Neutrons and Fundamental Symmetries

Theory — Lecture 2

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Symmetry Tests with Neutrons

"Windows" on New Physics

Some examples (see Chen-Yu Liu's lectures for more!)

(Can be cast as searches for new light scalars….)

- Searches for new sources of CP violation: *namely, permanent electric dipole moment (EDM); time-dependent EDMs as probes of ultralight dark matter*
- Searches for baryon number violation: *esp. quark probes of Majorana dynamics*
- Searches for new S,T degrees of freedom in beta-decay

Electric & Magnetic Dipole Moments

A permanent EDM breaks P & T

$$\mathcal{H} = -\mu\frac{\vec{S}}{S}\cdot\vec{B} - d\frac{\vec{S}}{S}\cdot\vec{E}$$

Maxwell Equations…

$$\vec{B} \xleftrightarrow{P} \vec{B} \quad \vec{E} \xleftrightarrow{P} -\vec{E} \quad \vec{S} \xleftrightarrow{P} \vec{S}$$

$$\vec{B} \xleftrightarrow{T} -\vec{B} \quad \vec{E} \xleftrightarrow{T} \vec{E} \quad \vec{S} \xleftrightarrow{T} -\vec{S}$$

MDM: P even, T even

EDM: P odd, T odd

$\longrightarrow$ under CPT, CP is also broken

Electric & Magnetic Dipole Moments

Taken relativistically for fermion f with charge -e

$$\mathcal{H} = e\bar{\psi}_f \gamma^\mu \psi_f A_\mu + a_f \frac{1}{4} \bar{\psi}_f \sigma^{\mu\nu} \psi_f F_{\mu\nu} + d_f \frac{i}{2} \bar{\psi}_f \sigma^{\mu\nu} \gamma_5 \psi_f F_{\mu\nu}$$

photon field A_μ $\qquad$ $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$

$$\mu_f = g_f \frac{e}{2m_f} \qquad g_f = 2 + 2a_f$$

a_f is an anomalous magnetic moment

For an elementary fermion a_f and d_f can only be generated through loop corrections (N.B. D>4)

Operator Mass Dimension Memo

Predictive power in QFT demands than D cannot be > 4

The action $\mathcal{S}$

$$\mathcal{S} = \int d^4x \mathcal{L}$$

To make S dimensionless, we must have dim[$\mathcal{L}$] = 4.

Recall $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$ and $m\bar{\psi}\psi$

Thus $F_{\mu\nu}F^{\mu\nu}$ → dim[A^μ]=1 also dim[ψ]=3/2

$$\mathrm{dim}[\bar{\psi}\sigma^{\mu\nu}\psi F_{\mu\nu}] = 5$$

Note in chiral basis

$$m\bar{\psi}\psi = m(\bar{\psi}_L\psi_R + \bar{\psi}_R\psi_L) \quad \psi_{\substack{L \\ R}} \equiv \frac{1}{2}(1 \mp \gamma_5)$$

$$\bar{\psi}\gamma^\mu\psi = (\bar{\psi}_L\gamma^\mu\psi_L + \bar{\psi}_R\gamma^\mu\psi_R)$$

EDMs & Sensitivity to New Physics

The electric and (anomalous) magnetic moments change chirality

$$\bar{\psi}\sigma^{\mu\nu}\psi = (\bar{\psi}_L\sigma^{\mu\nu}\psi_R + \bar{\psi}_R\sigma^{\mu\nu}\psi_L)$$

$$\bar{\psi}\sigma^{\mu\nu}\gamma_5\psi = (\bar{\psi}_L\sigma^{\mu\nu}\gamma_5\psi_R + \bar{\psi}_R\sigma^{\mu\nu}\gamma_5\psi_L)$$

By dimensional analysis we infer the scaling

New Physics Scale

$$d_f \sim e\frac{\alpha}{4\pi}\frac{m_f}{\Lambda^2}\sin\phi_{\mathrm{CP}}$$

$$d_{d\,\mathrm{quark}} \sim 10^{-3}e\frac{m_d(\mathrm{MeV})}{\Lambda(\mathrm{TeV})^2} \sim 10^{-25}\frac{1}{\Lambda(\mathrm{TeV})^2}e-\mathrm{cm}$$

Note ILL limit on neutron EDM:

$d_n < 3\times10^{-26}$ e-cm @ 90%CL [Pendlebury et al., 2015]

EDM experiments have (at least) TeV scale sensitivity

EDMs in the SM

The contribution from the CKM matrix first appears in three-loop order!

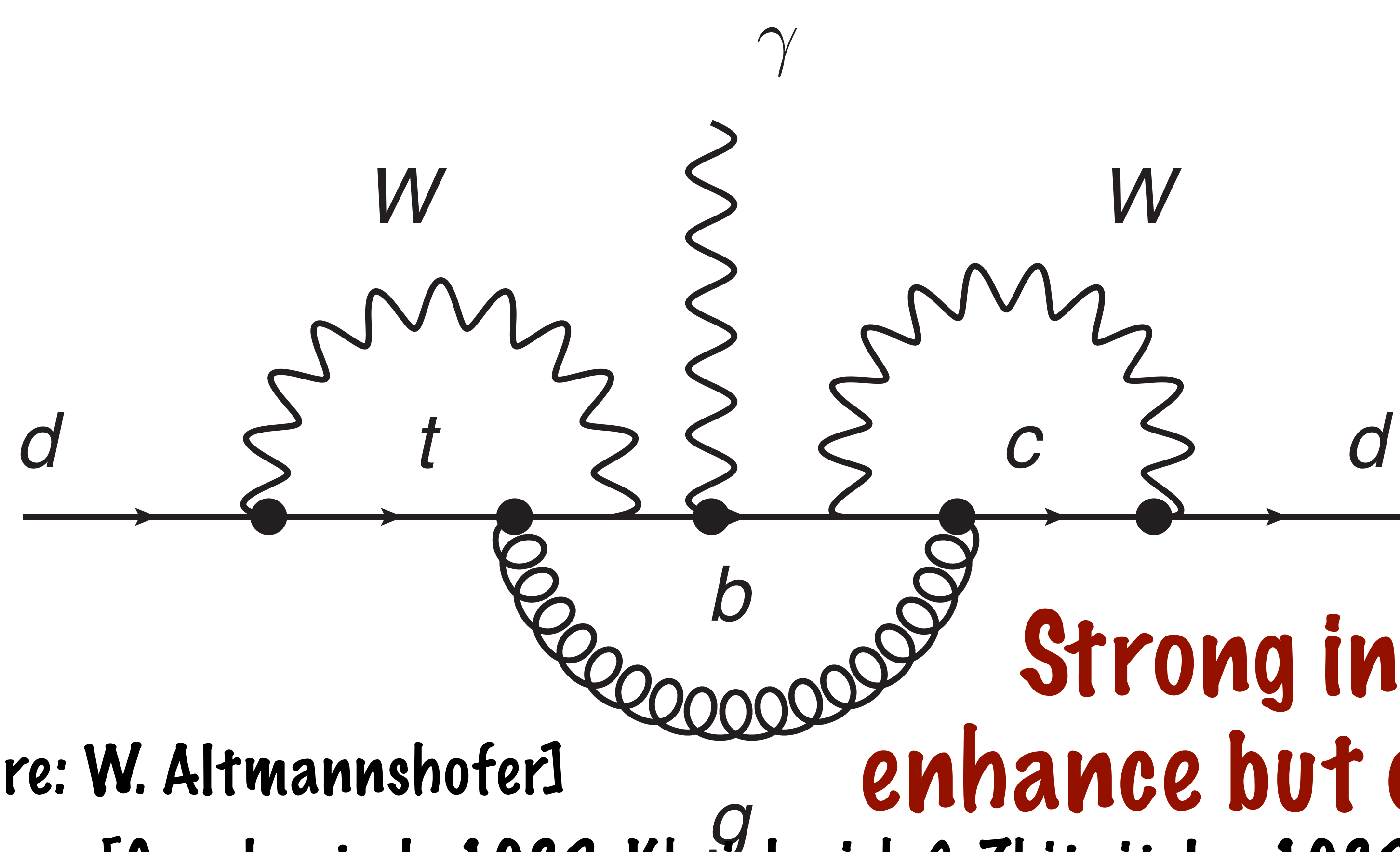
The EDM is flavor diagonal, so that…

at one-loop order no "Im V…" piece survives

at two-loop order the "Im V…" piece vanishes [Shabalin, 1978]

at three-loop order the gluon-mediated terms dominate

[Khriplovich, 1986]



$|d_d| \sim 10^{-34}$ e-cm

[Czarnecki & Krause, 1997]

Inaccessibly small!

[figure: W. Altmannshofer]

Strong interaction effects can enhance but only by $10^{2 \text{ or } 3}$ in neutron

[Gavela et al., 1982: Khriplovich & Zhitnitsky, 1982; Mannel & Uraltsev, 2012;... Seng, 2015]

Lepton EDMs in the SM

The contribution from the CKM matrix first appears in four-loop order!

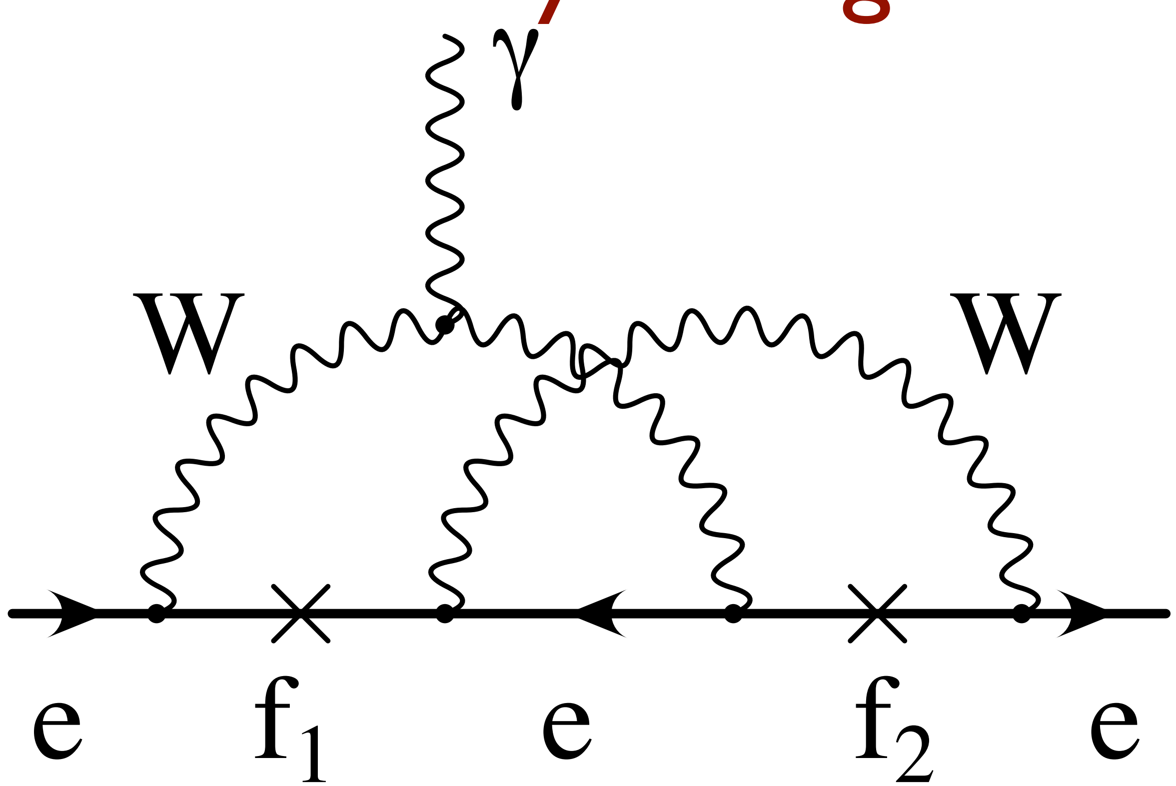
cf. d_e^{eff} *from CPV e-N*
[Pospelov & Ritz, 2013]

$d_e \sim 10^{-44}$ e-cm [Khriplovich & Pospelov, 1991]

Majorana neutrinos can enhance a lepton EDM

[Ng & Ng, 1996]

but not nearly enough to make it "visible"



For "fine tuned" parameters

$d_e \lesssim 10^{-33}$ e-cm

[Archambault, Czarnecki, & Pospelov, 2004]

Look to CPV in ν oscillations to probe leptogenesis!

Expected Physics BSM?

Models with weak scale supersymmetry have been very popular...

Here every fermion has a boson partner (and vice versa)

Because they...

