alessandro Mirizzi

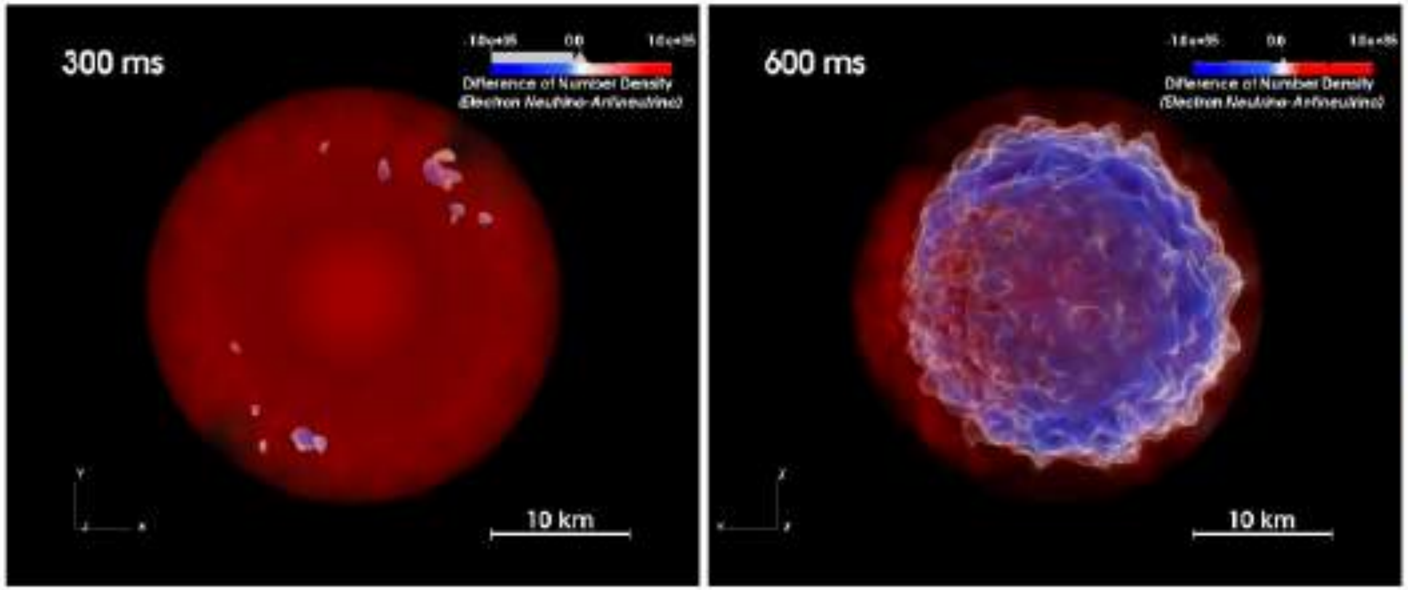
Fast Flavor Conversion in Dense Neutrinos?

- Neutrino flavor conversion *not included* in traditional transport simulations (of core-collapse SNe, neutron star mergers)
- Potentially relevant for energy transfer (explosion mechanism), nucleosynthesis in neutrino-driven outflows, and for SN neutrino signal
- Large matter effect suppresses usual flavor conversion in deep layers, MSW conversion at hundreds km studied by post-processing
- However, interacting dense neutrino gas supports collective flavor modes
- Nontrivial angle-distributions of ν_e vs $\overline{\nu}_e$ enable fast flavor modes" with instabilities on scales of meters
- Amounts to pair annihilation $\nu_e + \overline{\nu}_e \to \nu_x + \overline{\nu}_x$ on refractive level (order G_F)
- Relevant conditions fulfilled in realistic simulations?
  (Recently a preprint nearly every week on this subject by different groups worldwide)
- Do we have the right criteria?
- If effect is real, how does unstable neutrino field develop and what is the practical impact on core-collapse physics?

