Prospettive nella fisica del neutrino

Consiglio di Sezione I.N.F.N.

Padova 6 maggio 2008

Ferruccio Feruglio
Universita' di Padova

1. Neutrinoless double beta decay

2. ϑ_{13}

3. absolute scale of neutrino mass

4. $\mu \to e\,\gamma$ and LFV

5. Neutrinos from extragalactic sources

- at the border of our current knowledge about neutrinos
- reflect my theoretical prejudices
- long term projects (neutrino factories, beta beams,...) not covered!

Summary of data [Fogli, NOVE 2008]

$m_\nu < 2.2\, eV \quad (95\%\, CL)$ (lab)

$\sum_i m_i < 0.2 \div 1 \quad eV$ (cosmo)

$\Delta m^2_{atm} \equiv \left|\Delta m^2_{32}\right| = (2.38 \pm 0.27) \times 10^{-3}\ \mathrm{eV}^2$

$\Delta m^2_{sol} \equiv \Delta m^2_{21} = \left(7.66 \pm 0.35\right) \times 10^{-5}\ \mathrm{eV}^2$

$[2\sigma \quad \text{errors}\,(95\%\ \text{C.L.})]$

$\sin^2\vartheta_{13} < 3.2 \times 10^{-2}$ [2.] $\vartheta_{13} < 10.3^0$

$\sin^2\vartheta_{23} = 0.45\ {}^{+0.16}_{-0.09}$ $\vartheta_{23} = \left(42.1^{+9.2}_{-5.3}\right)^0$

$\sin^2\vartheta_{12} = 0.326^{+0.05}_{-0.04}$ $\vartheta_{12} = \left(34.8^{+3.0}_{-2.5}\right)^0$

violation of individual lepton number implied by neutrino oscillations

Summary of unkowns

[3.] absolute neutrino mass scale is unknown

$\mathrm{sign}\,[\Delta m^2_{32}]$ unknown

[complete ordering (either normal or inverted hierarchy) not known]

δ, α, β unknown

[CP violation in lepton sector not yet established]

[1.] violation of total lepton number not yet established

1. Neutrinoless double beta decay : (A,Z)->(A,Z+2)+2e$^-$

motivations: - establish (B-L) violation [Majorana neutrino masses]
- absolute neutrino mass
- neutrino mass ordering

theoretical interest: call Λ_L the scale of (B-L) violation

$$m_\nu = y\frac{v^2}{\Lambda_L} \longleftrightarrow m_f = \frac{y_f}{\sqrt{2}}v$$

smallness of m_ν due to $\frac{v}{\Lambda_L} << 1$

$$m_\nu \approx \sqrt{\left|\Delta m^2_{32}\right|} \approx 0.05\ \text{eV} \rightarrow \quad \Lambda_L \approx 10^{15}\ \text{GeV}$$

not that far from GUT scale

- B-L violated, in general, when attempting to unify particle interactions (GUTs)
- global quantum numbers expected to be violated at some level by quantum gravity effects

