Acknowledgements:
Numerous physics colleagues who have educated me over the years

Parity Violation at Jefferson Lab and Beyond

Search for Violation of Symmetries
Lecture II

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University of Massachusetts, Amherst

CNUGS26, Jefferson Lab
June 4, 2026

Rationale for Flow of Lectures 1 & 2

- Friday's lectures are primarily focused on how Jefferson Lab is unique in parity-violating electron scattering (PVES) measurements.
- In order to put the PVES physics reach in context, it is important to know enough about the foundations of electroweak unification in the standard model in general and weak neutral current interactions in particular.
- Next, to understand PVES potential for BSM searches, one must have general knowledge about worldwide BSM efforts, especially as it relates to violations of fundamental symmetries.

Outline of Lecture 2

- Overview of the 4 Classes of Measurements (my classification)
- Neutrino Physics
- Discrete Symmetries
- Tour of Searches for Violation of Accidental Symmetries
- Summary

Fundamental Particles and Forces

The Standard Model of Strong and Electroweak Interactions

FERMIONS matter constituents spin = 1/2, 3/2, 5/2, …

Leptons spin =1/2

Flavor	Mass GeV/c^2	Electric charge
ν_L lightest neutrino*	$(0–0.13)\times10^{-9}$	0
e electron	0.000511	–1
ν_M middle neutrino*	$(0.009–0.13)\times10^{-9}$	0
μ muon	0.106	–1
ν_H heaviest neutrino*	$(0.04–0.14)\times10^{-9}$	0
τ tau	1.777	–1

Quarks spin =1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.002	2/3
d down	0.005	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	173	2/3
b bottom	4.2	–1/3

BOSONS force carriers spin = 0, 1, 2, …

Unified Electroweak spin = 1

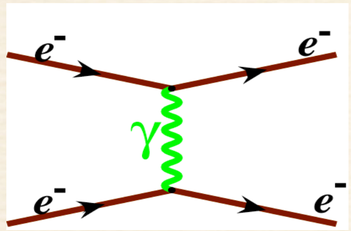
Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.39	–1
W^+ W bosons	80.39	+1
Z^0 Z boson	91.188	0

Strong (color) spin =1

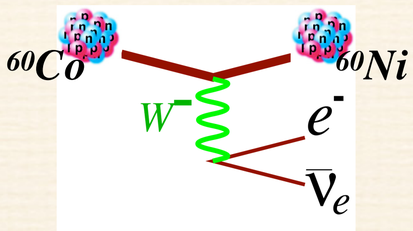
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H^0 spin 0

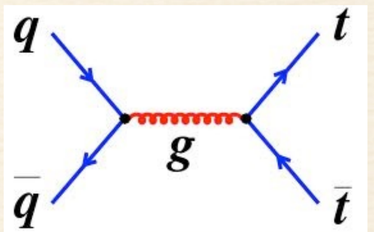
electromagnetic (EM)



Weak



strong



Were there other superweak forces in the early universe?
Was there a single unified superforce in the early universe?
Do quarks and leptons have substructure?

Example Particle Physics Questions

How do protons, neutrons and nuclei emerge from quarks and gluons?
Are there fundamentally new emergent properties of protons and nuclei?
…

Example Nuclear Physics Questions

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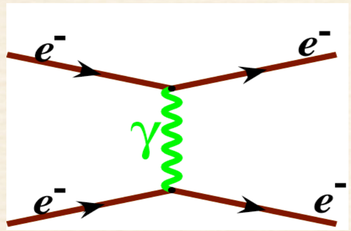
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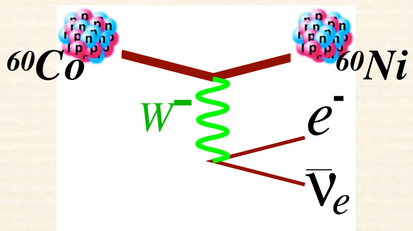
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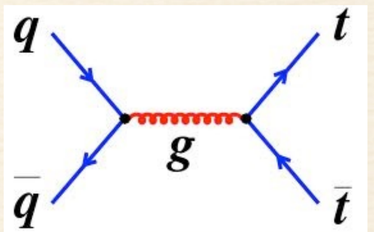
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Example Particle Physics Questions

Example Nuclear Physics Questions

Artificial Separation

BSM Searches must be as model-independent as possible

Comprehensive Experimental Strategy

The High Energy Frontier: Collider Physics

The Cosmic Frontier: Particle, Nuclear and Gravitational Astrophysics

A comprehensive search for clues requires, in addition:

The Intensity/Precision Frontier

BSM Searches must be as model-independent as possible

Comprehensive Experimental Strategy

The High Energy Frontier: Collider Physics

The Cosmic Frontier: Particle, Nuclear and Gravitational Astrophysics

A comprehensive search for clues requires, in addition:

The Intensity/Precision Frontier

- ★ **Measurements of Neutrino Properties**
- ★ **Searches for Violation of Accidental (?) Symmetries**
- ★ **Direct and Indirect Searches for Dark Matter**
- ★ **Precise Measurements of SM observables**

Neutrino Physics

Neutrinos are Special: First Hint of BSM

$e^-, \mu^-, \tau^- \Rightarrow Q = -e;$

$\nu_e, \nu_\mu, \nu_\tau \Rightarrow Q = 0$

$\begin{pmatrix} \nu \\ l^- \end{pmatrix}_L \quad l^-_R \quad \nu_R$

$\pm 1/2 \quad 0 \quad 0 \Rightarrow T_3$

$$Q = T_3 + Y/2$$

$Y_{\nu_L} = -1 \qquad \boxed{Y_{\nu_R} = 0}$

Right-handed neutrino has no gauge interactions

A Model of Leptons (Steven Weinberg, 1967)

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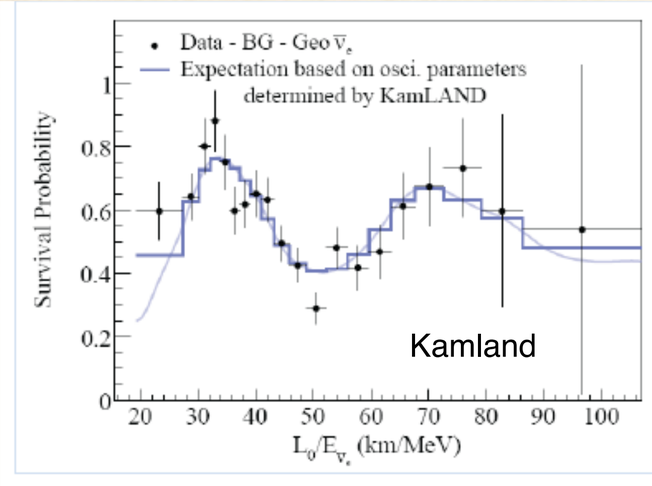
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ν oscillations: they are massive! There must be right-handed neutrino states



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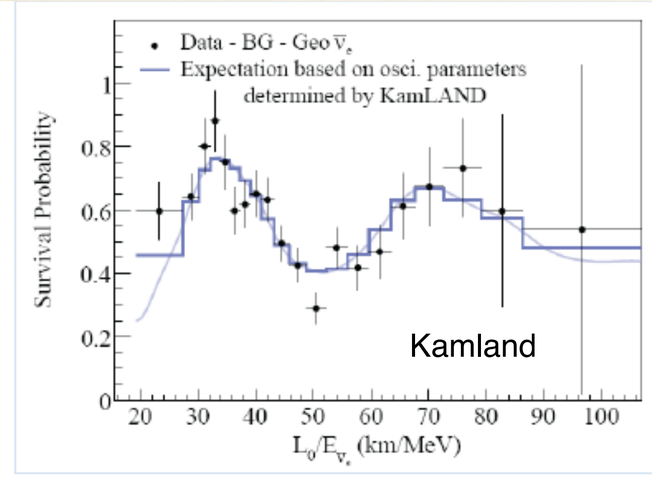
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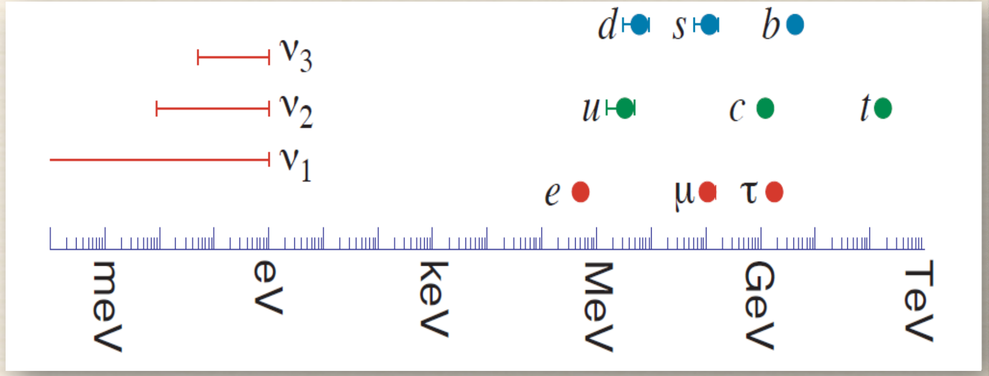
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- **Why are neutrinos so light?**
- **What is the mass scale?**
- **Neutrino mass generation?**
- **Neutrino mixing matrix**
- **Neutrino CP violation**
- **Are neutrinos Majorana particles?**



K. Scholberg

Long Baseline Neutrino Physics

The neutrinos $\nu_{e,\mu,\tau}$ of definite flavor

($W \rightarrow e\nu_e$ or $\mu\nu_\mu$ or $\tau\nu_\tau$)

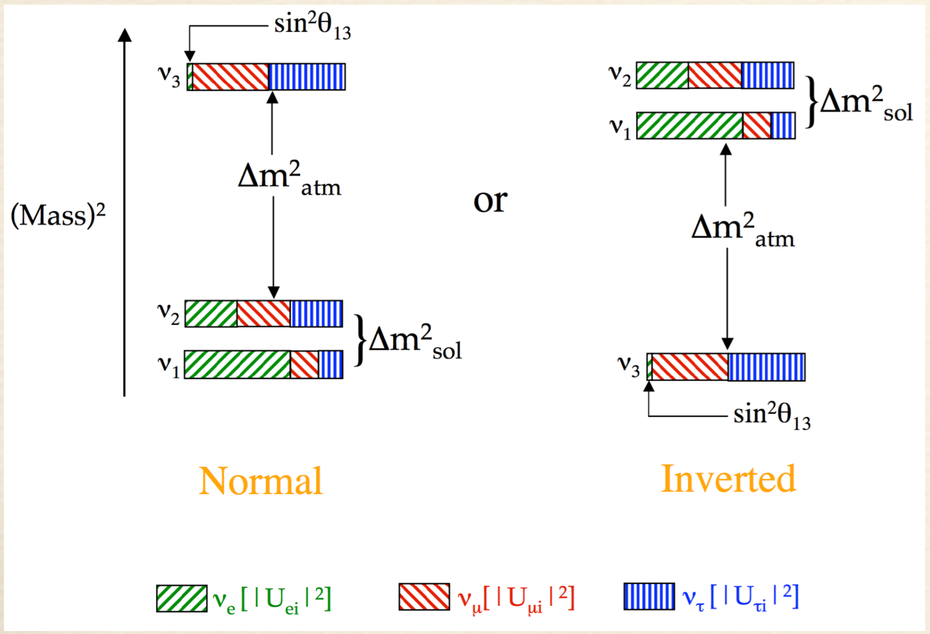
are superpositions of the mass eigenstates:

$$|\nu_\alpha> = \sum_i U^*_{\alpha i} |\nu_i> \ .$$

Neutrino of flavor α = e, μ, or τ

Unitary Leptonic Mixing Matrix

Neutrino of definite mass m_i



Long-baseline neutrino oscillation experiments





K2K

KEK to Kamioka

250 km, 5 kW



MINOS (+)

FNAL to Soudan

734 km, 400+ kW



CNGS

CERN to LNGS

730 km, 400 kW



NOνA

FNAL to Ash River

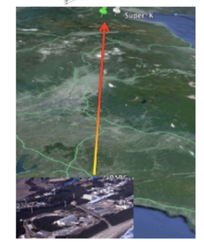
810 km, 400-900+ kW



T2K

J-PARC to Kamioka

295 km, 380-830 kW ➔>1 MW



LBNF/DUNE

FNAL to Homestake

1300 km, 2-2.4 MW tunable

Hyper-K

J-PARC to Kamioka

295 km, 750 kW

(➔1.3 MW)







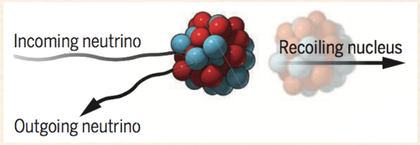


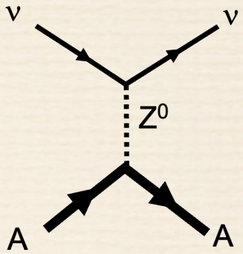
+ ESSνSB

+ farther future nu factories...

Other Neutrino Initiatives

- **Coherent Neutrino Scattering (CEνNS)**





  - *Detector recoiling nucleus from elastic neutrino scattering*
  - *Large number of experiments pursuing both accelerator and reactor-based measurements over a range of nuclei*
  - *New exploration of few 10's of MeV inelastic neutrino scattering: relevance for axial-current*
- **Absolute Neutrino Mass**
  - *Precision measurements of the end points in the beta decay spectrum to look for a deviation from zero mass (just momentum conservation)*
  - *Karlsruhe Tritium Neutrino Experiment (KATRIN) completion (late 2020's) ~ 200 meV, the next frontier is ~ 40 meV with Project-8 (mid-2030s)*
  - *Complementary efforts (^{163}Ho, ultra-low-Q processes) for cross-checks and sterile neutrinos*

The most compelling direction motivated by neutrino mass is the following…

Detour: Discrete Symmetries

Discrete Symmetries

Parity P $\quad x, y, z \rightarrow -x, -y, -z \quad P\psi(\vec{r}) = \psi(-\vec{r})$

$$P^2 = I$$ Group has 2 elements, P and I

$$[H, P] = 0 \Rightarrow H\psi = E\psi \ \& \ P\psi = \pi\psi \Rightarrow \pi = \pm 1$$

If hamiltonian is invariant under parity transformations,
then π is conserved and observable

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Charge Conjugation C $\quad C|p\rangle = |\bar{p}\rangle$

All quantum numbers flip sign
except mass and spin

particles that are its own anti-particles are eigenstates of C

$C|\gamma\rangle = -|\gamma\rangle \Rightarrow \pi^0 \to \gamma\gamma \Rightarrow C|\pi^0\rangle = +|\pi^0\rangle \Rightarrow \pi^0 \to \gamma\gamma\gamma$

forbidden

Parity Symmetry

If Hamiltonian is invariant under parity transformations,
then π is conserved and observable

Particle Classification S^{π} e.g. pions: 0^{-} pseudoscalar mesons

Tau-theta puzzle (1956) $\theta^{+} \rightarrow \pi^{+}\pi^{0}$ (P=+1) $\tau^{+} \rightarrow \pi^{+}\pi^{0}\pi^{0}$ (P=-1)

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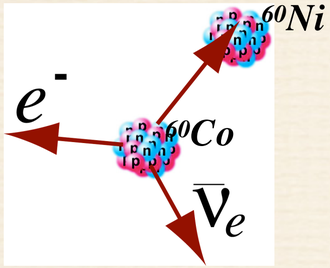
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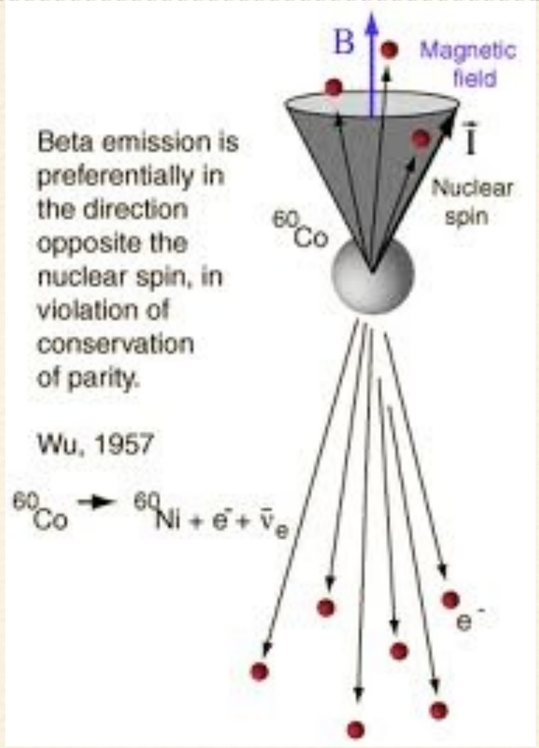
same mass but different parities! Lee and Yang propose:

The SAME particle is produced in strong interactions, but
decays via weak interactions;
P conserved in strong interactions, but not in weak interactions

Parity Violation in Weak Interactions



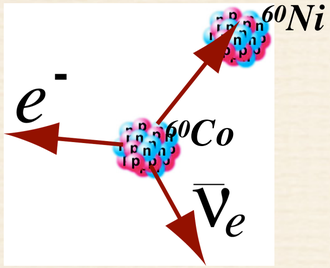
Weak decay of ^{60}Co Nucleus



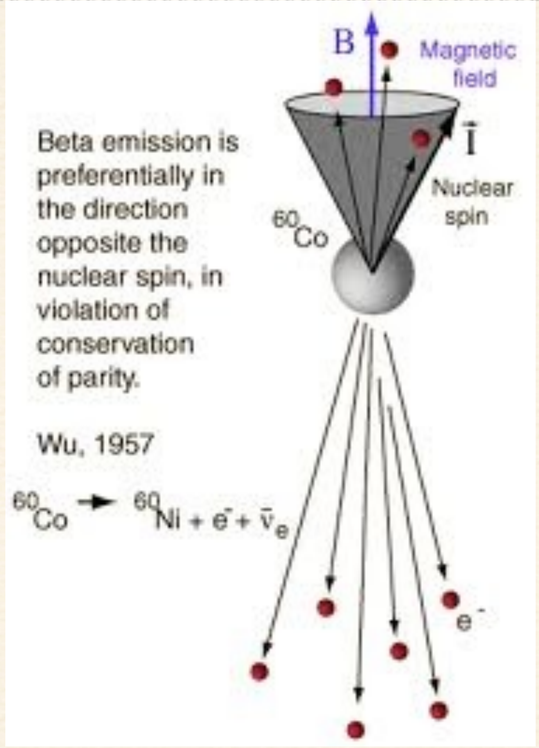
Parity Violation in Weak Interactions

parity transformation (reflection)

$$x, y, z \rightarrow -x, -y, -z$$



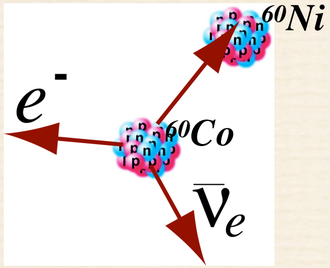
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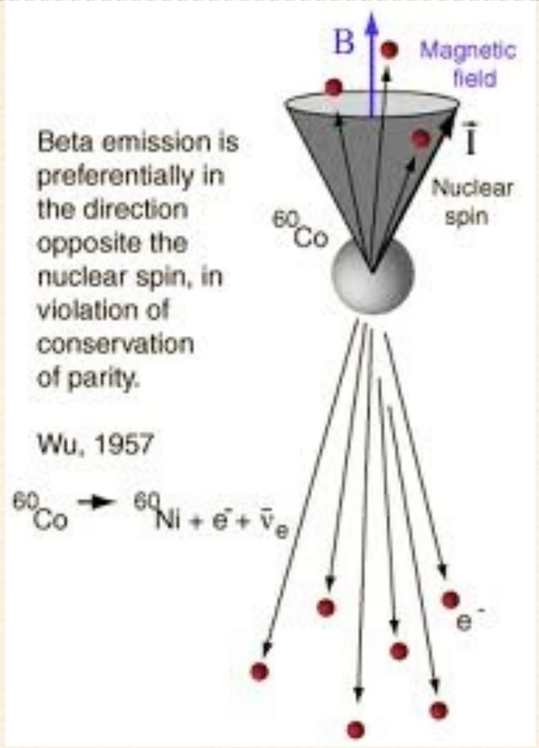
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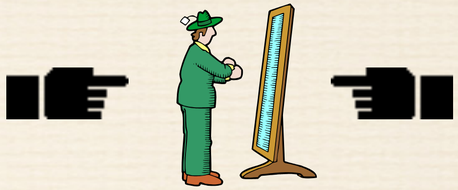
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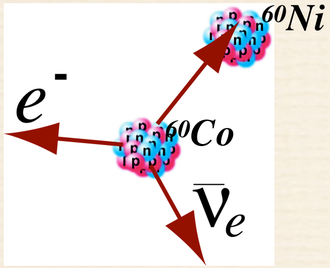


