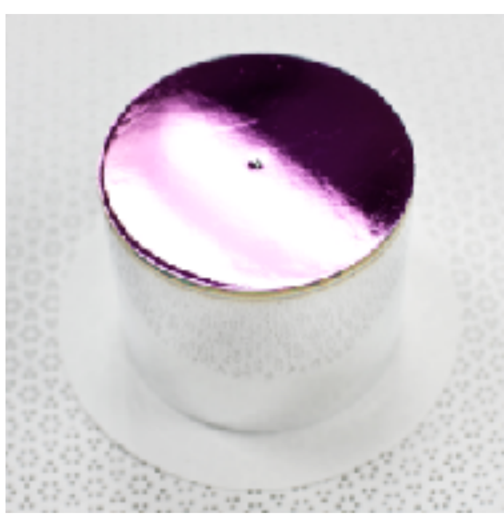


The Neutrino's Mysterious Mass

Jason Detwiler
REU Meeting
July 31, 2017

The Ubiquitous Neutrino

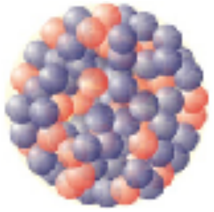
1 neutrino for every ~3 photons

The Sun in Neutrinos

Credit: SuperKamiokande
Actual size of sun: ~one pixel

The Neutrino

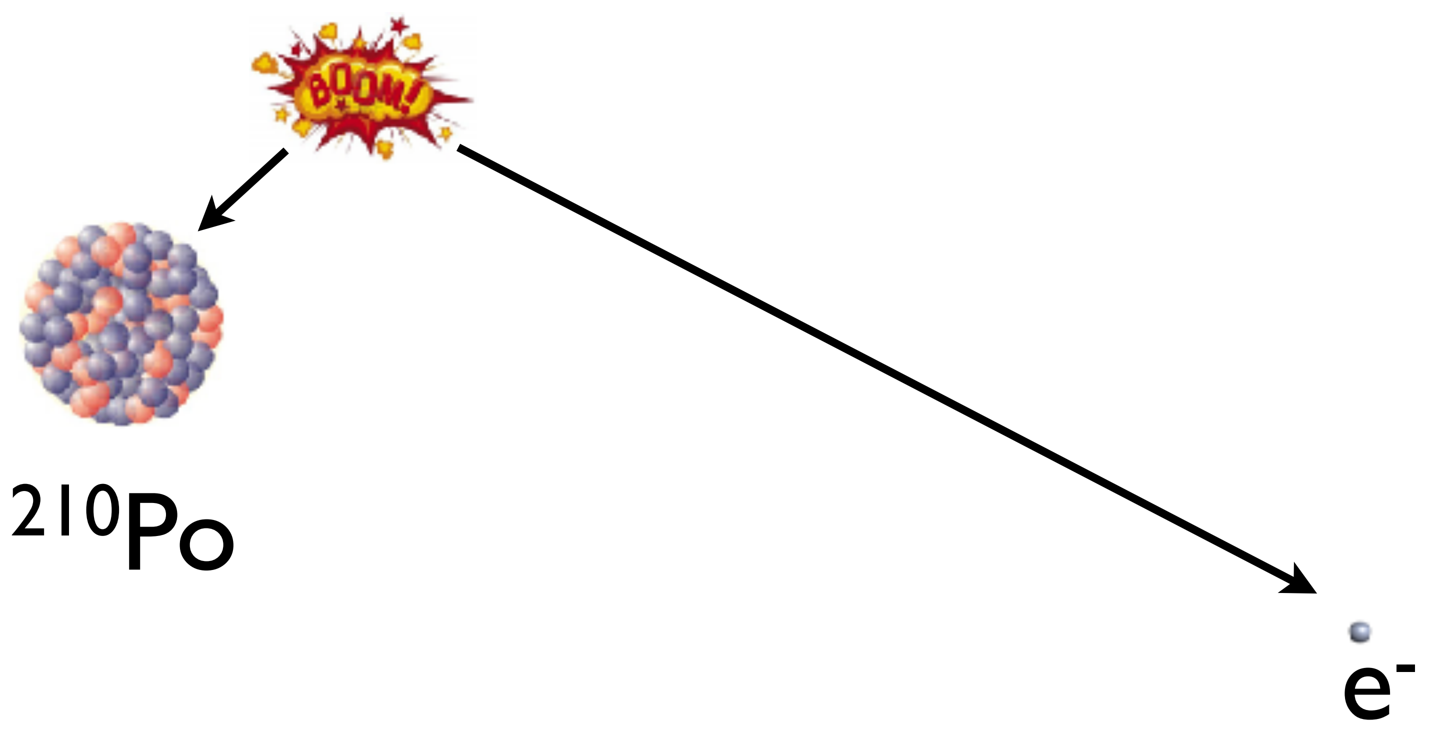
Meitner and
Hahn (1911):



^{210}Bi

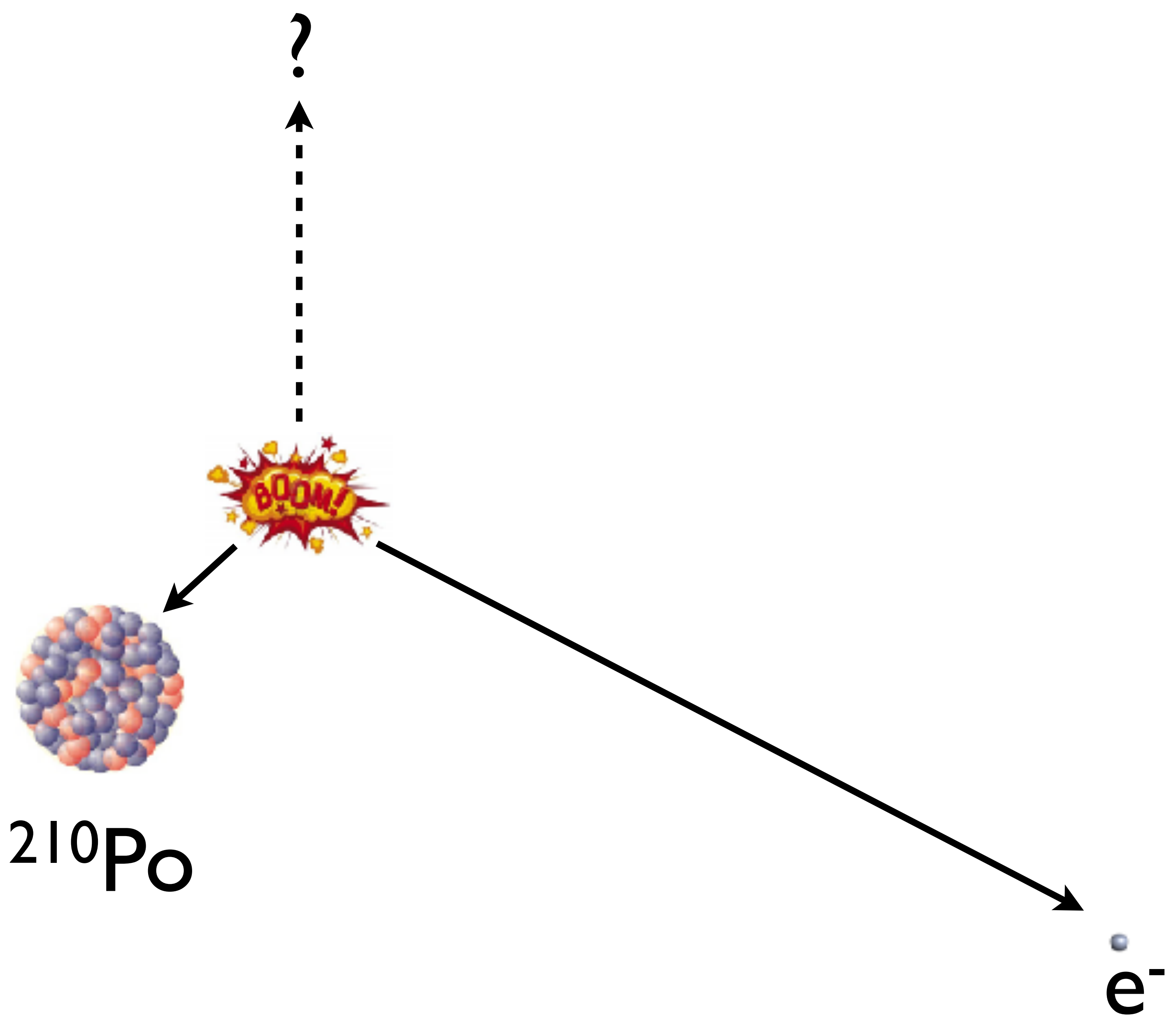
The Neutrino

Meitner and Hahn (1911):



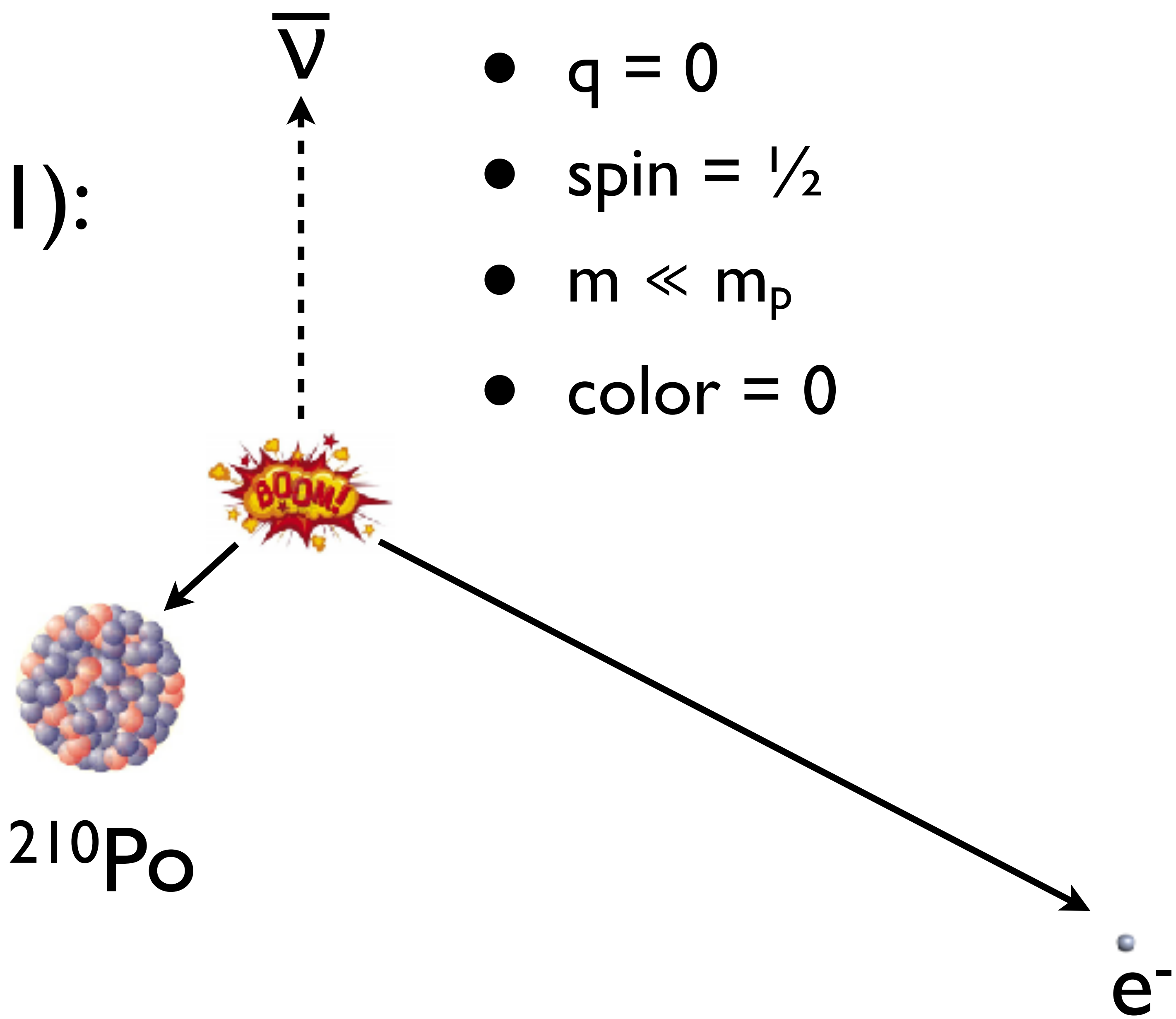
The Neutrino

Meitner and Hahn (1911):



The Neutrino

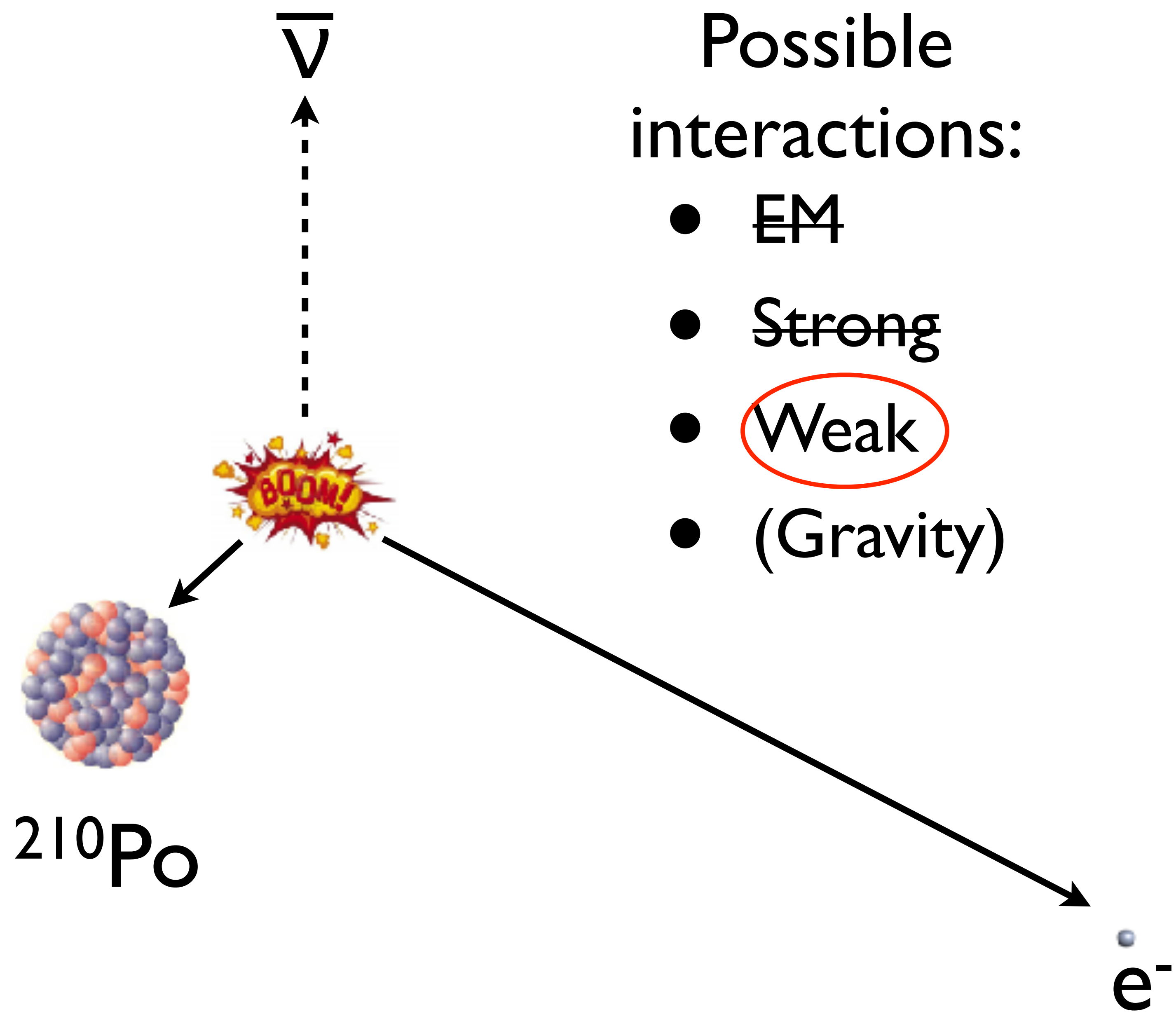
Wolfgang Pauli (1931):



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

The Neutrino

Enrico Fermi (1934):
"Little neutral one"

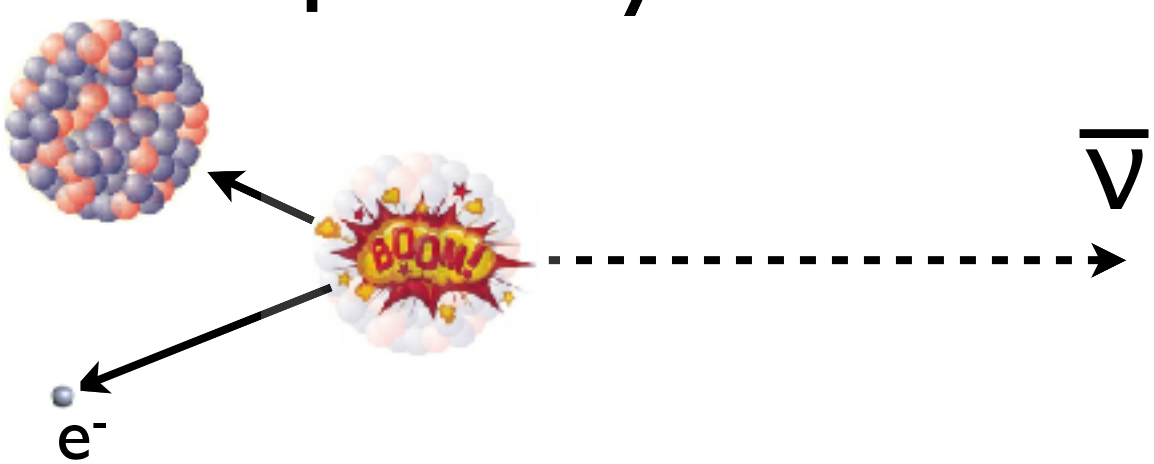


Possible interactions:

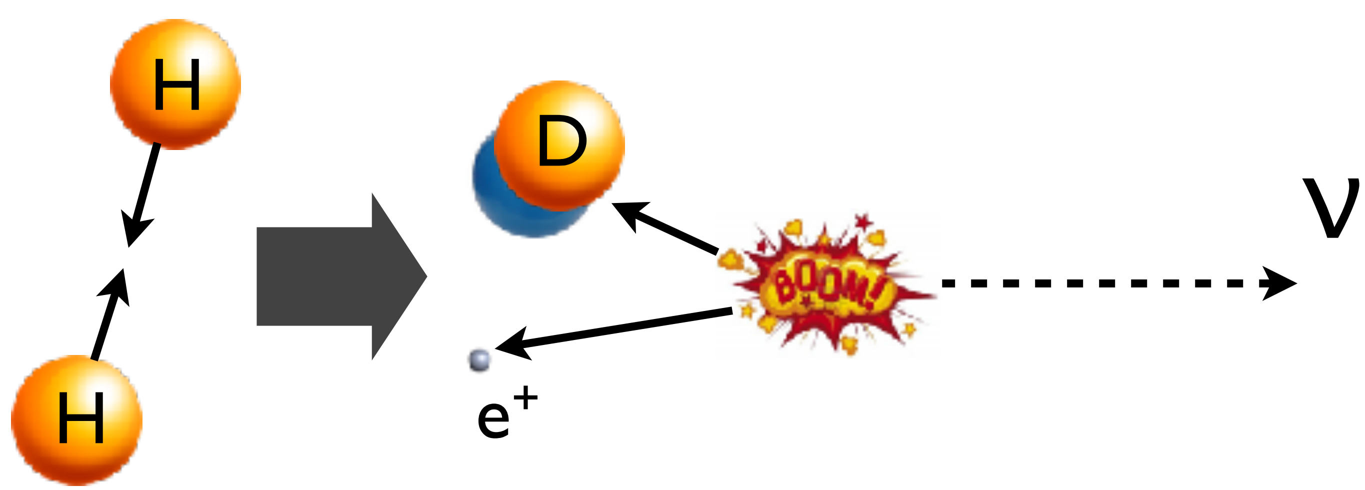
- ~~EM~~
- ~~Strong~~
- Weak
- (Gravity)

