Properties and Manifestations of Neutrinos

Francesco Vissani

INFN, LNGS Theory Group

An overview of the recent achievements in neutrino physics, organized in 3 parts: phenomenology, theory and ν astronomy.

More info in the review with Strumia *"Neutrino Masses and Mixings and ..."*, that will be updated and purged accounting for feedback, comments, corrections, criticisms on: `http://astrumia.web.cern.ch/astrumia/review.html`. Also included results with Cirelli, Marandella (phenom.); with Bajc, Melfo, Senjanović (theory); with Costantini, Ianni, Pagliaroli (ν astr.).

1 Oscillations, neutrino masses, and all that

The only evidence (or strong hint?) of neutrino masses comes from oscillations. The potential of this phenomenon was immediately understood by Pontecorvo and it is today clear to everybody.

Other approaches, such as the search of imprints on the β-decay spectrum are at the moment producing upper bounds. Perhaps the exception is $0\nu2\beta$, a process possible for massive Majorana neutrinos.

It is probably fair to say that a reference minimal picture with 3 massive ν accounts for the main experimental facts.

Simple and useful: 2F vacuum oscillations formulæ

$$P_{\nu_\ell \to \nu_\ell} = 1 - \sin^2 2\theta \cdot \sin^2(\Delta m^2 L / 4E)$$

Notes: *1)* $\sin^2 \to 1/2$ *when averaged,*
2) the symmetry $\theta \to 90^\circ - \theta$*,*
3) the maximum effect is for $\theta = 45^\circ$

Enough to explain the observations of:

1. SK (ν_{atm}), K2K & MINOS (ν_μ accel.) $\theta_{23} \sim 45^\circ$
2. CHOOZ ($\bar{\nu}_e$ react.) $\theta_{13} < 8^\circ$
3. KamLAND ($\bar{\nu}_e$ react.) $\theta_{12} \sim 34^\circ$
4. Gallex/GNO-SAGE (solar ν_e, low E_ν) (same angle)
5. LSND, Karmen ($\bar{\nu}_e$ from π^+ at rest) [if it is true!] $\theta_{14} \sim 1^\circ$

[P_{ee} for solar neutrinos energies – and beyond]

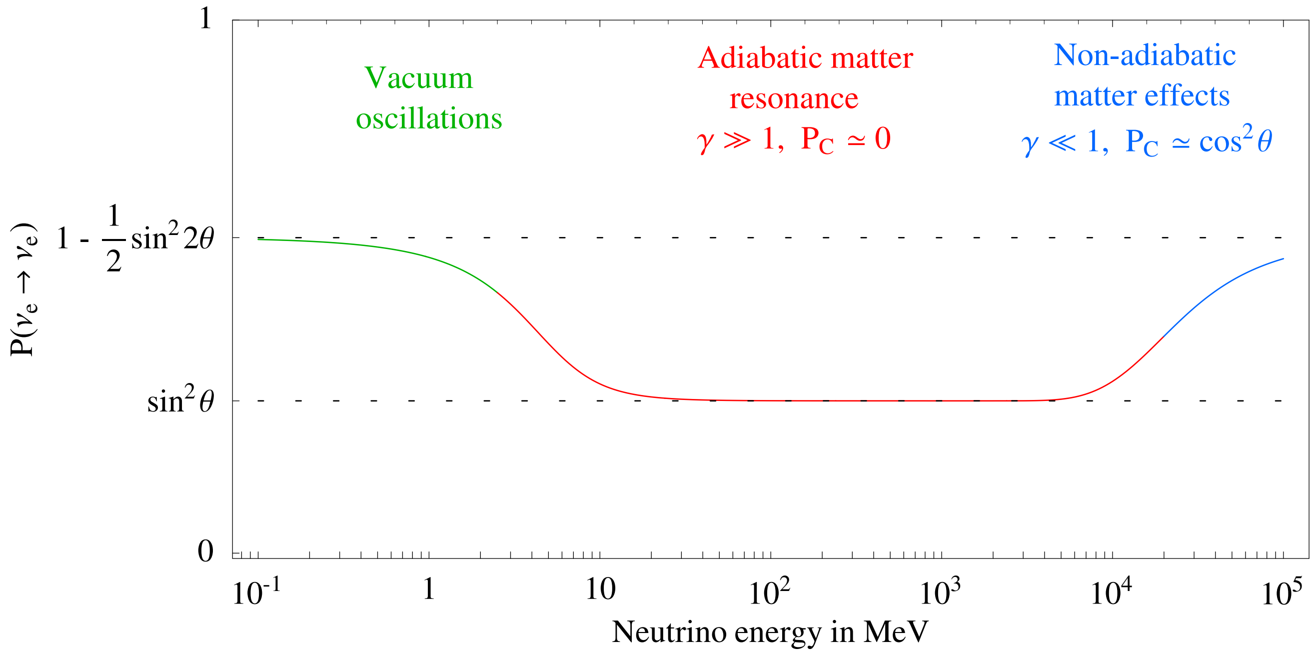


Figure 1: *Solar ν_e of relatively high energy undergo MSW (matter enhanced) conversion: the symmetry $\theta \to 90° - \theta$ is broken and $\theta = \theta_{12}$ can be determined by observations, e.g., at SNO (SK).*

Status of the three flavor picture

When we assume oscillations, the main experimental observations determine 2 mass differences squared and 2 mixing angles:

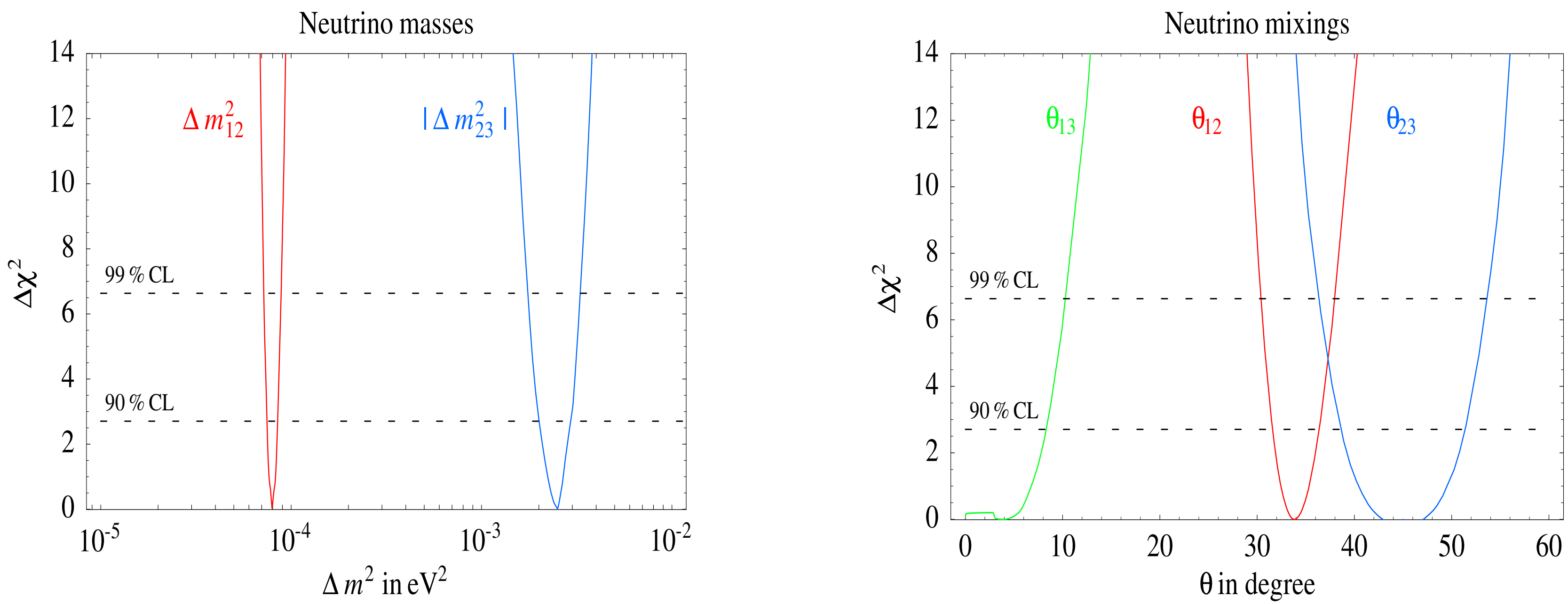


Figure 2: *Summary of what we know on the parameters of oscillations, the CP phase being simply unknown; Δm^2_{23} is improving.*

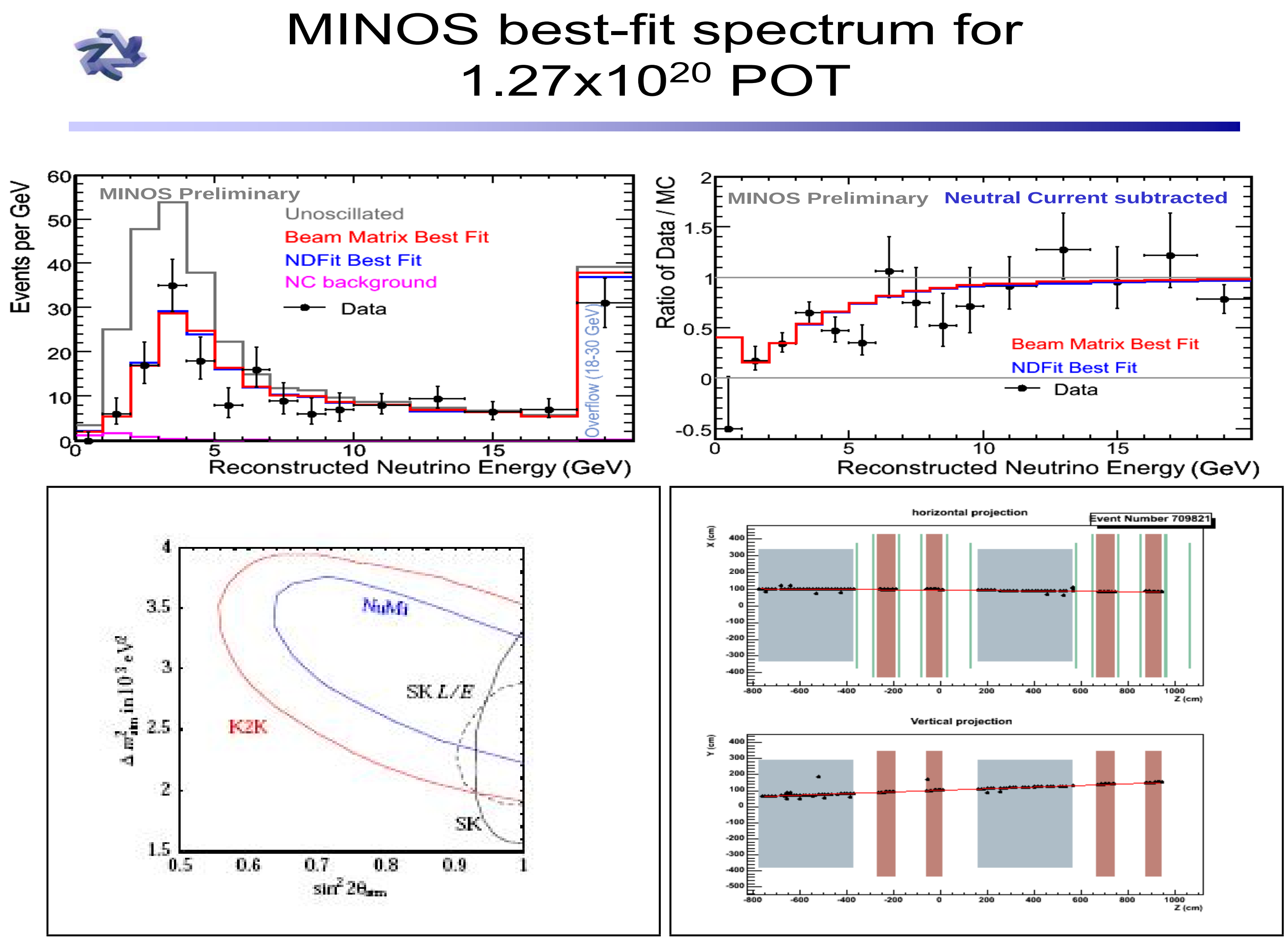


Figure 3: 1^{st} *MINOS results; impact on oscillations;* 1^{st} *event in OPERA.*

[next steps with ν experiments]

Solar ν (BOREXINO, KAMLAND, SNO)
Measure beryllium and low energy neutrinos; improve on θ_{12}; geo-ν; unexpected such as long wavelength oscillations, CPT viol. ...

