Beyond the Standard Model: An Overview

Theory — Lecture 1

Susan Gardner

Department of Physics and Astronomy
University of Kentucky
Lexington, KY

Fundamental Neutron Physics
Summer School (FNPSS)
North Carolina State University
[July, 2018]

Research supported by the U.S. Dept. of Energy Office of Nuclear Physics
under DE-FG02-96ER40989

Overview

- **Fundamental Symmetry Tests as "Windows" on New Physics [Lecture 1]**

The pattern of *"fundamental" symmetry violation gave rise to the* **Standard Model of particle interactions**… *we continue to use symmetry tests as probes of ("new") physics beyond the Standard Model*

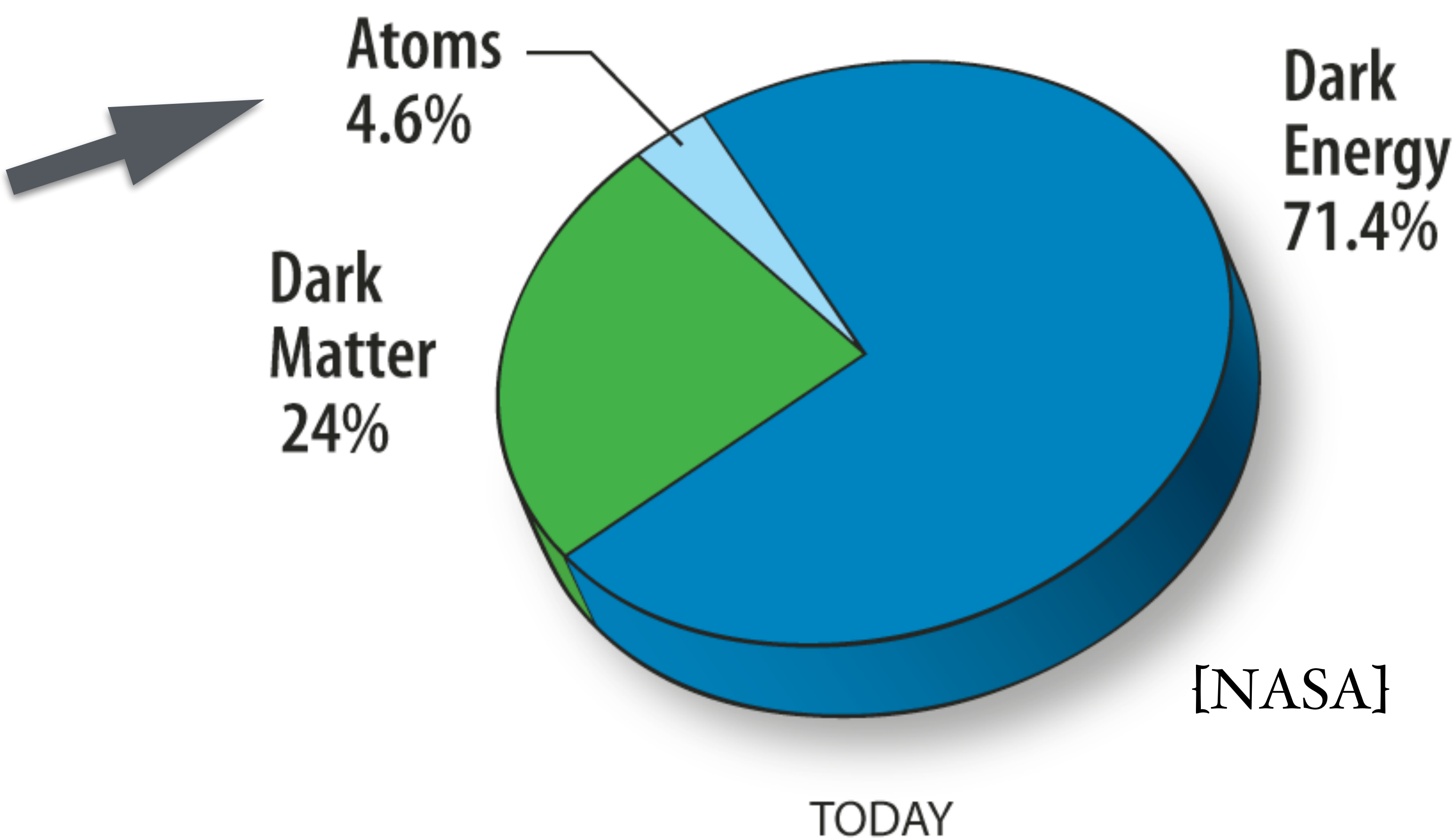
Why would we expect new physics to exist?

- **Neutrons & "Hidden Sectors": Searching for Ultralight Axions and More [Lecture 2]**

Two Numbers

Drive new physics searches

Why is the cosmic energy budget in baryons so small? (and what is everything else?!)



And the cosmic baryon asymmetry

$$\eta = n_{\text{baryon}}/n_{\text{photon}} = (5.96 \pm 0.28) \times 10^{-10}$$

so large? (And how does the neutrino get its mass?)

A Cosmic Baryon Asymmetry (BAU)

Assessments in two different epochs agree!

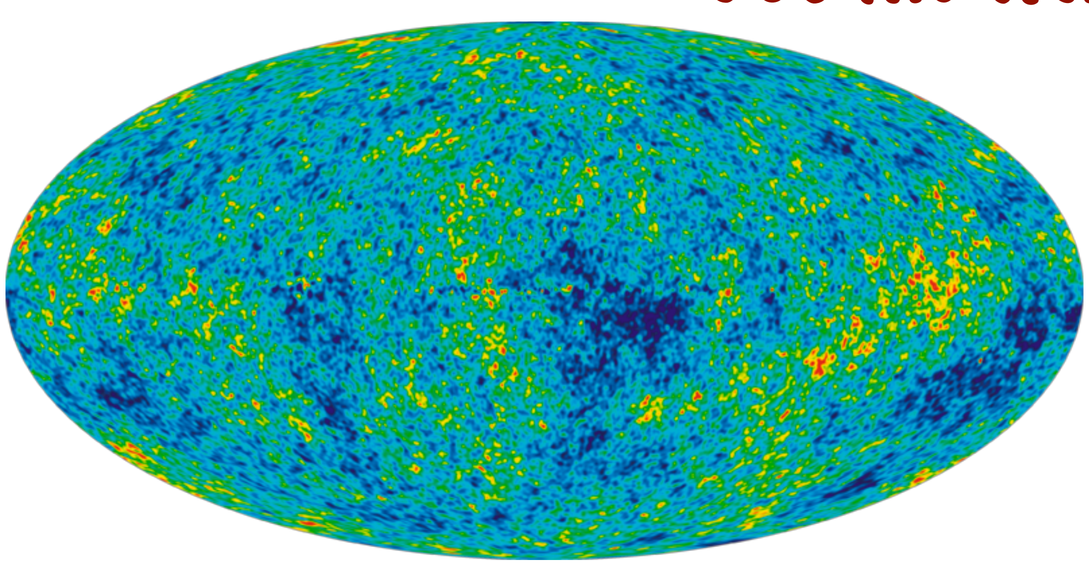
[George Gamow, AIP]

Big-Bang Nucleosynthesis (BBN)

"α, β, γ" Alpher, Bethe, Gamow, "The Origin of the Chemical Elements," 1948

Lightest Elements are made in the Big-Bang, but prediction depends on the BAU

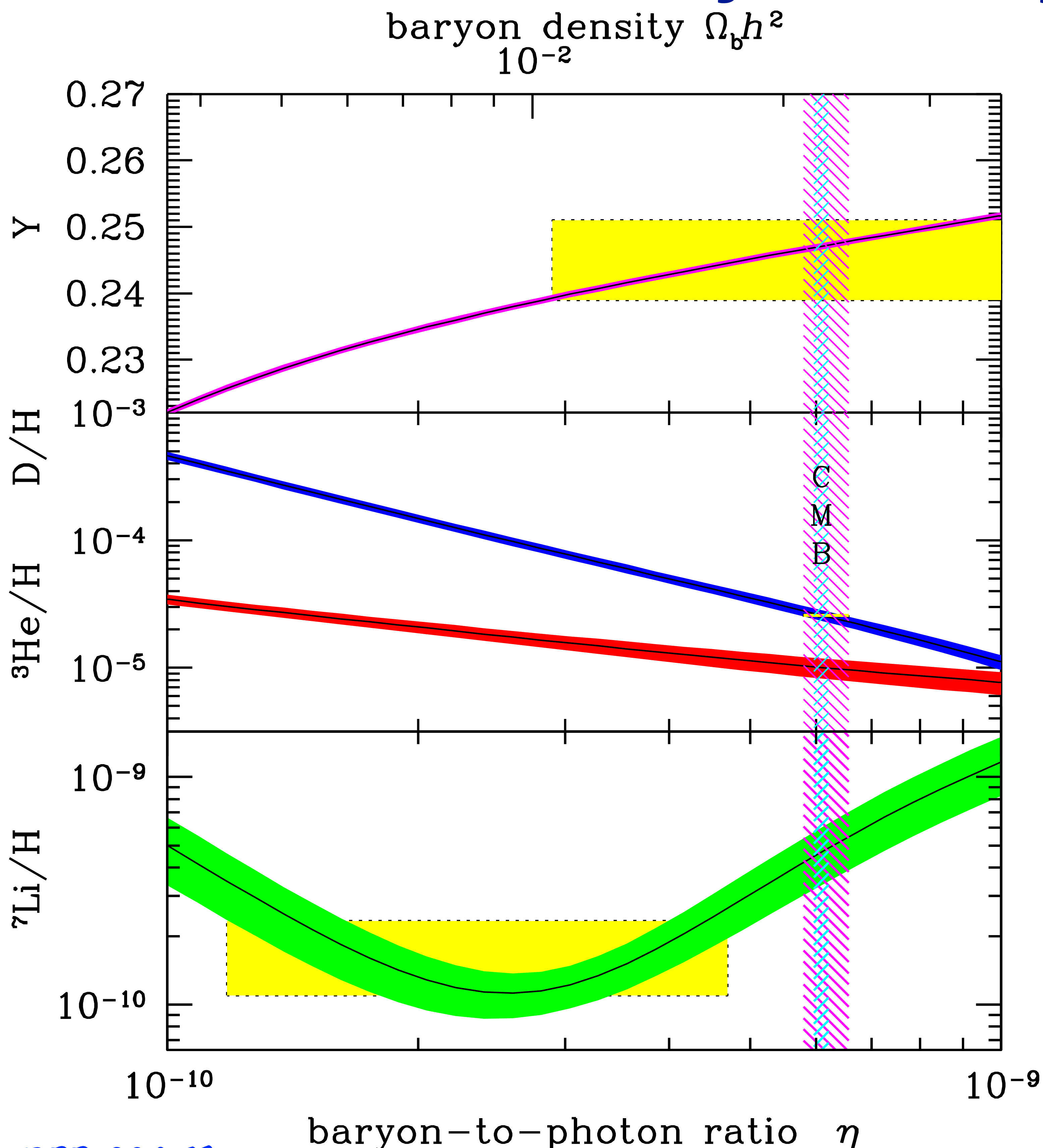
Cosmic Microwave Background (CMB)



Dicke, Peebles, Roll, & Wilkinson, 1965; Penzias & Wilson, 1965

Pattern of Acoustic Peaks reveals baryonic matter

A Cosmic Baryon Asymmetry



BAU from BBN & observed D/H & ^{4}He/H concordance

BAU from CMB is more precise

[Both @ 95% CL]

[PDG, RPP, 2017]

A Cosmic Baryon Asymmetry

Confronting the observed D/H abundance with big-bang nucleosynthesis yields a baryon asymmetry: [Steigman, 2012]

$$\eta = n_{\rm baryon}/n_{\rm photon} = (5.96 \pm 0.28) \times 10^{-10}$$

By initial condition?

We interpret the CMB in terms of an inflationary model, so that this seems unlikely. [Krnjaic, PRD 96 (2017)]

From particle physics?

The particle physics of the early universe can explain this asymmetry if B, C, and CP violation exists in a non-equilibrium environment. [Sakharov, 1967]

Non-equilibrium dynamics are required to avoid "washout" of an asymmetry by back reactions

The Puzzle of the Missing Antimatter

The baryon asymmetry of the universe (BAU) derives from physics beyond the standard model!

The SM almost has the right ingredients:

B? Yes, at high temperatures

C and CP? Yes, but CP is "special"

Note BAU estimates even with a **light** Higgs are much too small

[Farrar and Shaposhnikov, 1993; Gavela et al., 1994; Huet and Sather, 1995.] $\eta < 10^{-26}$

Non-equilibrium dynamics? No. (!)

The discovered Higgs particle is of 125 GeV in mass; for this mass lattice simulations reveal there is **no** electroweak phase transition. [e.g., Aoki, Csikor, Fodor, Ukawa, 1999]

So that the SM mechanism fails altogether

Recipes for a Baryon Asymmetry?

New ν physics might operate!

Perspective

Our dark-dominated universe and its baryon asymmetry speaks to possible **hidden (or visible?!)** particles, interactions, symmetries and more that we may yet discover

Such new physics could arise at either

i) **high energies** with $\mathcal{O}(1)$ couplings to SM particles

Here low energy & collider studies are complementary

– or –

→ ii) **low energies** with **very weak** couplings to SM particles

Largely unexplored! Low energy studies have unique discovery potential!

Indirect Detections of New Physics

Past particle discoveries have been presaged by signals in low-energy experiments

Some Examples:

Small $K \rightarrow \mu^+\mu^-$ rate suggests the "charm" quark

→ Glashow, Iliopoulos, Maiani, 1970: discovery of J/ψ @ SLAC and BNL in 1974

Observation of $K_L \rightarrow \pi^+\pi^-$ (CP violation!) suggests a third generation of quarks

→ Kobayashi & Maskawa, 1973: direct discovery of b quark in 1977 at Fermilab

Observation of a parity-violating asymmetry in e-^{2}H deep-inelastic scattering suggests the Z_0 gauge boson

→ C. Y. Prescott et al., 1978: direct discovery of the Z_0 in 1983 at CERN

Fundamental Symmetries & The Rise of the Standard Model

Model Building

The SM is a local quantum field theory based on an exact local gauge symmetry

To build it we must choose:

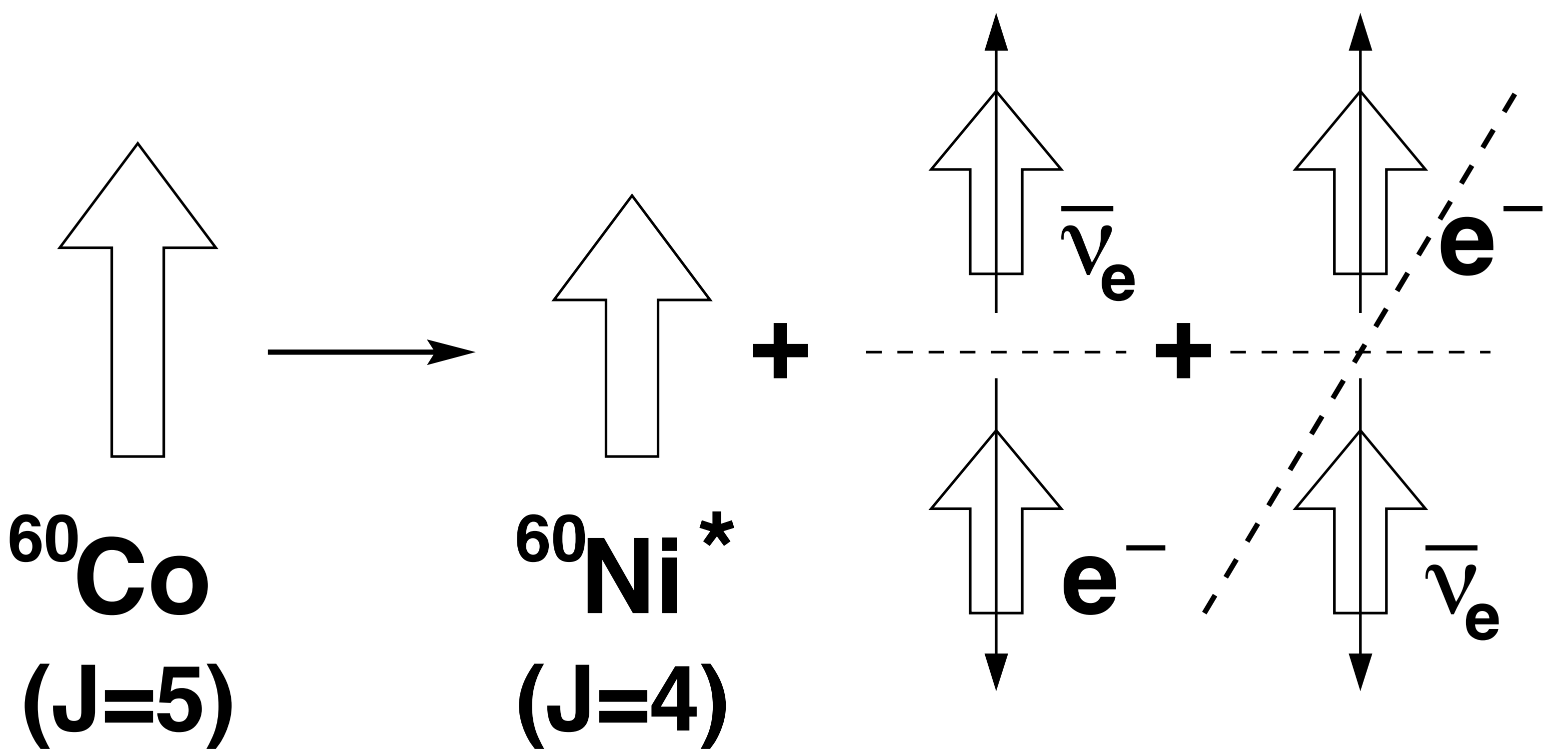
- The gauge group(s) — here $SU(3)_{color} \times SU(2)_{left} \times U(1)_{Y}$
- The particle content, its group representations, and charge assignments

On the Discrete Symmetries

C, P, T and all that

Weak interactions violate parity P

[Wu, Ambler, Hayward, Hoppes, Hudson, 1957]



Nature can distinguish L from R: $\bar{\nu}_e$ is R-handed!

Intensity: $I_e(\theta) = 1 - \frac{\vec{J}\cdot\vec{p}_e}{E_e}$ ⟵ odd under $\vec{p}_e \to -\vec{p}_e$

On the Discrete Symmetries

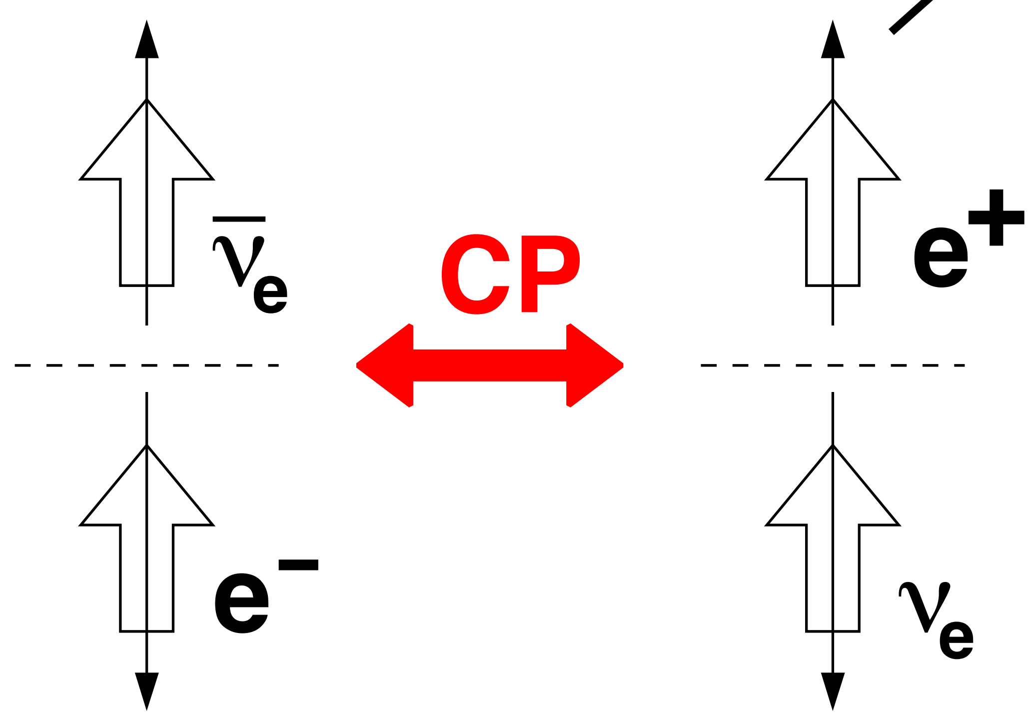
C, P, T and all that

Under charge-conjugation C:

$$\Gamma(\pi^- \to e^- \bar{\nu}_R) \longrightarrow \Gamma(\pi^+ \to e^+ \nu_R)$$

0 : C is violated

However



[N.B. CP is also broken!]

sterile!

