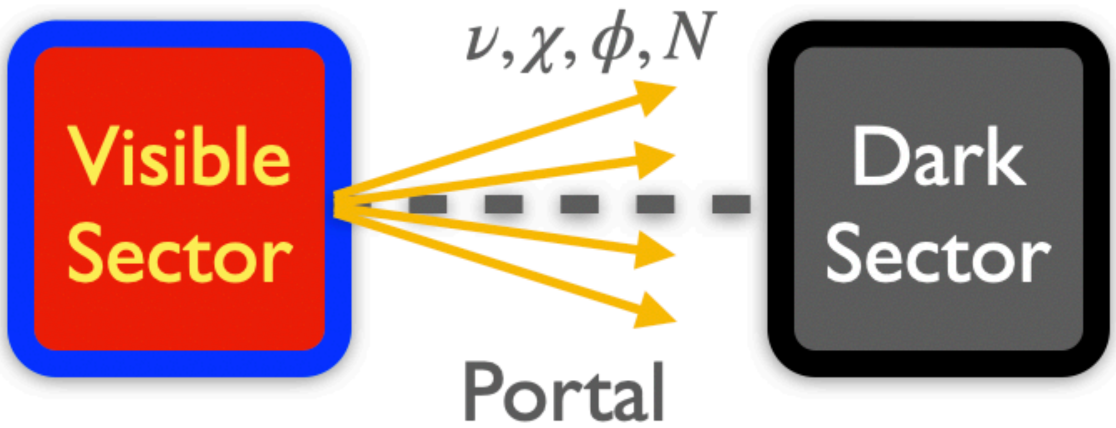
Dark Sector Theory



Brian Batell
University of Pittsburgh

14th International Neutrino Summer School 2023
Fermilab, August 7-18, 2023

Resources

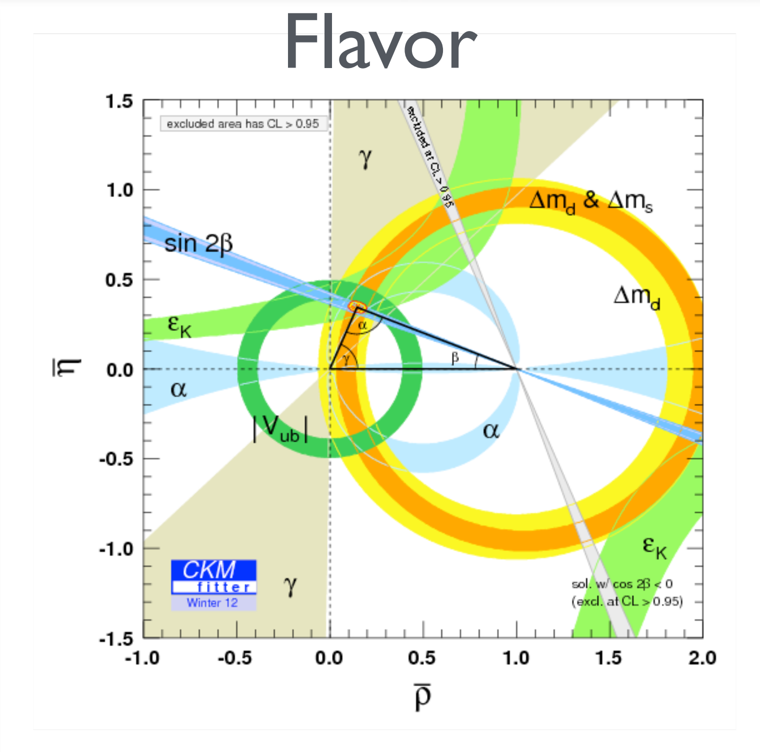
- Dark Sector Studies with Neutrino Beams (Snowmass Whitepaper)
  https://arxiv.org/abs/2207.06898
- Snowmasss 2021 RF6 Dark Sector Physics Report
  https://arxiv.org/abs/2209.04671
- Basic Research Needs for Dark Matter Small Projects New Initiatives
  https://science.osti.gov/-/media/hep/pdf/Reports/Dark_Matter_New_Initiatives_rpt.pdf
- Physics Beyond Colliders at CERN: BSM Working Group Report
  https://arxiv.org/abs/1901.09966
- U.S. Cosmic Visions: New Ideas in Dark Matter 2017: Community Report
  https://arxiv.org/abs/1707.04591
- Dark Sectors 2016 Workshop: Community Report
  https://arxiv.org/abs/1608.08632

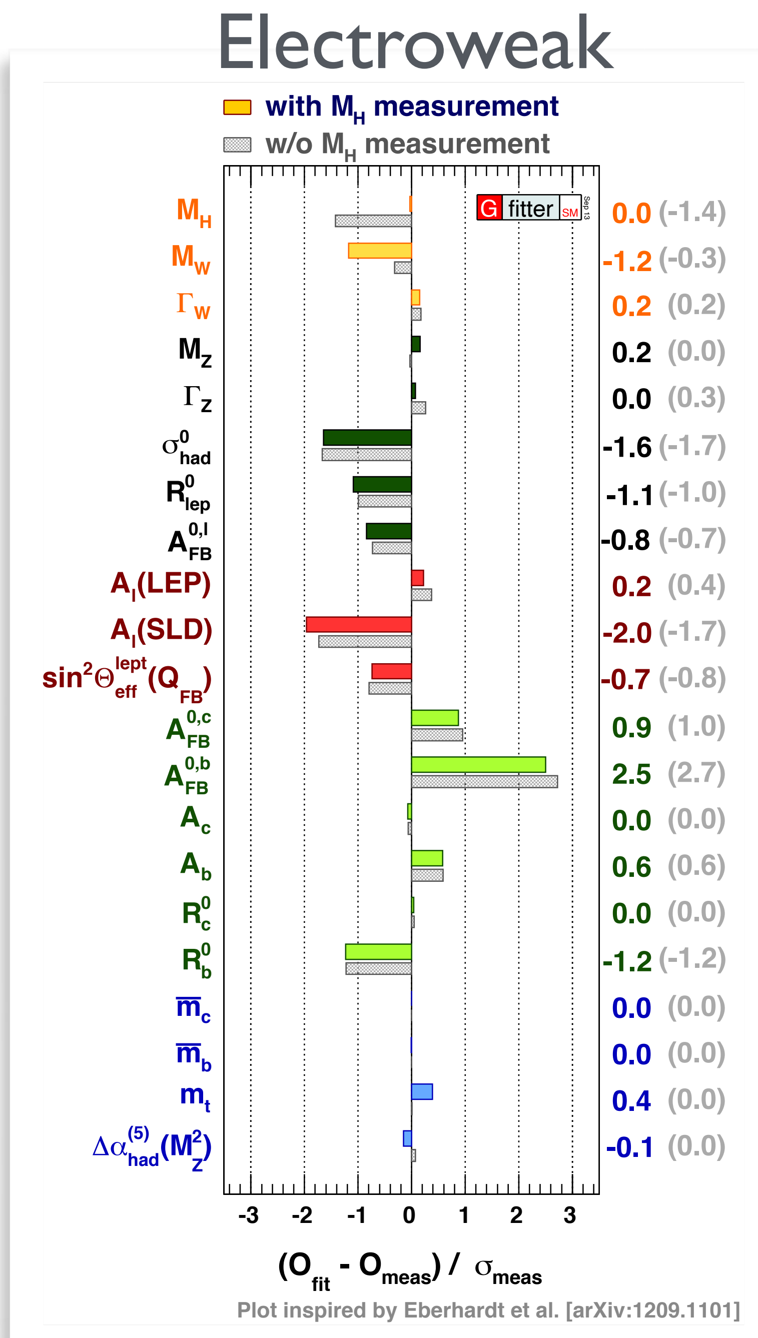
- **Lecture 1:**
  - **Dark sectors motivation and overview**
  - **Minimal portals: theory and phenomenology**

- **Lecture 2:**
  - **Light thermal dark matter**
  - **Muon anomalous magnetic moment**
  - **Hierarchy problem**

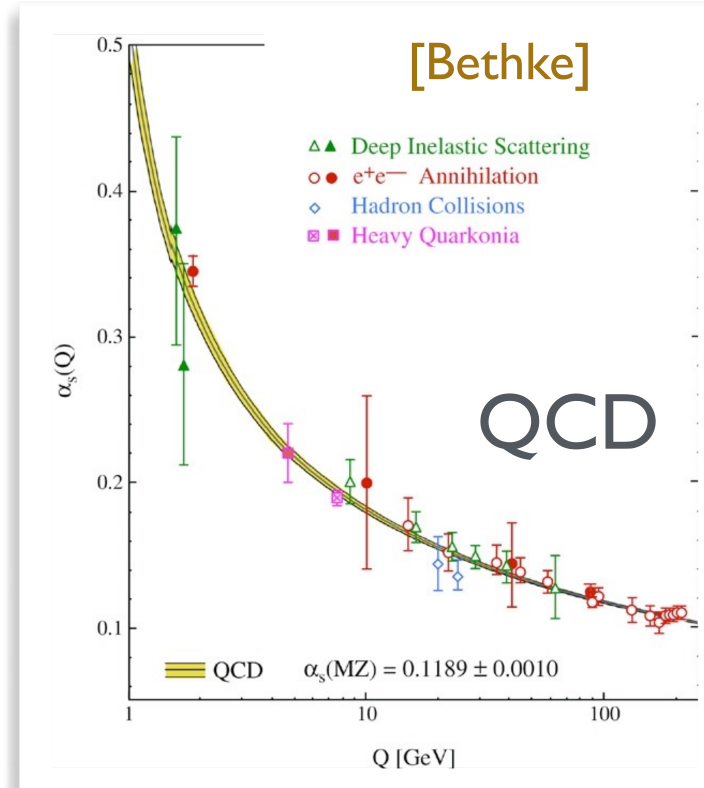
Motivation

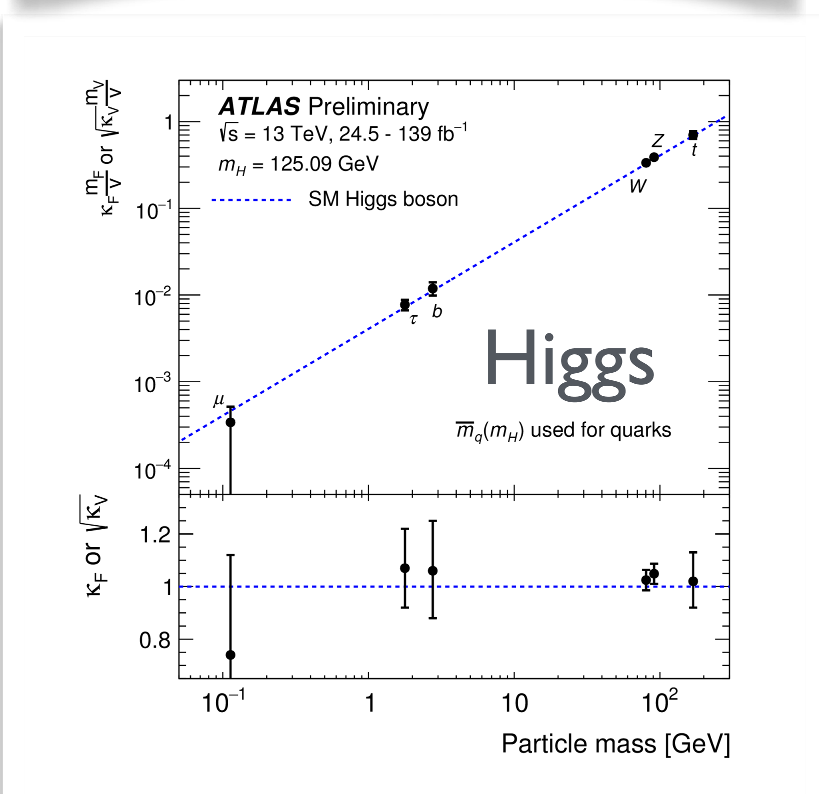
The triumph of the Standard Model…

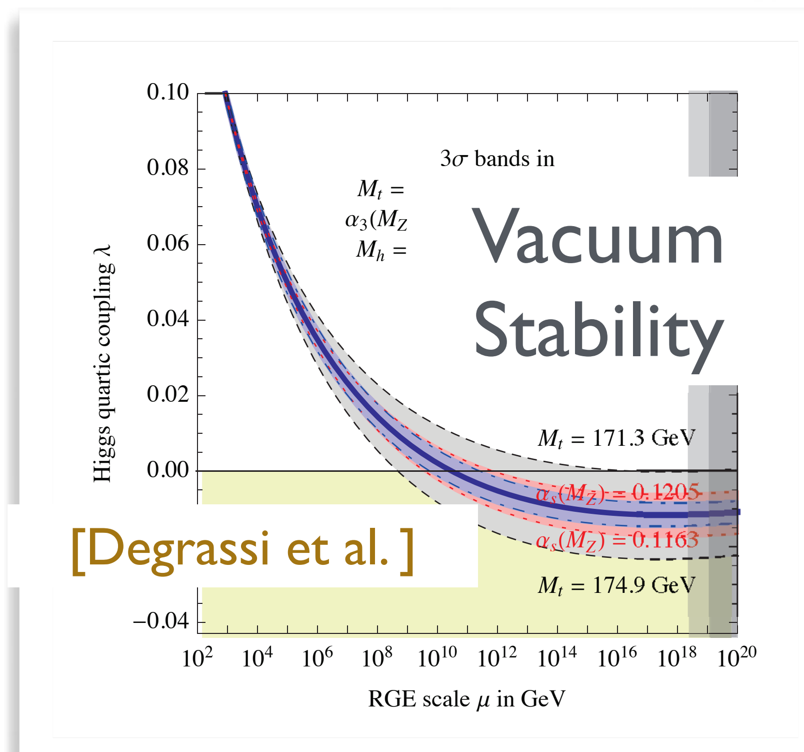




[GFitter Collaboration]







…and it’s eventual demise!

Empirical facts requiring new dynamics:

- Neutrino masses
- Dark matter
- Matter-antimatter asymmetry

Conceptual puzzles:

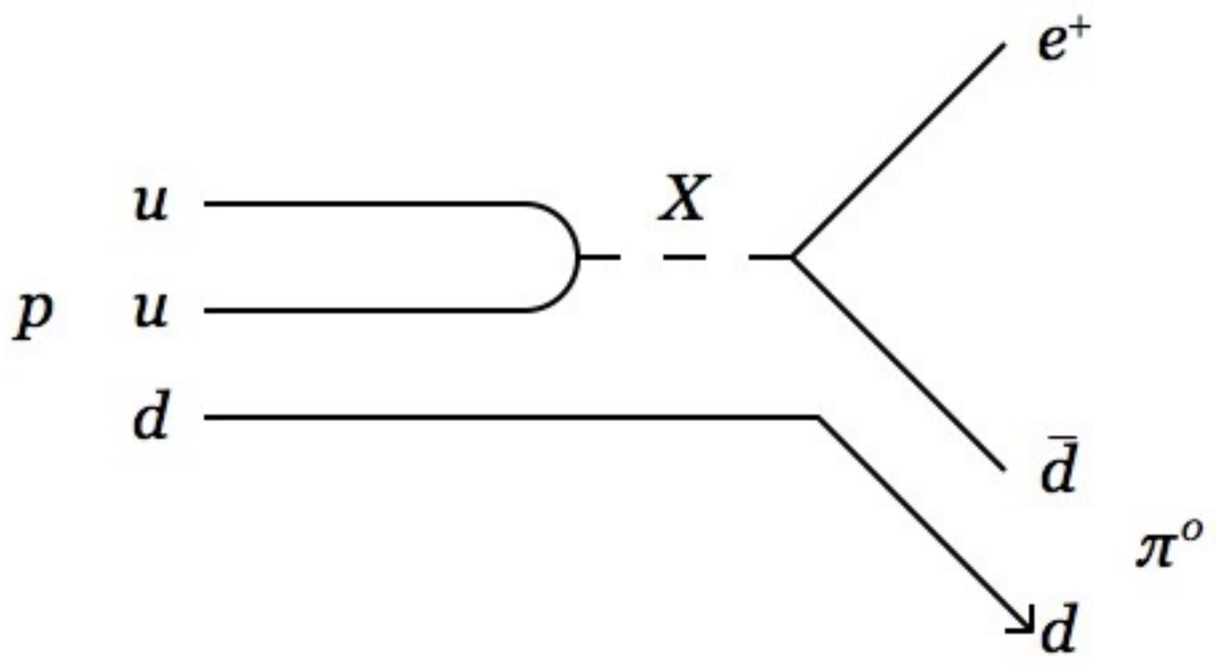
- Naturalness (Higgs Mass & C.C.)
- Flavor puzzle
- Strong CP problem
- Grand unification
- Inflation
- Quantum gravity

These puzzles strongly suggest there is physics beyond the Standard Model!


Naturalness? Baryon Asymmetry?
Strong CP? Neutrino Mass?
Flavor Puzzle? Dark Matter?
Unification? Inflation?
Quantum Gravity? ...
Where is the new physics?
√s = 8,13 TeV, 20.3-139 fb⁻¹
March 2021
ATLAS Preliminary
Limits at 95% CL
Observed limits
Expected limits
m(t̃₁) [GeV]
m(χ̃₁⁰) [GeV]

Possibilities for new physics:

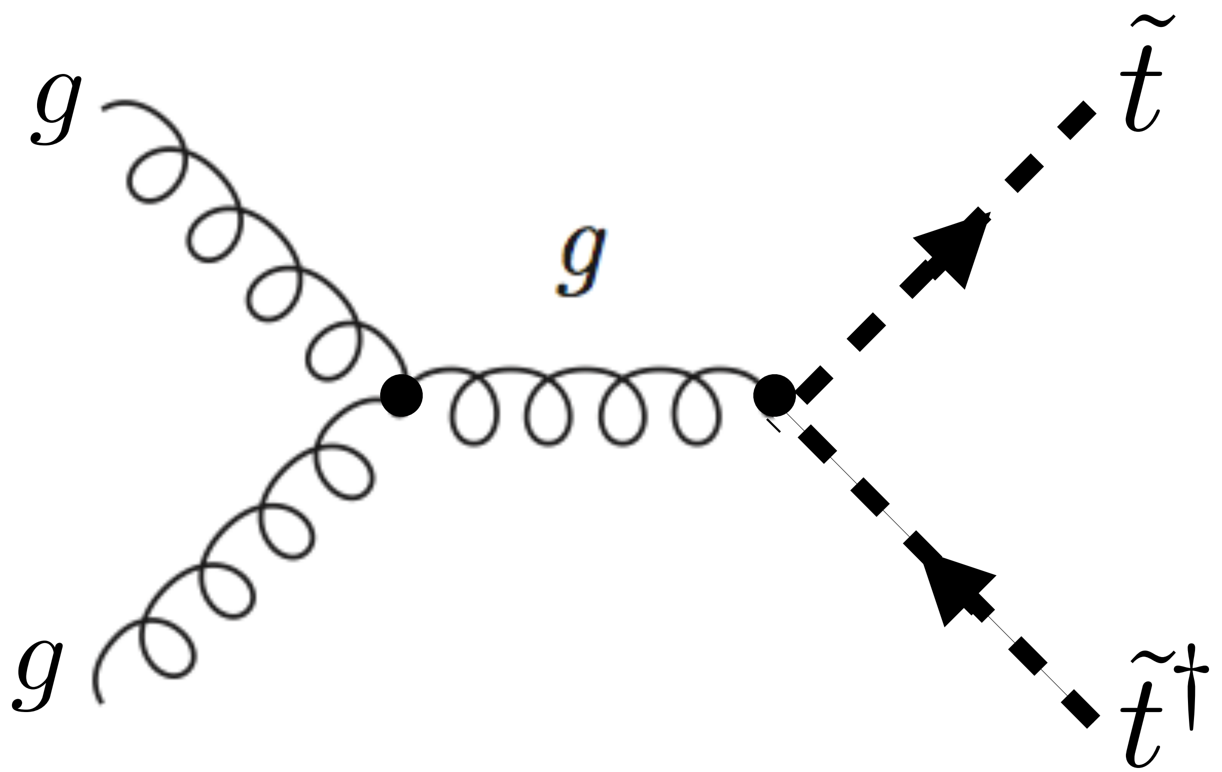
#1. New *heavy states* states; masses much larger than the weak scale



Search for anomalous phenomena or rare processes
using precision measurements

Possibilities for new physics:

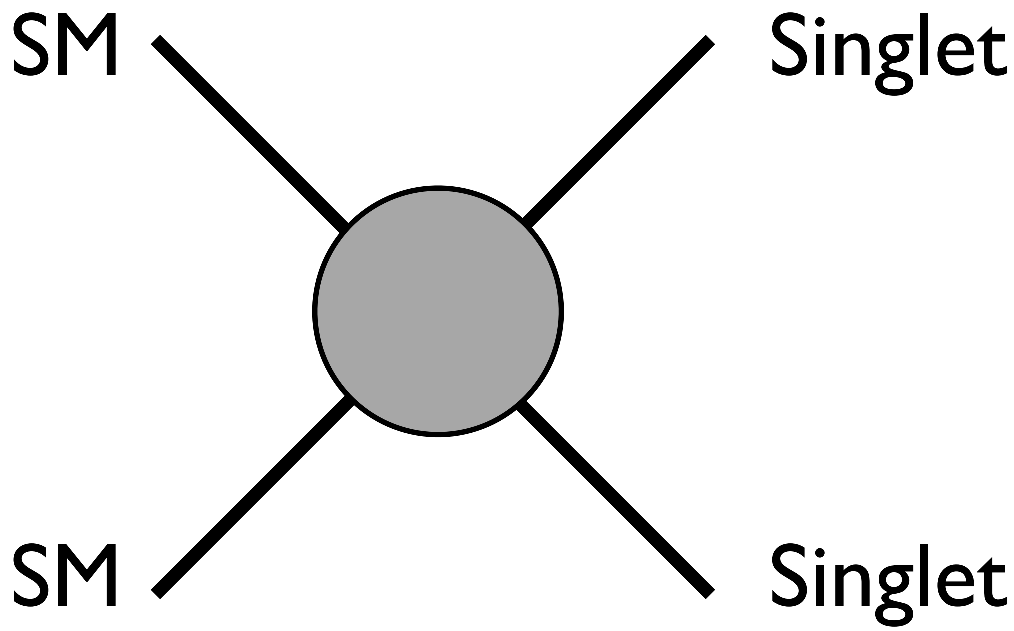
#2. New *light* charged states; masses near the weak scale ~ 100 GeV



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

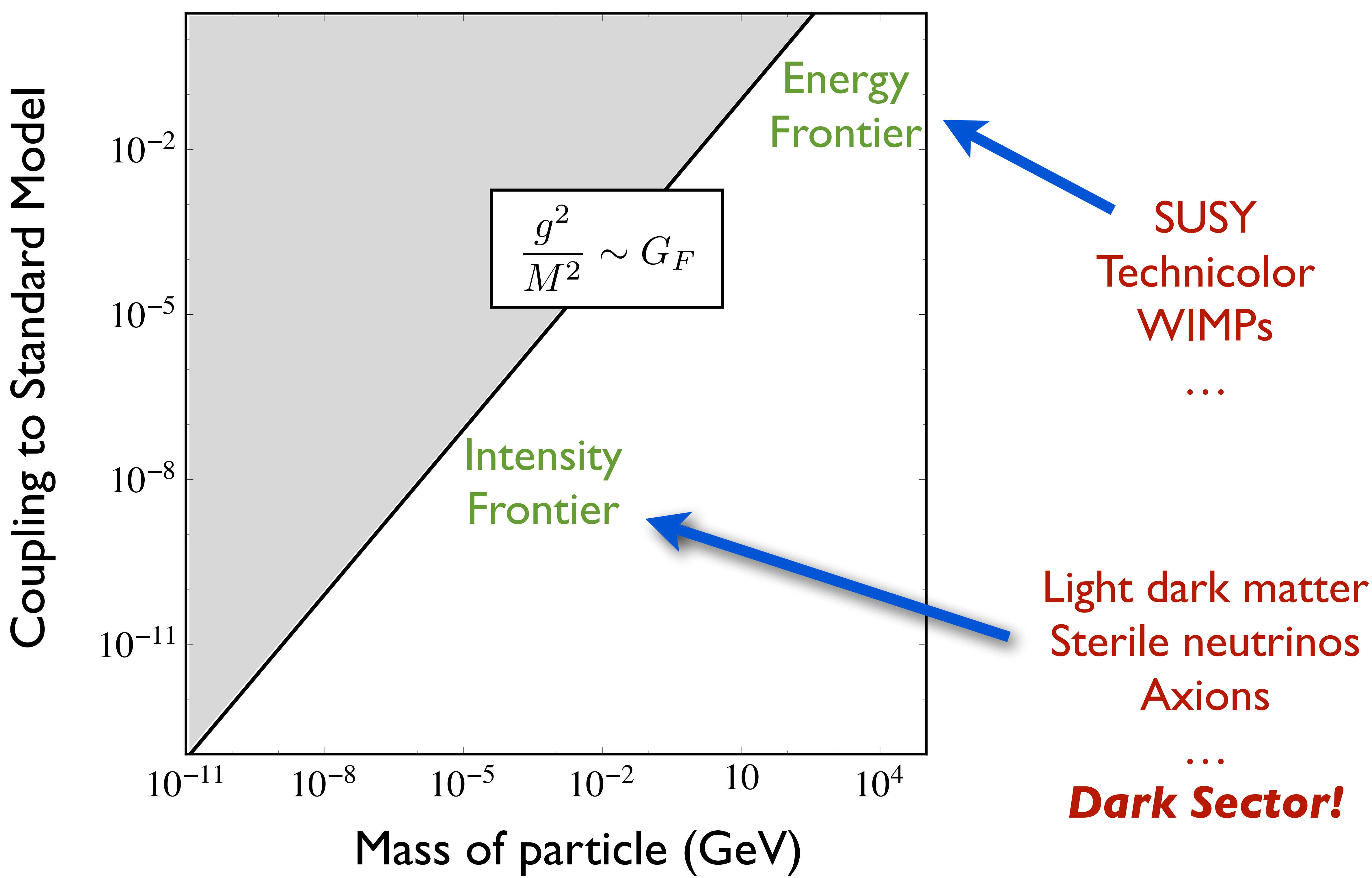


Generic "Portal"

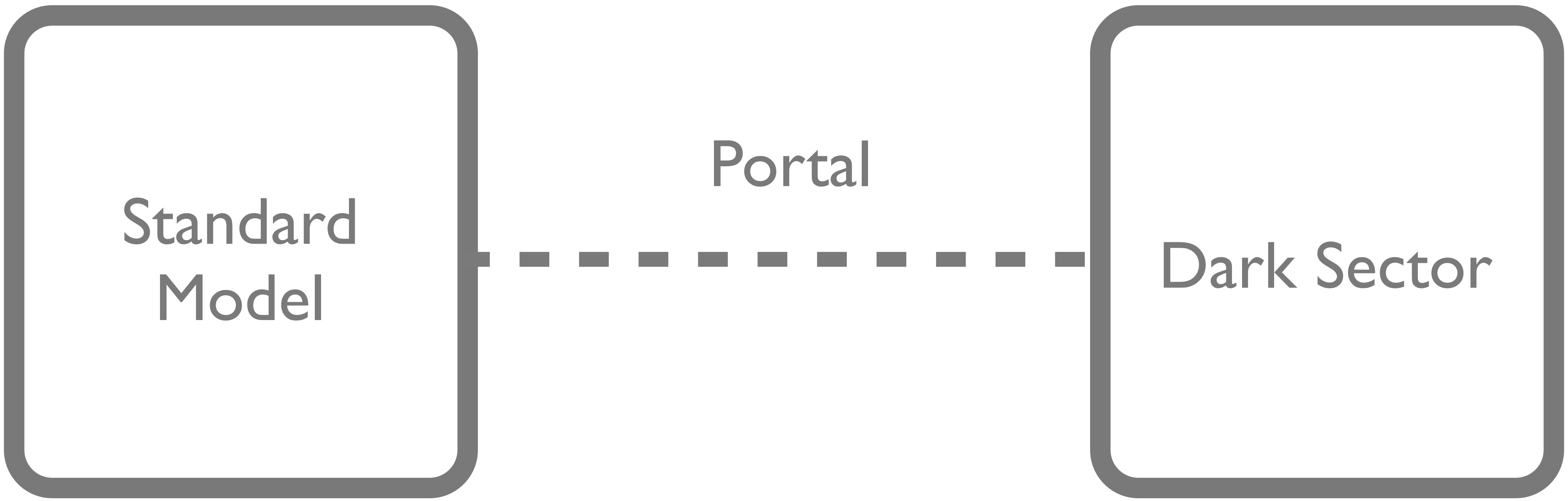
$$\mathcal{L} \supset \frac{\mathcal{O}_{\rm SM}^{(p)} \mathcal{O}_{\rm singlet}^{(q)}}{\Lambda^{p+q-4}}$$

Probe these states directly using high intensity experiments

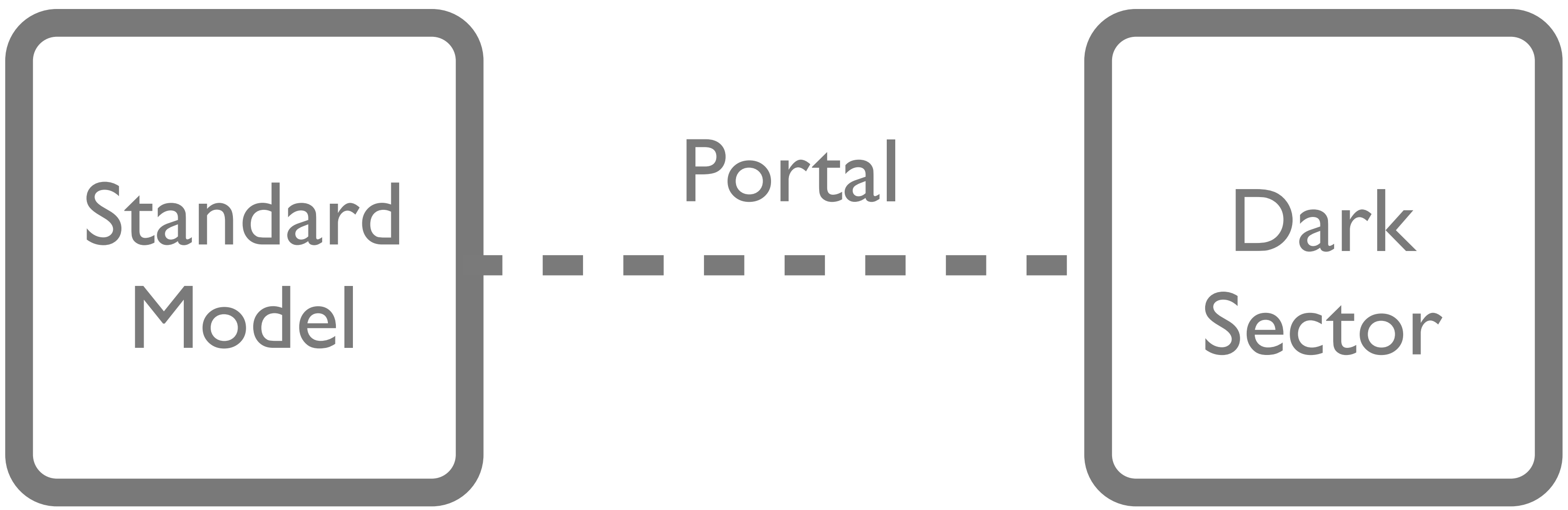
Where is the new physics?



The dark sector paradigm



What is a dark sector?*



- 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
  - A mediator may connect the visible and dark sectors through a "portal"
  - Dark matter, sterile neutrinos, axions …, could be part of such a sector

*Our working definition; will vary depending on person, context, etc.

Portals / mediators

- We can classify dark sector models based on the mediator particle or "portal"
- There are three minimal renormalizable portals that couple neutral mediators to gauge invariant SM operators:

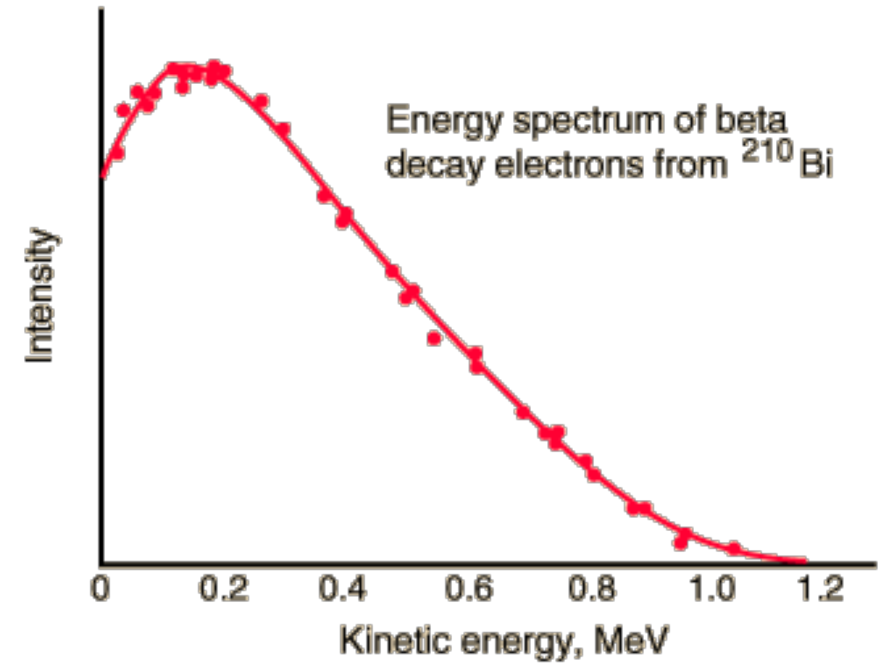
$\frac{\epsilon}{2\cos\theta_W} F'_{\mu\nu} B^{\mu\nu}$	Vector Portal
$(A\,S + \lambda\,S^2)\,H^\dagger H$	Higgs Portal
$yNLH$	Neutrino portal

- Beyond these, we can consider gauging certain anomaly free combinations of the SM symmetries (e.g., $B-L, L_\mu - L_\tau,$ etc.) or anomalous symmetries (e.g., $B, L, \ldots$), scalars coupled via higher dimension operators (e.g., axion portals), …
- The mediator can be straightforwardly coupled to other particles in the dark sectors, e.g., dark matter

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

How do we study neutrinos?

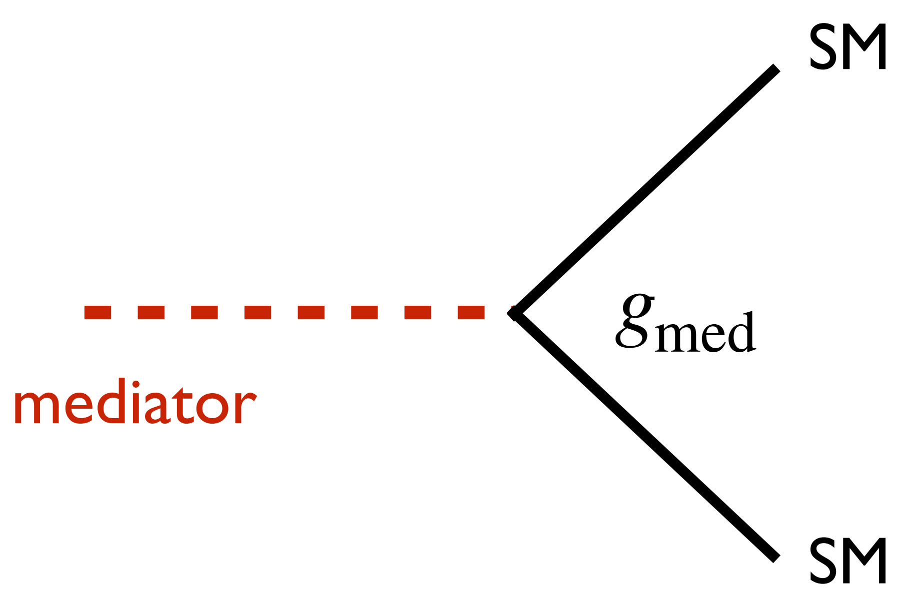
- (Weak) Decays of heavy particles ($\mu, \tau, \mathrm{hadrons}, W, Z, t$)
- Reactors
- Accelerators
- Astrophysical systems (stars, supernovae, cosmic-rays ...)

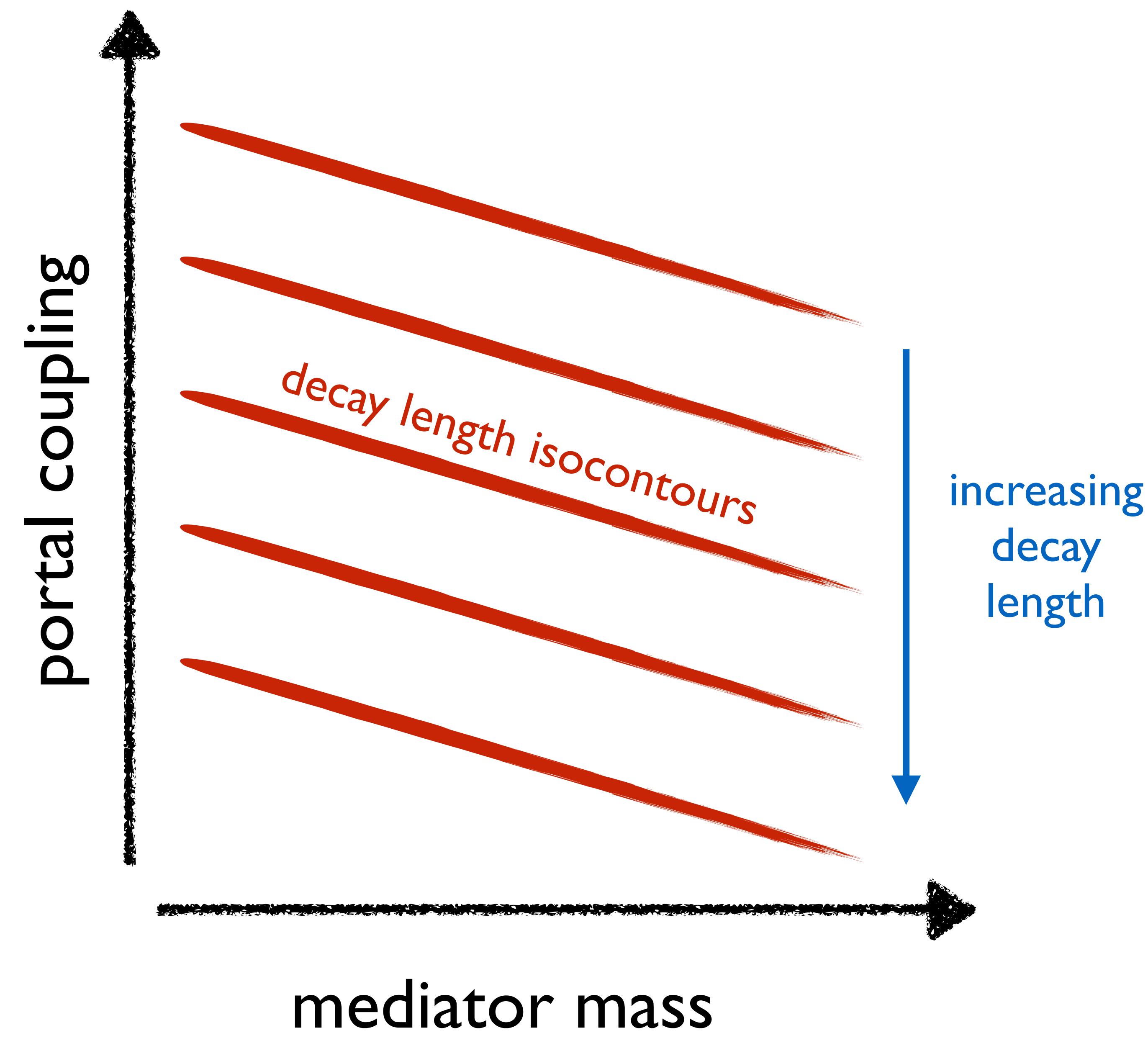
We can use similar means to study dark sectors

Minimal portals

Minimal portals

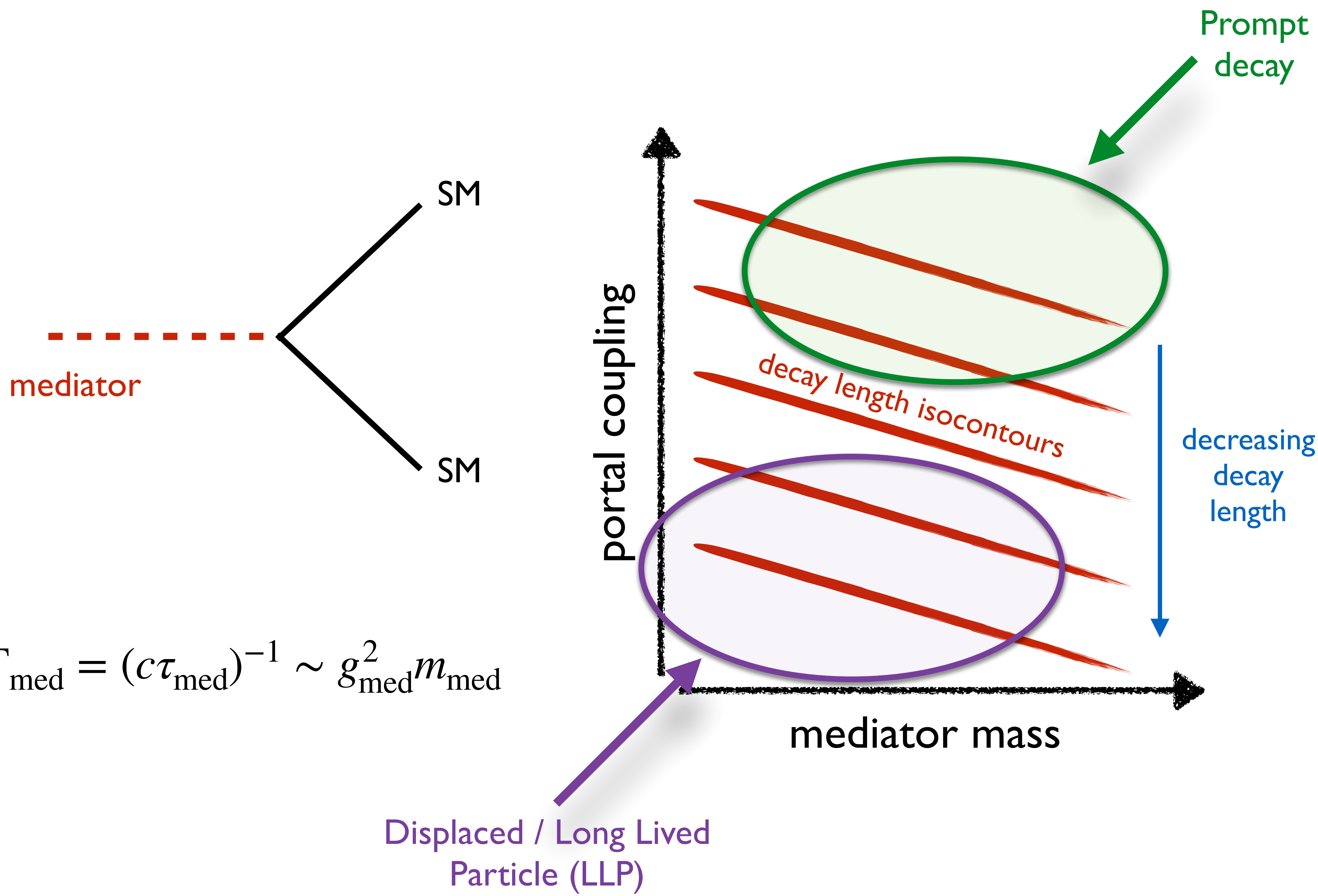
- Assume other dark sector states are heavier than the mediator. The physics of the mediator is then characterized in a simple mass — coupling parameter space
- The mediator is produced and decays back to visible SM final states through the same portal coupling (mediator can be prompt or displaced / long lived)





$$\Gamma_{\rm med} = (c\tau_{\rm med})^{-1} \sim g_{\rm med}^2 m_{\rm med}$$

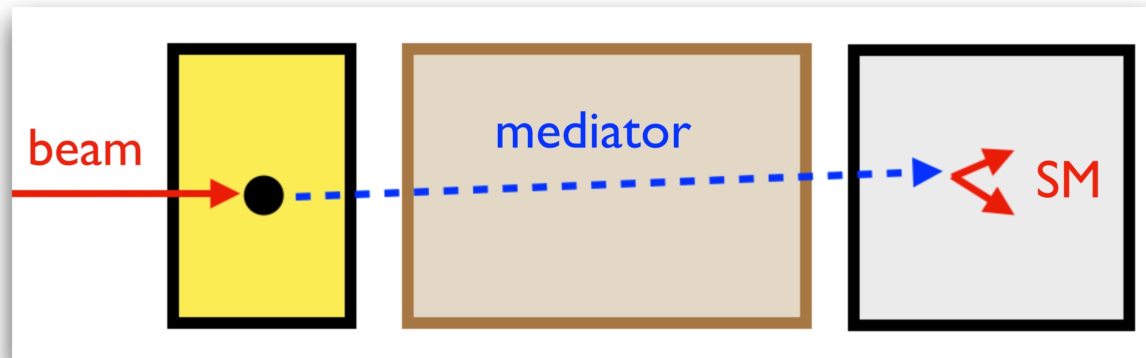
Visible decays of the mediator



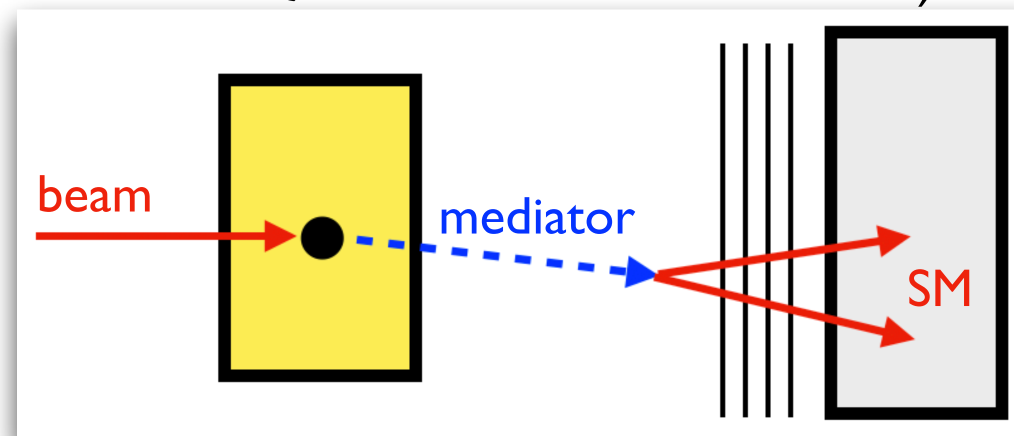
$$\Gamma_{\text{med}} = (c\tau_{\text{med}})^{-1} \sim g_{\text{med}}^2 m_{\text{med}}$$

