PRIN 2012

Theoretical astroparticle physics

Phenomenology of ν masses and mixings (Bari Unit)

FRANCESCO CAPOZZI
PhD student
Università degli Studi di Bari - INFN

Research activity - Bari group

- Phenomenology of neutrino oscillations and mass hierarchy
- Neutrinoless double beta decay
- Collective effects in supernova neutrinos

Neutrino oscillations

In the 3ν framework, the mixing matrix U is:

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U^* \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

where $c_{ij}=\cos\theta_{ij}$ and $s_{ij}=\sin\theta_{ij}$

3 mixing angles
θ_{12}, θ_{13}, θ_{23}

1 phase δ
(CPV for $\delta\neq 0,\pi$)

Oscillations depend on mass differences. Assuming $m_2>m_1$:

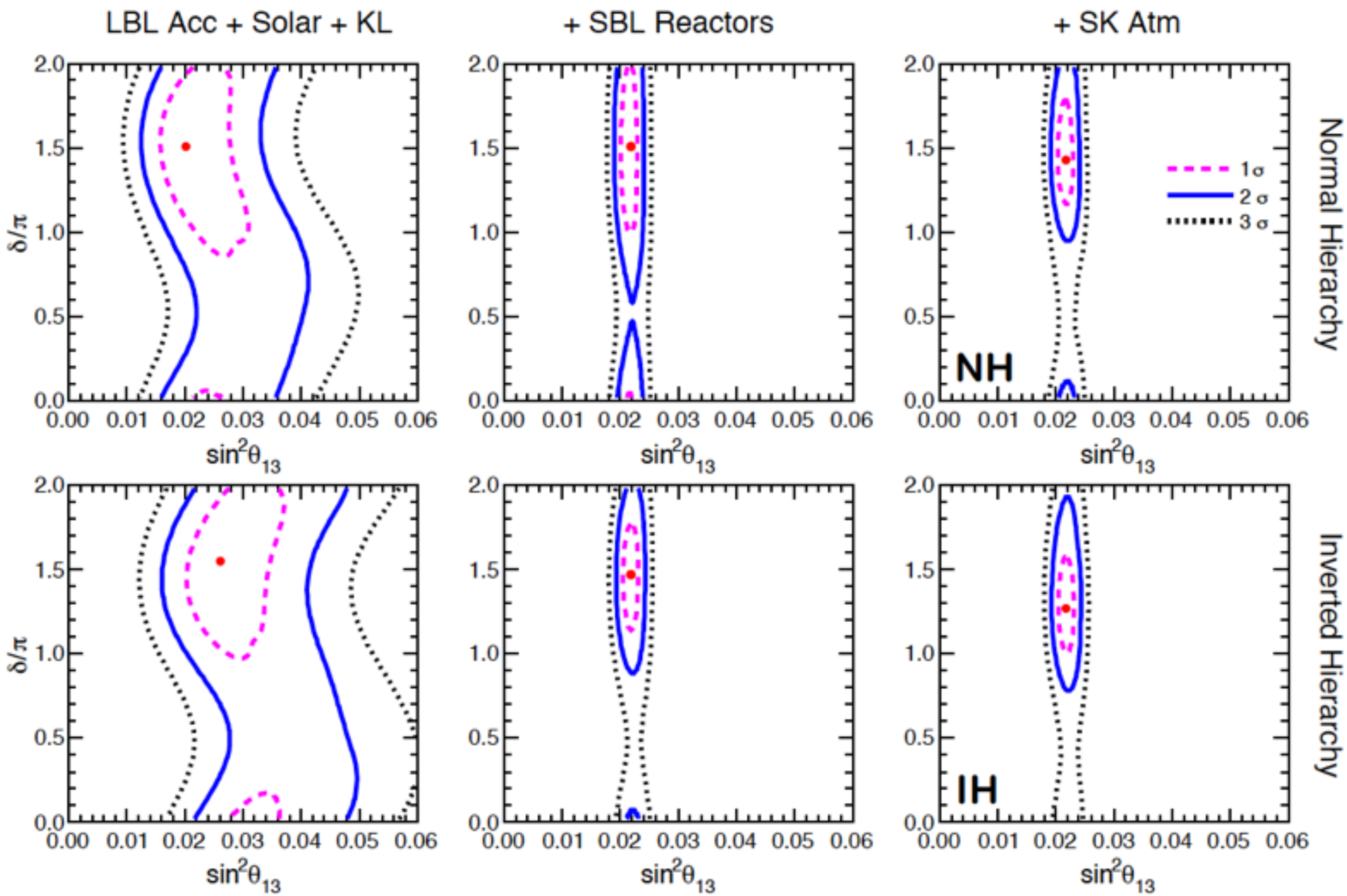
$$\delta m^2 = m_2^2 - m_1^2 > 0 \quad \ll \quad \Delta m^2 = m_3^2 - \frac{m_2^2 + m_1^2}{2}$$

"SOLAR" "ATMOSPHERIC"

If $\Delta m^2>0$ we are in **NORMAL HIERARCHY**
If $\Delta m^2<0$ we are in **INVERTED HIERARCHY**

Global analysis

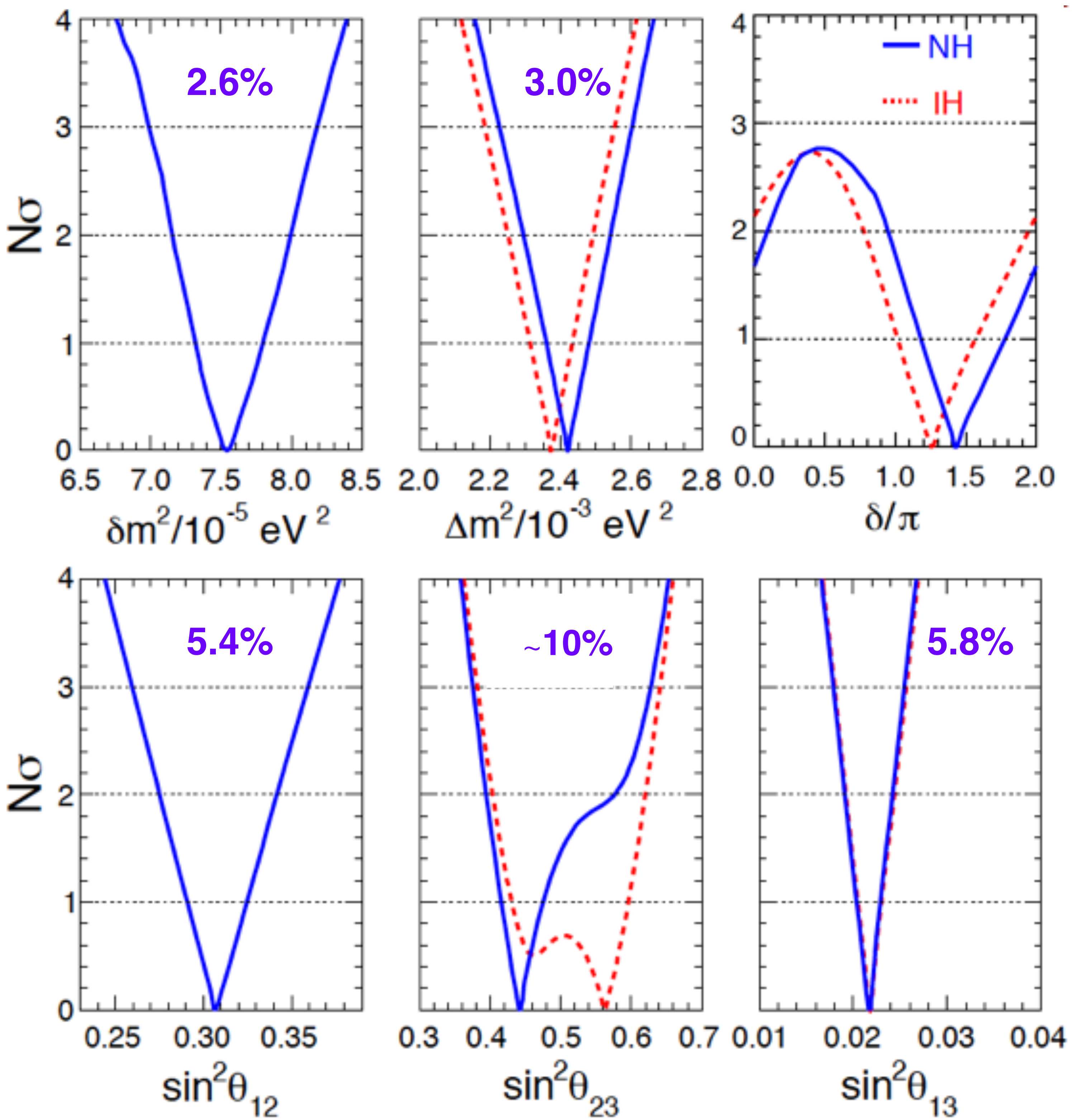
(based on arXiv:1312.2878, F. Capozzi, G. L. Fogli, E. Lisi, A. Marrone, D. Montanino, A. Palazzo)



