TPC 2016

beyond the Standard Model ?

- Higgs discovery and… still the Standard Model
- wimp miracle ?

neutrinos

- only physics beyond the standard model, but still veiled in mystery
- cosmology, astronomy, pyramids,..

why are the weak interactions so weak ?

The Standard Model

ANNO IV · VOL. II · N. 12 QUINDICINALE 31 DICEMBRE 1933 · XII

LA RICERCA SCIENTIFICA

ED IL PROGRESSO TECNICO NELL'ECONOMIA NAZIONALE

Tentativo di una teoria dell'emissione dei raggi "beta"

Nota del prof. ENRICO FERMI

Riassunto: Teoria della emissione dei raggi β delle sostanze radioattive, fondata sull'ipotesi che gli elettroni emessi dai nuclei non esistano prima della disintegrazione ma vengano formati, insieme ad un neutrino, in modo analogo alla formazione di un quanto di luce che accompagna un salto quantico di un atomo. Confronto della teoria con l'esperienza.

$$\frac{G_F}{(\hbar c)^3} = \frac{\sqrt{2}}{8}\frac{g^2}{m_W^2} = 1.1663787(6) \times 10^{-5}\ \mathrm{GeV}^{-2}$$

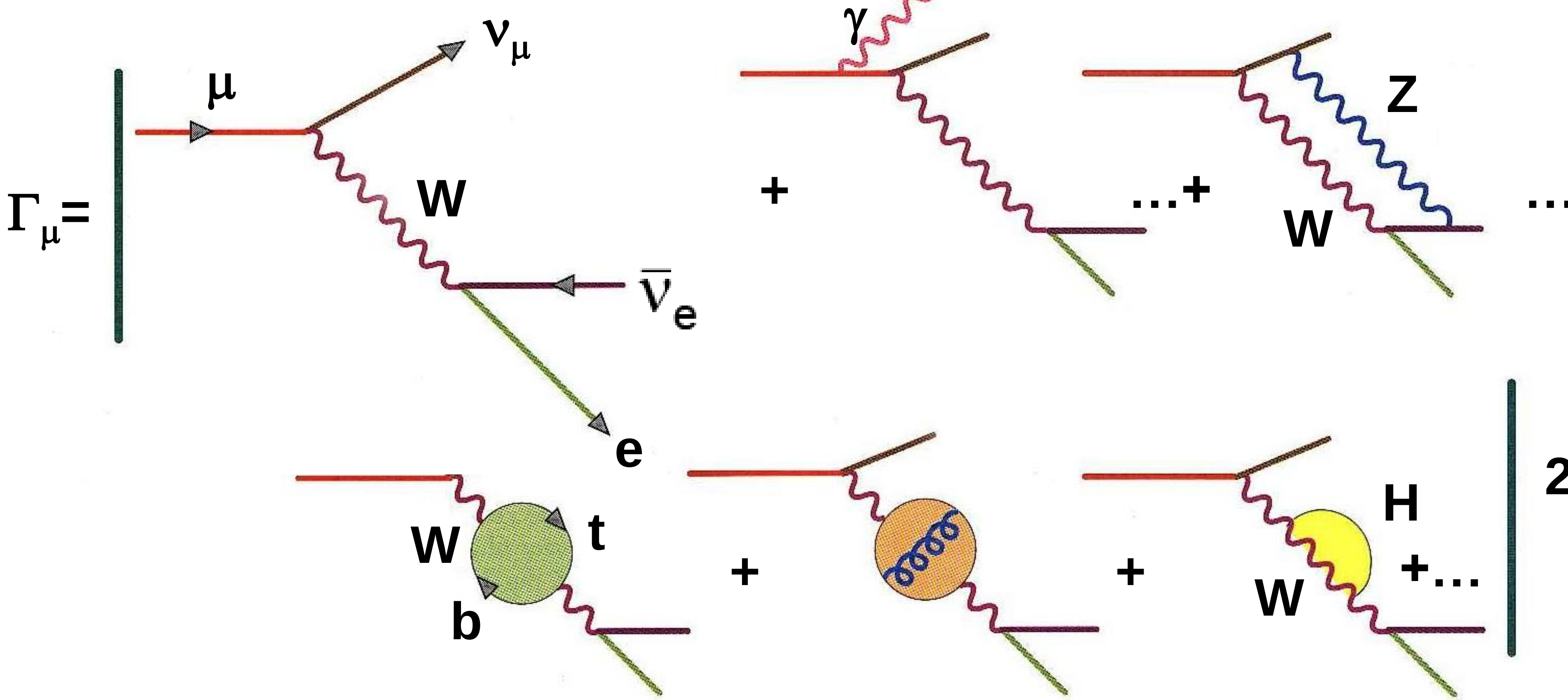
Fermi 1933

neutrino; e l'energia liberata nel processo si ripartirebbe comunque tra i due corpuscoli in modo appunto che l'energia dell'elettrone possa prendere tutti i valori da 0 fino ad un certo massimo. Il neutrino d'altra parte, a causa della sua neutralità elettrica e della piccolissima massa, avrebbe un potere penetrante così elevato da sfuggire praticamente ad ogni attuale metodo di osservazione. Nella teoria che ci proponiamo di esporre ci metteremo dal punto di vista della ipotesi dell'esistenza del neutrino.

LA RICERCA SCIENTIFICA, anno IV, vol. II, N. 12, 31 dicembre 1933

Tentativo di una teoria dell'emissione dei raggi "beta"

Nota del prof. ENRICO FERMI



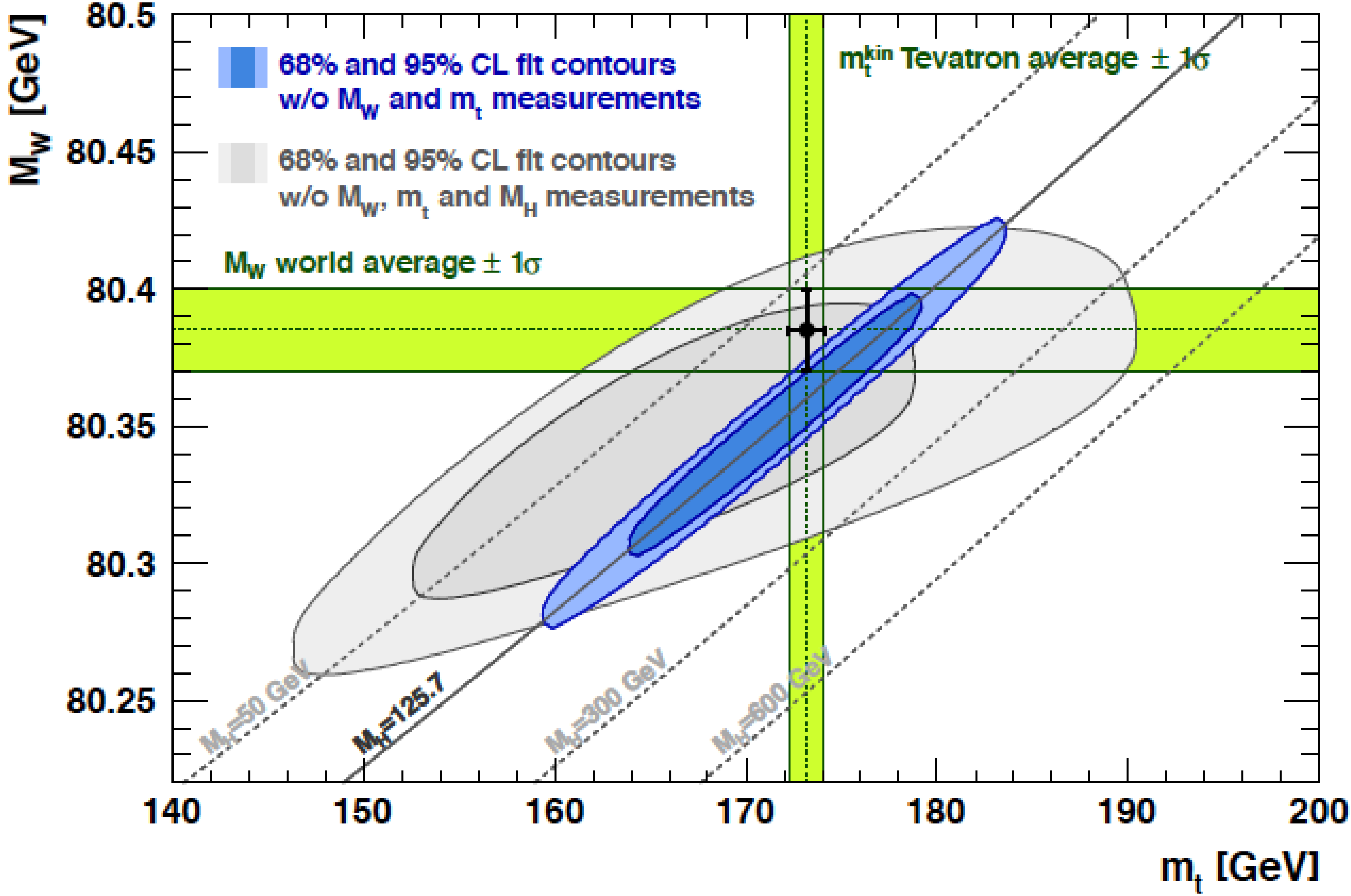
$$G_\mu = \left(\frac{\pi\,\alpha}{\sqrt{2}M_W^2}\right)\left(\frac{1}{\left(1 - M_W^2 / M_Z^2\right)}\right)\left(1 + \Delta r\right)$$

effective Fermi theory of weak interactions (1934) is modified by rare effects from high energies with scale $\Lambda = M_W$

precision electroweak measurements

Parameter	Input value	Free in fit	Fit result incl. M_H	Fit result not incl. M_H	Fit result incl. M_H but not exp. input in row
M_H [GeV][(o)]	125.7 ± 0.4	yes	125.7 ± 0.4	94^{+25}_{-22}	94^{+25}_{-22}
[illegible]	80.385 ± 0.015	–	80.367 ± 0.007	80.380 ± 0.012	80.359 ± 0.011
[illegible]	2.085 ± 0.042	–	2.091 ± 0.001	2.092 ± 0.001	2.091 ± 0.001
M_Z [GeV]	[illegible]	yes	91.1878 ± 0.0021	91.1874 ± 0.0021	91.1983 ± 0.0116
Γ_Z [GeV]	[illegible]	–	2.4954 ± 0.0014	2.4958 ± 0.0015	2.4951 ± 0.0017
σ^0_{had} [nb]	[illegible]	–	41.479 ± 0.014	41.478 ± 0.014	41.470 ± 0.015
R^0_ℓ	[illegible]	–	20.740 ± 0.017	20.743 ± 0.018	20.716 ± 0.026
$A^{0,\ell}_{FB}$	[illegible]	[illegible]	0.01627 ± 0.0002	0.01637 ± 0.0002	0.01624 ± 0.0002
A_ℓ [(*)]	[illegible]	[illegible]	[illegible]	0.1477 ± 0.0009	0.1468 ± 0.0005[(†)]
$\sin^2\theta^\ell_{\mathrm{eff}}(Q_{FB})$	[illegible]	[illegible]	[illegible]	$0.23143^{+0.00010}_{-0.00012}$	0.23150 ± 0.00009
A_c	0.670 ± 0.027	[illegible]	[illegible]	$0.6682^{+0.00042}_{-0.00035}$	0.6680 ± 0.00031
A_b	0.923 ± 0.020	–	[illegible]	0.93468 ± 0.00008	0.93463 ± 0.00006
$A^{0,c}_{FB}$	0.0707 ± 0.0035	–	[illegible]	[illegible]	0.0738 ± 0.0004
$A^{0,b}_{FB}$	0.0992 ± 0.0016	–	[illegible]	[illegible]	0.1034 ± 0.0004
R^0_c	0.1721 ± 0.0030	–	[illegible]	[illegible]	0.17223 ± 0.00006
R^0_b	0.21629 ± 0.00066	–	0.21474 ± 0.00003	[illegible]	0.21473 ± 0.00003
$\overline{m}_c$ [GeV]	$1.27^{+0.07}_{-0.11}$	yes	$1.27^{+0.07}_{-0.11}$	[illegible]	–
$\overline{m}_b$ [GeV]	$4.20^{+0.17}_{-0.07}$	yes	$4.20^{+0.17}_{-0.07}$	[illegible]	–
m_t [GeV]	173.18 ± 0.94	yes	173.52 ± 0.88	[illegible]	[illegible]
$\Delta\alpha^{(5)}_{\mathrm{had}}(M^2_Z)$ [(△▽)]	2757 ± 10	yes	2755 ± 11	2757 ± 11	[illegible]
$\alpha_s(M^2_Z)$	–	yes	0.1191 ± 0.0028	0.1192 ± 0.0028	[illegible]
$\delta_{th} M_W$ [MeV]	$[-4, 4]_{\mathrm{theo}}$	yes	4	4	[illegible]
$\delta_{th}\sin^2\theta^\ell_{\mathrm{eff}}$ [(△)]	$[-4.7, 4.7]_{\mathrm{theo}}$	yes	-1.4	4.7	–

[(o)] Average of ATLAS ($M_H = 126.0 \pm 0.4$ (stat) ± 0.4 (sys)) and CMS ($M_H = 125.3 \pm 0.4$ (stat) ± 0.5 (sys)) measurements assuming no correlation of the systematic uncertainties (see discussion in Sect. 2). [(*)] Average of LEP ($A_\ell = 0.1465 \pm 0.0033$) and SLD ($A_\ell = 0.1513 \pm 0.0021$) measurements, used as two measurements in the fit. [(†)] The fit w/o the LEP (SLD) measurement gives $A_\ell = 0.1474^{+0.0008}_{-0.0009}$ ($A_\ell = 0.1467^{+0.0006}_{-0.0004}$).
[(△)] In units of 10^{-5}. [(▽)] Rescaled due to α_s dependency.



68% and 95% CL fit contours
w/o M_W and m_t measurements
68% and 95% CL fit contours
w/o M_W, m_t and M_H measurements
M_W world average ± 1σ
m_t^{kin} Tevatron average ± 1σ
M_H=50 GeV
M_H=125.7
M_H=300 GeV
M_H=600 GeV
M_W [GeV]
80.5
80.45
80.4
80.35
80.3
80.25
140
150
160
170
180
190
200
m_t [GeV]

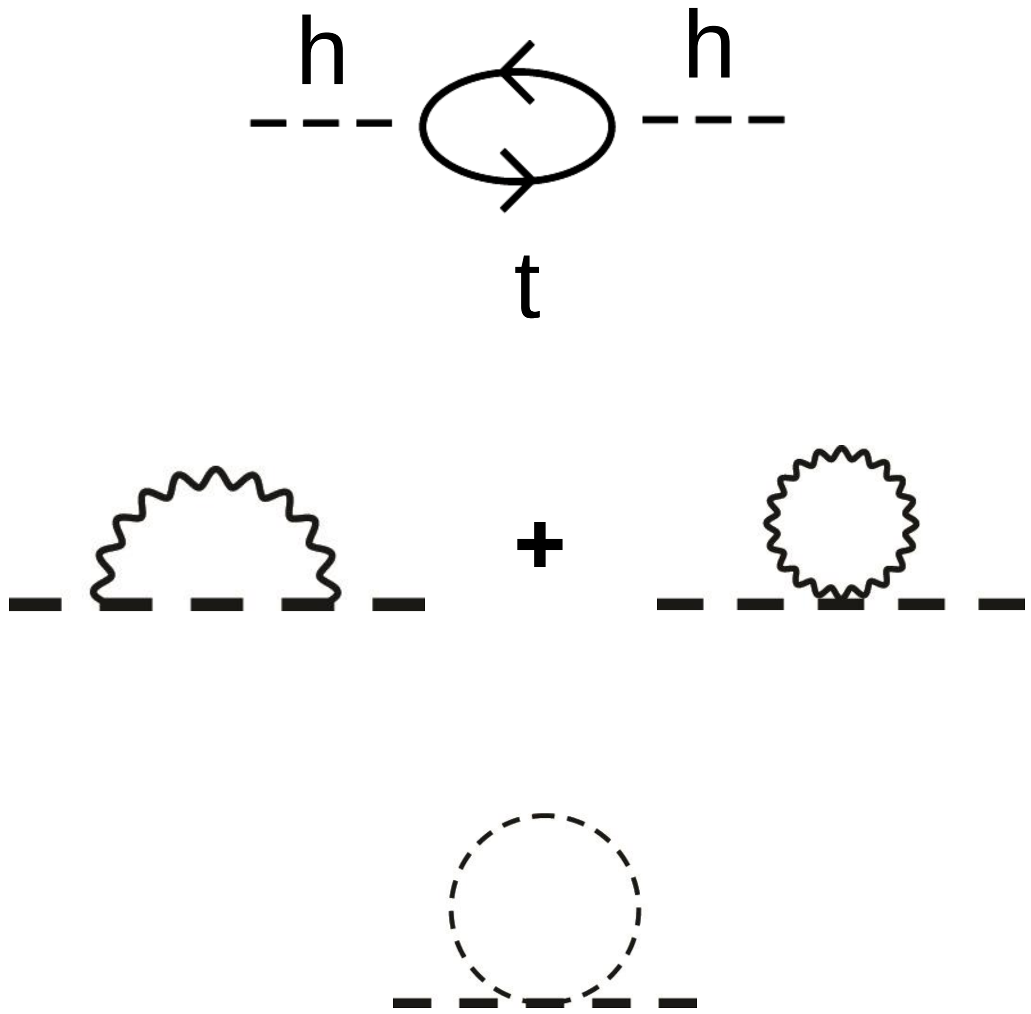
so the higgs exists,

but that does not solve the problem

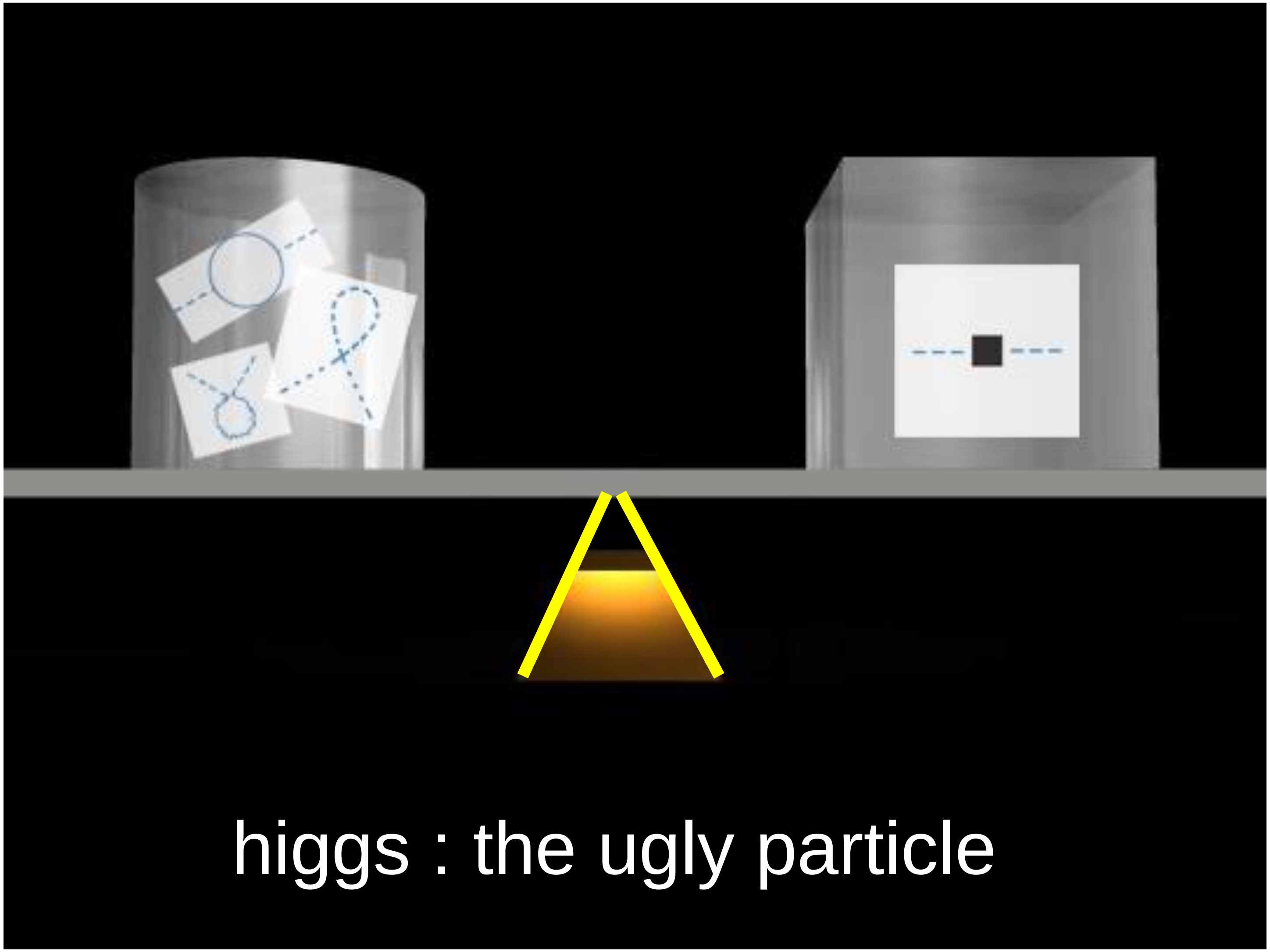
top

W,Z

higgs



control of the higgs mass


higgs : the ugly particle

new high energy effects with scale Λ must control the higgs mass or….

