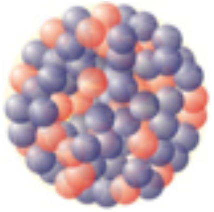
To Be or Not To Be:

Majorana Neutrinos, Grand Unification, and the Existence of the Universe

Jason Detwiler
Assistant Professor, University of Washington
Aug. 3, 2015

The Neutrino

Meitner and Hahn (1911):



^{210}Bi

("Radium E")

The Neutrino

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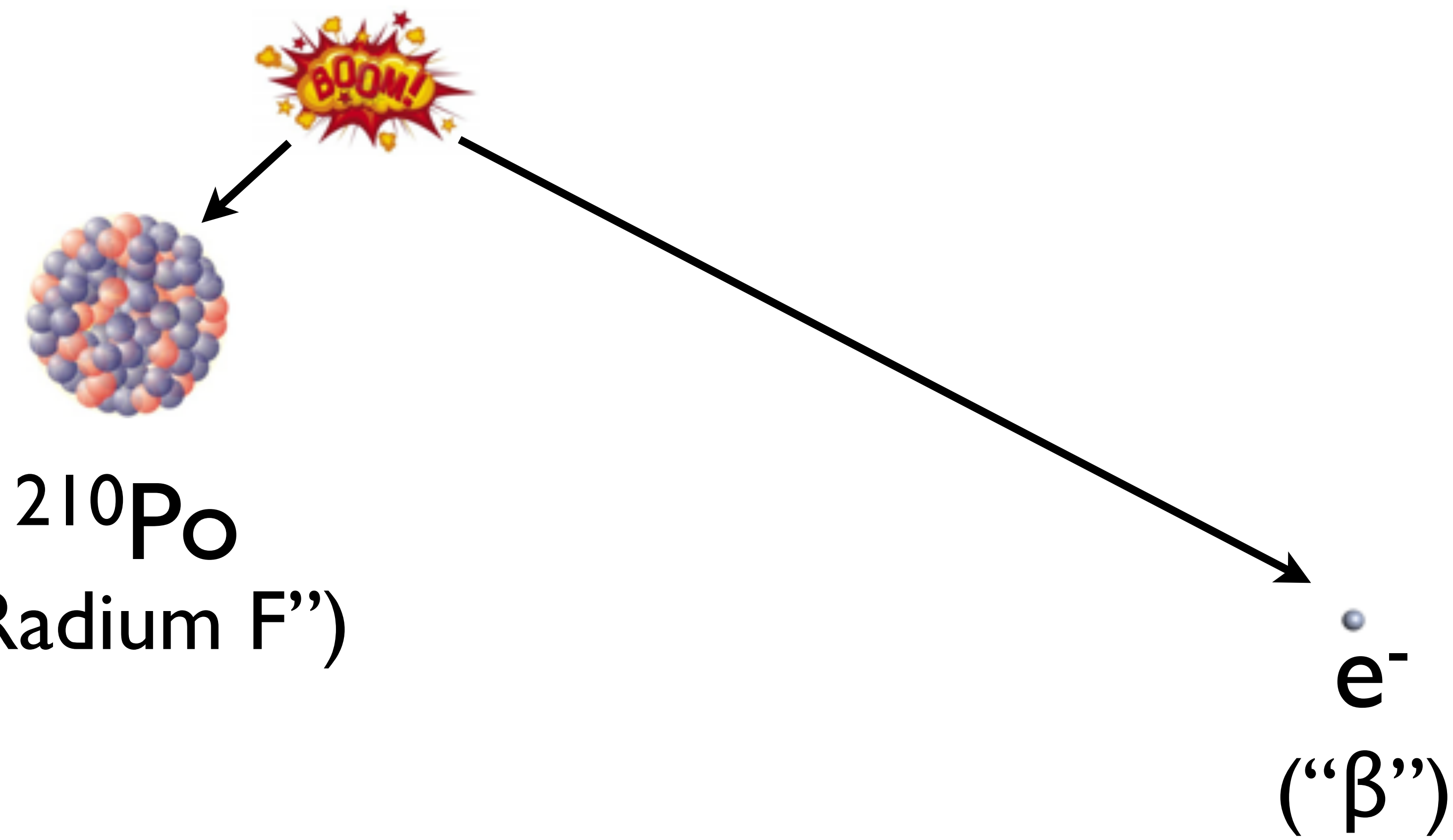

The Neutrino

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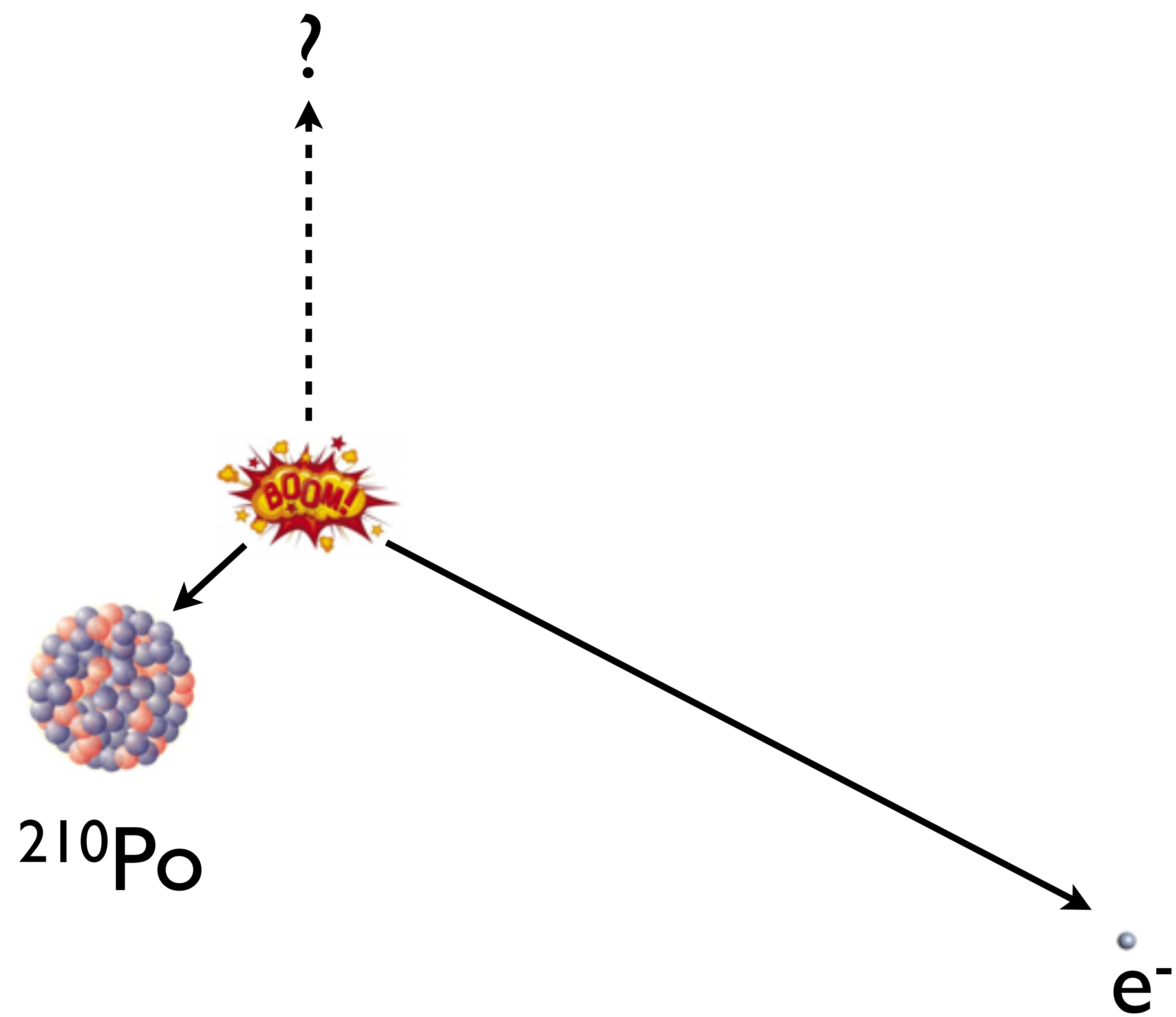
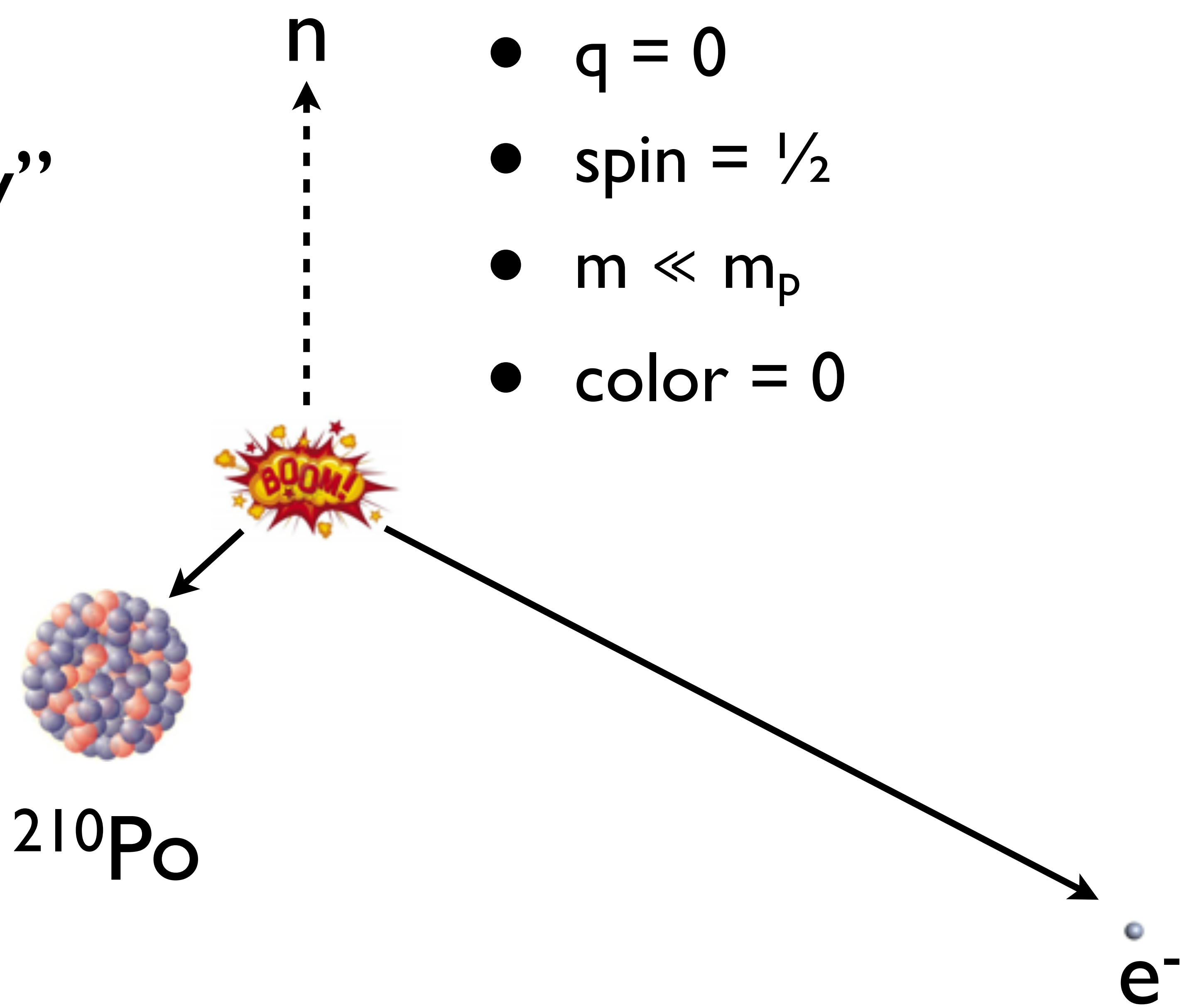


The Neutrino

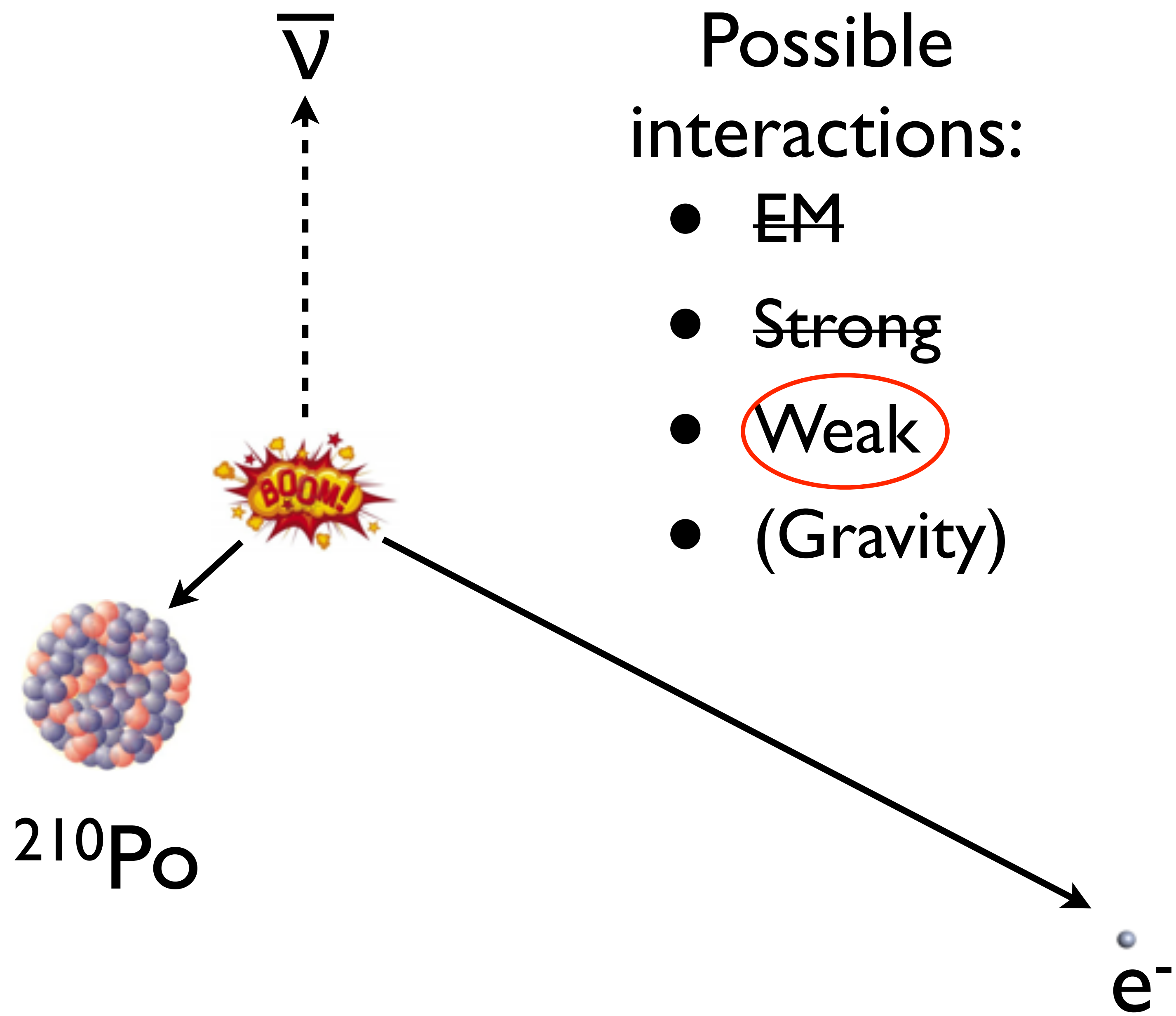
Wolfgang Pauli's
"desparate remedy"
(1931):

- $q = 0$
- spin = ½
- $m \ll m_p$
- color = 0



The Neutrino

Enrico Fermi (1934):
"Little neutral one"



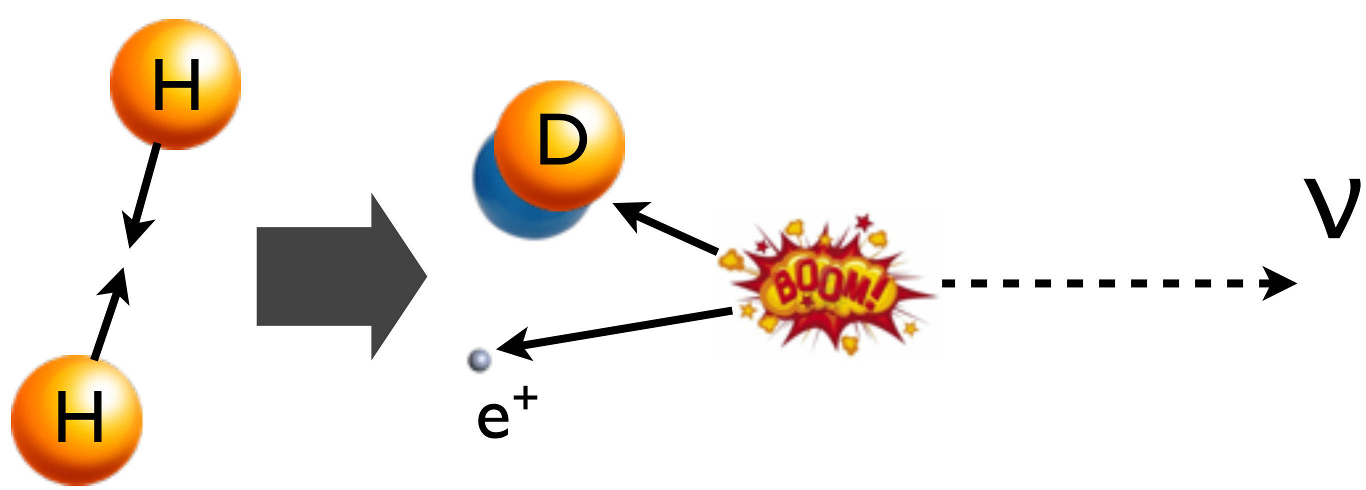
Possible interactions:

- ~~EM~~
- ~~Strong~~
- Weak
- (Gravity)

Neutrinos and Antineutrinos

β^- decay

H fusion



Neutrinos and Antineutrinos

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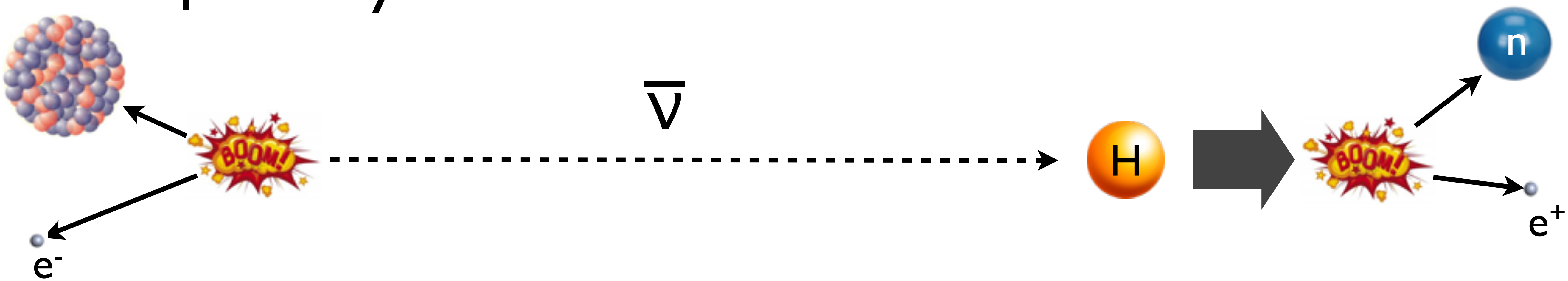

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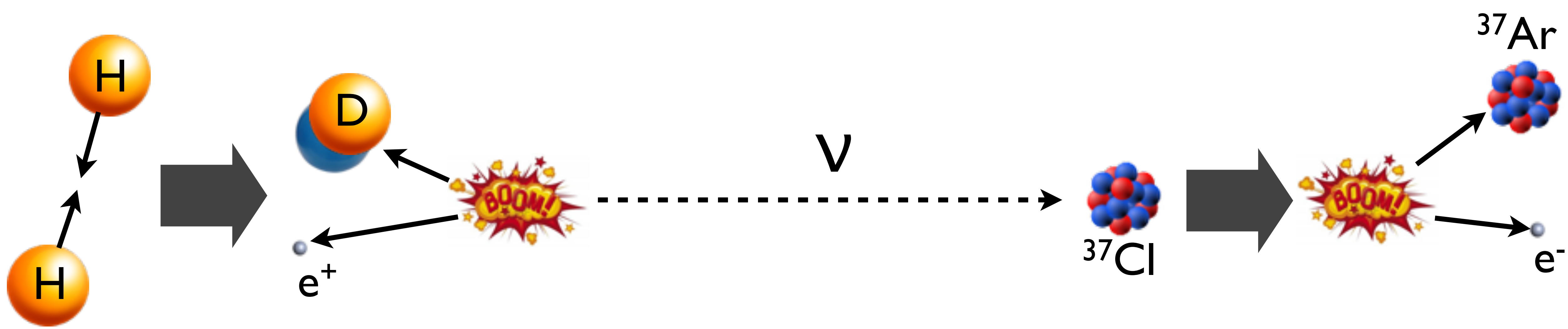
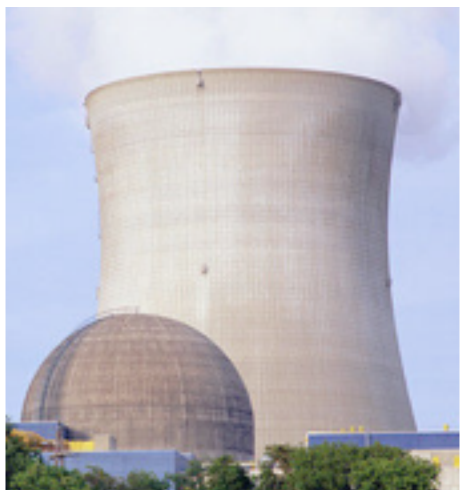


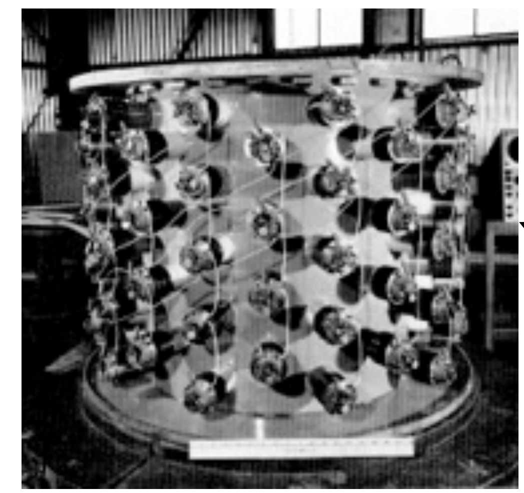
Neutrinos and Antineutrinos

Nuclear Reactor



$\bar{\nu}$

Scintillator (C_xH_y)



PMTs

The Sun

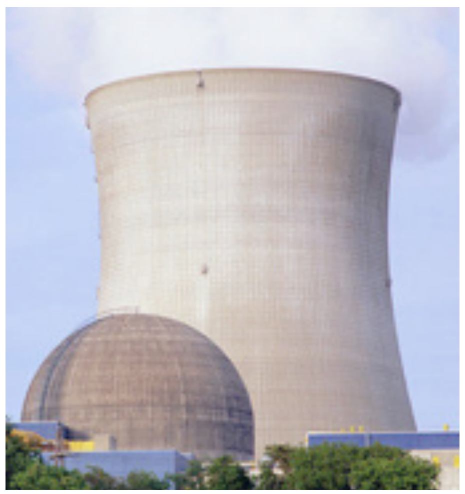
ν

Cleaning fluid (Cl)