Enter SM leptons: $\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L \quad e^-_R \quad (\mathrm{NO} \quad \nu_{e\,R}!)$

weak doublet ($T_3=\pm 1/2$; $Y=-1/2$) & singlet ($T_3=0$; $Y=-1$)

N.B. Engineered to give $m_\nu = 0$! (in the SM)

Theories of New Physics

And how to discover evidence for them

There was a time when the motivation for new physics searches came from theoretical "wants"… e.g.,

- The Higgs (SM!) could not be too heavy, or the weak sector would not be "perturbative"
- The scalar sector of the SM required finely tuned inputs to control the impact of loop radiative corrections

With new gauge theories the needed cancellations could be "natural"… and could be discovered through the appearance of **new**, massive particles

Enter models with supersymmetry or extended gauge groups ("little Higgs")…

Theories of New Physics

Some "theoretically motivated" examples

- **Supersymmetry**
  makes a one-to-one correspondence between the boson and fermion content of the theory, and the quadratic divergences cancel exactly to all orders in perturbation theory.
- **Technicolor**
  makes the Higgs a composite built of heavy "technifermions", aping chiral dynamics in QCD.
- **A Strongly Coupled Higgs Sector**
  makes the perturbative bounds on the Higgs mass moot.
- **"Extra" Dimensions**
  models let gravity see spacetime dimensions which other particles cannot, explaining why gravity is weak at the TeV scale.
- **Little Higgs**
  models give new gauge bosons couplings arranged so that the quadratic divergences cancel to one loop order.

All predict new phenomena at the TeV scale.

For which there is no evidence as yet

Effective Field Theory & New Physics

Enter a "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

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

Symmetries guide their construction [Weinberg, 1979]

Here assume SM electroweak symmetry [Buchmuller & Wyler, 1986; Grzadkowski et al., 2010]

We can consider all the terms that appear order by order to study CP violation or non-standard ν interactions or...

N.B. targeted searches….

The Standard Model

Glashow-Salam-Weinberg model

The GSW model has the $\gamma, W^{\pm}, Z^0, g$ as gauge bosons, a complex scalar φ and three generations of quarks and leptons, organized in (electroweak) left-handed doublets and right-handed singlets:

$$\begin{pmatrix} u \\ d \end{pmatrix}_L \quad u_R\,, d_R$$

Since $W^{\pm}$ carries electric charge, electromagnetism "lies across" $SU(2)_L \times U(1)_Y$: $Q = T_3 + Y$

φ is in a doublet and has $Y=1/2$

The exact gauge symmetry can be hidden through the choice of vacuum for the scalar potential: this process does not give new massless states but rather gives 3 gauge bosons mass

The Standard Model

Fermion Masses

We cannot give the fermions mass as in free Dirac theory because

$$m_f\bar{\psi}\psi = m_f(\bar{\psi}_L\psi_R + \bar{\psi}_R\psi_L) \quad \text{with} \quad \psi_{L,R} = \frac{1}{2}(1 \mp \gamma_5)\psi$$

violates electroweak gauge invariance! (Y is not 0!)

We must use the Higgs mechanism! E.g., m_e ; v ="vev"

$$\mathcal{L} = -\lambda_e \bar{E}_L \varphi e_R + \text{H.c.} \Longrightarrow -\frac{1}{\sqrt{2}}\lambda_e v \bar{e}_L e_R + \text{H.c.}$$

$$\varphi_0 = \frac{1}{\sqrt{2}}\binom{0}{v}$$

For 3 generations of quarks:

$$\mathcal{L}_{\text{q}} = -\lambda_d^{ij}\bar{Q}_L^i \varphi d_R^j - \lambda_u^{ij}\bar{Q}_L^i \epsilon\varphi u_R^j + H.c.$$

CP is broken if $\lambda_{u,d}$ are complex!

The Standard Model

Quark Masses and Mixings

The $\lambda_{u,d}$ can be anything!
They are only constrained by experiment!
Rotating to a basis in which the quark masses are diagonal we find

$$u'^{\,i}_L = \mathcal{U}^{ij}_u u^i_L \quad ; \quad d'^{\,i}_L = \mathcal{U}^{ij}_d d^i_L$$

at the price of

$$J^\mu_{W+} = \frac{1}{\sqrt{2}} \bar{u}^i_L \gamma^\mu d^i_L$$

$$= \frac{1}{\sqrt{2}} \bar{u}'^{\,i}_L \gamma^\mu (\mathcal{U}^\dagger_u \mathcal{U}_d)_{ij} d'^{\,i}_L$$

Note "V-A" law is automatic!

This is V_{CKM}!

CP violation in the SM

Observed effects appear through quark mixing under the weak interaction

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix}_{\text{weak}} = V_{\text{CKM}} \begin{pmatrix} d \\ s \\ b \end{pmatrix}_{\text{mass}} \quad ; \quad V_{\text{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

Cabibbo-Kobayashi-Maskawa (CKM) has hierarchical mixing

$$V_{\text{CKM}} = \begin{pmatrix} 1 - \frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

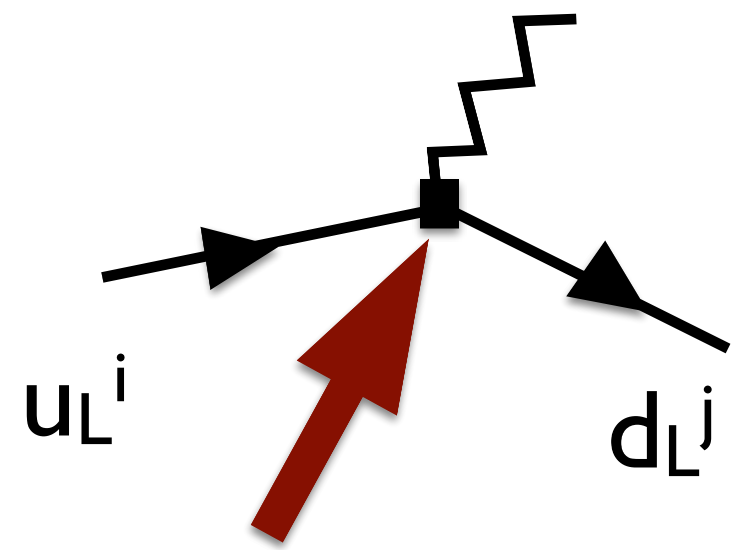
[Wolfenstein, 1983]

The CKM Matrix is a unitary 3x3 matrix with 4 parameters in the Standard Model

What is also possible but **not seen** is CP violation from QCD — because the n EDM has not been observed!

CP violation in the SM

How phases are necessary for CP violation

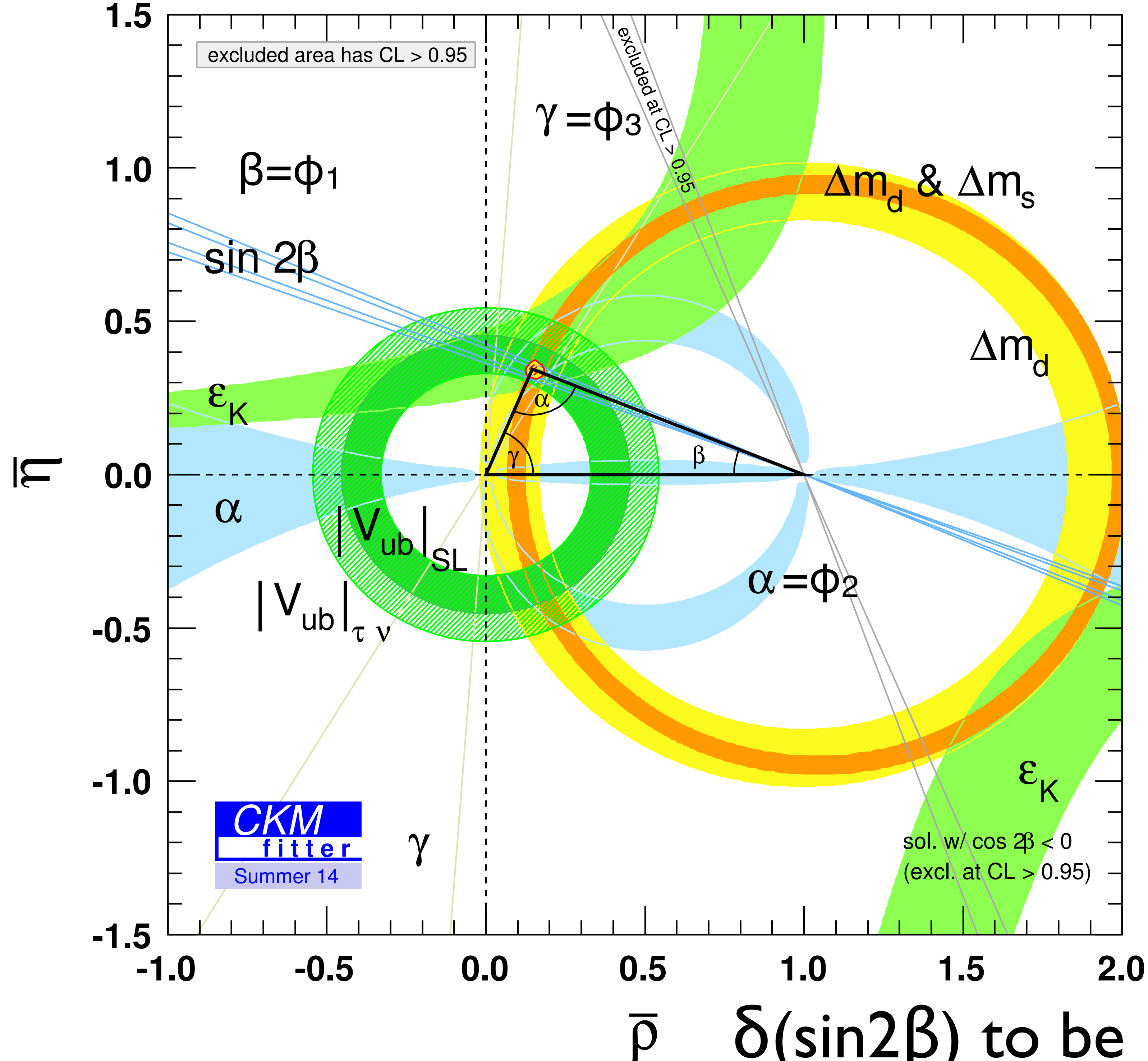


$\sim V_{ij}^*$

Im V_{ij} distinguishes the amplitude for $b \to s u \bar{u}$ from its Hermitian conjugate ($\bar{b} \dots$ decay)

Testing the CKM Paradigm

The CKM matrix describes the flavor and CP violation observed in charged-current processes



The single CP phase is decidedly nonzero

[CKM Fitter: Charles et al., 1501.05013]

N.B. lattice QCD plays a key role!

[Golob, Trabelsi, & Urquijo (Belle II), 2015]

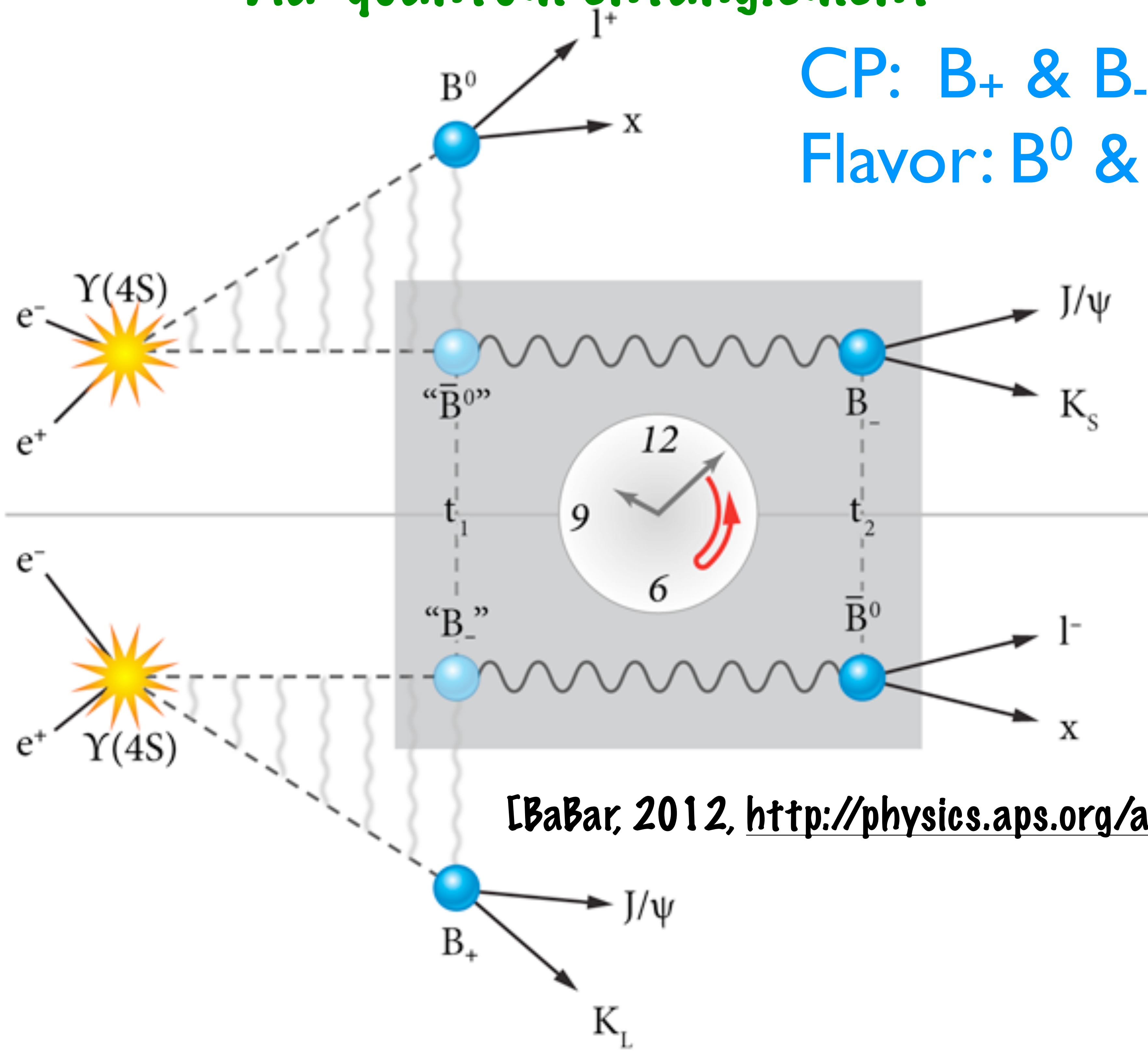
$\delta(\sin 2\beta)$ to be reduced ~10x at Belle II!

On the Discrete Symmetries

Direct Observation of T violation in the B system via "quantum entanglement"

CP: B_+ & B_-

Flavor: B^0 & $\overline{B}^0$



[BaBar, 2012, http://physics.aps.org/articles/v5/129]

Standard Model Scorecard

The Standard Model, save for the established existence of neutrino masses (and nagging anomalies such as the muon g-2, the proton radius puzzle, and apparently violations of lepton flavor universality in B physics), is consistent with all known terrestrial experiments

Hadronic parity violation (w/i the SM) is a last poorly understood sector

The patterns of fermion mass and mixings (and indeed the value of the weak scale itself) find no explanation within the SM

Generally the SM leaves many questions unanswered — and cannot address the BAU nor the existence of dark matter or energy

Symmetry Tests with Neutrons

"Windows" on New Physics

Some examples…

- 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

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

CP, B-L breaking searches involve new operators

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

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

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

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

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

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

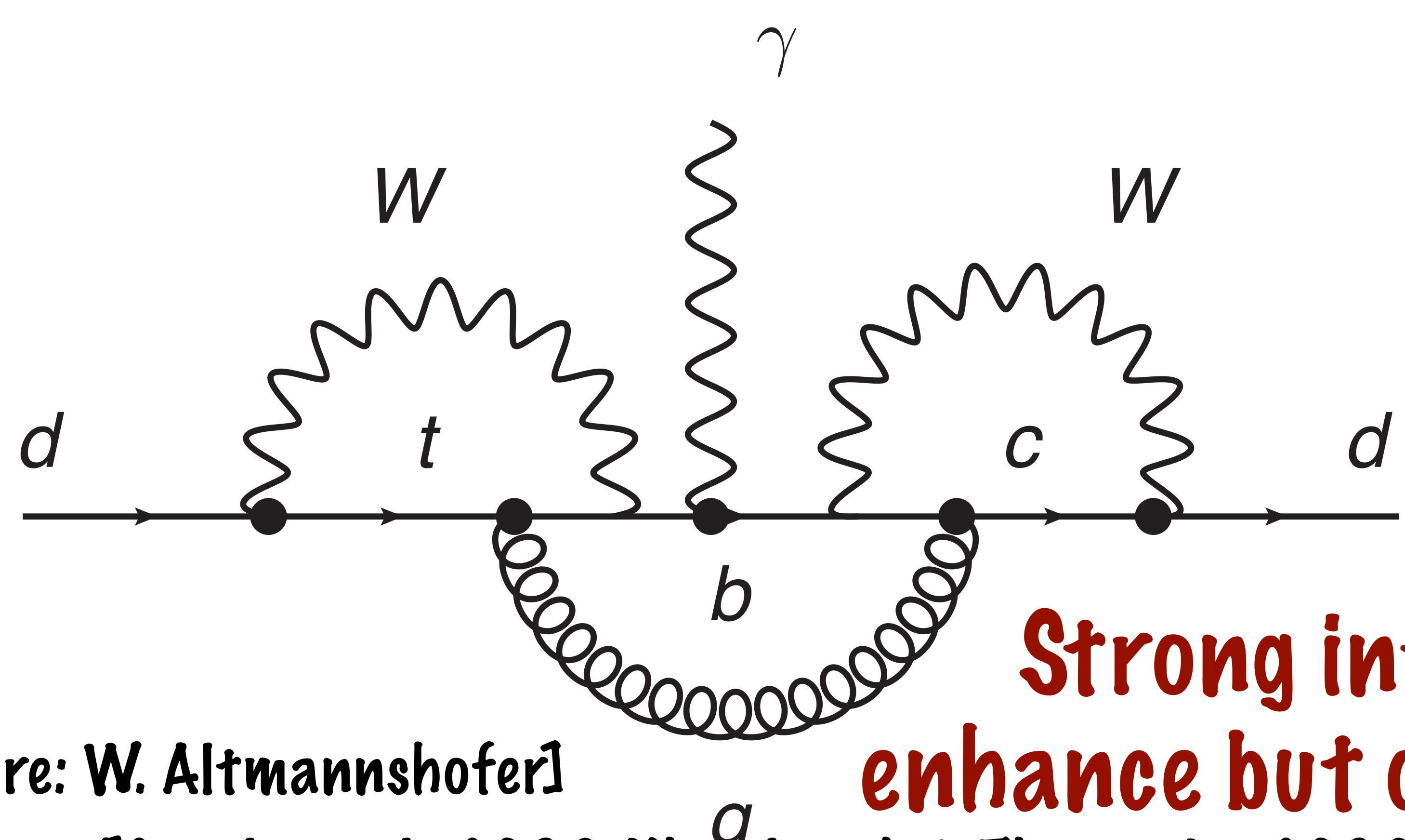
The contribution from the CKM matrix first appears in three-loop order!