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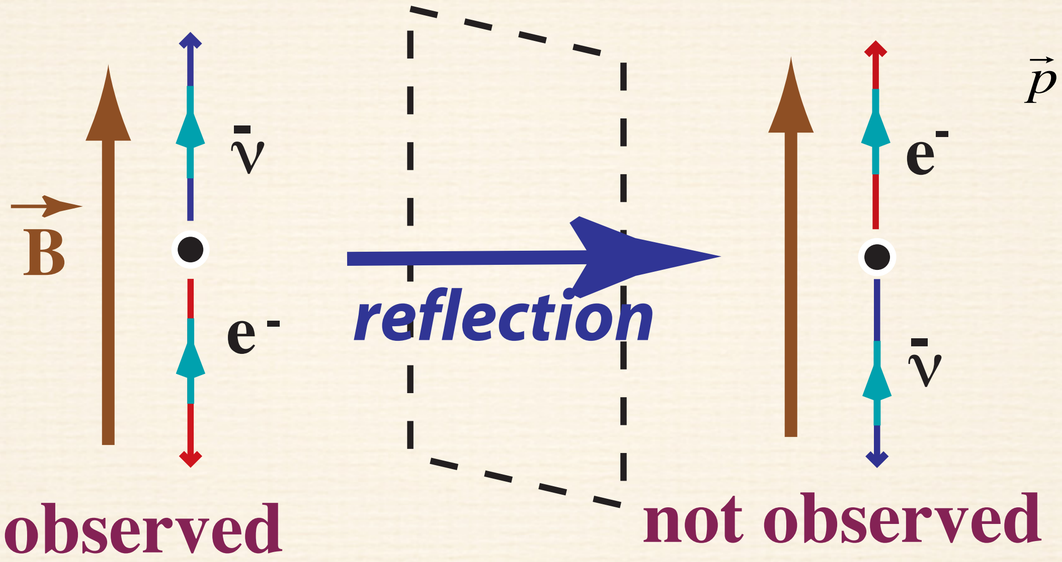
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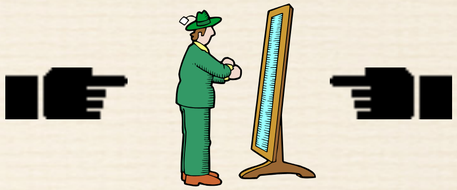
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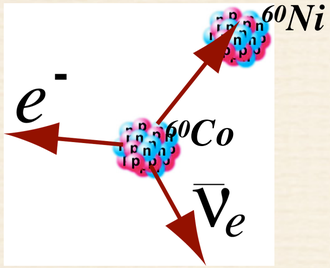


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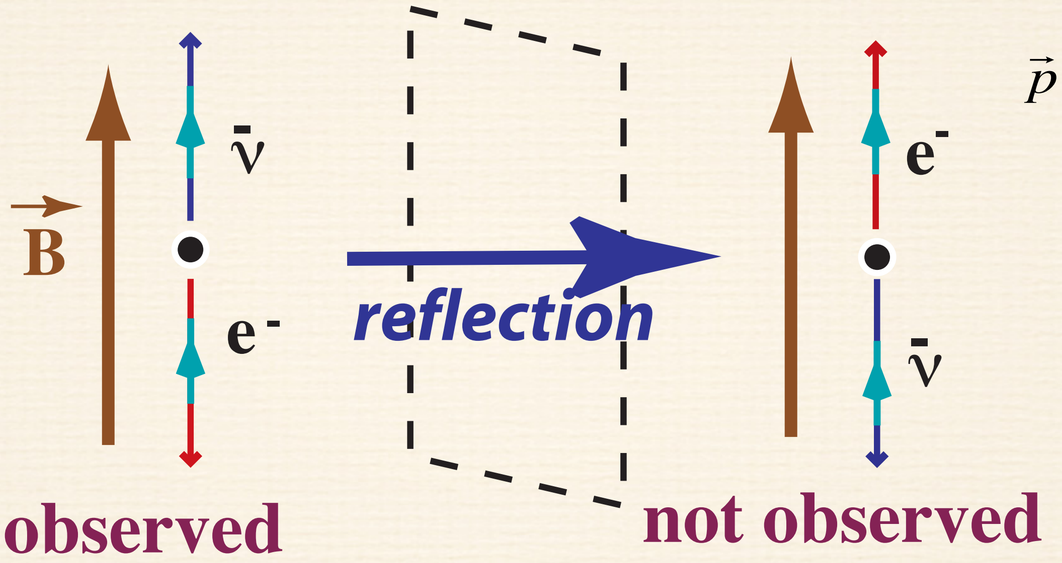
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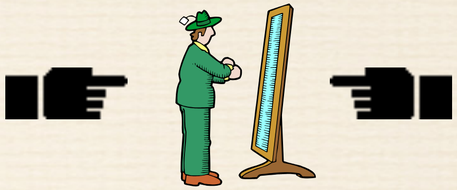
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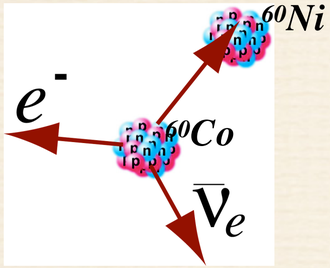
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helicity/chirality

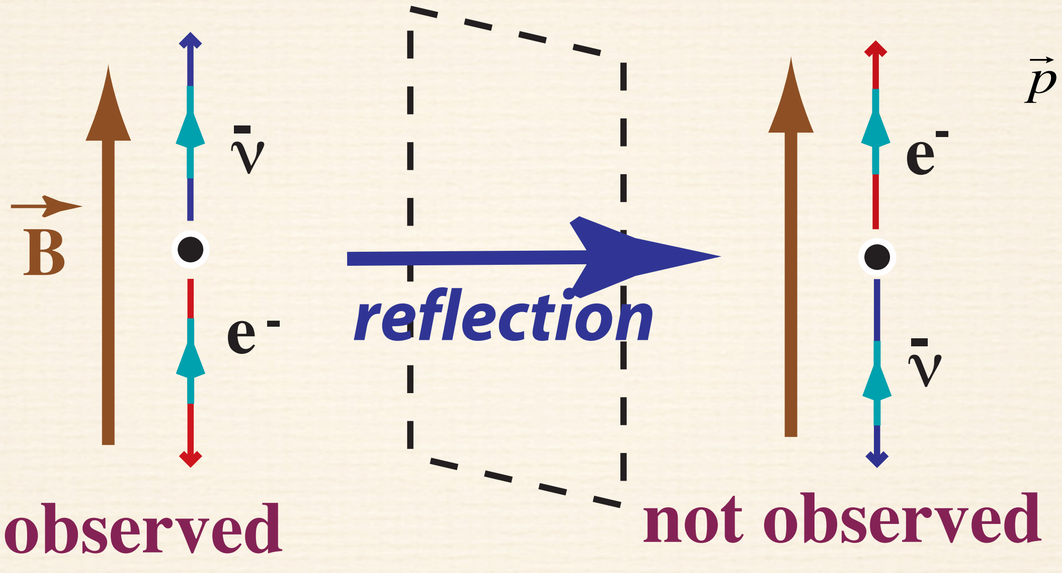
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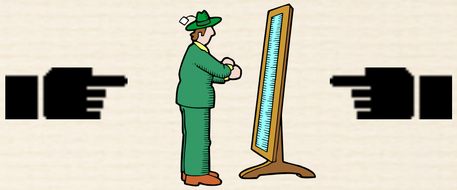
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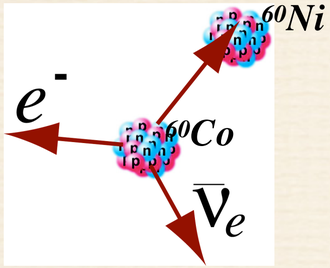
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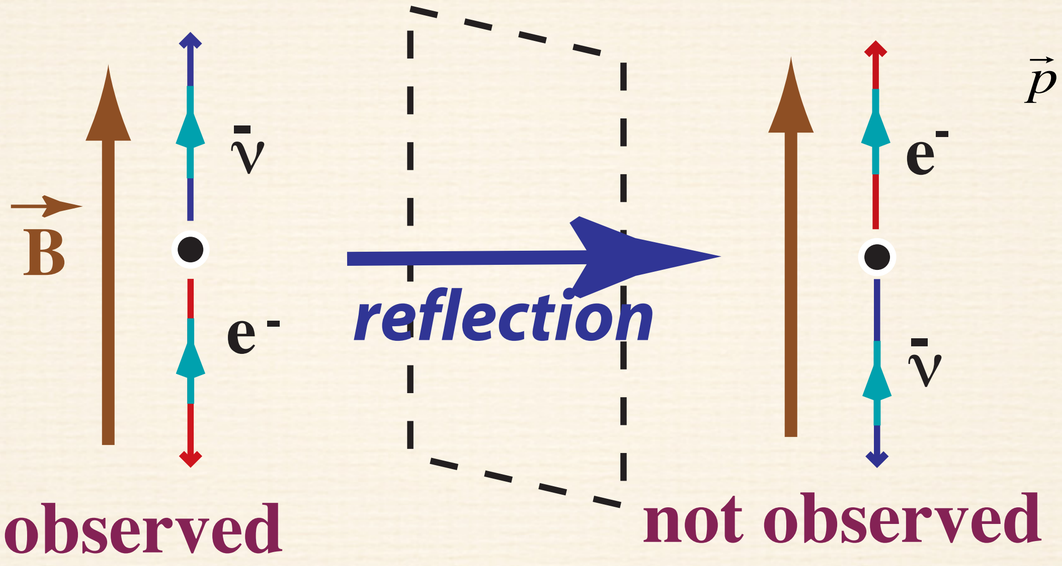
Parity Violation in Weak Interactions

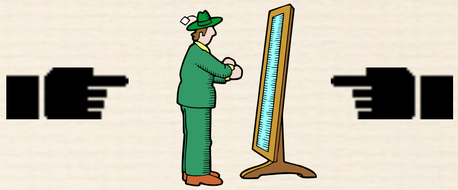
parity transformation (reflection)

$$x, y, z \rightarrow -x, -y, -z$$



Weak decay of ^{60}Co Nucleus





$$\vec{p} \rightarrow -\vec{p}, \quad \vec{L} \rightarrow \vec{L}, \quad \vec{s} \rightarrow \vec{s}$$

matter particles have spin = 1/2

$$h = \frac{\vec{s} \bullet \vec{p}}{|\vec{s}||\vec{p}|} = \pm 1$$

handedness or *helicity/chirality*

Feynman and Gell-Mann proposed the the "V-A" form of the weak interaction

Vector and and Axial-Vector components to the "current" that describes the interaction

Mirror reflection flips sign of helicity

Left-handed ⟺ *right-handed*

Only left-handed particles can mediate W bosons

(right-handed anti-particles)

Neutral Kaon System

$$\tau^+ = \theta^+ = K^+ \equiv \bar{s}u$$

Also K-: Opposite "strangeness" quantum numbers

$$K^0 \equiv \bar{s}d \quad \& \quad \bar{K}^0 \equiv s\bar{d}$$

Also opposite strangeness: are they distinct?

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If CP is conserved:

$K_1 \to \pi\pi$ $K_2 \to \pi\pi\pi$ allowed

$K_1 \to \pi\pi\pi$ $K_2 \to \pi\pi$ forbidden

Kaon Oscillations and Regeneration

Elegant Prediction: Existence of K_2

two pion decay lifetime much shorter than three pion case

start with K^0's; have near and far detectors; 2 pions in near detector, 3 pions in far detector

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start with K^0's: contains K_1's and K_2's → drift region (vacuum) → K_2's only: antiK^0's!

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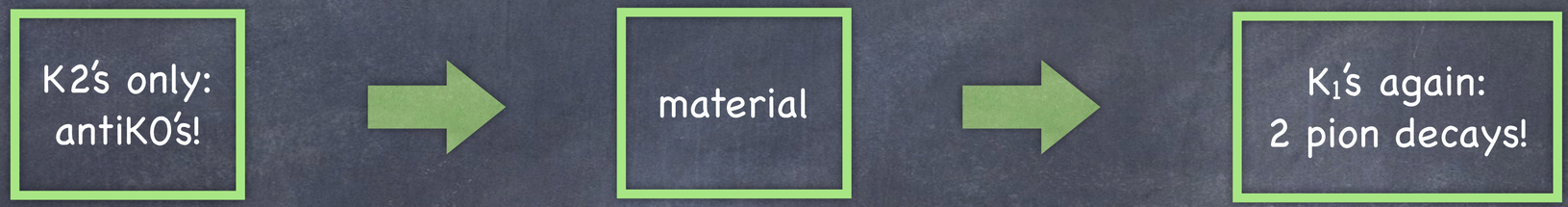
Anti-K^0's have much larger cross-section to scatter off nuclei

K2's only: antiK0's! → material → K_1's again: 2 pion decays!

Cronin, Fitch and Tourley

Discovery of CP Violation

Startling observation: take material away and some residual 2 pion decays remain!!!!



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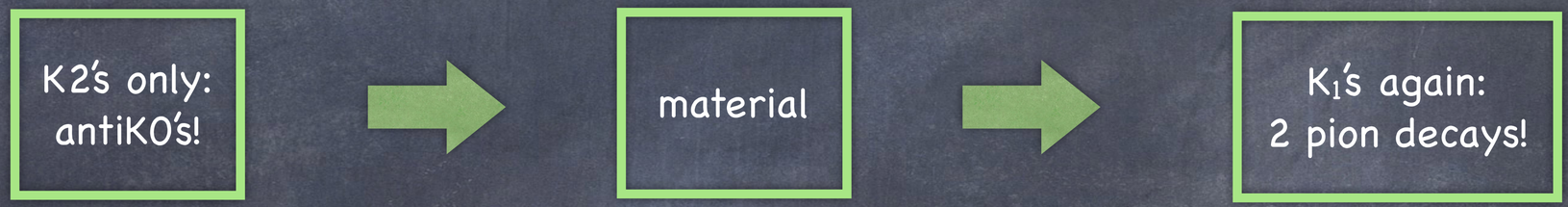
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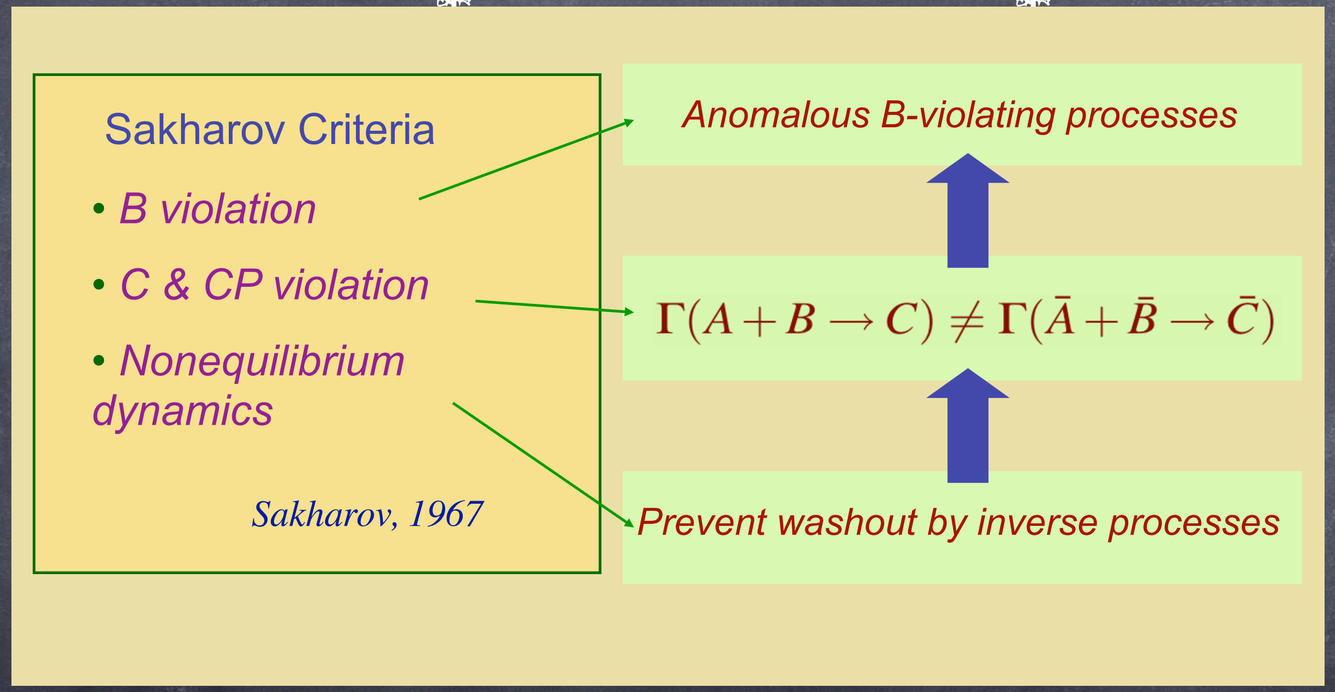


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Matter Anti-Matter Asymmetry



CP violation in the weak interactions requires 3 generations of quarks:

Ensures quark mixing matrix has complex phase

However, electroweak CP phase explains Kaons; insufficient for consideration above

Incorporating Quantization

Are there other symmetries at low energies?

Are they exact?

If approximate, were they unbroken in the early universe?

Electric Charge is conserved

Charge is quantized

sum of initial charges = sum of final charges

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quark (baryon) # violations suppressed on general grounds based on the symmetries of the electroweak Lagrangian

Additive Conservation Laws

Dirac free particle Lagrangian $\overline{\psi}\left(i\gamma^{\mu}\partial_{\mu}-m\right)\psi$

global phase transformation $\psi\longrightarrow e^{iq\alpha}\psi$

U(1) Invariance: conserved current $\partial_{\mu}J^{\mu}=0$ $J^{\mu}=q\,\overline{\psi}\,\gamma^{\mu}\psi$

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*Similarly, SM Lagrangian invariant under global phase transformations associated with total baryon number **B** and total lepton number **L***

$q\rightarrow e^{i\phi_{q}}q \qquad l\rightarrow e^{i\phi_{L}}l$

$J^{B}_{\mu}=\frac{1}{3}\left(\overline{u}_{\gamma_{\mu}}u+\bar{d}\,\gamma_{\mu}d+\ldots\right)$

$J^{L}_{\mu}=\bar{e}\,\gamma_{\mu}e+\overline{\nu}_{e_{L}}\gamma_{\mu}\nu_{eL}+\ldots$

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0 −1 +1 +1 0 +1 0

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Neutrinos only interact via the weak interaction, which is parity-violating

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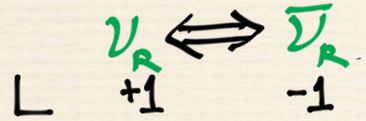
Lepton Number Conservation not required

Double-Beta Decay

A Profound Question

In 1937, Majorana discovered that a simple modification to Dirac's equation leads to the possibility to describe **electrically neutral**, massive spin-1/2 fermions with **real** fields!