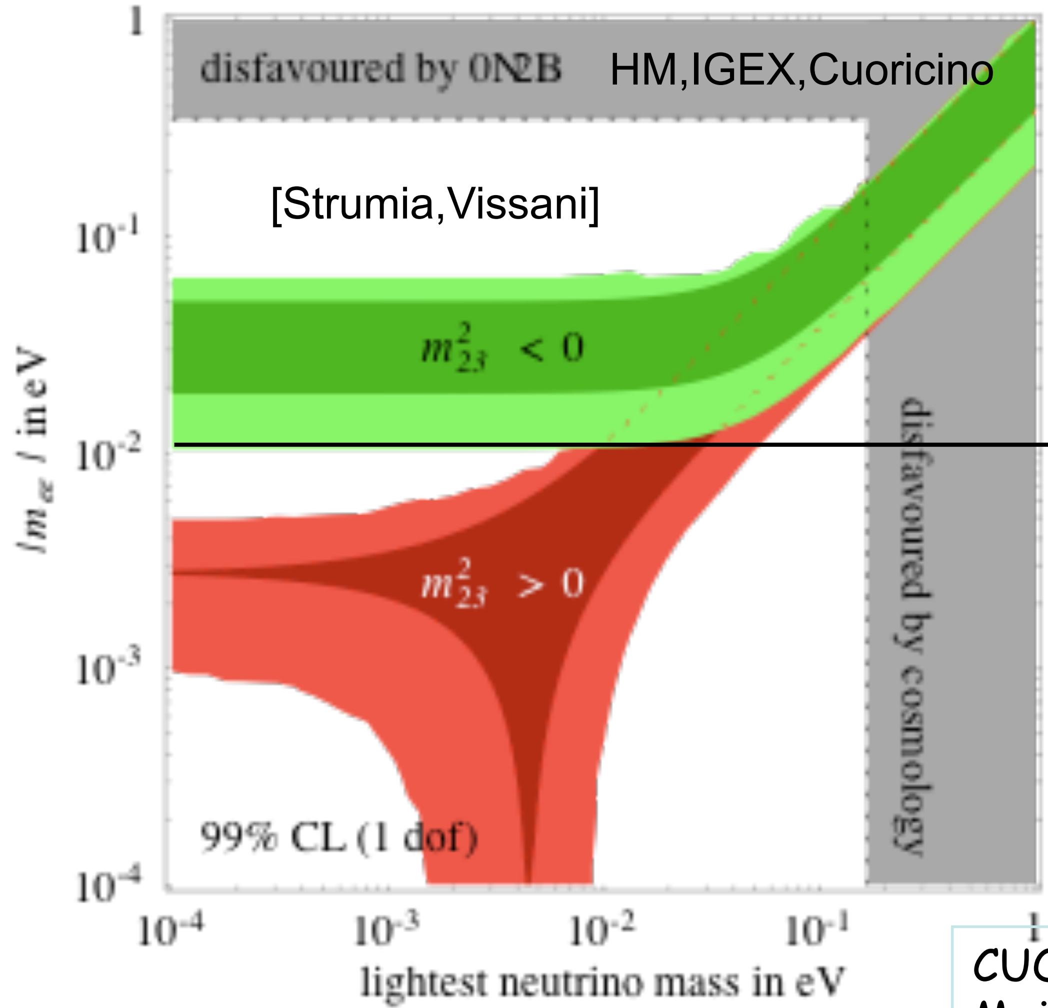
$$\Lambda_L \approx 10^{15}\ GeV$$

independent indication of a new physical threshold around the GUT scale

- many GUTs contain ν^c
- heavy ν^c exchange produces a specific version of neutrino masses (see-saw mechanism)
- B-L violation welcome in baryognesis
- out-of-equilibrium, CP violating decay of ν^c can drive baryogenesis through leptogenesis

$$|m_{ee}| = \left|\sum_i U_{ei}^2 m_i\right| = \left|\cos^2\vartheta_{13}(\cos^2\vartheta_{12}\ m_1 + \sin^2\vartheta_{12} e^{2i\alpha}\ m_2) + \sin^2\vartheta_{13} e^{2i\beta}\ m_3\right|$$

[notice the two phases α and β, not entering neutrino oscillations]



from the current knowledge of $(\Delta m_{ij}^2, \vartheta_{ij})$ we can estimate the expected range of $|m_{ee}|$

future expected sensitivity on $|m_{ee}|$

10 meV

a positive signal would test both (B-L)-violation and the absolute mass spectrum at the same time!

Cuore $T_{1/2}^{0\nu}(^{130}Te) \geq 3.0 \times 10^{24}\ y$ (90% C.L.)

$\langle m_{ee} \rangle \leq 0.19 \div 0.68\ eV$

CUORE	^{130}Te	(30-50) meV
Majorana	^{76}Ge	(20-70) meV
GERDA	^{76} Ge	(90-290) meV (phase II)
		10 meV (phase III ?)
KamLAND	^{136}Xe	100 meV ?

2. ϑ_{13}

motivations: - fundamental parameter of mixing matrix
- future development of the field depends on the size of ϑ_{13}:
leptonic CP violation, sign of Δm^2_{31}, matter effects

$$8J_{CP} = \cos\vartheta_{13}\sin 2\vartheta_{13}\sin 2\vartheta_{12}\sin 2\vartheta_{23}\sin\delta$$

- a tiny ϑ_{13} might signal an underlying symmetry
[Tri-Bimaximal mixing scheme]

$$U_{PMNS} = \begin{pmatrix} \frac{2}{\sqrt{6}} & \frac{1}{\sqrt{3}} & 0 \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{2}} \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \end{pmatrix} + \underbrace{\text{small corrections}}_{<\text{few percent}}$$

$$U_{PMNS} = \begin{pmatrix} O(1) & O(1) & \leq O(1) \\ O(1) & O(1) & O(1) \\ O(1) & O(1) & O(1) \end{pmatrix}$$

TB scheme is already in excellent agreement with ϑ_{12}
[and with ϑ_{23} too, though the exp error is larger]

$$\sin^2\vartheta_{12} = 0.326^{+0.05}_{-0.04}$$

$$\sin^2\vartheta_{12}\big|_{TB} = \frac{1}{3}$$

2σ

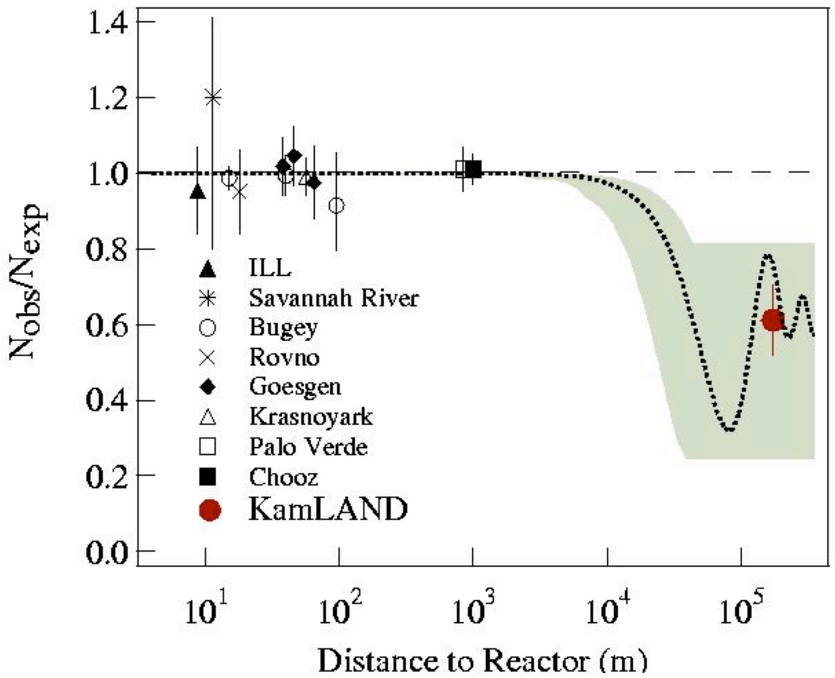
the theoretically preferred way of measuring ϑ_{13} is through the electron neutrino (antineutrino) survival probability

