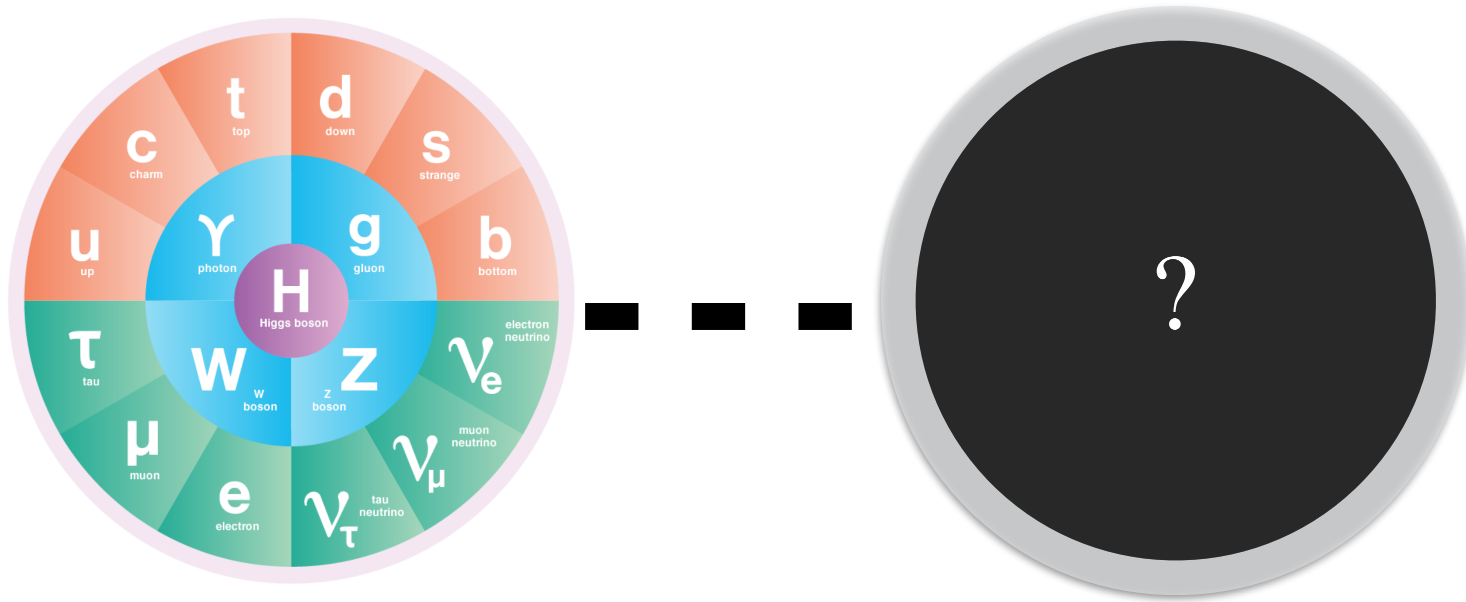
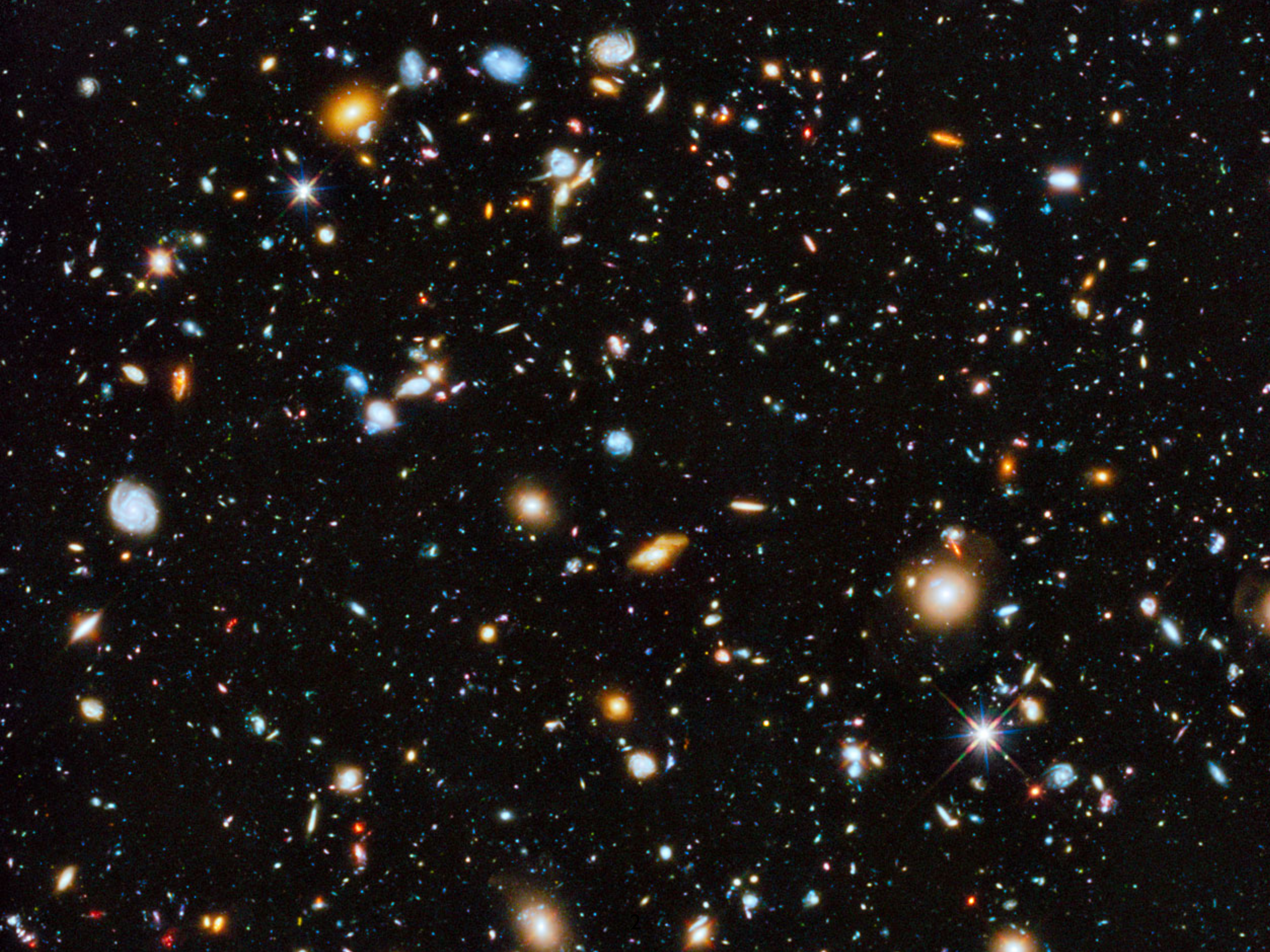
Portals to the Dark Sector

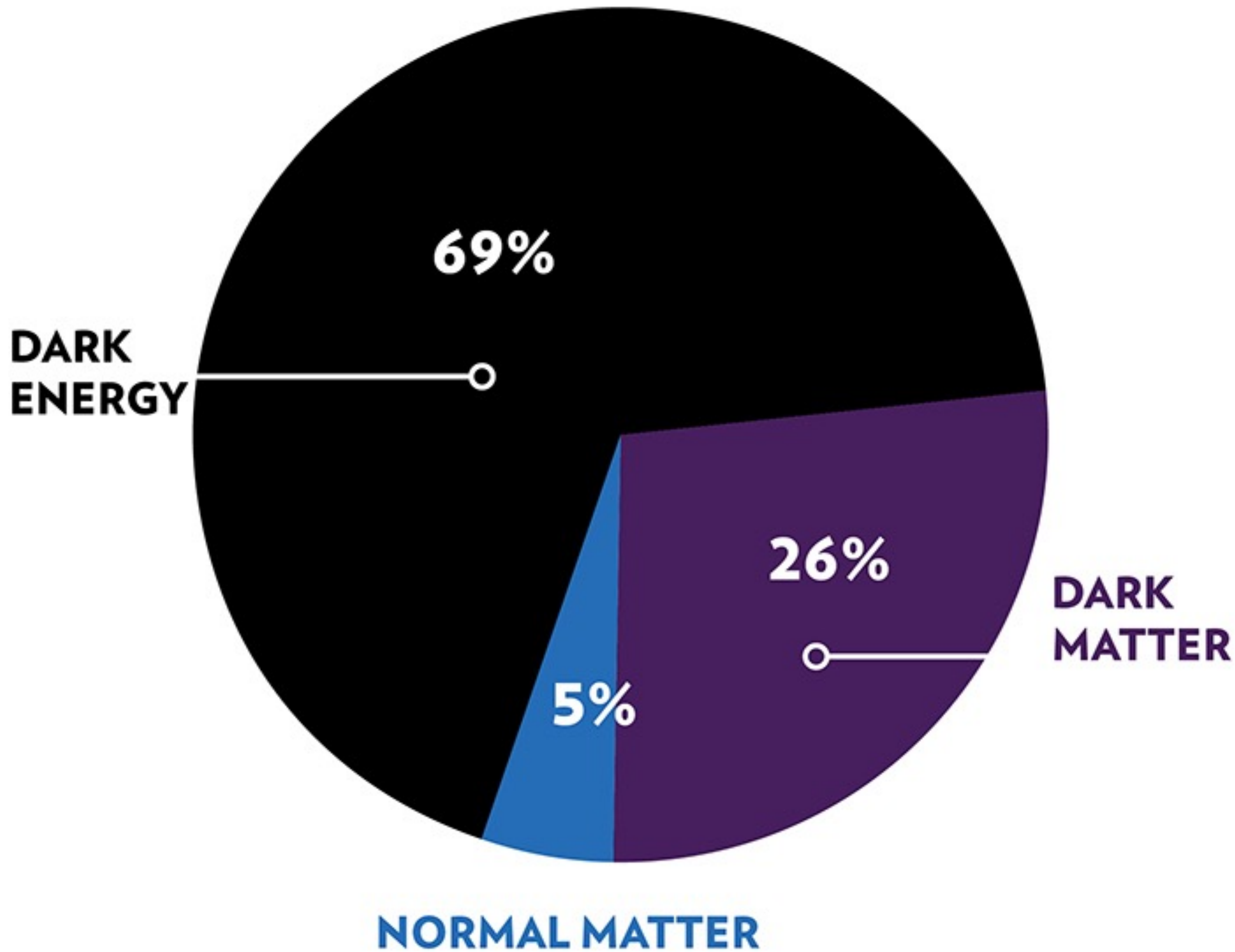


Brian Batell
University of Pittsburgh

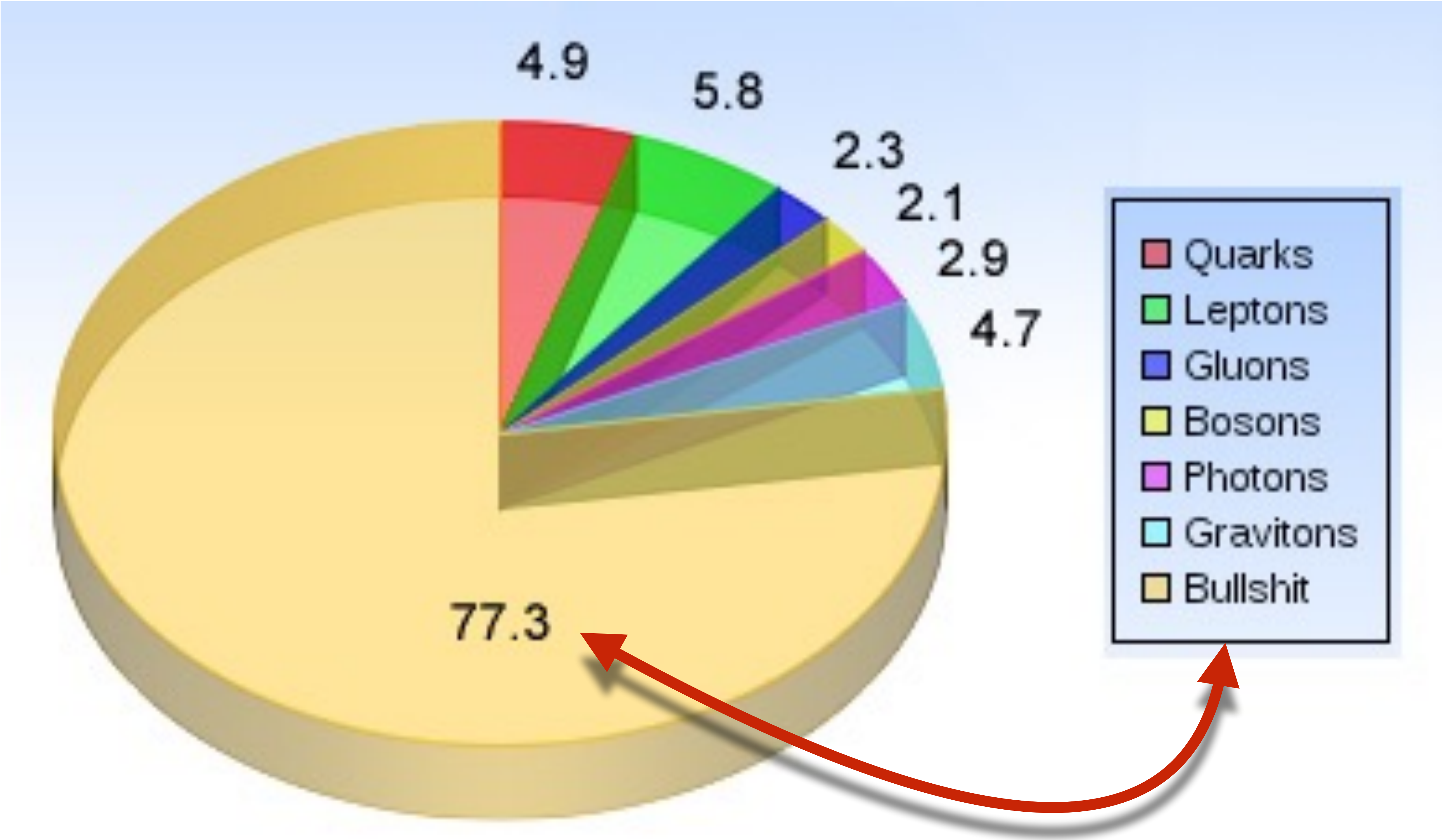
GGI Tea Breaks Theory Colloquium
March 24, 2021



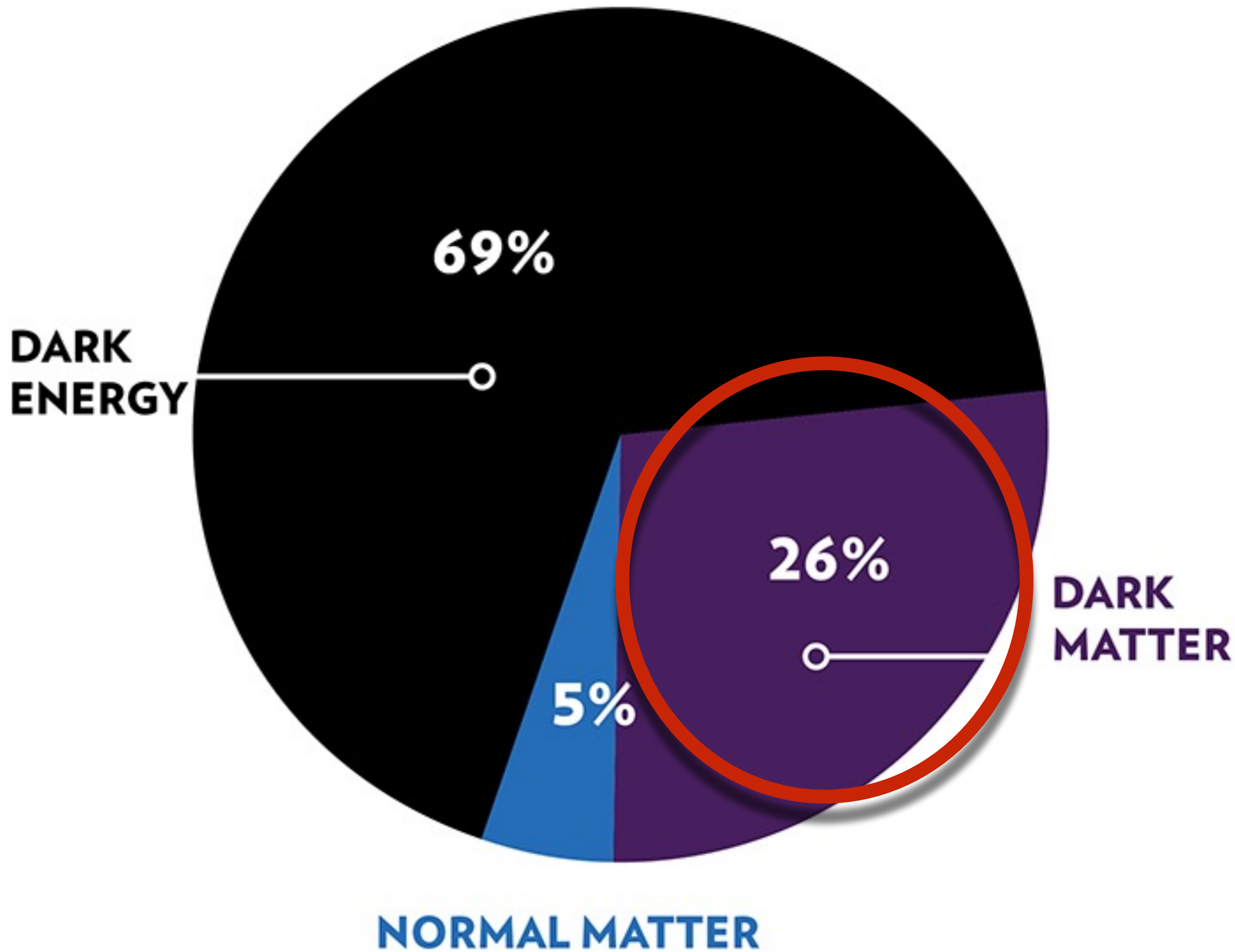
The Energy Budget of the Universe



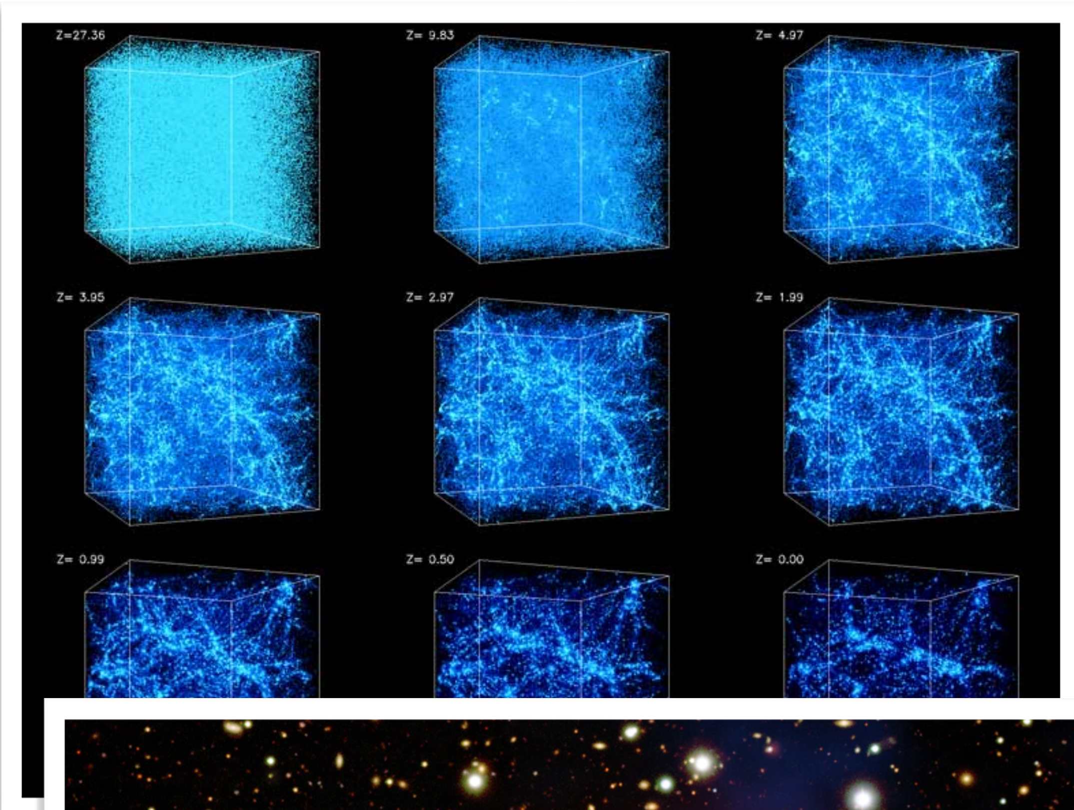
We've made progress in our understanding...

