CAP Congress - SFU - June 2019

EDMs and Dark Sectors

Adam Ritz

University of Victoria

[work with Shohei Okawa & Maxim Pospelov: 0905.05219]

Motivating Questions…

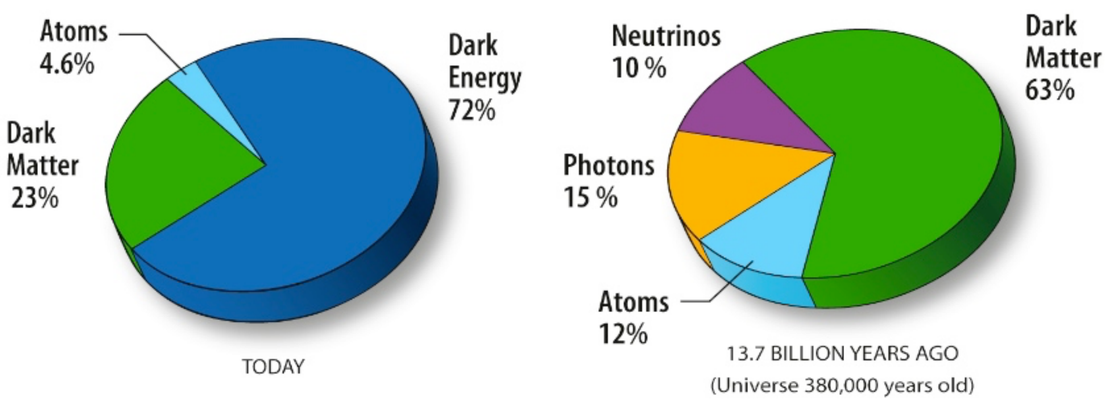
Sakharov's criteria for generating a baryon asymmetry are over 50 years old!

VIOLATION OF CP INVARIANCE, C ASYMMETRY, AND BARYON ASYMMETRY OF THE UNIVERSE

A. D. Sakharov
Submitted 23 September 1966
ZhETF Pis'ma 5, No. 1, 32-35, 1 January 1967

The theory of the expanding Universe, which presupposes a superdense initial state of matter, apparently excludes the possibility of macroscopic separation of matter from antimatter; it must therefore be assumed that there are no antimatter bodies in nature, i.e., the

- *Developed at a time before there was clear evidence for dark matter or neutrino mass, and now there are even more questions…*



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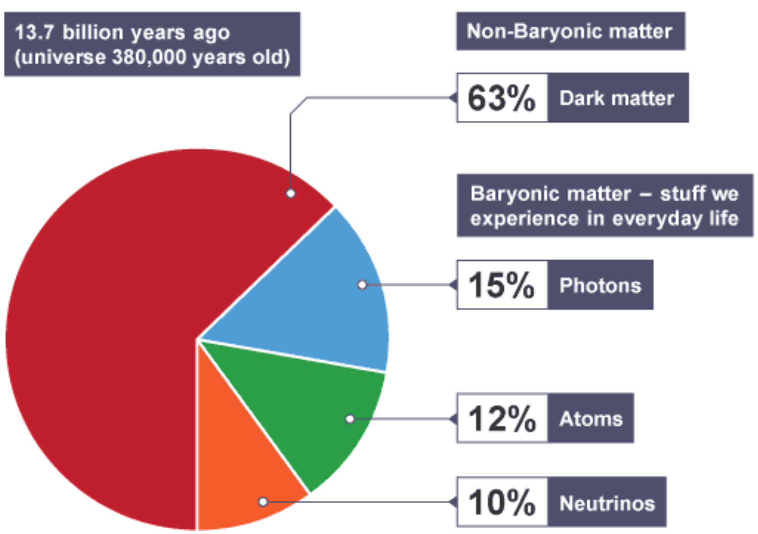

Questions

- Baryon asymmetry?
  and
- Identity of Dark Matter?
- DM-genesis?
- Neutrino mass?
- Lepton asymmetry?

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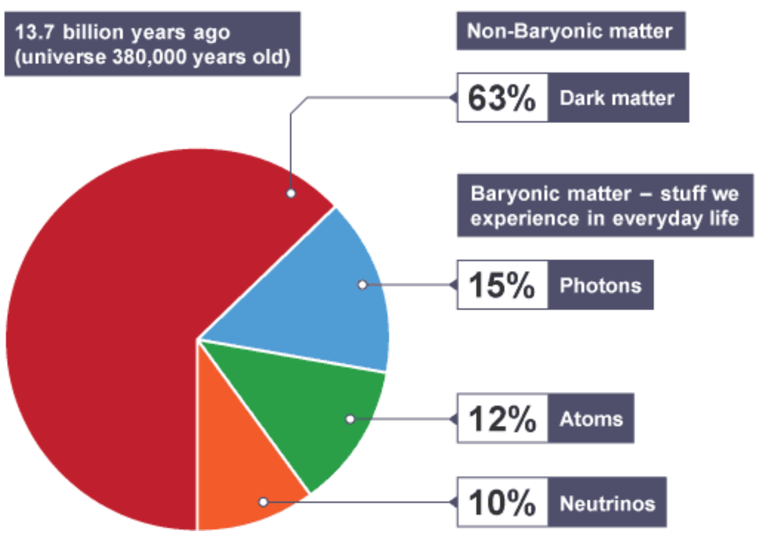

Questions

- Baryon asymmetry?
  and
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- Lepton asymmetry?

⇒ Common theme - CP violation required in one sector or another

EDMs as precision probes

EDMs are powerful (amplitude-level) probes for new CP/T violation

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

Paramagnetic EDMs

$|d_e^{\mathrm{equiv}}| < 1.1 \times 10^{-29}\, e\mathrm{cm}$

Harvard/Yale (ThO)
[Andreev et al. '18]

JILA, NIST (HfF^+)
[Cairncross et al. '17]

Imperial (YbF)
[Hudson et al. '11]

Diamagnetic EDMs

$|d_{\mathrm{Hg}}| < 7.4 \times 10^{-30}\, e\mathrm{cm}$

U Washington (Hg)
[Graner et al '16]

U Michigan (Xe)
[Rosenberry & Chupp '01]

Argonne (Ra)
[Bishof et al '16]

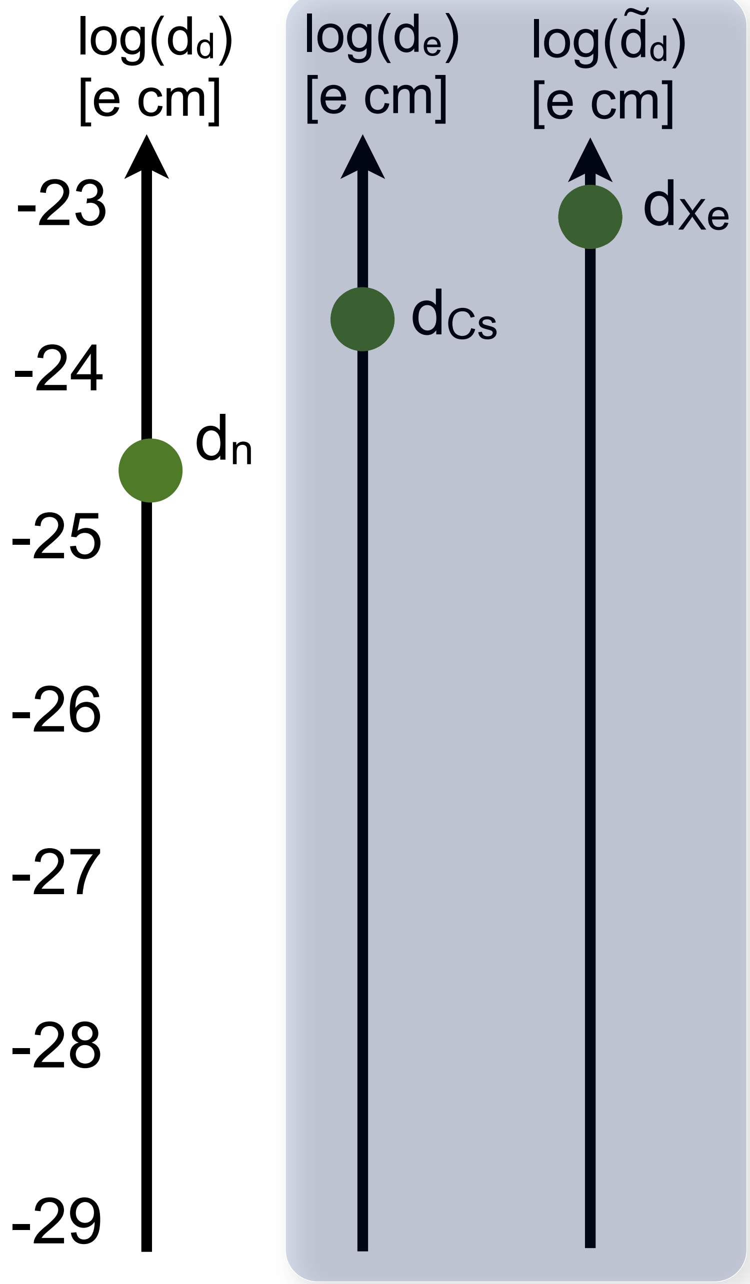
Neutron EDM

$|d_n| < 3 \times 10^{-26}\, e\mathrm{cm}$

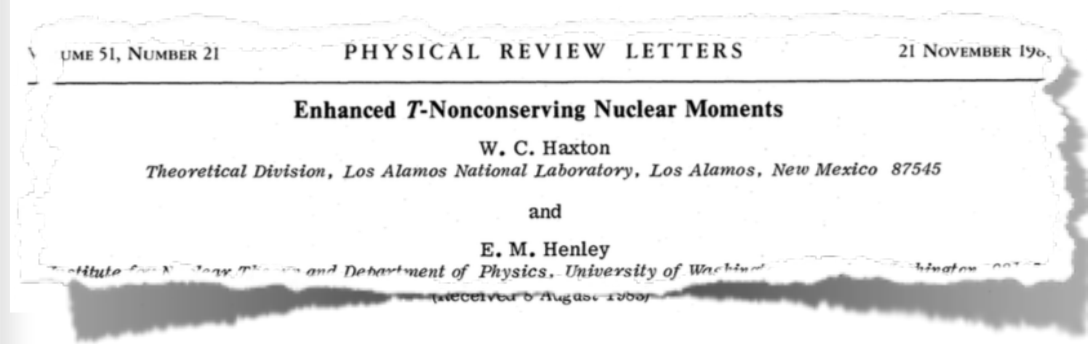
Sussex/RAL/ILL
[Baker et al. '06,
Pendlebury et al '15]