$$\delta_q m^2 = \frac{3}{16\pi^2 v^2}(2m_W^2 + m_Z^2 + m_h^2 - 4m_t^2)\Lambda_{SM}^2$$

$$\left|\frac{\delta_q m^2}{m^2}\right| = \left|\frac{\delta v^2}{v^2}\right| \leq 10\% \Rightarrow \boxed{\Lambda_{SM} \lesssim 2-3\ \text{TeV}}$$

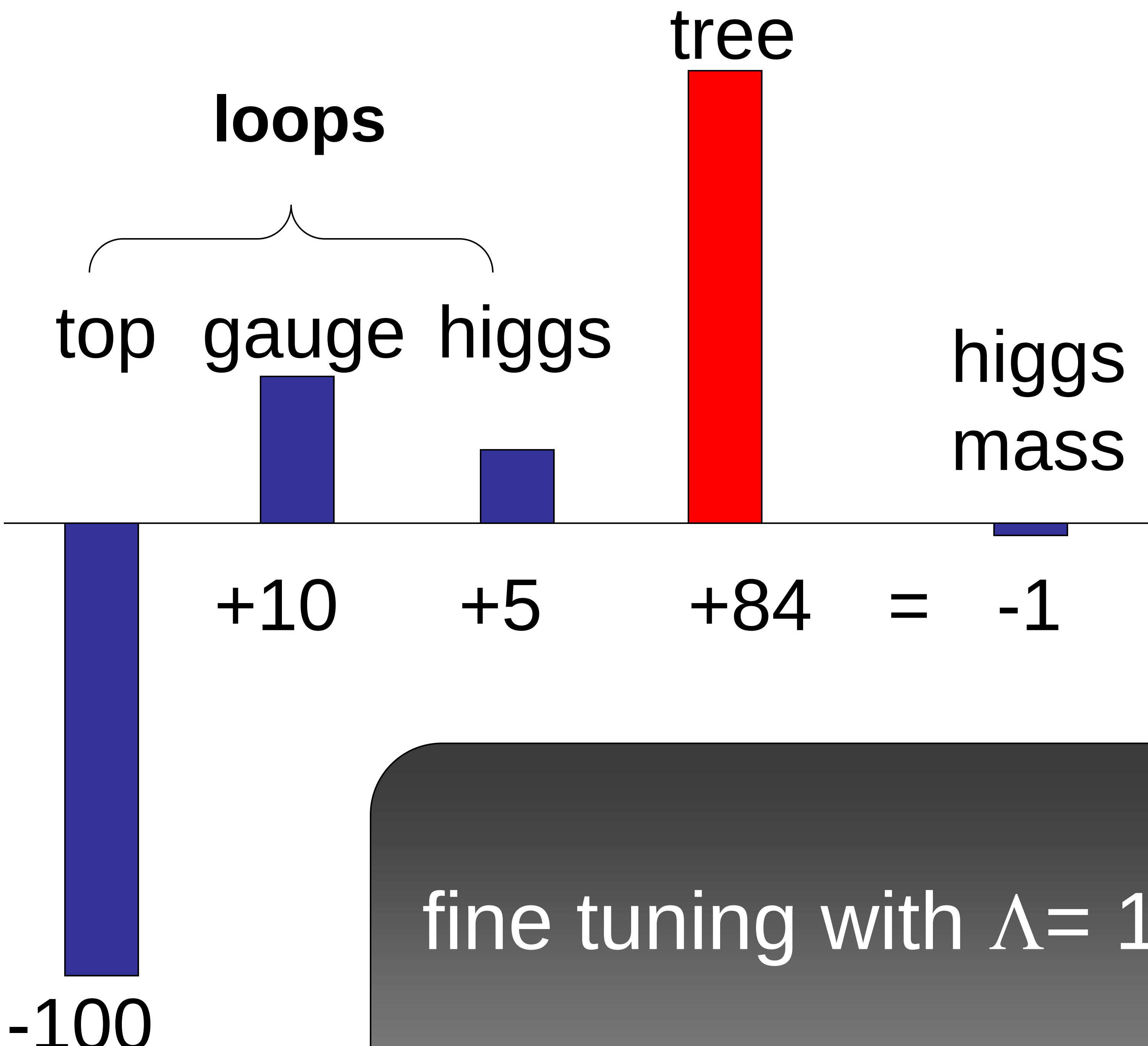
tension with accuracy of the tests of the Standard Model !!!

unless (Veltman)

$$2m_W^2 + m_Z^2 + m_h^2 - 4m_t^2 \simeq 0$$ → m_h ~ 210~225 GeV

effective Fermi theory of weak interactions (1934) is modified by rare effects from high energies with scale $\Lambda = M_W$

effective Standard Model of weak interactions (1978) is modified by rare effects from high energies with scale Λ = ?



fine tuning with Λ= 10TeV

higgs and nothing else…

made possible by :

- anthropics
- or, new physics

conclusion:

there must be new physics

other fine-tuning problems as opportunities for new physics

- higgs mass more than 10^{-2}
- baryogenesis more than 10^{-10}
- cosmic coincidence:
  factor 2 out of 10^{-60}
- cosmological constant more than 10^{-120}

baryon asymmetry in the early Universe

Quark	AntiQuark
10,000,000,001	10,000,000,000

quarks and antiquarks have annihilated away except for a tiny difference

other fine-tuning problems as opportunities for new physics

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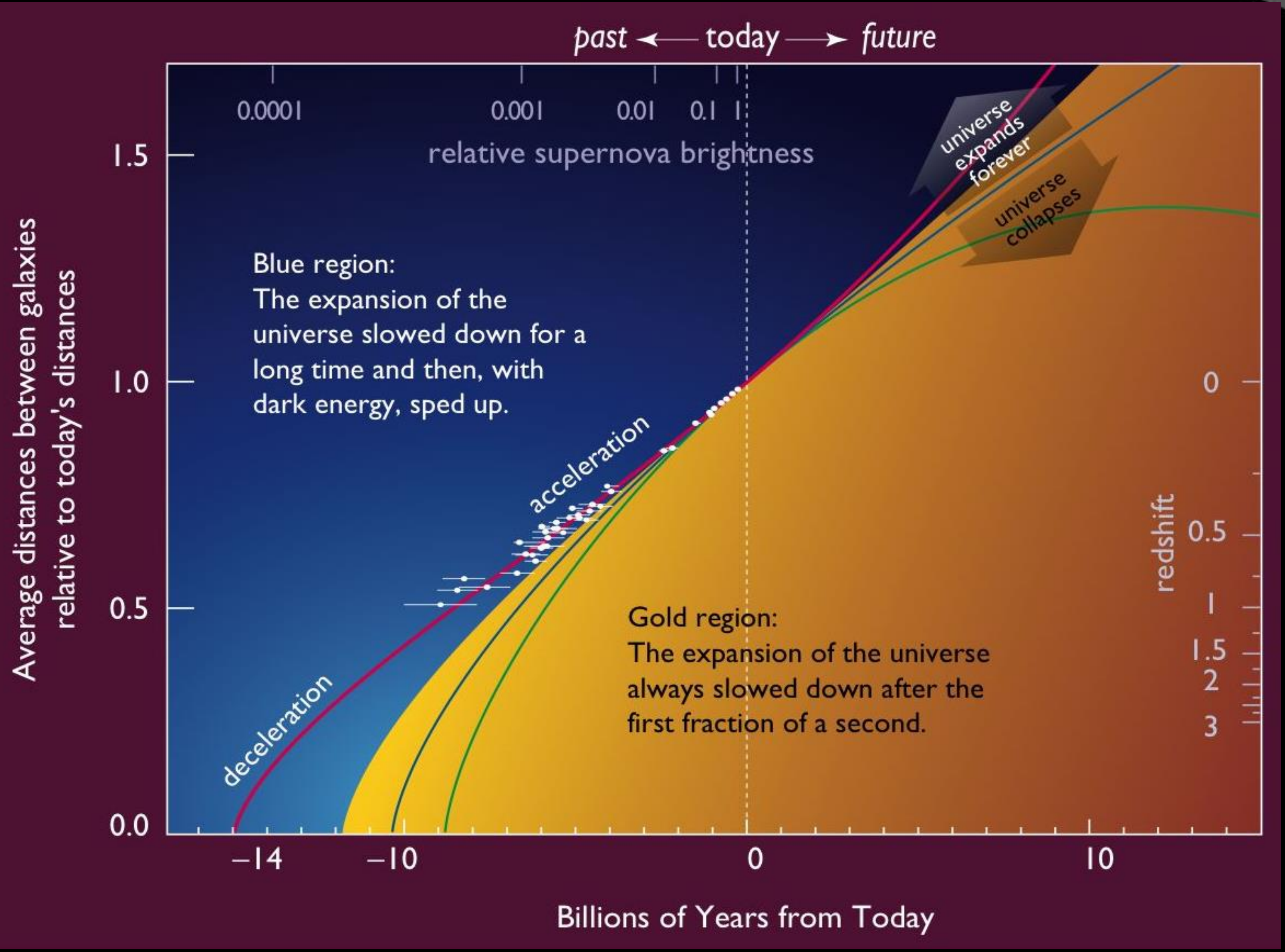
- baryogenesis more than 10^{-10}
- cosmic coincidence:
  factor 2 out of 10^{-60}
- cosmological constant more than 10^{-120}

cosmic coincidence (why now?)

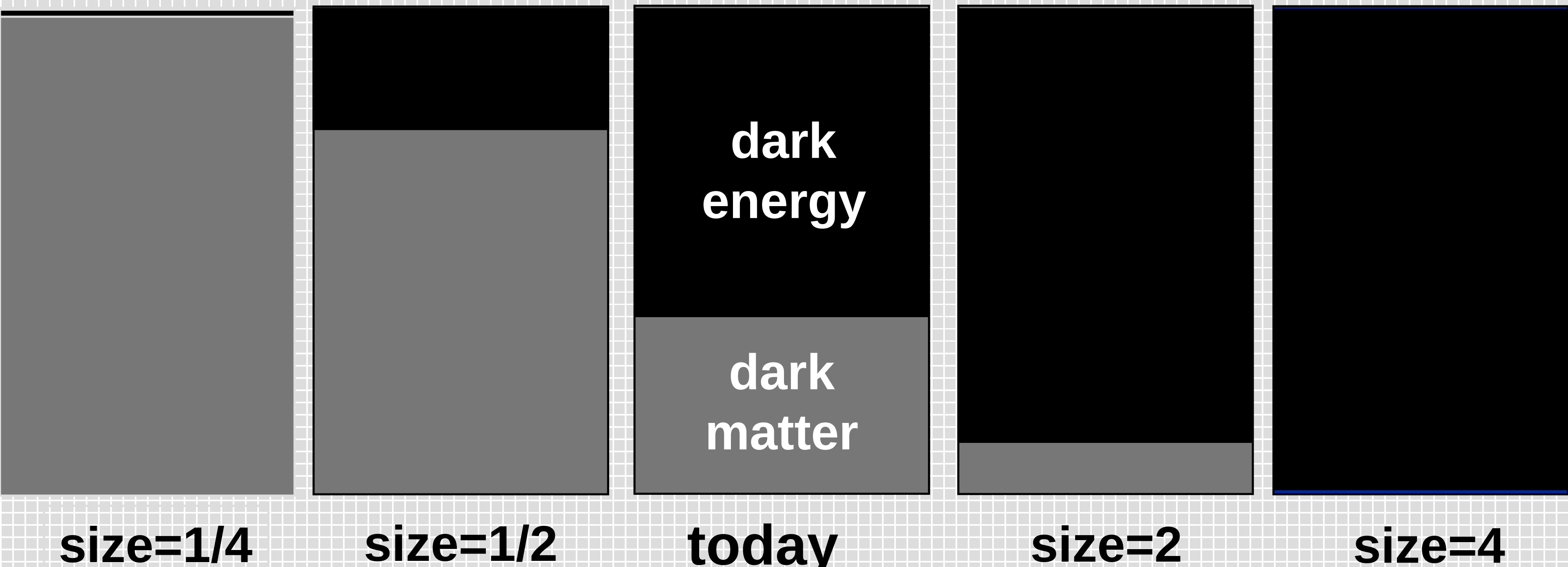


matter to radiation and radiation to dark energy

cosmic coincidence: why now ?

think of the energy in Λ as the level of the quantum "sea" :

at most times in history, matter is either drowned or absent



other fine-tuning problems as opportunities for new physics

- higgs mass more than 10^{-2}
- baryogenesis more than 10^{-10}
- cosmic coincidence:
  factor 2 out of 10^{-60}
- cosmological constant more than 10^{-120}

the cosmological constant

e.g. energy of the vacuum = Σ (0-point energies)

$$\Lambda = \int^{M_{Pl}} \frac{1}{2}\hbar w = \int^{M_{Pl}} \frac{1}{2}\hbar\sqrt{k^2+m^2}\, d^3k \sim M_{Pl}{}^4$$

→ Universe cools before we appear

$$\mathit{instead}\ \mathrm{L} \sim (10^{-30} M_{Pl})^4 \sim (10^{-3} eV)^4$$

we are definitely missing something…

the dark energy problem at the end of the 19th century:

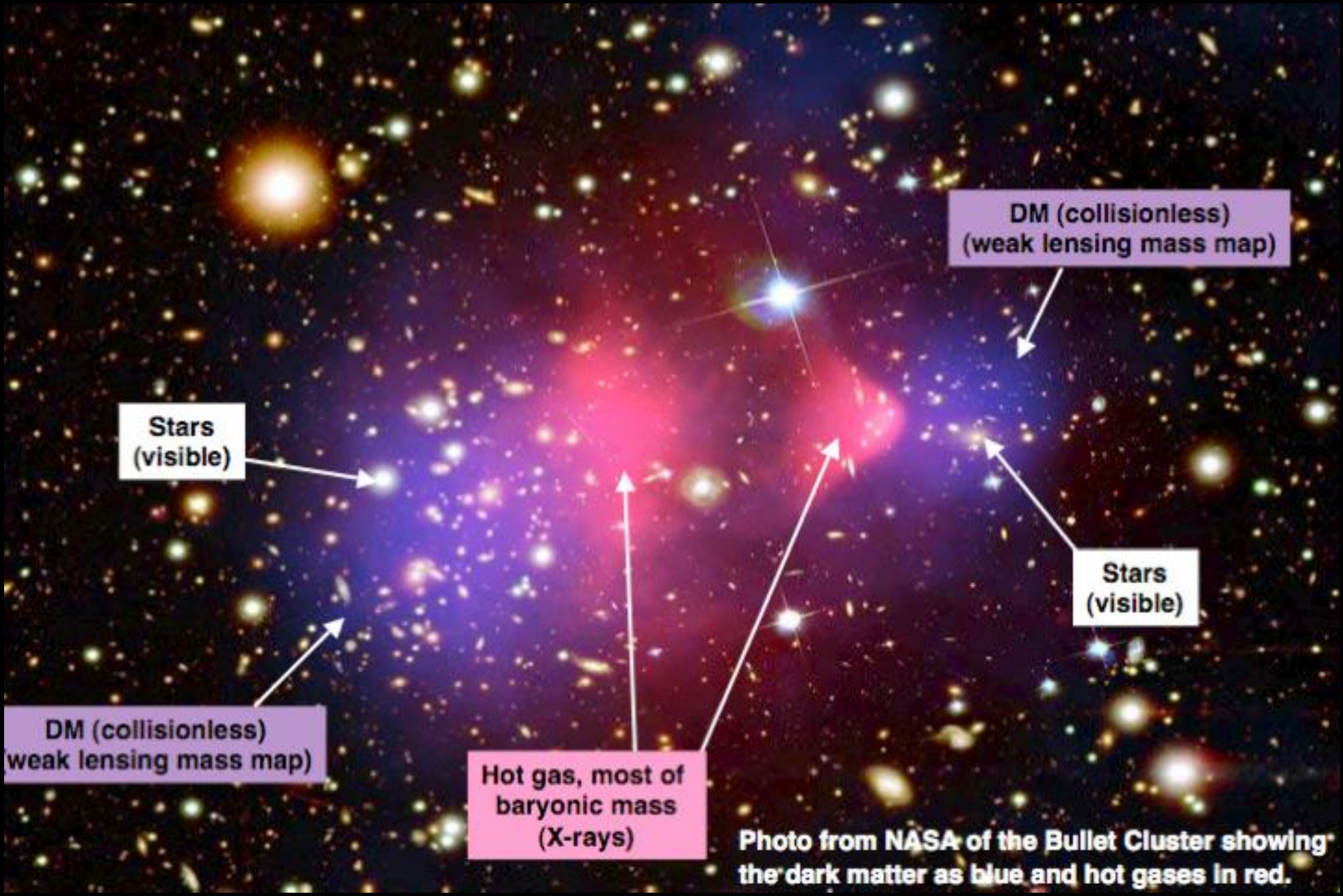
- geology and Darwin's evolution established the age of the sun to be larger than ~ 100 million years
- Lord Kelvin: neither chemistry, nor gravity can supply the required energy
- neither chemistry nor gravity solved this problem