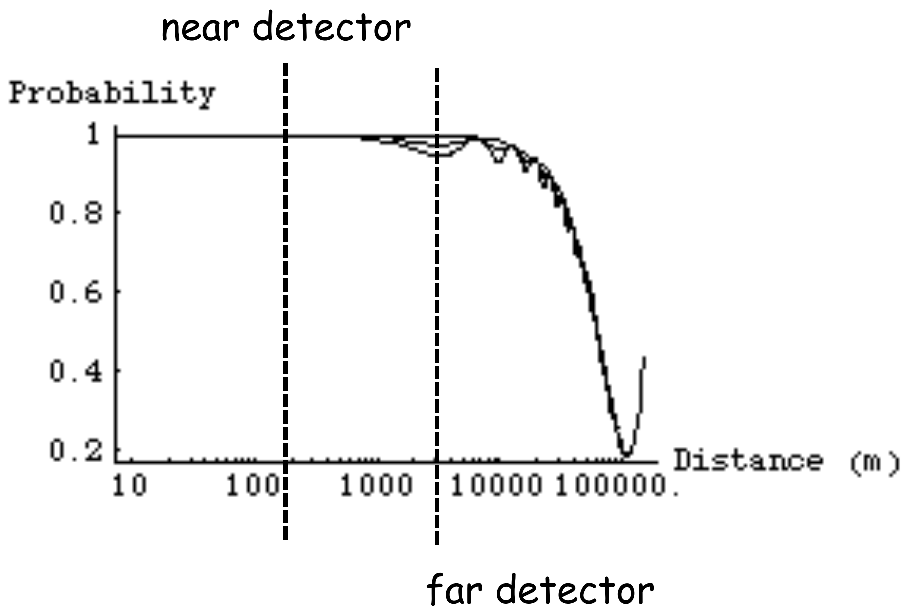
$$P(\nu_e \to \nu_e) = 1 - \sin^2 2\vartheta_{13} \sin^2 \frac{\Delta m^2_{31} L}{4E} - \alpha^2 \sin^2 2\vartheta_{12} \left(\frac{\Delta m^2_{31} L}{4E} \right)^2 + \ldots.$$

$$\alpha \equiv \frac{\Delta m^2_{21}}{\Delta m^2_{31}}$$

[no dependence on δ,
no dependence on
sign of Δm^2_{13},
no dependence on
matter effects]

in practice, this is not an easy task…



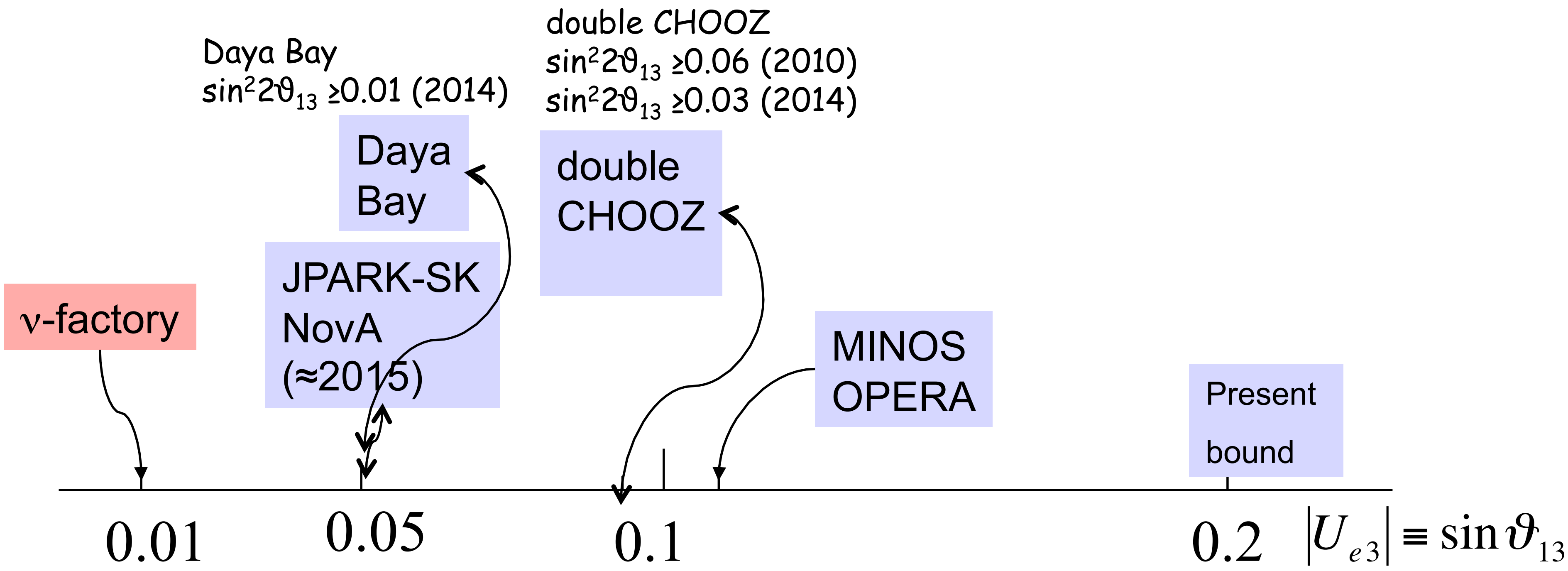


alternatively: exploit the dependence on ϑ_{13} of conversion probability between muon and electron neutrinos in LBL experiments
[which however depends on additional parameters such as δ, the sign of Δm^2_{31}, matter effects, octant of ϑ_{23}, ...]

