Overview of Light Dark Matter at Accelerators

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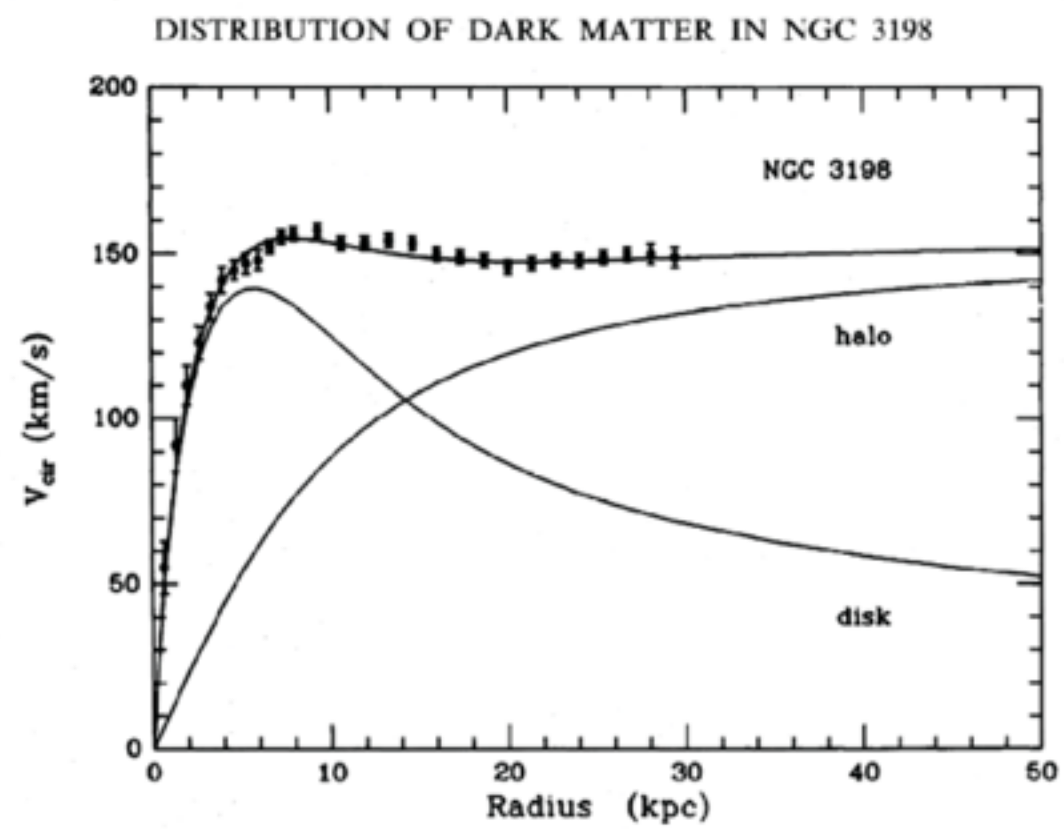
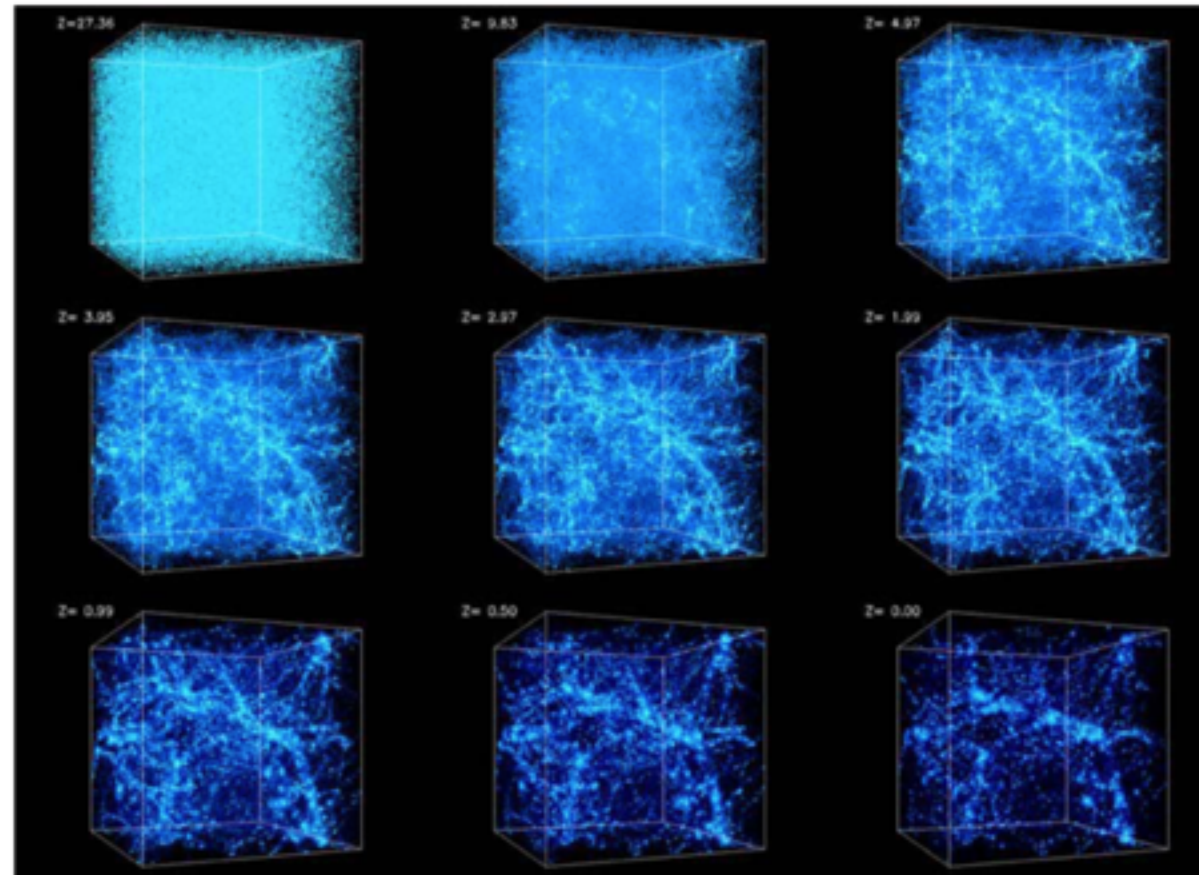
University of Pittsburgh

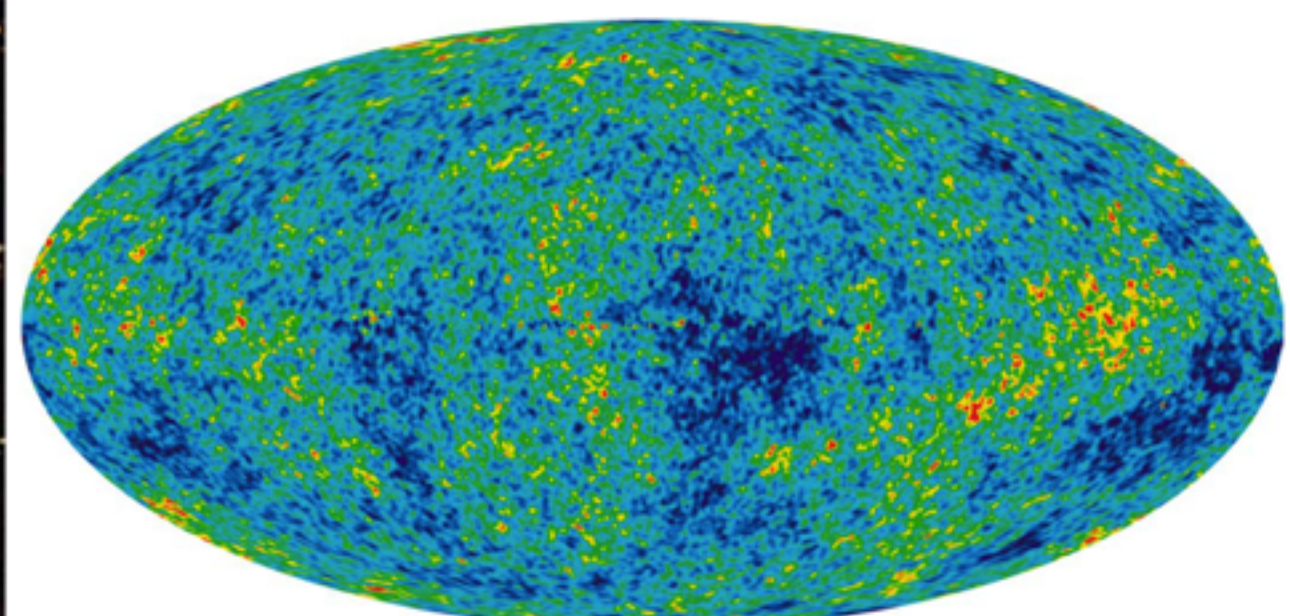
LDMA 2019
November 20-22, 2019

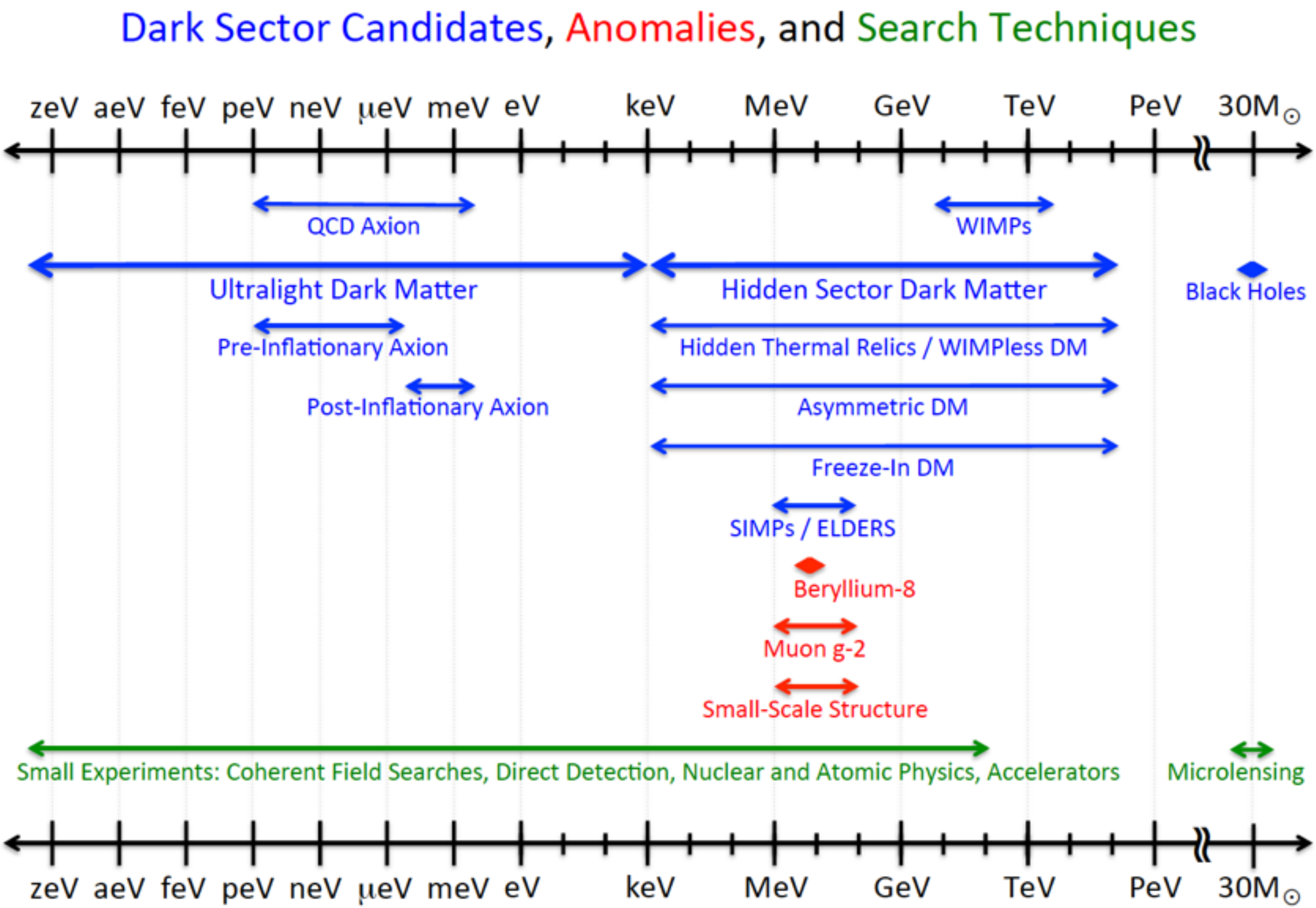
Dark Matter



DISTRIBUTION OF DARK MATTER IN NGC 3198
NGC 3198
halo
disk
V_{cir} (km/s)
Radius (kpc)
0
50
100
150
200
0
10
20
30
40
50



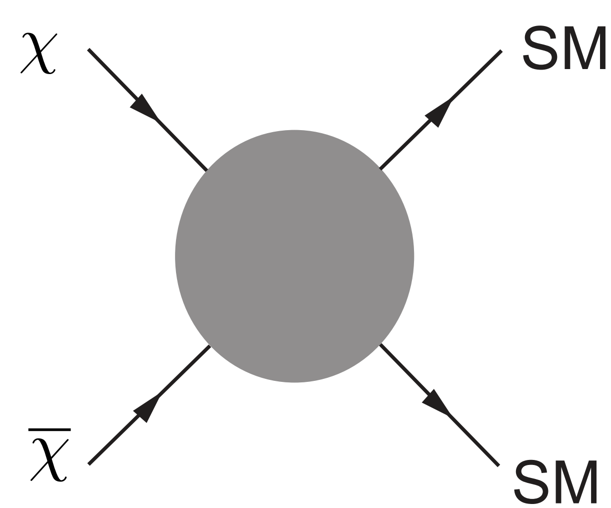


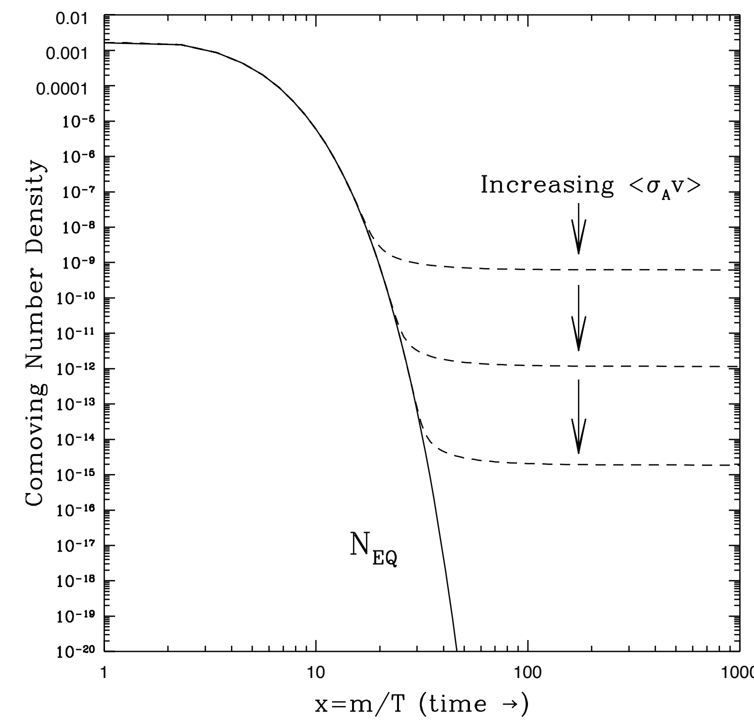


From Cosmic Visions community study 1707.04591

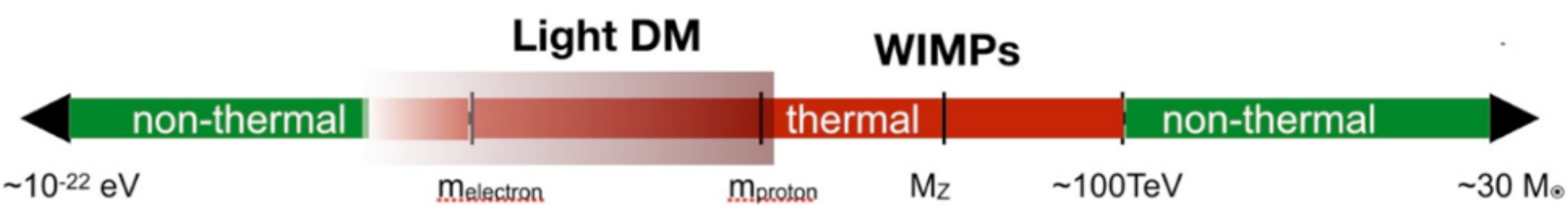
Thermal Freezeout

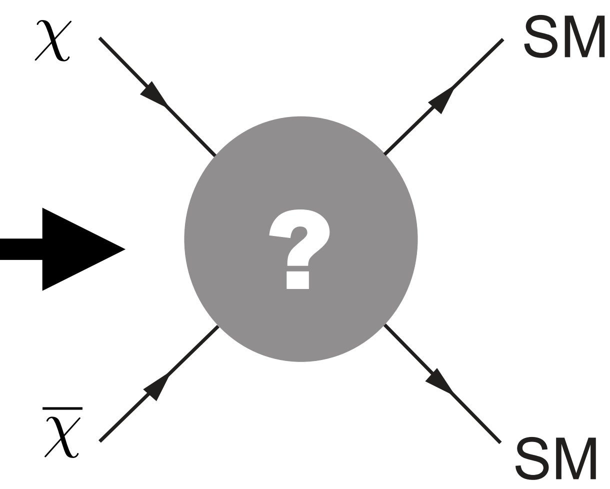
- Dark matter produced from reactions in the hot plasma
- Requires non-gravitational dark matter interactions





