Acknowledgements:
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Many thanks to numerous collaborators for ideas, photos, slides, text….

The EIC and the Global Search for New Physics at High Luminosity

SM Tests and BSM Searches
Lecture I

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Introductory Comments

- Student background and preparation varies..
  - Some of you perhaps already have been introduced to nuclear and particle physics at an advanced level but not all of you...
  - You have been getting an excellent set of pedagogical lectures
- As you complete doctoral research and move on, you will learn to cope with imperfect knowledge on things unrelated to your own projects
  - Qualitative understanding (at a minimum) of the breadth of nuclear and particle physics is critical to help select interesting problems to work on
  - I am an experimentalist! I will focus on measurements, but theory is critical!
- I will concentrate on the "big picture" in the BSM search subfield
  - Necessary "general knowledge" when focused on other subfields (e.g. QCD)

Rationale for Lecture Flow

- As I will elaborate, Beyond the Standard Model (BSM) searches in accelerator experiments are typically "parasitic" or "opportunistic".
- In order to identify opportunities in new machines (such as EIC), it is important to know enough about BSM initiatives worldwide so you dont waste time looking at parameter space already ruled out by others.
- Therefore, in Lecture 1 will provide a broad overview of the BSM landscape relevant to potential EIC opportunities. Lecture 2 will focus on reviewing these opportunities. As you will see in lecture 2, most of the ideas are nascent; you all can potentially pick up problems for further study once you get beyond your PhD and start independent research

Outline of Lecture 1

- Overview of the 4 Classes of Measurements (my classification)
- Broad Context for the Experiments Pursued and the Tools
- A Tour of the Most Important BSM Search Strategies
- Connect to EIC right at the end and set up Lecture 2
- 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

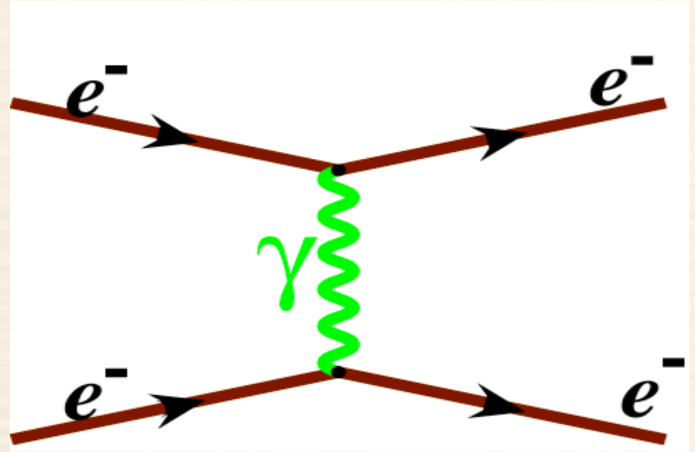
Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W⁻	80.39	−1
W⁺ (W bosons)	80.39	+1
Z^0 Z boson	91.188	0

Strong (color) spin =1

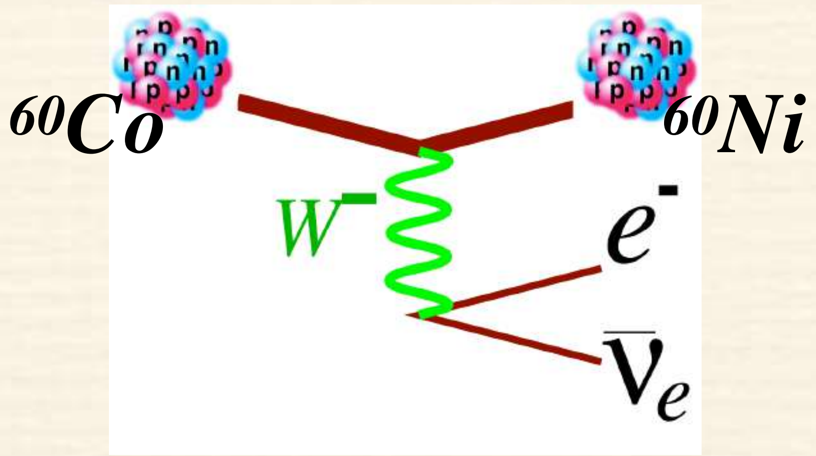
Name	Mass GeV/c^2	Electric charge
g gluon	0	0

H^0 spin 0

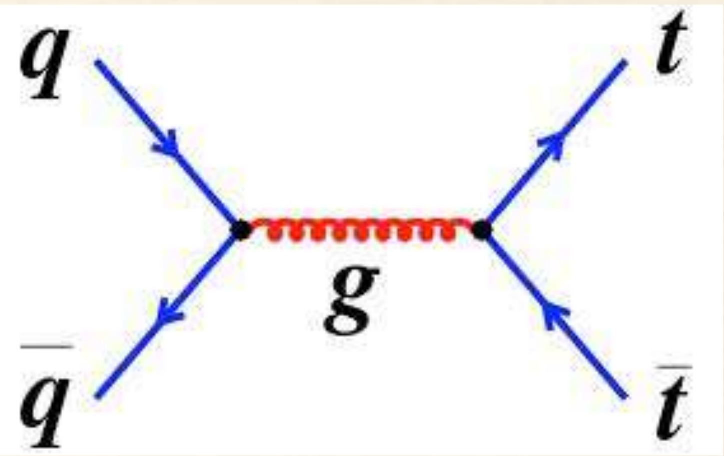
electromagnetic (EM)



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

Example Particle Physics Questions

Example Nuclear Physics Questions

Artificial Separation

Glashow, Weinberg and Salam: $SU(2)_L$ X $U(1)_Y$

Electroweak Interactions

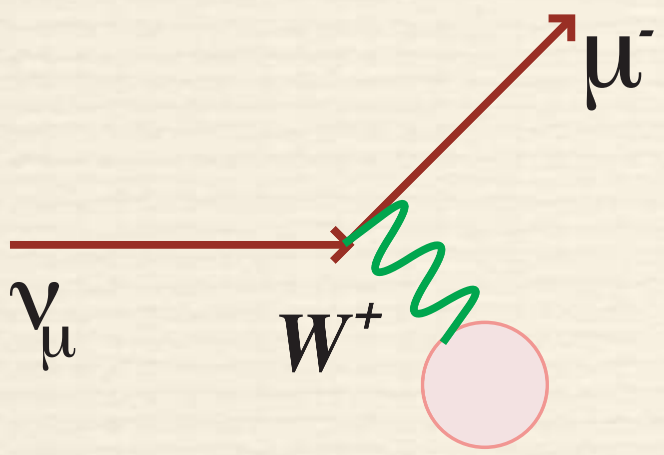
At the EIC, we plan to gain insights on QCD; we probe the nuclei via the electroweak interaction

One free parameter: weak mixing angle θ_W

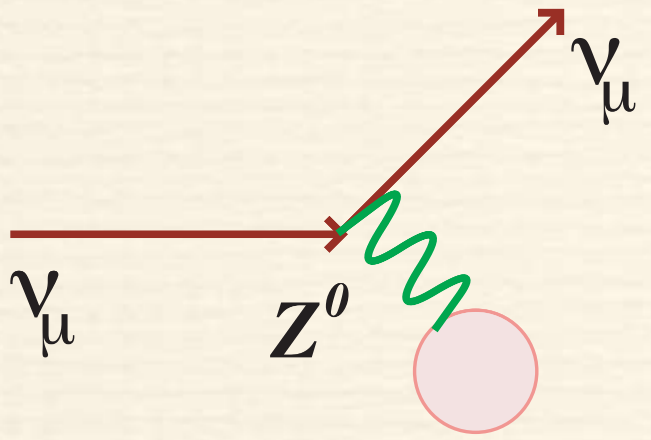
$$\tan\theta_W = \frac{g'}{g}$$

$$e = g\sin\theta_W$$

$$A_\mu = B^0_\mu \cos\theta_W + W^0_\mu \sin\theta_W$$
$$Z_\mu = W^0_\mu \cos\theta_W - B^0_\mu \sin\theta_W\,.$$



Charged Current



Neutral Current

Higgs Mechanism + Renormalizability

$$\sin^2\theta^0_W = \left(\frac{e^0}{g^0}\right)^2 = 1 - \left(\frac{M^0_W}{M^0_Z}\right)^2$$

- **Why is the weak boson scale 100 GeV?**
- **Why are there 3 generations of particles?**
- **How did matter come to dominate over anti-matter?**
- **Were there as yet unobserved new forces in the early universe?**
- **Is there a unifying framework to describe all forces?**
- **Why are neutrinos so light?**
- **Why is the top so heavy?**
- **...**

Any new machine could potentially provide novel insights on fundamental questions

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

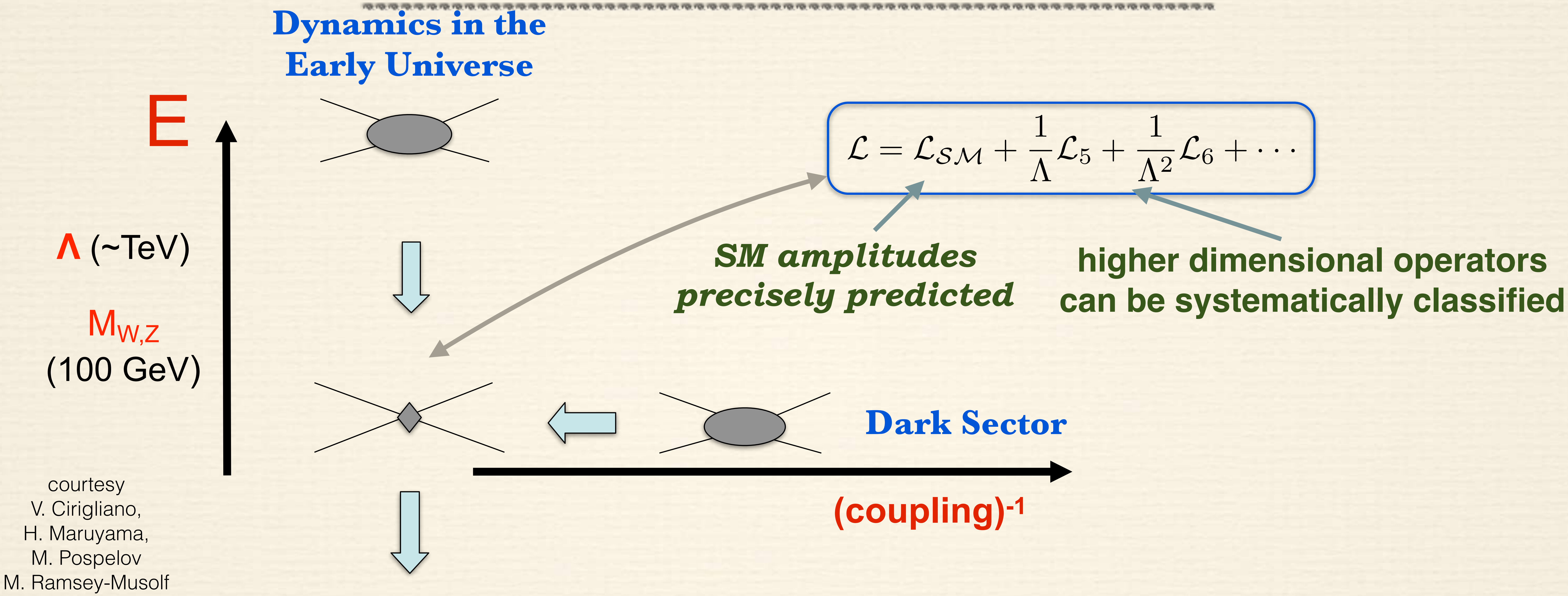
A comprehensive search for clues requires, in addition:

The Intensity/Precision Frontier

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

Observables at scales at or lower than the scale of EW Symmetry Breaking

Intensity Frontier Strategy



Discoveries and Insights about Big Questions

Measurements push several experimental parameters to the extreme such as intensity, luminosity, volume, radio-purity, resolution, precision, accuracy....

In most cases, observables exploit a symmetry principle

V. Cirigliano

General BSM EFT Framework

Describe new physics originating at $\Lambda >> v_{ew}$ through local operators of increasing mass dimension

[$\Lambda \leftrightarrow M_{BSM}$] $C_i\ [g_{\rm BSM},\ M_a/M_b]$

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{SM} + \frac{C^{(5)}}{\Lambda} O^{(5)} + \sum_i \frac{C_i^{(6)}}{\Lambda^2} O_i^{(6)} + \ldots$$

Weinberg 1979, Wilczek-Zee 1979, Buchmuller-Wyler 1986,

Grzadkowski-Iskrzynksi- Misiak-Rosiek 2010, Alonso, Jenkins, Manohar, Trott 2013 …

“Standard Model EFT” (SMEFT):

- ★ Build operators out of SM fields
- ★ Impose Lorentz + SM gauge symmetry
- ★ Organize operators according to mass dimension

power counting in E/Λ, M_W/Λ.

Two Classes of Operators

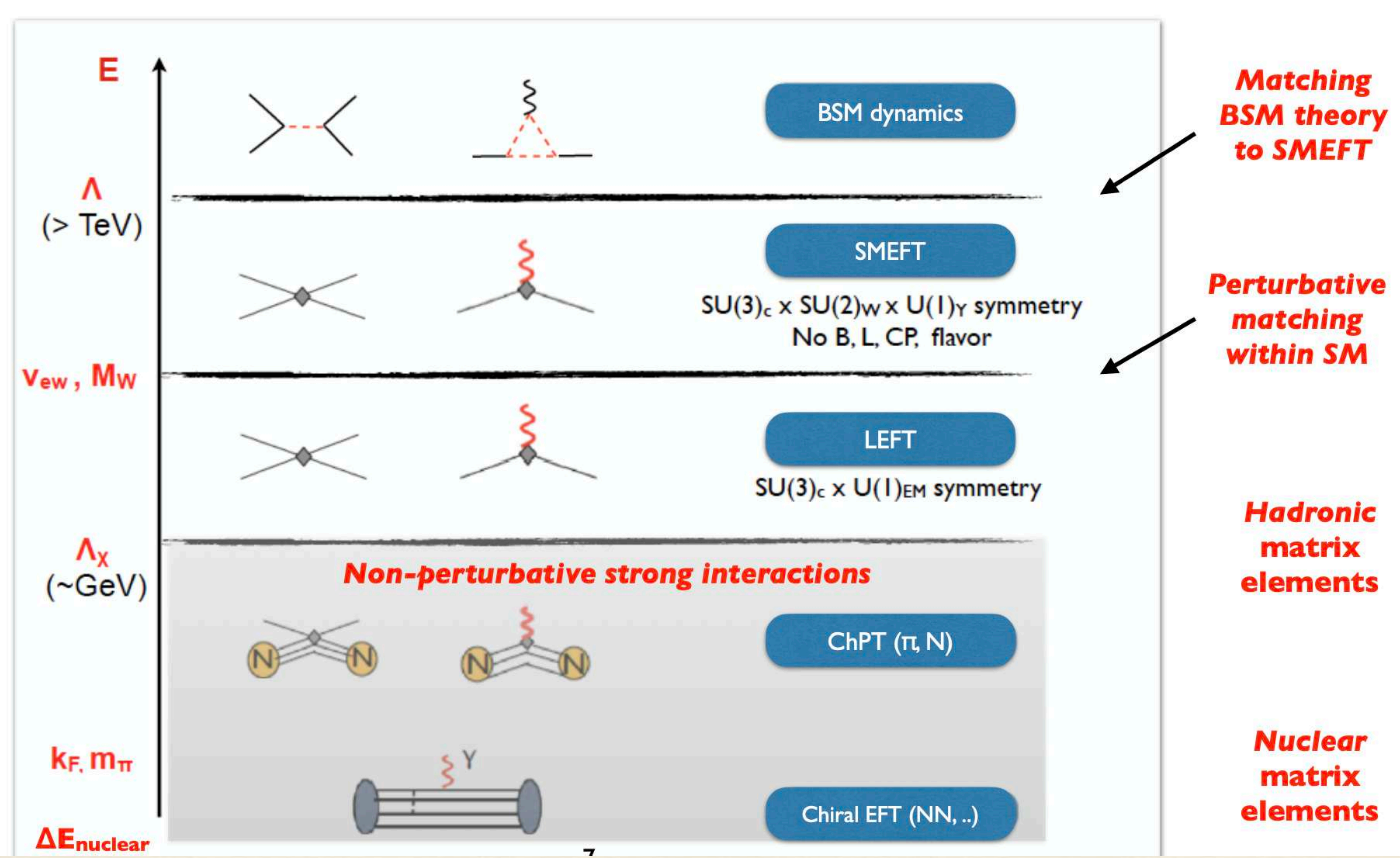
Operators that violate approximate or exact symmetries of the SM: mediate rare or forbidden processes (proton decay, 0νββ, EDMs, μ→e, quark flavor violation, …)

Operators that give corrections to SM “allowed” processes: probe them with precision measurements (muon g-2, weak decays, electron scattering ...)

Connecting Scales

V. Cirigliano

To connect new physics to low-energy, use a tower of EFTs in which SMEFT is the SM-BSM link



Intense beams, ultra-high precision, exotic nuclei, table-top experiments, rare processes....

Tools to Probe BSM Physics

Intensity Frontier Experimental Facilities/Initiatives/Programs

- ***Electron Beams:*** *charged current couplings, weak mixing angle, dark photons*
  - ➡ *Jefferson Lab, Mainz MESA*
- ***Muons, Kaons, Pions:*** *Lifetimes, Precision Bus, Flavor Universality, muon g-2, EDMs*
  - ➡ *BNL, PSI, TRIUMF, FNAL, J-PARC*
- ***Neutrino Beams:*** *Oscillations, PMNS matrix, CP-violation*
  - ➡ *Fermilab, KEK, CERN*
- ***Neutrons:*** *Lifetime, Asymmetries, EDM*
  - ➡ *LANSCE, NIST, SNS, other international labs..*
- ***Underground Detectors:*** *Direct Dark Dark Matter, Double-Beta Decay*
  - ➡ *SURF, SNOLAB, LNGS, Jinping, Kamioka…*
- ***Nuclei:*** *Precision Weak Decays, Atomic Parity Violation, EDMs*
  - ➡ *FRIB, ANL, TAMU, Tabletop…*

The EIC can contribute and complement several of these topics

Neutrinos are Special: First Hint of BSM

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

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

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

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

$$Q = T_3 + Y/2$$

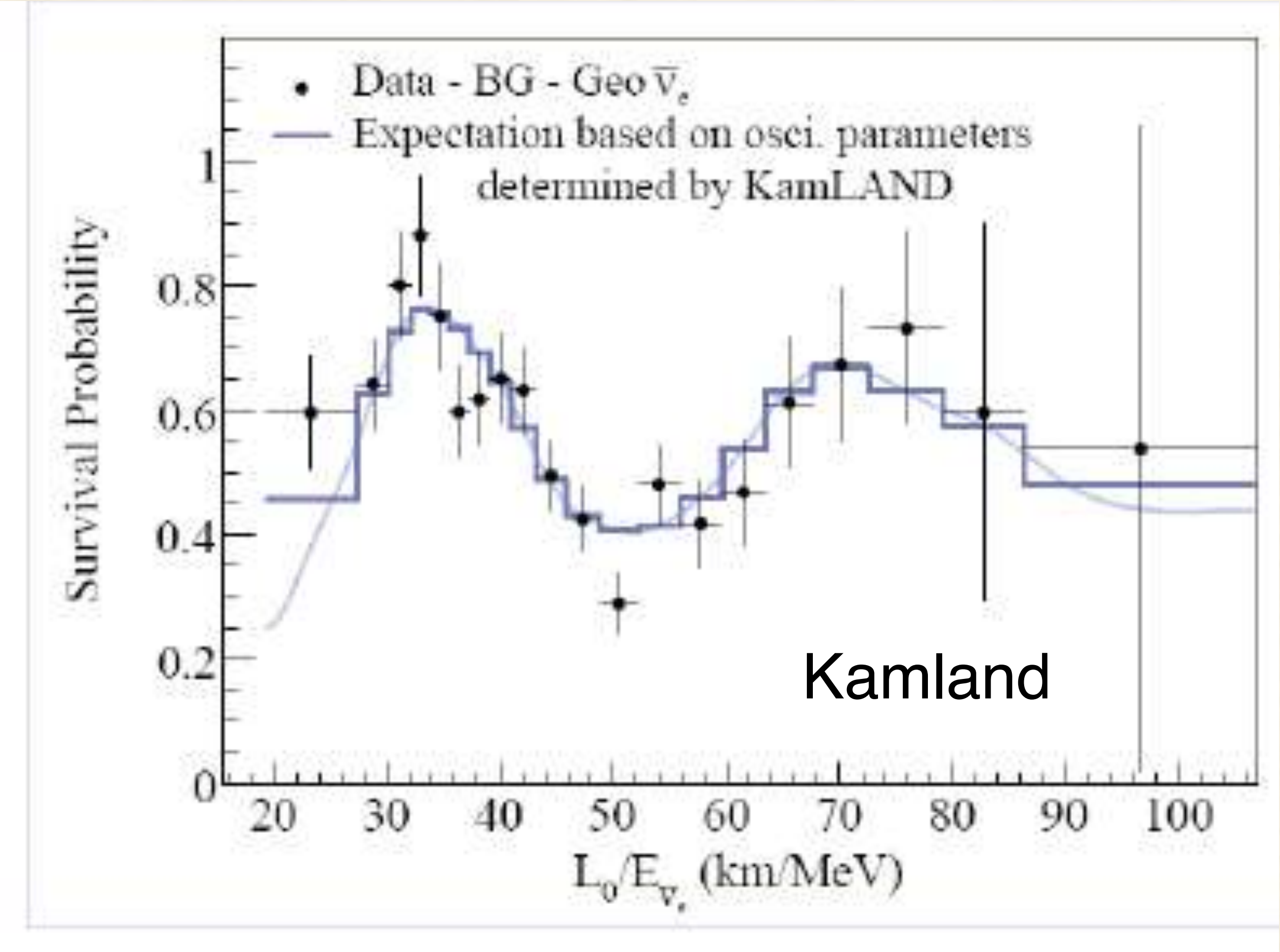
$Y_{\nu_L} = -1 \quad \boxed{Y_{\nu_R} = 0}$

Right-handed neutrino has no gauge interactions

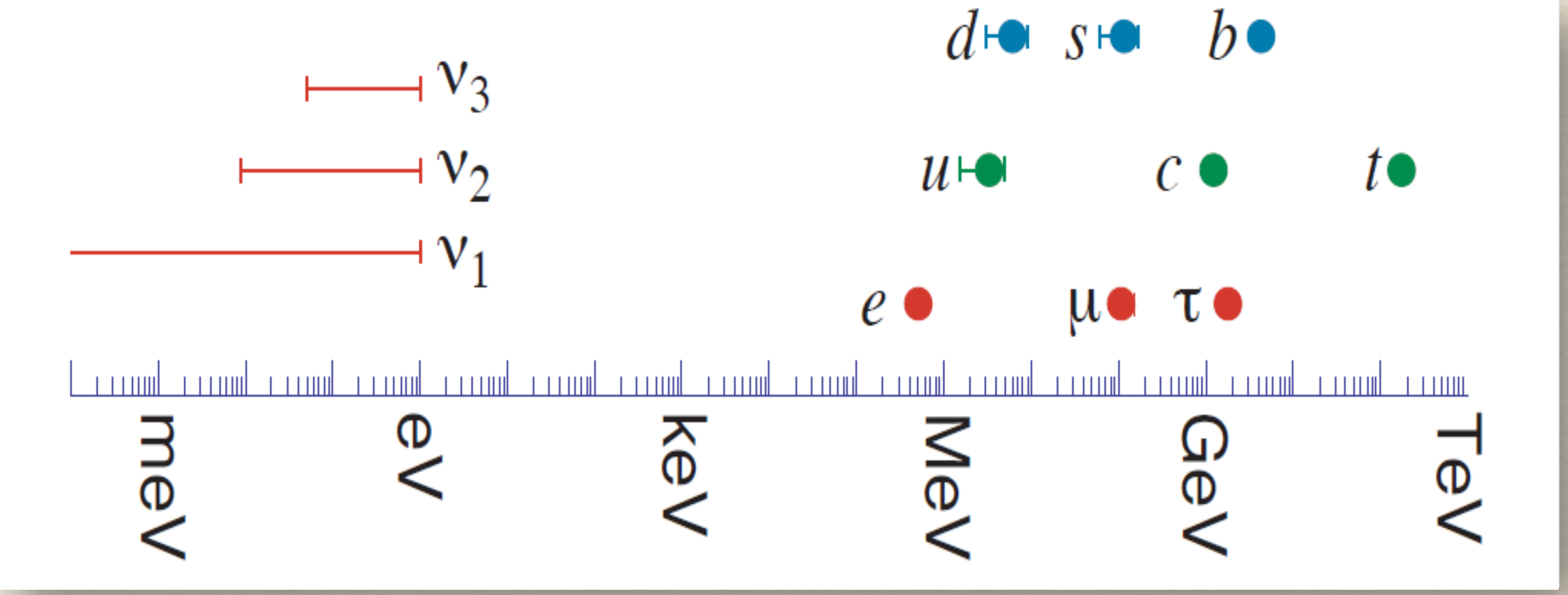
A Model of Leptons (Steven Weinberg, 1967)