Experimental approaches

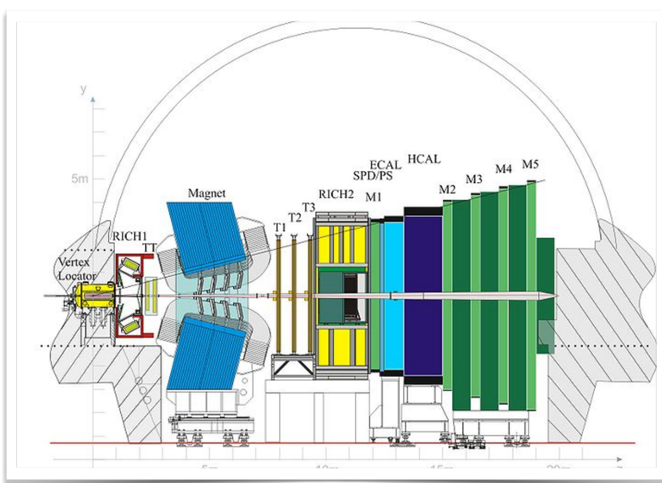
Beam dump (DUNE, ICARUS, SBND, SHADOWS,…)



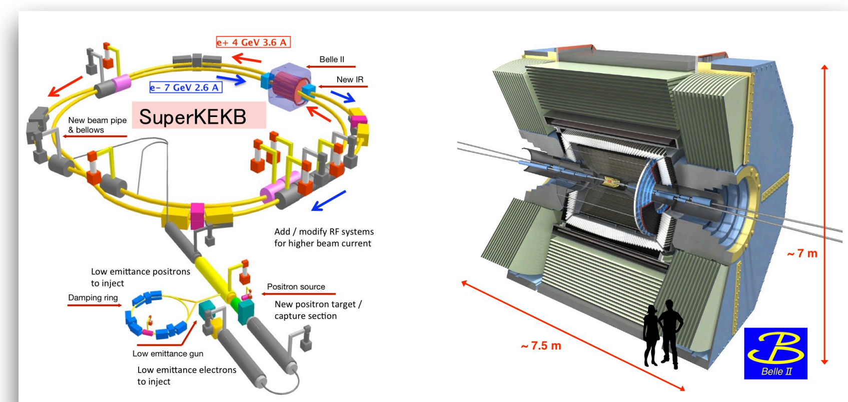
Fixed target spectrometer (HPS, DarkQuest, NA64, LDMX,M³…)



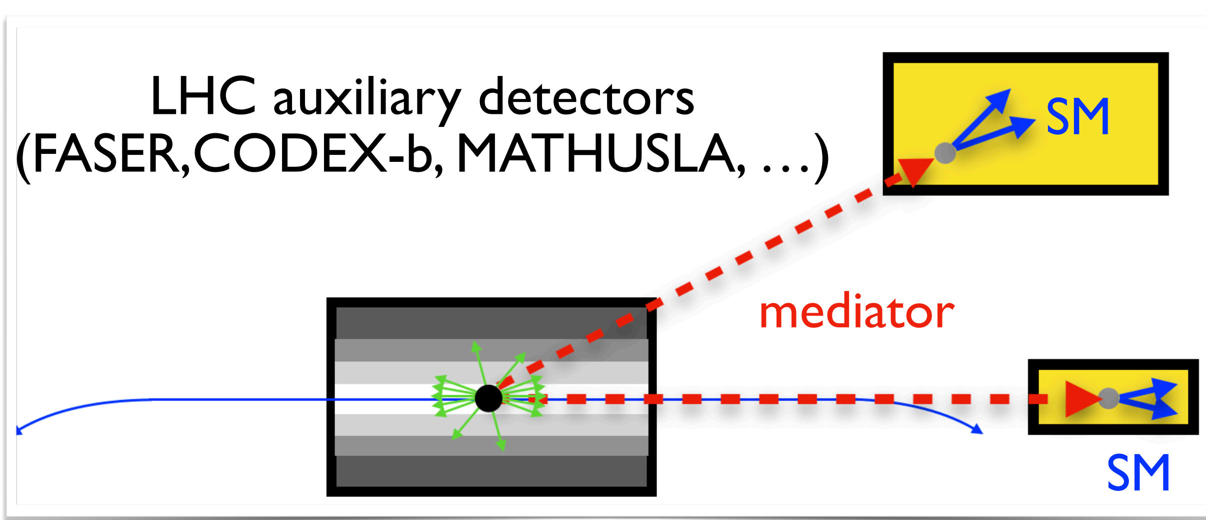
LHC main detectors (LHCb, CMS, ATLAS,…)



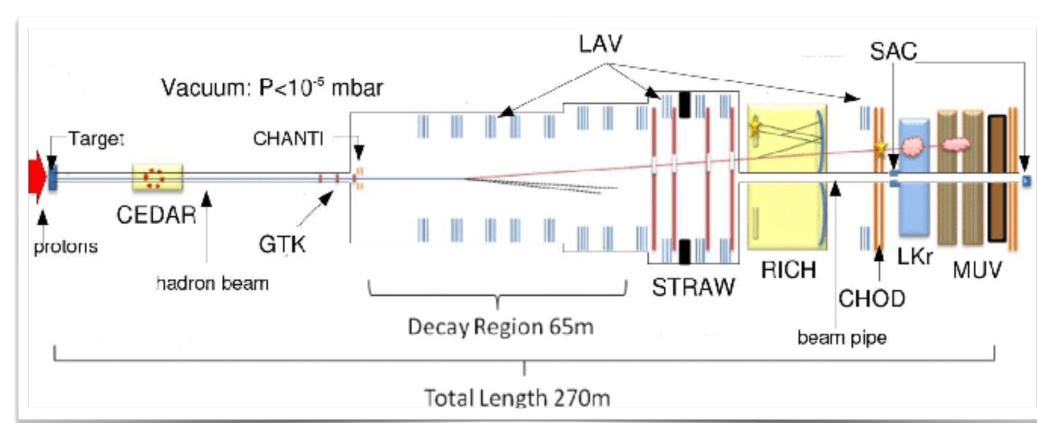
e^+e^-colliders (e.g., Belle II, …)



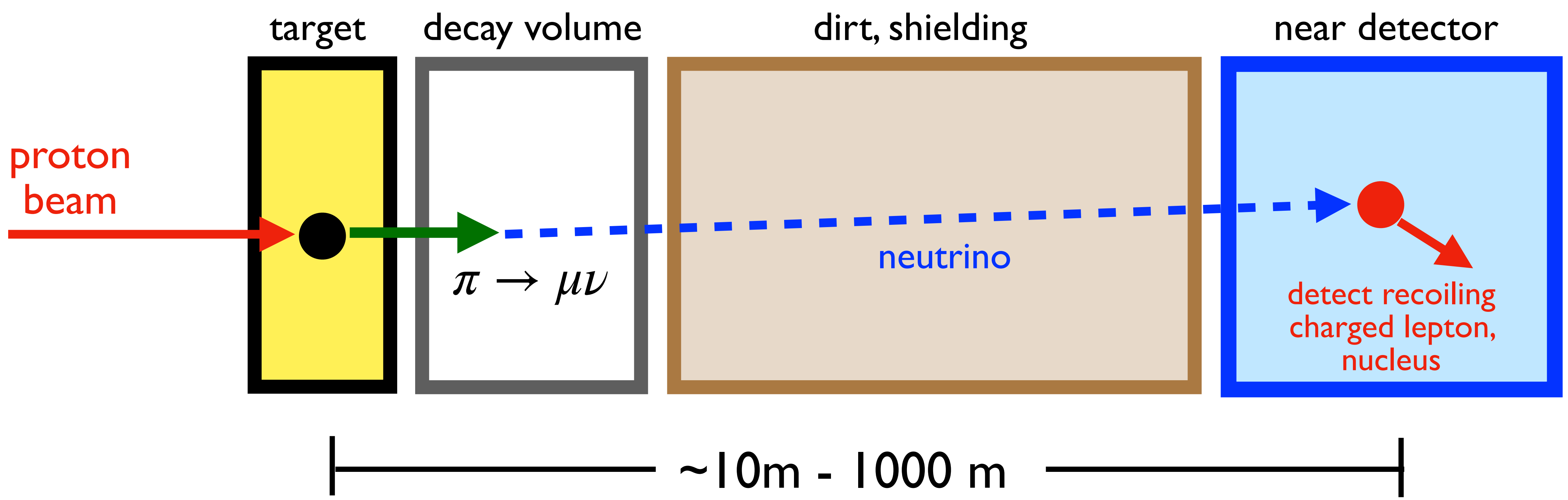
LHC auxiliary detectors (FASER,CODEX-b, MATHUSLA, …)



Meson/Lepton facilities (NA62, PIONEER, REDTOP, Mu3e,…)

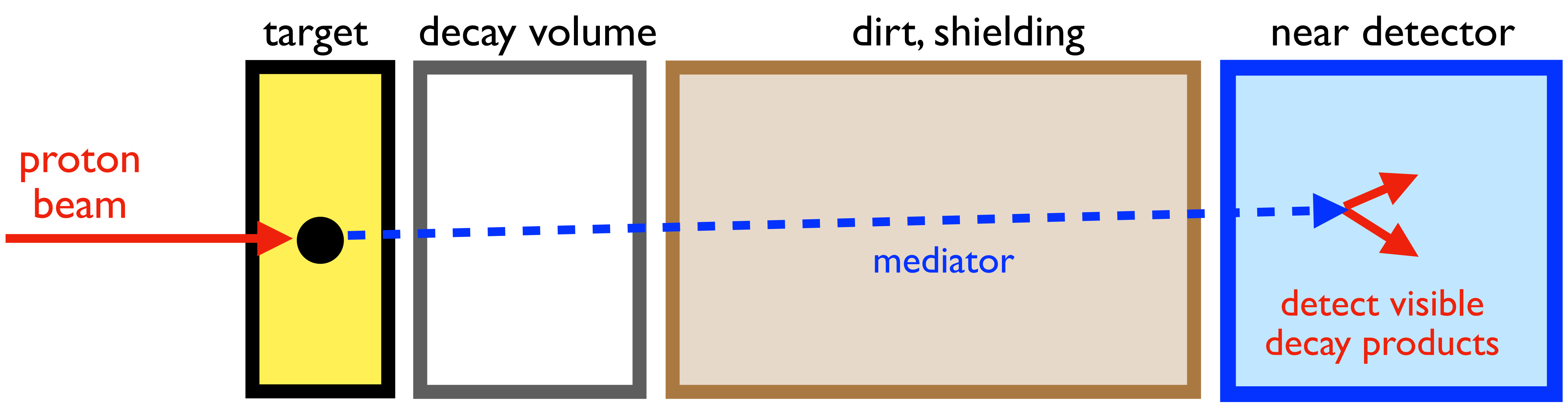


Accelerator neutrino beam experiments



- High intensity proton beam - fixed target experiment — enormous collision luminosities
- Large acceptance due to forward kinematics, short baselines, large volume detectors
- Modern neutrino detectors enjoy excellent particle ID and reconstruction capabilities
- These features also extend to searches for dark sector particles

Dark mediators at accelerator neutrino experiments



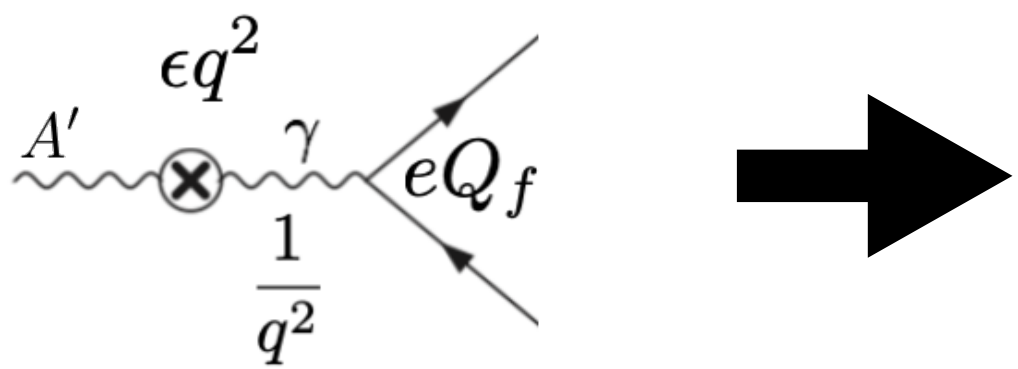
- Searches can be done with existing and near future accelerator neutrino experiments, e.g., MicroBooNE, SBND, ICARUS, NOvA, T2K, COHERENT, CCM, DUNE…

Dark photon / vector portal

- Introduce a new U(1) gauge boson — a dark photon A' — with Lagrangian

$$\mathcal{L} \supset -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} - \frac{\epsilon}{2}F_{\mu\nu}F'^{\mu\nu} + \frac{1}{2}m^2_{A'}A'_\mu A'^\mu + \sum_f Q_f\, e\, A_\mu \bar{f}\gamma^\mu f$$

- We can treat the kinetic mixing as an interaction, i.e.,



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

- Or we can diagonalize the Lagrangian via

  — See exercises

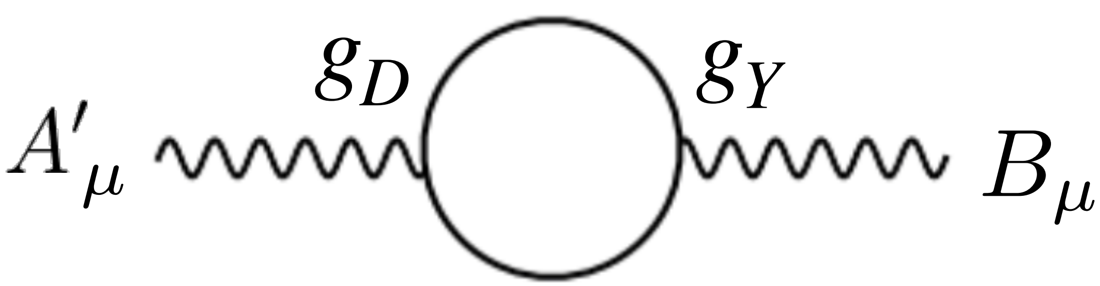
$$\begin{aligned} A_\mu &\to A_\mu - \epsilon A'_\mu, \\ A'_\mu &\to A'_\mu. \end{aligned}$$

- This gives the interaction: $\mathcal{L} \supset \sum_f Q_f\, e\, A'_\mu \bar{f}\gamma^\mu f$

The origin of kinetic mixing

- It is possible that the kinetic mixing is present at tree level, so that it is a free parameter
- Even if not present at tree-level, it can be generated radiatively from loops of particles containing both hypercharge and dark charge

[Holdom]

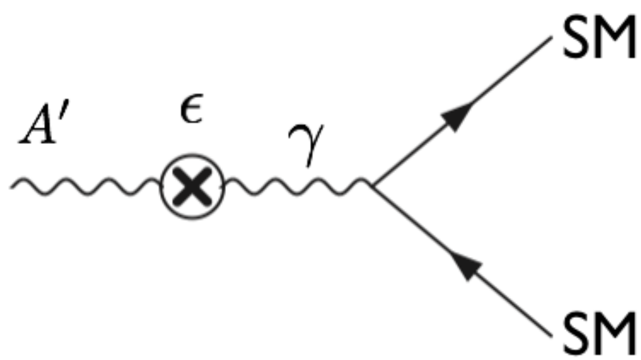


$$\epsilon \sim \frac{g_Y g_D}{16\pi^2} N \log\left(\frac{M_{UV}}{\mu}\right)$$

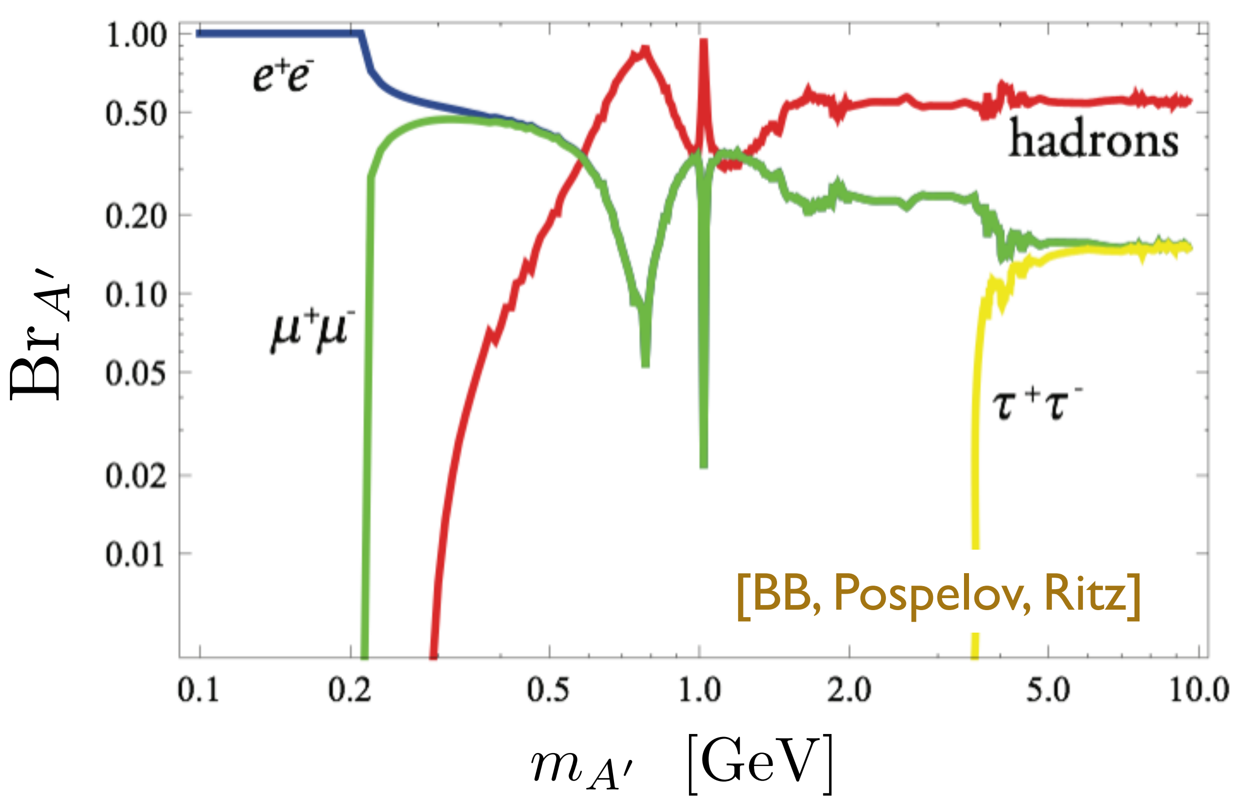
- This naturally gives kinetic mixing at the level of $\epsilon \sim 10^{-3}$ or smaller
- Arguments can be given for even smaller kinetic mixing in grand unified theories and string theory

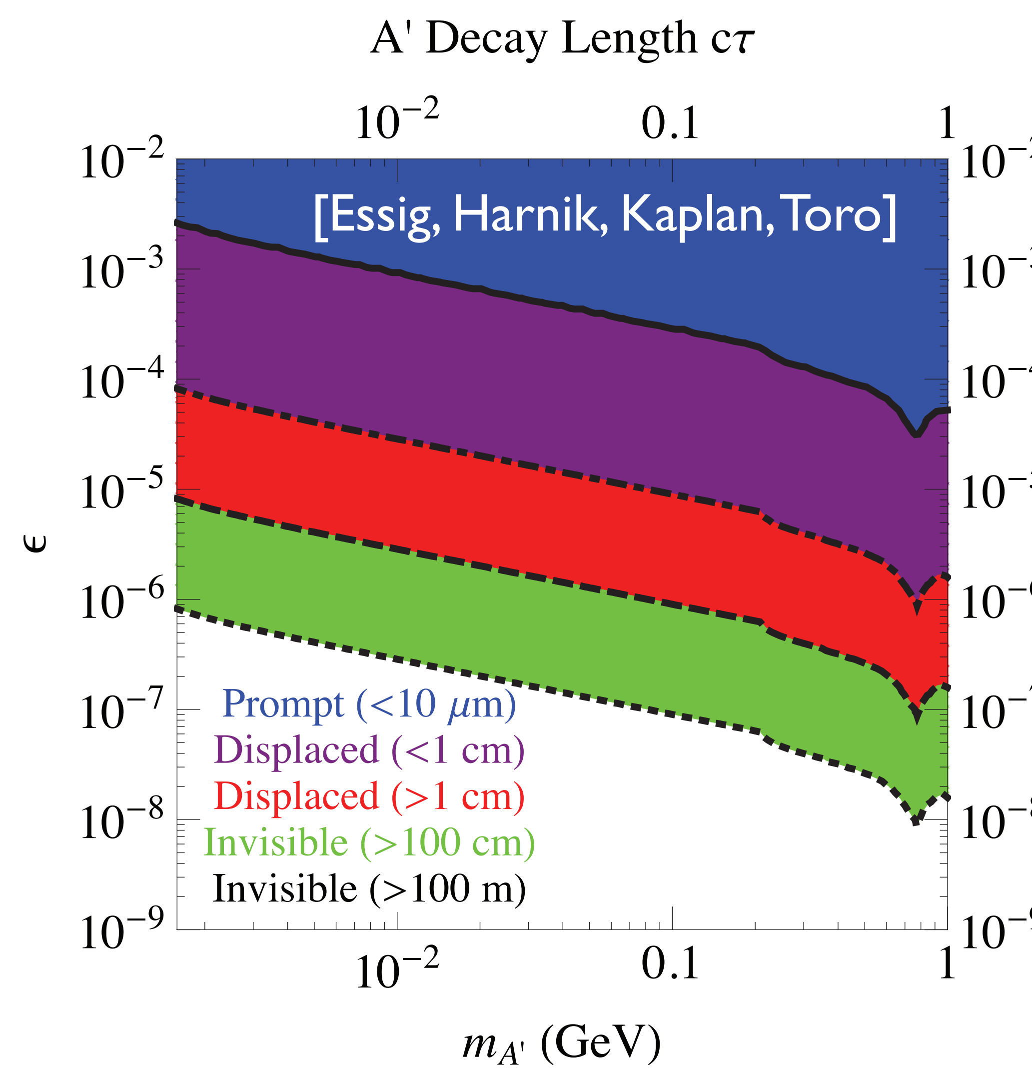
Dark photon decays

- The dark photon couples democratically to charged particles via kinetic mixing



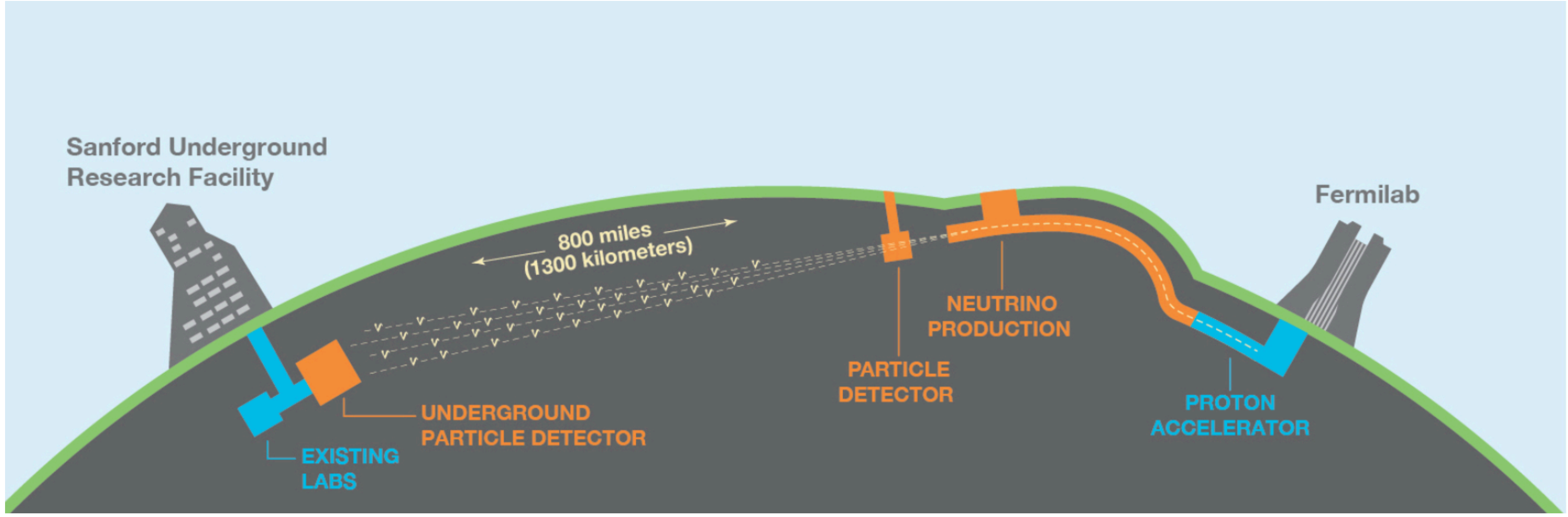
$$\Gamma_{A'} \sim \epsilon^2 \alpha \, m_{A'}$$



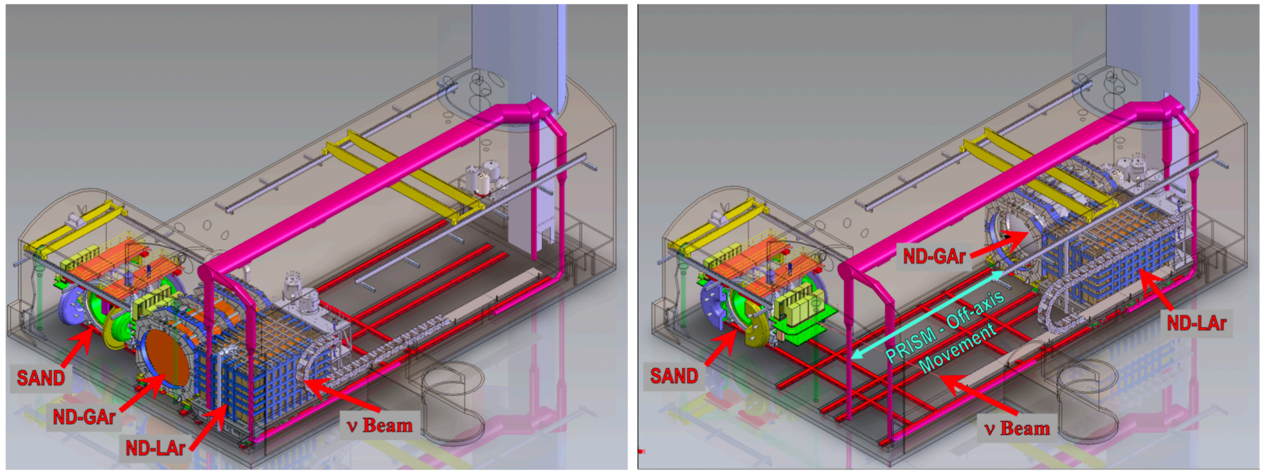


Dark sector searches at DUNE near detector

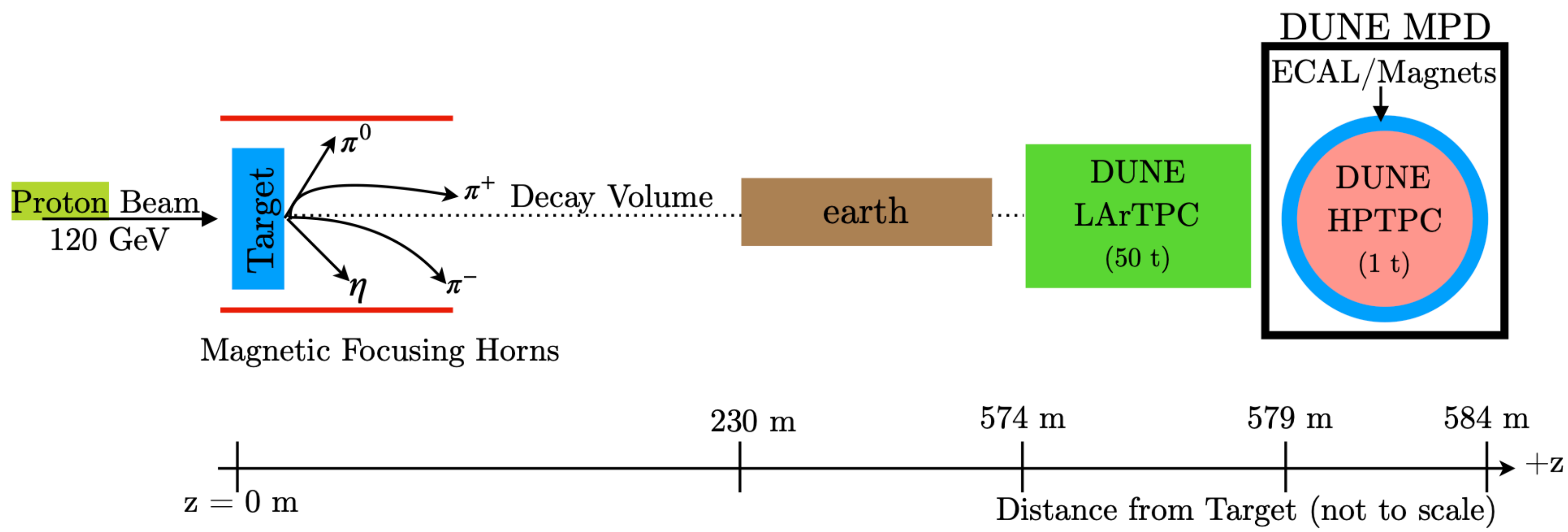
- 120 GeV proton beam on graphite target, ~ 10^{22} POT (~ten years)

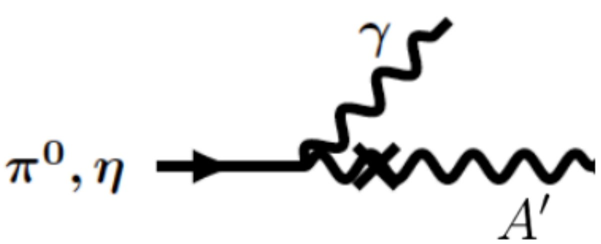


- DUNE near detector complex, 574 m downstream of target, several components:
  - ND-LAr — 100 ton liquid argon TPC
  - ND-GAr — 1 ton gaseous Argon TPC, magnetized, surrounded by ECAL
  - PRISM — near detector moveable up to 30 m (50 mrad) off-axis

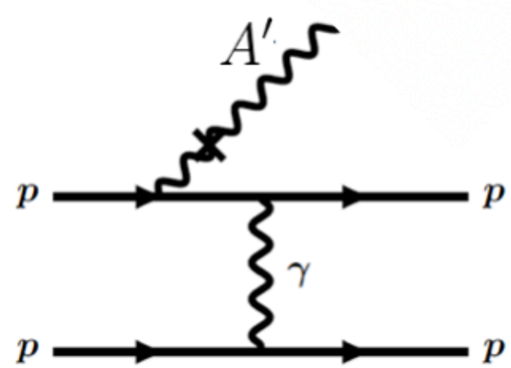


Dark photon production at DUNE

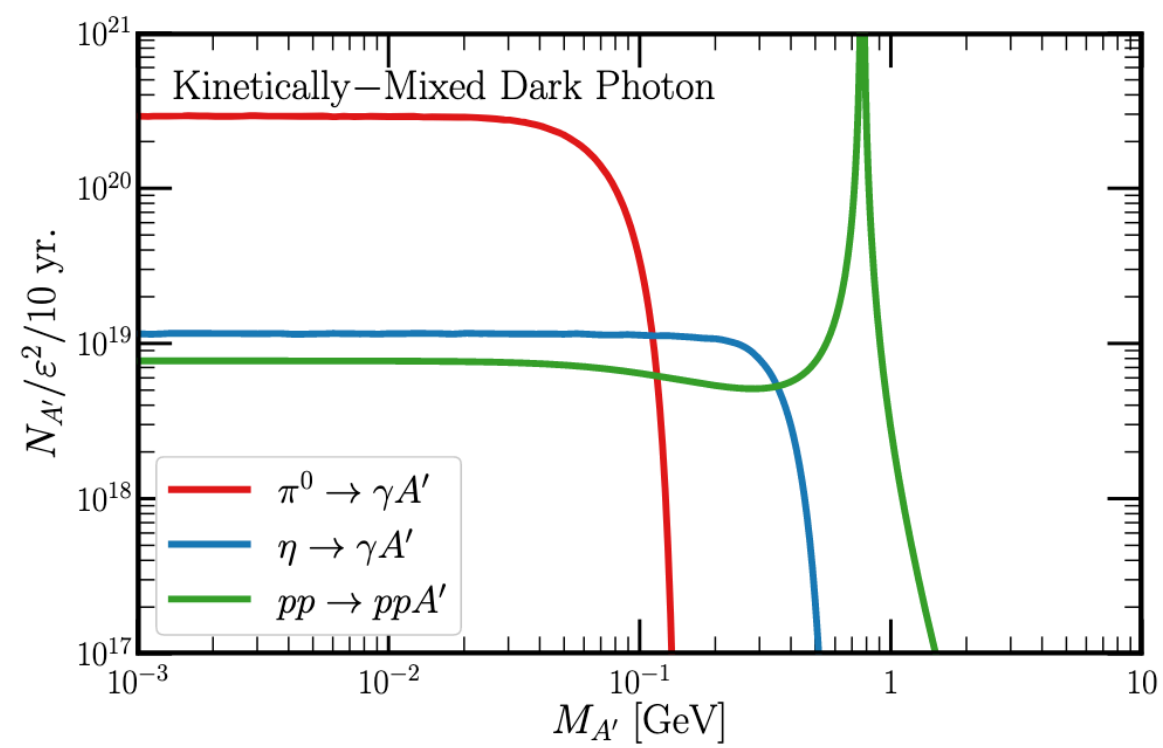




Neutral meson decays



Proton Bremsstrahlung



[Berryman, de Gouvea, Fox, Kayser, Kelly, Raaf]

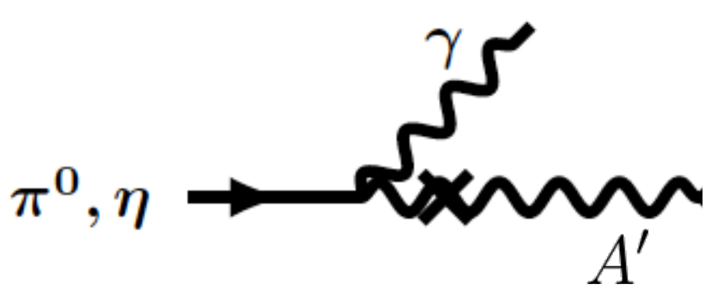
Estimate of dark photon yield at DUNE MPD

$$N_{\text{event}} = N_{\text{POT}}\, X_{A'}\, \text{Br}(A' \to \text{vis})\, \epsilon_{\text{det}}$$

where

N_{POT}	Number of protons on target
$X_{A'} = \dfrac{\sigma_{A'}}{\sigma_{\text{tot}}}$	Production fraction (number of A' per POT)
$\text{Br}(A' \to \text{vis})$	Visible branching ratio (= unity for minimal dark photon)
ϵ_{det}	Probability for A' to decay in detector (should be convoluted with detector efficiencies)

e.g., A' from π^0 decay



$$X_{A'} = X_{\pi^0}\, \text{Br}(\pi^0 \to \gamma A')$$

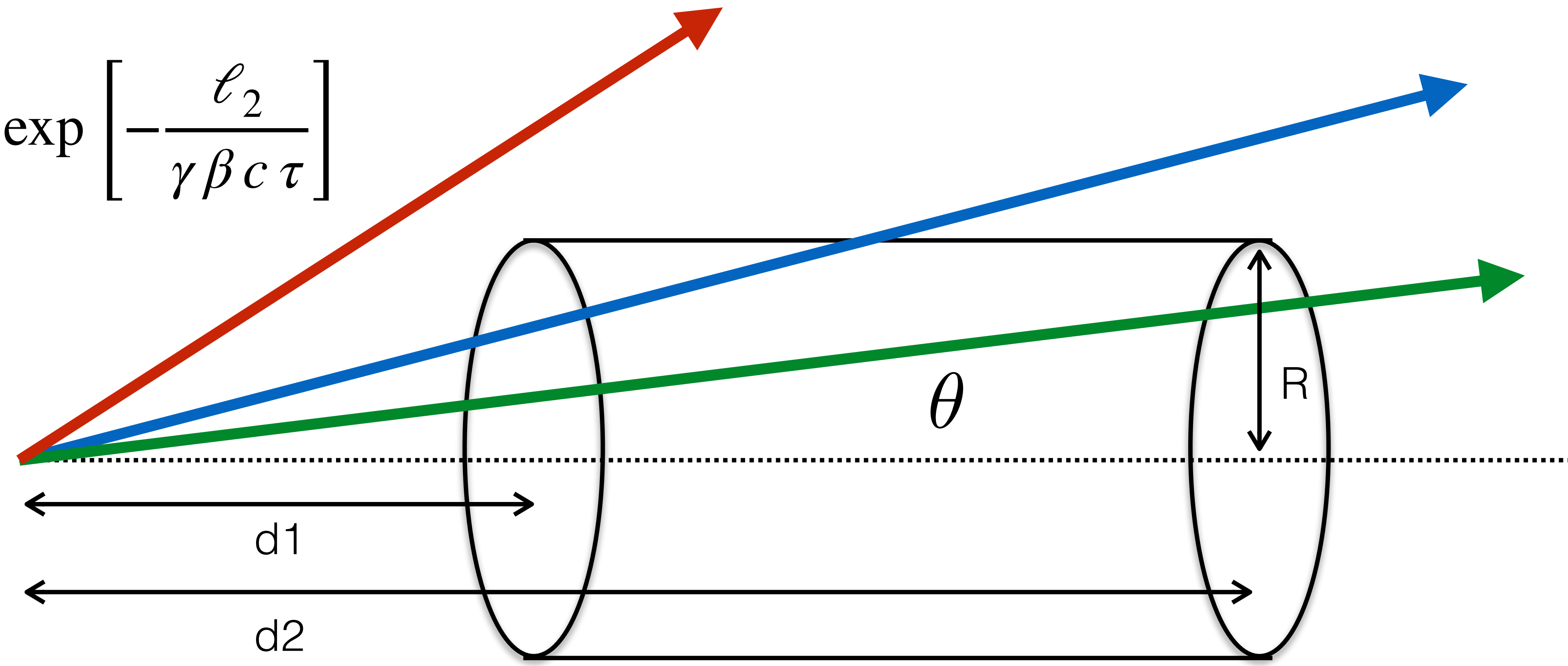
$$\text{Br}(\pi^0 \to \gamma A') = 2\epsilon^2 \left(1 - \frac{m_{A'}^2}{m_{\pi^0}^2}\right)^3$$

$\epsilon_{\rm det}$

Consider idealized cylindrical detector geometry. Simulate A' events and look at their trajectories. There are three possibilities depending on the angle theta, shown below as red, blue and green trajectories. For red trajectories, $\epsilon_{\rm det} = 0$. For blue/green trajectories, we have

$$\epsilon_{\rm det} = \exp\left[-\frac{\ell_1}{\gamma\,\beta\,c\,\tau}\right] - \exp\left[-\frac{\ell_2}{\gamma\,\beta\,c\,\tau}\right]$$

In one of the exercises you will determine ℓ_1 and ℓ_2 for each trajectory for the idealized cylindrical detector at right



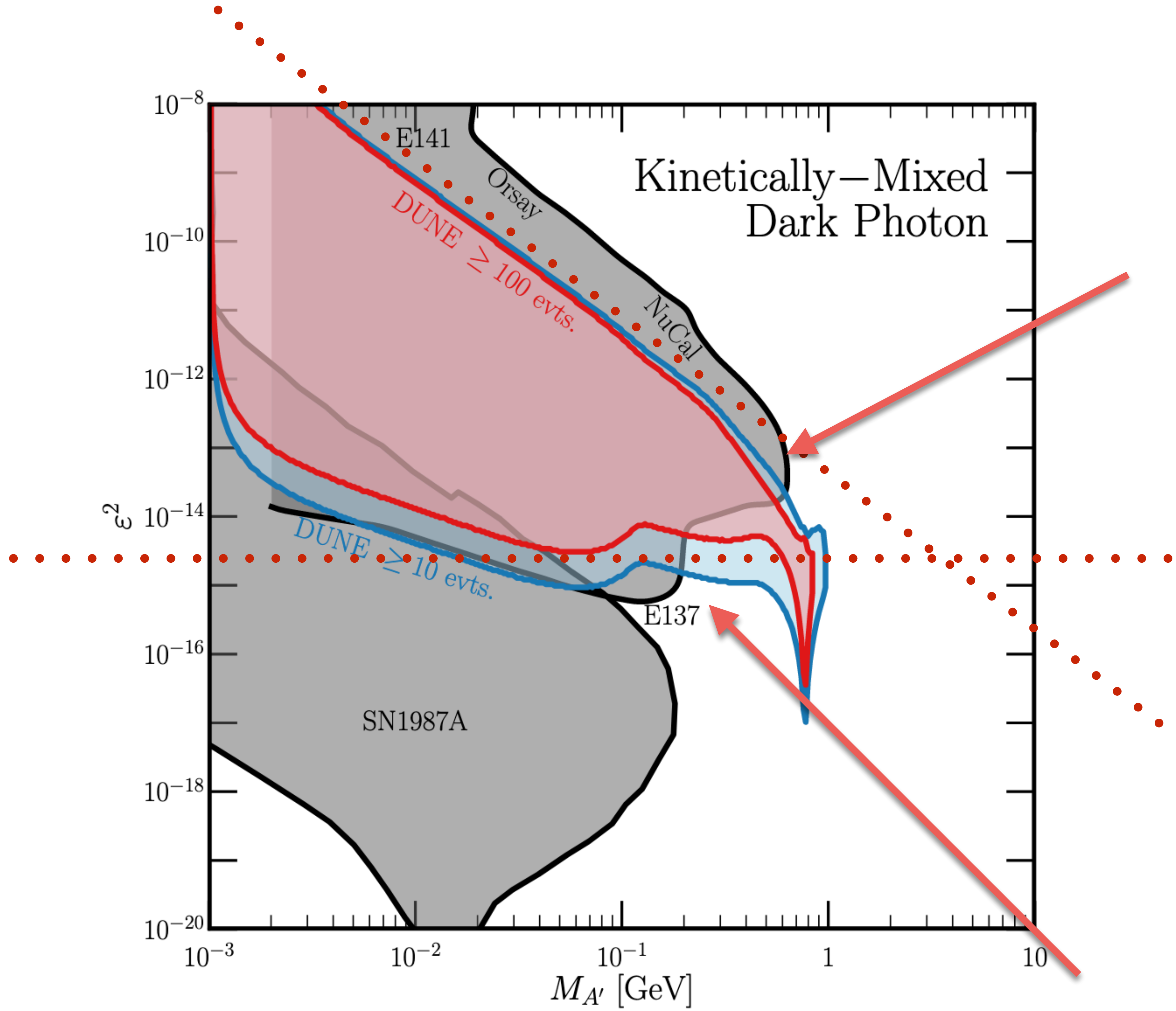
[Note: not drawn to scale]