Courtesy of Alessandro Mirizzi

Evidence for Fast Flavor Instability in 3D Supernova Models

R. Glas, H.-T. Janka, F. Capozzi, M. Sen, B. Dasgupta, A. Mirizzi and G. Sigl, arXiv:1912.00274



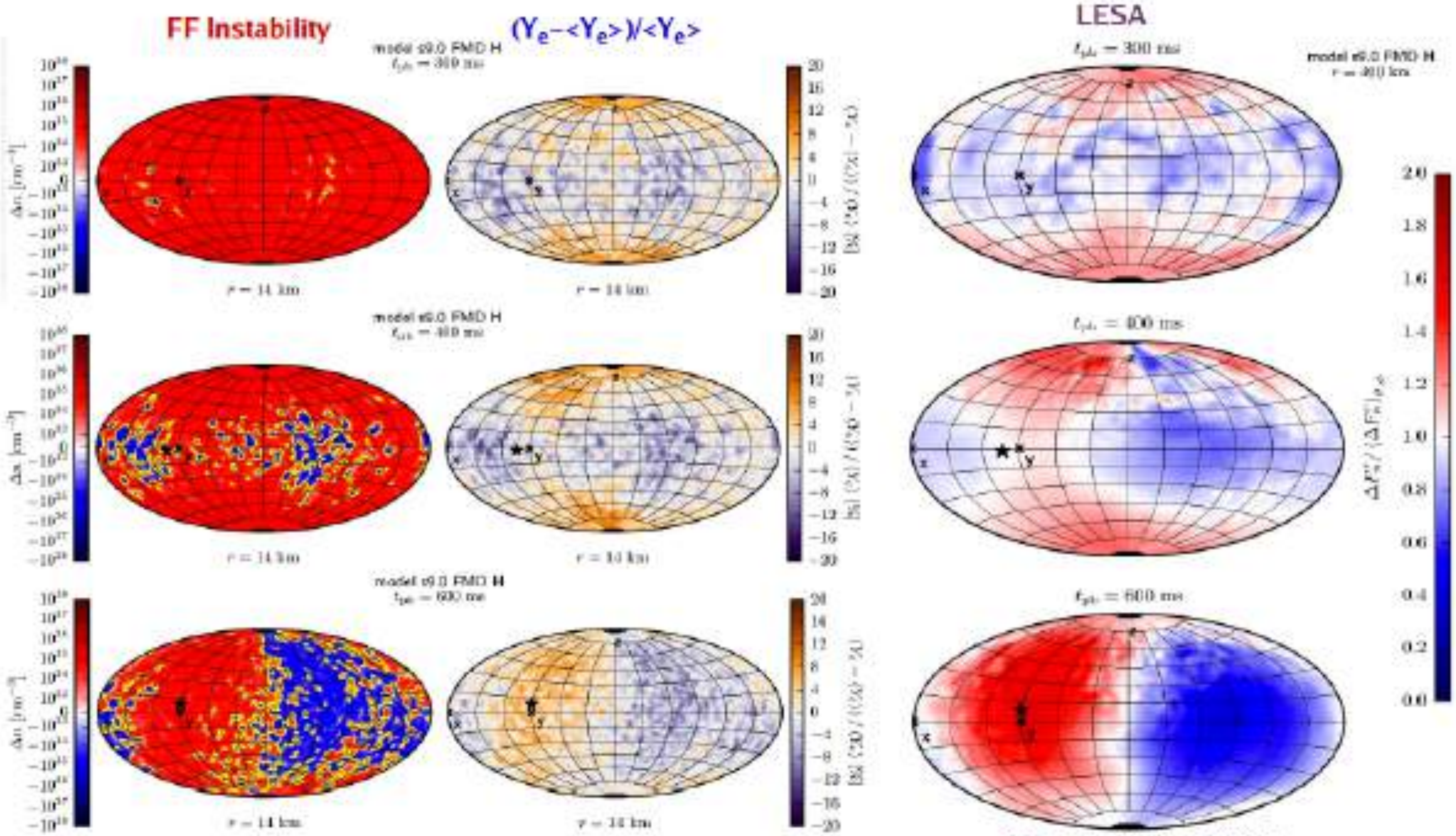
Glas et al., arXiv:1912.00274

- Fast flavor instability is diagnosed inside of newly formed neutron stars (NSs).
- Instability regions are thin boundary layers of volumes where n($\bar{\nu}_e$) > n(ν_e)
- Regions grow with time in convective shell of the NS, favored by decreasing electron fraction and high temperatures.

Courtesy of Alessandro Mirizzi

Evolution of Fast Flavor Instability inside Neutron Stars

Instability regions (yellow) show anti-correlation with growth of LESA



Glas et al., arXiv:1912.00274

Courtesy of Alessandro Mirizzi

Combined search of Core-collapse SNe with MeV neutrinos and GWs

Activity:

-Combined search of Supernovae with Low-energy neutrinos data provided by LVD, Kamland, IceCube, Borexino and GWs data of LIGO and Virgo.

-Study of new way to disentangle real signal From the noise in order to increase the statistical significance of observed coincidences.

-Study of statistical way to combine GW and neutrinos Data.

GSSI Members:
G. Pagliaroli, Researcher [0.4 FTE]
M. Drago, Postdoc [1 FTE]
O. Halim, PhD [1 FTE]

In collaboration with:

1. MIT, Roma Tor Vergata

Courtesy of Giulia Pagliaroli

Joint GW-ν Search

Leonor *et al.*, Class. Quantum Grav. 27 (2010) 084019

False Alarm Rate GW back. Rate Neutrino back. Rate Time coincidence window

$$\boxed{\mathrm{FAR} = R_{GW}(\eta)\cdot R_{\nu}(\xi)\cdot 2w}$$

- **FAR=1/1000 years and at least 2 neutrinos in coincidence with a gravitational wave trigger.**
- w=10 sec to accomodate most emission models