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]



[figure: W. Altmannshofer]

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

[Czarnecki & Krause, 1997]

Inaccessibly small!

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!

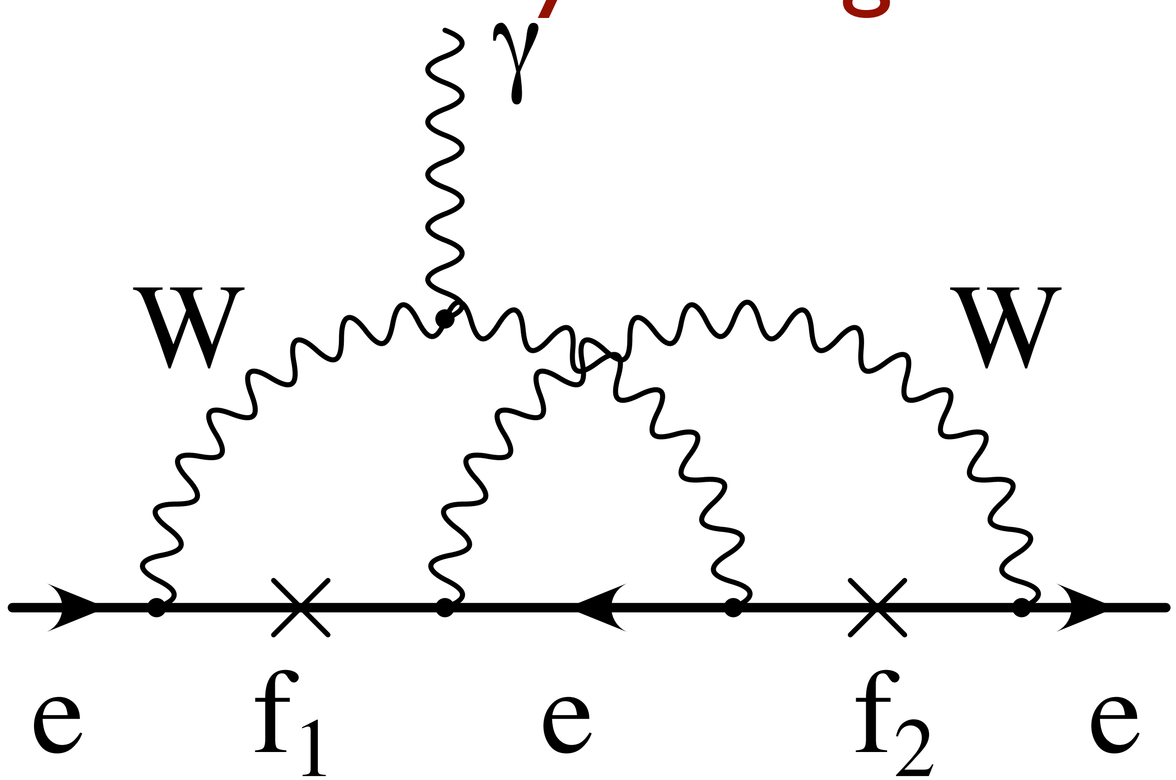
cf. d_e^{eff} from CPV e-N
[Pospelov & Ritz, 2013]

$d_e \sim 10^{-44}$ 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...

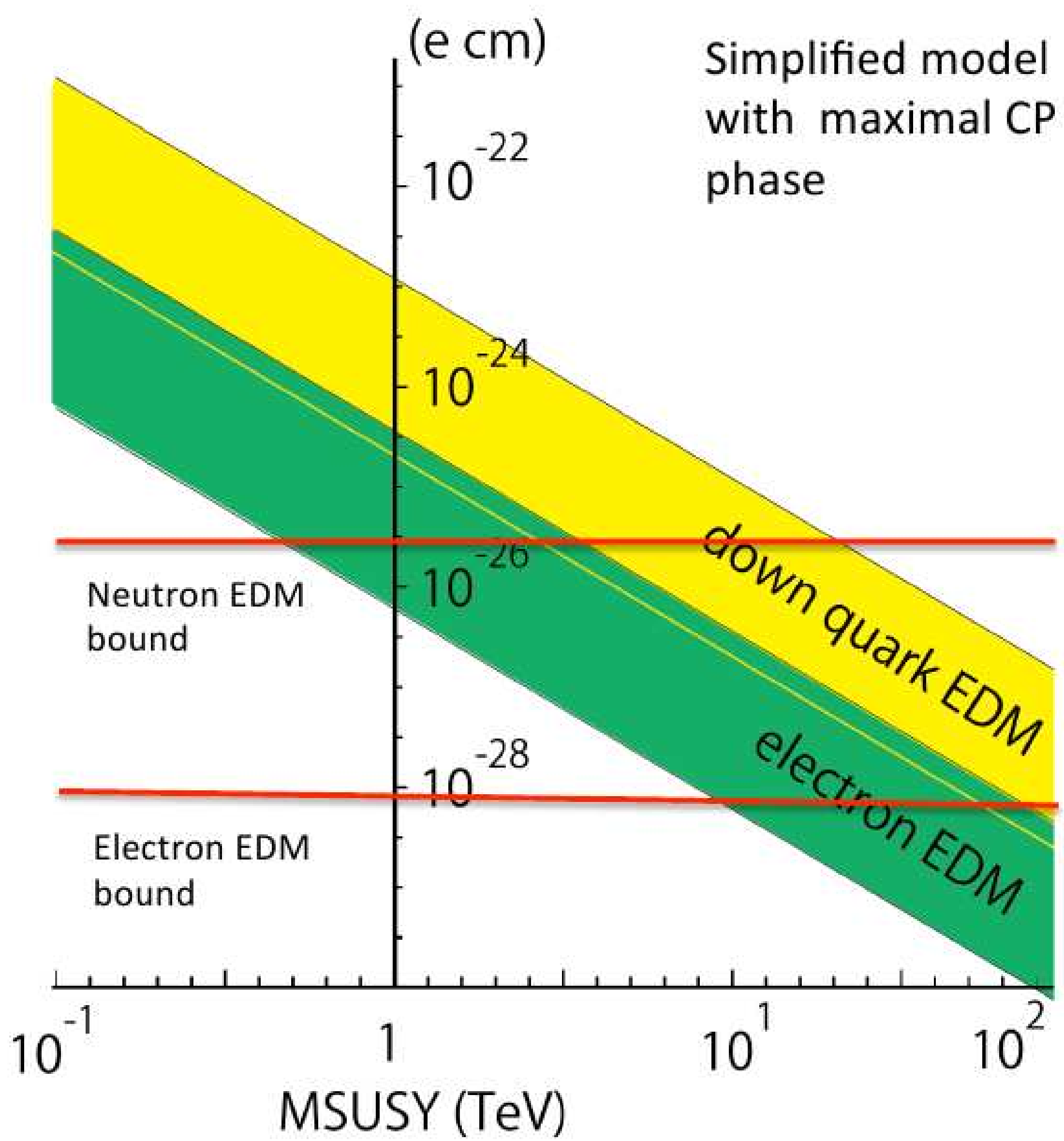
- can explain "why" the weak scale M_Z , M_W is so much lower than the Planck scale
- can possess a dark-matter candidate
- can potentially explain the cosmic baryon asymmetry
- ...

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

EDM 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 &.... (stay tuned!)

Origins of the Neutrino Mass

The Majorana mass and $0\,\nu\,\beta\beta$ 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 $0\,\nu\,\beta\beta$ decay

However, $0\,\nu\,\beta\beta$ 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-n̄ Transitions

It has long been thought that *n*-*n̄* oscillations could shed light on the mechanism of

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

The observation of *n*-*n̄* 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*-*n̄* 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)]

Effective Lagrangian

Neutron interactions with B-L violation & electromagnetism

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

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

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

Summary

- 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 noted 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

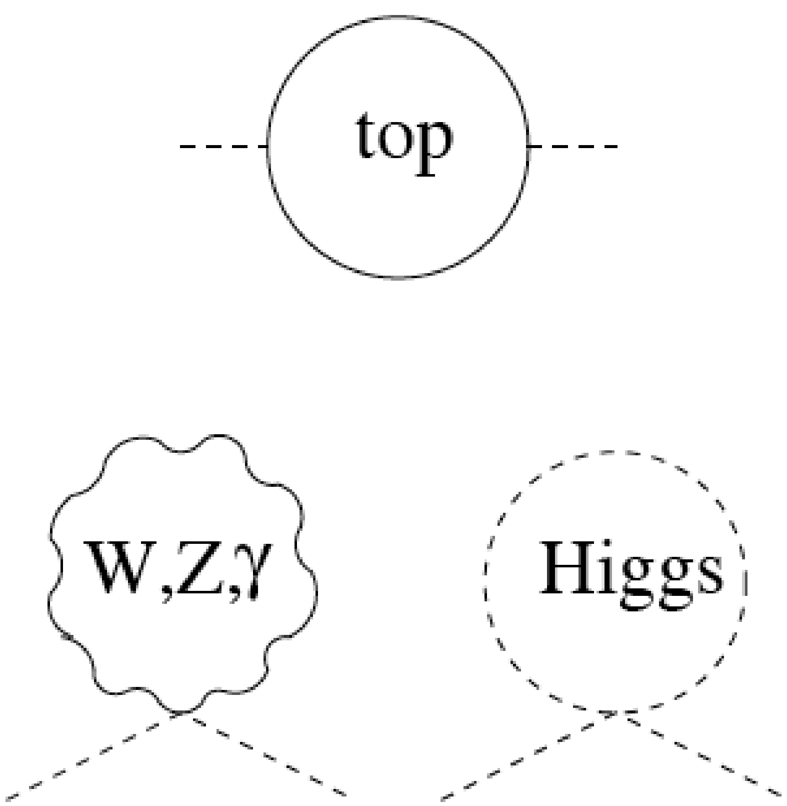
Backup Slides

“Fine Tuning” in the SM

The Standard Model is theoretically consistent to arbitrarily high energy scales. However, its incompleteness makes us think that new physics – i.e., physics not included in the SM – must enter at some energy scale Λ.

Theories with fundamental scalars (the Higgs) are particularly sensitive to the value of Λ. Let’s look at the quantum corrections to the Higgs mass M_H.

$$V_{\text{Higgs}} = -\mu^2\phi^\dagger\phi + \frac{\lambda}{4!}(\phi^\dagger\phi)^2$$



[Schmaltz, hep-ph/0210415]

The λ term, e.g., yields

$$\delta\mu^2 \propto \lambda \int^\Lambda d^4k \frac{1}{k^2 - M_H^2} \sim +\lambda\Lambda^2$$

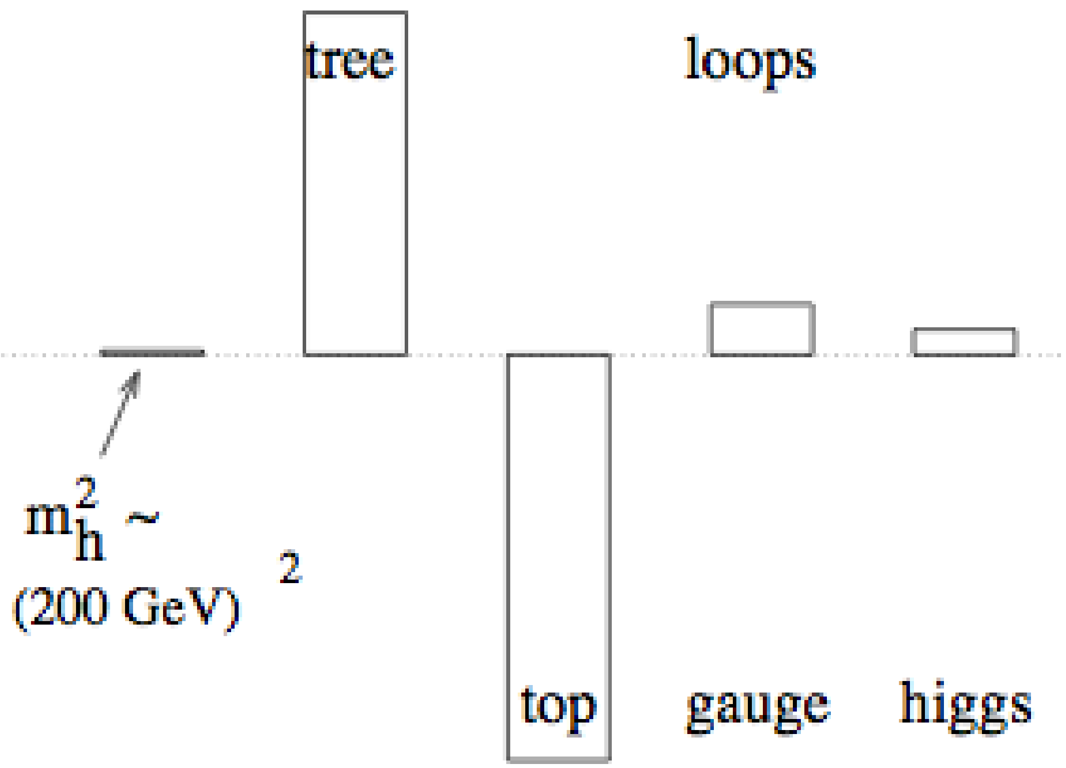
thus $\Longrightarrow M_H^2 = \mu^2 - \lambda c \Lambda^2$

For perturbation theory to make sense λ cannot be too large; this limits M_H to few $\times$ 100 GeV. [Dicus, Mathur, Phys. Rev. D7, 3111 (1973); Lee, Quigg, Thacker, Phys. Rev. D16, 1519 (1977)]

For $\Lambda \sim M_{GUT}$ the required tuning of μ is to 1 part in 10^{26}!!

"Fine Tuning" in the SM

Once again we suppose Standard Model is an effective theory, valid for scales $E \leq \Lambda$. What is Λ? At one-loop level, we have found large corrections to the tree-level Higgs mass μ.



[Schmaltz, hep-ph/0210415]

N.B. fermion and boson loop contributions have *opposite sign*.

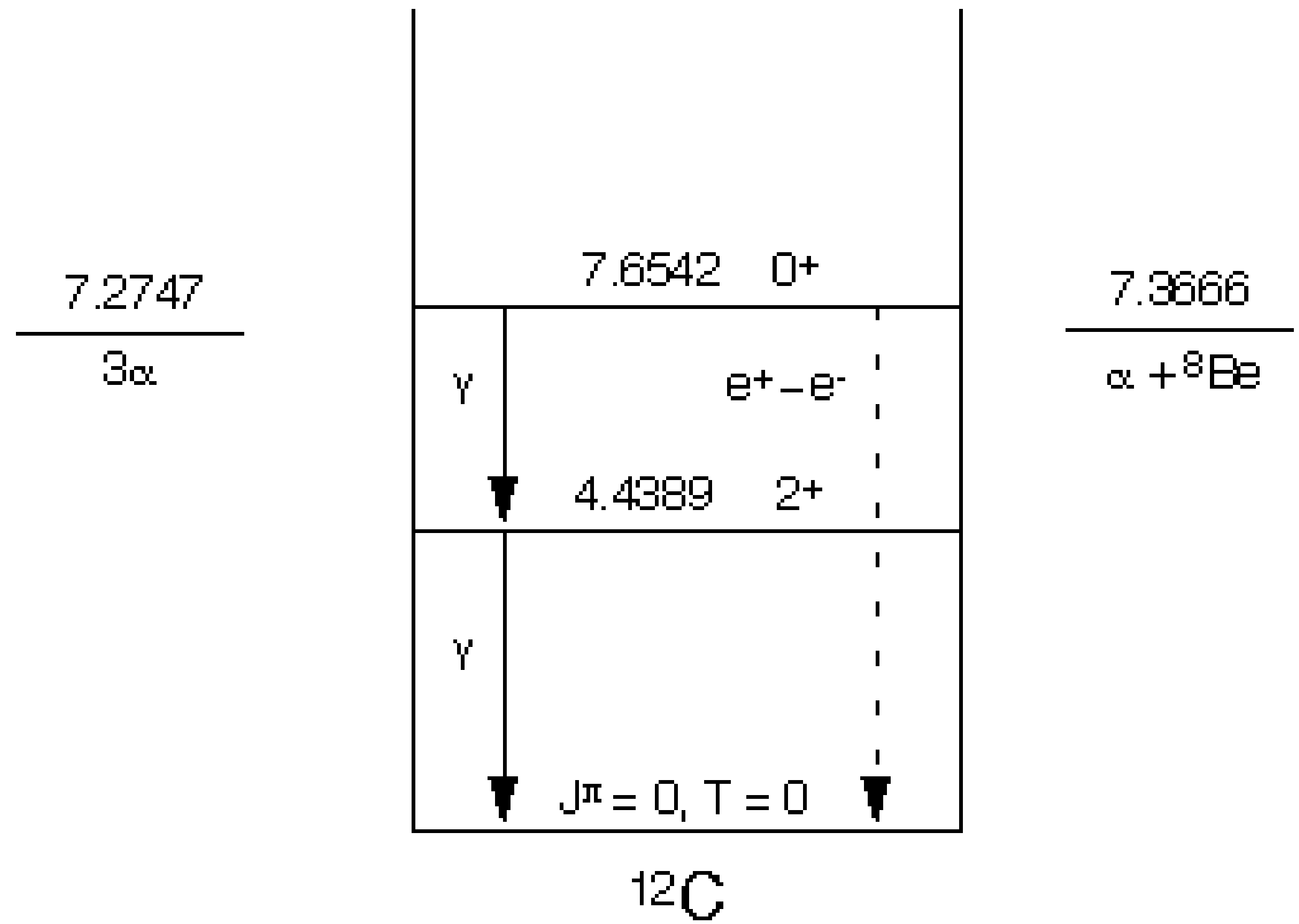
As Λ is reduced from the Planck (or GUT) scale, the fine tuning required to yield the Higgs mass required by perturbative arguments mitigates.

At $\Lambda = 10$ TeV, μ must be tuned to merely one part in 100.

Thus we have a theoretical argument for new physics at $\Lambda \sim \mathcal{O}(1\,TeV)$

New physics can make the cancellations natural. Thus we stabilize the numerical value of M_H under radiative corrections, even if we cannot answer why $M_H \ll M_P$.

“Fine Tuning” Exists in Nature



[Hoyle, 1953; Dunbar, Pixley, Wenzel, Whaling, 1953]

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…

$$\vec{B} \overset{P}{\longleftrightarrow} \vec{B} \quad \vec{E} \overset{P}{\longleftrightarrow} -\vec{E} \quad \vec{S} \overset{P}{\longleftrightarrow} \vec{S}$$

$$\vec{B} \overset{T}{\longleftrightarrow} -\vec{B} \quad \vec{E} \overset{T}{\longleftrightarrow} \vec{E} \quad \vec{S} \overset{T}{\longleftrightarrow} -\vec{S}$$

MDM: P even, T even
EDM: P odd, T odd

$\longrightarrow$ under CPT, CP is also broken

Operator Analysis of EDMs

The flavor-diagonal effective Lagrangian at ~1 GeV

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

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

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

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

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

[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!