+ Ar detector

Neutrinos and Antineutrinos

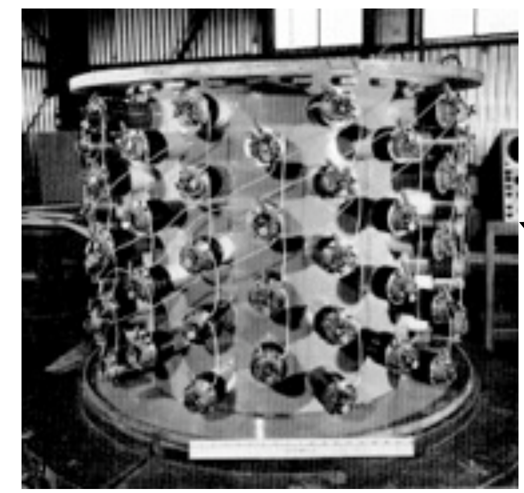
Nuclear Reactor



$\bar{\nu}$

Cowan and Reines (1956)

Scintillator (C_xH_y)



PMTs

The Sun

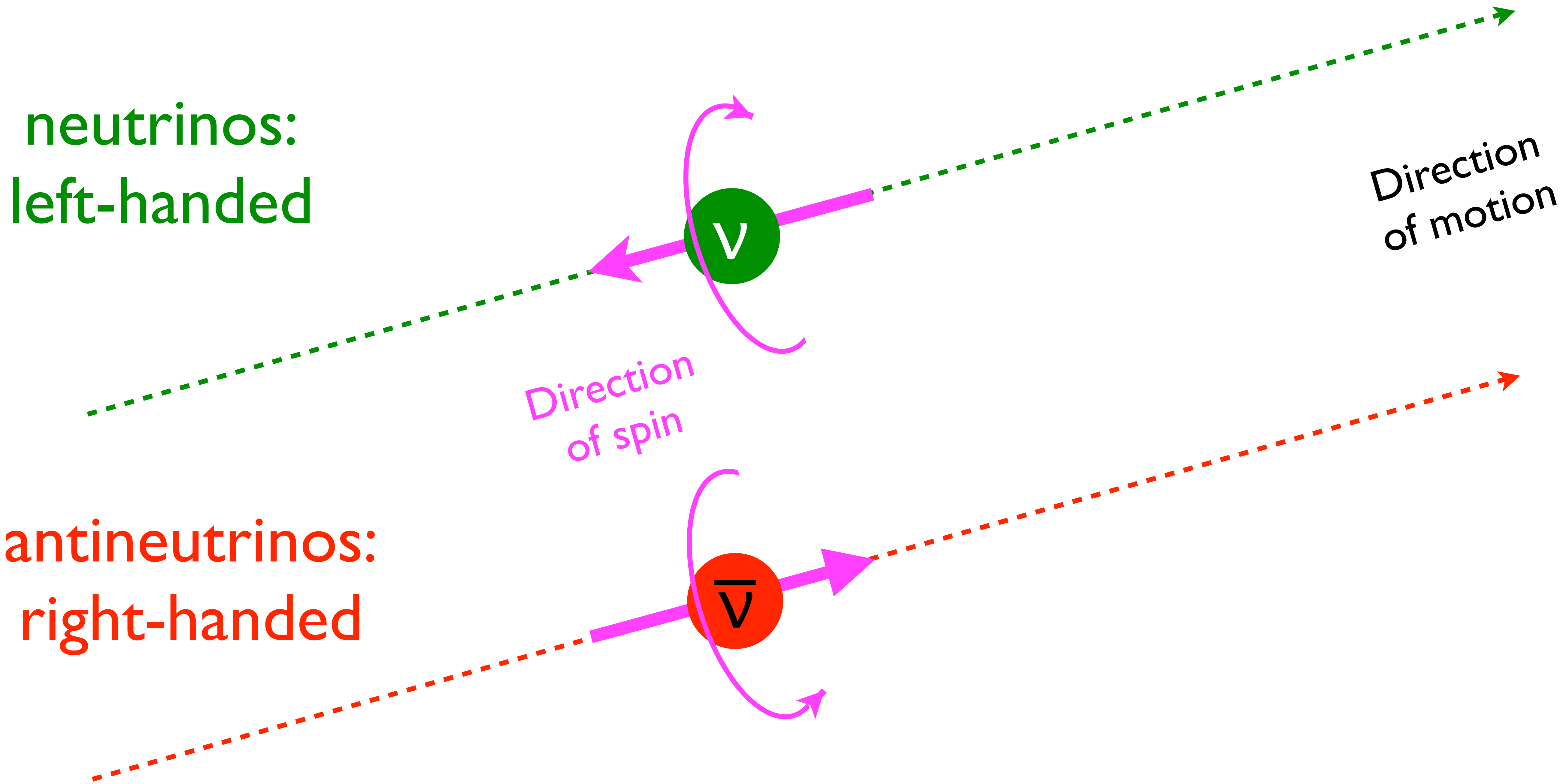
ν

Ray Davis Jr. (1964)

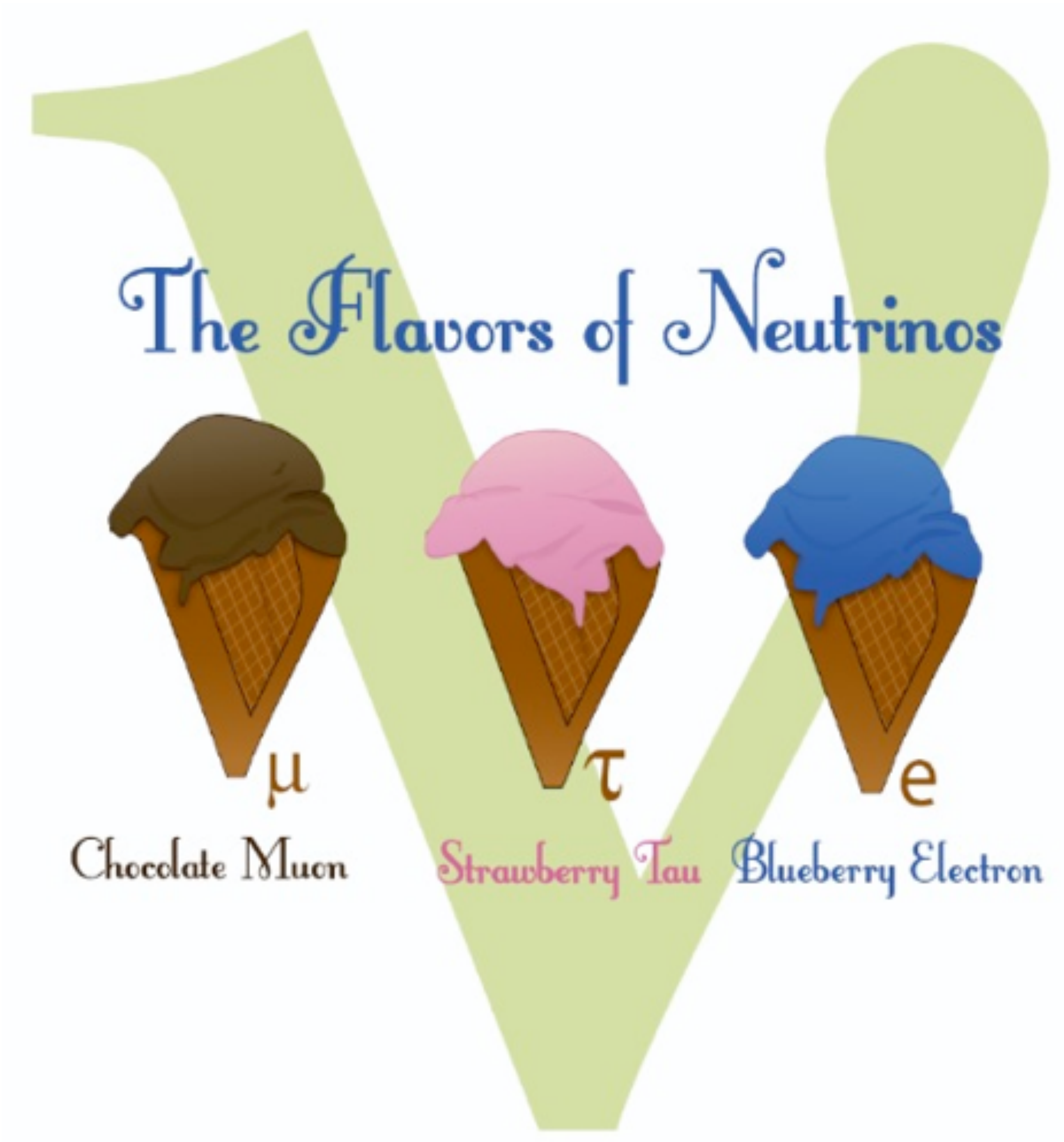
Cleaning fluid (Cl)

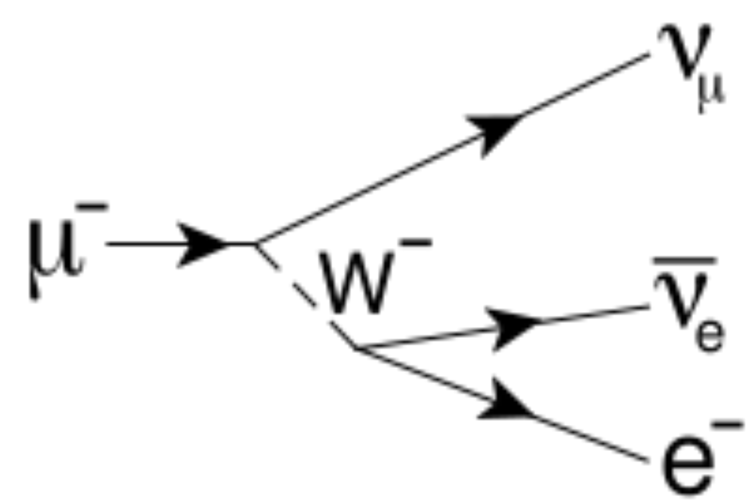
+ Ar detector

Neutrino Handedness

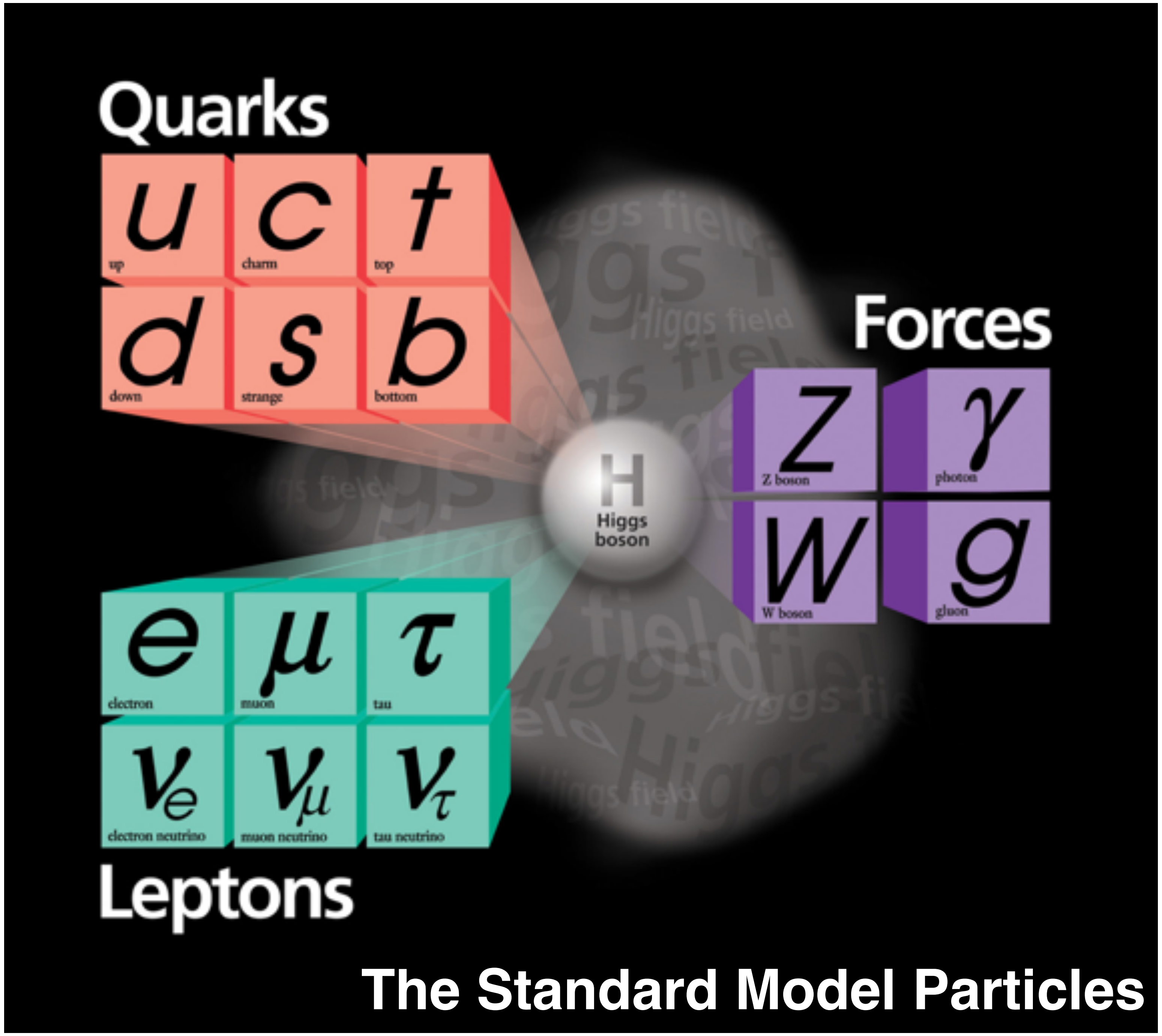


Neutrino Flavors





Standard Model Neutrinos



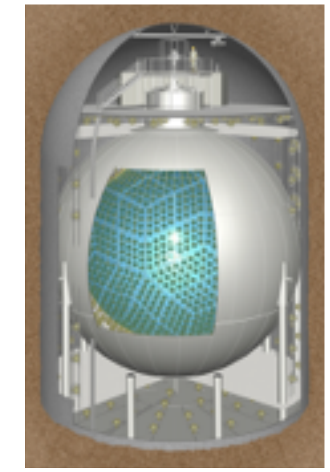
- $q = 0$
- color = 0
- spin = ½
- 3 flavors (e, μ, τ)
- left-handed ν, right-handed $\bar{\nu}$
- $m_\nu < 2$ eV (m_e / 250000)

$m_\nu = 0$?

Credit: Fermilab

Neutrino Oscillation

$\bar{\nu}_e$ partially $\bar{\nu}_x$ $\bar{\nu}_e$



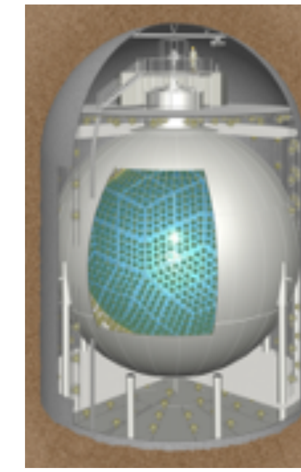
*KamLAND Collaboration, Phys. Rev. D **83**, 052002 (2011).*

Neutrino Oscillation

$\bar{\nu}_e = U_{e1}\bar{\nu}_1 + U_{e2}\bar{\nu}_2 + U_{e3}\bar{\nu}_3$

$\bar{\nu}_e$ partially $\bar{\nu}_x$ $\bar{\nu}_e$

$|m_2^2 - m_1^2|$



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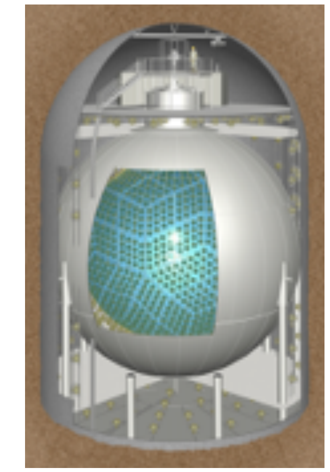

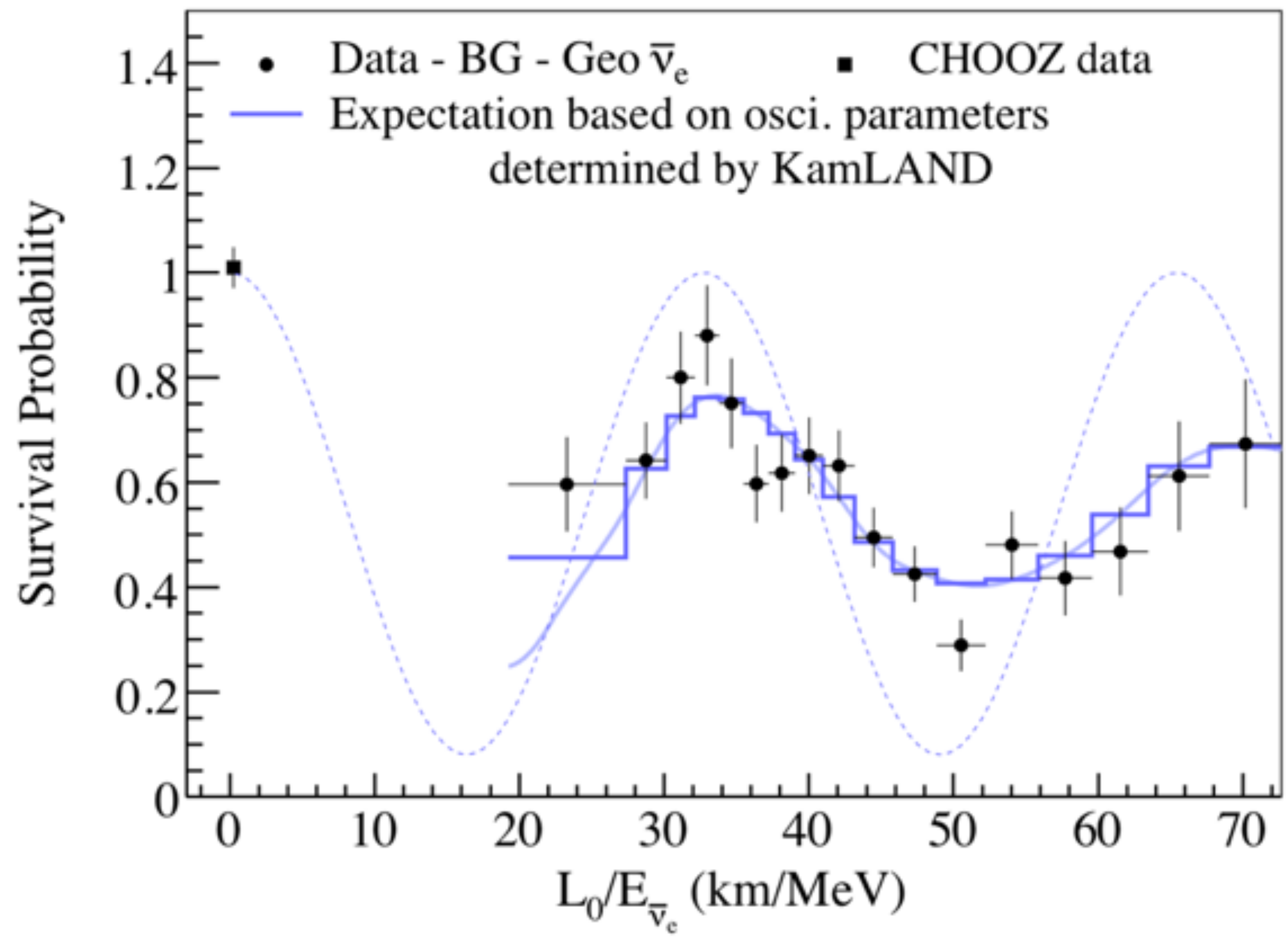

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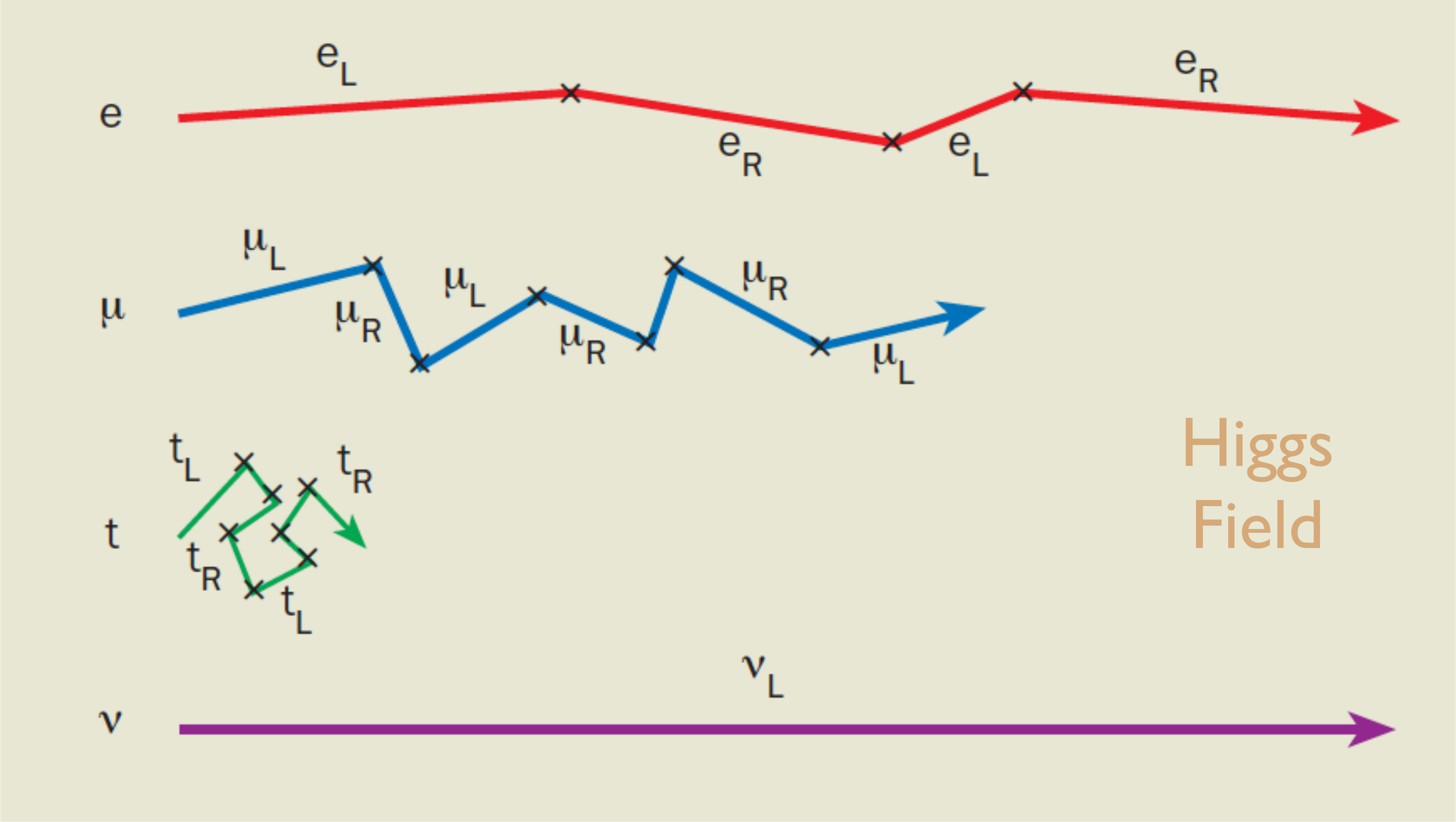
Incorporating ν Mass