Original formulation of the Standard Model: *ν* massless and no right-handed state

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



- **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 $\tau\nu_\tau$)

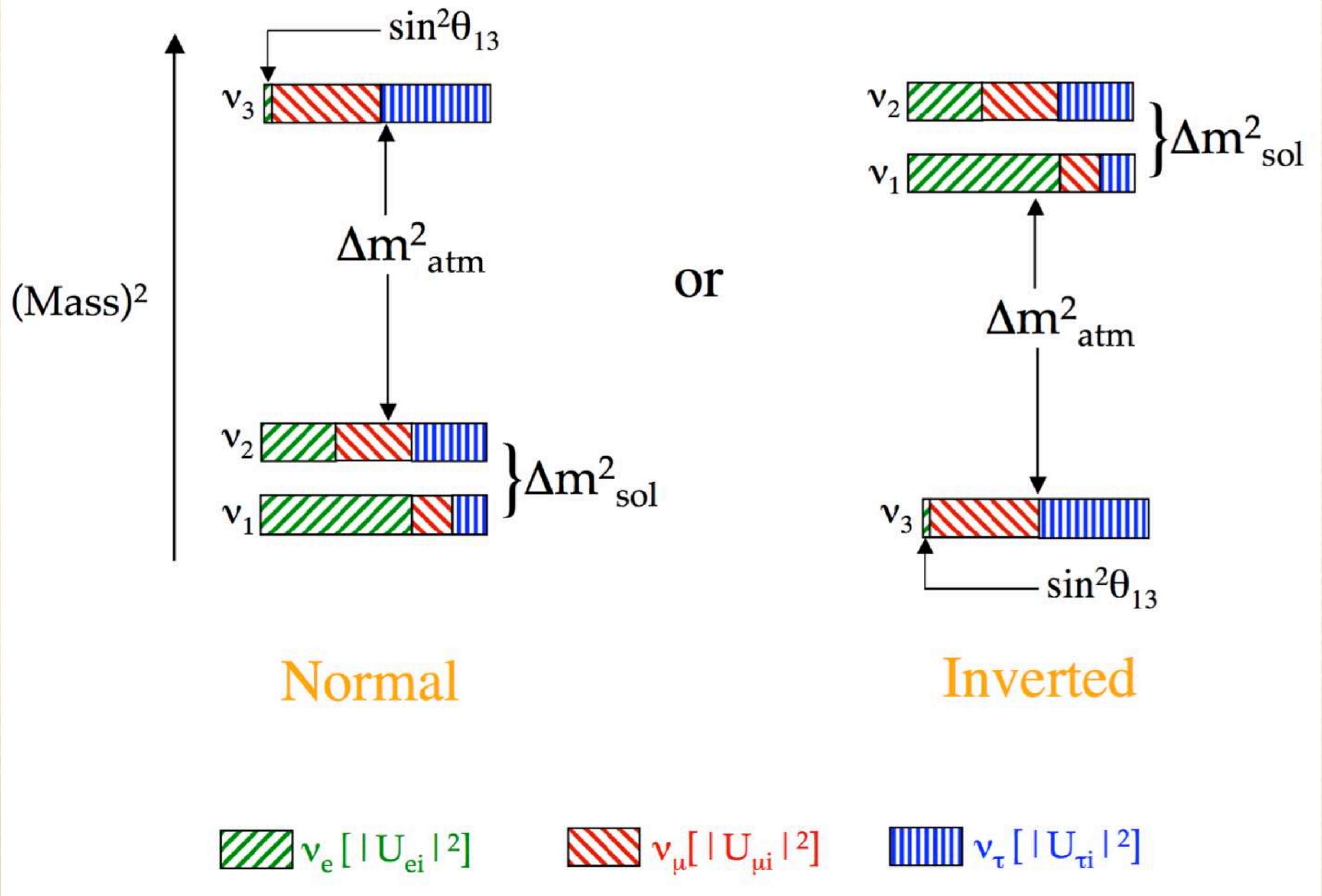
are superpositions of the mass eigenstates:

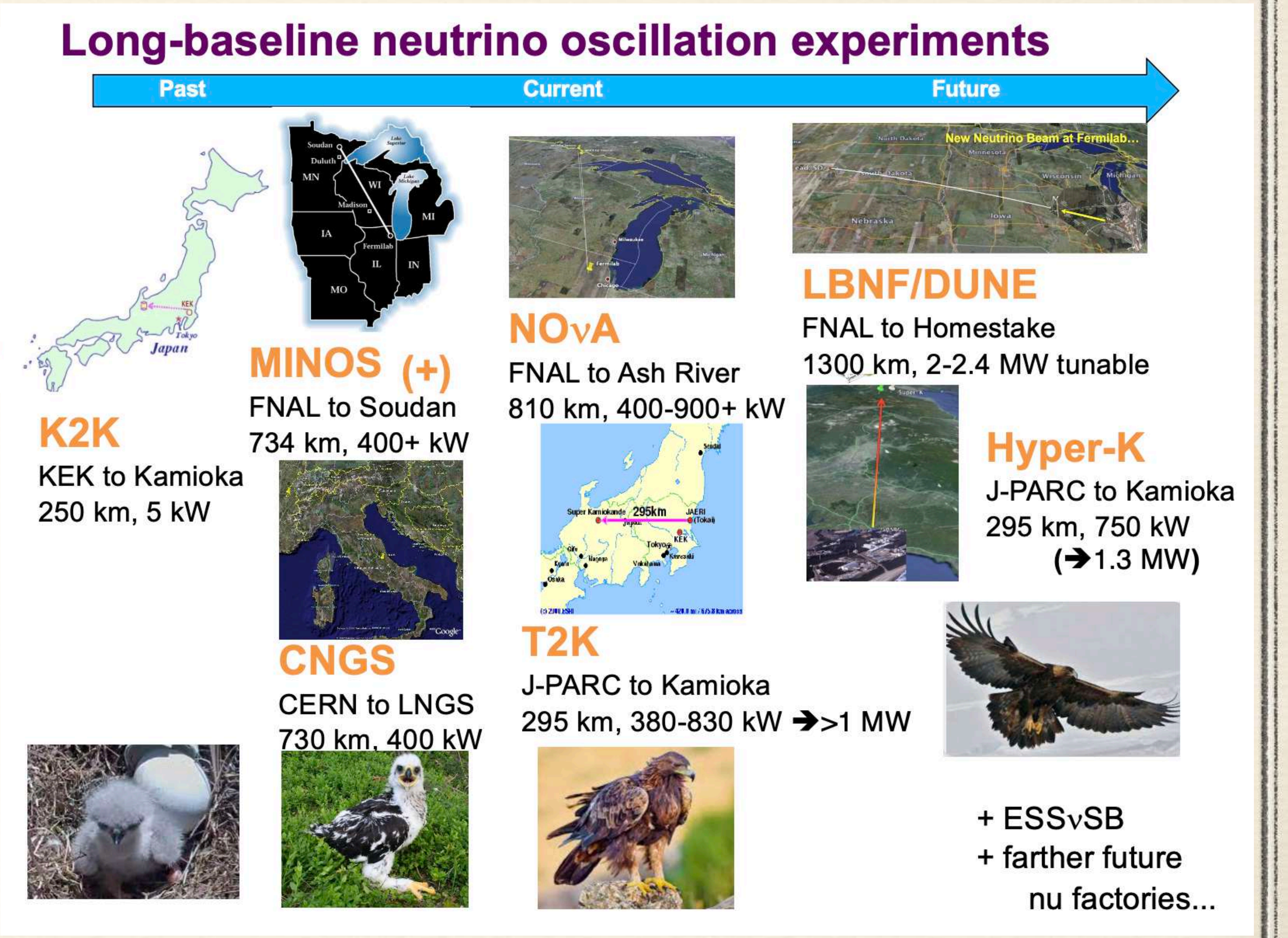
$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i} |\nu_i\rangle \ .$$

Neutrino of flavor $\alpha = e, \mu$, or τ

Unitary Leptonic Mixing Matrix

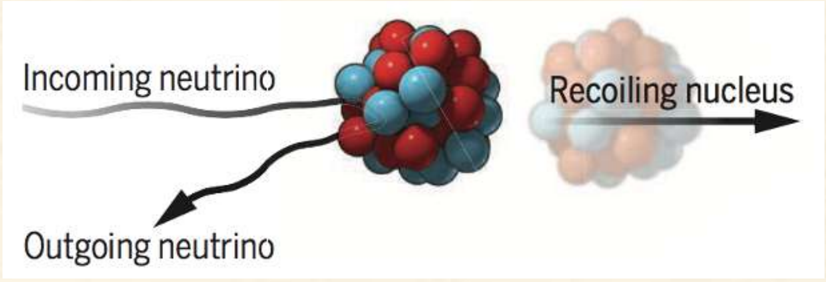
Neutrino of definite mass m_i

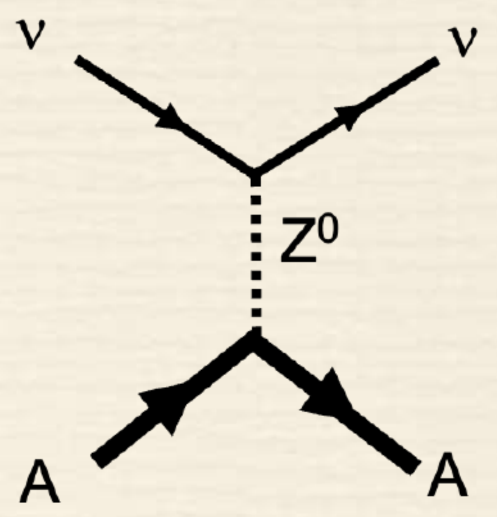




Other Neutrino Initiatives

- **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…

Conservation Law Detour

An Exact Symmetry implies a Conservation Law

Baryon Number

$p \rightarrow e^+ \pi^0$ Proton Decay

B +1 0 0 Forbidden if B is conserved

$\pi^+ \rightarrow \mu^+ \nu_\mu \Rightarrow \nu_\mu N \rightarrow \mu^- X$ but not $\mu^+ X$

L 0 -1 +1 +1 0 +1 0 -1 0

- *Only B-L strictly conserved in the Standard Model*
- *B+L is violated due to anomalies*
- *No fundamental reason to expect B and L to be conserved (assuming only 4 forces in Nature)*

Introduce Lepton Number:

$$L_{e^-} = L_{\nu_e} = -L_{e^+} = -L_{\bar{\nu}_e} = +1$$

This is encoded into the Standard Model Feynman Rules

What if CHIRALITY is the key rather Lepton Number?

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

$\mu^+ \leftarrow \pi^+ \rightarrow \nu_L \Rightarrow \nu_L \rightarrow \mu^-$ $\nu_R \rightarrow \mu^+$

Lepton Number Conservation not required

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

$$\nu_R \Leftrightarrow \bar{\nu}_R$$

$L \quad +1 \qquad -1$

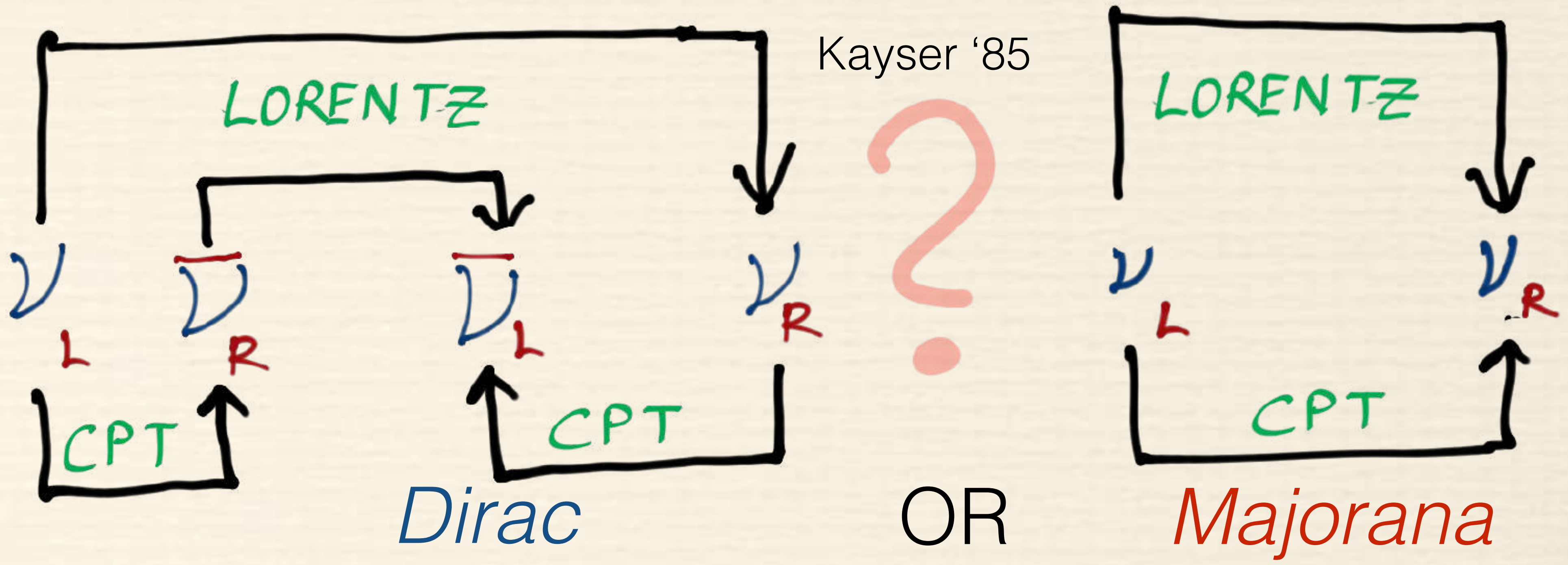
Majorana Neutrino

L is violated

No experimental observation precludes this possibility

The question conceptually is:

Kayser '85



The most pragmatic approach to discover the Majorana nature of neutrinos is to search for **Lepton Number Violation (LNV)**

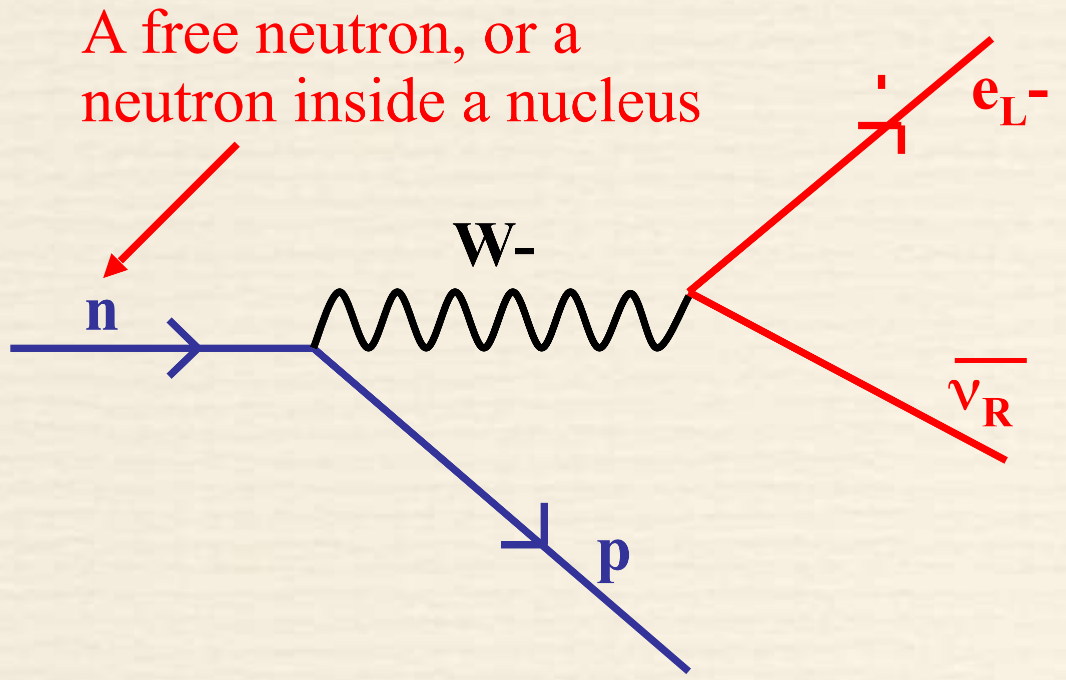
Practically: discover **Neutrinoless Double-Beta Decay** **(0νββ)**

*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

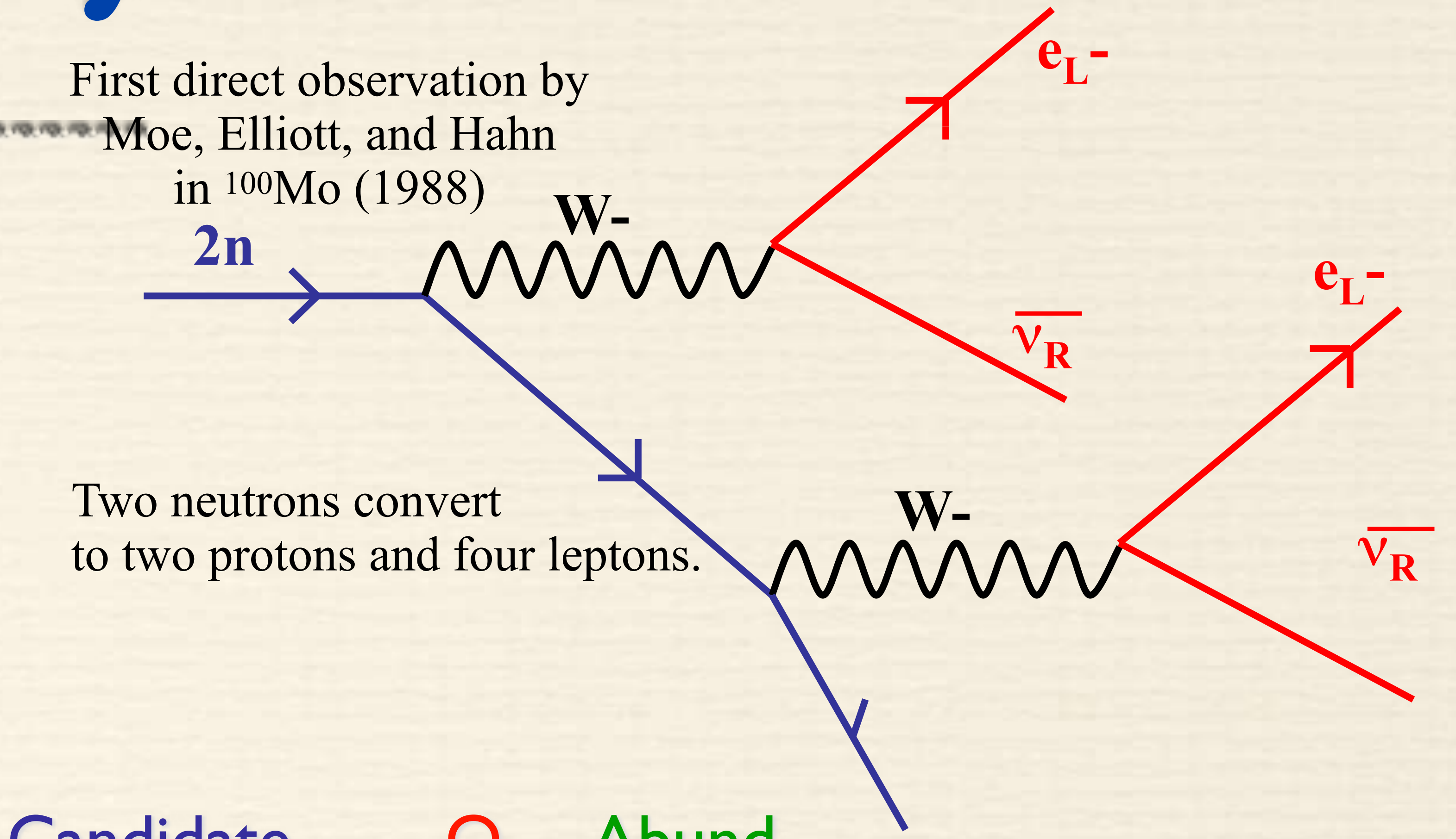
Lepton Number Conserving Standard Model Process

Double-Beta Decay



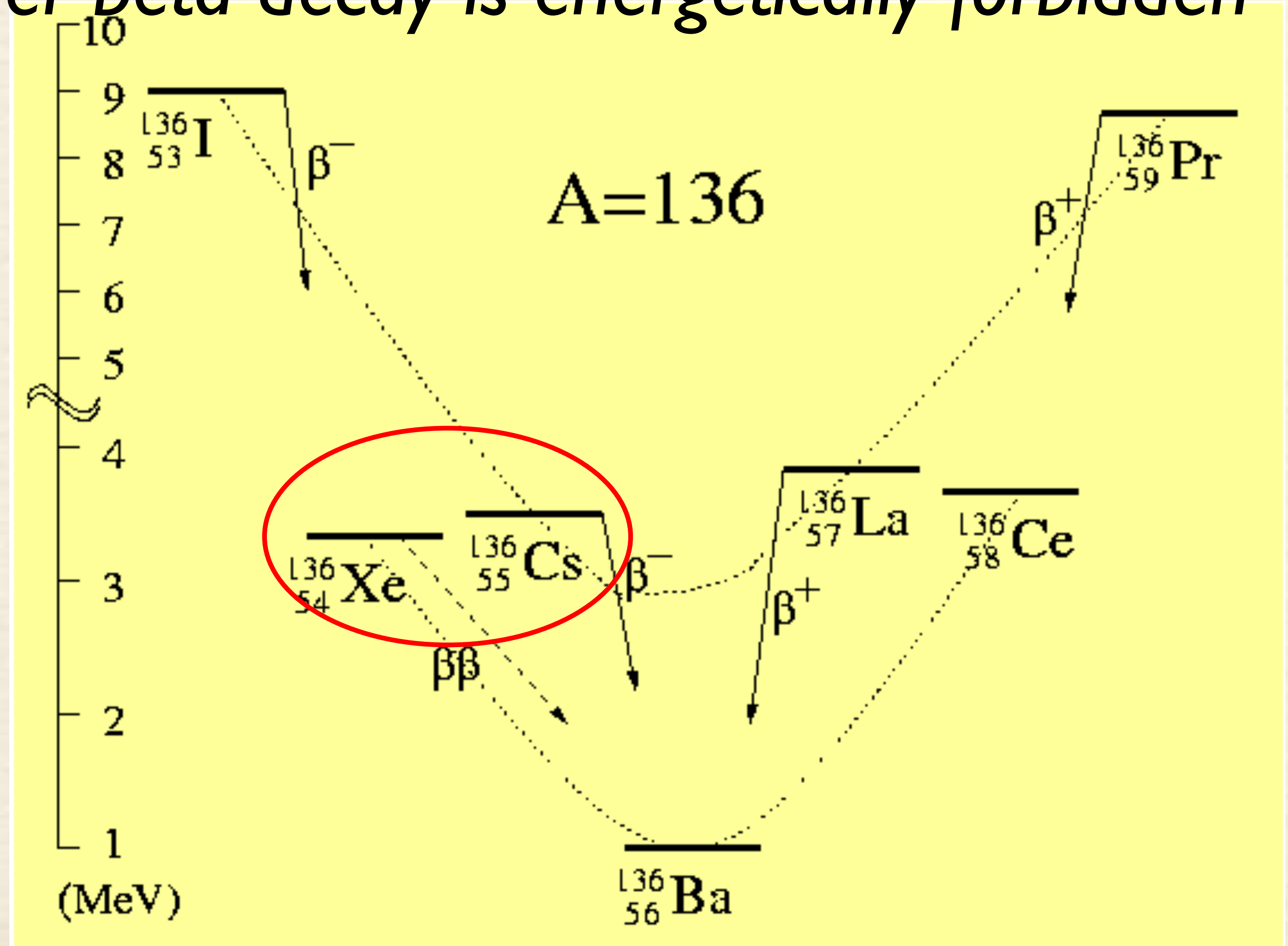
Nuclear Double-Beta Decay with the emission of two betas and neutrinos

Suggested by Maria Goeppert-Mayer in 1935!