For the relatively "low" value $\sin^2\theta_{13}$~0.02 preferred by SBL reactors (and Solar + KL) data, the appearance signal in T2K is maximized by CP violating $\delta \simeq 1.5\pi$. SK Atm lowers a bit this value.

Global analysis

(based on arXiv:1312.2878, F. Capozzi, G. L. Fogli, E. Lisi, A. Marrone, D. Montanino, A. Palazzo)



- **Preference for CP violating δ~1.4π and sinδ<0.**
- **Preference for non-maximal θ_{23} (octant instability).**
- **$\chi^2_{min}(NH)-\chi^2_{min}(IH)=-0.3$. No hierarchy information yet.**

Mass hierarchy from atmospheric ν (PINGU)

(based on arXiv:1503.01999, F. Capozzi, E. Lisi, A. Marrone)

Mass hierarchy from matter effects in Earth core and mantle (NH for ν e IH for $\overline{\nu}$): θ_{13} (matter) ≫ θ_{13} (vacuum).

PINGU measures ν_α spectrum (α=e,μ) which depends on E (energy) and θ (zenith angle)

Osc. independent

$$N^{\alpha}_{ij}(E_\nu,\theta) = \overbrace{V^{\alpha}_{\rm eff}(E_\nu) \otimes \sigma(E_\nu) \otimes \Phi^{\alpha}(E_\nu,\theta)} \otimes P^{\alpha}(E_\nu,\theta) \otimes R^{\alpha}(E_\nu,\theta)$$

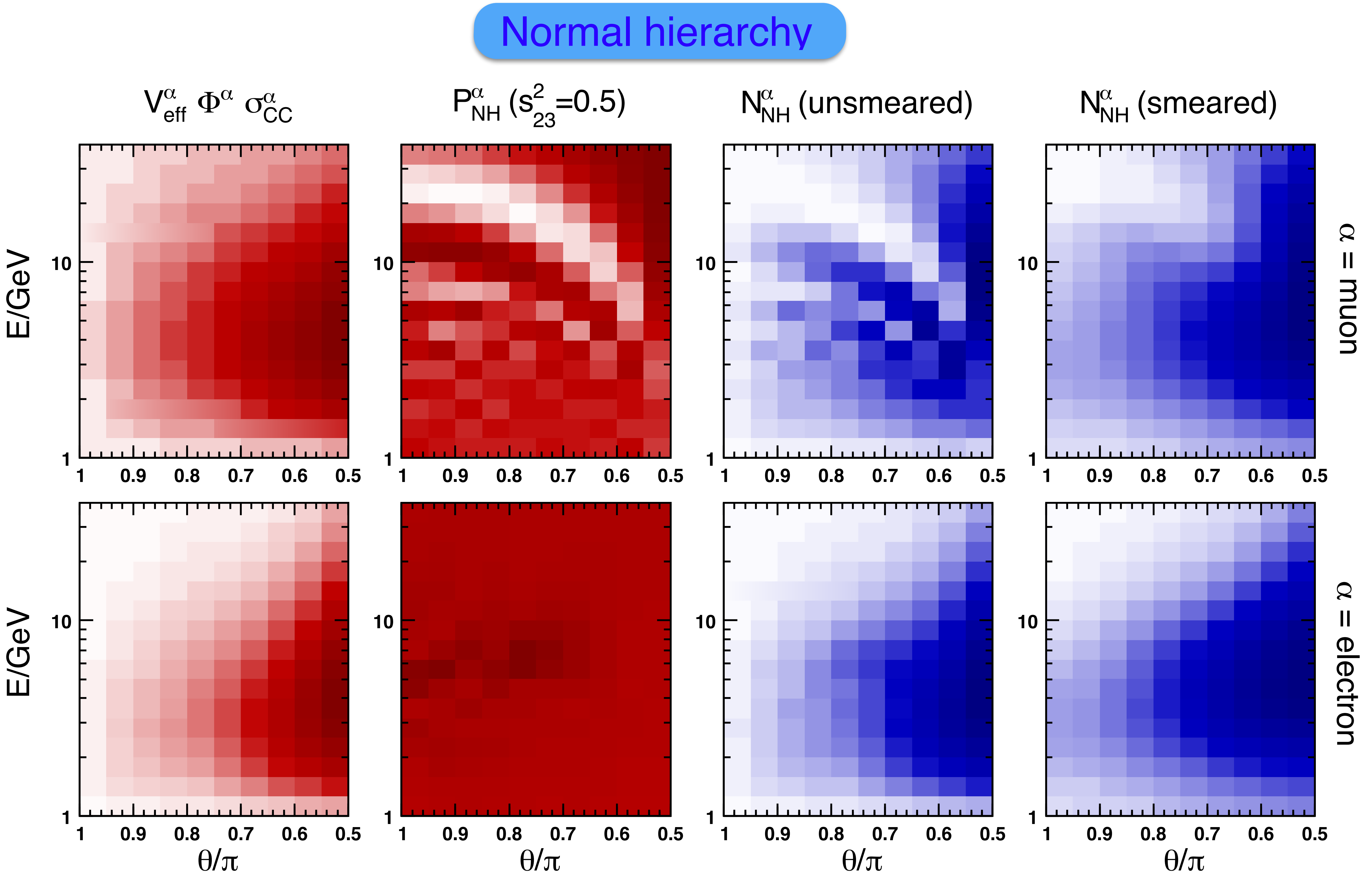
volume — **cross sec.** — **flux** — **Osc. prob.** — **Res. function (gaussian)**