H. Murayama, Physics World (May 2002).

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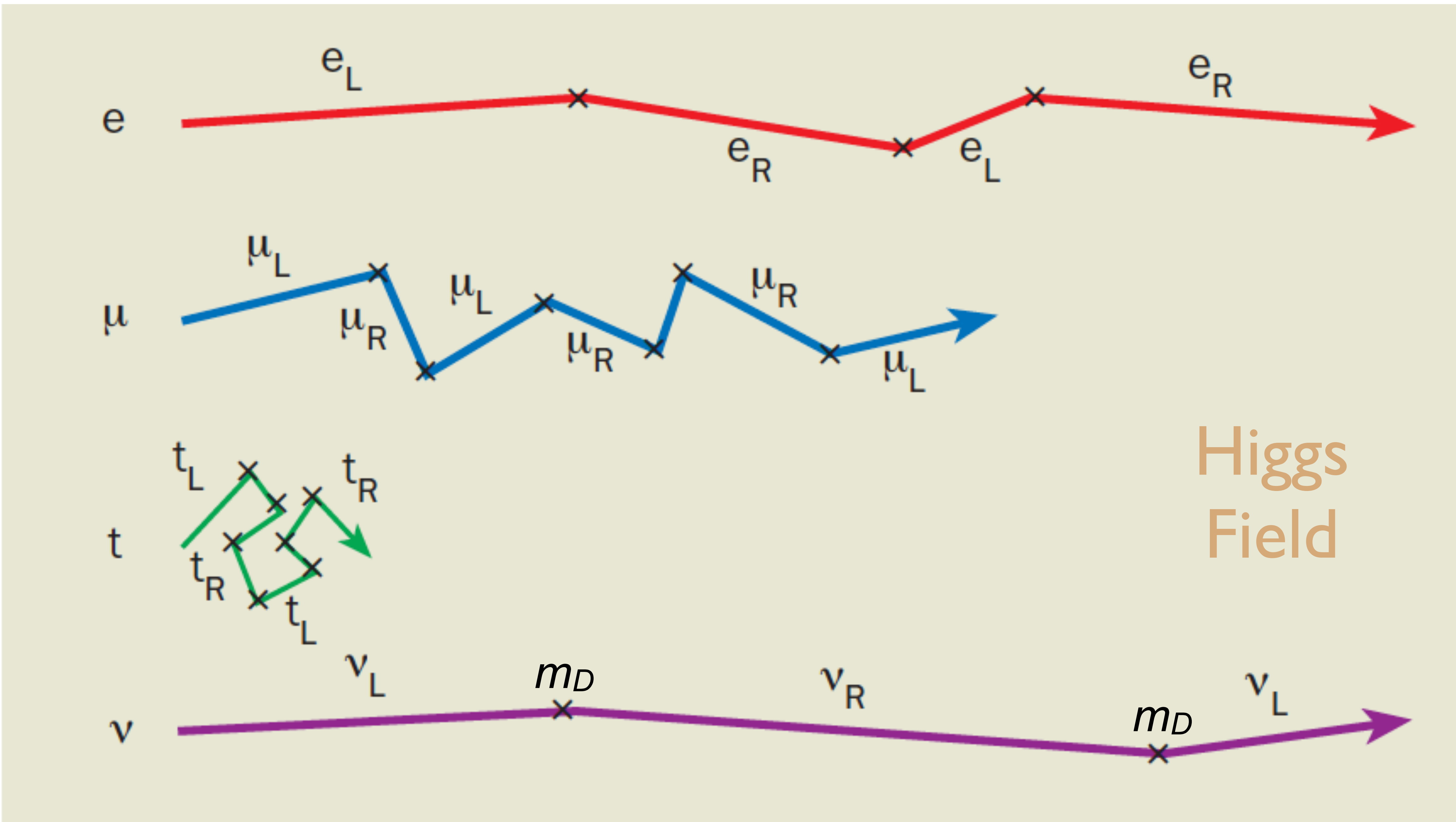

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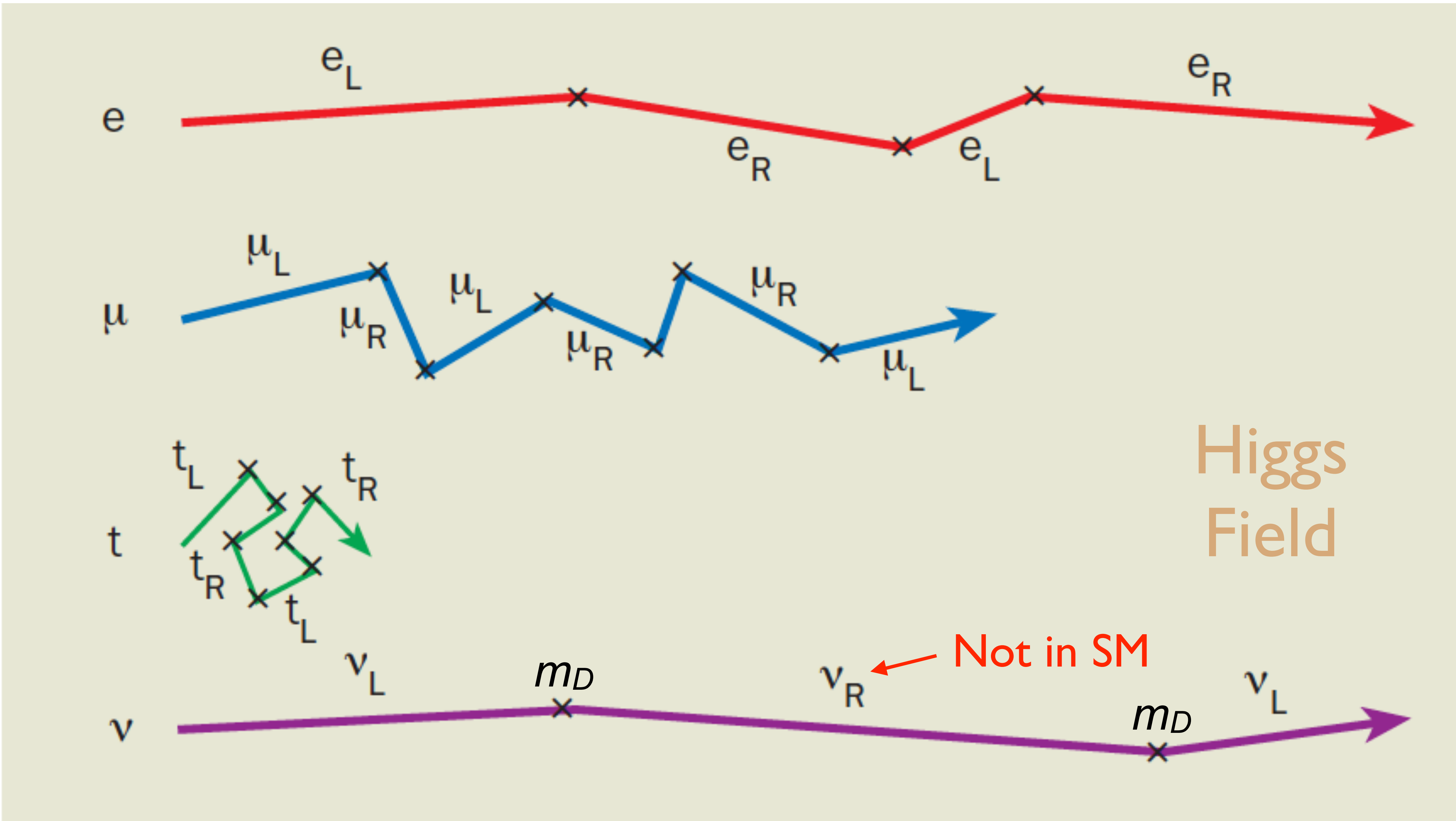

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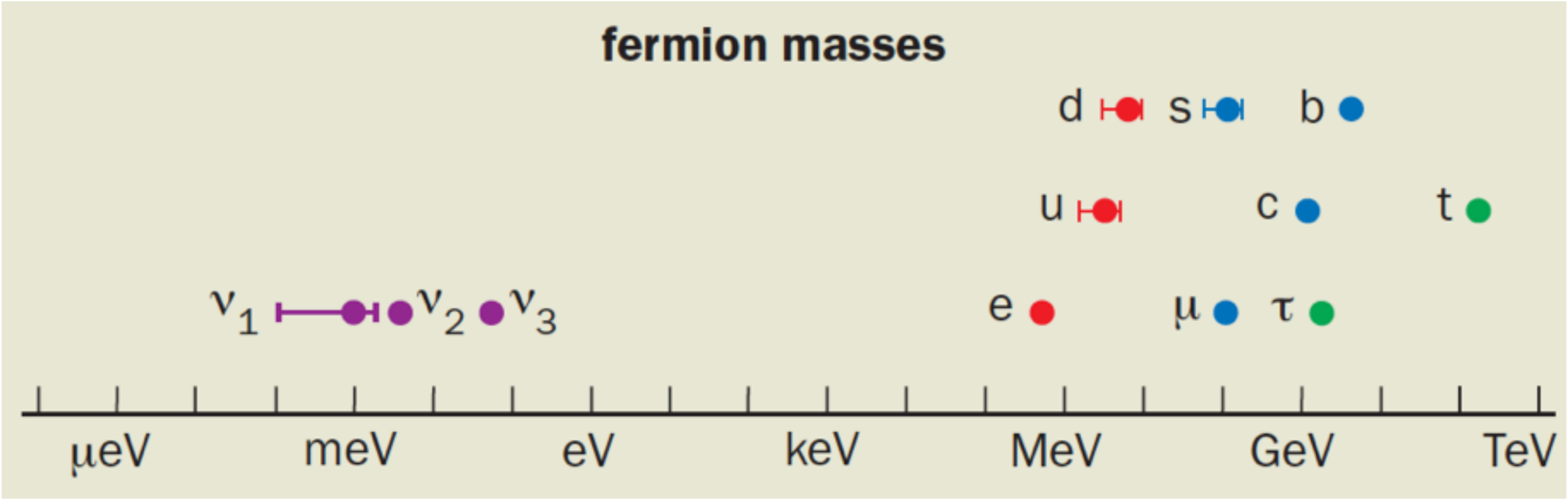

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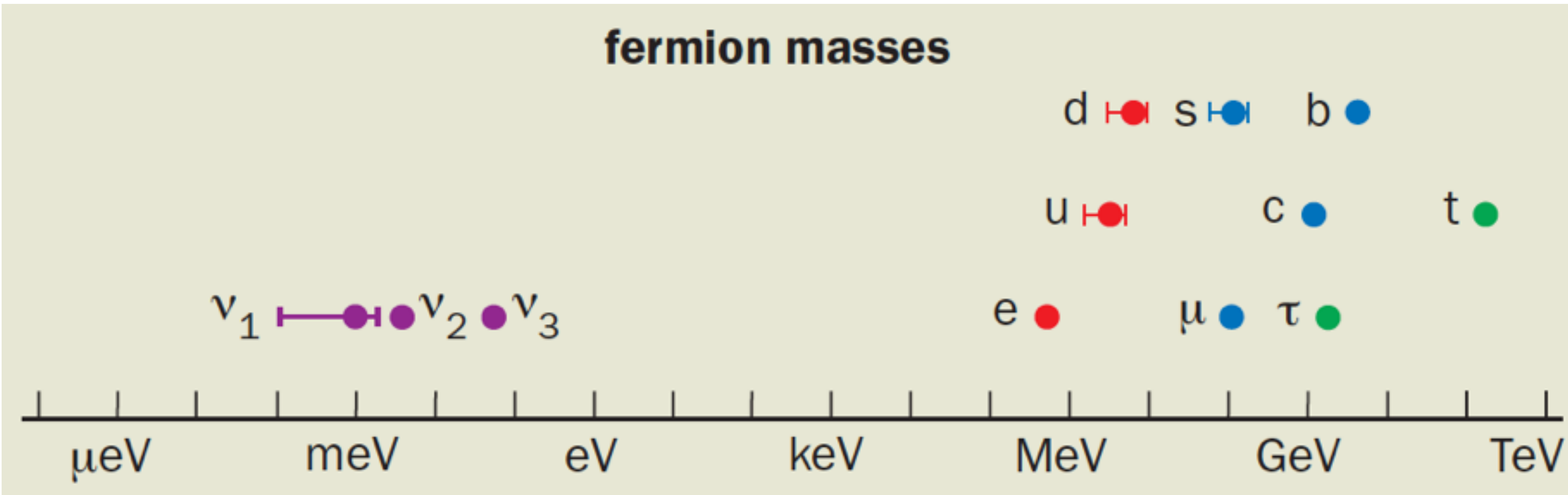
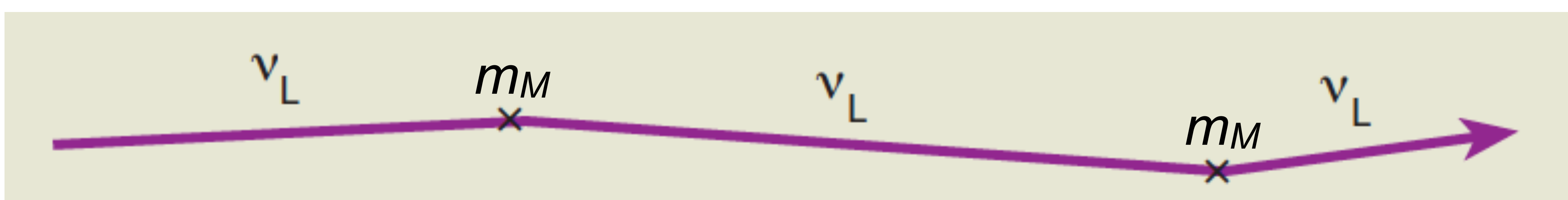


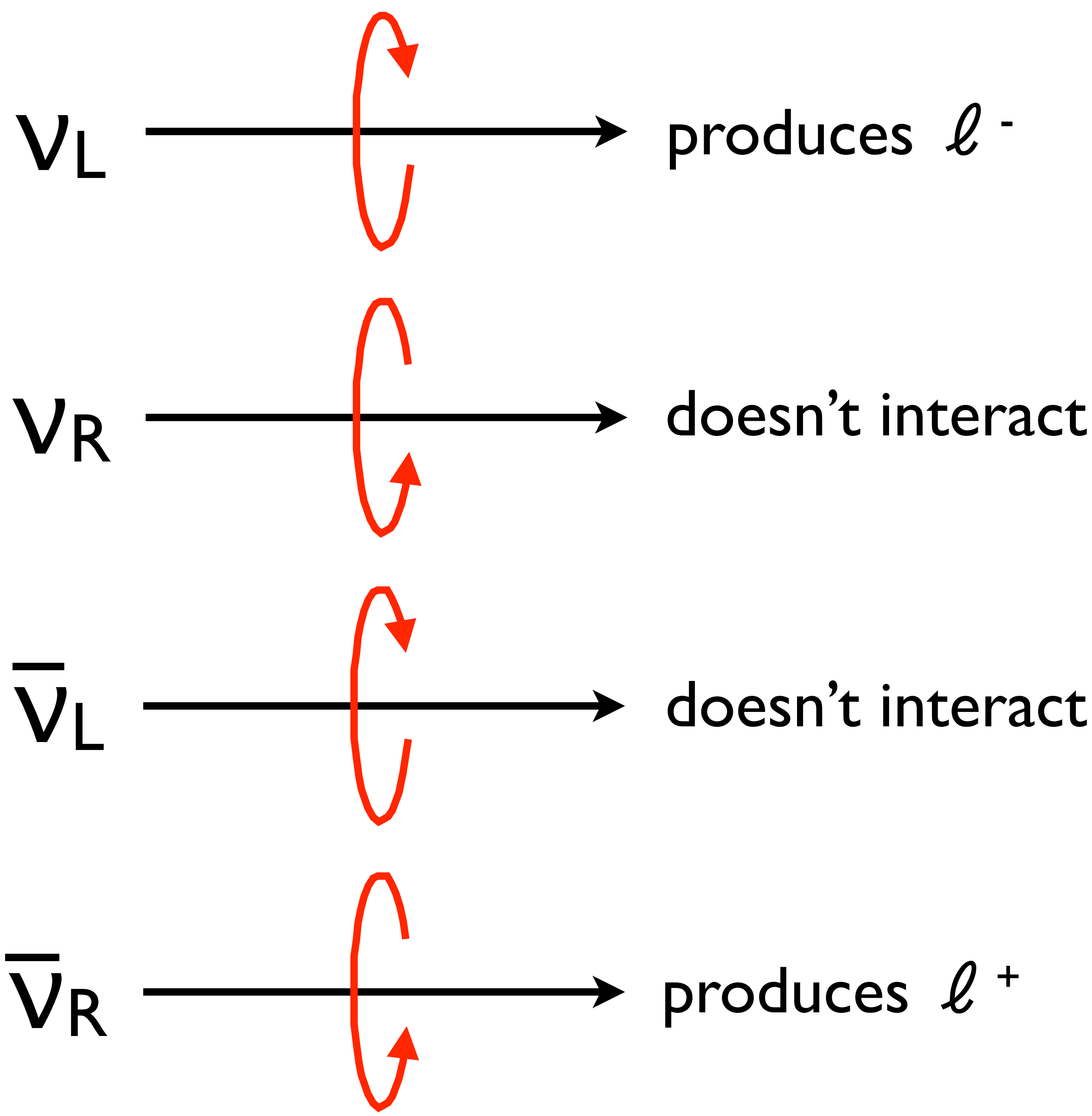
Ettore Majorana



E. Majorana, Il Nuovo Cimento **14**, 171 (1937).
English translation: Soryushiron Kenkyu **63**, 149 (1981).

Dirac vs Majorana ν

Dirac ($\nu \neq \bar{\nu}$)



Following B. Kayser.
See also: Jentschura and Wundt, J. Phys. G **41**, 075201 (2014).

Dirac vs Majorana ν

Dirac ($\nu \neq \bar{\nu}$)

ν_L → produces ℓ^-

ν_R → doesn't interact

$\bar{\nu}_L$ → doesn't interact

$\bar{\nu}_R$ → produces ℓ^+

Majorana ($\nu = \bar{\nu}$)

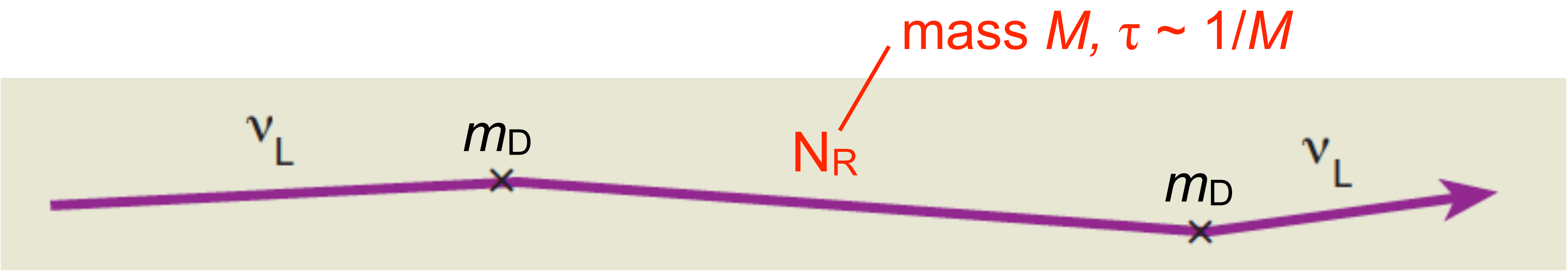
$\overset{(-)}{\nu}_L$ → produces ℓ^-

$\overset{(-)}{\nu}_R$ → produces ℓ^+

- Requires Q = -Q = 0
- Implies L is not conserved

Following B. Kayser.
See also: Jentschura and Wundt, J. Phys. G **41**, 075201 (2014).