A neutrino can therefore be its own anti-particle



Majorana Neutrino

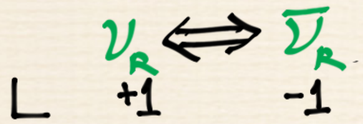
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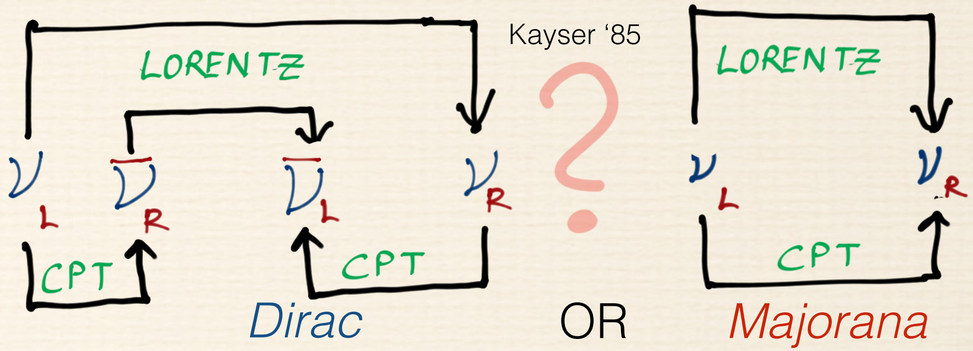


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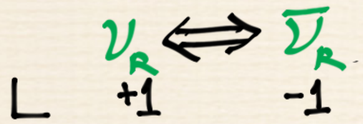
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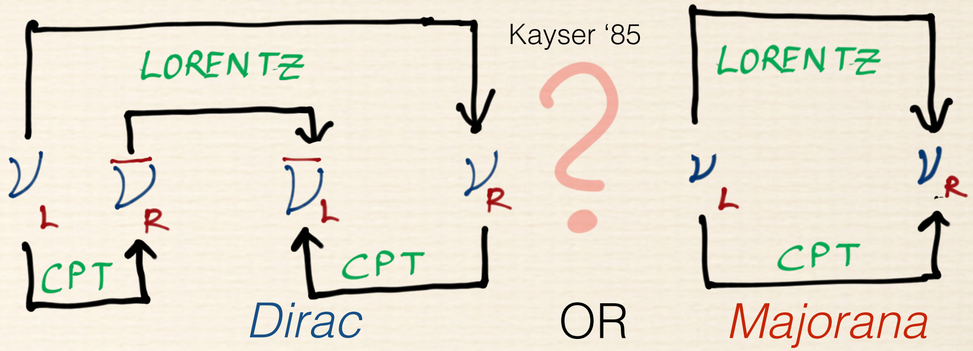


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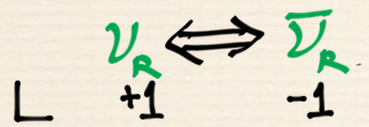
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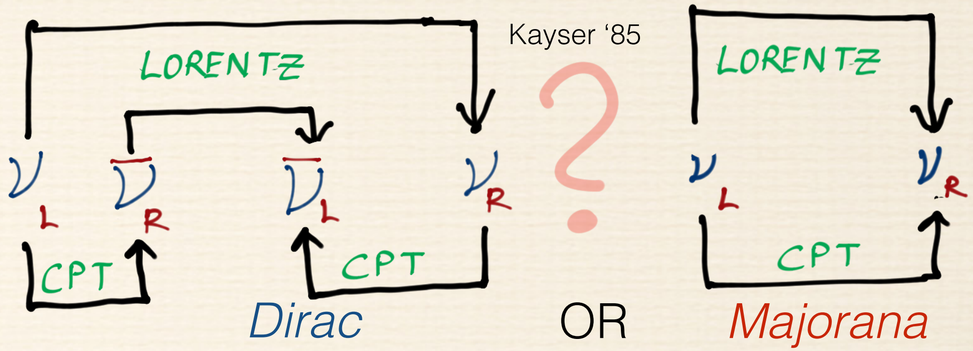


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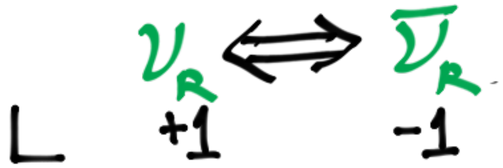
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*If L-violation is observed unambiguously, it implies that there exists a way to convert an anti-neutrino to a neutrino, a **Majorana mass** amplitude*

A new heavy scale for physics beyond the SM

Dirac and Majorana Masses

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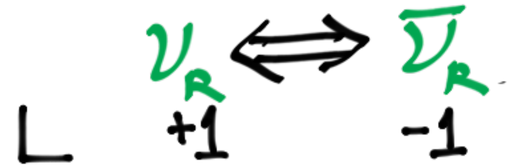
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If $\nu_R \Leftrightarrow \bar{\nu}_R$ Majorana Neutrino

L: ν_R (+1), $\bar{\nu}_R$ (−1)

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After spontaneous symmetry breaking: $m_D \equiv g_\nu \frac{v}{\sqrt{2}}$

$$\mathcal{L}_{D+M} = -\frac{1}{2} \begin{pmatrix} \bar{\nu}_L & \bar{\nu}_R^c \end{pmatrix} \begin{pmatrix} 0 & m_D \\ m_D & m_M \end{pmatrix} \begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix} + h.c.$$

Lepton Number Conservation or Not?

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2 self-conjugate states, each with left- and right-handed components

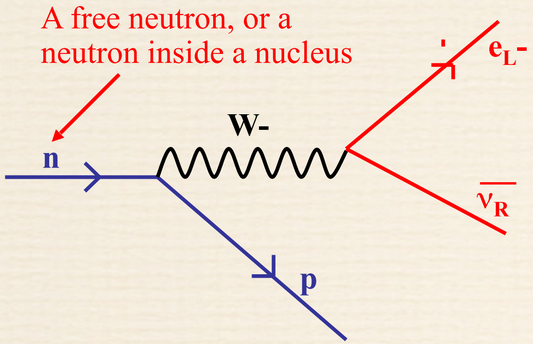
Natural explanation of light neutrino masses

Plausible explanation for matter-antimatter asymmetry (leptogenesis)

A new heavy scale for physics beyond the SM

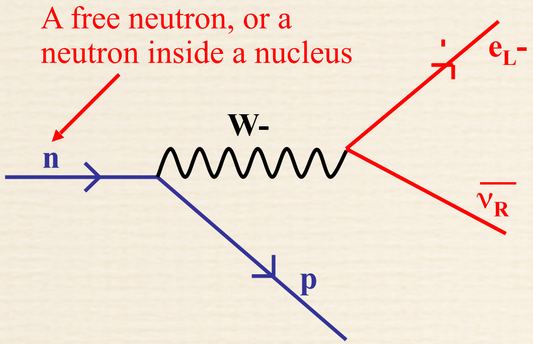
Lepton Number Conserving Standard Model Process

Double-Beta Decay



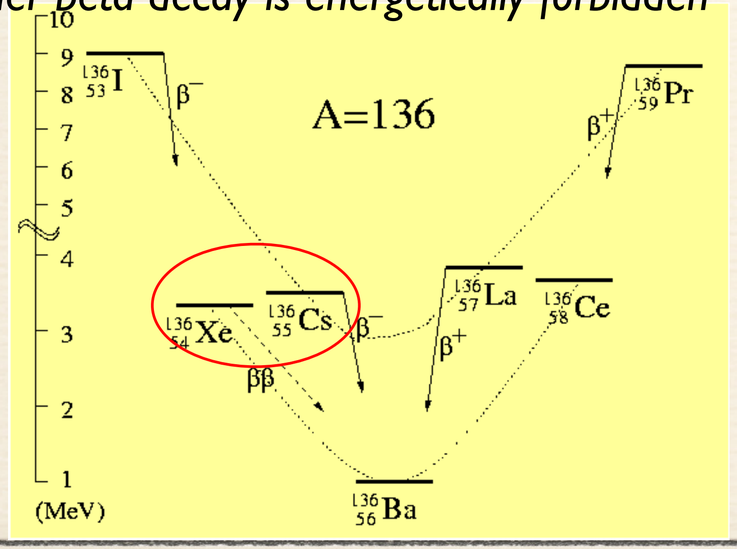
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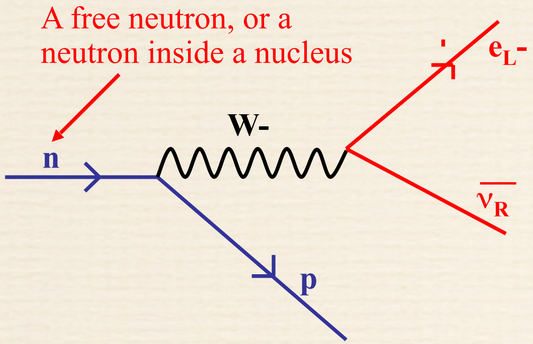
Double-beta decay:

a second-order process only detectable if first order beta decay is energetically forbidden



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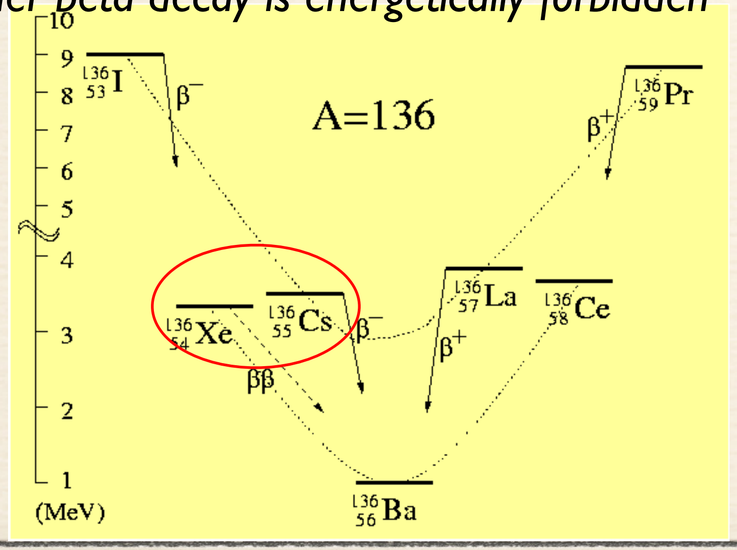
Double-Beta Decay



Nuclear Double-Beta
Decay with the emission of
two betas and neutrinos

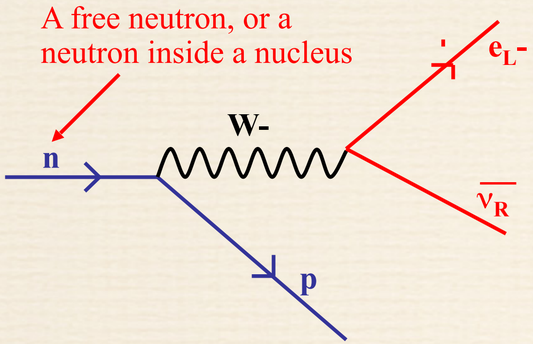
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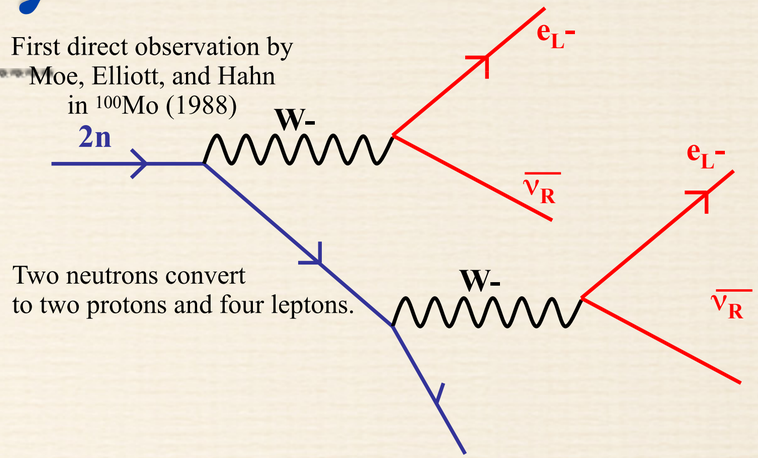
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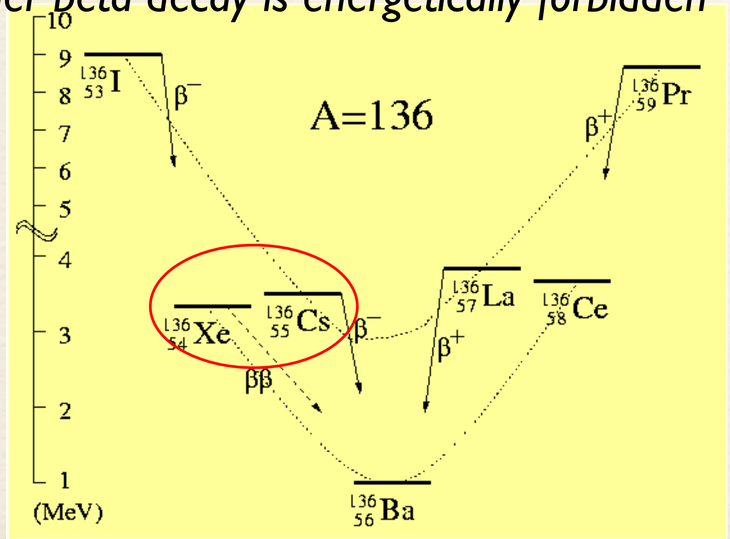
Nuclear Double-Beta Decay with the emission of two betas and neutrinos

Suggested by Maria Goeppert-Mayer in 1935!



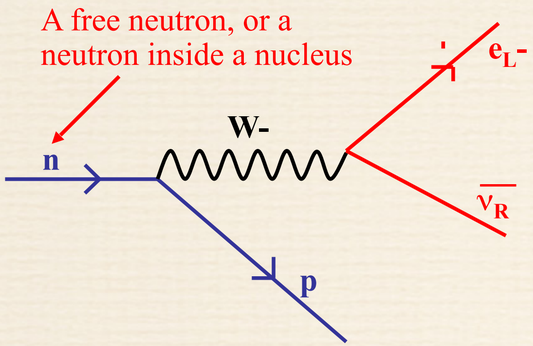
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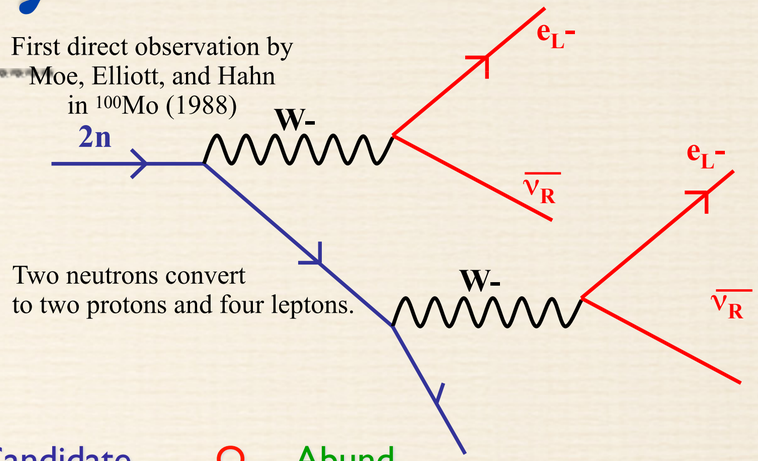
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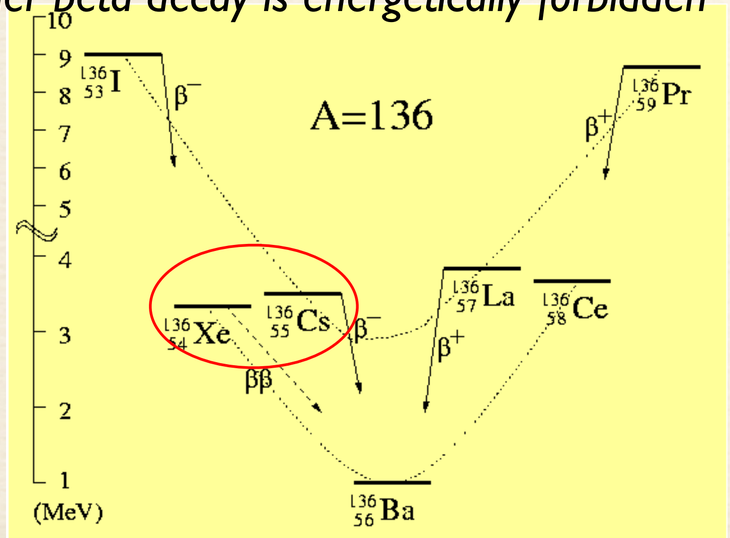
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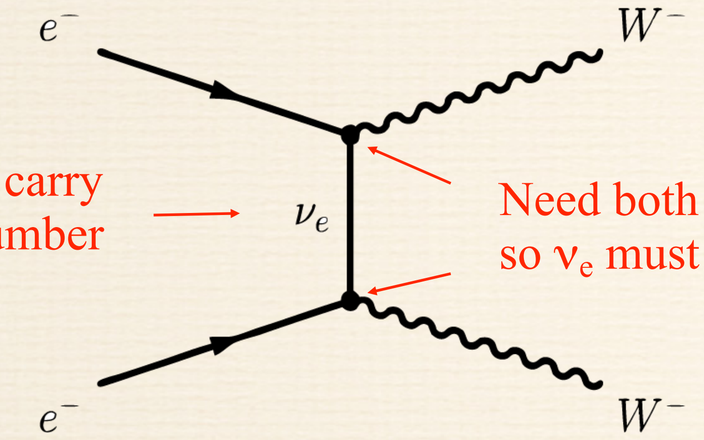
Candidate nuclei with Q>2 MeV

Candidate	Q (MeV)	Abund. (%)
^{48}Ca→^{48}Ti	4.271	0.187
^{76}Ge→^{76}Se	2.040	7.8
^{82}Se→^{82}Kr	2.995	9.2
^{96}Zr→^{96}Mo	3.350	2.8
^{100}Mo→^{100}Ru	3.034	9.6
^{110}Pd→^{110}Cd	2.013	11.8
^{116}Cd→^{116}Sn	2.802	7.5
^{124}Sn→^{124}Te	2.228	5.64
^{130}Te→^{130}Xe	2.533	34.5
^{136}Xe→^{136}Ba	2.479	8.9
^{150}Nd→^{150}Sm	3.367	5.6

Neutrinoless Double-Beta Decay

L +1 +1 0 0

$e^- + e^- \Longrightarrow W^- + W^-$



must not carry lepton number

Need both helicities, so ν_e must be massive

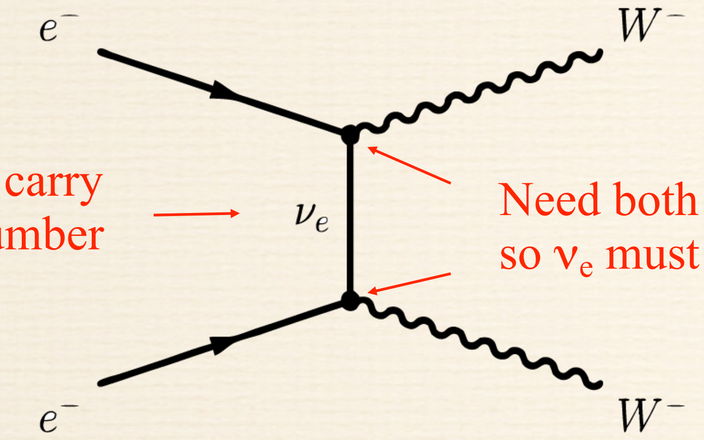
Lepton number changes by two units: ΔL=2

For light neutrinos, this cross-section is unobservably small

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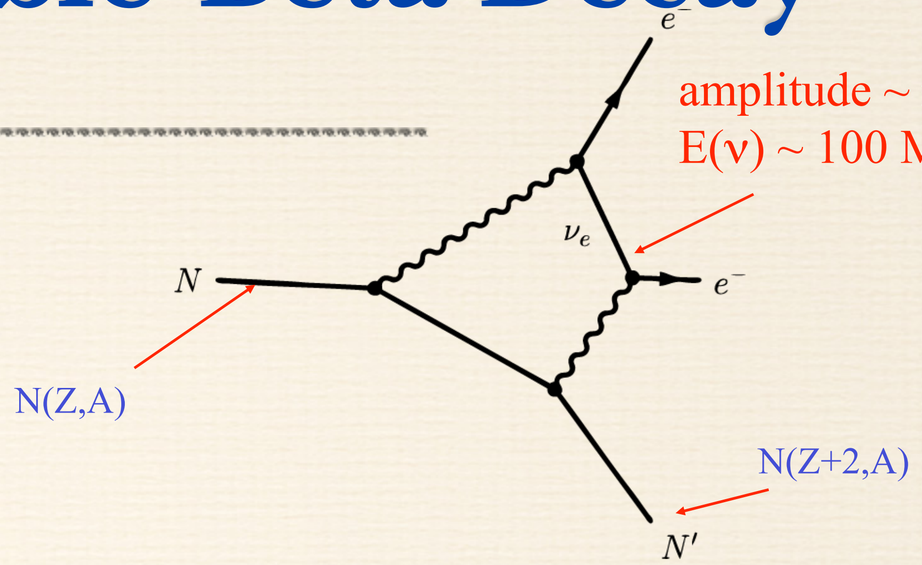


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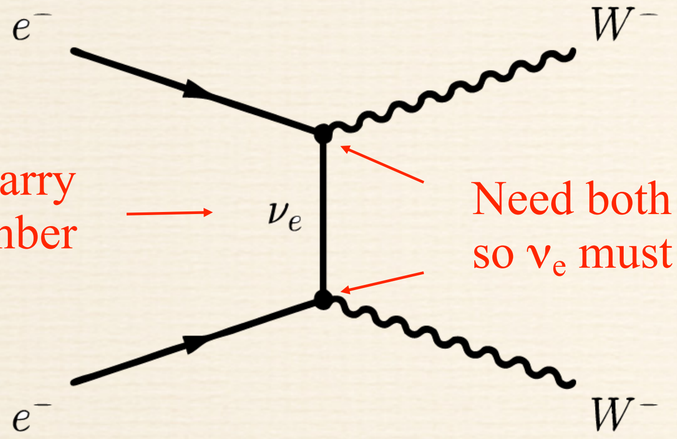