(+ many experiments in development around the world, *including at TRIUMF*)

Looking back ~ 35 years



Limited EDM sensitivity through para- and diamagnetic atoms circa 1985…



VOLUME 51, NUMBER 21 PHYSICAL REVIEW LETTERS 21 NOVEMBER 198…

Enhanced *T*-Nonconserving Nuclear Moments

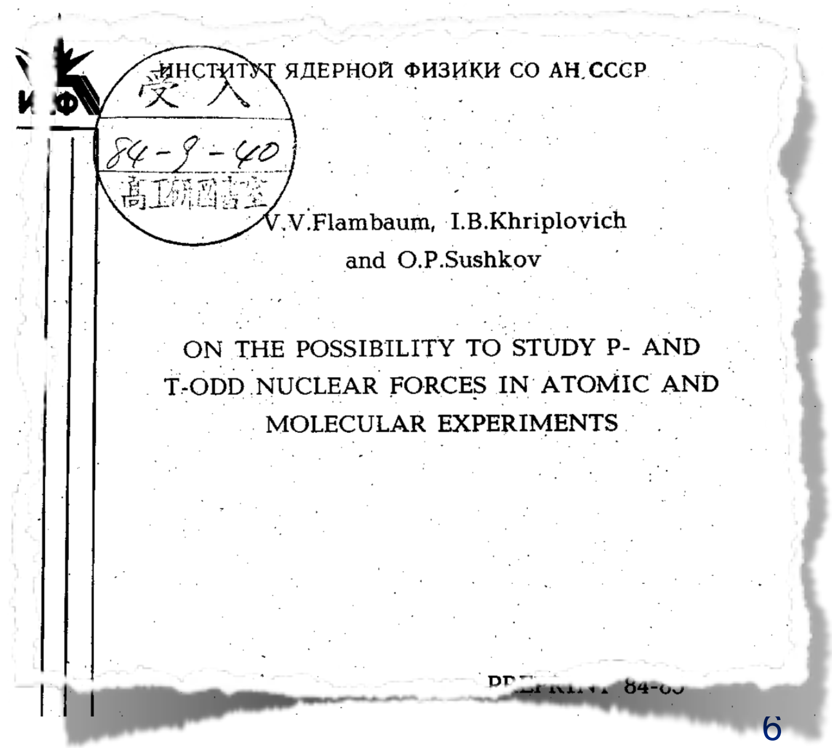
W. C. Haxton

Theoretical Division, Los Alamos National Laboratory, Los Alamos, New Mexico 87545

and

E. M. Henley

…and Department of Physics, University of Wa…



ИНСТИТУТ ЯДЕРНОЙ ФИЗИКИ СО АН СССР

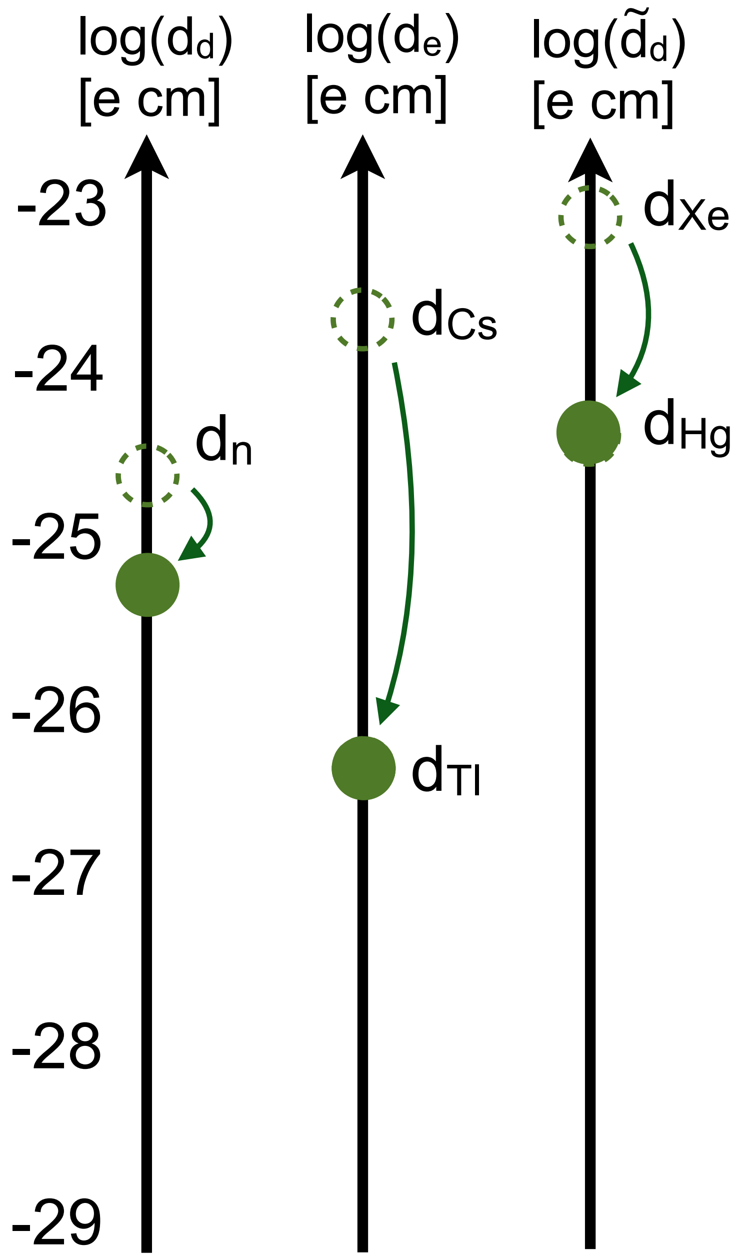
受入 84-9-40 高エ研図書室

V.V.Flambaum, I.B.Khriplovich and O.P.Sushkov

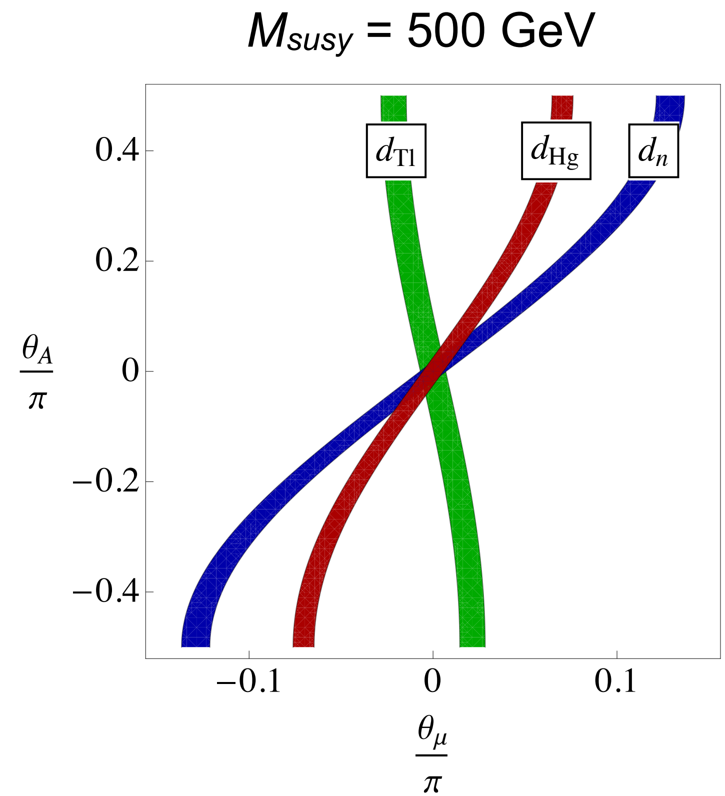
ON THE POSSIBILITY TO STUDY P- AND T-ODD NUCLEAR FORCES IN ATOMIC AND MOLECULAR EXPERIMENTS