Atmospheric ν (Mton WČ, ICECUBE, or 'fine grained')
L/E and θ_{23}; θ_{13} requires $\mathcal{O}$(Mton) mass. The detectors should be multipurpose: again for solar ν, nucleon decay, supernova ν ...

Artificial beams (NUMI, CNGS; T2K, NOνA; 2CHOOZ)
Confirming oscillations; find θ_{13}! (see next figure)

[the missing mixing]

In order to proceed with oscillations (=with mass hierarchy and with CP phase) the first step is to know the size of the mixing θ_{13}.

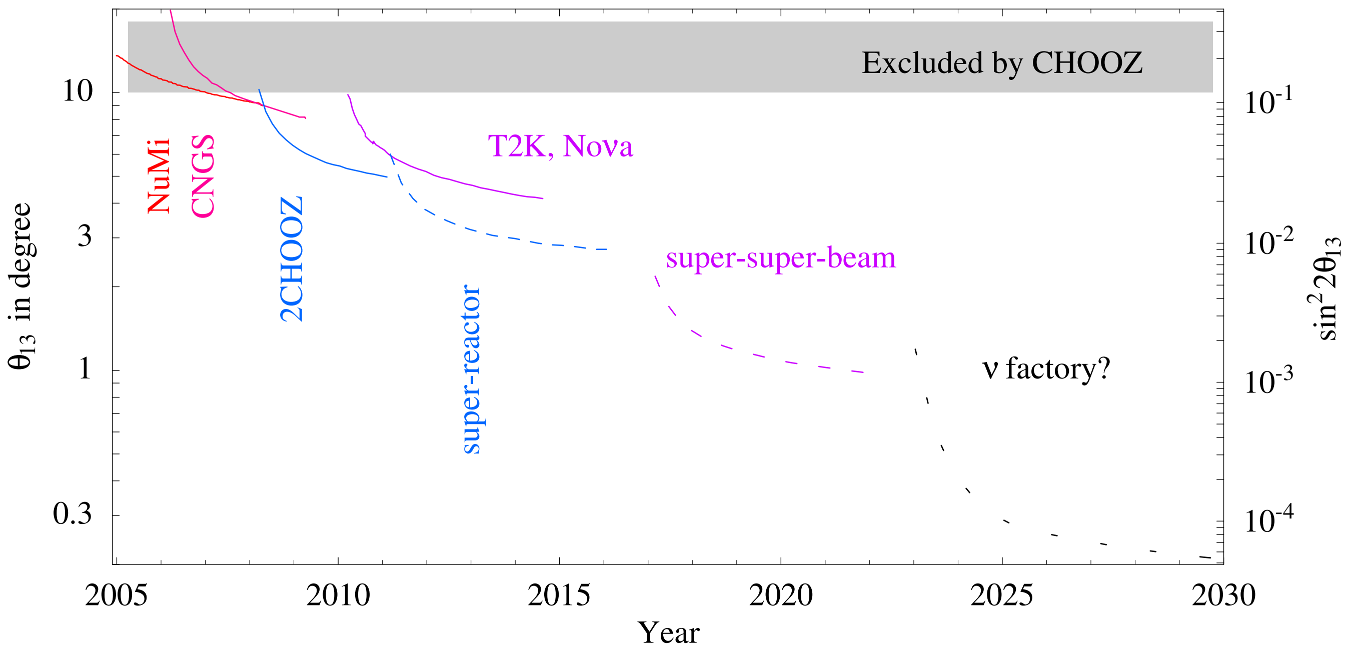


Figure 4: *Expected sensitivity of planned and future experiments.*

Other observables

Besides oscillations, there are other probes of ν masses.

1. $m_\beta^2 = \sum_i |U_{ei}^2| \times m_i^2$ — β-decay
2. $m_{\rm cosm} = \sum_i m_i$ — cosmology
3. $M_{ee} = | \sum_i U_{ei}^2 \times m_i |$ — $0\nu 2\beta$-decay

Last one assuming Majorana mass $\mathcal{L} \sim \nu_L^t M \nu_L$ with $M = U^* m U^\dagger$

- *More observables possible, but none reaches a useful sensitivity.*
- *Correct in 3F picture: e.g., "large" ν mass means kinks in β spectrum.*
- *If Dirac mass: $7 = 9 - 2$ param.s & $0\nu 2\beta$ absent, the rest unchanged.*

[e.g., $0\nu2\beta$ - neutrinoless double beta decay]