→ Rutherford did

we are definitely missing something…

axions?

particle dark matter: two colliding galaxy clusters



neutrinos: the sun and the Earth

$$\nu_3 = \left(\frac{\nu_\mu + \nu_\tau}{\sqrt{2}}\right) + |s_{13}| e^{i\delta} \nu_e$$

$$\nu_2 = \sin\theta_\odot \nu_e + \cos\theta_\odot \left(\frac{\nu_\mu - \nu_\tau}{\sqrt{2}}\right)$$

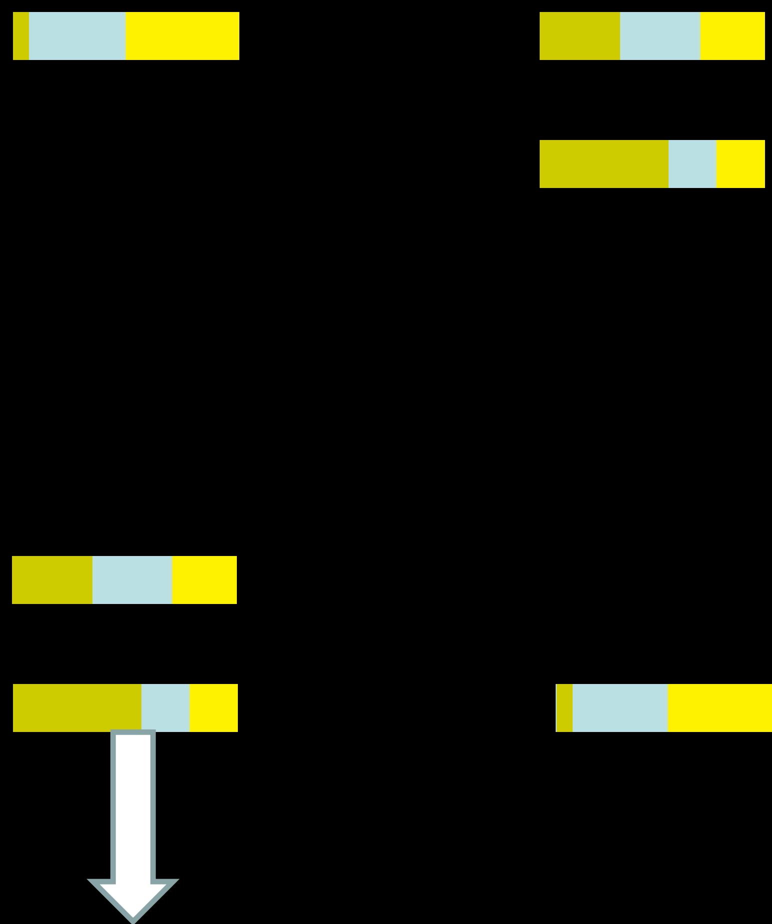
$$\nu_1 = -\cos\theta_\odot \nu_e + \sin\theta_\odot \left(\frac{\nu_\mu - \nu_\tau}{\sqrt{2}}\right)$$

neutrinos: full time employment

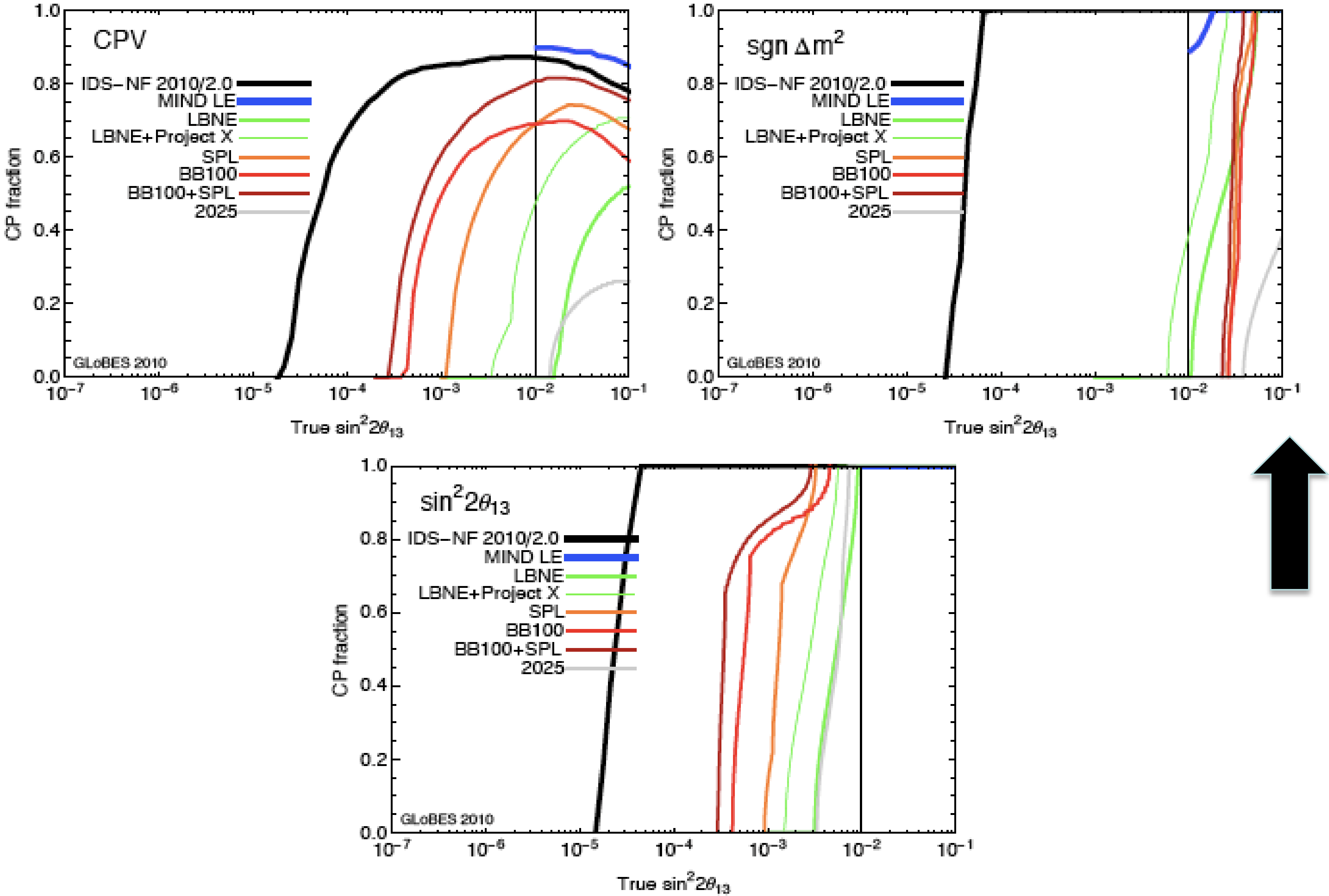
hierarchy ?

θ_{13} ?, δ ?

$(\theta_{23} = \frac{\pi}{4})$?



mass ?


CPV
IDS−NF 2010/2.0
MIND LE
LBNE
LBNE+Project X
SPL
BB100
BB100+SPL
2025
GLoBES 2010
CP fraction
True $\sin^2 2\theta_{13}$
sgn Δm^2
IDS−NF 2010/2.0
MIND LE
LBNE
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SPL
BB100
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2025
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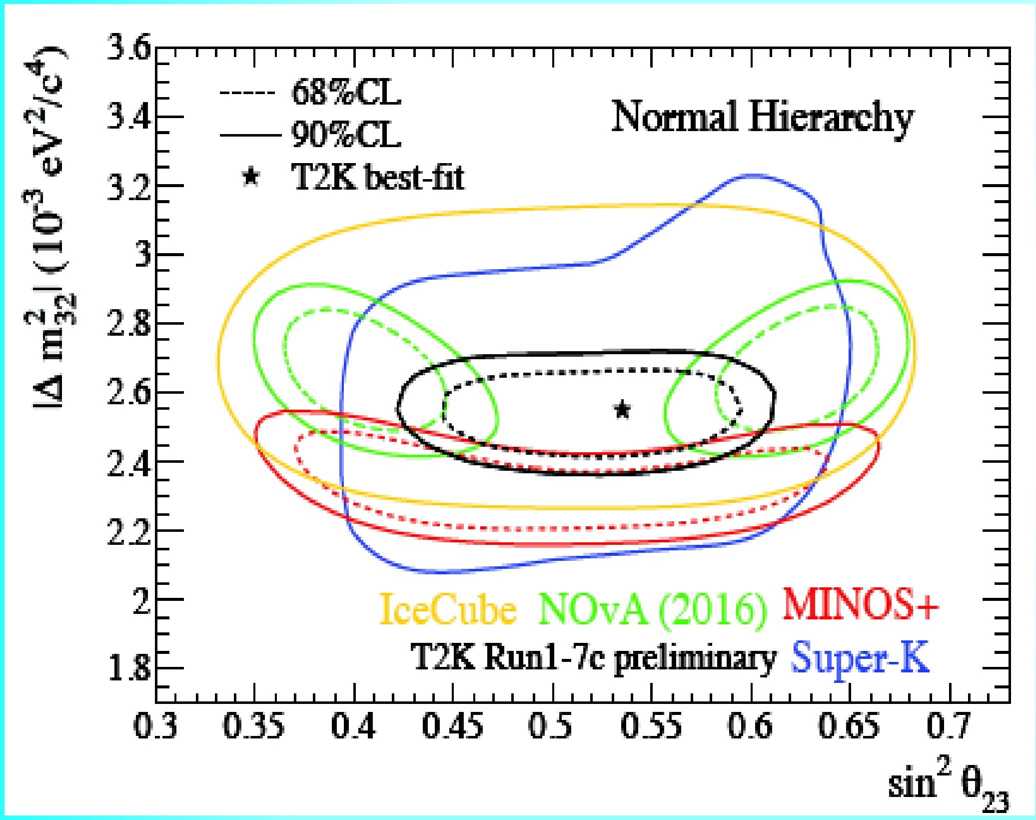
BB100
BB100+SPL
2025
GLoBES 2010
CP fraction
True $\sin^2 2\theta_{13}$

2-3 mixing: geography vs. new physics



US vs Japan or
New physics?

J. Hartnell, NOW2016

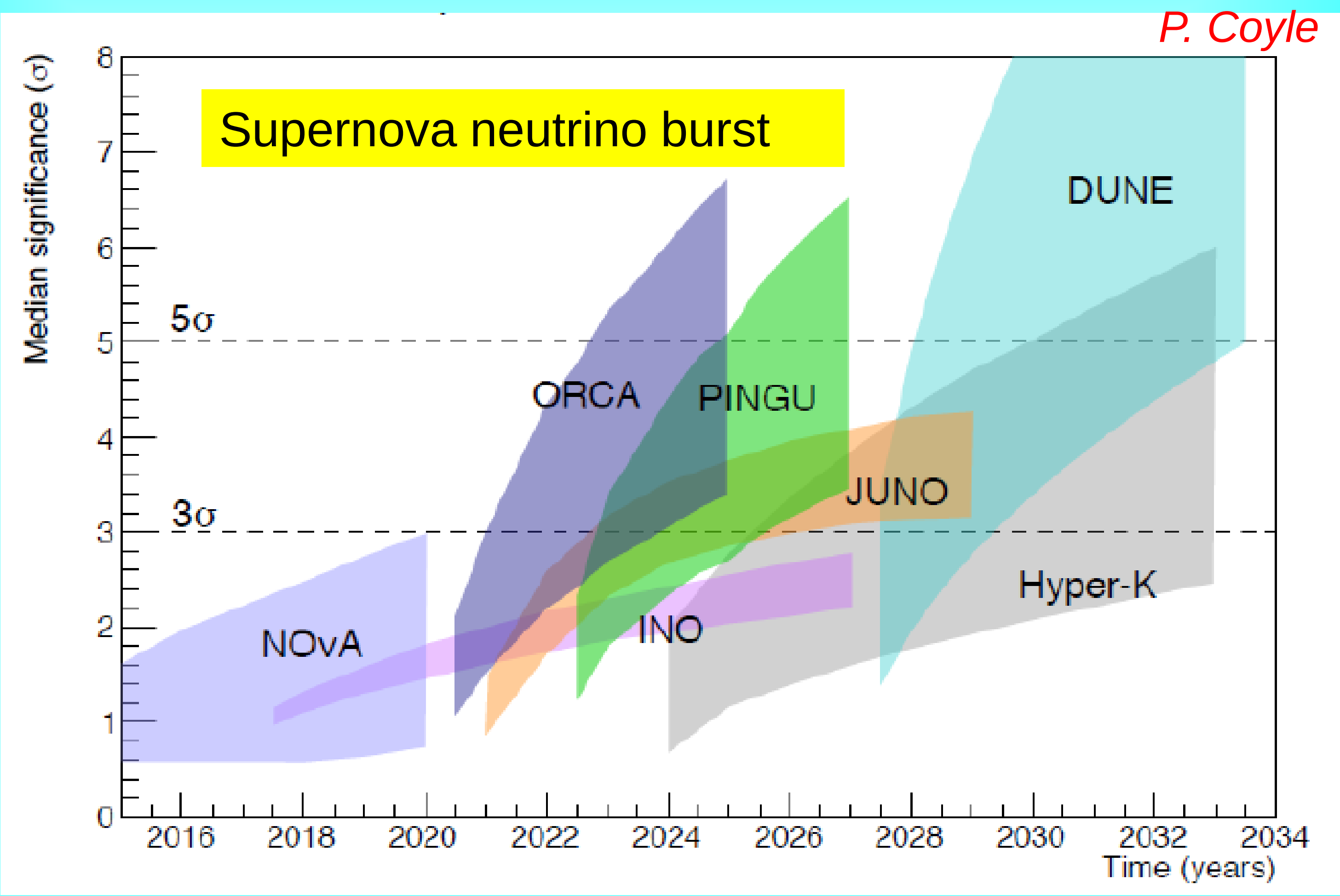
NOvA:

$\sin^2\theta_{23} = 0.40 +0.03/-0.02$

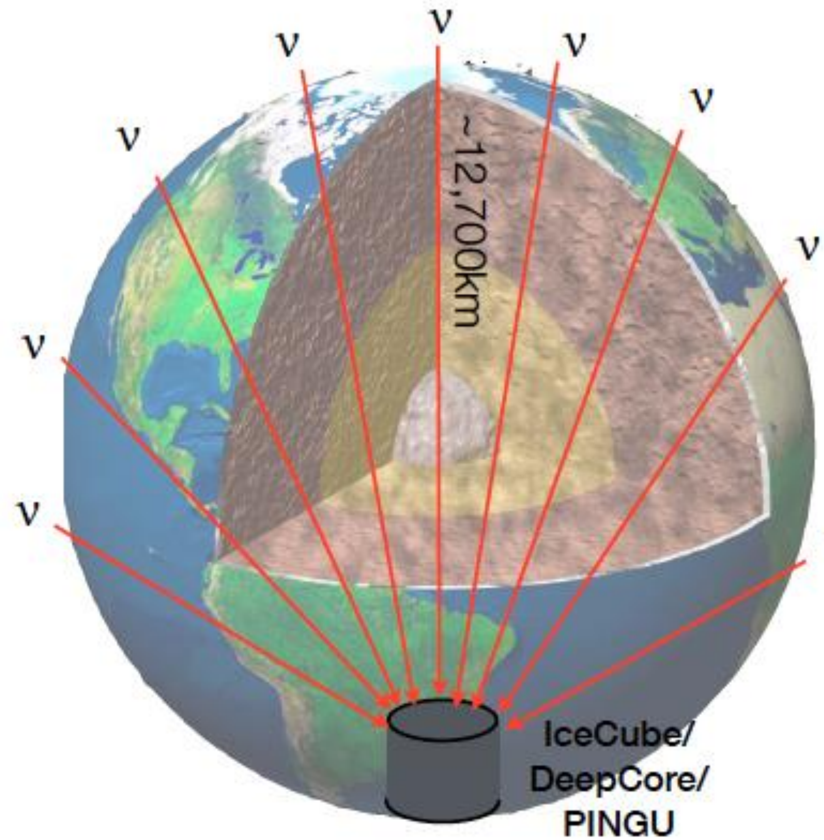
Maximal mixing
excluded at 2.5 σ

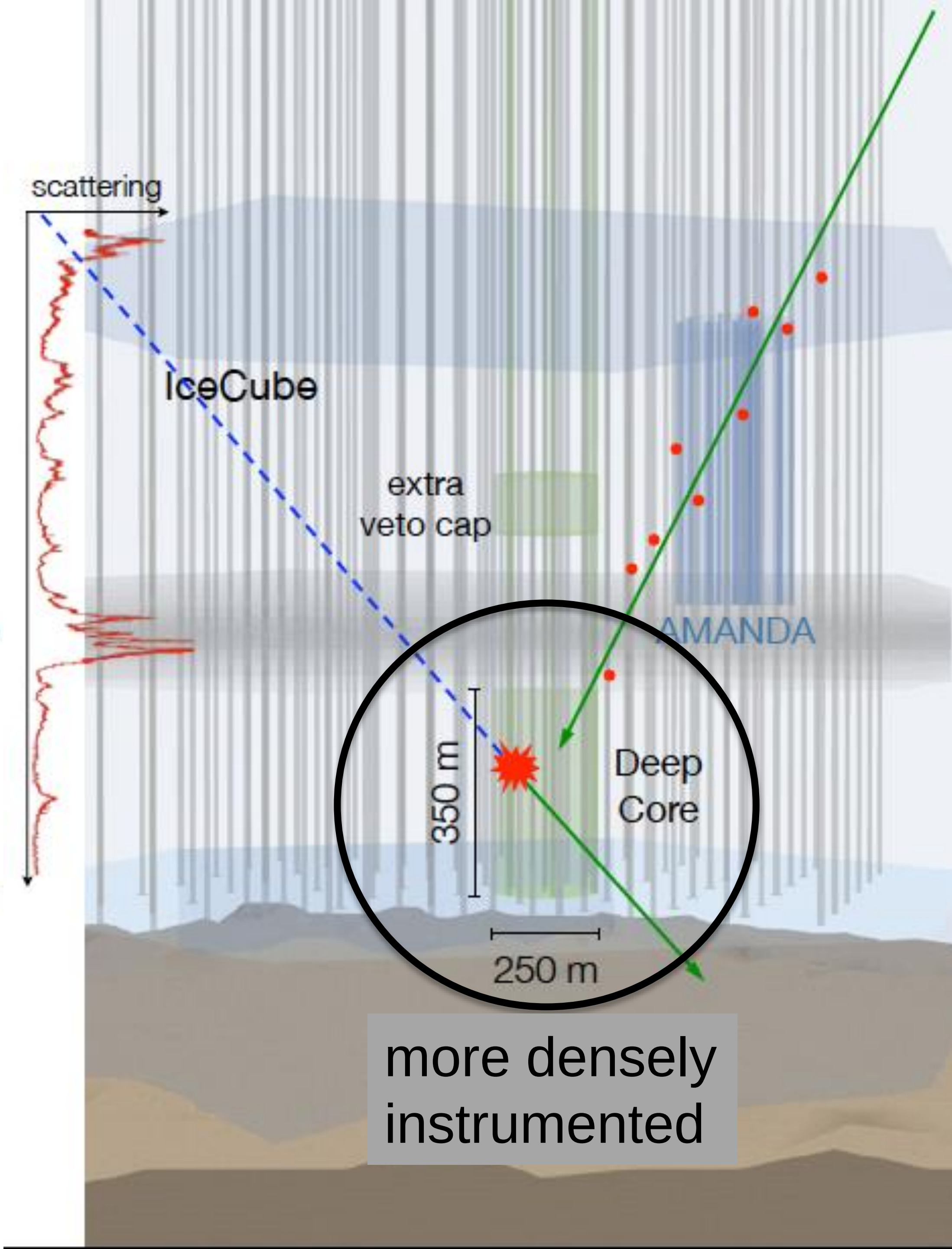
T2K + SK atmospheric
are consistent
with maximal mixing