PREPRINT 84-…

Looking back ~ 15-20 years



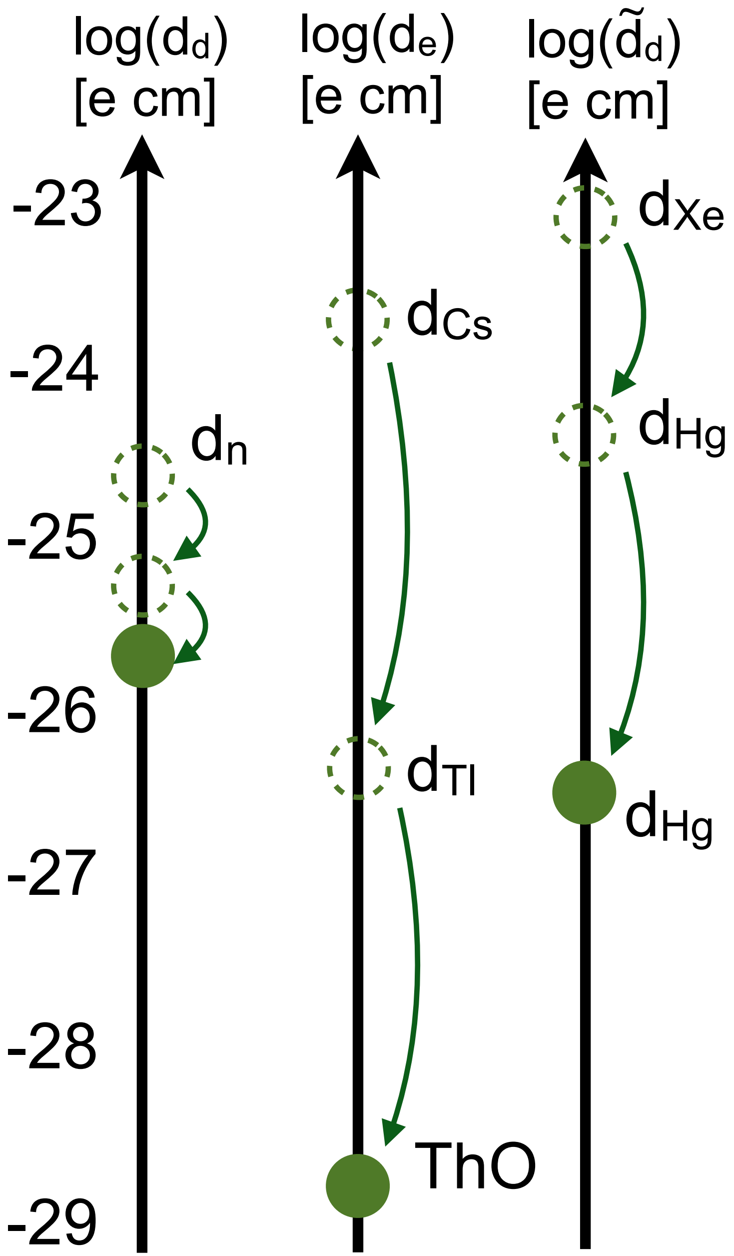
Multiple probes (e.g. of SUSY) with complementary sensitivity in the LEP era…



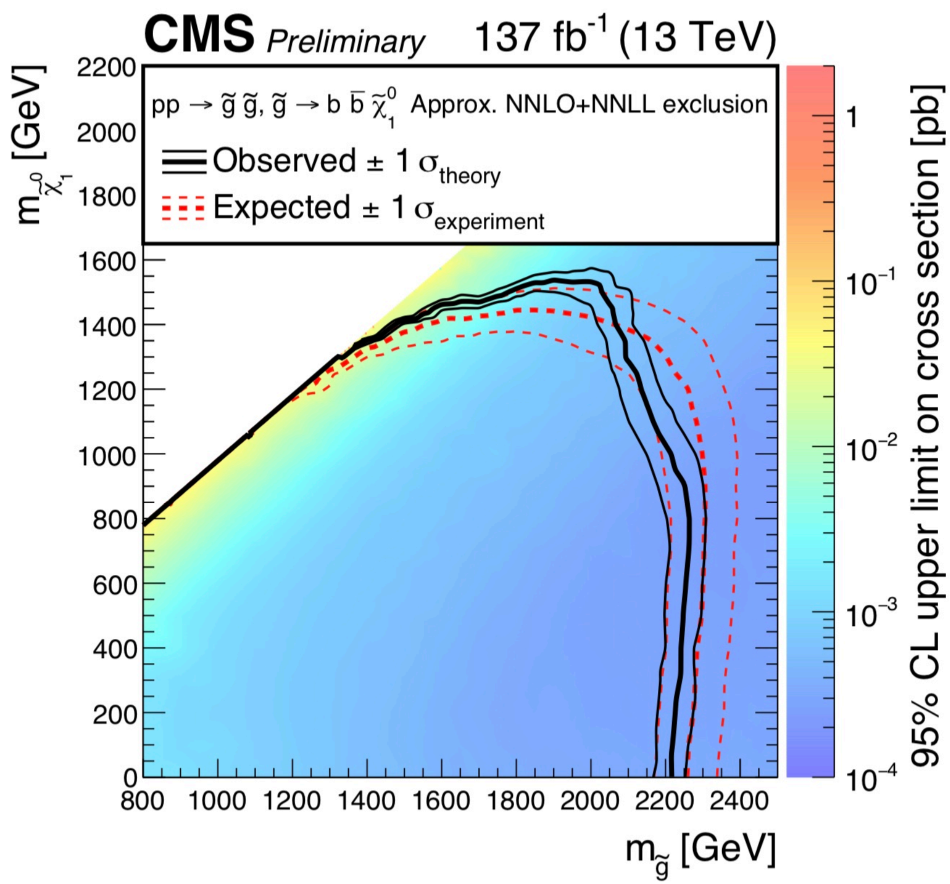
$$d \sim (\text{loop}) \times \frac{m_f}{\Lambda^2} \sim 10^{-25} e\text{cm} \left(\frac{1\,\text{TeV}}{\Lambda}\right)^2$$

(assuming O(1) CP phases)

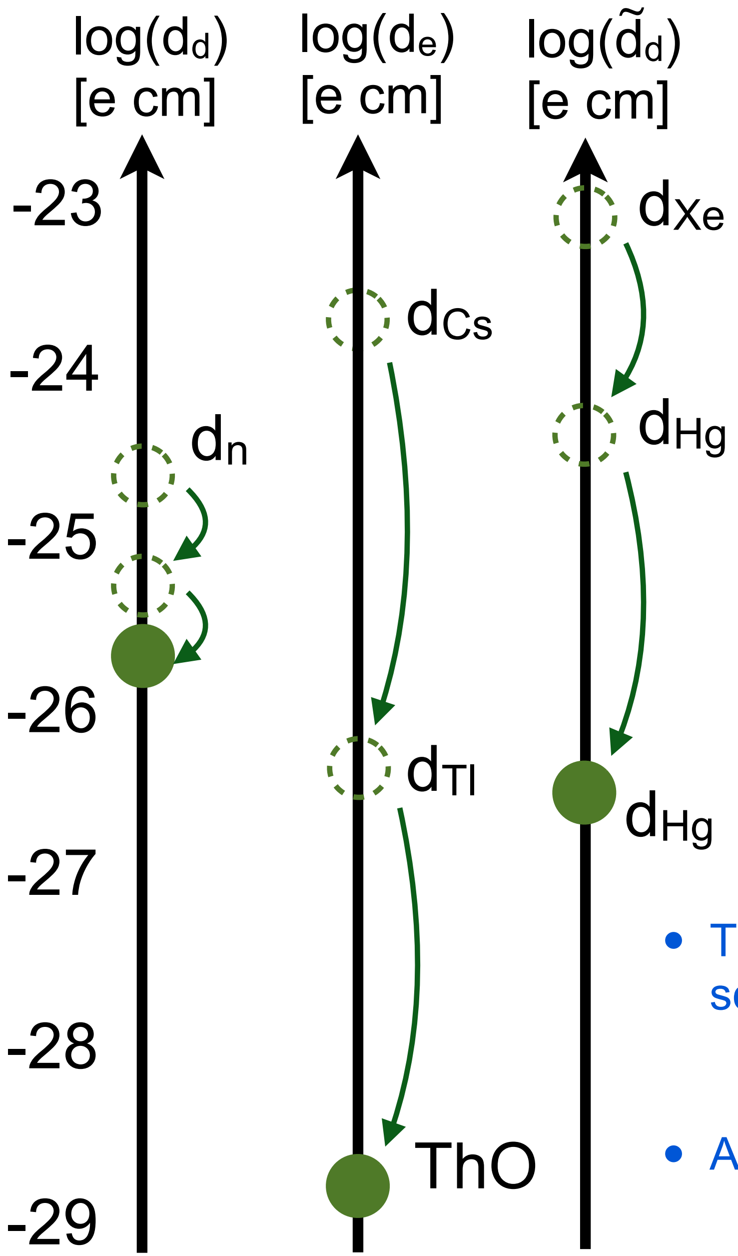
Looking back ~ 0 years

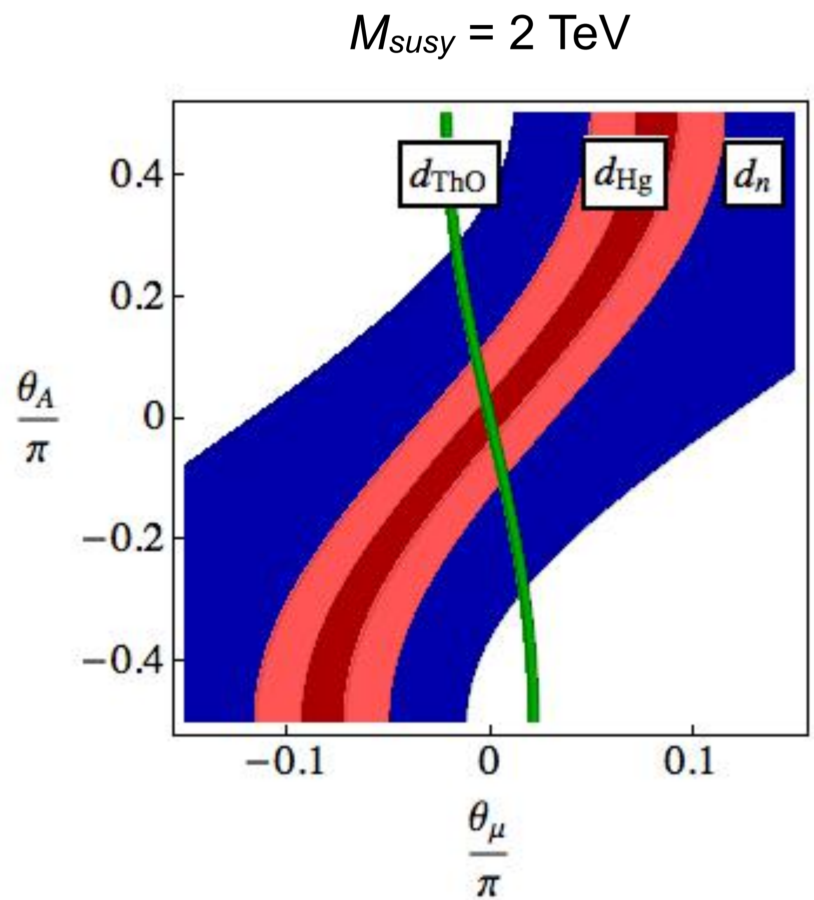


Comparison with direct mass limits on new (strongly-interacting) particles [Moriond '19]