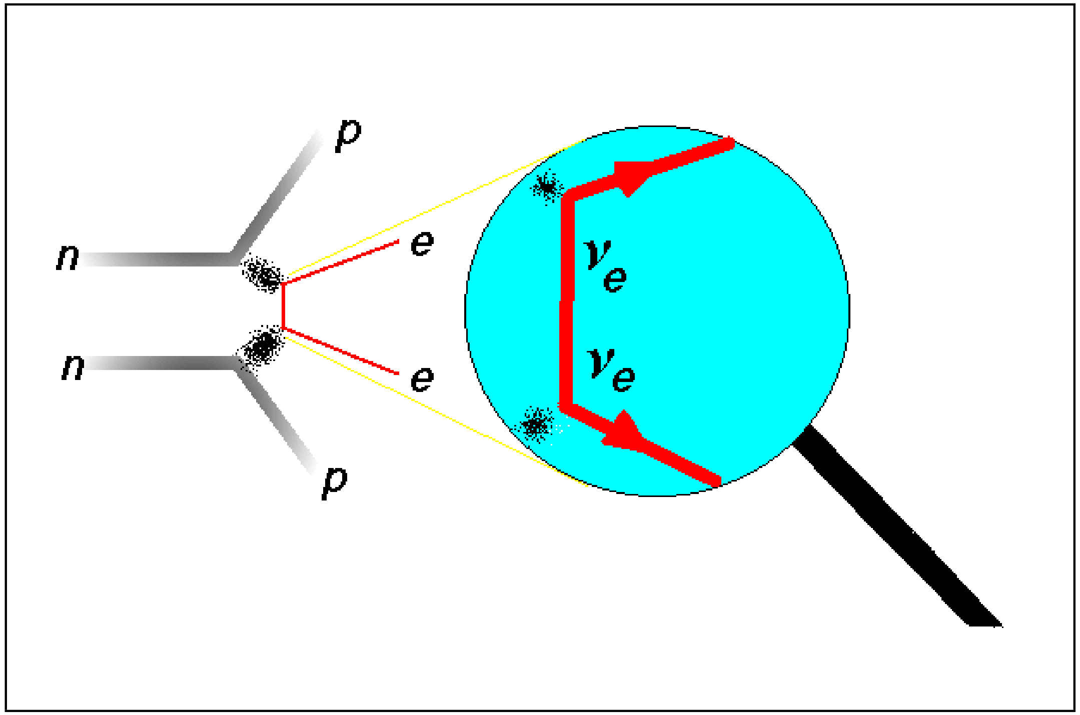


Figure 5: $(A, Z) \to (A, Z+2) + 2e^-$ *arises with* $\Delta L_e = 2$, *e.g., Majorana neutrino masses, with structure* $\nu_L^t M \nu_L$. *If the* β*-decay is forbidden,* $0\nu2\beta$ *could be searched seen as a peak in the endpoint of* $2\nu2\beta$.

[already seen?]

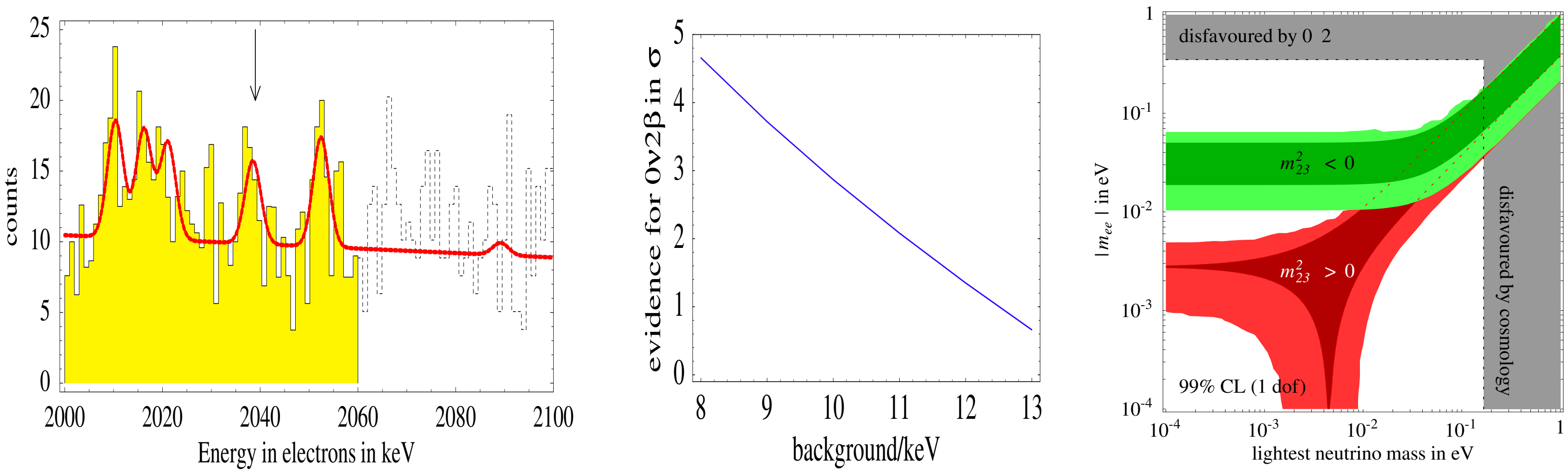


Figure 6: *a) Final Heidelberg-Moscow spectrum (yellow) and possible peaks (red) resulting from a fit. b) Confidence level of the* $0\nu2\beta$ *peak as a function of the background level. c) Expectations for* $0\nu2\beta$ *on the basis of oscillations; the lightest* ν *mass is a free parameter.*

2 Theoretical particle physics aspects

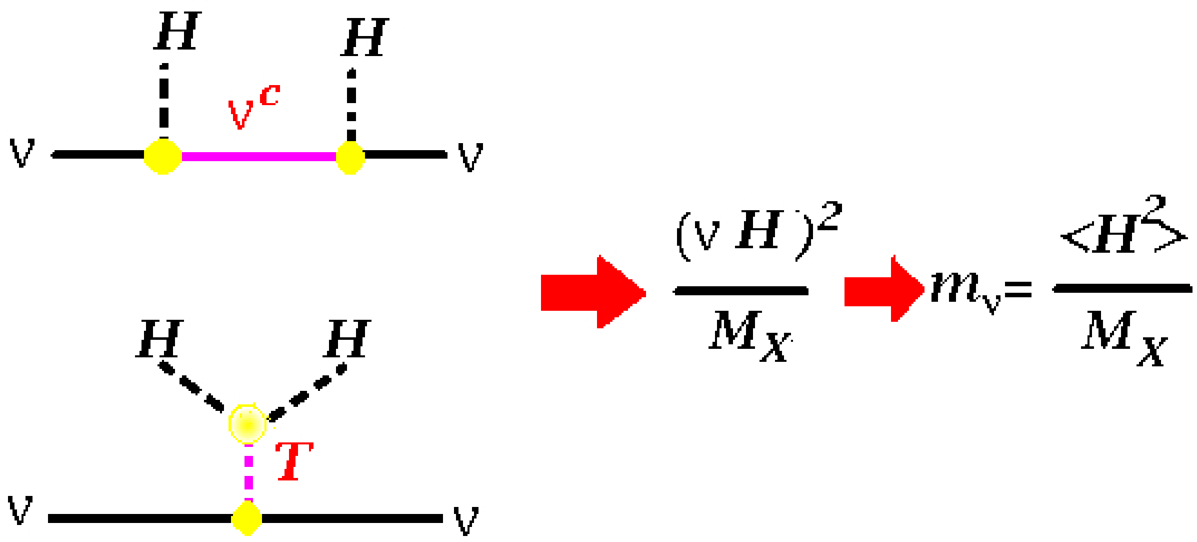
Some people think that a Dirac neutrino mass $\bar{\nu}_L \nu_R$ is more economical (or attractive) than Majorana's.