CHALLENGES

- Can't distinguish ν and $\overline{\nu}$ ($\sigma_\nu \neq \sigma_{\overline{\nu}}$)
- Not perfect resolution on E, θ
- Spectral shape systematics

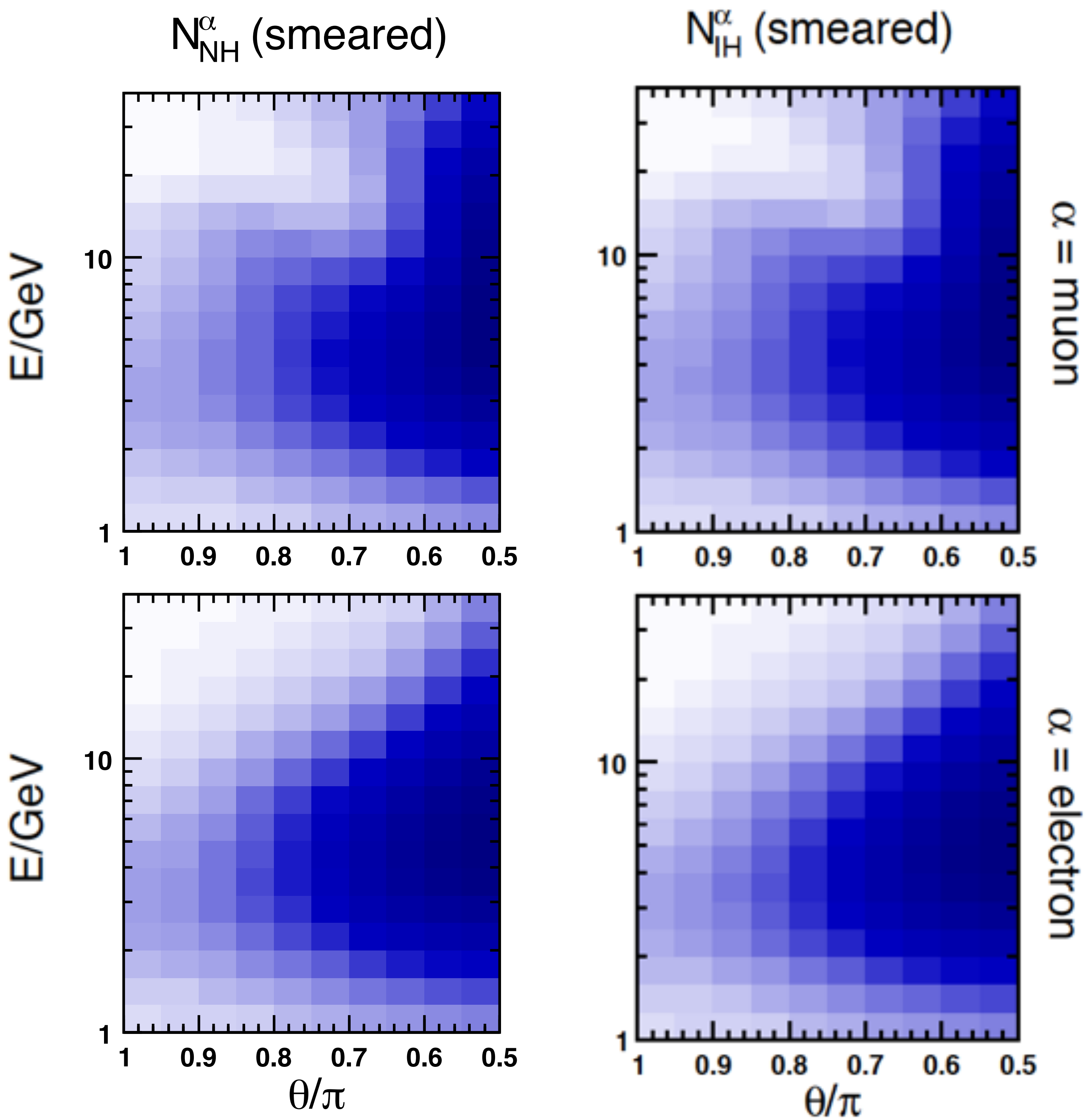
Mass hierarchy from atmospheric ν (PINGU)

(based on arXiv:1503.01999, F. Capozzi, E. Lisi, A. Marrone)



Mass hierarchy from atmospheric ν (PINGU)

(based on arXiv:1503.01999, F. Capozzi, E. Lisi, A. Marrone)



Difference connected to mass hierarchy are O(few %).
Do we know spectral shape at the percent level?

SYSTEMATICS

standard

OSCILLATIONS + NORMALIZATION

known shape errors

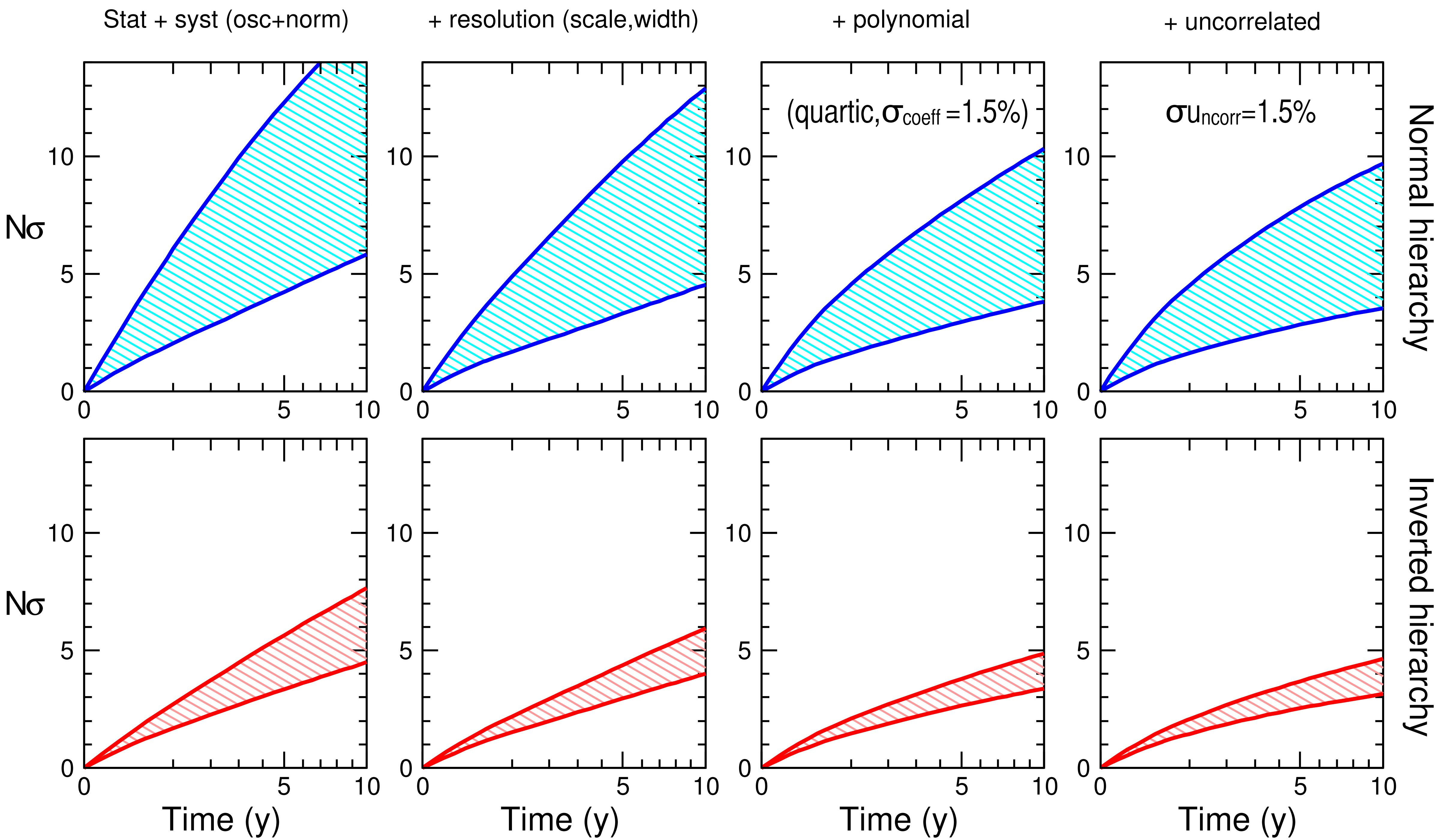
+ RESOL (WIDTH,SCALE)

