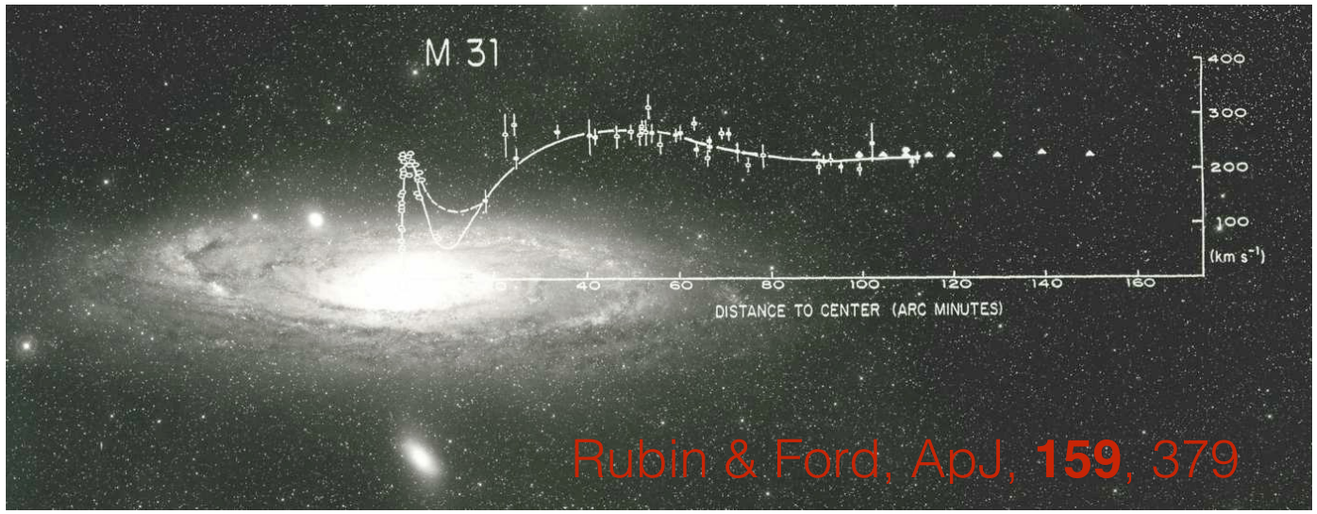
Dark Matter in a Dark Sector

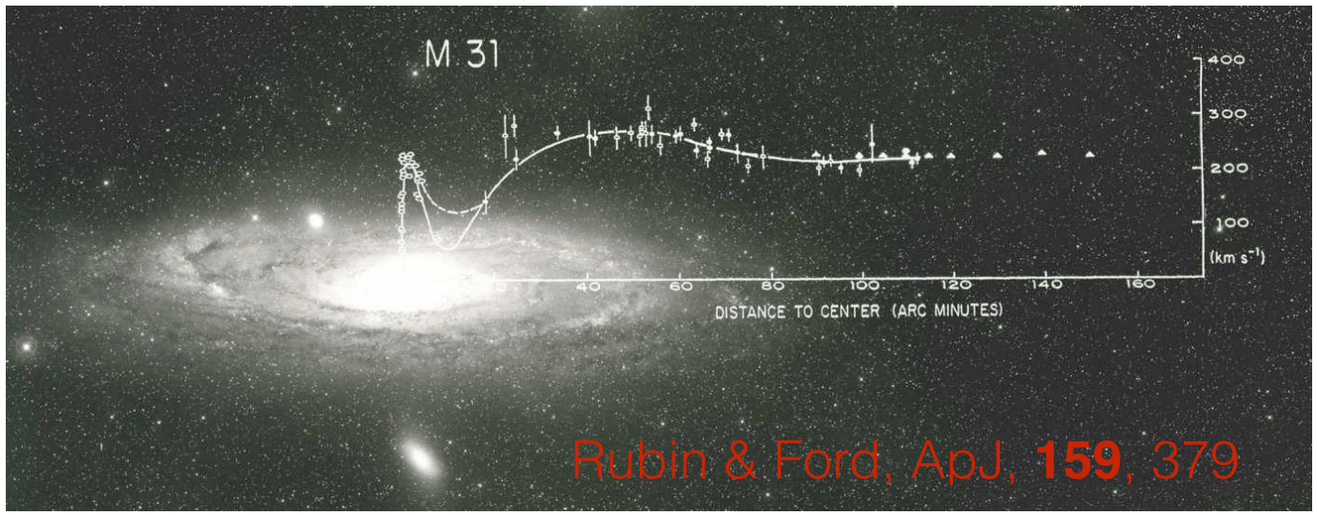
David McKeen

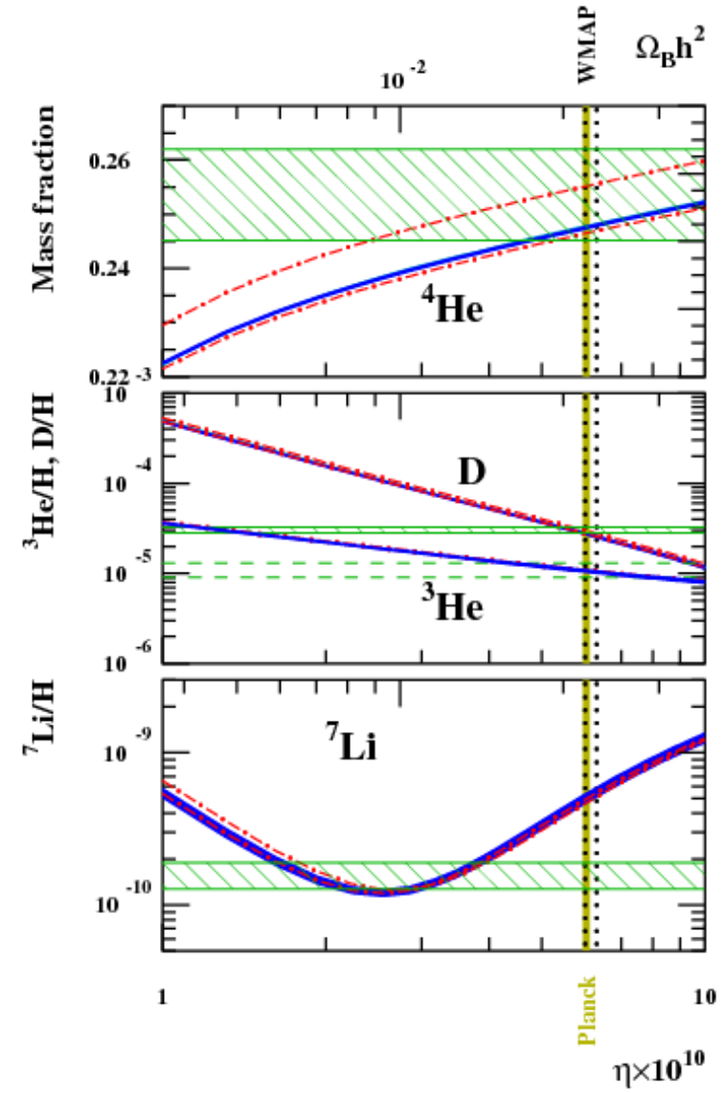
TRIUMF

CAP Congress 2019
DM Symposium Day
June 4, 2019



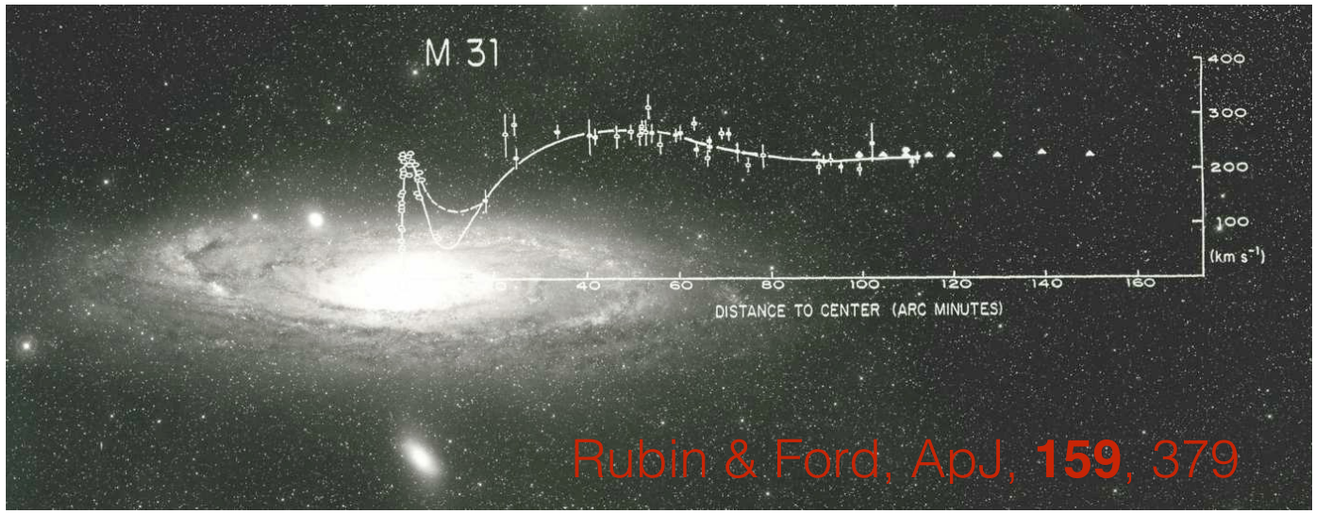
Rubin & Ford, ApJ, **159**, 379

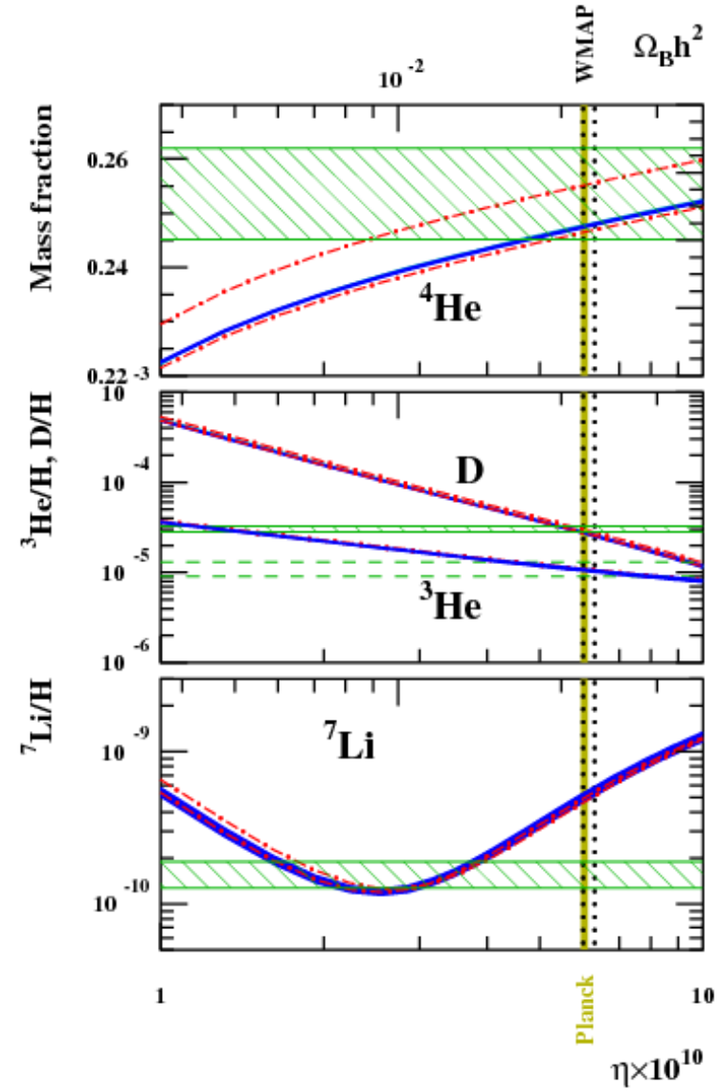

M 31
400
300
200
100
(km s⁻¹)
40
60
80
100
120
140
160
DISTANCE TO CENTER (ARC MINUTES)
Rubin & Ford, ApJ, 159, 379


WMAP
$\Omega_B h^2$
10^{-2}
Mass fraction
0.26
0.24
0.22
^{4}He
^{3}He/H, D/H
10^{-3}
10^{-4}
10^{-5}
10^{-6}
D
^{3}He
^{7}Li/H
10^{-9}
10^{-10}
^{7}Li
1
10
Planck
$\eta\times10^{10}$

