OVERVIEW OF NEUTRINO PHYSICS

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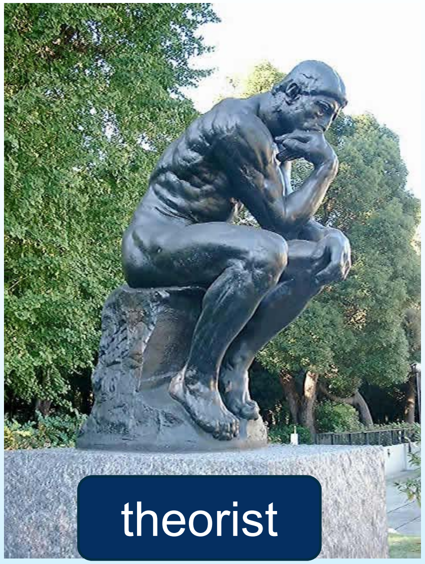
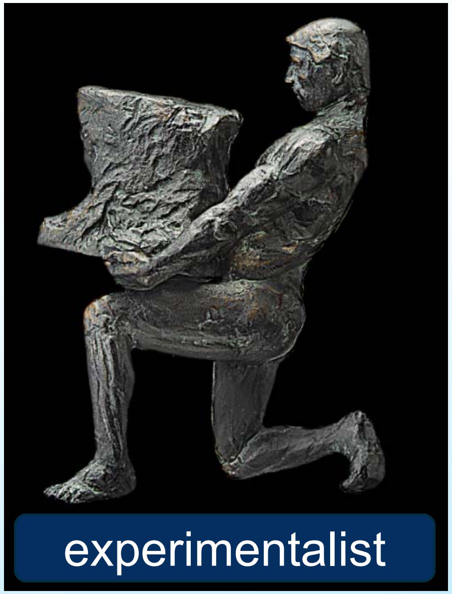
Preamble or excuse

http://www.takaratomy-arts.co.jp/specials/pandanoana/kangaenai/

I have been working on accelerator-based long baseline neutrino oscillation experiments and recently on R&D of double β-decay detector.





- This 40' opening talk by theorist in last two conferences.
- Next talk, accelerator-based neutrino.
- The latest results will come from each projects in this workshop
- What should I talk??? Why & Why?
- As a result, I will talk about subjects which I am unfamiliar in front of experts! Many mistakes, biases and Questions!

Be patient!

Neutrino Oscillation and neutrinoless double beta decay = Physics of MASS

What we know – mass of fermions-

u

$m_u = 2.2^{+0.5}_{-0.4}$ MeV

d

$m_d = 4.7^{+0.5}_{-0.3}$ MeV

s

$m_s = 95^{+9}_{-3}$ MeV

c

$m_c = 1.275^{+0.025}_{-0.035}$ GeV

b

Mass $m = 4.18^{+0.04}_{-0.03}$ GeV

t

$I(J^P) = 0(\frac{1}{2}^+)$

Charge $= \frac{2}{3}\ e$ Top $= +1$

Mass (direct measurements) $m = 173.0 \pm 0.4$ GeV [a,b] (S = 1.3)
Mass (from cross-section measurements) $m = 160^{+5}_{-4}$ GeV [a]
Mass (Pole from cross-section measurements) $m = 173.1 \pm 0.9$ GeV

e

$J = \frac{1}{2}$

Mass $m = (548.579909070 \pm 0.000000016) \times 10^{-6}$ u
Mass $m = 0.5109989461 \pm 0.0000000031$ MeV

μ

$J = \frac{1}{2}$

Mass $m = 0.1134289257 \pm 0.0000000025$ u
Mass $m = 105.6583745 \pm 0.0000024$ MeV

τ

$J = \frac{1}{2}$

Mass $m = 1776.86 \pm 0.12$ MeV

Neutrino Mixing

The following values are obtained through data analyses based on the 3-neutrino mixing scheme described in the review "Neutrino Mass, Mixing, and Oscillations" by K. Nakamura and S.T. Petcov in this *Review*.

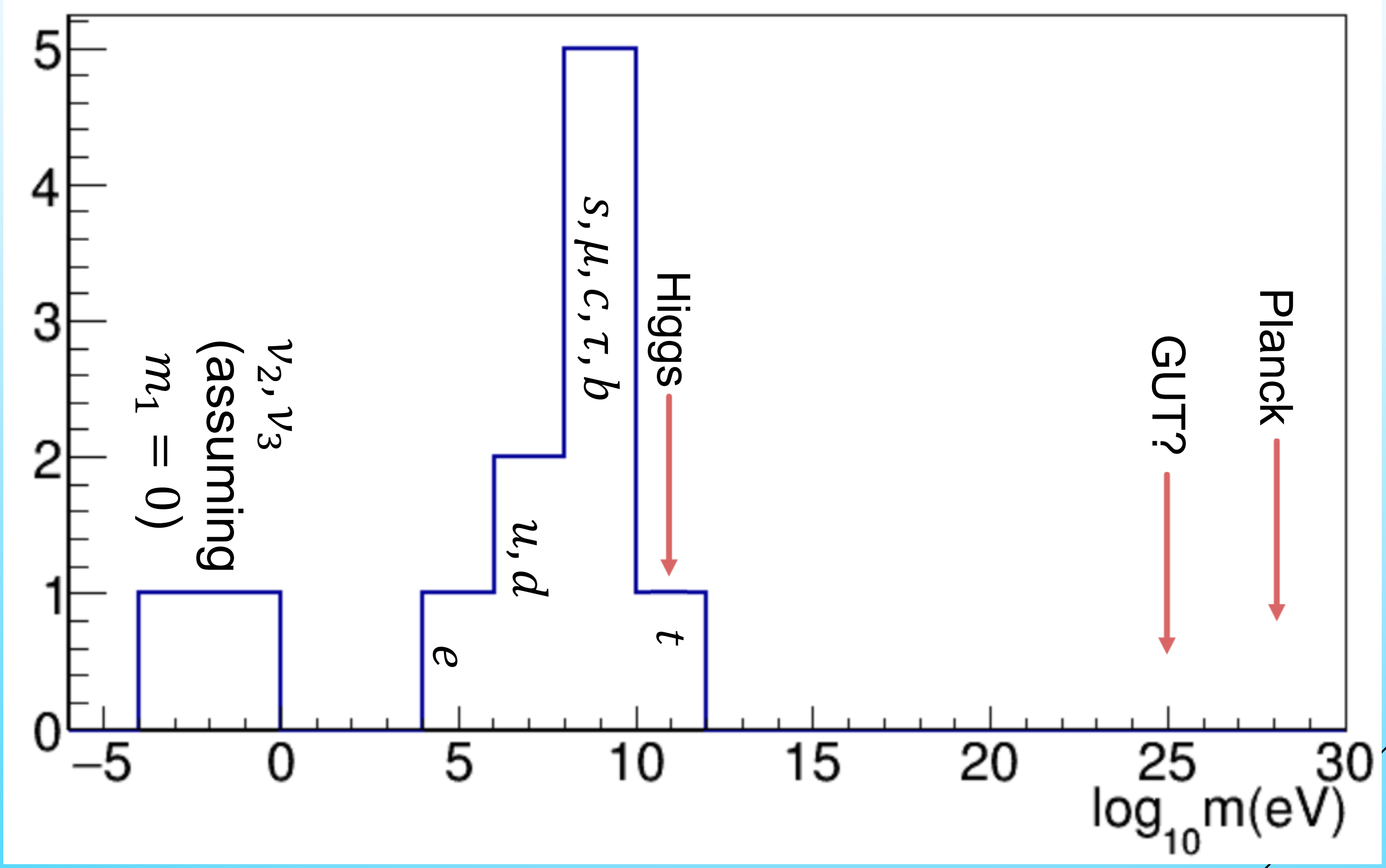
$\sin^2(\theta_{12}) = 0.307 \pm 0.013$
$\Delta m^2_{21} = (7.53 \pm 0.18) \times 10^{-5}$ eV^2
$\sin^2(\theta_{23}) = 0.421^{+0.033}_{-0.025}$ (S = 1.3) (Inverted order, quad. I)
$\sin^2(\theta_{23}) = 0.592^{+0.023}_{-0.030}$ (S = 1.1) (Inverted order, quad. II)
$\sin^2(\theta_{23}) = 0.417^{+0.025}_{-0.028}$ (S = 1.2) (Normal order, quad. I)
$\sin^2(\theta_{23}) = 0.597^{+0.024}_{-0.030}$ (S = 1.2) (Normal order, quad. II)
$\Delta m^2_{32} = (-2.56 \pm 0.04) \times 10^{-3}$ eV^2 (Inverted order)
$\Delta m^2_{32} = (2.51 \pm 0.05) \times 10^{-3}$ eV^2 (S = 1.1) (Normal order)
$\sin^2(\theta_{13}) = (2.12 \pm 0.08) \times 10^{-2}$

data), etc. the Planck Collaboration reported the updated upper limit on the sum of the neutrino masses [78], which, depending on the data-set used, varies in the interval: $\sum_j m_j < (0.340 - 0.715)$ eV, 95% CL. Adding data on the Baryon Acoustic Oscillations (BAO) lowers the limit to [78]:

$$\sum_j m_j < 0.170\ eV, \quad 95\%\ \text{CL}.$$

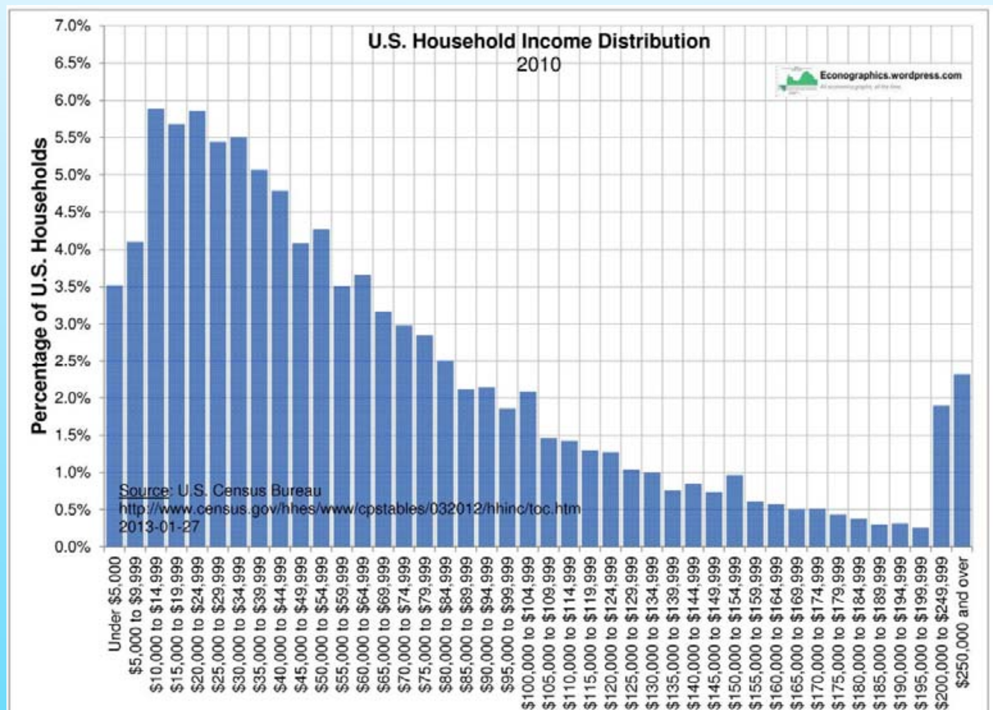
As an experimentalist,
I made a mass distribution plot.

log distribution of elementary fermion mass



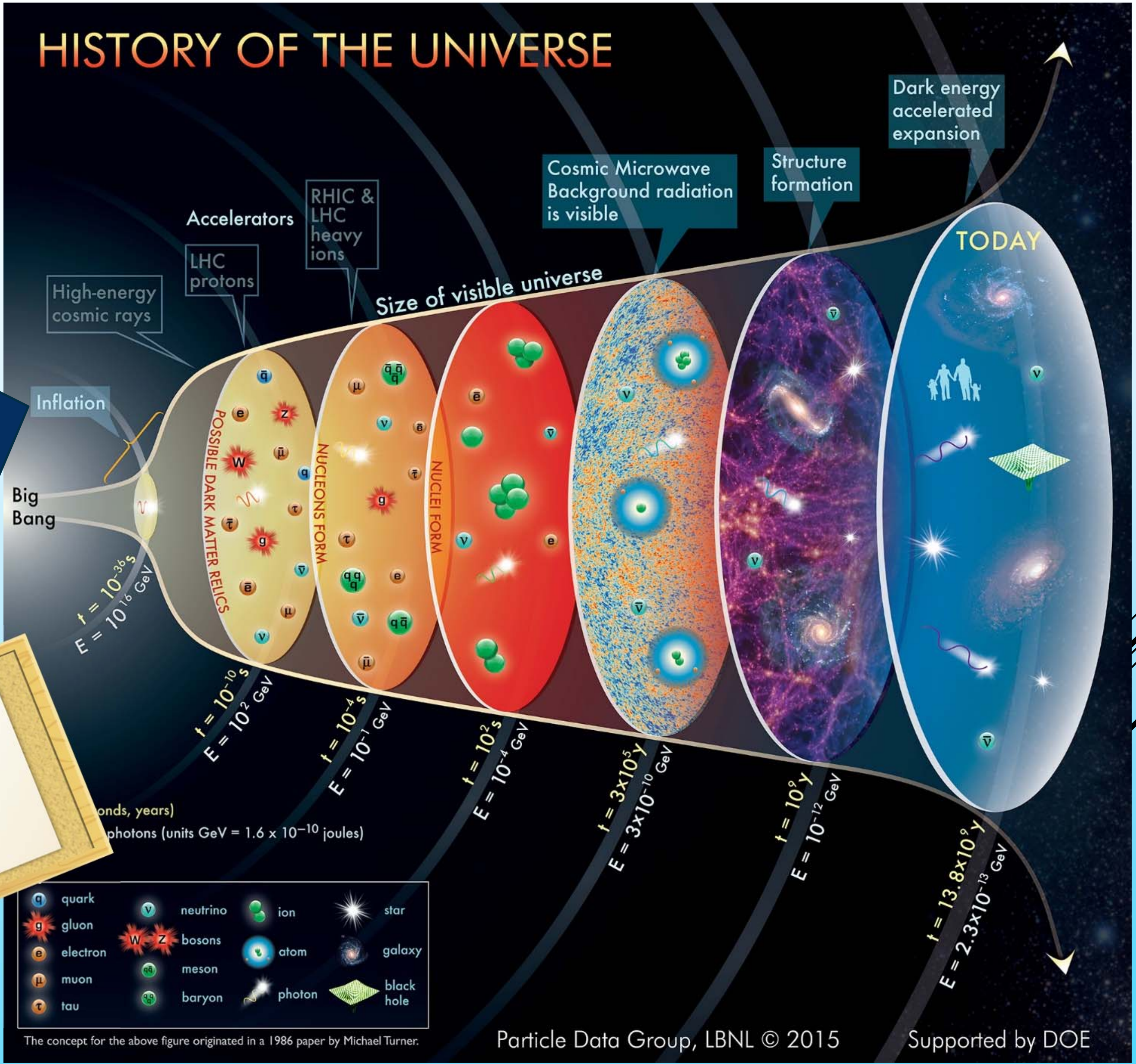
log-normal distribution

- Wikipedia, “a continuous probability distribution of a random variable whose logarithm is normally distributed. A log-normal process is the statistical realization of the multiplicative product of many independent random variables, each of which is positive. “
- example: annual incomes, reserve of oil fields
- People has n opportunities to multiply one’s income. n follows normal distribution, but each time your income multiplicatively increase.



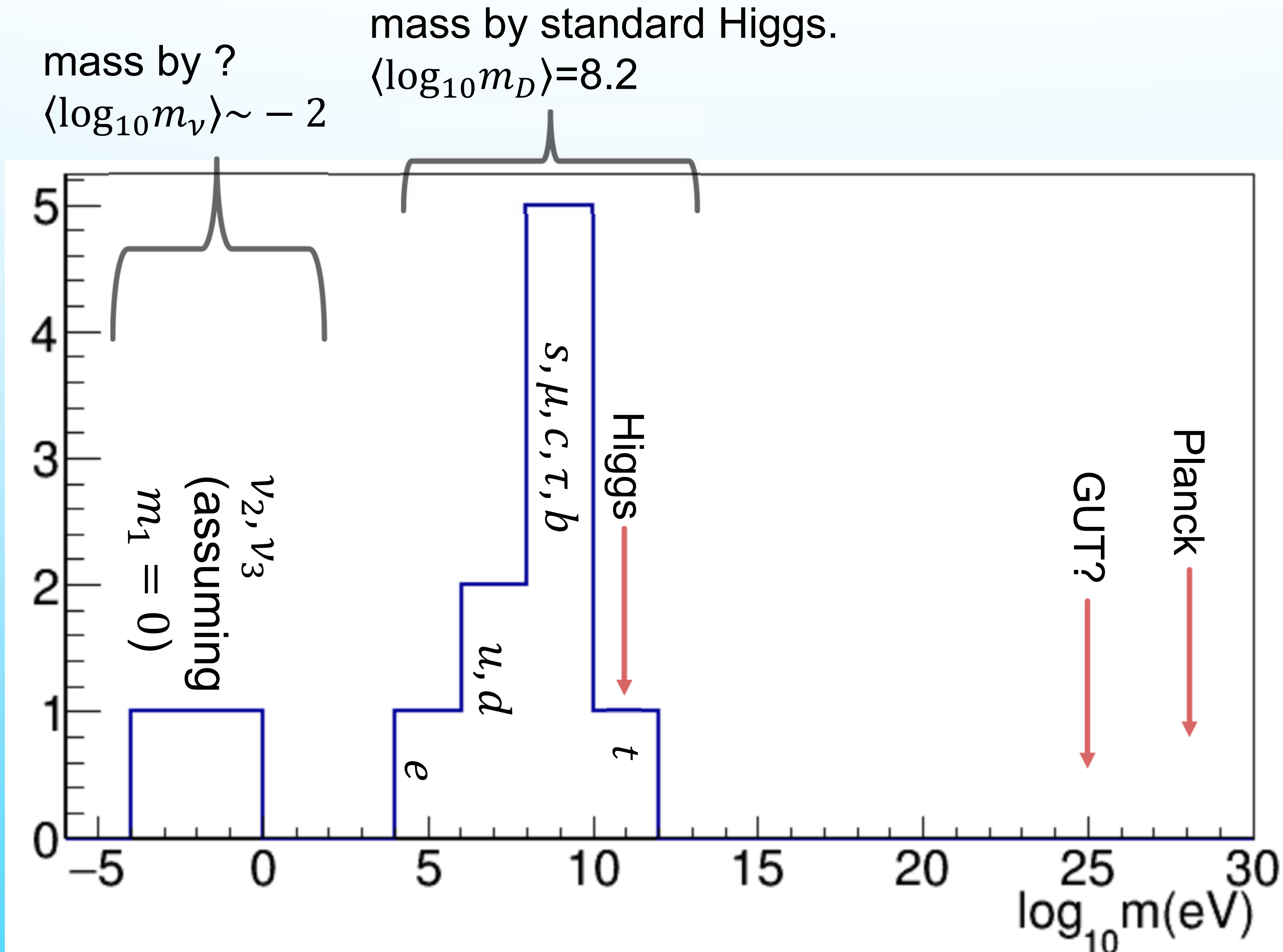
For example, I can imagin

Universe expanded exponentially.
If particle mass (Yukawa coupling) is inversely proportional to the space size, time fluctuation of mass determination results in log-normal distribution.



Q. Fantasy?

What is the origin of mass?

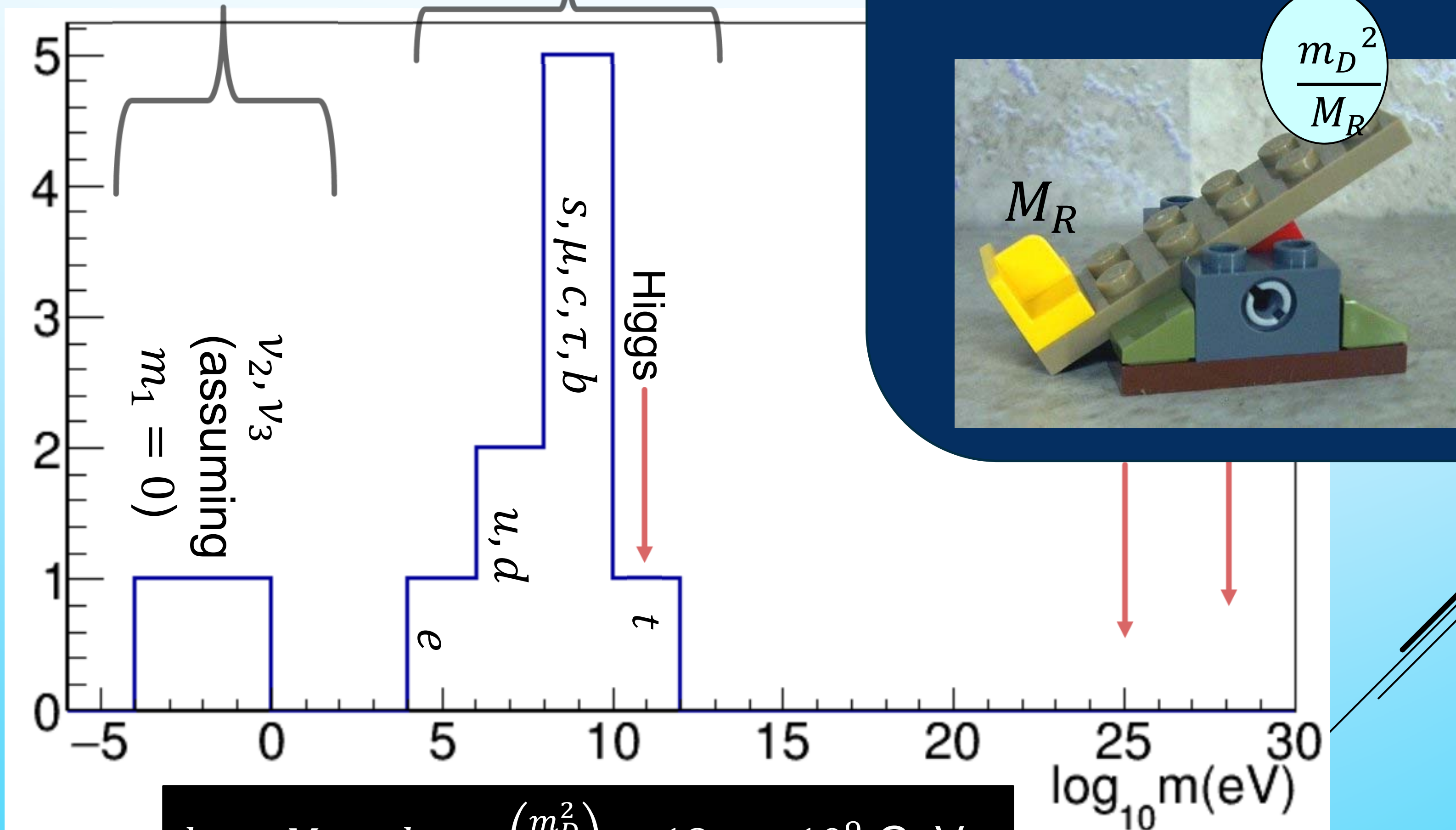


Minkowski,('77), Yanagita('79), GellMannn, Ramondo, Slansky('79),Glashow('79)