> *However, this requires adding a ν_R, a particle without SM gauge interactions; thus, a Majorana mass $\nu_R^t M \nu_R$ is always possible. The new mass scale M has nothing to do with M_W.*
>
> *Also: adding ν_R makes the spectrum fully left-right symmetric, that suggests strongly that SU(2)$_R$ has a dynamical meaning.*

This is why I like better (and hereon consider) only Majorana masses.

Seesaw as an answer and as a question

Light ν masses could witness the existence of new physics scale:



Is this situation ☺ , or it is ☹ ? Probably, it is simply 😐 .

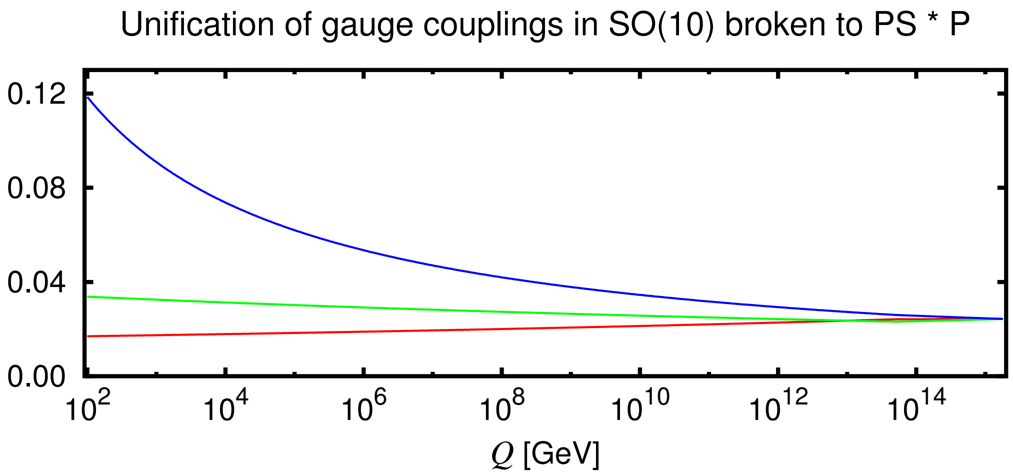
More discussion follows.

The power of GUT

The spinor of 16 of SO(10) contains all fermions of SM, including ν_R

Consider a non-supers. SO(10) model where gauge unif. happens via

$$\text{SO(10)} \xrightarrow{54_H} \text{Pati-Salam}\times\text{Parity} \xrightarrow{126_H} \text{SM}$$



ν *masses get tied to gauge scales,* $M_{interm.} \approx 5 \times 10^{13}$ *GeV.*

(Buccella *et al* proved that it has rapid $p \to \pi^0 e^+$. Perhaps excluded but for the definitive sentence we need studying fermion masses and heavy spectrum)

Why leptonic mixings $\gg$ quark mixings?

Is this question meaningful? Surely, we have not the right to ask why the electron is so much lighter than the top in the SM.

It is funny and perhaps instructive that in SO(10) models, for certain choices of the Higgs fields we have the opposite problem:

$$|V_{cb}| = \frac{m_s}{m_b} \times \cos 2\theta_{atm} \;\Rightarrow\; \frac{1}{20} < \frac{1}{100}$$

My opinion is simply that some interesting questions like this have to be discussed within motivated and well-specified extensions of the SM.

2.1 Do we descend from ν's?

The SM is *quantitatively* unable to produce the baryon asymmetry in the course of the big-bang (the program of Sakharov). But since we should modify SM anyways, what about the model with massive ν?

The decay of $N = \nu_R + \nu_R^c$ can produce a lepton asymmetry, that SM non-perturbative effect translate into a baryon asymmetry (Fukugita & Yanagida); this is very promising, despite model dependence.

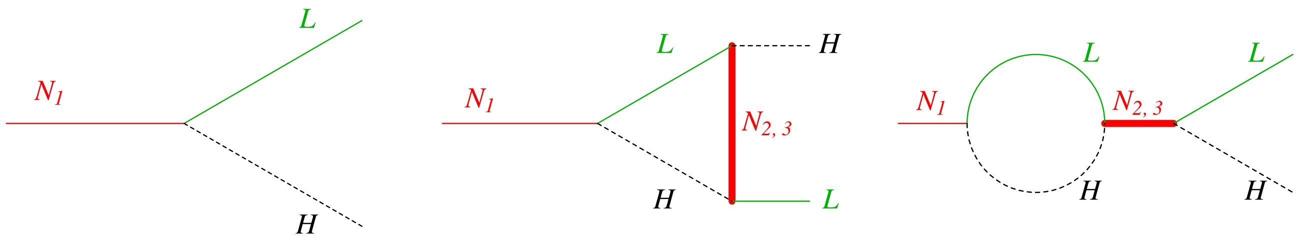


Figure 7: *The interference term leads to CP violation.*

3 Neutrino astronomy & astrophysics

There is a wide interest in the detection of neutrinos from cosmic sources. This is largely an open field.

Oscillations and other particle physics effects (on ν and/or on the sources) can affect the observables in many ways.

Yet there are large uncertainties on the expectations, so that the primary aim seems to be ν astronomy & astrophysics.

That's why the title and why I focus on these aspects in the last 4 pages.

Core collapse supernovæ

Super-K, LVD, KamLAND, SNO, Baksan, ... [10 MeV range]

Most of the gravitational energy from the formation of a neutron star (black hole) ~ 10 % $M_\odot \times c^2$, goes in thermalized ν radiation emitted in ~ 10 s.

A definitive theory of the explosion and of ν emission is lacking.

SN1987A GAVE US THE ONLY ν SIGNAL WE HAVE.

Observations seems to be consistent with expectations, despite several puzzles in the interpretation: average energy KII $=$ IMB$/2$; excess of directionality; large number of Baksan events; Mont Blanc events.

