Dedicated to the memory of Giorgio Giacomelli

History of neutrinos by Pontecorvo

(Sov. Phys. Usp. 26, 1983, 1087)

- Tab.I, from radioactivity to nu-discovery
- Tab.II, from muon-properties to **V-A**
- Tab.III, from HE-nu and flavor to **SM**
- Tab.IV, nu-astrophysics, astronomy, cosmology

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Neutrinoless double beta decay

- Tab.I, from radioactivity to nu-discovery
- Tab.II, from muon-properties to **V-A** → Oscillations
- Tab.III, from HE-nu and flavor to **SM** → Nucleon decay?
- Tab.IV, nu-astrophysics, astronomy, cosmology → Solar, SN, cosmic neutrinos

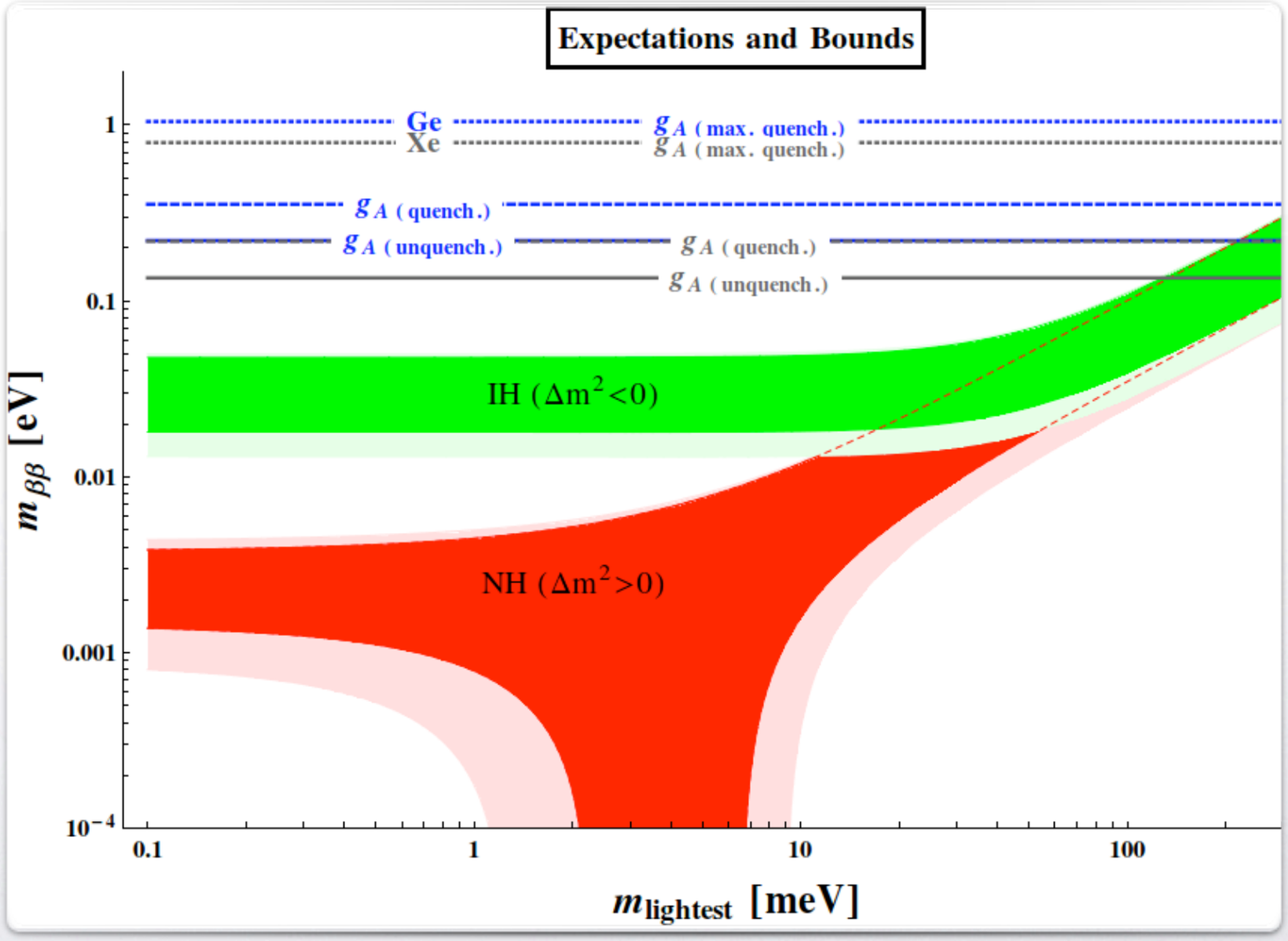
NEUTRINOLESS DOUBLE BETA DECAY AND NEUTRINO MASSES

- Neat expectations from oscillations for Majorana neutrinos
  (FV 99, updated by Marcocci & Dell'Oro, GSSI).

- Iachello calculations add confidence in our understanding of the matrix elements (IBM2~QRPA)

- Tellurium soon will contribute; many new ideas and setups.

- But ... how it was possible to overlook the renormalization of the axial coupling for so long?



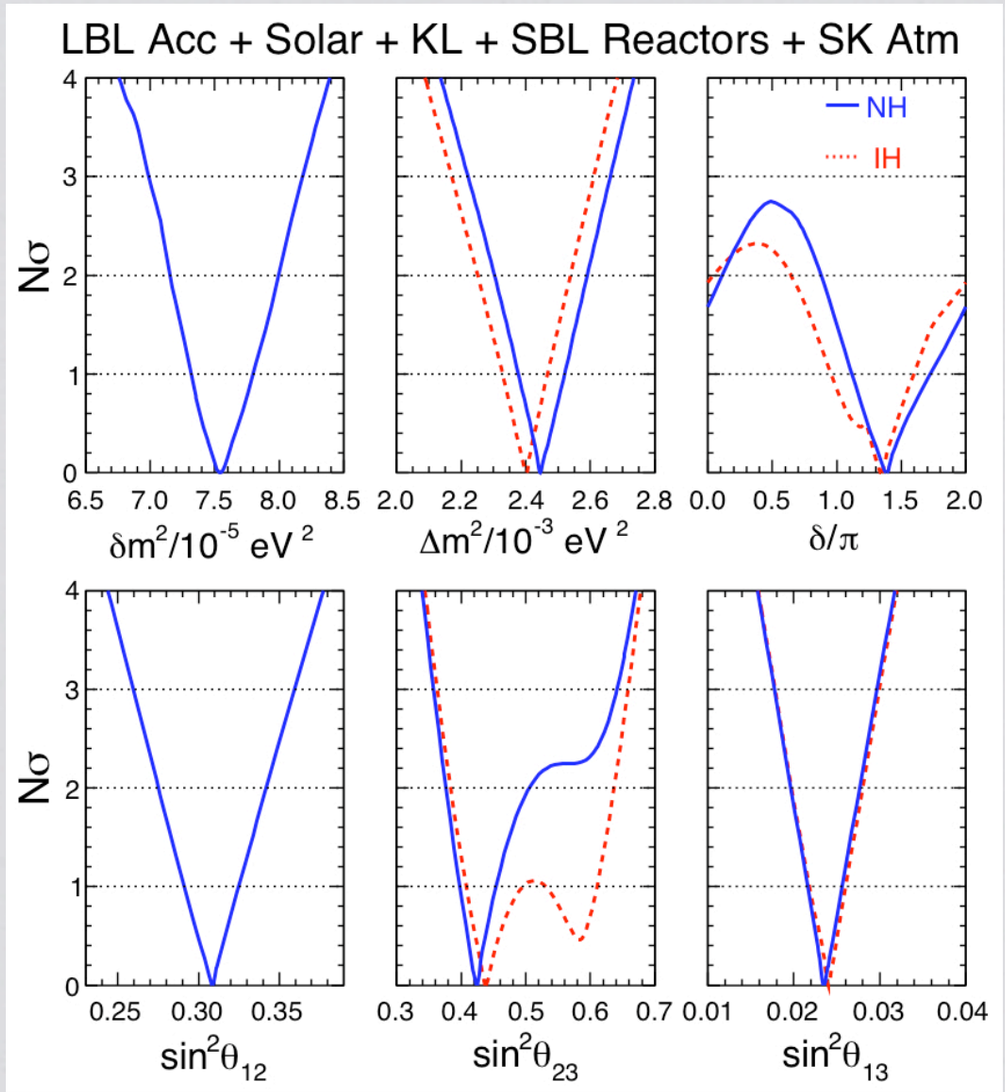
Oscillations: Role of global fits

* Based on sound hypothesis: 3 neutrinos exist for sure.

* These fits have been very useful in the past, e.g., theta13 hint.

* They will probably remain useful, e.g., CP-phase agrees with T2K.