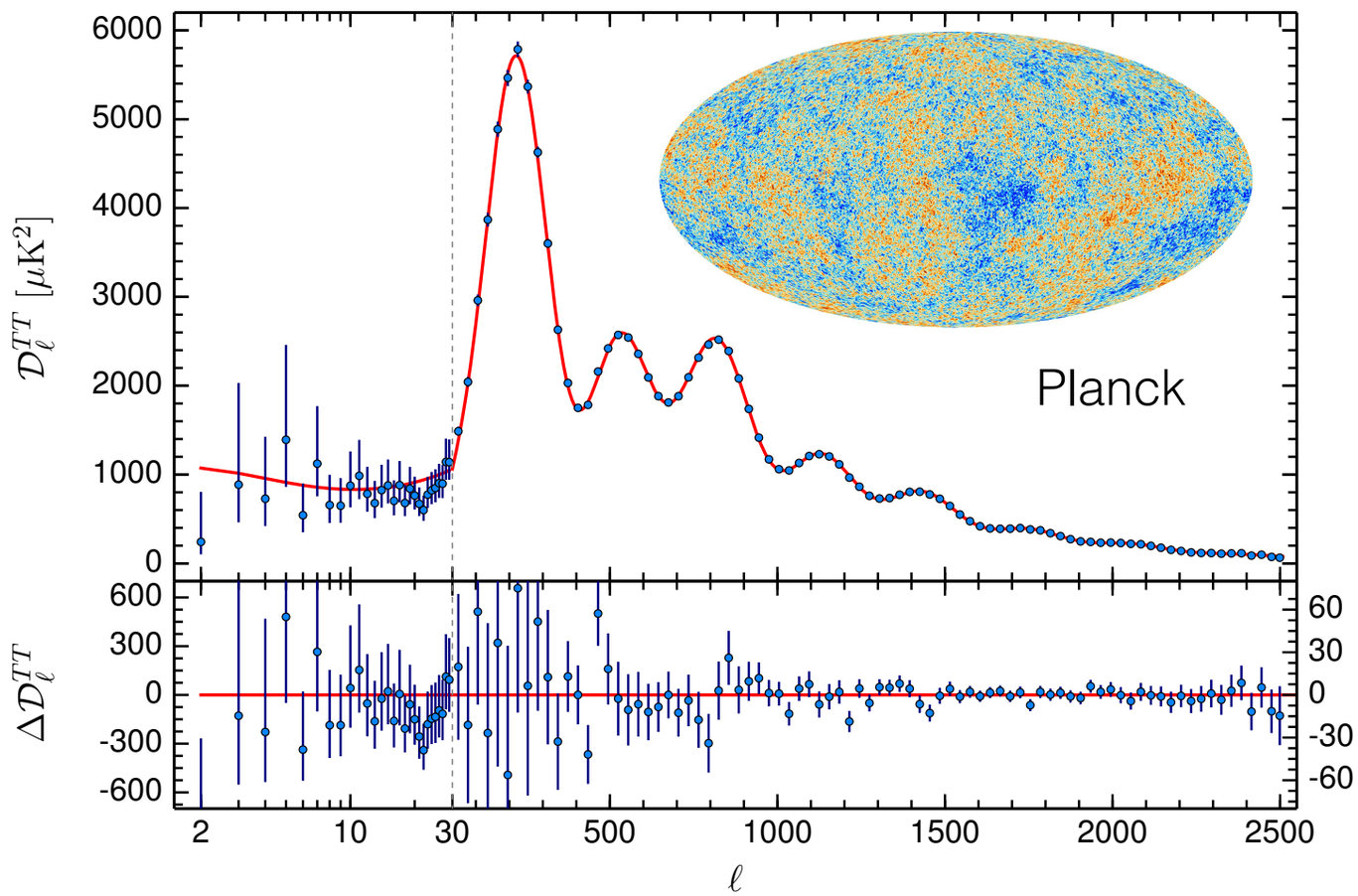
Coc, Uzan,

TRIUMF

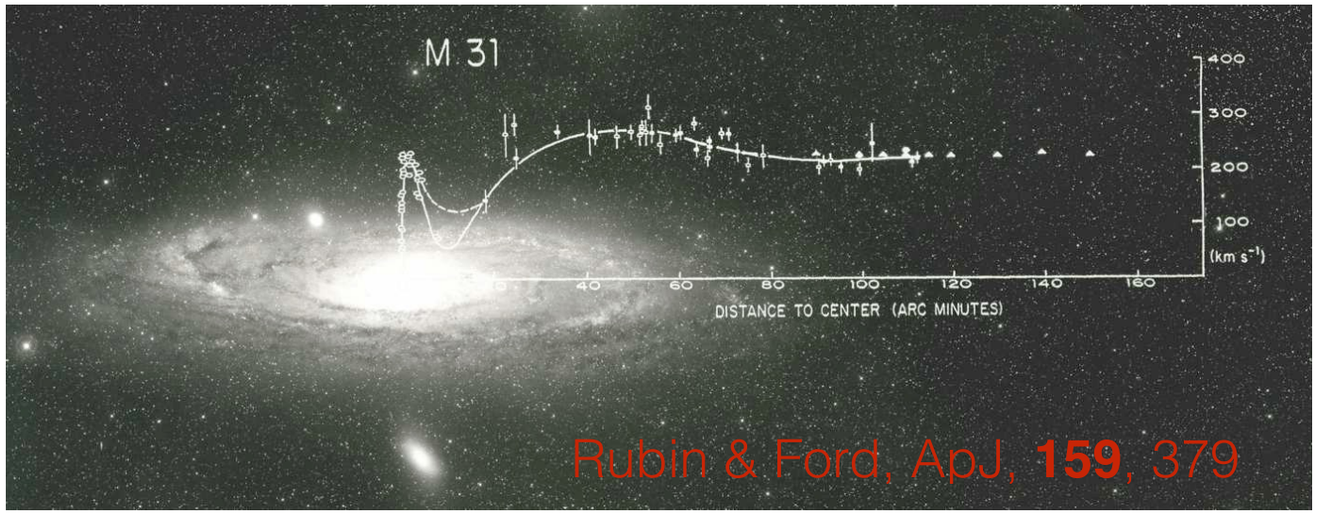




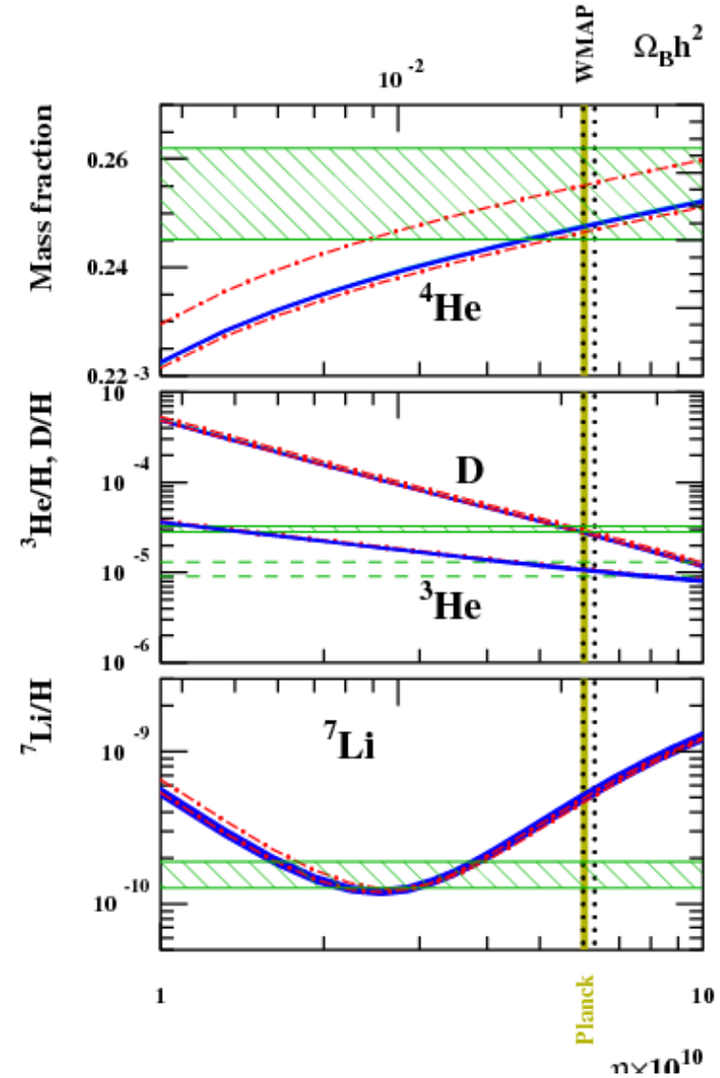
Coc, Uzan,



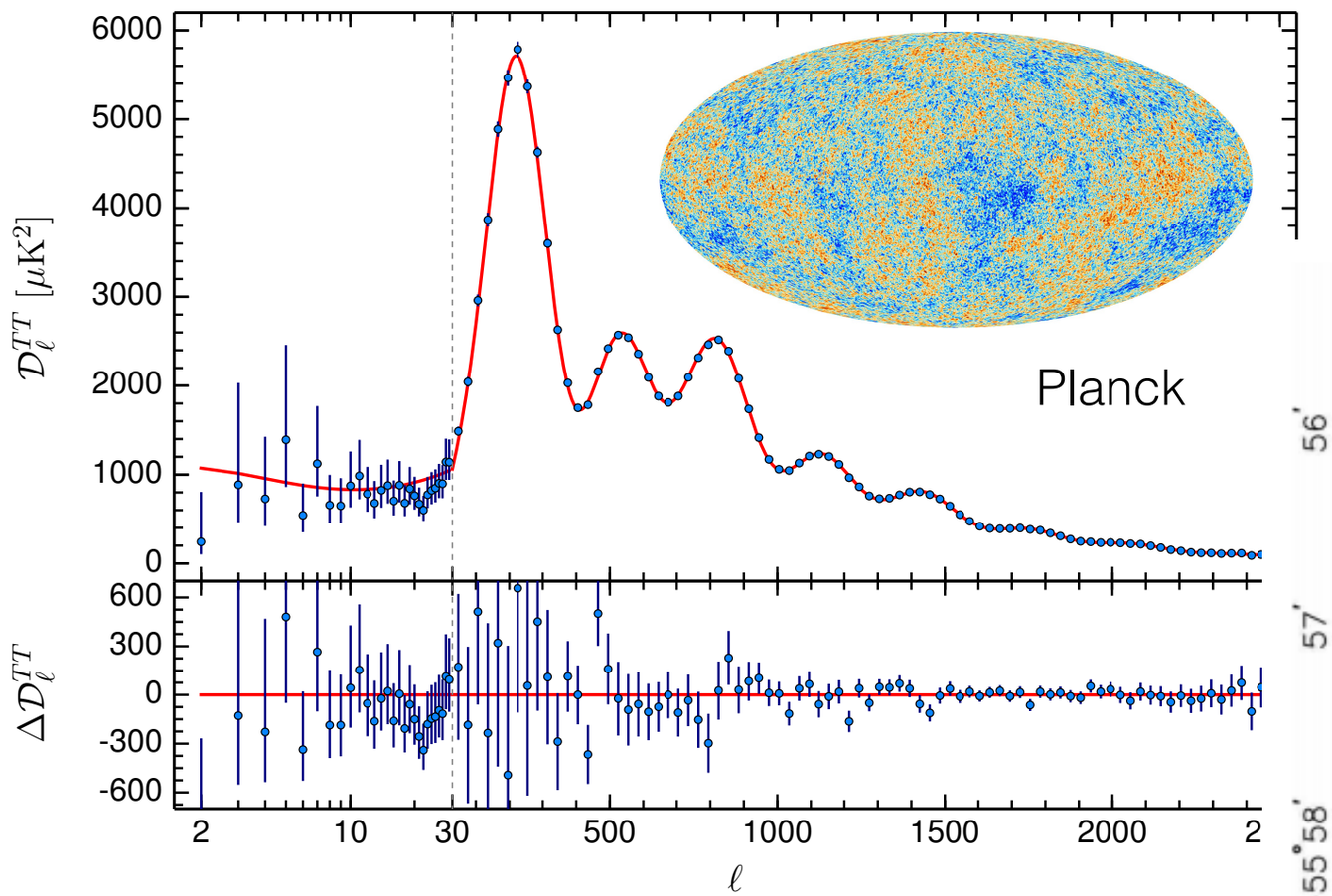
TRIUMF

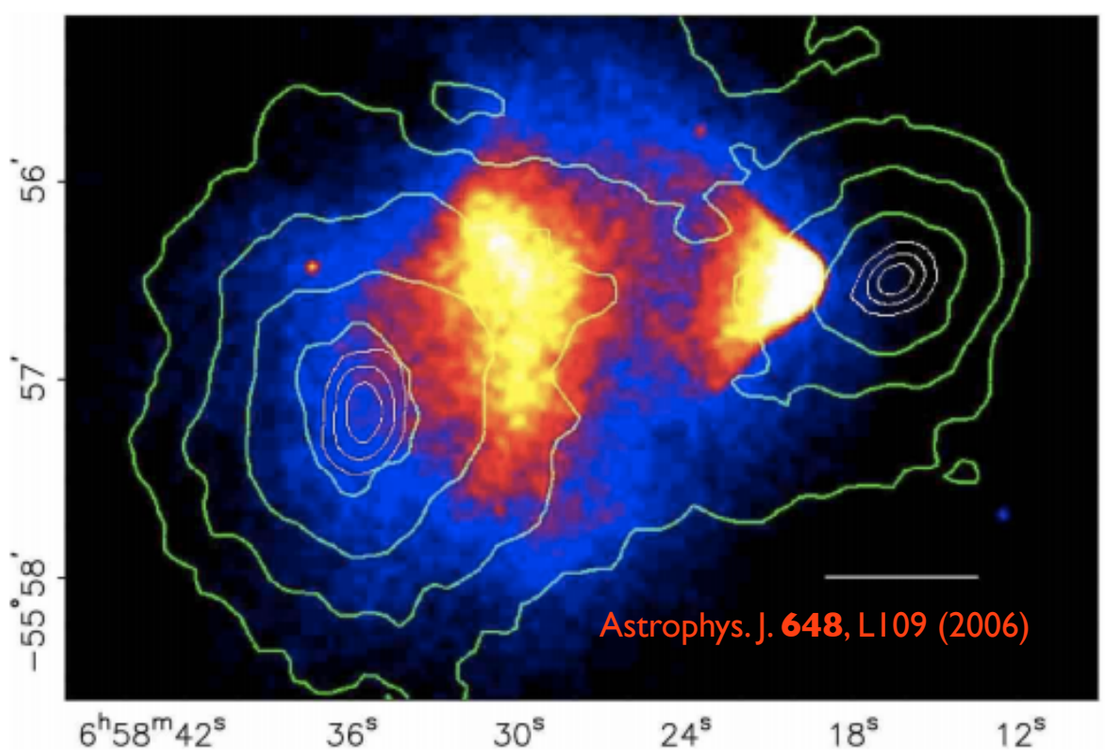


Rubin & Ford, ApJ, **159**, 379



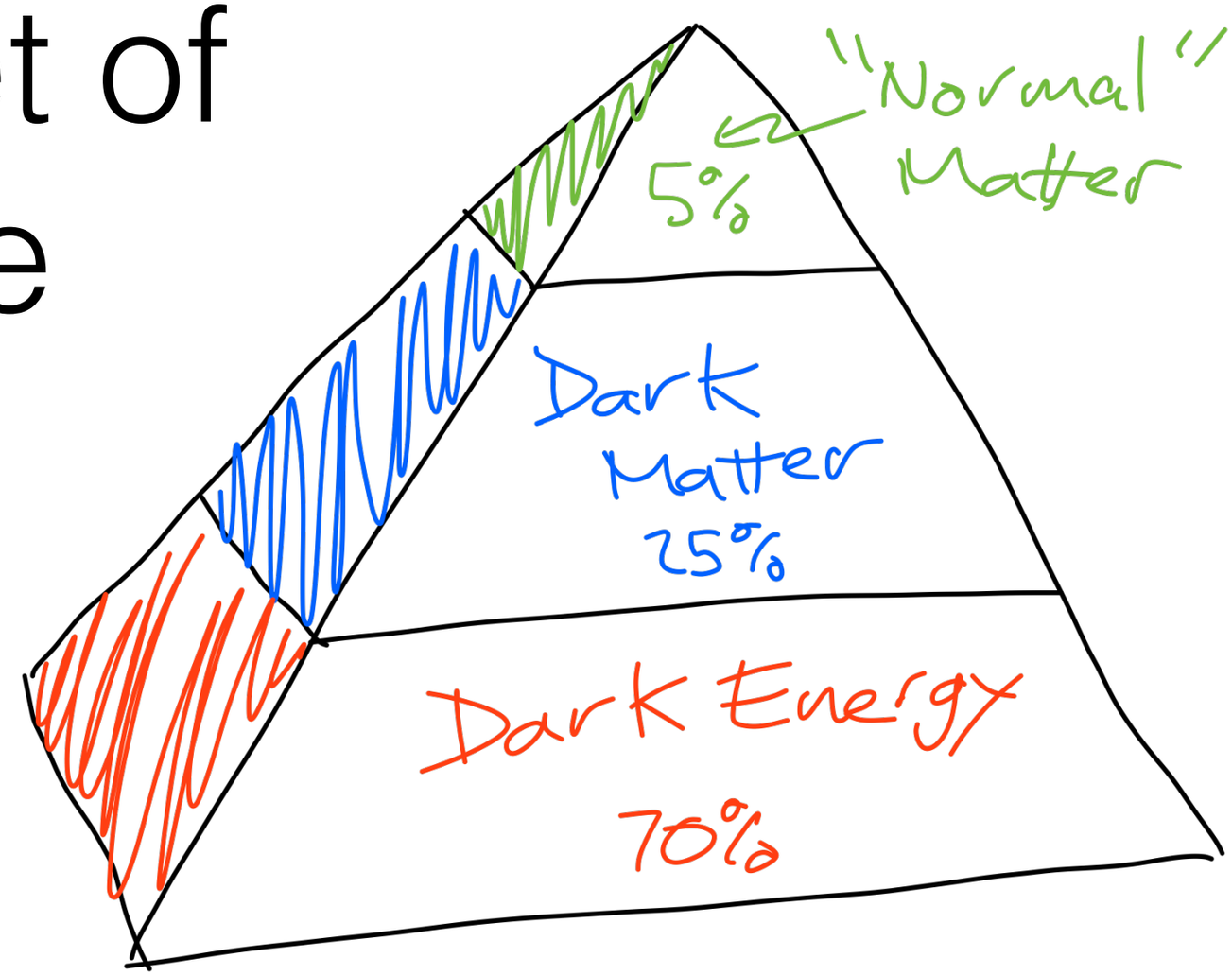
Coc, Uzan,



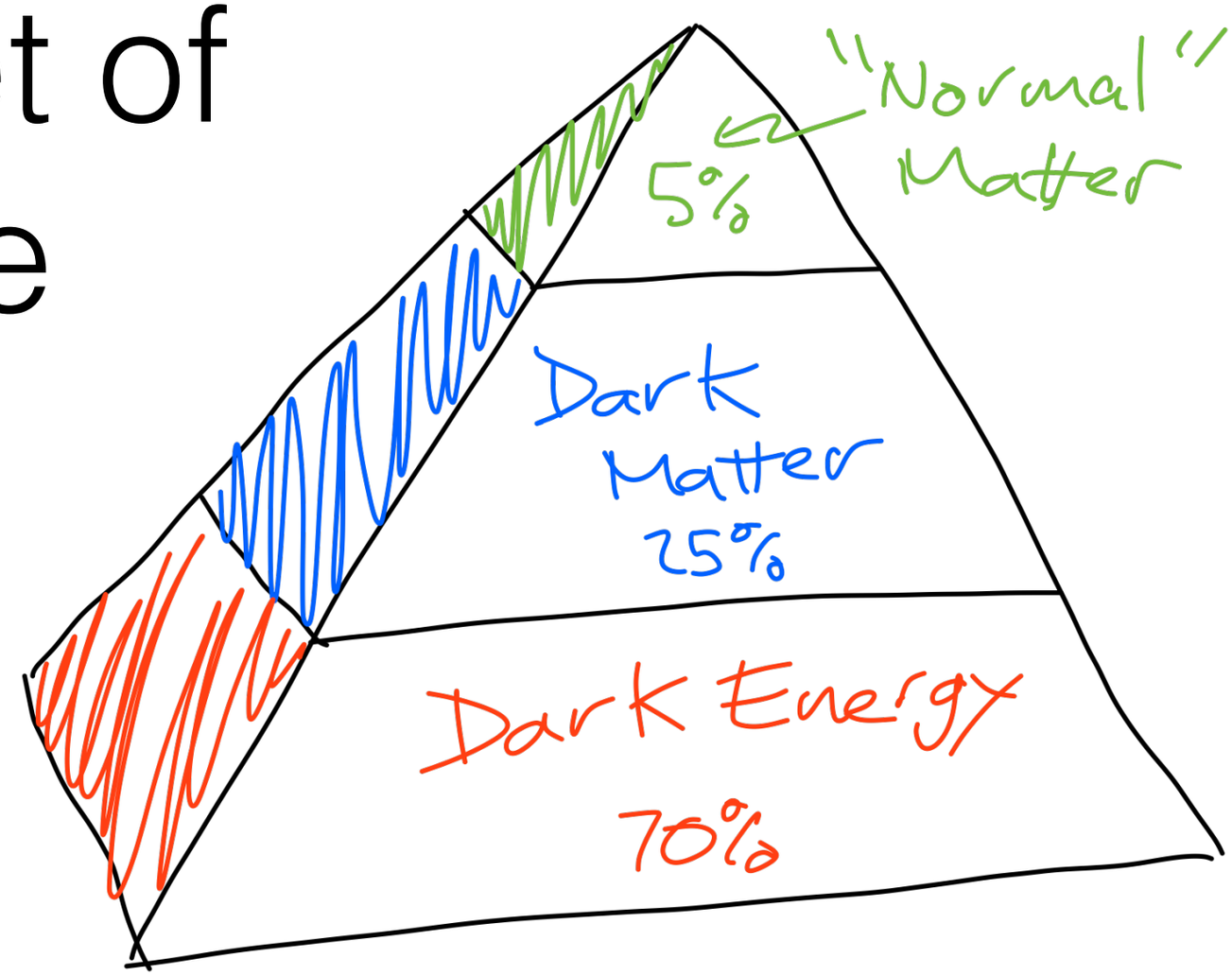


Astrophys. J. **648**, L109 (2006)

Energy Budget of the Universe

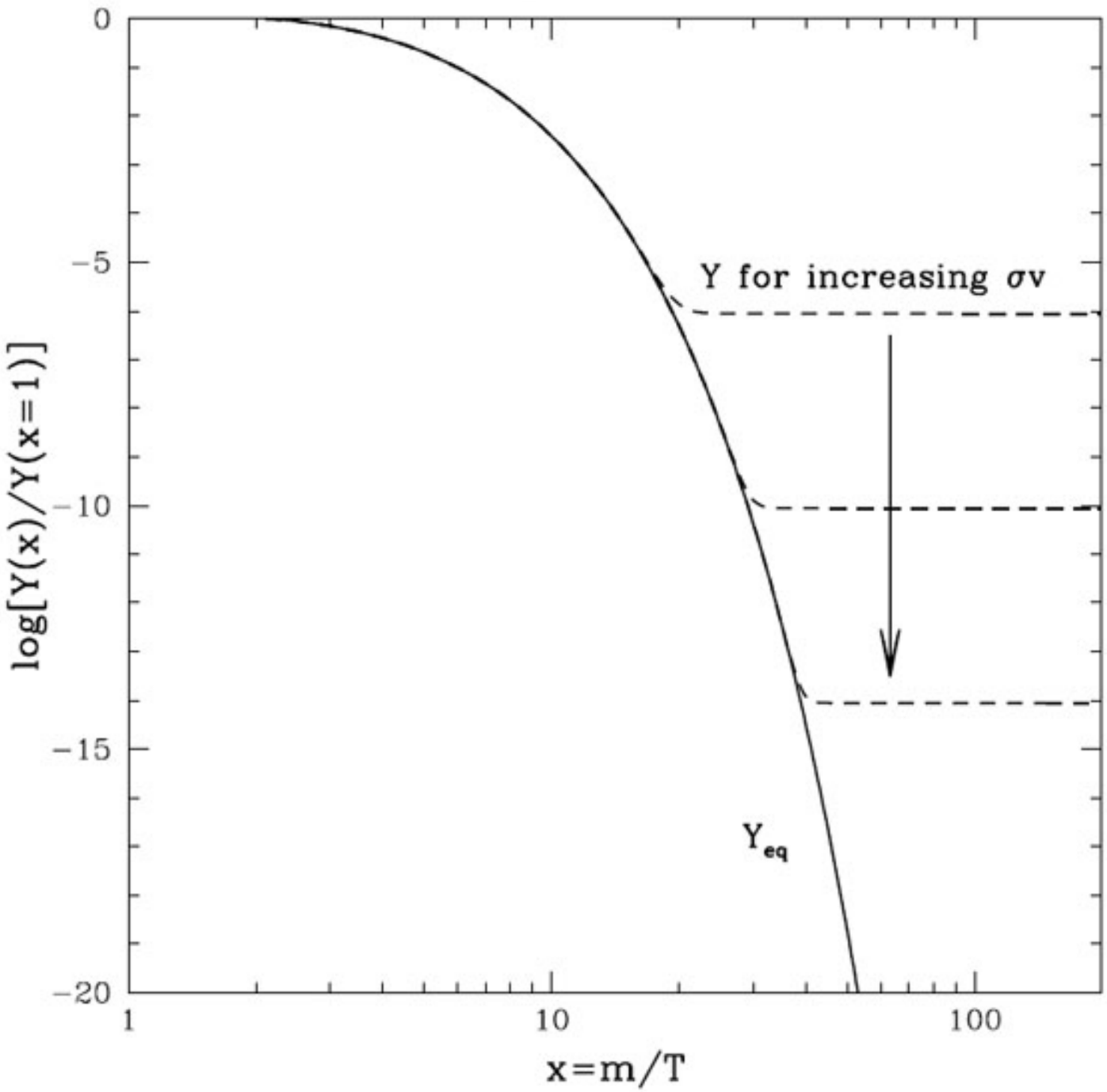


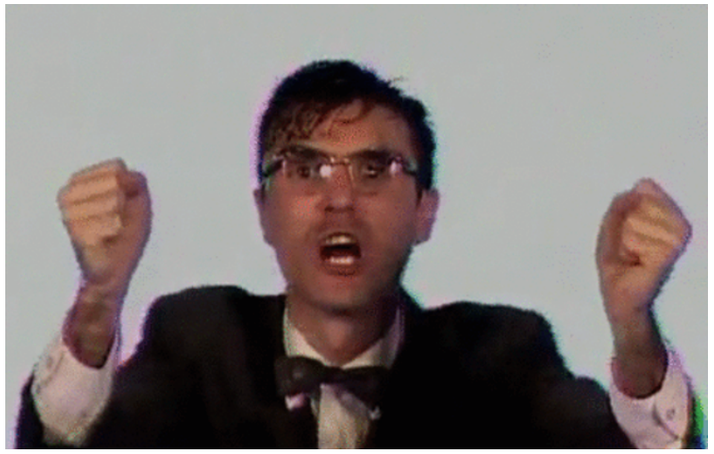
Energy Budget of the Universe



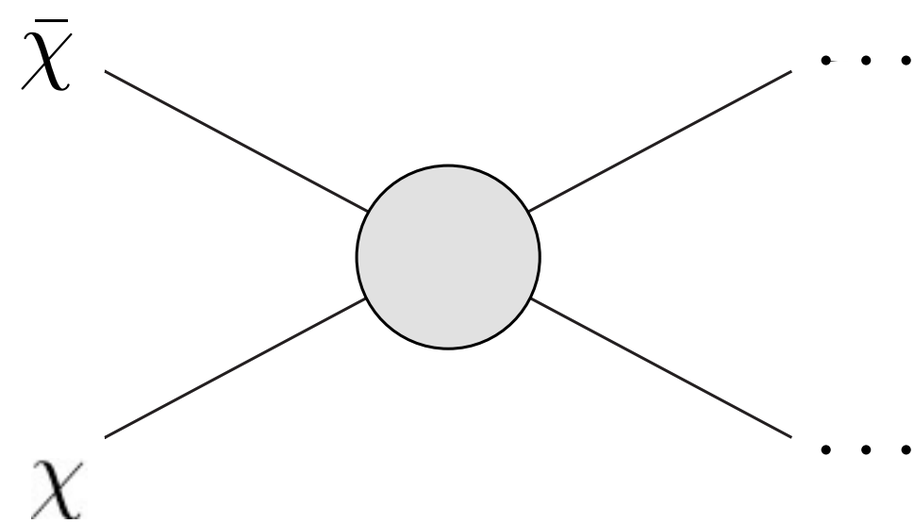
We need dark matter

Well, how did it get here? (And go away?)

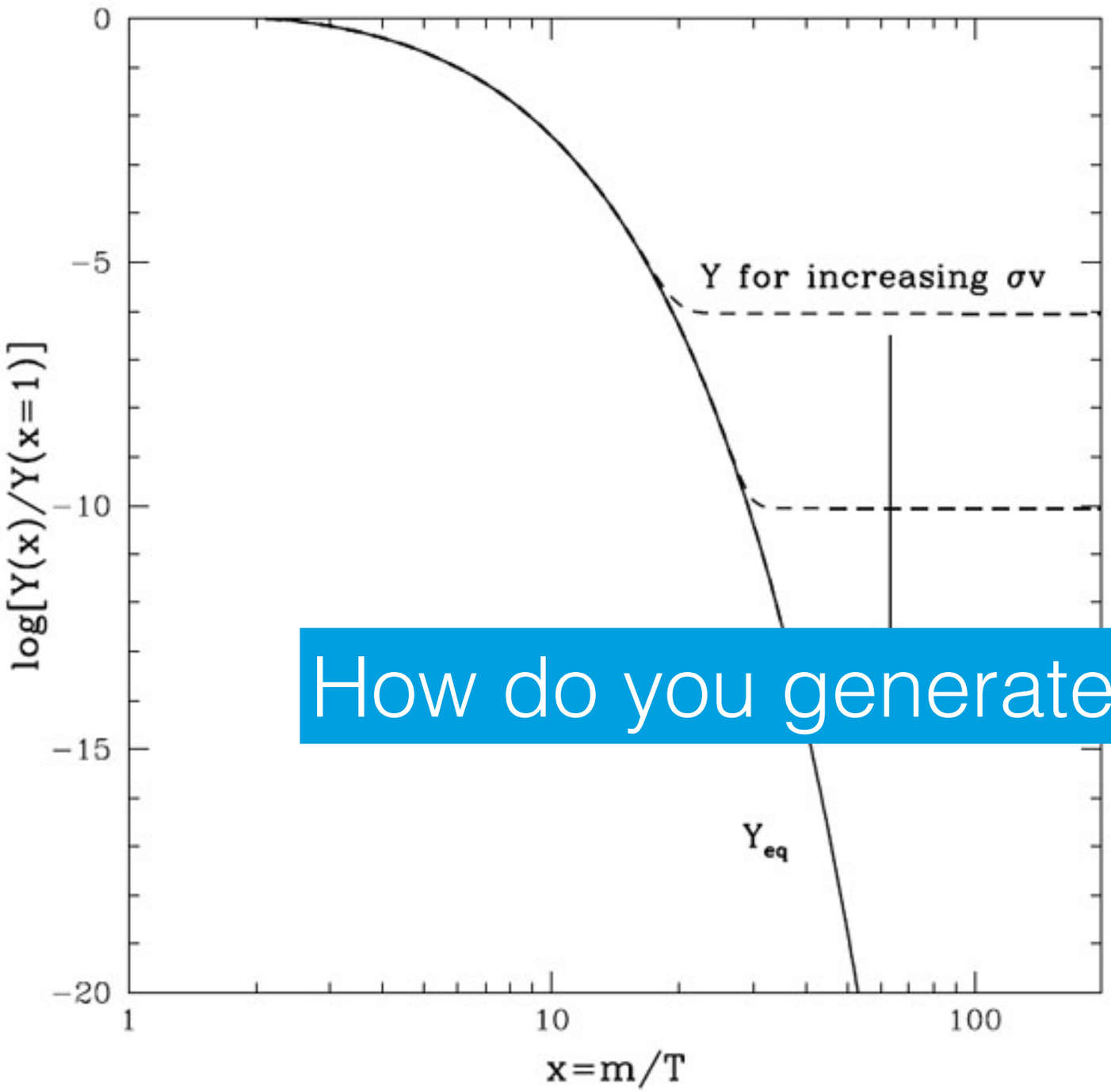




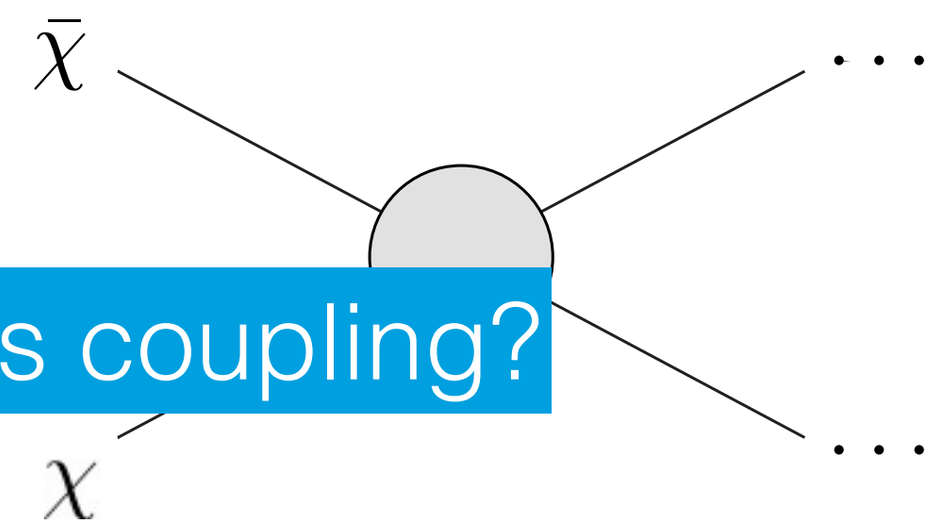
Needs a coupling to (lighter) stuff



Well, how did it get here? (And go away?)



Needs a coupling to (lighter) stuff



How do you generate this coupling?

