Status of Light Dark Sectors

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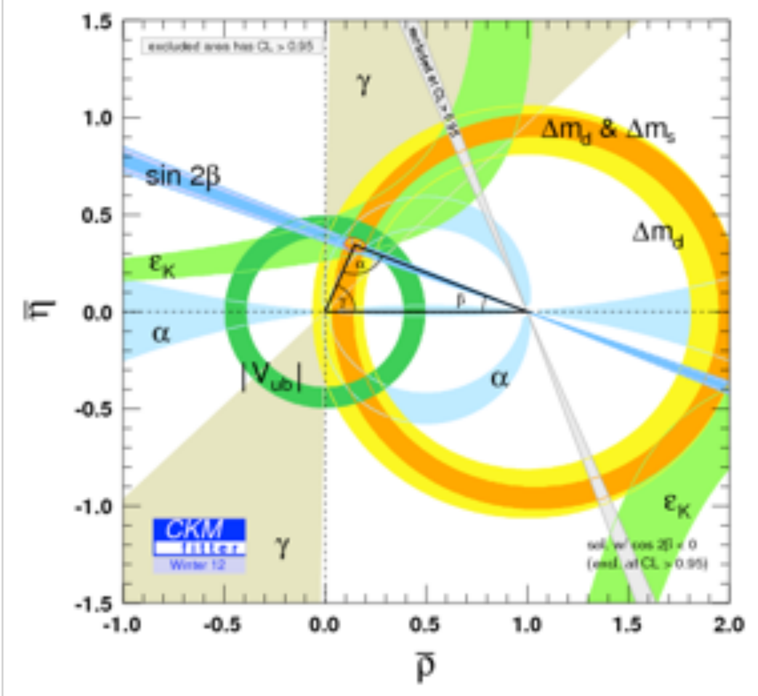
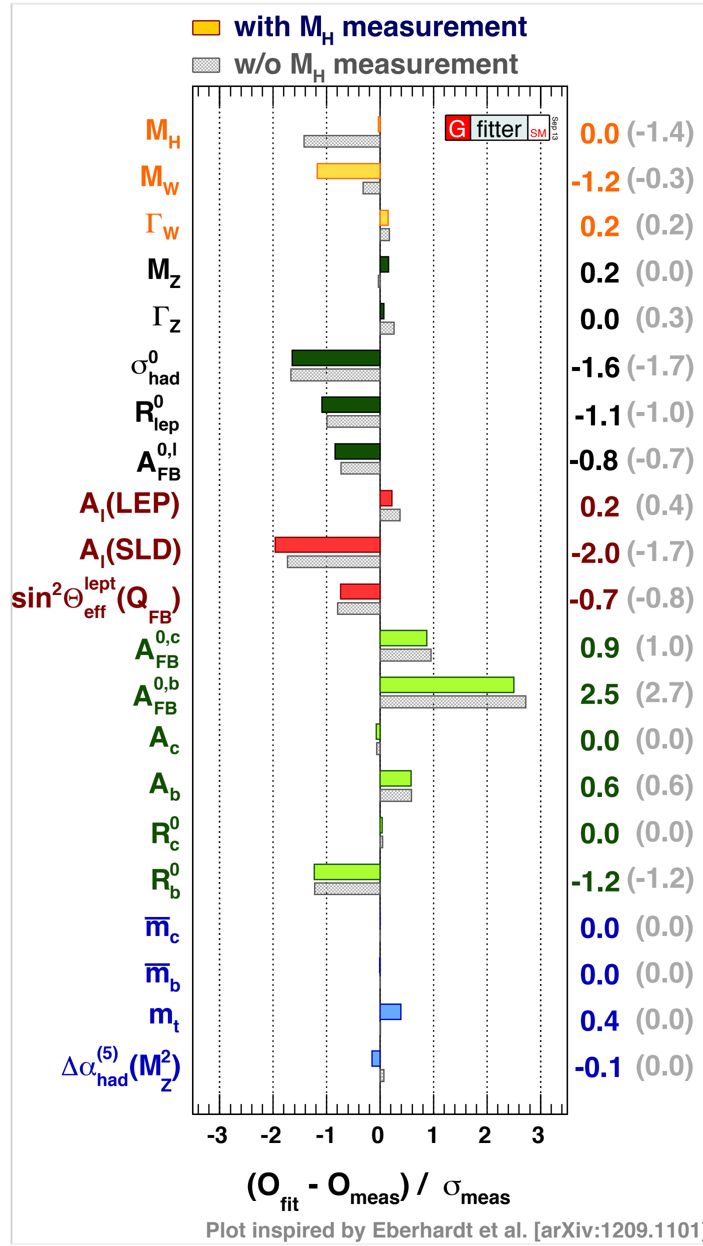
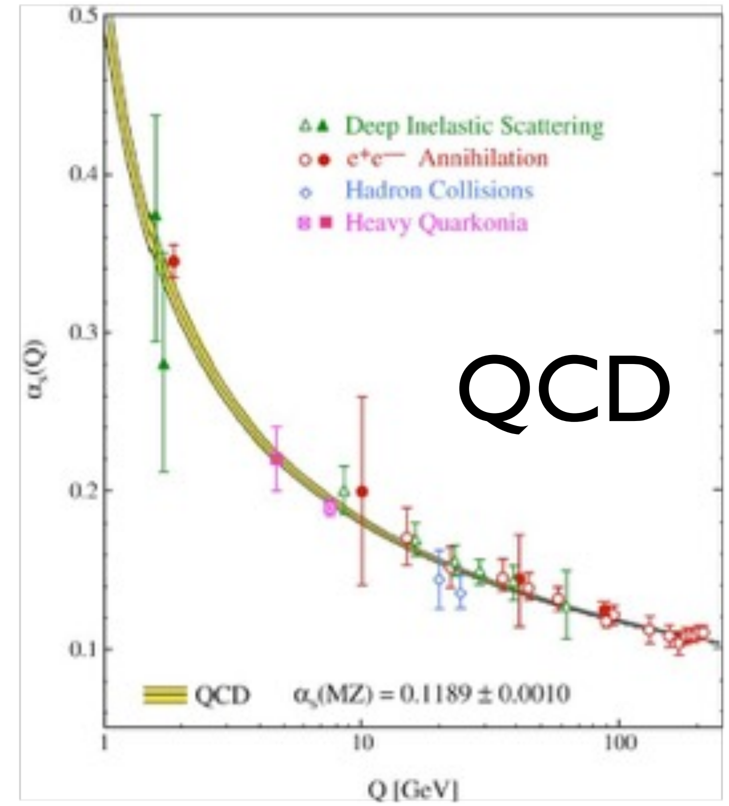
The Standard Model works really well!!

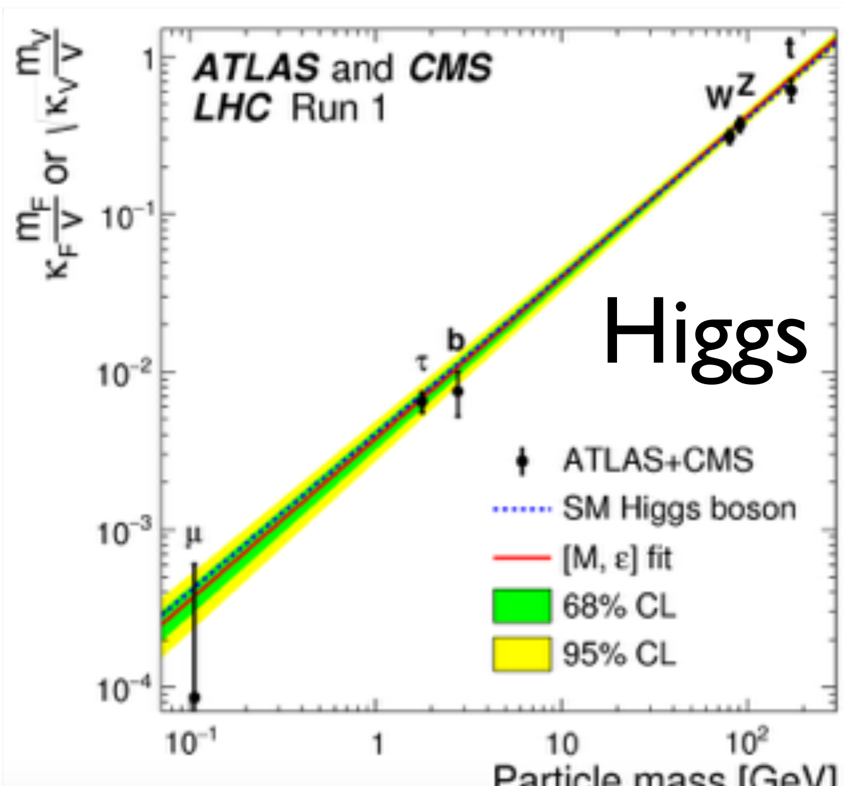
Flavor

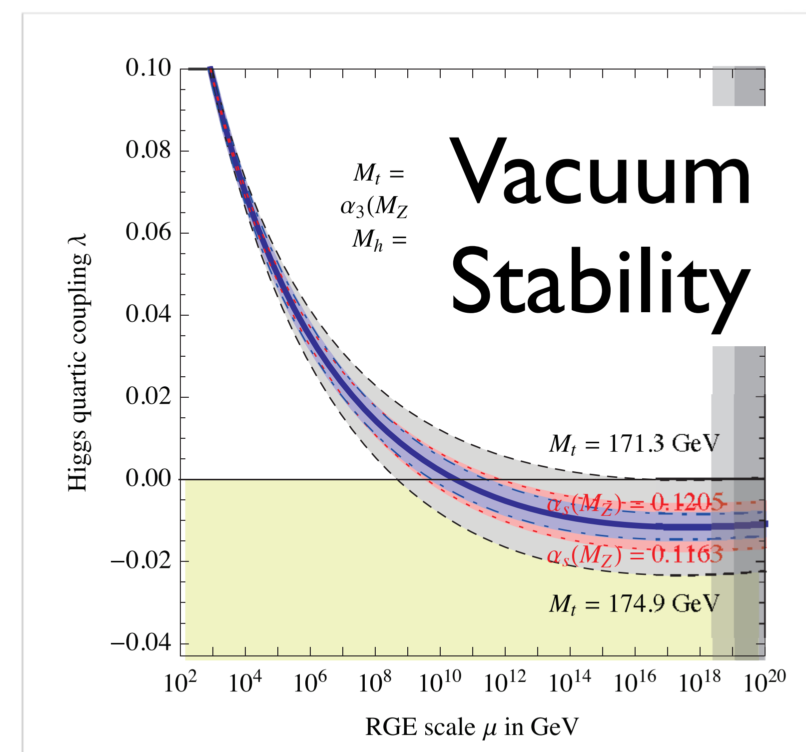


Electroweak









Empirical facts requiring new dynamics:

- Dark Matter
- Neutrino Masses
- Matter-Antimatter Asymmetry of the Universe

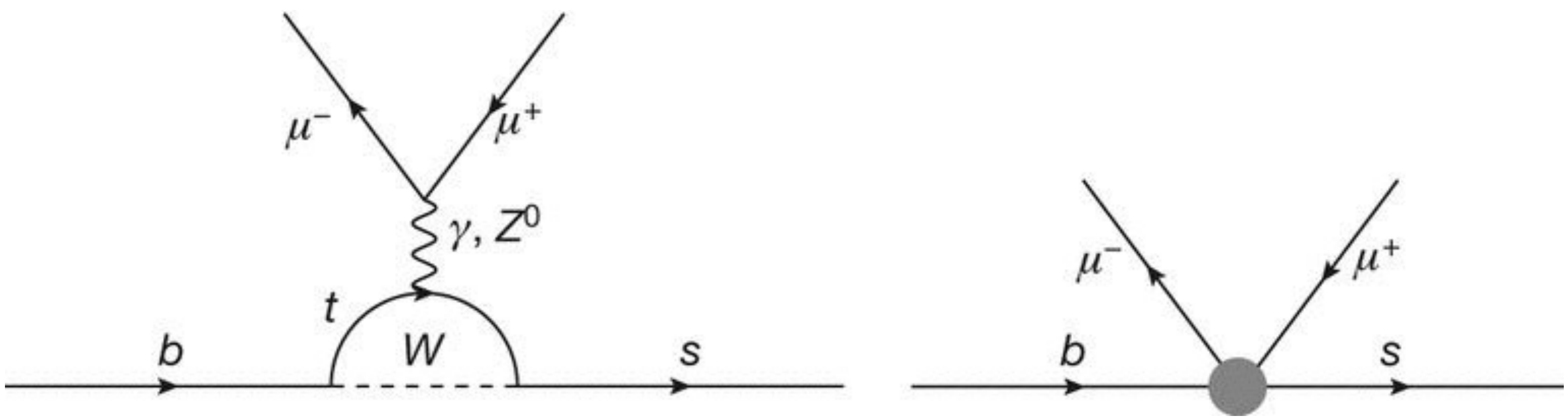
Conceptual mysteries & hints:

- Naturalness (Higgs Mass & C.C.)
- Fermion Masses and Flavour Puzzle
- Strong CP Problem
- Grand Unification
- Inflation
- Quantum Gravity

These problems strongly suggest there is particle physics beyond the Standard Model

Possibilities for new physics:

#1. New *heavy* states states; masses much larger than the weak scale

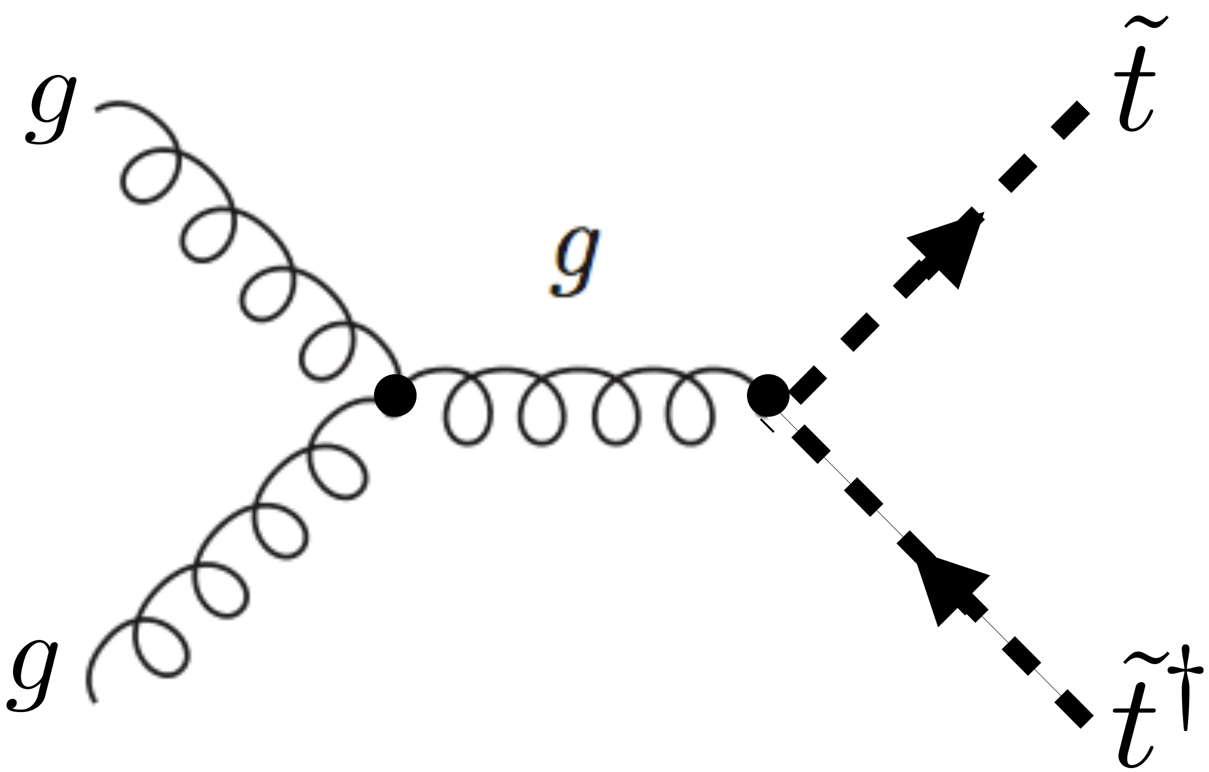


[See talk by J. Mattias]

Search for anomalous phenomena or rare processes
with precision measurements

Possibilities for new physics:

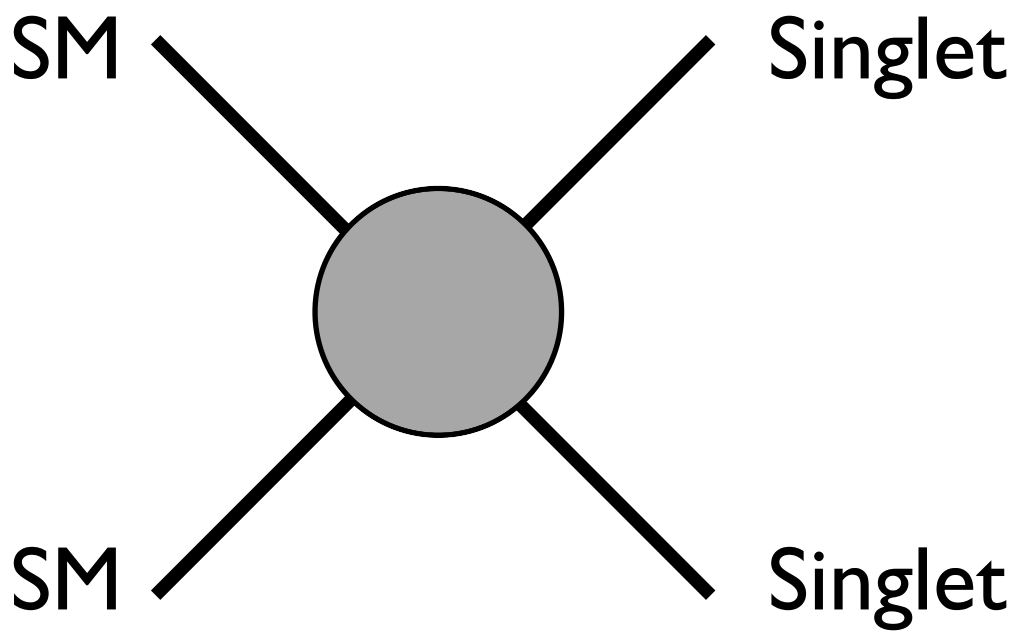
#2. New *light* charged states; masses near the weak scale ~ 100 GeV



Produce states directly at high energy colliders like LHC

Possibilities for new physics:

#3. New *light* **gauge singlet** states, masses can be below the weak scale

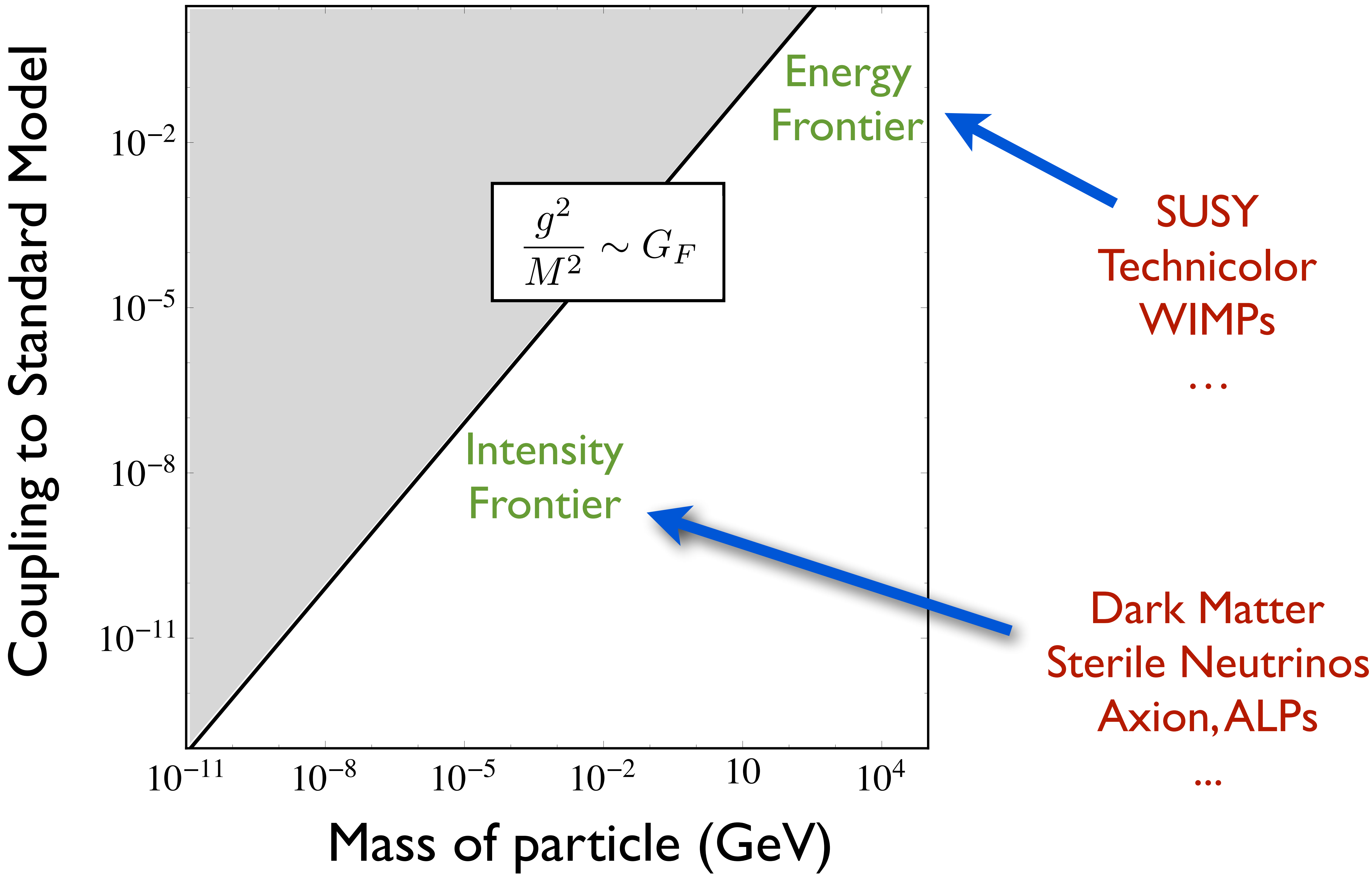


Generic "Portal"

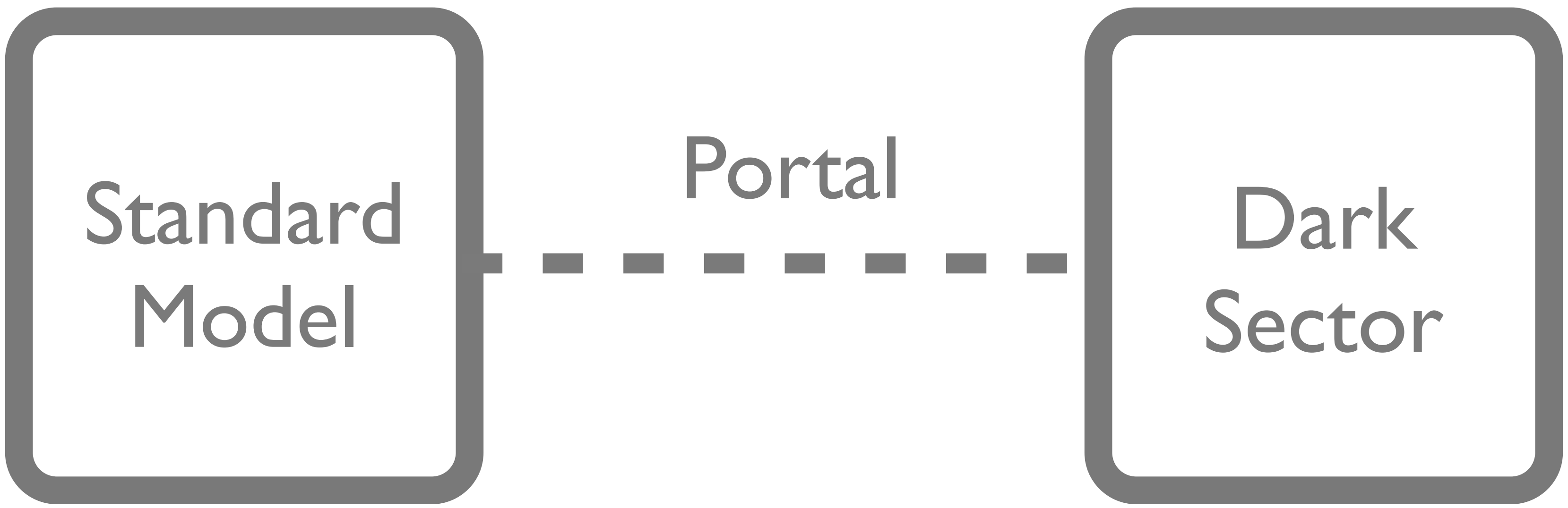
$$\mathcal{L} \supset \frac{\mathcal{O}_{\rm SM}^{(p)}\mathcal{O}_{\rm singlet}^{(q)}}{\Lambda^{p+q-4}}$$

Probe these states directly using high intensity/precision experiments

Where is the New Physics?