Seesaw?

mass by ?
$\langle \log_{10} m_\nu \rangle \sim -2$

mass by standard Higgs.
$\langle \log_{10} m_D \rangle$=8.2



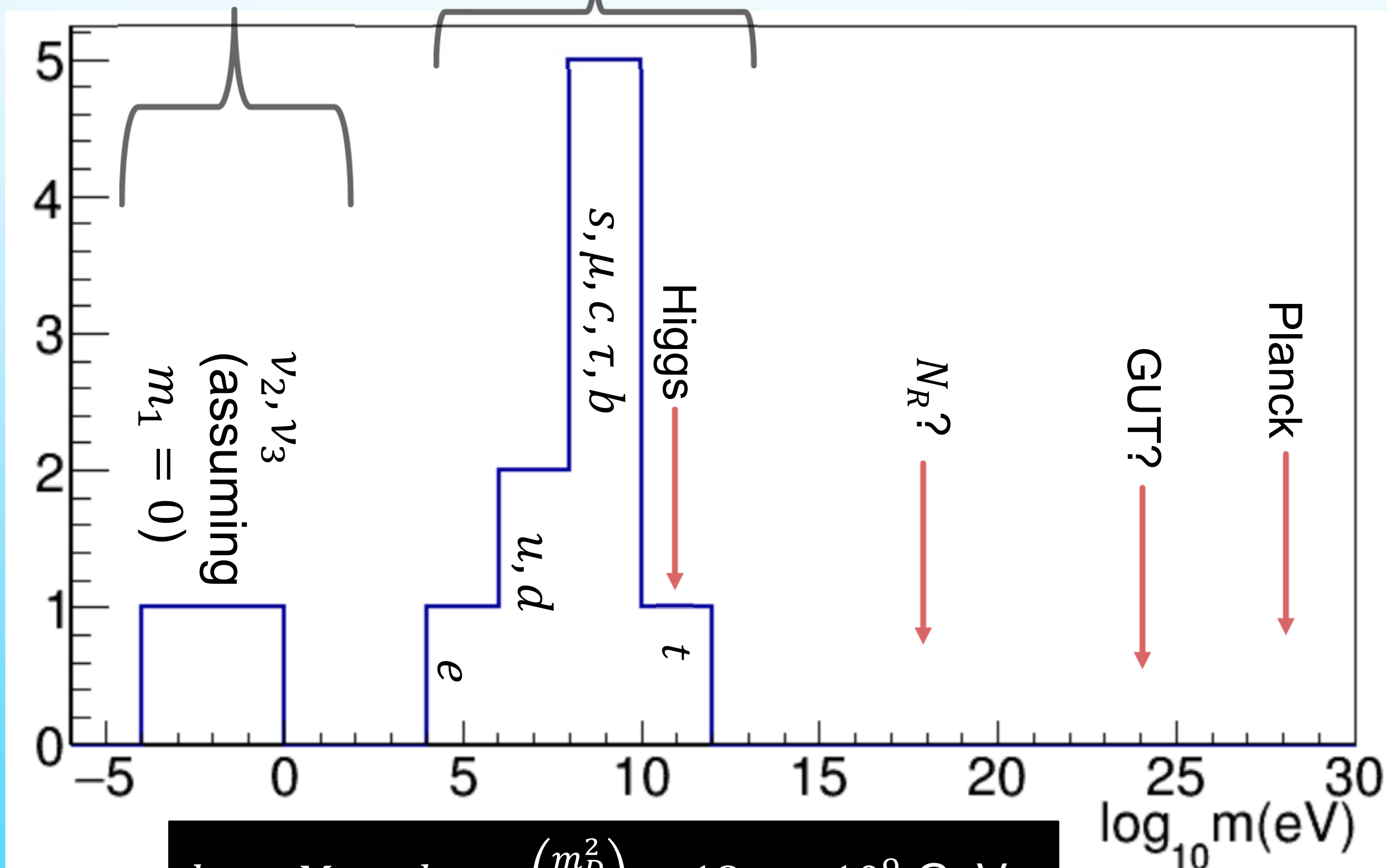
If neutrino is Majorana-type,

$$\text{mass term} = (\bar{N}_L, \bar{N}_R) \begin{pmatrix} 0 & m_D \\ m_D & M_R \end{pmatrix} \begin{pmatrix} N_L \\ N_R \end{pmatrix}$$

↓ diagonalize

$$log_{10} M_R = log_{10}\left(\frac{m_D^2}{m_\nu}\right) = 18 \ \rightarrow \ 10^9 \text{ GeV}$$

Neutrino mass is suppressed by very high energy physics?



$$log_{10} M_R = log_{10}\left(\frac{m_D^2}{m_\nu}\right) = 18 \;\rightarrow\; 10^9 \text{ GeV}$$

Mixing between mass eigenstates

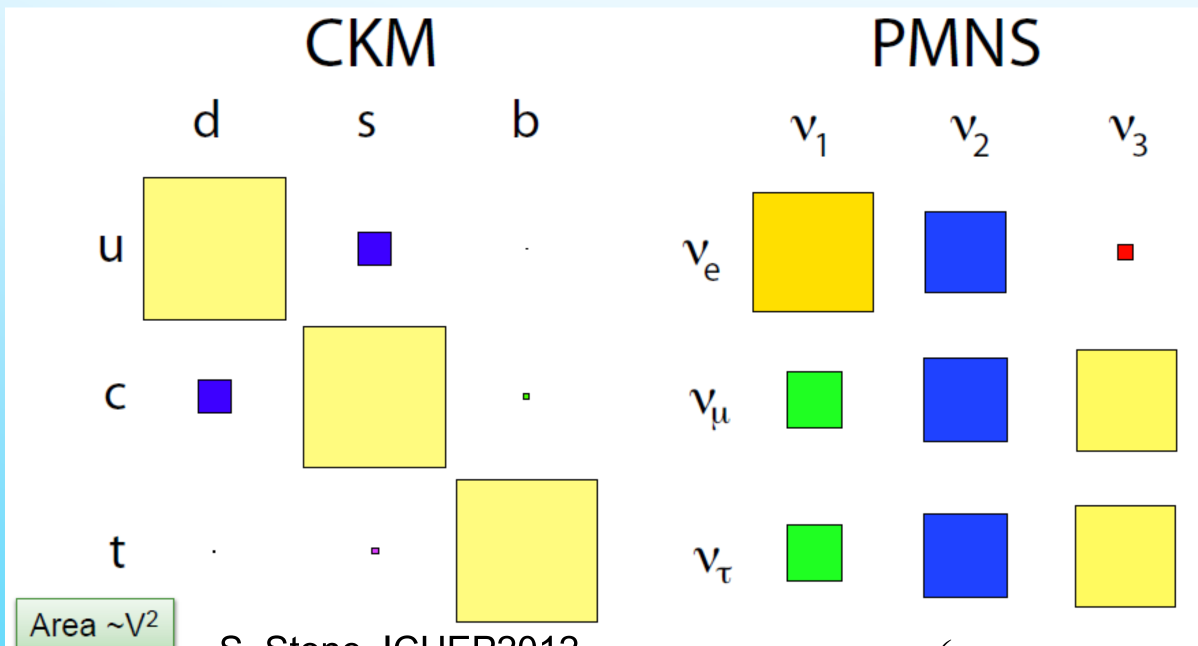
- up-type vs. down-type in quark
- charged vs. neutral in lepton

quark

$$U_{CKM} \approx \begin{pmatrix} 0.97 & 0.22 & 0.004 \\ 0.22 & 1.0 & 0.04 \\ 0.008 & 0.04 & 1.0 \end{pmatrix}$$

lepton

$$U_{PMNS} \approx \begin{pmatrix} 0.82 & 0.55 & 0.14 \\ -0.47 & 0.53 & 0.71 \\ 0.31 & -0.65 & 0.69 \end{pmatrix}$$



S. Stone, ICHEP2012

	quark	lepton
θ_{12}	14°	34°
θ_{23}	2.3°	46°
θ_{13}	0.2°	8.3°

$$\mathrm{U_{PMNS}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & +c_{23} & +s_{23} \\ 0 & -s_{23} & +c_{23} \end{pmatrix} \begin{pmatrix} +c_{13} & 0 & +s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & +c_{13} \end{pmatrix} \begin{pmatrix} +c_{12} & +s_{12} & 0 \\ -s_{12} & +c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$(c_{ij} = \cos\theta_{ij}, s_{ij} = \sin\theta_{ij})$$

Mixing between mass eigenstates

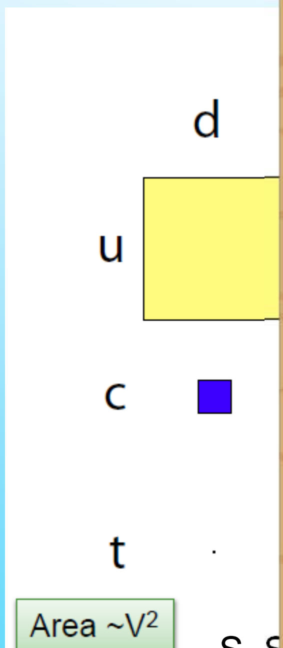
up-type vs. down-type in quark

charged vs. neutral in lepton

quark

$U_{CKM} \approx$

$$\begin{matrix} 0.14 \\ 0.71 \\ 0.69 \end{matrix}$$



S. S

Q. about Yukawa coupling (~diagonal matrix)

Did Fermions pick up similar weight particles as partner?

Or did partners pick up similar weight?

lepton
34°
46°
8.3°

$$U_{PMNS} = \begin{pmatrix} 0 & +c_{23} & +s_{23} \\ 0 & -s_{23} & +c_{23} \end{pmatrix} \begin{pmatrix} 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & +c_{13} \end{pmatrix} \begin{pmatrix} +c_{12} & +s_{12} & 0 \\ -s_{12} & +c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

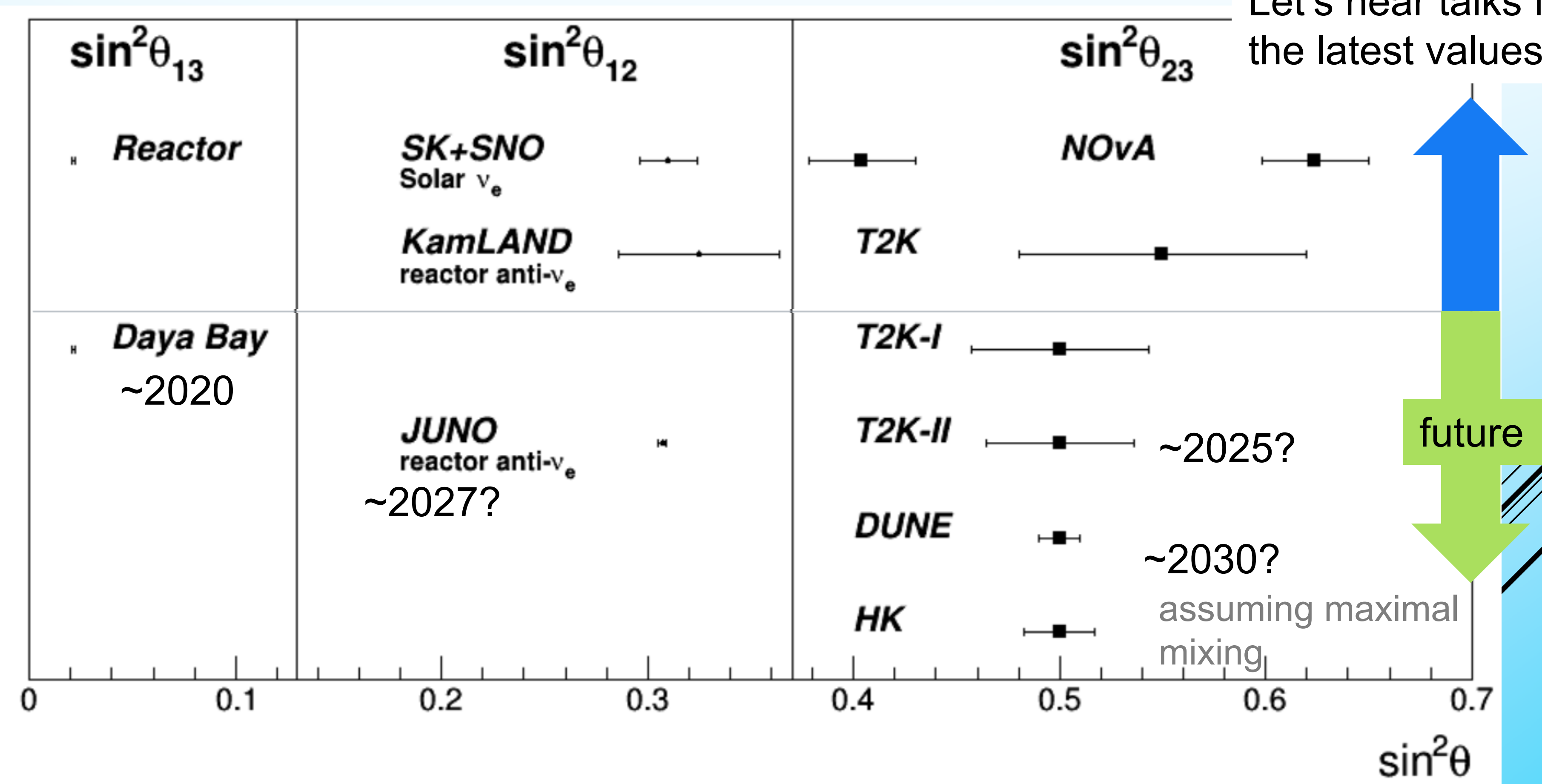
$$(c_{ij} = \cos\theta_{ij}, s_{ij} = \sin\theta_{ij})$$

Prospect of mixing angle determination
High precision and redundant measurements

Prospect of mixing angle determination
High precision and redundant measurements

* may not be precise comparison

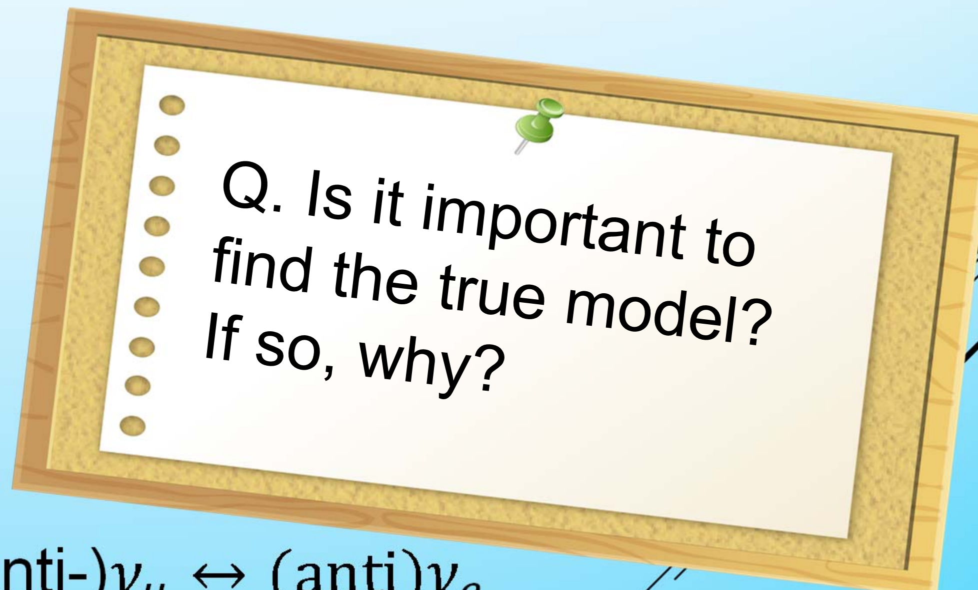
PDG18
Let's hear talks for the latest values.



Ploted $\sin^2\theta$ to see the size of mixing

Mass Ordering

- normal $(m_1 < m_2 < m_3)$ or inverted $(m_3 < m_1 < m_1)$?
- Big impact for neutrinoless double-beta decay search
  - ✓ normal ordering → lighter $m_{\beta\beta}$
  - ✓ Detector necessary ~1 ton vs $\gtrsim$100 ton



- two ways proposed

A) Matter effect in Earth for (anti-)$\nu_\mu \leftrightarrow (\mathrm{anti})\nu_e$

B) Amplitude difference for two frequencies

Mass Ordering

A) Matter effect in Earth for (anti-)$\nu_\mu \leftrightarrow$ (anti)ν_e

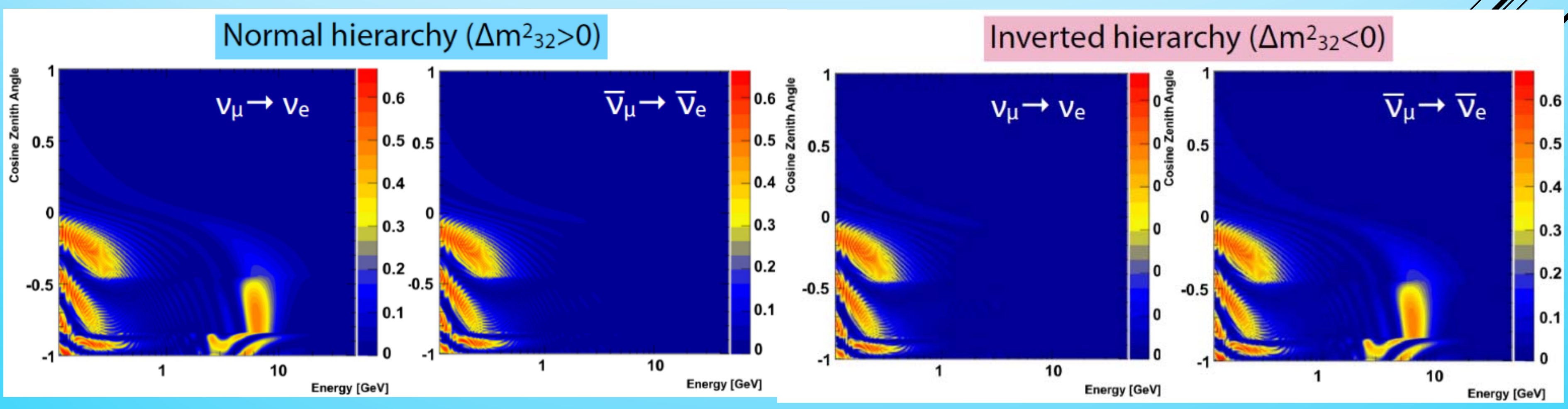
$$H = U_{PMNS}\begin{pmatrix} 0 & 0 & 0 \\ 0 & \frac{\Delta m^2_{21}}{2E} & 0 \\ 0 & 0 & \frac{\Delta m^2_{31}}{2E} \end{pmatrix} U^*_{PMNS} + \begin{pmatrix} \pm\frac{2\sqrt{2}G_F n_e E}{2E} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

sign different for NO and IO

sign different for ν and $\bar{\nu}$

Especially, resonance happens at $E = \frac{\Delta m^2 \cos 2\theta}{2\sqrt{2}G_F n_e}$

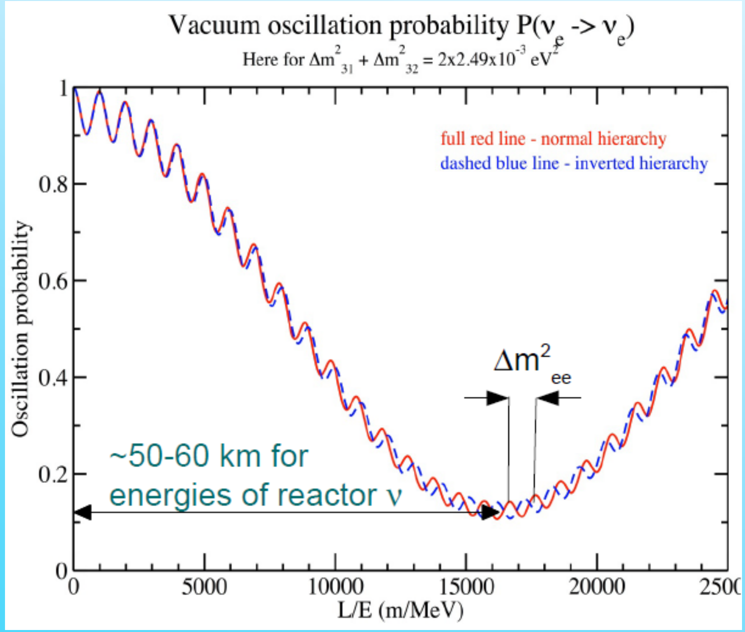
Effect of Earth matter has not yet observed due to relatively small $\sin^2 2\theta_{13}$



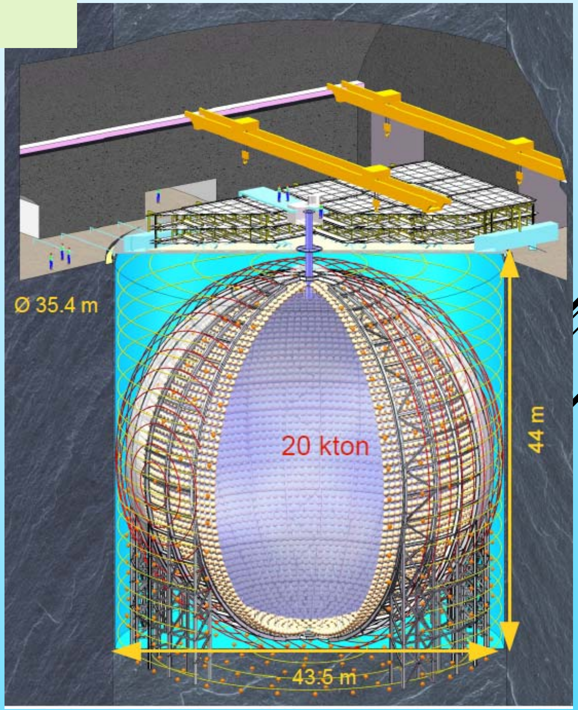
Mass Ordering
B) Amplitude difference for two frequencies

$$P(\bar{\nu}_e \to \bar{\nu}_e)$$
$$= (\text{leading term})$$
$$- \sin^2 2\theta_{13} \left(\underbrace{\cos^2\theta_{12}}_{0.69} \sin^2 \Delta m^2_{31} \frac{L}{4E} + \underbrace{\sin^2\theta_{12}}_{0.31} \sin^2 \Delta m^2_{32} \frac{L}{4E} \right)$$

$\Delta m^2_{31} > \Delta m^2_{32}$ for NO
$\Delta m^2_{31} < \Delta m^2_{32}$ for IO