$$P(\nu_\mu \to \nu_e) = \sin^2 2\vartheta_{13} \sin^2 \vartheta_{23} \frac{\sin^2\left[(1-\hat{A})\Delta_{31}\right]}{(1-\hat{A})^2} + \ldots$$

$$\Delta_{31} \equiv \frac{\Delta m^2_{31} L}{4E} \qquad \hat{A} \equiv \frac{2\sqrt{2} G_F n_e E}{\Delta m^2_{31}}$$

a simplified view:



is ϑ_{23} maximal? $\vartheta_{23} = \left(42.1^{+9.2}_{-5.3}\right)^0$

$$\vartheta_{23} \approx \frac{\pi}{4}$$

$$\Downarrow$$

$$\delta\vartheta_{23} \approx \frac{\sqrt{\delta P_{\mu\mu}}}{2}$$

i.e. a small uncertainty on $P_{\mu\mu}$ leads to a large uncertainty on θ_{23}

$\delta(\sin^2\theta_{23})$ reduced by future LBL experiments from $\nu_\mu \to \nu_\mu$ disappearance channel

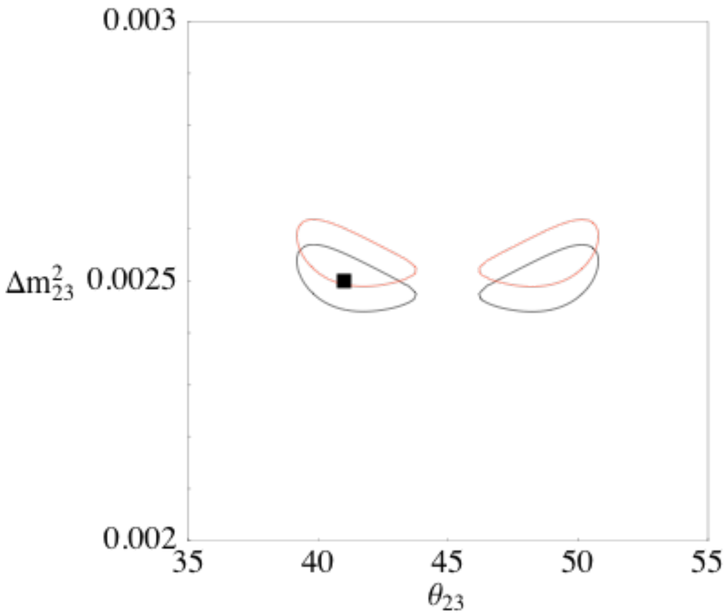
$$P_{\mu\mu} \approx 1 - \sin^2 2\vartheta_{23} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right)$$

- no substantial improvements from conventional beams
- superbeams (e.g. T2K in 5 yr of run)

$$\delta P_{\mu\mu} \approx 0.01$$

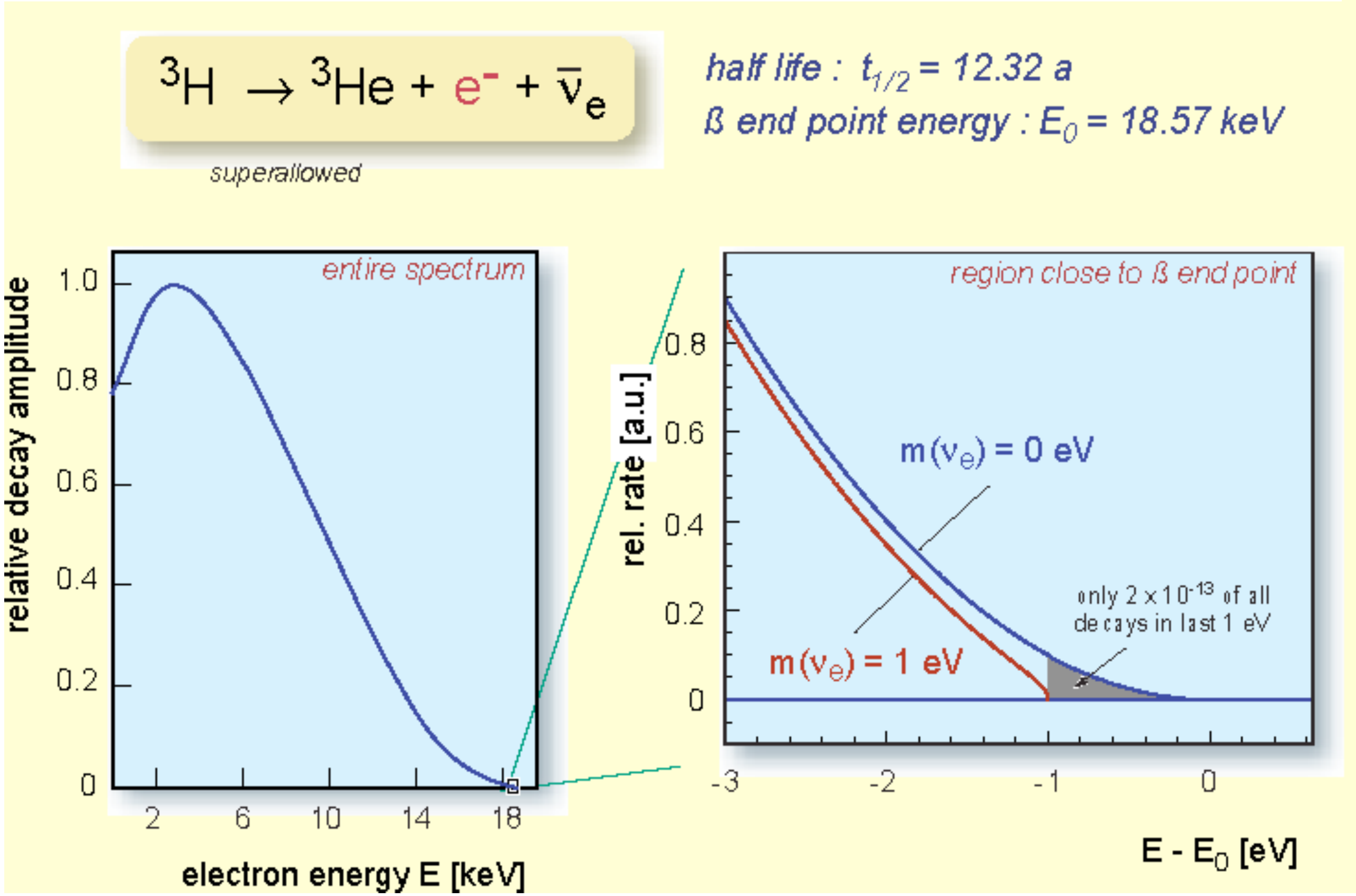
$$\delta\vartheta_{23} \approx 0.05\,\text{rad} \leftrightarrow 2.9^0$$