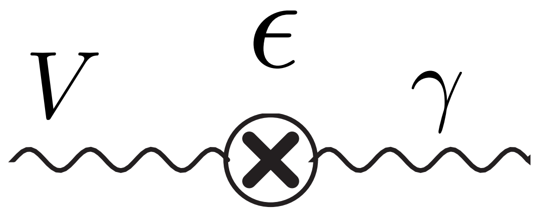
The Dark Sector Paradigm



- Set of new particles with following properties:
  - Gauge singlets - not charged under SM gauge symmetries
  - May be very light, well below weak scale ~100 GeV
  - They may interact weakly with ordinary matter through a "portal"

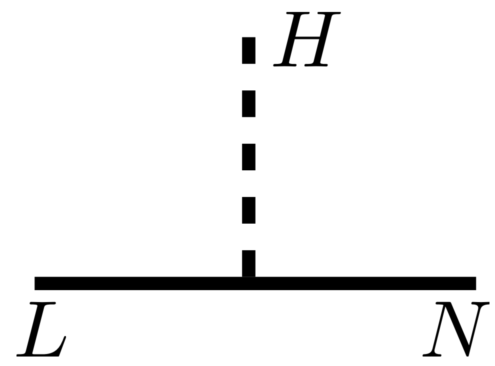
Portals

$$\frac{\epsilon}{2} B_{\mu\nu} V^{\mu\nu}$$



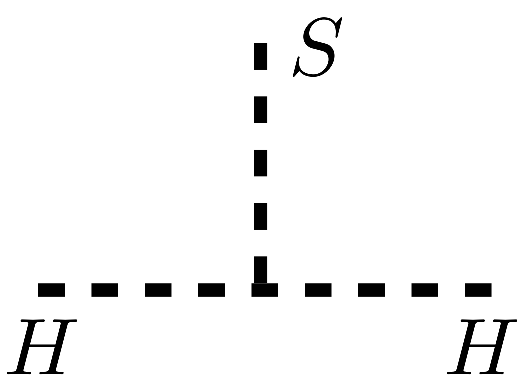
Vector Portal

$$y L H N$$



Neutrino portal

$$(\mu S + \lambda S^2) H^\dagger H$$



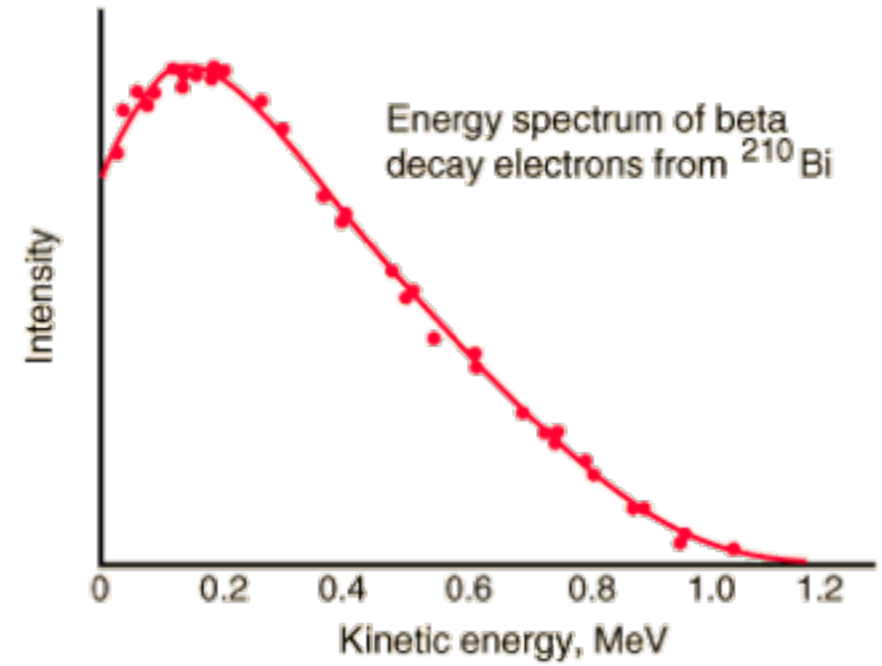
Higgs Portal

Motivations for Dark Sectors

- Dark Matter
- Neutrino Mass
- Strong CP (axion)
- Flavor (flavons)
- SUSY (SUSY breaking, gravitino)
- Inflation
- Electroweak naturalness (Neutral Naturalness, Relaxion, NNaturalness)

Historical precedent

- In 1930s, the "Standard Model" was photon, electron, nucleons
- Beta decay: $n \to p + e^-$



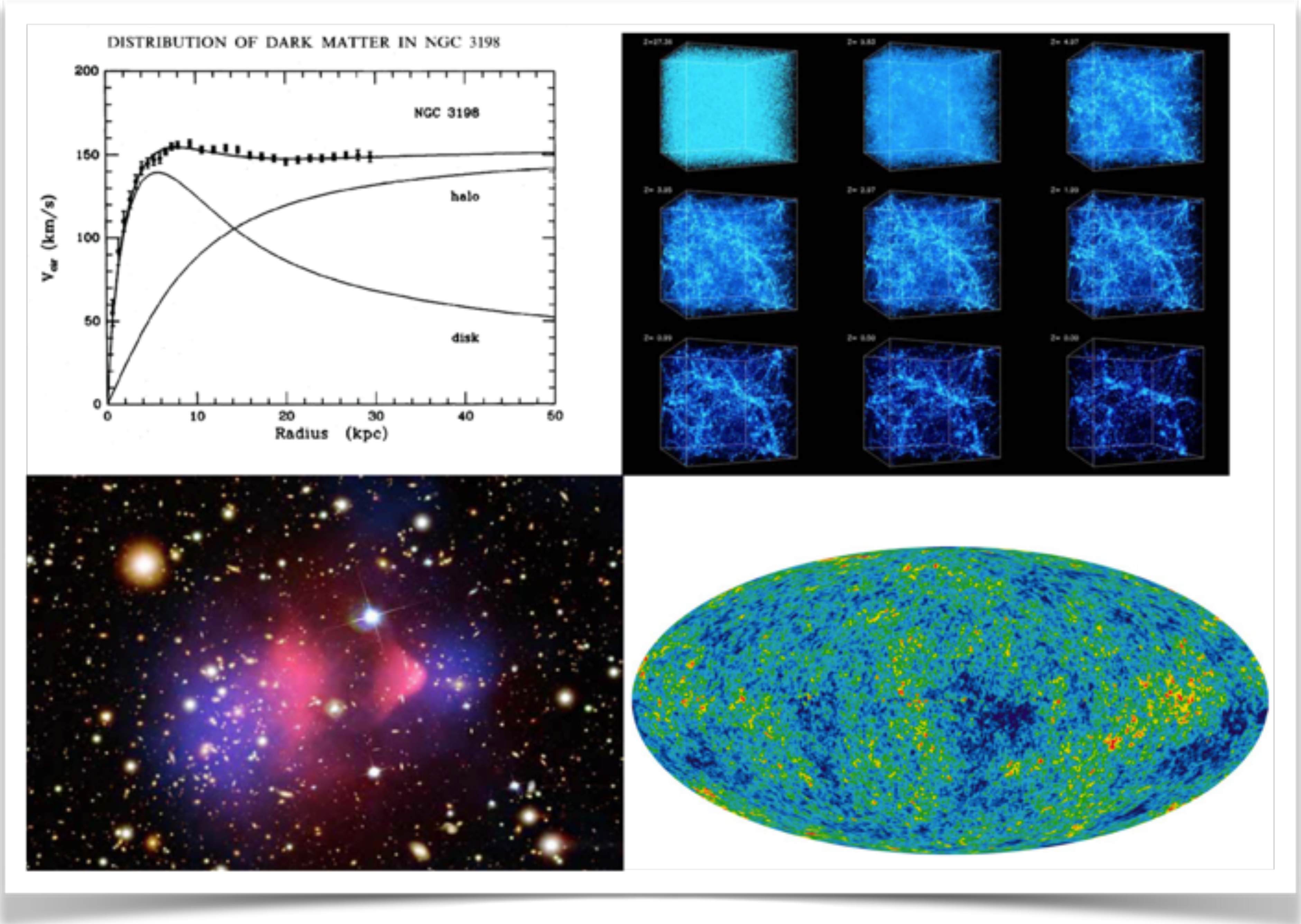
Continuous spectrum!

- Pauli proposes a radical solution - the neutrino!

$$n \to p + e^- + \bar{\nu}$$

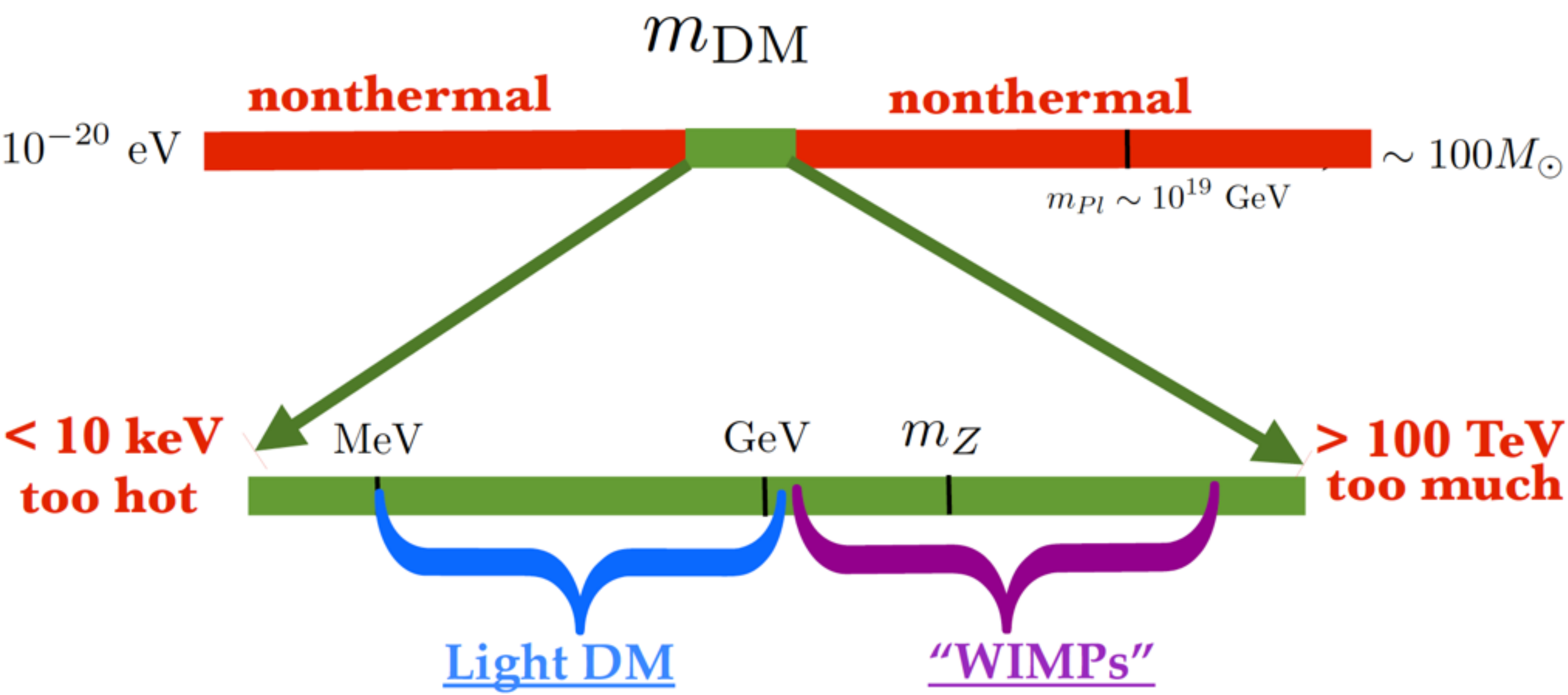
- Perfect example of a dark sector
  - neutrino is electrically neutral (QED gauge singlet)
  - very weakly interacting and light
  - interacts with "Standard Model" through "portal" - $(\bar{p}\gamma^\mu n)(\bar{e}\gamma_\mu \nu)$

Dark Matter



- Disparate range of gravitational evidence
- Search for non-gravitational DM interactions top priority

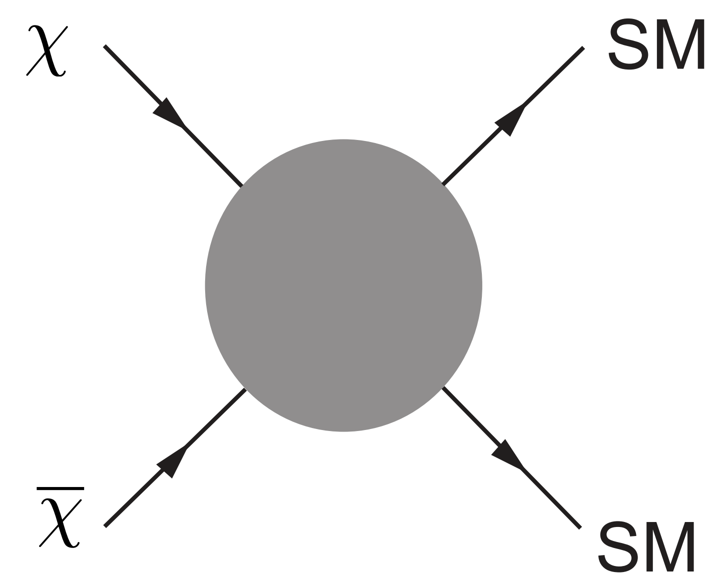
Thermal Dark Matter Window

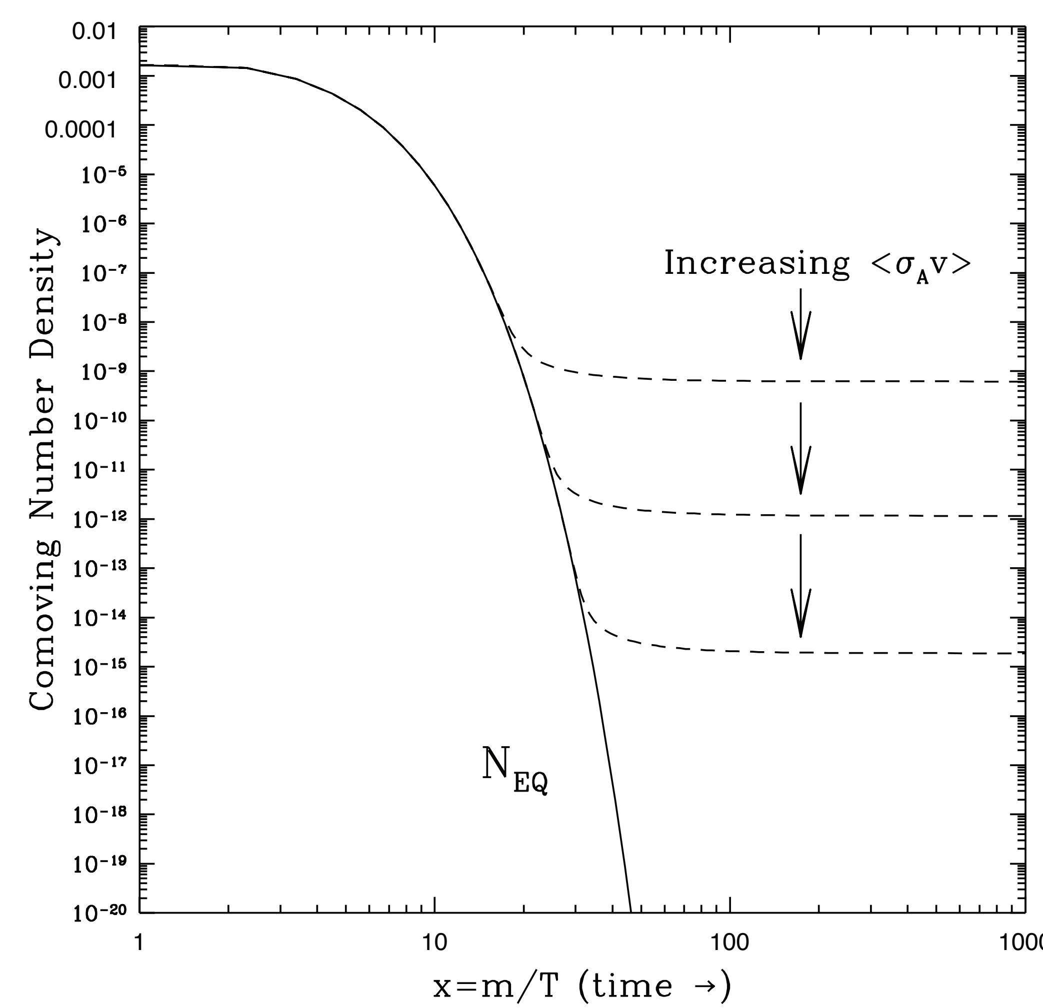


[Figure from G. Krnjaic]

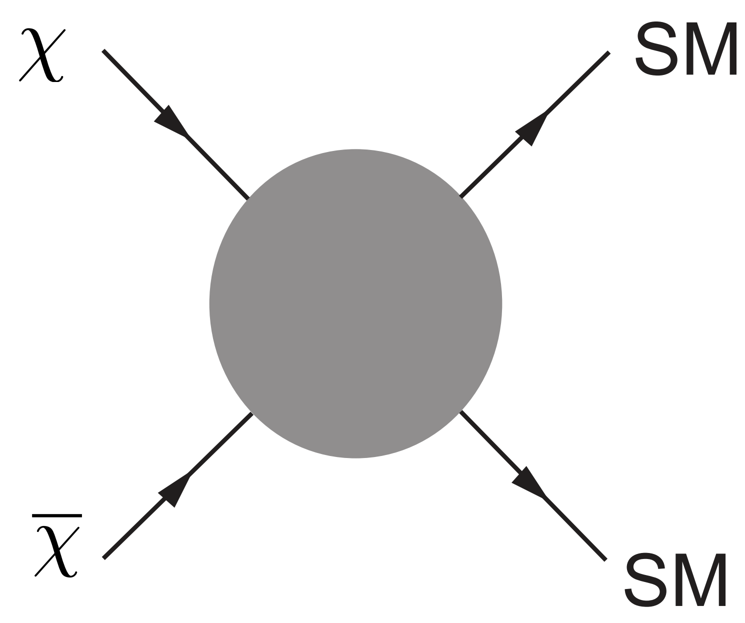
Dark matter production via thermal freeze-out

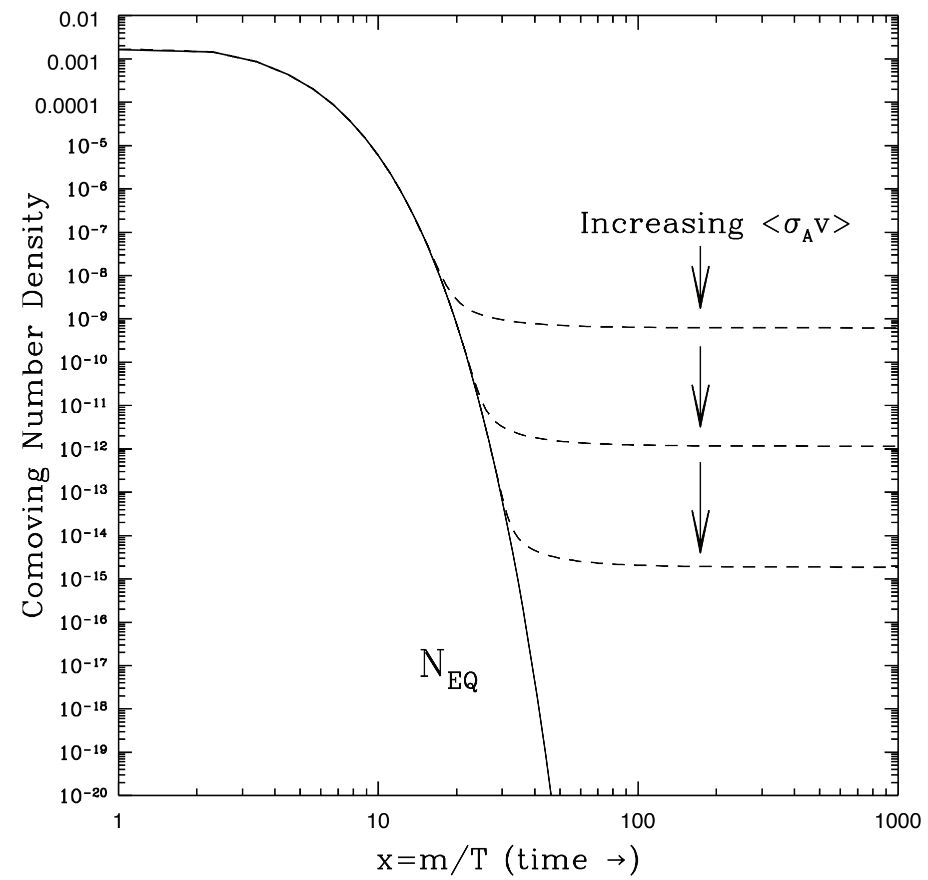
- At early times, $T \gg m_\chi$, both DM annihilation and production (inverse annihilation) are efficient
- As temperature drops, $T \lesssim m_\chi$, DM production is kinematically disfavored, and DM begins to annihilate away
- However, Hubble expansion causes DM dilution, making DM annihilation more and more rare
- Eventually, DM will freeze-out, once annihilation rate becomes smaller than the Hubble rate
- Relic abundance of DM controlled by the annihilation cross section $\langle \sigma v \rangle$





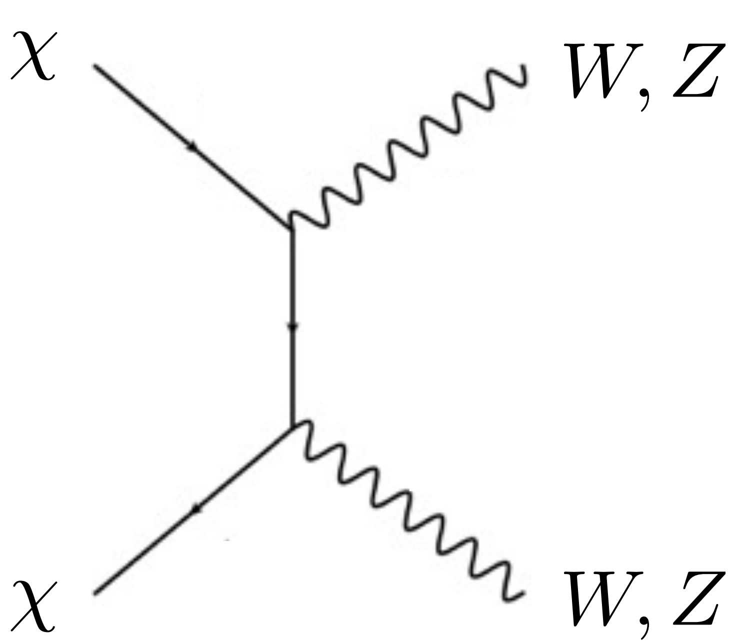
Thermal freeze-out





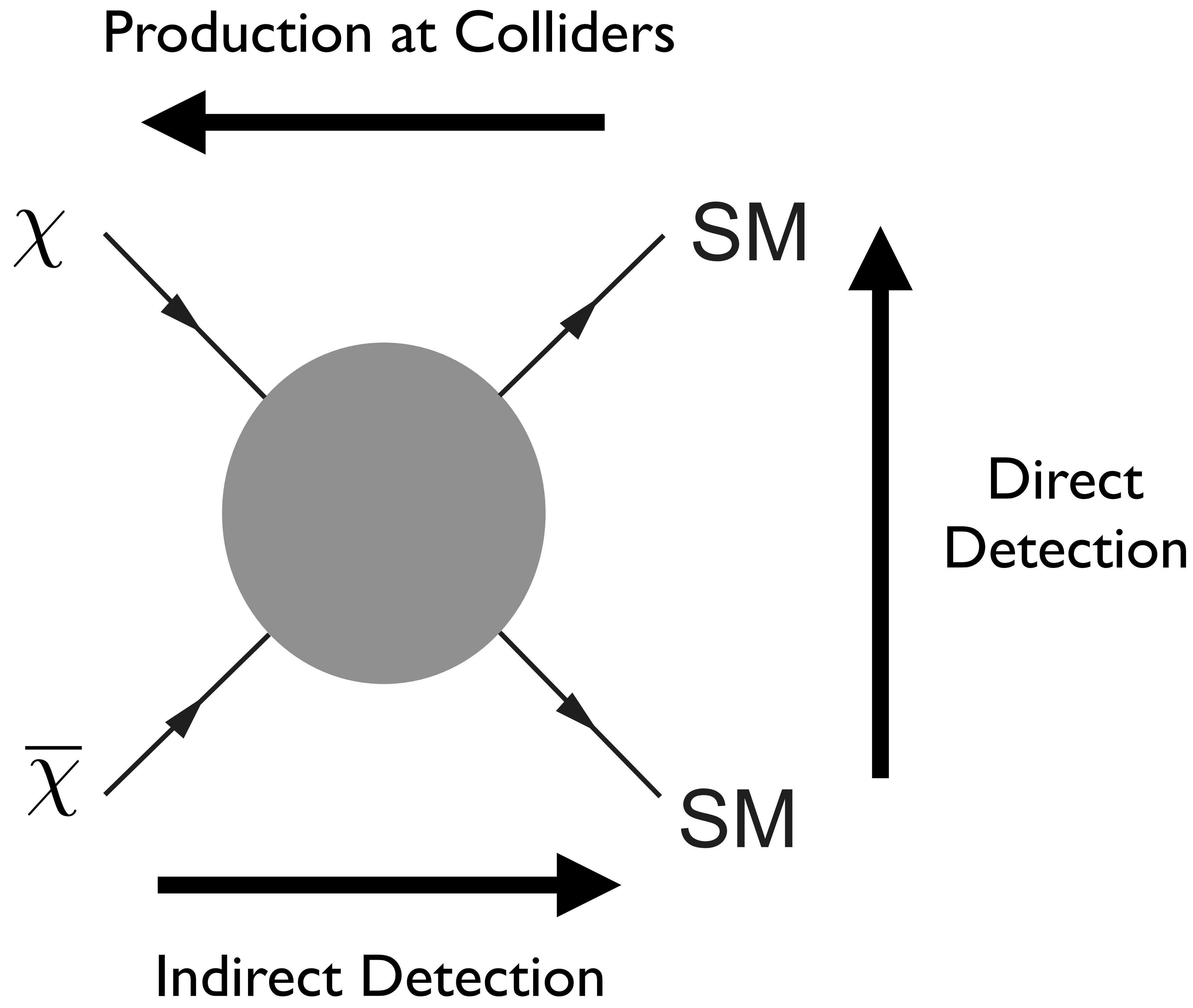
$$\Omega_\chi \approx 0.1 \left(\frac{\text{pb}}{\langle \sigma v \rangle} \right)$$