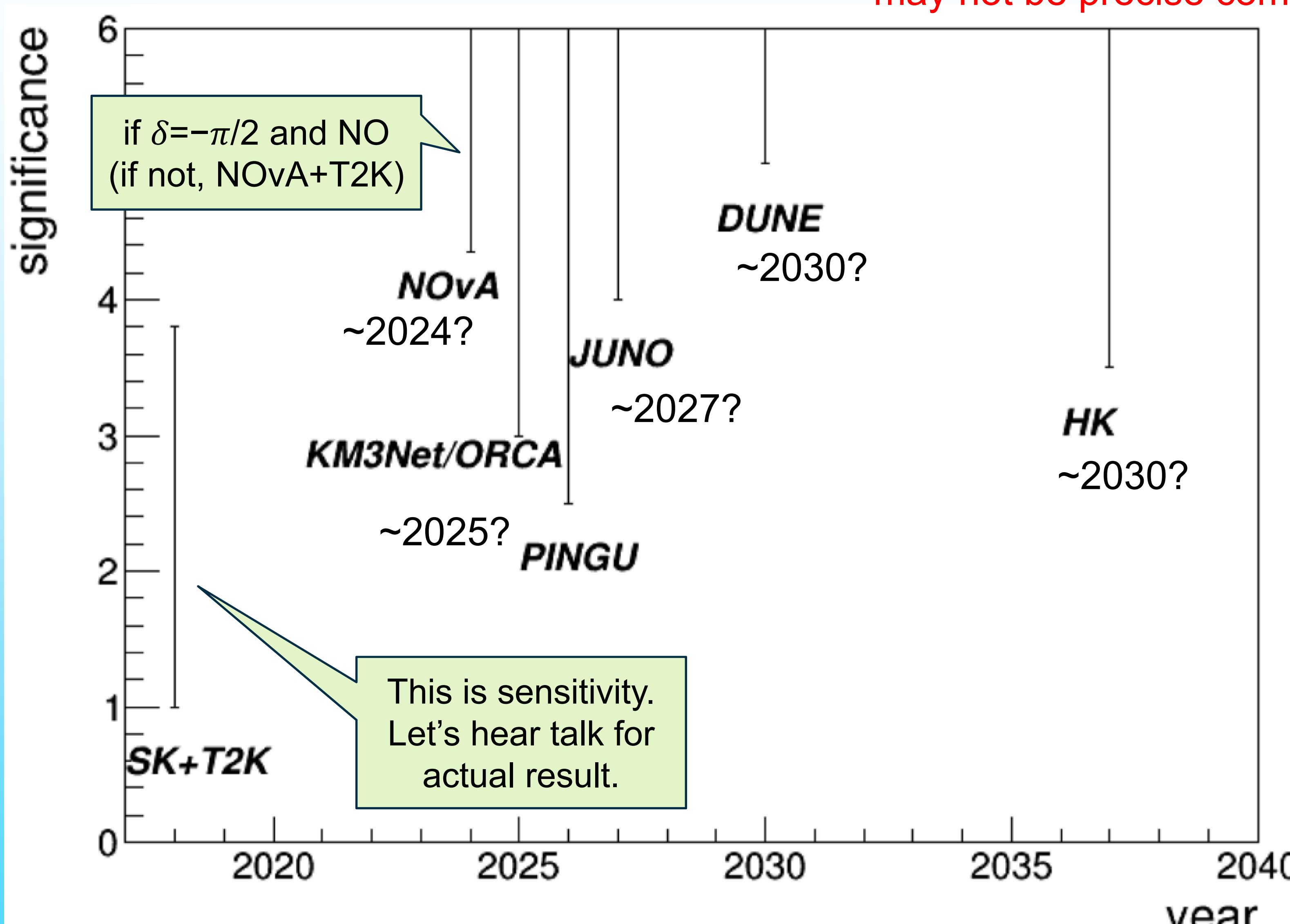


JUNO



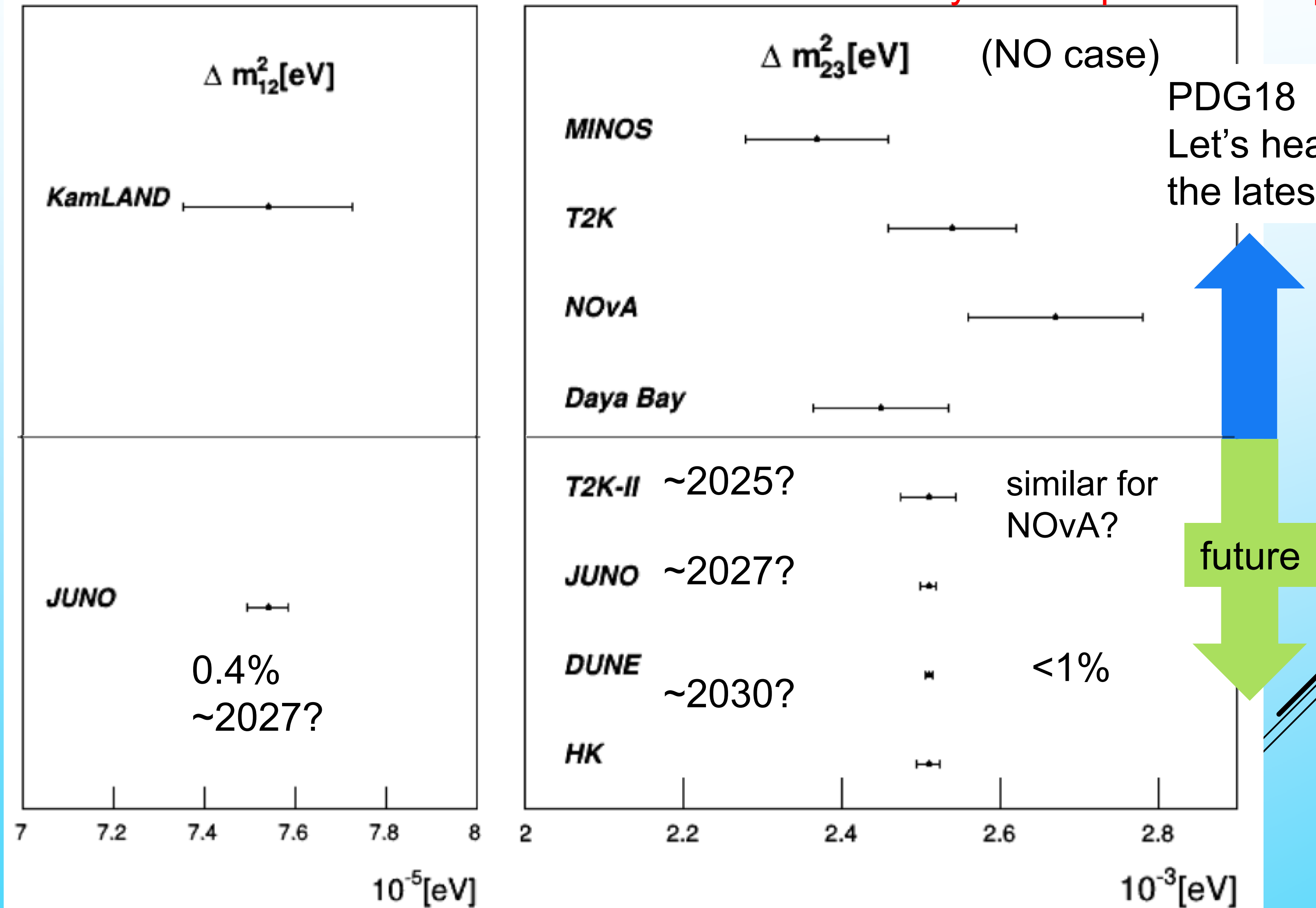
Prospect of Mass Ordering determination

* may not be precise comparison



Prospect of Δm^2 determination
High precision and redundant measurements

* may not be precise comparison



Dirac CP phase

$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & +c_{23} & +s_{23} \\ 0 & -s_{23} & +c_{23} \end{pmatrix} \begin{pmatrix} +c_{13} & 0 & +s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & +c_{13} \end{pmatrix} \begin{pmatrix} +c_{12} & +s_{12} & 0 \\ -s_{12} & +c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$(c_{ij} = \cos\theta_{ij}, s_{ij} = \sin\theta_{ij})$$

- Quark case δ_{CP}^{CKM}~$60°$~$70°$

  looks large, but cannot explain matter-dominant universe.

- Lepton case $\delta_{CP}^{MNS} \sim -90°$??? → Accelerator long baseline

- δ_{CP} is dependent on definition.

  Jarlskog Invariant : independent of definition.

  show the size of CP violation effect.

$$J_{CP} \equiv Im\left(U_{\mu 3}U_{e3}^{*}U_{e2}U_{\mu 2}^{*}\right) = \frac{1}{8}\sin 2\theta_{12}\sin 2\theta_{23}\sin 2\theta_{13}\cos\theta_{13}\sin\delta_{CP}$$

$$J_{CP}^{CKM} \approx 3 \times 10^{-5}$$

$$J_{CP}^{PMNS} \approx 0.033\sin\delta_{CP}$$

Leptonic CPV can be much larger than Quark's

δ_{CP} may or may not be related to matter-dominant universe, but…

δ_{CP} may cause CPV which is sufficiently large to produce matter-dominant universe

Leptogenesis

- CPV in $N_R \rightarrow l^{\pm} + H^{\mp}$ etc.→ Lepton asymmetry

  → sphaleron → Baryon asymmetry

PDG2015 “NEUTRINOMASS,MIXING, AND OSCILLATIONS”

A value of $|\sin\theta_{13}\sin\delta| \gtrsim 0.09$, and thus $\sin\theta_{13} \gtrsim 0.09$, is a necessary condition for a successful “flavoured” leptogenesis with hierarchical heavy Majorana neutrinos when the CP violation required for the generation of the matter-antimatter asymmetry of the Universe is provided entirely by the Dirac CP violating phase in the neutrino mixing matrix [191]. This condition is comfortably compatible both with the measured value of $\sin^2\theta_{13}$ and with the best fit value of $\delta \cong 3\pi/2$.

191. S. Pascoli, S.T. Petcov, and A. Riotto, Phys. Rev. **D75**, 083511 (2007) and Nucl. Phys. **B774**, 1 (2007); E. Molinaro and S.T. Petcov, Phys. Lett. **B671**, 60 (2009).

$|\sin\theta_{13}\sin\delta| \geq 0.09 \;\rightarrow\; |\sin\delta| \geq 0.58$

Majorana CP phase

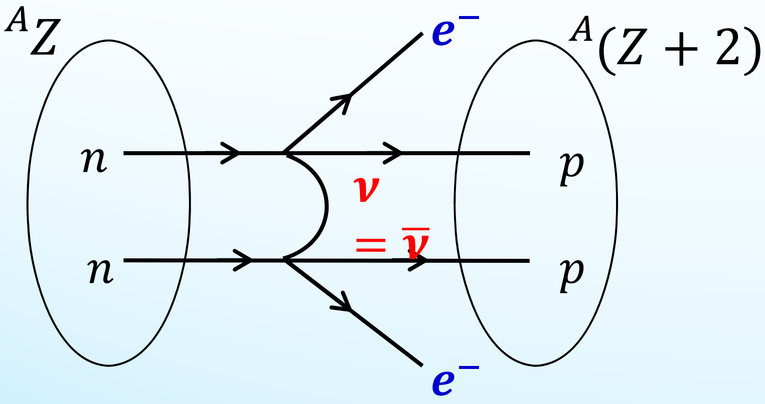
- If neutrino is Majorana type,

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & +c_{23} & +s_{23} \\ 0 & -s_{23} & +c_{23} \end{pmatrix} \begin{pmatrix} +c_{13} & 0 & +s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & +c_{13} \end{pmatrix} \begin{pmatrix} +c_{12} & +s_{12} & 0 \\ -s_{12} & +c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\frac{\alpha_{21}}{2}} & 0 \\ 0 & 0 & e^{i\frac{\alpha_{31}}{2}} \end{pmatrix}$$

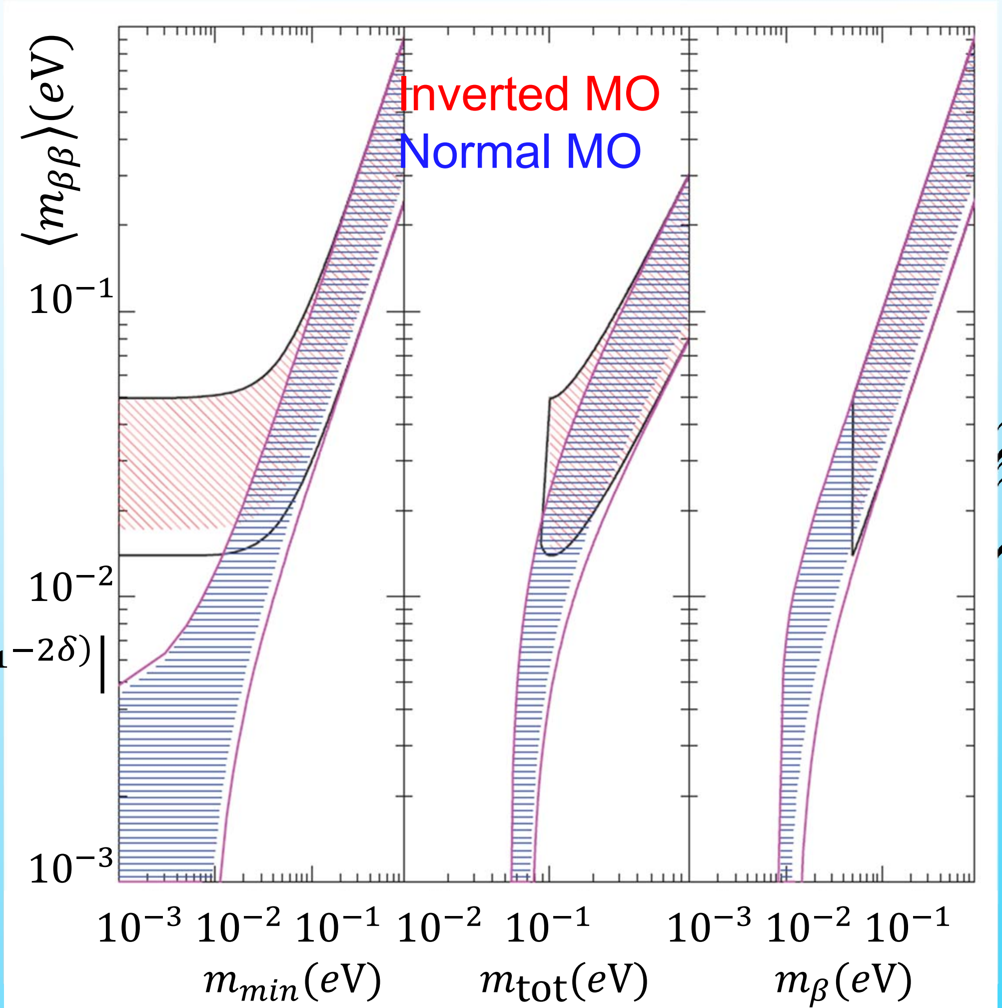
$$\left(c_{ij} = \cos\theta_{ij}\,, s_{ij} = \sin\theta_{ij}\right)$$

Another two CP phases which cannot be accessible by oscillation

Neutrinoless double-beta decay



hatched width by Majorana-phases
slide line Majorana-phases+oscillation par.
uncertainty 90% uncertainty.



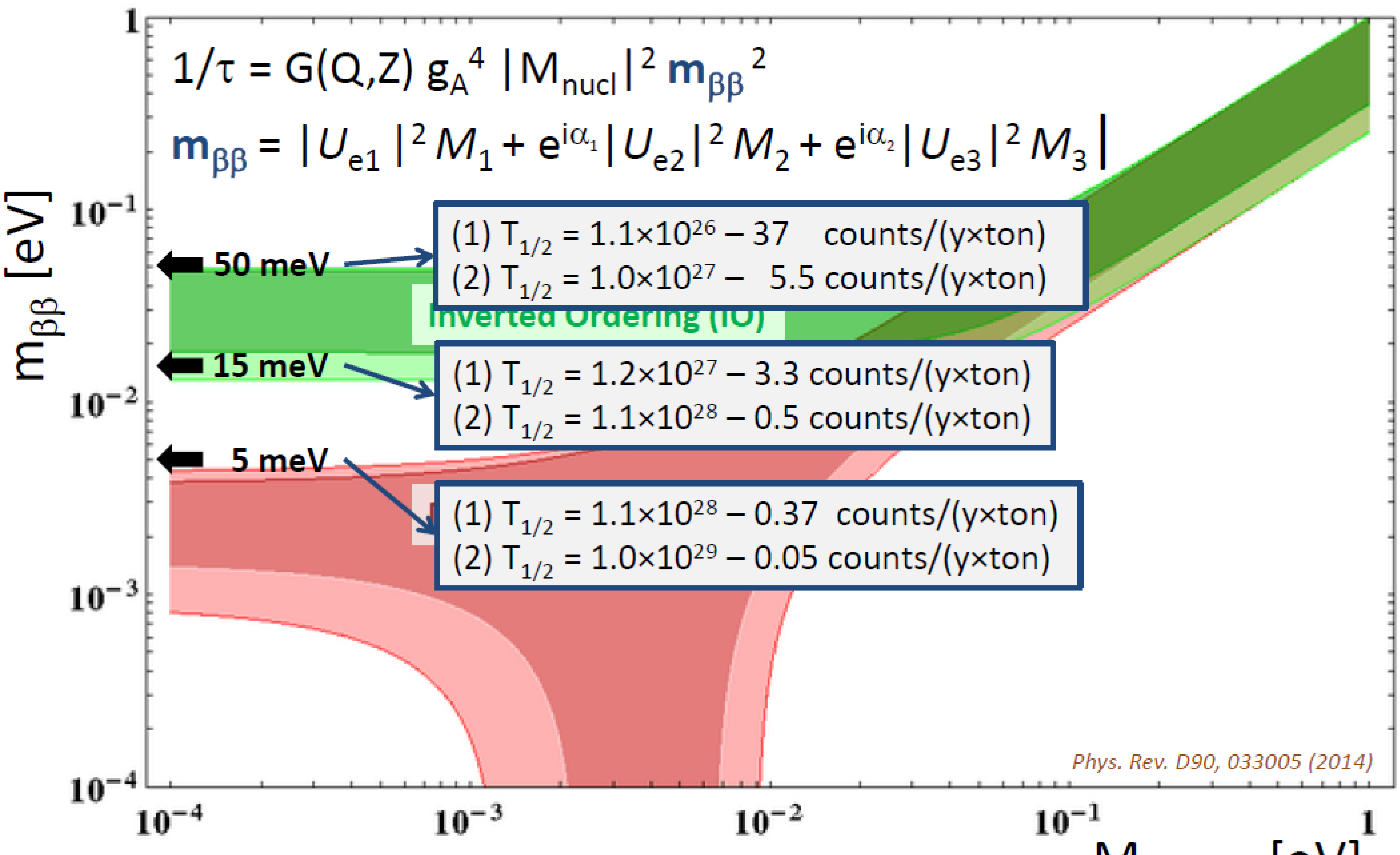
$$\left(T^{0\nu}_{1/2}\right)^{-1} = G^{0\nu} \cdot |M^{0\nu}|^2 \cdot \langle m_{\beta\beta}\rangle^2$$

$$\langle m_{\beta\beta}\rangle^2 = \left|\sum_i U_{ei}^2 m_{\nu_i}\right|^2$$

$$= \left|\left(m_1 c_{12}^2 + m_2 s_{12}^2 e^{i\alpha_{21}}\right) c_{13}^2 + m_3 s_{13}^2 e^{i(\alpha_{31} - 2\delta)}\right|$$

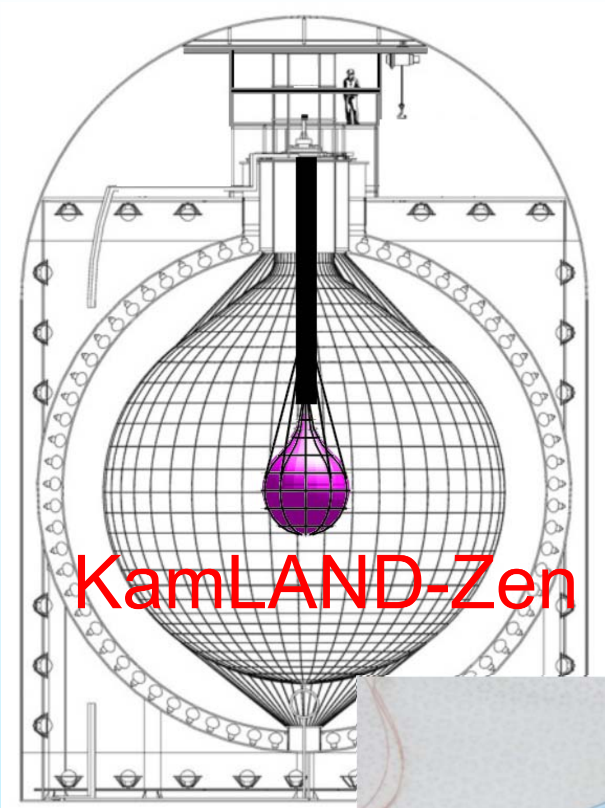
If measured, <u>absolute mass</u> and possibly <u>Majorana phase</u>

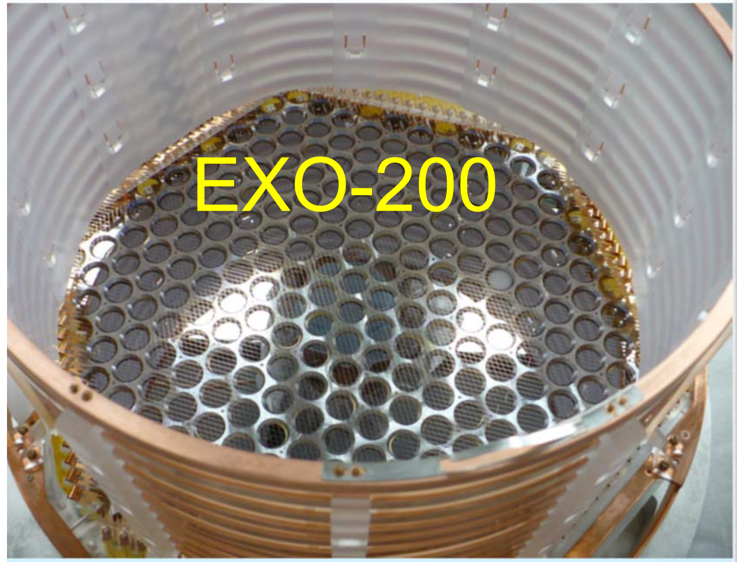
How difficult is it?