Neutrinos and Antineutrinos

β^- decay

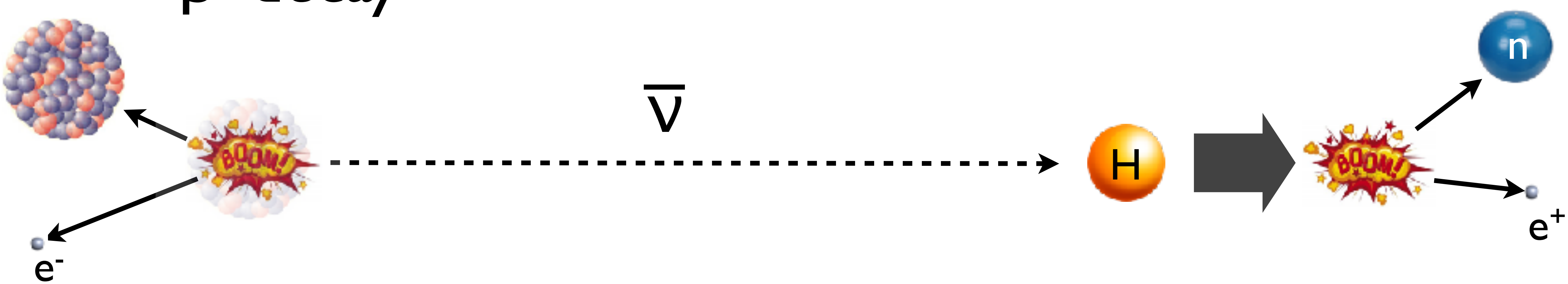


H fusion

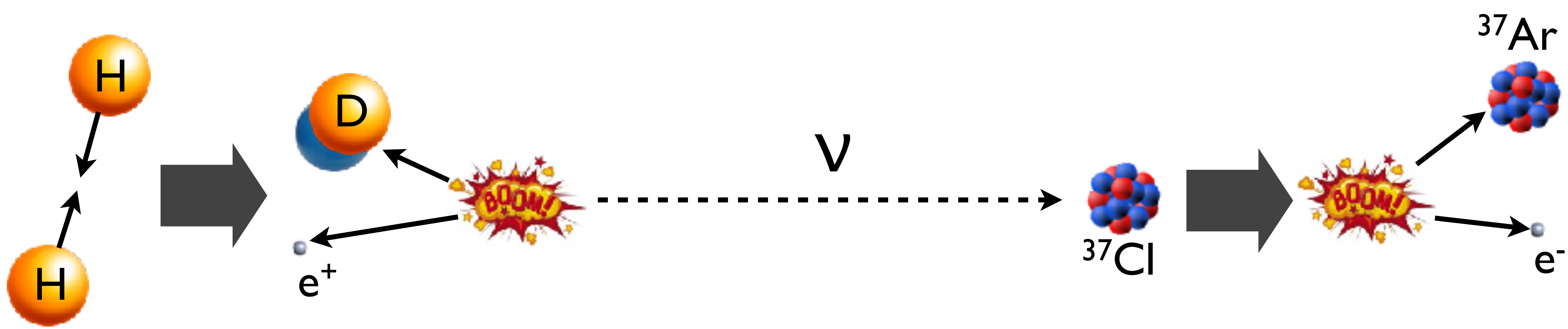


Neutrinos and Antineutrinos

β^- decay



H fusion

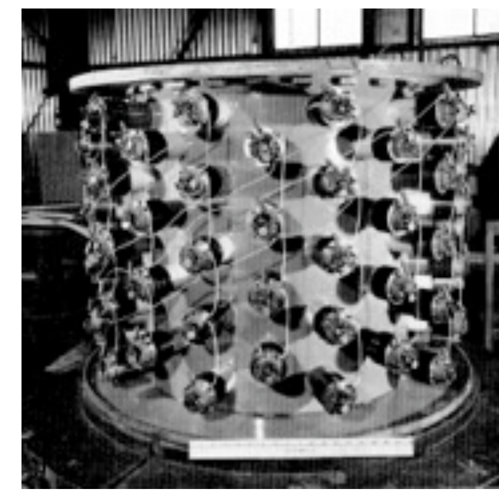


Neutrinos and Antineutrinos

Nuclear Reactor

$\bar{\nu}$

Scintillator (C_xH_y)



PMTs

The Sun

ν

Cleaning fluid (Cl)

\+ Ar detector

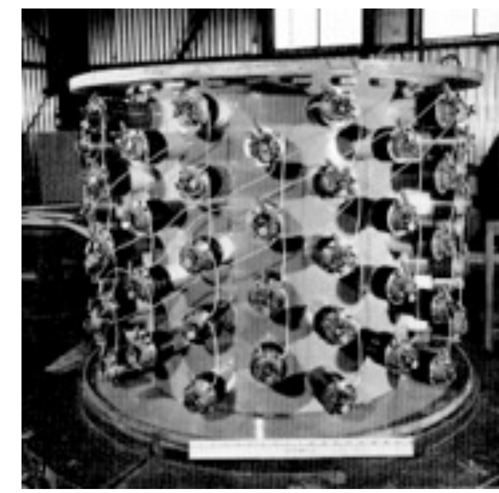
Neutrinos and Antineutrinos

Nuclear Reactor

$\bar{\nu}$

Cowan and Reines (1956)

Scintillator (C_xH_y)



PMTs

The Sun

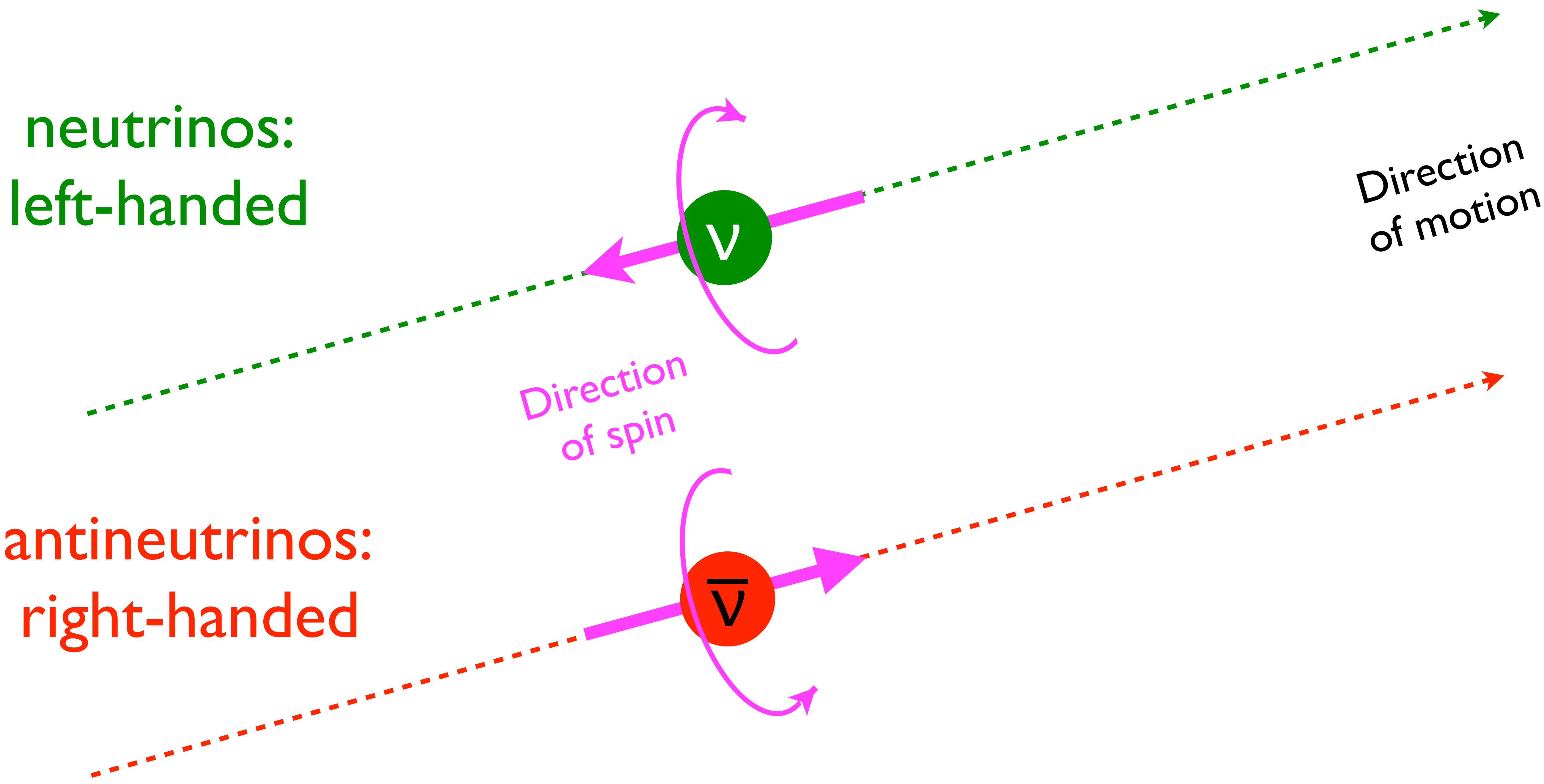
ν

Ray Davis Jr. (1964)

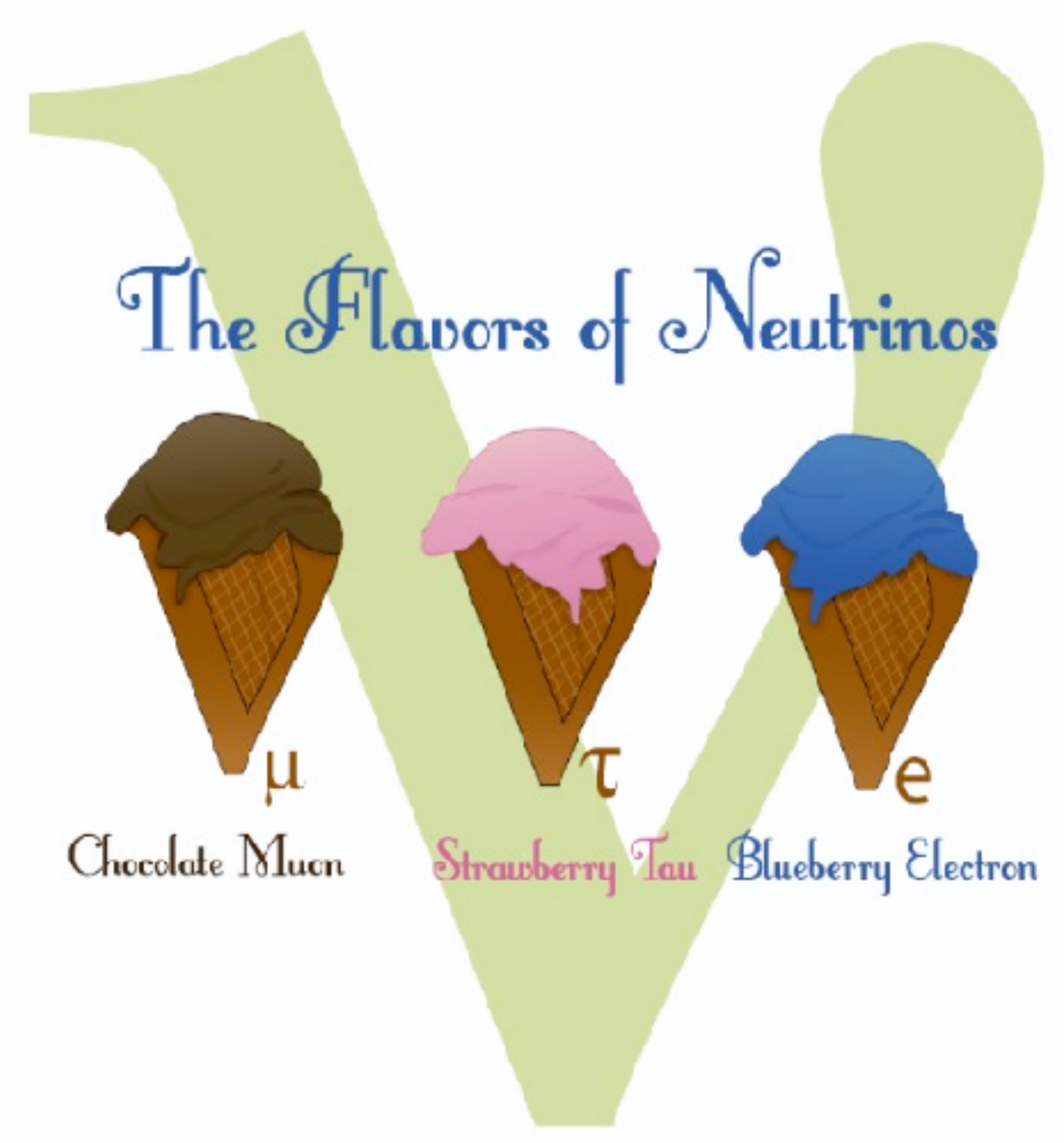
Cleaning fluid (Cl)

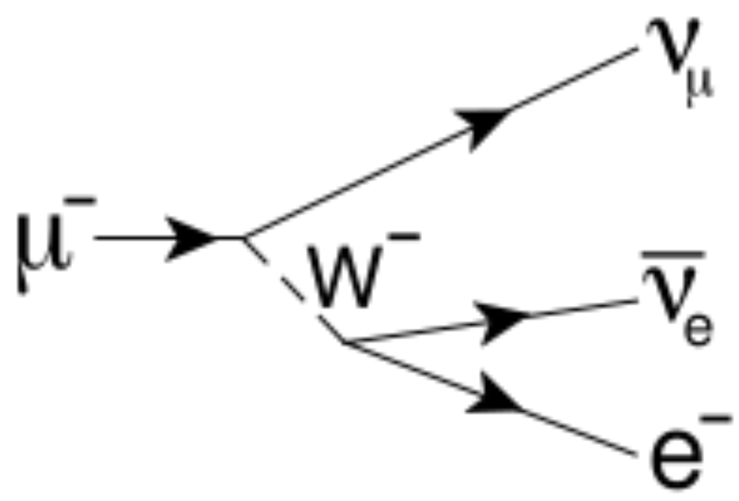
+ Ar detector

Neutrino Handedness

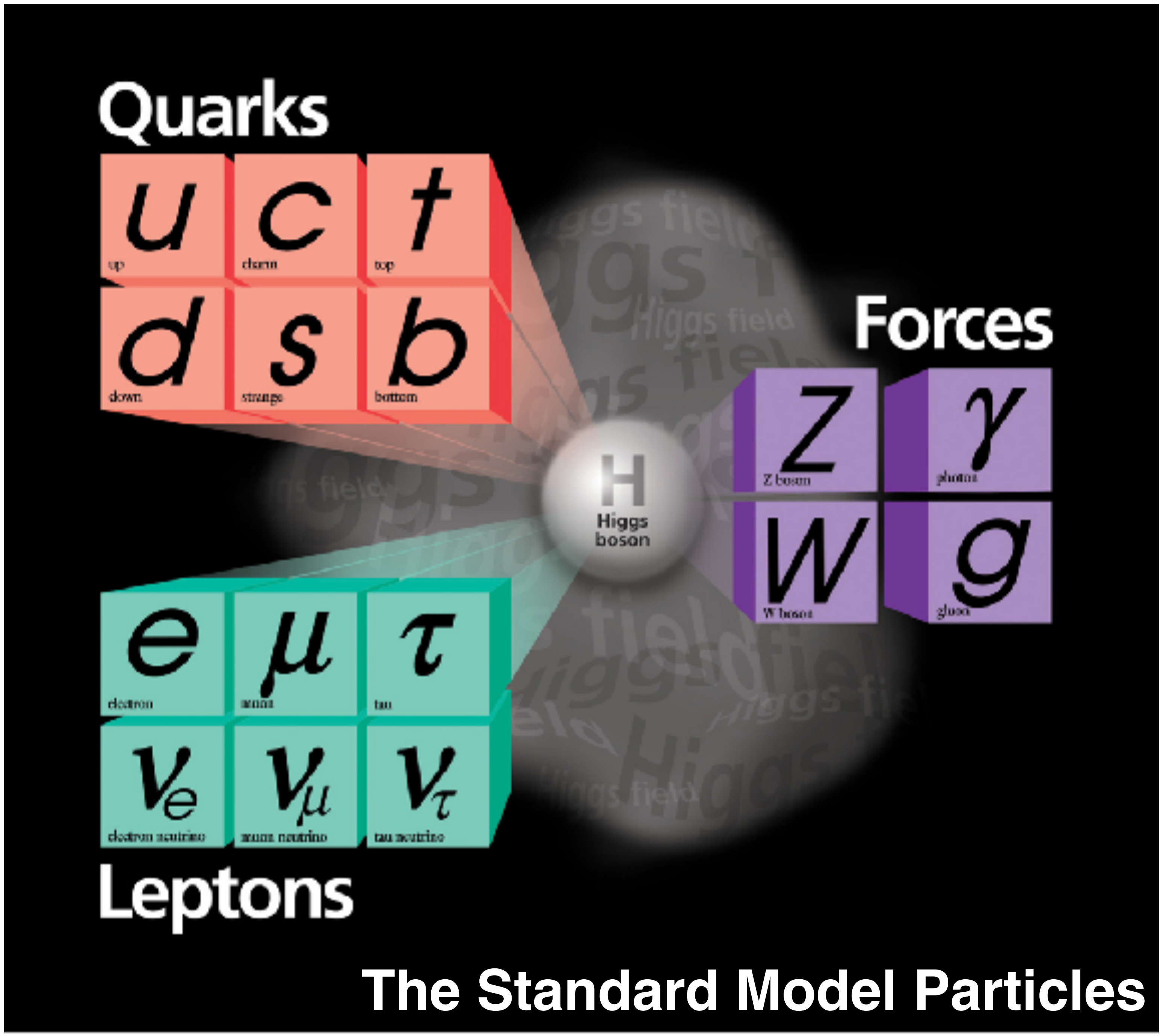


Neutrino Flavors





Standard Model Neutrinos



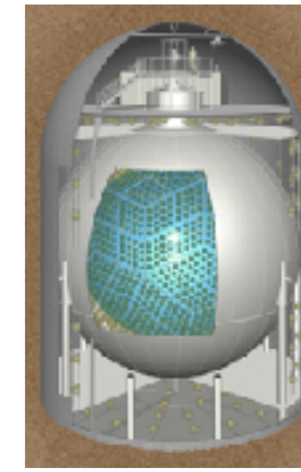
- $q = 0$
- color = 0
- spin = ½
- 3 flavors (e, μ, τ)
- left-handed ν, right-handed $\bar{\nu}$
- $m_\nu < 2$ eV (m_e / 250000)

$m_\nu = 0$?