Seesaw Mechanism



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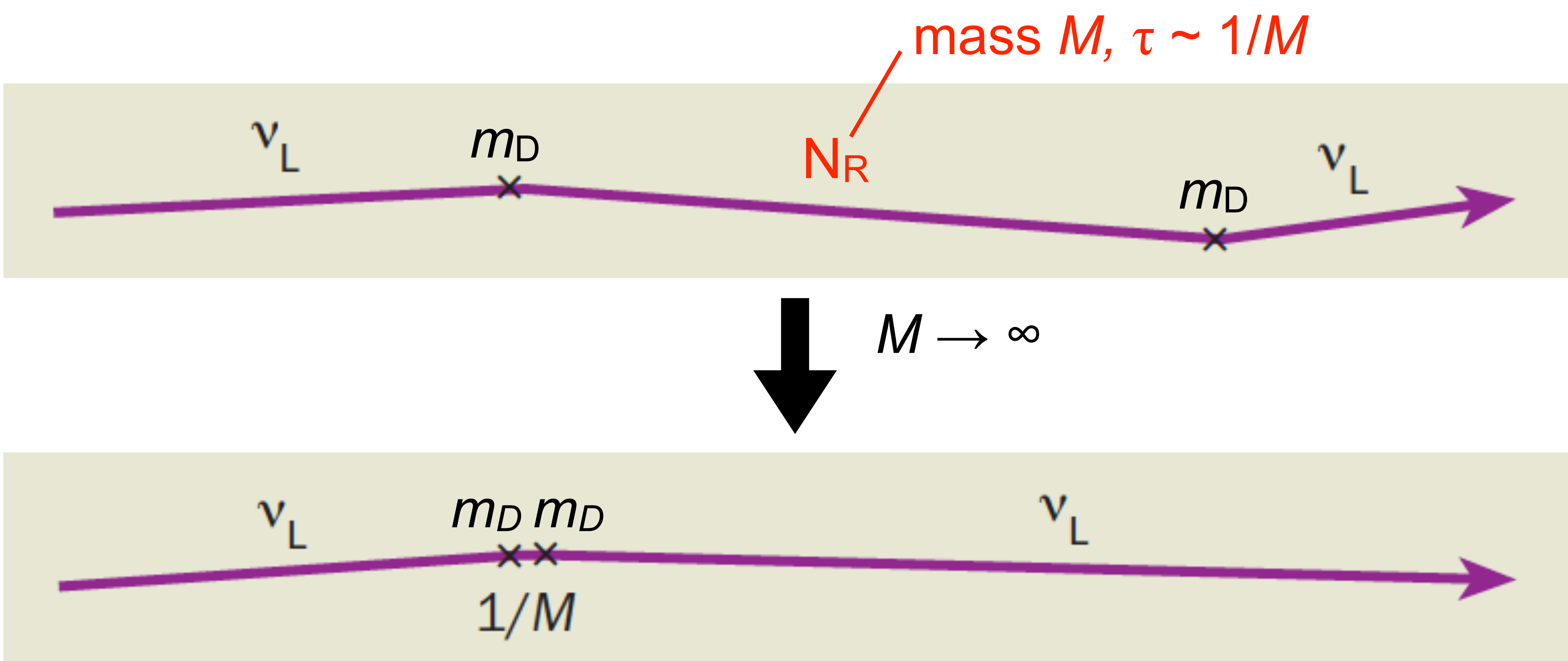

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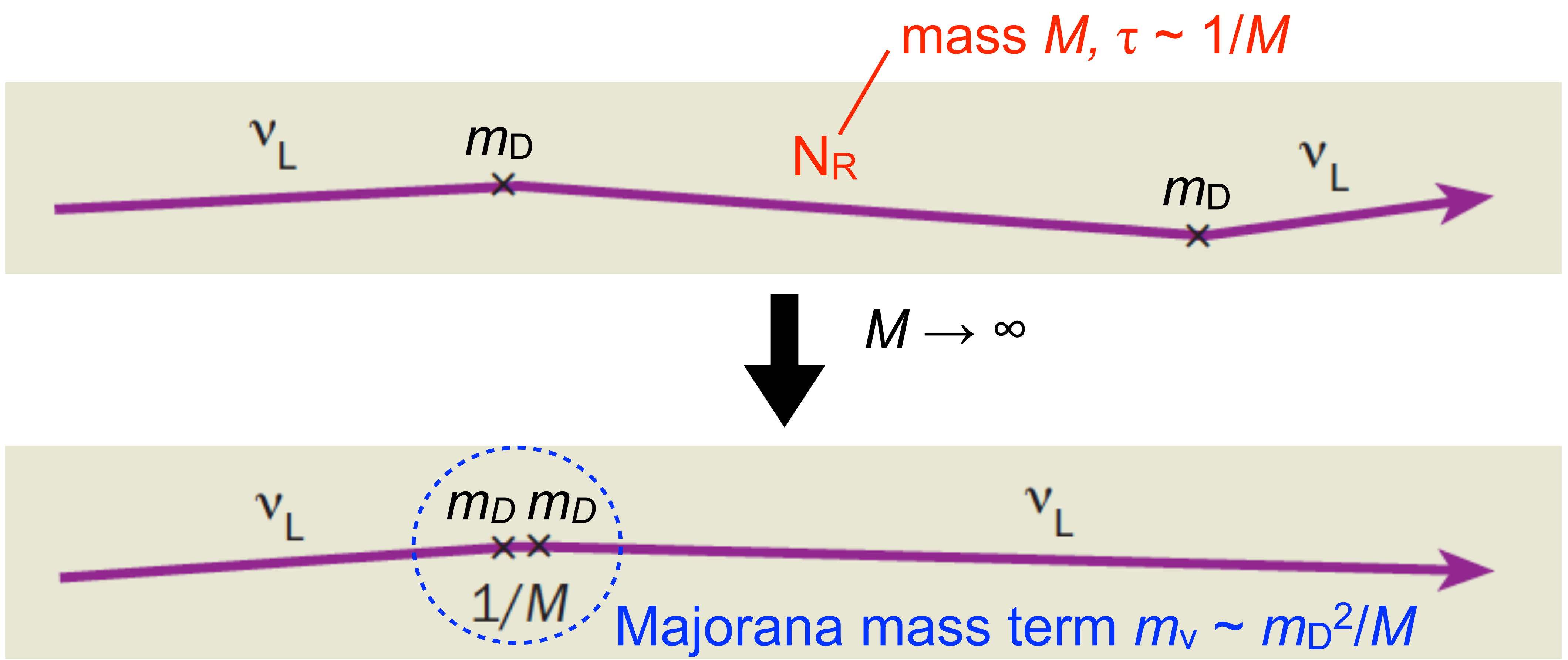

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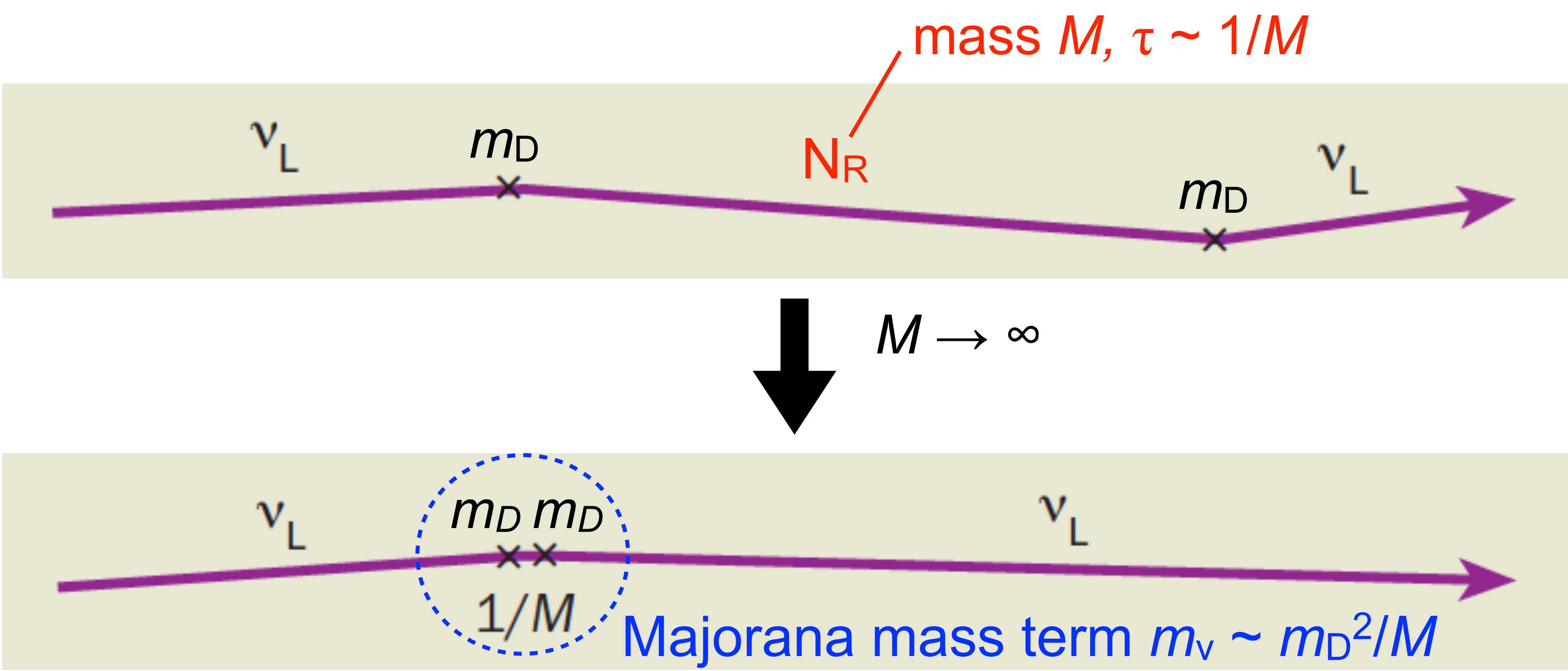
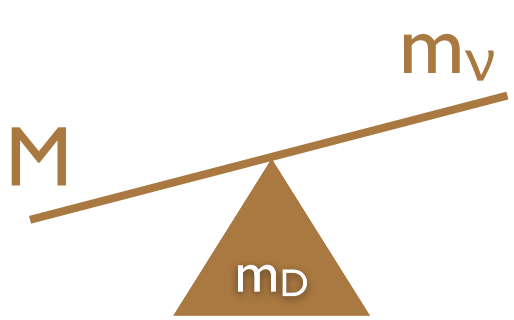
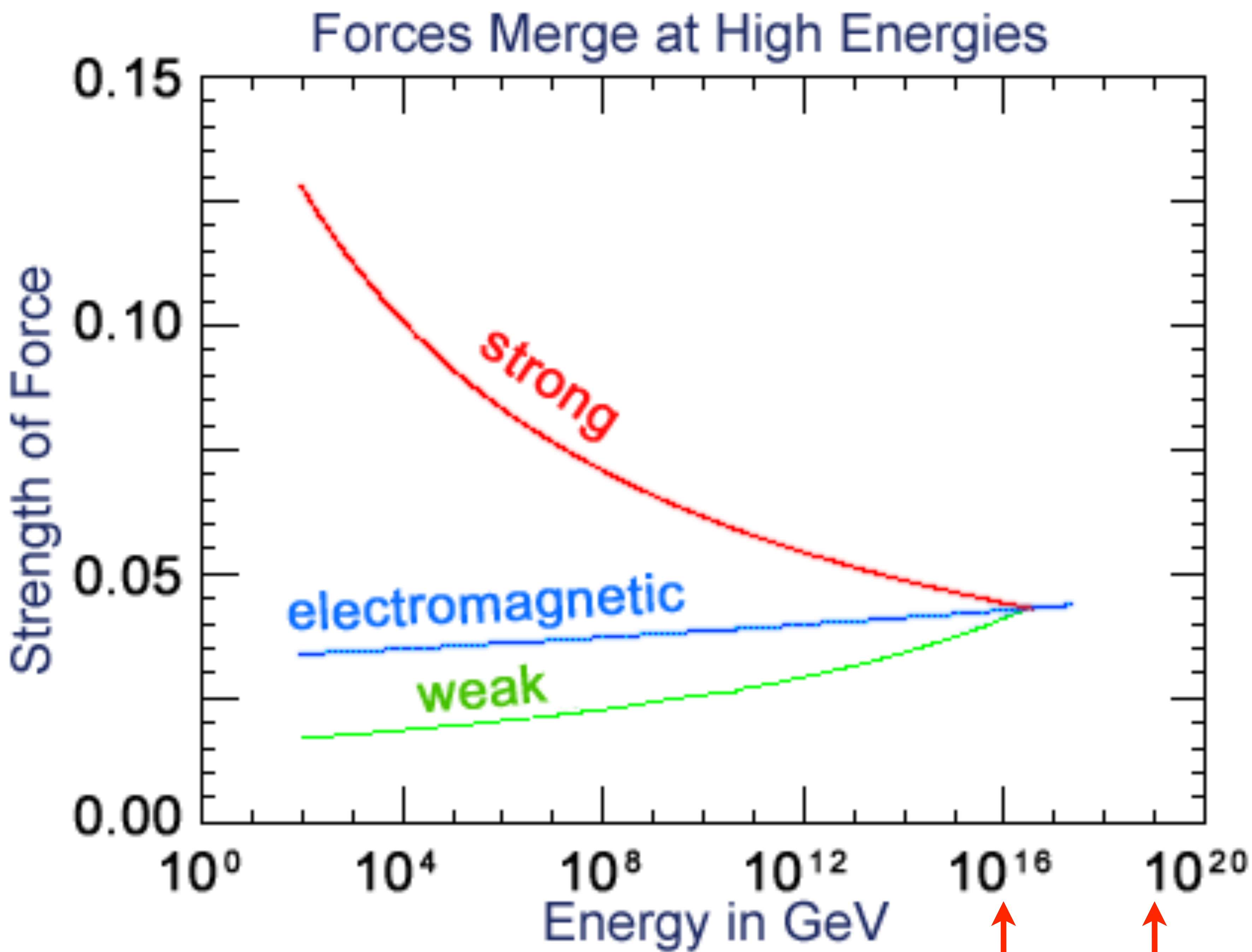




for m_D ~ GeV-TeV:

m_ν ~ meV-eV ↔ M ~ 10^{16}-10^{19} GeV

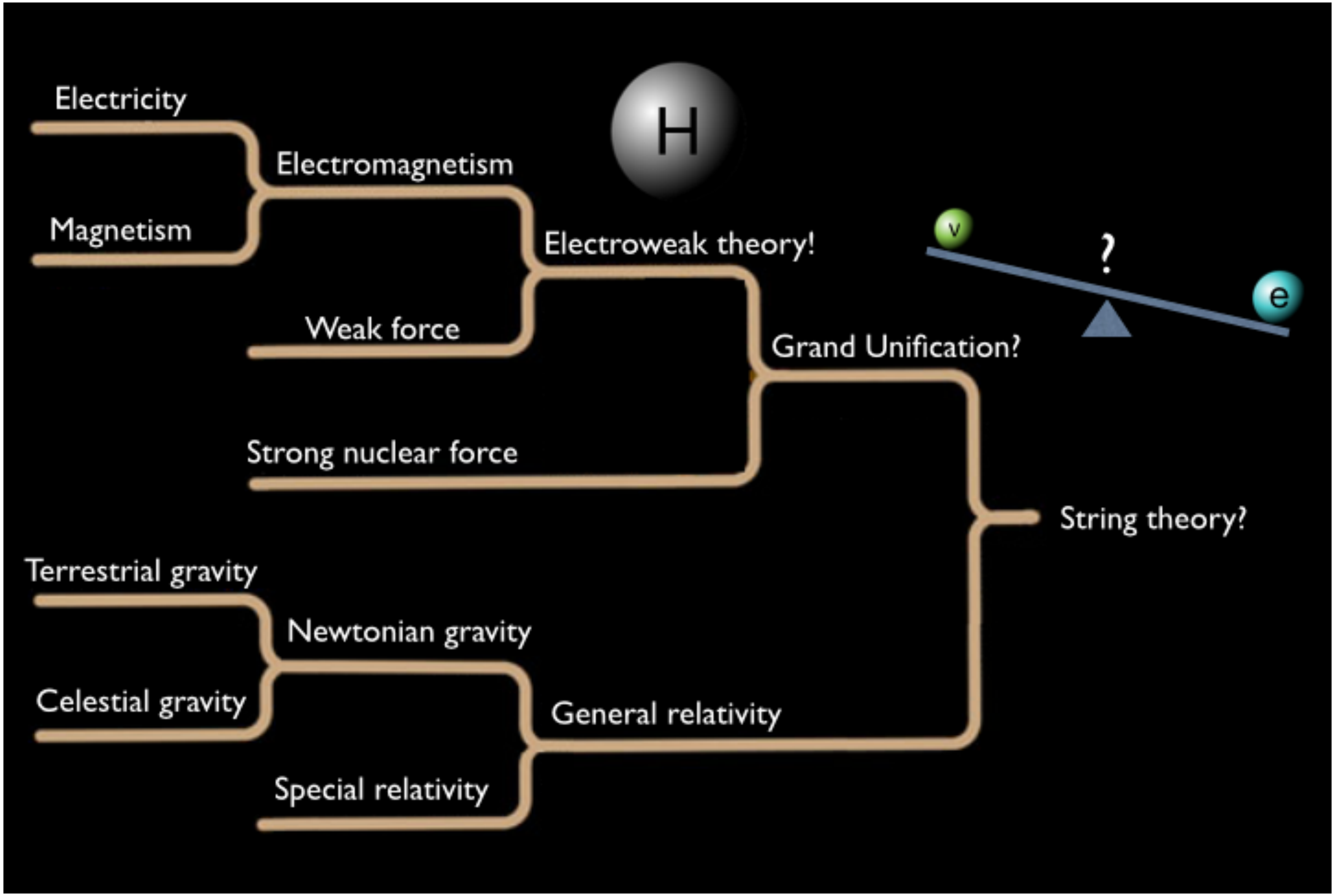
Grand Unification



GUT scale

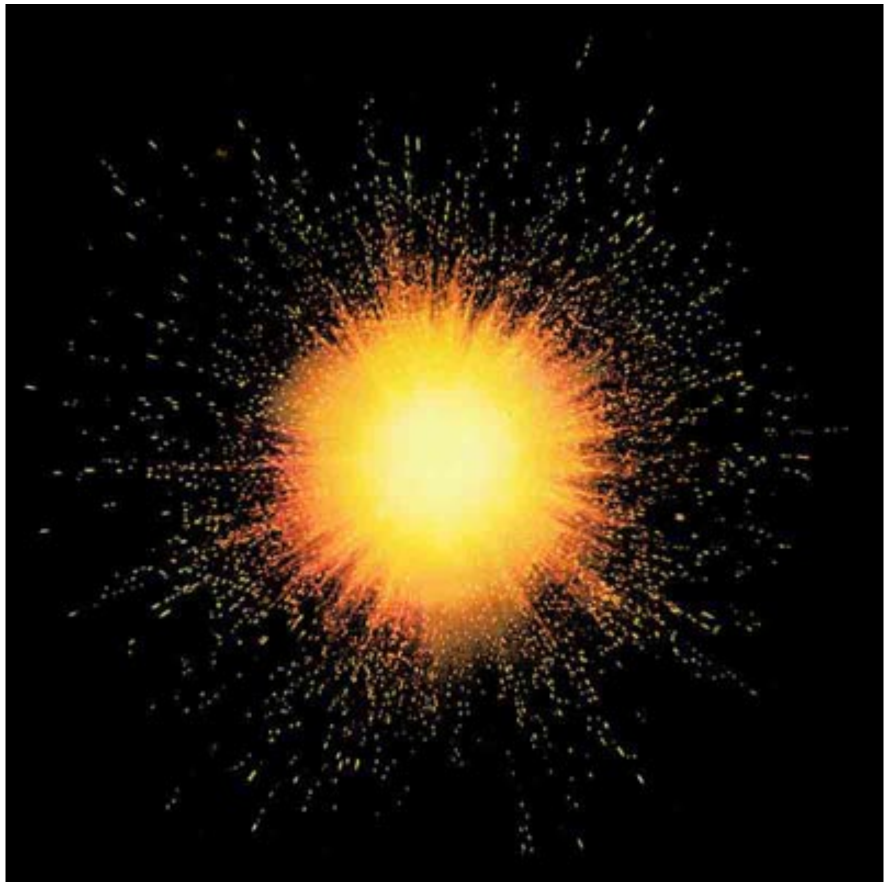
Plank scale $= \sqrt{\hbar c/G}$

Grand Unification



Matter-Antimatter Asymmetry

The Big Bang



matter + antimatter

The Universe Today

matter only

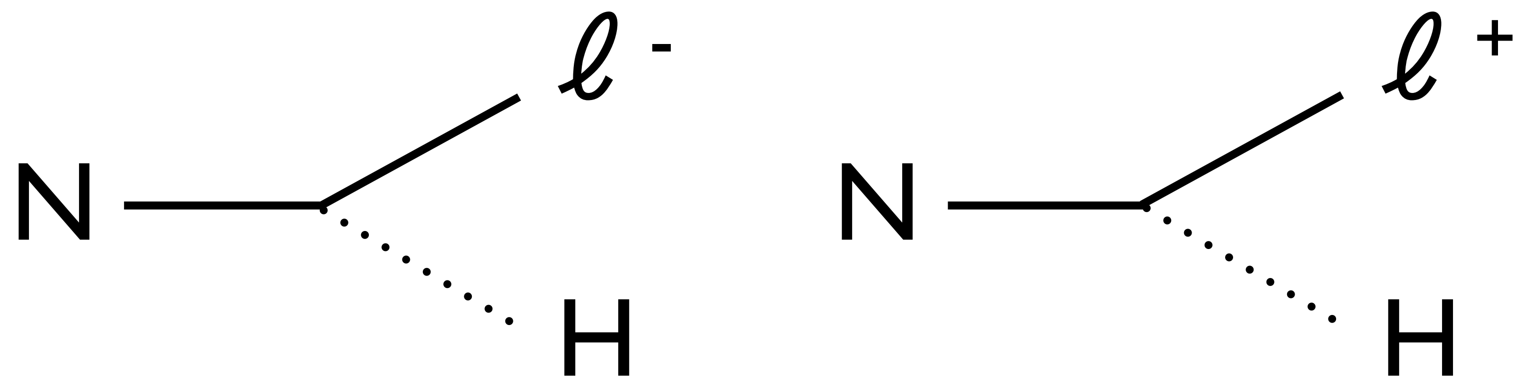
Sakharov Conditions

- Interactions out of thermal equilibrium
- C (charge) and CP (charge-parity) violation
- Baryon number violation (baryogenesis)

 A. Sakharov, JETP **5**, 24 (1967).

Leptogenesis

- Decay of heavy Majorana neutrino (N) into SM leptons ($\ell^{\pm}$) and Higgs (H):



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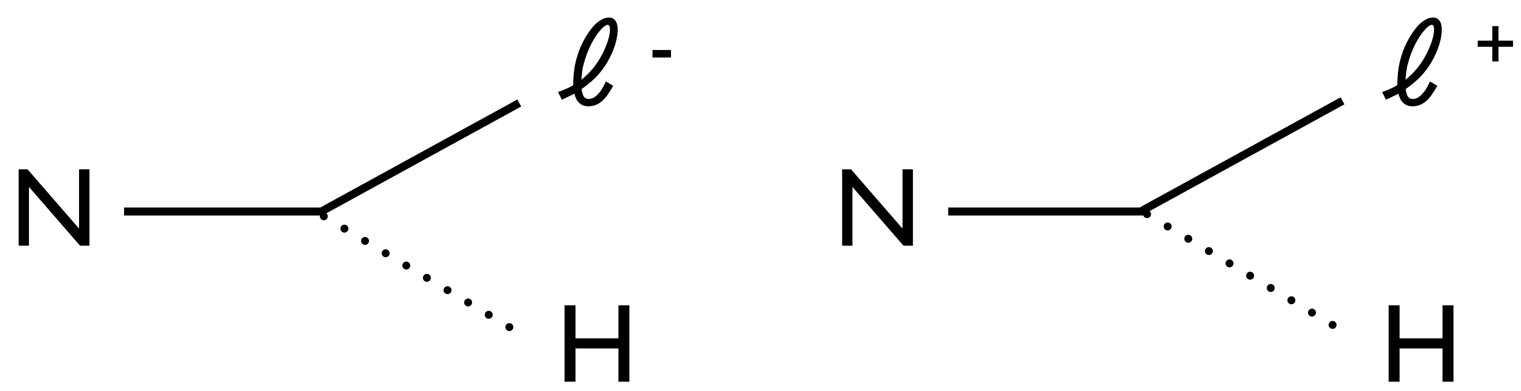
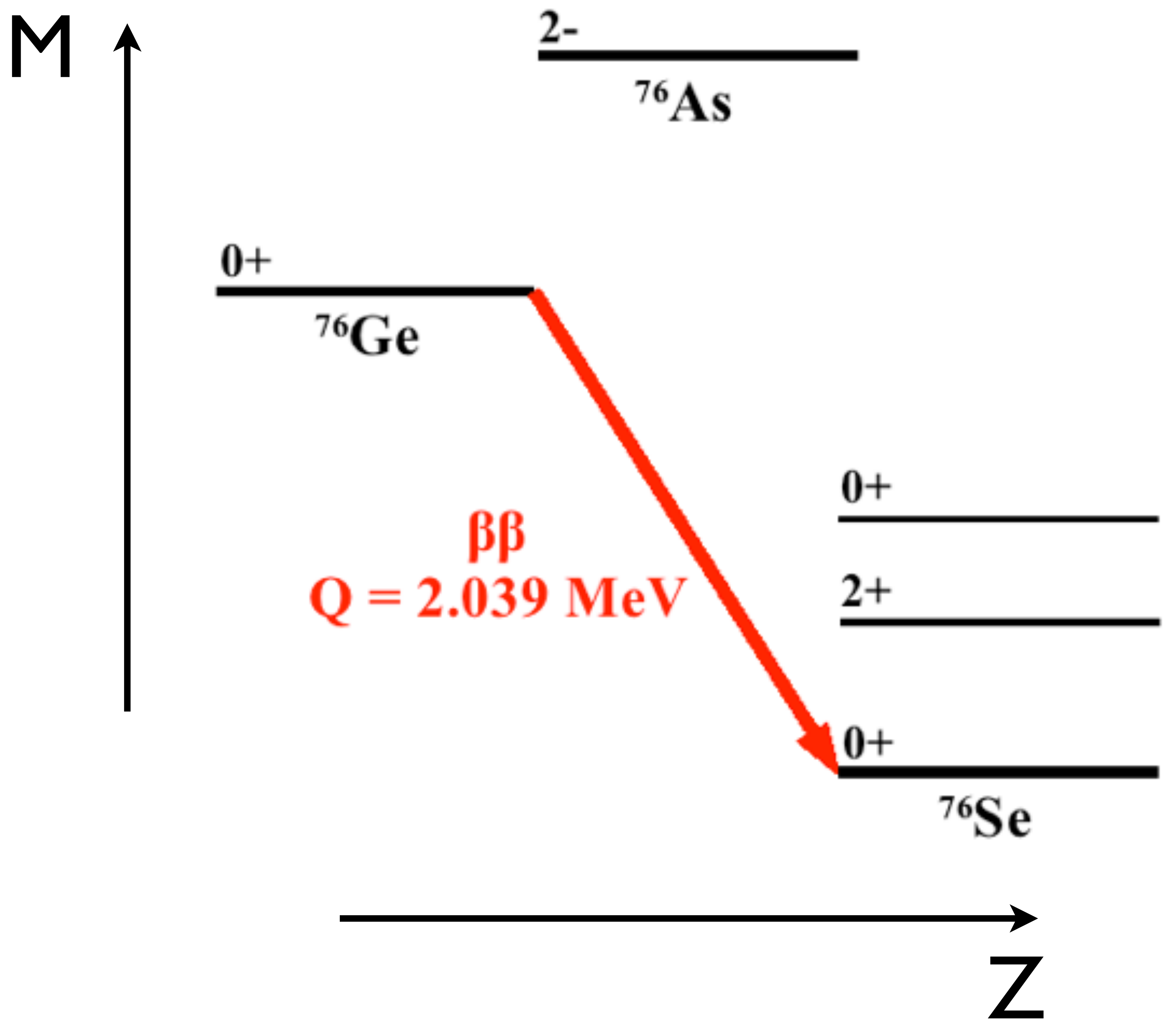


- CP violation in ν sector could give these different branching ratios
- SM processes could convert L to B: baryogenesis!
- Majorana neutrinos could be the reason we exist!

