TRIUMF Science Week - July 2017

Dark Sectors at the Precision/Intensity Frontier

Adam Ritz
University of Victoria

Motivating Questions…

Sakharov's criteria for generating a baryon asymmetry are 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 anti-matter; 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…*
- *Now matter-genesis, and precision cosmology generally, provides even more empirical motivation for BSM physics...*

Understanding the matter content

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

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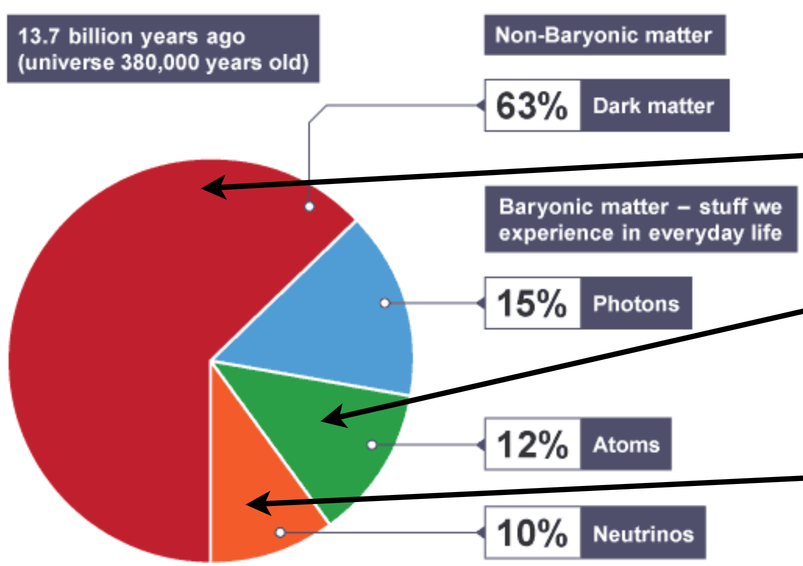
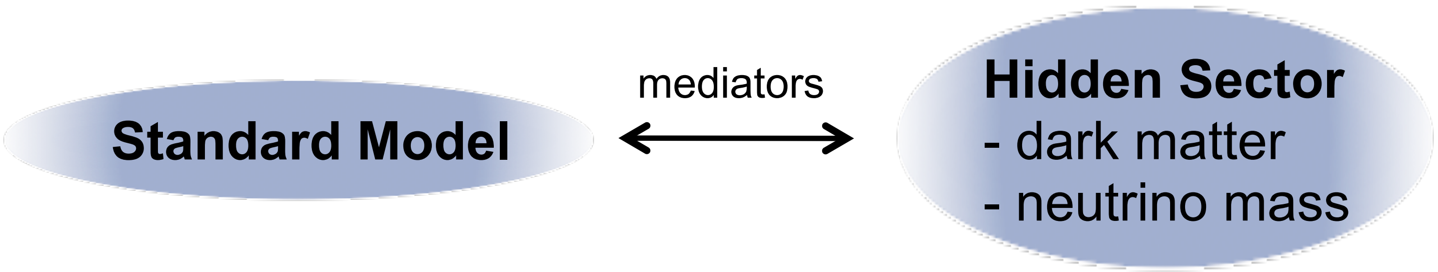


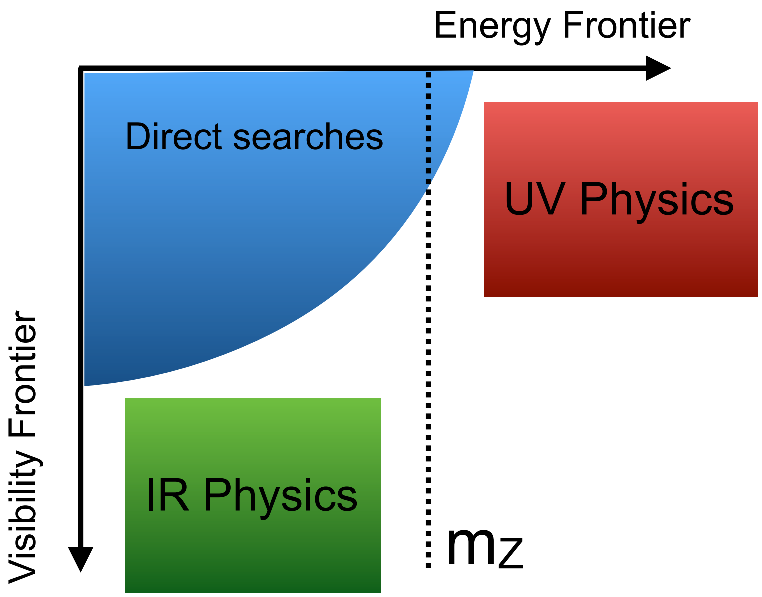
Questions

- Identity of DM?
- DM-genesis?
- Baryogenesis?
- Neutrino mass?
- Lepton asymmetry?

New physics in a dark/hidden sector

Arguably, most *empirical* evidence for new physics (e.g. neutrino mass, dark matter) doesn't point a priori to a specific mass scale, but rather to a hidden (or dark) sector, neutral under the SM.





May contain *light states*, if neutral under the SM gauge group, flavour-diagonal, etc

E.g. Neutrino mass

- UV - via Weinberg op $(HL)(HL)/\Lambda_{UV}$
- IR - via light (RH) singlet fields

E.g. Dark Matter

- UV - WIMPs, neutralinos, etc
- IR - axions, sterile neutrinos, etc

➠ all options deserve exploration, so what theoretical guidance is there...?

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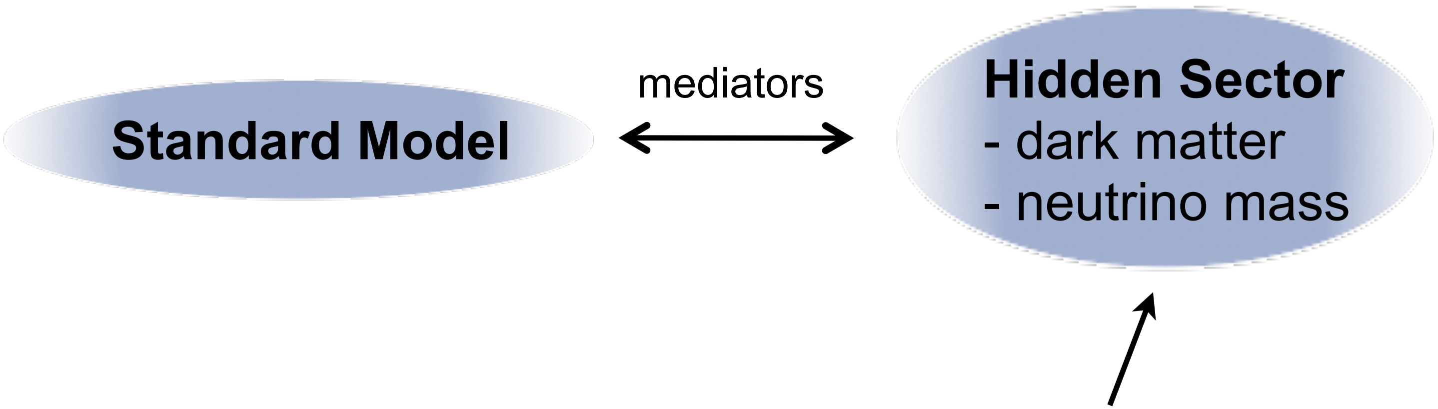

Difficult to be systematic in analyzing a generic hidden sector...

New physics in a dark/hidden sector

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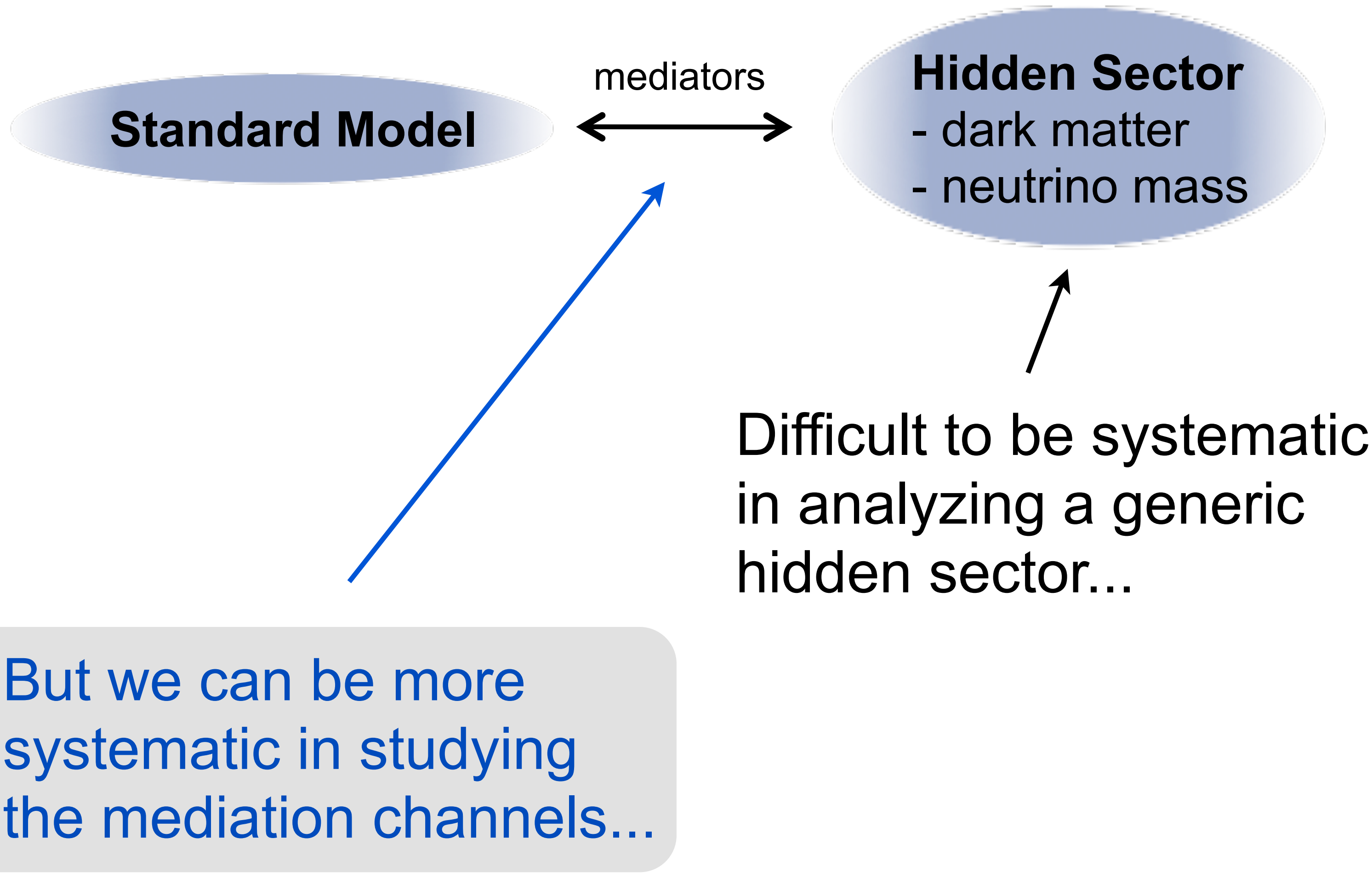

EFT for a (neutral) hidden sector

Standard Model ⟷ mediators ⟷ **Hidden Sector**

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

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

- Vector portal*: $\mathcal{L} = -\frac{\kappa}{2} B^{\mu\nu} V_{\mu\nu}$ [Okun; Holdom; Foot et al]
- Higgs portal: $\mathcal{L} = -H^\dagger H (AS + \lambda S^2)$ [Patt & Wilczek]
- Neutrino portal: $\mathcal{L} = -Y_N^{ij} \bar{L}_i H N_j$

*Alternate Notation : $\kappa = \epsilon, \quad V_\mu = A'_\mu$

Many more UV-sensitive interactions at dim ≥ 5

EFT for a (neutral) hidden sector

Standard Model $\longleftrightarrow$ (mediators) **Hidden Sector**

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Naturally introduces force mediators (V, S), that e.g. can enable sufficient light dark matter annihilation in the early universe

EFT for a (neutral) hidden sector

Standard Model $\longleftrightarrow$ (mediators) **Hidden Sector**

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Naturally incorporates models of neutrino mass, and leptogenesis, and a scalar singlet can aid EW baryogenesis via a 1st order phase transition.

EFT for a (neutral) hidden sector

mediators

Standard Model $\longleftrightarrow$ **Hidden Sector**

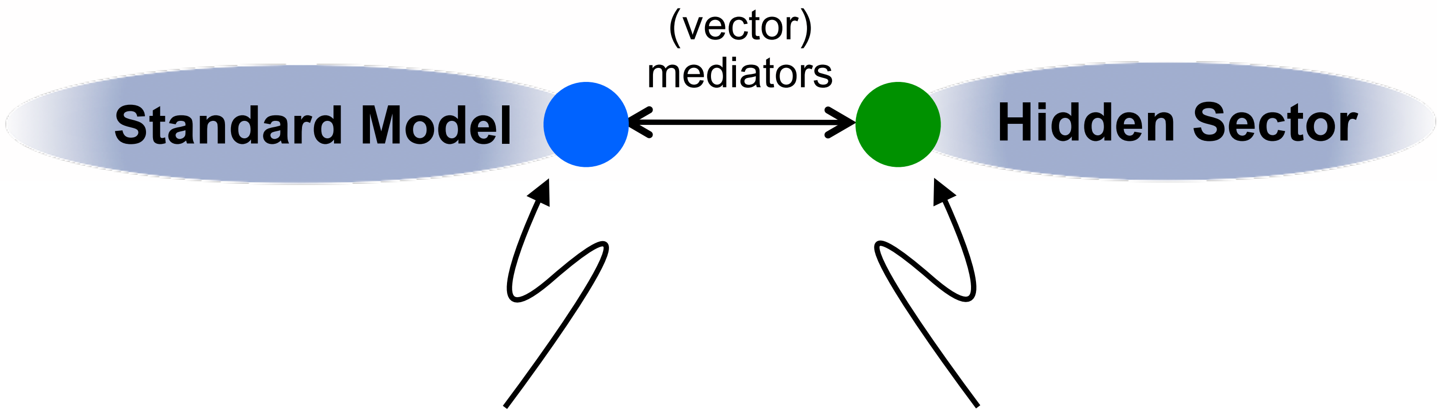
$$\mathcal{L} = \sum_{n=k+l-4} \frac{\mathcal{O}_k^{(SM)} \mathcal{O}_l^{(med)}}{\Lambda^n} \sim \mathcal{O}_{portals} + \mathcal{O}\left(\frac{1}{\Lambda}\right)$$

IR mediation

- Vector portal: $\mathcal{L} = -\frac{\kappa}{2} B^{\mu\nu} V_{\mu\nu} \longrightarrow \kappa V_\mu J^\mu_{\rm EM}$
- Higgs portal: $\mathcal{L} = -ASH^\dagger H \longrightarrow \frac{Av^2}{m_h^2} S J_S$
- Neutrino portal: $\mathcal{L} = -Y_N^{ij} \bar{L}_i H N_j \longrightarrow v Y_N^{ij} \bar{\nu}_i N_j$

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

Experimental probes of the portals & light NP



Experimental probes

- Precision corrections
  - e.g. lepton g-2, EDMs
- rare (visible) decays
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- anomalous NC-like scattering
  - e.g. fixed target production plus anomalous NC-like scattering, $O(\kappa^2 \times \kappa^2\alpha')$

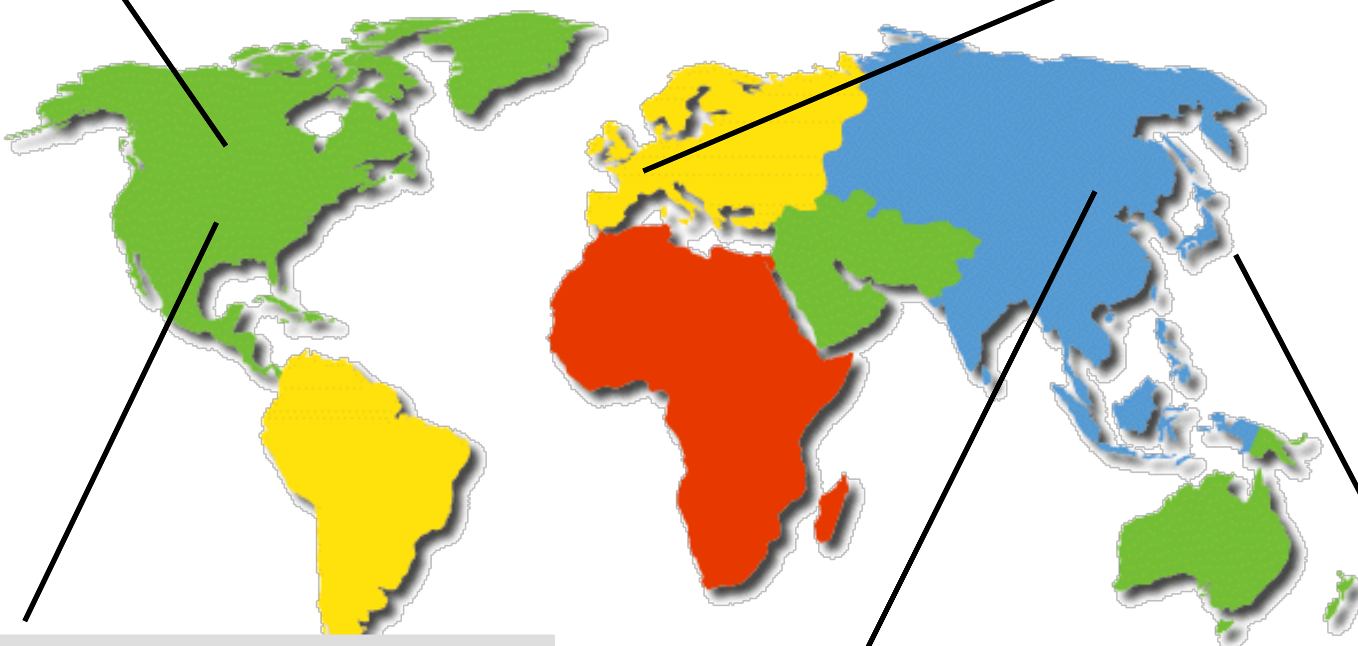
(also astrophysics & cosmology)

Ongoing efforts (colliders, fixed targets,...)