WIMP Miracle



$$\langle \sigma v \rangle \sim \frac{\pi \alpha_W^2}{m_\chi^2} \sim 1\,\text{pb} \times \left(\frac{\alpha_W}{(1/30)} \right)^2 \left(\frac{\text{TeV}}{m_\chi} \right)^2$$

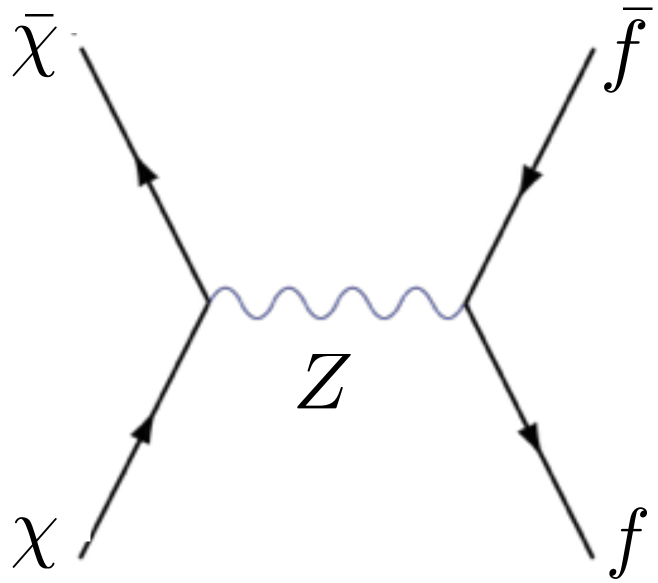
WIMP Phenomenology



[See talk by M. Cirelli]

Lee-Weinberg Bound

Light DM interacting through weak interactions generically overproduced

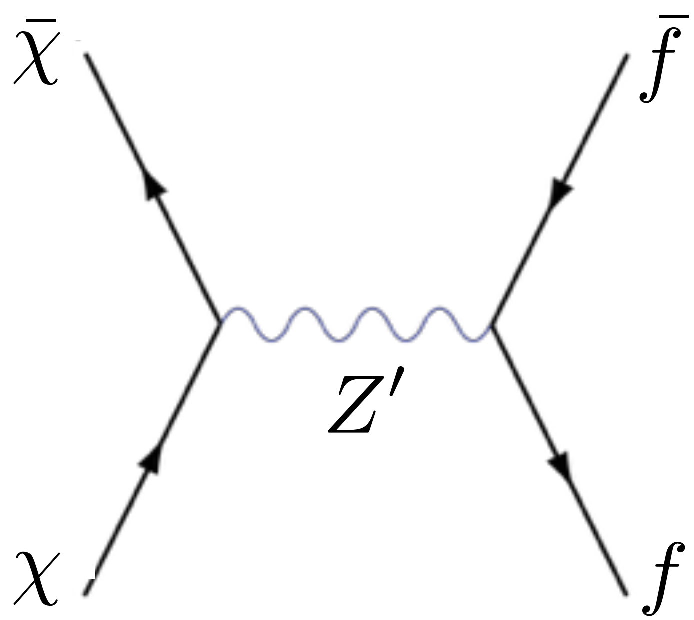


$$\mathcal{L} \sim G_F [\bar{\chi}\,\Gamma\,\chi][\bar{f}\,\Gamma\,f]$$

$$\langle \sigma v \rangle \sim \frac{G_F^2 m_\chi^2}{\pi} \approx 1\,\mathrm{pb} \times \left(\frac{m_\chi}{5\,\mathrm{GeV}}\right)^2$$

$$\Rightarrow \quad m_\chi \gtrsim \mathcal{O}(\mathrm{GeV})$$

Lee-Weinberg bound is evaded if new light mediators are present



$$\mathcal{L} \supset g_\chi\, Z'_\mu\, \bar{\chi}\,\Gamma^\mu\,\chi + g_f\, Z'_\mu\, \bar{f}\,\Gamma^\mu\, f$$

$$\langle \sigma v \rangle \sim \frac{g_\chi^2\, g_f^2\, m_\chi^2}{m_{Z'}^4} \sim 1\,\mathrm{pb} \times \left(\frac{g_\chi}{0.5}\right)^2 \left(\frac{g_f}{0.001}\right)^2 \left(\frac{m_\chi}{100\,\mathrm{MeV}}\right)^2 \left(\frac{1\,\mathrm{GeV}}{m_{Z'}}\right)^4$$

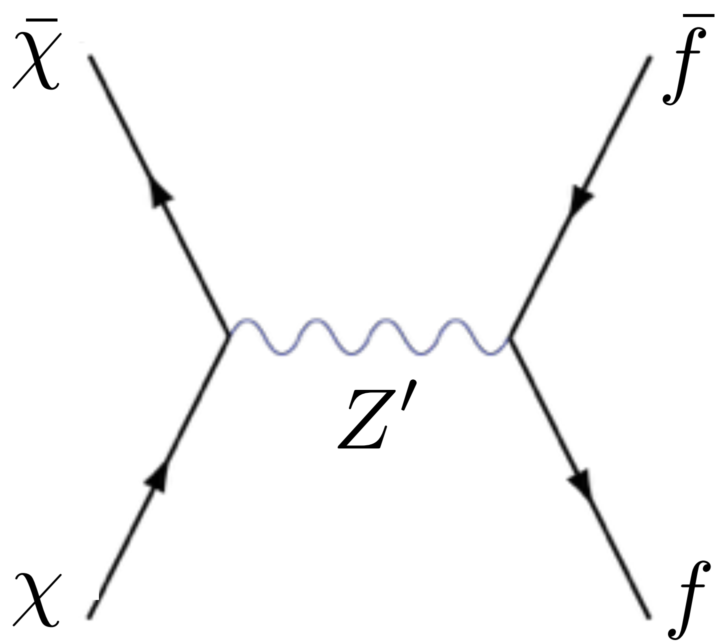
[Boehm, Fayet]

Direct vs. Secluded Annihilation

Two characteristic regimes:

$$\mathcal{L} \supset g_\chi \, Z'_\mu \, \bar{\chi} \, \Gamma^\mu \, \chi + g_f \, Z'_\mu \, \bar{f} \, \Gamma^\mu \, f$$

1. Direct annihilation: $m_\chi < m_{Z'}$

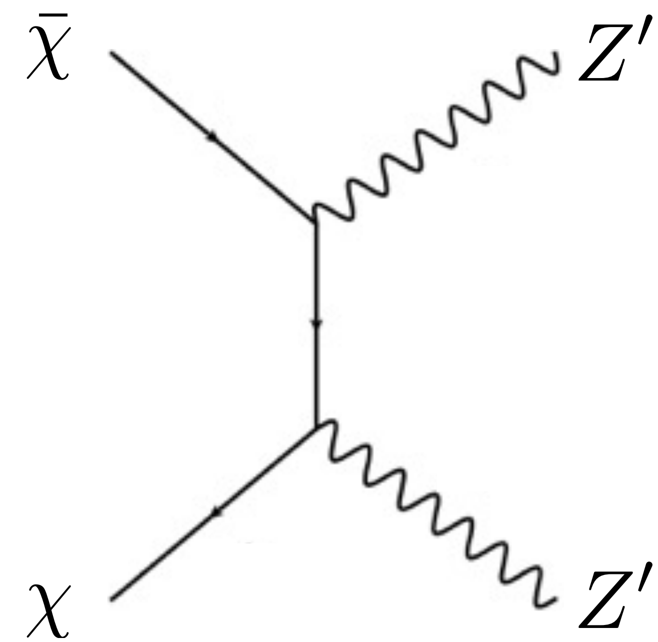


$$\langle \sigma v \rangle \sim \frac{g_\chi^2 \, g_f^2 \, m_\chi^2}{m_{Z'}^4}$$

Requires sizable portal coupling to deplete DM abundance

[Boehm, Fayet]

2. "Secluded annihilation: $m_\chi > m_{Z'}$



$$\langle \sigma v \rangle \sim \frac{g_\chi^4}{8\pi m_\chi^2}$$

Requires only minuscule portal coupling to maintain kinetic equilibrium

[Pospelov, Ritz, Voloshin]

Dark sector models

- We can classify models based on the mediator particle.
- There are a few simple models that use one of the renormalizable "portals"

$$(AS + \lambda S^2)H^\dagger H \qquad \text{Higgs Portal}$$

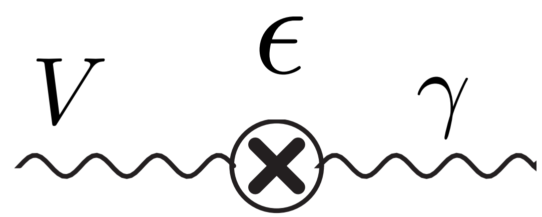
$$yLHN \qquad \text{Neutrino portal}$$

$$-\frac{\kappa}{2}B_{\mu\nu}V^{\mu\nu} \qquad \text{Vector Portal}$$

- Beyond this, we can consider gauging certain anomaly free combinations of the SM symmetries, e.g., $B-L, L_\mu - L_\tau$, etc.
- In general we can also consider gauging anomalous symmetries, or consider scalar particles coupled through higher dimension operators (e.g., axion portal)
- Finally, we can straightforwardly couple the dark matter to the mediator

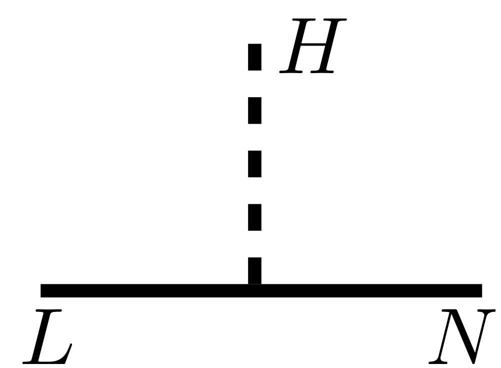
Portals

$\frac{\epsilon}{2} B_{\mu\nu} V^{\mu\nu}$



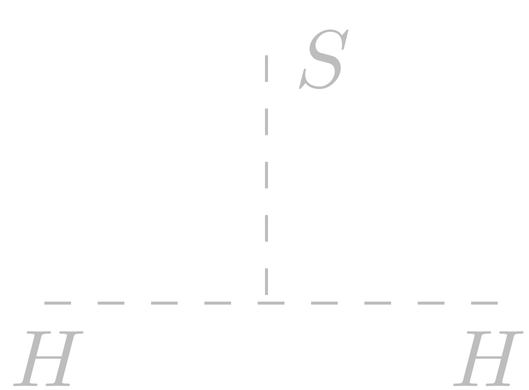
Vector Portal

$y L H N$



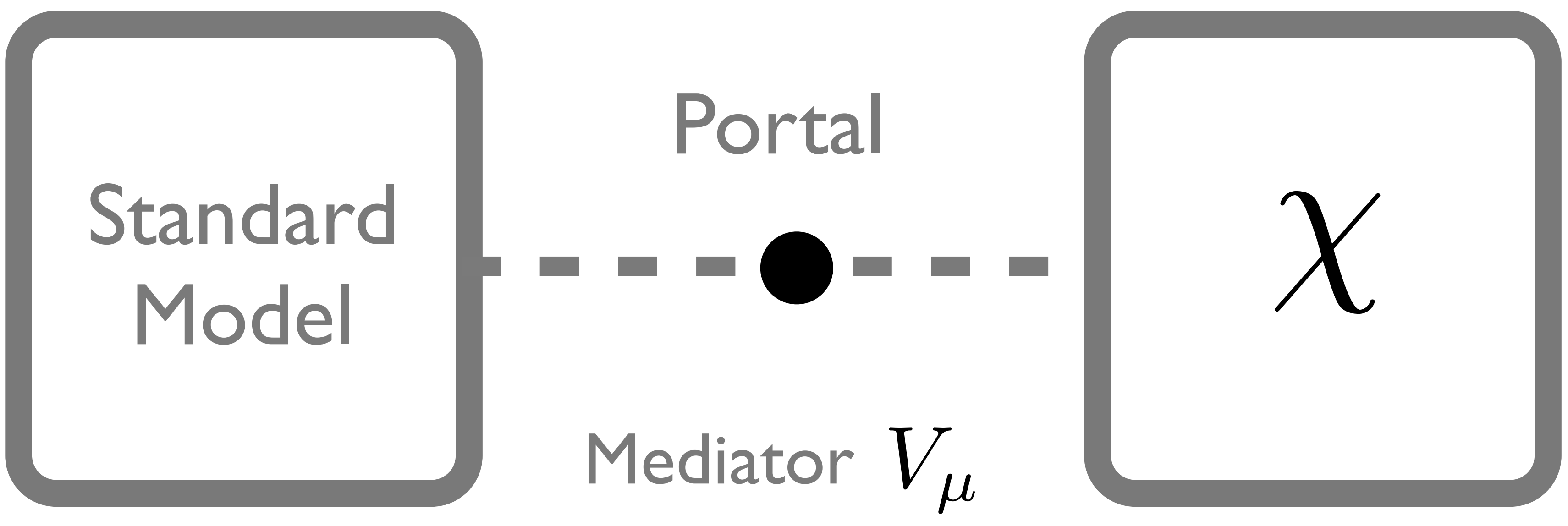
Neutrino portal

$(\mu S + \lambda S^2) H^\dagger H$



Higgs Portal

Vector Portal Dark Matter



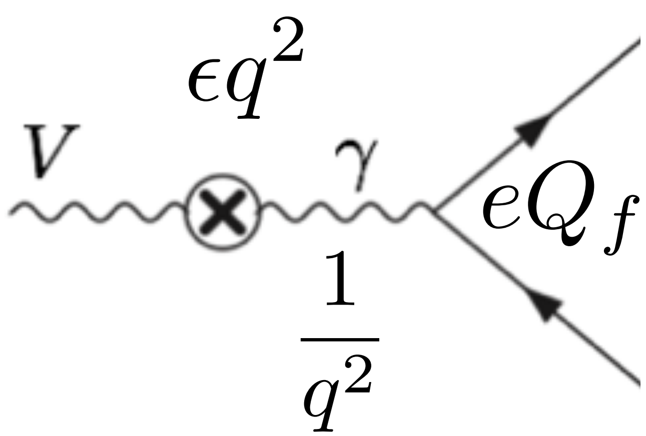
$$\frac{\epsilon}{2} B_{\mu\nu} V^{\mu\nu} + g_D V_\mu \bar{\chi} \gamma^\mu \chi$$

Dark photon model

[Holdom]
[Pospelov, Ritz, Voloshin]
[Arkani-Hamed, Finkbeiner, Slatyer, Weiner]

$$\mathcal{L} \supset -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}V_{\mu\nu}V^{\mu\nu} - \frac{\epsilon}{2}F_{\mu\nu}V^{\mu\nu} + \frac{1}{2}m_V^2 V_\mu V^\mu + \sum_f Q_f e A_\mu \bar{f}\gamma^\mu f + g_D V_\mu \bar{\chi}\gamma^\mu \chi$$

- V_μ is the dark photon; χ is the dark matter; Four parameters $m_V, m_\chi, \epsilon, g_D$
- We can treat the kinetic mixing as an interaction, e.g.,



$\epsilon\, e\, Q_f$ "Milli-dark charge"

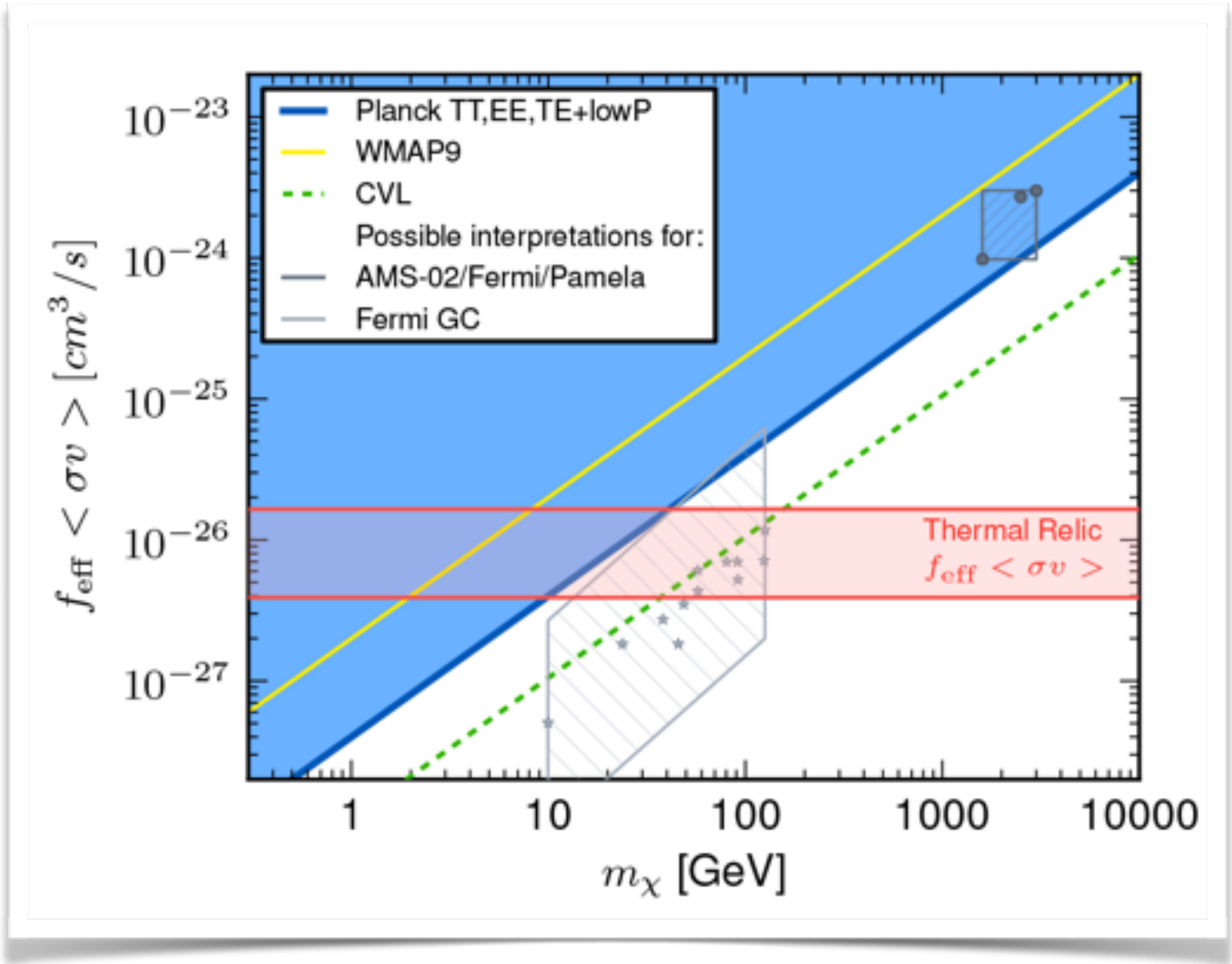
- Or we can diagonalize the Lagrangian via

$$A_\mu \rightarrow A_\mu - \epsilon V_\mu,$$
$$V_\mu \rightarrow V_\mu.$$

- This gives the interaction: $\mathcal{L} \supset \sum_f Q_f\, \epsilon\, e\, V_\mu\, \bar{f}\gamma^\mu f$
- Both direct and secluded annihilation are possible; phenomenology is different in each case

CMB as a probe of the dark sector

- The cosmic microwave background provides a sensitive test of DM annihilation around the epoch of recombination
- If the annihilation products include energetic photons, electrons, this will modify ionization history, leaving imprints on the CMB anisotropies



arXiv:1502.01589

- Current constraints probe thermal dark matter candidates below about 10 GeV

[see, e.g., Slatyer, Padmanabhan, Finkbeiner]

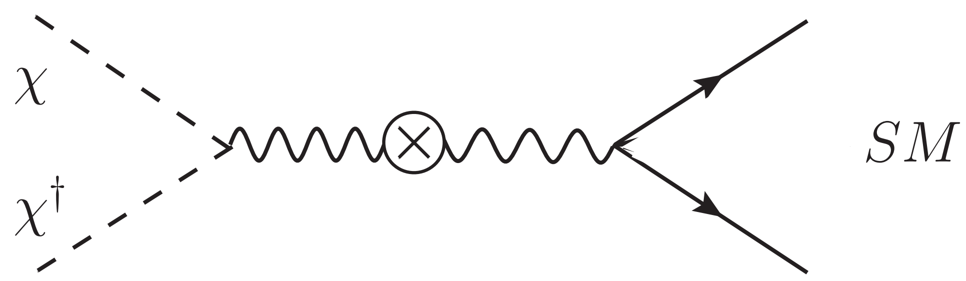
A closer look at the CMB bounds

- The CMB bounds depend on the particle physics model and DM cosmology
- In general, the DM annihilation cross section can be written as

$$\langle \sigma v \rangle = a + b v^2 + \ldots$$

- DM was highly non-relativistic during the recombination epoch, and therefore the bounds can be evaded if annihilation proceeds in the p-wave

- In the dark photon model, p wave annihilation to the SM occurs if DM is a scalar

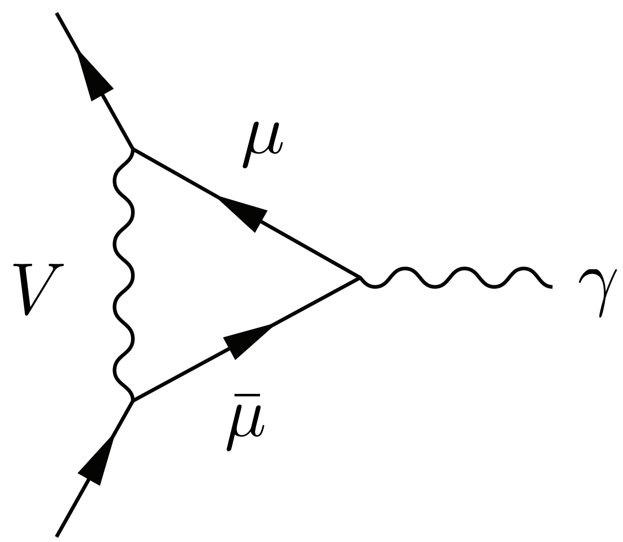


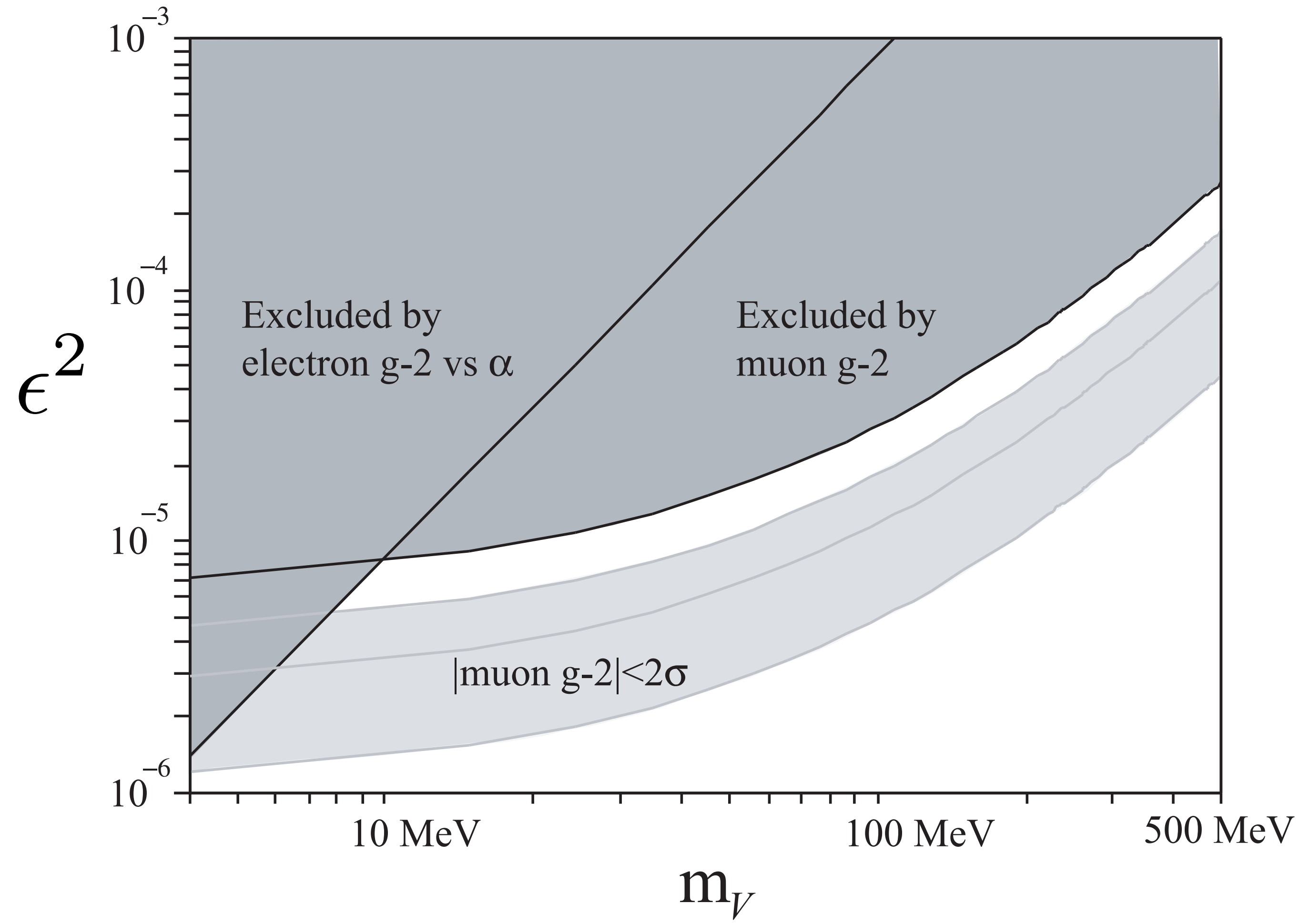
-Vector mediator has J = 1
-scalars are spin = 0;
-Conservation of J requires L = 1