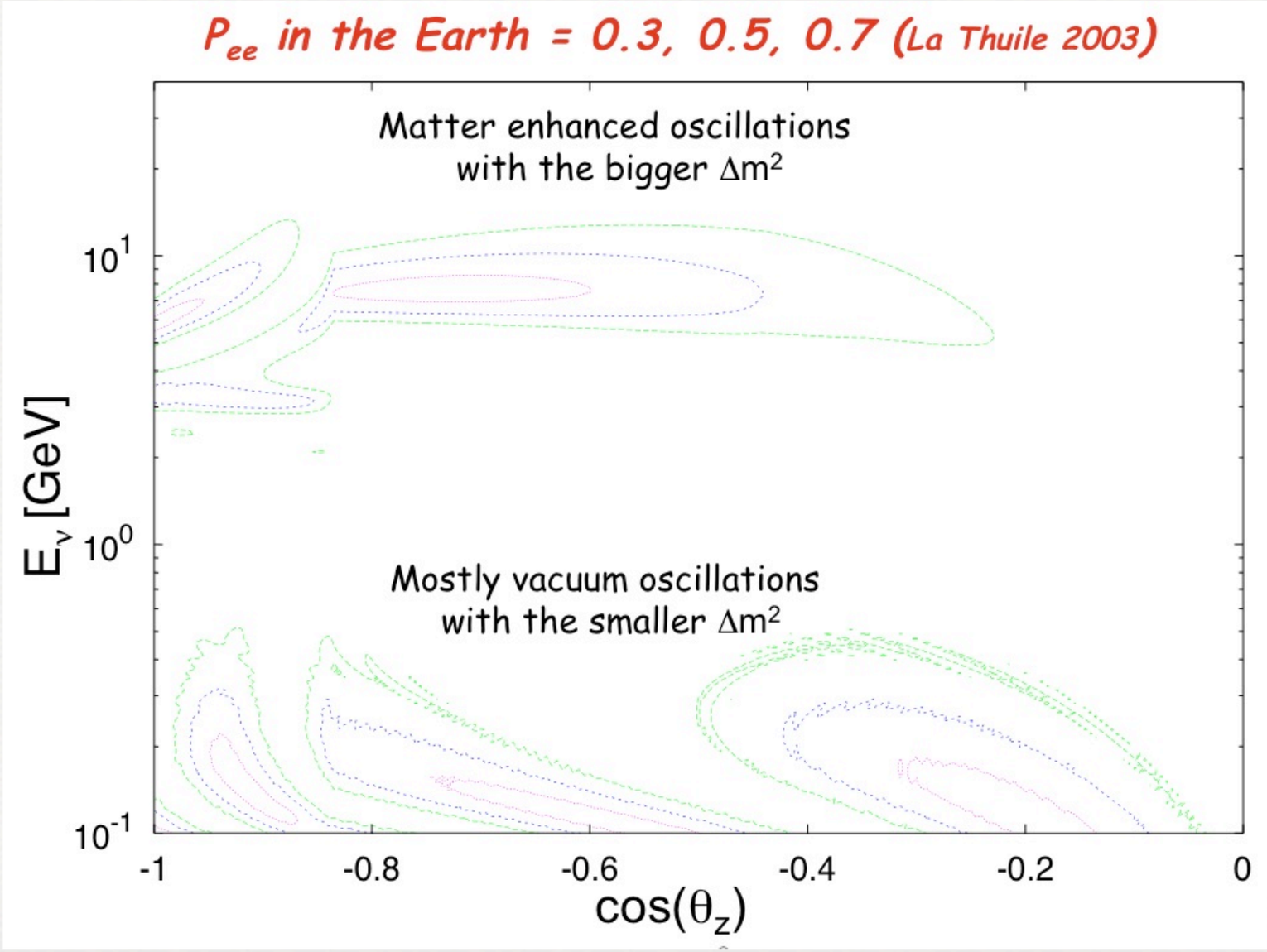
* Also useful for interpretations including other neutrinos.



Capozzi et al., 1312.2878

-N.D.E.

- Initially -N.D.E.=nucleon decay experiment.
- A lot of valuable experimental work. Predictions are vague. Supersymmetry is unseen.
- Excellent results with atmospheric neutrinos. Today -N.D.E. =neutrino detection experiment.



- HyperKamiokande will study CP by long-baseline oscillations, continuing both scientific lines and doing much more: e.g., supernova neutrinos.
- PINGU/ORCA can be thought as an extension, to contribute to unveil hierarchy via atmospheric neutrinos of many GeV.
  Akhmedov et al, JHEP 2013

(again in Pontecorvo's review, sect.11)

The expenditure of resources has been justified, but one should neither underestimate the importance of high-energy neutrino physics, nor overestimate it. This is not pessimism, but an appeal to avoid routine.

Maximum matter effect

With optimal distance, difference between normal and inverted hierarchy is 30%.

A muon neutrino beam of 6-8 GeV and with 10^{20} p.o.t. yields 1000 muons in a 1 Mton detector at 6-8 Mm (~30º).

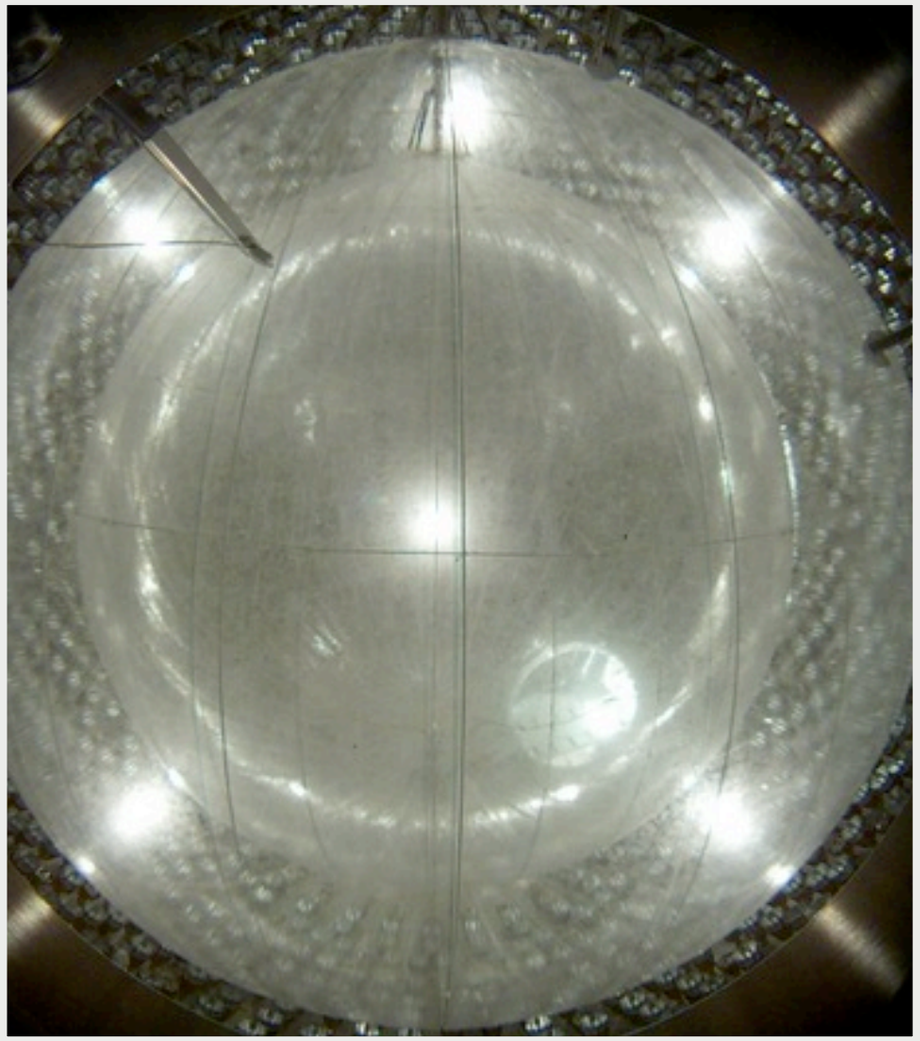
Lujan-Peschard et al., EPJC 2013

WHY SCINTILLATORS

- Geoneutrinos (Kamland, Borexino)
- Be, pep; future pp, CNO (Borexino)
- Reactor neutrinos and mass hierarchy (JUNO)
  Petcov et al, PLB 2002.
- NC events from supernovae with