improvement by about a factor 2



T2K-1
90% CL
black = normal hierarchy
red = inverted hierarchy
true value 41^0
[courtesy by Enrique Fernandez]

3. absolute scale of neutrino mass (laboratory)



$$m_\nu < 2.2\,eV \quad (95\%\ CL)$$

future sensitivity [Katrin 2009-2015] 0.2 eV

3. absolute scale of neutrino mass (cosmology)

massive ν suppress the formation of small scale structures

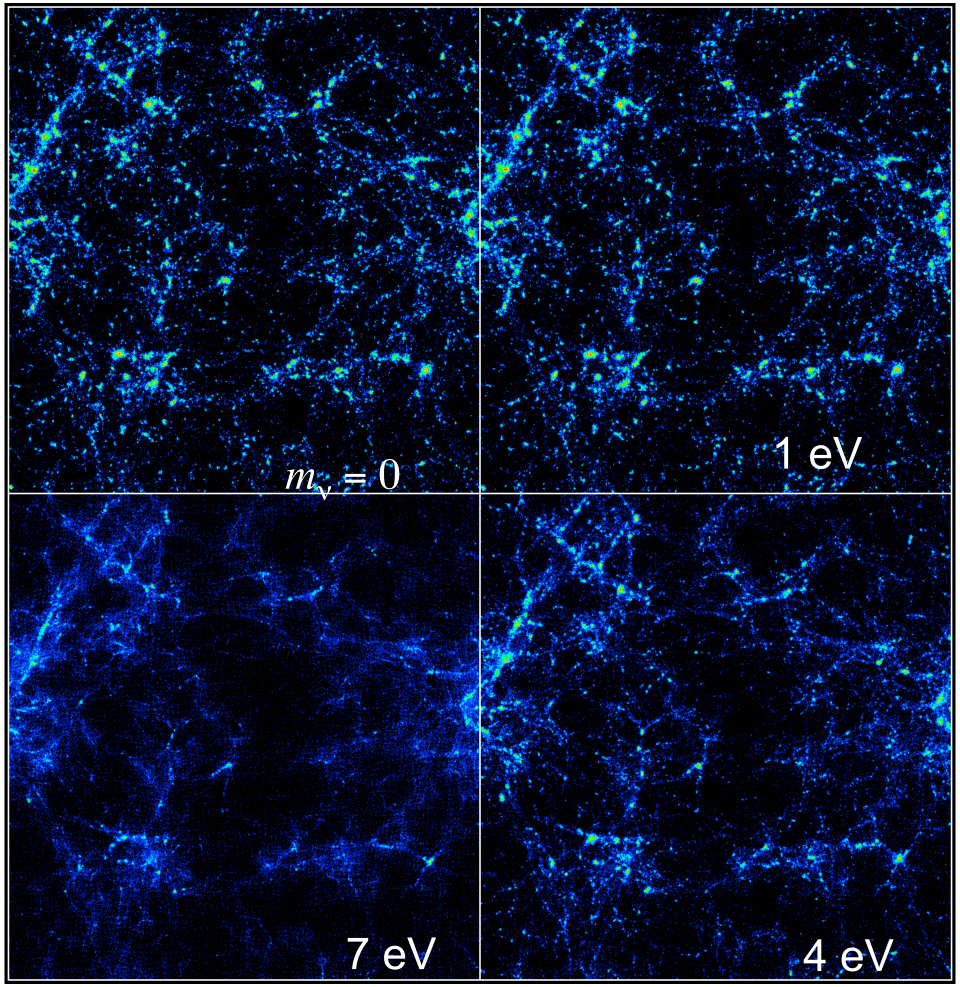
$$\sum_i m_i < 0.2 \div 1 \quad eV$$

depending on
- assumed cosmological model
- set of data included
- how data are analyzed

$$k_{\rm nr} \approx 0.026 \left(\frac{m_\nu}{1\,\rm eV}\right)^{1/2} \Omega_m^{1/2} h\,{\rm Mpc}^{-1}.$$

The small-scale suppression is given by

$$\left(\frac{\Delta P}{P}\right) \approx -8\frac{\Omega_\nu}{\Omega_m} \approx -0.8\left(\frac{m_\nu}{1\,\rm eV}\right)\left(\frac{0.1N}{\Omega_m h^2}\right)$$



$$\delta(\vec{x}) \equiv \frac{\rho(\vec{x}) - \bar{\rho}}{\bar{\rho}}$$

$$\langle \delta(\vec{x}_1)\delta(\vec{x}_2)\rangle = \int \frac{d^3k}{(2\pi)^3} e^{i\vec{k}\cdot(\vec{x}_1-\vec{x}_2)} P(\vec{k})$$

next CMB satellite
+ weak gravitational lensing
+ improved galaxy survey

$$\sum m_i < (0.02 \div 0.08)\ \text{eV}\ (1\sigma)$$

[2015?]