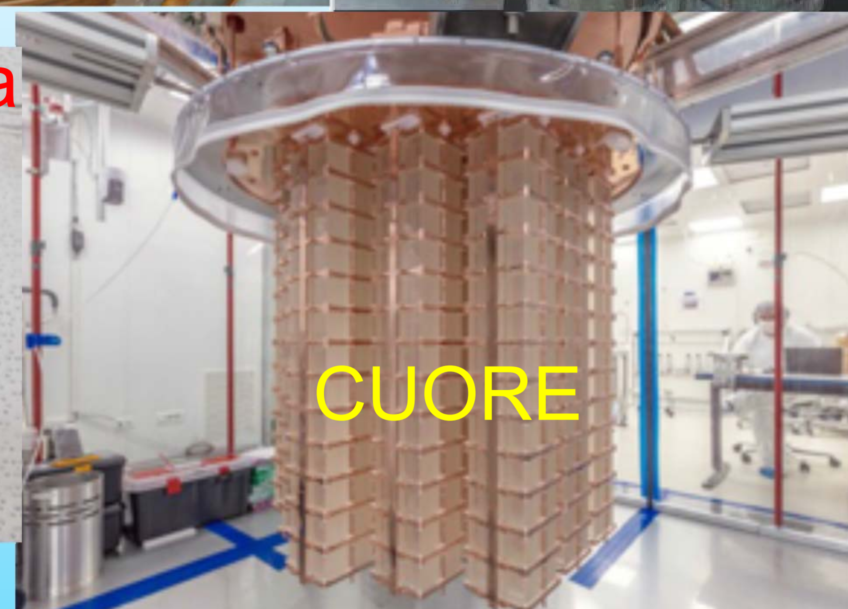


A. Giuliani “The Mid and Long Term Future of Neutrinoless Double Beta Decay”, Neutrino 2018

Neutrinoless double-β decay

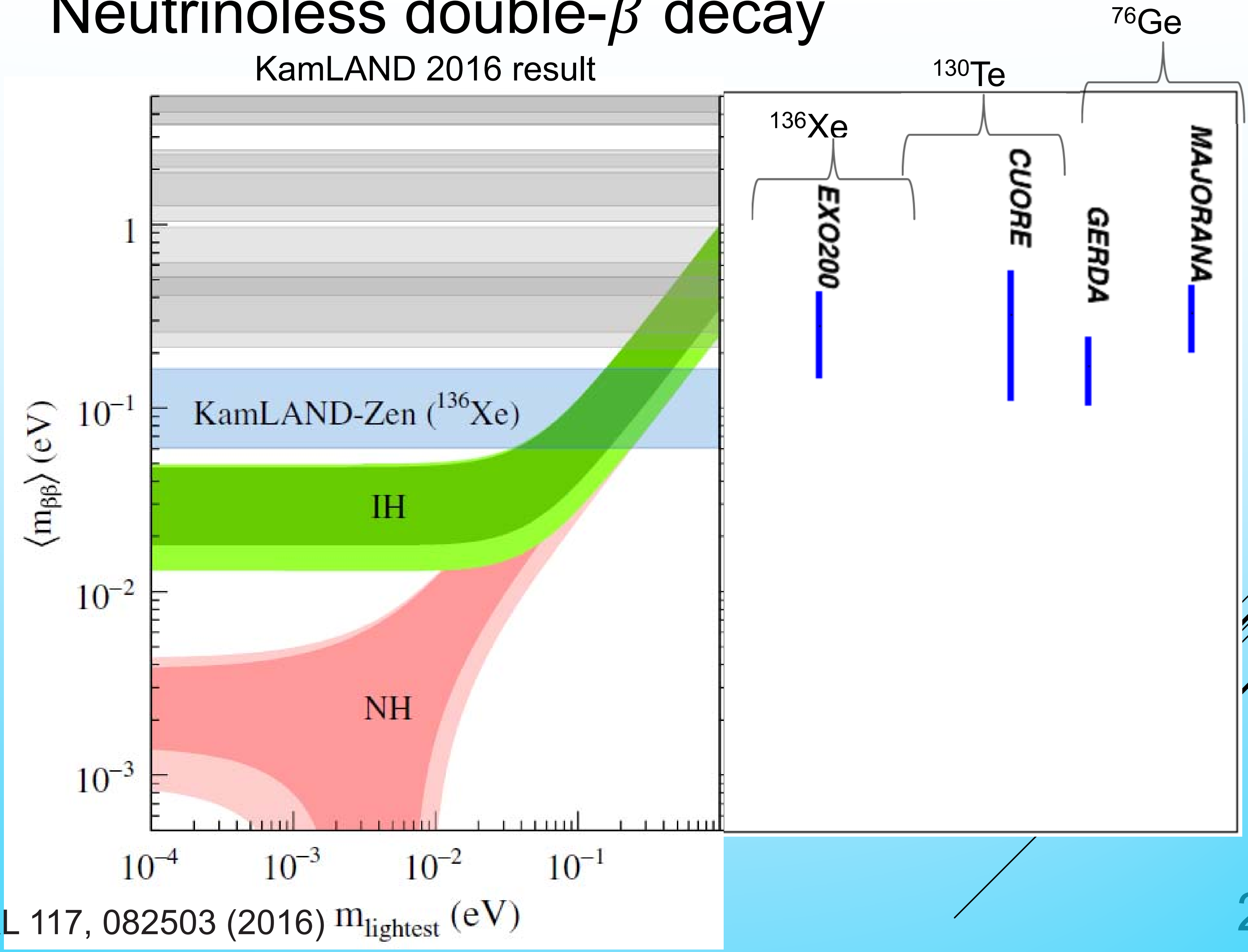






Neutrinoless double-β decay

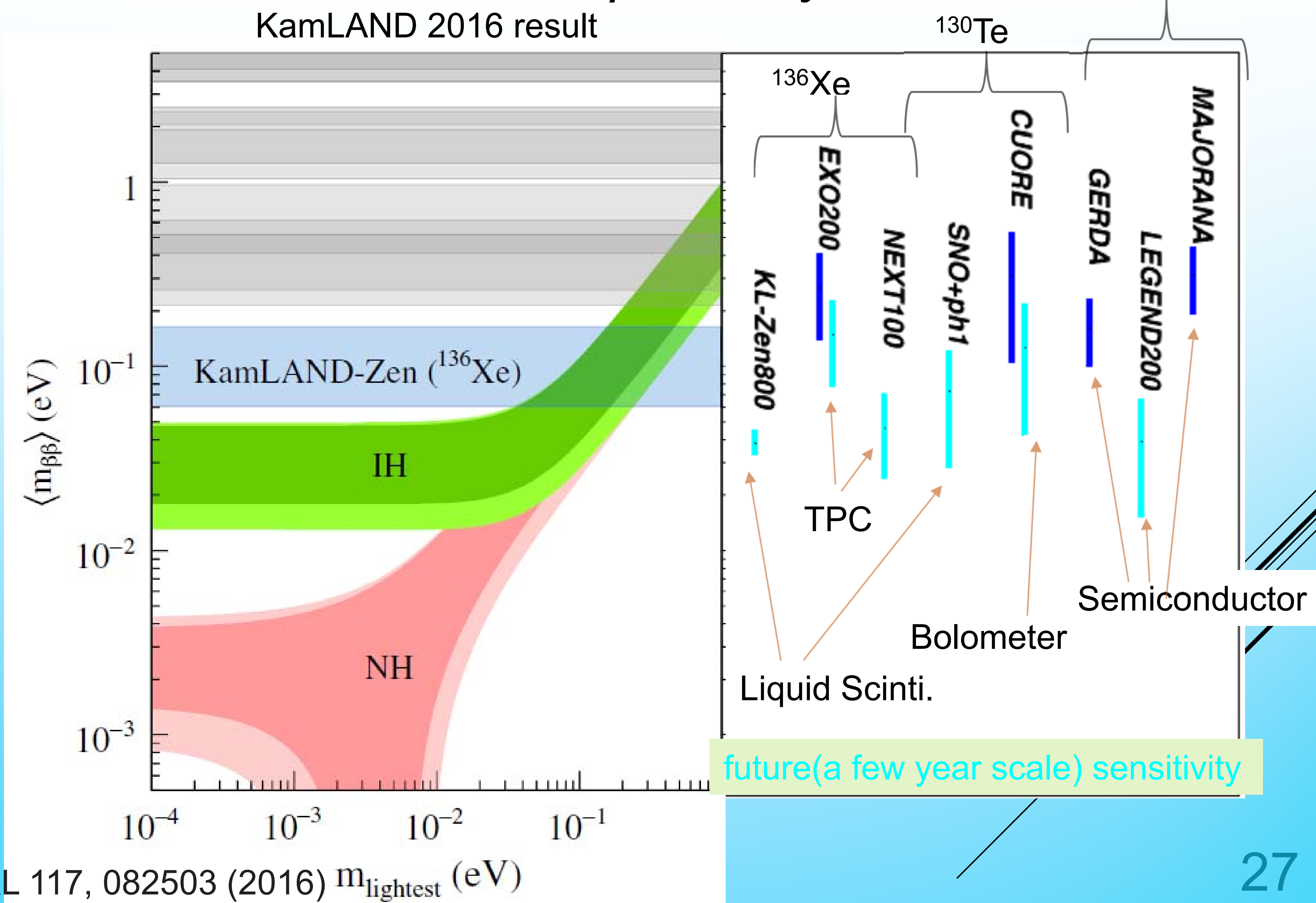
Recent release



PRL 117, 082503 (2016)

Neutrinoless double-β decay

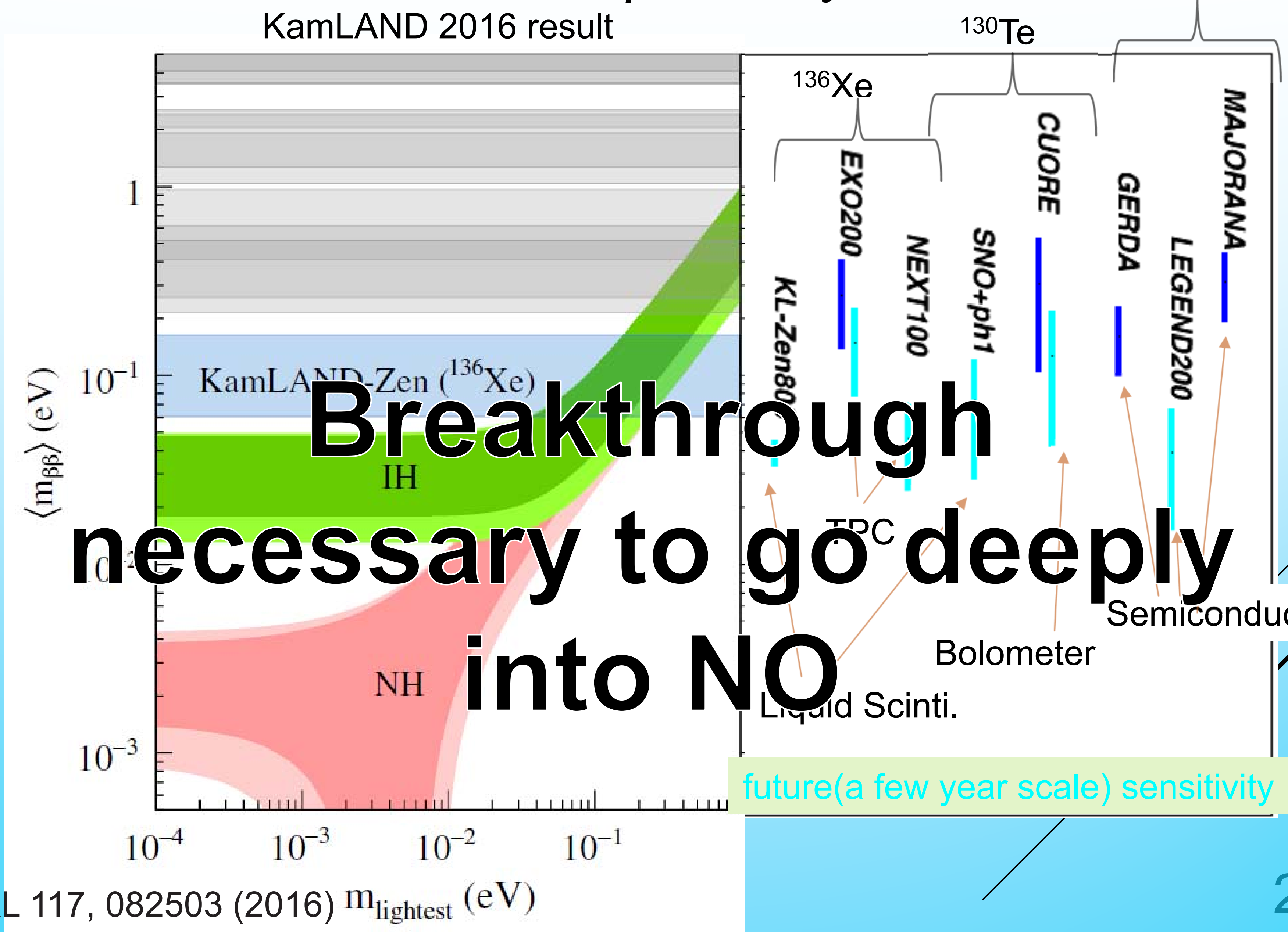
Recent release



PRL 117, 082503 (2016)

Neutrinoless double-β decay

Recent release

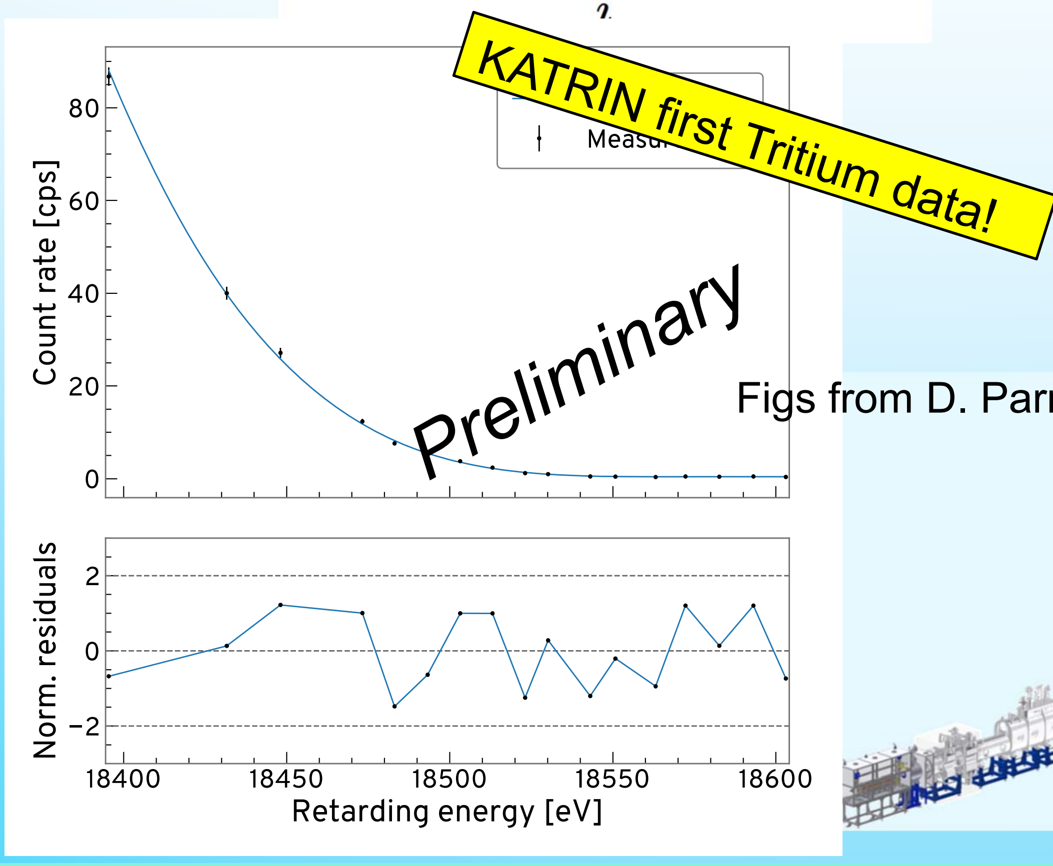


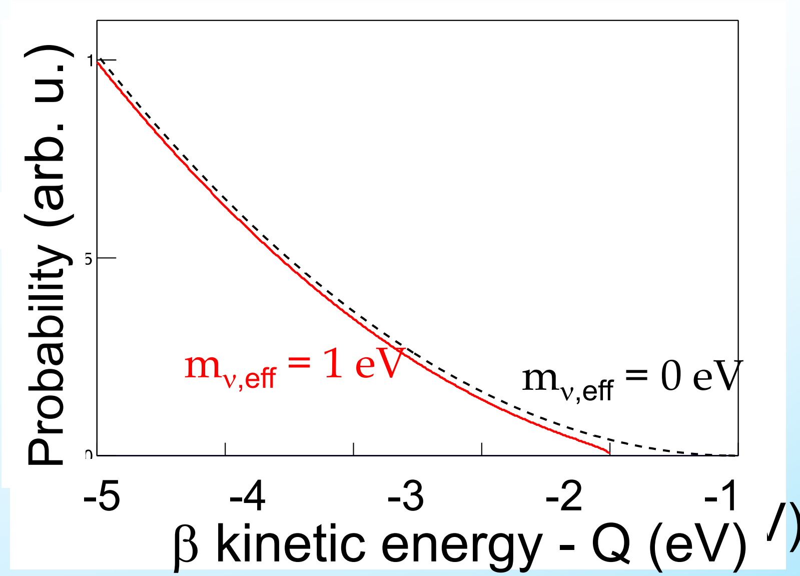
Breakthrough necessary to go deeply into NO

PRL 117, 082503 (2016)

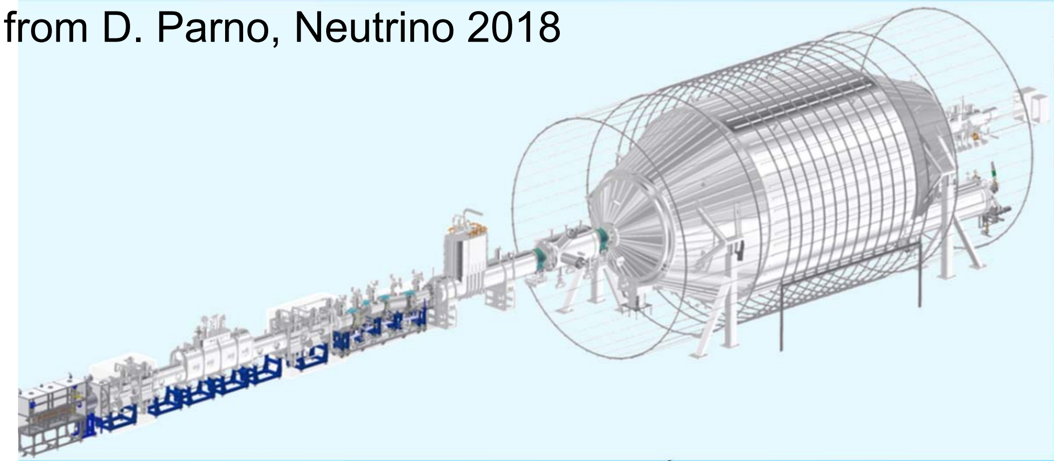
Direct mass measurement by β-decay end point

$$m^2_{\nu,eff} = \sum_i^3 |U_{ei}|^2 m_i^2$$





Figs from D. Parno, Neutrino 2018



- KATRIN Sensitivity : 0.24 eV in 5 years
- Other brand-new projects following, but lower sensitivity yet

Constraint from Cosmology

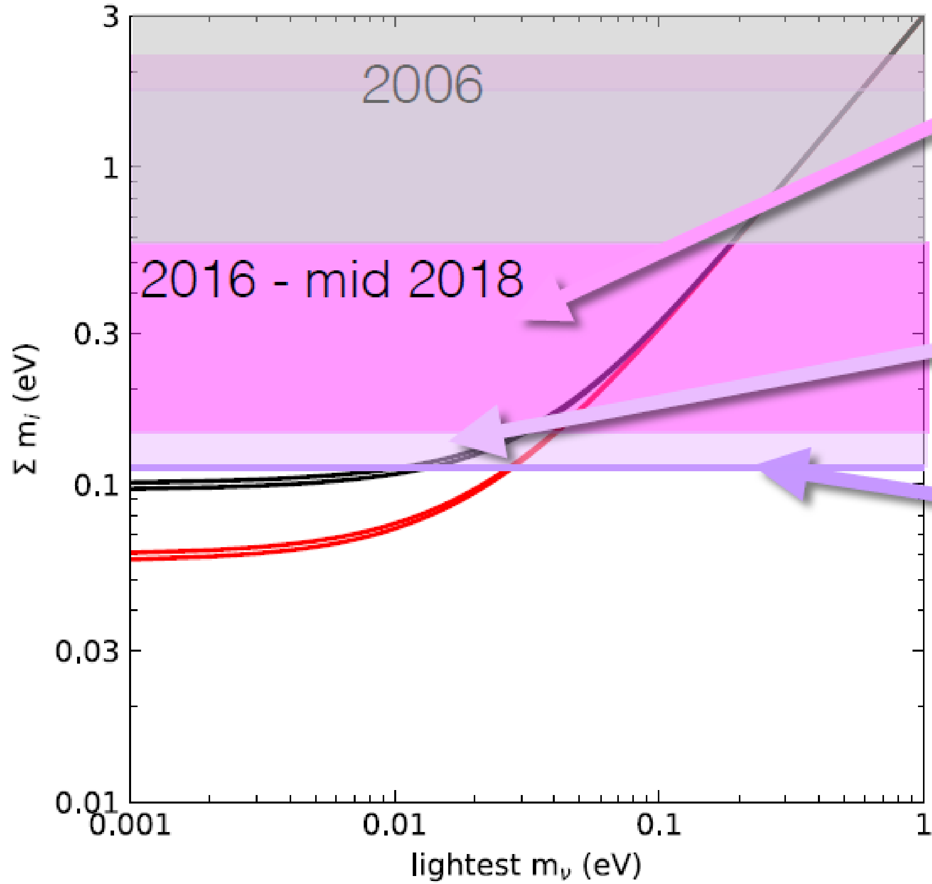
Relic ν background

- relativistic=radiation at early time (during CMB acoustic oscillation)
- non-relativistic=dark matter at late time (during structure formation)
- N_{eff} and $\sum m_\nu$ change both CMB and matter power spectra in peculiar manner
  - N_{eff} : effective number of neutrino species = relativistic energy density excluding that by photons, in units of one neutrino. Sterile ν, if mix with active ν should be counted.
  - $\sum m_\nu$: total light ν mass, $m_1 + m_2 + m_3(+m_4 \ldots)$
- Current bound $N_{eff} = 3.04 \pm 0.18$ (note. 3.045 for standard three ν)

Constraint from Cosmology

95%CL upper bounds on $\Sigma_i m_i$ for 7 parameters

summed mass



CMB only: Planck,
w/o high-l polarisation and lensing…
$\Sigma_i m_i$ < 590 to 140 meV (95%CL)

CMB + conservative LSS :

- Planck 2016 {TT+SIMLow+lensing} + BAO:
  $\Sigma_i m_i$ < **170 meV** (95%CL)
- Planck 2016 {TTTEEE+SIMLow} + BAO:
  $\Sigma_i m_i$ < **120 meV** (95%CL)

- Planck 2015 + Lyman-α:
  $\Sigma_i m_i$ < **120 meV** (95%CL)

[Planck col.] 1605.02985; Cuesta et al. 2016;
Palanque-Delabrouille et al. 1506.05976;
Vagnozzi et al. 1701.08172;
PDG "Neutrino Cosmology" [JL & Verde]

… harder to avoid bounds with simple cosmological model extensions

J. Lesgourgues "Neutrino Properties from Cosmology", neutrino2018

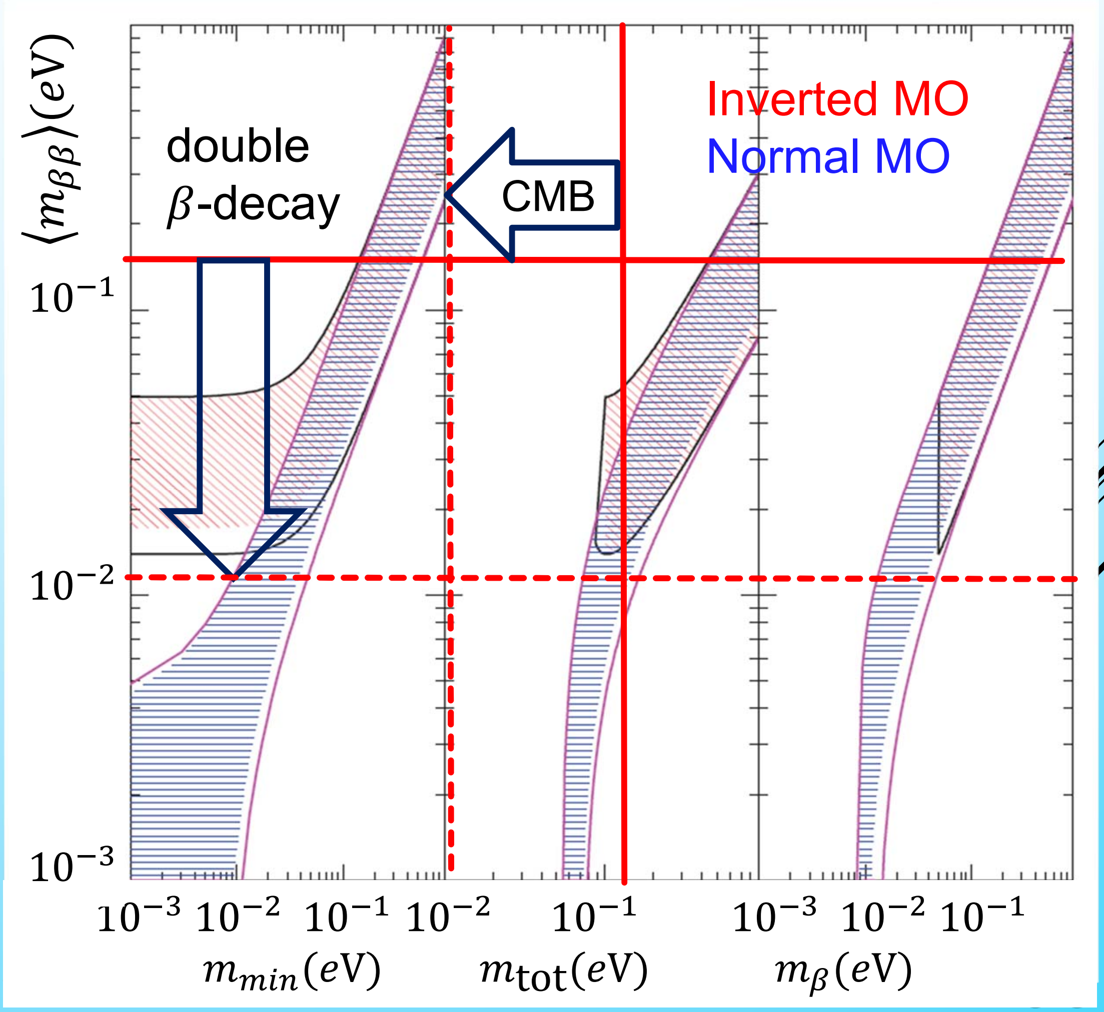
Neutrino and the new physics or nuclear physics?