Double-Beta Decay



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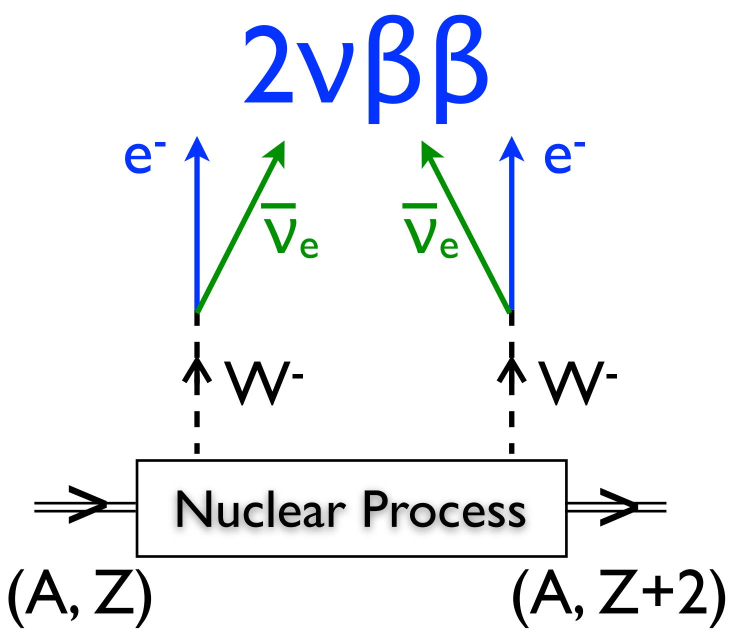
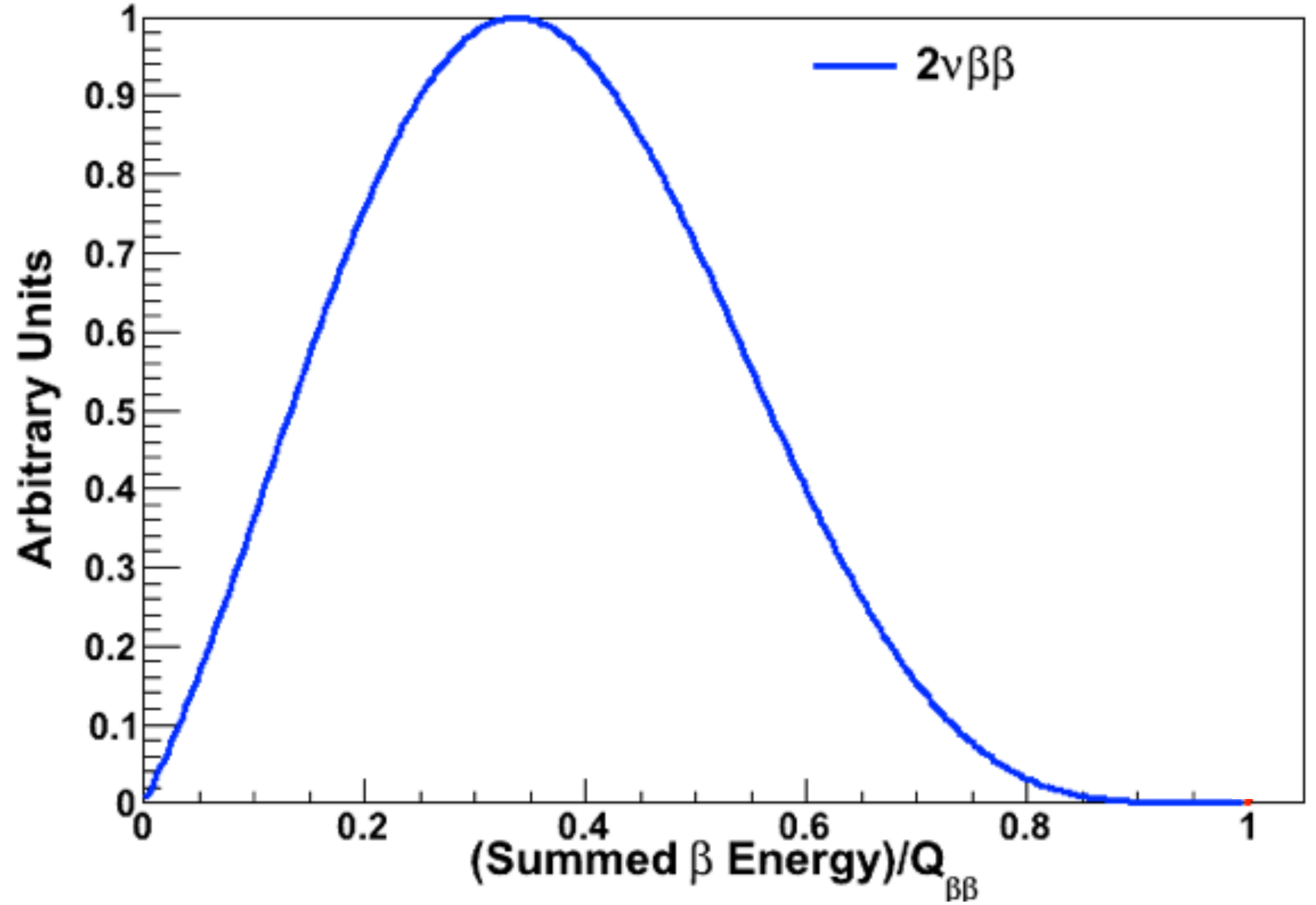
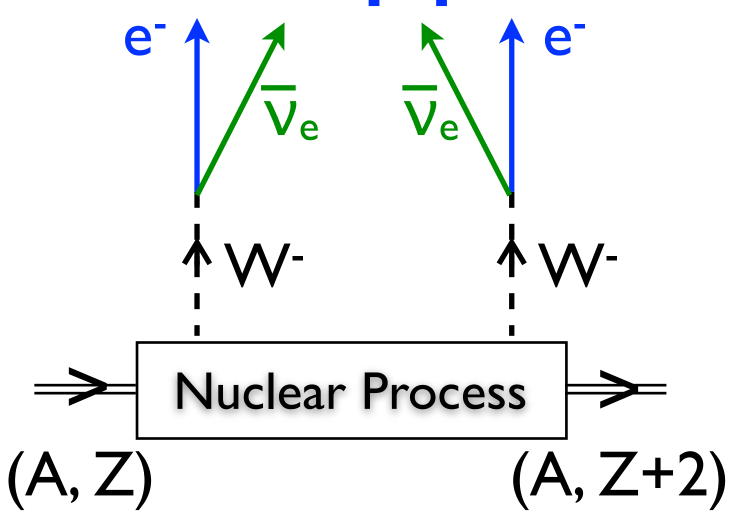


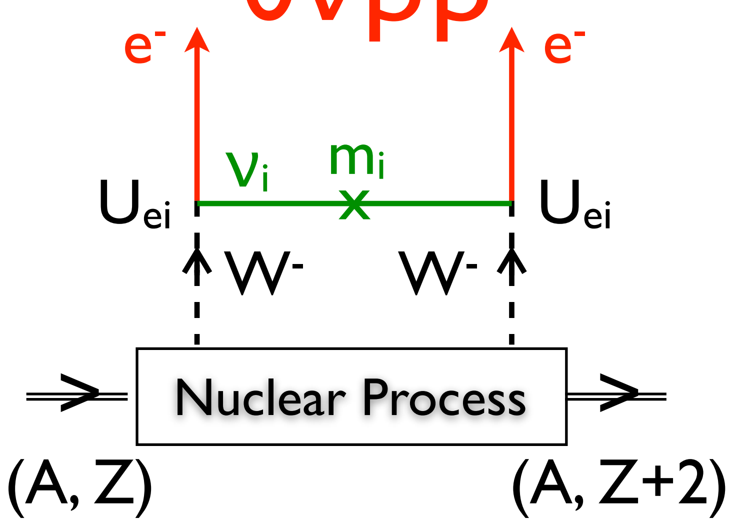


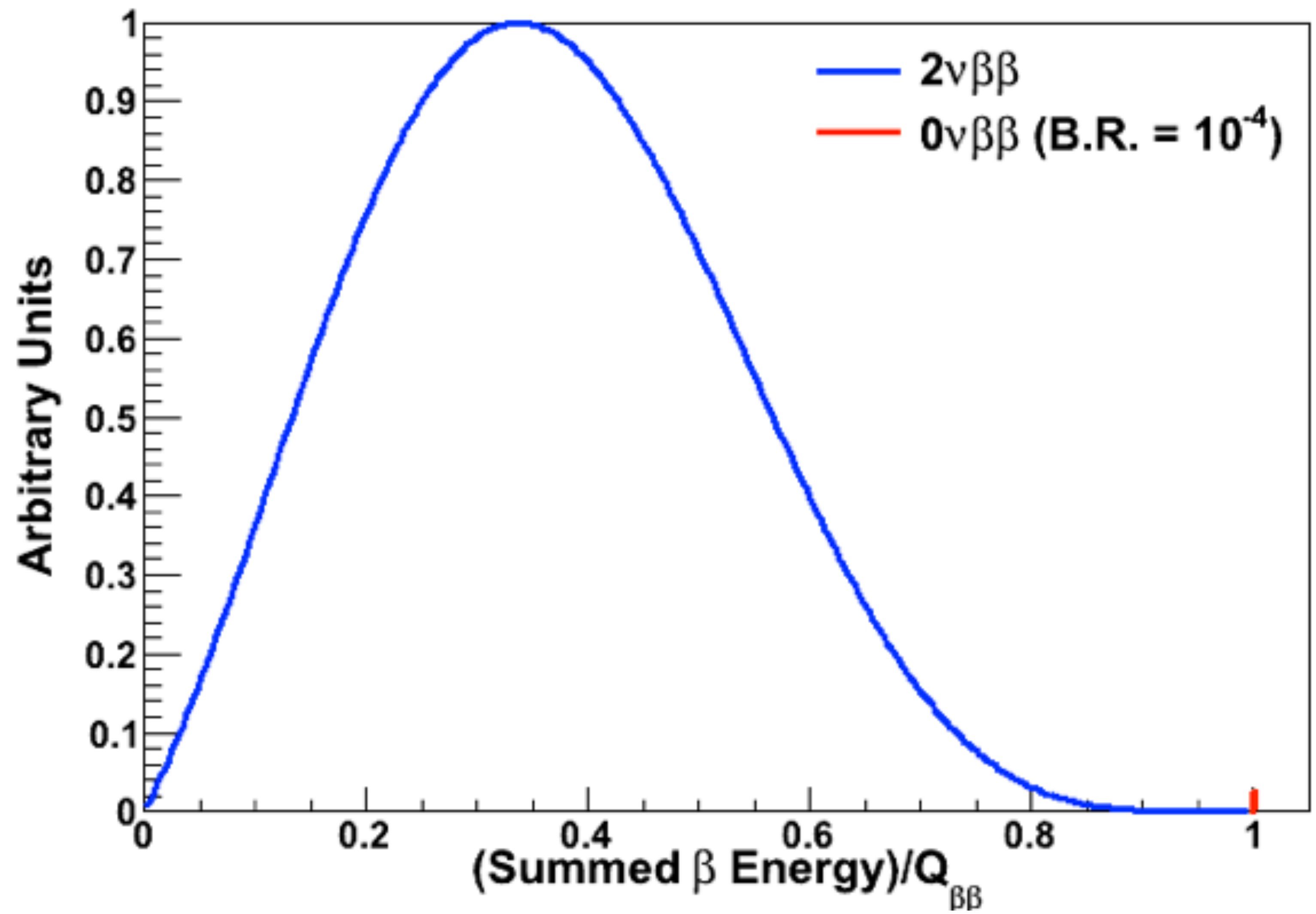
Double-Beta Decay

2νββ



0νββ

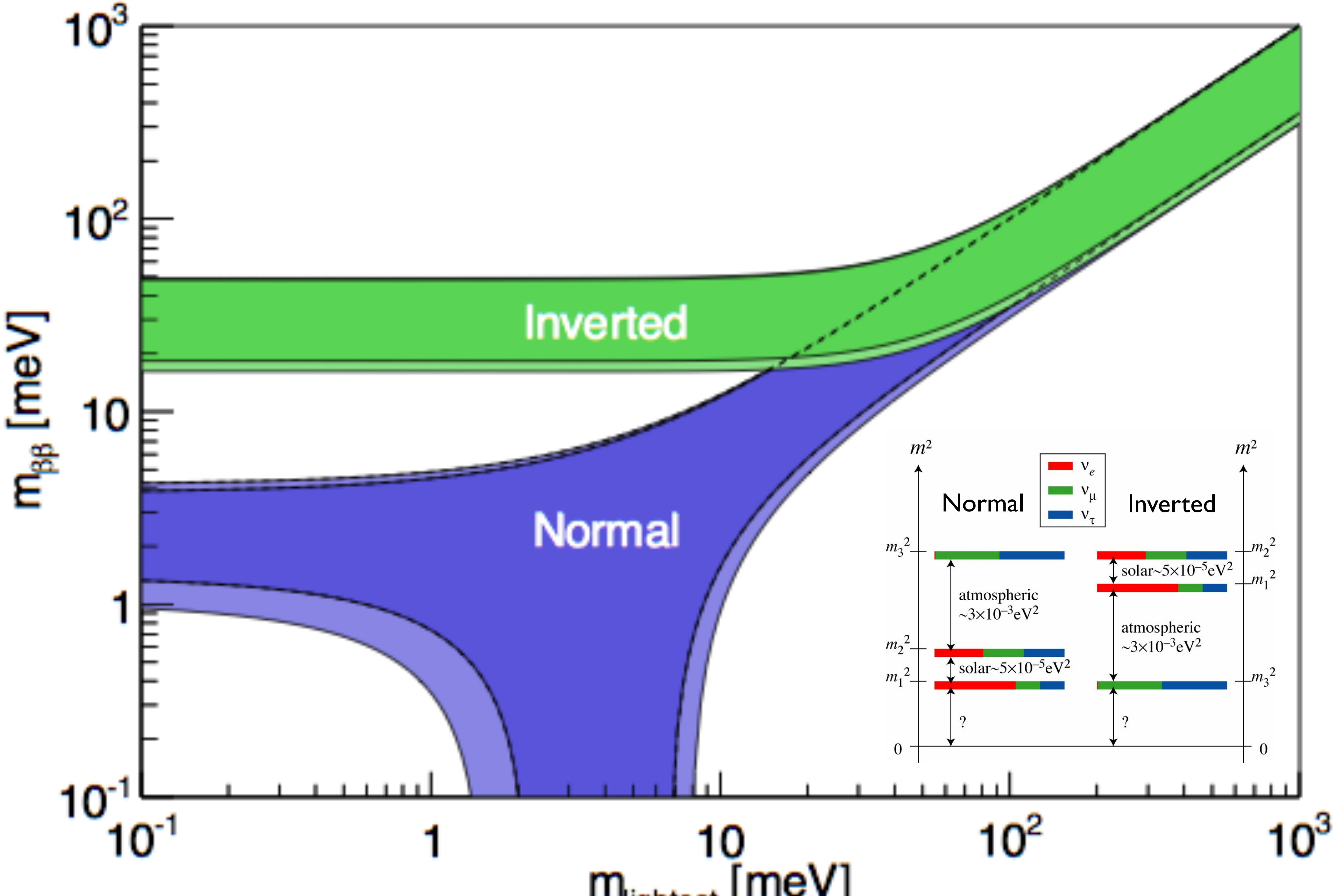




$$\Gamma_{1/2}^{0\nu} = G^{0\nu}\, |M^{0\nu}|^2\, \langle m_{\beta\beta} \rangle^2$$

$$\langle m_{\beta\beta} \rangle \equiv |\, \Sigma\, m_i\, U_{ei}^2\, |$$

Double-Beta Decay



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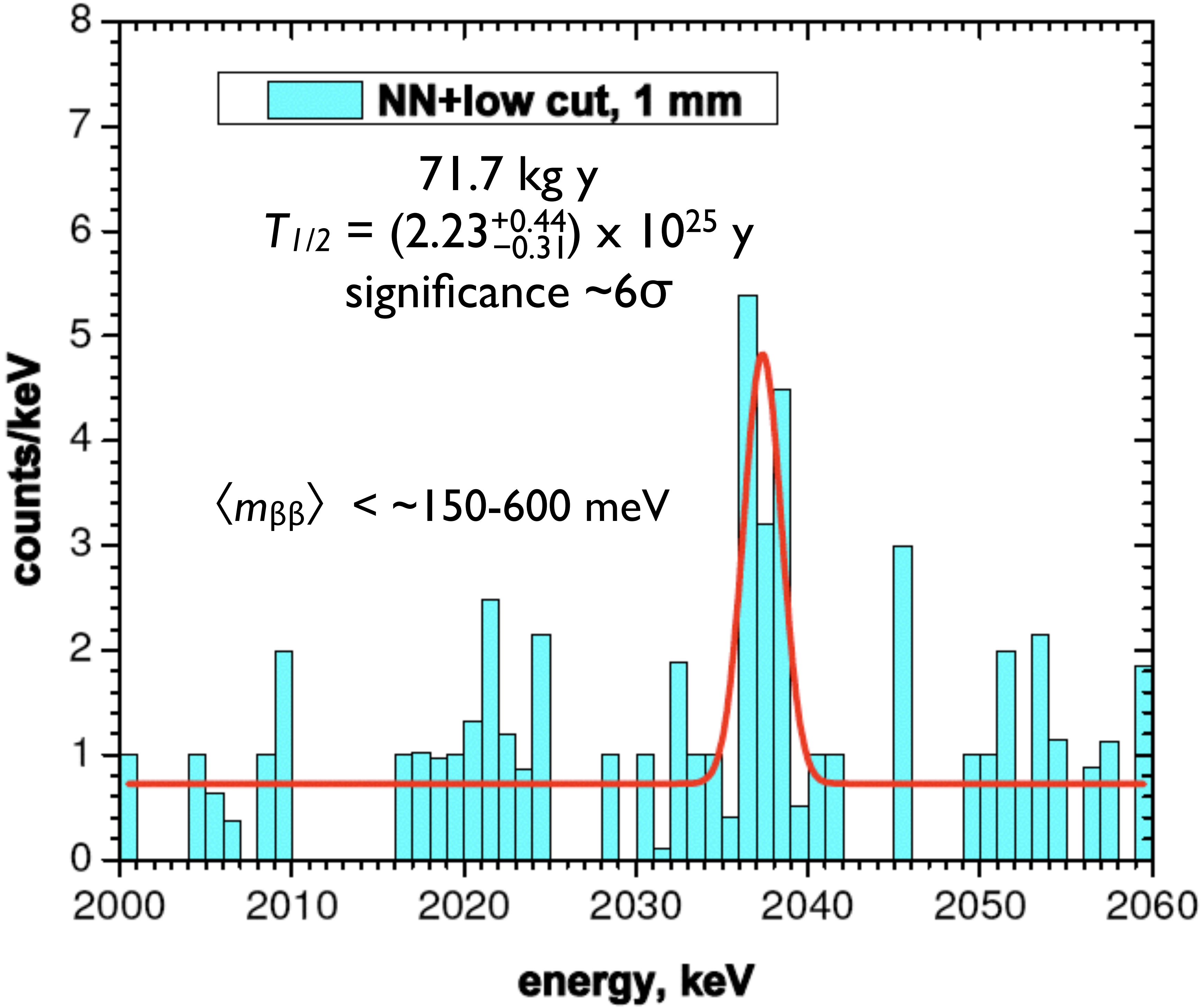
A. Schubert, H. Murayama

Claimed Observation



 Klapdor Kleingrothaus *et al.*, Mod. Phys. Lett. A **21** (2006) p 1547.