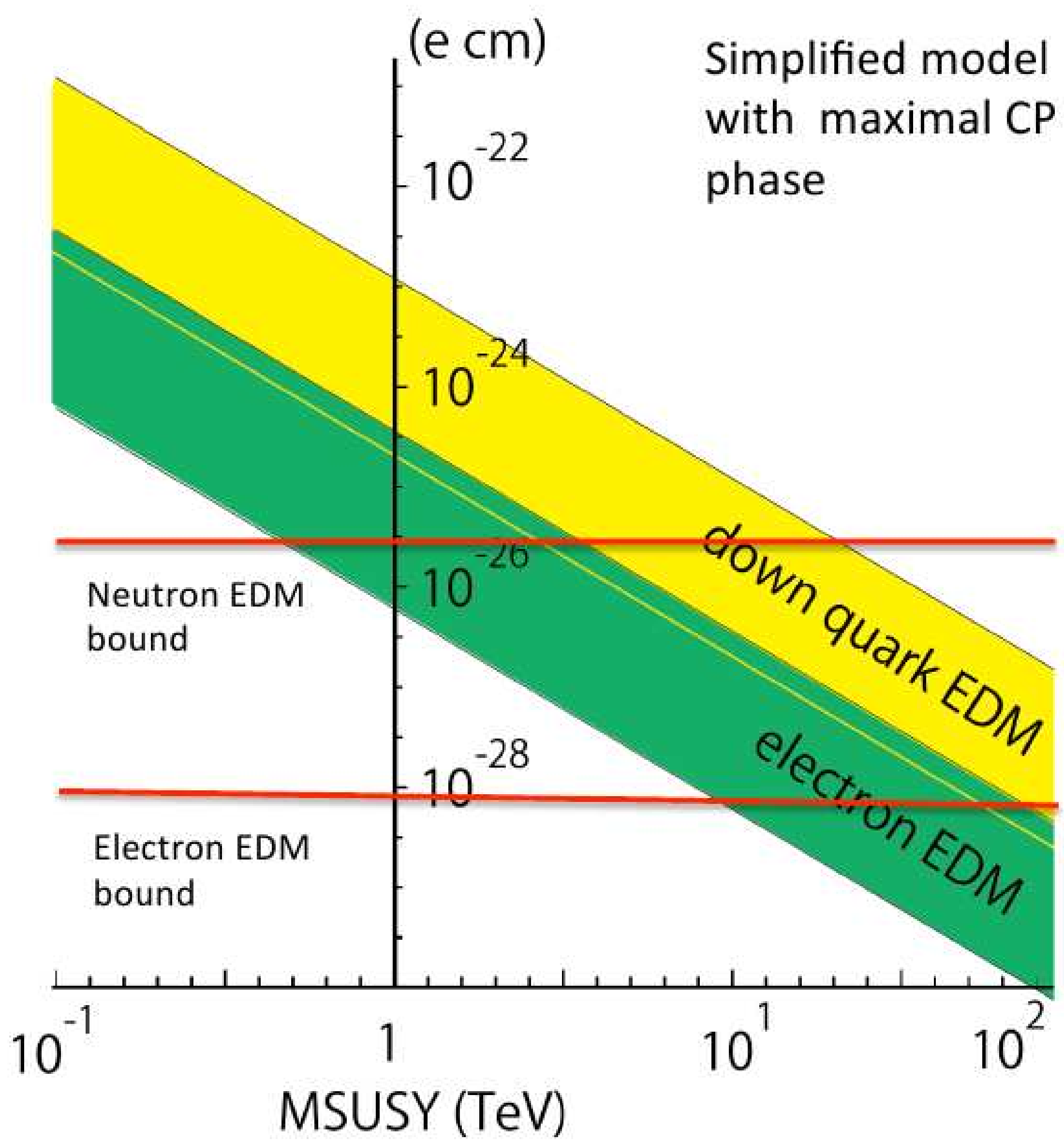
- can explain "why" the weak scale M_Z , M_W is so much lower than the Planck scale
- can possess a dark-matter candidate
- can potentially explain the cosmic baryon asymmetry
- ...

But the predicted effects have not yet been seen....

★ Many new CP phases!

EDMs & the SUSY CP Problem

Models with O(1) CP phases & weak scale supersymmetry



(Hisano @ Moriond EW 2014)

[Figure: W. Altmannshofer]

An EDM can now appear at one loop!

EDM bounds push super partner masses far above the TeV scale!

Different models can make the pertinent CP phases effectively small...

LHC results now suggest "decoupling" is a partial answer

Model Independent Analysis Framework

Suppose new physics enters at an energy scale

$$E > \Lambda$$

Then for $E < \Lambda$ we can extend the SM as per

$$\mathcal{L}_{\rm SM} \Longrightarrow \mathcal{L}_{\rm SM} + \sum_i \frac{c_i}{\Lambda^{D-4}} \mathcal{O}_i^D \,,$$

where the new operators have mass dimension D>4
and we impose $SU(2)_L \times U(1)$ gauge invariance
on the operator basis [Buchmuller & Wyler, 1986; Grzadkowski et al., 2010]

We can consider all the CP-violating terms that appear at a fixed D

Operator Analysis of EDMs

The flavor-diagonal effective Lagrangian at ~1 GeV

$$\mathcal{L}_{\dim 4} \supset \bar{\theta}\alpha_s G\tilde{G}$$

can appear in the IR even if an axion acts [Chien et al., arXiv:1510.00725, JHEP 2016]

$$\mathcal{L}_{\text{“}\dim 6\text{”}} \supset \sum_{q=u,d,s}\left(d_q\bar{q}F\sigma\gamma_5 q + \tilde{d}_q\bar{q}G\sigma\gamma_5 q\right) + \sum_{l=e,\mu} d_l\bar{l}F\sigma\gamma_5 l$$

$$\mathcal{L}_{\dim 6} \supset w g_s^3 GG\tilde{G} + \sum_{f,f',\Gamma} C'_{ff'}(\bar{f}\Gamma f')_{LL}(\bar{f}\Gamma f')_{RR}$$

$$\mathcal{L}_{\text{“}\dim 8\text{”}} \supset \sum_{q,\Gamma} C_{qq}\bar{q}\Gamma q\bar{q}\Gamma i\gamma_5 q + C_{qe}\bar{q}\Gamma q\bar{e}\Gamma i\gamma_5 e + \cdots$$

[Ritz, CIPANP, 2015]

Many sources: note effective hierarchy imposed by $SU(2)\times U(1)$ gauge invariance (chirality change!)

Limits on new CPV sources often taken “one at a time”

Operator Analysis of EDMs

Connecting from high to low scales

A single TeV scale CPV source may give rise to multiple GeV scale sources

Explicit studies of operator mixing & running effects are now available

[Chien et al., arXiv:1510.00725, JHEP 2016; Cirigliano, Dekens, de Vries, Merenghetti, 2016 & 2016]

Lattice QCD studies of single-nucleon matrix elements also exist
Enter isoscalar & isovector tensor charges...

[Bhattacharya et al., 2015 & 2016; Gupta et al., arXiv:1801.03130]

Determining the parameters of the low energy effective Lagrangian experimentally is a distinct problem

Can all the low-energy CPV sources be determined?

★ Need to interpret EDM limits in complex systems: atoms, molecules, and nuclei

{See M.J. Ramsey-Musolf next week!}

Permanent EDMs in Complex Systems

A fundamental EDM points along the particle's spin, breaking both T and P

$$\mathcal{H} = -d\vec{E}\cdot\frac{\vec{S}}{S} - \mu\vec{B}\cdot\frac{\vec{S}}{S}$$

Applied electric fields can be enormously enhanced in atoms and molecules [Purcell and Ramsey, 1950]

Searches in different systems:

paramagnetic & diamagnetic & the neutron

ACME (ThO) [Baron et al., 2014]

YbF [Hudson et al., 2011]

[Fr] Tl [Regan et al., 2002]

Hg [Graner et al., 2016]

Xe [Rosenberry & Chupp, 2001]

Ra [Bishof et al., 2016]

n [Pendlebury et al., 2015]

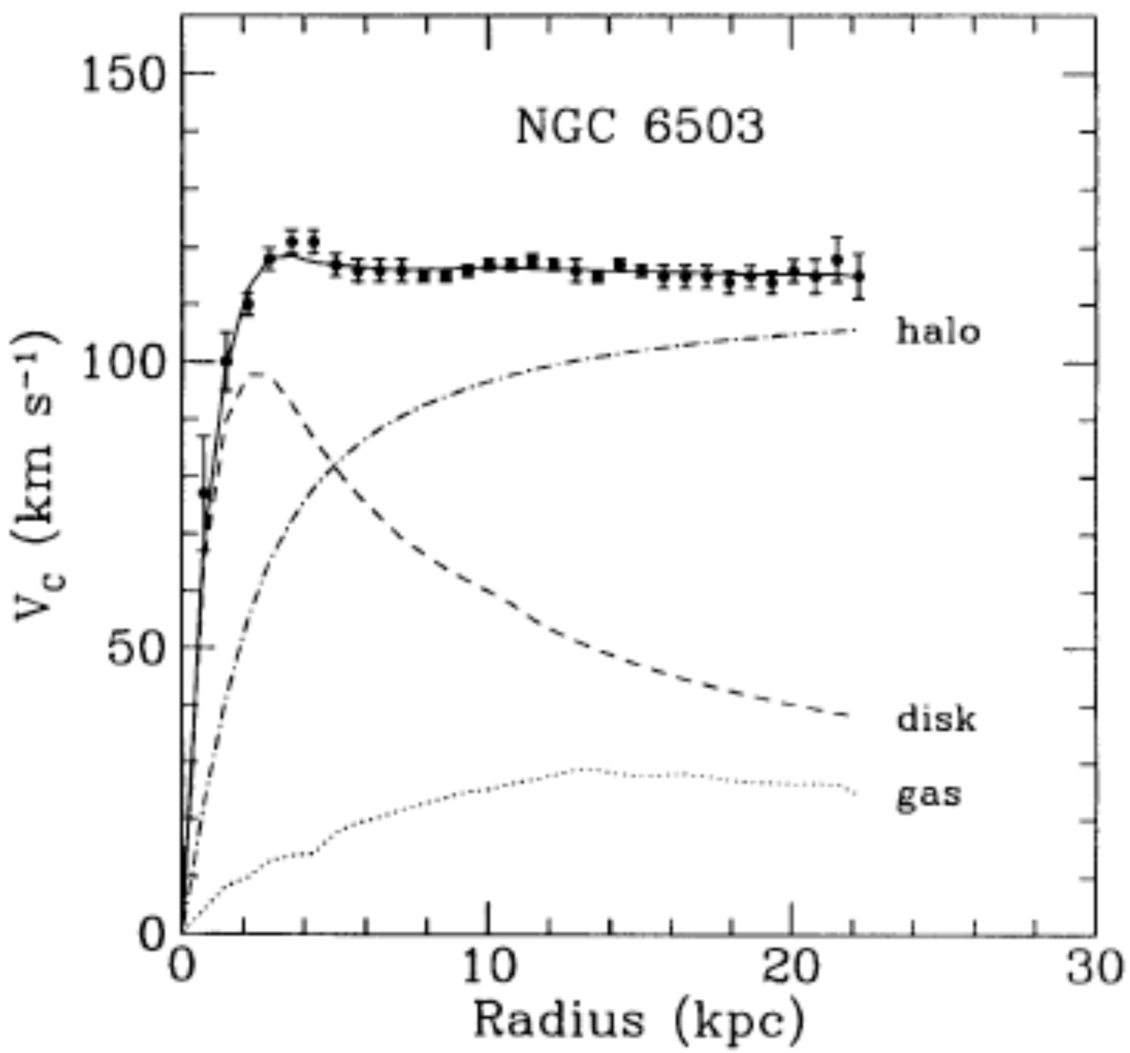
with many more (& more methods) under development!