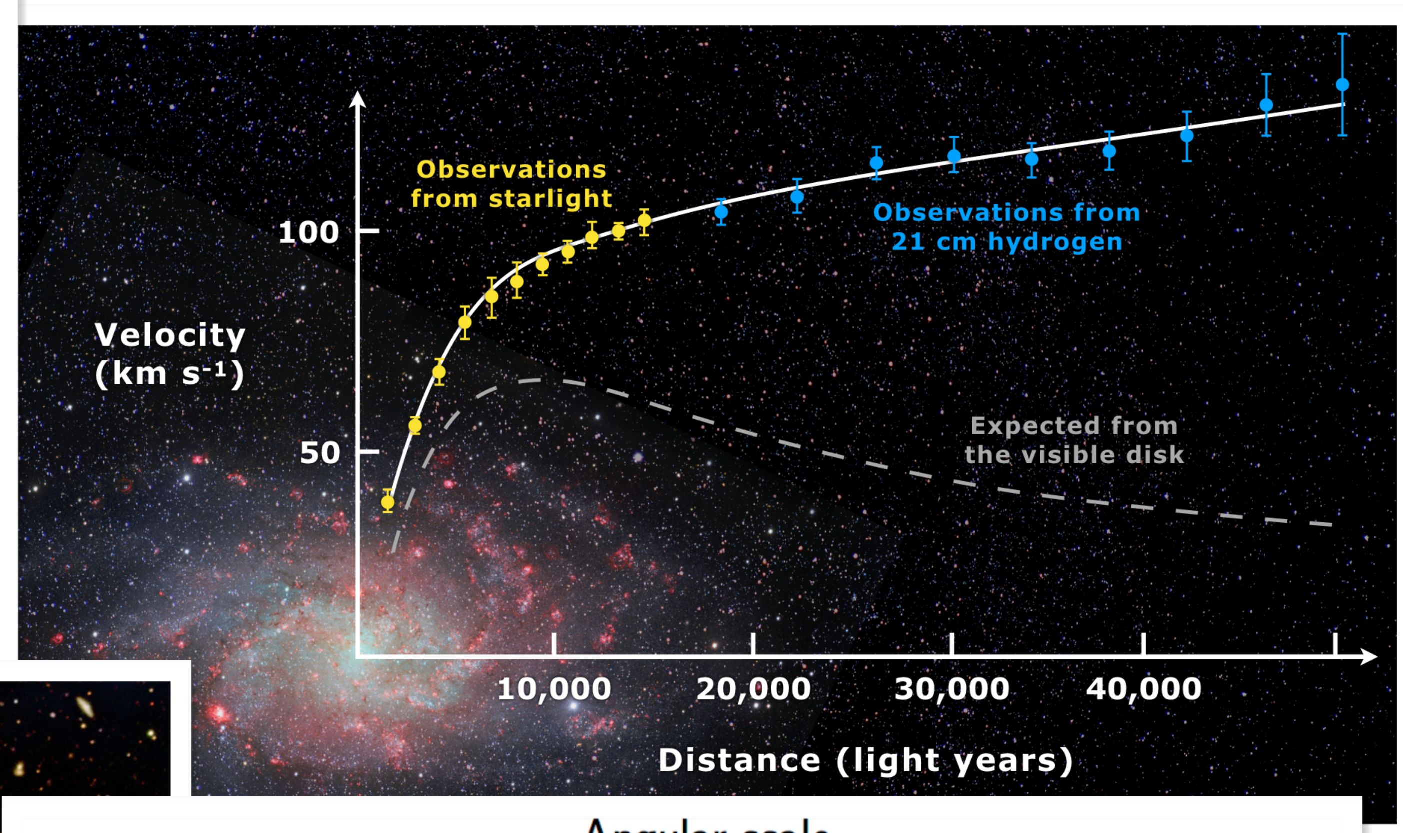


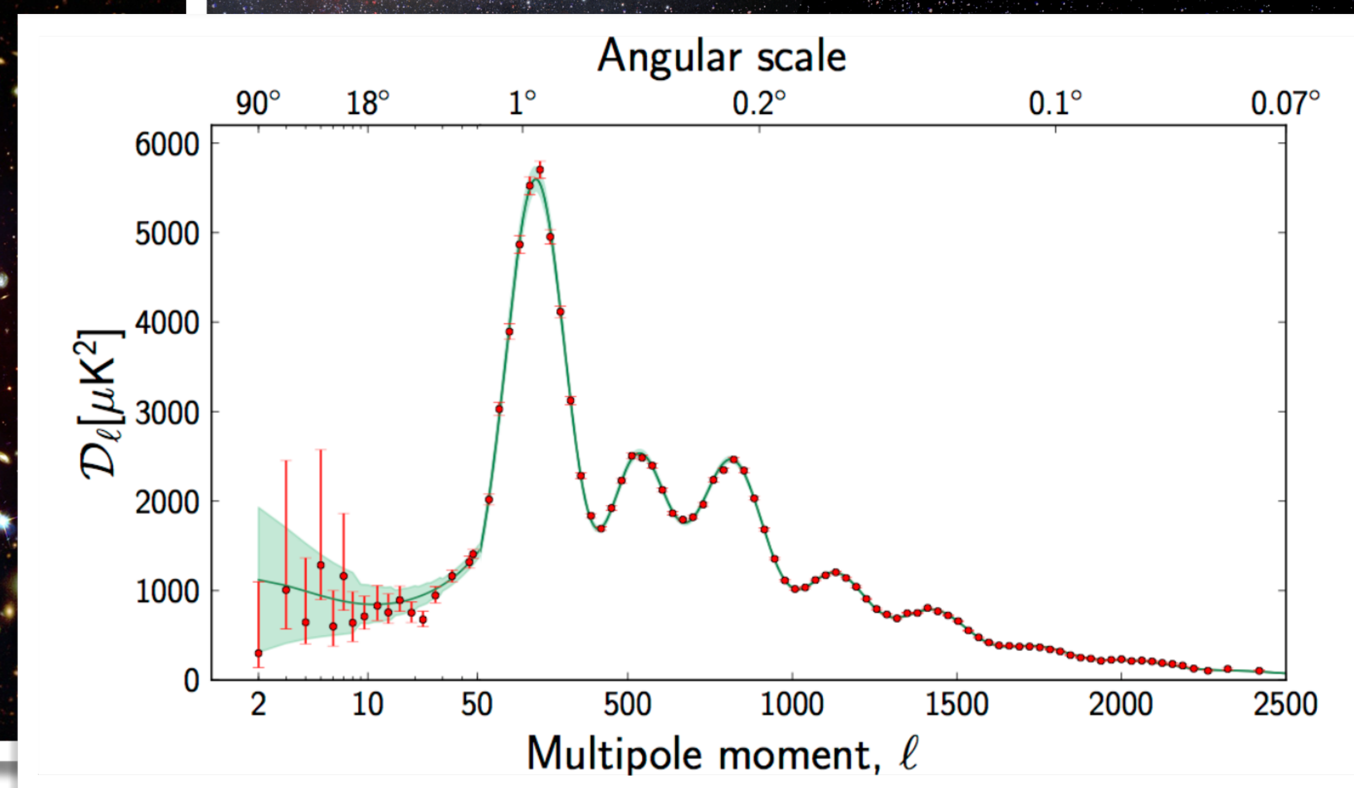
Dark Matter



Gravitational Evidence for Dark Matter

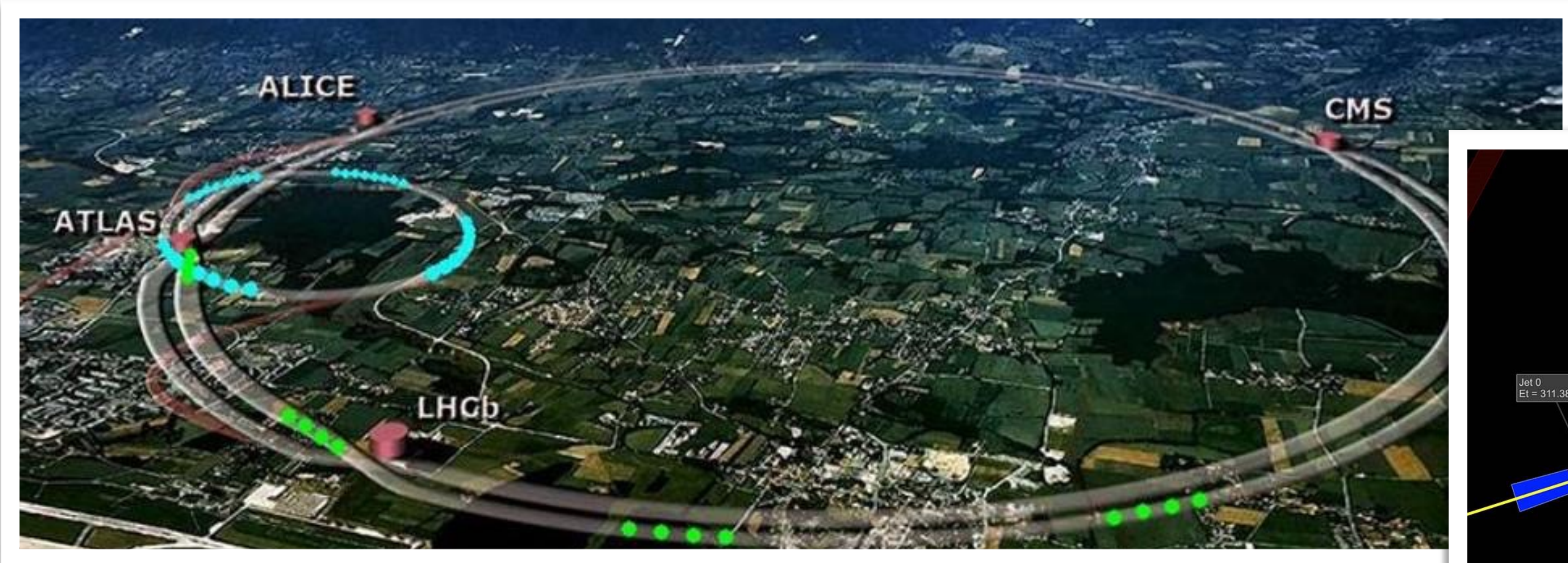


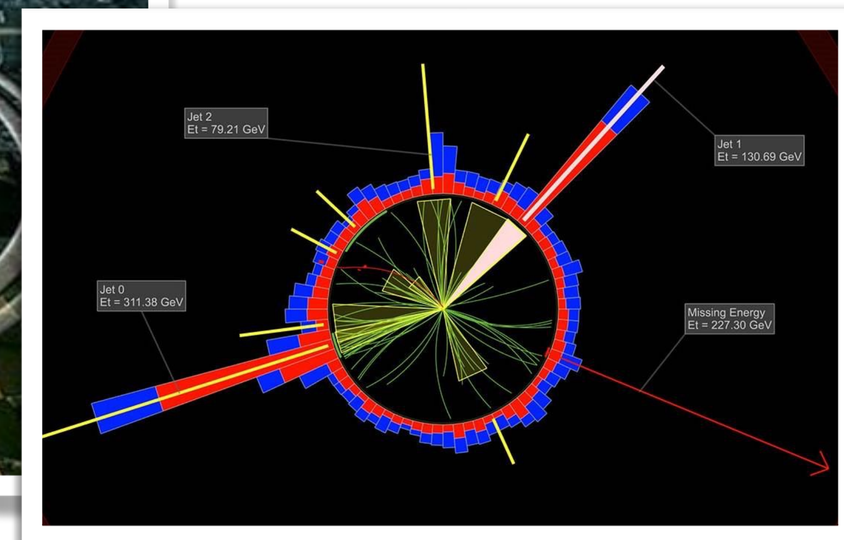


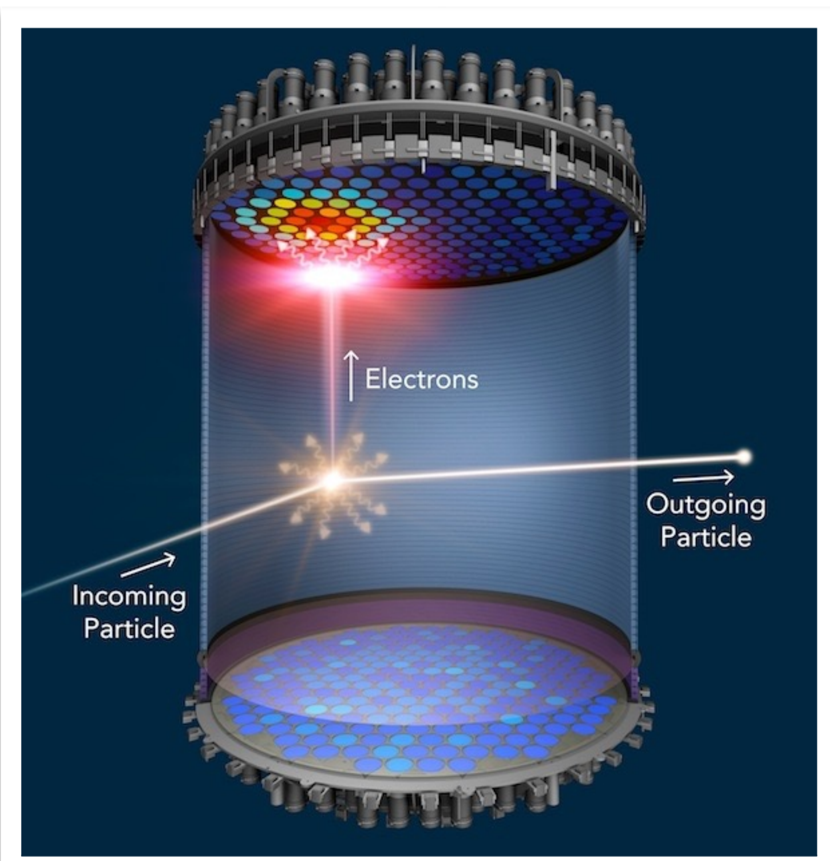


The search for non-gravitational dark matter interactions is a top priority today

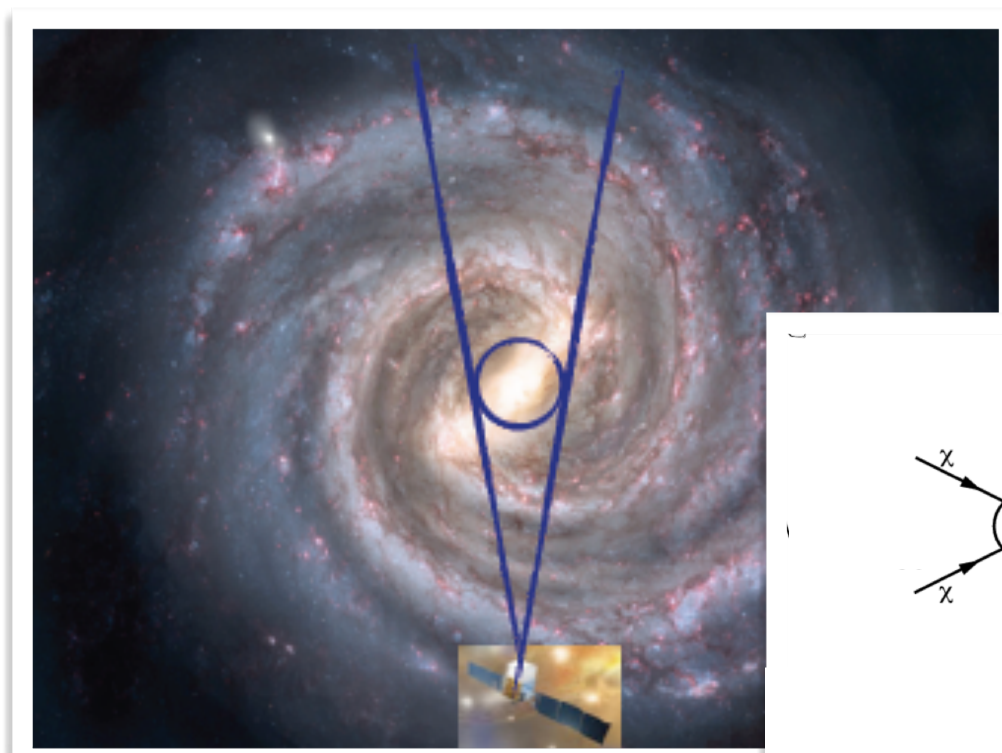
Collider



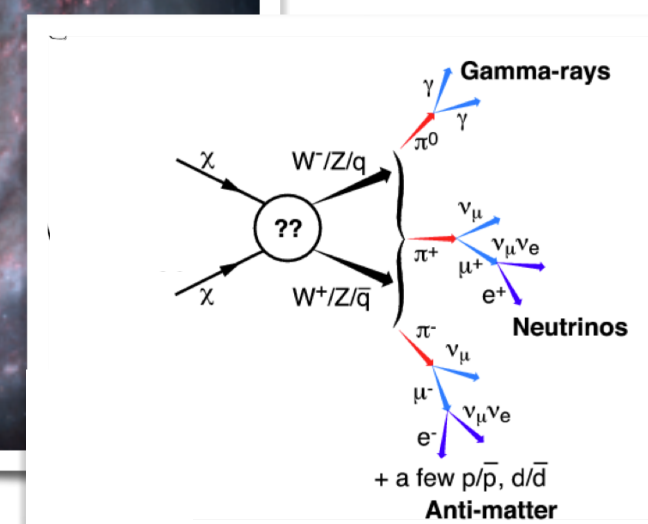




Direct Detection



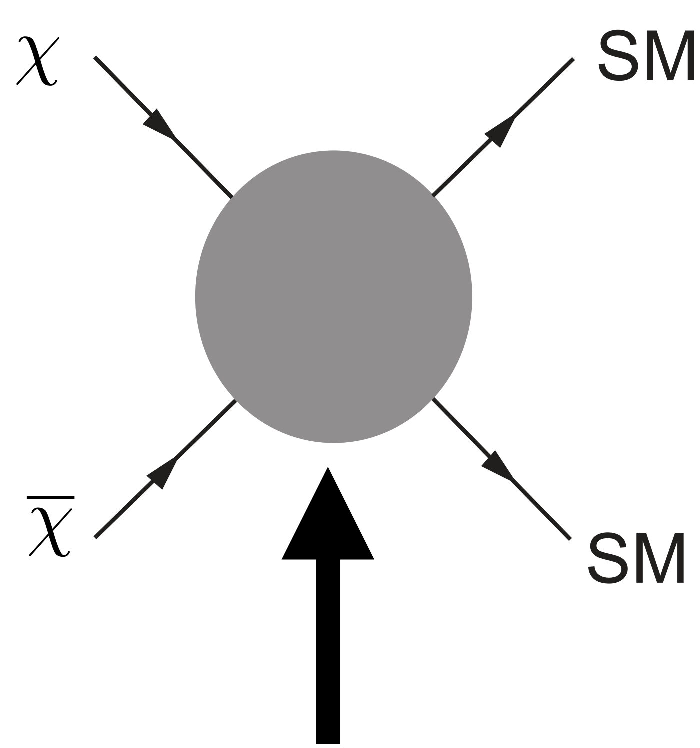
Indirect Detection



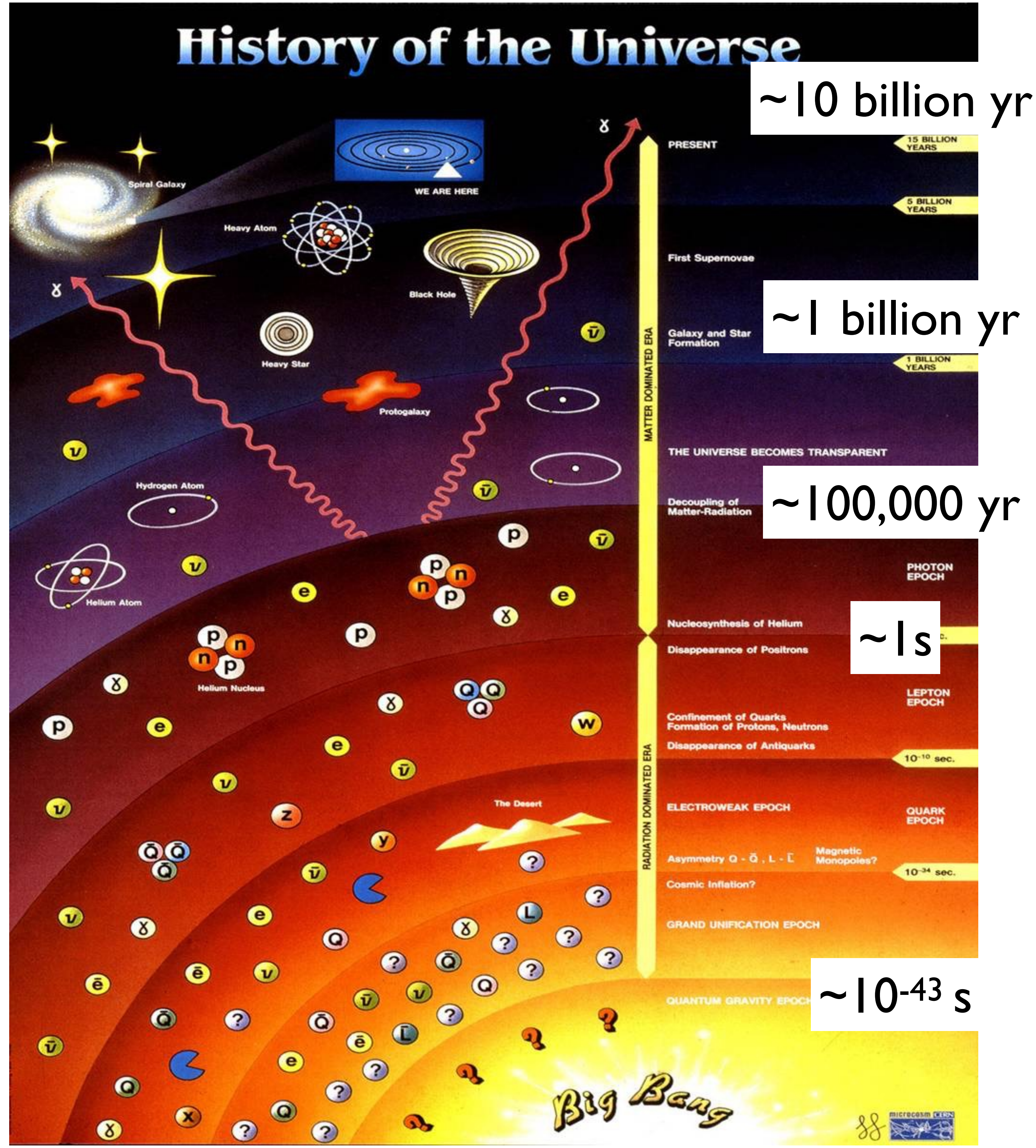
Is there any good reason to expect dark matter to have non-gravitational interactions?

Cosmological Genesis of Dark Matter

Dark matter may have been produced from particle reactions in the hot plasma during the Big Bang



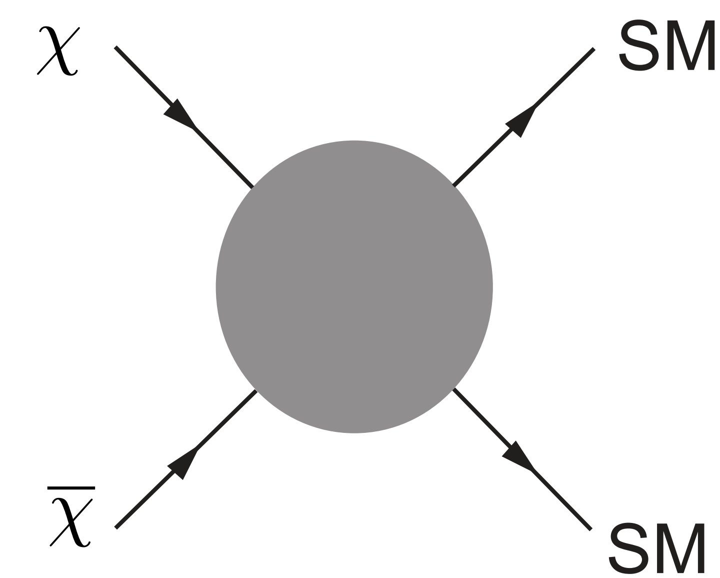
Suggests non-gravitational interactions with normal matter

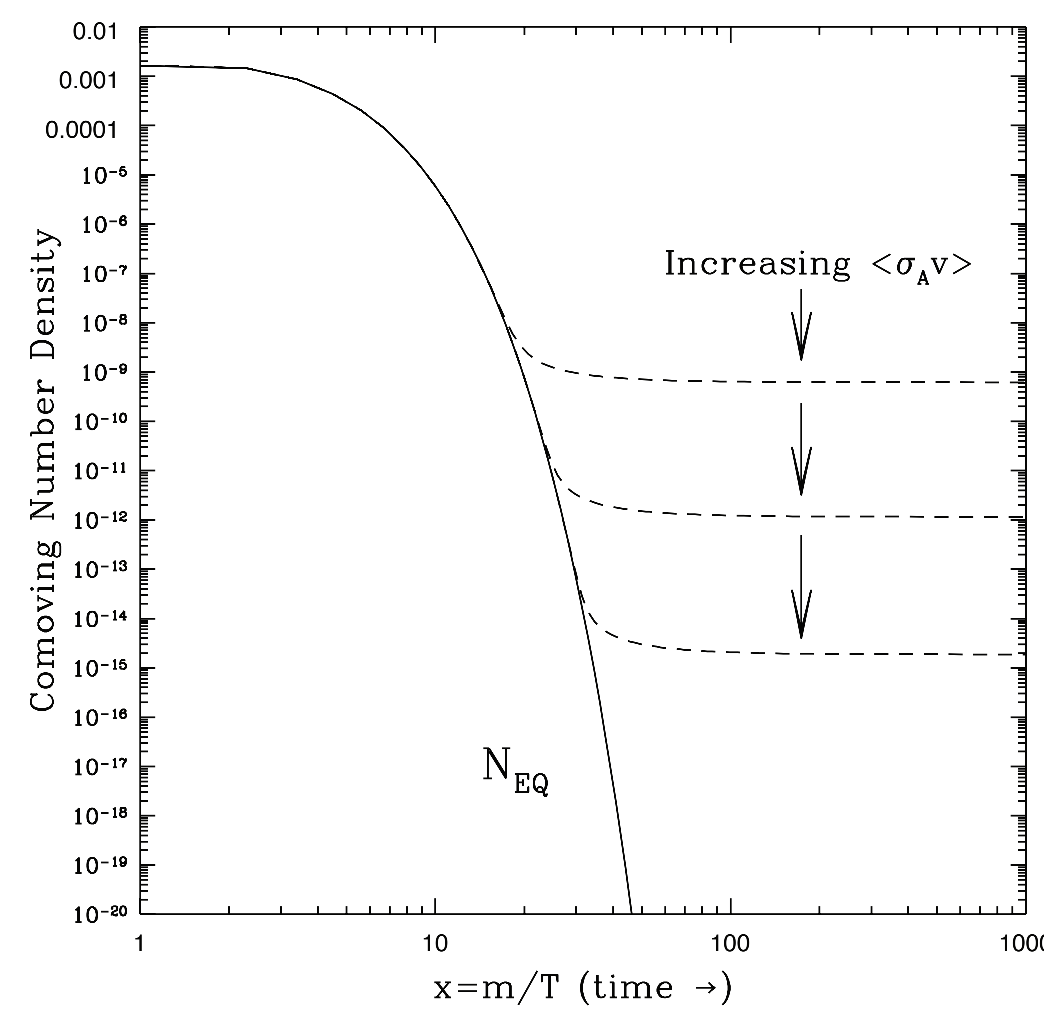


Dark Matter as a Thermal Relic

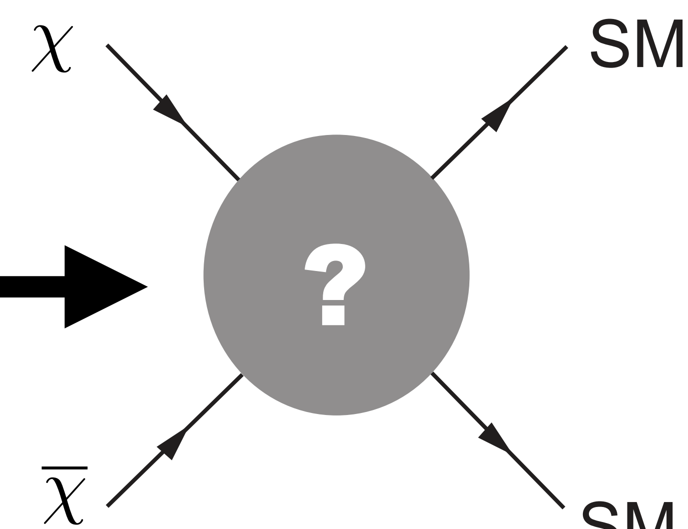
- At early times, $T \gg m_\chi$, both DM annihilation and production (inverse annihilation) are efficient
- As temperature drops, $T \lesssim m_\chi$, DM production is kinematically disfavored, and DM begins to annihilate away
- Eventually, DM freeze-out occurs when annihilation rate becomes smaller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

$$\Omega_\chi h^2 \sim 0.1 \left(\frac{\text{pb}}{\langle \sigma v \rangle} \right)$$



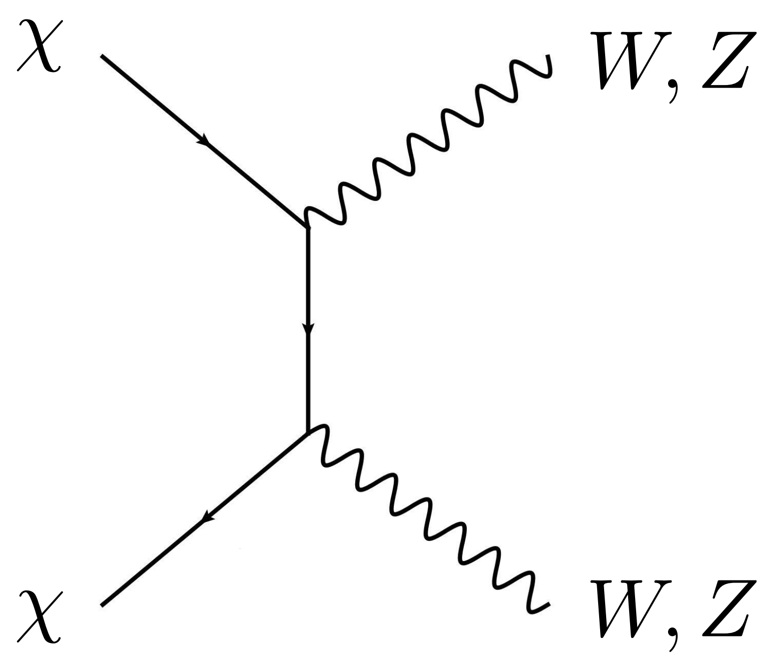


What's here?



