Electron Beams and New Physics

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University of Pittsburgh

Developing New Directions in Fundamental Physics (DND) 2020
4-6 November 2020

Outline

- Motivations for light BSM physics - ***dark sectors***
- Overview of electron beam fixed target experiments
  - Visible searches
  - Dark matter scattering searches
  - Missing energy/momentum
- Outlook

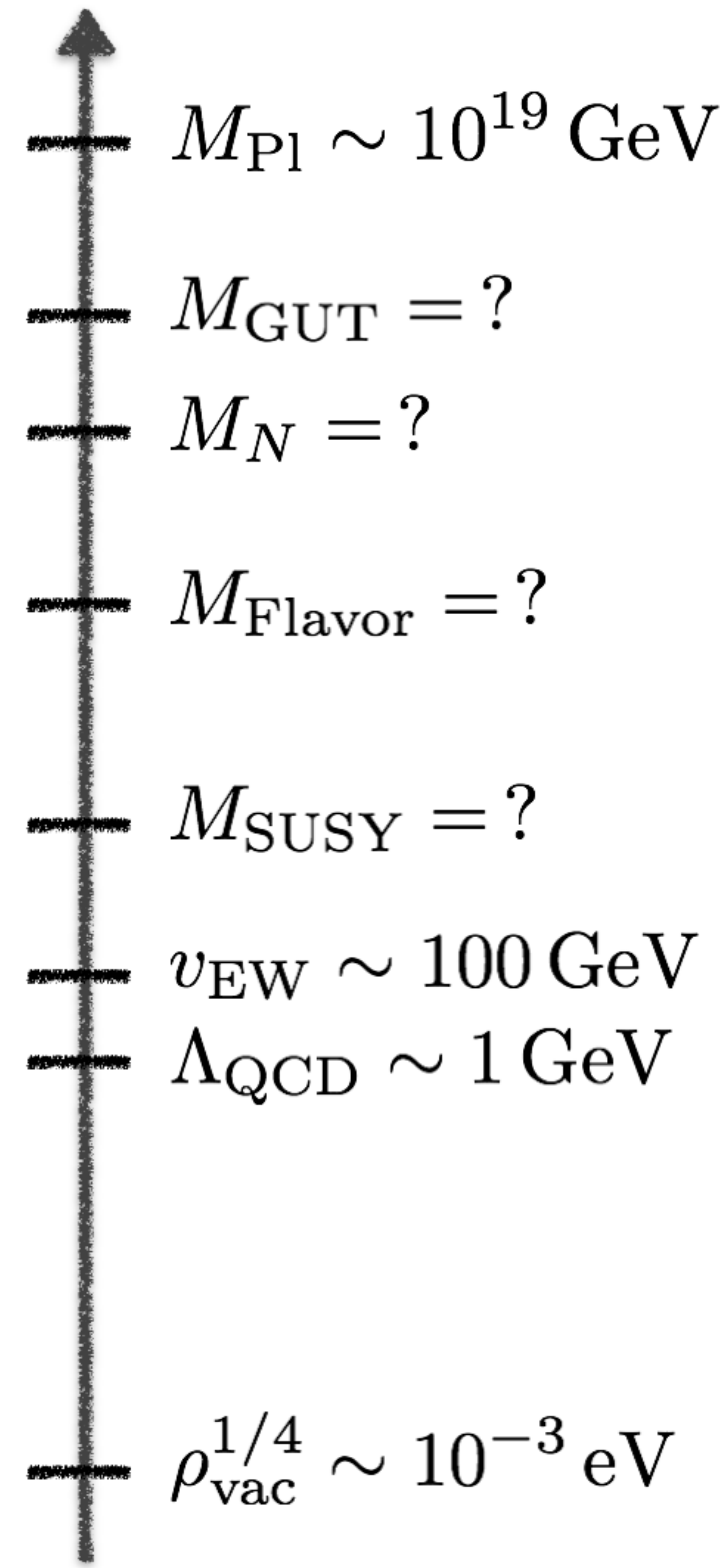
Why New Physics?

Conceptual mysteries & hints:

- Hierarchy Problem
- Cosmological Constant Problem
- Fermion Masses/Flavor Puzzle
- Strong CP Problem
- Grand Unification
- Quantum Gravity

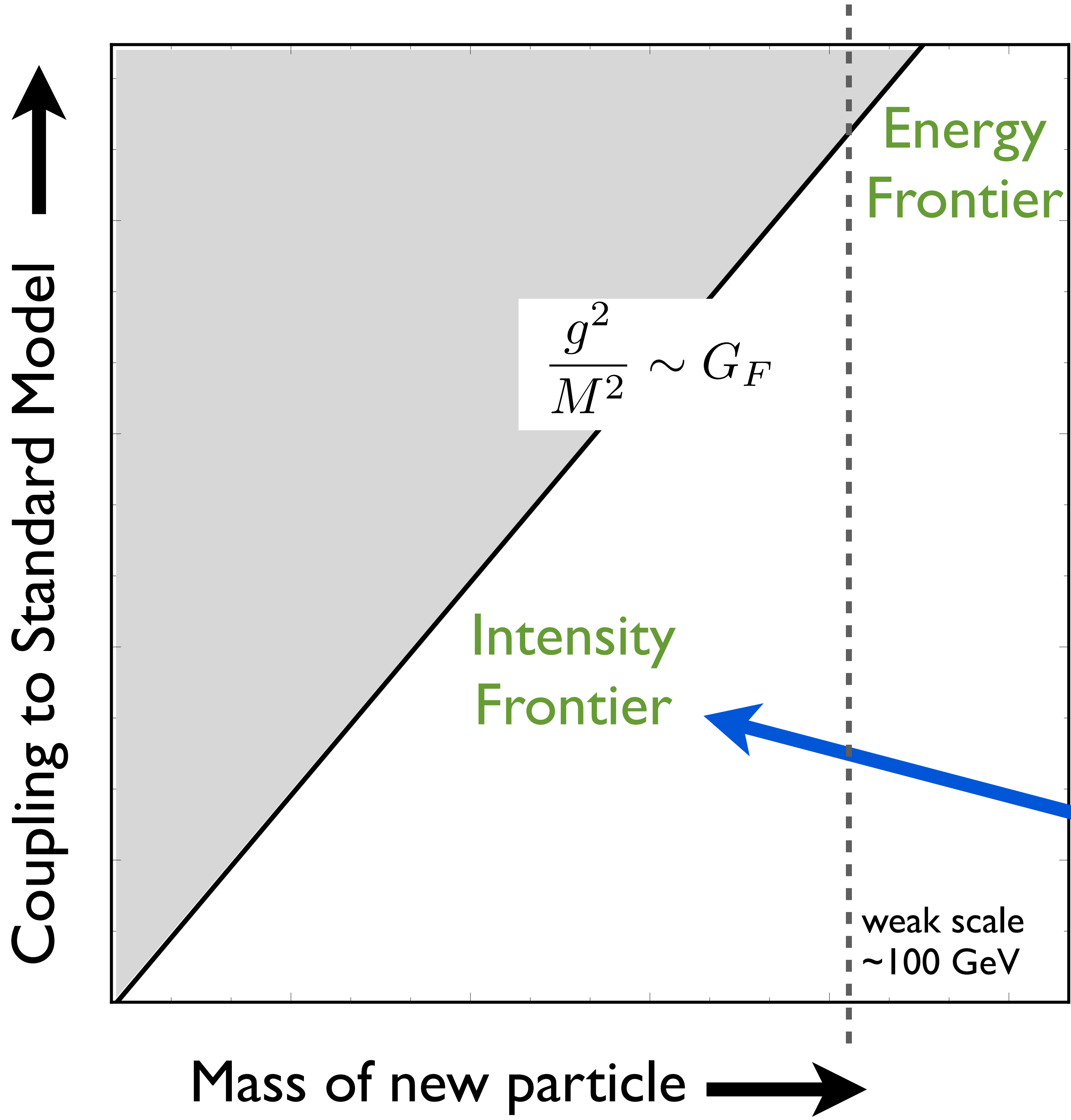
Empirical facts requiring new dynamics:

- Dark Matter
- Neutrino Masses
- Matter-Antimatter Asymmetry



Where should we look? What is the scale of new physics?

Where is the New Physics?



Supersymmetry
Technicolor
WIMP DM
. . .

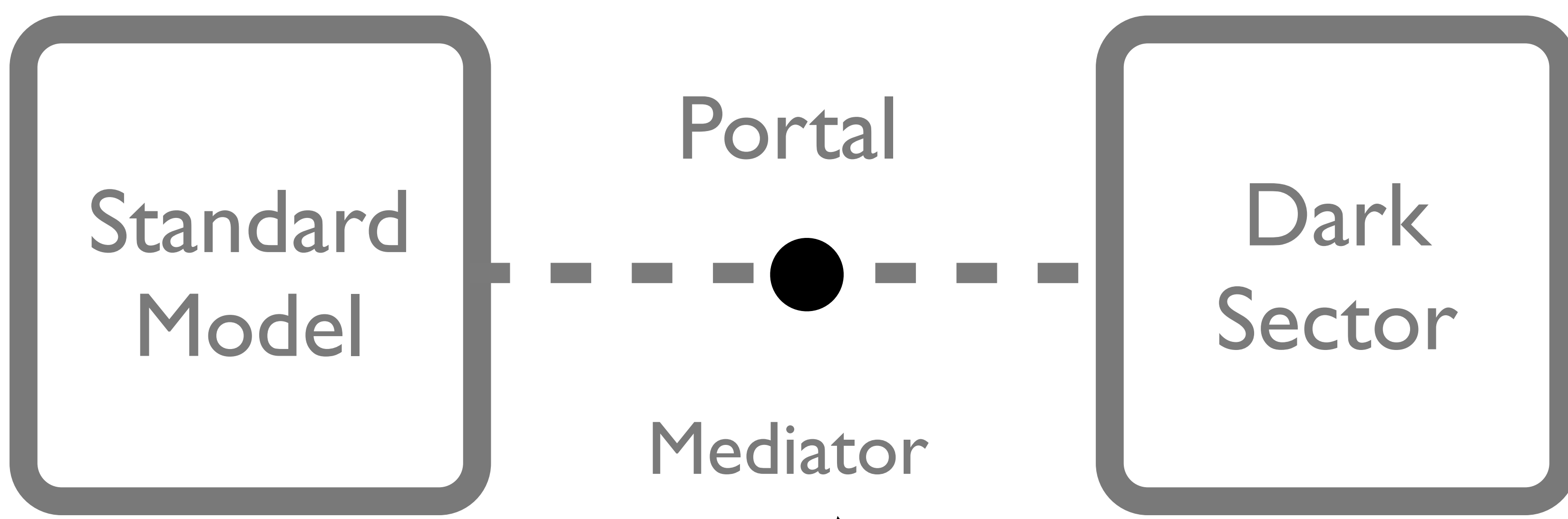
Dark matter
Axion, ALPs
Sterile neutrinos
. . .
A Dark Sector?