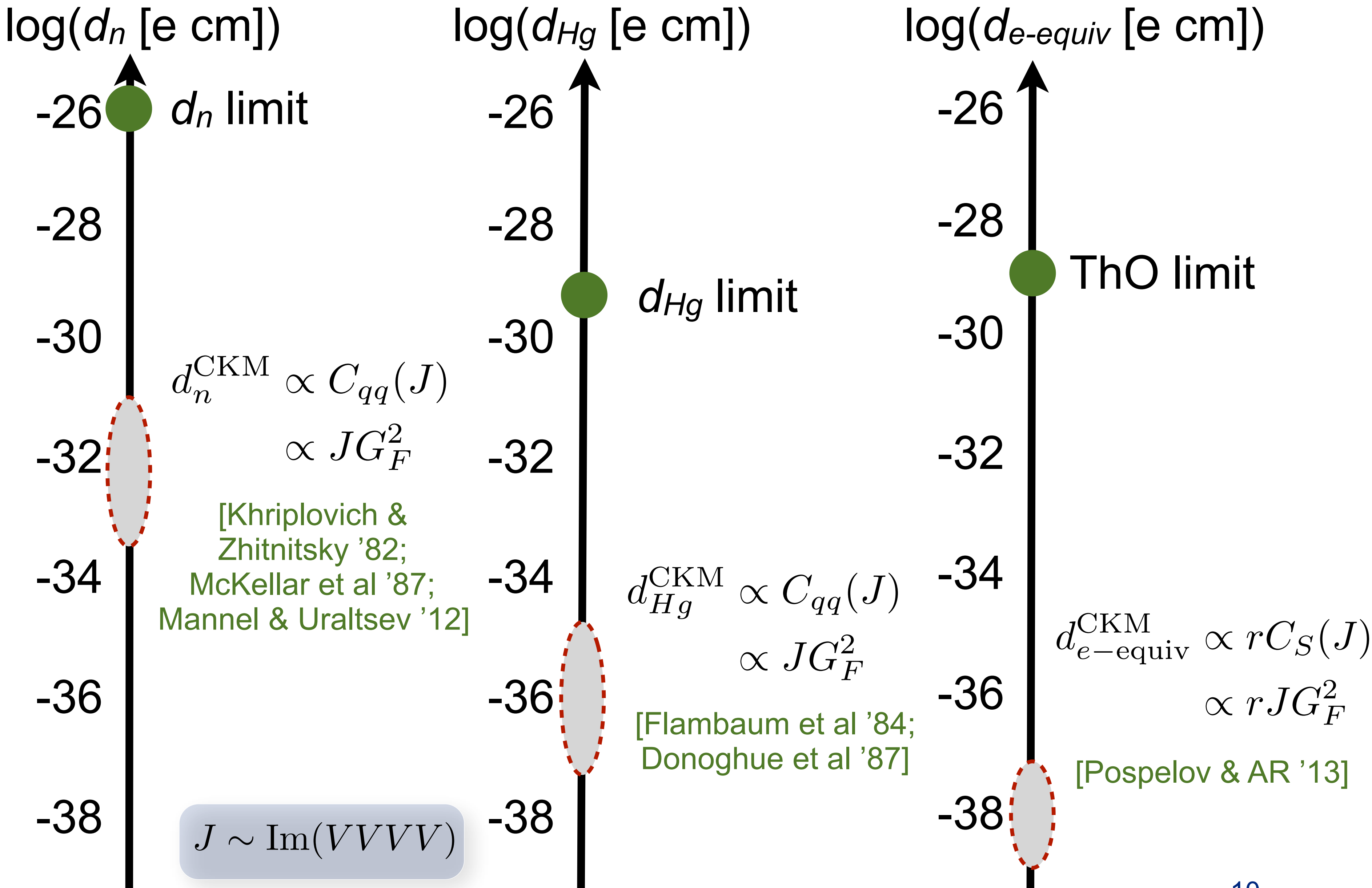
Looking back ~ 0 years





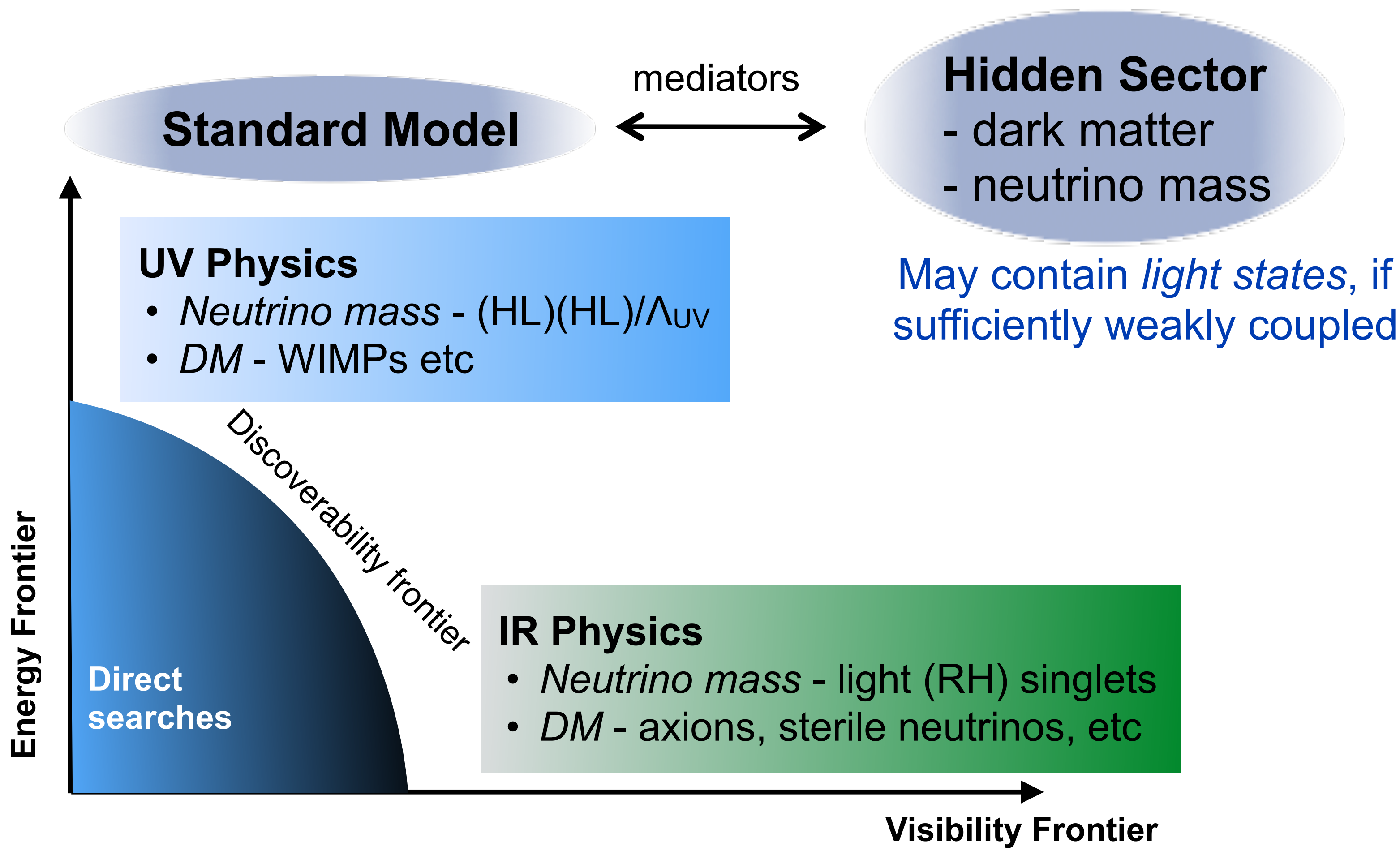
- The electron EDM is now one of few probes of PeV scale SUSY [McKeen, Pospelov & AR '13; Altmannshofer et al '13; Fuyuto et al '13]
- Also probes certain CP-odd Higgs couplings at %-level [McKeen, Pospelov & AR '12; Harnik et al '12; Fan & Reece '13]

EDMs in the Standard Model (CKM phase)



