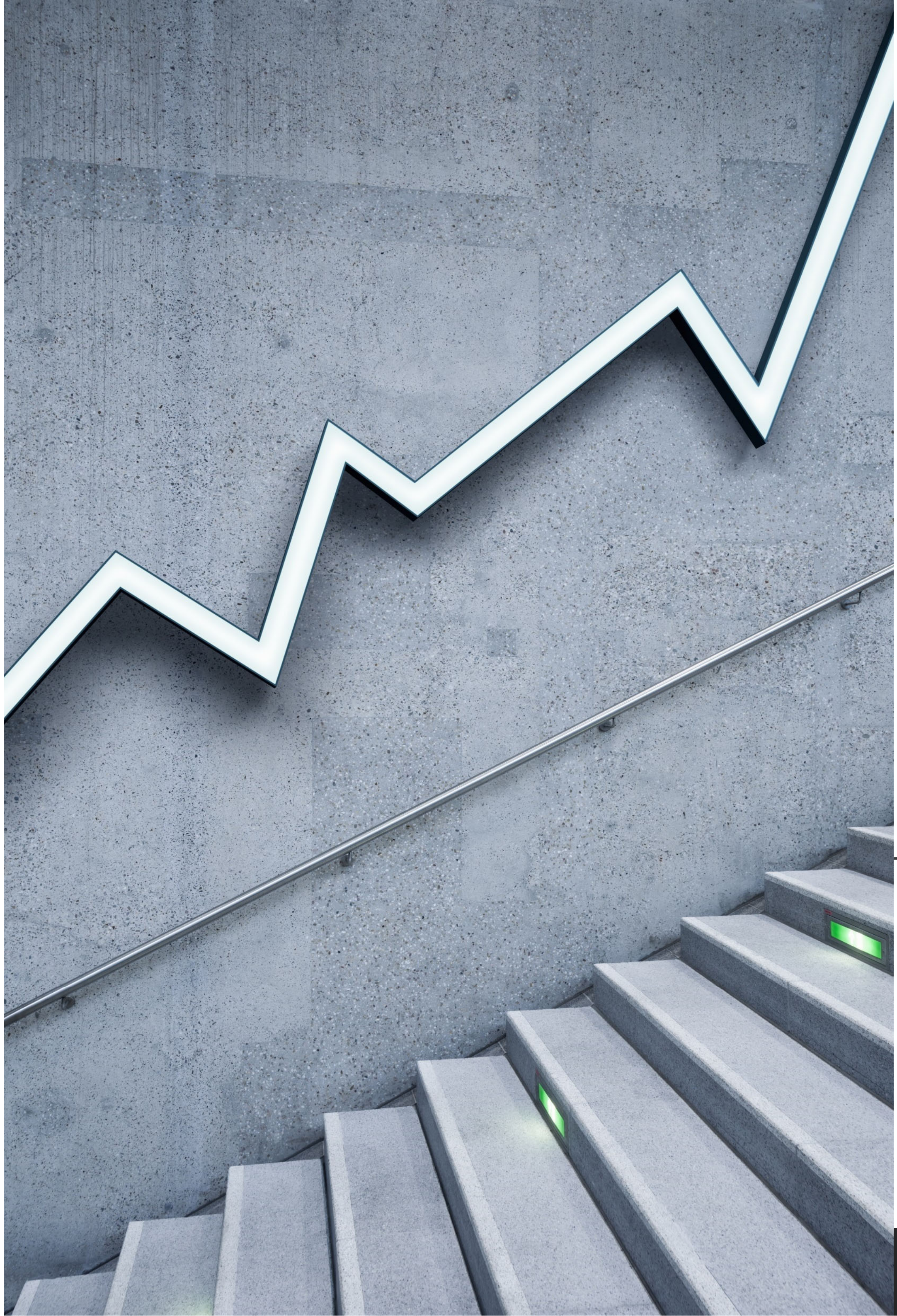
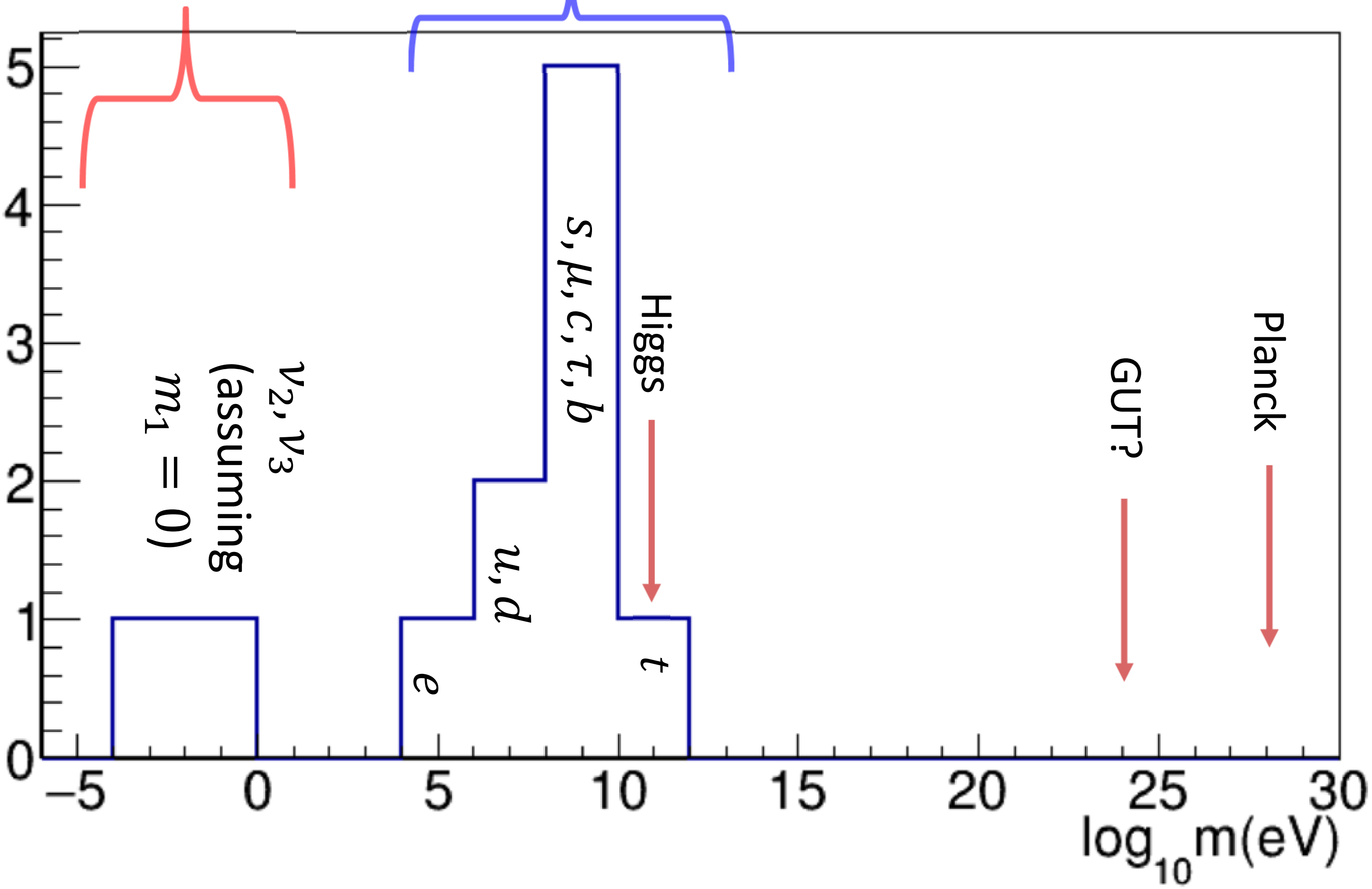


どこまで探すのか、どこまで探せばいいのか、0νββ

市川 温子 (東北大学)

What is the origin of mass?

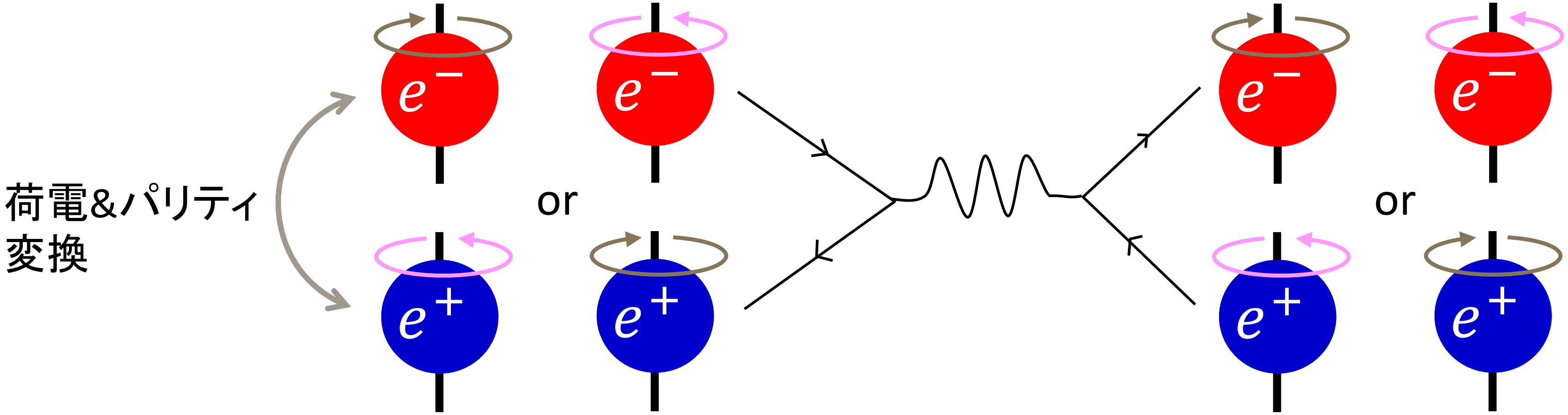


mass by ?
$\langle \log_{10} m_\nu \rangle \sim -2$

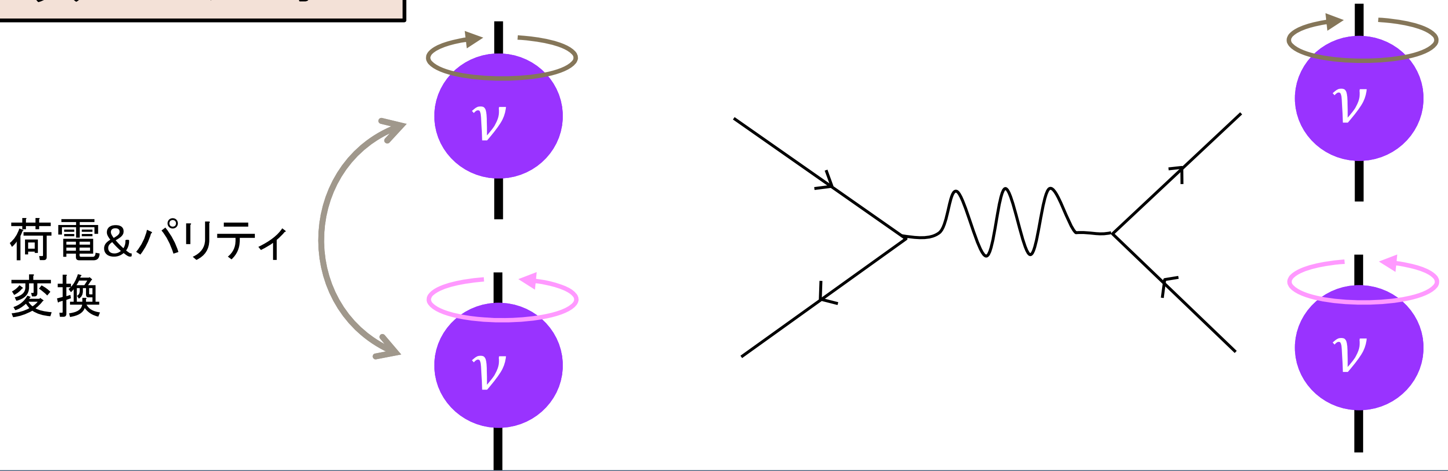
mass by standard Higgs.
$\langle \log_{10} m_D \rangle = 8.2$