- Viable mass range between MeV - 100 TeV in simplest scenarios



What's here? → 

"WIMP" regime: $1\,\mathrm{GeV} \lesssim m_\chi \lesssim 100\,\mathrm{TeV}$

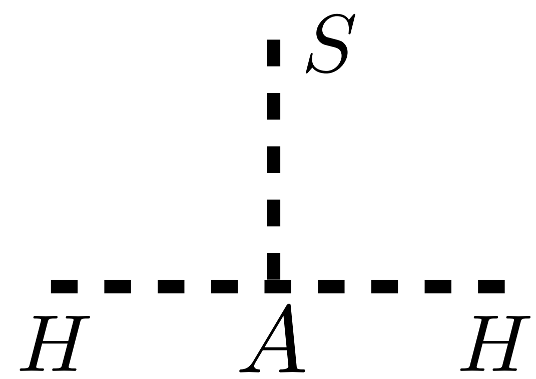
- Weak interaction, Higgs portal, BSM mediator (Z', sfermion, etc.),…

Light DM regime: $m_\chi \lesssim 1\,\mathrm{GeV}$

- Lee-Weinberg bound; suggests new light mediator [Boehm, Fayet]
  - Renormalizable Portals
  - Gauge anomaly-free SM symmetry $(B-L, L_\mu - L_\tau, \ldots)$
  - Gauge anomalous symmetry, couple light scalar via higher dimension operators (e.g., axion portal), …

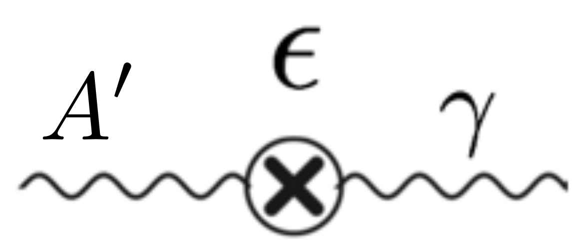
Renormalizable Portals

$AH^\dagger HS$



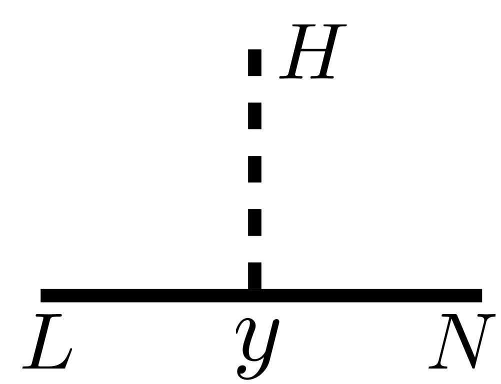
Higgs Portal

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



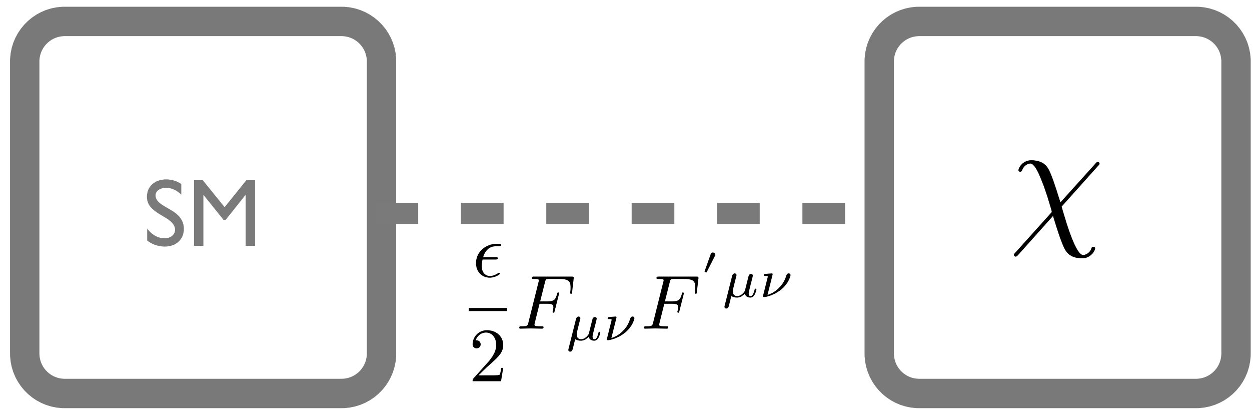
Vector Portal

$yLHN$



Neutrino portal

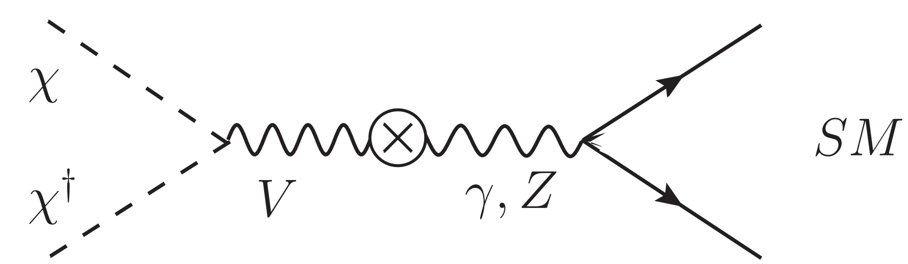
Benchmark model: vector portal dark matter



[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: $m_\chi, m_{A'}, \alpha_D, \epsilon$
- Can obtain correct relic abundance



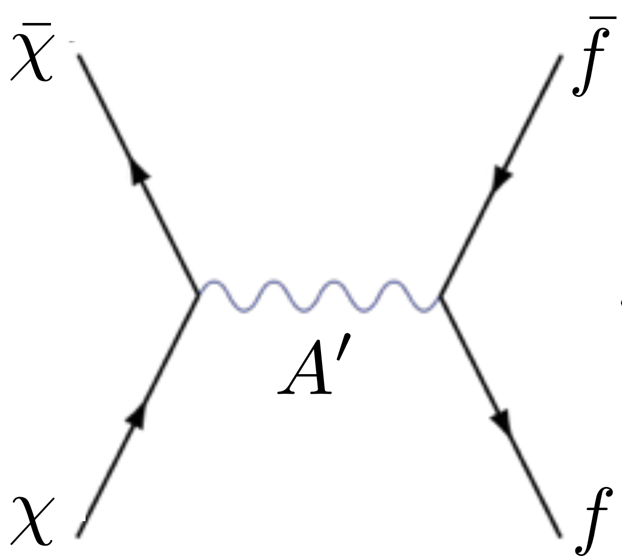
- CMB bounds evaded due to p-wave annihilation
- Variations in cosmology and phenomenology obtained by changing mediator, or dark matter properties - important to explore all options

Direct vs. Secluded Annihilation

Two characteristic regimes:

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

[Boehm, Fayet]

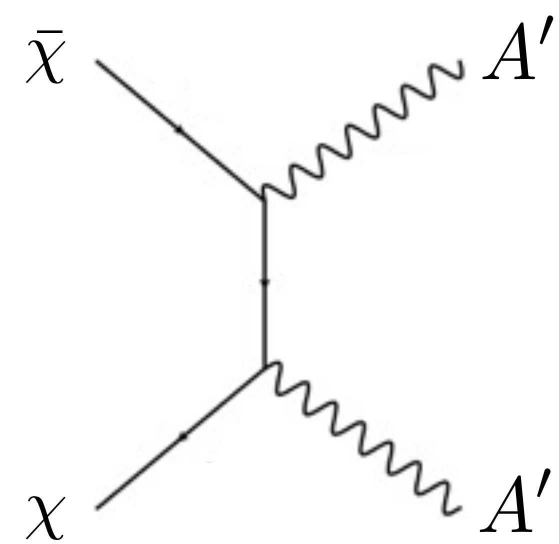


$$\langle \sigma v \rangle \sim \frac{\epsilon^2 \alpha_D m_\chi^2}{m_{A'}^4}$$

Requires sizable portal coupling
to deplete DM abundance

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

[Pospelov, Ritz, Voloshin]



$$\langle \sigma v \rangle \sim \frac{\alpha_D^2}{m_\chi^2}$$

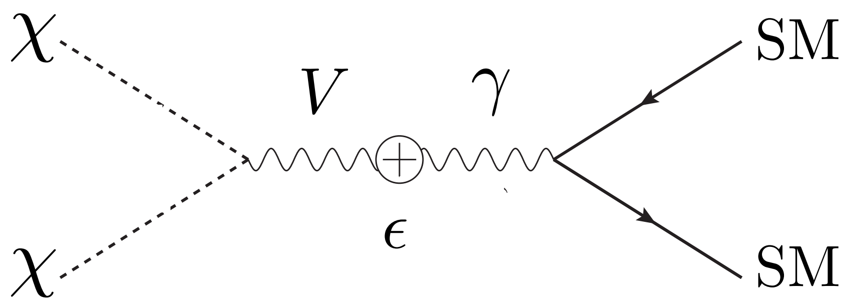
Requires only minuscule portal coupling
to maintain kinetic equilibrium

$m_{A'} > 2m_\chi$: search for invisible dark photon decays

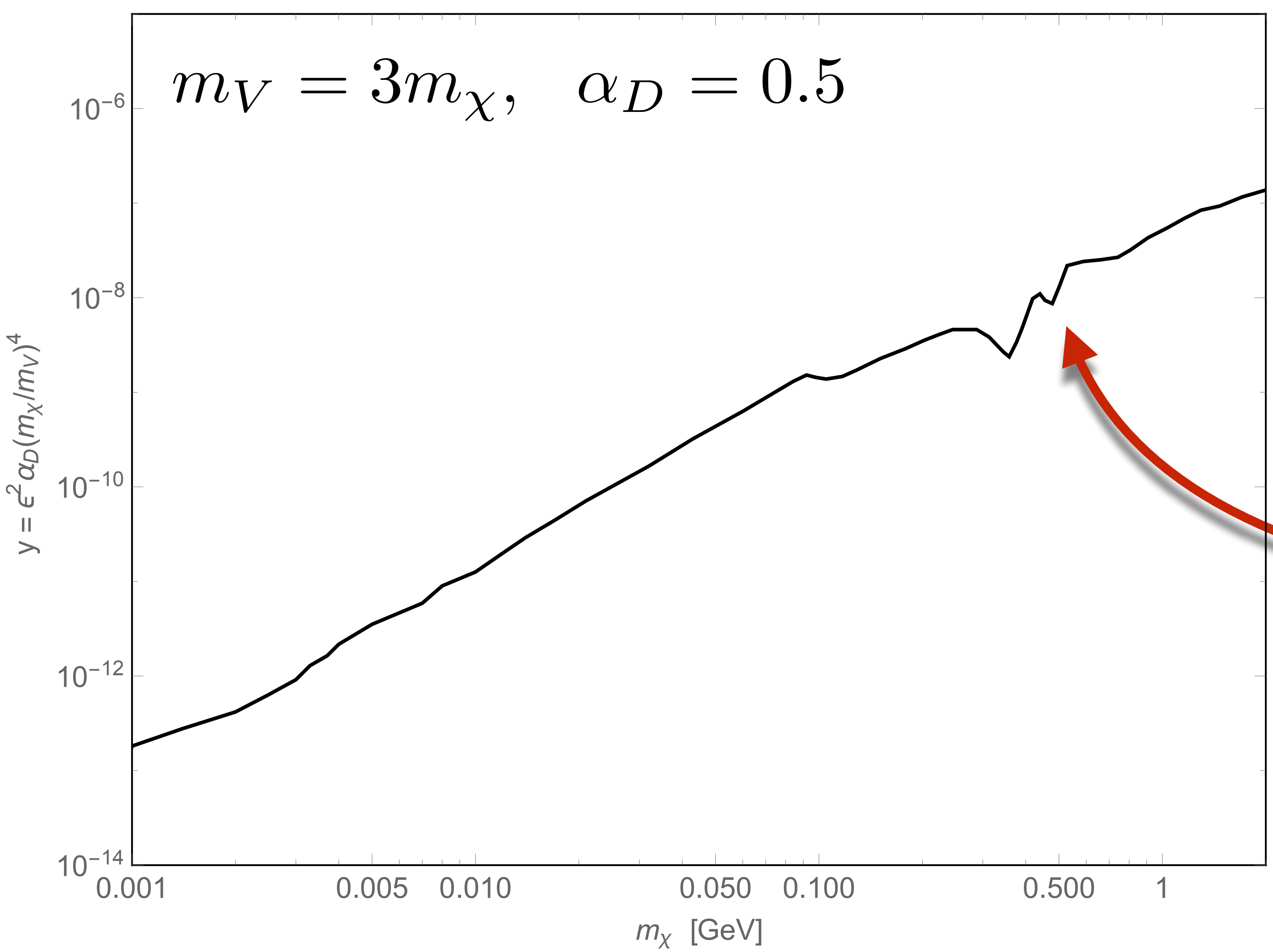
$m_{A'} < 2m_\chi$: search for visible dark photon decays

Thermal target (direct annihilation)

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



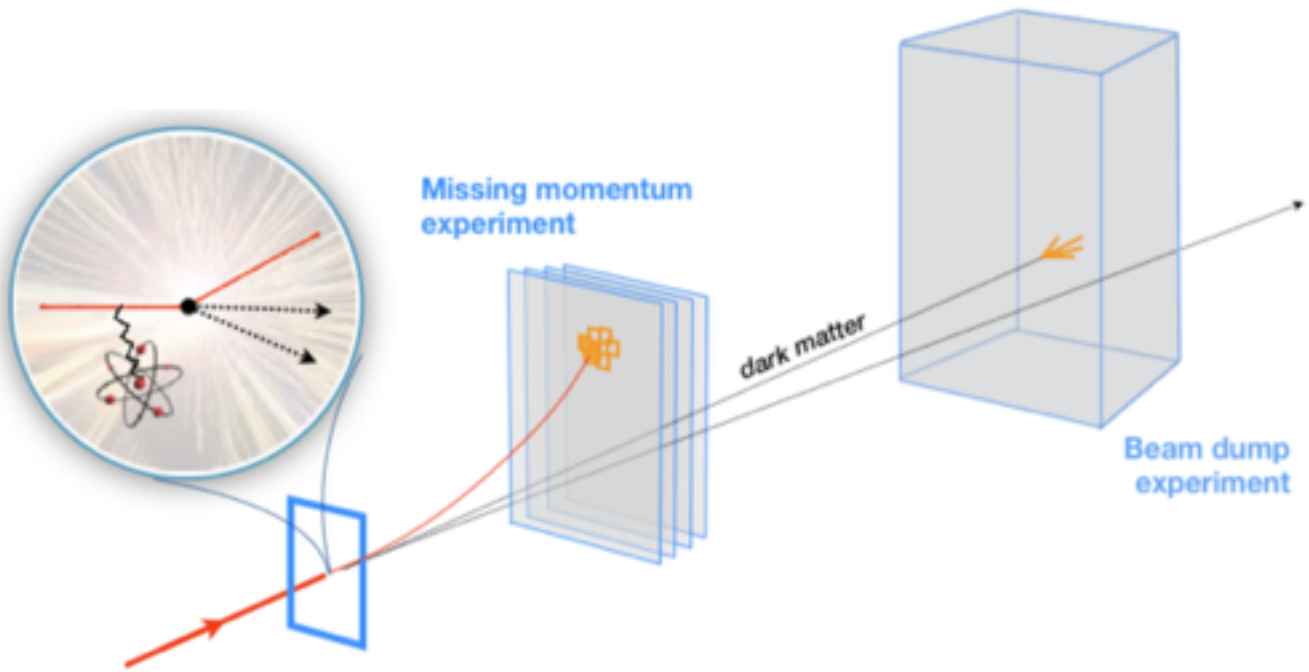
DM annihilation



observed DM abundance predicted along this line

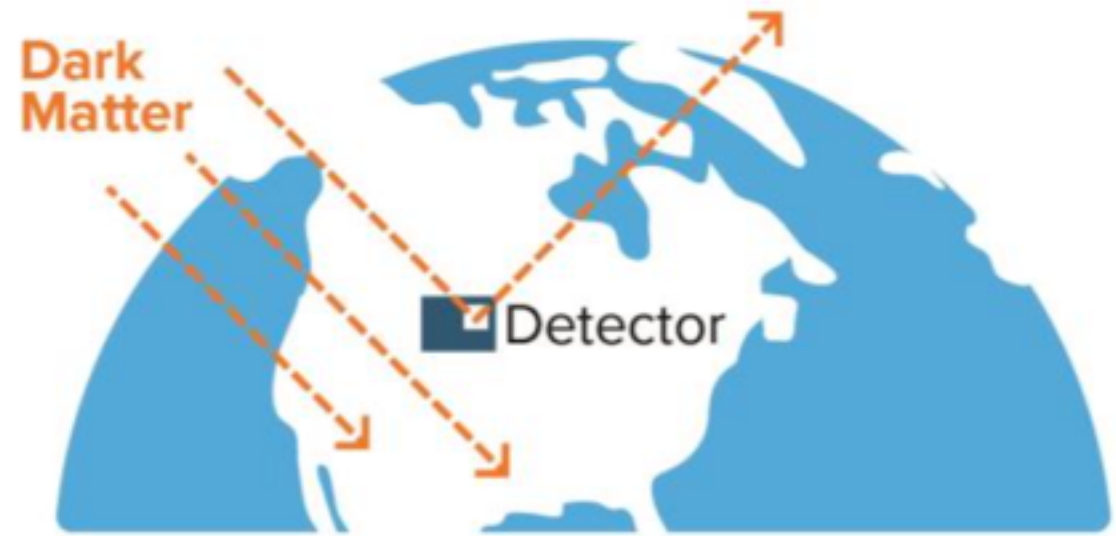
[Izaguirre, Krnjaic, Schuster, Toro]