[Pospelov & Ritz, 2005; Engel, Ramsey-Musolf, & van Kolck, 2013; Jung, 2013; Chupp et al., 2017]

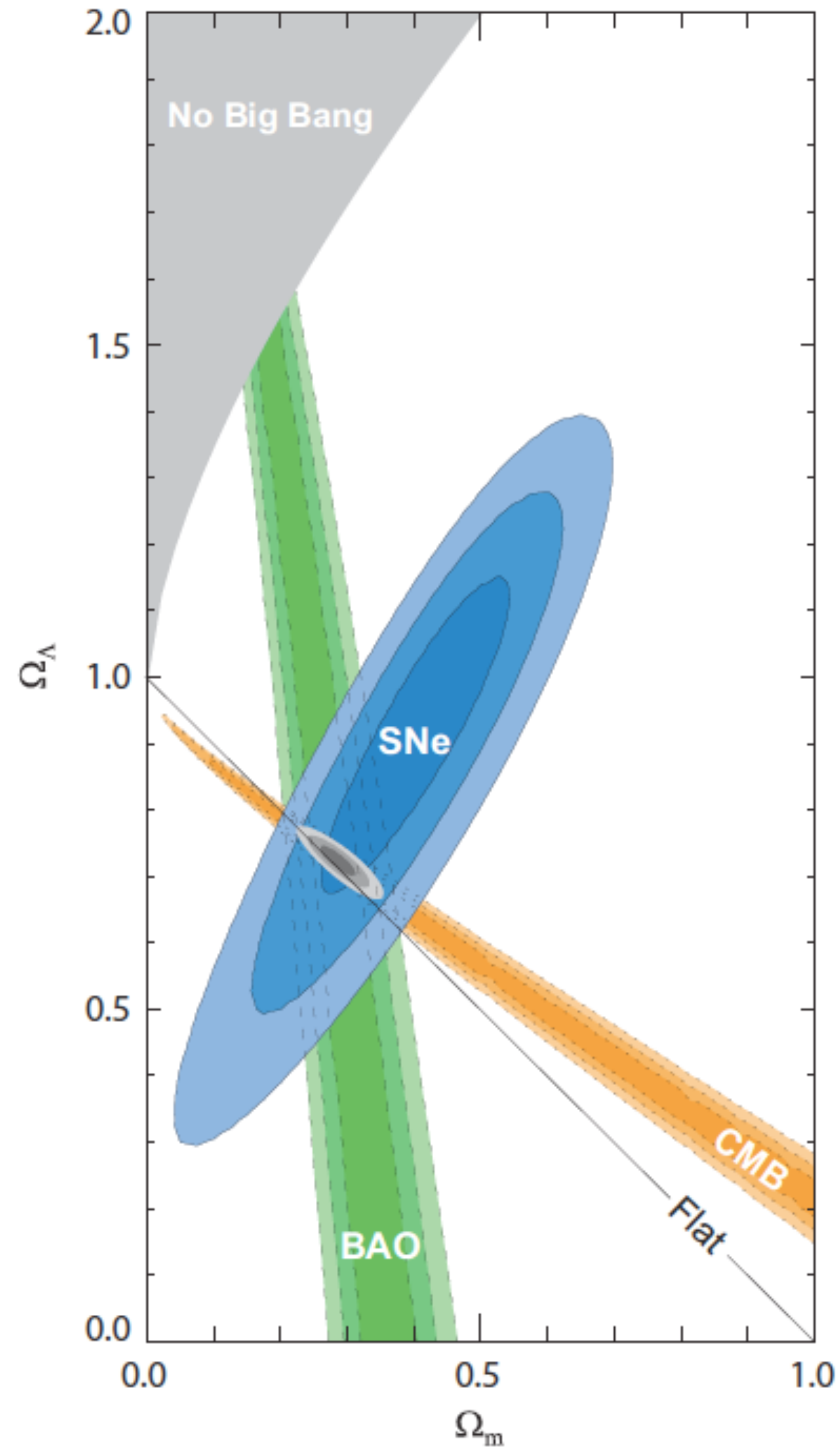
Permanent EDMs
Searches & Dark Matter

Observational Evidence for Dark Matter ranges from "local" to cosmic scales

Galactic Rotation Curves:
[e.g., from Begeman, Broeils, and Sanders, 1991]



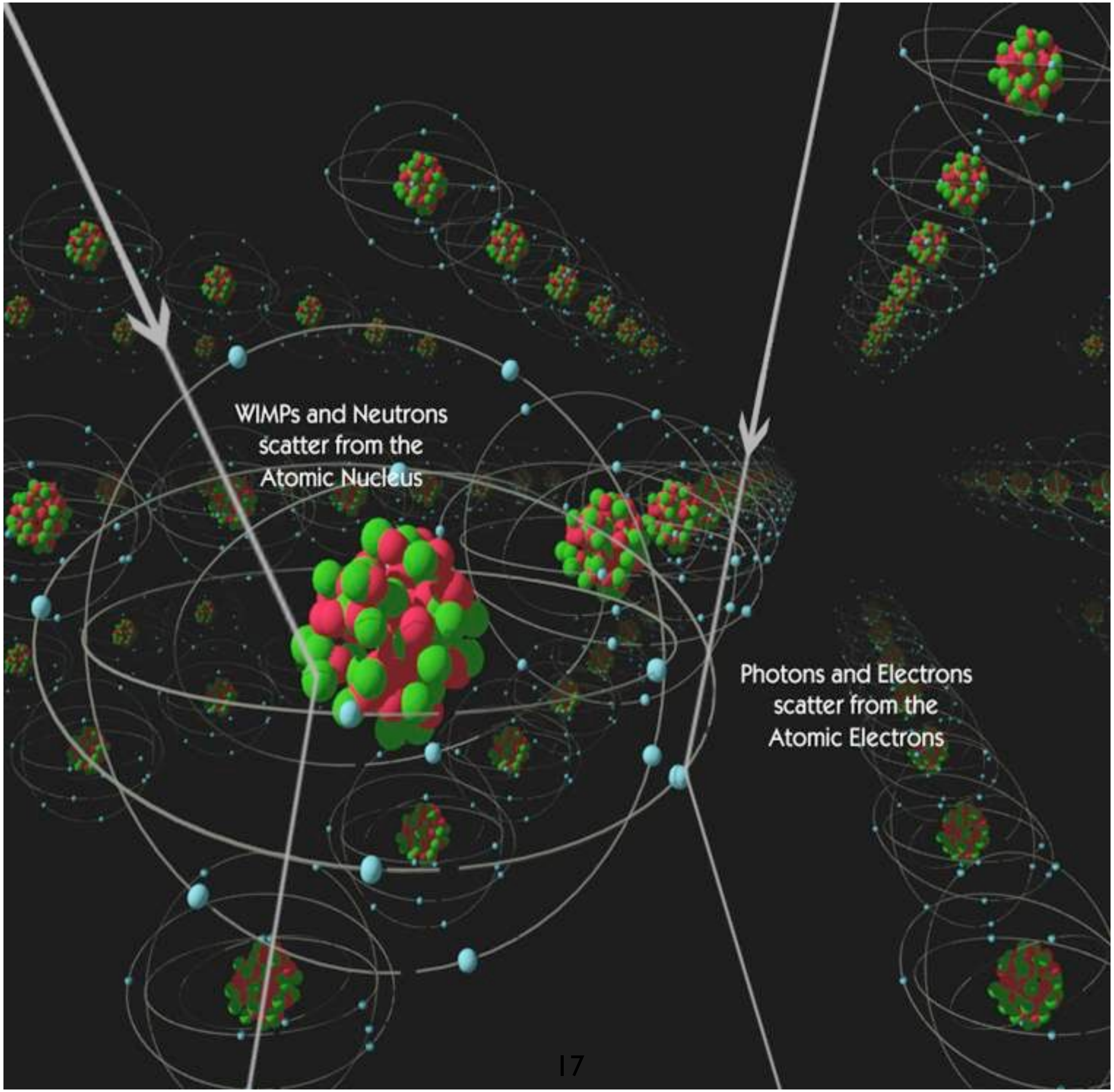
The observed circular speed does not track the luminous mass.



Most of the cosmic energy budget is of an unknown form!

Direct Detection: Dark Matter "WIMPs"

[from cdms.berkeley.edu; note Drukier & Stodolsky, 1984; Goodman & Witten, 1985]



$M_{WIMP} \sim 100$ GeV

Dark Matter & the CMB

Opening the axion window....

Observations of the CMB power spectrum constrain the ratio of tensor (gravitational wave) to scalar (density fluctuations) power r

$r < 0.07$ at 95% C.L. [Ade et al., PRL 116 (2016) 031302] (BICEP2 + Keck + Planck)]

This quantity has not been detected making ultralight (axion-like) dark matter ($m_a \sim 10^{-22}$ eV) **"fuzzy (quantum wave) dark matter" possible....**

[Hu, Barkana, Gruzinov, PRL 85 (2000) 1158;
Schive, Chiueh, Broadhurst, Nat. Phys. 10 (2014) 496...;
Graham & Rajendran, PRD 84 (2011) 055013,... for direct detection prospects]

Direct Detection: Ultralight Dark Matter

A new paradigm: axion-like dark matter

The axion originally appears as a solution to the strong CP violation (in QCD) and emerges from spontaneously broken Peccei-Quinn symmetry

Here we consider an axion-like particle which is not tied to that origin

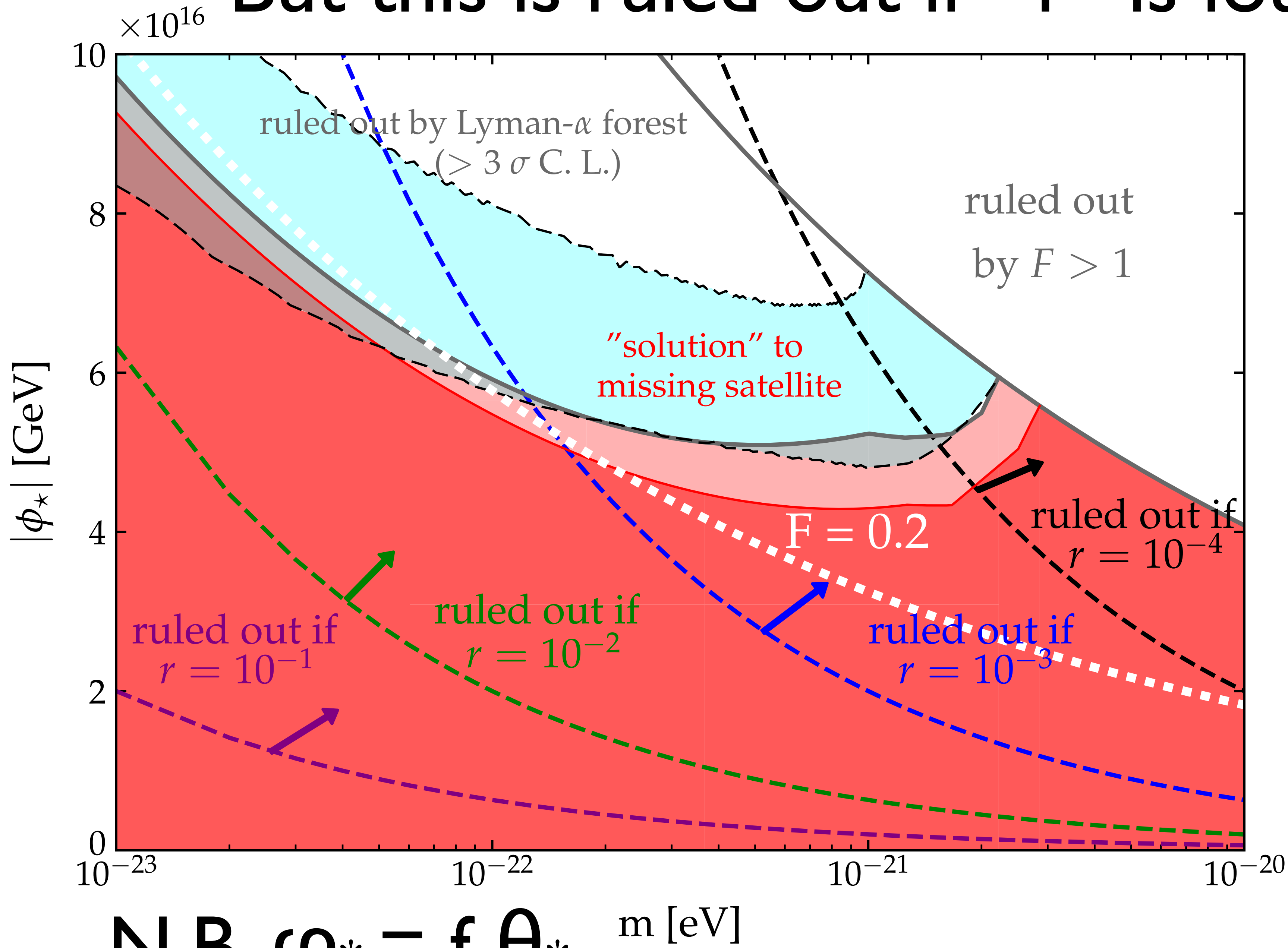
An ultralight axion can induce a time-varying EDM!

(Axions possess a vast parameter space….)