4. μ->e γ

motivations: - additional test of individual lepton number violation [up to now seen only in neutrino oscillations]

$$\nu_e \to \frac{1}{\sqrt{2}}\left(\nu_\mu + \nu_\tau\right) \qquad [\text{solar: SK, Kamland, SNO, Borexino}]$$

$$\nu_\mu \to \nu_\tau \qquad [\text{atm: SK, K2K, MINOS, OPERA}]$$

main goal:
establish tau neutrino appearance

$$\boxed{L_{mass} = -e^c m_e e + \frac{1}{2} \nu m_\nu \nu + h.c.}$$

μ->e γ belongs to a "family" of physical effects

$$\boxed{L_{eff} = L_{mass} + i\frac{e}{M^2} e^c\left(\sigma^{\mu\nu} F_{\mu\nu}\right)\mathcal{M}\, e + h.c.}$$

lepton electric dipole moments d_i,
anomalous magnetic moments a_i,

$$\mu \to e\gamma \quad \tau \to \mu\gamma \quad \tau \to e\gamma$$

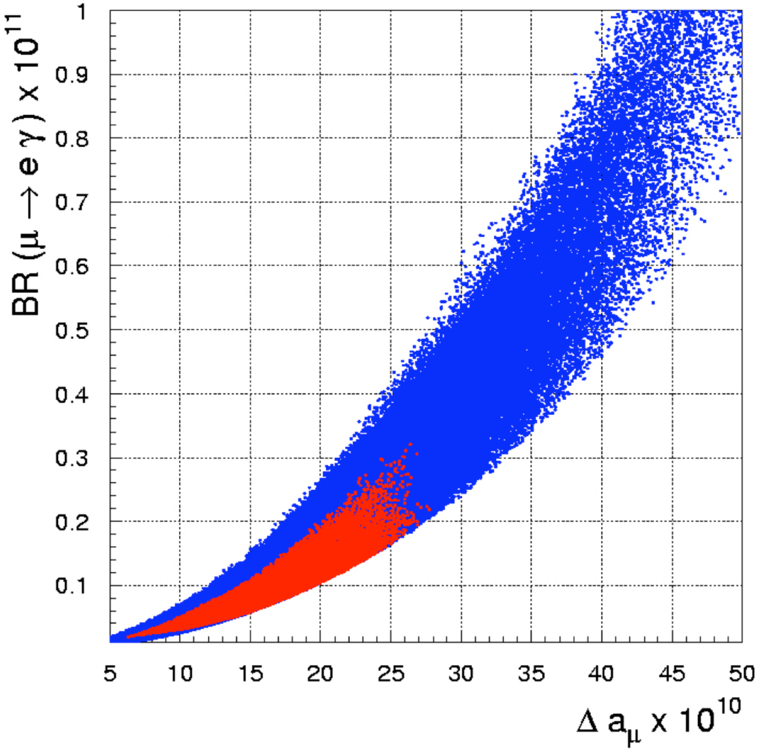
even in the most conservative case, we expect a contribution to μ->e γ, at some level

$$\mathcal{M} \propto m_e + \alpha\, m_e \left(m_\nu^+ m_\nu\right)\frac{\Lambda_L^2}{v^4} + \ldots$$

the important point for an observable effect is M ≈ TeV [in the range of interest for LHC]

we have a 3σ indication from (g-2)μ that this is the case!

$$\delta a_\mu \approx 30 \times 10^{-10} \Rightarrow M \approx 2.7\ TeV$$



μ->e γ versus muon (g-2)

[Isidori, Mescia, Paradisi, Temes 0703035]

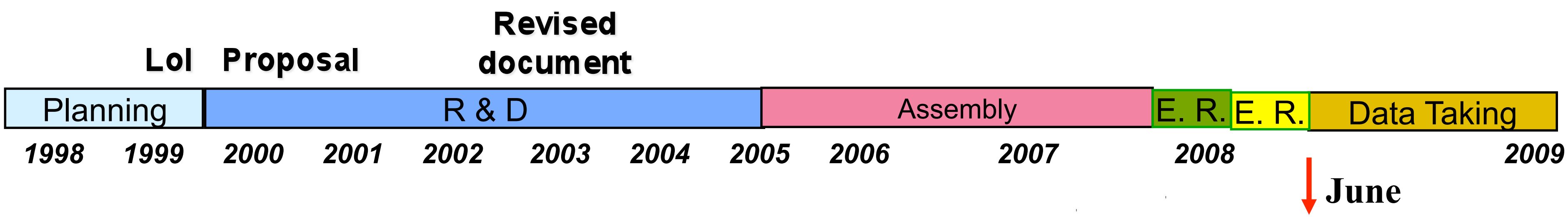
Figure 1: Expectations for $\mathcal{B}(\mu \to e\gamma)$ and vs. $\Delta a_\mu = (g_\mu - g_\mu^{\rm SM})/2$, assuming $|\delta_{LL}^{12}| = 10^{-4}$. The plots have been obtained employing the following ranges: 300 GeV $\leq M_{\tilde{\ell}} \leq$ 600 GeV, 200 GeV $\leq M_2 \leq$ 1000 GeV, 500 GeV $\leq \mu \leq$ 1000 GeV, $10 \leq \tan\beta \leq 50$, and setting $A_U = -1$ TeV, $M_{\tilde{q}} = 1.5$ TeV.