Canada?
TRIUMF (ARIEL)

[Talk by L. Doria]

Europe
CERN (ATLAS,CMS,LHCb,NA62,NA64)
Mainz (MAMI,MESA)
Frascati (DAΦNE)

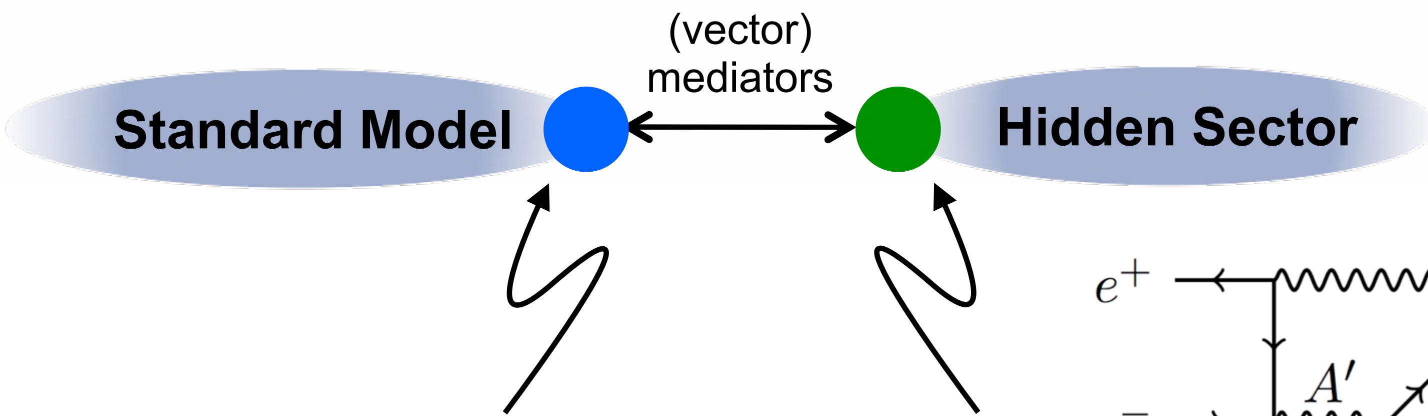


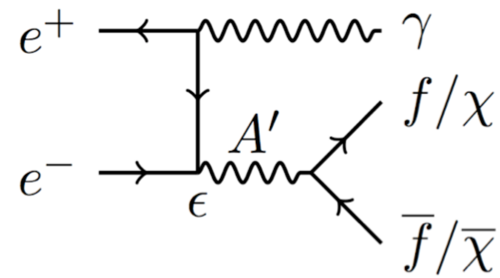
USA
SLAC (LDMX?)
JLab (HPS,APEX,Moller,BDX,...)
FNAL (MiniBooNE,SBND)
Cornell (MMAPS,PADME?)

China
BEPC II (BES III)

Japan
J-PARC
KEK (Belle-II)

Experimental probes of the portals & light NP





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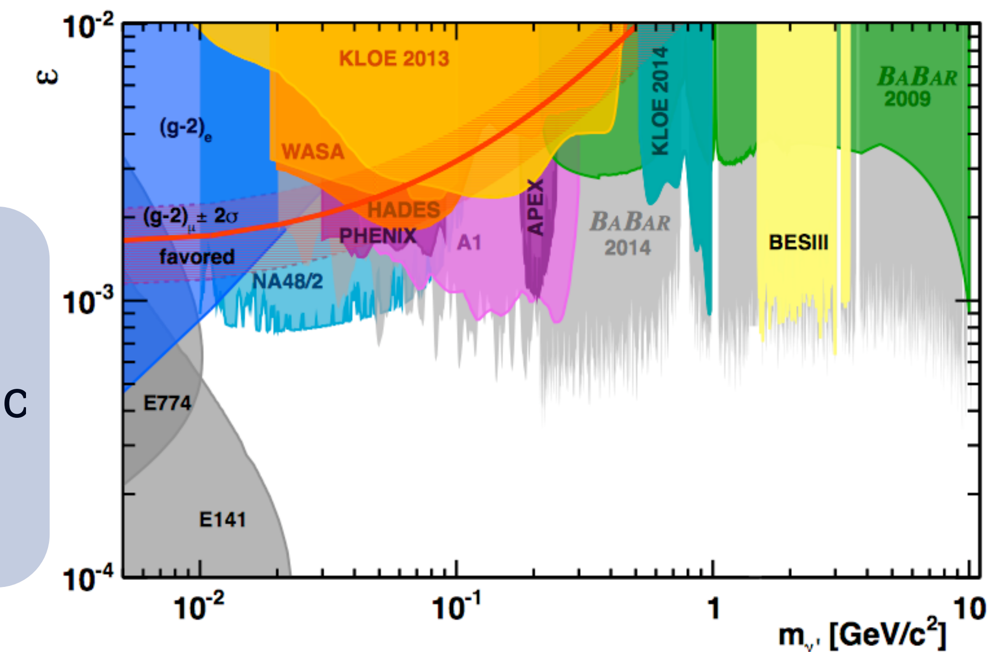
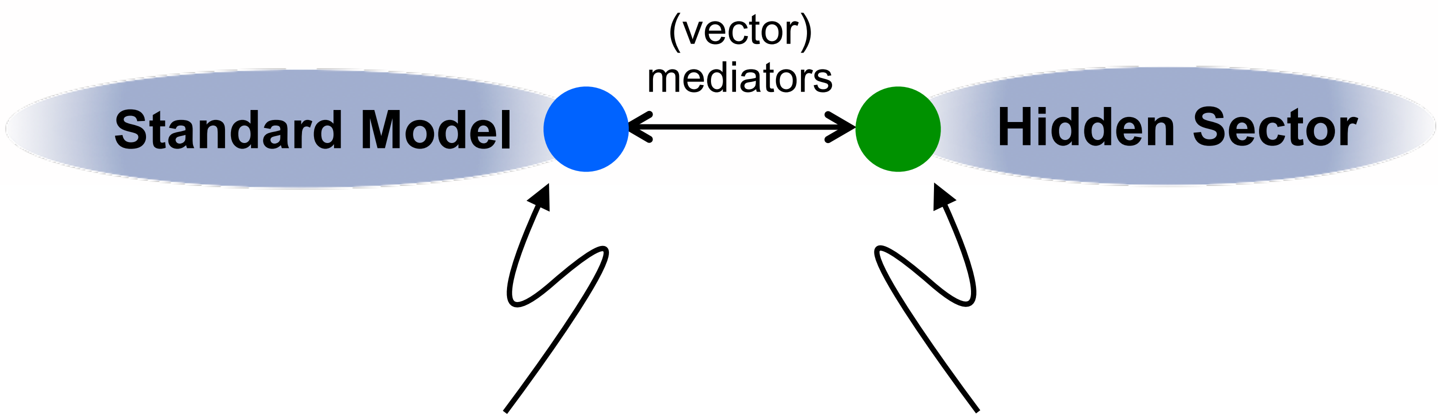


[BESIII 2017]

Experimental probes of the portals & light NP



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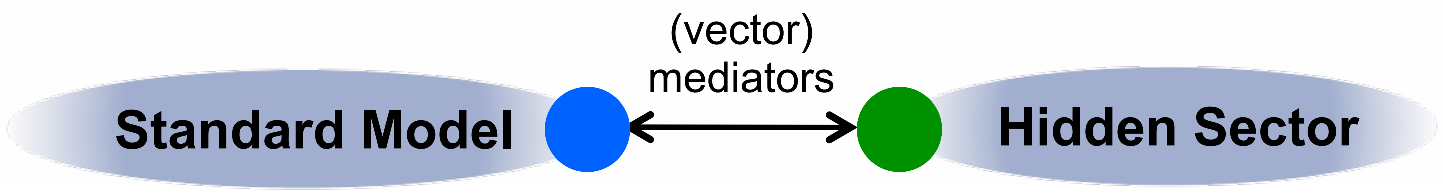
  - e.g. fixed target production plus anomalous NC-like scattering, O(κ^2 x $\kappa^2\alpha'$)

(also astrophysics & cosmology)

E.G. probes of the vector portal

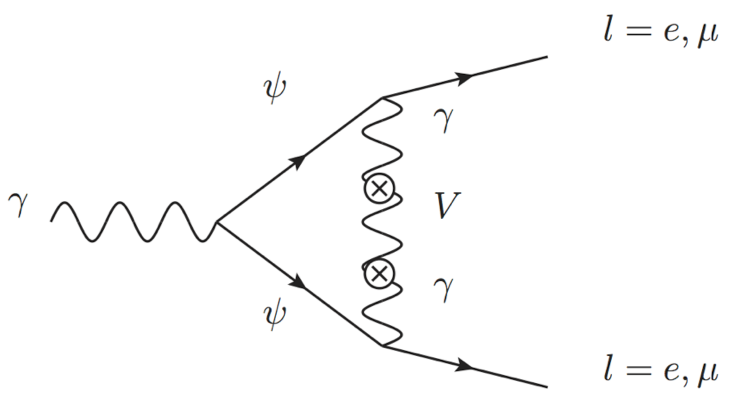


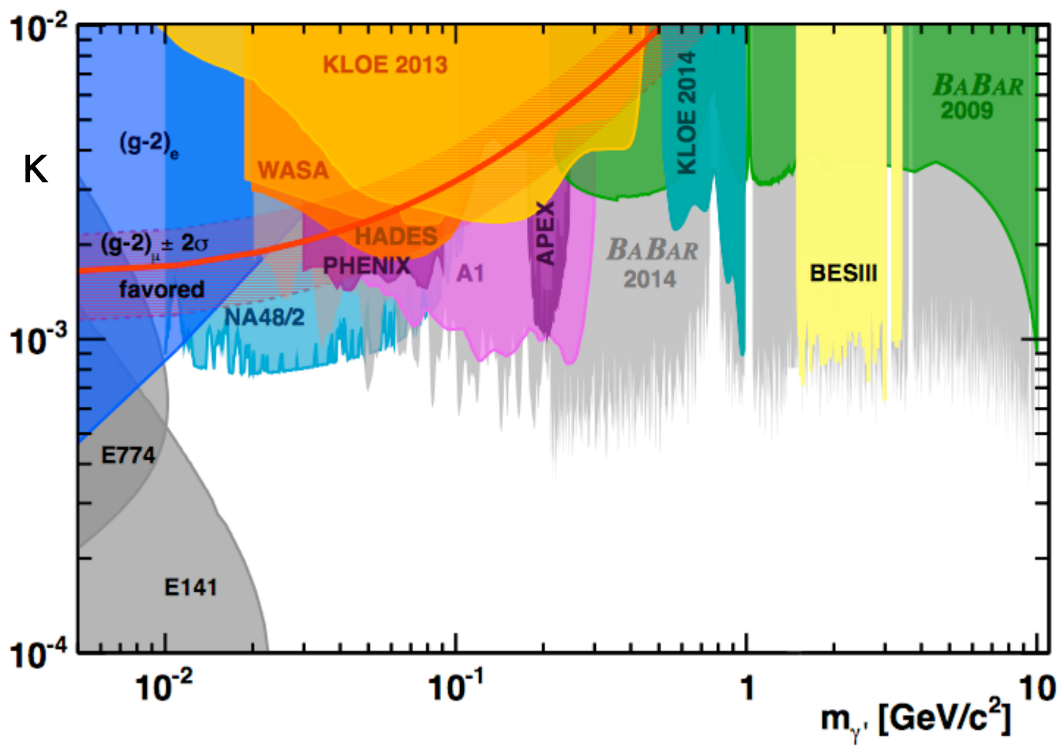
$$a_l^V = \frac{\alpha\kappa^2}{2\pi} \times \begin{cases} 1 & m_l \gg m_V \\ 2m_l^2/(3m_V^2) & m_l \ll m_V \end{cases}$$

[Pospelov '08]

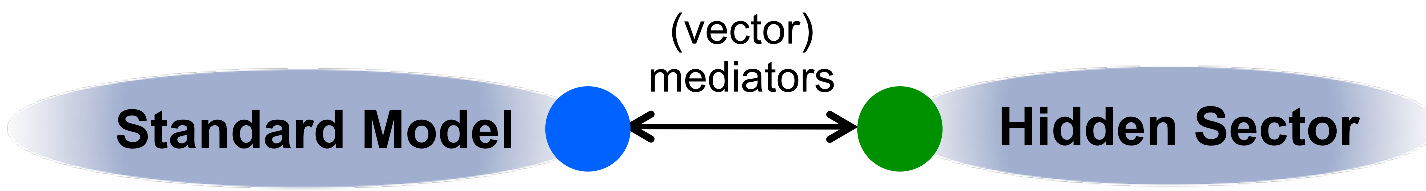
[BESIII 2017]

- Precision corrections
  - e.g. lepton g-2





E.G. probes of the neutrino portal



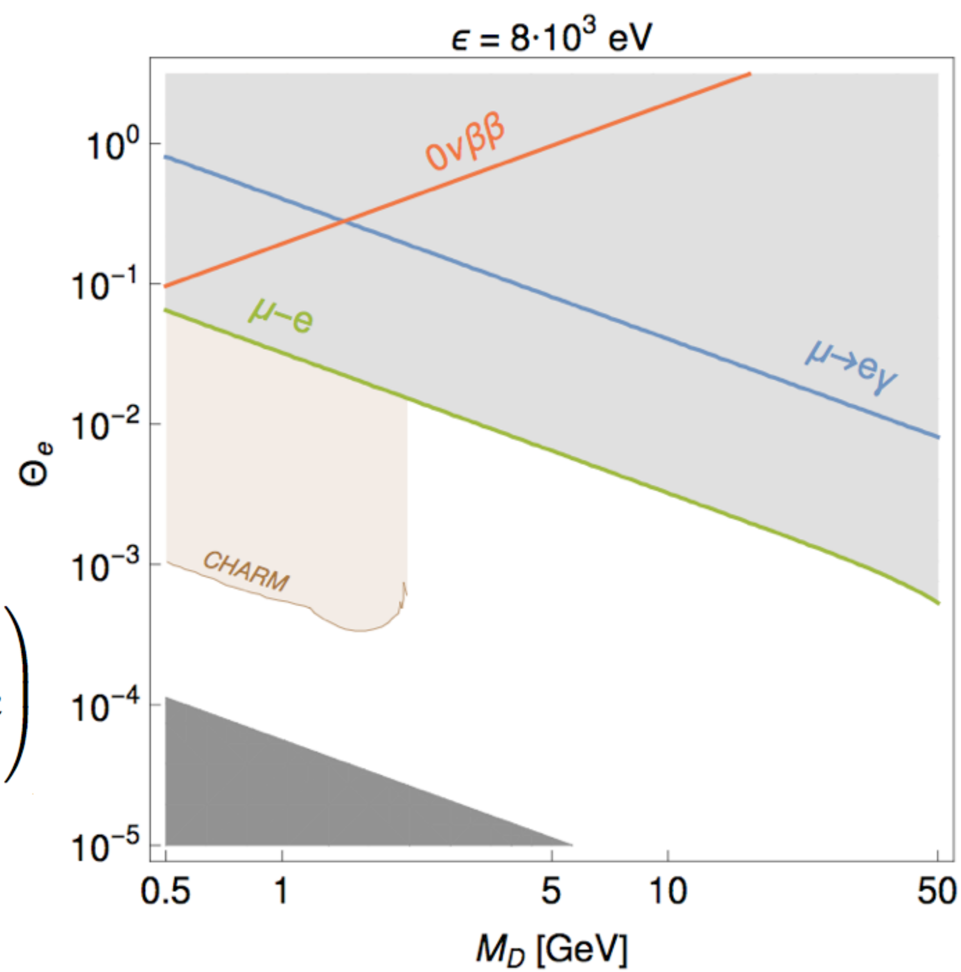
Inverted seesaw:
(two singlets per flavor)

- Precision corrections
  - e.g. LFV, LNV

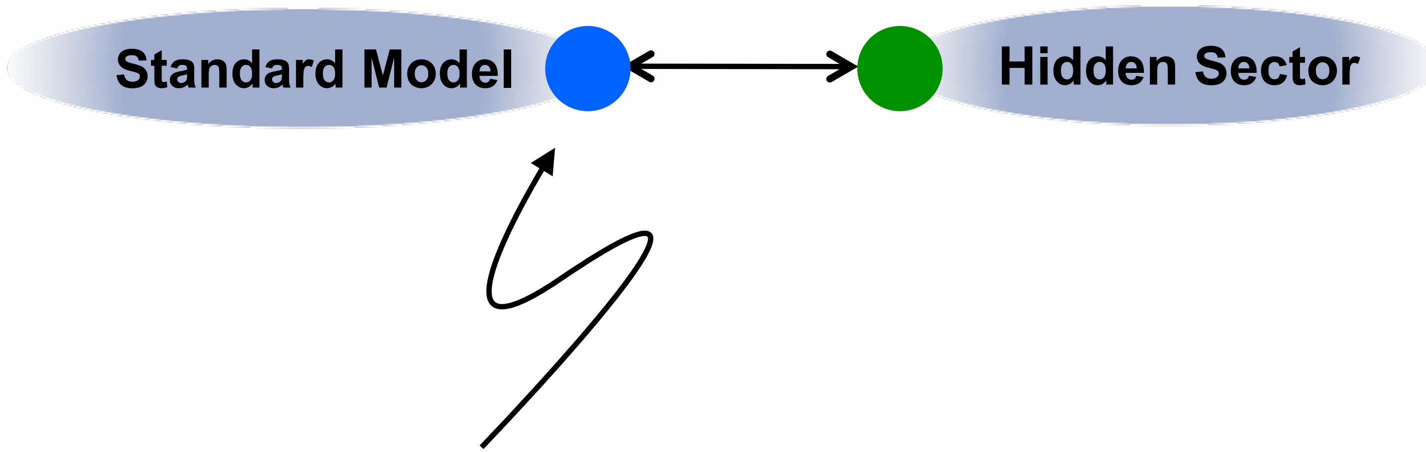
$$\mathcal{L}_\nu \supset (\nu_L \quad N_R \quad N_S) \begin{pmatrix} 0 & m_D & 0 \\ m_D & 0 & M_D \\ 0 & M_D & \epsilon \end{pmatrix} \begin{pmatrix} \nu_L \\ N_R \\ N_S \end{pmatrix}$$

Focus on GeV-scale singlet states

[Le Dall, Pospelov & AR '15]



