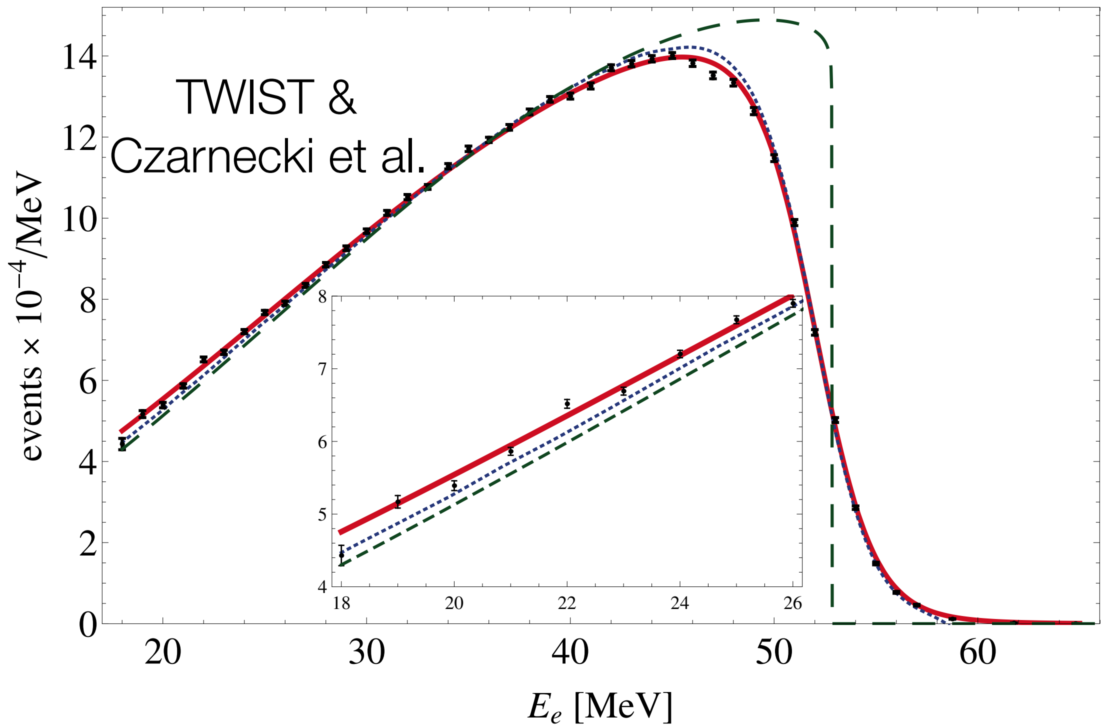
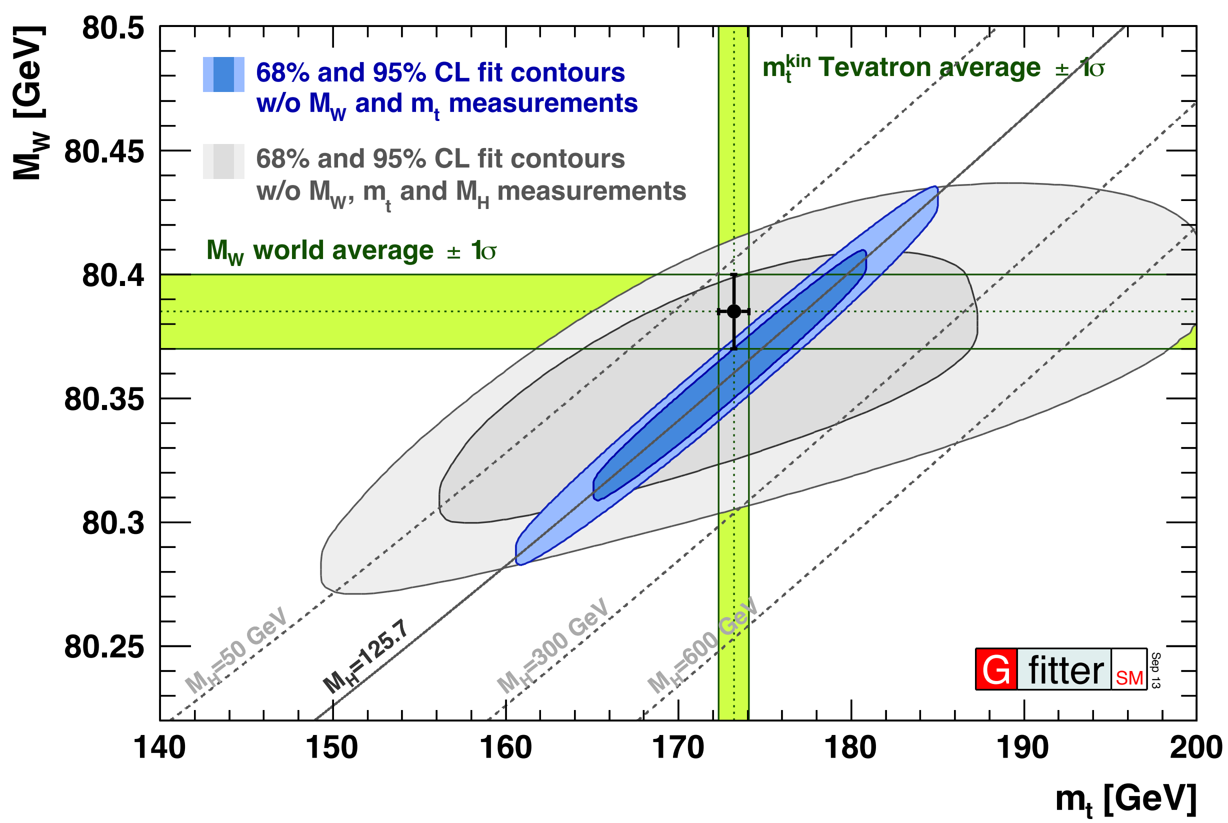
Theory of Dark Photons and Dark Sectors

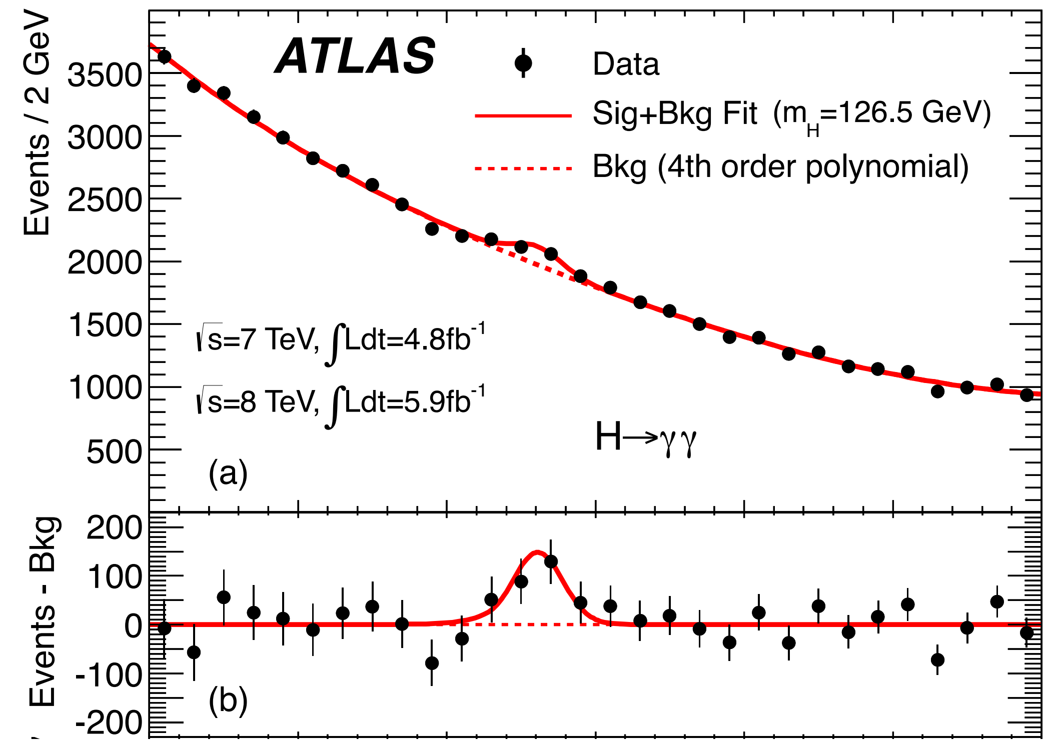
David McKeen
TRIUMF

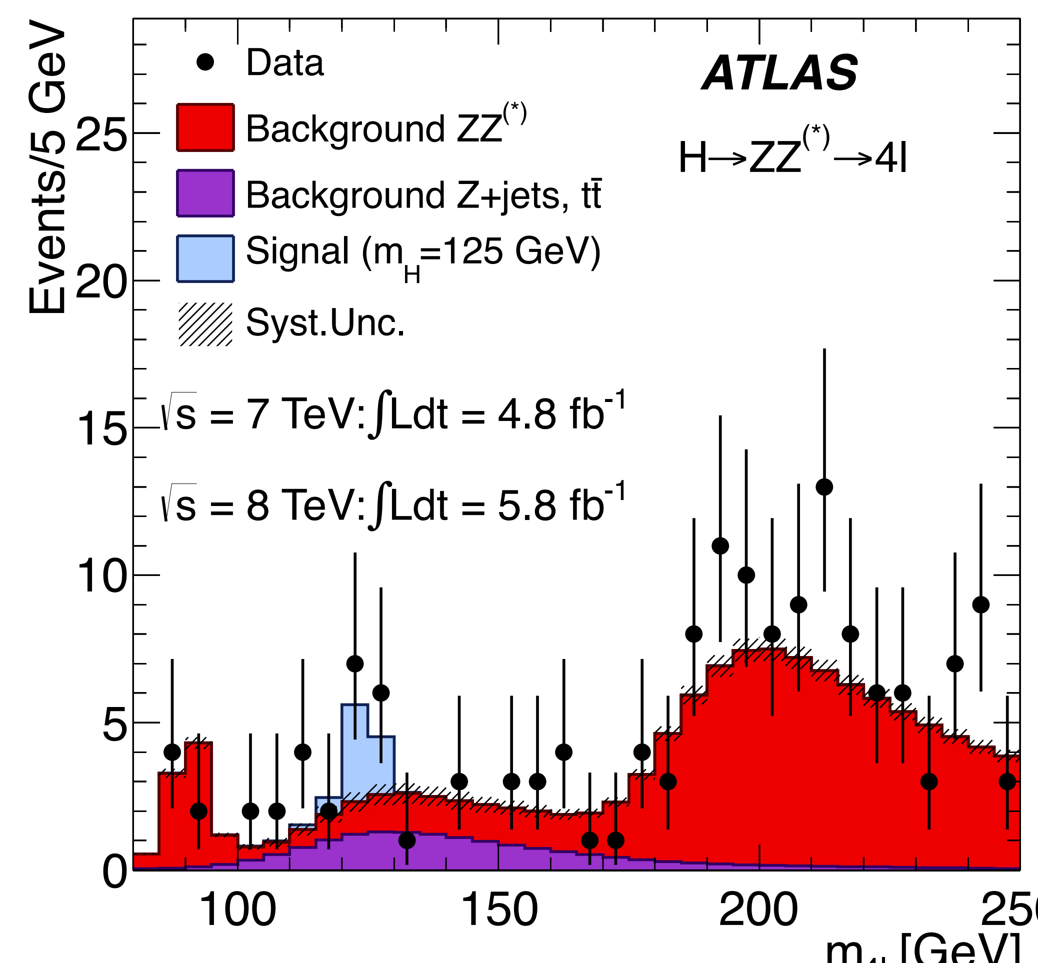
ARIEL Science Workshop
July 18, 2018

The Standard Model works!