Credit: Fermilab

Neutrino Oscillation

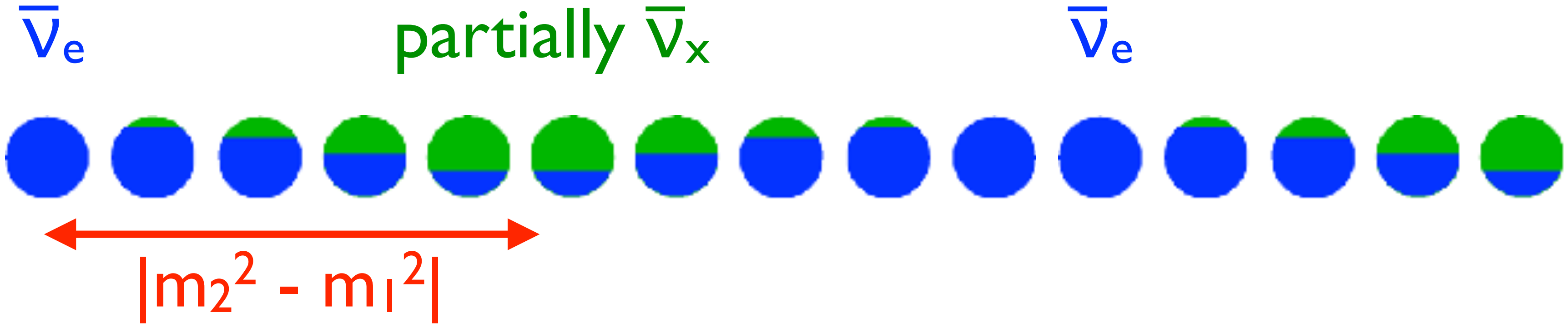
$\bar{\nu}_e$ partially $\bar{\nu}_x$ $\bar{\nu}_e$

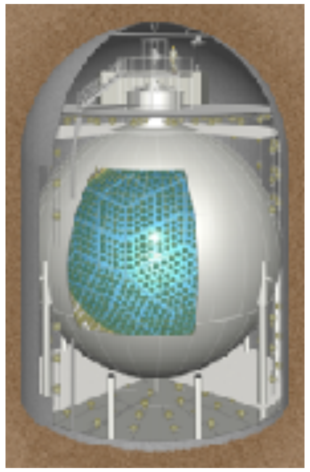


*KamLAND Collaboration, Phys. Rev. D **83**, 052002 (2011).*

Neutrino Oscillation

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





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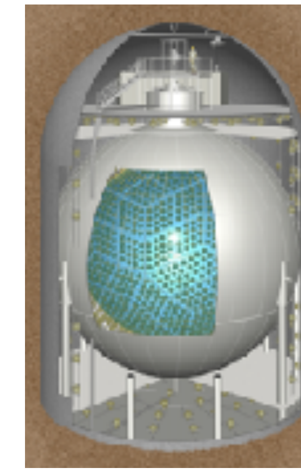
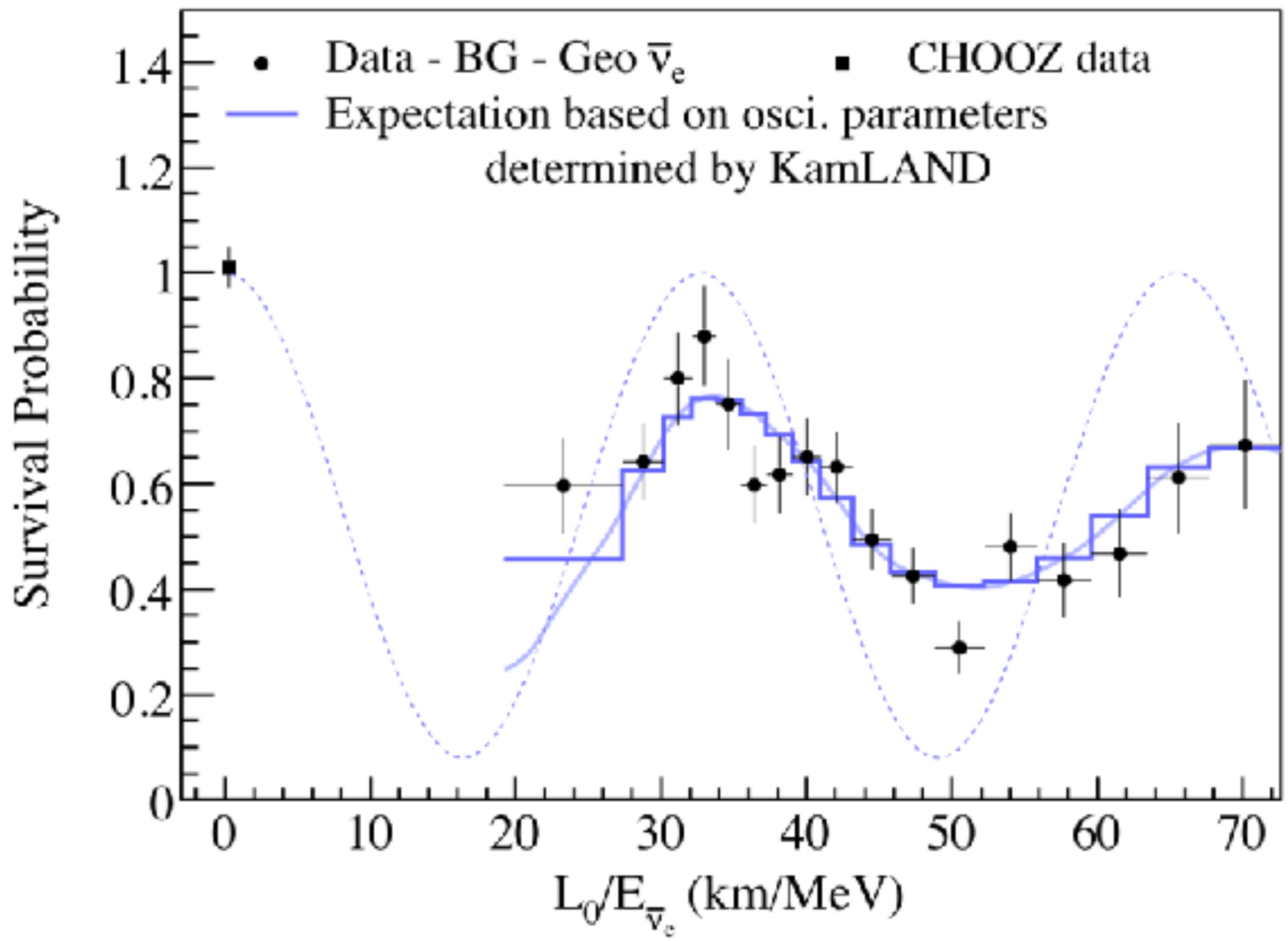
Neutrino Oscillation

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

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

$|m_2^2 - m_1^2|$





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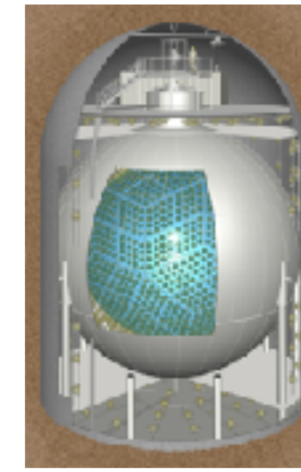
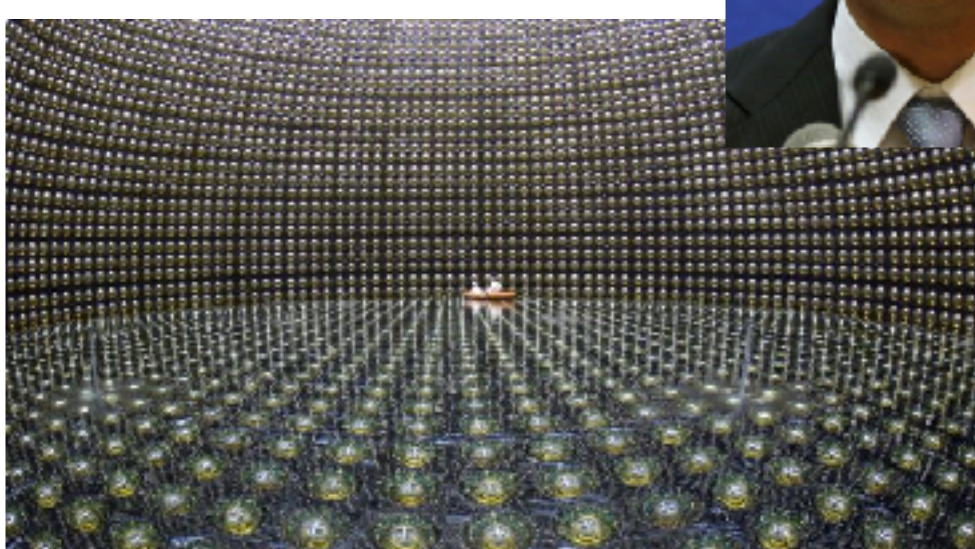
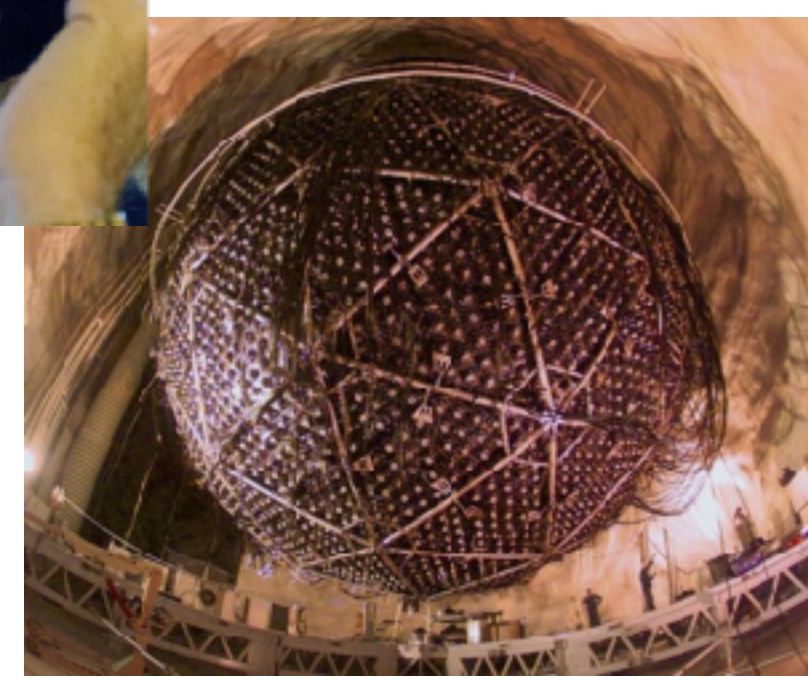
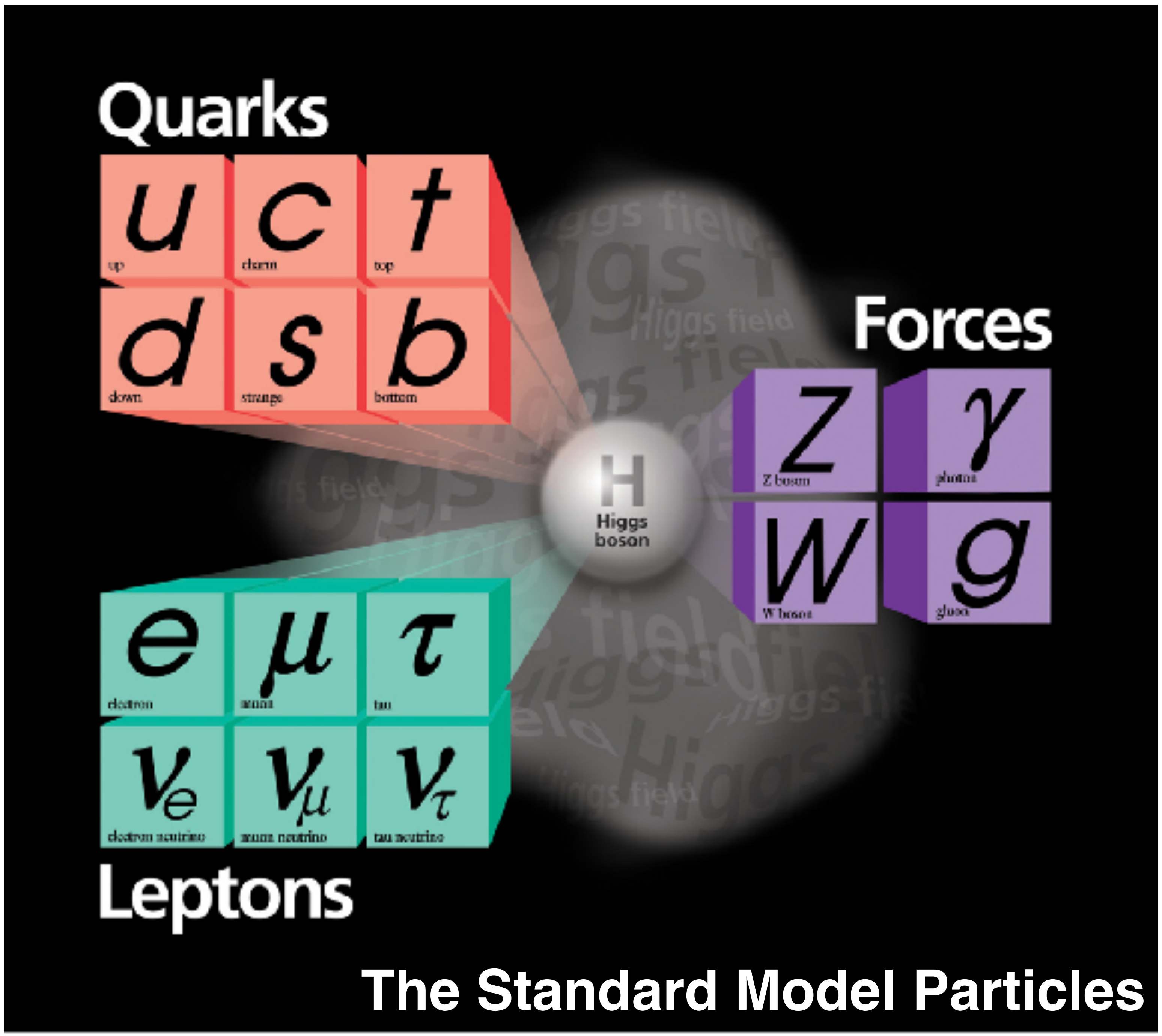






Standard Model Neutrinos

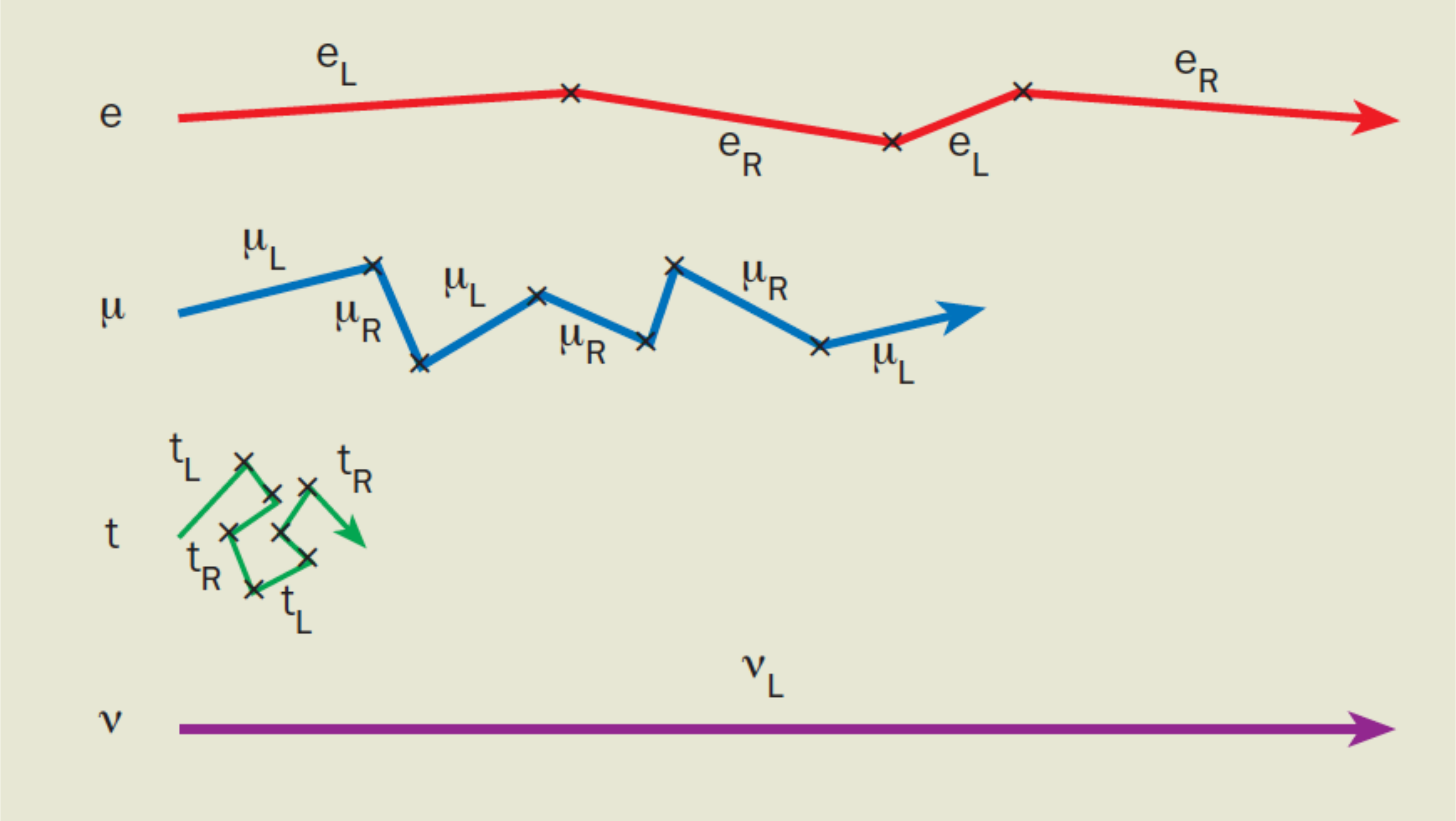


- $q = 0$
- color = 0
- spin = ½
- 3 flavors (e, μ, τ)
- left-handed ν,
  right-handed $\bar{\nu}$
- $0.02 \text{ eV} < m_\nu < 2 \text{ eV}$

- How light *are* they?
- Where is the right-handed ν?