Weakly Interacting Massive Particle (WIMP)

- Dark matter may be charged under the electroweak interaction (e.g., neutralino in the MSSM)

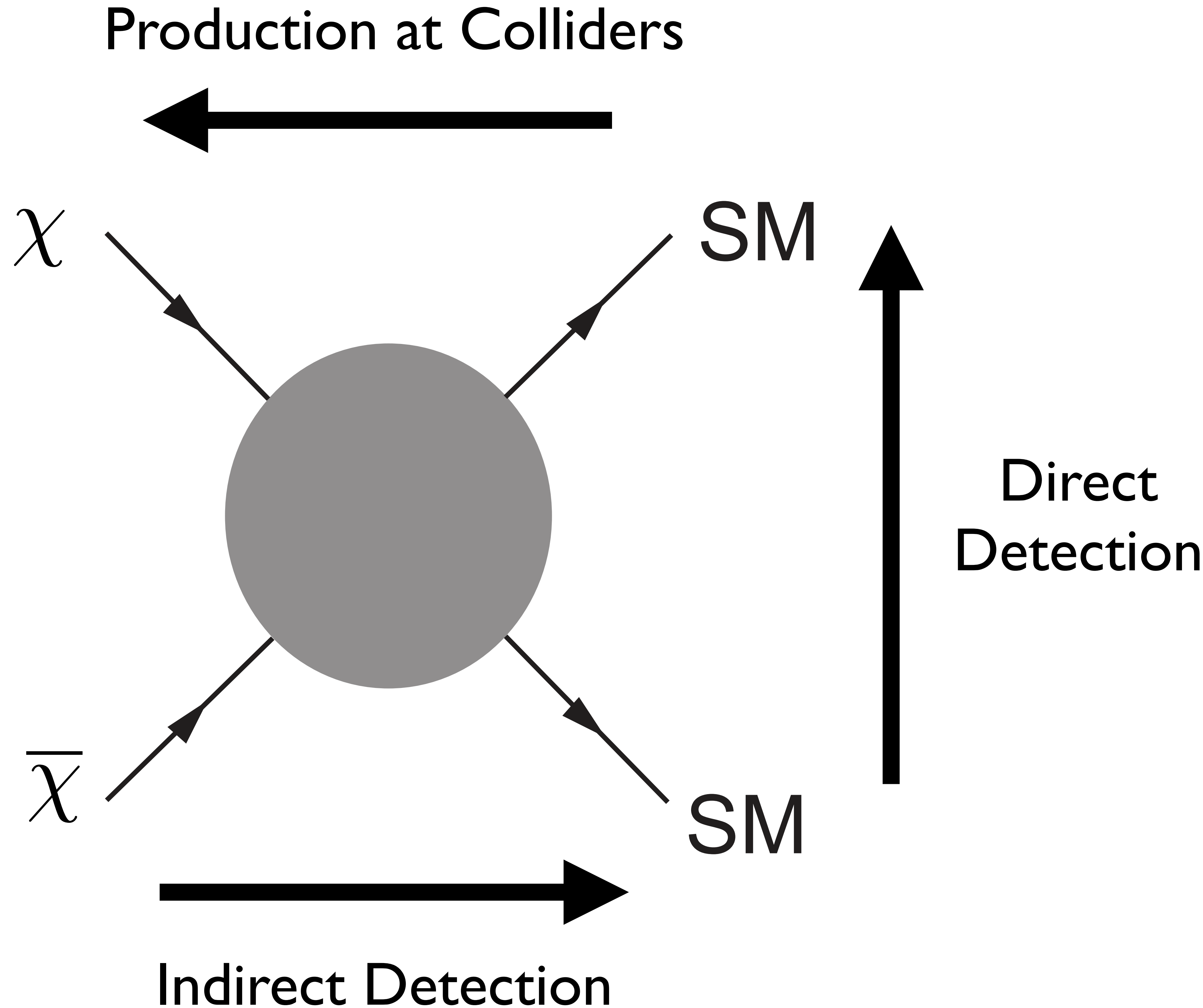


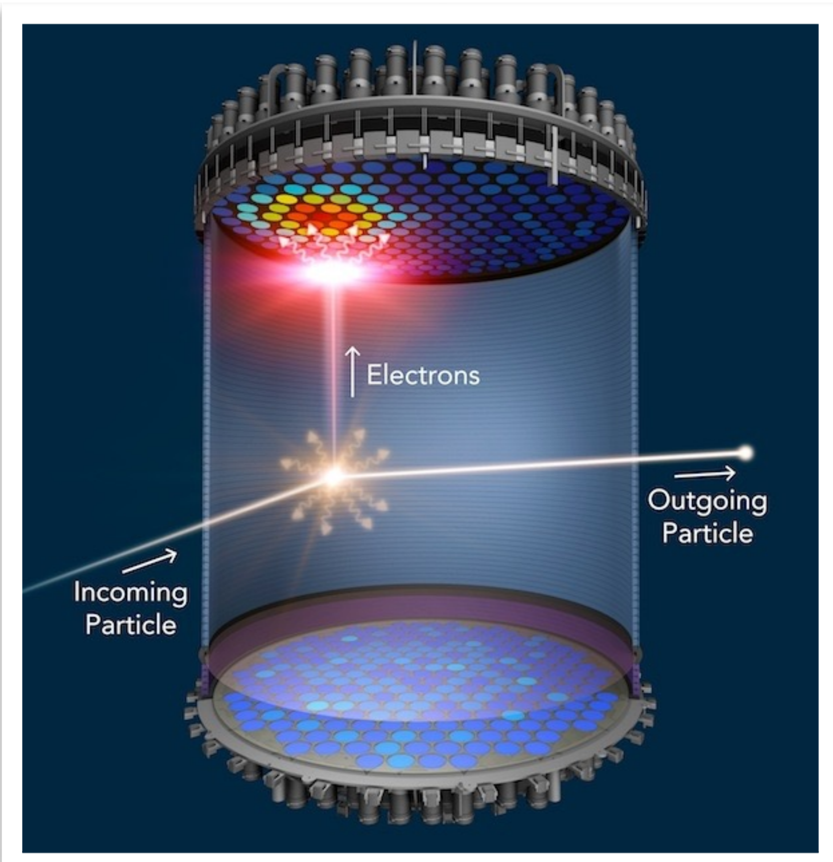
$$\langle \sigma v \rangle \sim \frac{\pi \alpha_W^2}{m_\chi^2} \sim 1\,\mathrm{pb} \times \left(\frac{\alpha_W}{(1/30)} \right)^2 \left(\frac{\mathrm{TeV}}{m_\chi} \right)^2$$

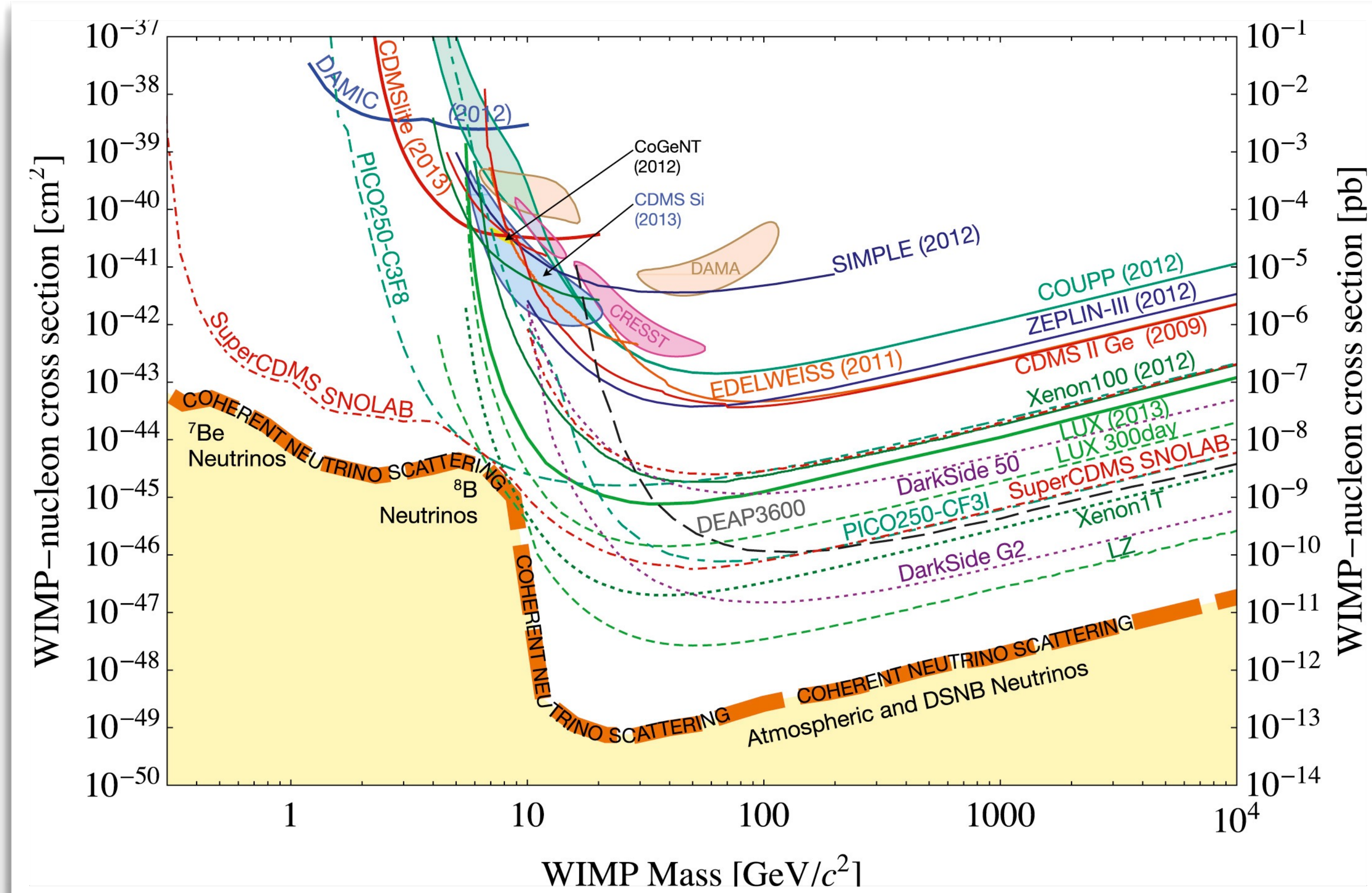
- Dark matter with weak interactions and weak scale mass is produced with the observed relic abundance

$\Rightarrow$ **“WIMP Miracle”**

WIMP Phenomenology







[Phys. Dark Univ., 4, (2014) 92-97]

So far, there are no signs of WIMPs

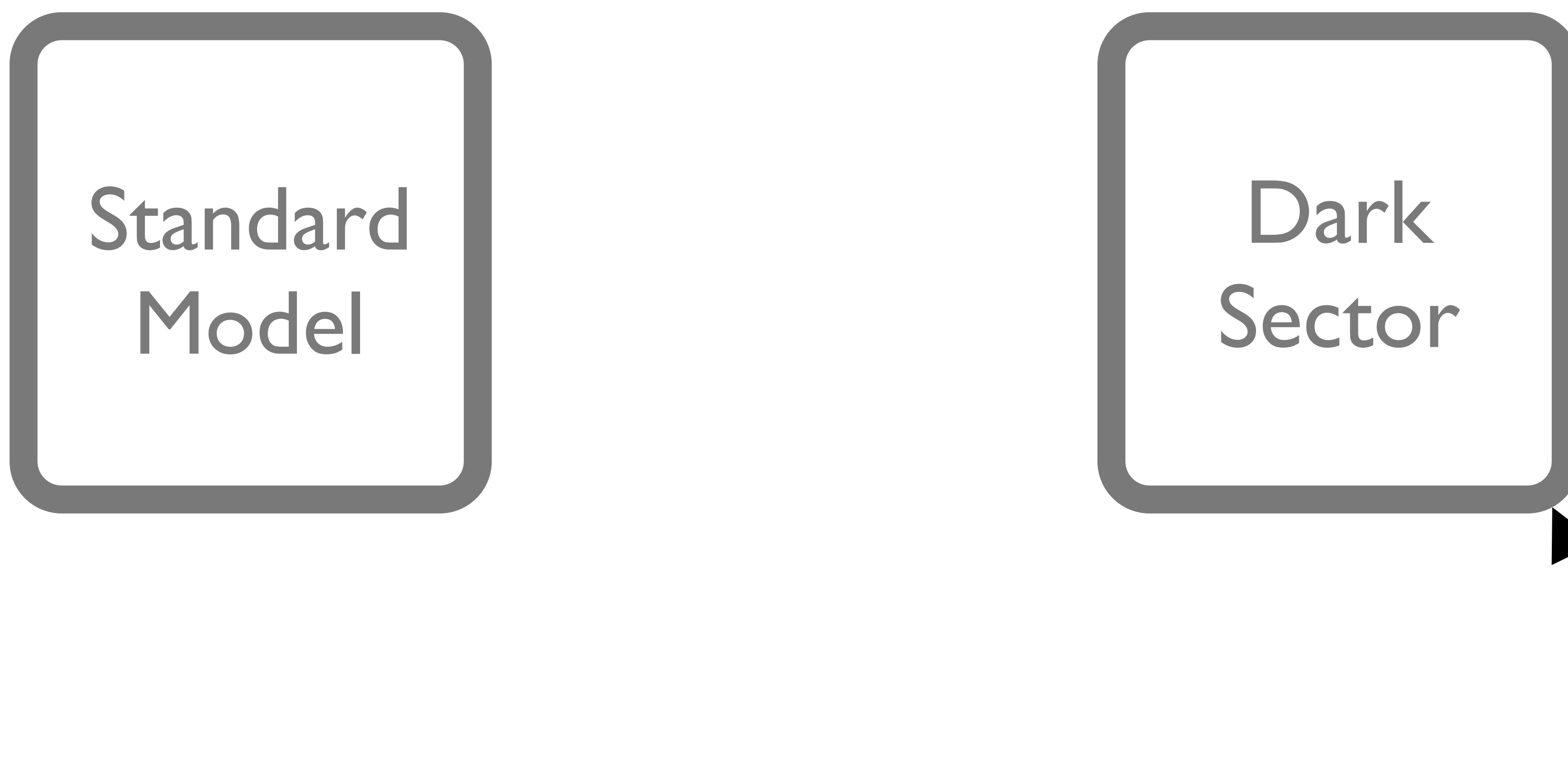
The WIMP framework is well-motivated and we should continue searching for WIMPs

It's also time to open our minds and consider other possibilities for dark matter

What if dark matter does not experience the known forces of nature?

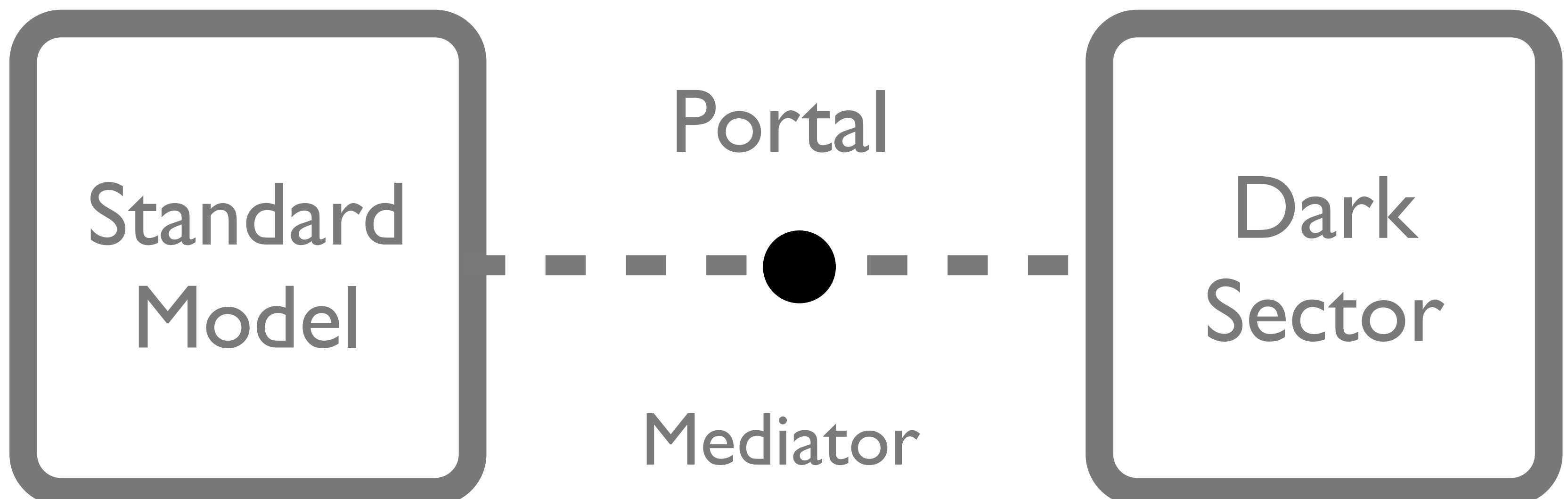
The Dark Sector Paradigm

The Dark Sector Paradigm



- Dark matter
- Dark forces
- Other dark particles

The Dark Sector Paradigm

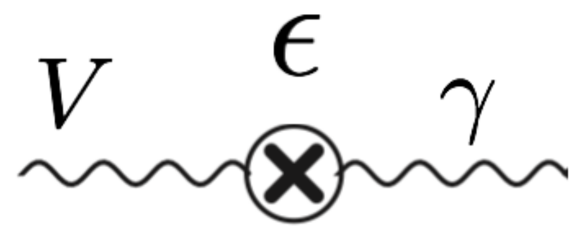


Non-gravitational interaction with ordinary matter

- Dark matter
- Dark forces
- Other dark particles

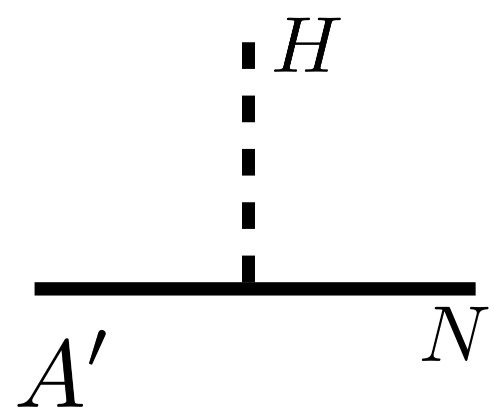
Portals

$$\frac{\epsilon}{2}F_{\mu\nu}F'^{\mu\nu}$$



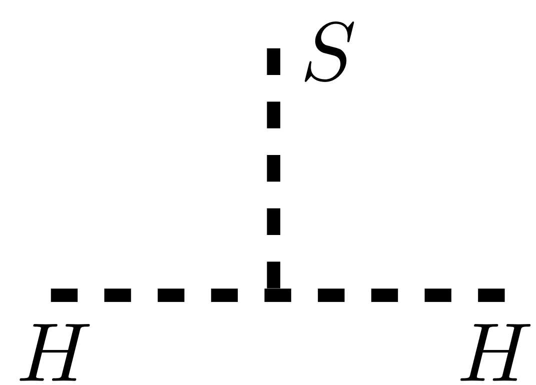
Vector Portal

$$yLHN$$



Neutrino portal

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



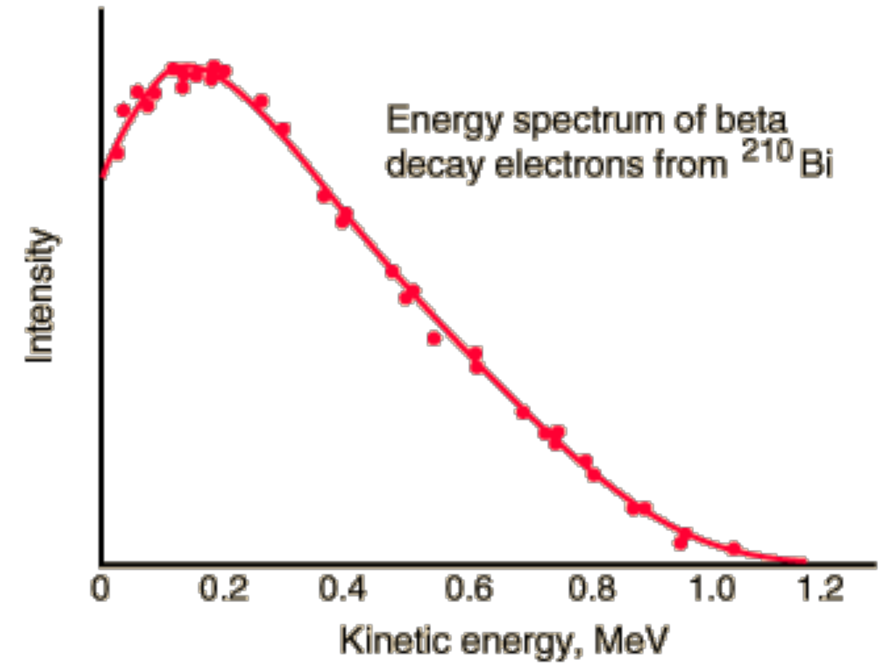
Higgs Portal

Portals may mediate non-gravitational interactions between dark matter and ordinary matter

History lesson - 1930s:

- Back then, the "Standard Model" was photon, electron, nucleons

- Beta decay: $n \to p + e^-$



Continuous spectrum!

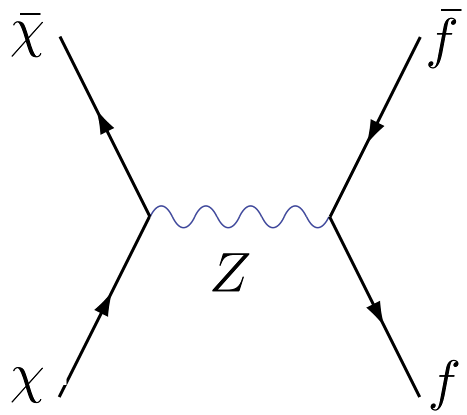
- Pauli proposes a radical solution - the neutrino!

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

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

Lee-Weinberg Bound

Light thermal DM interacting via weak interactions generically overproduced



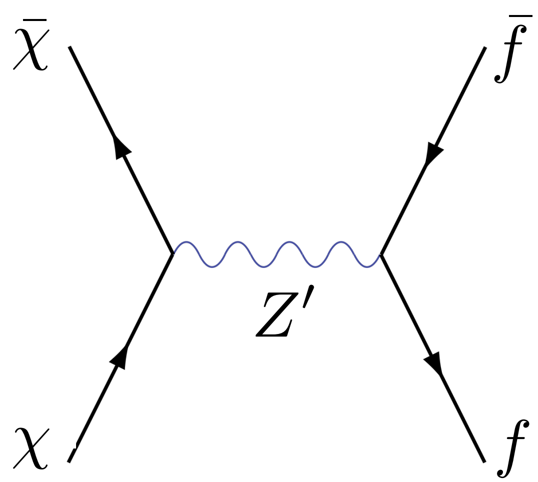
$$\mathcal{L} \sim G_F [\bar{\chi}\, \Gamma\, \chi][\bar{f}\, \Gamma\, f]$$

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

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

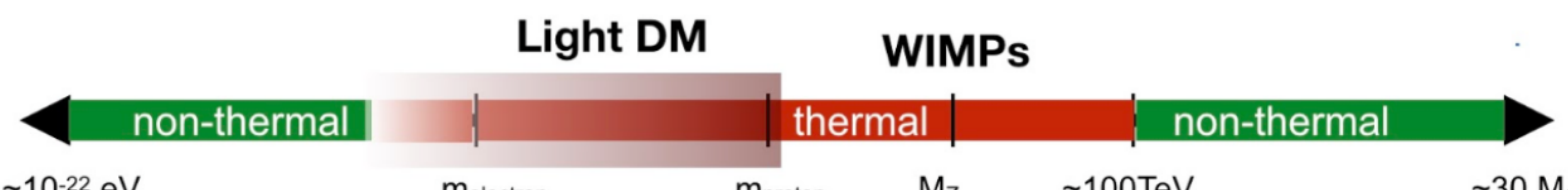
Lee-Weinberg bound evaded with new light mediators

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



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

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

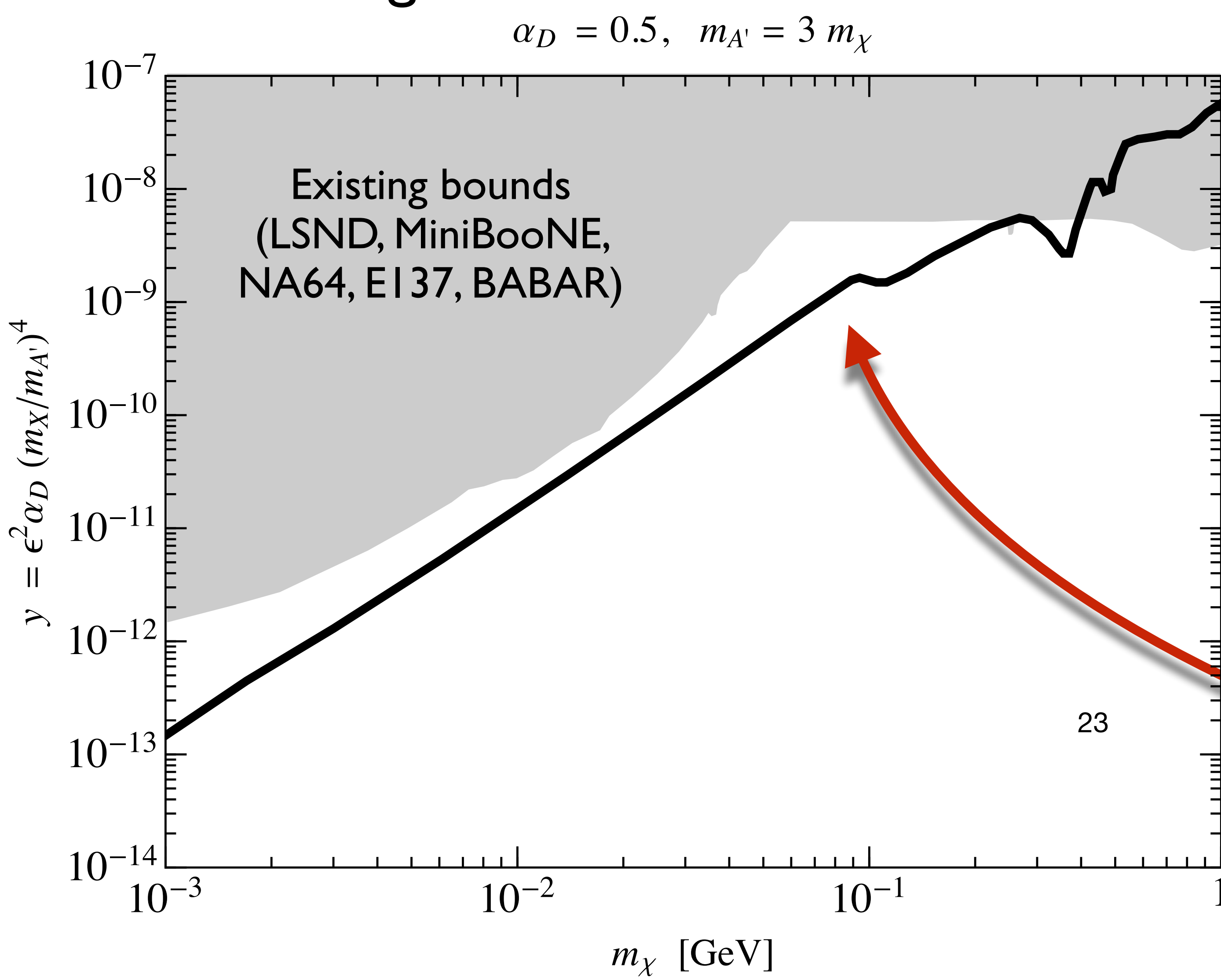


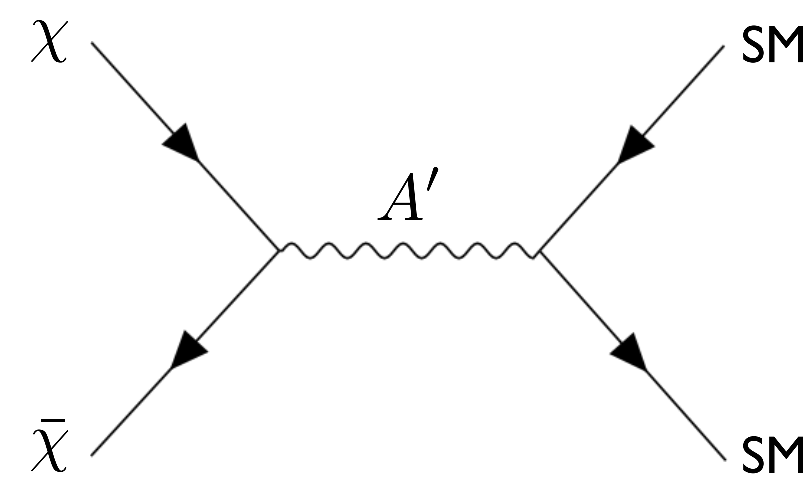
Benchmark model: Vector Portal Dark Matter

[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:





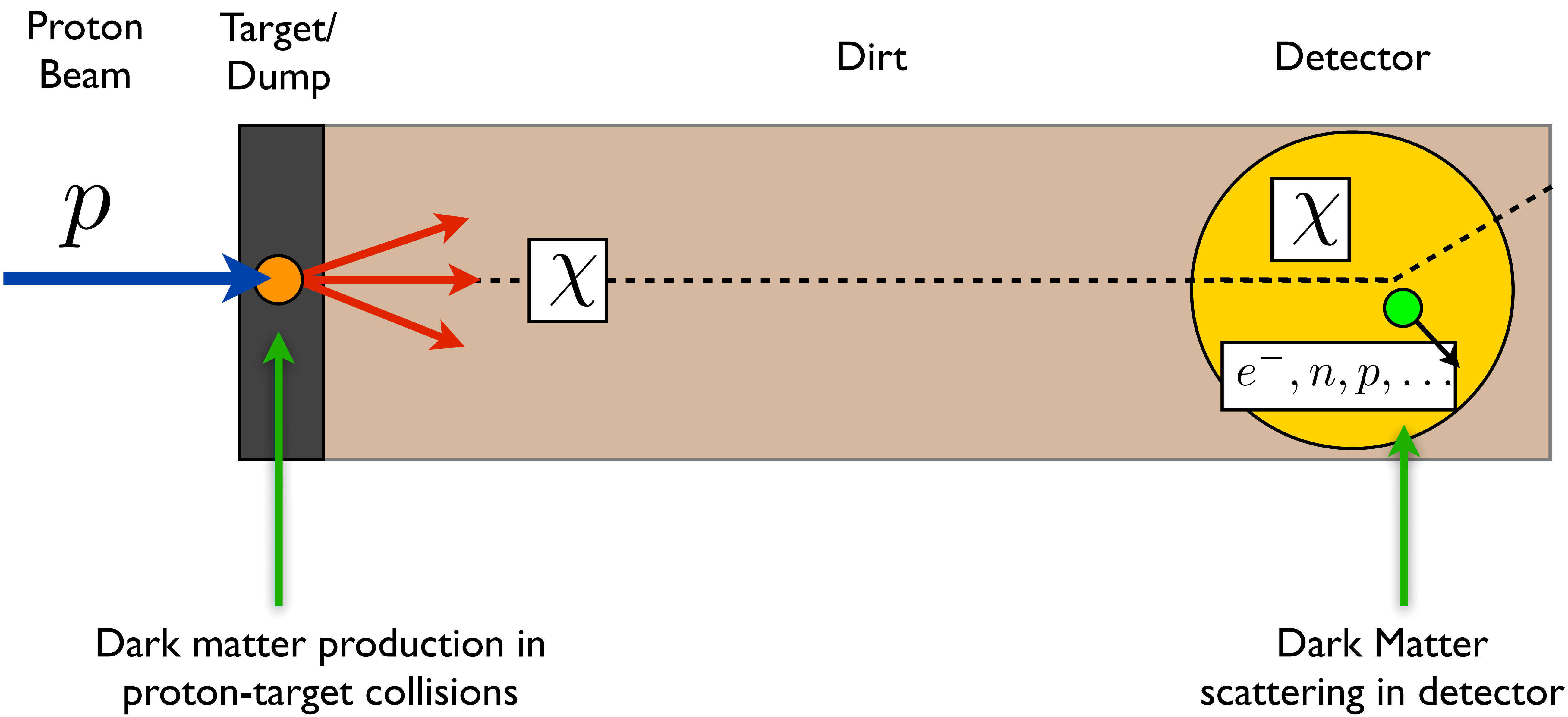
$$\langle \sigma v \rangle \sim \frac{\epsilon^2 \alpha_D \alpha m_\chi^2}{m_V^4} \sim \frac{y}{m_\chi^2}$$

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

Observed DM relic abundance predicted along this line

[Izaguirre, Krnjaic, Schuster, Toro]

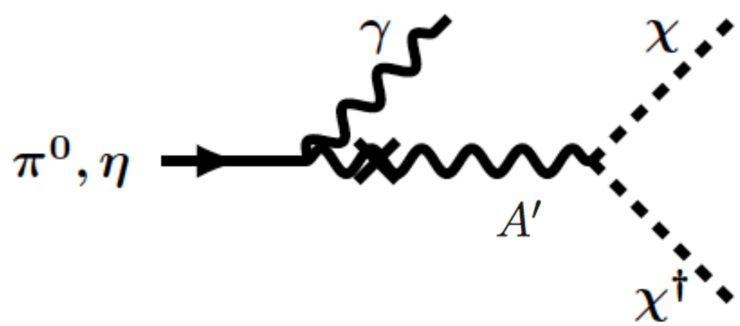
Proton Beam Dump Dark Matter Searches



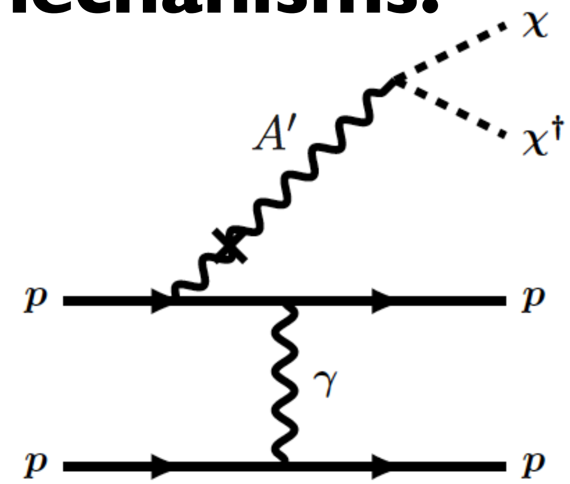
- Can be done with existing and near future accelerator neutrino experiments, e.g., MiniBooNE, NOvA, T2K, MicroBooNE, SBND, ICARUS, DUNE…

[BB, Pospelov Ritz]
[deNiverville, Pospelov Ritz]
[McKeen, deNiverville, Ritz]
[Coloma, Dobrescu, Frugiuele, Harnik]
[Kahn, Krnjaic, Thaler, Toups]
… many others

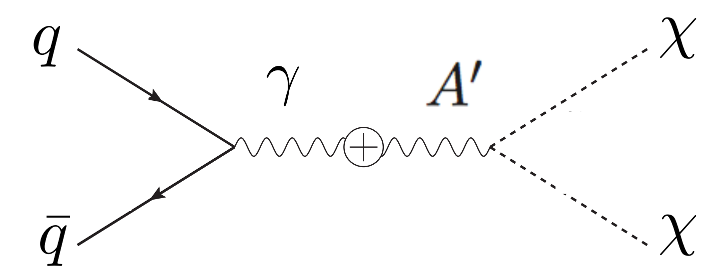
Dark matter production mechanisms:



Neutral mesons decays

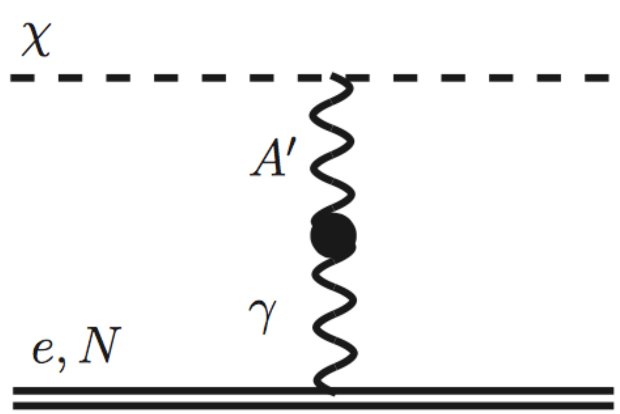


Bremsstrahlung + vector meson mixing

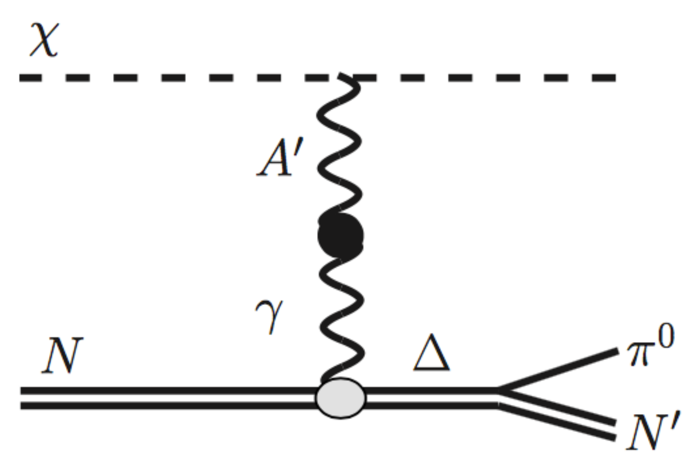


Direct production

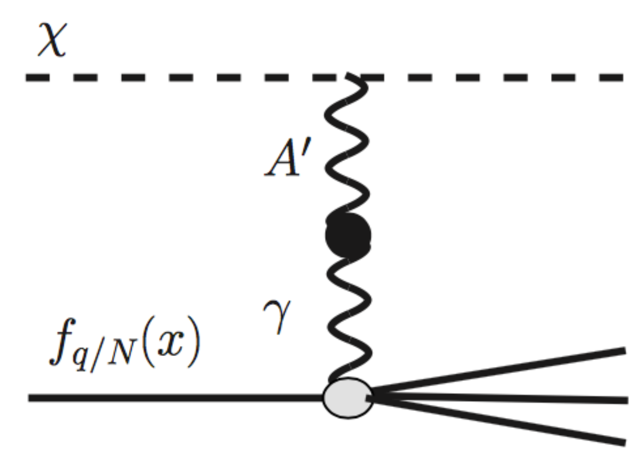
Dark matter detection via scattering:



Elastic electron, nucleon , nucleus (coherent) scattering



Inelastic neutral pion production

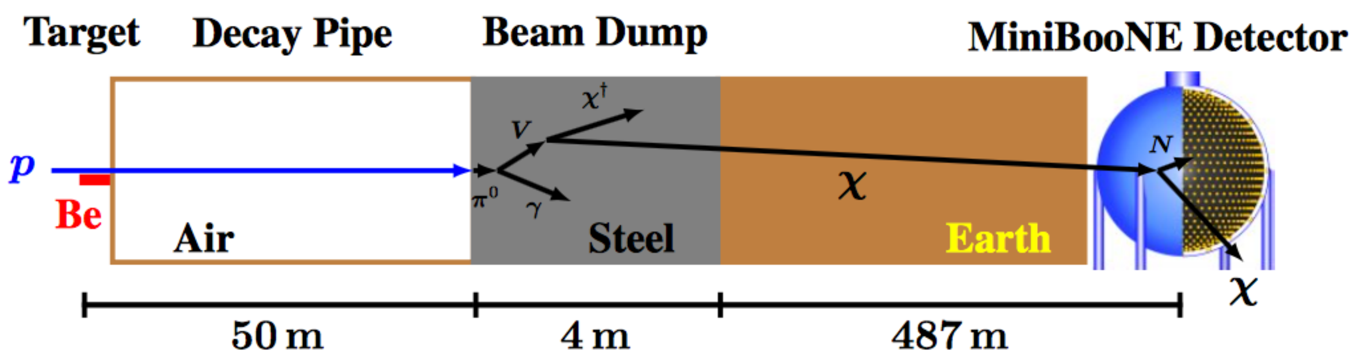


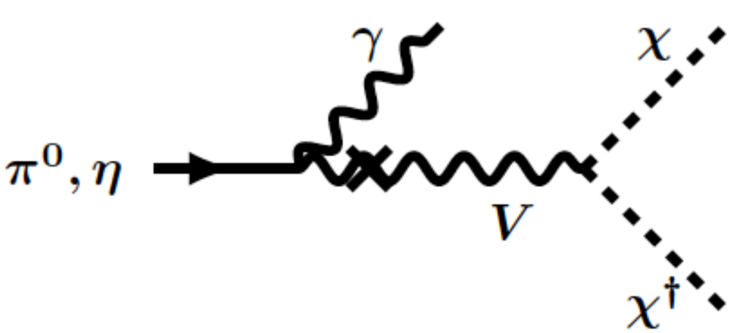
Deep inelastic scattering

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

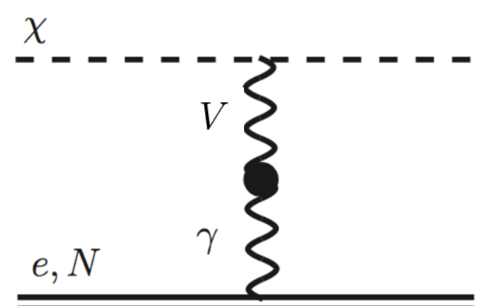
- Publicly available proton beam fixed target DM simulation tool developed by P. deNiverville (LANL)

MiniBooNE-DM @ FNAL

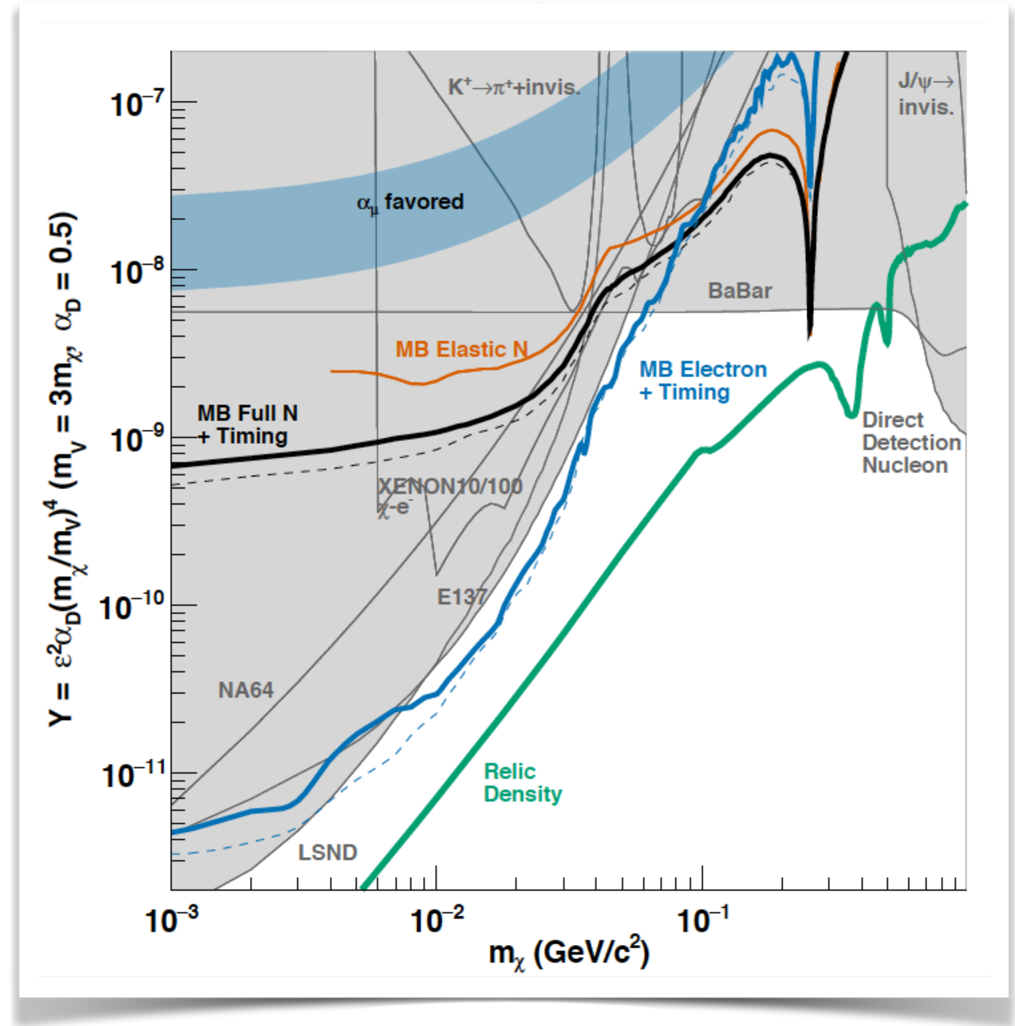




Production



Detection



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

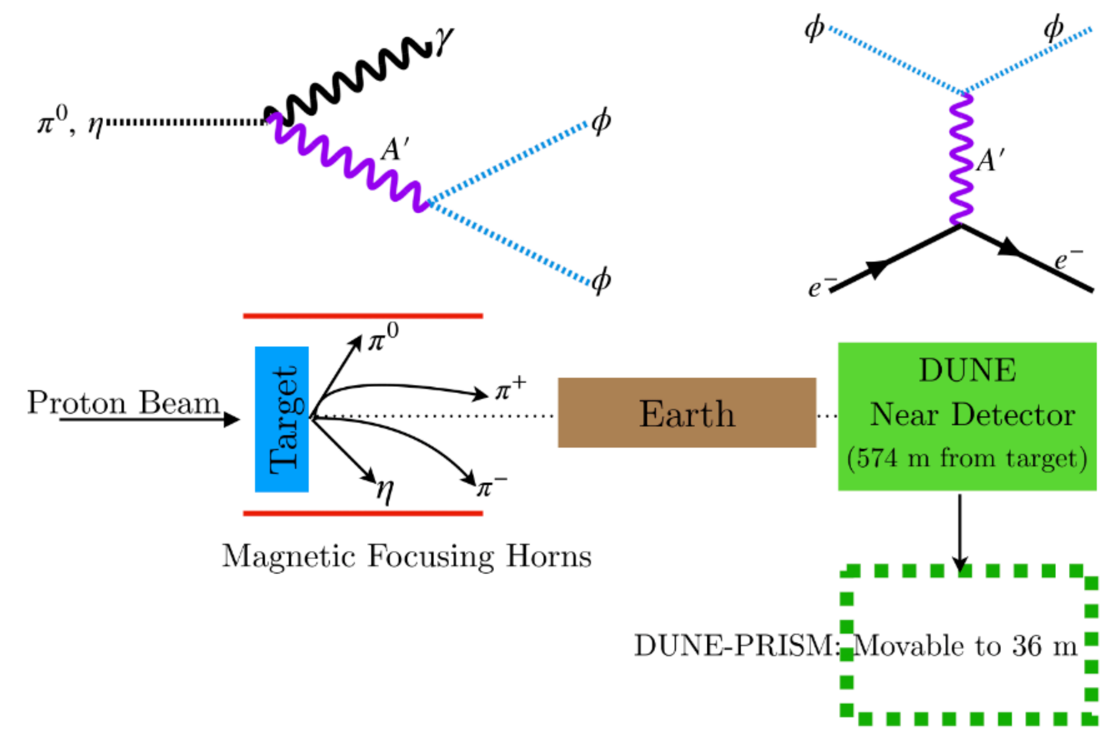
- 8 GeV protons on iron dump; 800 ton mineral oil detector
- Dedicated off target / beam dump run mode, collected 1.9E20 POT
- Leading limits on vector portal dark matter model for ~ 100 MeV mass range
- Demonstrates proton beam dump as an effective search method for light dark matter

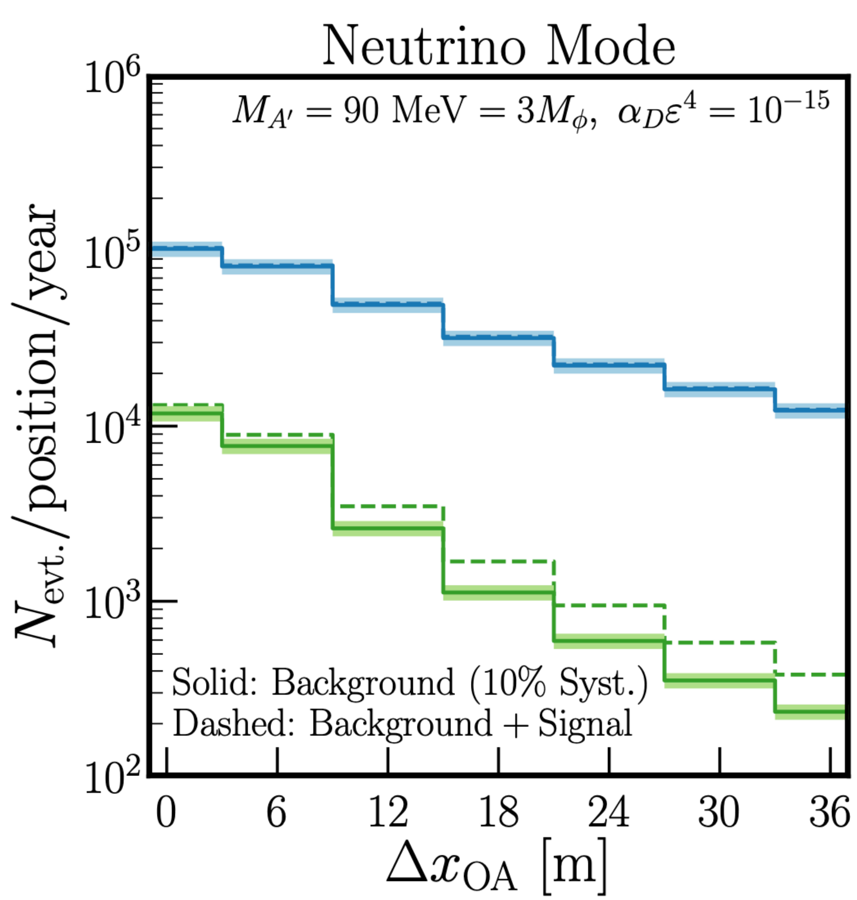
DUNE-PRISM @ FNAL

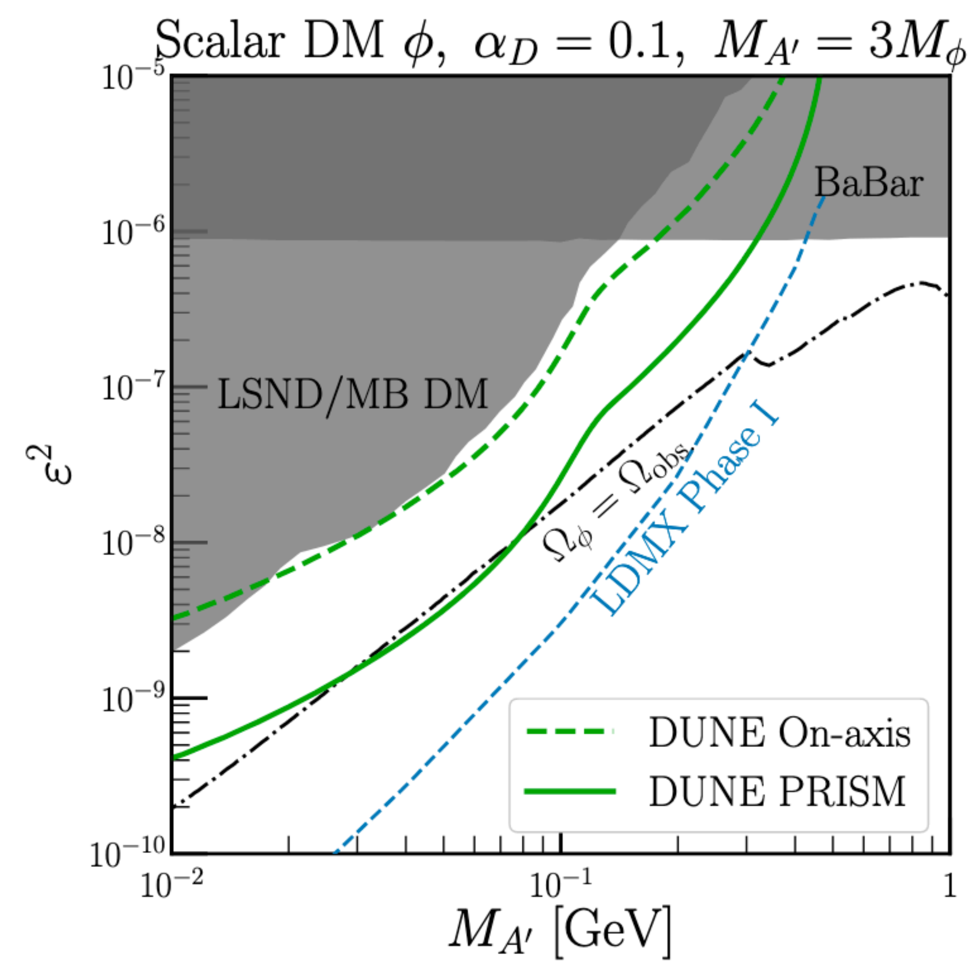
[De Romeri, Kelly, Machado]

[Breitbach, Buonocore, Frugiuele Kopp, Mittnacht]

- 120 GeV protons on graphite target
- DUNE-PRISM movable near detector allows sensitive search to light dark matter
- DM-to-neutrino flux increases as detector is moved off axis
  - Neutrinos produced through decay of charged mesons, which are focused by magnetic horn
  - DM produced through decay of unfocused neutral mesons

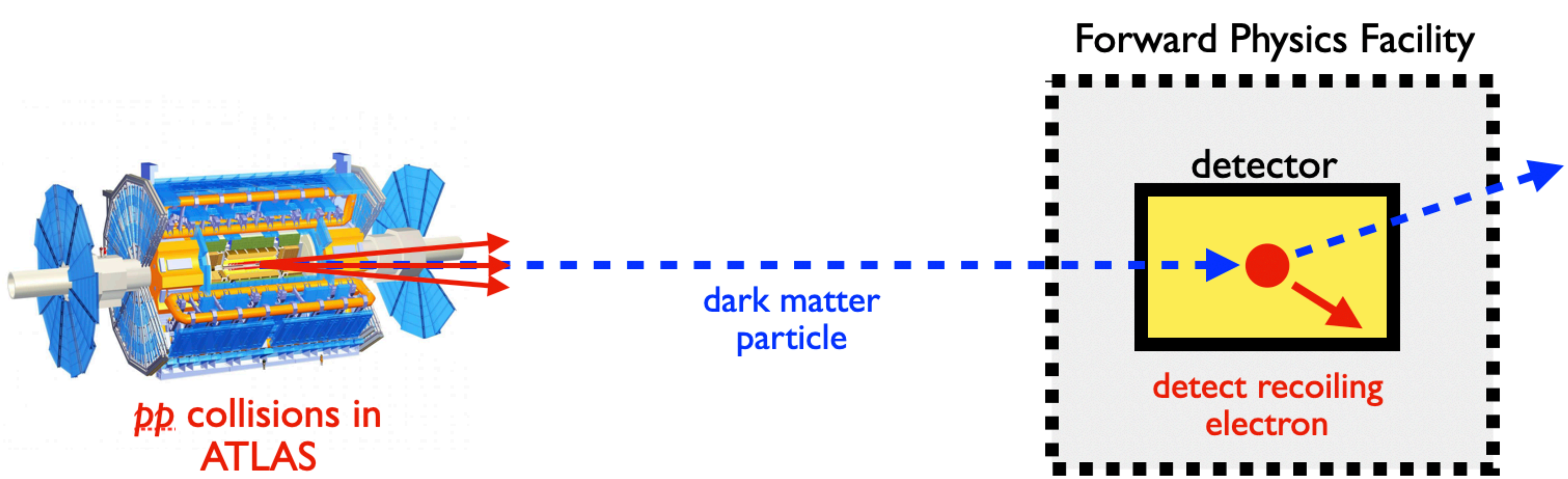




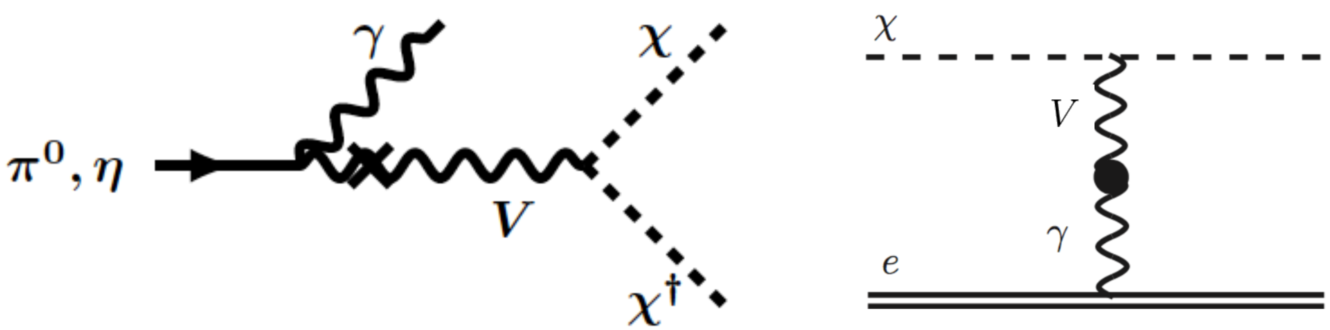


Dark Matter in the far-forward region at the LHC

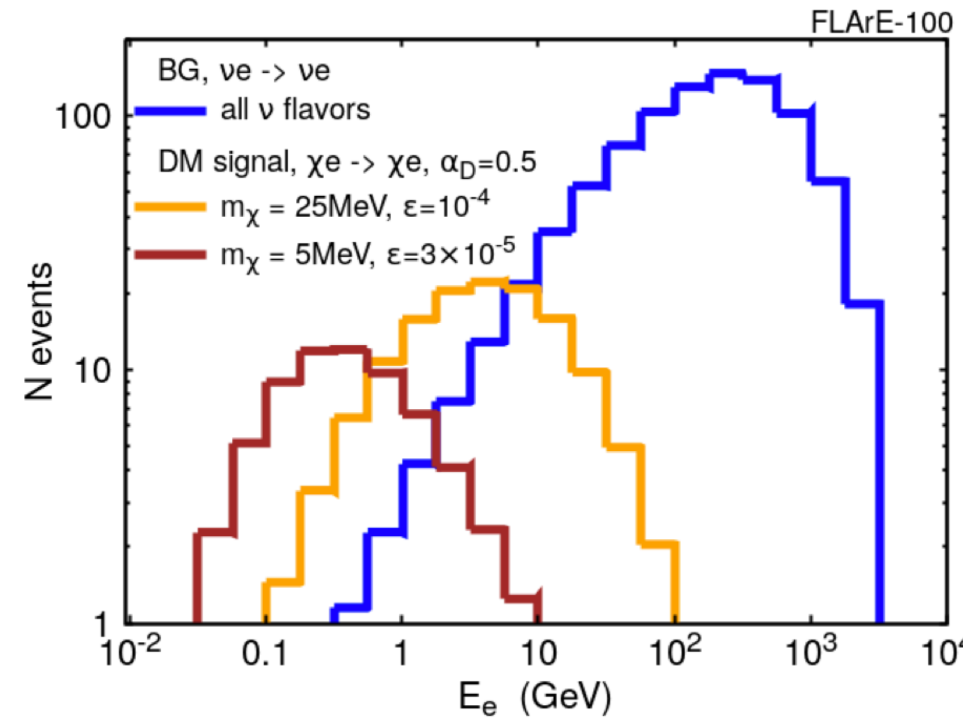
- Total LHC pp cross section is ~100 mb, and mainly directed in the forward region
  - Energetic, low p_T, light particles, e.g., ~ 10^{17} pions, TeV energies, mrad angles
  - The **FASER** experiment will exploit this to search for long-lived, light, weakly interacting particles [Feng, Galon, Kling, Trojanowski]
- There is a proposal to construct a larger Forward Physics Facility for the HL-LHC era - see the kickoff workshop for physics opportunities: https://indico.cern.ch/event/955956
- Can also use this approach to search for light dark matter [BB, Feng, Trojanowski]



