Is the Neutrino its Own Antiparticle?

Jason Detwiler
CENPA

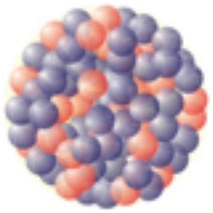
REU Summer Seminar Series
University of Washington, Seattle, WA
July 22, 2013

Outline

- What's a neutrino?
- The case for Majorana neutrinos
- Probing the nature of the neutrino with neutrinoless double-beta decay

What's a Neutrino?

Meitner and Hahn (1911):



^{210}Bi

What's a Neutrino?

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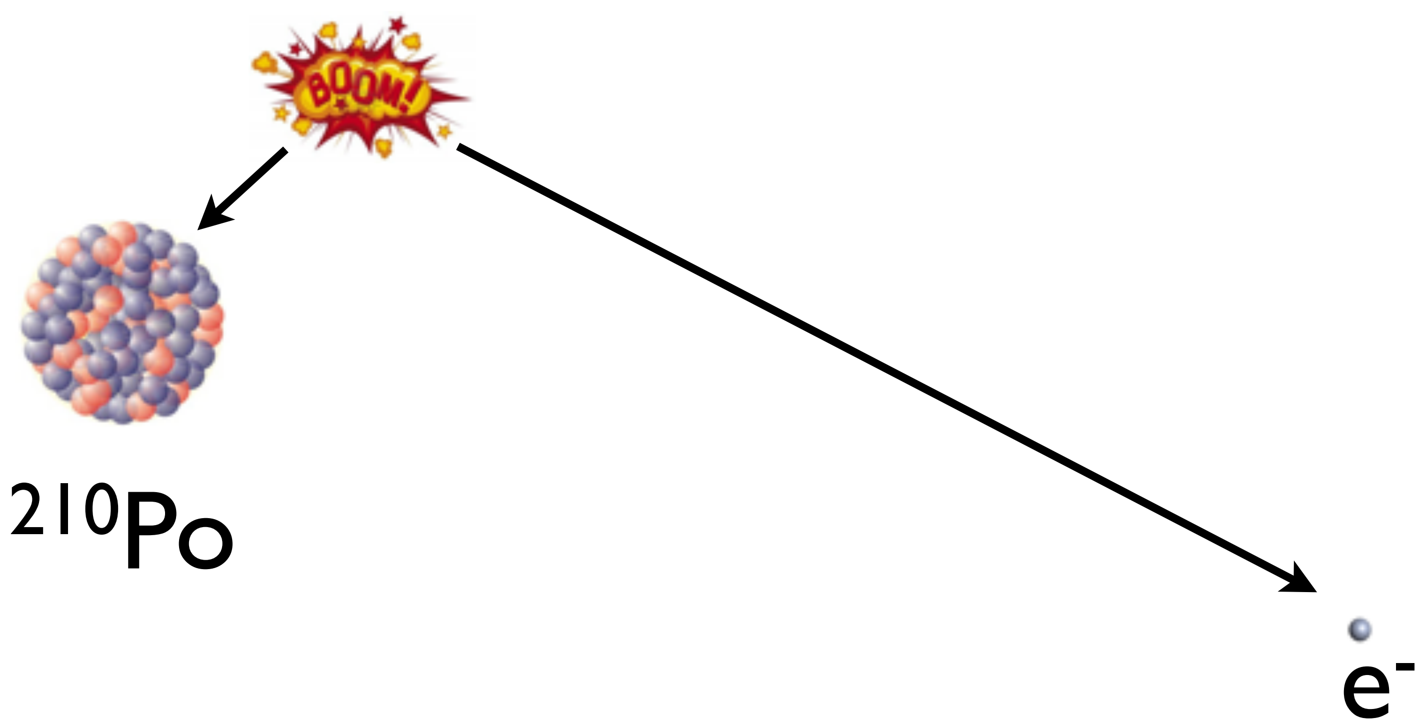
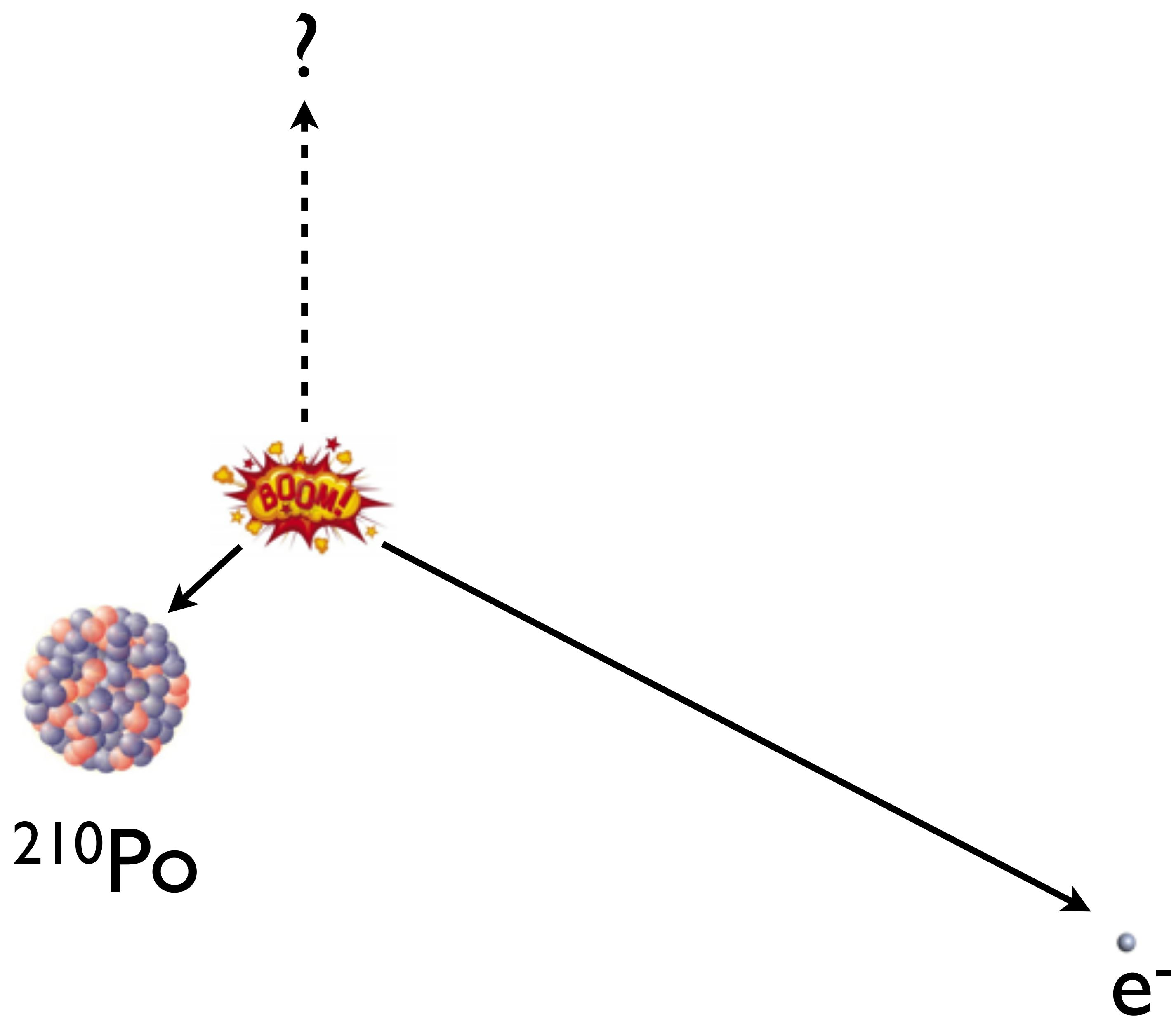


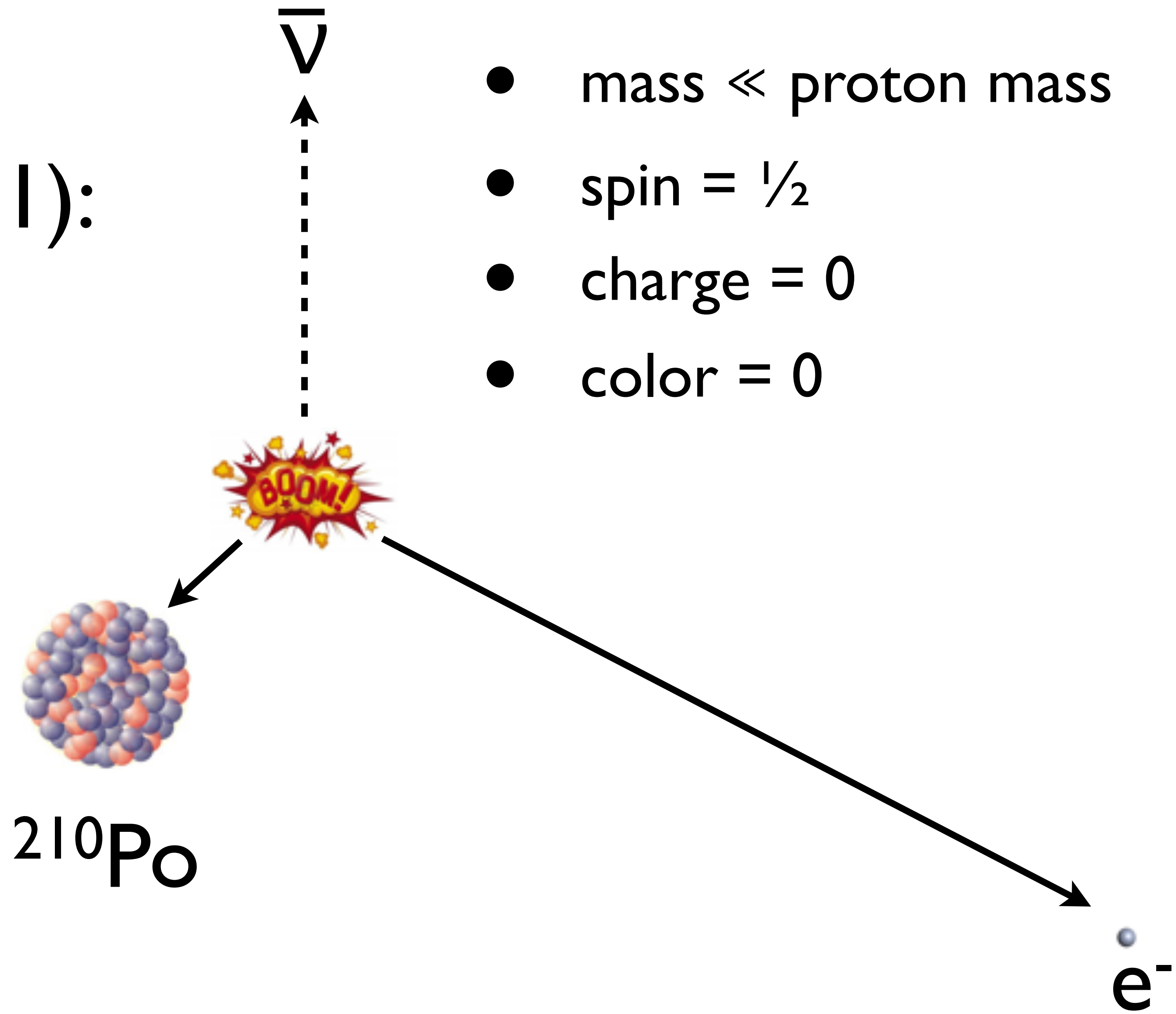
What's a Neutrino?

Meitner and Hahn (1911):



What's a Neutrino?

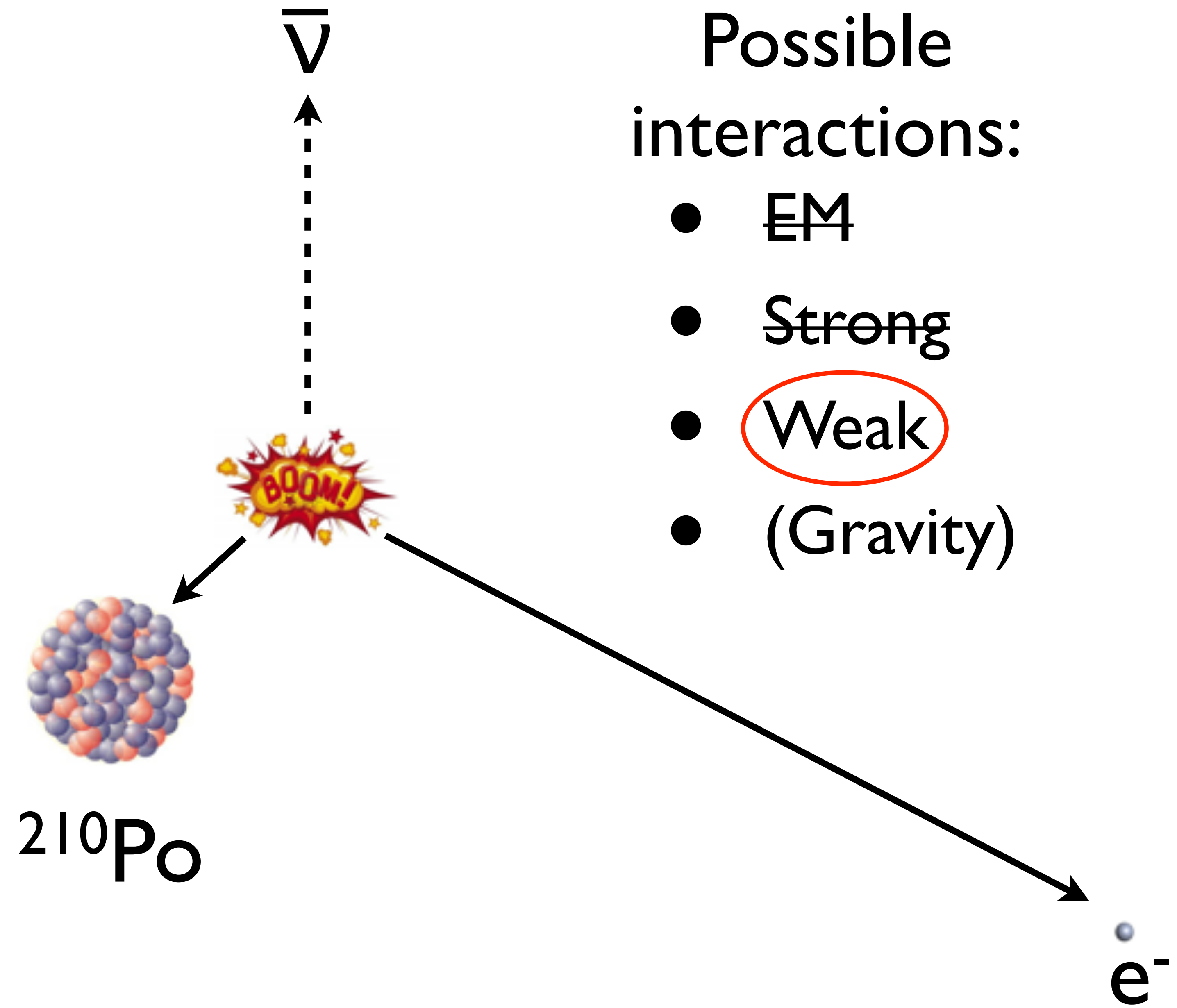
Wolfgang Pauli (1931):



- mass ≪ proton mass
- spin = ½
- charge = 0
- color = 0

What's a Neutrino?

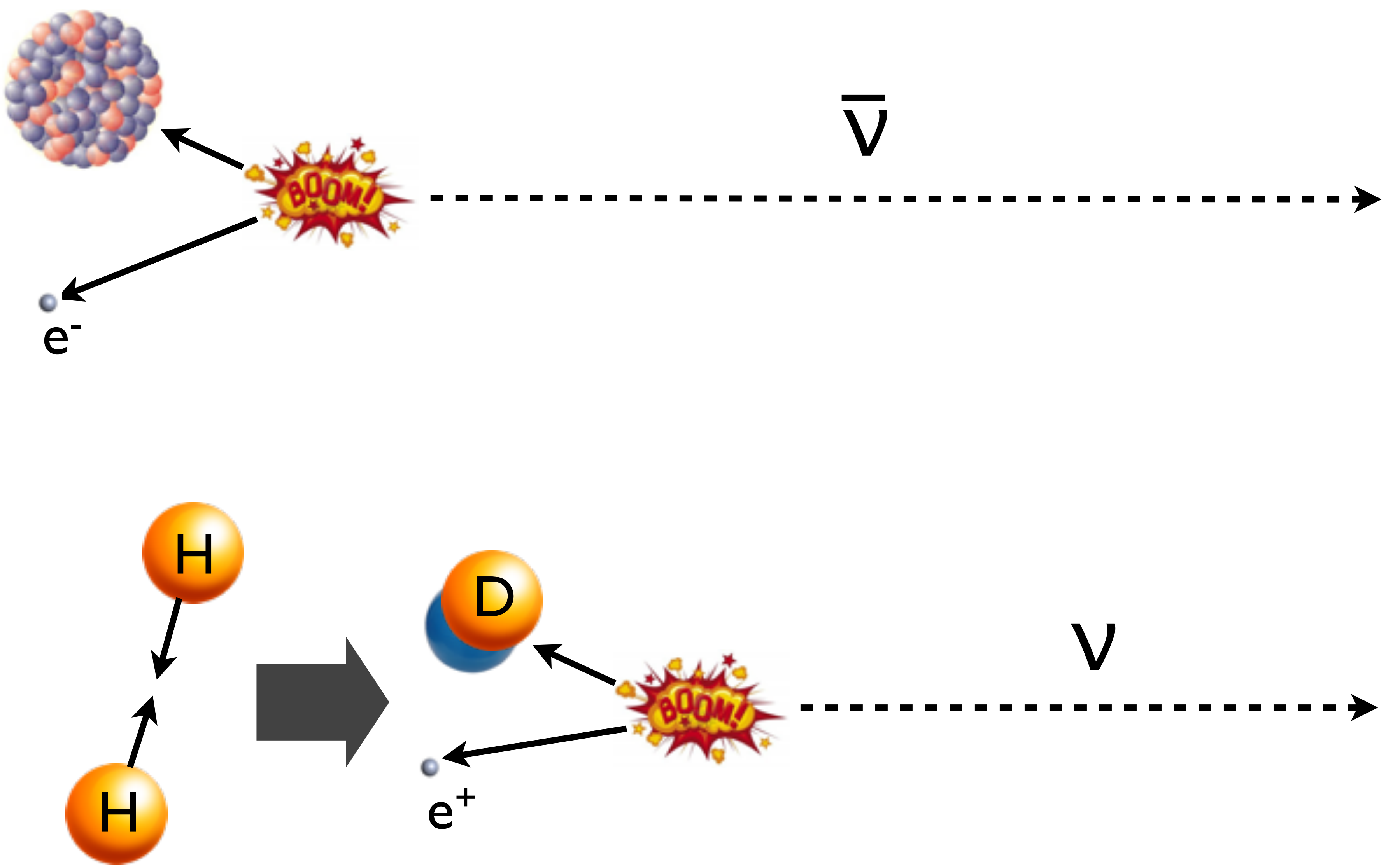
Enrico Fermi (1934):
"Little neutral one"



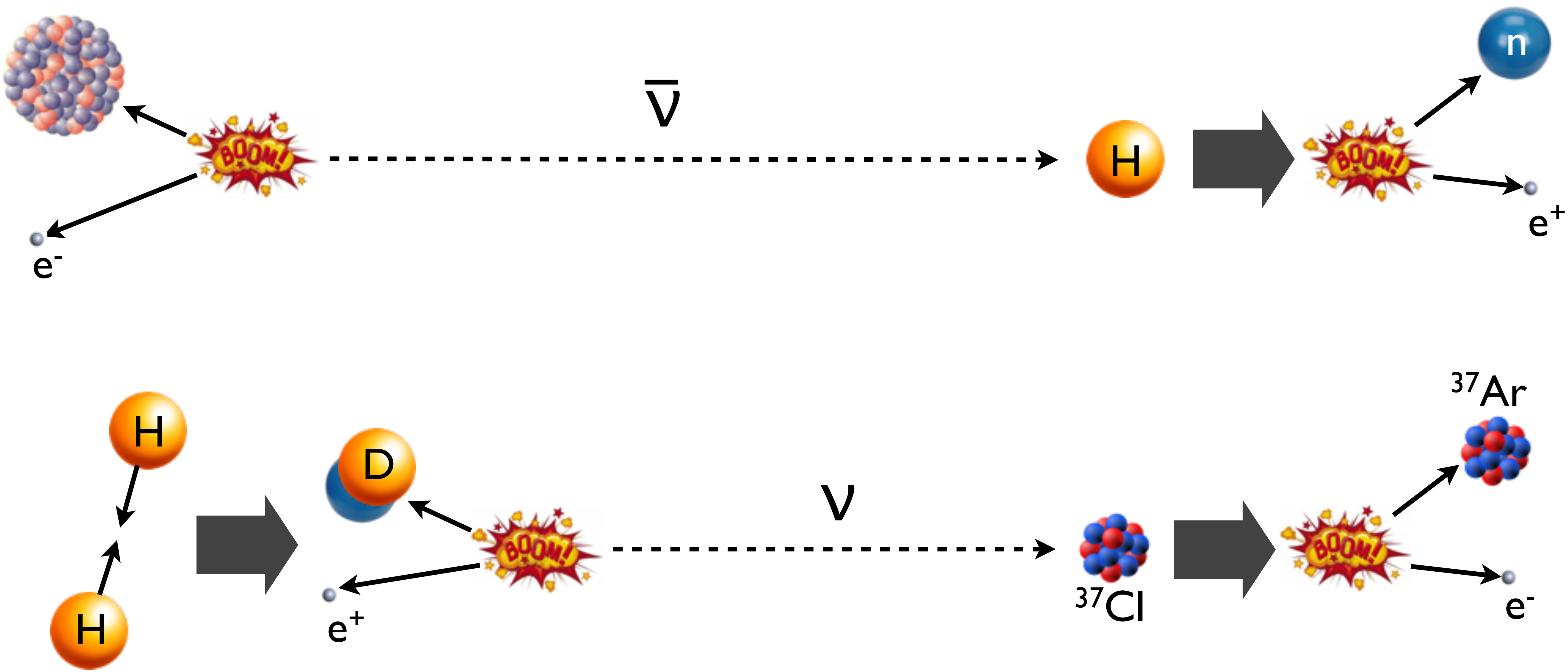
Possible interactions:

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

Detecting Neutrinos and Antineutrinos



Detecting Neutrinos and Antineutrinos



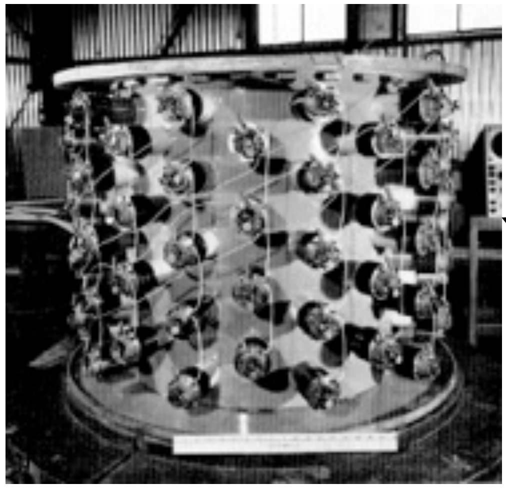
Detecting Neutrinos and Antineutrinos

Nuclear Reactor

$\bar{\nu}$

Cowan and Reines (1956)

Scintillator (C_xH_y)