Ultralight Axion Window

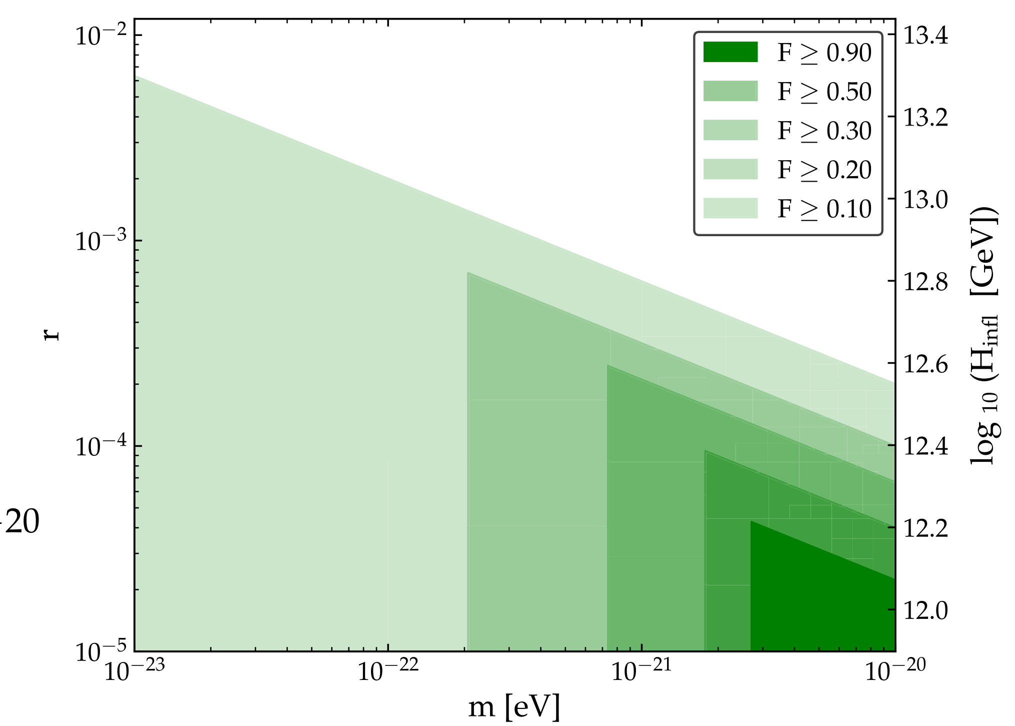
A new pseudoscalar boson (not connected to QCD) can explain the "dark matter"!

But this is ruled out if "r" is found to be too big!

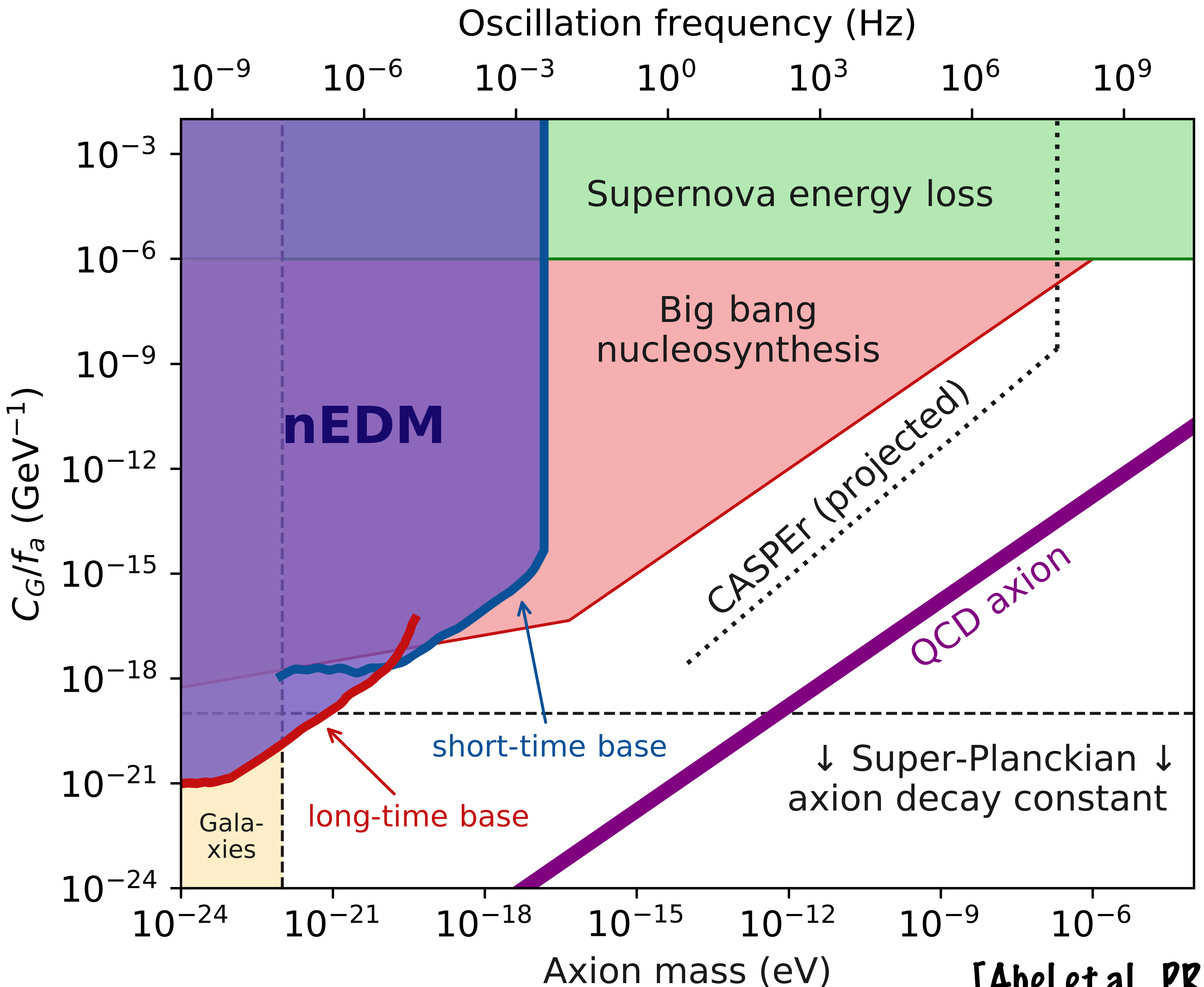


N.B. $\varphi_* = f_a \theta_*$

Kobayashi et al., PRD 96 (2017) 123514



Direct Detection: Ultralight Dark Matter



[Abel et al., PRX, 2017]

Gauge Theories of a Hidden Sector

Only a Few "Sizeable" Portals Exist

$$\mathcal{L}_{\dim\leq 4} = \kappa B^{\mu\nu}V_{\mu\nu} - H^\dagger H(AS + \lambda S^2) - Y_N LHN$$

[Batell, Pospelov, and Ritz, 2009; Le Dall, Pospelov, Ritz, 2015]

- Vector Portal
- Higgs Portal
- Neutrino Portal

All deserve systematic study;
N.B. low E Higgs portal
constrained by rare B, K decays

Here we focus on vector portals

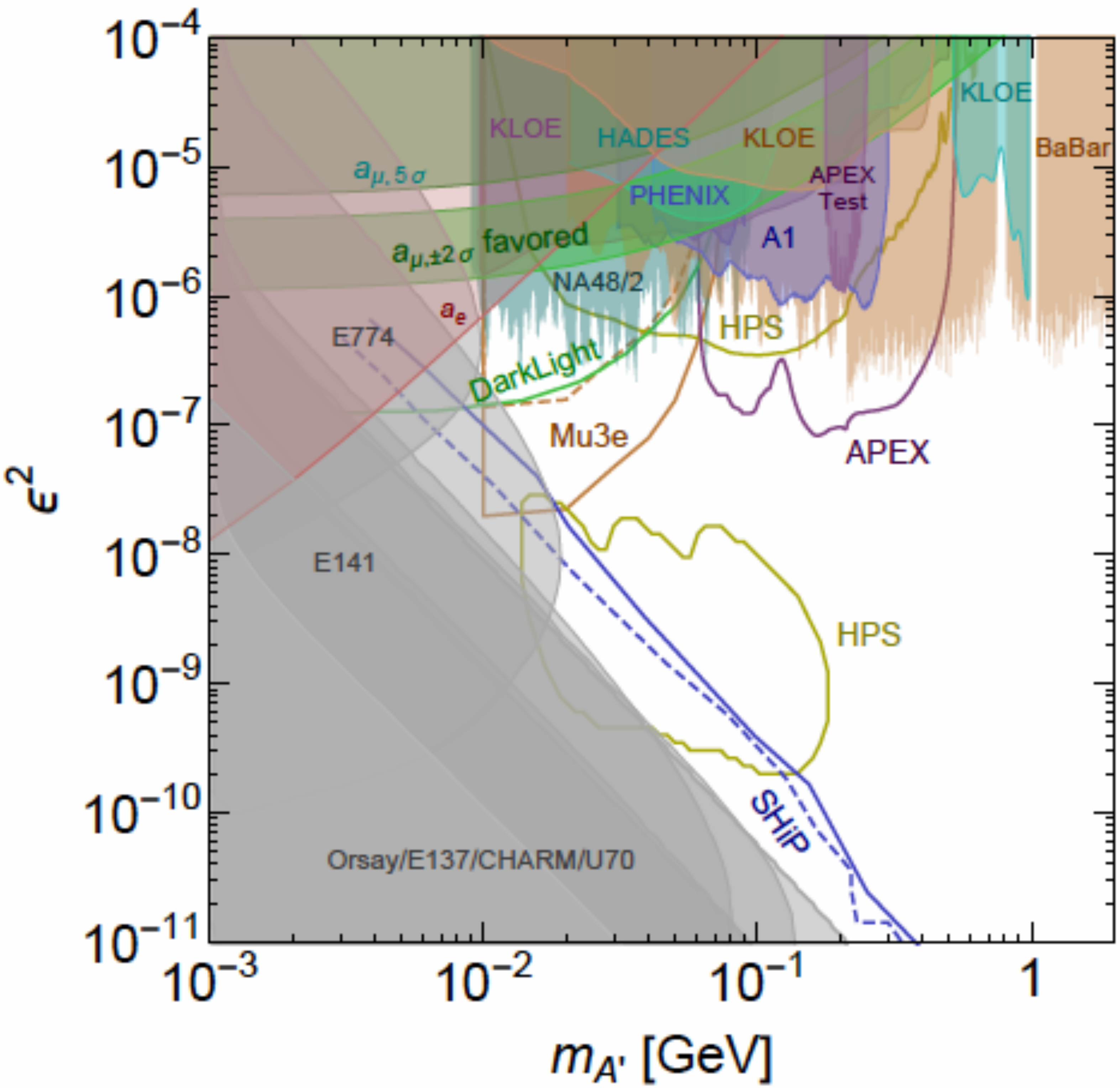
Enter the dark photon A´and its field strength tensor $V^{\mu\nu}$

$$\mathcal{L}_{A'} = \frac{1}{2}\kappa B^{\mu\nu}V_{\mu\nu} - \frac{1}{4}V_{\mu\nu}V^{\mu\nu} + \frac{1}{2}m^2_{A'}A'^{\mu}A'_{\mu}$$

→ Note "kinetic mixing" of visible & hidden sectors

Dark Photon Decays to Visibles (Only)

Exclude a "dark" explanation of the muon g-2 anomaly



But this may only speak to our assumptions…

Higher-Mass Dimension Portals

These generate "long distance" effects in that they are mediated by new, light degrees of freedom

cf. with the axion: long range effects from a dimension 5 operator

$$\frac{1}{F}(\partial_\mu a)\bar{f}i\gamma_5\gamma^\mu f \quad \longleftrightarrow \quad g_{P_f} a\bar{f}i\gamma_5 f \ \text{ with } \ g_{P_f} = \frac{m_f}{F}$$

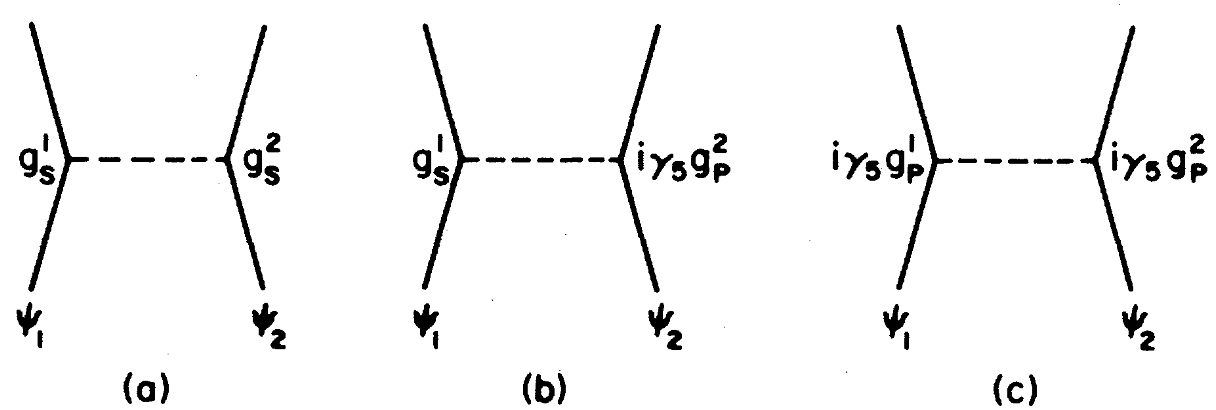


FIG. 1. Graphs for the potentials of Eqs. (4), (5), and (6). (a) (Monopole),[2] (b) monopole-dipole, (c) (dipole).[2]

$$V_{\rm dd} \sim \frac{g_{P_f}^2}{m_f^2 r^3}\left[\hat{\sigma}_1\cdot\hat{\sigma}_2\left(1+\frac{r}{\lambda}\right) - 3(\hat{\sigma}_1\cdot\hat{r})(\hat{\sigma}_2\cdot\hat{r})\left(1+\frac{r}{\lambda}+\frac{r^2}{3\lambda^2}\right)\right]e^{-r/\lambda}$$

[Moody & Wilczek, 1984; Terrano, Adelberger, Lee, & Heckel, arXiv:1508.02463]

New Spin-Dependent Forces?