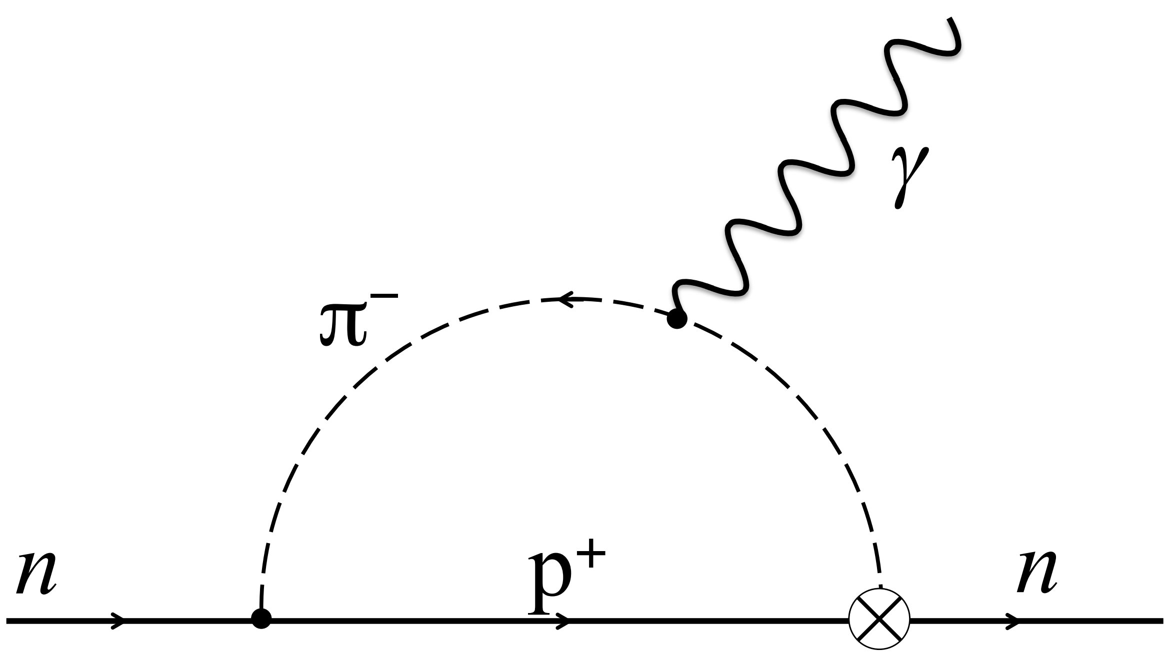
[Pospelov & Ritz, 2005; Engel, Ramsey-Musolf, & van Kolck, 2013; Jung, 2013; Chupp et al., 2017]

Permanent EDMs: 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

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.

Neutron-Antineutron Conversion

Different mechanisms are possible

- * n-n̄ 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-n̄ 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]

Neutrons and “Hidden Sectors”

Theory — Lecture 2

Susan Gardner

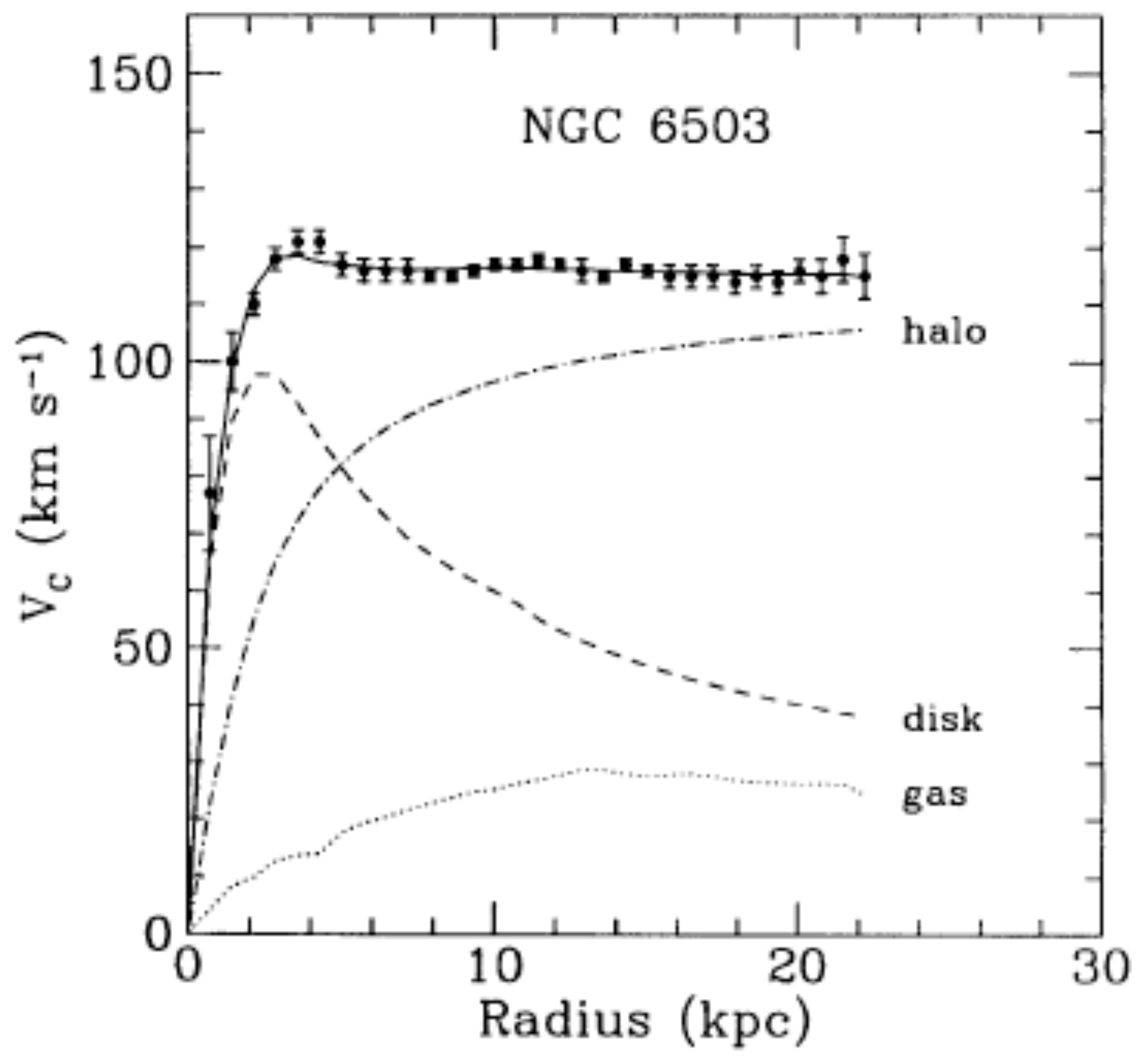
Department of Physics and Astronomy
University of Kentucky
Lexington, KY

Research supported by the U.S. Dept. of Energy Office of Nuclear Physics under DE-FG02-96ER40989

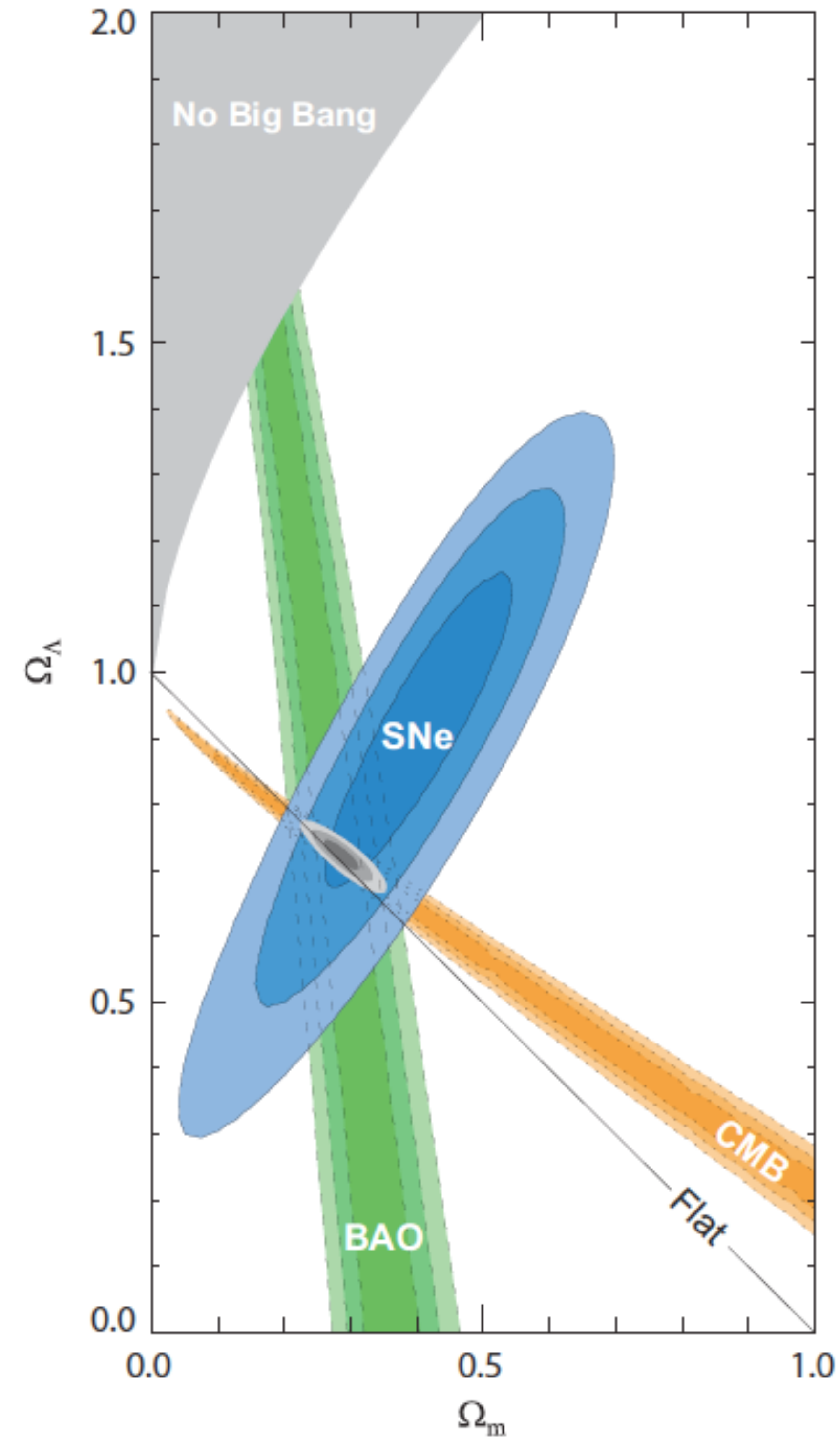
Fundamental Neutron Physics Summer School (FNPSS)
North Carolina State University
[July, 2018]

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!

Dark-Matter (DM) Knowns

We do know DM must be...

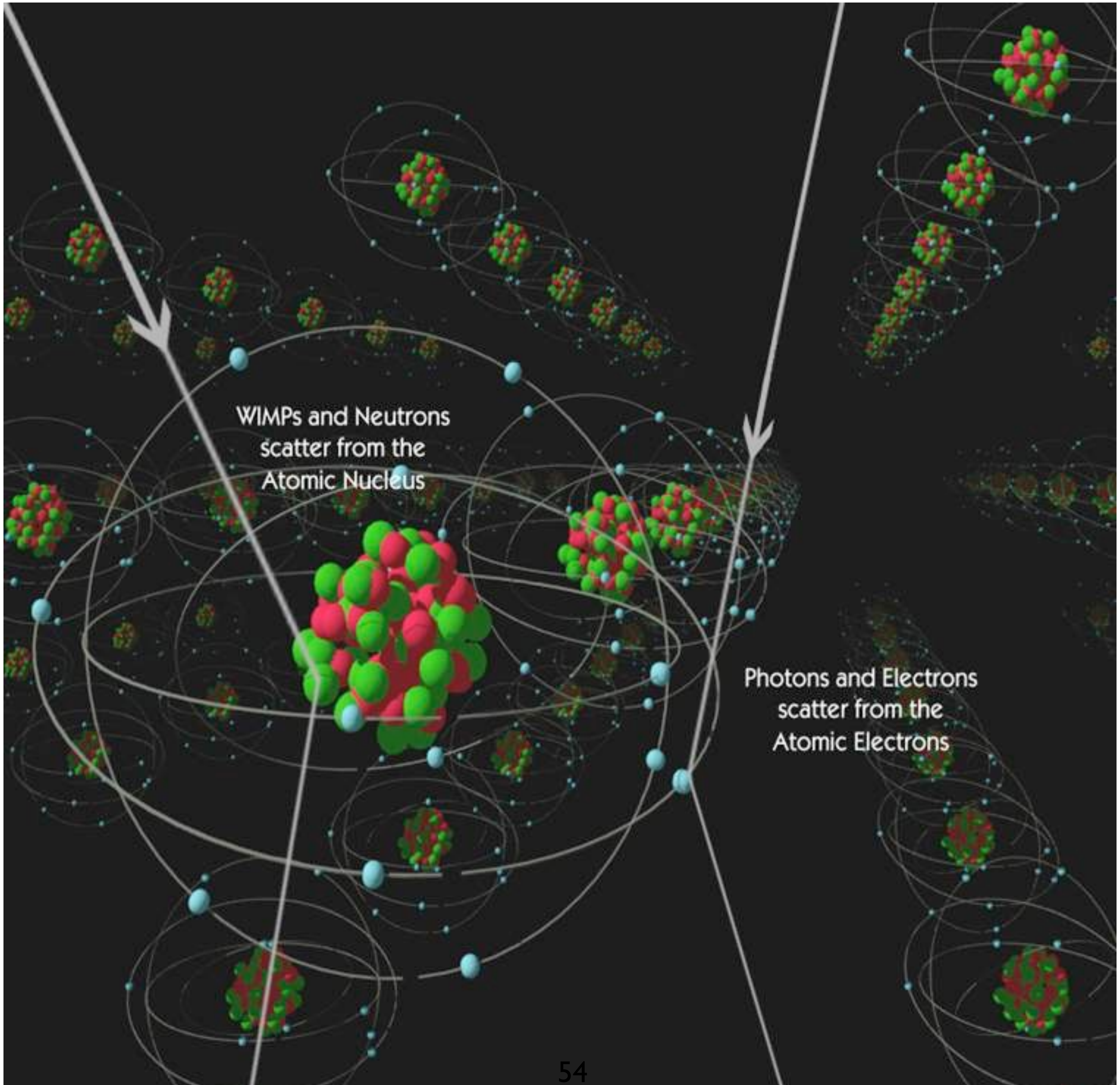
- stable or effectively on Gyr time scales
- not "hot" - i.e., not relativistic at the time it decoupled from matter in the cooling early Universe
- have no substantial strong or electromagnetic charge

It has long been thought that if DM were produced as a "thermal relic" that it would be a Weakly Interacting Massive Particle or "WIMP"

Such candidates appear in models with weak-scale supersymmetry (MSSM)

Direct Detection: Dark Matter "WIMPs"

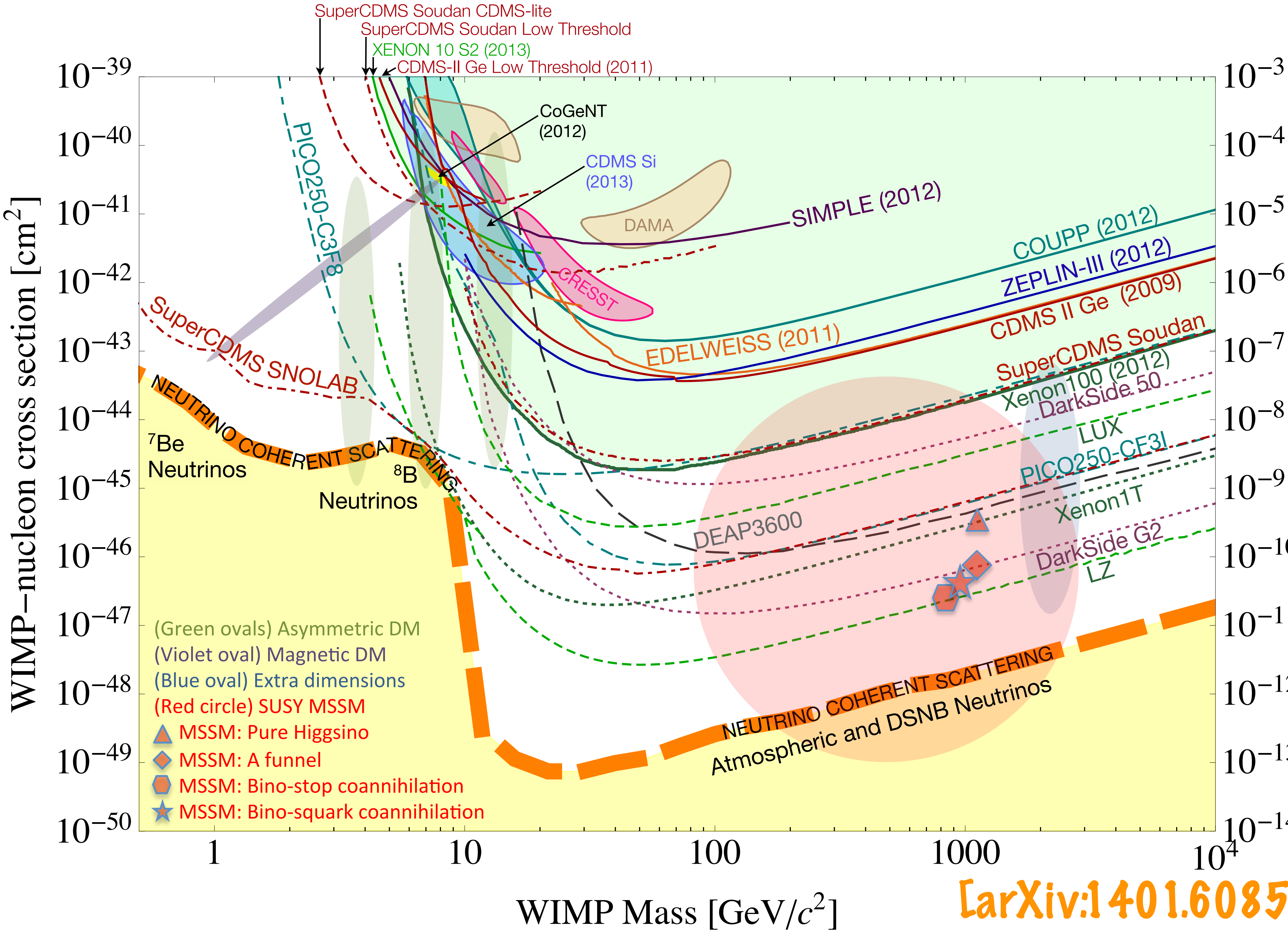
[from cdms.berkeley.edu; note Drukier & Stodolsky, 1984; Goodman & Witten, 1985]



M_{WIMP} ~ 100 GeV

Direct Detection: Dark Matter “WIMPs”

Limits rely on local DM density and velocity distribution

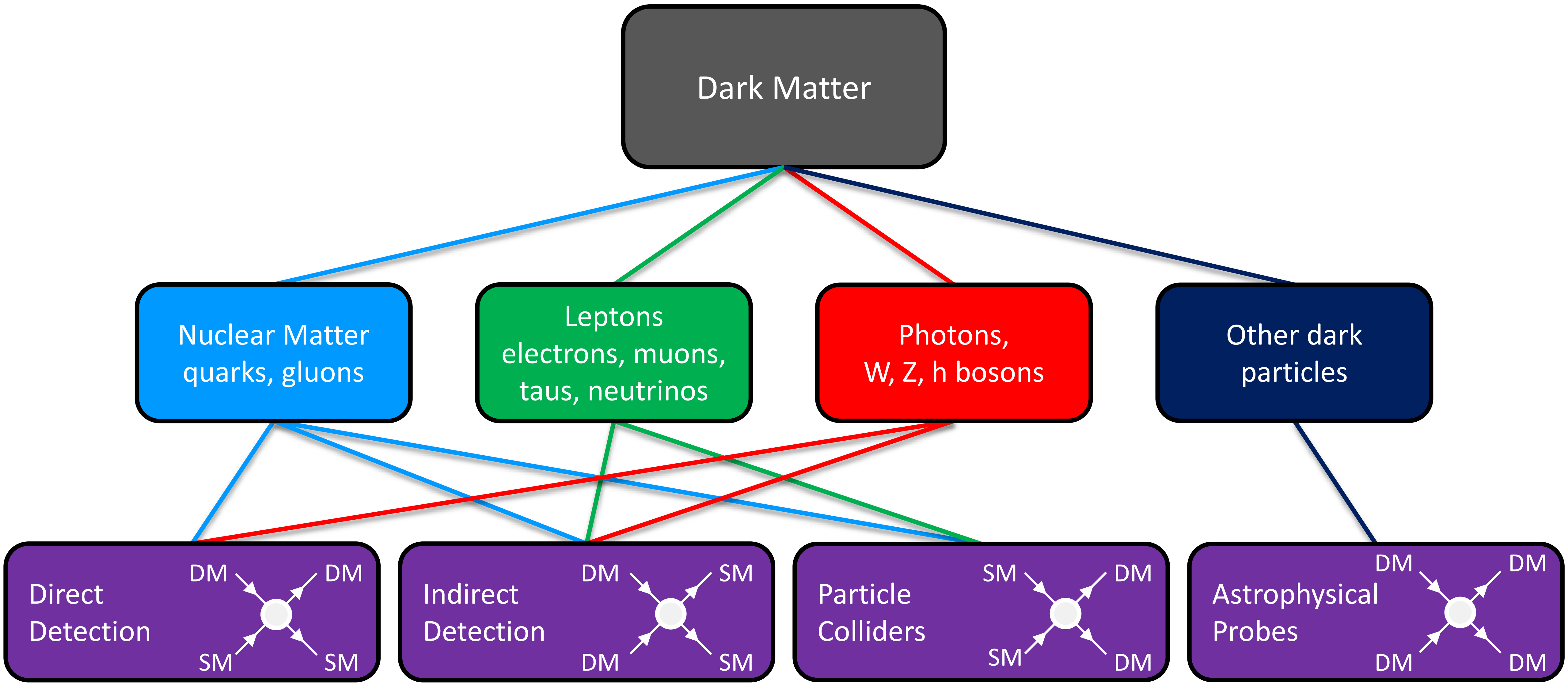


[arXiv:1401.6085]

Broader Search Strategies?