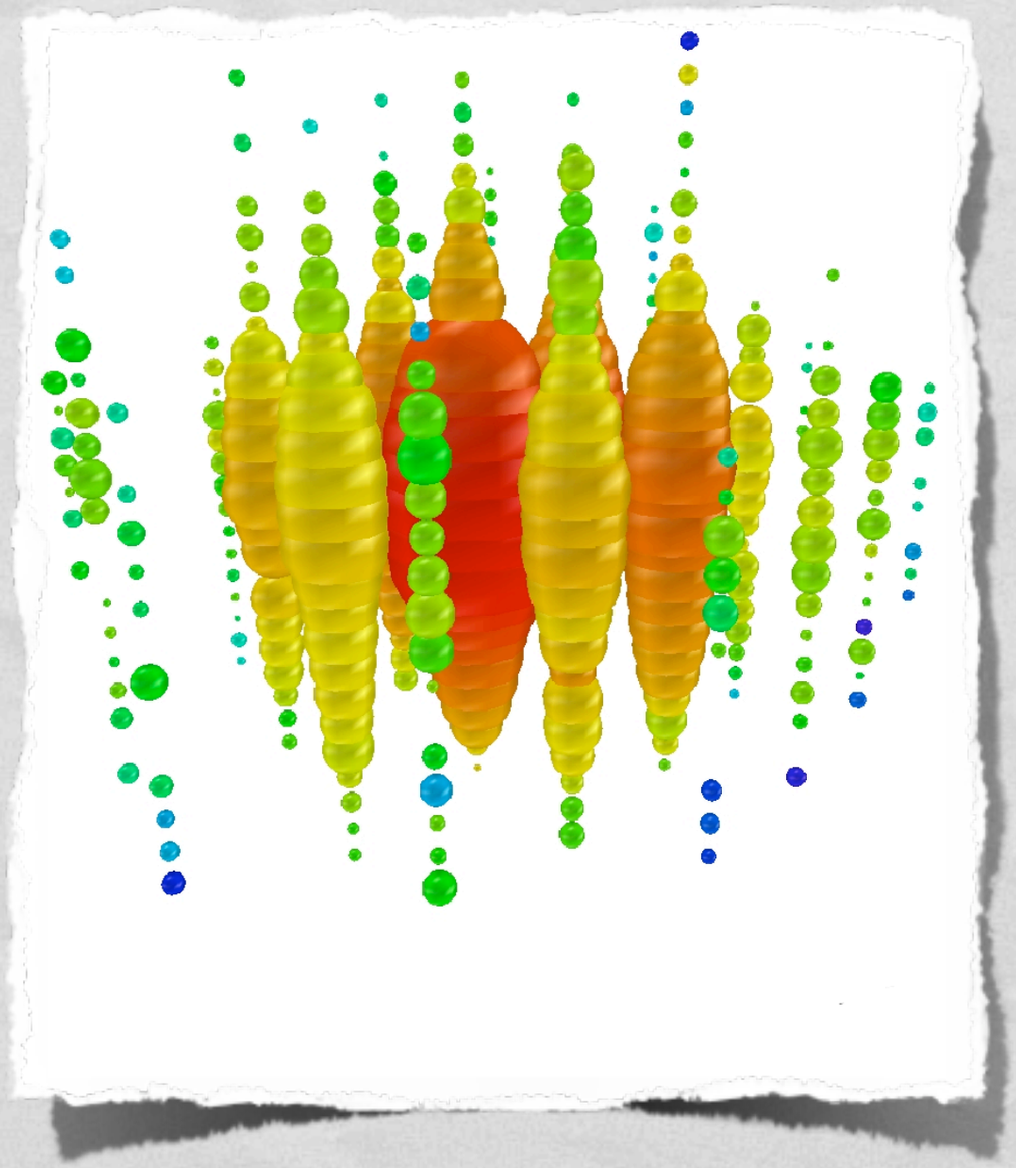
  $\nu + C \rightarrow \nu + C^{*}(15.1\ \mathrm{MeV})$

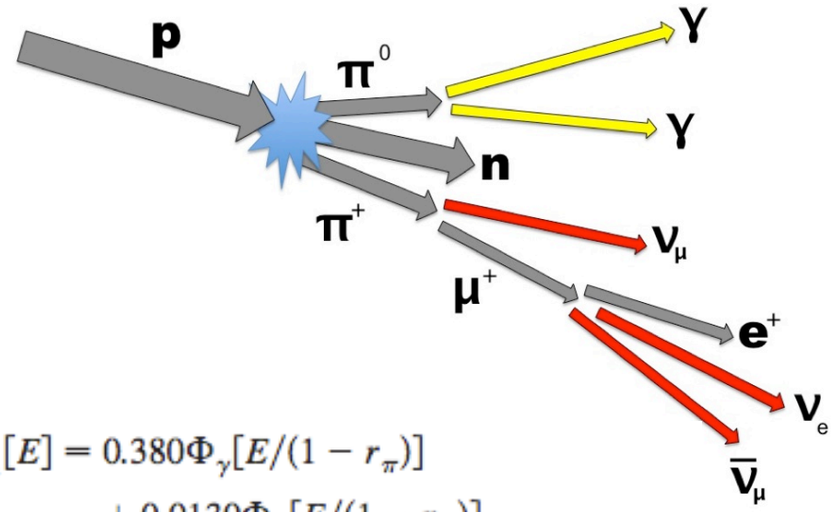
  (present generation tags IBD but presumably small)
- But only 0.01-0.04 relic neutrinos per kton x year.
  FV et al, A&A 2011



ULTIMATE ENERGY FRONTIER

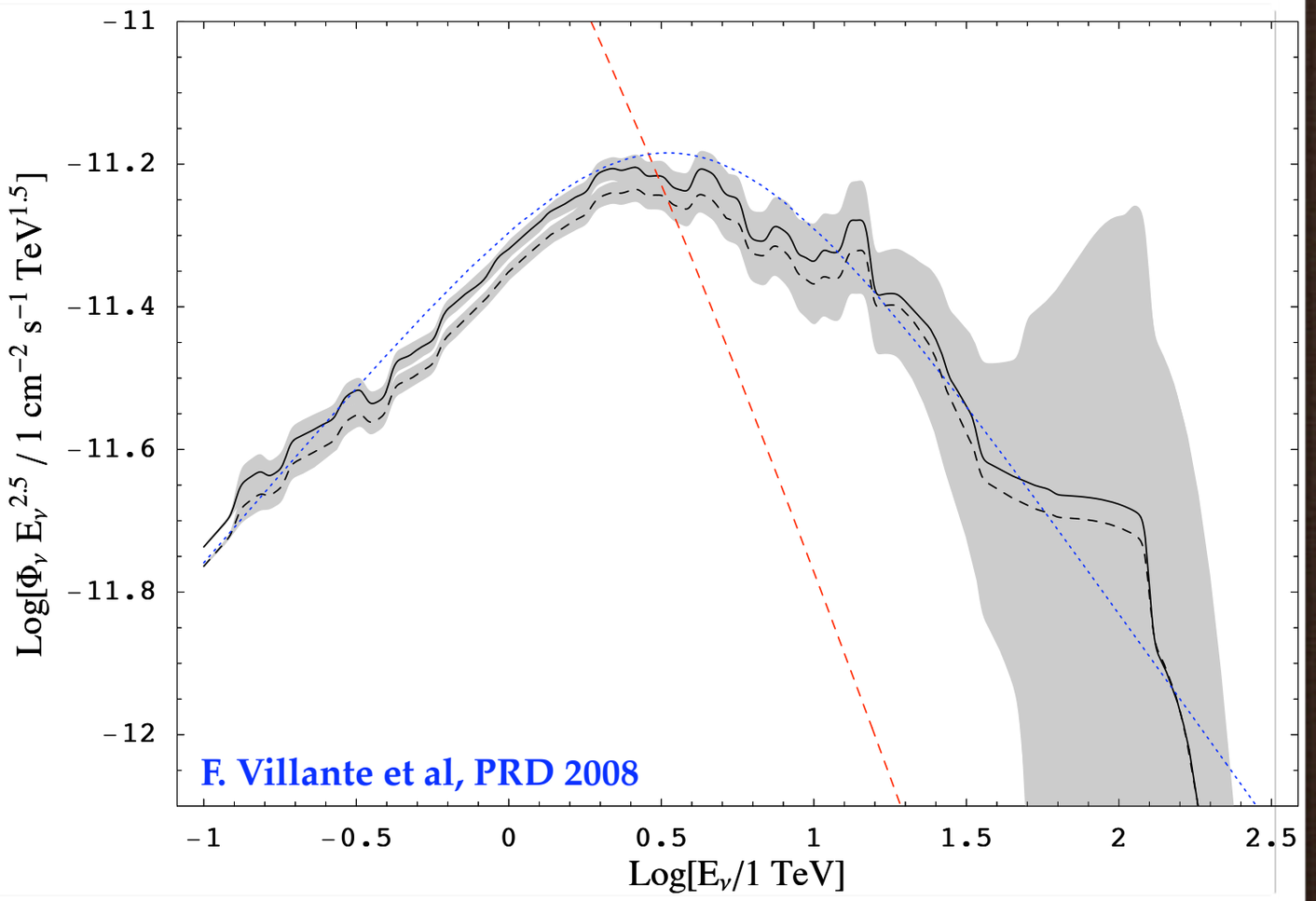
- Neutrinos till few PeV (!) seen at IceCUBE.
- Almost uniform distribution.
- A lot to learn from flavor.
  E.g., FV et al, JCAP 2013
- HUGE (vetoed) detectors could be the way to proceed.
- Synergy with gamma ray of 10-100 TeV region.