Race for the mass hierarchy



one half million atmospheric neutrinos…



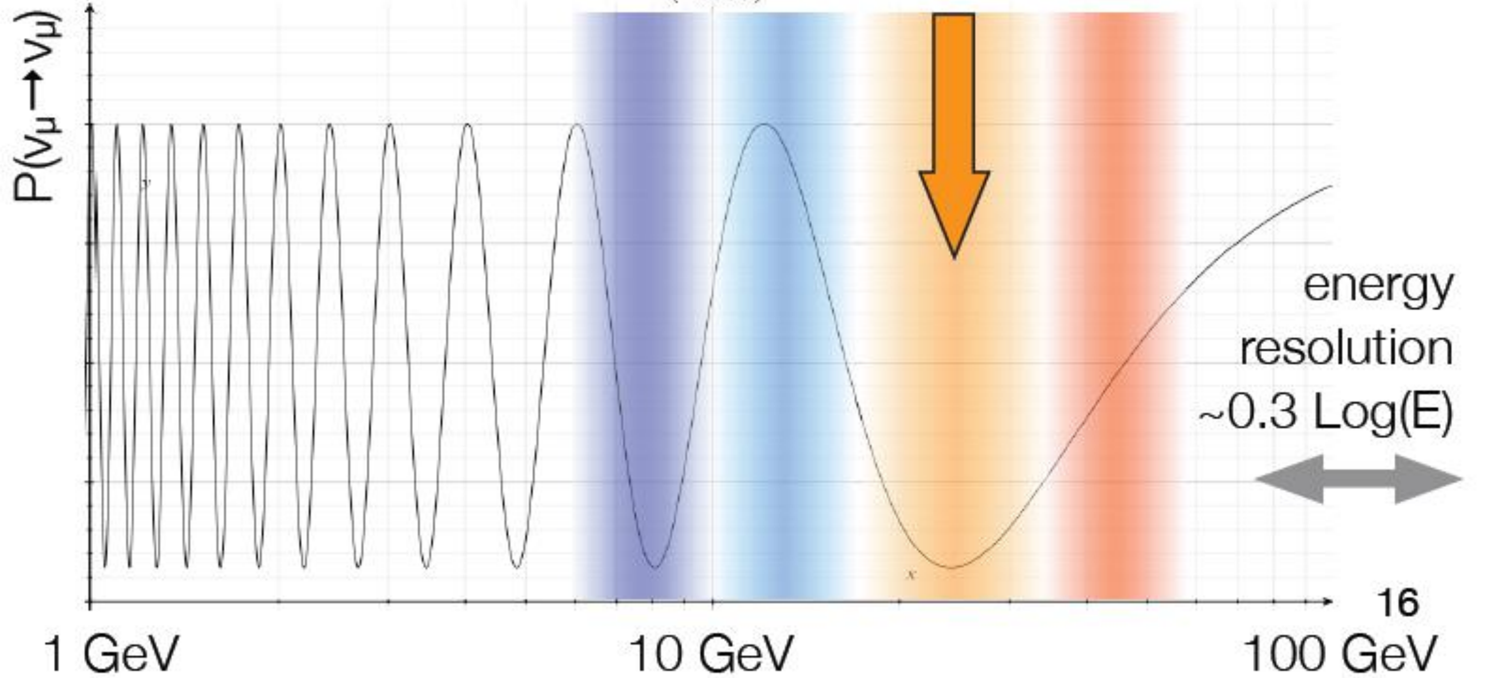


more densely instrumented

IceCube

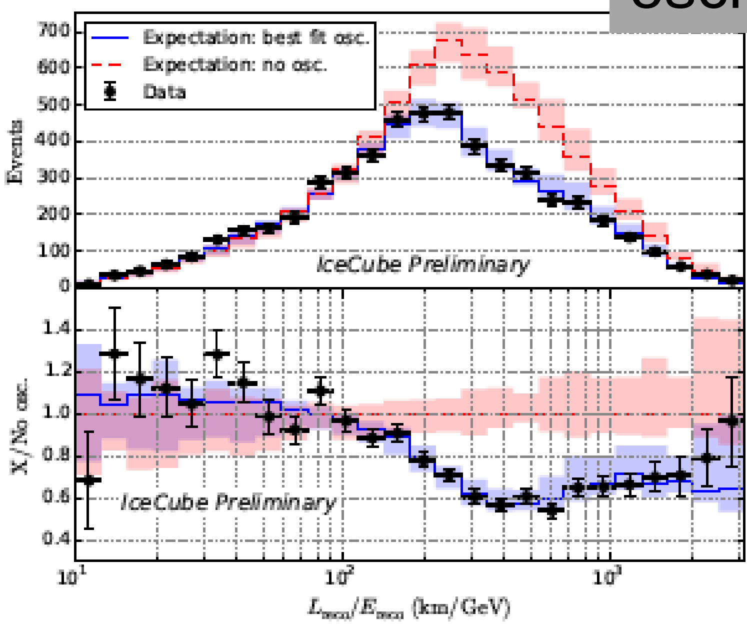
DeepCore

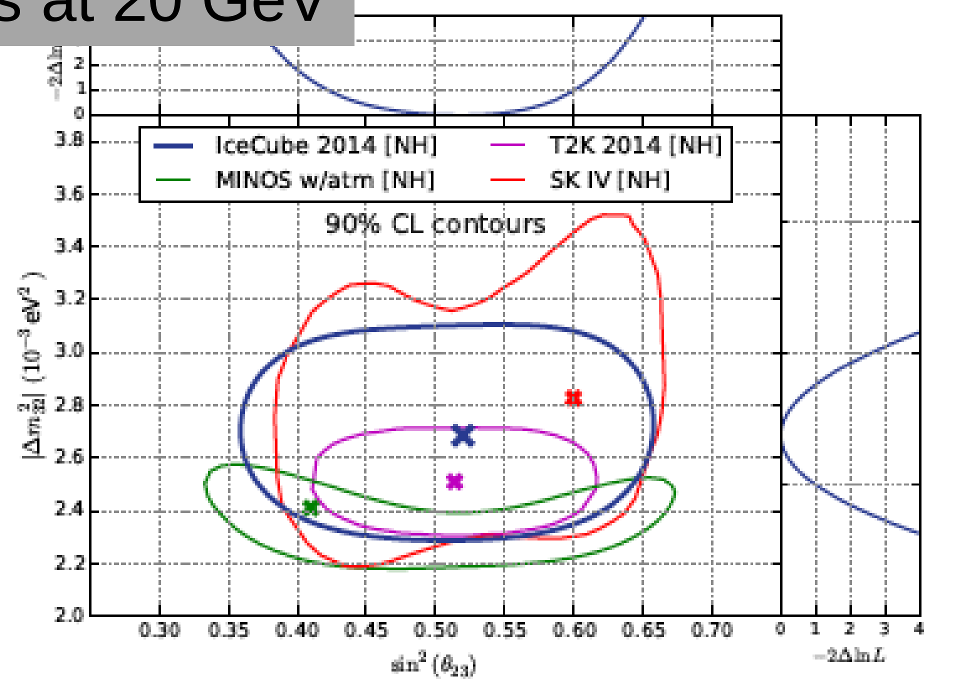
PINGU

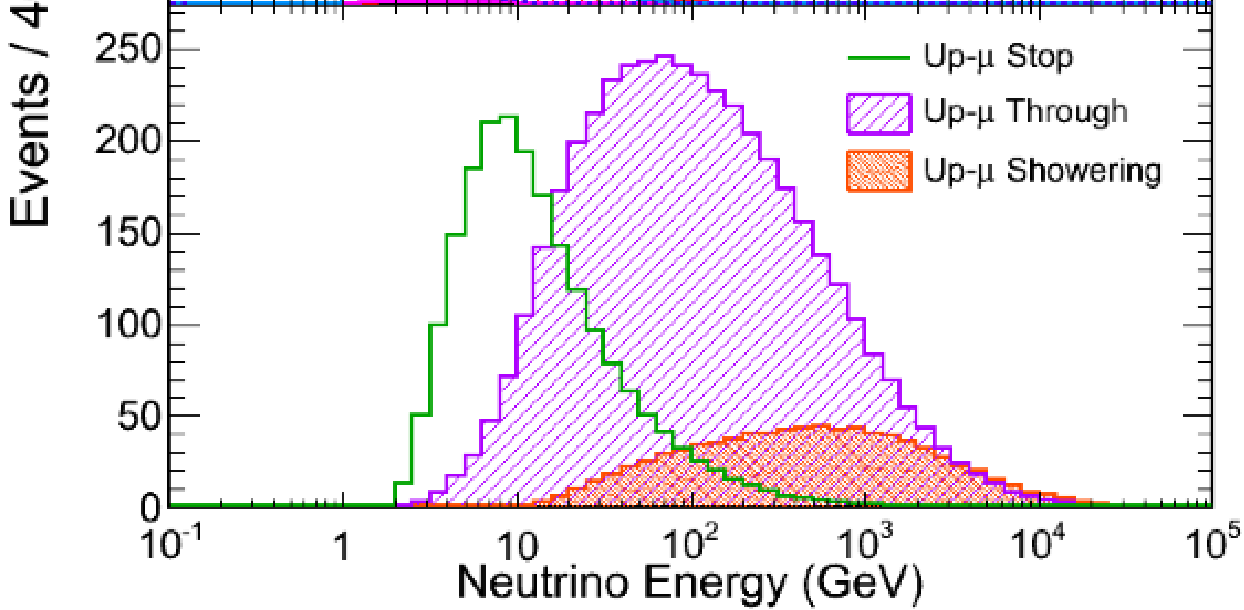


16

oscillations at 20 GeV







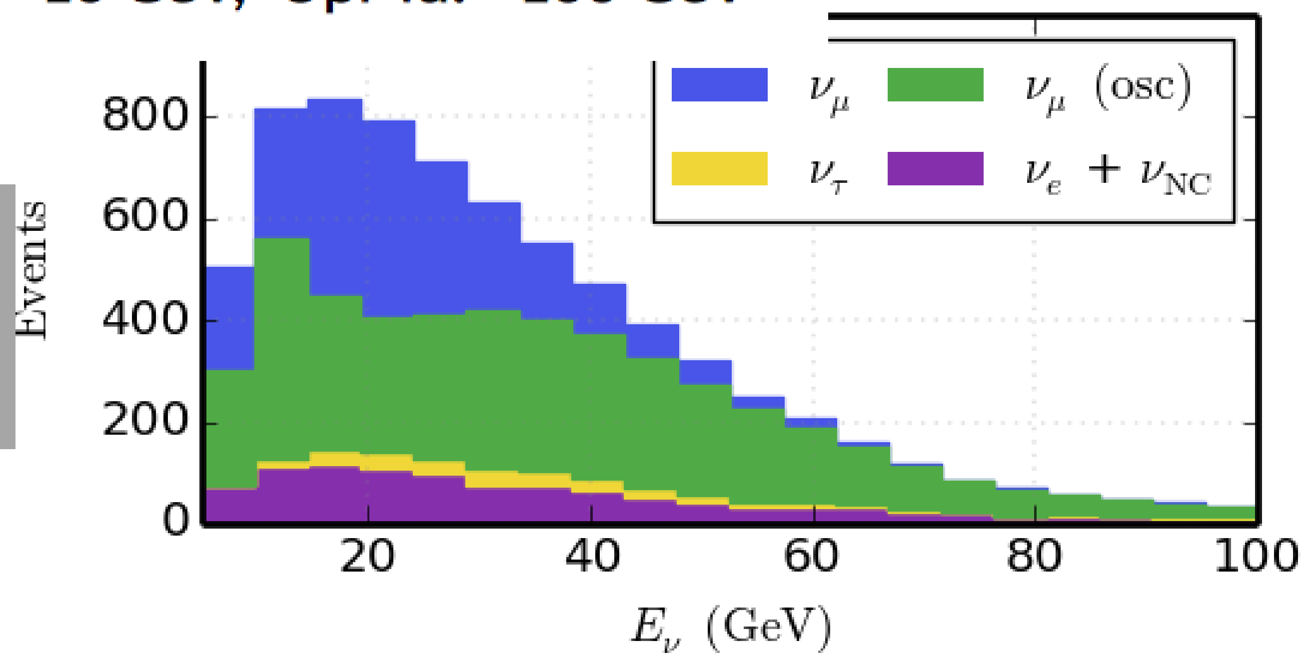
SuperK

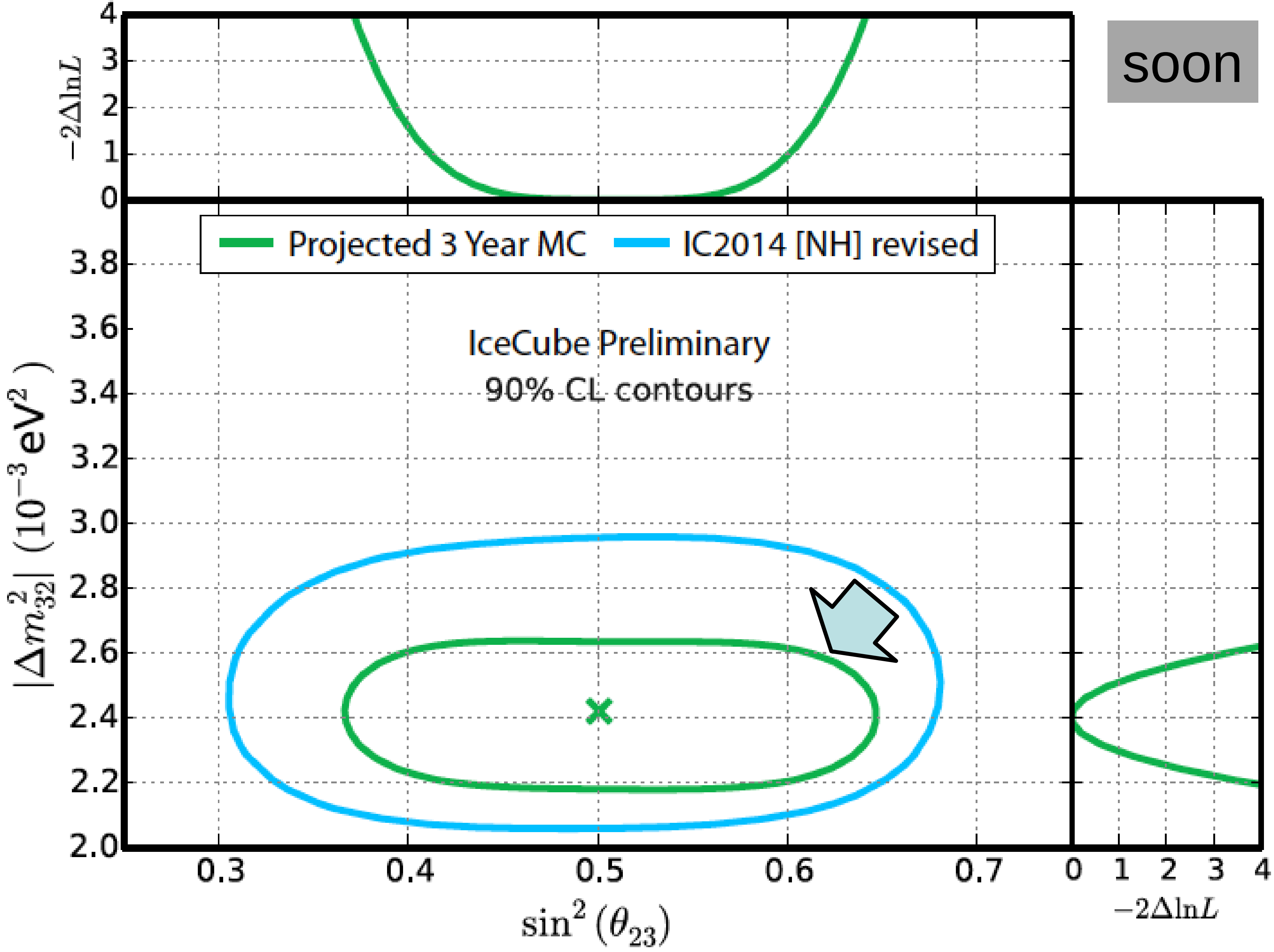
~ 1 GeV

- Average energies
  - FC: ~1 GeV , PC: ~10 GeV, UpMu:~ 100 GeV

IceCube

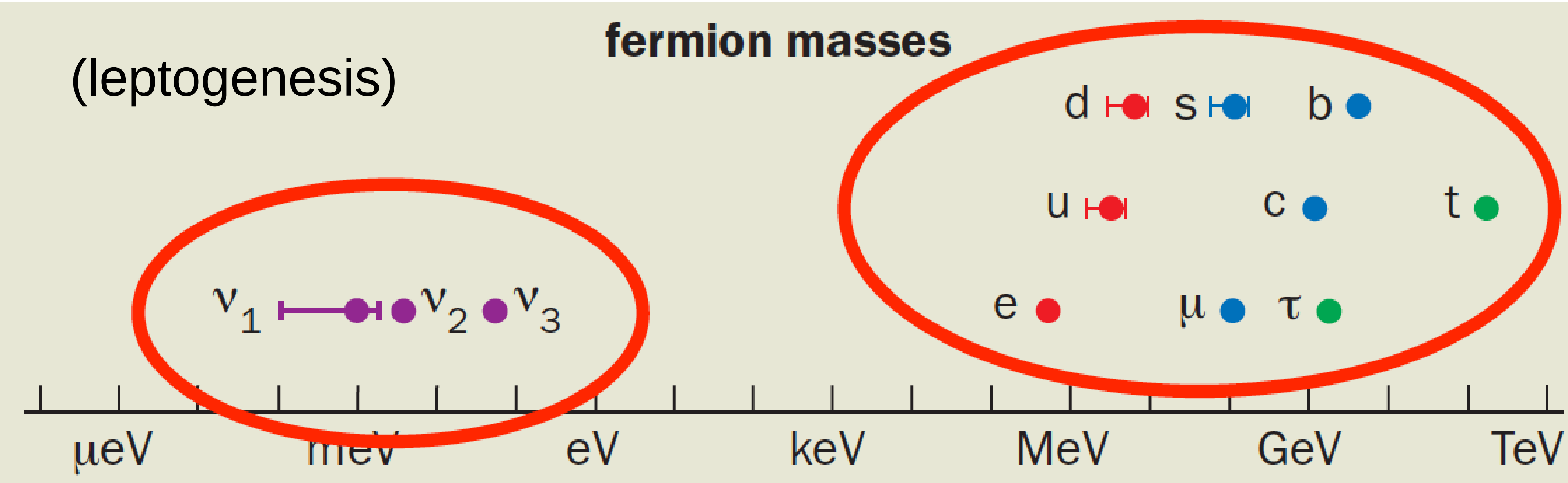
6 GeV < E_{reco} < 56 GeV





soon
Projected 3 Year MC
IC2014 [NH] revised
IceCube Preliminary
90% CL contours
$-2\Delta\ln L$
$|\Delta m^2_{32}|\ (10^{-3}\mathrm{eV}^2)$
$\sin^2(\theta_{23})$
$-2\Delta\ln L$