Courtesy of Giulia Pagliaroli

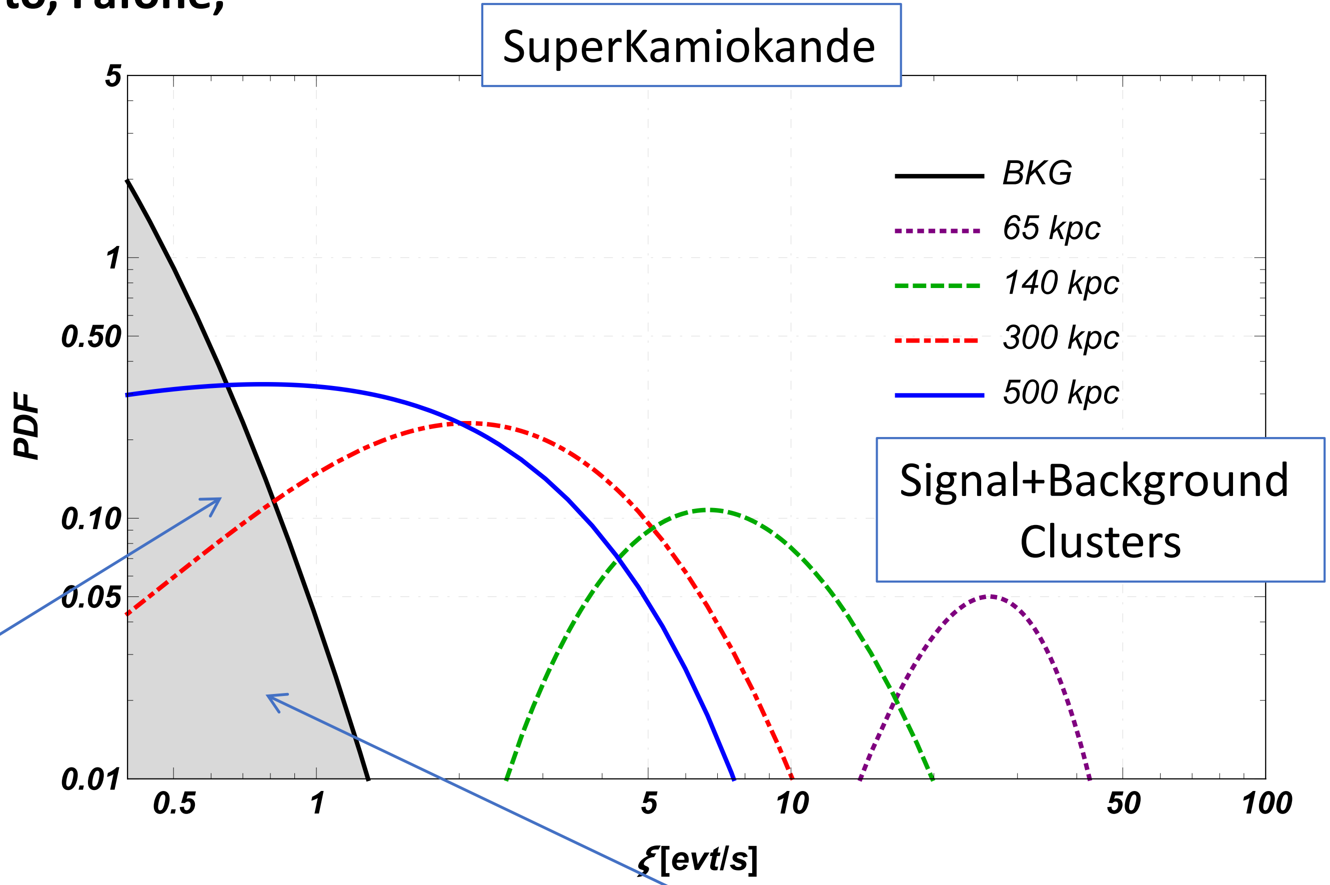
Background-Signal separation

Casentini, Pagliaroli, Vigorito, Fafone,
JCAP 1808 (2018) n.08,010

Probability density Distributions

$$\xi_i = \frac{m_i}{\Delta t_i}$$

Pure Background Clusters



SuperKamiokande

Signal+Background Clusters

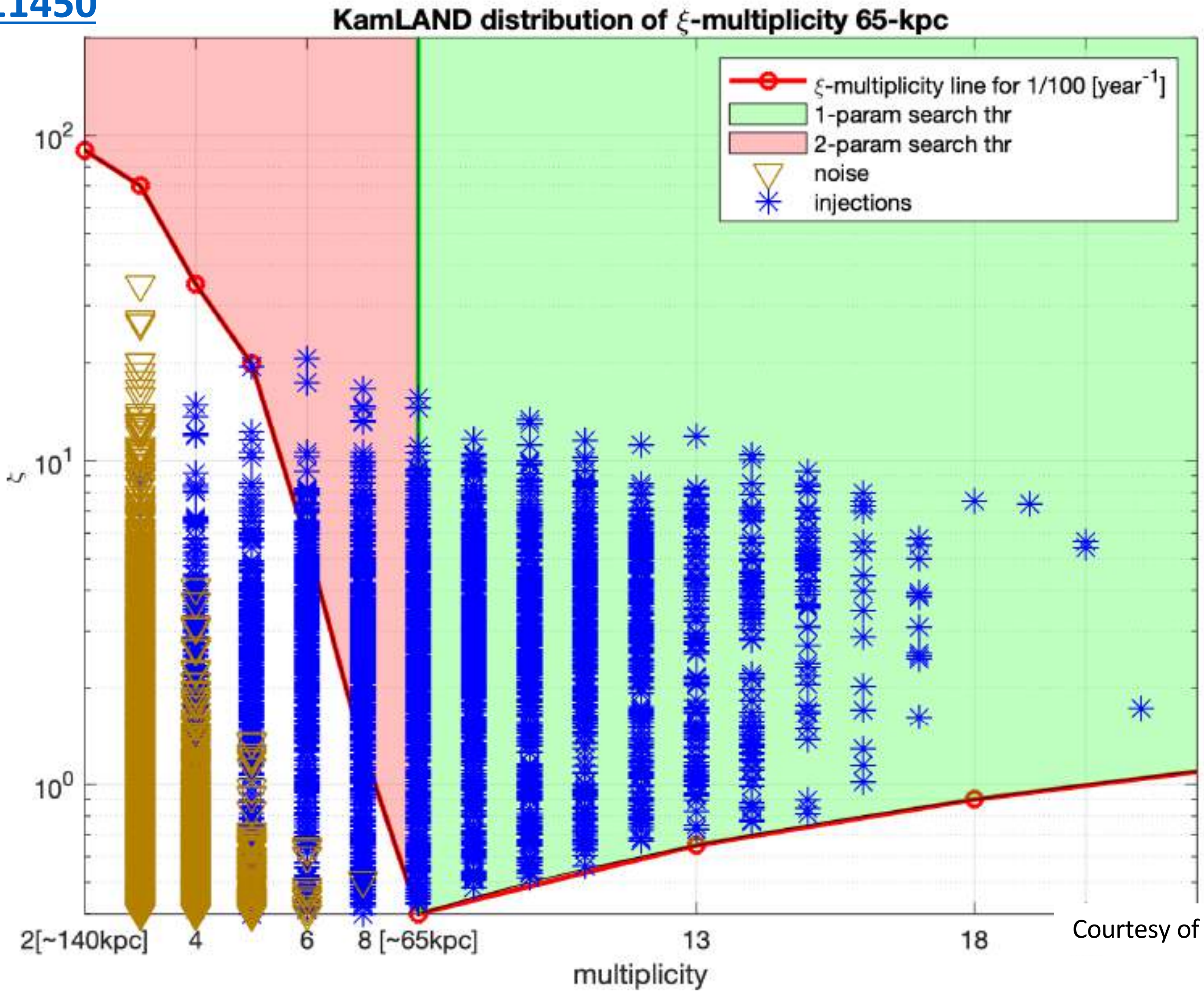
$$F_i^{im} = \left[f_i^{im} - 8640 \times \sum_{k=m_i}^{m_i+n;\, n\leq(20\xi-m_i)} P(k) N_k \int_{k/20}^{\xi} f(\xi)\, d\xi \right] [\mathrm{day}^{-1}].$$