Complementarity is important!

Possible DM couplings to different SM particles can be revealed in different ways....



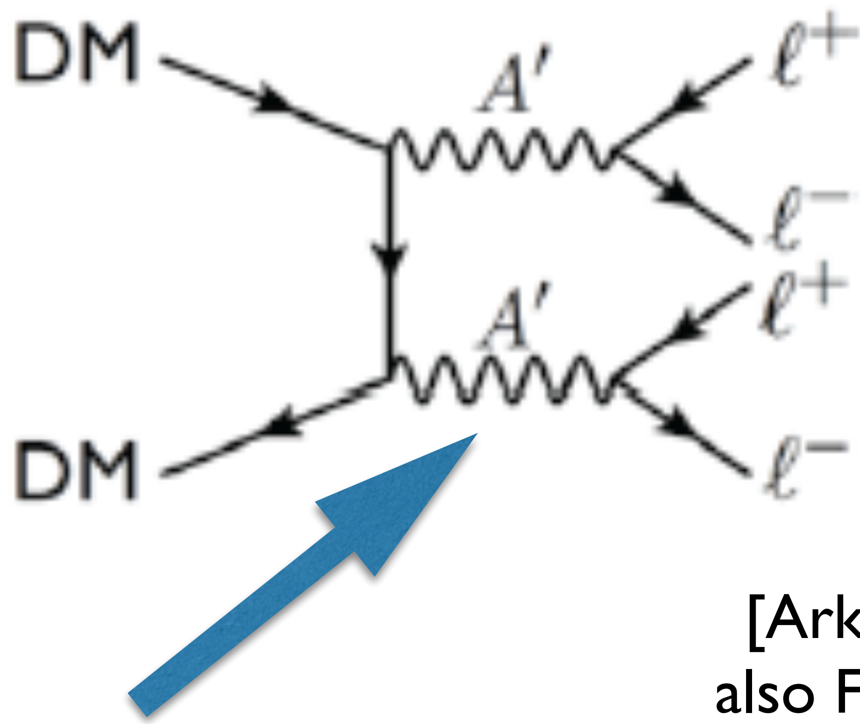
"shake it, break it, bake it"

[arXiv:1401.6085]

Hunting Hidden Forces

"Early" e^+ and e^- excesses in the gamma-ray sky from dark matter annihilation

N.B. Fermi LAT results (& others), 2008-9



Could explain size of excesses if new GeV-scale gauge bosons exist

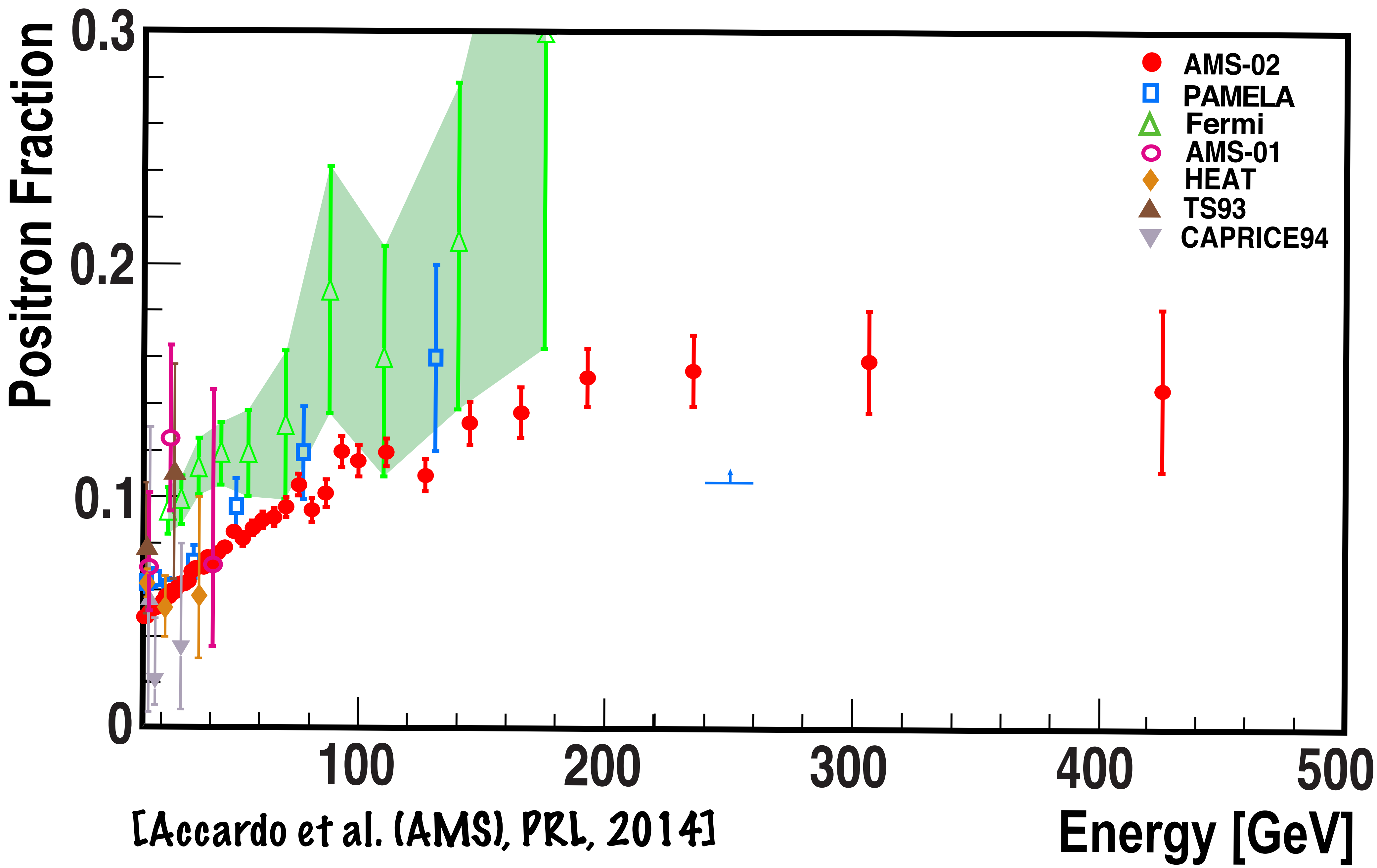
[Arkani-Hamed, Finkbeiner, Slatyer, Weiner, 2009; also Fox & Poppitz, 2009,…Pospelov 2009 (μ g-2)]

new gauge boson is a "portal" to a hidden sector

Plausible conventional explanations now exist, but the possibility was opened nonetheless….

Excess Positrons?

Hunting the high-energy sky for dark matter annihilation



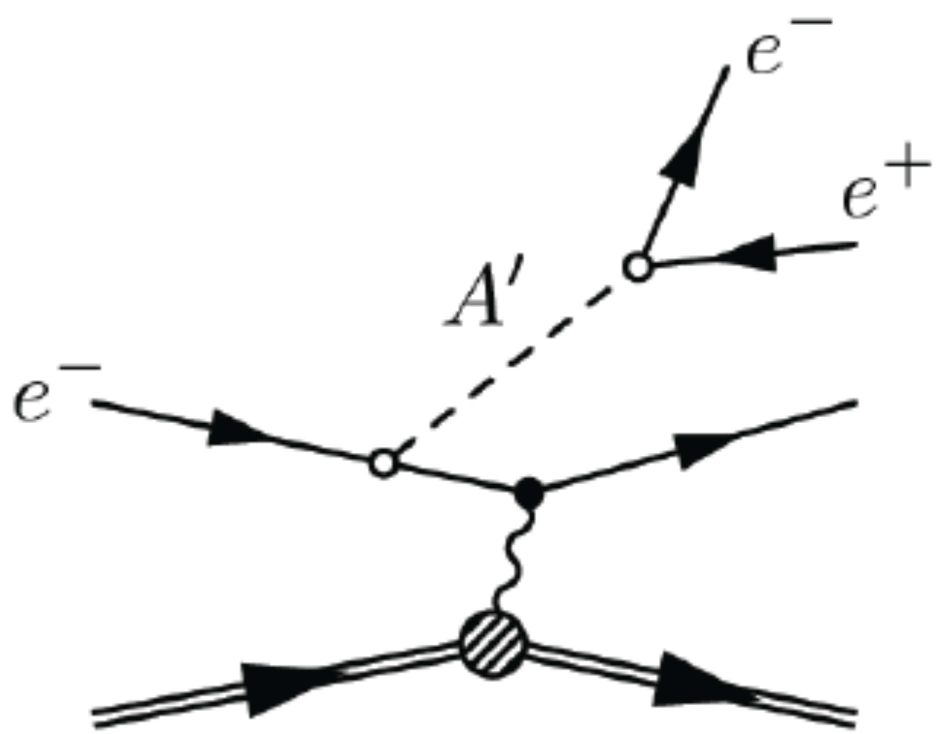
[Accardo et al. (AMS), PRL, 2014]

- But the determined spectrum (thus far) is smooth…

Dark Photons

Hunting new forces in fixed target experiments

The interactions that generate DM annihilation could also be discovered at accelerators:



[E.g., Bjorken, Essig, Schuester, Toro, 2009]

The new gauge boson could stem from a dark electromagnetism, and the photon and dark photon could mix

But different gauge symmetries (& portals) are possible!

New Gauge Bosons

We may only be able to probe part of a rich dark sector

E.g., let A′ be the gauge field of a U(1)′ group

But Coulomb-like DM-DM forces do not appear to exist, so that the A′ must have mass…

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{\varepsilon}{2} F^{Y,\mu\nu} F'_{\mu\nu} - \frac{1}{4} F'^{\mu\nu} F'_{\mu\nu} + M_{A'}^2 A'^{\mu} A'_{\mu} + \ldots$$

With $A_\mu \to A_\mu - \varepsilon A'_\mu$ the A′ couples to SM fermions with strength Qeε [Holdom, 1986]

⟹ Note "kinetic mixing" of visible & hidden sectors

Gauge Theories of a Hidden Sector

Only a Few "Sizeable" Portals Exist

$$\mathcal{L}_{\mathrm{dim}\leq 4} = \frac{\kappa}{2} V^{\mu\nu} F'_{\mu\nu} - H^\dagger H (AS + \lambda S^2) - Y_N L H N$$

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

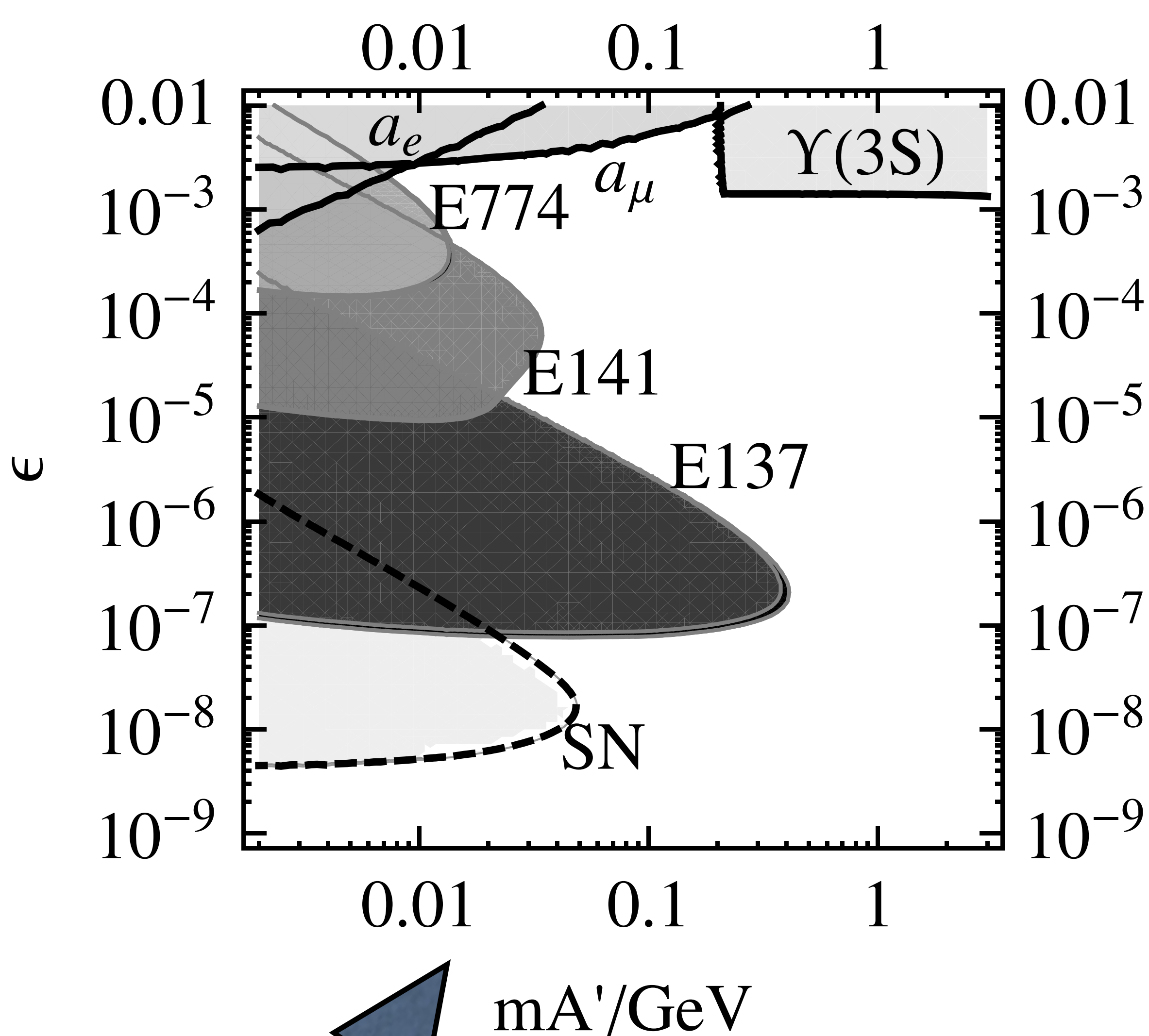
- Vector Portal
- Higgs Portal
- Neutrino Portal

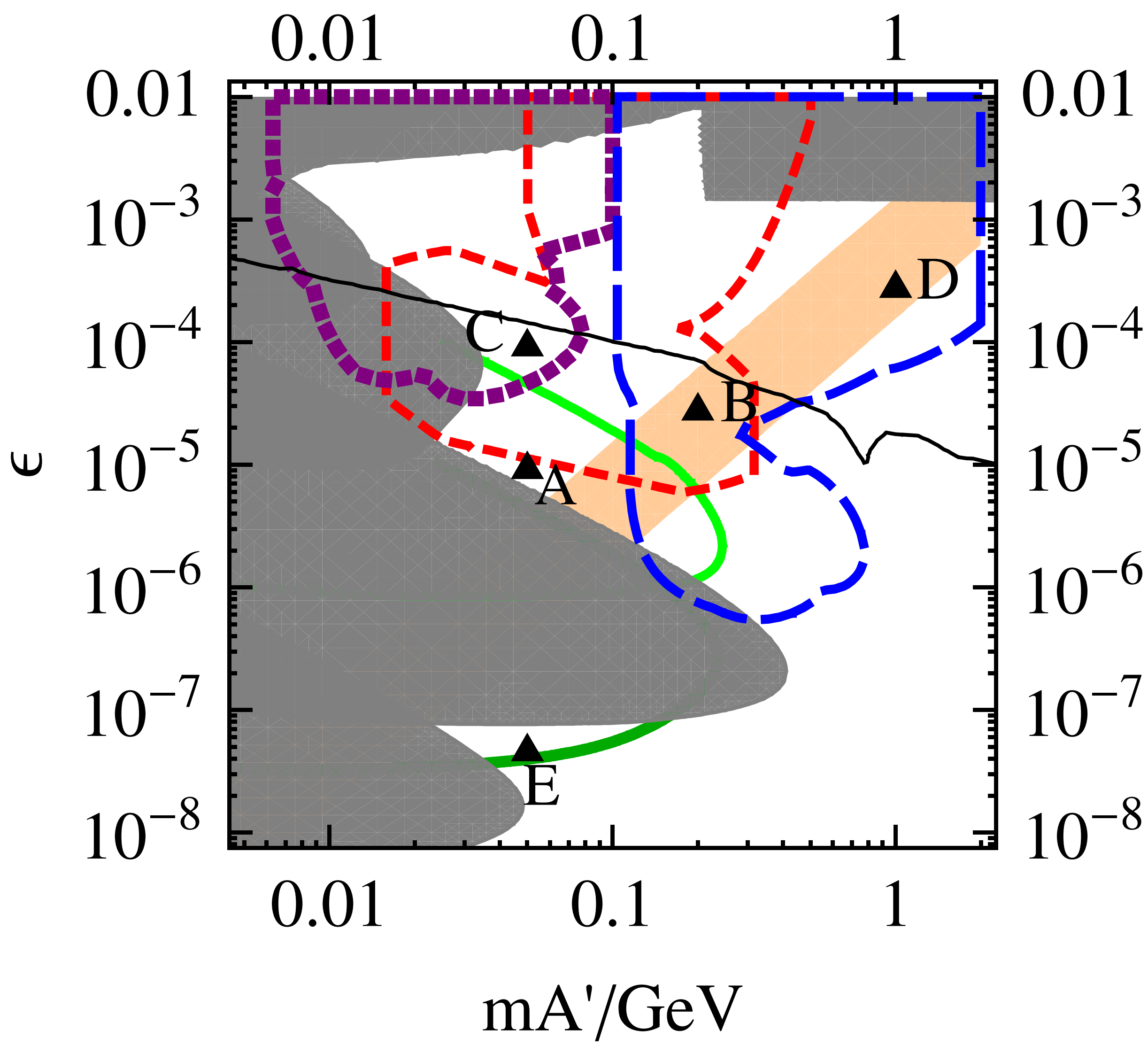
All deserve systematic study; N.B. low E Higgs portal & rare B and K decay constraints!