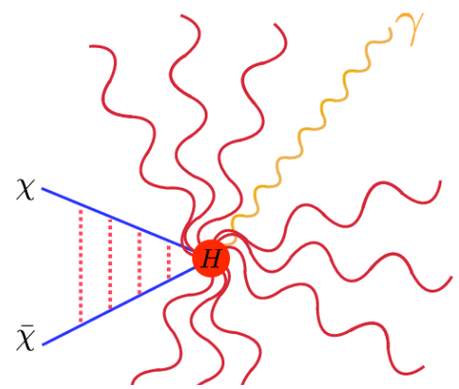
Electroweak interactions? (WIMP)

Nice because you get the right amount

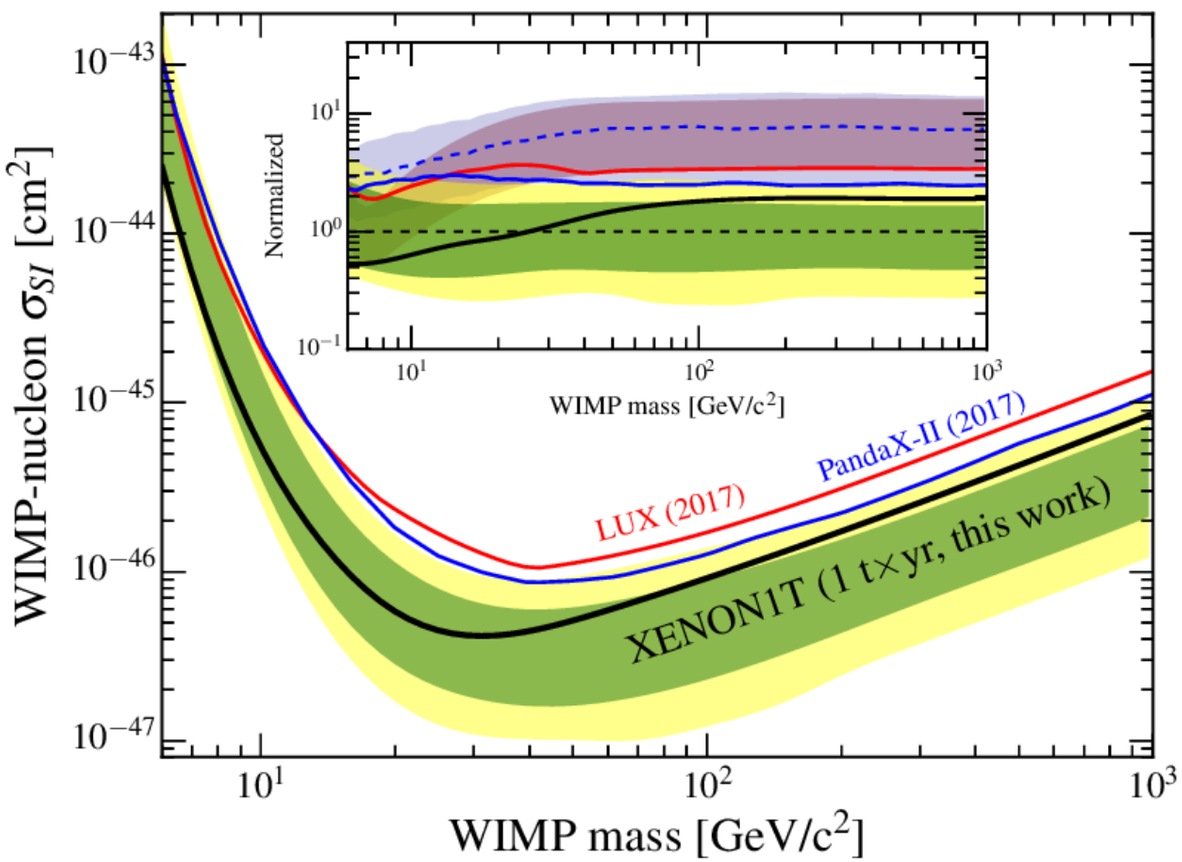
$$\Omega h^2 \sim \frac{1}{\langle \sigma v \rangle} \sim \frac{m^2}{g^4} \sim 0.1 \left(\frac{m}{m_{\rm EW}}\right)^2 \left(\frac{g_{\rm EW}}{g}\right)^4$$

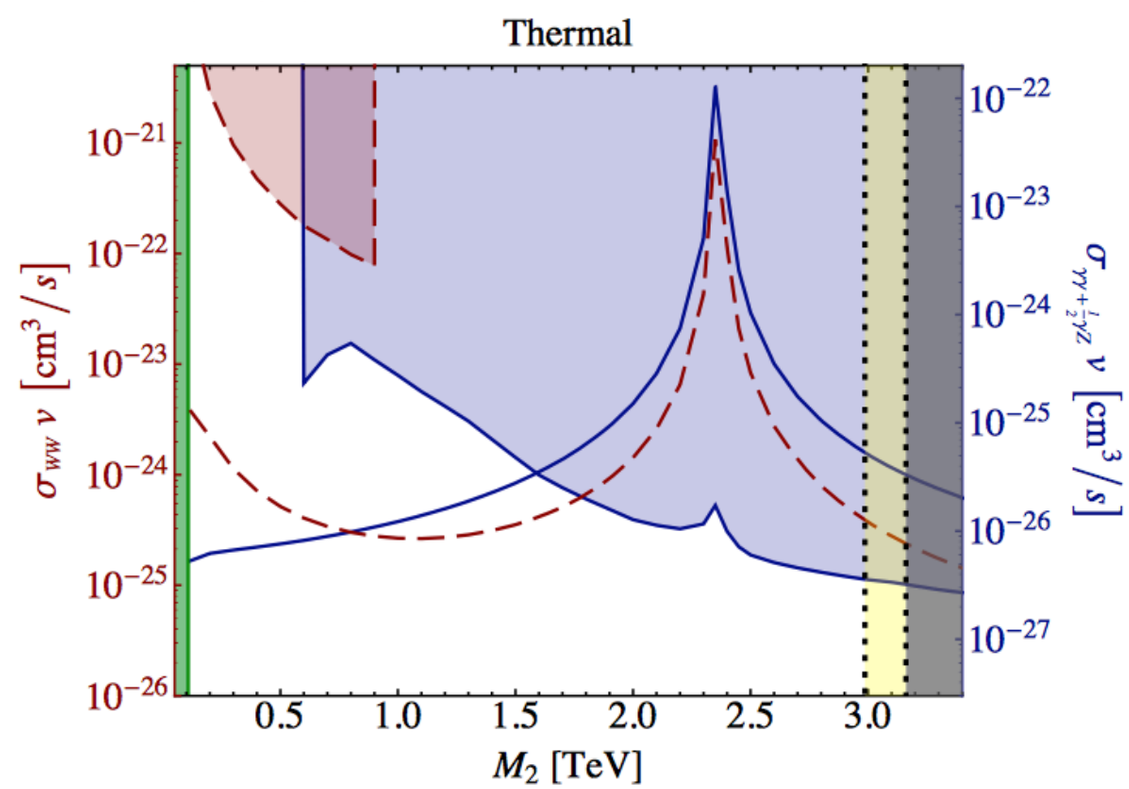
Very (too) detectable!

$$\sigma_{\rm DD} \sim \frac{G_F^2 \mu^2}{\pi} Y^2 \sim 10^{-39}\ {\rm cm}^2 \left(\frac{Y}{1/2}\right)^2$$



Cohen et al.
Baumgart et al., …





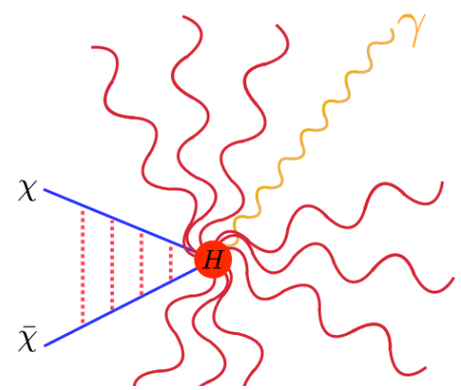
Electroweak interactions? (WIMP)

Nice because you get the right amount

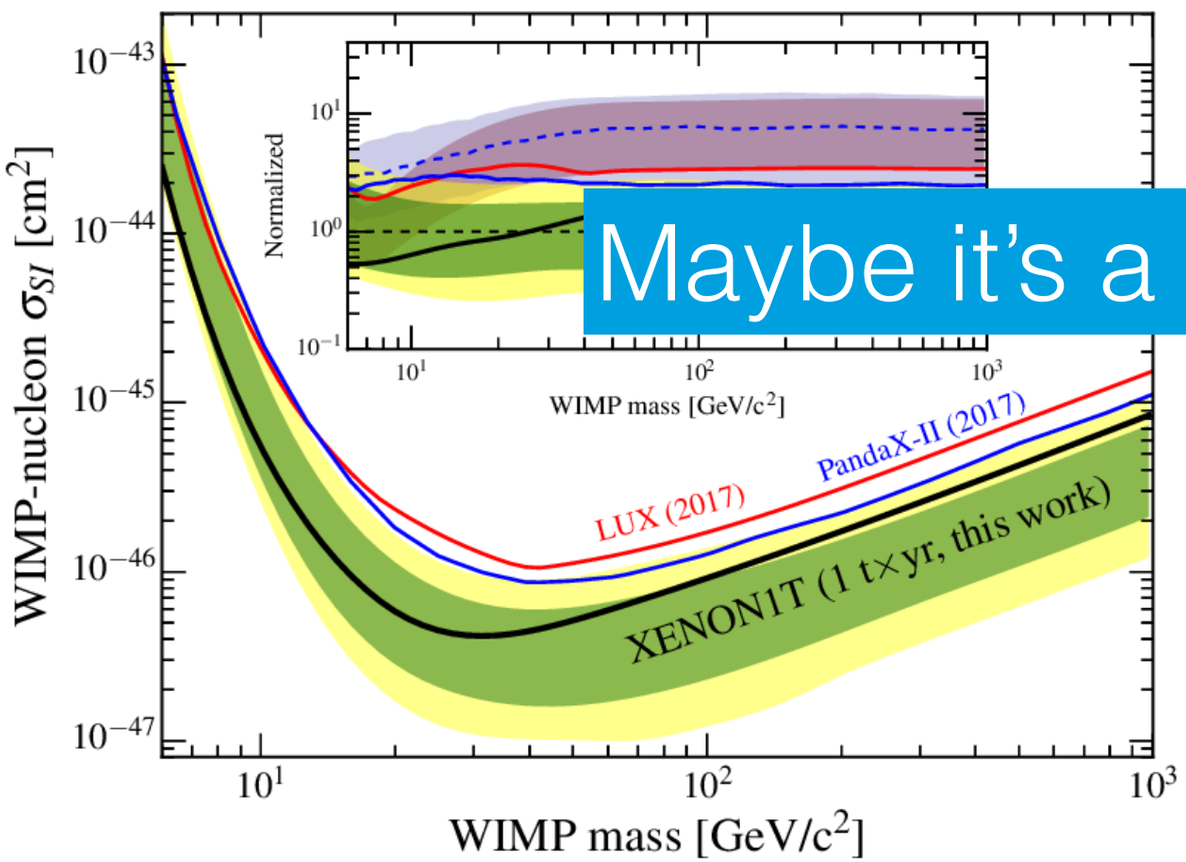
$$\Omega h^2 \sim \frac{1}{\langle \sigma v \rangle} \sim \frac{m^2}{g^4} \sim 0.1 \left(\frac{m}{m_{\rm EW}}\right)^2 \left(\frac{g_{\rm EW}}{g}\right)^4$$

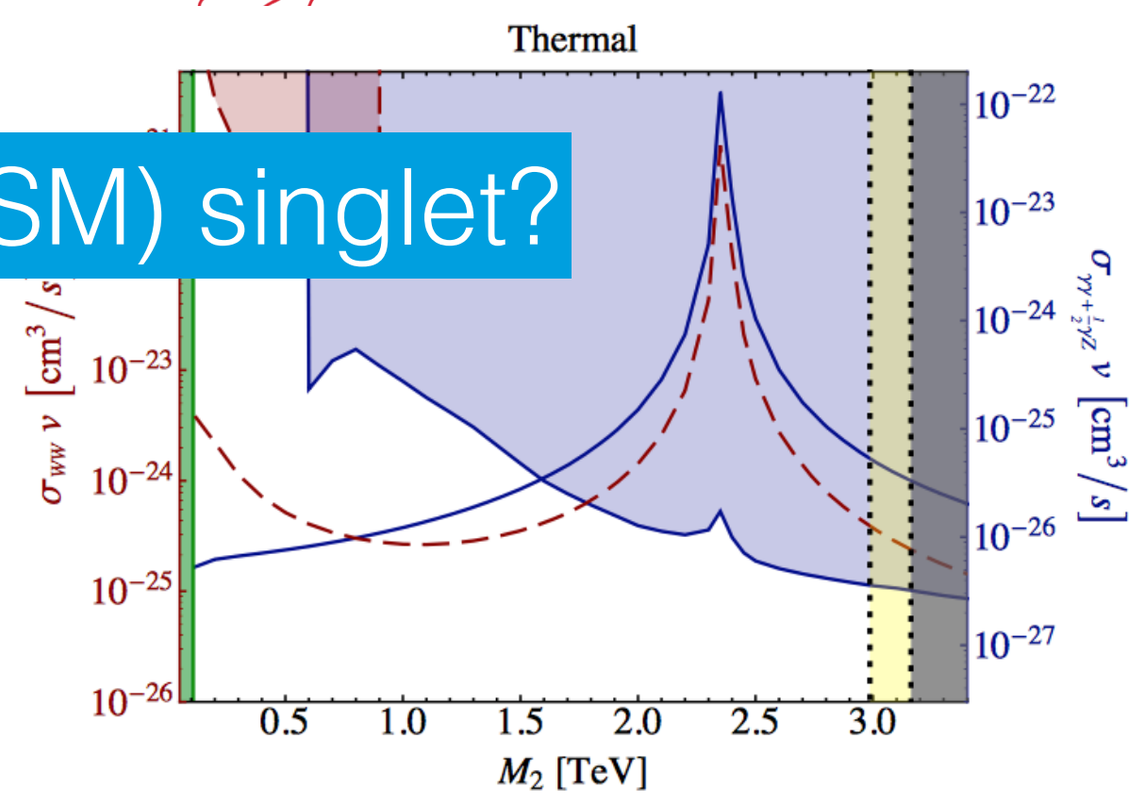
Very (too) detectable!

$$\sigma_{\rm DD} \sim \frac{G_F^2 \mu^2}{\pi} Y^2 \sim 10^{-39}\ {\rm cm}^2 \left(\frac{Y}{1/2}\right)^2$$



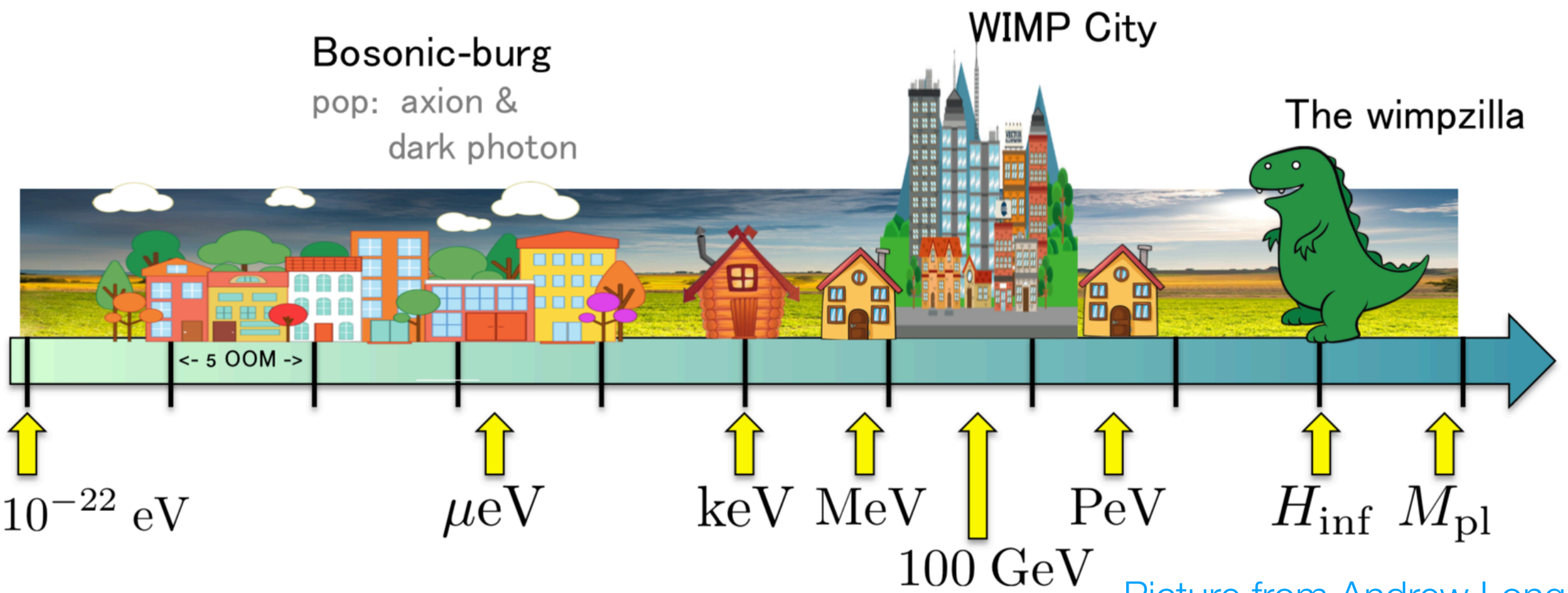
Cohen et al.
Baumgart et al., …





Maybe it's a (SM) singlet?

Beyond WIMPS, dark matter candidates span orders of magnitude in mass



Picture from Andrew Long

Boson

Boson or Fermion

However…

Cosmological Lower Bound on Heavy-Neutrino Masses

Benjamin W. Lee[a]
Fermi National Accelerator Laboratory,[b] *Batavia, Illinois 60510*

and

Steven Weinberg[c]
Stanford University, Physics Department, Stanford, California 94305
(Received 13 May 1977)

Lee-Weinberg bound for light dark matter implies new annihilation channel

$$m_L (N_A/\sqrt{N_F})^{0.51} \gtrsim 5.2 \text{ GeV}$$

However…

Cosmological Lower Bound on Heavy-Neutrino Masses

Benjamin W. Lee[a]
Fermi National Accelerator Laboratory,[b] *Batavia, Illinois 60510*

and

Steven Weinberg[c]
Stanford University, Physics Department, Stanford, California 94305
(Received 13 May 1977)

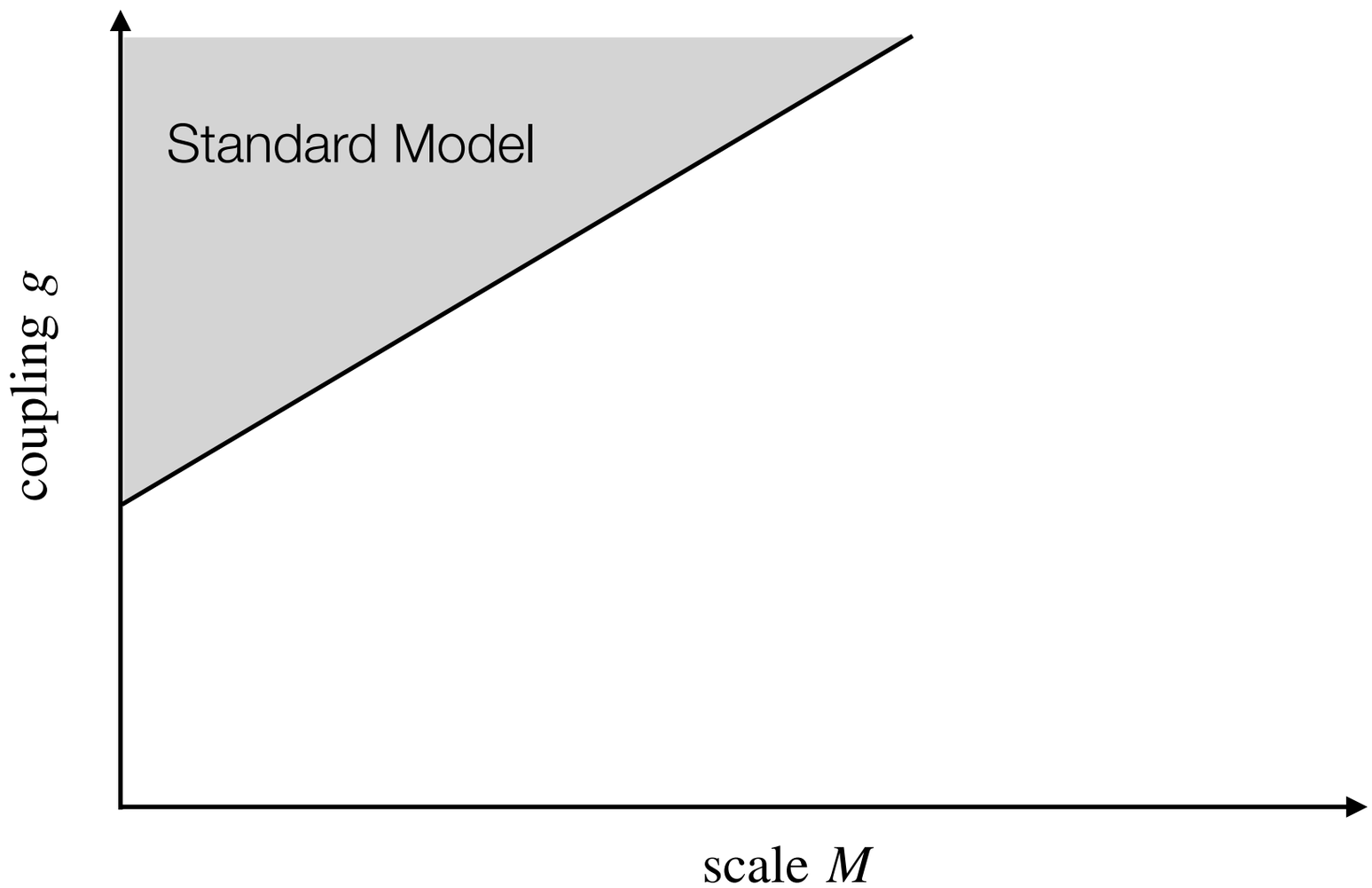
Lee-Weinberg bound for light dark matter implies new annihilation channel

$$m_L (N_A/\sqrt{N_F})^{0.51} \gtrsim 5.2 \text{ GeV}$$

Light dark matter often requires new states!

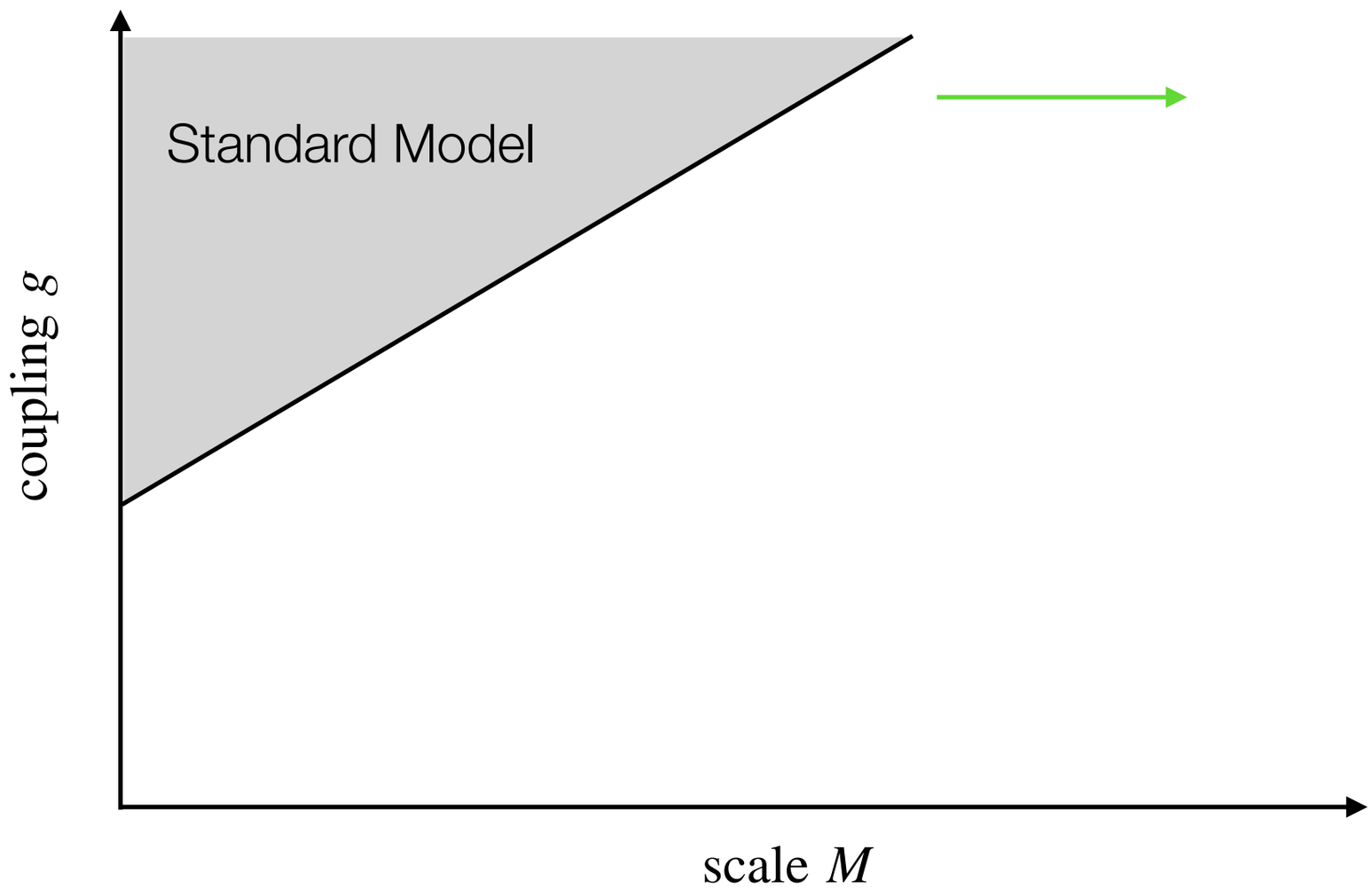
Life at the frontier of the Standard Model

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



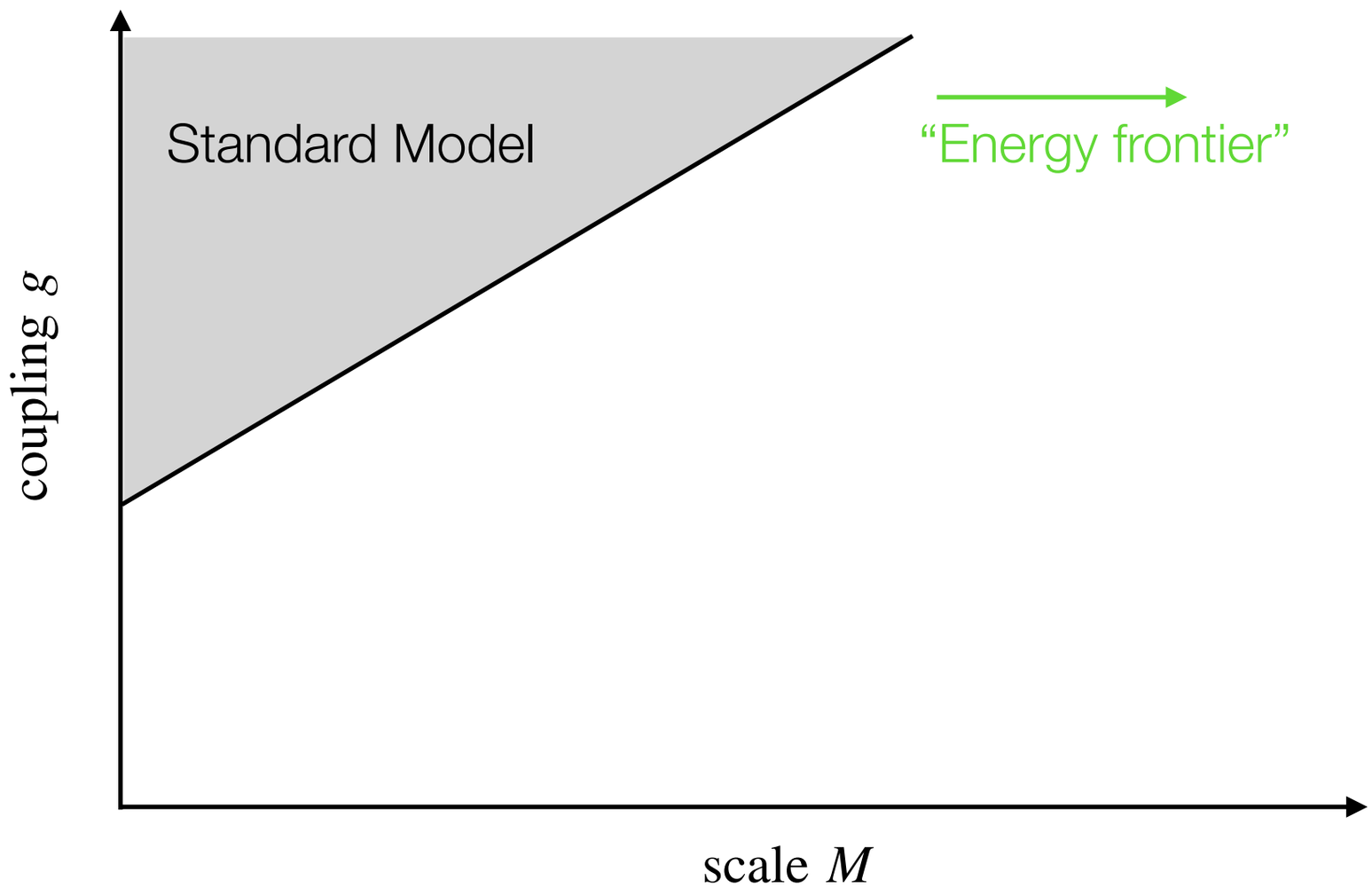
Life at the frontier of the Standard Model