In the limit of high statistics we must take into account possible residual correlated and uncorrelated uncertainties, which may not have a definite parametrization. For correlated, we use quartic polynomial in (E,θ)

Mass hierarchy from atmospheric ν (PINGU)

(based on arXiv:1503.01999, F. Capozzi, E. Lisi, A. Marrone)

Bands ⟷ $\sin^2\theta_{23} \in [0.4, 0.6]$



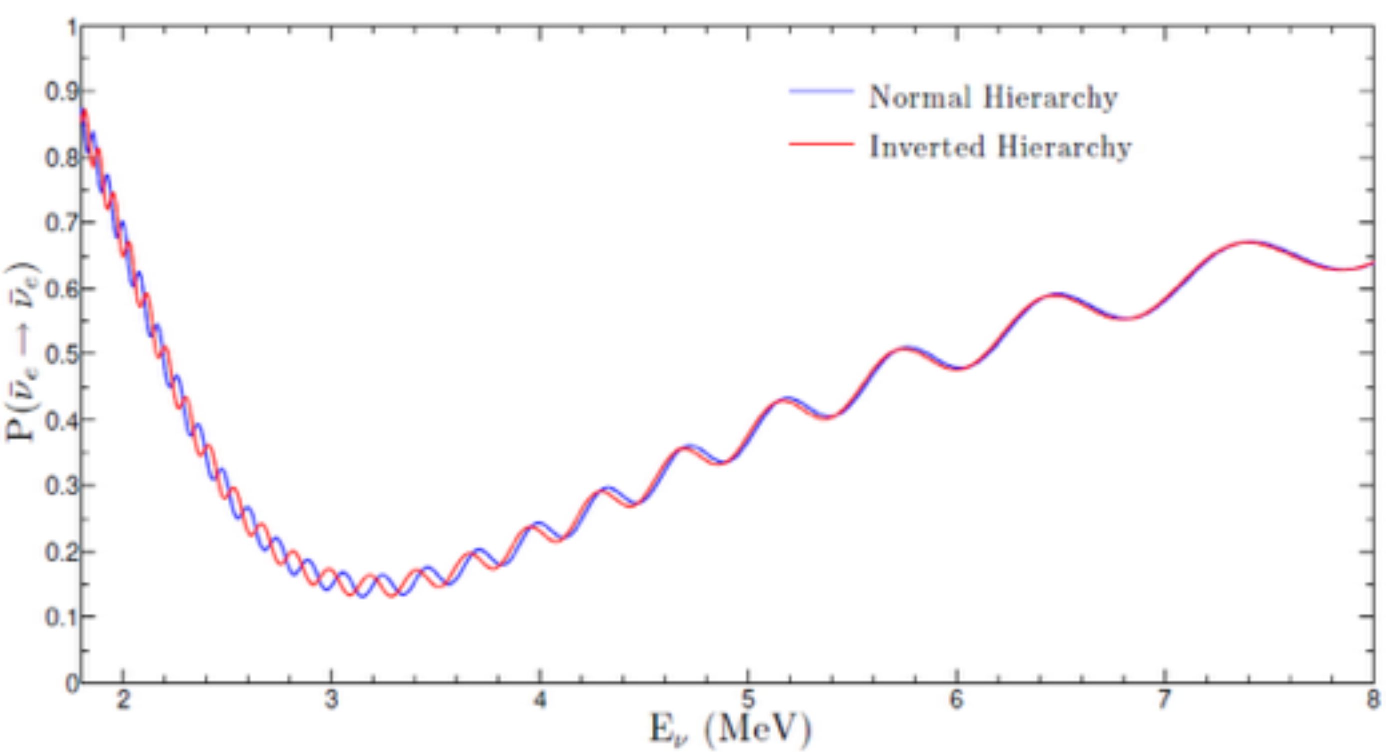
Including all systematics (right panel) there is a **reduction in hierarchy sensitivity of ~35% (~40%) after 5 (10) years** with respect to the left panel, which refers to standard systematics. Further studies are needed.

Mass hierarchy from MBL reactor ν (JUNO)

(based on arXiv:1309.1638, F. Capozzi, E. Lisi, A. Marrone)

If baseline ~50 km, we can probe neutrino mass hierarchy through the study of the channel $\overline{\nu}_e \rightarrow \overline{\nu}_e$

The experiments are sensitive to short wavelength oscillations (θ_{13}, Δm^2), to long wavelength oscillations (θ_{12}, δm^2), and to their tiny interference (mass hierarchy)



REQUIREMENTS

→ **EXPERIMENTAL:**
High statistics,
High resolution

→ **THEORETICAL:**
Very accurate
theoretical calc.