- Asymmetric DM, Split DM (inelastic) also evade CMB bounds

Vector portal (and cousins) often motivated by anomalies

Example: Muon Anomalous Magnetic Moment (~ 3σ)



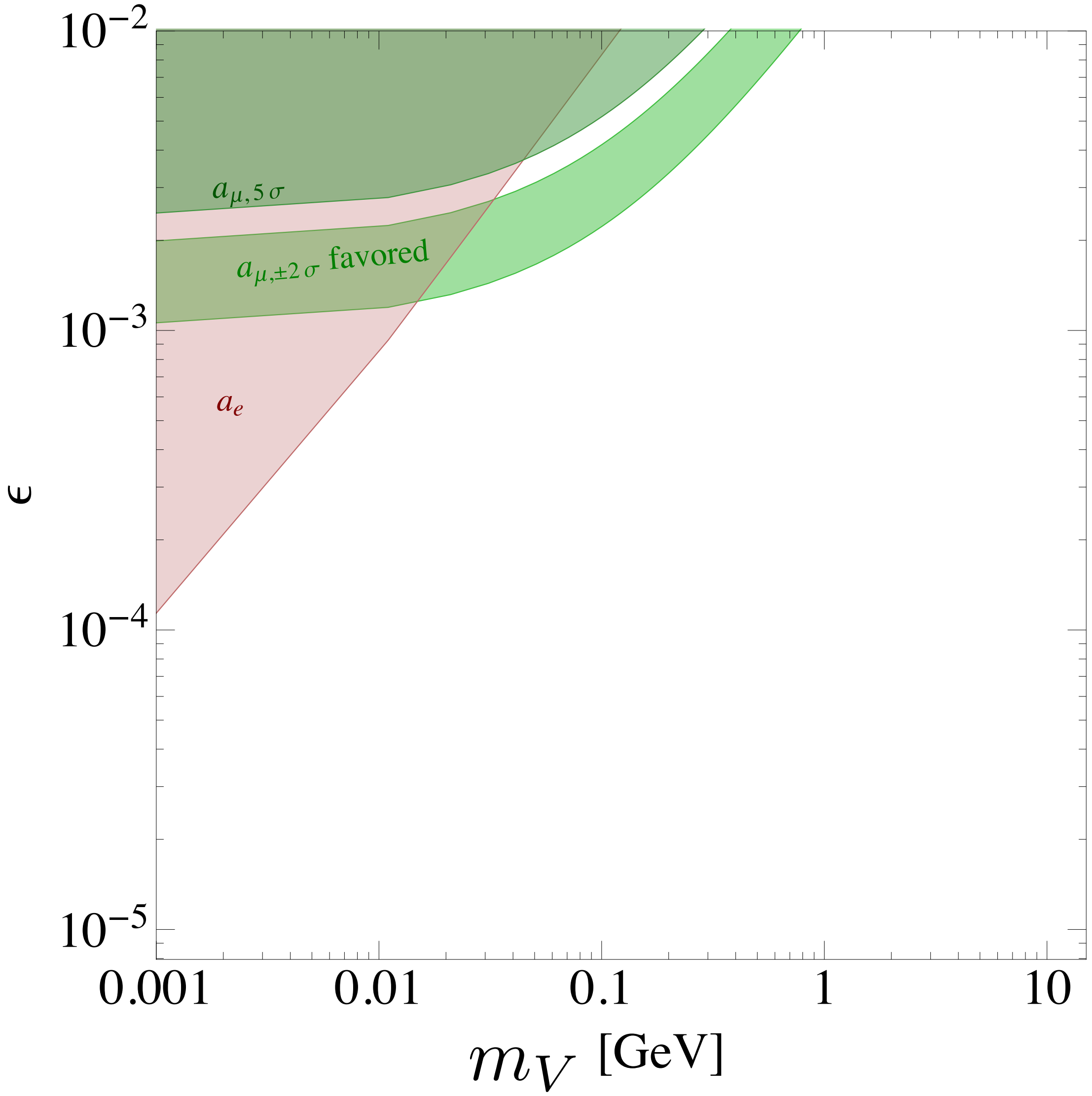


Fayet, Pospelov

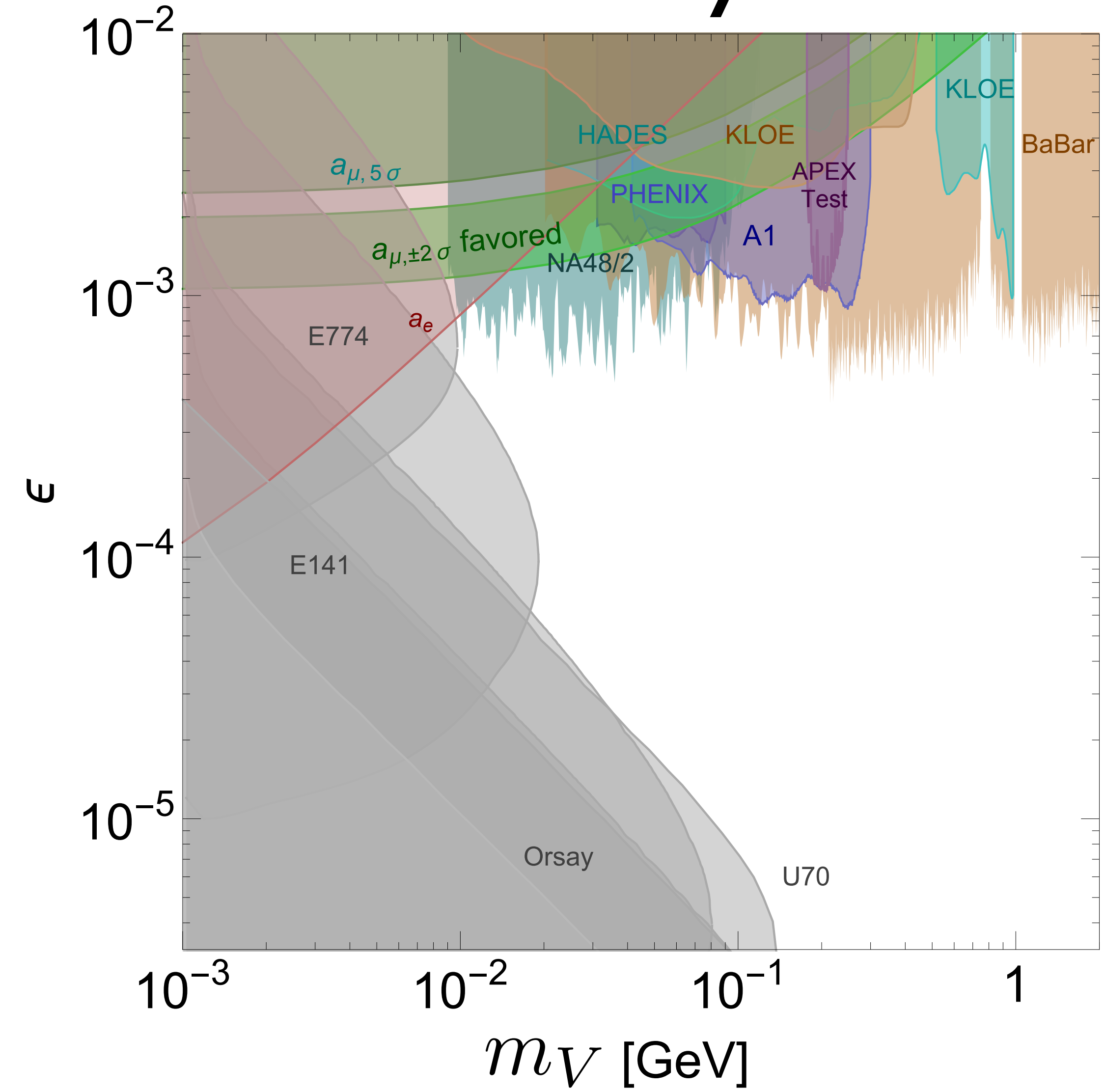
[See also talk by C. Davies]

Significant progress has been made in the last decade

2008

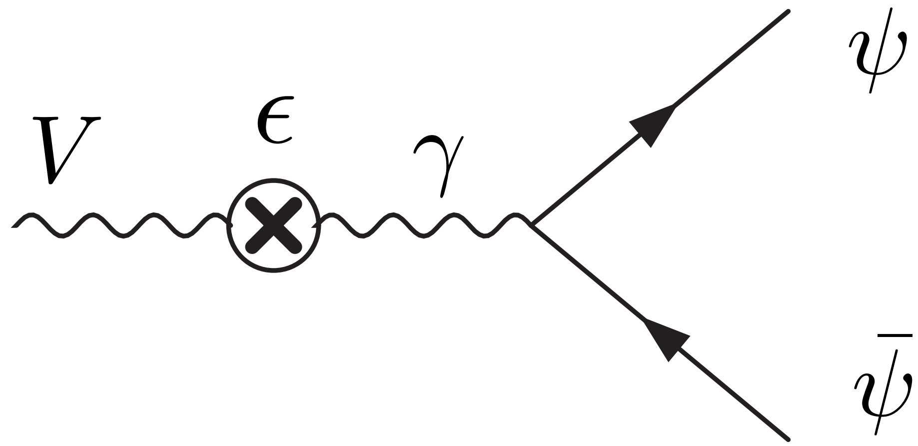


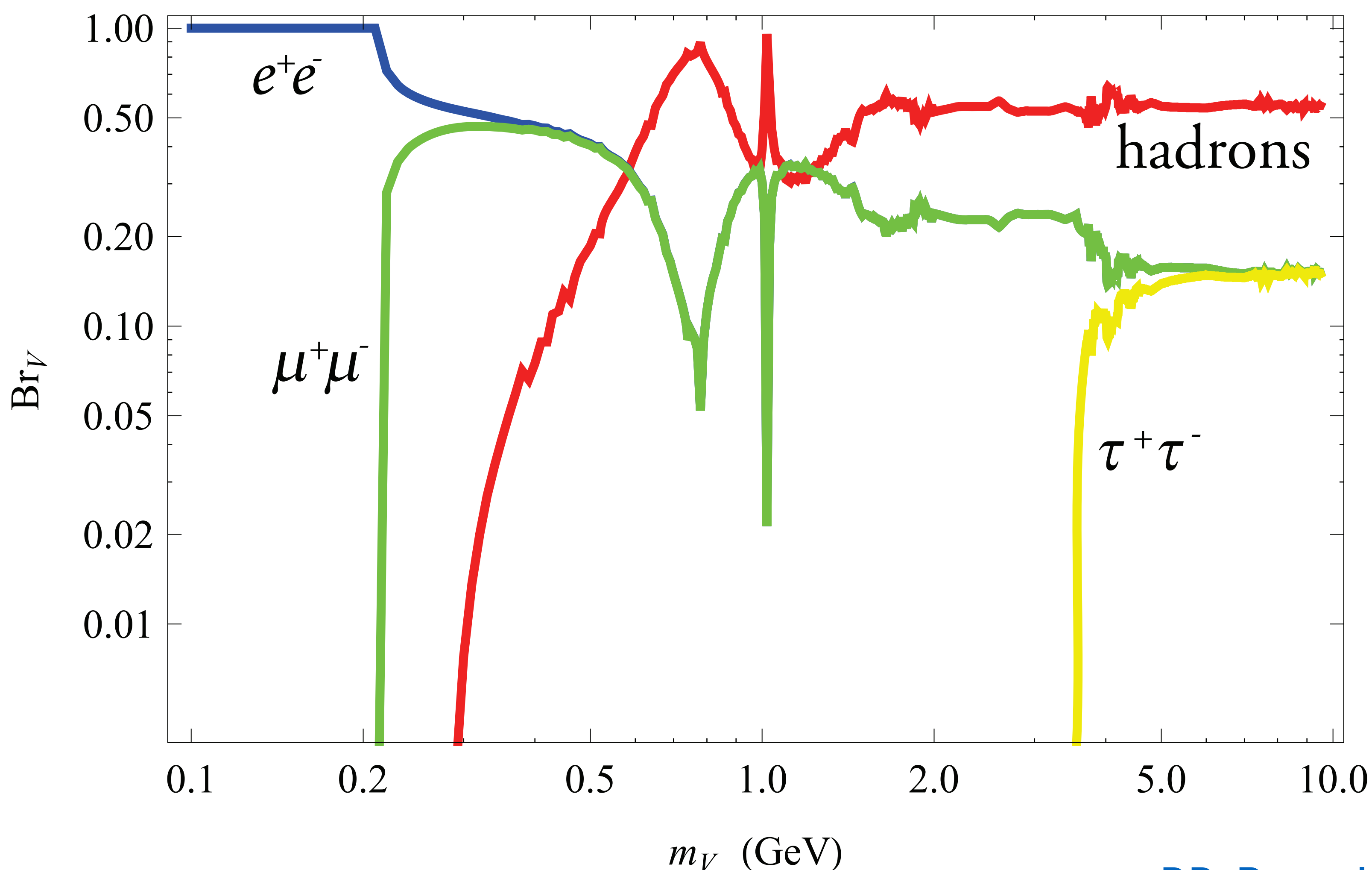
Today



Figs. from R. Essig

Dark photon decays





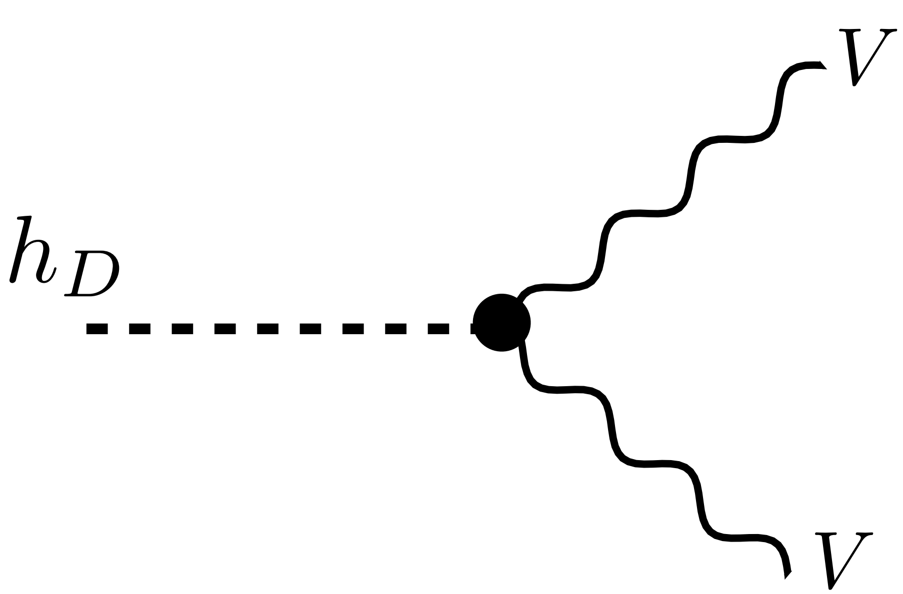
BB, Pospelov, Ritz

How is the dark photon mass generated?

Dark Higgs

$$\mathcal{L} = -\frac{1}{4}V_{\mu\nu}^2 - \frac{\kappa}{2}V_{\mu\nu}F^{\mu\nu} + |D_\mu\phi|^2 - V(\phi)$$

$$\phi = (v' + h')/\sqrt{2}, \quad \Rightarrow \quad \mathcal{L}_{int} = -\frac{\kappa}{2}V_{\mu\nu}F^{\mu\nu} + \frac{m_V^2}{v'}h'V_\mu^2 \; + \ldots$$

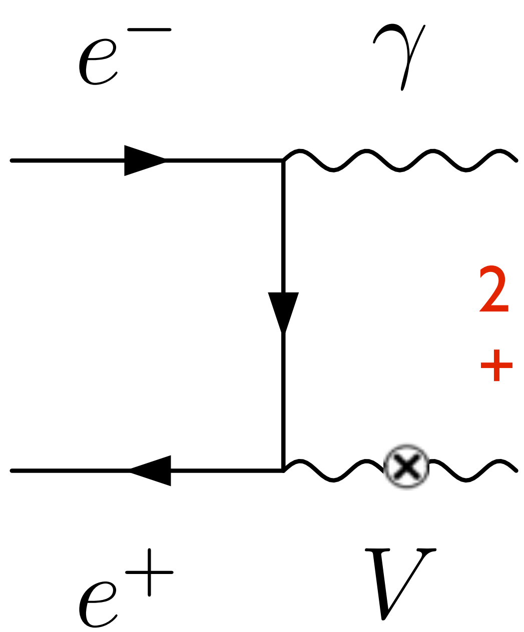


⇒ Production and decay of Dark Higgs through vector portal

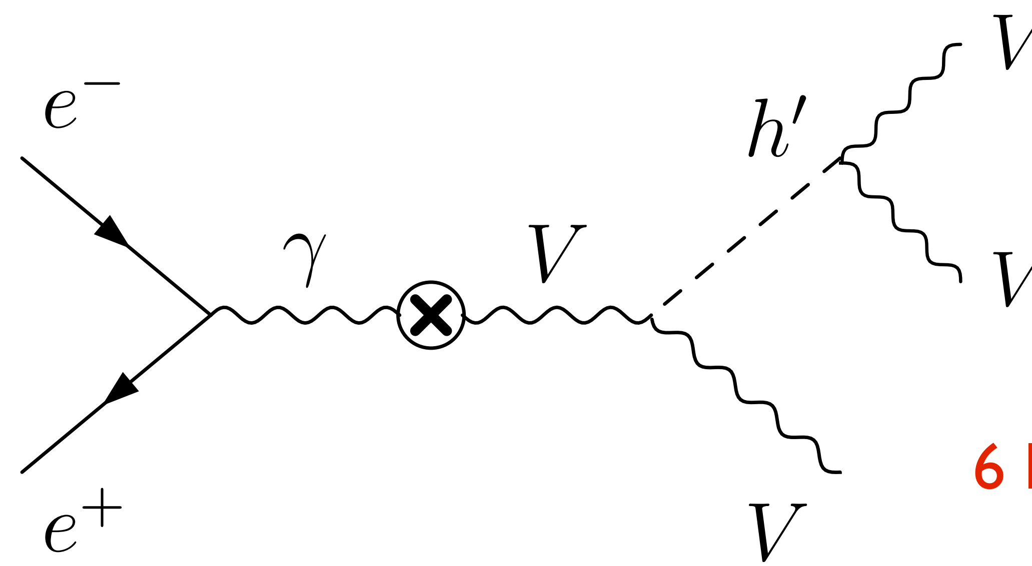
BB, Pospelov, Ritz

BB, Pospelov, Ritz;
Essig Schuster, Toro;
Reece Wang;

Low-energy e+e- colliders

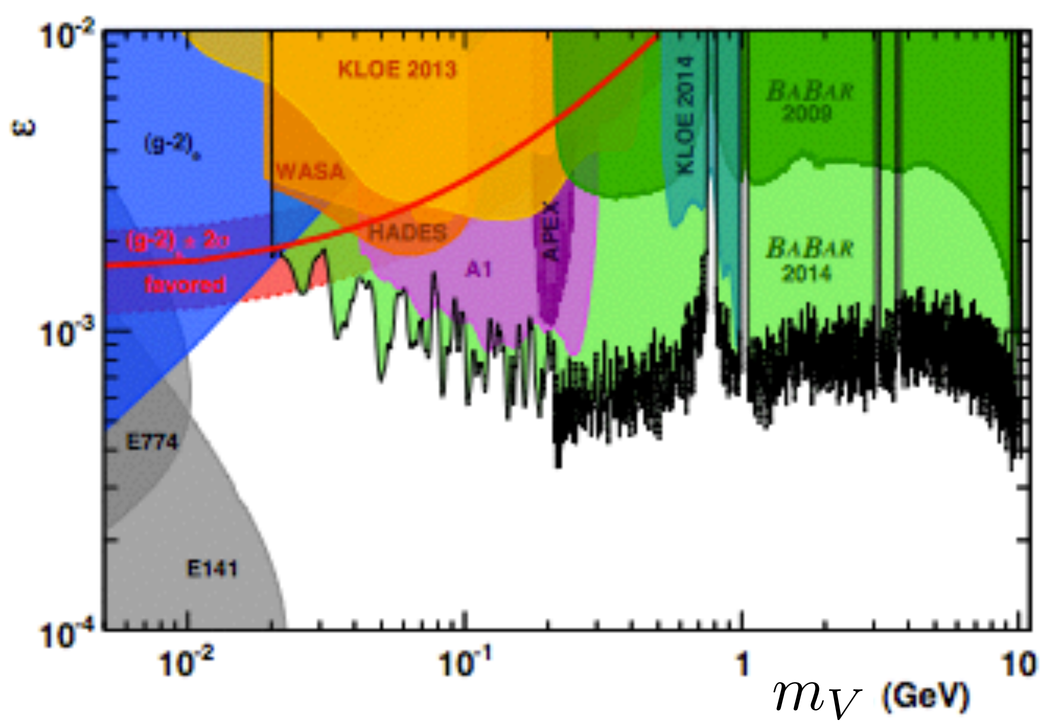


2 leptons
+ photon

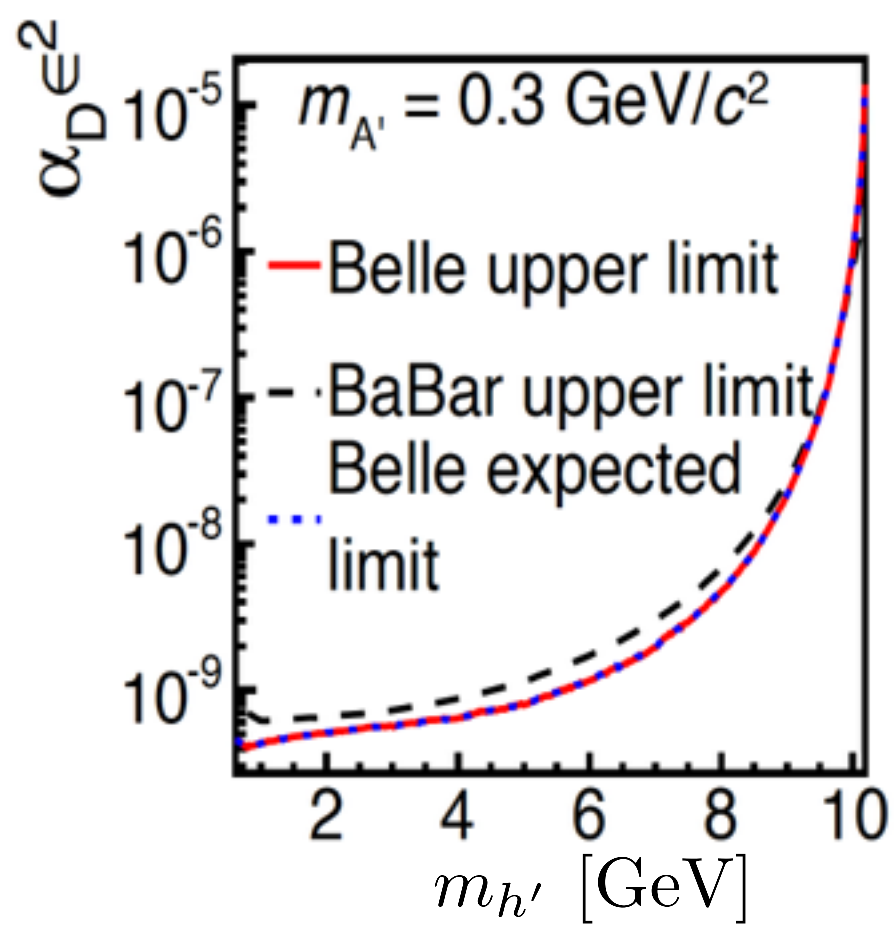


6 leptons

Dark sector searches at B-factories

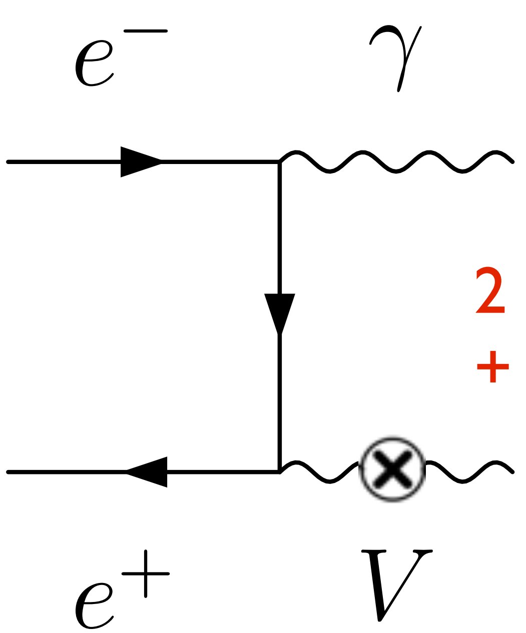


BaBAR, (2014)