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



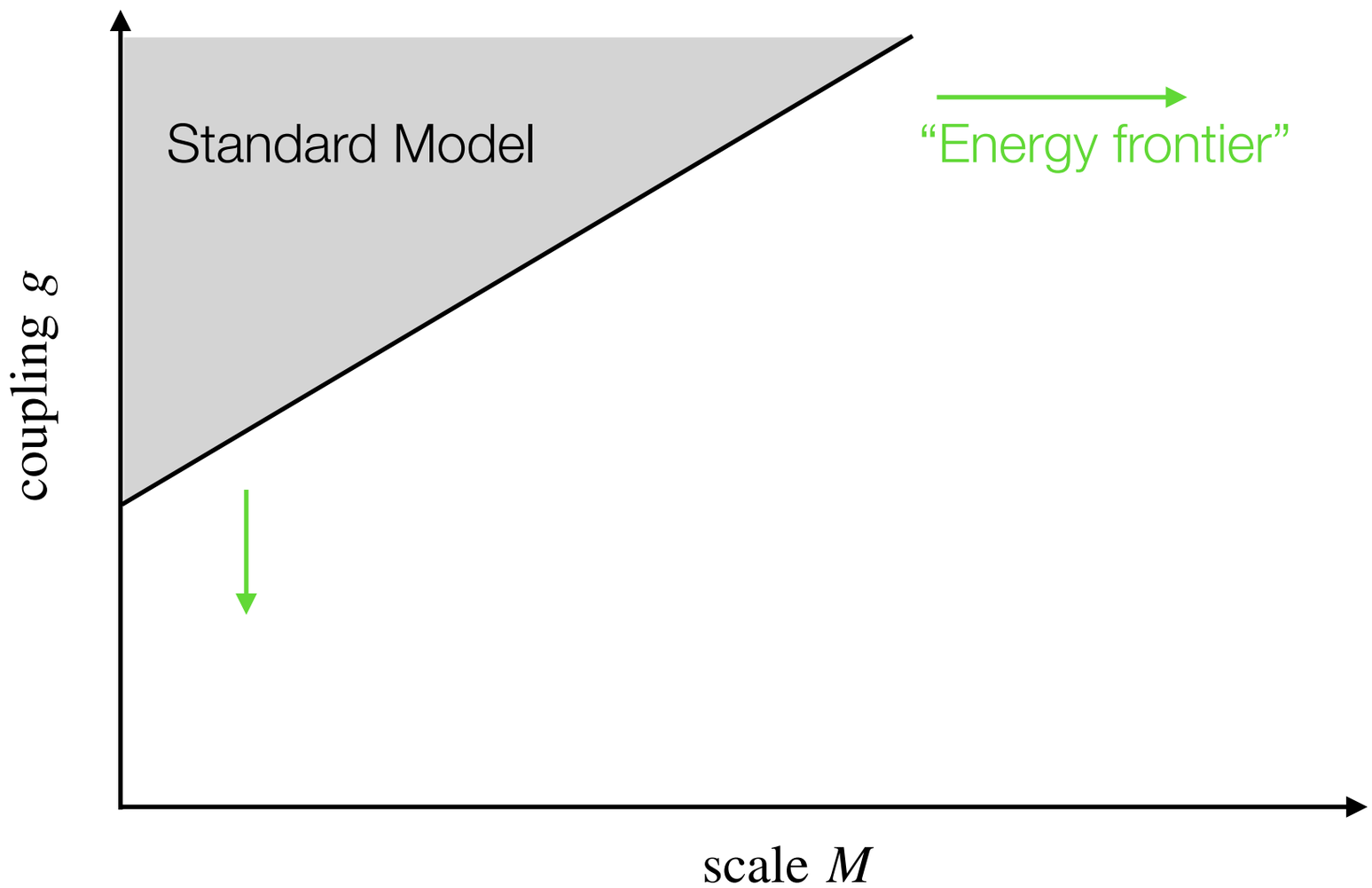
Life at the frontier of the Standard Model

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



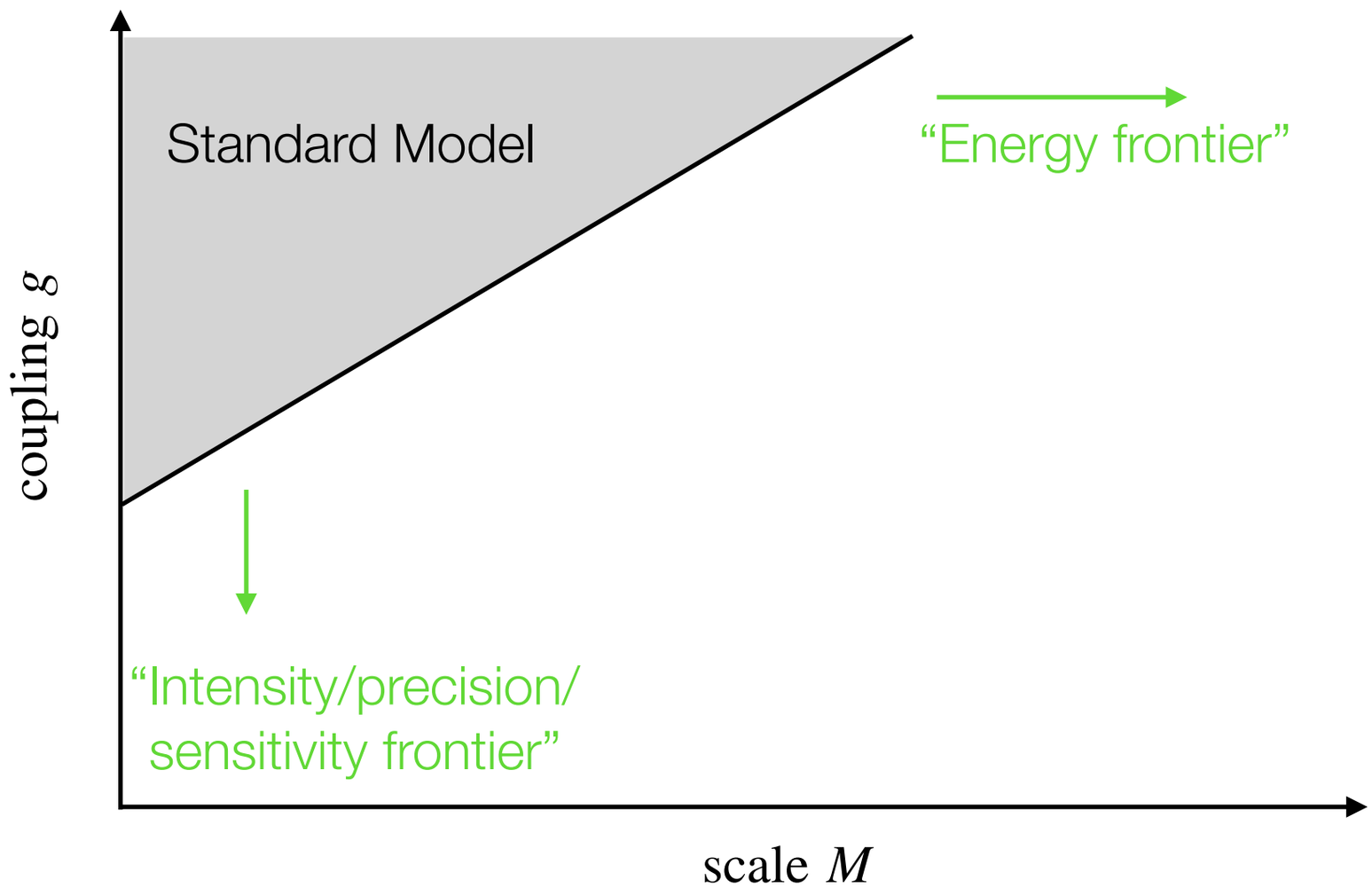
Life at the frontier of the Standard Model

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



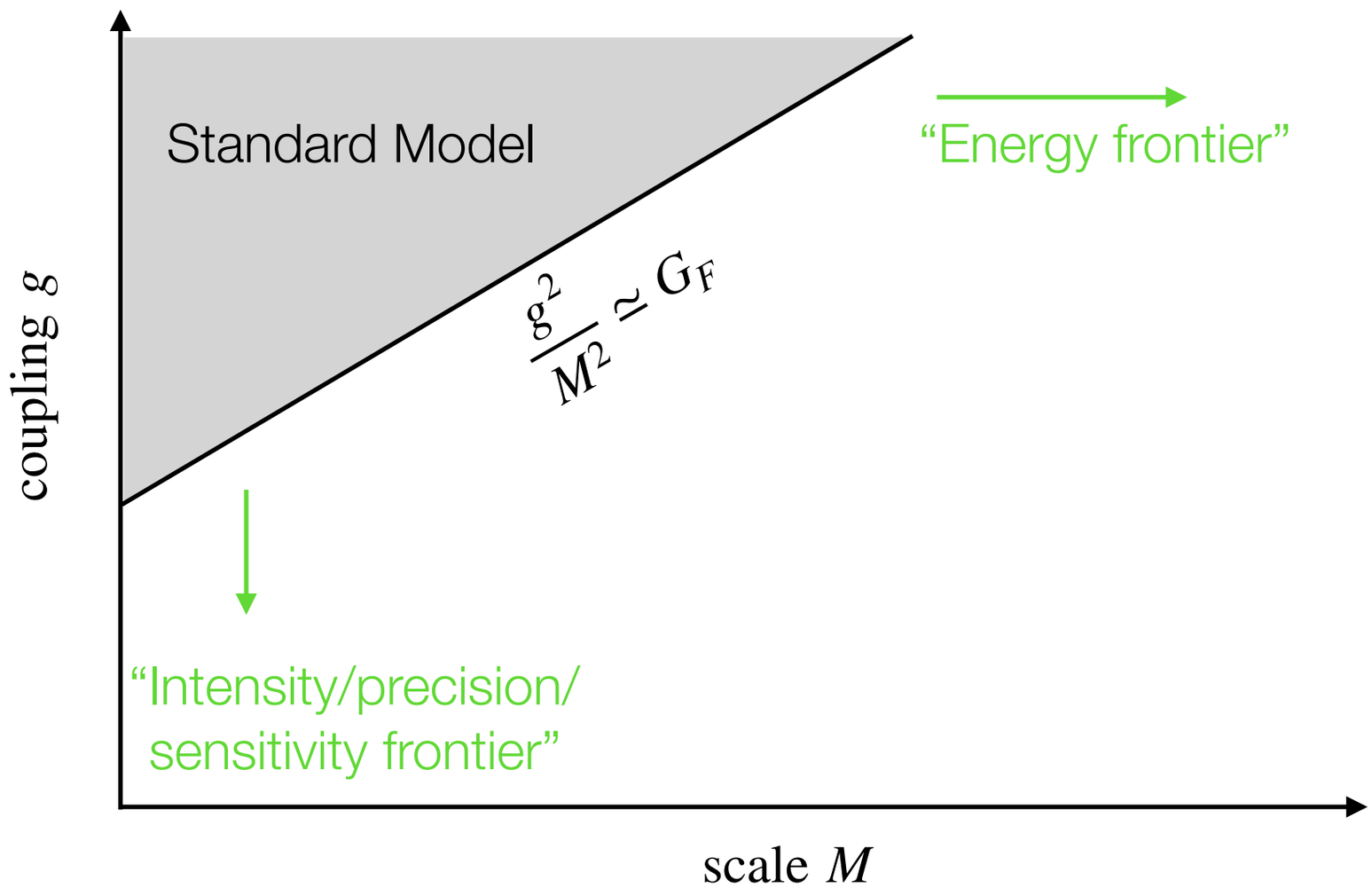
Life at the frontier of the Standard Model

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



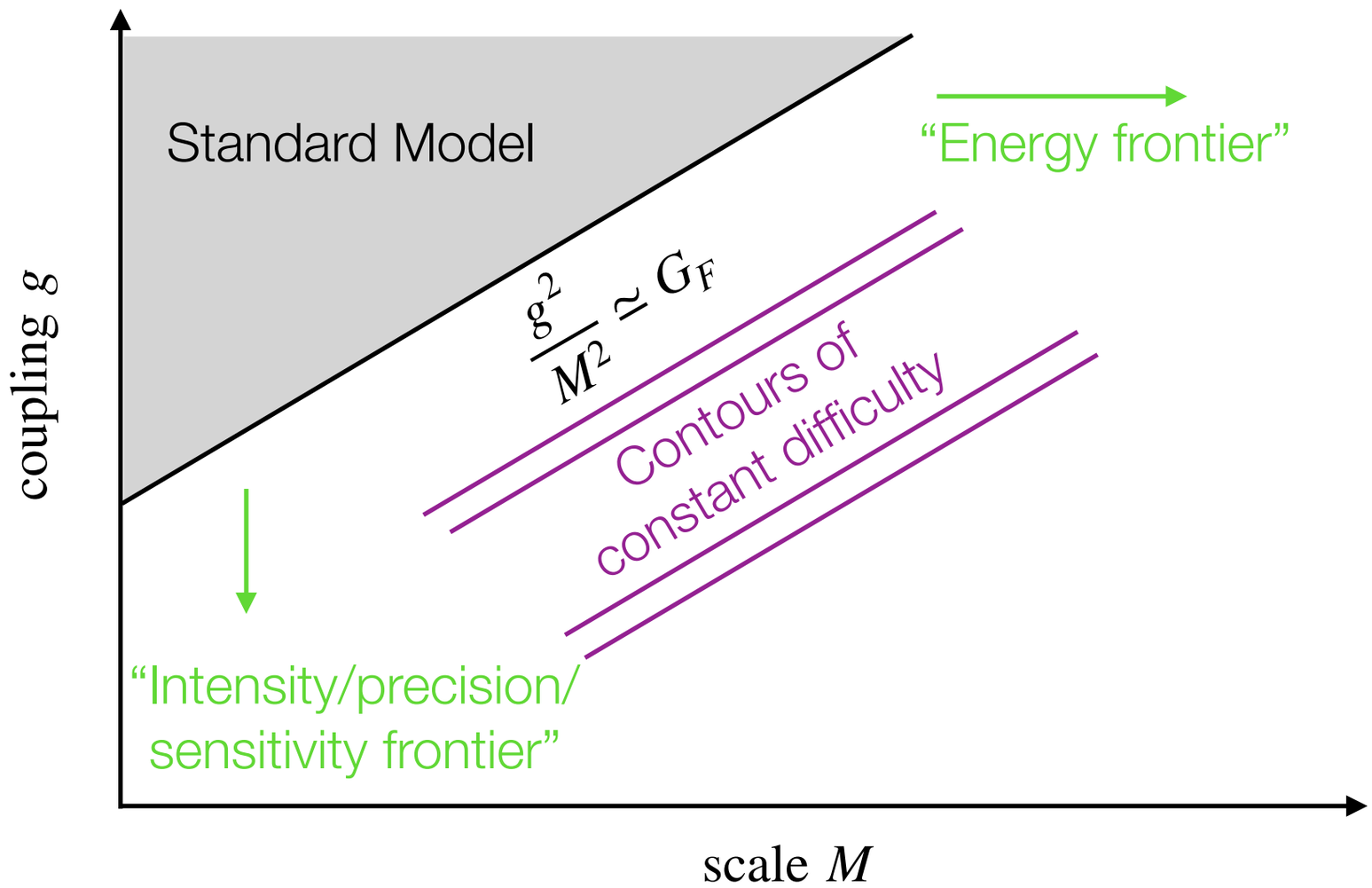
Life at the frontier of the Standard Model

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



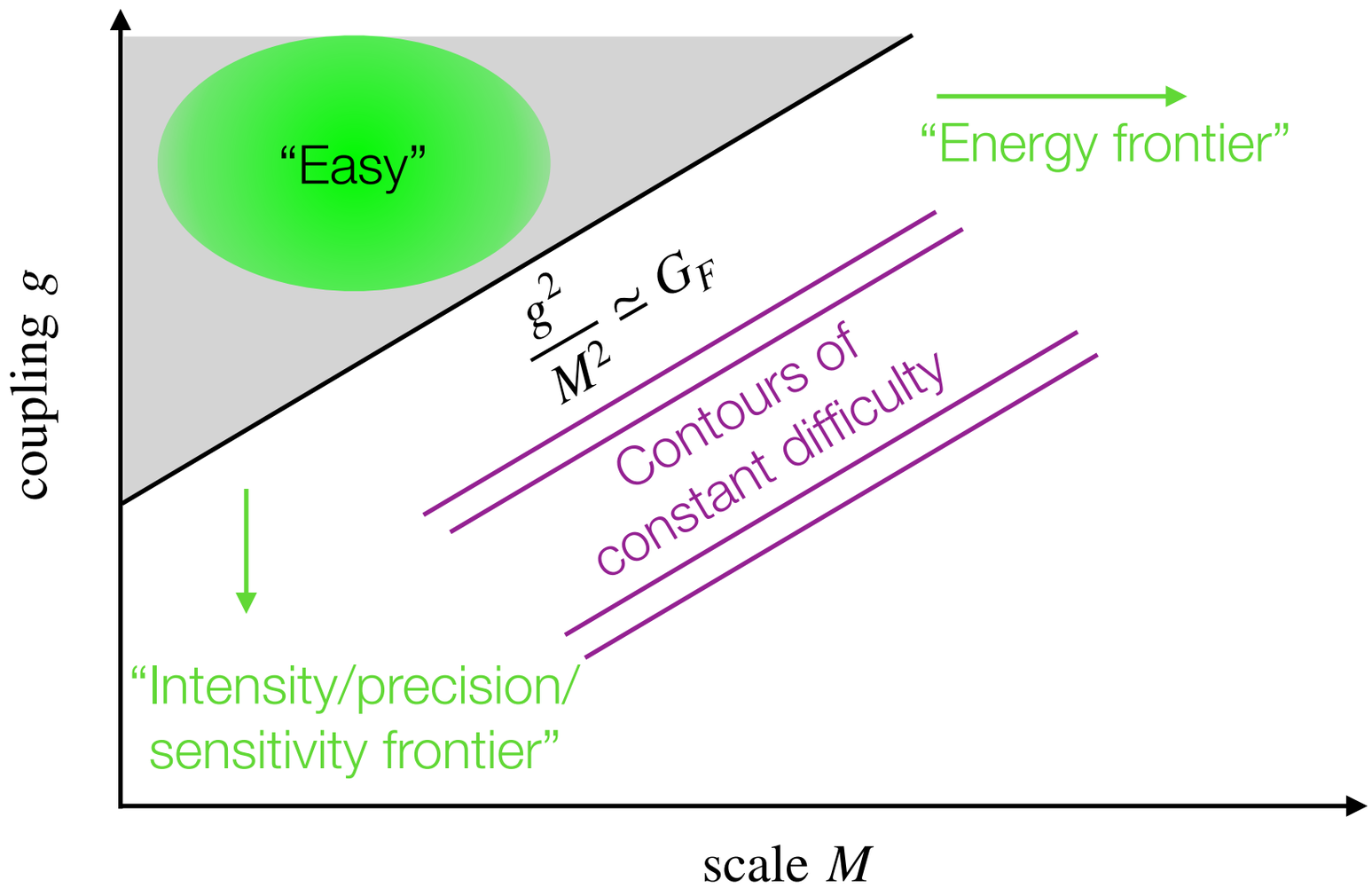
Life at the frontier of the Standard Model

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



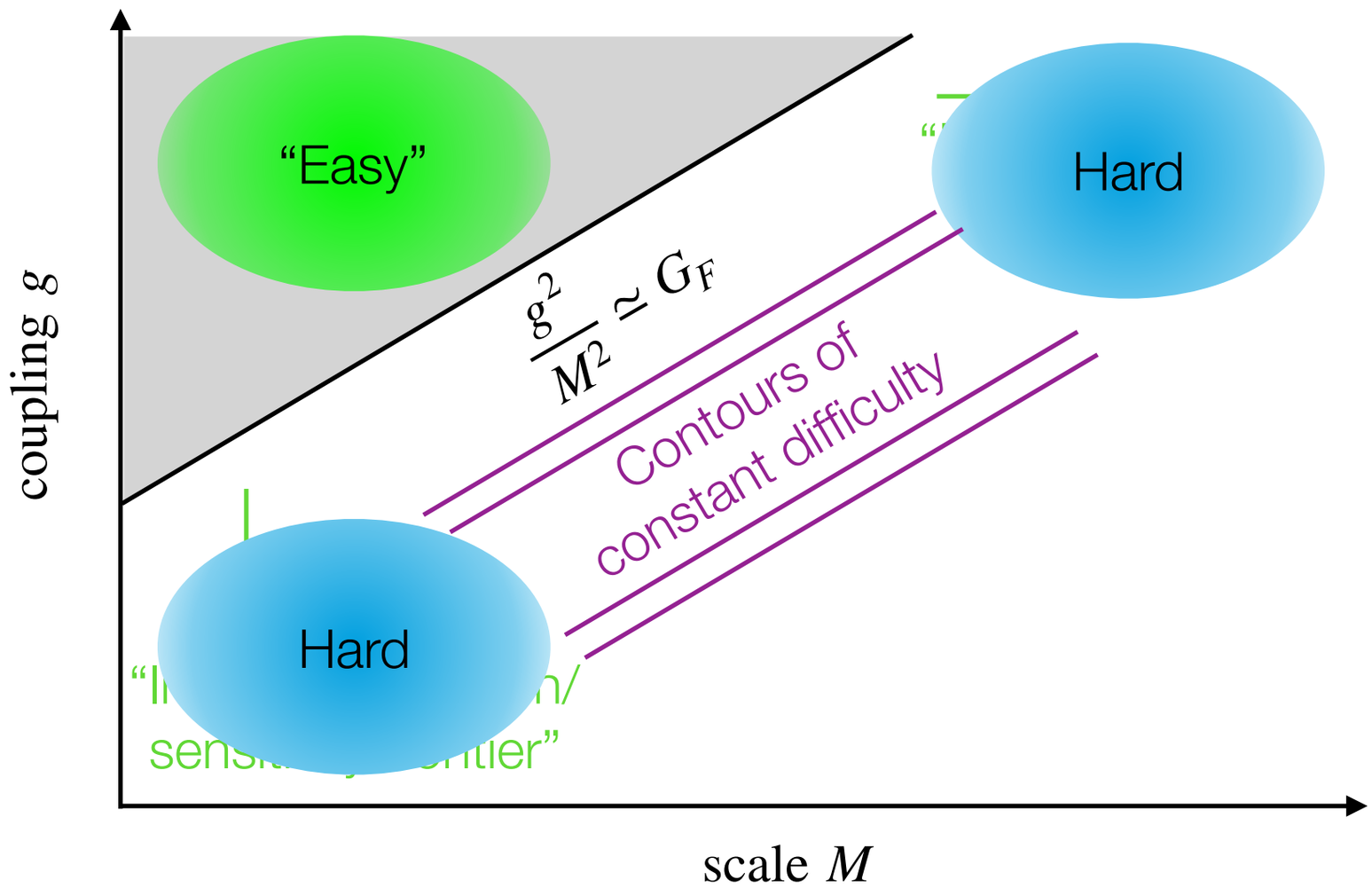
Life at the frontier of the Standard Model