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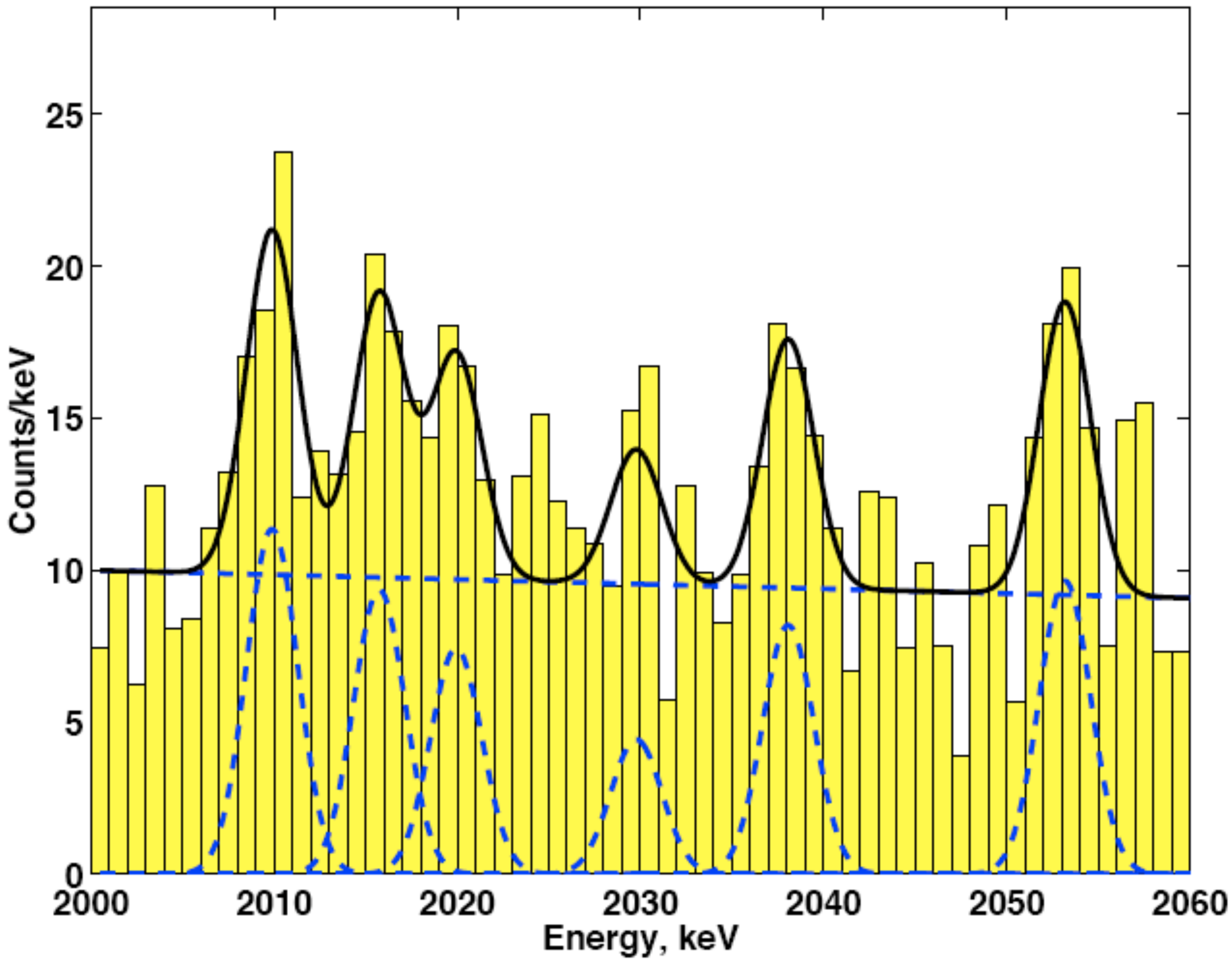
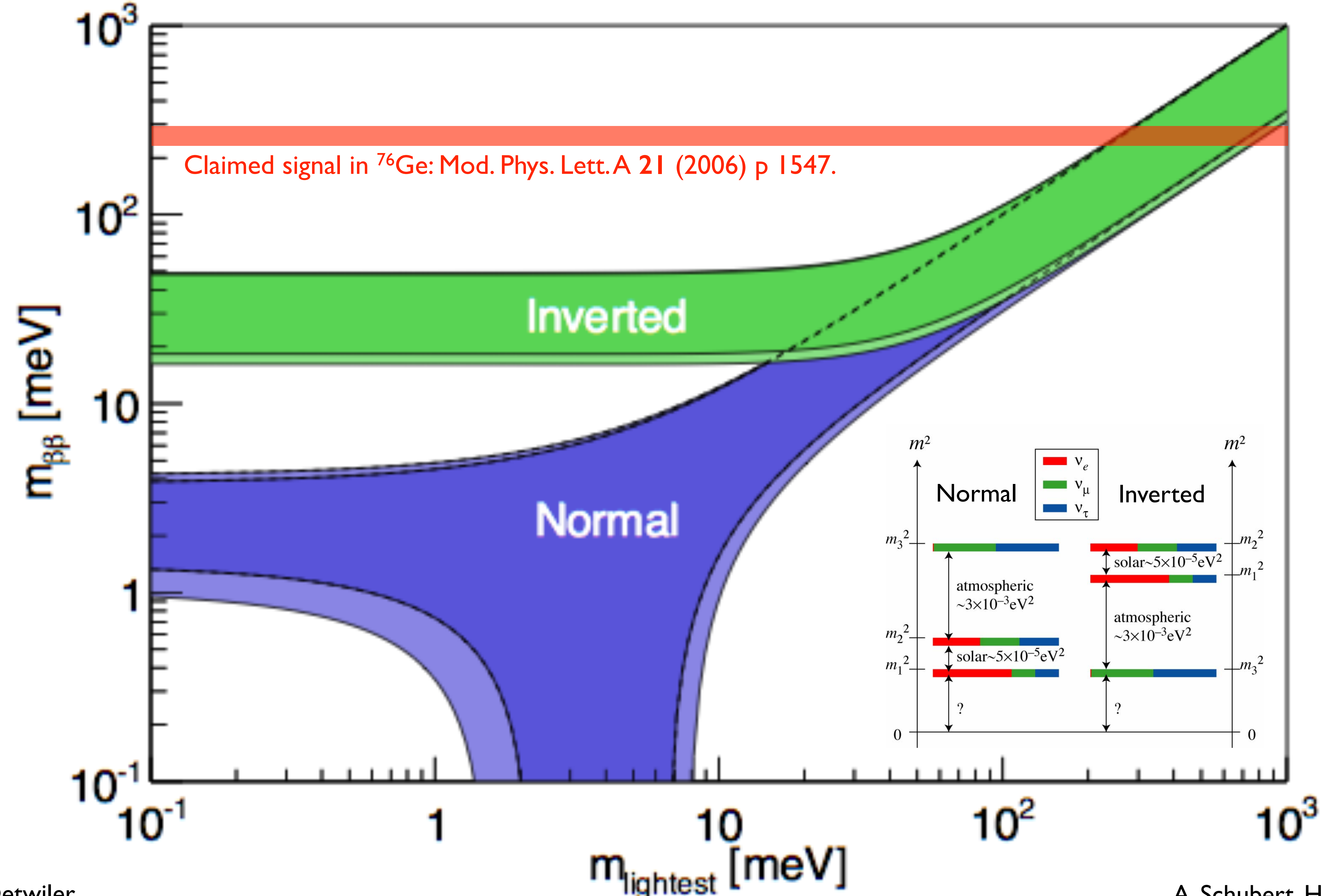


 Klapdor Kleingrothaus *et al.*, Phys. Lett. B **586**, 198 (2004).

Double-Beta Decay



A. Schubert, H. Murayama

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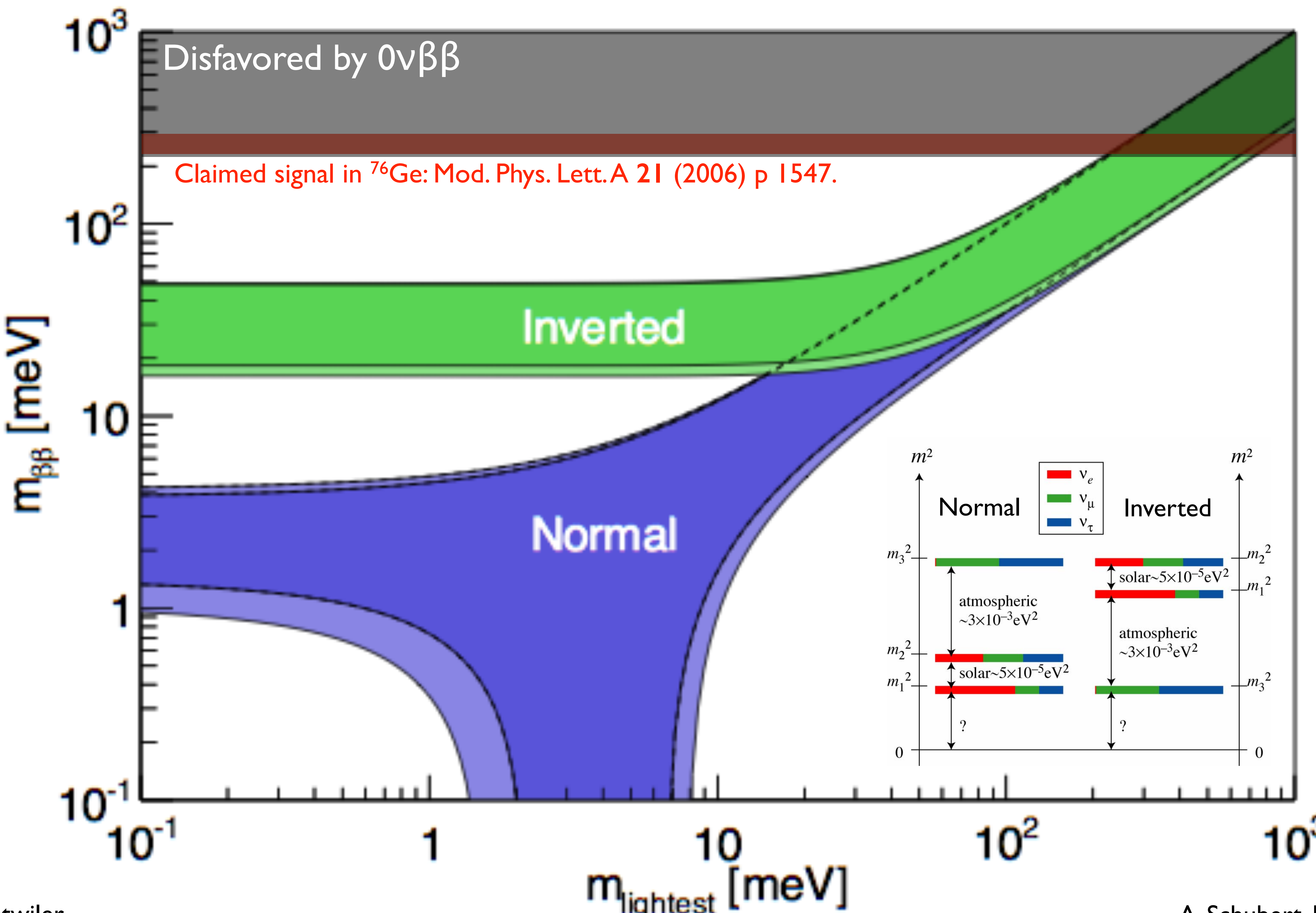

Jason Detwiler

A. Schubert, H. Murayama

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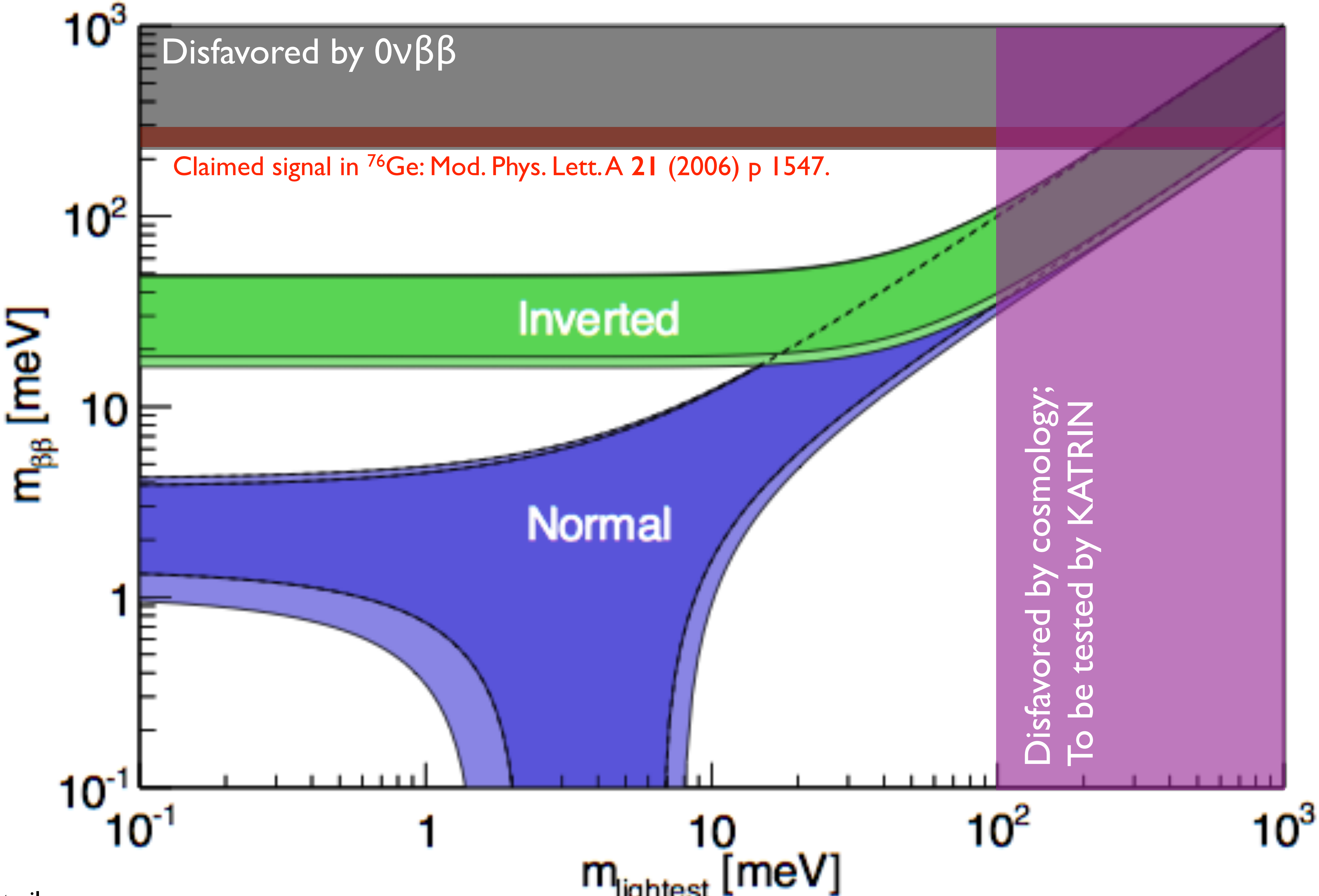

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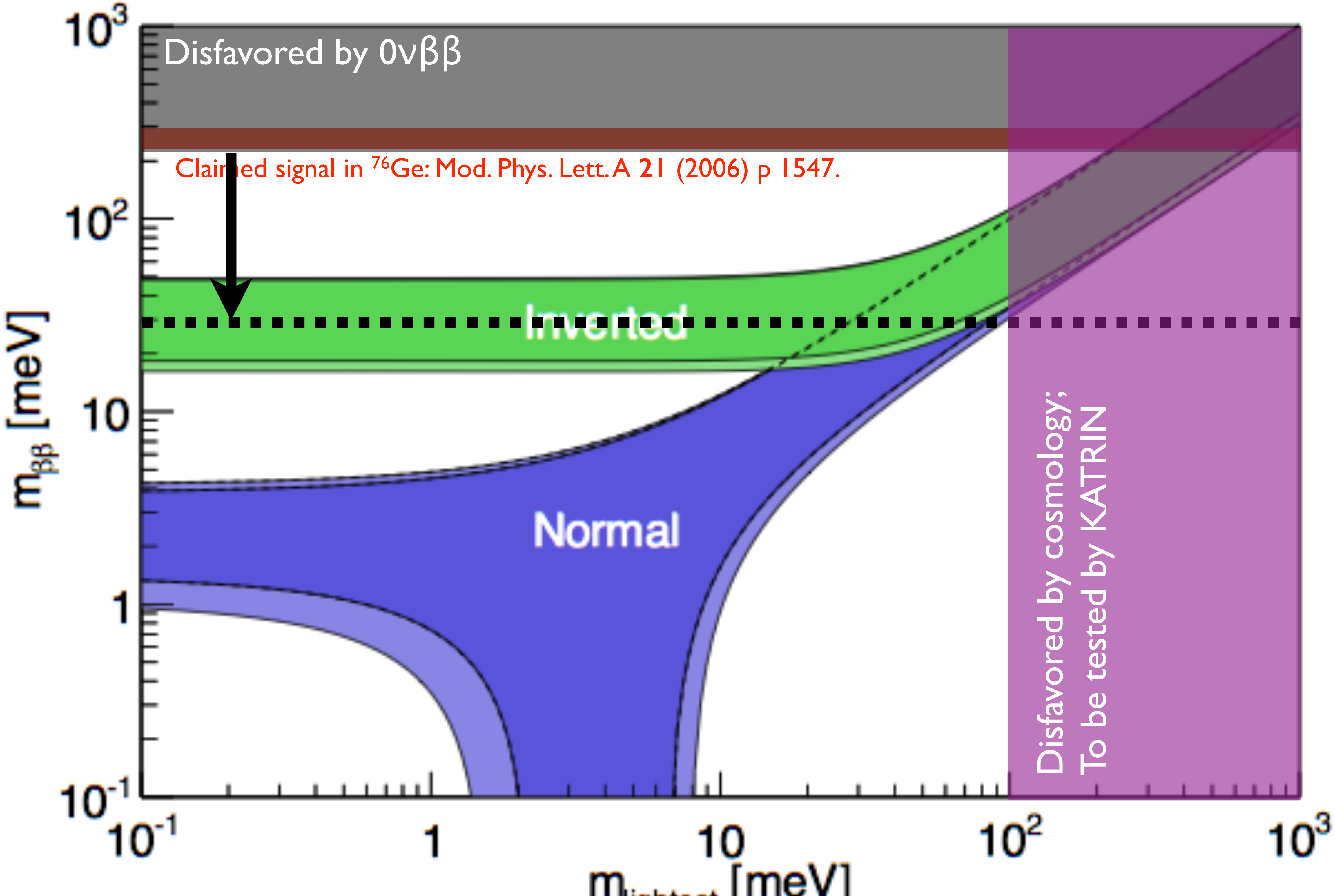

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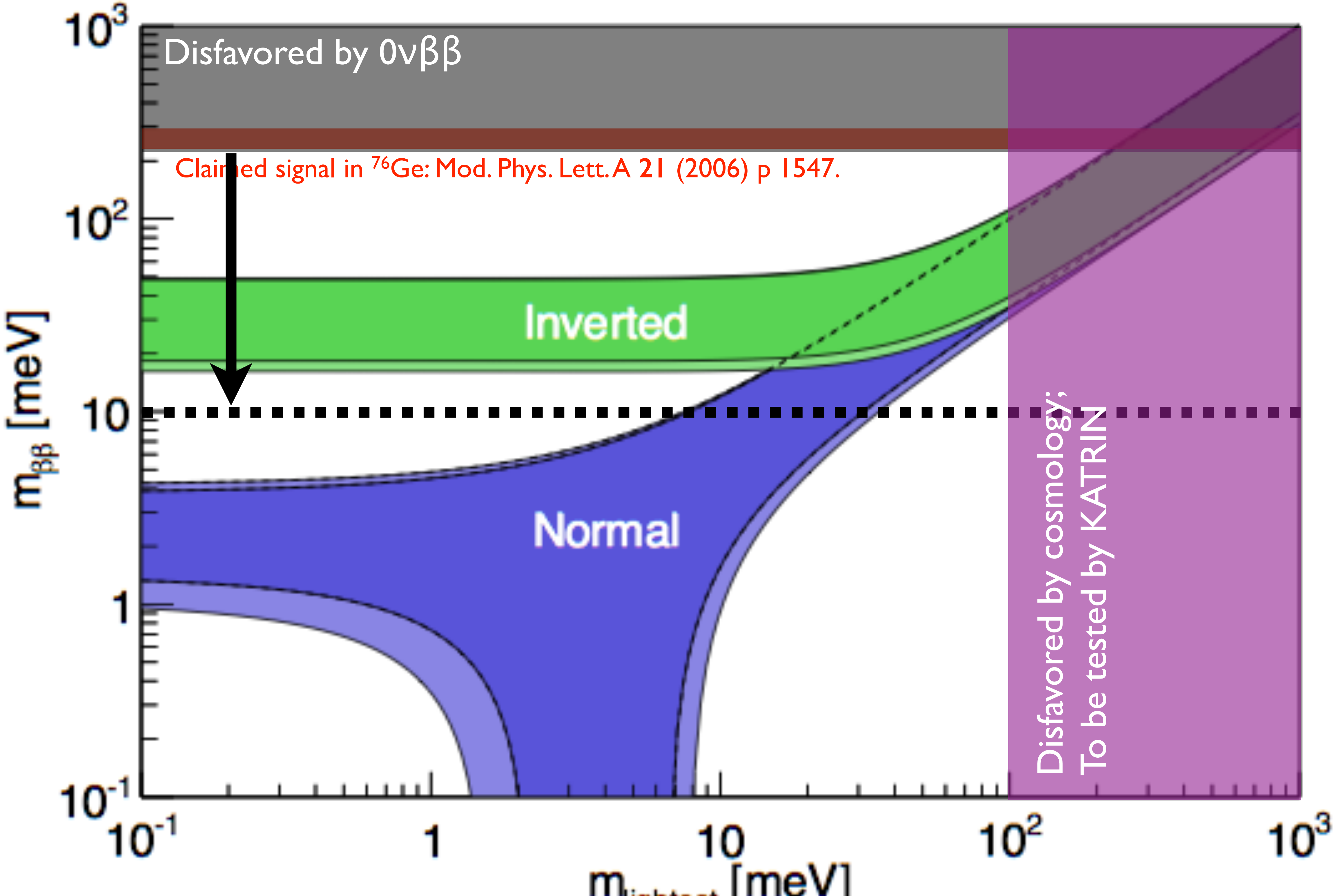

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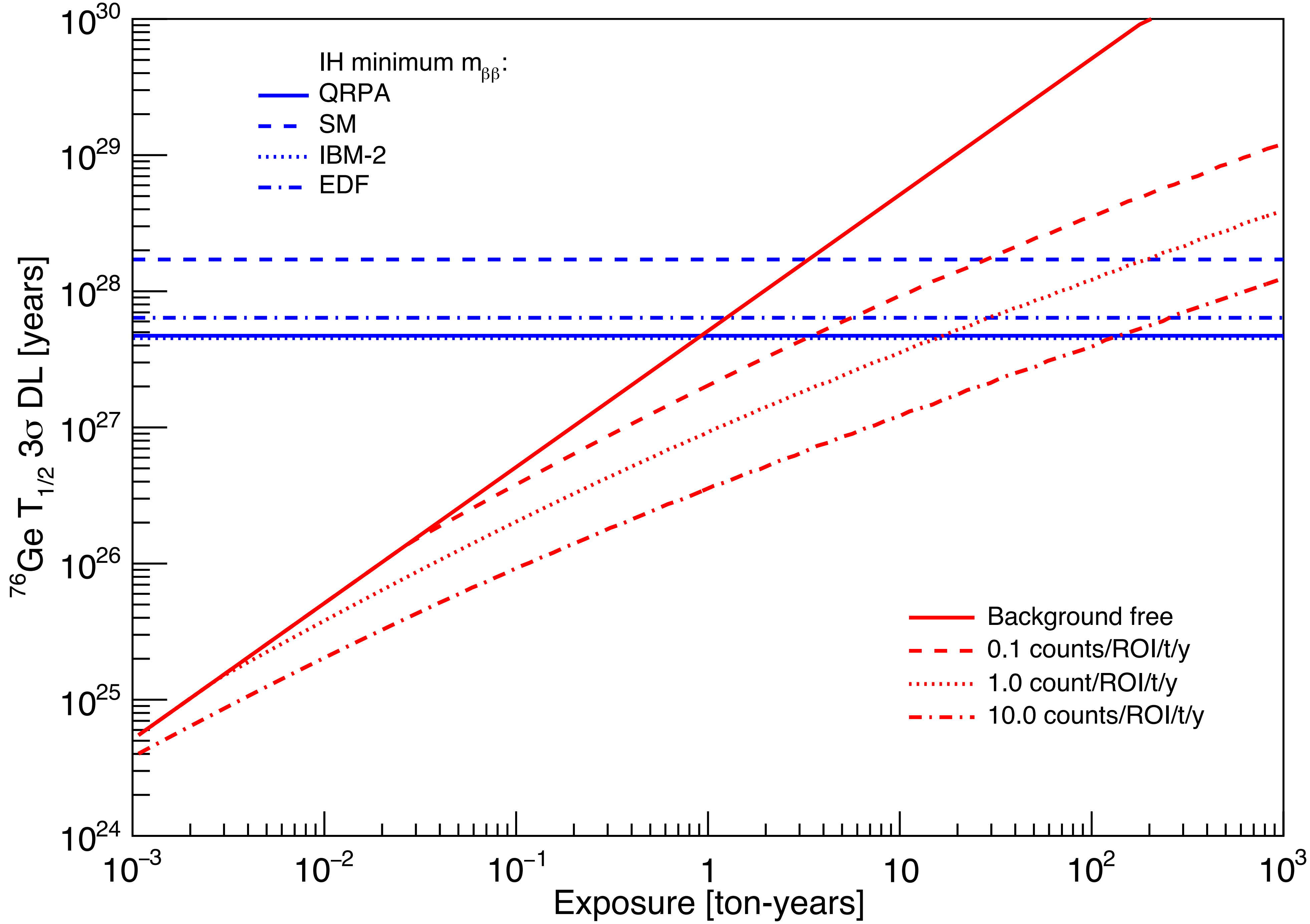
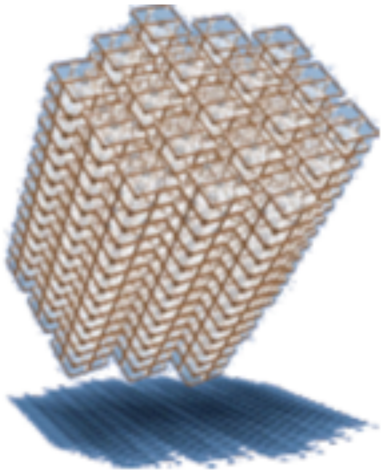
Testing the Inverted Hierarchy