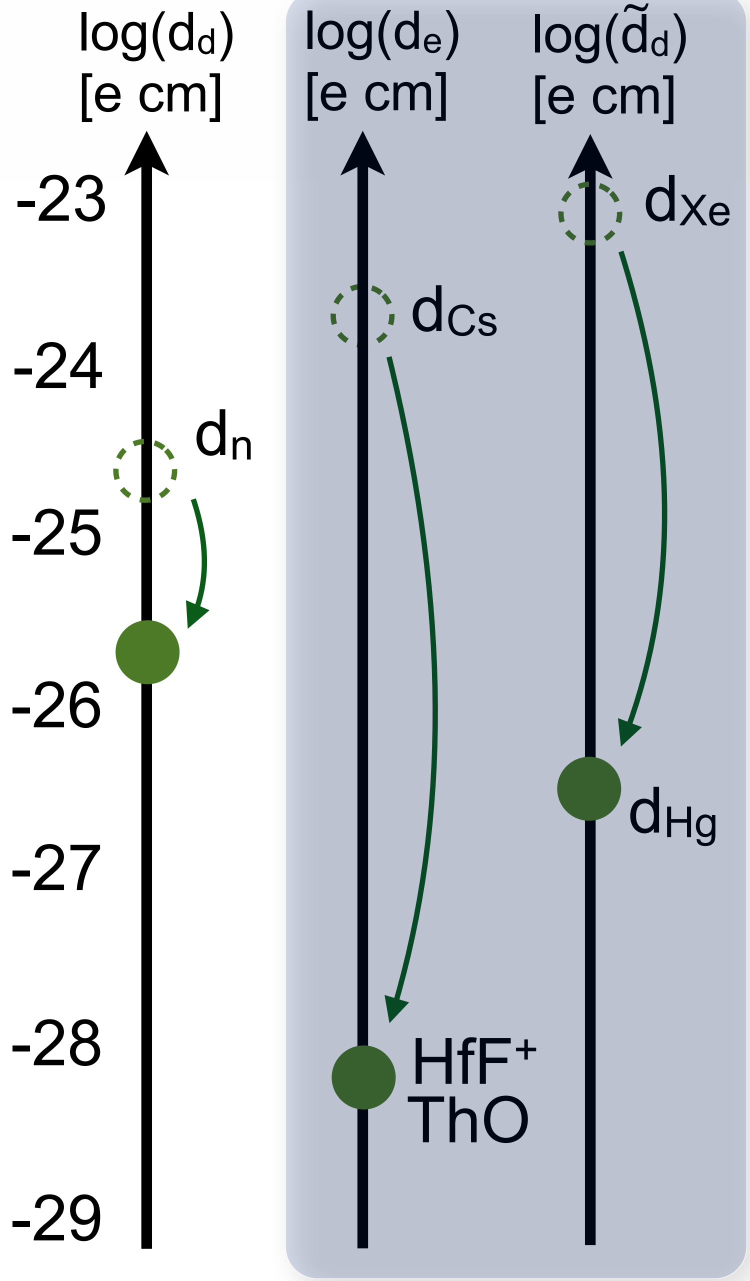
Experimental probes of the portals & light NP



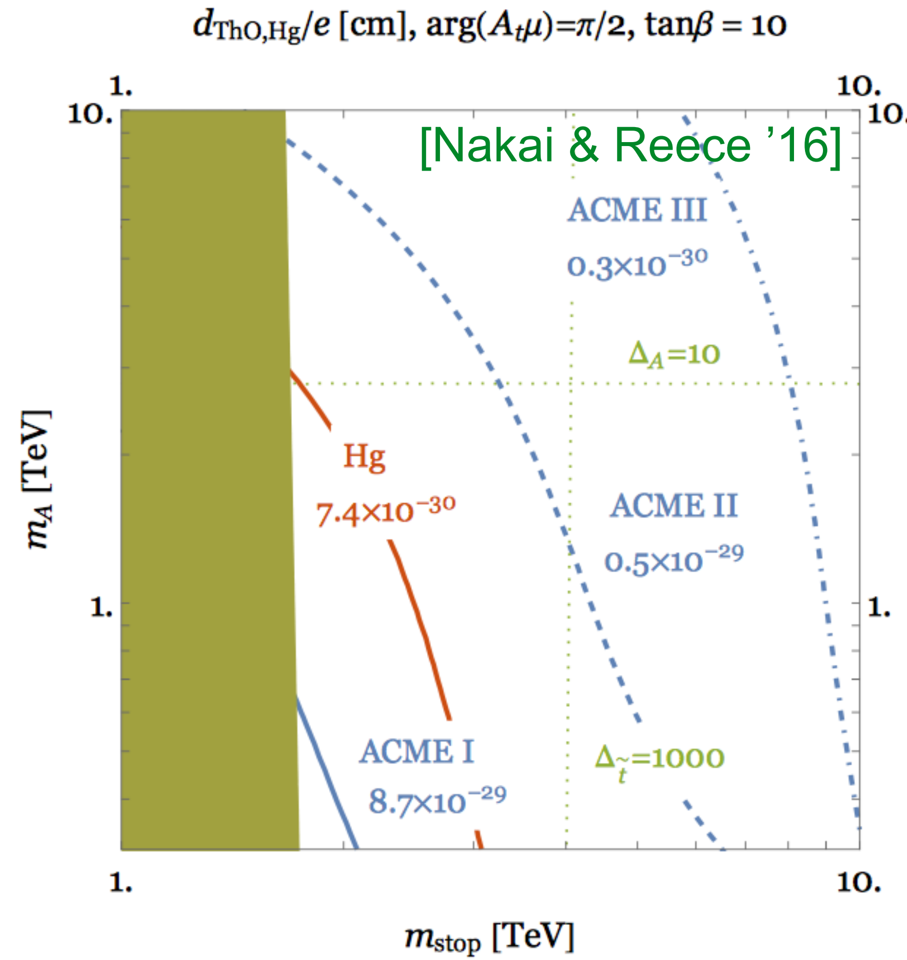
- Precision corrections
  - e.g. EDMs

What about sources of CP-violation within this framework (e.g. for baryogenesis)?

EDM Sensitivity over the past 30 years



Improvement in AMO EDM limits since ~1985… [Haxton & Henley '83; Flambaum et al '84]



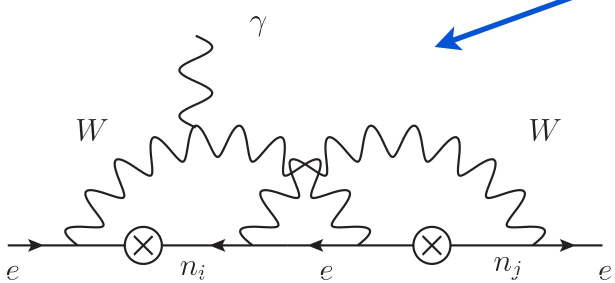
Complementarity to direct energy frontier searches maintained into the LHC era.

EDM Sensitivity to light (UV-complete) hidden sectors

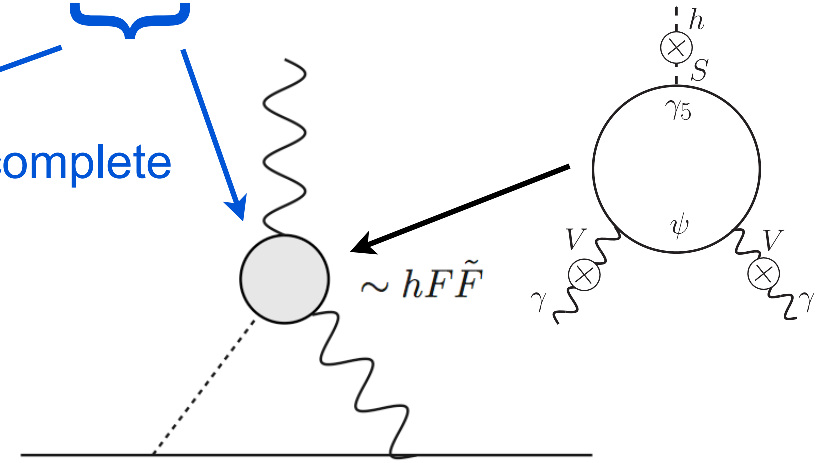
Standard Model ⟷ Hidden Sector

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

UV complete



[Archambault et al ’04]



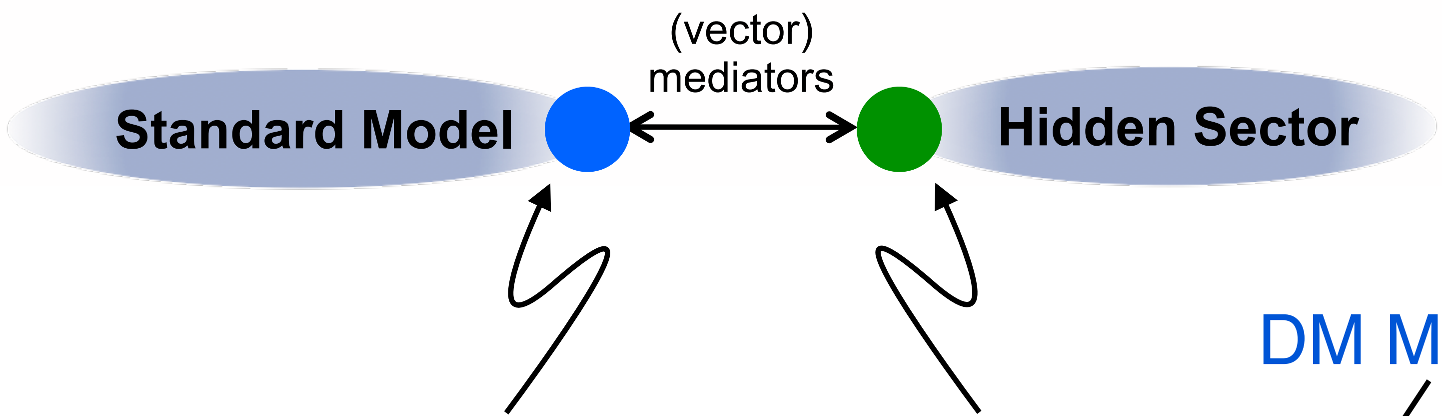
$$d_e(\text{“}\theta_{\rm mixing}\text{”}) \lesssim 10^{-33} e \cdot cm$$

$$d_e(\text{“}\theta_{\rm mixing}\text{”}) \lesssim 10^{-32} e \cdot cm$$

- At current sensitivity levels, lepton EDMs primarily probe NP with new UV dofs, unlike other precision probes such as LFV, LNV, muon g-2, etc.
- Similar statements apply to hadronic EDMs (n, Hg), although detections at current precision can be interpreted in terms of $\theta_{\rm QCD}$.

[Le Dall, Pospelov & AR ’15]

Experimental probes of the portals & light NP



DM Models!

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(also astrophysics & cosmology)

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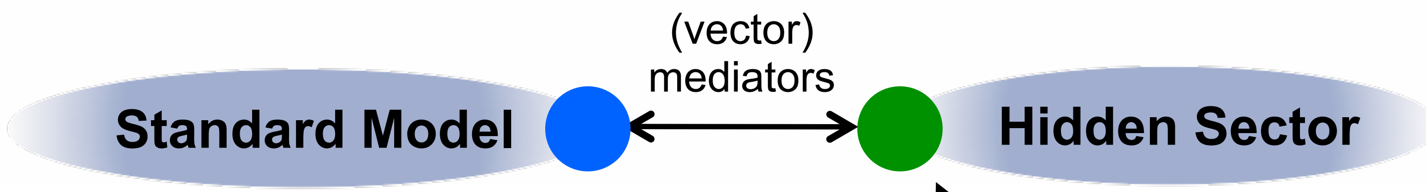
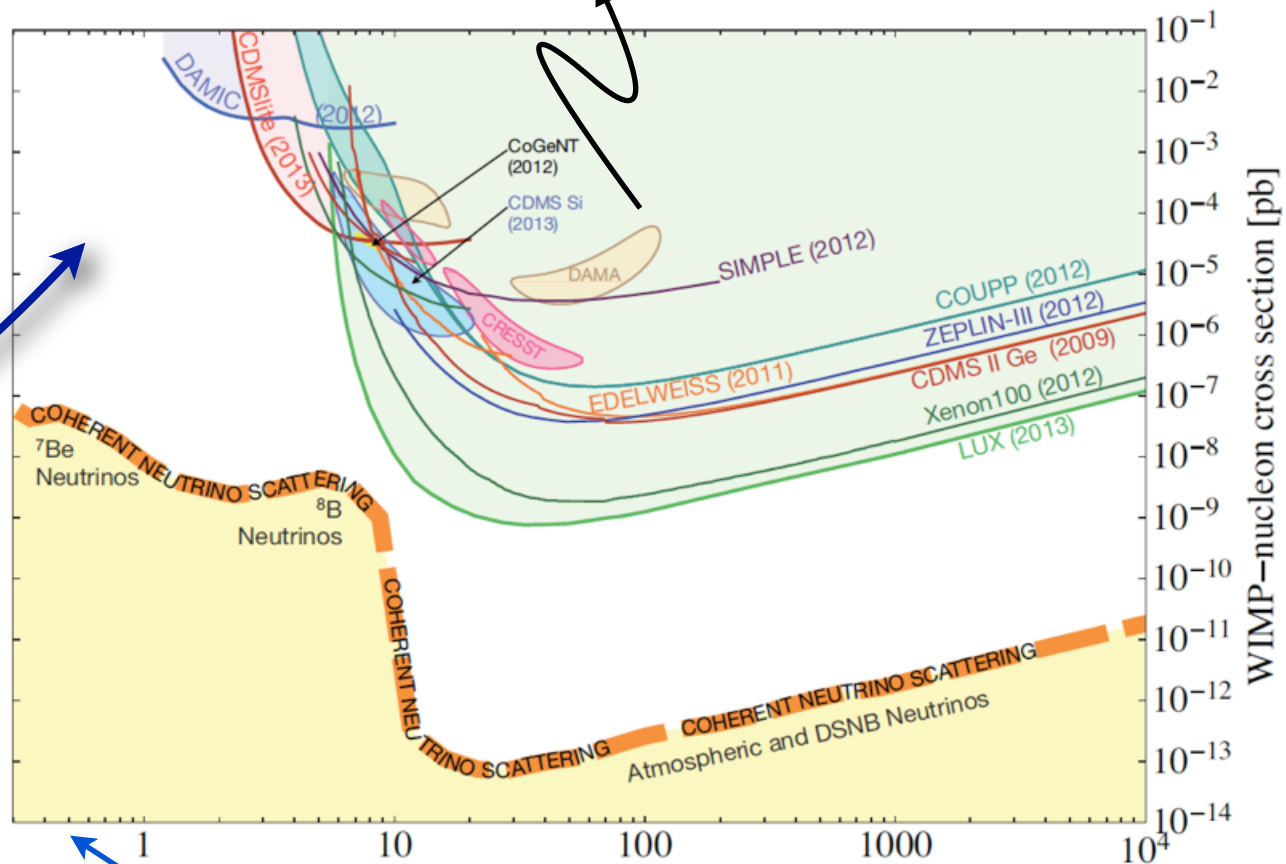


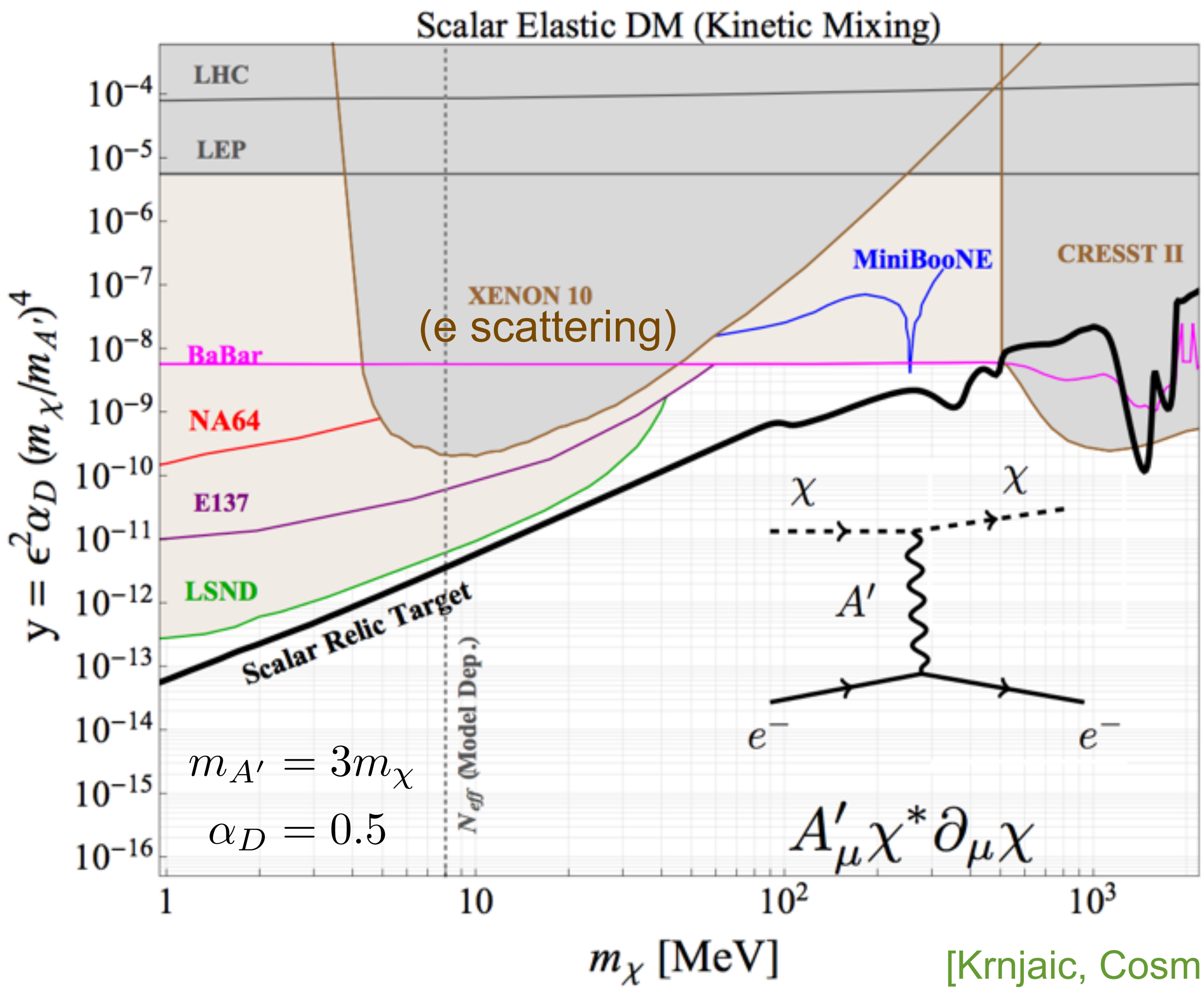


Sensitivity to halo DM with $v \sim 10^{-3}$ drops for m<O(GeV), due to recoil energy thresholds.