PMTs

The Sun

ν

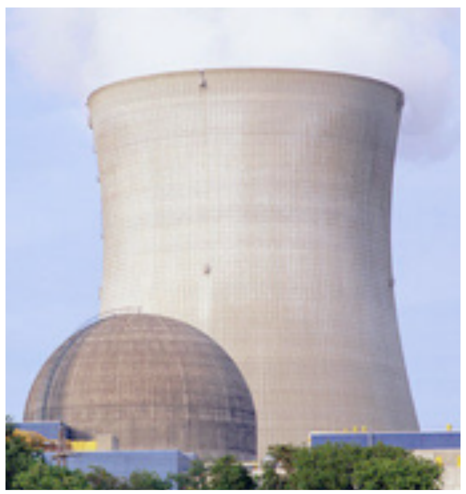
Ray Davis Jr. (1964)

Cleaning fluid (Cl)

+ Ar detector

Detecting Neutrinos and Antineutrinos

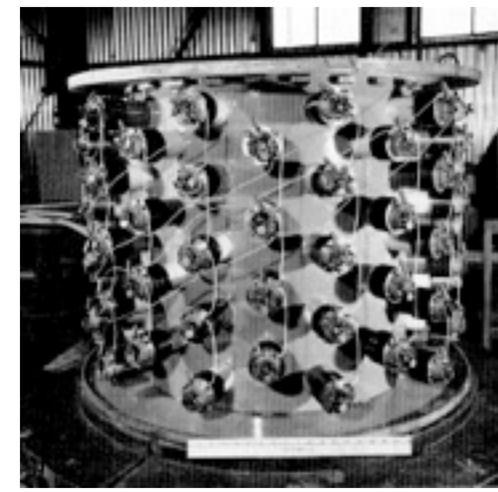
Nuclear Reactor



$\bar{\nu}_R$

Cowan and Reines (1956)

Scintillator (C_xH_y)



PMTs

The Sun

ν_L

Ray Davis Jr. (1964)

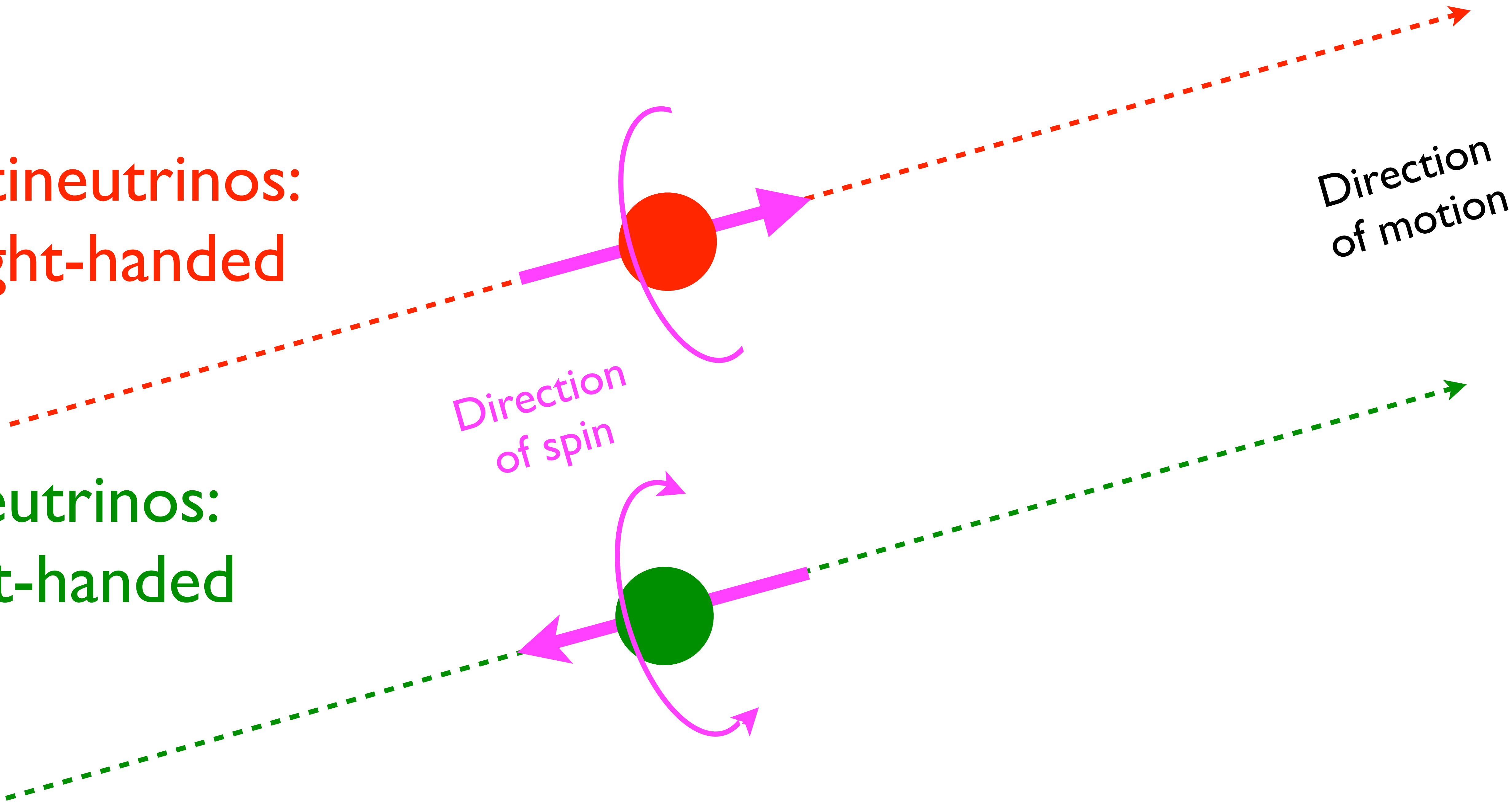
Cleaning fluid (Cl)