"Neutrino mass mechanism" for double beta decay

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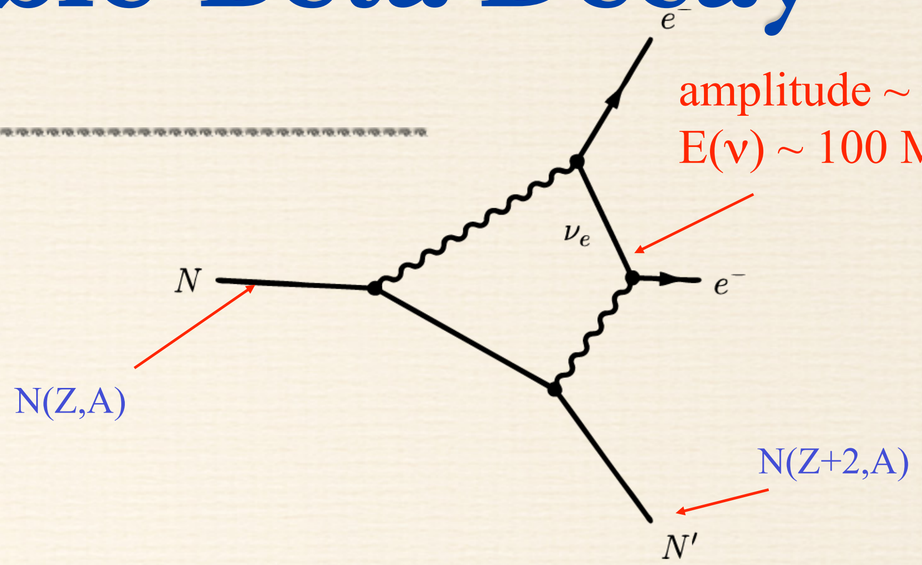


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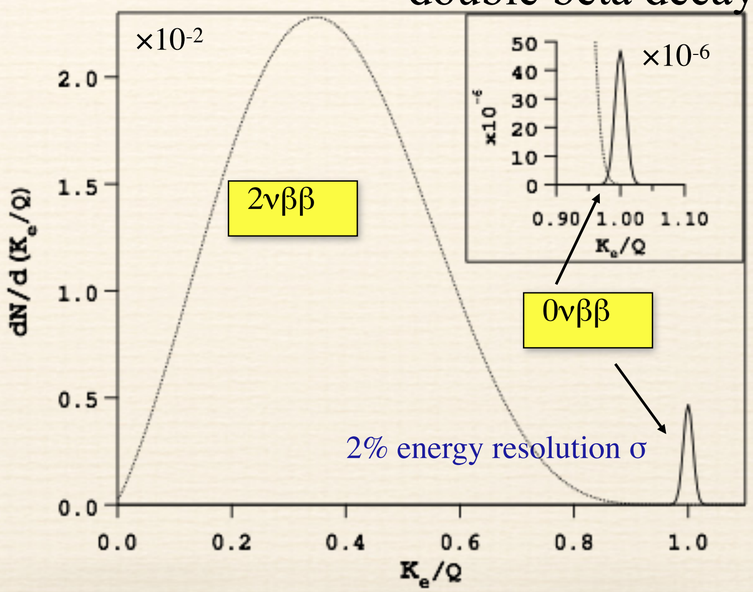
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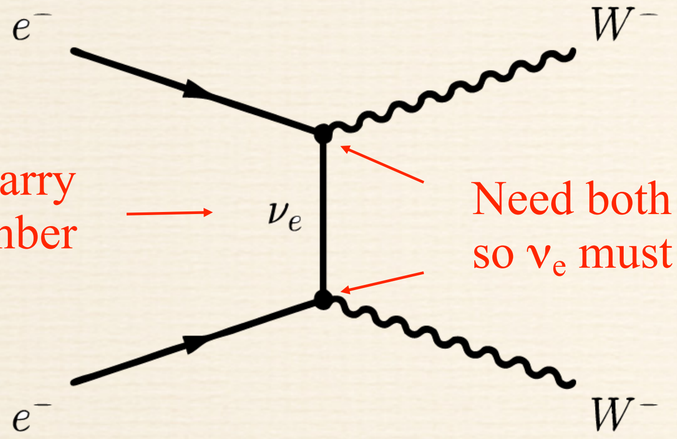
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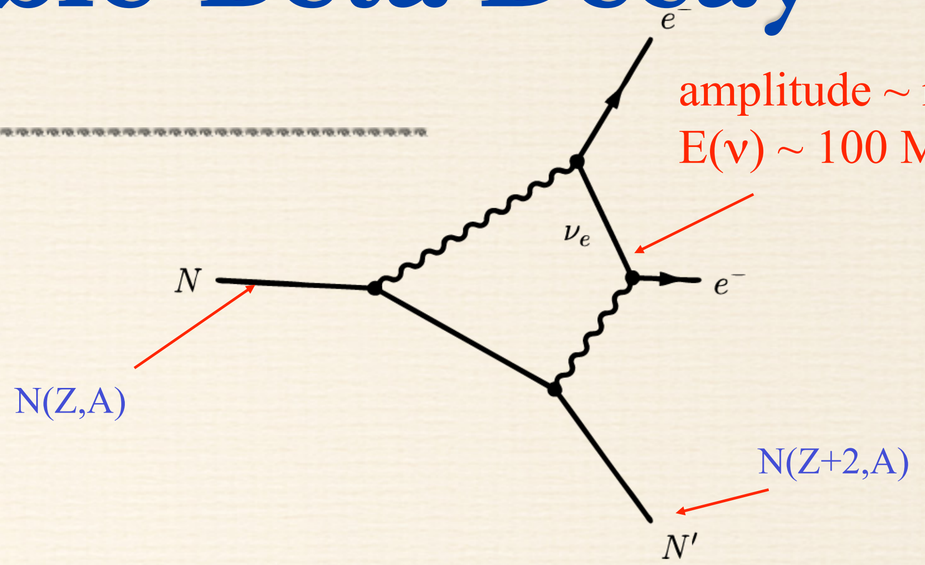


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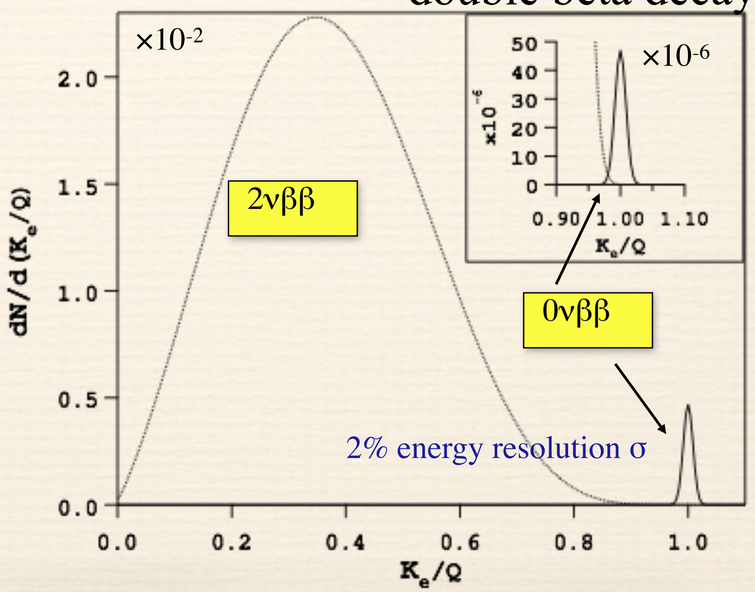
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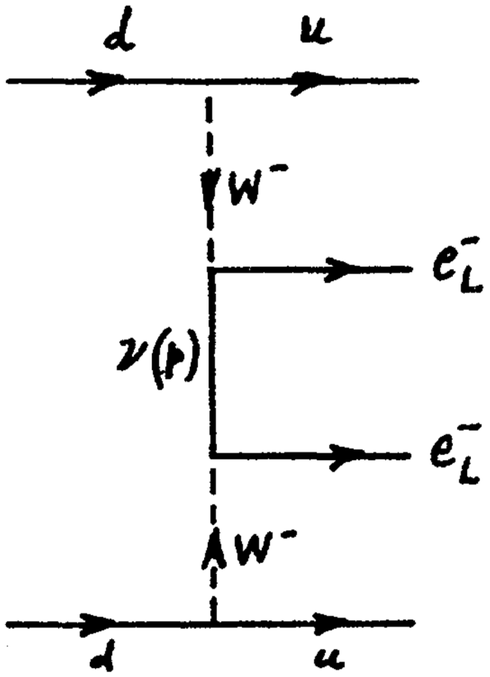


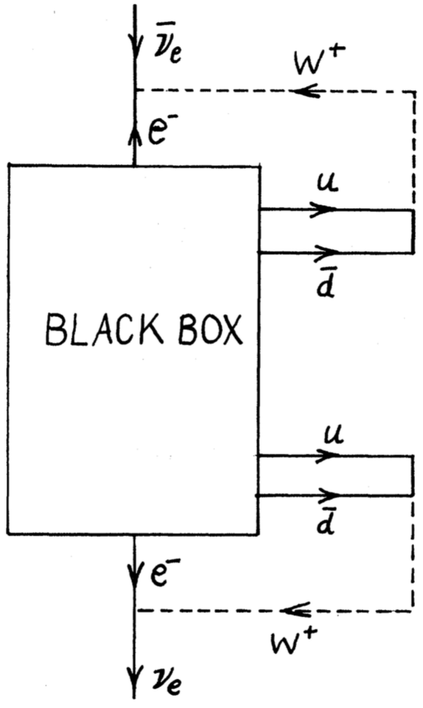
If observed, it would unambiguously signal that Lepton Number is NOT a conserved quantity, and that neutrinos are Majorana particles i.e. their own anti-particles

Schechter and Valle, PRD 25, Vol. 11 (1982)

A Theorem

*If neutrinoless double-beta decay occurs, there exists a way to convert an anti-neutrino to a neutrino, a **Majorana mass** amplitude*

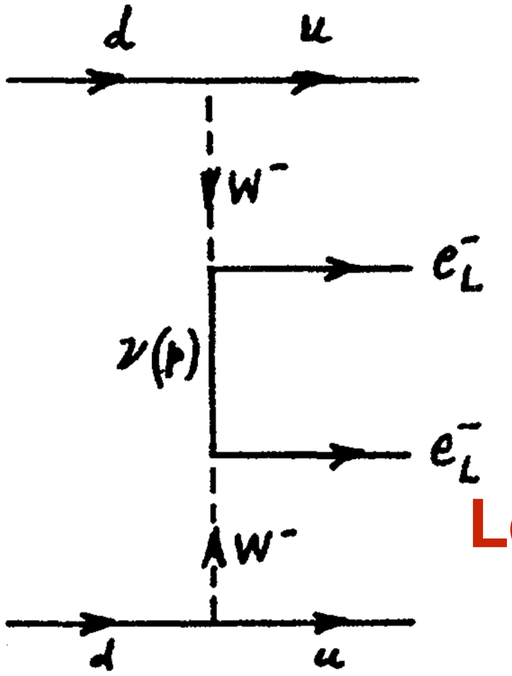




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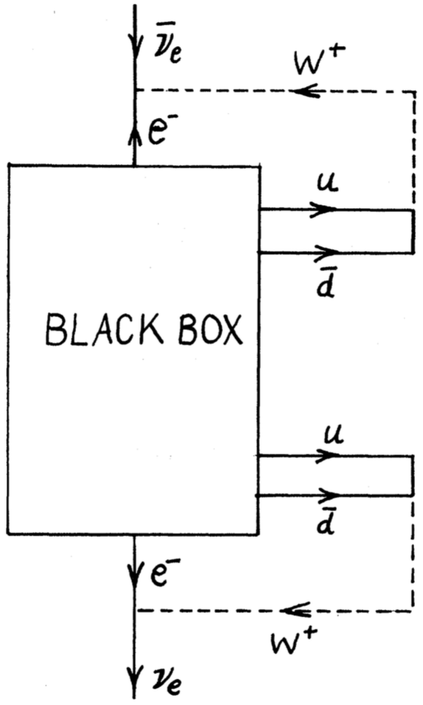
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No caveats:

0νββ

Lepton Number Violation and Majorana Neutrinos



Experiments: Very Long Half-Lives!

Typical $2\nu\beta\beta$ half-life is very long:
second-order weak process

$$\frac{1}{T_{\frac{1}{2}}^{0\nu}} = G^{2\nu}(Q,Z)\left|M^{2\nu}\right|^2$$

Atomic mass affected by nuclear pairing term:
even A nuclei occupy 2 parabolas,
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$$\frac{1}{G^{2\nu}} \simeq 10^{20} \text{ years}$$

Choose nuclei where single beta decay forbidden

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$\alpha \frac{m}{Q^2}$ $(Q \sim m_e)$ Phase Space Factor $G \sim G_F^4 g_A^4 m_e^5$

$M(A,Z)$ Nuclear Matrix Element

η Particle Physics of the Black Box

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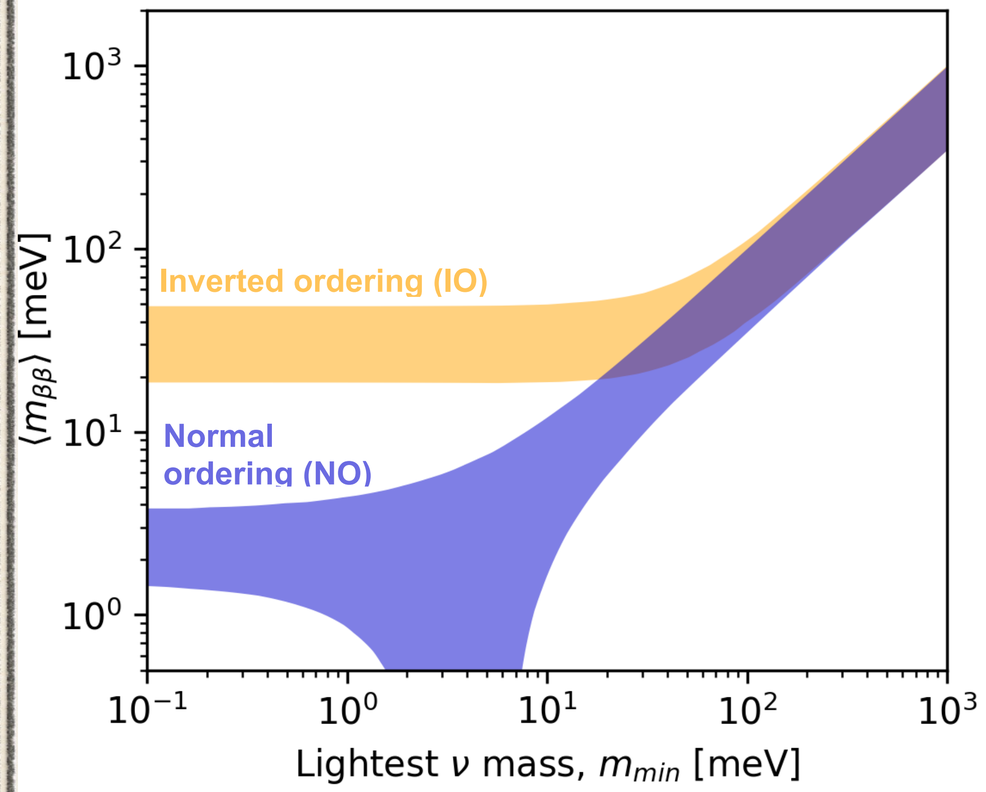
But a large number of BSM theories give rise to effective higher dimensional operators that can dramatically change the predicted half-life

$\frac{1}{\Lambda}\mathcal{L}_5$ **10^{15} GeV** $\frac{1}{\Lambda^5}\mathcal{L}_9$ **multi-TeV**

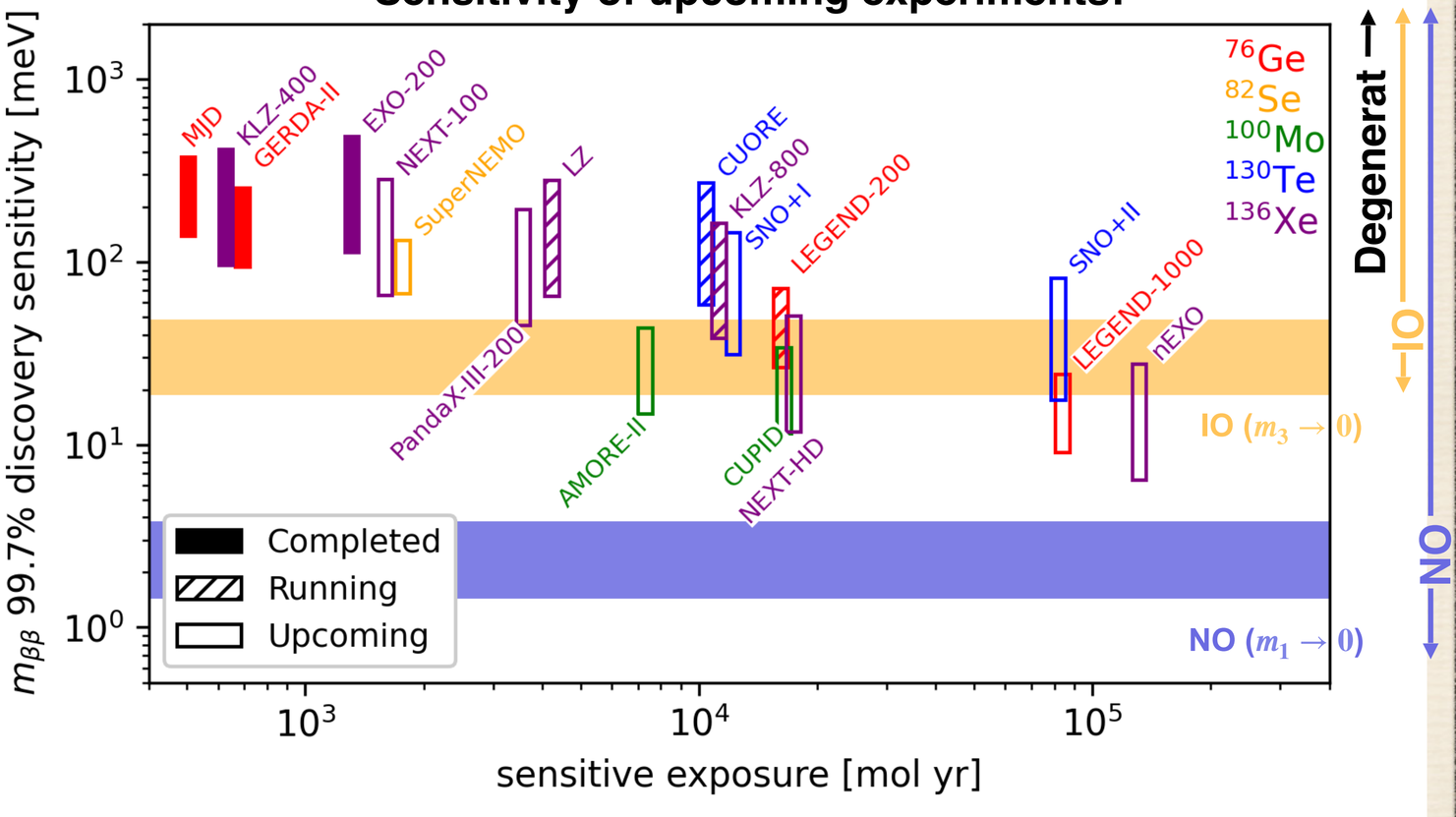
Slide courtesy: Dave Moore

Summary of Past and Present Projects

Parameter space vs. mass of lightest ν:



Sensitivity of upcoming experiments:



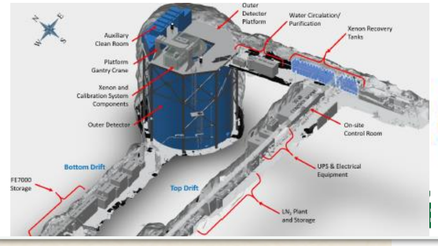
Unfortunately, US nuclear physics funding uncertainties make it unlikely that all upcoming experiments will be done in the next decade

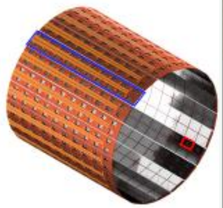
Slide courtesy: Vincenzo Cirigliano

Ton Scale Experimental Proposals

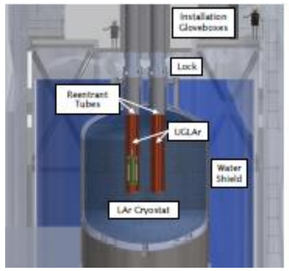
- The emerging ton-scale program consists of three experiments using three different isotopes and fielding very different experimental technologies: **CUPID** (^{100}Mo), **LEGEND-1000** (^{76}Ge), and **nEXO** (^{136}Xe).
- These three experiments have undergone a US DOE portfolio review and are ready to start construction