Accelerators



From Dark Matter Small Projects New Initiatives Report

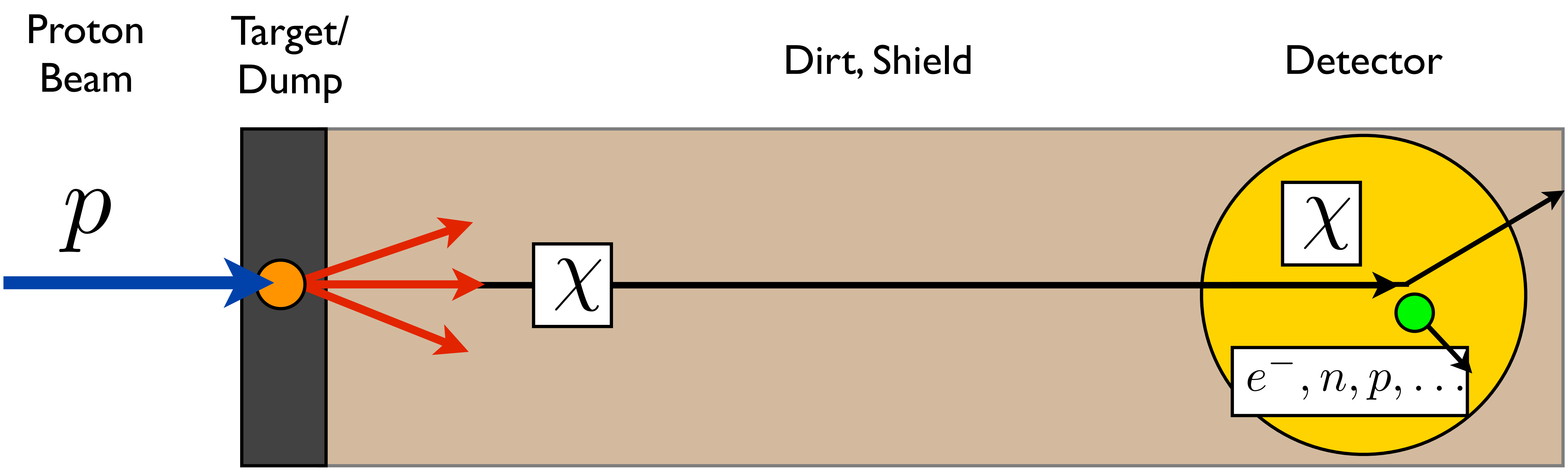
Direct Detection



See overview talk by R. Essig (and many others at this meeting)

Complementary approaches - need both to discern the structure of dark sector

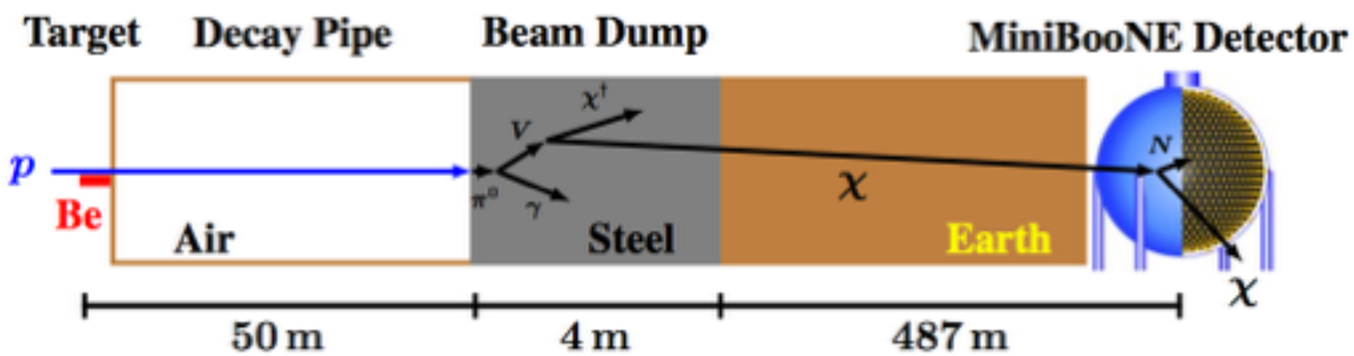
Proton Beam Dump Searches for Light Dark Matter

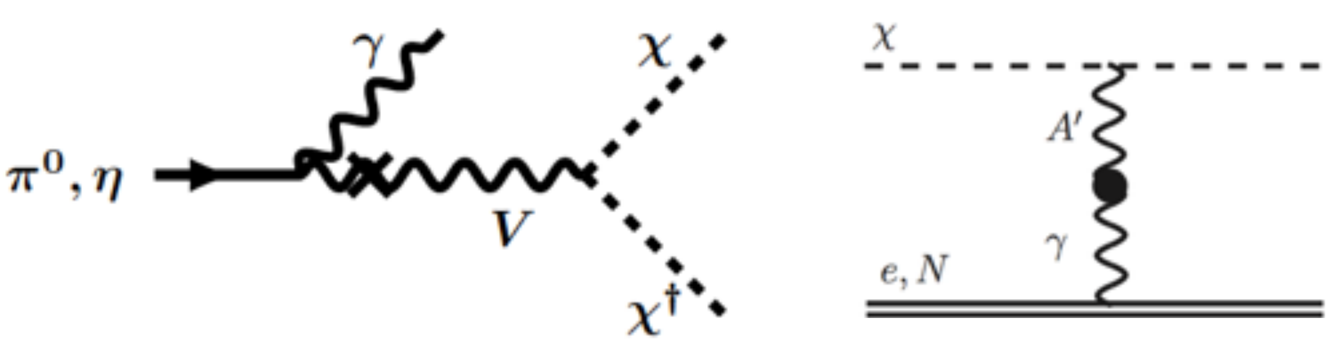


See also talk by Oliver Lantwin

[BB, Pospelov Ritz, '09]
[deNiverville, Pospelov Ritz, '11]
[McKeen, deNiverville, Ritz, '12]
[Dobrescu, Frugiuele, '14]
[Kahn, Krnjaic, Thaler, Toups, '14]
...

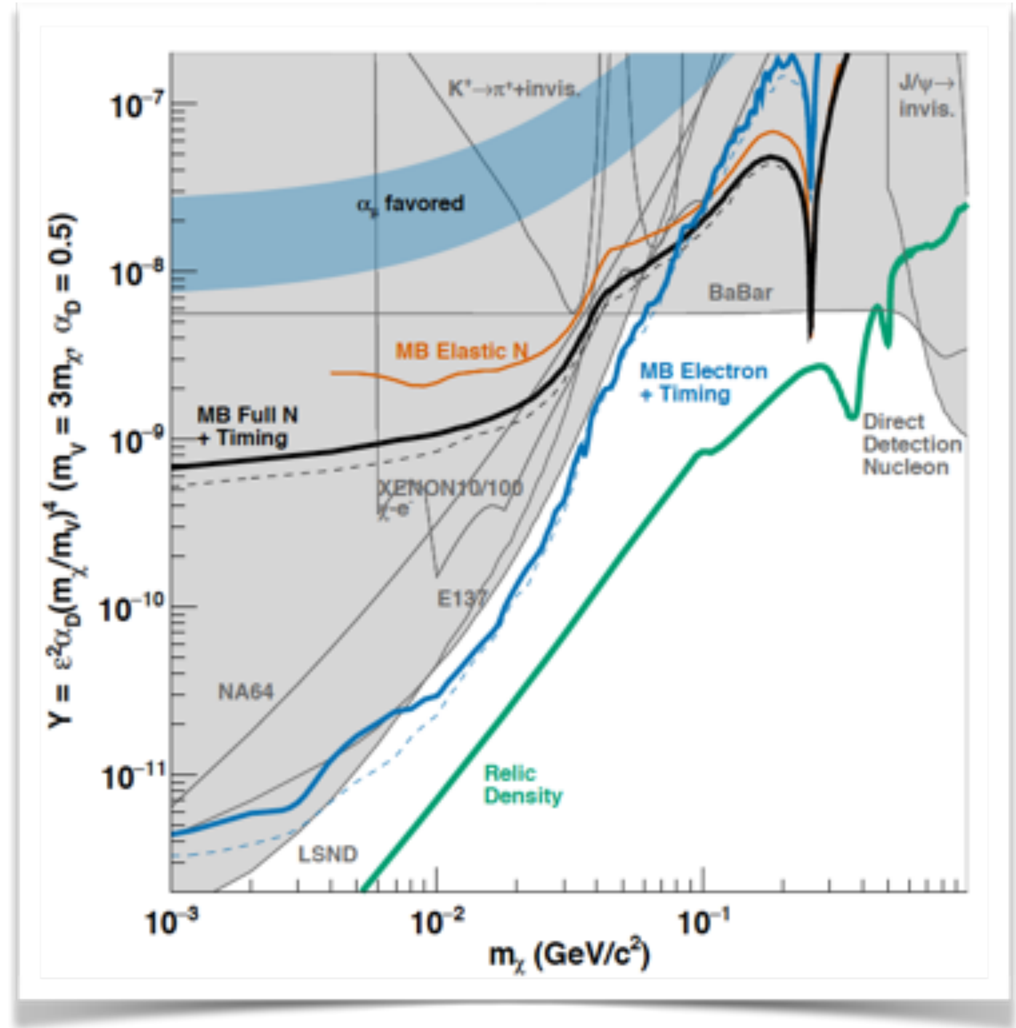
MiniBooNE-DM @ FNAL





Production

Detection



[MiniBooNE-DM 1807.06137]

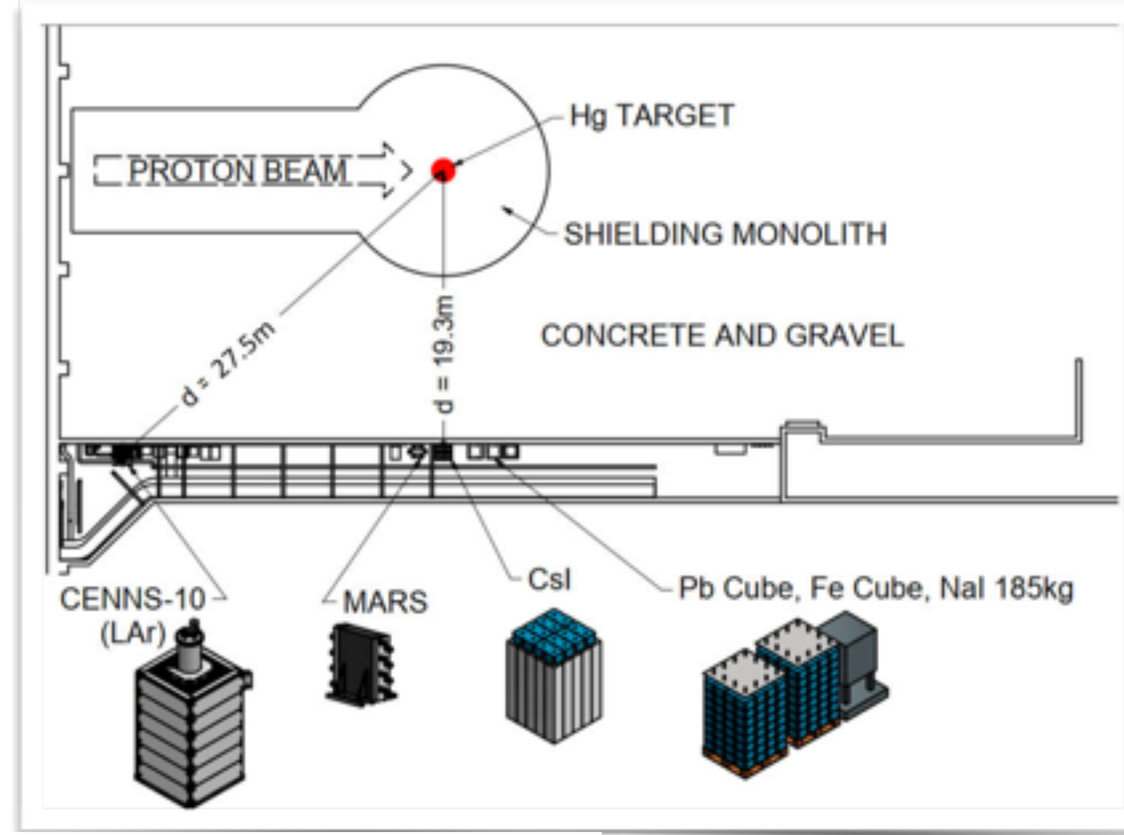
- 8 GeV protons on iron dump; 800 ton mineral oil detector
- Dedicated off target / beam dump run mode, collected 1.9E20 POT
- Leading limits on dark photon model for ~ 100 MeV mass range and large α_D
- Demonstrates proton beam dump as an effective search method for light dark matter

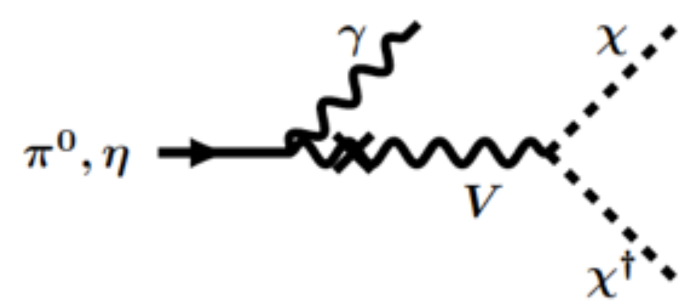
COHERENT @ ORNL

- First observation of Coherent Elastic Neutrino Nucleus Scattering (CEvNs)

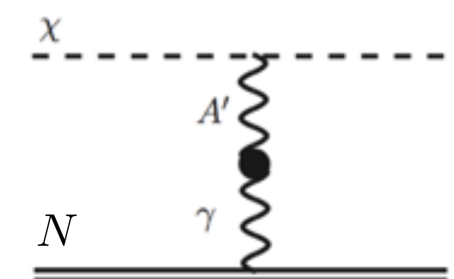
  [Science 357 (2017) no.6356, 1123-1126]

- COHERENT also sensitive to sub-GeV dark matter [deNiverville, Pospelov, Ritz] [Ge, Shoemaker]
- 1 GeV proton beam on mercury target
- Suite of detectors located ~ 20 m off axis
- DM Sensitivity study for planned 750 kg liquid argon scintillation detector:

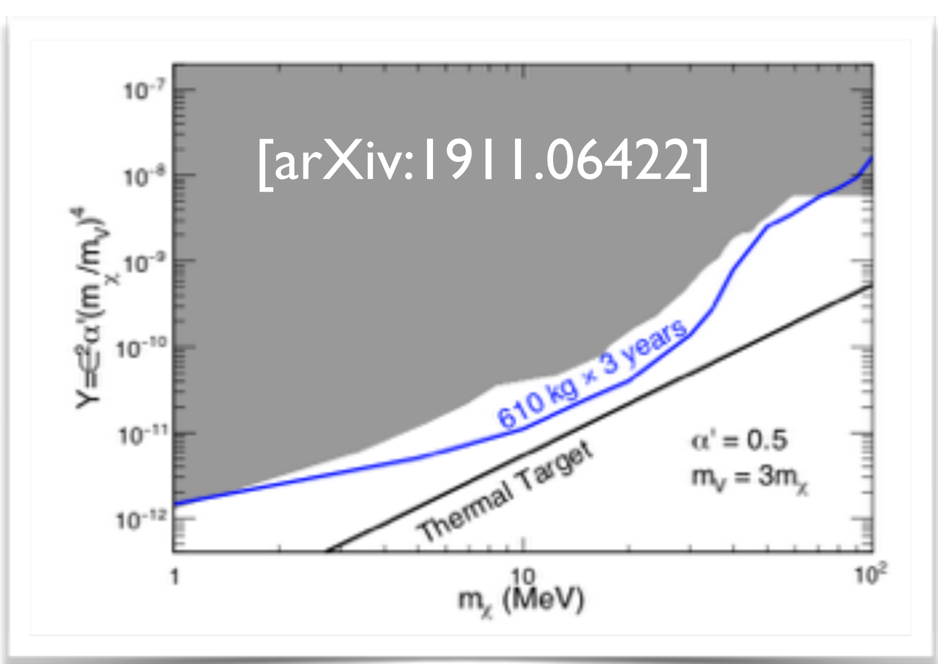


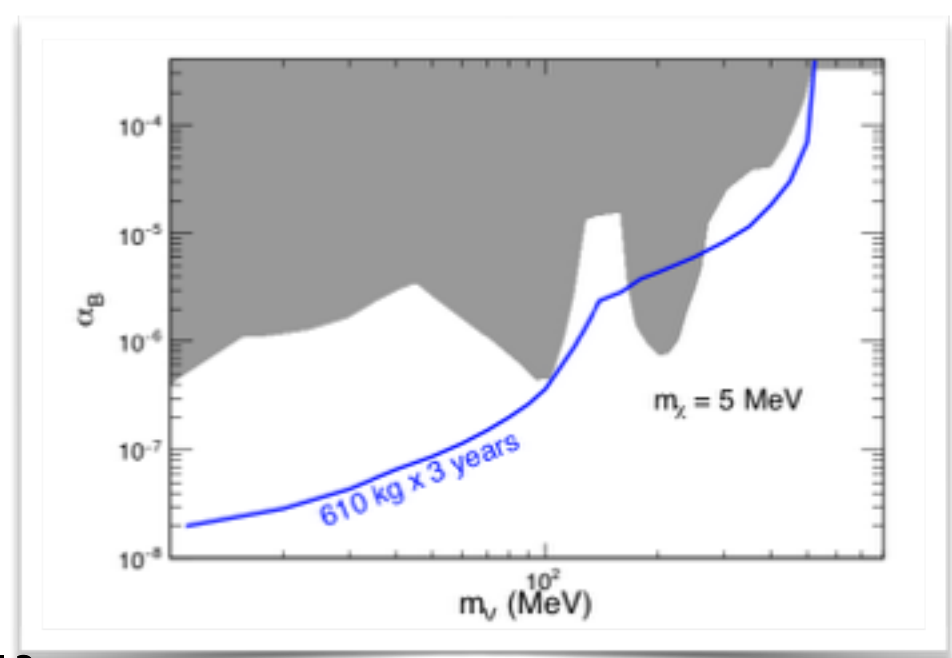


Production via Neutral mesons decays



Elastic NC nucleon or electron scattering

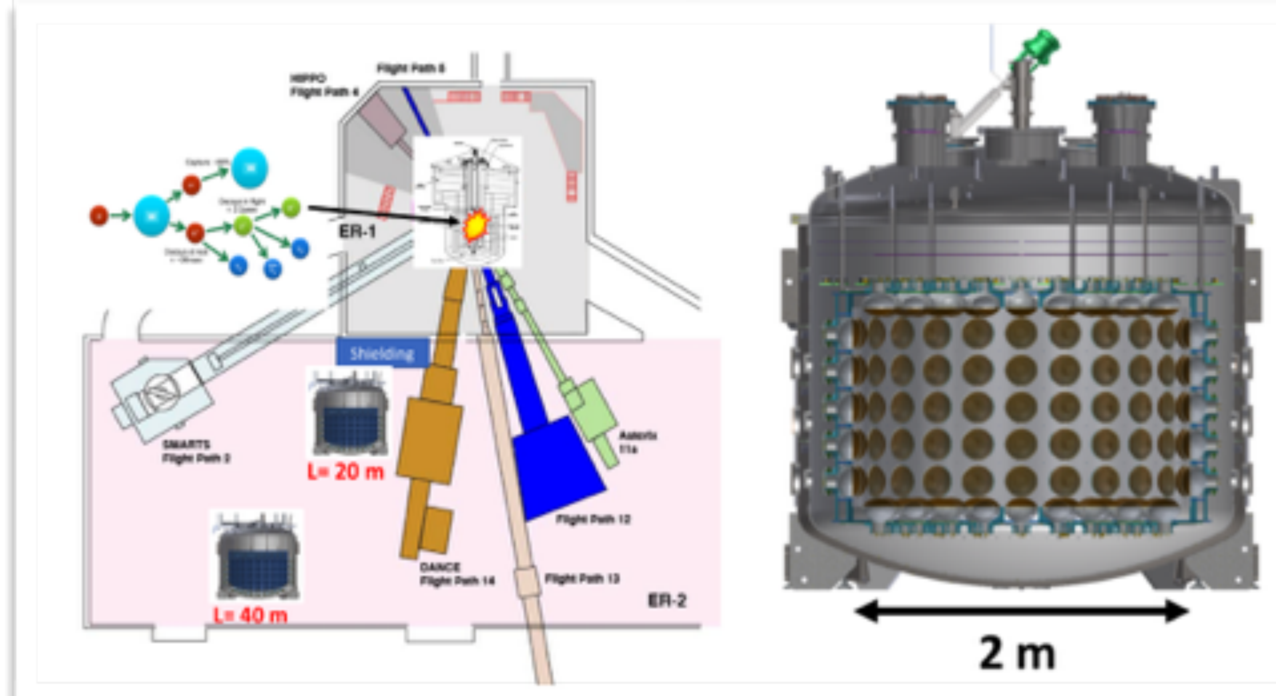


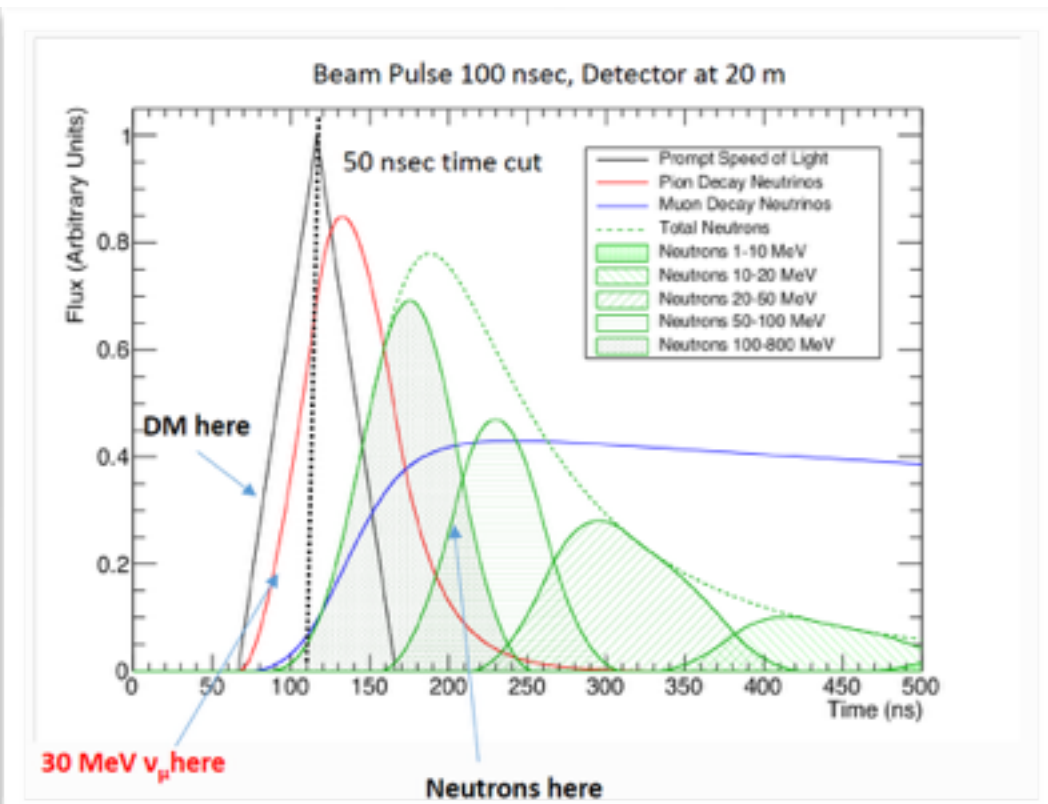


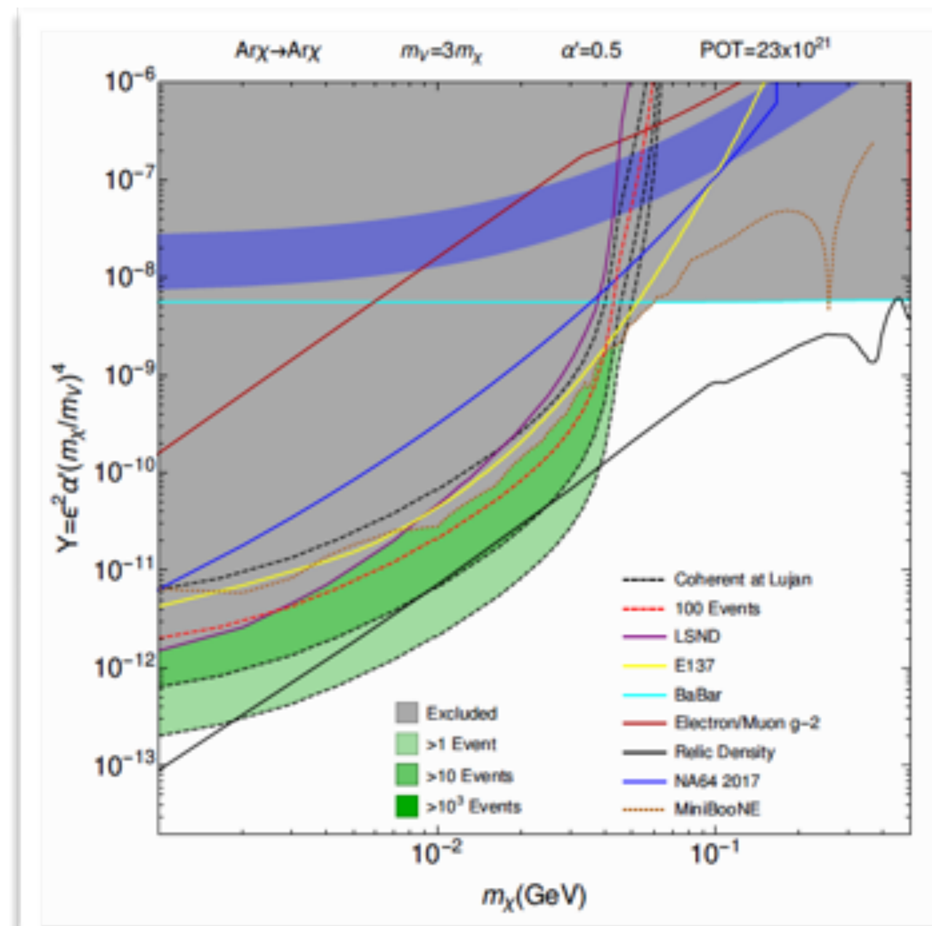
Leptophobic model

CCM @ LANL

- Primary goal: measure CEvNS and search for eV - scale sterile neutrinos
- 800 MeV protons on tungsten target
- 10 ton Liquid Argon Scintillation detector x 2 (near and far locations)
- Second detector funded through US DOE Dark Matter New Initiatives Award
- DM signal is prompt, backgrounds are delayed

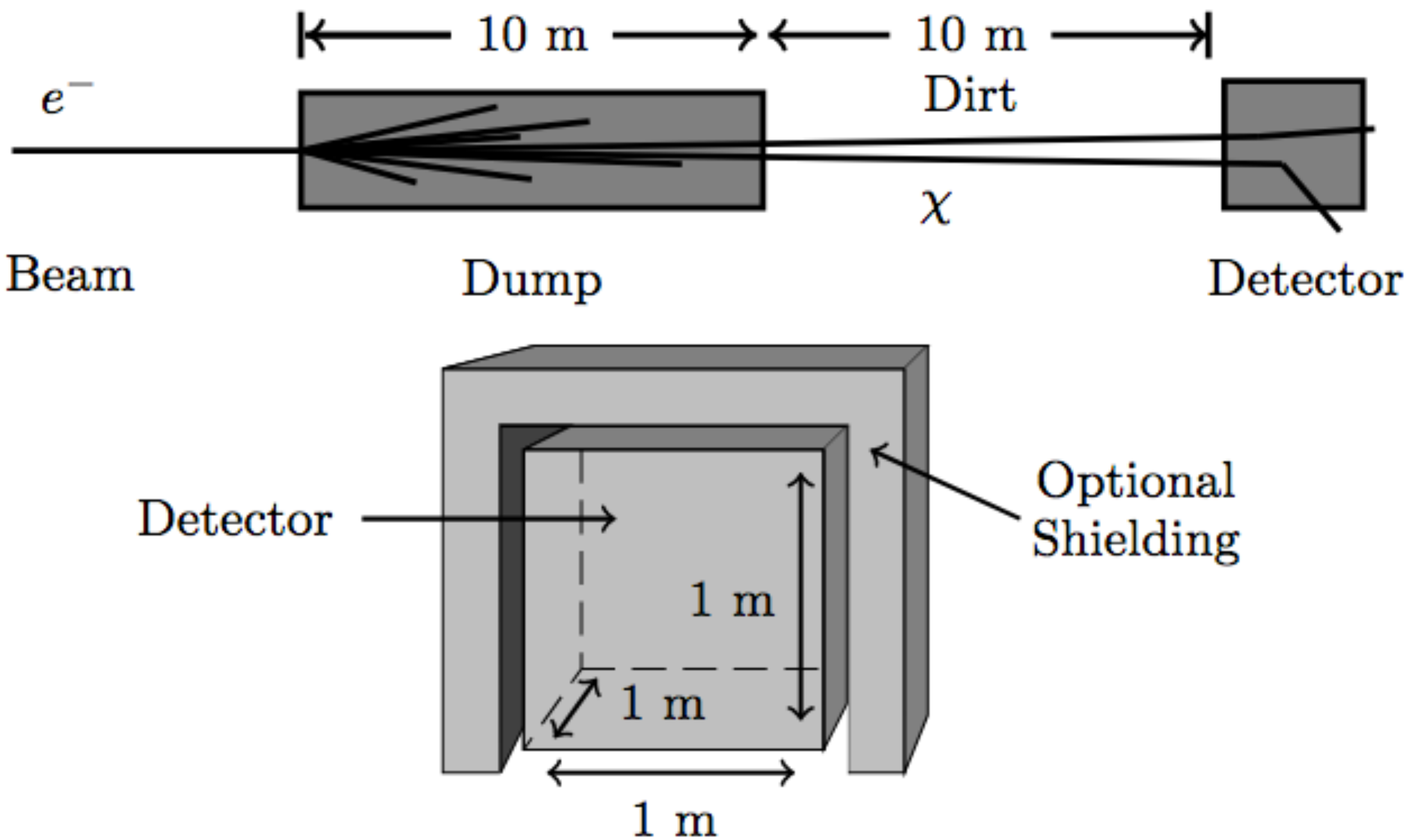






Figures from R. Van De Water & P. deNiverville

Electron Beam Dump Searches for Light Dark Matter



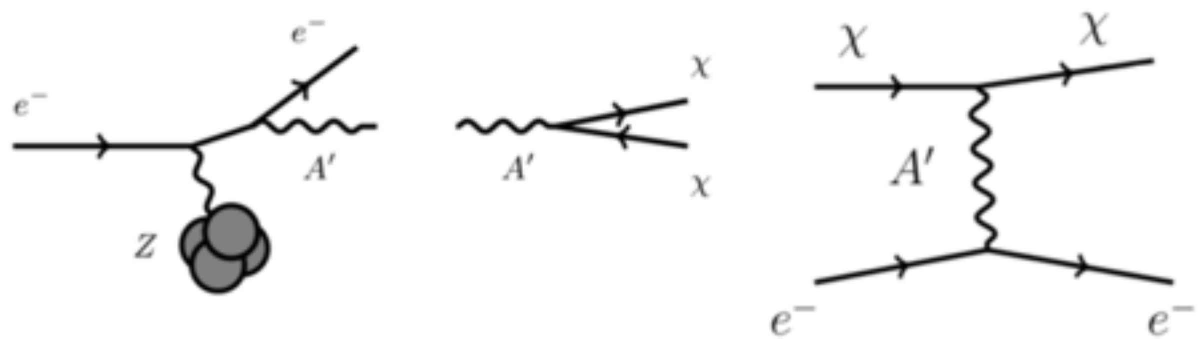
[Izaguirre, Krnjaic, Schuster, Toro]