Courtesy of Giulia Pagliaroli

Results with the new FIM

Expanding Core-Collapse Supernova Search Horizon of Neutrino Detectors

O. Halim_ C. Vigorito,_C. Casentini G.Pagliaroli M. Drago_V. Fafone, e-Print:**arXiv:1911.11450**



Courtesy of Giulia Pagliaroli

Results with the new FIM

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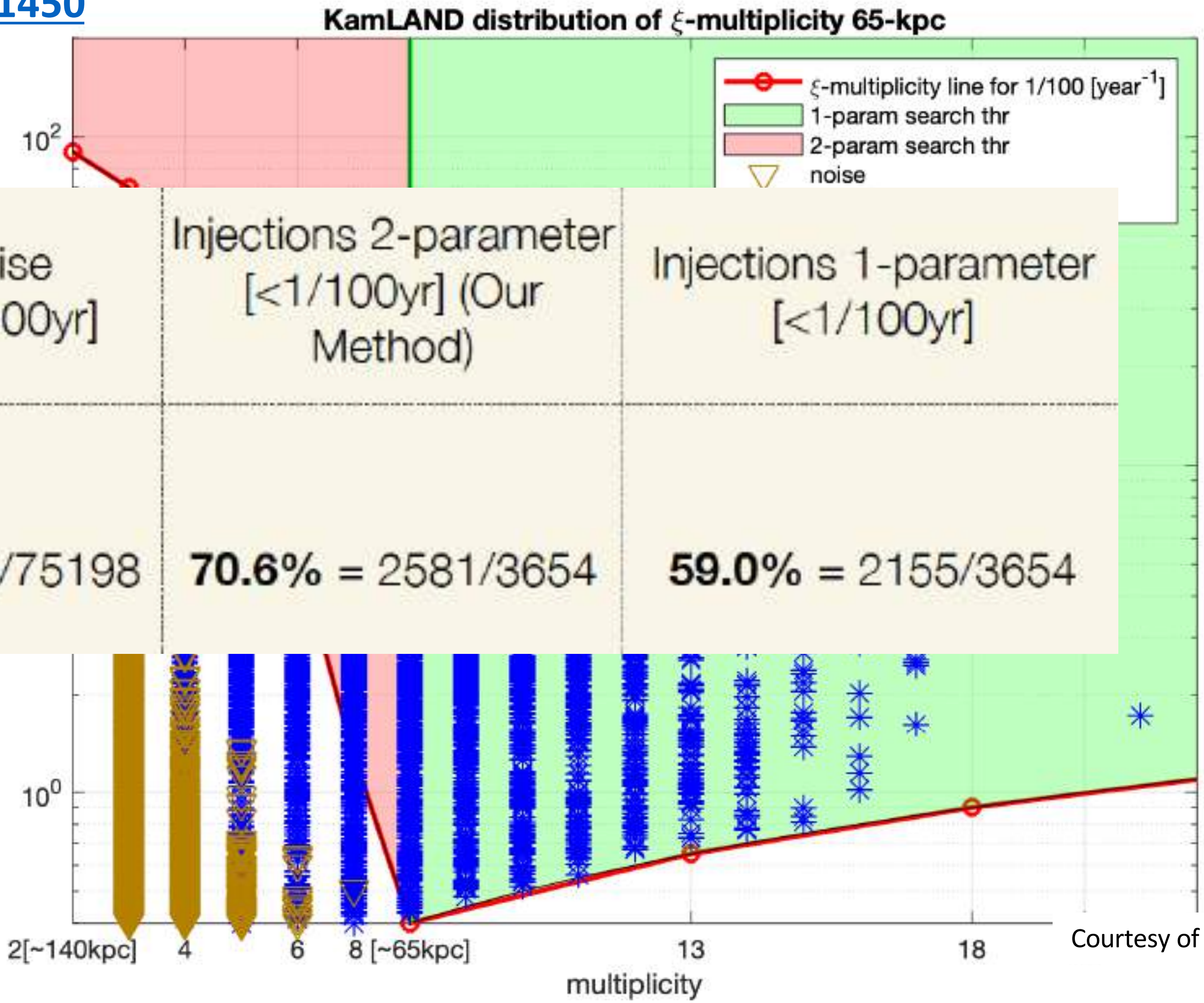
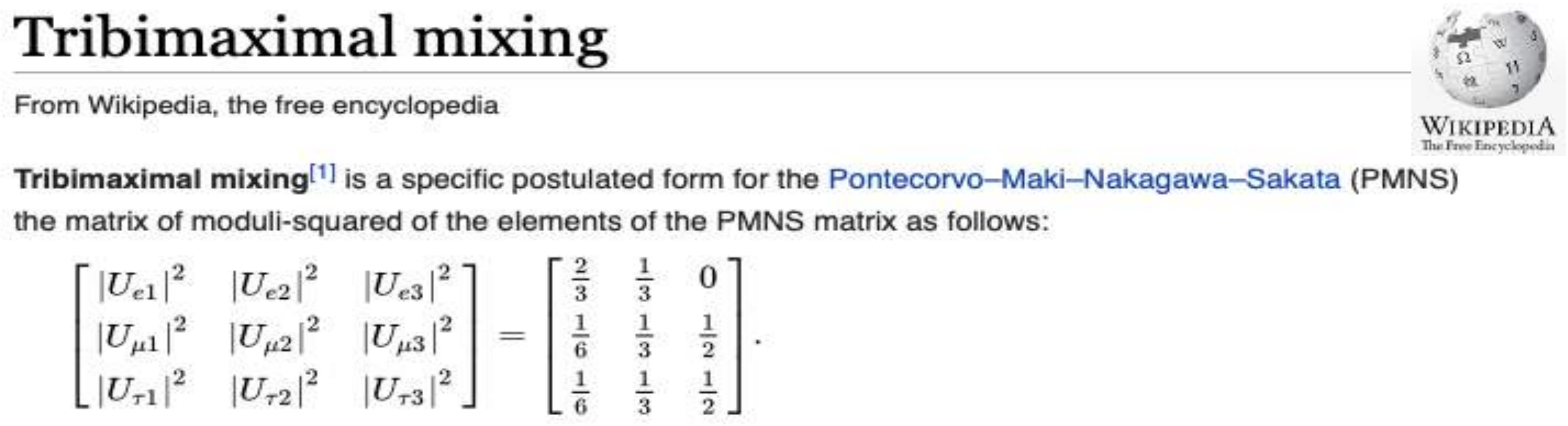