New physics in a dark/hidden sector

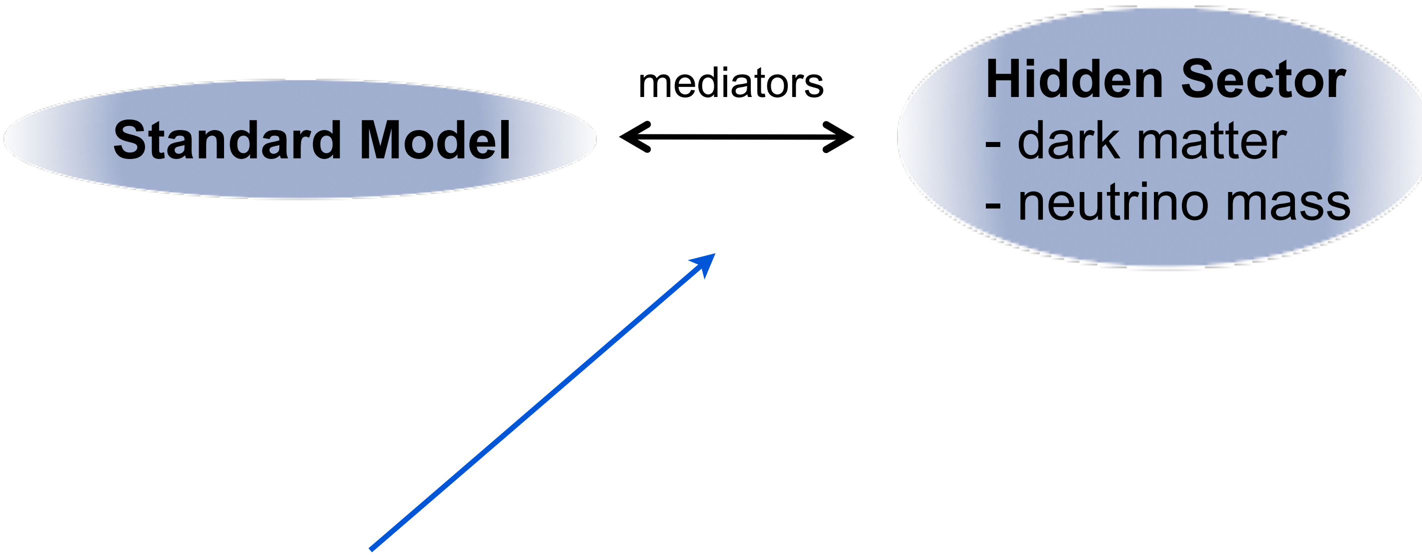
E*mpirical* evidence for new physics (e.g. *neutrino mass, dark matter*) arguably points to a hidden/dark sector, but not directly to a specific mass scale



➠ a huge parameter space a priori, so what theoretical guidance is there?

New physics in a dark/hidden sector

Given a very large ‘model-space’ a priori, its useful to develop an EFT expansion, assuming the hidden sector is *SM-neutral*



Easier to be systematic if we focus first on the mediation channels...

Substantial research effort over the past decade….

[See review talk at CAP by D. McKeen]

EFT for a (neutral) hidden sector

Standard Model $\xleftrightarrow[\text{(+ gravity)}]{\text{mediators}}$ **Dark Sector**

Generic interactions are irrelevant (dimension > 4), but there are three ***UV-complete relevant or marginal "portals"*** to a ***neutral hidden sector***, unsuppressed by the (possibly large) NP scale Λ

$$\mathcal{L} = \sum_{n=k+l-4} \frac{c_n}{\Lambda^n} \mathcal{O}_k^{(\mathrm{SM})} \mathcal{O}_l^{(\mathrm{med})} = \mathcal{L}_{\mathrm{portals}} + \mathcal{O}\left(\frac{1}{\Lambda}\right)$$

$$= -\frac{\epsilon}{2} B^{\mu\nu} A'_{\mu\nu} - H^\dagger H (AS + \lambda S^2) - Y_N^{ij} \bar{L}_i H N_j + \mathcal{O}\left(\frac{1}{\Lambda}\right)$$

Vector portal [Okun; Galison & Manohar; Holdom; Foot et al]

Higgs portal [Patt & Wilczek]

Neutrino portal

Many more UV-sensitive interactions at dim ≥ 5

EFT for a (neutral) hidden sector

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Vector portal **Higgs portal** **Neutrino portal**

Naturally incorporates minimal models of neutrino mass, and leptogenesis

EFT for a (neutral) hidden sector - IR mediation

Standard Model $\xleftrightarrow[\text{(+ gravity)}]{\text{mediators}}$ **Dark Sector**

Generic interactions are irrelevant (dimension > 4), but there are three *UV-complete* relevant or marginal “portals” to a neutral hidden sector, unsuppressed by the (possibly large) NP scale Λ

$$\mathcal{L} = \sum_{n=k+l-4} \frac{c_n}{\Lambda^n} \mathcal{O}_k^{(\mathrm{SM})} \mathcal{O}_l^{(\mathrm{med})} = \mathcal{L}_{\mathrm{portals}} + \mathcal{O}\left(\frac{1}{\Lambda}\right)$$

Vector portal **Higgs portal** **Neutrino portal**

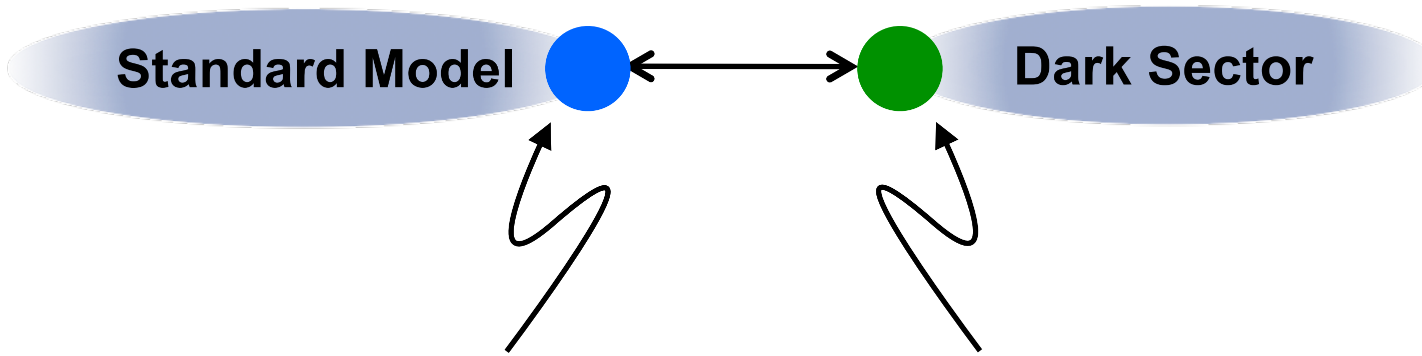
$$= -\frac{\epsilon}{2} B^{\mu\nu} A'_{\mu\nu} - H^\dagger H (AS + \lambda S^2) - Y_N^{ij} \bar{L}_i H N_j + \mathcal{O}\left(\frac{1}{\Lambda}\right)$$

$$\downarrow \qquad\qquad \downarrow \qquad\qquad \downarrow$$

$$\epsilon A'_\mu J^\mu_{\mathrm{EM}} \qquad \frac{Av^2}{m_h^2} S J_S \qquad v Y_N^{ij} \bar{\nu}_i N_j$$

Universal couplings to EM/scalar currents at low energy, so hidden sector models have correlated observable effects

Some experimental signatures



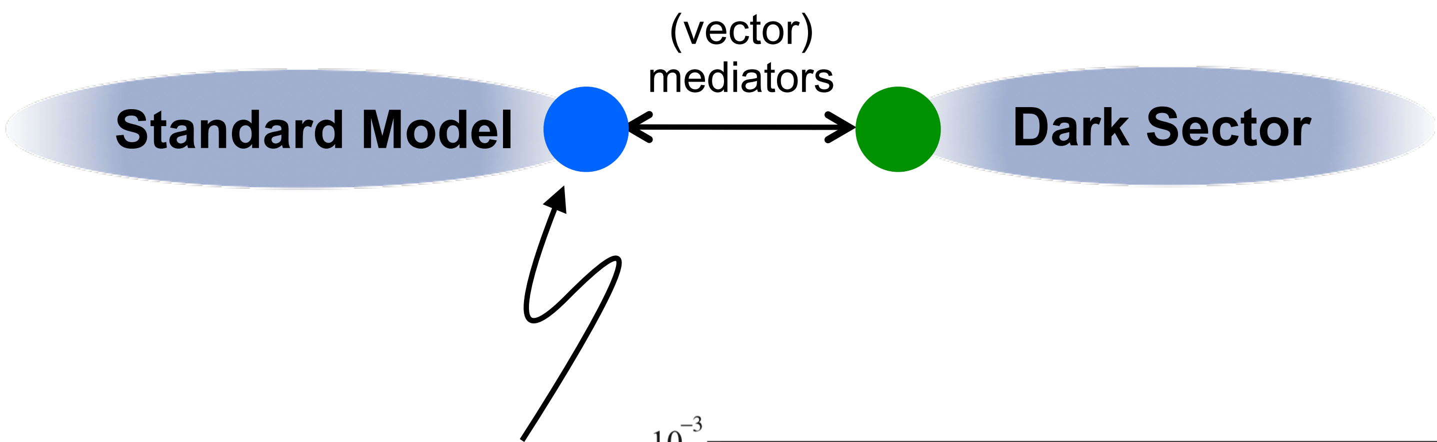
"Visible" and "hidden" signatures

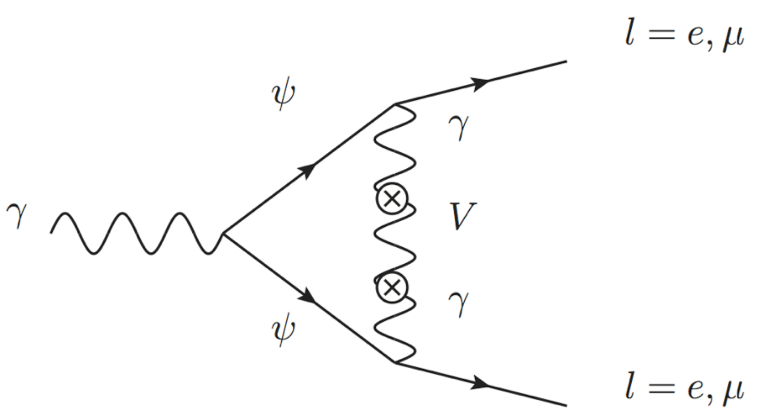
- Precision corrections
- Rare (visible) decays
- Astrophys/cosmology