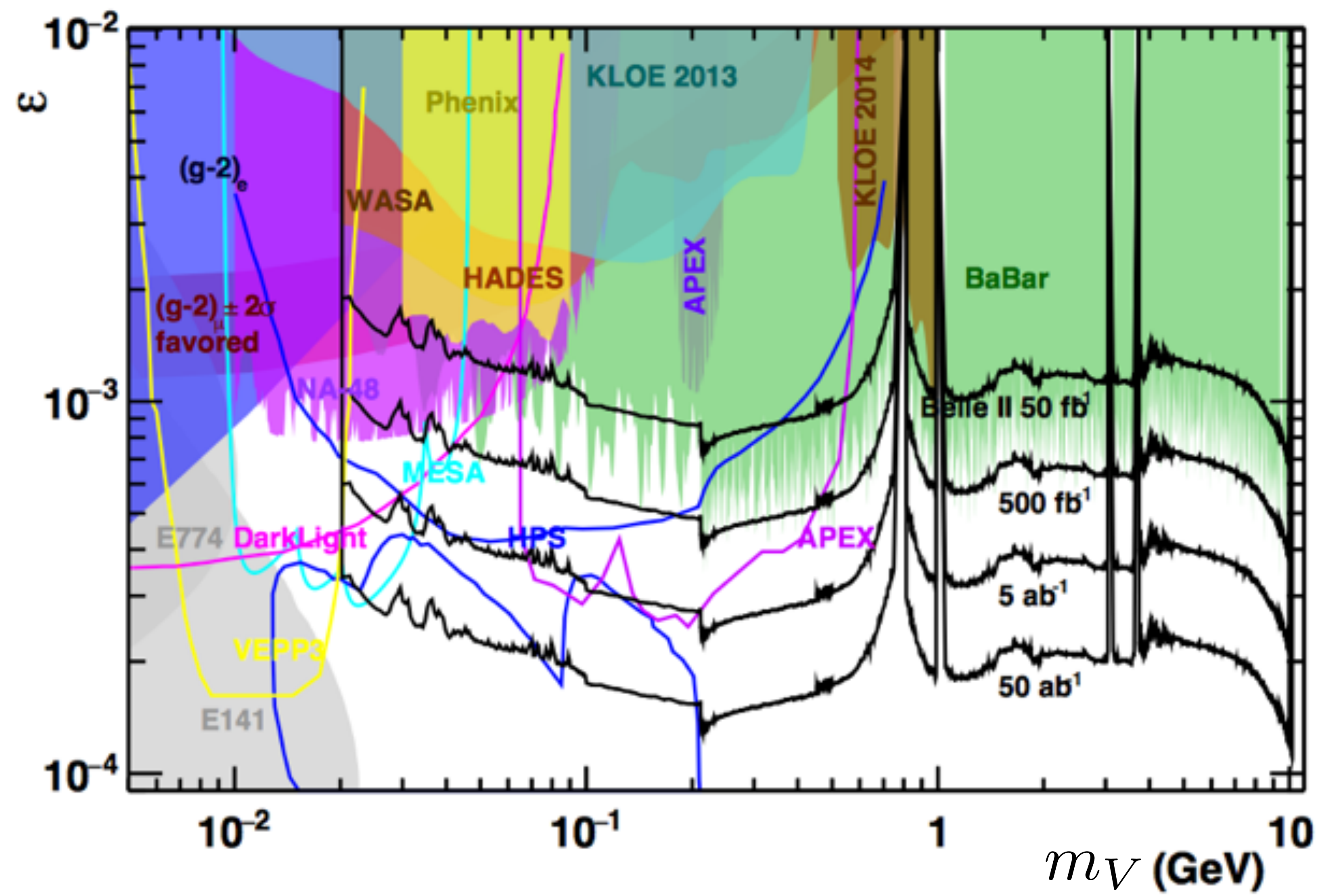


BELLE, (2015)

Belle II

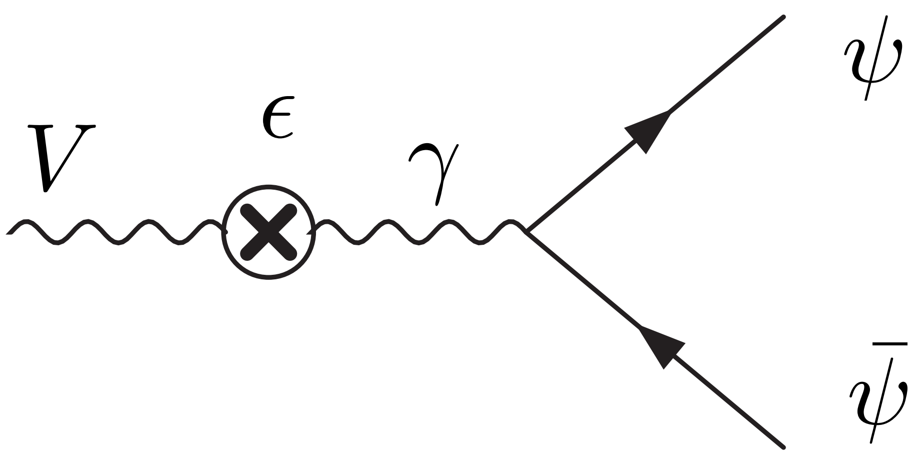


2 leptons
+ photon

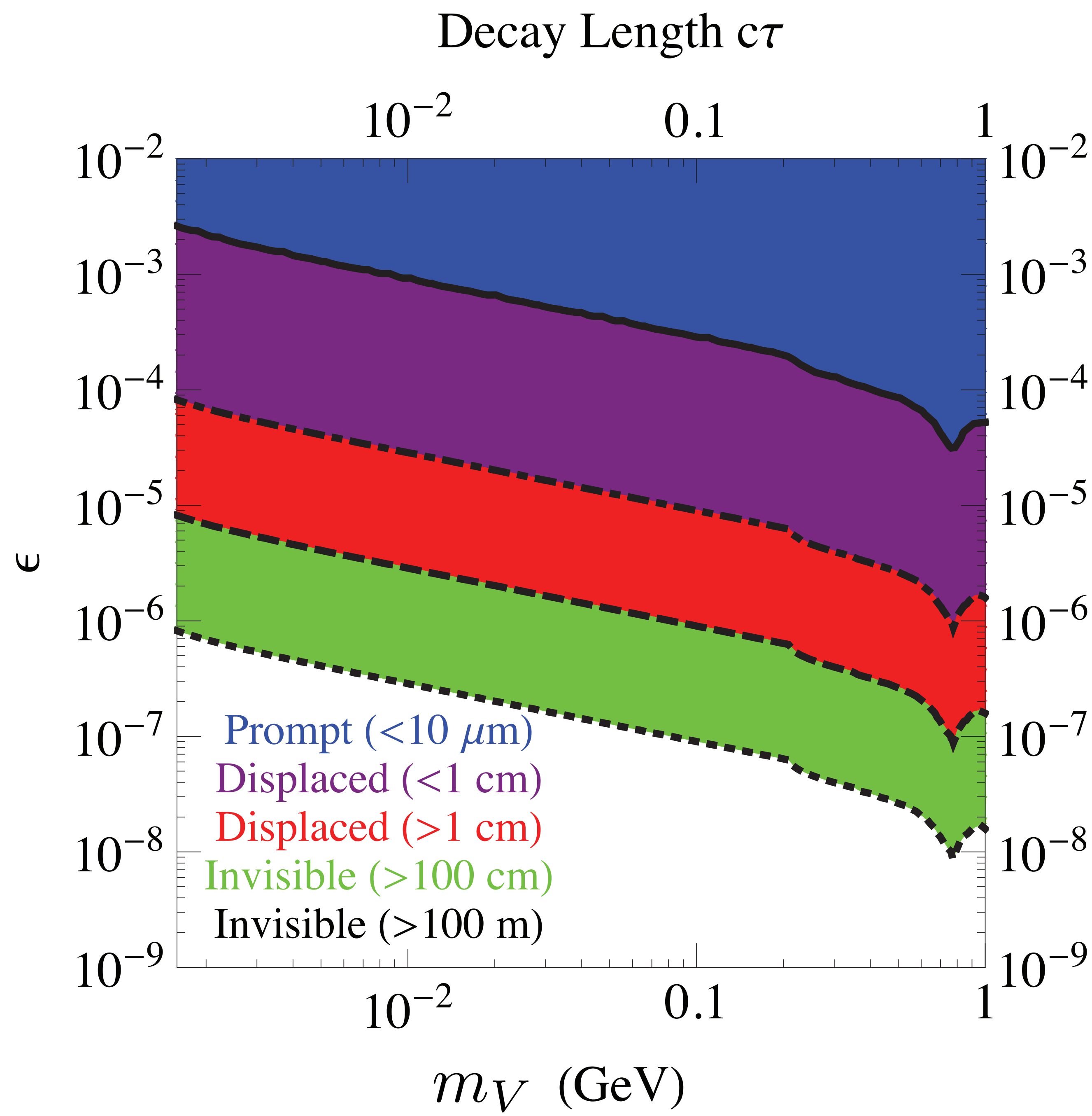


Belle II projections
(Fig. from C. Hearty)

Lifetime



$$\Gamma_V \sim \epsilon^2 \alpha m_V \quad \Rightarrow \quad c\tau_V \sim \frac{1}{\epsilon^2 \alpha m_V}$$

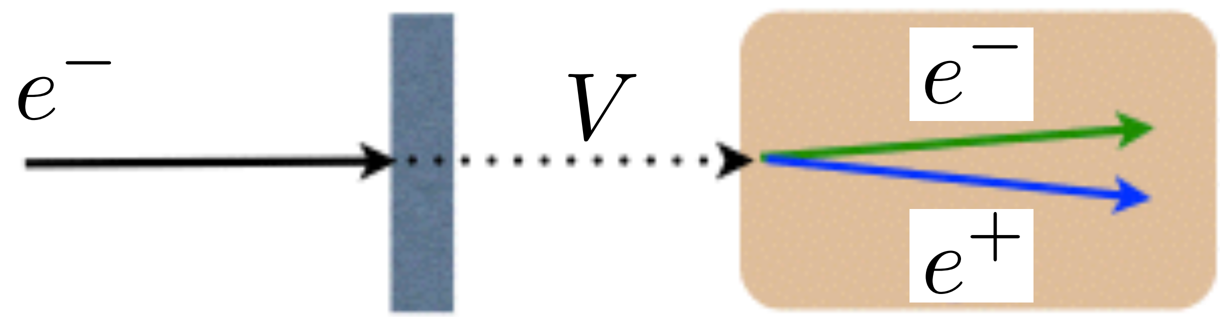


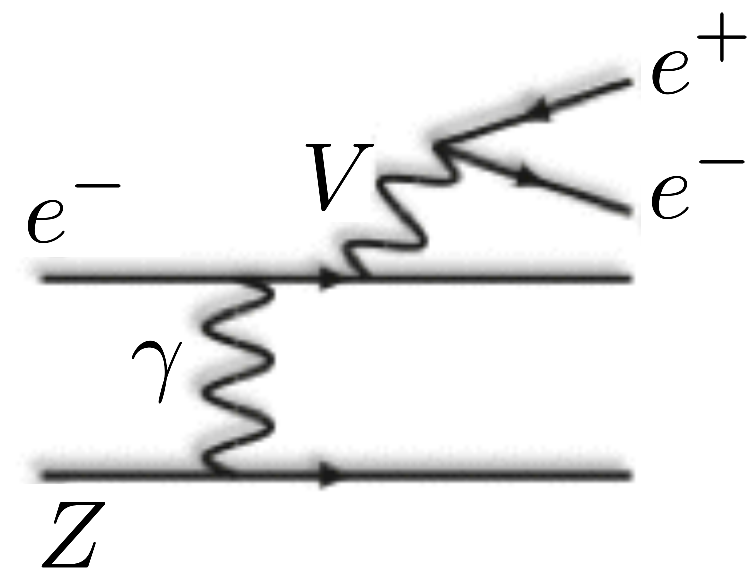
Essig, Harnik, Kaplan, Toro

- Depending on lifetime, one can search for a bump in the invariant mass distribution or a displaced vertex/long-lived particle

Electron beam dump/fixed target experiments

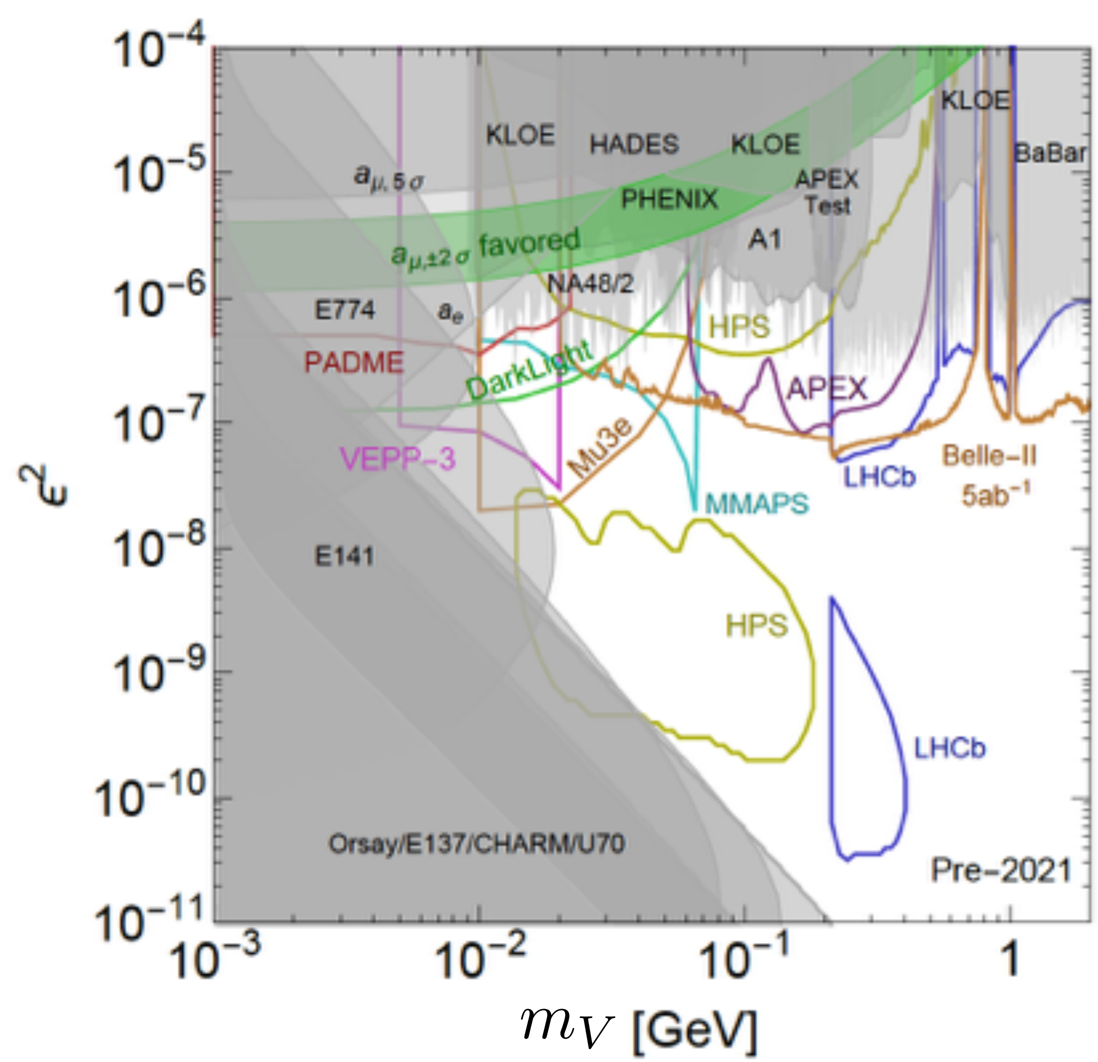
Bjorken, Essig, Schuster, Toro;
Freytsis, Ovanesyan, Thaler;
Andreas, Niebuhr, Ringwald;





- Look for a e^+e^- resonance or displaced vertex

- Current/planned experiments(APEX,HPS,MAMI, DarkLight,VEPP-3, MESA, mu3e, SHiP...) will cover a lot of new ground!



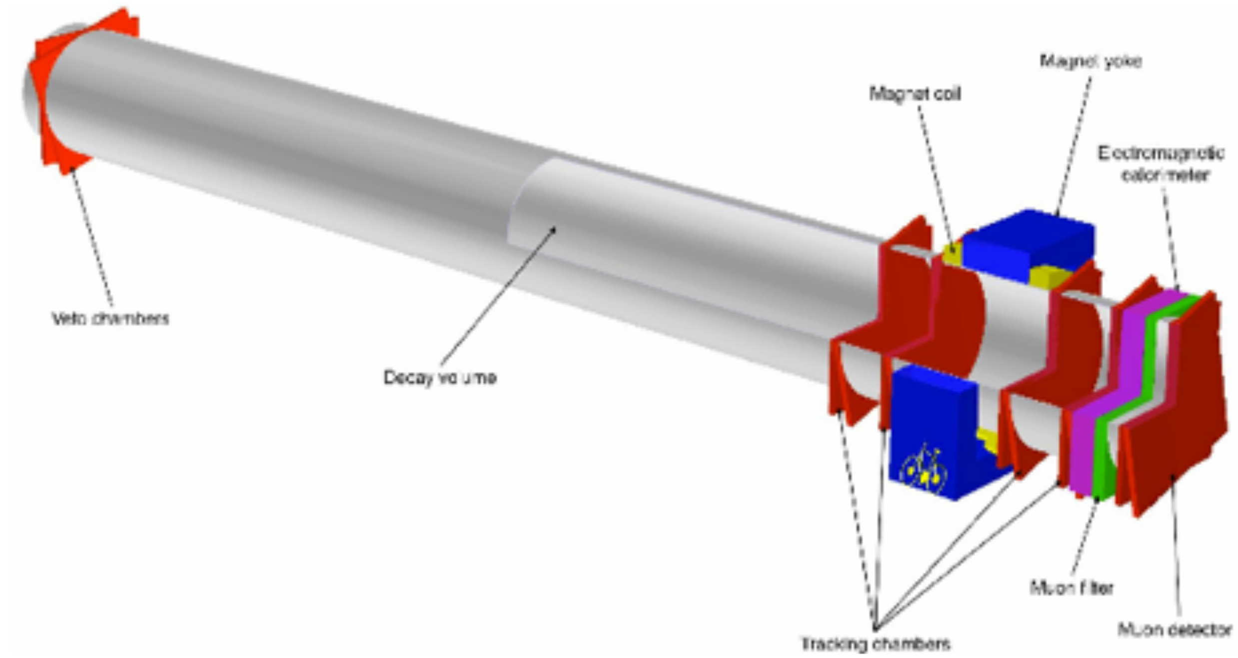
SHiP experiment
(Search for Hidden Particles)

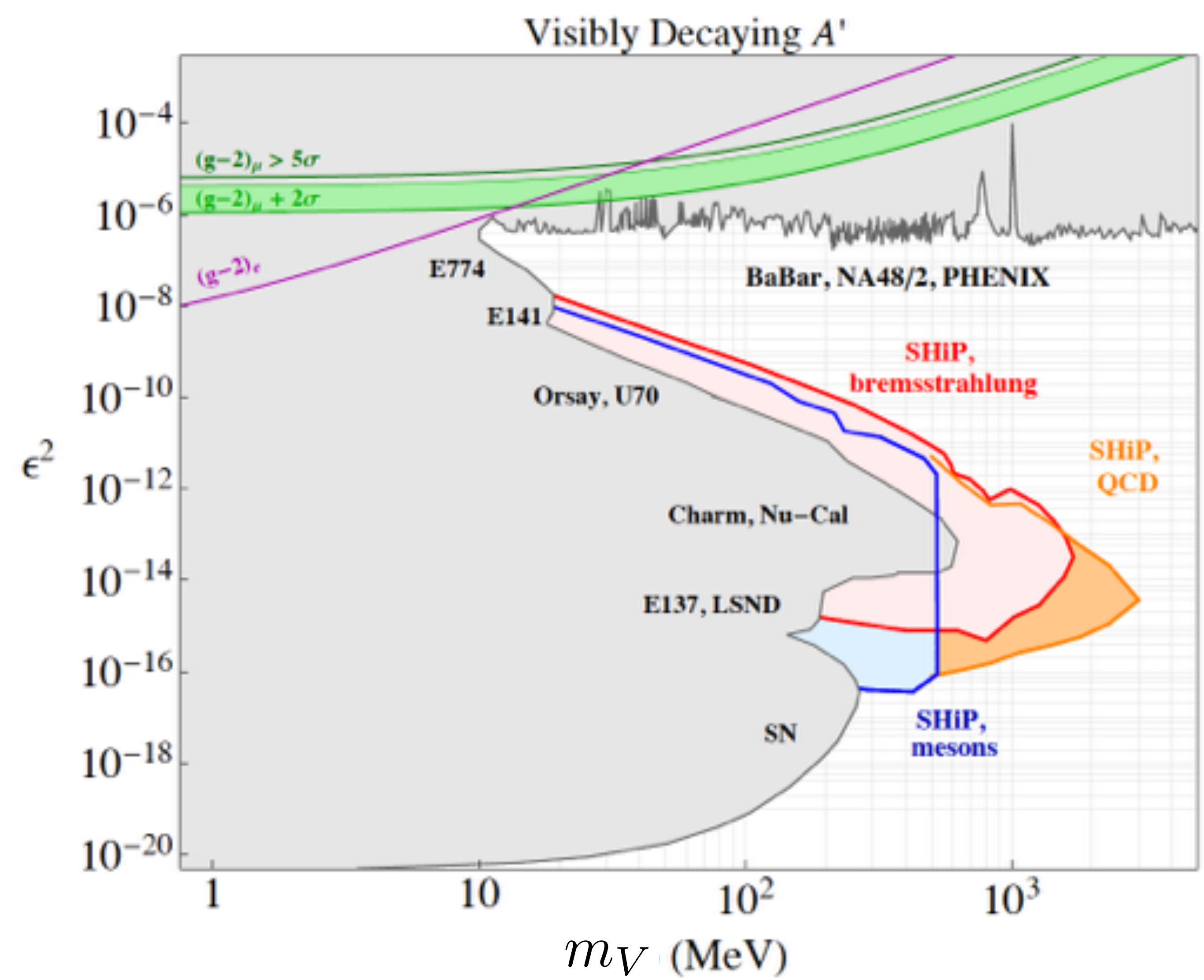
http://www.cern.ch/ship

- New fixed target facility proposed at CERN

- 400 GeV protons,
$\sim 10^{20}$ protons-on-target

- Powerful capability to search for weakly interacting, long-lived particles that decay visibly





Dark photons at LHCb

Ilten, Soreq, Thaler, Williams, Xue

Two proposals:

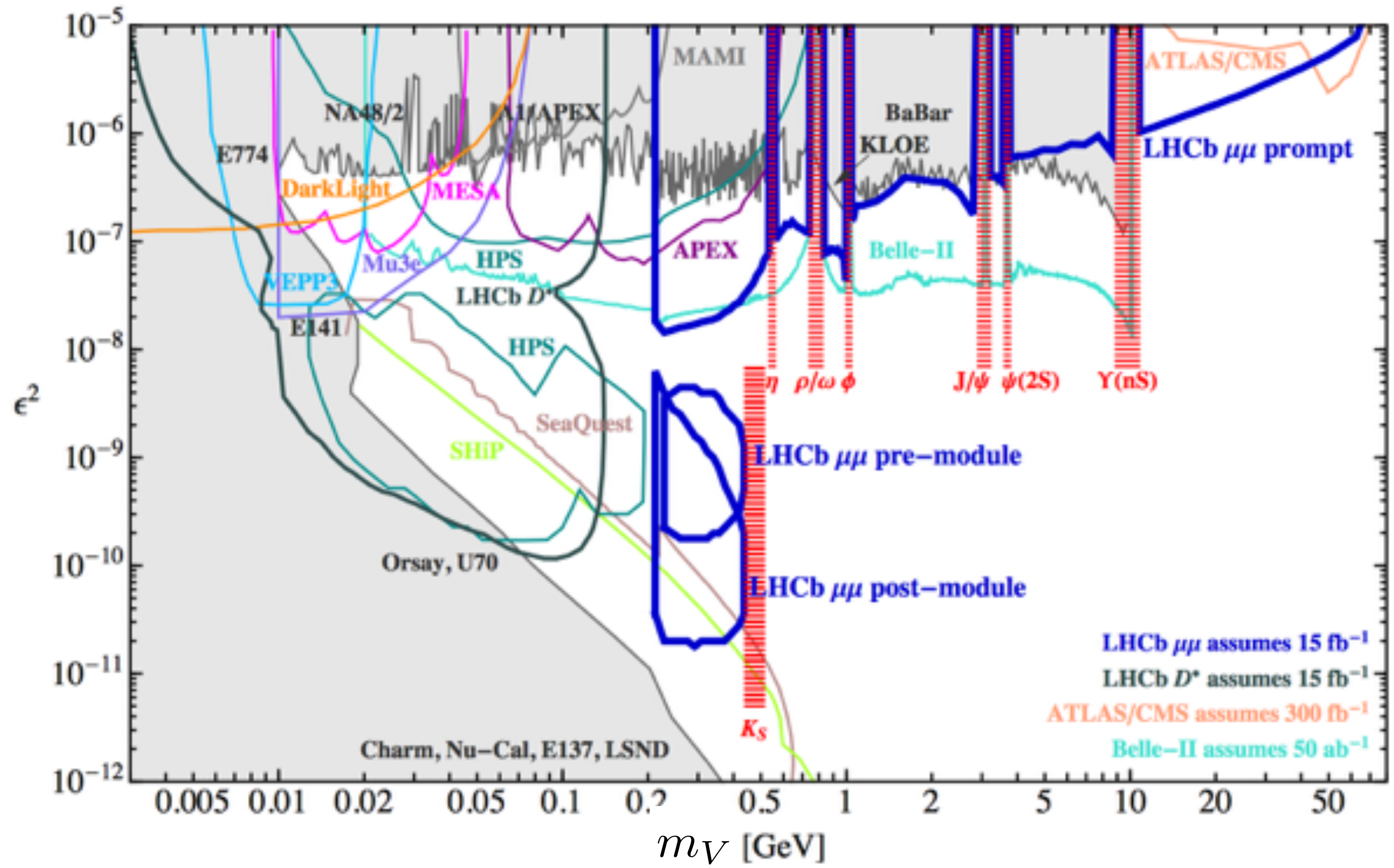
- Exclusive search:

$$D^{*0} \to D^0 A', \quad A' \to e^+ e^-$$

- Inclusive search

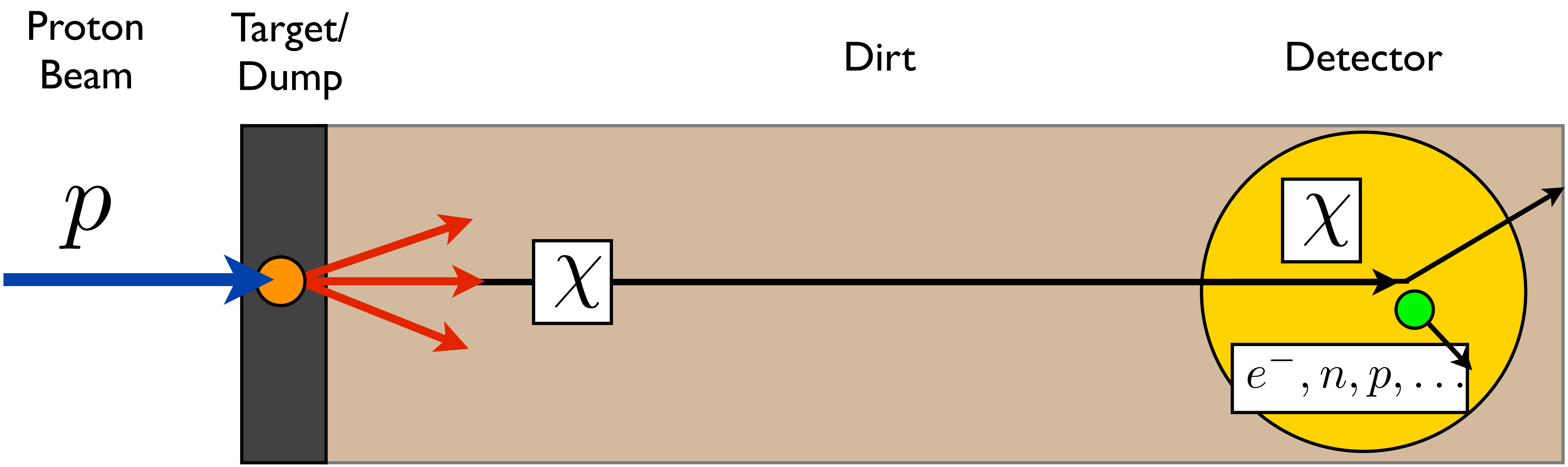
$$pp \to X A' \to X \mu^+ \mu^-$$

see 1710.02867 for first LHCb limits (1.6/fb)



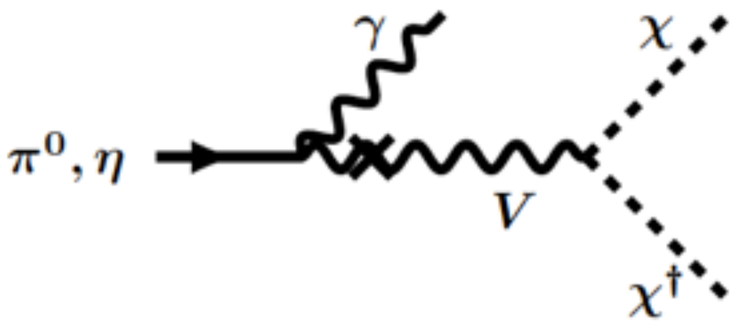
- Both displaced vertex and resonance searches are possible

Beam Dump Search for Light Dark Matter

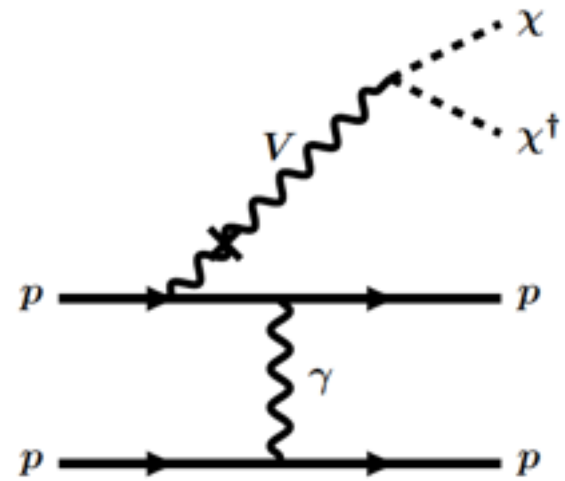


[BB, Pospelov Ritz]
[deNiverville, Pospelov Ritz]
[McKeen, deNiverville, Ritz]

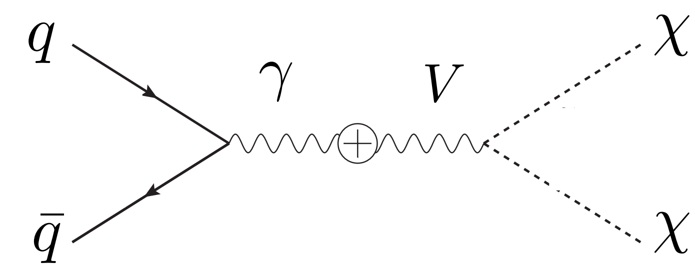
Production of the DM beam



Neutral mesons decays

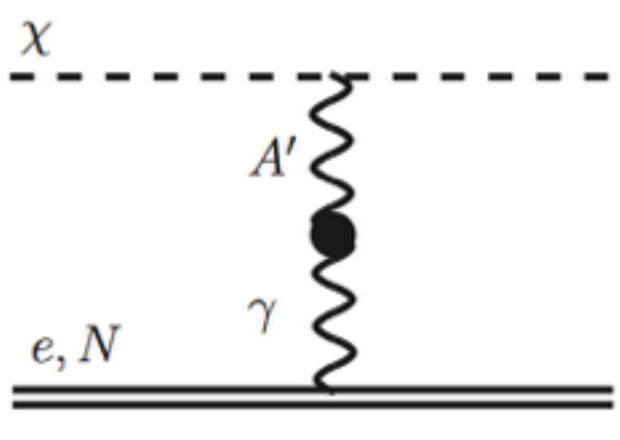


Bremsstrahlung + vector meson mixing

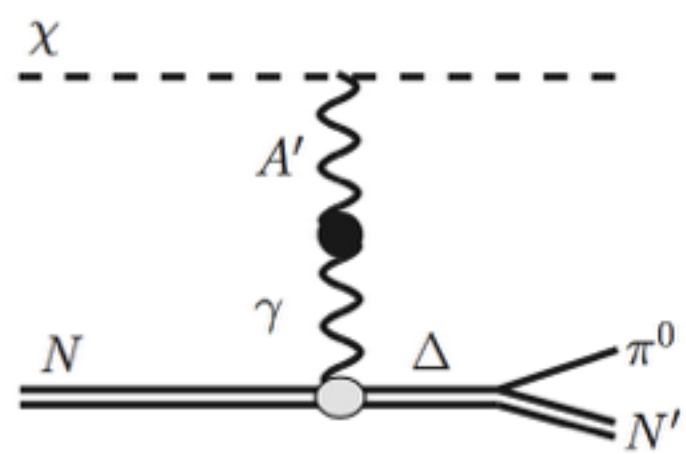


Direct production

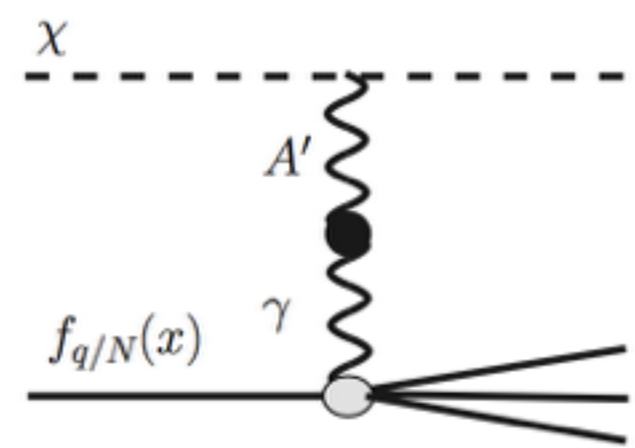
Detection of DM via scattering



Elastic NC nucleon or electron scattering



Inelastic NC neutral pion - like scattering



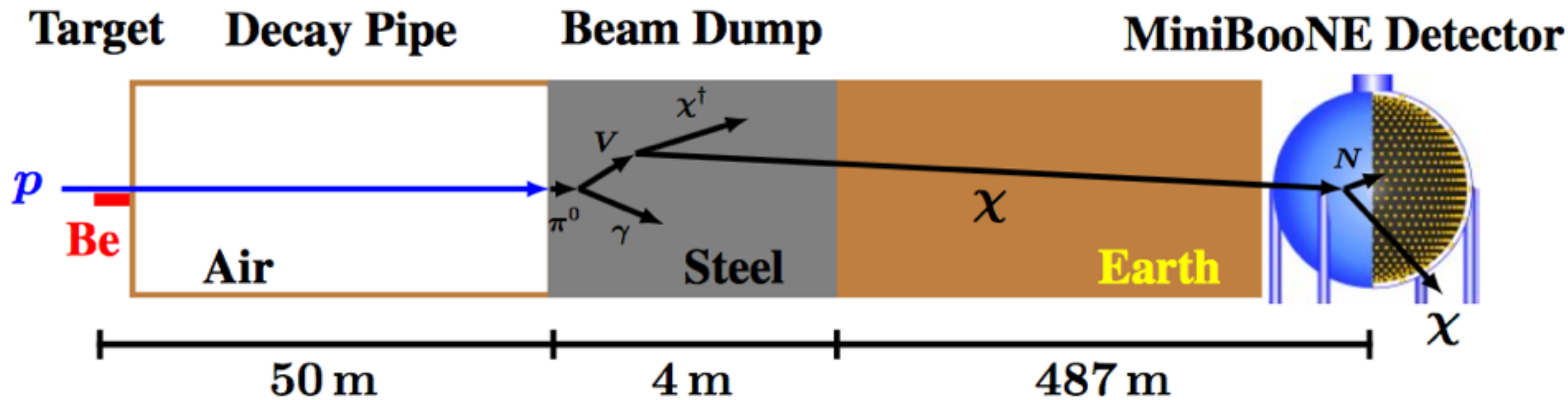
Deep Inelastic scattering

- `BdNMC`: Publicly available proton beam fixed target DM simulation tool developed by Patrick deNiverville (U.Victoria) and collaborators

  [deNiverville, Chen, Pospelov, Ritz] https://github.com/pgdeniverville/BdNMC/releases

MiniBooNE Dedicated Dark Matter Search

[arXiv:1702.02688
PRL **118**, 221803 (2017)]

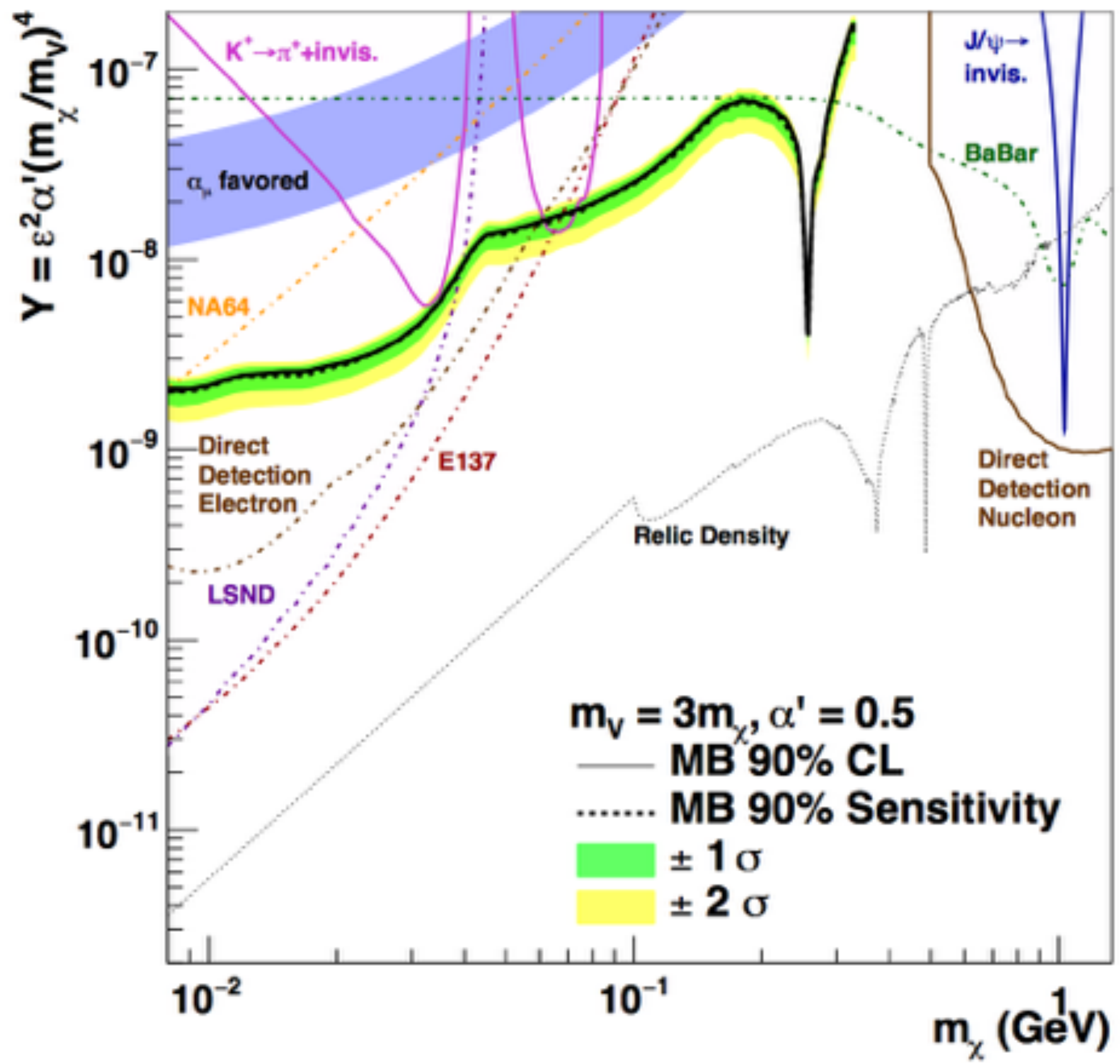


- Dedicated off target / beam dump run mode
- Neutrino flux significantly reduced (~1/30), DM production unaffected
- Ran from Nov. 2013 - Sep. 2014 - collected 1.9E20 POT

MiniBooNE-DM search

[arXiv:1702.02688
PRL **118**, 221803 (2017)]

- DM-nucleon channel

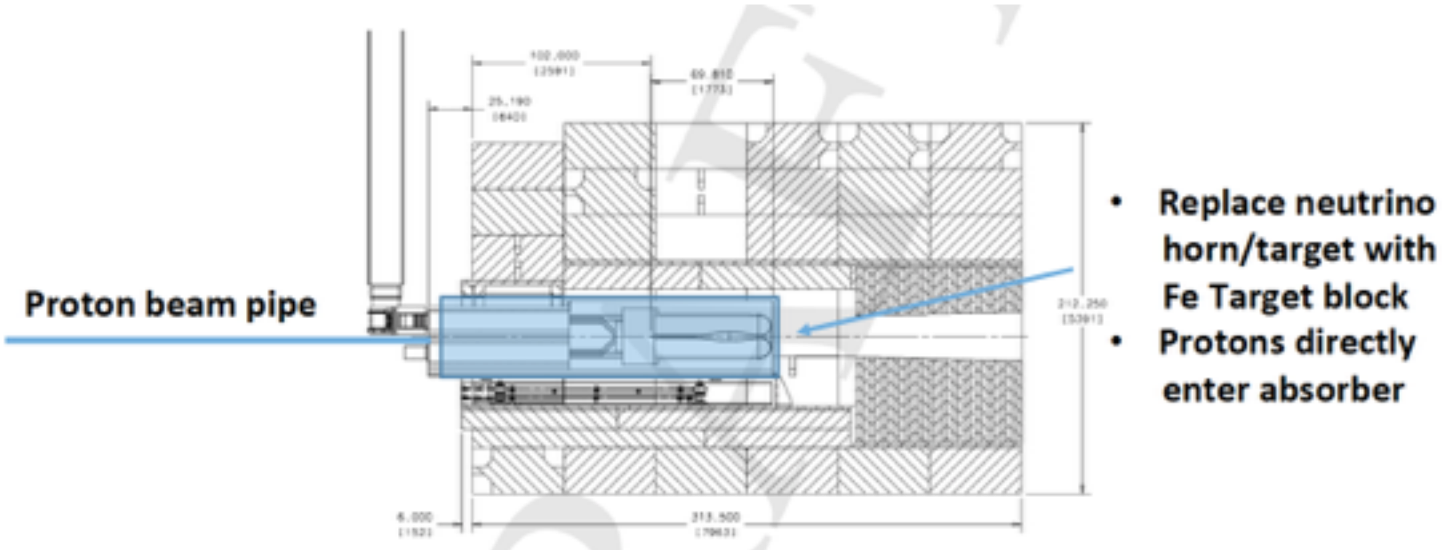


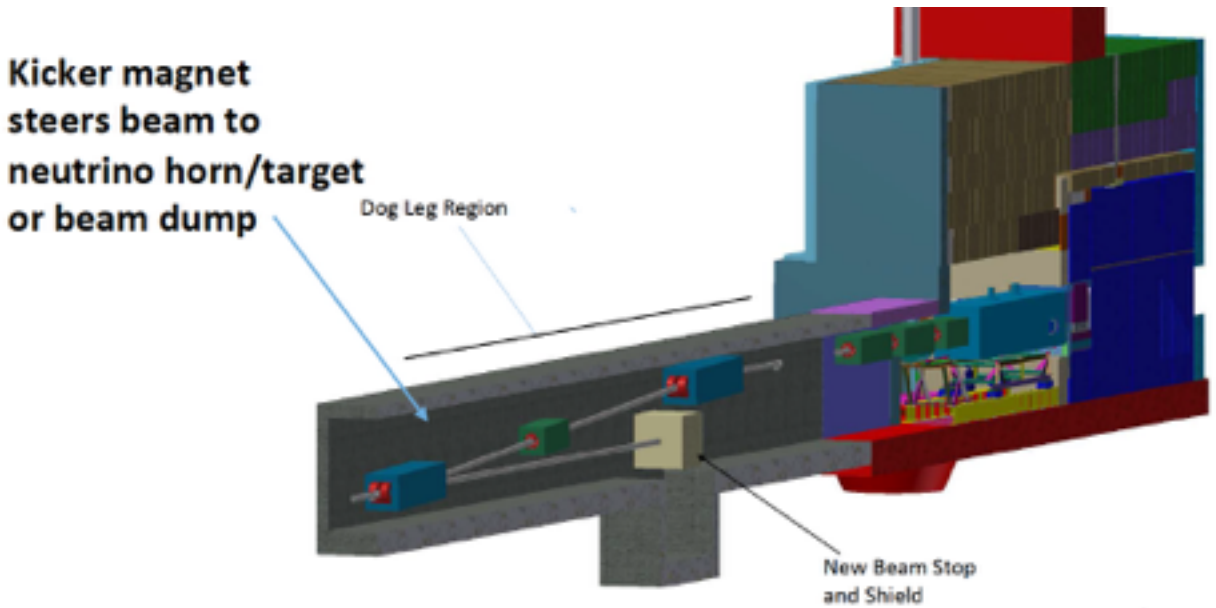
- Ongoing analysis in electron and inelastic neutral pion channel
- Utilize timing to reject neutrino background

Future dark matter searches at Fermilab

Motivation: expand physics drivers of Short and Long Baseline Neutrino programs with dark sector searches

- Option 1: Upgrade Booster Neutrino Beam Dump
- Reduce neutrino background by up to 3 orders of magnitude



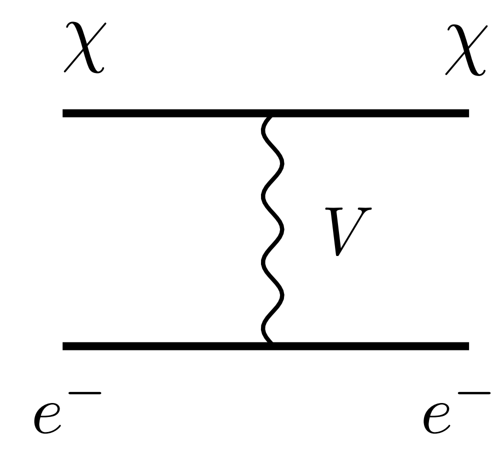


- Option 2: New beam dump target station
- Run concurrently with neutrino experiments

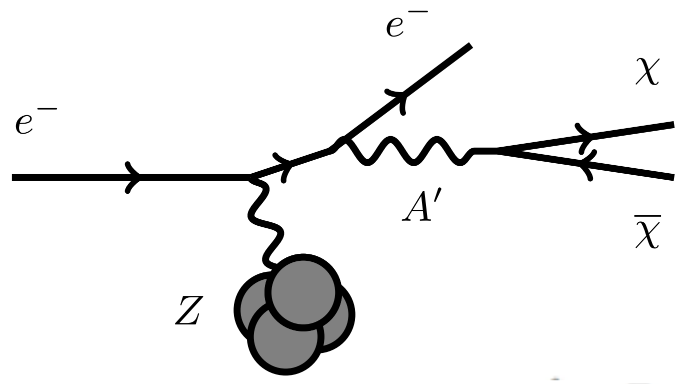
Figs. from R. Van de Water

Many other approaches to search for light dark matter!

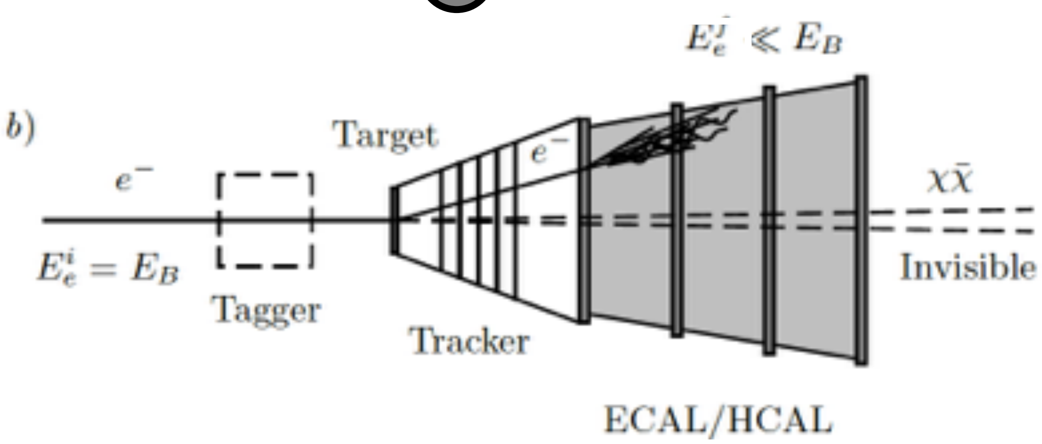
- New direct detection techniques for light dark matter



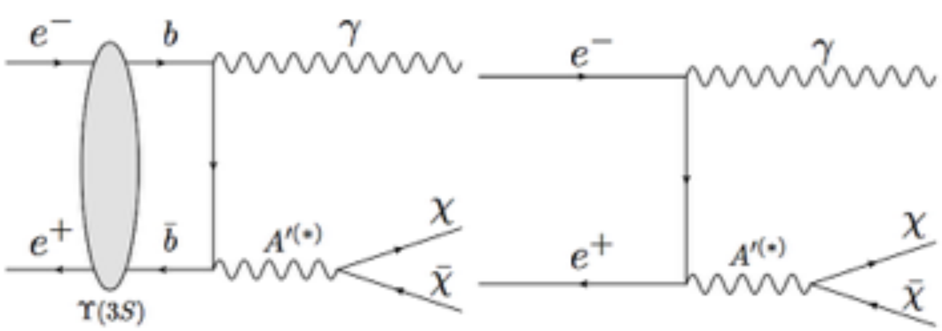
- Electron beam dump experiments



- Fixed target missing momentum experiments



- Low energy colliders (meson factories)



Many other new ideas to search for light dark matter!

iCal export | More | US/Eastern | English

U.S. Cosmic Visions: New Ideas in Dark Matter

23-25 March 2017 *Stamp Student Union, University of Maryland, College Park*
US/Eastern timezone

Search

- **Overview**
- Scientific Programme
- Timetable
- Contribution List
- Author index
- Registration
  - Registration Form
- List of registrants

A workshop focusing on potential new small-scale projects in the U.S. Dark Matter search program will be held at the University of Maryland, College Park March 23-25, 2017.