The assumed parameters for DUNE MPD detector are

$$d_1 = 579\,\mathrm{m},\quad d_2 = 584\,\mathrm{m},\quad R = 2.5\,\mathrm{m}$$

Check each trajectory in the simulation and compute a weighted value for $\epsilon_{\rm det}$

DUNE sensitivity to dark photons

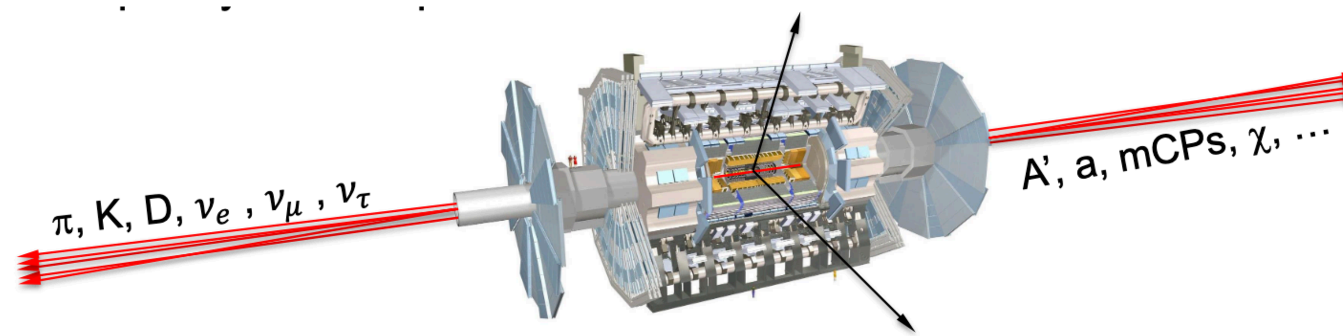


Lifetime too short, A' doesn't reach detector

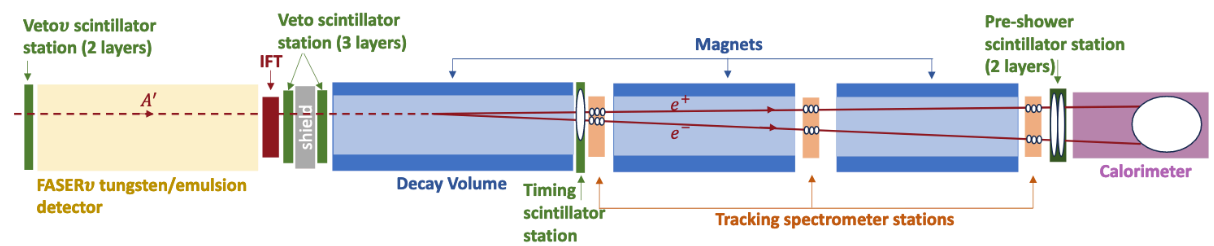
Production rate too small, Lifetime too long

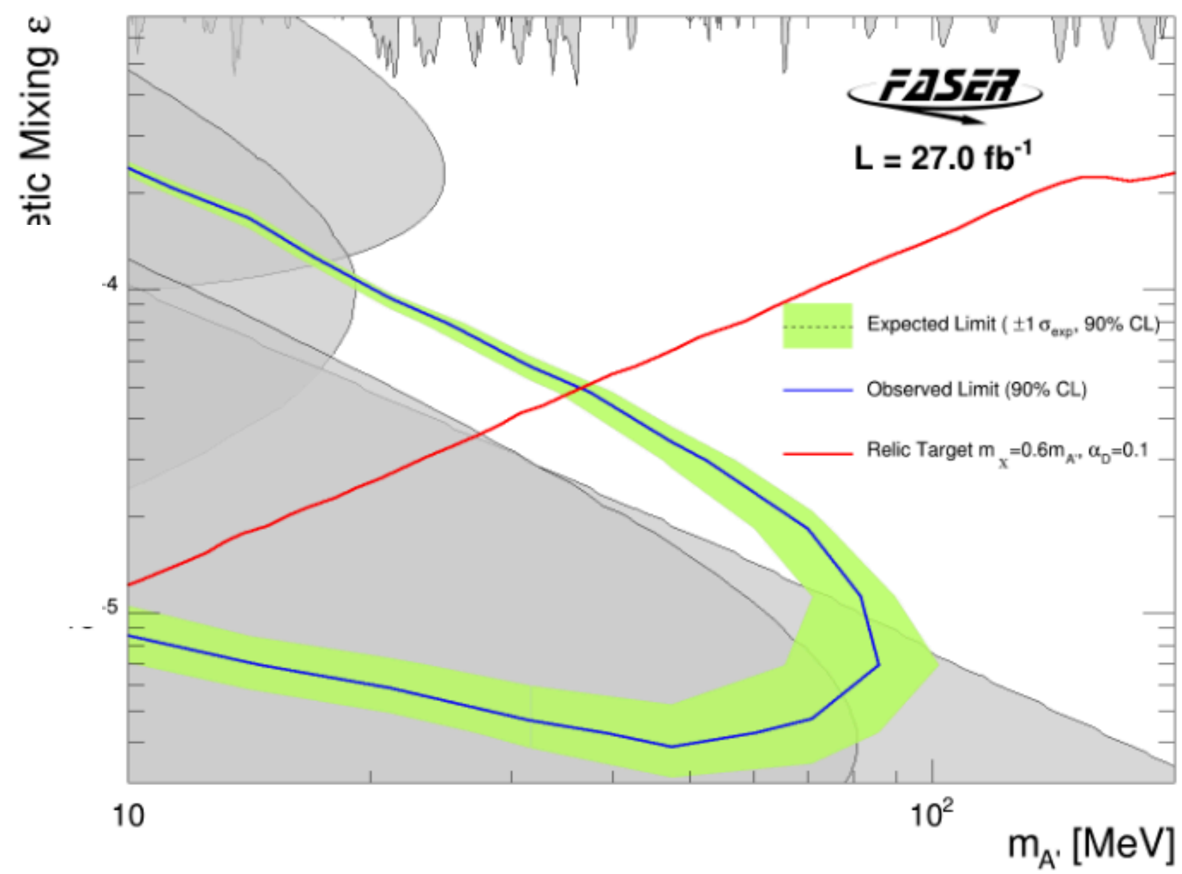
[Berryman, de Gouvea, Fox, Kayser, Kelly, Raaf]

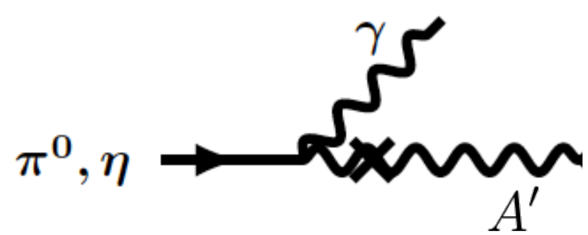
Dark photon search at FASER

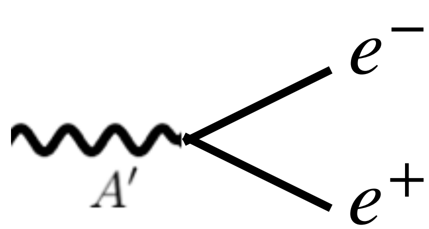


- Total LHC pp cross section is ~100 mb, and is directed in the forward region
- FASER is located in the far forward region of the LHC, 480 m downstream of IP
- First FASER search sets world leading limits on dark photons!





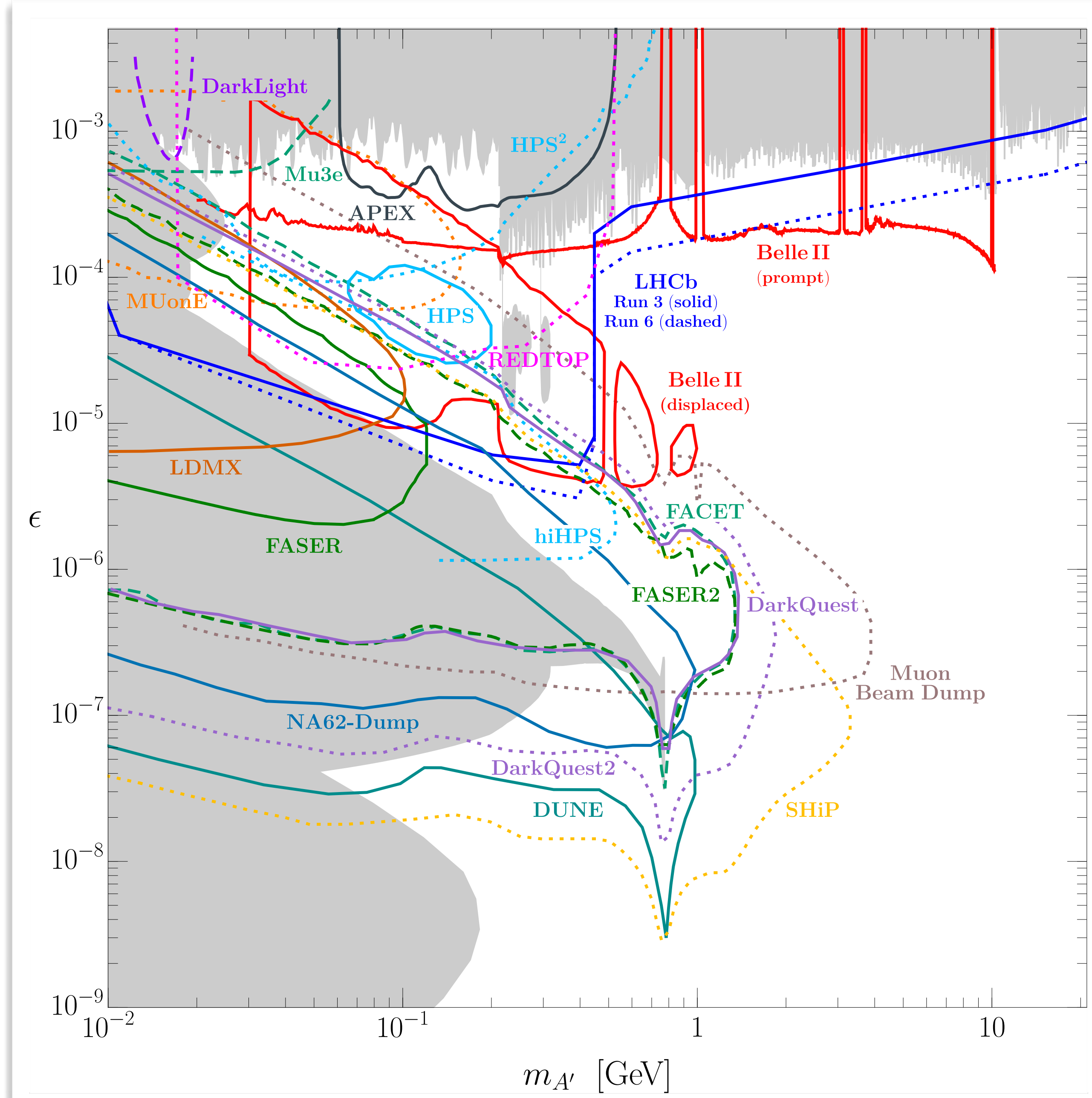
production 

decay, signal 

[FASER Collab., 2308.05587]

Visible dark photon outlook

- Operating experiments (LHCb, Belle II, FASER, HPS) will cover low mass, large mixing region
- DUNE (w/near detector) will probe small mixings ($\epsilon \sim 10^{-8} - 10^{-6}$) for masses below ~ 1 GeV
- Exciting opportunities for DarkQuest and FASER2 to probe intermediate mixings ($\epsilon \sim 10^{-7} - 10^{-5}$) for masses below ~ 1 GeV
- Viable thermal dark matter can be realized over the entire parameter space (more on this tomorrow…)



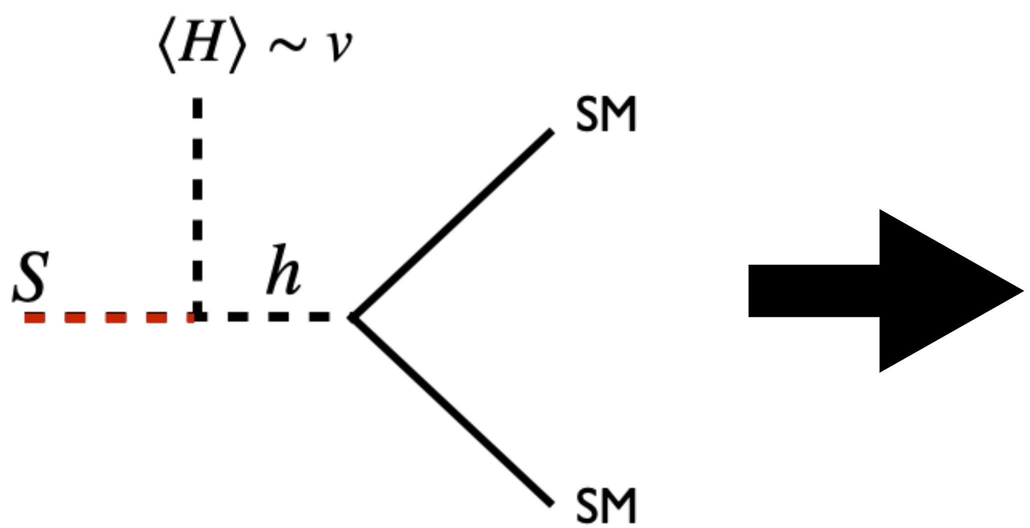
[arXiv:2207.06905]

Dark scalar / Higgs portal

- The basic Lagrangian for the model is given by

$$\mathscr{L} \supset \frac{1}{2}(\partial_\mu S)^2 - \frac{1}{2}m_S^2 S^2 + (AS + \lambda S^2)\,|H|^2$$

- Symmetry breaking generates dark scalar — Higgs mass mixing:



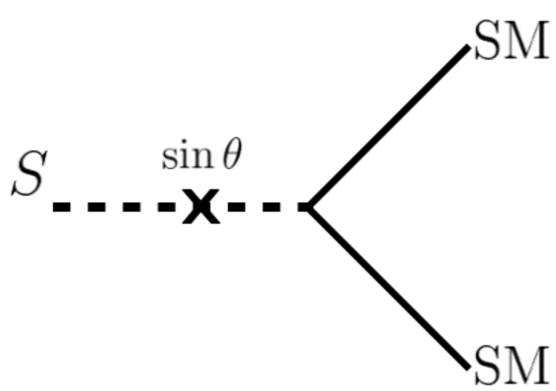
$$\sin\theta \sim \frac{Av}{m_h^2} \qquad (m_S \ll m_h)$$

- The scalar inherits the couplings of the Higgs:

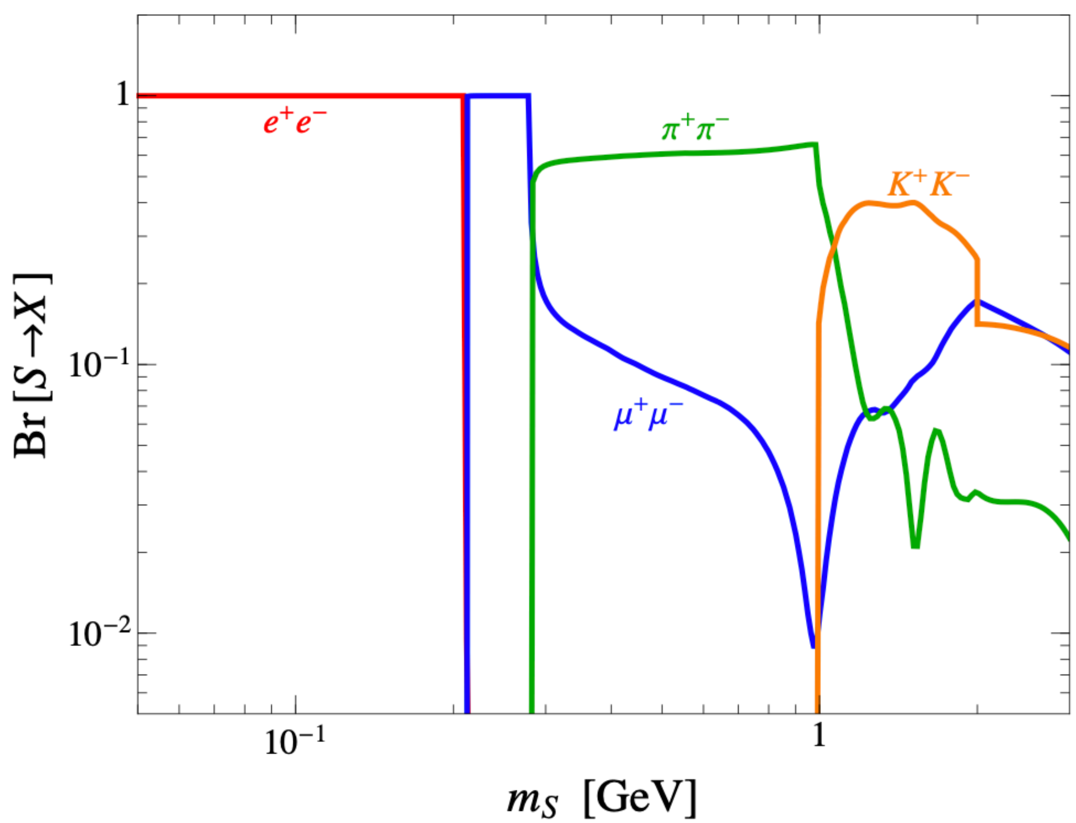
$$\mathscr{L} \supset \sin\theta\, S \left(\frac{2m_W^2}{v} W_\mu^+ W^{\mu-} + \frac{m_Z^2}{v} Z_\mu Z^\mu - \sum_f \frac{m_f}{v} \bar{f} f \right)$$

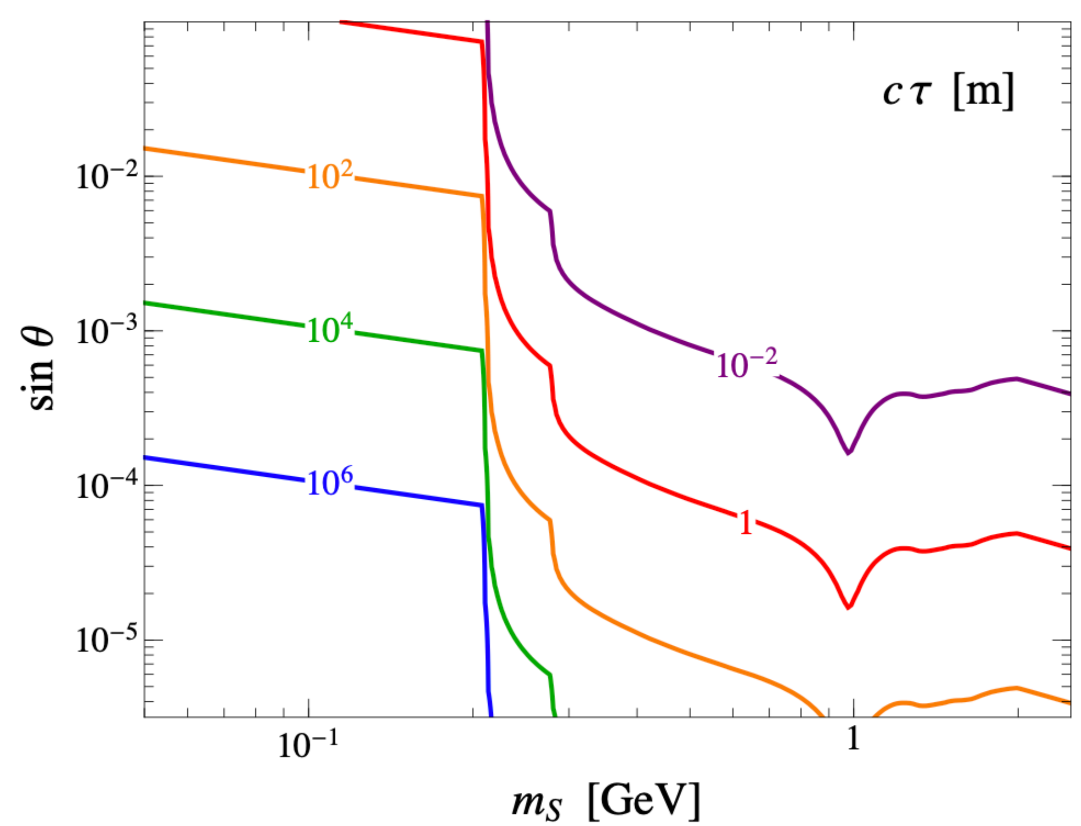
Dark scalar decays

- Dark scalar couples proportionally to the mass of the particle



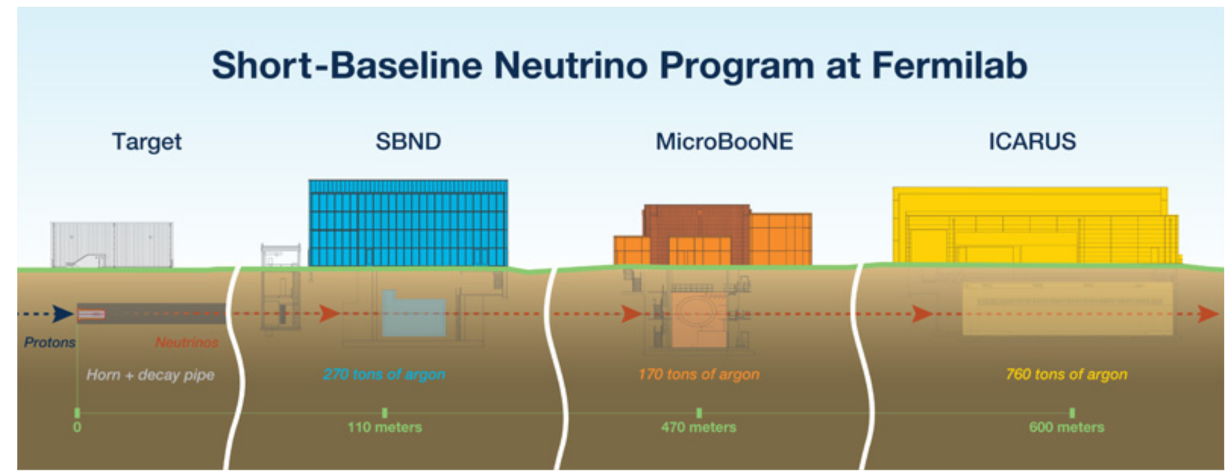
$$\Gamma_S \sim \sin^2\theta \frac{m_{\rm SM}^2}{v^2} m_S$$

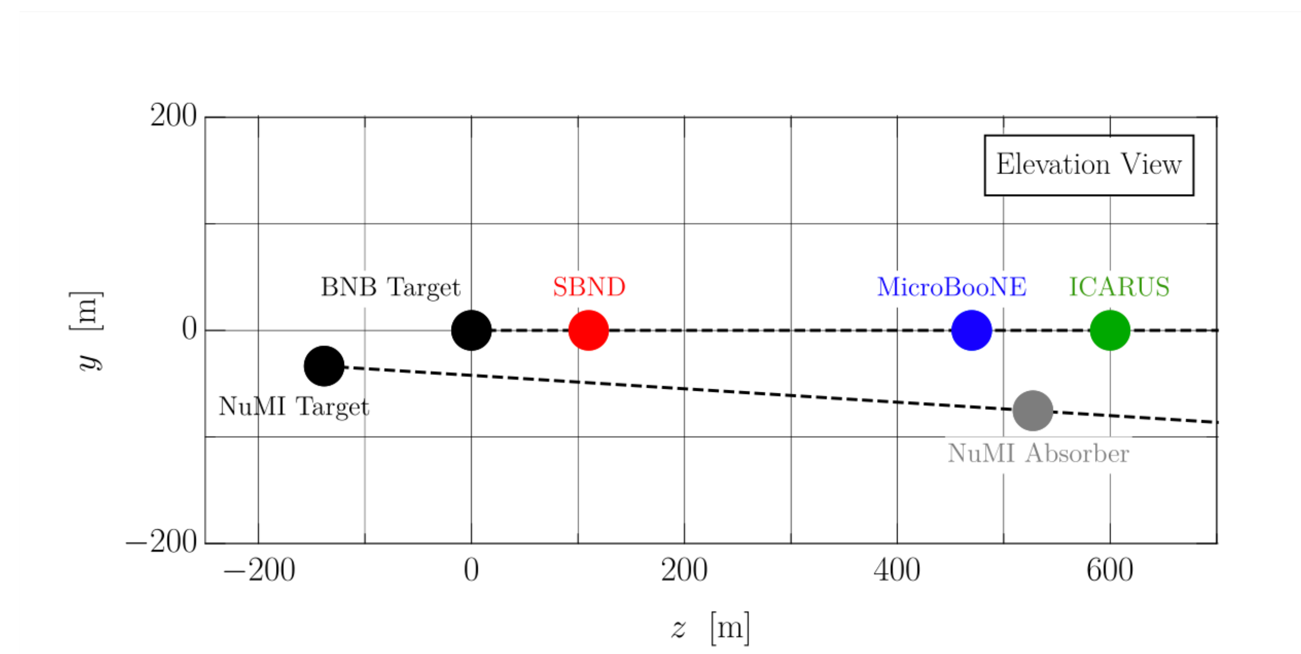




Short Baseline Neutrino Experiments @ FNAL

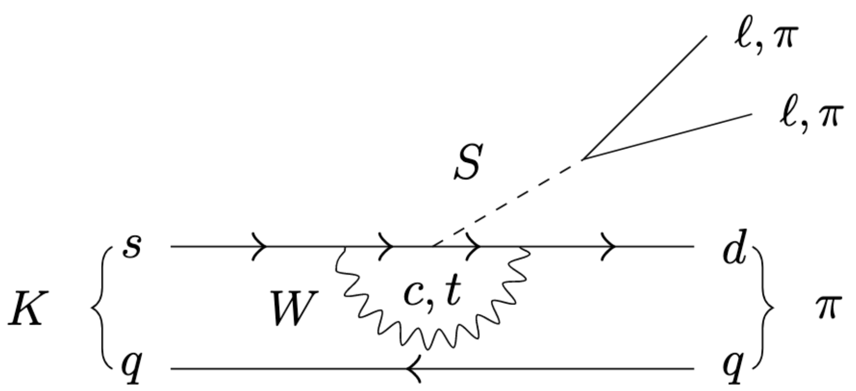
- SBND, MicroBooNE, ICARUS
- Liquid argon time projection chamber detectors
- Located along the Booster Neutrino Beam (8 GeV protons)
- MicroBooNE & ICARUS slightly off axis from the 120 GeV FNAL NuMi Beam.
- Primary goal is search for eV-scale sterile neutrinos
- Excellent prospects to probe dark sector particles

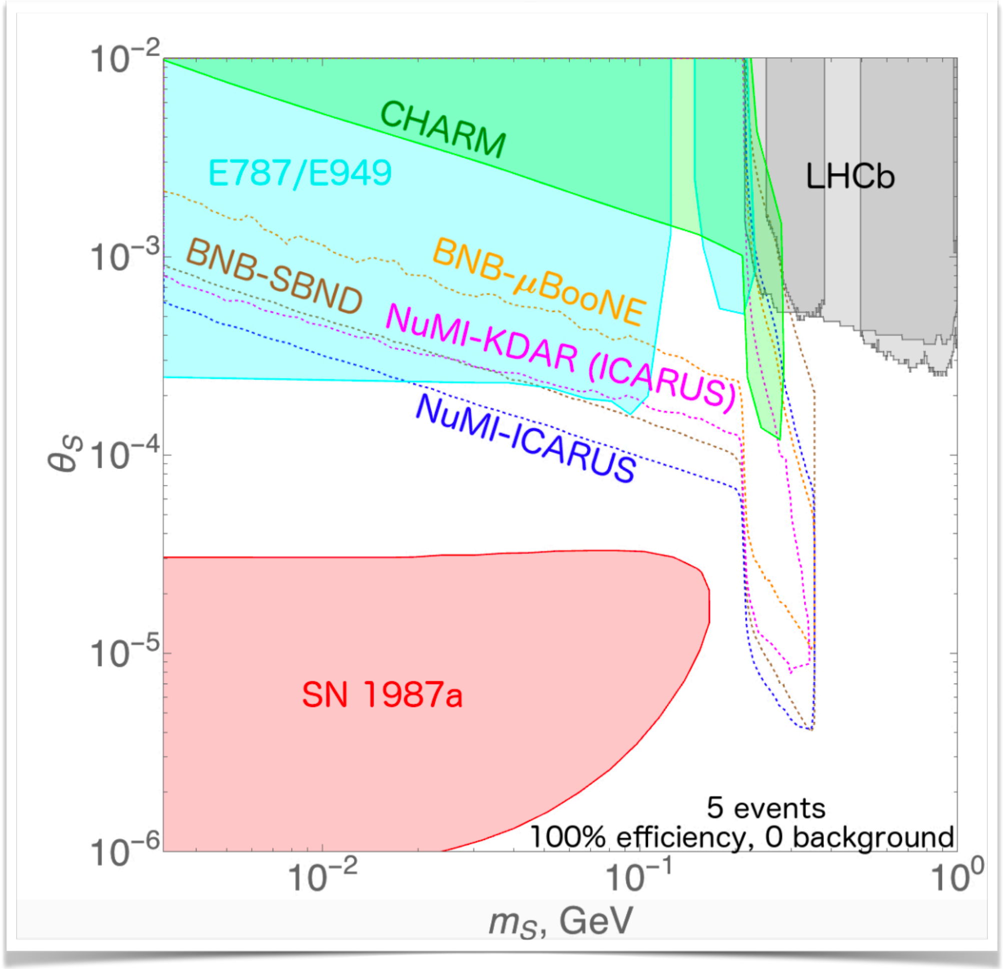




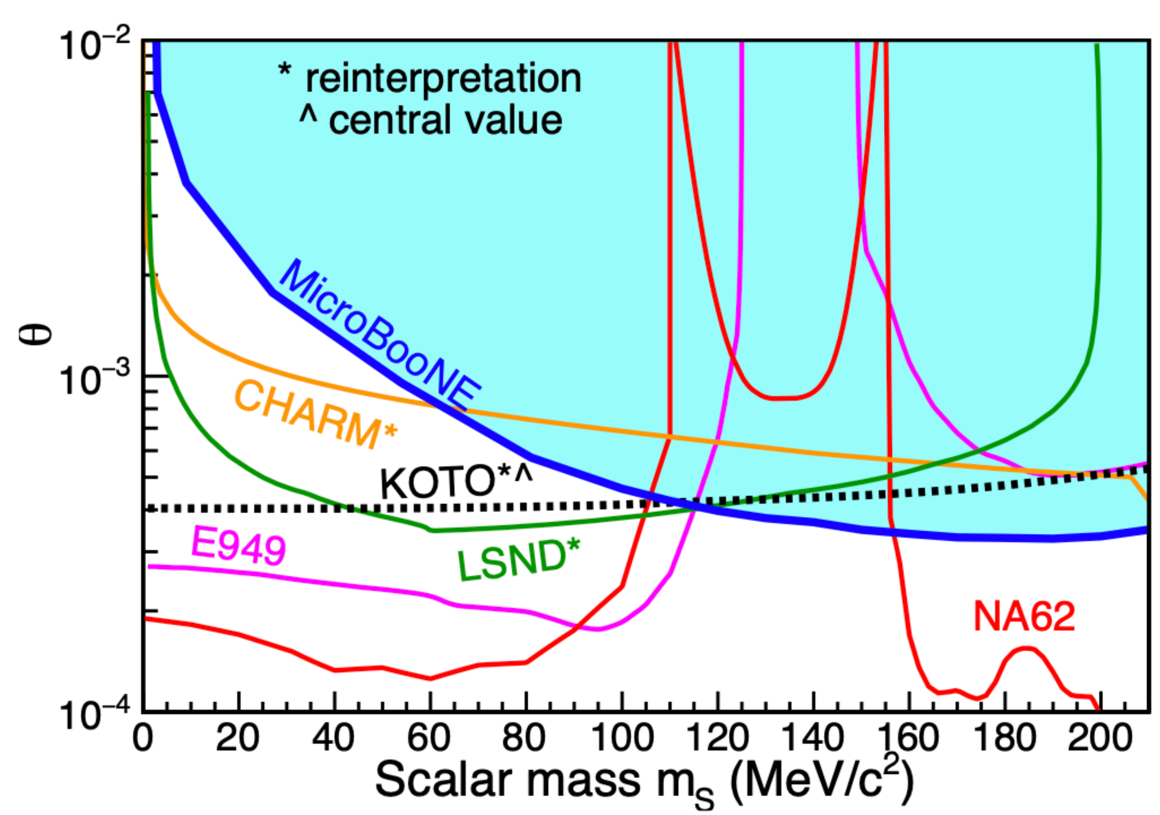
Higgs portal scalars at FNAL Short Baseline Experiments

- Kaons produced in proton collisions at Booster or NuMi can decay to dark scalars
- Long lived scalars travel to the SBN detectors and decay to leptons or pions





[BB, Berger, Ismail]



[MicroBooNE, Phys. Rev. Lett 127 (2021) 15, 151803]

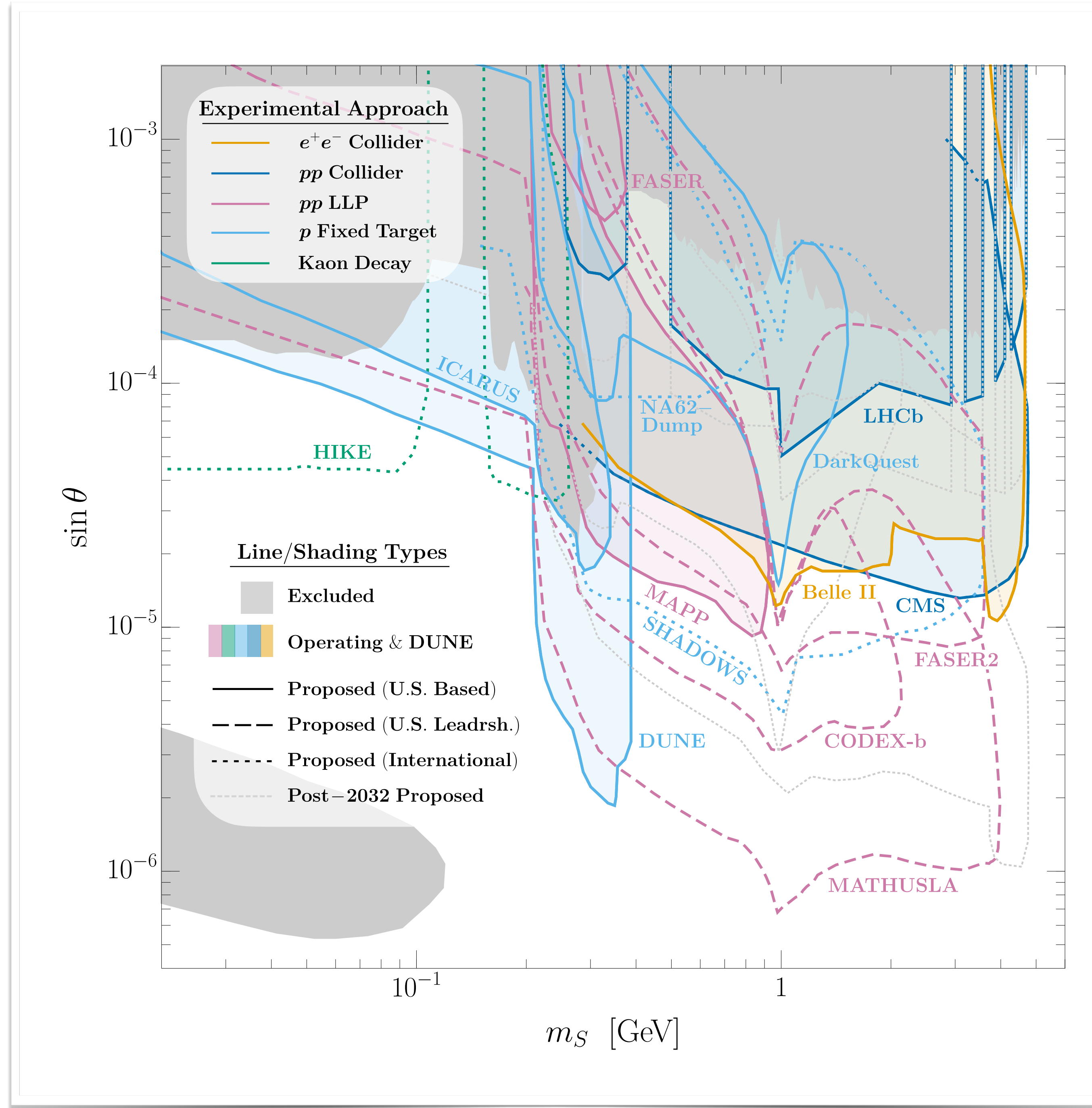
Dark scalar / Higgs portal outlook

- Operating experiments (ICARUS, LHCb, CMS, Belle II, FASER, MoDEL-MAPP) will cover substantial regions of parameter space below ~5 GeV

- DUNE (w/near detector) will have powerful sensitivity to light scalars produced in Kaon decays

- Exciting opportunities for DarkQuest, FASER2, CODEX-b, MATHUSLA, SHADOWS, HIKE to extend the reach to smaller mixing angles

- Viable thermal dark matter can be realized over the entire parameter space



[arXiv:2207.06905]

Heavy neutral lepton / neutrino portal

- The basic Lagrangian for the model is given by

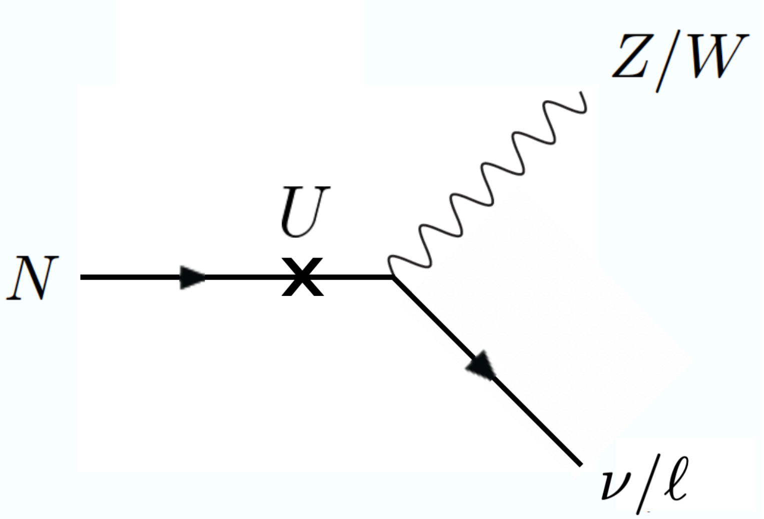
$$\mathscr{L} \supset N^\dagger \bar{\sigma}^\mu \partial_\mu N - \left[\frac{1}{2} M NN + y LHN + \mathrm{h.c.}\right]$$

Fig. from Khalil, Moretti

- Seesaw mechanism — mass mixing:

$$(\nu \;\; N) \begin{pmatrix} 0 & yv \\ yv & M \end{pmatrix} \begin{pmatrix} \nu \\ N \end{pmatrix} \implies m_\nu \sim \frac{y^2 v^2}{M}, \quad m_N \sim M$$

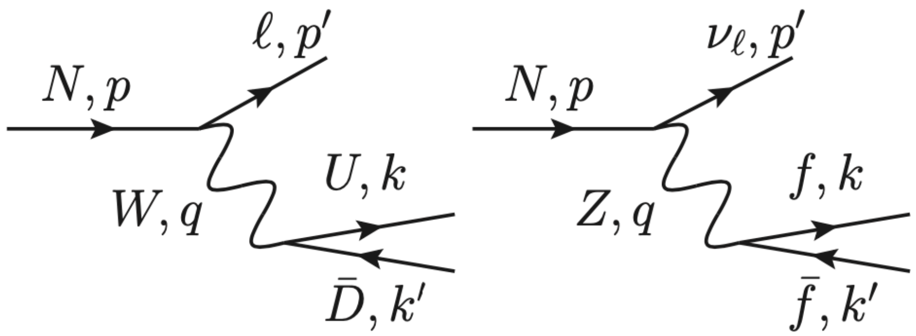
- Heavy neutrino, or heavy neutral lepton (HNL), inherits weak interaction of light neutrino



- Interaction strength suppressed by mixing angle, denoted U. The HNL couplings depend in detail on lepton flavor structure

Heavy neutral lepton decays

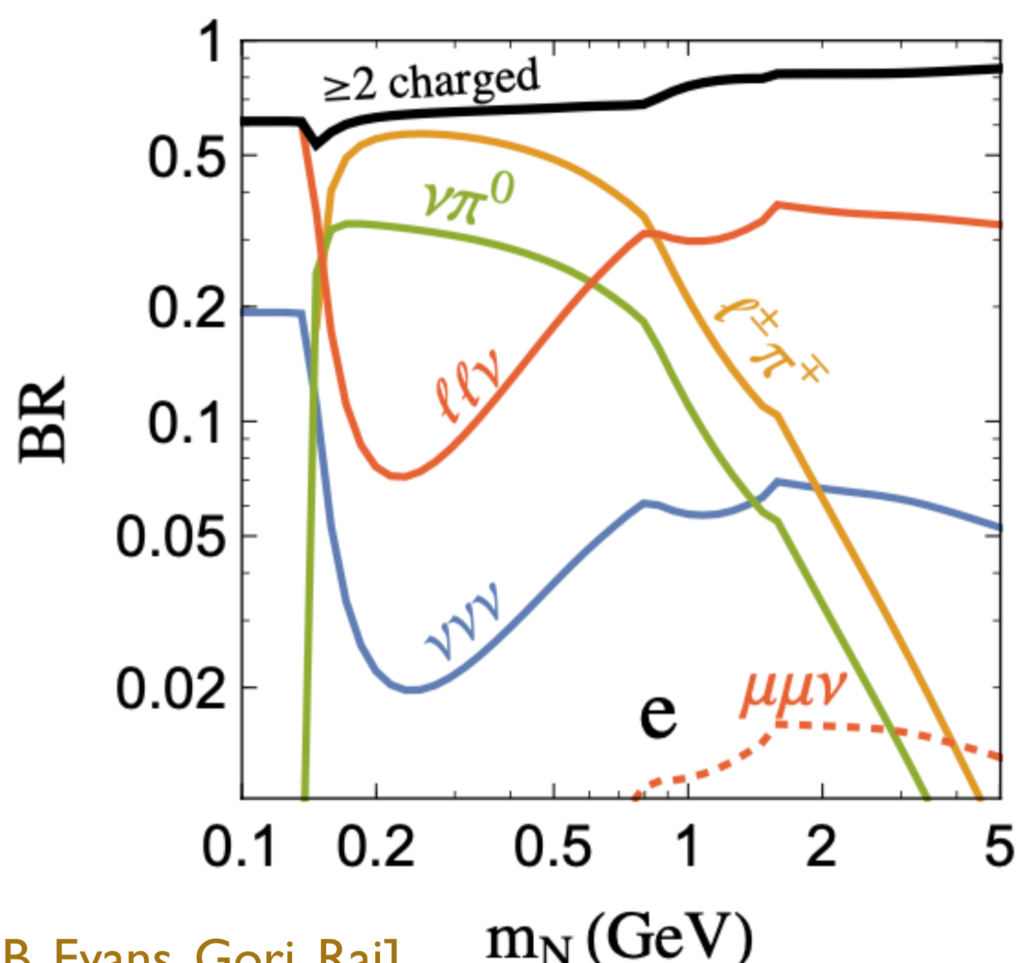
- HNLs decay via charged and neutral current reactions:



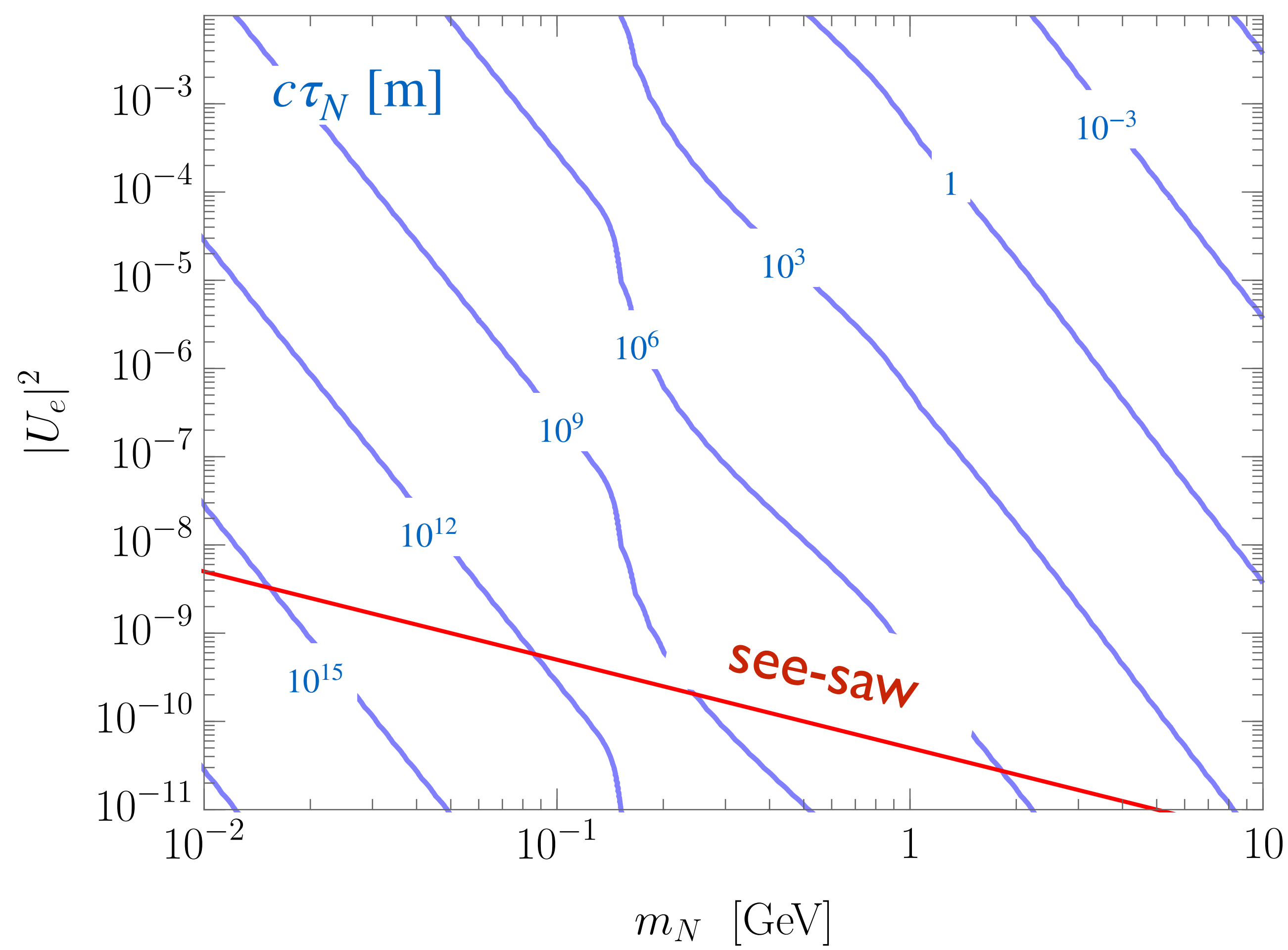
$$\Gamma_N \sim |U|^2 G_F^2 m_N^5$$

[See e.g., Bondarenko, Boyarsky, Gorbunov, Ruchayskiy]

- Example: electron-flavor dominance



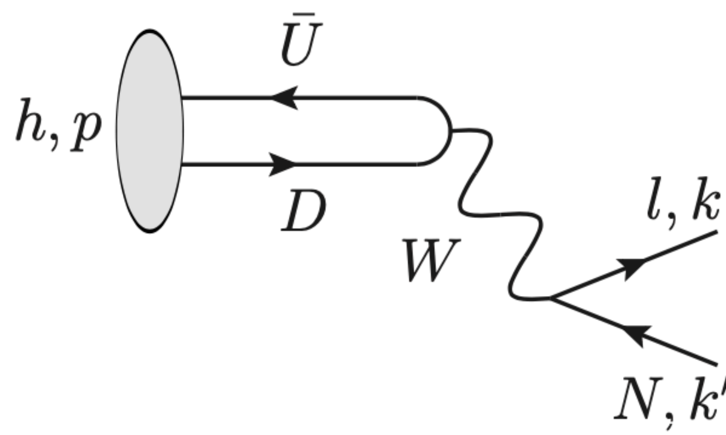
[BB, Evans, Gori, Rai]

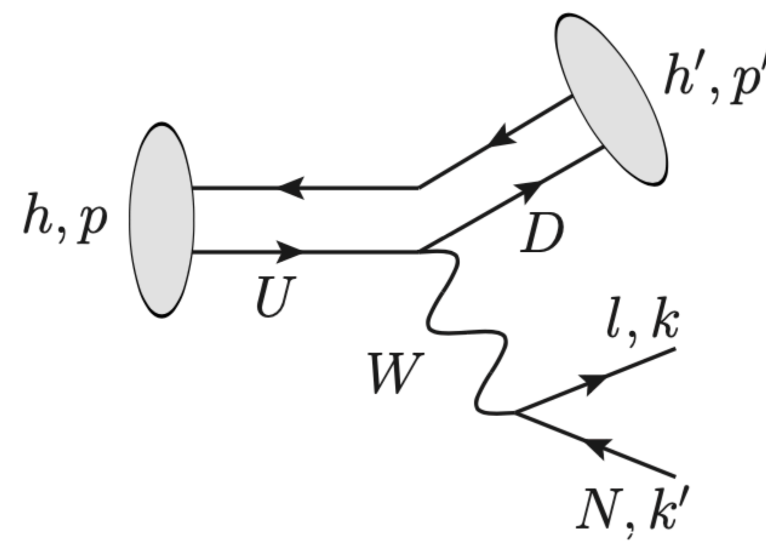


Production of heavy neutral leptons

- Much like ordinary neutrinos, HNLs may be produced through weak interaction decays of hadrons, leptons, and W, Z bosons.

- Example: 2- and 3-body meson decays:



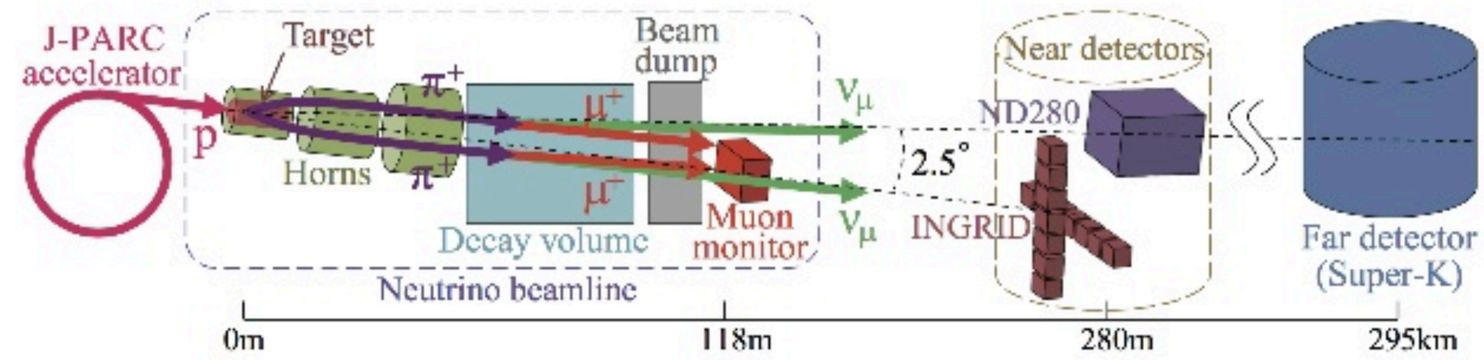


$$\mathrm{Br}(P \to \ell_i N) \simeq \tau_P \frac{G_F^2}{8\pi} f_P^2 \, m_P \, m_N^2 \, |V_{\alpha\beta}|^2 \, |U_i|^2,$$

2-body charged meson decay to *N*

- 3-body meson decays, although phase space suppressed, do not suffer from the CKM or chirality flip suppressions characteristic of the two body decays and can be important

T2K/ND280 @ JPARC



- 30 GeV proton beam on graphite target, ~ 10^{21} POT
- ND280 near detector located 280m from target (comprised of several subcomponents);

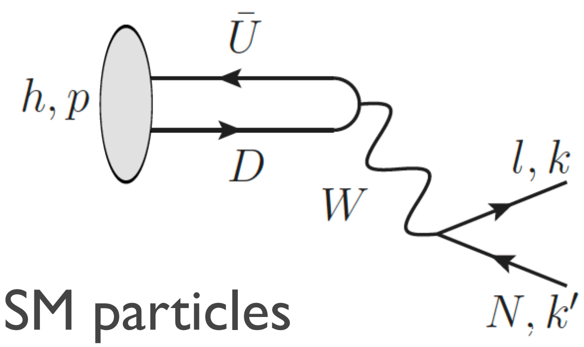
Heavy neutral lepton search at T2K/ND280

[Asaka, Eijima, Watanabe]

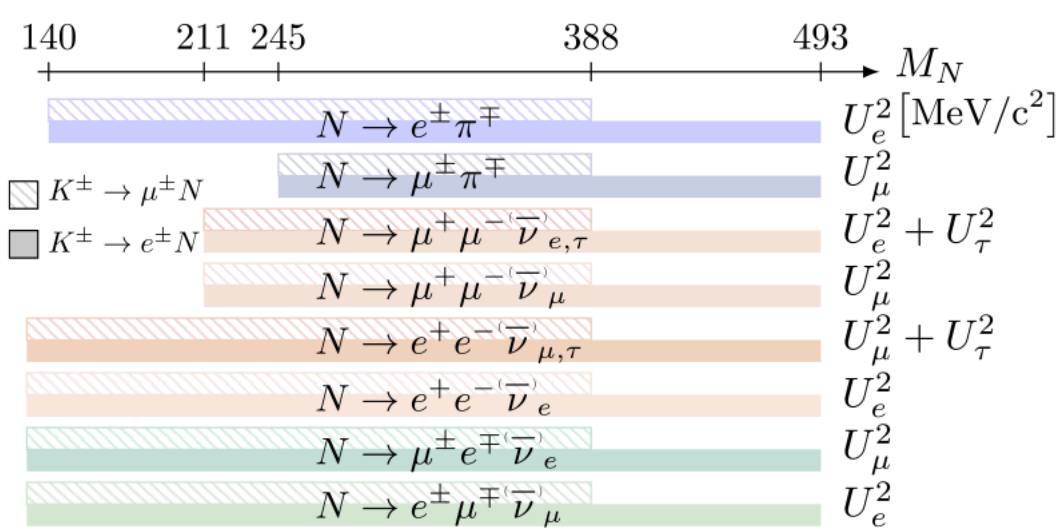
[T2K Collaboration, PRD 100, 052006 (2019)]

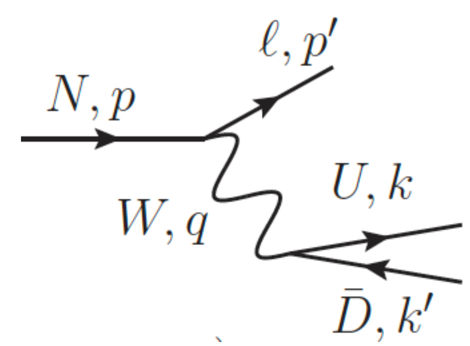
- Kaons produced in proton collisions decay to HNLs

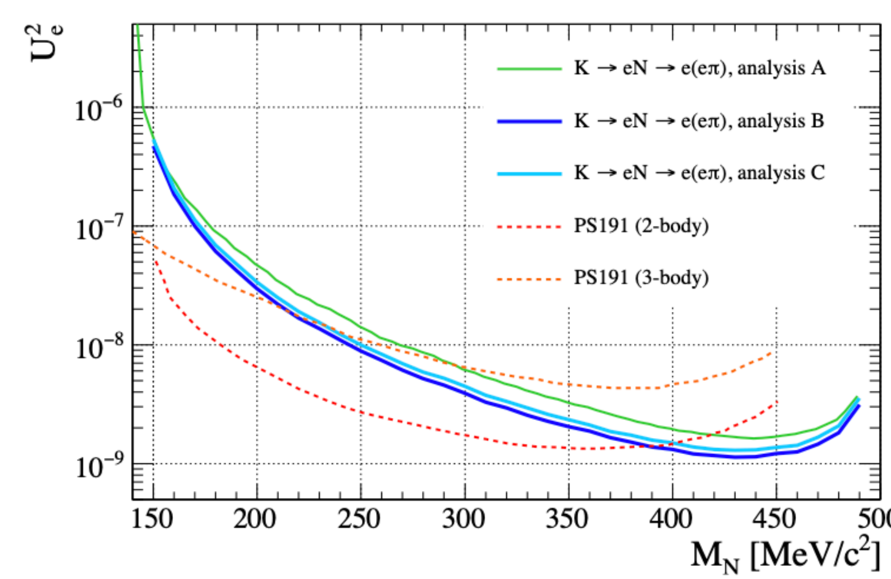
$$(K^{\pm} \to \ell_{\alpha}^{\pm} N,\ \alpha = e, \mu)$$



- Long-lived HNLs then decay to visible SM particles



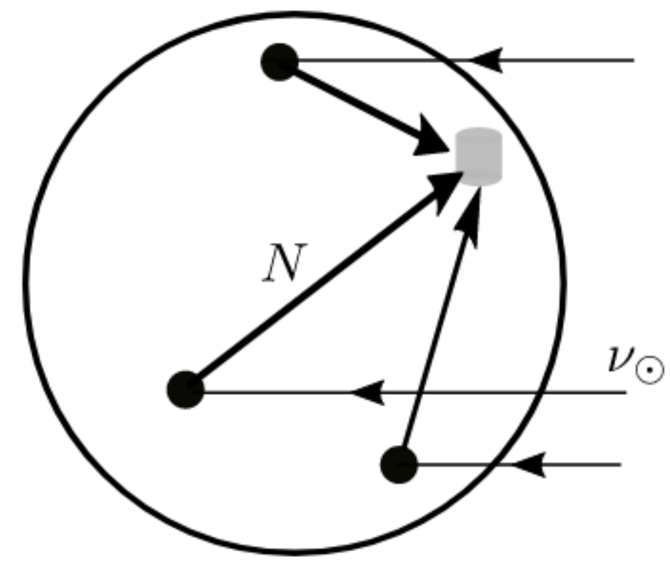


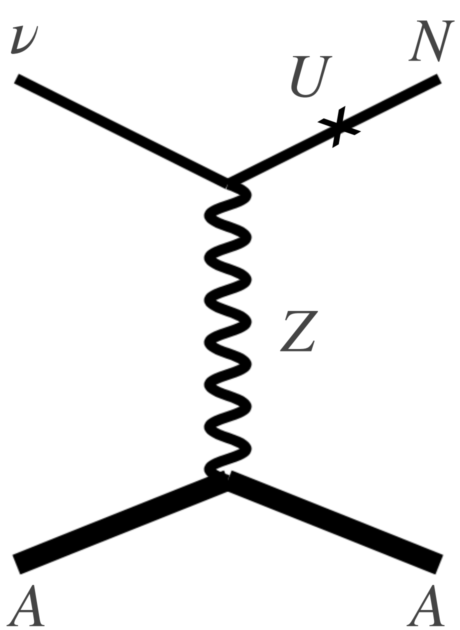


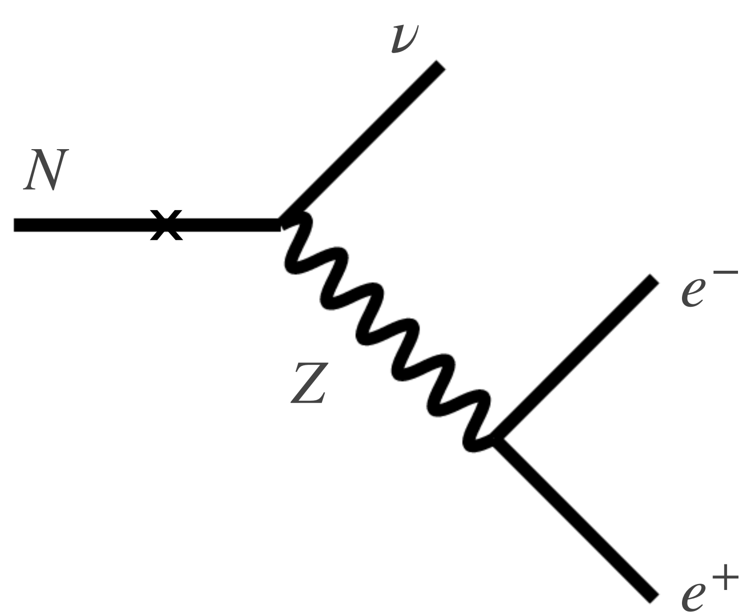
Solar-ν up-scattering @ Borexino

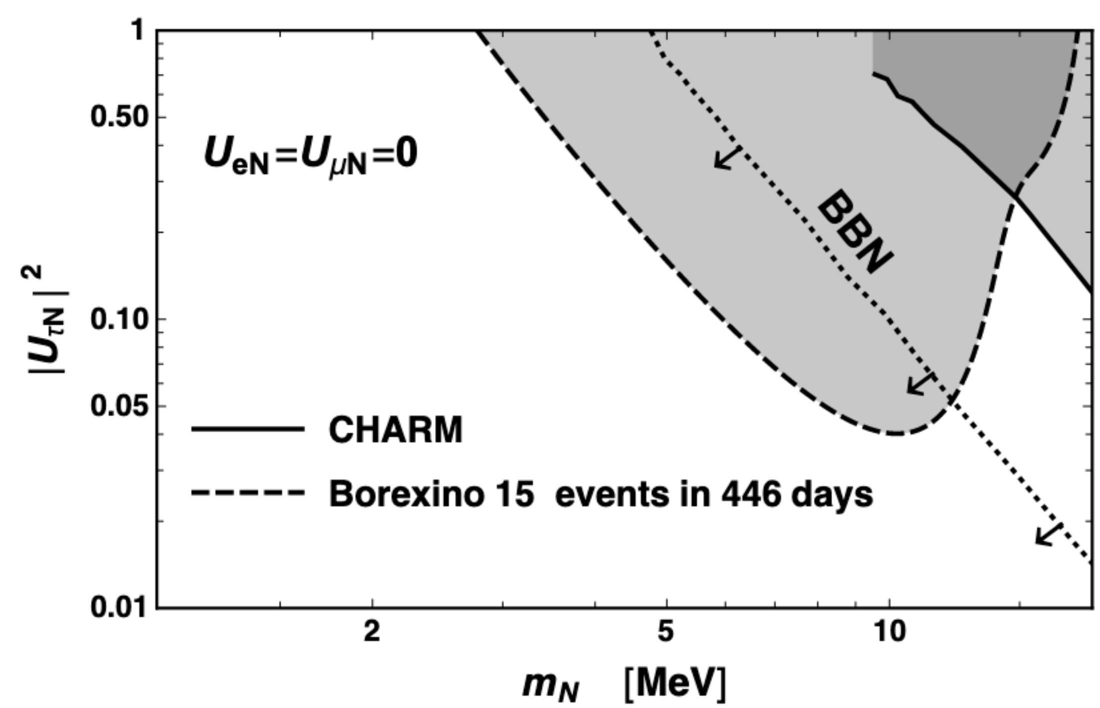
[Plestid]

- In the sun, electron neutrinos with energies 0.1 - 10 MeV are produced through various nuclear reactions
- Due to neutrino oscillations, a substantial flux of all neutrino flavors arrives at Earth
- Neutrinos may up-scatter in Earth to MeV-scale HNLs, which then decay in large volume neutrino detectors





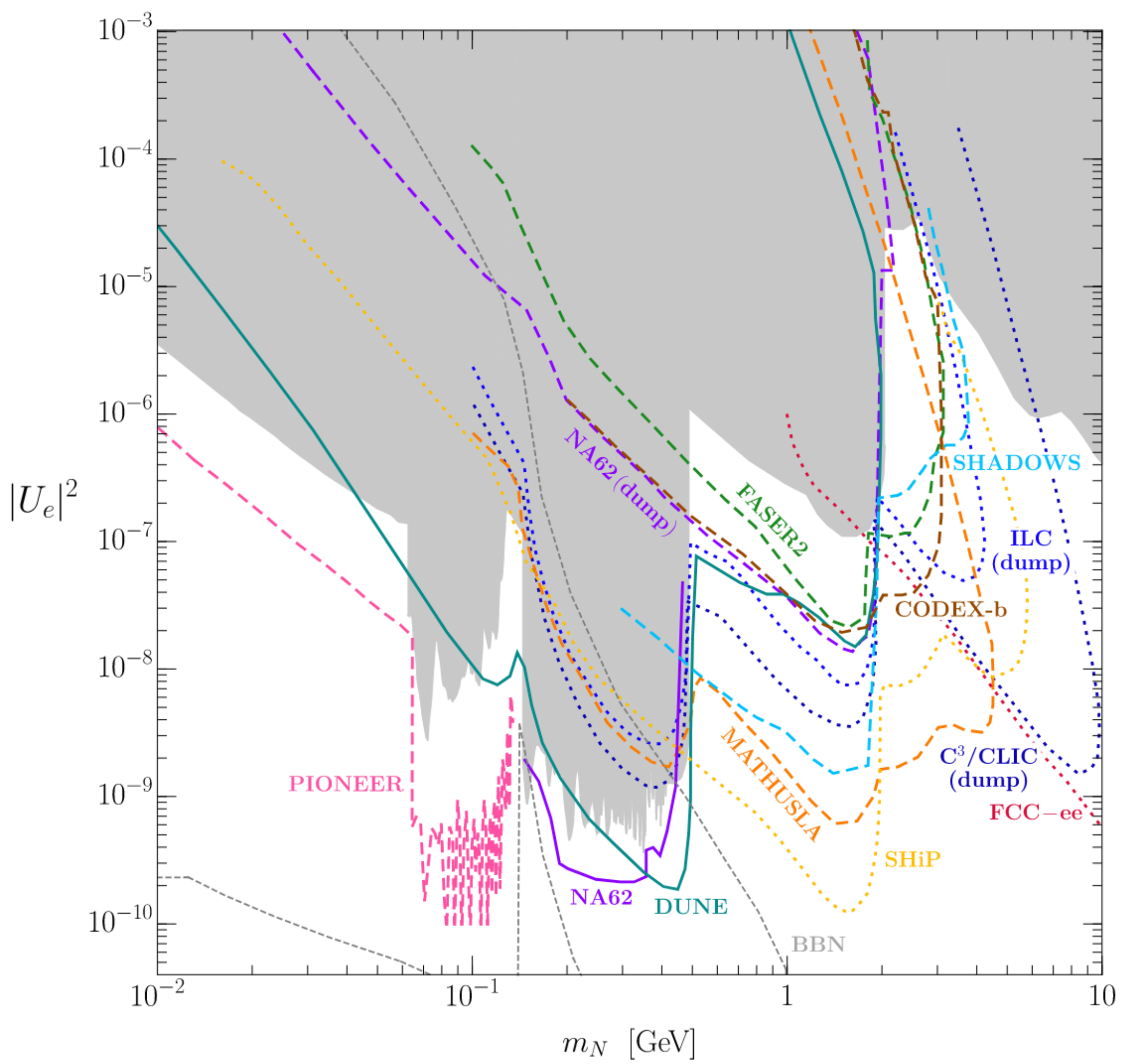




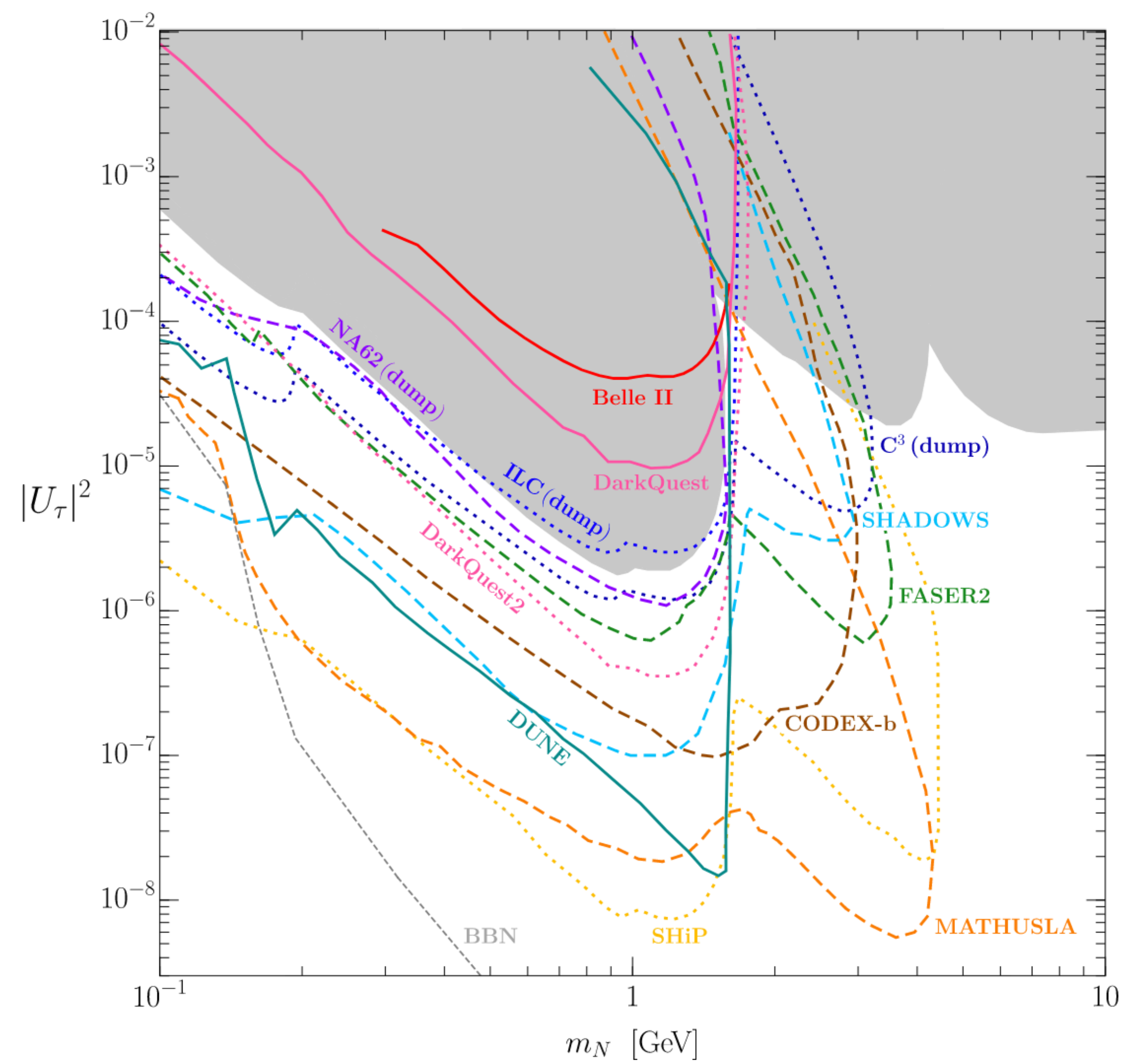
Heavy neutral lepton / neutrino portal outlook

- Promising opportunities for DUNE, PIONEER, DarkQuest, FASER2, CODEX-b, MATHUSLA, SHADOWS, and others to extend the reach to smaller mixing angles

electron-flavor dominance



tau-flavor dominance



Beyond the minimal portals

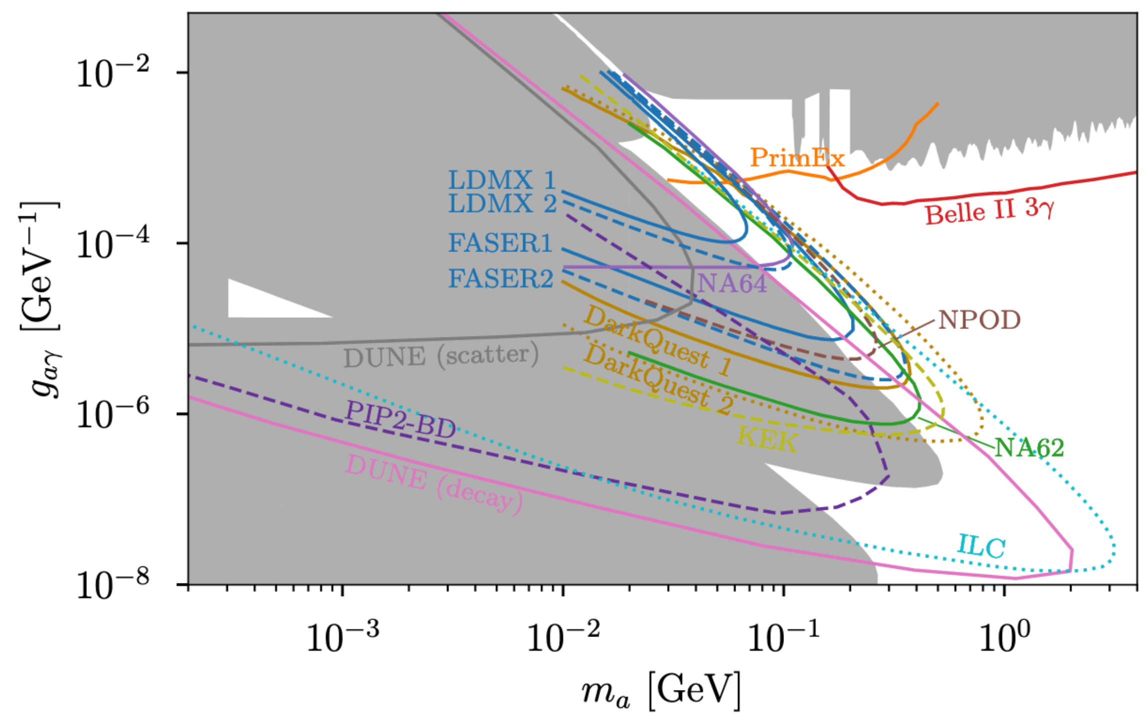
(a few highlights…)

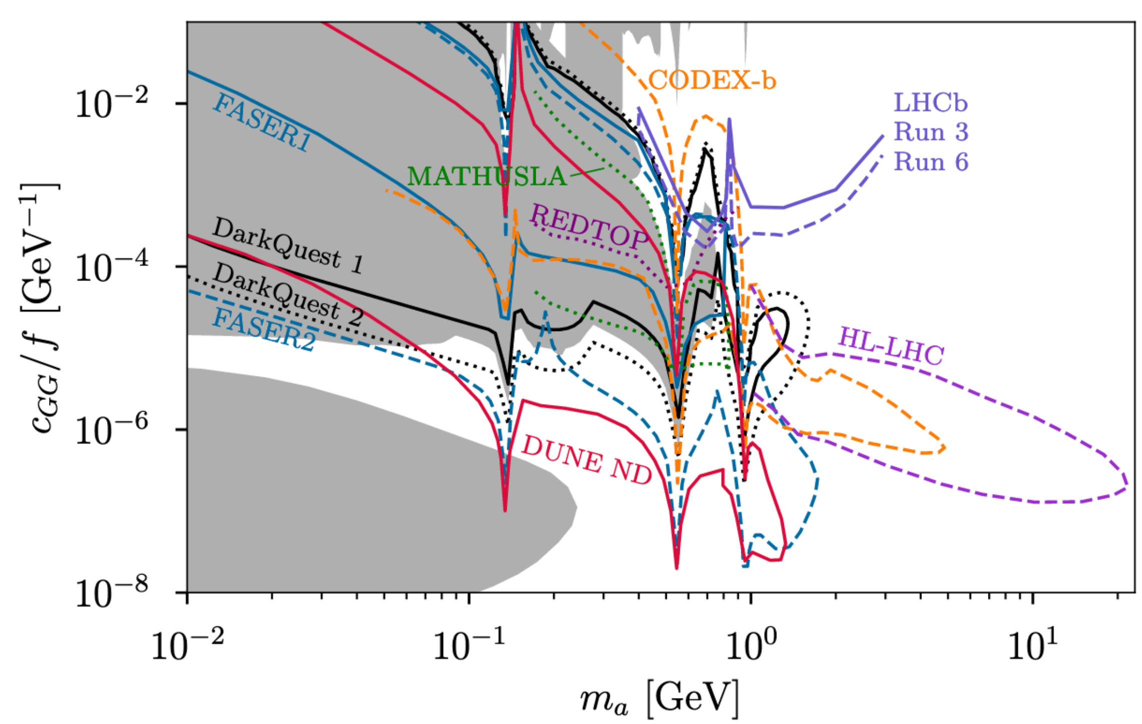
Axion portal

- Axion-like-particles (ALPs) are parity-odd pseudo-Nambu-Goldstone bosons
- ALPs arise from spontaneously broken global symmetries or from compactifications of extra dimensional gauge fields
- The QCD axion provides a particular realization which addresses the strong CP problem
- ALPs may couple to the SM through various higher dimensional operators — axion portals — e.g.,

$$\mathcal{L} \supset c_{\gamma\gamma}\frac{\alpha}{4\pi}\frac{a}{f}F_{\mu\nu}\widetilde{F}^{\mu\nu} + c_{GG}\frac{\alpha_s}{4\pi}\frac{a}{f}G^a_{\mu\nu}\widetilde{G}^{a,\,\mu\nu}$$

- A variety of experiments, including ATLAS, CMS, DUNE, Belle-II, FASER(2), DarkQuest, and others will explore new ALP parameter space in years ahead





[arXiv:2207.06905, Figs. from N. Blinov]

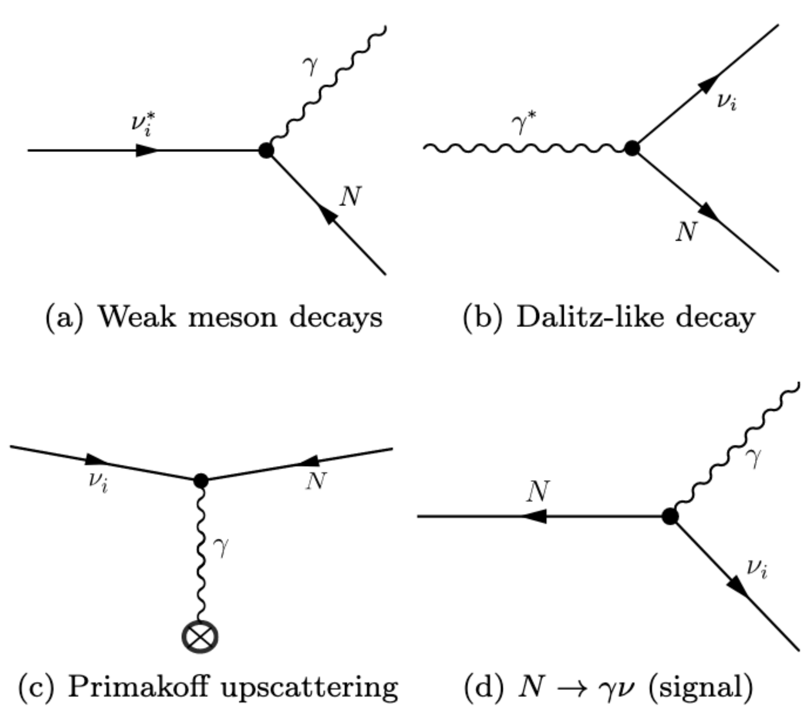
Neutrino dipole portal

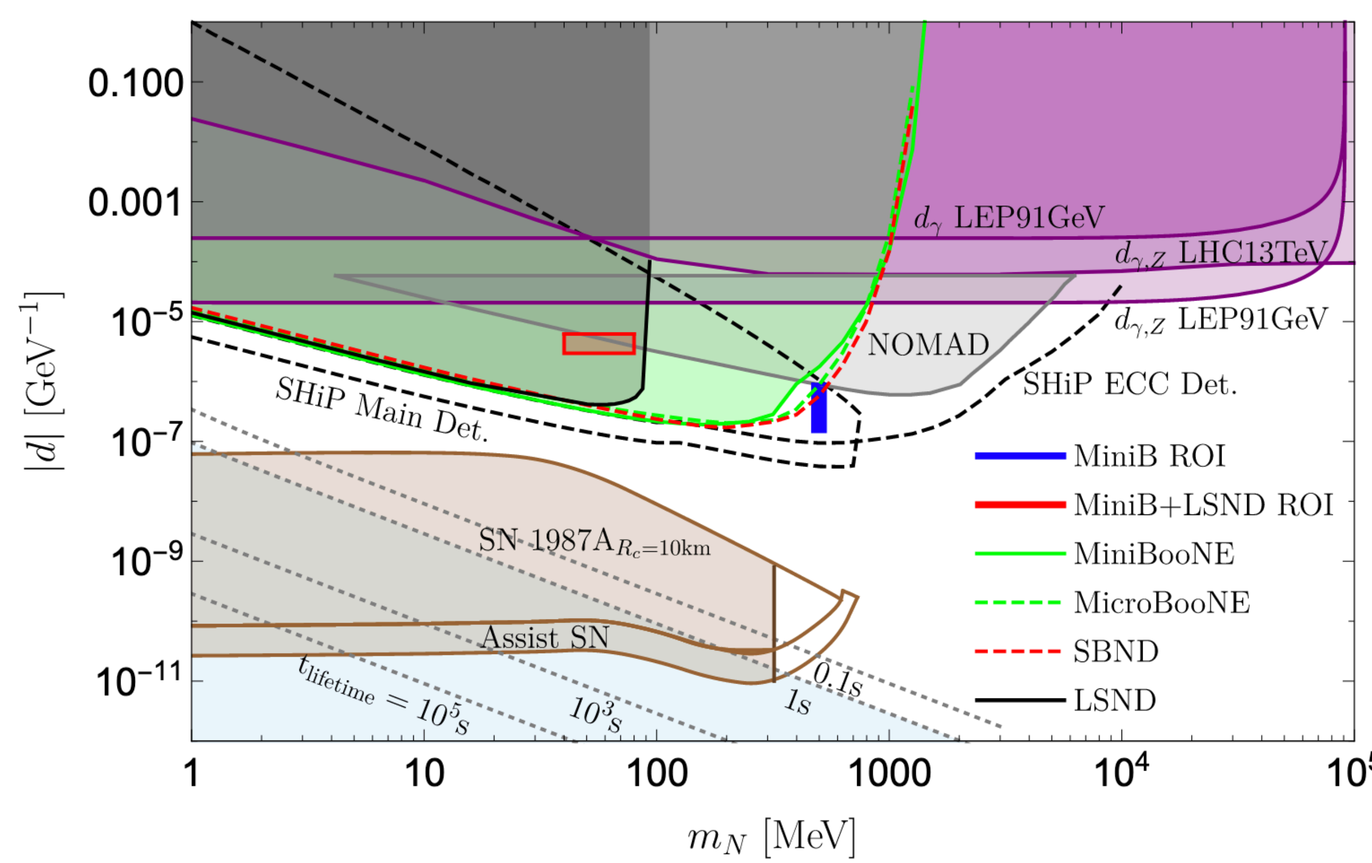
[Magill, Plestid, Pospelov, Tsai]

- Heavy neutral leptons may have other couplings beyond the weak interactions
- One interesting example comes in the form of generic dipole interactions between neutrinos, HNLs and photons, e.g.,

$$\mathcal{L} \supset \bar{N}(i\partial\!\!\!/ - m_N)N + (d\bar{\nu}_L \sigma_{\mu\nu} F^{\mu\nu} N + h.c).$$

- This leads to new HNL production mechanisms and decays



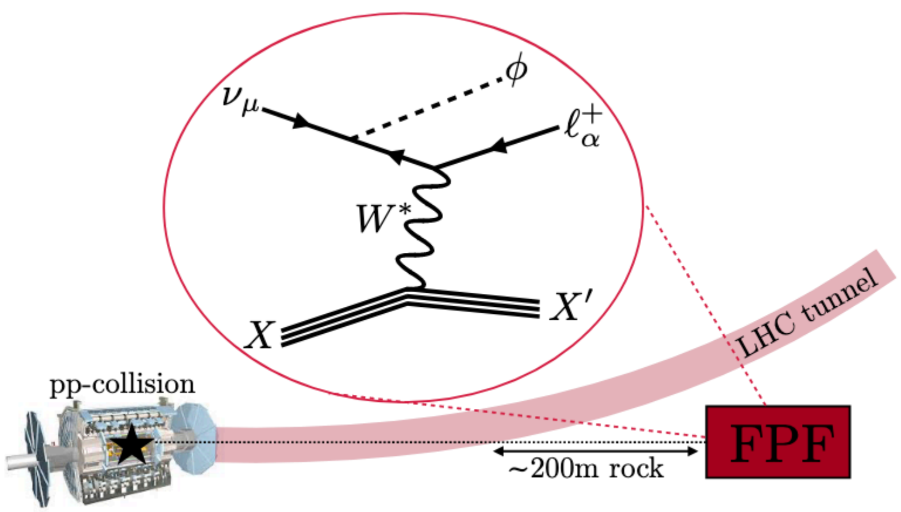


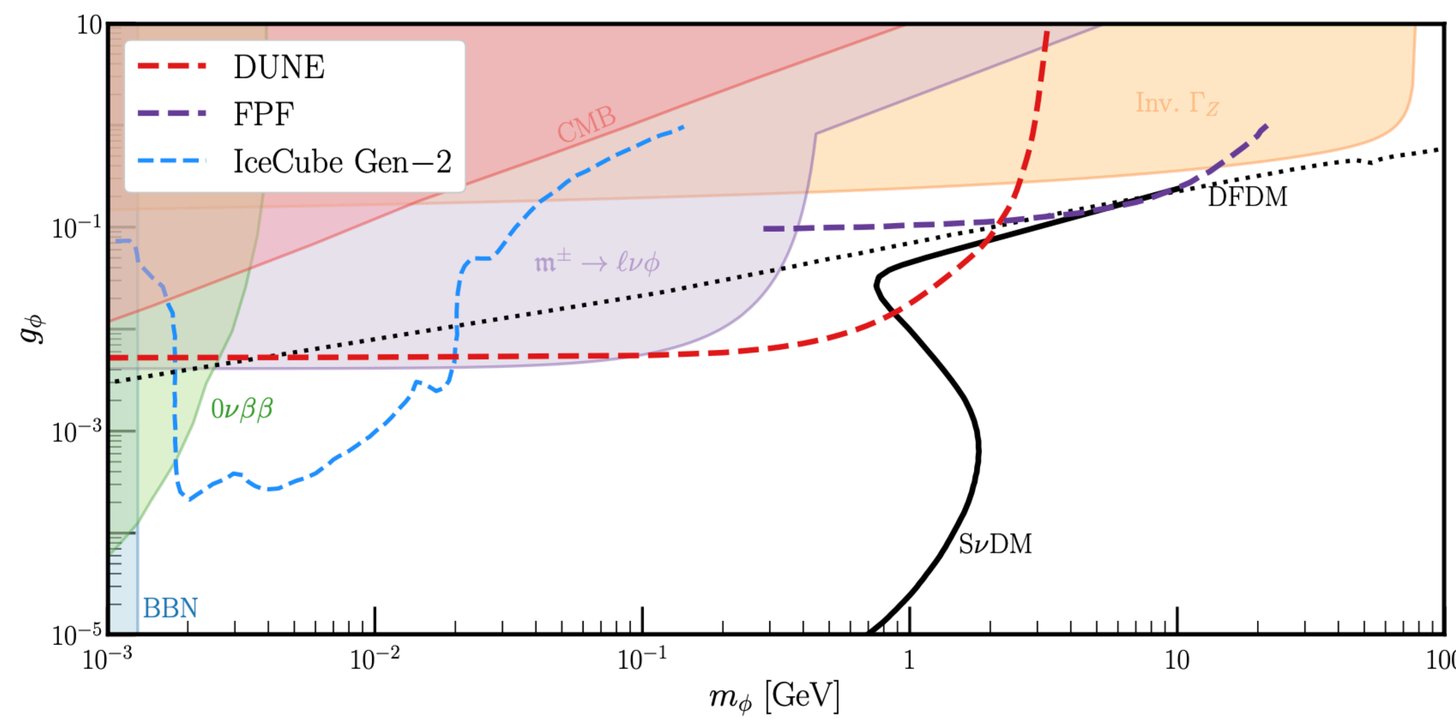
Neutrinophilic mediators

- Dark mediators may preferentially couple to neutrinos and are thus a prime target for neutrino experiments
- Consider a neutrinophilic scalar mediator: $$\mathscr{L} \supset \frac{(L_\alpha H)(L_\beta H)\,\phi}{\Lambda^2_{\alpha\beta}} \to g_\phi^{\alpha\beta}\,\nu_\alpha \nu_\beta \phi$$
- This leads to a mono-neutrino signature at DUNE and neutrino detectors in the far forward region of the LHC