→ **PHENOMENOLOGICAL:**
Refined stat/syst analysis

Mass hierarchy from MBL reactor ν (JUNO)

(based on arXiv:1309.1638, F. Capozzi, E. Lisi, A. Marrone)

THEORETICAL CALCULATIONS

- Accurate and analytical expression for $P(\overline{\nu}_e \rightarrow \overline{\nu}_e)$ including matter effects and multiple reactors
- Inclusion of nucleon recoil in the IBD

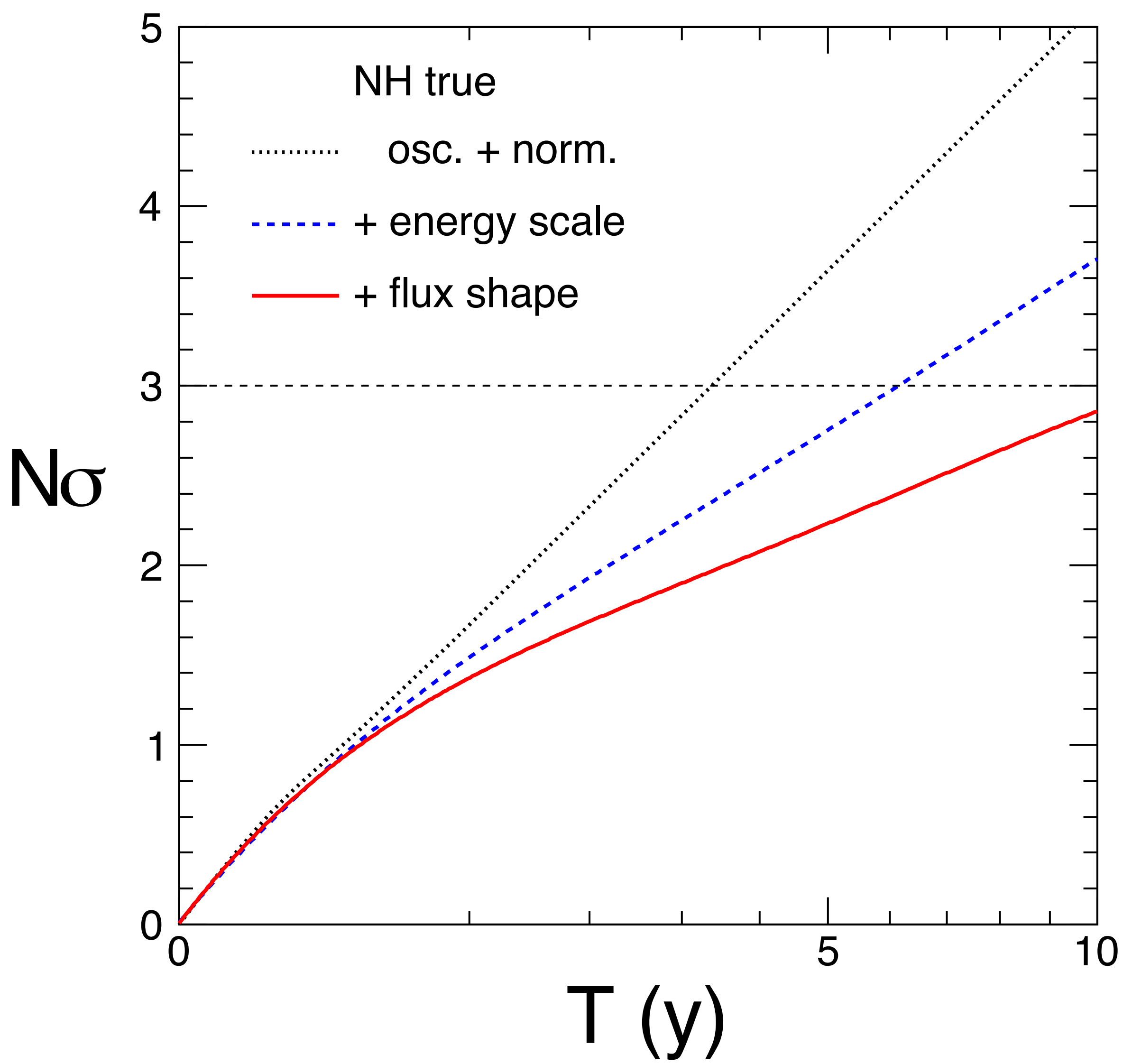
SYSTEMATICS

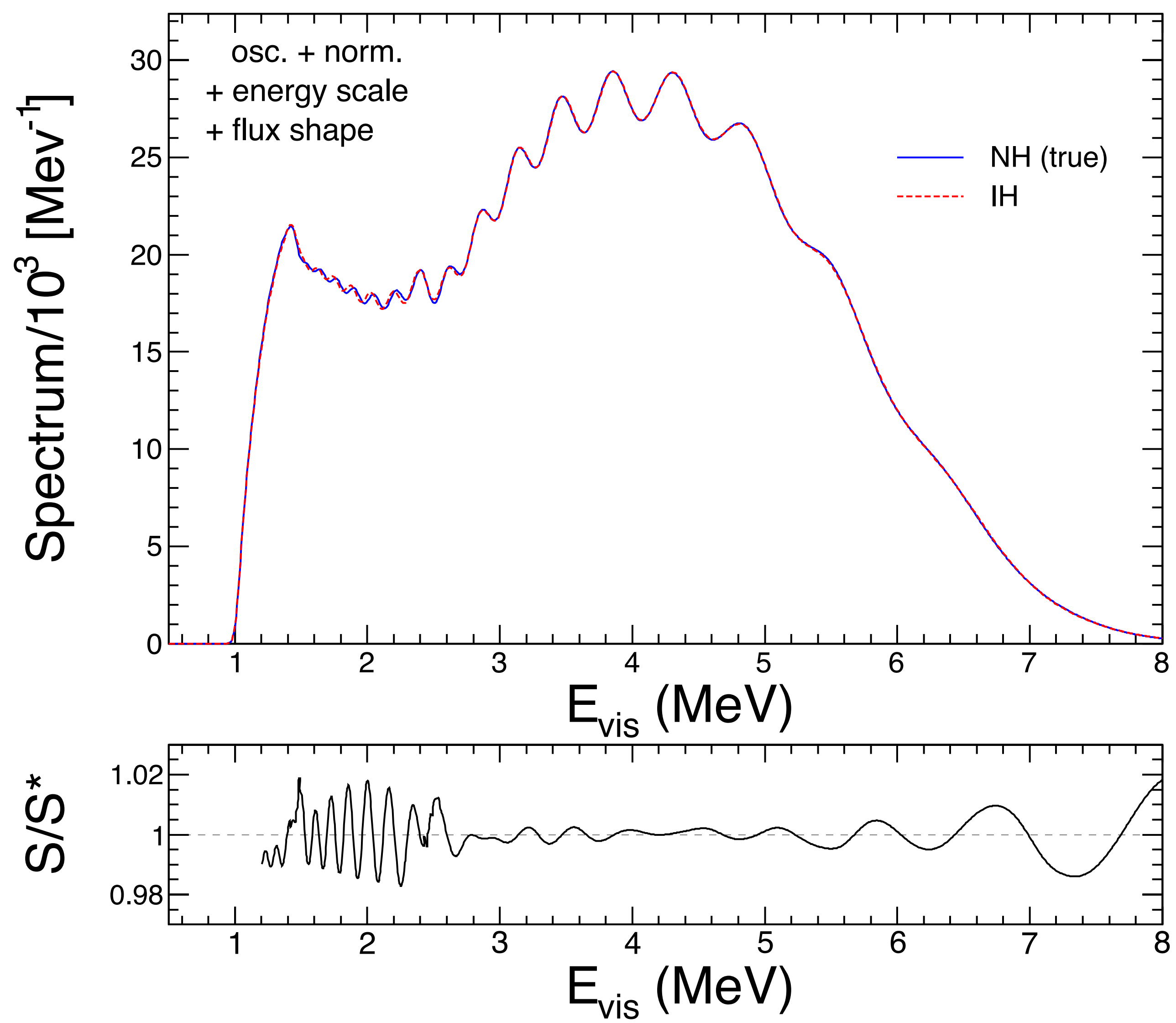
- Background of geo-ν and ν from far reactors
- Variations of $\theta_{13}, \Delta m^2_{ee}, \theta_{12}, \delta m^2$ (current bounds)
  Normalization: global (reactor), U and Th (geo-ν)
- Energy scale and flux shape (polynomial)