See also talks by L. Marsicano, M. Christmann

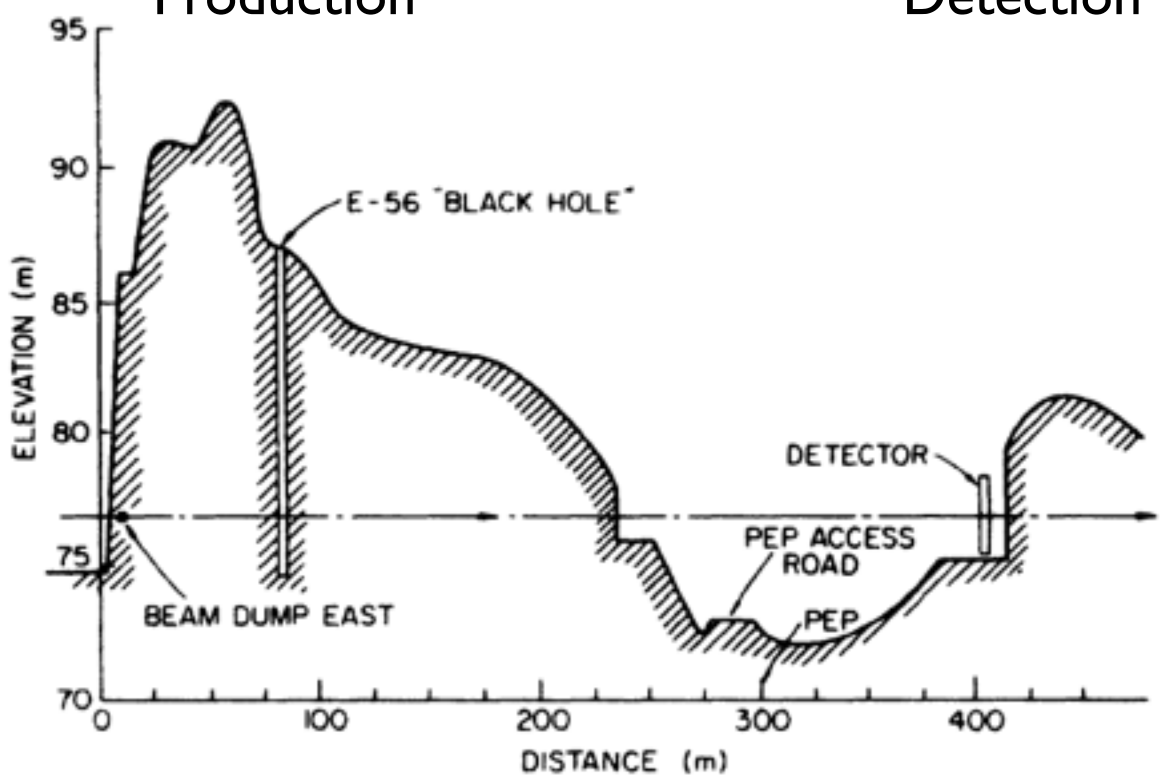
SLAC Beam Dump E137

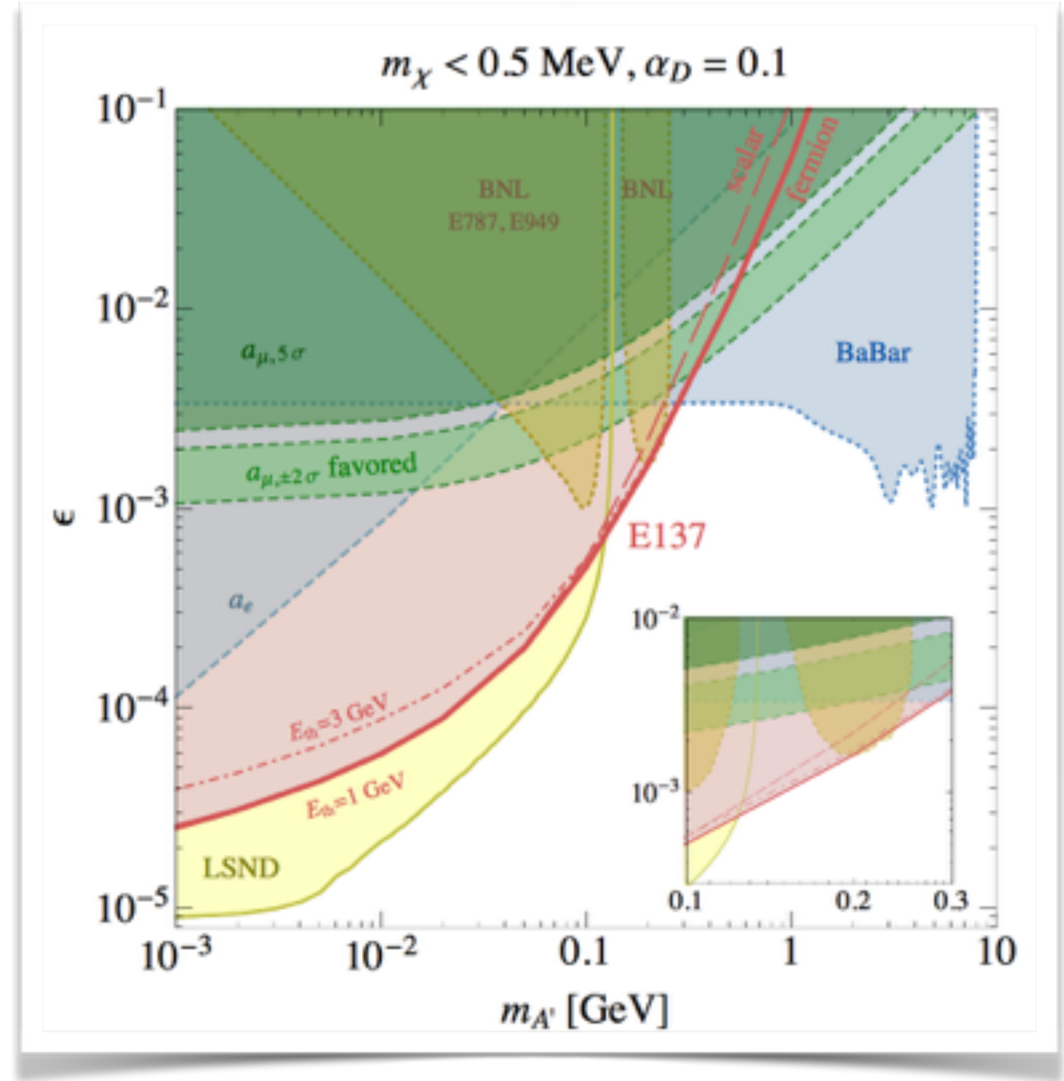
[BB, Essig, Surujon '14]
[Bjorken et al., (E137 Collaboration '88]

- 20 GeV electron beam; 30 C dumped
- Water - aluminum target
- Shower calorimeter, 400 m from dump



Production Detection

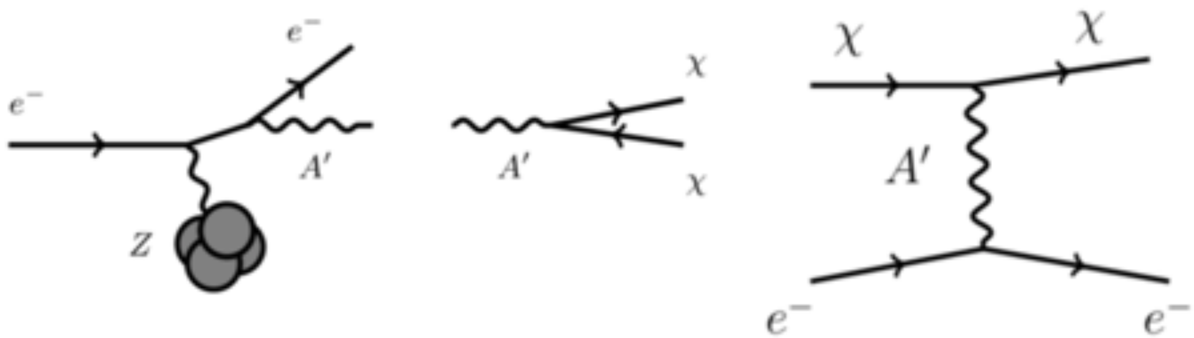




Provides proof-of-principle for future electron beam dump experiments

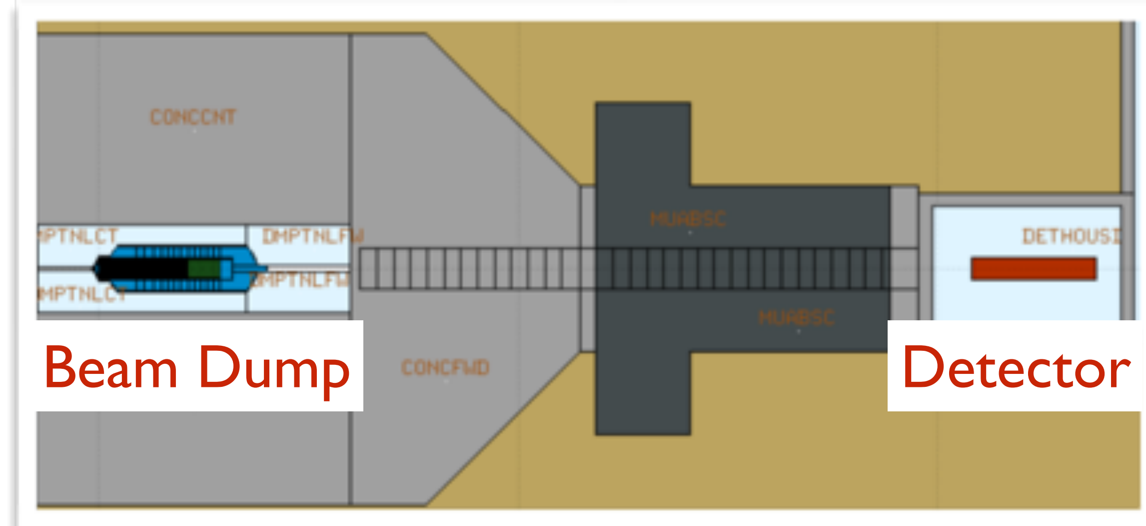
BDX @ JLAB

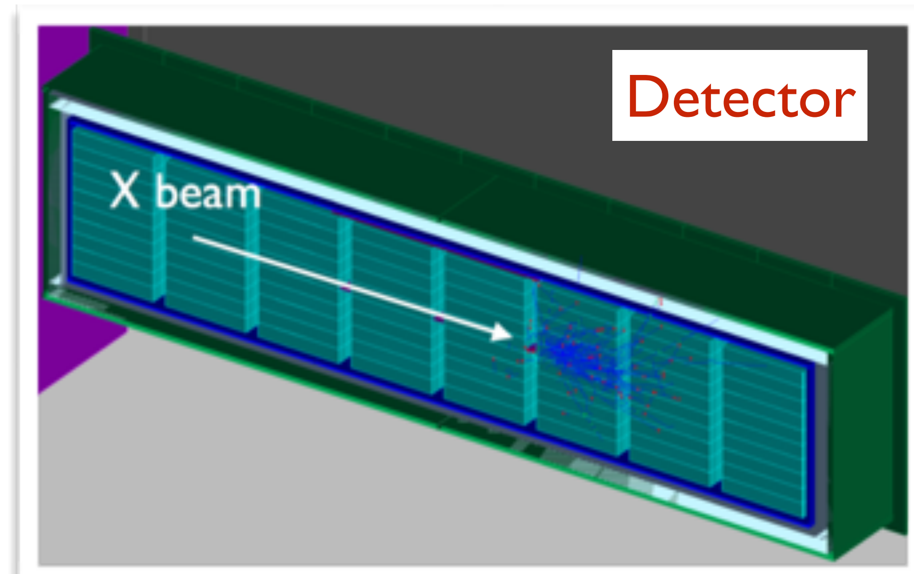
- 11 GeV electron beam on Water-Aluminum dump
- ECAL detector located 20m downstream

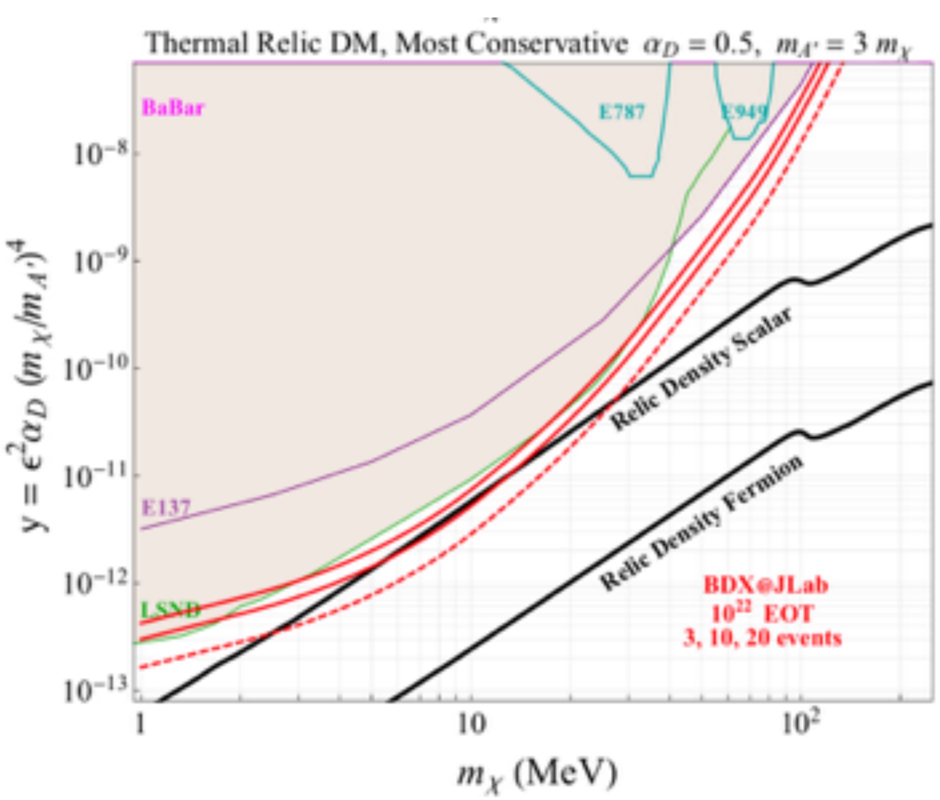


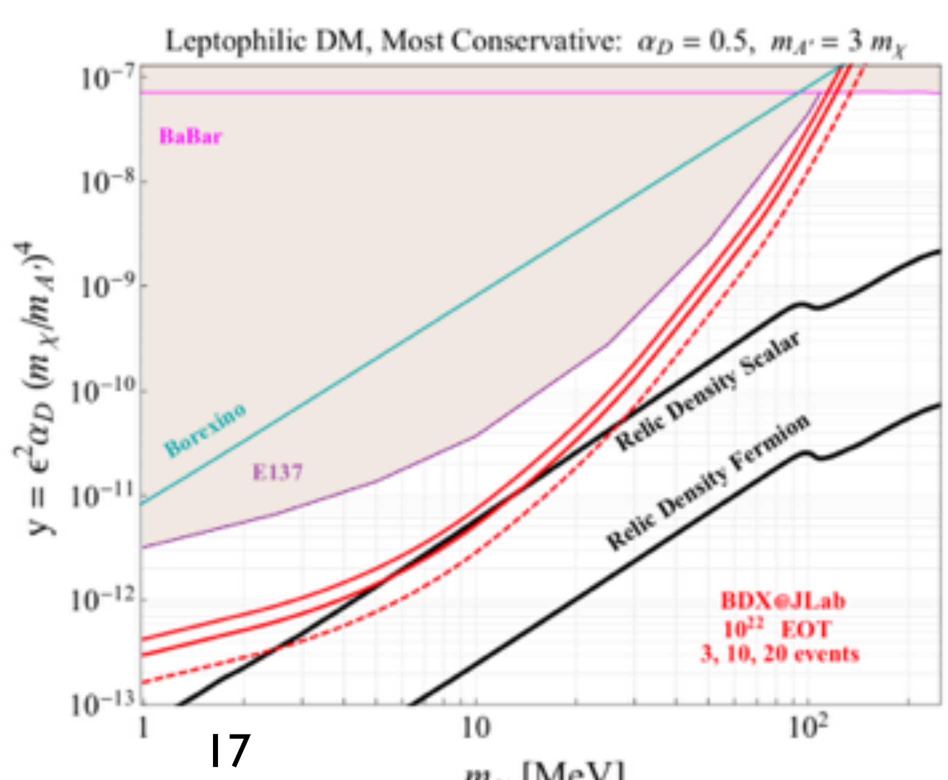
Production Detection

- Approved by JLAB PAC for 10^{22} EOT run



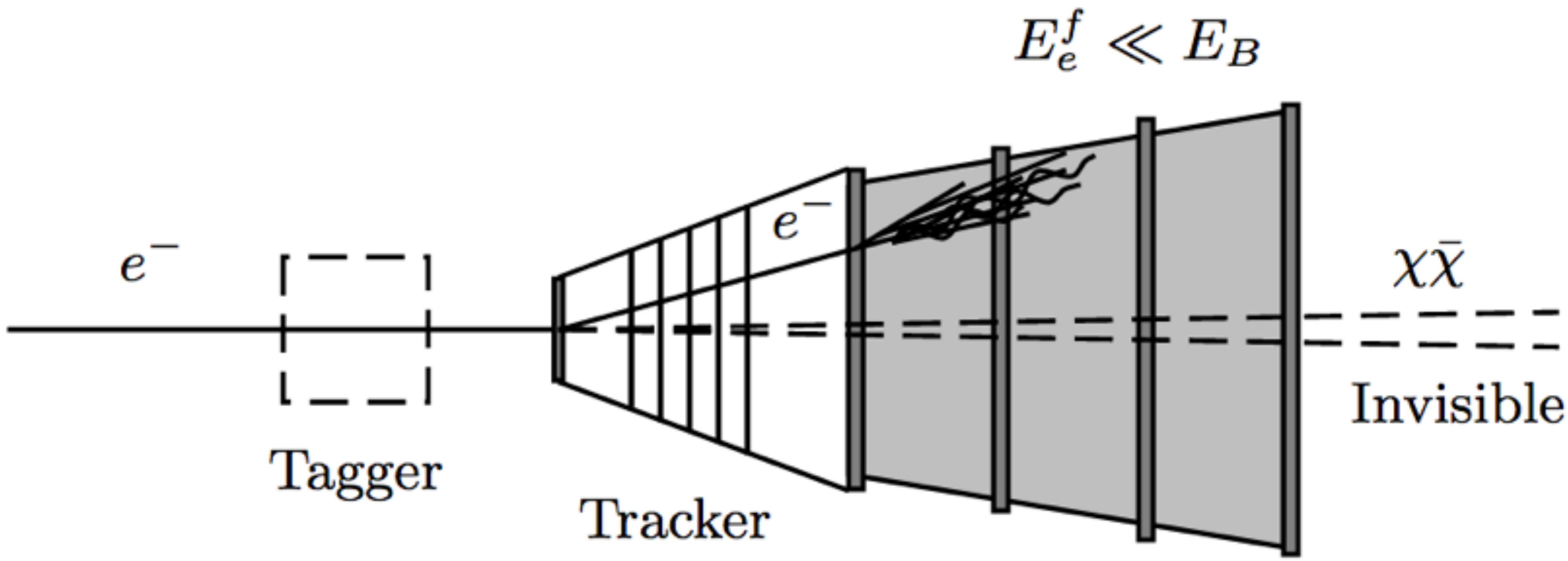






BDX proposal
1607.01390

Missing energy / momentum searches for dark matter

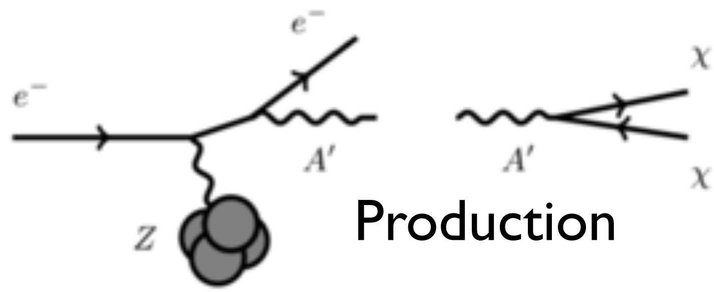


[Andreas. et al]