Double-beta decay:

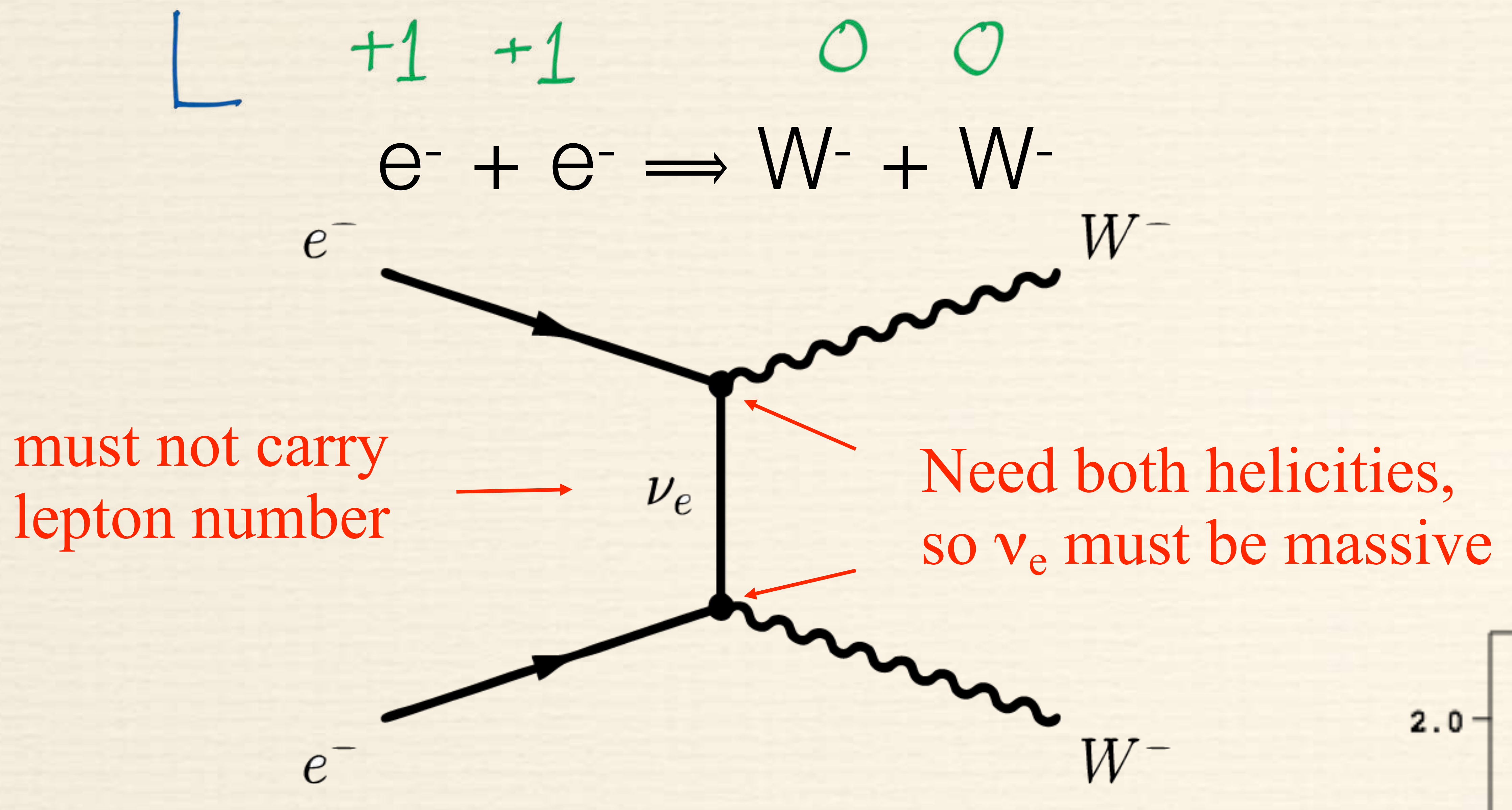
a second-order process only detectable if first order beta decay is energetically forbidden



Candidate nuclei with Q>2 MeV

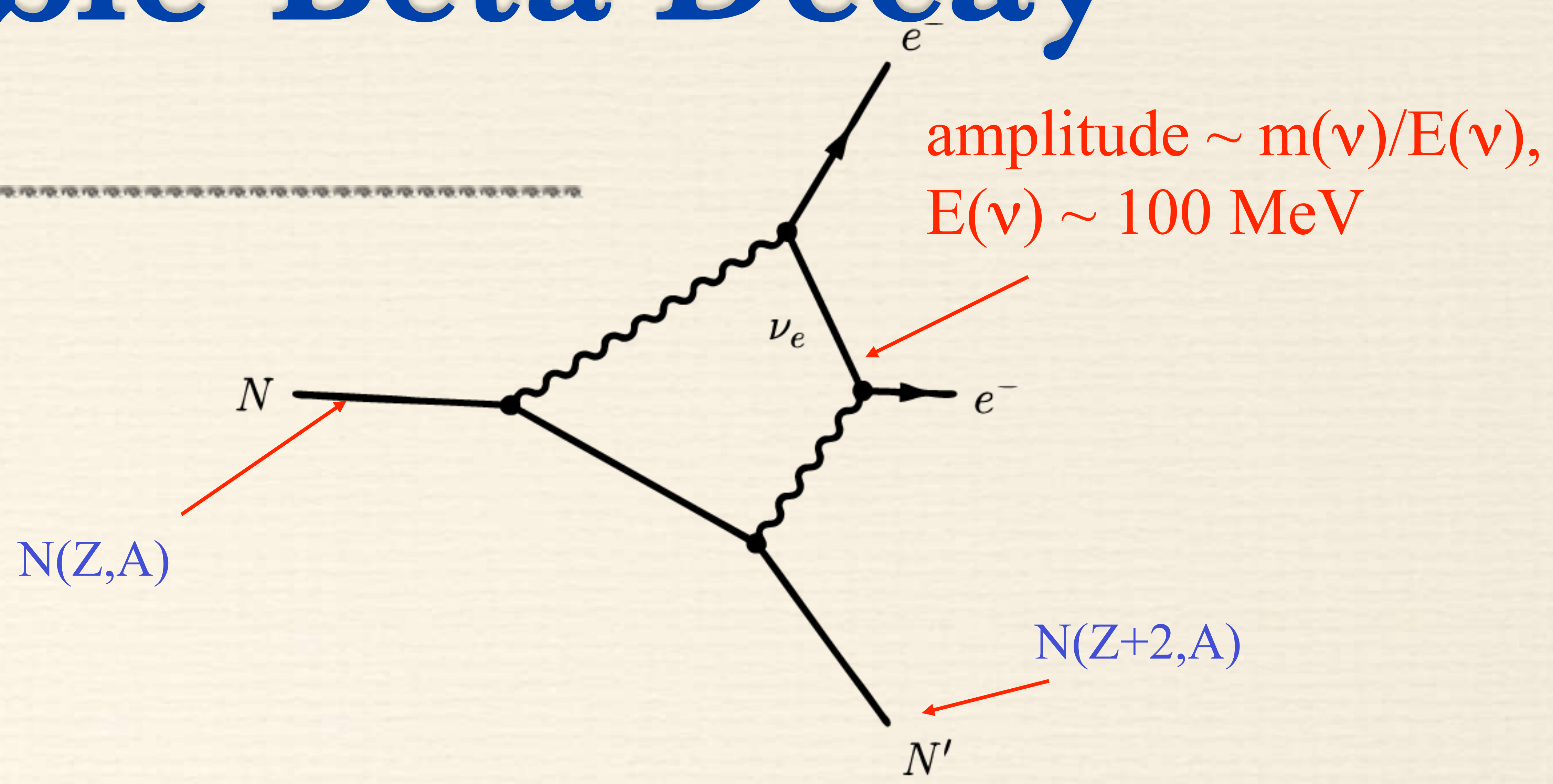
Candidate	Q (MeV)	Abund. (%)
^{48}Ca→^{48}Ti	4.271	0.187
^{76}Ge→^{76}Se	2.040	7.8
^{82}Se→^{82}Kr	2.995	9.2
^{96}Zr→^{96}Mo	3.350	2.8
^{100}Mo→^{100}Ru	3.034	9.6
^{110}Pd→^{110}Cd	2.013	11.8
^{116}Cd→^{116}Sn	2.802	7.5
^{124}Sn→^{124}Te	2.228	5.64
^{130}Te→^{130}Xe	2.533	34.5
^{136}Xe→^{136}Ba	2.479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

Neutrinoless Double-Beta Decay

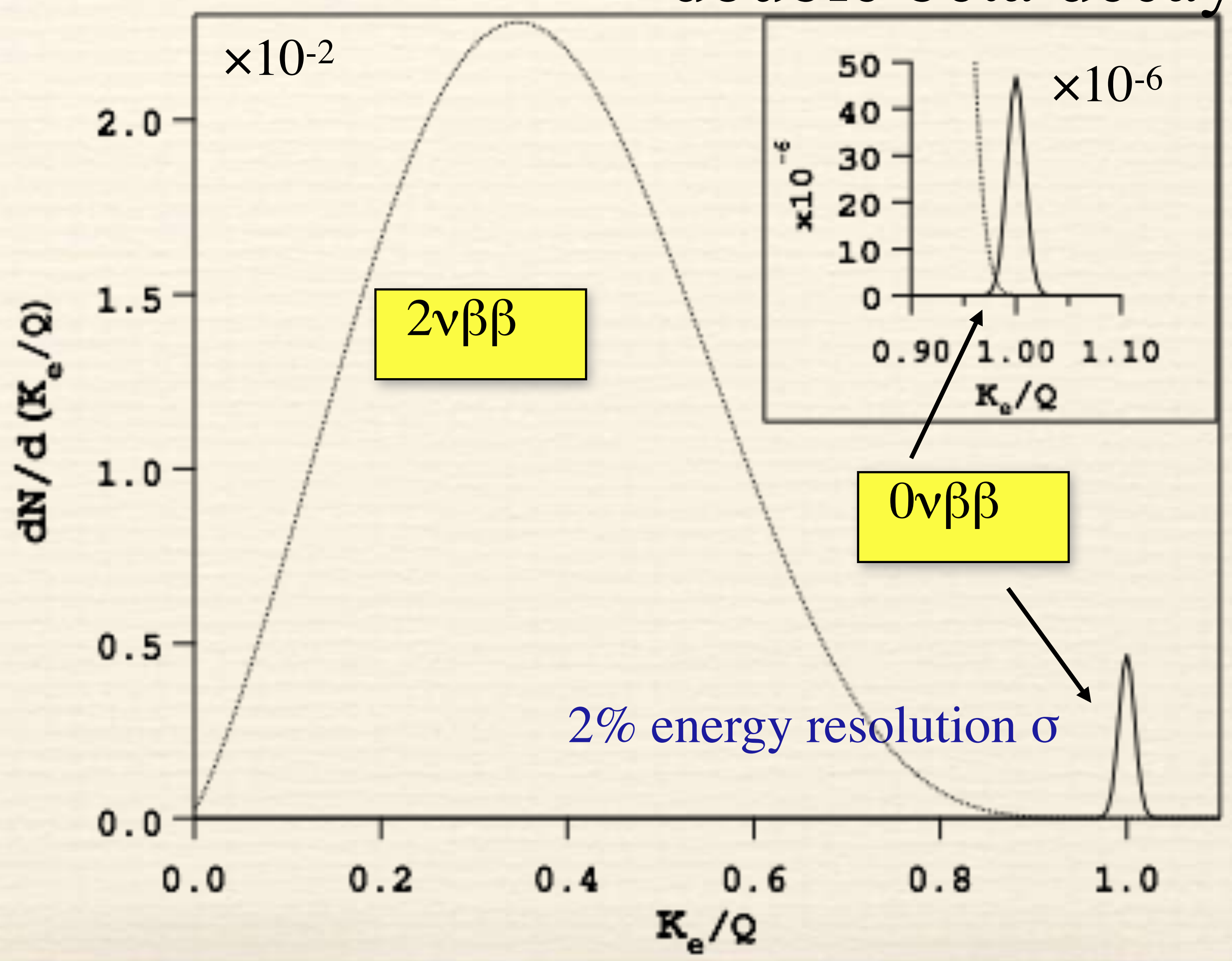


Lepton number changes by two units: ΔL=2

For light neutrinos, this cross-section is unobservably small



"Neutrino mass mechanism" for double beta decay



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

Experiments: Very Long Half-Lives!

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

$$\frac{1}{T^{0\nu}_{\frac{1}{2}}} = G^{2\nu}(Q,Z)|M^{2\nu}|^2$$

Atomic mass affected by nuclear pairing term: even A nuclei occupy 2 parabolas, even-even below odd-odd

$$\frac{1}{G^{2\nu}} \simeq 10^{20} \text{ years}$$

Choose nuclei where single beta decay forbidden

but double-beta decay is possible

A potential 0$\nu\beta\beta$ half-life will be even longer!

Transition Probability

$$\Gamma^{0\nu} = G(Q,Z)|M(A,Z)\eta|^2$$

$\alpha\frac{m}{Q^2}$ $(Q \sim m_e)$ 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

For light neutrino exchange

All 3 neutrinos will contribute: $\eta \sim m \rightarrow \langle m_{\beta\beta} \rangle = \sum_i U_{ie}^2 m_i$ (PMNS Matrix → U)

$m_{\beta\beta} \sim 1$ eV $\Longrightarrow T_{1/2} \sim 10^{24}$ years

$m_{\beta\beta} \sim 0.1$ eV $\Longrightarrow T_{1/2} \sim 10^{26}$ years

$m_{\beta\beta} \sim 0.01$ eV $\Longrightarrow T_{1/2} \sim 10^{28}$ years

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

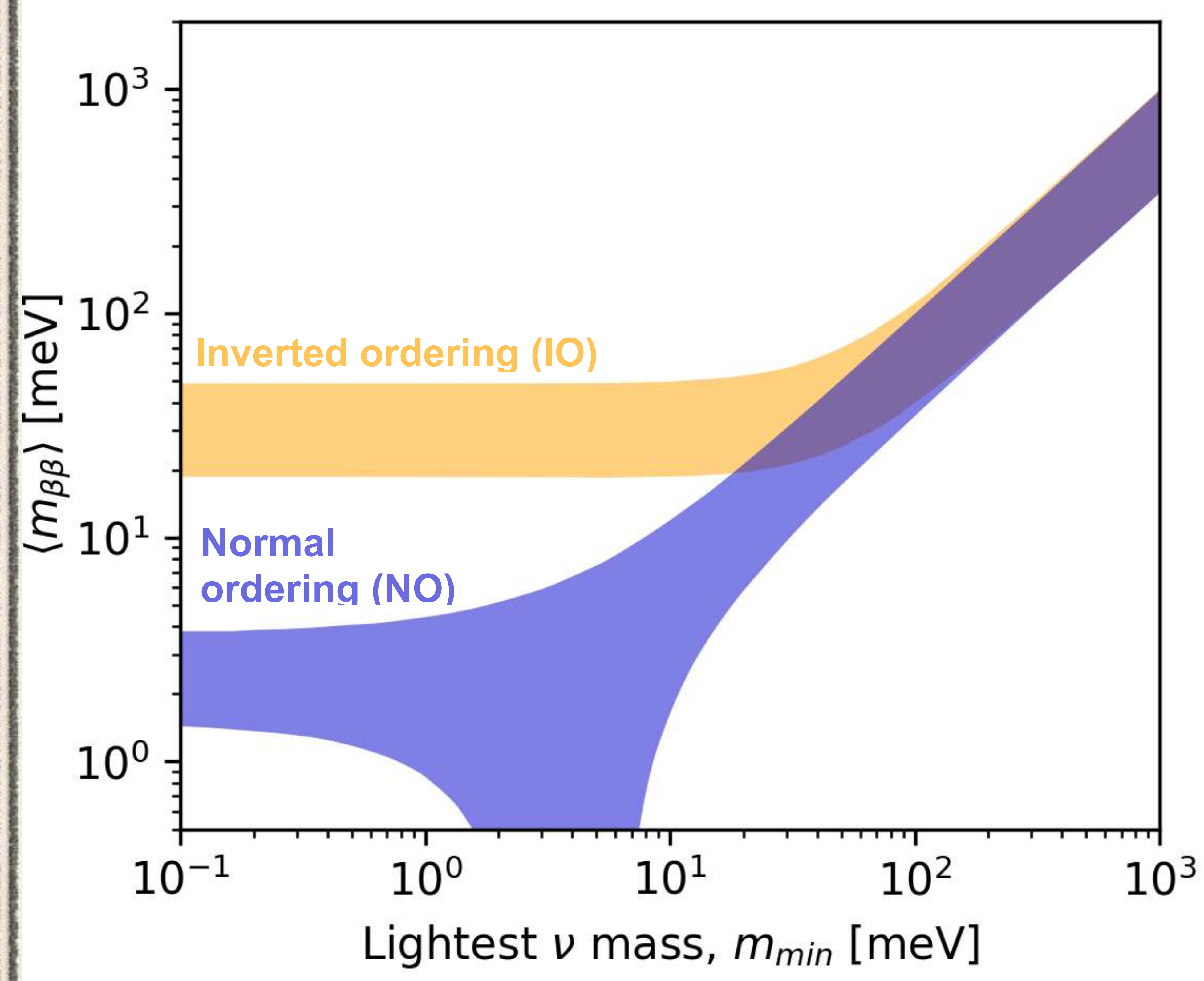
$\frac{1}{\Lambda}\mathcal{L}_5$ — **10^{15} GeV**

$\frac{1}{\Lambda^5}\mathcal{L}_9$ — **multi-TeV**

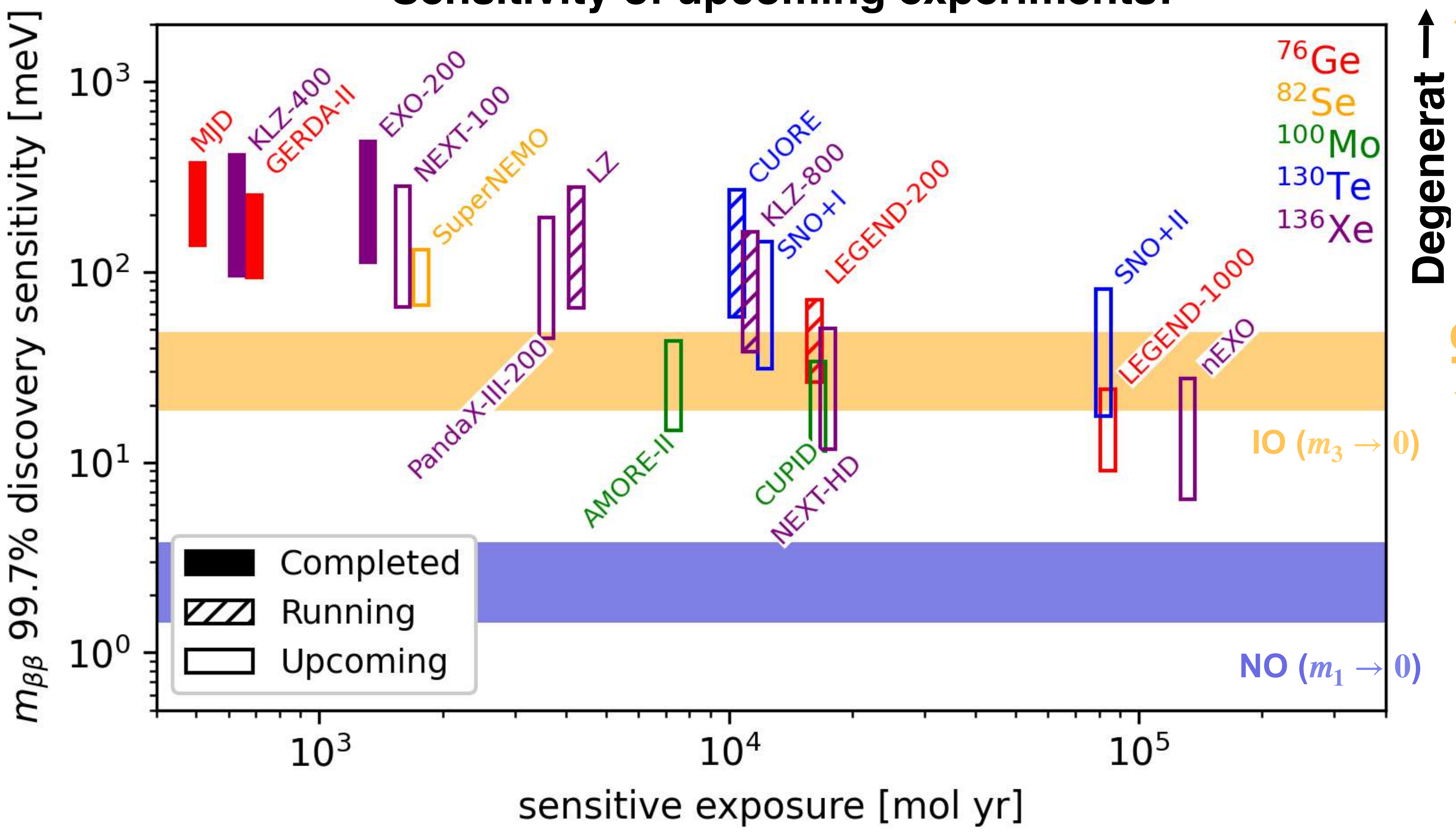
Slide courtesy: Dave Moore

Summary of Past and Present Projects

Parameter space vs. mass of lightest ν:



Sensitivity of upcoming experiments:



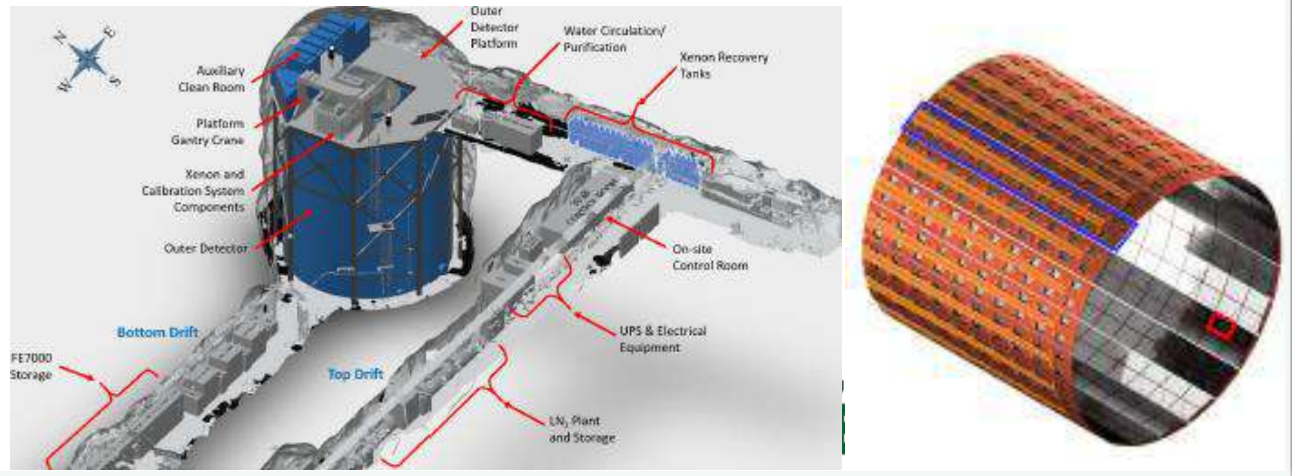
Unfortunately, US nuclear physics funding uncertainties make it unlikely that all upcoming experiments will be done in the next decade

Slide courtesy: Vincenzo Cirigliano

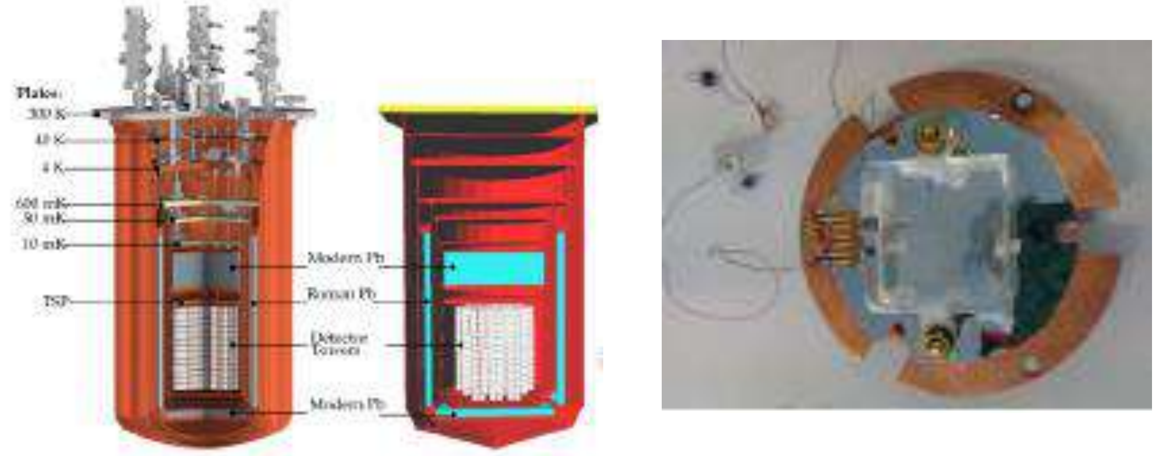
Ton Scale Experimental Proposals

- 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

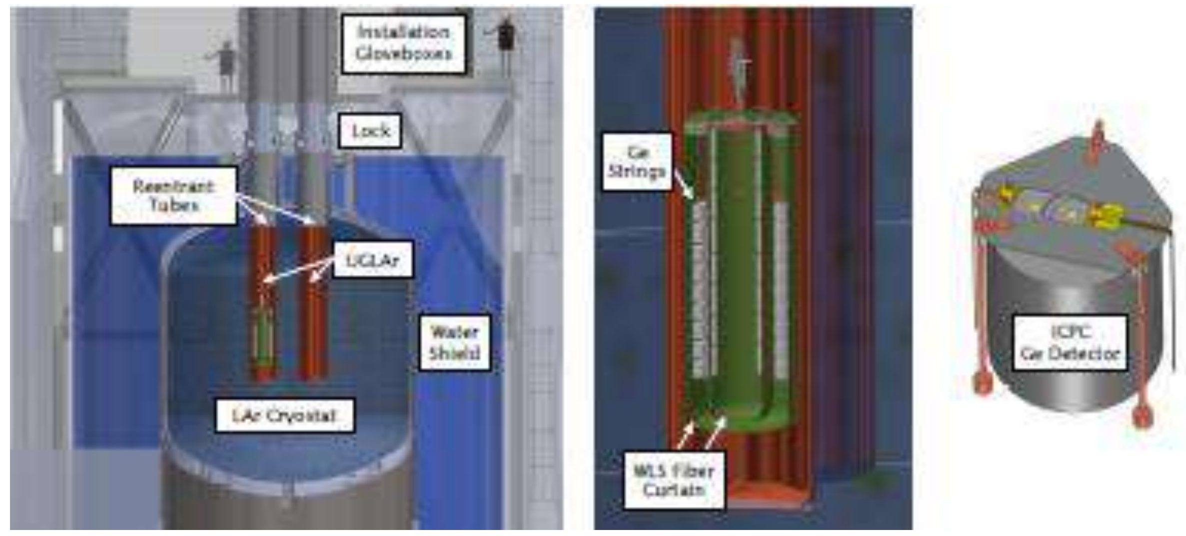
nEXO: Liquid Xe Time Projection Chamber

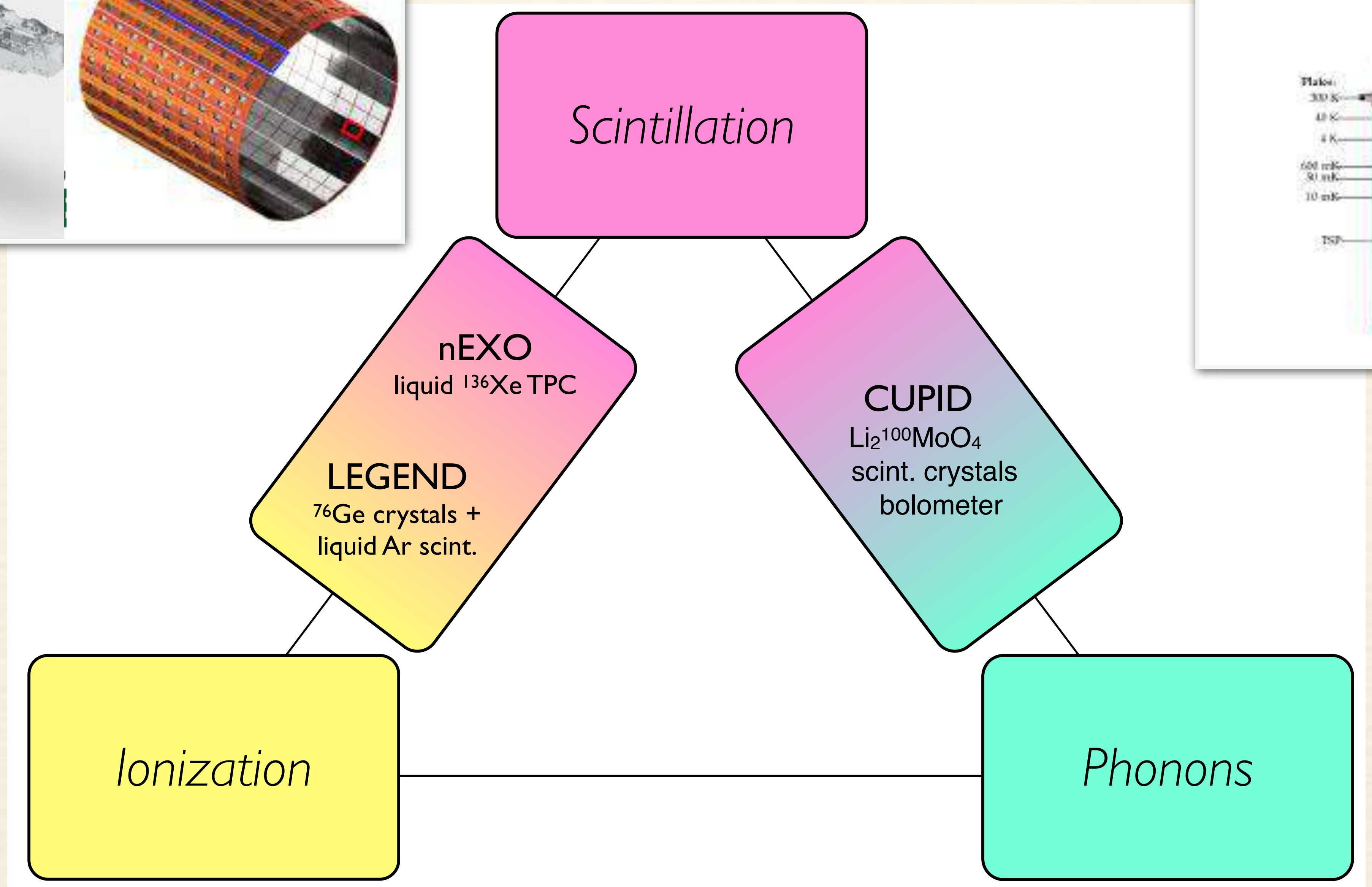


CUPID: Scintillating Crystal Bolometer



LEGEND: High Purity Ge Crystals

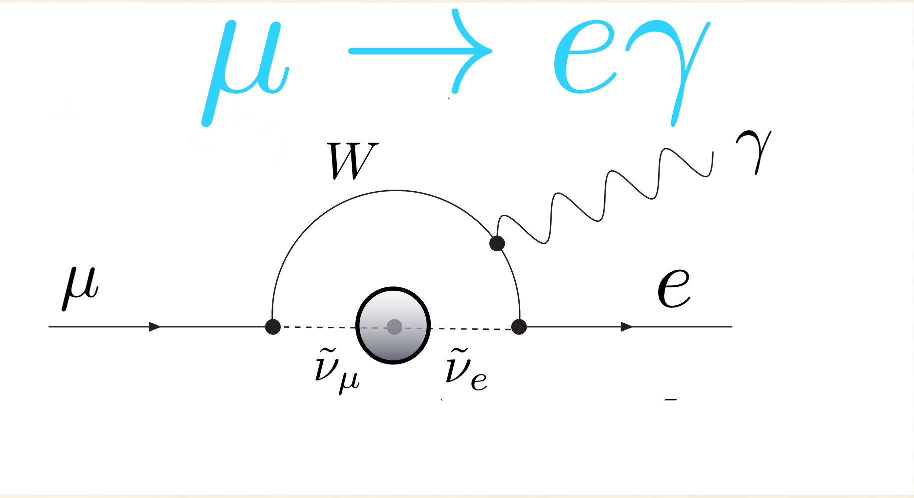




Time scale to complete all 3 experiments is highly uncertain

Charged Lepton Flavor Violation (CLFV)

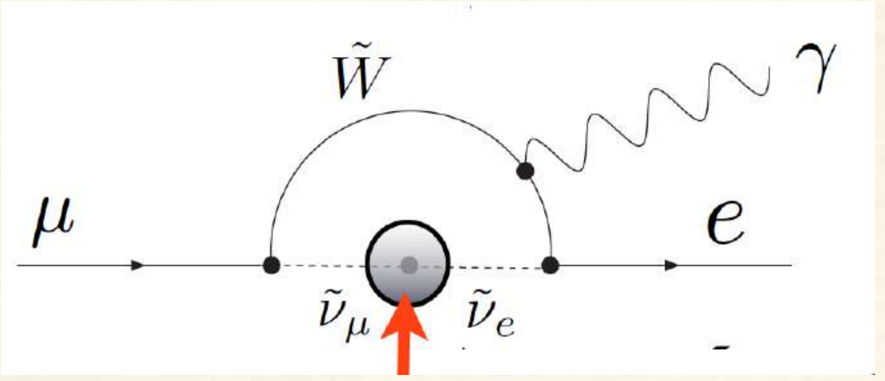
Is lepton flavor conservation exact? No! **Neutrino Oscillations!**



SM BR: 10^{-54}!

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

Slepton mixing in SUSY



$$\mathrm{BR}(\mu \to e\gamma) \sim 10^{-15}$$

$$\mathrm{BR}(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_{i=2,3} U^*_{\mu i} U_{ei} \frac{\Delta m^2_{1i}}{M^2_W}\right|^2 < 10^{-54}$$

tiny standard model branching fraction

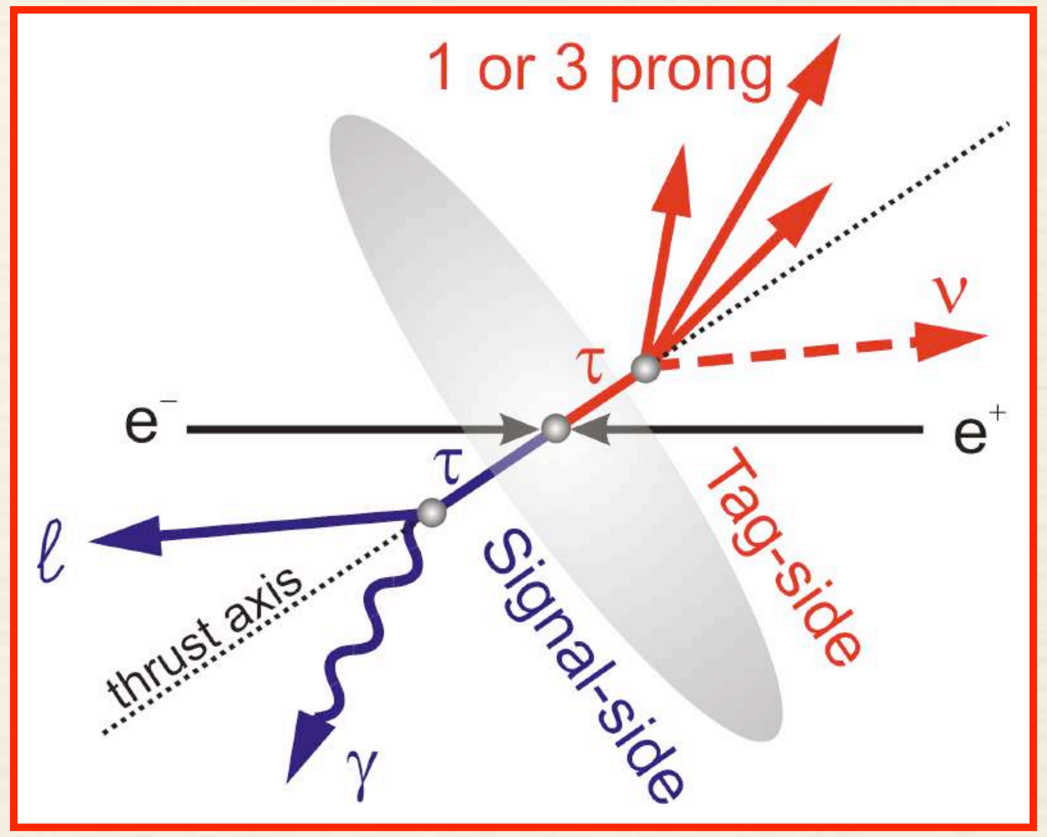
Major experimental searches are ongoing; mass reach depends on flux and sensitivity of technique

$$\mathcal{L}_{\mathrm{eff}} = \mathcal{L}_{\mathrm{SM}} + \frac{C_{\mu e}}{\Lambda^2}\bar{e}_L\sigma^{\alpha\beta}\mu_R\Phi F_{\alpha\beta}$$

μ or τ ⟶ eγ, 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

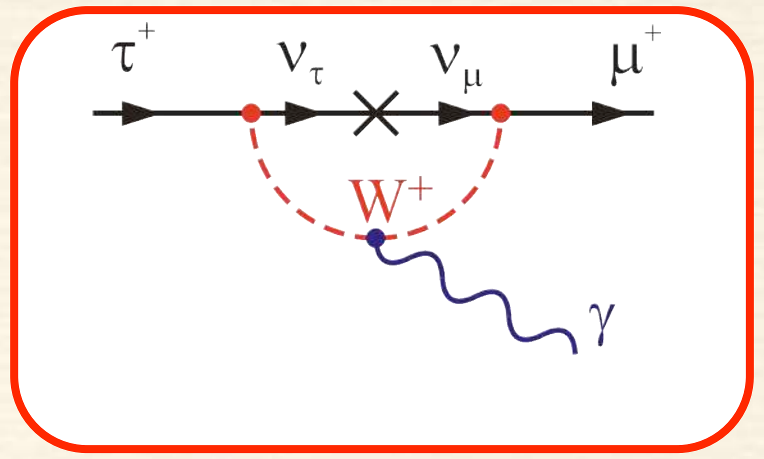
- $\mu^+ \rightarrow e^+\gamma$ (PSI)
  - MEG II, finished first run
  - BR $(\mu^+ \rightarrow e^+\gamma) < 3.1 \times 10^{-13}$ @ 90% CL
  - expect $\approx 4.2 \times 10^{-14}$ after a few years

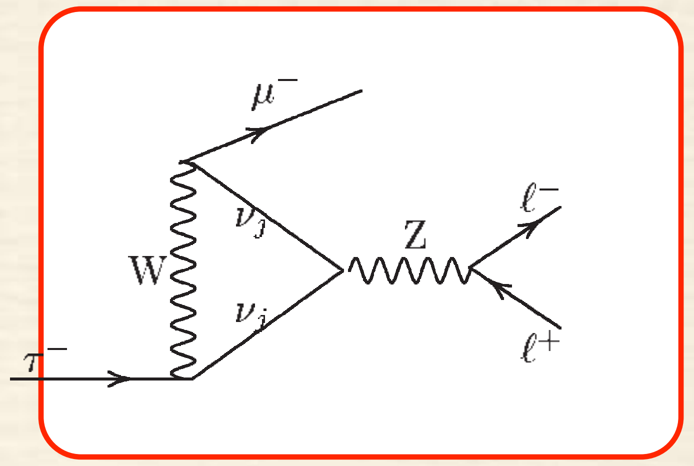
- $\mu^+ \rightarrow 3e$ (PSI)
  - Mu3e experiment (*Hesketh et al., 2204.00001*)
  - SES of 2×10^{-15}

- $\mu^- N \rightarrow e^- N$ (FNAL, J-PARC)
  - Mu2e, COMET (both $\approx (6-8) \times 10^{-17}$ @ 90% CL around end of decade

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

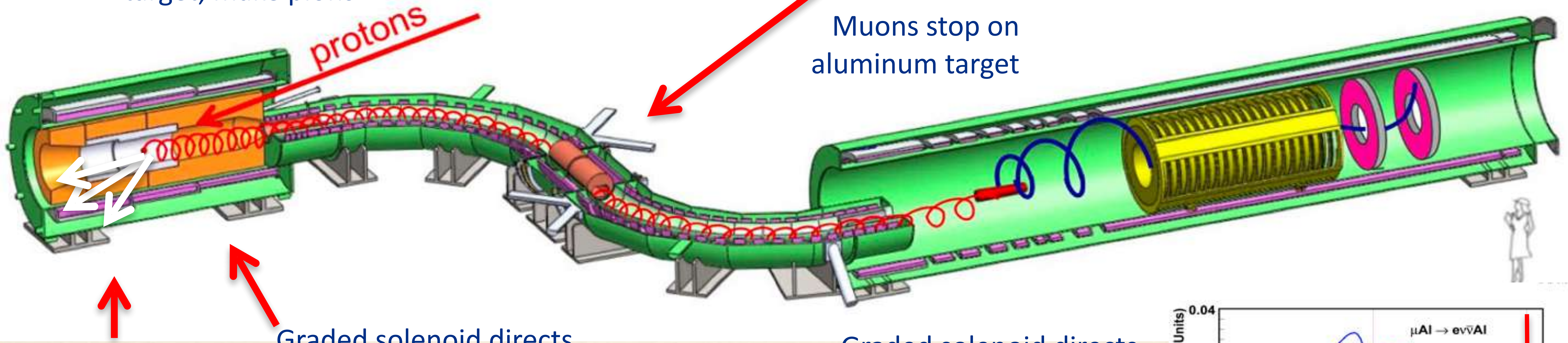
Mu2e at FNAL Overview

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

Curved transport solenoid provides sign and momentum selection and avoids line of sight from production target to detector