+ Ar detector

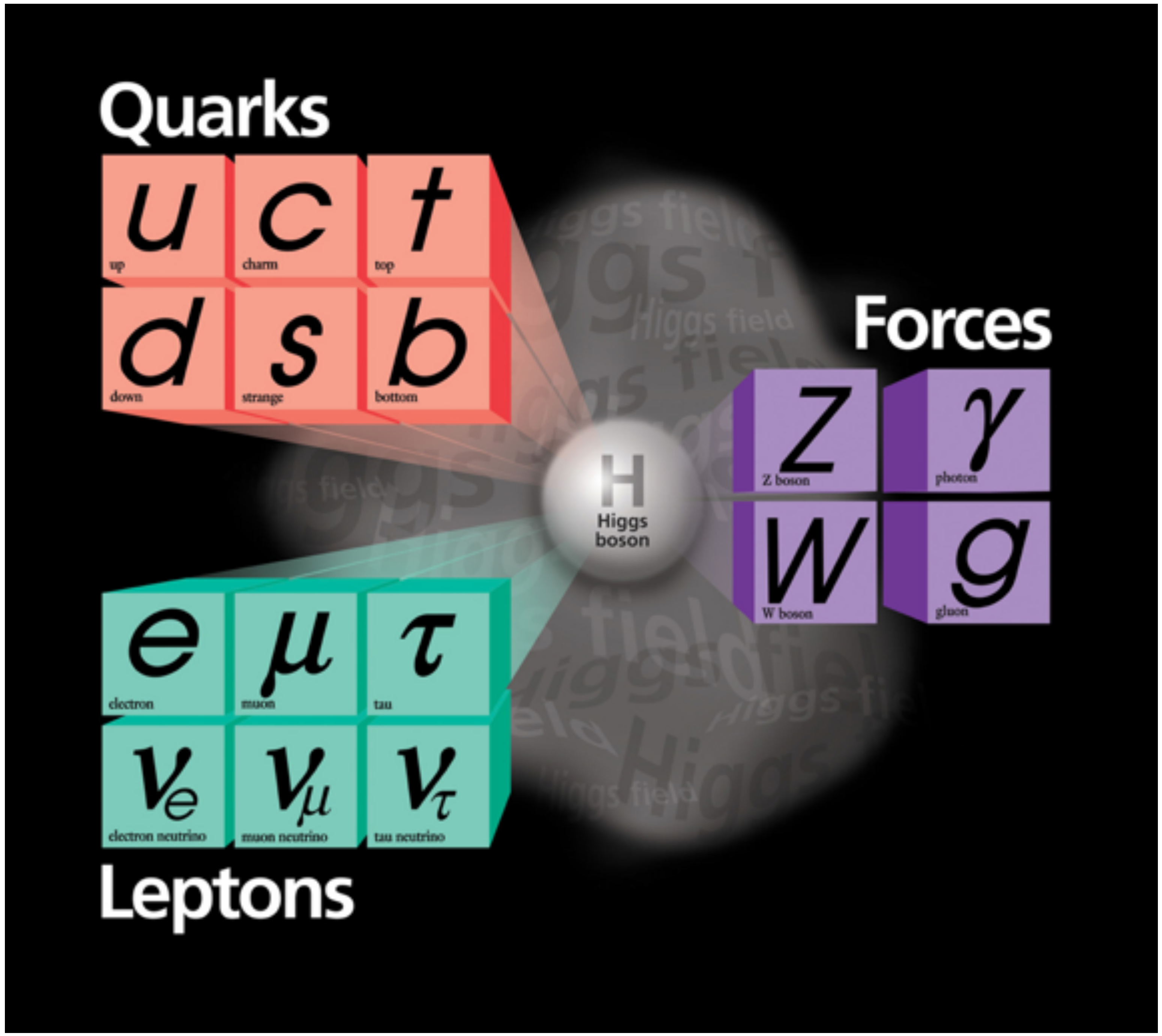
Neutrino Handedness

antineutrinos:
right-handed

neutrinos:
left-handed

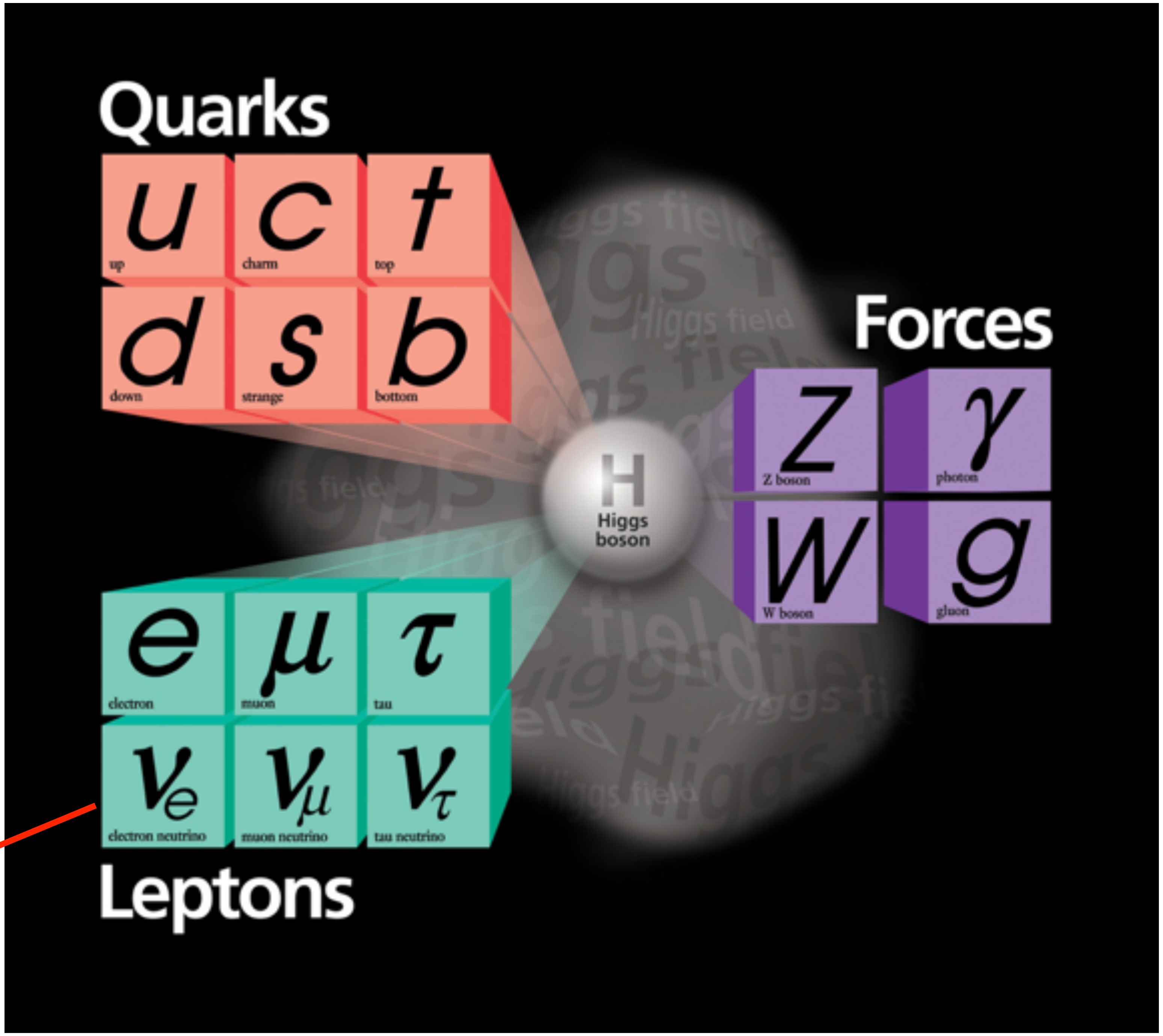


Standard Model Particles



Credit: Fermilab

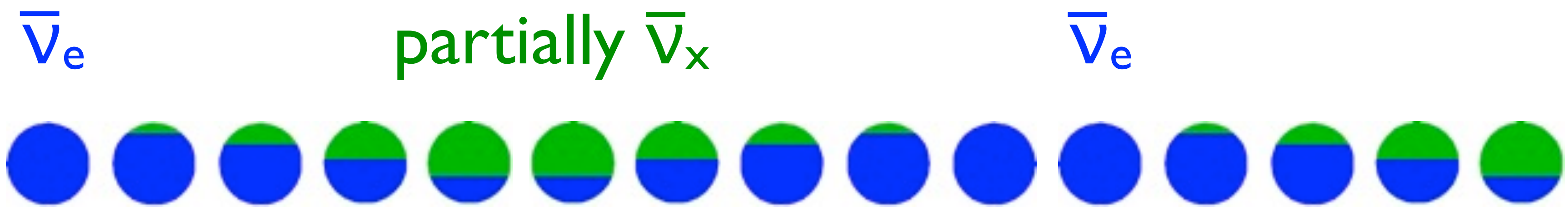
Standard Model Particles

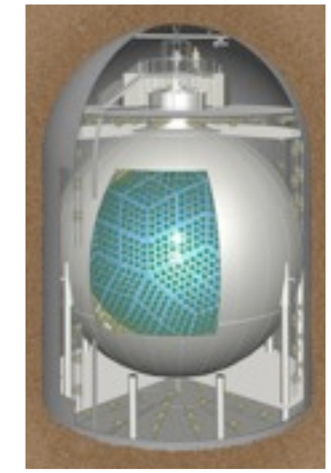


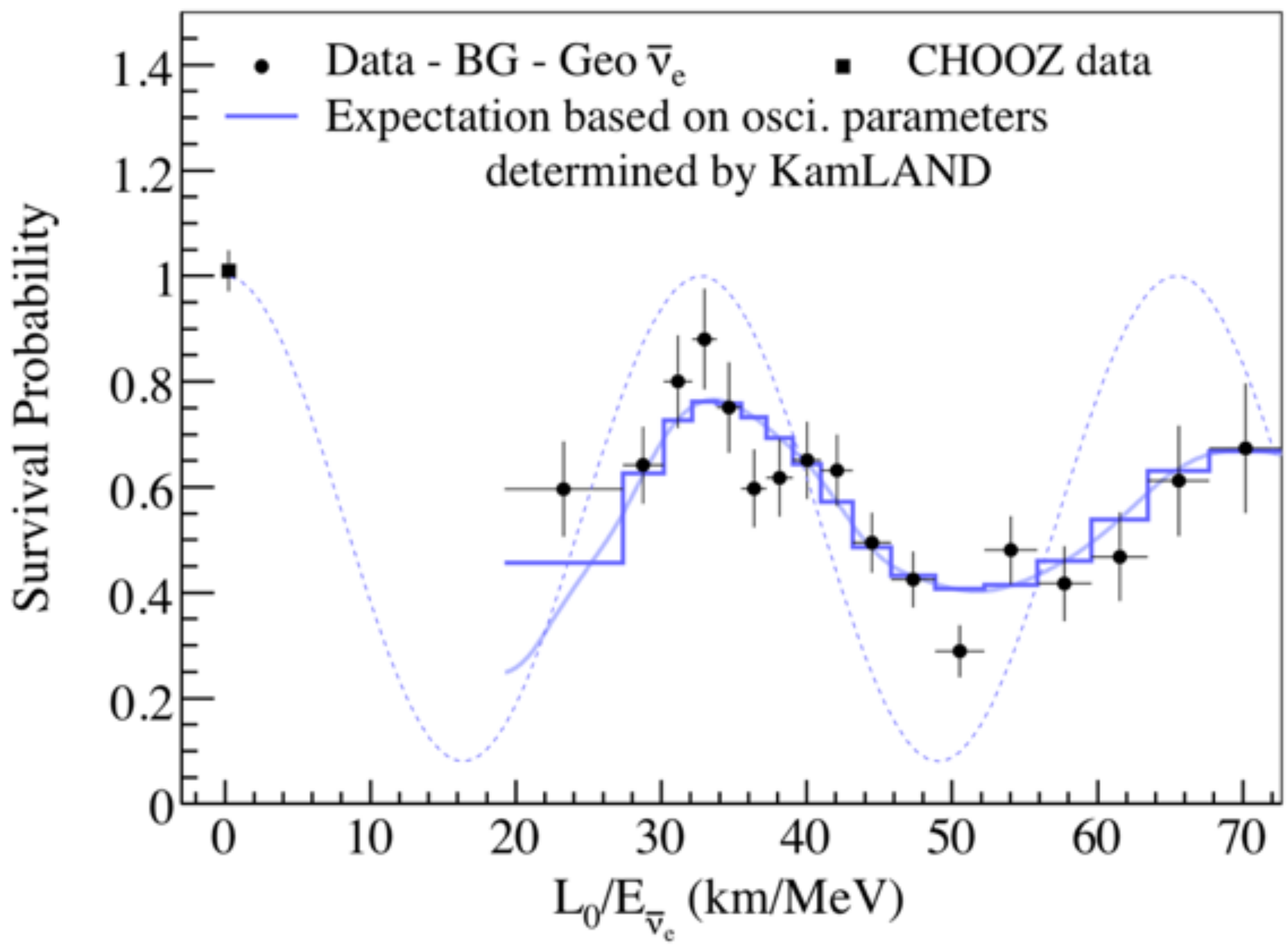
m = 0,
left-handed
only

Credit: Fermilab

Neutrino Oscillation

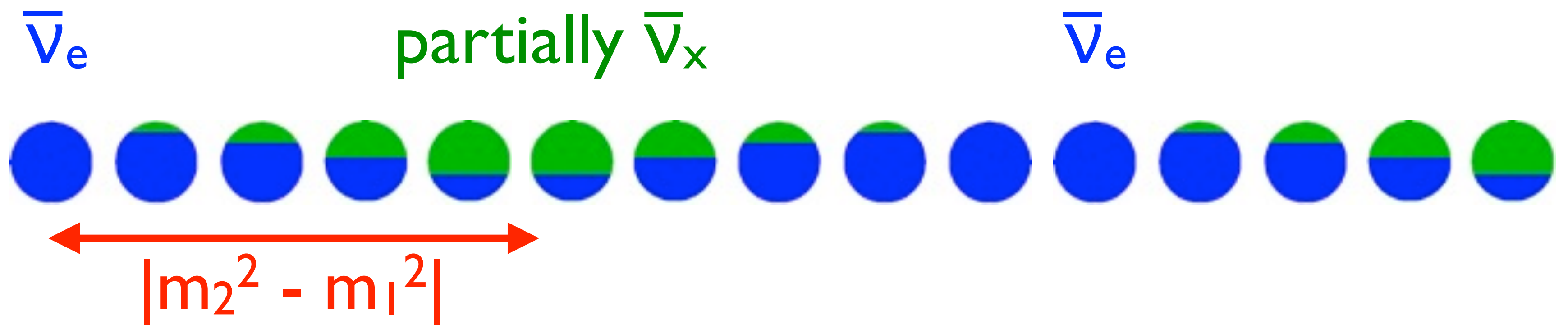


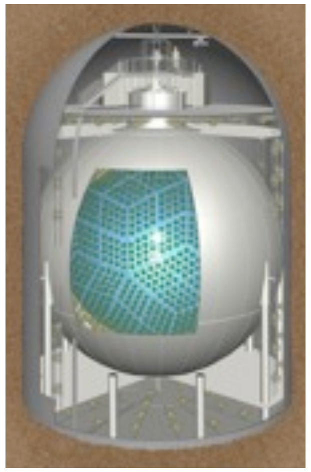


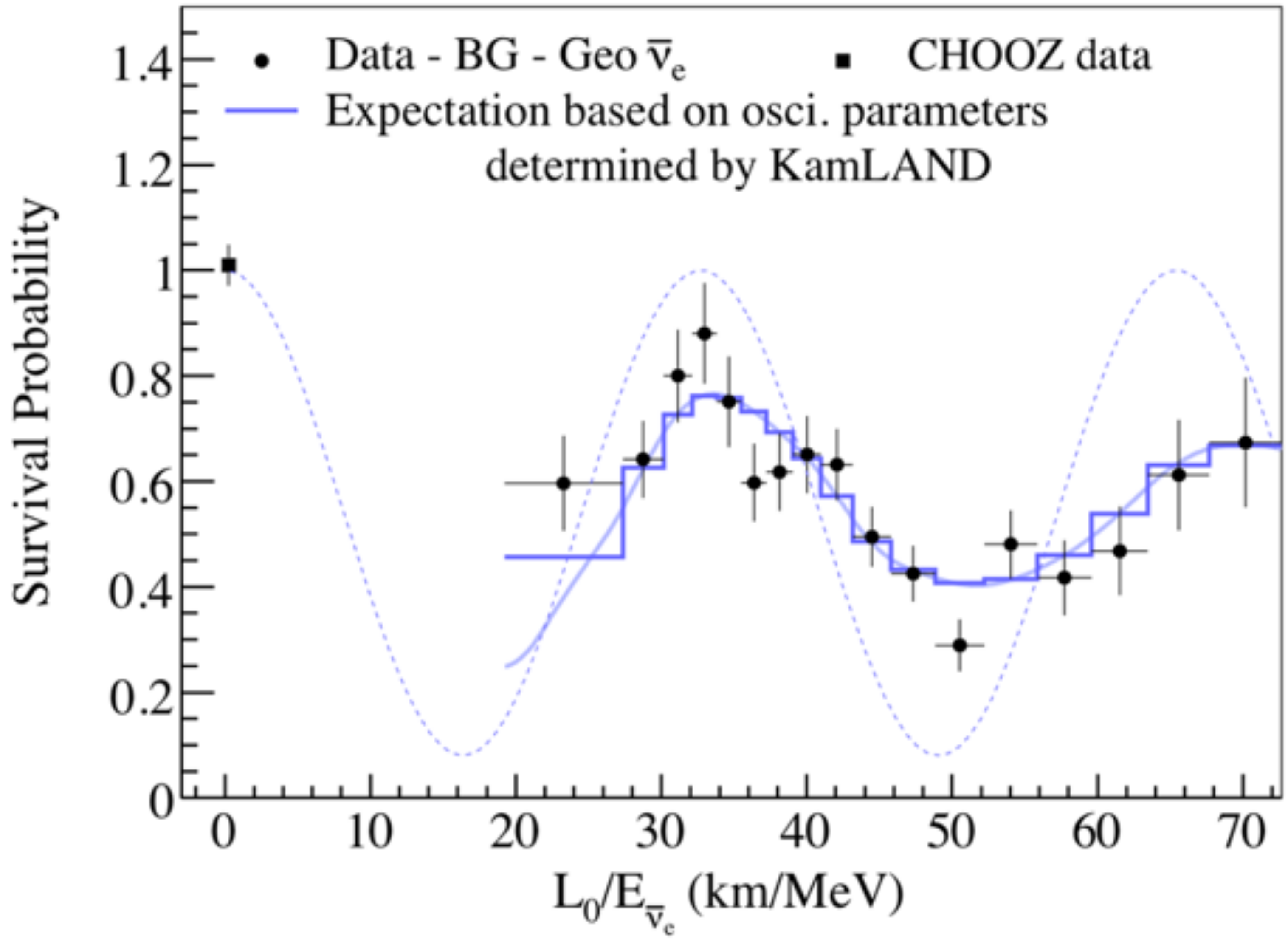


Neutrino Oscillation

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







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

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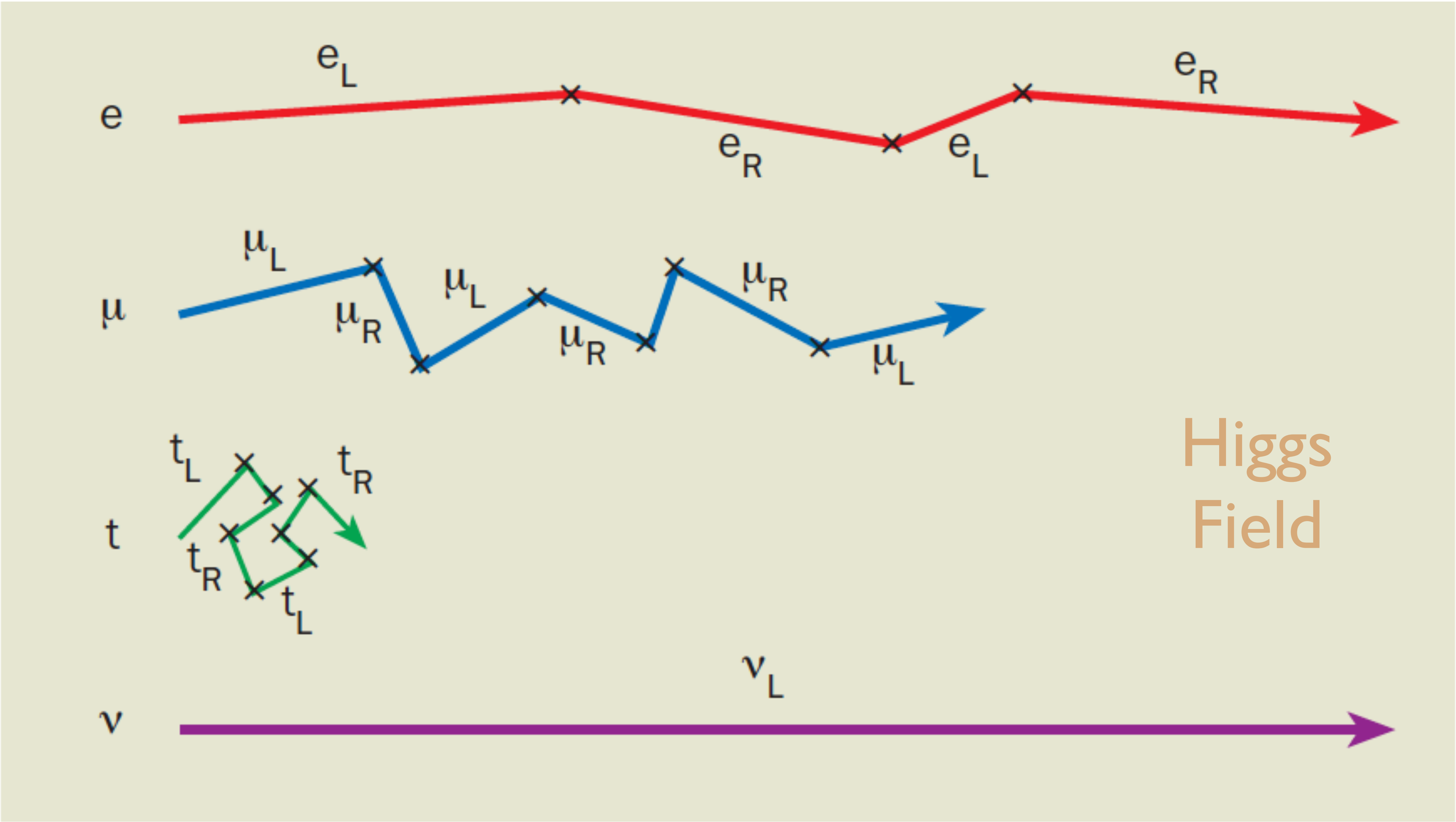
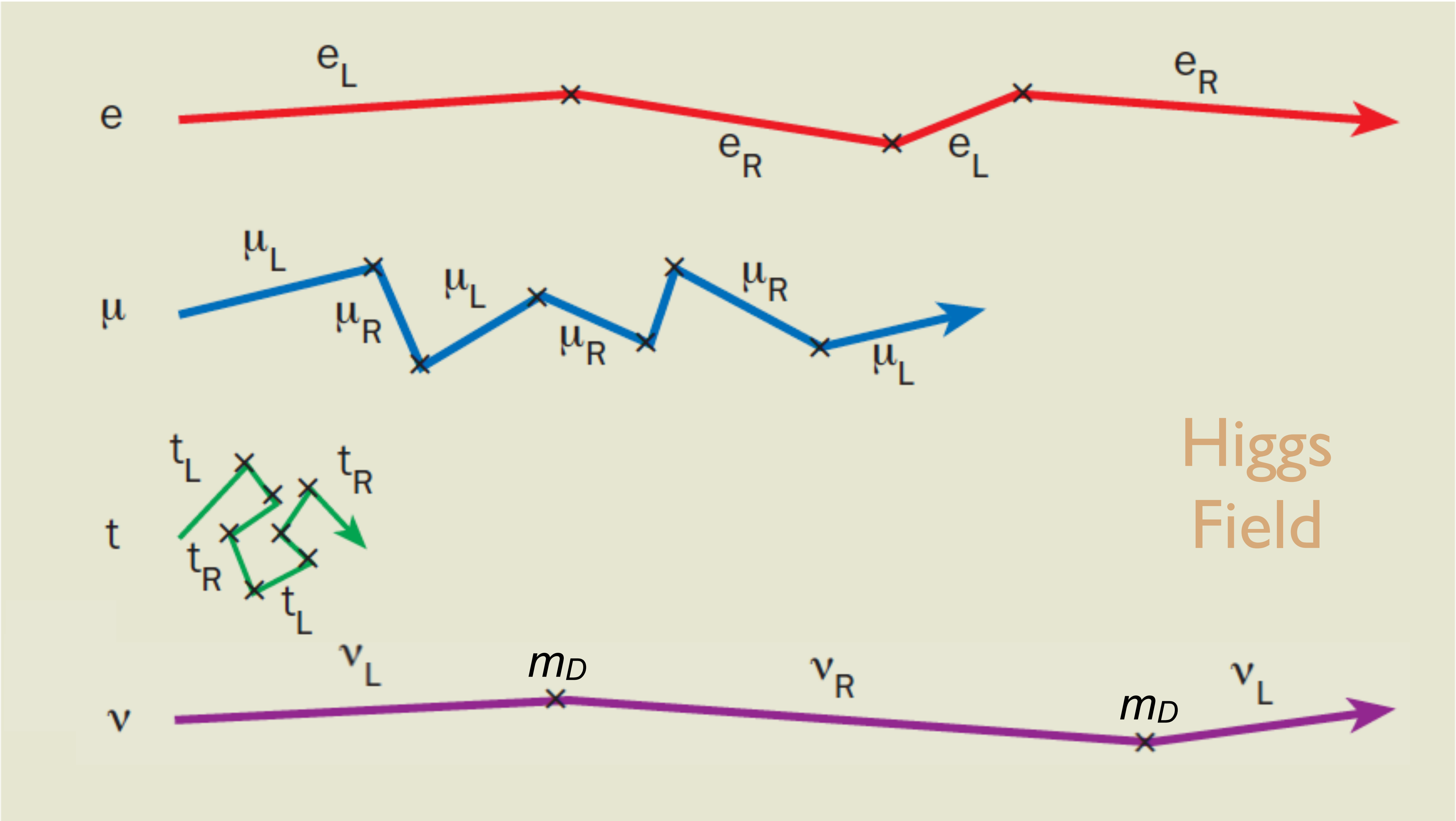
Incorporating ν Mass



Incorporating ν Mass



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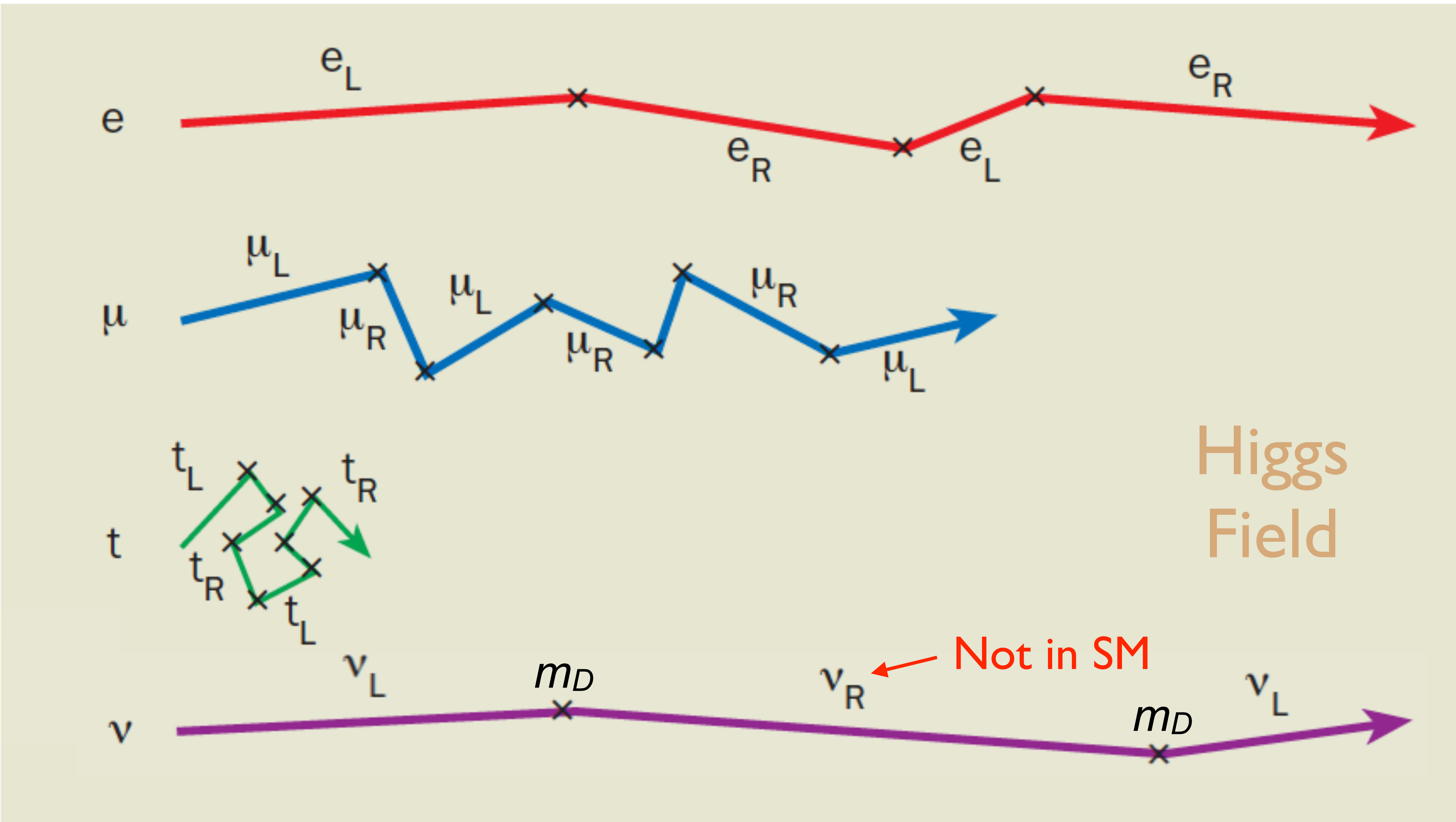

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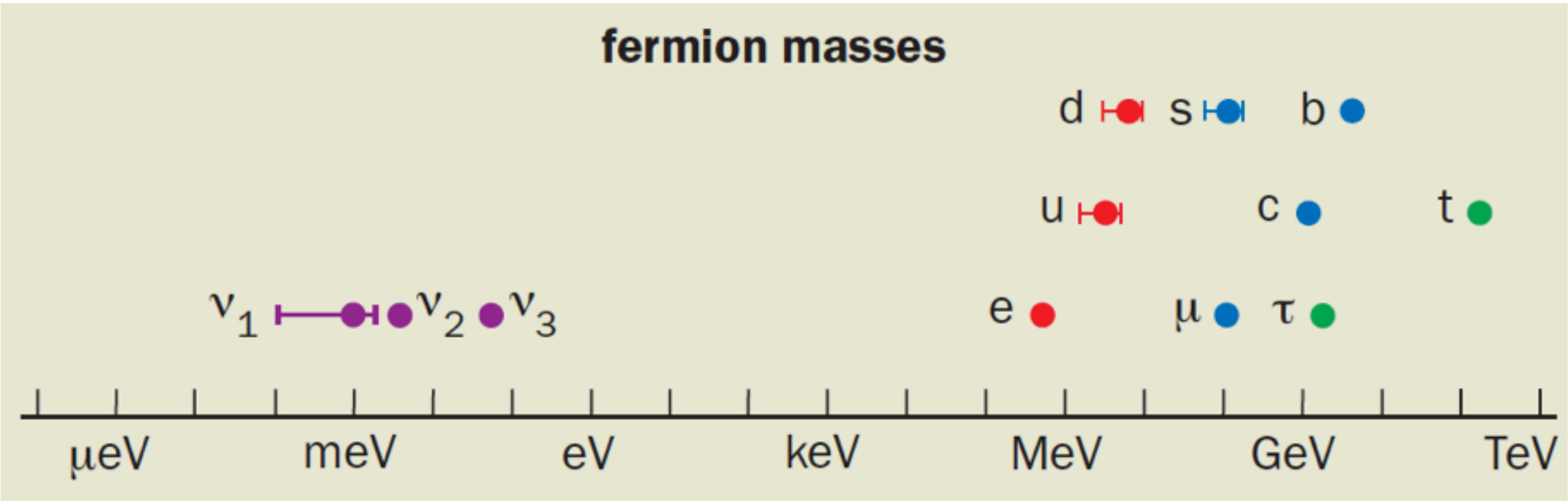

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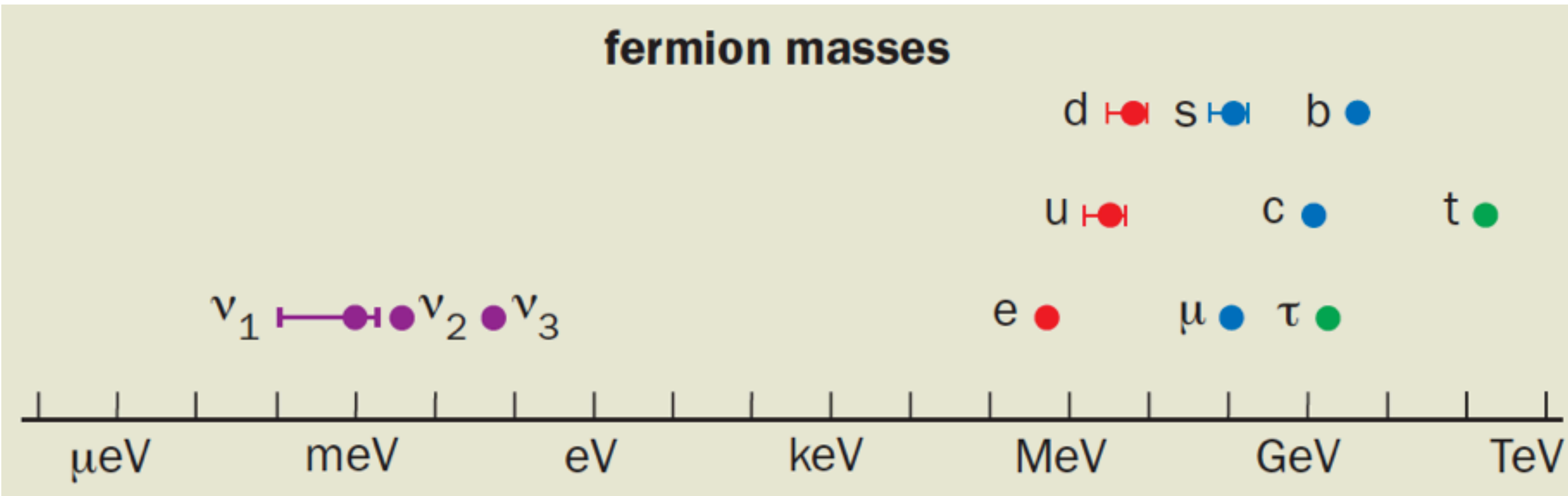
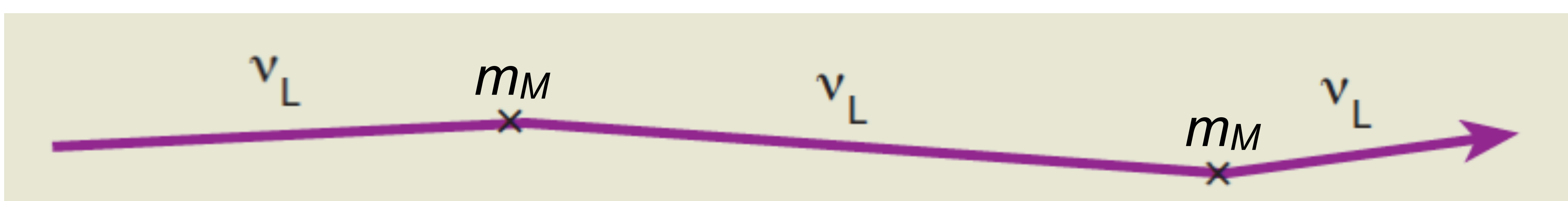