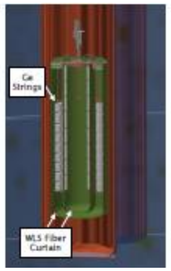
nEXO: Liquid Xe Time Projection Chamber



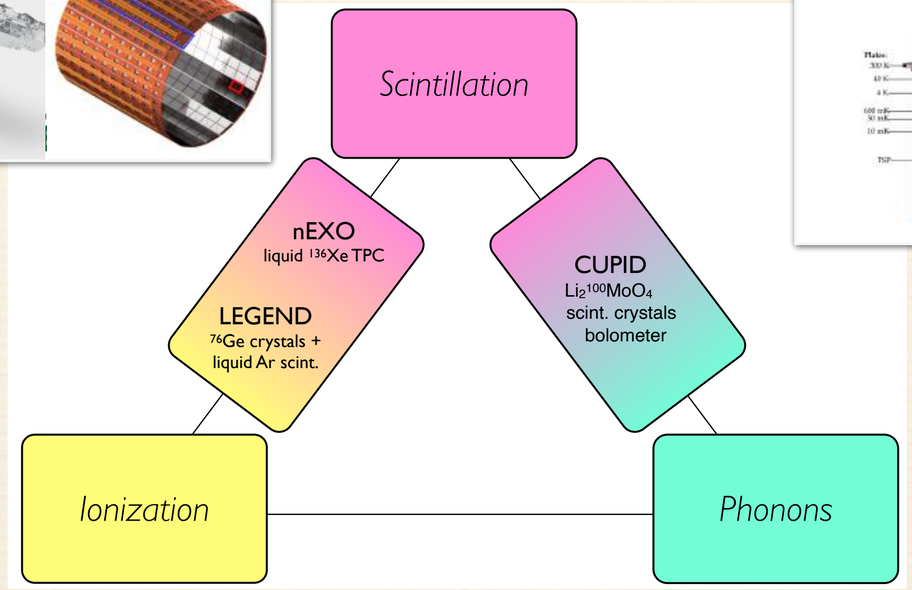


LEGEND: High Purity Ge Crystals

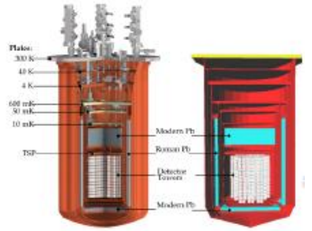


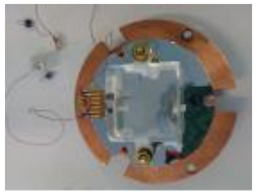






CUPID: Scintillating Crystal Bolometer





Time scale to complete all 3 experiments is highly uncertain

Charge Lepton Flavor Violation

Charged Lepton Flavor Violation (CLFV)

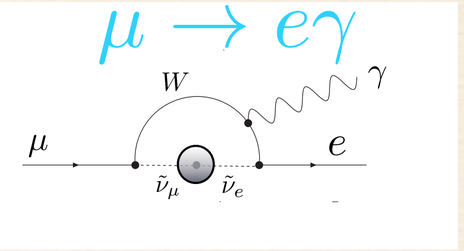
Is lepton flavor conservation exact? No! **Neutrino Oscillations!**

- **ν's have mass!** ***individual lepton flavors are not conserved***
- **Therefore Lepton Flavor Violation occurs in Charged Leptons too**

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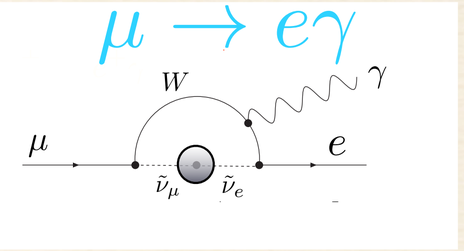
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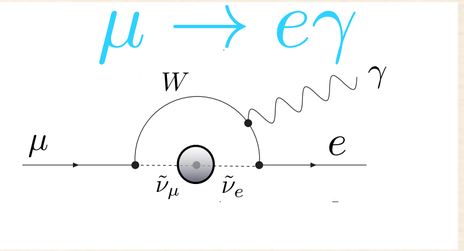
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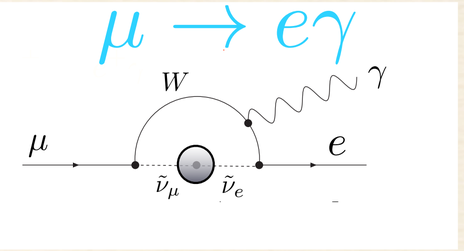
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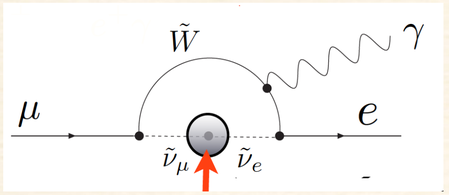
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Slepton mixing in SUSY



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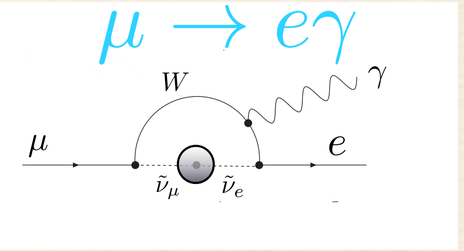
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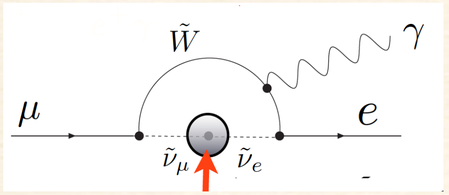
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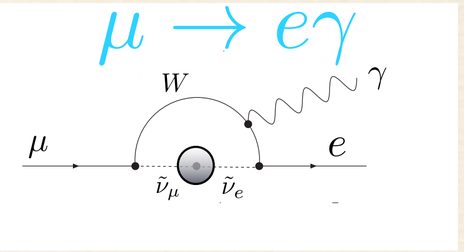
Major experimental searches are ongoing; mass reach depends on flux and sensitivity of technique

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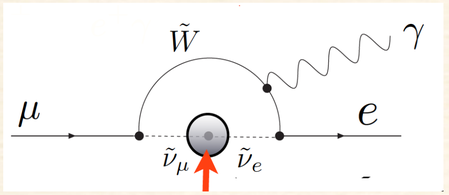
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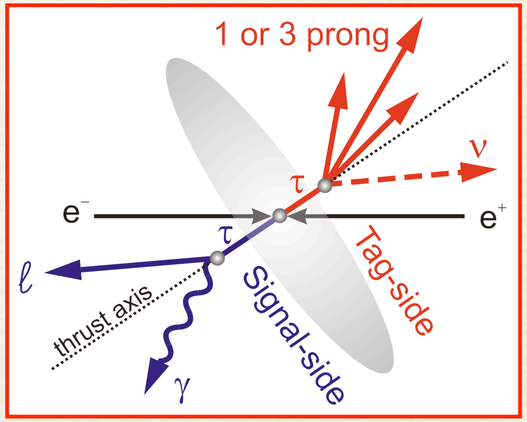
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μ or $\tau \longrightarrow e\gamma$, e^+e^-e, $K_L \to \mu e$, ...

Need very high fluxes for required statistical reach

New high intensity kaon & muon beams and high luminosity e+e- colliders all over the world



Tau Decays at e+e- colliders

Slide courtesy: Bob Bernstein

CLFV Initiatives

- $\mu^+ \to e^+\gamma$ (PSI)
  - MEG II, finished first run
  - BR ($\mu^+ \to e^+\gamma$) $< 3.1 \times 10^{-13}$ @ 90% CL
  - expect $\approx 4.2 \times 10^{-14}$ after a few years

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- $\mu^- N \to e^- N$ (FNAL, J-PARC)
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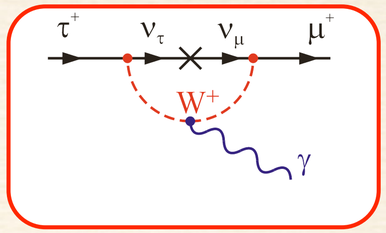
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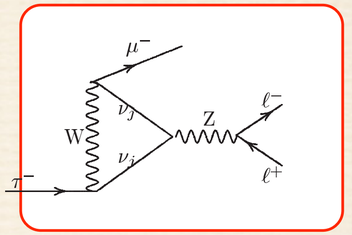
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τ processes also suppressed in Standard Model but less:

Lee, Shrock Phys.Rev.D16:1444,1977





Pham, hep-ph/9810484

Good News:
Beyond SM rates can be orders of magnitude larger than in associated muon decays

Bad News:
τ's hard to produce:
~10^{10} τ/*yr* vs >10^{11} μ/*sec* in upcoming muon experiments

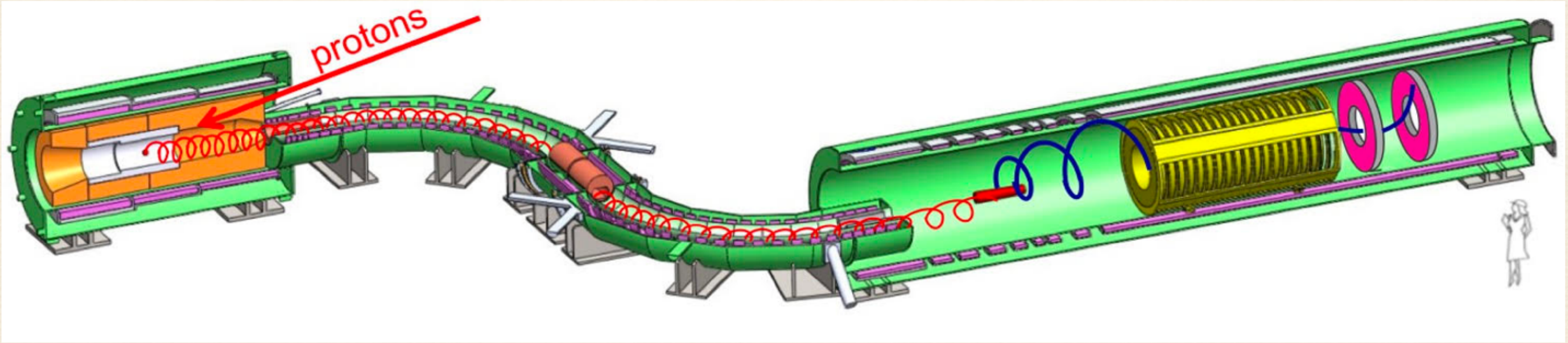
- Rough analogy to neutrinos: muon CLFV is "θ_{12}" ; anything involving the τ is in the θ_{13} or θ_{23} sector

- Colliders can also probe CLFV-violating Higgs decays

Slide courtesy: Brendan Casey

Mu2e at FNAL Overview

25m of solenoids designed to maximize captured muons and remove backgrounds (10^{10} stopped μ/sec)

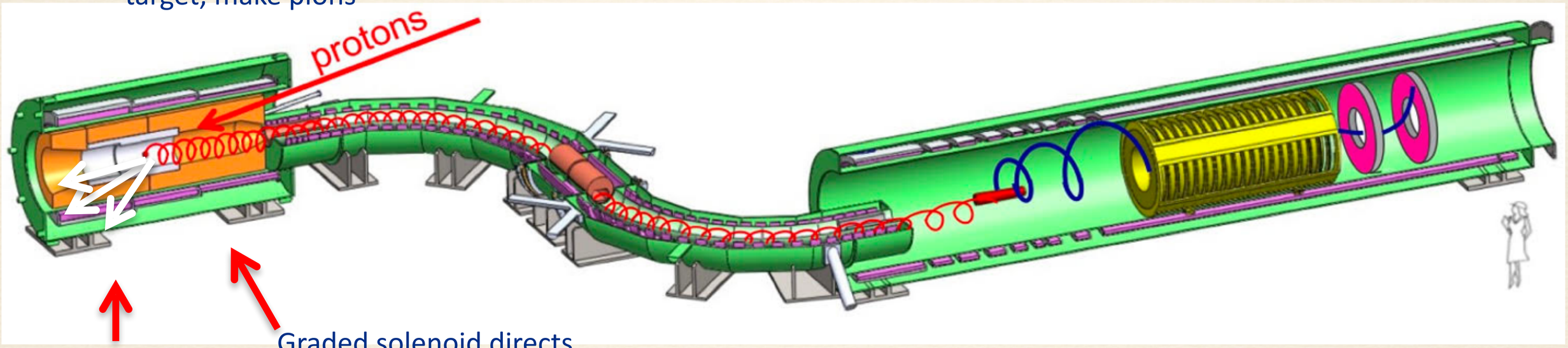


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Protons enter here, hit target, make pions



High momentum Backgrounds exit out the front

Graded solenoid directs low momentum particles into transport solenoid

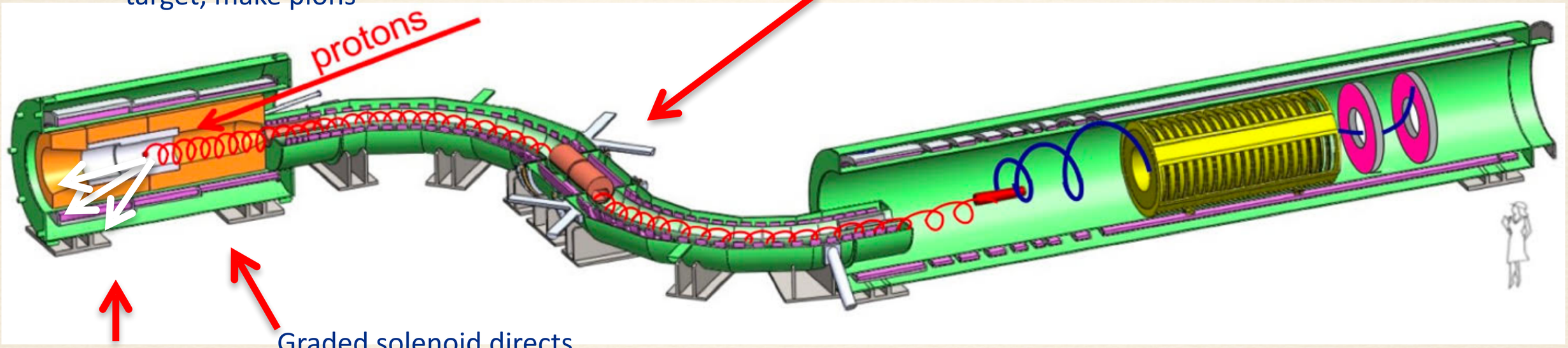
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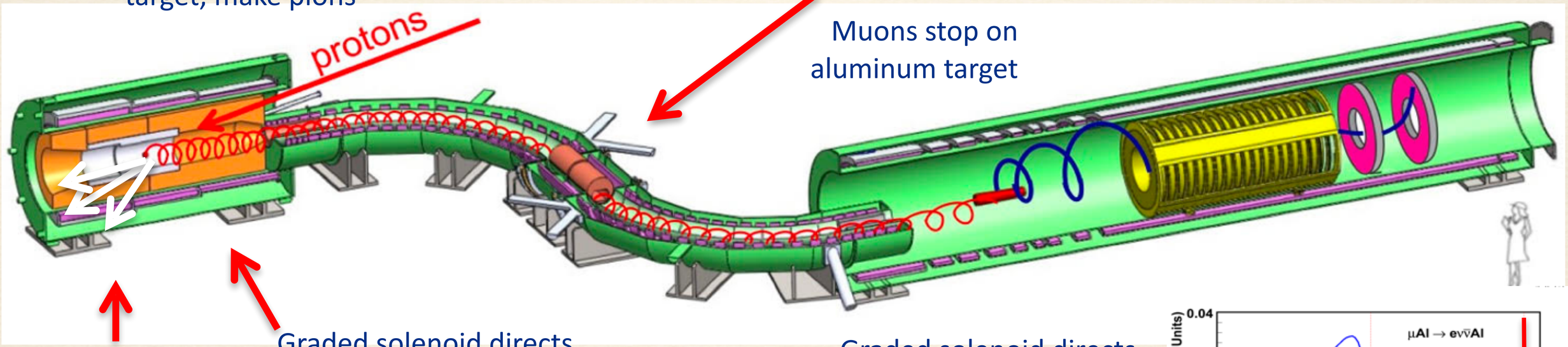
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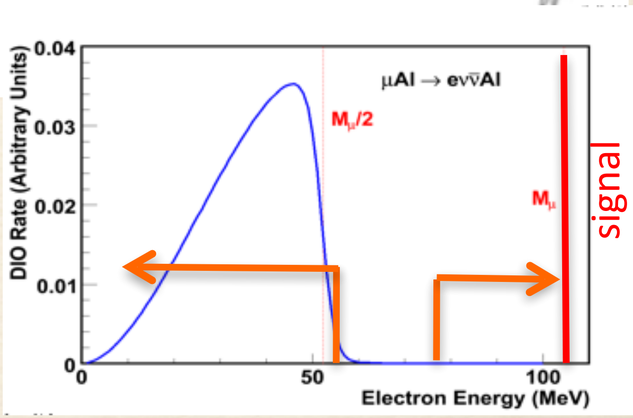


Muons stop on aluminum target

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Graded solenoid directs electrons to the detector



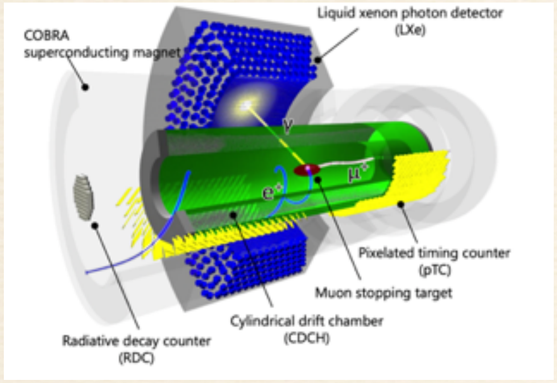
"Hollow" tracker has low acceptance for SM decays and high acceptance for signal

Slide courtesy: Brendan Casey

Other Experiments pursuing CLFV

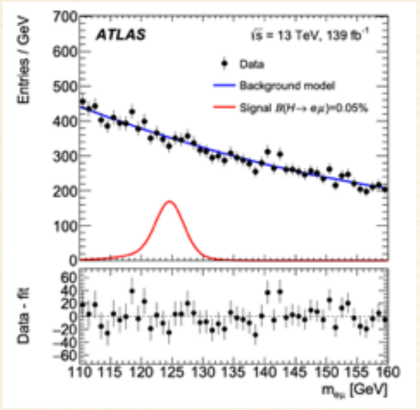
MEG-II

Data on tape



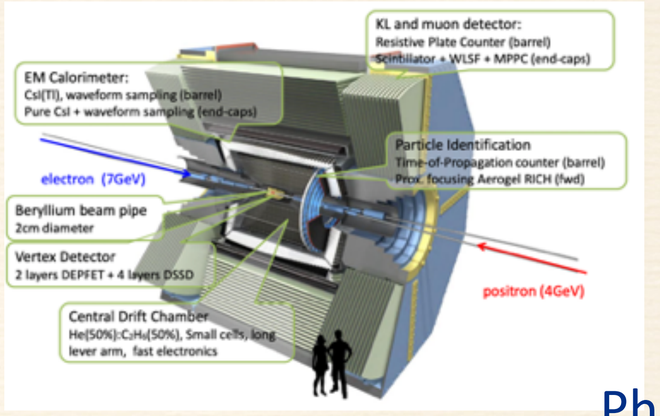
LHC

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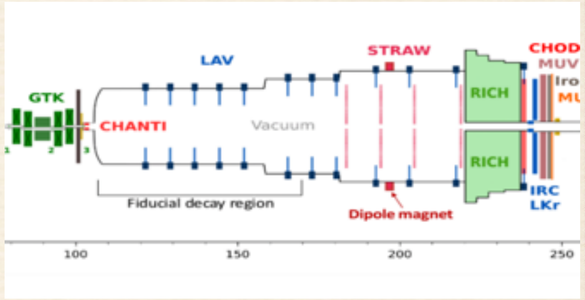
Belle II

Data on tape



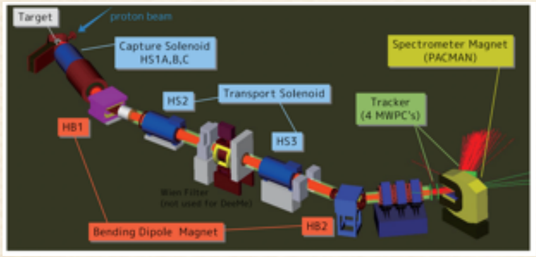
NA62

Data on tape



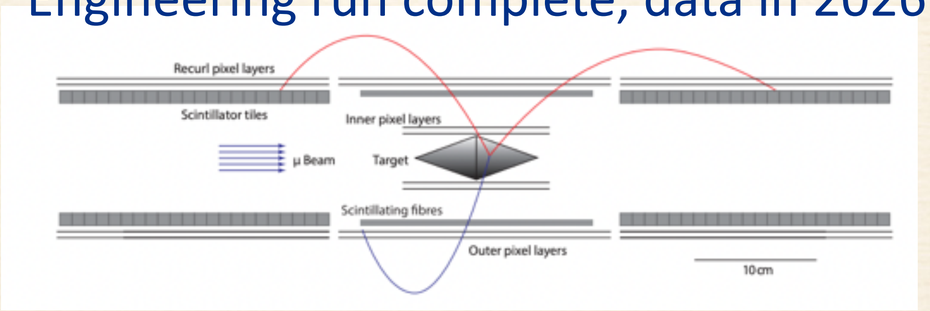
DeeMee

Engineering run complete



Mu3e

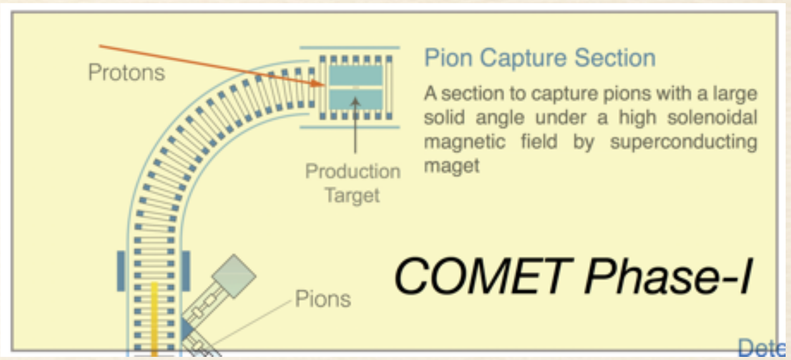
Engineering run complete, data in 2026



COMET

Phase-1 Solenoid in place.