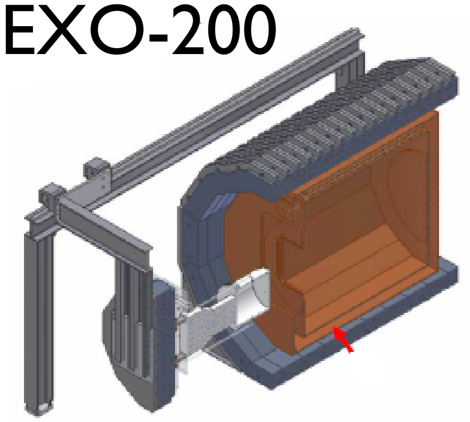


0νββ Experiments

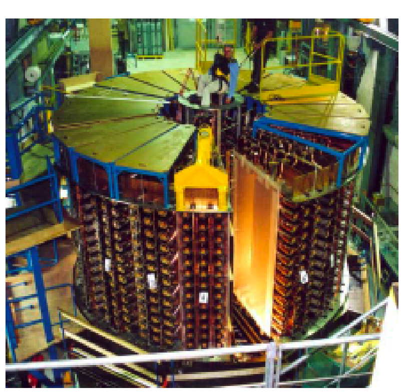
CUORE



EXO-200



NEMO3

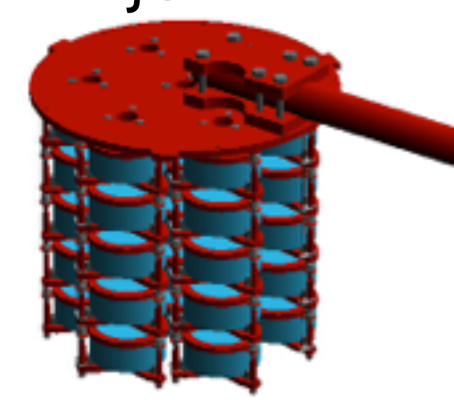


Collaboration	Isotope	Technique	mass (0νββ isotope)	Status
AMoRE	Mo-100	CaMoO4 bolometers (+ scint.)	5	Construction
CANDLES	Ca-48	305 kg CaF_2 crystals - liq. scint	0.3 kg	Operating
CARVEL	Ca-48	$^{48}CaWO_4$ crystal scint.	16 kg	R&D
GERDA I	Ge-76	Ge diodes in LAr	15 kg	Operating
GERDA II	Ge-76	Point contact Ge in LAr	20 kg	Construction
MAJORANA DEMONSTRATOR	Ge-76	Point contact Ge in Lead	26 kg	Construction
1TGe (GERDA & MAJORANA)	Ge-76	Best of GERDA + MJD	~tonne	R&D
NEMO3	Mo-100 Se-82	Foils with tracking	6.9 kg 0.9 kg	Complete
SuperNEMO Demonstrator	Se-82	Foils with tracking	7 kg	Construction
SuperNEMO	Se-82	Foils with tracking	100 kg	R&D
MOON	Mo-100	Mo sheets	200 kg	R&D
CAMEO	Cd-116	$CdWO_4$ crystals	21 kg	R&D
COBRA	Cd-116, Te-130	CdZnTe detectors	10 kg	Operating / Construction
CUORICINO	Te-130	TeO_2 Bolometer	11 kg	Complete
CUORE-0	Te-130	TeO_2 Bolometer	11 kg	Operating
CUORE	Te-130	TeO_2 Bolometer	206 kg	Construction
SNO+	Te-130	0.3% ^{nat}Te in liquid scint.	800 kg	Construction
KamLAND-ZEN	Xe-136	2.7% in liquid scint.	370 kg	Operating
KamLAND2-ZEN	Xe-136	2.7% in liquid scint.	~tonne	R&D
NEXT-100	Xe-136	High pressure Xe TPC	10 kg	Construction
EXO-200	Xe-136	Xe liquid TPC	160 kg	Operating
nEXO	Xe-136	Xe liquid TPC	5 tonnes	R&D
DCBA	Nd-150	Nd foils & tracking chambers	30 kg	R&D