All parameters are floating with Markov chain Montecarlo

Mass hierarchy from MBL reactor ν (JUNO)

(based on arXiv:1309.1638, F. Capozzi, E. Lisi, A. Marrone)

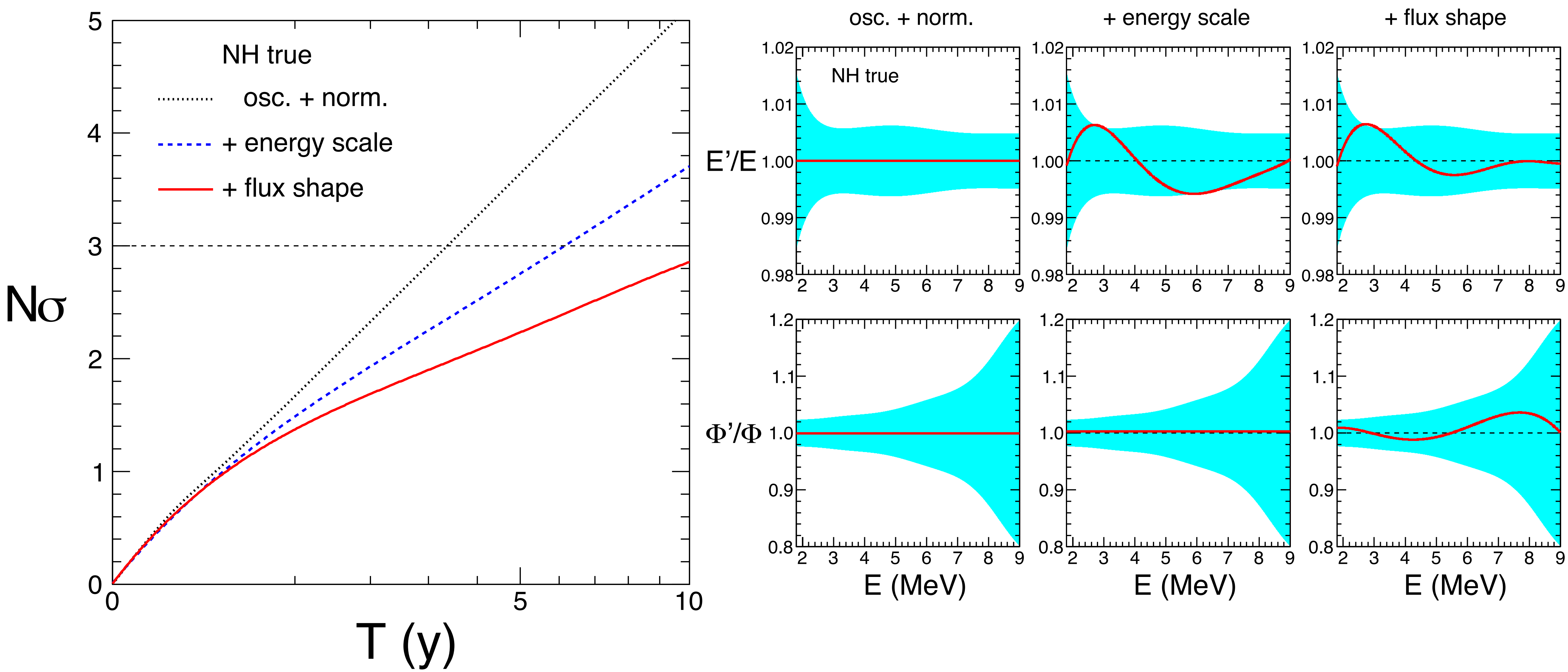




Assuming the standard systematics (osc. + norm., dotted black curve) hierarchy sensitivity can reach about 5σ in 10 years. With current spectral uncertainties (red curve) hierarchy sensitivity may not reach 3σ after 10 years.

Mass hierarchy from MBL reactor ν (JUNO)

(based on arXiv:1309.1638, F. Capozzi, E. Lisi, A. Marrone)



Assuming the standard systematics (osc. + norm., dotted black curve) hierarchy sensitivity can reach about 5σ in 10 years. With current spectral uncertainties (red curve) hierarchy sensitivity may not reach 3σ after 10 years.

DEGENERACIES IN 0νββ

(based on arXiv:1506.04058, E. Lisi, A. M. Rotunno, F. Simkovic)

$$T_i^{-1} = G_i^j |M_i^j| (\lambda^j)^2$$

G^j_i = Kinematical phase space

M^j_i = Nuclear matrix element

λ^j = LNV parameter

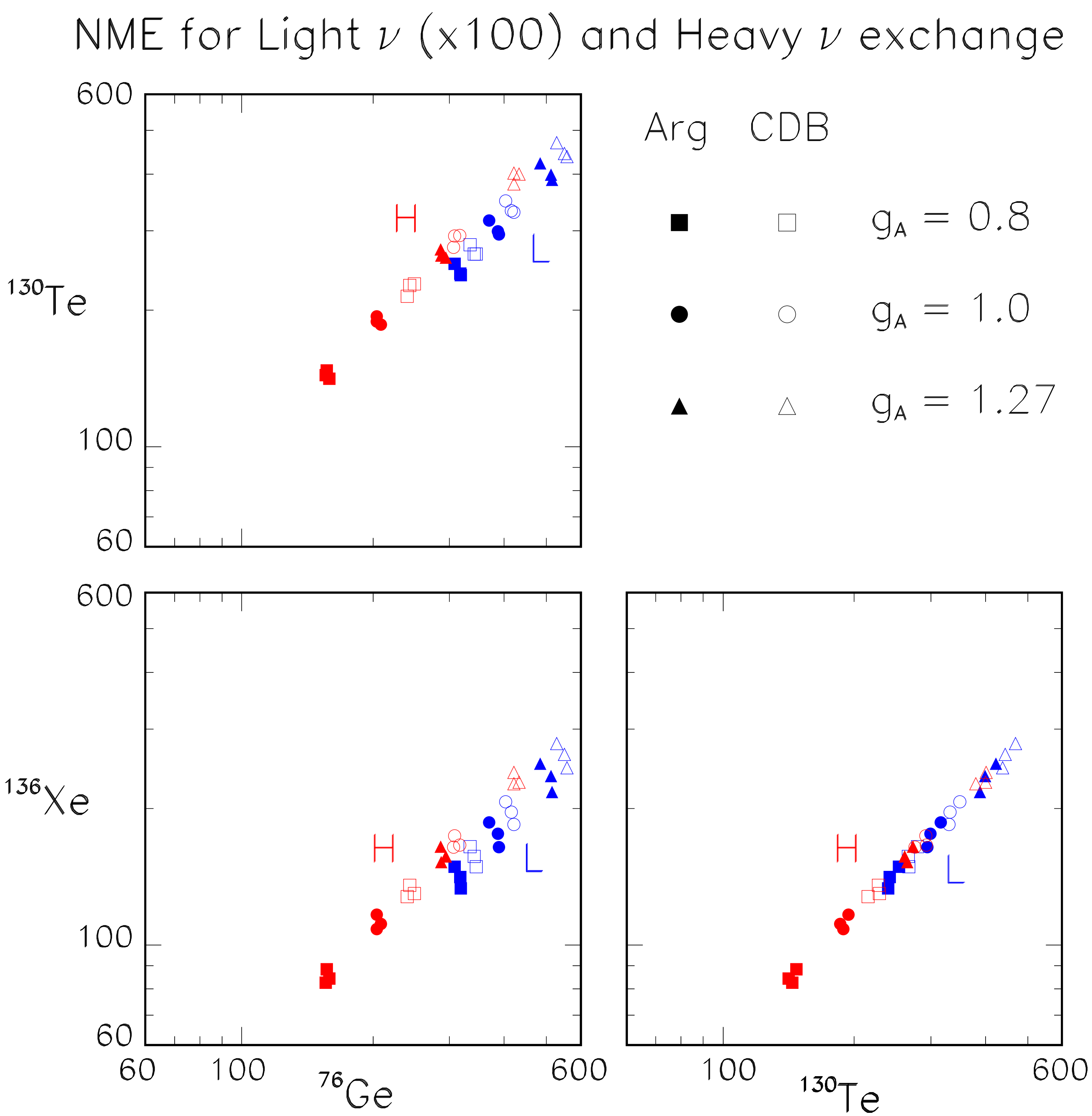
The uncertainties on M_i^j make challenging the disentanglement of the particle physics mechanisms behind $0\nu\beta\beta$, even with multi-isotope data