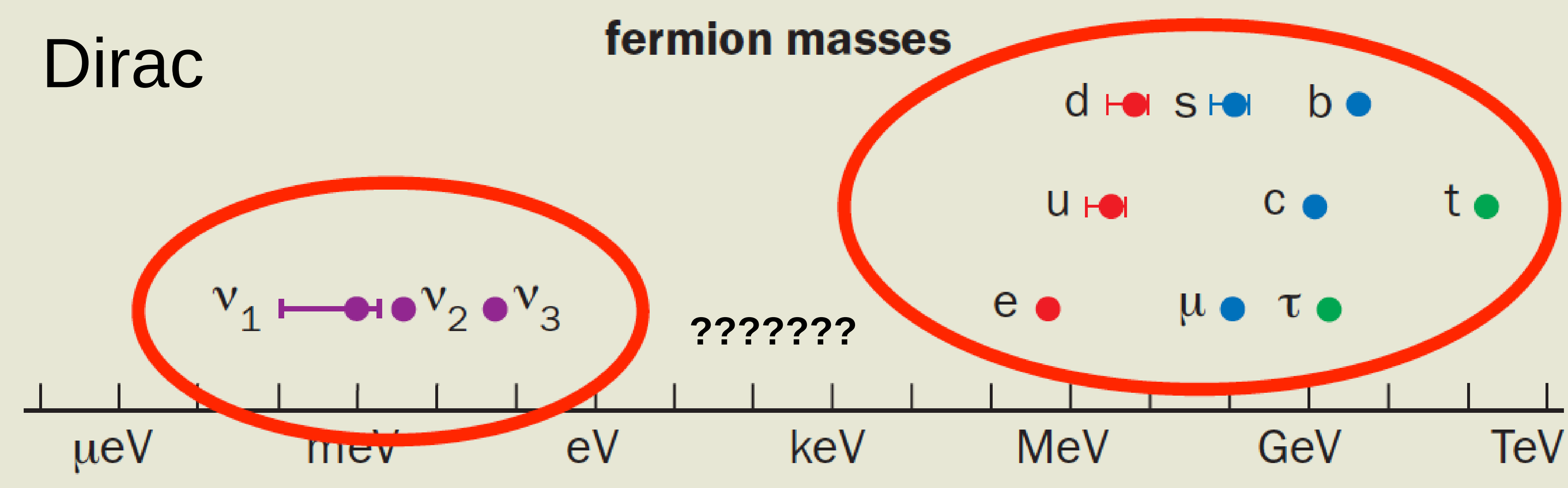
neutrinos probe BSM physics just like LHC



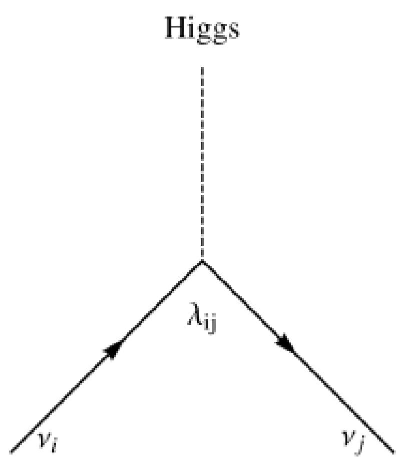
$m_\nu = 0$ → new symmetry

$m_\nu \neq 0$ → new degrees of freedom beyond the SM

m small → new physics



$$-\mathcal{L}_{\rm Dirac} = \bar{\nu}_L m_\nu \nu_R + h.c. \leftrightarrow \bar{L}\tilde{\Phi}\lambda\nu_R + h.c.$$



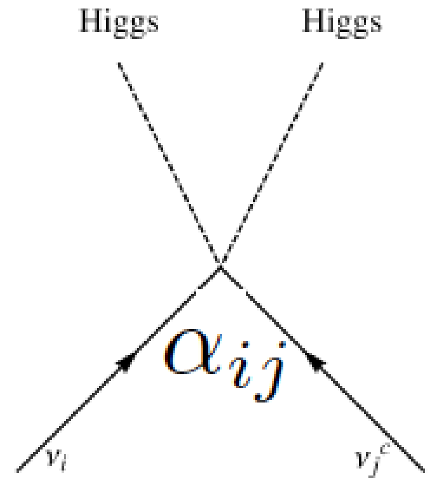
$$m_\nu \sim \lambda v$$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{PMNS}(\theta_{12}, \theta_{23}, \theta_{13}, \delta, \ldots) \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$-\mathcal{L}_{\text{Majorana}} = \bar{\nu}_L m_\nu \nu_L^c + h.c. \;\leftrightarrow\; \bar{L}\tilde{\Phi}\;\alpha\;\tilde{\Phi}L^c + h.c.$$

Weinberg

$$\alpha = \frac{Y_\nu}{\Lambda}$$



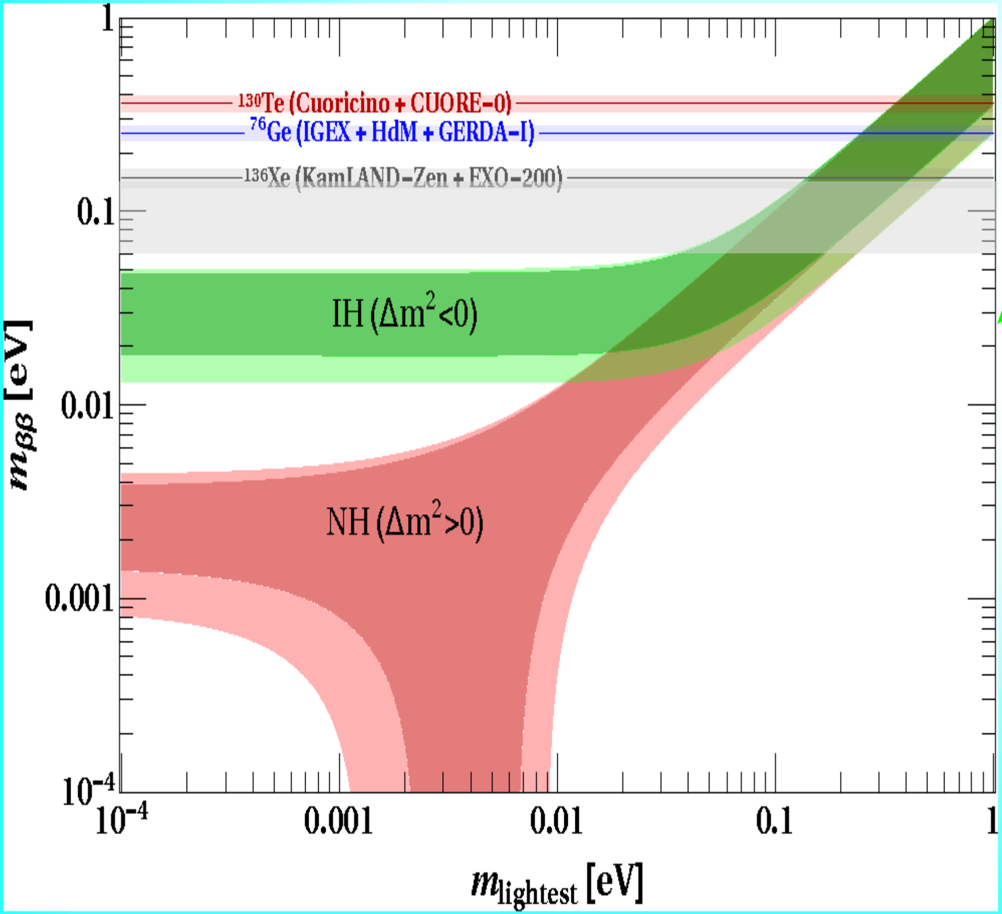
$$m_\nu = Y\frac{v^2}{\Lambda}$$

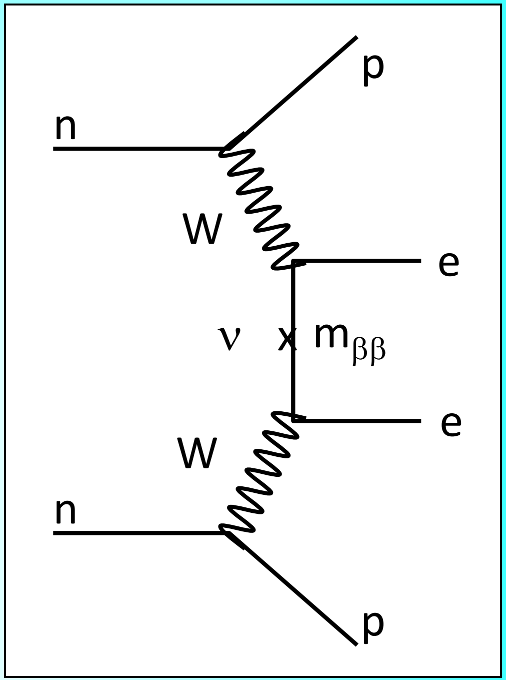
$$m_f(\text{charged}) \sim Yv, \quad m_\nu \sim Y\frac{v^2}{\Lambda}$$

BSM with large scale Λ naturally accommodates small neutrino masses; new physics banned to ~ 10^{14} GeV

Double beta decay

$m_{\beta\beta} = U_{e1}^2 m_1 + U_{e2}^2 m_2 e^{\iota\alpha} + U_{e3}^2 m_3 e^{\iota\phi}$





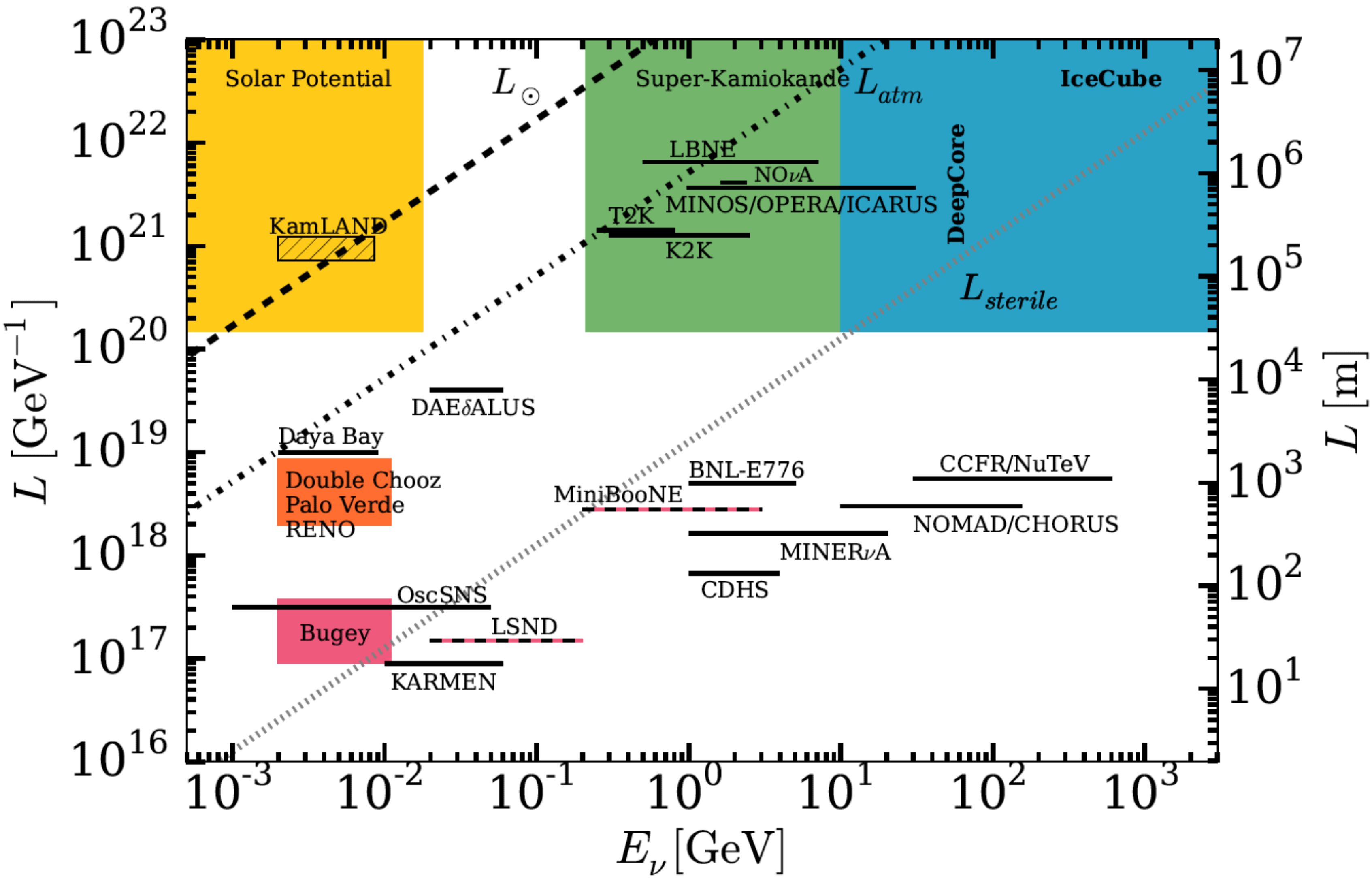
KamLAND-Zen

$m_{\beta\beta}$ < (60 – 161) meV, 90% CL
Depending on NME

A.Gando, et al, 1605.02889 [hep-ex]

Approaching IH band

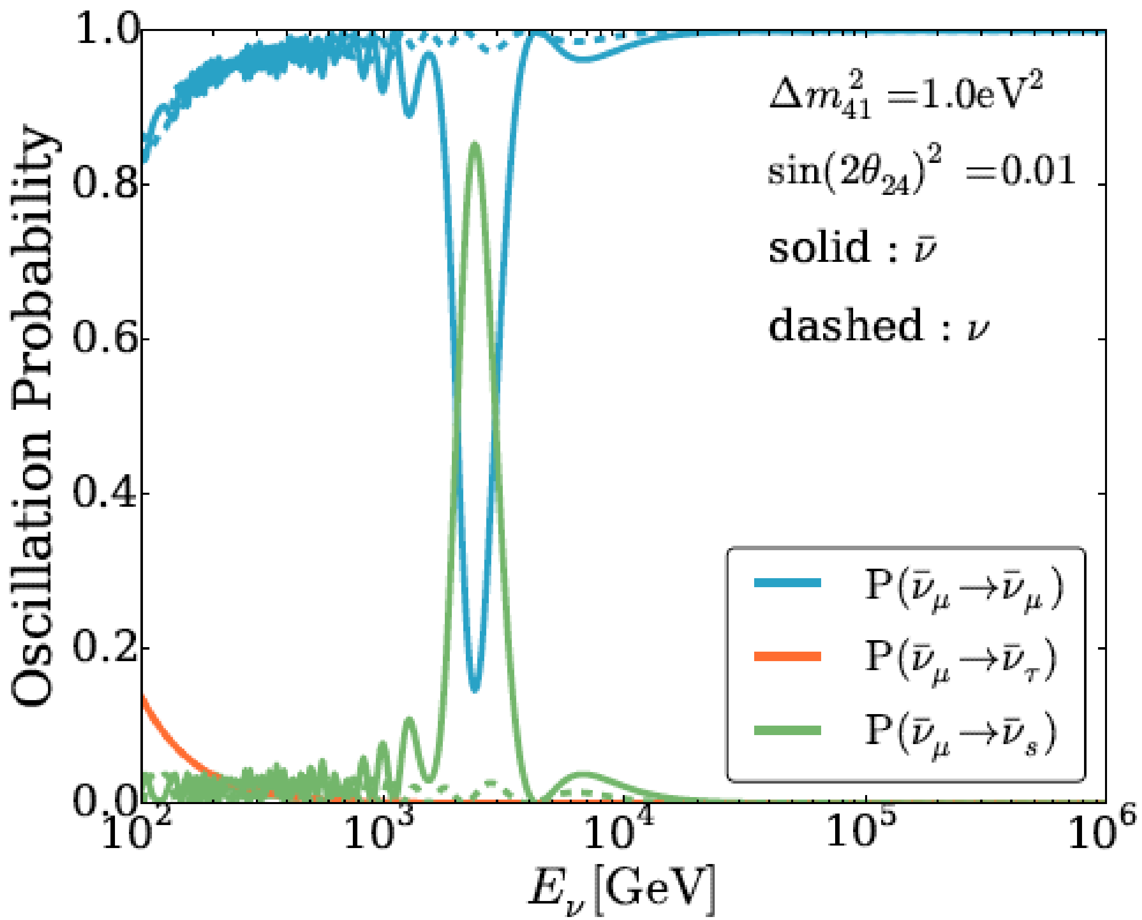
Experiments: $L_{\rm osc} = 2\pi \frac{E}{\Delta m^2} \mid \Delta m^2_{\rm LSND} = 1 eV^2$