ニュートリノは、他のフェルミオンとはちょっと違うかもしれない

ディラック・フェルミオン

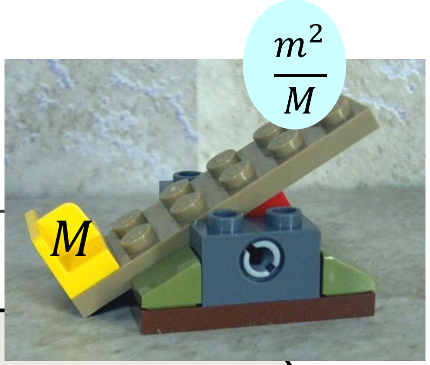


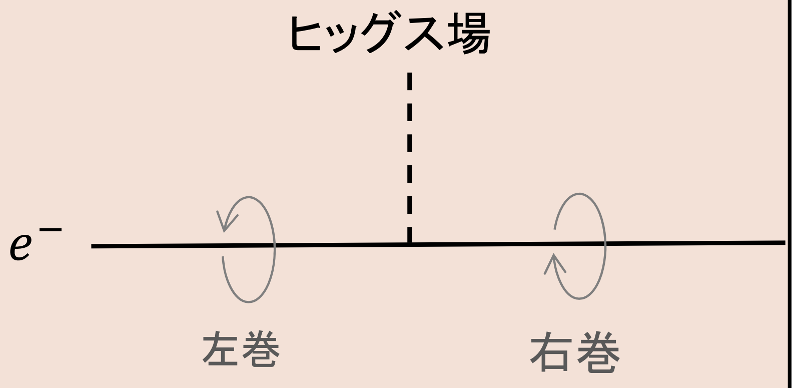
マヨラナ・フェルミオン



ニュートリノがディラック・フェルミオンなのかマヨラナ・フェルミオンなのかは、わかっていない。

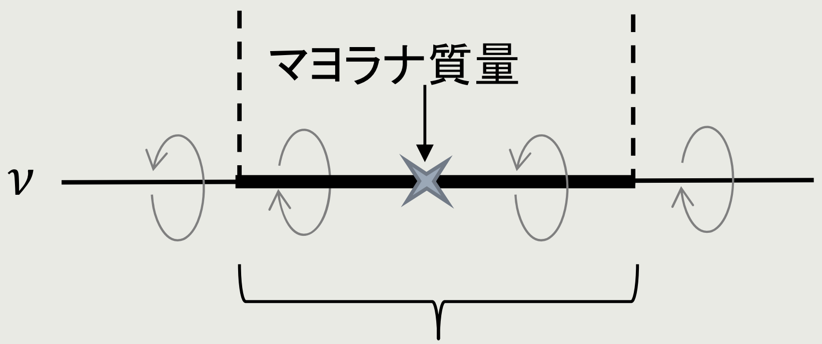
シーソー模型





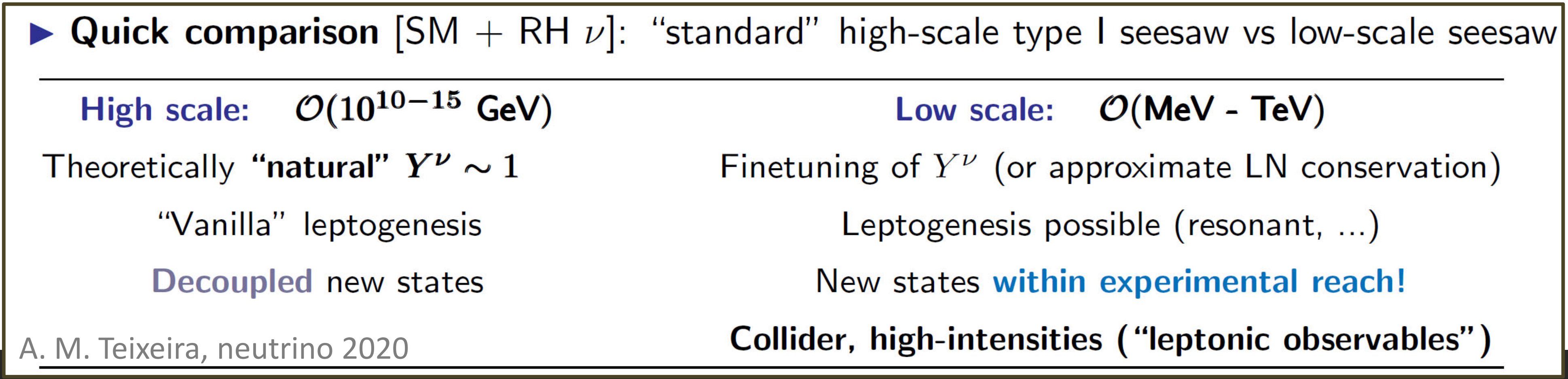
電子などの質量の与えられ方

ヒッグス場　　ヒッグス場



マヨラナ質量が重いと、ヒッグス場との相互作用で得られる質量が小さくなる

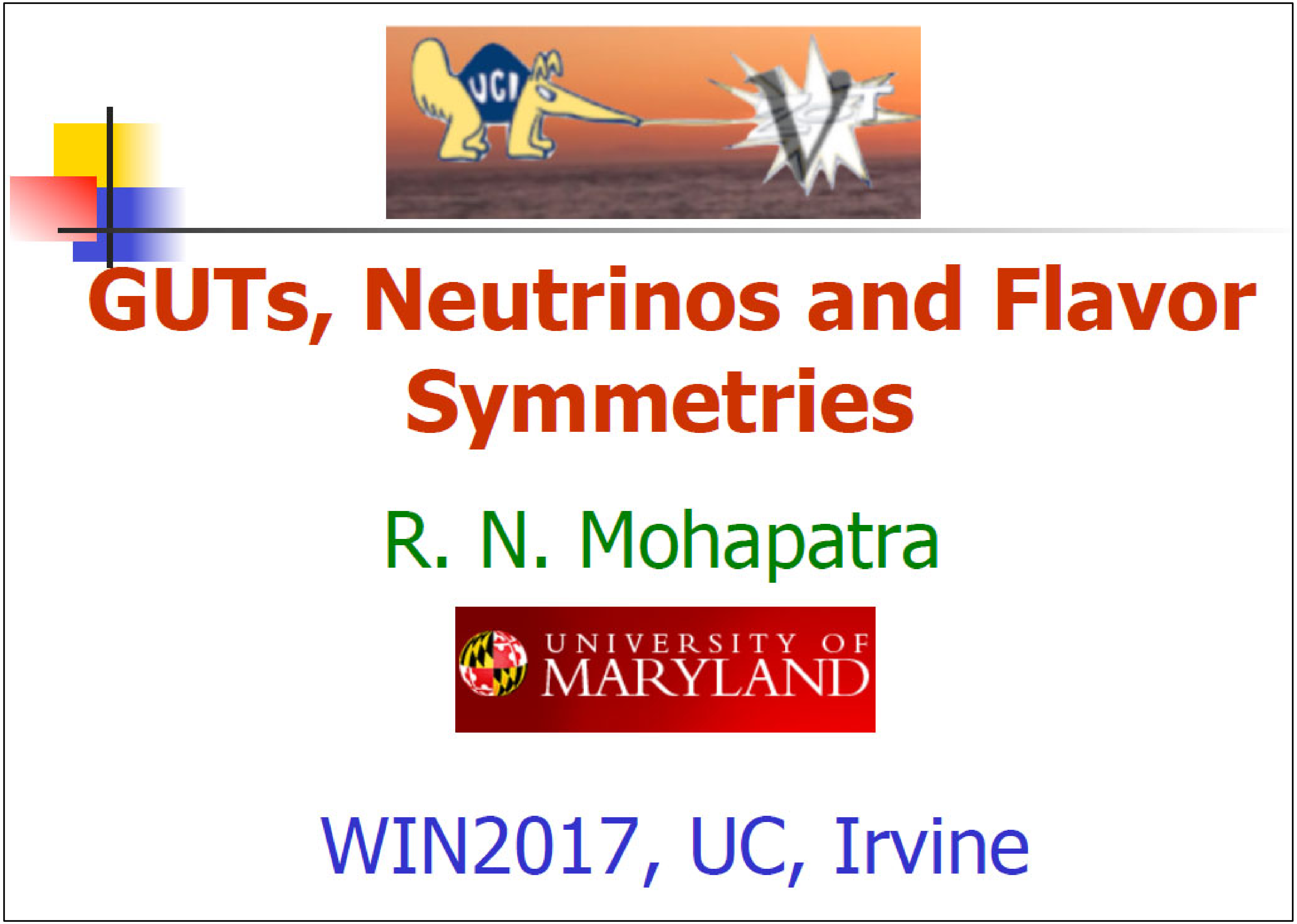
シーソー模型における質量の与えられ方の一例



▶ **Quick comparison** [SM + RH ν]: “standard” high-scale type I seesaw vs low-scale seesaw

High scale: $\mathcal{O}(10^{10-15}$ **GeV)**	**Low scale:** $\mathcal{O}$**(MeV - TeV)**
Theoretically **“natural”** $Y^\nu \sim 1$	Finetuning of Y^ν (or approximate LN conservation)
“Vanilla” leptogenesis	Leptogenesis possible (resonant, ...)
Decoupled new states	New states **within experimental reach!**
	Collider, high-intensities (“leptonic observables”)

A. M. Teixeira, neutrino 2020



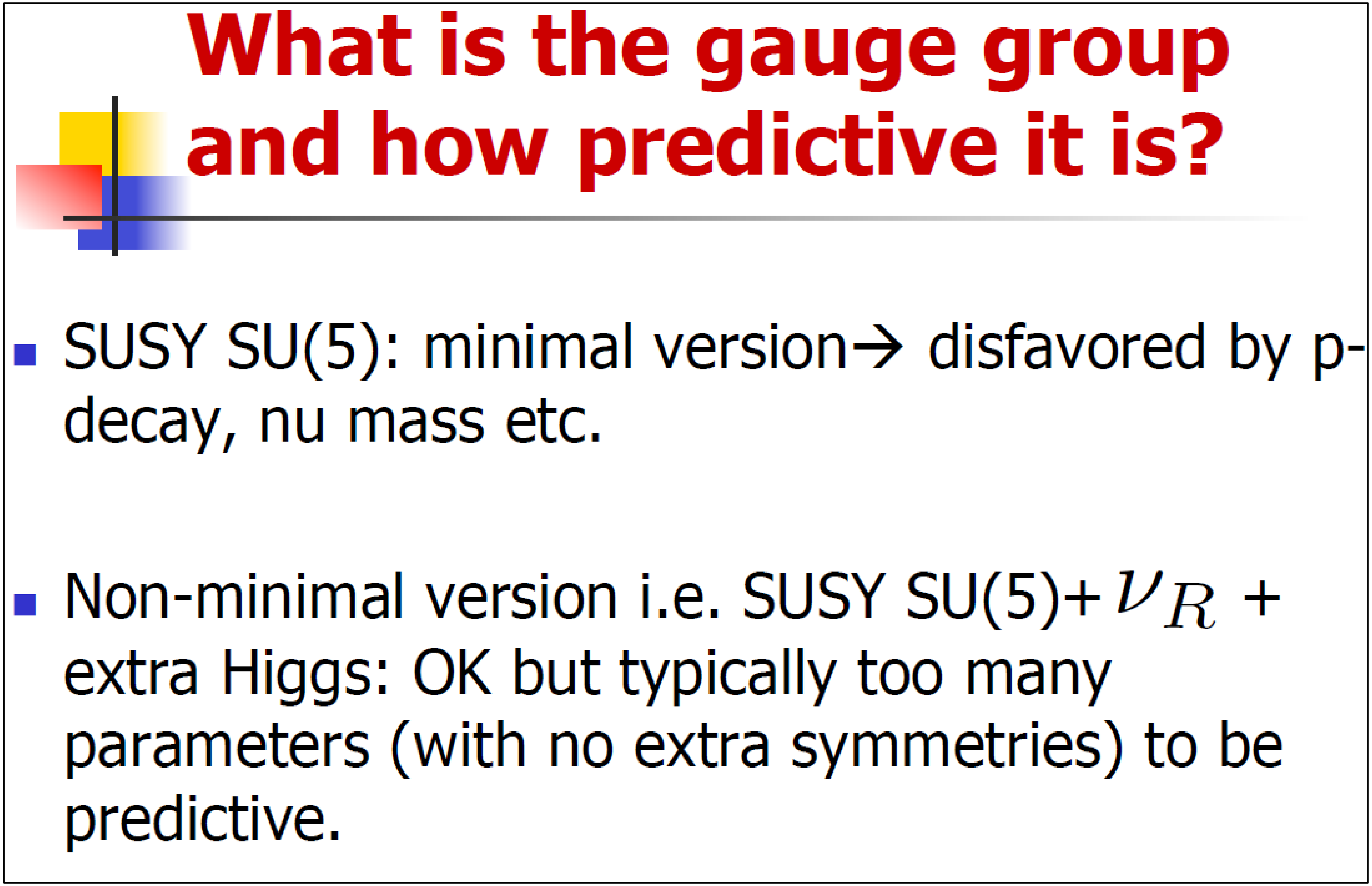
GUTs, Neutrinos and Flavor Symmetries

R. N. Mohapatra

UNIVERSITY OF MARYLAND

WIN2017, UC, Irvine

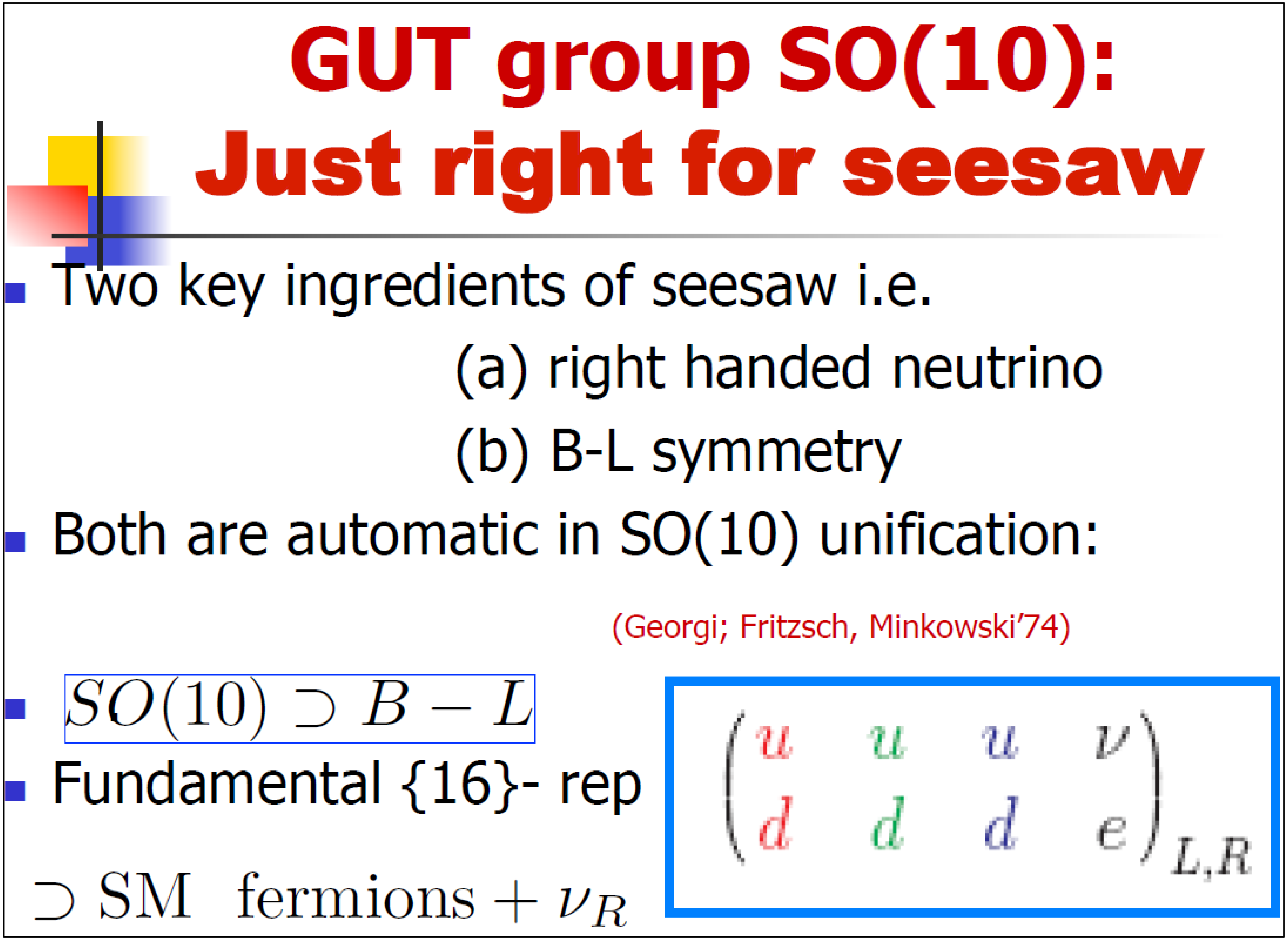
https://indico.fnal.gov/event/9942/contributions/116734/attachments/75717/90810/WIN_2017_final3-Mohapatra.pdf



What is the gauge group and how predictive it is?

- SUSY SU(5): minimal version→ disfavored by p-decay, nu mass etc.
- Non-minimal version i.e. SUSY SU(5)+ν_R + extra Higgs: OK but typically too many parameters (with no extra symmetries) to be predictive.

https://indico.fnal.gov/event/9942/contributions/116734/attachments/75717/90810/WIN_2017_final3-Mohapatra.pdf



GUT group SO(10): Just right for seesaw

- Two key ingredients of seesaw i.e.