Dark Sectors allow for sub-GeV mass thermal relic DM models (e.g. "light WIMPs"), accessible at intensity frontier experiments

Direct detection & Intensity frontier searches

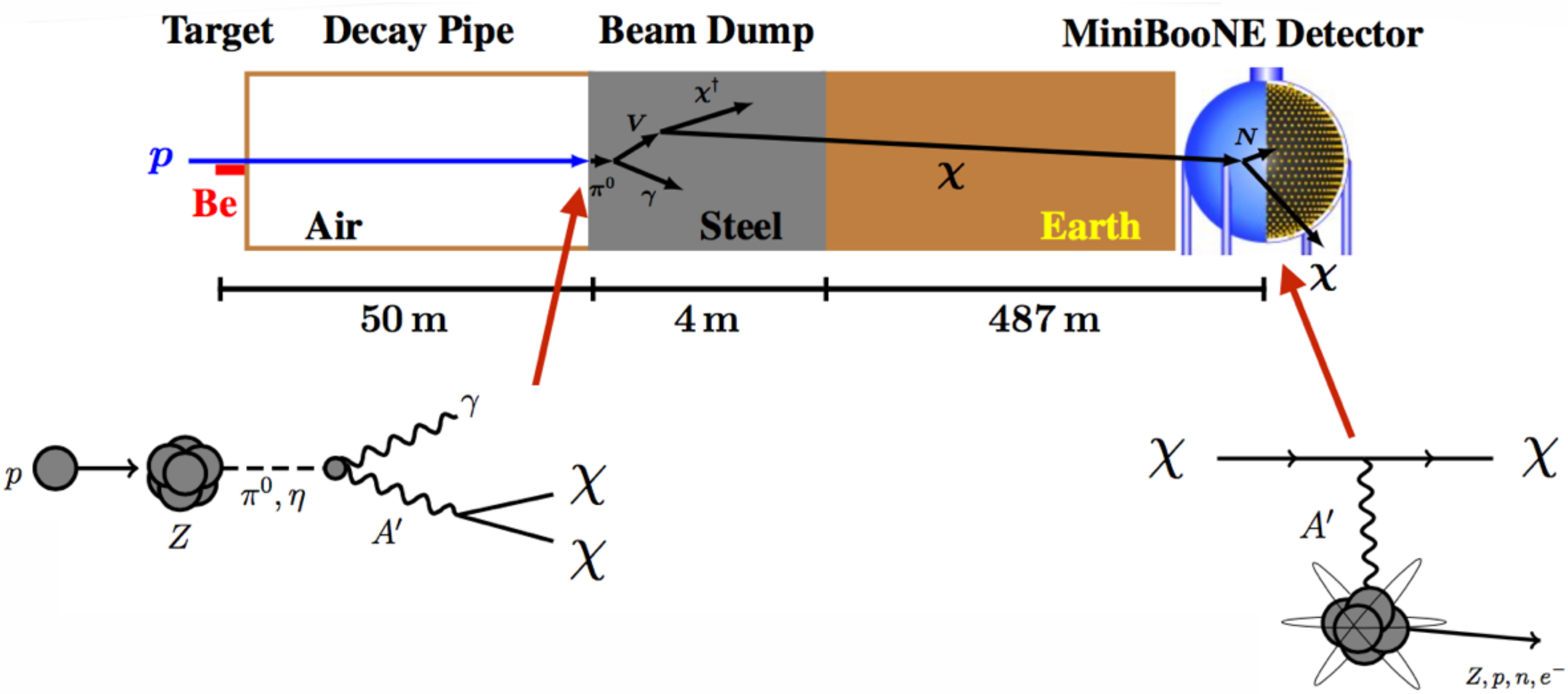
Hidden sector scalar/pseudo-Dirac fields (x) coupled to the vector portal are good DM candidates, accessible at the intensity frontier... [Batell, Pospelov, AR, deNiverville, McKeen, Essig, Schuster, Izaguirre, Krnjaic, Kahn, Morrissey, …]



[Krnjaic, Cosmic Visions 2017]

E.G. fixed target probes using neutrino detectors (MiniBooNE)

Basic idea: use the neutrino (near) detector as a dark matter detector, looking for recoil, but now from a relativistic beam.



Align the beam off-target, to minimize the neutrino background

[Batell et al ’09, ’14, deNiverville et al ’11, ‘12 ’16, + MiniBooNE ’12, Dobrescu et al ‘15]

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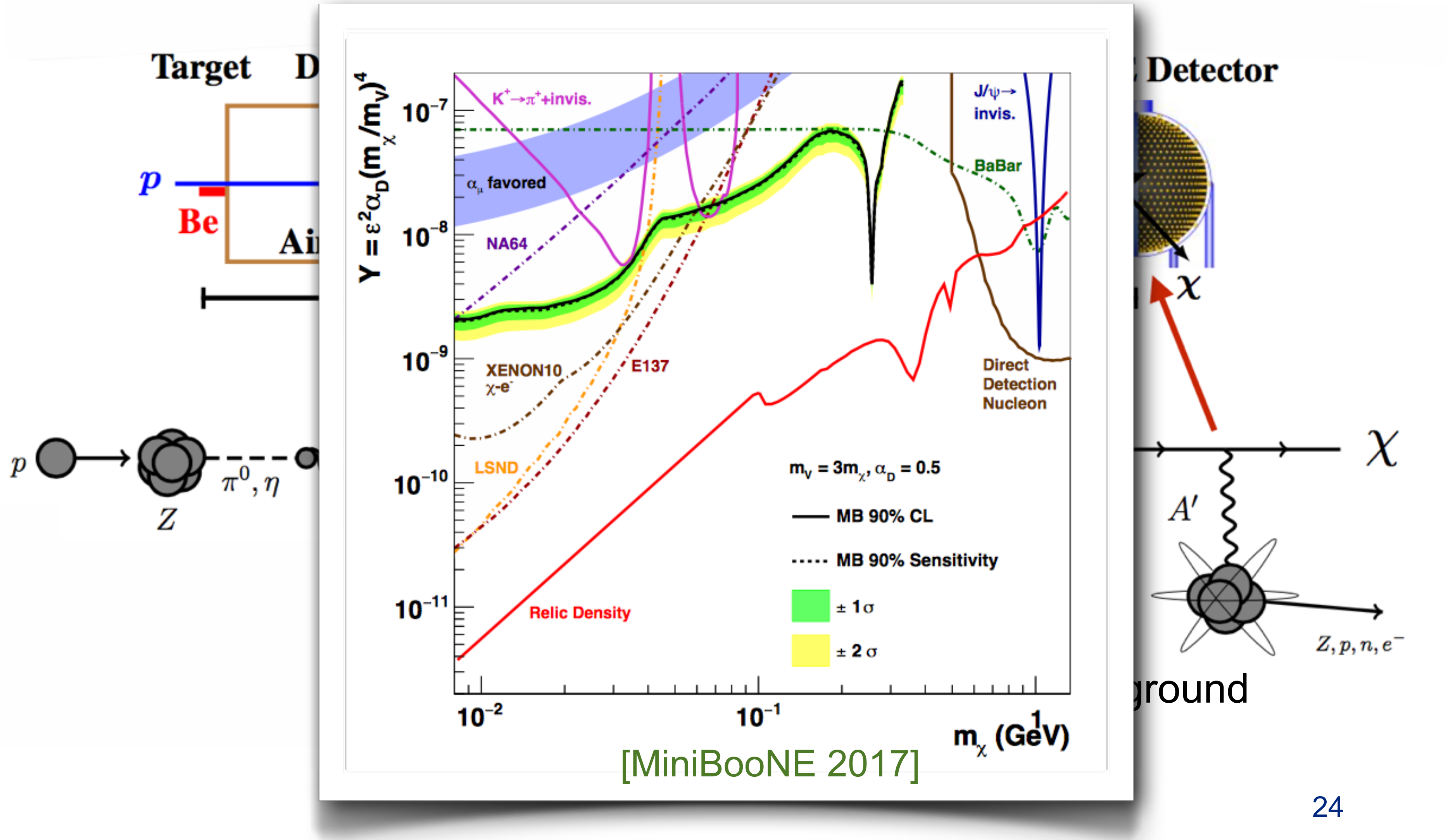
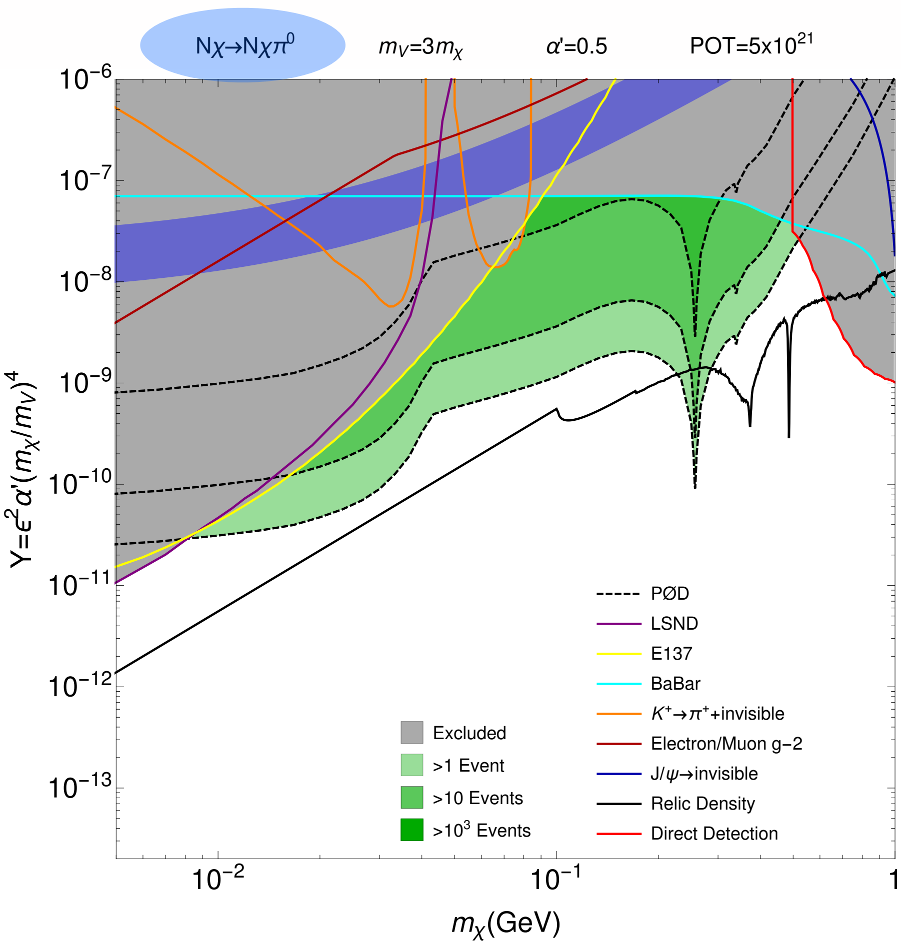


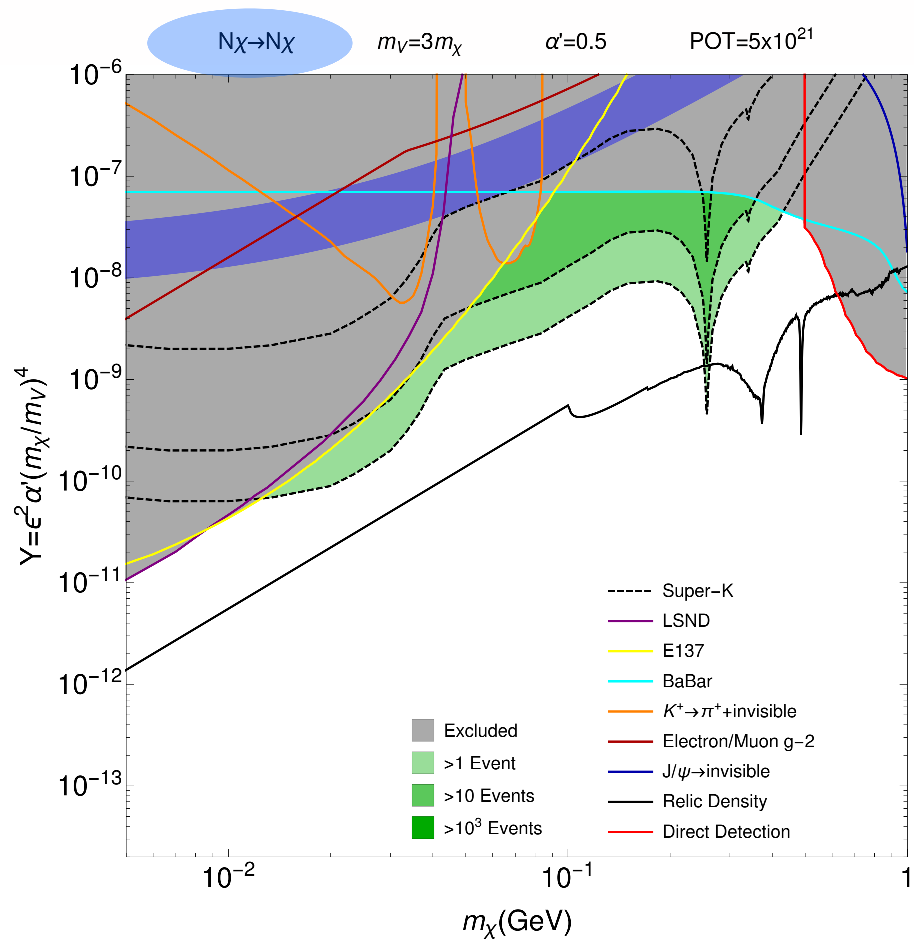
[MiniBooNE 2017]

Sample event rates - T2K

[deNiverville et al ’12, ’16]



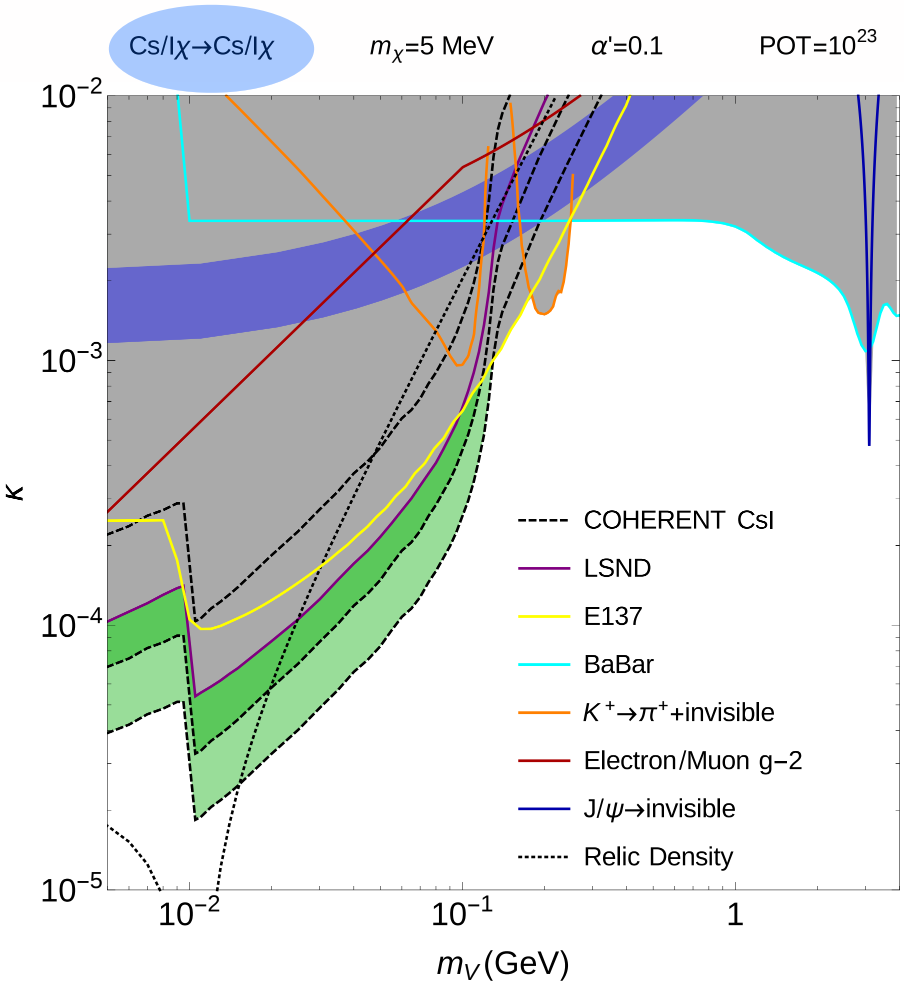
ND280 - P0D



SuperK

Future Neutrino facilities

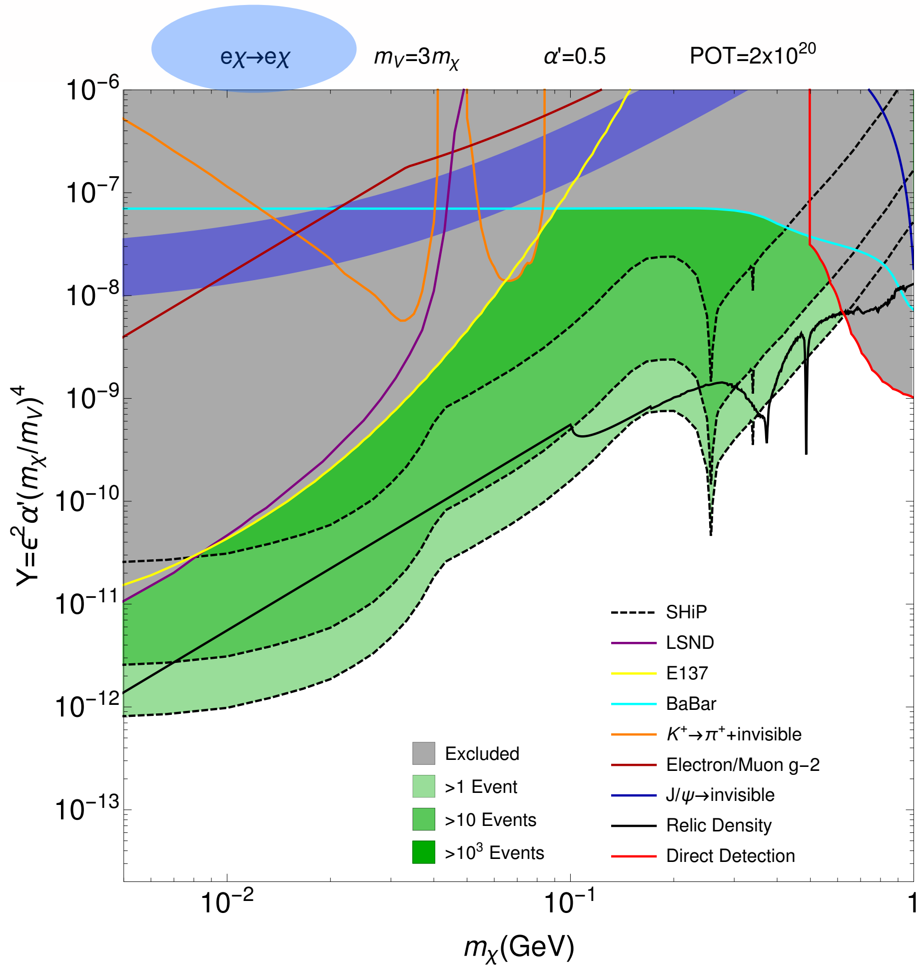
COHERENT (SNS)