Focus: the dark photon A′ and the **vector portal**

Dark Photon Parameter Space is Vast

Different experimental strategies for different regions



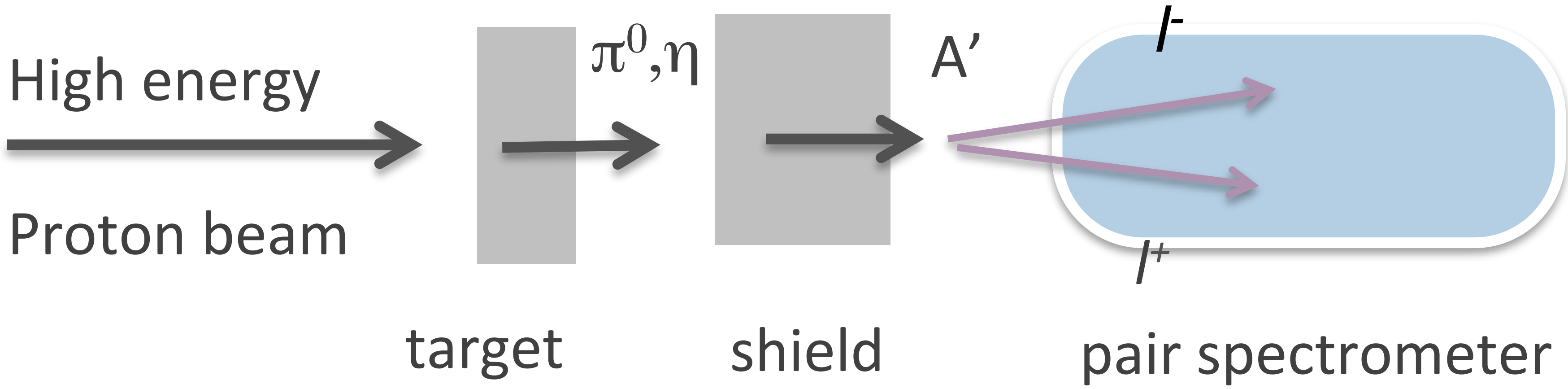


[Bjorken, Essig, Schuster, and Toro, 2009]

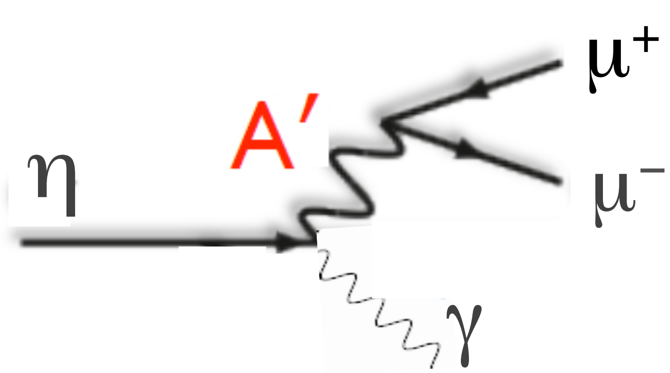
"Beam dump" (displaced production & detection vertices in matter) studies yield powerful constraints

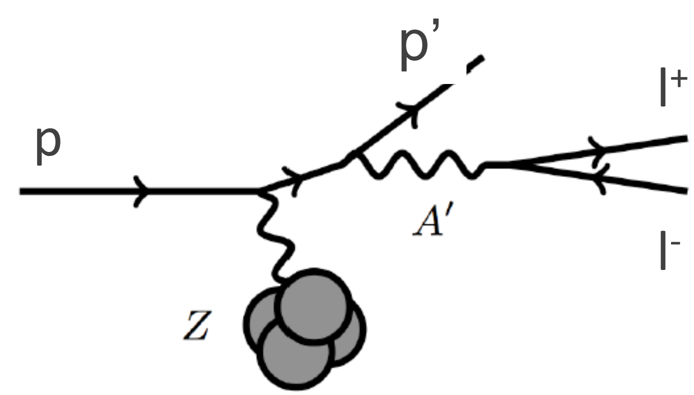
Dark Photon Parameter Space is Vast

Studies also possible through SeaQuest/E906 at Fermilab



Offering distinct windows on a vector portal...





Radiative π^0, η decays

[Batell, Pospelov, and Ritz, 2009; Gninenko, 2011]

Proton bremsstrahlung

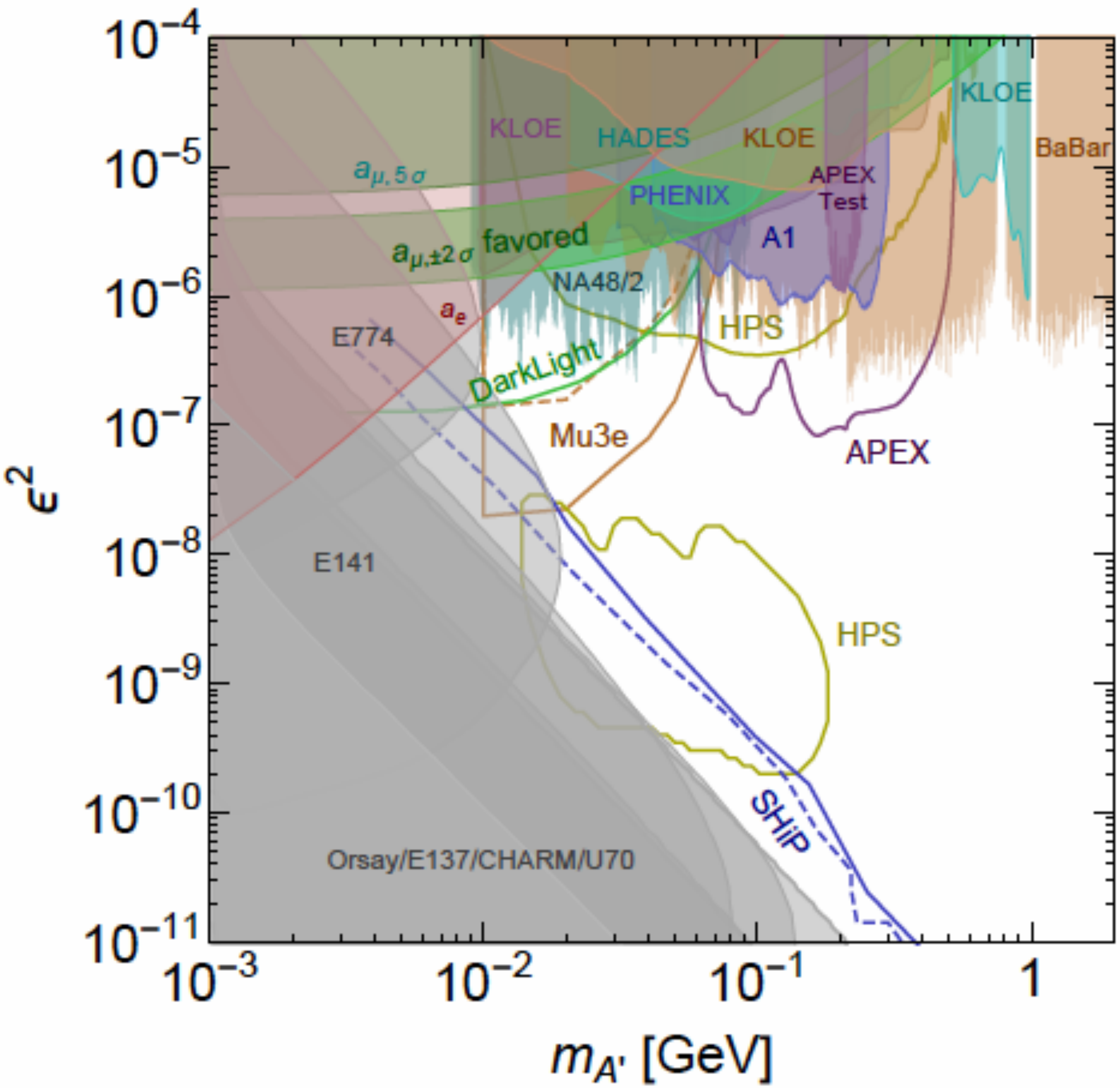
[Bluemlein and Brunner, 2011 & 2013]

[SG, Holt, Tadepalli, 2015; Gori et al., 2018] **Also in Drell-Yan...**

Dark Photon Decays to Visibles (Only)

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

[Pospelov, 2009]



But this may only speak to our assumptions…

Gauge Theories of the Hidden Sector

There are many possible vector portals - but only some are "anomaly free"

Typical to consider Abelian groups as $F^{\mu\nu}$ is gauge invariant

- $U(1)_Y$ or $U(1)_{em}$: enter the dark photon and A-A′ mixing [Holdom, 1986…]

- $U(1)_Y$ with an extended Higgs sector : now mixing with both the photon and Z occurs – enter the Z_d
  [Davoudiasl, Lee, Marciano, 2014]

- $U(1)_B$ but not anomaly free [Nelson & Tetradis, 1989; Tulin, 2014; Dobrescu & Frugiuele, 2014…]

- $U(1)_{\mu-\tau}$ [Altsmannshofer, Gori, Pospelov, & Yavin, 2014]

Model for the Be-8 IPC anomaly

There's no unique choice, but here's one:

[Feng, Fornal, Galon, SG, Smolinsky, Tait, Tanedo, 2016]

- Gauge the $U(1)_{B-L}$ global symmetry of the SM
- This is anomaly-free with the addition of 3 sterile neutrinos
- Generically the B-L boson mixes with the photon:

$$\varepsilon_u : \quad \frac{2}{3}\varepsilon + \frac{1}{3}\varepsilon_{B-L} \qquad\qquad \varepsilon_\nu : \quad -\varepsilon_{B-L}$$

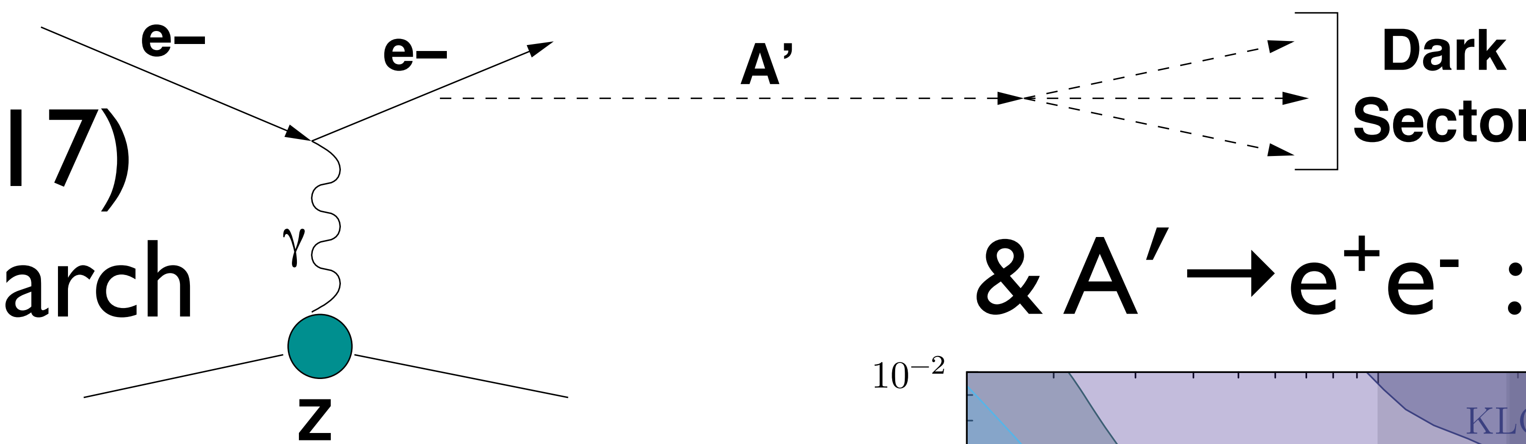
$$\varepsilon_d : \quad -\frac{1}{3}\varepsilon + \frac{1}{3}\varepsilon_{B-L} \qquad\qquad \varepsilon_e : \quad -\varepsilon - \varepsilon_{B-L} \ ,$$

- For $\varepsilon + \varepsilon_{B-L} \approx 0$, we get both $\varepsilon_u \approx \varepsilon/3$ and $\varepsilon_d \approx -2\varepsilon/3$ (protophobia) and $\varepsilon_e << \varepsilon_{u,d}$!
- The neutrino X-charge is too large. This problem is mitigated if X is heavier, then ε_{B-L} can be smaller. It can be remedied in different ways – e.g., by mixing with X-charged sterile neutrinos.

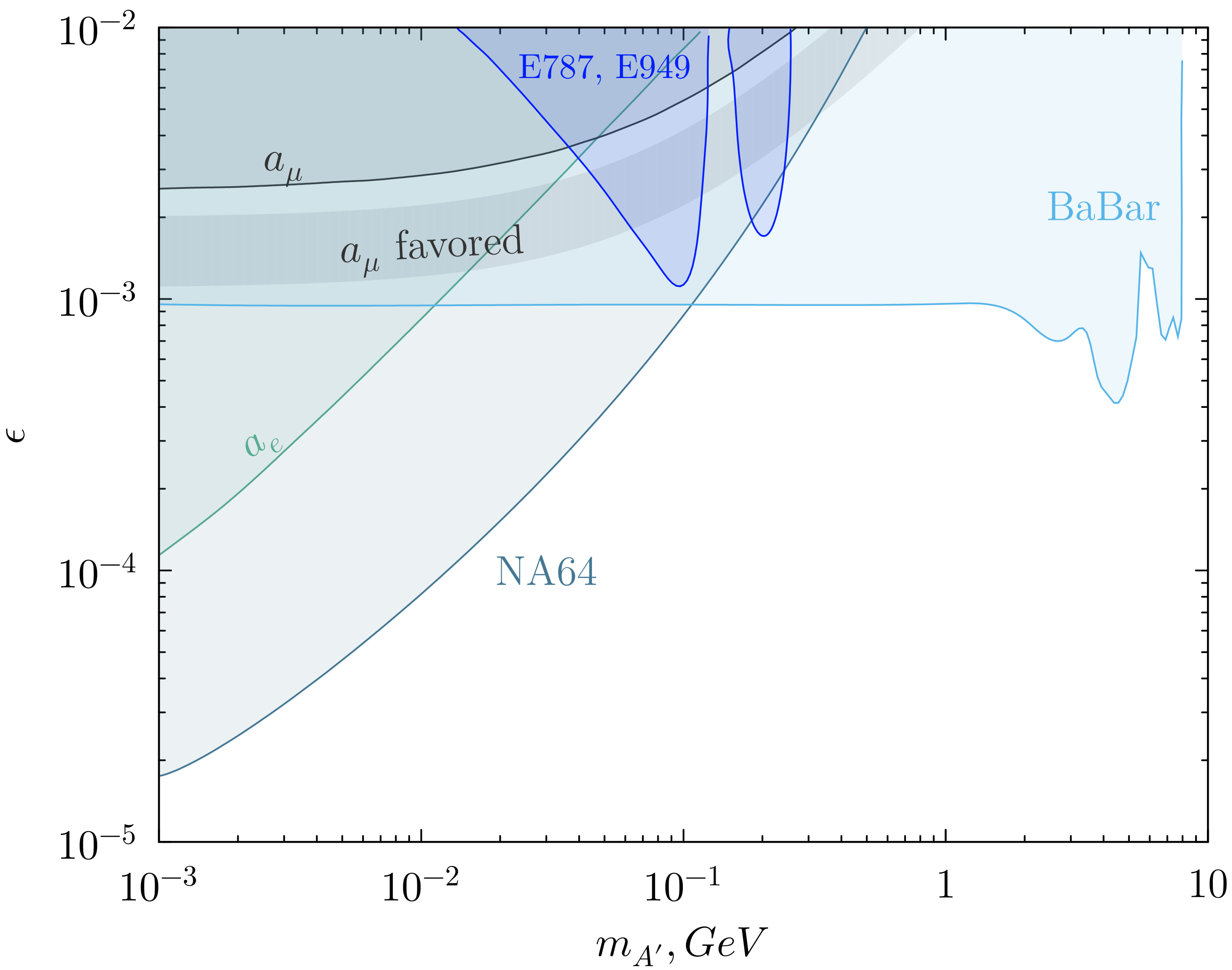
Other model possibilities are being developed….

Opportunities in Neutron β Decay?

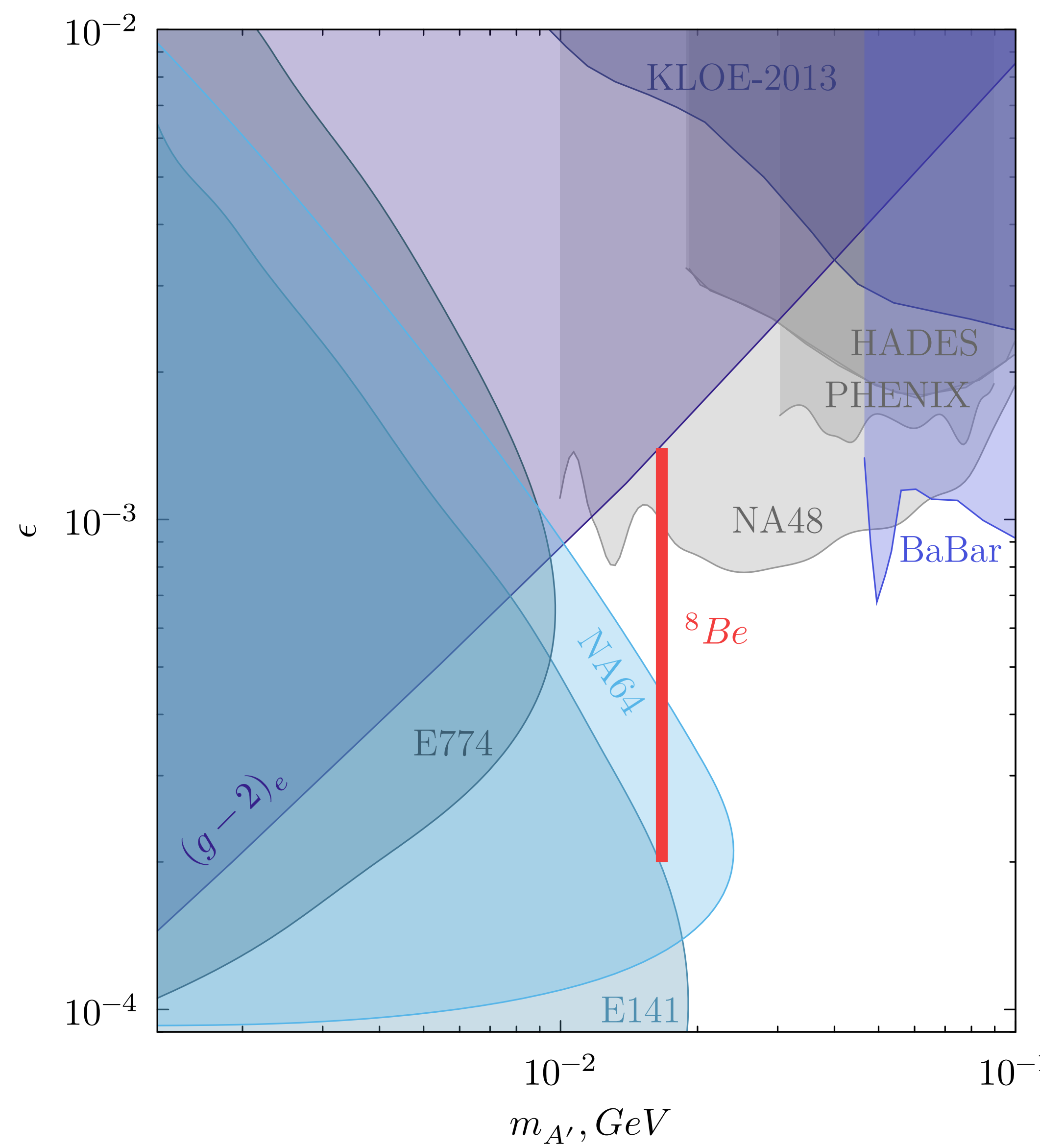
Dark bremsstrahlung could impact the β spectrum....



cf. NA64 (2017)
“invisibles” search



& $A' \rightarrow e^+e^-$: (2018)



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

[Weinberg 1977, Wilczek 1977]

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….)