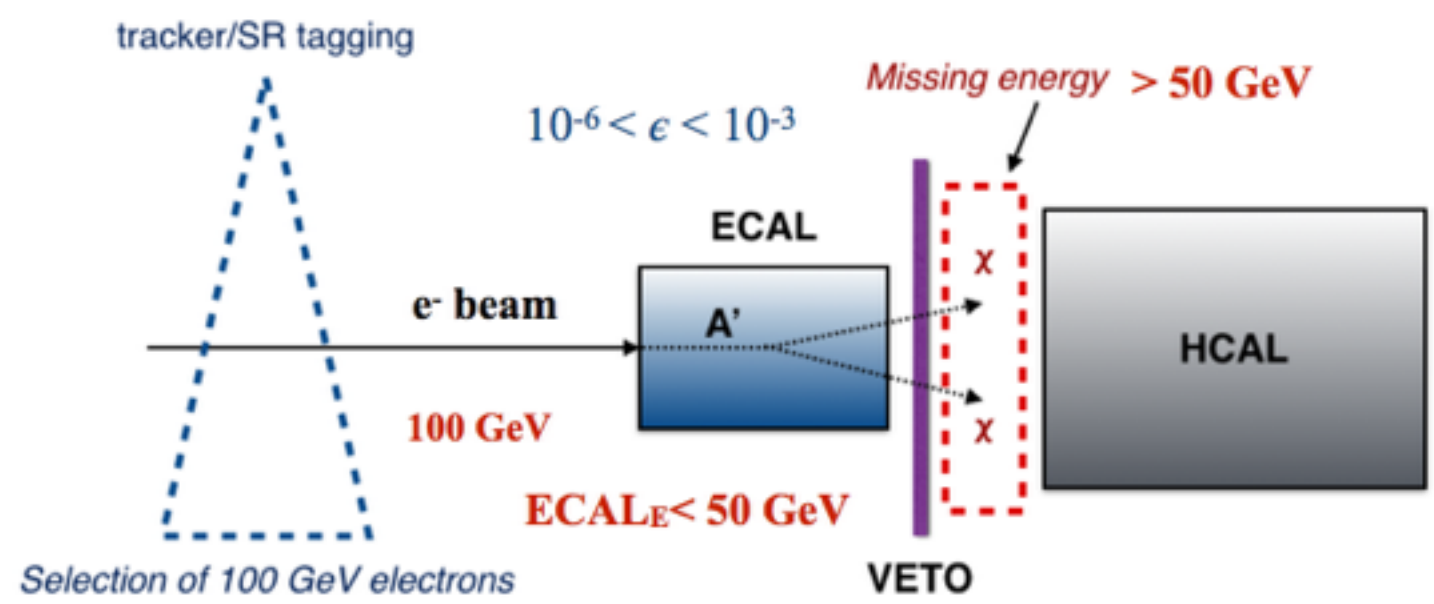
[Izaguirre, Krnjaic, Schuster, Toro]

NA64 @ CERN

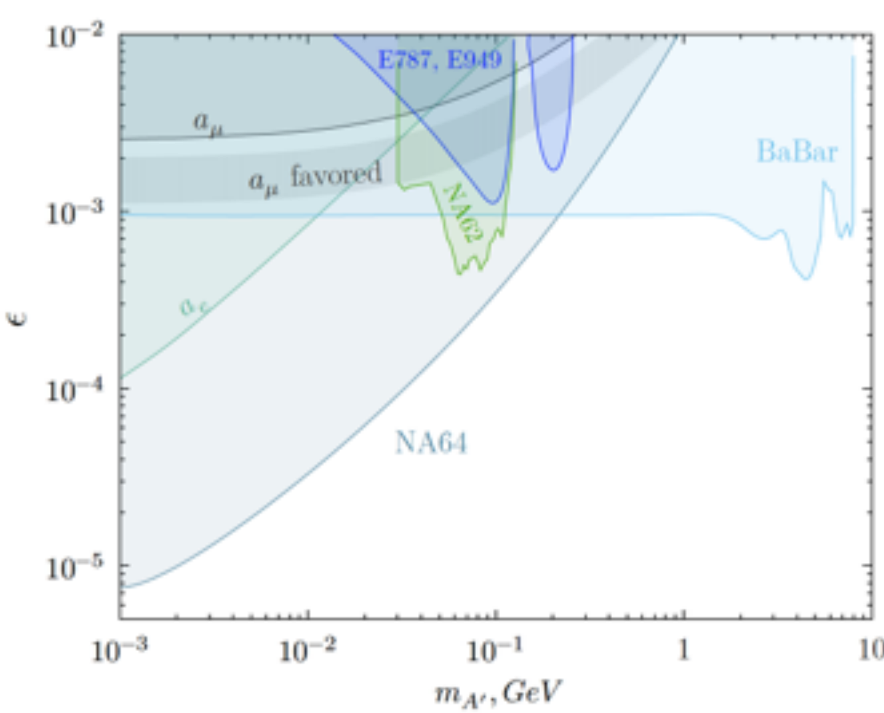
- 100 GeV electron beam incident on ECAL
- Dark matter produced in ECAL and carries most of the beam energy

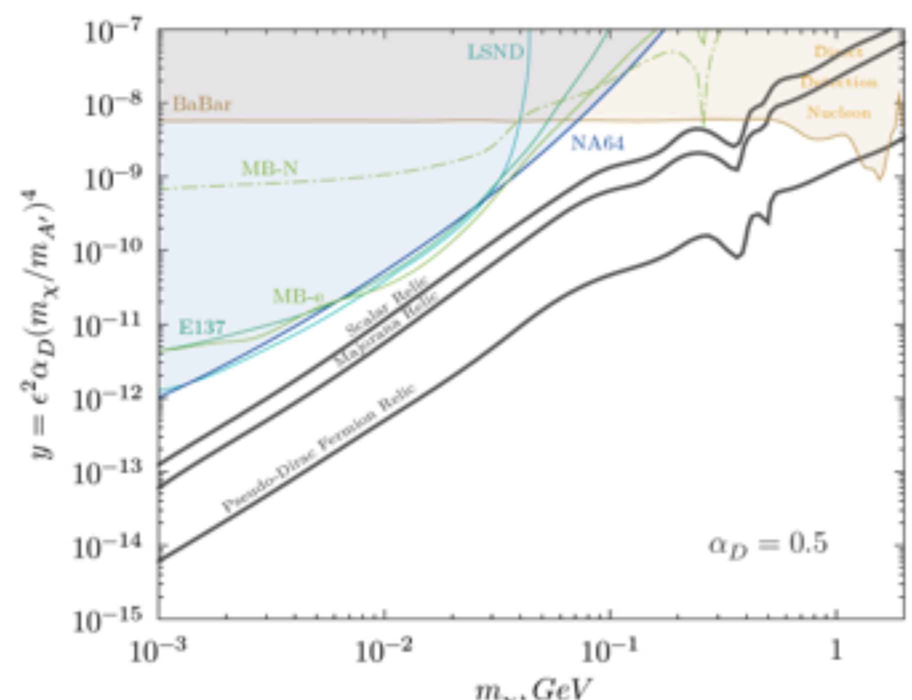


Production



- 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

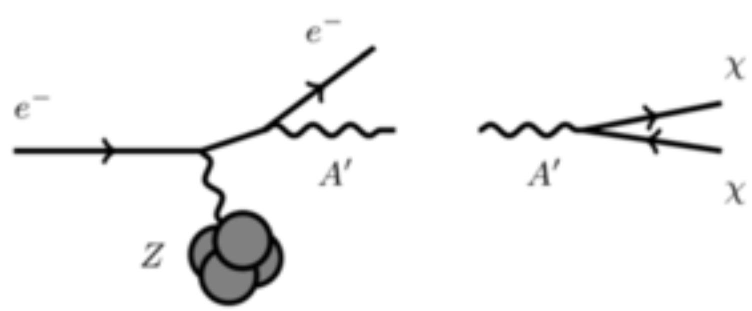


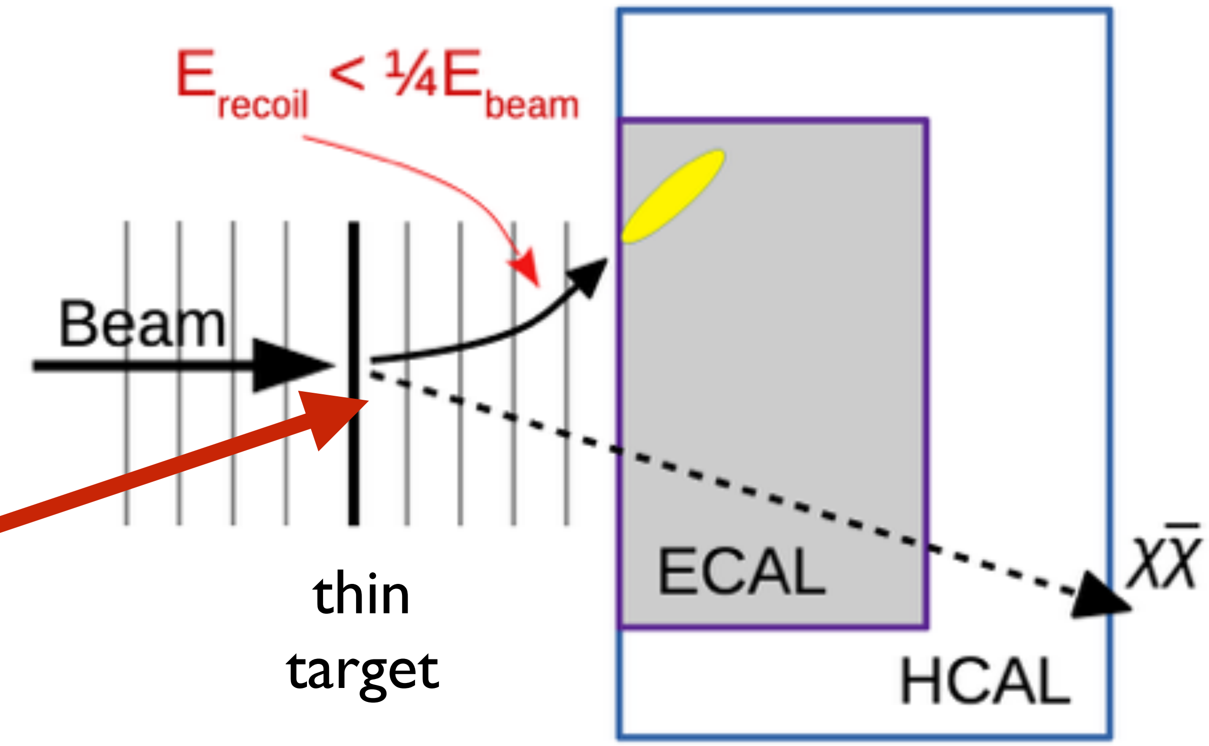


See talk by M. Hösgen

LDMX

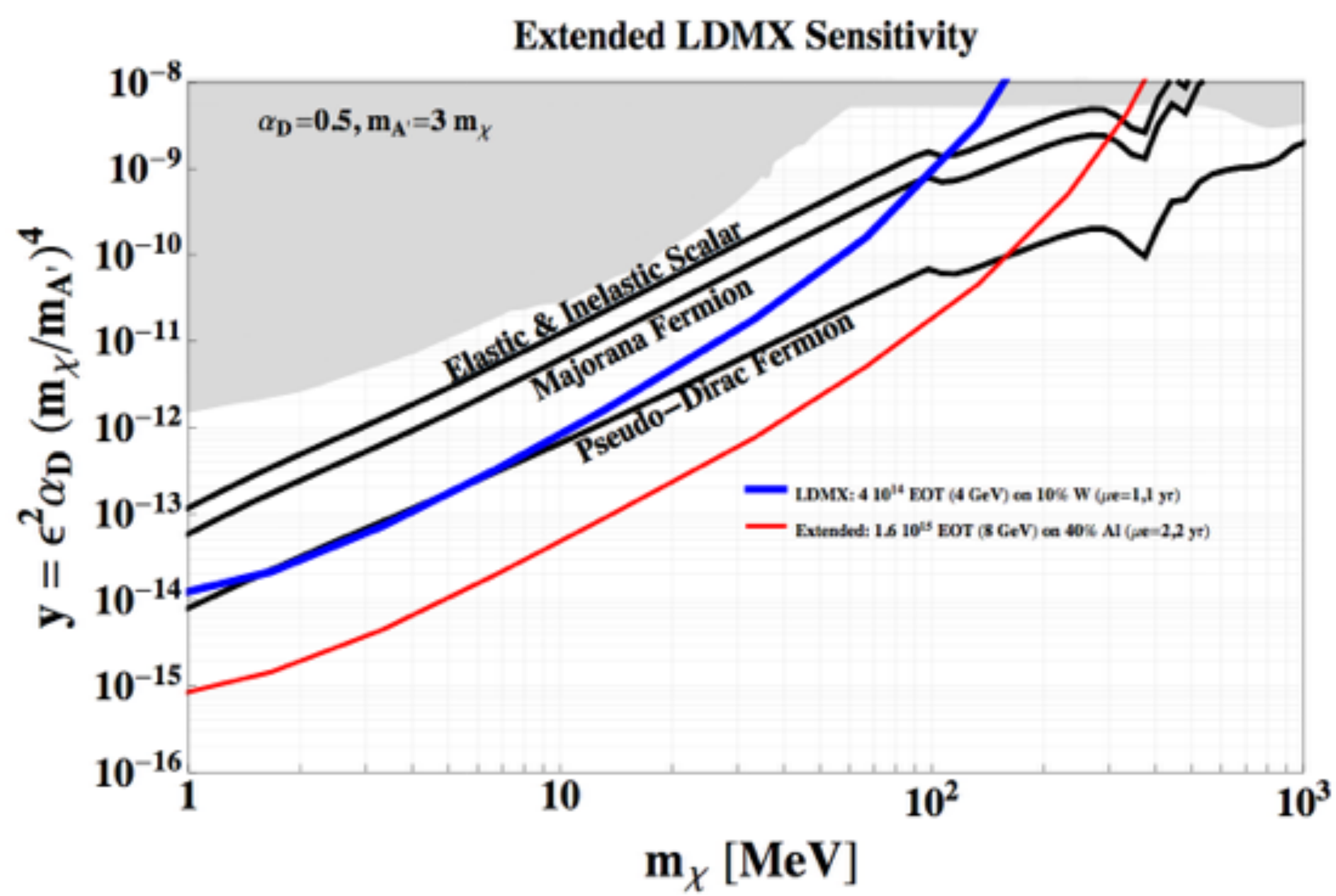
- Proposed electron beam experiment utilizing missing momentum technique





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

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



See talk by R. Pöttgen

Initial design study, 1808.05219

Muon beam fixed target experiments

[Gninenko, Krasnikov, Matveev]
[Chen, Pospelov, Zhong]
[Khan, Krnjaic, Tran, Whitbeck]

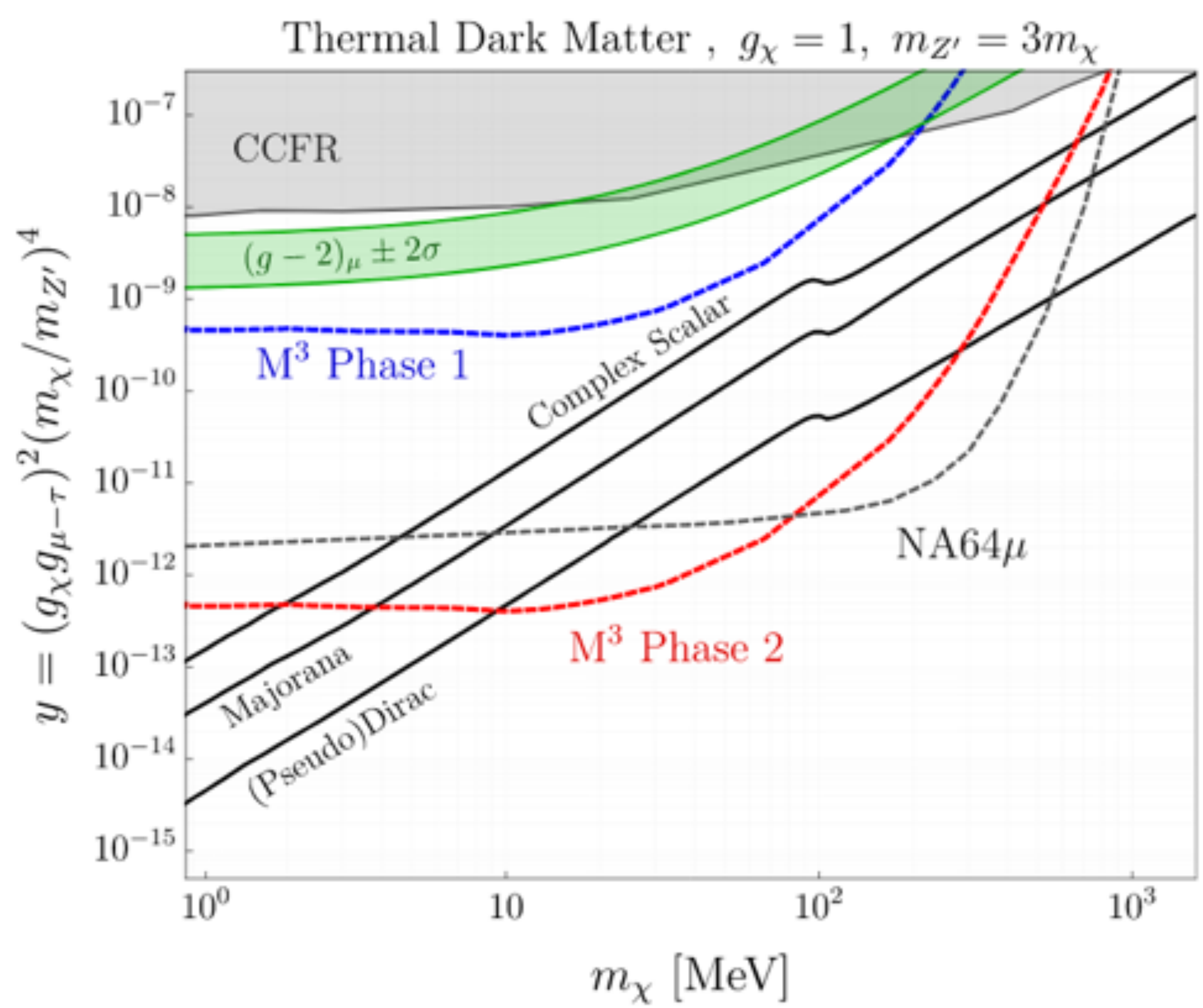
- Motivated by muon g-2 discrepancy, suggesting a muon-philic mediator

$$g_S S \bar{\mu}\mu \quad \text{(scalar)} \quad , \quad g_V V_\alpha \bar{\mu}\gamma^\alpha \mu \quad \text{(vector)}$$