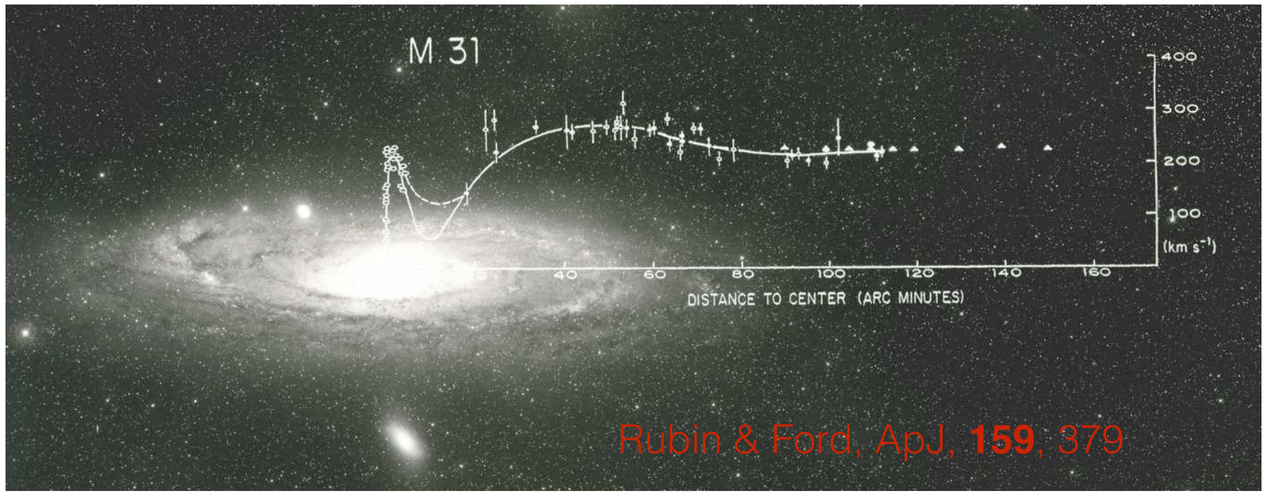


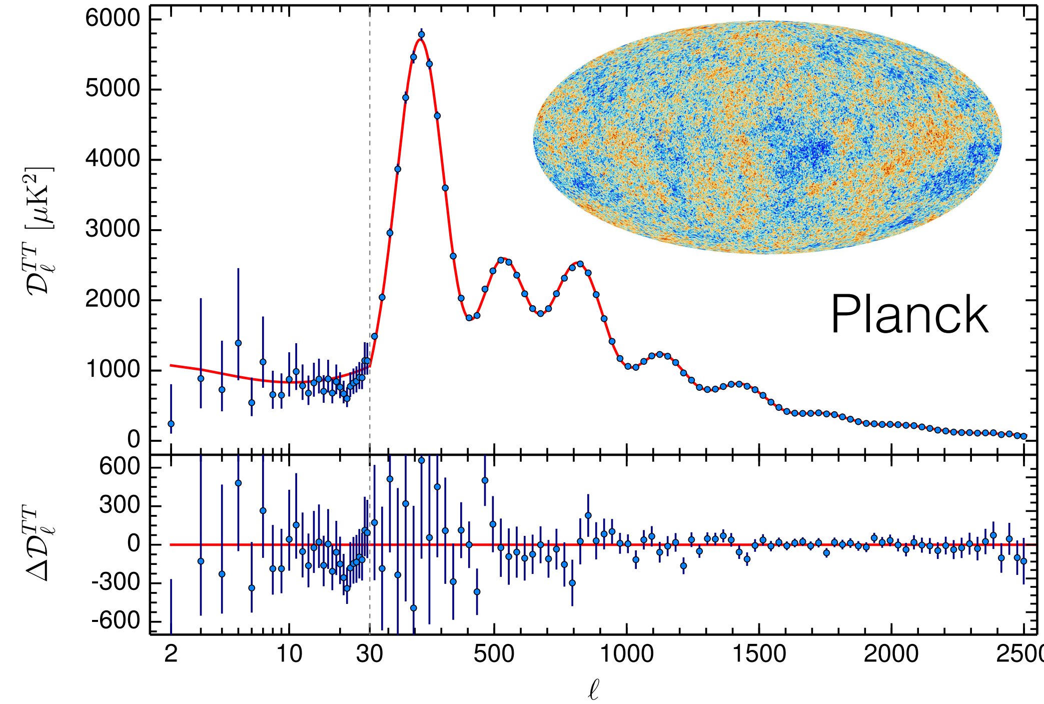


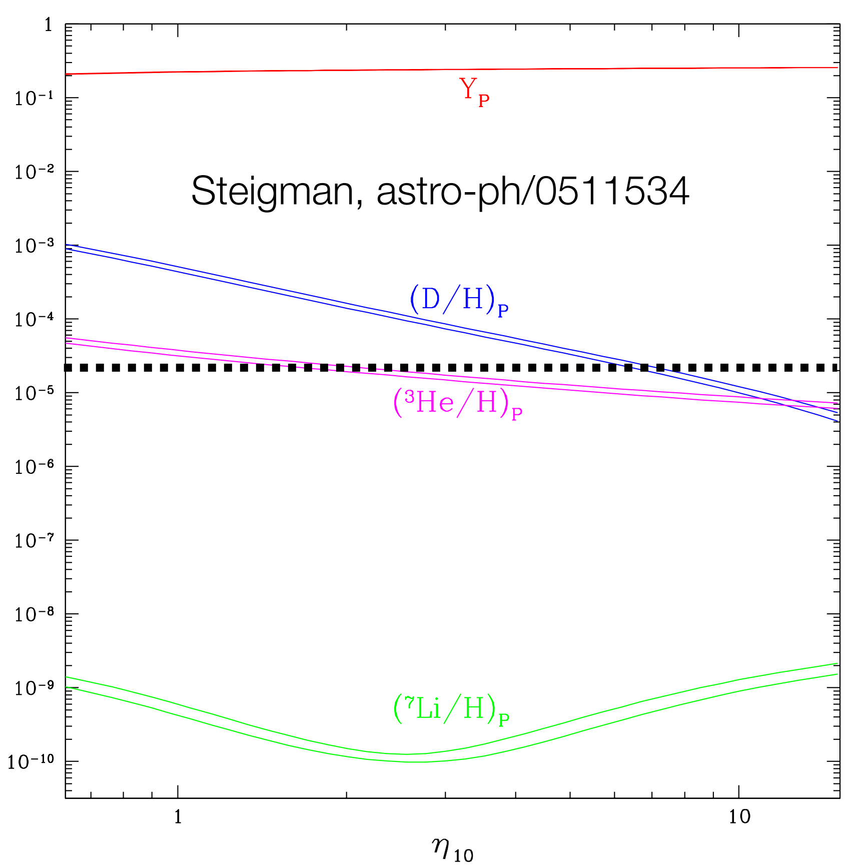


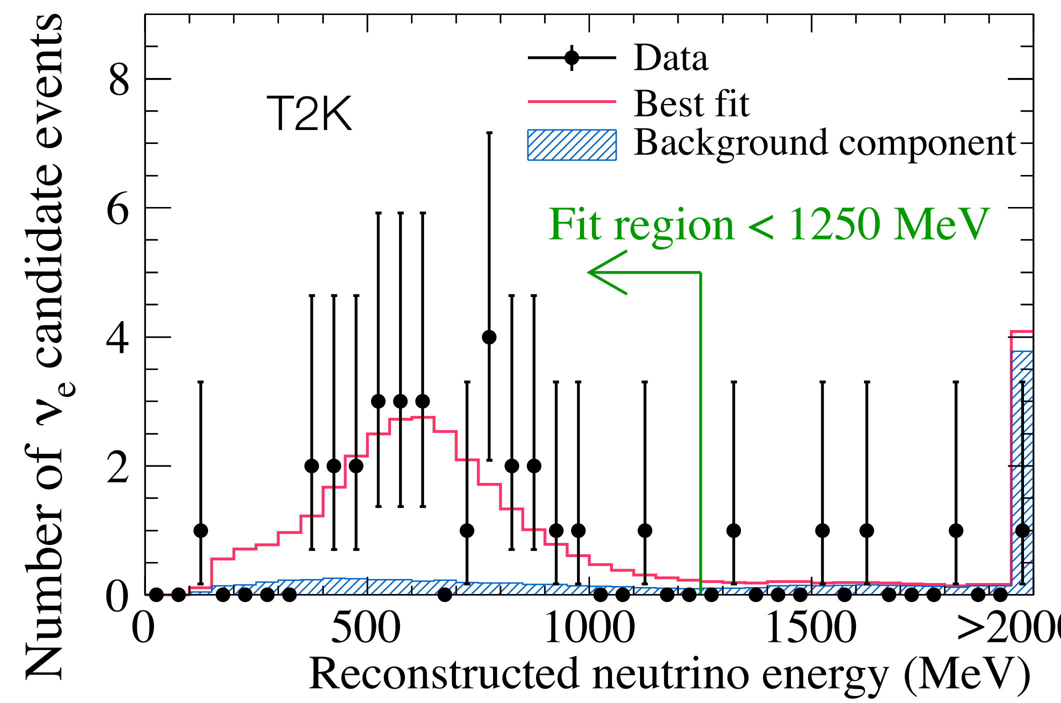


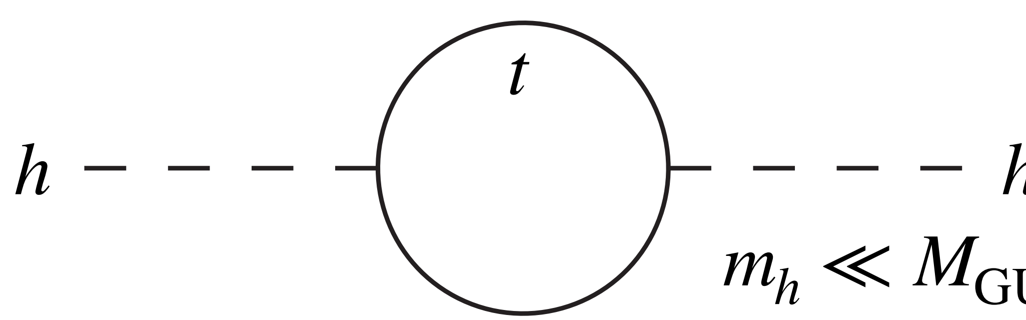
But there are issues…





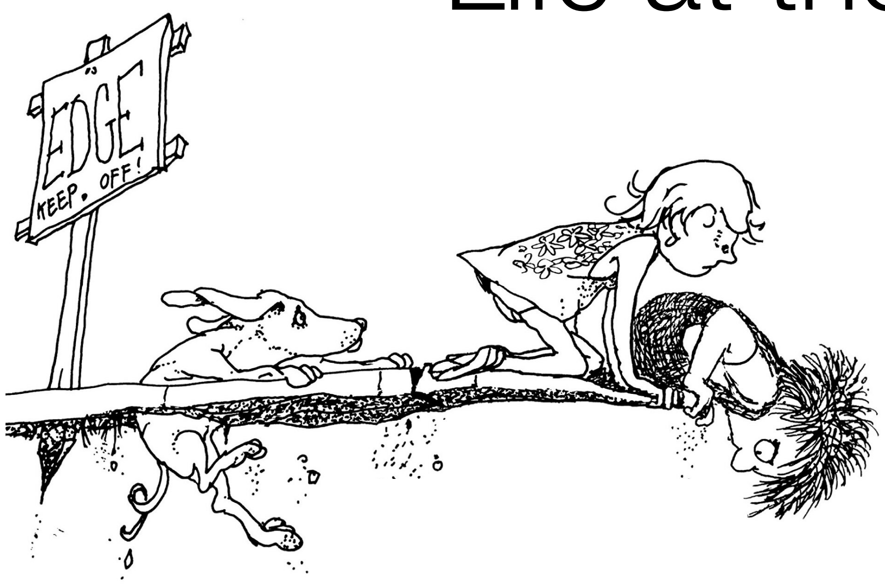




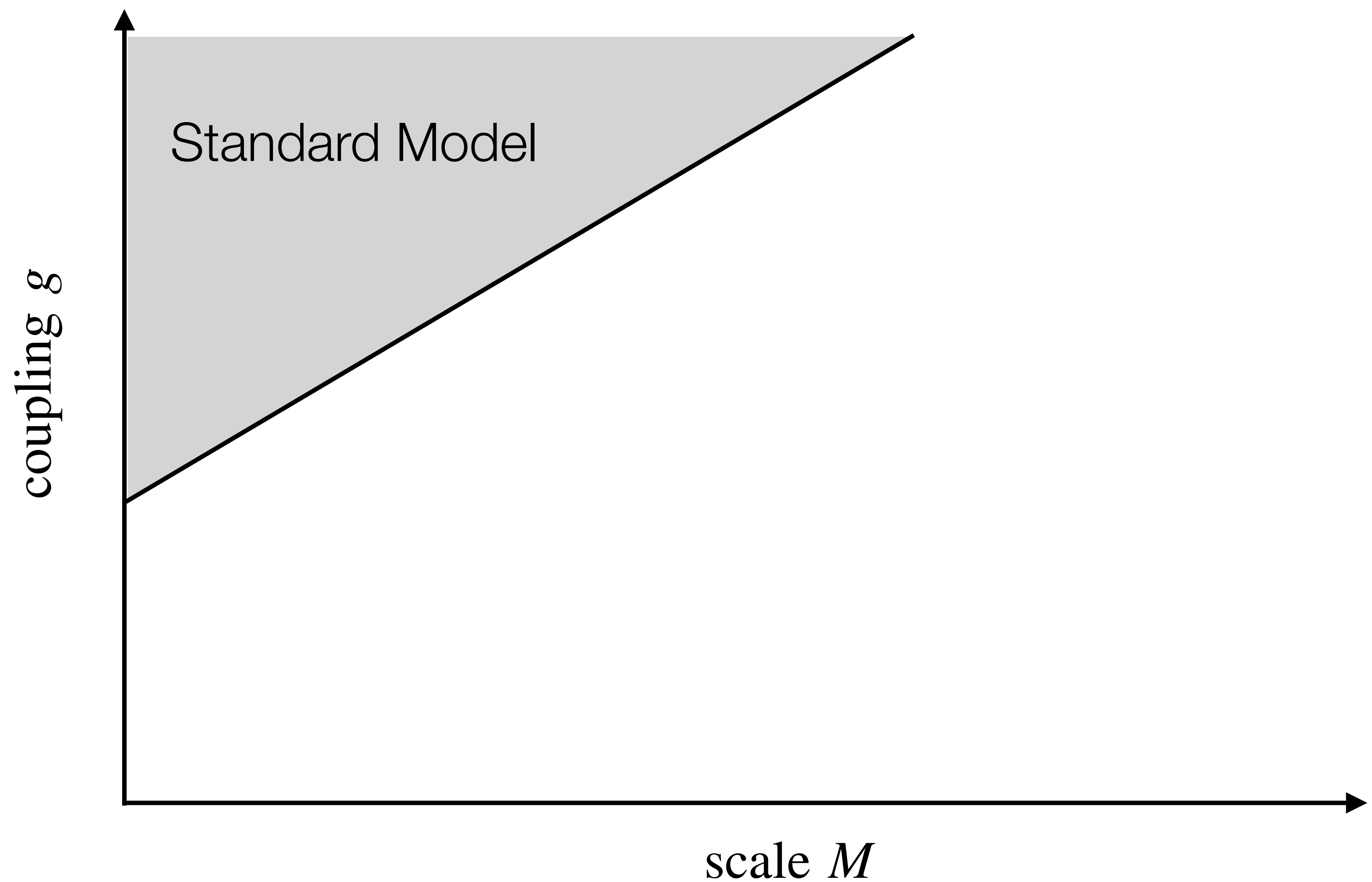


$$m_h \ll M_{\rm GUT}, M_{\rm Planck}, \ldots$$

Life at the frontier of the Standard Model



Can generally parametrize new effects in terms of coupling and energy/distance^{-1} scale



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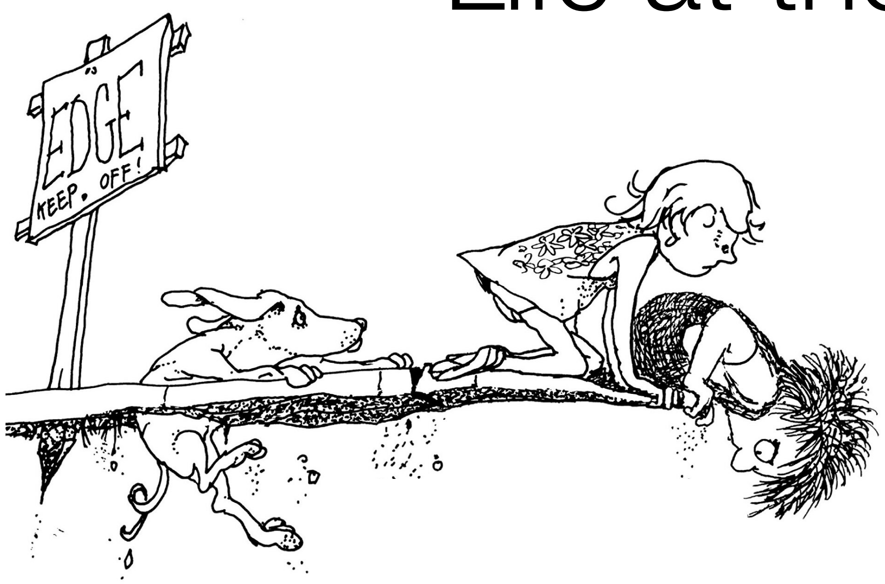

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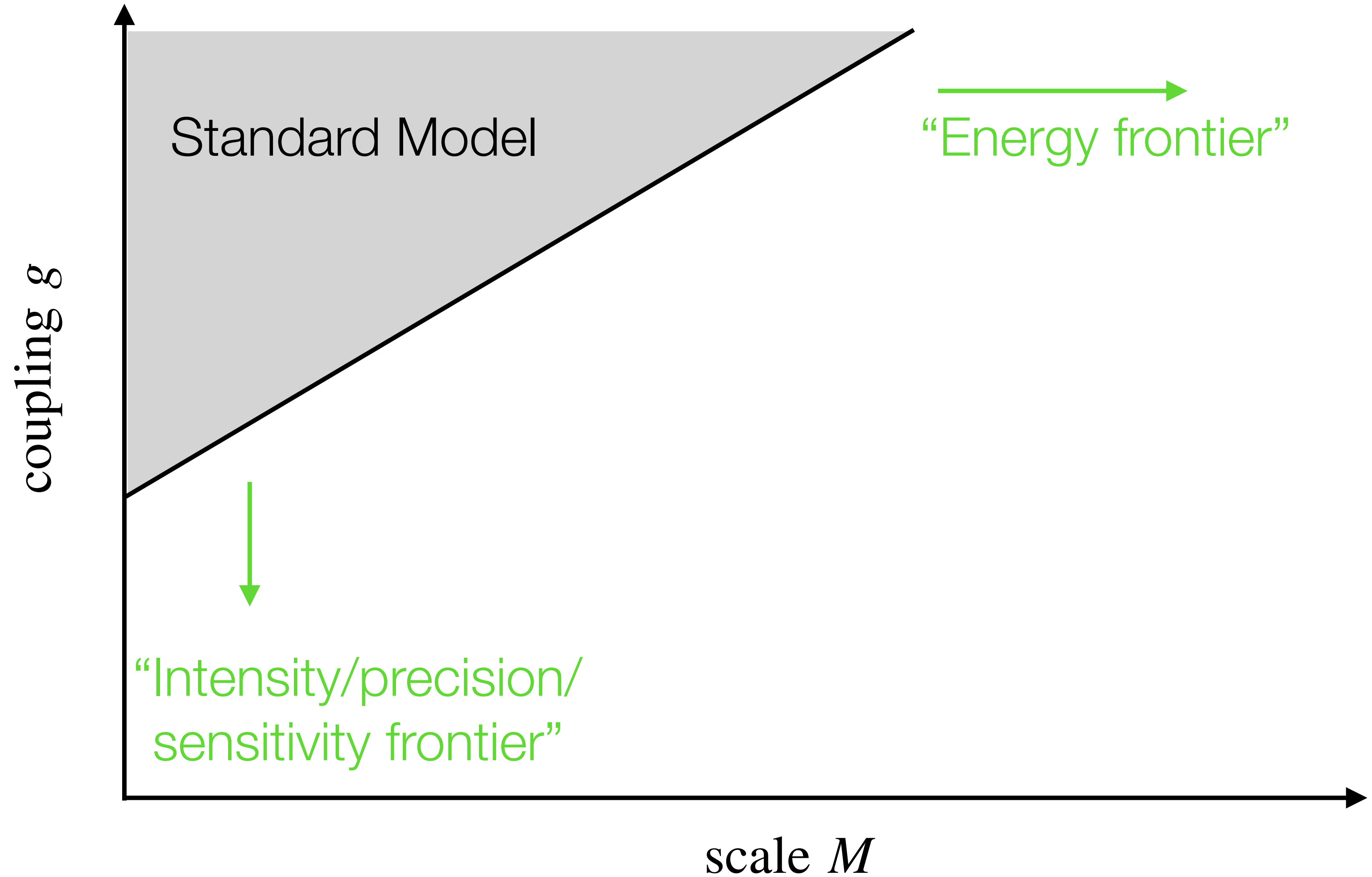

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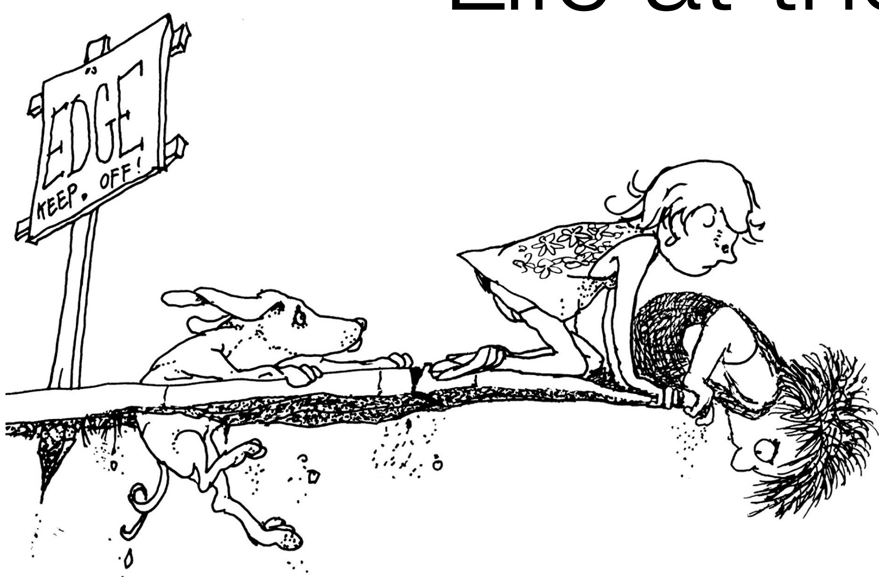

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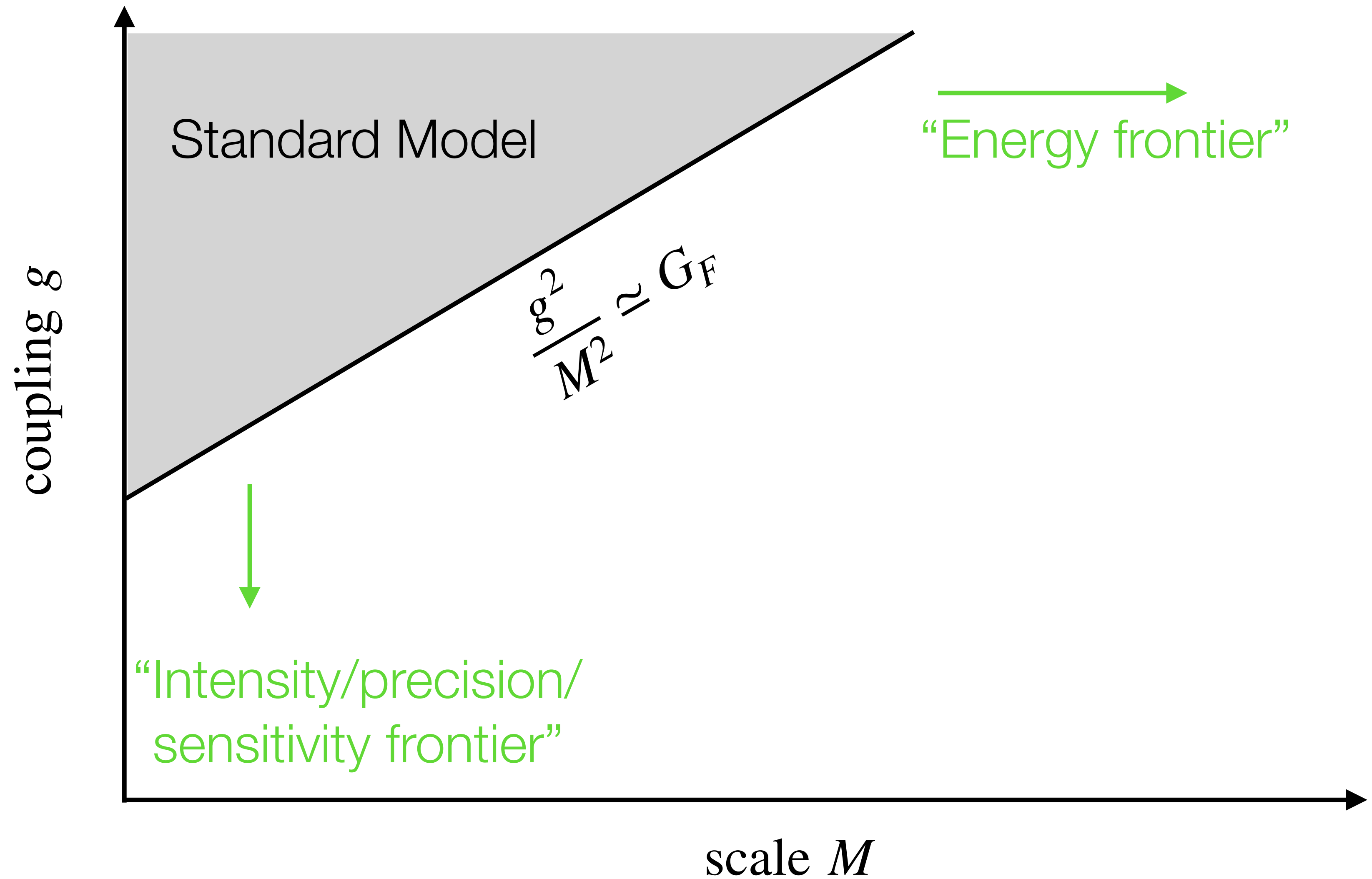