Some Thoughts on the Strong CP Problem

The SM has other "fine-tuning" problems

The following term can appear within QCD

$$\mathcal{L}_\theta = \frac{g^2}{32\pi^2}\theta_{\rm QCD} F_a^{\mu\nu}\tilde{F}_{\mu\nu a}$$

as can a similar term from the quark masses, so that

$$\theta_{\rm QCD} \Longrightarrow \bar{\theta} = \theta_{\rm QCD} + \theta_{\rm Yukawa}$$

Neither term needs to be small but
the experimental limit on the n EDM implies

$$\bar{\theta} \ll 10^{-10}$$

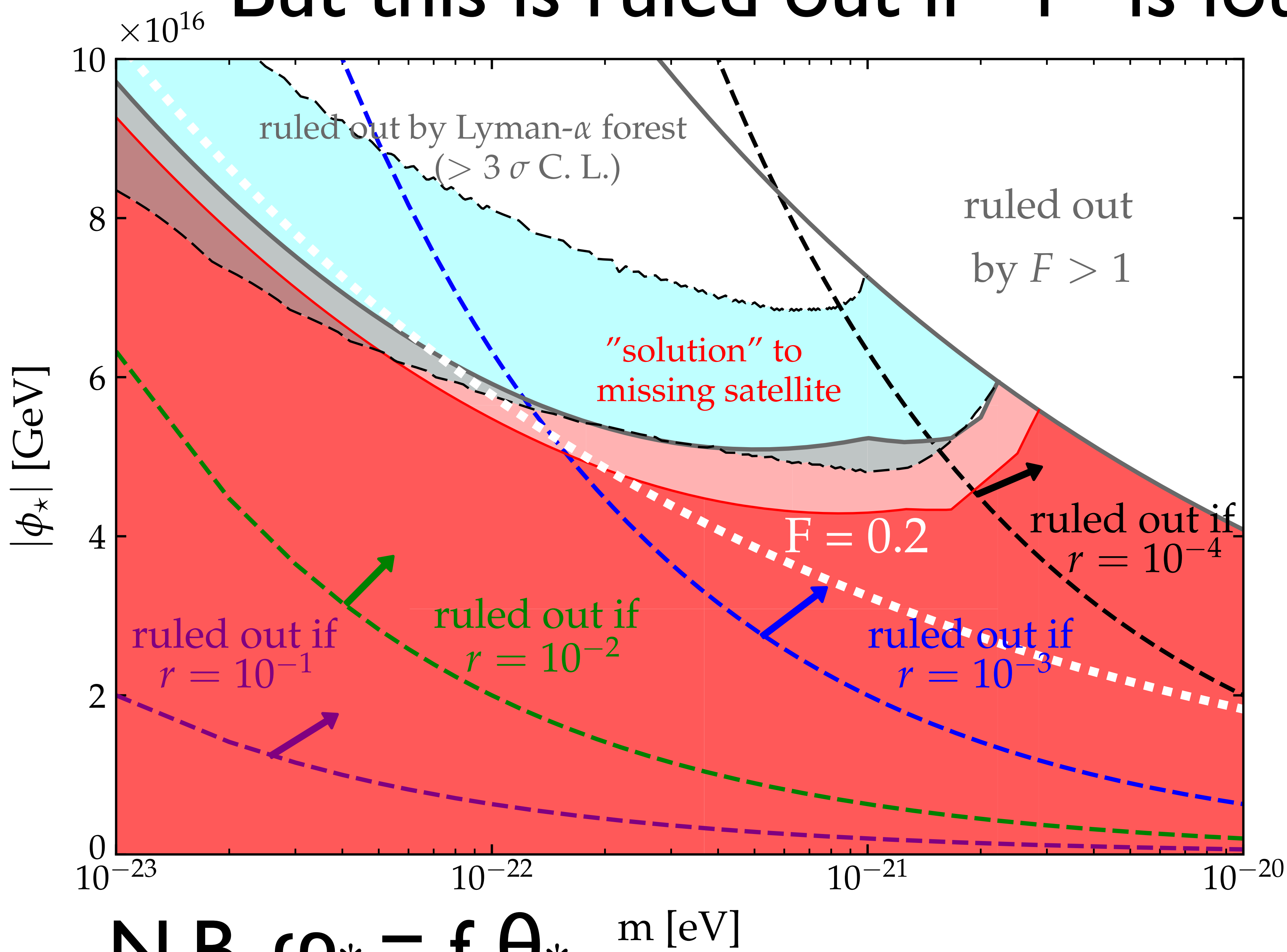
Why is "δ" ~ 1?!

Many discussed resolutions… here Peccei-Quinn…

Ultralight Axion Window

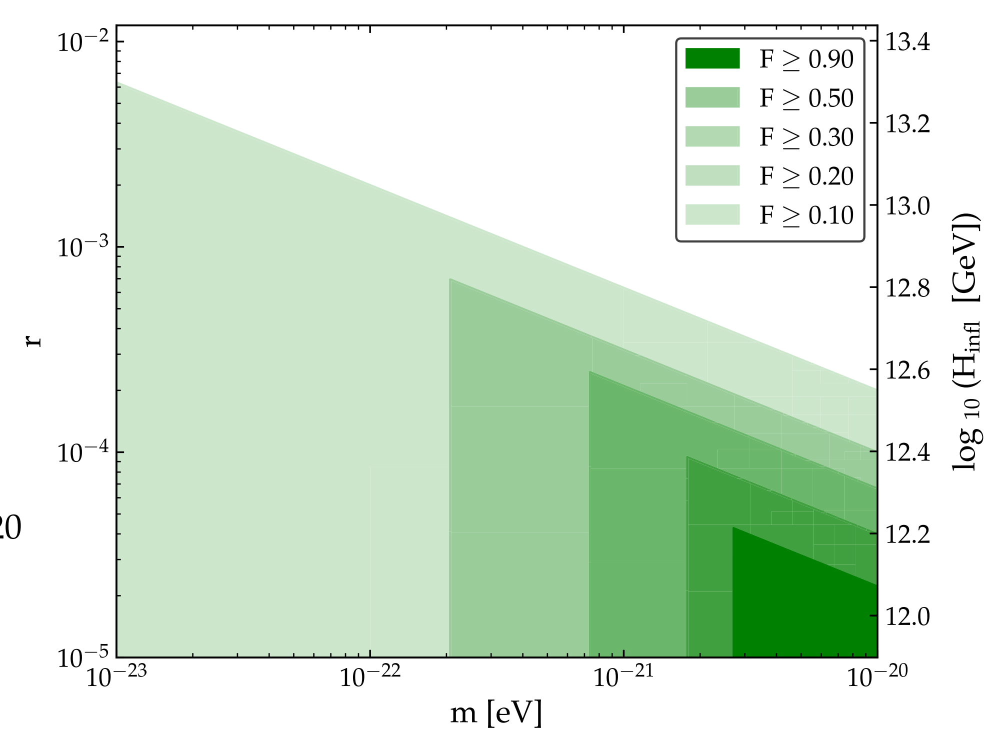
A new pseudoscalar boson (not connected to QCD) can explain the "dark matter"!

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

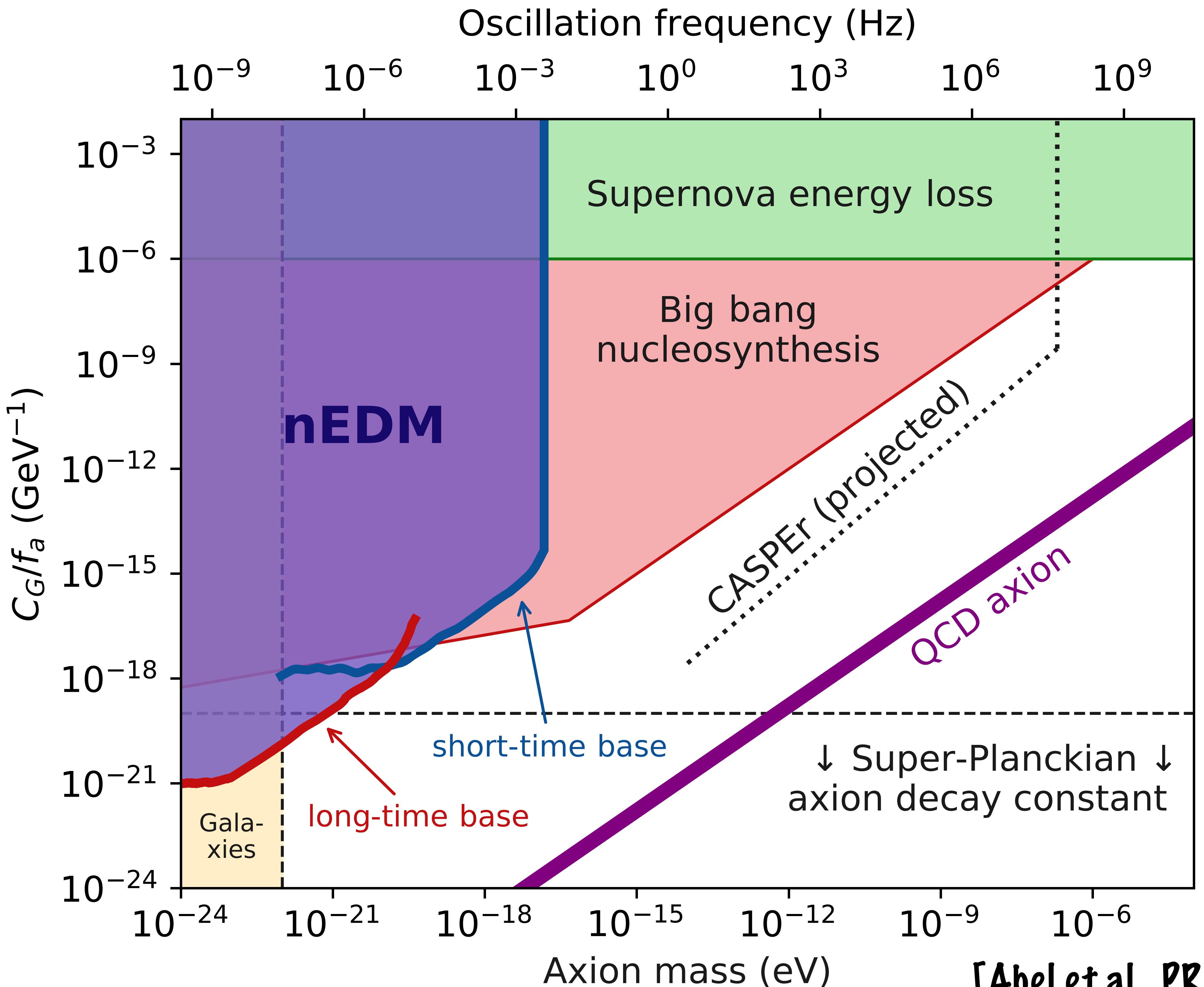


N.B. $\varphi_* = f_a \theta_*$

Kobayashi et al.,
PRD 96 (2017) 123514



Direct Detection: Ultralight Dark Matter



[Abel et al., PRX, 2017]

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

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

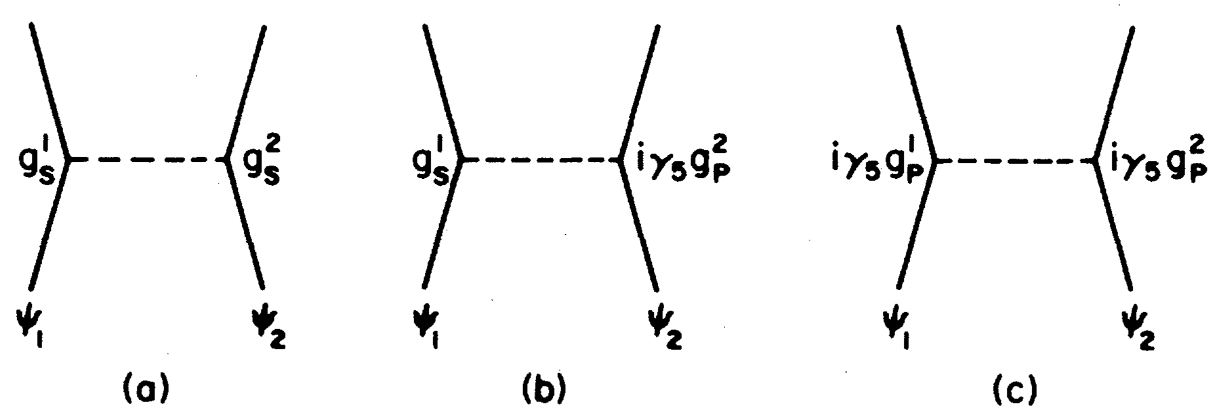


FIG. 1. Graphs for the potentials of Eqs. (4), (5), and (6). (a) (Monopole),[2] (b) monopole-dipole, (c) (dipole).[2]

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

[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

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

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

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

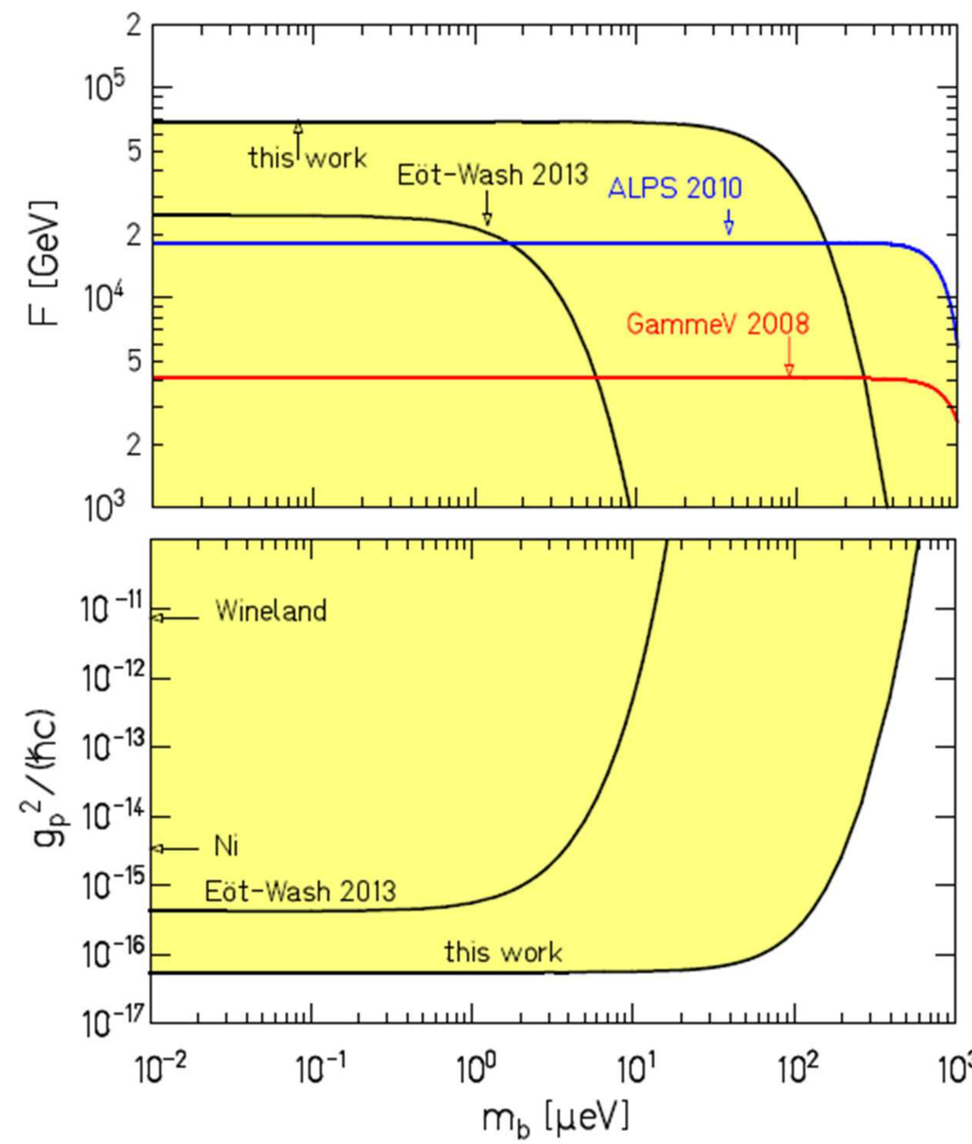


FIG. 4: Bottom: exotic dipole-dipole limits from this work and Ref. [5]. Arrows indicate the infinite-range constraints from Refs. [12, 13]. Electron $g-2$ constraints are at the 10^{-10} level[14]. Top: limits on the symmetry-breaking scale from this work and Refs. [15, 16]. The shaded areas are excluded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

Summary

Weakly coupled physics at low energies is its own frontier!

Neutron experiments, even if devoted to other "primary" measurements, can play an important role

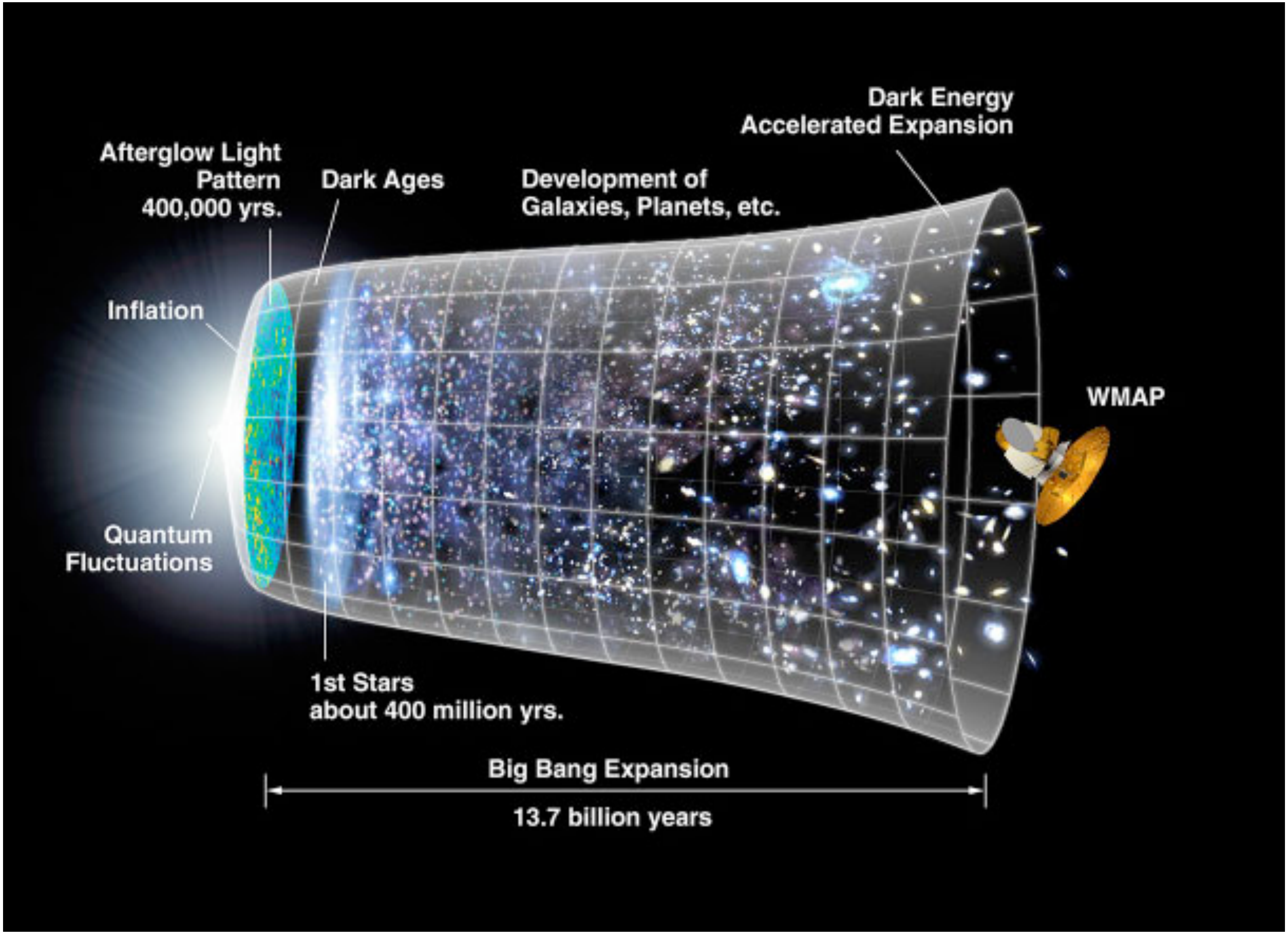
Dedicated efforts to detect new long range forces (& using neutrons) are ongoing

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

Backup Slides

A Matter-Dominated Universe

[http://www.nasa.gov/vision/universe/starsgalaxies/wmap_pol.html]



Gauge Theories of the Hidden Sector

Enter kinetic mixing

Consider the dark photon...

$$\mathcal{L}_{A'} = \frac{\varepsilon}{2} F^{Y\,\mu\nu} F'_{\mu\nu} - \frac{1}{4} F'^{\mu\nu} F'_{\mu\nu} + \frac{1}{2} m^2_{A'} A'^{\mu} A'_{\mu}$$

Diagonalization and field definition yields

$$A^{\mu} \longrightarrow A^{\mu} - \varepsilon A'^{\mu} \text{ but } Z - A' \text{ mixing } \mathcal{O}(\varepsilon m^2_{A'}/M^2_Z)$$

[Bjorken, Essig, Schuster, and Toro, 2009…]

Thus the A′ couples to SM fermions.