[Kelly, Zhang]

[Kelly, Kling, Tuckler, Zhang]





[arXiv:2207.06898, Fig. From K. Kelly]

- Scattering of high energy astrophysical neutrinos with the CνB impacts observed energy spectrum at IceCube

[Esteban, Pandey, Brdar, Beacom]

Lecture 1 Summary

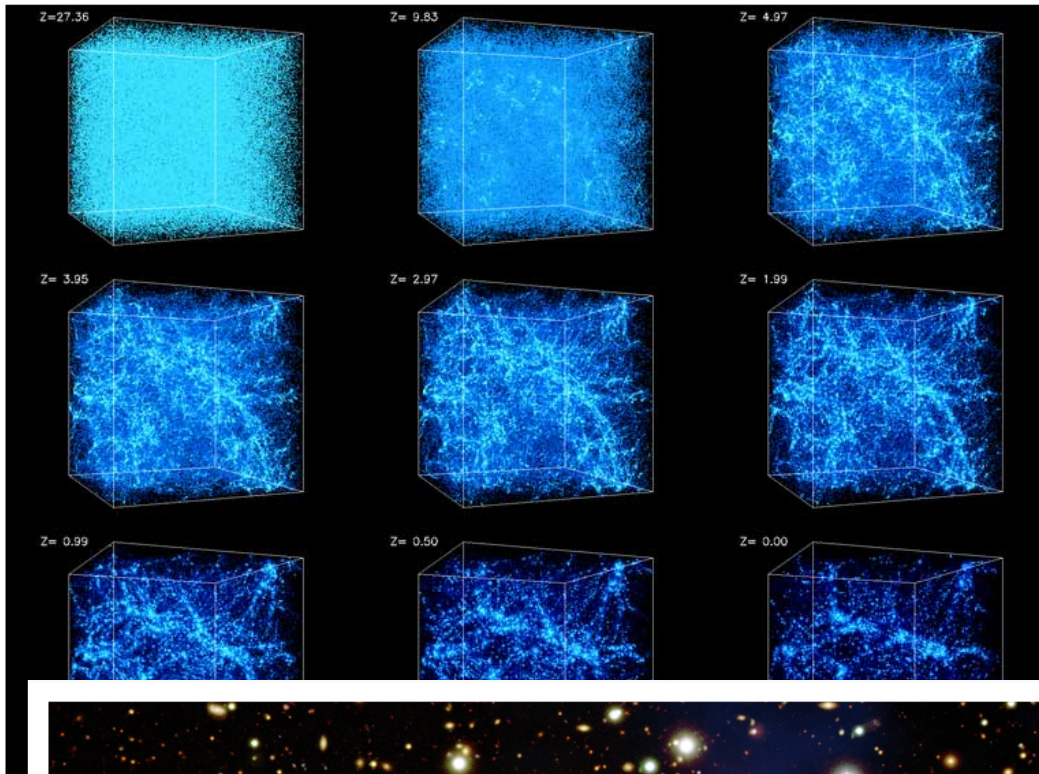
- Nature could be harboring a dark sector — a new set of particles that do not experience the familiar forces of the SM
- The dark sector could be light and communicate with the visible sector through a feeble portal interaction
- This leads to a variety of novel testable phenomena at current and future neutrino experiments
- In this lecture we surveyed the theory and phenomenology of the minimal portal models
- Next, we will explore some some applications of dark sectors tomorrow…

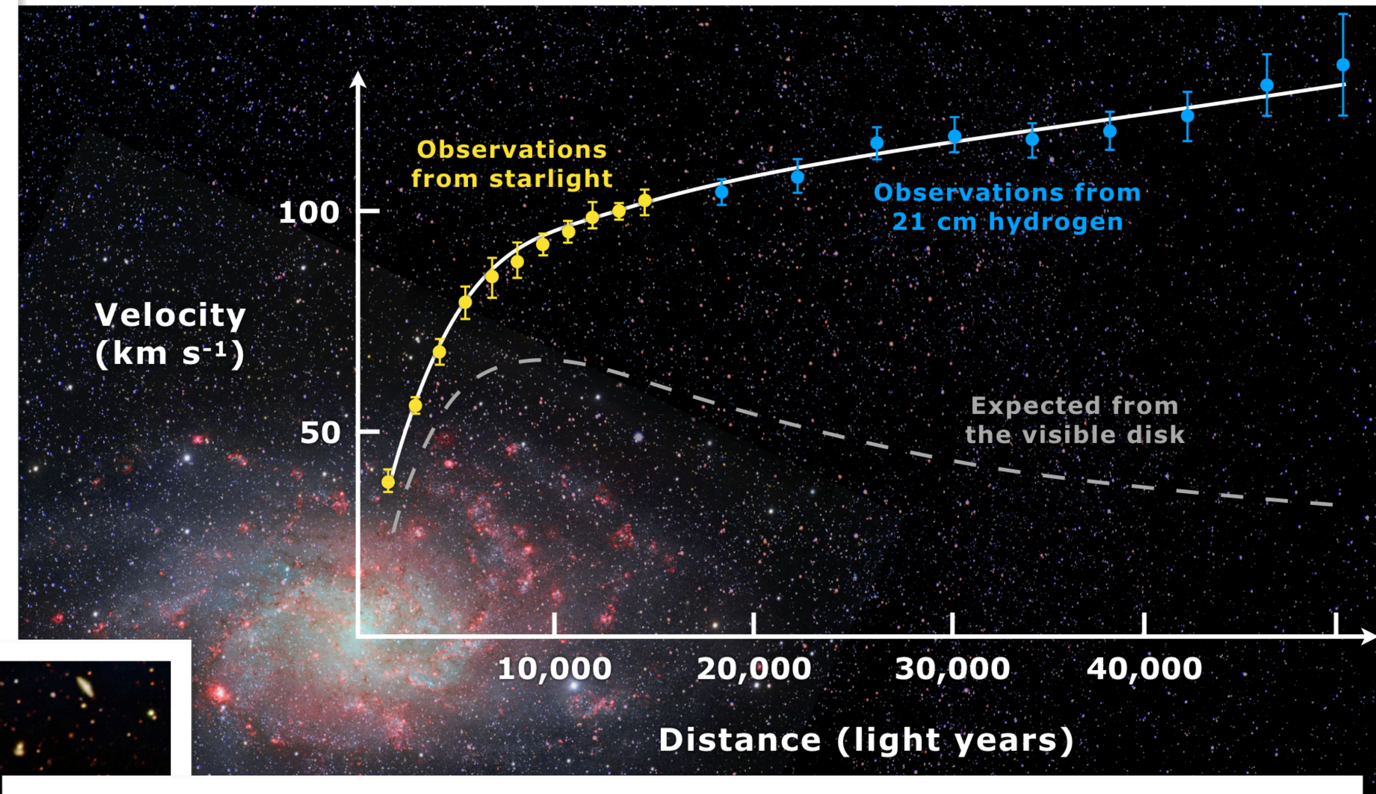
- **Lecture 1:**
  - **Dark sectors motivation and overview**
  - **Minimal portals: theory and phenomenology**

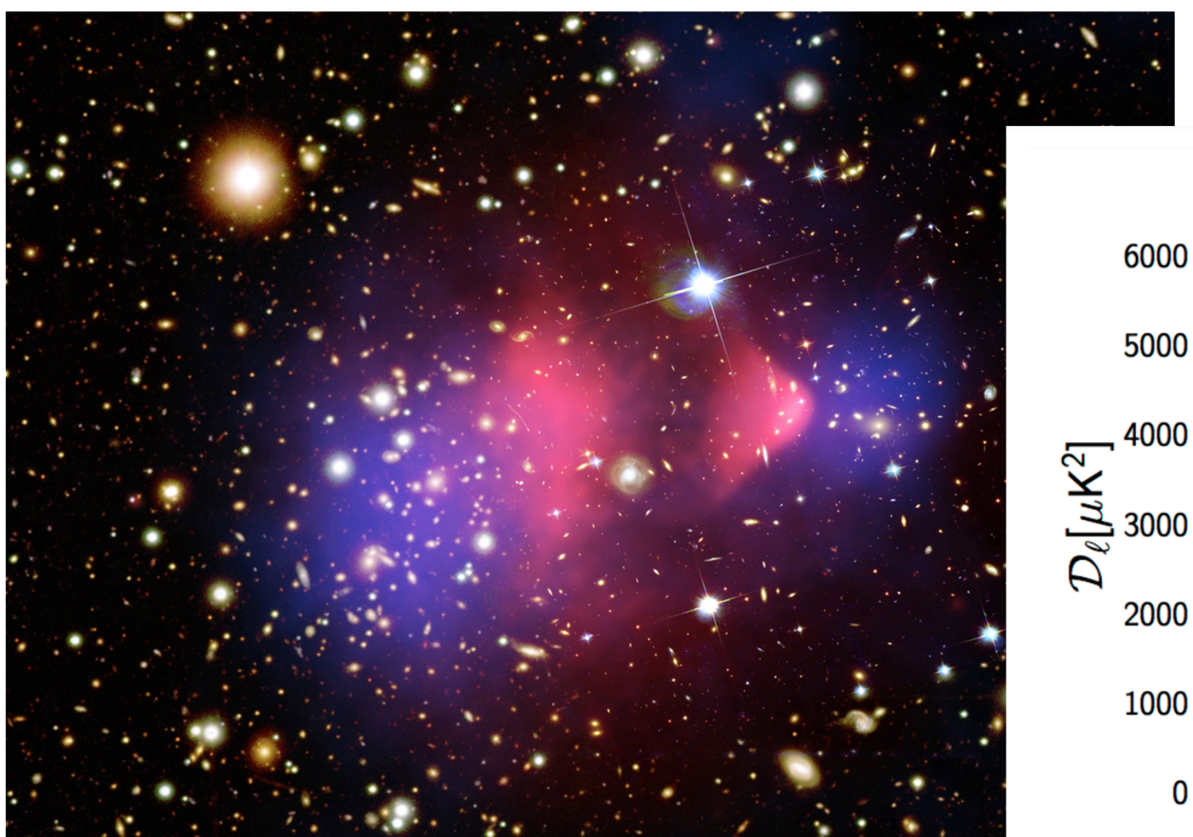
- **Lecture 2:**
  - **Light thermal dark matter**
  - **Muon anomalous magnetic moment**
  - **Hierarchy problem**

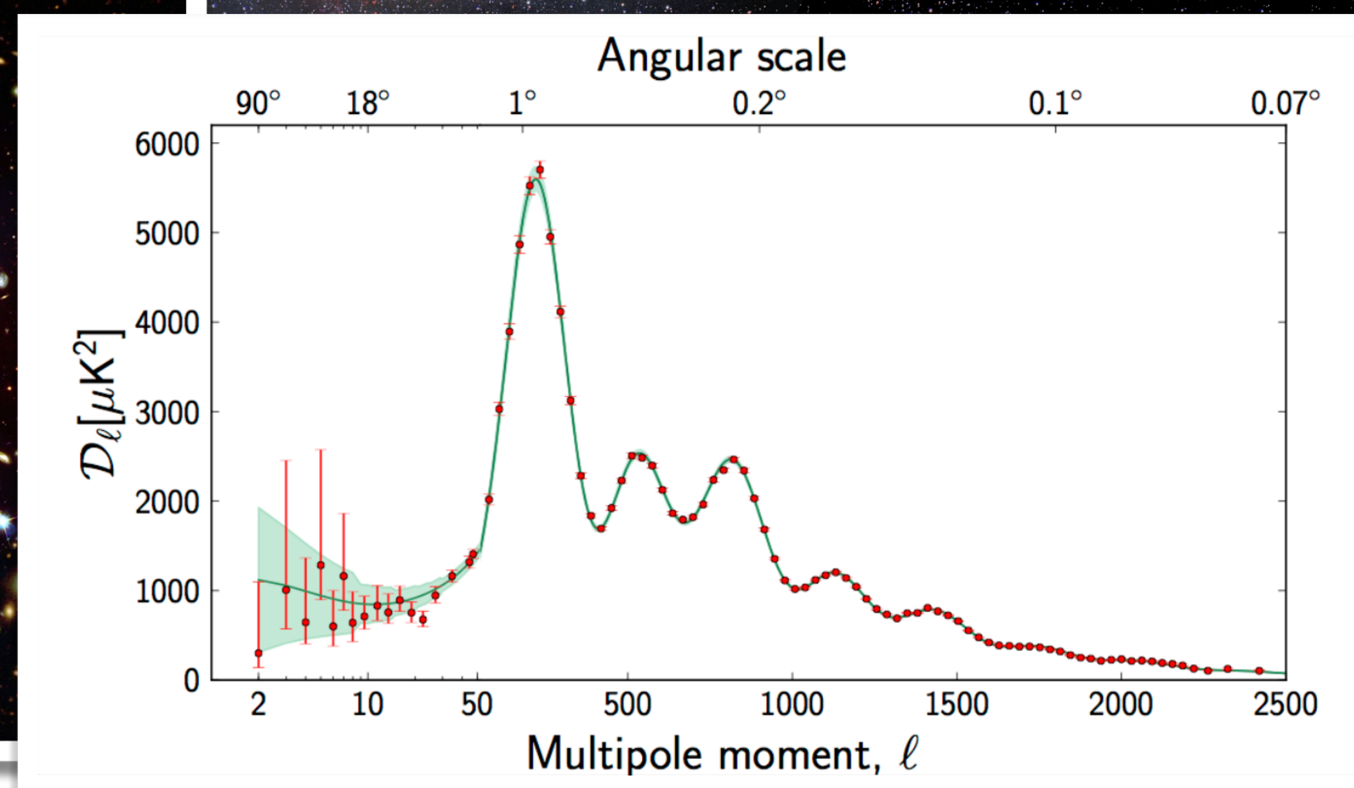
Light thermal dark matter

Dark Matter


Z=27.36
Z= 9.83
Z= 4.97
Z= 3.95
Z= 2.97
Z= 1.99
Z= 0.99
Z= 0.50
Z= 0.00


Observations from starlight
Observations from 21 cm hydrogen
Velocity (km s⁻¹)
100
50
Expected from the visible disk
10,000
20,000
30,000
40,000
Distance (light years)



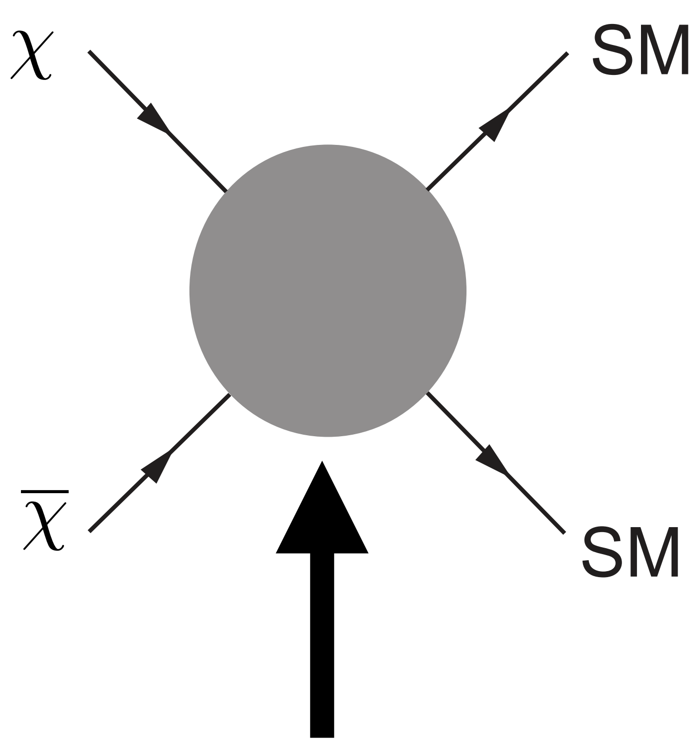

Angular scale
90°
18°
1°
0.2°
0.1°
0.07°
$\mathcal{D}_\ell [\mu K^2]$
6000
5000
4000
3000
2000
1000
0
2
10
50
500
1000
1500
2000
2500
Multipole moment, ℓ

Microscopic properties of dark matter?

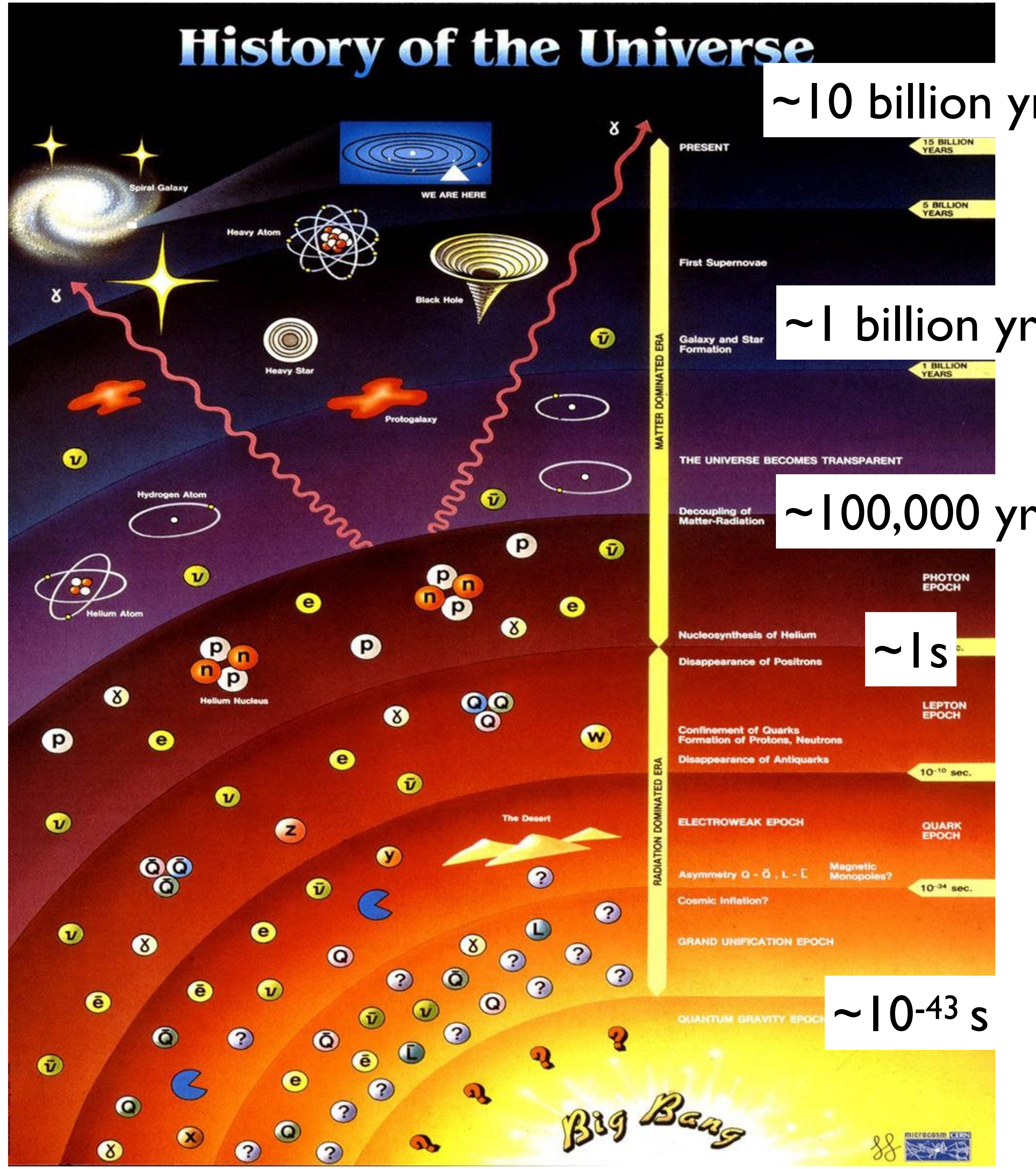
- Is it a particle?
- Mass (scale)?
- Multi-component? Dark sector?
- Stable?
- Non-gravitational interactions with the SM?

Cosmological genesis of dark matter

DM may have been thermally produced from the hot plasma during the Big Bang



Requires non-gravitational interactions with normal matter

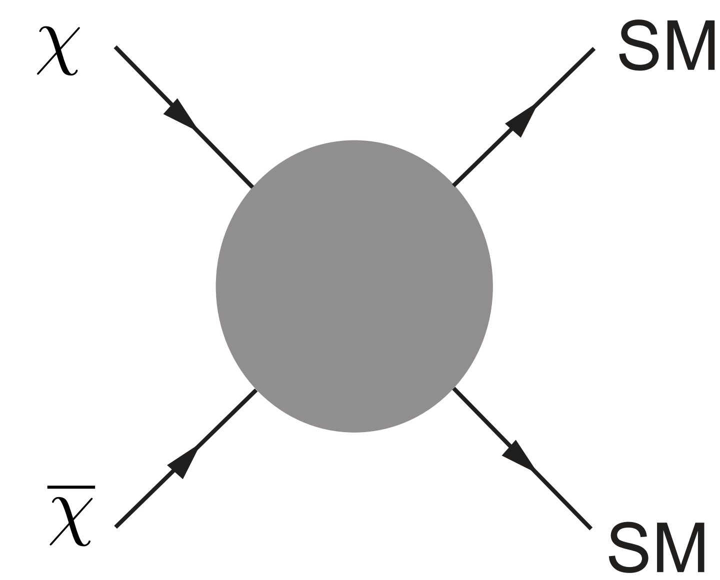


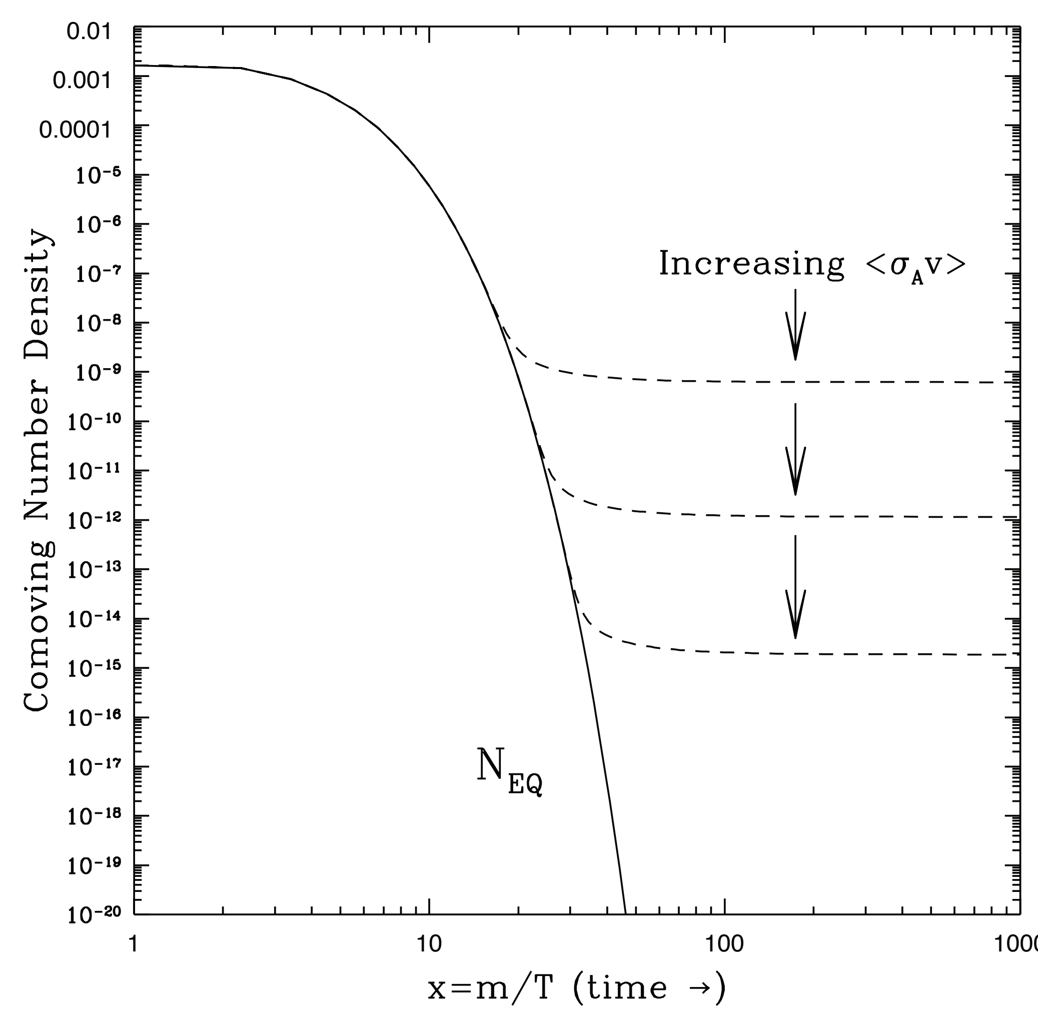
Dark matter production via thermal freezeout

- At early times, $T \gg m_\chi$, both DM production and annihilation are efficient
- As temperature drops, $T \lesssim m_\chi$, DM production is kinematically disfavored, and DM begins to annihilate away
- Eventually, DM will freeze-out, once annihilation rate becomes smaller than the Hubble rate
- Relic abundance of DM controlled by the annihilation cross section
- Comparing to the measured value from CMB, $\Omega_{\rm DM} \sim 0.26$, find the correct abundance is obtained if

$$\langle \sigma v \rangle \sim 1\,\mathrm{pb} \sim 3 \times 10^{-26}\,\mathrm{cm}^3\,\mathrm{s}^{-1}$$

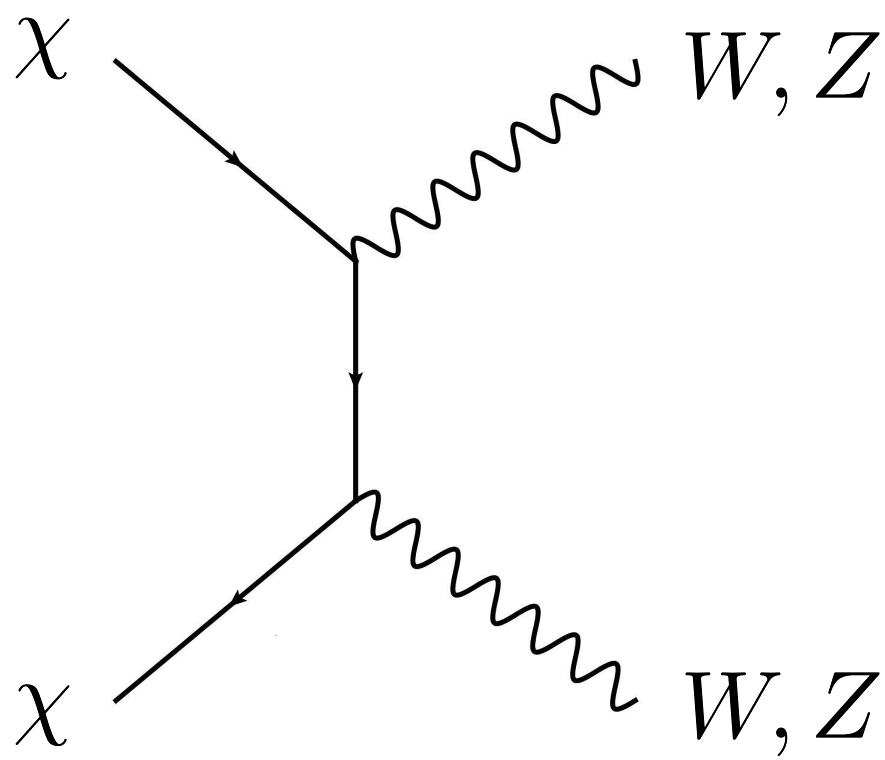
— See backup slides for more details





WIMP Miracle

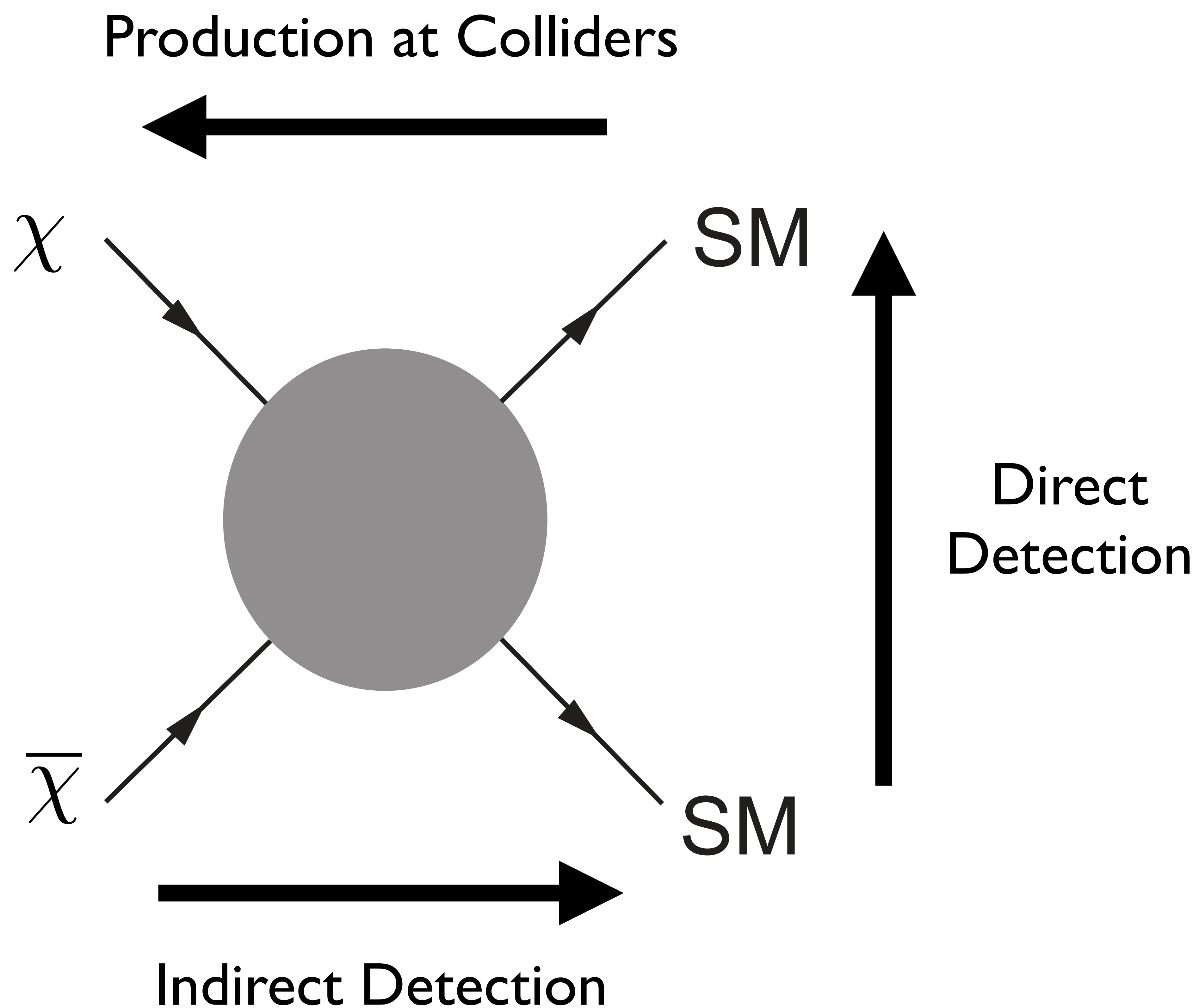
- Consider Dark Matter that is part of an electroweak multiplet that dominantly annihilates to weak gauge bosons (e.g. Higgsino or Wino in SUSY)



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

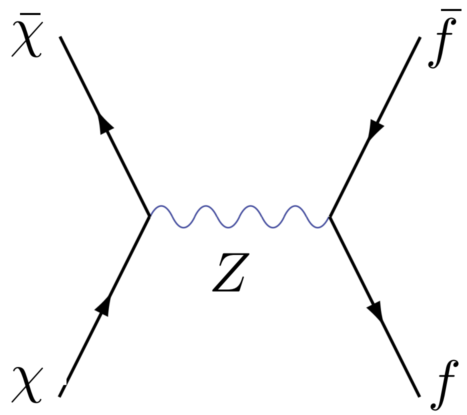
- Especially compelling in tandem with motivation for new physics at the TeV scale from the hierarchy problem

WIMP phenomenology



Light dark matter — Lee-Weinberg bound

Light thermal DM interacting via weak interactions generically overproduced



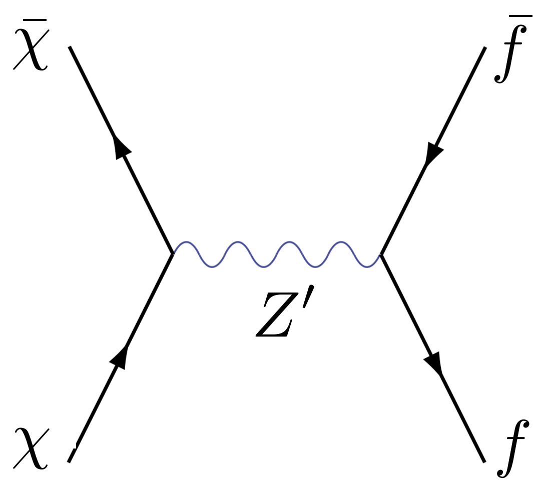
$$\mathcal{L} \sim G_F [\bar{\chi}\,\Gamma\,\chi][\bar{f}\,\Gamma\,f]$$

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

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

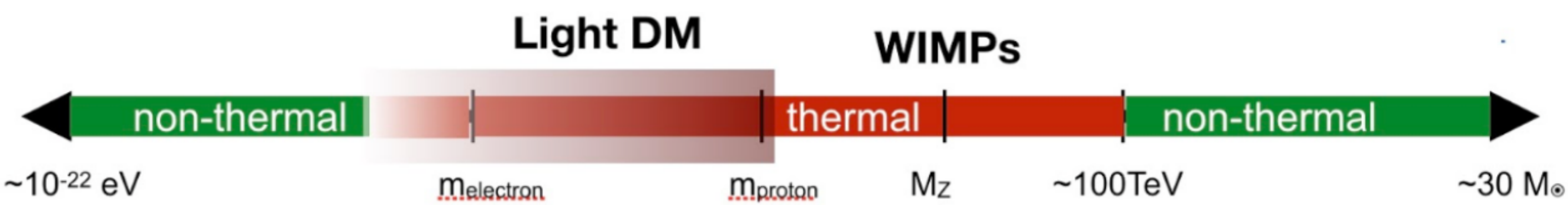
Lee-Weinberg bound evaded with new light mediators

[Boehm, Fayet]
[Pospelov, Ritz, Voloshin]
[Feng, Kumar]



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

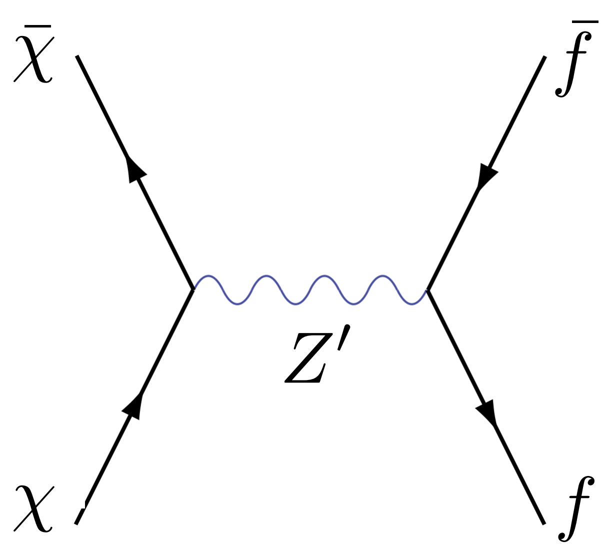
$$\langle \sigma v \rangle \sim \frac{g_\chi^2\, g_f^2\, m_\chi^2}{m_{Z'}^4} \sim 1\,\mathrm{pb} \times \left(\frac{g_\chi}{0.5}\right)^2 \left(\frac{g_f}{0.001}\right)^2 \left(\frac{m_\chi}{100\,\mathrm{MeV}}\right)^2 \left(\frac{1\,\mathrm{GeV}}{m_{Z'}}\right)^4$$



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: $m_\chi < m_{Z'}$

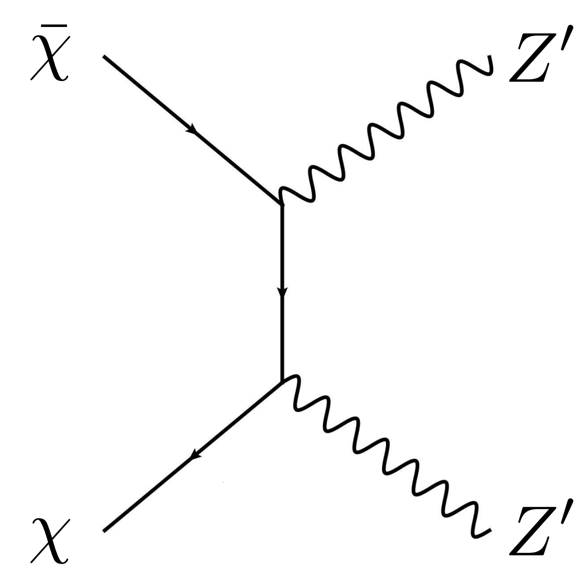


$$\langle \sigma v \rangle \sim \frac{g_\chi^2 \, g_f^2 \, m_\chi^2}{m_{Z'}^4}$$

Requires sizable portal coupling to deplete DM abundance

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

[Pospelov, Ritz, Voloshin]



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

Requires only minuscule portal coupling to maintain kinetic equilibrium

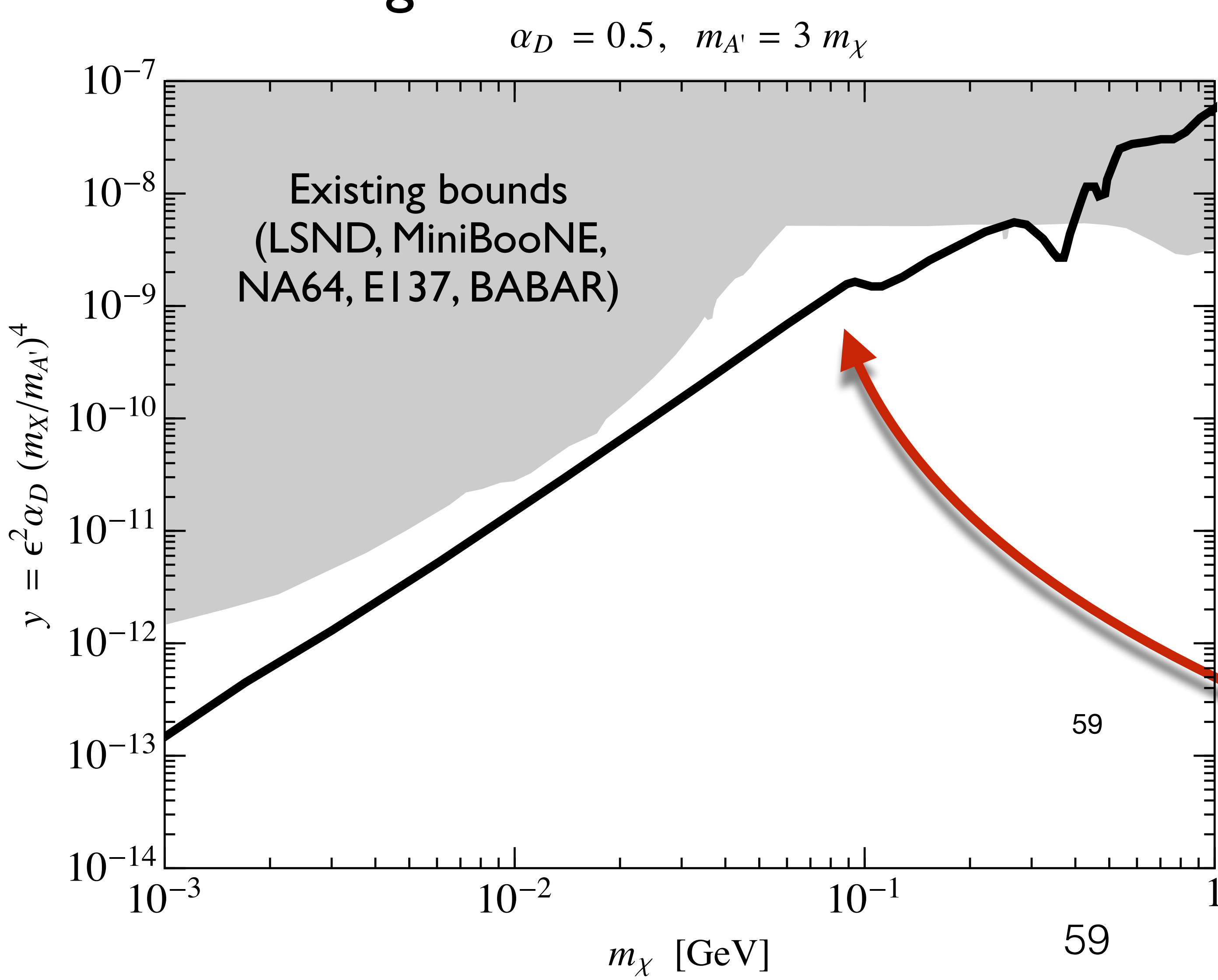
- $m_{Z'} > 2m_\chi$: search for invisible mediator decays and dark matter
- $m_{Z'} < 2m_\chi$: search for visible mediator decays (see Lecture 1)