The Dark Sector Paradigm

The Dark Sector Paradigm

Dark matter,
Axions, ALPs,
Sterile neutrinos,
Other dark particles…

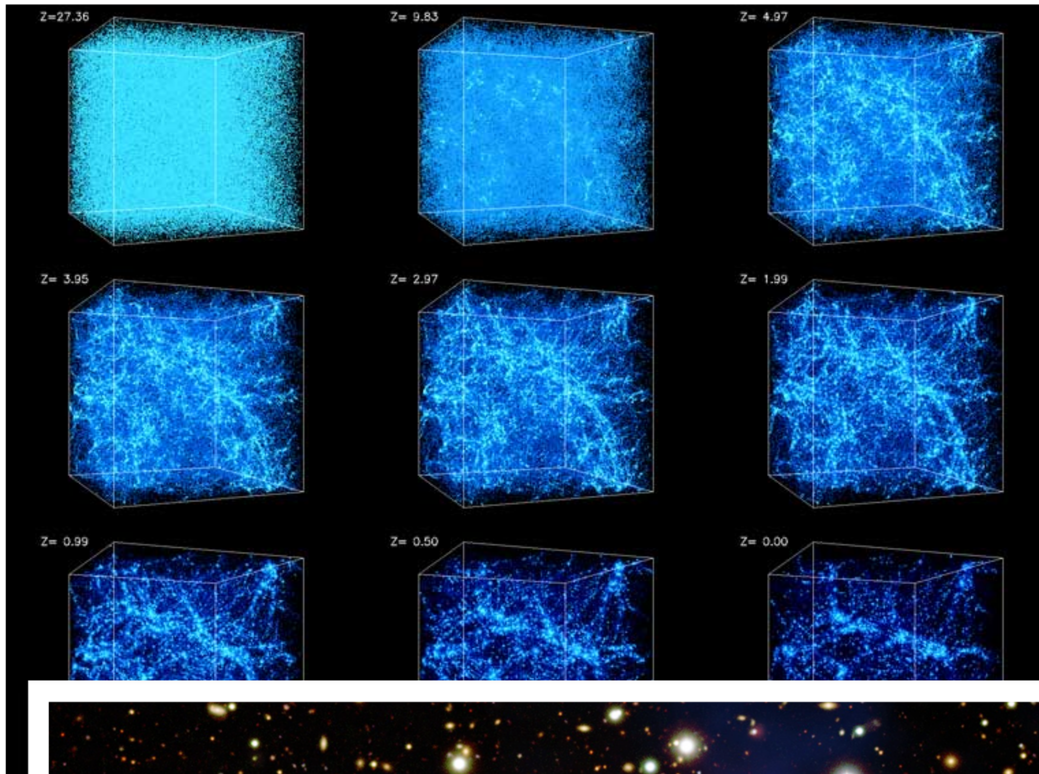
The Dark Sector Paradigm



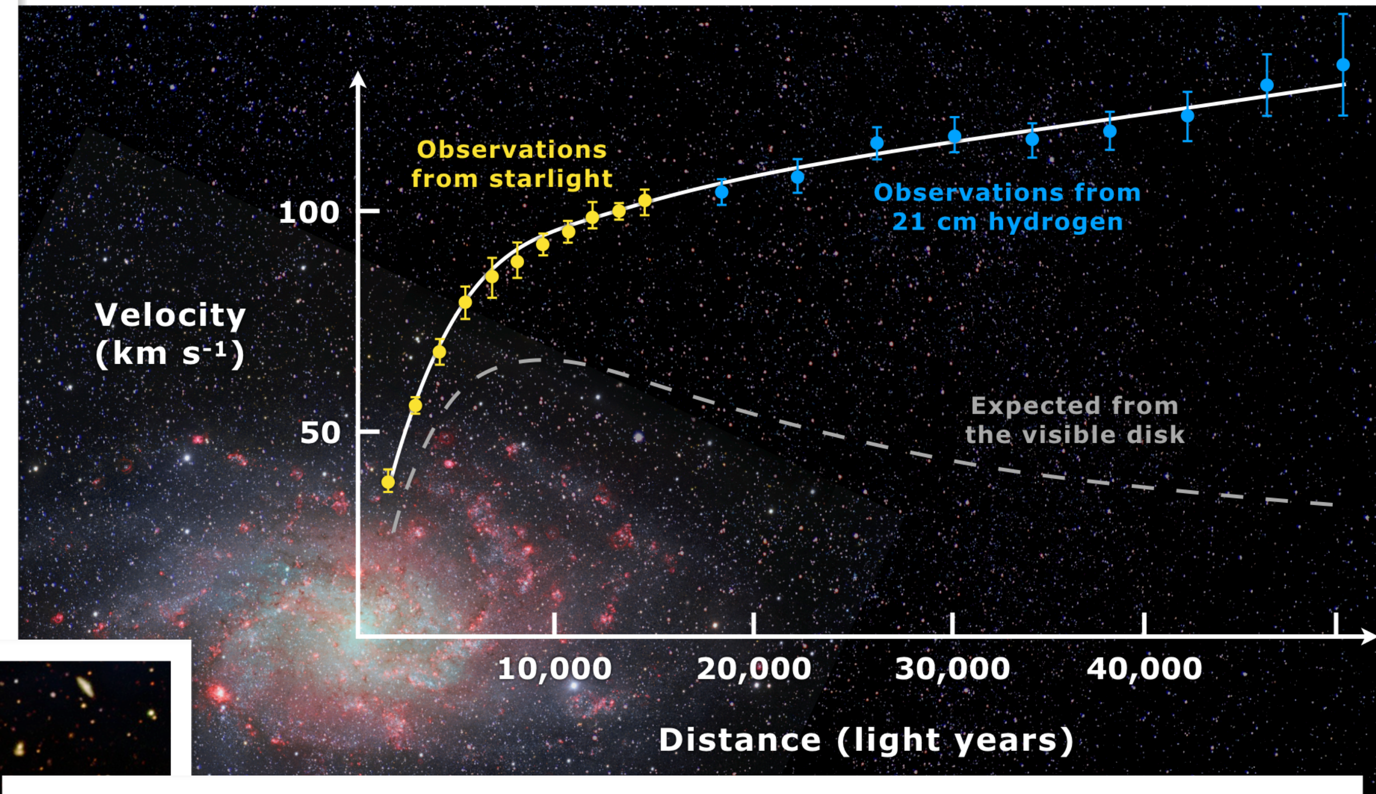
"Portal" interaction with ordinary matter

Dark matter,
Axions, ALPs,
Sterile neutrinos,
Other dark particles…

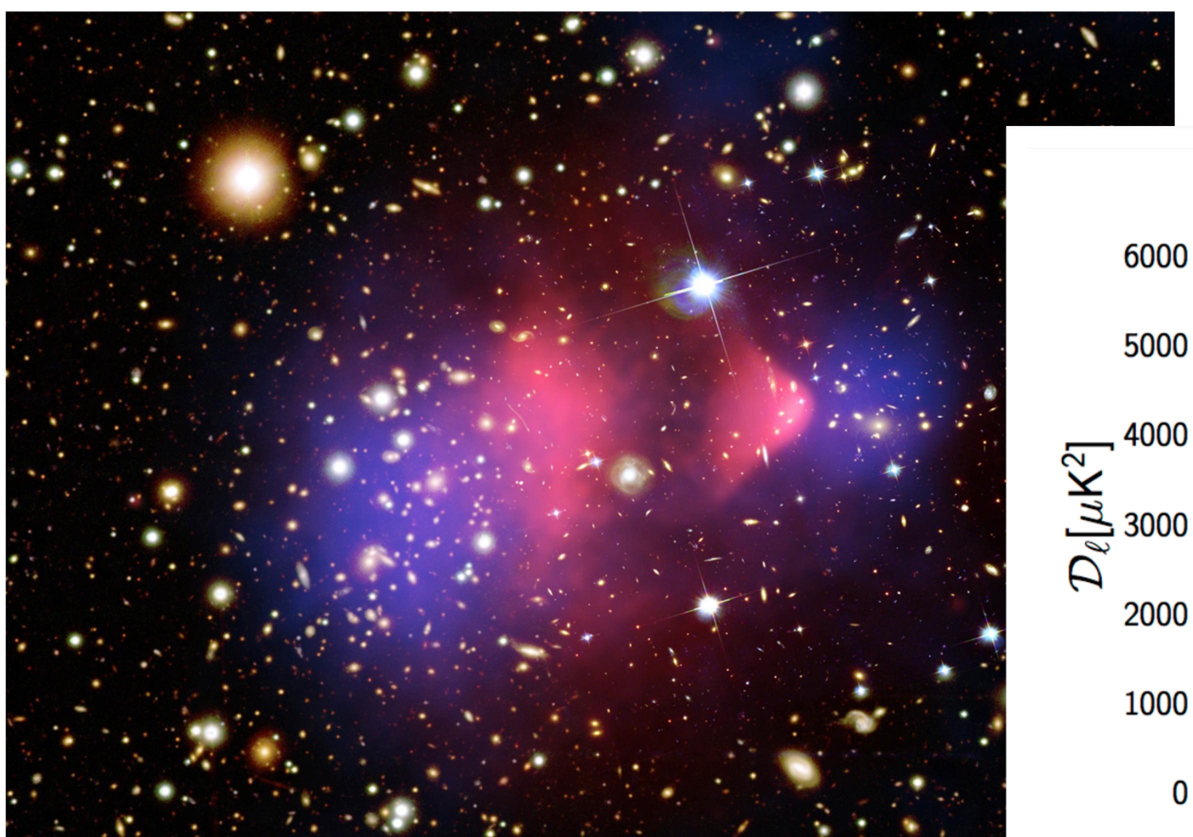
Dark Matter

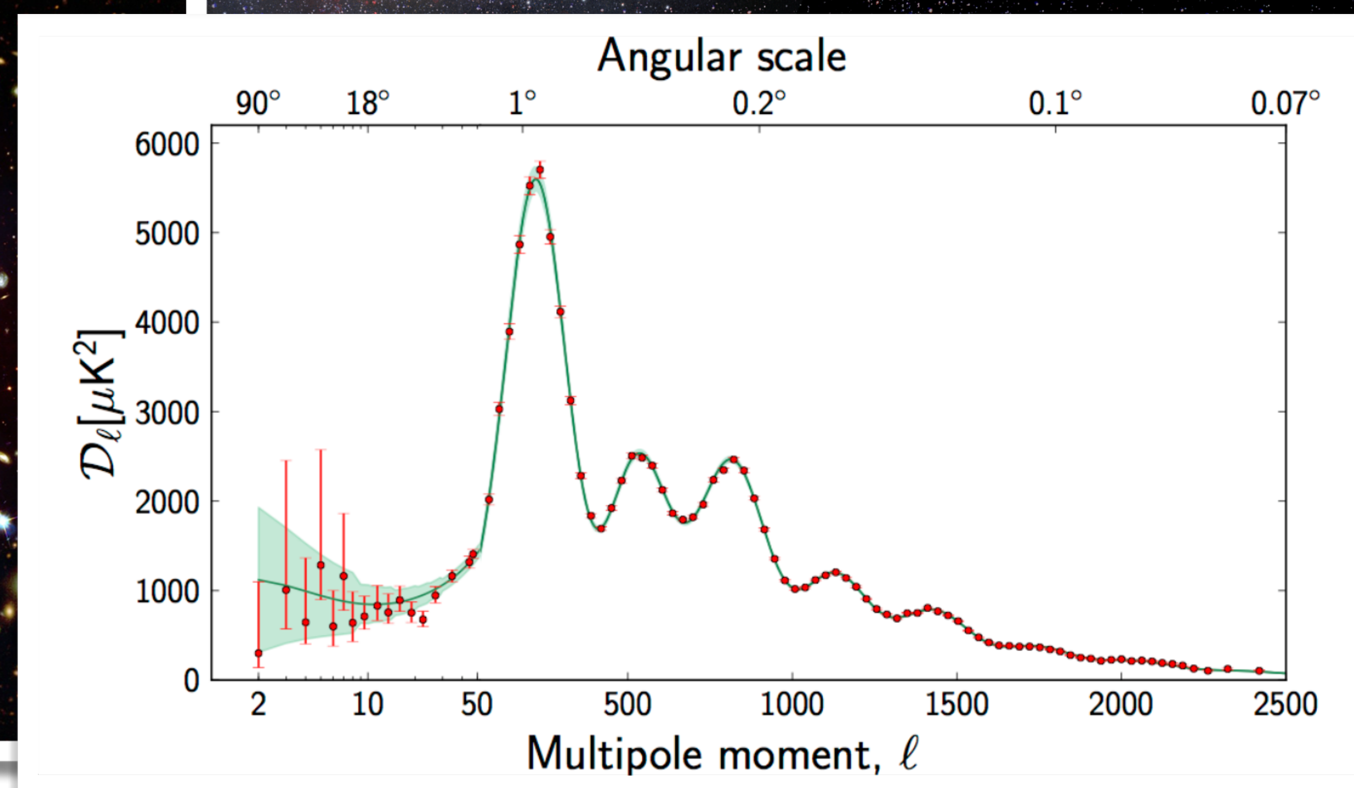


Z=27.36
Z= 9.83
Z= 4.97
Z= 3.95
Z= 2.97
Z= 1.99
Z= 0.99
Z= 0.50
Z= 0.00



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)