  (a) right handed neutrino

  (b) B-L symmetry
- Both are automatic in SO(10) unification:

(Georgi; Fritzsch, Minkowski'74)

- $\boxed{SO(10) \supset B-L}$
- Fundamental {16}- rep

$\supset \text{SM} \quad \text{fermions} + \nu_R$

$$\begin{pmatrix} u & u & u & \nu \\ d & d & d & e \end{pmatrix}_{L,R}$$

https://indico.fnal.gov/event/9942/contributions/116734/attachments/75717/90810/WIN_2017_final3-Mohapatra.pdf

SUSY not essential for coupling unif. in SO(10)

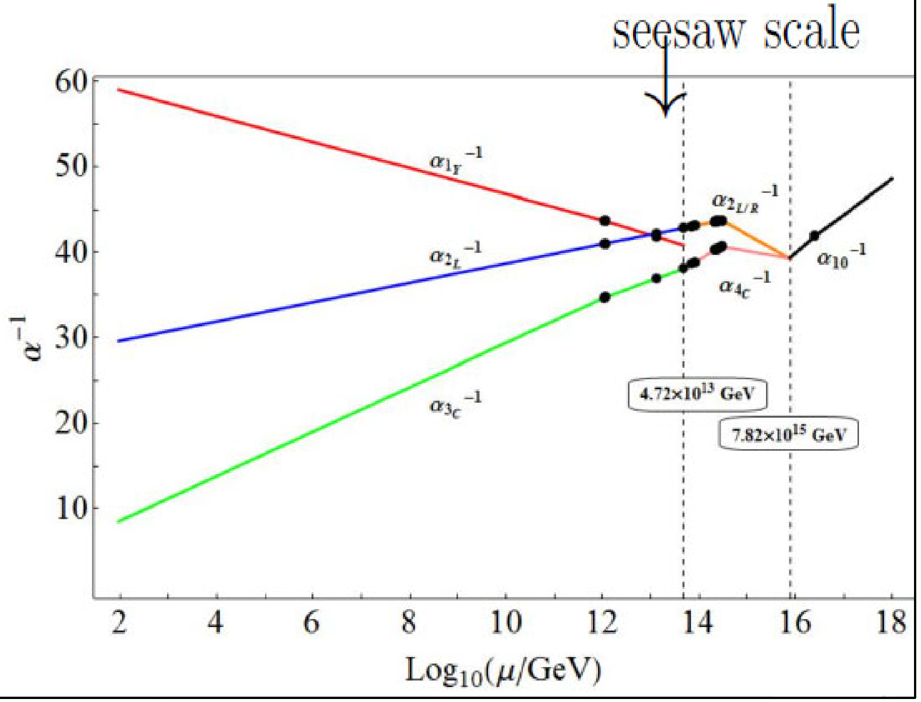
- Non-SUSY SO(10) unification→ correct $\sin^2\theta_W$

(Chang, RNM, parida'83; Chang, RNM,Parida,Gipson,Marshak'85; Deshpande, Keith, Pal'93; RNM, Parida'93; Bertolini, diLuzio, Malinsky'09;Altarelli, Meloni'13)

- Predicts seesaw scale out of 2-step unification
- p-decay signal

$$p \to e^+\pi^0$$

(Babu, Khan'2015)



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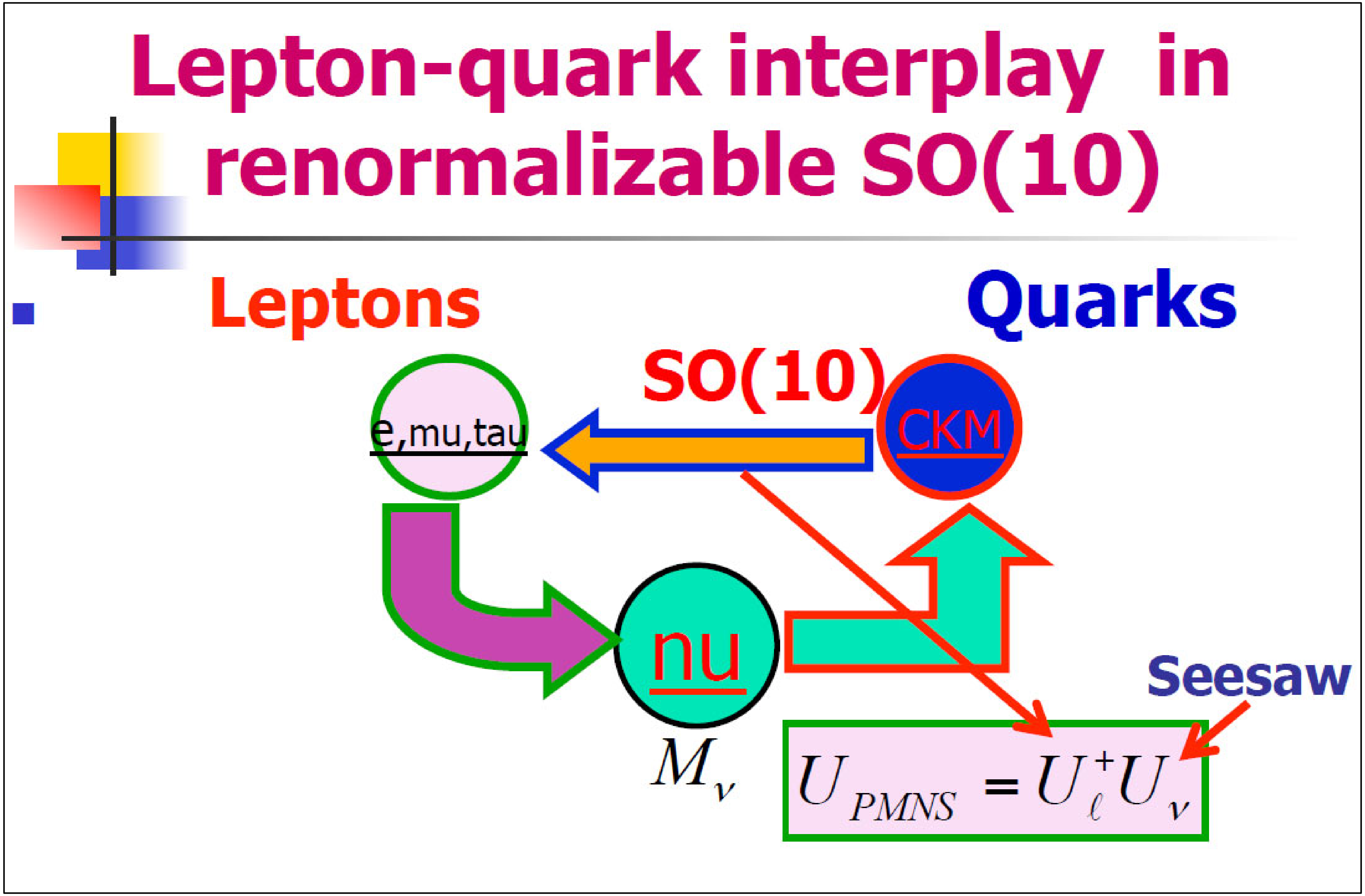


Lepton-quark interplay in renormalizable SO(10)

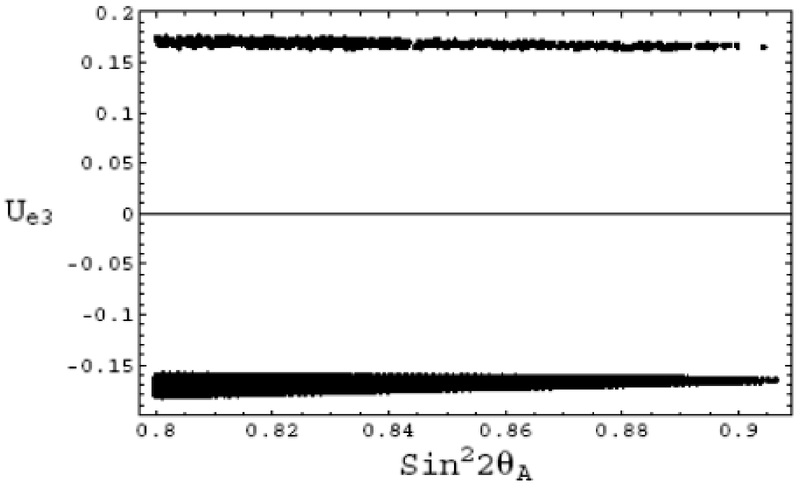
M_ν

$U_{PMNS} = U_\ell^+ U_\nu$

https://indico.fnal.gov/event/9942/contributions/116734/attachments/75717/90810/WIN_2017_final3-Mohapatra.pdf

Successes of renormalizable SUSY SO(10)

- Works quantitatively: (10+126)
- *Predicts normal hierarchy*:



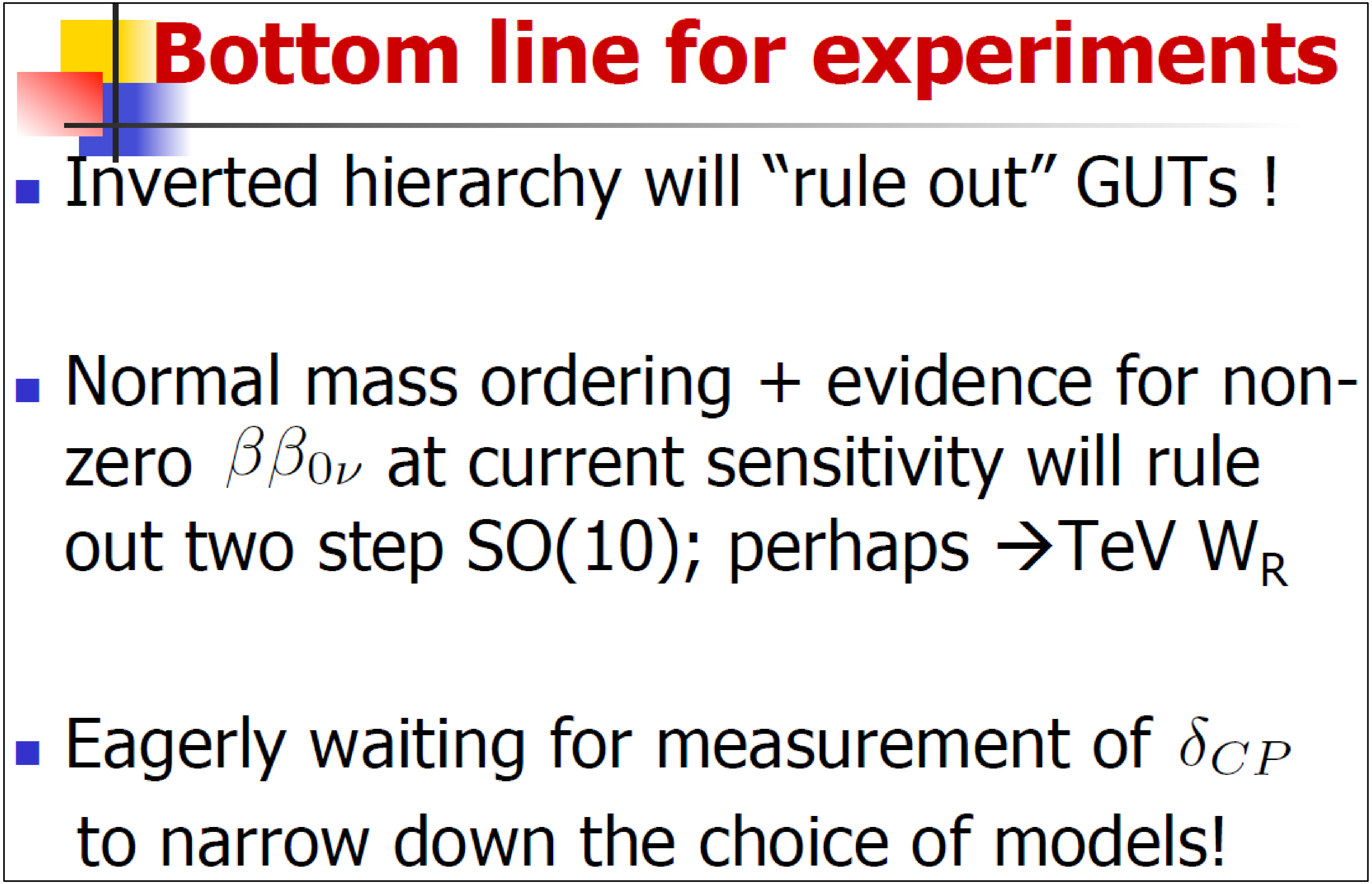
- ★ θ_{12}, θ_{23} large
- ★ $\theta_{13} \approx \lambda$ "large" (Goh, RNM, Ng, 03 ; Babu, Macesanu'05)

★ $\frac{m_{solar}}{m_{atmos}} \sim \lambda$

- $\theta_{13} \cong 0.15$

Also predictive and works for non-susy SO(10)+U(1)$_{PQ}$!

https://indico.fnal.gov/event/9942/contributions/116734/attachments/75717/90810/WIN_2017_final3-Mohapatra.pdf



Bottom line for experiments

- Inverted hierarchy will “rule out” GUTs !
- Normal mass ordering + evidence for non-zero $\beta\beta_{0\nu}$ at current sensitivity will rule out two step SO(10); perhaps →TeV W_R
- Eagerly waiting for measurement of δ_{CP} to narrow down the choice of models!

https://indico.fnal.gov/event/9942/contributions/116734/attachments/75717/90810/WIN_2017_final3-Mohapatra.pdf