interesting relation with ϑ_{13}

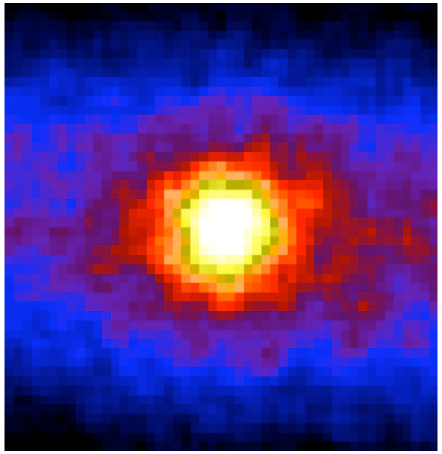
[L. Calibbi, Faccia, Masiero, Vempati hep-ph/0610241]

MEG time scale [from Bemporad's talk at NOVE 2008]

new engineering run from April 15th 2008
start of data taking in June 2008
goal: hope to get a significant result before entering the LHC era
Measurements and detector simulation make us confident that we can reach the SES of 4×10^{-14} to $\mu \to e\gamma$ (90% C.L. limit BR 10^{-13}) and possibly below…



5. Neutrino telescopes



this is a picture of the sun
reconstructed from neutrinos

up to now, only two astrophysical objects have been identified as neutrino sources: the sun and supernova SN1987A

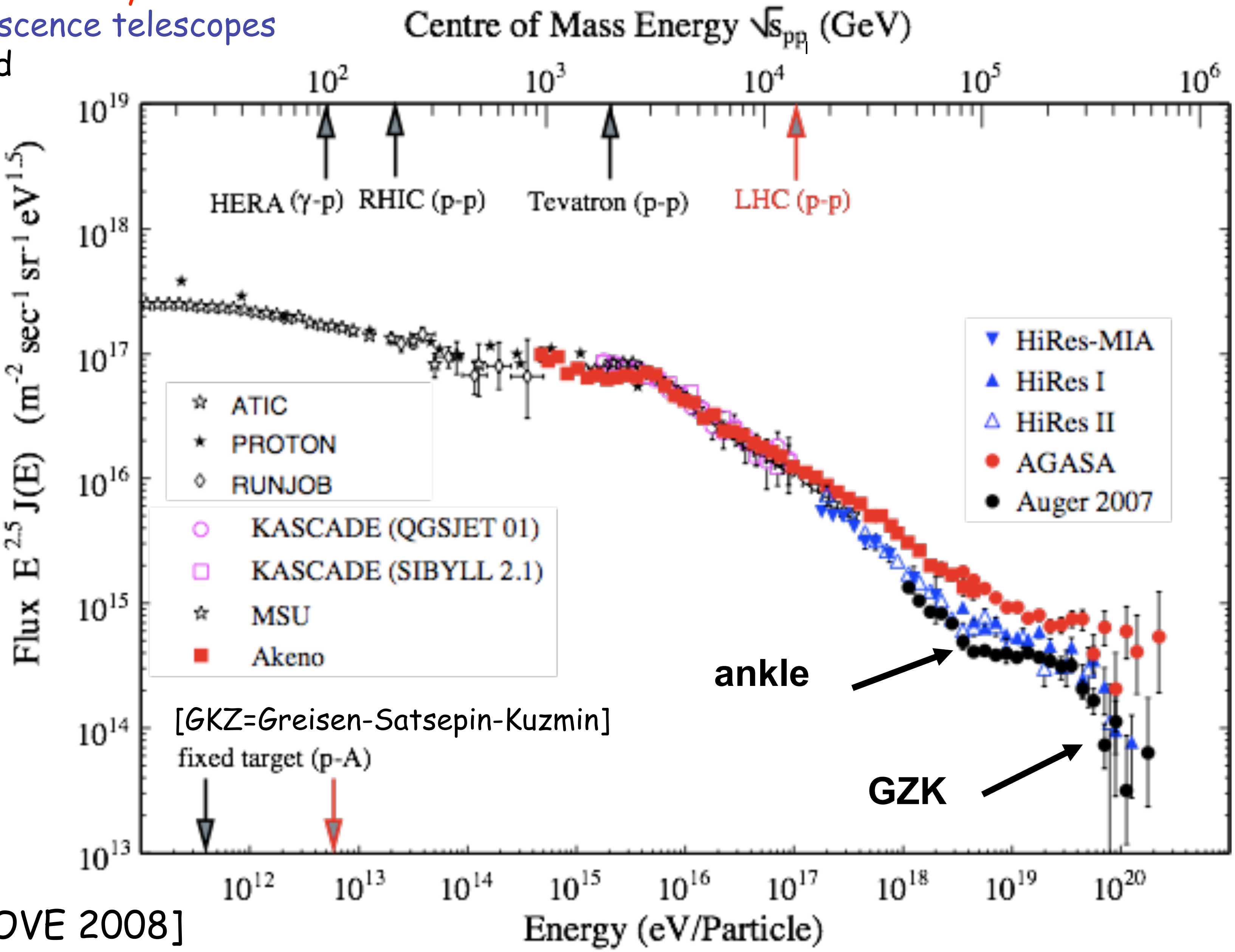
- sun
  direct observation of nuclear reactions in the core of the sun [only very recently we could study nuclear reactions at the sun energies directly in the lab (LUNA)]

- supernovae
  direct observation of the core collapse process

motivations:
- UHE neutrinos are believed to accompany UHECRs, escaping from remote regions that are opaque to em radiation
- identification of sources of UHECRs [GRB, AGN, decay of ultraheavy particles…]
- unique probe of the physics of these sources