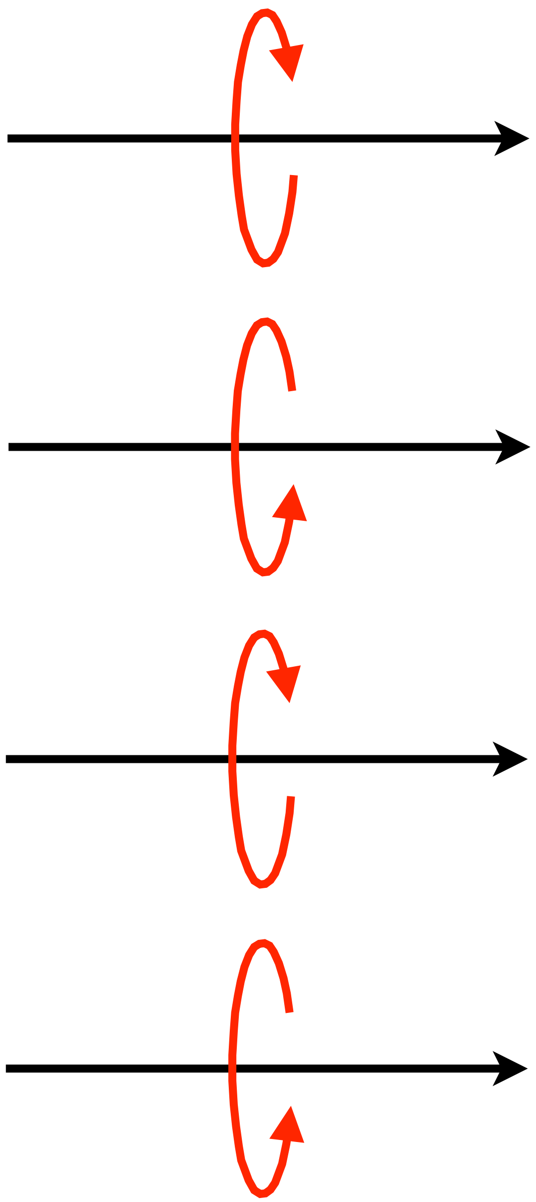
Ettore Majorana



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

Dirac vs Majorana neutrinos

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



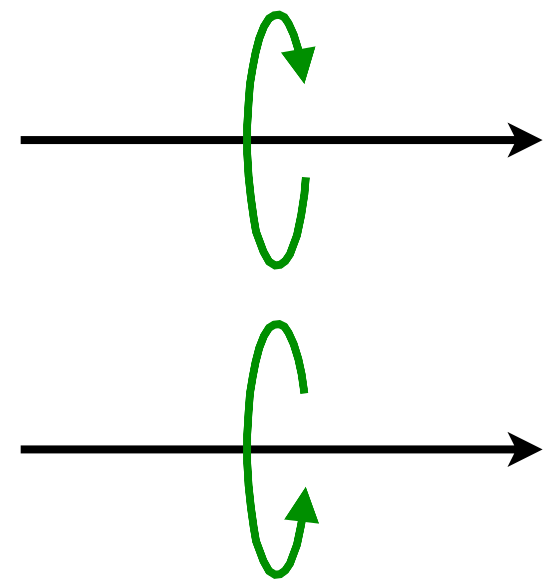
ν_L — produces ℓ^-

ν_R — doesn't interact

$\bar{\nu}_L$ — doesn't interact

$\bar{\nu}_R$ — produces ℓ^+

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

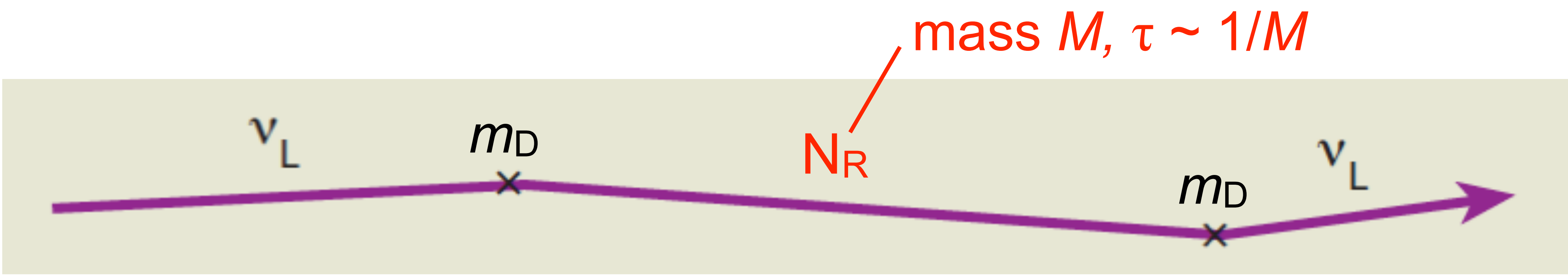


$\overset{(-)}{\nu}_L$ — produces ℓ^-

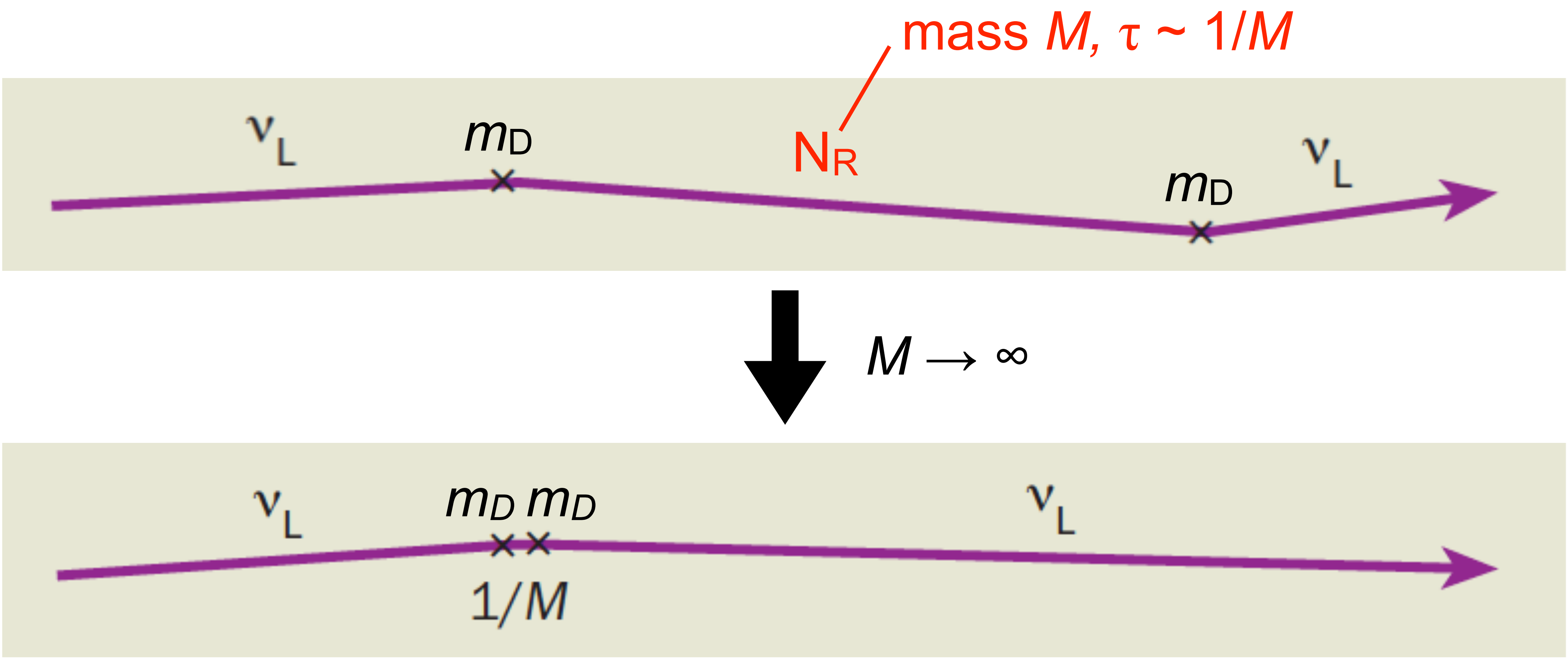
$\overset{(-)}{\nu}_R$ — produces ℓ^+

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

Seesaw Mechanism



Seesaw Mechanism



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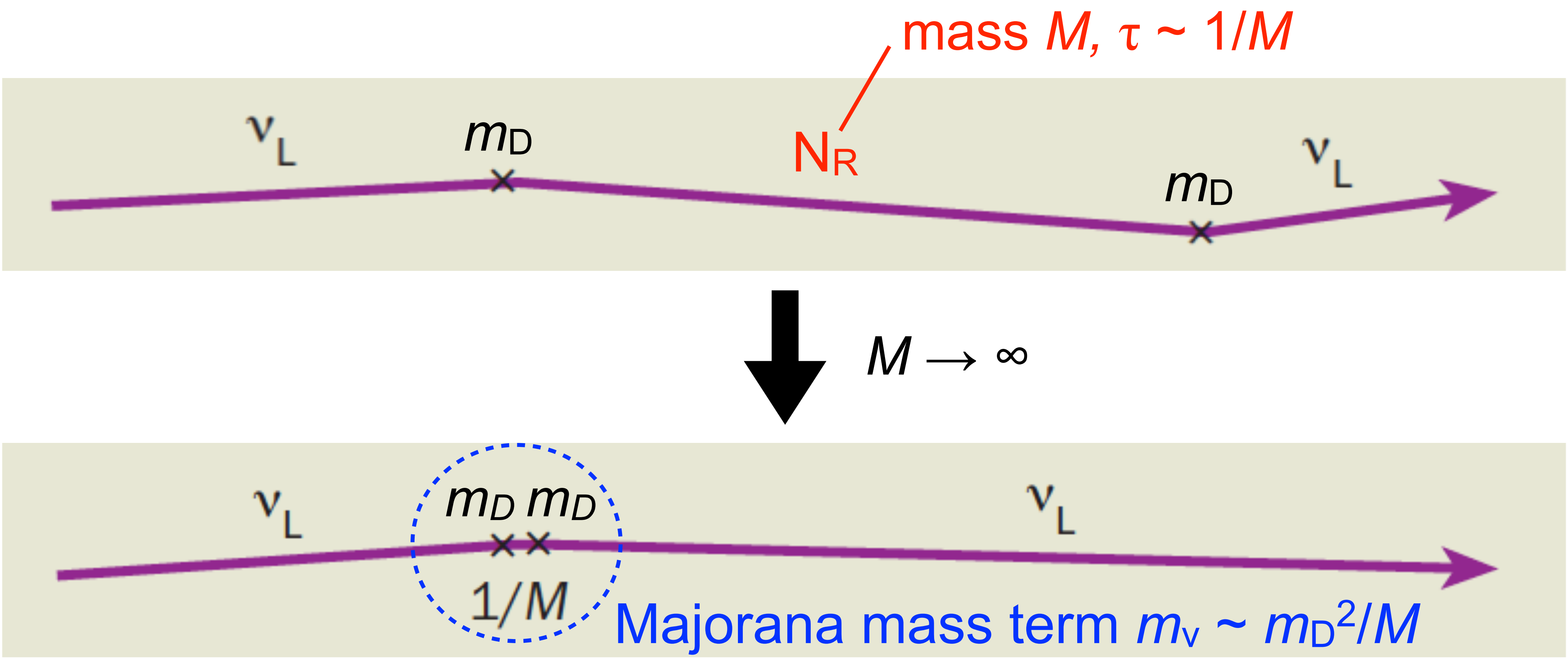

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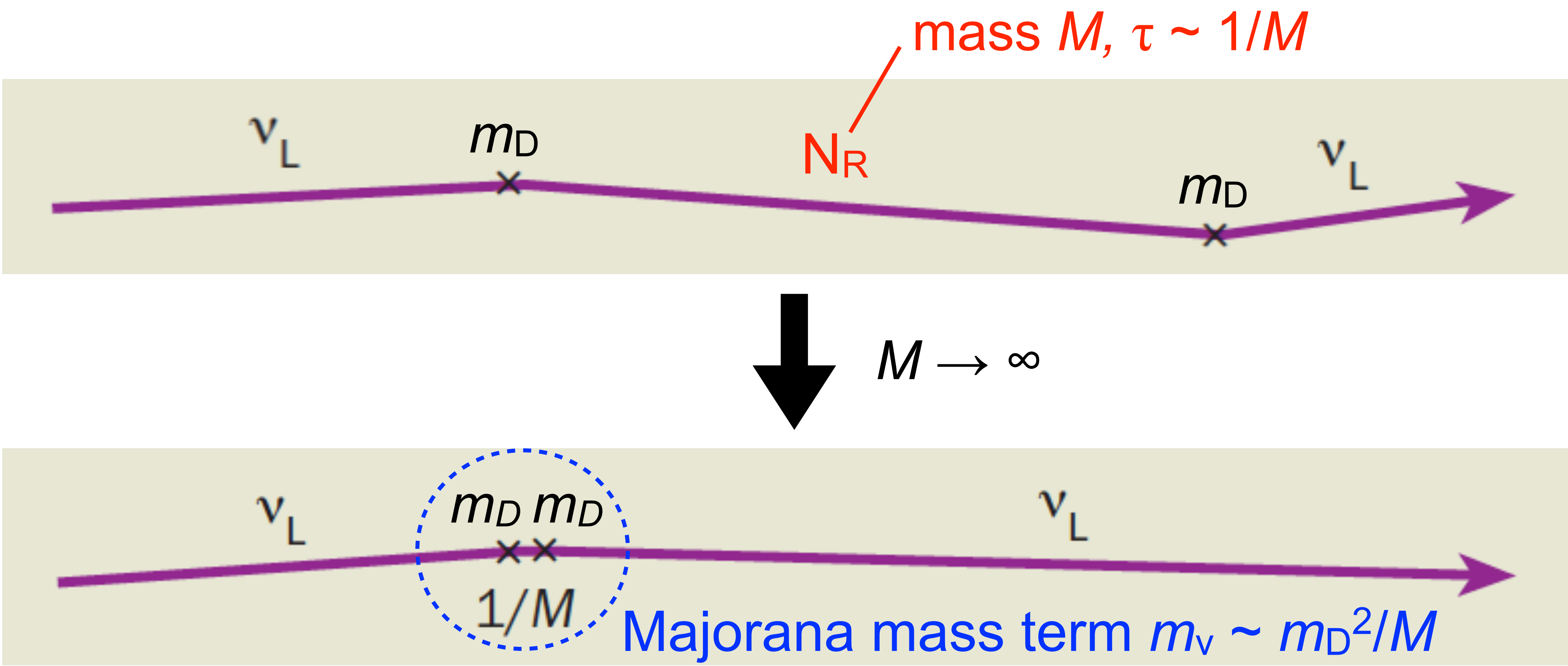
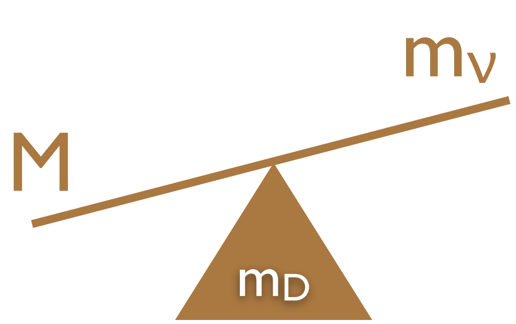
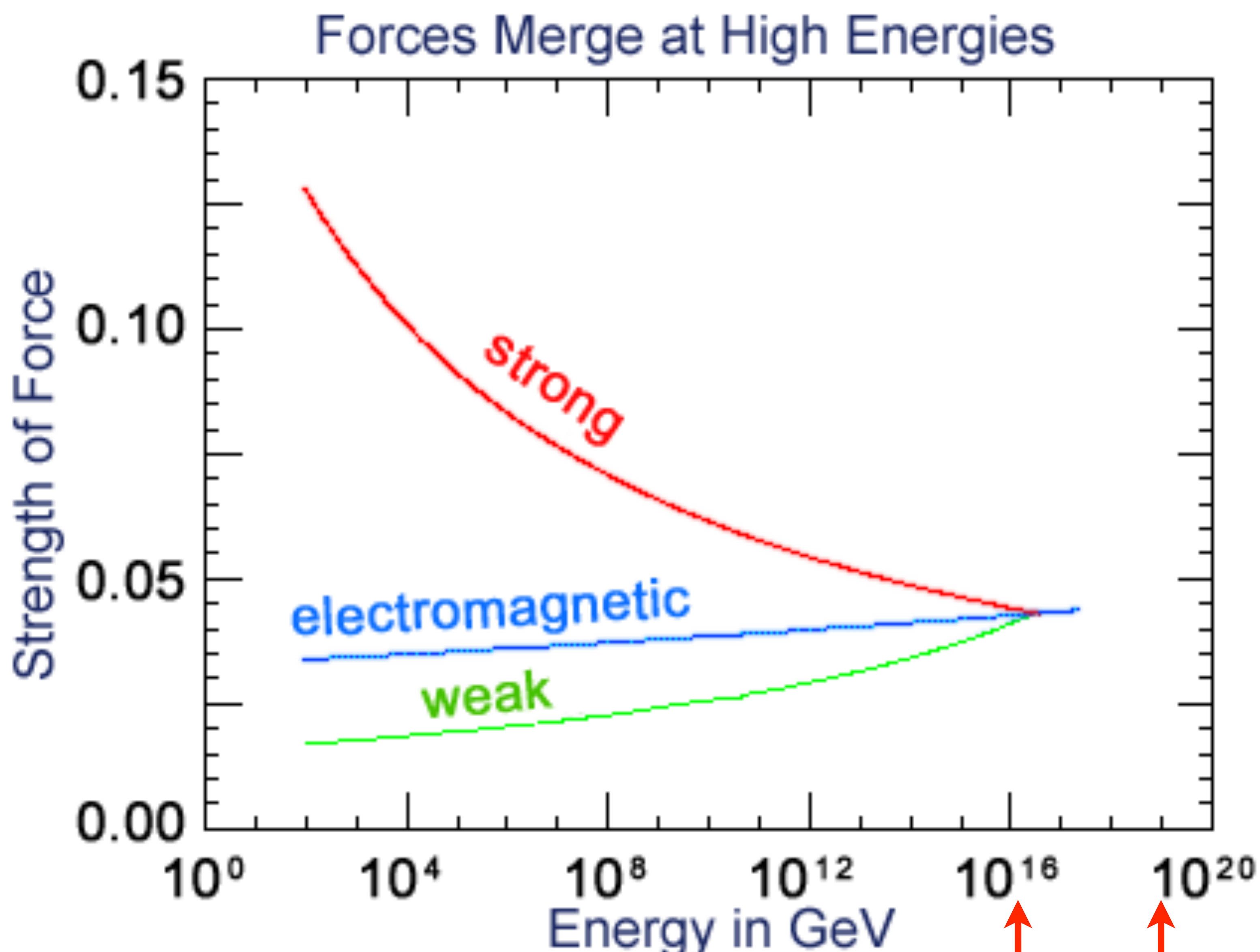




for m_D ~ GeV-TeV:

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

Grand Unification

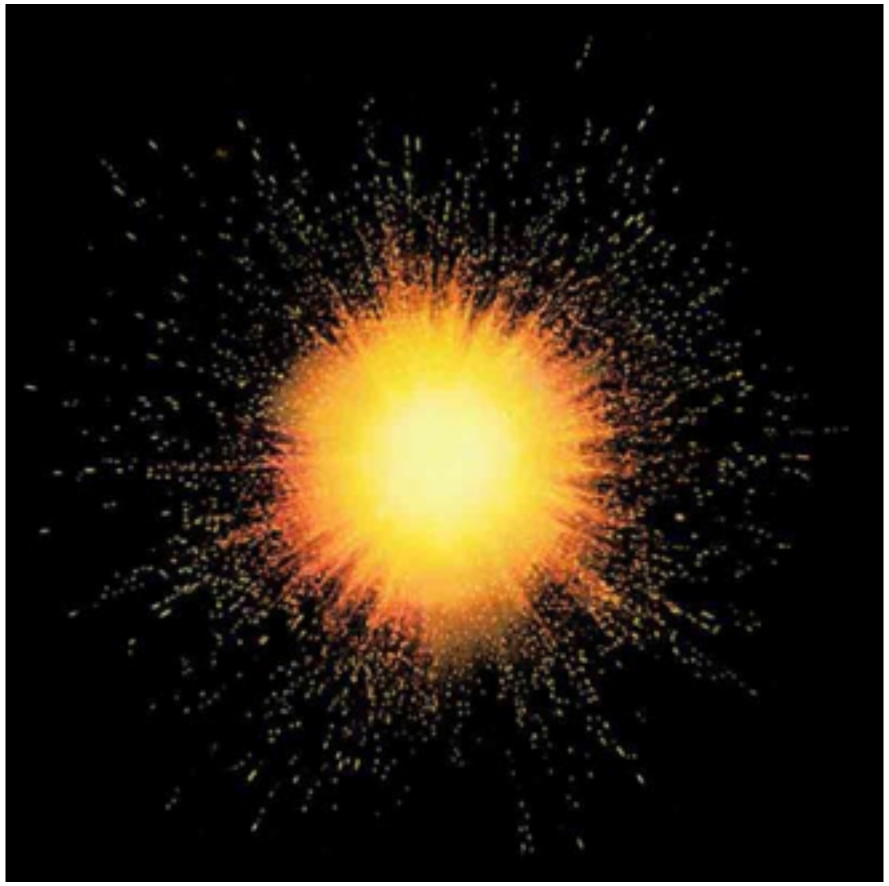


GUT scale

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

Matter-Antimatter Asymmetry

The Big Bang



matter + antimatter

The Universe Today

matter only

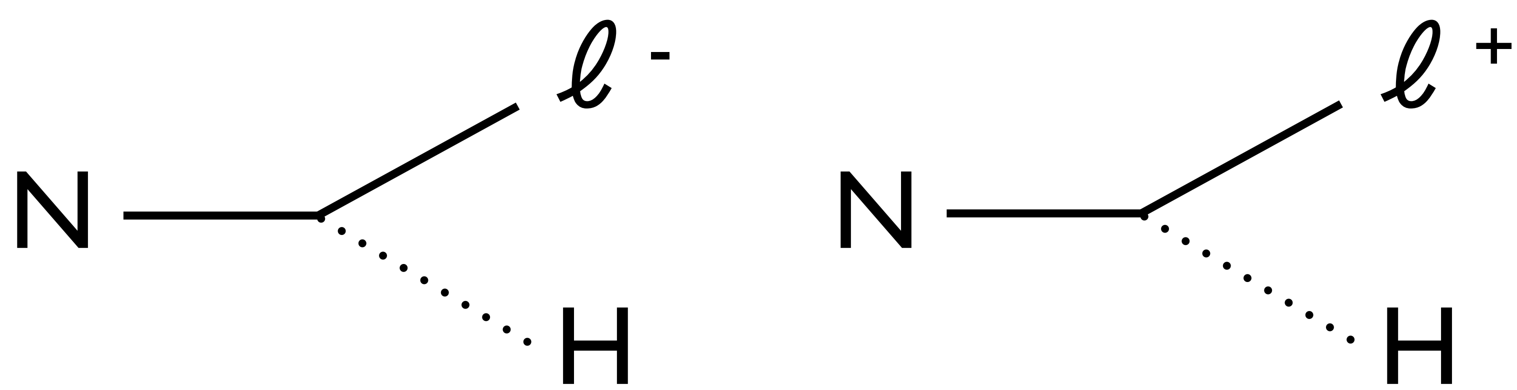
Sakharov Conditions

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

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

Leptogenesis

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



- 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 at all!

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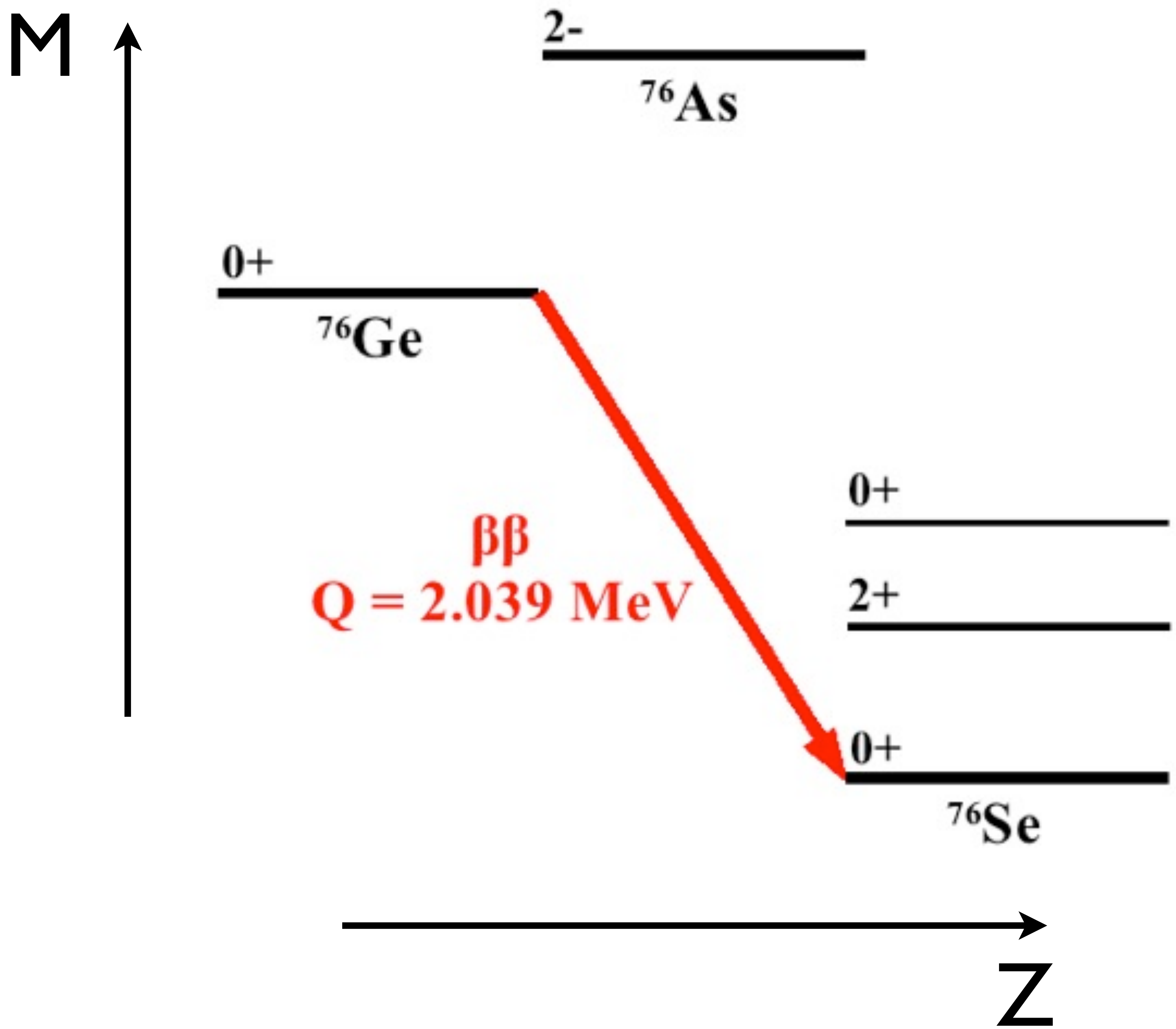
Double-Beta Decay