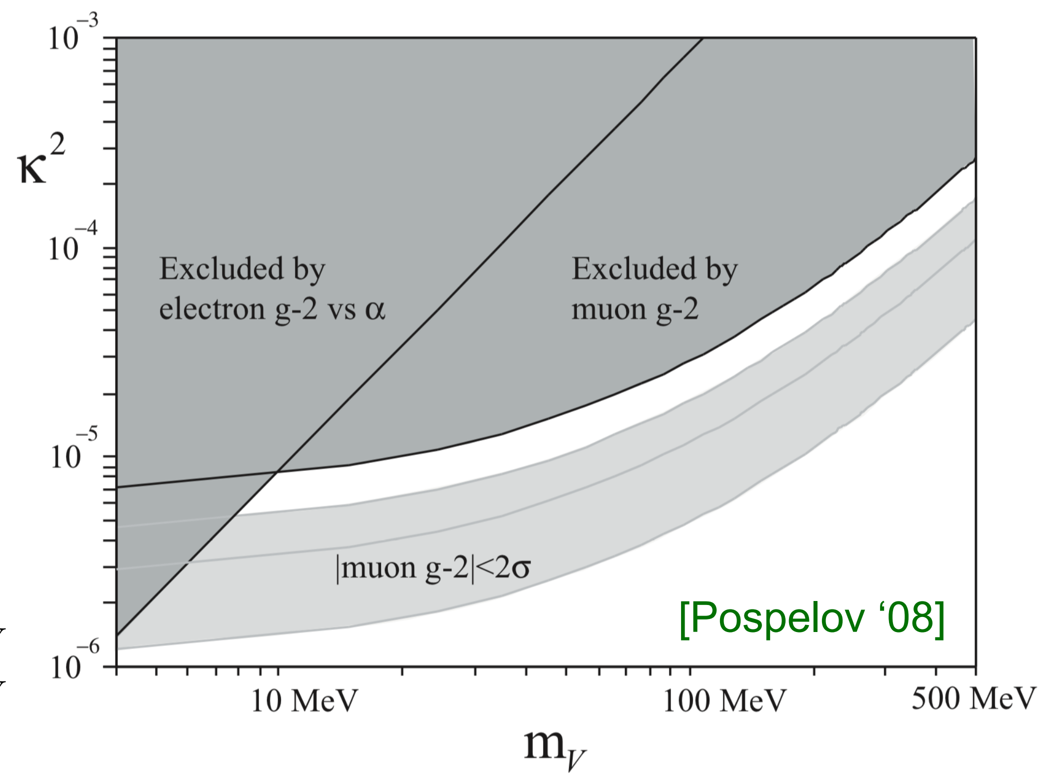
- Rare (invisible) decays/E_{miss}
- Anomalous NC-like scattering
- Astrophys/cosmology

Significant complementarity between precision & intensity

E.g. precision corrections (vector portal)

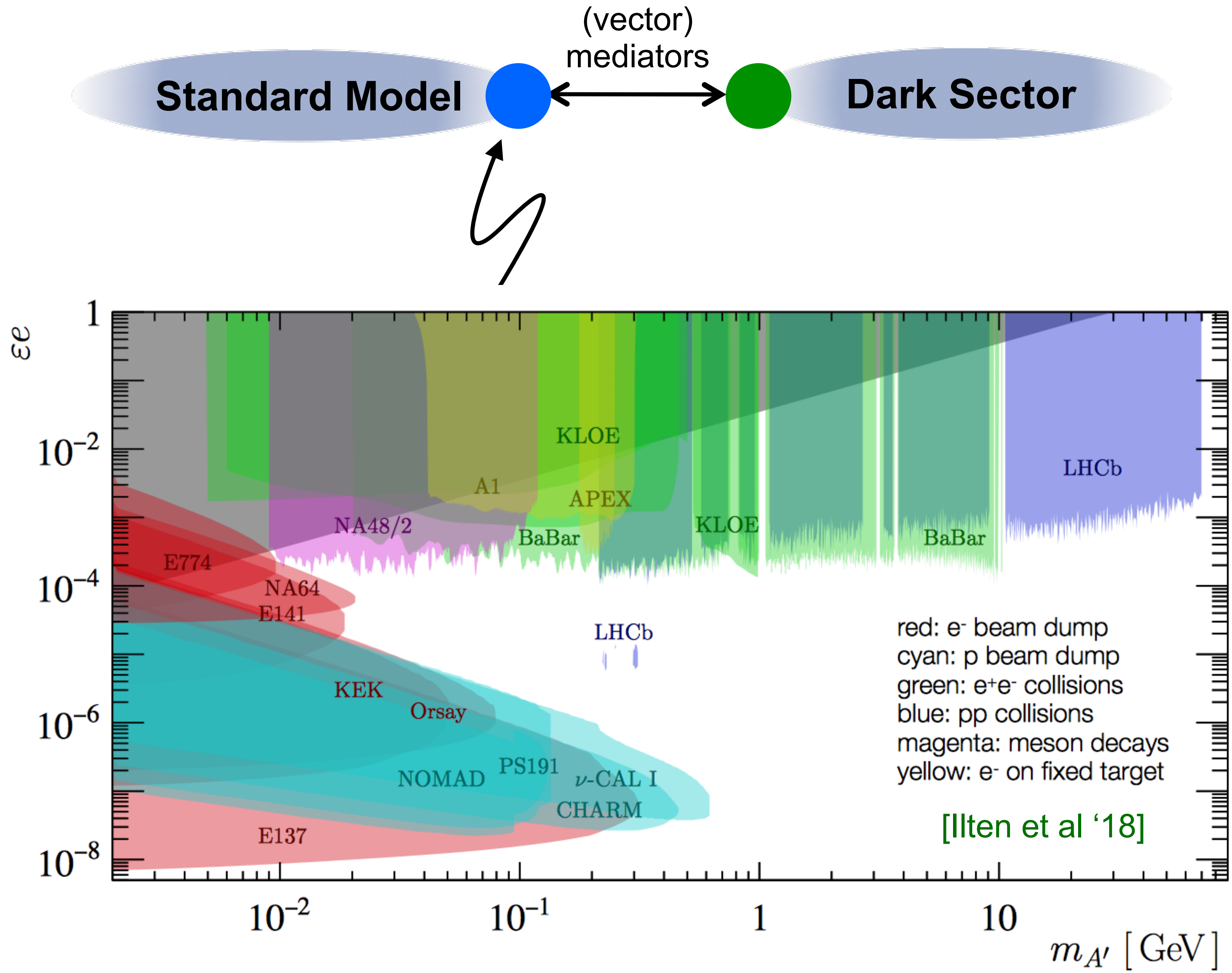


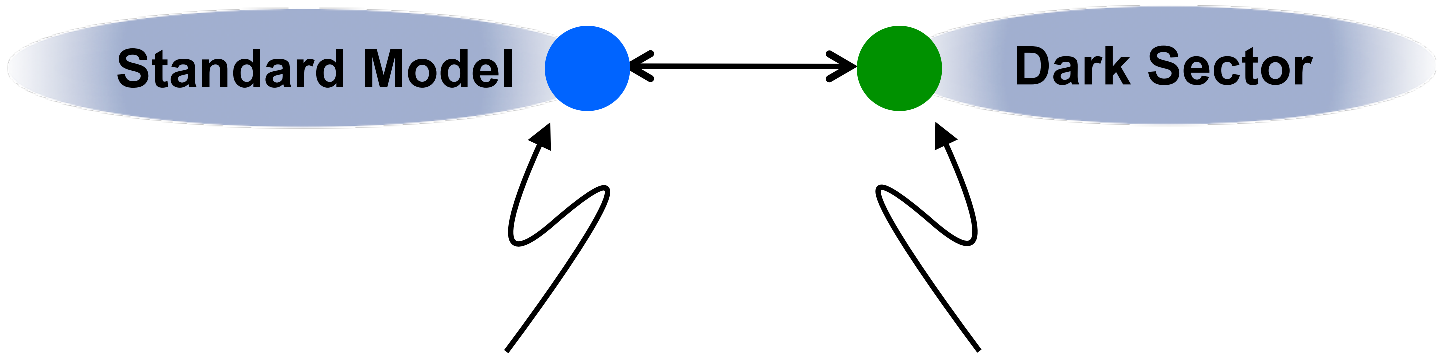




$$a_l^V = \frac{\alpha\kappa^2}{2\pi} \times \begin{cases} 1 & m_l \gg m_V \\ 2m_l^2/(3m_V^2) & m_l \ll m_V \end{cases}$$

E.g. precision corrections (vector portal)





“Visible” and “hidden” signatures

- Precision corrections
  - e.g. EDMs

What about sources of CP-violation within this framework?