In ~10 years,

- ✓ Oscillation → $\Delta m_{21}^2, \Delta m_{32}^2$, MO
- ✓ CMB → $m_1 + m_2 + m_3$
- ✓ Double-β → $m_{\beta\beta}$
- ✓ β → m_β

If inconsistent,

- Non-standard interaction
- $|\Delta L| = 2$ lepton # violation
- sterile-ν
- cosmological problem
- ….



DBD life time is affected by $|\Delta L| = 2$ new physics.

$$T_{1/2}^{0\nu\beta\beta} \approx 10^{25}\mathrm{yr} \rightarrow \Lambda_{LNV} \approx 1\ \mathrm{TeV}$$

$$T_{1/2}^{0\nu\beta\beta} \approx 10^{25}\mathrm{yr} \rightarrow m_\nu \approx 0.1\ \mathrm{eV}$$

F.Deppisch, neutrino 2016

neutrinoless double-β decay

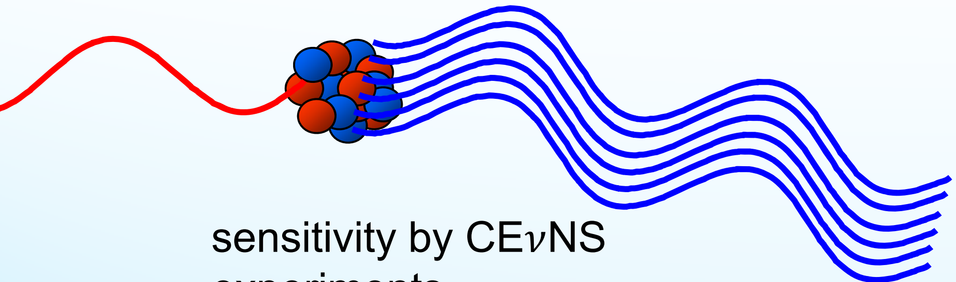
$$\left(T_{1/2}^{0\nu}\right)^{-1} = G^{0\nu} \cdot |M^{0\nu}|^2 \cdot \langle m_{\beta\beta} \rangle^2$$

$|M^{0\nu}|^2$: nuclear matrix element

- cannot be directly measured
  - only partial strength
- factor 2~3 different for different calculation
- axial current coupling constant g_A might be significantly smaller in nuclei

$$\left(T_{1/2}^{0\nu}\right)^{-1} \propto g_A^4$$

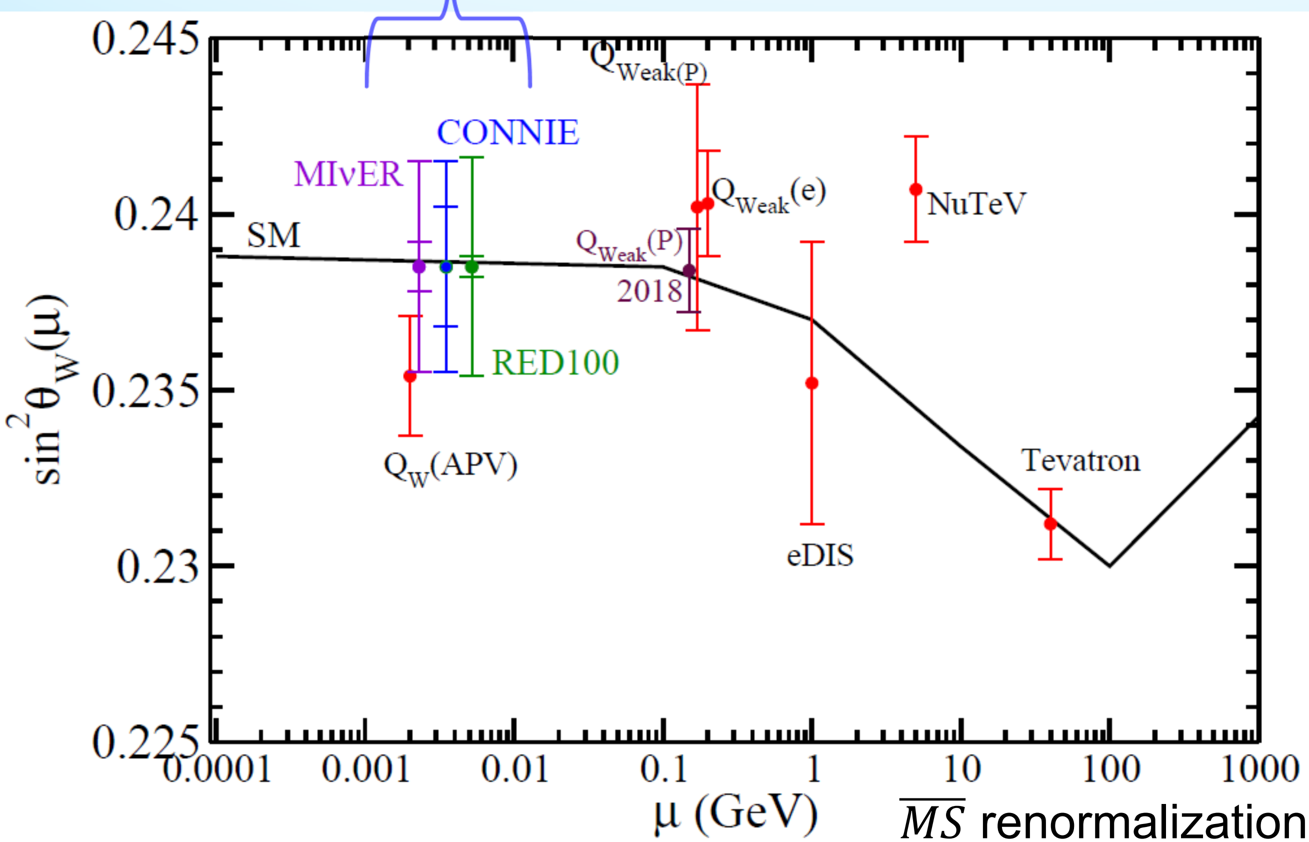
Coherent Elastic Neutrino-Nucleus Scattering (CEνNS)



- Summation at amplitude level

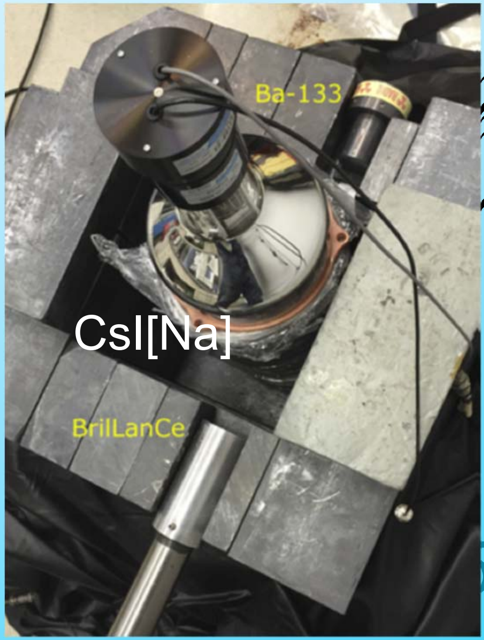
$$\sigma \approx \frac{G_F^2 N^2}{4\pi} E_\nu^2$$

sensitivity by CEνNS experiments



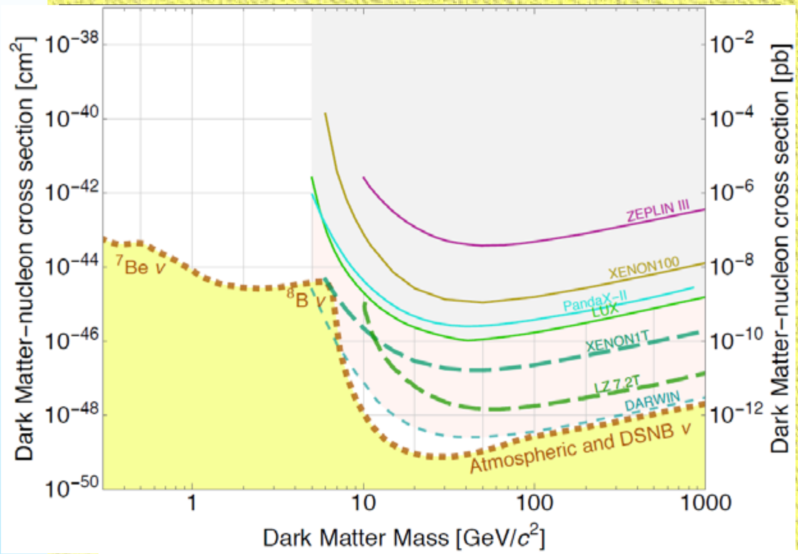
$\overline{MS}$ renormalization

- First detection by COHERENT. and many projects following.
- Let's hear!



H. Wong "Neutrino-nucleus Coherent Scattering with Reactor and Solar Neutrinos", neutrino2018

Prospects of Observing solar νA_{el} in Xe ...

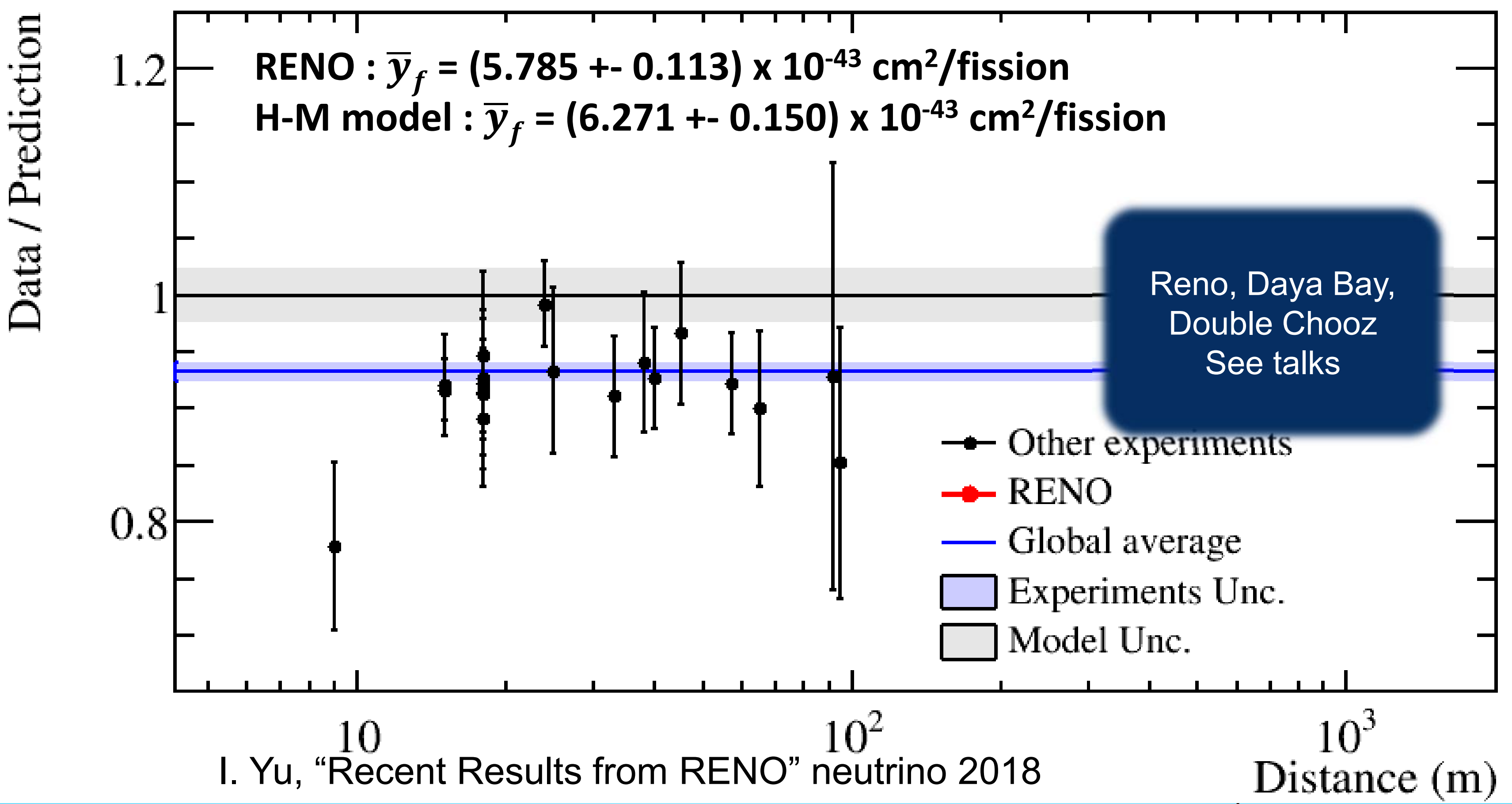


Expectation values of events in XENONnT, in 20 t·y exposure	No discrimination	99.75% ER discrimination
Signal (μ_s)		
6 GeV/c^2 WIMP ($\sigma = 2 \cdot 10^{-46}$ cm^2)	0.68	0.27
10 GeV/c^2 WIMP ($\sigma = 2 \cdot 10^{-47}$ cm^2)	4.65	1.86
100 GeV/c^2 WIMP ($\sigma = 2 \cdot 10^{-48}$ cm^2)	7.13	2.85
1 TeV/c^2 WIMP ($\sigma = 2 \cdot 10^{-47}$ cm^2)	8.85	3.54
Background		
Total ER (μ_{bER})	1000	2.5
NR from neutrons	-	-
NR from CNNS (μ_{bNR})	11.8	4.7

- ☑ Typical threshold for Liq-Xe experiments with "(S1,S2)" for ER/NR differentiation is light yield corresponding to "averaged" <~4 keVnr>, nominally too high for solar νA_{el}
  - ➢ Large spread in event-wise *keVnr⇔light yield* conversion (Poisson, energy resolution, fiducial non-uniformity) ⇒ thorough understanding necessary
  - ➢ Observable 0.2-0.3 events / ton-year *(~5 events in 20 t-y XE-nT ; ~100 events in 400 t-y DARWIN)*
- ☑ "S2-Only" has lower "<~1 keVnr>" threshold , rates much larger *(~90 events / ton-year)* ; but no ER/NR discrimination ⇒ suppression & understanding of ER background crucial

Thanks: Consultation with K. Ni & L. Baudis

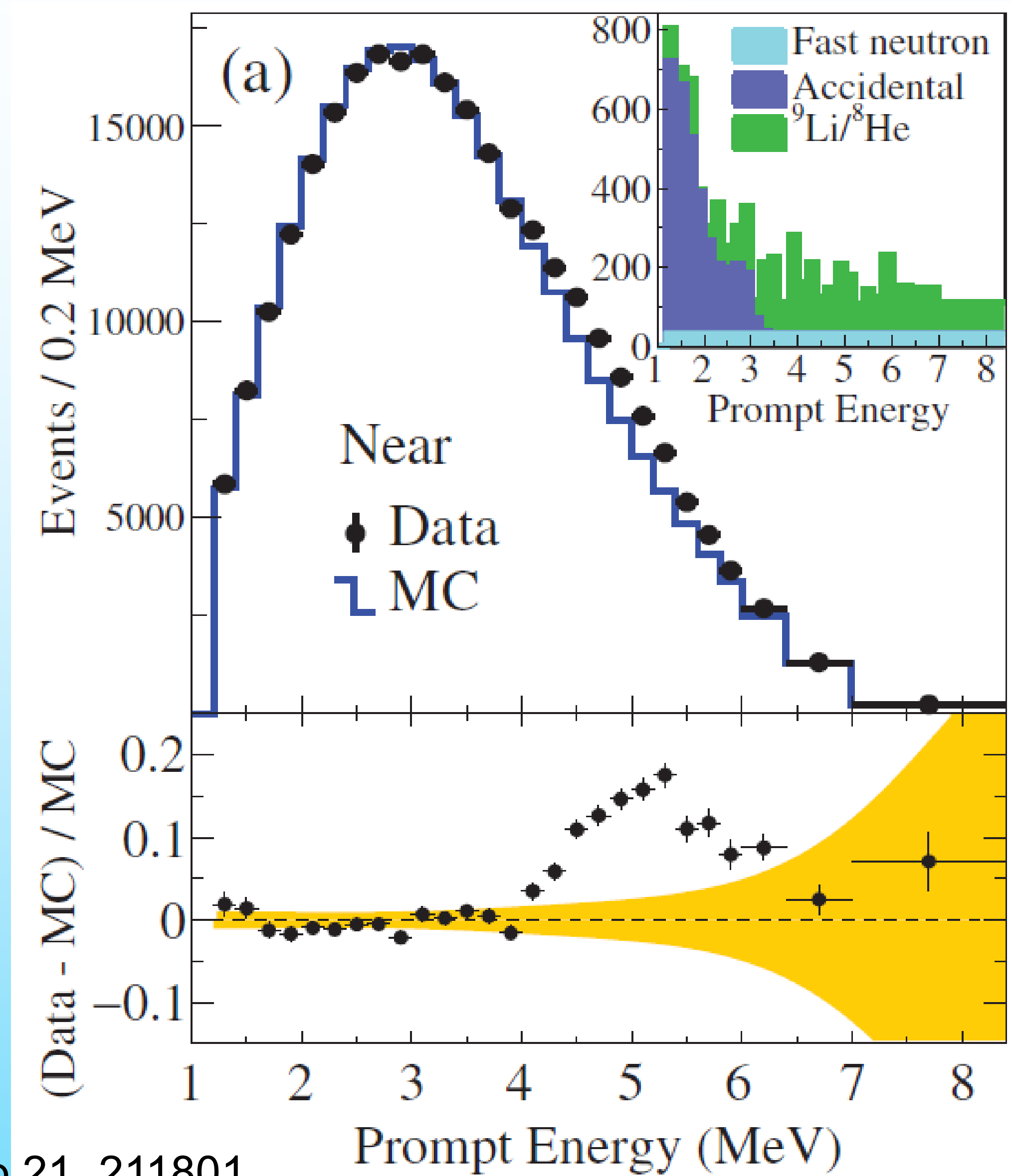
Reactor `anomaly'



I. Yu, "Recent Results from RENO" neutrino 2018

Reactor another issue

- Excess at ~5 MeV all for RENO/Daya Bay/Double Chooz
- Right plot by RENO with 458-days data
- Let's hear updates



Phys.Rev.Lett. 116 (2016) no.21, 211801

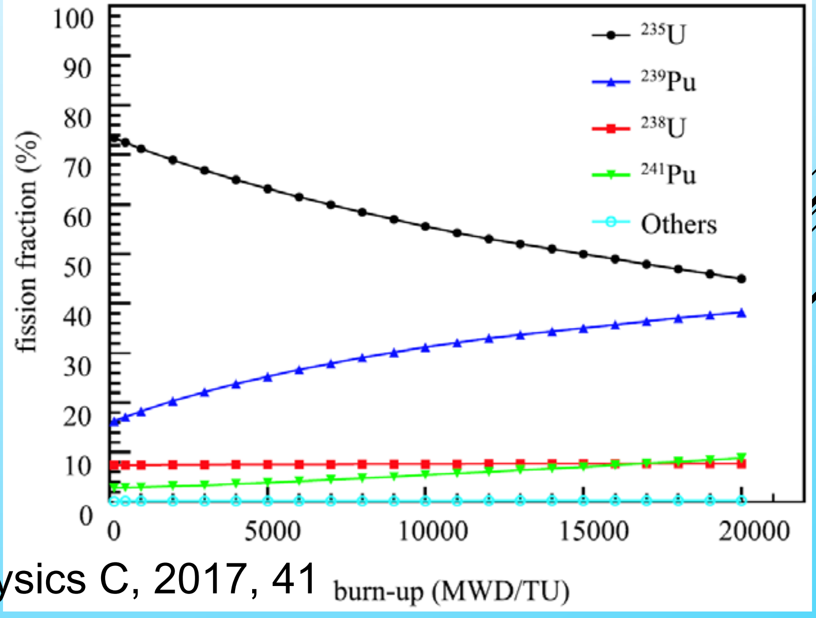
Reactor `anomaly' could be ~1eV sterile ν, but…

- Reactor flux predicted by using measured fission β-spectra and/or nuclear databases for > 1000 daughters and > 6000 β-branches
- $\bar{\nu}_e$ spectrum of each β-decay :

$$S(E_e, Z, A) = \frac{G_F^2}{2\pi^3} p_e E_e (E_0 - E_e)^2 C(E) F(E_e, Z, A)(1 + \delta_{corr}(E_e, Z, A))$$

Recent measurements with fuel evolution giving hints.