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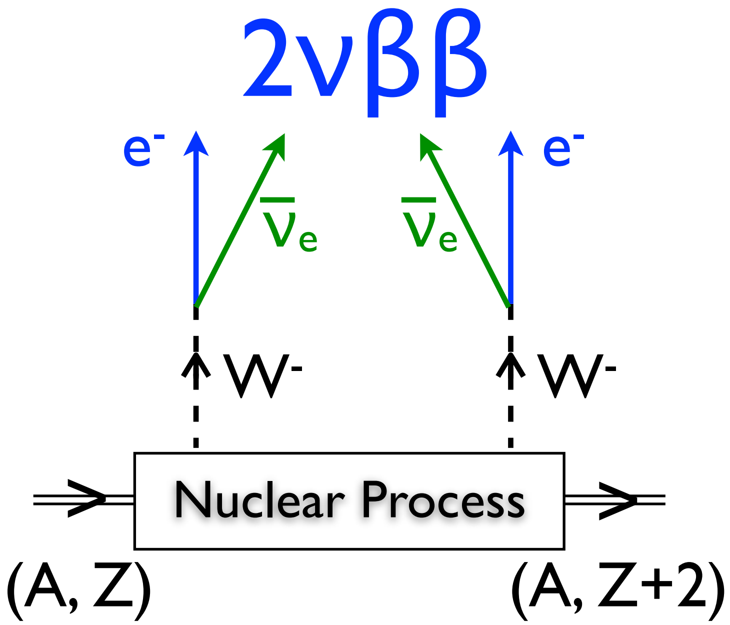
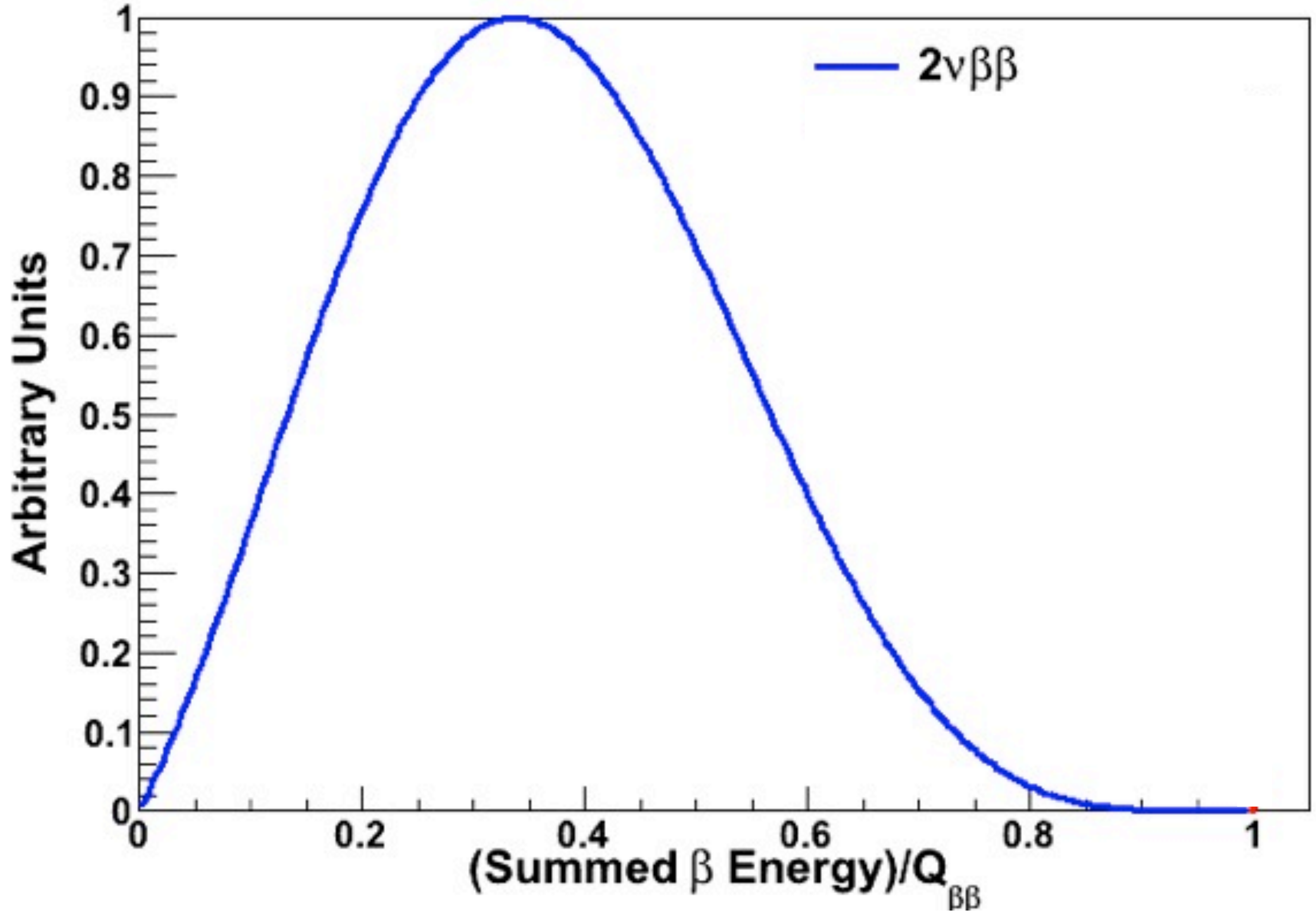
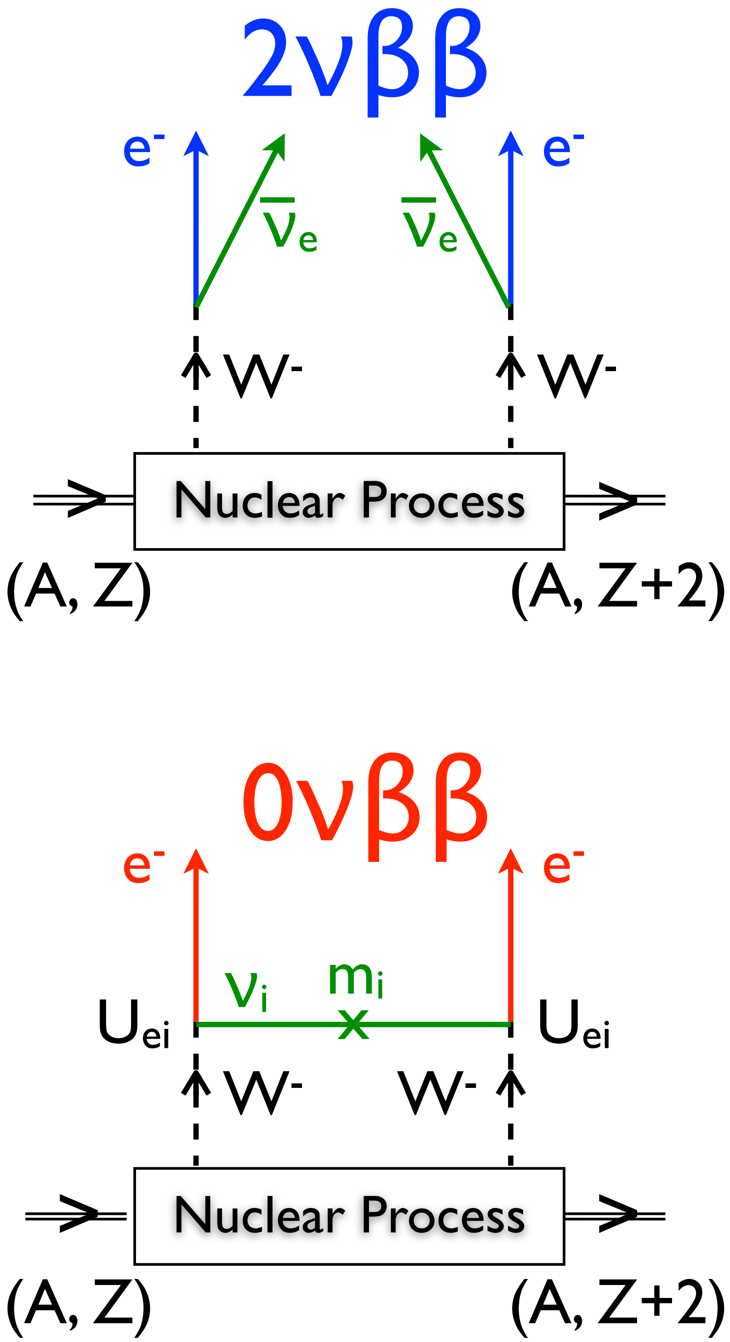
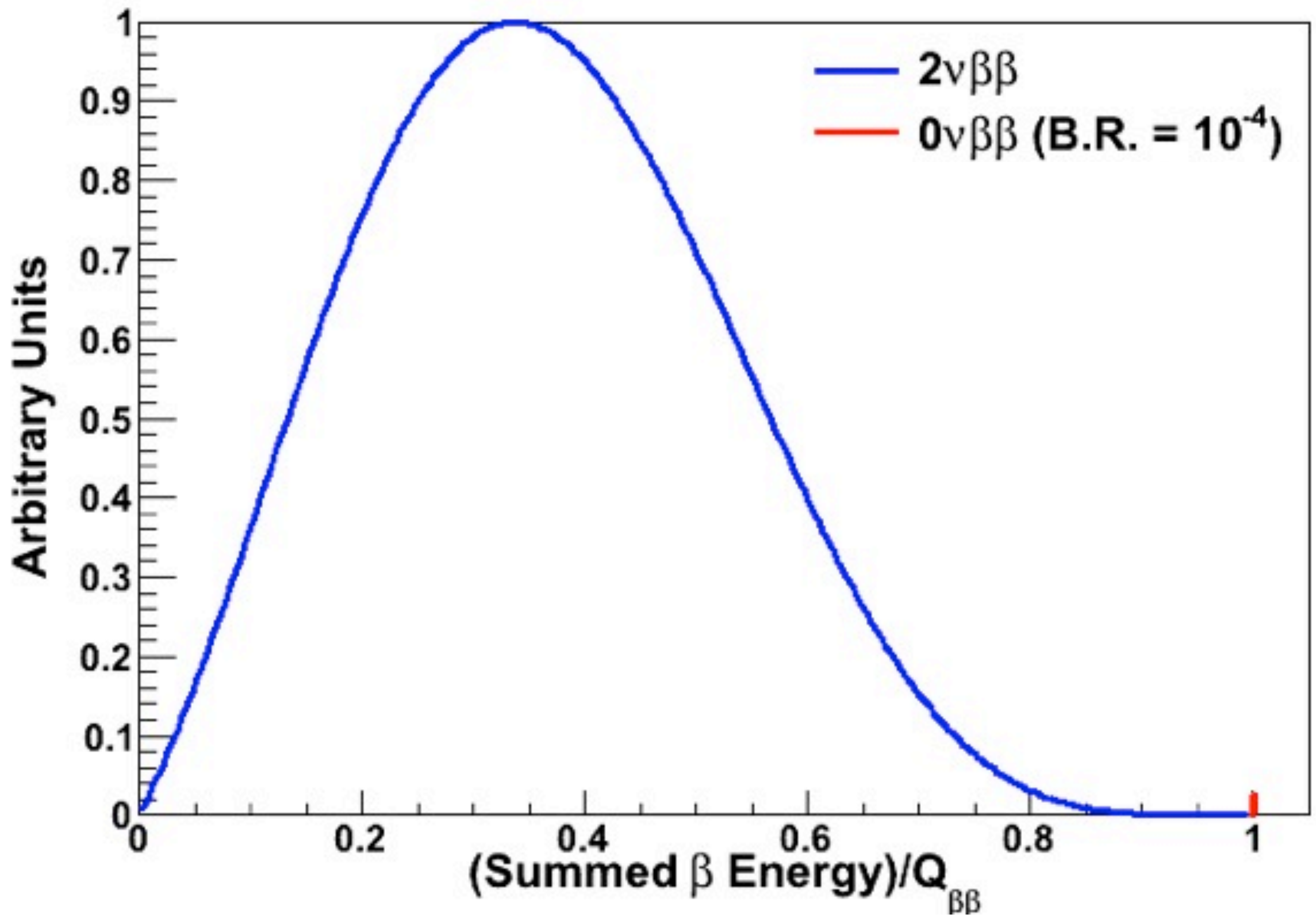




0νββ Decay



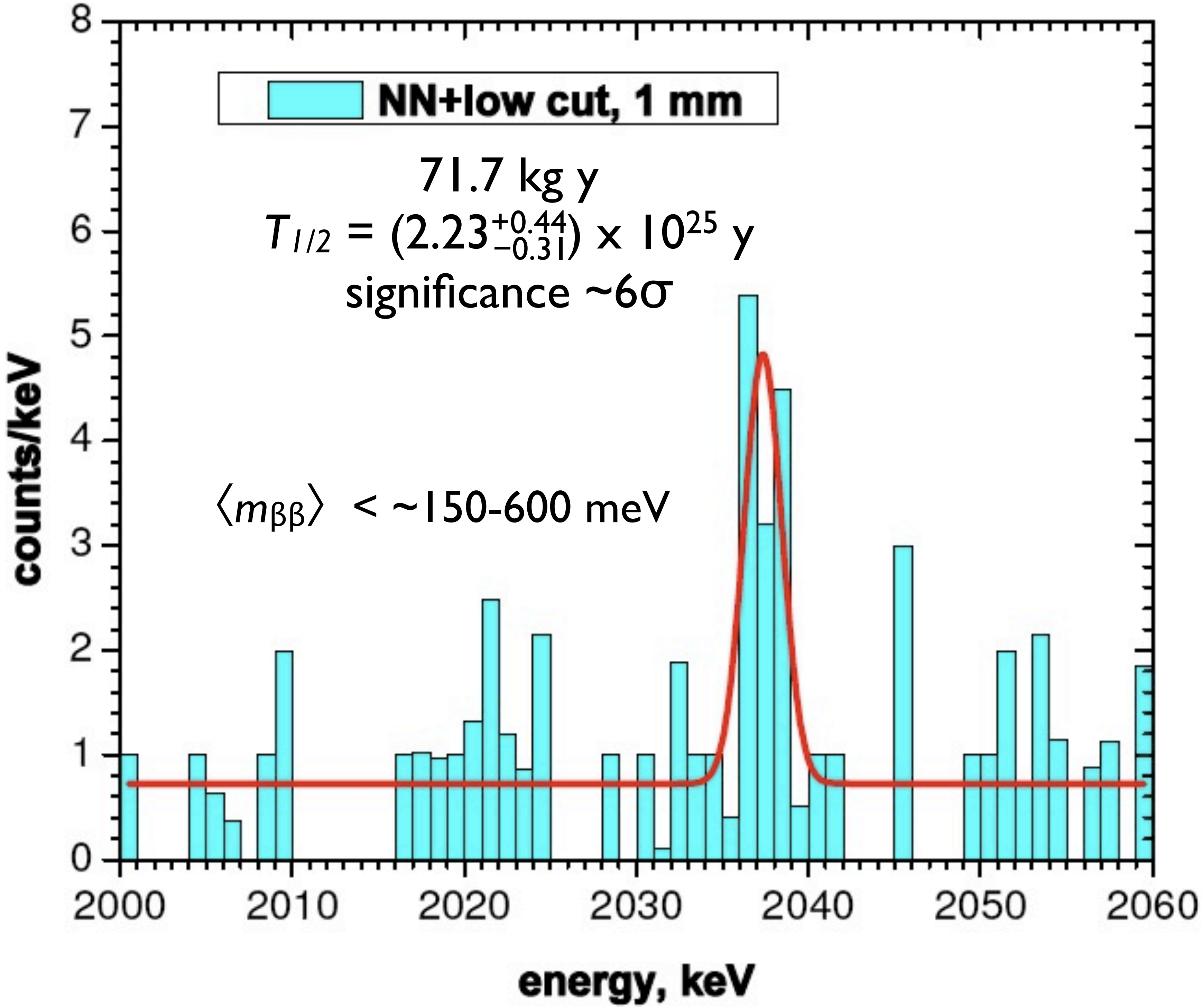


$$\Gamma_{1/2}^{0\nu} = G^{0\nu} |M^{0\nu}|^2 \langle m_{\beta\beta} \rangle^2$$

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

Claimed Observation

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



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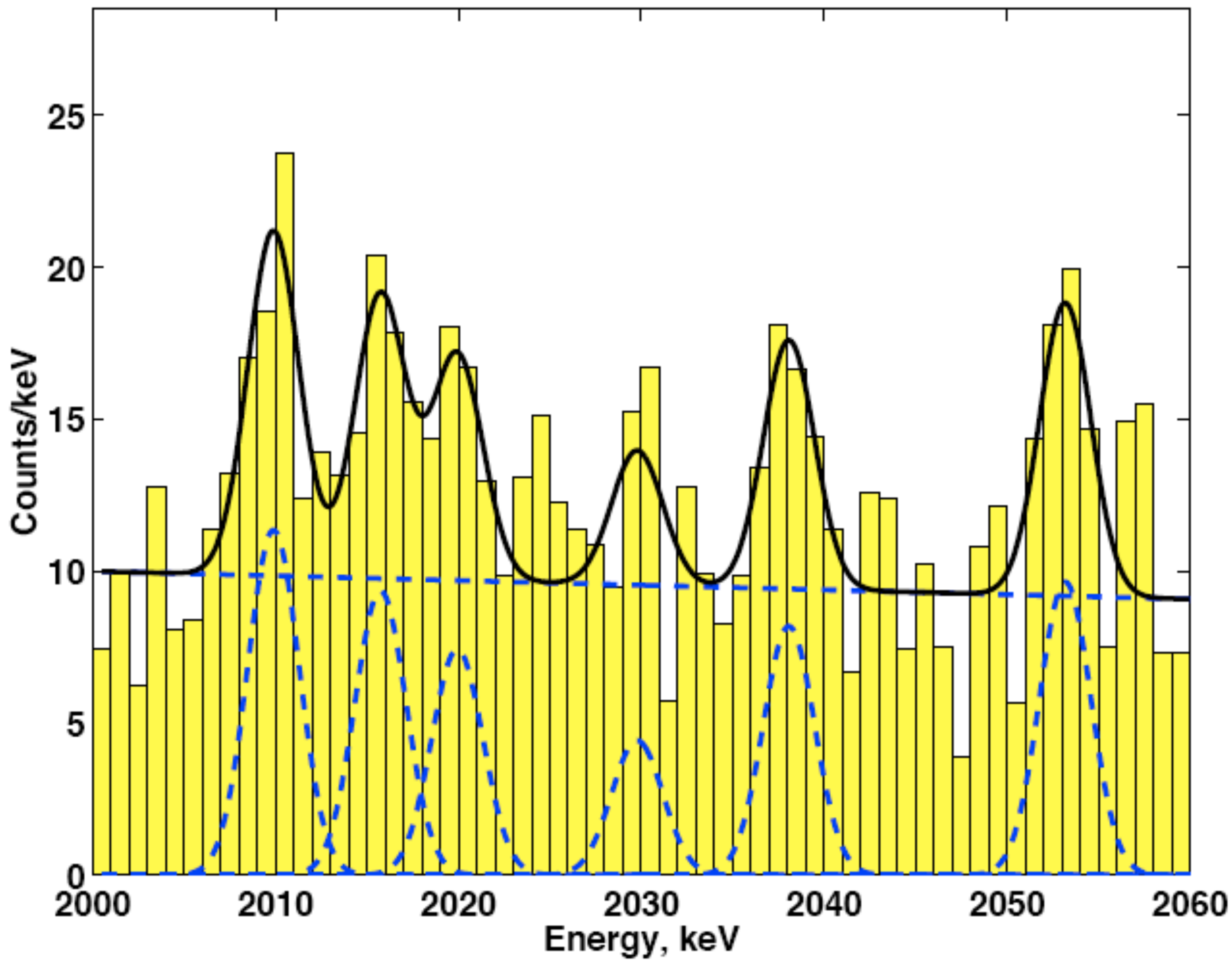
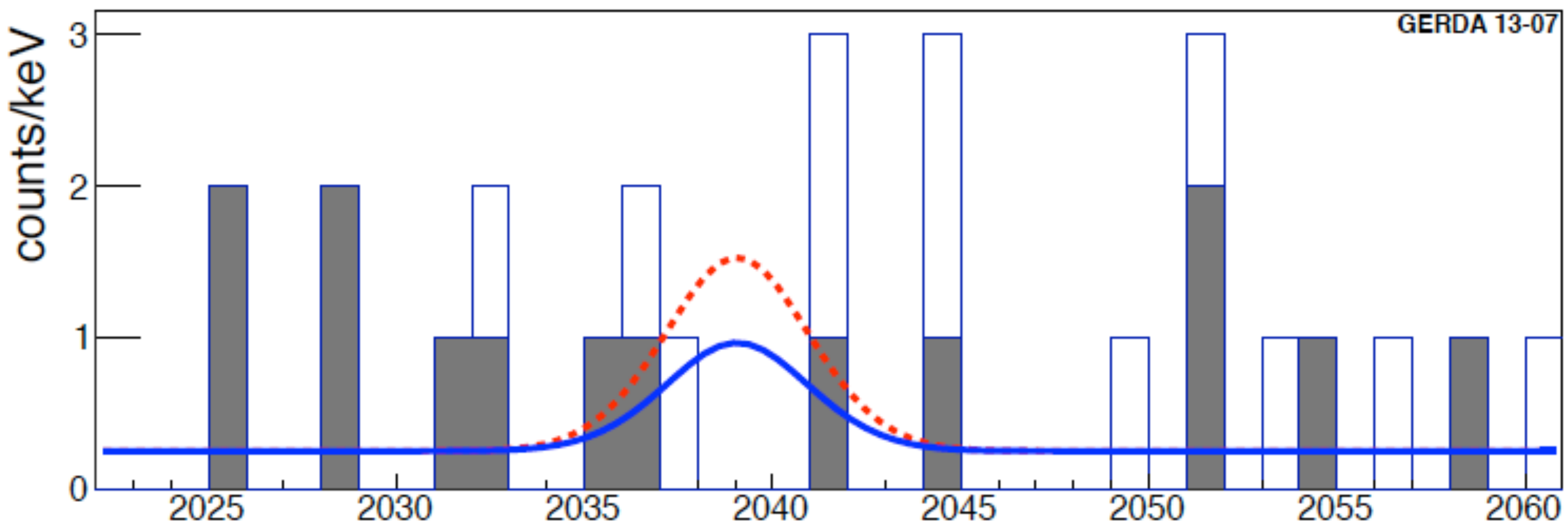
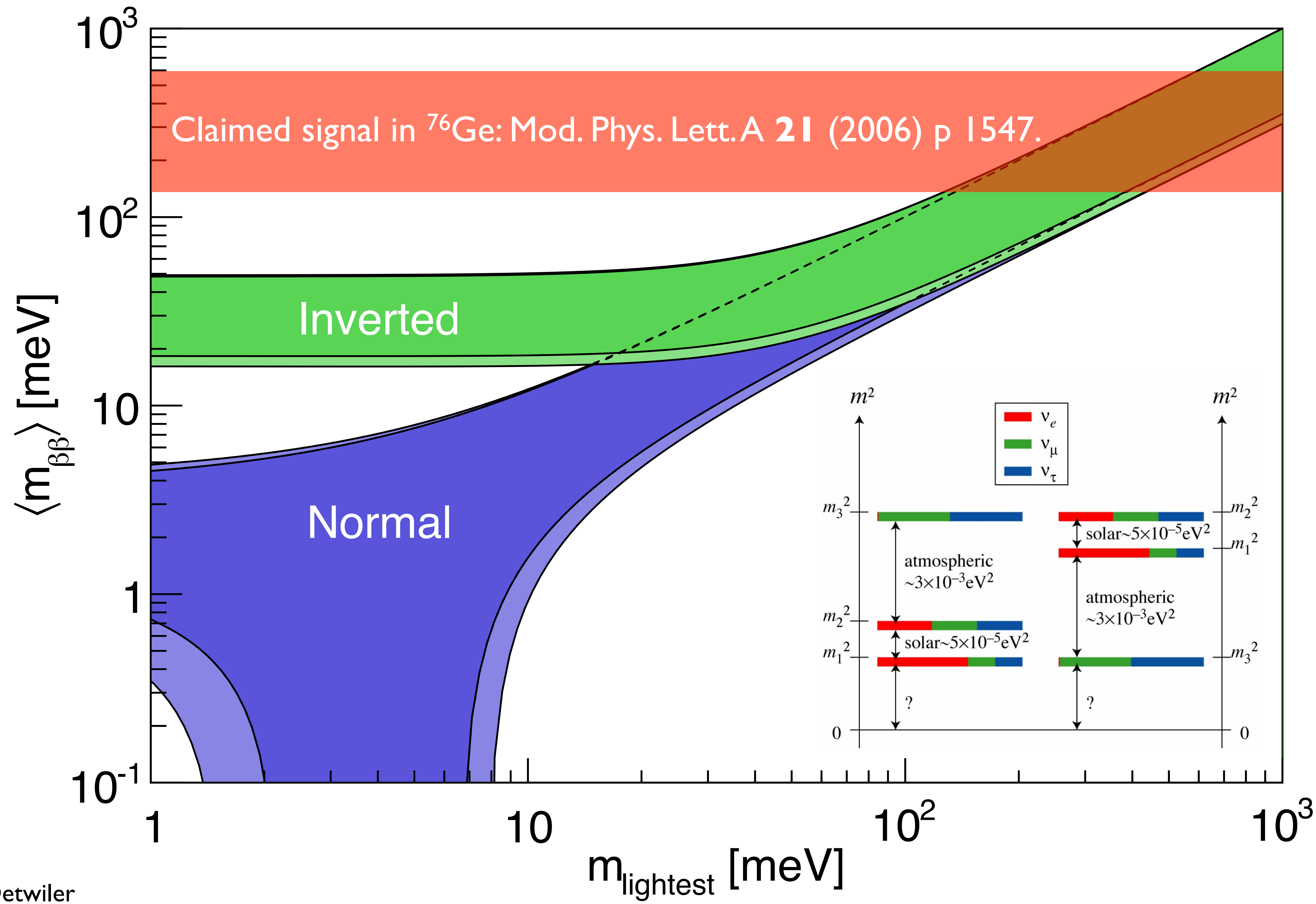


Klapdor Kleingrothaus *et al.*, Phys. Lett. B **586**, 198 (2004).