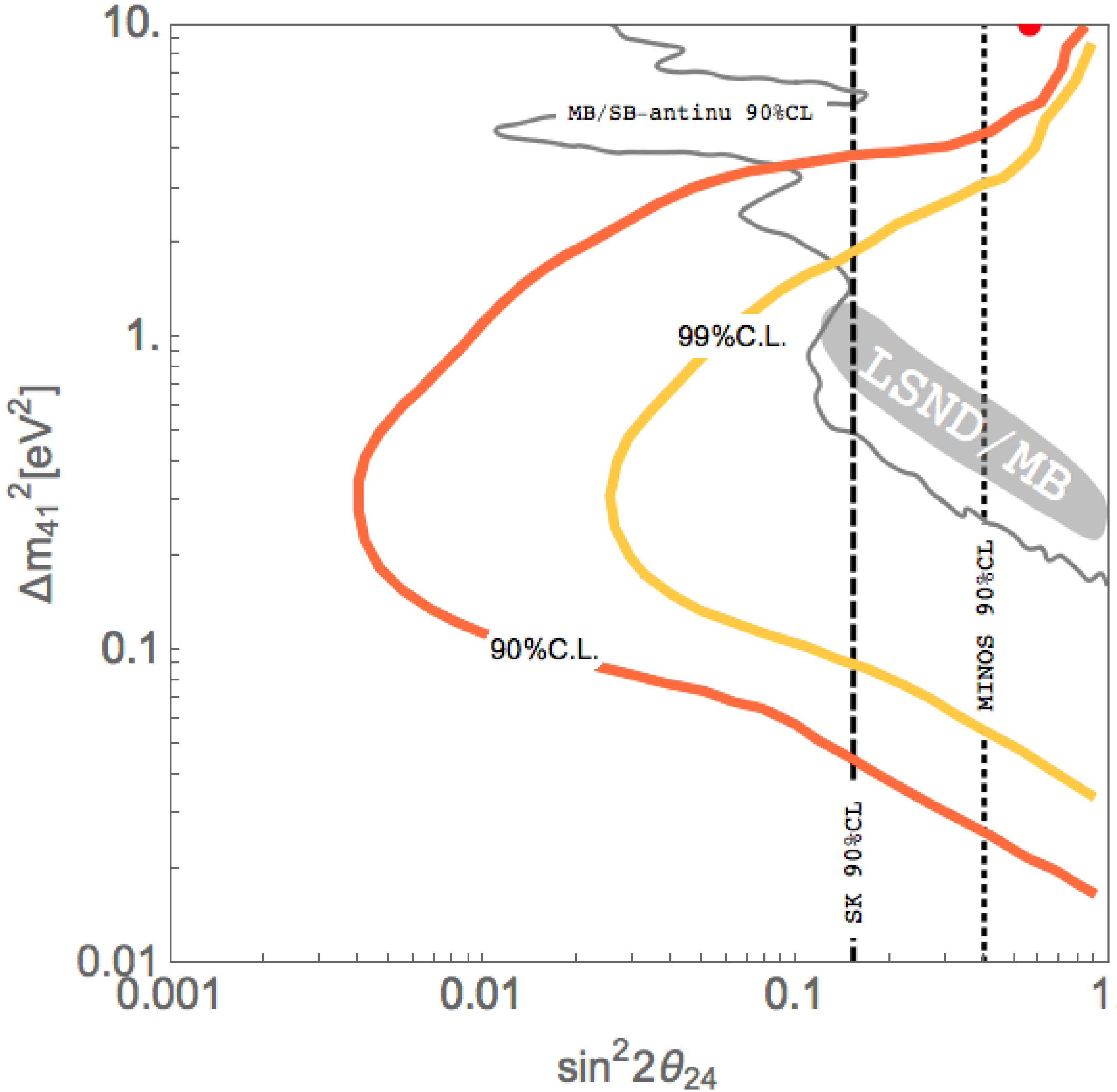


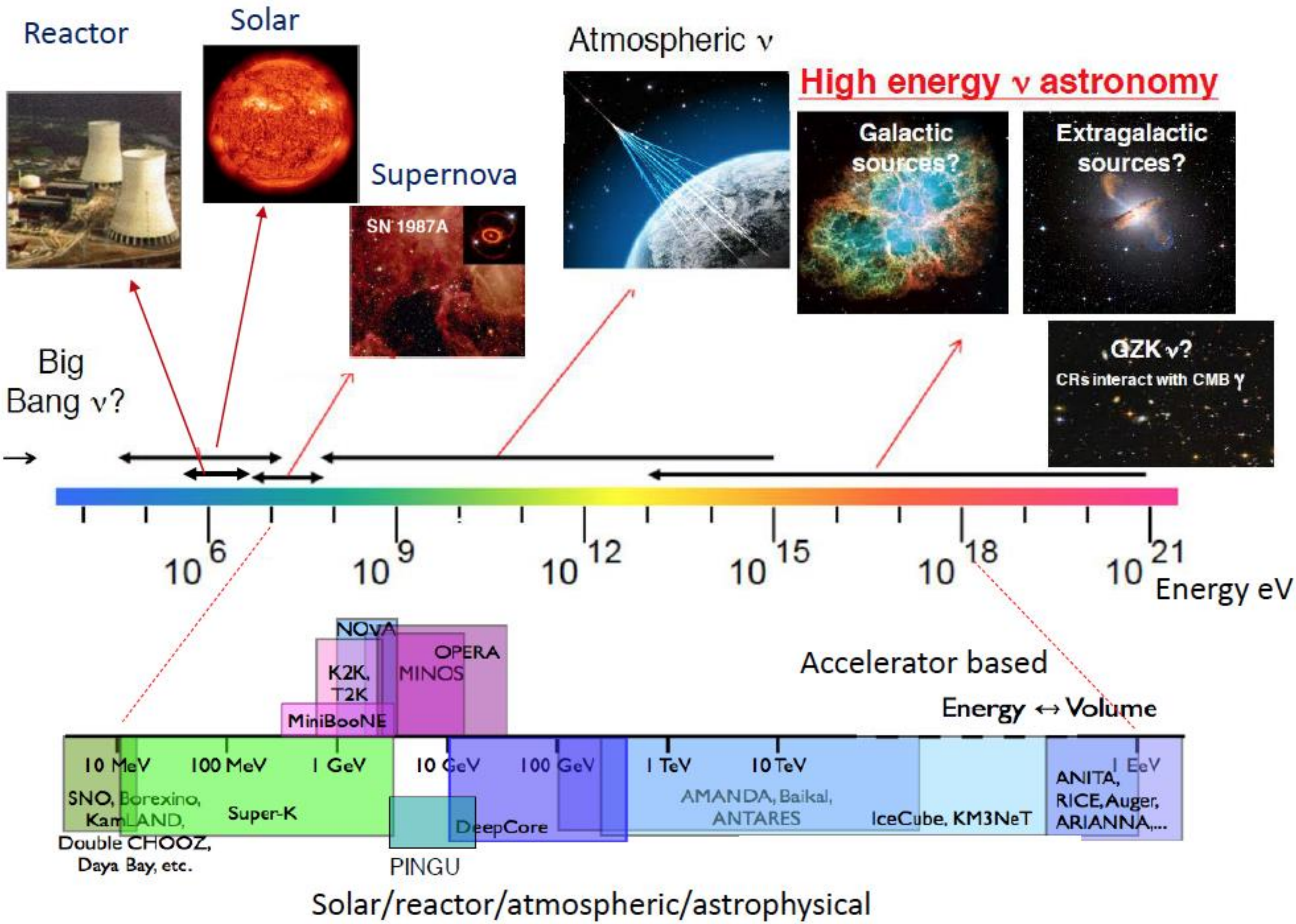
eV sterile neutrino → Earth MSW resonance for TeV neutrinos

In the **Earth** for sterile neutrino $\Delta m^2 = O(1eV^2)$ the MSW effect happens when

$$E_\nu = \frac{\Delta m^2 \cos 2\theta}{2\sqrt{2} G_F N} \sim O(TeV)$$



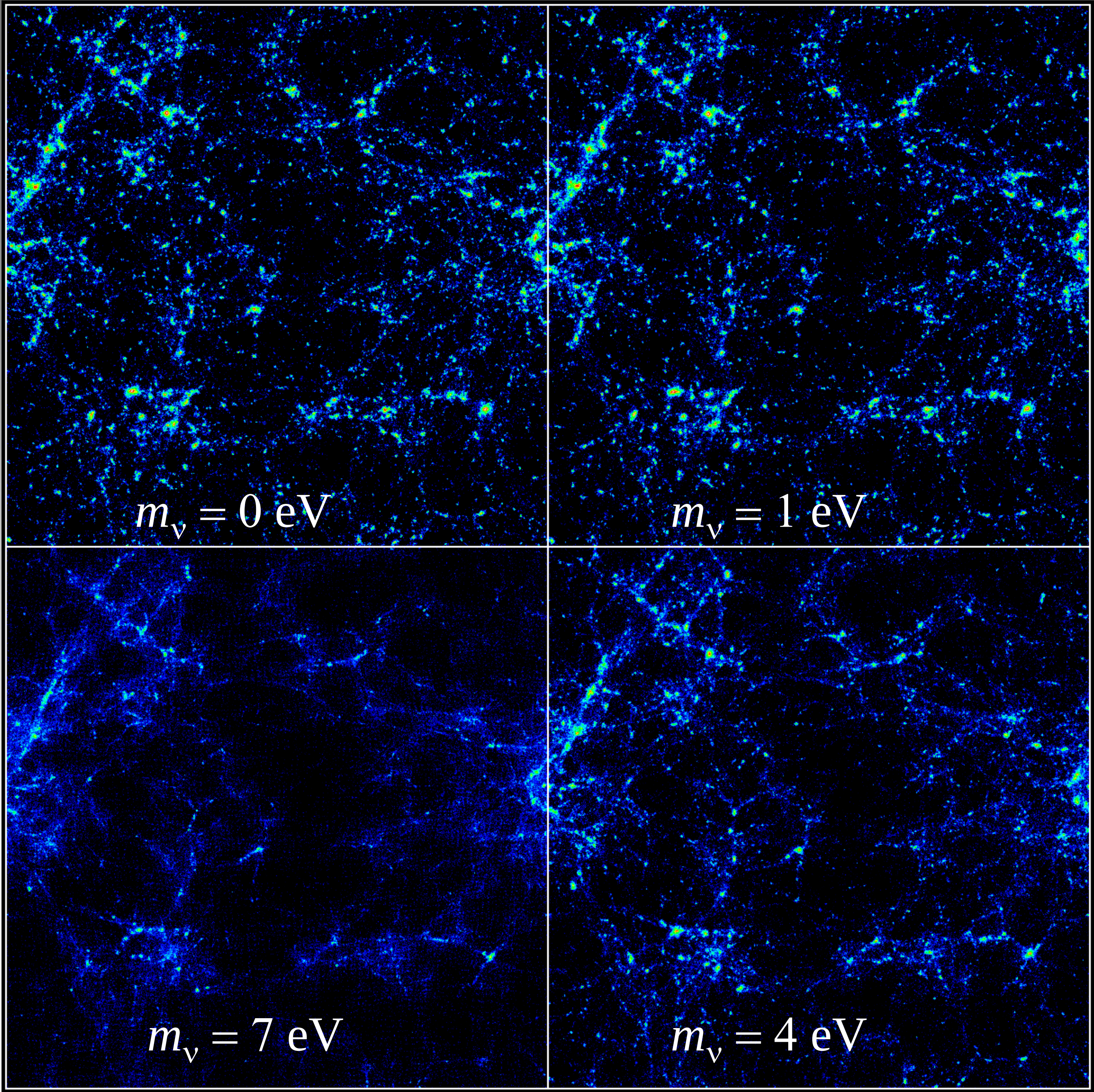

10.
1.
0.1
0.01
0.001
0.01
0.1
1.
$\Delta m_{41}{}^2[eV^2]$
$\sin^2 2\theta_{24}$
MB/SB-antinu 90%CL
99%C.L.
90%C.L.
LSND/MB
SK 90%CL
MINOS 90%CL



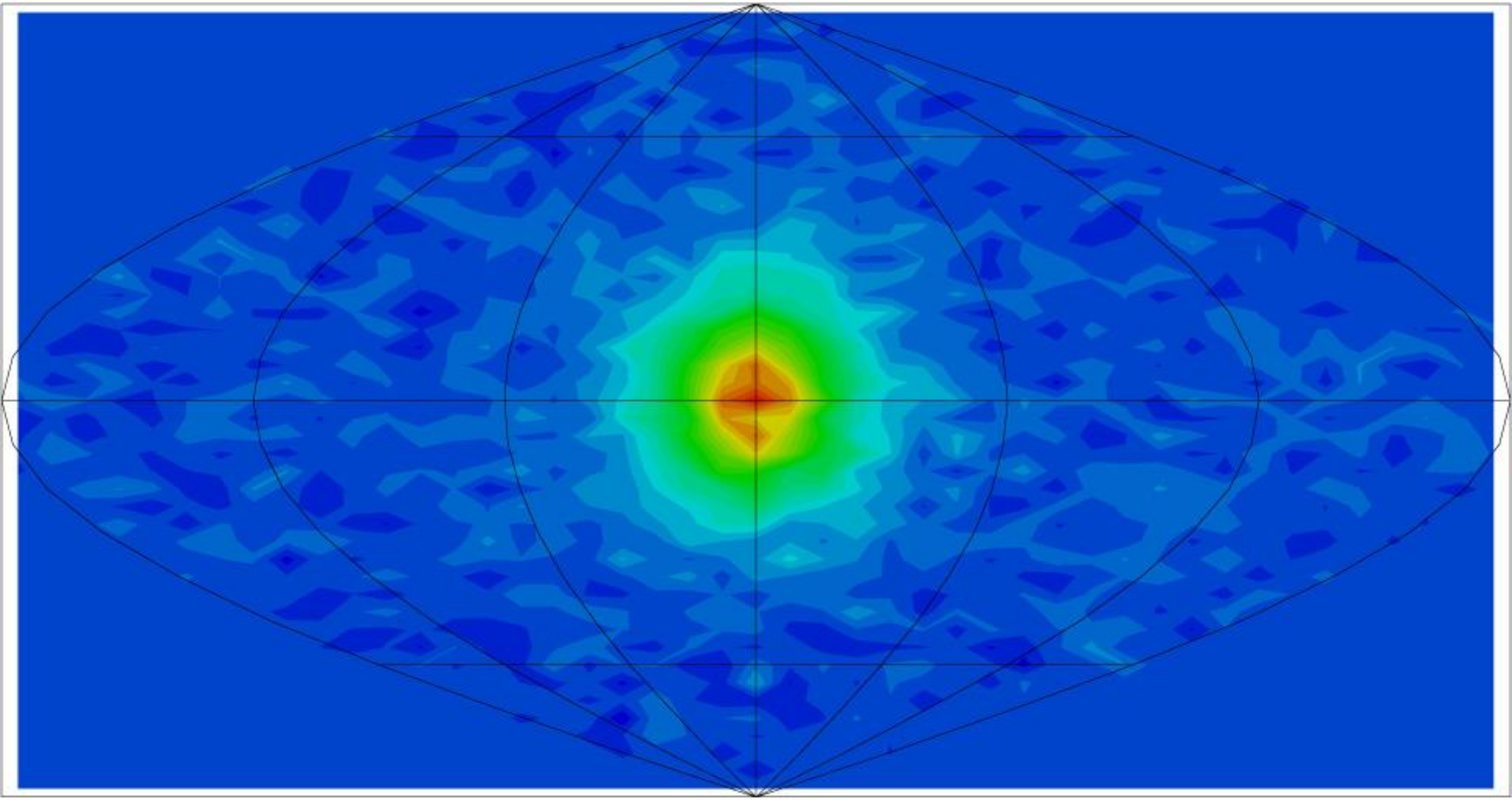
Reactor
Solar
Supernova
SN 1987A
Atmospheric ν
High energy ν astronomy
Galactic sources?
Extragalactic sources?
GZK ν?
CRs interact with CMB γ
Big Bang ν?
10^6
10^9
10^12
10^15
10^18
10^21
Energy eV
NOνA
OPERA
K2K, T2K
MINOS
MiniBooNE
Accelerator based
Energy ↔ Volume
10 MeV
100 MeV
1 GeV
10 GeV
100 GeV
1 TeV
10 TeV
1 EeV
SNO, Borexino, KamLAND, Double CHOOZ, Daya Bay, etc.
Super-K
PINGU
DeepCore
AMANDA, Baikal, ANTARES
IceCube, KM3NeT
ANITA, RICE, Auger, ARIANNA,...
Solar/reactor/atmospheric/astrophysical