Noise	Noise [<1/100yr]	Injections 2-parameter [<1/100yr] (Our Method)	Injections 1-parameter [<1/100yr]
75198	0% = 0/75198	**70.6%** = 2581/3654	**59.0%** = 2155/3654

Courtesy of Giulia Pagliaroli

Neutrinos and fundamental Physics

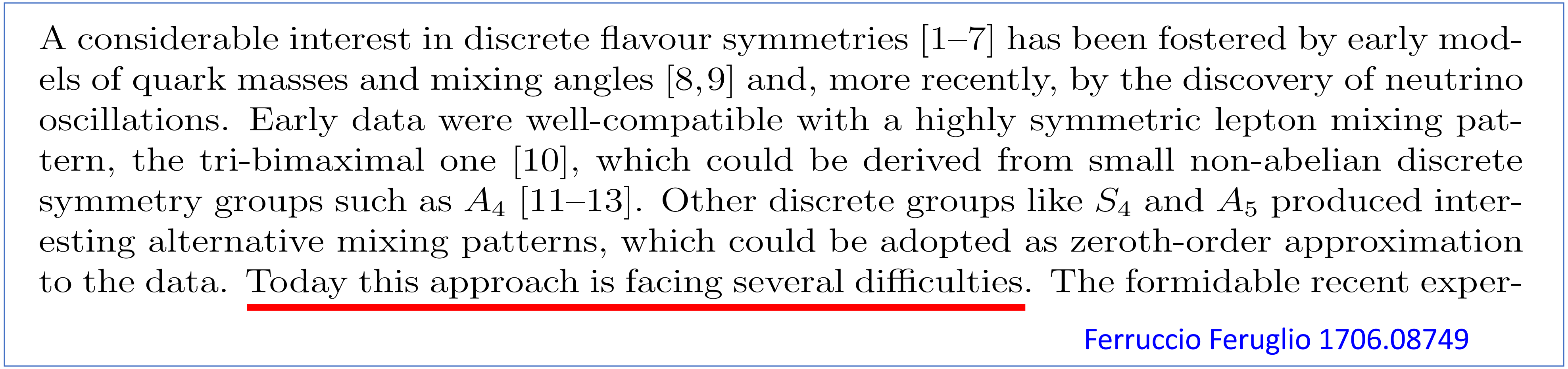


Tribimaximal mixing

From Wikipedia, the free encyclopedia

Tribimaximal mixing[1] is a specific postulated form for the Pontecorvo–Maki–Nakagawa–Sakata (PMNS)
the matrix of moduli-squared of the elements of the PMNS matrix as follows:

$$\begin{bmatrix} |U_{e1}|^2 & |U_{e2}|^2 & |U_{e3}|^2 \\ |U_{\mu1}|^2 & |U_{\mu2}|^2 & |U_{\mu3}|^2 \\ |U_{\tau1}|^2 & |U_{\tau2}|^2 & |U_{\tau3}|^2 \end{bmatrix} = \begin{bmatrix} \frac{2}{3} & \frac{1}{3} & 0 \\ \frac{1}{6} & \frac{1}{3} & \frac{1}{2} \\ \frac{1}{6} & \frac{1}{3} & \frac{1}{2} \end{bmatrix}.$$



A considerable interest in discrete flavour symmetries [1–7] has been fostered by early models of quark masses and mixing angles [8,9] and, more recently, by the discovery of neutrino oscillations. Early data were well-compatible with a highly symmetric lepton mixing pattern, the tri-bimaximal one [10], which could be derived from small non-abelian discrete symmetry groups such as A_4 [11–13]. Other discrete groups like S_4 and A_5 produced interesting alternative mixing patterns, which could be adopted as zeroth-order approximation to the data. Today this approach is facing several difficulties. The formidable recent exper-