Dates: from March 23, 2017 08:00 to March 25, 2017 13:04

Timezone: US/Eastern

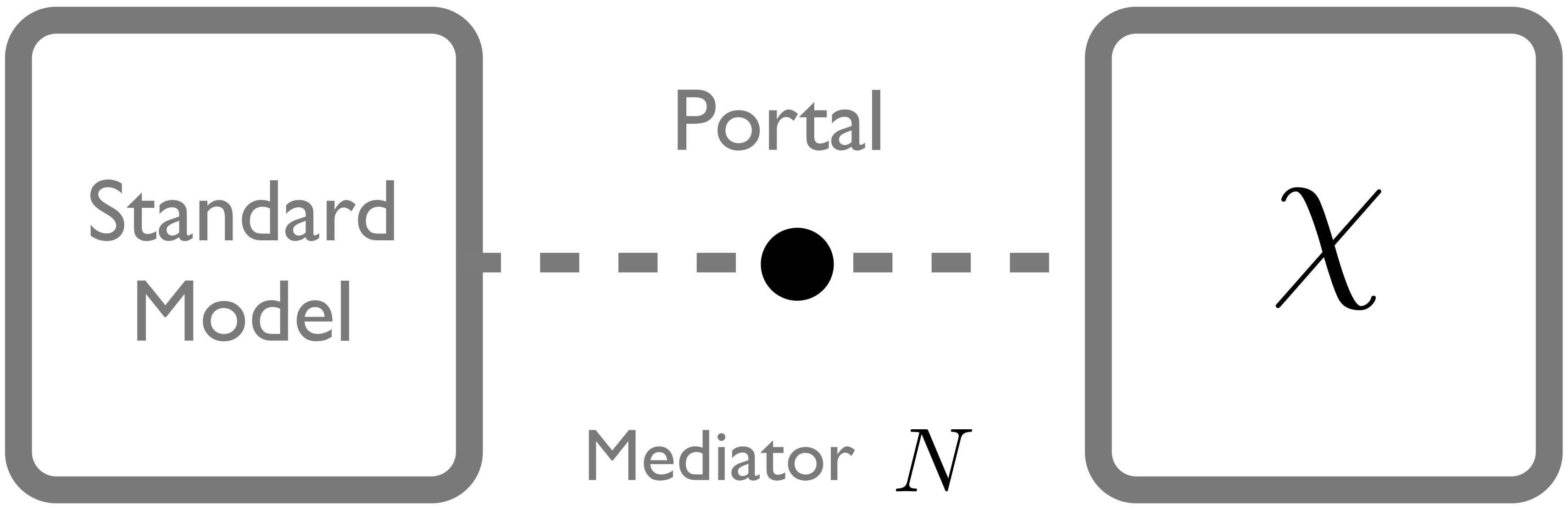
Location: *Stamp Student Union, University of Maryland, College Park*
University of Maryland
College Park MD 20742 USA

Chairs: Cushman, Priscilla
Flaugher, Brenna
Hall, Carter
Hewett, JoAnne
Roe, Natalie
Prof. Incandela, Joseph
Belloni, Alberto

Material: Instructions for remote participation
Travel, accommodations, and logistics

Additional info: *The following is the request by the DoE HEP office:*

Neutrino Portal Dark Matter

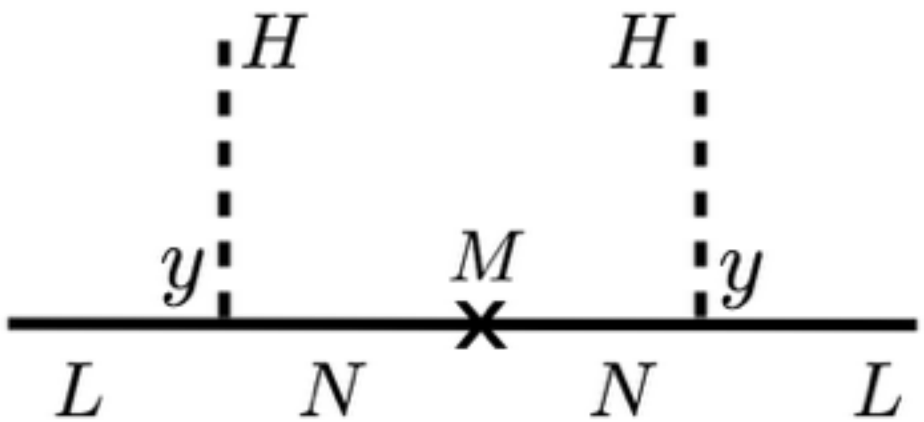


$$yLHN + \lambda N\chi\phi + \text{h.c.}$$

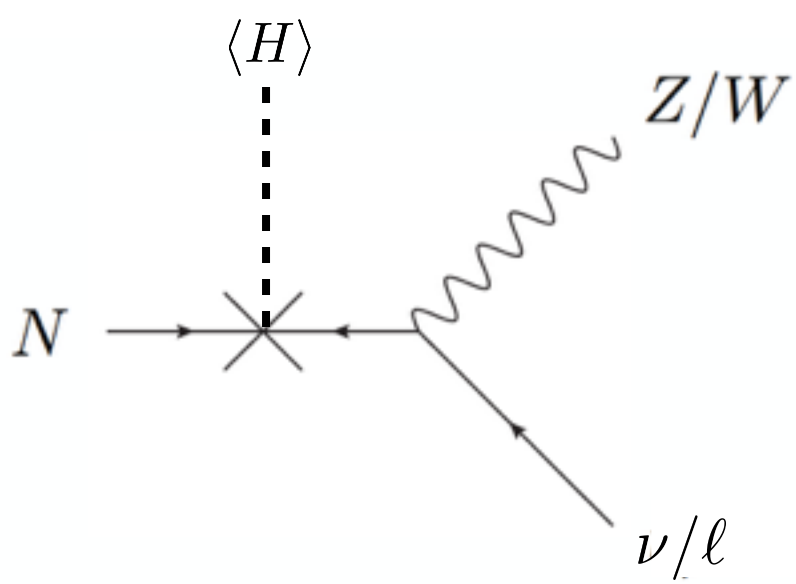
Type I Seesaw

Minkowski; Yanagida; Mohapatra, Senjanovic; Gell-Mann, Ramond, Slansky; Schechter, Valle

$$yLHN + \frac{1}{2}MN^2 + \text{h.c.}$$



$$m_\nu \sim \frac{y^2 v^2}{M}$$



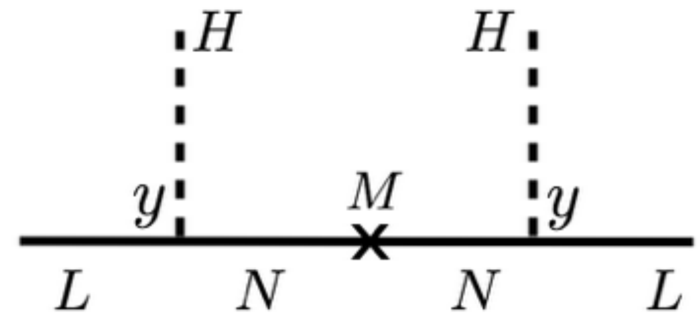
$$U \frac{g}{\sqrt{2}} W_\mu^- \ell^\dagger \bar{\sigma}^\mu N + \text{h.c.} + \ldots$$

$$U \sim \frac{yv}{M} \sim \sqrt{\frac{m_\nu}{M}} \sim 10^{-5} \times \left(\frac{m_\nu}{0.05\ \text{eV}}\right)^{1/2} \left(\frac{\text{GeV}}{M}\right)^{1/2}$$

Minimal Neutrino Portal DM (Type I seesaw)

$$\mathcal{L} \supset -\frac{1}{2}m_\phi^2\phi^2 - \left[\frac{1}{2}m_N NN + \frac{1}{2}m_\chi \chi\chi + yLHN + \lambda N\phi\chi + \text{h.c.}\right]$$

- Mediator is a Majorana sterile neutrino N
- Dark sector consists of a Majorana fermion χ and a real scalar ϕ
- Type I Seesaw mechanism generates small masses for light neutrinos



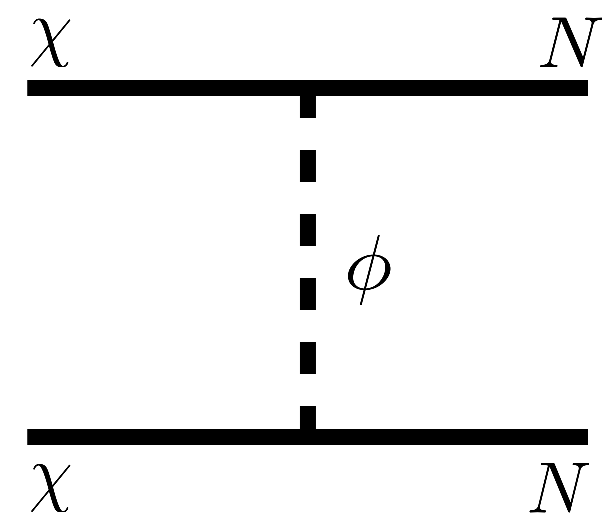
$$m_\nu \sim \frac{y^2 v^2}{2m_N}$$

- For masses in the thermal window, neutrino Yukawa coupling is tiny

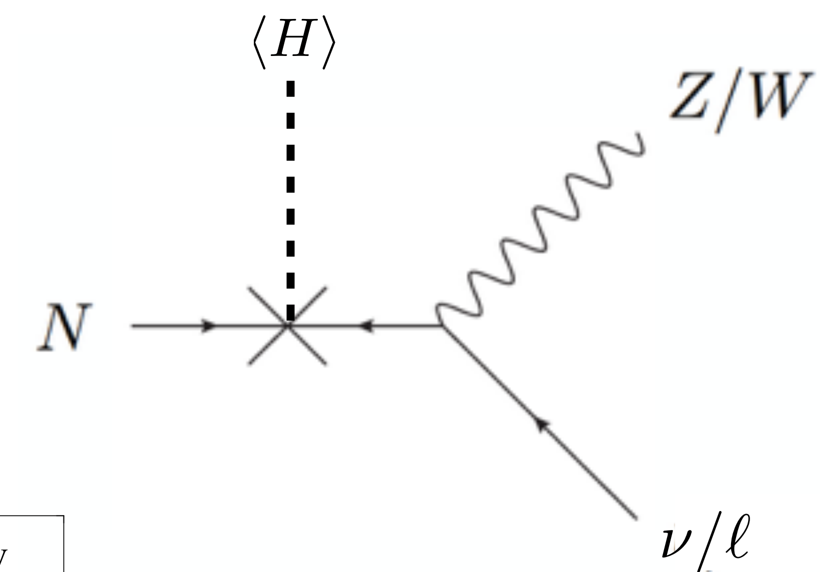
$$y \simeq 10^{-6}\,(m_N/v)^{1/2}$$

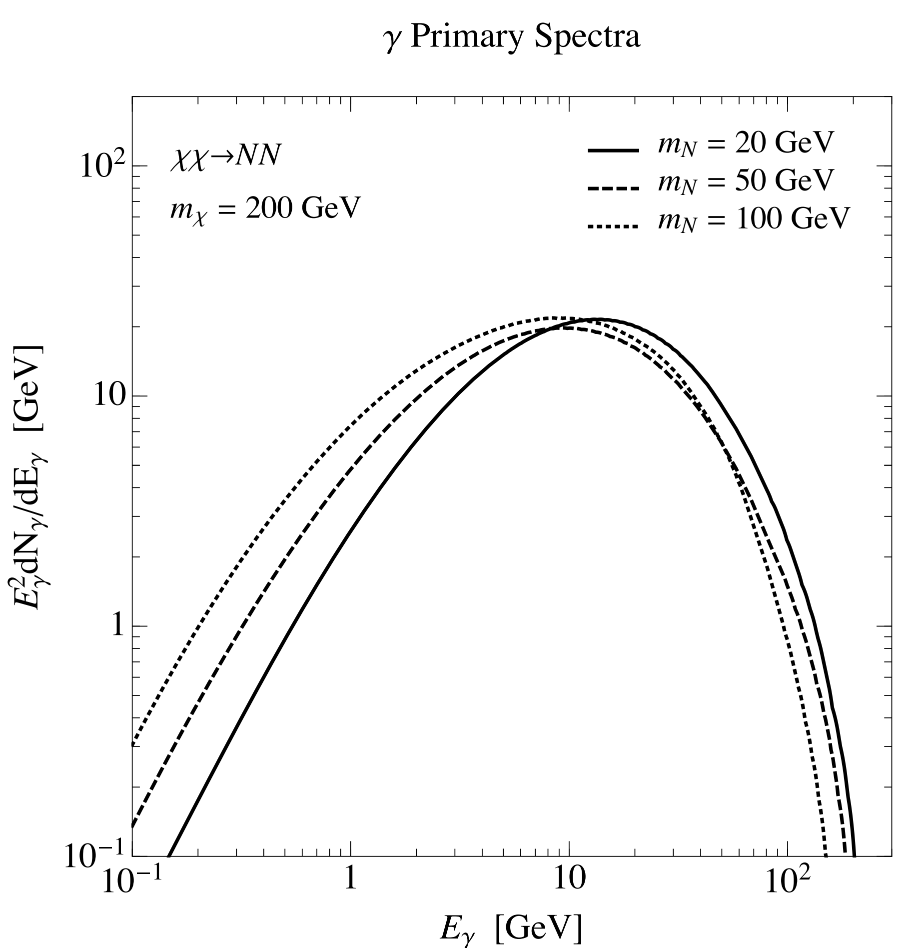
- Direct annihilation to light neutrinos is inefficient, and direct detection, accelerator tests of this scenario are challenging
- Secluded annihilation is still viable, and indirect detection offers a probe

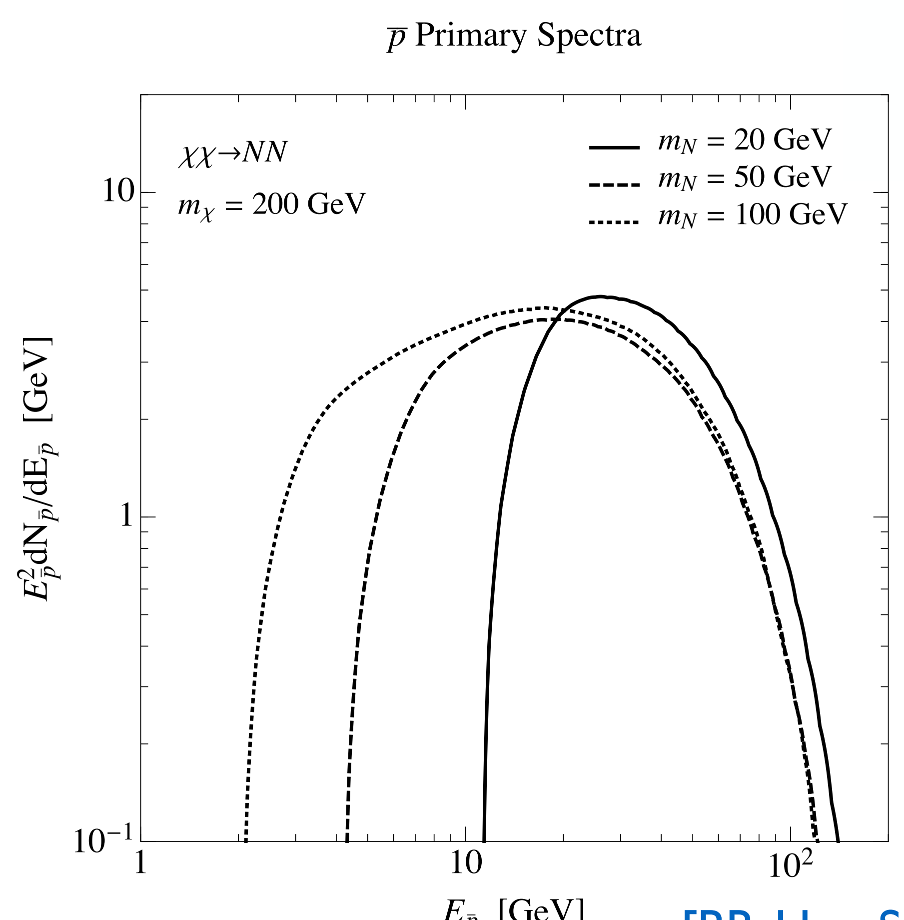
Secluded Annihilation $m_\chi > m_N$



- Annihilation $\chi\chi \to NN$ is efficient
- Indirect detection: gamma-rays, antiprotons from DM annihilation, distortion of CMB anisotropies
- Can be probed by Fermi, AMS-02, Planck, …



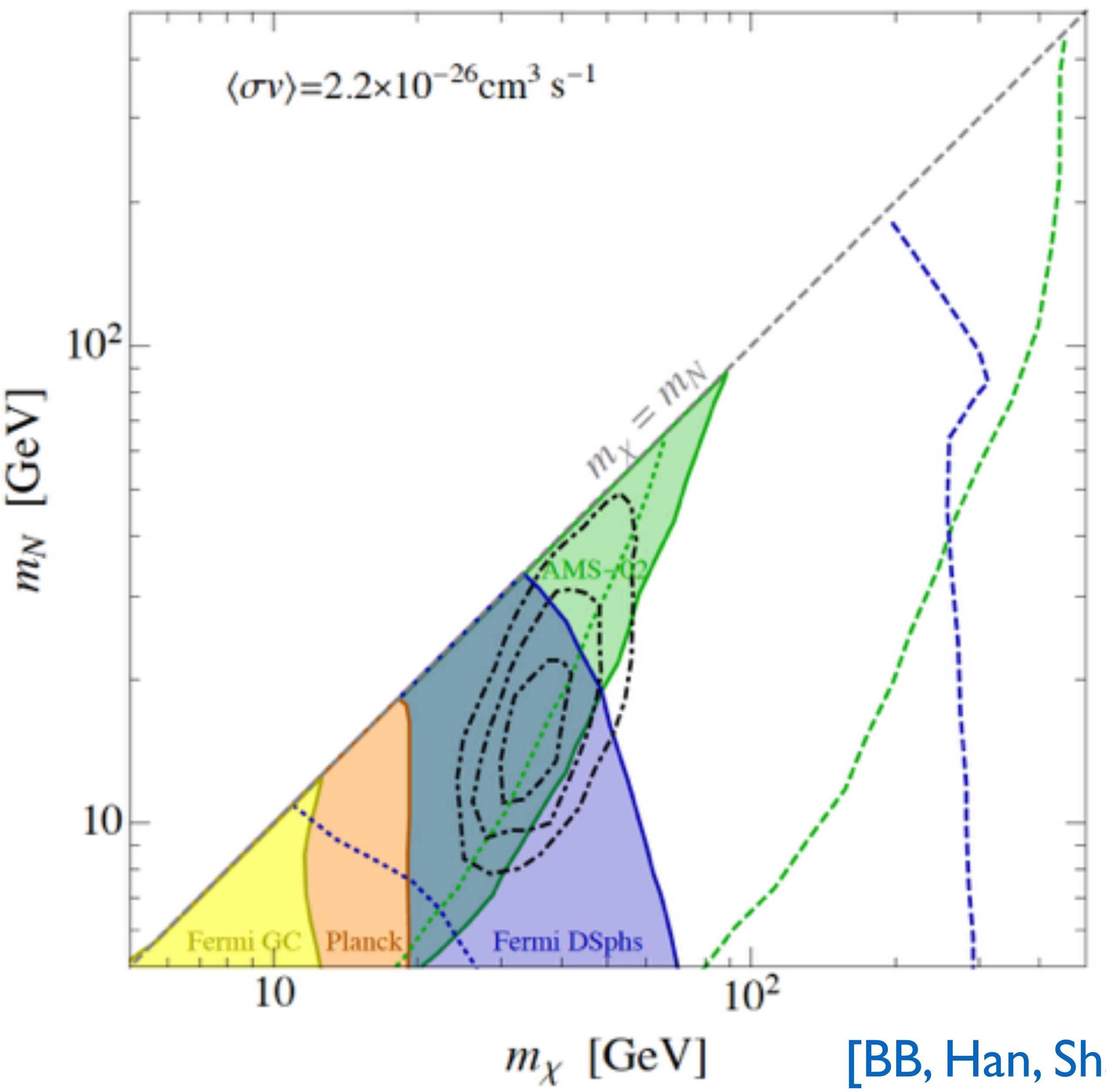




Spectra display mild dependence on sterile neutrino masses

[BB, Han, Shams Es Haghi]

Indirect detection constraints



[BB, Han, Shams Es Haghi]

For related studies, see also

Tang, Zhu
Ibarra, Lopez-Gehler, Molinaro, Pato
Campos, Queiroz, Yaguna, Weniger

Dirac Neutrino Portal

[Bertoni, Ipek, Nelson, McKeen]
[BB, Han, McKeen, Shams Es Haghi]

$$-\mathcal{L} \supset m_\phi^2 \, |\phi|^2 + m_\chi \, \bar{\chi}\chi + m_N \, \bar{N} N$$
$$+ \left[\lambda_\ell \, \bar{L}_\ell \hat{H} N_R + \phi \, \bar{\chi} \, (y_L N_L + y_R N_R) + \text{h.c.} \right]$$

- Mediator is a (pseudo-)Dirac sterile neutrino
- Dark sector consists of a Dirac fermion χ and a complex scalar ϕ
- An approximate lepton number symmetry allows for light SM neutrinos even if the Yukawa coupling λ_ℓ (and active sterile mixing) is large

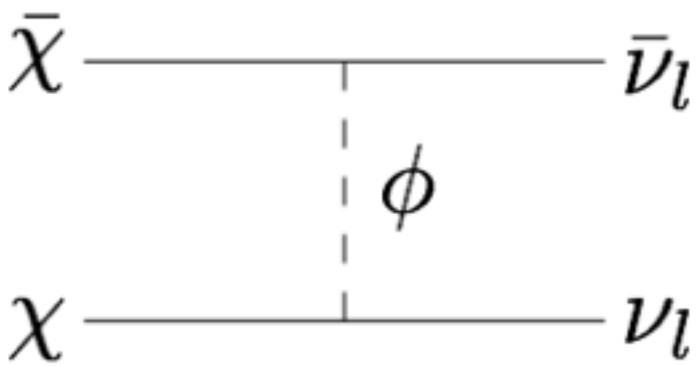
$$\nu_4 = \begin{pmatrix} U_{N4}^* N_L + \sum_\ell U_{\ell 4}^* \nu_{\ell L} \\ N_R \end{pmatrix} \quad U_{\ell 4} = \frac{\lambda_\ell v}{m_4}, \qquad |U_{N4}| = \frac{m_N}{m_4} = \sqrt{1 - \sum_\ell |U_{\ell 4}|^2}.$$

- Large mixing allows for a sizable DM - SM neutrino coupling

$$y_L \, \phi \, \bar{\chi}_R \, N_L + \text{h.c.}$$
$$\to y_L \, |U_{N4}| \, \phi \, \bar{\chi}_R \, \nu_{4L} - y_L \sqrt{1 - |U_{N4}|^2} \, \phi \, \bar{\chi}_R \, \nu_{lL} + \text{h.c.}$$