Includes V-production via pion capture: $\pi^- + p \to n + V$

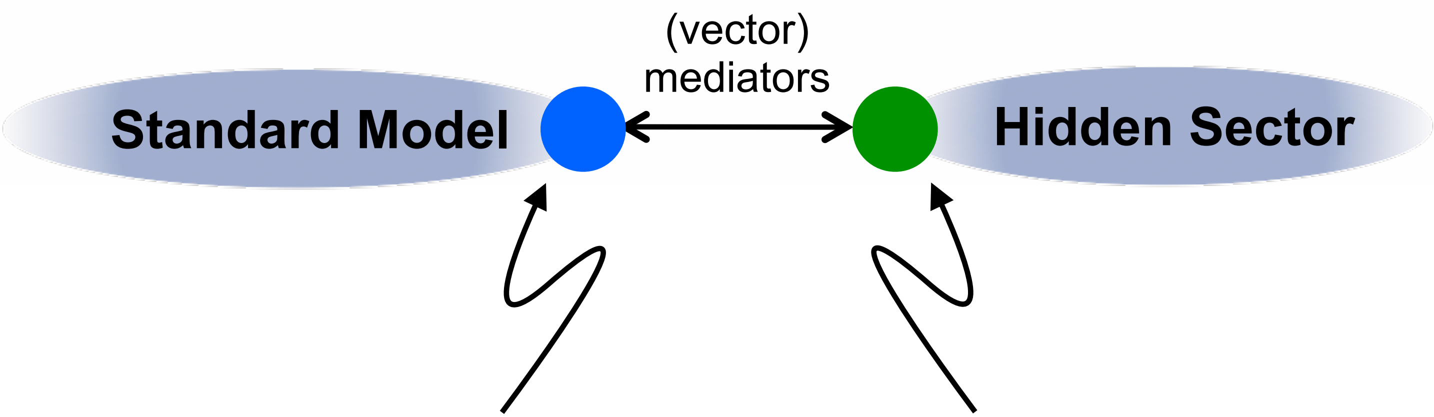
[deNiverville et al '15]

SHiP (LArTPC at 100m)



[deNiverville et al '16]

Experimental probes of the portals & light NP



Experimental probes

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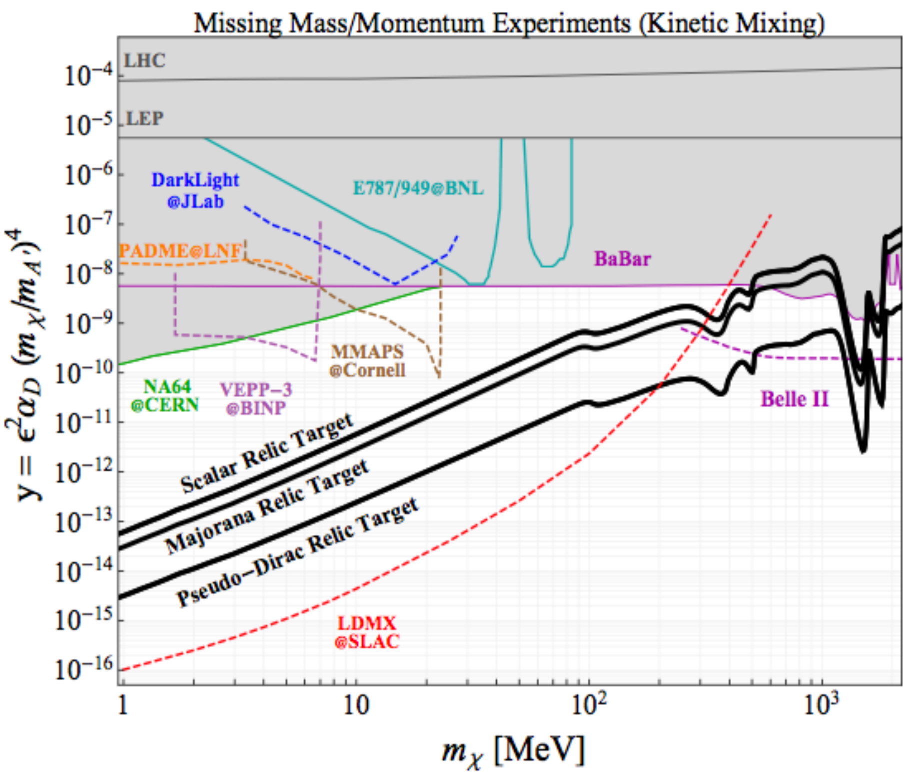
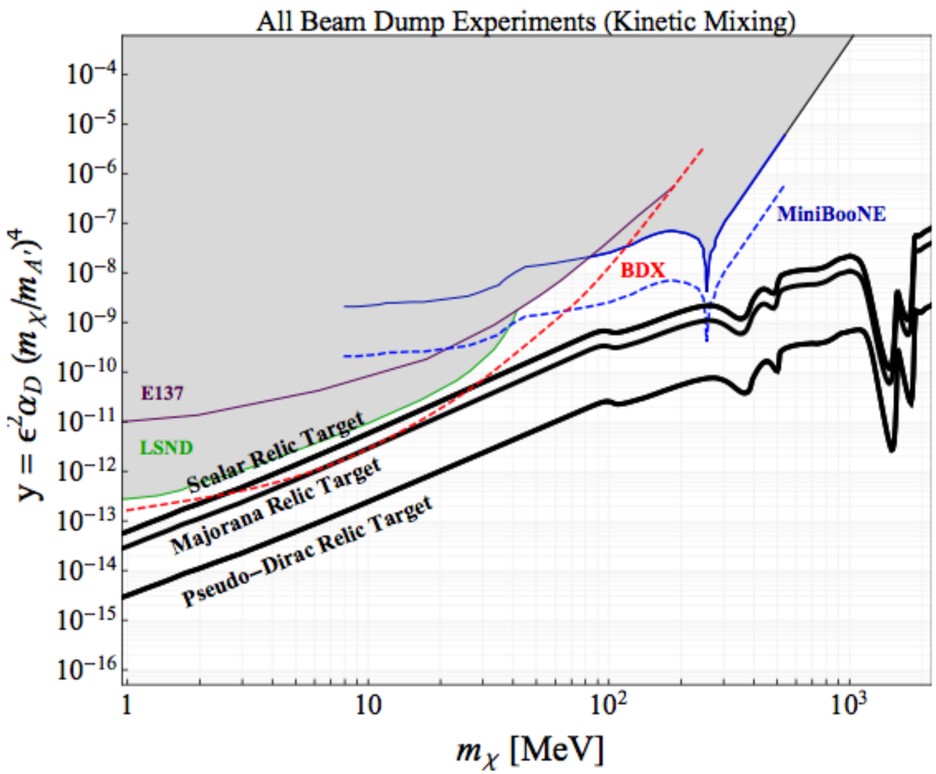
(also astrophysics & cosmology)

Future reach in e/p channels...

Missing Mass/Mtm

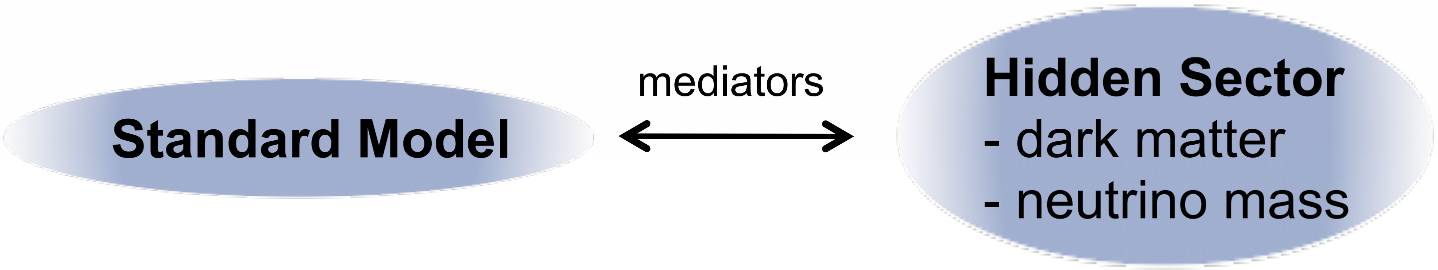


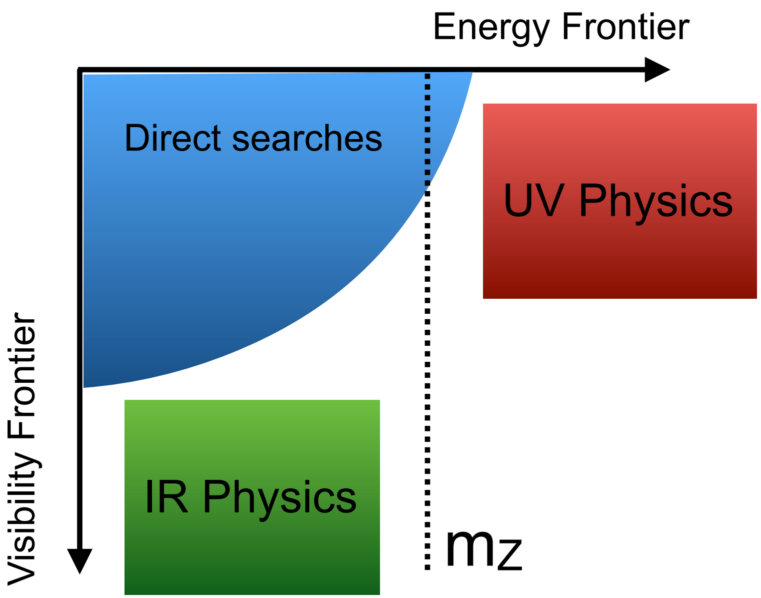
Scattering



[B. Echenard, E. Izaguirre, WG3 Summary, Cosmic Visions 2017]

Summary



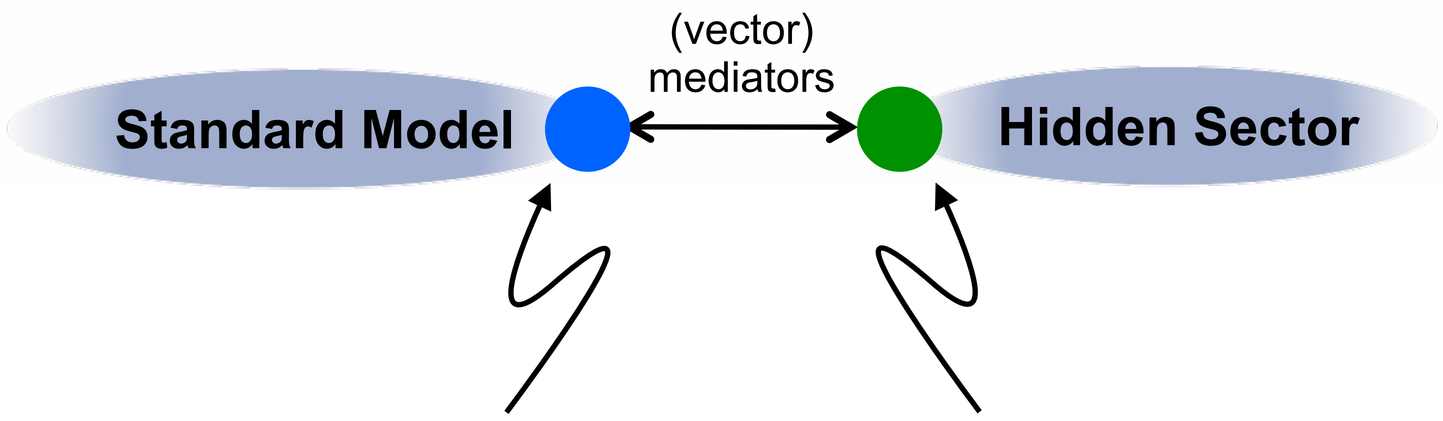


Empirical motivations for new physics suggest dark/hidden sectors, which can contain light (sub-EW scale) degrees of freedom:

- EFT arguments focus attention on the "portal interactions".
- Active experimental efforts at the precision and intensity frontier over the past 7-8 years.
- Overlap with high-intensity fixed target & collider programs (e.g. neutrino experiments), and potential for synergistic analyses.

Extra Material

Experimental probes of the portals & light NP



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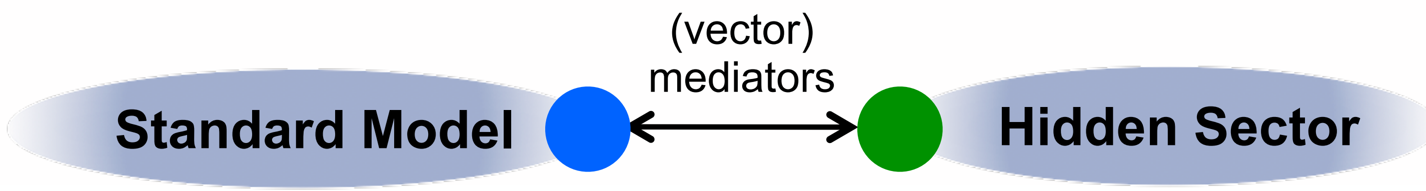
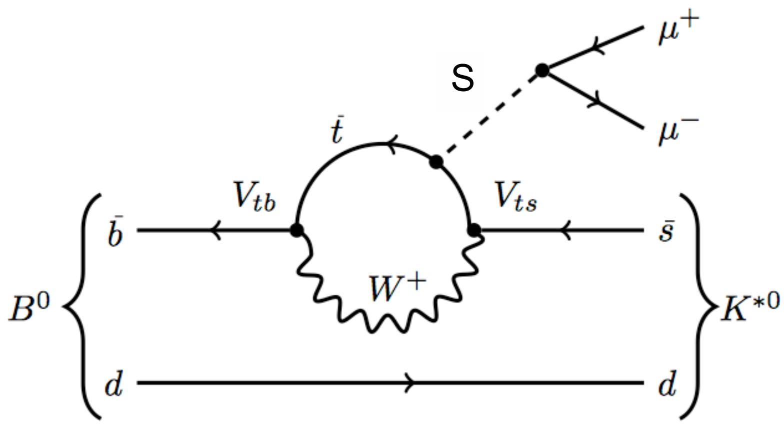
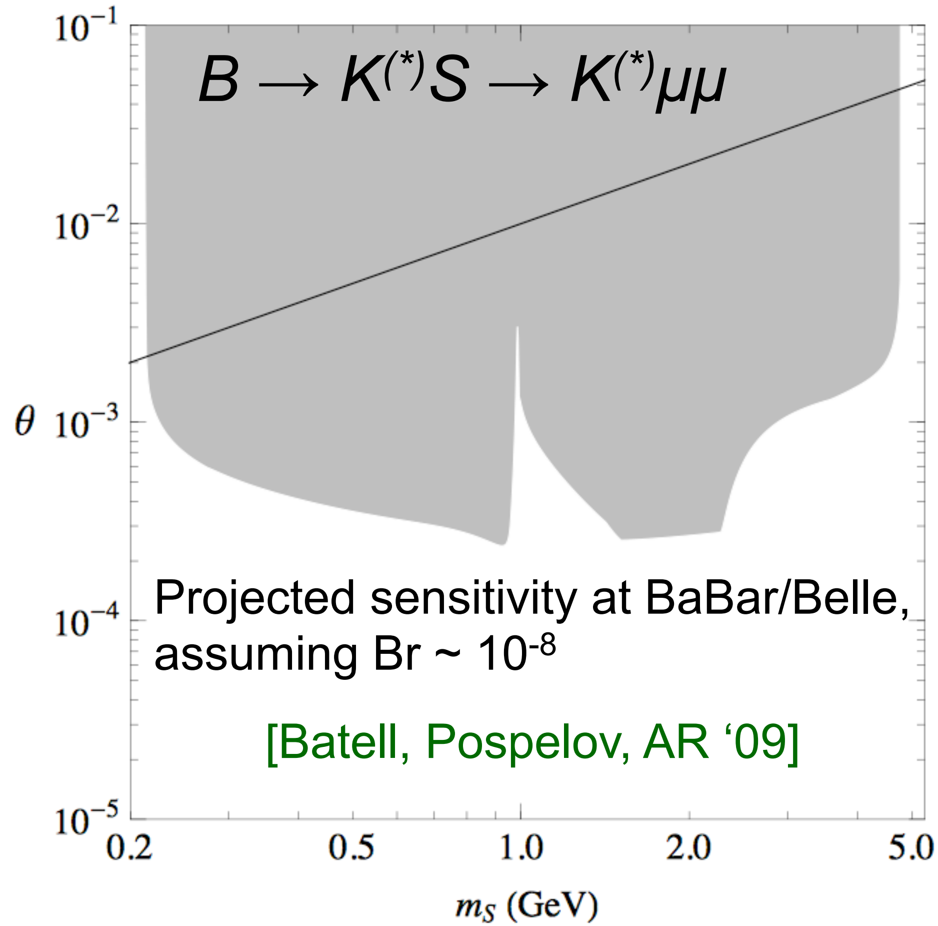
E.G. Probes of the scalar portal

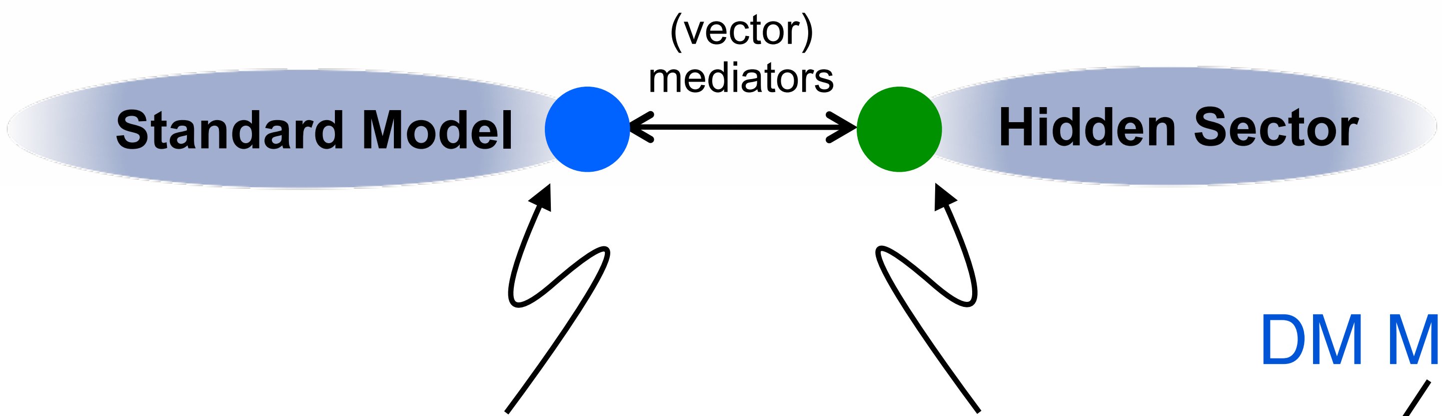




- rare (visible) decays
  - e.g. collider/fixed target production plus e.g. leptonic A' decays, O(κ²) x Br(SM)



Experimental probes of the portals & light NP



DM Models!