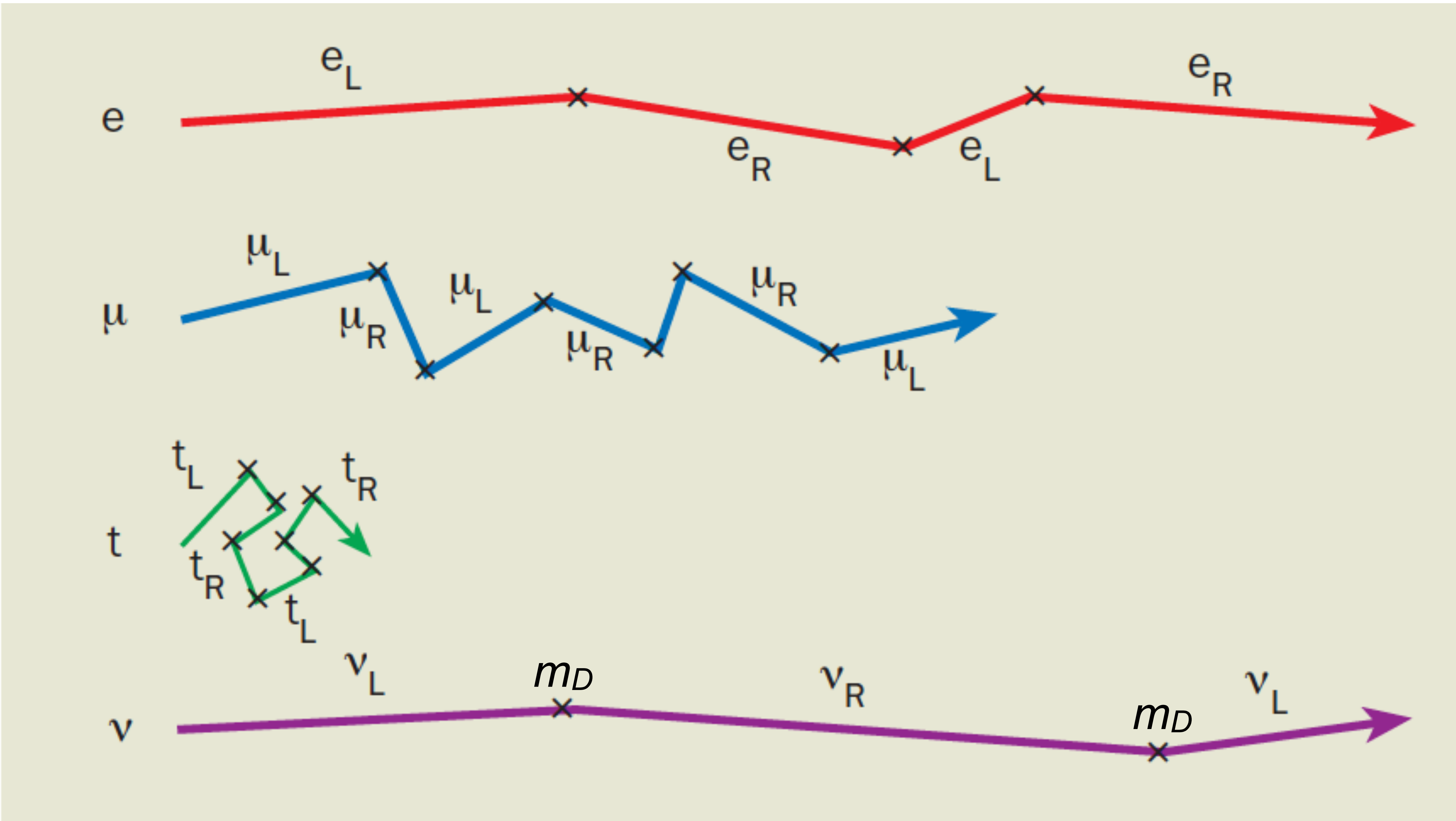
Credit: Fermilab

Incorporating ν Mass

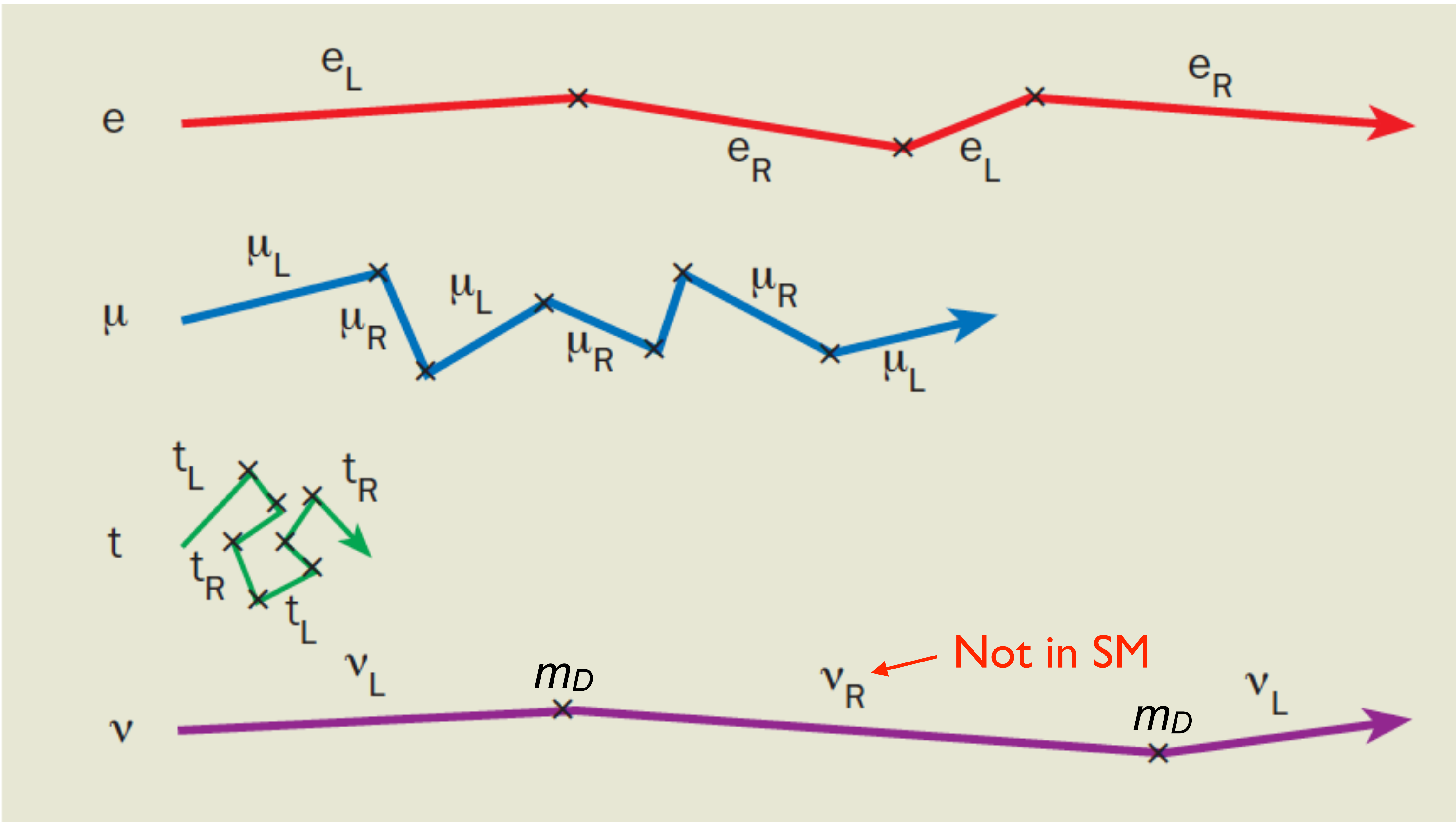


H. Murayama, Physics World (May 2002).

Incorporating ν Mass

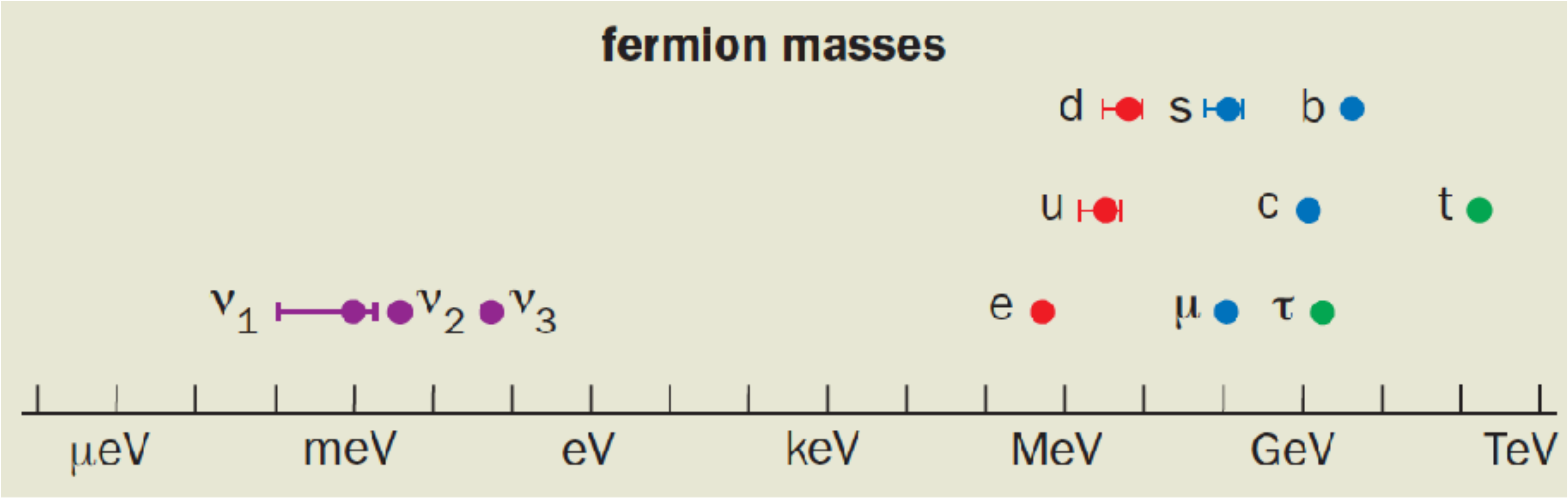


Incorporating ν Mass



H. Murayama, Physics World (May 2002).

Incorporating ν Mass



The Majorana Equation

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

The Majorana Equation

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

The Majorana Equation

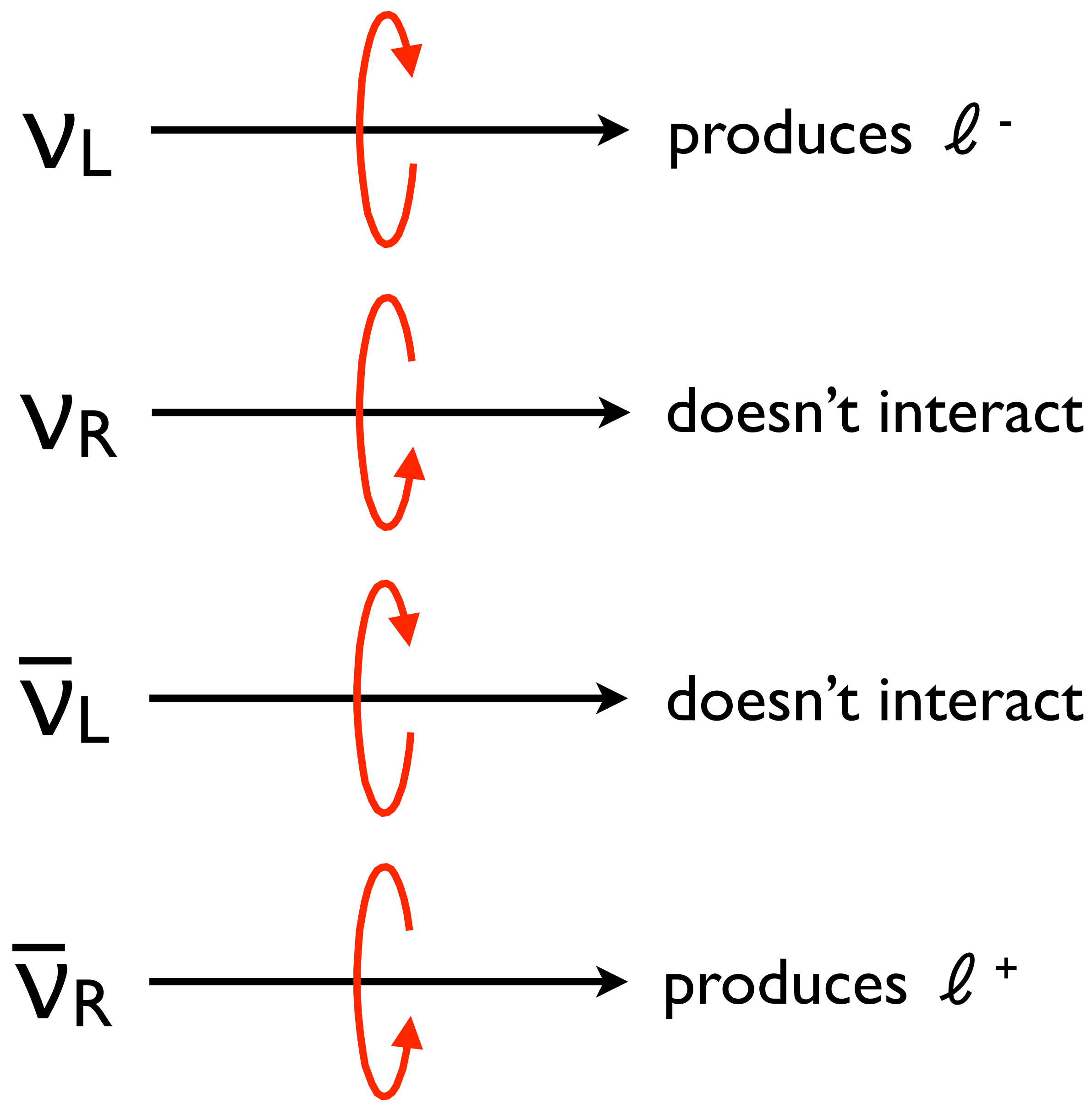
Schrodinger: $$i\frac{\partial}{\partial t}\Psi + \frac{1}{2m}\nabla^2\Psi = 0$$

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

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

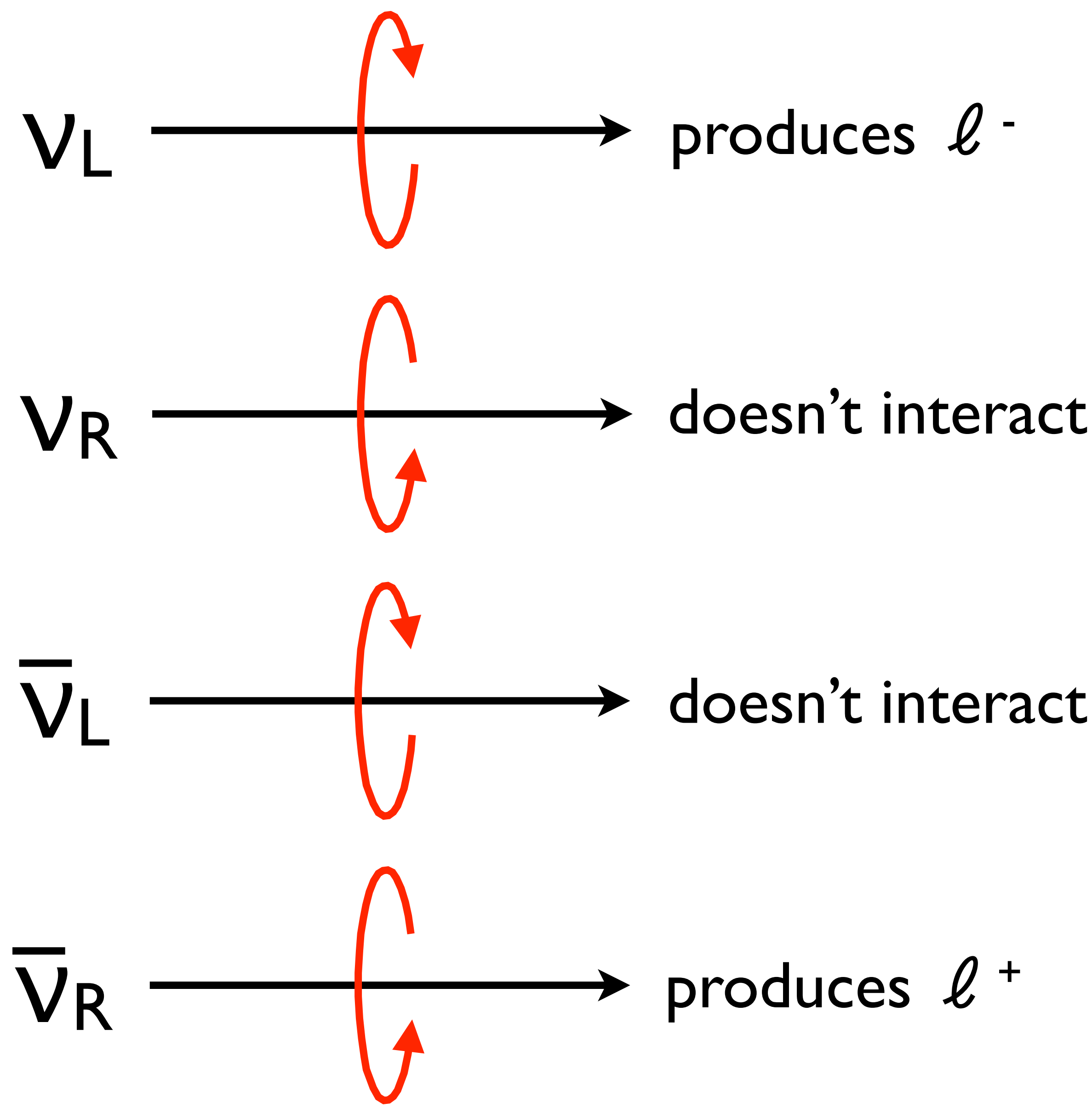
E. Majorana, Il Nuovo Cimento **14**, 171 (1937).
English translation: Soryushiron Kenkyu **63**, 149 (1981).

Dirac neutrinos

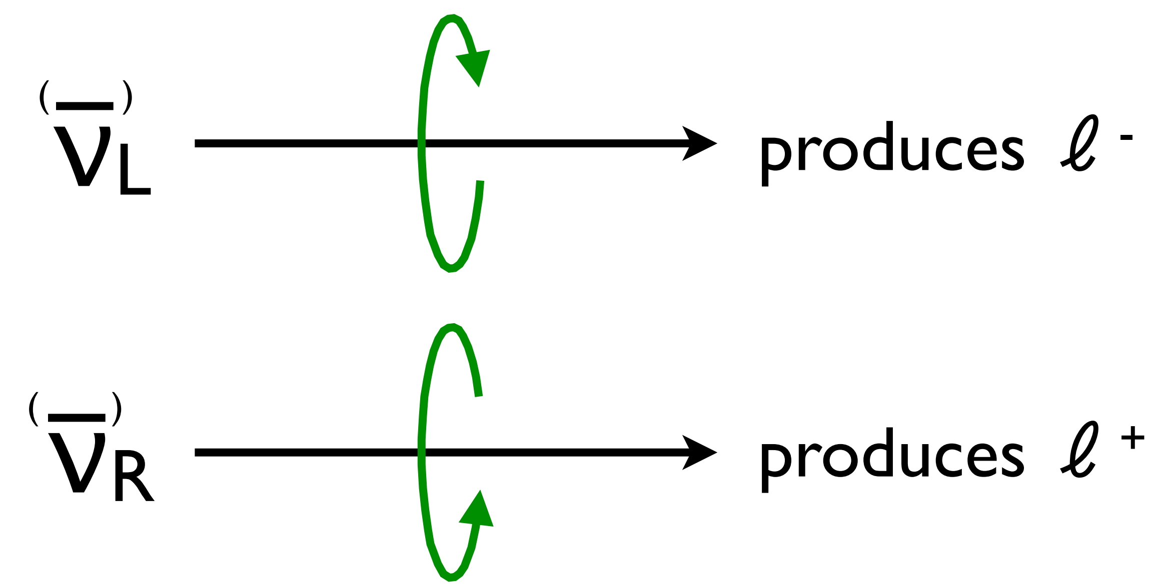


Majorana: $\nu = \bar{\nu}$

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

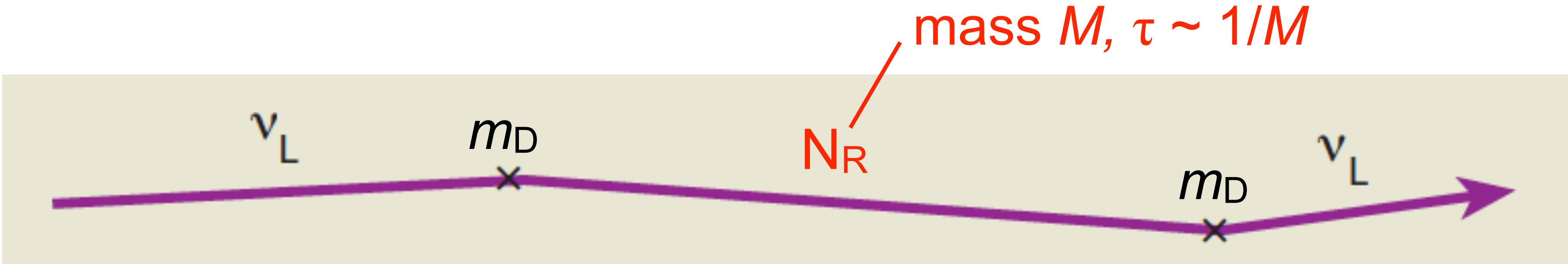


Majorana ($\nu = \bar{\nu}$)



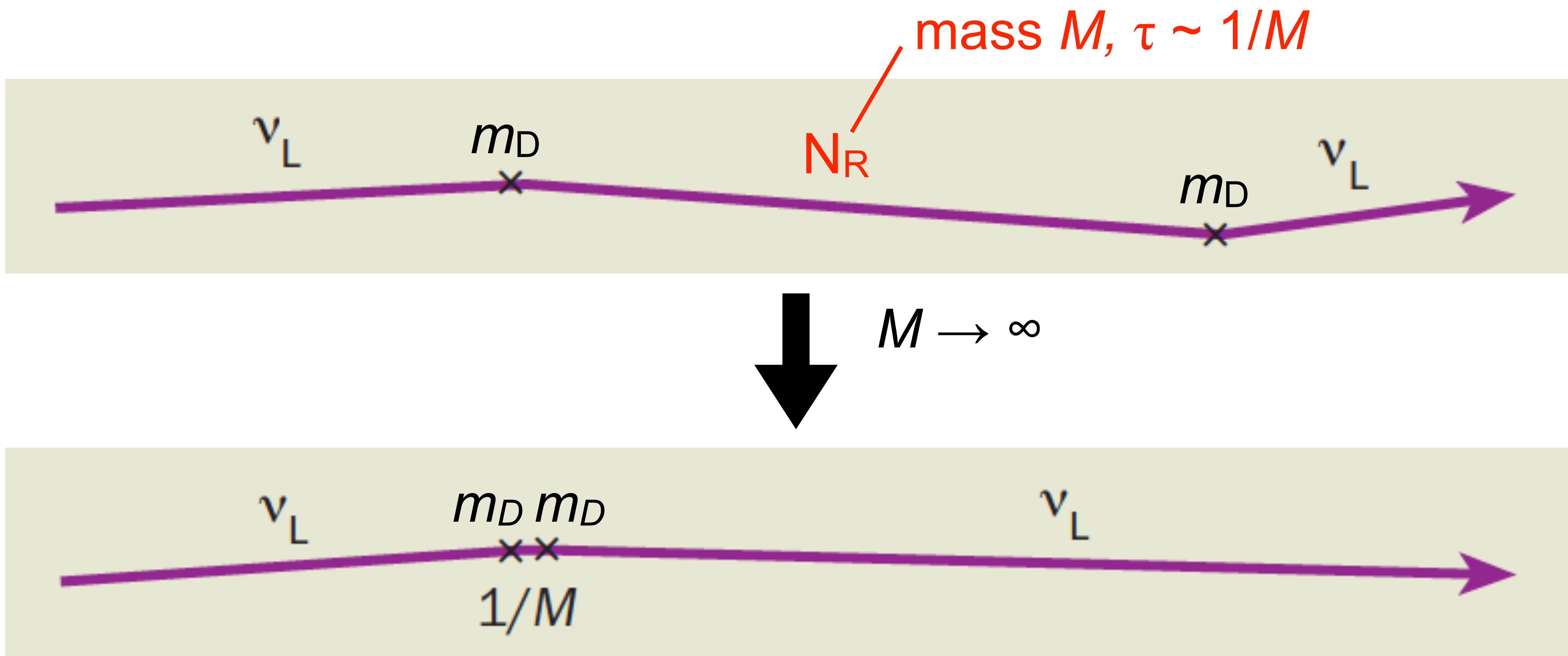
- Requires Q = -Q = 0
- Appear "naturally" in Grand Unification theories, explains why ν are so much lighter than e, μ, τ
- Implies Lepton number is not conserved

Seesaw Mechanism



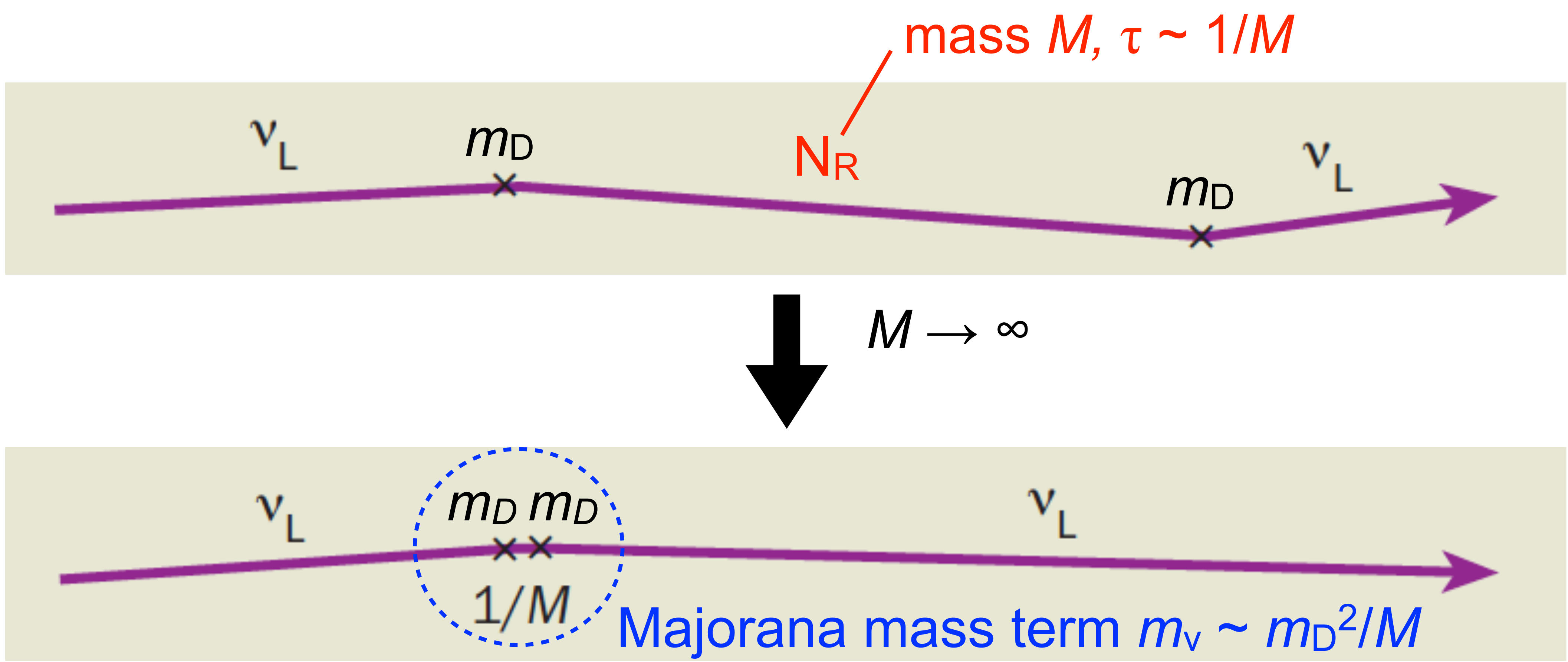
 H. Murayama, Physics World (May 2002).