$$\Phi_{\nu_\mu}[E] = 0.380\Phi_\gamma[E/(1-r_\pi)] + 0.0130\Phi_\gamma[E/(1-r_K)] + \int_0^1 \frac{dx}{x} k_{\nu_\mu}[x]\Phi_\gamma[E/x], \quad (30)$$

$$k_{\nu_\mu}[x] = x^2(15.34 - 28.93x) = 0.0165 + 0.1193x + 3.747x^2 - \ldots = (1-x)^2(-0.6698 + 6.588x), \ldots$$



Gammas and Neutrinos

E.g., the gamma of H.E.S.S., if assumed to derive from CR collisions, allow us to know the neutrino flux from RX J1713.3946.

other neutrinos

- Probing oscillations into sterile neutrinos with cosmology, astrophysics and experiments

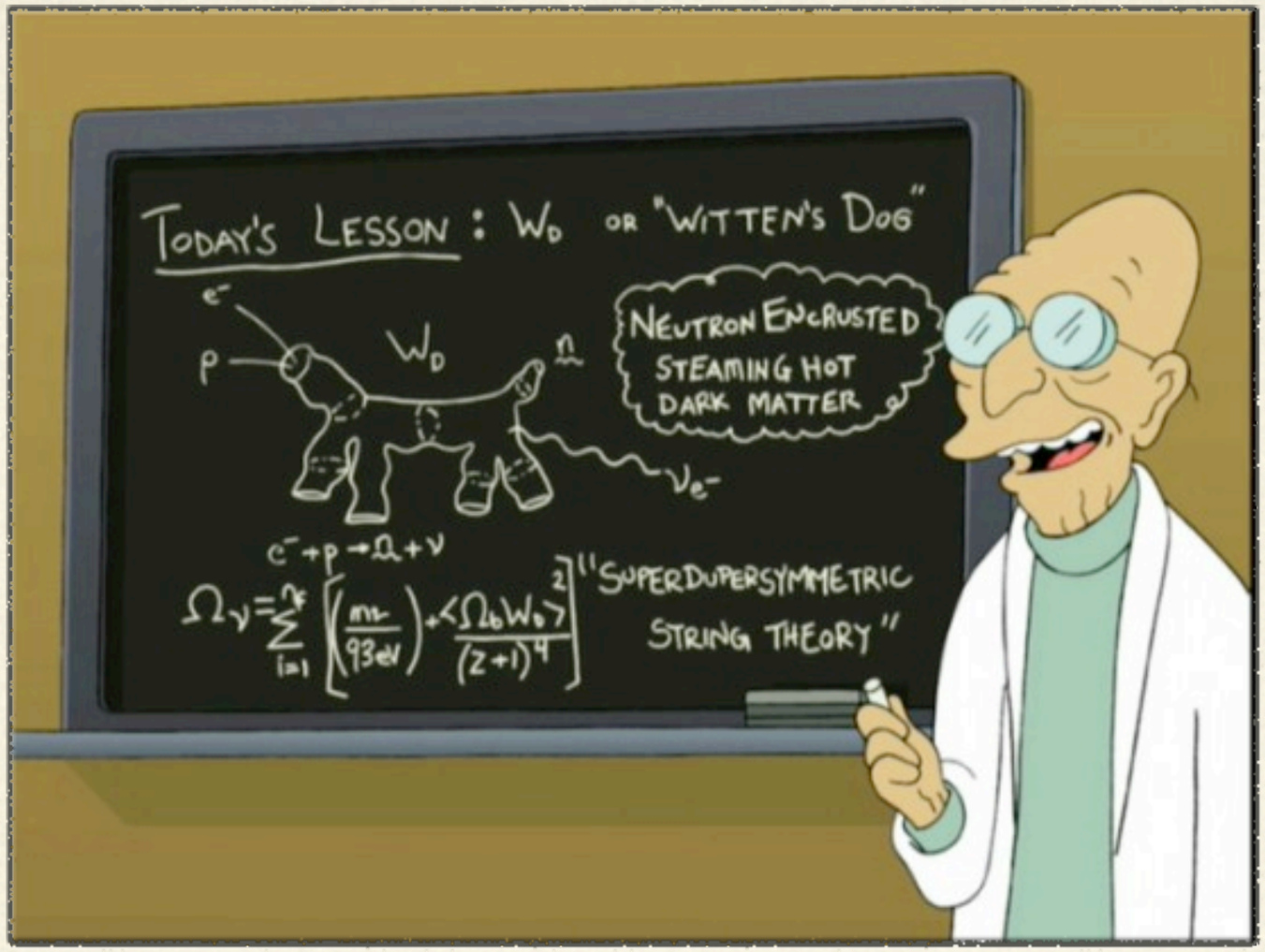
  10 year ago, 4 authors, 49 pages, 11 citations/year.

- Light Sterile Neutrinos: A White Paper

  2 years ago, 187 authors, 269 pages, 96 citations/year.

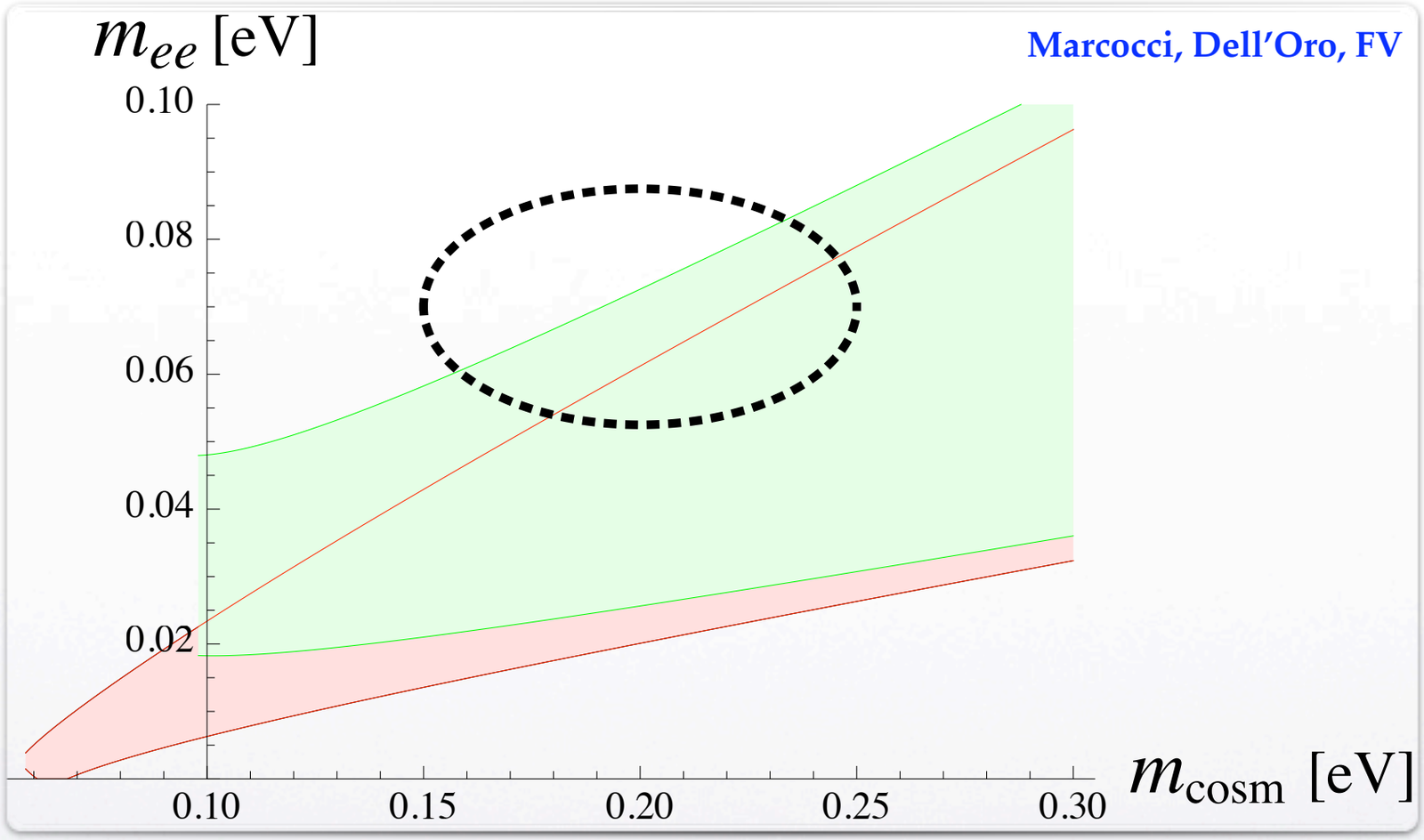
The former discussed observables, LSND, inconsistencies. The latter emphasized anomalies from reactor, Gallium, cosmology and **"provides motivations for a new round of measurements"**.