adding hot neutrino dark matter erases small structure

$$\frac{\rho}{\rho_{crit}} = 0.02\,\frac{m_\nu}{1eV}$$



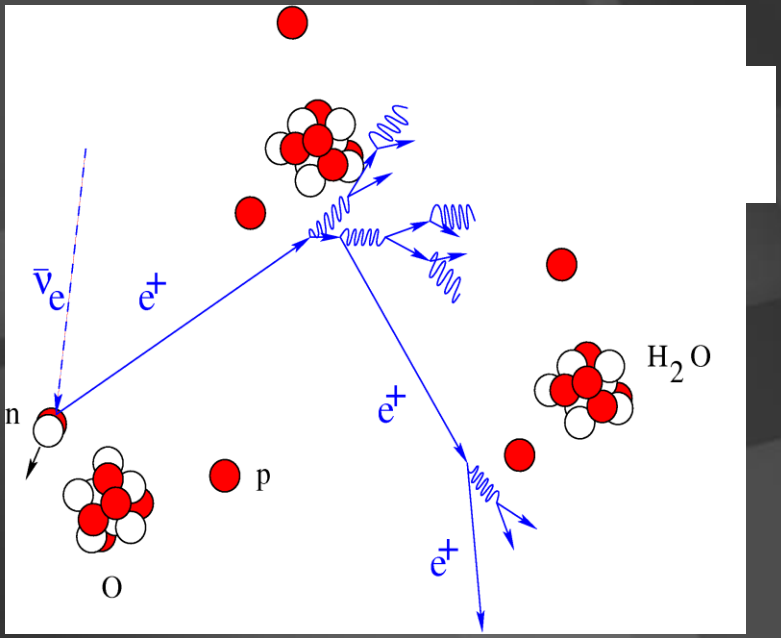
neutrino picture of the sun

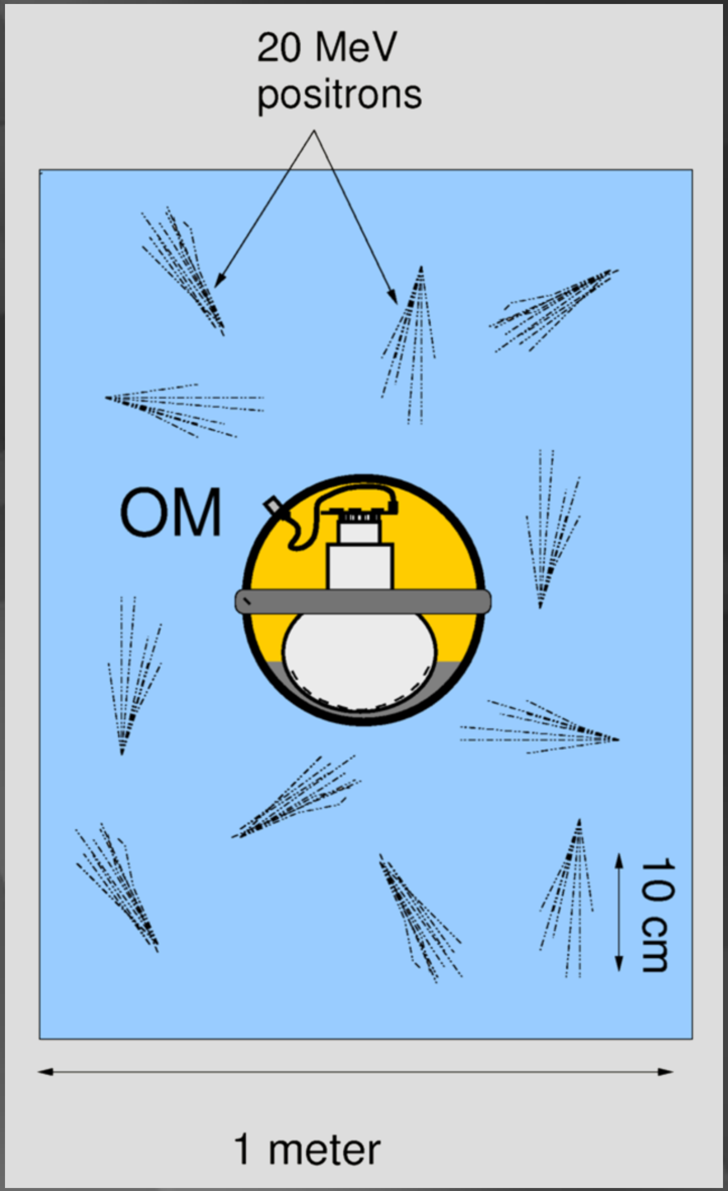


Superkamiokande

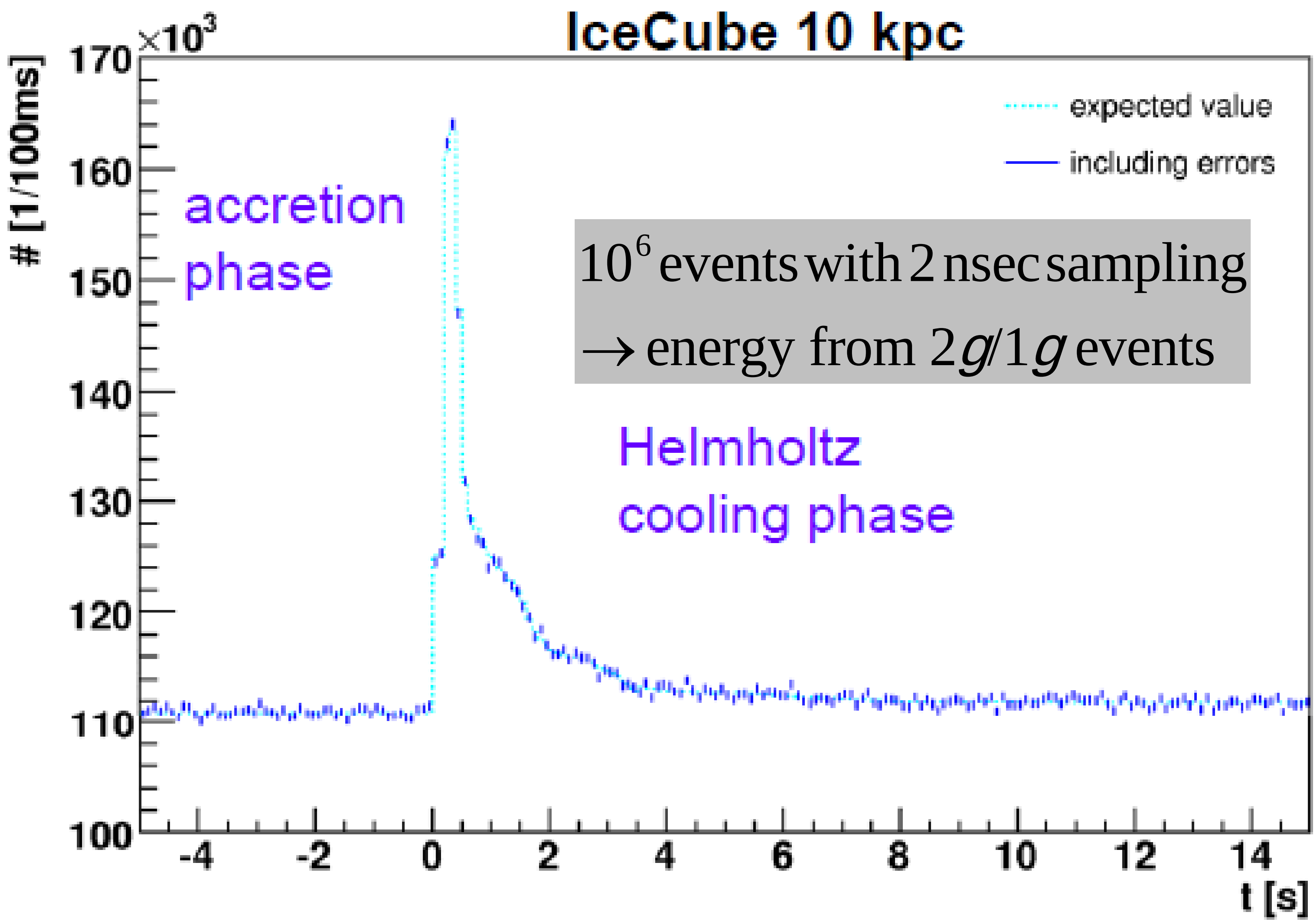
supernova 1987a: 24 neutrinos, thousands of papers

supernova burst: light from $\bar{\nu}_e + p \rightarrow n + e^+$

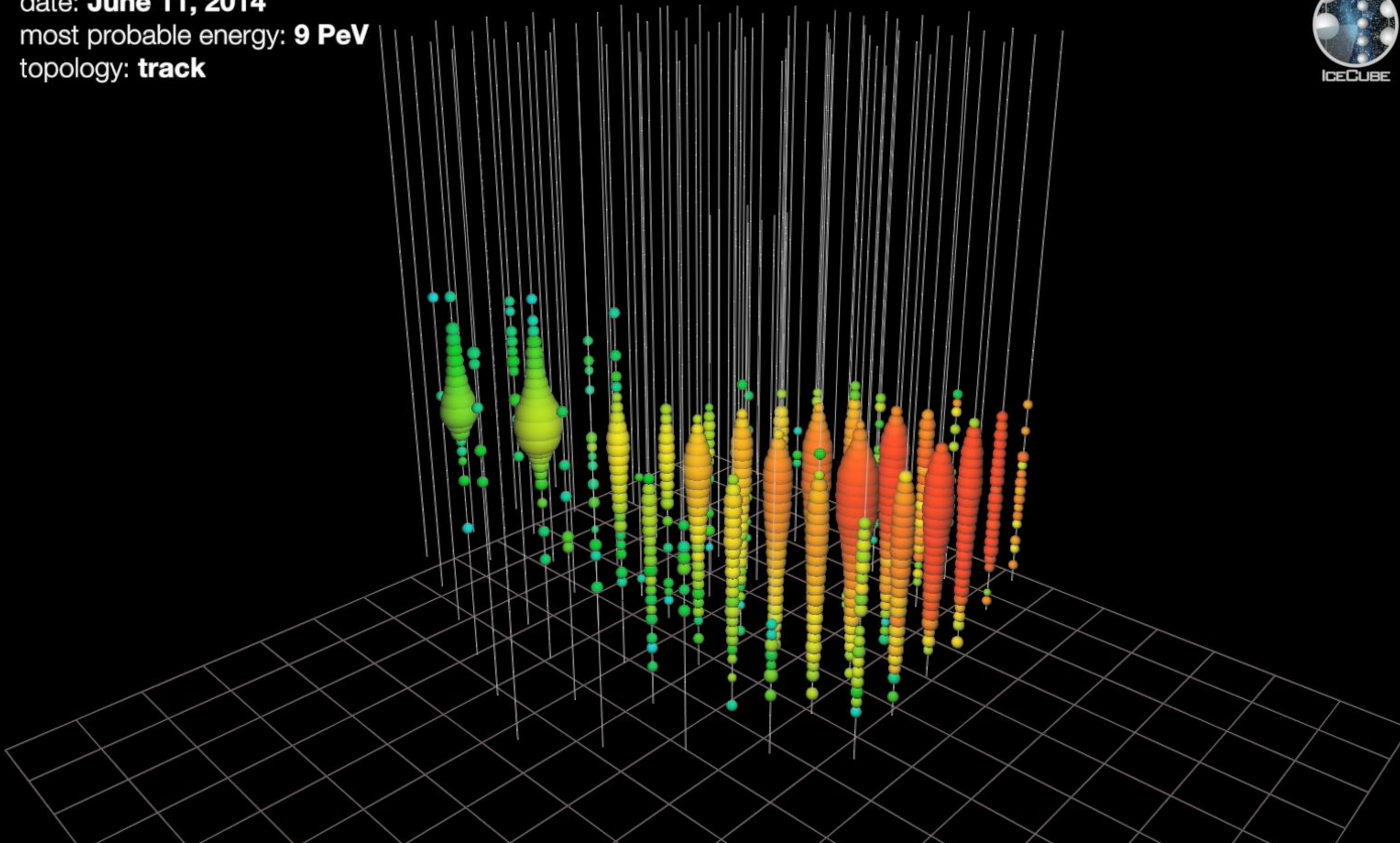




- ☞ PMT noise low (280 Hz)
- ☞ detect correlated rate increase on top of PMT noise when supernova neutrinos pass through the detector


IceCube 10 kpc
×10³
[1/100ms]
t [s]
expected value
including errors
accretion
phase
Helmholtz
cooling phase
10⁶ events with 2 nsec sampling
→ energy from 2g/1g events
170
160
150
140
130
120
110
100
-4
-2
0
2
4
6
8
10
12
14

date: **June 11, 2014**
most probable energy: **9 PeV**
topology: **track**



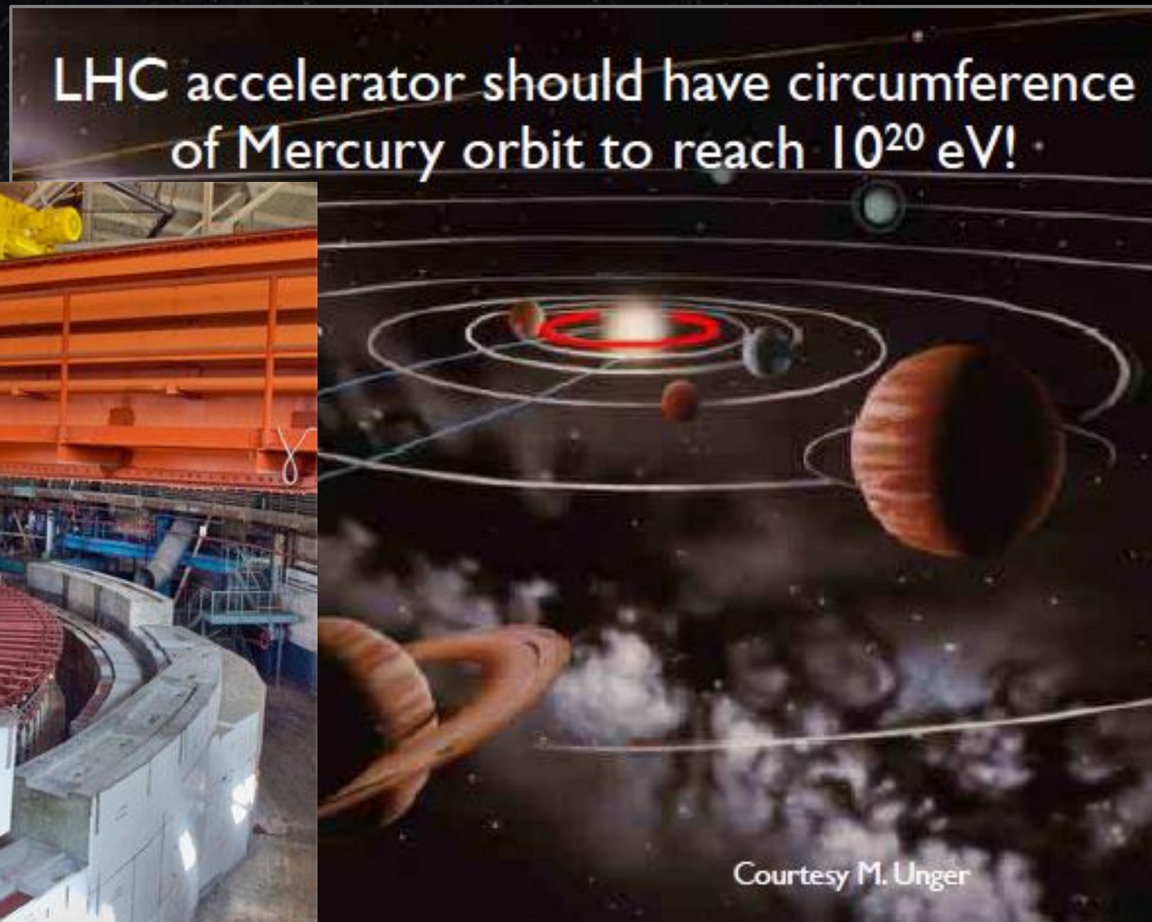
- the existence of PeV neutrino events can yield dramatic limits on any possible Lorentz invariance violation: superluminal particles lose their energy to Cherenkov radiation, even in vacuum

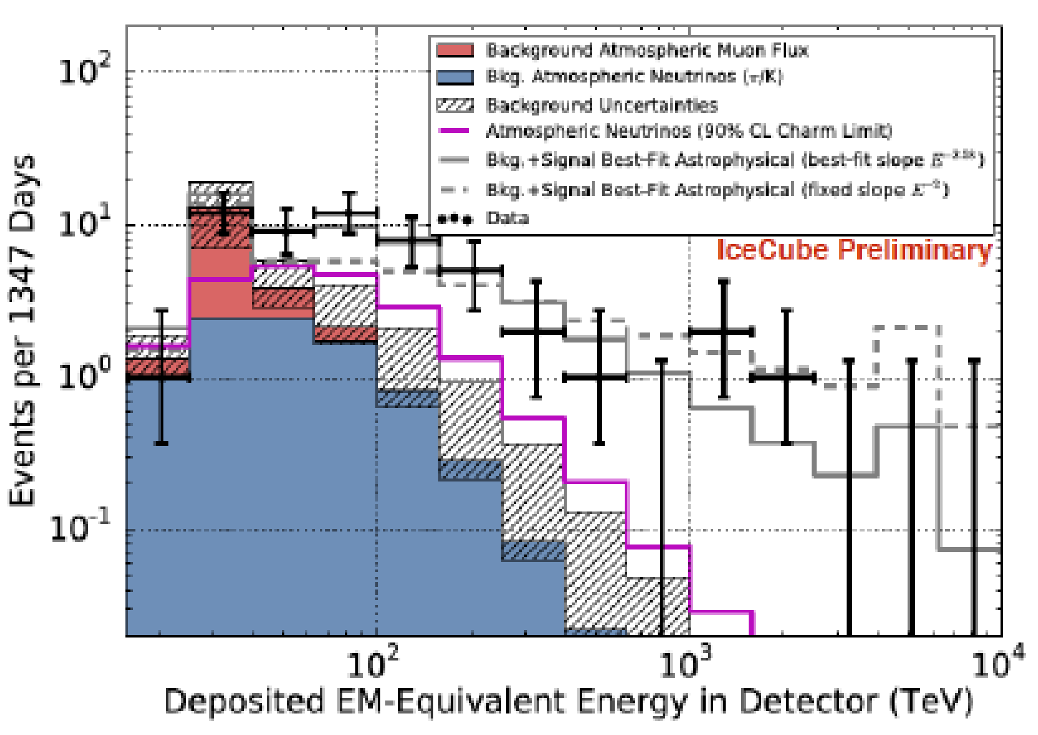
$$\nu \rightarrow \nu e^{+} e^{-}$$

- sensitivity δ increases dramatically with distance d and observed energy E

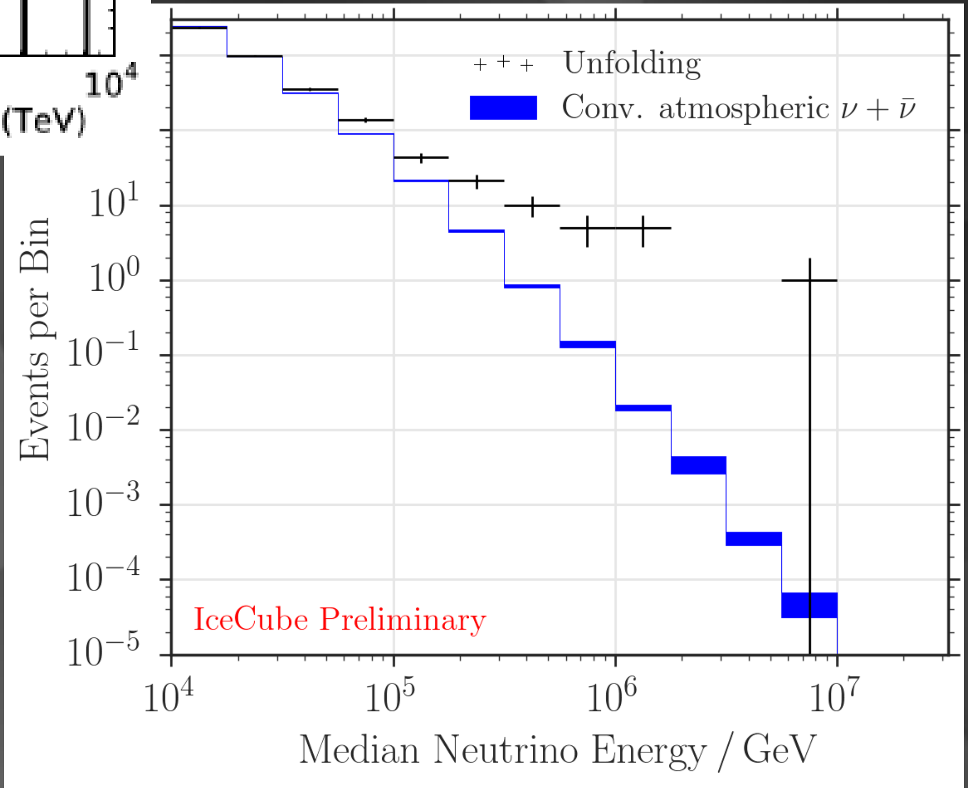
$$\delta = \frac{\mathrm{v}_{\nu}^{2} - c^{2}}{c^{2}} = a\, d^{-\frac{1}{3}} E^{-\frac{5}{3}}$$