[on the 12 events in Kamiokande-II]

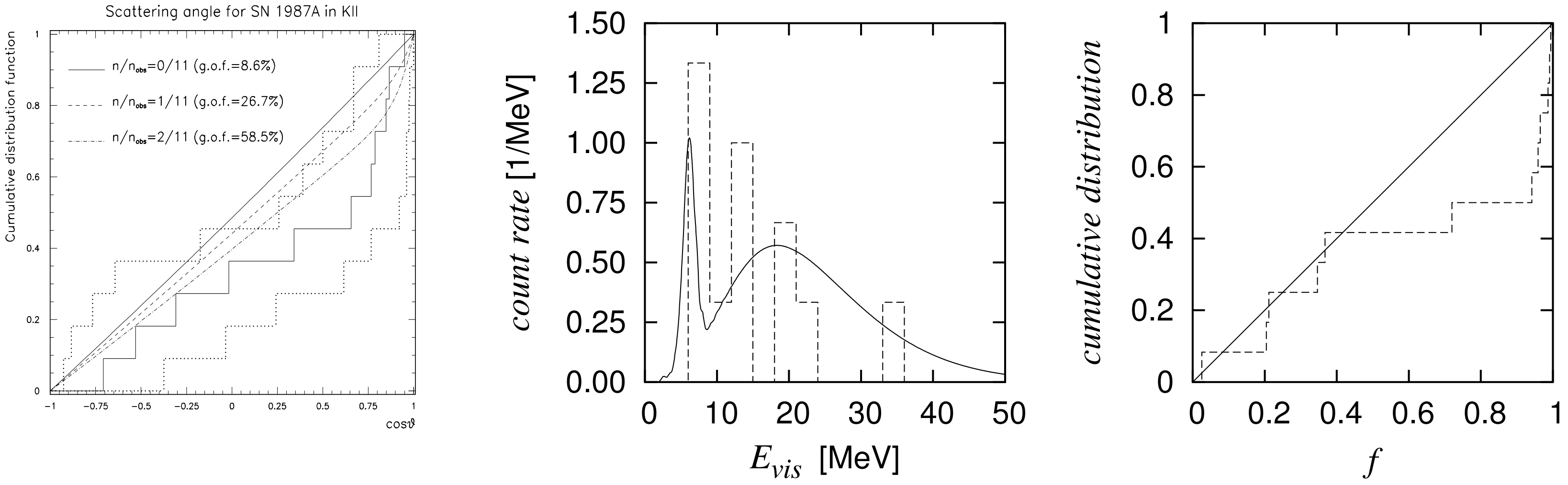


Figure 8: *Distributions on the angle with SN1987A (cumulative), on the energy (differential); on the volume (cumulative). The 1^{st} plot shows the possible presence of a elastic scattering event(s); the last two suggest background events of low energy* <u>*and*</u> *on the periphery of the detector.*

Supernova remnants (SNR)

IceCUBE, KM3NeT [TeV-PeV range]

Strongly suspected to be the accelerators of CR in our Galaxy:
Baade & Zwicky 34, Fermi 49-54, Ginzburg & Syrovatsky 64

New VHE γ-rays observations (H.E.S.S., Magic) suggest $pp \to \pi^0\ X$.

> *Neutrinos are also produced $pp \to \pi^\pm\ X$ and in principle can give a smoking gun in large neutrino telescopes*

A POSSIBLE PROBLEM: THE LOW COUNTING RATES.

A nearby SNR, Vela Jr (still to be studied in details) could be the best hope for ν telescopes in the Mediterranean sea. In the meantime ...

[H.E.S.S. measured one SNR spectrum in details]

Just after 1^{st} Cangaroo data, Alvarez-Muñiz & Halzen discussed RX J1713.7-3946 as a ν source. Now more reliable predictions can be made:

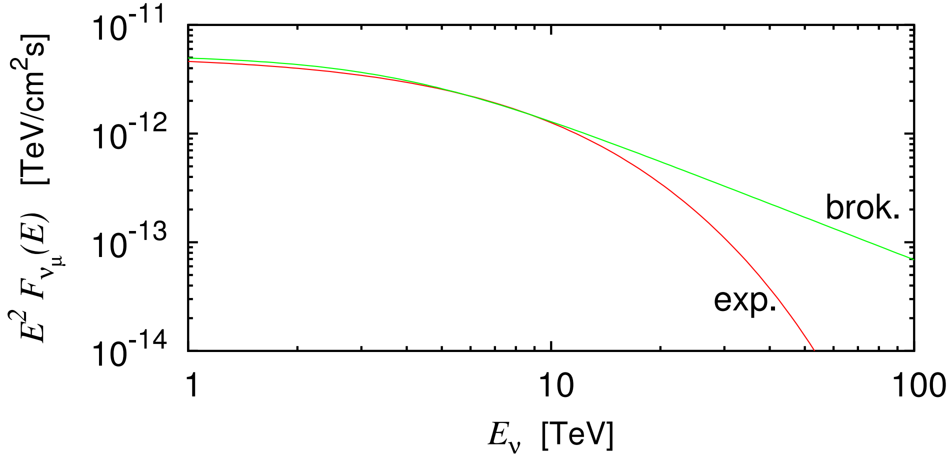


Figure 9: *ν spectrum as calculated from H.E.S.S. γ-ray observations.*

An ideal telescope in Mediterranean sea could see $\sim 5\ \mu^\pm$ per km^2 per year. The observed cut will mean hard times with the background.

4 Conclusions and outlook

Neutrino physics is providing us new data, surprises and lot of excitement. More interesting observations, measurements and even discoveries can be expected for the near future.

Theoretical particle physics of ν is in a more difficult position. Several open questions regard ultrahigh energy scales. Yet, I feel that several ideas deserve to be explored/updated (GUT, leptogenesis, etc.). Also, theory offers connections with other fields & observables.

Finally, I wish to recall that νs do not belong exclusively to *particle* physics! Interesting ν things are happening in other sectors of physics and there is a lot of work to be done–also for theorists, I hope.

Thanks for the attention!

A Appendices

Just a few backup slides, in case you want to know more on:

- the MSW effect, with formulae;
- the interpretation of LSND anomaly, today;
- other hypothetical neutrino sources;
- the "standard" interpretation of SN1987A neutrinos;
- the quality of H.E.S.S. observations of SNR.