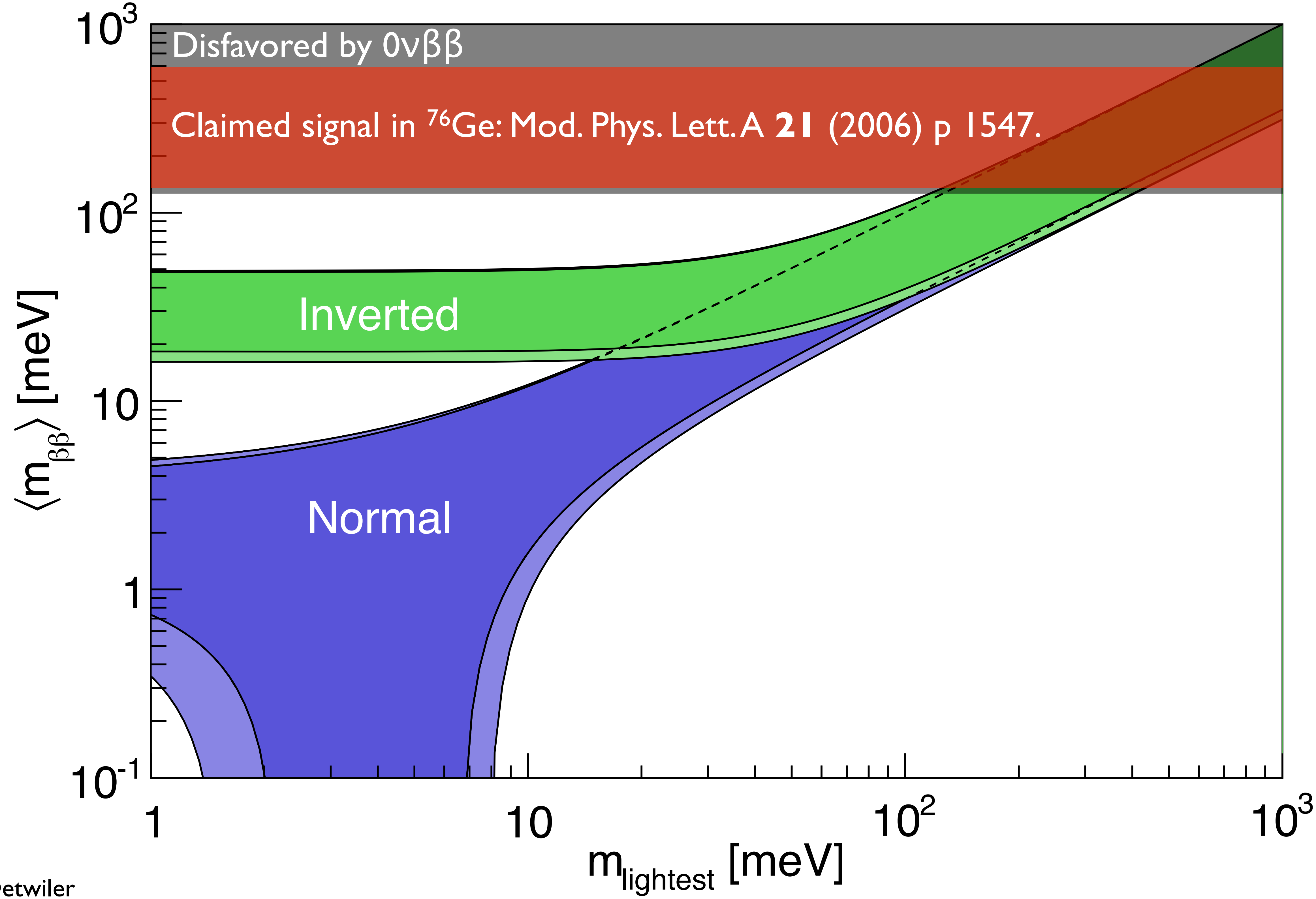
New GERDA Result



Double-Beta Decay



Double-Beta Decay



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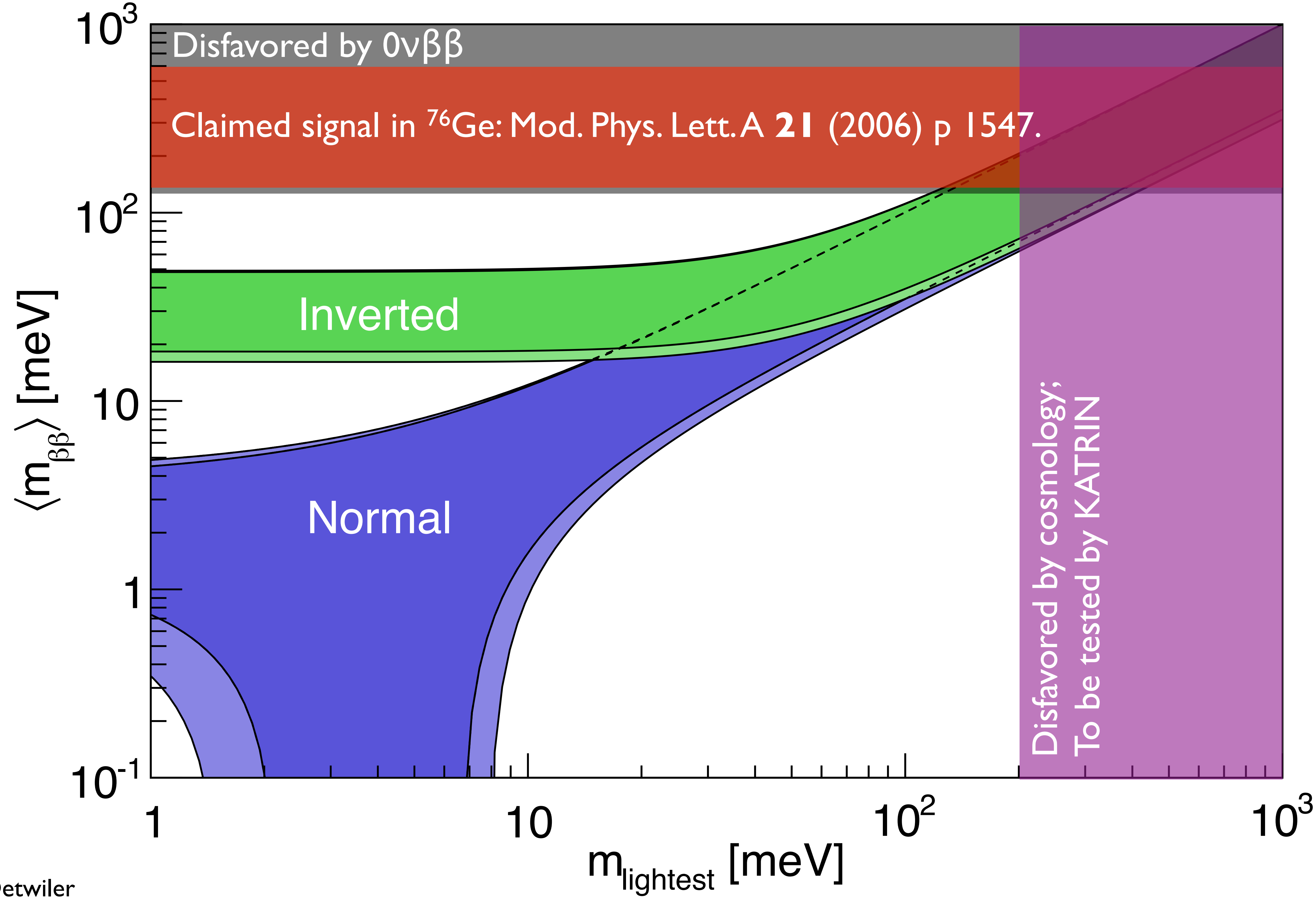
Double-Beta Decay



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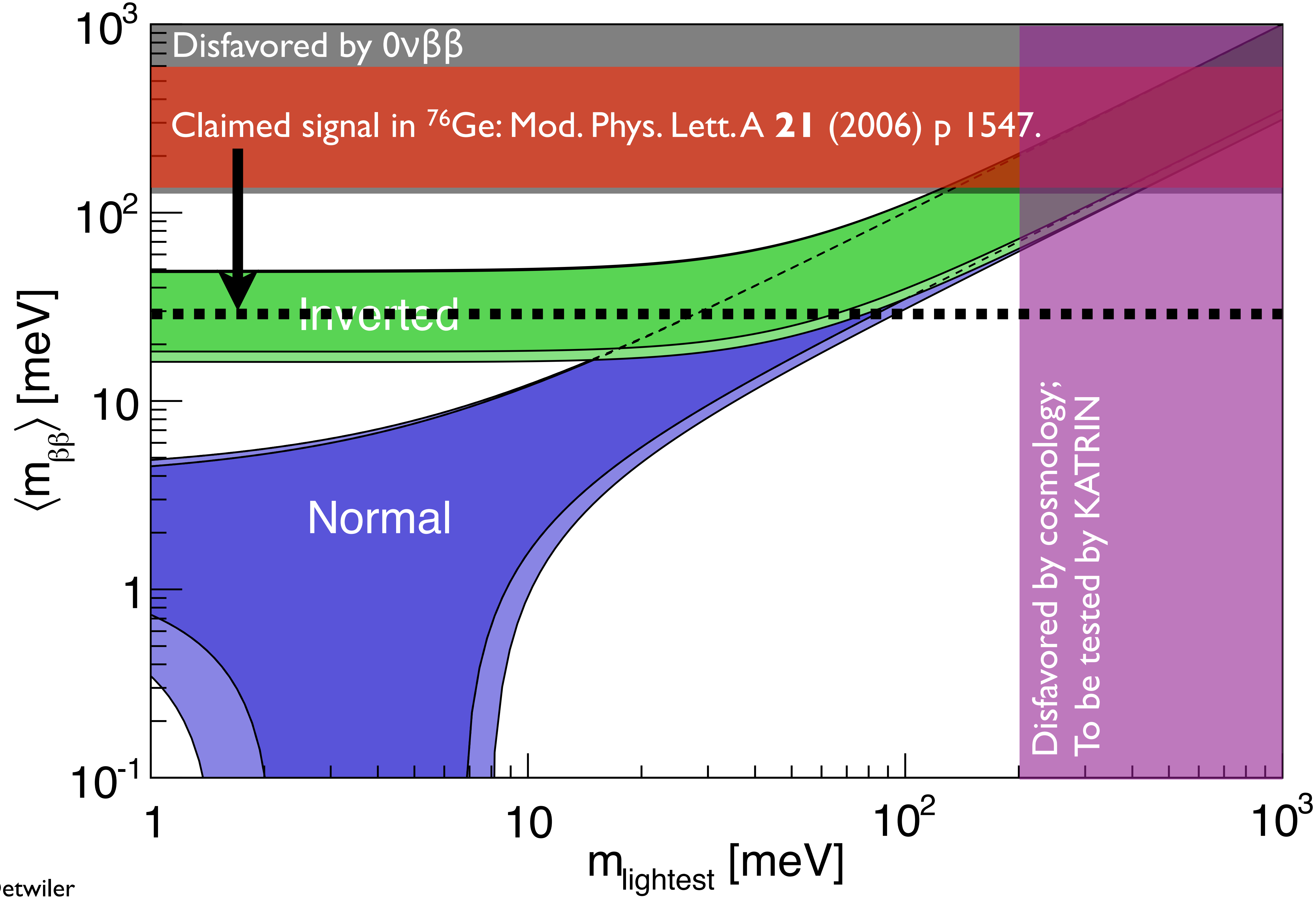
Double-Beta Decay



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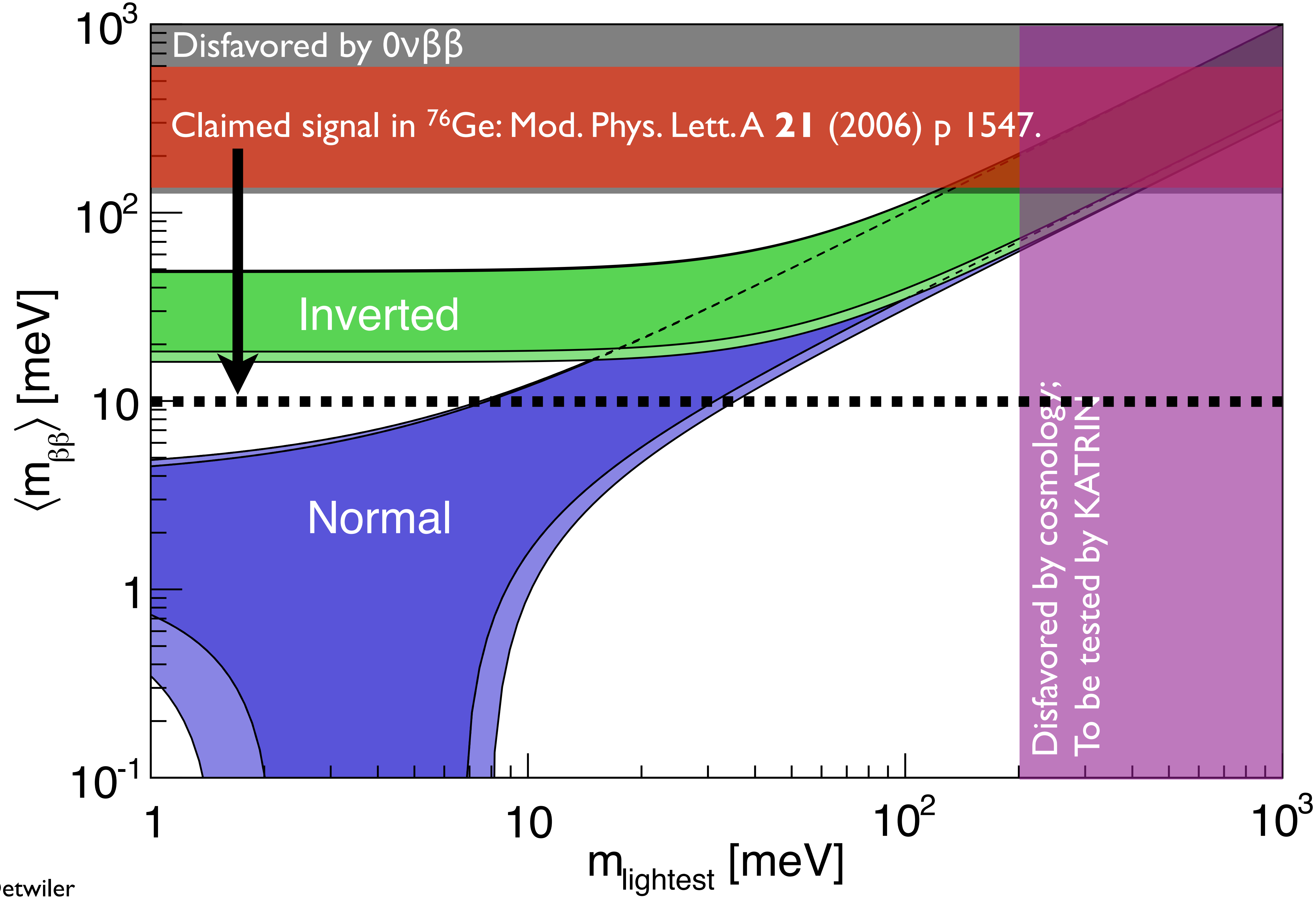
Double-Beta Decay



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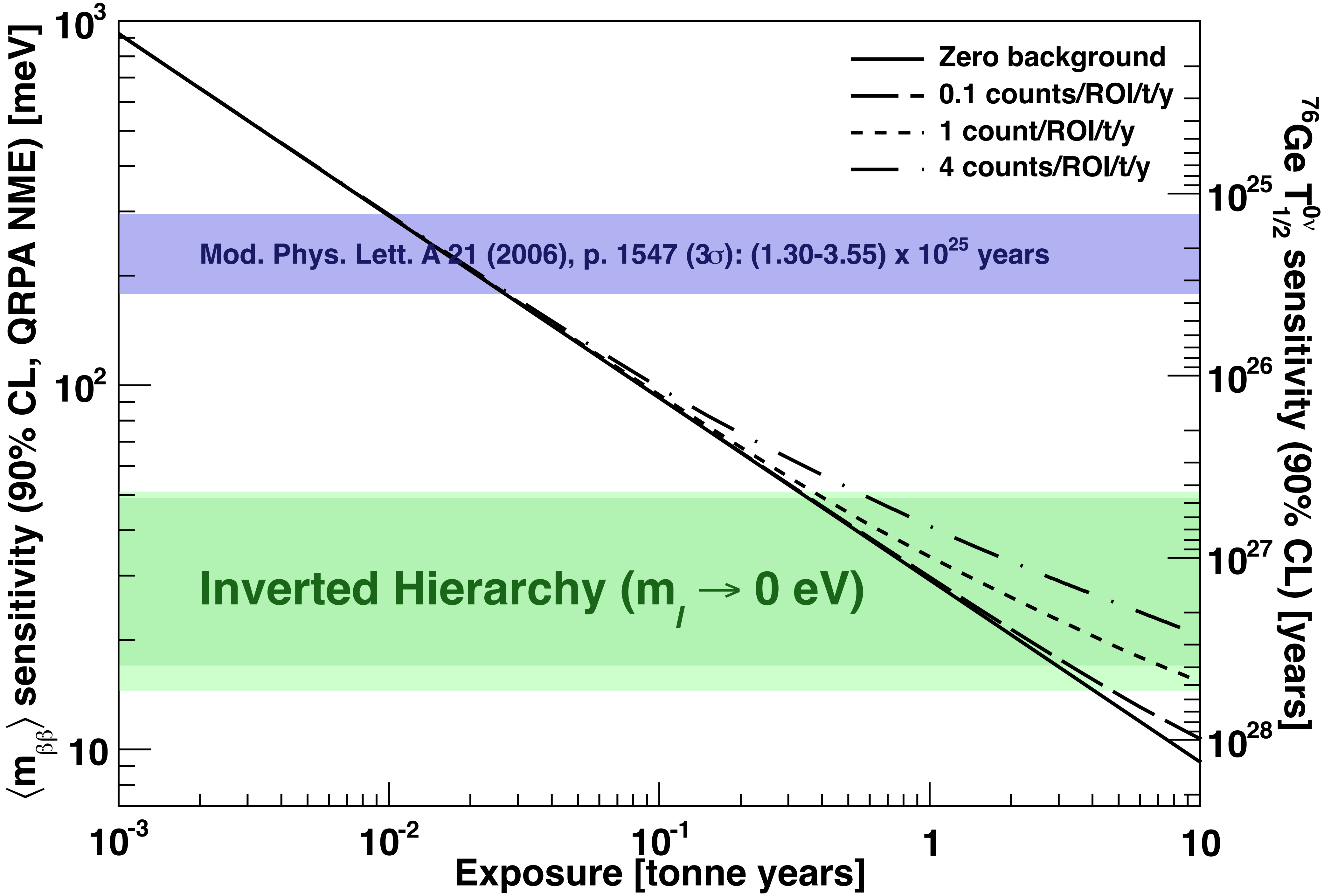
Testing the Inverted Hierarchy



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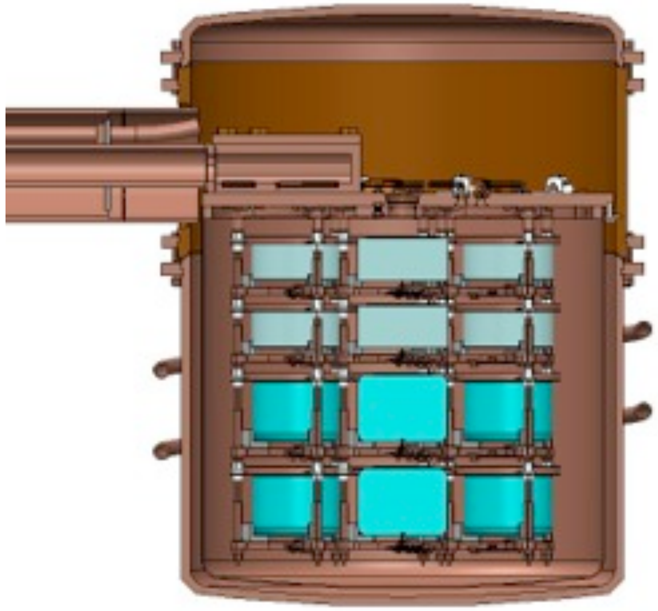
0νββ Experiments