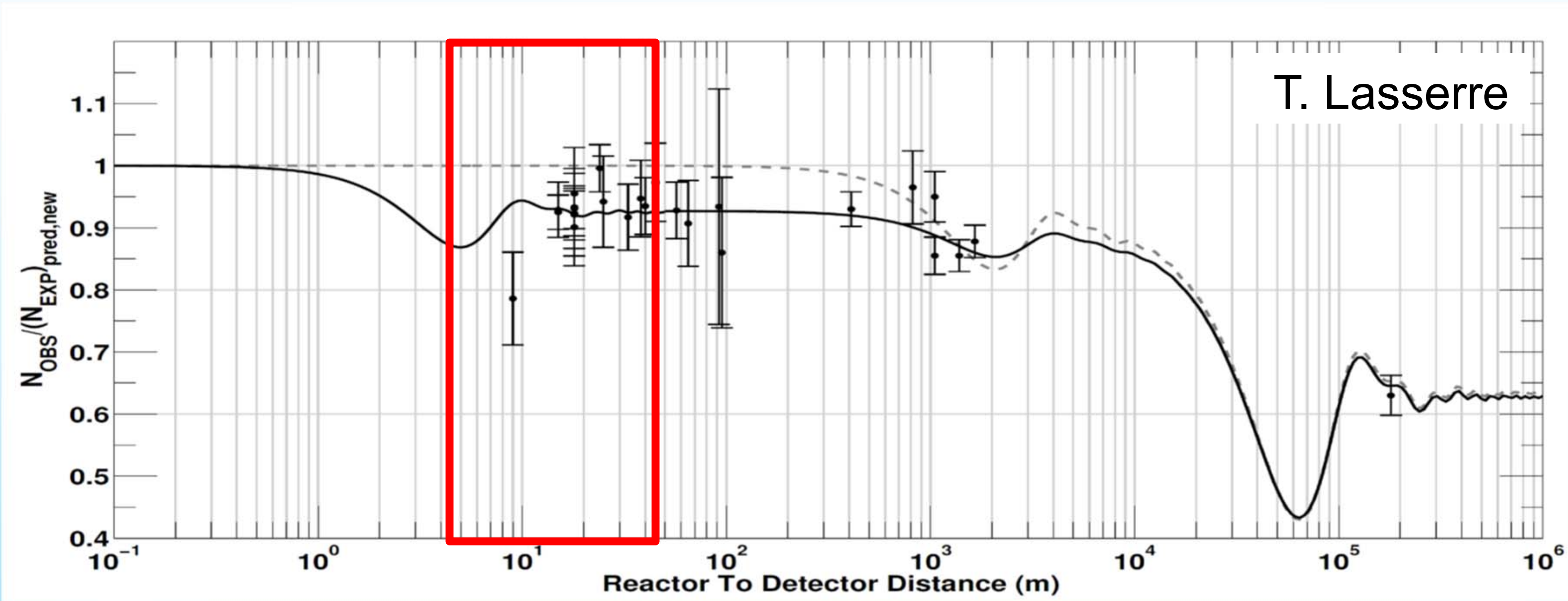
- correlation with fuel composition change
- Maybe, in coming talks

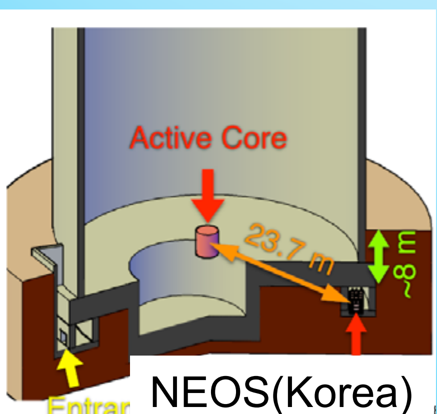


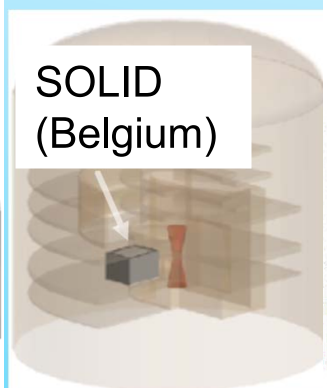
Daya Bay, Chinese Physics C, 2017, 41

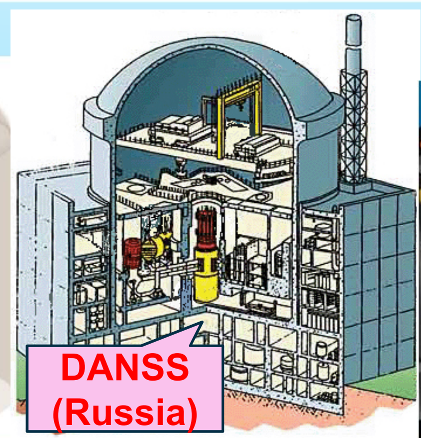
Very short baseline experiments

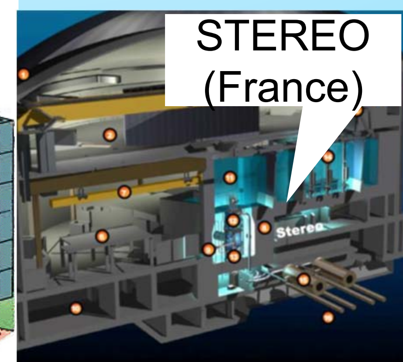
- Tring to catch oscillation feature (L/E dependence)

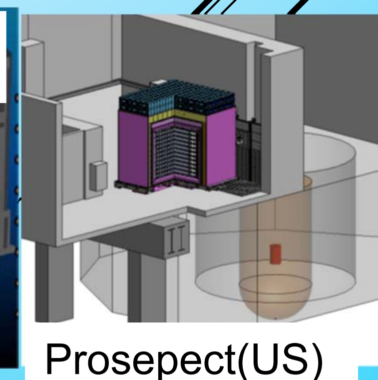








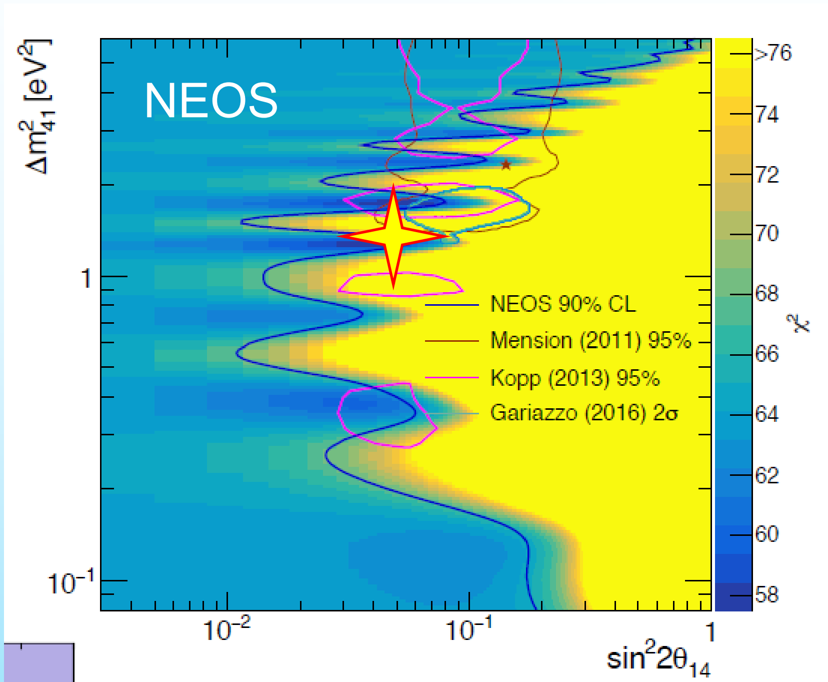


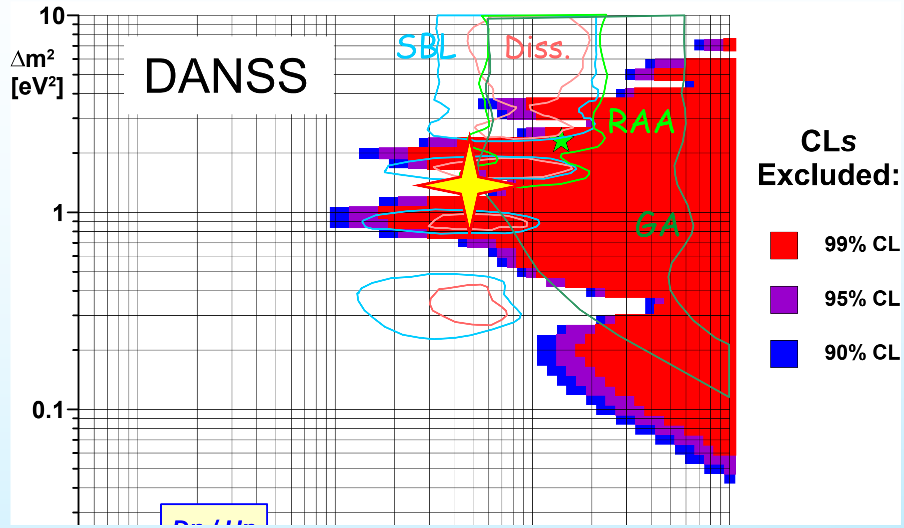


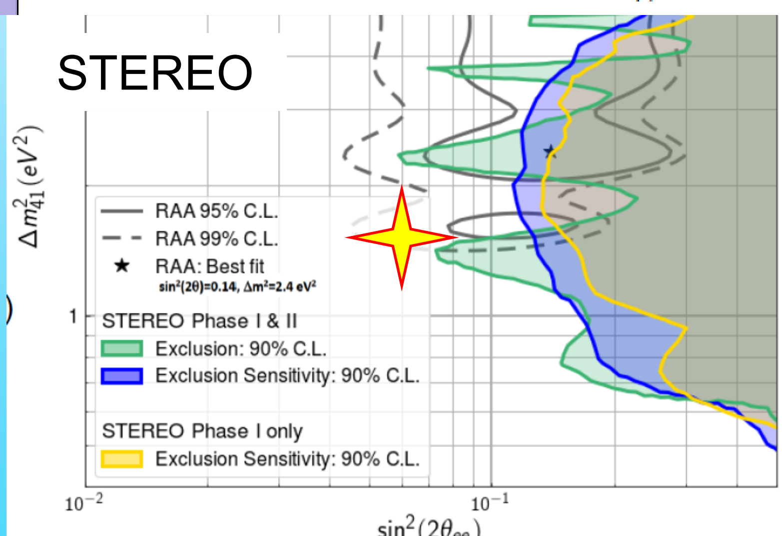
!??

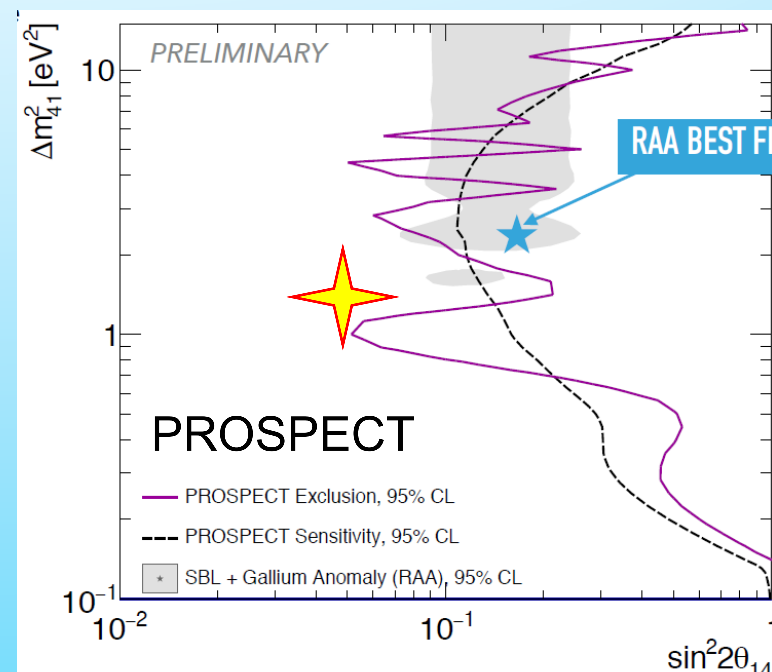
Let's hear talks!

Plots from neutrino2018 talks









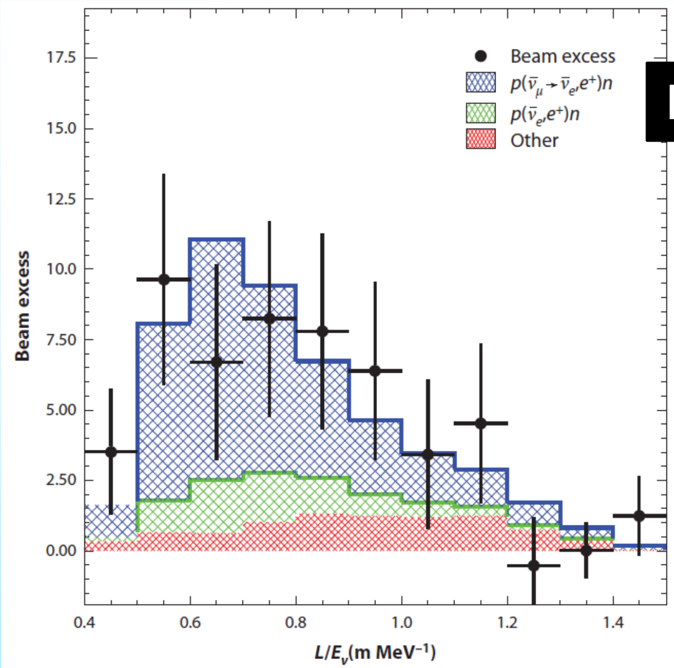
Atmospheric and accelerator experiments

- Flux prediction affected by hadron production uncertainty
- neutrino-nucleus interaction

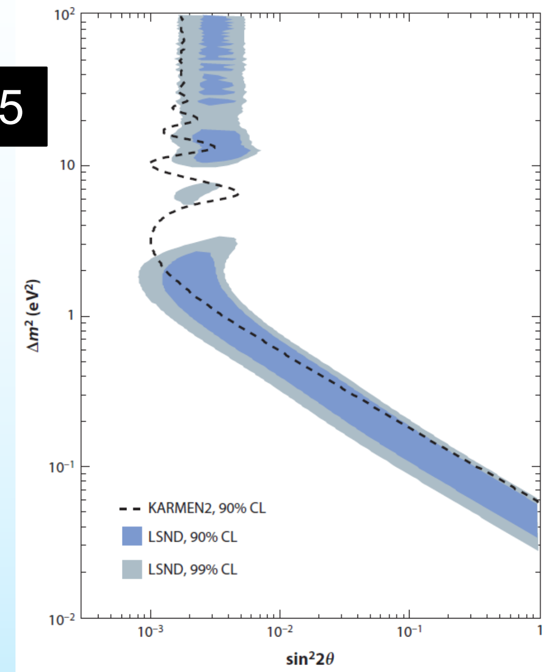
  ....

Let's hear talks!

LSND & MiniBooNE anormaly



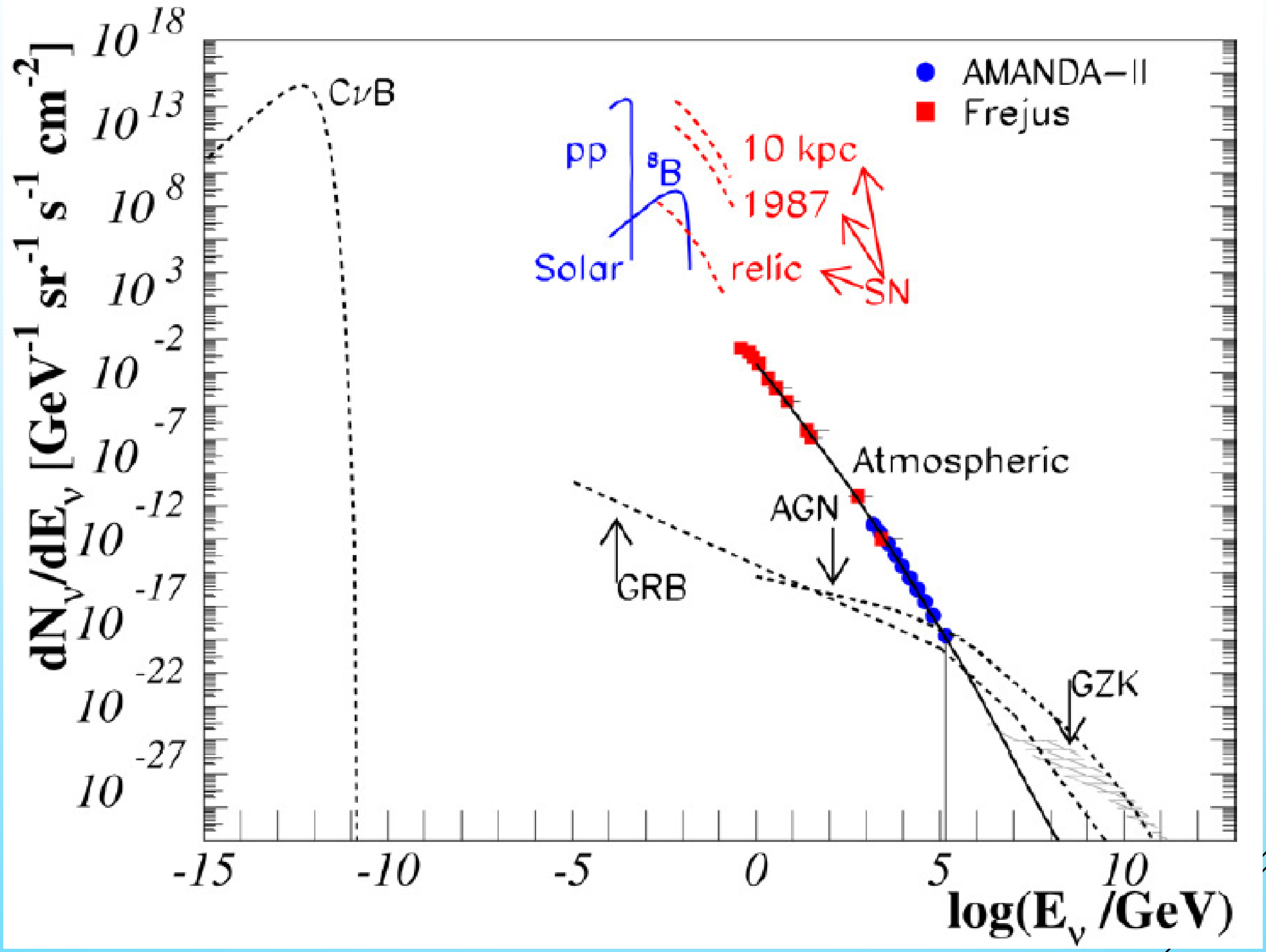
LSND, 1995



- New (positive) results from MiniBooNE!
- Conflicting with ICECUBE, MINOS+, Daya Bay if mixing with 4th ν
- Acc. short baseline experiments in FNAL and J-PARC will investigate. IsoDAR, too.
- Let's hear talks.

Neutrino as a window to Universe

astrophysical neutrino spectrum

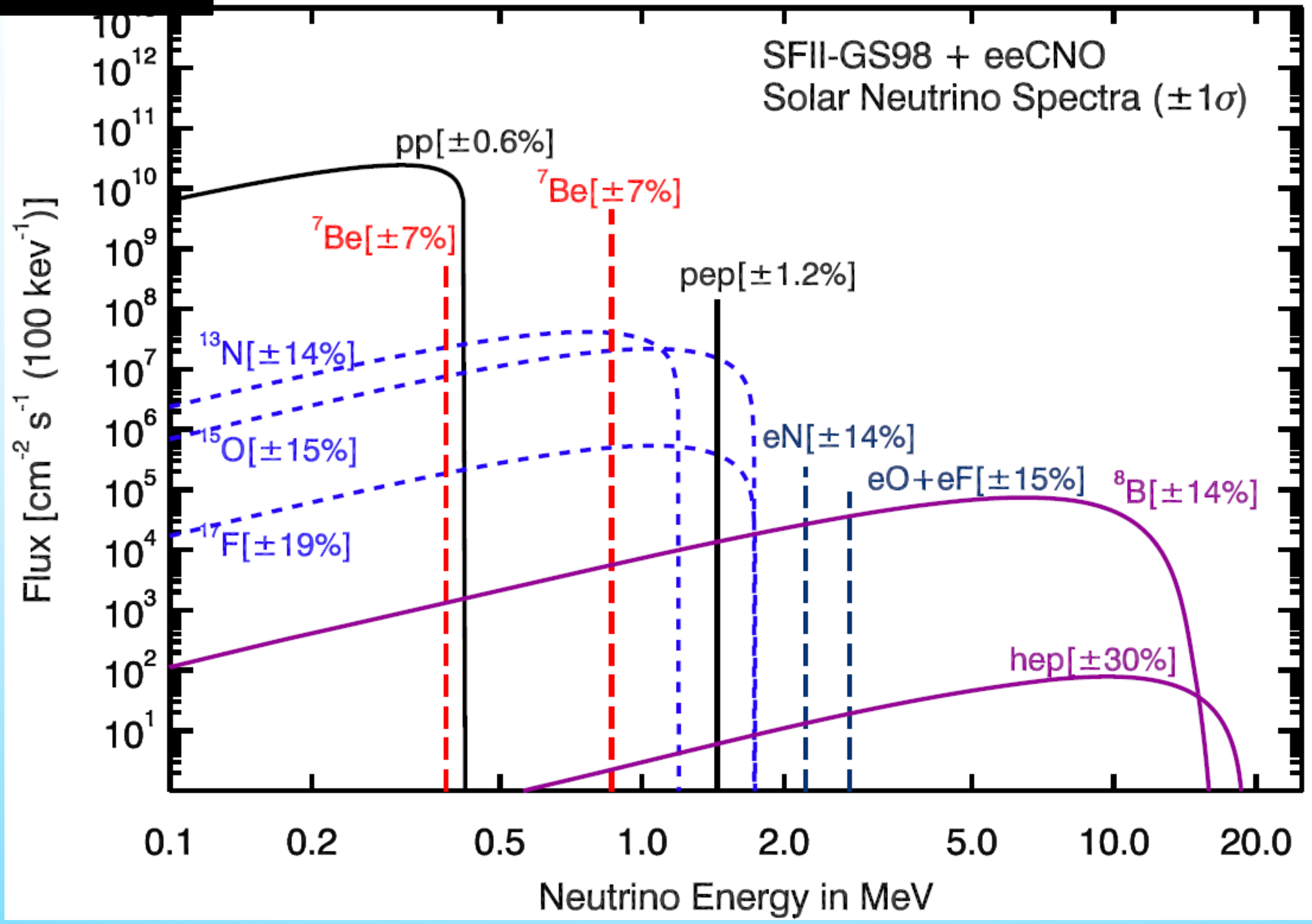


J. Becker, Phys. Rept. 458 (2008)173

Solar neutrino

Predicted flux

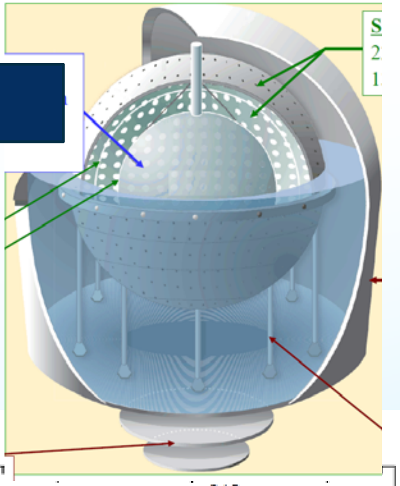
A. Serenelli, Eur.Phys.J. A52 (2016) no.4, 78