The anomalies are few σ only. A coherent picture does not seem to emerge yet. Things are still in a phase of evolution - Planck, H_0, Daya Bay... When things are confuse, better to formulate clear questions.



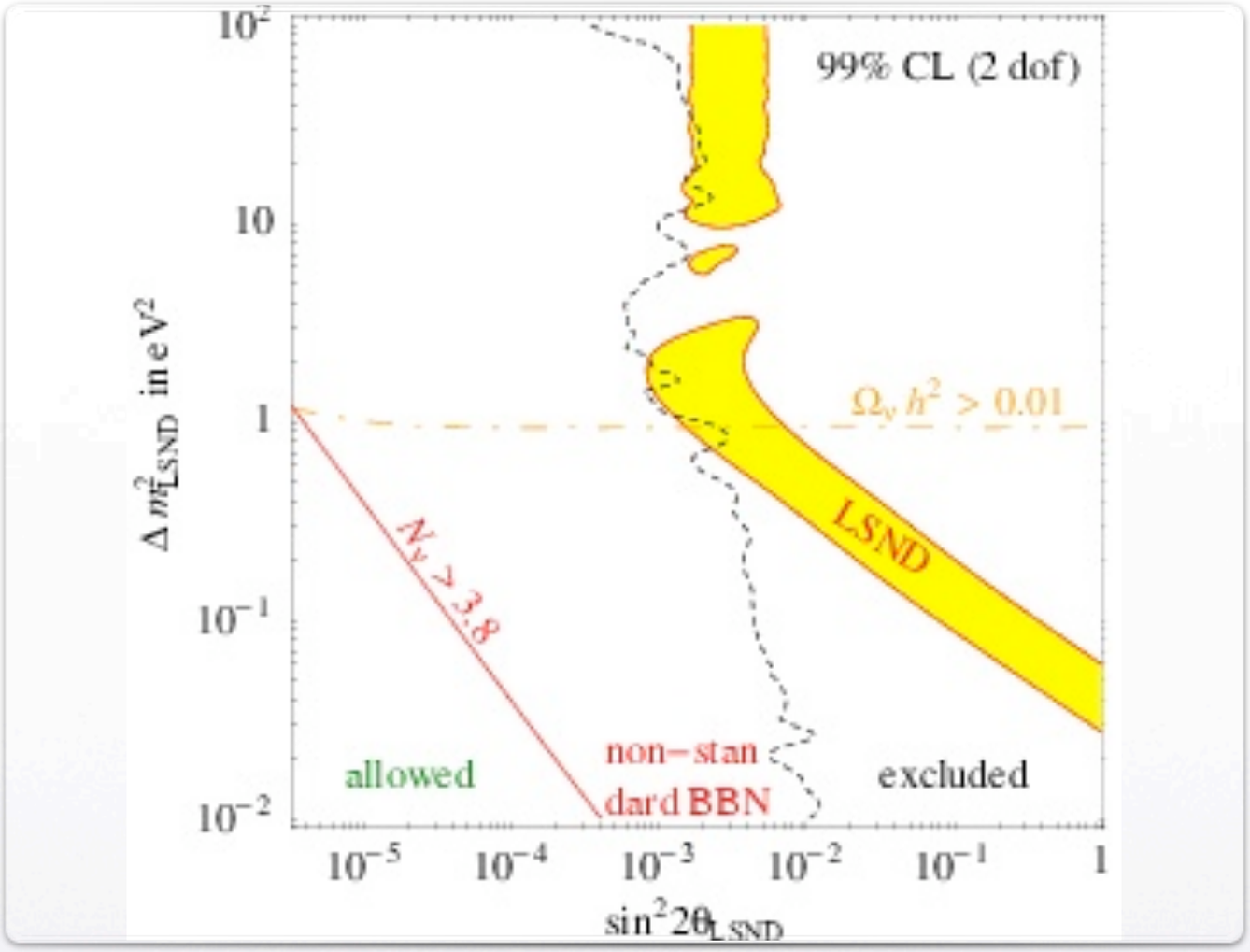
How theorists can/should help future neutrino experiments? Are we on the right track? And more specifically, are we sure that the mix of nuclear, particle and astro physics, that has lead to so many progresses in this field, is still firmly in our hands?