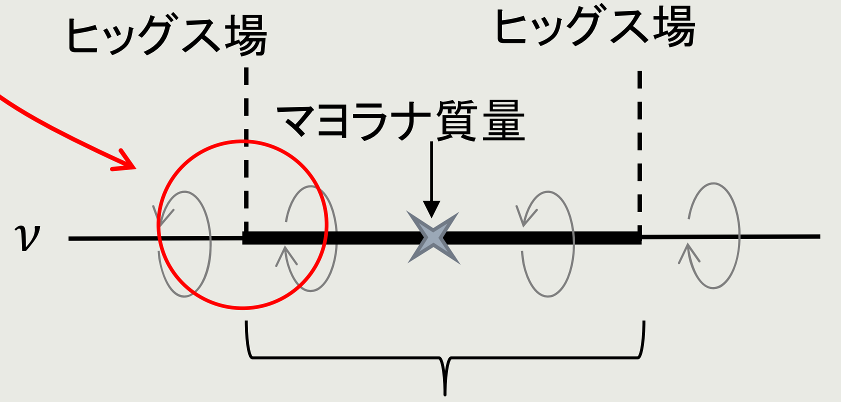
レプトジェネシス

現代の宇宙の物質の量を説明するには、初期宇宙で6×10^{-10}のmatter-antimatter asymmetryが生成されたはず。

- 標準模型では、生成できない。

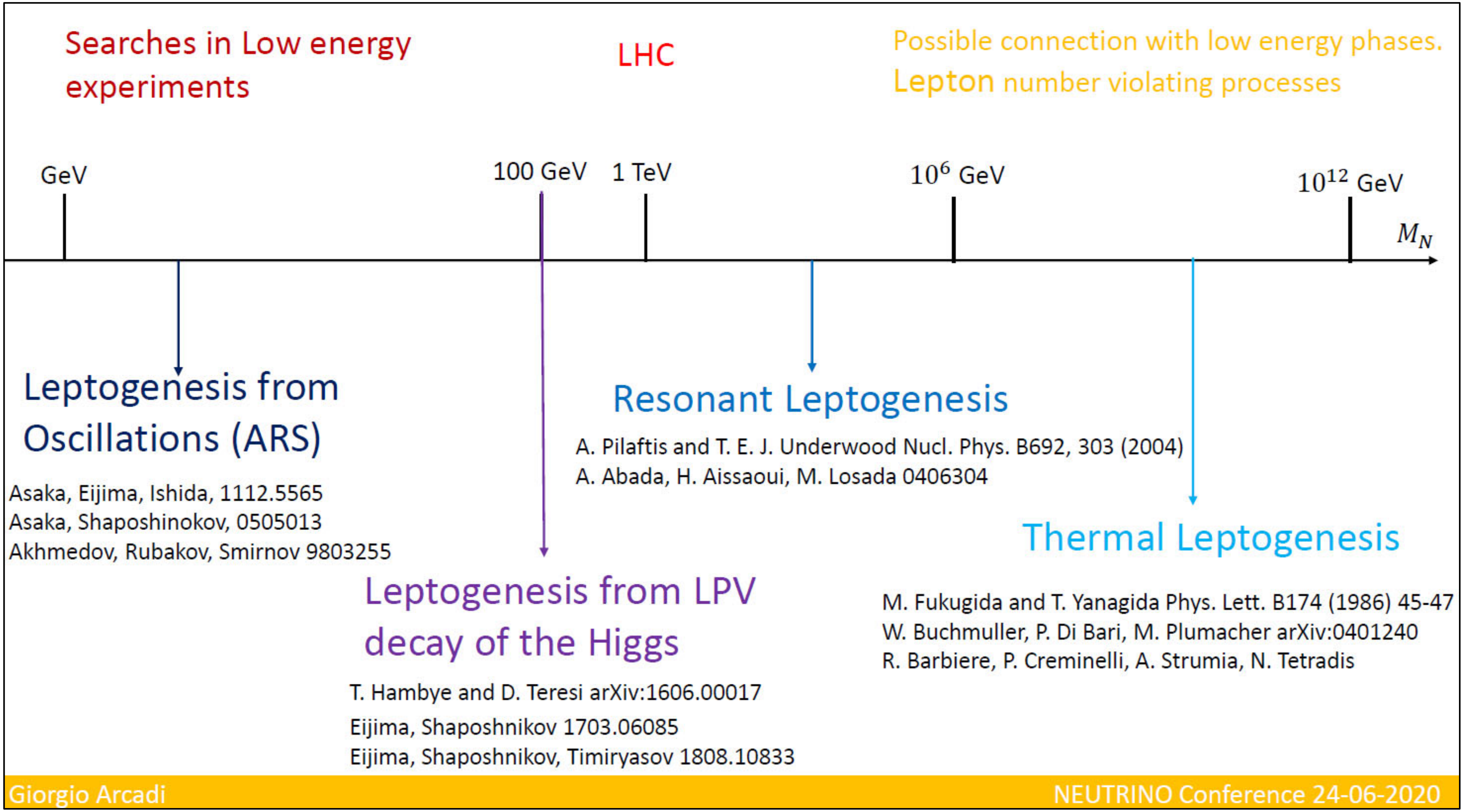
（標準的な）レプトジェネシス

- N_R(重い右巻きニュートリノ)の崩壊で軽いνとHiggsを生成。この時にCPの破れ→レプトン数の生成
- スファレロン過程　（標準理論で許される過程。）
  - 宇宙初期の真空の遷移で、B-Lを一定に保った状態で粒子を生成。
  - レプトン数→バリオン数が生成



マヨラナ質量が重いと、ヒッグス場との相互作用で得られる質量が小さくなる

シーソー模型における質量の与えられ方の一例



Searches in Low energy experiments

LHC

Possible connection with low energy phases.
Lepton number violating processes

Leptogenesis from Oscillations (ARS)

Asaka, Eijima, Ishida, 1112.5565
Asaka, Shaposhinokov, 0505013
Akhmedov, Rubakov, Smirnov 9803255

Leptogenesis from LPV decay of the Higgs

T. Hambye and D. Teresi arXiv:1606.00017
Eijima, Shaposhnikov 1703.06085
Eijima, Shaposhnikov, Timiryasov 1808.10833

Resonant Leptogenesis

A. Pilaftis and T. E. J. Underwood Nucl. Phys. B692, 303 (2004)
A. Abada, H. Aissaoui, M. Losada 0406304

Thermal Leptogenesis

M. Fukugida and T. Yanagida Phys. Lett. B174 (1986) 45-47
W. Buchmuller, P. Di Bari, M. Plumacher arXiv:0401240
R. Barbiere, P. Creminelli, A. Strumia, N. Tetradis

Giorgio Arcadi

NEUTRINO Conference 24-06-2020

微調整問題を無視すれば、SUSYはない方がいいらしい。(再加熱温度が低くなってしまう。)

ニュートリノがマヨラナ粒子かどうか確かめることが、すごく重要

人類が予想している10^{10} ~10^{15} GeVの物理が正しいかどうかを垣間見る

二重ベータ崩壊

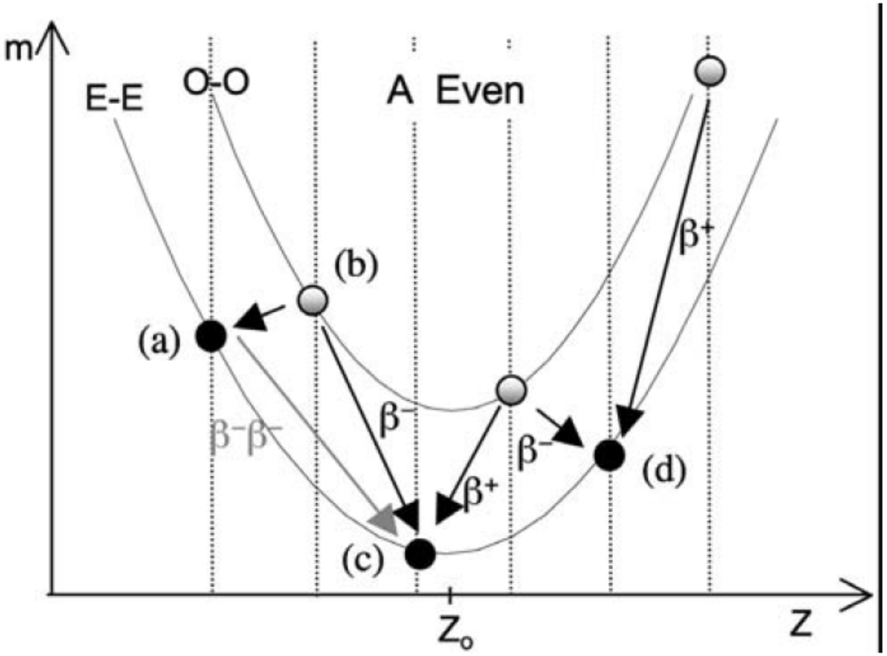
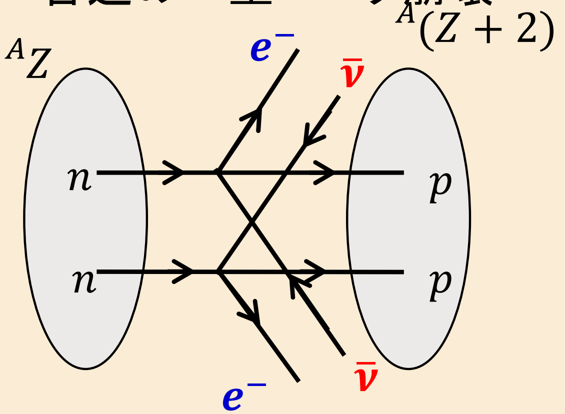


Figure 2. Ground state mass parabola for isobaric nuclei, showing the necessary configuration for double beta decay. Only the one (a) on the even-even (E-E) shell, whose β-decay is blocked (b) but which could decay via two subsequent steps (c) is allowed to do double beta decay. The shift of the parabola of the odd-odd (O-O) nuclei is due to the nuclear pairing energy.

普通の二重ベータ崩壊



稀だけどたまに起きる

K. Zuber, Double Beta Decay, Contemp. Phys. 45 (2004) 491-502

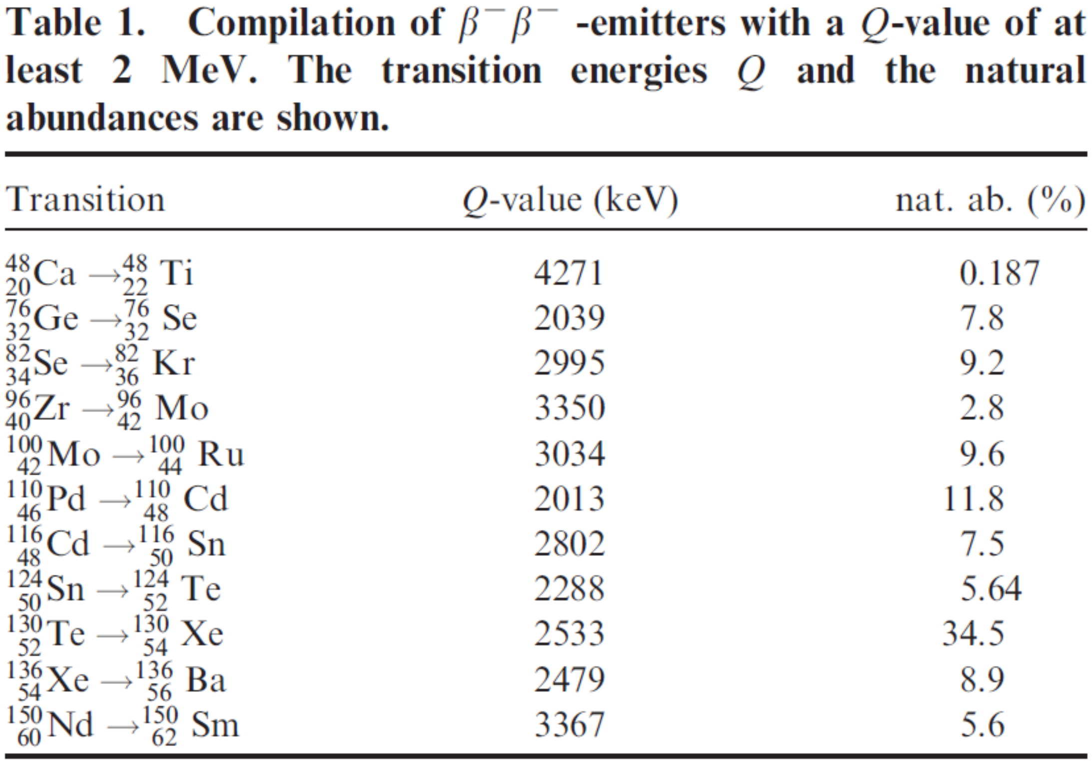
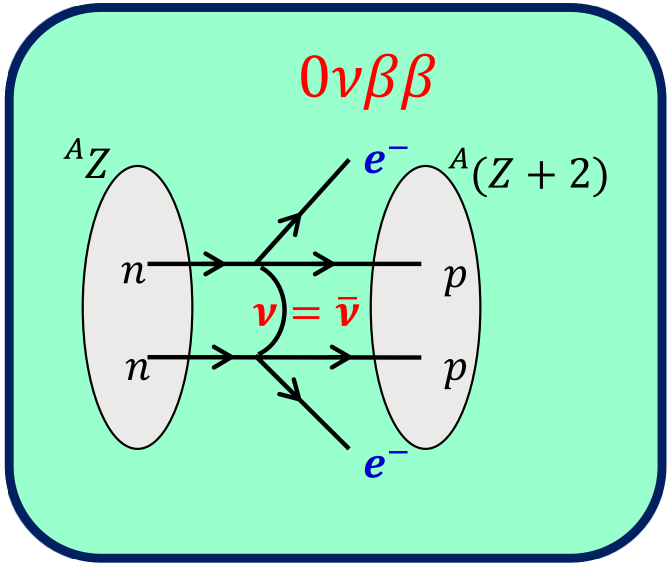
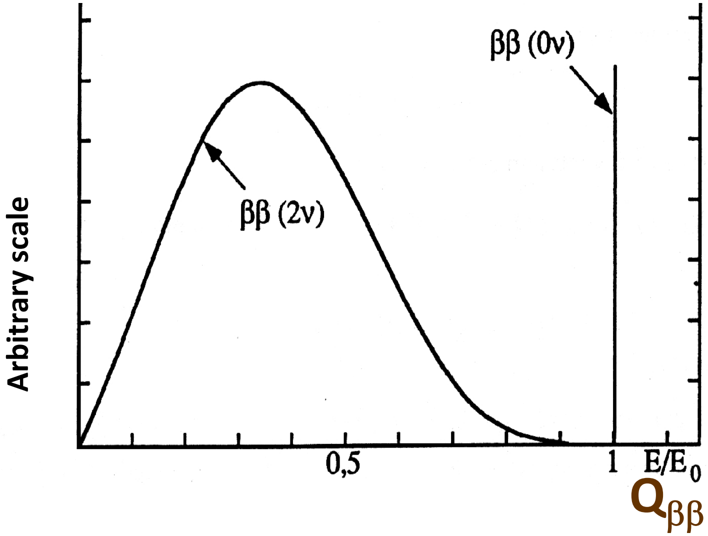


Table 1. Compilation of $\beta^-\beta^-$ -emitters with a Q-value of at least 2 MeV. The transition energies Q and the natural abundances are shown.

Transition	Q-value (keV)	nat. ab. (%)
$^{48}_{20}\mathrm{Ca} \rightarrow {}^{48}_{22}\mathrm{Ti}$	4271	0.187
$^{76}_{32}\mathrm{Ge} \rightarrow {}^{76}_{32}\mathrm{Se}$	2039	7.8
$^{82}_{34}\mathrm{Se} \rightarrow {}^{82}_{36}\mathrm{Kr}$	2995	9.2
$^{96}_{40}\mathrm{Zr} \rightarrow {}^{96}_{42}\mathrm{Mo}$	3350	2.8
$^{100}_{42}\mathrm{Mo} \rightarrow {}^{100}_{44}\mathrm{Ru}$	3034	9.6
$^{110}_{46}\mathrm{Pd} \rightarrow {}^{110}_{48}\mathrm{Cd}$	2013	11.8
$^{116}_{48}\mathrm{Cd} \rightarrow {}^{116}_{50}\mathrm{Sn}$	2802	7.5
$^{124}_{50}\mathrm{Sn} \rightarrow {}^{124}_{52}\mathrm{Te}$	2288	5.64
$^{130}_{52}\mathrm{Te} \rightarrow {}^{130}_{54}\mathrm{Xe}$	2533	34.5
$^{136}_{54}\mathrm{Xe} \rightarrow {}^{136}_{56}\mathrm{Ba}$	2479	8.9
$^{150}_{60}\mathrm{Nd} \rightarrow {}^{150}_{62}\mathrm{Sm}$	3367	5.6

“ニュートリノを伴わない二重ベータ崩壊”($0\nu\beta\beta$)





- ニュートリノが“マヨラナ質量”を持つ場合にのみ起きる。

“Observation of neutrinoless double-beta (0νββ) decay would signal violation of total lepton number conservation. The process can be mediated by an exchange of a light Majorana neutrino, or by an exchange of other particles. However, the existence of 0νββ-decay requires a nonvanishing Majorana neutrino mass, no matter what the actual mechanism is.” PDG2020

Lifetime for standard Majorana case

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

phase space factor

nuclear matrix element

有効ニュートリノ質量

$$\langle m_{\beta\beta}\rangle^2 = \left|\sum_i U_{ei}^2 m_{\nu_i}\right|^2 = \left|\left(m_1 c_{12}^2 + m_2 s_{12}^2 e^{i\alpha_{21}}\right)c_{13}^2 + m_3 s_{13}^2 e^{i(\alpha_{31}-2\delta)}\right|^2$$

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.