The origin of cosmic rays: the oldest problem





confirmation!
flux of muon neutrinos
through the Earth



neutrinos of all flavors
interacting inside
IceCube

neutral pions

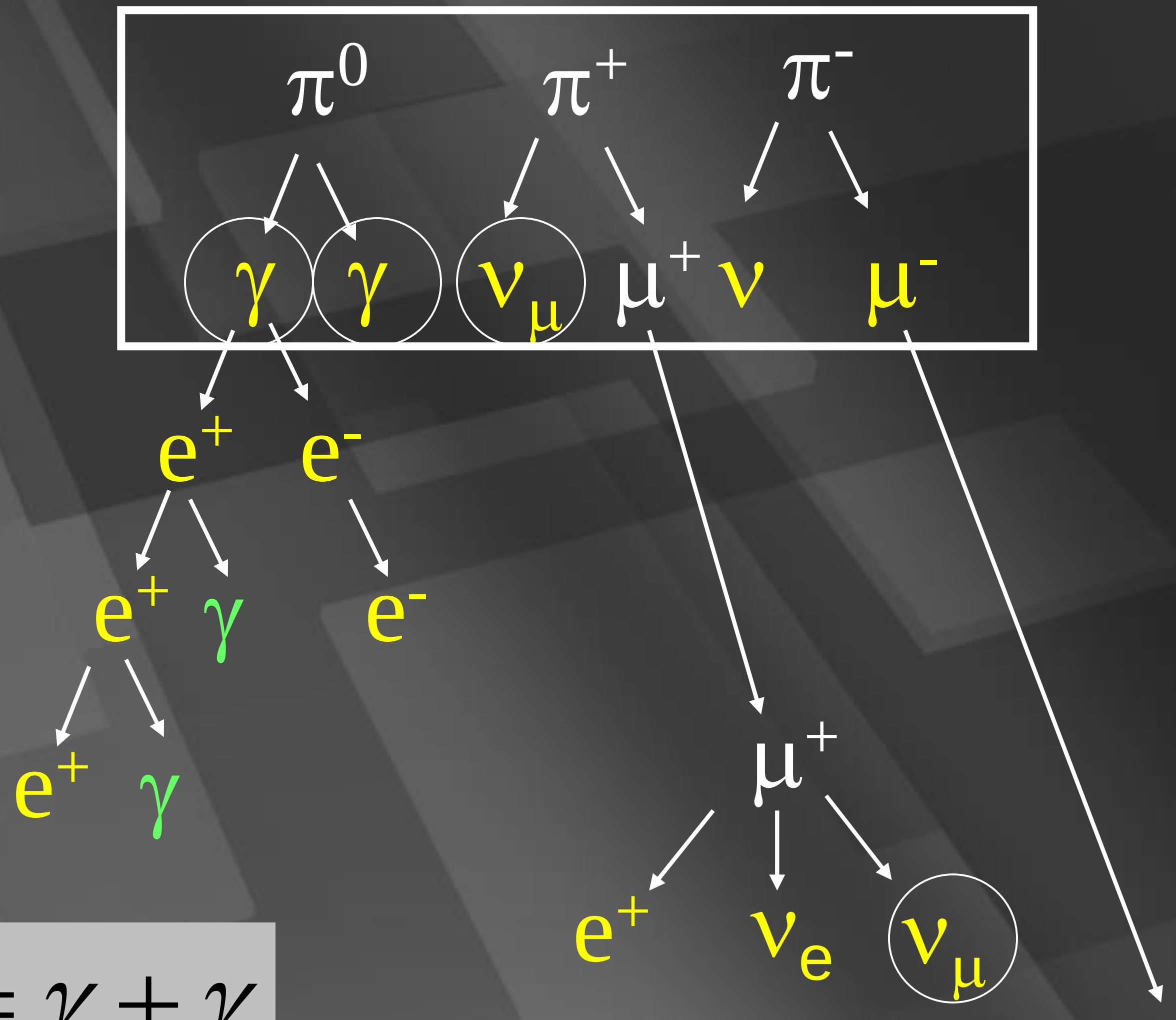
are observed as

gamma rays

charged pions

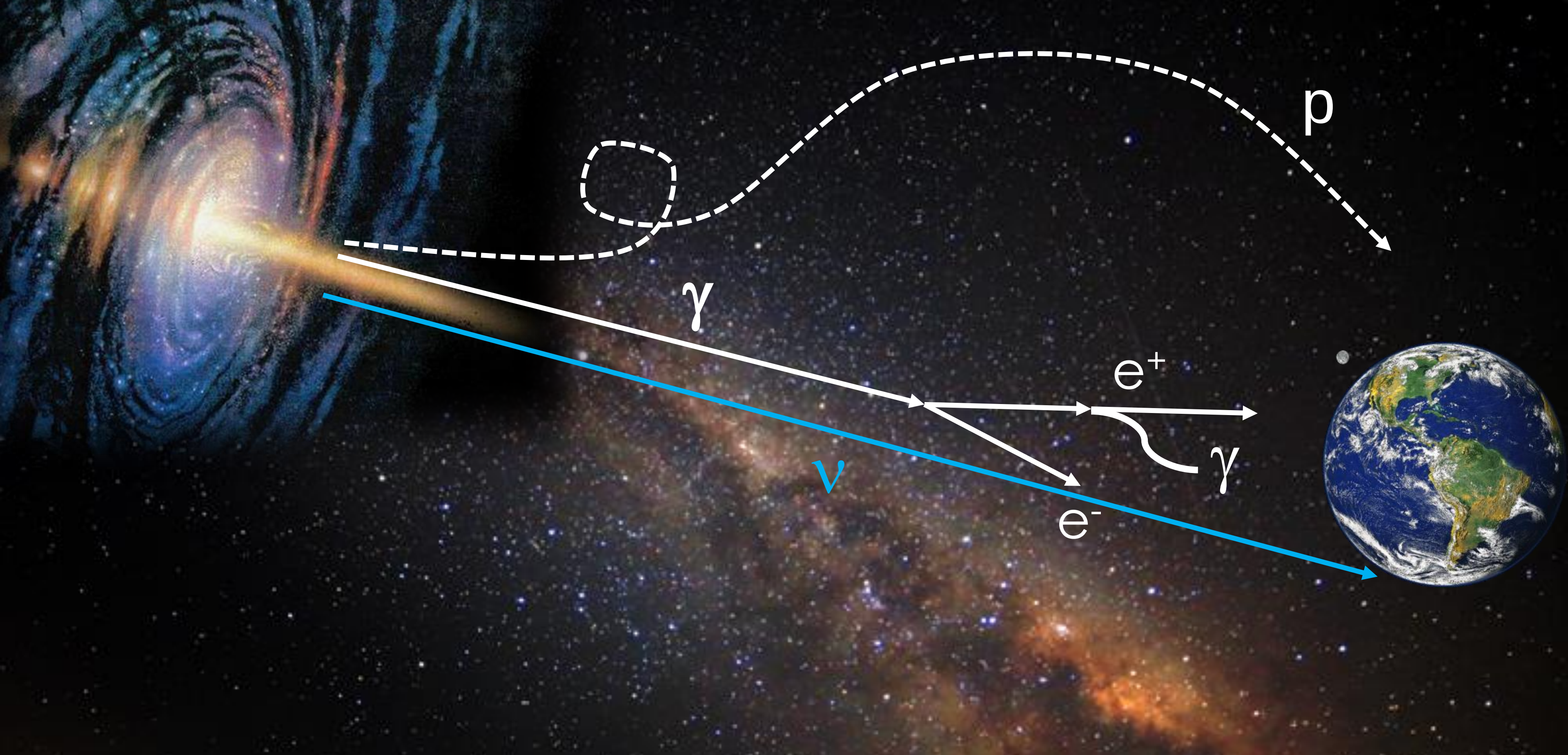
are observed as

neutrinos

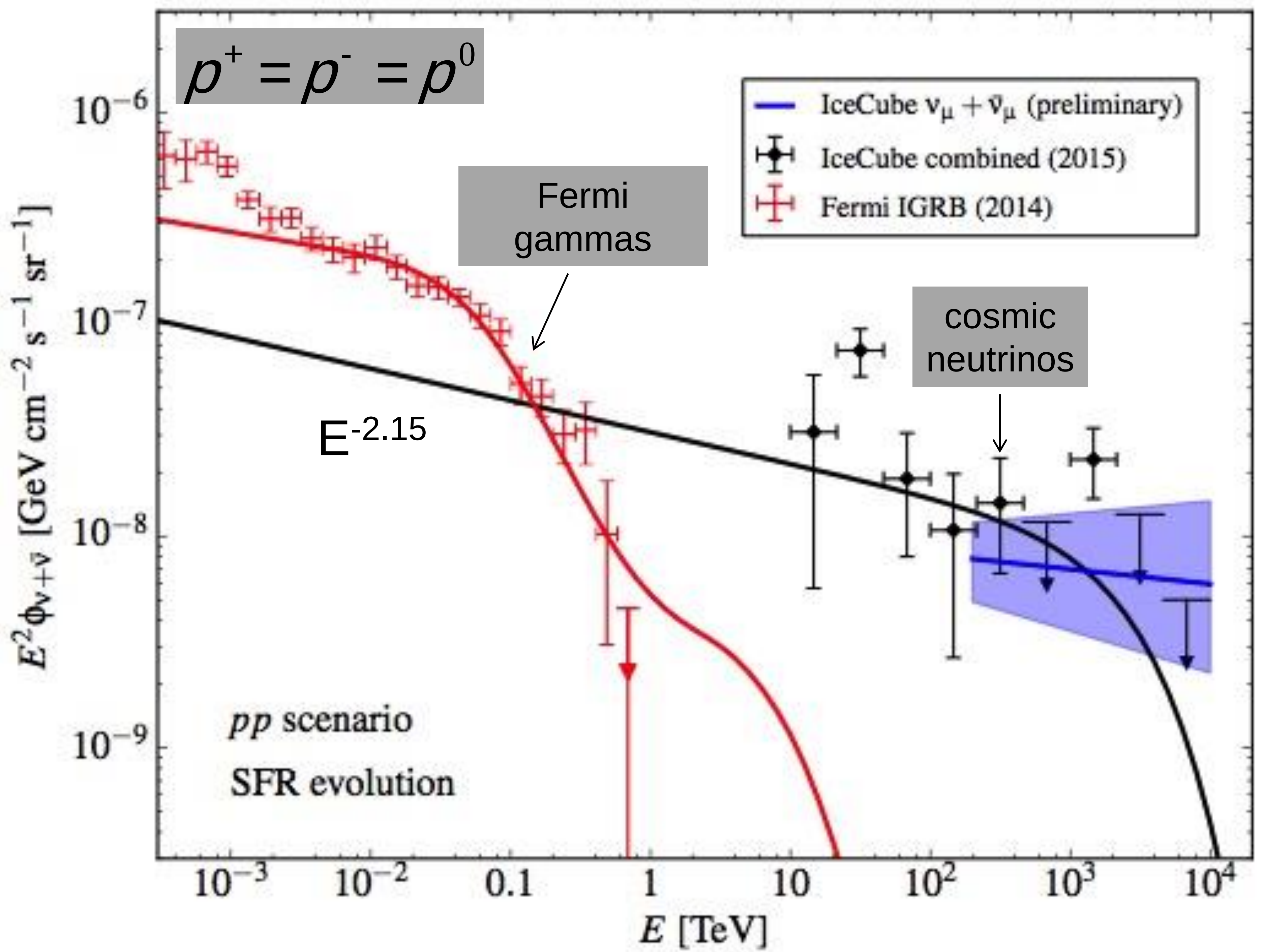


$$\nu_\mu + \bar{\nu}_\mu = \gamma + \gamma$$

gamma rays accompanying IceCube neutrinos interact with interstellar photons and fragment into multiple lower energy gamma rays that reach earth



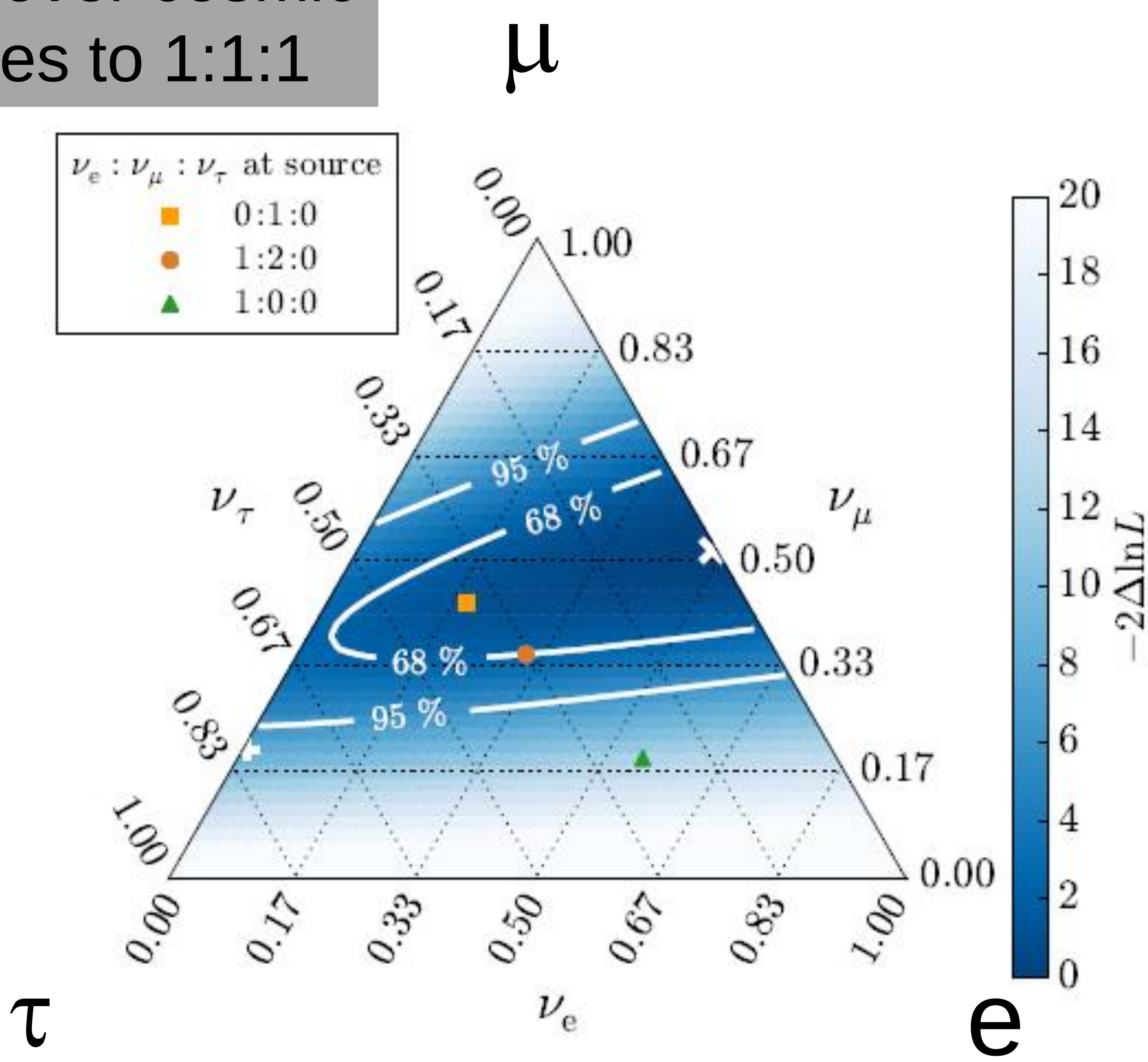
neutrinos do not interact and image the sky in regions from which even X-rays cannot escape



$p^+ = p^- = p^0$
IceCube $\nu_\mu + \bar{\nu}_\mu$ (preliminary)
IceCube combined (2015)
Fermi IGRB (2014)
Fermi gammas
cosmic neutrinos
$E^{-2.15}$
pp scenario
SFR evolution
$E^2\Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
E [TeV]

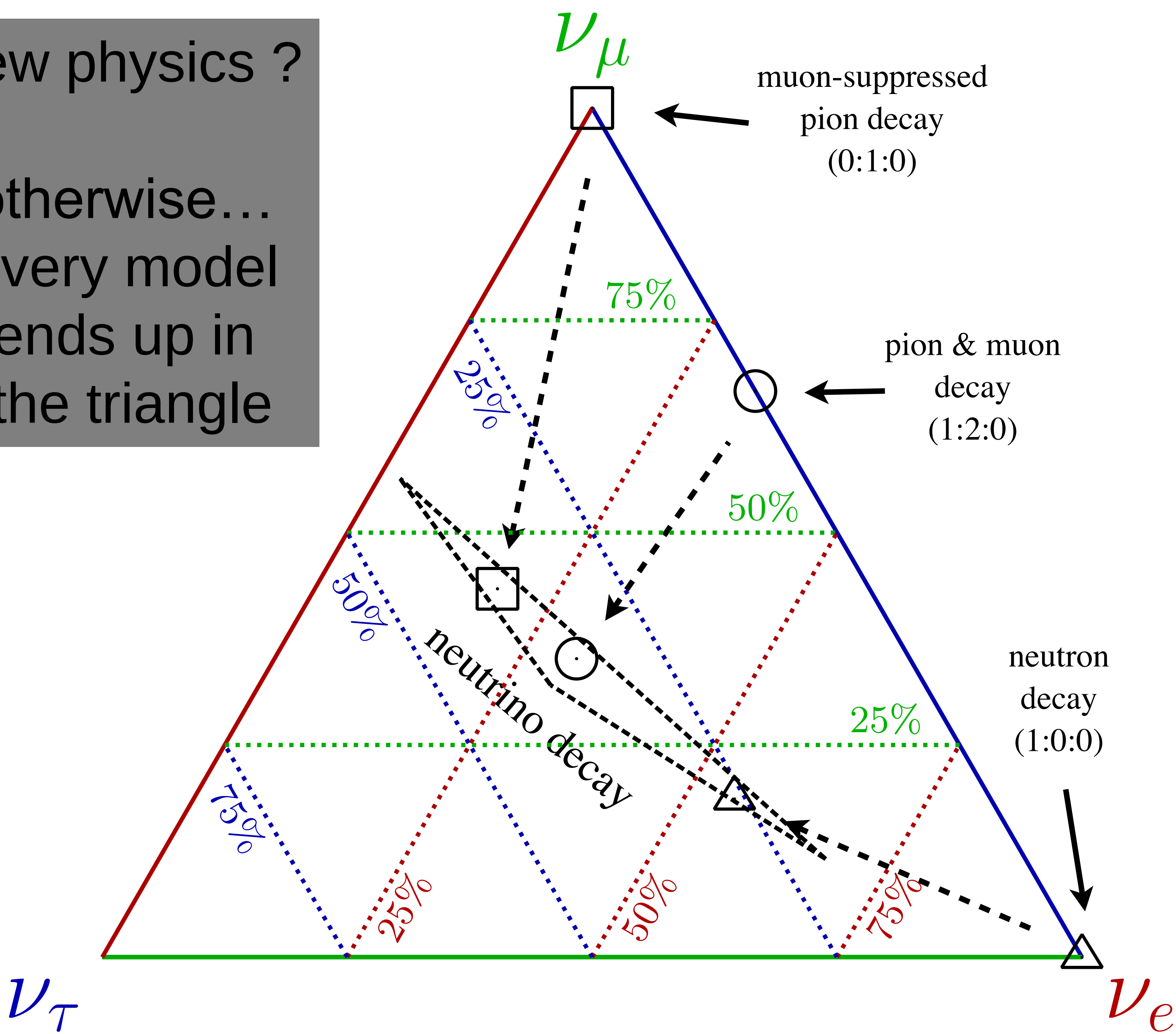
- energy density of neutrinos in the non-thermal Universe is the same as that in gamma-rays
- at some level common Fermi-IceCube sources?
  → multimessenger campaign of telescope follow-up of IceCube real-time neutrino alerts

oscillate over cosmic distances to 1:1:1



new physics ?

otherwise…
every model
ends up in
the triangle



merci

→ to the speakers for excellent talks

→ to the organizers for their superb hospitality