A.1 $\nu_\odot$'s feel the matter effect at high energy

$\nu_e e \to \nu_e e$ contributes an additional term to the Hamiltonian of propagation in matter: $\delta H_\nu = \mathrm{diag}(1,0,0) \times \sqrt{2}\, G_F\, \rho_e(x)$:

$$\nu_e = \begin{cases} \cos\theta\ \nu_1 + \sin\theta\ \nu_2 \to \cos\theta\ \nu_1 + \sin\theta\ \nu_2\ e^{i\infty}, & E < 1 \text{ MeV} \\ \nu_2(\rho) \to \nu_2(0) \equiv \nu_2, & E > 5 \text{ MeV} \end{cases}$$

taking the overlap with ν_e,

$$P_{ee} = \begin{cases} \cos^4\theta + \sin^4\theta \sim 0.6, & \text{Gallex/GNO \& SAGE} \\ \sin^2\theta \sim 0.3, & \text{SNO, SK} \end{cases}$$

A.2 LSND before MiniBOONE

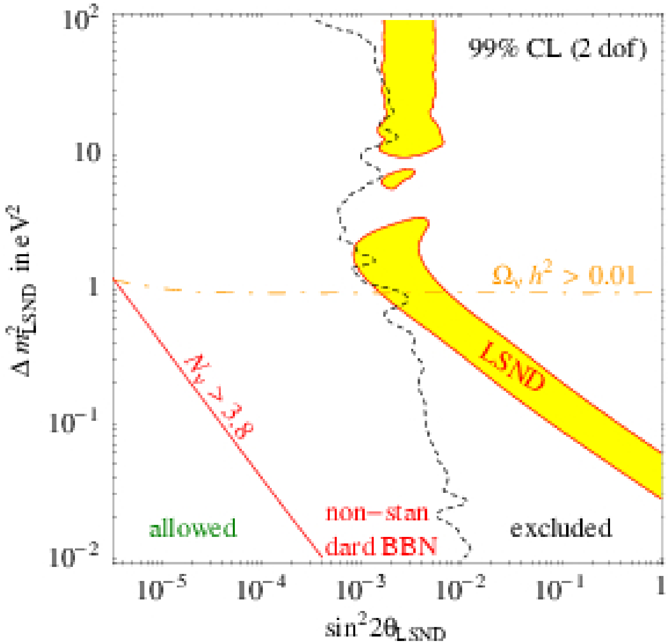


Figure 10: *Interpretation of LSND in the 3+1 scheme. the allowed region is compared with the excluded one (both at 99 %). Also shown: BBN region with* $N_\nu = 3.8$ *and cosmological region with* $\Omega_\nu h^2 = 0.01$*.*

A.3 Frontiers and exotics

Auger, ANITA [EeV range]

AGN as plausible sources of UHE CR and thus of ν *and/or possibly* cosmogenic ν from collisions with CMB (Berezinsky & Zatsepin 69)

IceCUBE, KM3NeT, Mton WČ [GeV-TeV range]

Annihilation of dark matter in Earth or Sun

[if you can dream we will detect some DM neutrinos...]

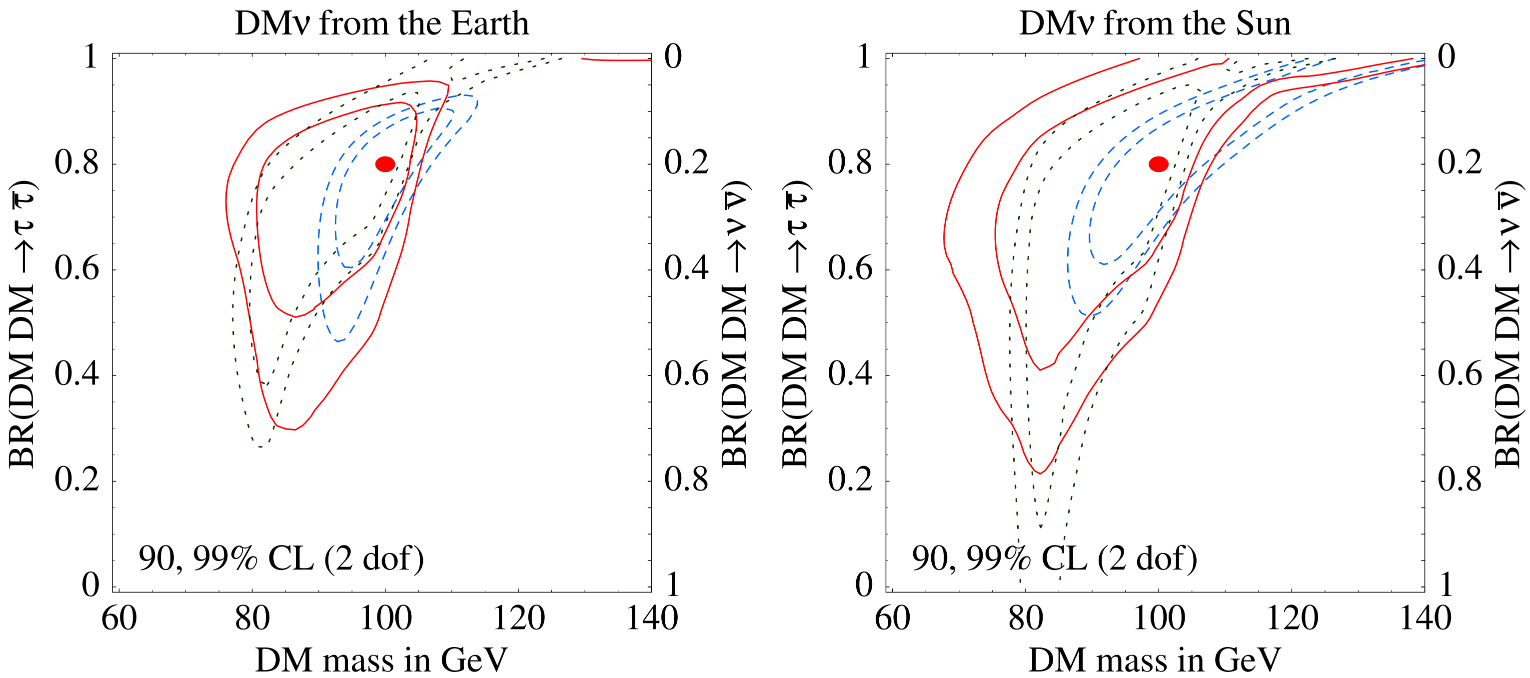


Figure 11: *Reconstruction of the DM properties from hypothetical samples of 1000 thoroughgoing μ, 100 contained μ, 200 showers.*