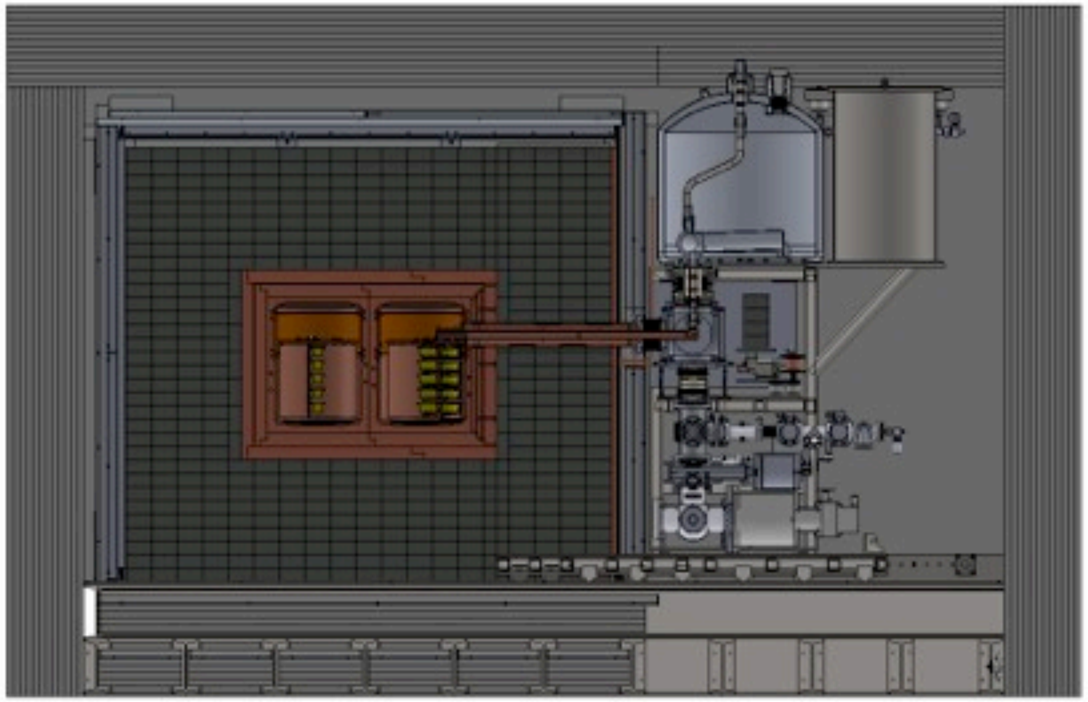
Experiment	Isotope	Mass	Technique	Present Status	Location
AMoRE[89,90]	^{100}Mo	50 kg	$CaMoO_4$ scint. bolometer crystals	Development	Yangyang
CANDLES[91]	^{48}Ca	0.35 kg	CaF_2 scint. crystals	Prototype	Kamioka
CARVEL[92]	^{48}Ca	1 ton	CaF_2 scint. crystals	Development	Solotvina
COBRA[93]	^{116}Cd	183 kg	^{enr}Cd CZT semicond. det.	Prototype	Gran Sasso
CUORE-0[69]	^{130}Te	11 kg	TeO_2 bolometers	Construction - 2012	Gran Sasso
CUORE[69]	^{130}Te	203 kg	TeO_2 bolometers	Construction - 2013	Gran Sasso
DCBA[94]	^{150}Ne	20 kg	^{enr}Nd foils and tracking	Development	Kamioka
EXO-200[57]	^{136}Xe	160 kg	Liq. ^{enr}Xe TPC/scint.	Operating - 2011	WIPP
EXO[70]	^{136}Xe	1-10 t	Liq. ^{enr}Xe TPC/scint.	Proposal	SURF
GERDA[71]	^{76}Ge	≈35 kg	^{enr}Ge semicond. det.	Operating - 2011	Gran Sasso
GSO[95]	^{160}Gd	2 ton	Gd_2SiO_5:Ce crys. scint. in liq. scint.	Development	
KamLAND-Zen[96]	^{136}Xe	400 kg	^{enr}Xe disolved in liq. scint.	Operating - 2011	Kamioka
LUCIFER[97,98]	^{82}Se	18 kg	ZnSe scint. bolometer crystals	Development	Gran Sasso
MAJORANA[77,78,79]	^{76}Ge	26 kg	^{enr}Ge semicond. det.	Construction - 2013	SURF
MOON [99]	^{100}Mo	1 t	^{enr}Mofoils/scint.	Development	
SuperNEMO-Dem[87]	^{82}Se	7 kg	^{enr}Se foils/tracking	Construction - 2014	Fréjus
SuperNEMO[87]	^{82}Se	100 kg	^{enr}Se foils/tracking	Proposal - 2019	Fréjus
NEXT [82,83]	^{136}Xe	100 kg	gas TPC	Development - 2014	Canfranc
SNO+[84,85]	^{150}Nd	55 kg	Nd loaded liq. scint.	Construction - 2013	SNOLab

Construction Operation

The MAJORANA DEMONSTRATOR (MJD)



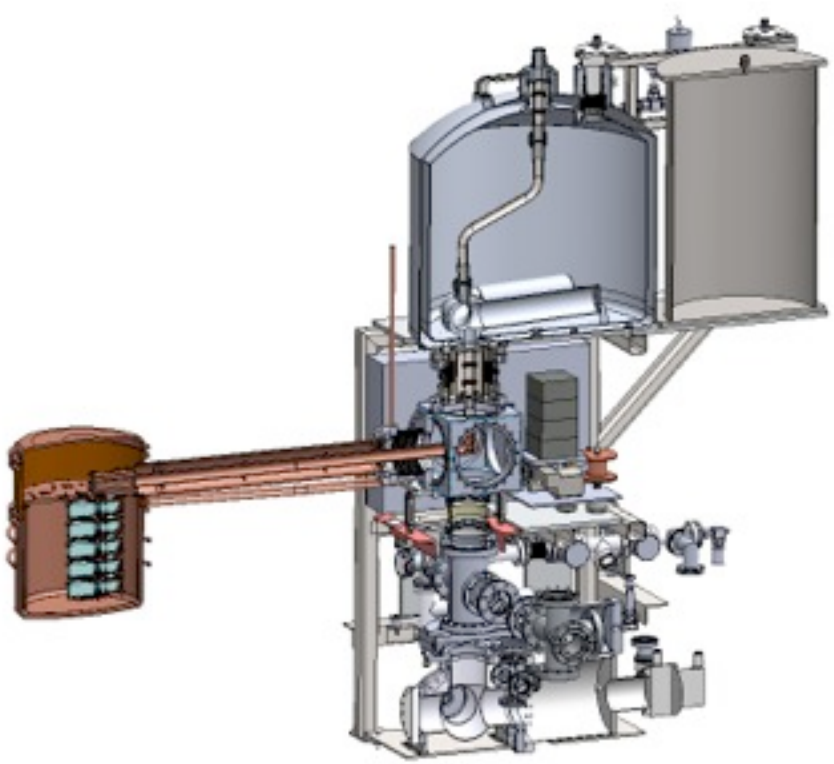
- Located 4850' underground at Sanford Underground Research Facility
- 40-kg of Ge detectors, 30-kg enriched to 86% in ^{76}Ge
- 2 independent cryostats made of ultra-clean, electroformed Cu
- Compact Pb and Cu shield + muon veto
- Background goal: 3 counts in the 0νββ peak region of interest in a one tonne-year exposure

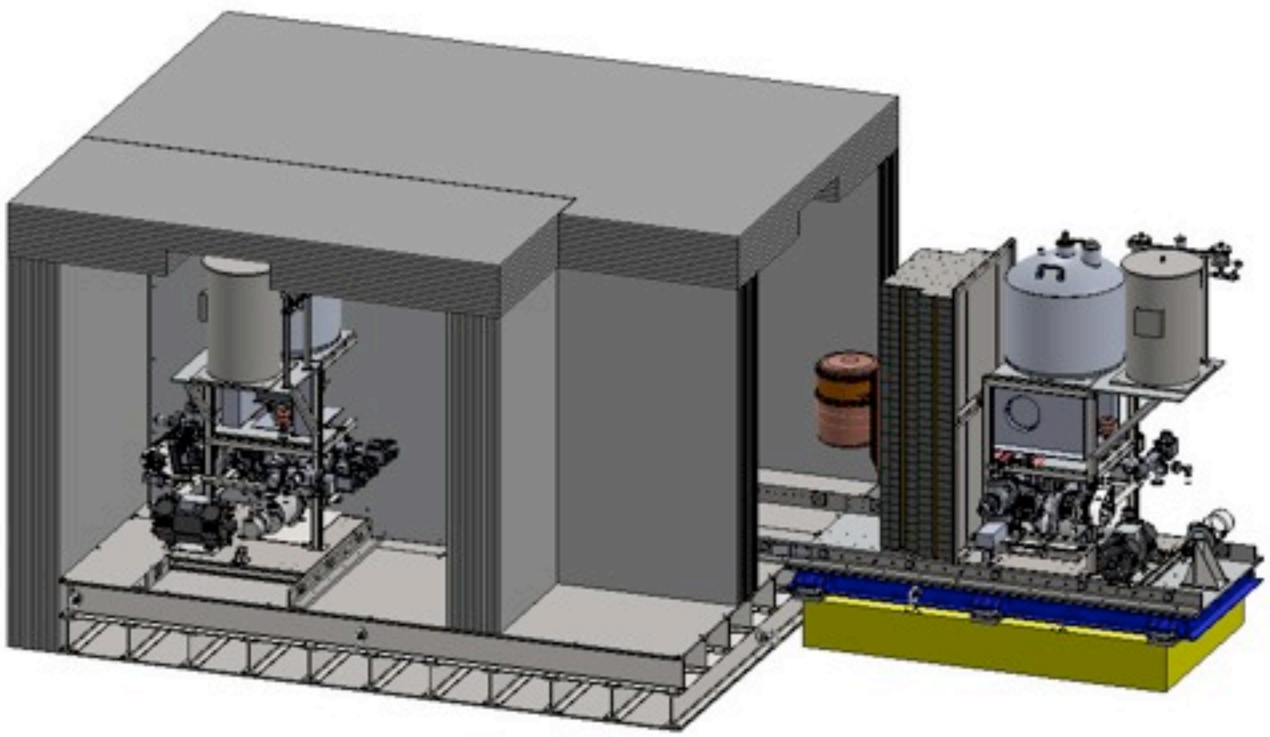


Funded by DOE Office of Nuclear Physics and NSF Particle Astrophysics, with additional contributions from international collaborators.

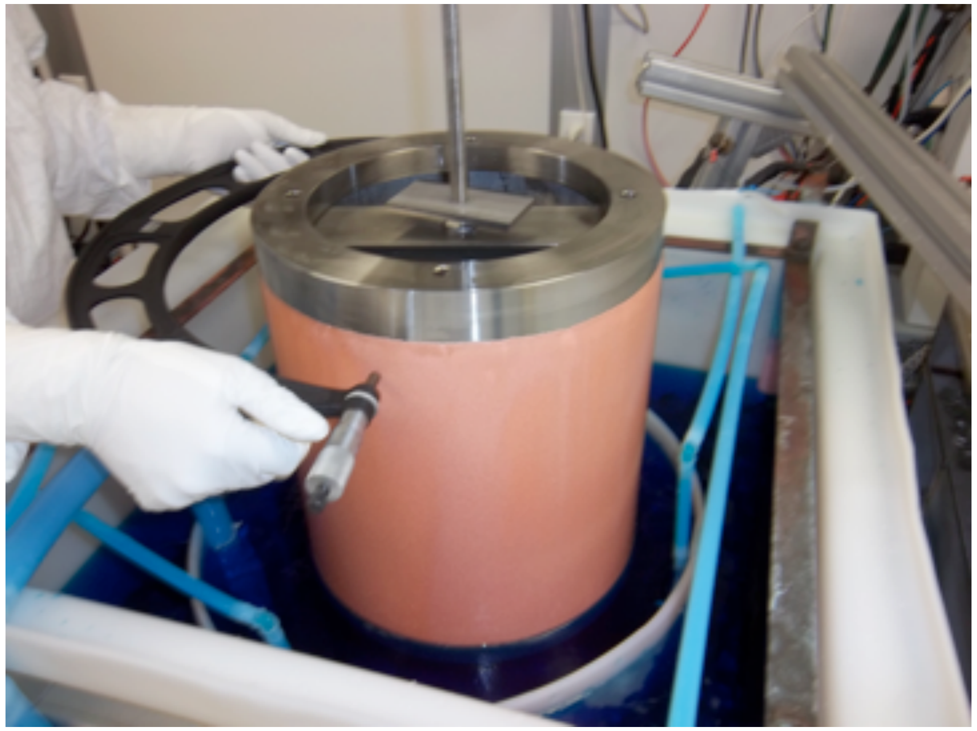
MJD Implementation

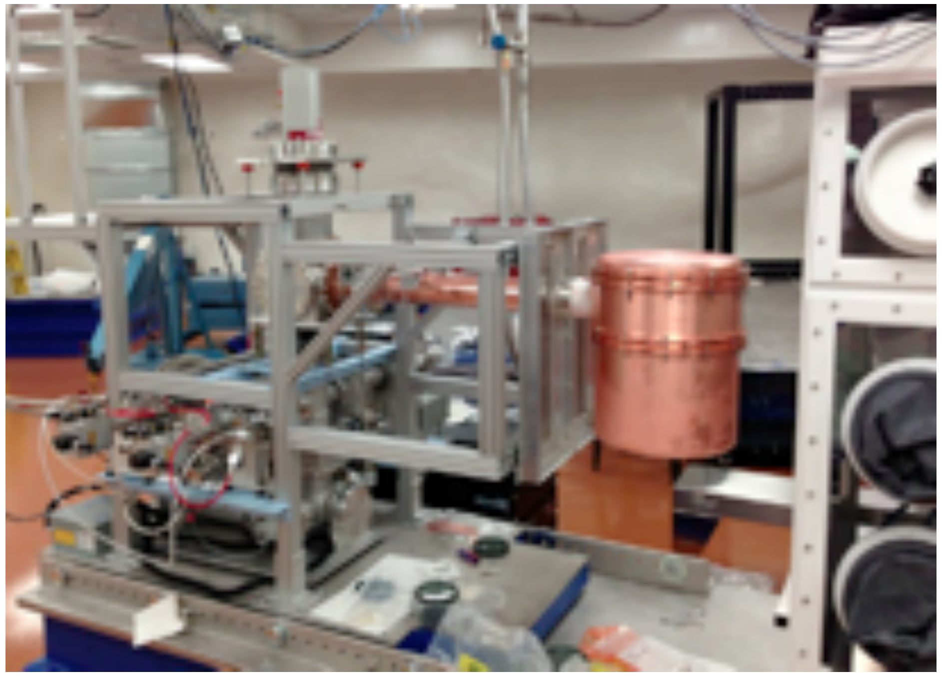
- Prototype Cryostat (2 strings, natGe): Summer 2013
- Cryostat 1 (3 strings enrGe & 4 strings natGe): Late 2013
- Cryostat 2 (7 strings enrGe): Fall 2014





MJD Construction



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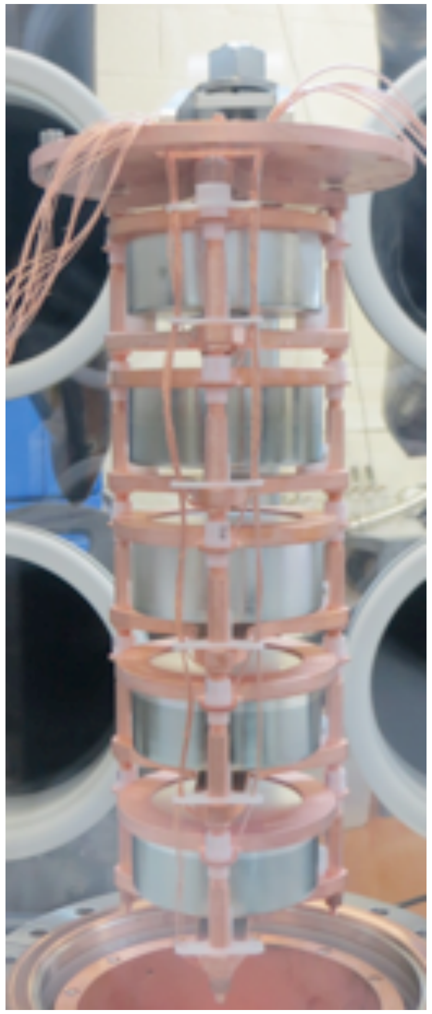


MJD Collaboration

Other MJD Physics

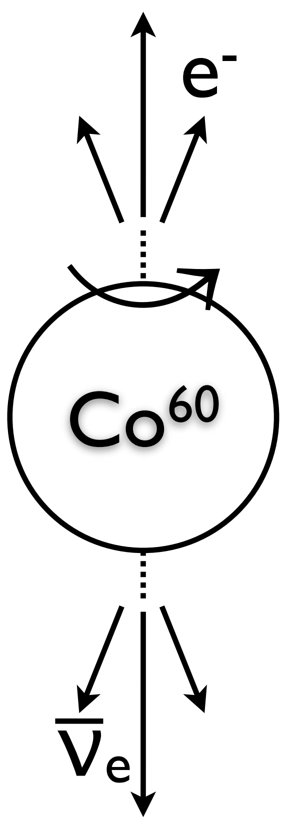
- Light WIMP dark matter
- Solar axions
- Pauli exclusion principle violation
- Neutrino magnetic moment
- Electron decay

Summary

- Neutrinos continue to give us new mysteries to solve
- 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!

Neutrino Handedness

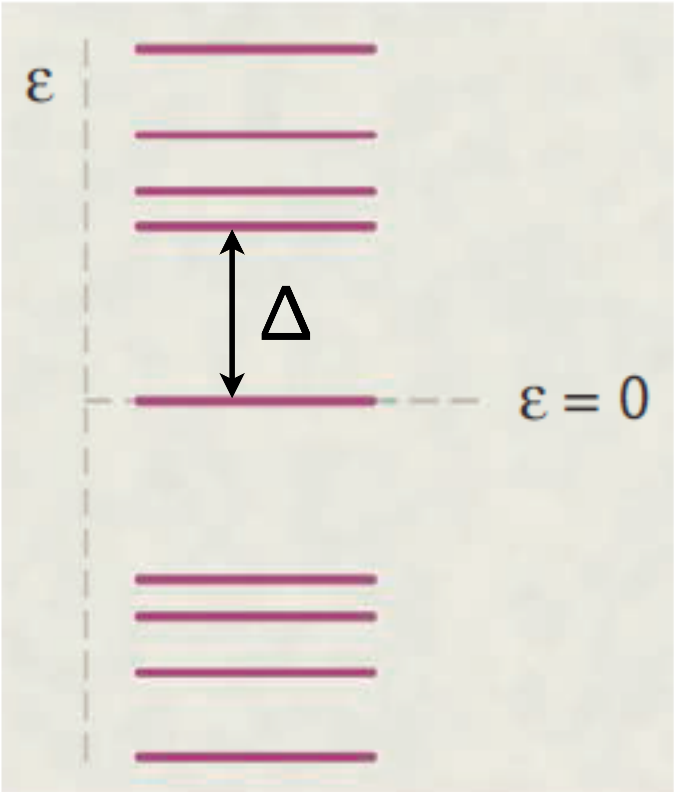
C.S. Wu et al. (1957)



The Majorana Fermion

$$\sigma^{\mu}_{\pm}\partial_{\mu}\chi_{\pm} \pm m\sigma_2\chi^{*}_{\pm} = 0$$

- $CPT[\chi_{\pm}(x^{\mu})] = \mp i\chi_{\pm}(-x^{\mu})$
- Particle physics: $\chi = \bar{\chi}$
- Condensed matter: charge-neutral, zero-energy quasi-particle



Brouwer, Science **336**, 989 (2012).

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

Dirac ν

ν_L → produces ℓ^-

ν_R → doesn't interact

$\bar{\nu}_L$ → doesn't interact

$\bar{\nu}_R$ → produces ℓ^+

Majorana ν

$\overset{(-)}{\nu}_L$ → produces ℓ^-

$\overset{(-)}{\nu}_R$ → produces ℓ^+

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

The Majorana Equation

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

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The Majorana Equation

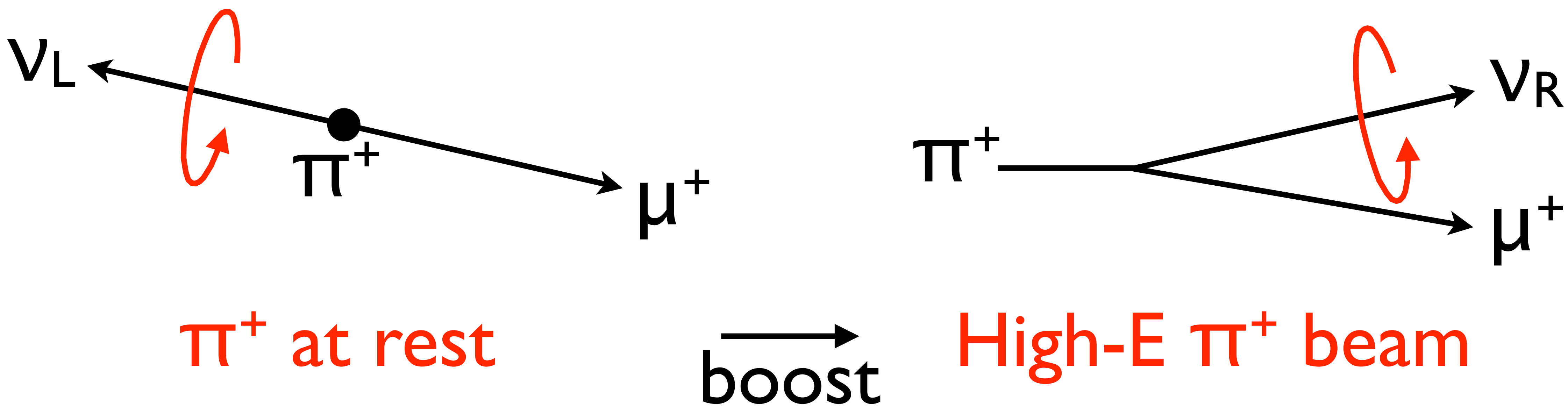
Schrodinger: $$i\frac{\partial}{\partial t}\Psi + \frac{1}{2m}\nabla^2\Psi = 0$$

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

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

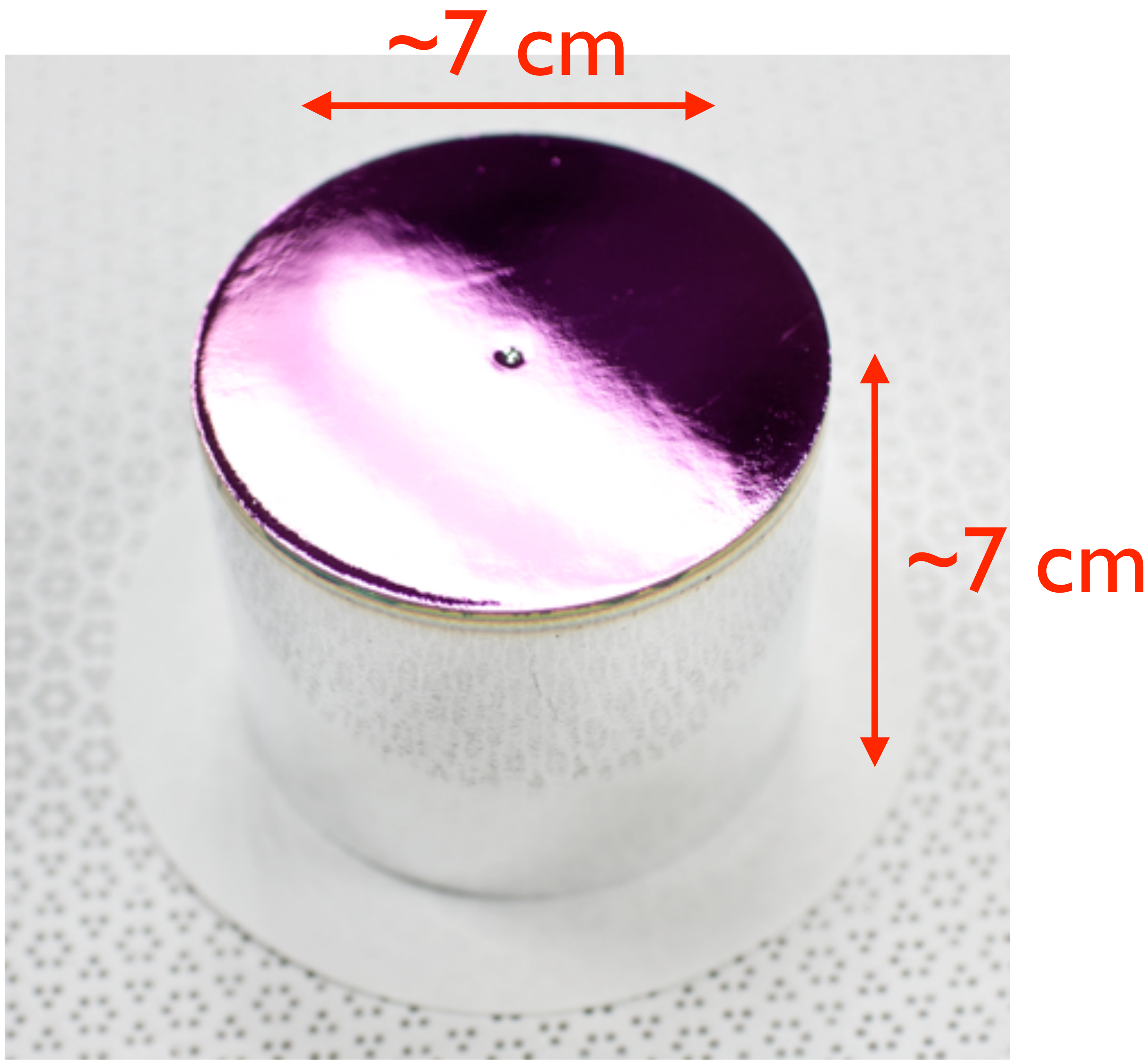
E. Majorana, Il Nuovo Cimento **14**, 171 (1937).
English translation: Soryushiron Kenkyu **63**, 149 (1981).