ANALYSIS METHOD

- Calculations in the QRPA approximation
- i = 1, 2, 3 = $^{76}Ge, ^{130}Te, ^{136}Xe$
- j = 1, 2 = light, heavy Majorana neutrino exchange
- g_A = 0.8, 1.0, 1.27 potential = CD-Bonn, Argonne

DEGENERACIES IN $0\nu\beta\beta$

(based on arXiv:1506.04058, E. Lisi, A. M. Rotunno, F. Simkovic)



- For a given decay mechanism, the nuclear model uncertainties are degenerate with the LNV parameter λ^j
- The two different mechanisms (L and H) are largely degenerate with one another

Supernova neutrinos

(based on arXiv:1503.03485, A. Mirizzi, G. Mangano, N. Saviano)

In high density SN regions, evolution becomes non linear. These locks the oscillations among modes in some energy ranges.

Collective phenomena take place.

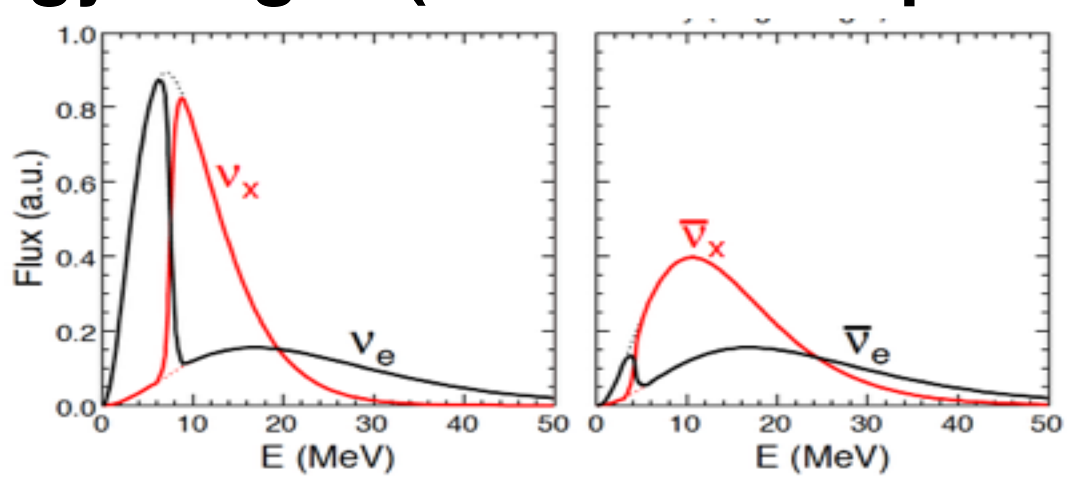
$$H = H_{\rm vac} + H_{\rm matter} + H_{\nu\nu}$$

$$H_{\nu\nu} = \sqrt{2} G_F \int \frac{d^3 q}{(2\pi)^3} (1 - \cos\theta_{pq}) \left(\rho(\vec{q}) - \bar{\rho}(\vec{q})\right)$$

1) Synchronized oscillations: **all neutrinos oscillate with the same frequency**

2) Bipolar oscillations: **Coherent $\nu_e\bar{\nu}_e \leftrightarrow \nu_x\bar{\nu}_x$ oscillations even for extremely small mixing angle (only for inverted hierarchy)**

3) Spectral splits: **ν_e and $\bar{\nu}_x$ (ν_e and $\bar{\nu}_x$) spectra interchange completely only within certain energy ranges (because of lepton number conservation)**