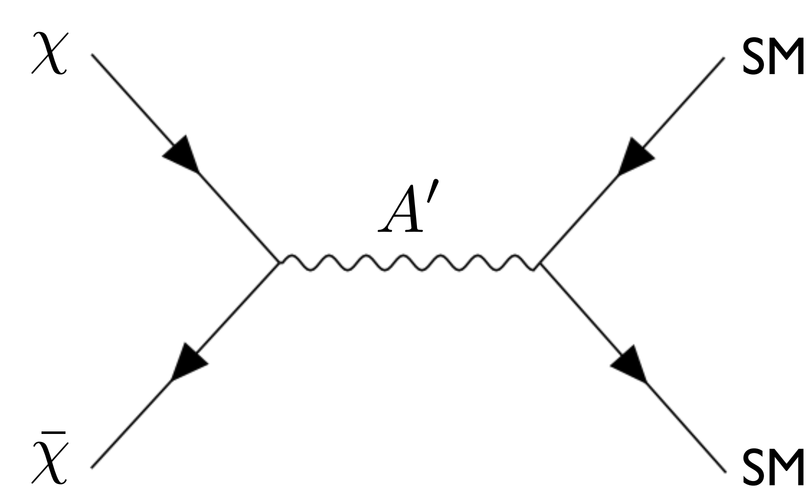
Benchmark model: vector portal dark matter

[Holdom]
[Pospelov, Ritz, Voloshin]
[Hooper, Zurek]
[Arkani-Hamed, et al]
…

$$\mathcal{L} \supset |D_\mu \chi|^2 - m_\chi^2 |\chi|^2 - \frac{1}{4}(F'_{\mu\nu})^2 + \frac{1}{2} m_{A'}^2 (A'_\mu)^2 - \frac{\epsilon}{2} F'_{\mu\nu} F^{\mu\nu} + \ldots$$

- Dark photon mediates interaction between DM and SM
- 4 new parameters: $m_\chi, m_{A'}, \alpha_D, \epsilon$
- Thermal target:





$$\langle \sigma v \rangle \sim \frac{\epsilon^2 \alpha_D \alpha m_\chi^2}{m_V^4} \sim \frac{y}{m_\chi^2}$$

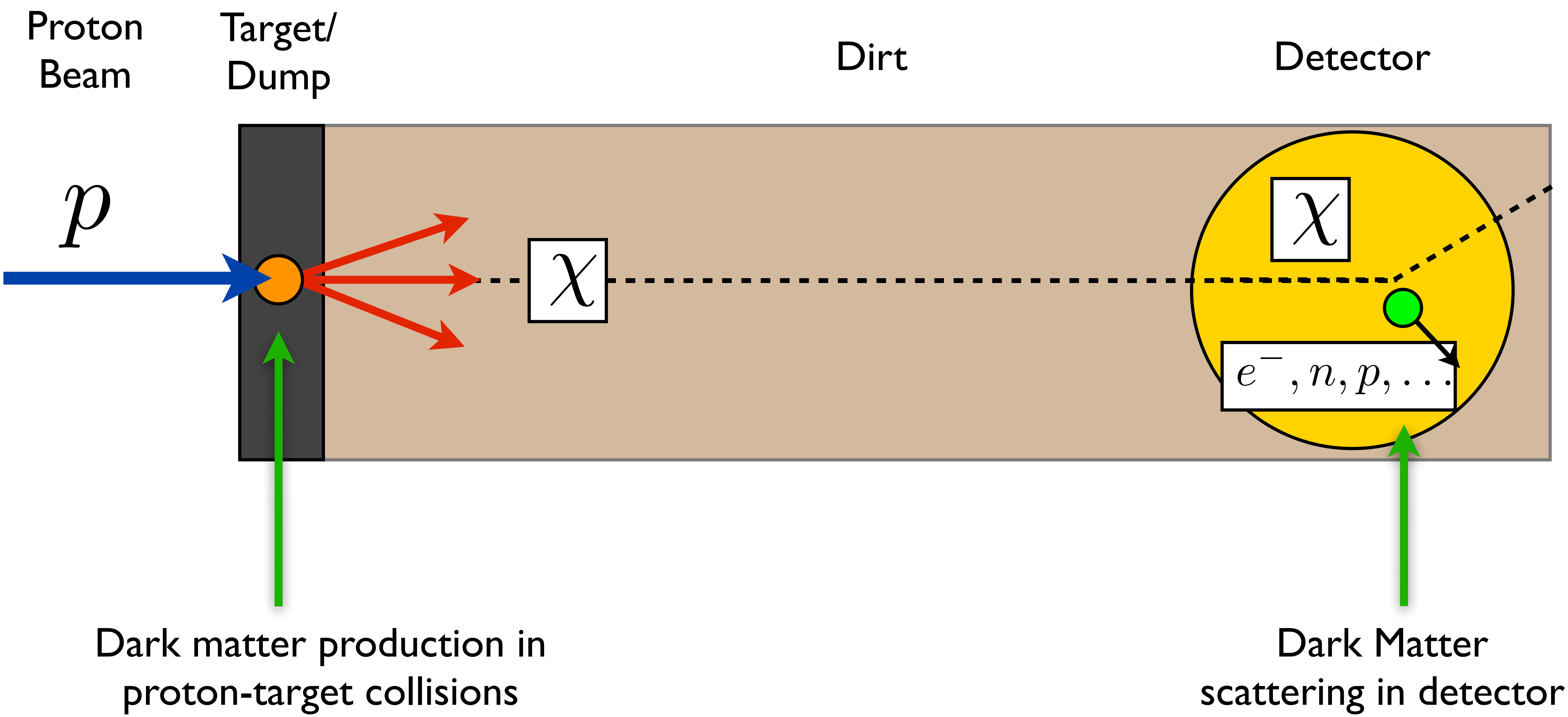
$$y \equiv \epsilon^2 \alpha_D (m_\chi / m_{A'})^4$$

Observed DM relic abundance predicted along this line

[Izaguirre, Krnjaic, Schuster, Toro]

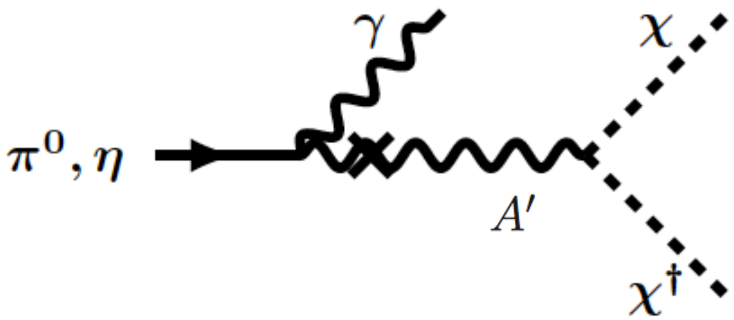
Proton beam dump dark matter searches

[BB, Pospelov Ritz]

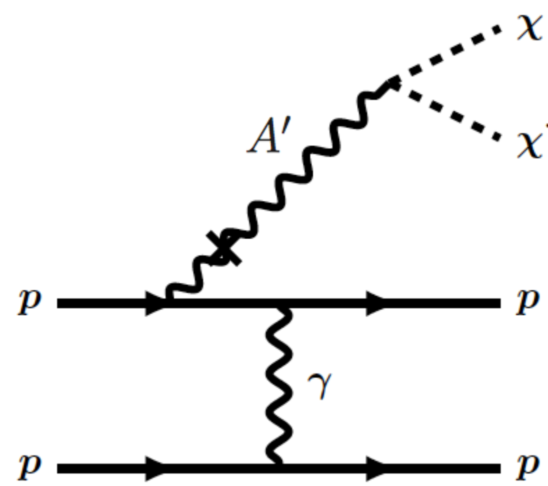


- DM searches can be done with existing and near future accelerator neutrino experiments, e.g., MicroBooNE, SBND, ICARUS, NOvA, T2K, COHERENT, CCM, DUNE…

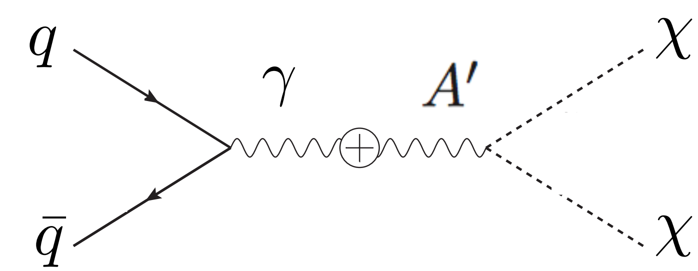
Dark matter production mechanisms:



Neutral mesons decays

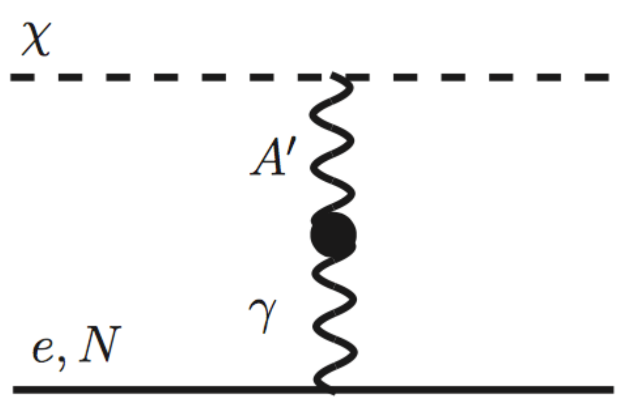


Bremsstrahlung + vector meson mixing

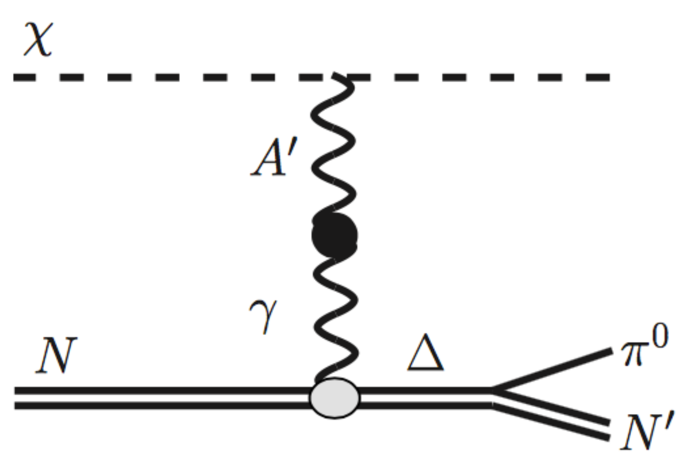


Direct production

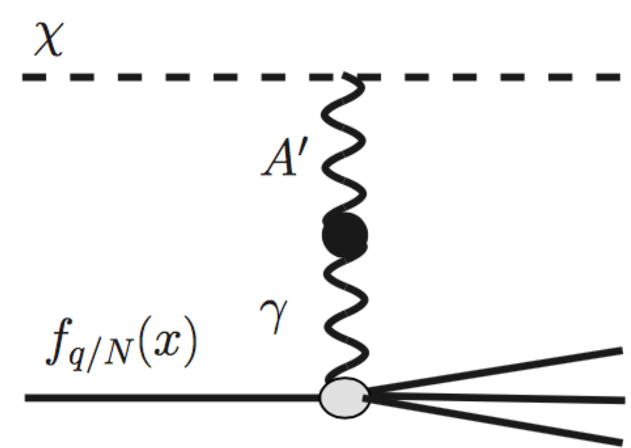
Dark matter detection via scattering:



Elastic electron, nucleon , nucleus (coherent) scattering

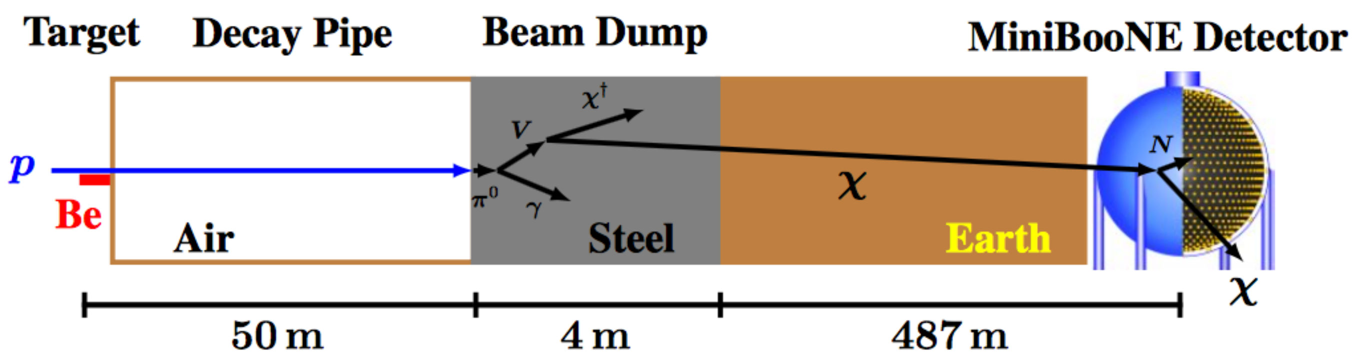


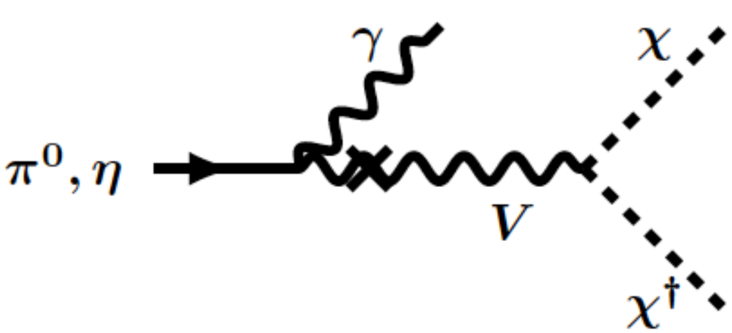
Inelastic neutral pion production



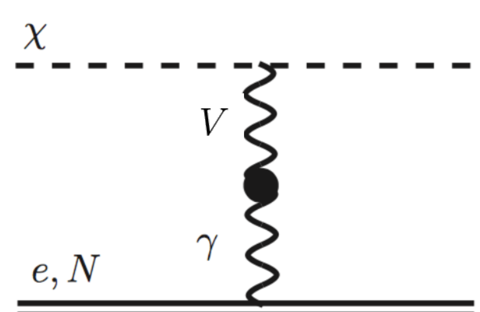
Deep inelastic scattering

MiniBooNE-DM @ FNAL

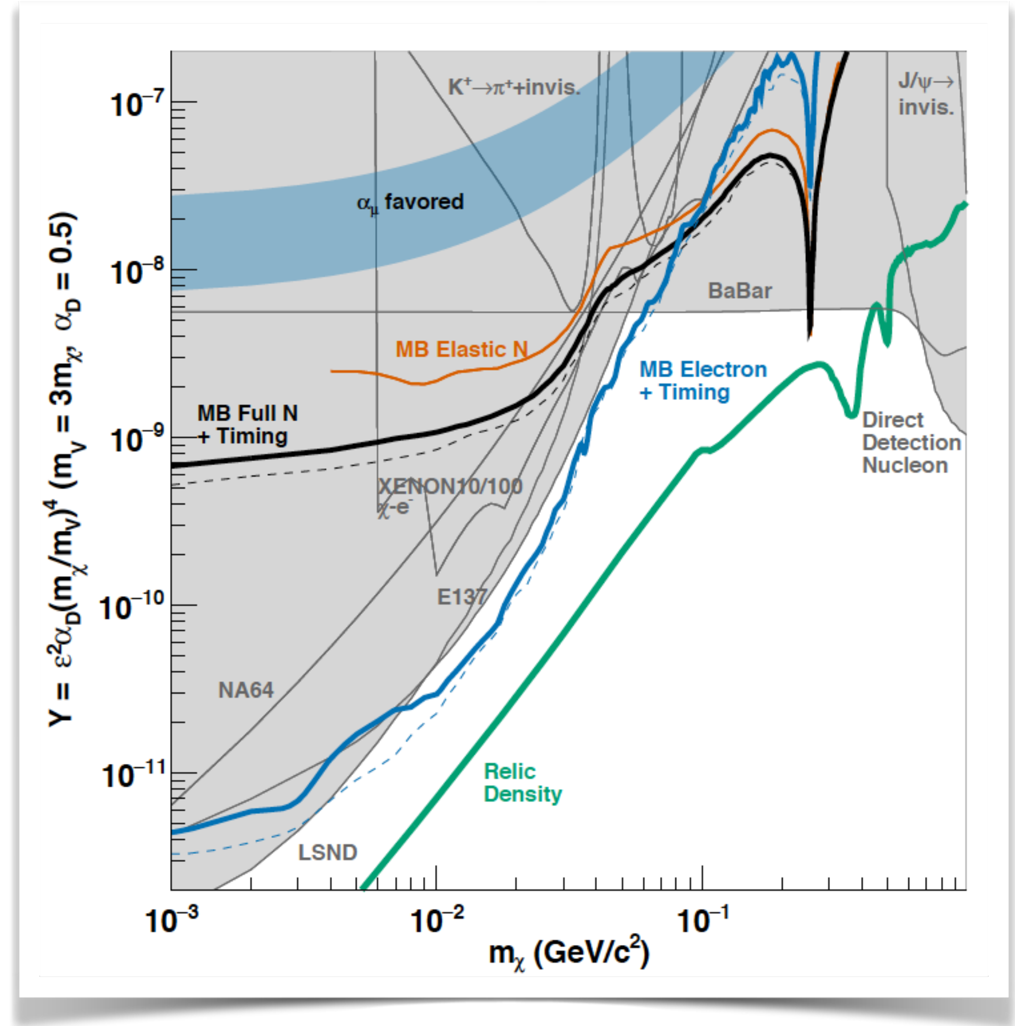




Production



Detection



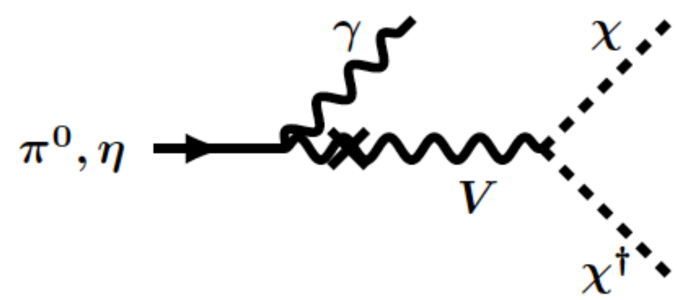
[MiniBooNE-DM Phys. Rev. D (2018) 11, 112004]

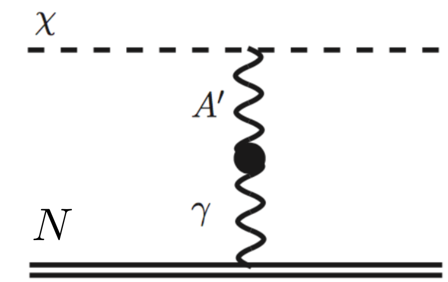
- 8 GeV protons on iron dump; 800 ton mineral oil detector
- Dedicated off target / beam dump run mode, collected 1.9E20 POT
- Leading limits on vector portal dark matter model for ~ 100 MeV mass range
- Demonstrates proton beam dump as an effective search method for light dark matter

GeV-scale CEνNS Experiments

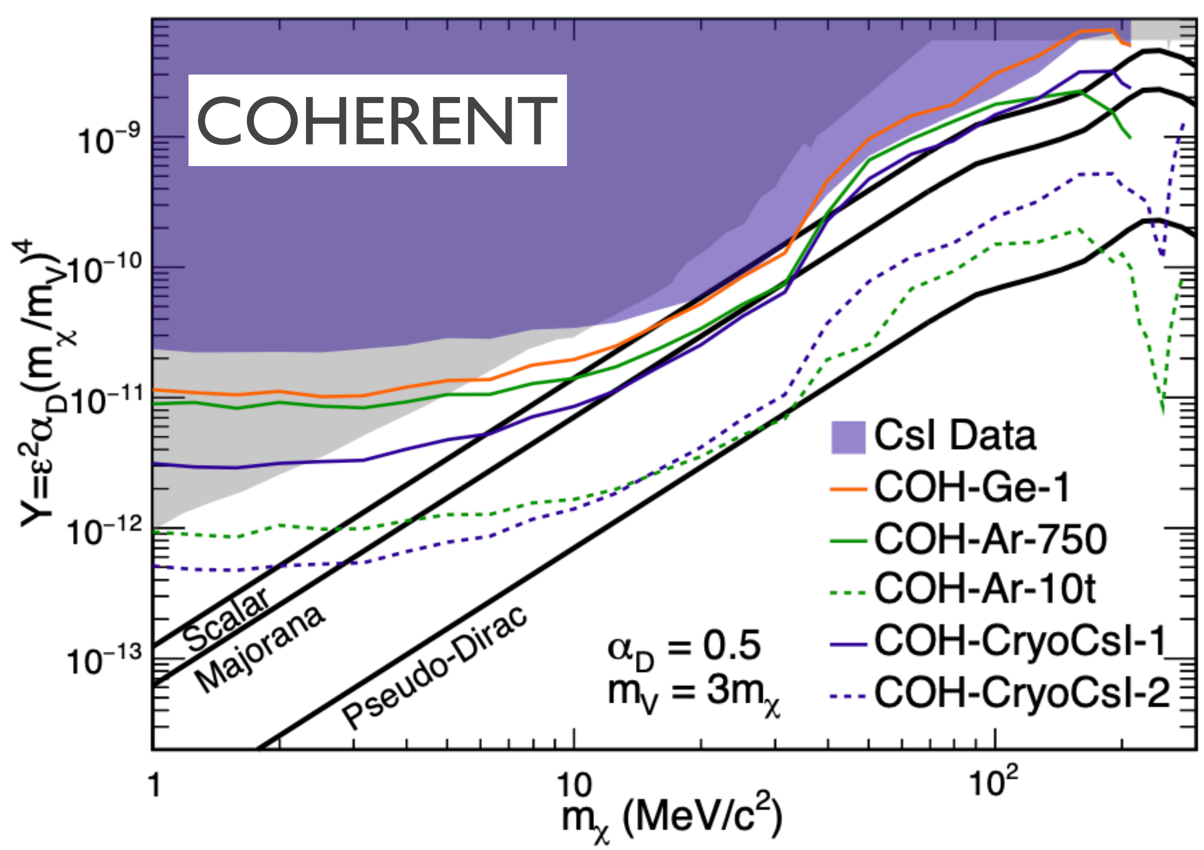
- Recent observation of Coherent Elastic Neutrino Nucleus Scattering (CEvNS) by COHERENT! [Science 357 (2017) no.6356, 1123-1126]

- CEνNS experiments can probe light dark matter: [deNiverville, Pospelov, Ritz] [Ge, Shoemaker]

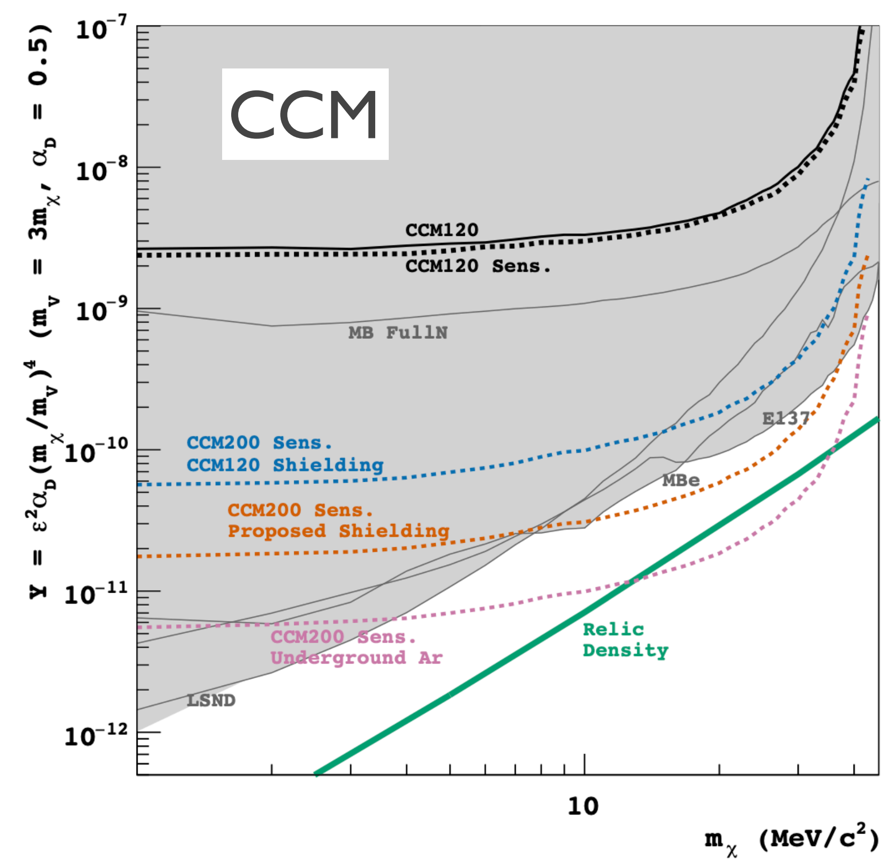




- Example: COHERENT@ORNL and CCM@LANL limits/sensitivity to vector portal DM



[COHERENT Collaboration, 2110.11453]



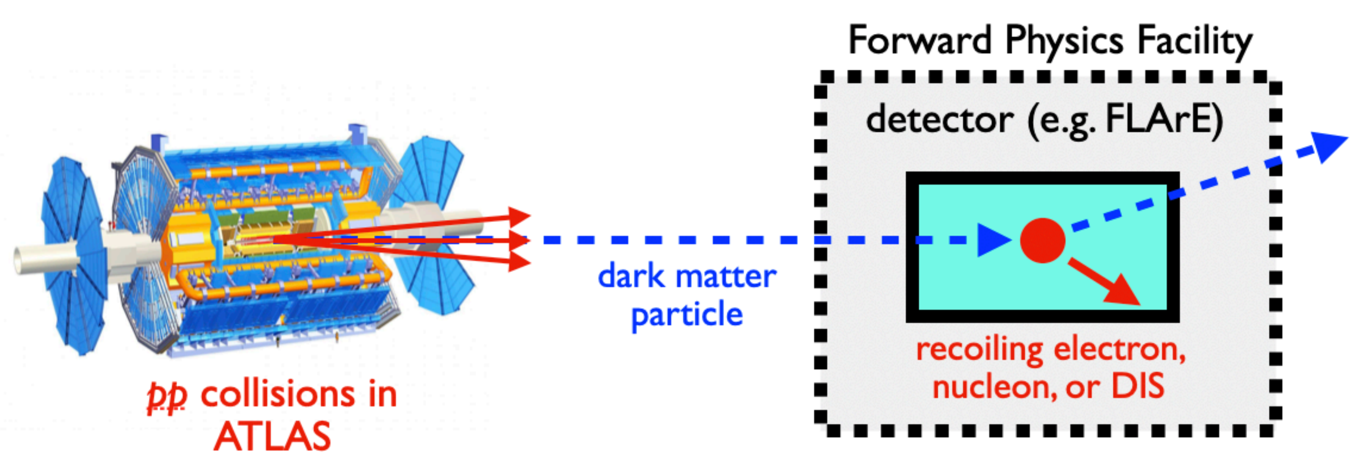
[CCM Collaboration, 2105.14020]

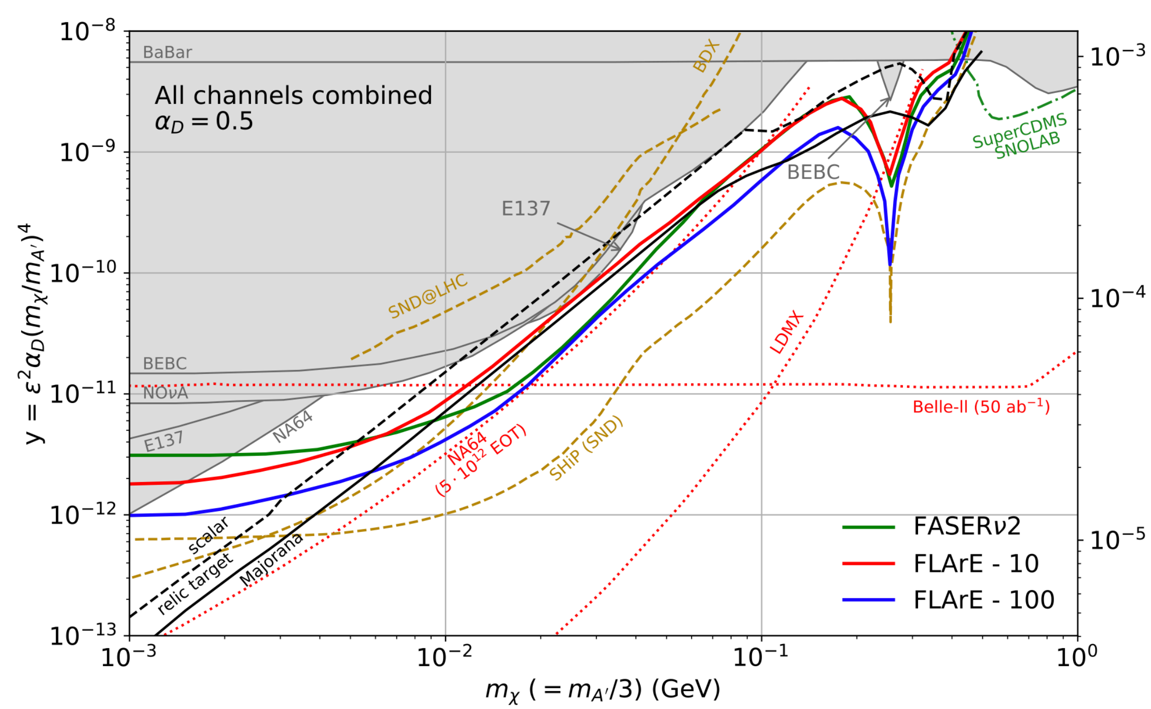
Forward LHC $\nu-$experiments (FASERν, FLArE, …)

- Total LHC pp cross section is ~100 mb, and is directed in the forward region
  - Copious source of TeV energy neutrinos
  - First observation of collider-produced neutrinos by FASER [FASER collab., arXiv:2303.14185]
  - Exciting prospects at FASERν, SND@LHC (Run 3) and FASERν2, FLArE, FORMOSA (HL-LHC)

- Dark sectors can also be explored with forward LHC experiments
  - For full physics case, see Forward Physics Facility whitepaper [arXiv:2203.05090]

- Example: vector portal dark matter

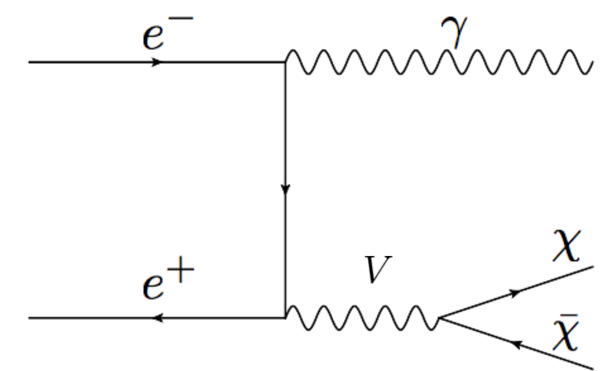




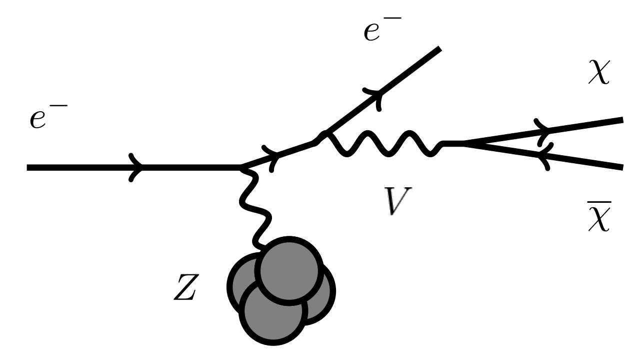
[BB, Feng, Feig, Ismail, Kling, Abraham, Trojanowski]

Many exciting ideas to search for vector portal dark matter

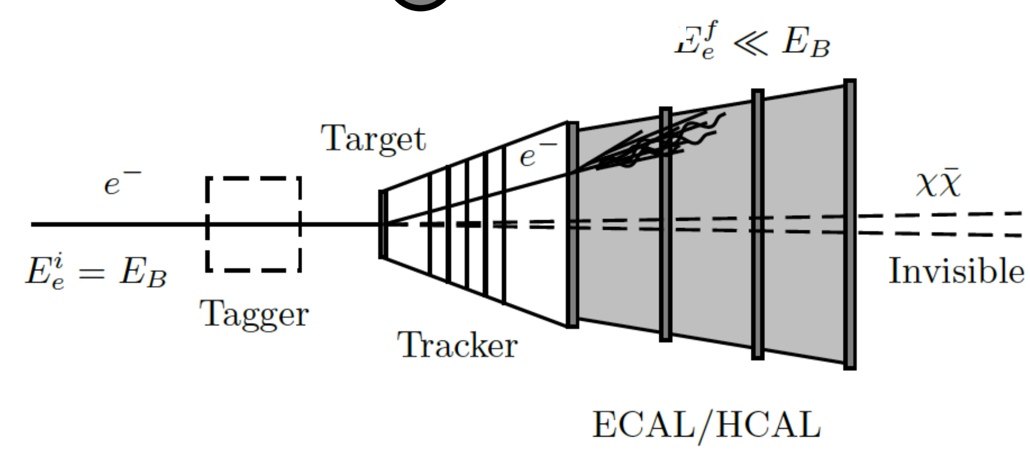
- Electron-positron colliders (e.g., Belle II)



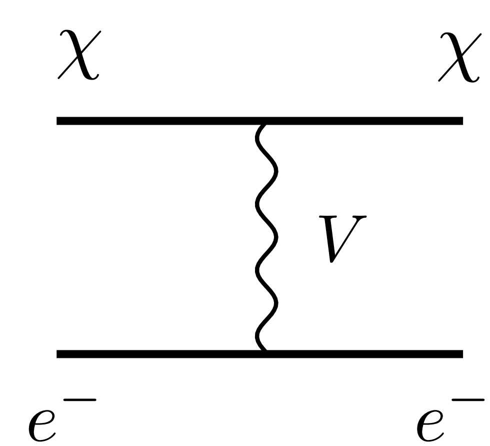
- Electron beam fixed-target / beam dump experiments (e.g., BDX)



- Fixed target missing energy / momentum experiments (NA64, LDMX)



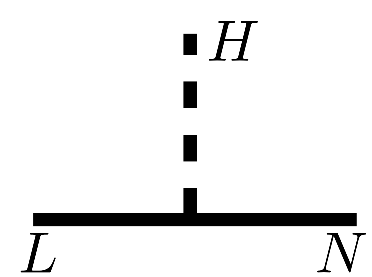
- Light DM direct detection experiments (e.g., SENSEI)

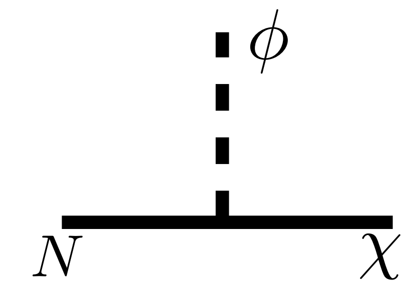


Neutrino portal dark matter with seesaw

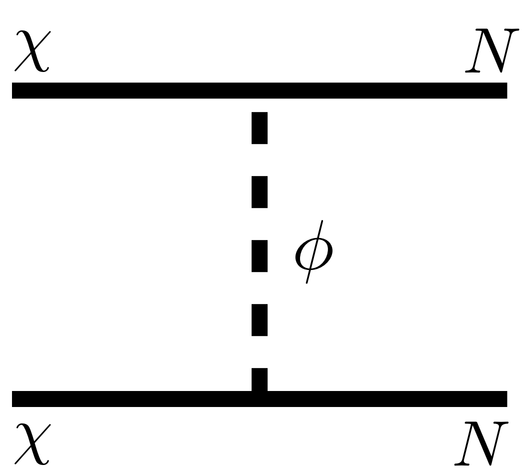
[BB, Han, Shams Es Haghi]

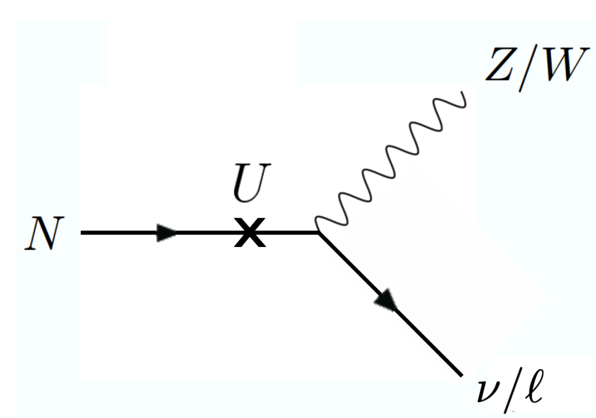
$$\mathcal{L} \supset -\frac{1}{2}m_\phi^2\phi^2 - \left[\frac{1}{2}m_N NN + \frac{1}{2}m_\chi \chi\chi + yLHN + \lambda N\phi\chi + \text{h.c.}\right]$$

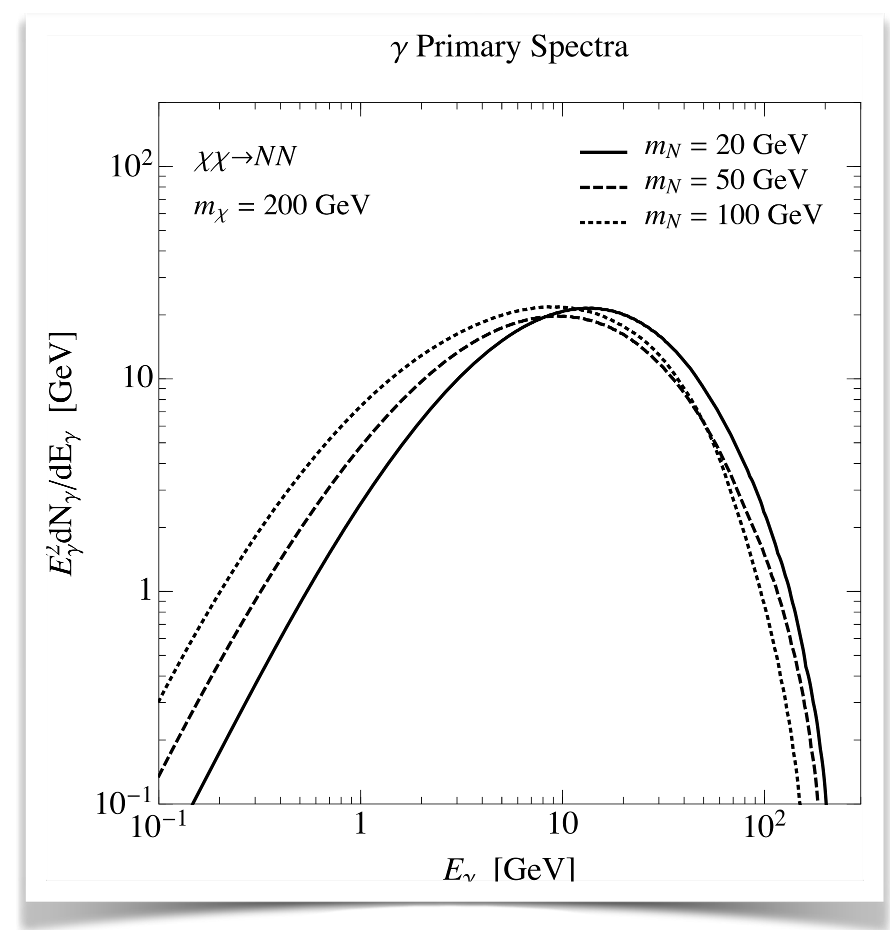




- Seesaw mechanism can generate small masses for light neutrinos.
- Mixing angle *U* expected to be small, annihilation to SM neutrinos inefficient
- Relic abundance obtained from secluded dark matter annihilation to heavy neutrinos
- Indirect detection offers a probe:
  - gamma-rays,
  - antiprotons,
  - distortion of microwave background anisotropies

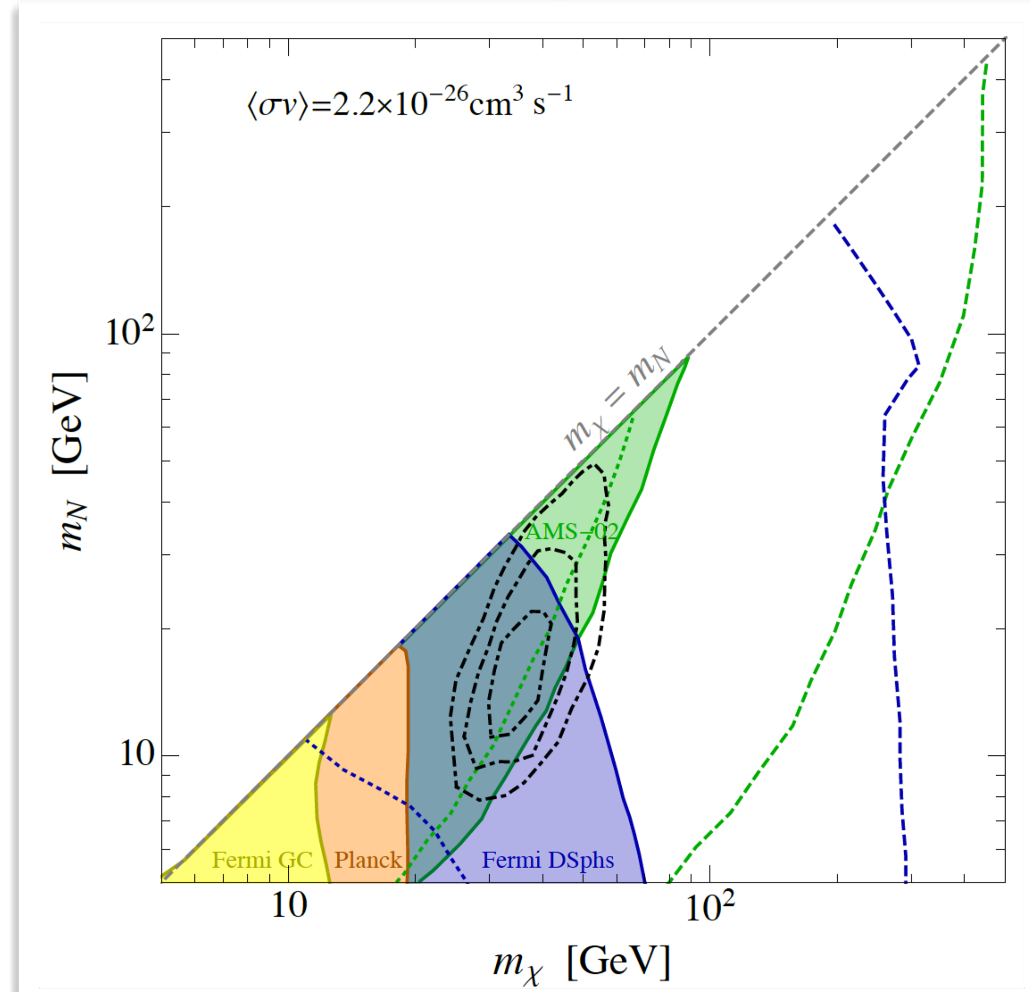






Indirect detection of neutrino portal DM

- Thermal relic dark matter below ~ 60 GeV is constrained by indirect probes:
  - *Fermi* gamma ray observations from Milky Way dwarf spheroidal galaxies
  - *AMS-02* antiprotons observations
- *Fermi* GeV Galactic Center excess interpretation is in tension with these constraints
- *Fermi* will eventually have sensitivity to $m_\chi \gtrsim 100\,\mathrm{GeV}$
- *Cherenkov Telescope Array* will be able to probe TeV-mass dark matter

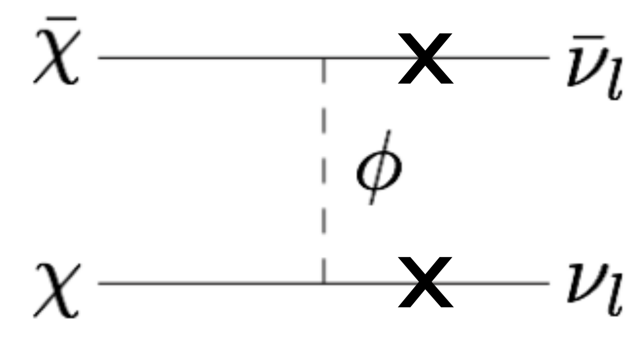


[BB, Han, Shams Es Haghi]

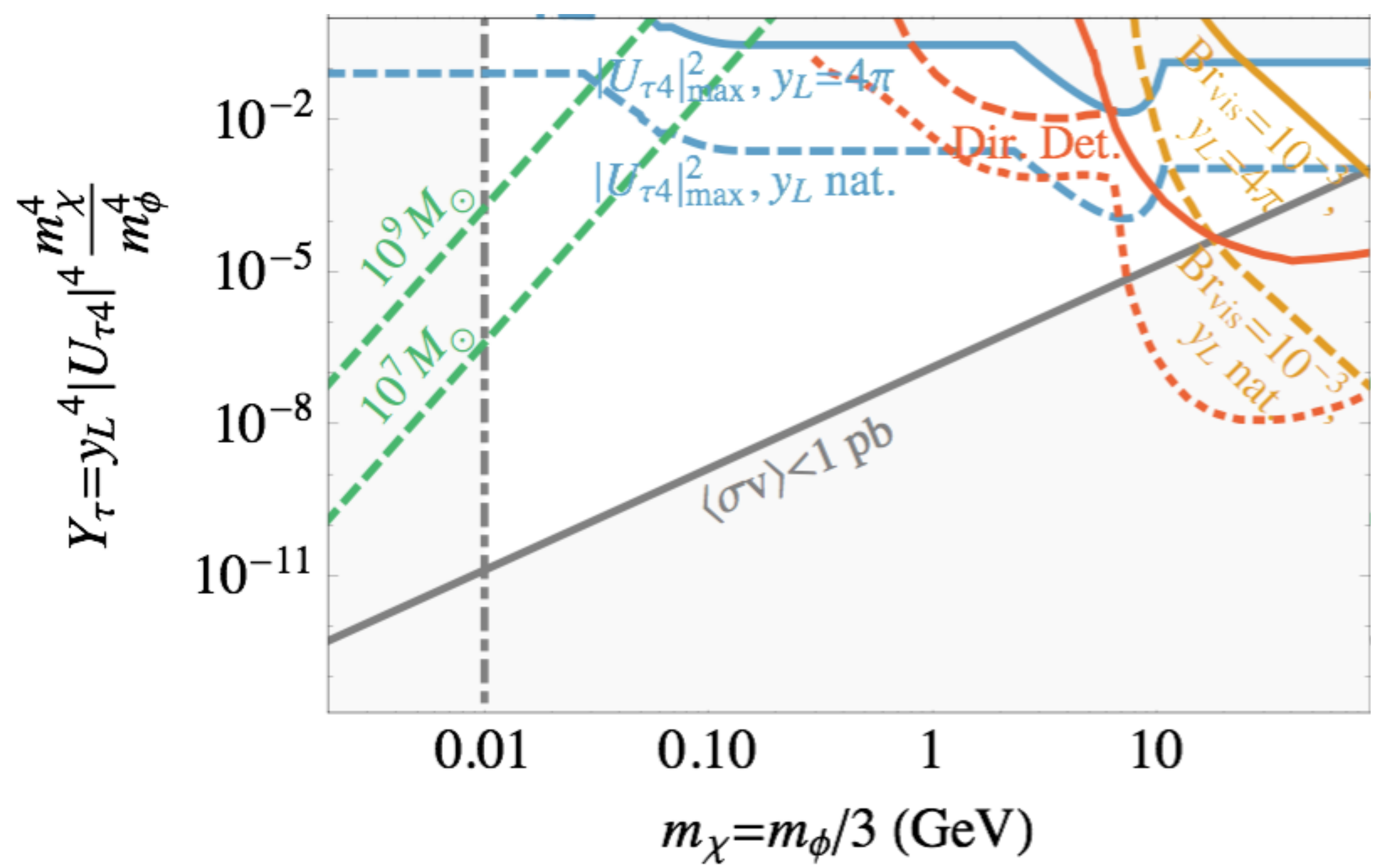
Neutrino portal dark matter with lepton number symmetry

[BB, Han, McKeen, Shams Es Haghi]

- Lepton number symmetry: no light neutrino mass generated by heavy neutrino mixing
- In this model, the heavy neutrino can have a large mixing angle
- Annihilation to ordinary light neutrinos leads to the observed DM abundan
- Signatures:
  - Rare Meson Decays
  - PMNS non-unitarity
  - Electroweak measurements
  - Invisible Higgs, Z decays
  - Direct Detection
  - Small scale structure

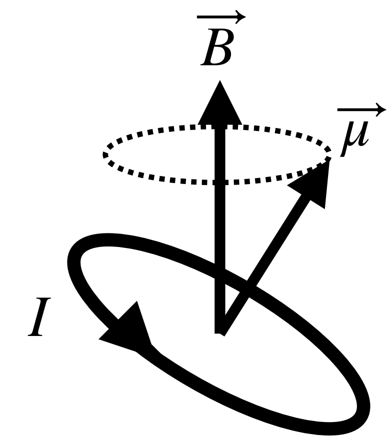


$\propto U^2$



Muon anomalous magnetic moment

What is "$g-2$"?