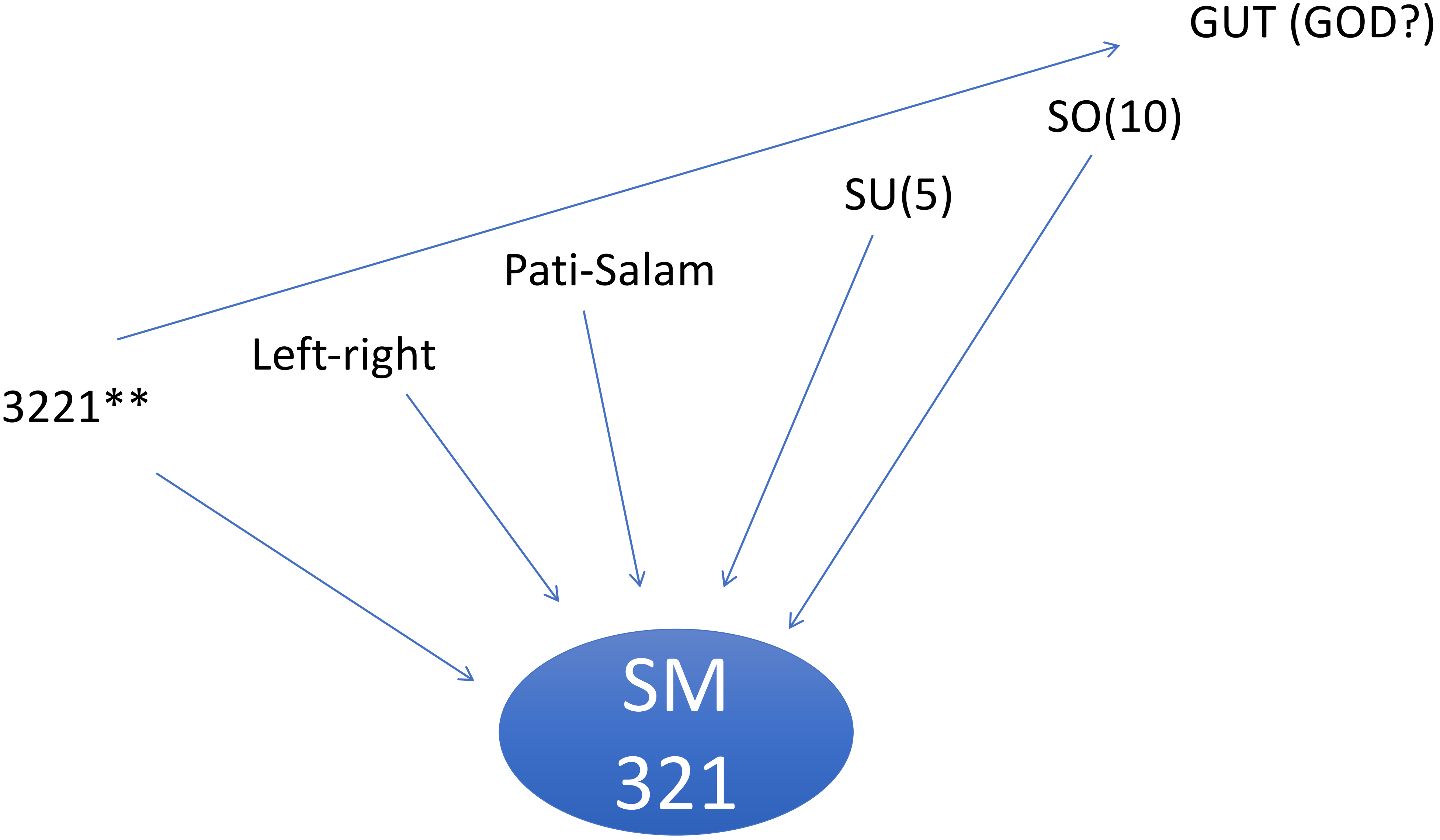
Ferruccio Feruglio 1706.08749

-Non-vanishing reactor angle and deviation from atmospheric maximality;
-Inclusion of many scalars and large corrections from higher order contributions;
-Quark sector not naturally included;

ANARCHY vs flavor symmetry? Or……..

Chianese e Morisi

……..just GAUGE SYMMETRIES?



GUT (GOD?)

SO(10)

SU(5)

Pati-Salam

Left-right

3221**

SM
321

** work in progress: ***W’***: Calabresi, Fiorillo, Miele, Morisi

AN EXAMPLE: MINIMAL SO(10)