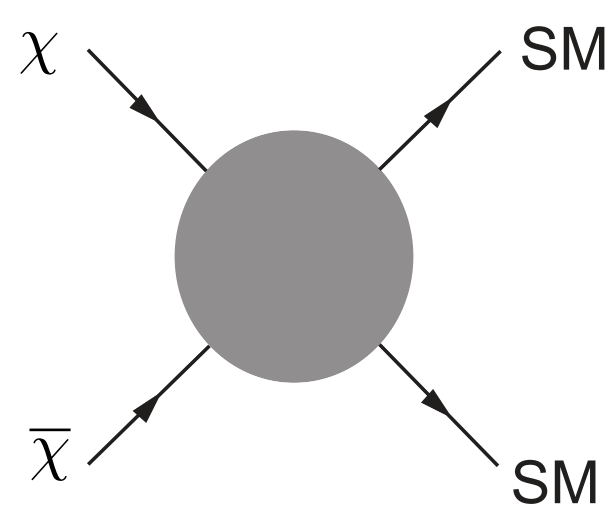


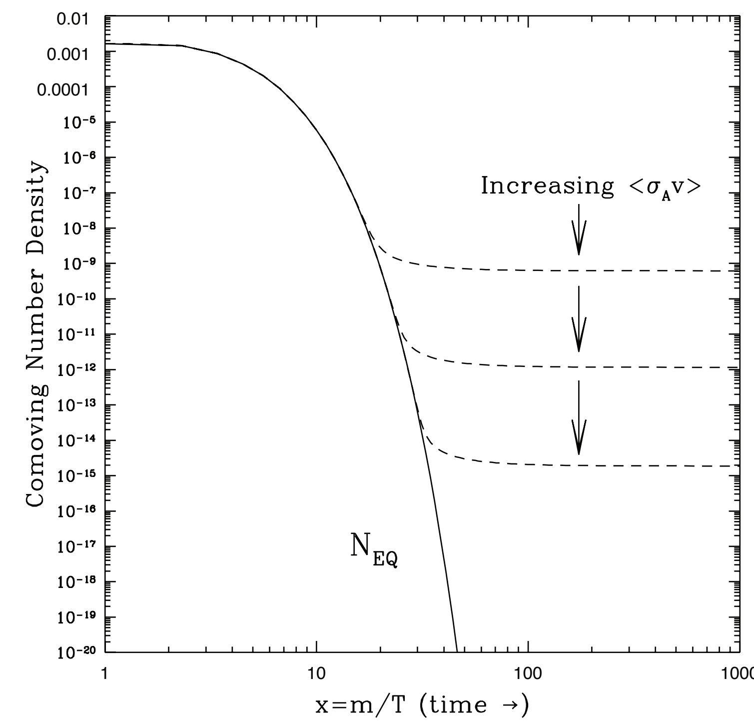


Angular scale
90°
18°
1°
0.2°
0.1°
0.07°
$\mathcal{D}_\ell[\mu K^2]$
6000
5000
4000
3000
2000
1000
0
2
10
50
500
1000
1500
2000
2500
Multipole moment, ℓ

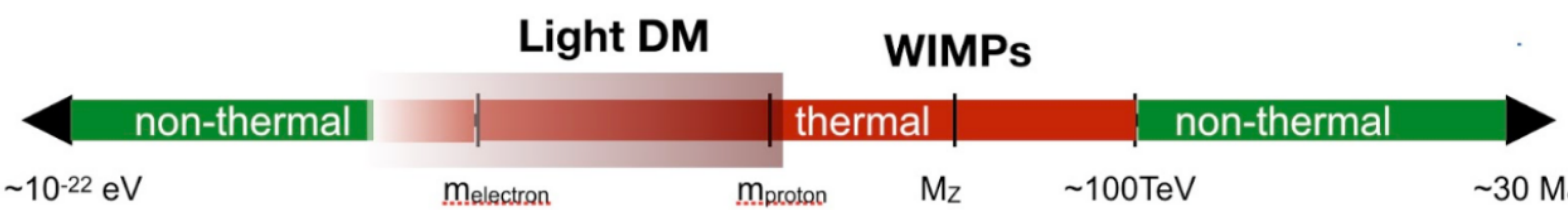
Thermal Freezeout

- Dark matter produced from reactions in the plasma during the Big Bang
- Requires *non-gravitational* dark matter interactions

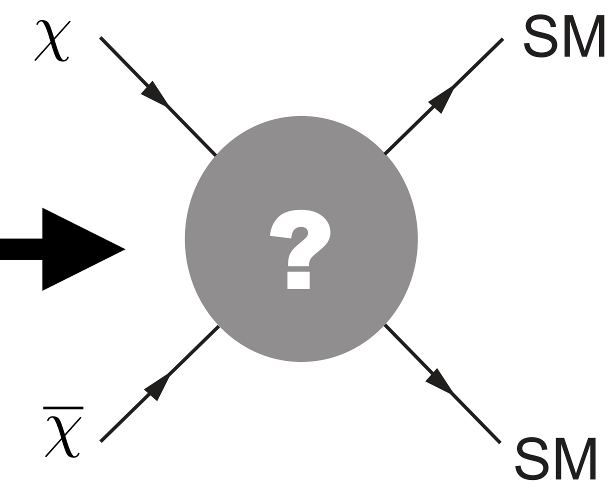




- Viable mass range between MeV - 100 TeV in simplest scenarios



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

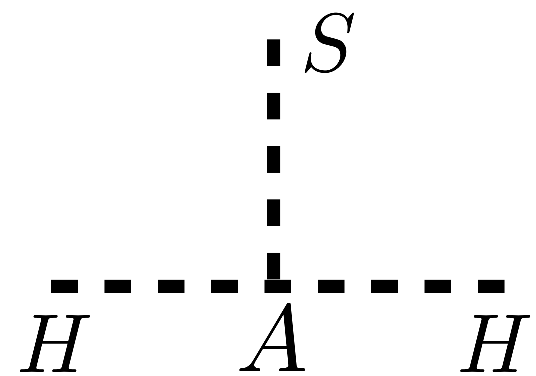
- Lee-Weinberg bound; suggests new light mediator

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

  - 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), …

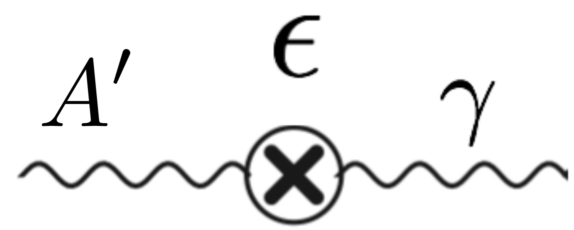
Renormalizable Portals

$$AH^\dagger H S$$



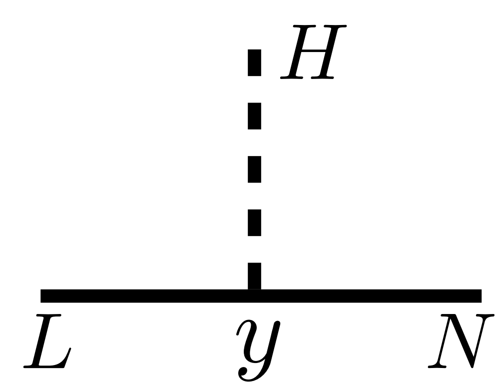
Higgs Portal

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



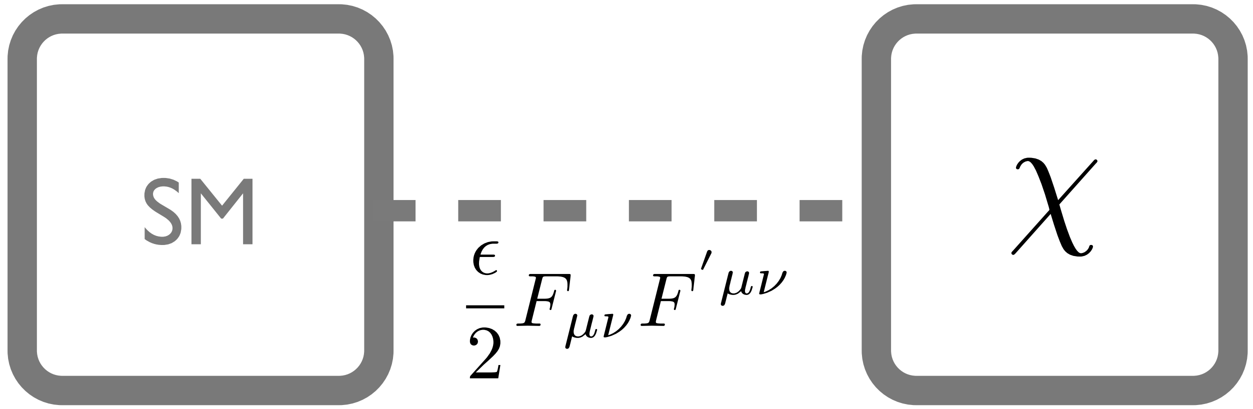
Vector Portal

$$yLHN$$



Neutrino portal

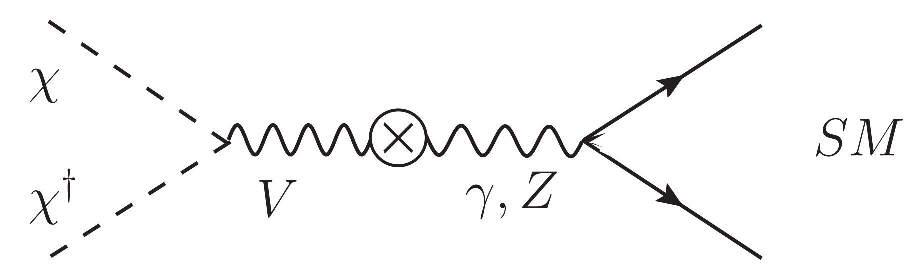
Benchmark Model: Vector Portal Dark Matter



[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



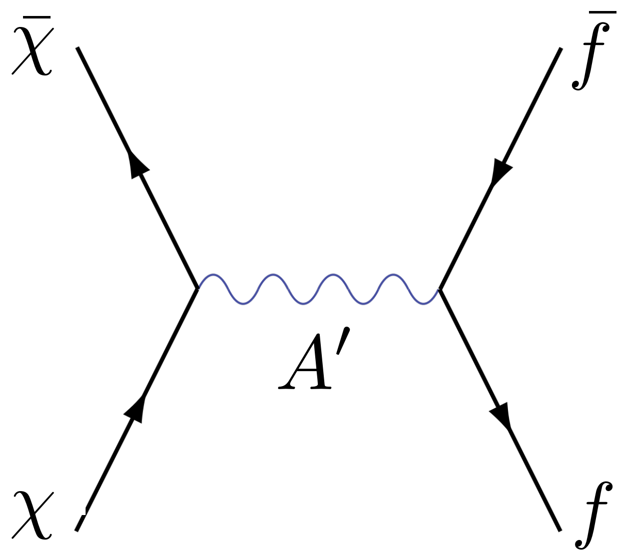
- CMB bounds evaded due to p-wave annihilation
- Variations in cosmology and phenomenology obtained by changing mediator, or dark matter properties - important to explore all options

Direct vs. Secluded Annihilation

Two characteristic regimes:

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

[Boehm, Fayet]

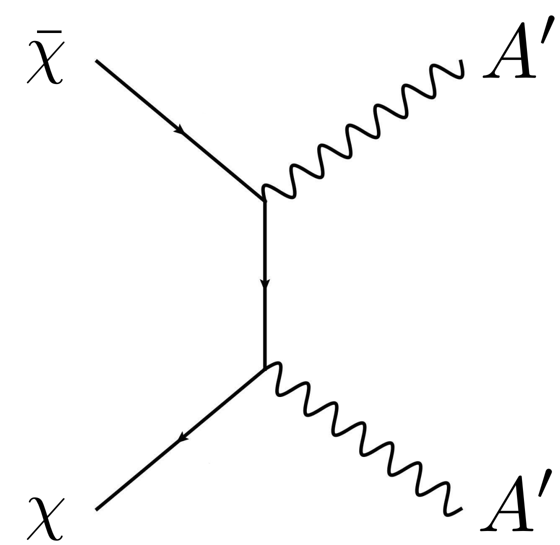


$$\langle \sigma v \rangle \sim \frac{\epsilon^2 \alpha_D m_\chi^2}{m_{A'}^4}$$

Requires sizable portal coupling to deplete DM abundance

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

[Pospelov, Ritz, Voloshin]