Such outcomes have long been associated with the effects of ultralight pseudo-Goldstone bosons (pGB)

And w/ T, P-violating forces from an axion-like boson

[Moody & Wilczek, 1984]

N.B. new, strong limits on spin-dependent forces from pGB exchange

N.B. new physics scale F

$$m_b \leq 500\mu\mathrm{eV}\,; \quad \lambda \sim 1/m_b$$

$$g_p = m_f/F\,; \quad m_b = \Lambda^2/F$$

[Terrano, Adelberger, Lee, & Heckel, arXiv:1508.02463]

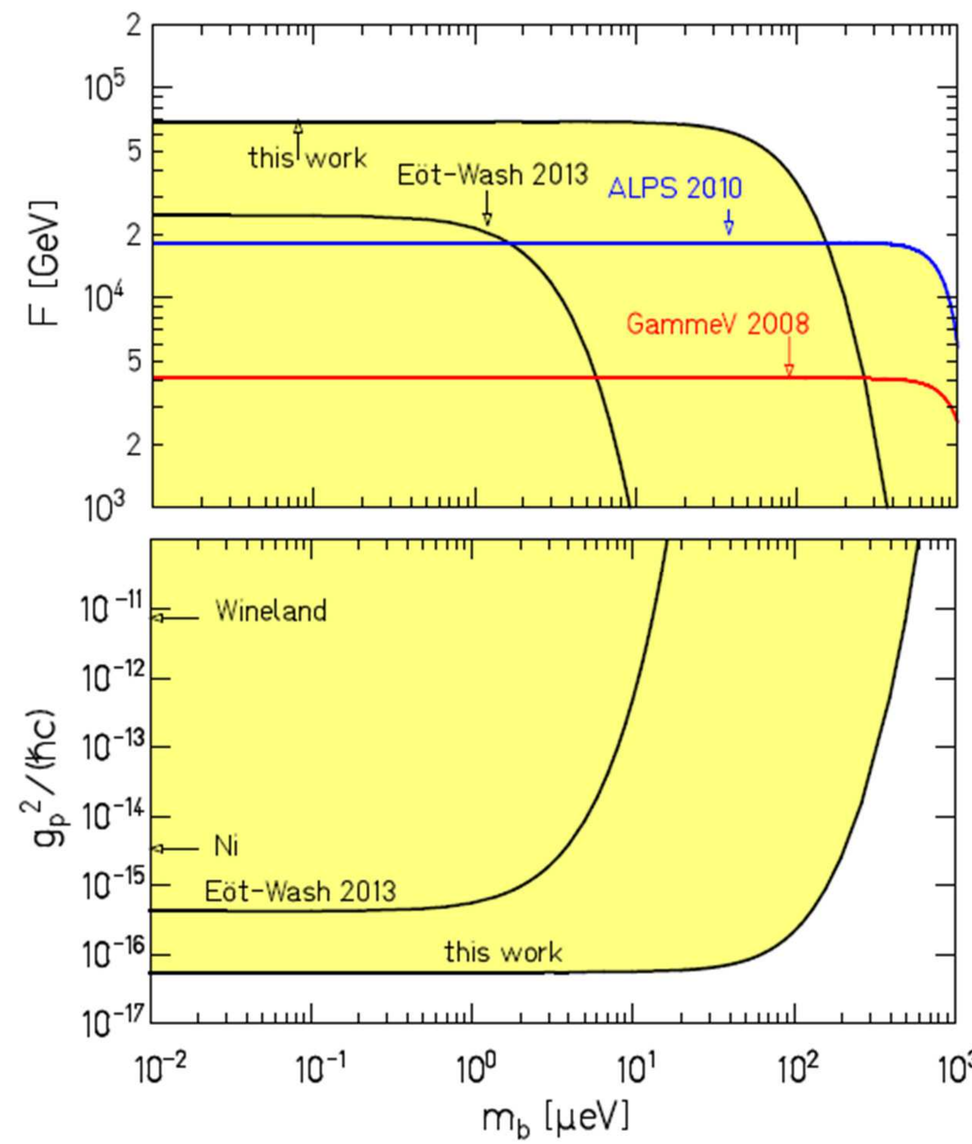


FIG. 4: Bottom: exotic dipole-dipole limits from this work and Ref. [5]. Arrows indicate the infinite-range constraints from Refs. [12, 13]. Electron $g-2$ constraints are at the 10^{-10} level[14]. Top: limits on the symmetry-breaking scale from this work and Refs. [15, 16]. The shaded areas are excluded at 2σ.

Summary

EDMs are sensitive to new sources of CP violation at the TeV scale and beyond

Although CP is not a symmetry of the Standard Model, the SM "background" is completely negligible for the planned new generation of experiments

EDMs of nucleons, light nuclei, atoms, molecules can probe different new sources of CP violation

EDM experiments can also be used to limit the appearance of ultralight (axion-like) dark matter &....

Searches for Baryon Number Violation

Origins of the Neutrino Mass

The Majorana mass and 0 ν ββ decay

A neutrino can have a Majorana mass if B-L symmetry is broken

(Enter the Weinberg operator $(v_{\underline{weak}}{}^2/\Lambda_{new})\ \nu_L{}^T C\ \nu_L$)

→ Or (and) the neutrino could have a Dirac mass

(Enter the right-handed neutrino & the Higgs mechanism)

But only B-L violation permits 0 ν ββ decay

However, 0 ν ββ decay need not mediated by the exchange of a light Majorana ν (other sources could act); though its observation would show it effectively exists

[Schechter & Valle, 1982]

Mechanisms of 0ν ββ decay

Why the energy scale of B-L violation matters

If it is generated by the Weinberg operator, then SM electroweak symmetry yields $m_\nu = \lambda v_{\rm weak}^2/\Lambda$. If $\lambda \sim 1$ and $\Lambda \gg v_{\rm weak}$, then naturally $m_\nu \ll m_f$!
N.B. if $m_\nu \sim 0.2$ eV, then $\Lambda \sim 1.6 \times 10^9$ GeV!

Alternatively it could also be generated by higher dimension $|\Delta L| = 2$ operators, so that m_ν is small just because $d \gg 4$ and Λ need not be so large.

[EFTs: Babu & Leung, 2001; de Gouvea & Jenkins, 2008 and many models]

Can we establish the scale of $\mathcal{B} - \mathcal{L}$ violation in another way?

N.B. searches for same sign dilepton final states at the LHC also constrain the higher dimension ("short range") operators. [Helo, Kovalenko, Hirsch, and Päs, 2013]

Here we consider B-L violation in the quark sector: via n-$\bar{\rm n}$ transitions

B-L Violation & n-$\bar{n}$ Transitions

It has long been thought that *n*-$\bar{n}$ oscillations could shed light on the mechanism of

- Baryogenesis [Kuzmin, 1967]
- Neutrino mass [Mohapatra and Marshak, 1980]

The observation of *n*-$\bar{n}$ transformations would reveal that $\mathcal{B} - \mathcal{L}$ is indeed broken.

Extracting the scale of $\mathcal{B} - \mathcal{L}$ breaking from such a result can be realized through a matrix element computation in lattice QCD. There has been much progress towards this goal.

[Buchoff, Schroeder, and Wasem, 2012; Buchoff and Wagman, 2016; Syritsen, Buchoff, Schroeder, and Wasem, 2016]

In contrast to proton decay, *n*-$\bar{n}$ probes new physics at “intermediate” energy scales. The two processes can be generated by **d=6** and **d=9** operators, respectively.

Crudely, $\Lambda_{p\,decay} \geq 10^{15}\,\mathrm{GeV}$ and $\Lambda_{n\bar{n}} \geq 10^{5.5}\,\mathrm{GeV}$.

Observing a neutron-antineutron transition would show that B-L violation does exists at an intermediate (~100 TeV) scale….

Neutron-Antineutron Transitions

Can be realized in different ways

Enter searches for

- neutron-antineutron oscillations (free n's & in nuclei)

"spontaneous"
& thus sensitive to
environment

$$\mathcal{M} = \begin{pmatrix} M_n - \mu_n B & \delta \\ \delta & M_n + \mu_n B \end{pmatrix}$$

$$P_{n\to\bar{n}}(t) \simeq \frac{\delta^2}{2(\mu_n B)^2}\left[1 - \cos(2\mu_n B t)\right]$$

- dinucleon decay (in nuclei)
  (limited by finite nuclear density)
- neutron-antineutron conversion (NEW!)

[SG & Xinshuai Yan, arXiv:1710.09292, PRD 2018 (also arXiv:1602.00693, PRD 2016)]

n - n̄ Transitions & Spin

Spin can play a role in a "mediated" process

A neutron-antineutron **oscillation** is a spontaneous process & thus the spin does not ever flip

However,

$$\mathcal{O}_4 = \psi^T C\gamma^\mu\gamma_5\psi\,\partial^\nu F_{\mu\nu} + \mathrm{h.c.}$$

$n(+) \to \bar{n}(-)$ occurs directly because the interaction with the current flips the spin.

This is concomitant with $n(p_1, s_1) + n(p_2, s_2) \to \gamma^*(k)$, for which only $L = 1$ and $S = 1$ is allowed via angular momentum conservation and Fermi statistics. [Berezhiani and Vainshtein, 2015]

Here $e + n \to \bar{n} + e$, e.g., so that the experimental concept for "$n\bar{n}$ conversion" would be completely different.

Effective Lagrangian

Neutron interactions with B-L violation & electromagnetism

$$\mathcal{L}_{\text{eff}} \supset -\frac{1}{2}\mu_n \bar{n}\sigma^{\mu\nu} n F_{\mu\nu} - \frac{\delta}{2} n^T C n - \frac{\eta}{2} n^T C \gamma^\mu \gamma^5 n j_\mu + \text{h.c.}$$

$$[\, Qej^\nu = \partial_\mu F^{\mu\nu} \,]$$

magnetic moment

$n \to \bar{n}$ oscillation

$n \to \bar{n}$ conversion

"spontaneous" → oscillation

[SG & Xinshuai Yan, arXiv: 1710.09292]

Since the quarks carry electric charge, a BSM model that generates neutron-antineutron oscillations can also generate conversion

Neutron-Antineutron Conversion

Different mechanisms are possible

* n-$\bar{n}$ conversion and oscillation could share the same "TeV" scale BSM sources
  → Then the quark-level conversion operators can be derived noting the quarks carry electric charge

* n-$\bar{n}$ conversion and oscillation could come from different BSM sources
  → Then the neutron-level conversion operators could also be different

Note studies of scattering matrix elements of Majorana dark matter [Kumar & Marfatia, PRD, 2013]

Summary (BNV)