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



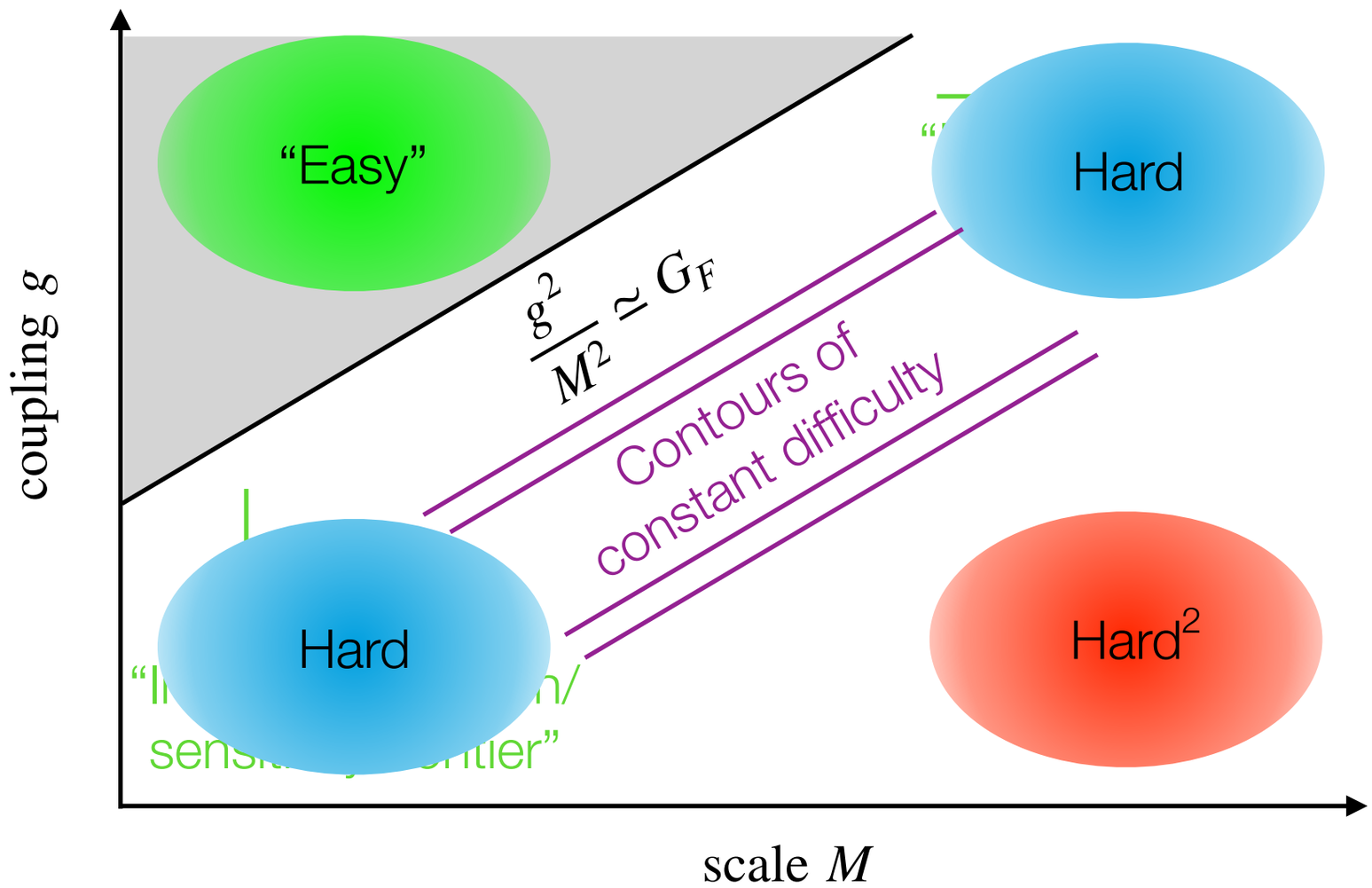
Life at the frontier of the Standard Model

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



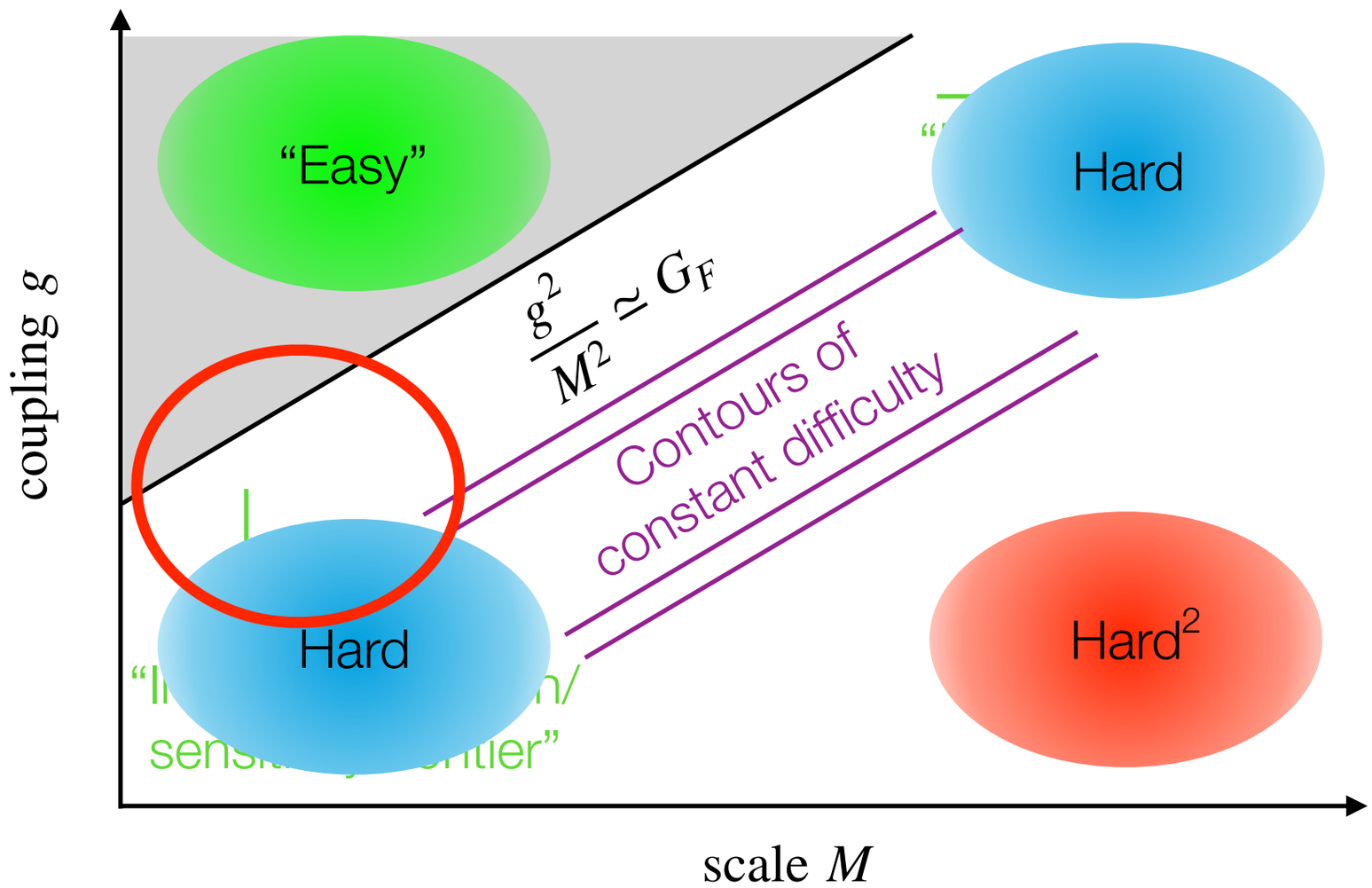
Life at the frontier of the Standard Model

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



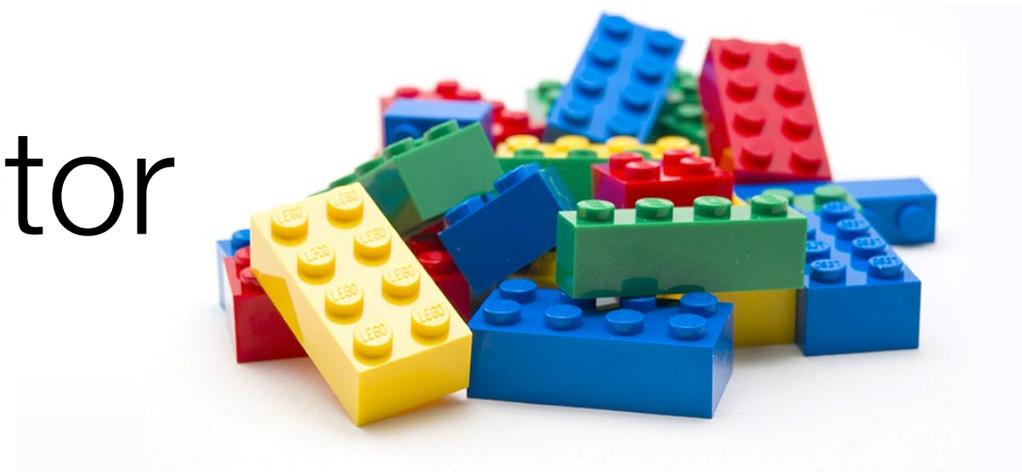
Life at the frontier of the Standard Model

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



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

Building a Dark Sector



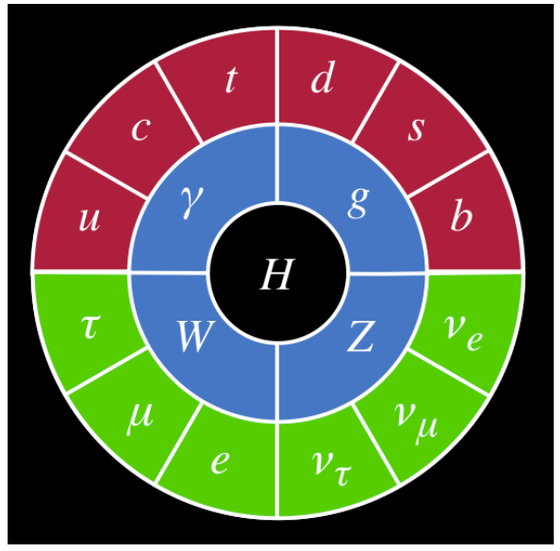
Standard Model gauge symmetries/
forces & particle content:

$$SU(3)_c \times SU(2)_L \times U(1)_Y \xrightarrow{\text{EWSB}} SU(3)_c \times U(1)_{\rm em}$$

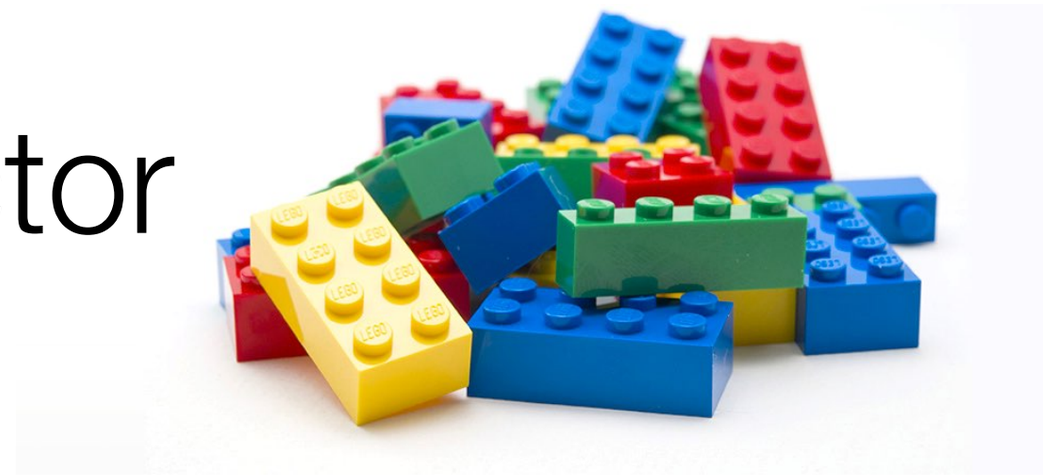
$$G^a_\mu,\ W^b_\mu,\ B_\mu \to G^a_\mu,\ A_\mu$$

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

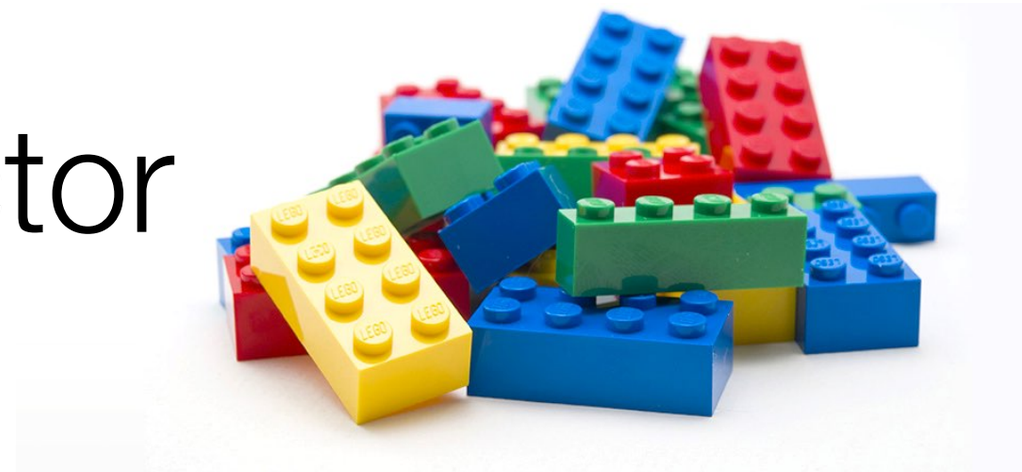
$$H = \begin{pmatrix} \rho^+ \\ v + h + \rho^0 \end{pmatrix}$$



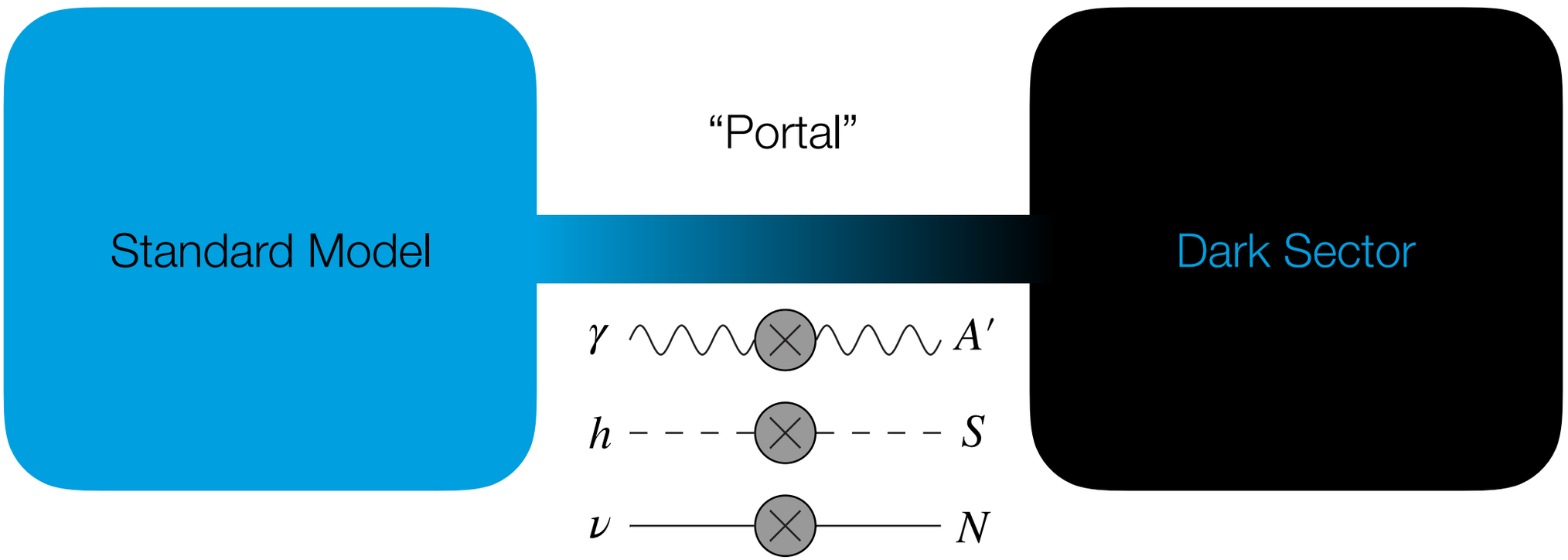
Building a Dark Sector



Building a Dark Sector



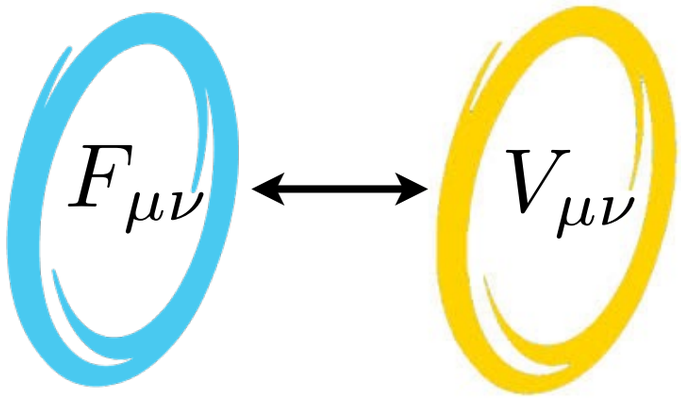
A dark sector is uncharged under SM forces: strong, weak, E&M



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

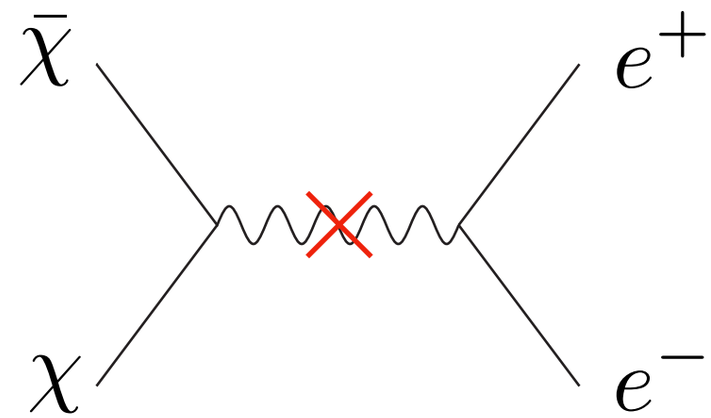
- photon—coupling proportional to SM particle electric charge
- Higgs boson—coupling proportional to SM particle mass
- Neutrinos—couplings only via weak interactions

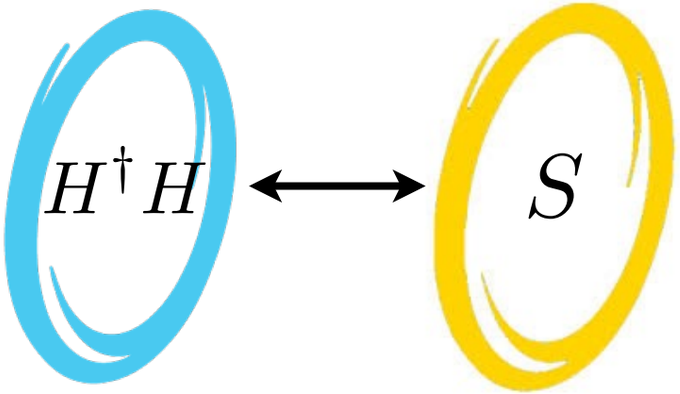
DM through portals



$$\mathcal{L}_{\rm mix} = \frac{\epsilon}{2} F^{\mu\nu} F'_{\mu\nu}$$

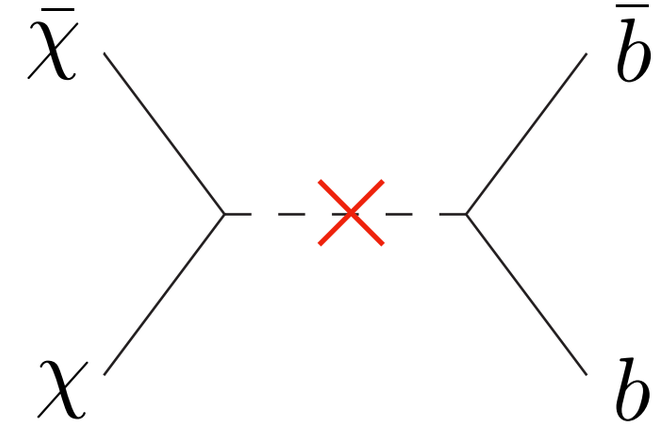
"Vector Portal"
("Kinetic Mixing")

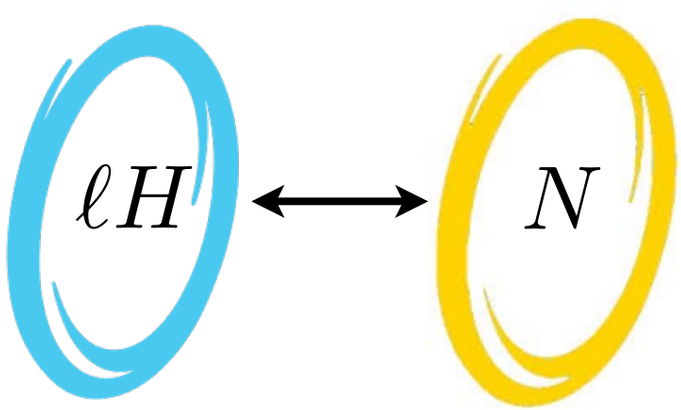




$$\mathcal{L}_{\rm mix} = A H^\dagger H S \to 2AvhS$$

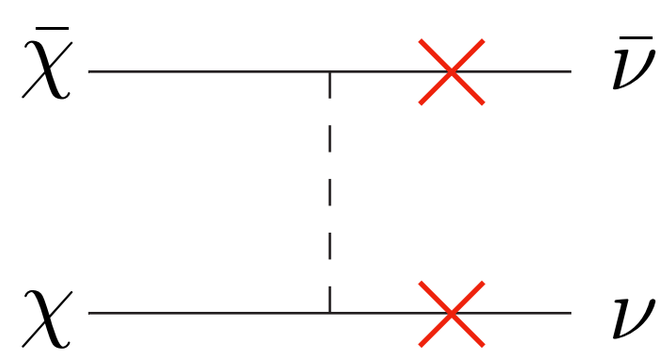
"Higgs Portal"





$$\mathcal{L}_{\rm mix} = \bar{L} H N + \text{h.c.}$$
$$\to v \bar{\nu} N + \text{h.c.}$$

"Neutrino Portal"