BACKUP SLIDES



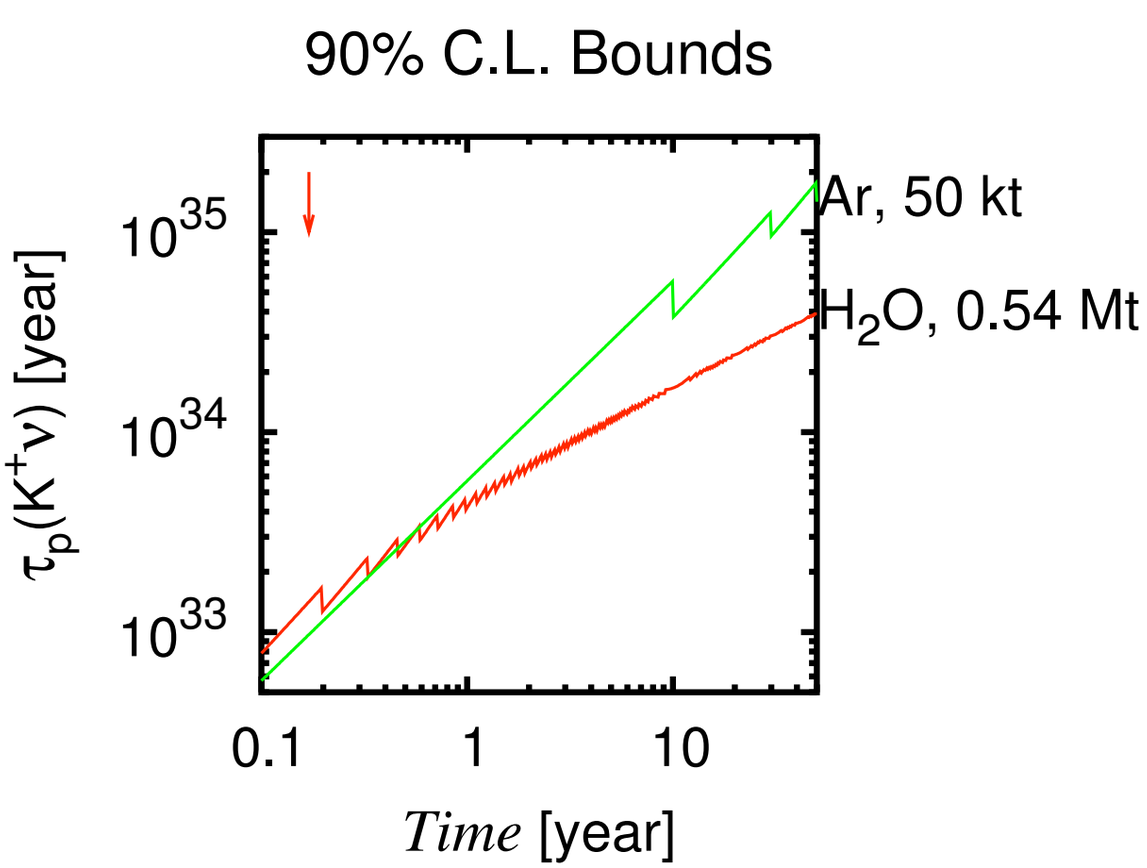
a neutrinoless night dream

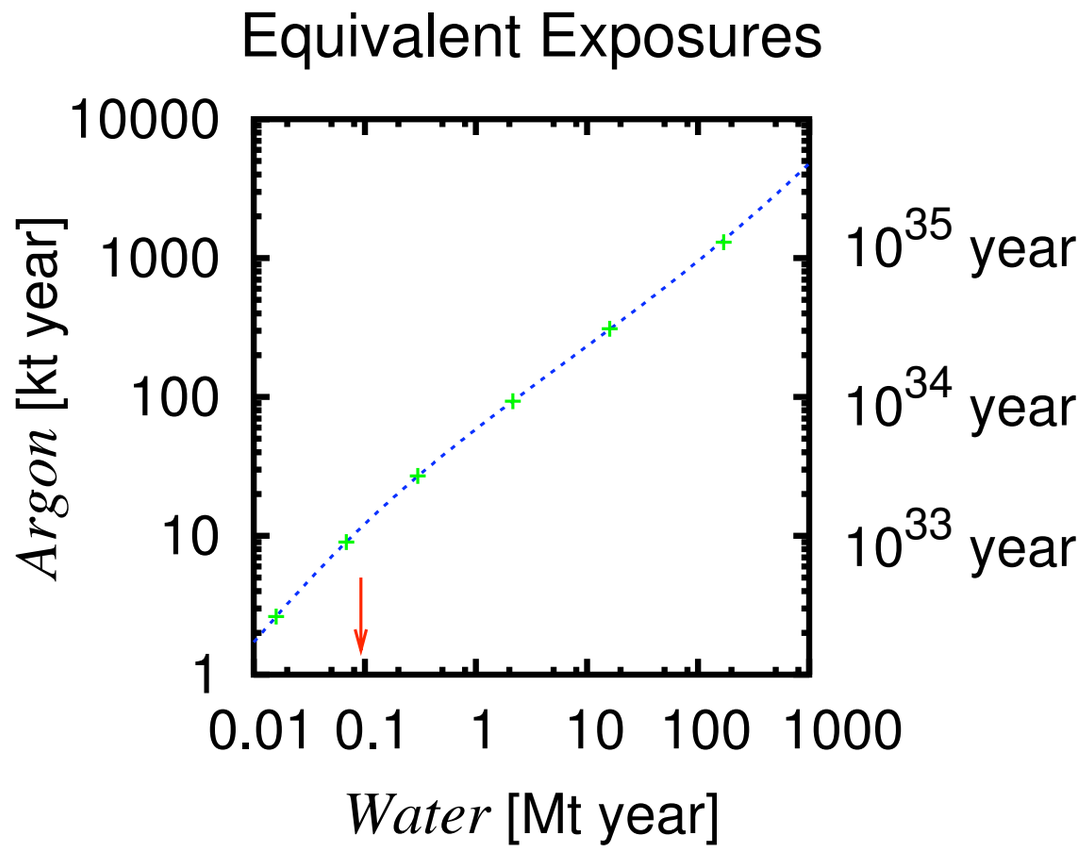
Cirelli et al, 2004



tension of 3+1 neutrino interpretation

on proton decay in susy



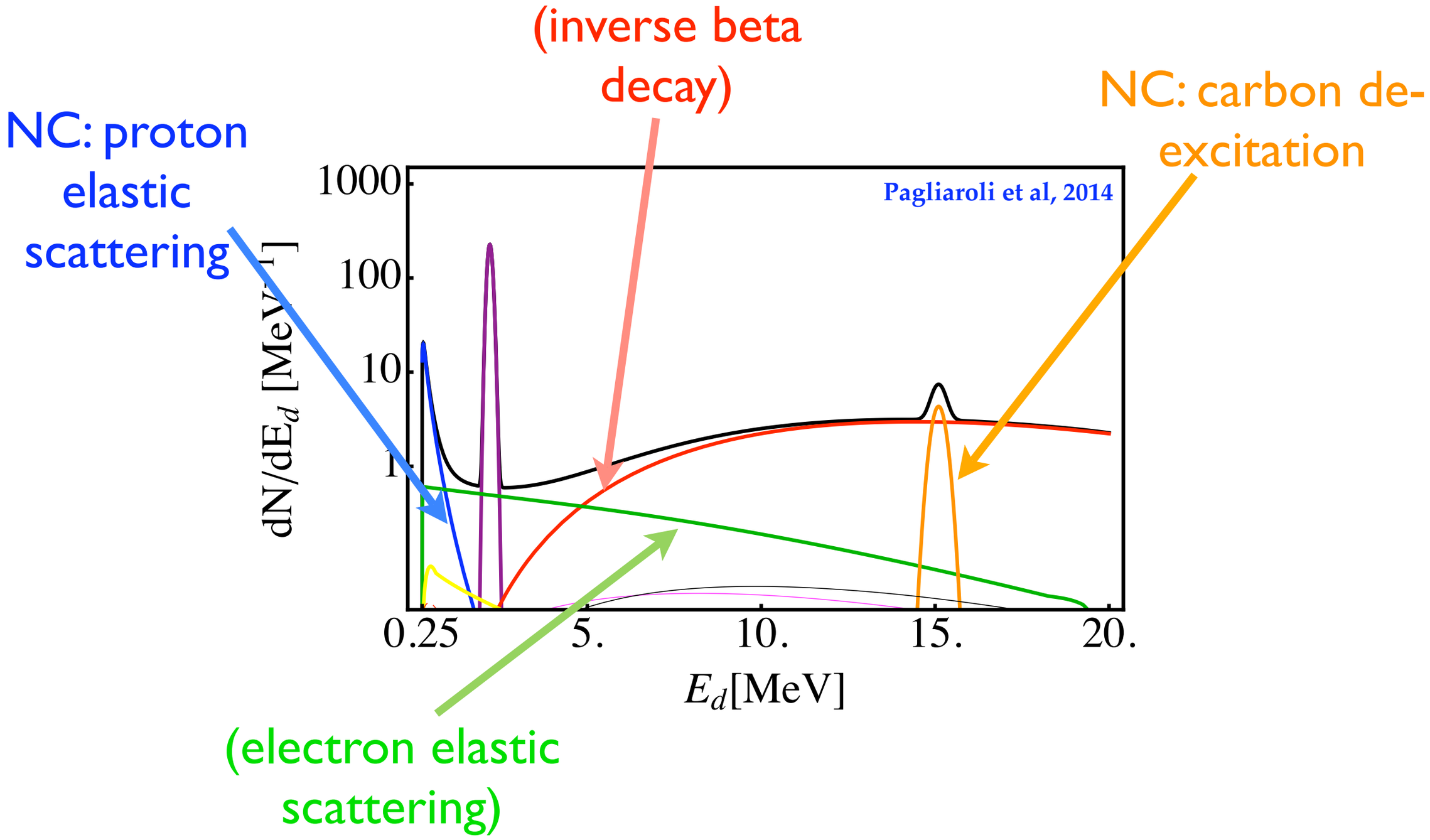


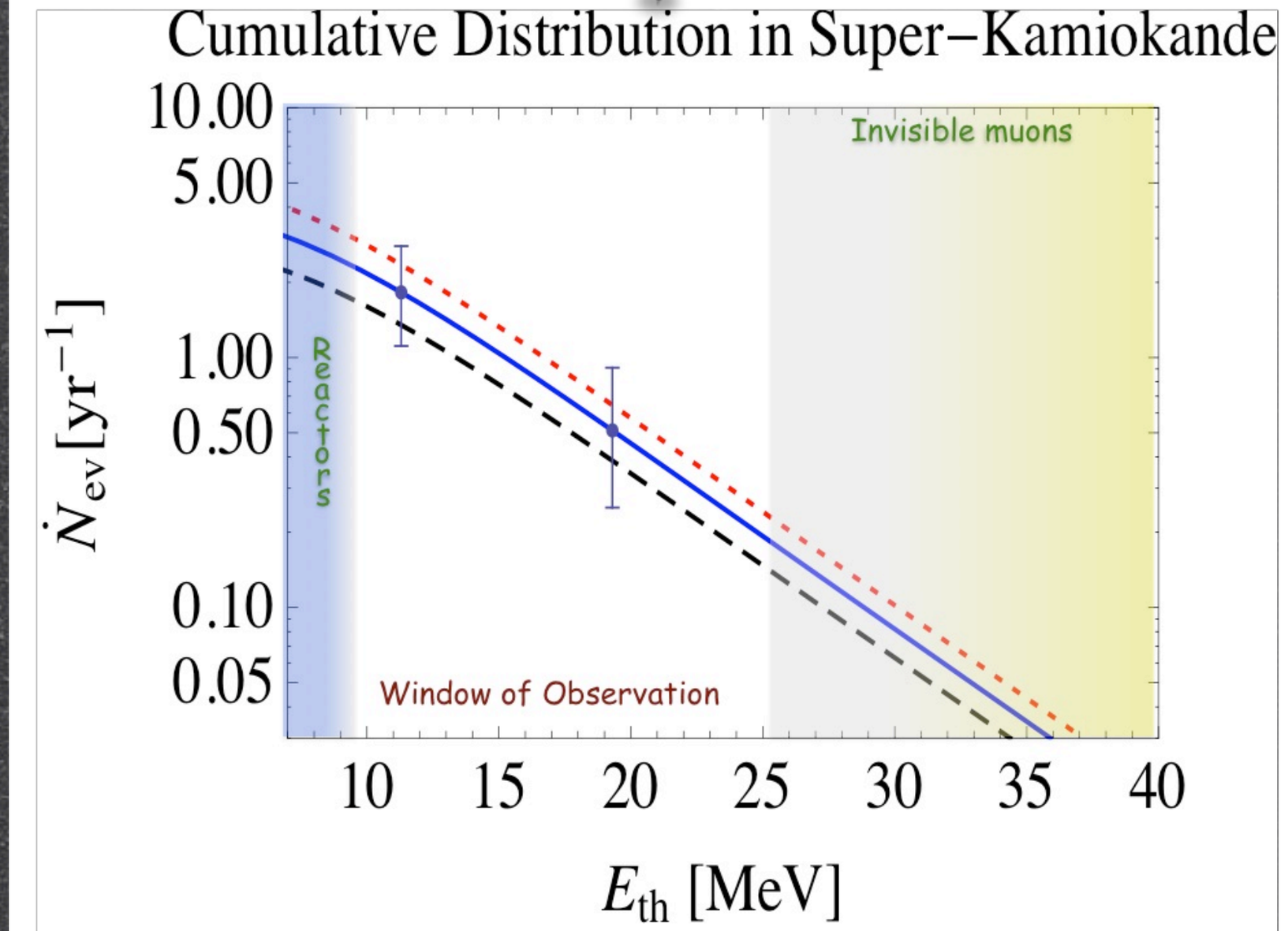
Sensitivity to proton decay into Kaon antineutrino. Systematics not included. Water, ϵ=14.6% and bkgr=14/(Mton x yr) (2methods, summed); Argon, ϵ=97% and bkgr=1/(Mton x yt). Impact of statistical fluctuations, factor of ≈2.