Experimental probes

- Precision corrections
  - e.g. lepton g-2, EDMs
- rare (visible) decays
  - e.g. collider/fixed target production plus e.g. leptonic A' decays, $O(\kappa^2)$ x Br(SM)

- rare (invisible) decays/missing E
  - e.g. collider production plus missing energy in decays and scattering, $O(\kappa^2)$ x Br(Hid)
- anomalous NC-like scattering
  - e.g. fixed target production plus anomalous NC-like scattering, $O(\kappa^2 \text{ x } \kappa^2\alpha')$

(also astrophysics & cosmology)

"Minimal" sub-GeV DM model

mediators

Standard Model ⟷ **Hidden Sector**

$$\mathcal{L} = -\frac{1}{4}V_{\mu\nu}^2 - \frac{\kappa}{2}V_{\mu\nu}F^{\mu\nu} - \frac{1}{2}m_V^2 V_\mu^2 + |D_\mu \chi|^2 - m_{\rm DM}^2|\chi|^2 + \cdots$$

⇓

$$\mathcal{L}_{\rm int} = -\kappa e V_\mu J^\mu_{\rm em}$$

A' - couples to the SM via the EM current

⇓

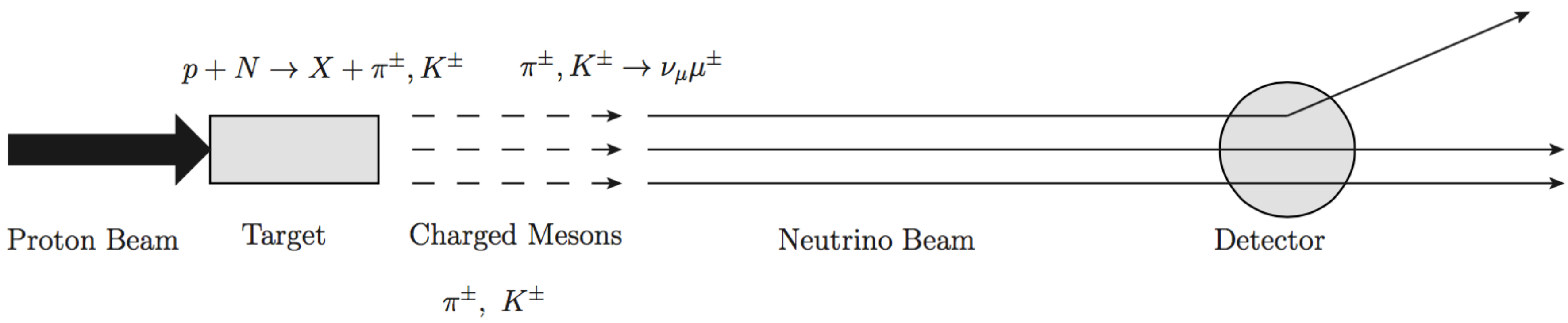
DM candidate, coupled through U(1)', with "fine structure constant" α'

- Allows viable sub-GeV thermal relic DM candidates [Boehm et al '03, Fayet '04,'06; Pospelov, AR, Voloshin '07; Hooper & Zurek '08].
- For $m_{DM} < m_V$, the correct relic density fixes a specific relation between $\{\kappa, \alpha', m_V, m_{DM}\}$ [Pospelov, AR & Voloshin '07]

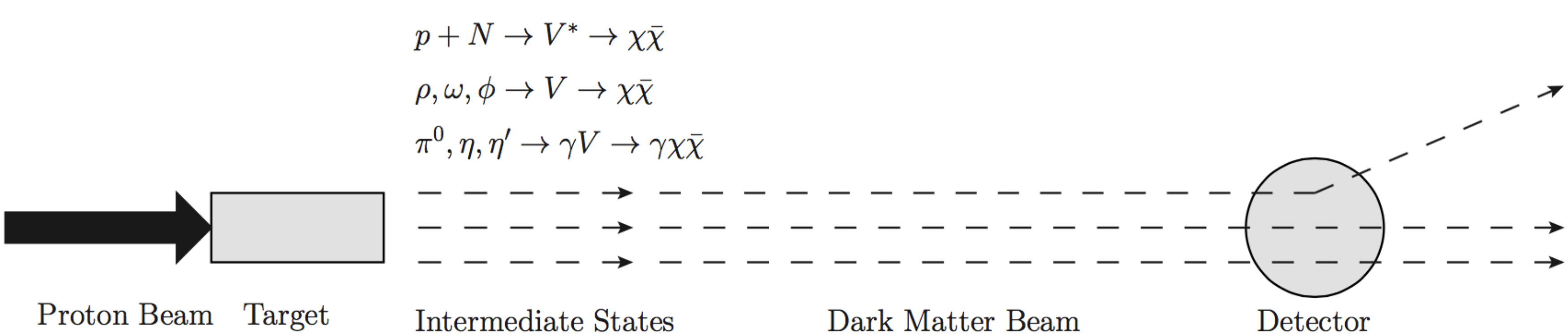
(NB: notation κ = ε for some later plots)

Fixed target probes - Neutrino Beams

[Batell et al ’09, ’14, deNiverville et al ’11, ‘12 ‘16]



Basic idea: use the neutrino (near) detector as a dark matter detector, looking for recoil, but now from a relativistic beam.

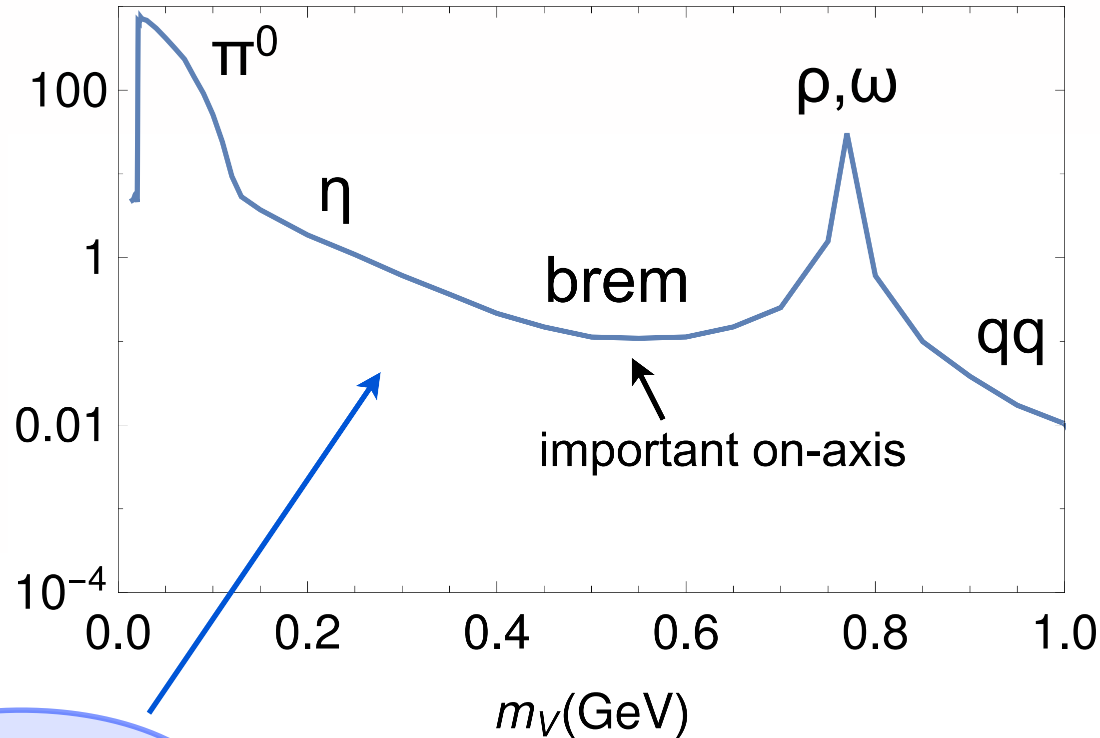


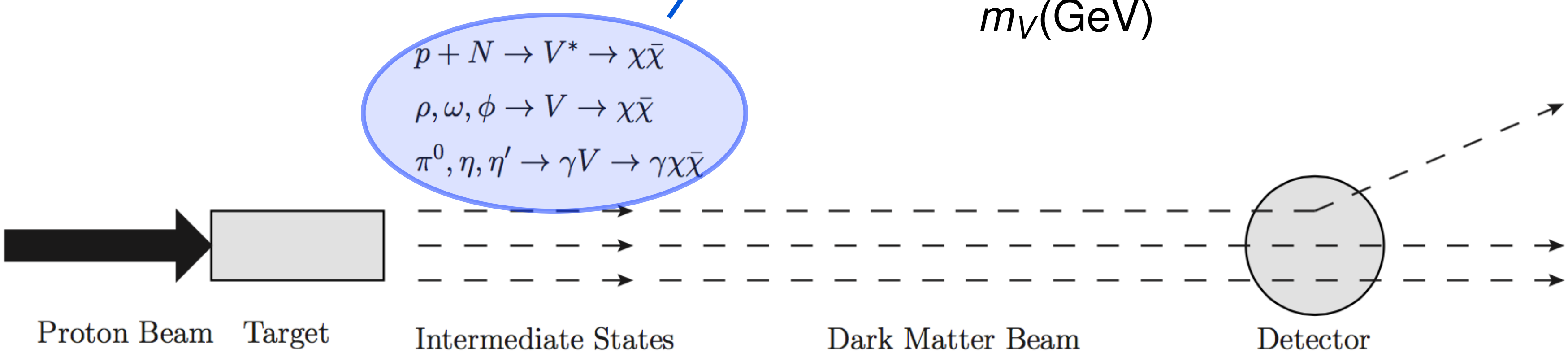
Fixed target - DM production

[deNiverville et al, to appear]

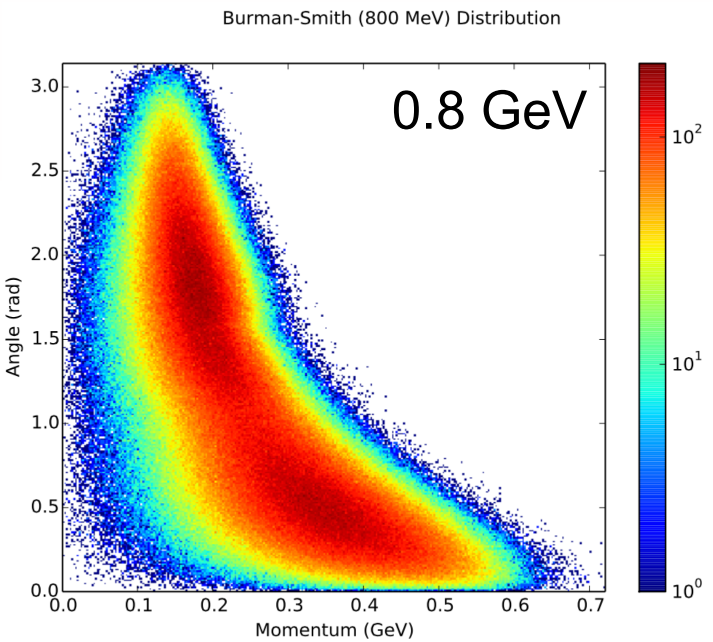
Unnormalized production rate at e.g. MiniBooNE (vector mediator)

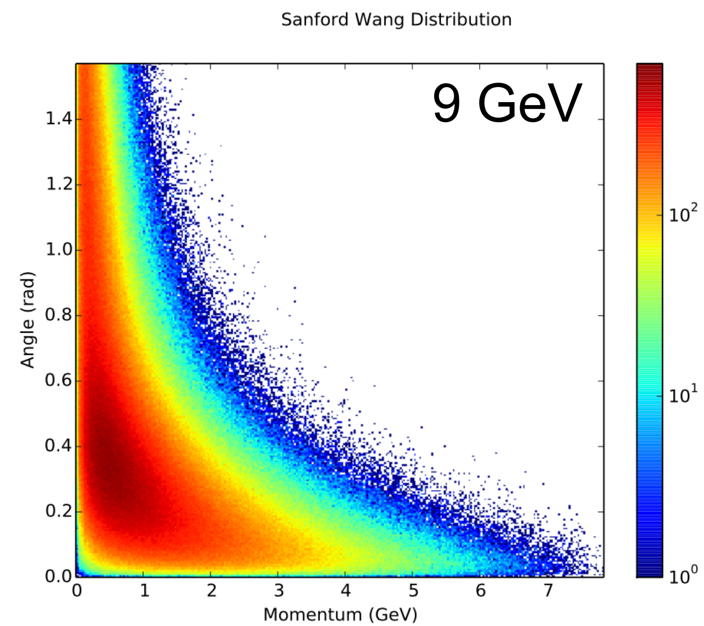
- NB: some components of production model can be validated with data, but not all...

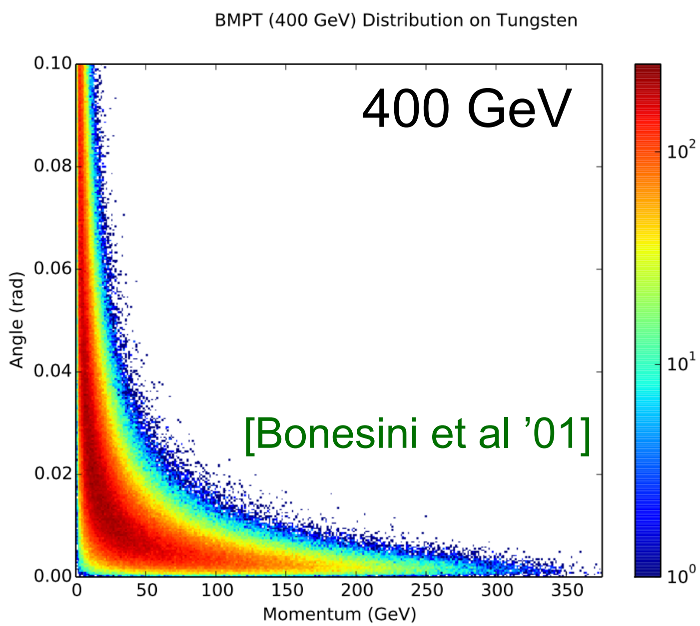




DM Production - π, η distributions



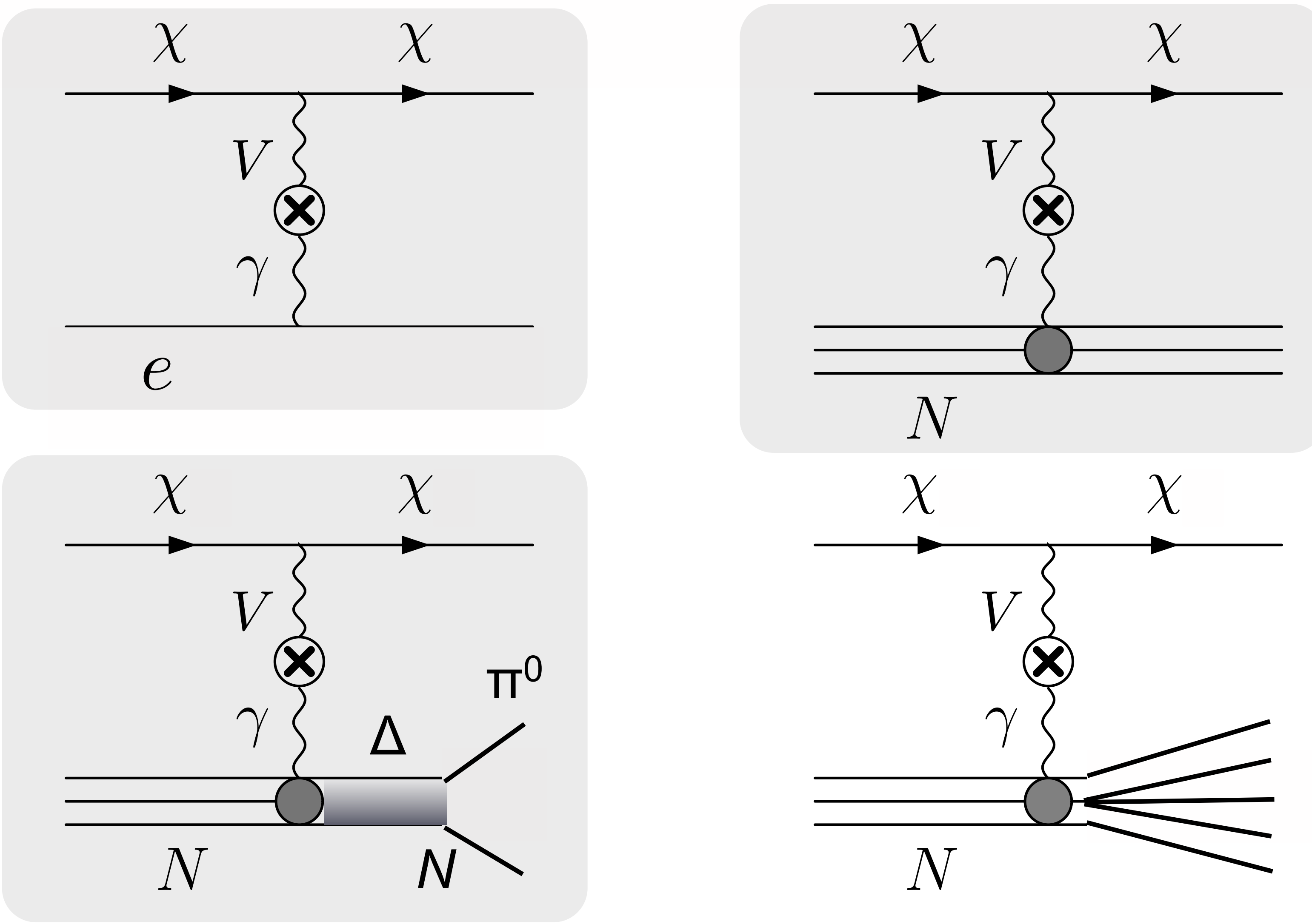




- Rate for π^0,η given by averaging rates for π^+, π^-
- calibrated for thin targets, so will broaden for an absorber
- *charged mesons are magnetically focused, and neutrino energy spectrum has a lower peak*

Signatures

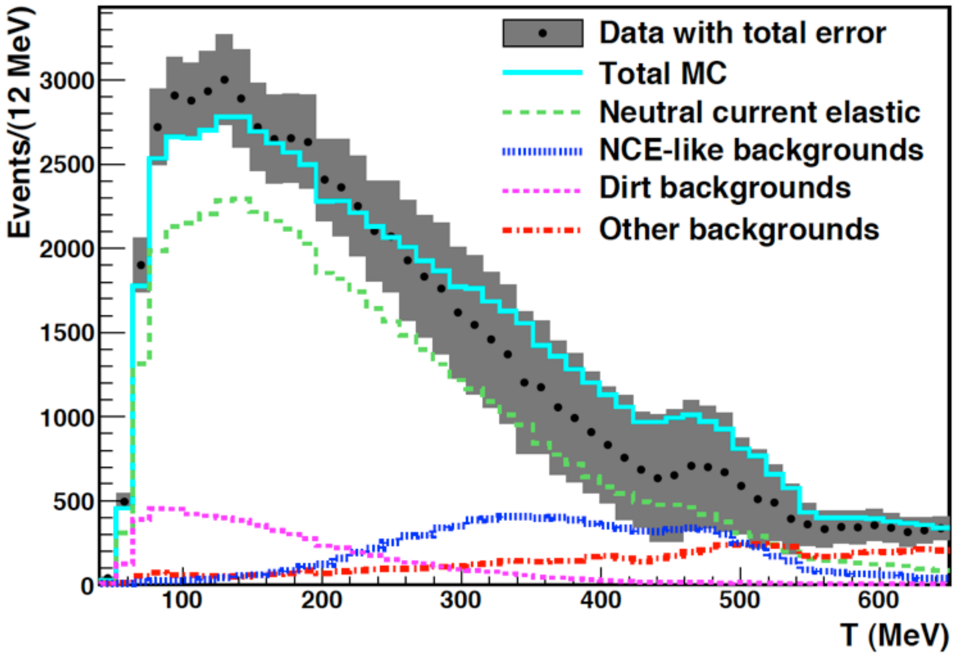
Characteristic DM (in)elastic scattering signatures



Mimics scattering of neutrinos, which provide dominant background.