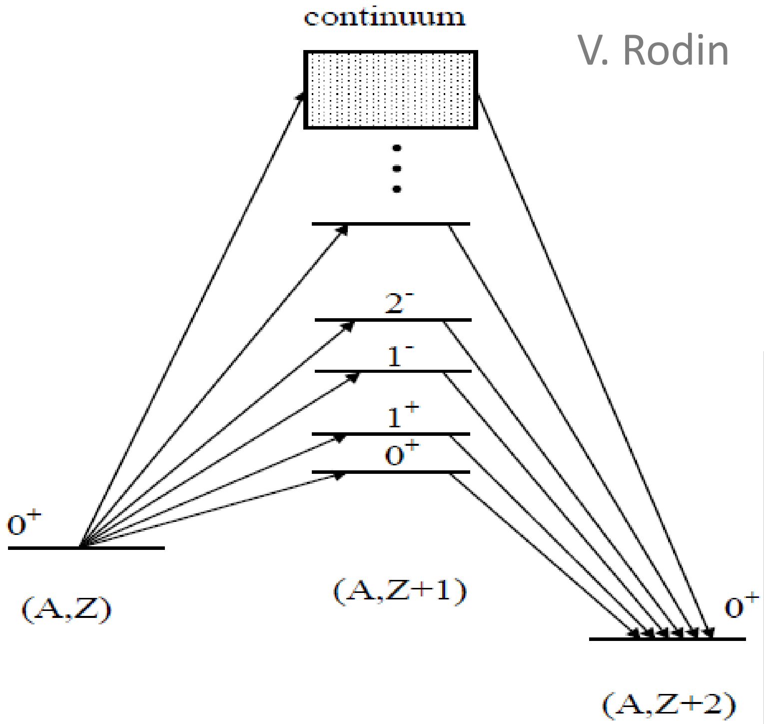
有効ニュートリノ質量が10分の１になると、寿命は100倍(TДT)

寿命の感度は、

バックグランドフリーだと ∝ 崩壊核x時間

バックグランドリミテッドだと∝ √崩壊核x時間

Nuclear matrix element



V. Rodin

J. Menéndez, Neutrino 2020

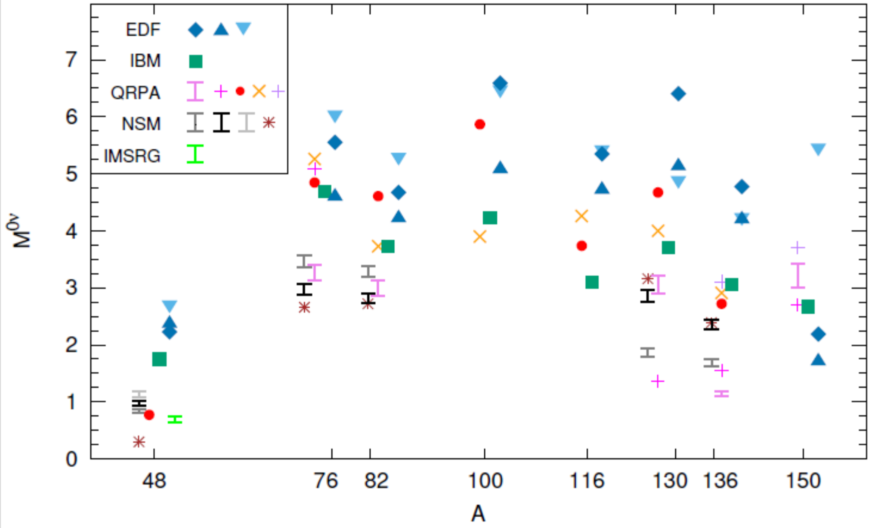
$0\nu\beta\beta$ decay nuclear matrix elements

Large difference in nuclear matrix element calculations: factor $\sim 2-3$

$$\langle 0_f^+ | \sum_{n,m} \tau_n^- \tau_m^- \sum_x H^x(r)\, \Omega^x\, | 0_i^+ \rangle$$

Ω^x = Fermi ($\mathbb{1}$), GT ($\sigma_n \sigma_m$), Tensor

$H(r)$ = neutrino potential



M. Agostini, G. Benato, J. Detwiler, JM, F. Vissani, in preparation

EDF: large NMEs

QRPA: wider range

NSM: small NMEs

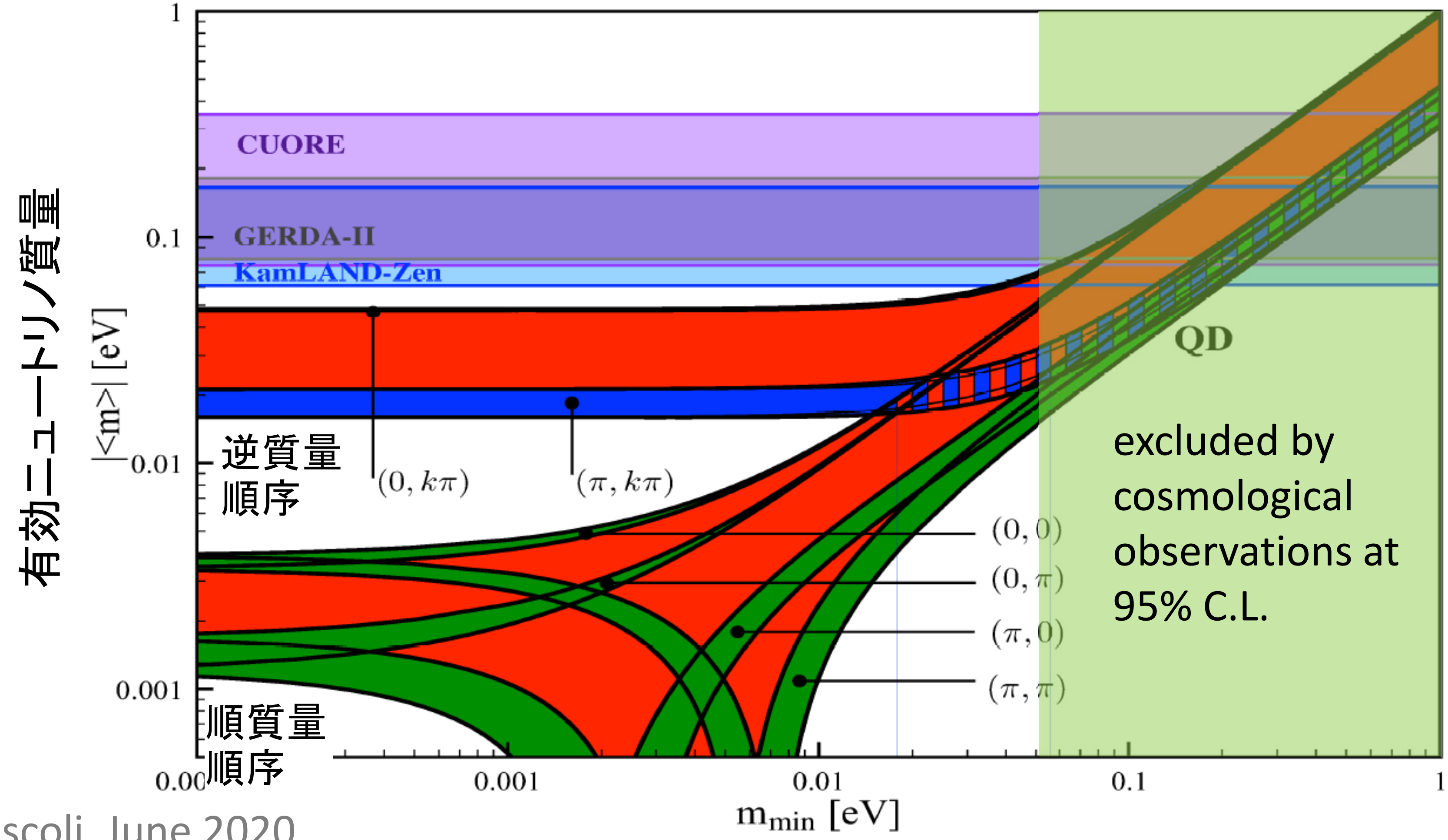
IMSRG ab initio

^{48}Ca NME: quite small

(no 2b currents)

Current limit

- ✓ 青とか緑は、マヨラナCP位相の値を、CP conservingなある値に固定した場合。振動パラメータの不定性のために幅がある。
- ✓ 赤は、マヨラナ位相を振った場合。



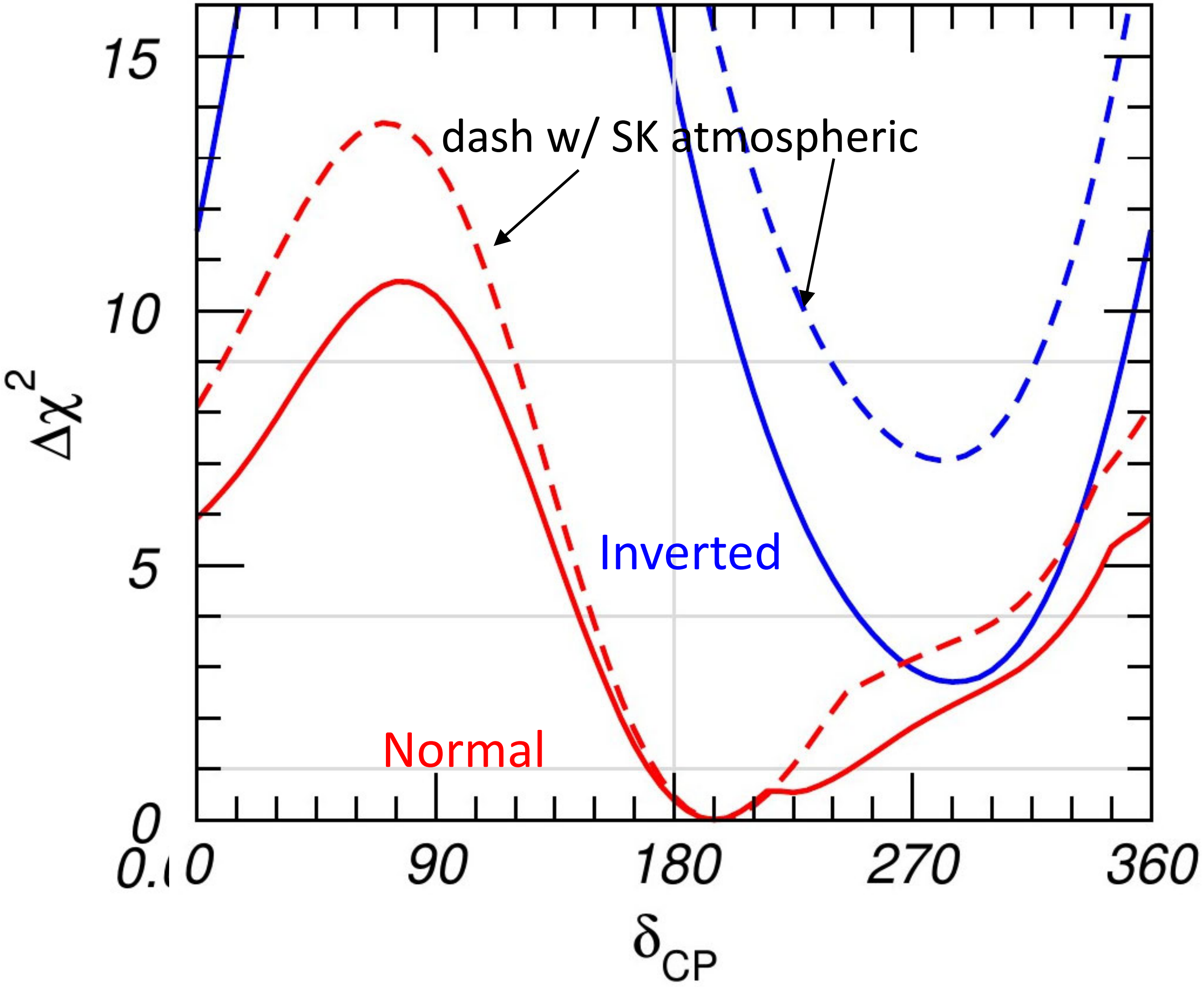
excluded by cosmological observations at 95% C.L.

S. Pascoli, June 2020

質量順序

Home

v5.0: Three-neutrino fit based on data available in July 2020



T2K&NOvA&JUNOでmass orderingは(2020年代中頃に)5σで決まる可能性が高い。

実験で抑えられている範囲でパラメータをランダムに振ると

順質量順序　　　　　　　　　　逆質量順序

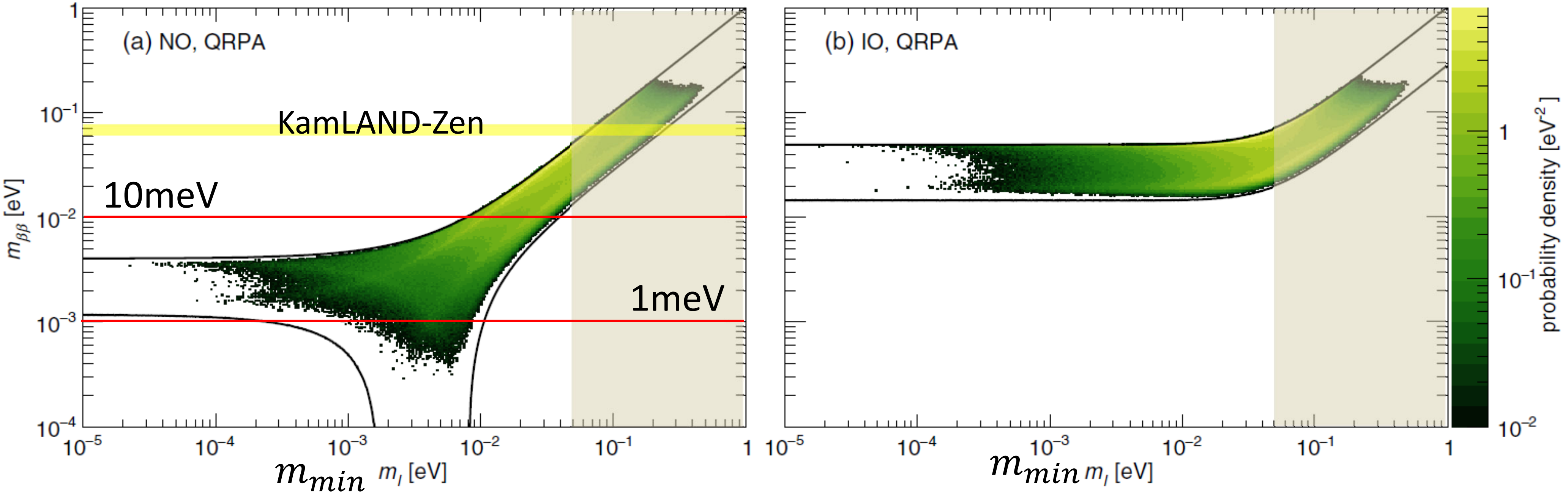
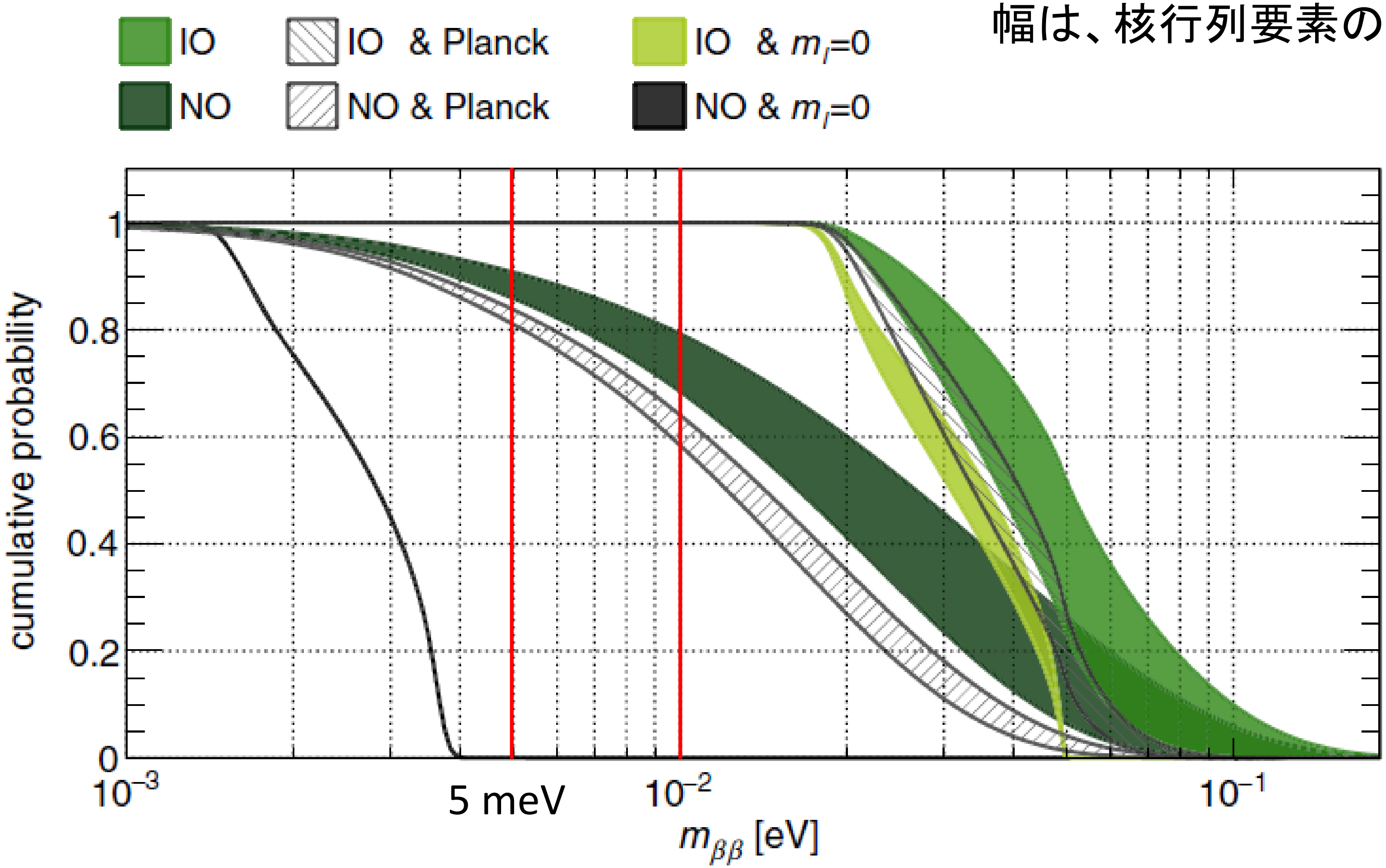