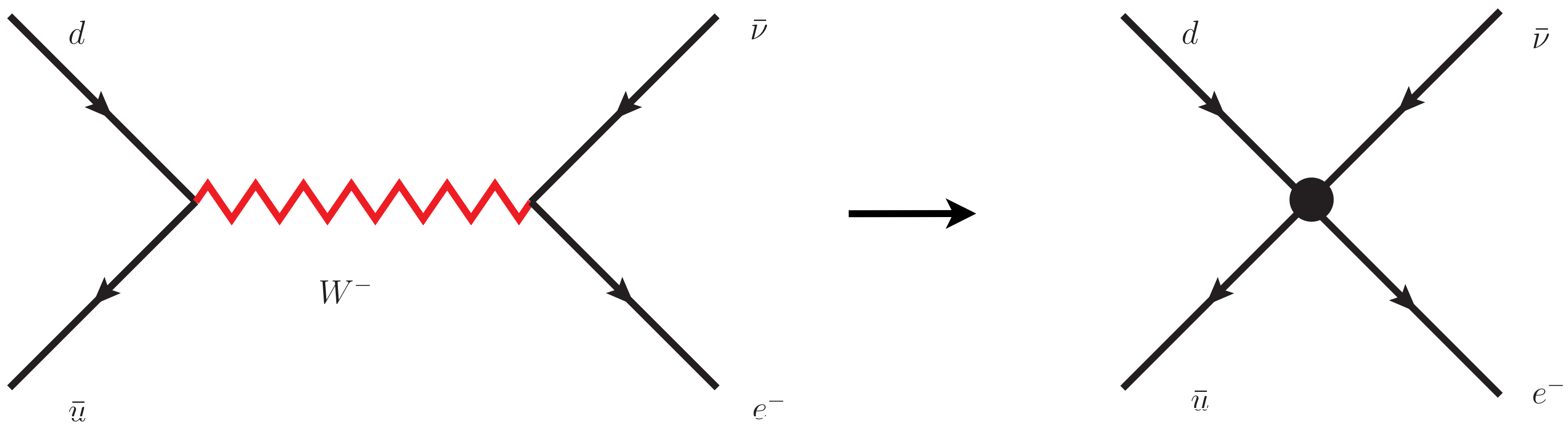
- The discovery of B-L violation would reveal the existence of dynamics beyond the Standard Model
- The energy scale of B-L violation speaks to different explanations as to why the neutrino is light (A "TeV scale" mechanism could also generate B-L violation in the quark sector)
- We have discussed neutron-antineutron conversion, i.e., neutron-antineutron transitions as mediated by an external current (as via scattering)
- Neutron-antineutron conversion is not sensitive to medium effects and can also yield limits on the neutron's Majorana mass. It can also lead to the discovery of B-L violation in its own right
- Experiments with intense low-energy electron or neutron beams can also be used to search for B-L violation

Beta Decay Searches
for new S, T degrees of freedom

BSM Searches at Low Energies

The interplay of precision and energy reach

That the charged weak current of the SM is universal and respects a "V-A" law is captured by



$SU(2)_L \times U(1)$ $\quad\quad$ $G_F \sim g^2/M_W^2$

New physics searches at low energy trade on the ability to test the pattern of the SM through precision measurement

Analysis Framework

!!

Suppose new physics enters at energies beyond a scale Λ

Then for $E < \Lambda$ we can extend the SM as per

$$\mathcal{L}_{\rm SM} \Longrightarrow \mathcal{L}_{\rm SM} + \sum_i \frac{c_i}{\Lambda^{D-4}} \mathcal{O}_i^D \,,$$

where the new operators have mass dimension D>4

Symmetries guide their construction [Weinberg, 1979]

We impose $SU(2)_L \times U(1)$ gauge invariance on the operator basis (flavor physics constraints)

New physics can enter as (i) new operators or as (ii) modifications of c_i for operators in the SM

cf. non-V-A tests with tests of CKM unitarity

Theoretical Framework

$$\mathcal{L}^{\mathrm{eff}} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{1}{\Lambda_i^2} O_i \Longrightarrow \mathcal{L}_{\mathrm{SM}} + \frac{1}{v^2} \sum_i \hat{\alpha}_i O_i \,,$$

with $\hat{\alpha}_i = v^2/\Lambda_i{}^2$. [Buchmuller & Wyler, 1986; Grzadkowski et al., 2010; Cirigliano, Jenkins, González-Alonso, 2010; Cirigliano, González-Alonso, Graesser, 2013]

Radiative correction*!

$$\begin{aligned}
\mathcal{L}^{\mathrm{eff}} = -\frac{G_F^{(0)} V_{ud}}{\sqrt{2}} \Big[& \Big(1 + \delta_\beta\Big)\ \bar{e}\gamma_\mu(1-\gamma_5)\nu_e \cdot \bar{u}\gamma^\mu(1-\gamma_5)d \\
+ \quad & \epsilon_L\ \bar{e}\gamma_\mu(1-\gamma_5)\nu_\ell \cdot \bar{u}\gamma^\mu(1-\gamma_5)d + \tilde{\epsilon}_L\ \bar{e}\gamma_\mu(1+\gamma_5)\nu_\ell \cdot \bar{u}\gamma^\mu(1-\gamma_5)d \\
+ \quad & \epsilon_R\ \bar{e}\gamma_\mu(1-\gamma_5)\nu_\ell \cdot \bar{u}\gamma^\mu(1+\gamma_5)d + \tilde{\epsilon}_R\ \bar{e}\gamma_\mu(1+\gamma_5)\nu_\ell \cdot \bar{u}\gamma^\mu(1+\gamma_5)d \\
+ \quad & \epsilon_S\ \bar{e}(1-\gamma_5)\nu_\ell \cdot \bar{u}d + \tilde{\epsilon}_S\ \bar{e}(1+\gamma_5)\nu_\ell \cdot \bar{u}d \\
- \quad & \epsilon_P\ \bar{e}(1-\gamma_5)\nu_\ell \cdot \bar{u}\gamma_5 d - \tilde{\epsilon}_P\ \bar{e}(1+\gamma_5)\nu_\ell \cdot \bar{u}\gamma_5 d \\
+ \quad & \epsilon_T\ \bar{e}\sigma_{\mu\nu}(1-\gamma_5)\nu_\ell \cdot \bar{u}\sigma^{\mu\nu}(1-\gamma_5)d + \tilde{\epsilon}_T\ \bar{e}\sigma_{\mu\nu}(1+\gamma_5)\nu_\ell \cdot \bar{u}\sigma^{\mu\nu}(1+\gamma_5)d \\
+ \quad & \text{h.c.}\ .
\end{aligned}$$

*[Sirlin, 1974, 1978, 1982; Marciano & Sirlin, 1986, 2006; Czarnecki, Marciano, & Sirlin, 2004]

Note right-handed neutrinos appear explicitly

QCD (hadron matrix elements) also play a key role!

Theoretical Framework

Fixing the Fermi constant

$$G_F^{(0)}/\sqrt{2} = g^2/8M_W^2 \quad \text{is fixed from muon decay}$$

$$\mathcal{L}_{\mu\to e\bar{\nu}_e\nu_\mu} = -4\,G_F^{(0)}\,(1+\delta_\mu+\epsilon_\mu)\;\; \bar{e}_L\gamma_\mu\nu_{eL}\cdot\bar{\nu}_{\mu L}\gamma^\mu\mu_L \;\;+\;\; \text{h.c.}$$

[van Ritbergen & Stuart, 2000]

[N.B. MuLan expt, Chitwood, 2007]

$$G_\mu \equiv G_F^{(0)}(1+\delta_\mu+\epsilon_\mu)$$

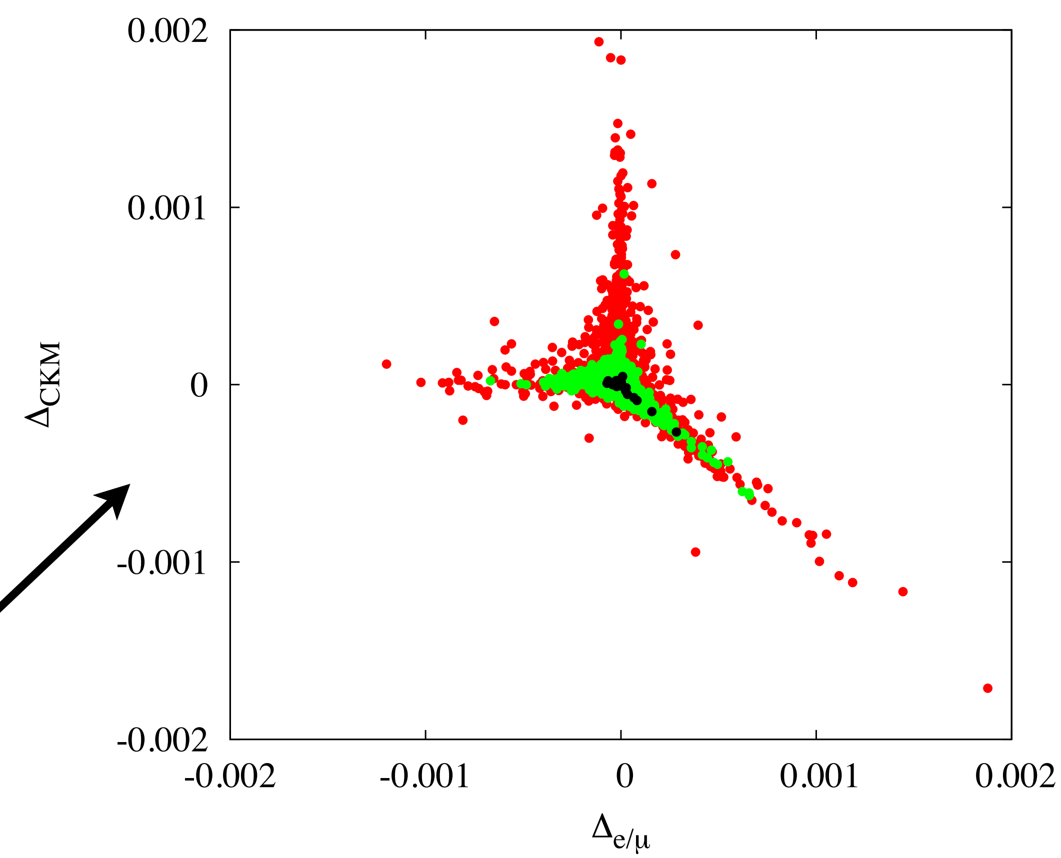
New physics!

Thus testing CKM unitarity probes weak universality!

Also each extracted V_{ij} can contain BSM effects

N.B. explicit studies in the MSSM...

[Kurylov & Ramsey-Musolf, 2002; Bauman, Erler, Ramsey-Musolf, 2012]



Theoretical Framework

On non "V-A" currents

$$
\begin{aligned}
\mathcal{L}^{\rm eff} = -\frac{G_F^{(0)} V_{ud}}{\sqrt{2}} \Big[& \Big(1+\delta_\beta\Big)\ \bar{e}\gamma_\mu(1-\gamma_5)\nu_e \cdot \bar{u}\gamma^\mu(1-\gamma_5)d \\
+ \quad & \epsilon_L\ \bar{e}\gamma_\mu(1-\gamma_5)\nu_\ell \cdot \bar{u}\gamma^\mu(1-\gamma_5)d + \tilde{\epsilon}_L\ \ \bar{e}\gamma_\mu(1+\gamma_5)\nu_\ell \cdot \bar{u}\gamma^\mu(1-\gamma_5)d \\
+ \quad & \epsilon_R\ \ \bar{e}\gamma_\mu(1-\gamma_5)\nu_\ell \cdot \bar{u}\gamma^\mu(1+\gamma_5)d\ +\ \tilde{\epsilon}_R\ \ \bar{e}\gamma_\mu(1+\gamma_5)\nu_\ell \cdot \bar{u}\gamma^\mu(1+\gamma_5)d \\
+ \quad & \epsilon_S\ \ \bar{e}(1-\gamma_5)\nu_\ell \cdot \bar{u}d\ +\ \tilde{\epsilon}_S\ \ \bar{e}(1+\gamma_5)\nu_\ell \cdot \bar{u}d \\
- \quad & \epsilon_P\ \ \bar{e}(1-\gamma_5)\nu_\ell \cdot \bar{u}\gamma_5 d\ -\ \tilde{\epsilon}_P\ \ \bar{e}(1+\gamma_5)\nu_\ell \cdot \bar{u}\gamma_5 d \\
+ \quad & \epsilon_T\ \bar{e}\sigma_{\mu\nu}(1-\gamma_5)\nu_\ell \cdot \bar{u}\sigma^{\mu\nu}(1-\gamma_5)d\ +\ \tilde{\epsilon}_T\ \bar{e}\sigma_{\mu\nu}(1+\gamma_5)\nu_\ell \cdot \bar{u}\sigma^{\mu\nu}(1+\gamma_5)d \\
+ \quad & \text{h.c.}\ .
\end{aligned}
$$

ϵ_S , ϵ_T enter

in linear order!