Seesaw Mechanism



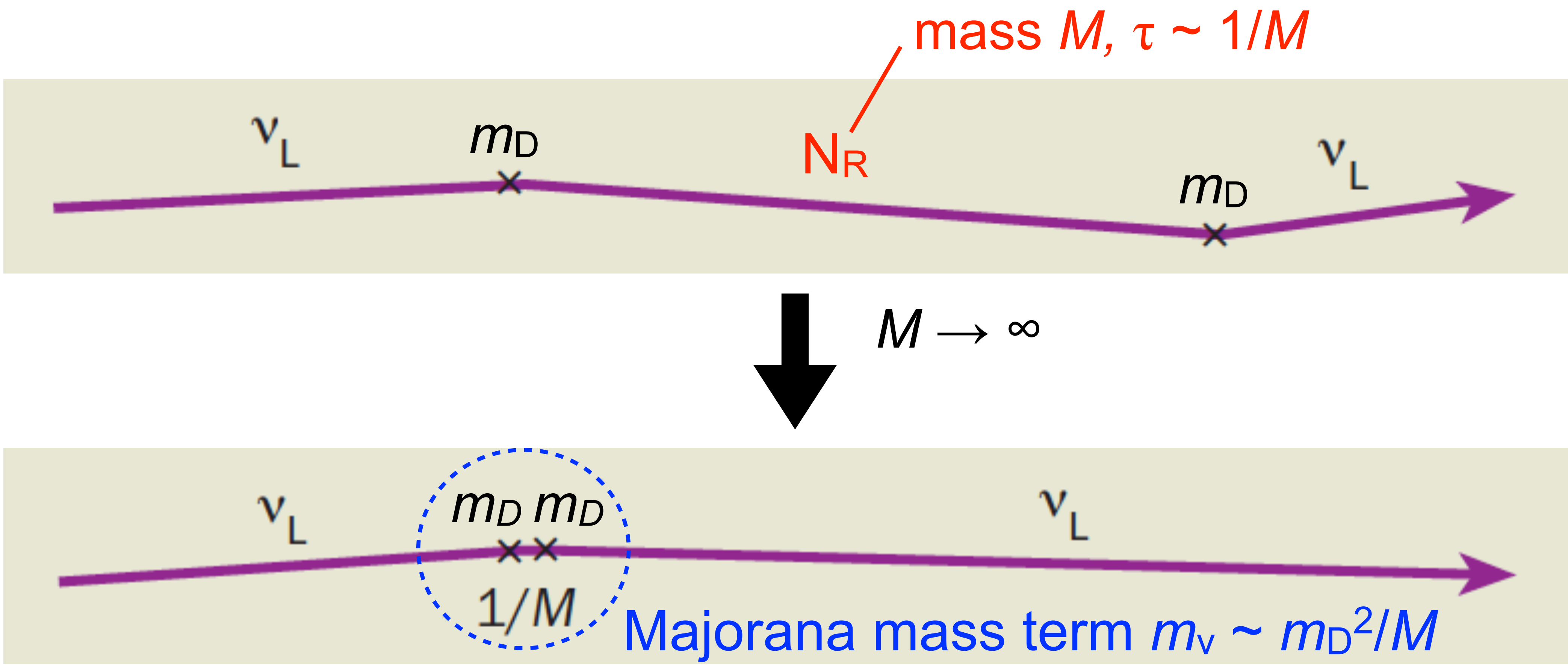
 H. Murayama, Physics World (May 2002).

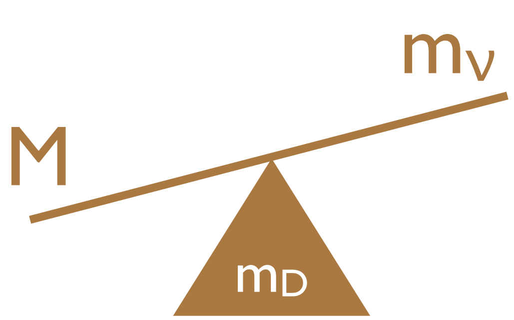
Seesaw Mechanism



 H. Murayama, Physics World (May 2002).

Seesaw Mechanism

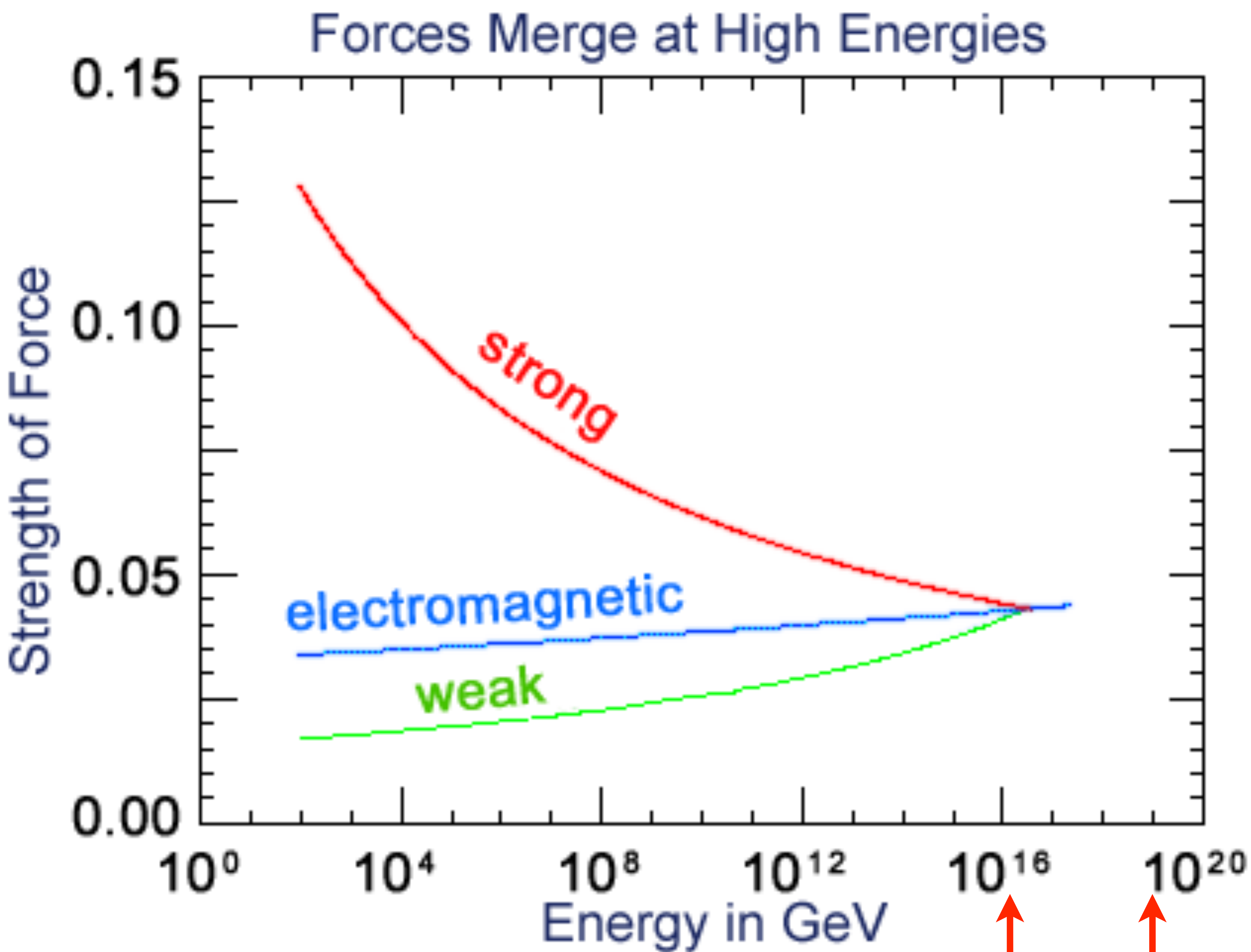




for $m_D \sim$ GeV-TeV:

$m_\nu \sim$ meV-eV $\leftrightarrow$ $M \sim 10^{16}$-10^{19} GeV

Grand Unification

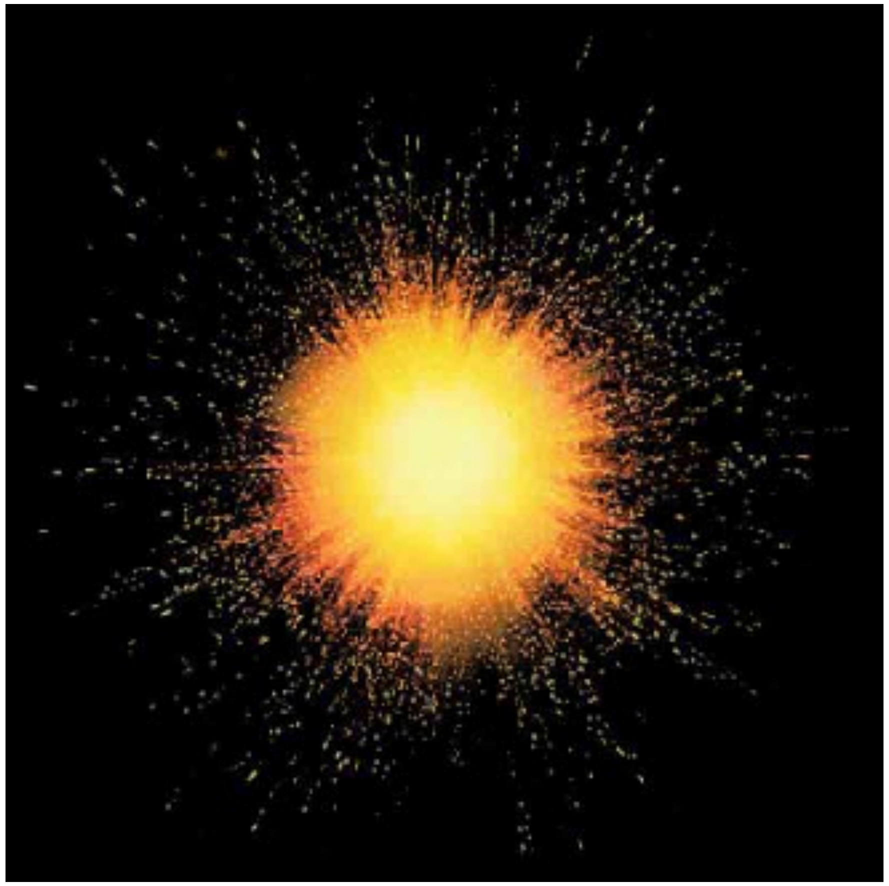


GUT scale

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

Matter-Antimatter Asymmetry

The Big Bang



matter + antimatter

The Universe Today

matter only

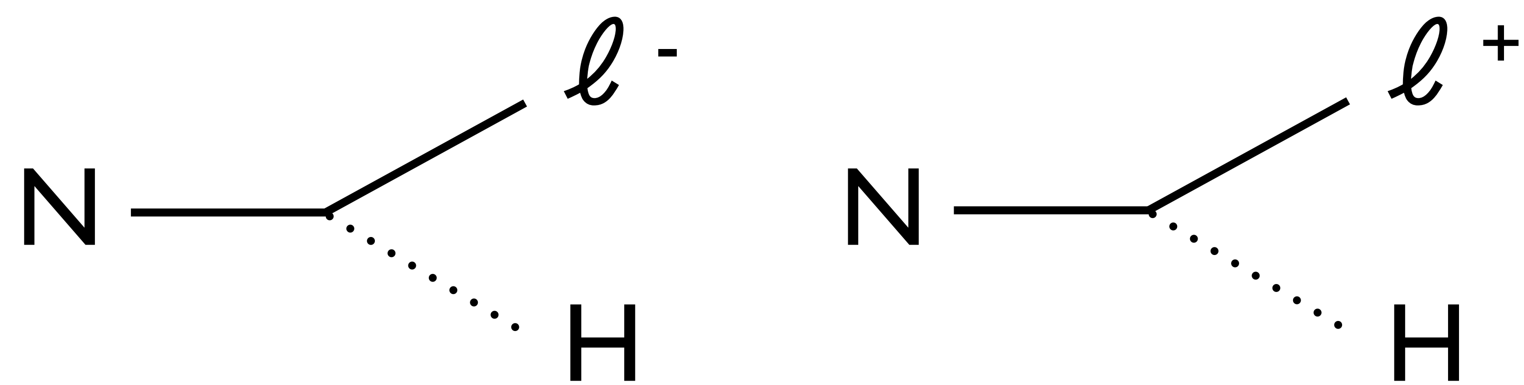
Sakharov Conditions

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

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

Leptogenesis

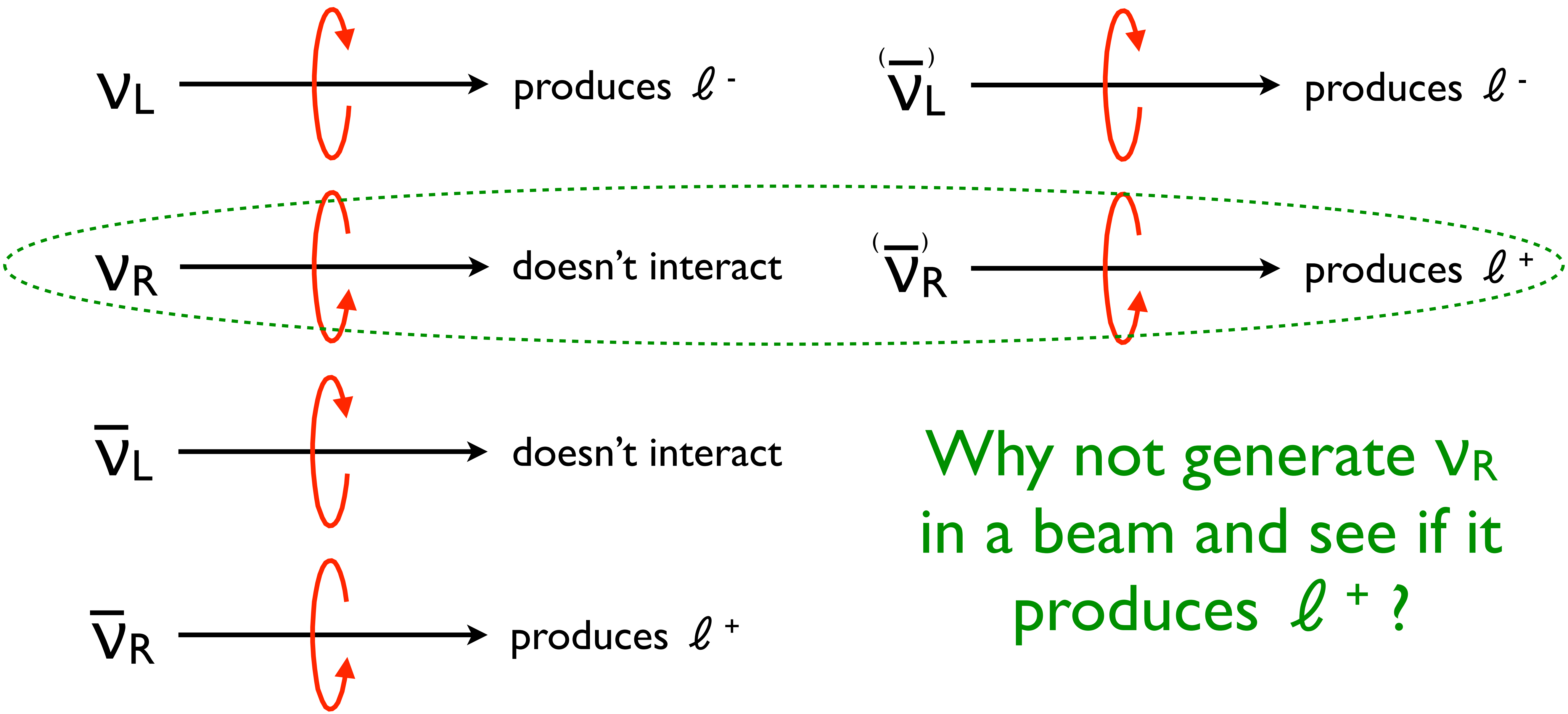
- Decay of heavy Majorana neutrino (N) into SM leptons ($\ell^{\pm}$) and Higgs (H):



- 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!