FIG. 1. Marginalized posterior distributions for $m_{\beta\beta}$ and m_l for NO (a) and IO (b). The solid lines show the allowed parameter space assuming 3σ intervals of the neutrino oscillation observables from NuFIT [12]. The plot is produced assuming QRPA NMEs and the absence of mechanisms that drive m_l or $m_{\beta\beta}$ to 0. The probability density is normalized by the logarithm of $m_{\beta\beta}$ and m_l.

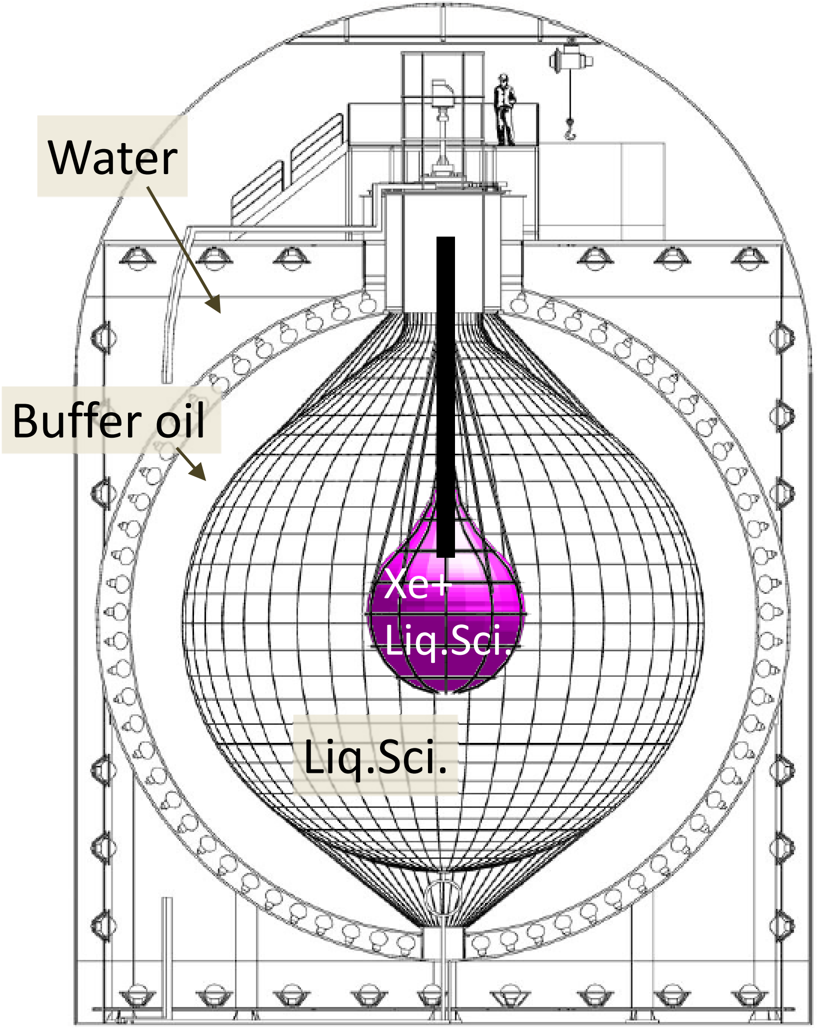
PRD 96, 053001 (2017)

実験で抑えられている範囲でパラメータをランダムに振ると

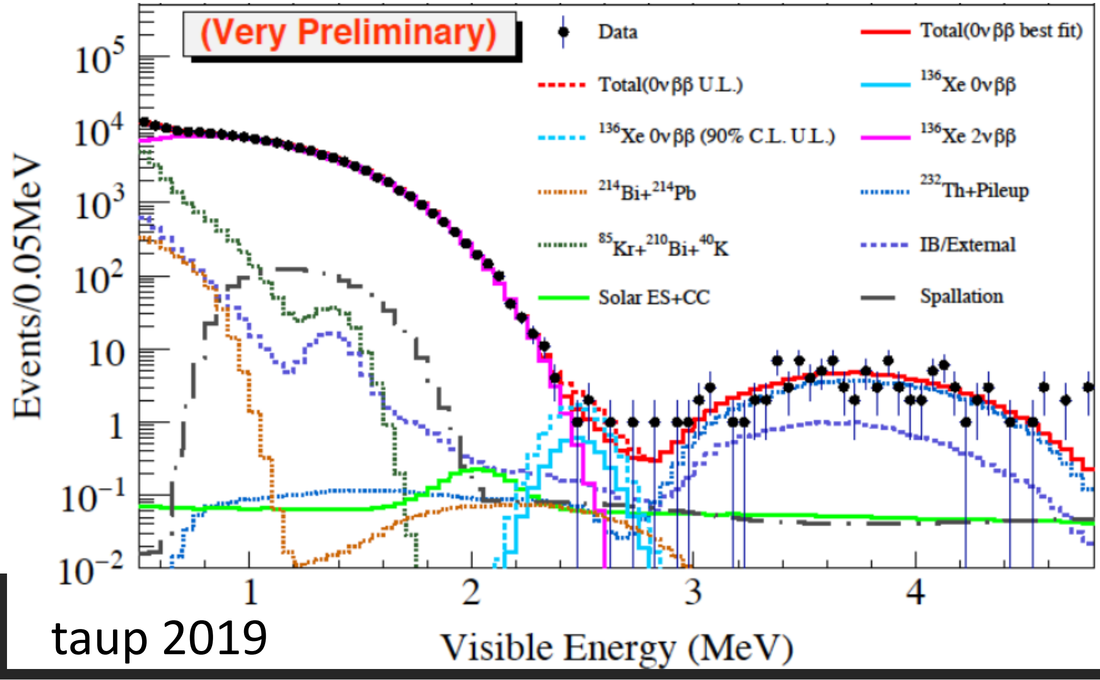
幅は、核行列要素の不定性



Front-Runner 1 : KamLAND-Zen



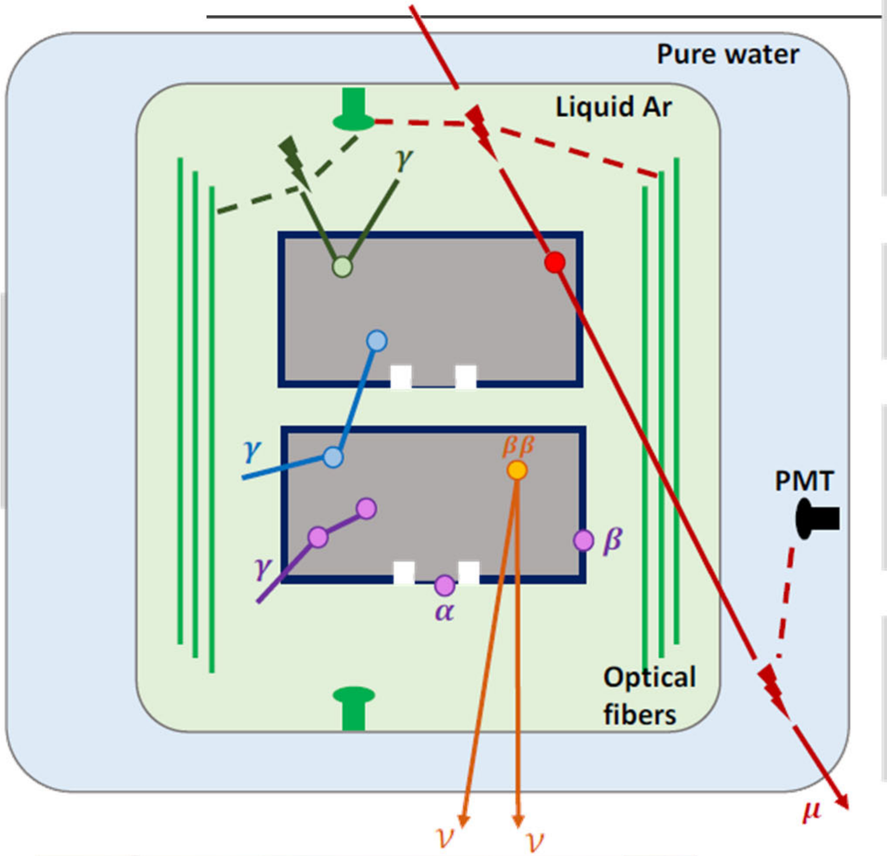
- ✓ 90%-enriched ^{136}Xe dissolved in Liq. Scinti.
  - 2011 ~ 2015 : 320 ~ 380 kg
  - 2019 - : 745 kg
- ✓ Active shielding by ultra-low background liquid scintillator
- ✓ Pre-activity cut by timing information