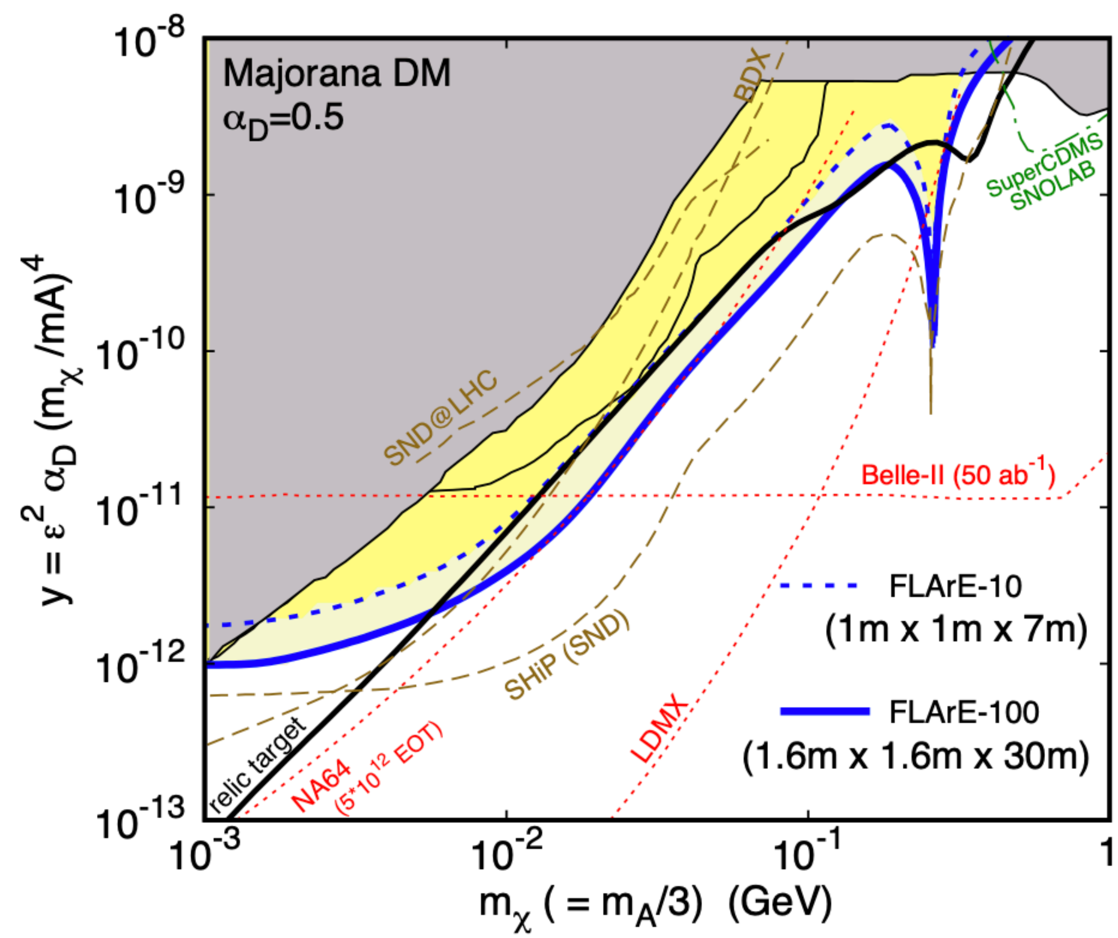
Dark Matter in the far-forward region at the LHC



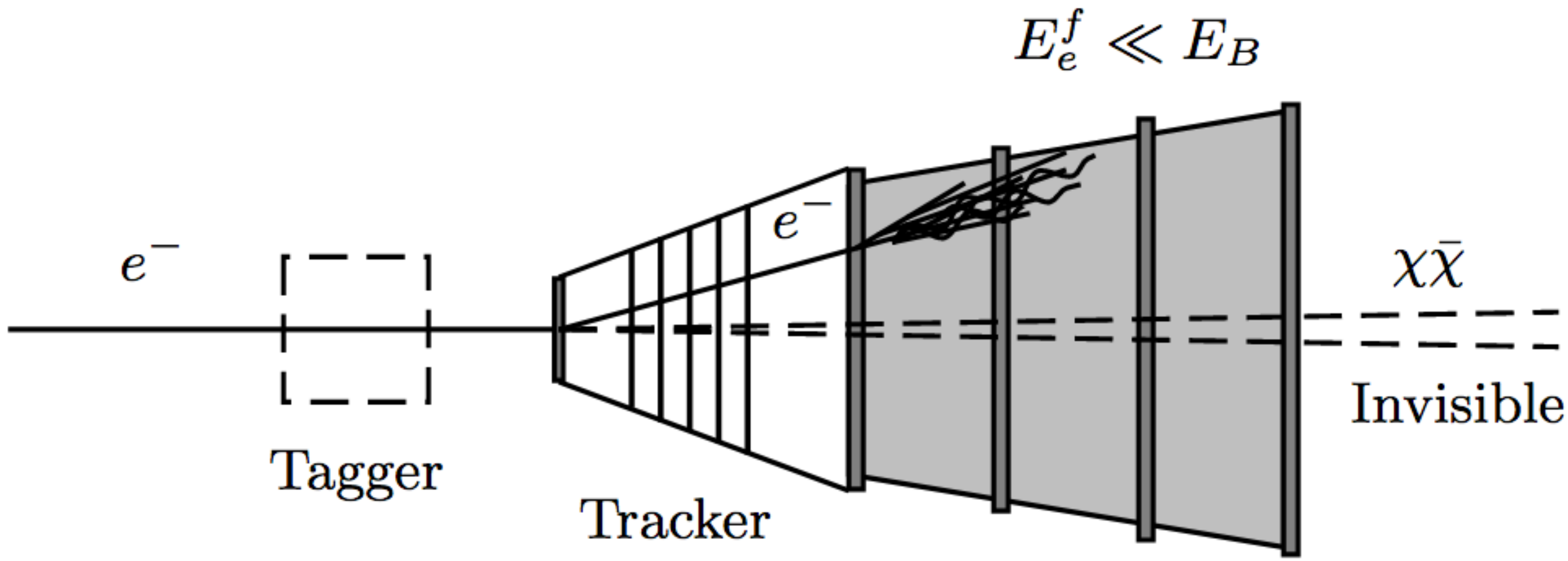
Production Detection



- Two detector options considered:
  - FASERν2 : Emulsion Detector 10-ton scale
  - FLArE : LArTPC 10, 100 - ton scale
- Kinematic, topological cuts can mitigate neutrino backgrounds
- FASERν2, FLArE can probe a significant region of cosmologically motivated parameter space



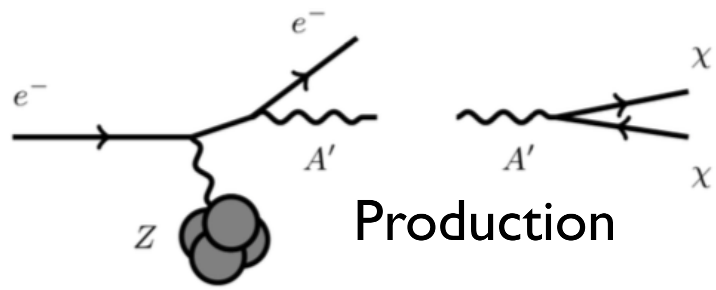
Missing energy / momentum searches for dark matter



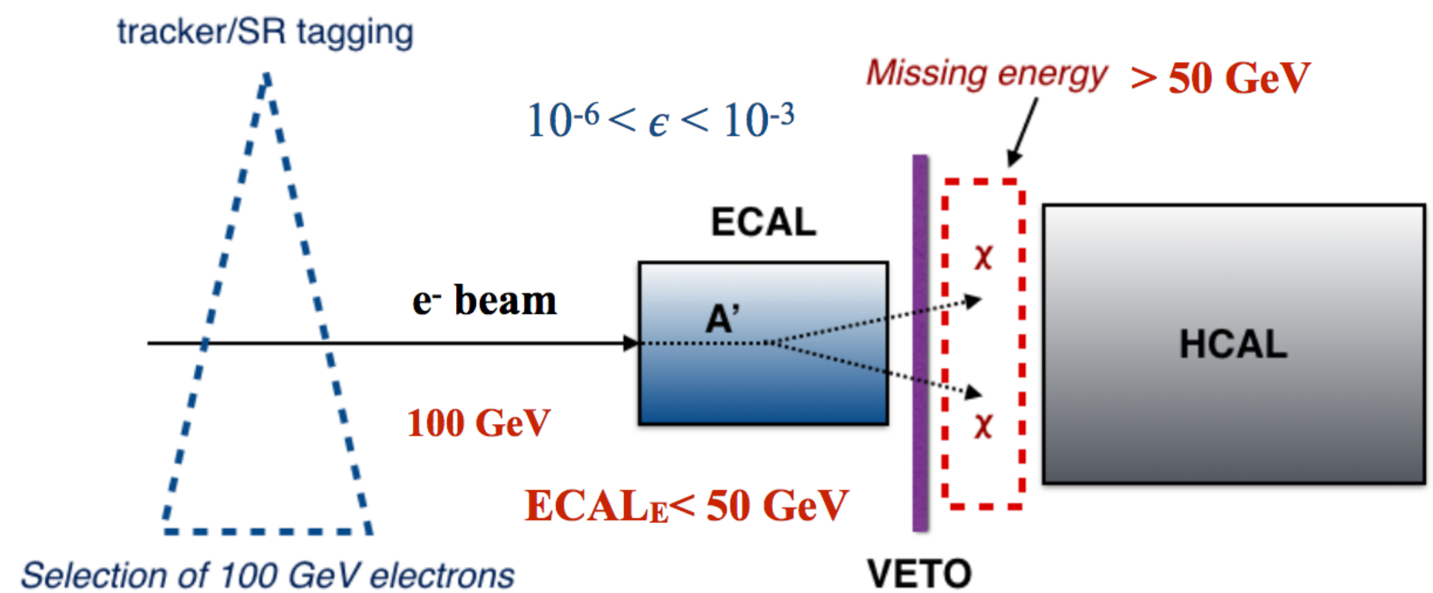
[Andreas. et al]
[Izaguirre, Krnjaic, Schuster, Toro]
[Kahn, Krnjaic, Tran, Whitbeck]

NA64 @ CERN

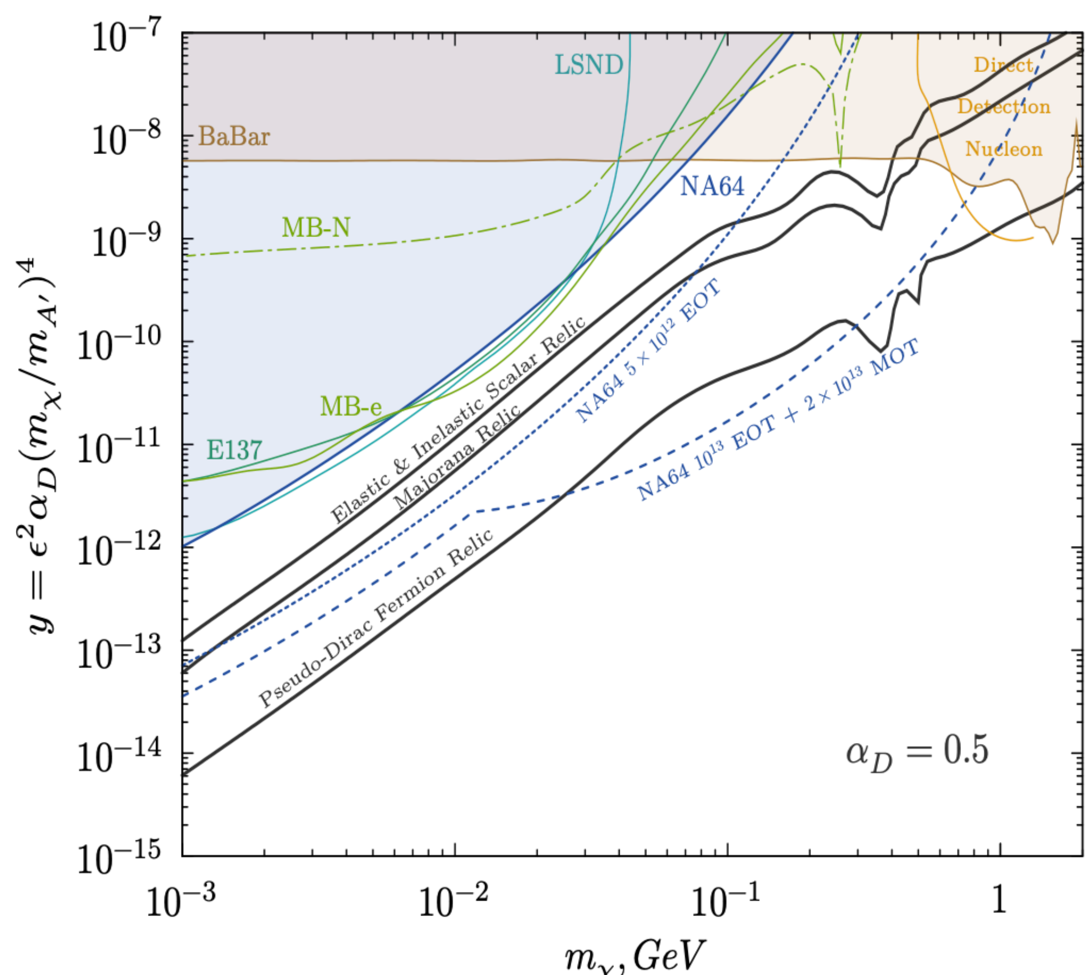
- 100 GeV electron beam incident on ECAL
- Dark matter produced in ECAL and carries most of the beam energy



Production



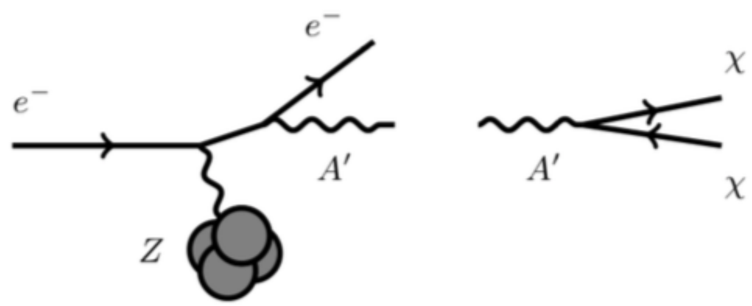
- Large missing energy signature (small energy deposition in ECAL, no energy deposition in HCAL)
- 2.84 x 10^{11} EOT - best limits on invisibly decaying dark photon below 300 MeV
- Future datasets with electron and muon beams can probe a significant parts of the thermal relic targets

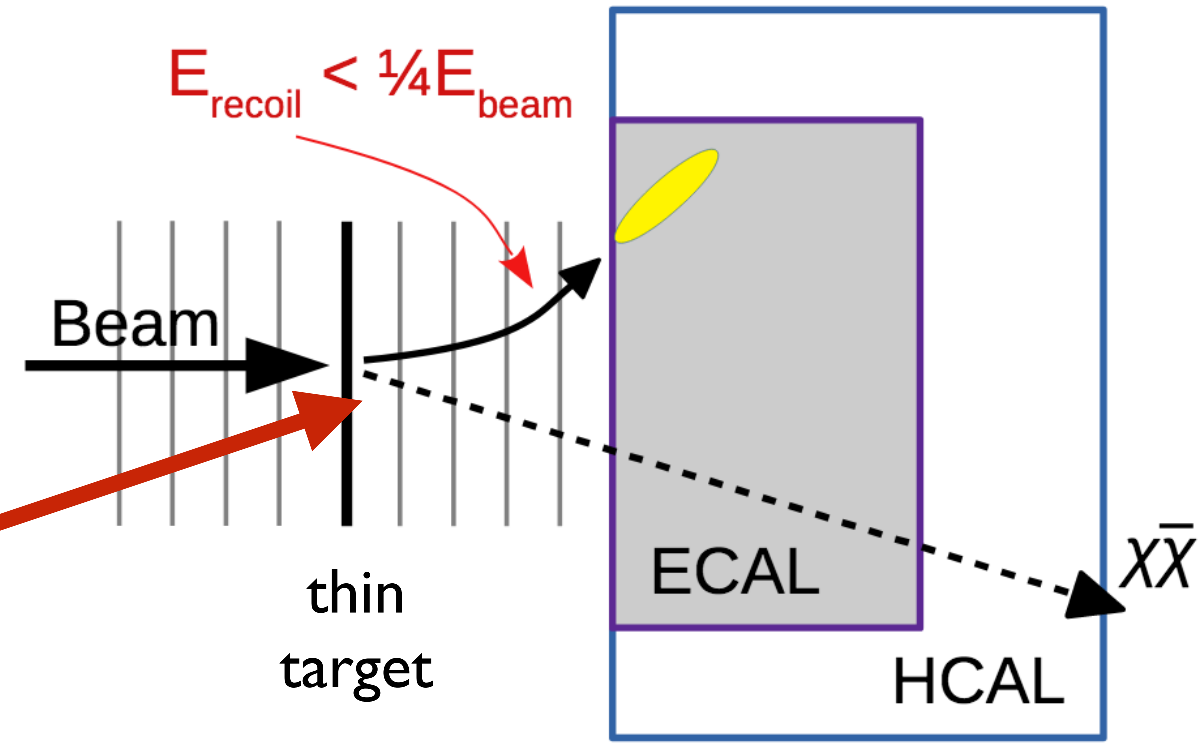


1903.07899

LDMX @ SLAC

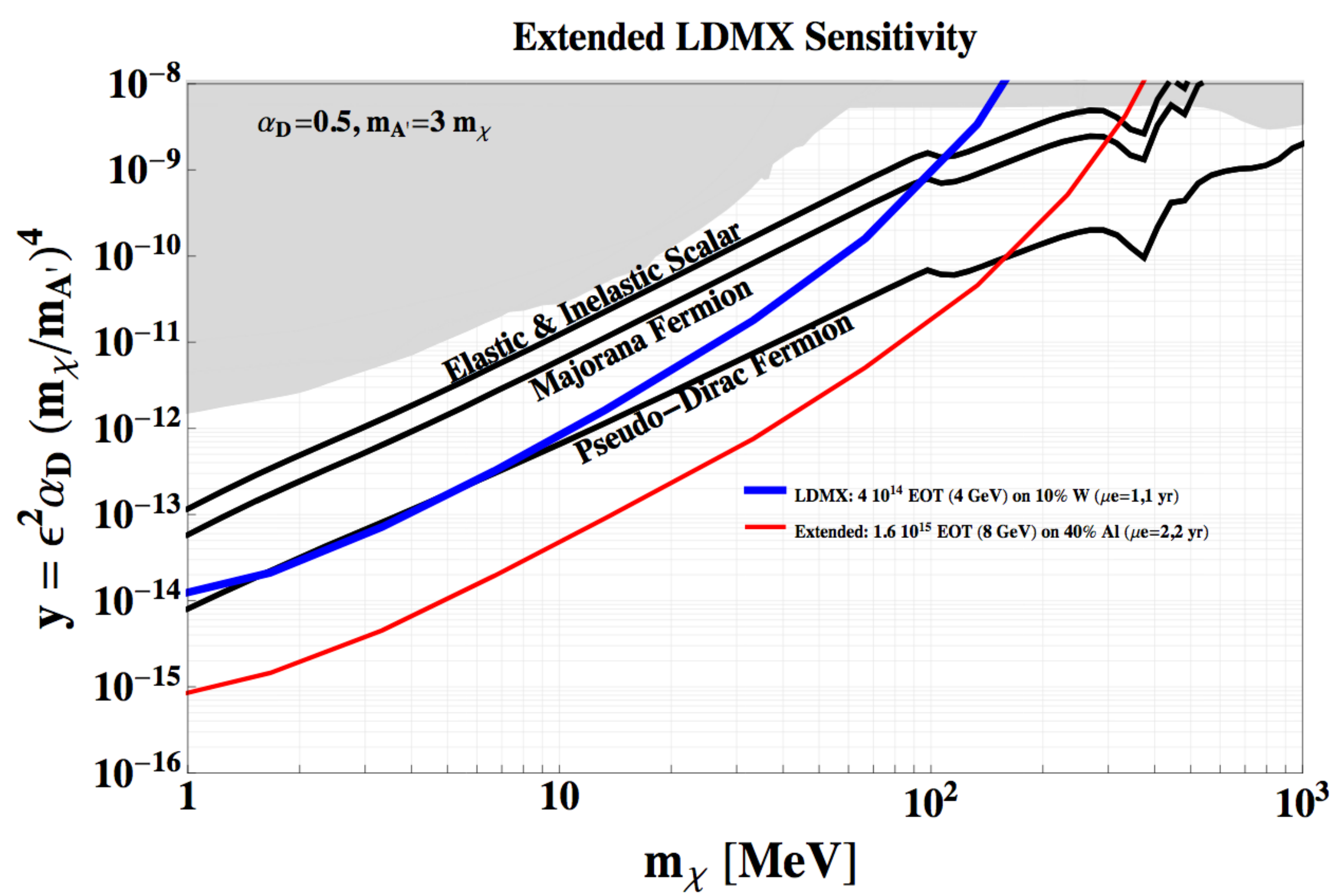
- Proposed electron beam experiment utilizing missing momentum technique





- More kinematic handles to reject backgrounds, discriminate final state electrons from photons

- Can cover most thermal targets, irrespective of dark matter particle nature



Initial design study, 1808.05219

Electron-positron colliders

- Large cross sections, high luminosities, hermetic detectors; complementary to fixed target experiments

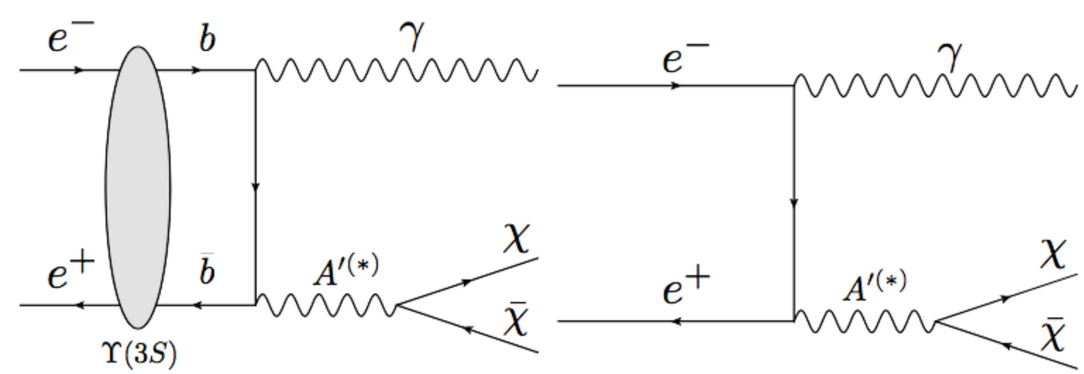
- Invisible dark photon: mono-photon signature - peak in recoil mass spectrum

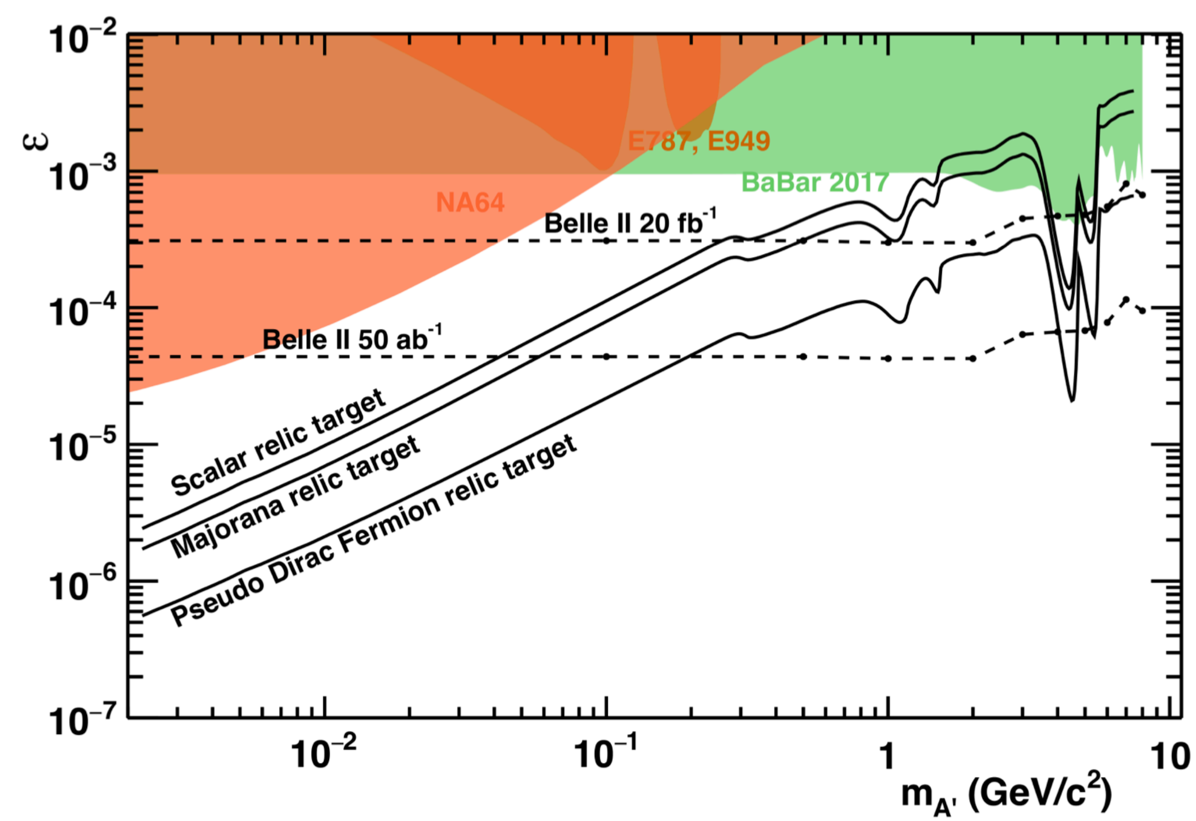
  [Izaguirre, Krnjaic, Schuster, Toro]
  [Essig, Mardon, Papucci, Volansky, Zhong]

- BABAR places strongest limits for dark photon masses between 100 MeV - 10 GeV [BABAR, 1702.03327]

- Belle II will collect O(50/ab), and will be able to probe new parameter space with early data.