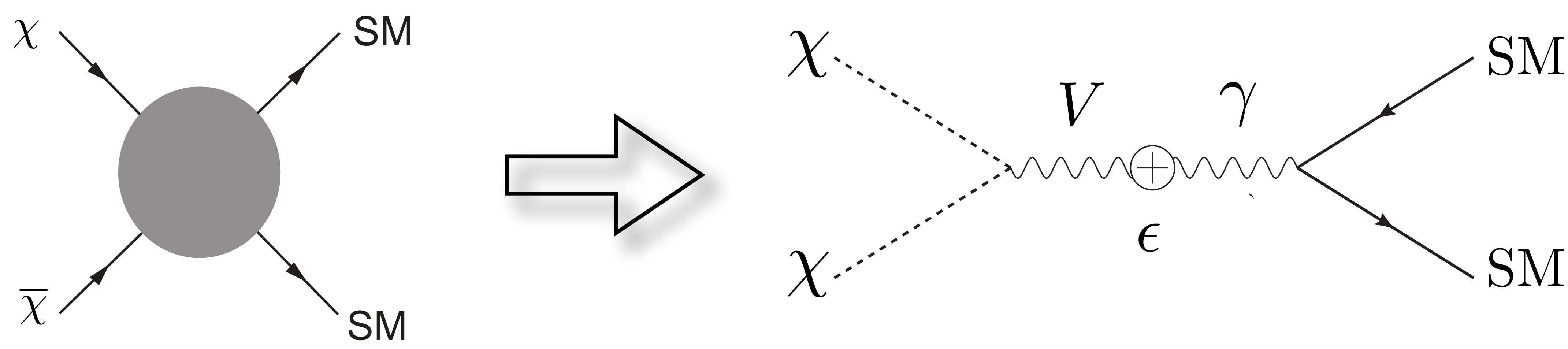
$$\langle \sigma v \rangle \sim \frac{\alpha_D^2}{m_\chi^2}$$

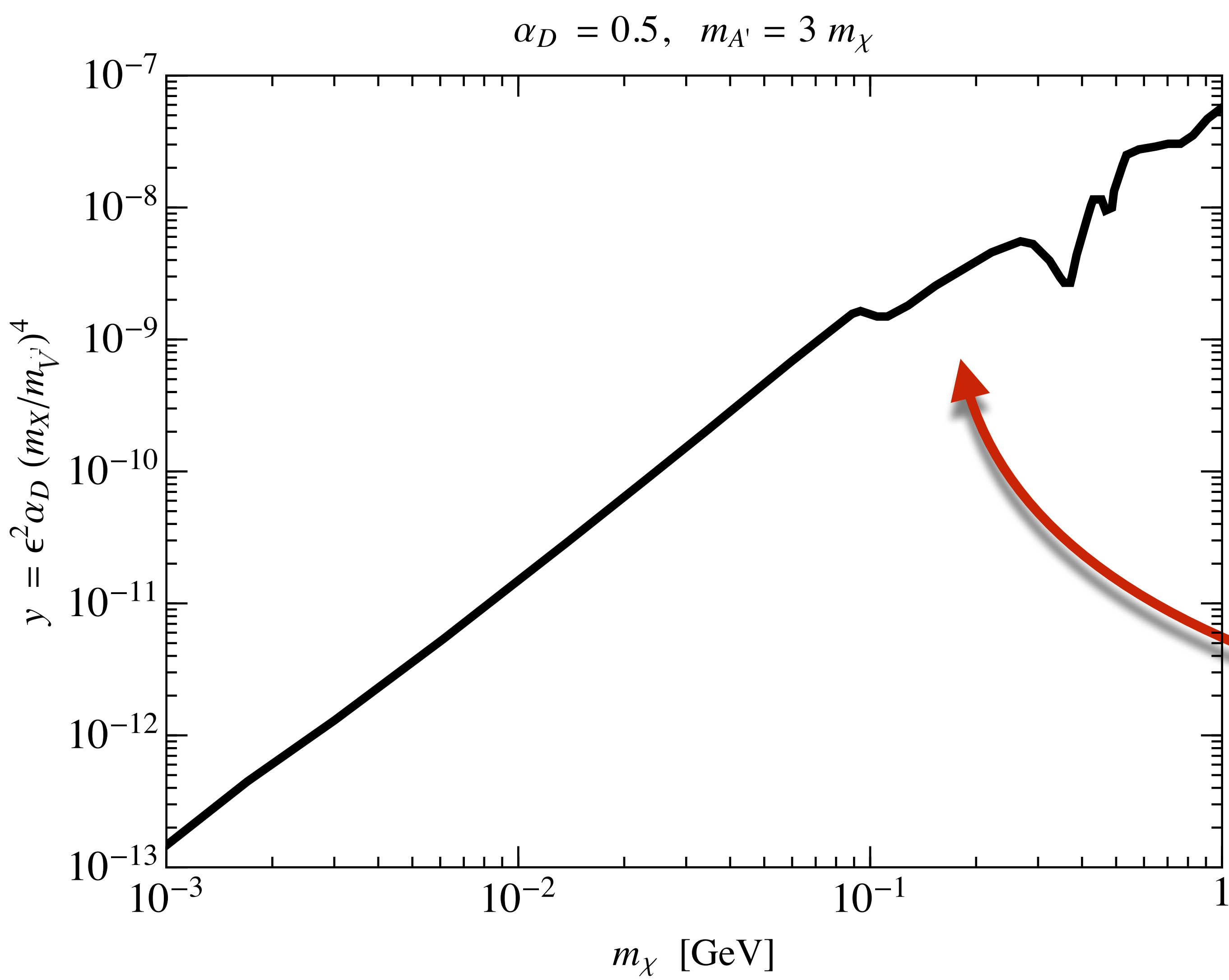
Requires only minuscule portal coupling to maintain kinetic equilibrium

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

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

Relic Abundance of Vector Portal Dark Matter





Interaction strength

Dark Matter Mass

DM annihilation cross section:

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

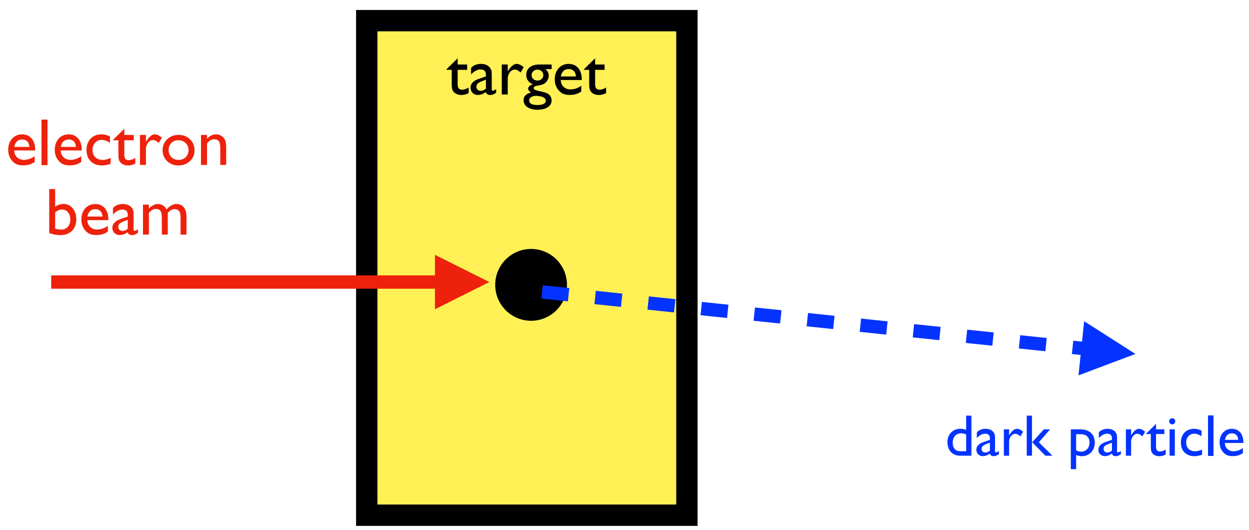
$$y = \epsilon^2 \alpha_D \left(m_\chi / m_V\right)^4$$

Observed dark matter relic abundance predicted along this line

See talk by N. Blinov

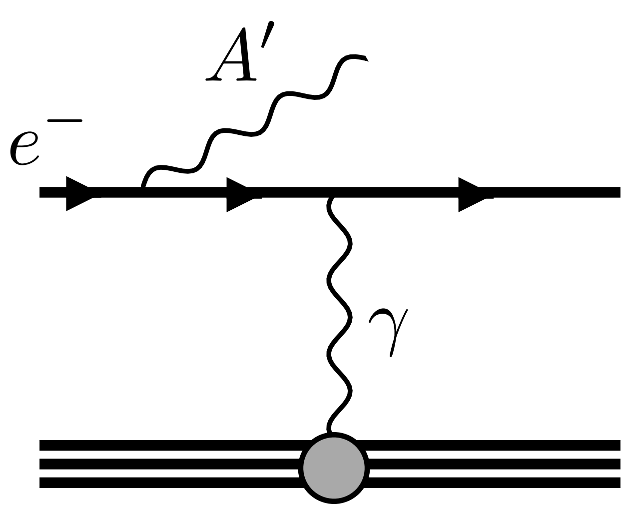
Exploring Dark Sectors With Electron Beams

Dark Particle Production in Electron Fixed Target Experiments

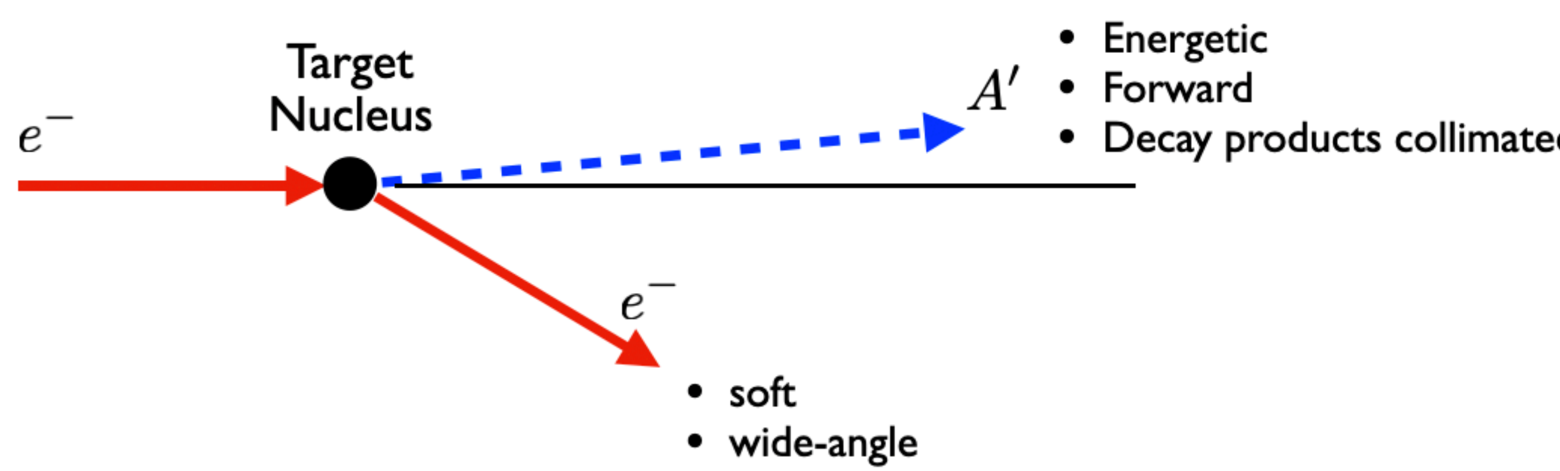


Advantages:

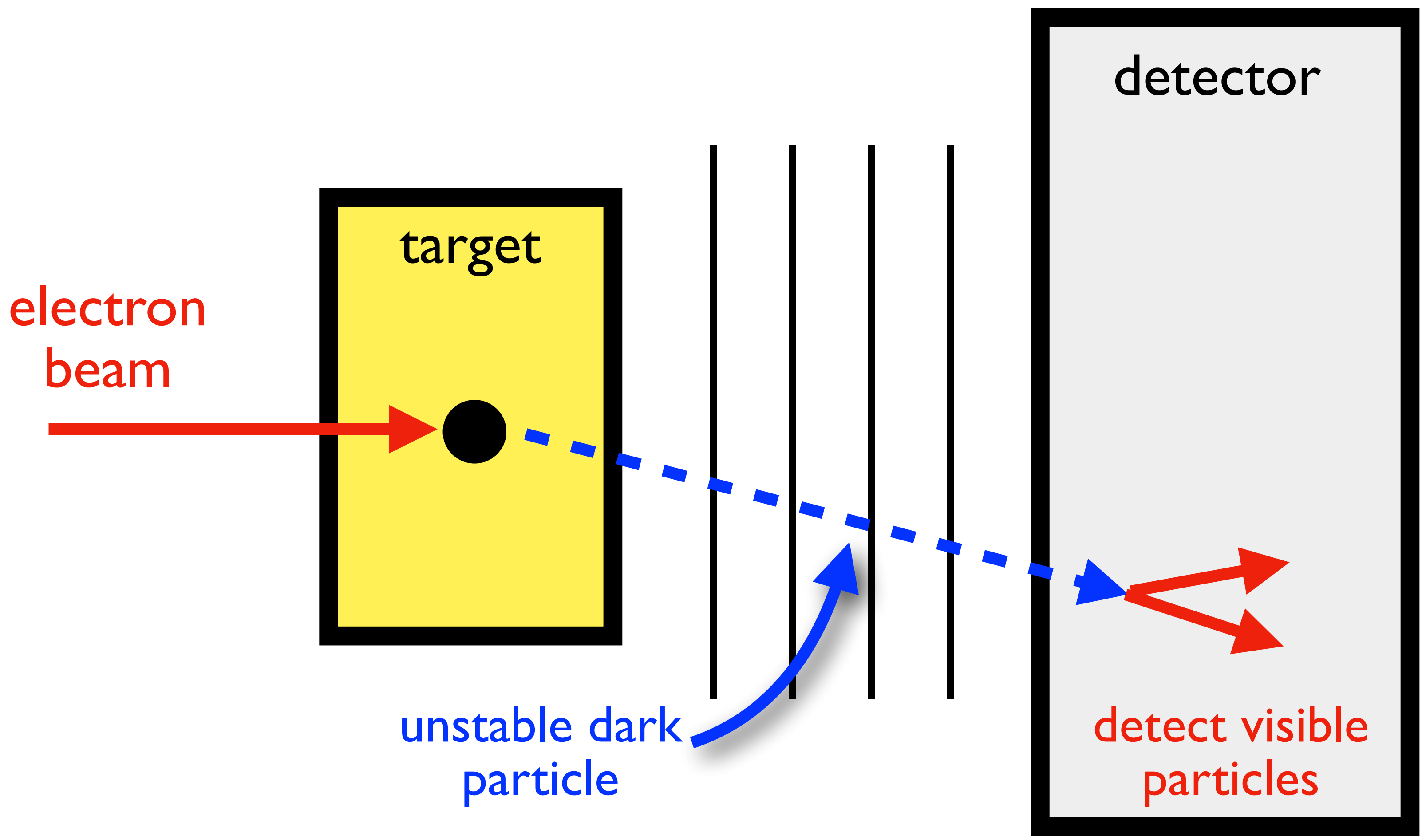
- high collision luminosity
- forward kinematics
- large production rates
- clean experimental environment



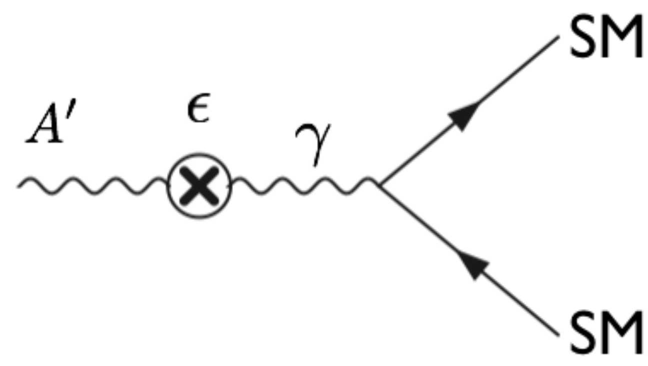
Dark Photon Production via Bremsstrahlung



Visible Decays

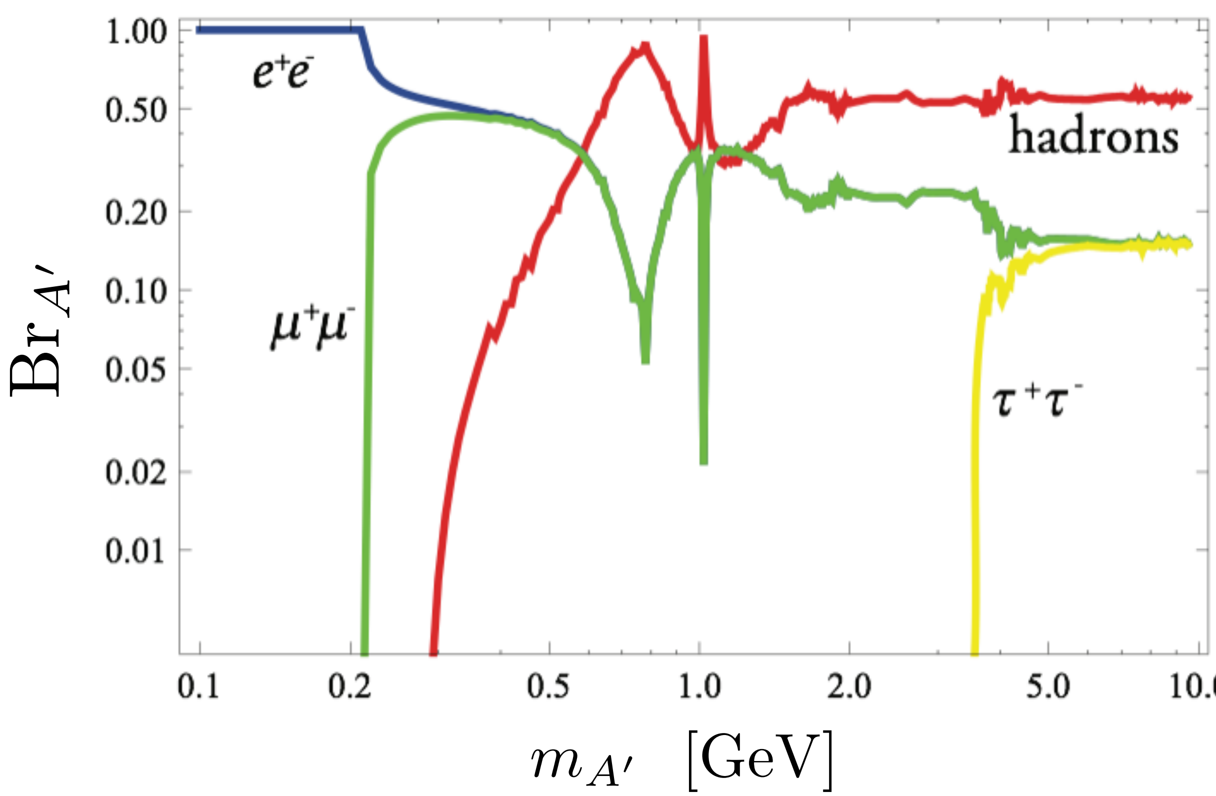


Visibly Decaying Dark Photons

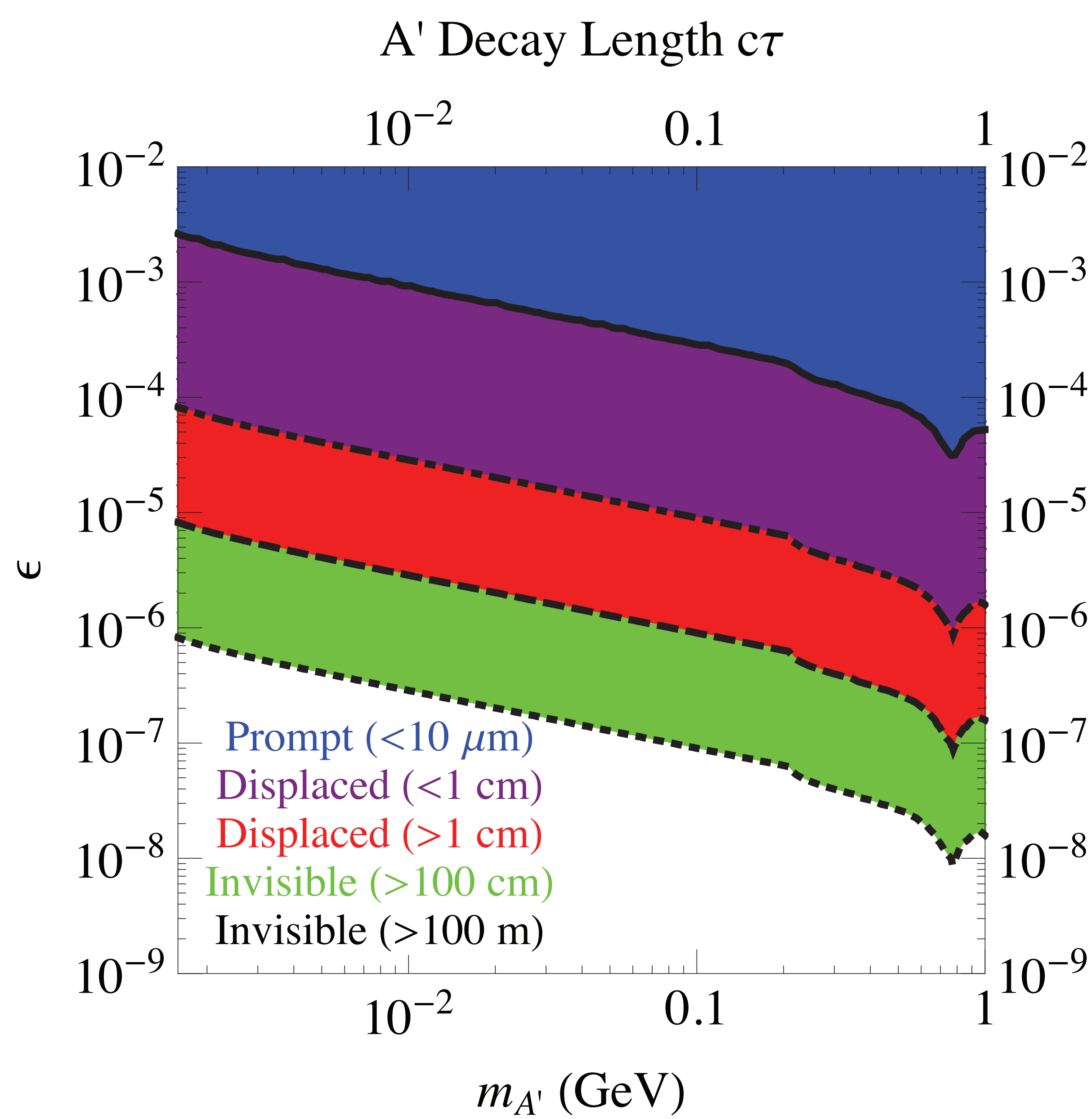


$$\Gamma_{A'} \sim \epsilon^2 m_{A'}$$

- Typically occurs if dark photon is lightest particle in dark sector
- Bump hunt or displaced/long-lived particle searches possible



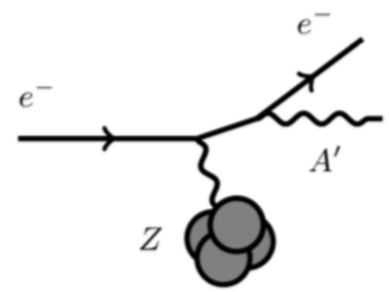
[BB, Pospelov, Ritz]



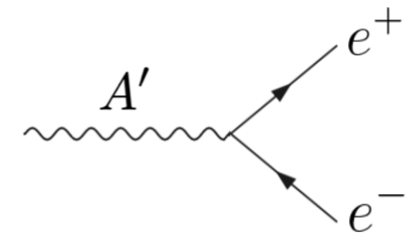
[Essig, Harnik, Kaplan, Toro]