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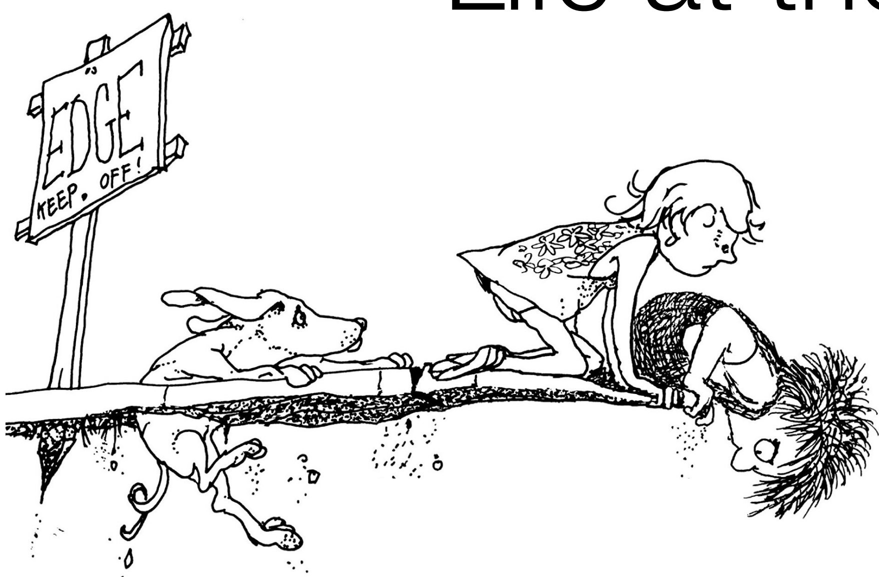

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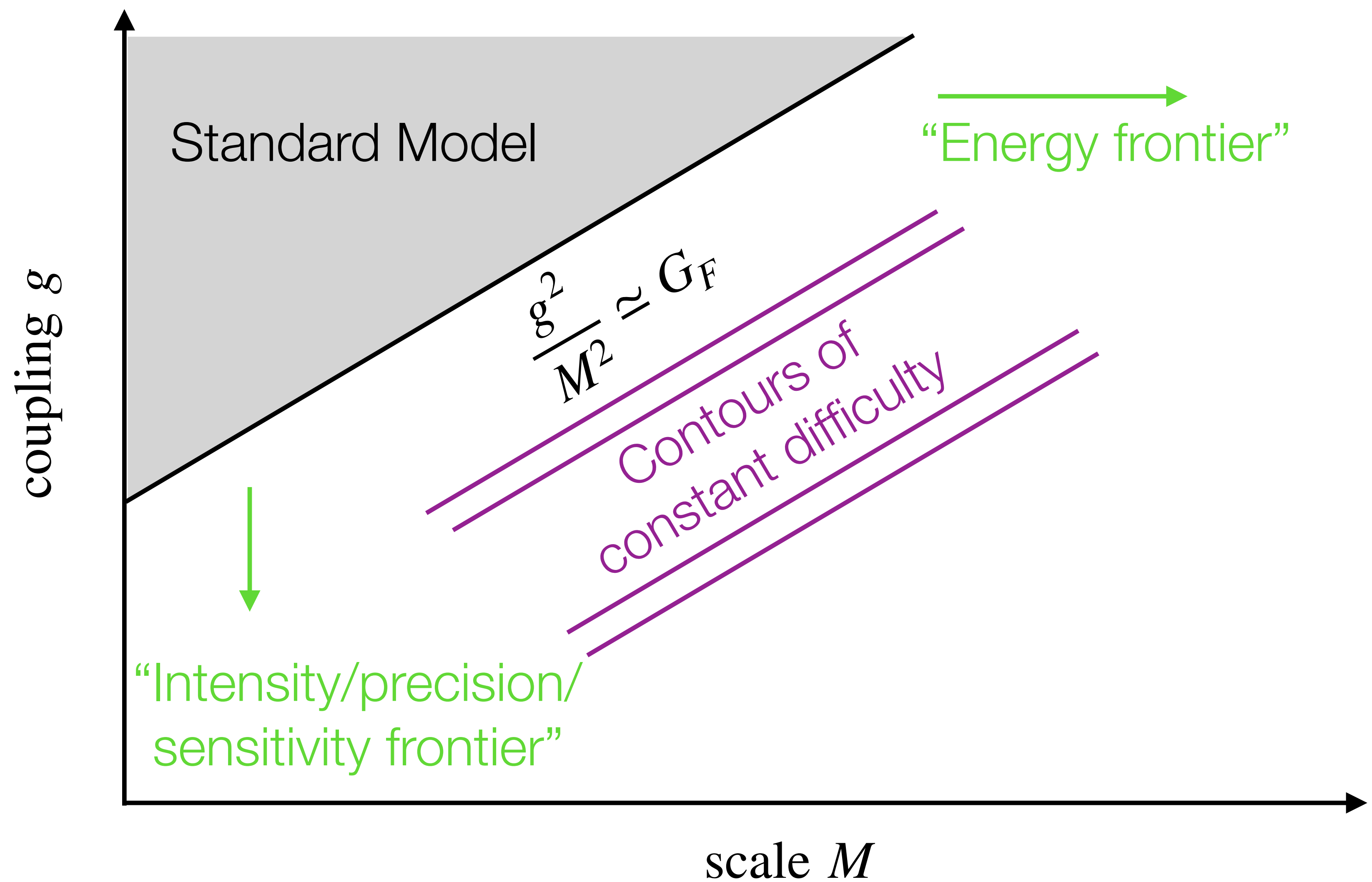

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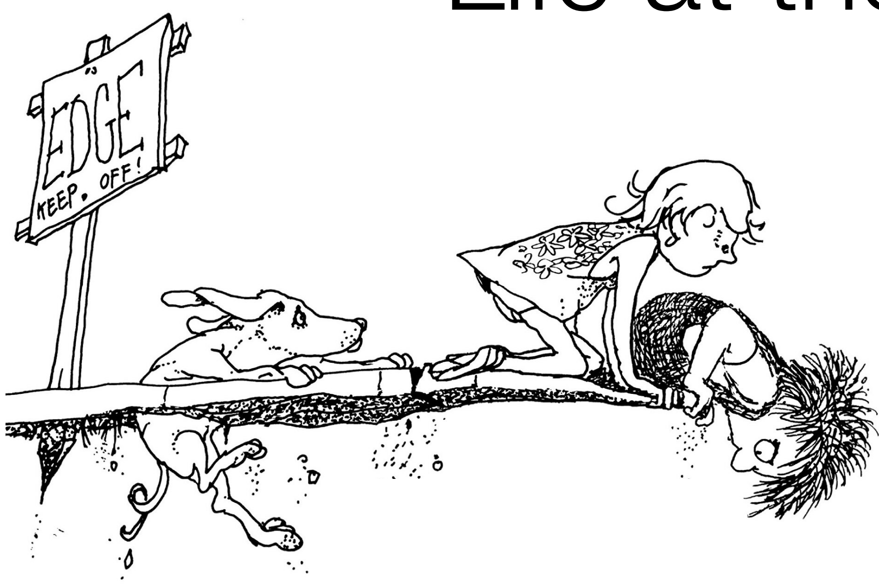

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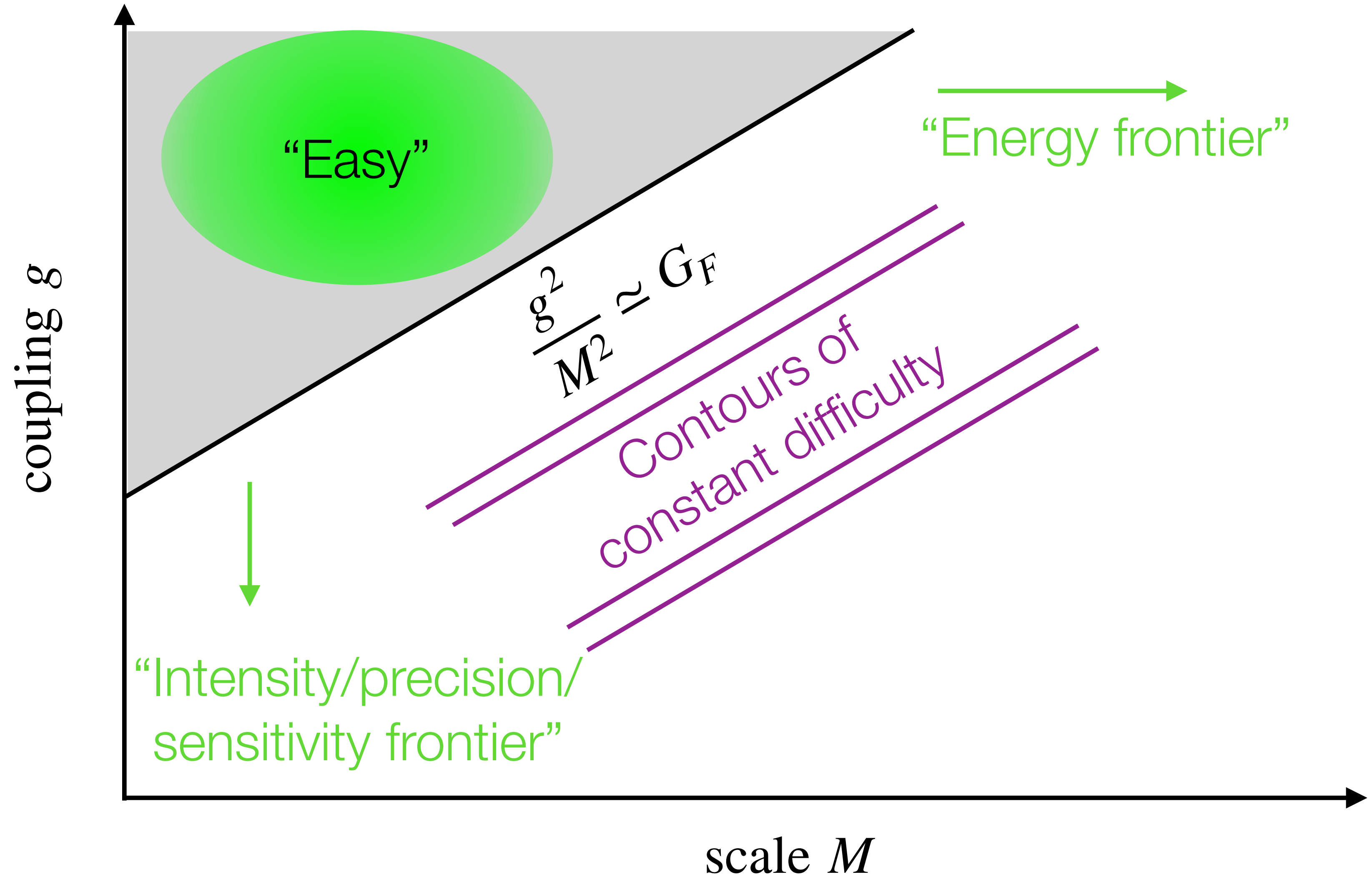

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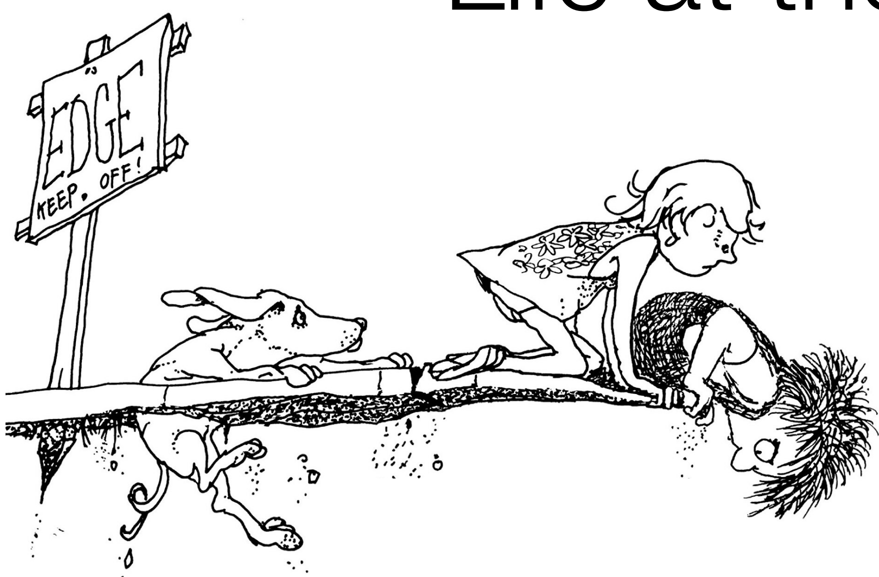
Life at the frontier of the Standard Model



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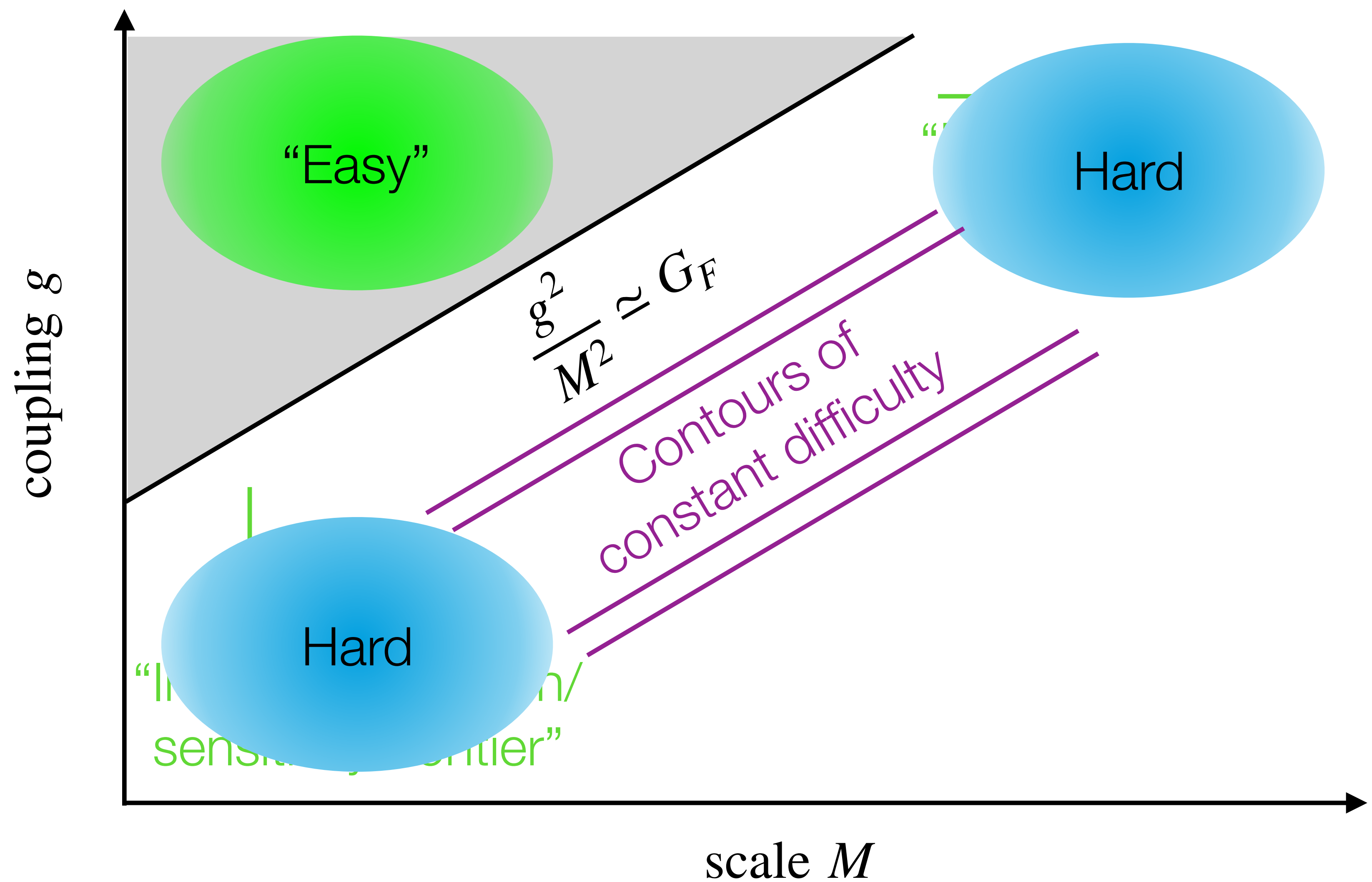

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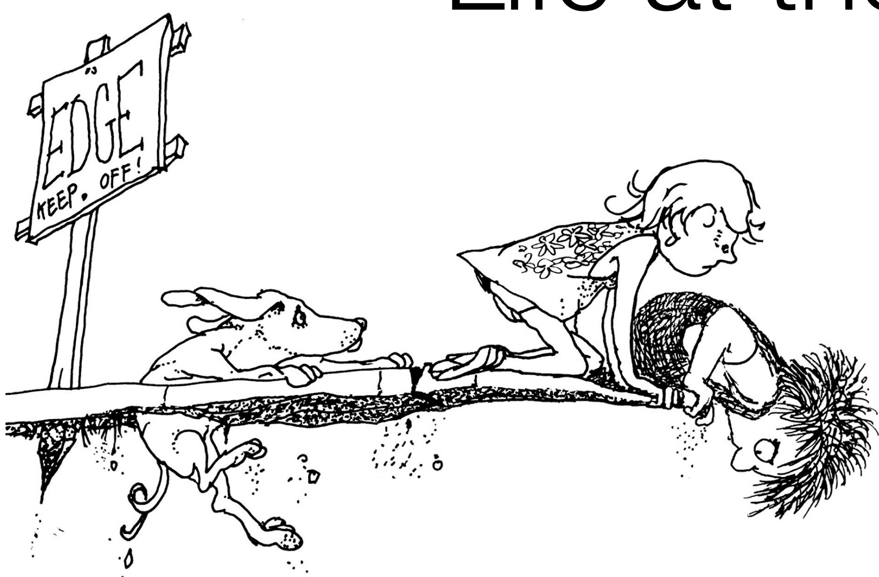