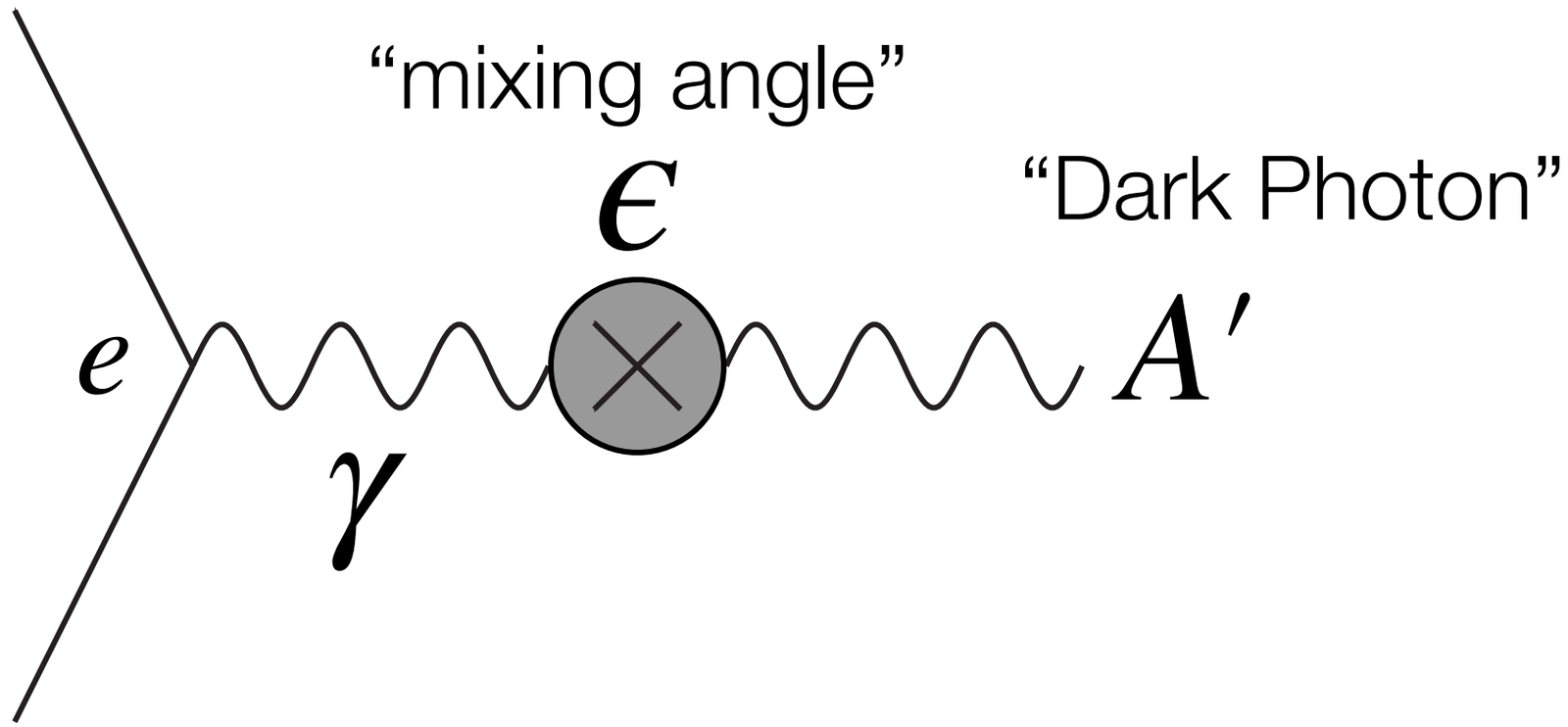


Vector Portal

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

Okun '82
Galison & Manohar '84
Holdom '86

SM particle
e.g. electron

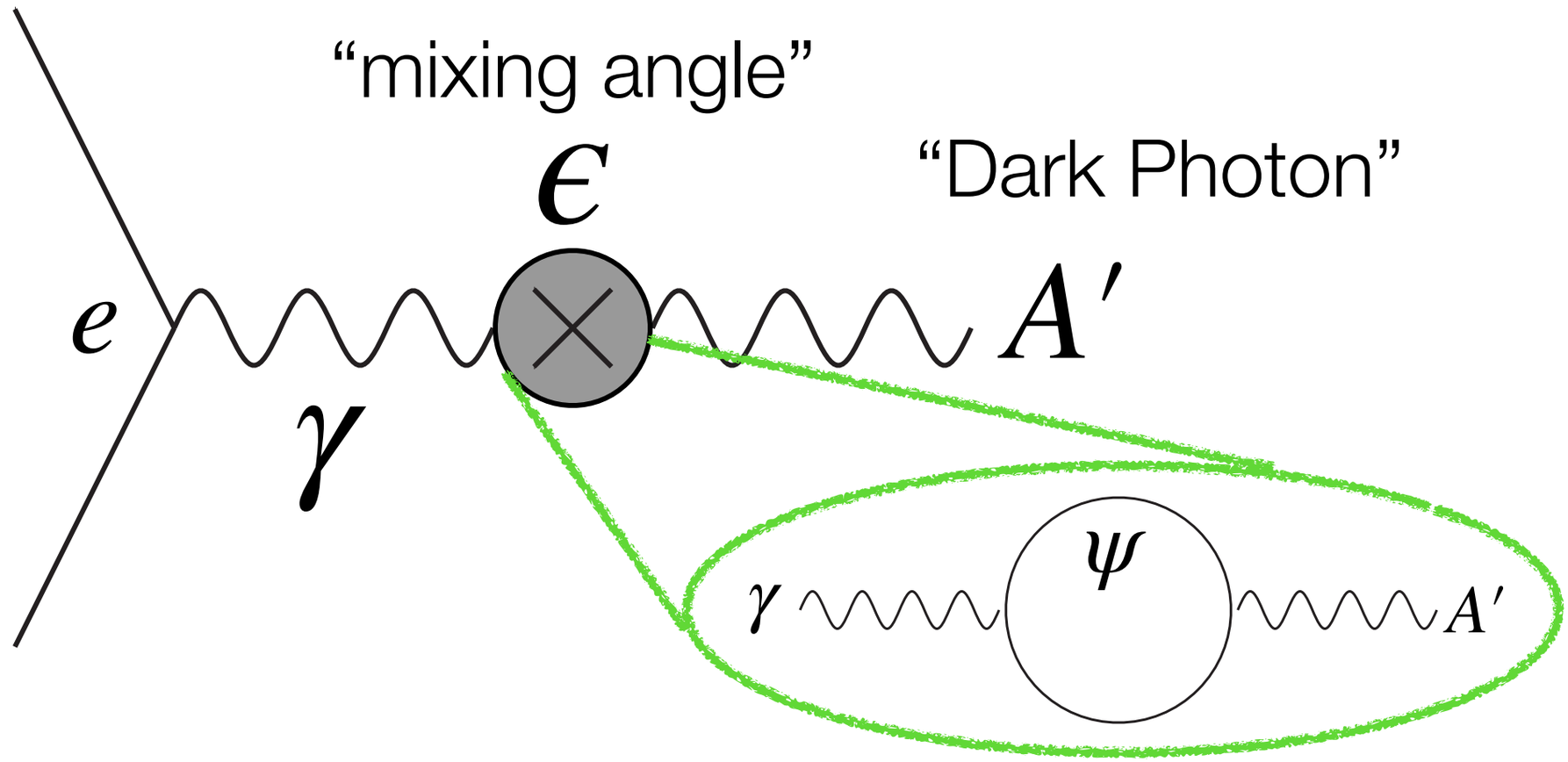


Vector Portal

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

Okun '82
Galison & Manohar '84
Holdom '86

SM particle
e.g. electron



Natural set of parameters

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

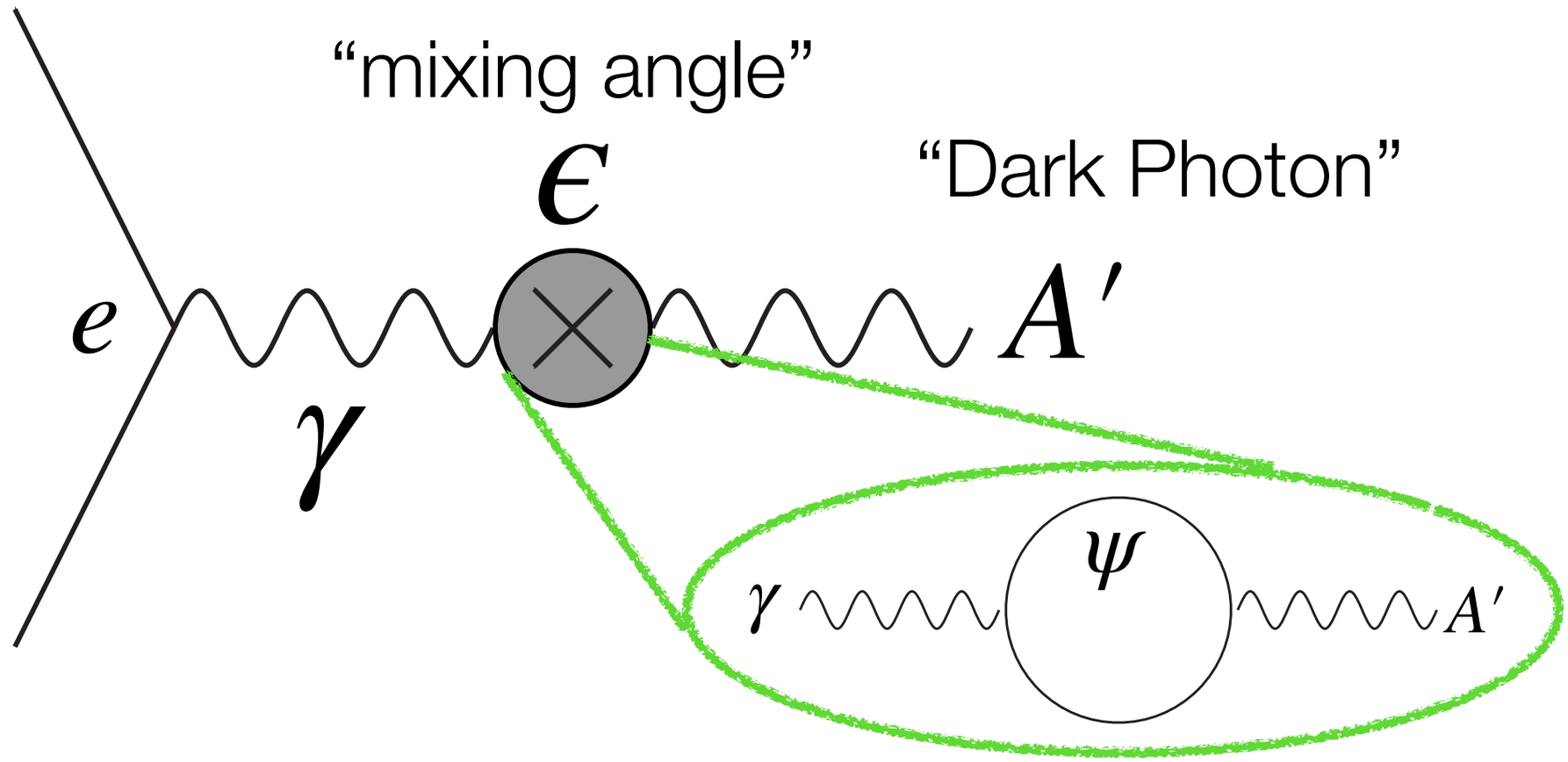
$$m_{A'} \sim \mathrm{MeV} - \mathrm{GeV}$$

Vector Portal

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

Okun '82
Galison & Manohar '84
Holdom '86

SM particle
e.g. electron



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

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

Natural set of parameters

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

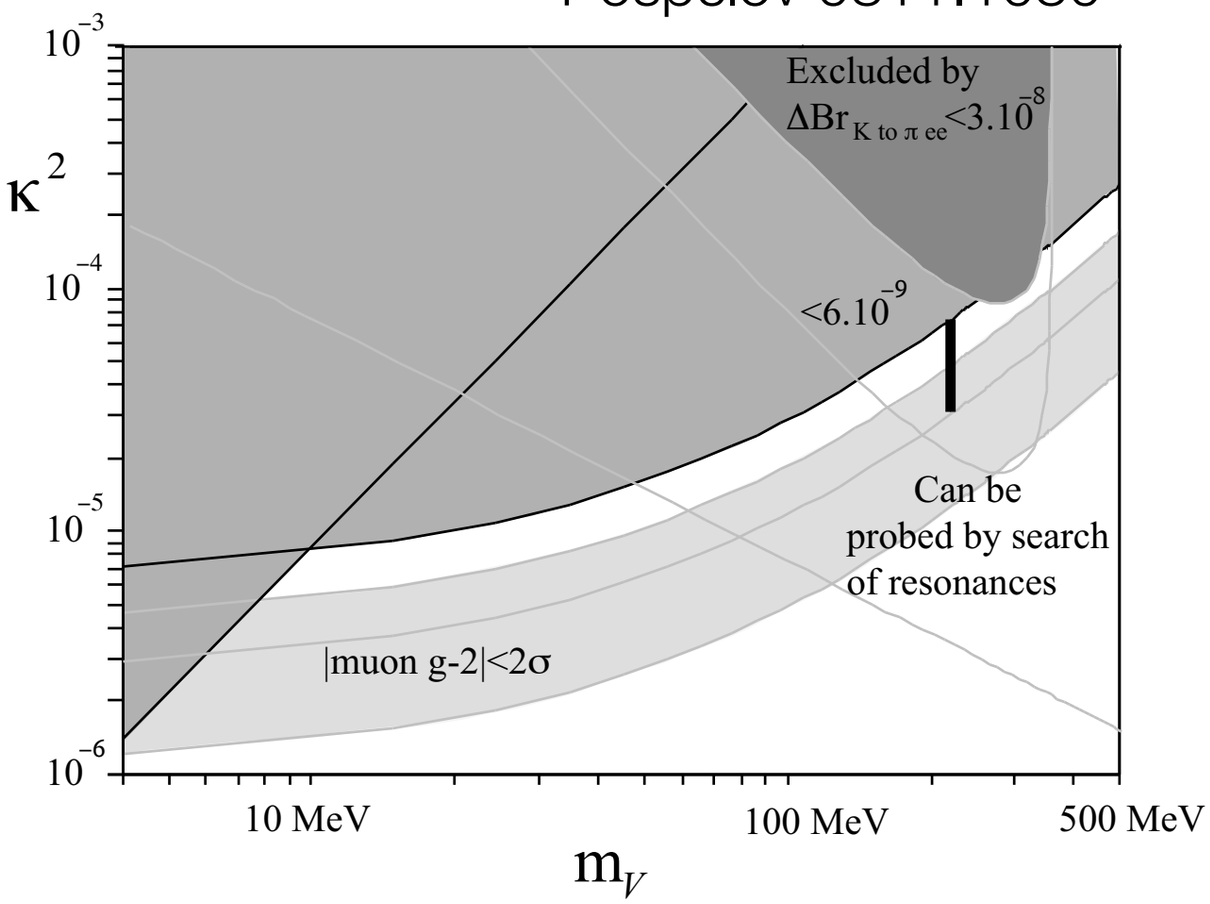
$$m_{A'} \sim \mathrm{MeV} - \mathrm{GeV}$$

Vector Portal

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

Okun '82
Galison & Manohar '84
Holdom '86

Pospelov 0811.1030

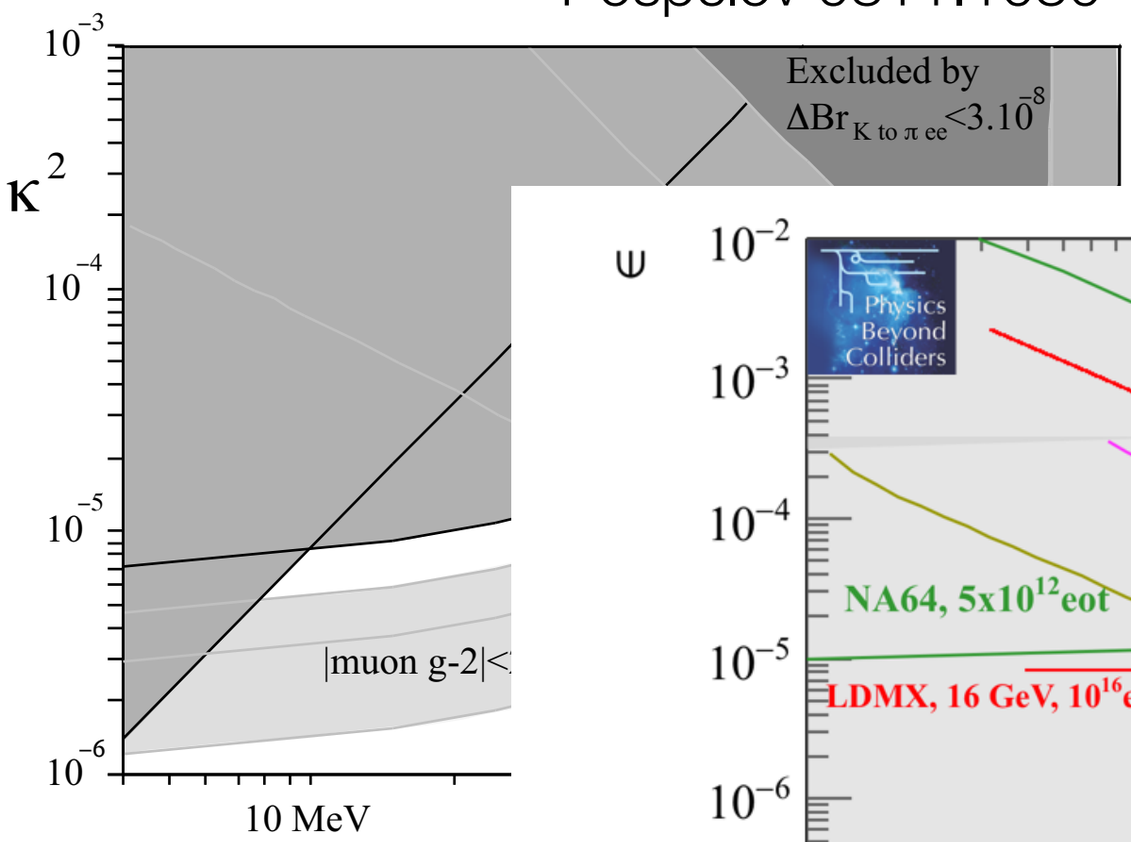


Vector Portal

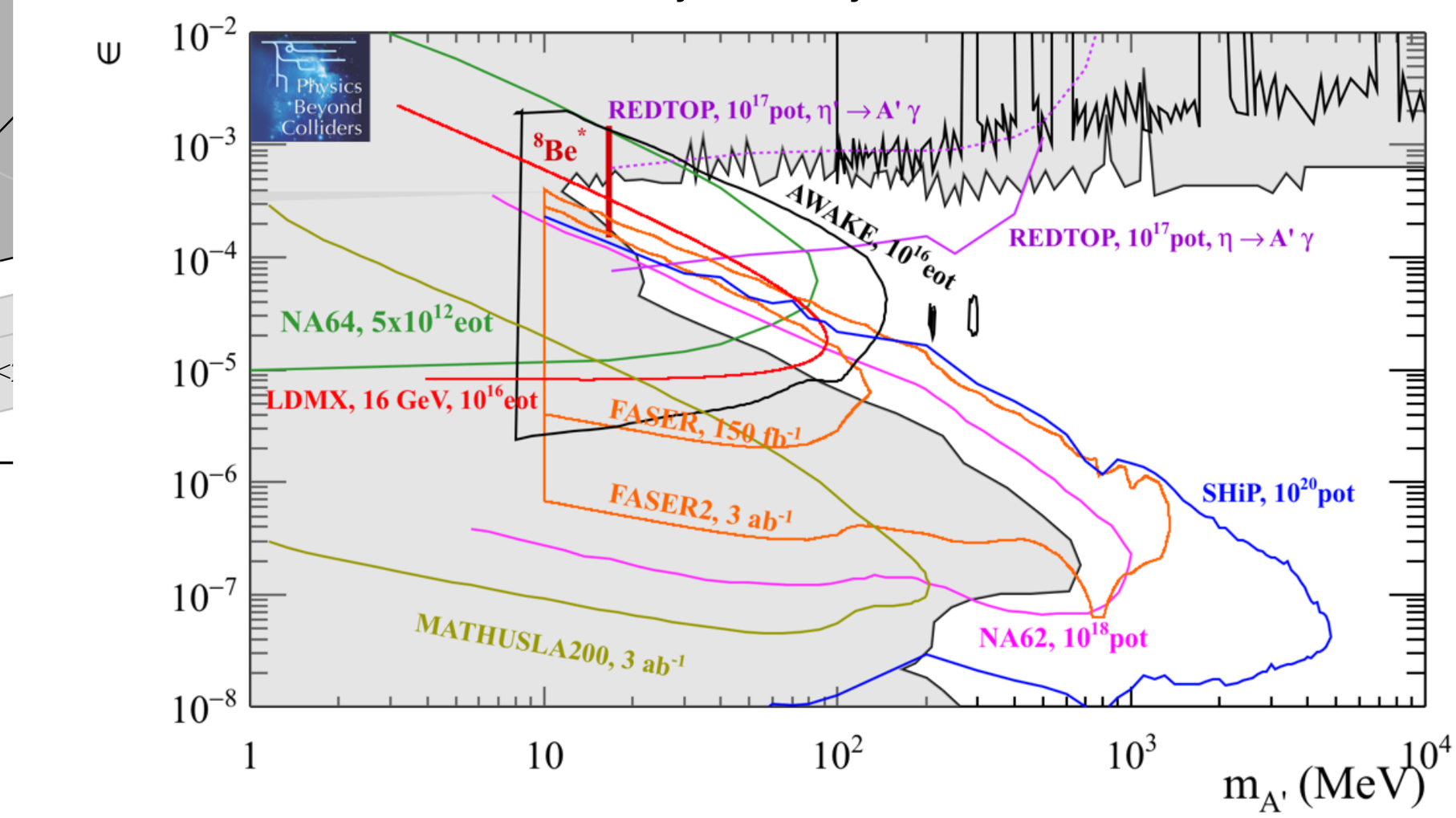
$$\mathcal{L} \supset \frac{\epsilon}{2} F^{\mu\nu} F'_{\mu\nu}$$

Okun '82
Galison & Manohar '84
Holdom '86

Pospelov 0811.1030



Physics Beyond Colliders 1901.09966

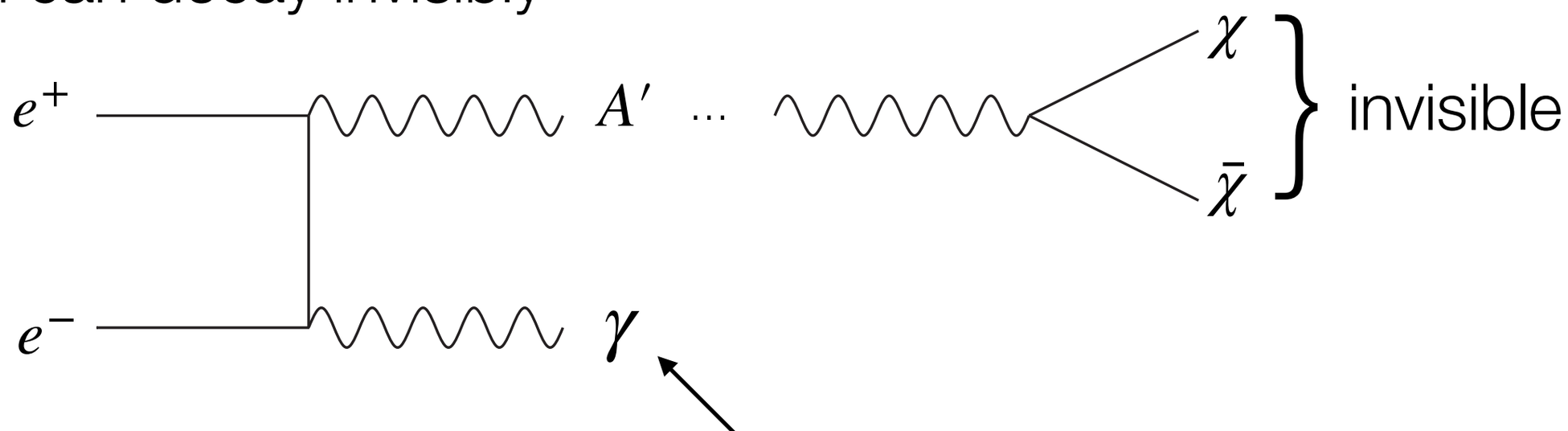


Lots of progress and future work here

Vector Portal to DM

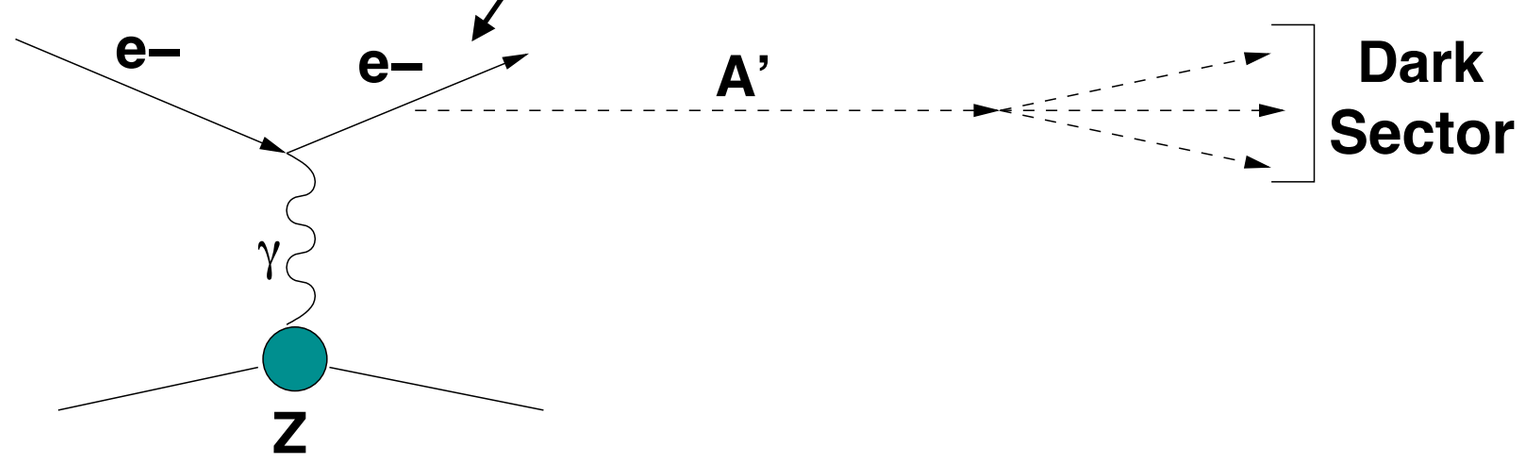
If coupled to dark matter, dark photon can decay invisibly ⇒ Searches are different!

At B-factories (see talk by C. Hearty)



Observe these

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

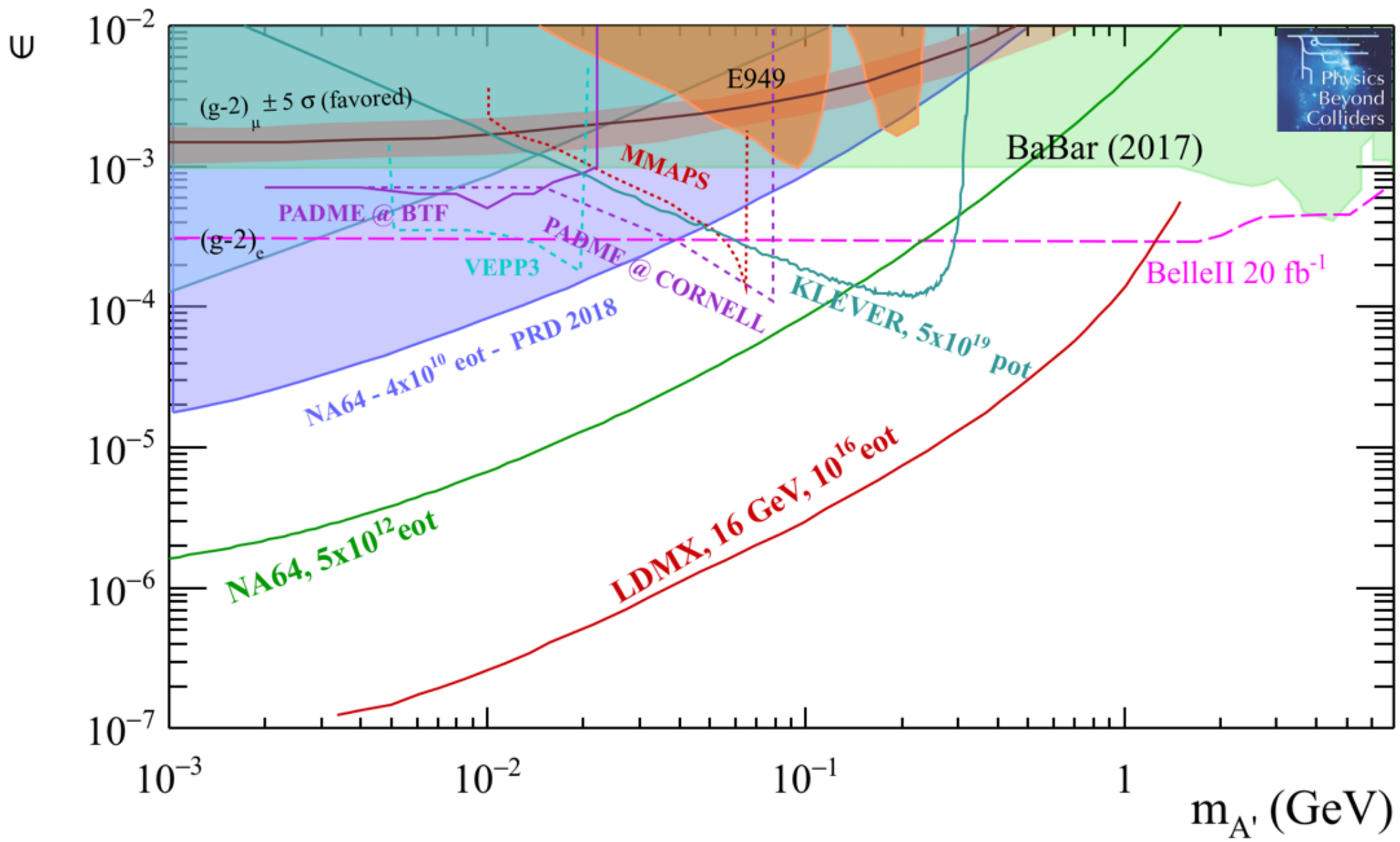


See talk by M. Diamond for fixed targets

Vector Portal to DM

If coupled to dark matter, dark photon can decay invisibly ⇒ Searches are different!