APEX@JLAB

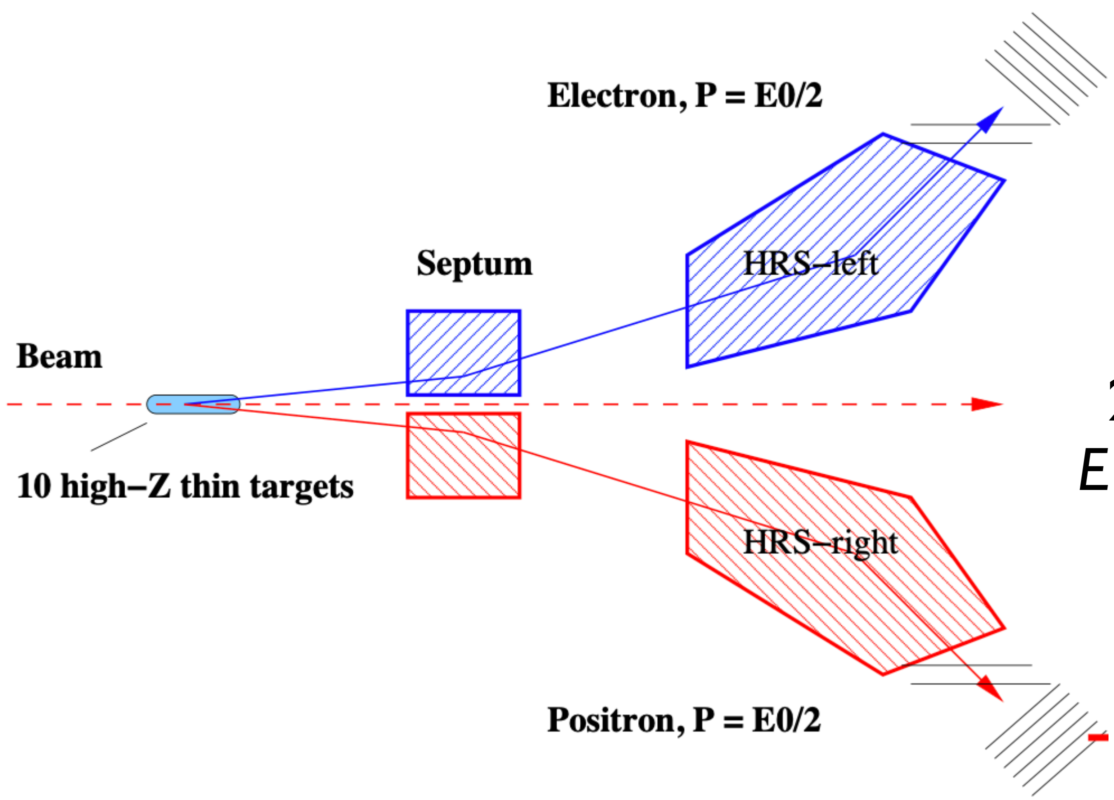
- Multi-GeV electron beam;
- High Z thin target
- High resolution spectrometer
- Search for prompt di-electron pair



Production



Detection



APEX
2019 Run,
E = 2.2 GeV

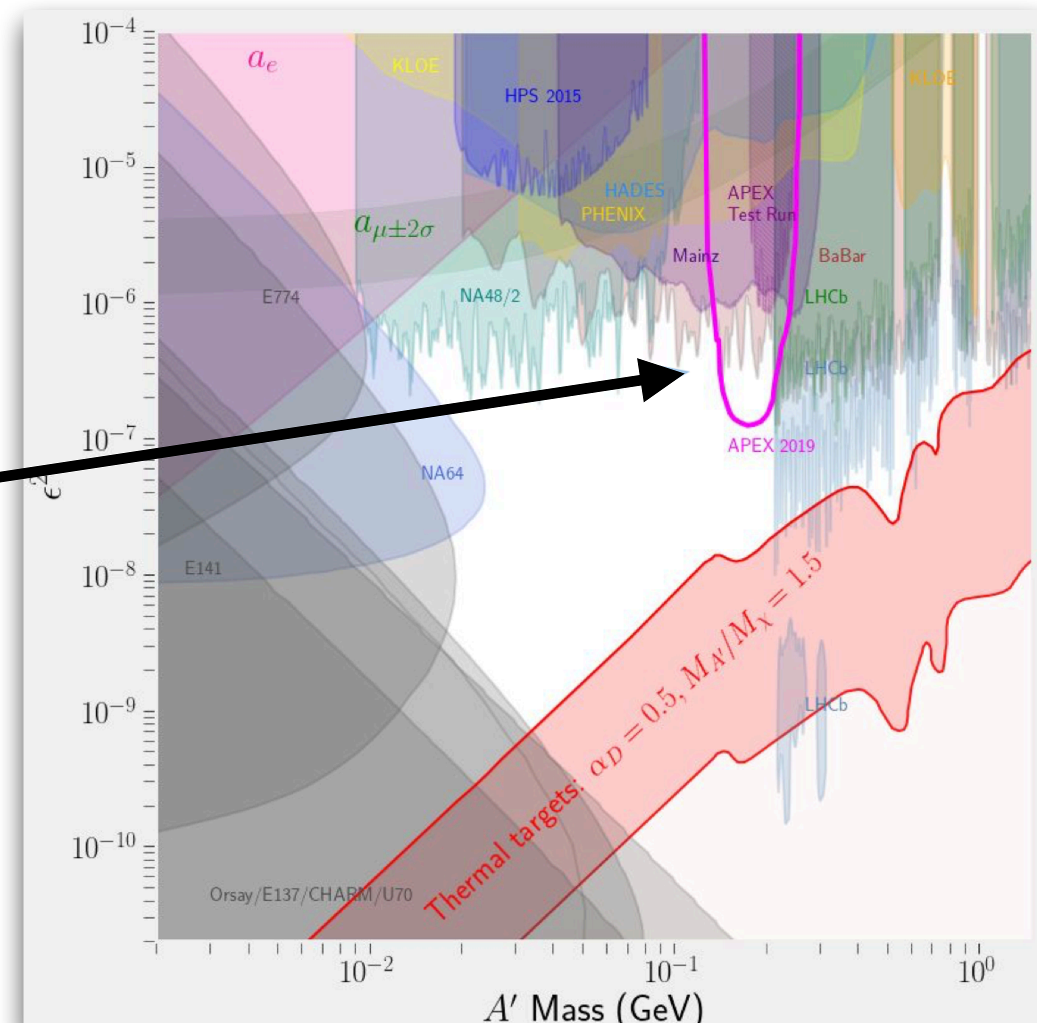
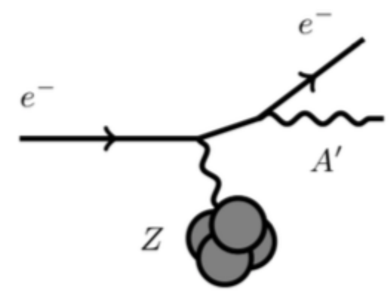


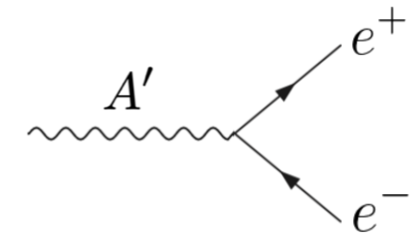
Fig. from O. Moreno, talk at LDMA 2019

HPS@JLAB

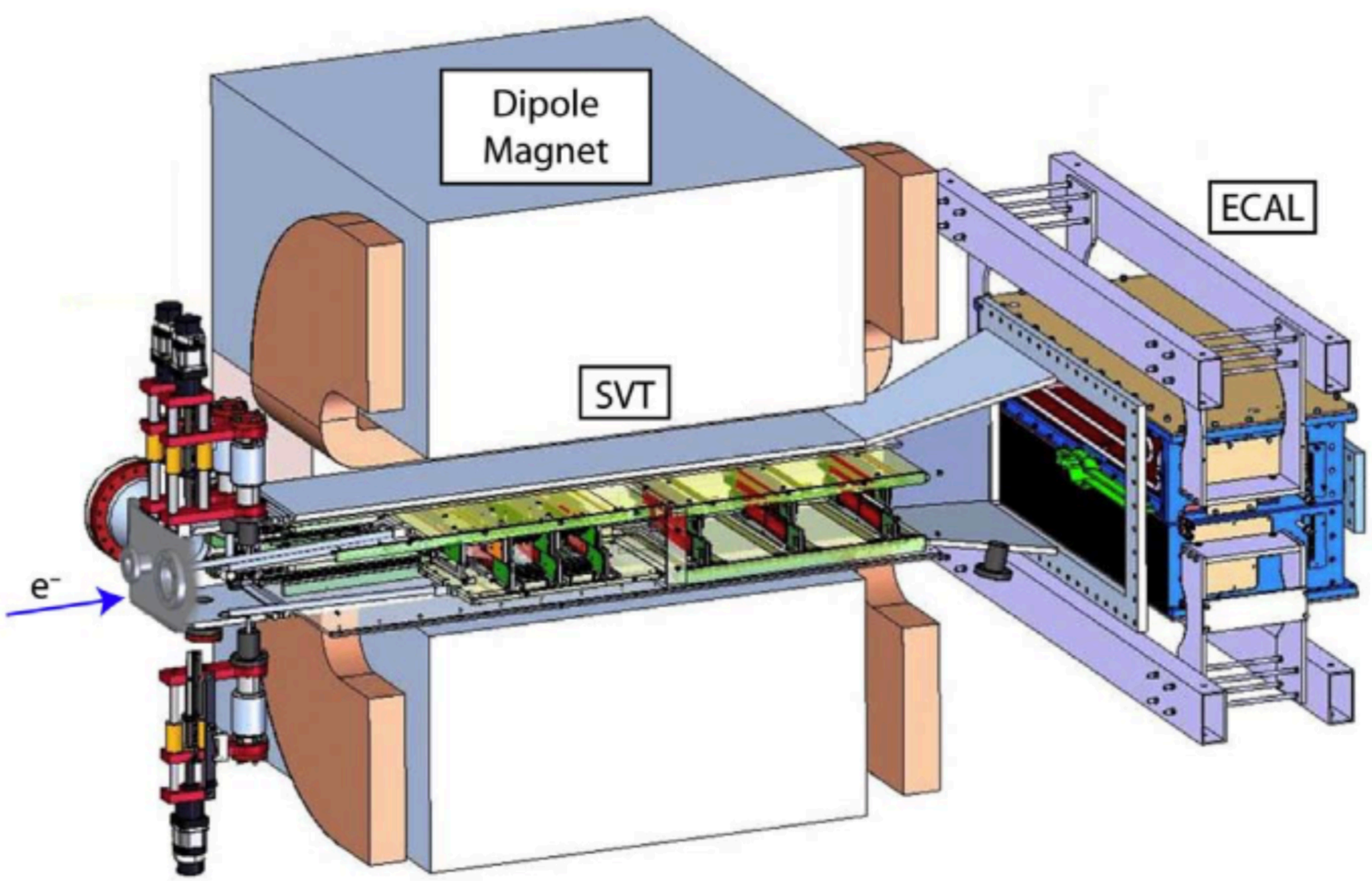
- Multi-GeV electron beam;
- High Z thin target
- Silicon vertex tracker + ECA
- Both prompt and displaced dark photon searches are possible