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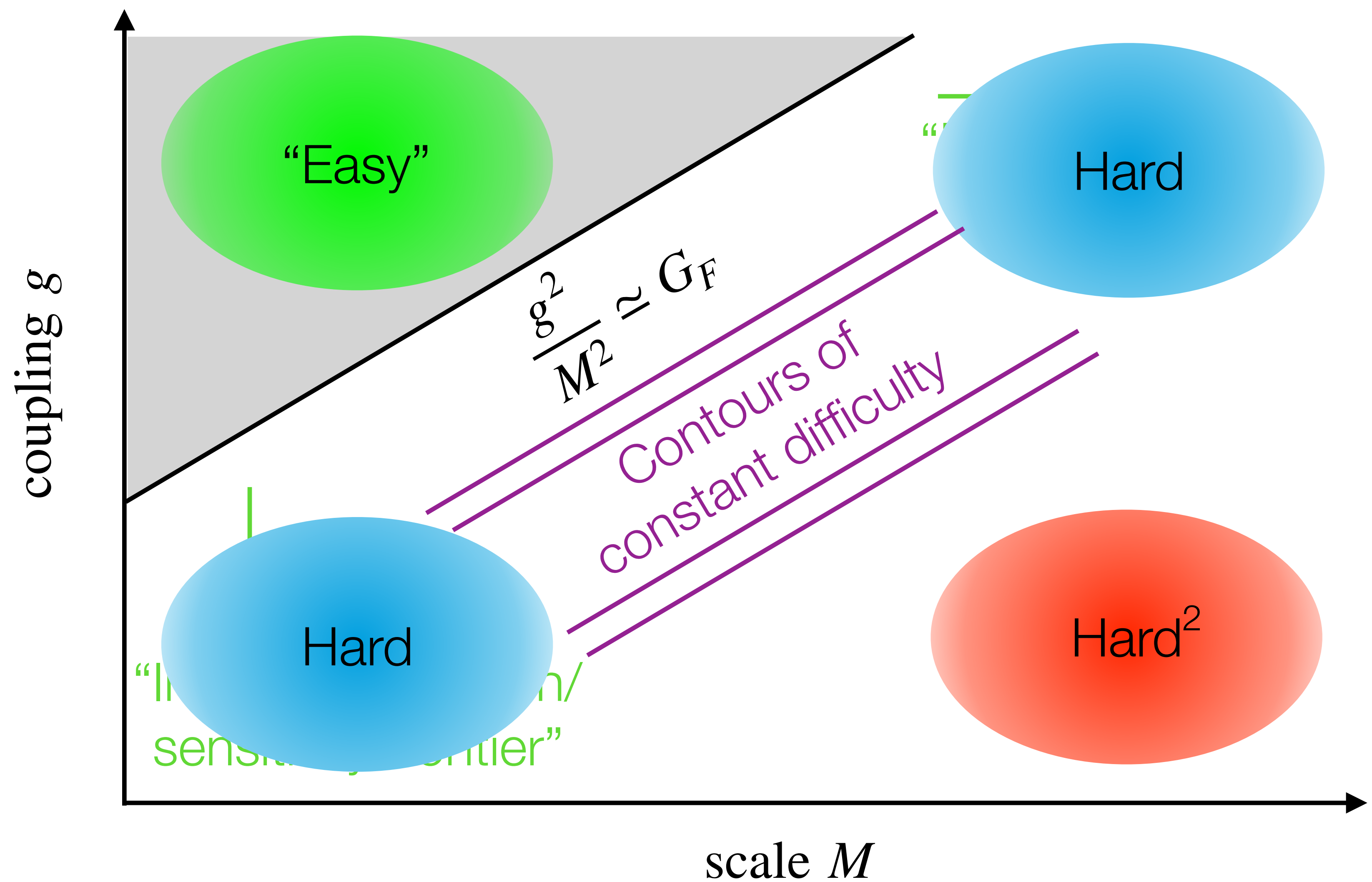

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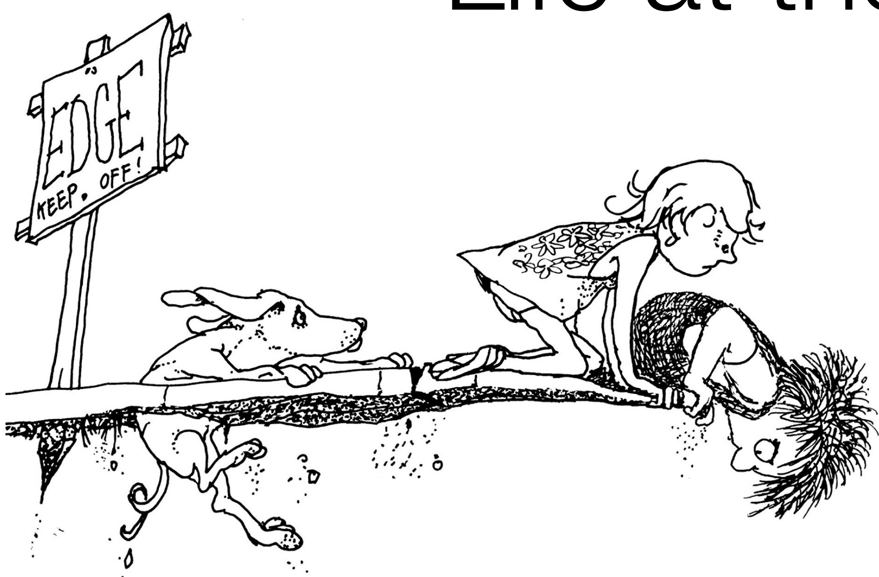

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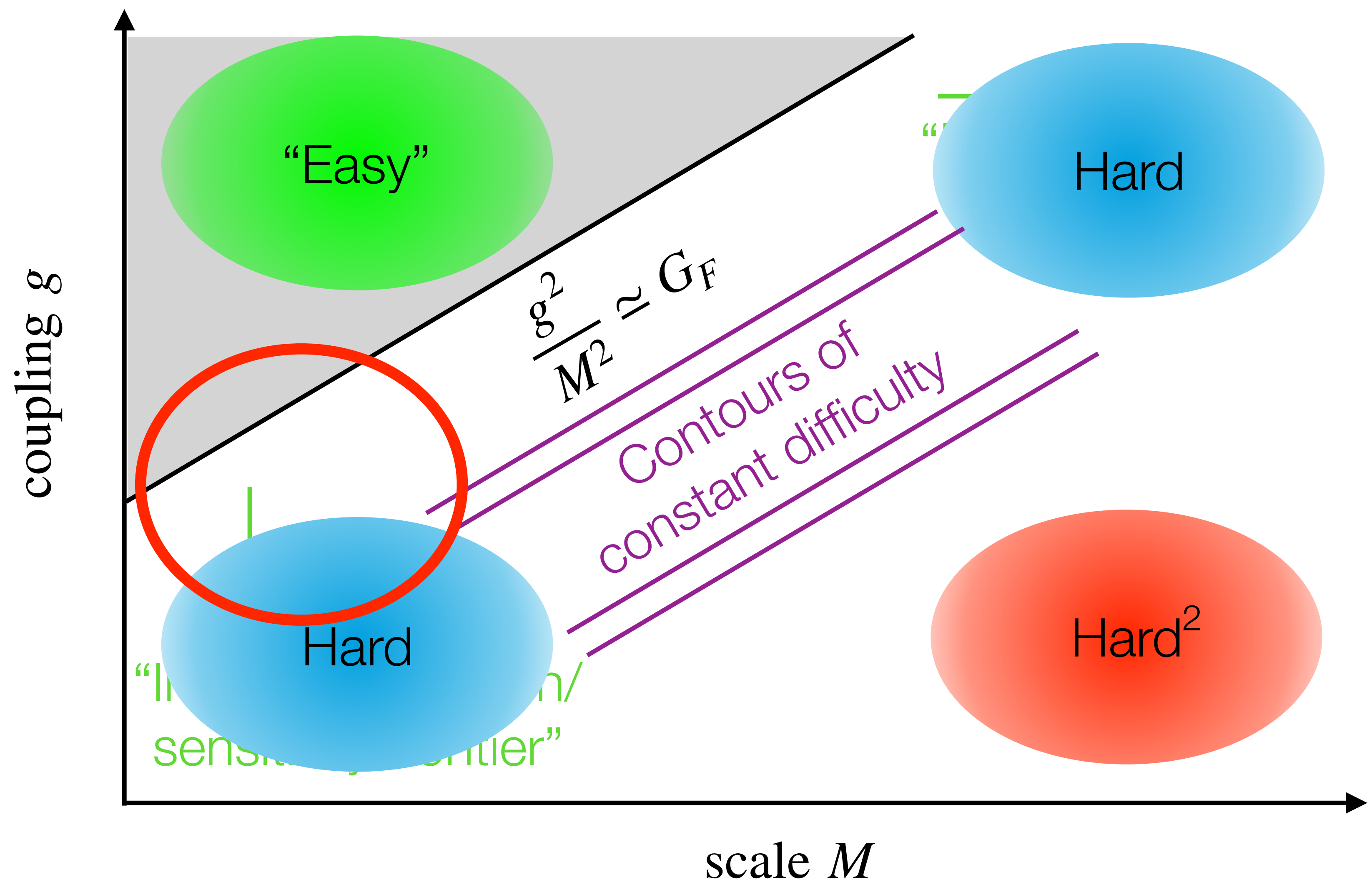
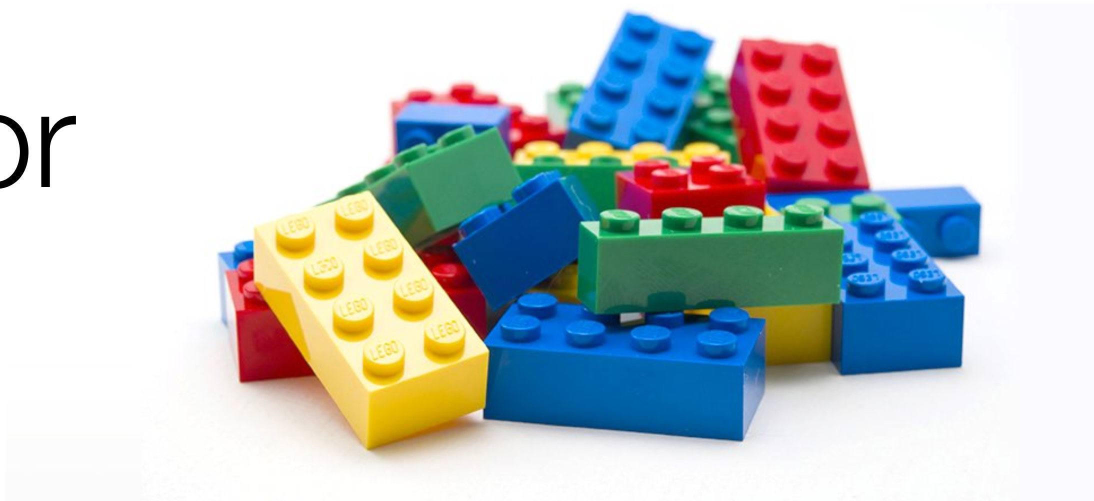


How do you couple light stuff "at the frontier" without disturbing the success of the SM?

Building a Dark Sector

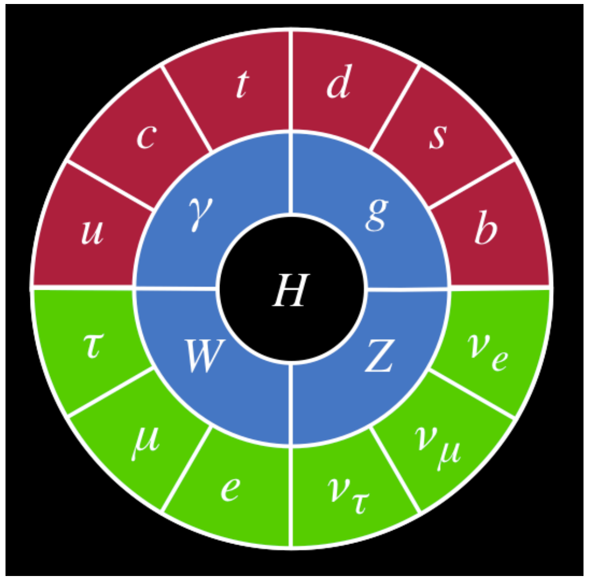


Standard Model gauge symmetries/ forces & particle content:

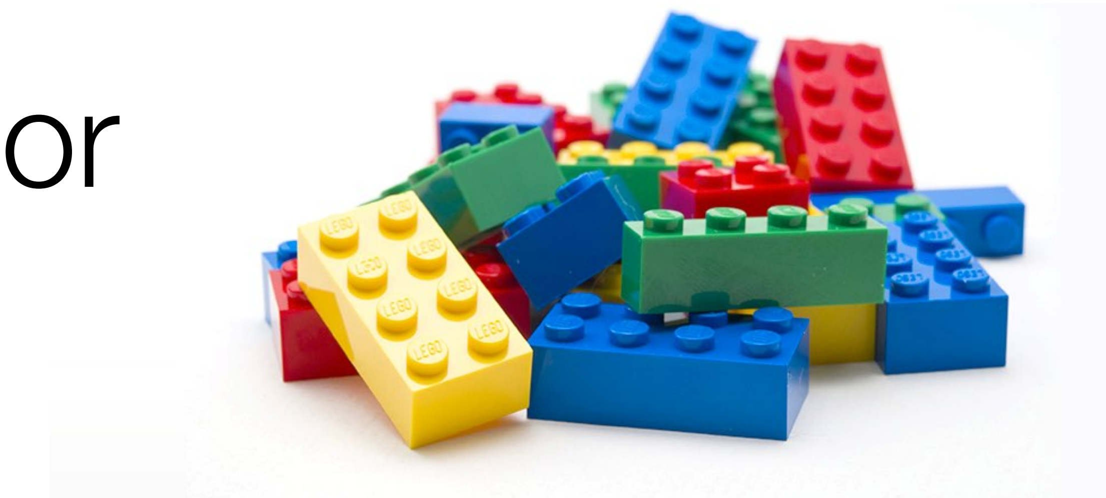
$$SU(3)_c \times SU(2)_L \times U(1)_Y \xrightarrow{\text{EWSB}} SU(3)_c \times U(1)_{\text{em}}$$
$$G^a_\mu,\ W^b_\mu,\ B_\mu \to G^a_\mu,\ A_\mu$$

$$\left.\begin{array}{l} L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}, e_R \\[2em] Q = \begin{pmatrix} u_L \\ d_L \end{pmatrix}, u_R, d_R \end{array}\right\} \times 3$$

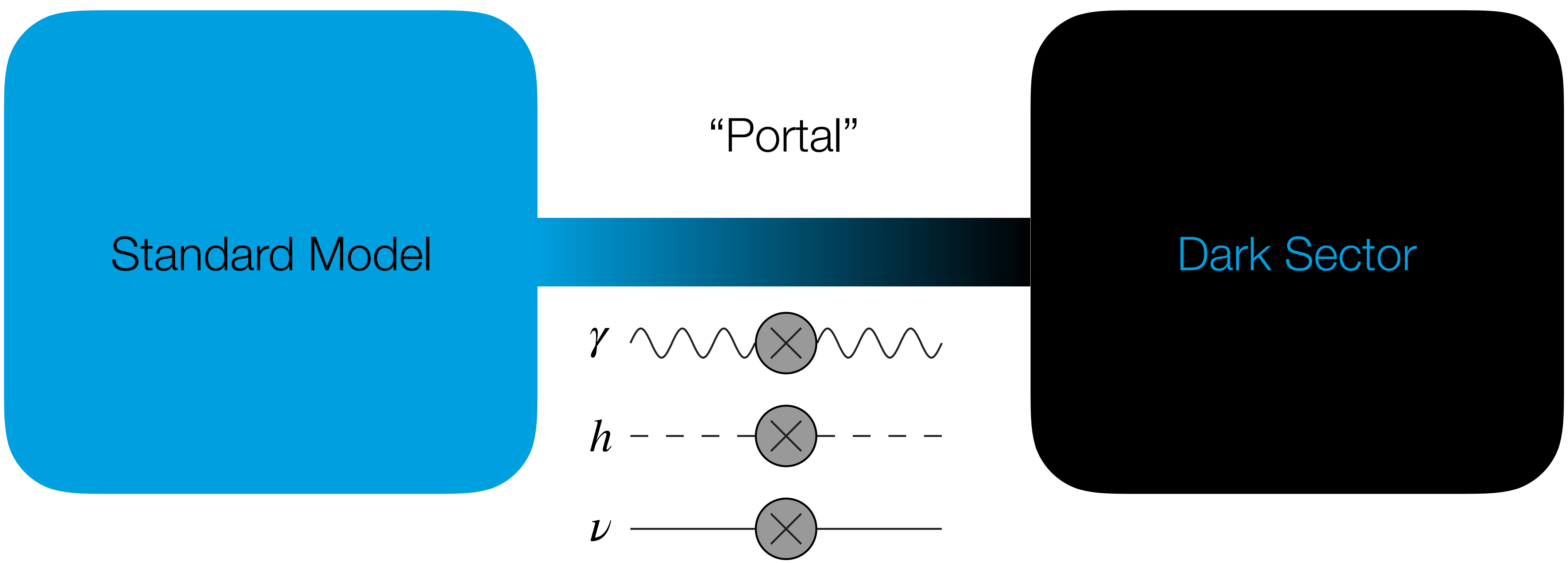
$$H = \begin{pmatrix} \rho^+ \\ v + h + \rho^0 \end{pmatrix}$$



Building a Dark Sector



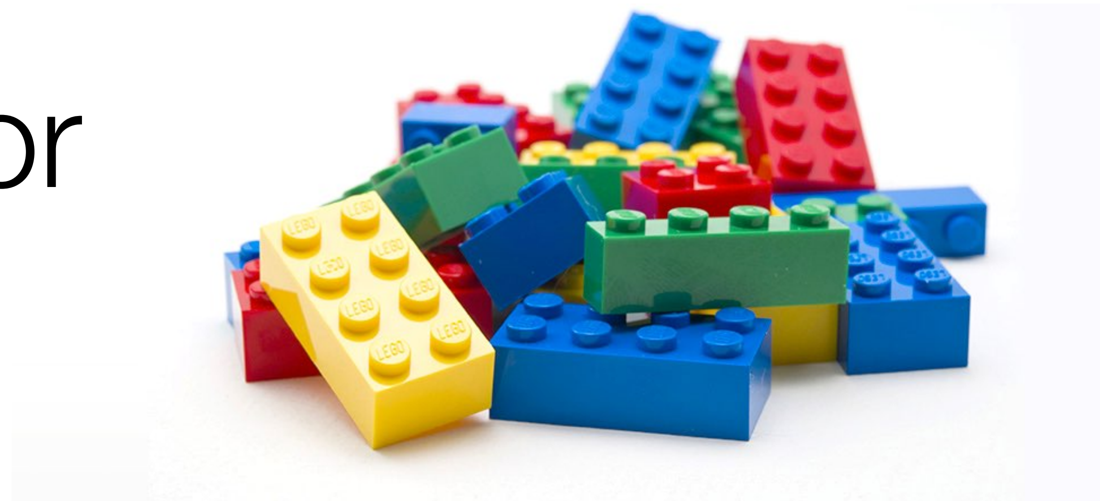
A dark sector is uncharged under SM forces: strong, weak, E&M



But can be connected via a "portal"—mixing with SM particles

- photon—coupling proportional to SM particle electric charge
- Higgs boson—coupling proportional to SM particle mass
- Neutrinos—couplings only via weak interactions

Building a Dark Sector



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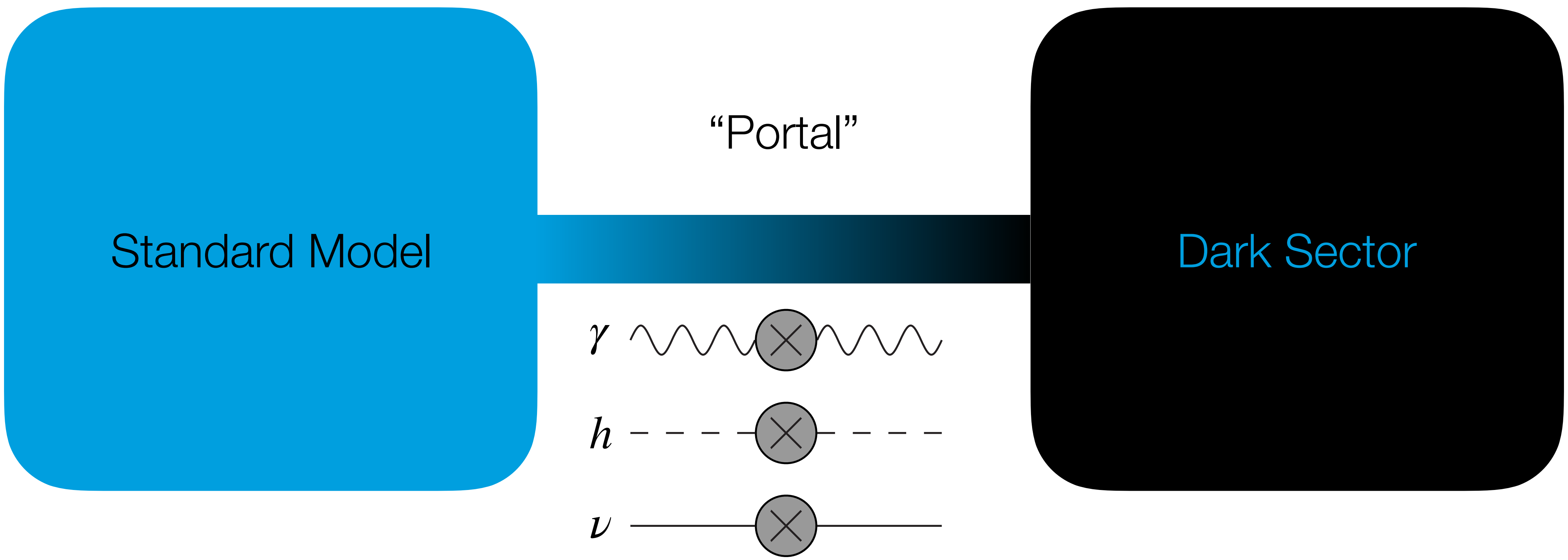