- Searches also being done at other flavor factories, e.g. BESIII, KLOE



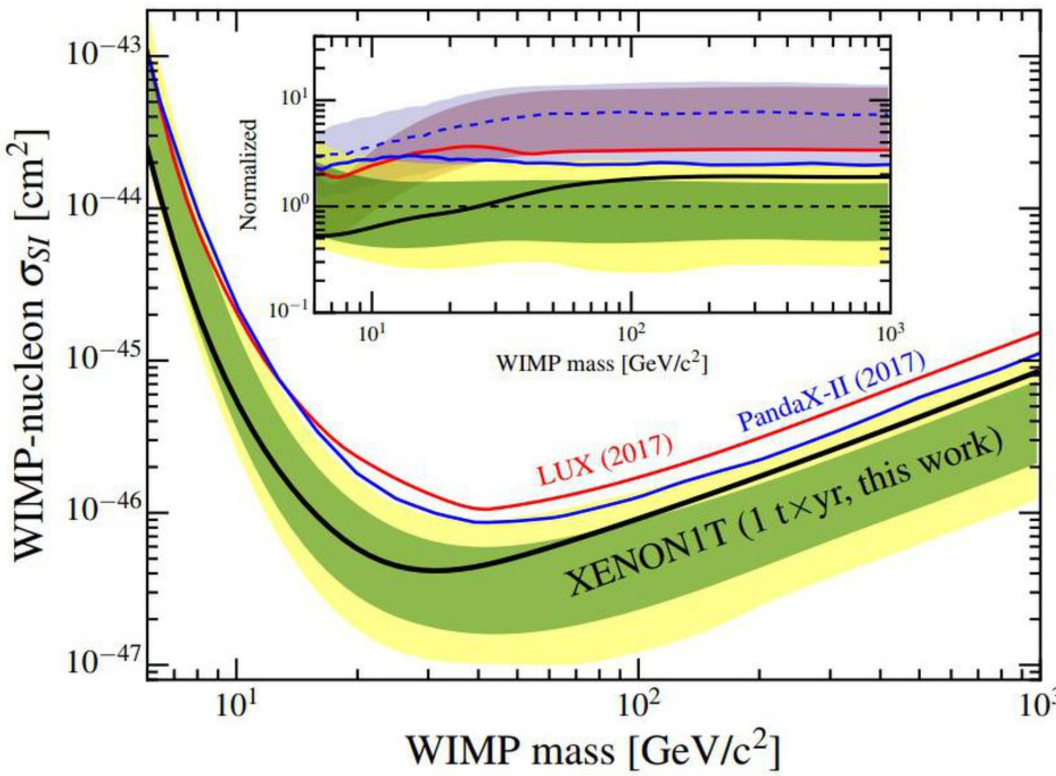


[Belle II Physics Book, 1808.10567]

Direct Detection of sub-GeV Dark Matter

- Traditional direct detection through nuclear recoils loses sensitivity to dark matter lighter than about 1 GeV

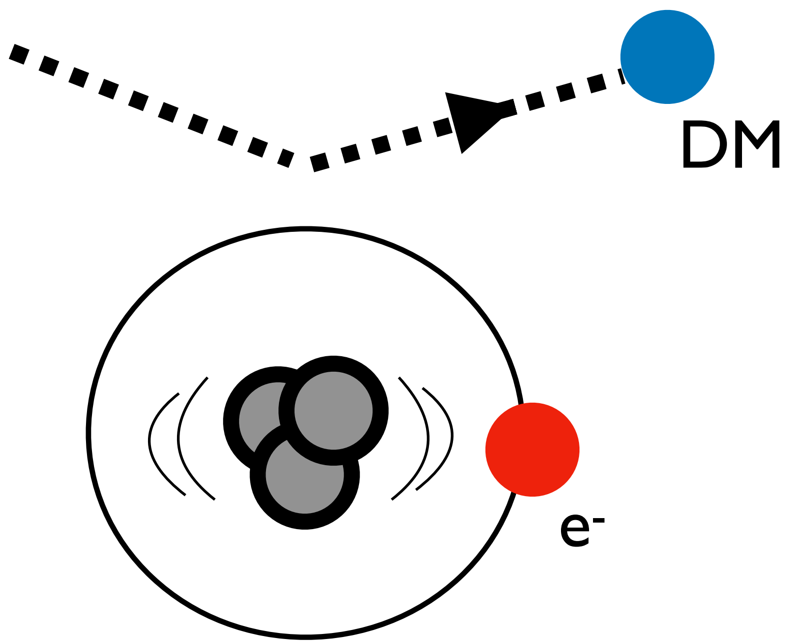
- A number of novel approaches to sub-GeV dark matter direct detection are being pursued, including



- Dark matter-electron scattering (e.g., in noble liquids, semiconductors,…)
- Dark matter-nuclear scattering (e.g., via Migdal effect and bremsstrahlung)
- Dark matter scattering off collective modes in molecules and in crystals (e.g., phonons, plasmons and magnons)

[see work by e.g., Caputo, Esposito, Geoffray, Graham, Griffin, Hochberg, Ibe, Kaplan, Kahn, Knapen, Krnjaic, Griffin, Lin, Lisanti, Melia, Mitridate, Nakano, Polosa, Pradler, Pyle, Rajendran, Schutz, Shoji, Sun, Suzuki, Trickle, Walters, Yu, Zhang, Zhao, Zurek,…]

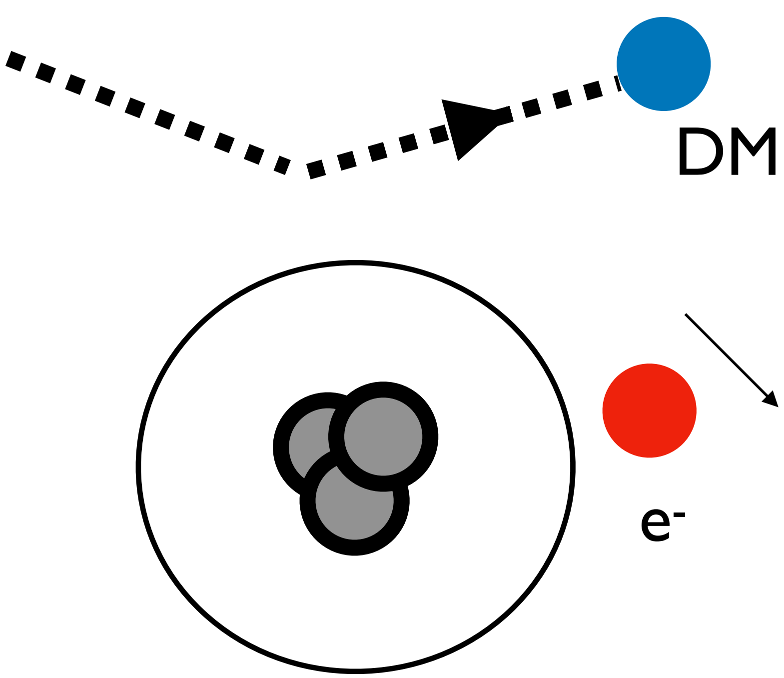
DM-nuclei scattering



$$E_R = \frac{q^2}{2m_N} \sim \frac{\mu_{\chi N}^2 v_\chi^2}{m_N} \approx 1\,\mathrm{keV}\left(\frac{m_\chi}{\mathrm{GeV}}\right)^2\left(\frac{130\,\mathrm{GeV}}{m_N}\right)$$

DM-electron scattering

[Essig, Mardon, Volansky]

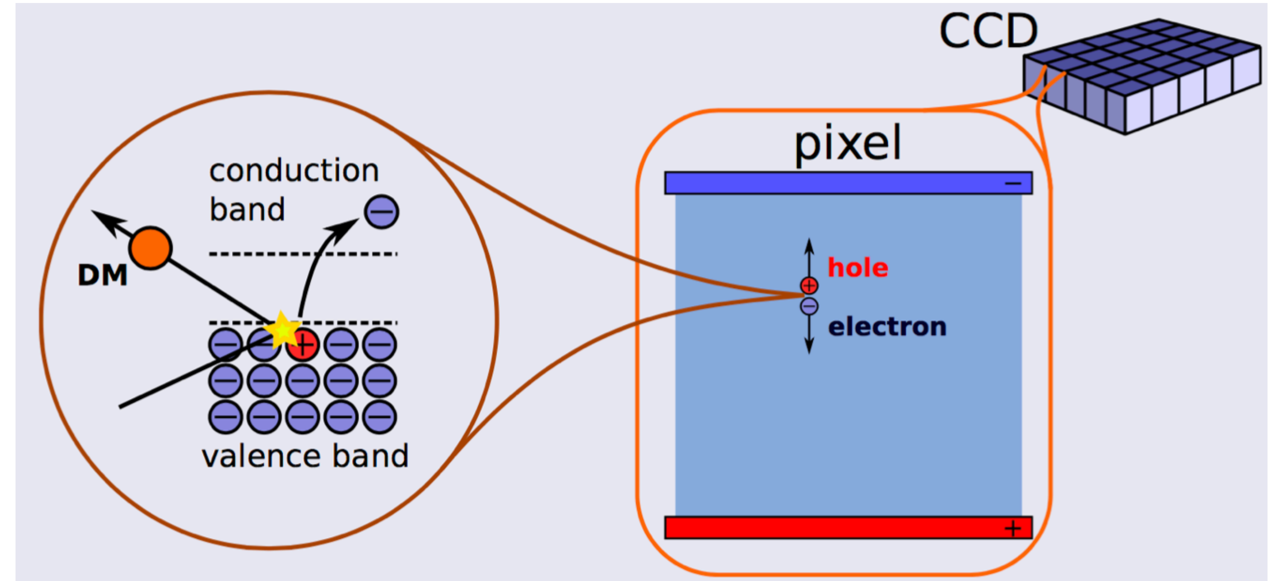


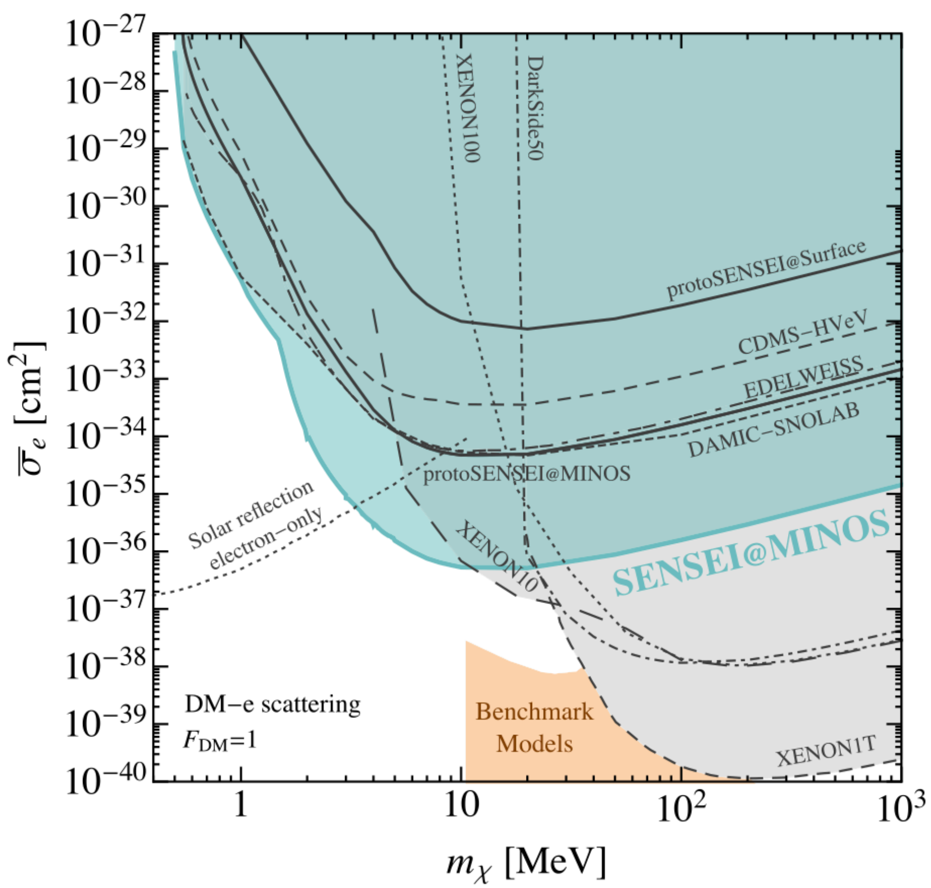
$$\frac{1}{2}m_\chi v_\chi^2 > \Delta E_{\mathrm{binding}} \longrightarrow m_\chi \gtrsim 1\,\mathrm{MeV}\left(\frac{\Delta E_{\mathrm{binding}}}{1\,\mathrm{eV}}\right)$$

$$E_R \sim qv \sim (m_e\alpha)v \approx 4\,\mathrm{eV}$$

SENSEI

- Silicon Skipper-CCD detector sensitive to DM-electron scattering
- Repeated sampling of allows for precise measurement of pixel charge — ultra-low noise and low threshold
- First results using 2 gram x 24 day exposure sets leading limits in 1-10 MeV mass range





[SENSEI Collaboration PRL, 125, 171802]

- Projections for future Si-Skipper CCD experiments

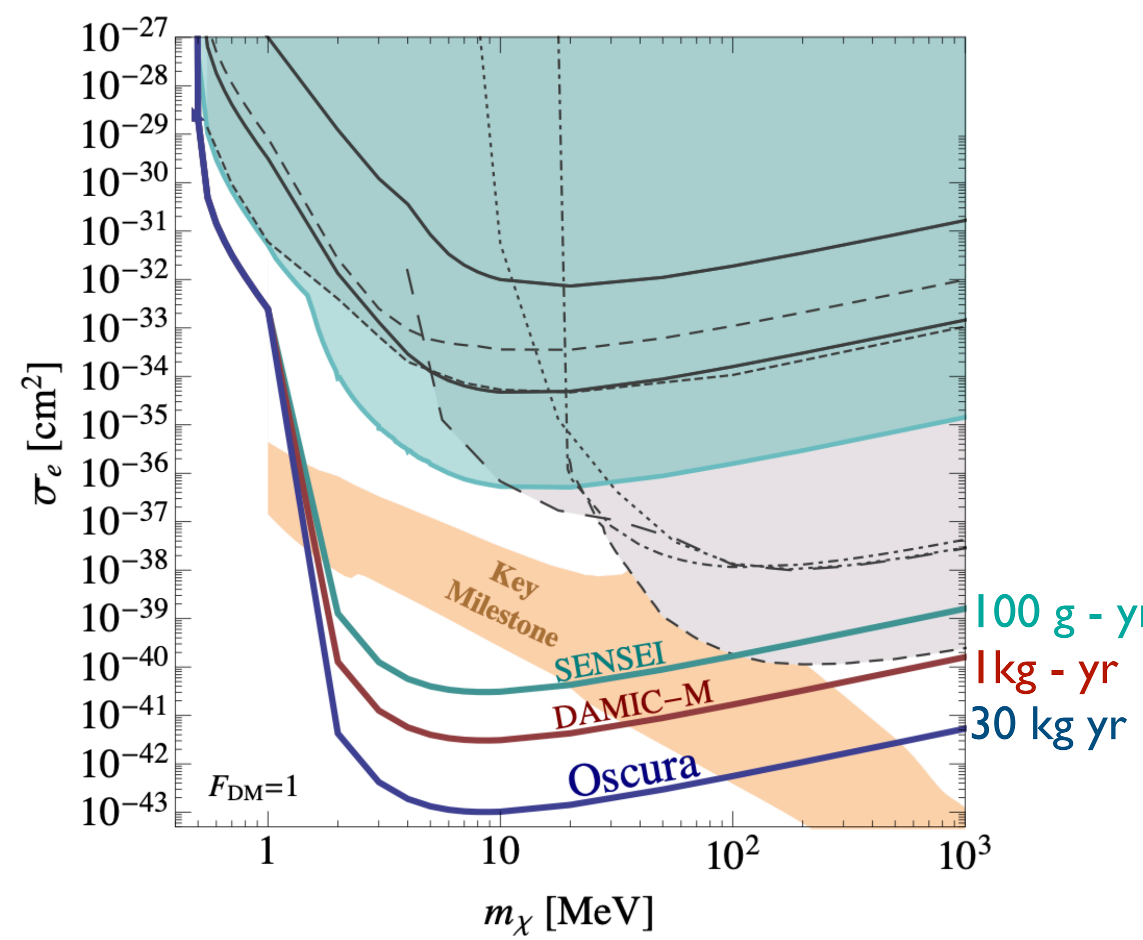


Figure from T.T.Yu

Neutrino Portal and Seesaw Mechanism

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

- Neutrinos have a tiny non-zero mass (10^{-10} smaller than the proton mass!)

[2015 Nobel Prize to T. Kajita and A. McDonald]

- Seesaw mechanism for neutrino mass:

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

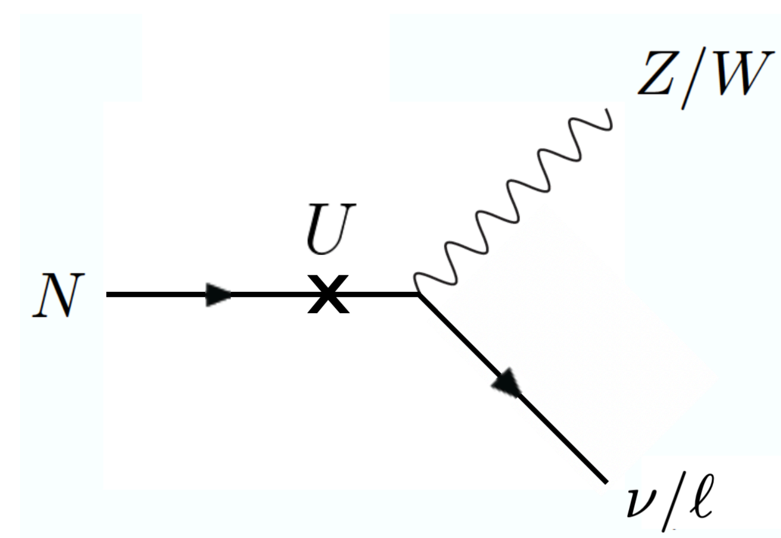
From Khalil, Moretti

- Mass mixing:

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

- Heavy neutrino inherits weak interaction of light neutrino

- Interaction strength suppressed by mixing angle *U*



Neutrino Portal Dark Matter

[Bertoni, Ipek, Nelson, McKeen]
[BB, Han, McKeen, Shams Es Haghi]
[See also Boehm, Fayet, Schaeffer]

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

- Approximate lepton number symmetry allows for light SM neutrinos even if the Yukawa coupling λ_ℓ (and active sterile mixing) is large

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

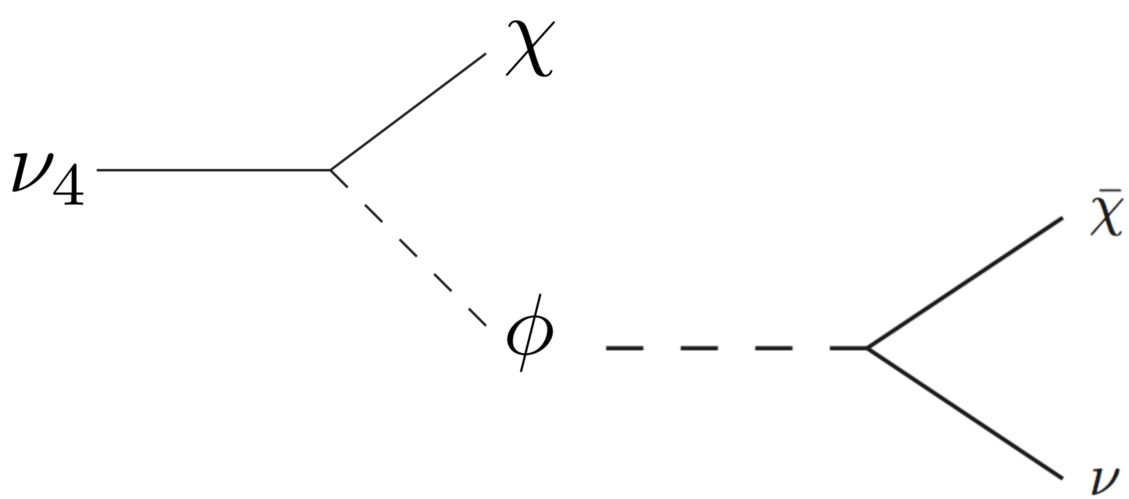
- Large mixing allows for a sizable DM - SM neutrino coupling

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

- Important implications for cosmology and phenomenology

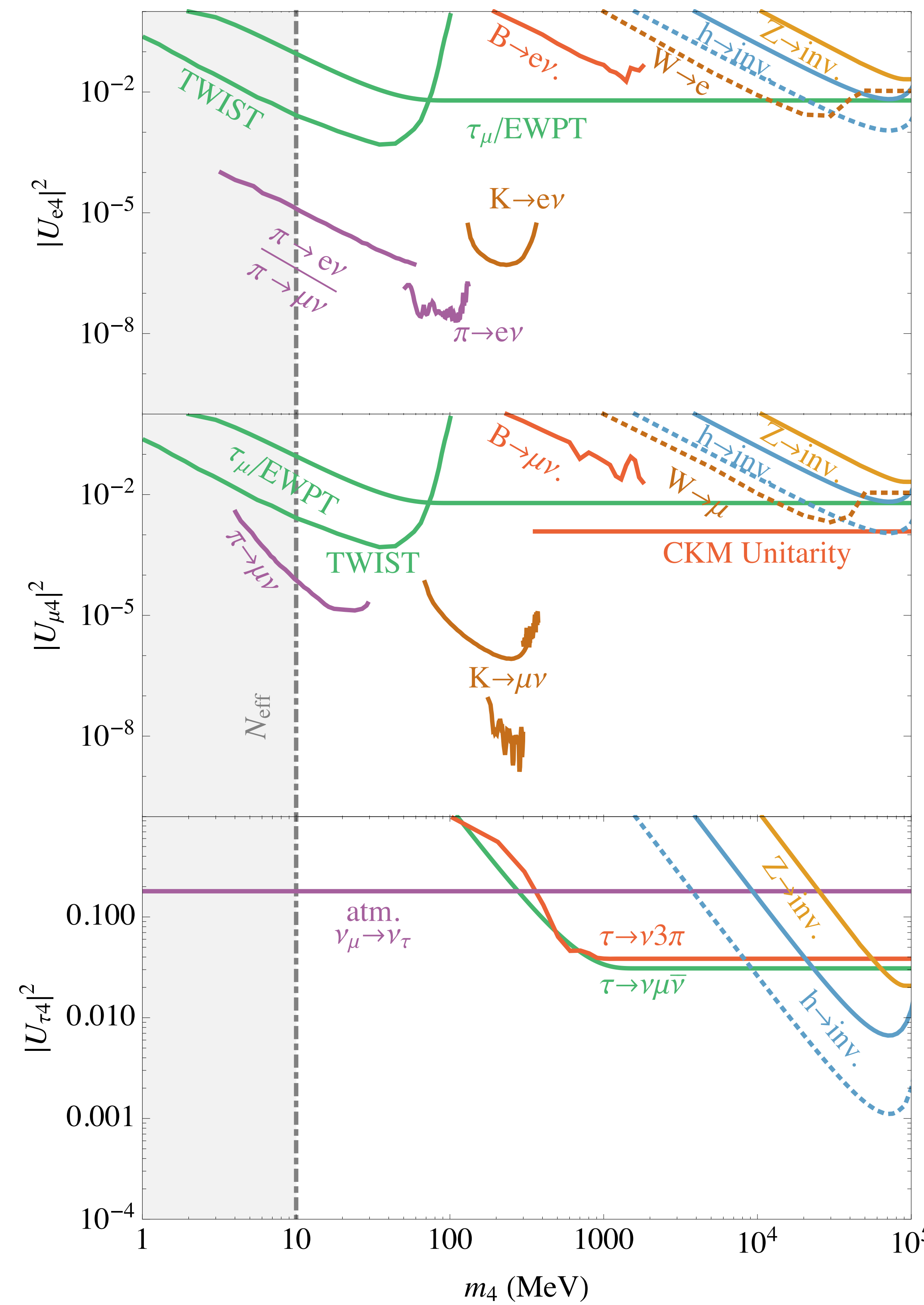
“Invisible” Sterile Neutrino

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

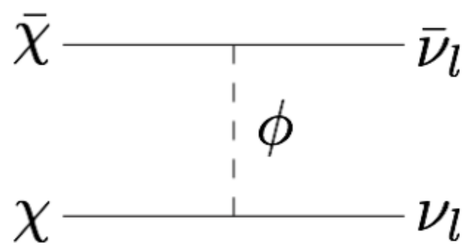


Phenomenology

- 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)