A.4 A standard interpretation of SN1987A

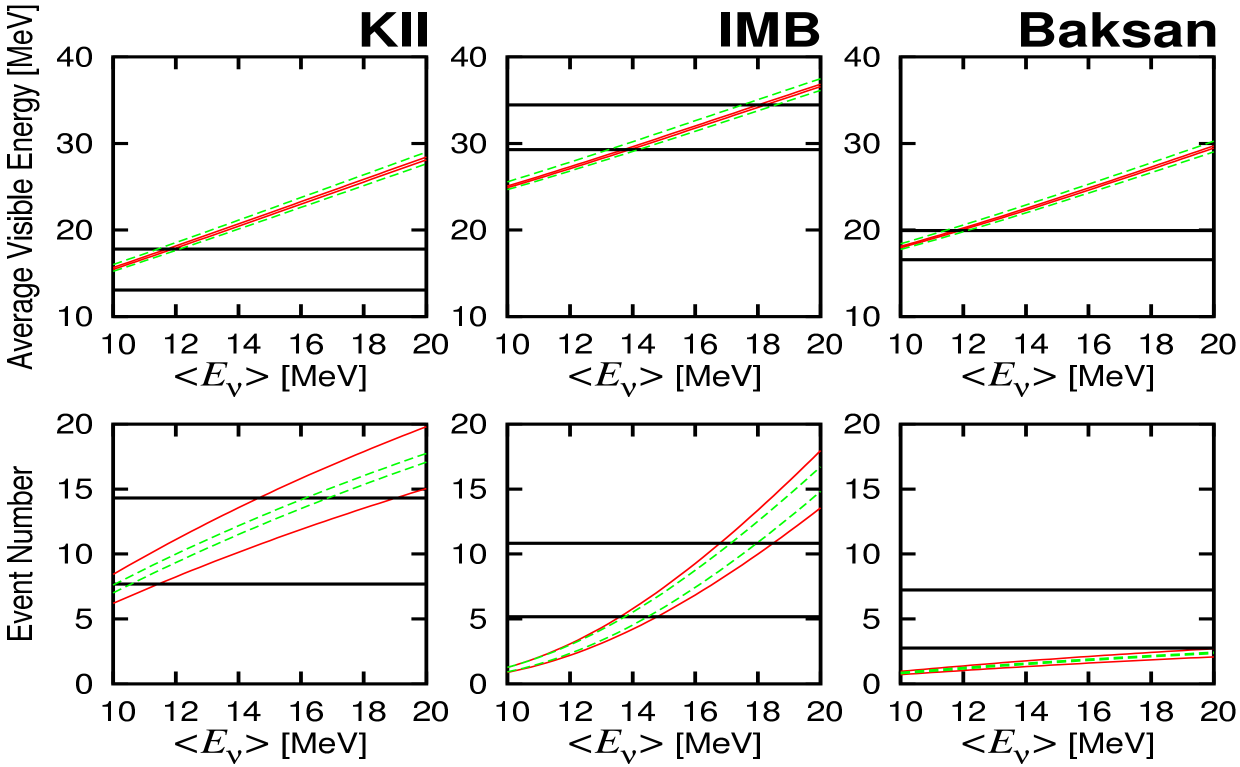


Figure 12: *Horizontal lines, experimental values; inclined lines, theoretical values, as a function of the average antineutrino energy. Assumes that all events are* $\bar{\nu}_e p \to n e^+$ *('inverse beta decay').*

A.5 RX J1713.7-3946 as seen by H.E.S.S.

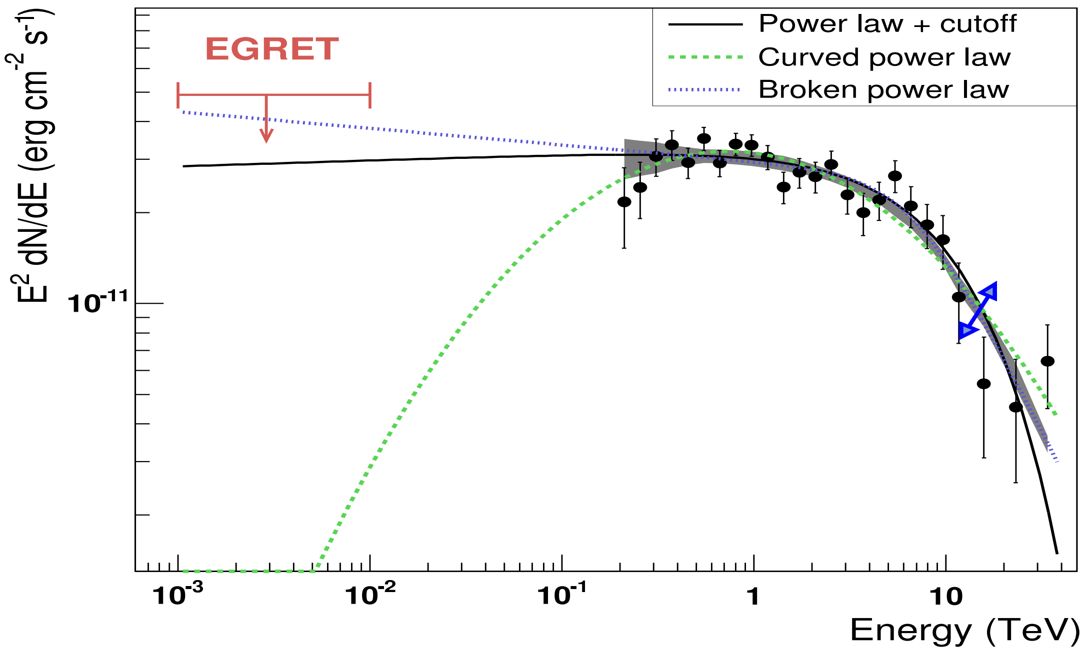


Figure 13: *Determination of VHE γ spectrum by the H.E.S.S. telescope along with phenomenological fits. Hadronic origin (i.e., from CR) suggested/favored, but essential to exclude a leptonic (i.e., from $e^{\pm}$) origin.*