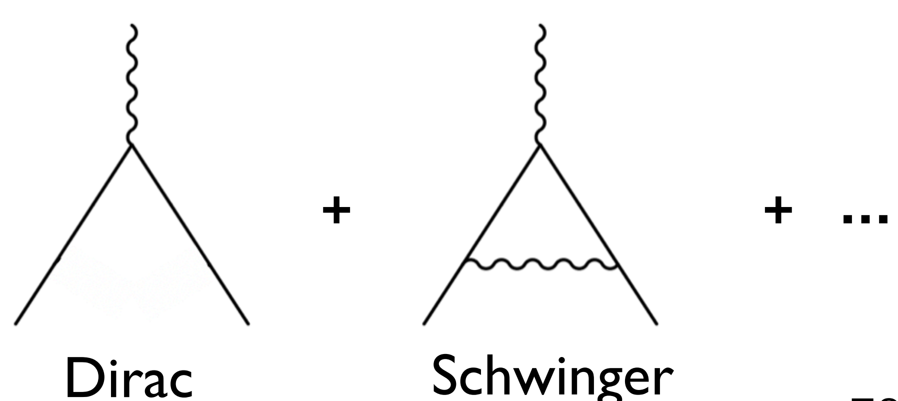
- Classically, a magnetic dipole moment, $\vec{\mu}$, experiences a torque in the presence of a magnetic field and undergoes Larmor precession.
- In quantum mechanics, charged particles such as electrons and muons have spin angular momentum and in turn have intrinsic magnetic dipole moments:

$$\vec{\mu}_\ell = g_\ell \left(\frac{q}{2m_\ell} \right) \vec{S}$$

- The Dirac equation predicts $g_\ell = 2$ exactly, while QED predicts small corrections to this result, referred to as the *anomalous magnetic moment:*

$$g_\ell = 2(1 + a_\ell) \longrightarrow a_\ell = \frac{(g_\ell - 2)}{2}$$

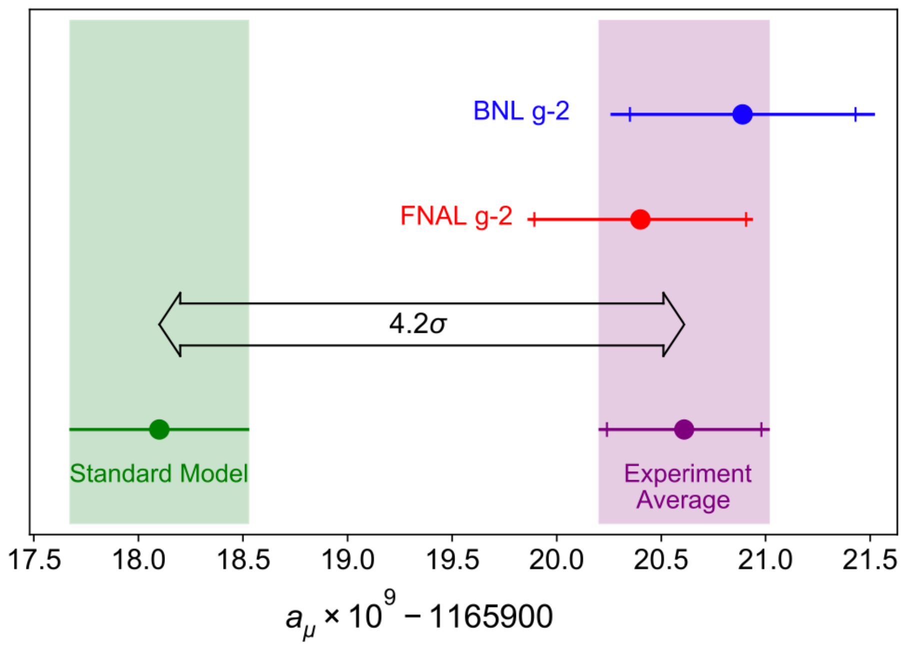
- The anomalous magnetic moment of the electron was discovered experimentally by several groups in 1947-48 and calculated by Schwinger in 1948:



$$a_\ell = \frac{\alpha}{2\pi} + \dots$$

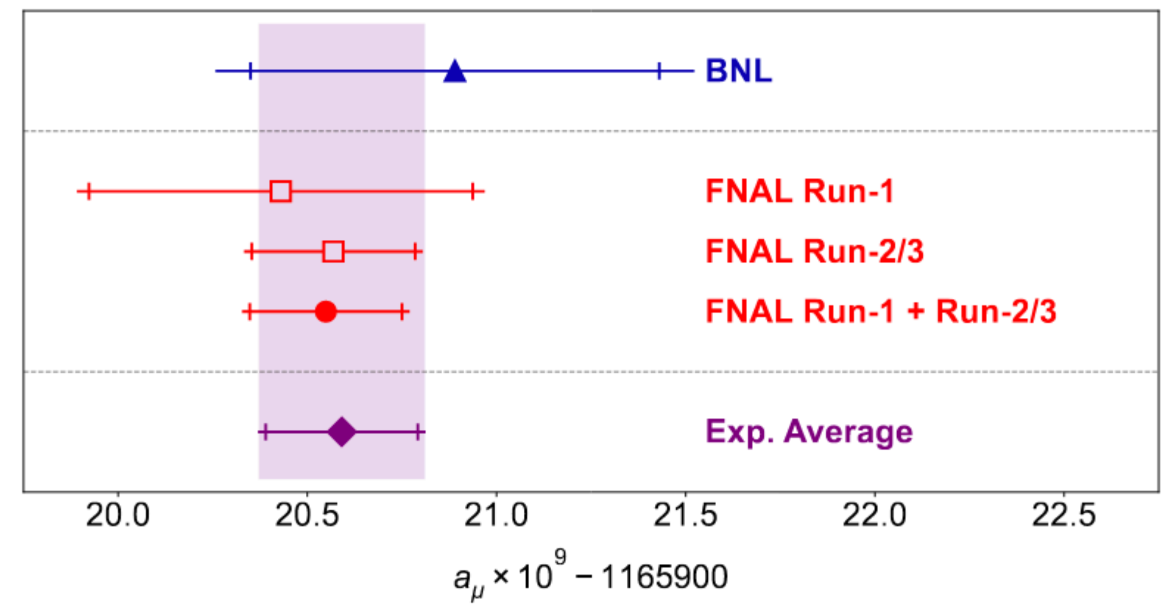
Fermilab Muon $g-2$ results

March 2021



[Muon g-2 Collab., 2308.06230]

August 2023



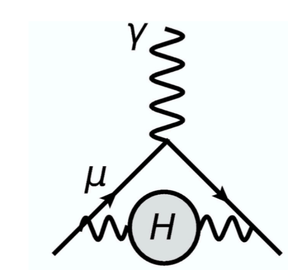
[Muon g-2 Collab., PRL 126, 141801 (2021)]

Muon g-2 Theory Initiative SM prediction: $a_\mu(\mathrm{SM}) = 116\ 591\ 810(43) \times 10^{-11}$

Combined FNAL/BNL result: $a_\mu(\mathrm{Exp}) = 116\ 592\ 059(22) \times 10^{-11}$

Difference: $a_\mu(\mathrm{Exp}) - a_\mu(\mathrm{SM}) = (249 \pm 48) \times 10^{-11}$

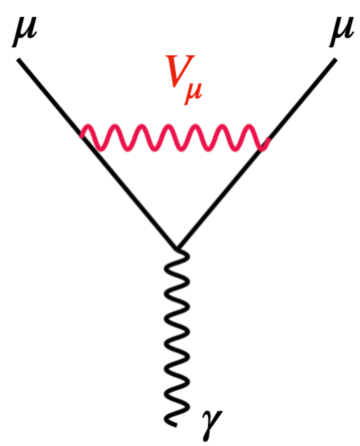
- There are several tensions in the hadronic vacuum polarization contribution, and more work is needed to clarify the SM prediction



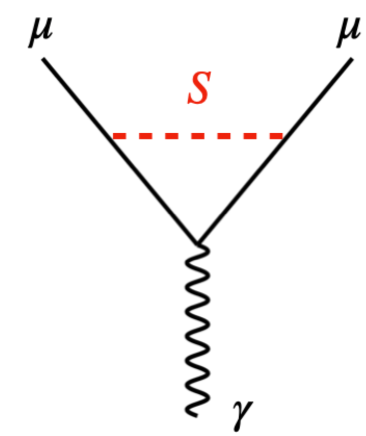
Muon-philic forces and $(g-2)_\mu$

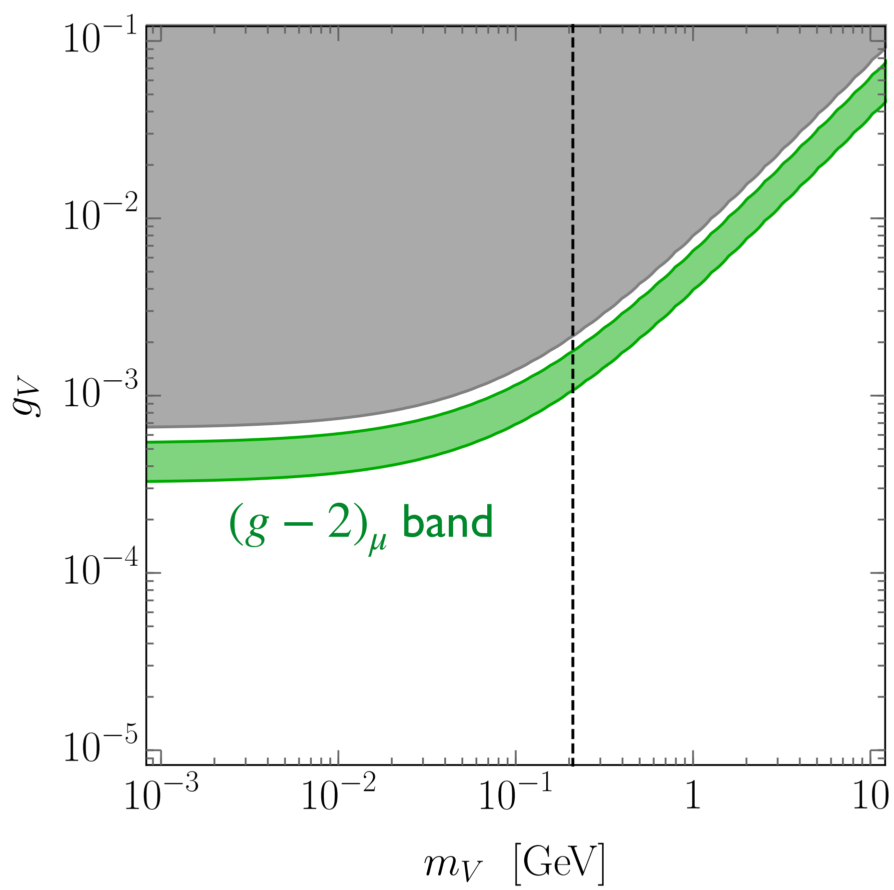
- Muons may experience new vector or scalar mediated forces which provide a contribution to $(g-2)_\mu$

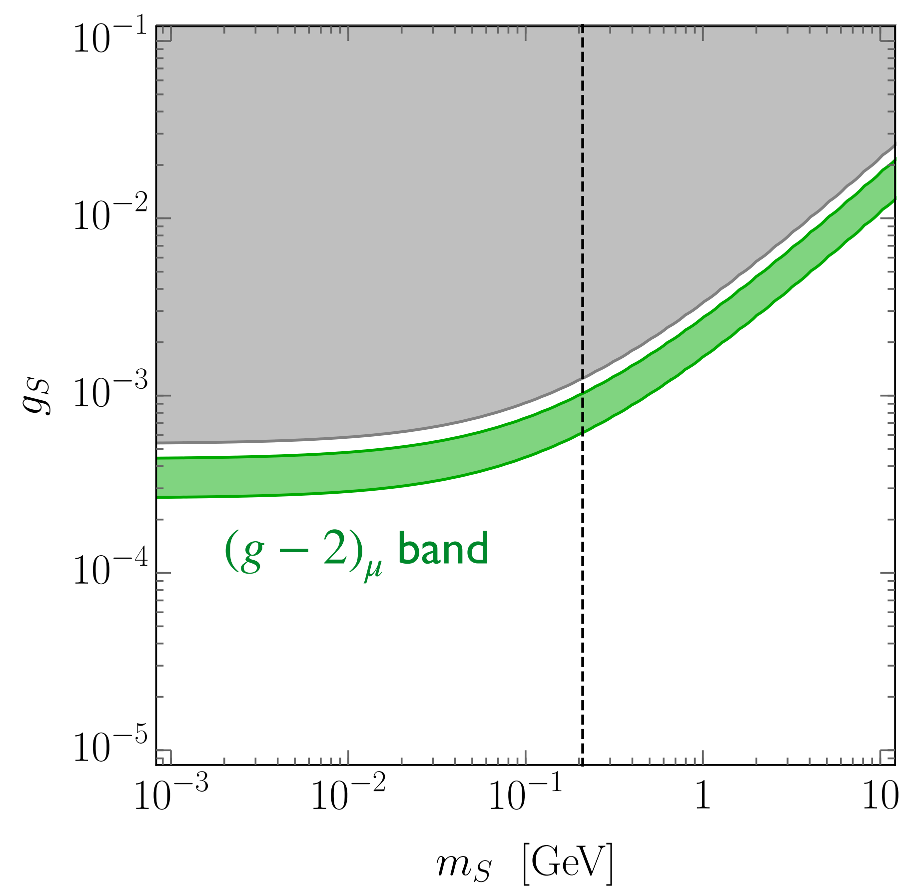
$$\mathscr{L} \supset g_V V_\mu \bar{\mu}\gamma^\mu \mu$$



$$\mathscr{L} \supset g_S S \bar{\mu} \mu$$







Muon-philic vector : $L_\mu - L_\tau$ gauge boson

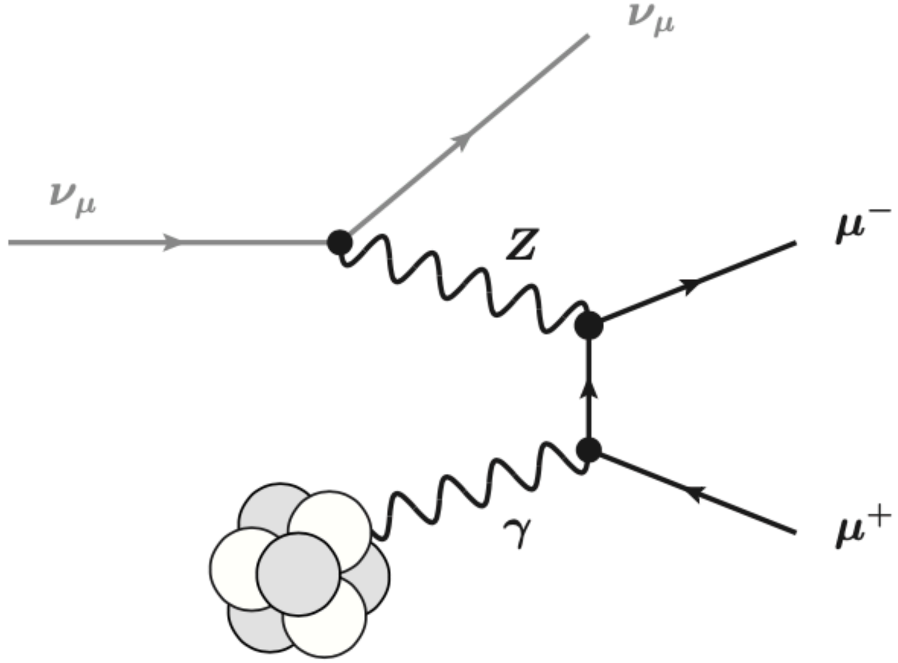
[He, Joshi, Lew, Volkas]

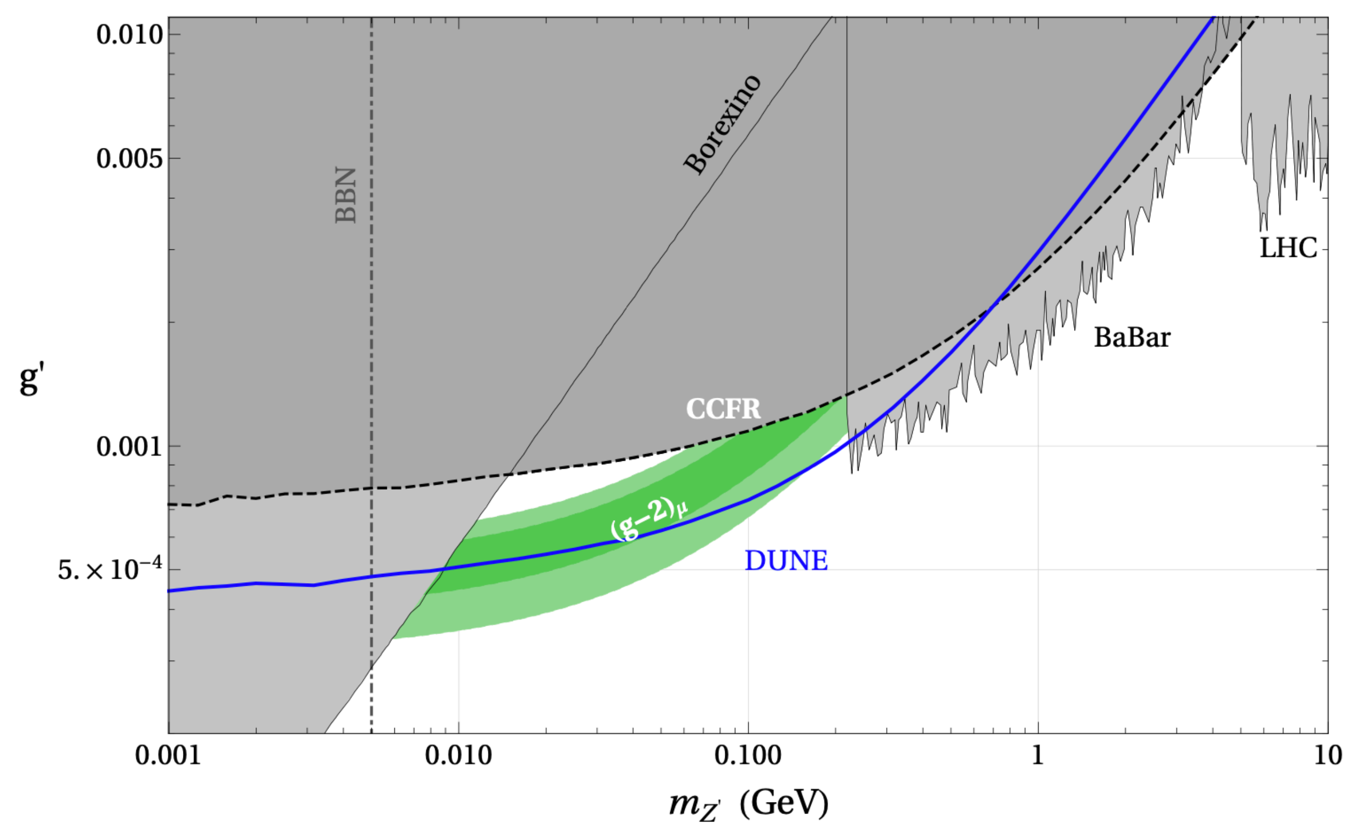
- A viable UV complete model for $(g-2)_\mu$ is a new $L_\mu - L_\tau$ gauge boson

$$\mathcal{L}_{L_\mu - L_\tau} = g' Z'_\alpha \Big[(\bar{\mu}\gamma^\alpha \mu) - (\bar{\tau}\gamma^\alpha \tau) + (\bar{\nu}_\mu \gamma^\alpha P_L \nu_\mu) - (\bar{\nu}_\tau \gamma^\alpha P_L \nu_\tau) \Big] \ ,$$

- For $m_{Z'} < 2m_\mu$, the vector decays invisibly to neutrinos and is only weakly constrained

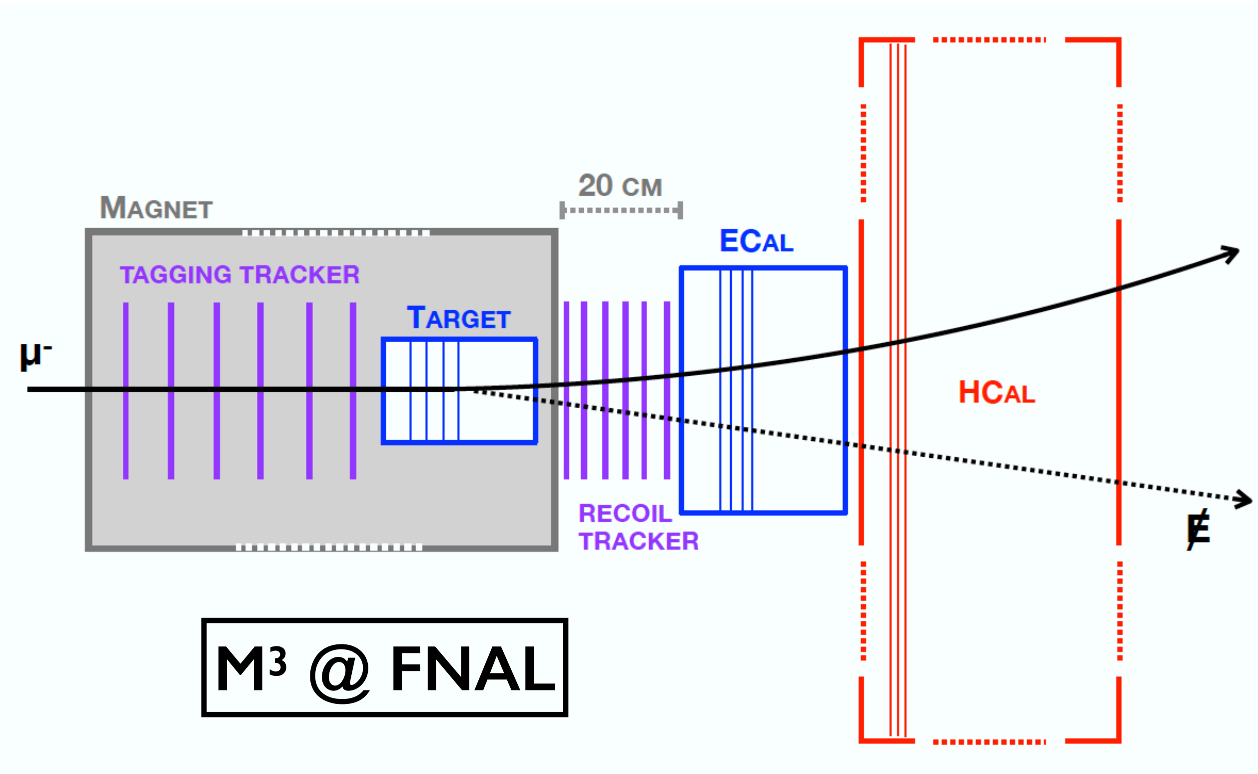
- This will give a contribution to the neutrino trident process, which can be probed at the DUNE near detector



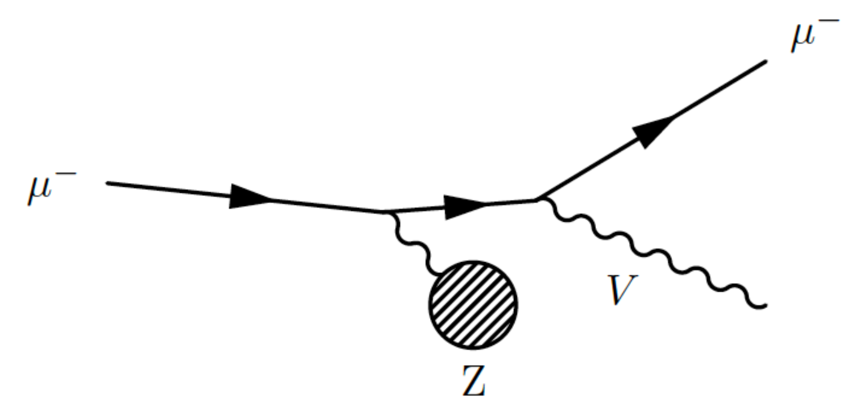


[Altmannshofer, Gori, Martın-Albo, Sousa, Wallbank]

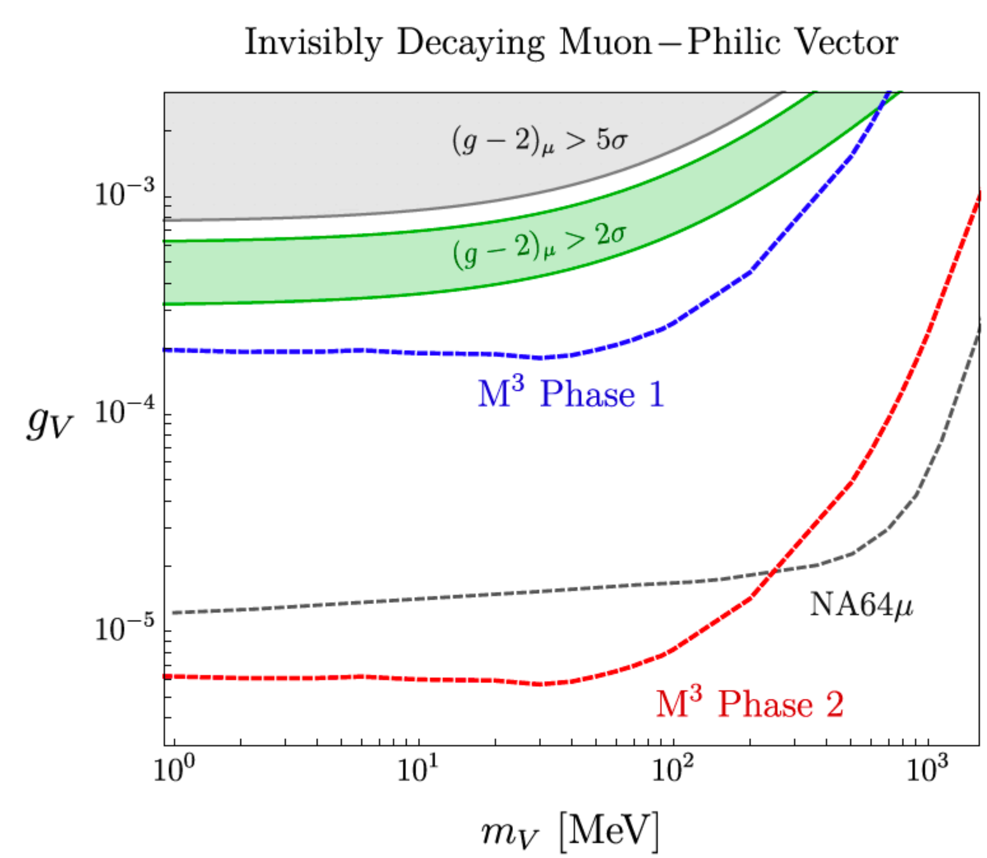
Muon-beam missing energy/momentum experiments



[Gninenko, Krasnikov, Matveev]
[Kahn, Krnjaic, Tran, Whitbeck]



Mediator decays to DM, neutrinos, or is long-lived



- Muon beam impinges on a thick target
- Mediator inherits significant fraction of beam energy
- Signal : recoil muon with momentum measured by recoil tracker, missing momentum
- ECAL and HCAL used to veto backgrounds
- M3 @ FNAL and NA64 @ CERN

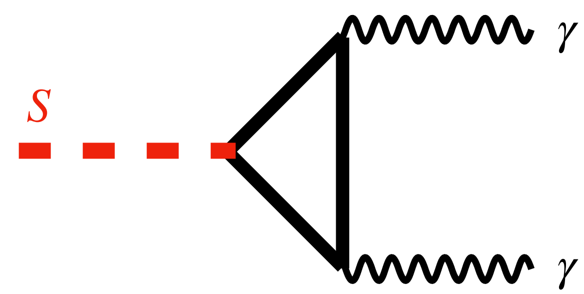
Muon-philic scalar

[Chen, Davoudiasl, Marciano, Zhang, '15]
[Chen, Pospelov, Zhong, '17]
[BB, Freitas, Ismail, McKeen, '17]

- Model

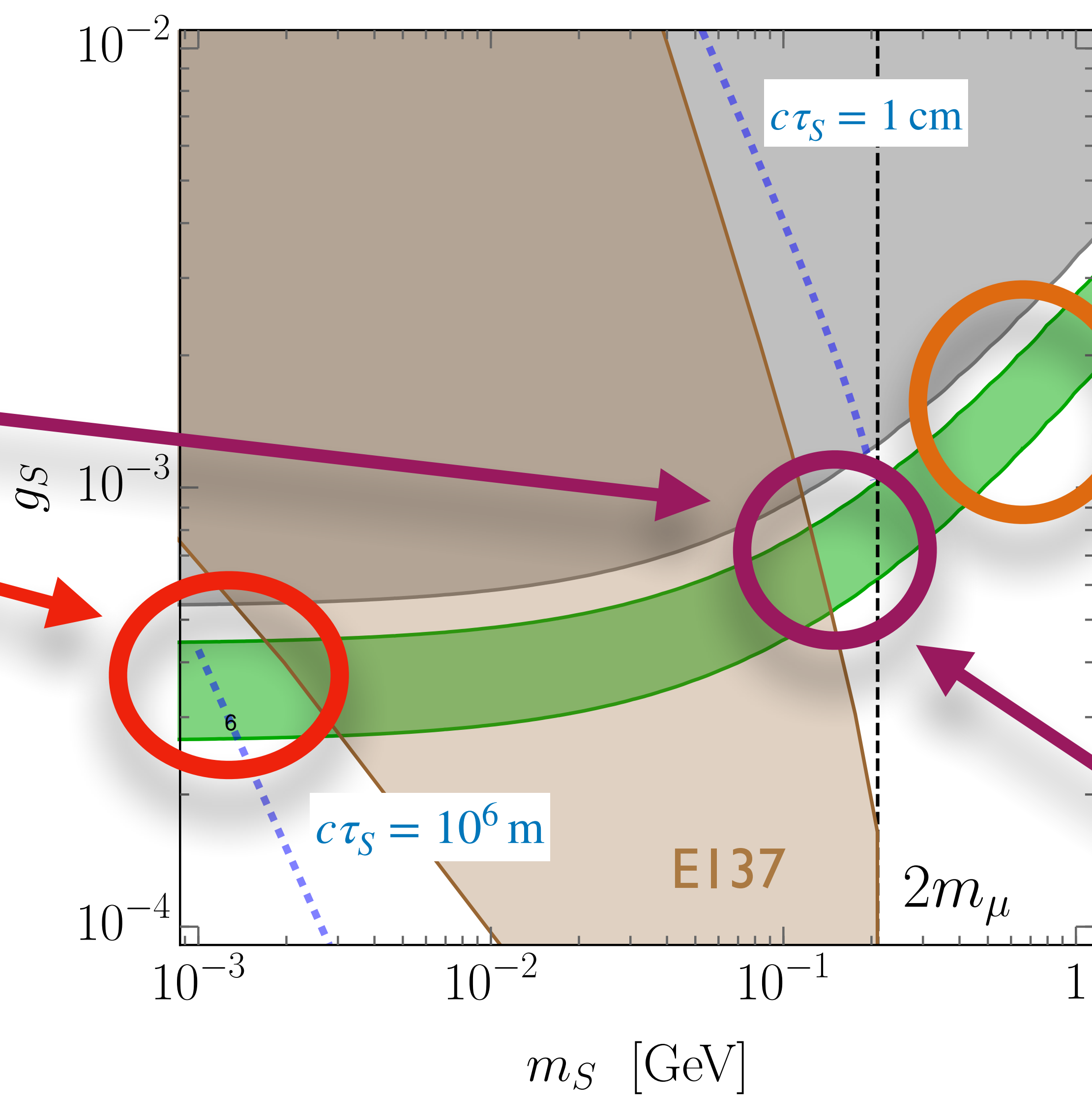
$$\mathcal{L} = -g_S\, S\, \overline{\mu}\mu - \frac{1}{4\Lambda} S F_{\mu\nu} F^{\mu\nu}$$

- Minimal scenario: photon coupling generated at one loop from the muon coupling:



$$\frac{1}{4\Lambda} \sim \frac{g_S\, \alpha}{4\pi m_\mu}$$

Muon missing momentum search can be performed in both open regions



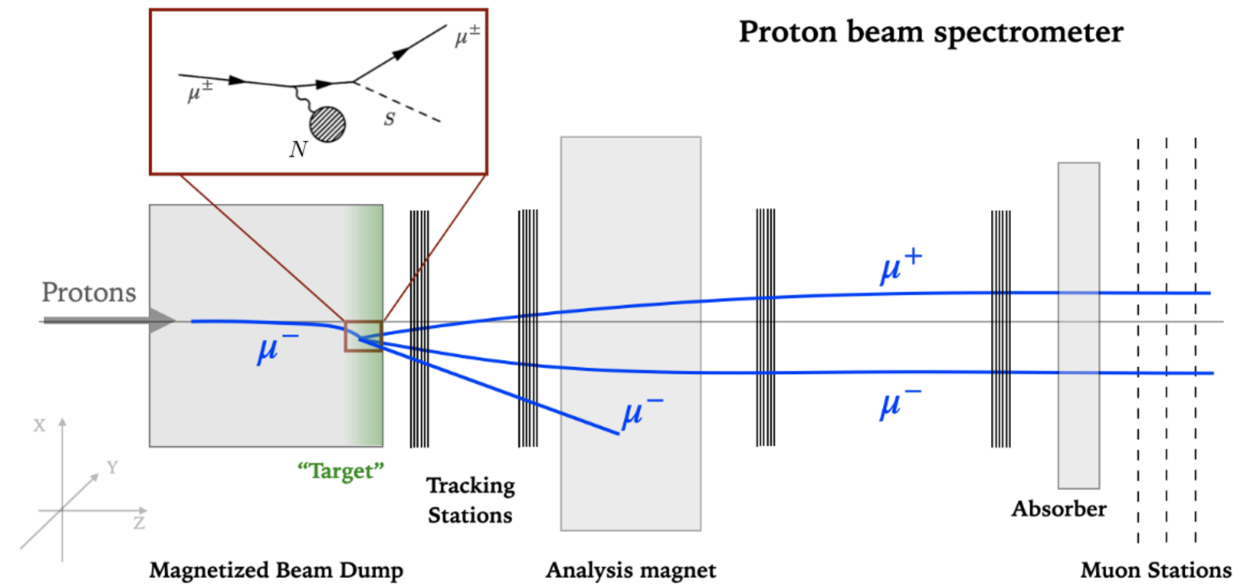
Blue dotted line indicates scalar decay length

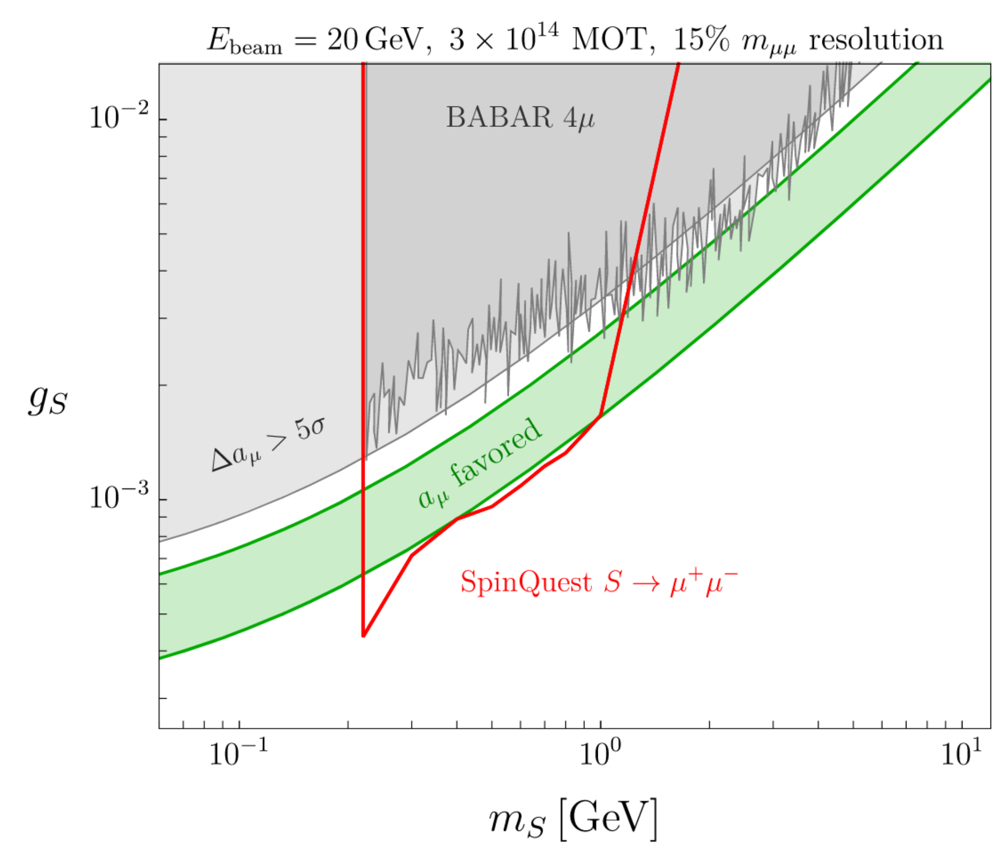
Search for prompt dimuon resonance above dimuon threshold

Search for displaced diphoton resonance below diumon threshold

Muon-philic scalars at SpinQuest @ FNAL

- 120 GeV protons impinge on magnetized beam dump
- Magnetic field (KMAG), 4 tracking stations, muon ID system, Electromagnetic calorimeter
- A large secondary flux of muons is produced in the primary proton-target collisions.
- Subsequent collisions of these muons in the dump can produce mediators, which then promptly decay to dimuon pairs
- SpinQuest can probe the $(g-2)_\mu$ favored region above the dimuon threshold