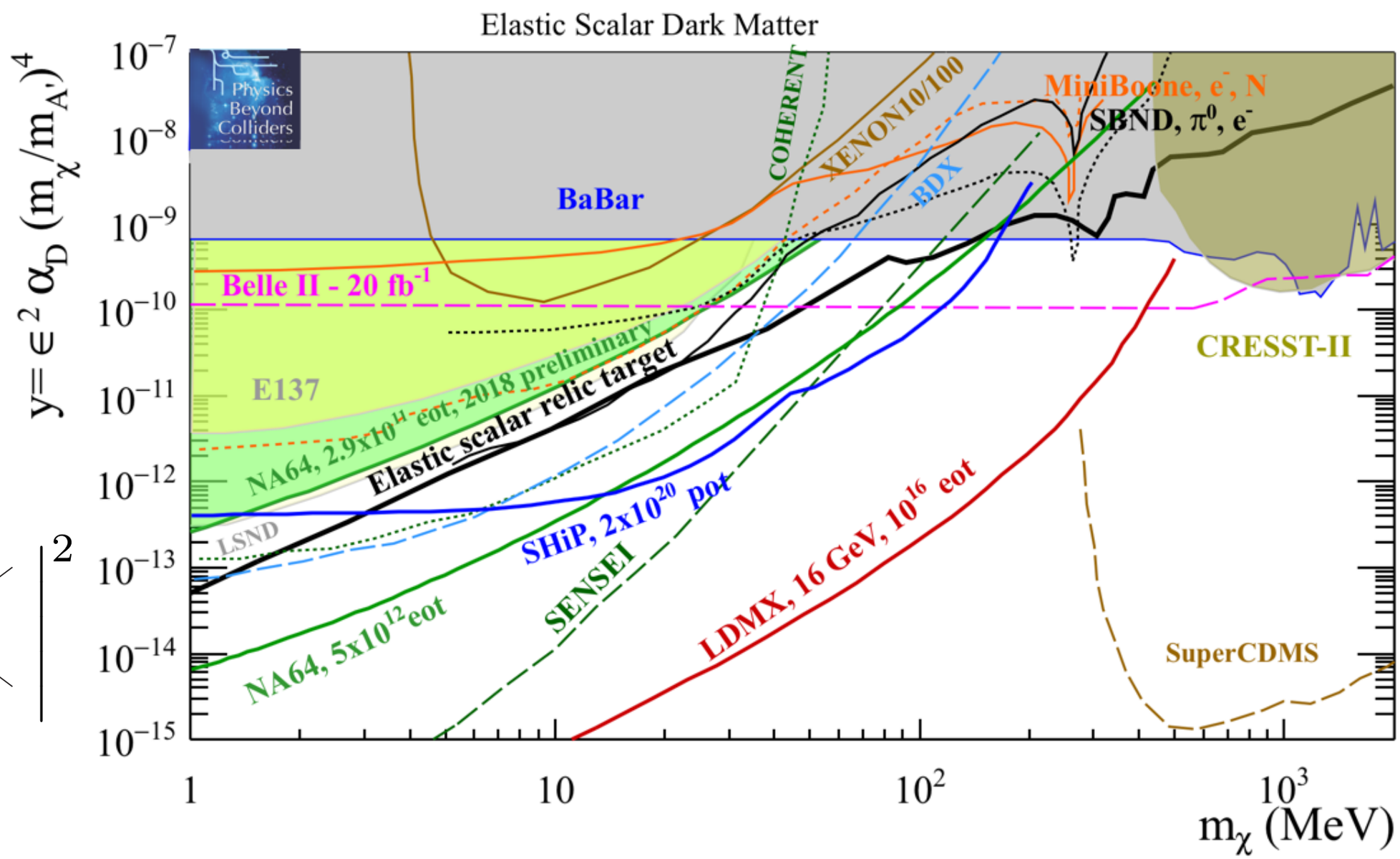
Physics Beyond Colliders 1901.09966

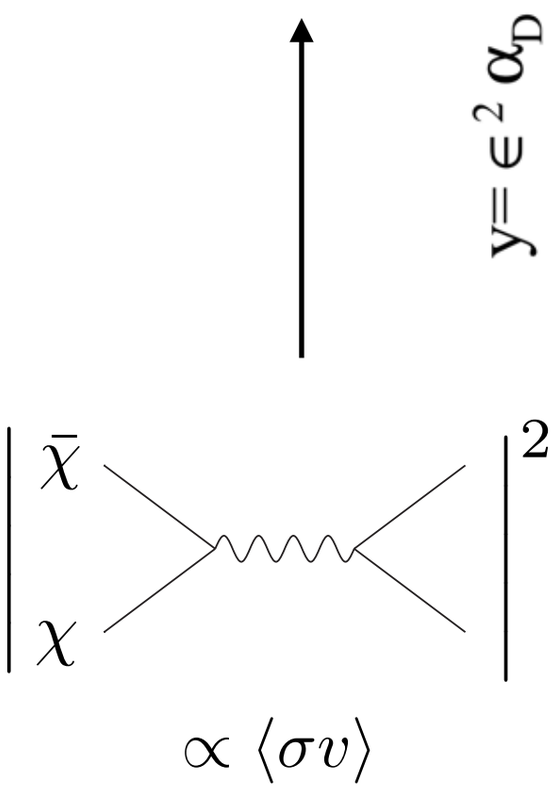


Vector Portal to DM

If coupled to dark matter, dark photon can decay invisibly ⇒ Searches are different!

Physics Beyond Colliders 1901.09966

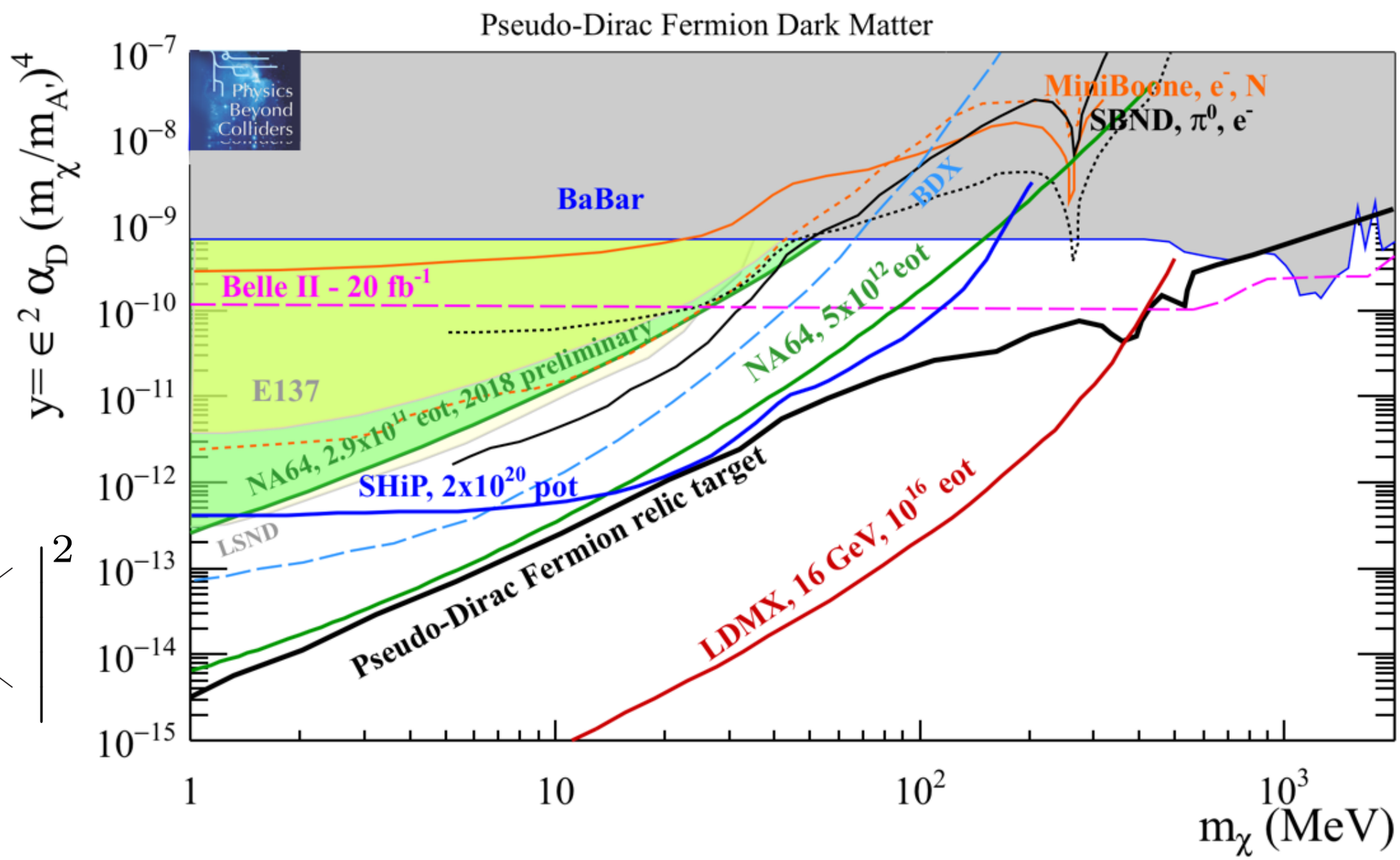


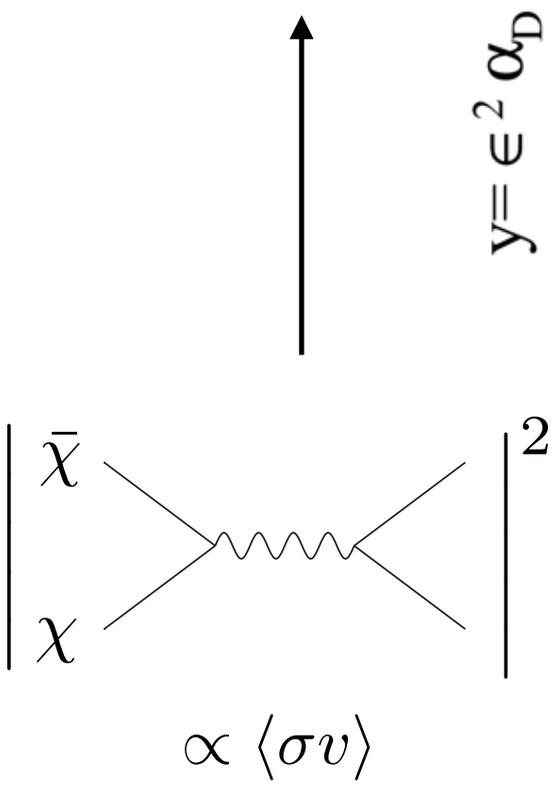


Vector Portal to DM

If coupled to dark matter, dark photon can decay invisibly ⇒ Searches are different!

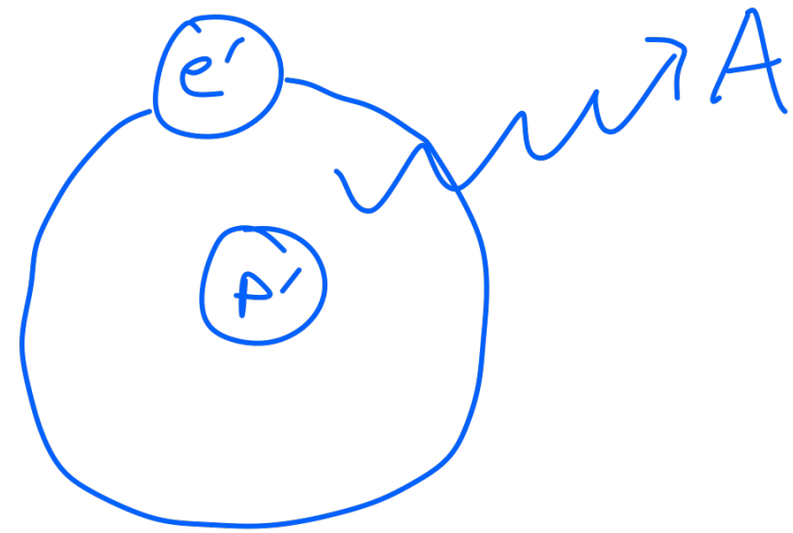
Physics Beyond Colliders 1901.09966





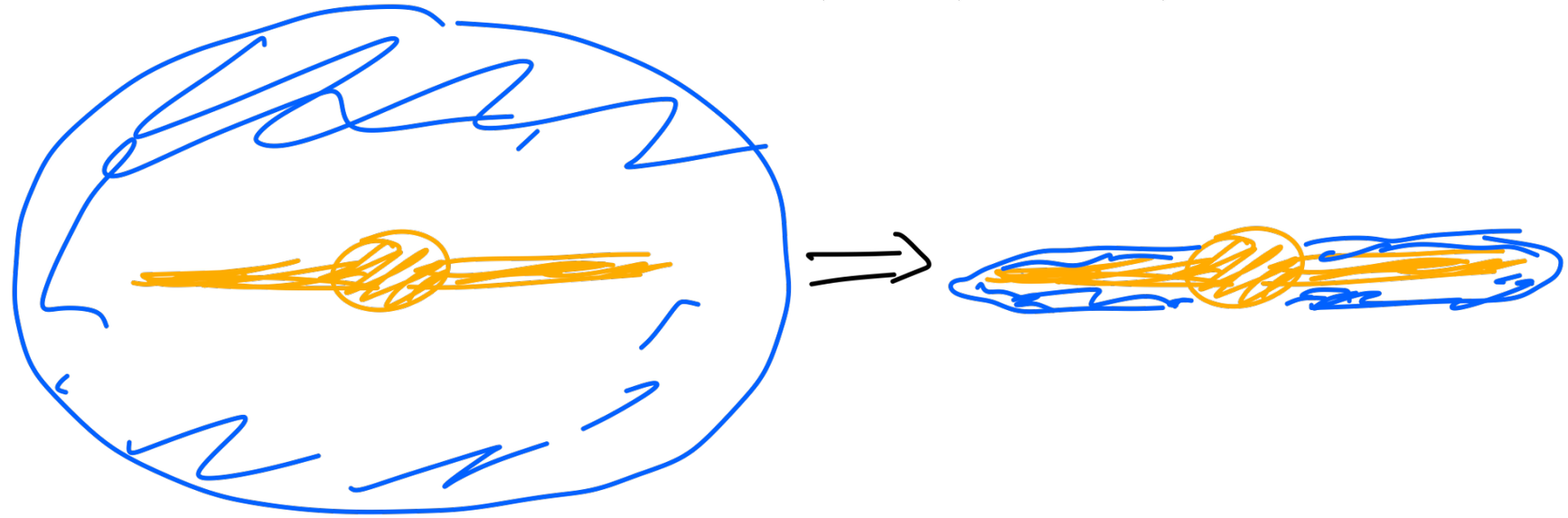
More Complicated Dark Sector

Dark sector could have a more complicated structure, e.g. forming "dark atoms" that can cool



Fan, Katz, Randall, Reece '13

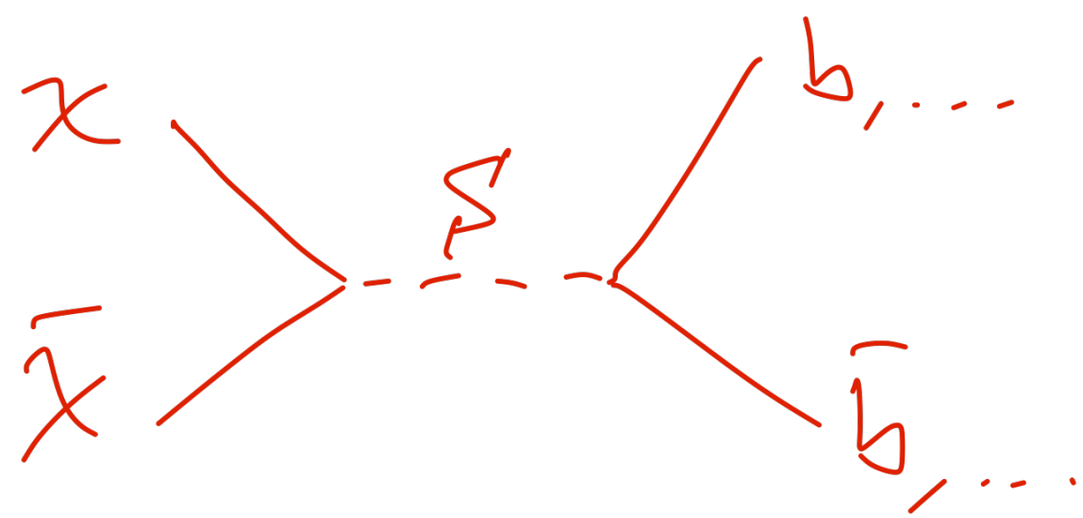
Form "dark disk"



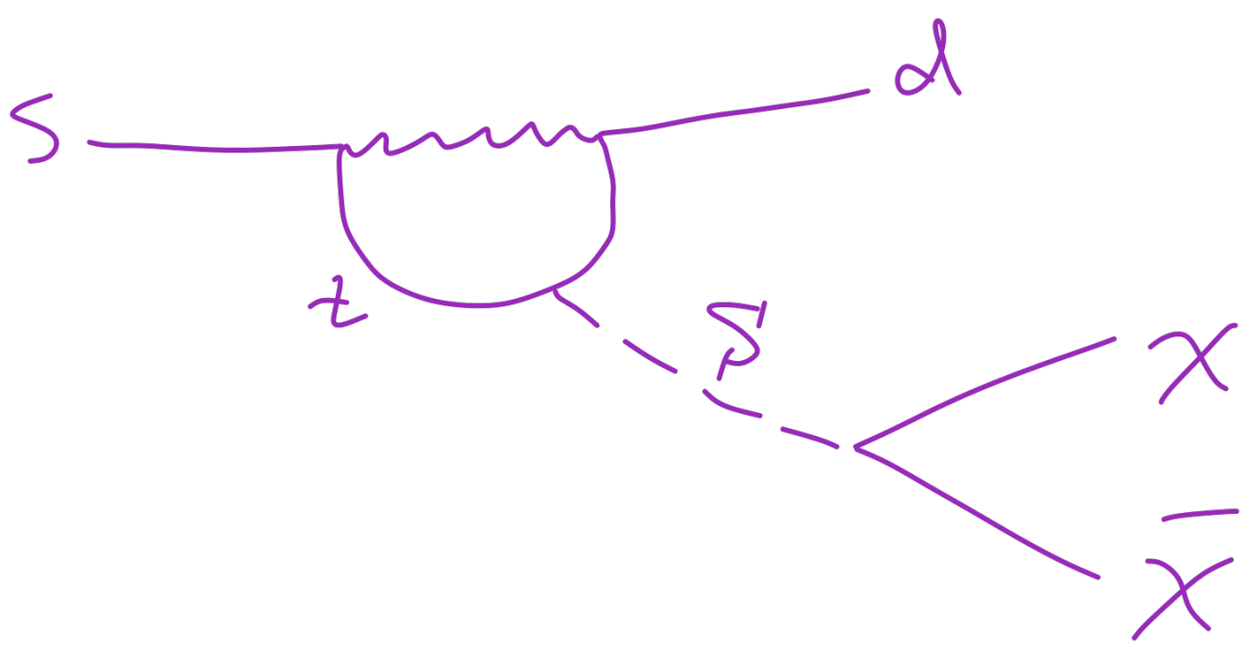
However, constraints from stellar motion, gravitational lensing, breaking up ultrafaint dwarf galaxies—see Ghalsasi & McQuinn+…

How about the Scalar Portal to DM?

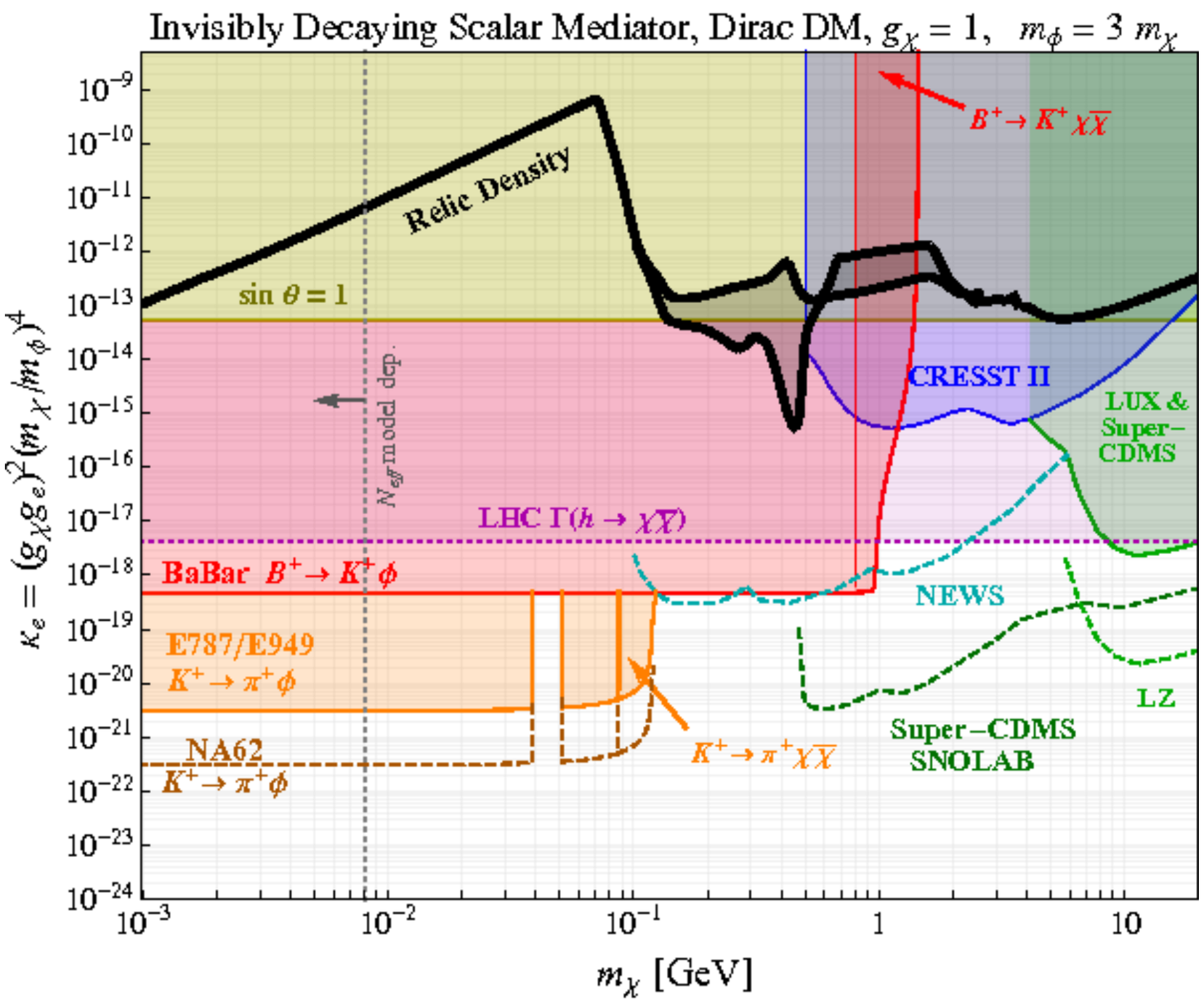
DM now couples to heavy stuff



But QM means it also couples to light stuff!