Engineering run complete



All have unique sensitivity to regions of CLFV parameter space and all have discovery potential 'around the corner'

The race is on!

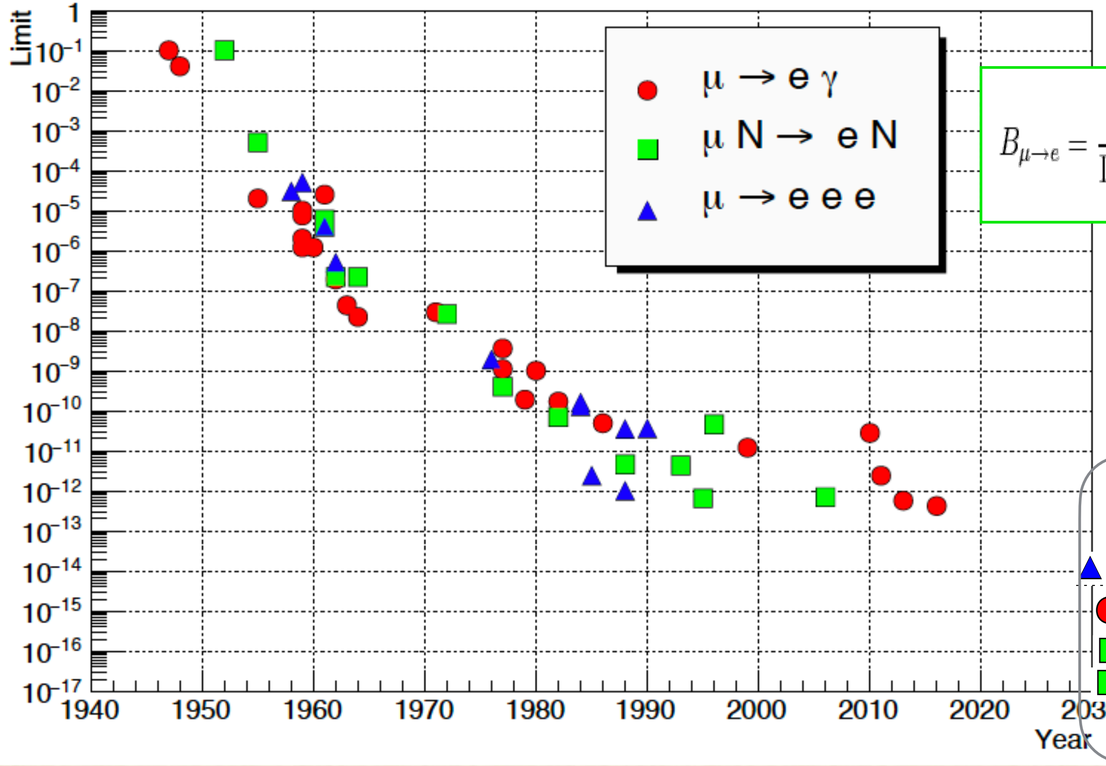
CLFV across Energy Scales

- Decays of μ, τ (and mesons)

$$\mu \to e\gamma, \quad \mu \to e\bar{e}e, \quad \mu\,(A,Z) \to e\,(A,Z) \qquad M_\mu - \overline{M}_\mu \qquad \mu \to ea$$

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Modified from Calibbi-Signorelli 1709.00294



$$B_{\mu\to e} = \frac{\Gamma(\mu^- + (Z,A) \to e^- + (Z,A))}{\Gamma(\mu^- + (Z,A) \to \nu_\mu + (Z-1,A))}$$

Ongoing / planned

MEG-II DeeMee
Mu3e
Mu2e, COMET
Mu2e-II
AMF - PRISM

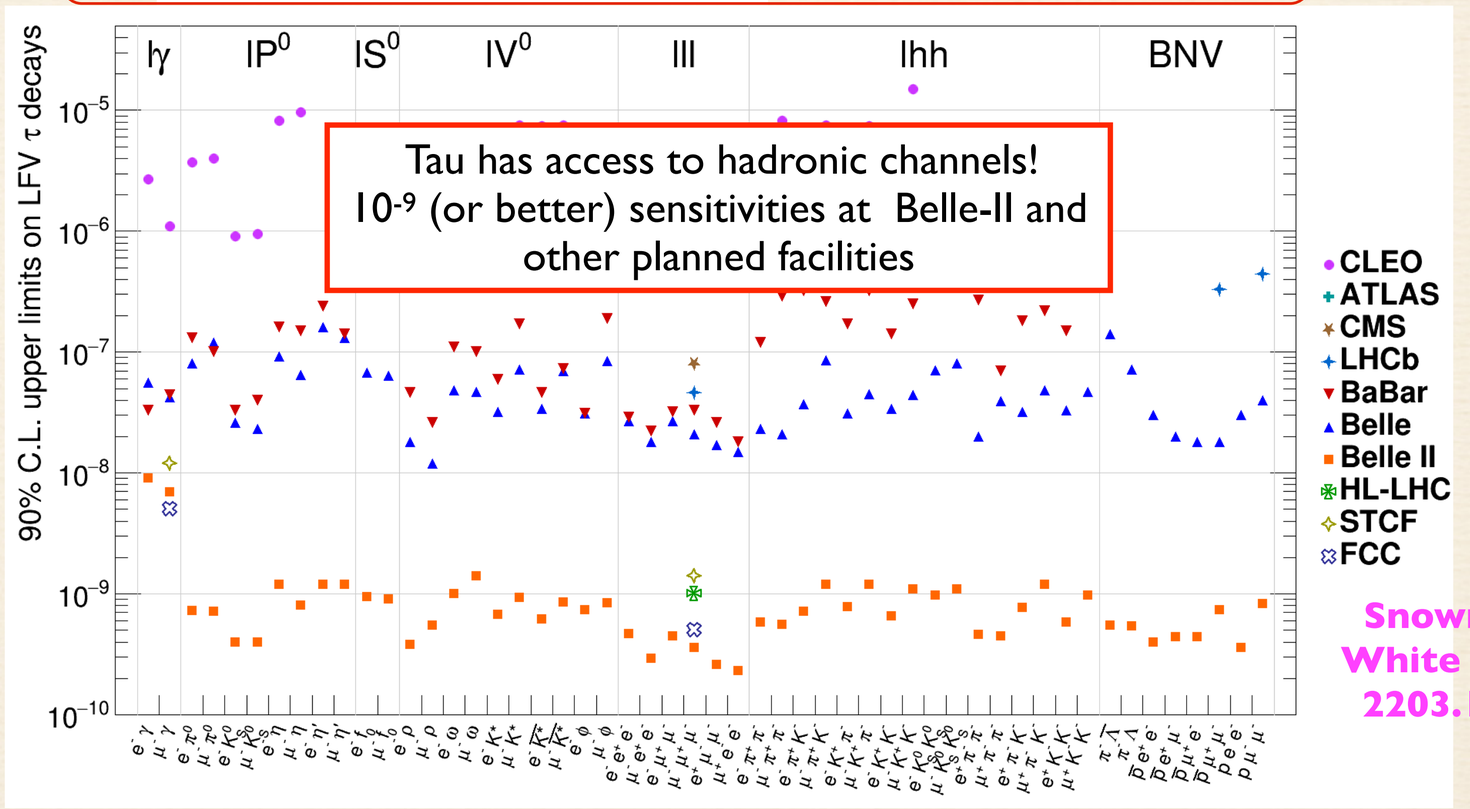
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Snowmass White Paper 2203.14919

Electric Dipole Moment Searches

Permanent Electric Dipole Moment (EDM)

The renormalizable field theories such as the ones that describe strong and electroweak interactions conserve CPT: e.g. masses and lifetimes of particle and anti-particle

CP violation therefore implies T violation

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Fundamental Particle with EDM $\vec{d}$ and magnetic moment $\overrightarrow{\mu}$

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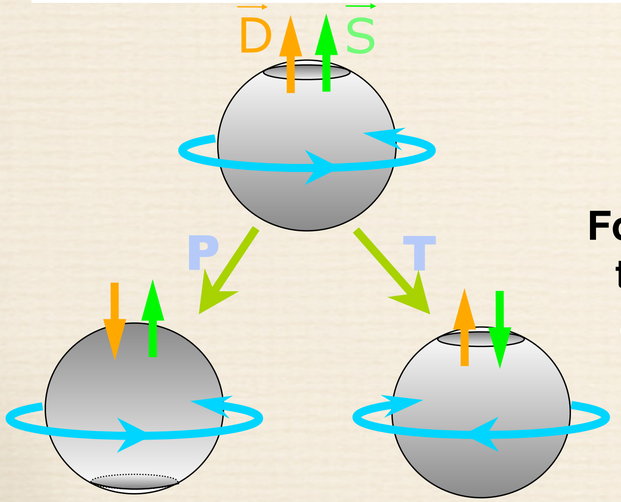
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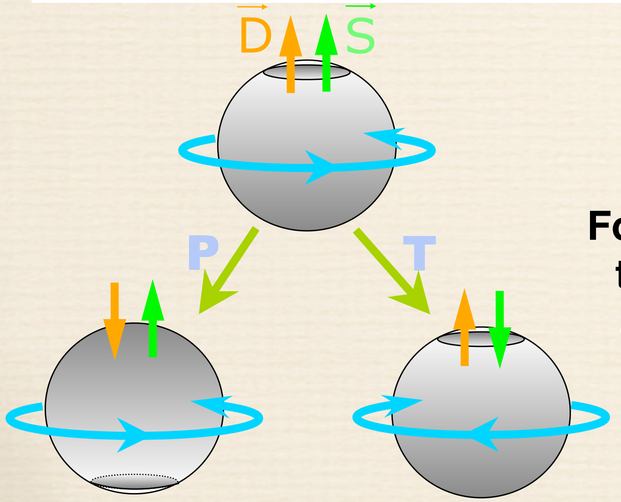
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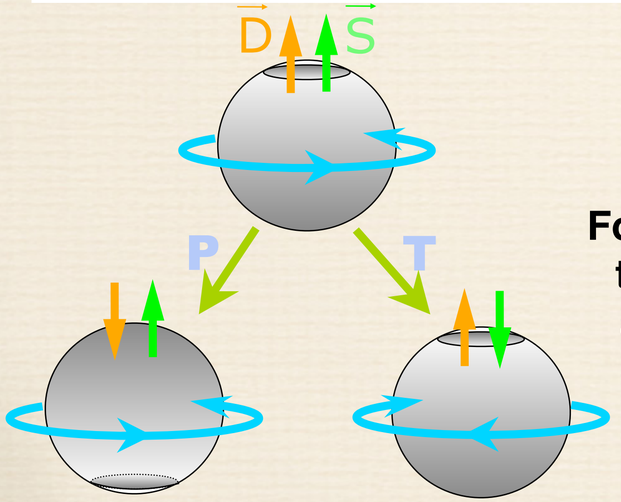
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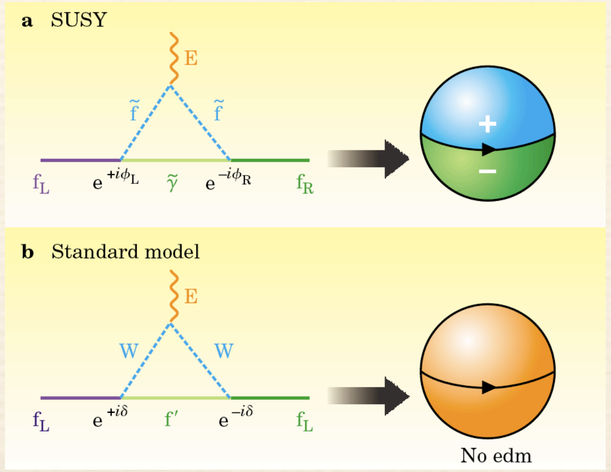
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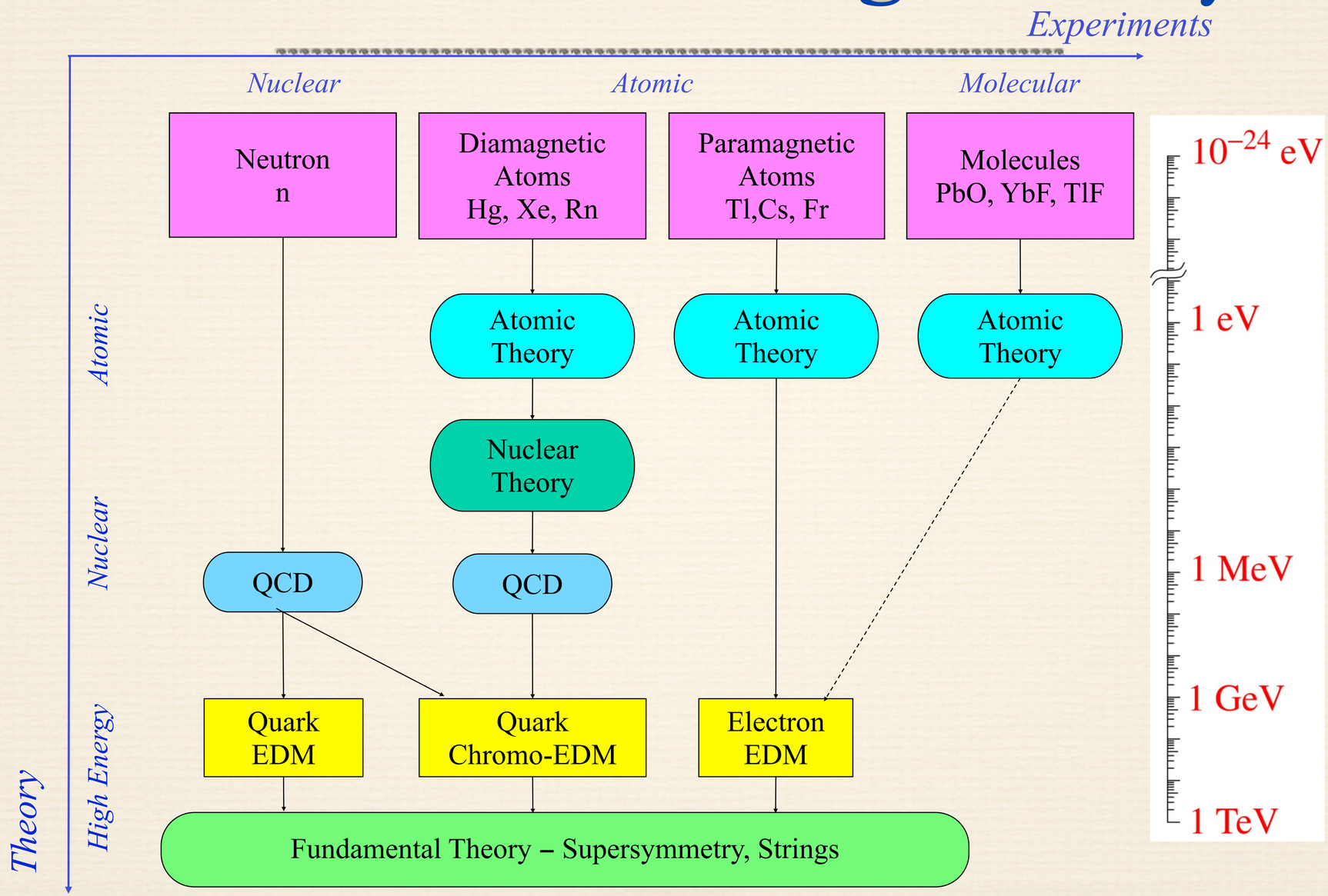


raw sensitivity:

$d \sim (m \times e)/\Lambda^2$

$d \sim 10^{-27}$: $\Lambda \sim 100$ TeV

EDMs: Connecting Theory

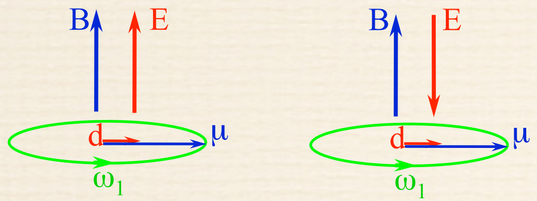


Basic Experimental Approach

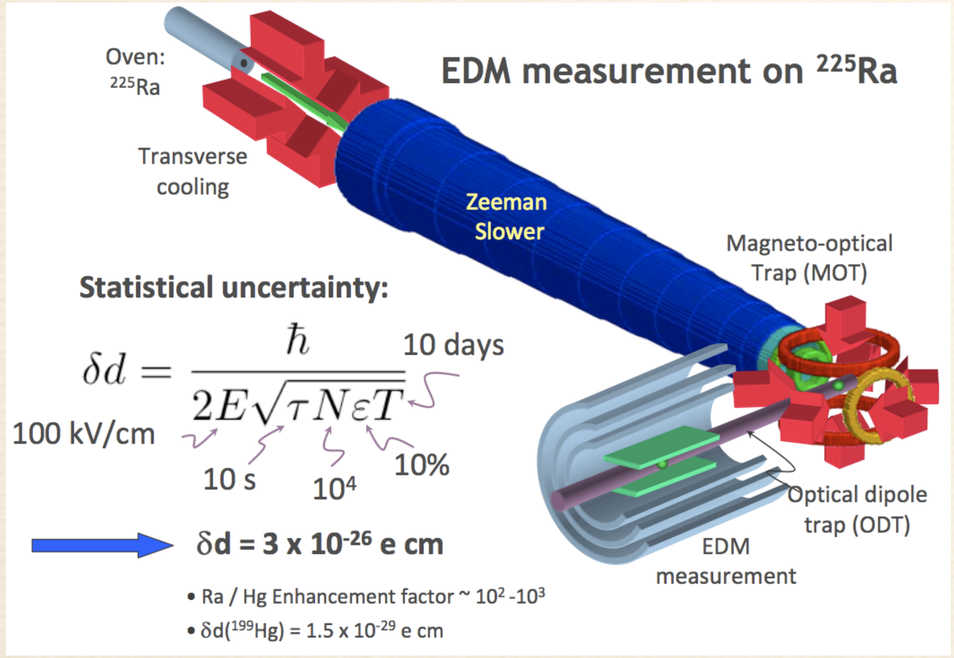
Courtesy:
M. Romalis, Z-T. Lu, B. Filippone