But can be connected via a "portal"—mixing with SM particles

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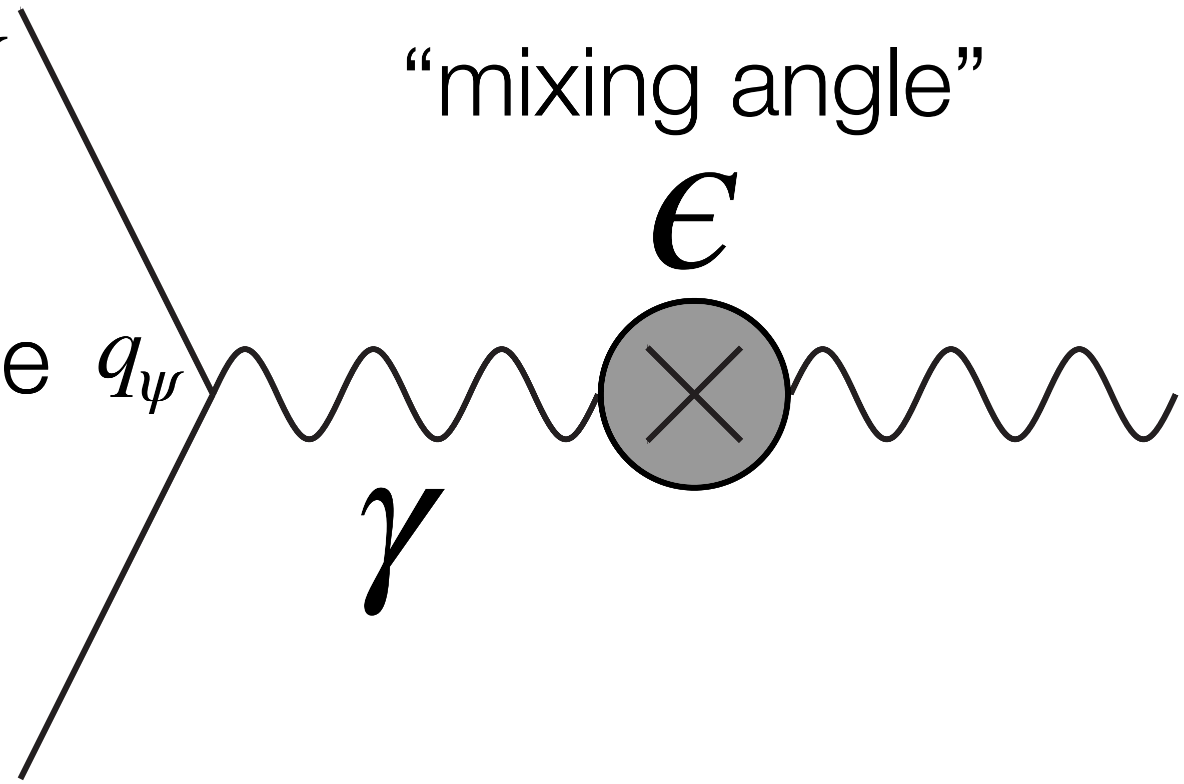
Okun ’82
Galison & Manohar ’84
Holdom ‘86

Minimal Vector Portal



$$\mathcal{L} \supset \frac{\epsilon}{2} F^{\mu\nu} F'_{\mu\nu}$$

Kinetic mixing

Natural set of parameters

$$\epsilon \sim 10^{-3} - 10^{-6}$$

$$m_{A'} \sim \mathrm{MeV} - \mathrm{GeV}$$

Charged SM particles couple to A' with strength proportional to ϵ

$$\mathcal{L} \supset -\epsilon e A'_\mu (\bar{e}\gamma^\mu e + \bar{\mu}\gamma^\mu \mu + \dots)$$

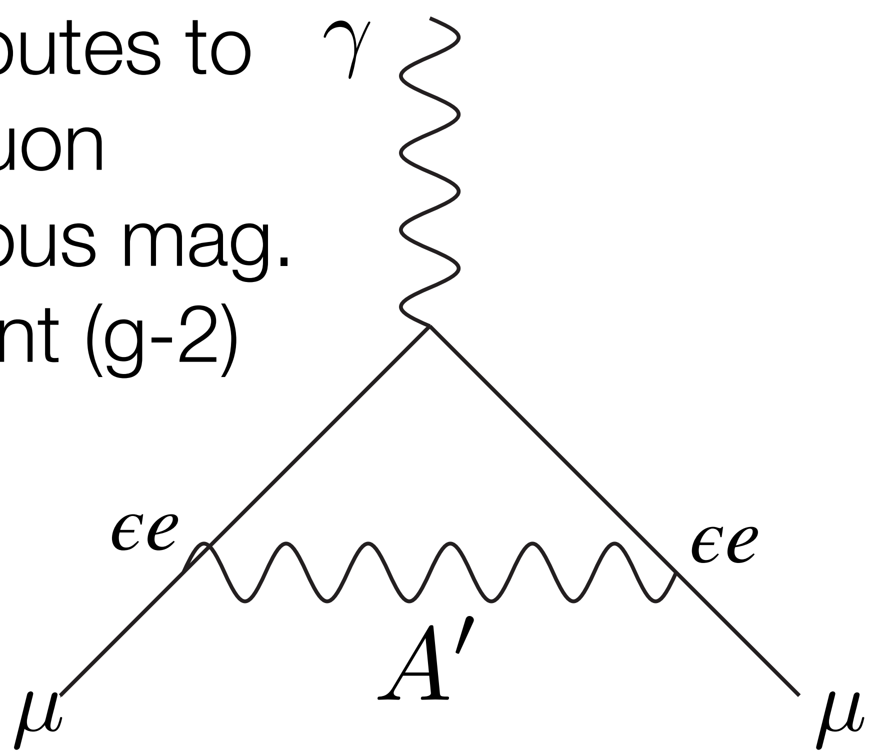
A'decays to (kinematically allowed) charged particles

$$A' \to e^+e^-, \mu^+\mu^-, \pi^+\pi^-$$

Vector Portal

Increased interest in this possibility beginning about 10 years ago

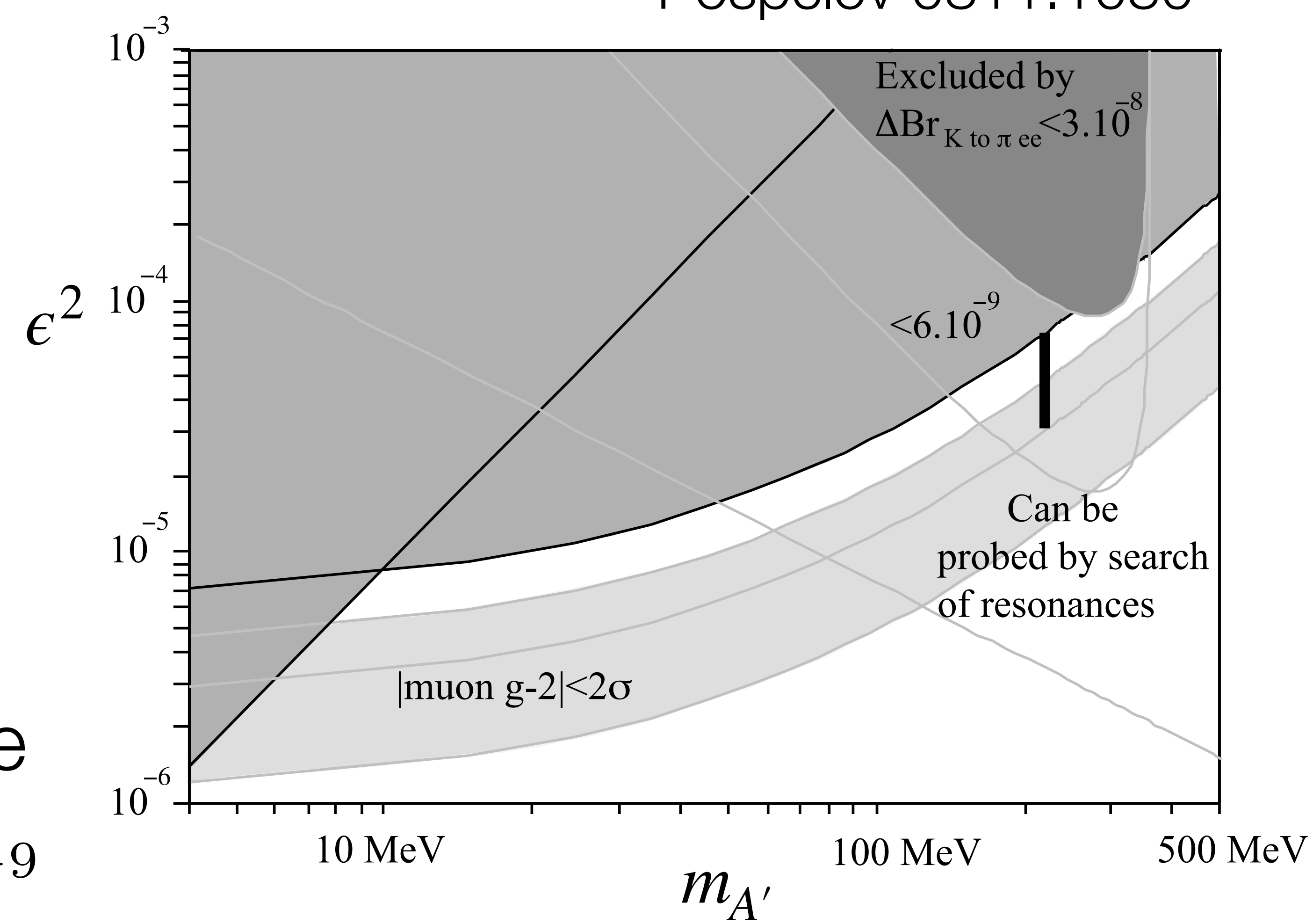
Contributes to muon anomalous mag. Moment (g-2)



Can explain present difference between theory and measured value

$$(\Delta a_\mu)_{\rm exp} - (\Delta a_\mu)_{\rm th} \simeq (3 \pm 1) \times 10^{-9}$$

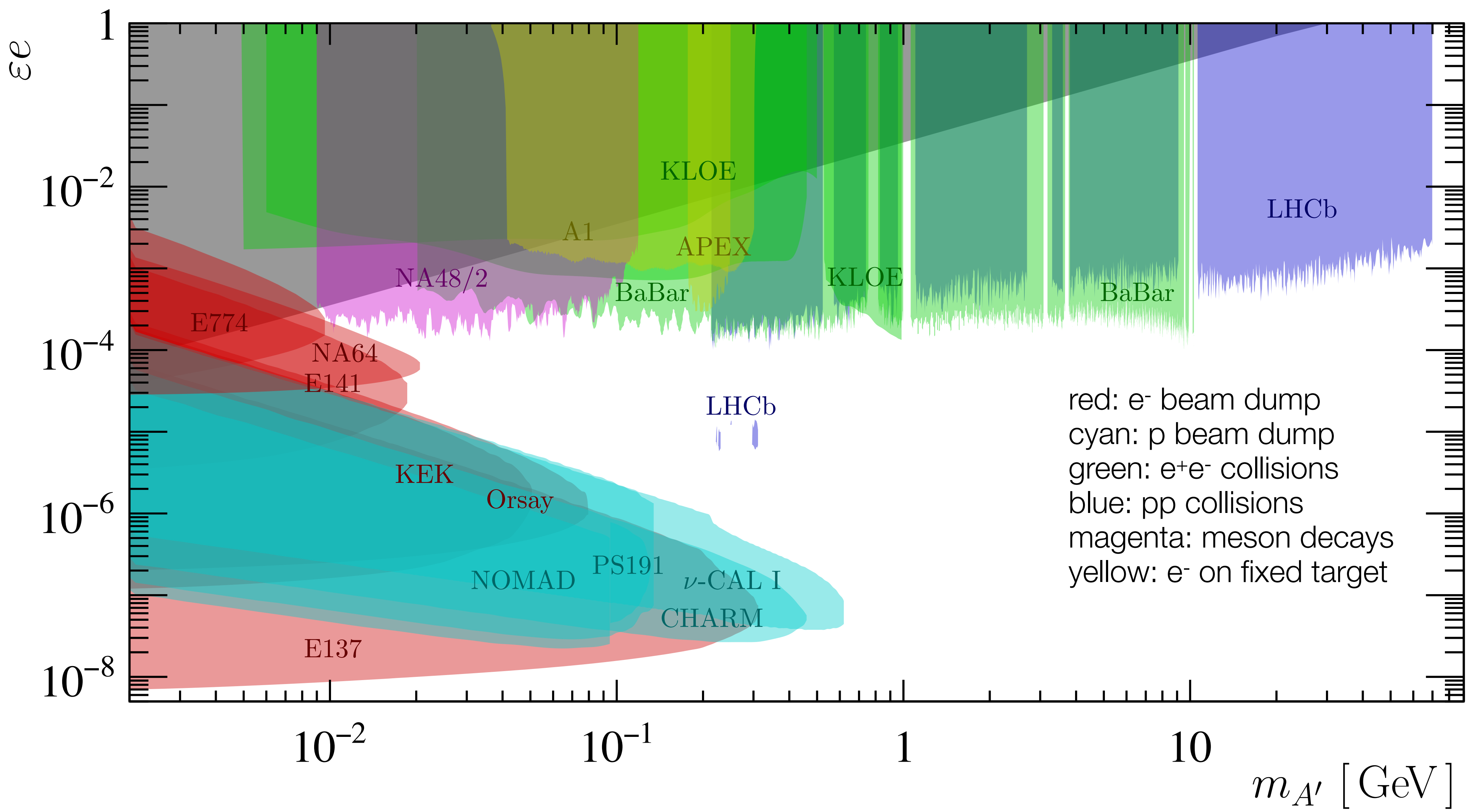
Pospelov 0811.1030



Also astrophysical motivations (Pospelov & Ritz; Arkani-Hamed, Finkbeiner, Slatyer, & Weiner)

Vector Portal Today

Huge amount of progress since 2008…



Ilten, Soreq, Williams, & Xue
[1801.04847]

Vector Portal Today

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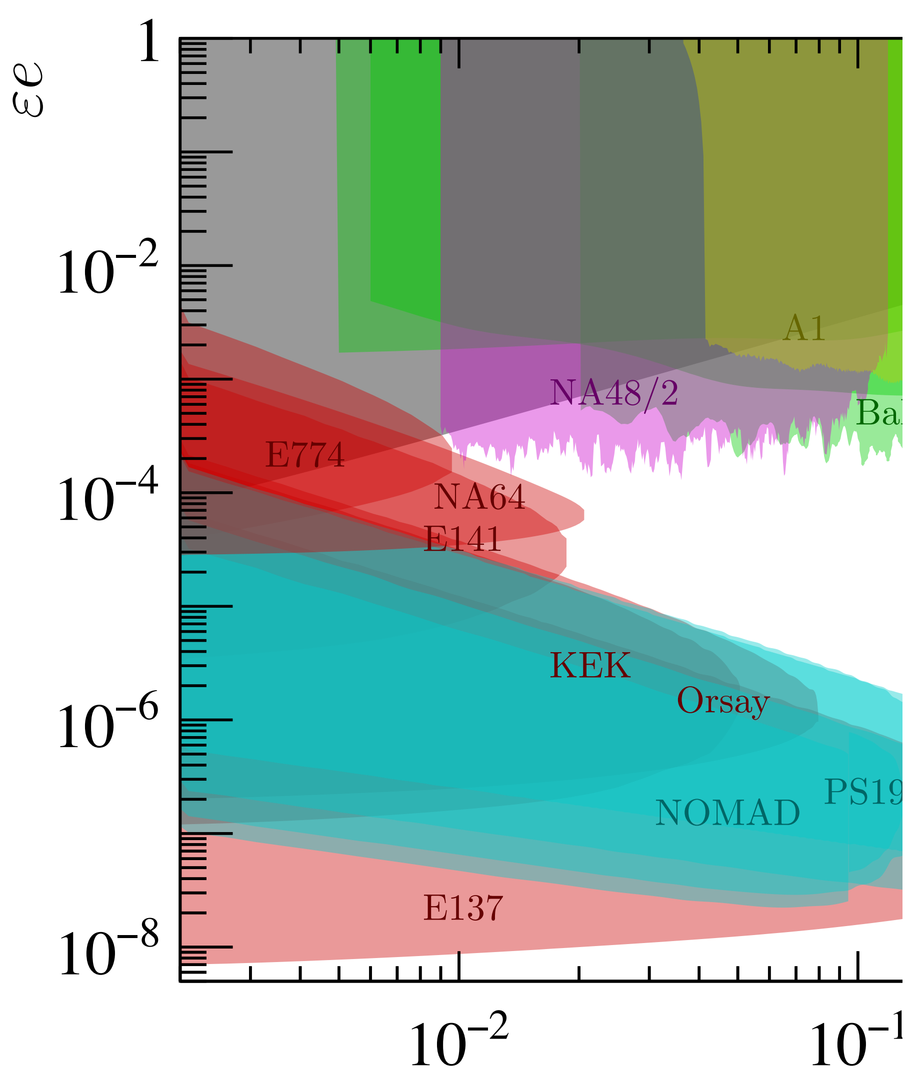
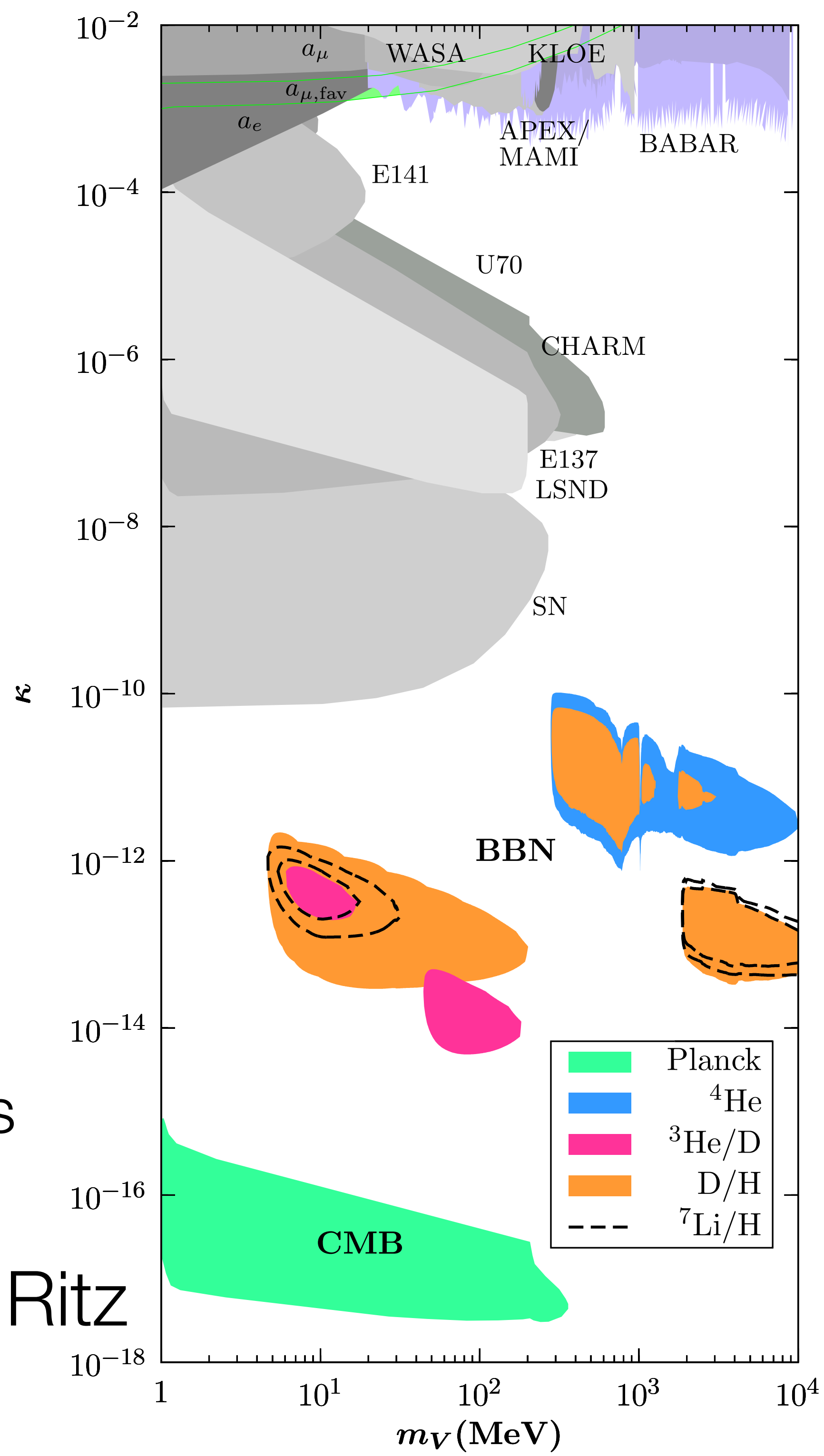
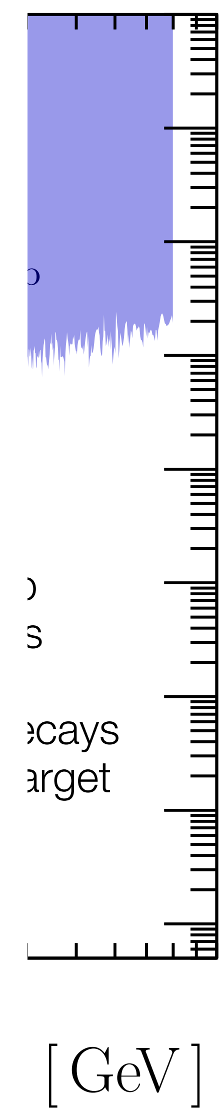