Direct annihilation to light SM neutrinos

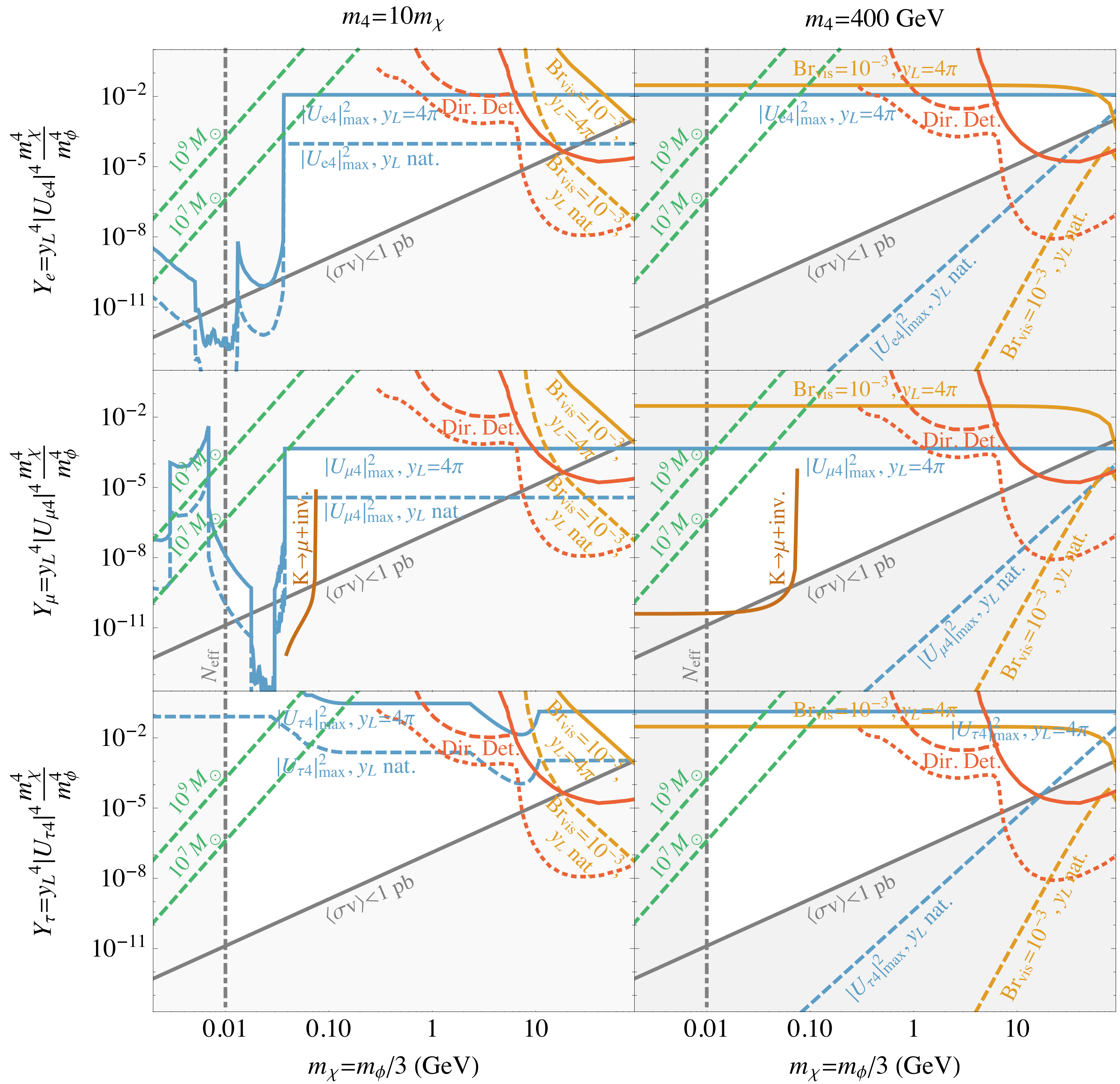


$$\propto U^2$$

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

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

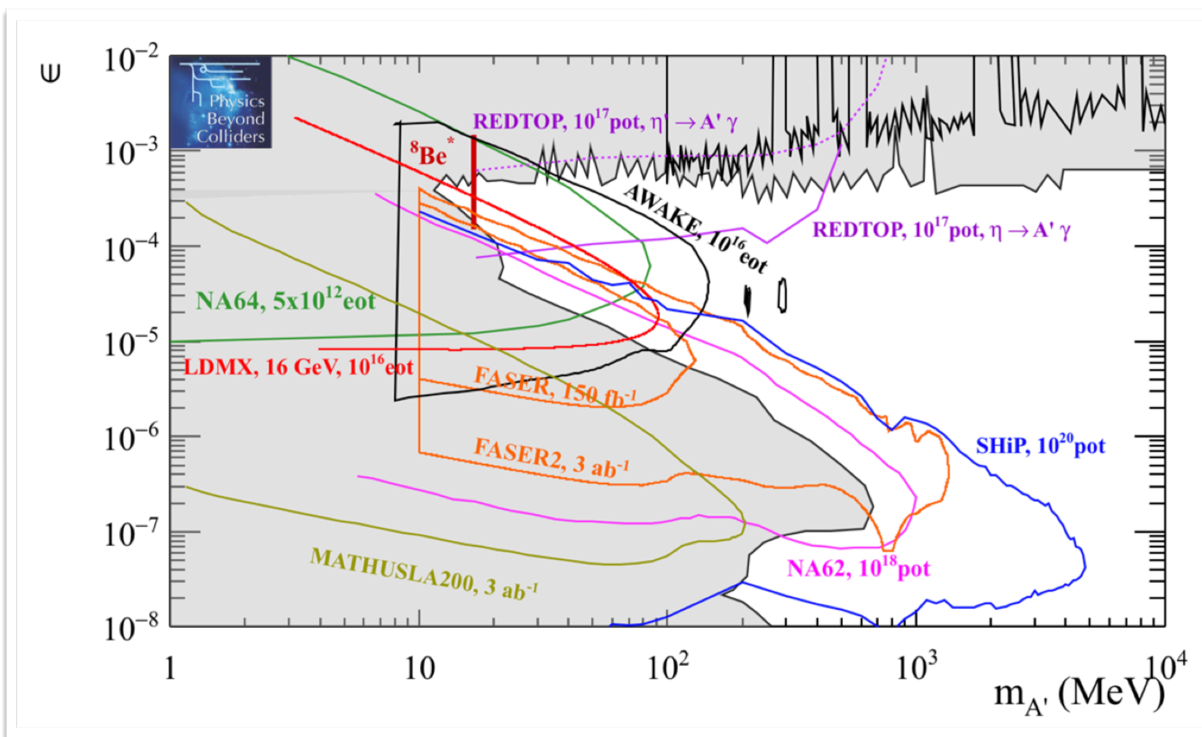
- Represent conservative constraints on the thermal hypothesis
- New ideas to probe remaining open parameter space are welcome!



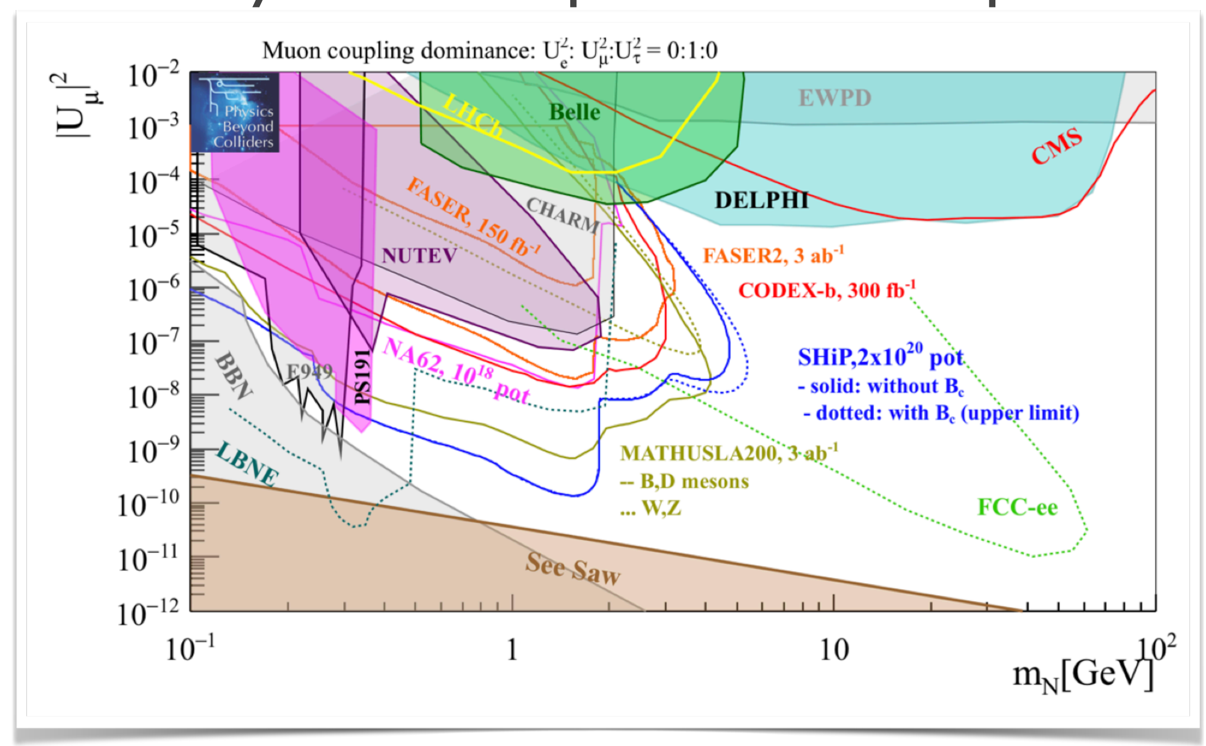
Visible Decays of Portal Mediators

[Physics Beyond Colliders Report, 1901.09966]

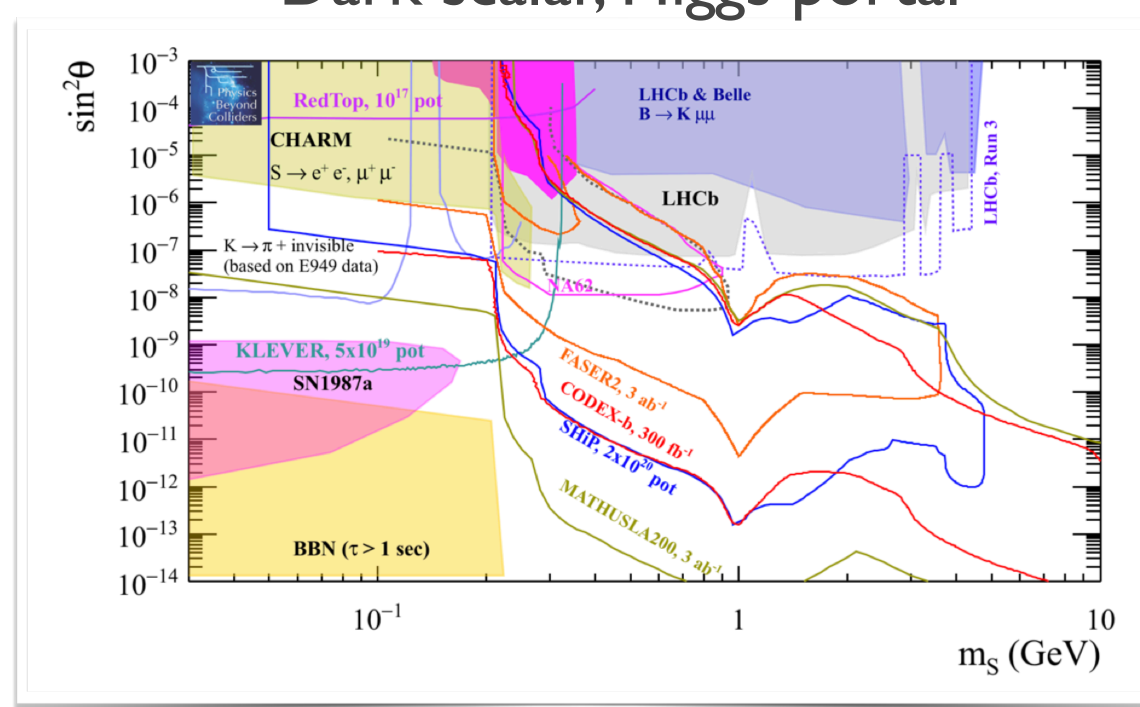
Dark photon, vector portal



Heavy neutral lepton, neutrino portal



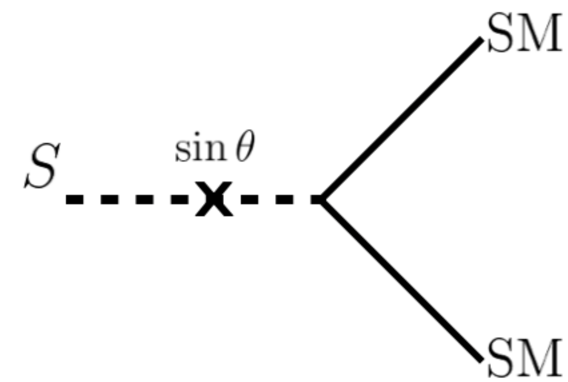
Dark scalar, Higgs portal



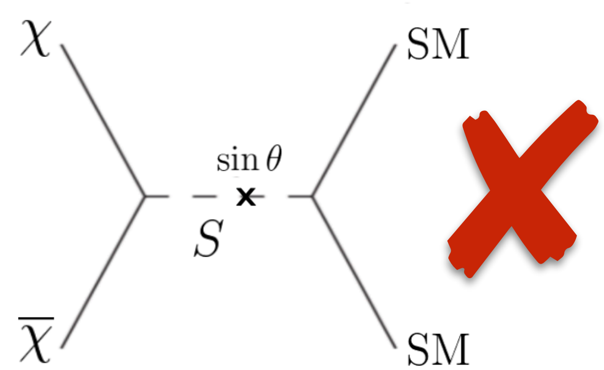
Higgs Portal to the Dark Sector

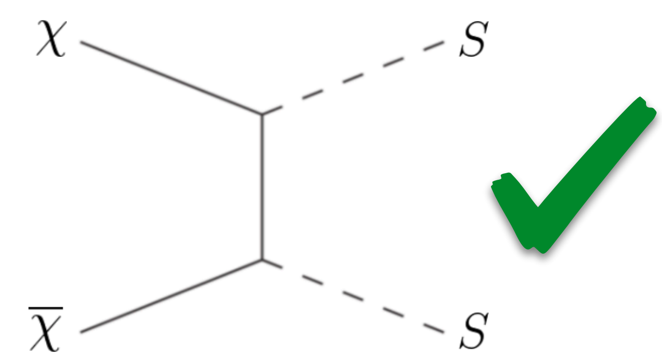
- Dark scalar couples just like Higgs, but with couplings suppressed by mixing angle

$$-\mathcal{L} \supset (AS + \lambda S^2) H^\dagger H \quad \Rightarrow \quad \sin\theta \, \frac{m_f}{v} \, S \, \bar{\psi}\psi + \ldots$$

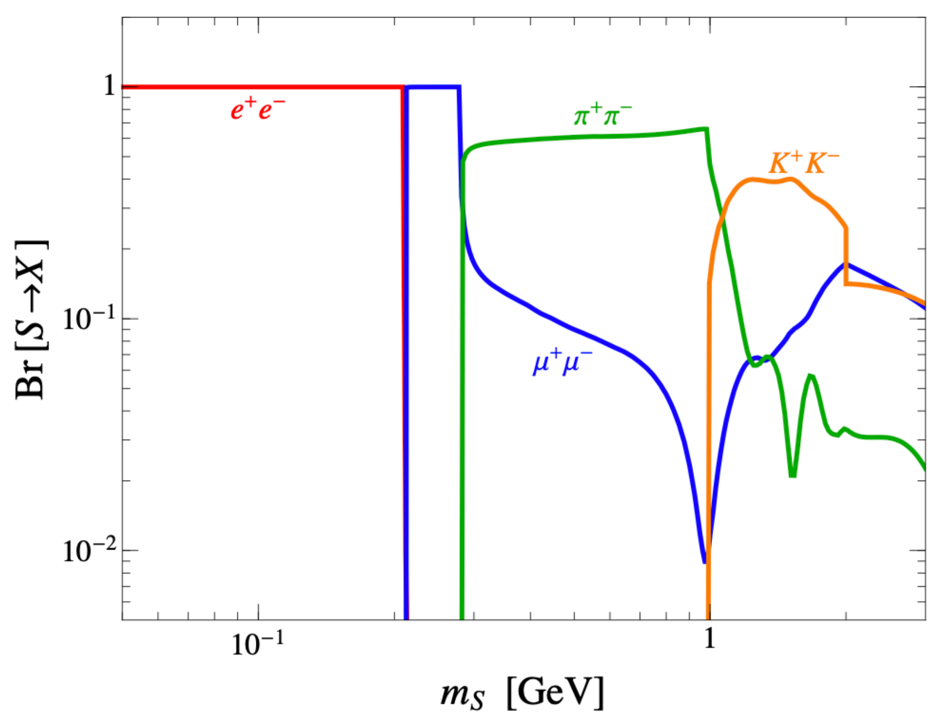


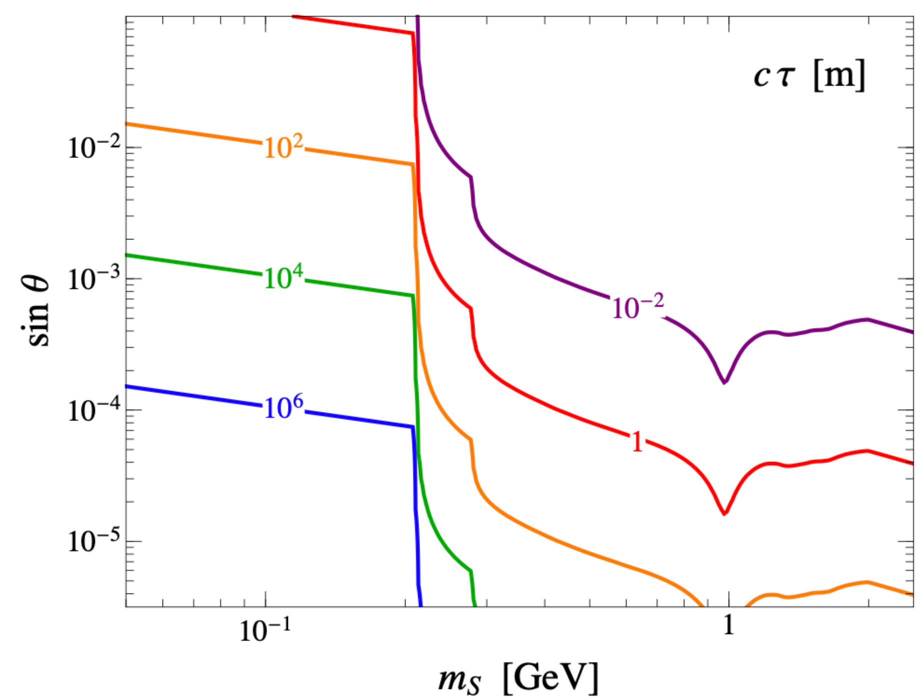
- Past experiments strongly constrain dark matter annihilating to SM through the Higgs portal [Krnjaic '15]





- Expect dark matter is heavier than scalar and scalars decay to visible particles

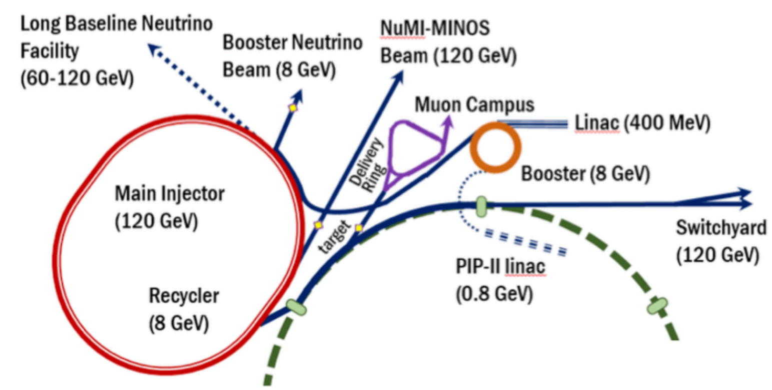


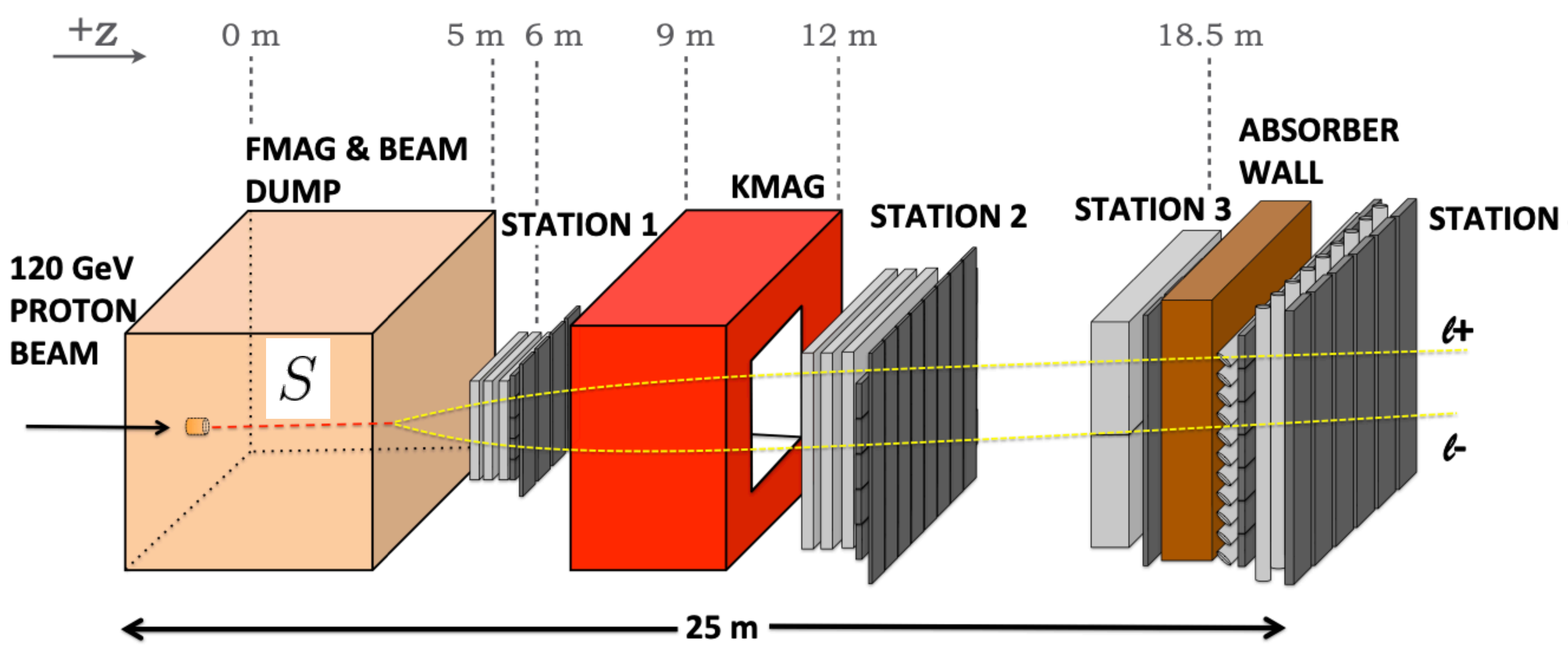


Scalar may be long-lived!

Higgs Portal at Fermilab
DarkQuest Experiment

- DarkQuest is a proposed upgrade of the Fermilab SeaQuest nuclear physics experiment
- 120 GeV protons from the Fermilab Main Injector impinge on ~ 5m iron beam dump
- Magnetic field (KMAG), 4 tracking stations, muon ID system, Electromagnetic calorimeter

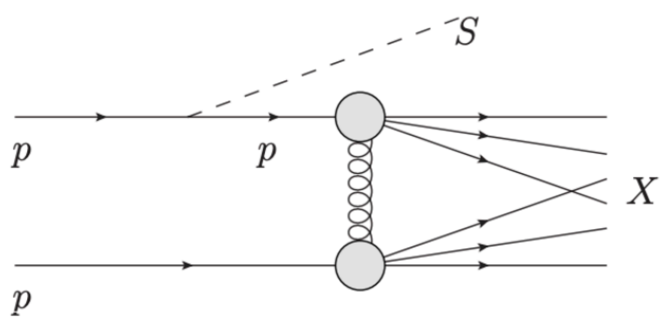




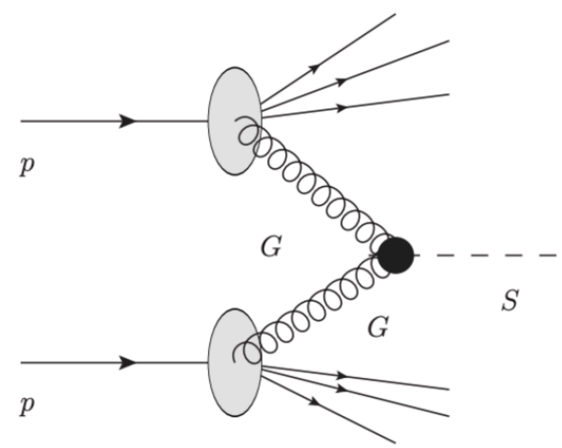
Higgs Portal at Fermilab DarkQuest Experiment

[Berlin, Gori, Schuster, Toro]
[BB, Evans, Gori, Rai]

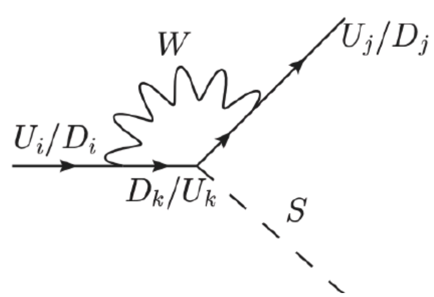
- Dark scalar production:



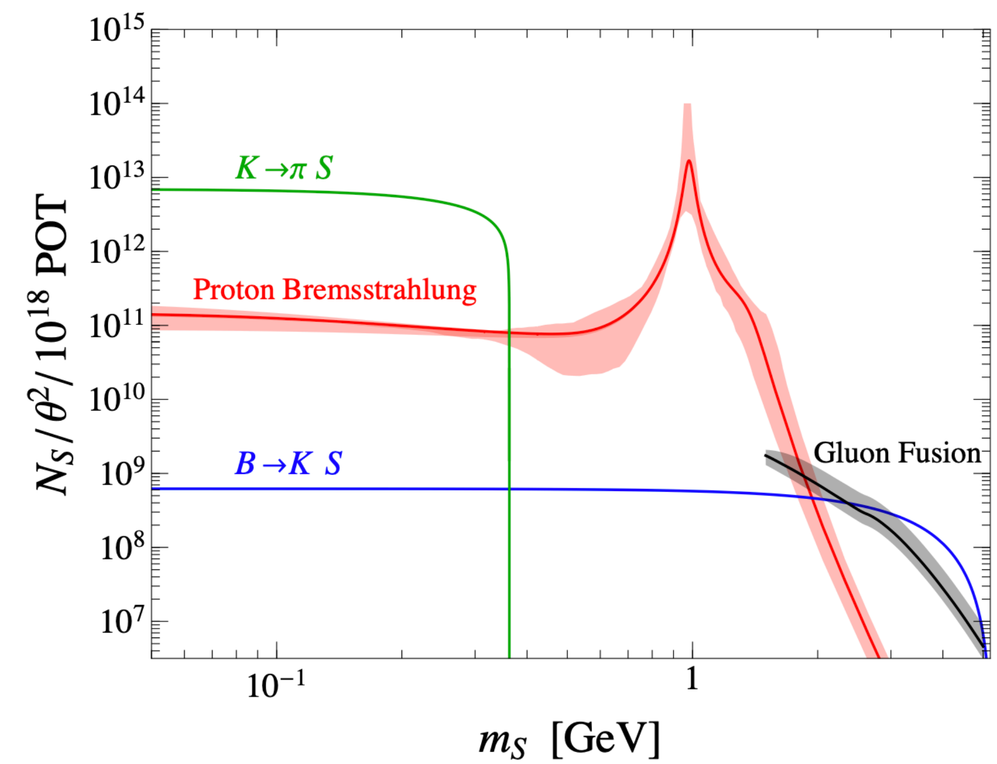
Proton Bremsstrahlung

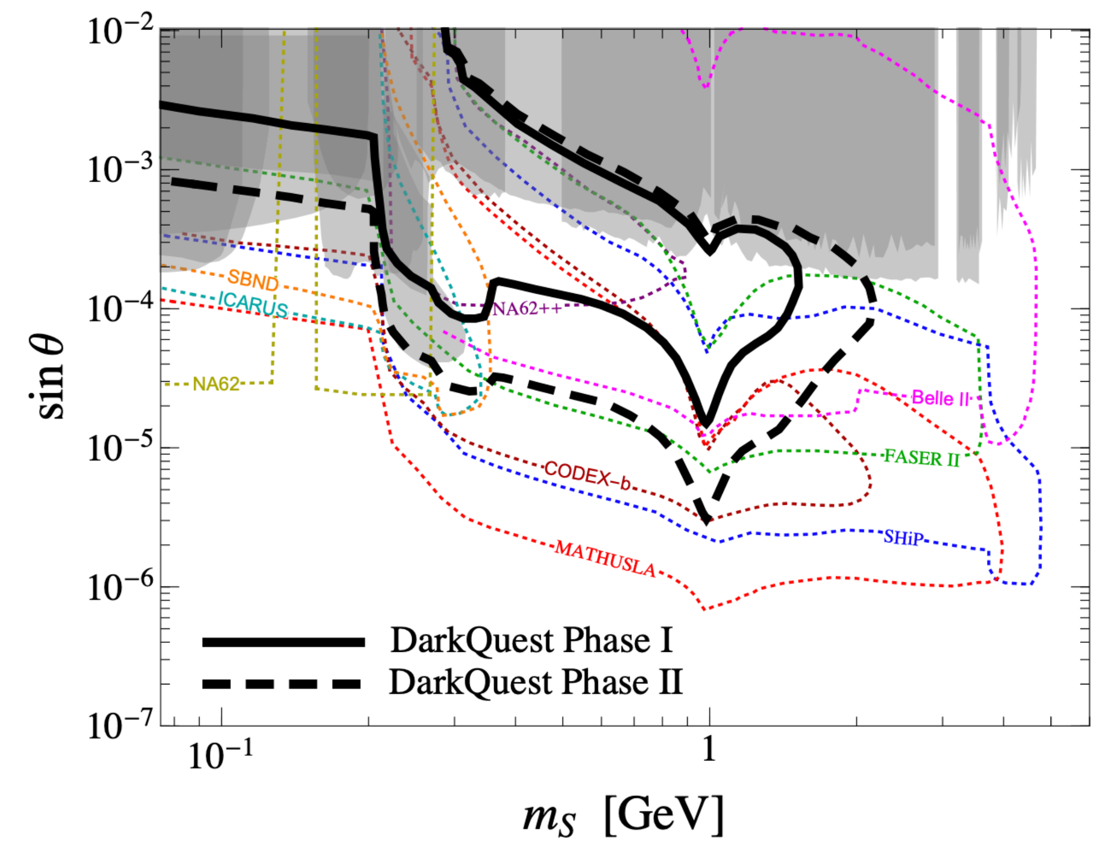


Gluon fusion



Meson decay



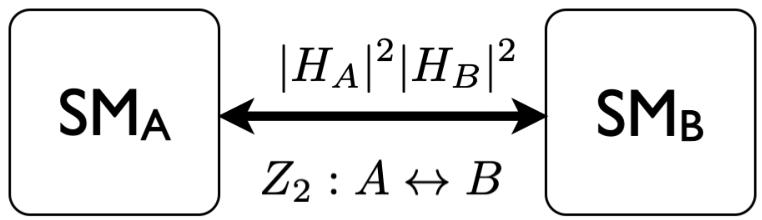


- DarkQuest will have excellent sensitivity to GeV scale Higgs portal scalars
  - Phase I: 10^{18} POT, 5-6m decay region
  - Phase II: 10^{20} POT, 7-12m decay region

Dark sectors may play a role in addressing other puzzles in nature

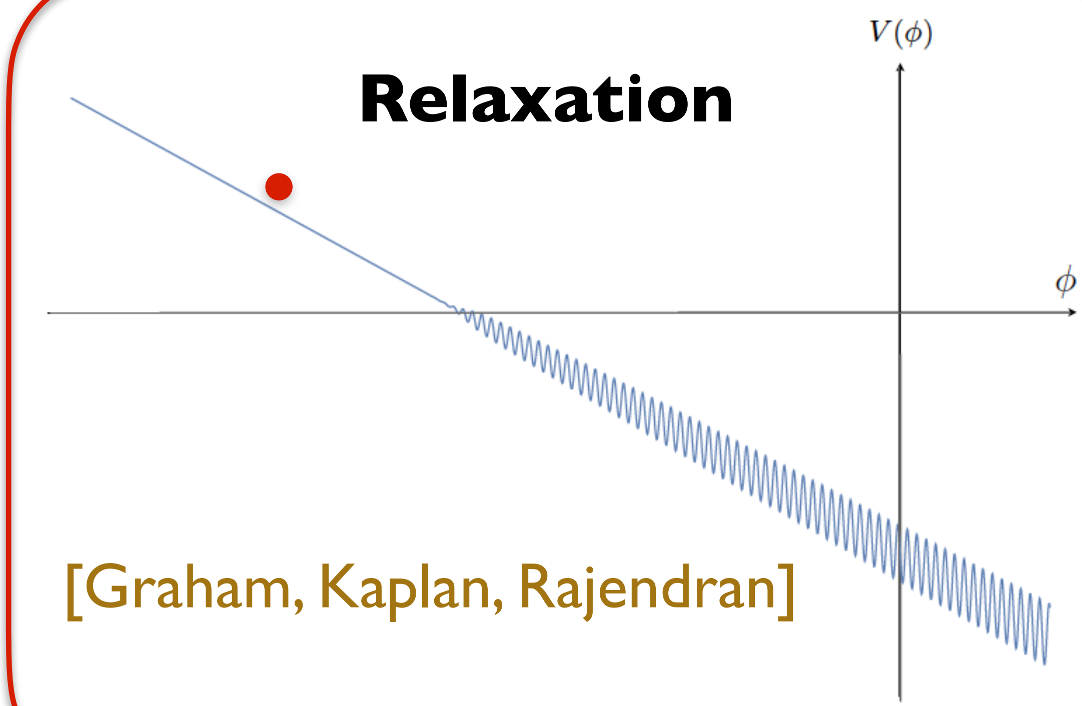
Dark Sectors and the Hierarchy Problem

Twin Higgs



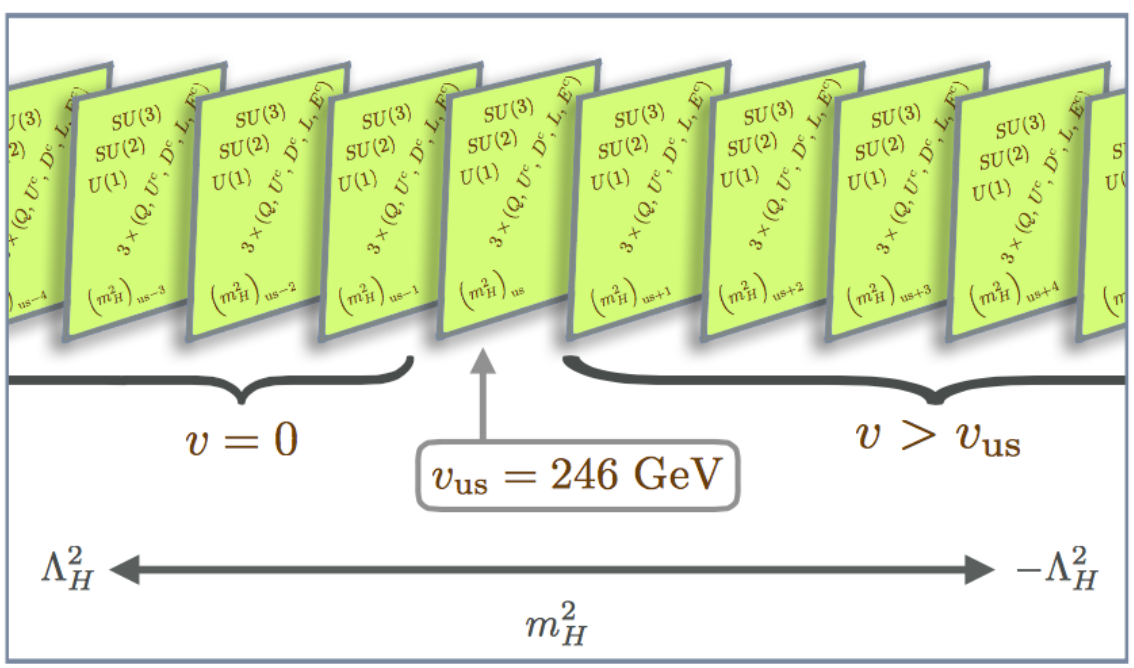
[Chacko, Harnik, Goh]
[Barbieri, Gregoire, Hall]

Relaxation



[Graham, Kaplan, Rajendran]

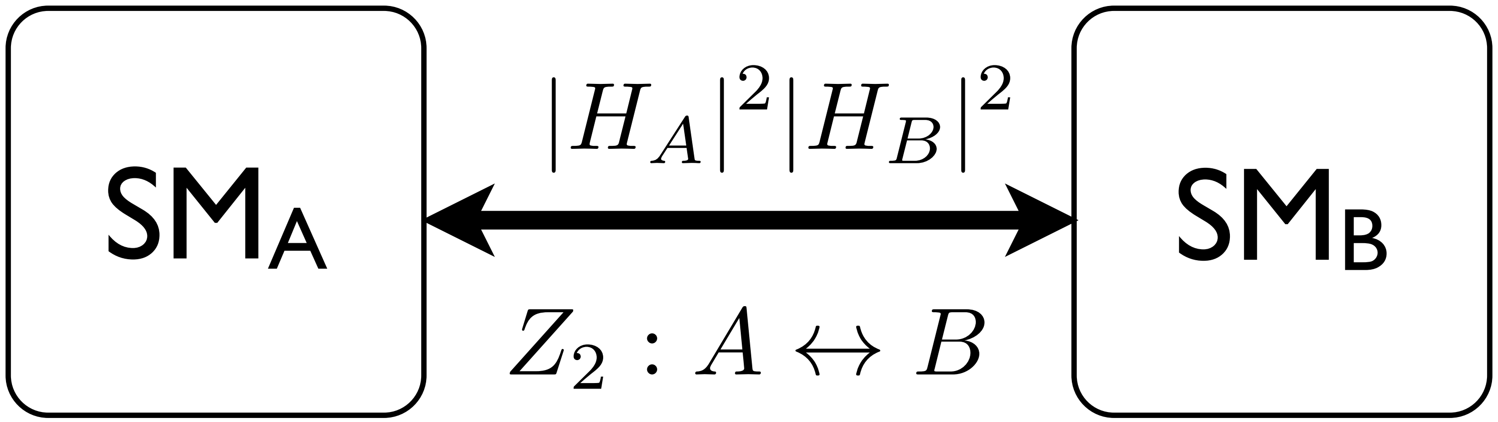
NNaturalness



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

The Twin Higgs

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



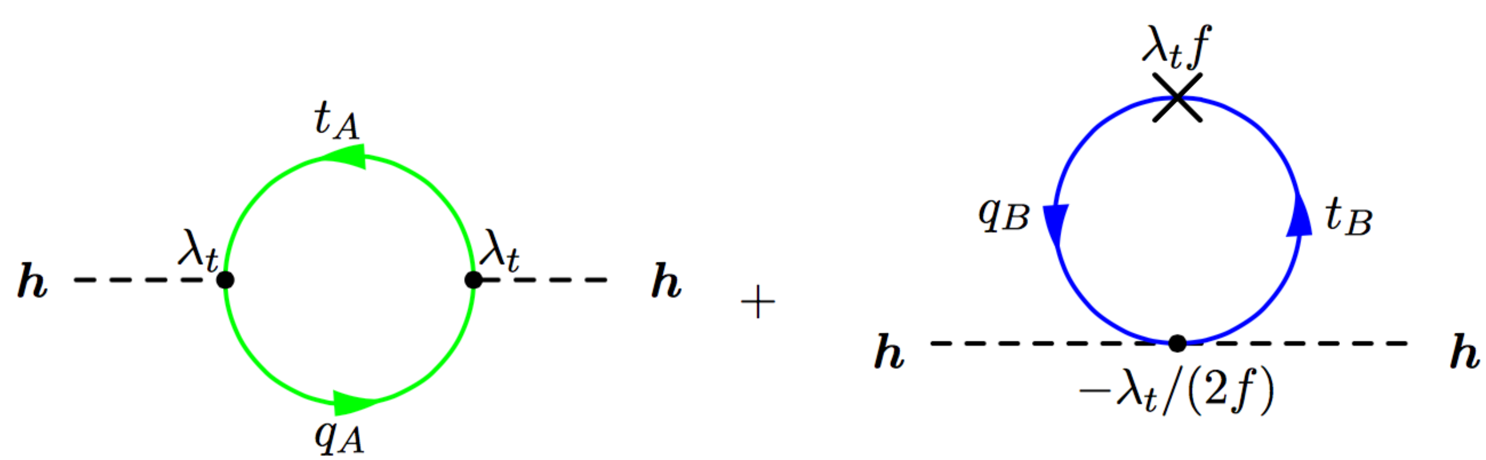
Scalar potential has approximate SU(4) symmetry

$$\mathcal{H} = \begin{pmatrix} H_A \\ H_B \end{pmatrix} \quad \Rightarrow \quad \langle \mathcal{H} \rangle = f$$

7 pNGB, 4 of these form SM Higgs doublet

$Z_2 : A \leftrightarrow B$ forces radiative correction to scalar mass to be SU(4) symmetric $\Rightarrow$ No correction to pNGB Higgs mass

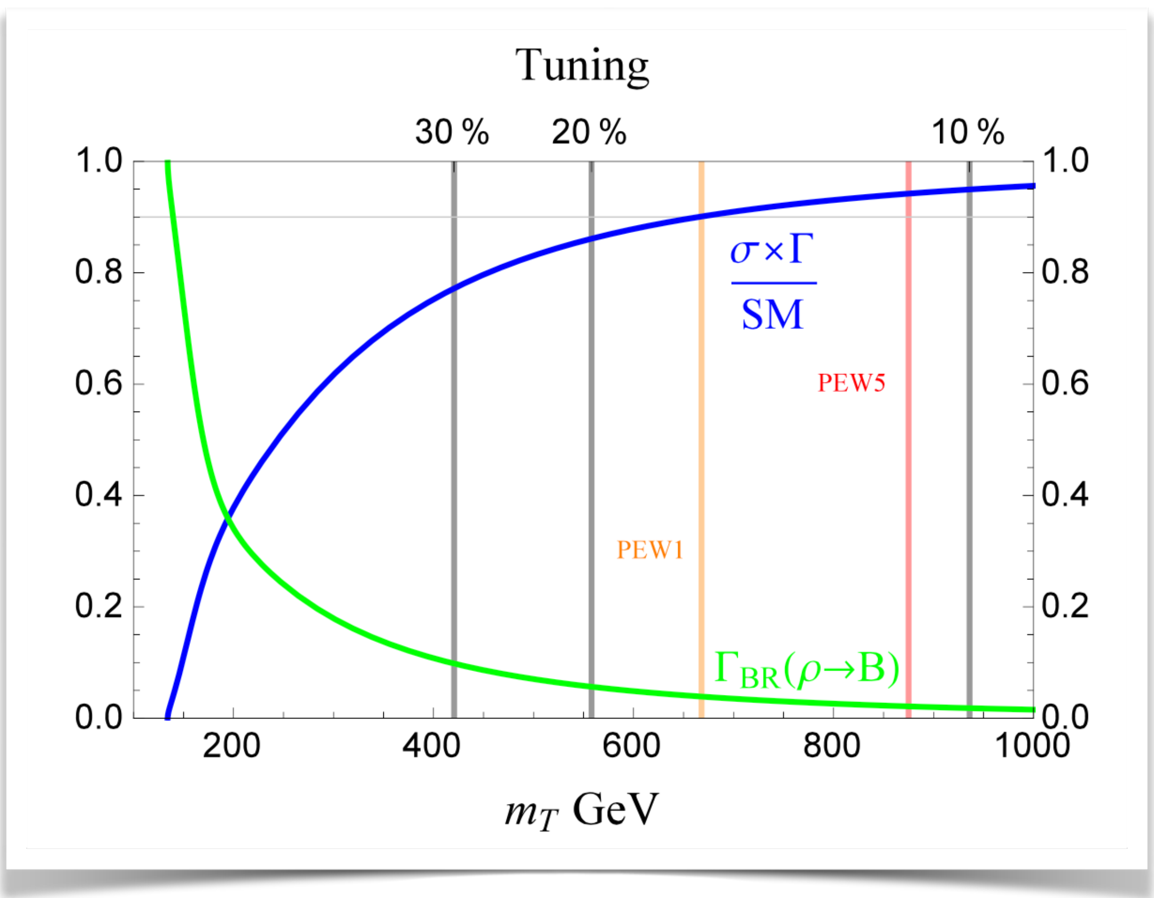
Neutral fermionic top partners



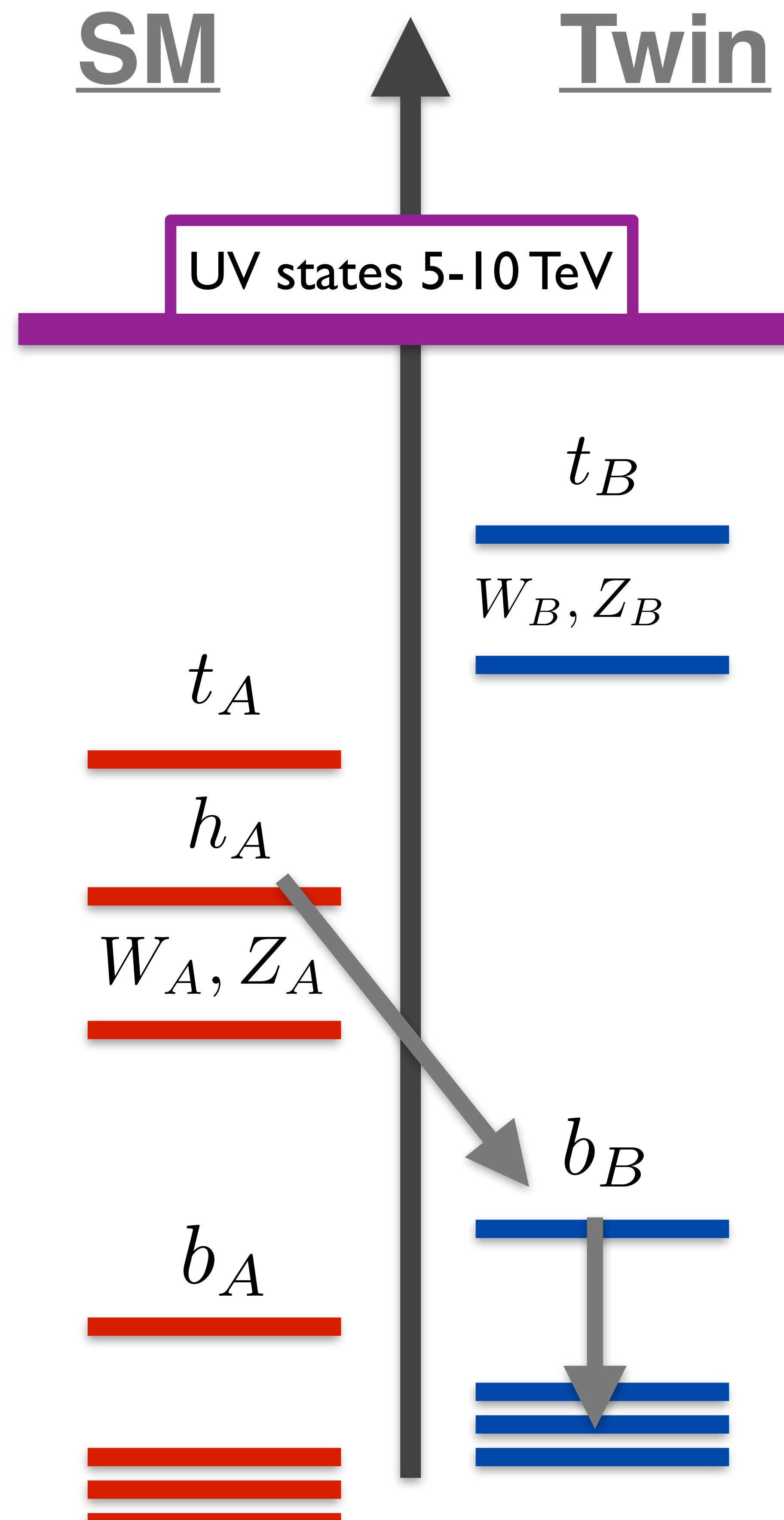
Note: small Z_2 breaking is required to obtain desired vacuum alignment

Mirror Symmetric Twin Higgs

- Exact copy of the SM in the mirror sector
- Phenomenology:
  - Higgs portal $|H_A|^2|H_B|^2$
  - Reduced Higgs coupling to SM states
  - $h_A \to b_B \bar{b}_B \to \text{invisible}$



[Burdman, Chacko, Harnik, de Lima, Verhaaren]



Dynamical Breaking of Twin Gauge and Z_2 Symmetries

[BB, Verhaaren]
[see also Liu, Weiner]

- Add hypercharged or colored scalars in both sectors. Assume $\boldsymbol{Z_2}$ is "exact"

$$\boxed{\begin{array}{c}\mathrm{SM}_{\mathbf{A}} \\ + \\ \Phi_A \sim (1,1,Y)_A\end{array}} \quad \xleftrightarrow{\;\;Z_2\;\;} \quad \boxed{\begin{array}{c}\mathrm{SM}_{\mathbf{B}} \\ + \\ \Phi_B \sim (1,1,Y)_B\end{array}}$$

- Vacuum spontaneously breaks twin hypercharge and $\boldsymbol{Z_2}$: $\qquad \langle \Phi_A \rangle = 0 \qquad \langle \Phi_B \rangle = f_\Phi$

- An effective $\boldsymbol{Z_2}$-breaking mass term causes $\langle H_A \rangle \ll \langle H_B \rangle$:

$$V \supset \delta_{H\Phi}(|\Phi_A|^2 - |\Phi_B|^2)(|H_A|^2 - |H_B|^2) \to -\delta_{H\Phi} f_\Phi^2 (|H_A|^2 - |H_B|^2)$$

- New dynamical fermion mass terms are allowed in the twin sector $\qquad \lambda\, \Phi_B\, \psi_B\, \psi'_B \to \lambda\, f_\Phi\, \psi_B\, \psi'_B$

Couplings of Φ_B and Twin Fermion Masses $(Y=1)$

$$-\mathcal{L}_{Y=1} \supset \frac{1}{2}\lambda_1\,\Phi_B^+\,L_B\,L_B + \frac{c_1}{\Lambda}\,\Phi_B^-\,L_B\,H_B\,\bar{\ell}_B + \frac{c_2}{\Lambda}\,\Phi_B^+\,Q_B\,H_B^\dagger\,\bar{u}_B + \frac{c_3}{\Lambda}\,\Phi_B^-\,Q_B\,H_B\,\bar{d}_B + \text{h.c.}$$

$$\supset \lambda_1\,f_\Phi\,\nu_B\,\ell_B + \frac{c_1\,v_B f_\Phi}{\sqrt{2}\Lambda}\,\nu_B\,\bar{\ell}_B + \frac{c_2\,v_B f_\Phi}{\sqrt{2}\Lambda}\,d_B\,\bar{u}_B + \frac{c_3\,v_B f_\Phi}{\sqrt{2}\Lambda}\,u_B\,\bar{d}_B + \text{h.c.},$$

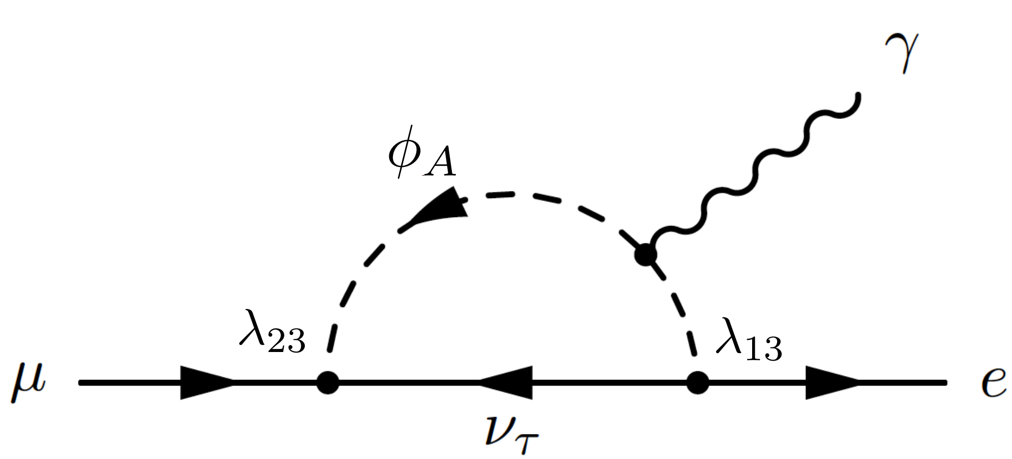
$\Rightarrow$

- Twin neutrinos married to charged leptons,
- Twin up quarks married to down quarks
- Maximum size of twin mass between 10 GeV - 1 TeV

Can potentially realize Fraternal Twin Higgs dynamically [Craig,Katz,Strassler, Sundrum]

Interplay between twin fermion masses and precision tests:

- E.g. Lepton Flavor Violation $\quad \lambda\,\Phi_A L_A L_A + \lambda\,\Phi_B L_B L_B$



$$\text{Br}(\mu\to e\gamma) = \tau_\mu \frac{\alpha\,|\lambda_{13}^*\,\lambda_{23}|^2|\,m_\mu^5}{2^{14}\,3^2\,\pi^4\,m_\phi^4}$$

$$\simeq 4.2\times 10^{-13}\left(\frac{300\text{ GeV}}{m_\phi}\right)^4\left(\frac{\sqrt{|\lambda_{13}^*\,\lambda_{23}|}}{0.02}\right)^4$$

A vibrant experimental program to search for dark sectors is emerging!

Resources:

- Dark Sectors 2016 Workshop: Community Report

  https://arxiv.org/abs/1608.08632

- U.S. Cosmic Visions: New Ideas in Dark Matter 2017: Community Report

  https://arxiv.org/abs/1707.04591

- Physics Beyond Colliders at CERN: Beyond the Standard Model Working Group Report

  https://arxiv.org/abs/1901.09966

- Basic Research Needs for Dark Matter Small Projects New Initiatives

  https://science.osti.gov/-/media/hep/pdf/Reports/Dark_Matter_New_Initiatives_rpt.pdf

Outlook

- Dark matter provides strong empirical evidence for physics beyond the Standard Model.

- Cosmological origin of dark matter provides motivation for non-gravitational interactions with normal matter.

- The dark sector paradigm is well-motivated and leads to a rich variety of phenomena associated with dark matter, with potential connections to other fundamental puzzles in nature.

- Testing these scenarios requires new experimental strategies; many exciting ideas are being explored

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

Symmetry Magazine

Thanks!