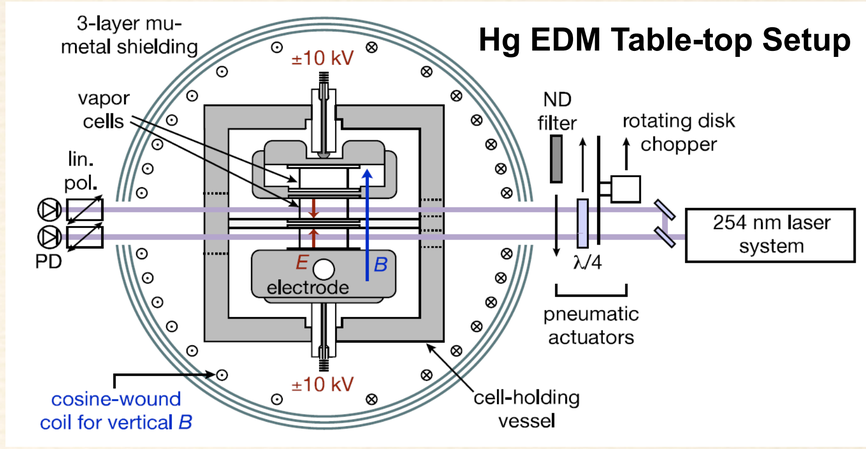
- Measure spin-precession frequencies

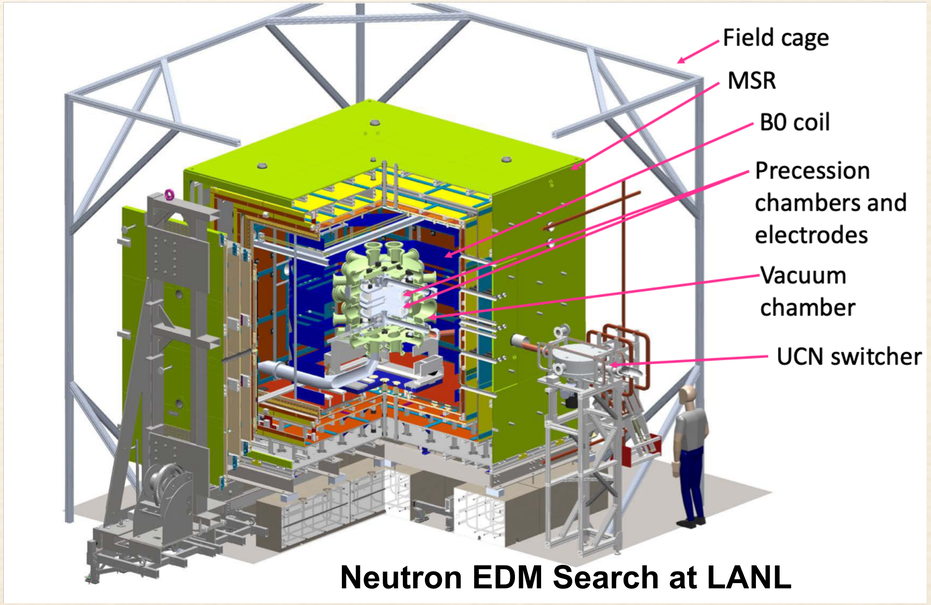
$$H = -\vec{\mu} \times \vec{B} - \vec{d} \times \vec{E}$$



$$\omega_1 = \frac{2\mu B + 2dE}{\hbar} \qquad \omega_2 = \frac{2\mu B - 2dE}{\hbar} \qquad \omega_1 - \omega_2 = \frac{4dE}{\hbar}$$







Courtesy: D Kawall and J. Singh

EDM Summary/Future

	Result	95% u.l.
	Paramagnetic systems	
Xe^m	$d_A = (0.7 \pm 1.4) \times 10^{-22}$	3.1×10^{-22} e cm
Cs	$d_A = (-1.8 \pm 6.9) \times 10^{-24}$	1.4×10^{-23} e cm
	$d_e = (-1.5 \pm 5.7) \times 10^{-26}$	1.2×10^{-25} e cm
	$C_S = (2.5 \pm 9.8) \times 10^{-6}$	2×10^{-5}
	$Q_m = (3 \pm 13) \times 10^{-8}$	2.6×10^{-7} $\mu_N R_{Cs}$
Tl	$d_A = (-4.0 \pm 4.3) \times 10^{-25}$	1.1×10^{-24} e cm
	$d_e = (6.9 \pm 7.4) \times 10^{-28}$	1.9×10^{-27} e cm
YbF	$d_e = (-2.4 \pm 5.9) \times 10^{-28}$	1.2×10^{-27} e cm
ThO	$d_e = (-2.1 \pm 4.5) \times 10^{-29}$	9.7×10^{-29} e cm
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HfF^+	$d_e = (0.9 \pm 7.9) \times 10^{-29}$	1.6×10^{-28} e cm
	Diamagnetic systems	
^{199}Hg	$d_A = (2.2 \pm 3.1) \times 10^{-30}$	7.4×10^{-30} e cm
^{129}Xe	$d_A = (0.7 \pm 3.3) \times 10^{-27}$	6.6×10^{-27} e cm
^{225}Ra	$d_A = (4 \pm 6) \times 10^{-24}$	1.4×10^{-23} e cm
TlF	$d = (-1.7 \pm 2.9) \times 10^{-23}$	6.5×10^{-23} e cm
n	$d_n = (-0.21 \pm 1.82) \times 10^{-26}$	3.6×10^{-26} e cm
	Particle systems	
μ	$d_\mu = (0.0 \pm 0.9) \times 10^{-19}$	1.8×10^{-19} e cm
τ	$\mathrm{Re}(d_\tau) = (1.15 \pm 1.70) \times 10^{-17}$	3.9×10^{-17} e cm
Λ	$d_\Lambda = (-3.0 \pm 7.4) \times 10^{-17}$	1.6×10^{-16} e cm

The best limit on atomic EDM:

EDM(^{199}Hg) < 0.74x10^{-29} e-cm (95% C.L.)

PRL 116:161601 (2016)

- **Planned and ongoing CP-violation search experiments** using ^{129}Xe atoms, ^{225}Ra atoms, ^{173}YbOH molecules, and ^{205}TlF molecules **are poised to match or exceed** the new physics sensitivity of **the state-of-the-art ^{199}Hg EDM experiment** by about an order of magnitude.

- Several **next generation** CP-violation search schemes using **pear-shaped nuclei inside of molecules** are currently being developed and have new physics sensitivities that are **several orders of magnitude beyond the state-of-the-art ^{199}Hg EDM experiment**.

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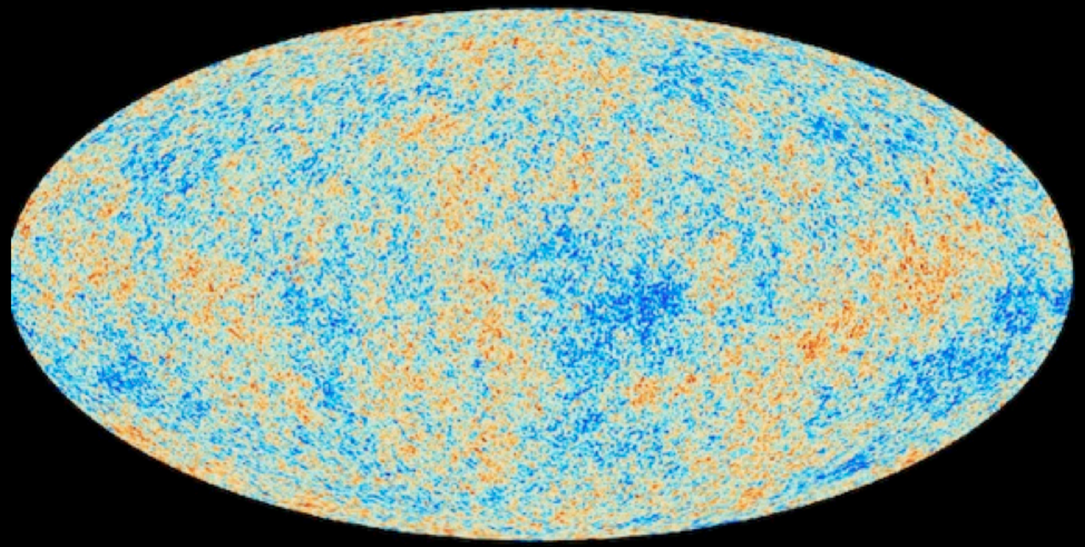
- Several **next generation** CP-violation search schemes using **pear-shaped nuclei inside of molecules** are currently being developed and have new physics sensitivities that are **several orders of magnitude beyond the state-of-the-art ^{199}Hg EDM experiment**.

To go past 10^{-28} e cm for the neutron and 10^{-30} for nuclei will need new ideas and upgrades in the 2030s

Dark Matter Searches

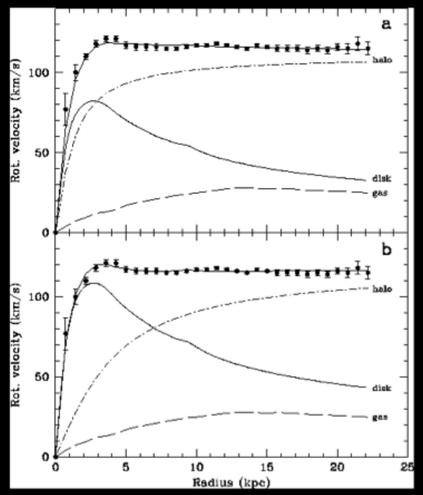
Dark Matter

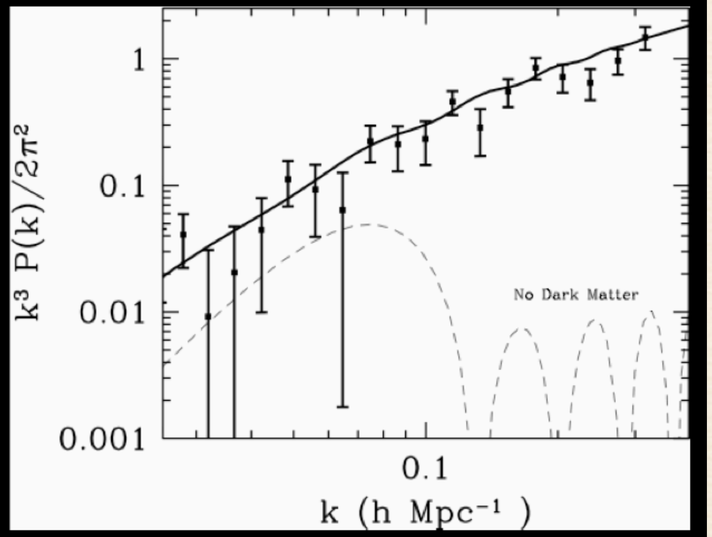
H. Lippencott





- Galaxy rotation curves
- Galaxy clusters and collisions
- Large scale structure
- Cosmic microwave background

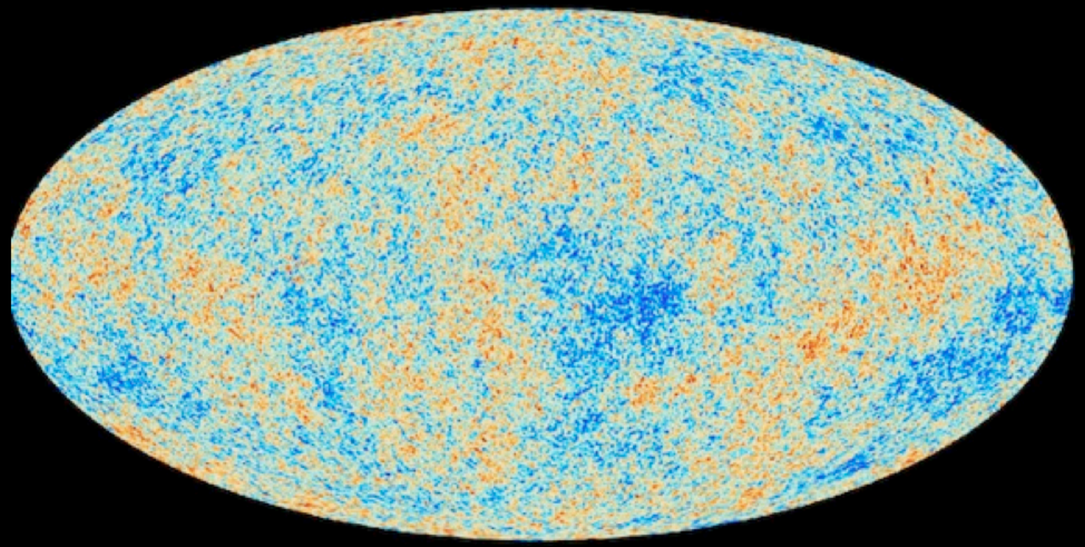




A Large Body of Indirect Evidence primarily from Astrophysics/Cosmology

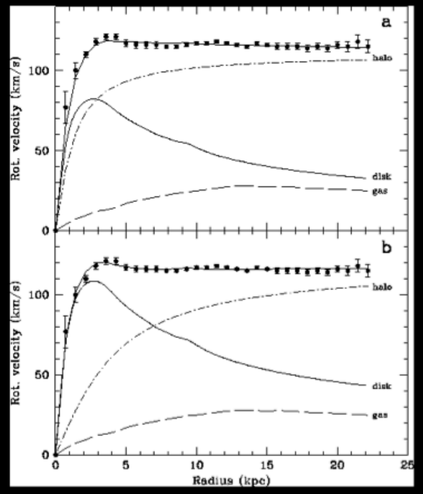
Dark Matter

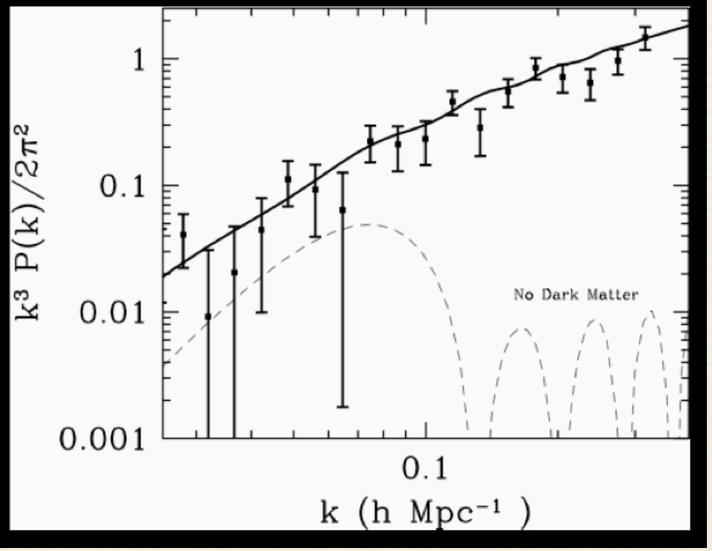
H. Lippencott





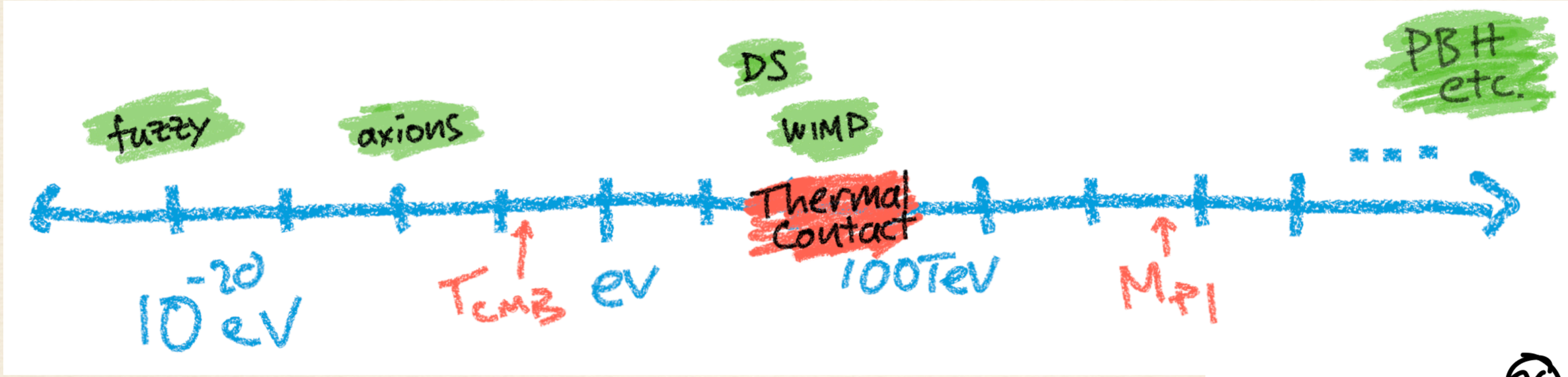
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Courtesy: D. McKeen

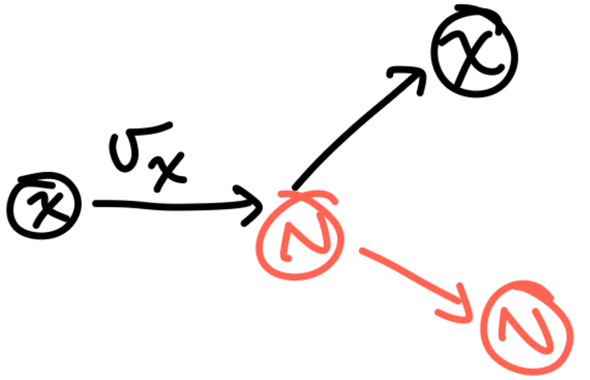
Dark Matter: Large Parameter Space



Thermally produced dark matter

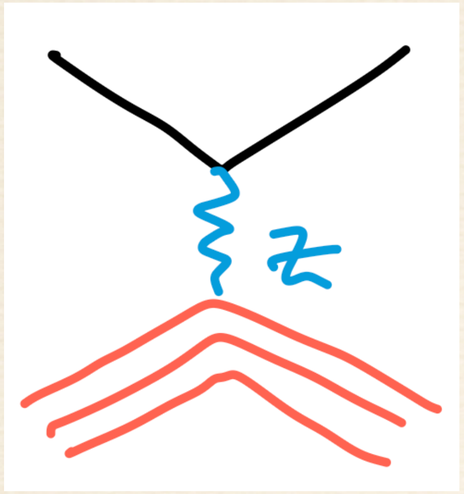
A particle with weak scale mass and weak coupling can obtain the correct dark matter density: WIMP Miracle

Attractive solution to simultaneously solve dark matter particle origin and puzzles regarding electroweak symmetry breaking



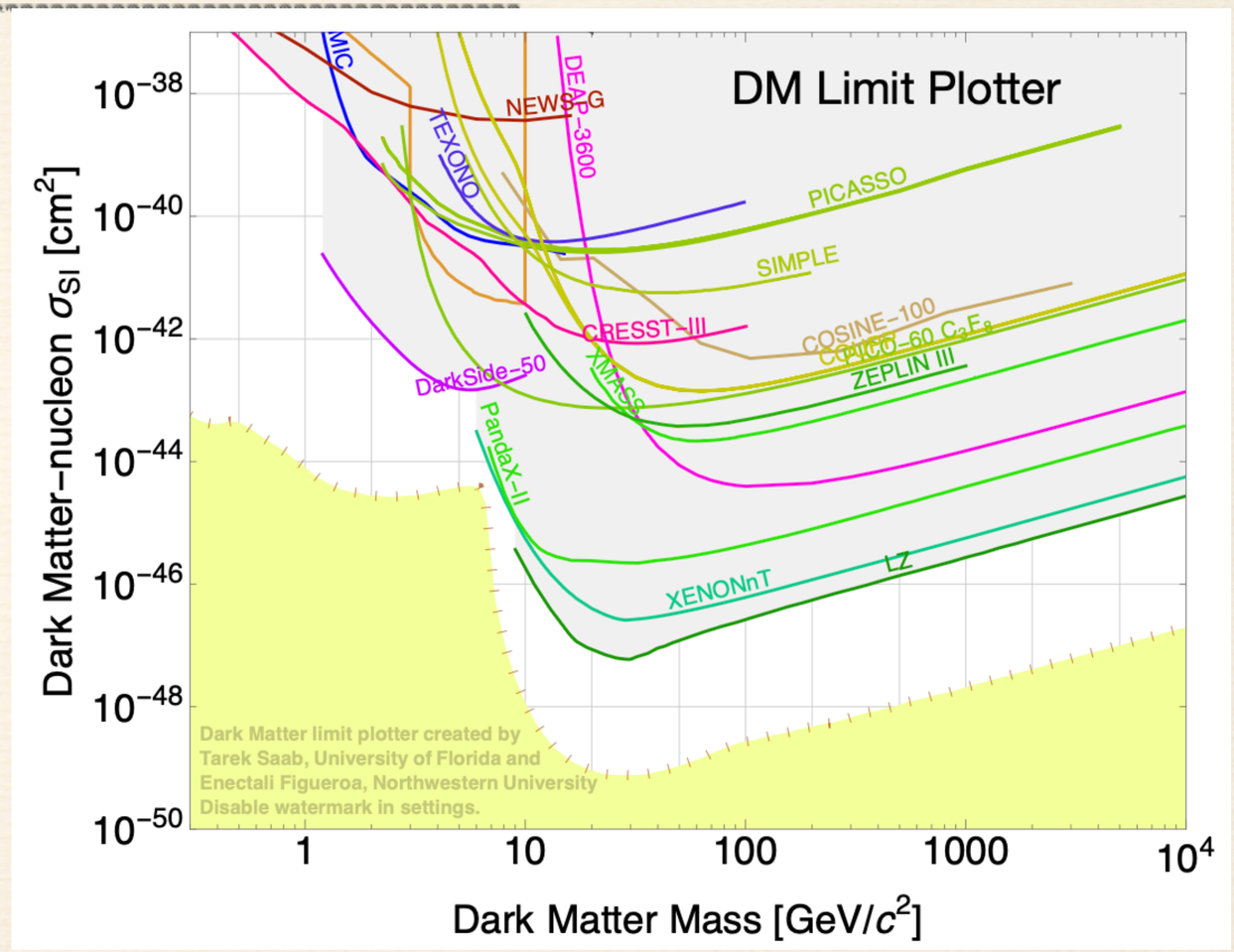
$$E_{\text{recoil}} \leq \frac{2\mu_{\chi N}^2 v_\chi^2}{m_N} \sim \mathcal{O}(10\ \text{keV}) \text{ for } v_\chi \sim 10^{-3}c$$