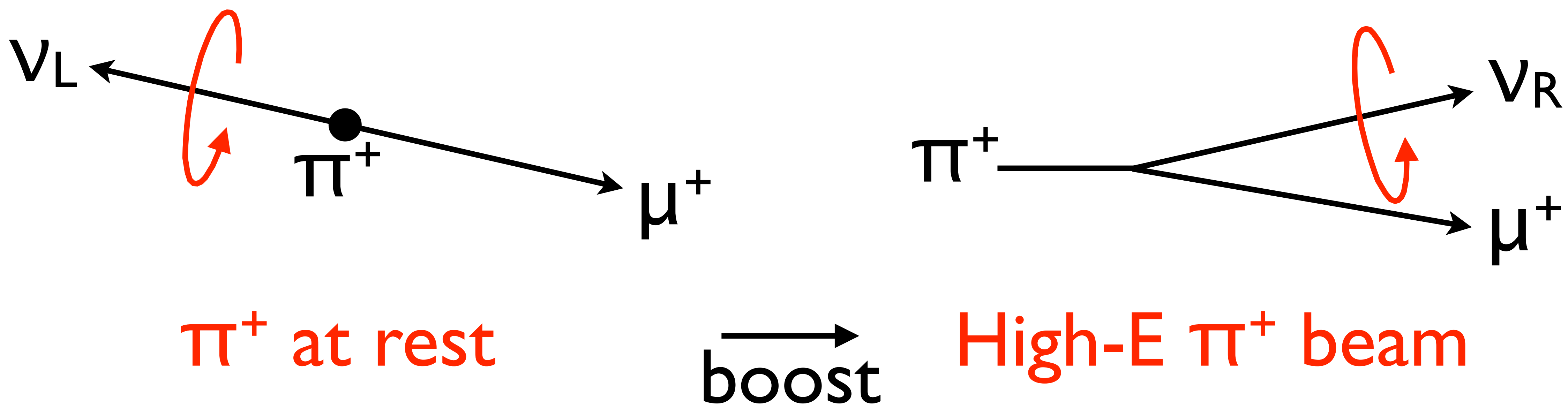
Testing $\nu = \bar{\nu}$

Dirac ν | Majorana ν



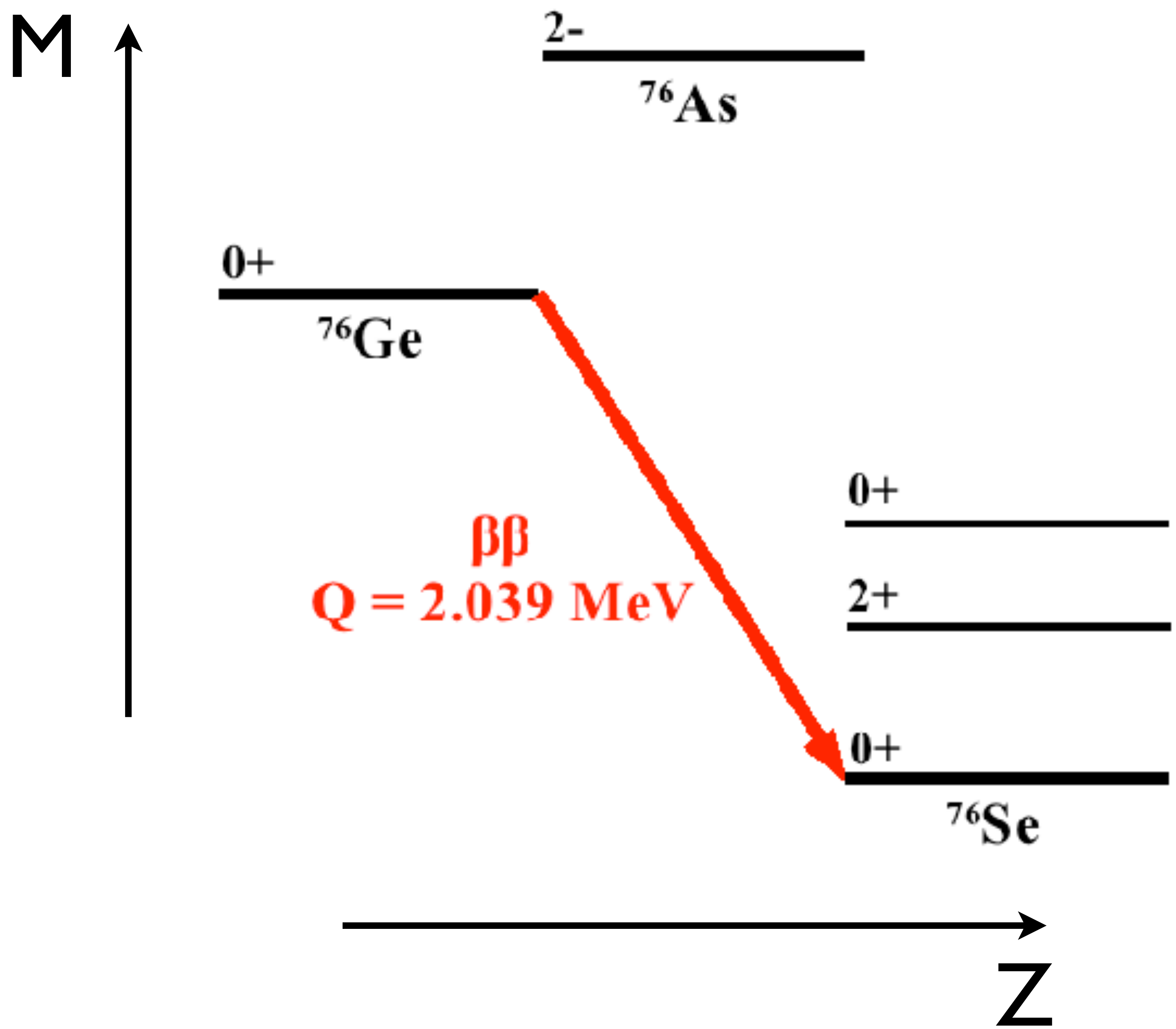
Why not generate ν_R in a beam and see if it produces ℓ^+?

Testing $\nu = \bar{\nu}$



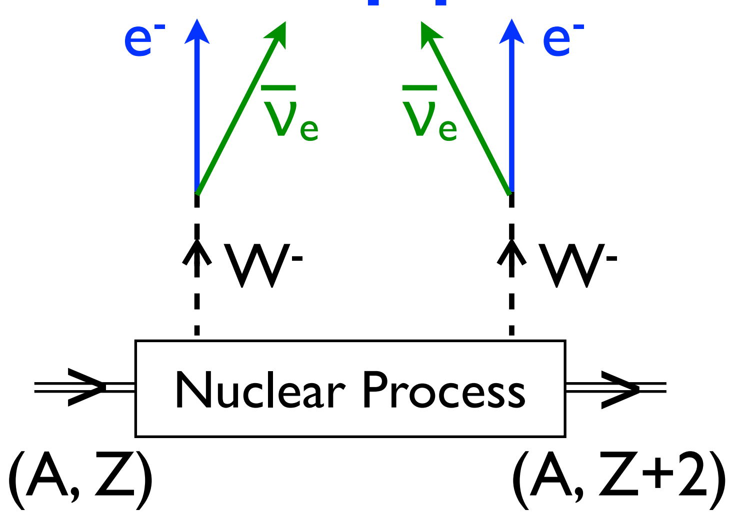
- Boost so that π^+ beam faster than ν_L from decay at rest: requires $E_\pi > 4$ PeV (n.b. LHC = 14 TeV)
- Fraction of decays with helicity flipped: $<10^{-15}$
- *"Since L-violation comes only from Majorana ν masses, any attempt to observe it will be at the mercy of the ν masses."*
  - B. Kayser

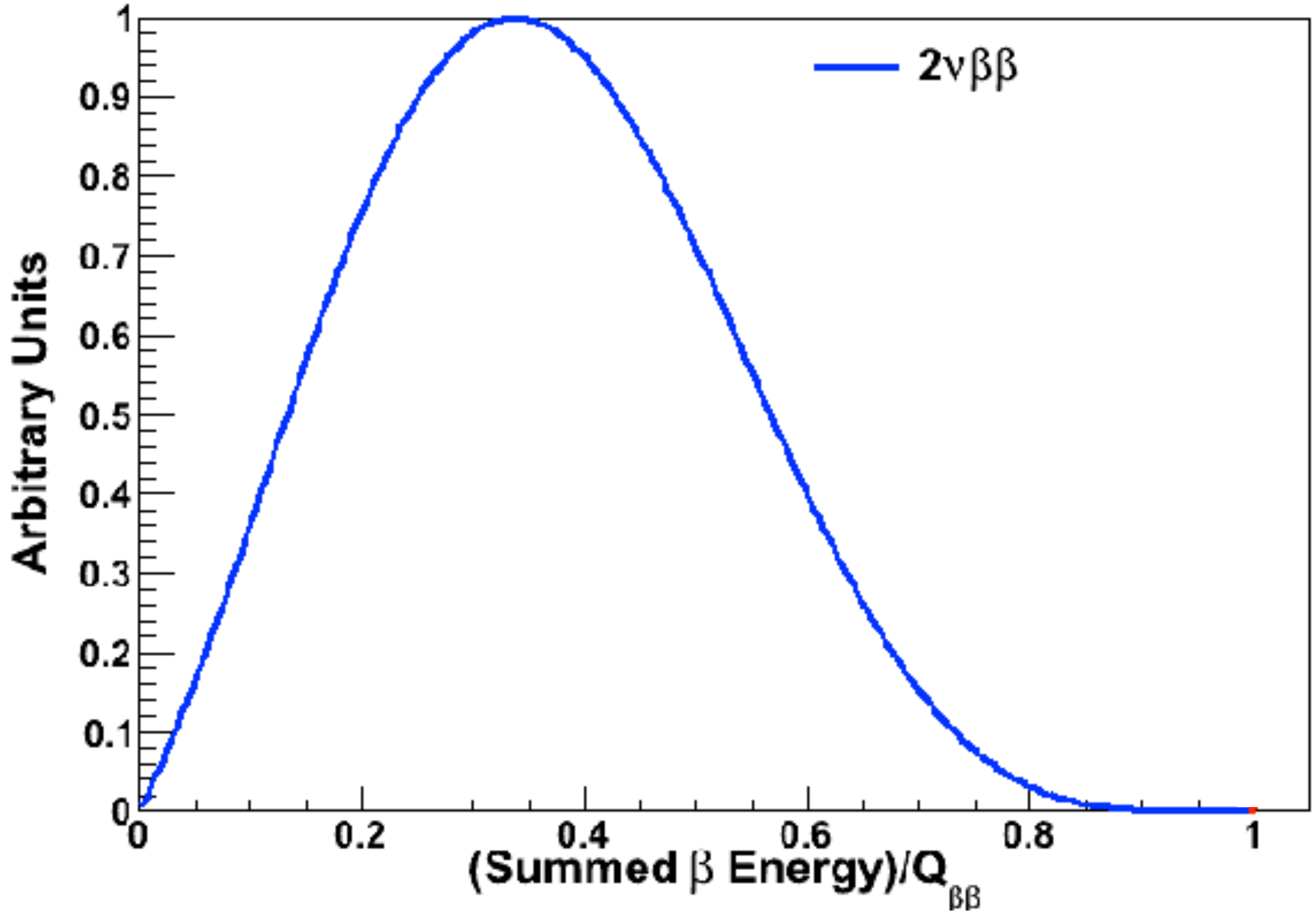
Double-Beta Decay



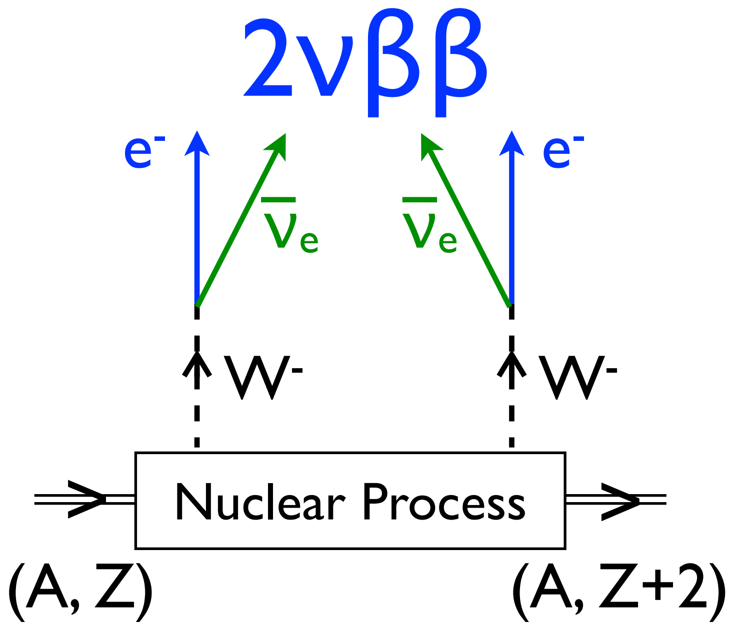
Double-Beta Decay

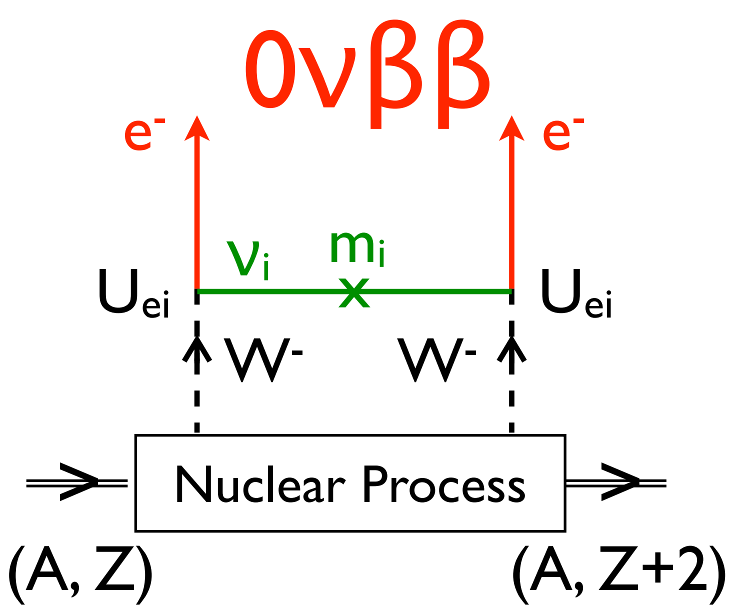
2νββ

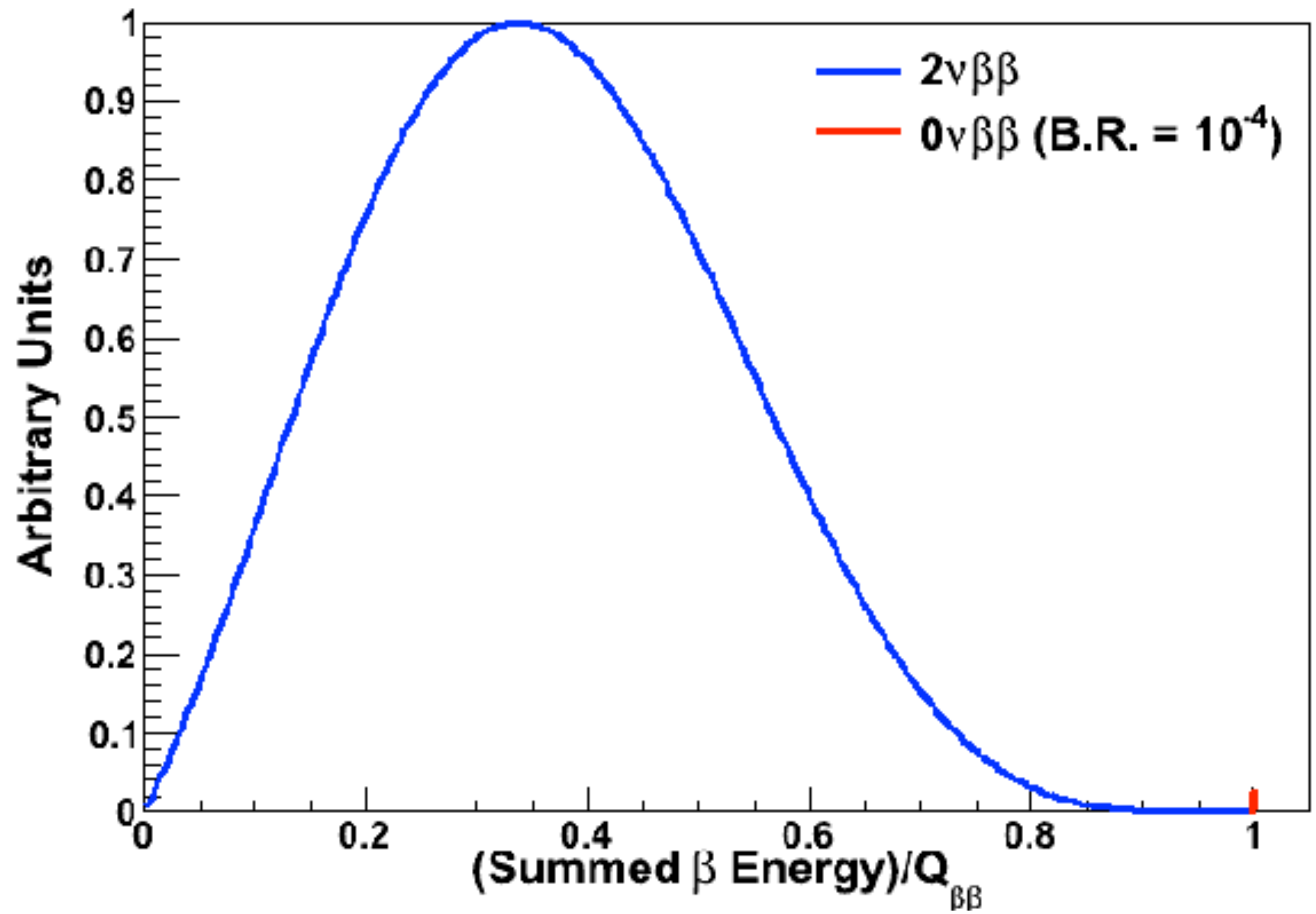




0νββ Decay







$$T_{1/2} = 1/G\,|M|^2\, m_{\beta\beta}^2$$

$$m_{\beta\beta} \equiv \left|\, \Sigma\, m_i\, U_{ei}^2 \,\right|$$

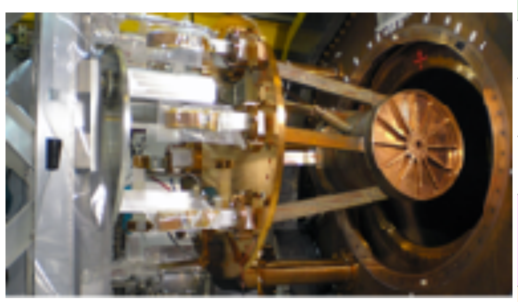
$0\nu\beta\beta$ Experiments

Collaboration	Isotope	Technique	mass ($0\nu\beta\beta$ 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	Complete
CUORE	Te-130	TeO$_2$ Bolometer	206 kg	Operating
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