Complete | Construction | Operating

GERDA

MAJORANA

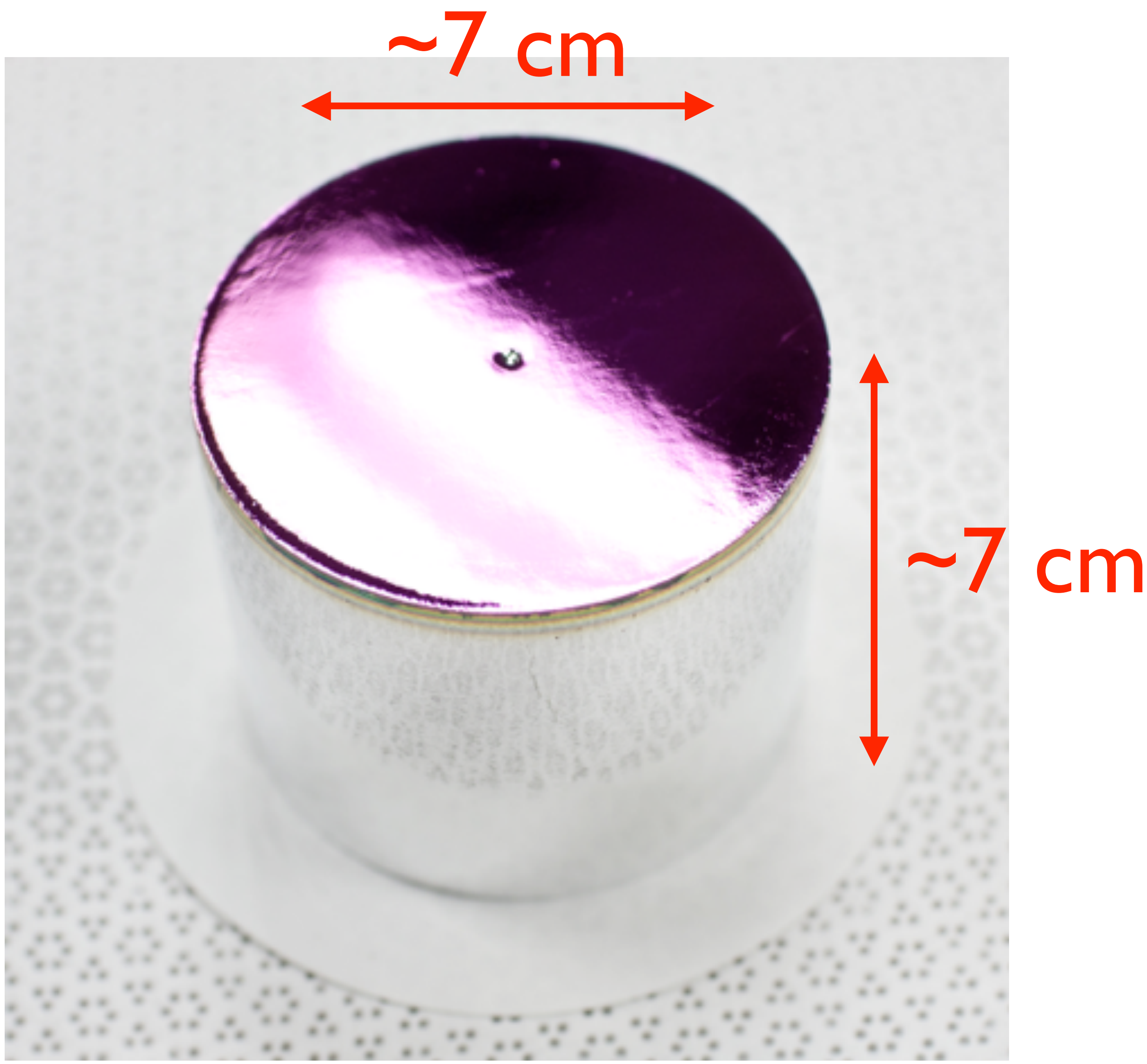


CANDLES

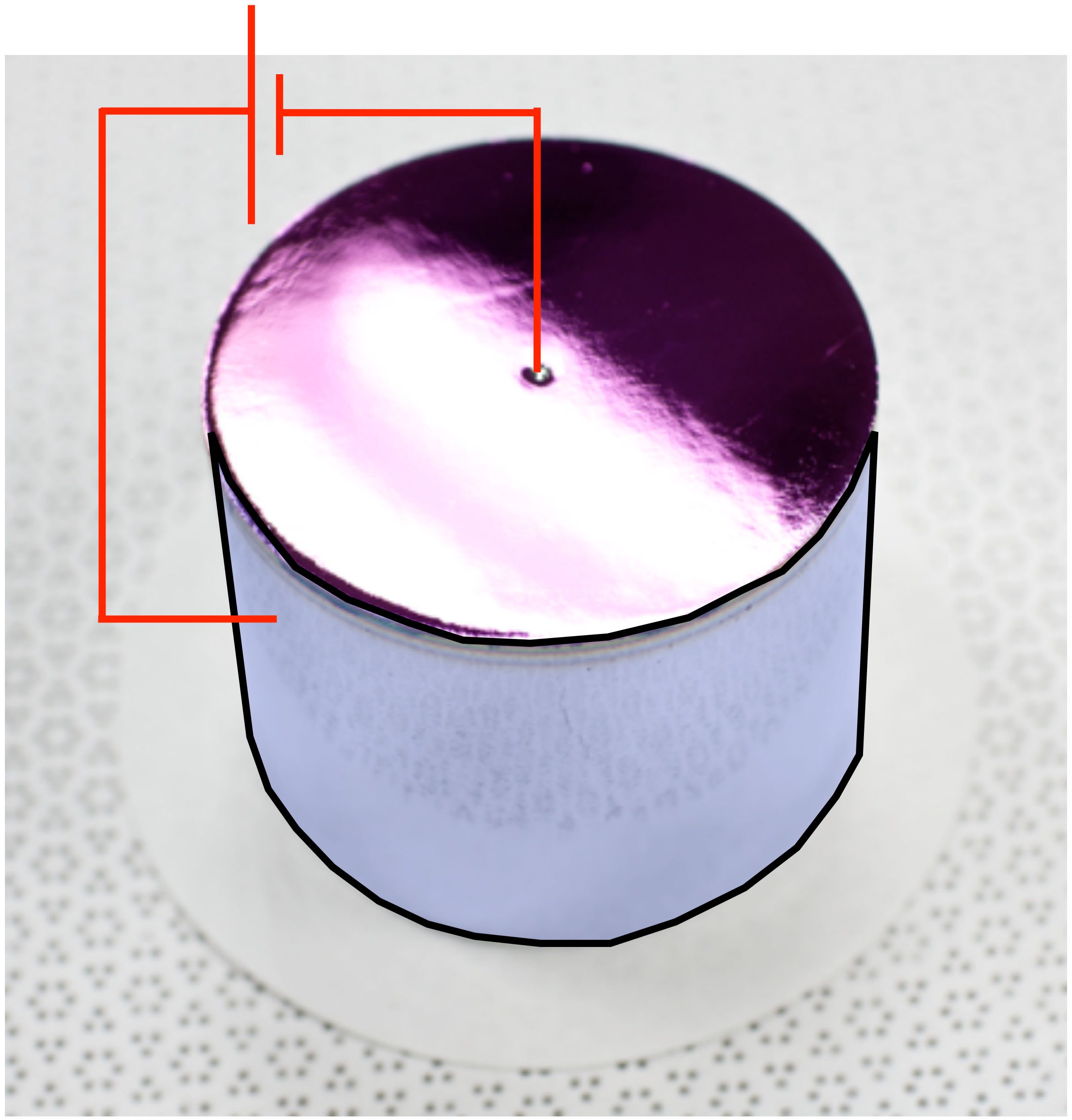
Jason Detwiler

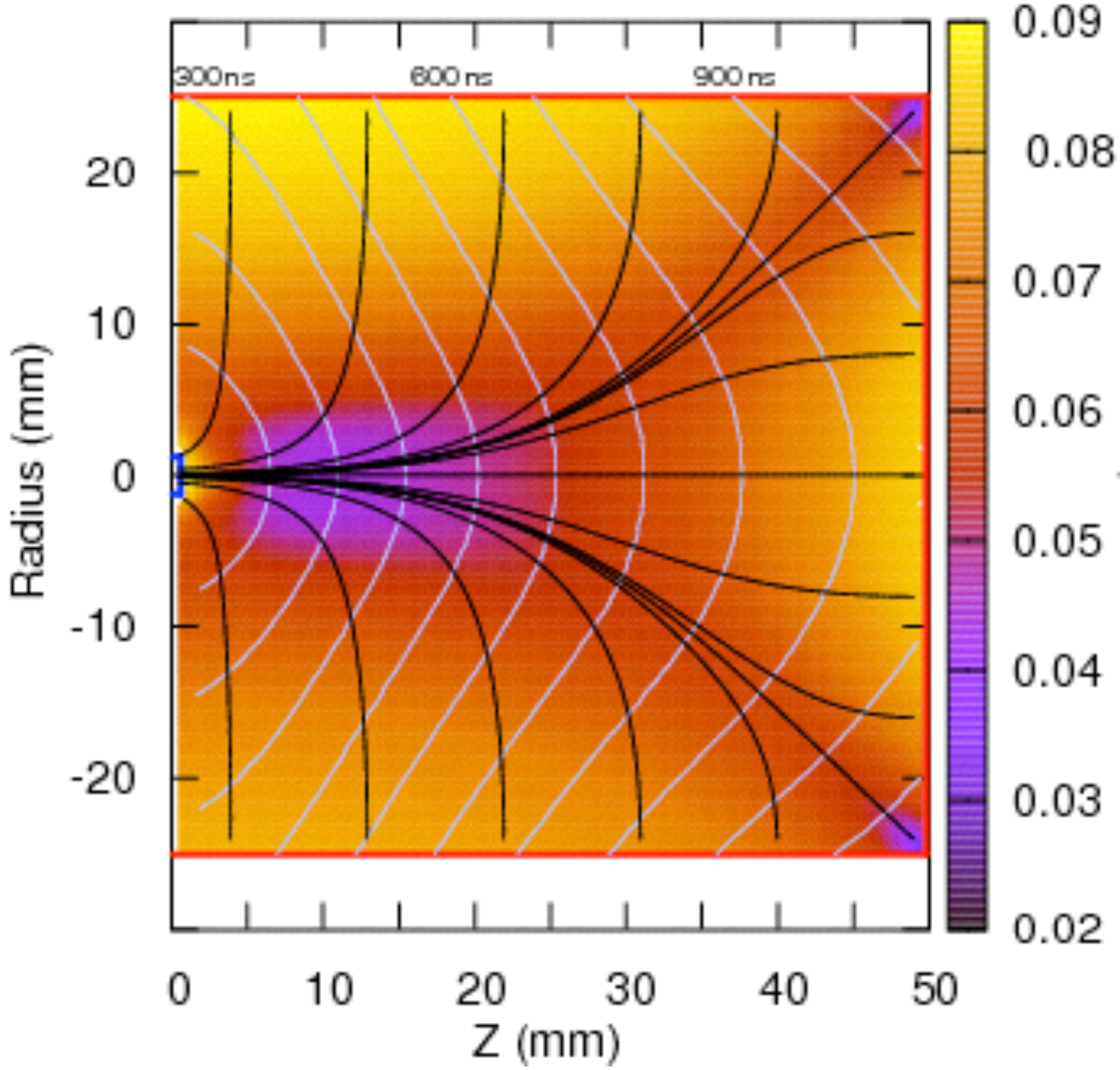
From J. F. Wilkerson

Germanium Detectors



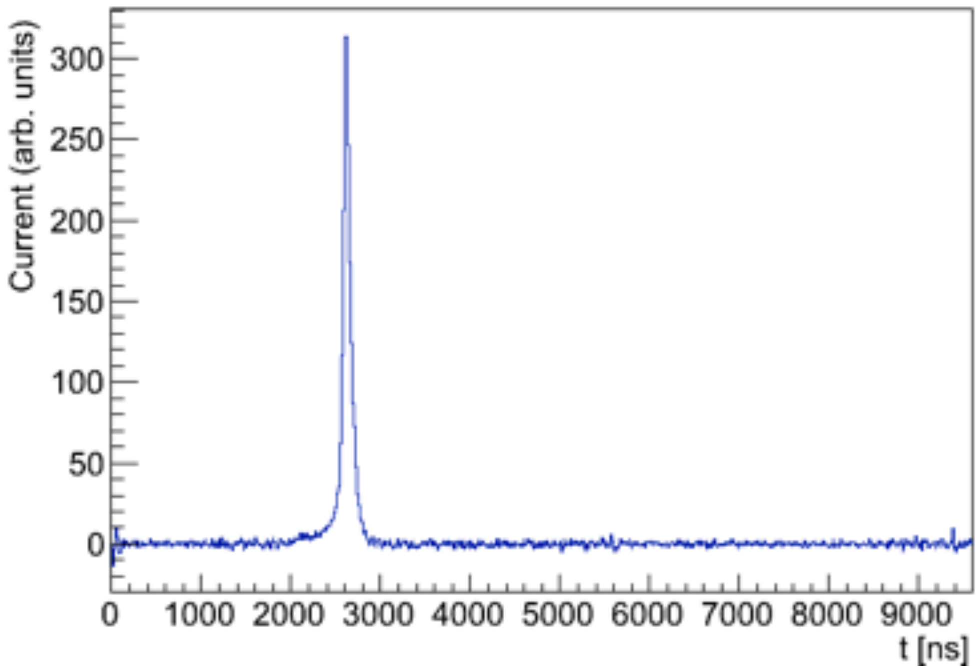
Germanium Detectors

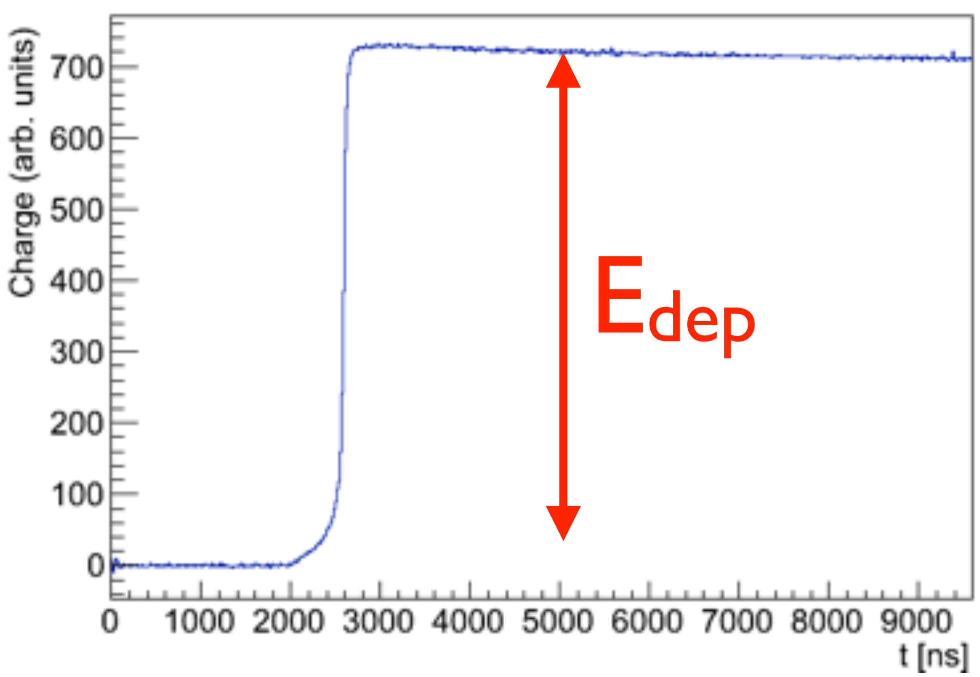


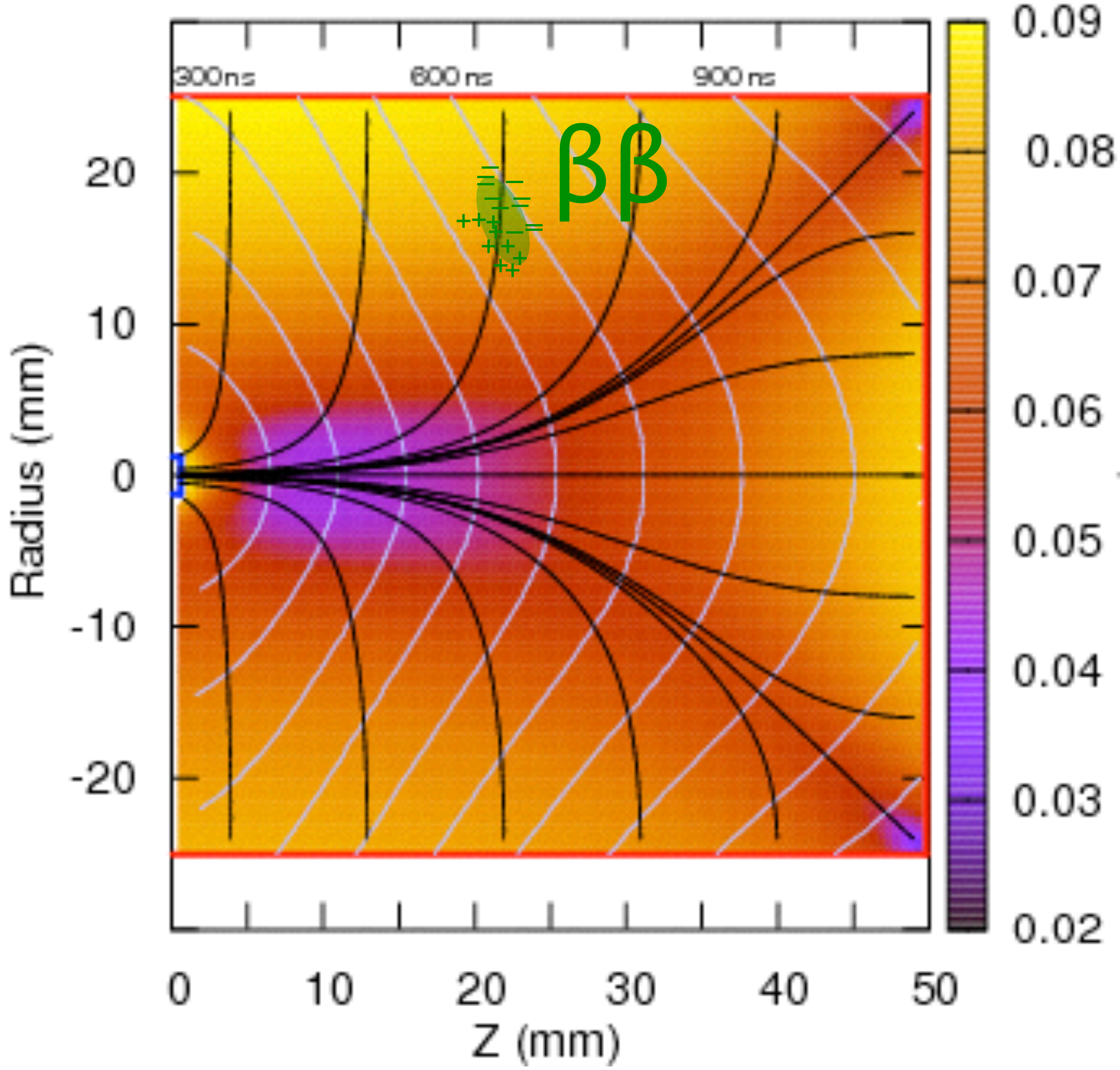


Hole v_{drift} (mm/ns) w/ paths, isochrones

Germanium Detectors



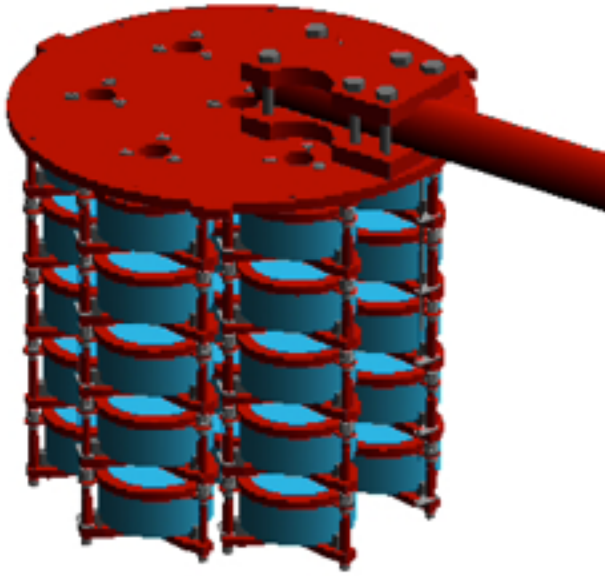




Hole v_{drift} (mm/ns) w/ paths, isochrones

The MAJORANA DEMONSTRATOR

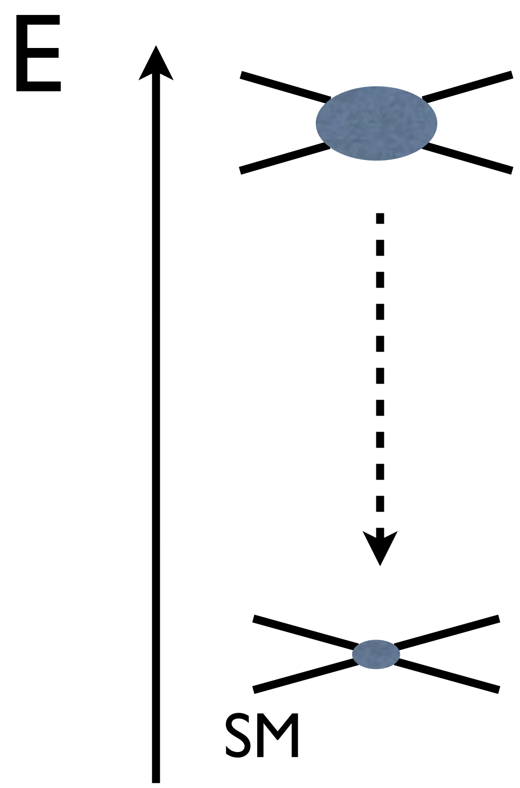
- Goal: x100 reduction in background vs. previous efforts using clean materials, hit patterns, pulse-shapes
- Located at the 4850' level of Sanford Underground Laboratory in SD
- Modules:
  - Prototype: 3 strings ^{nat}Ge (completed!)
  - Module 1: ~20 kg ^{enr}Ge (running now!)
  - Module 2: ~10 kg ^{enr}Ge + ~10 kg ^{nat}Ge (under construction!)



Summary

- Majorana neutrinos may give us insights into Grand Unification and the Matter-Antimatter Asymmetry of the Universe.
- $0\nu\beta\beta$ experiments are the only known way to probe this aspect of the neutrino. Definitive tests of inverted hierarchy Majorana neutrinos are within reach.

Effective Theory



$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{\lambda}\mathcal{L}_5 + \frac{1}{\lambda^2}\mathcal{L}_6 + \ldots$$

Majorana mass term

- L is "accidentally" conserved in the in the SM
- B, L often connected in GUTs

The Majorana Equation

Schrodinger: $$i\frac{\partial}{\partial t}\Psi + \frac{1}{2m}\nabla^2\Psi = 0$$

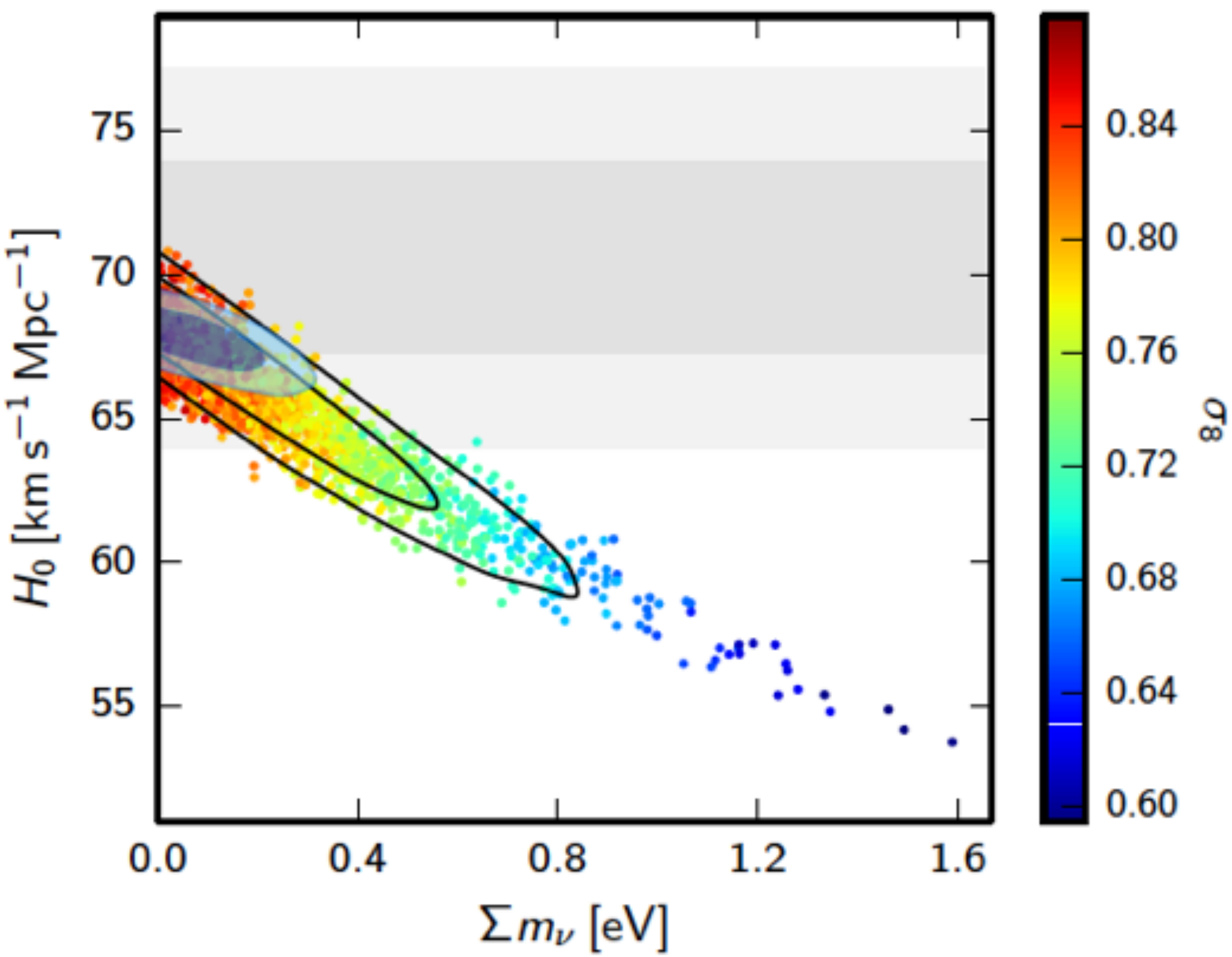
Dirac: $$-i\gamma^\mu\partial_\mu\psi + m\psi = 0$$

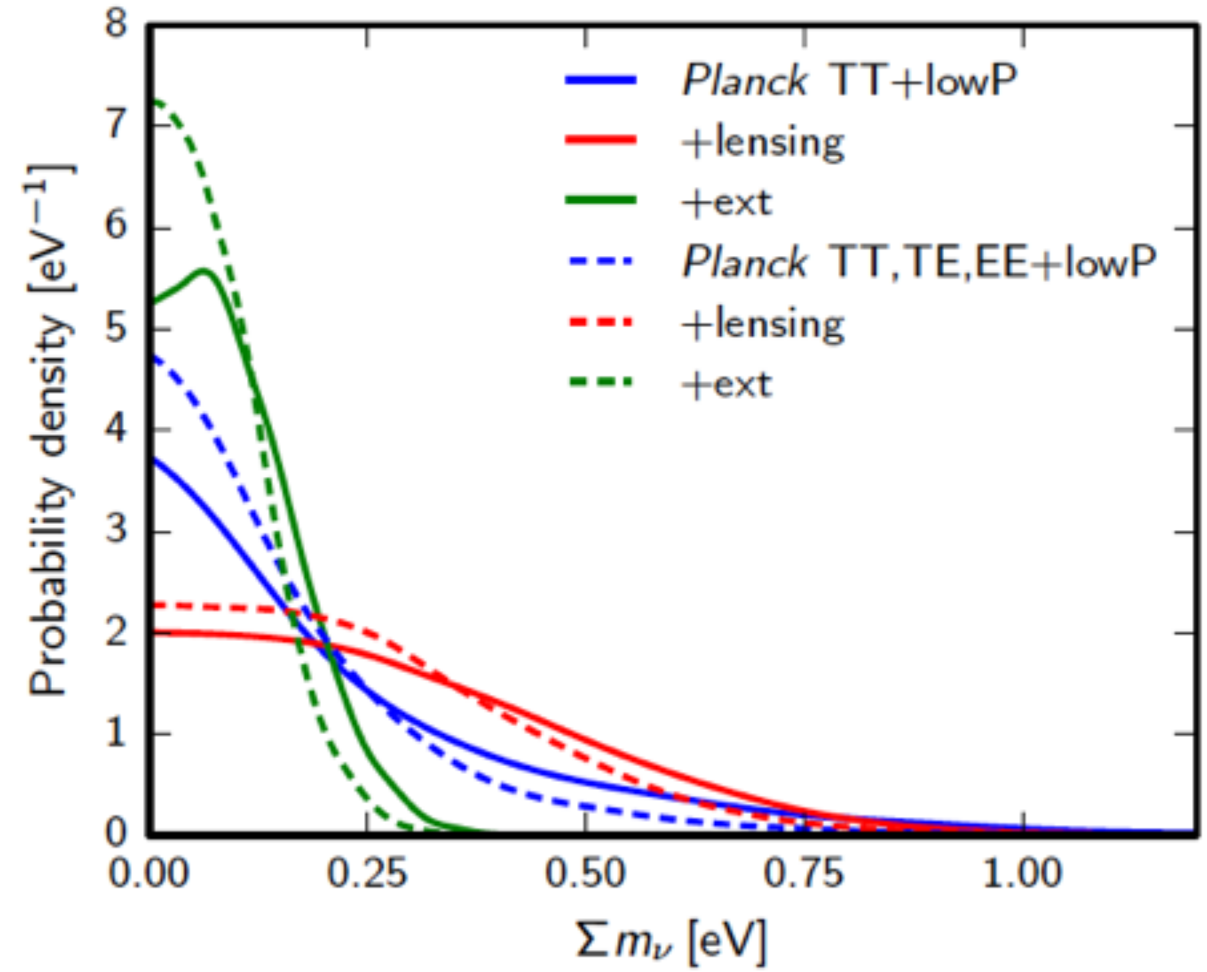
Majorana: $$\sigma^\mu_\pm\partial_\mu\chi \pm m\sigma_2\chi^* = 0$$

E. Majorana, Il Nuovo Cimento **14**, 171 (1937).
English translation: Soryushiron Kenkyu **63**, 149 (1981).

Planck 2015

$$\left.\begin{aligned}\sum m_\nu &< 0.23\ \text{eV}\\ \Omega_\nu h^2 &< 0.0025\end{aligned}\right\}\ 95\%,\ \textit{Planck}\ \text{TT+lowP+lensing+ext.}$$



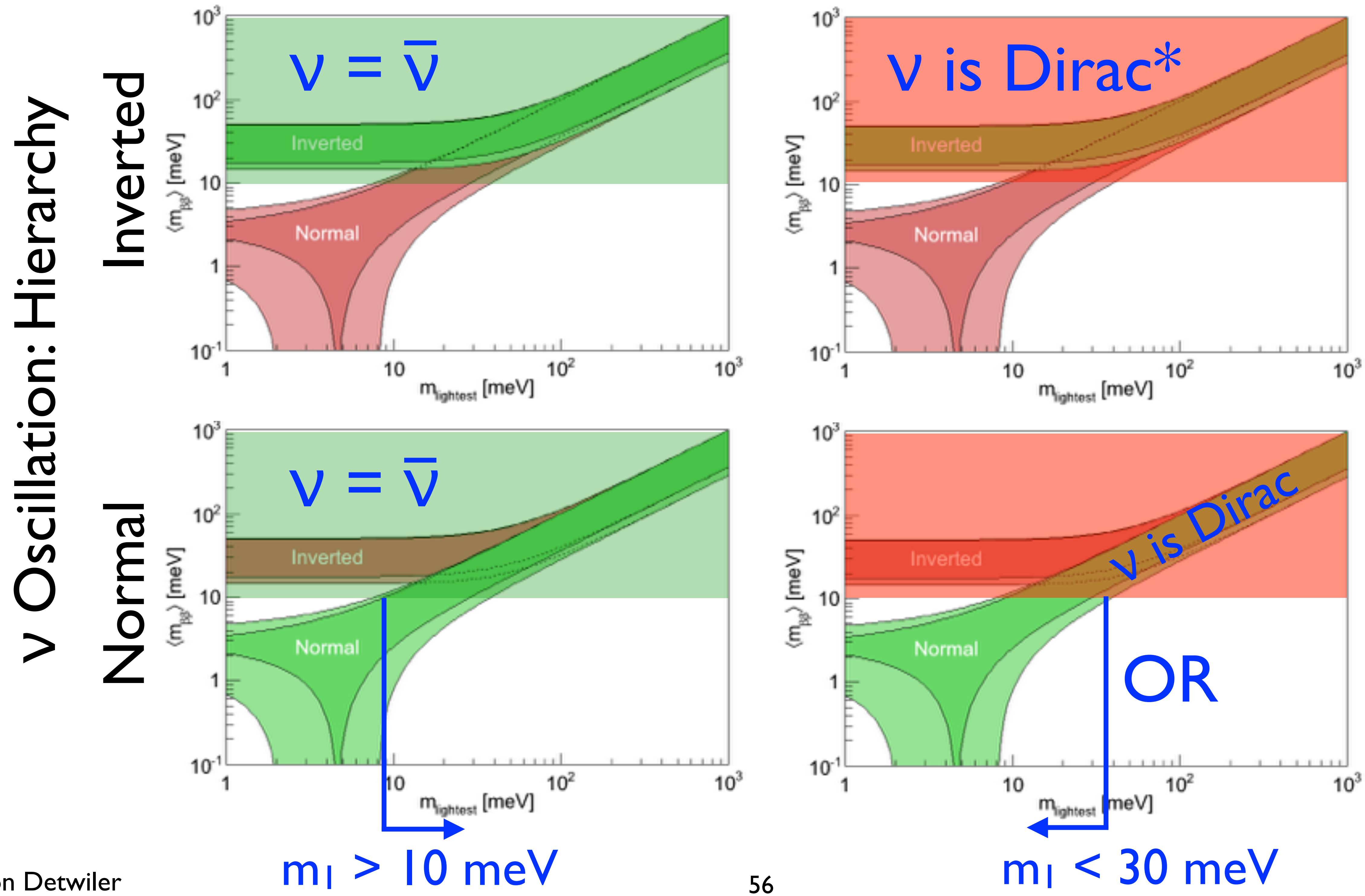


Planck 2015 XIII, arXiv:1502.01589v2

Combination with ν Oscillation

Next-Generation 0νββ Decay

Observed | Not observed

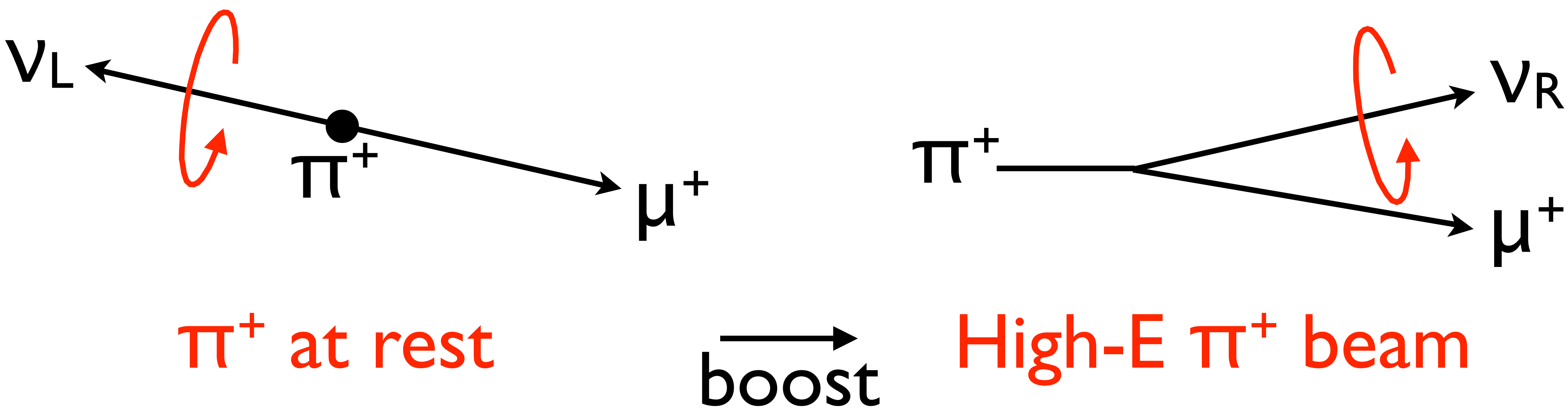


Testing $\nu = \bar{\nu}$ (I)

Dirac ν		Majorana ν	
ν_L	produces ℓ^-	$\overset{(-)}{\nu}_L$	produces ℓ^-
ν_R	doesn't interact	$\overset{(-)}{\nu}_R$	produces ℓ^+
$\bar{\nu}_L$	doesn't interact		
$\bar{\nu}_R$	produces ℓ^+		

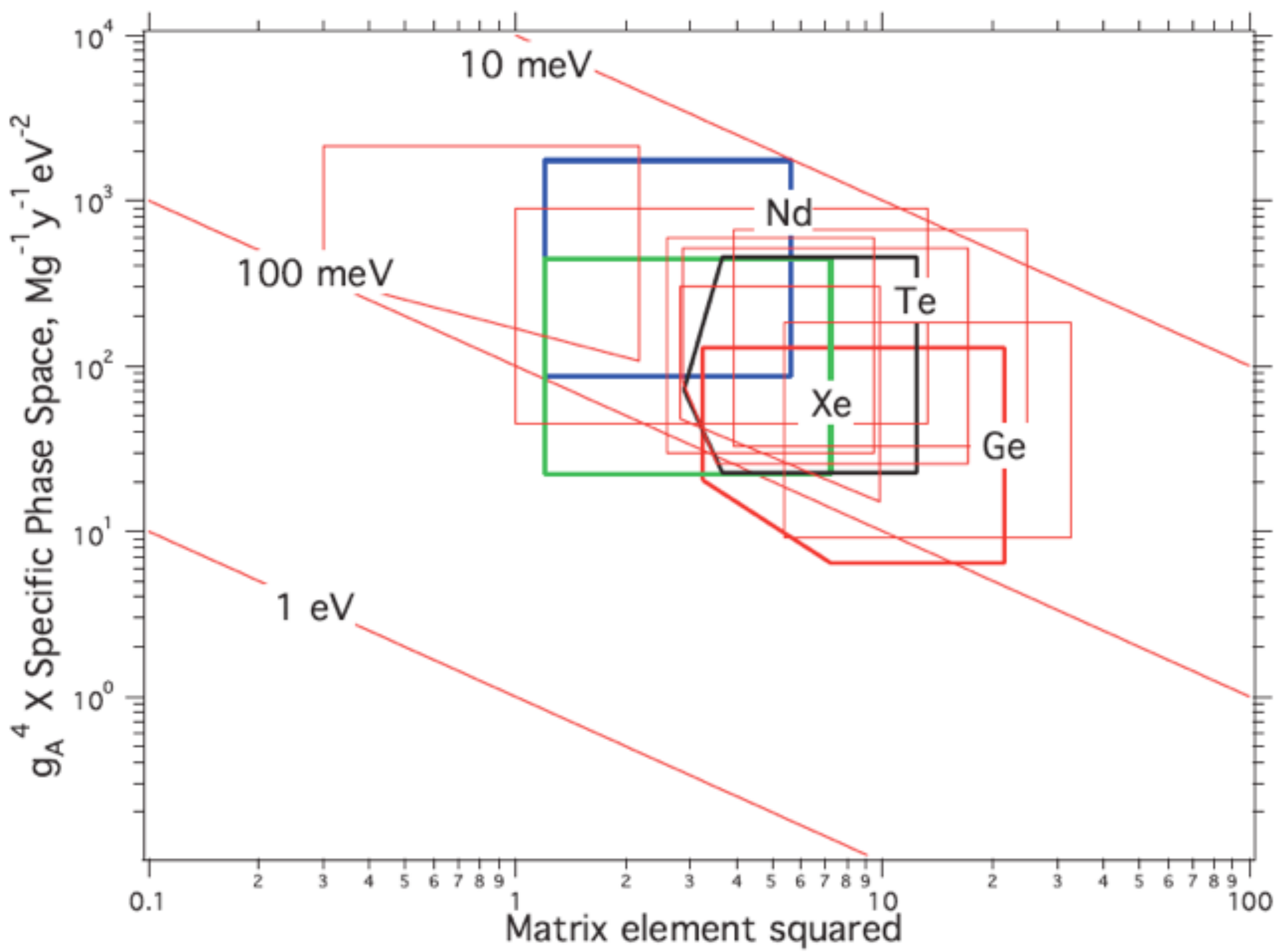
Why not generate ν_R in a beam and see if it produces ℓ^+?

Testing $\nu = \bar{\nu}$ (I)



- Boost so that π^+ beam faster than ν_L from decay at rest: requires $E_\pi > 4$ PeV (n.b. LHC = 14 TeV)
- Fraction of decays with helicity flipped: $<10^{-15}$
- *"Since L-violation comes only from Majorana ν masses, any attempt to observe it will be at the mercy of the ν masses."*
  - B. Kayser

No *a priori* isotope preference



R.G.H. Robertson, Mod. Phys. Lett. A **28**, 1350021 (2013).