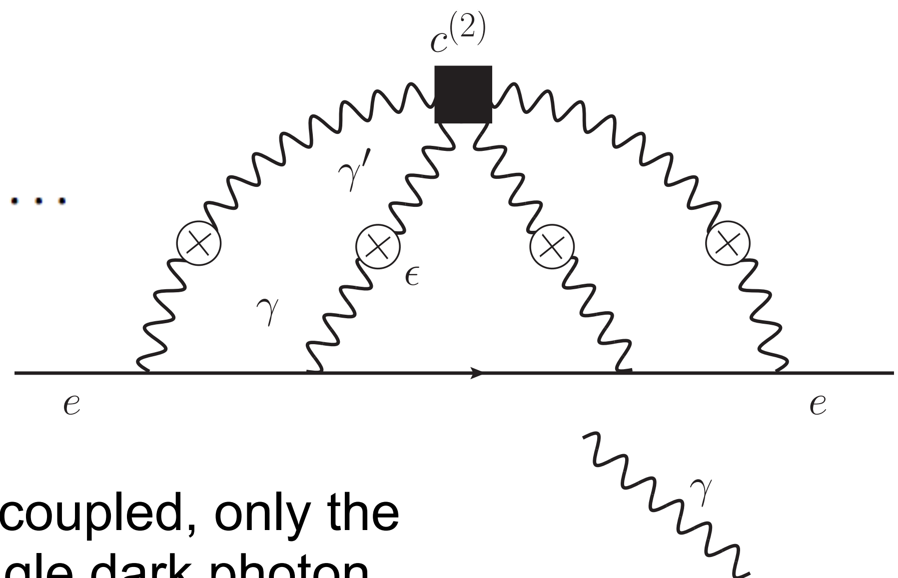
EDMs from dark sectors

Standard Model ⟷ **Dark Sector**

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm portals}(\underbrace{\mathcal{O}_3, \mathcal{O}_4}) + \mathcal{L}_{\rm hid}$$

- Vector portal

$$\mathcal{L}_{\rm hid} = \frac{c^{(2)}}{\Lambda^4}(F'_{\mu\nu}F'^{\mu\nu})(F'_{\alpha\beta}\tilde{F}'^{\alpha\beta}) + \cdots$$



If the electroweak sector is fully decoupled, only the vector portal remains, and for a single dark photon, the leading CP-odd operator is of dimension 8, leading to a suppressed 3-loop EDM

[Okawa, Pospelov & AR ’19]

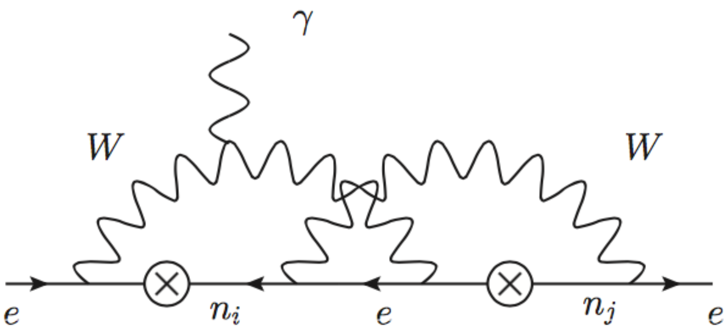
EDMs from dark sectors

Neutrino portal

- Requires at least 2 singlet fermions

$$\mathcal{L}_{\text{hidden}} = M_N \bar{N}^c N + h.c.$$

$$\Rightarrow \quad d_e \lesssim 10^{-33}\, e \cdot \text{cm}$$



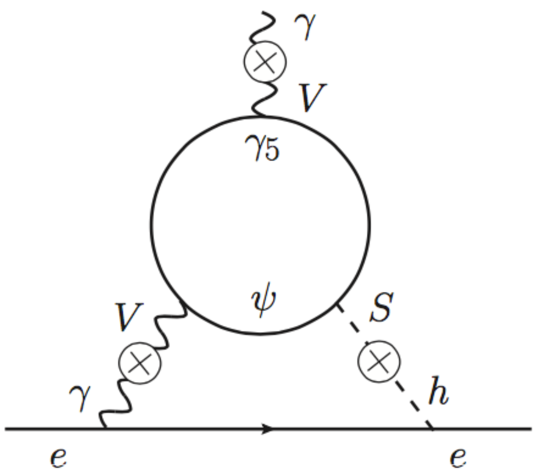
[Archambault, Czarnecki and Pospelov, 0406089; Le Dall, Pospelov and Ritz, 1505.01865; Ng and Ng, 9510306]

Vector and scalar portal (Dark Barr-Zee mechanism)

- $\mathcal{L}_{\text{hidden}} = Y_S\, S \bar{\psi} i \gamma_5 \psi$ (ψ : dark fermion)
- electron EDM induced via "dark EDM"

$$\bar{e}\sigma^{\mu\nu}\gamma_5 e F'_{\mu\nu} \to \bar{e}\sigma^{\mu\nu}\gamma_5 e \frac{\Box F_{\mu\nu}}{m^2_{A'}}$$

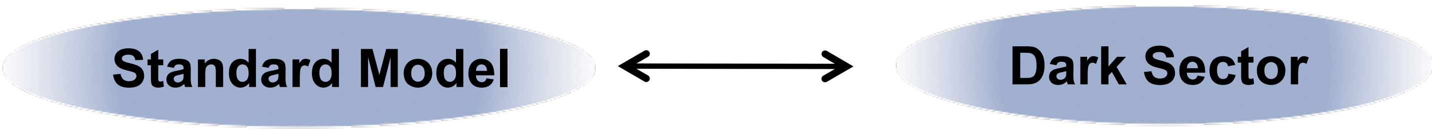
$$\Rightarrow \quad d_e \sim 4 \times 10^{-33}\, e \cdot \text{cm} \left(\frac{1\,\text{GeV}}{m_\psi}\right)\left(\frac{\epsilon}{10^{-4}}\right)^2\left(\frac{\theta_h}{10^{-3}}\right)$$



[Le Dall, Pospelov and Ritz, 1505.01865]

EDM suppressed by limit on 1-loop ("dark photon") correction to $(g\text{-}2)_e$

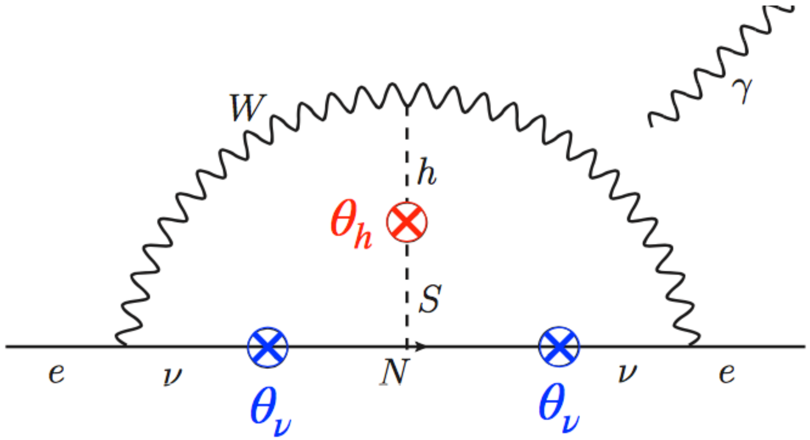
EDM via the "singlet portal"



$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm portals}(\underbrace{\mathcal{O}_3, \mathcal{O}_4}) + \mathcal{L}_{\rm hid}$$

$$-\mathcal{L}_{IR} = ASH^\dagger H + Y_N \bar{L} H N + \lambda_N S \bar{N} i\gamma_5 N$$

(* assume Dirac neutrino)



Overall EDM scale:

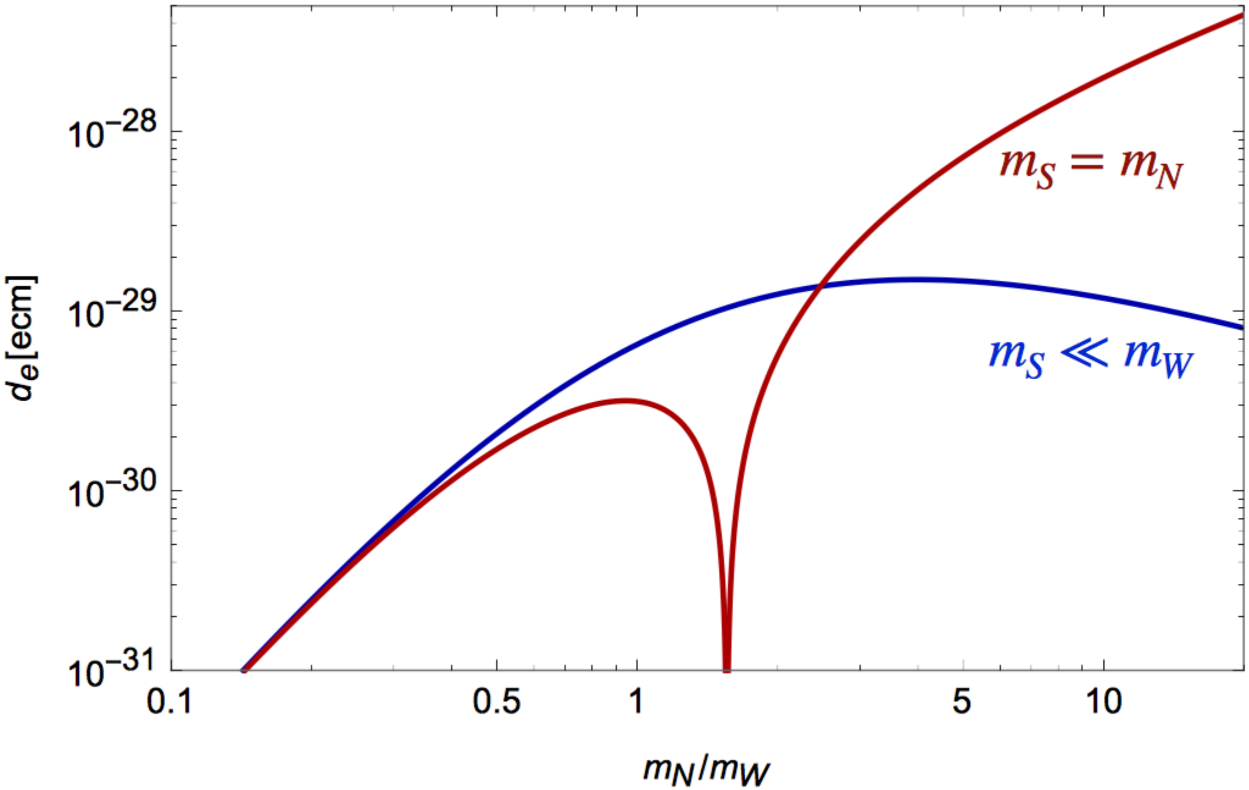
$$d_e \sim \frac{e}{(16\pi^2)^2} \cdot \theta_h \theta_\nu^2 \cdot \frac{m_e}{m_{NP}^2} \cdot \lambda_N \sim 4 \cdot 10^{-29}\, e \cdot {\rm cm} \times \left(\frac{\theta_h \theta_\nu^2}{10^{-3}}\right) \left(\frac{100\,{\rm GeV}}{m_{NP}}\right)^2 \left(\frac{\lambda_N}{1}\right)$$