Production



Detection



HPS projections

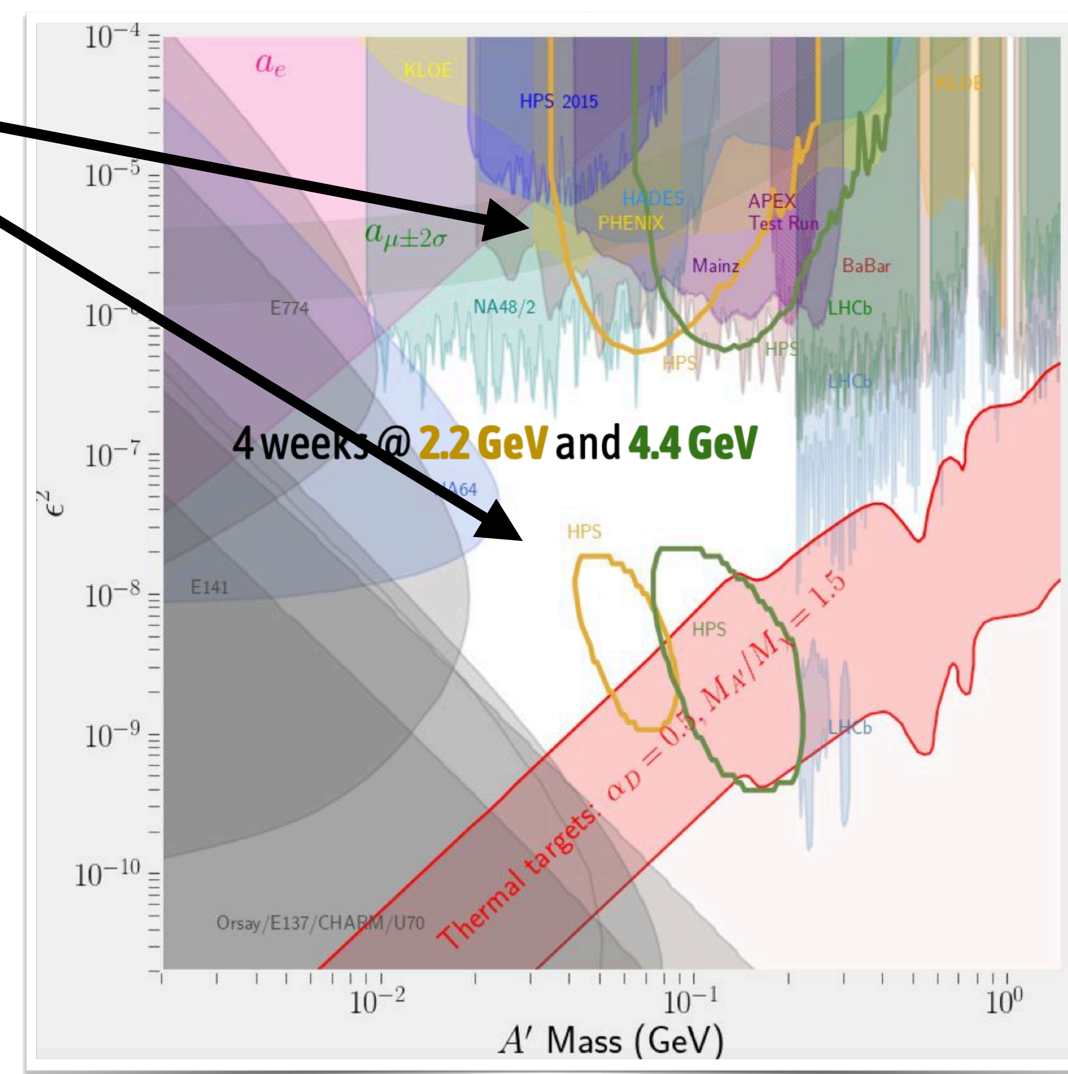
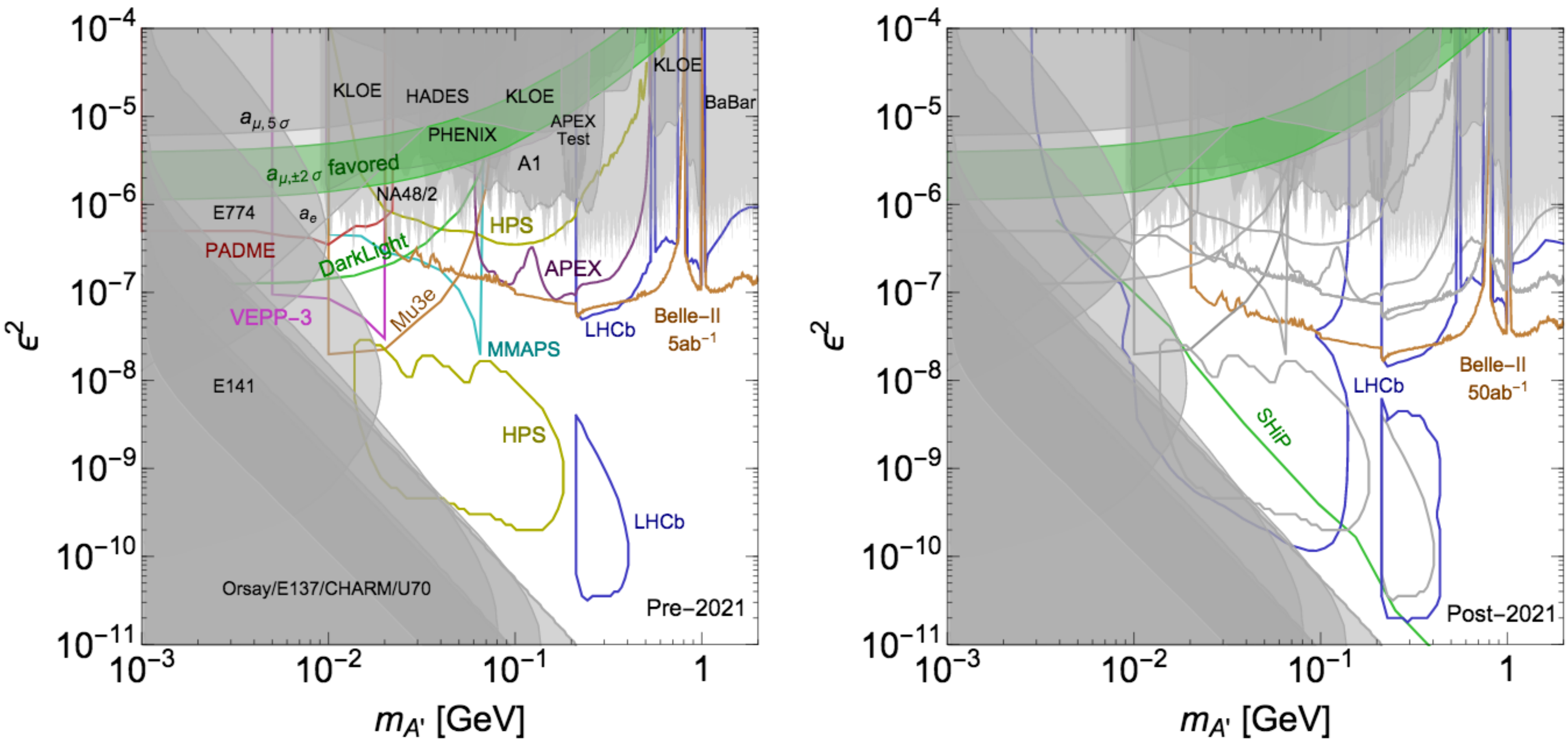


Fig. from O. Moreno, talk at LDMA 2019

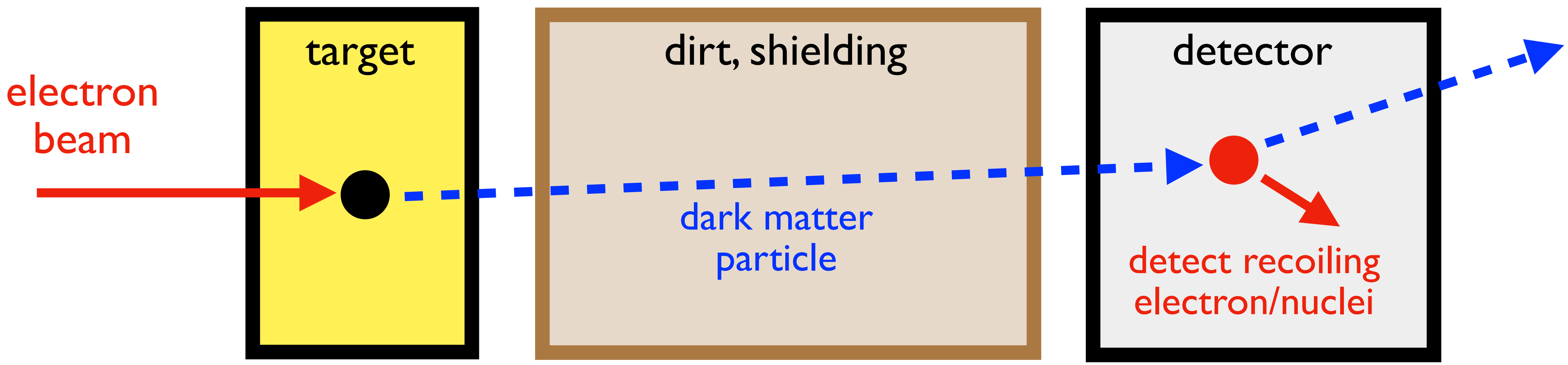
Minimal dark photon landscape

- Electron fixed-target experiments will play an important role in these explorations
  - APEX, MAGIX, HPS, DarkLight, …



Dark Sectors Community Report: 1608.08632

Dark matter scattering



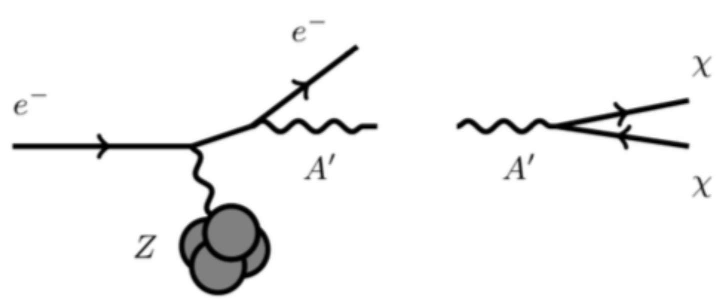
[BB, Pospelov, Ritz (p^+ beams)]

[Izaguirre, Krnjaic, Schuster, Toro]

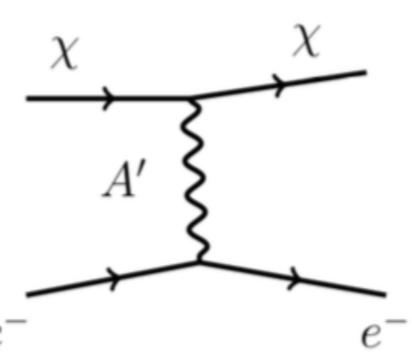
SLAC Beam Dump E137

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

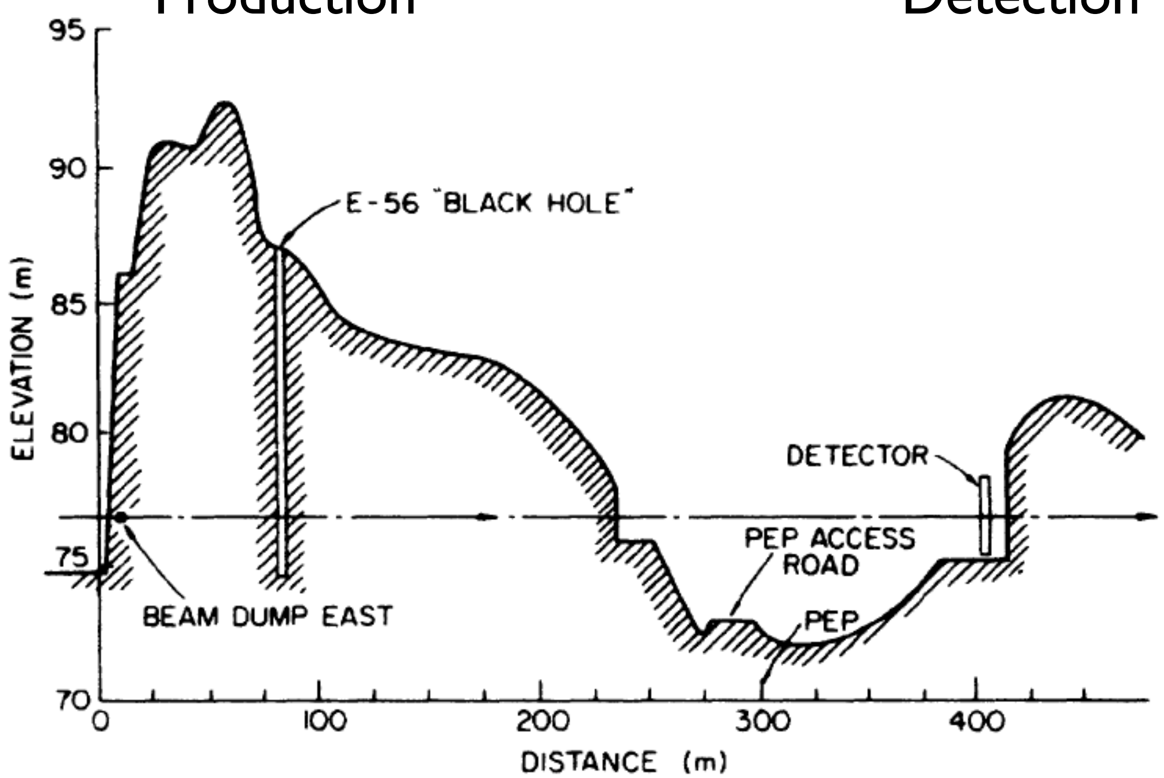
- 20 GeV electron beam; 30 C dumped
- Water - aluminum target
- Shower calorimeter, 400 m from dump