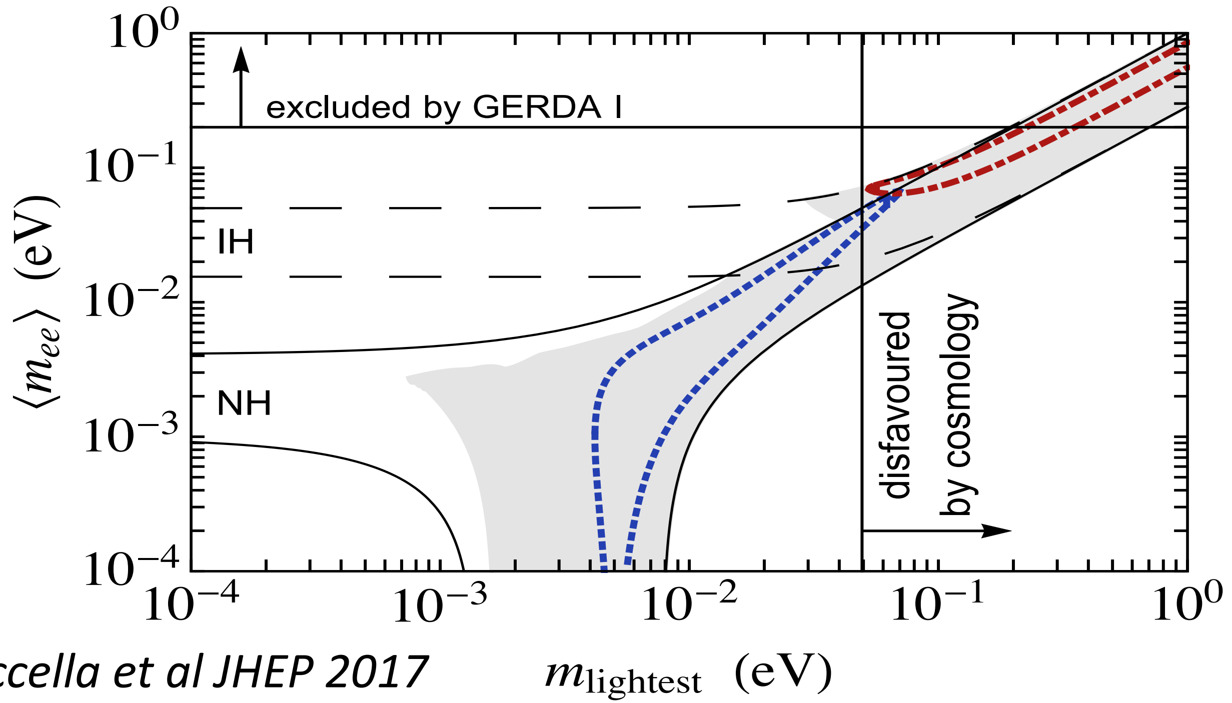
Abud, Buccella IJMPA 2001

- *Type-I seesaw dominant over type-II*:
  triplet vev suppressed by <**210**> vev
- ***10+126*** *(no **120**)*: Dirac neutrino mass symmetric
- *Dirac neutrino mass matrix ≈ up quark mass matrix:*
  rather a good approximation in fact <126> smaller than <10>
- *Upper limit on the heaviest right handed neutrino:* $M_{R3} \lesssim 10^{11}\ GeV$

$$M_R = -m_D^T \frac{1}{m_\nu} m_D$$

$$\boxed{\left| \frac{A^2}{m_1} + \frac{B^2}{m_2 e^{-2i\alpha}} + \frac{C^2}{m_3 e^{-2i\beta}} \right| \gtrsim \varepsilon}$$

$$A = \cos\theta_{12}\cos\theta_{23}\sin\theta_{13}e^{i\delta} - \sin\theta_{12}\sin\theta_{23}\,,$$
$$B = \sin\theta_{12}\cos\theta_{23}\sin\theta_{13}e^{i\delta} + \cos\theta_{12}\sin\theta_{23}\,,$$
$$C = \cos\theta_{13}\cos\theta_{23}\,,$$



Buccella et al JHEP 2017

Chianese e Morisi

Neutrino phenomenology from leptogenesis in SO(10)

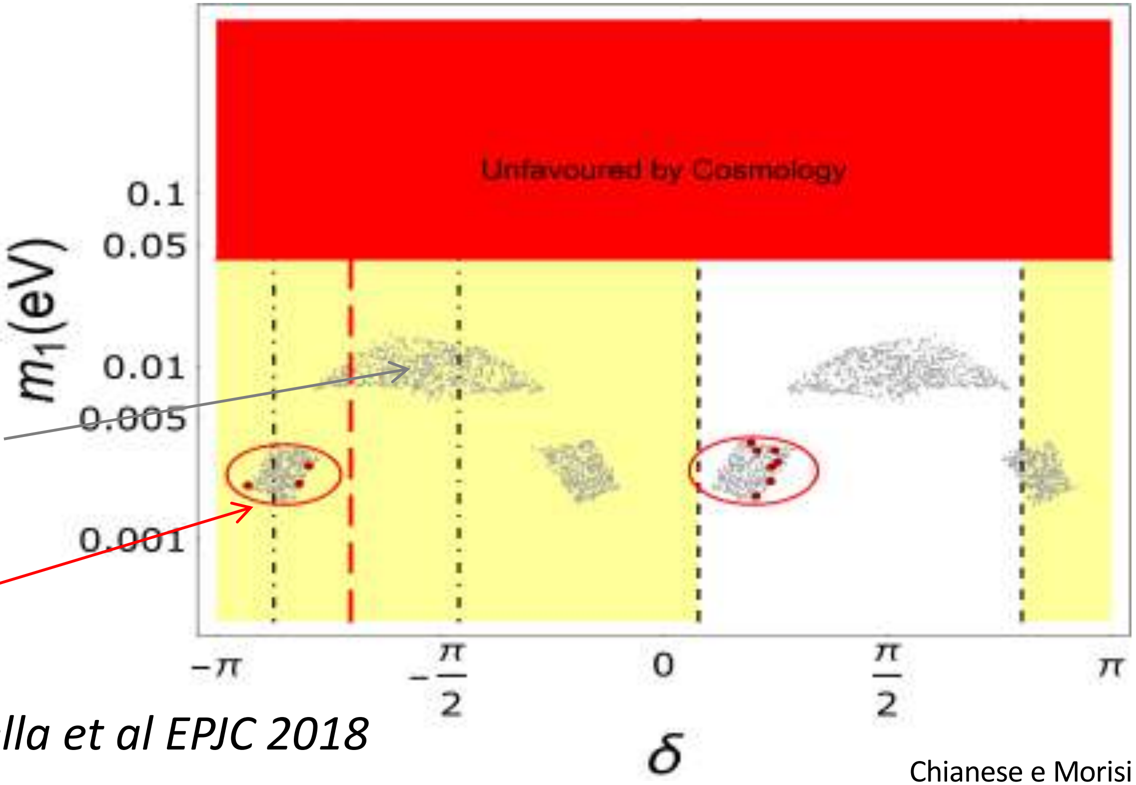
- *Type-I seesaw dominant over type-II*:
  triplet vev suppressed by <**210**> vev
- ***10+126** (no **120**)*: Dirac neutrino mass symmetric
- *Dirac neutrino mass matrix ≈ up quark mass matrix:*
  rather a good approximation in fact <**126**> smaller than <**10**>