This is quite close to the current bound, motivating a full computation of the relevant 2-loop diagrams…

[Okawa, Pospelov & AR '19]

Scaling of the induced electron EDM

$\theta_h \theta_\nu^2 = 10^{-2},\ \lambda_N = 1$ (maximum CP violation)



$$\theta_h = Av/(m_S^2 - m_h^2)$$

$$\theta_\nu \simeq \frac{Y_\nu v}{m_N} \simeq \frac{m_\nu}{m_N}$$

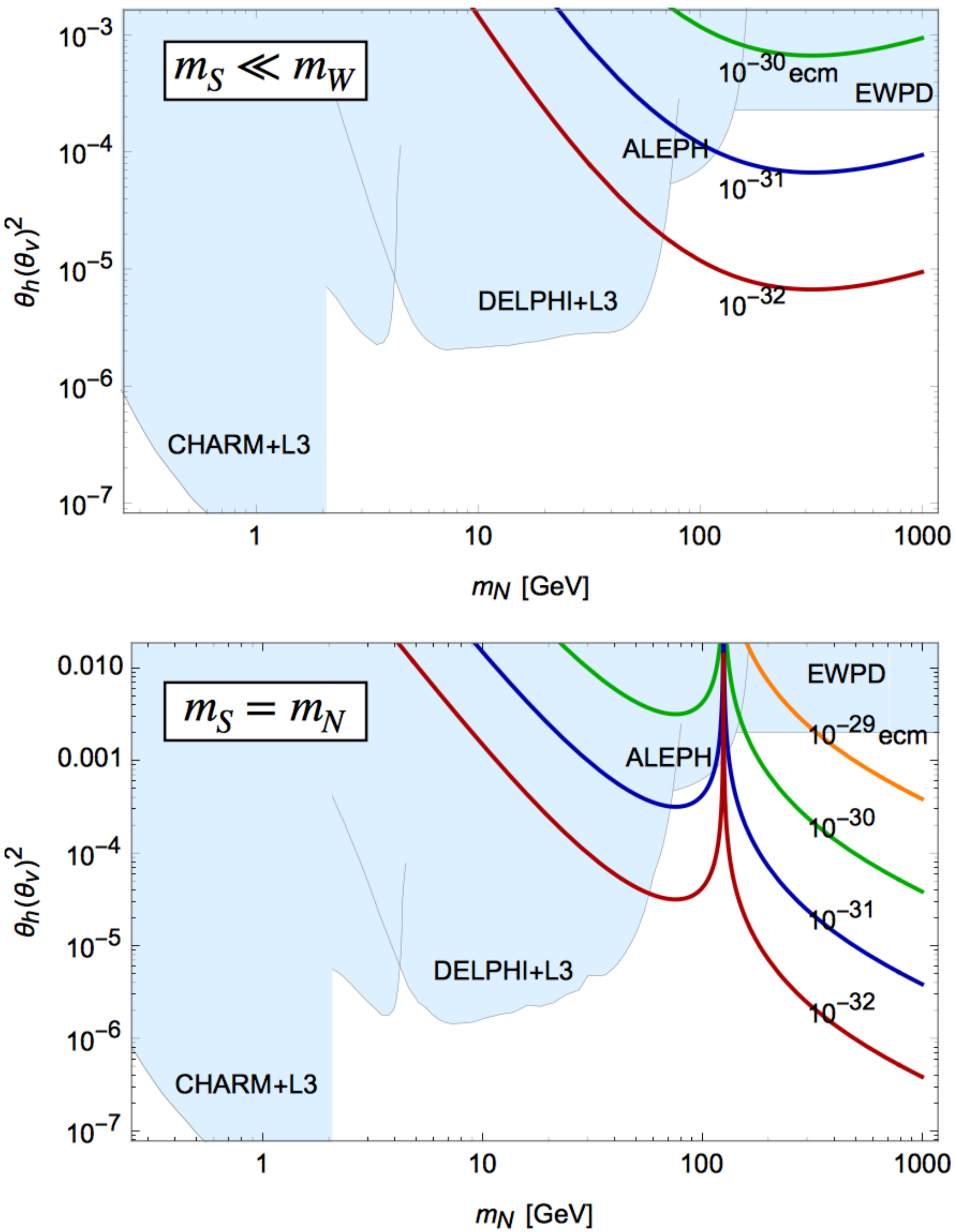
$$d_e \leq 1.1 \times 10^{-29}\,\mathrm{ecm}$$

(ACME collaboration, V. Andreev et al., 2018)

Note the weak decoupling for large m_N, similar to FCNCs

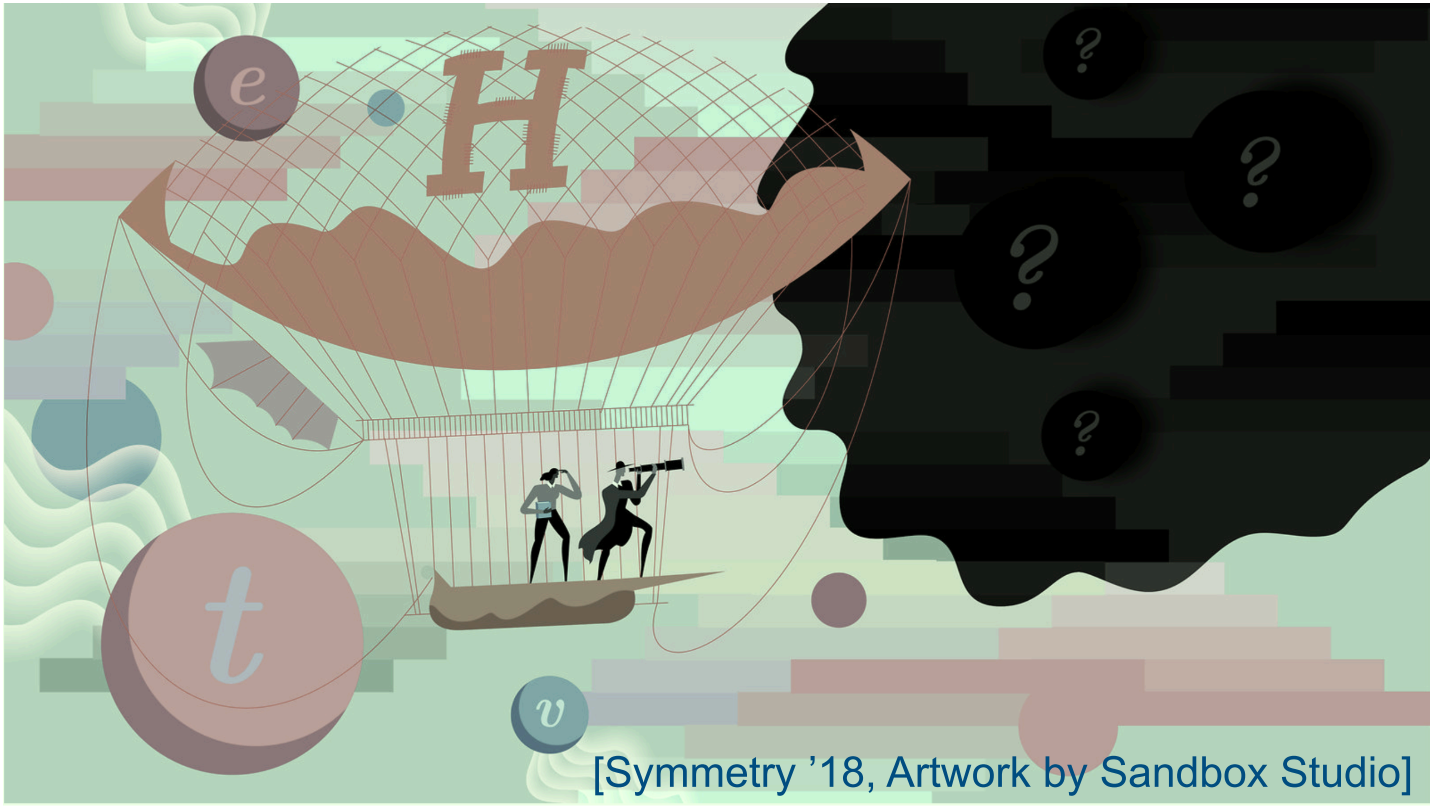
$$\int d^4q\, d^4k\, f_{\mathrm{scalar}}(q,k) \to \begin{cases} \frac{3}{4} \ln \frac{m_S^2}{m_N^2}, & m_N \ll m_S \\ \frac{1}{4} \frac{m_S^2}{m_N^2} \ln \frac{m_N^2}{m_S^2}, & m_S \ll m_N \end{cases}$$

Sensitivity to portal couplings



Assuming a maximal dark sector CP phase, existing EDM experiments (e.g. ACME) already have significant (and complementary) sensitivity to portal couplings for masses of ~ GeV and above

Summary/Outlook



- The problem of matter-genesis now goes beyond baryogenesis, but the Sakharov criteria, e.g. CP violation (and thus precision tests such as EDMs), remain central.

- Dark sectors, motivated by the need for dark matter and the generation of neutrino mass, may be probed in a manner that is complementary to colliders and fixed target experiments using precision experiments, e.g. EDMs
  - ➡ *Highlighted a sizeable 2-loop contribution to the electron EDM that is generic in the presence of the neutrino and Higgs (singlet) portals*