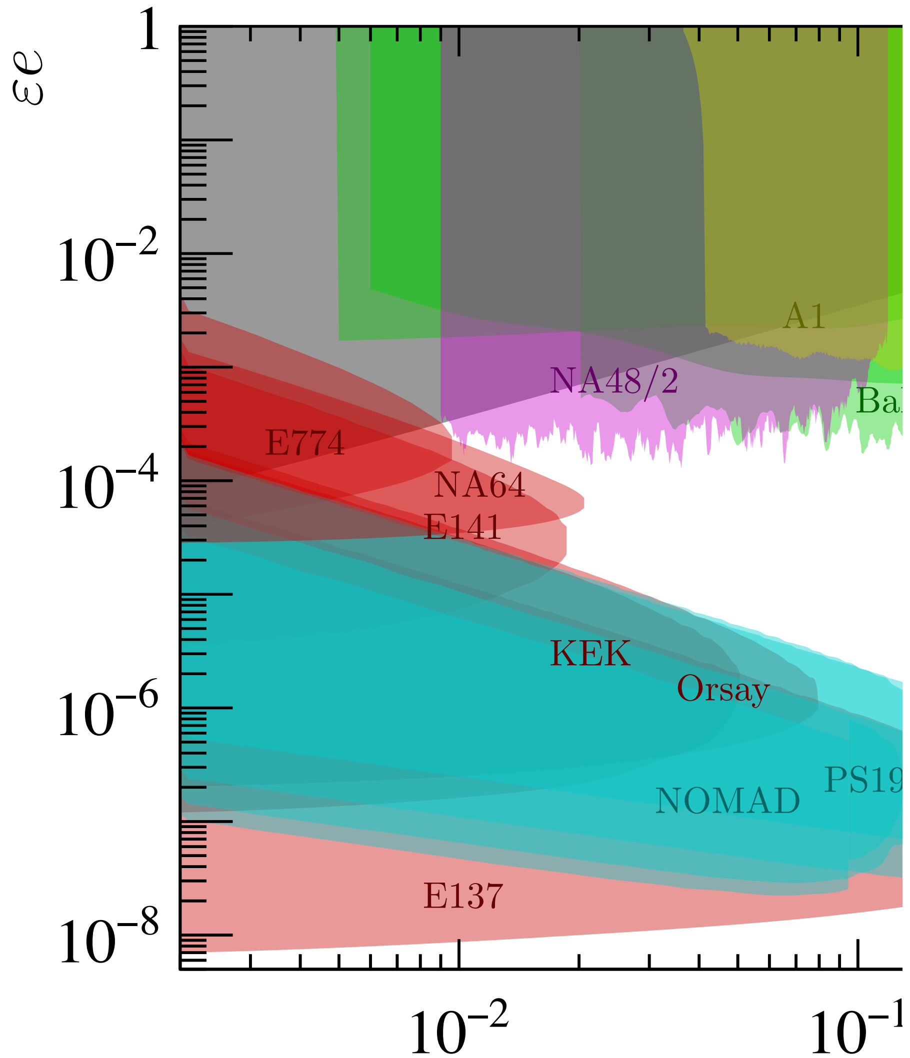


Cosmological &
Astrophysical probes

Fradette, Pospelov, & Ritz
[1407.0993]

Vector Portal Today

Huge amount of progress since 2008…



Cosmological &
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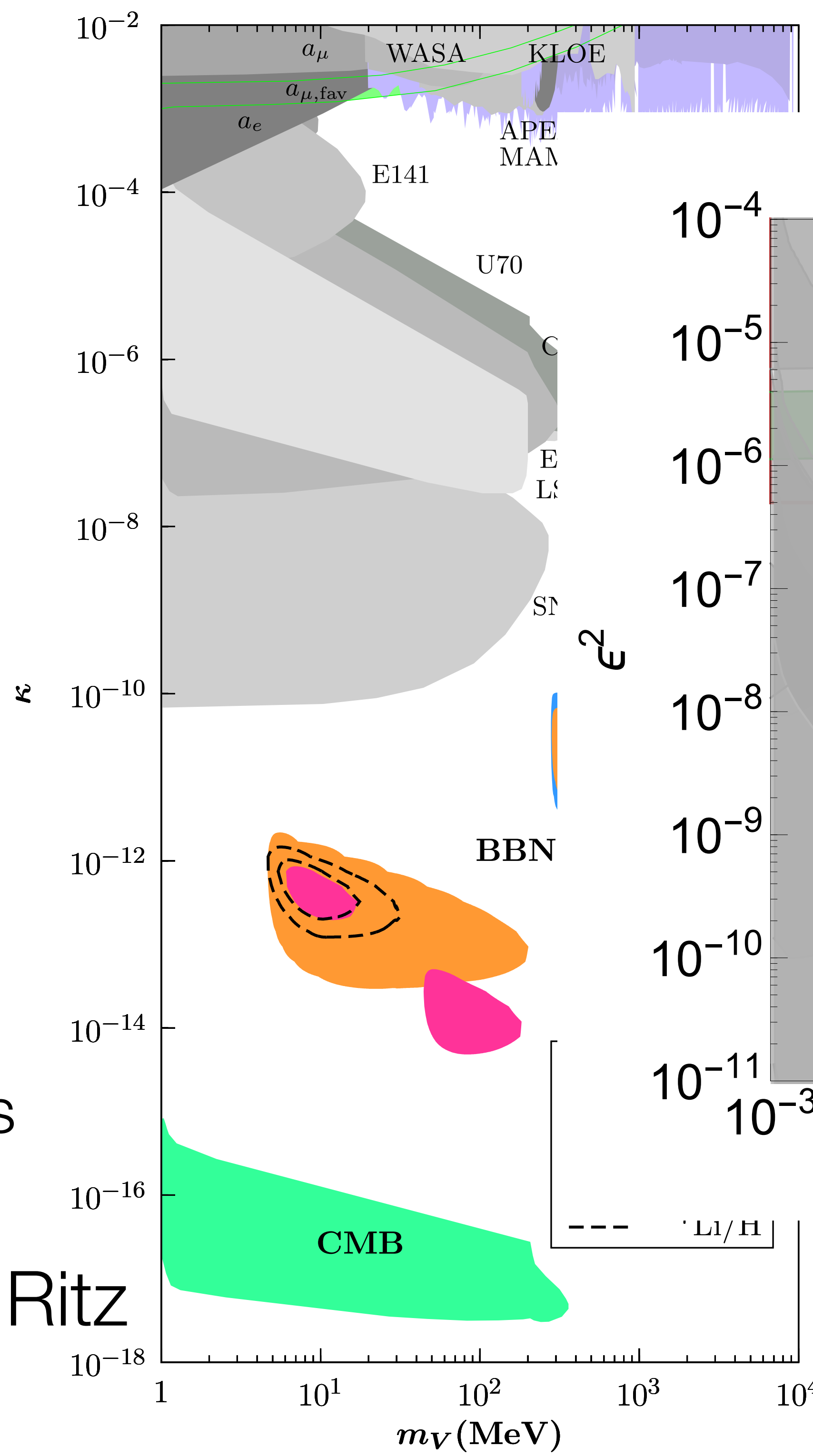
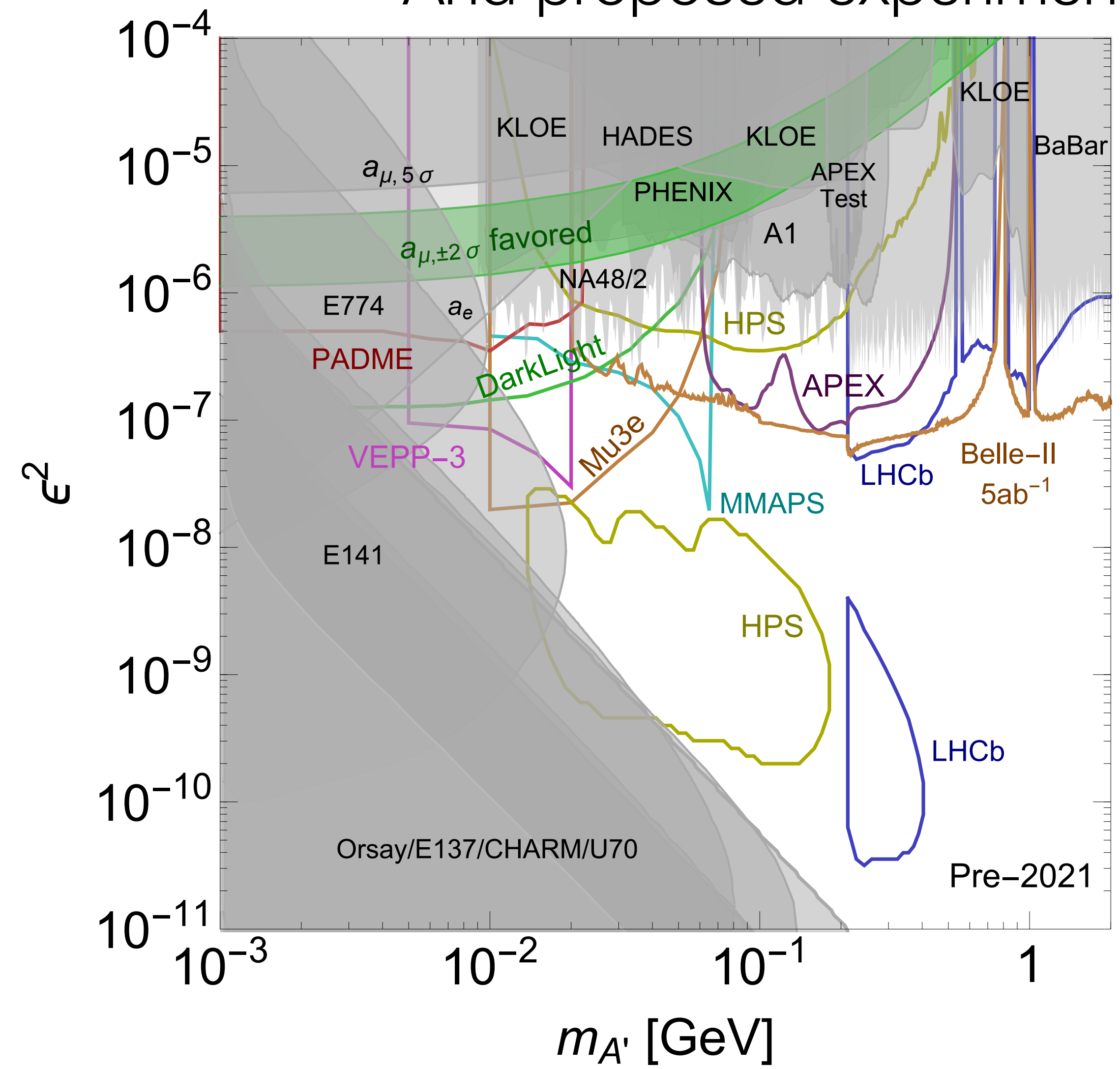


Fradette, Pospelov, & Ritz
[1407.0993]

And proposed experiments

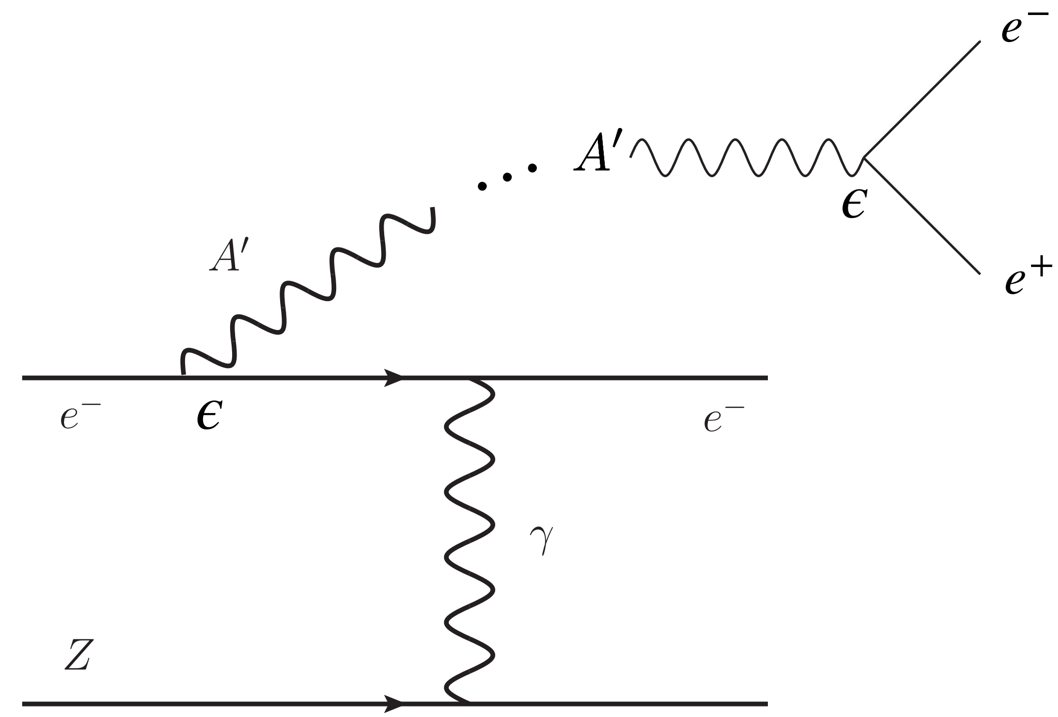


Dark sectors 2016
[1608.08632]

Production & Detection at a Beam Dump

Good way to probe weakly coupled, light stuff

Particle beam steered into a target⇒produce weakly coupled particle⇒it travels to detector and deposits energy (via decay in this case)