Neutrino backgrounds...

Neutrino elastic scattering provides a large background at all ν-beam facilities with a decay volume after the target, e.g. at MiniBooNE



~10^5 -10^6 scattering events, with neutral current cross-sections measured to O(18%)
[MiniBooNE '10]

➠ Counting experiments are not enough…

Neutrino backgrounds...

However, there are ways to enhance S/B

- Run as a "beam dump"
  - steer beam past target and into absorber. This removes decay volume, cuts down neutrino background by a large factor (but cannot run in "parasitic" mode, unless well off axis)

- Timing
  - time delay (Υ=10) = O(10ns), effective for higher mass
  - possible at MiniBooNE, also very effective at a far detector (e.g. T2K $\rightarrow$ SuperK)

- Energy cuts (especially if detector is off-axis)
  - neutrino beam peaks at lower energy
  - different scattering kinematics

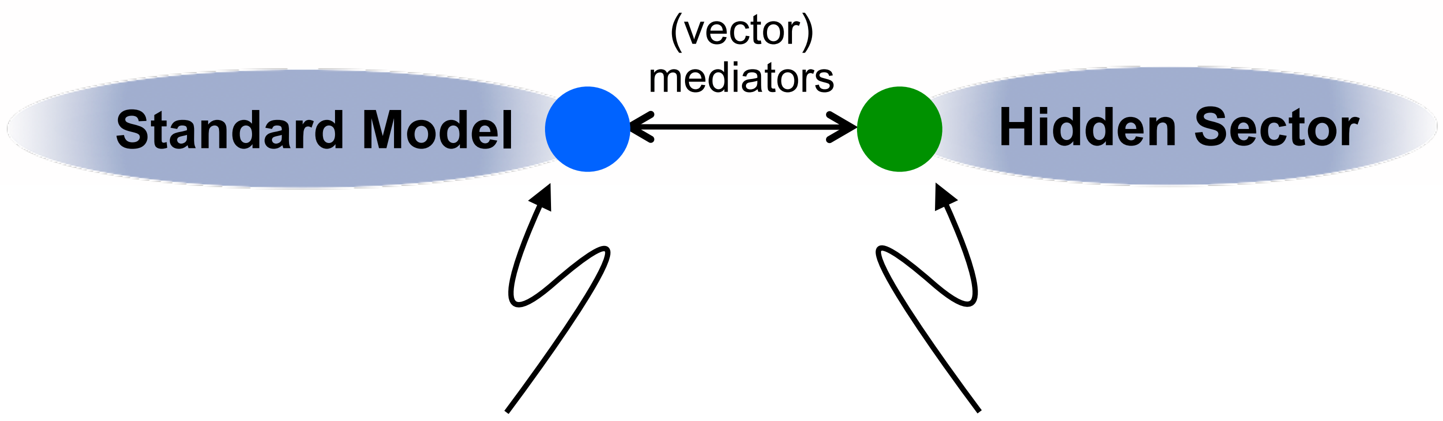
- Scattering angle cuts
  - forward angle cut very effective with electron scattering

Multiple techniques are being tested in the current MiniBooNE analysis

Experimental Facilities

- LSND
  - 800 MeV, 10^{23} POT, off-axis detector at 30m (no decay volume, so effectively a beam dump)
- MiniBooNE (absorber)
  - 9 GeV, $2x10^{20}$ POT, 650 ton on-axis detector at 450m
- T2K
  - 30 GeV beam, 10^{21} POT, 2^o off-axis detectors,
    - near (~2ton, 280m), far (~50 kton, Super-K)
- (also CHARM, MINOS,…)
- Future
  - COHERENT @ SNS (1 GeV, 10^{23} POT/yr, 90^o off-axis at 20m)
  - SHiP (400 GeV, 10^{20} POT, ~10 ton LArTPC on-axis at ~100m)
  - MicroBooNE & NOvA
  - LBNF/DUNE,…

Experimental probes of the portals & light NP



Experimental probes

- Precision corrections
  - e.g. lepton g-2, EDMs
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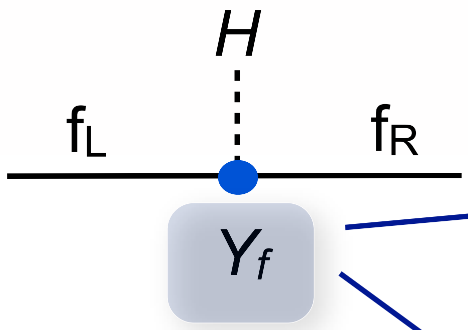
  - e.g. collider/fixed target production plus e.g. leptonic A' decays, $O(\kappa^2)$ x Br(SM)
- rare (invisible) decays/missing E
  - e.g. collider production plus missing energy in decays and scattering, $O(\kappa^2)$ x Br(Hid)
- anomalous NC-like scattering
  - e.g. fixed target production plus anomalous NC-like scattering, $O(\kappa^2 \times \kappa^2\alpha')$

(also astrophysics & cosmology)

CP (or T) Violation in the SM + ν-mixing



"unknown"

$$\delta_{PMNS} \sim ?$$

Depends on the mechanism of neutrino mass generation

"known"

$$m_f \sim Y_f^{\rm diag} \langle H \rangle$$

$$\sin(\delta_{\rm KM}) \propto {\rm Arg\,Det}[Y_u Y_u^\dagger, Y_d Y_d^\dagger]$$

$$\delta_{\rm KM} \sim \mathcal{O}(1)$$

Explains CP-violation in K and B meson mixing and decays

$$\sin(\bar\theta - \theta_0) \sim {\rm ArgDet}[Y_u Y_d]$$

$$\bar\theta < 10^{-10} \; !$$

Constrained experimentally (strong CP problem)

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

Harvard/Yale (ThO)
[Baron et al. '13]

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

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

$$|d_e^{\mathrm{equiv}}| < 8.7\times 10^{-29}\,e\mathrm{cm}$$

Diamagnetic EDMs

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

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

Argonne (Ra)
[Bishof et al '16]

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

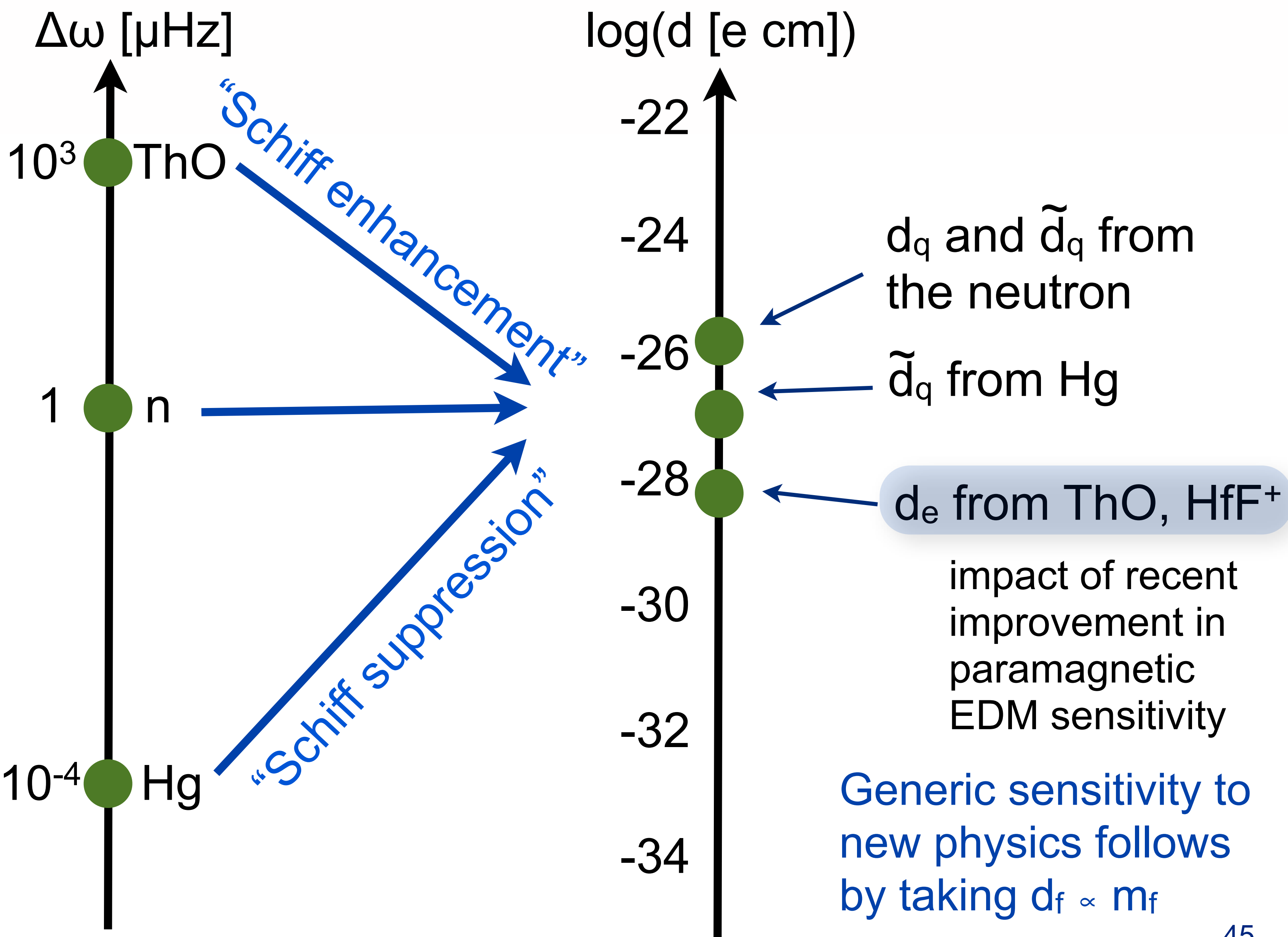
Neutron EDM

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

(and others in development around the world, including at *TRIUMF*)

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

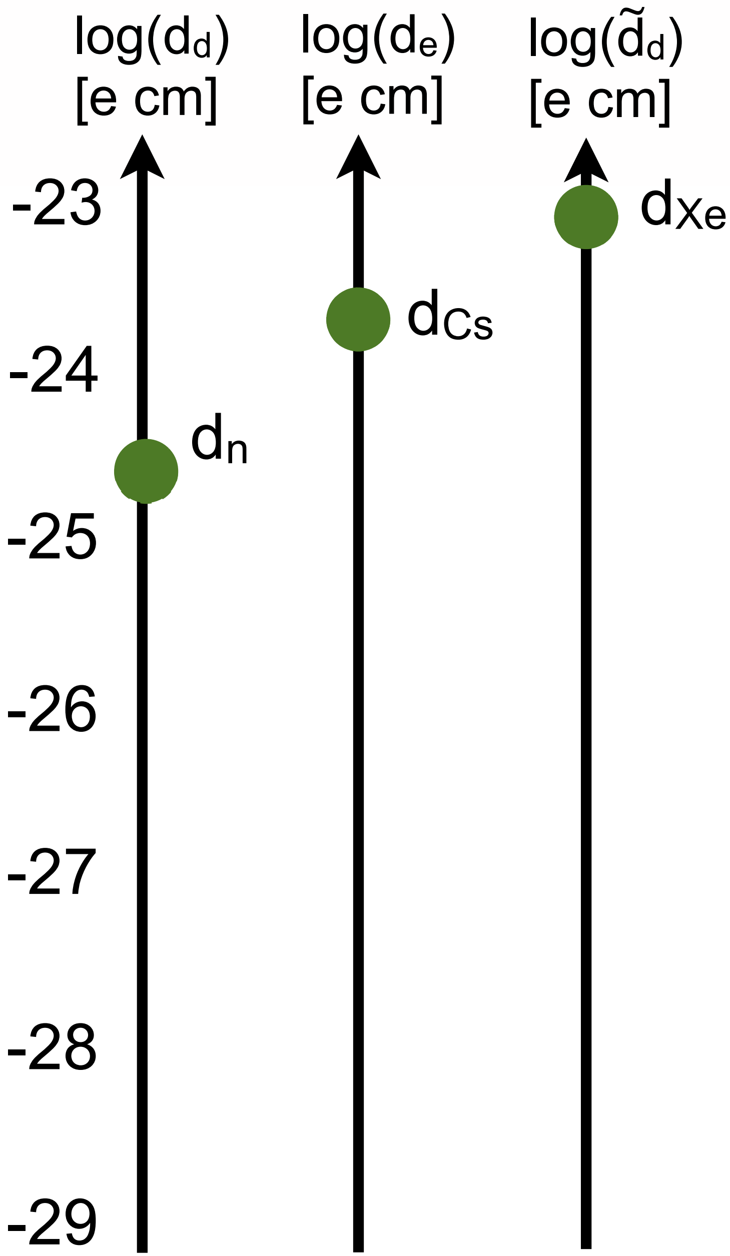
EDMs as precision probes...



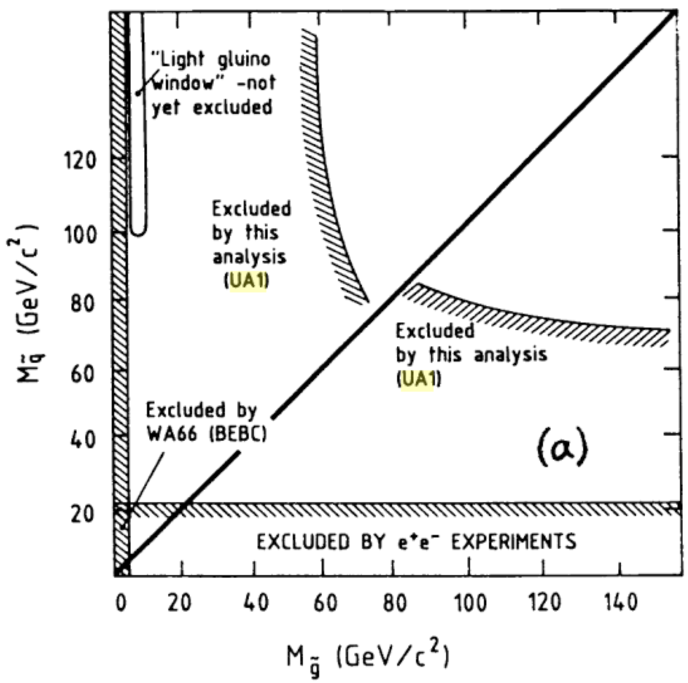
impact of recent improvement in paramagnetic EDM sensitivity

Generic sensitivity to new physics follows by taking $d_f \propto m_f$

Looking back ~30 years (~1985)…



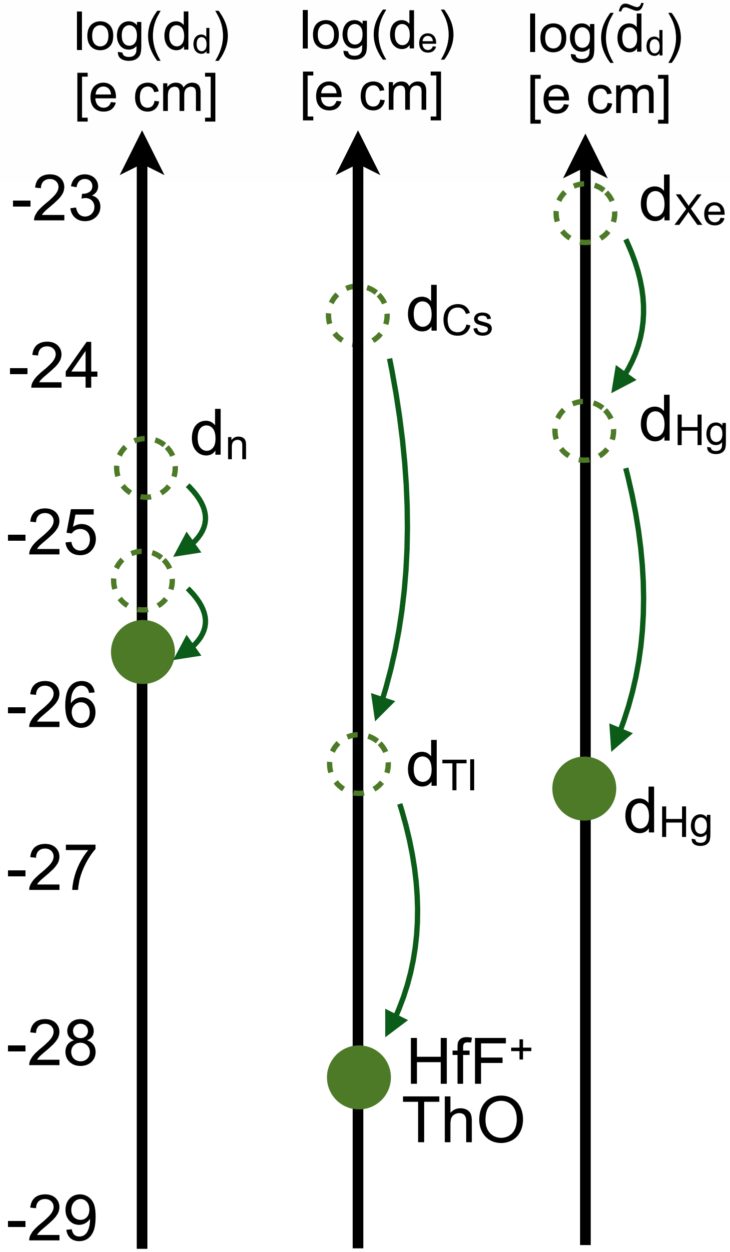
Comparison with direct mass limits on new (strongly-interacting) particles…