- Basic idea: muon beam incident on target:
  - Visible decays of mediator
  - Missing energy technique ($\mathrm{NA64}\mu$)
  - Missing momentum technique (M^3)

- $\mathrm{NA64}\mu$: 150 GeV beam, 10^12 MOT

- M3: 15 GeV beam
  - Phase I : 10^10 MOT
  - Phase II : 10^13 MOT



[Khan, et. al. , arXiv:1804.03144]

Electron-positron colliders

See talks by L Zani, V. Prasad

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

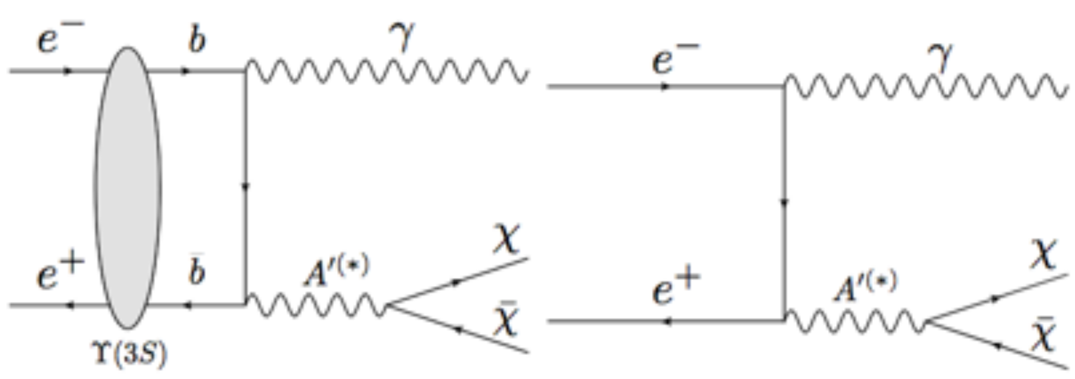
- Invisible dark photon: mono-photon signature - peak in recoil mass spectrum

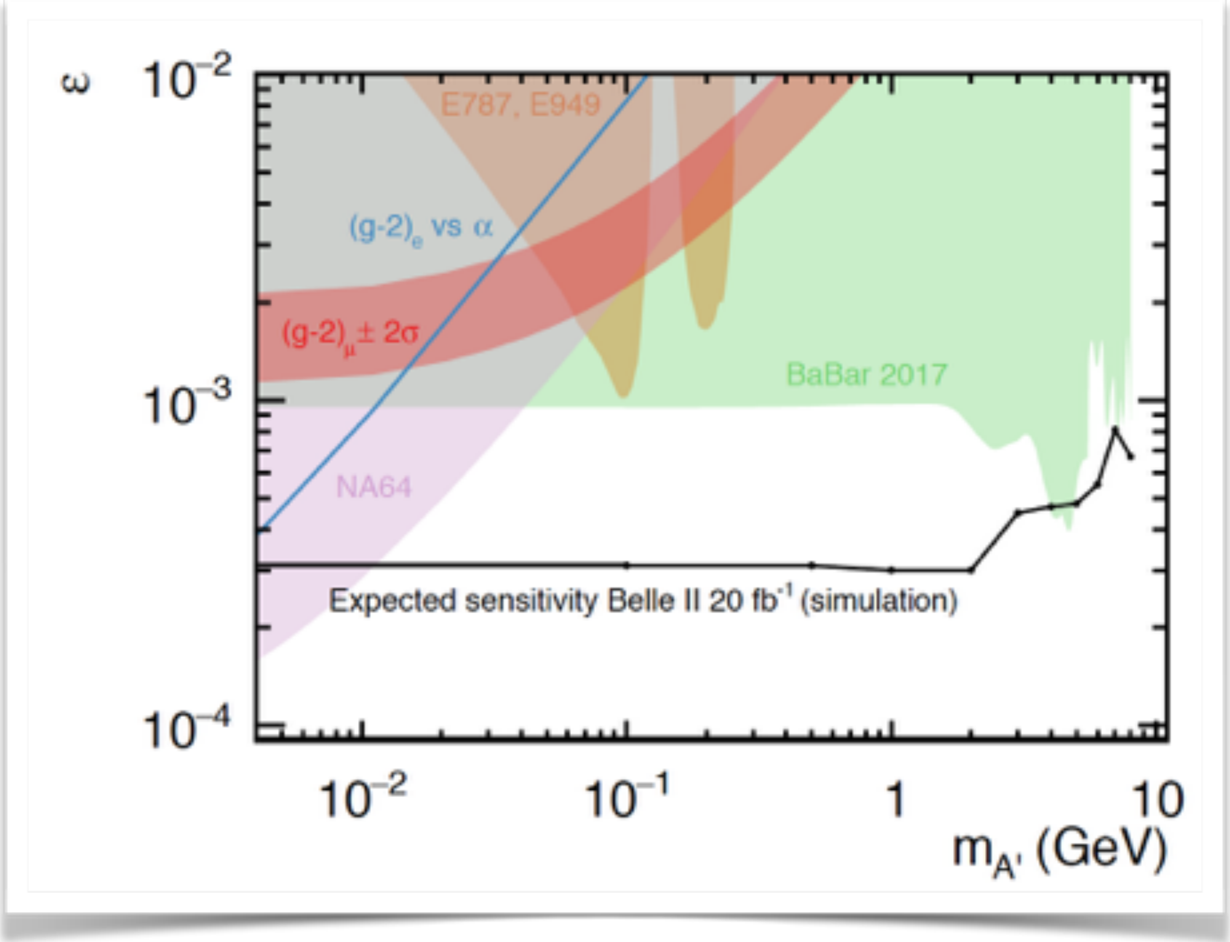
  [Izaguirre, Krnjaic, Schuster, Toro]
  [Essig, Mardon, Papucci, Volansky, Zhong]

- 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.

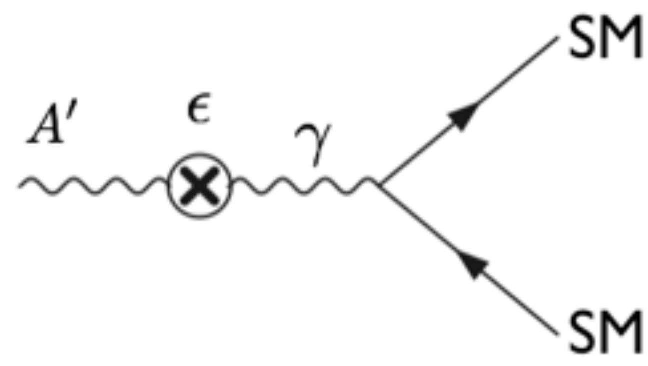
- Searches also being done at other flavor factories, e.g. BESIII, KLOE





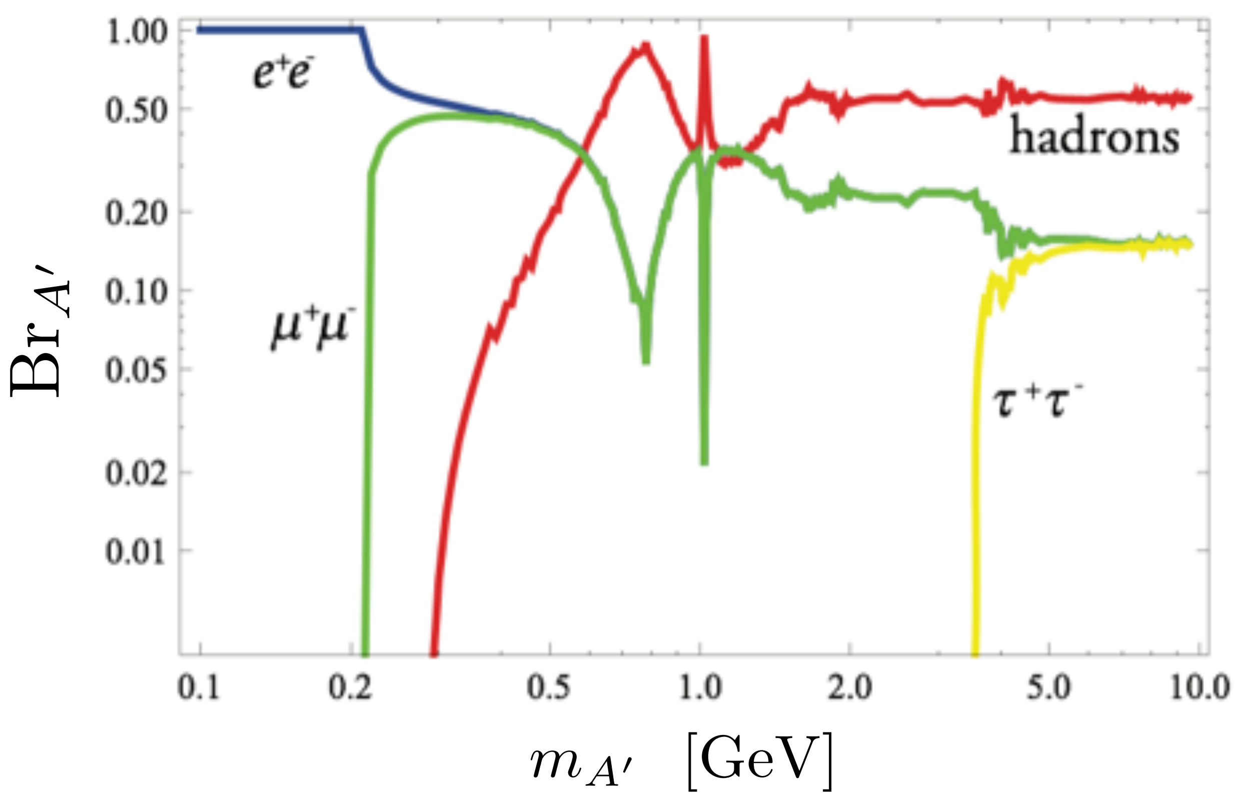
[Belle II Physics Book, 1808.10567]

Visible signals

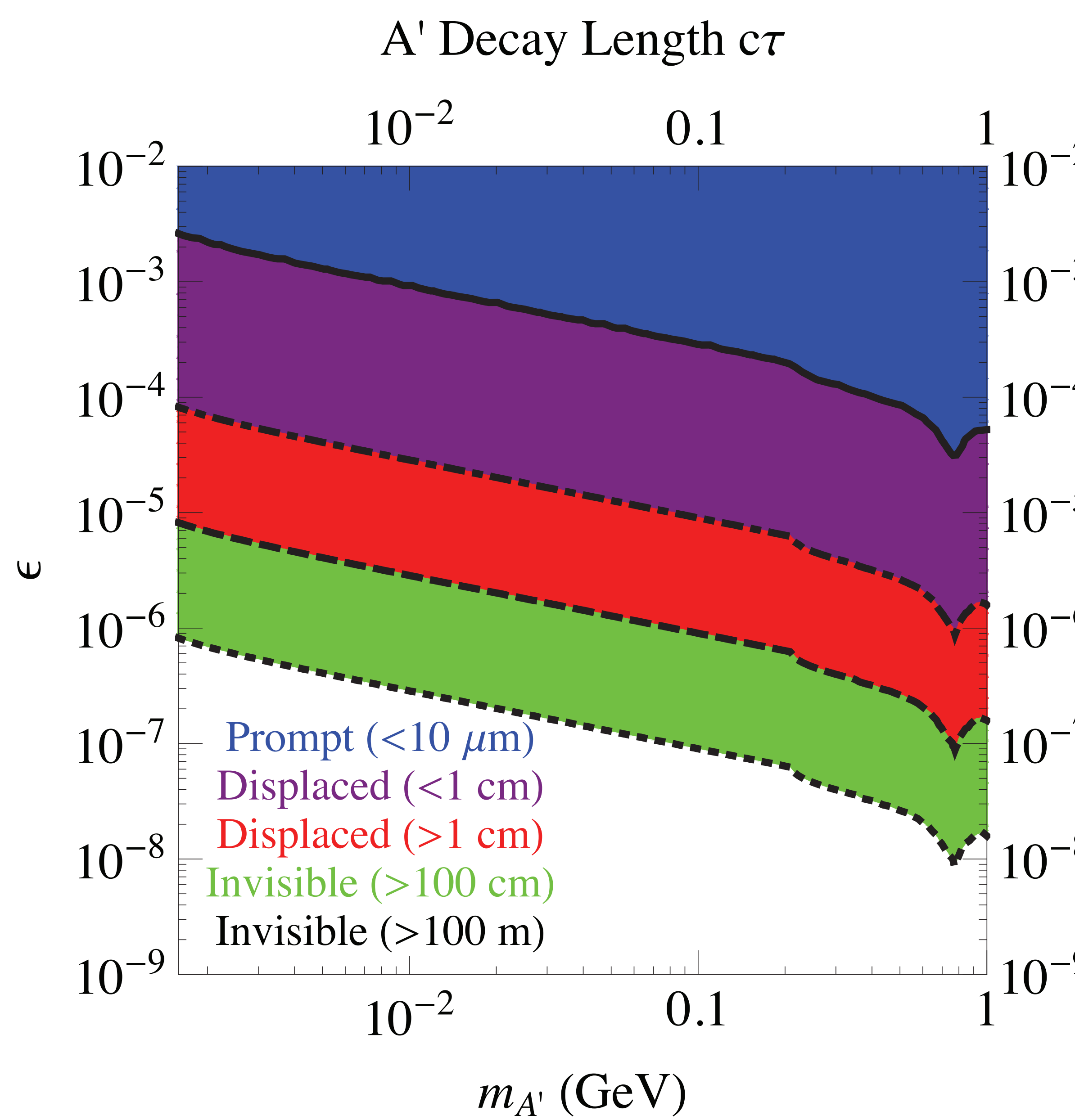


$$\Gamma_{A'} \sim \epsilon^2 m_{A'}$$

- Typically occur if mediator is lightest particle in dark sector

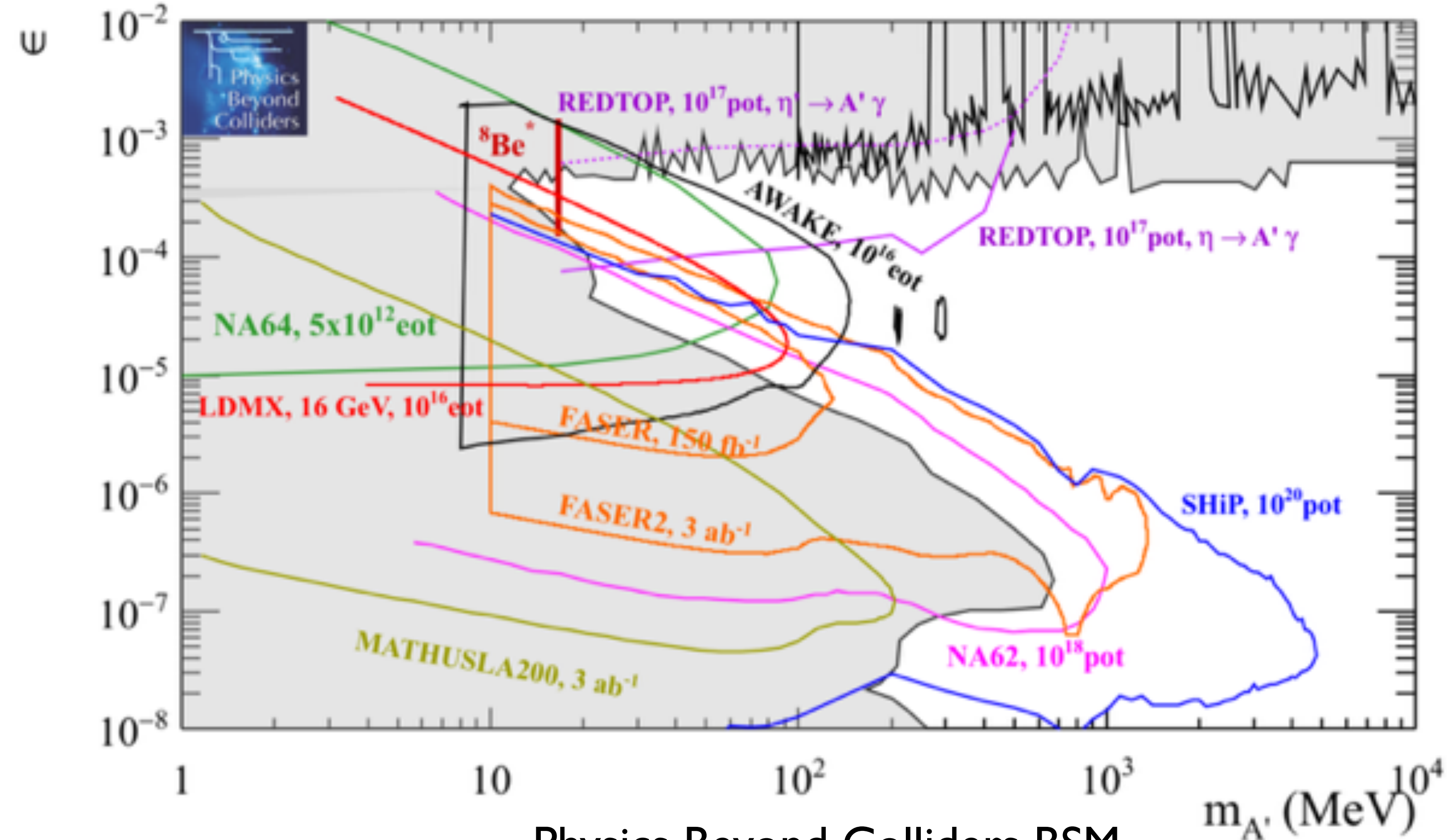


[BB, Pospelov, Ritz]