"most visible"

$$R_\pi \equiv \Gamma(\pi \to e\nu[\gamma])/\Gamma(\pi \to \mu\nu[\gamma]).$$

$\epsilon_L + \epsilon_R$	CKM unitarity
$\epsilon_L - \epsilon_R,\quad \epsilon_P,\quad \tilde{\epsilon}_P$	R_π
ϵ_S	$b,\ B\ \ [a,\ A]$
ϵ_T	$b,\ B\ \ [a,\ A],\ \ \pi \to e\nu\gamma$
$\tilde{\epsilon}_{\alpha\neq P}$	R_π

Theoretical Framework

Connecting to Lee and Yang....

$$\mathcal{H}_{int} = (\bar\psi_p\psi_n)(C_S\bar\psi_e\psi_\nu - C'_S\bar\psi_e\gamma_5\psi_\nu) + (\bar\psi_p\gamma_\mu\psi_n)(C_V\bar\psi_e\gamma^\mu\psi_\nu - C'_V\bar\psi_e\gamma^\mu\gamma_5\psi_\nu)$$
$$-(\bar\psi_p\gamma_\mu\gamma_5\psi_n)(C_A\bar\psi_e\gamma^\mu\gamma_5\psi_\nu - C'_A\bar\psi_e\gamma^\mu\psi_\nu) + (\bar\psi_p\gamma_5\gamma_\mu\psi_n)(C_P\bar\psi_e\gamma_5\psi_\nu - C'_P\bar\psi_e\psi_\nu)$$
$$+\frac{1}{2}(\bar\psi_p\sigma_{\lambda\mu}\psi_n)(C_T\bar\psi_e\sigma^{\lambda\mu}\psi_\nu - C'_T\bar\psi_e\sigma^{\lambda\mu}\gamma_5\psi_\nu) + h.c.$$

The terms appear in a one-to-one map....

$$\begin{aligned}
C_i &= \frac{G_F^{(0)}}{\sqrt{2}} V_{ud}\,\bar C_i \\
\bar C_V &= g_V\,(1+\delta_\beta+\epsilon_L+\epsilon_R+\tilde\epsilon_L+\tilde\epsilon_R) \\
\bar C'_V &= g_V\,(1+\delta_\beta+\epsilon_L+\epsilon_R-\tilde\epsilon_L-\tilde\epsilon_R) \\
\bar C_A &= -g_A\,(1+\delta_\beta+\epsilon_L-\epsilon_R-\tilde\epsilon_L+\tilde\epsilon_R) \\
\bar C'_A &= -g_A\,(1+\delta_\beta+\epsilon_L-\epsilon_R+\tilde\epsilon_L-\tilde\epsilon_R) \\
\bar C_S &= g_S\ (\epsilon_S+\tilde\epsilon_S) \\
\bar C'_S &= g_S\ (\epsilon_S-\tilde\epsilon_S) \\
\bar C_P &= g_P\ (\epsilon_P-\tilde\epsilon_P) \\
\bar C'_P &= g_P\ (\epsilon_P+\tilde\epsilon_P) \\
\bar C_T &= 4\,g_T\ (\epsilon_T+\tilde\epsilon_T) \\
\bar C'_T &= 4\,g_T\ (\epsilon_T-\tilde\epsilon_T)\ .
\end{aligned}$$

The "QCD parts" are now clearly identified; note, e.g., in n decay

$$\langle p(p_p)|\,\bar u\, d\,|n(p_n)\rangle \;=\; g_S(q^2)\ \bar u_p(p_p)\,u_n(p_n)$$

Enter lattice QCD....

[Bhattacharya et al., 2011]

Decay Correlations

$$\frac{d^3\Gamma}{dE_e d\Omega_e d\Omega_\nu} = \frac{1}{(2\pi)^5} p_e E_e (E_0 - E_e)^2 \xi \left\{ 1 + b\,\frac{m_e}{E_e} + a\,\frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + \langle \frac{\vec{J}}{J} \rangle \cdot \left[A\,\frac{\vec{p}_e}{E_e} + B\,\frac{\vec{p}_\nu}{E_\nu} + D\,\frac{\vec{p}_e \times \vec{p}_\nu}{E_e\,E_\nu} \right] + \ldots \right\}$$

[Jackson, Treiman, Wyld, 1957]

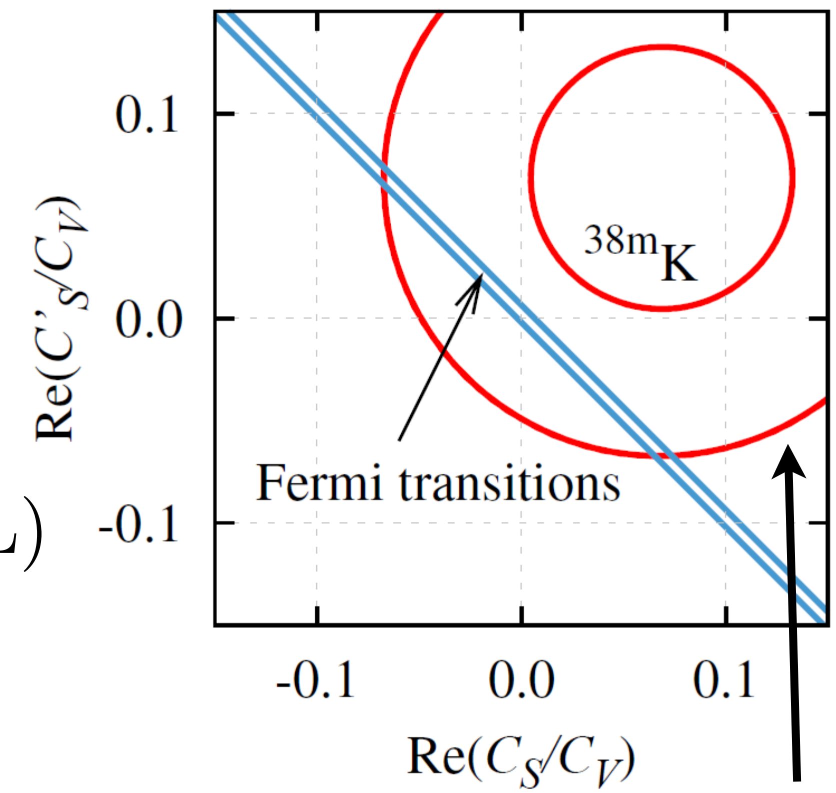
If $J \neq 1/2$

$$B(E_e) = B_0 + b_\nu m_e / E_e$$

Best limits on scalars come from superallowed Fermi transitions:

$$b_F = -\mathrm{Re}\left(\frac{C_S + C_S'}{C_V}\right) = -0.0022(43) \qquad (90\%\ \mathrm{CL})$$

[Hardy & Towner, 2009; for update see J. Hardy's talk!]



[Gorelov et al., 2005]

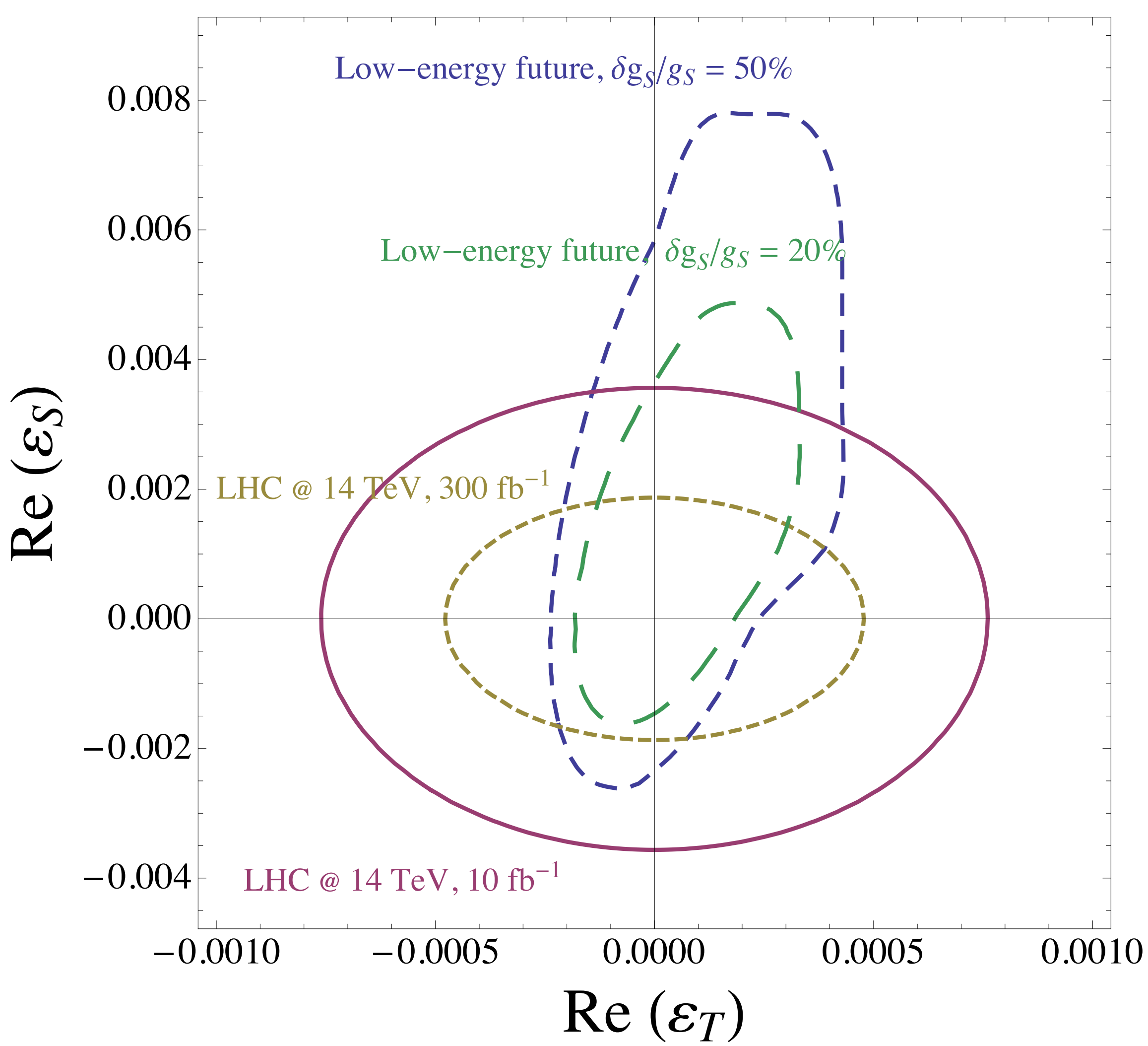
$$b = \frac{2\gamma}{1 + 3\lambda^2} \left[g_S\,\mathrm{Re}(\epsilon_S) - 12\lambda\, g_T\,\mathrm{Re}(\epsilon_T) \right],$$

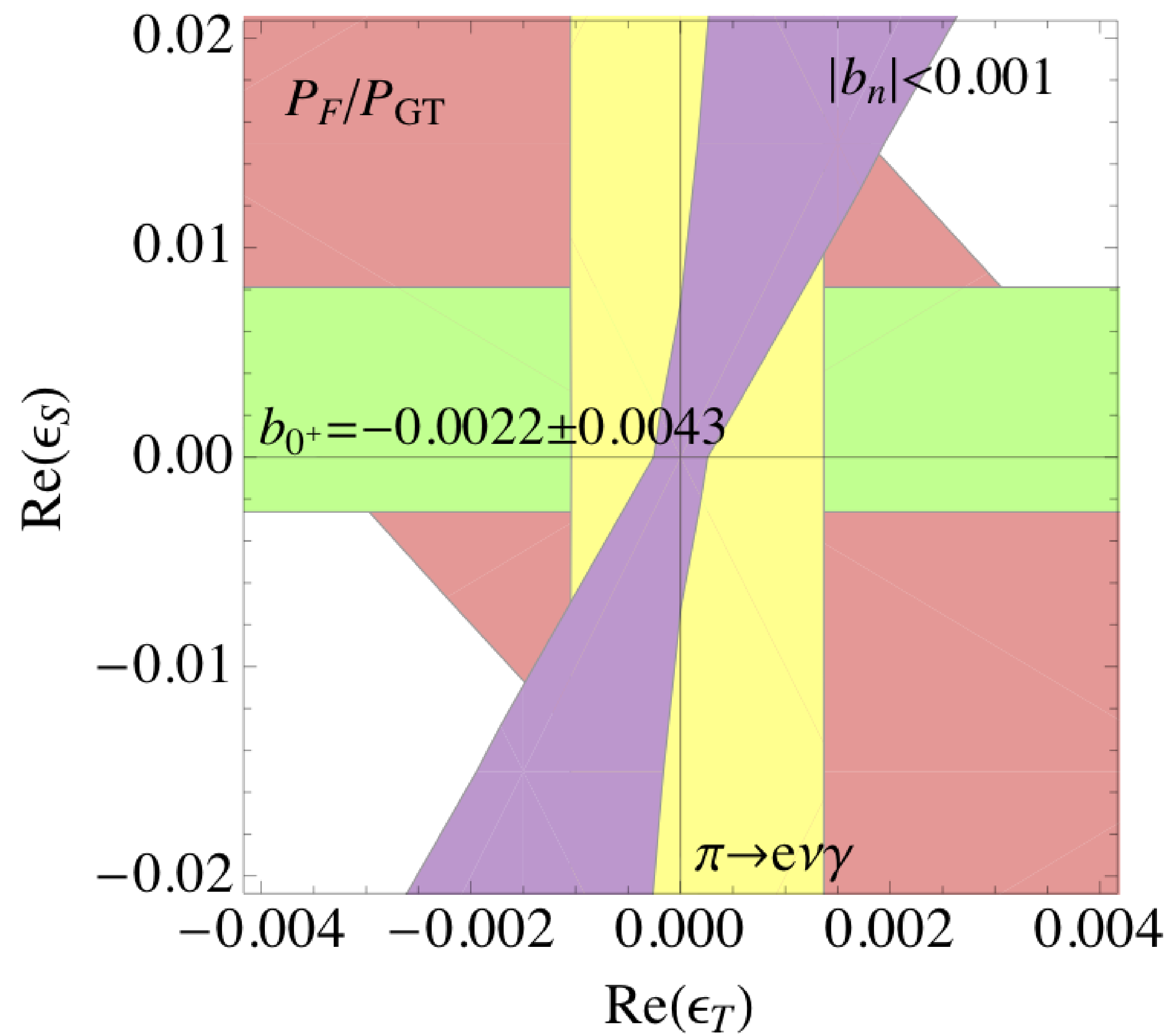
$$b_\nu = \frac{-2\gamma}{1 + 3\lambda^2} \left[g_S\,\mathrm{Re}(\epsilon_S)\,\lambda - 4 g_T\,\mathrm{Re}(\epsilon_T)\,(1 - 2\lambda) \right].$$

Decay Correlations

Connecting to the BSM low-energy constants requires QCD matrix elements

N.B. beta decay forecasts: $|b| < 10^{-3}$ [n, 6-He]





Lattice QCD calculations of BSM matrix elements of O(30%) precision already helpful!