Protons enter here, hit target, make pions

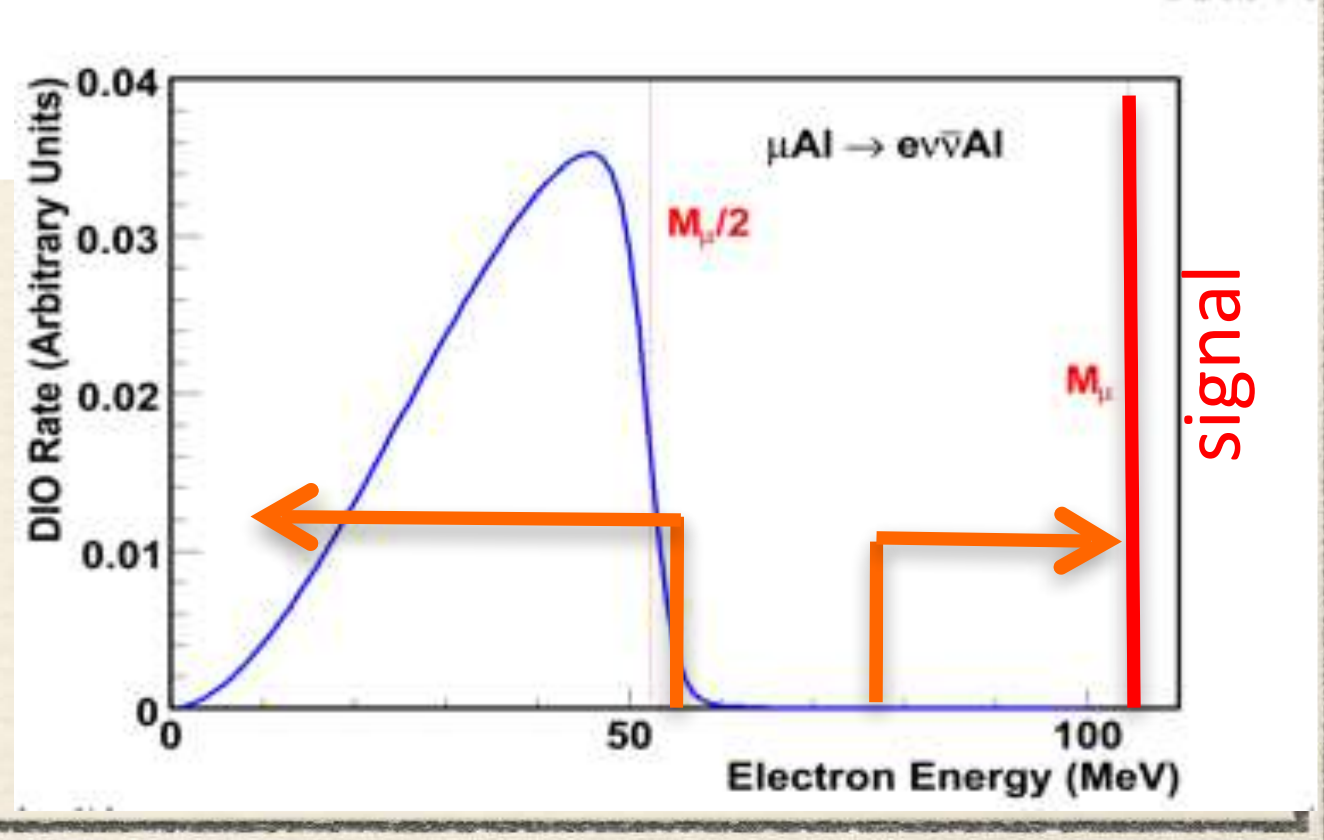
Muons stop on aluminum target



High momentum Backgrounds exit out the front

Graded solenoid directs low momentum particles into transport solenoid

Graded solenoid directs electrons to the detector

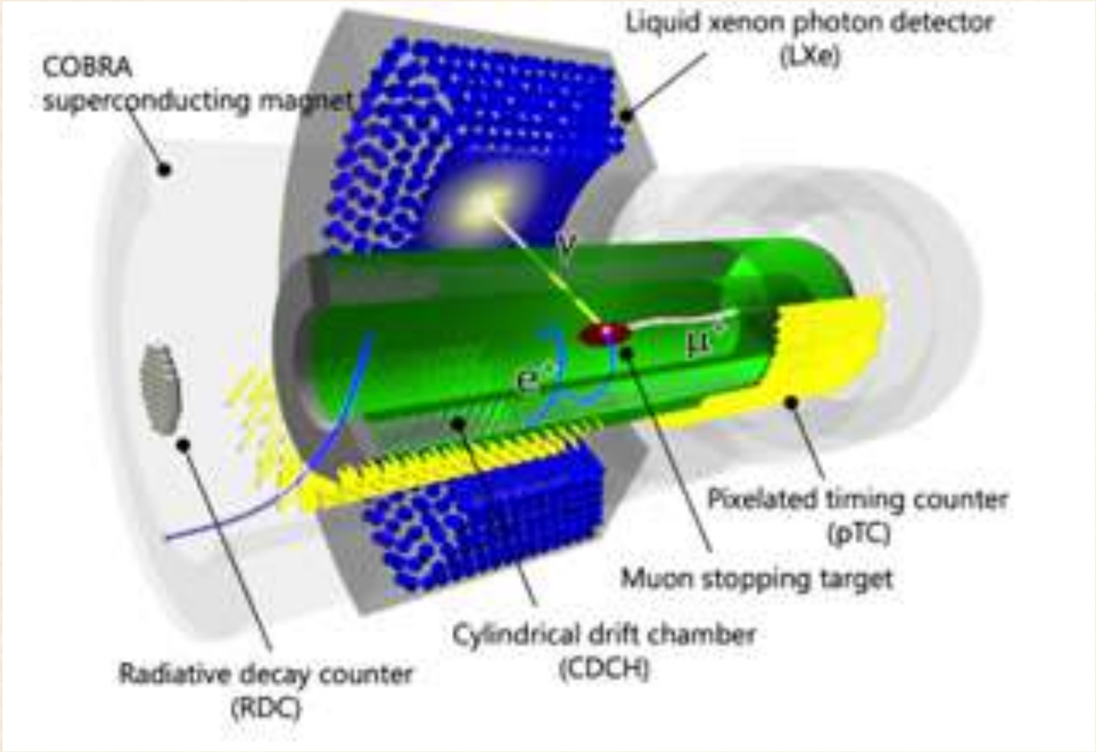


“Hollow” tracker has low acceptance for SM decays and high acceptance for signal

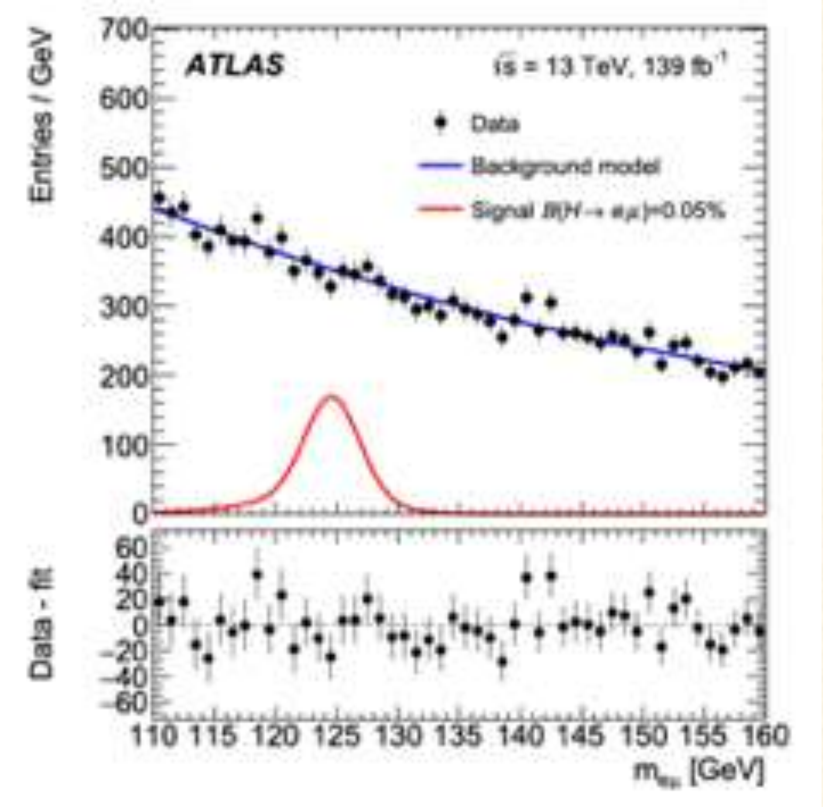
Slide courtesy: Brendan Casey

Other Experiments pursuing CLFV

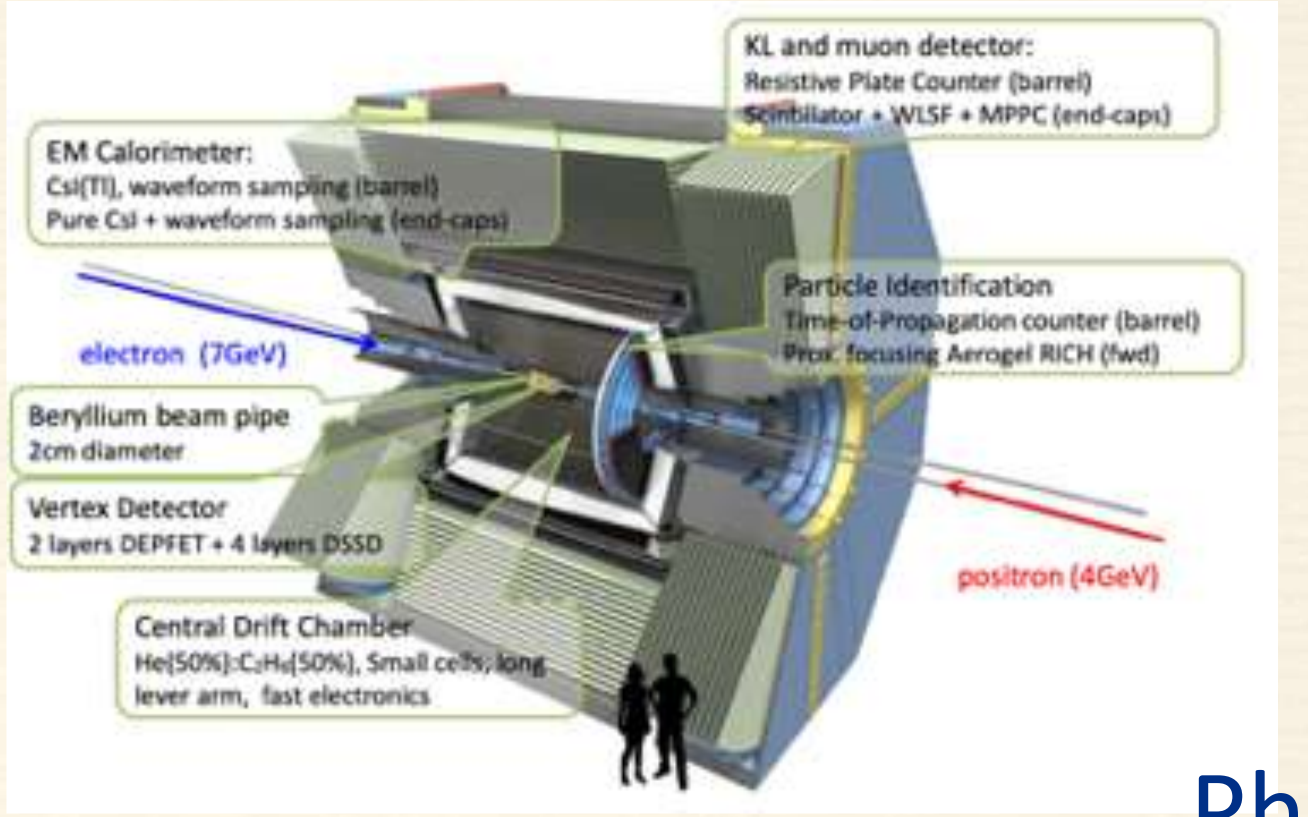
MEG-II
Data on tape



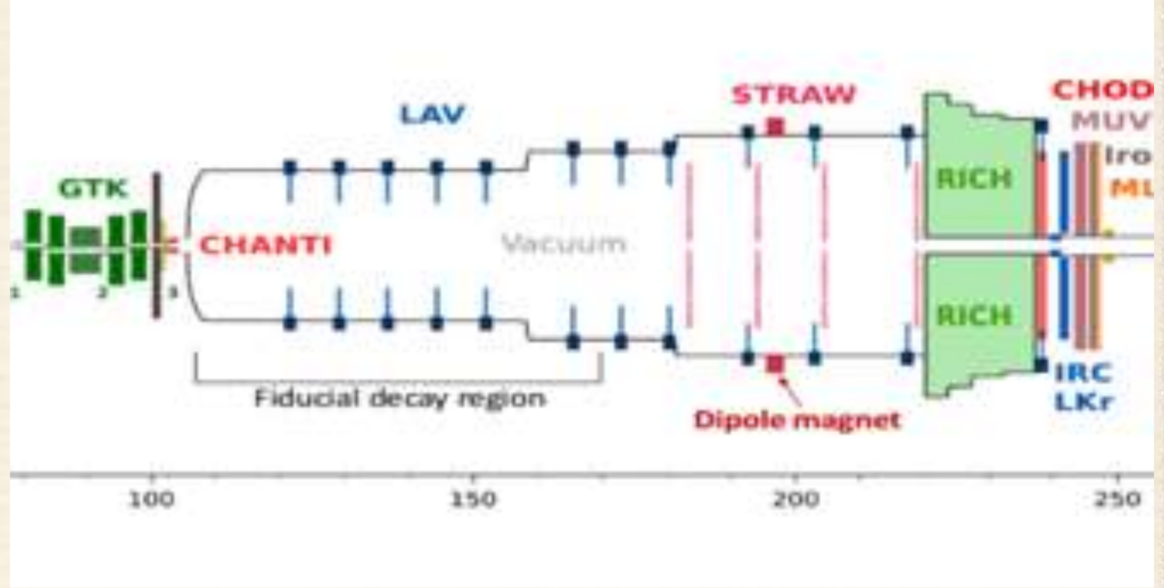
LHC
Data on tape



Belle II
Data on tape

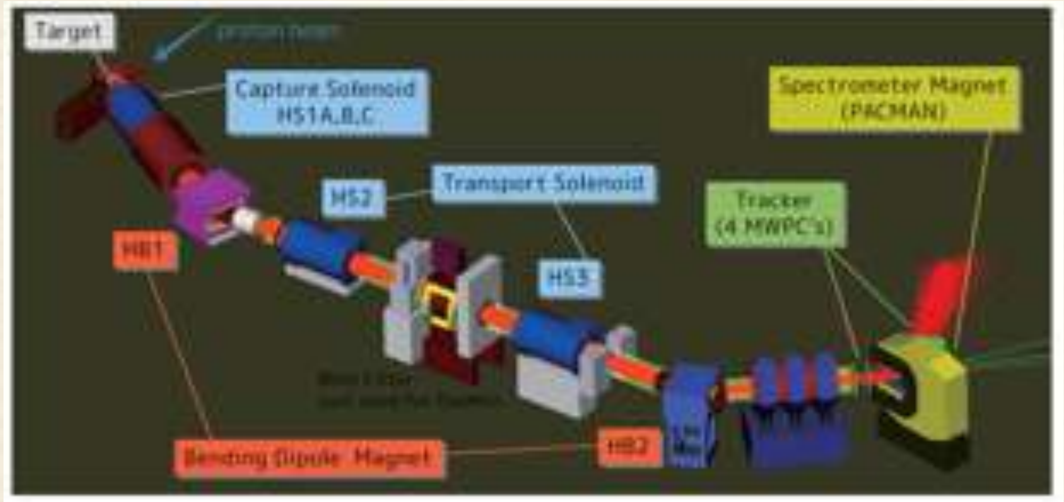


NA62
Data on tape

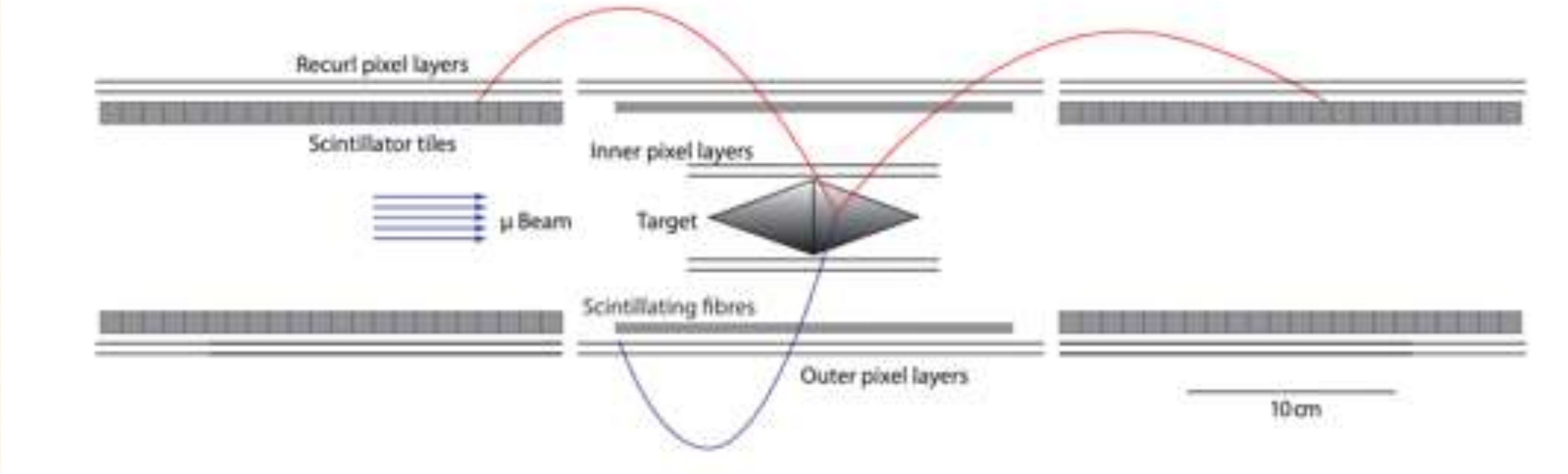


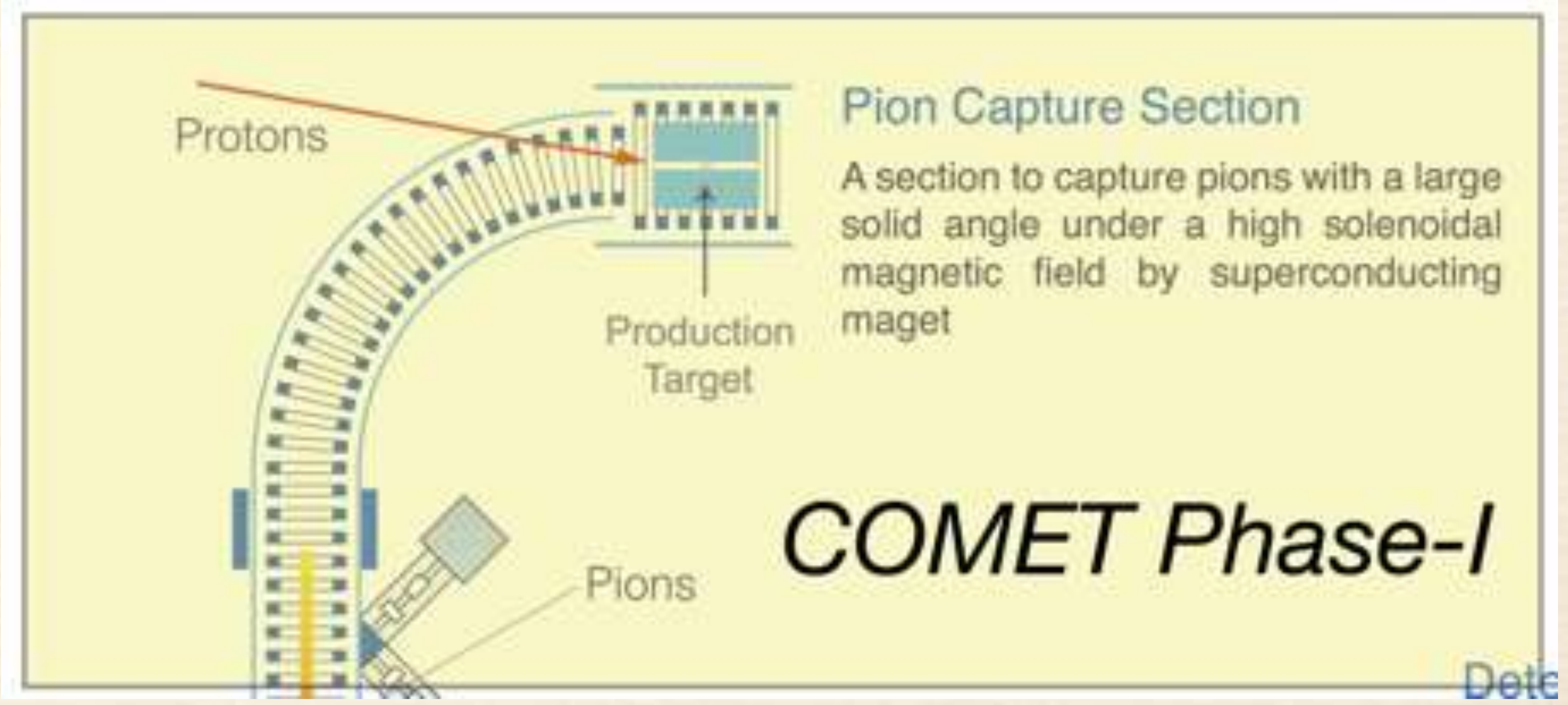
COMET
Phase-1 Solenoid in place.
Engineering run complete

DeeMee
Engineering run complete



Mu3e
Engineering run complete, data in 2026





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

The race is on!

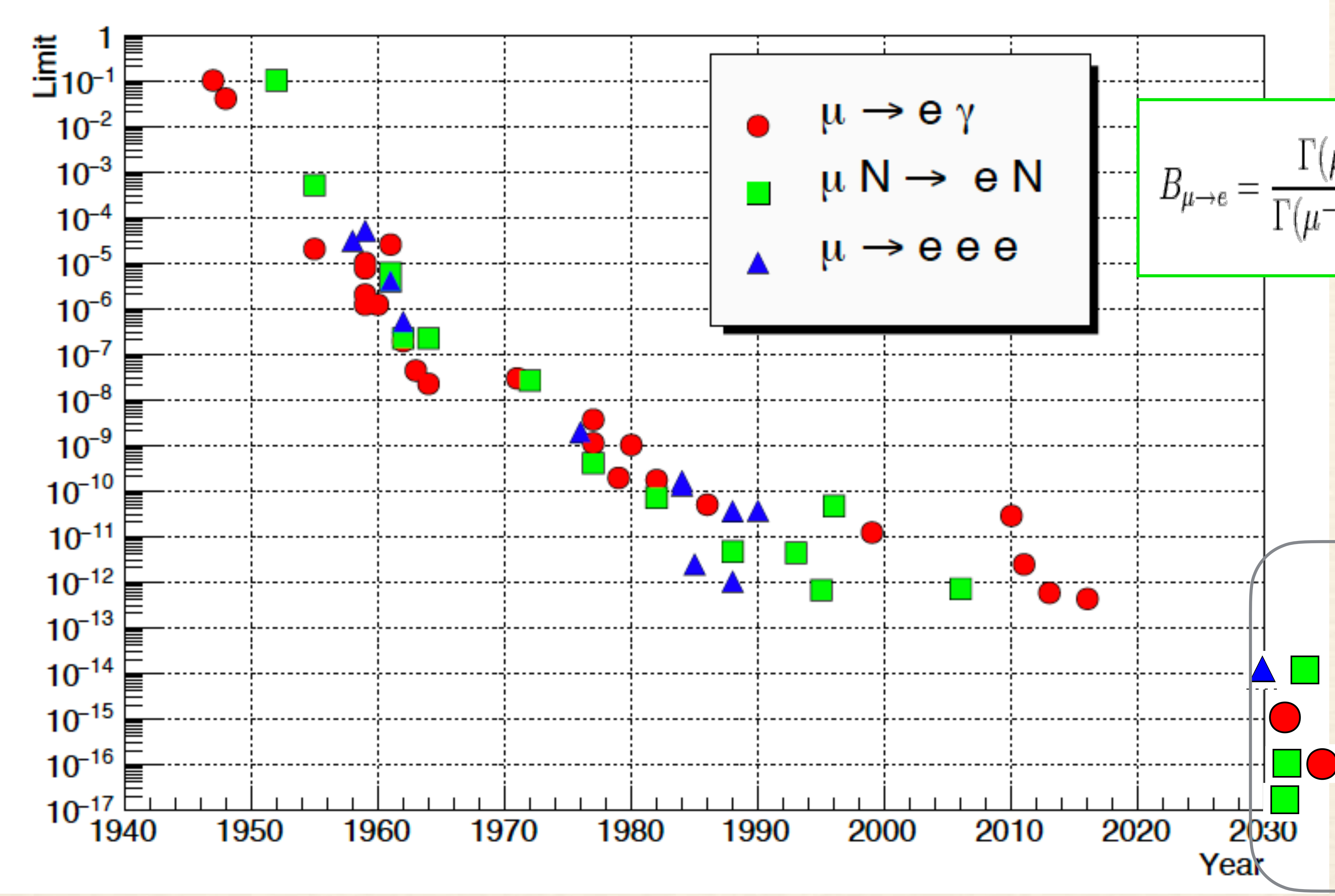
CLFV across Energy Scales

- Decays of μ, τ (and mesons)

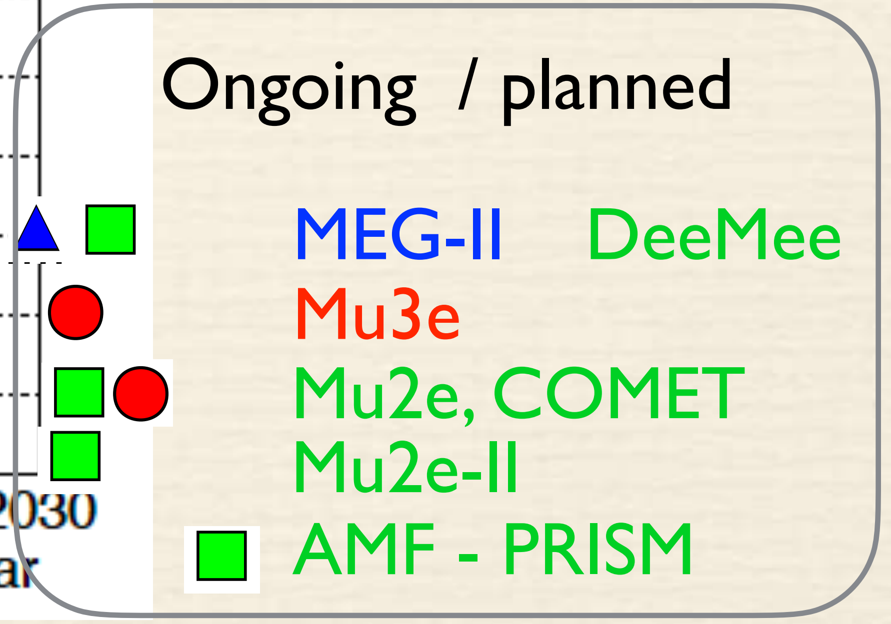
$$\mu \to e\gamma, \quad \mu \to e\bar{e}e, \quad \mu\,(A,Z) \to e\,(A,Z) \qquad M_\mu - \overline{M}_\mu \qquad \mu \to ea$$

$$\tau \to \ell\gamma, \quad \tau \to \ell_\alpha \bar{\ell}_\beta \ell_\beta, \quad \tau \to \ell Y \qquad Y = P, S, V, P\bar{P}, \ldots$$