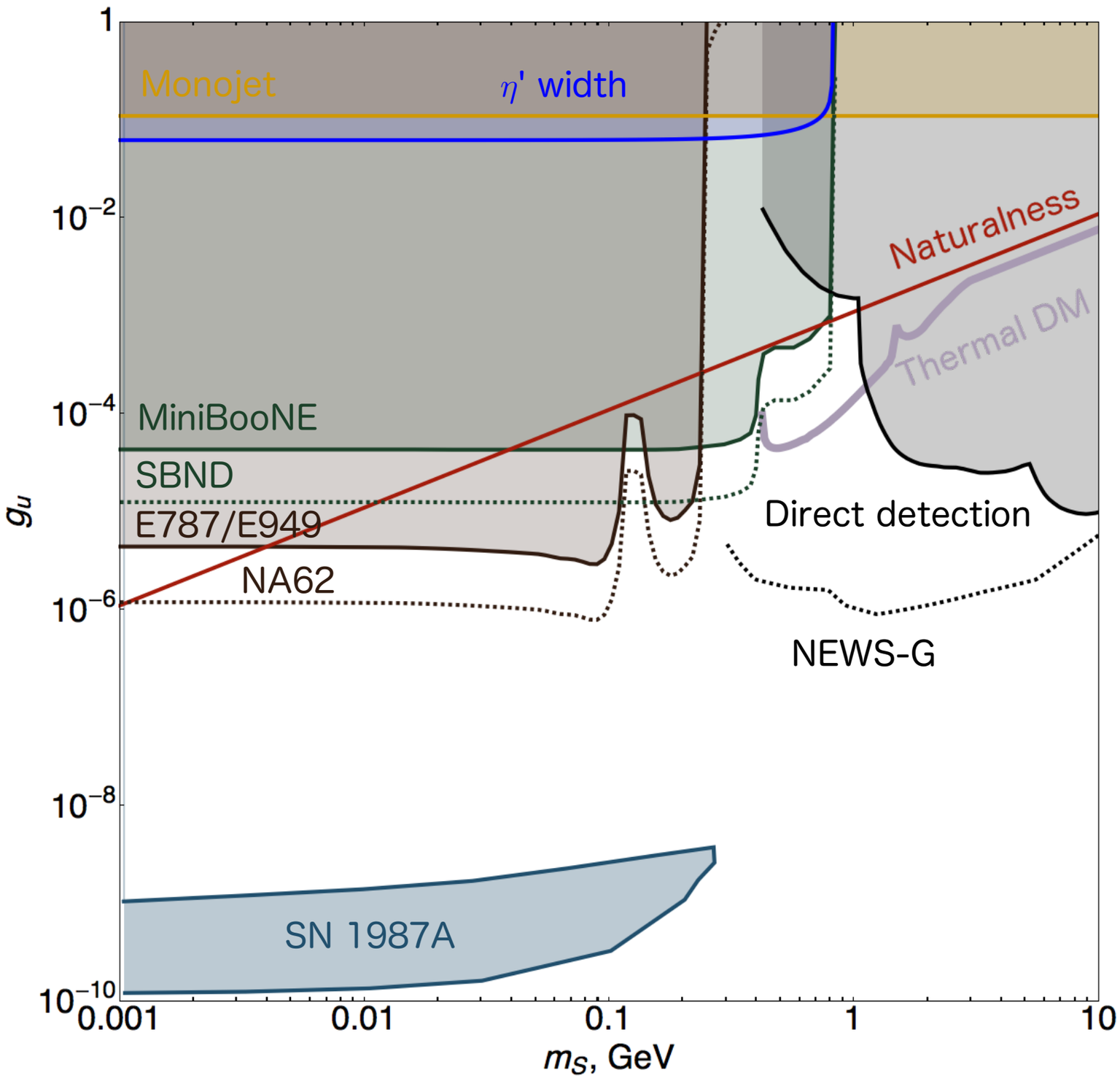
How about the Scalar Portal to DM?



Strong constraints from flavor & direct detection

Krnjaic arXiv:1512:04119

How about the Scalar Portal to DM?

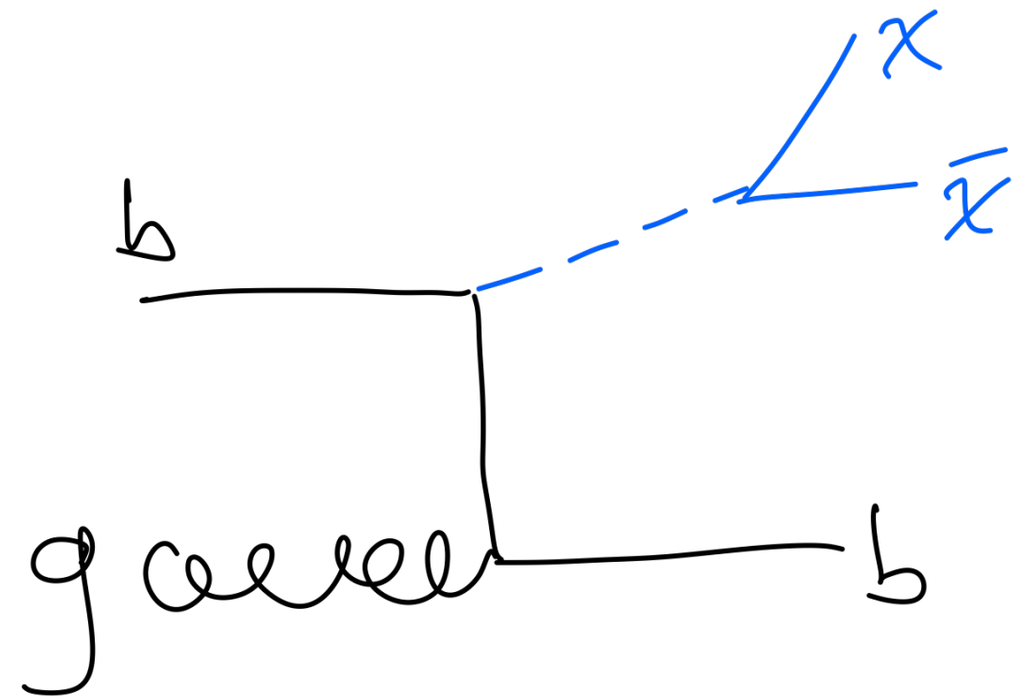


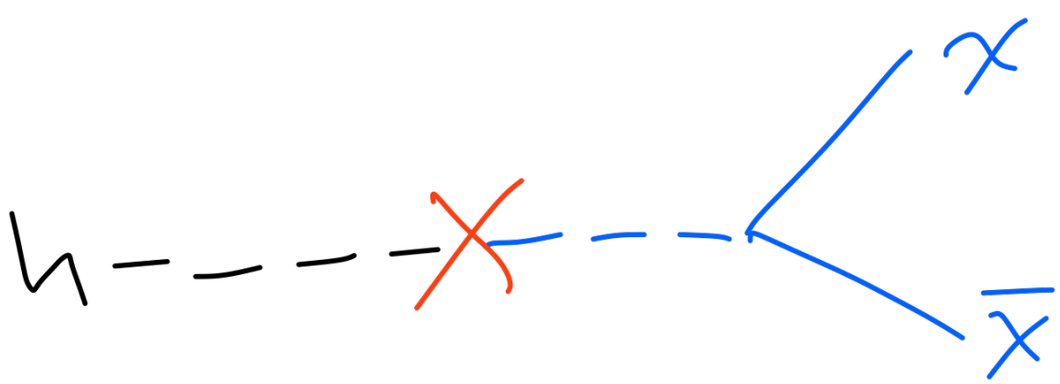
Coupling just to up quark opens up some space

B. Batell, A. Ismail, DM, A. Freitas arXiv:1812:05103

How about the Scalar Portal to DM?

Coupling to heavy stuff means collider production can be interesting





Mixing with Higgs leads to invisible Higgs decays

S. Ipek, DM, A. Nelson arXiv:1812:05103; Goncalves, Machado, No arXiv:1611.04593; +…

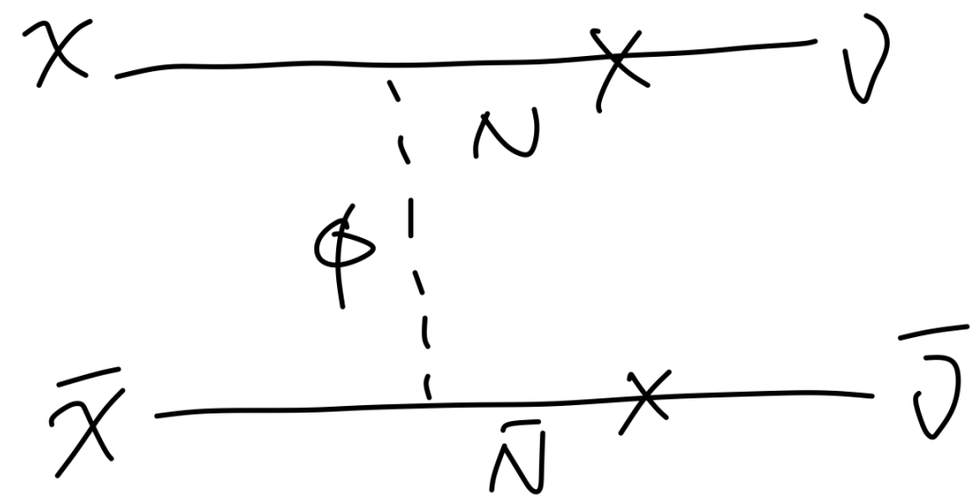
See talk by C. Anelli

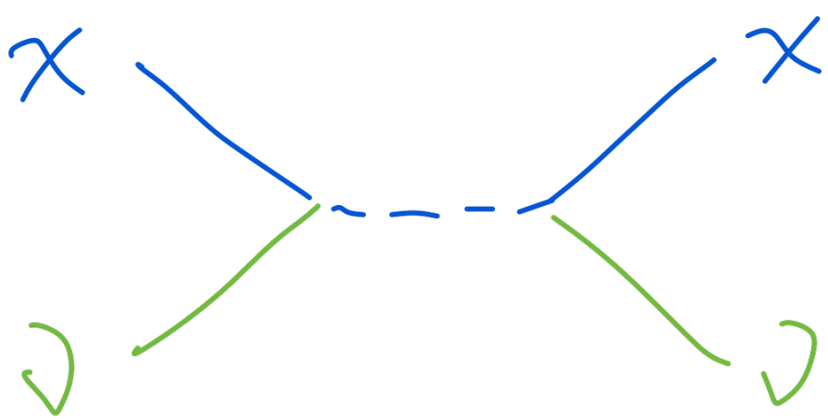
Neutrino Portal DM

Now DM interacts primarily with neutrinos

$$\mathcal{L} \supset \lambda \bar{N} H L + y \phi \bar{N} \chi + h.c.$$

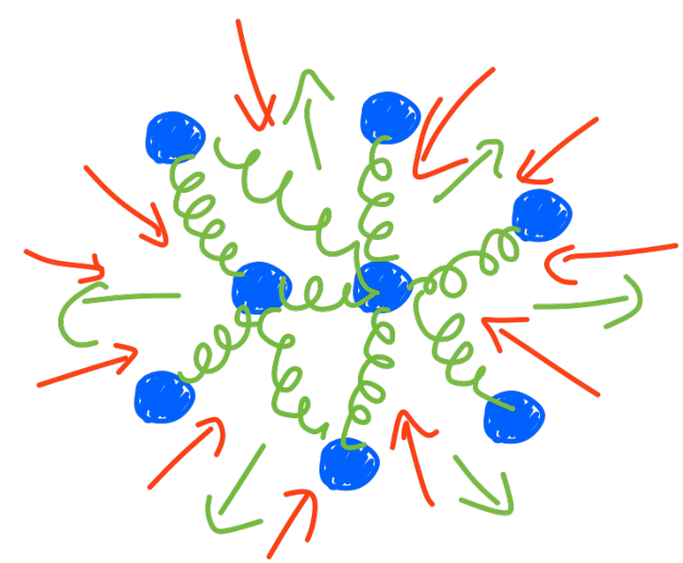
$$\to \lambda v \bar{\nu} N + y \phi \bar{N} \chi + h.c.$$





Challenging to probe!

Scattering on neutrinos can suppress structure formation

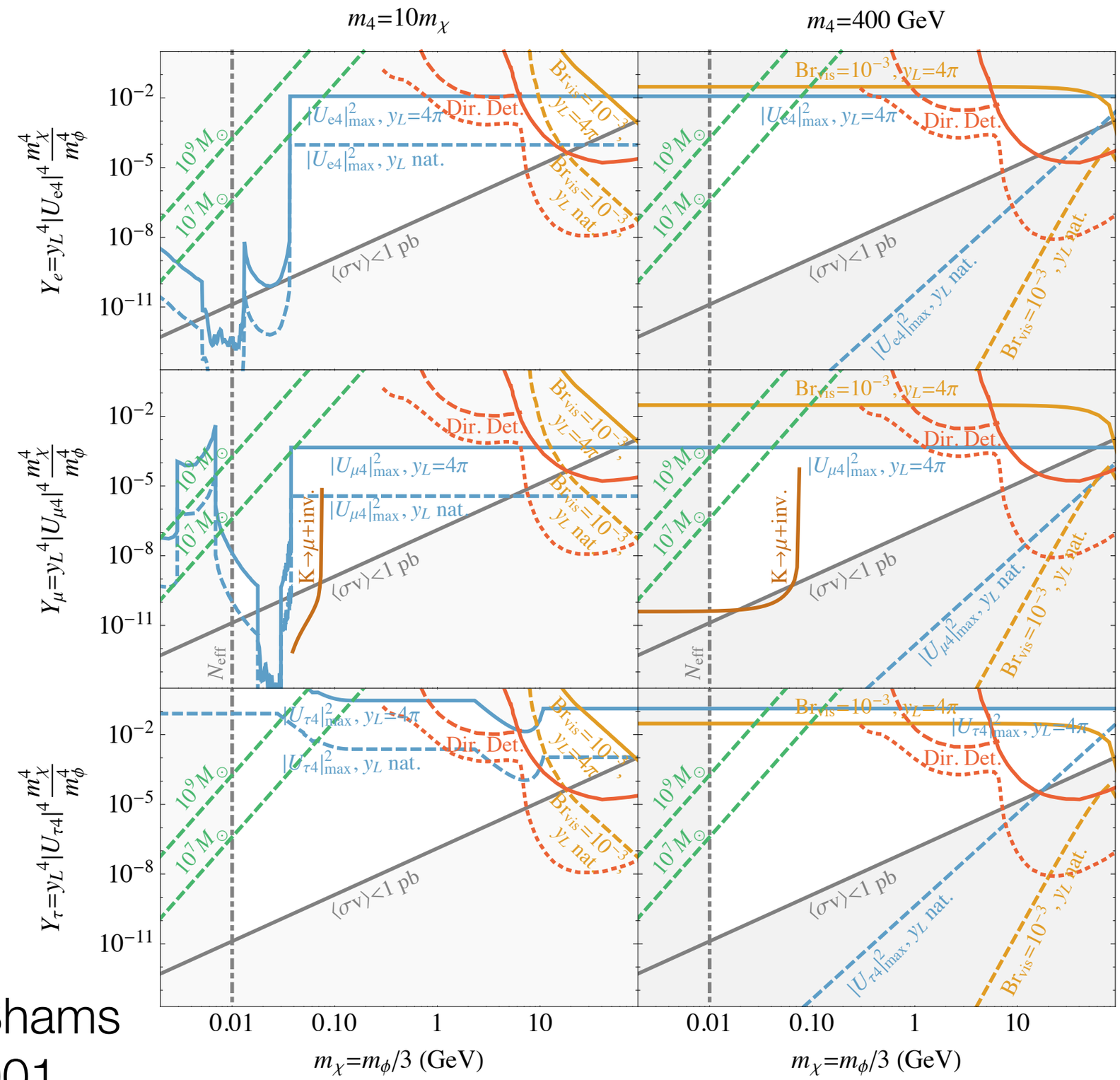


Gravity vs. Pressure

Neutrino Portal DM

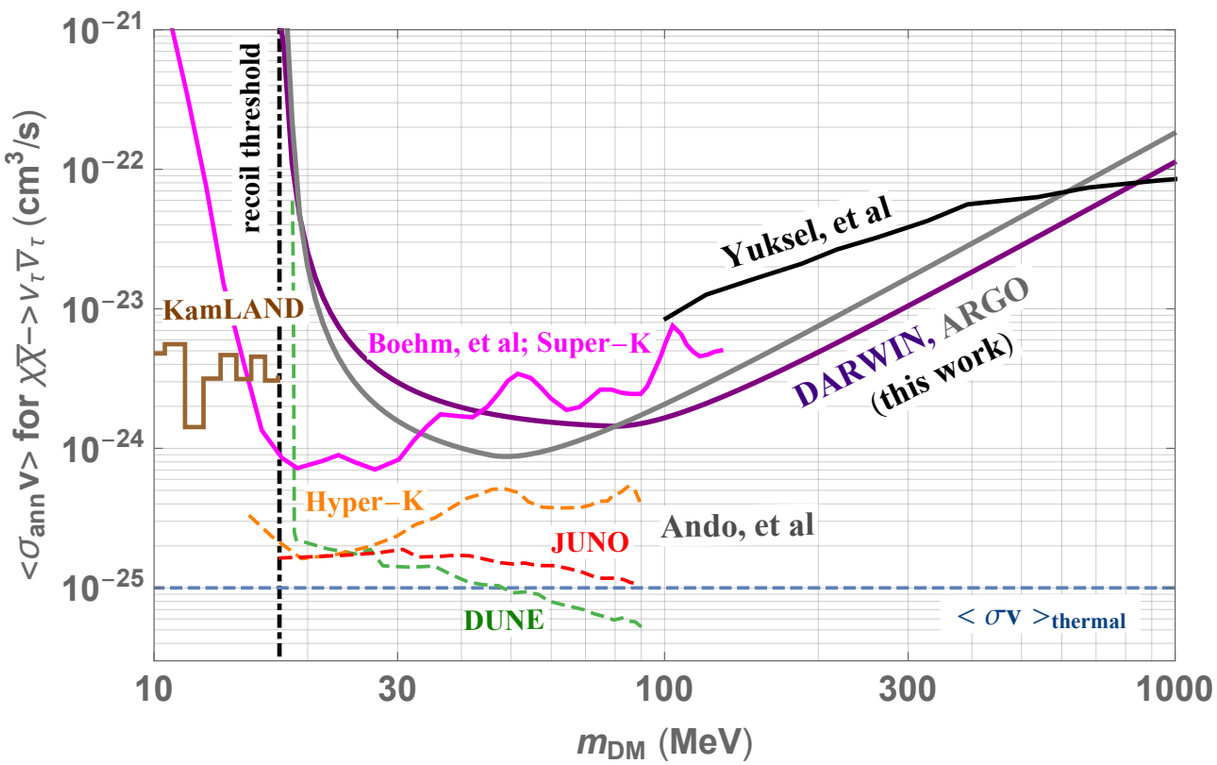
Challenging, especially for tau

But there are interesting probes



B. Batell, T. Han, DM, B. Shams Es Haghi arXiv:1709.7001

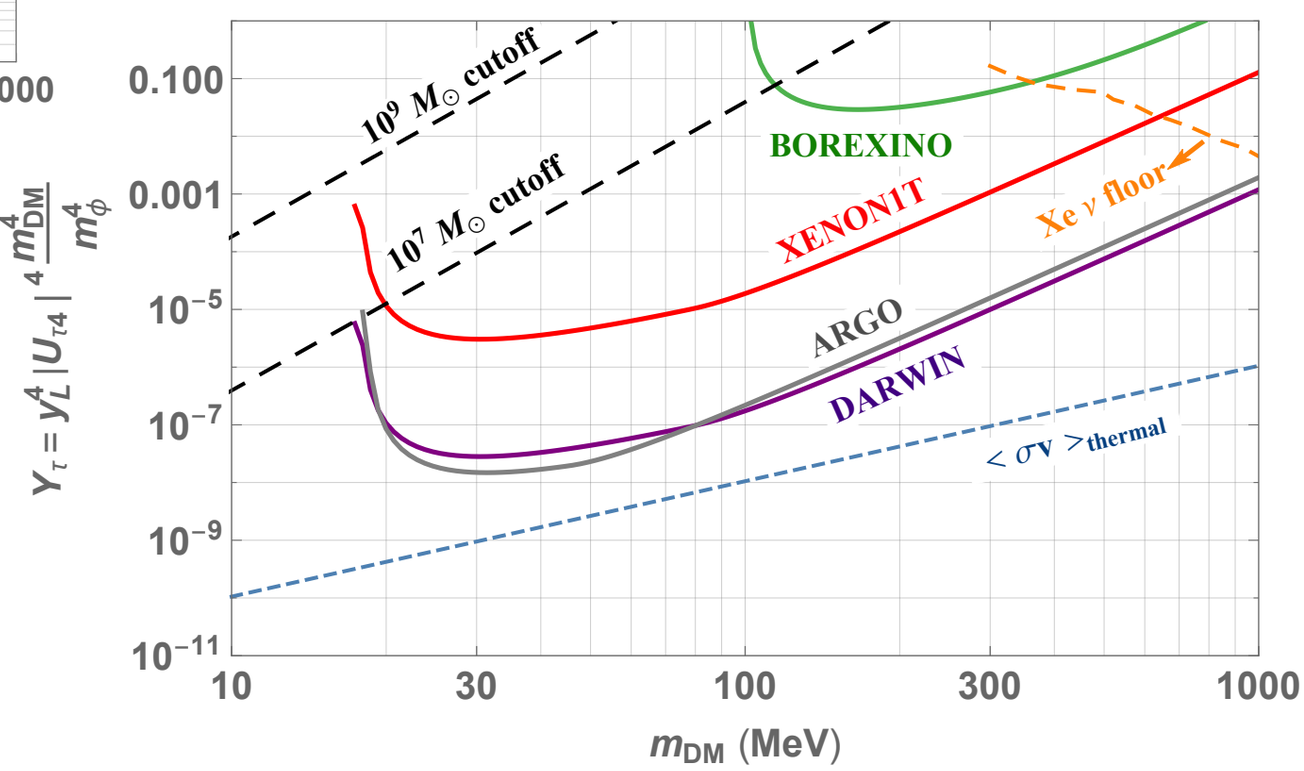
Neutrino Lines from DM Annihilation



$$\chi\bar{\chi} \to \nu\bar{\nu}$$

arXiv:1812.05102 with Nirmal Raj
Looking at large liquid noble detectors

See also Cherry & Shoemaker, Boehm et al., Beacom et al., talk by A. Vincent



Wrap up

DM may be part of a sector that is uncharged with respect to SM forces

There are a handful of benchmark possibilities (portals)

Can accommodate MeV-GeV scale DM easily

The phenomenological signatures in each differs qualitatively

Still lots to do! (And discover!)

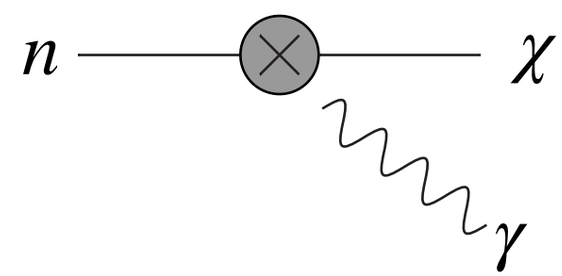
Back Up

Neutron Portal

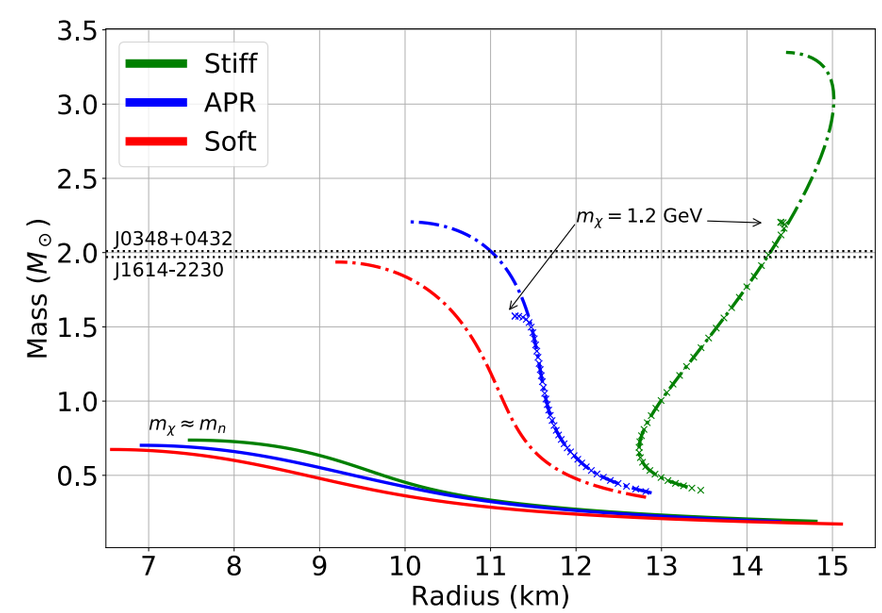
Recent interest in *neutron* portal

$$-\mathscr{L} \supset \delta \bar{n} \chi + \mathrm{h.c.}$$

Relevant for neutron lifetime anomaly



DM, Nelson, Reddy, Zhou PRL '18



Impact on neutron stars very important

Fully invisible model favored!
(See Cline and Cornell)