Abud, Buccella IJMPA 2001

$$M_R = -m_D^T \frac{1}{m_\nu} m_D$$

Once mD is fixed, namely mD = Mup, demanding compact MR eigenvalues follows a correlation bewtween neutrino paremeters

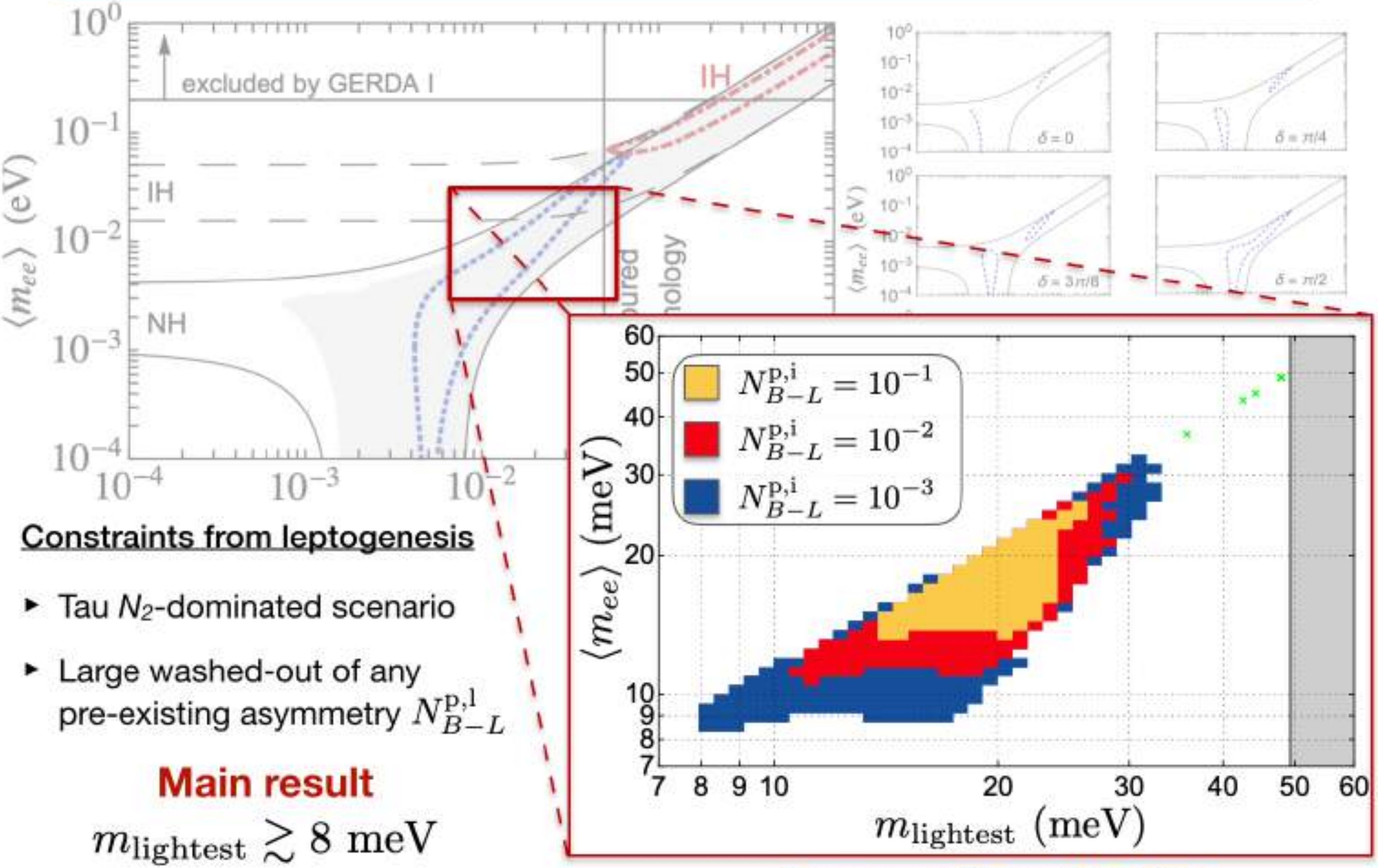
red points imposing baryogenesis via leptogenesis



Buccella et al EPJC 2018

Chianese e Morisi

Prediction on 0nbb from SO(10) + Leptogenesis



Constraints from leptogenesis

- Tau N_2-dominated scenario
- Large washed-out of any pre-existing asymmetry $N^{\mathrm{p,i}}_{B-L}$

Main result

$$m_{\mathrm{lightest}} \gtrsim 8\ \mathrm{meV}$$

*Chianese and Di Bari, **JHEP 1805***

Some questions

- Do we understand $\nu_{\odot}$ (the Sun) enough? Is MSW proved? What about Ga-xsec?
- How often core collapse events occur in the Milky Way?
- Are we ready for future supernova ν – or are we stuck in theoretical doubts?
- Do we understand sufficiently ν interactions in astrophysical conditions?
- Are events seen by IceCube really isotropic distributed? (through-going-μ below 200 TeV?)
- What do we aim to learn from E_ν>10 PeV? What is the composition of UHECR?
- Alternative ways to see Majorana neutrinos? Chances to probe other properties?
- Is there a chance to see relic (BBN) neutrinos?
- On which principles should we possibly build a theory of fermion masses?

Thank you to all contributors

#16 - ALESSANDRO MIRIZZI - PREMIO RODOLFO VALENTINO TERRA DEL MITO - NEW GENERATON 2014