taup 2019

Front–Runner 2 : GERDA

Y. Kermadic, neutrino2020

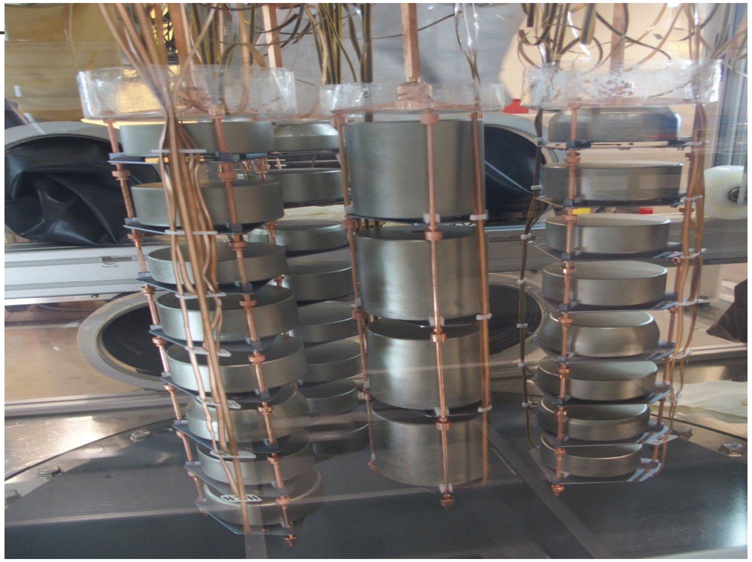


Pulse shape discrimination (PSD) for multi-site and surface α, β events

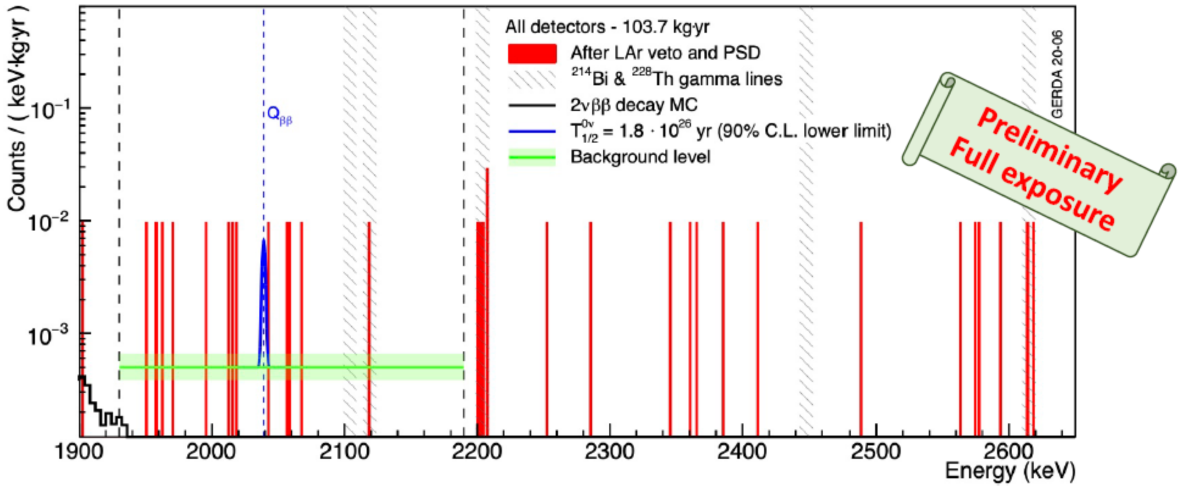
Ge detector anti-coincidence

LAr veto based on Ar scintillation light read by fibers and PMT

Muon veto based on Cherenkov light and plastic scintillator

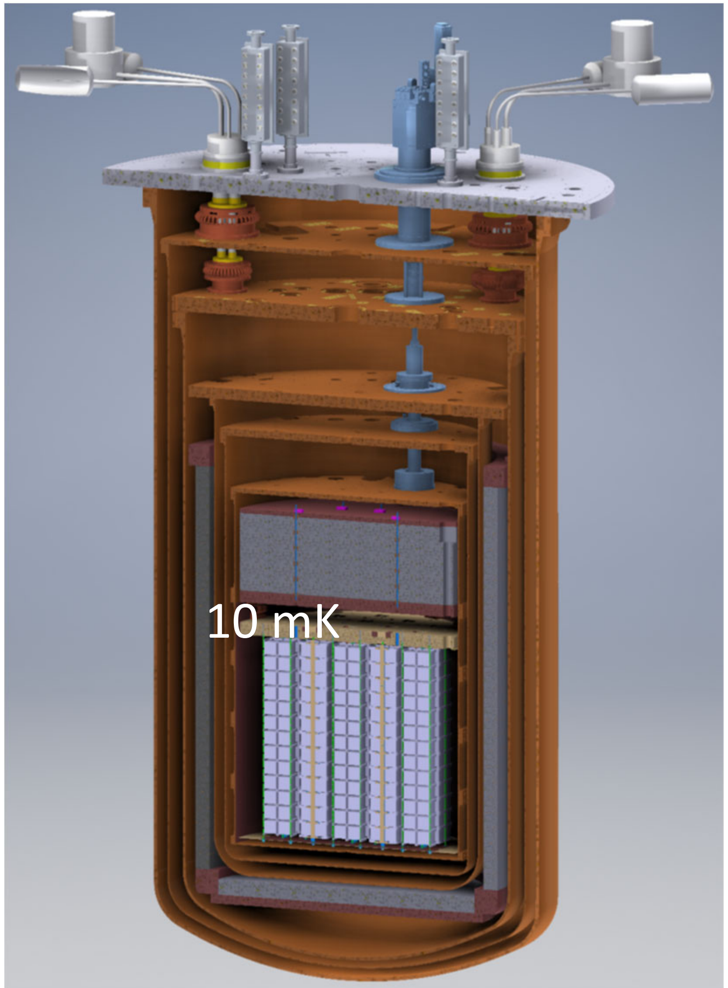


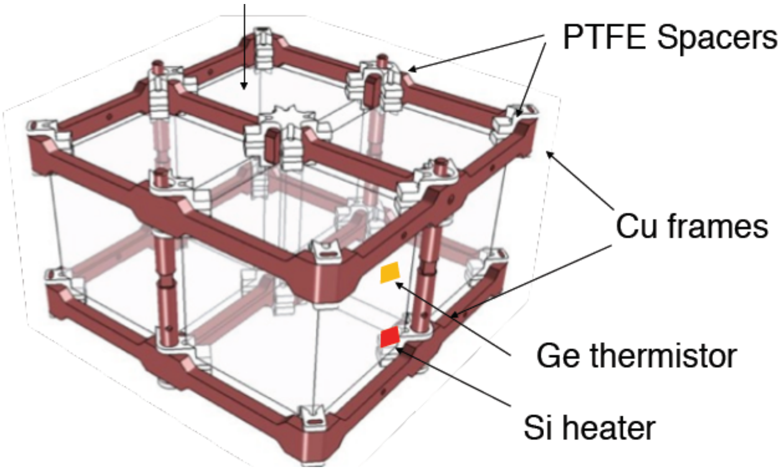
- ✓ 88%-enriched Germanium detector : 35.6 kg→44.2 kg
- ✓ Ultra-high energy resolution



Front-Runner 3 : CUORE

T. O’Donnell, neutrino 2020



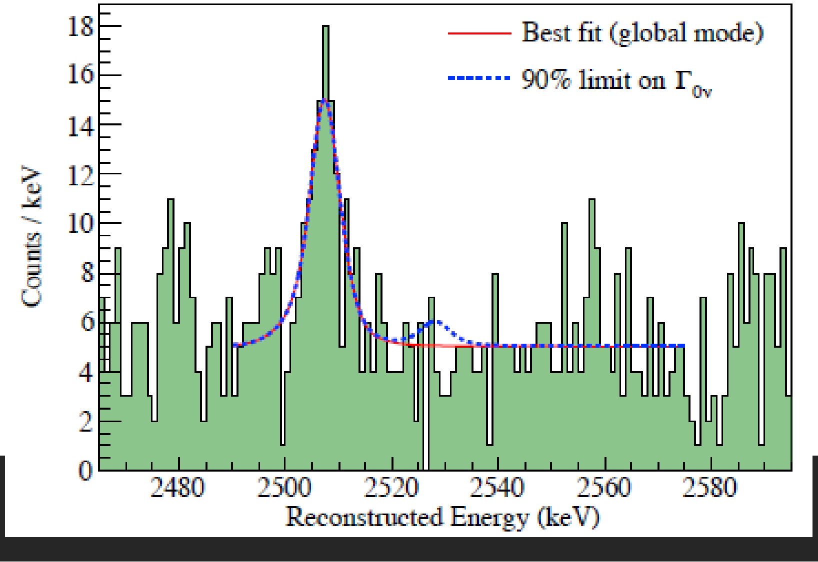


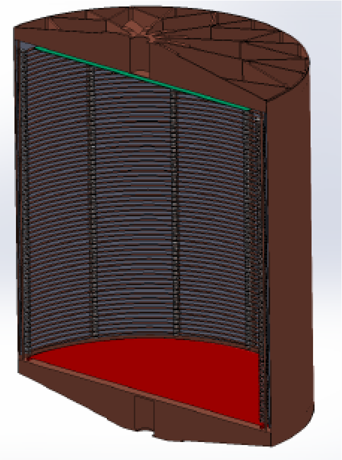
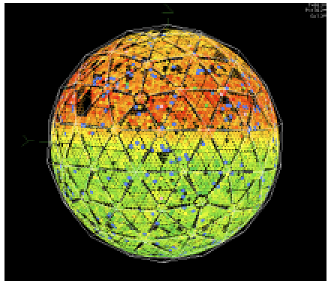
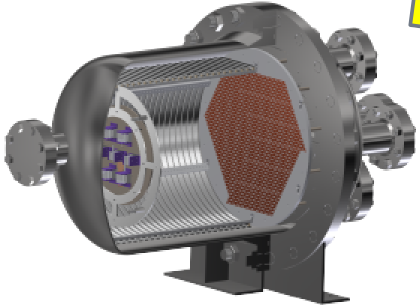
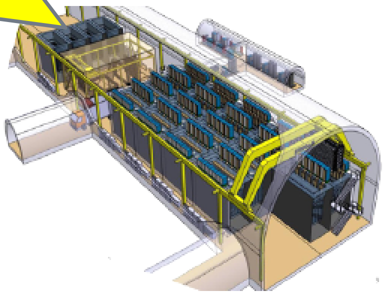
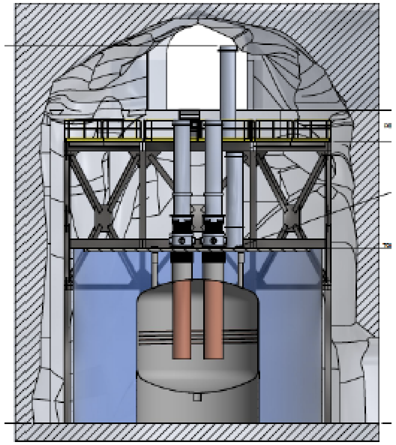
TeO$_2$ bolometer

^{130}Te : Natural abondance(34%), 206 kg

Very high energy resolution.

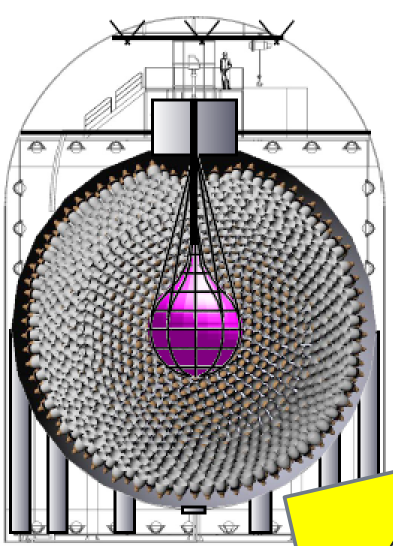
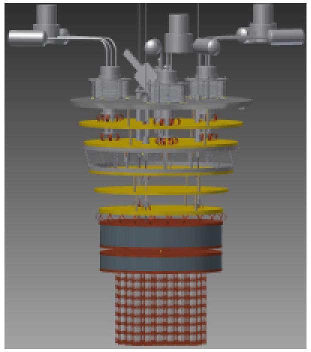
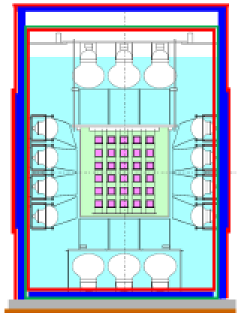
CUORE ROI Spectrum

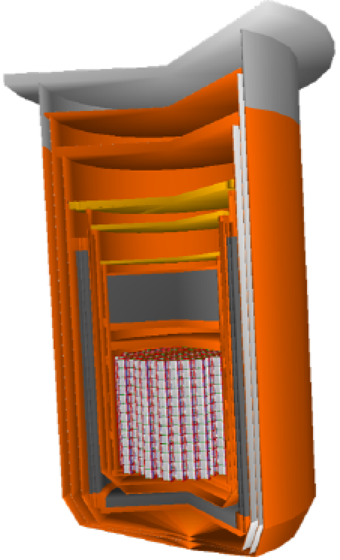


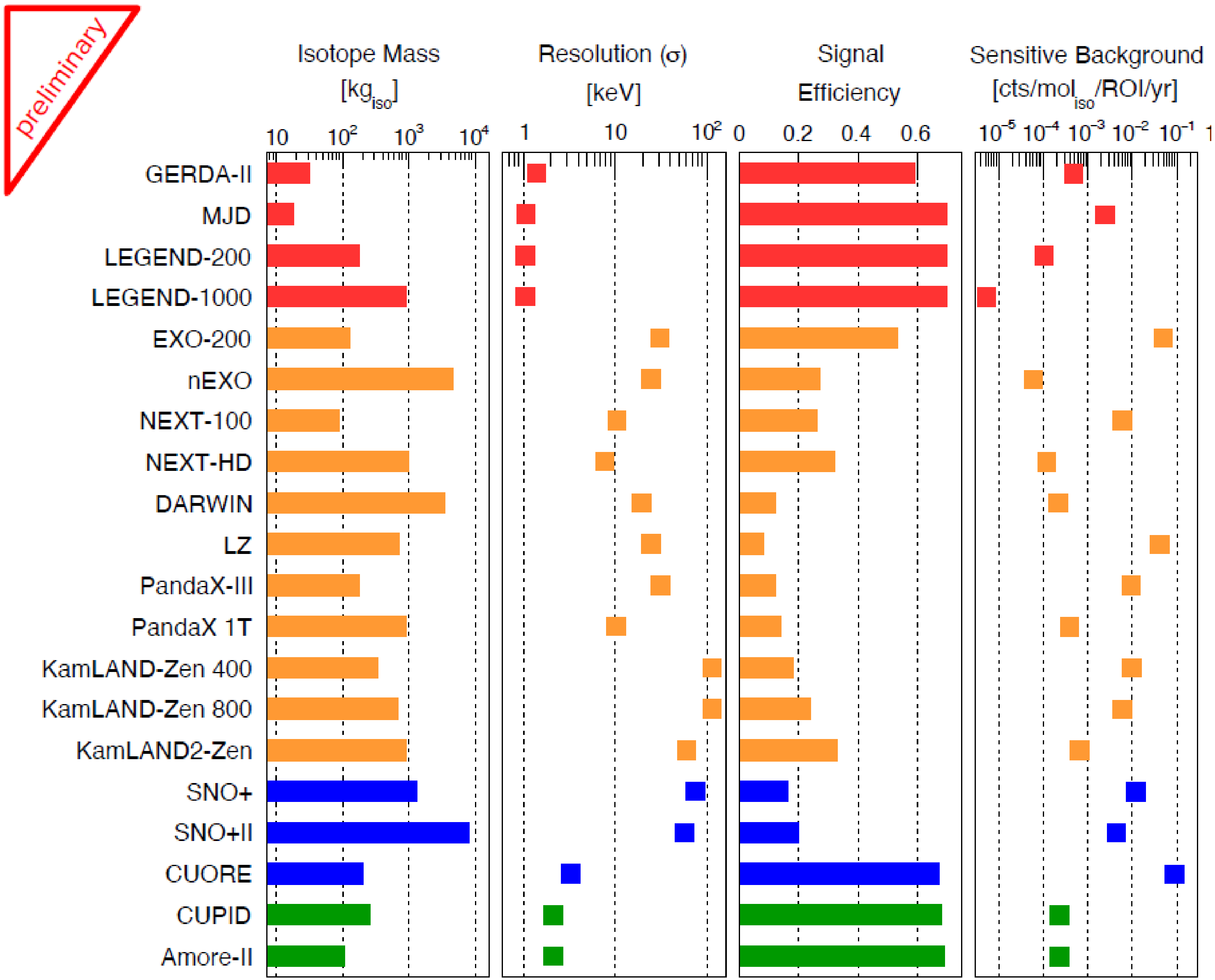






Future Neutrinoless Double-Beta Decay Experiments

Jason Detwiler, University of Washington
Neutrino 2020 - Virtual Meeting
1 July 2020