Courtesy: D. McKeen

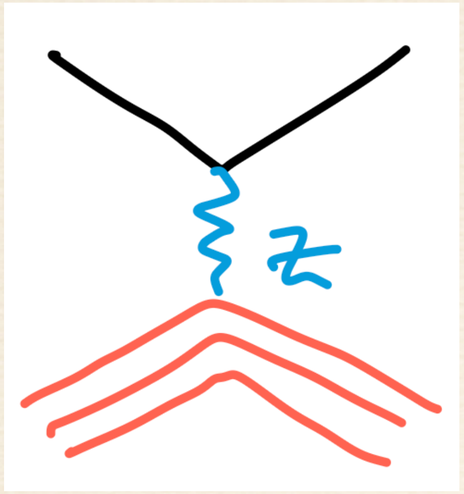


WIMP Search Status

- **Ongoing Program**
  - *Direct production: LHC*
  - *Direct Detection: LZ, ADMX-G2, DarkSide-20k, XENONnT, SuperCDMS*
  - *Spin-dependent and Ultra-Heavy: IceCube*
- **Next Phase**
  - *Support for one G3 experiment capable of completely reaching the "neutrino fog"*
  - *Will require upgrade of SURF to site in the US*

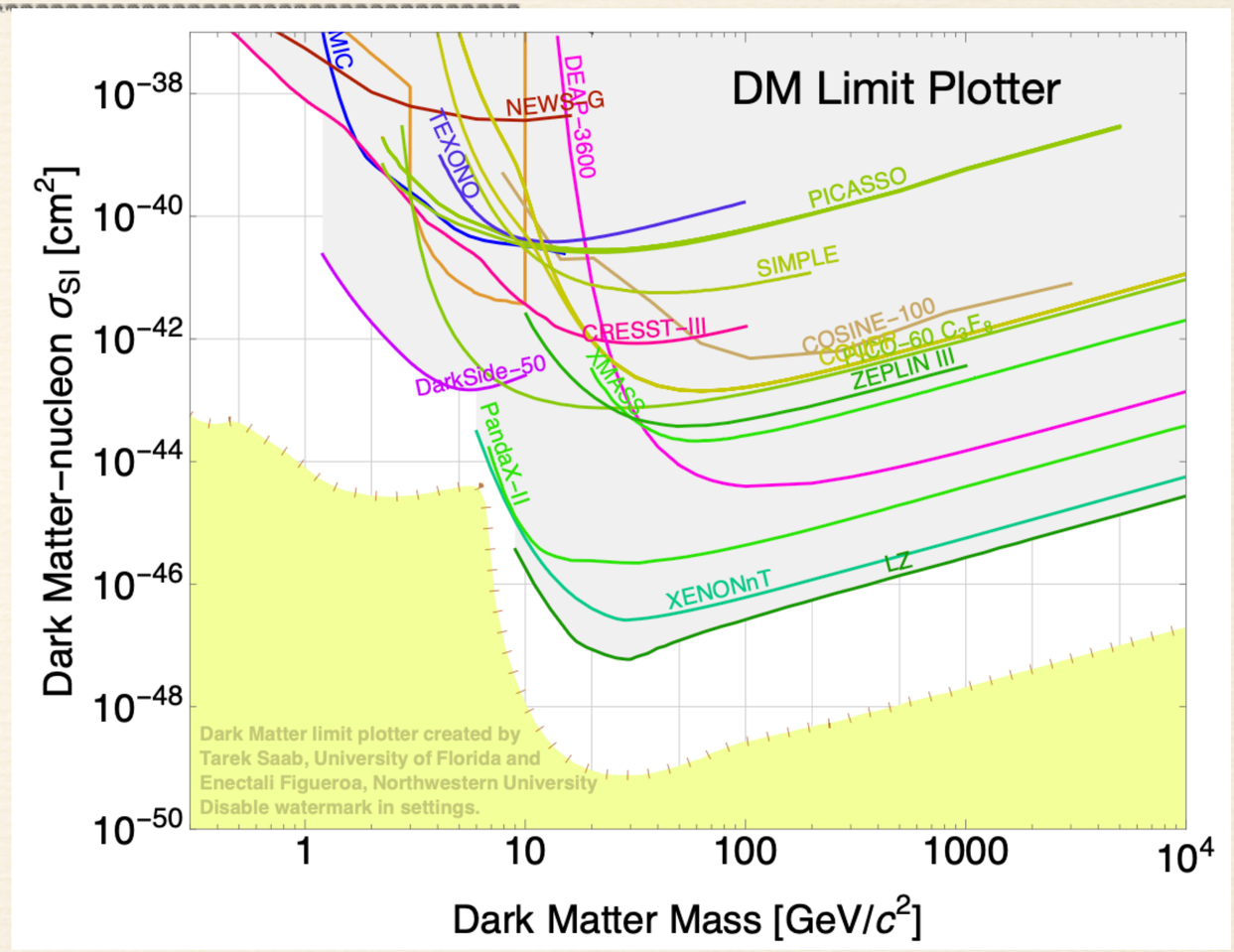


Courtesy: D. McKeen



WIMP Search Status

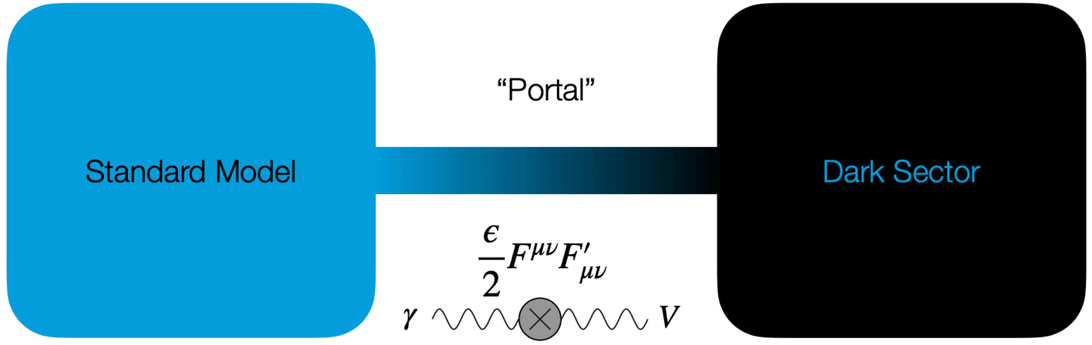
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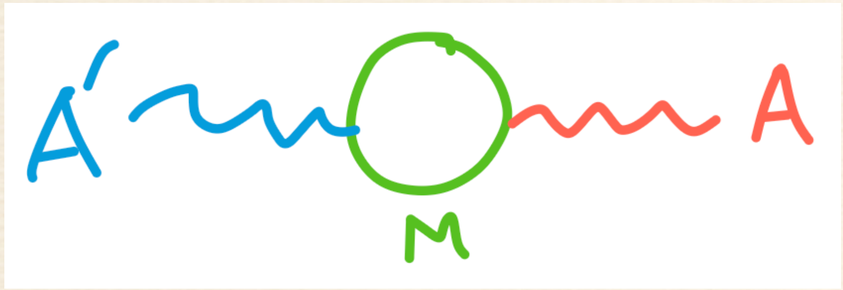


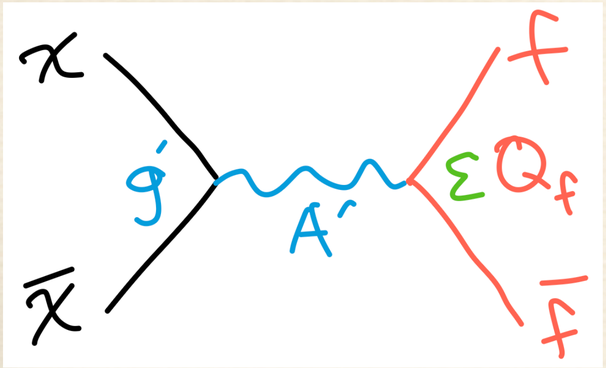
The next phase will require require multiple countries to band together to consolidate funding

Light Mediators: Dark Bosons

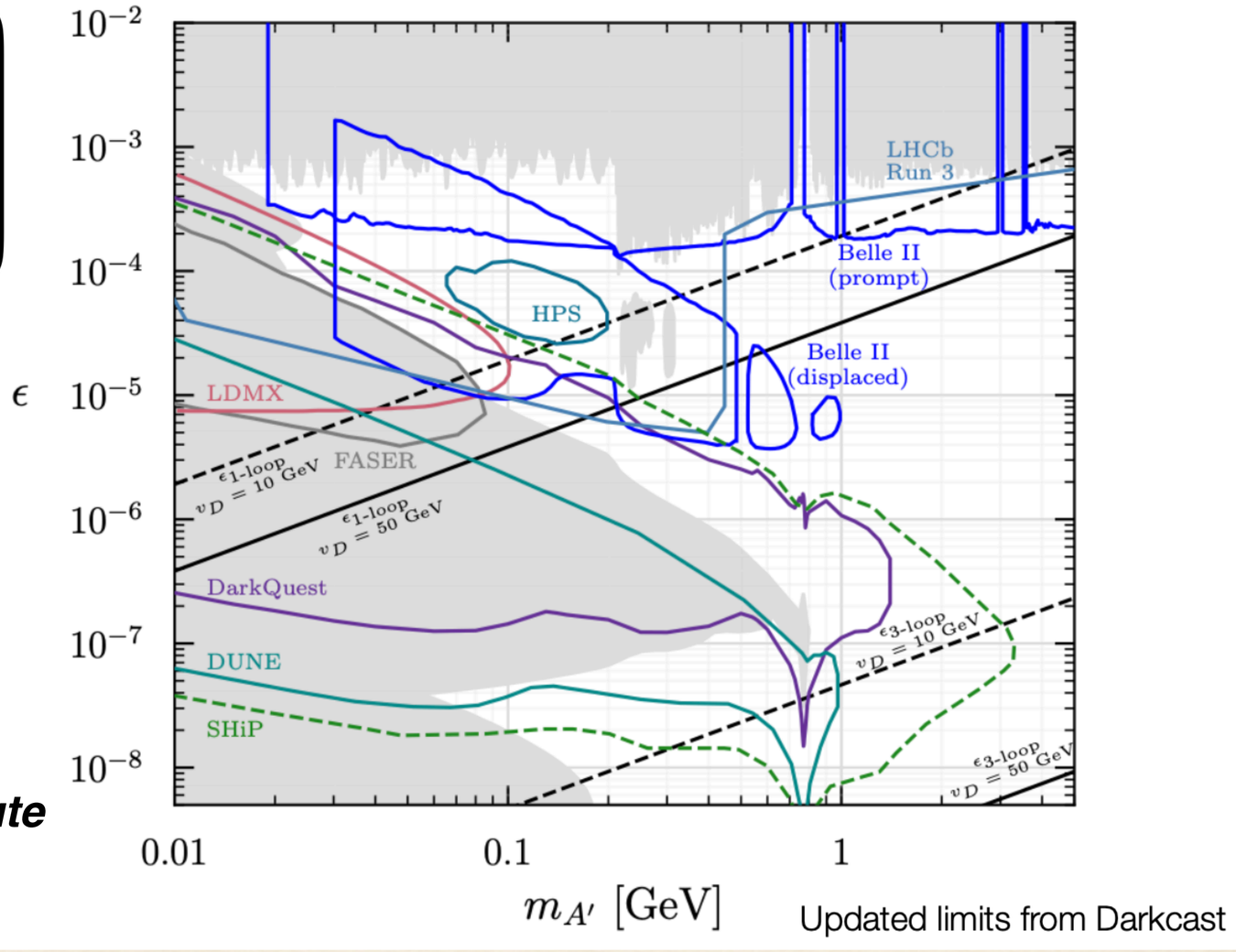
Courtesy: D. McKeen







JLab can contribute to cover the full parameter space

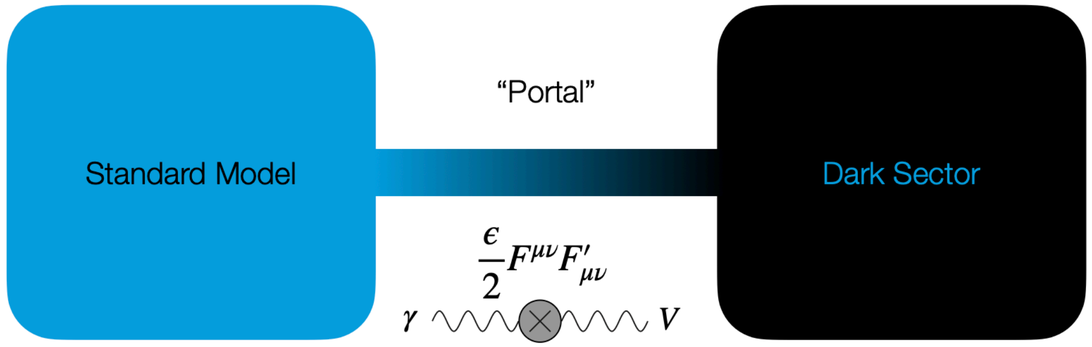


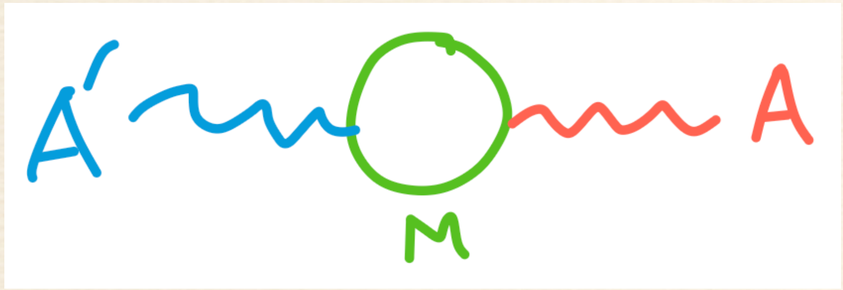
Updated limits from Darkcast

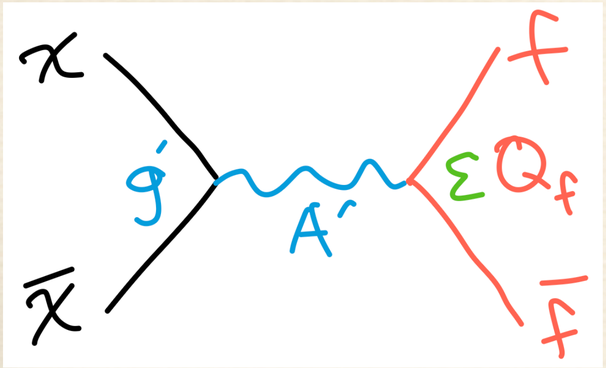
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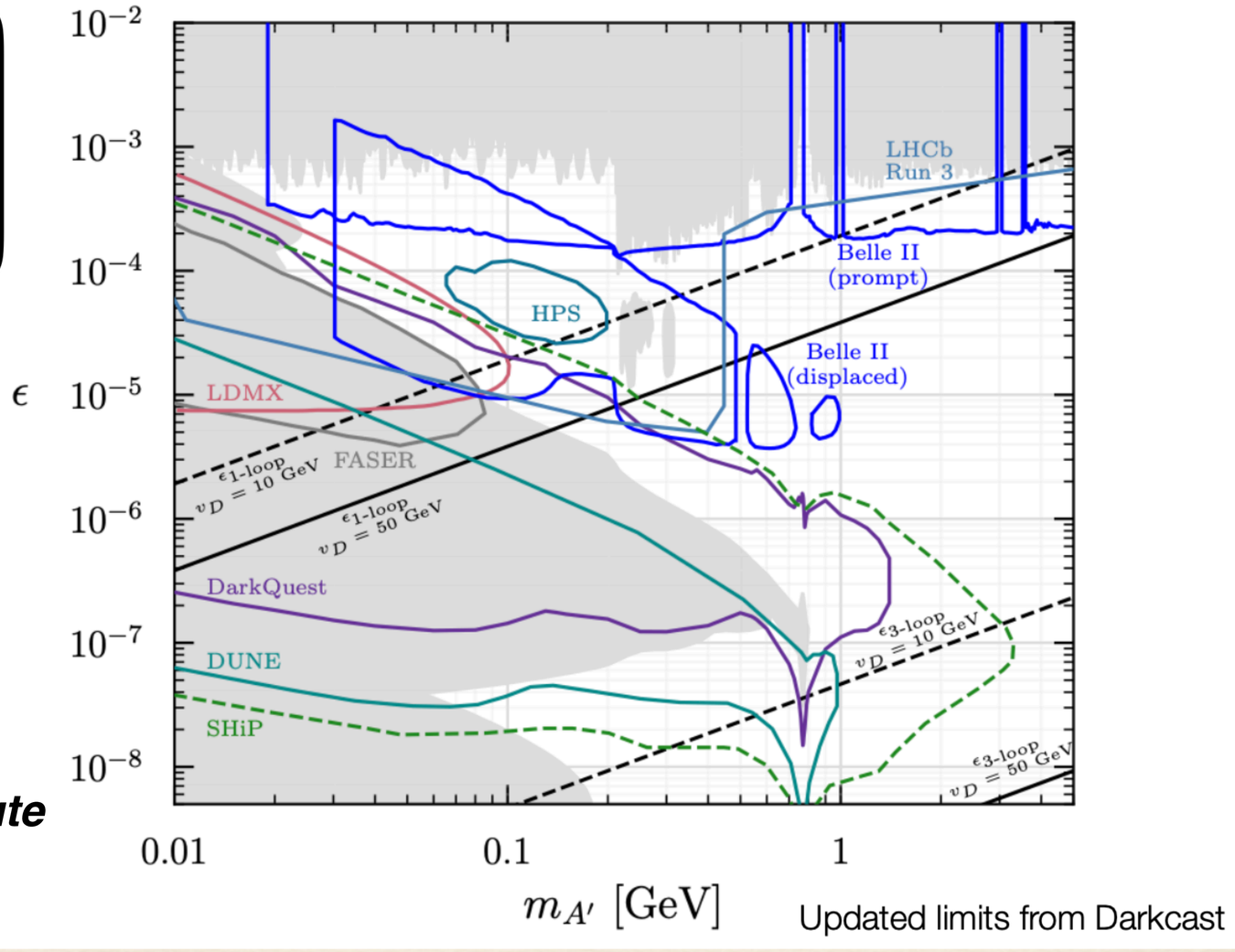
Dark Matter connected to SM particles via a "portal"



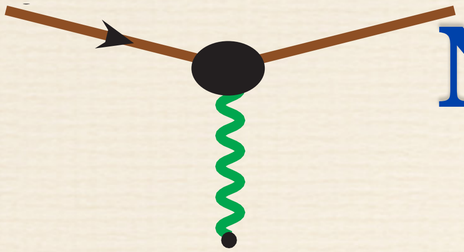




JLab can contribute to cover the full parameter space



Updated limits from Darkcast



New Physics via SMEFT

- **Violation of Lepton Number** — $\frac{1}{\Lambda}\mathcal{L}_5$ 10^{15} GeV; $\frac{1}{\Lambda^5}\mathcal{L}_9$ multi-TeV
  - ★ Neutrinoless Double-Beta Decay, muon and tau appearance at the EIC, MOLLER at JLab
- **Violation of Time Reversal Symmetry** — 100s of TeV
  - ★ Non-zero Electric Dipole Moment of the Electron, T-odd observables at the EIC
- **Violation of Charged Lepton Flavor** — 100s of TeV; $\frac{1}{\Lambda^2}\mathcal{L}_6$
  - ★ muon-to-electron conversion, tau appearance at the EIC
- **Flavor changing neutral currents** — 100s of TeV
  - ★ Rare pion and kaon decays, direct leptoquark production at EIC
- **Flavor conserving neutral currents** — 10s of TeV
  - ★ Precision weak mixing angle measurements at JLab and EIC

Symmetry Violation Search Summary

- **There is a world-wide effort to search for BSM Physics**
- **Neutrino Physics**
  - ***Pursuing a better understanding of neutrinos is an international endeavor in both nuclear and particle physics***
  - ***The search for the Majorana nature of neutrinos is one of the highest priorities***
- **All important approximate symmetries are being scrutinized**
  - ***Challenging experiments have been carried out, indirectly accessing energy scales well beyond the reach of direct searches at the LHC***
  - ***Even more challenging next generation experiments are being designed***
- **Dark Matter**
  - ***Direct detection remains completely elusive and new experiments are being designed to search with greater sensitivity***

Lecture 3 Tomorrow

- Historical Introduction to Parity-Violating Electron Scattering
- Weak Neutral Current Interactions and the Weak Mixing Angle
- First Low Energy Precision Measurement: SLAC E158
- Qweak and PVDIS
- Future: MOLLER, P2 and SoLID
- Summary