Bjorken, Essig, Schuster, & Toro, many since

e.g. SLAC E137

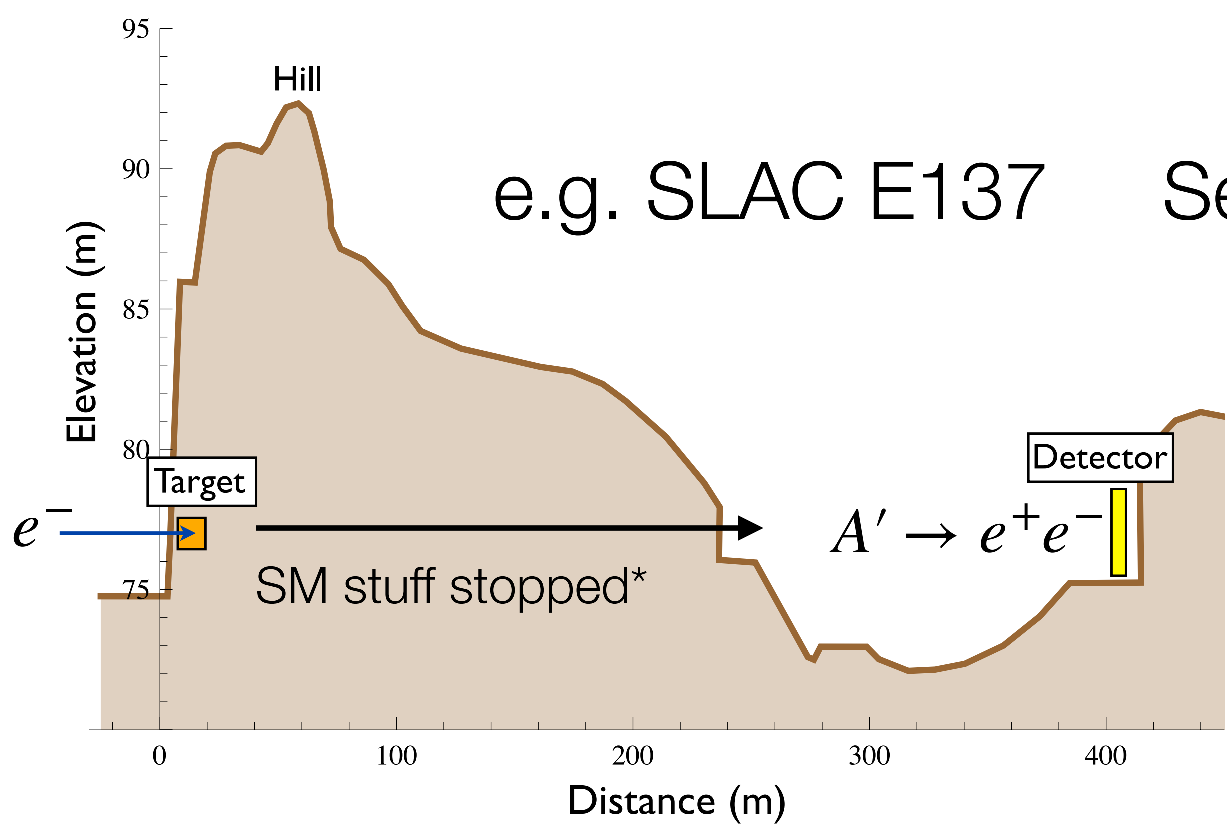
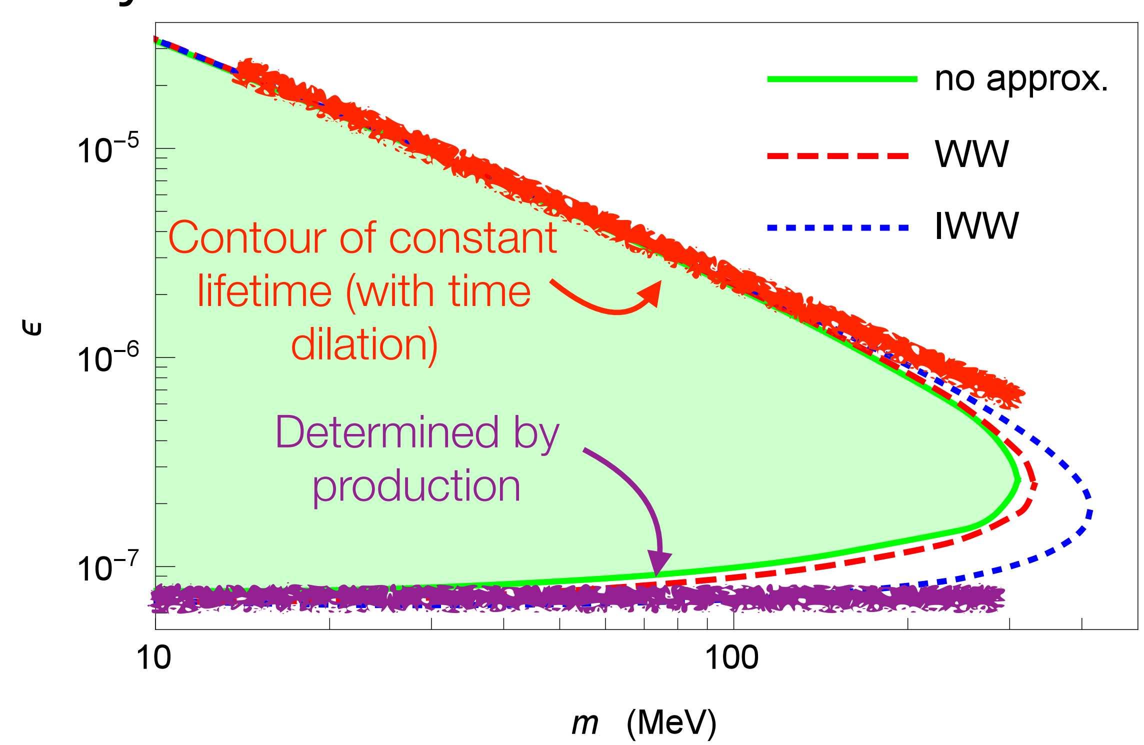


Fig. from Batell, Essig, Surujon

Sensitivity contours: [Liu, McKeen, Miller]



Vector Portal Today

This has become a very mature field

There are a number of proposed experiments aimed at searching

John Behr will talk later about opportunities with ARIEL e^- linac

This is very minimal—does the situation change if the dark sector is (even slightly) more complicated?

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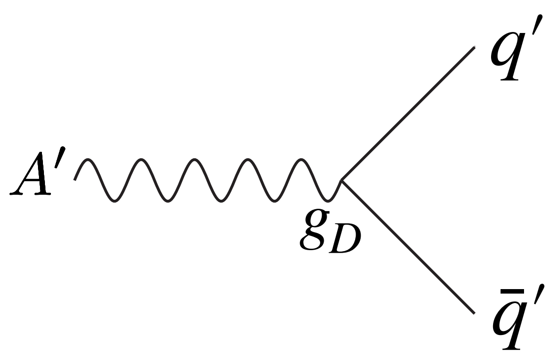
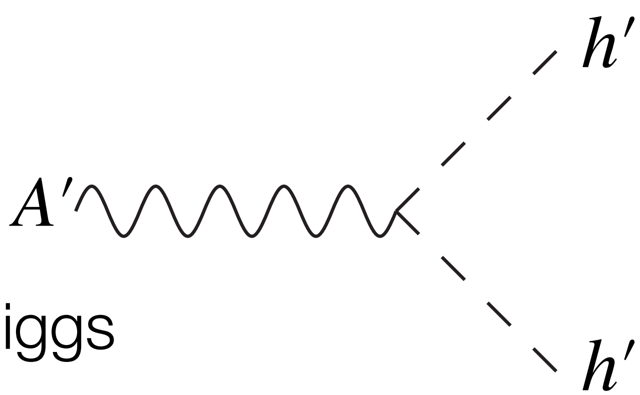
A Richer Dark Sector

There could also be new matter charged under the U(1)’ in the dark sector



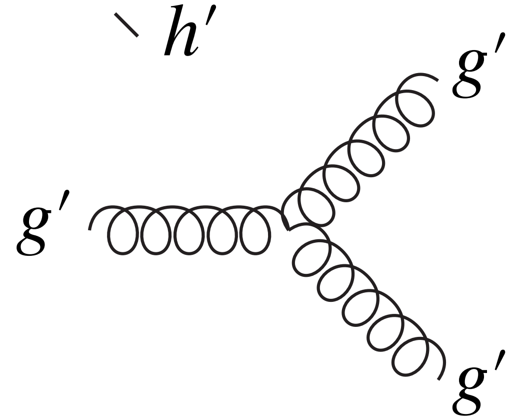
Dark fermions

Phenomenology can be quite different, see e.g. Forestell, Morrissey, & Sigurdson; Morrissey & Spray, …



Dark Higgs

These ideas could be related to weak scale mysteries: see e.g. “Hidden Valleys”: Strassler & Zurek; “Twin Higgs”: Chacko, Harnik, Goh, …



Dark gluons

…etc.

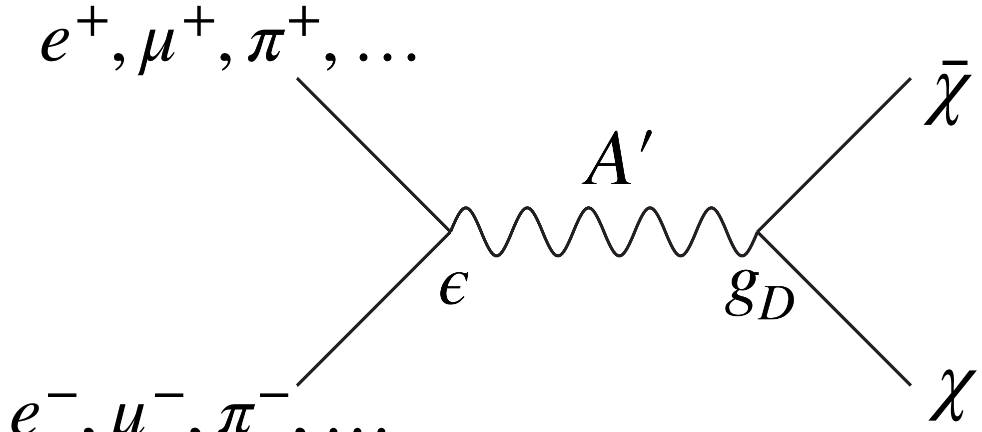
Just as in our sector, dark sector could contain stable states

⇒Dark matter?

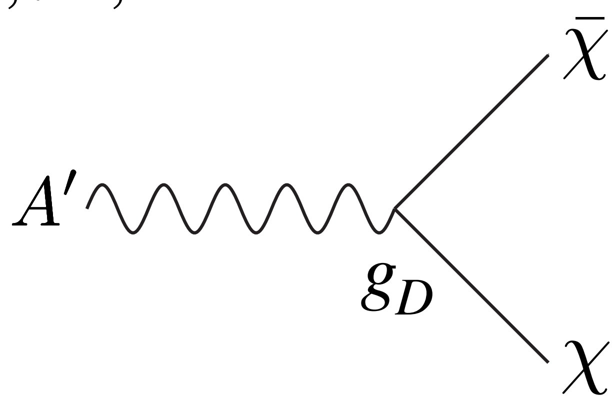
Vector Portal to DM

In addition to kinetic mixing with photon, couple dark photon to dark matter

$$\mathcal{L} \supset -g_D A'_\mu \bar{\chi}\gamma^\mu \chi$$

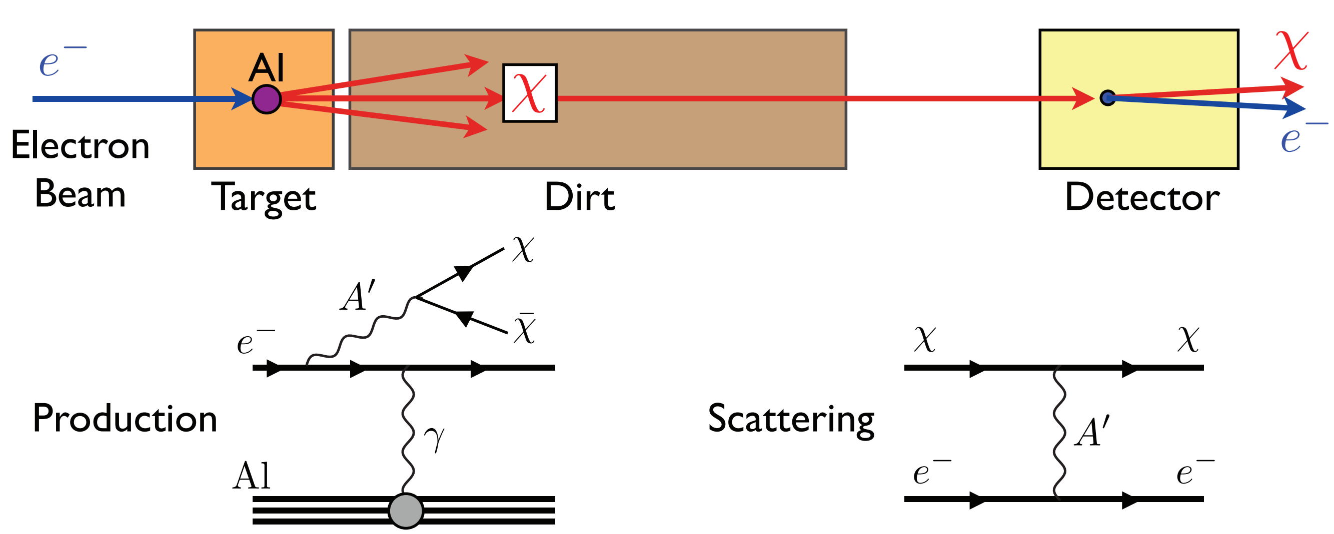


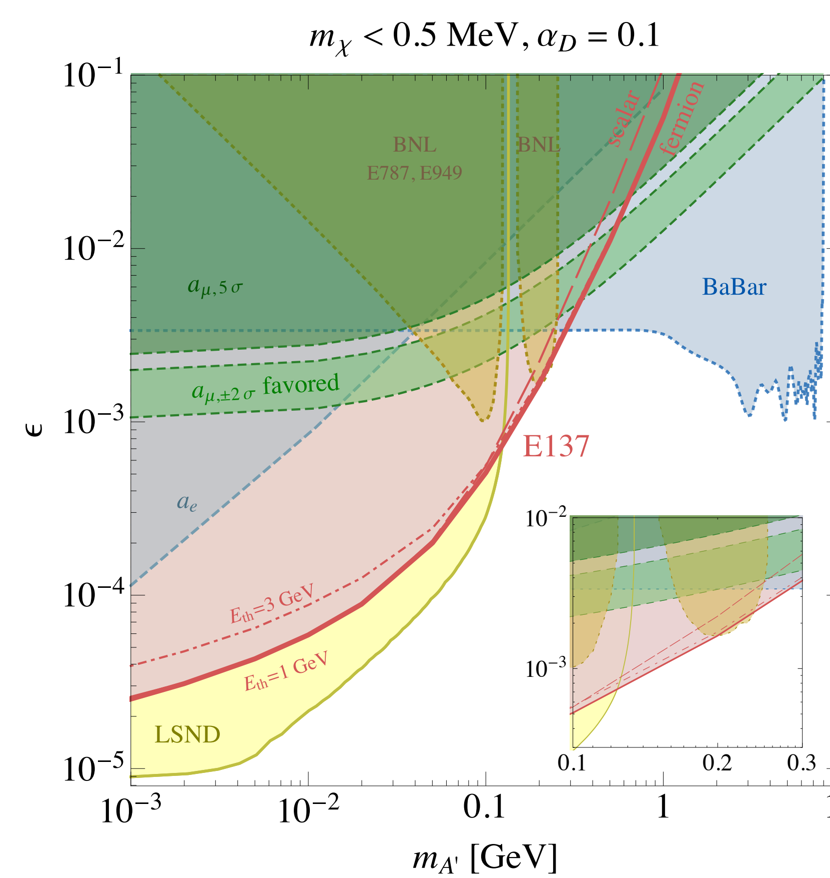
Allows for light dark matter to annihilate efficiently (avoid Lee-Weinberg bound)



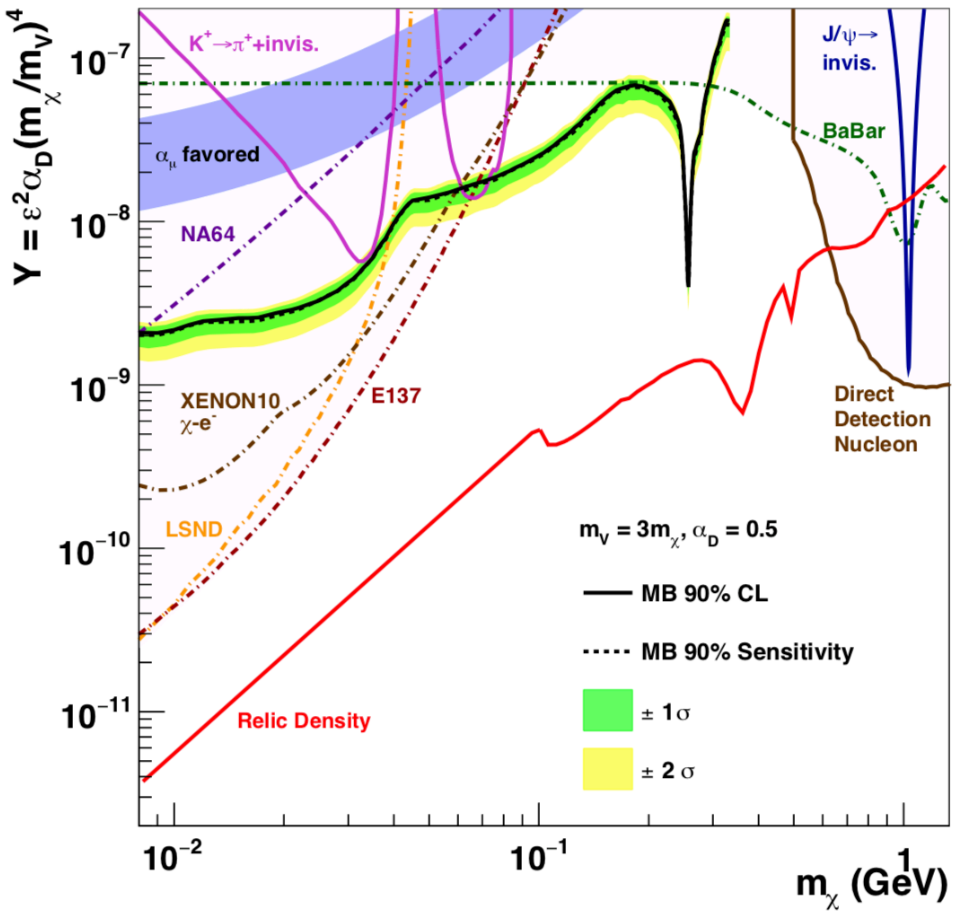
Dark photon decays now decays invisibly to DM—visible decay probes diminished—and signature at beam dumps is changed—DM scatters in detector

E137 study Batell, Essig, Surujon [1406.2698]





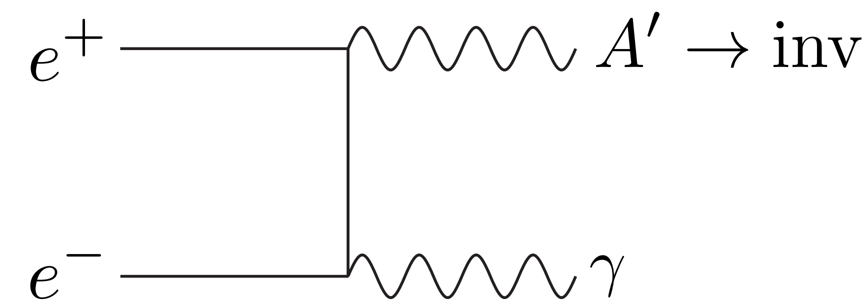
Vector Portal to DM



MiniBooNE 1702.02688 (PRL)

Can also search at proton beam dumps, i.e. accelerator neutrino experiments such as MiniBooNE

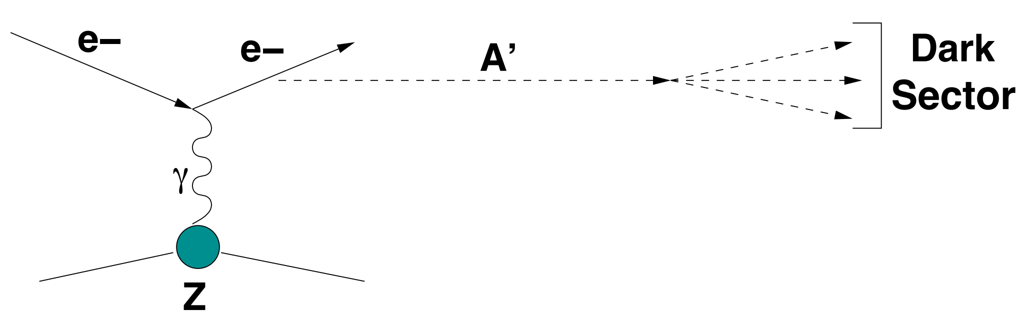
At B-factories like BaBar:

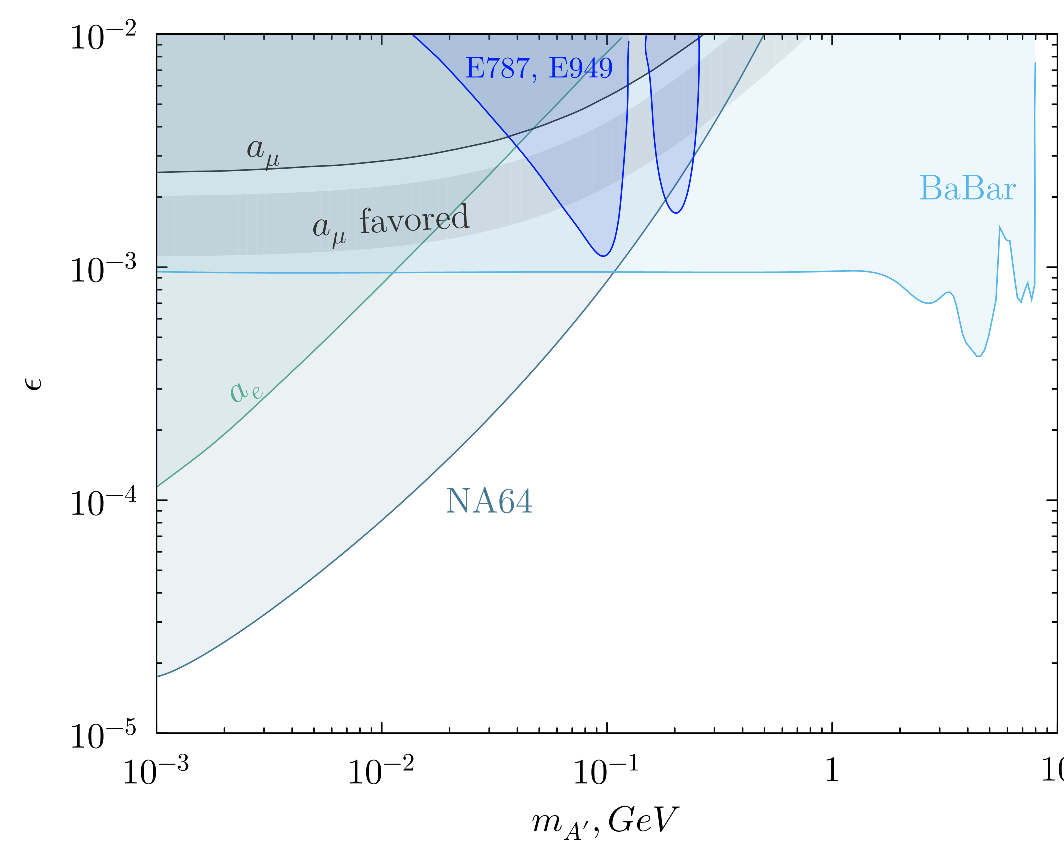


BaBar 1702.03327 (PRL)

NA64 electron beam dump into active target & search for missing energy

NA64 1710.00971 (PRD)





Vector Portal to DM

Qualitatively different phenomenology from minimal case

Could directly connect to major issue from cosmology and astrophysics: dark matter

Luca Doria's talk next will describe possibilities with e^- at ARIEL

Ongoing, active area of research

Wrap Up

The standard model is successful but has some shortcomings

Answers could come at low energy scales and small couplings—“portals” are helpful here

I only described one fairly simple “portal,” others (Higgs, neutrino,…) exist and are interesting

Ongoing, active area of research

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Back Up

TRIUMF

Other Portals

Portals: couplings via stuff uncharged w.r.t. SM

Leads to minimal difficulties incorporating hidden sectors

vector portal (kinetic mixing): $F_{\mu\nu} \longleftrightarrow F'_{\mu\nu}$

Higgs/ scalar portal: $H^\dagger H \longleftrightarrow S, S^2$

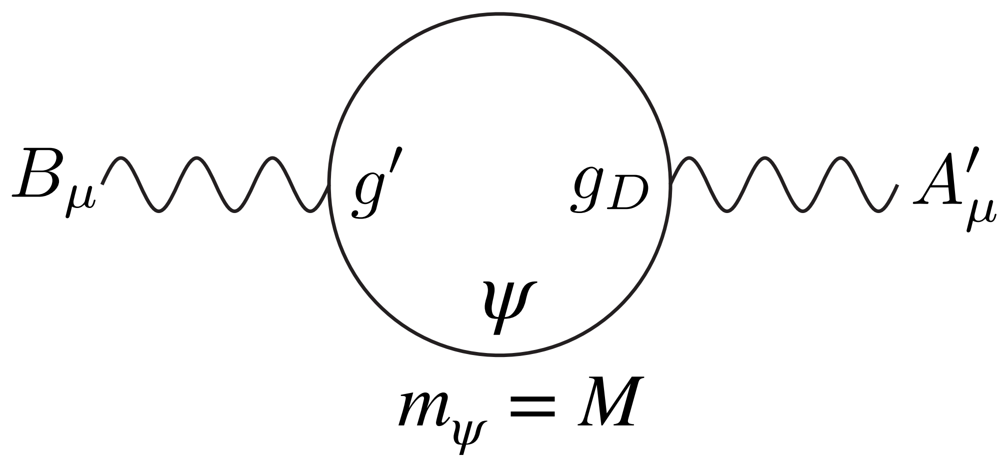
neutrino portal: $LH \longleftrightarrow N$

Minimal Vector Portal Details

Okun '82
Galison & Manohar '84
Holdom '86

New interaction is $\mathcal{L} \supset \dfrac{\epsilon}{2\cos\theta_{\mathrm{W}}} B^{\mu\nu} F'_{\mu\nu} \to \dfrac{\epsilon}{2} F^{\mu\nu} F'_{\mu\nu}$

From, e.g., heavy particle charged under hypercharge/E&M and U(1)'



$\Rrightarrow$

Diagonalized by $A \to A + \epsilon A'$

$\epsilon \sim \dfrac{g_D g'}{16\pi^2} \log \dfrac{M^2}{\Lambda^2}$ can have

$$\epsilon \sim 10^{-3} - 10^{-6}$$

$$m_{A'} \sim \mathrm{MeV} - \mathrm{GeV}$$

Charged SM particles couple to A' with strength proportional to ϵ

$$\mathcal{L} \supset -\epsilon e A'_\mu (\bar{e}\gamma^\mu e + \bar{\mu}\gamma^\mu \mu + \dots)$$

A'decays to (kinematically allowed) charged particles

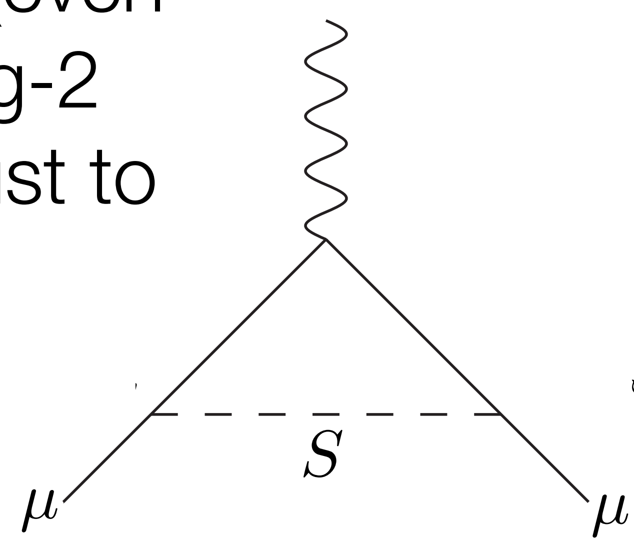
$$A' \to e^+e^-, \mu^+\mu^-, \pi^+\pi^-$$

Higgs Portal

Portal coupling: $\mathcal{L} \supset A\,|H|^2\, S \Rightarrow \quad \mathcal{L}_{\text{eff}} = \frac{1}{2}(\partial_\mu S)^2 - \frac{1}{2} m_S^2 S^2 + \xi_\psi \sum_\psi \frac{m_\psi}{v} \bar{\psi}\psi$

Coupling now proportional to particle mass

Simple Higgs portal very constrained (even if invisible). For g-2 solution couple just to leptons



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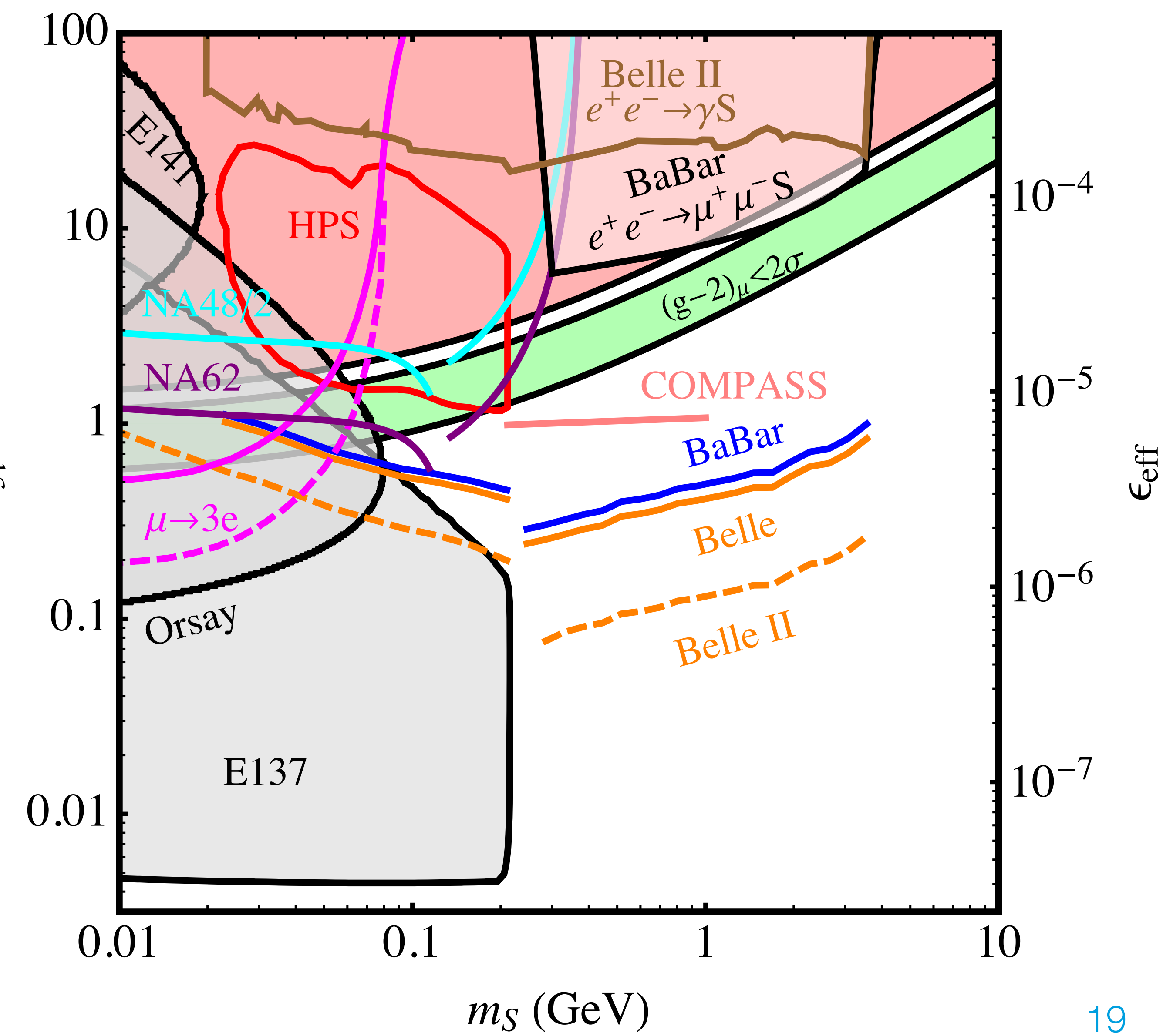
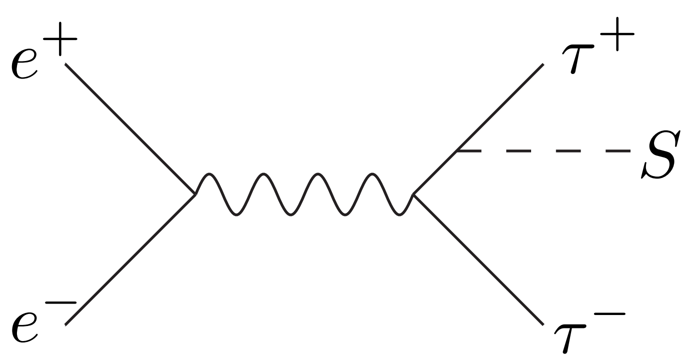


Coupling to electrons relatively suppressed, taus enhanced:



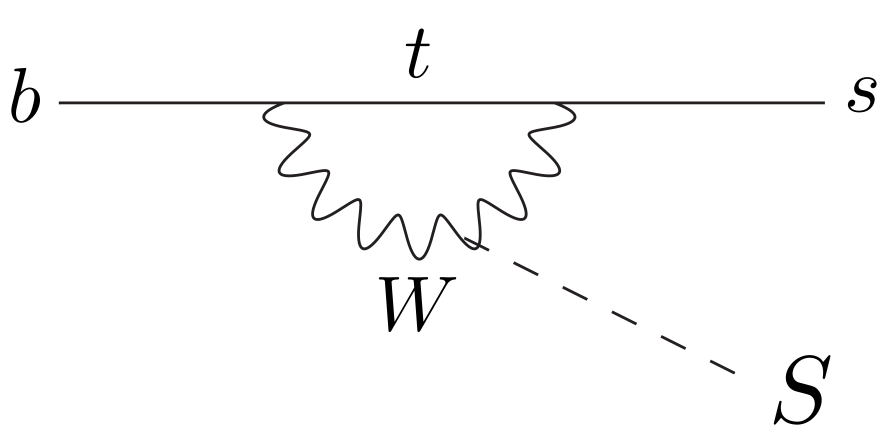
Higgs Portal

A UV completion involves lepton-specific 2HDM

$$\mathcal{L} \supset \left[A_{11} H_1^\dagger H_1 + A_{22} H_2^\dagger H_2 + A_{12}\left(H_1^\dagger H_2 + H_2^\dagger H_1\right)\right]\varphi$$
$$- \left(\bar{L} Y_e H_1 e_R + \bar{Q} Y_d H_2 d_R + \bar{Q} Y_u \tilde{H}_2 u_R + \text{h.c.}\right)$$

(See Chen, Davoudiasl, Marciano, Zheng for a different UV completion)

Residual FCNC in quark sector



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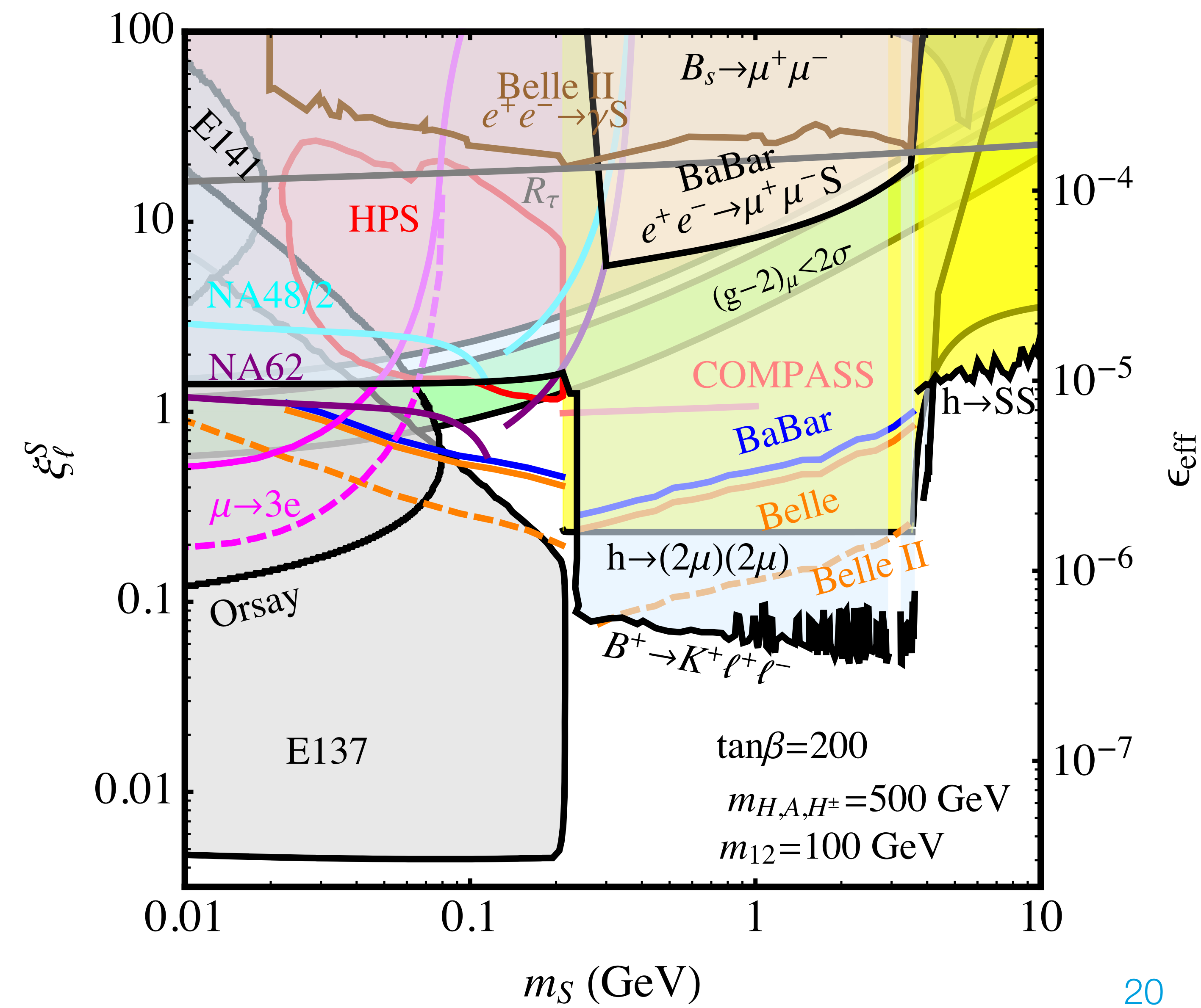
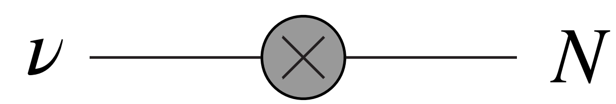


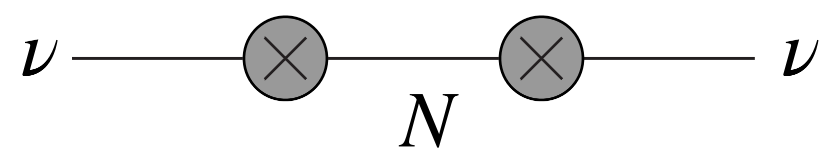
Neutrino Portal

Sterile neutrino is a "dark sector" state that mixes with neutrino

$$-\mathscr{L} \supset y\bar{L}HN + \mathrm{h.c.}$$



Two mixings generate neutrino mass:



We may have already discovered that Nature has chosen to use this portal

Neutrino portal to DM requires more complicated dark sector to keep DM stable

$$-\mathscr{L}_{\mathrm{eff}} \supset \frac{1}{\Lambda}\bar{L}H\phi\chi + \mathrm{h.c.}$$

Conserved charge keeps lighter one stable