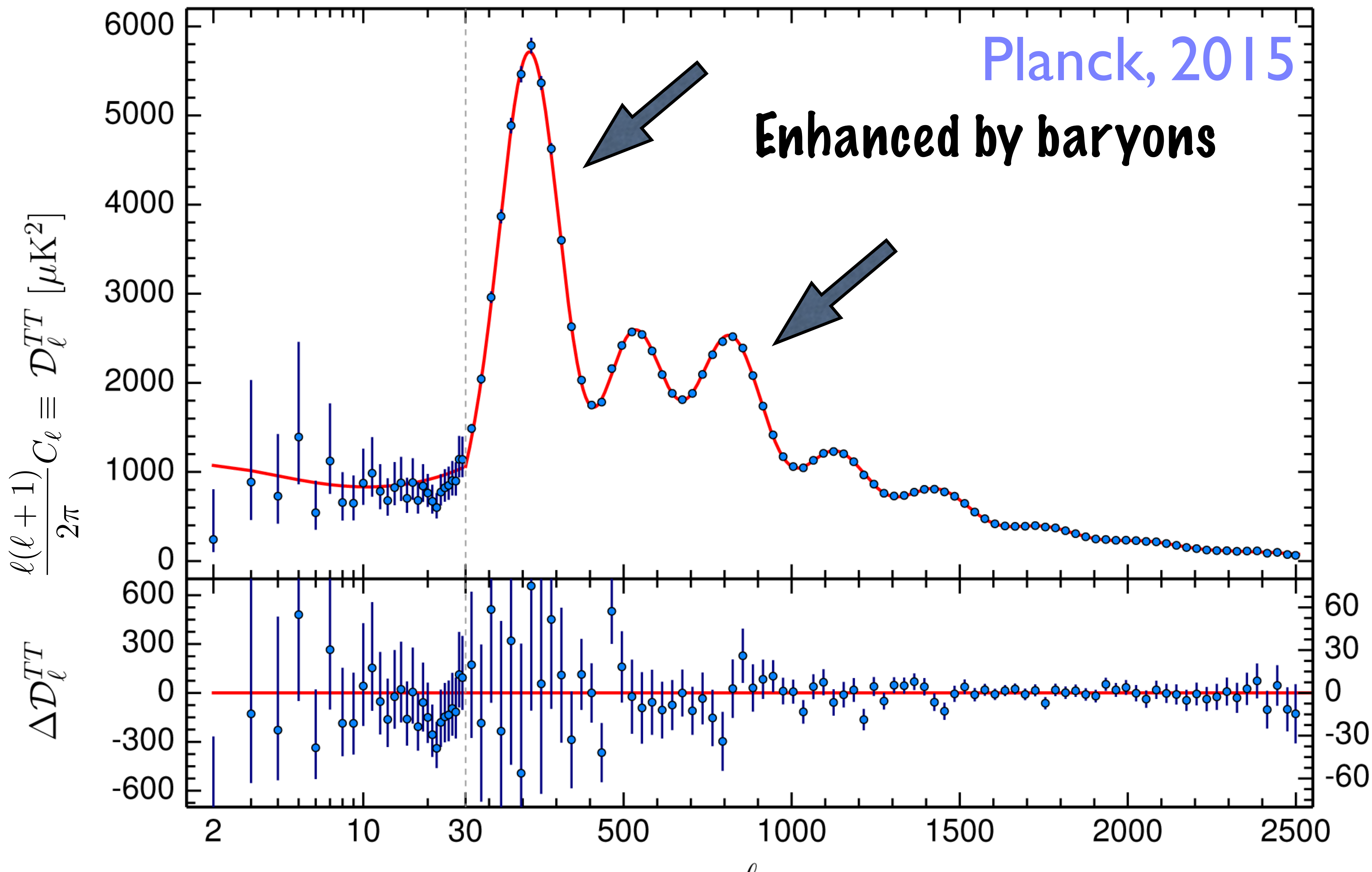
Now w/ an extended Higgs sector…

$$\mathcal{L}_{\mathrm{darkZ}} = -(\varepsilon e J^{\mu}_{\mathrm{em}} + \varepsilon_Z \frac{g}{2\cos\theta_W} J^{\mu}_{\mathrm{NC}}) Z_{d\,\mu}$$

[Davoudiasl, Lee, Marciano, 2014]

A Cosmic Baryon Asymmetry

Patterns of acoustic waves reveal net baryon number!



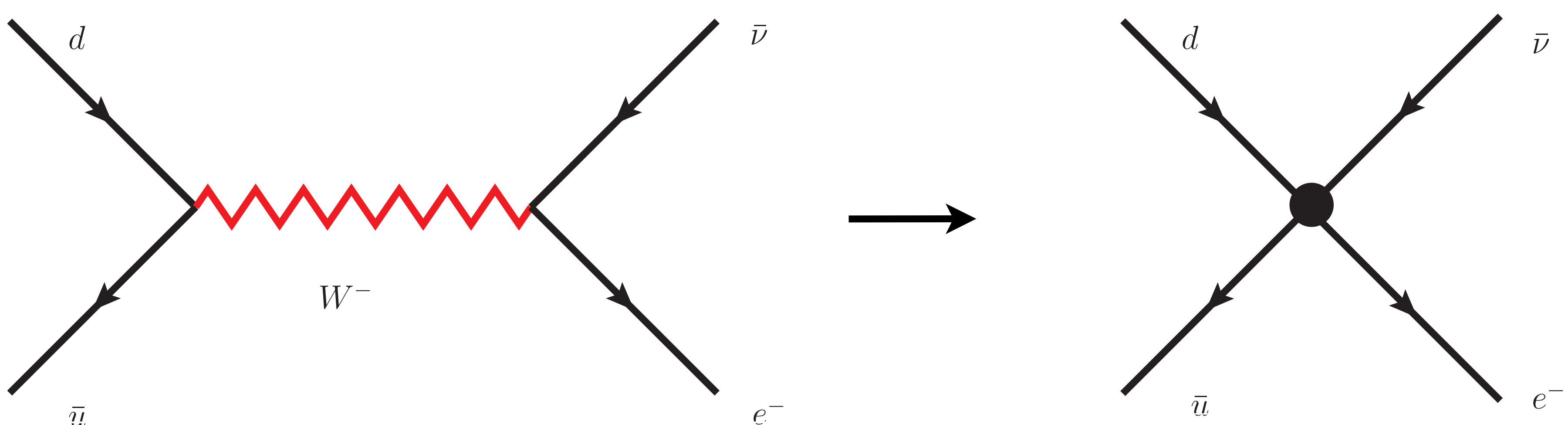
[https:wiki.cosmos.esa.int/planckpla2015/index.php/CMB_spectrum_%26_Likelihood_Code]

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



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

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

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

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*!

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

*[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

$G_F^{(0)}/\sqrt{2} = g^2/8M_W^2$ 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]

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

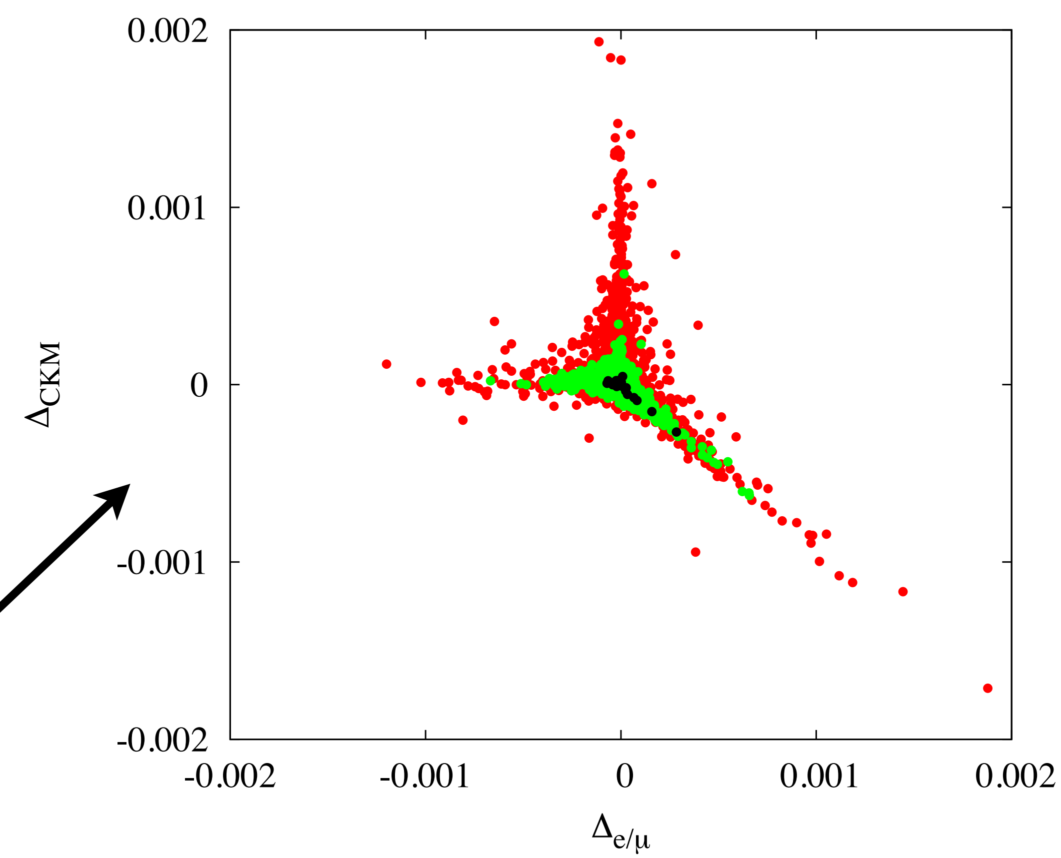
New physics!

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

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

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

ϵ_S , ϵ_T enter in linear order!

"most visible"

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

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....

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

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]

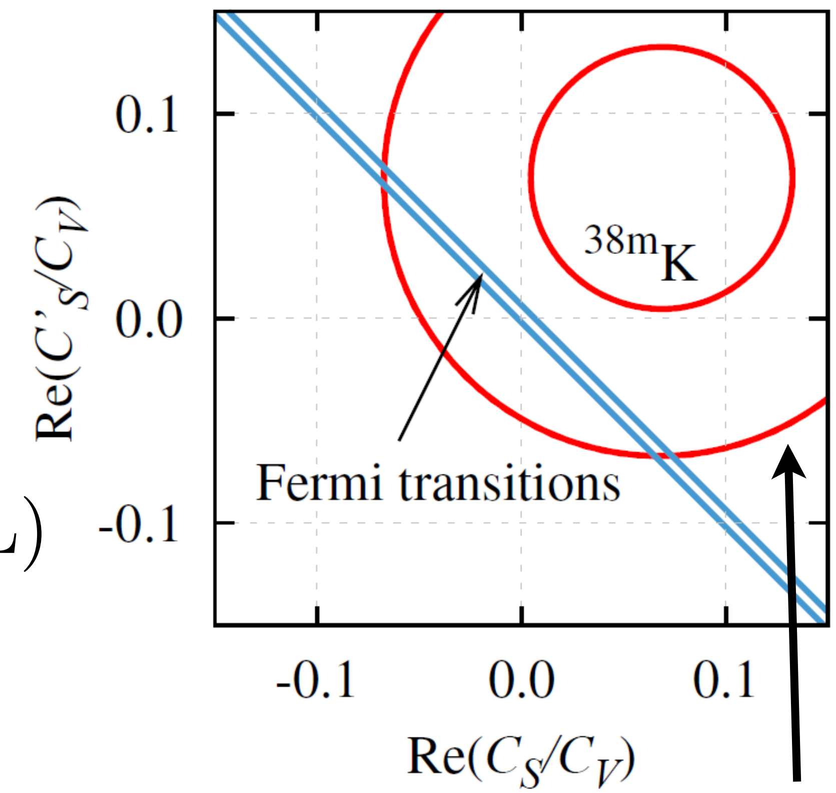
If $J \neq 1/2$

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

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]

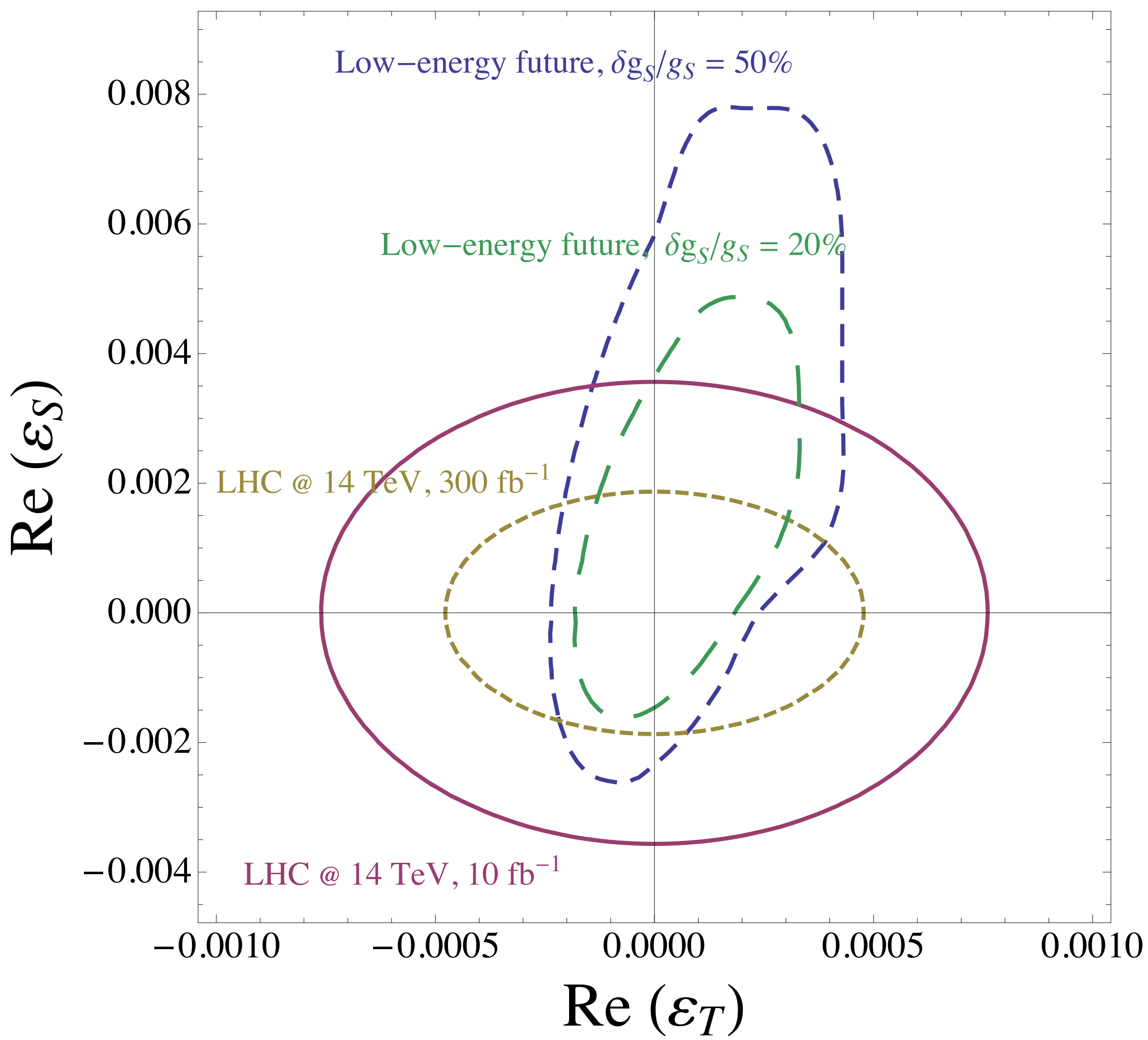
$$b = \frac{2\gamma}{1+3\lambda^2}\left[g_S\, \mathrm{Re}(\epsilon_S) - 12\lambda\, g_T\, \mathrm{Re}(\epsilon_T) \right],$$

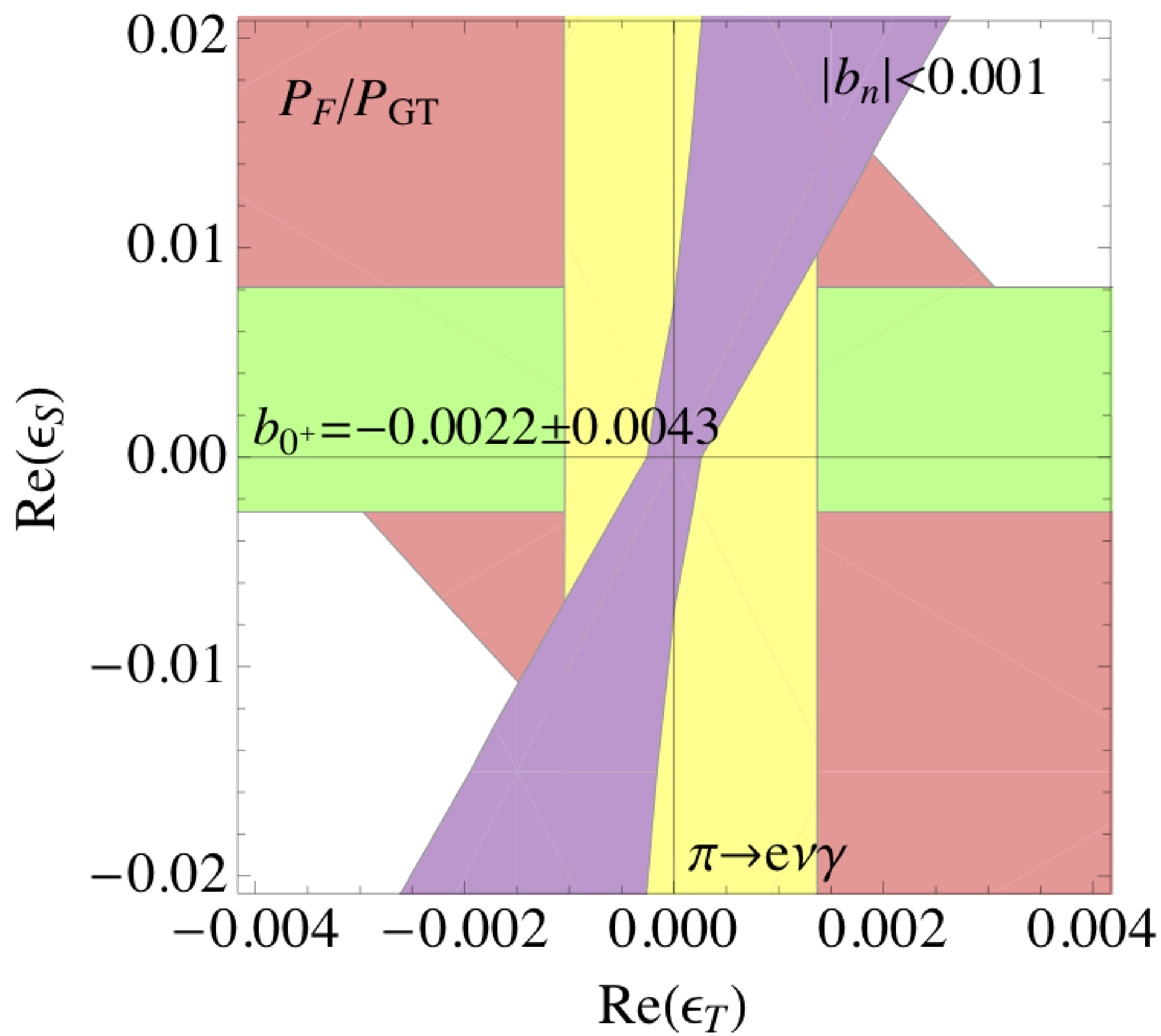
$$b_\nu = \frac{-2\gamma}{1+3\lambda^2}\left[g_S\, \mathrm{Re}(\epsilon_S)\, \lambda - 4 g_T\, \mathrm{Re}(\epsilon_T)\, (1-2\lambda) \right].$$

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....