"If LHC finds SUSY, motivations for the search even stronger."

FV at Cryodet1 (2006) and Cryodet2 (2007) meetings

supernova spectrum in Borexino

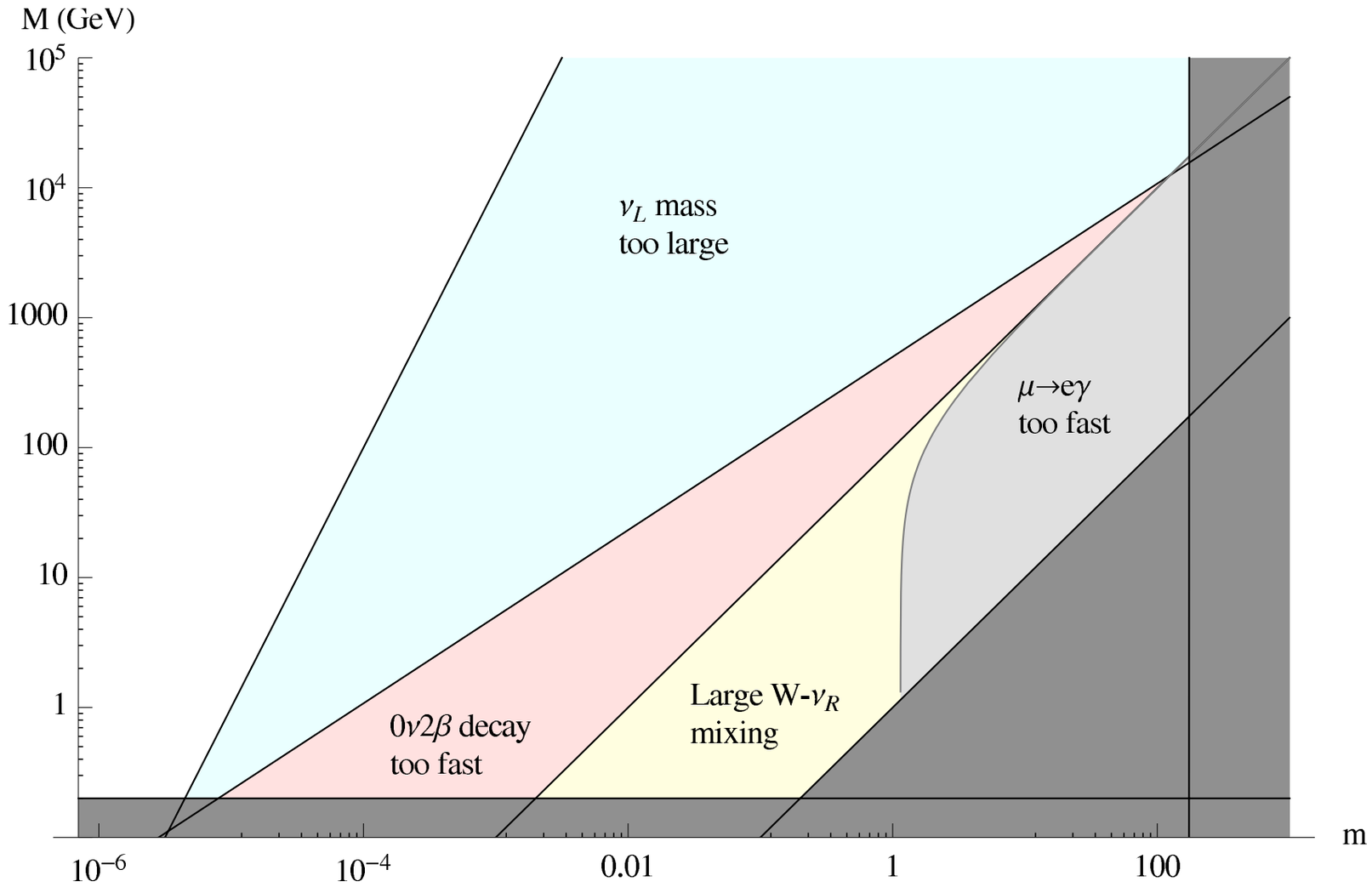




FV et al, A&A 2011

Expectation on relic supernova neutrinos, with errorbars from SN1987A and astronomy.

heavy neutrinos



Mitra et al, NPB 2012

The simplest models do not lead us to expect signals at colliders, due to a hierarchy of constraints.

Proposal to probe neutrino mass hierarchy:

1) Chose a pair (source, detector) whose distance maximizes MSW effect for muons.

2) Need just a muon detector of 1 Mton able to see 10-40 meters tracks.

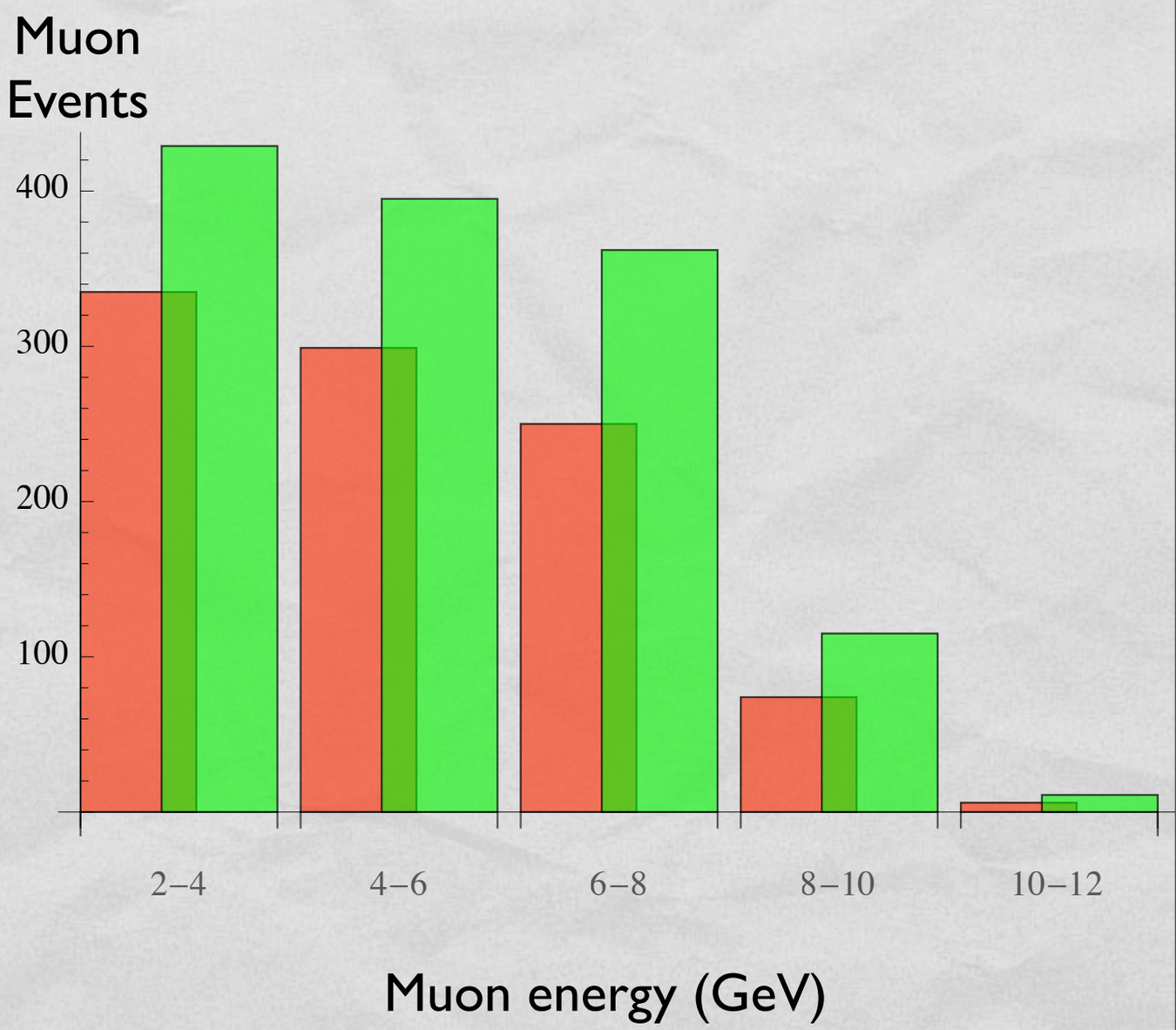
3) Use a conventional muon neutrino beam, from pion decay.