- Important implications for cosmology and phenomenology

Direct annihilation to light SM neutrinos $m_\chi > m_N$



$\propto U^2$

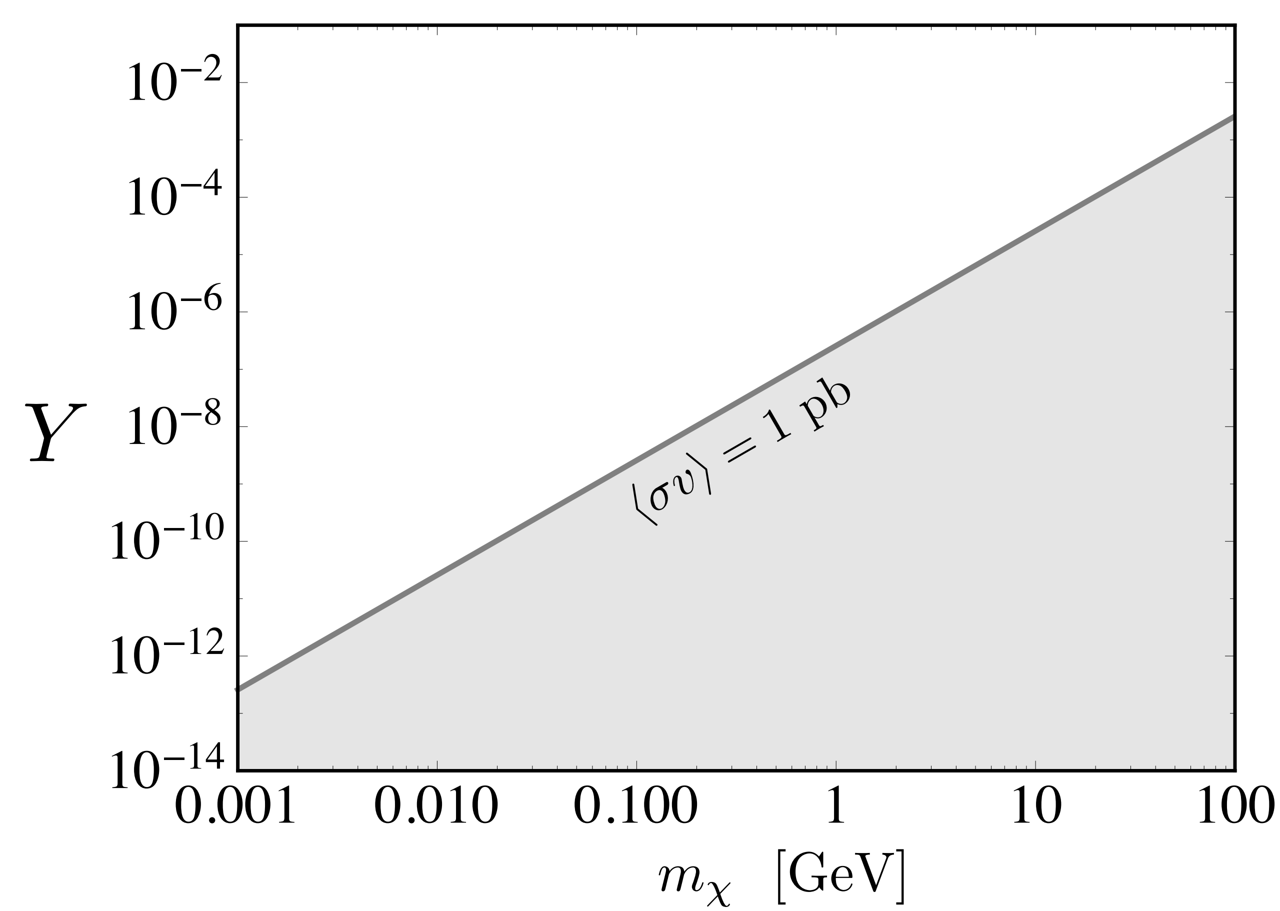
$$\langle \sigma v \rangle = \frac{y_L^4}{32\pi} \left(\sum_\ell |U_{\ell 4}|^2 \right)^2 \frac{m_\chi^2}{m_\phi^4} \left(1 + \frac{m_\chi^2}{m_\phi^2} \right)^{-2}$$
$$\simeq 1\,\mathrm{pb} \left(\frac{y_L \sqrt{\sum_\ell |U_{\ell 4}|^2}}{0.2} \right)^4 \left(\frac{10\,\mathrm{GeV}}{m_\chi} \right)^2 \left(\frac{3}{m_\phi / m_\chi} \right)^4,$$

- DM can be a thermal relic if mixing is large (due approx. lepton number)
- Thermal target in $m_\chi - Y$ plane:

$$Y \equiv y_L^4 \left(\sum_i |U_{i4}|^2 \right)^2 \frac{m_\chi^4}{m_\phi^4}$$

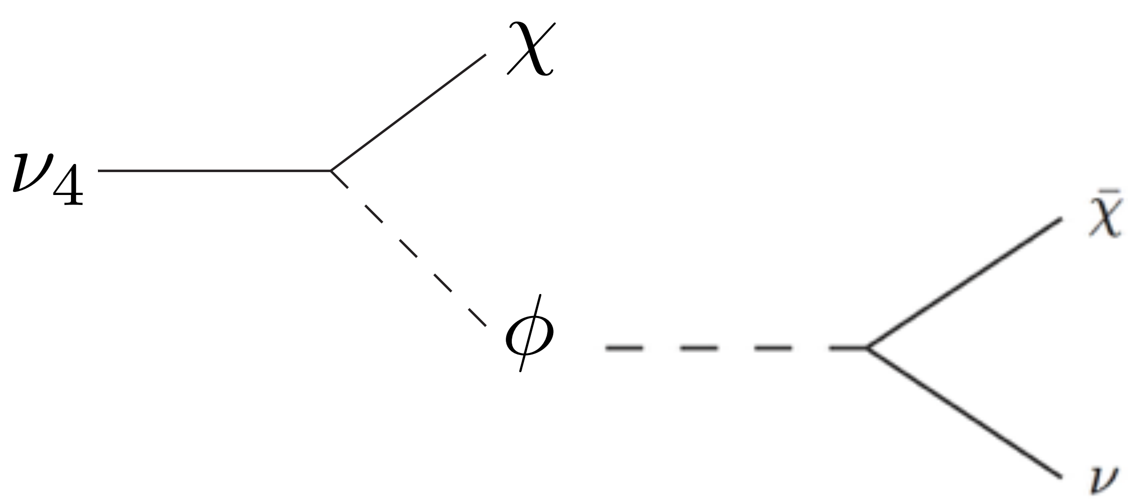
$$\langle \sigma v \rangle \simeq \frac{Y}{32\pi m_\chi^2}$$

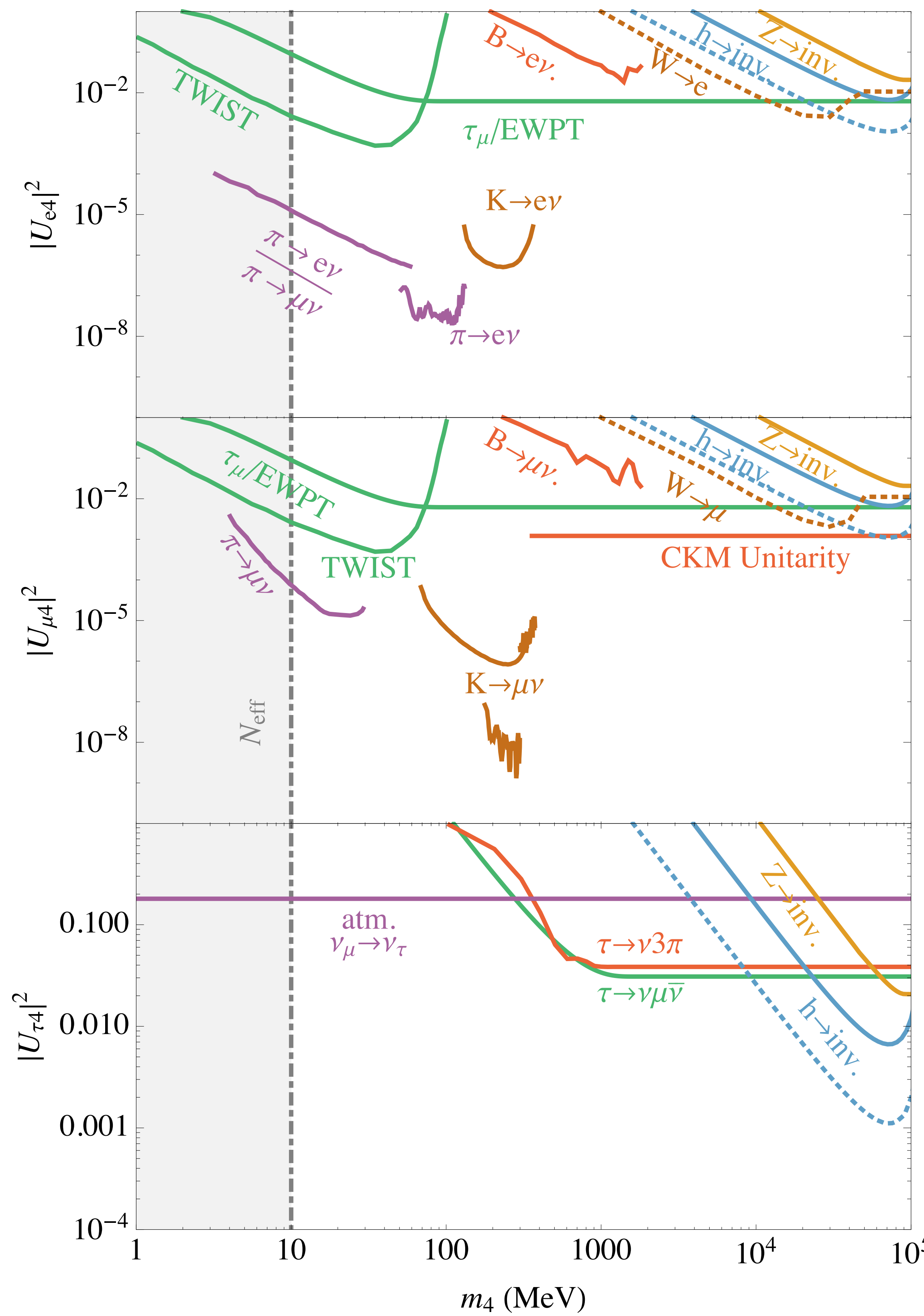
- Note that CMB constraints evaded



“Invisible” Sterile Neutrino

$$m_N > m_\phi, m_\chi$$





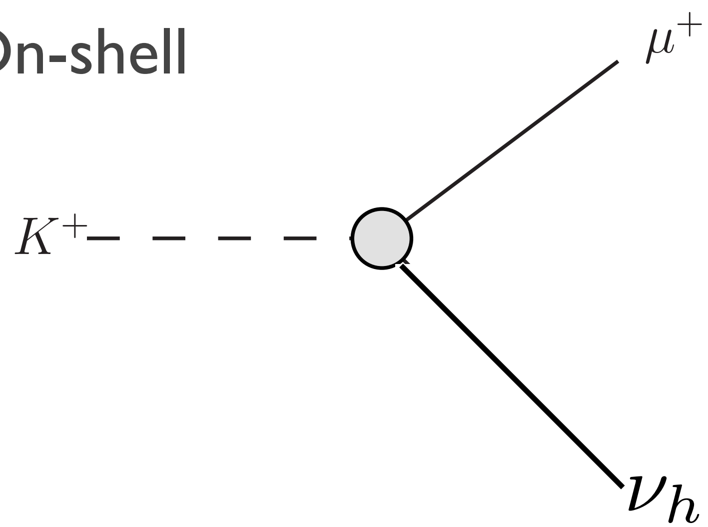
Phenomenology

- Fermi constant (muon lifetime); PMNS non-unitarity; EW precision; CKM unitarity
- Muon, tau, Meson decays (peak searches); lepton universality tests;
- Invisible Z, Higgs decays; Drell-Yan (W decays)
- Atmospheric oscillations (relevant for ν_τ)

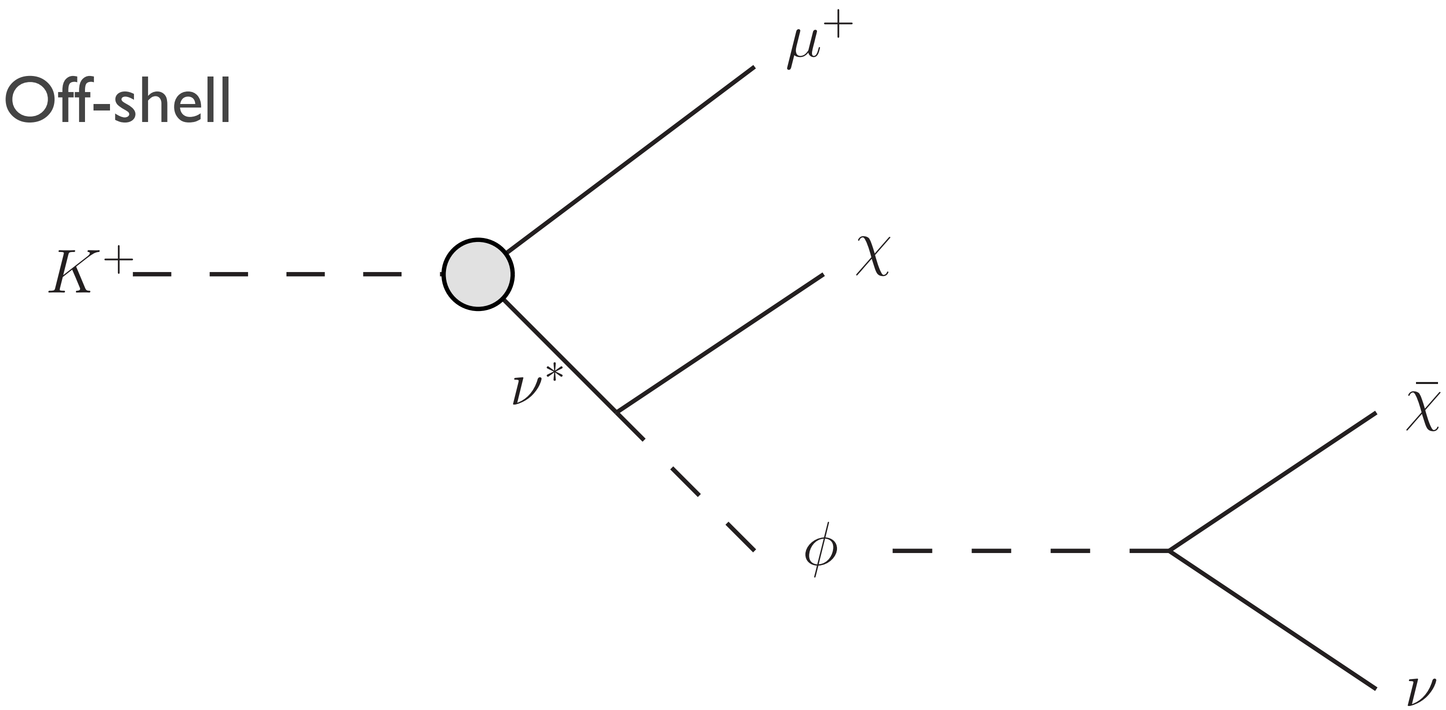
[Bertoni, Ipek, DM, & Nelson]
[BB, Han, McKeen, Shams Es Haghi]
[De Gouvea,Kobach]

Meson decays

On-shell

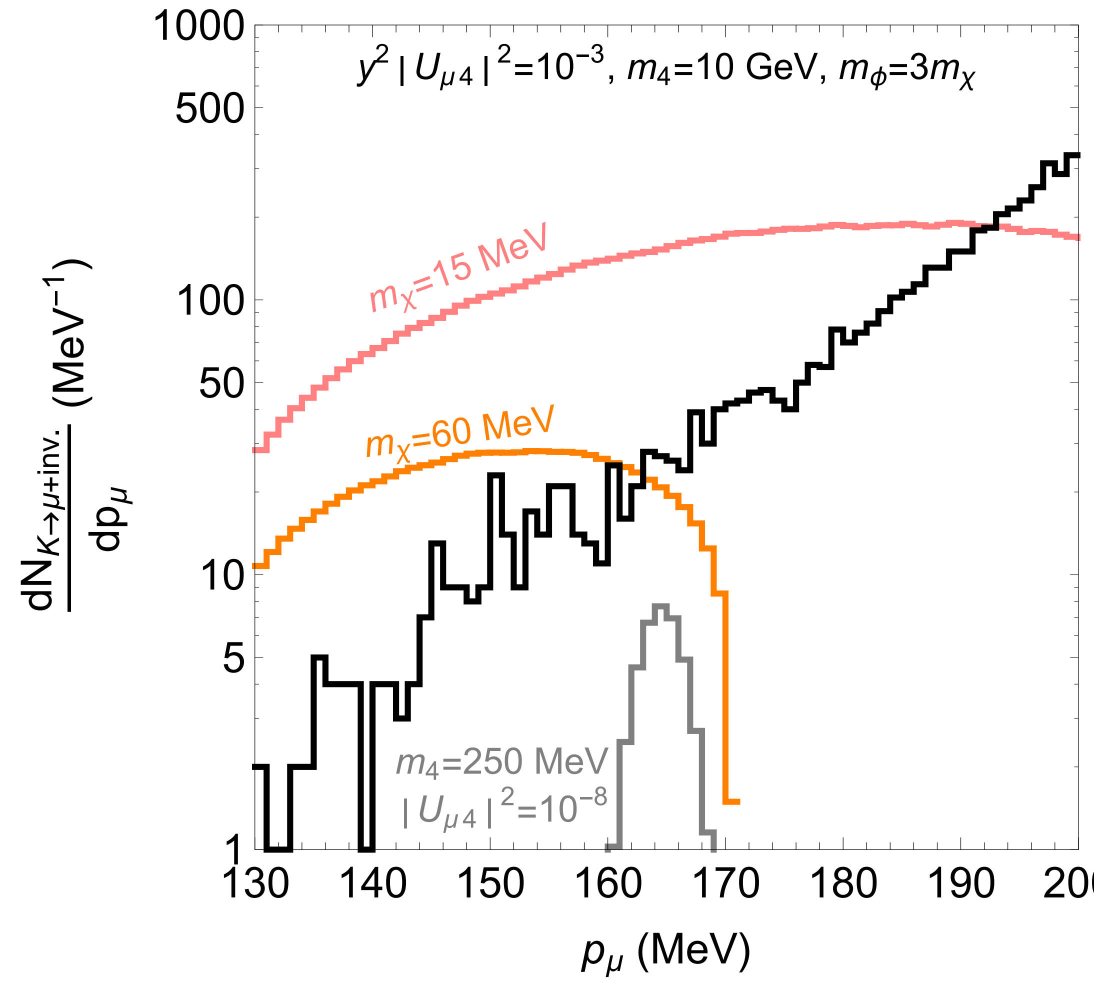


Off-shell



E949: 10^{12} kaons

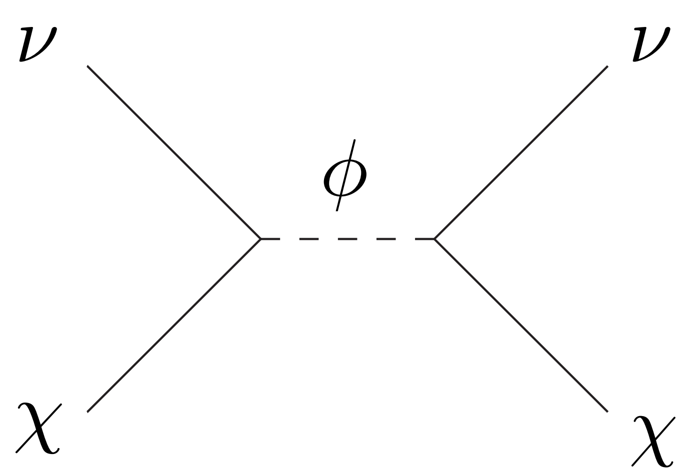
NA62 will collect ~ 1 order of magnitude more Kaons



Small scale structure

[Boehm, Fayet, Schaeffer]
[Boehm, Riazuelo, Hansen, Schaeffer]
[Boehm, Mathis, Devriendt, Silk]
[Bertoni, Ipek, McKeen, Nelson]
[Olivares-Del Campo Boehm, Palomares-Ruiz,Pascoli]

- Strong DM - neutrino scattering can delay DM kinetic decoupling
- Pressure due to DM-neutrino coupling resists gravitational collapse (analogous to coupled photon-baryon plasma)
- Formation of structures smaller than horizon size at DM kinetic decoupling are suppressed

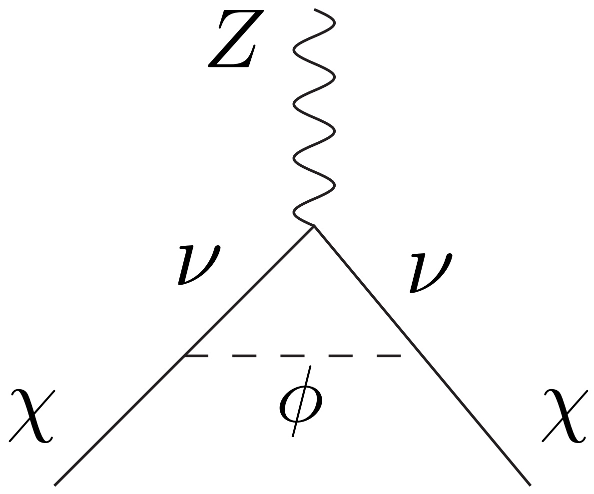


- Smallest structures observed via gravitational lensing have masses of order 10^8 solar masses
- Late kinetic decoupling leads to a lower bound on mass of gravitationally bound objects

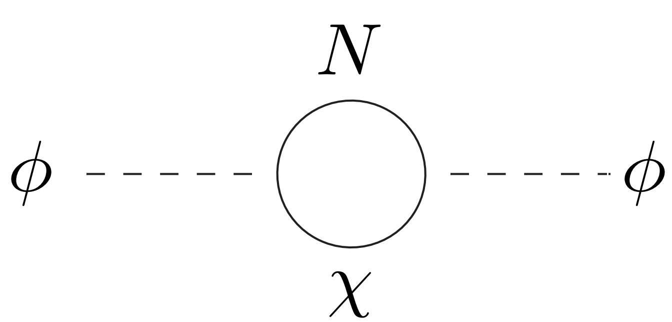
$$M > M_{\rm cutoff} = 10^8 M_{\rm solar} \left(\frac{T_d}{\rm keV} \right)^{-3}$$

Direct Detection

- DM acquires coupling to the Z boson at one loop;
- Leads to spin-independent coherent scattering
- Probes DM heavier than few GeV
- Constraints can be weakened if DM split; other probes are complementary



Naturalness of light scalar



$$\delta m_\phi^2 \sim \frac{y^2}{16\pi^2} m_N^2$$

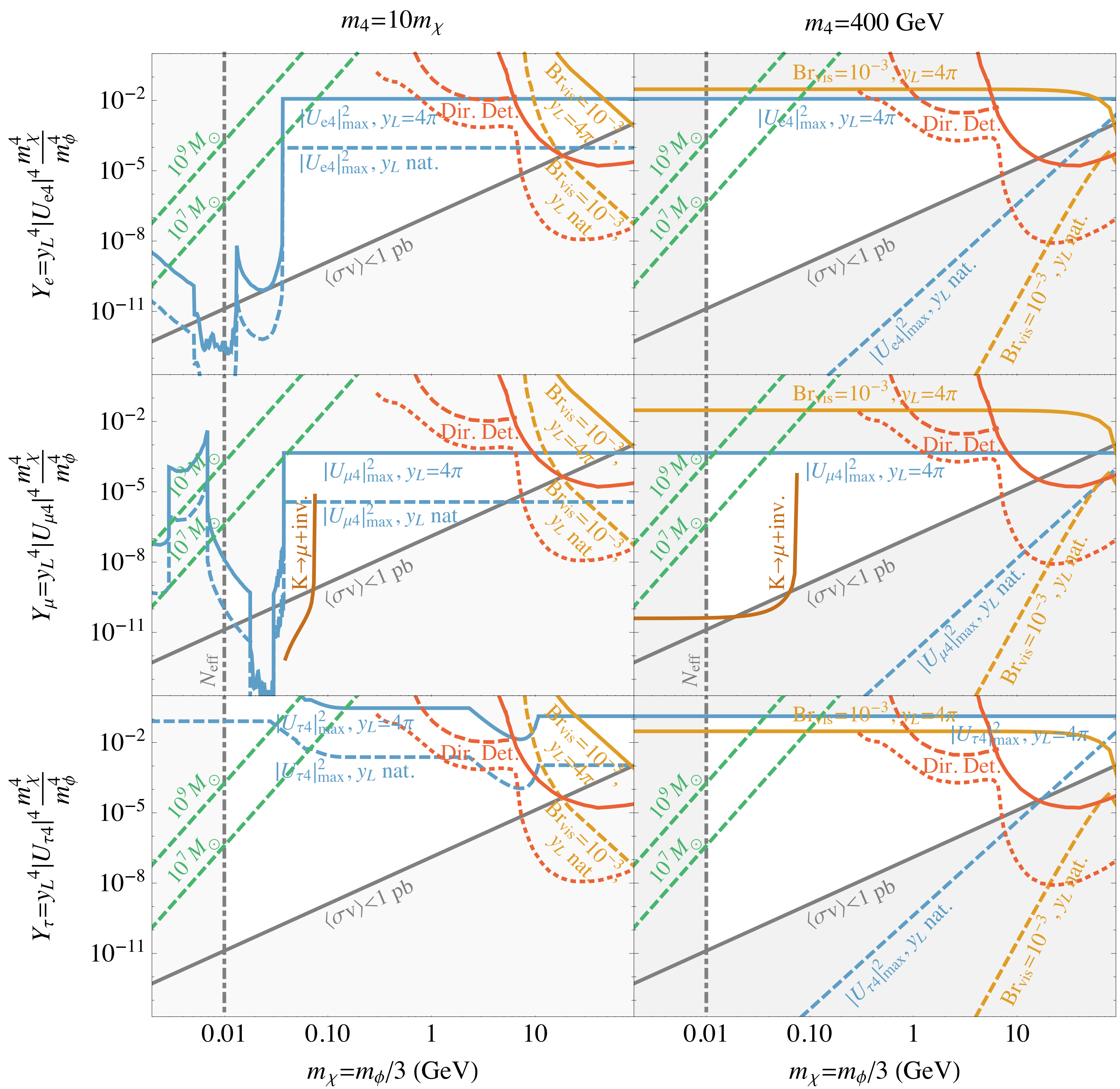
- Naturalness "constraint" is complementary to invisible neutrino constraints

Thermal target

$$Y \equiv y_L^4 \left(\sum_i |U_{i4}|^2 \right)^2 \frac{m_\chi^4}{m_\phi^4}$$

$$\langle \sigma v \rangle \simeq \frac{Y}{32\pi m_\chi^2}$$

- Represent conservative constraints on the thermal hypothesis
- New ideas to probe remaining open parameter space are welcome!



Outlook

- Dark sectors may play a role in addressing a number of outstanding mysteries in particle physics and cosmology

- Thermal dark matter implies coupling between DM and SM; requires new mediators, interactions for masses below ~ GeV

- Vector portal and neutrino portal provide two simple, motivated scenarios, each with its own rich and characteristic phenomenology

- Testing these scenarios requires new, complementary experimental strategies to the ones employed for WIMPs

- The dark sector could be much richer than the scenarios I've outlined. We've only scratched the surface on this subject!