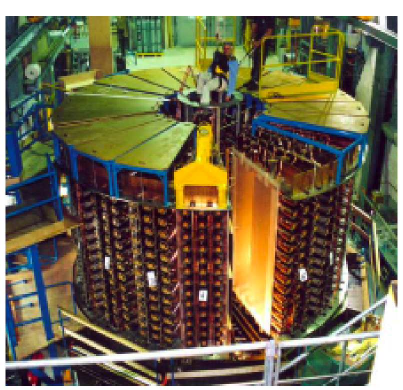
Complete | Construction | Operating

CUORE

EXO-200



NEMO3



GERDA

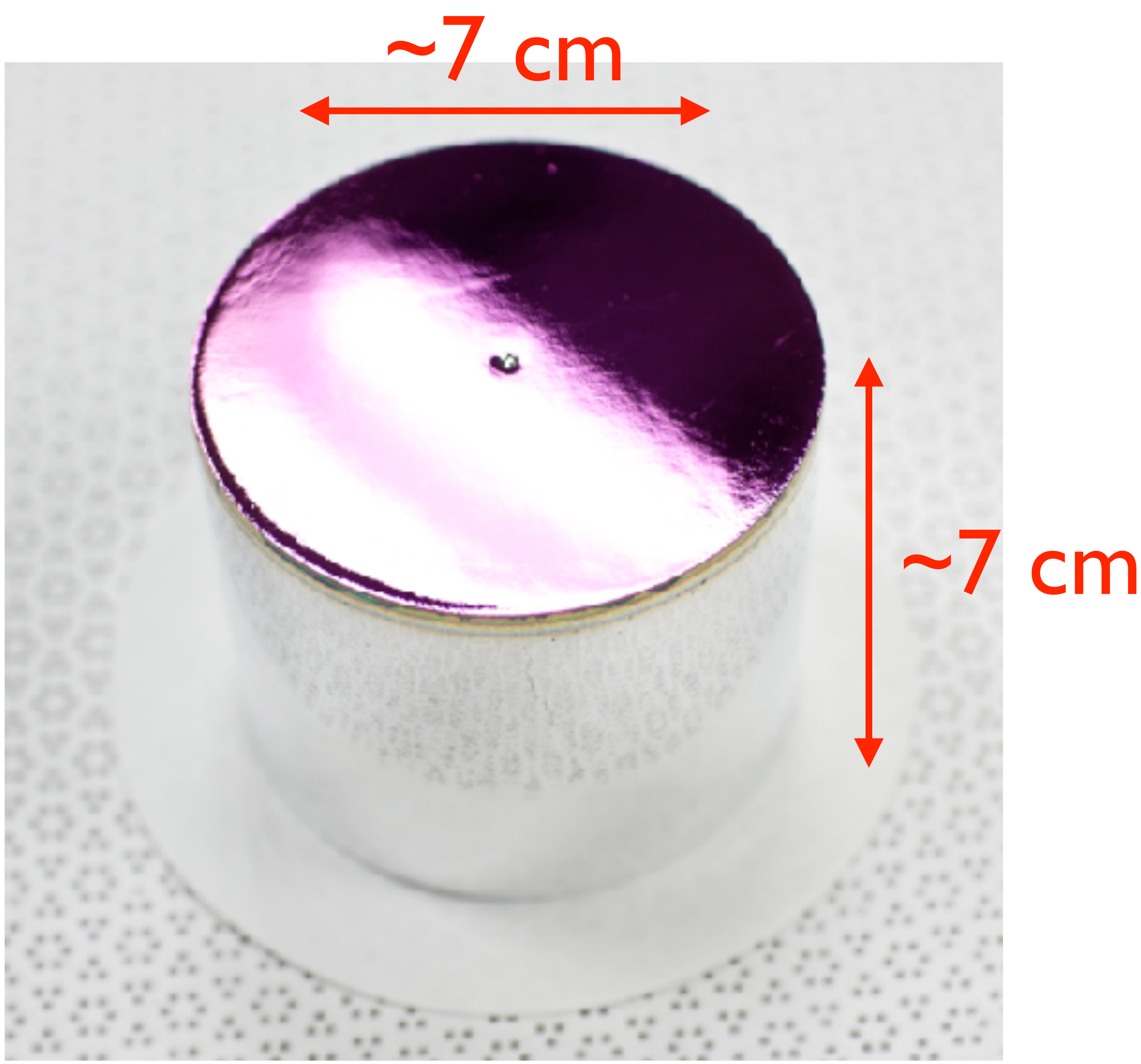
MAJORANA

CANDLES

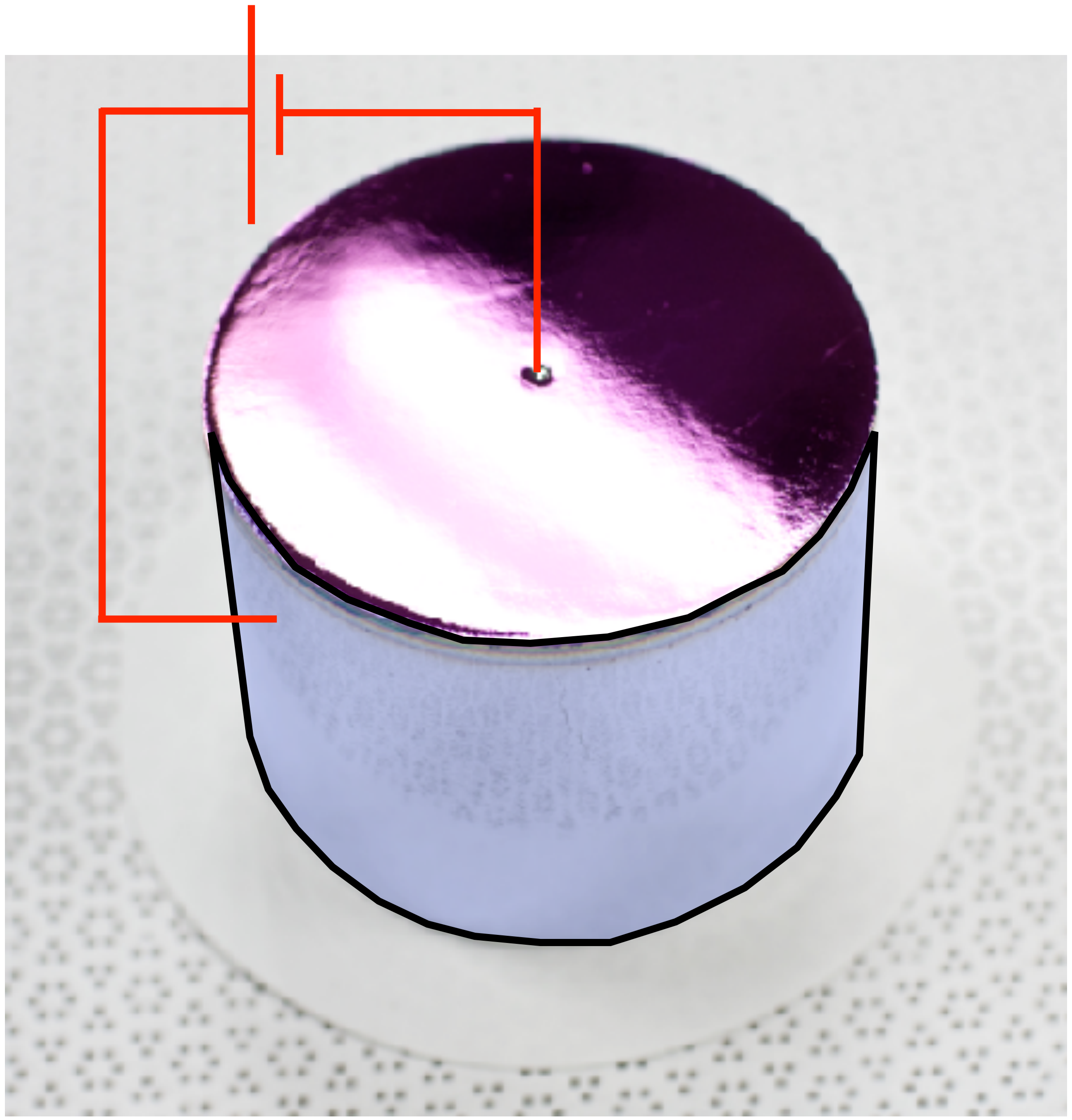
Jason Detwiler

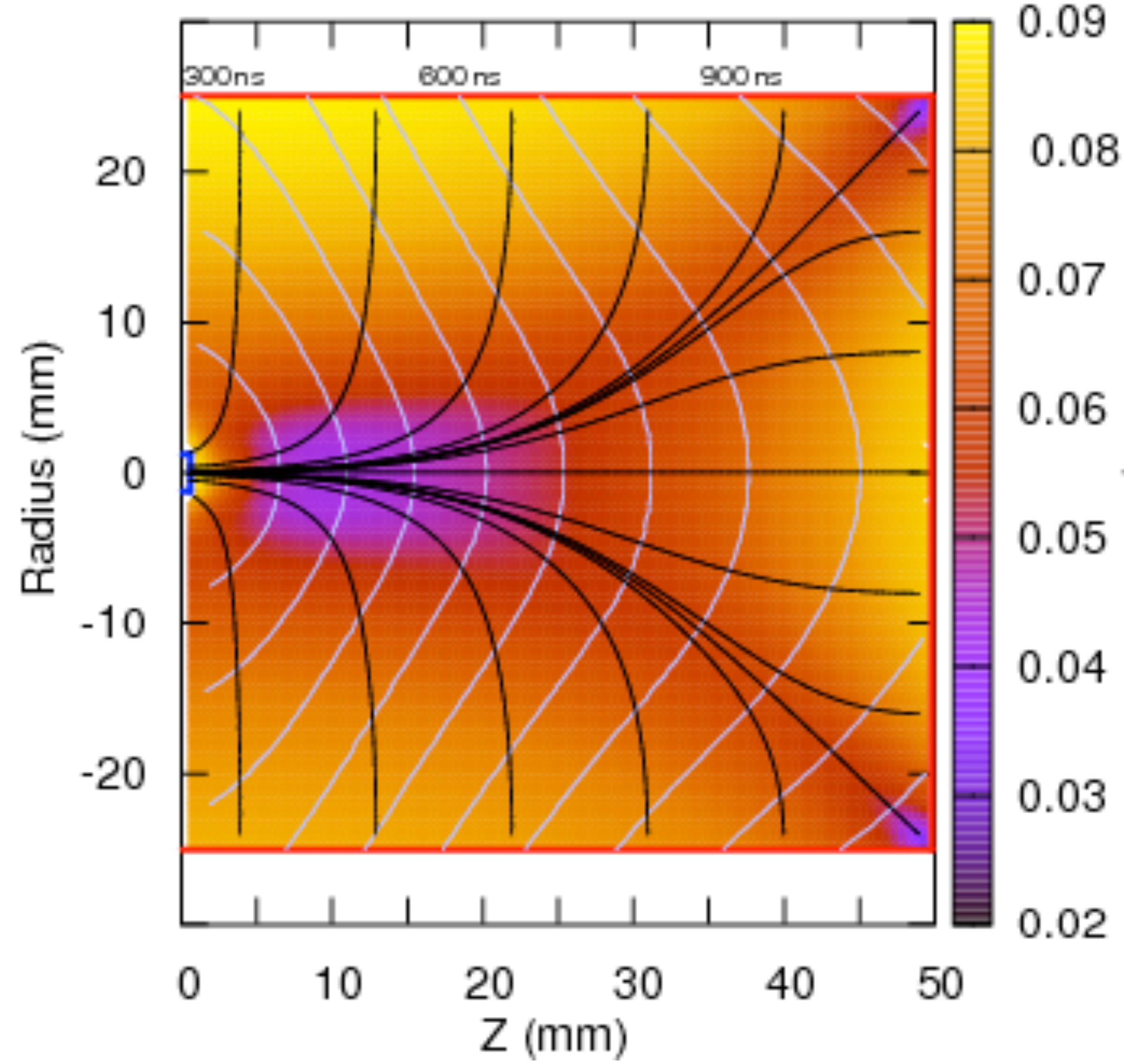
From J. F. Wilkerson

Germanium Detectors



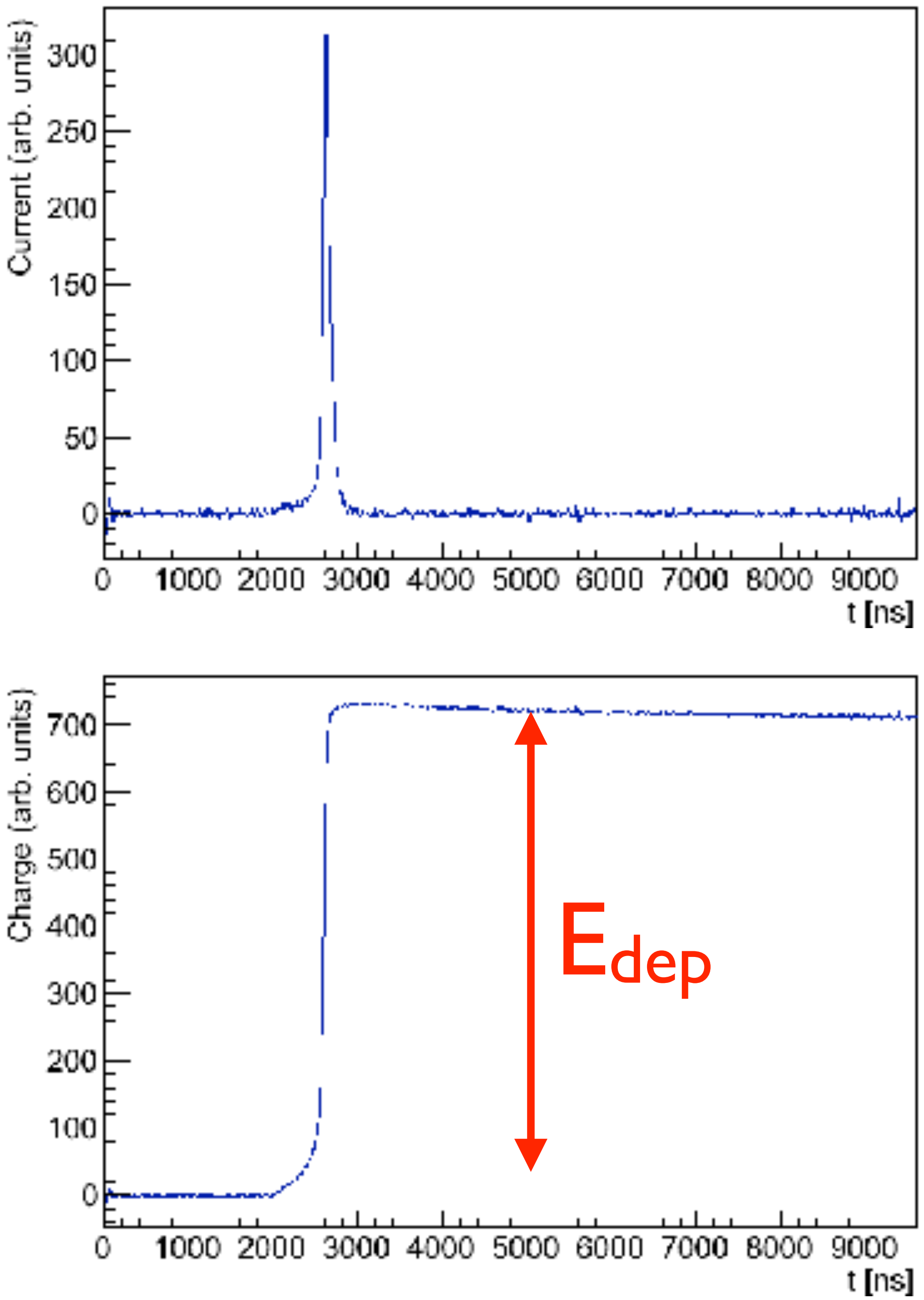
Germanium Detectors

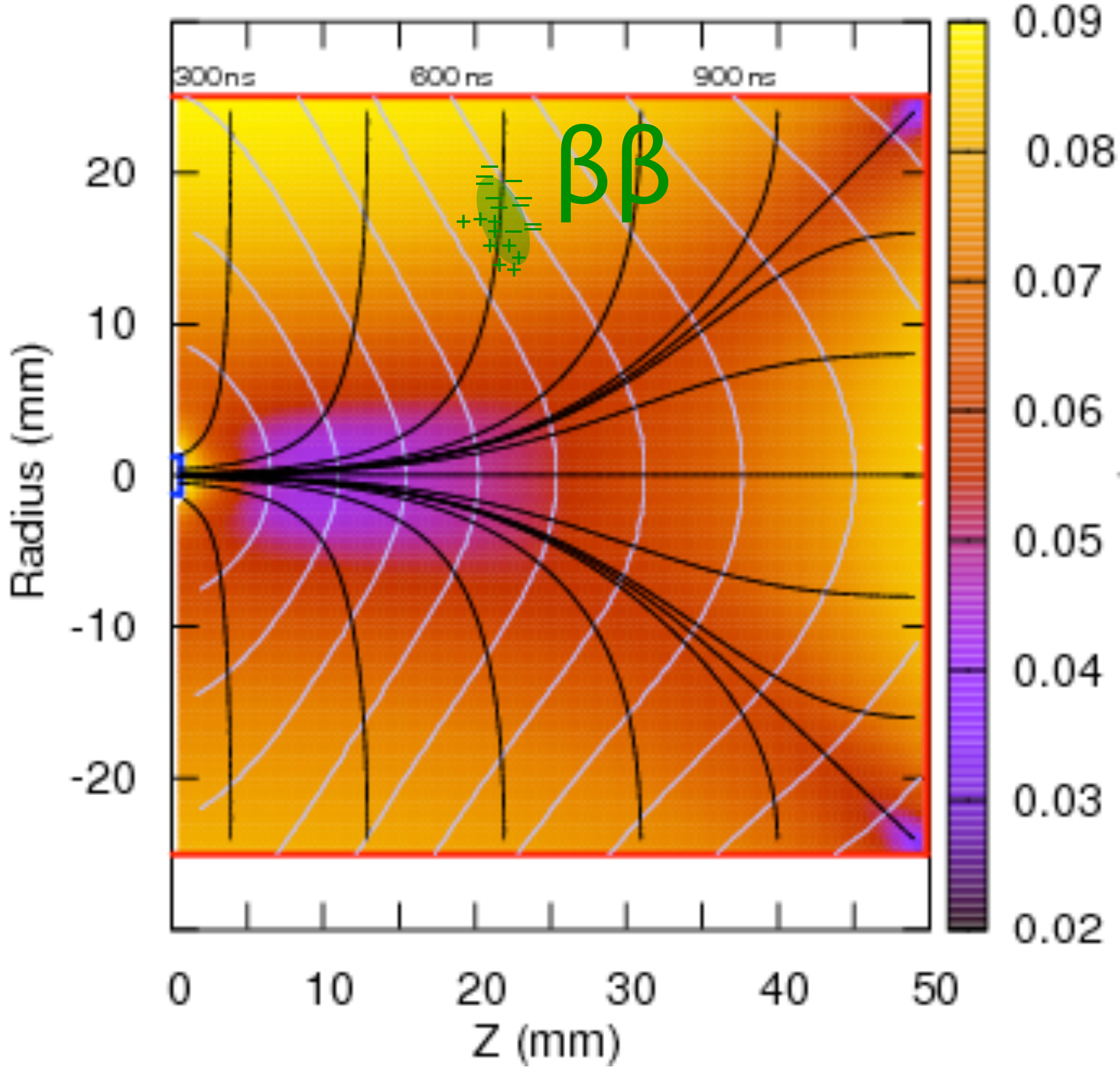




Hole v_{drift} (mm/ns) w/ paths, isochrones

Germanium Detectors

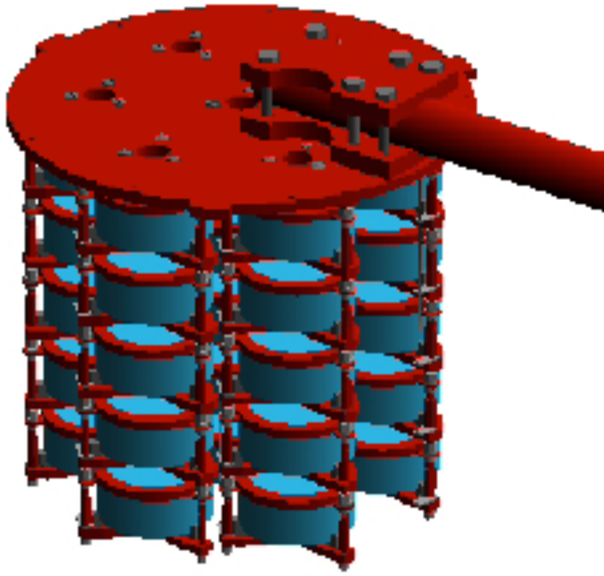




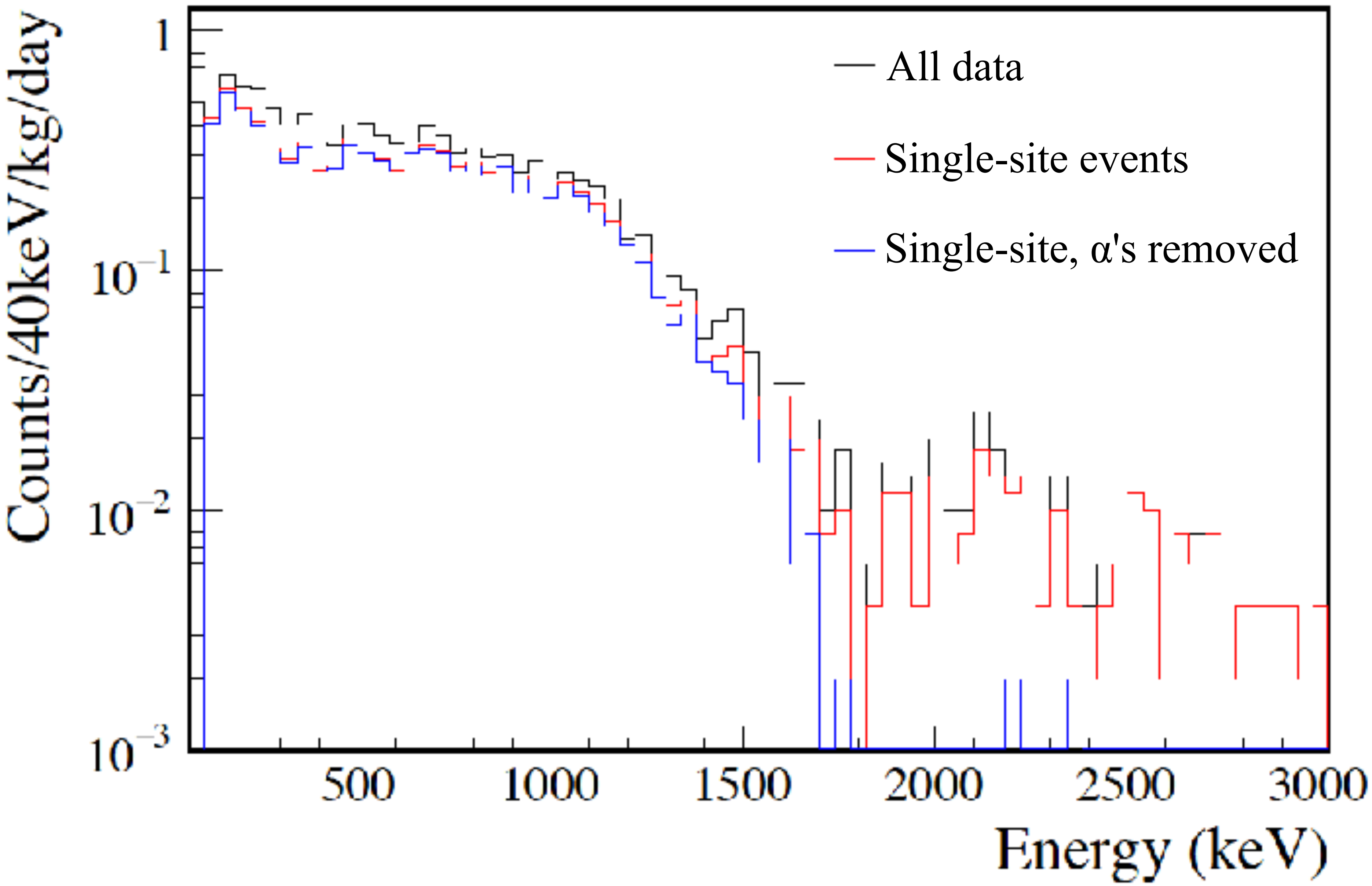
Hole v_{drift} (mm/ns) w/ paths, isochrones