Cosmic ray spectrum - 2008

AGASA: surface array
HiRes: fluorescence telescopes
Auger: Hybrid



[Matthiae NOVE 2008]

the existence of the GZK cutoff strongly supports a non-vanishing flux of UHE neutrinos (cosmogenic or GZK neutrinos)

most plausible mechanism for the GZK cutoff is pion photoproduction

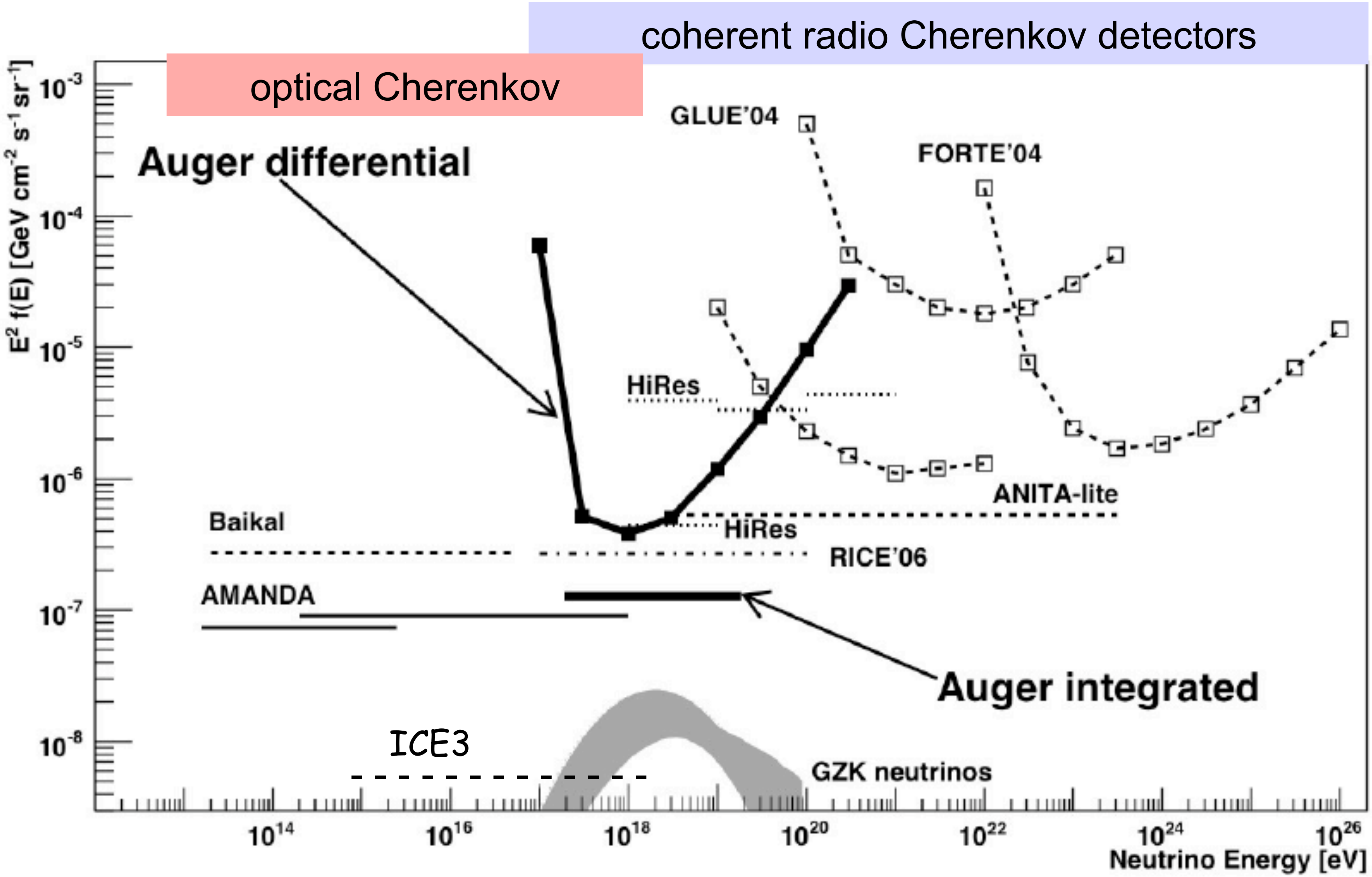
$$p + \gamma_{CMB} \rightarrow \Delta^{+} \rightarrow \begin{cases} p + \pi^{0} \\ n + \pi^{+} \end{cases}$$

$$n \rightarrow p + e + \boxed{\bar{\nu}_e}$$
$$\pi^{+} \rightarrow \mu^{+} + \boxed{\nu_\mu}$$
$$\mu^{+} \rightarrow e^{+} + \boxed{\nu_e + \bar{\nu}_\mu}$$

- additional contributions can be present

expected GZK neutrino flux has an uncertainty by a factor 2-4
- unknown CR spectrum at the source
- not precisely known CR composition
- cosmological evolution of the sources

- km-scale (gigaton) neutrino telescopes like ICE3 are needed to detect by optical Cerenkov effect these neutrinos



coherent radio Cherenkov detectors
optical Cherenkov
Auger differential
GLUE'04
FORTE'04
HiRes
ANITA-lite
Baikal
HiRes
RICE'06
AMANDA
Auger integrated
ICE3
GZK neutrinos
E^2 f(E) [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{14}
10^{16}
10^{18}
10^{20}
10^{22}
10^{24}
10^{26}
Neutrino Energy [eV]

Summary

1. Neutrinoless double beta decay

2. ϑ_{13}

3. absolute scale of neutrino mass

4. $\mu \to e\, \gamma$ and LFV

5. Neutrinos from extragalactic sources

I hope that in the near future we will discuss together the evidence for one or more of these effects!