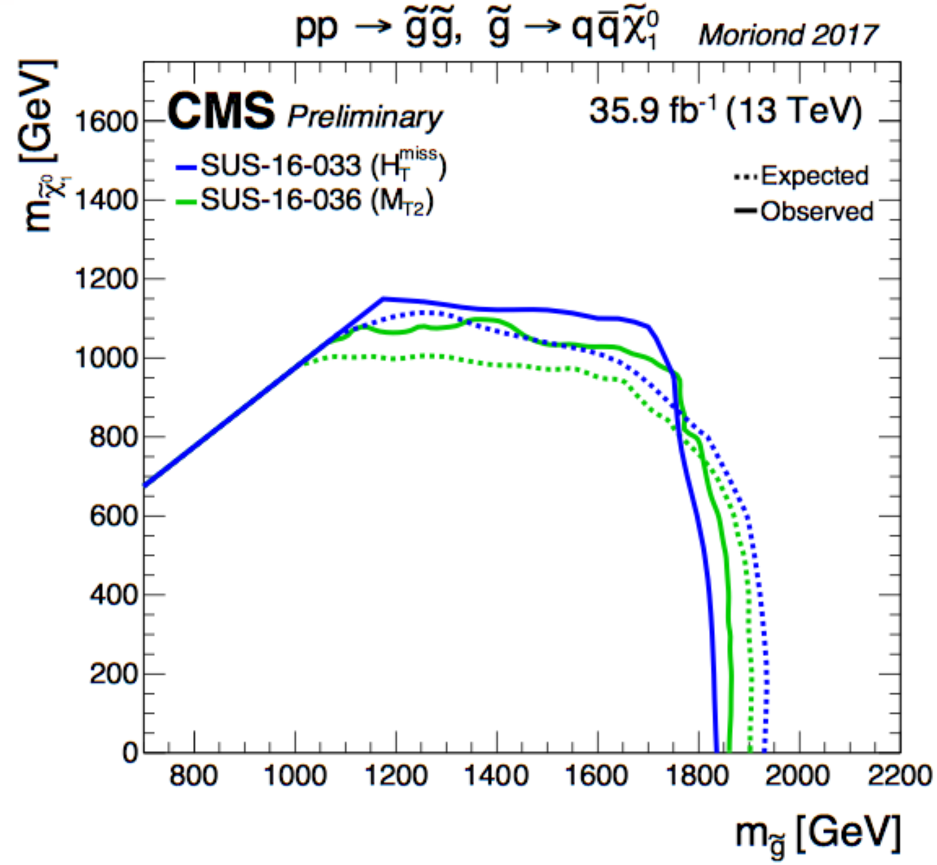
$$d \sim (\text{loop}) \times \frac{m_f}{\Lambda^2} \sim 10^{-25} e\text{cm} \left(\frac{1\,\text{TeV}}{\Lambda}\right)^2$$

(assuming O(1) CP phases)

Looking back 0 years…



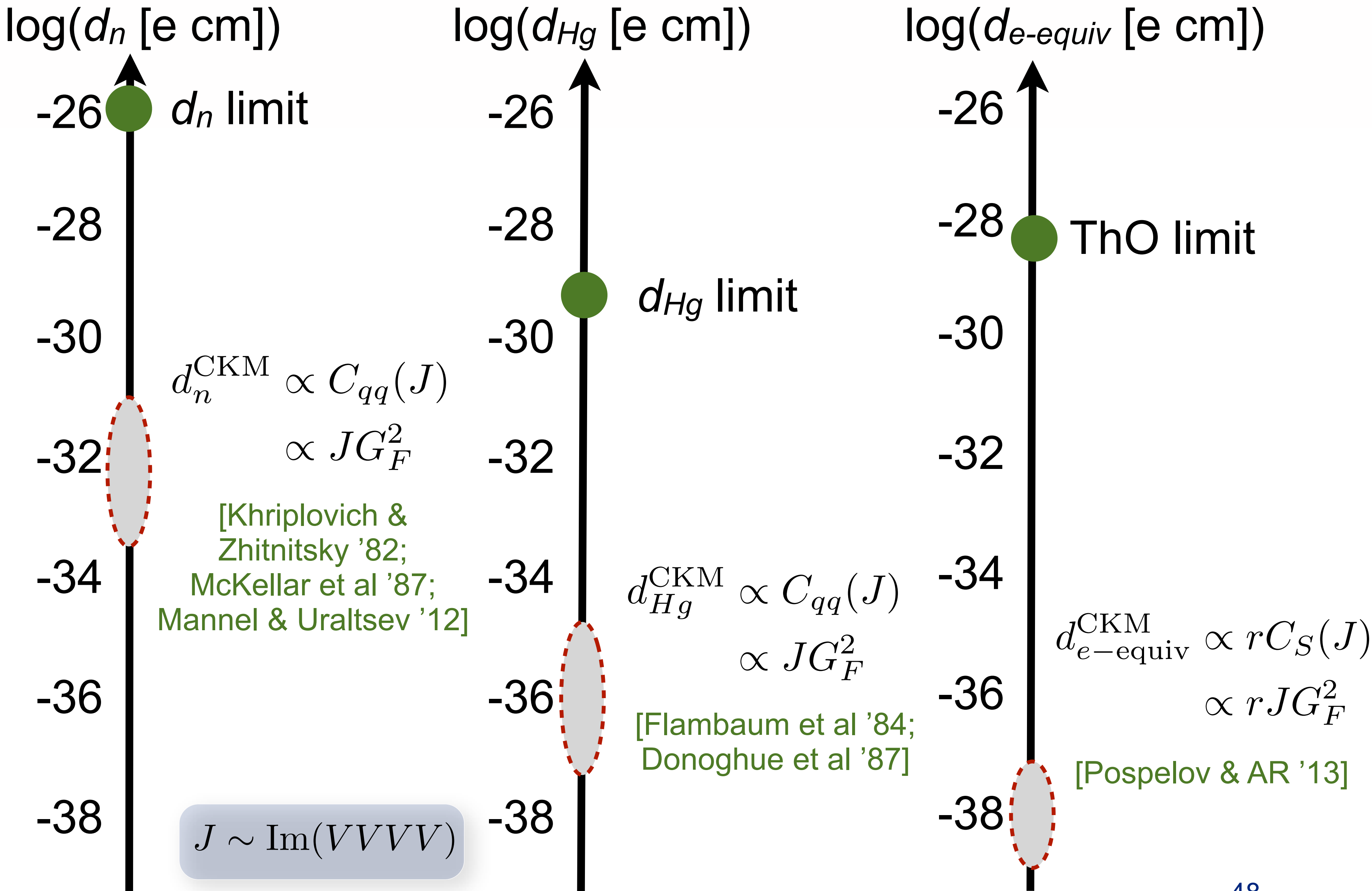
Comparison with direct mass limits on new (strongly-interacting) particles [Moriond '17]



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

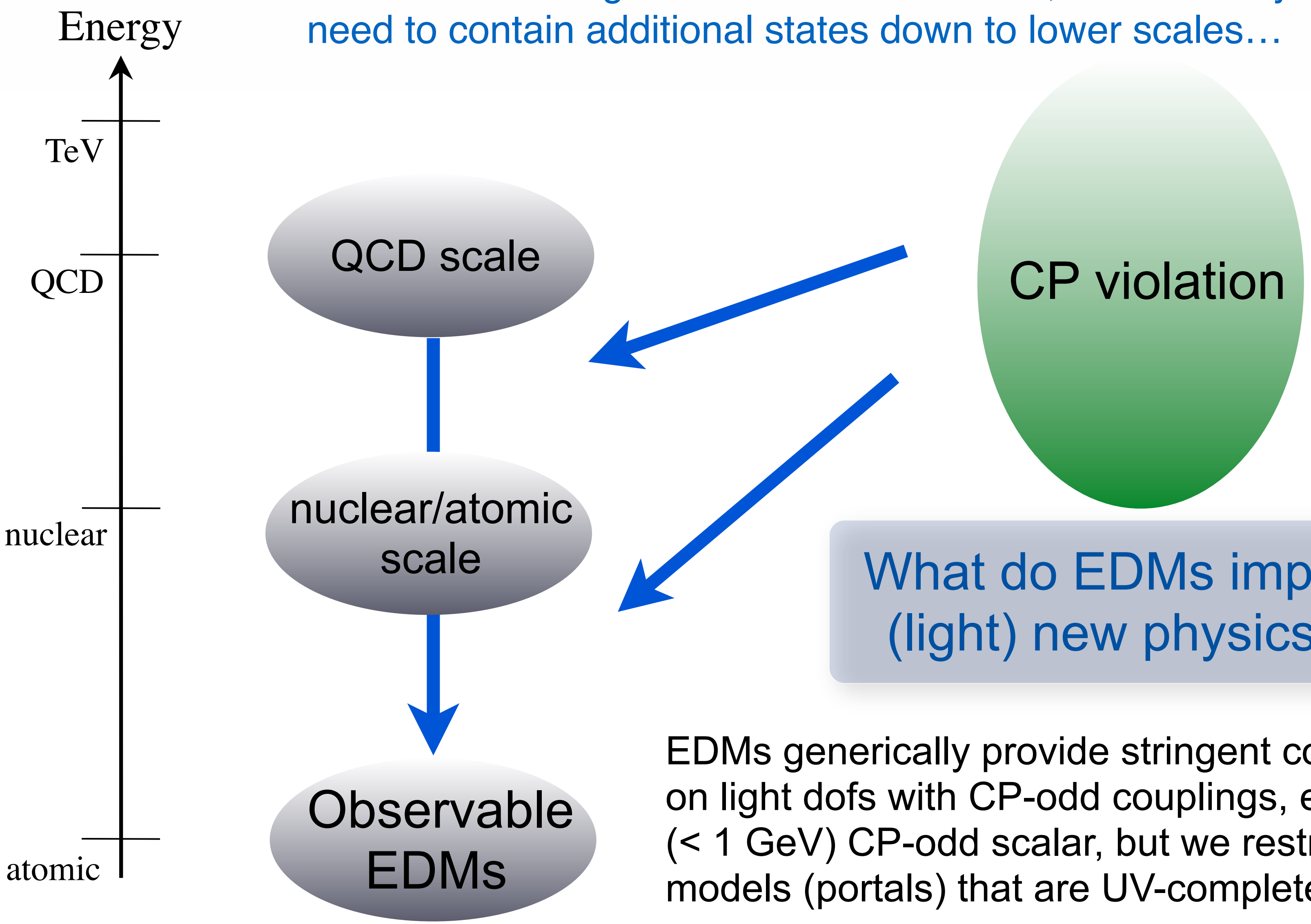
(assuming O(1) CP phases)

EDMs in the Standard Model (CKM phase)



CP-odd EFT

If CP violation originates in a hidden sector, the EFT may need to contain additional states down to lower scales…



What do EDMs imply for (light) new physics....?

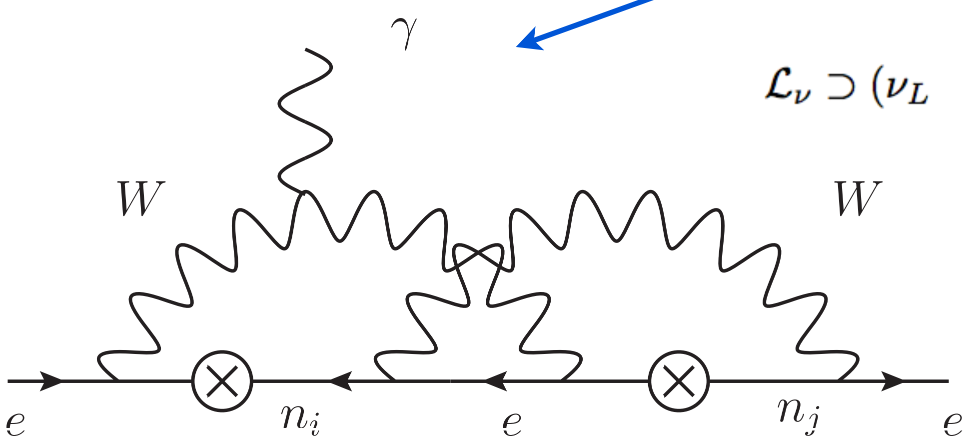
EDMs generically provide stringent constraints on light dofs with CP-odd couplings, e.g. a light (< 1 GeV) CP-odd scalar, but we restrict to models (portals) that are UV-complete...

EDM Sensitivity to light (UV-complete) hidden sectors

Standard Model ⟷ Hidden Sector

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

UV complete neutrino portal



$$\mathcal{L}_\nu \supset (\nu_L \quad N_R \quad N_S) \begin{pmatrix} 0 & m_{D_1} & m_{D_2} \\ m_{D_1} & M_R & \epsilon \\ m_{D_2} & \epsilon & M_S \end{pmatrix} \begin{pmatrix} \nu_L \\ N_R \\ N_S \end{pmatrix}$$

$$d_e \sim (3 \times 10^{-35} e{\rm cm}) \frac{m_{D_1}^2 m_{D_2}^2}{M^4} \frac{M_S^2 - M_R^2}{\rm GeV^2} \sin(2\eta)$$

➠ EDMs suppressed by constraints on light neutrino spectrum

$$d_e(\text{“}\theta_{\rm mixing}\text{”}) \lesssim 10^{-33} e \cdot cm$$

[Ng & Ng ’96; Archambault et al ’04; Le Dall, Pospelov & AR ’15]

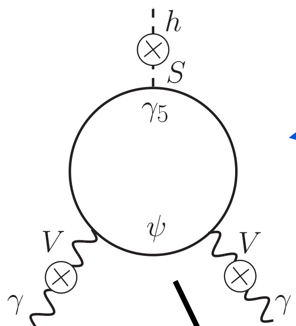
(CP-odd source relevant in the context of leptogenesis)

EDM Sensitivity to light (UV-complete) hidden sectors

Standard Model ⟷ Hidden Sector

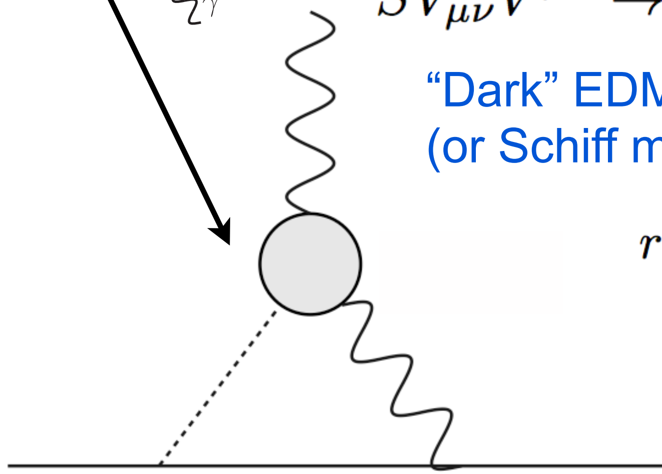
$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm portals}(\underbrace{\mathcal{O}_3, \mathcal{O}_4}) + \mathcal{L}_{\rm hid}$$

UV complete Higgs and vector portals



$$S V_{\mu\nu} \tilde{V}^{\mu\nu} \to \frac{i}{2} \bar{\psi}_e \sigma^{\mu\nu} \gamma_5 \psi_e V_{\mu\nu} \to \frac{i}{2} \bar{\psi}_e \sigma^{\mu\nu} \gamma_5 \psi_e \frac{\Box F_{\mu\nu}}{m_V^2}$$

"Dark" EDM generates an "EDM radius" operator (or Schiff moment)



$$r_{d_f}^2 = -\frac{|e|\alpha' \tilde{Y}_S m_f}{16\pi^3 v m_\psi m_V^2} \times \kappa^2 \theta \ln(m_\psi^2/m_S^2)$$

$$d_e \sim (Z\alpha m_e)^2 r_{d_e}^2$$

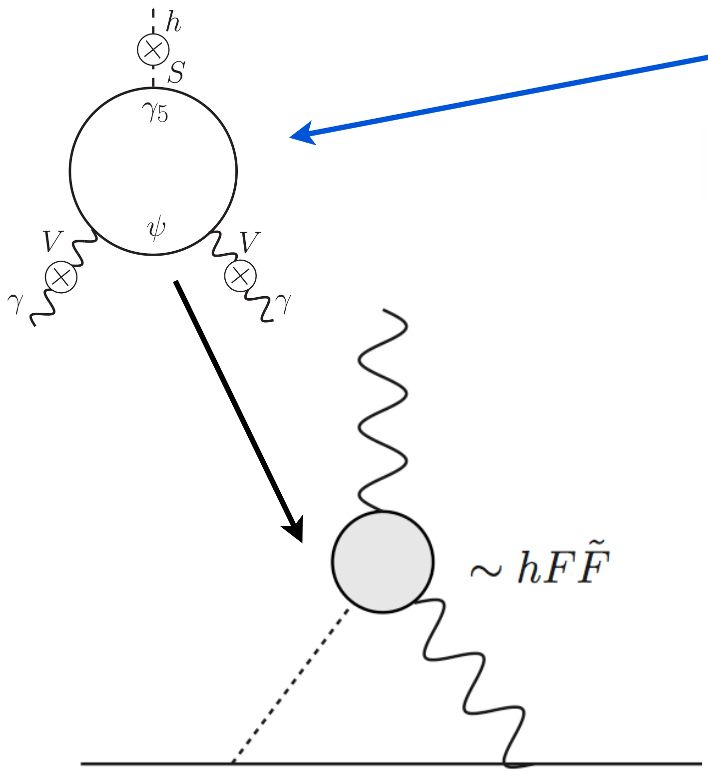
[Le Dall, Pospelov & AR '15]

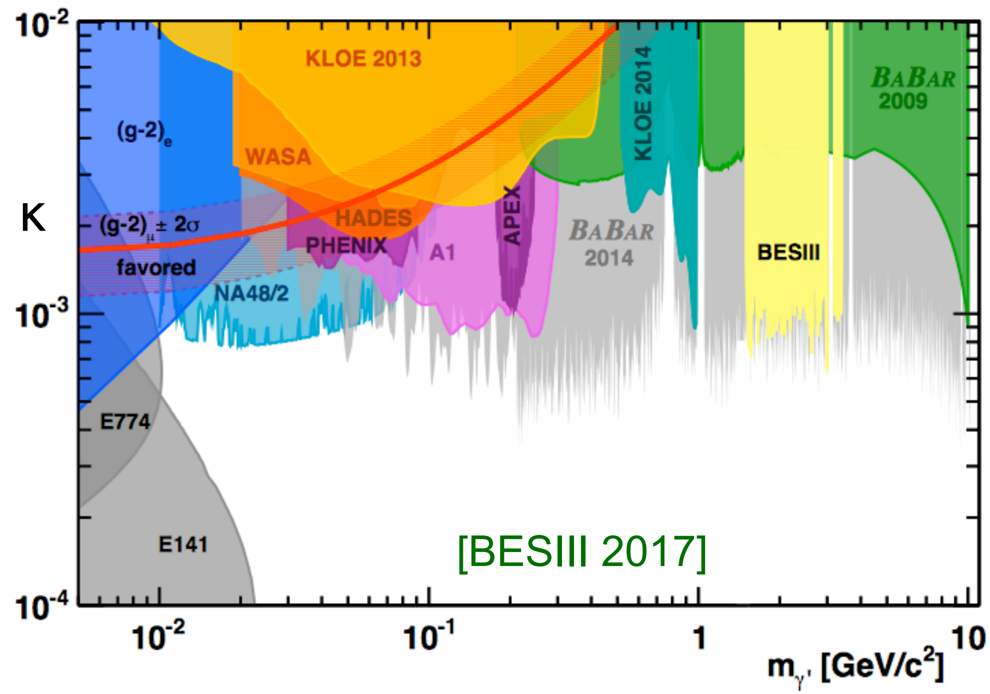
(CP-odd source of this kind recently applied to EWBG [Cline et al '17])

EDM Sensitivity to light (UV-complete) hidden sectors

Standard Model ⟷ Hidden Sector

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





$$d_e(\text{“}\theta_{\rm mixing}\text{”}) \lesssim 10^{-32} e \cdot cm$$

[Le Dall, Pospelov & AR ’15]

m_V [GeV]

➟ EDM suppressed by limit on 1-loop (“dark photon”) correction to $(g-2)_e$