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 (Jun 2014 - Jun 2015)
  - Module 1: ~20 kg ^{enr}Ge (May 2015 - present; low-BG from Jan 2016)
  - Module 2: ~10 kg ^{enr}Ge + ~10 kg ^{nat}Ge (Summer 2016 - present)

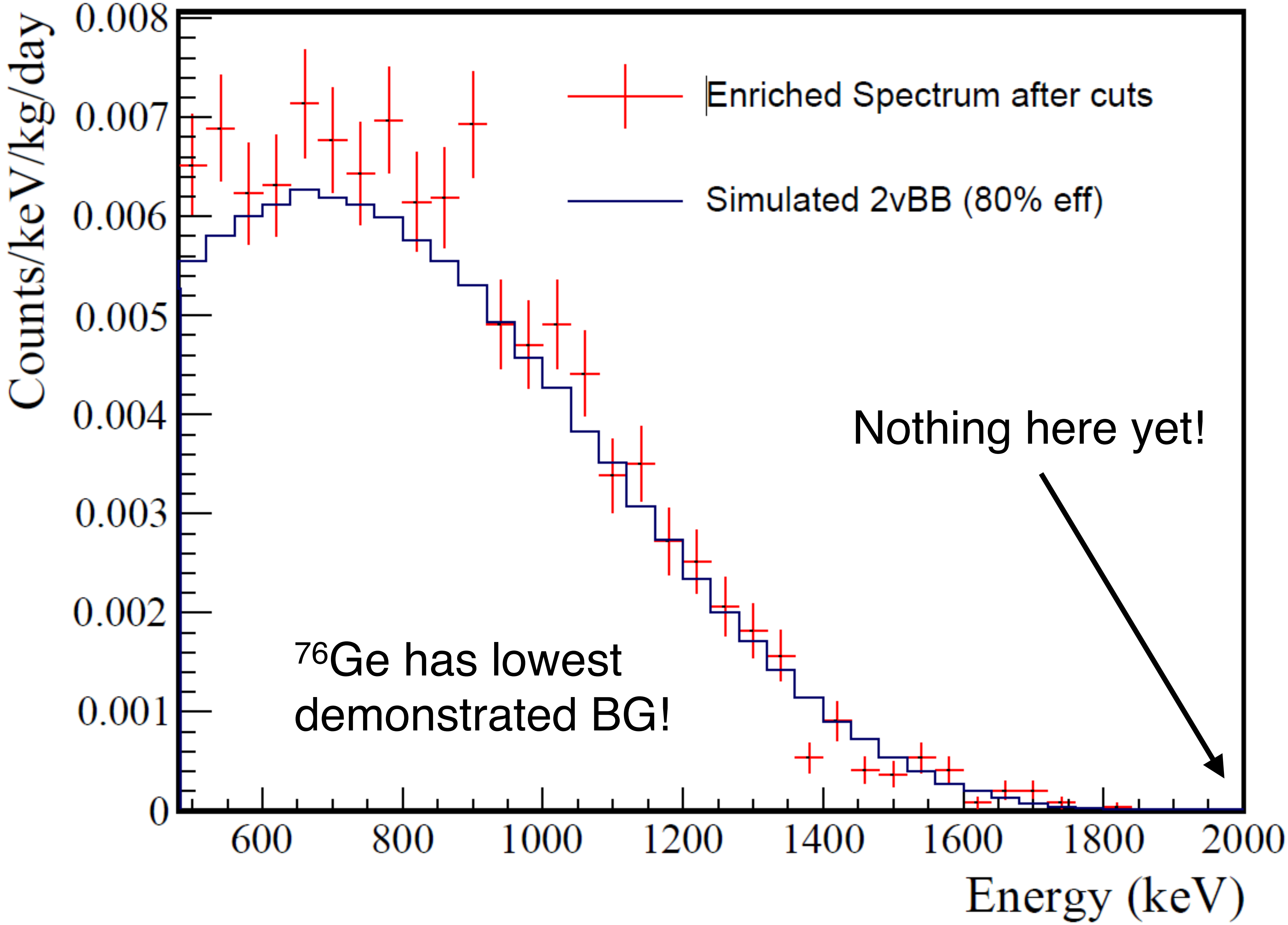


Preliminary Results



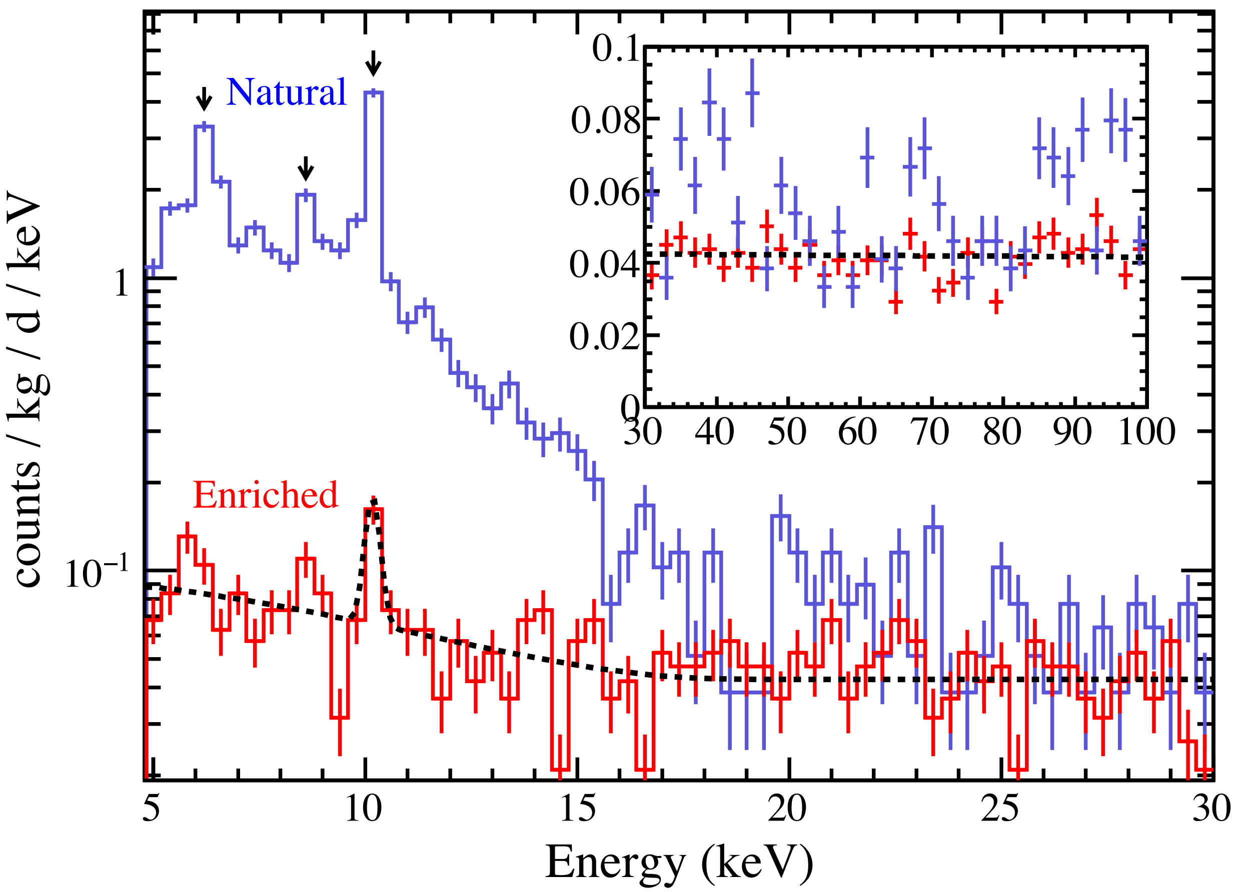
Campaign at UW to fully characterize α interactions

Preliminary Results

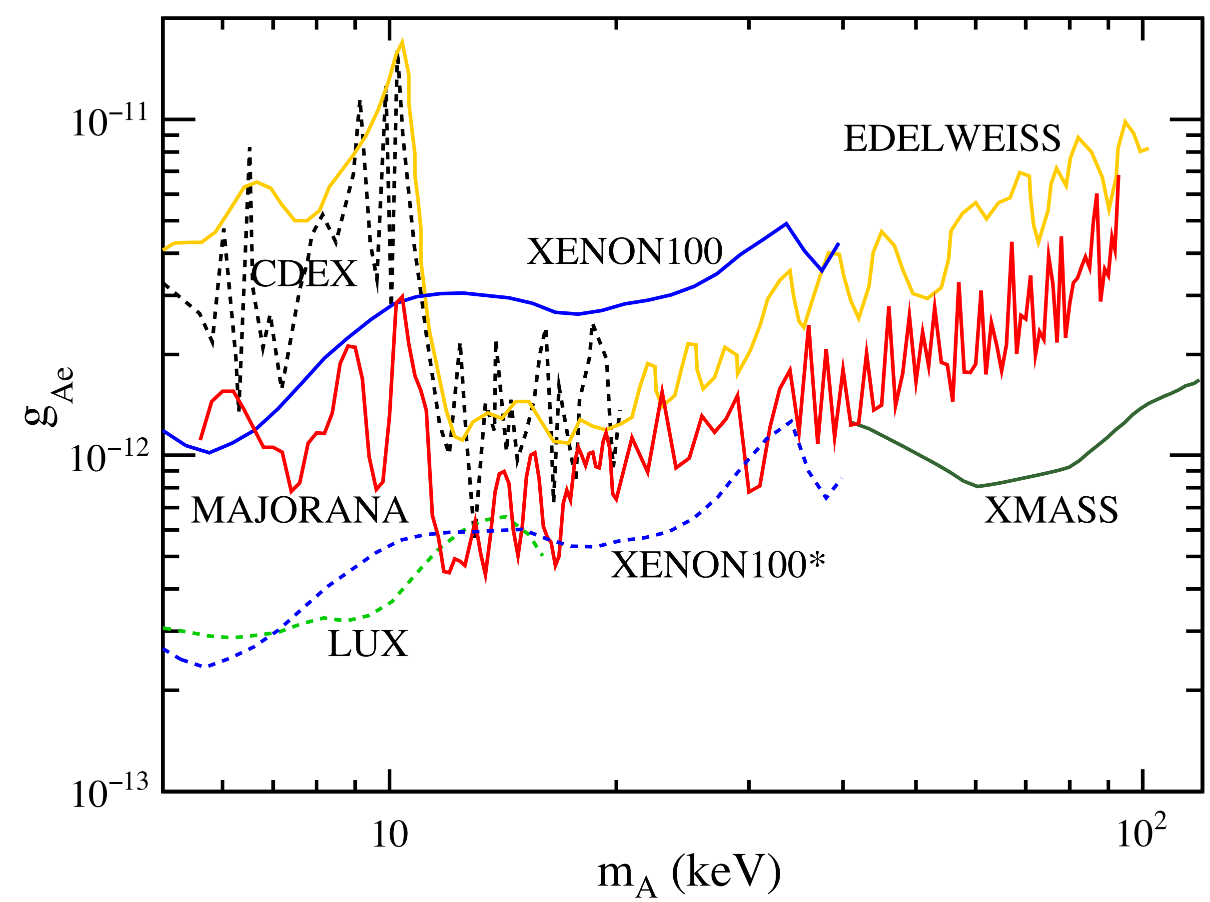


Low-Energy Physics

Data below 100 keV



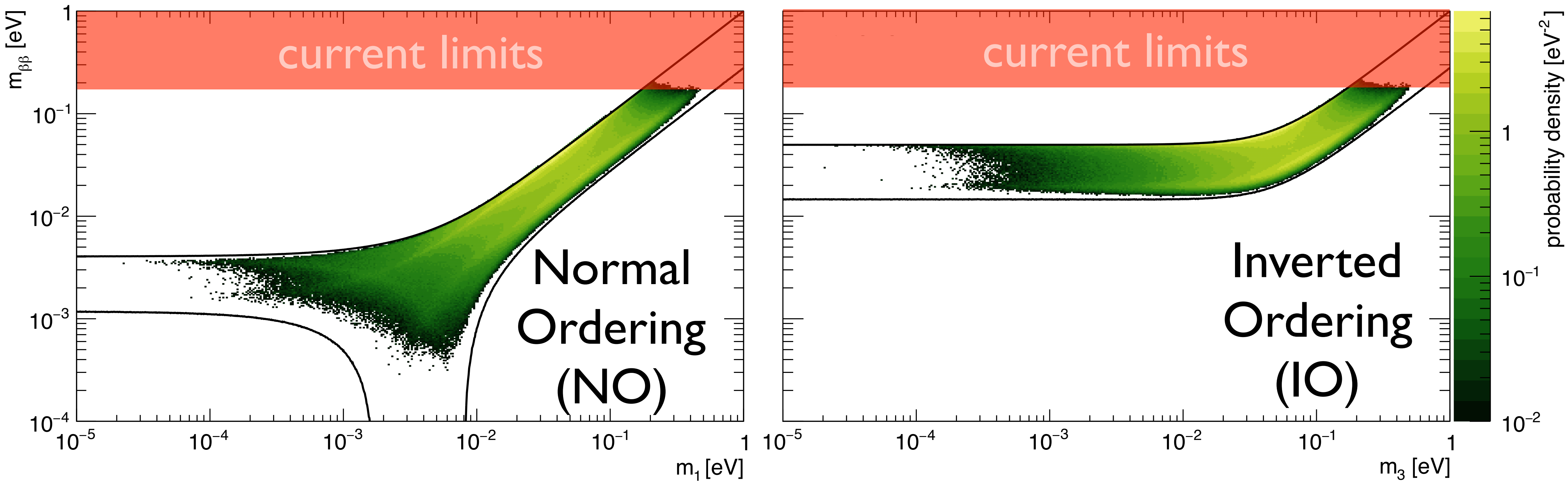
Bosonic Dark Matter Limits



Also places limits on solar axions, Pauli Exclusion Principle violation, electron decay…

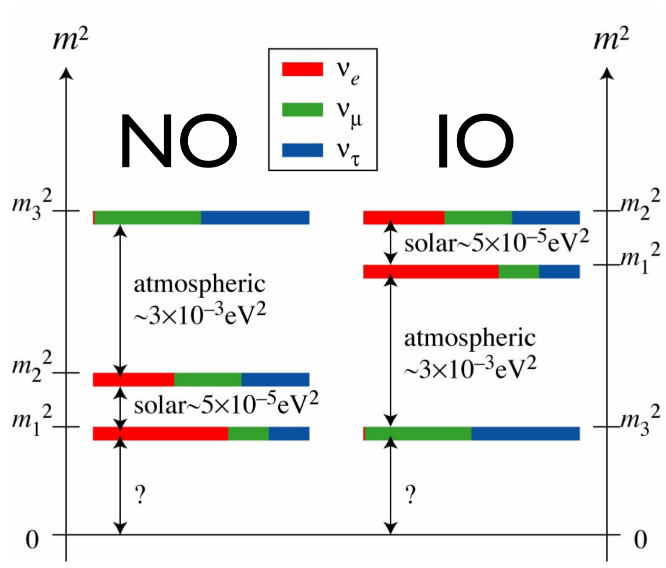
Phys. Rev. Lett. **118**, 161801 (2017).

Next-Generation Goals



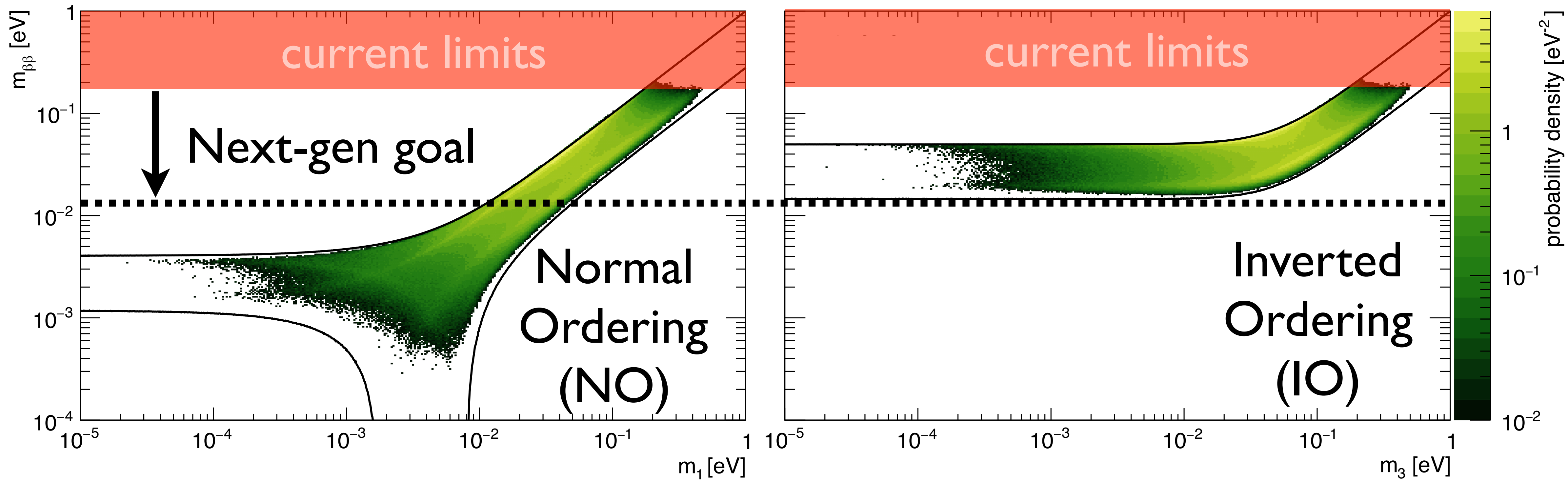
$T_{½} = 1/G\,|M|^2\, m_{\beta\beta}^2$

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



Parameter space weighted assuming non-vanishing lightest ν mass

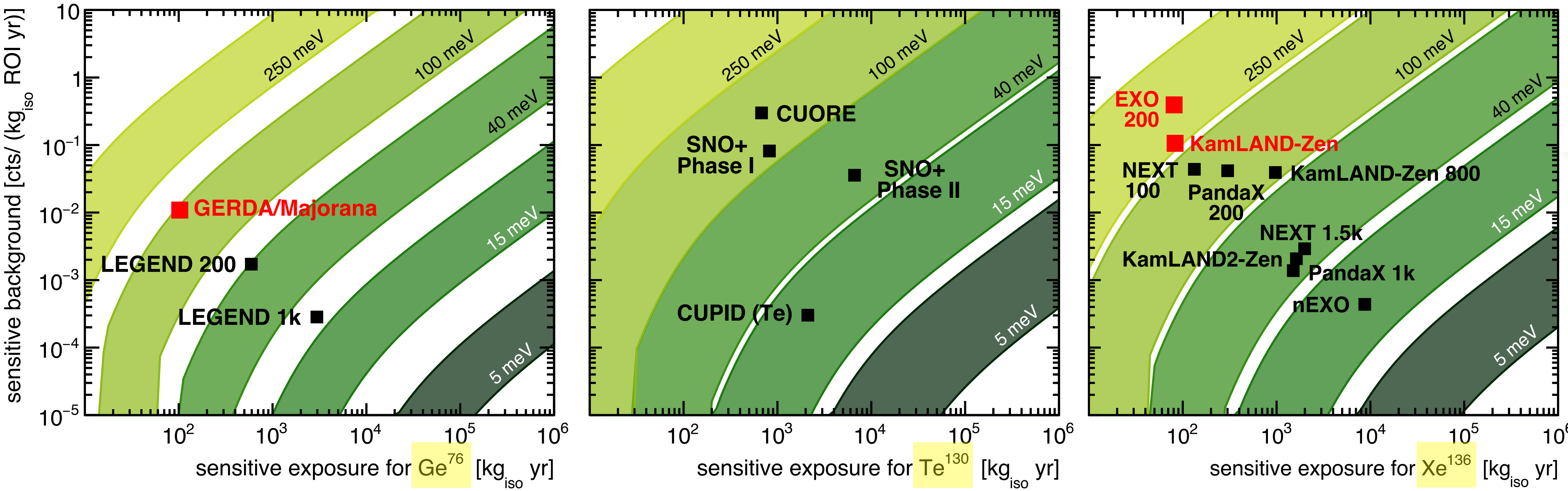
Next-Generation Goals



Cost: O($$10^8$)

(per experiment)

Next-Gen Experiments



- Red dots: published limits. Black dots: 3σ discovery sensitivities with 5 yrs live time
- Discovery sensitivity after 10 yr is ~√2 higher for all experiments
- Bands represent variation in nuclear matrix element calcs

Summary

- Neutrinos continue to give us new mysteries to solve
- Tests of Majorana neutrinos may give us insights into Grand Unification and why the Universe exists
- Next generation experiments will cover much of the remaining parameter space