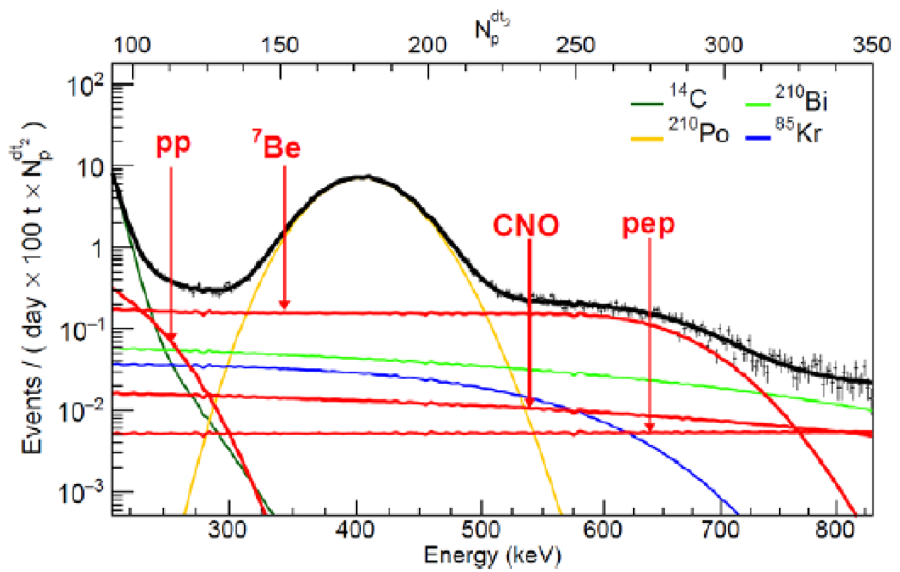
And the density is as high as $\rho = \sim 150\mathrm{g/cm}^3$ at the center.
Significant matter effect

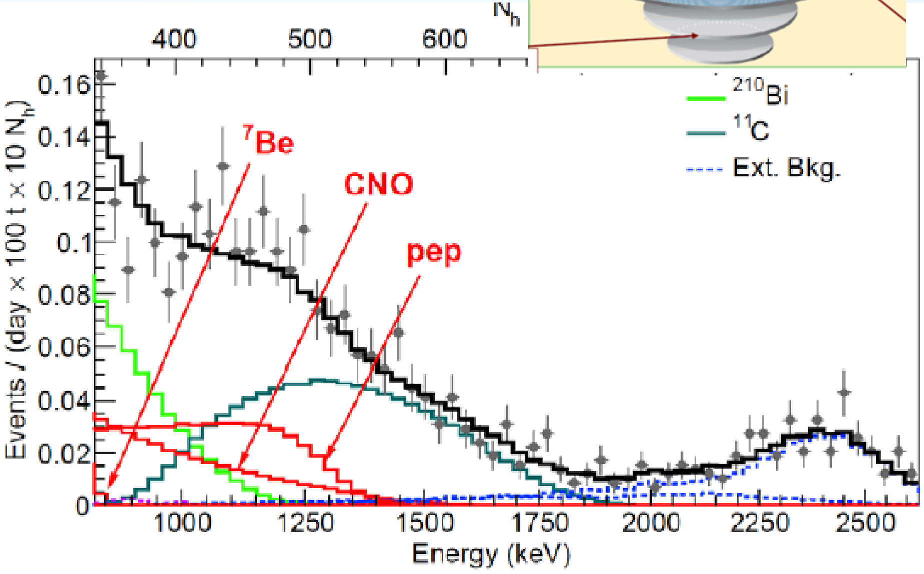
Borexino

Ethreshold=250keV



Data taking
phase I 2007~2010
phase II 2011~2017





O. Smirnov, "Solar neutrino from pp-chain and other results of Borexino" , neutrino 2018

>5σ for pep signal

Solar luminosity: **$L_\nu^{Borexino}$ = (3.9 ± 0.4) x 10^{33} erg/s**,
is in agreement with measured photon luminosity
L_γ = (3.846 ± 0.015) x 10^{33} erg/s

Supernovae neutrino waiting since 1987

K.Scholberg@ Rencontres du Vietnam, 2017

Summary of supernova neutrino detectors

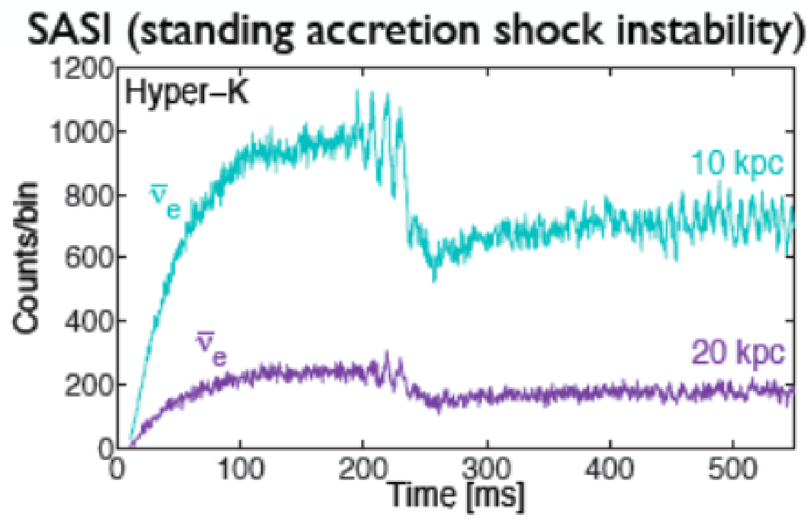
Galactic sensitivity

Extragalactic

Detector	Type	Location	Mass (kton)	Events @ 10 kpc	Status
Super-K	Water	Japan	32	8000	Running
LVD	Scintillator	Italy	1	300	Running
KamLAND	Scintillator	Japan	1	300	Running
Borexino	Scintillator	Italy	0.3	100	Running
IceCube	Long string	South Pole	(600)	(10^6)	Running
Baksan	Scintillator	Russia	0.33	50	Running
HALO	Lead	Canada	0.079	20	Running
Daya Bay	Scintillator	China	0.33	100	Running
NOvA	Scintillator	USA	15	3000	Running
MicroBooNE	Liquid argon	USA	0.17	17	Running
SNO+	Scintillator	Canada	1	300	Under construction
DUNE	Liquid argon	USA	40	3000	Future
Hyper-K	Water	Japan	540	110,000	Future
JUNO	Scintillator	China	20	6000	Future
PINGU	Long string	South pole	(600)	(10^6)	Future

plus reactor experiments, DM experiments...

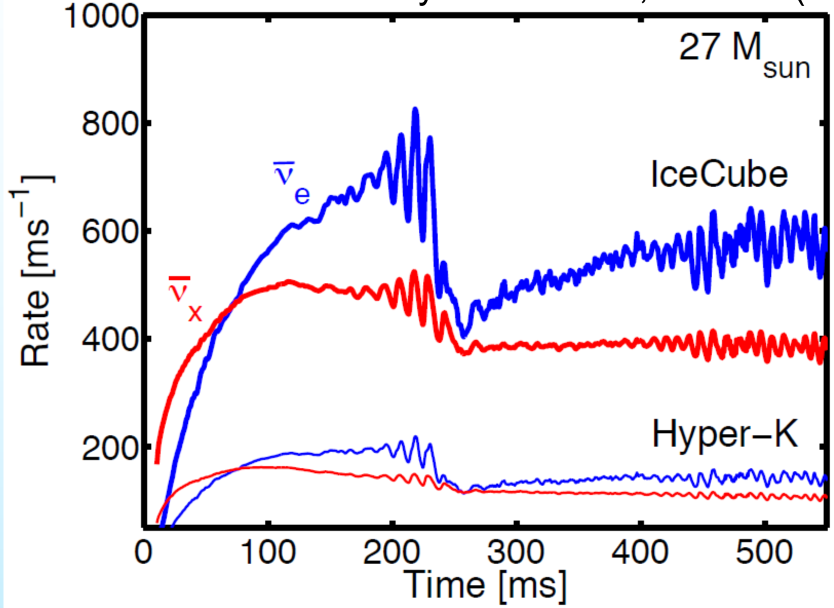
Supernova Burst neutrino expectation by Hyper-K, DUNE and IceCube



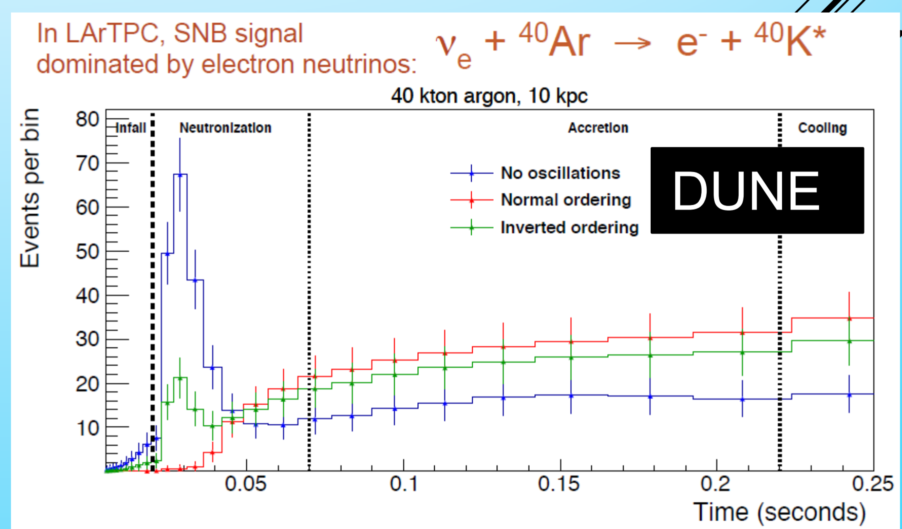
Sensitive to ~4Mpc.
Then, 0.3~1 events/yrs

Hyper-K

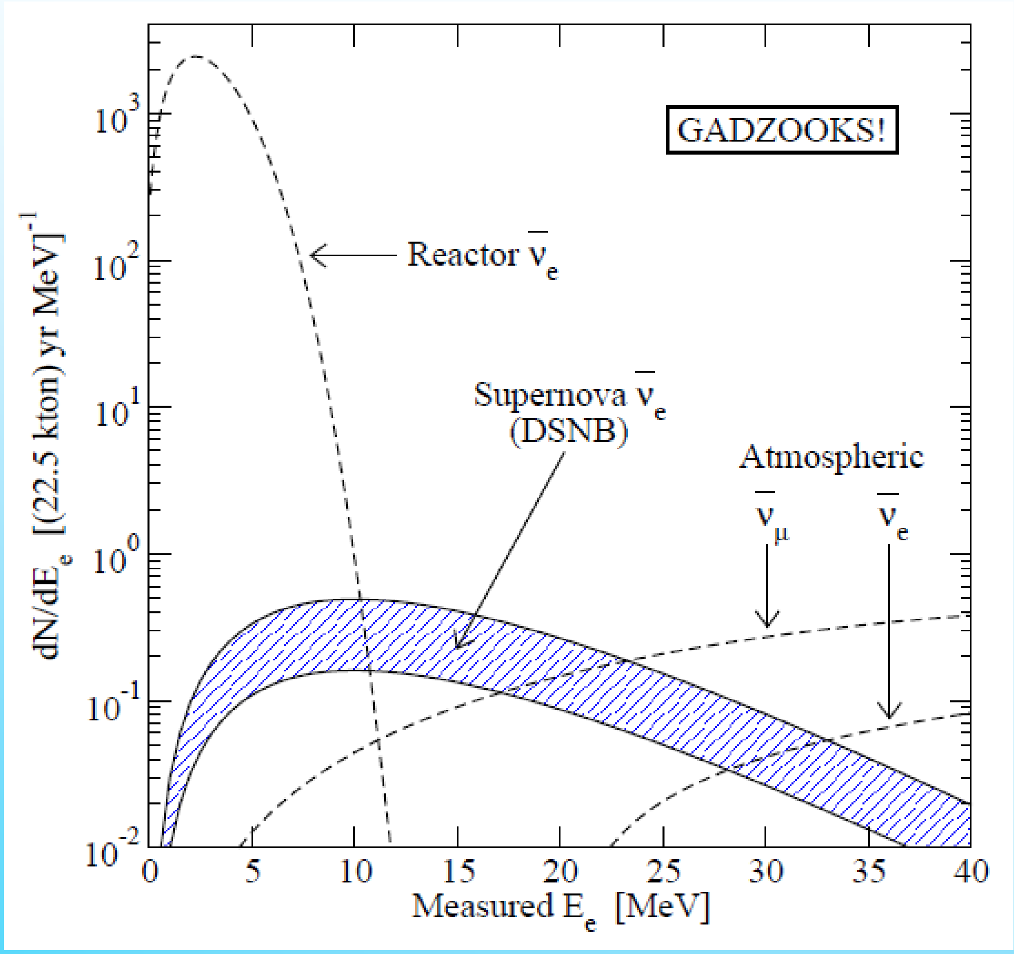
I.Tamborra et al. Phys. Rev. D 90, 045032 (2014)

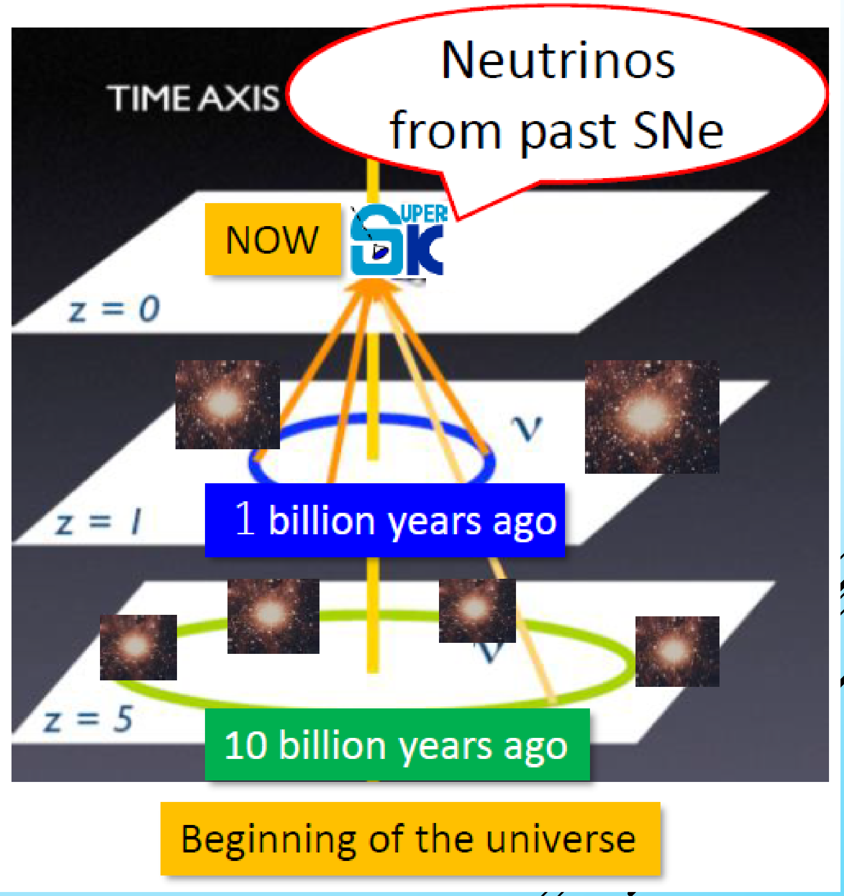


- Even $\nu - \nu$ interaction plays role
- Explosion mechanism, NS/BH formation
- multi-messenger observation



Supernova Relic Neutrino



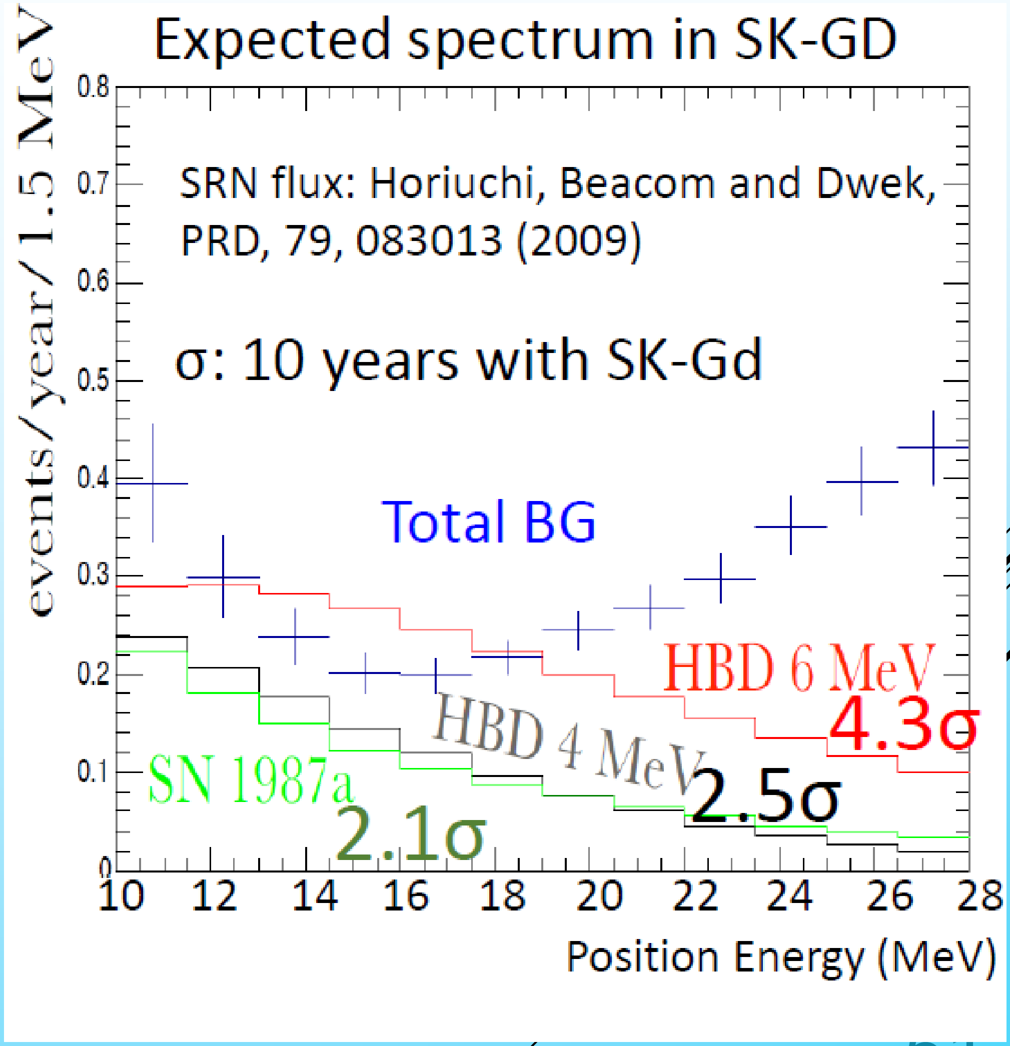


J. F. Beacom, M. R. Vagins, Phys.Rev.Lett. 93 (2004) 171101

SK-Gd project aiming to detect Supernova Relic Neutrino

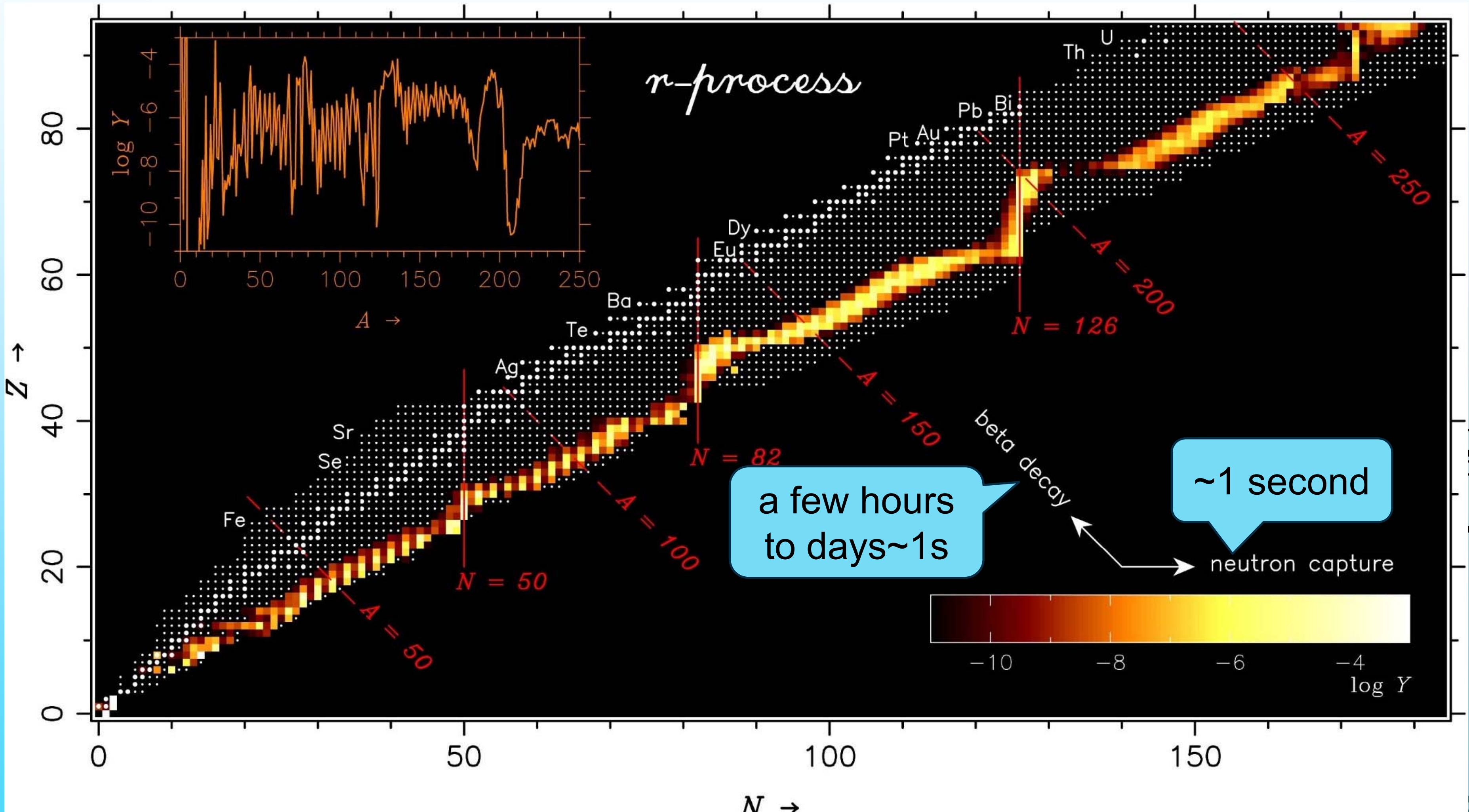
- dissolve Gd to SK water
- detect $\bar{\nu}_e + p \rightarrow e^+ + n$