Modified from Calibbi-Signorelli 1709.00294



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



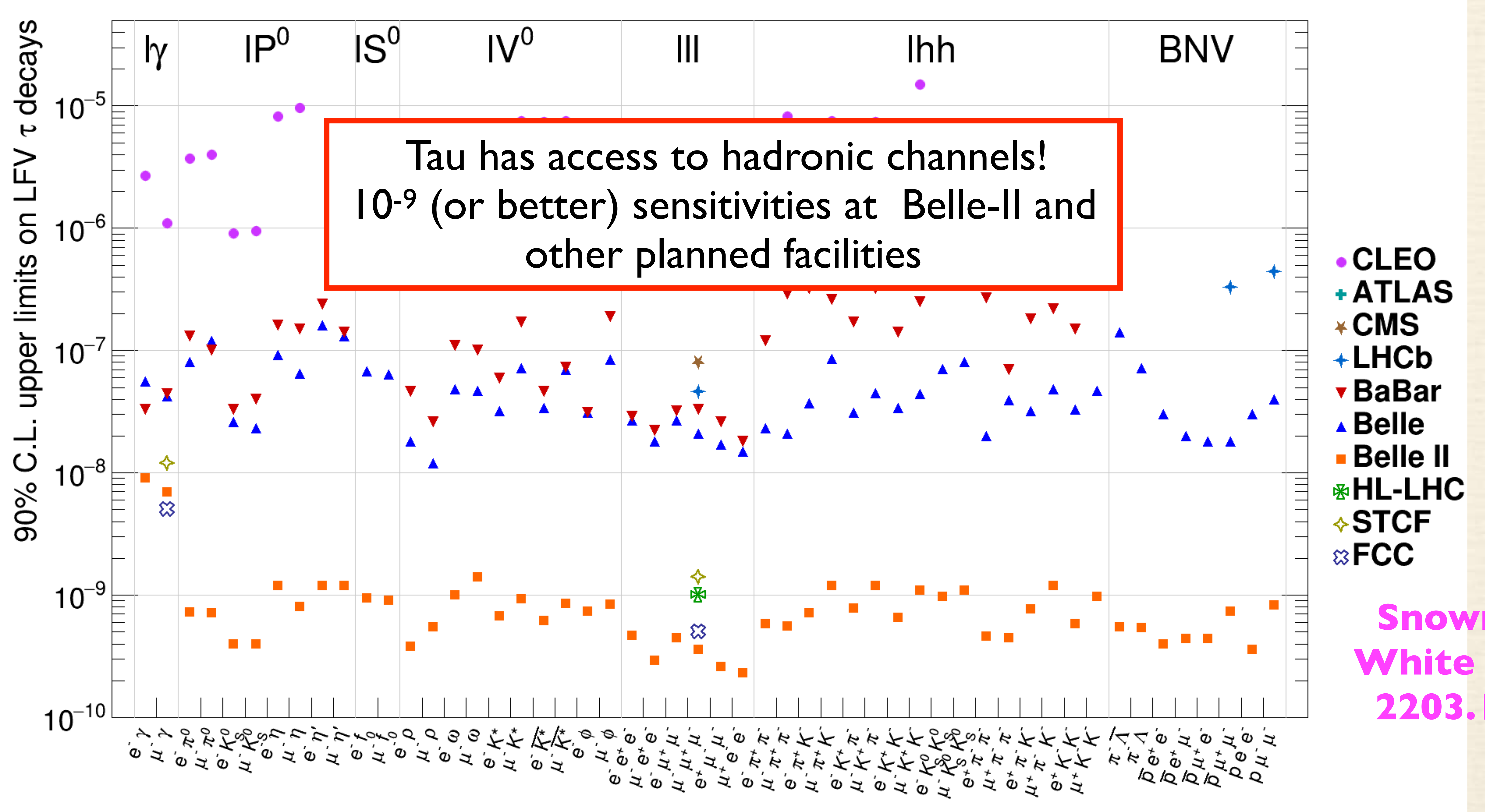
CLFV across Energy Scales

- Decays of μ, τ (and mesons)

EIC can compete for tau appearance but not muon appearance

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

$$\tau \to \ell\gamma, \quad \tau \to \ell_\alpha \bar{\ell}_\beta \ell_\beta, \quad \tau \to \ell Y \qquad Y = P, S, V, P\bar{P}, \ldots$$



Tau has access to hadronic channels!
10^{-9} (or better) sensitivities at Belle-II and other planned facilities

Snowmass White Paper 2203.14919

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

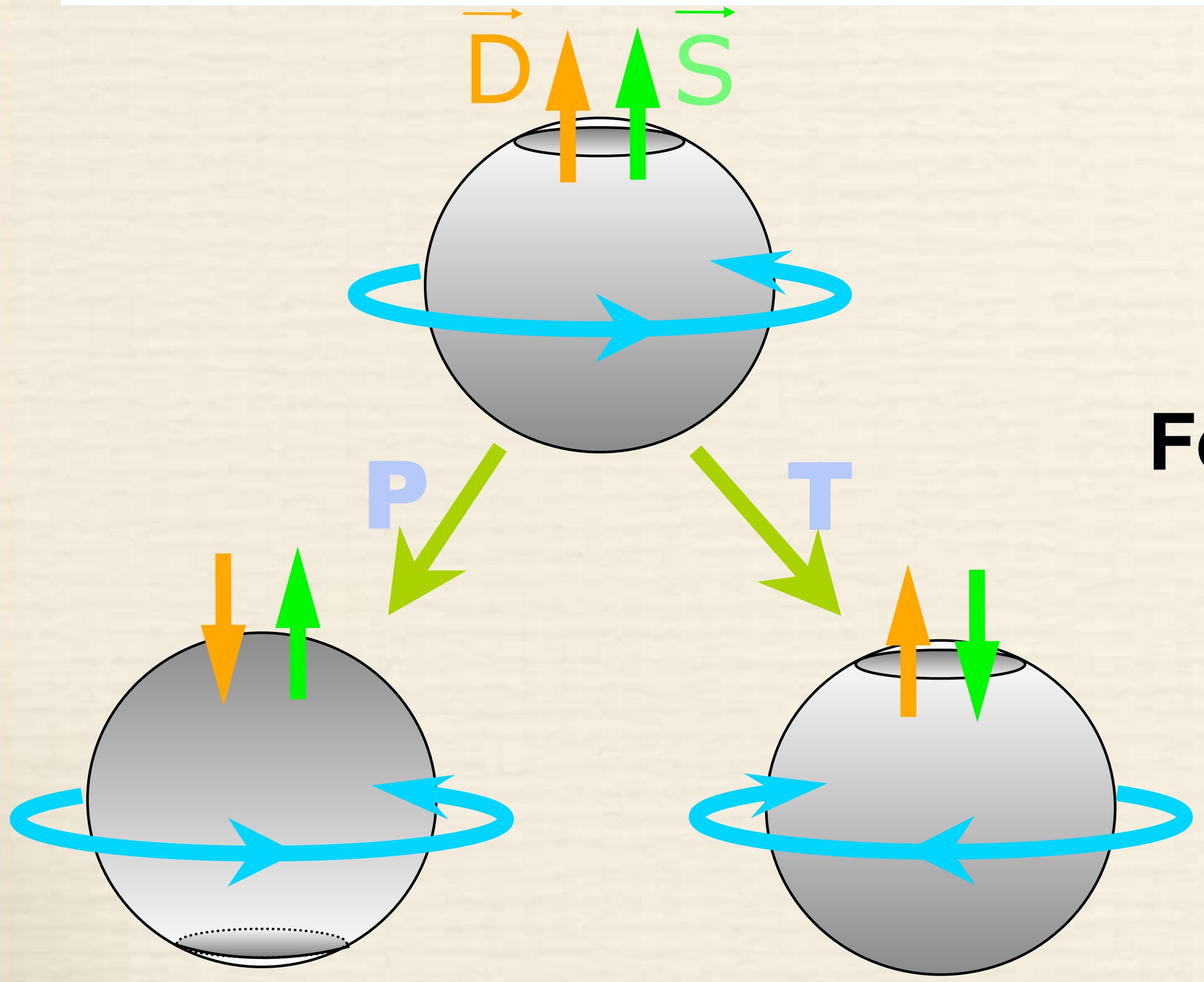
Fundamental Particle with EDM $\vec{d}$ and magnetic moment $\vec{\mu}$

$$H_{\text{Magnetic Dipole}} = -\vec{\mu}\cdot\vec{B} = -\mu\vec{\sigma}\cdot\vec{B}$$

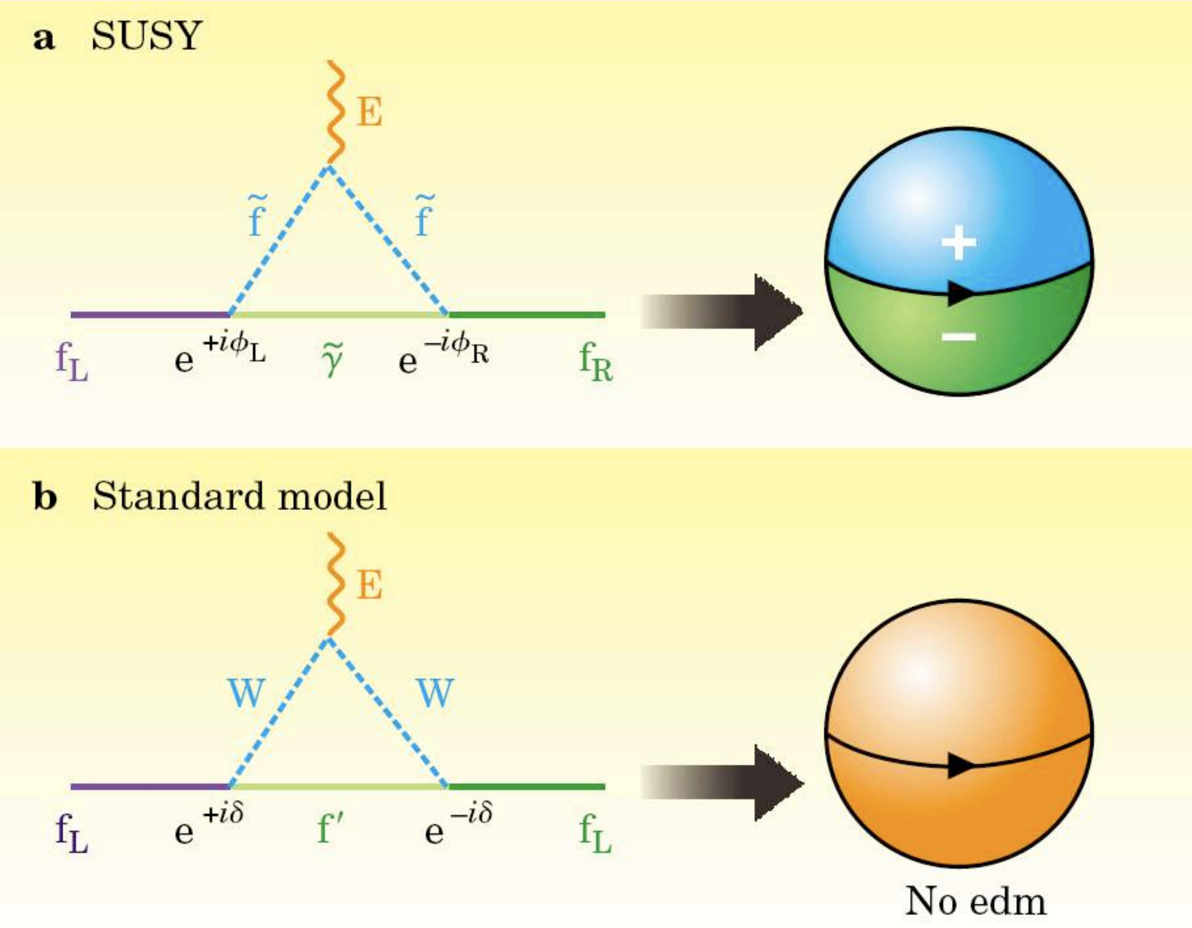
$$H_{\text{Electric Dipole}} = -\vec{d}\cdot\vec{E} = -d\vec{\sigma}\cdot\vec{E}$$

- $H_{\text{Magnetic Dipole}}$ is P-even and T-even
- $H_{\text{Electric Dipole}}$ is P-odd and T-odd !!!

In SM need at least 4 loops - predicts $|d_e| \leq 1 \times 10^{-38}$ e·cm



For a fundamental particle to have an EDM, both P and T must be violated

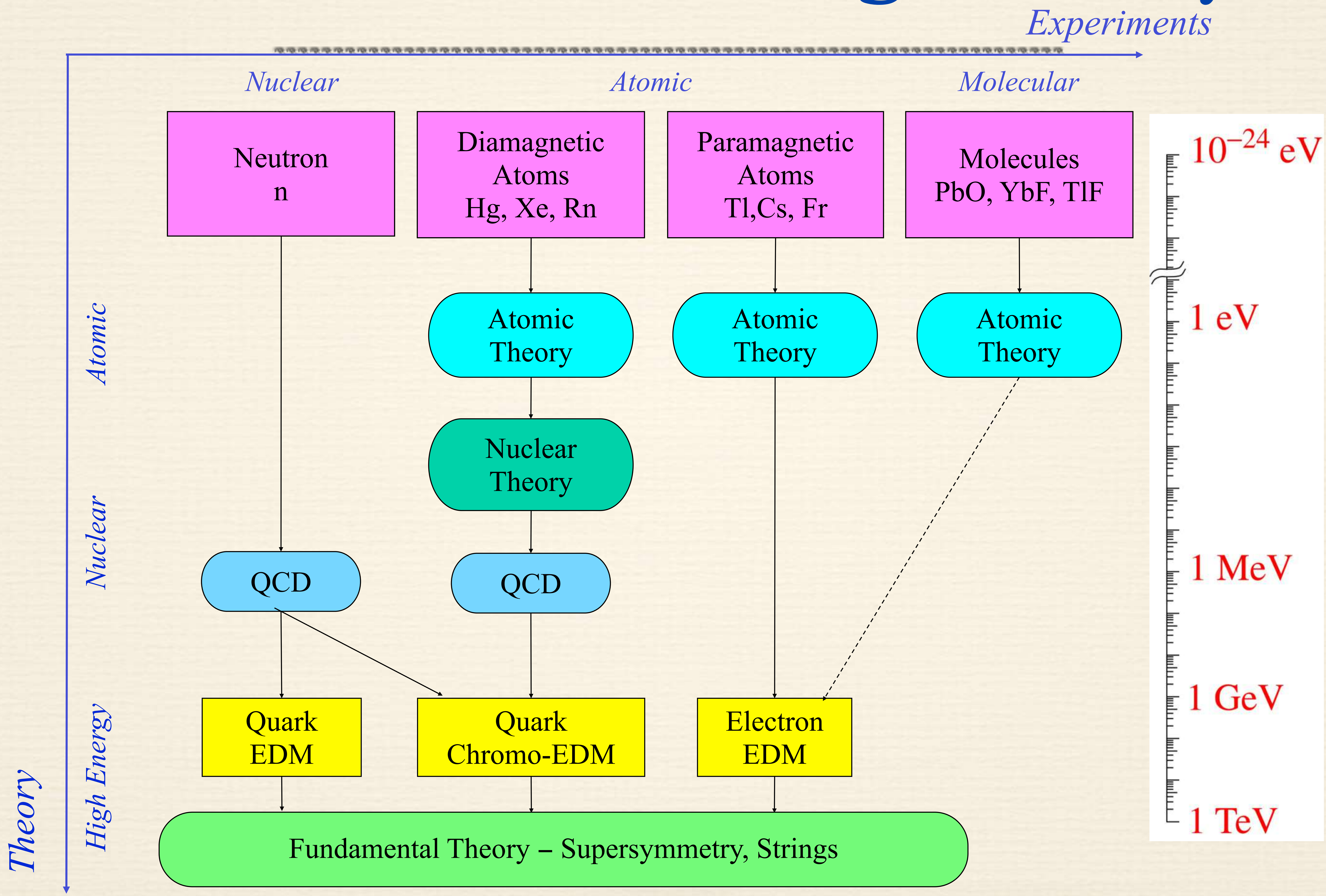


raw sensitivity:

d ~ (m x e)/Λ^2

d ~ 10^{-27}: Λ ~ 100 TeV

EDMs: Connecting Theory

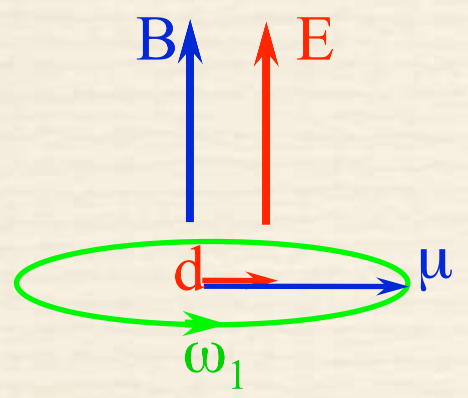


Basic Experimental Approach

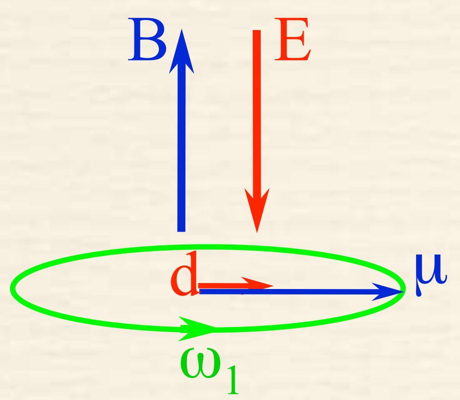
Courtesy:
M. Romalis, Z-T. Lu, B. Filippone

- Measure spin-precession frequencies

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

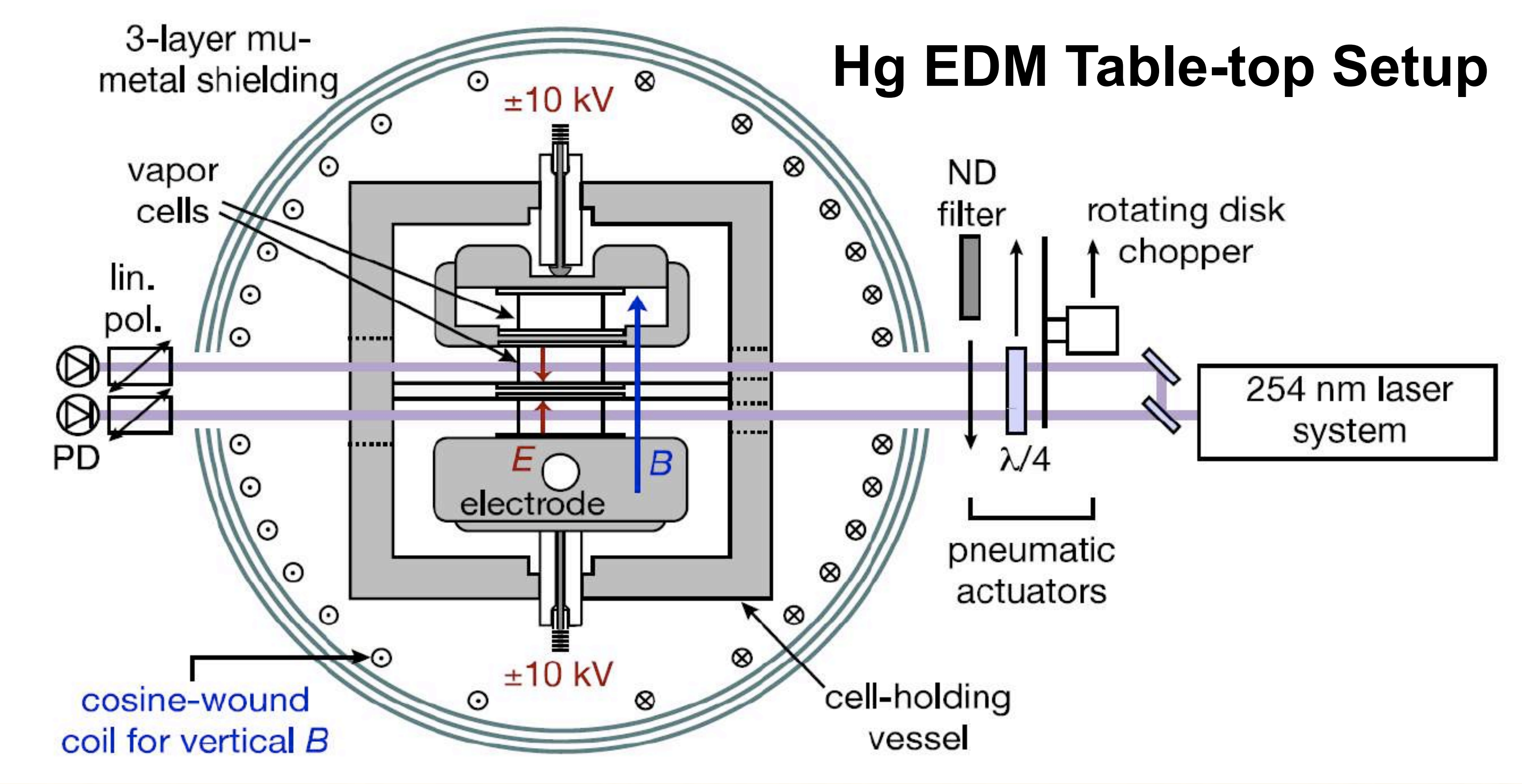


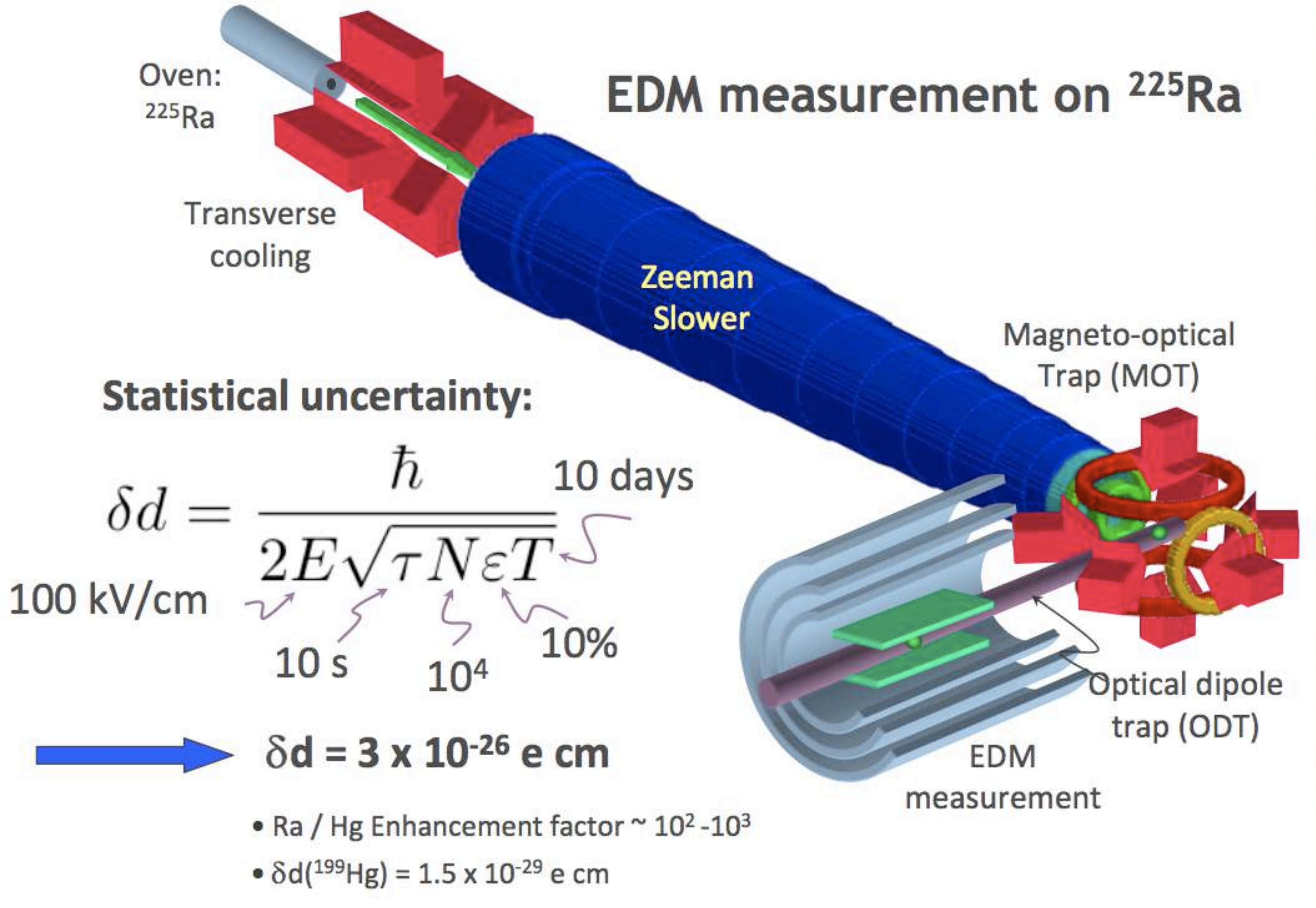
$$\omega_1 = \frac{2\mu B + 2dE}{\hbar}$$