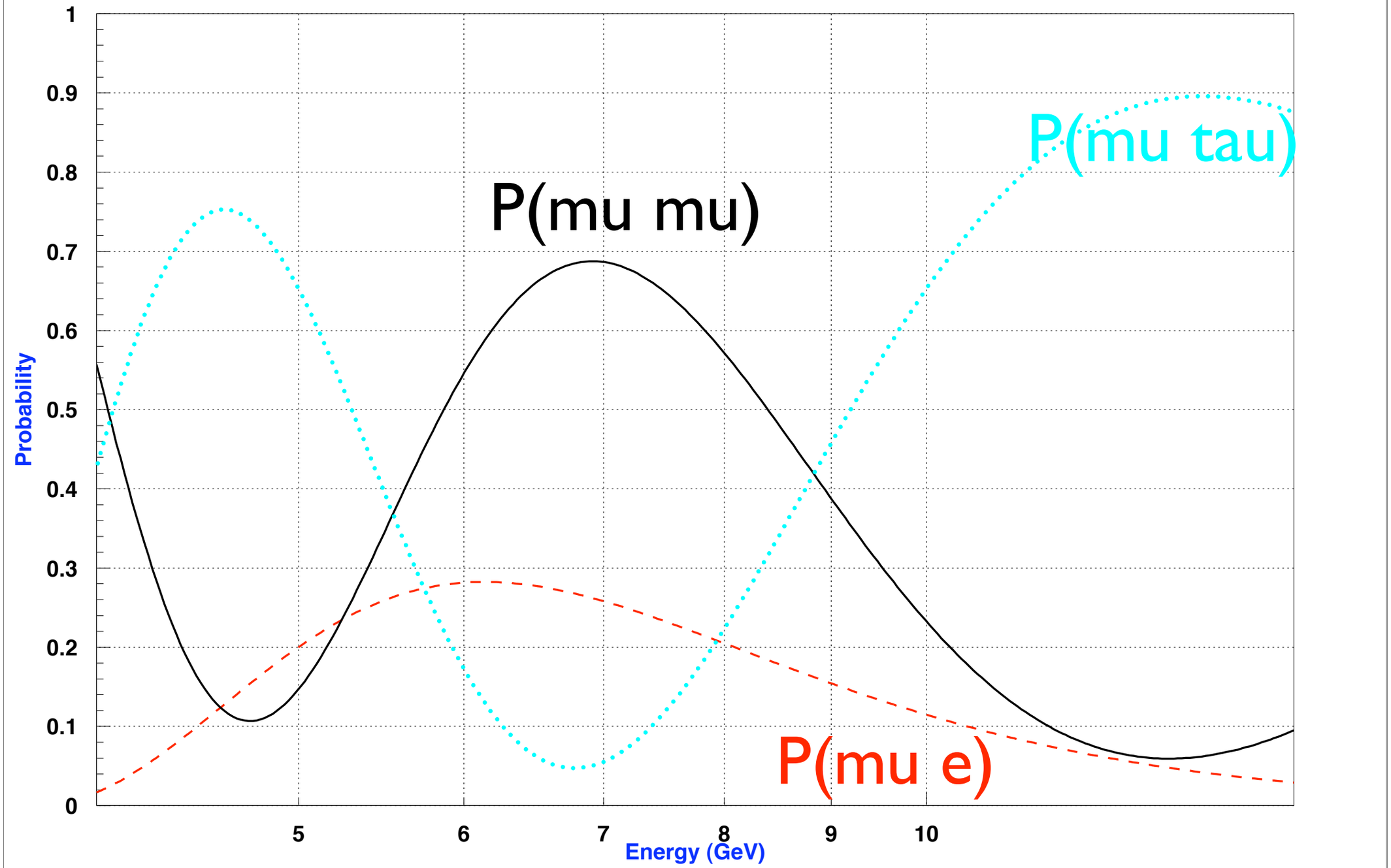
4) Evaluate the number of muon events.

RESULTS

- ... 950 events for normal hierarchy...
- ... and 1300 events for inverted hierarchy.
- A big 30% difference; bunched in time, directional, with a "hard" spectrum.

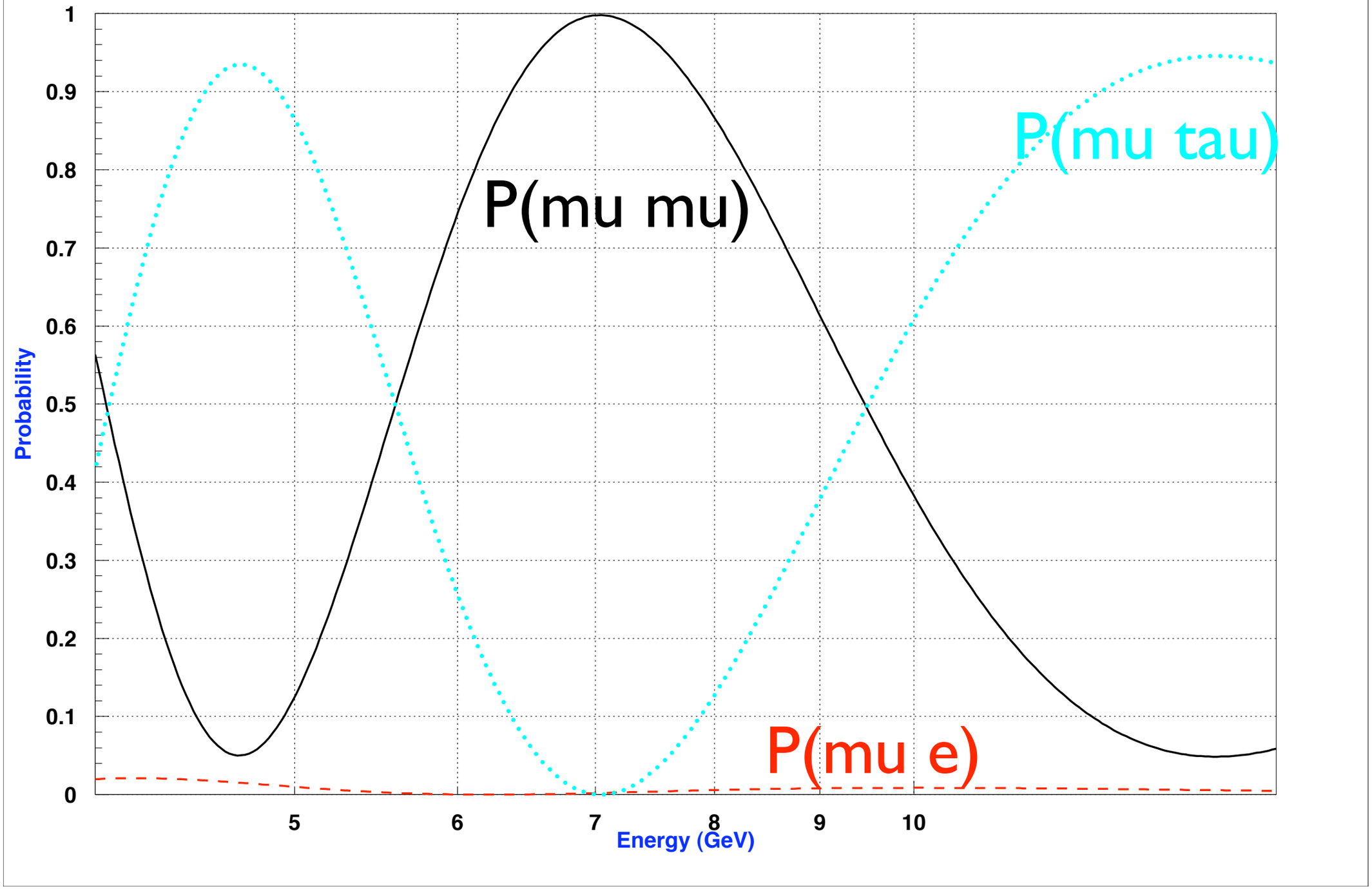
Lujan-Peschard et al., EPJC 2013





NORMAL HIERARCHY, 7000 km

http://pcbat1.mi.infn.it/~battist/cgi-bin/oscil/index.r



INVERSE HIERARCHY, 7000 km

http://pcbat1.mi.infn.it/~battist/cgi-bin/oscil/index.r