  neutron tagged by Gd neutron capture (~8 MeV γ's released.)
- Late 2019 or later



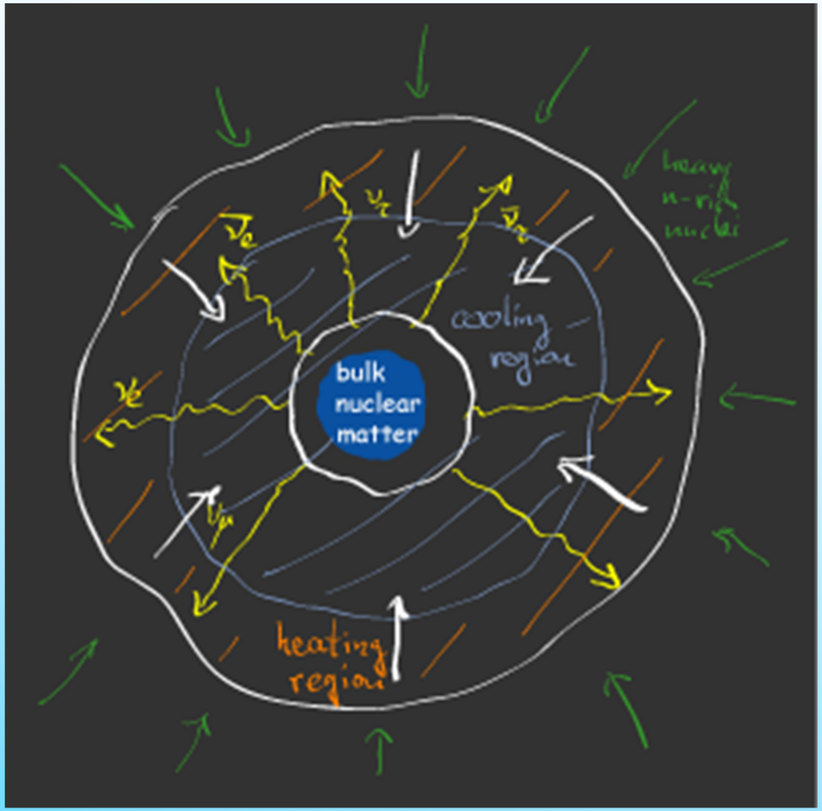
Origin of heavy elements and neutrino

- r(rapid)-process is necessary to produce gold etc.
- Requires $10^{20} \sim 10^{30}$ neutrons/cm^3



http://www.ph.sophia.ac.jp/~shinya/research/research.html

Origin of heavy elements and neutrino
Supernova explosion



Gravitational collapse of massive star

↓

Proto-Neutron star

↓

Explosion by neutrinos

Two reactions happen

- $\nu_e + n \rightarrow p + e^-$
- $\bar{\nu}_e + p \rightarrow n + e^+$

fraction of neutrons decreases

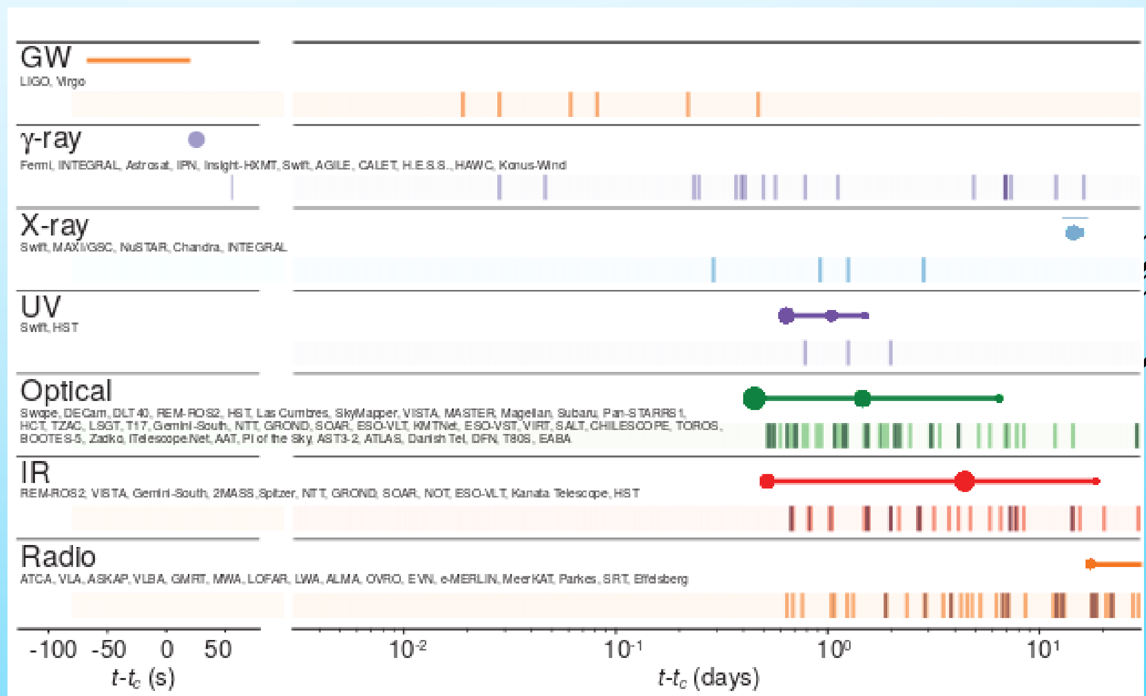
↓

r-process unlikely to happen

https://astro.physik.unibas.ch/fileadmin/user_upload/astro
physik-unibas-ch/liebendoerfer/Supernova_Models.html

Origin of heavy elements and neutrino

- Binary neutron-star merger
- Gravitational wave observation GW170817
  - ele. mag. observation of <u>kilonova</u> : thermal glow by radioactive decay of isotopes of the heavy elements
  - Binary neutron-star merger can be a dominant mode of r-process production



- high neutron fraction→ only heavy elements
- neutrino irradiation lower

  neutron fraction → light elements
- Observation of those neutrinos would be very interesting, but the event rate may be too low….

Astrophys.J. 848 (2017) no.2, L12

Ultra high energy cosmic ray

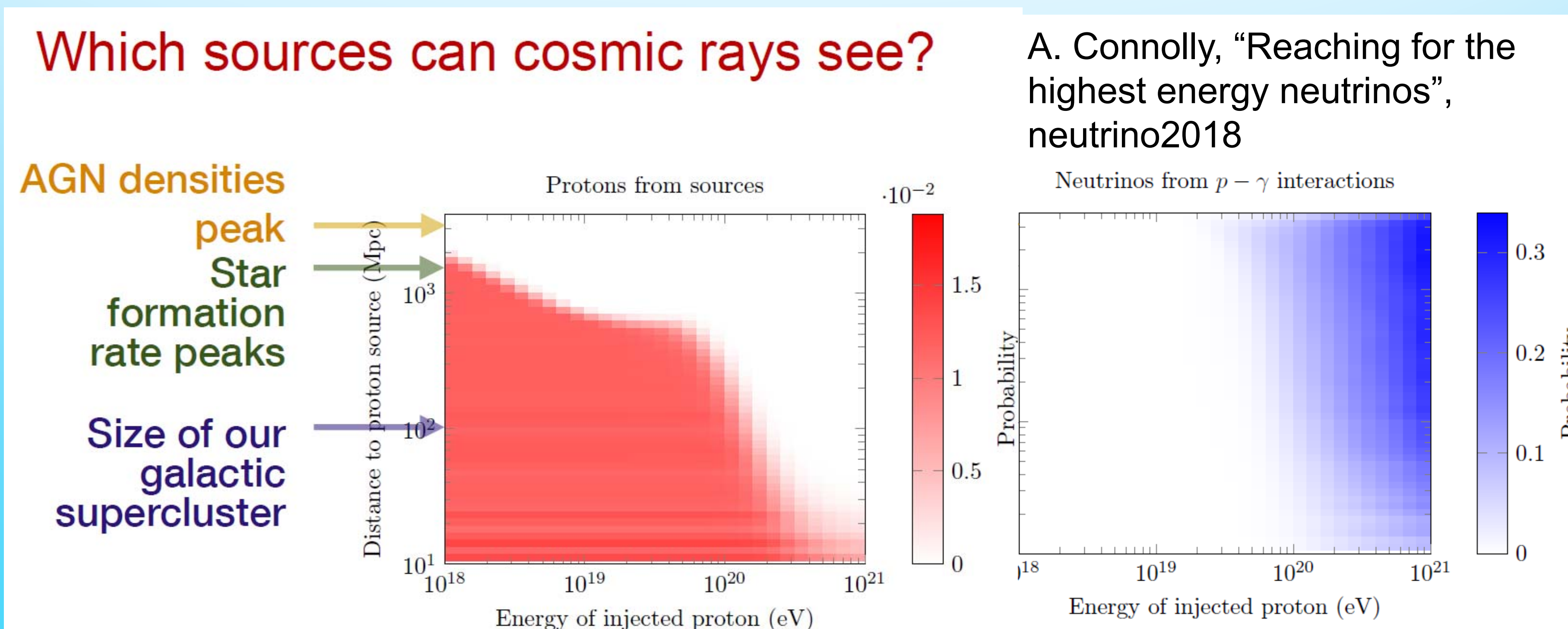
Accelerated by ?

CMB etc.

$$p + p/\gamma \rightarrow N + \pi^{\pm} + \pi^{0} + \cdots$$

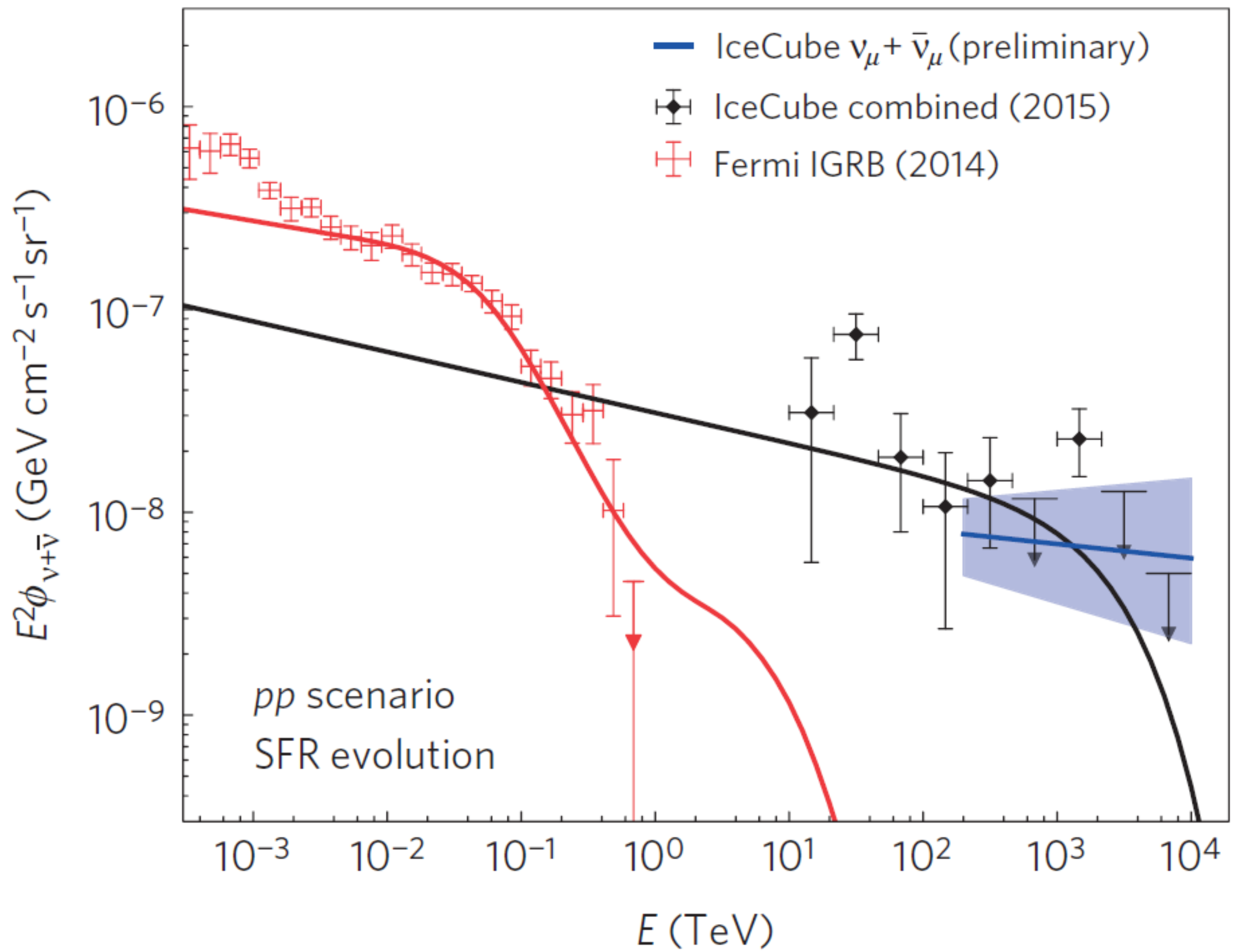
$\color{red}{\nu_\mu, \nu_e}$ $\qquad$ $\color{blue}{\gamma}$

50~100 PeV proton is necessary to produce 25 TeV~5 PeV neutrino



A. Connolly, "Reaching for the highest energy neutrinos", neutrino2018

Astrophysical γ-rays and neutrinos

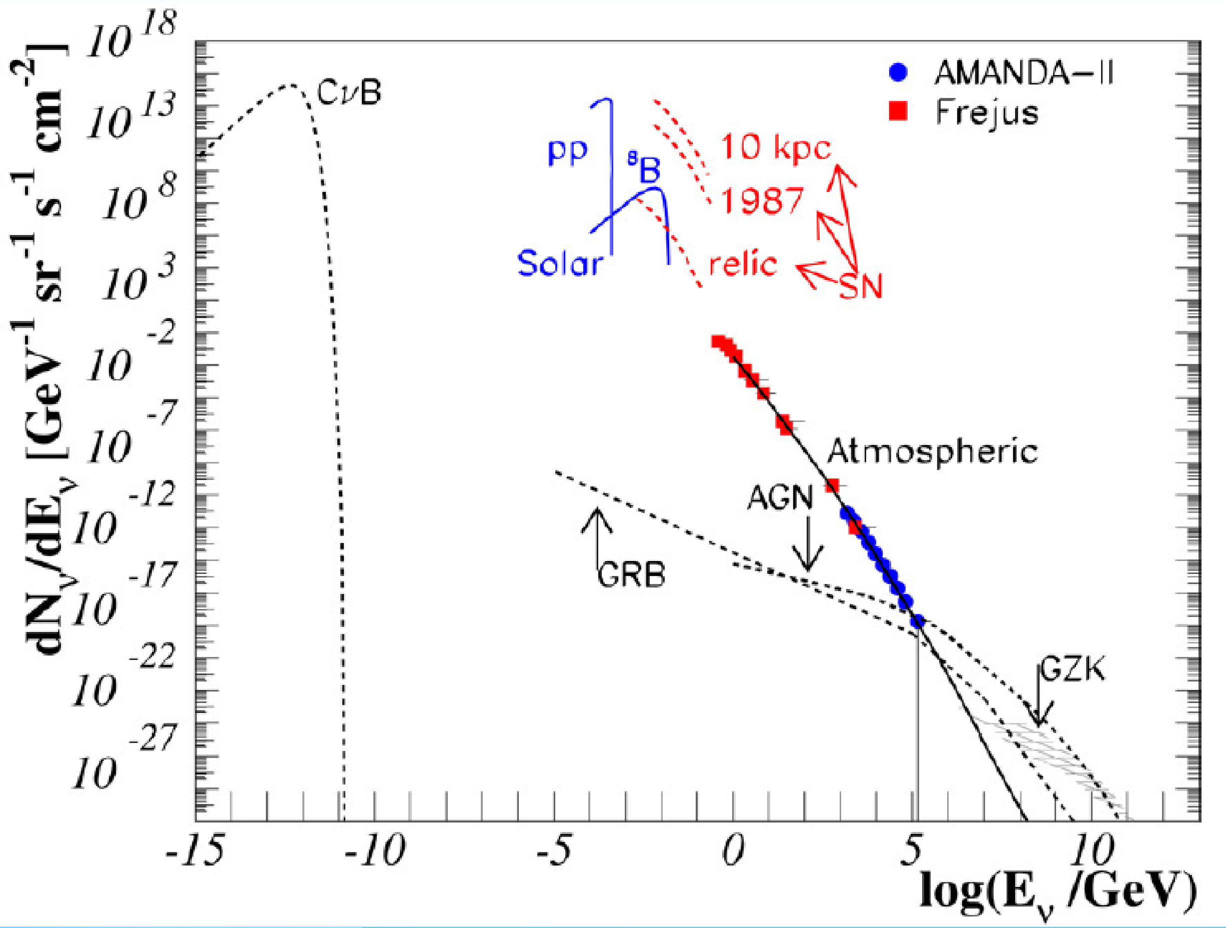


No evidence for point sources at this point

- Let's hear updates from IceCube
- Especially, multimessager observation : IceCube-170922A & Blazer TXS 0506+056

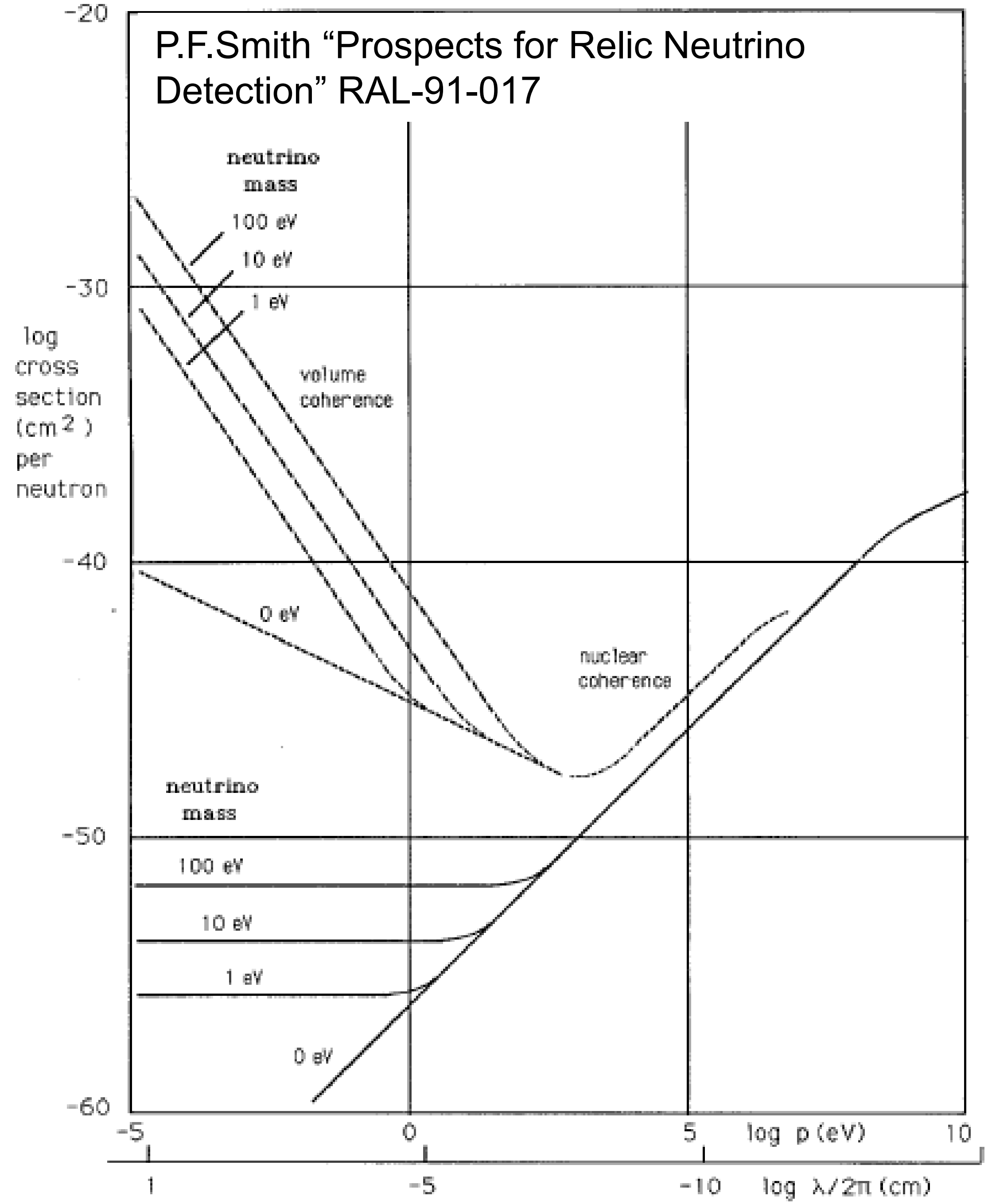
F.Halzen *"High-energy neutrino astrophysics"*, Nature Phys. 13 (2016) no.3, 232-238

Cosmic neutrino background (CνB)



J. Becker,
Phys. Rept. 458 (2008)173

Can see Universe 1s after Big Bang.
c.f. 380,000 years for CMB
λ~7 mm if m_ν =0
λ~0.6 mm if m_ν =10meV



CνB interaction

- Huge cross section thanks to volume coherence.
- If $\sigma = 10^{-35} cm^2$ and $\Phi = 10^{12}/cm^2 s$, $\nu_e + e^-$ interaction rate is $\sim 3/\mathrm{g} \cdot s$!
- But… almost no recoil with ~1mm^3 target

How to detect CνB?

- End point of electrons from Tritium β-decay
  - ✓ Proposed by S. Weinberg in 1962
  - ✓ a few projects trying direct ν mass measurements
- CνB by accelerator???

  Accelerate $^{3}\mathrm{He}$ and detect tritium and positron

  $^{3}\mathrm{He} + \bar{\nu}_e \to t + e^{+}$

  Necessary $^{3}\mathrm{He}$ energy = 520 TeV for $m_\nu =$100meV….

  (cf. 10 MeV for reactor $\bar{\nu}_e$)
- Superconducting detectors?

How to detect CνB?

Inspired this topic, one idea.

<u>$\bar{\nu}_\mu$ appearance experiment:</u>

✓ reactor ($\bar{\nu}_e \to \bar{\nu}_\mu$) +accelerator $p \to \mu^+ + n$

✓ $E_{th} = 19\ \mathrm{GeV}$

At J-PARC proton beam energy, cross section is comparable to that at E_ν =~1 GeV

There is a reactor.

I will calculate event rate during this workshop.

Conclusion

- To prepare this talk, I read through PDG reviews and neutrino2018 slides.

- Impressed by variety and high activity in this field!!!

$\bar{\nu}_\mu$ appearance experiment:

- reactor peak energy 3~4 MeV
  - baseline length 1.5 km
- Luminosity

$$\mathcal{L} = 2cN_p\rho_\nu$$

  - N_p for J-PARC
    - one turn case ~3E14 /s
    - storage ring 100m x3 straight section ~3E20 /s
  - ρ_ν for Tokai-Daini-nuclear pant
    - Thermal power 3 GW → 6E20 ν/s
    - $\frac{6E20}{4\pi r^2 c}$ =2.1E9/c /cm^3
  - $\mathcal{L}$=1.3E30 /s
- cross section
  - $\sqrt{s} = 1146$ MeV for $E_\nu = 3.5$ MeV ⇔ E_ν =231 MeV for fixed target
  - σ =1E-40 cm^2
- Event rate (storage case)

  1E-10 /s (times oscillation probability)
- Hmmmm