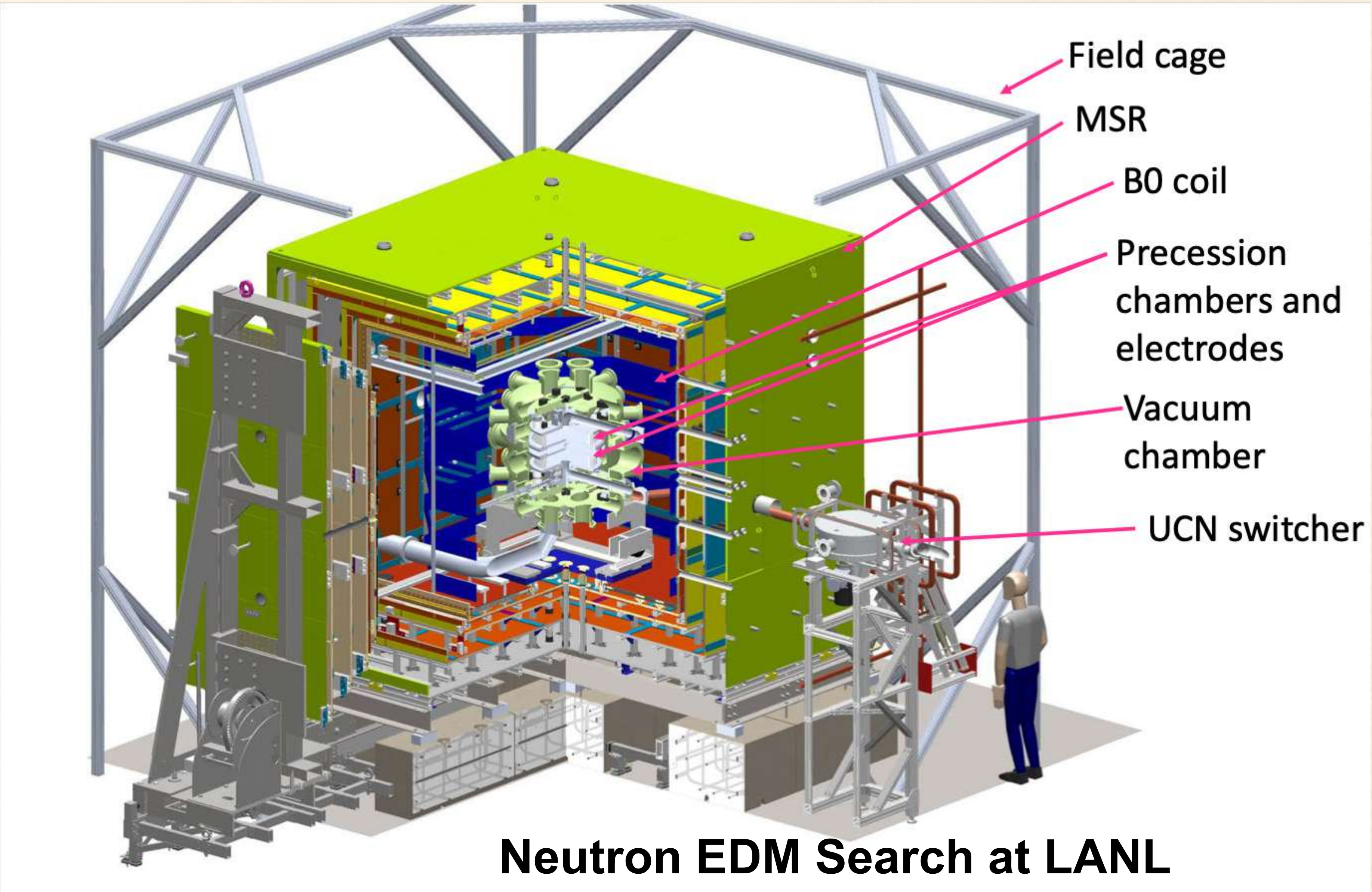


$$\omega_2 = \frac{2\mu B - 2dE}{\hbar}$$

$$\omega_1 - \omega_2 = \frac{4dE}{\hbar}$$







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
	$C_S = (-1.3 \pm 3.0) \times 10^{-9}$	6.4×10^{-9}
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) < 0.74×10^{-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.

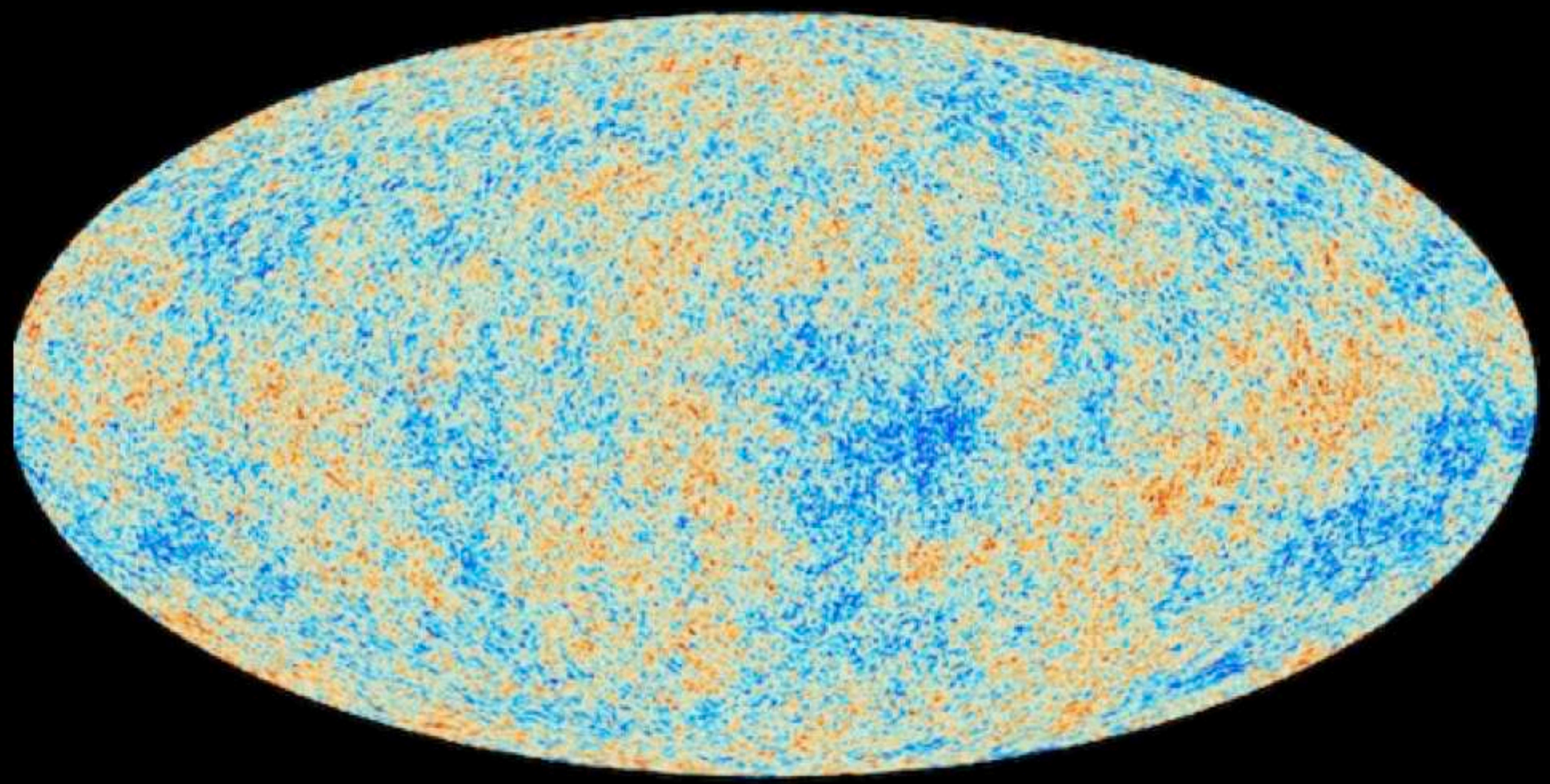
- Several **next generation** CP-violation search schemes using **pear-shaped nuclei inside of molecules** are currently being developed and have new physics sensitivities that are **several orders of magnitude beyond the state-of-the-art ^{199}Hg EDM experiment**.

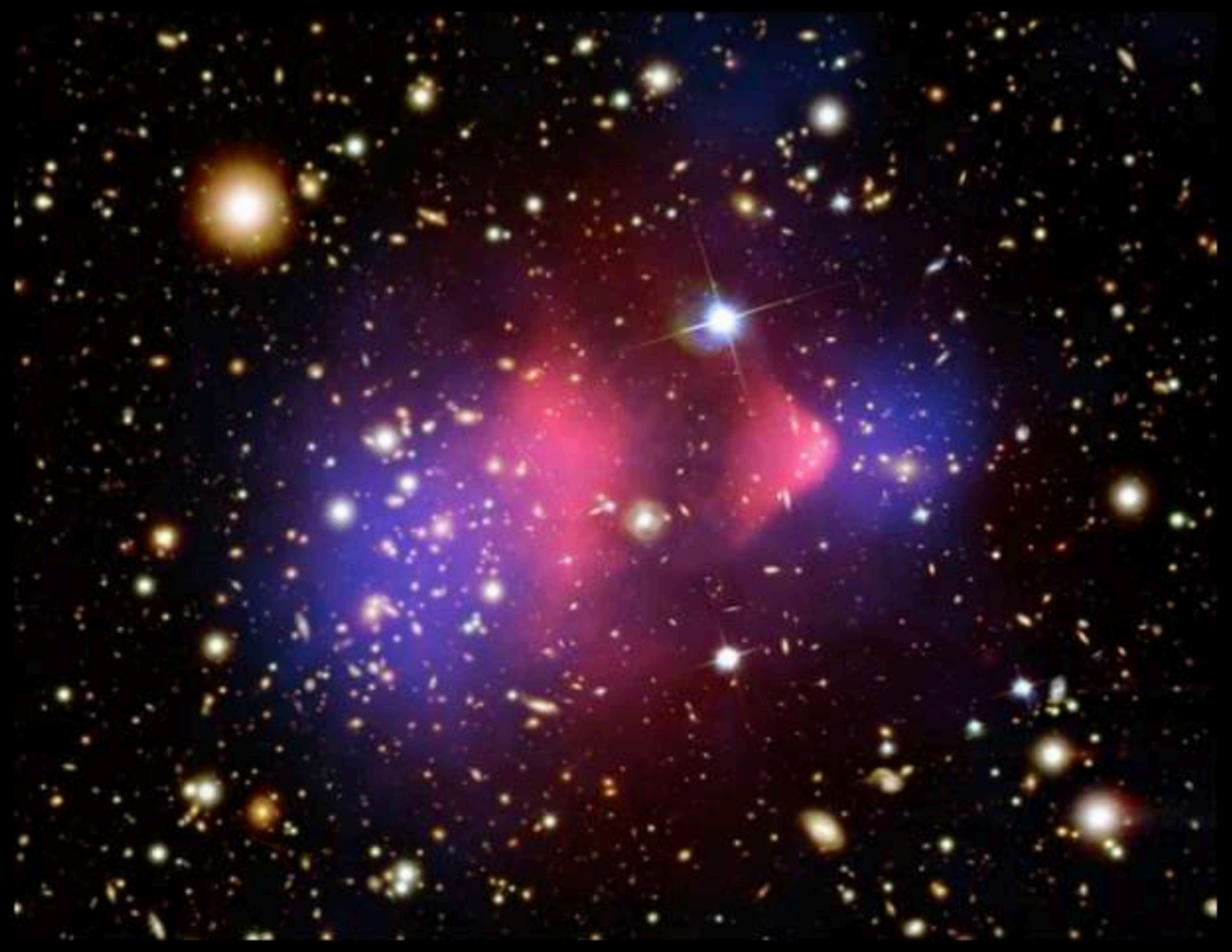
To go past 10^{-28} e cm for the neutron and 10^{-30} for nuclei will need new ideas and upgrades in the 2030s

A Large Body of Indirect Evidence primarily from Astrophysics/Cosmology

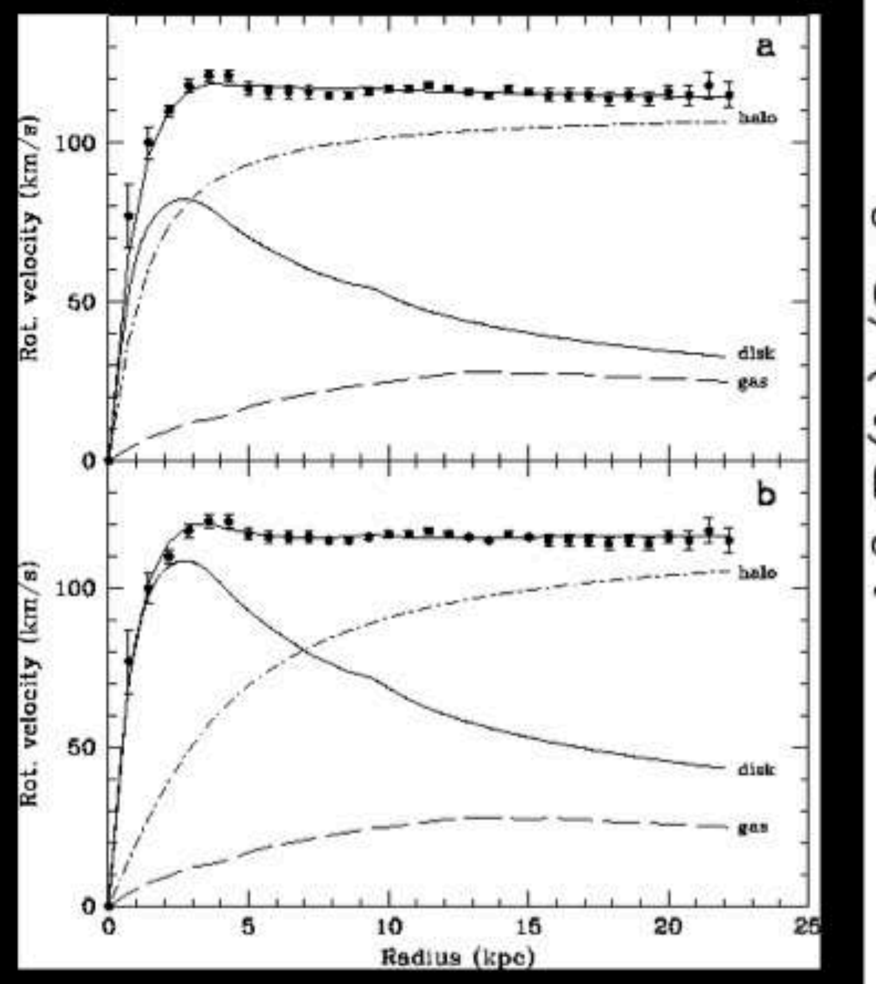
Dark Matter

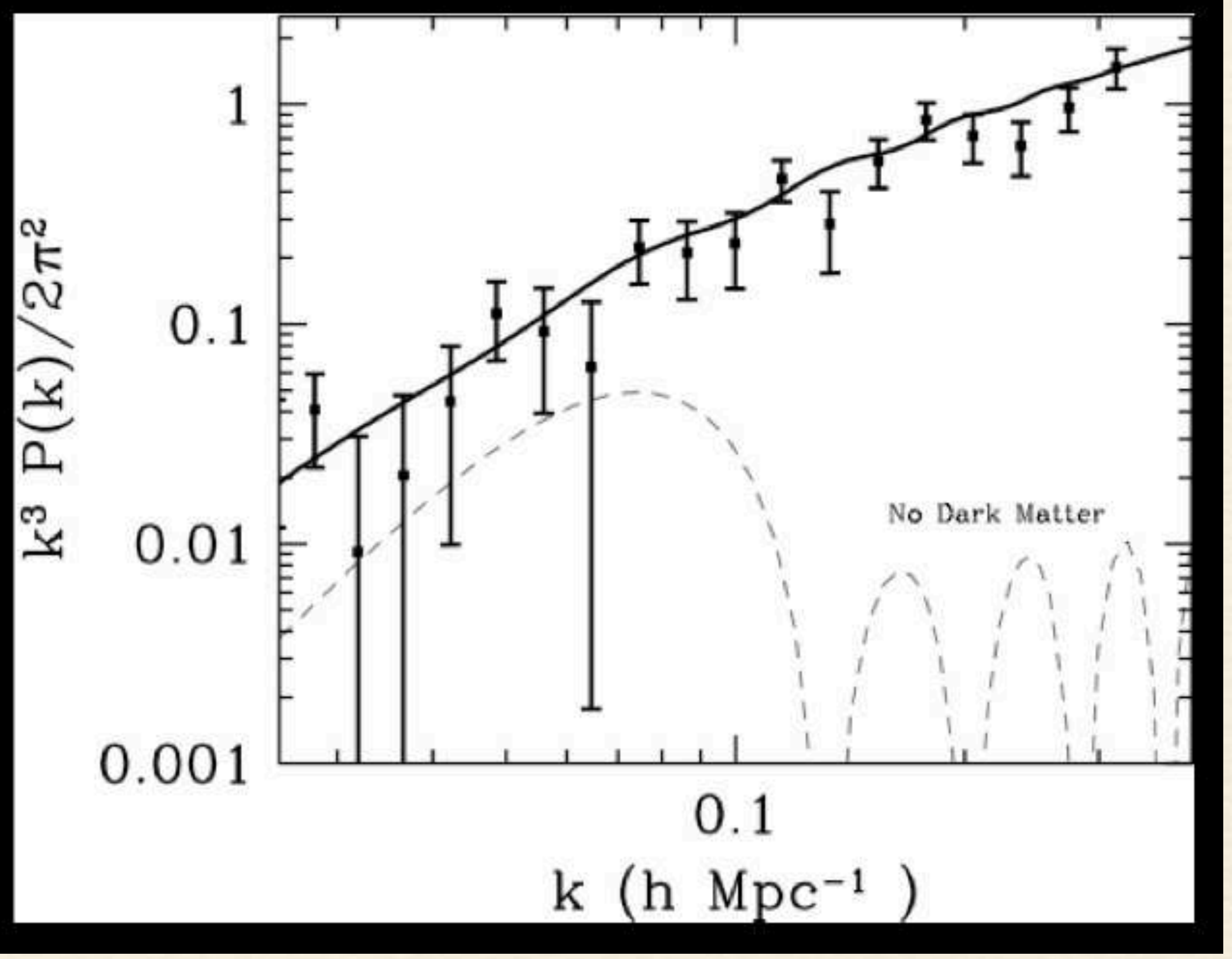
H. Lippencott





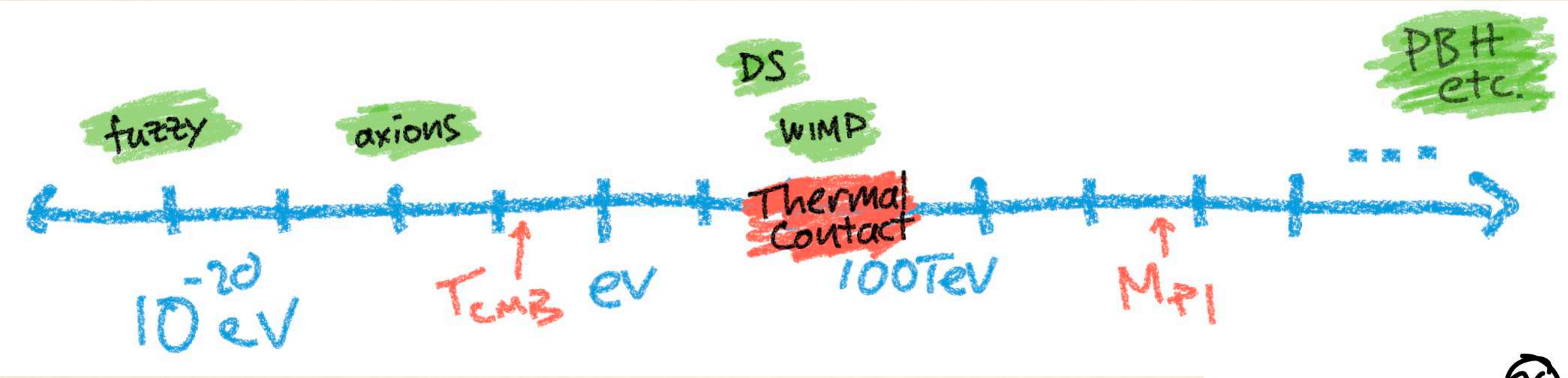
- Galaxy rotation curves
- Galaxy clusters and collisions
- Large scale structure
- Cosmic microwave background