Summary (β Decay)

If new physics exists beyond some high scale, an EFT framework links low-energy precision observables with QCD and new physics

The control of non-perturbative QCD (including ab initio nuclear matrix elements) immensely sharpens our probes of BSM physics through beta decay

But both the lifetime and correlation constants in neutron decay are essential to finding the limits of the V-A law

Although we have focused on real BSM couplings, imaginary ones are also possible and offer new windows on CP violation at low energies....

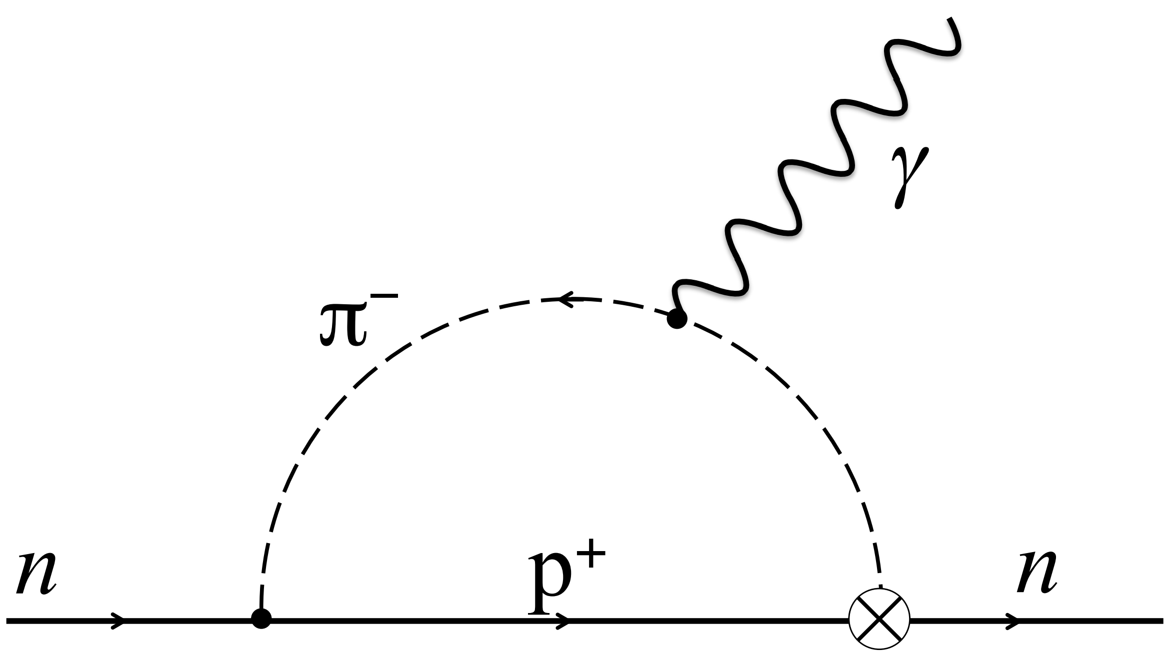
Backup Slides

Permanent EDMs: H$_{eff}$

BSM at nucleon and NN scales

[Engel, Ramsey-Musolf, & van Kolck, 2013; Chupp, Fierlinger, Ramsey-Musolf, Singh, 2017]

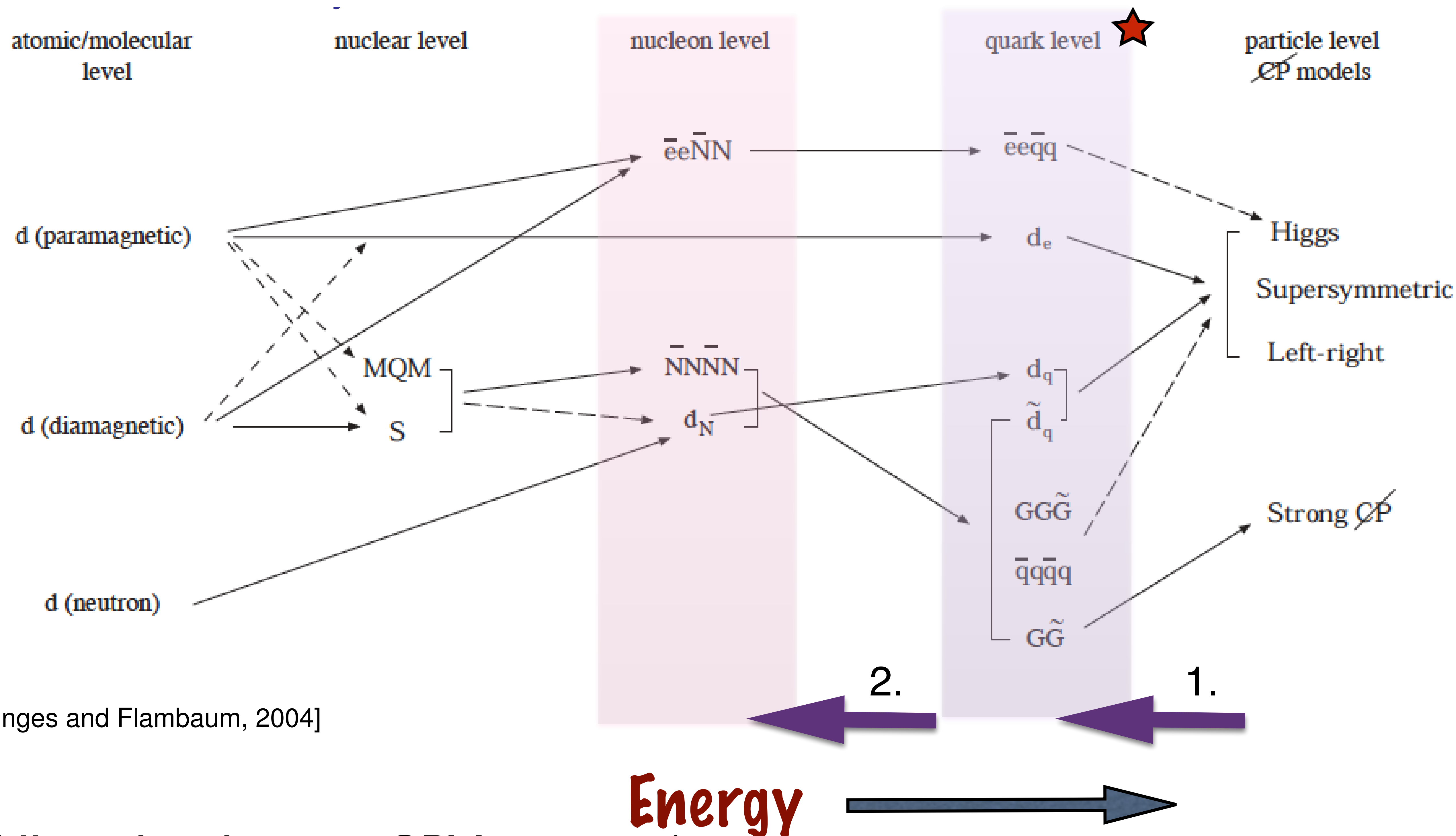
$$\mathcal{L}_{\pi NN}^{\mathrm{TVPV}} = -2\bar{N}\left(\bar{d}_0 + \bar{d}_1\tau_3\right) S_\mu N v_\nu F^{\mu\nu} + \bar{N}\left[\bar{g}_\pi^{(0)}\vec{\tau}\cdot\vec{\pi} + \bar{g}_\pi^{(1)}\pi^0 + \bar{g}_\pi^{(2)}\left(3\tau_3\pi^0 - \vec{\tau}\cdot\vec{\pi}\right)\right] N,$$



CPV πNN coupling constant source of non-perturbative enhancement

Heavy Atom & Molecular EDMs

Naturally involve multiple energy scales



[Ginges and Flambaum, 2004]

All probe distinct CPV sources!

Permanent Electric Dipole Moments

Atomic Scale Effects & Enhancements

Limits on the electron EDM d_e come from paramagnetic and (to a limited extent) diamagnetic atoms — and from molecules

Schiff Theorem (1963):

In the non-relativistic limit a neutral, point-like atom will shield an applied electric field, so that there is no atomic EDM even if $d_{nucleus}$ is not zero!

Schiff's theorem can be strongly violated by relativistic and finite-size effects!

In paramagnetic atoms & polar molecules relativistic effects dominate. Note in alkali atoms $d_{atom} \sim Z^3 \alpha^2 d_e$ ($d_{Tl} \sim 585 d_e + \ldots$!) [Sandars, 1965]

Permanent EDMs: H_{eff}

[Chupp, Fierlinger, Ramsey-Musolf, Singh, 2017]

1.

SM effective theory below EW scale: v≠0; 12 (+ $\bar{\theta}$) 1st generation LECs that couple to γ

0.

$\mathcal{O}_{fW}$	$(\bar{F}\sigma^{\mu\nu}f_R)\tau^I\Phi\, W^I_{\mu\nu}$	fermion $SU(2)_L$ dipole
$\mathcal{O}_{fB}$	$(\bar{F}\sigma^{\mu\nu}f_R)\Phi\, B_{\mu\nu}$	fermion $U(1)_Y$ dipole
$\mathcal{O}_{uG}$	$(\bar{Q}\sigma^{\mu\nu}T^A u_R)\widetilde{\varphi}\, G^A_{\mu\nu}$	u-quark Chromo EDM
$\mathcal{O}_{dG}$	$(\bar{Q}\sigma^{\mu\nu}T^A d_R)\varphi\, G^A_{\mu\nu}$	d-quark Chromo EDM
Q_{ledq}	$(\bar{L}^j e_R)(\bar{d}_R Q^j)$	CP-violating semi-leptonic
$Q^{(1)}_{lequ}$	$(\bar{L}^j e_R)\epsilon_{jk}(\bar{Q}^k u_R)$	
$Q^{(3)}_{lequ}$	$(\bar{L}^j \sigma_{\mu\nu} e_R)\epsilon_{jk}(\bar{Q}^k \sigma^{\mu\nu} u_R)$	
$\mathcal{O}_{\widetilde{G}}$	$f^{ABC}\widetilde{G}^{A\nu}_{\mu}G^{B\rho}_{\nu}G^{C\mu}_{\rho}$	CP-violating 3 gluon
$Q^{(1)}_{qugd}$	$(\bar{Q}^j u_R)\epsilon_{jk}(\bar{Q}^k d_R)$	CP-violating four quark
$Q^{(8)}_{qugd}$	$(\bar{Q}^j T^A u_R)\epsilon_{jk}(\bar{Q}^k T^A d_R)$	
$Q_{\varphi ud}$	$i\,(\tilde{\varphi}^\dagger D_\mu \varphi)\,\bar{u}_R\gamma^\mu d_R$	quark-Higgs

SM effective theory above EW scale

2.

H_{eff} at nuclear scales

chiral EFT:

[de Vries et al., 2011, 2012; Guo & Meissner, 2012...]

but only for few-nucleon systems