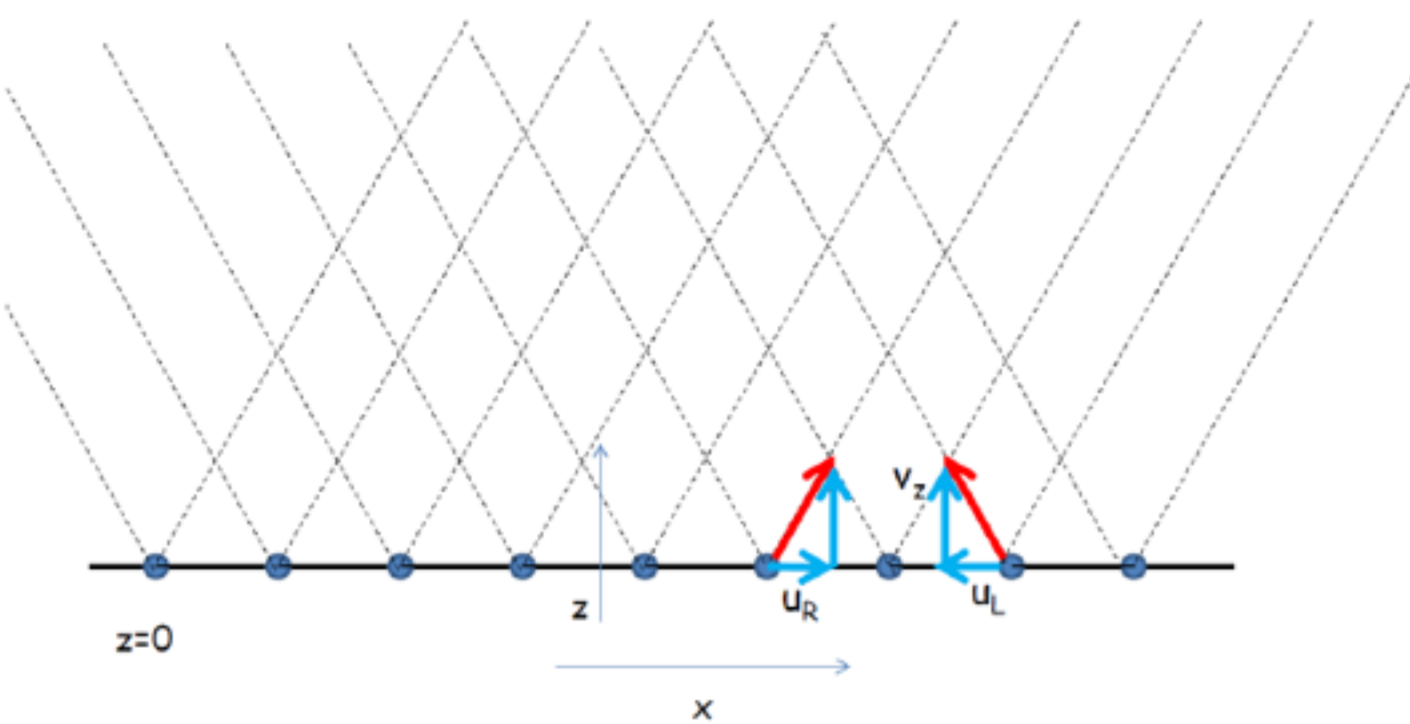


Supernova neutrinos

(based on arXiv:1503.03485, A. Mirizzi, G. Mangano, N. Saviano)

These phenomena are obtained assuming the bulb model (spherical, azimuthal and translational symmetry). Relaxing these hypotheses, instabilities may grow…

TOY MODEL



ν emitted by an infinite boundary at z=0, in only two directions (L,R). Assumed an excess of ν_e over $\overline{\nu}_e$ and normal hierarchy

$$P^3_{L,R}(x,0) = \langle P^3_{L,R}(x,0)\rangle + \epsilon \cos(k_0 x)$$

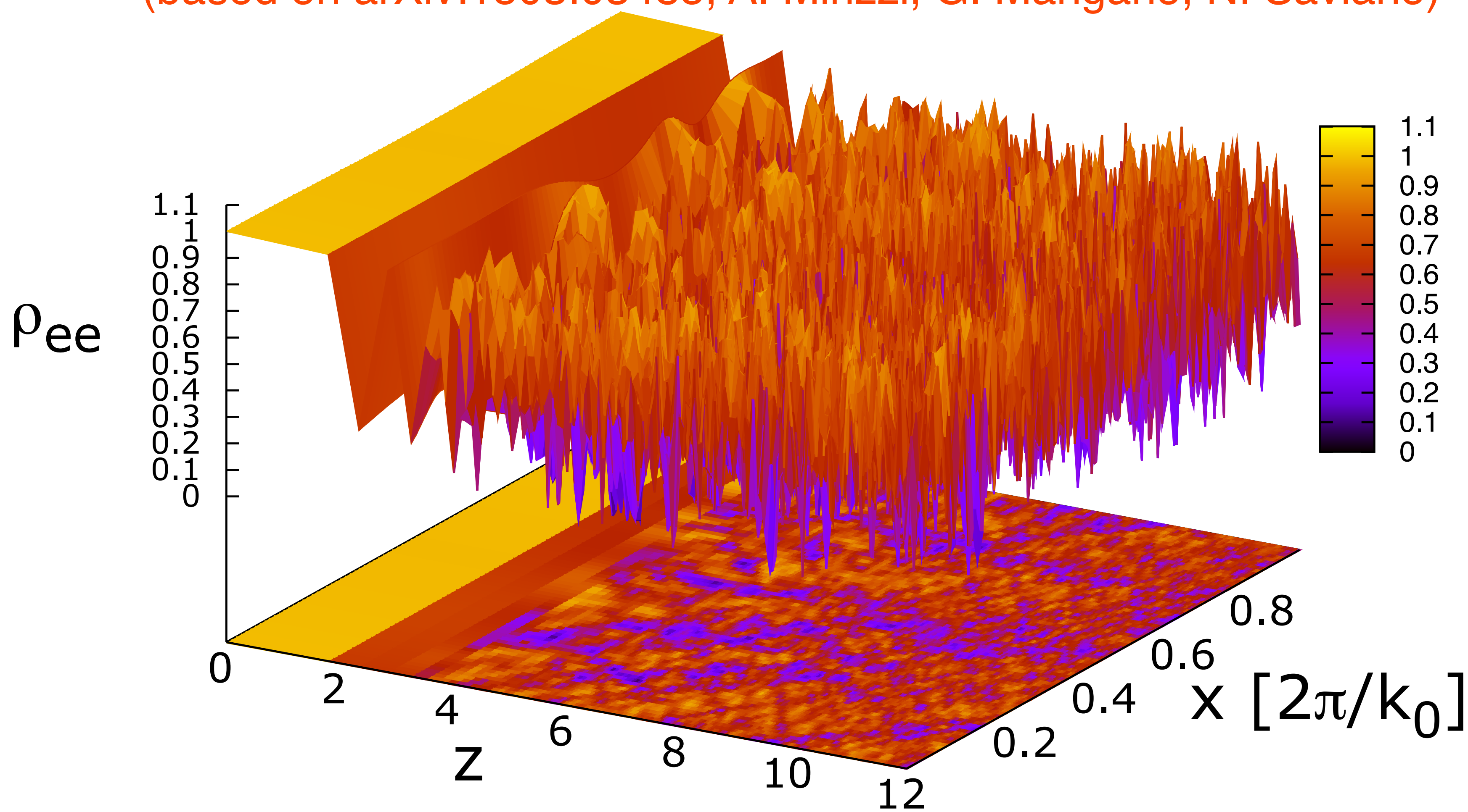
(Translational symmetry broken)

1% difference in the initial conditions of L and R modes

(L⟷R symmetry broken)

Supernova neutrinos

(based on arXiv:1503.03485, A. Mirizzi, G. Mangano, N. Saviano)



Till z=2.5 all the neutrinos oscillate in phase and the surfaces of equal phase are planes parallel to the radiating surface at z = 0. Then…

Large variations along the x direction at increasingly smaller scales

Coherent behavior of oscillations lost

$P^3_L(x,z) \neq P^3_R(x,z)$ (not shown)

Work in progress

- **(In)Stability and symmetry (breaking) of SN ν**

(F. Capozzi, A. Mirizzi *et al.*)

- **Refined Earth model for geo-ν analysis**

(E. Lisi in collaboration with PRIN-Ferrara)

- **Quenching of g_A in 0νββ and related weak processes**

(E. Lisi, A. Marrone, in collaboration with F. Simkovic *et al.*)

- **Updated global 3ν analysis of oscillation data after Summer 2015 Conferences**

(F. Capozzi, E. Lisi, A. Marrone, D. Montanino, A. Palazzo)

- **My PhD thesis**