Courtesy: D. McKeen

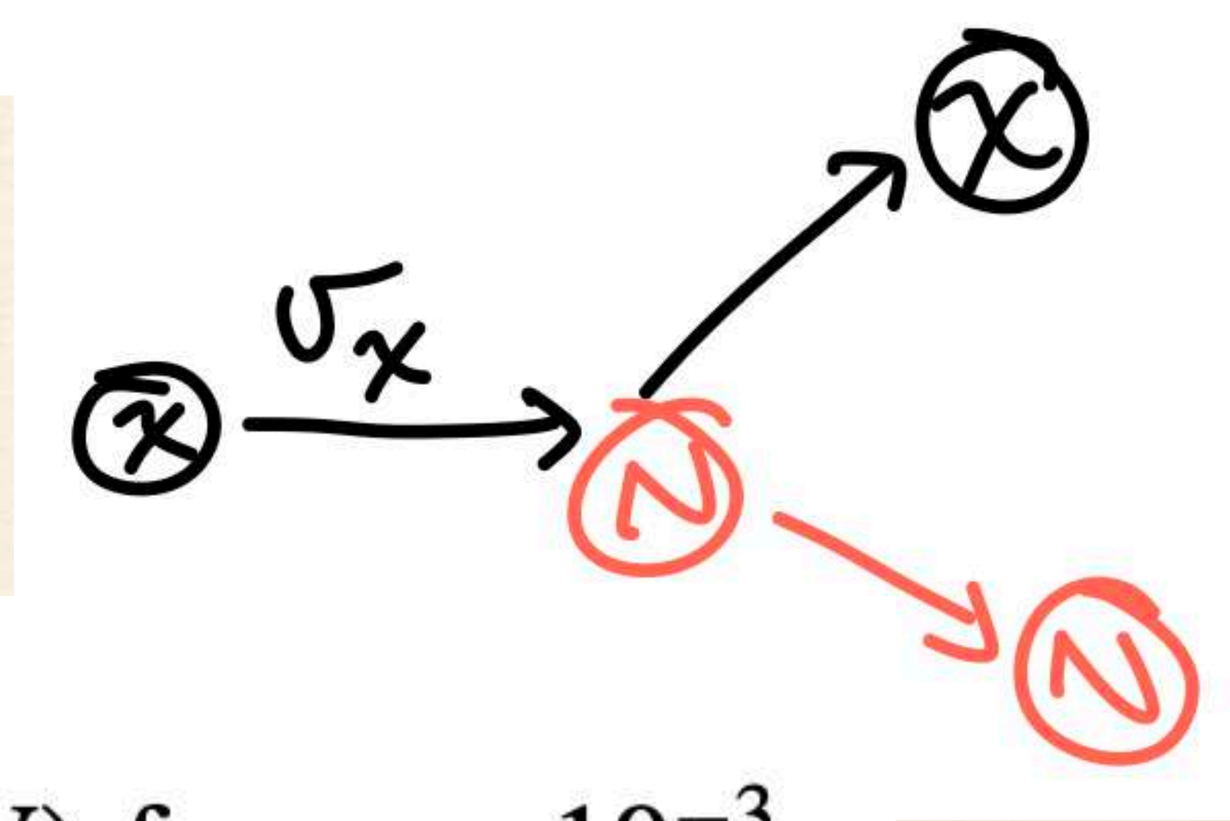
Dark Matter: Large Parameter Space



Thermally produced dark matter

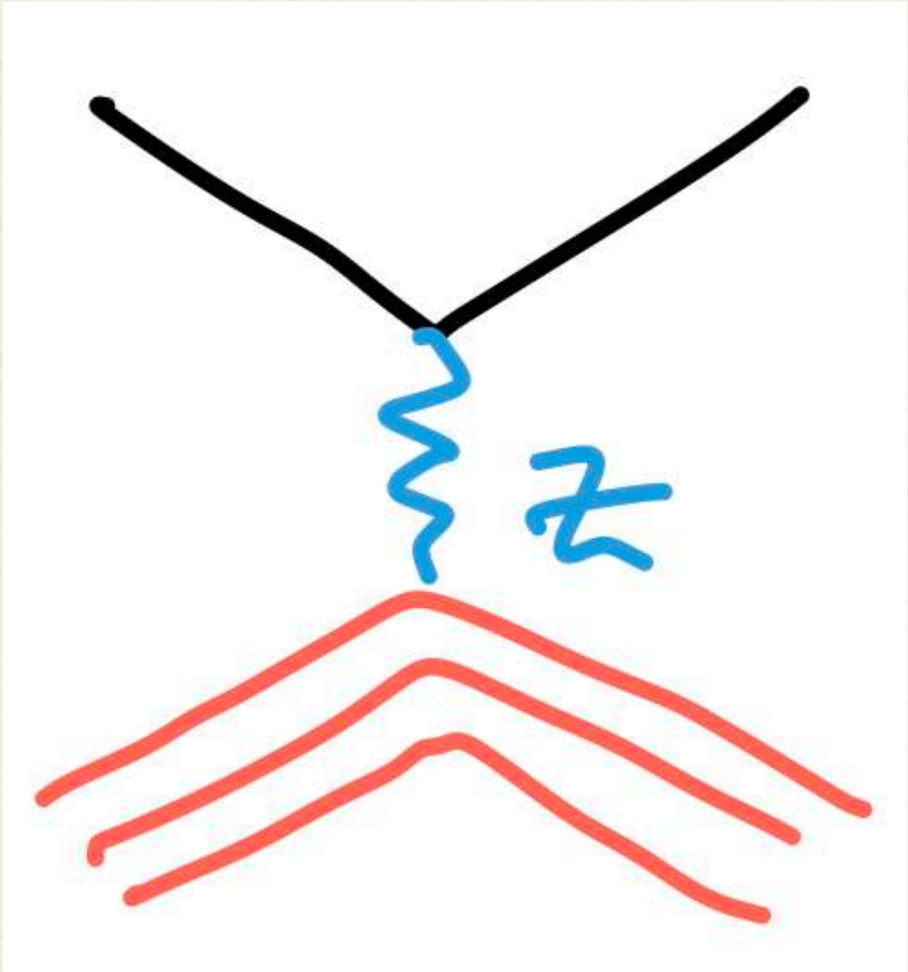
A particle with weak scale mass and weak coupling can obtain the correct dark matter density: WIMP Miracle

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



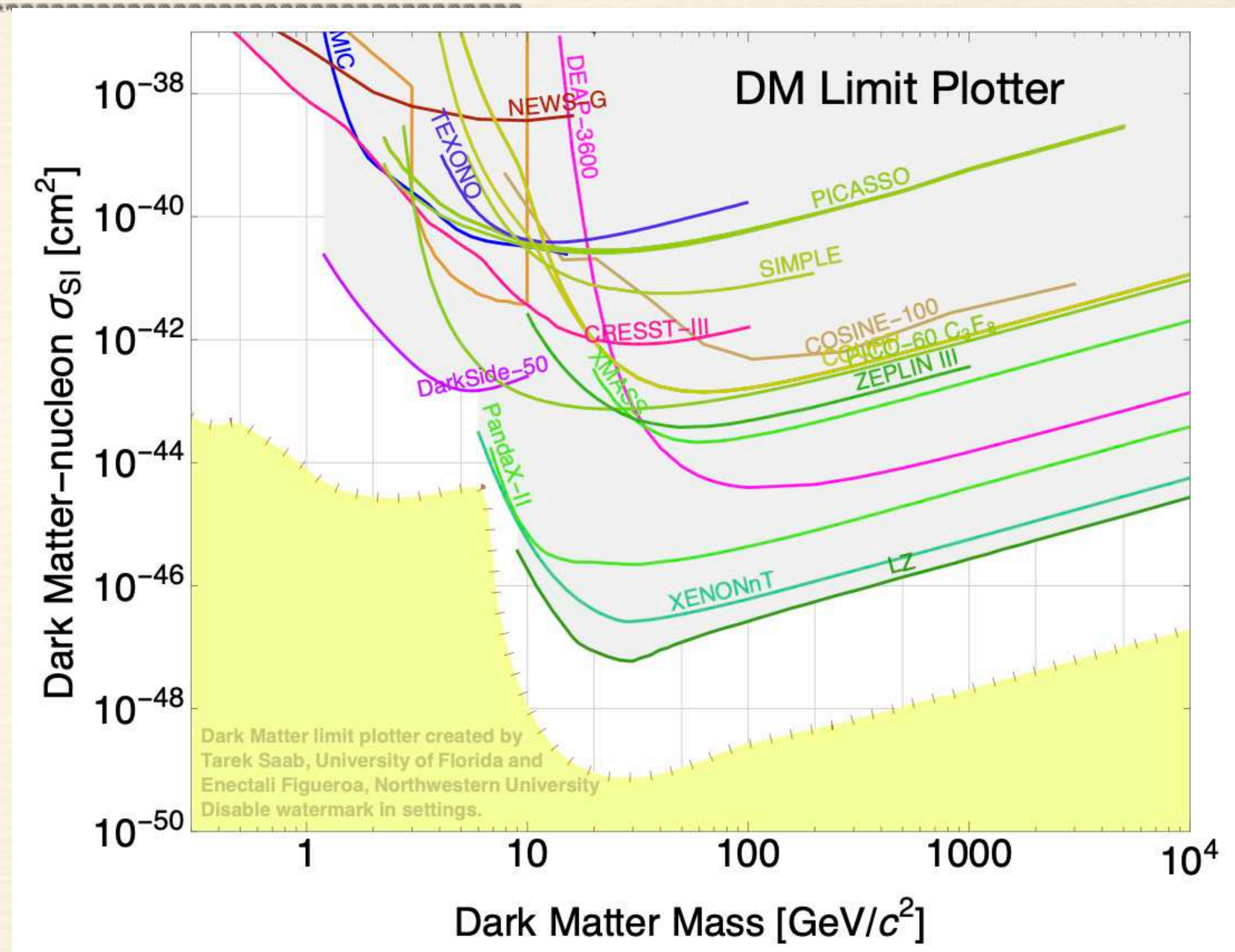
$$E_{\mathrm{recoil}} \leq \frac{2\mu_{\chi N}^2 v_\chi^2}{m_N} \sim \mathcal{O}(10\ \mathrm{keV})\ \text{for}\ v_\chi \sim 10^{-3}c$$

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***

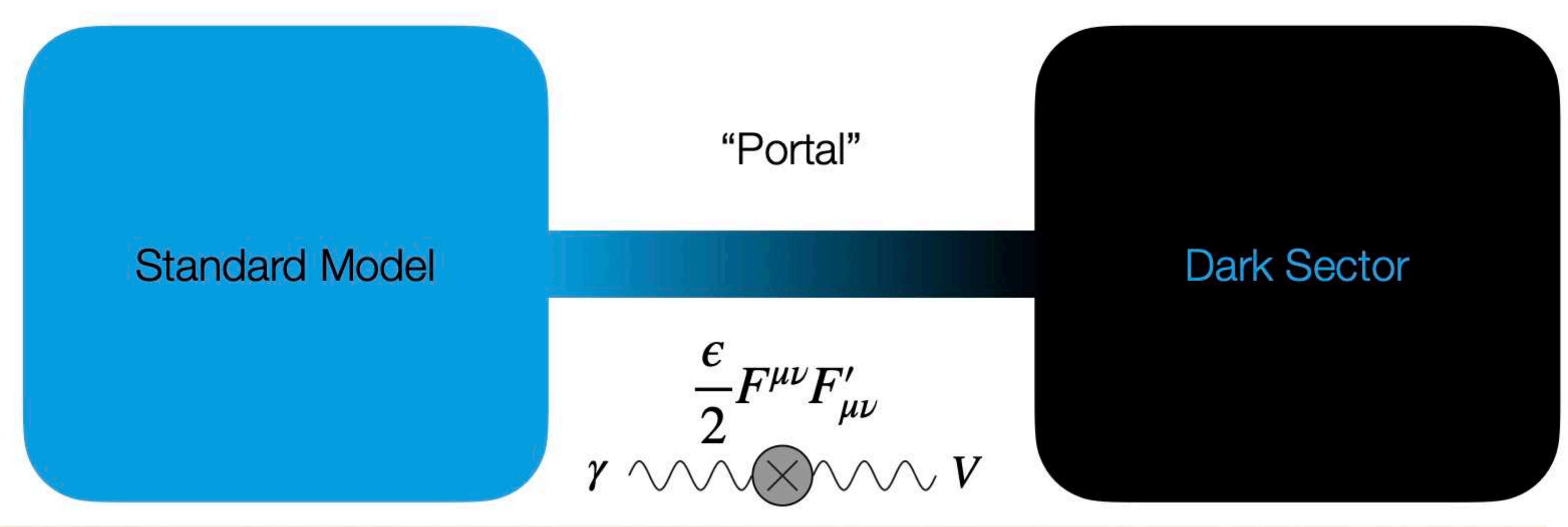


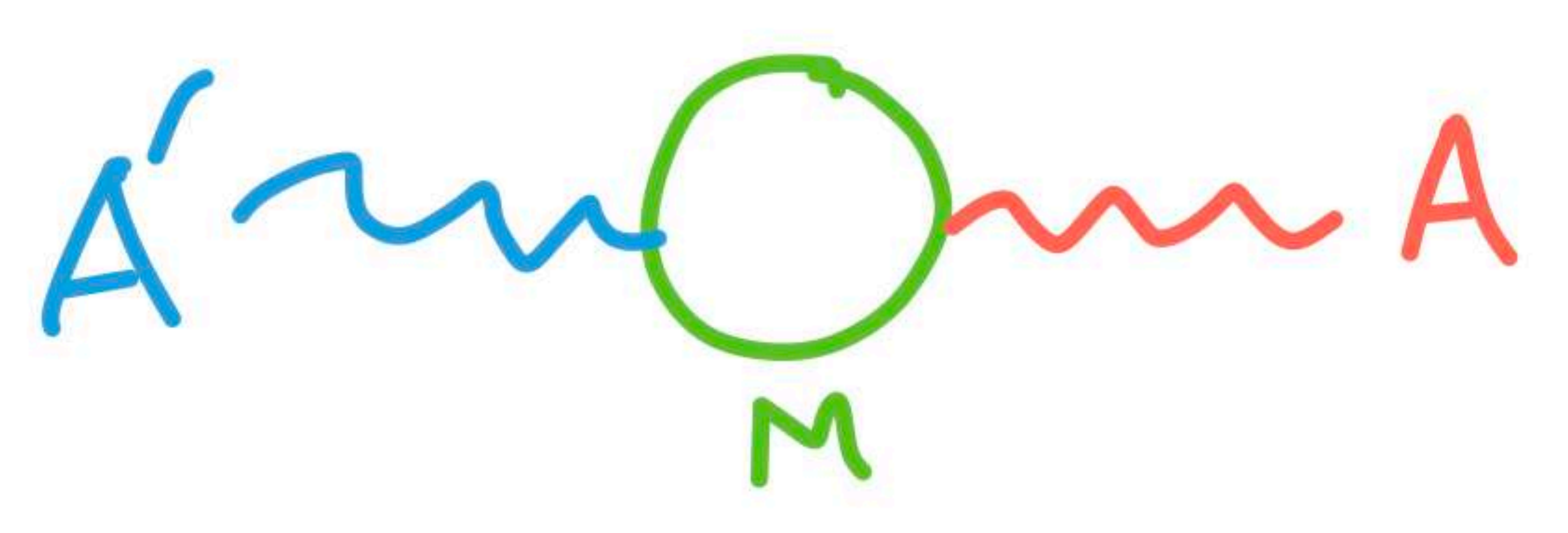
The next phase will require require multiple countries to band together to consolidate funding

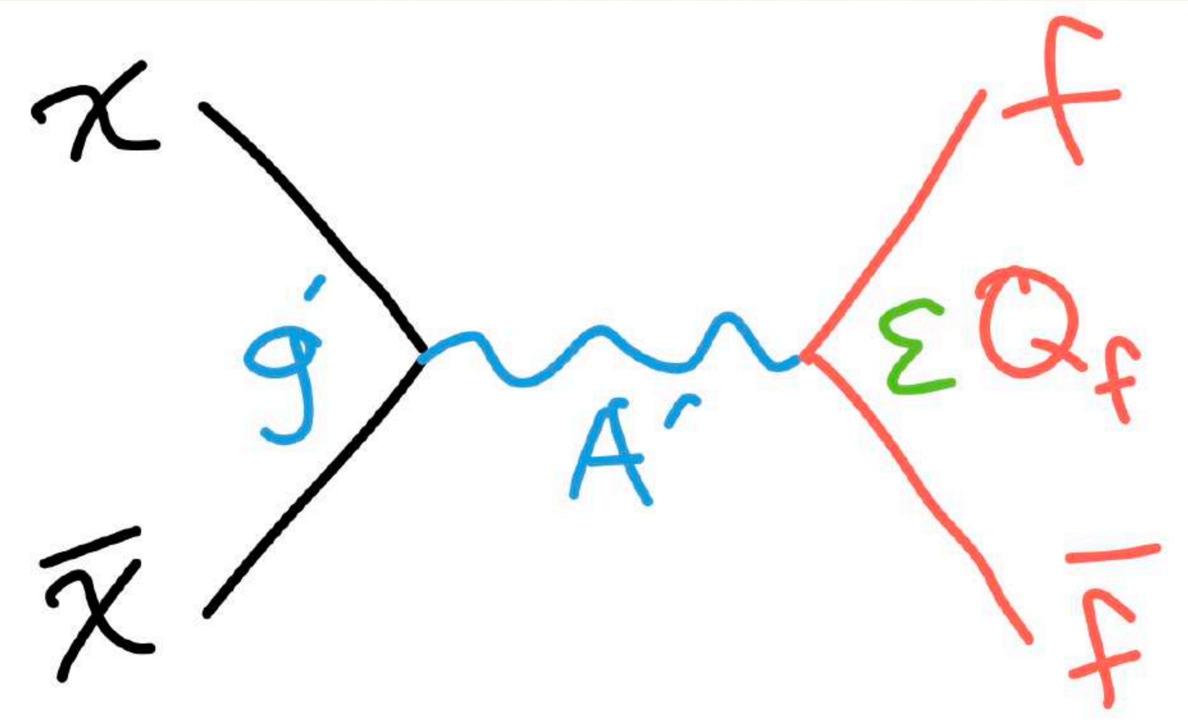
Light Mediators: Dark Bosons

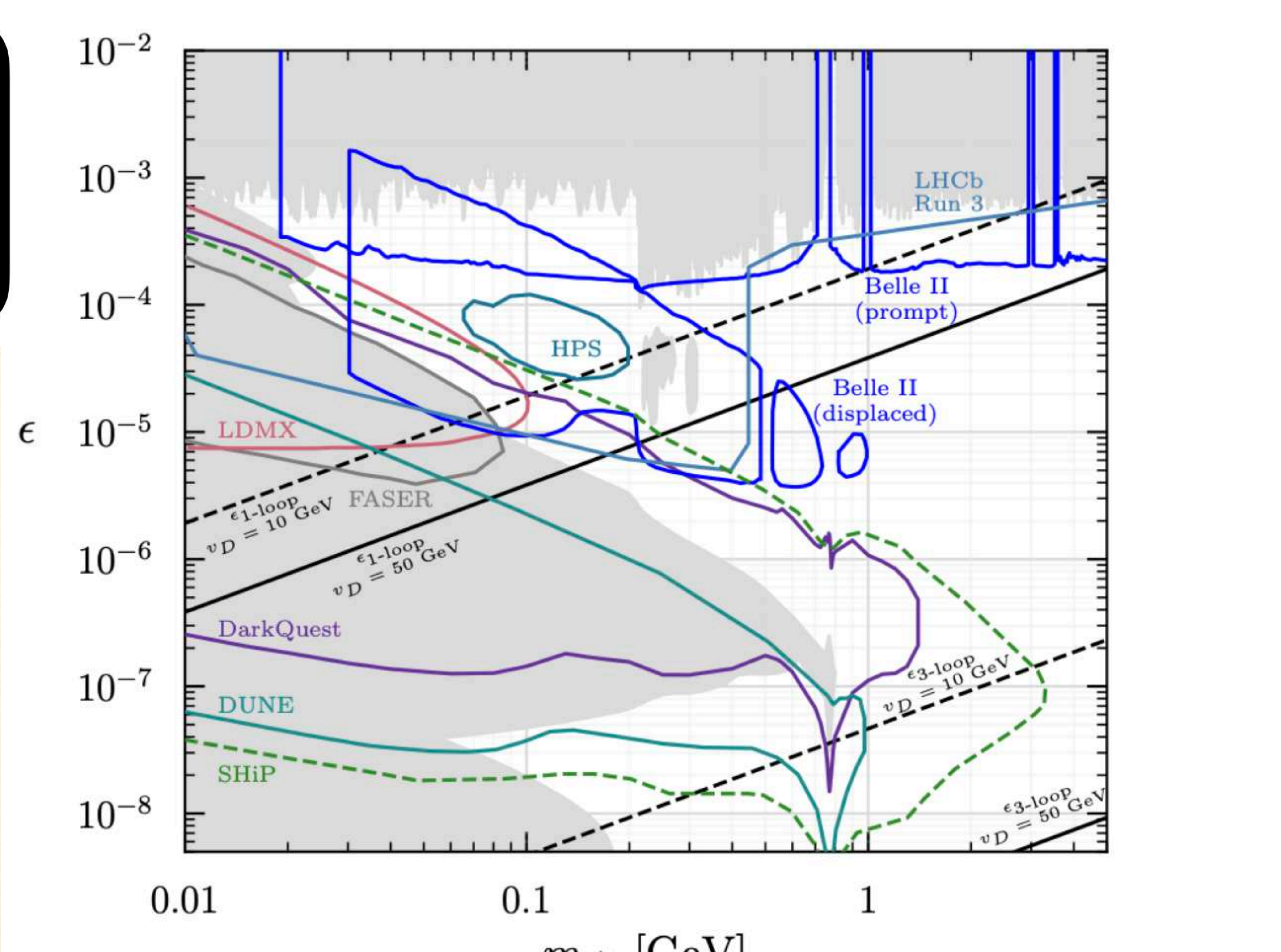
Courtesy: D. McKeen

Dark Matter connected to SM particles via a "portal"

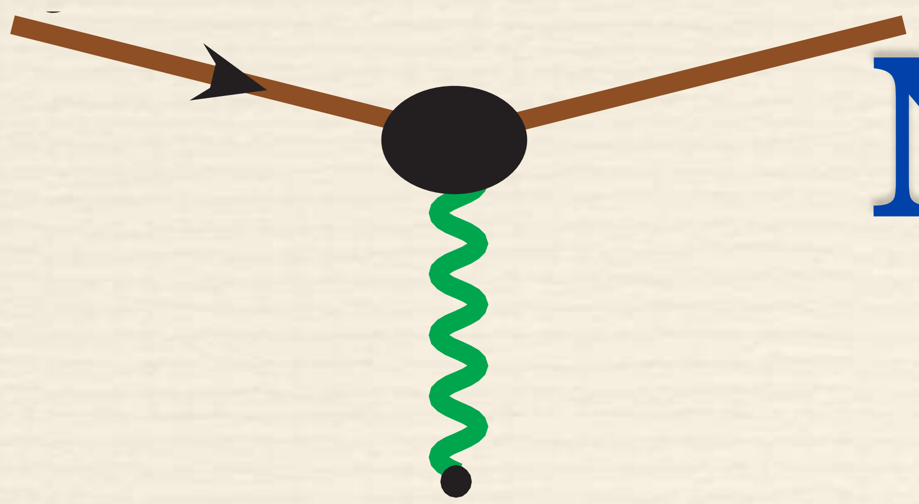








Updated limits from Darkcast



New Physics via SMEFT

Topics Relevant to EIC

$\frac{1}{\Lambda}\mathcal{L}_5$ $\frac{1}{\Lambda^5}\mathcal{L}_9$

- ✦ **Violation of Lepton Number** — 10^{15} GeV / multi-TeV
  - ★ Neutrinoless Double-Beta Decay, muon and tau appearance at the EIC
- ✦ **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 low energy and EIC

SM & BSM Topics at the EIC

- **Neutral and Charged Current Structure Functions**
  - ***Complementary probe of BSM 6-D operators: address flat directions in global SMEFT analysis***
  - ***Unpolarized and Polarized pdfs***
  - ***Weak Mixing Angle: both proton and deuteron***
  - ***Charged current measurements complementary to precision weak decays***
- **Charged Lepton Flavor Violation**
  - ***Tau appearance: strive for zero background***
  - ***Complementary lepton number search***
- **Other BSM Topics**
  - ***Inclusive and semi-inclusive single spin asymmetries***
  - ***Axion-like particle searches relevant to dark matter models***
  - ***T-odd observables***
  - ***…***

Center for Frontiers in Nuclear Science

New opportunities for beyond-the-Standard Model searches at the EIC

July 2025

https://indico.cfnssbu.physics.sunysb.edu/event/341/timetable/#20250722.detailed

Tomorrow's lecture

- Lepton-Nucleon Deep Inelastic Electroweak Scattering
- Weak Neutral Current Interactions and the Weak Mixing Angle
- Neutral Current Structure Function Reach
- A Menu of BSM Signatures at the EIC
- One Detailed Example: Charged Lepton Flavor Violation Search
- Summary and Outlook

BSM @ EIC Summary

- **Intensity Frontier**
  - *Absent direct particle discovery at the LHC, indirect BSM searches become central. In fact one could argue that certainly LHCb and even ATLAS and CMS are now Intensity Frontier experiments!*
- **Electron Ion Collider**
  - *Any new machine accessing new territory in intensity, luminosity, spin and center of mass energy space must be thoroughly explored for potential new BSM sensitivity*
  - *First ideas (Neutral currents, CLFV) have percolated for more than a decade*
  - *New ideas are continuing to come in…*
- **Sharpen the Science Case**
  - *It is now time to push the ideas that survive "on mass-shell"*
  - *Continue to explore new ideas while keeping a close eye on the rest of the BSM landscape*