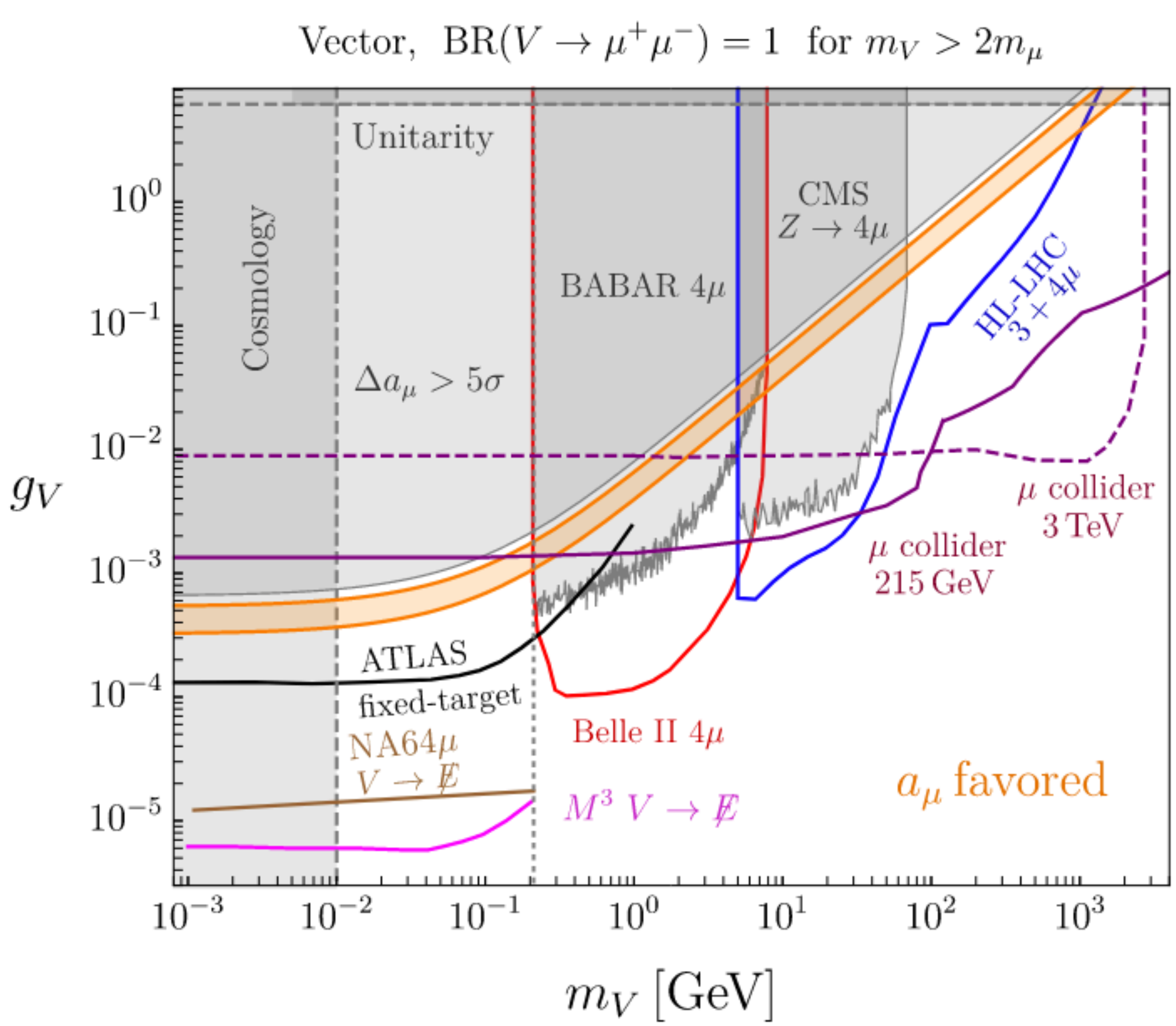




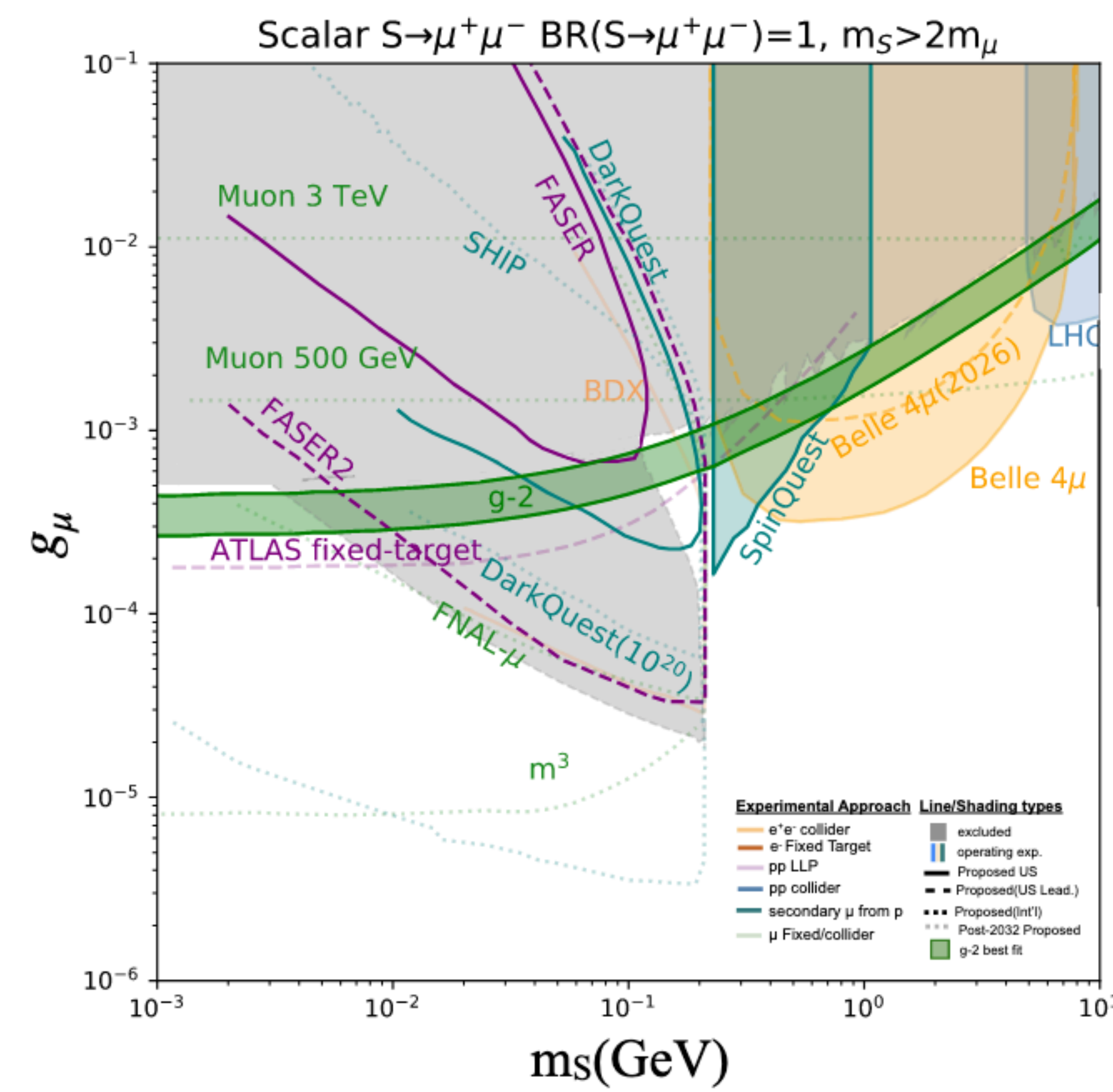
[Forbes, Herwig, Kahn, Krnjaic, Mantilla Suarez, Tran, Whitbeck]

Muon-philic forces and $(g-2)_\mu$ outlook

- There are exciting opportunities to test the muonphilic force explanation for $(g-2)_\mu$ solution, including at neutrino experiments, proton and muon fixed-target experiments, and colliders



[Capdevilla, Curtin, Kahn, Krnjaic]



[Harris, Schuster, Zupan]

Hierarchy problem

The Hierarchy problem

Higgs mass parameter is sensitive to short distance scales

→ Naively suggests new physics at the weak scale

- Basic EFT reasoning, "dimensional analysis"
- No other elementary scalars observed in nature
- History: Electron self-energy, Ginzburg-Landau, QCD pions, …

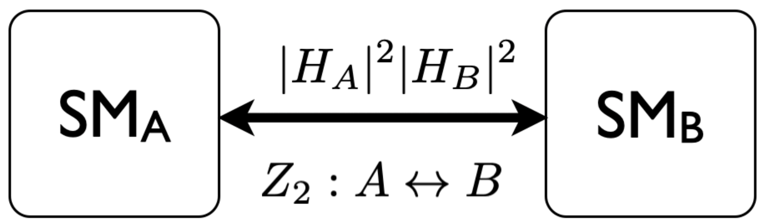
Paradox: No new physics observed at LHC (yet!)

- Maybe there is no problem? Perhaps the question is misguided…
- C.C. a bigger problem - Maybe "Naturalness" is like aether?(!)

Maybe the solution to the hierarchy problem is more subtle?

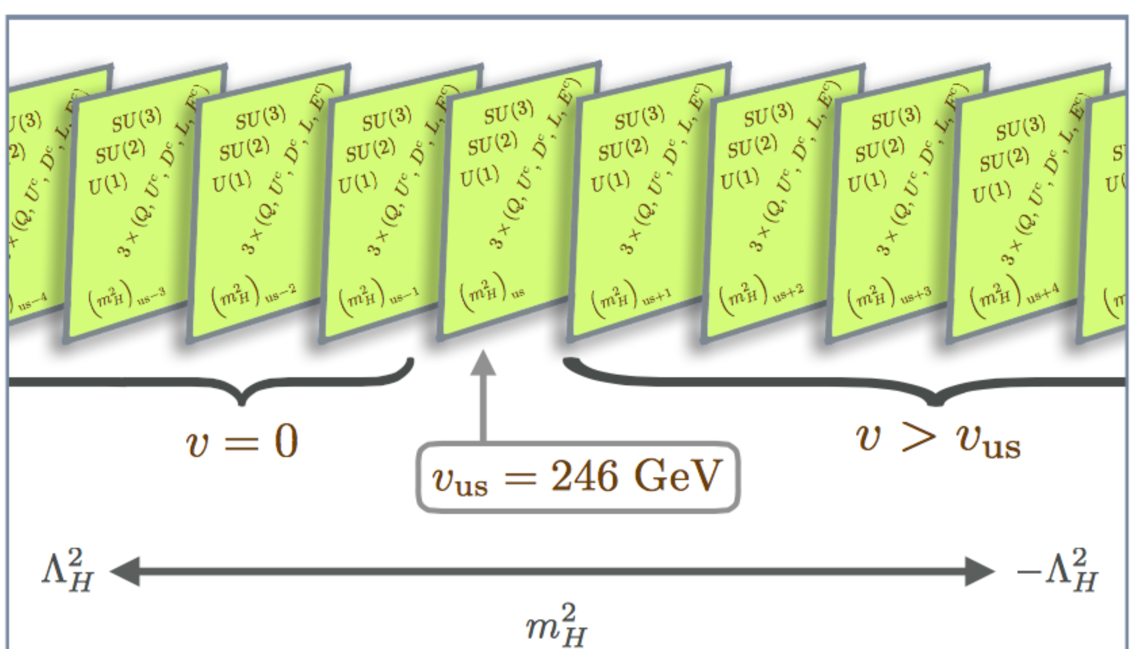
Dark Sectors and the Hierarchy Problem

Twin Higgs



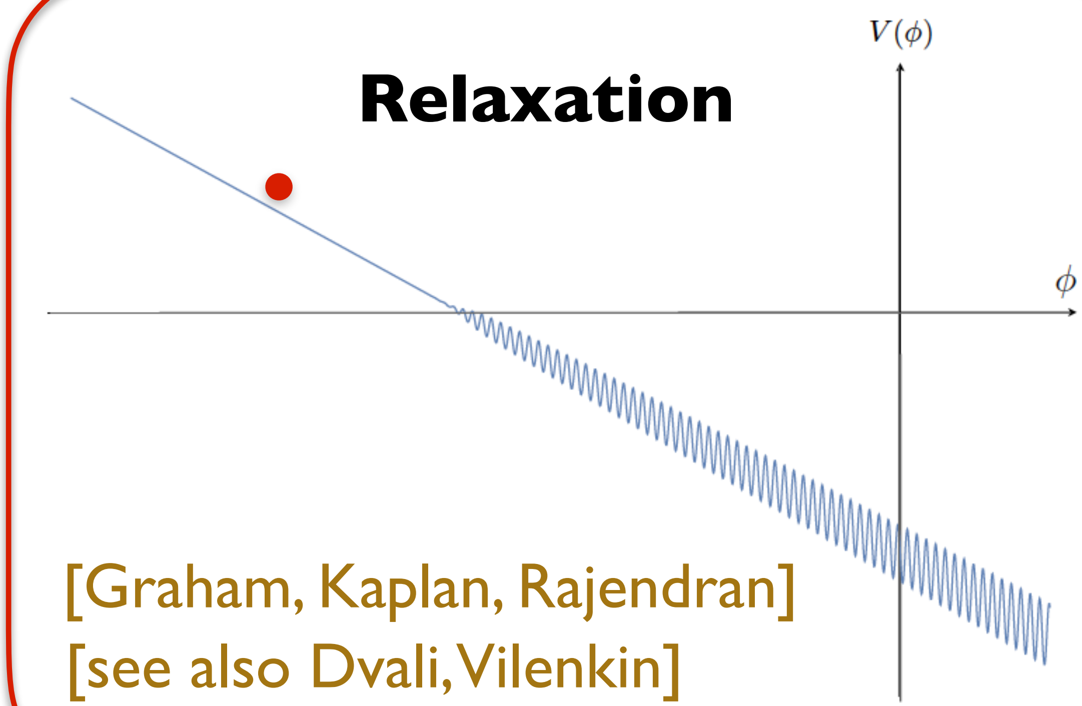
[Chacko, Harnik, Goh]
[Barbieri, Gregoire, Hall]

NNaturalness



[Arkani-Hamed, D'Agnolo, Cohen, Hook, Kim, Pinner]

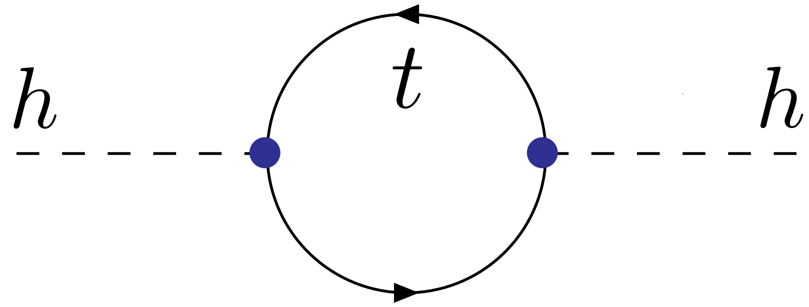
Relaxation



[Graham, Kaplan, Rajendran]
[see also Dvali, Vilenkin]

… and many other ideas!

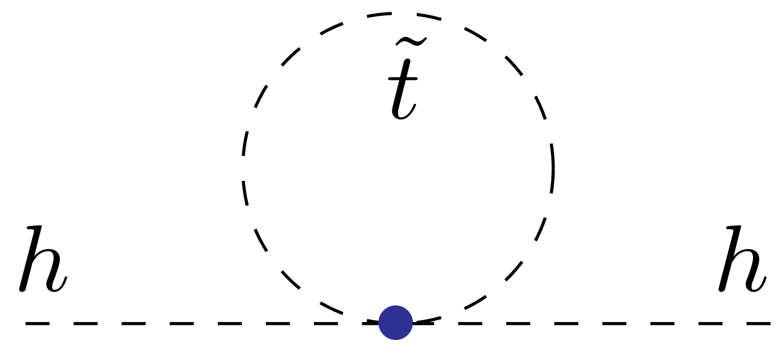
Hierarchy problem



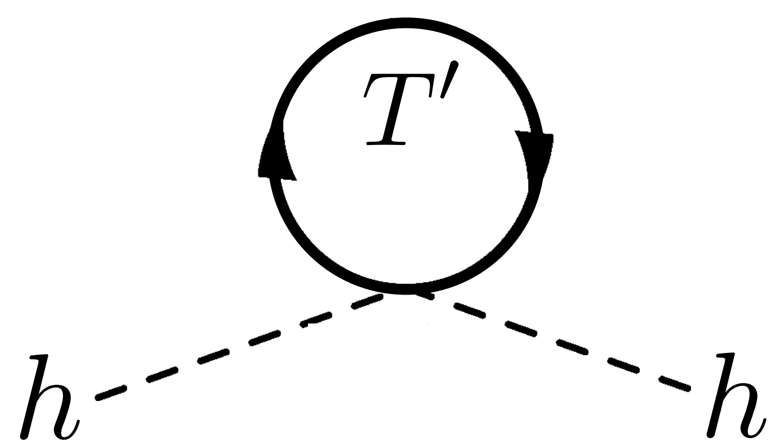
$$\delta m_h^2 = -\frac{3y_t^2}{8\pi^2}\Lambda^2$$

➡ Top Partners:

Stops
(SUSY)

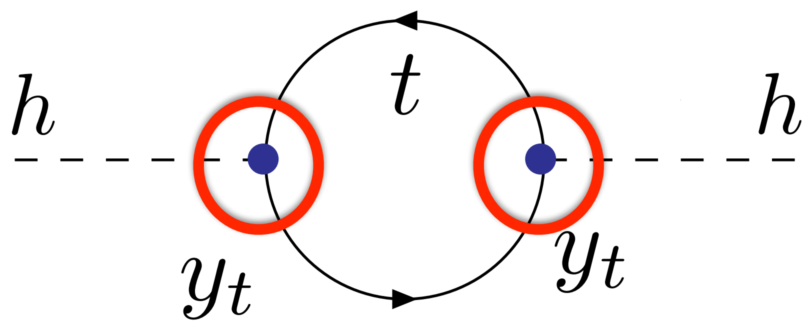


Fermionic T'
(Composite/pNGB Higgs)



Cancellation of Λ^2 due to

1. Supersymmetry or Global Symmetry → Equality of Couplings



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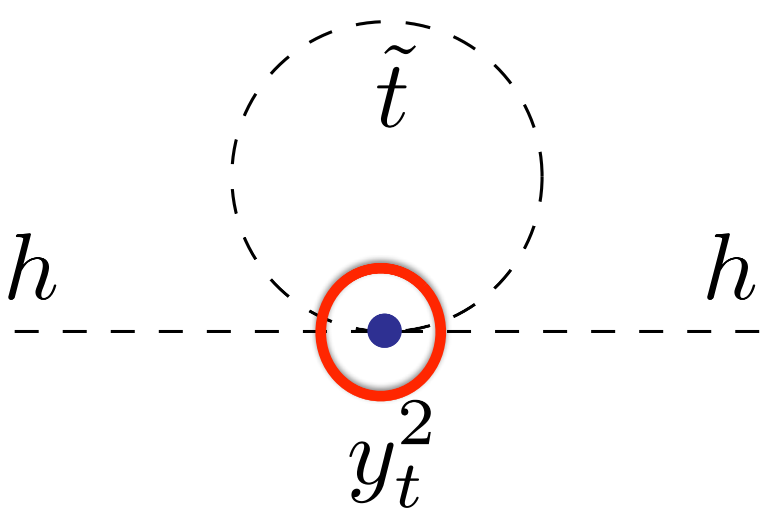
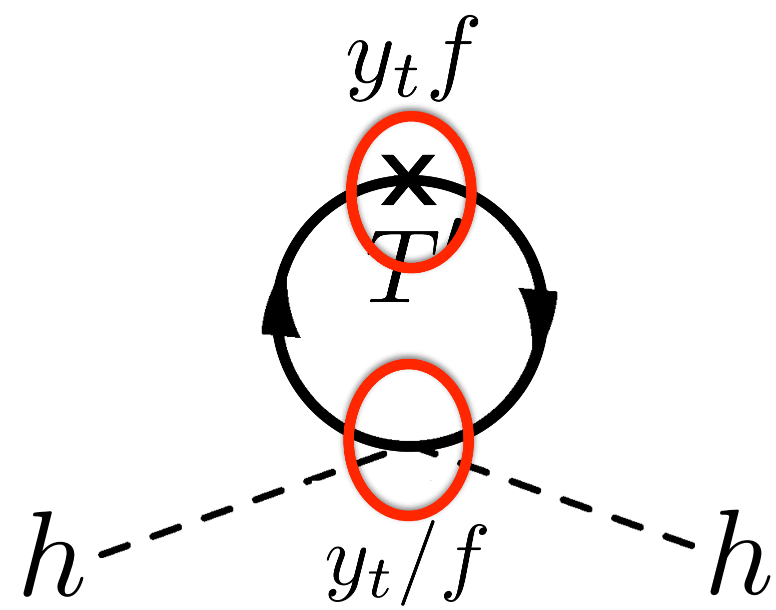
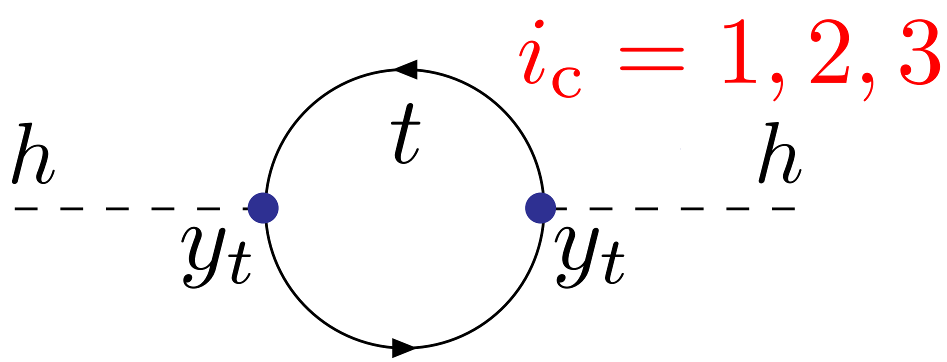


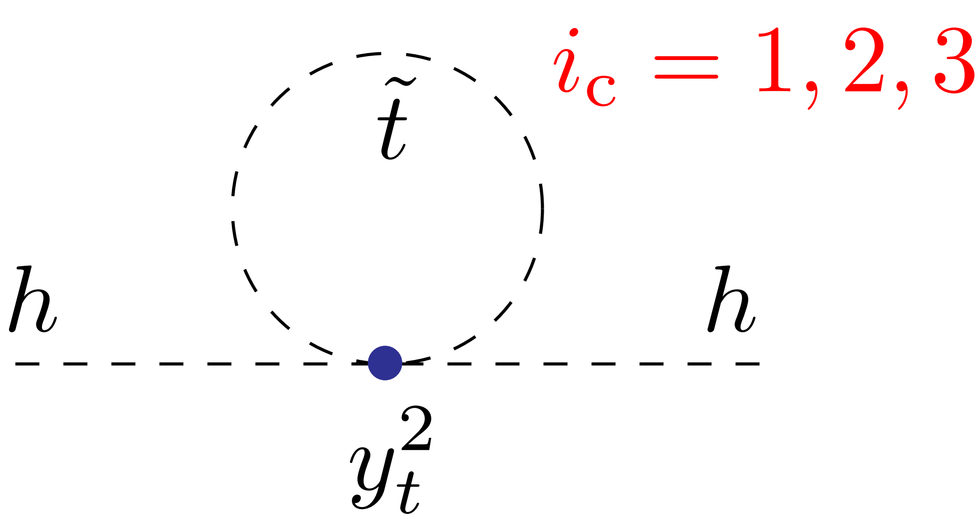


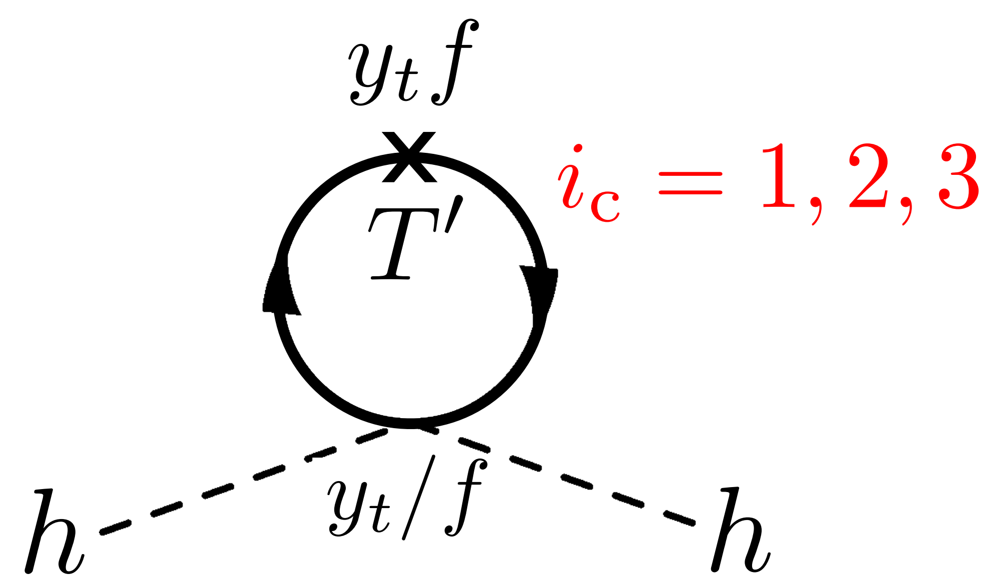
Cancellation of Λ^2 due to

2. $SU(3)_c$ → Equality of # d.o.f.



$$\delta m_h^2 = -\frac{3y_t^2}{8\pi^2}\Lambda^2$$





Cancellation of Λ^2 due to

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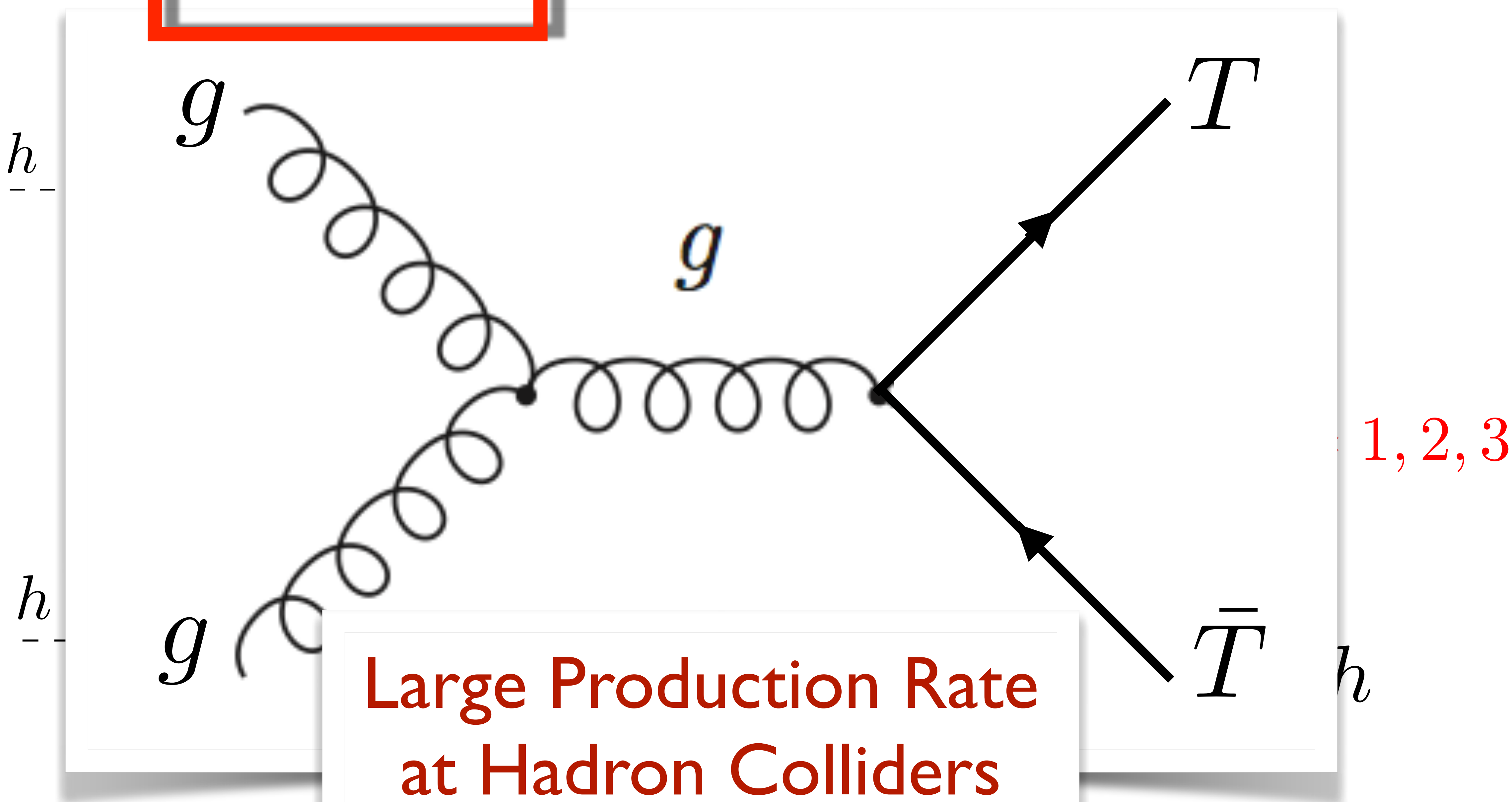
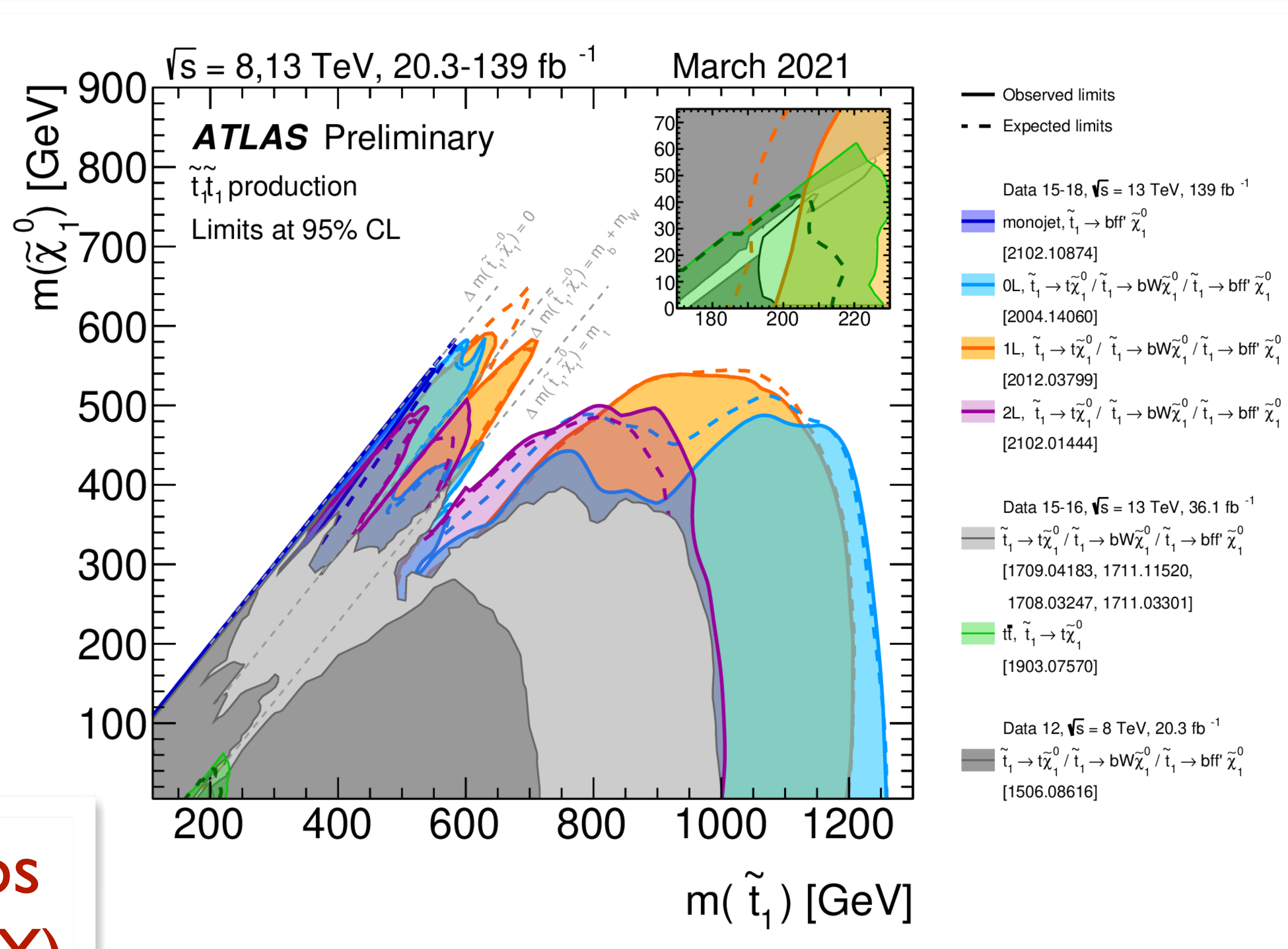


Large Production Rate at Hadron Colliders

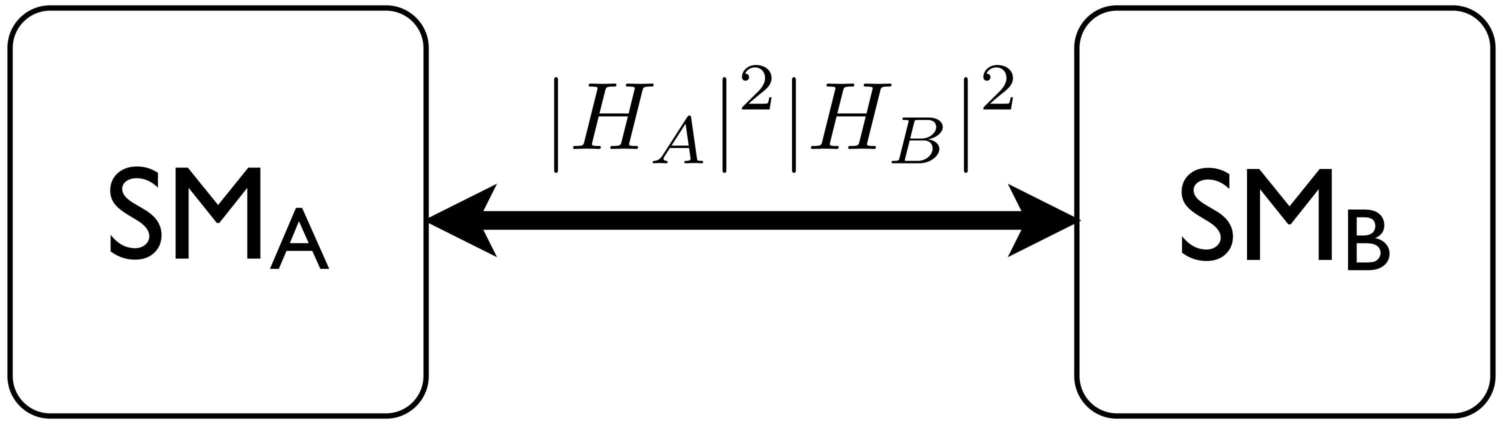
Where are the Top Partners?



Stops (SUSY)

Neutral Naturalness: The Twin Higgs

[Chacko, Goh, Harnik]



- Mirror copy of the Standard Model
- Higgs sector has an approximate global SU(4) symmetry

$$H = \begin{pmatrix} H_A \\ H_B \end{pmatrix} \qquad V(H) = -m^2 H^\dagger H + \lambda (H^\dagger H)^2$$

- The SM Higgs is a pseudo-Nambu-Goldstone Boson

$$\langle H \rangle = f \qquad SU(4) \to SU(3)$$

$n_G = 15 - 8 = 7$ pNGBs -- 4 of these (H_A) make up SM Higgs

The Twin Top

- Enlarge color to $SU(3)_A \times SU(3)_B \times Z_2$
- Yukawa: $\lambda_t \, H_A \, Q_A \, t^c_A + \lambda_t \, H_B \, Q_B \, t^c_B$

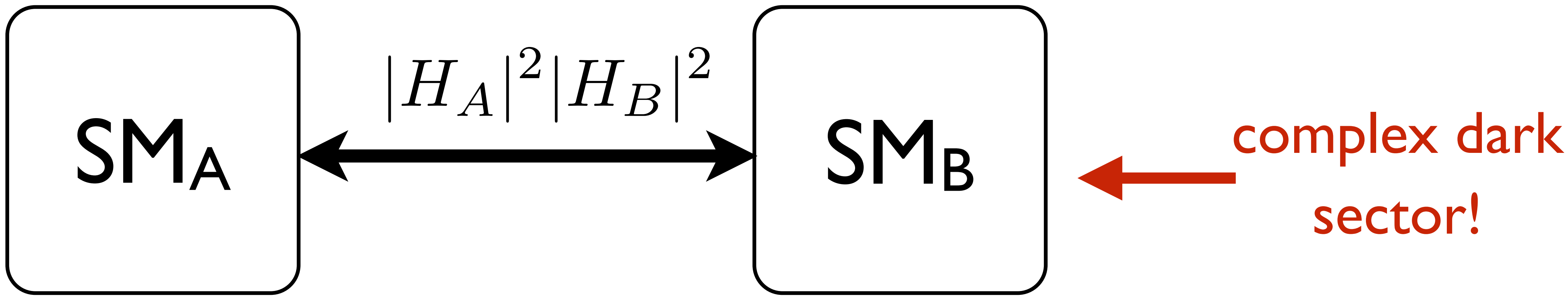
Coupling equality enforced by Z_2

Quadratic divergences: $$-\frac{3\lambda_t^2}{8\pi^2}\Lambda^2(|H_A|^2 + |H_B|^2) = -\frac{3\lambda_t^2}{8\pi^2}\Lambda^2|H|^2$$

Λ^2 respects $SU(4)$ - No mass induced for the pNGB Higgs

Color neutral top partners

Direct searches for top partners evaded!



Neutral naturalness models provide concrete, motivated examples of rich dark sectors!

- Many possibilities for neutrino mass generation
- Variety of dark matter candidates
- Novel effects on cosmology
- Dark sector astrophysics
- Rich phenomenology

[see review article, 2203.05531]

Outlook

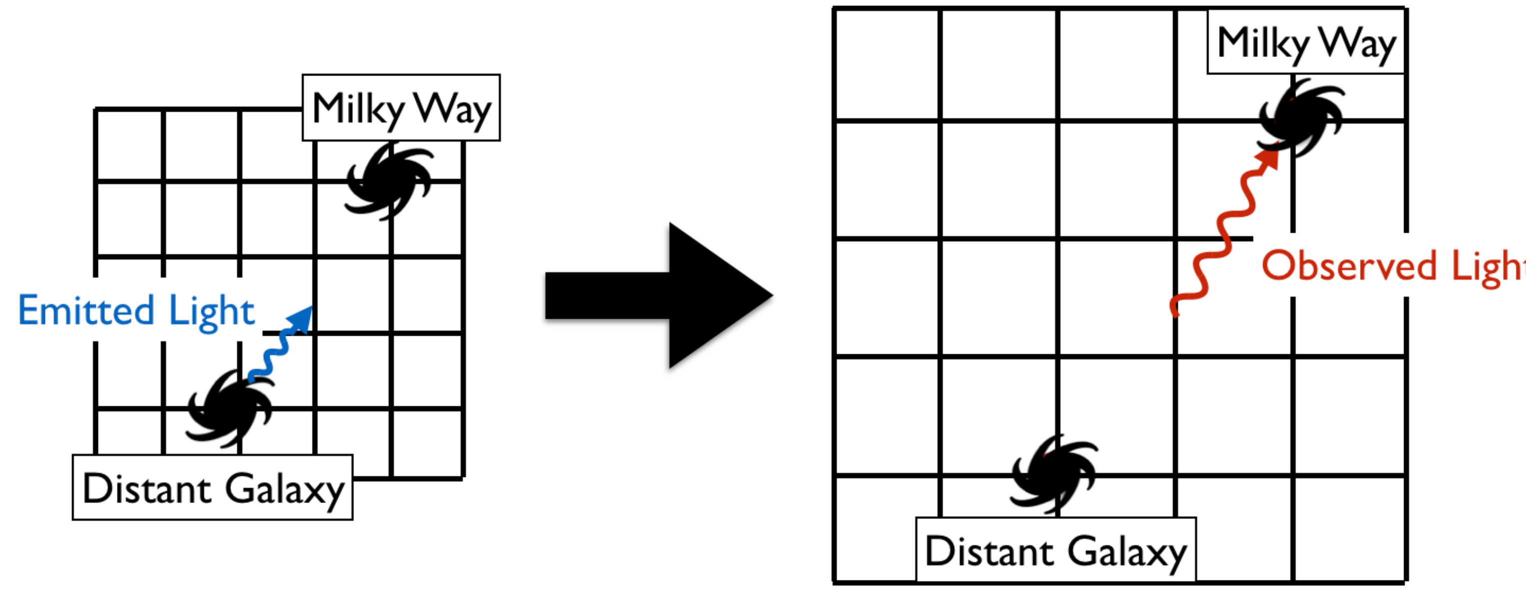
- There are many open problems that cannot be addressed within the Standard Model - dark sectors may provide solutions
- Thermal dark matter implies coupling between DM and SM; requires new mediators, interactions for masses below ~ GeV
- Dark sectors provide an interesting playground for BSM explanations of experimental anomalies, such as the muon anomalous magnetic moment
- Dark sectors may also play a role in addressing other questions, such as naturalness
- Testing these scenarios requires an array of complementary experimental strategies. There is still plenty of room for new ideas!

This is a very active field - stay tuned for more exciting developments!

Backup

FRW cosmology

- Our universe is expanding



- Expansion is encoded in the scale factor a(t)

$$ds^2 = g_{\mu\nu}(x)dx^\mu dx^\nu = -dt^2 + a(t)^2 d\mathbf{x}^2$$

- Dynamics governed by Einstein's equations

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi G T_{\mu\nu}$$

Friedmann Equation:

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho$$

- Three types of fluids influence the expansion: radiation, matter, and vacuum energy

Estimation of relic density

- Dark matter freeze-out occurs when the annihilation rate falls below the expansion rate

$$H(T_f) = \langle \sigma v \rangle n_\chi$$

Estimation of relic density

- Dark matter freeze-out occurs when the annihilation rate falls below the expansion rate

$$H(T_f) = \langle \sigma v \rangle n_\chi$$

- At early times, universe is radiation dominated

(Friedmann Eq)

$$H^2 = \frac{8\pi\rho}{3M_P^2}$$

(Radiation Energy density)

$$\rho = \frac{\pi^2}{30} g_* T^4$$

$$\Rightarrow \quad H \sim g_*^{1/2} \frac{T^2}{M_P}$$

$$\Rightarrow \quad n_\chi \sim g_*^{1/2} \frac{T_f^2}{M_P \langle \sigma v \rangle}$$

Estimation of relic density

- DM freeze-out occurs when the annihilation rate falls below the expansion rate

$$H(T_f) = \langle \sigma v \rangle n_\chi$$

- At early times, universe is radiation dominated

$$n_\chi \sim g_*^{1/2} \frac{T_f^2}{M_P \langle \sigma v \rangle}$$

- Once DM freezes out, the comoving density is constant.

(Comoving density or "yield")

$$Y_\chi = \frac{n_\chi}{s}$$

(Entropy density)

$$s = \frac{2\pi^2}{45} g_{*S} T^3$$

$$\Rightarrow \quad Y_\chi \sim g_*^{-1/2} \frac{1}{M_P \langle \sigma v \rangle T_f}$$

Estimation of relic density

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$$H(T_f) = \langle \sigma v \rangle n_\chi$$

- At early times, universe is radiation dominated

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- Once DM freezes out, the comoving density is constant.

$$Y_\chi \sim g_*^{-1/2} \frac{1}{M_P \langle \sigma v \rangle T_f}$$

- DM energy density today

(DM energy density)

$$\rho_\chi = m_\chi n_\chi = m_\chi Y_\chi s$$

(Critical energy density)

$$\rho_c = \frac{3 M_P^2 H^2}{8\pi}$$

freeze-out temp fraction

$$x_f = \frac{m_\chi}{T_f}$$

➡

$$\Omega_\chi = \left.\frac{\rho_\chi}{\rho_c}\right|_{T_0} = \frac{8\pi m_\chi Y_\chi s_0}{3 M_P^2 H_0^2} \sim g_*^{-1/2} \frac{x_f}{M_P^3 \langle \sigma v \rangle} \frac{s_0}{H_0^2}$$

Estimation of relic density

- DM freeze-out occurs when the annihilation rate falls below the expansion rate

$$H(T_f) = \langle \sigma v \rangle n_\chi$$

- At early times, universe is radiation dominated

$$n_\chi \sim g_*^{1/2} \frac{T_f^2}{M_P \langle \sigma v \rangle}$$

- Once DM freezes out, the comoving density is constant.

$$Y_\chi \sim g_*^{-1/2} \frac{1}{M_P \langle \sigma v \rangle T_f}$$

- DM energy density today

$$\begin{aligned}\Omega_\chi &\sim 30 \frac{x_f}{g_*^{1/2} M_P^3 \langle \sigma v \rangle} \frac{s_0}{H_0^2} \\ &\approx 0.1 \left(\frac{100}{g_*}\right)^{1/2} \left(\frac{x_f}{20}\right) \left(\frac{\text{pb}}{\langle \sigma v \rangle}\right)\end{aligned}$$

- Compare to measured value from CMB, $\Omega_\chi \simeq 0.27$; correct abundance obtained if

$$\langle \sigma v \rangle \sim 1\,\text{pb} \sim 3 \times 10^{-26}\,\text{cm}^3\,\text{s}^{-1}$$