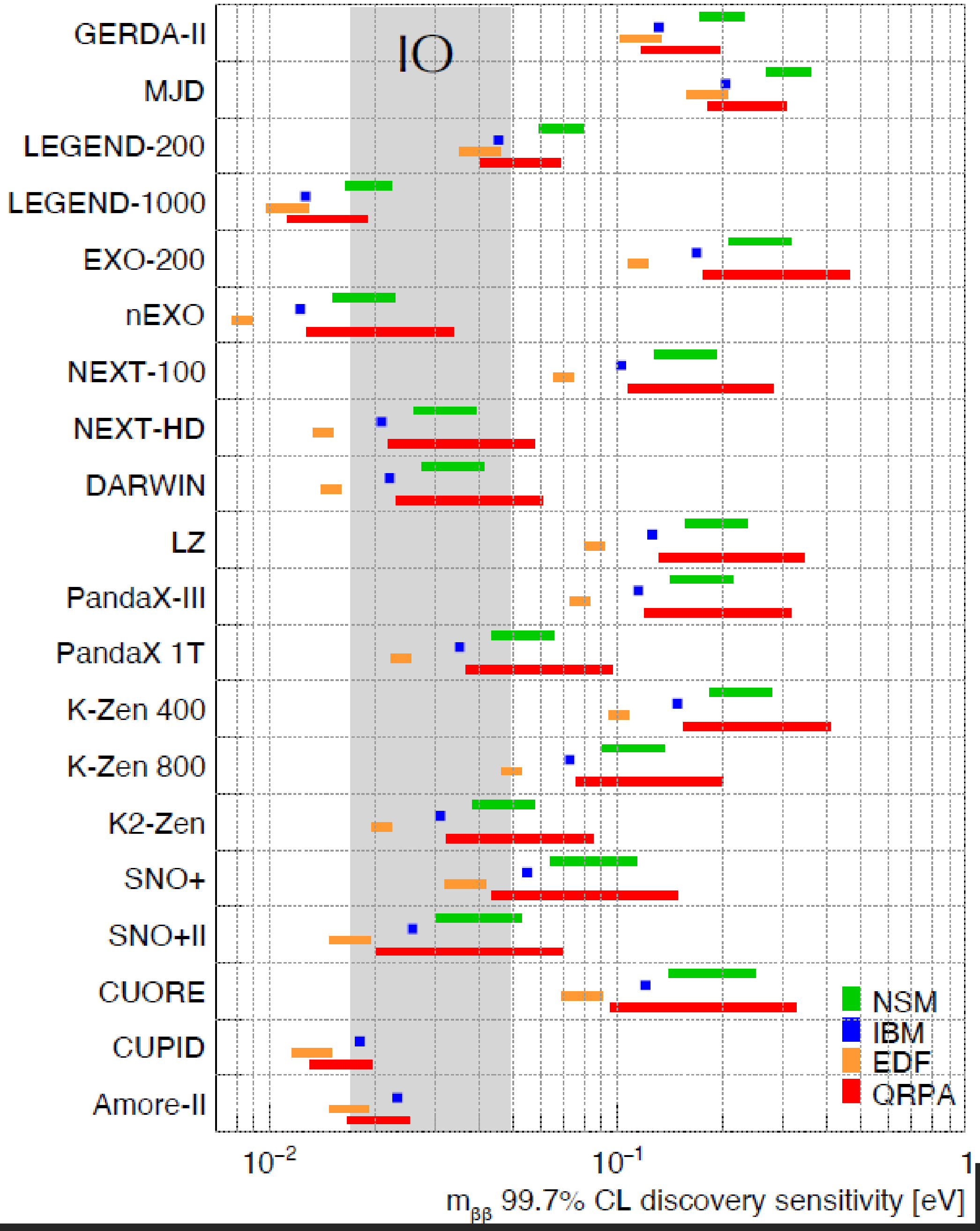




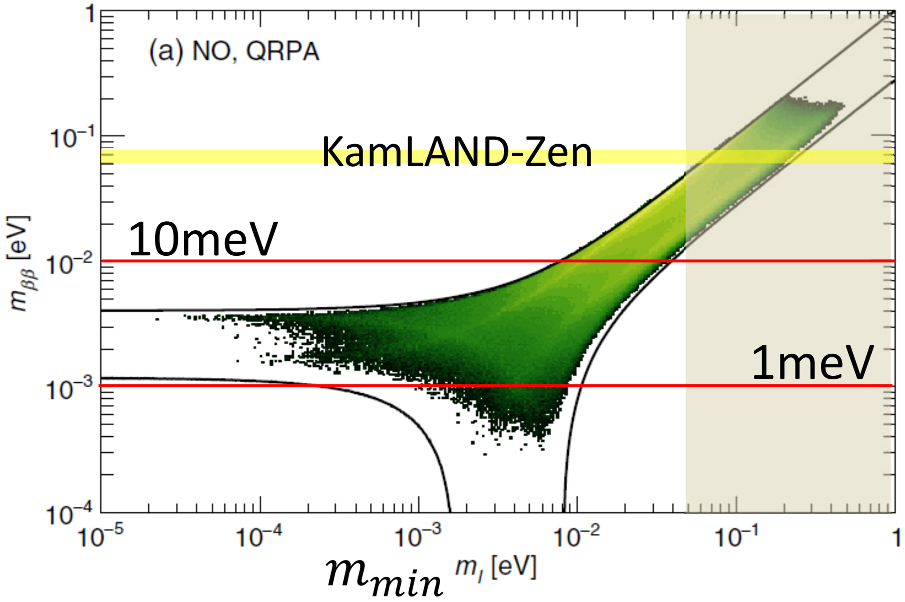
Agostini, Benato, JD, Menendez, Vissani

preliminary

Discovery Sensitivity Comparison



順質量順序



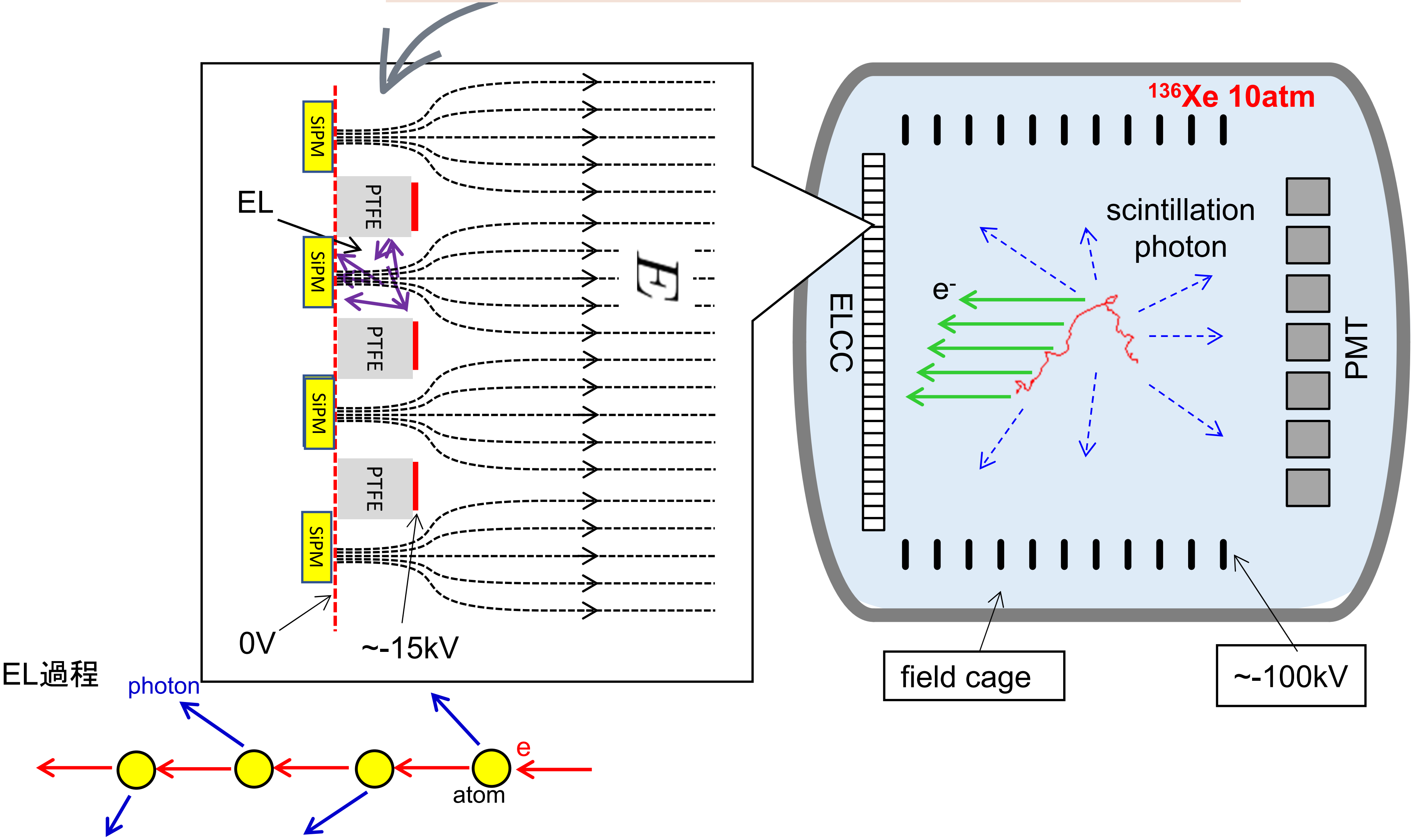
今の所、人類が到達できそう
なのは、10 meVくらいか？

J. Detwiler

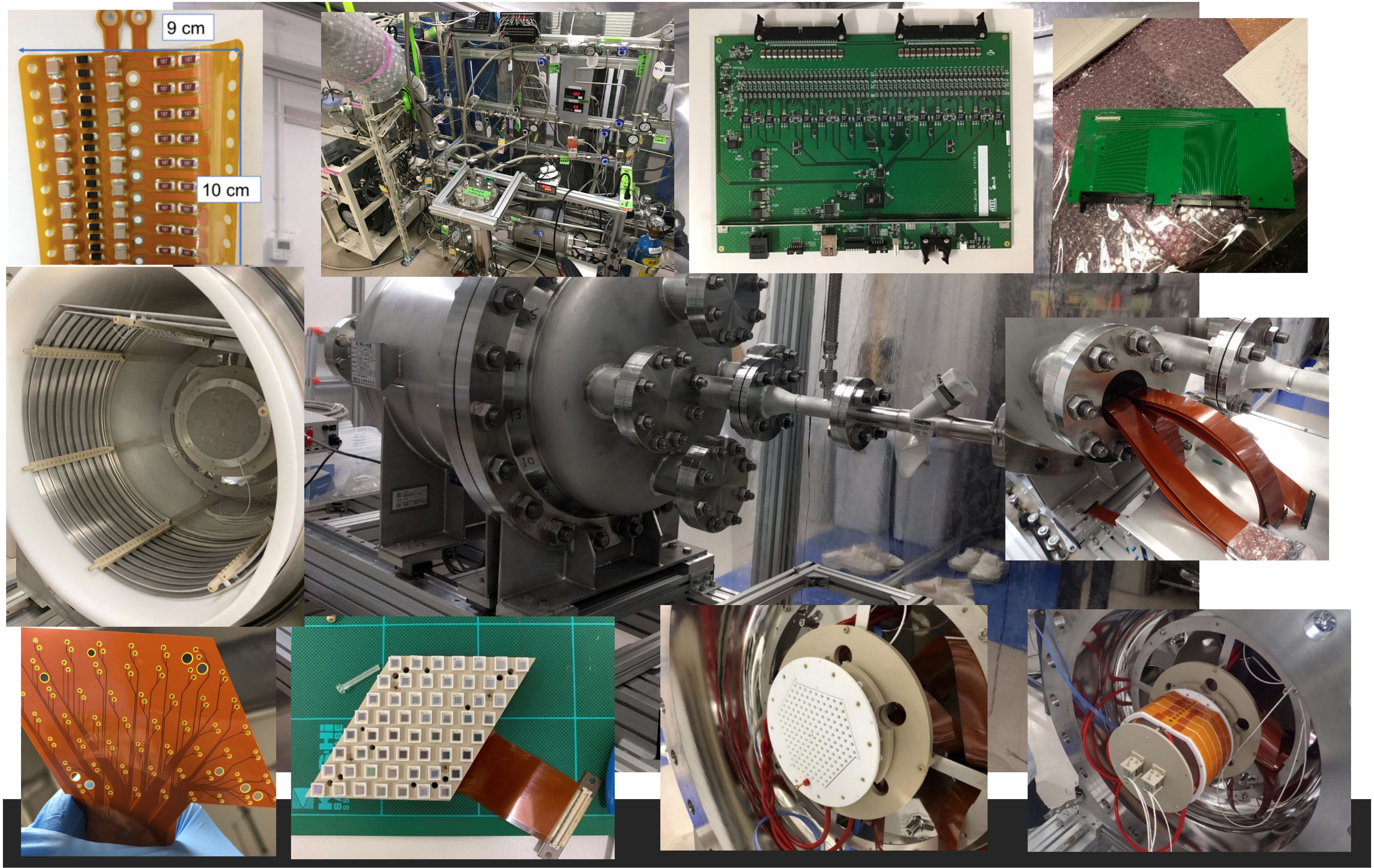
Agostini, Benato, JD, Menendez, Vissani

広告・やりがいのあるプロジェクトをお探しのあなたへ

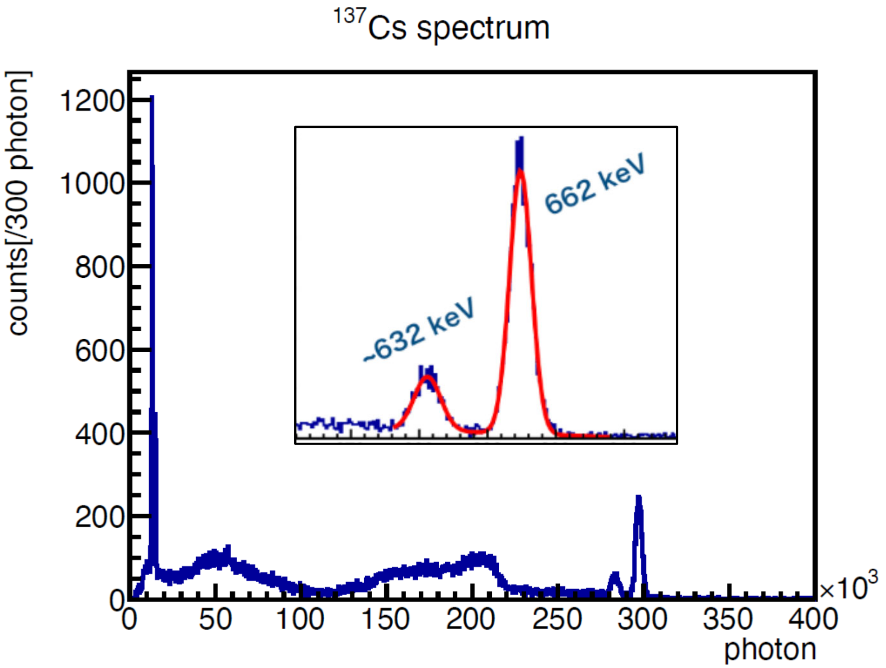
ELCC AXELグループ独自の読み出し機構
これにより、大きな検出器で高いエネルギー分解能を実現



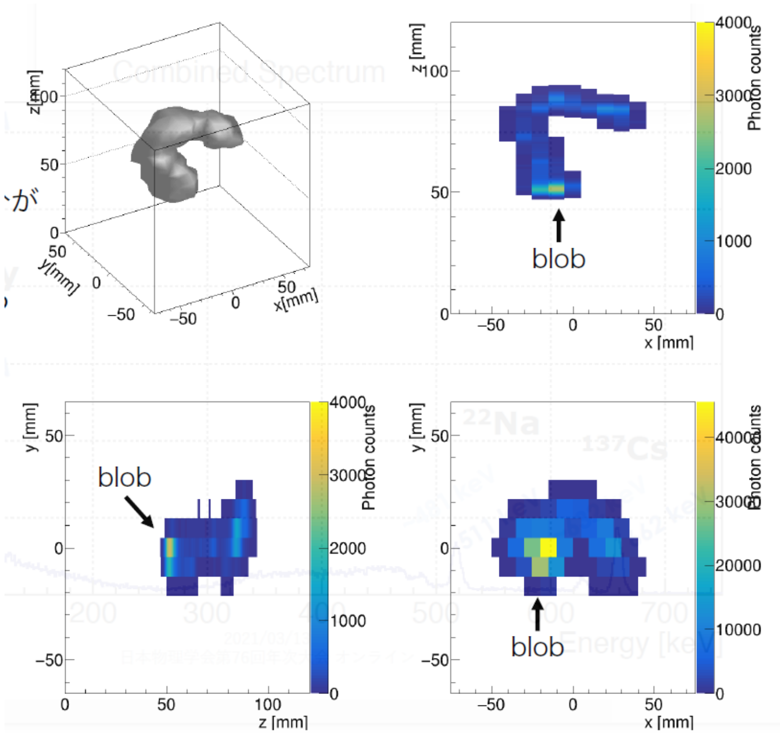
180L試作器



180L試作器 ⇒ 1,000L本機



Energy resolution(FWHM) 1.3%@662 keV
(0.67% expected at $Q_{\beta\beta}$)



662 keVのトラック

- 1,000L (Xe ~40kg) 検出器で$0\nu\beta\beta$探索へ

2023年 phase 1測定開始へ向けて、建設開始

数年で世界記録に到達？？？

1トン検出器への布石

まとめ

- すごく大事。GUTスケールの物理の可能性。
- $m_{\beta\beta}$ で1 meVまでは、とにかく頑張って探すべき

  ただし、現在の技術では10 meVを超えるのは厳しい
- 今の上限値のすぐ下にある可能性もある
- 見つかったら、次は、
  - 角度分布とか偏極度とか
  - 異なる核種
- AXEL、一緒にやりませんか？

  検出器本体以外にも、回路の開発などやることいろいろ