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

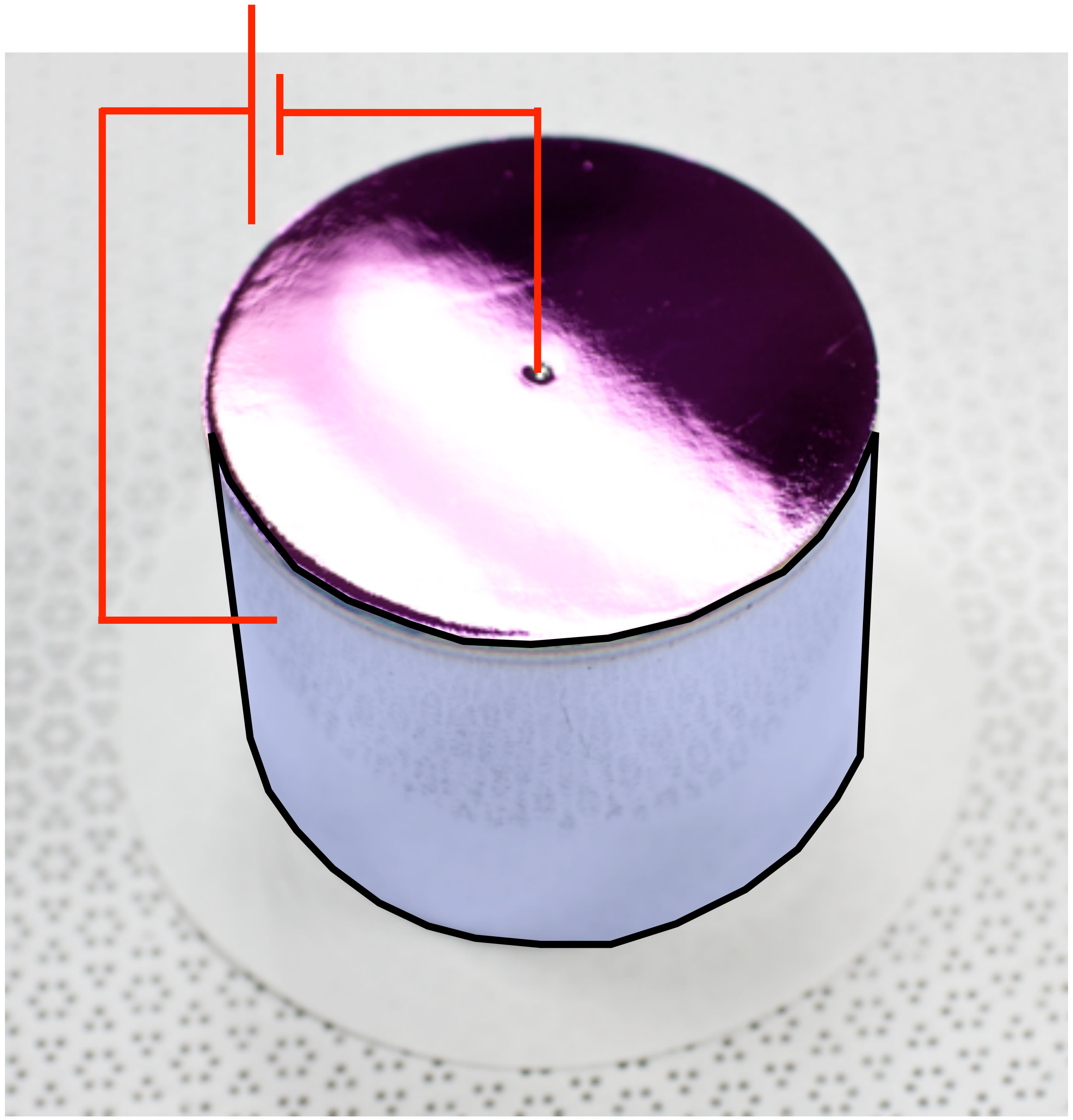


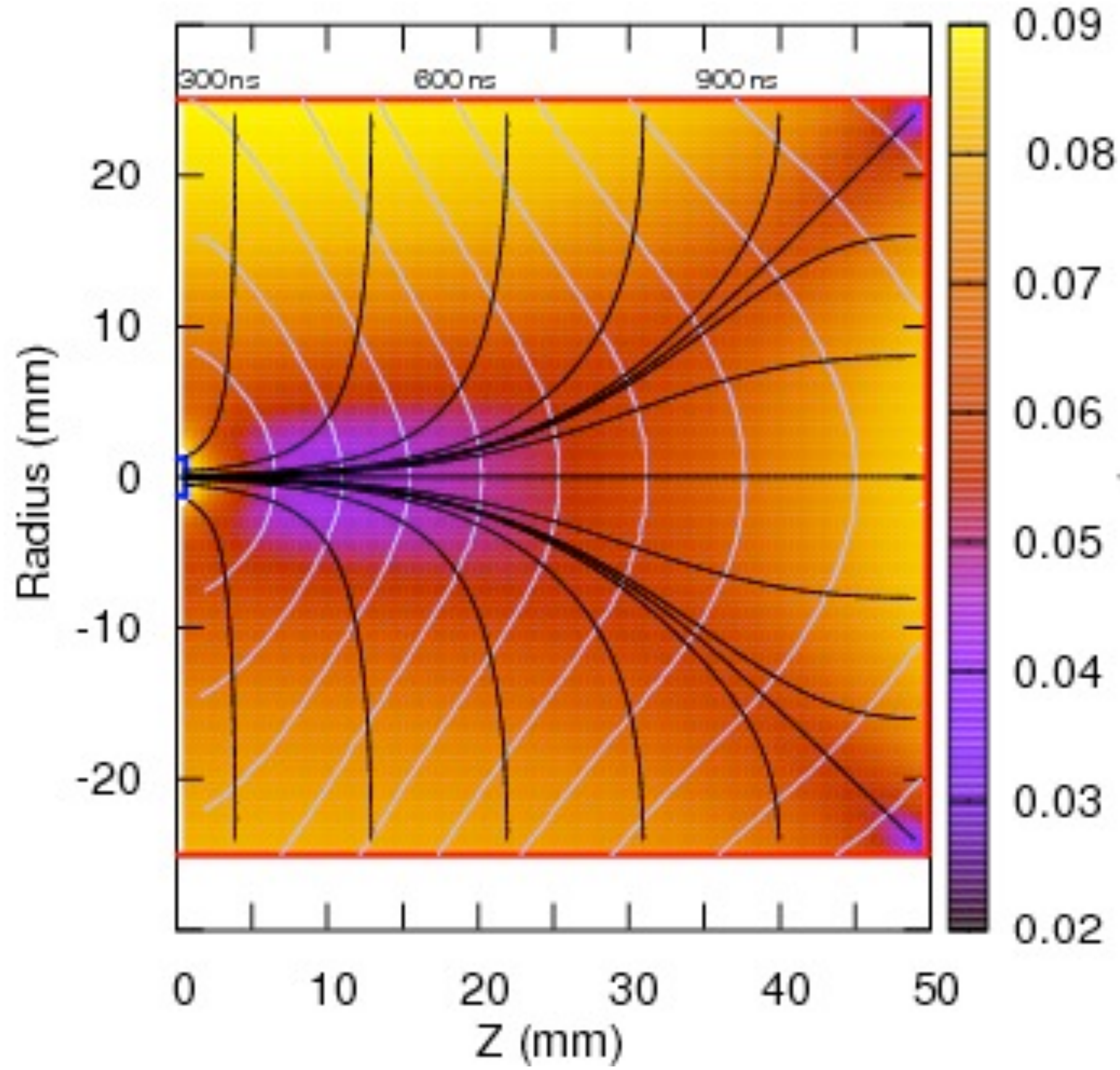
- Boost so that π^+ beam faster than ν_L from decay at rest: requires E_π > 4 PeV (n.b. LHC = 14 TeV)
- Fraction of decays with helicity flipped: $<10^{-15}$
- *"Since L-violation comes only from Majorana ν masses, any attempt to observe it will be at the mercy of the ν masses."* - B. Kayser

Germanium Detectors



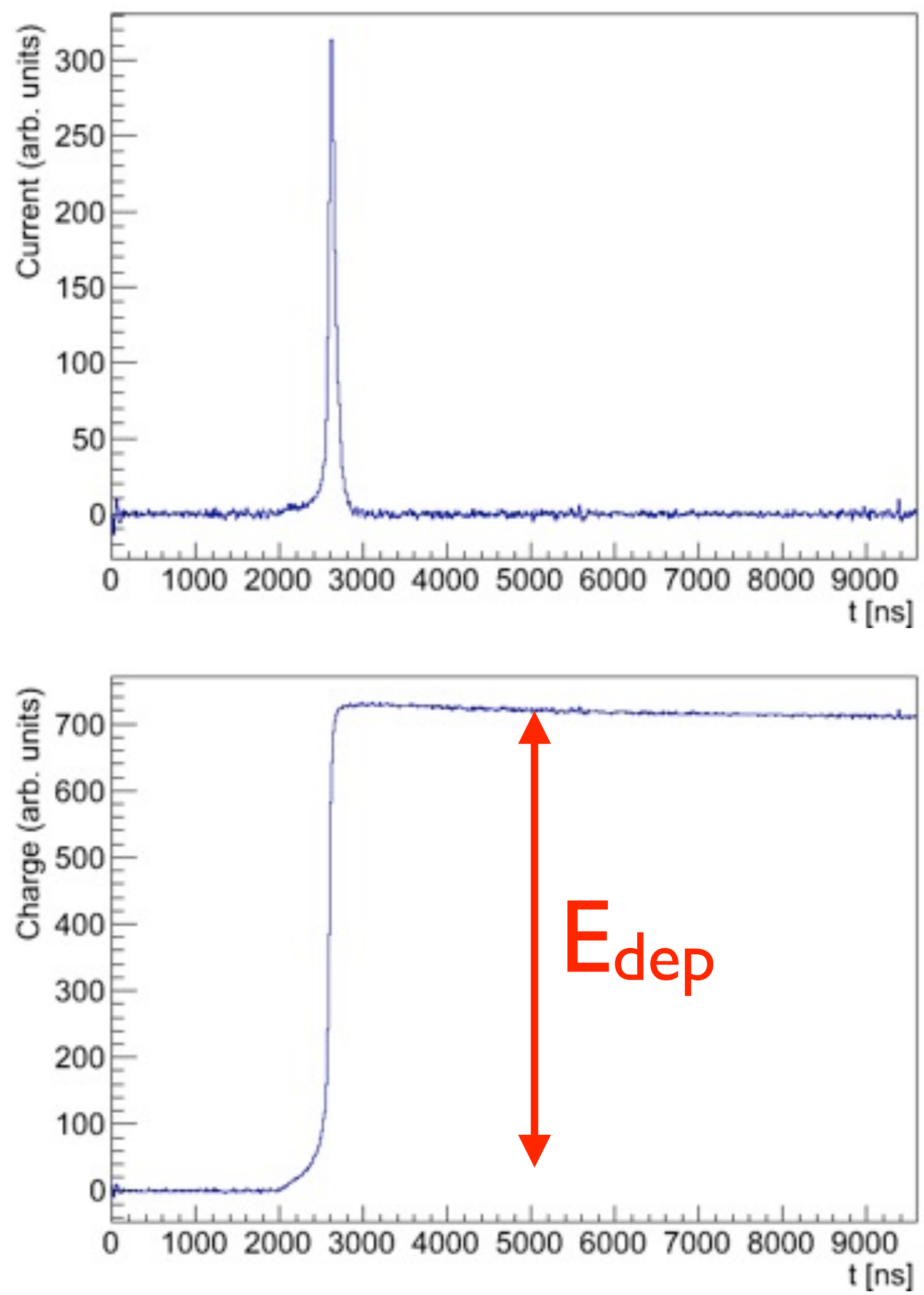
Point-Contact Ge Detectors

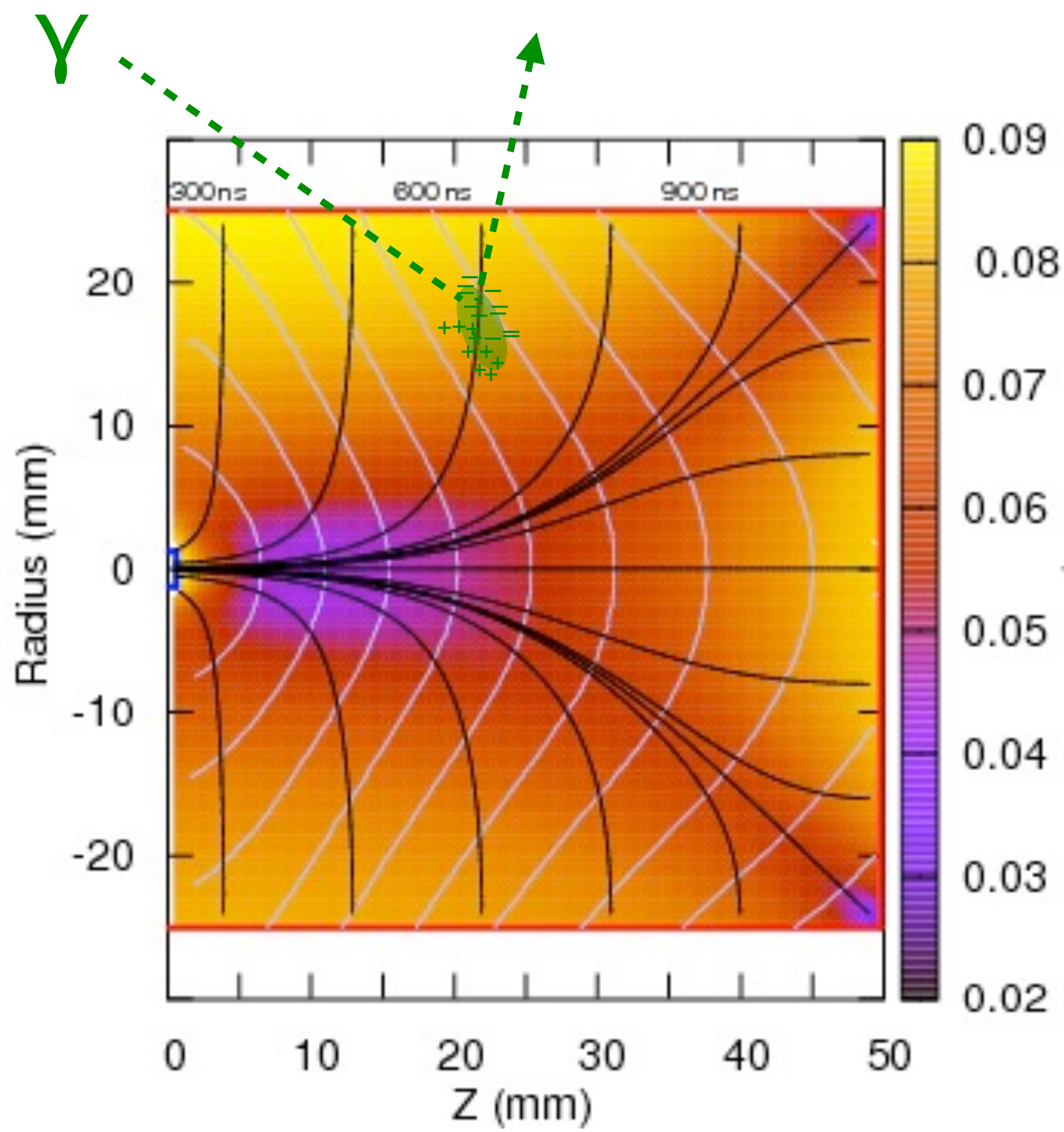




Hole v_{drift} (mm/ns) w/ paths, isochrones

Point-Contact Ge Detectors





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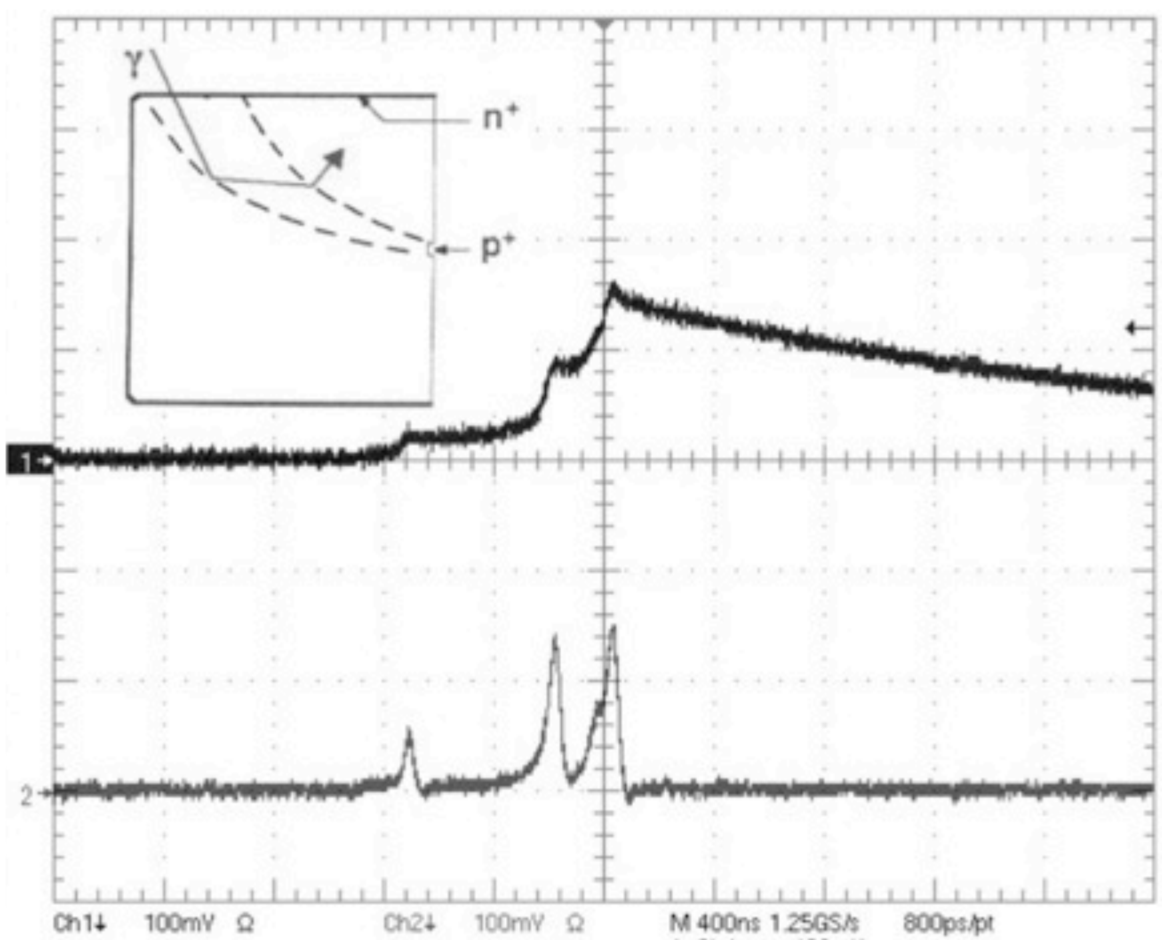

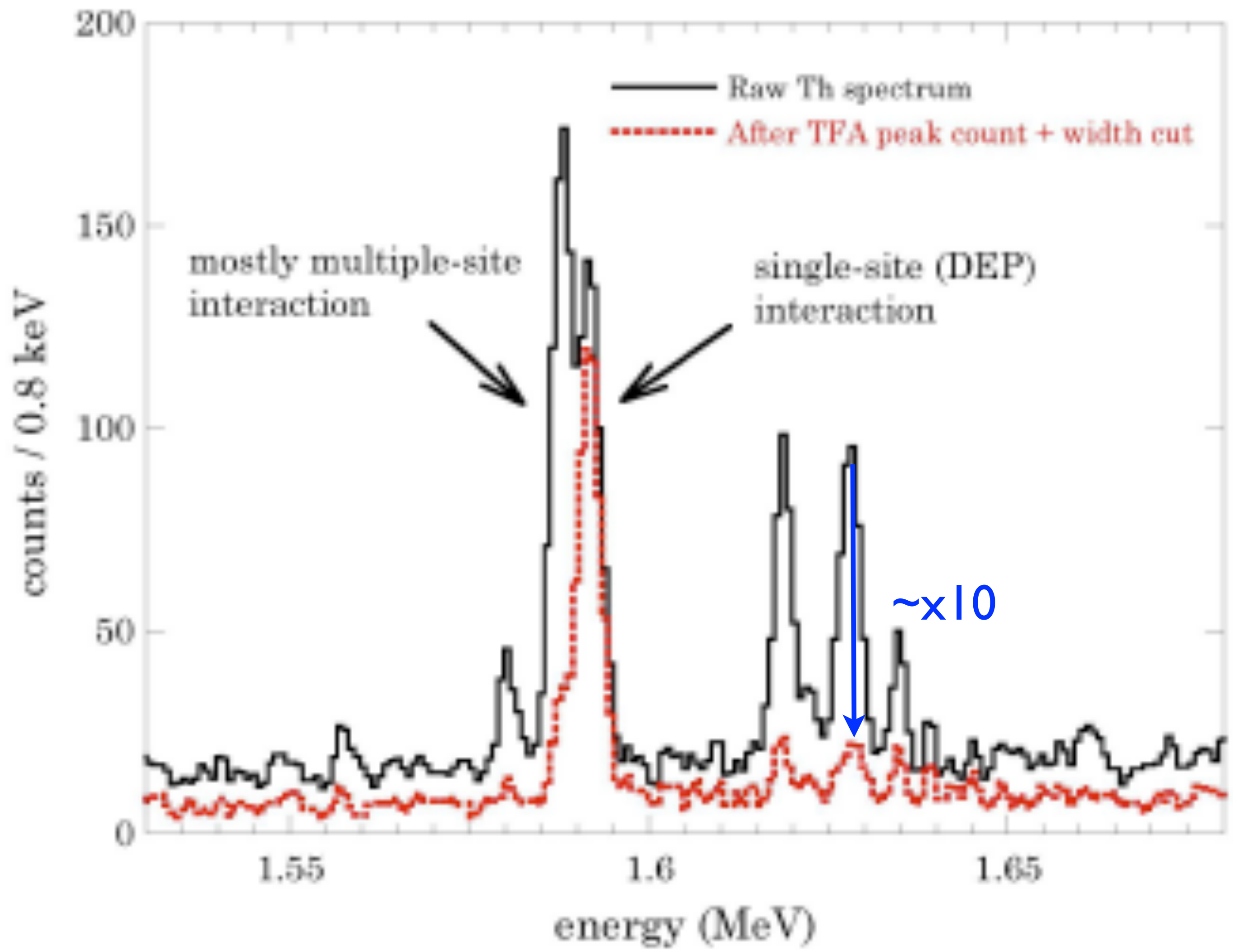

Barbeau et al., JCAP 09, 009 (2007).