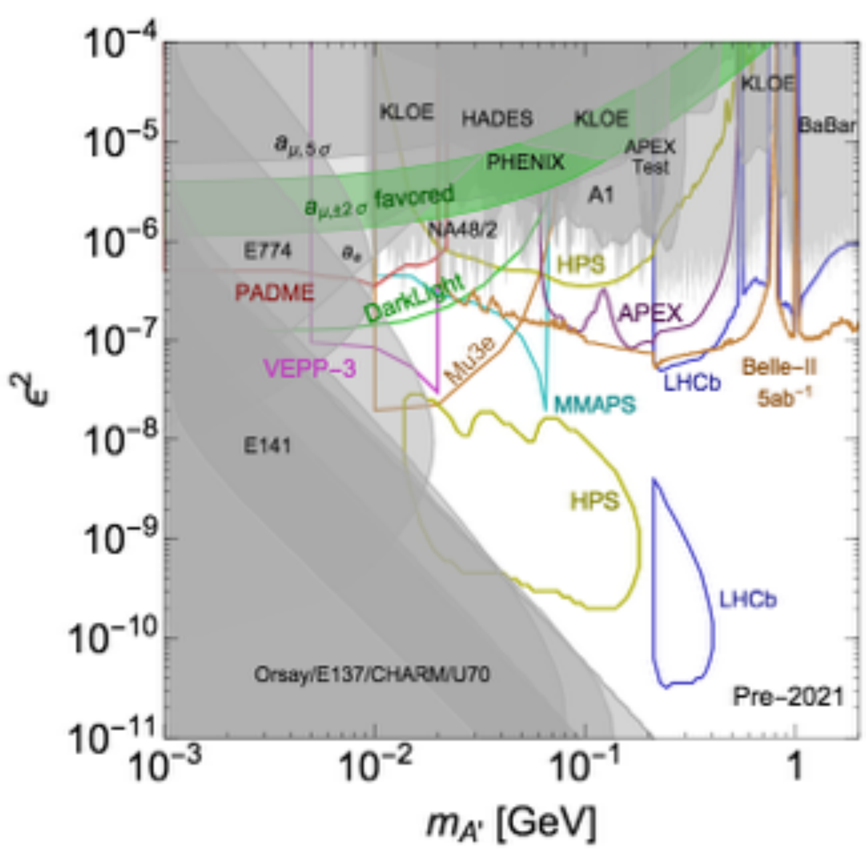
[Essig, Harnik, Kaplan, Toro]

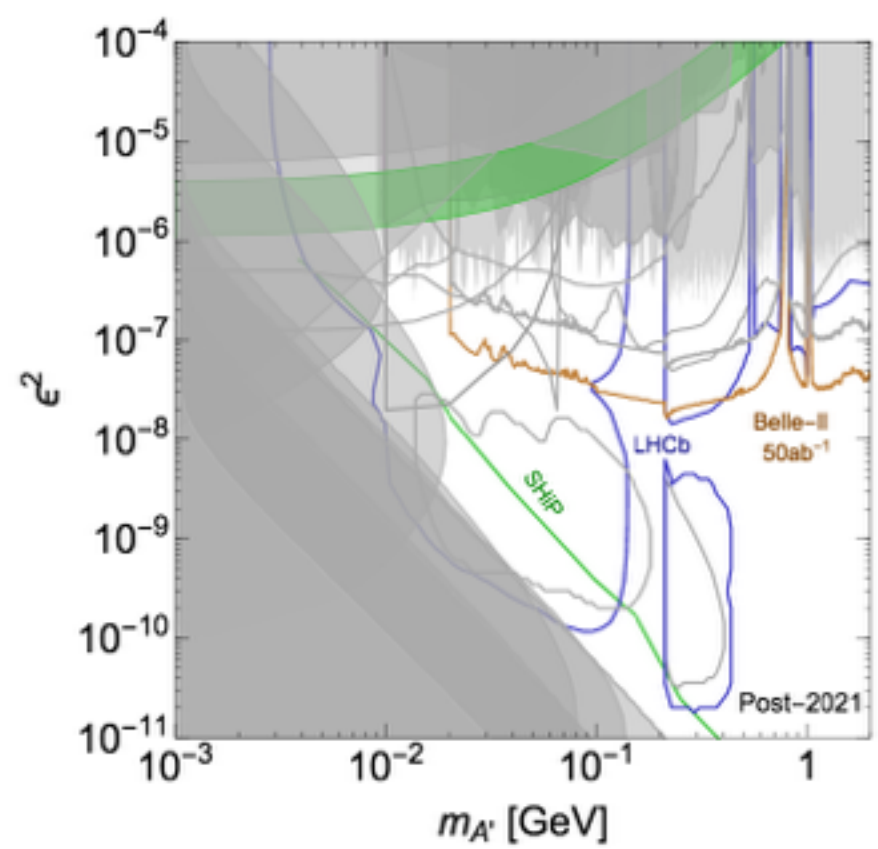
Visible dark photons



Physics Beyond Colliders BSM Working Group Report: 1901.09966

Dark Sectors Community Report: 1608.08632





See talks by
O. Moreno, R. Fantechi

I have mainly focused on the simplest vector portal scenario. There are many other interesting dark sector models.

- Change the particle nature / content / dynamics of the dark sector

  Spin, coupling structure, excited dark matter states, strongly interacting dark sector sector

- Change the mediator couplings to the SM

  Leptophobic, Leptophilic, flavor specific, mediator spin…,

This often leads to interesting alternatives for the cosmological production of dark matter and distinct phenomenological signals

See talks by C. Frugiuele, F. D'Eramo, R. Tito D'Agnolo, A. Berlin, E. Kufflik

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

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

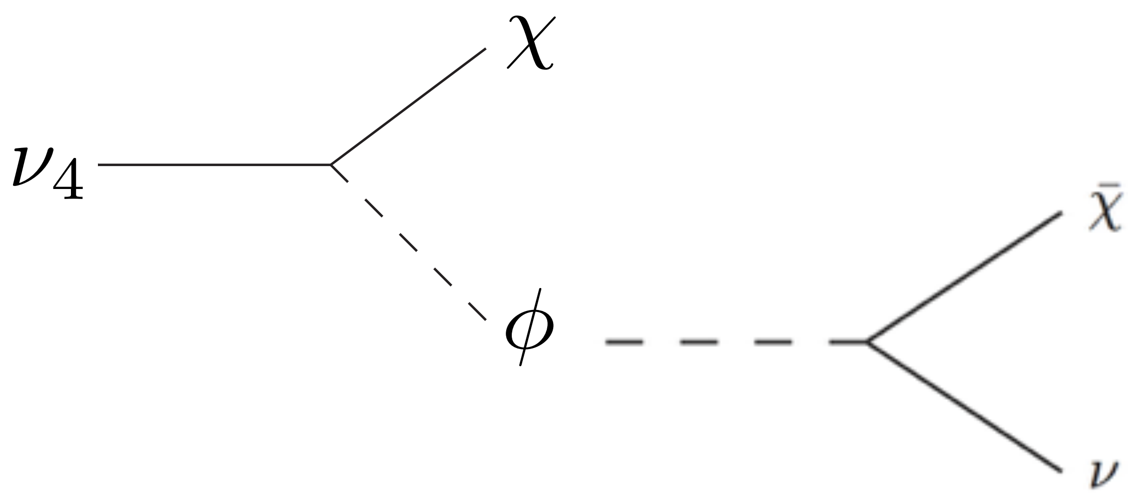
- Large mixing allows for a sizable DM - SM neutrino coupling

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

- Important implications for cosmology and phenomenology

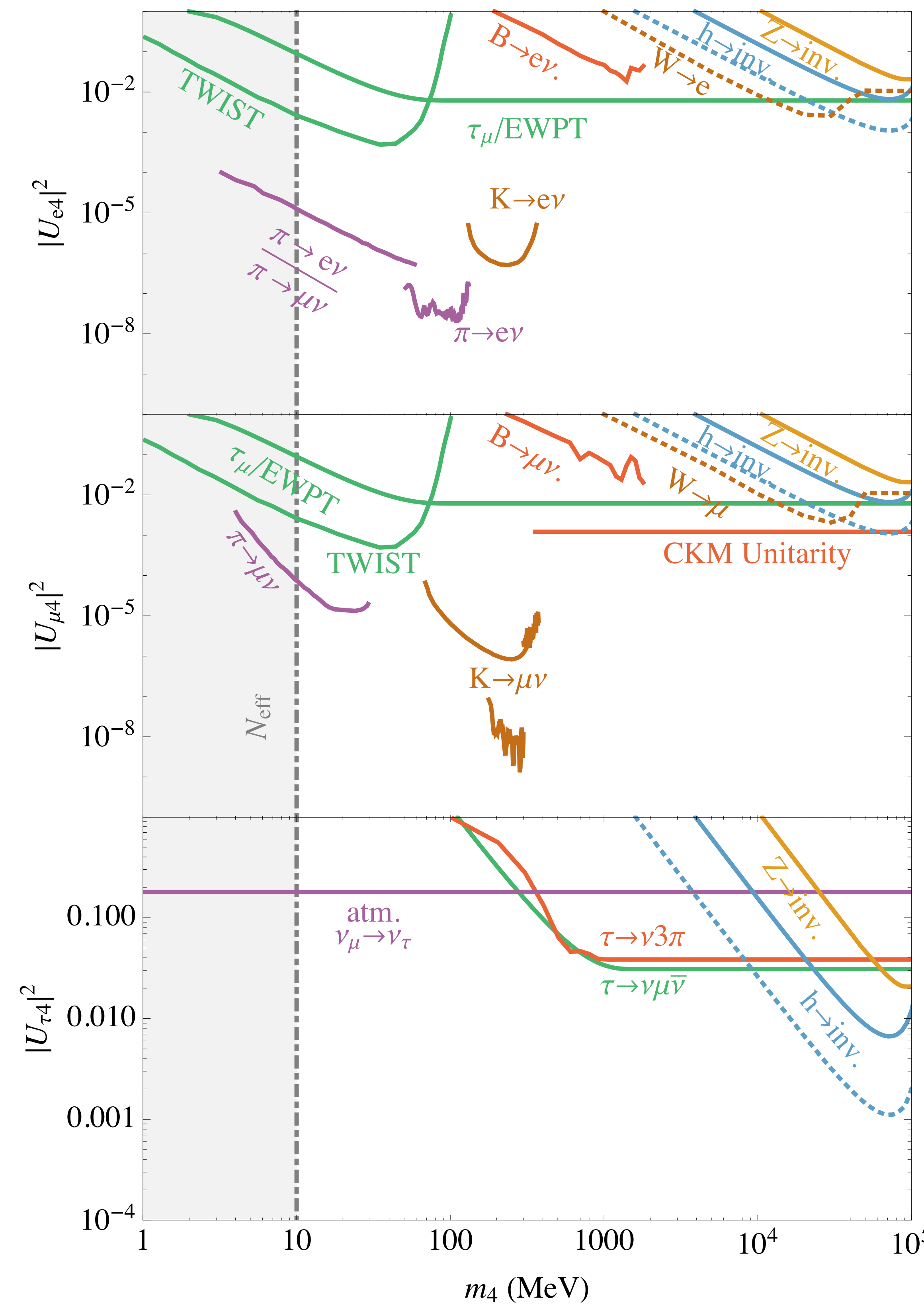
“Invisible” Sterile Neutrino

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

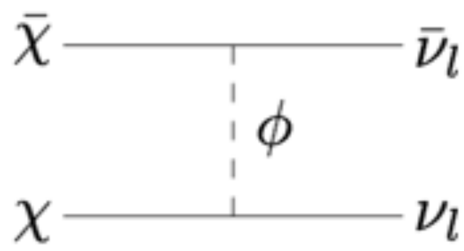


Phenomenology

- 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

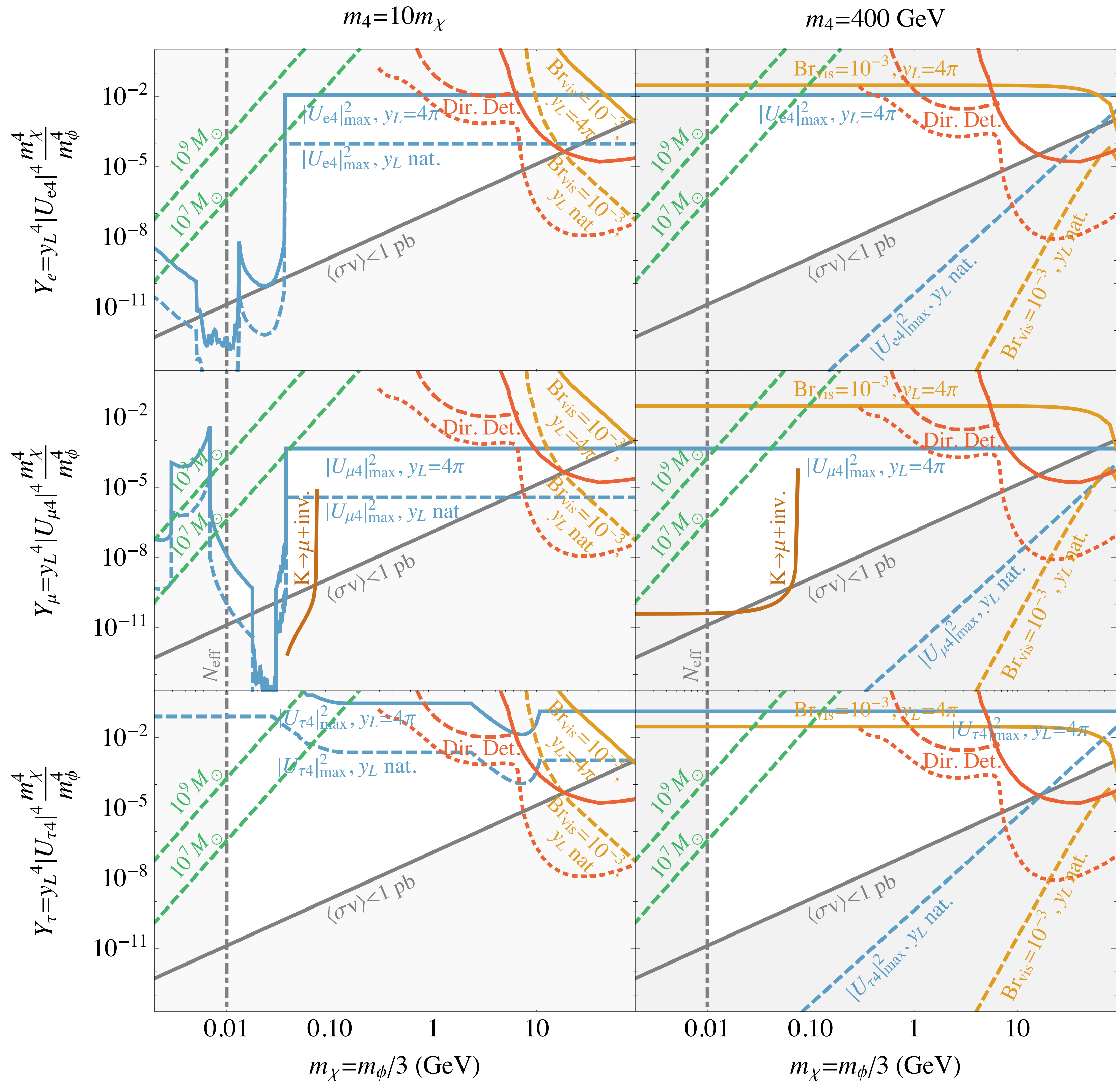


$$\propto U^2$$

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

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

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



Summary and Outlook

Dark matter is a profound mystery!

- Many candidates, mass scale is largely unconstrained, rich variety of phenomena. Lots of work ahead!

Accelerators provide an important tool to search for dark matter and exotic light particles.

- Complementary to direct detection
- Can decisively test certain thermal production scenarios
- Can provide information about dark sector structure

Still room for exploration in model and signature space

Many exciting experiments and results on the horizon!