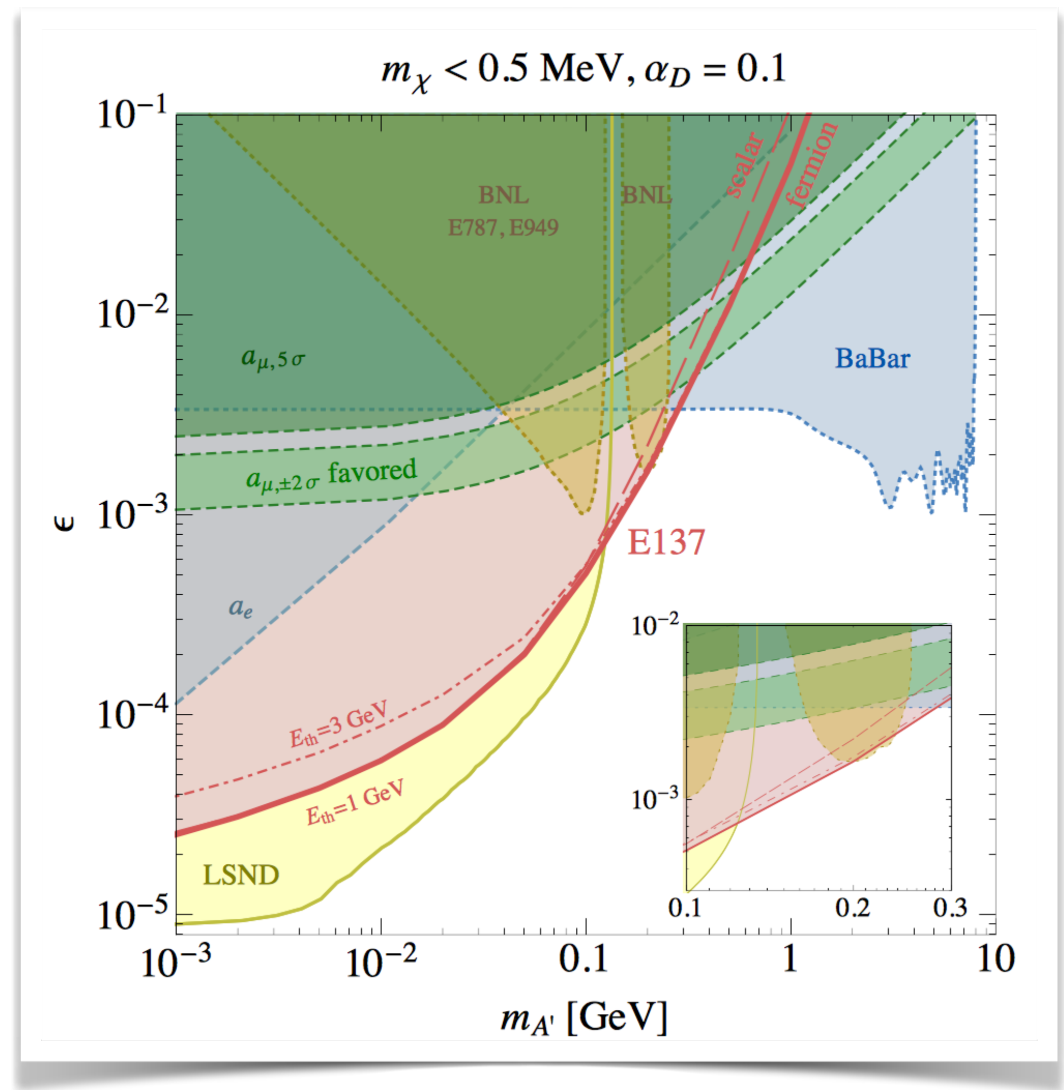


Production



Detection

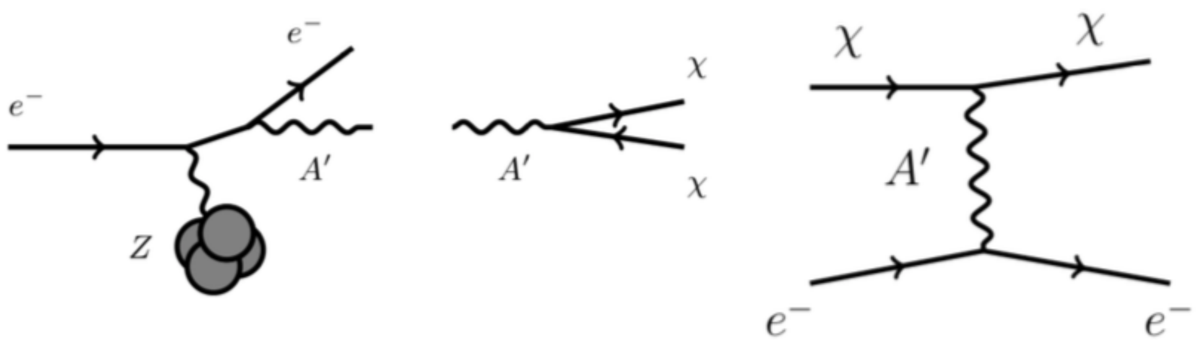




Provides proof-of-principle for future electron beam dump experiments

BDX @ JLAB

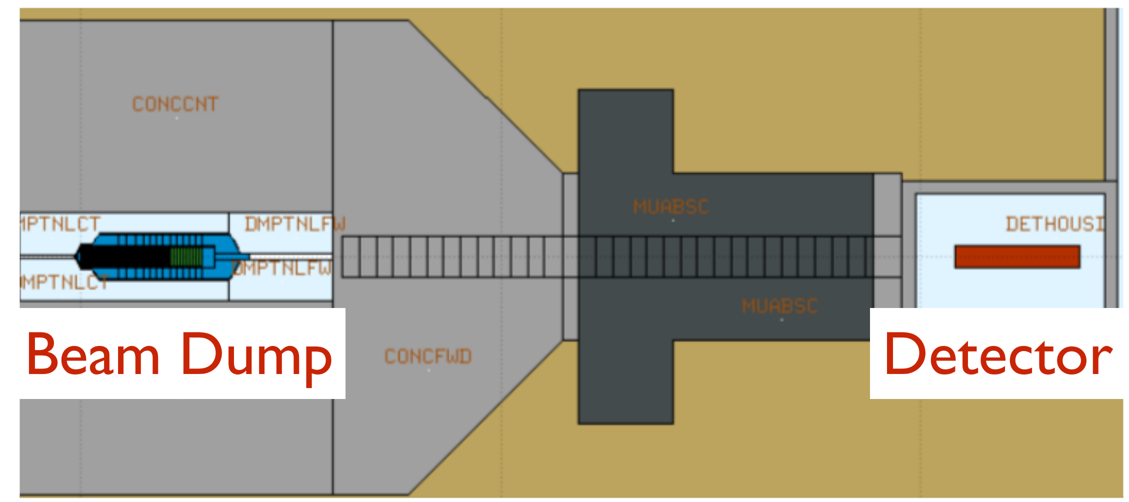
- 11 GeV electron beam on Water-Aluminum dump
- ECAL detector located 20m downstream

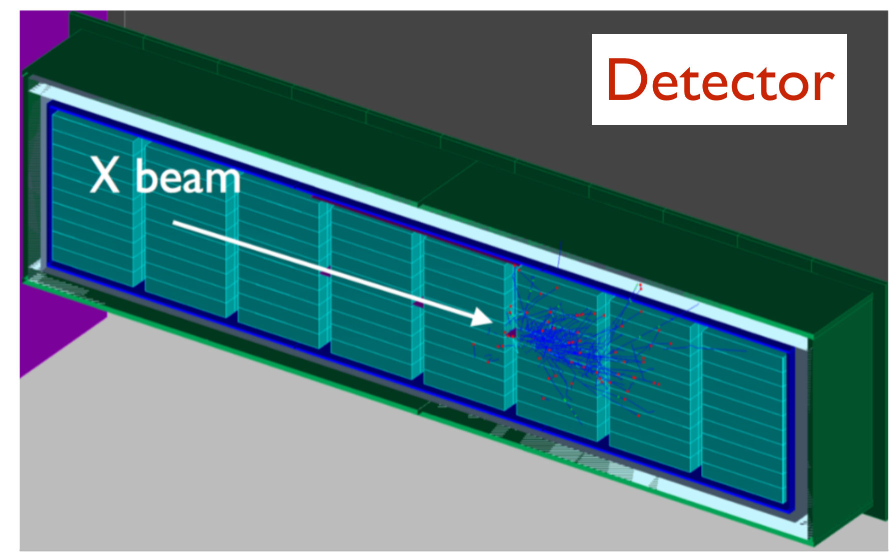


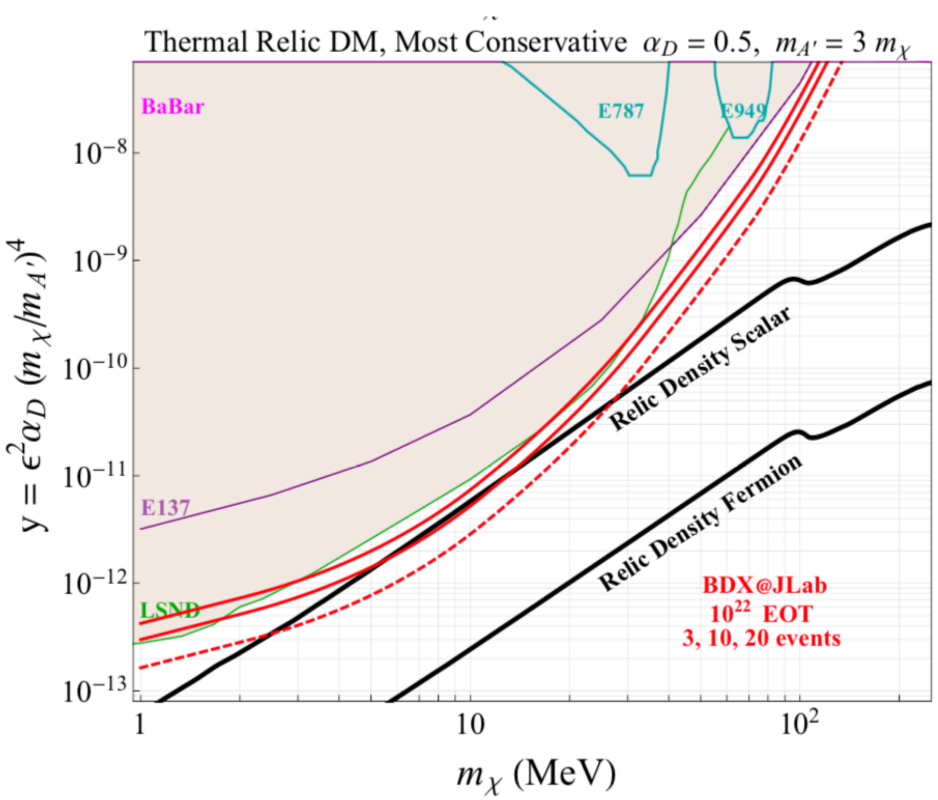
Production

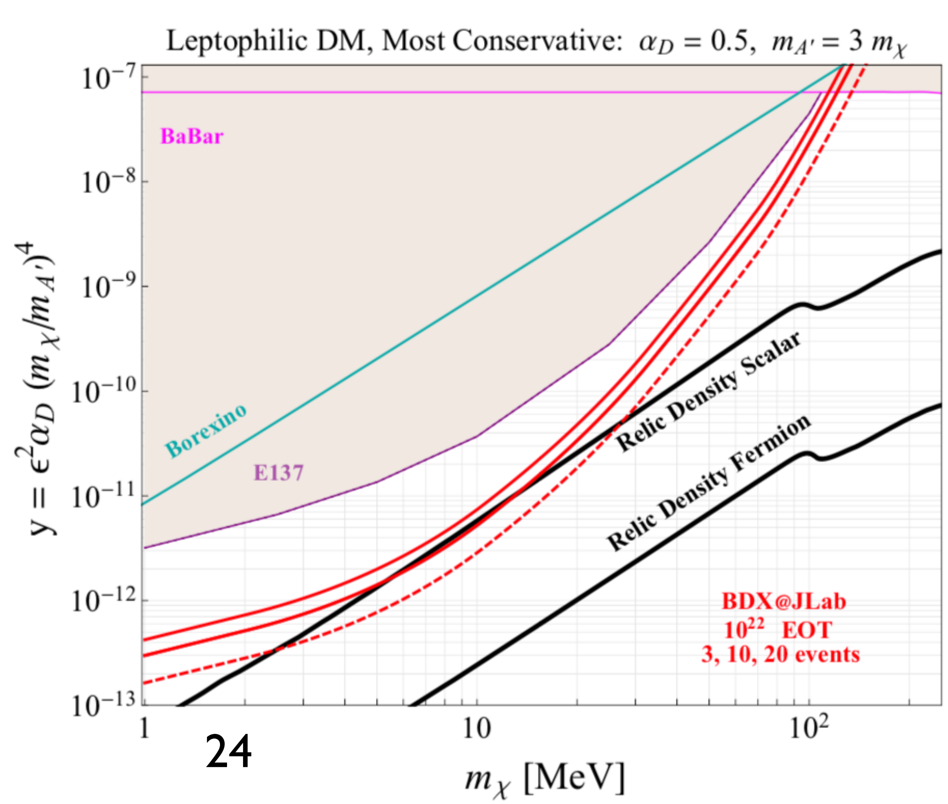
Detection

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



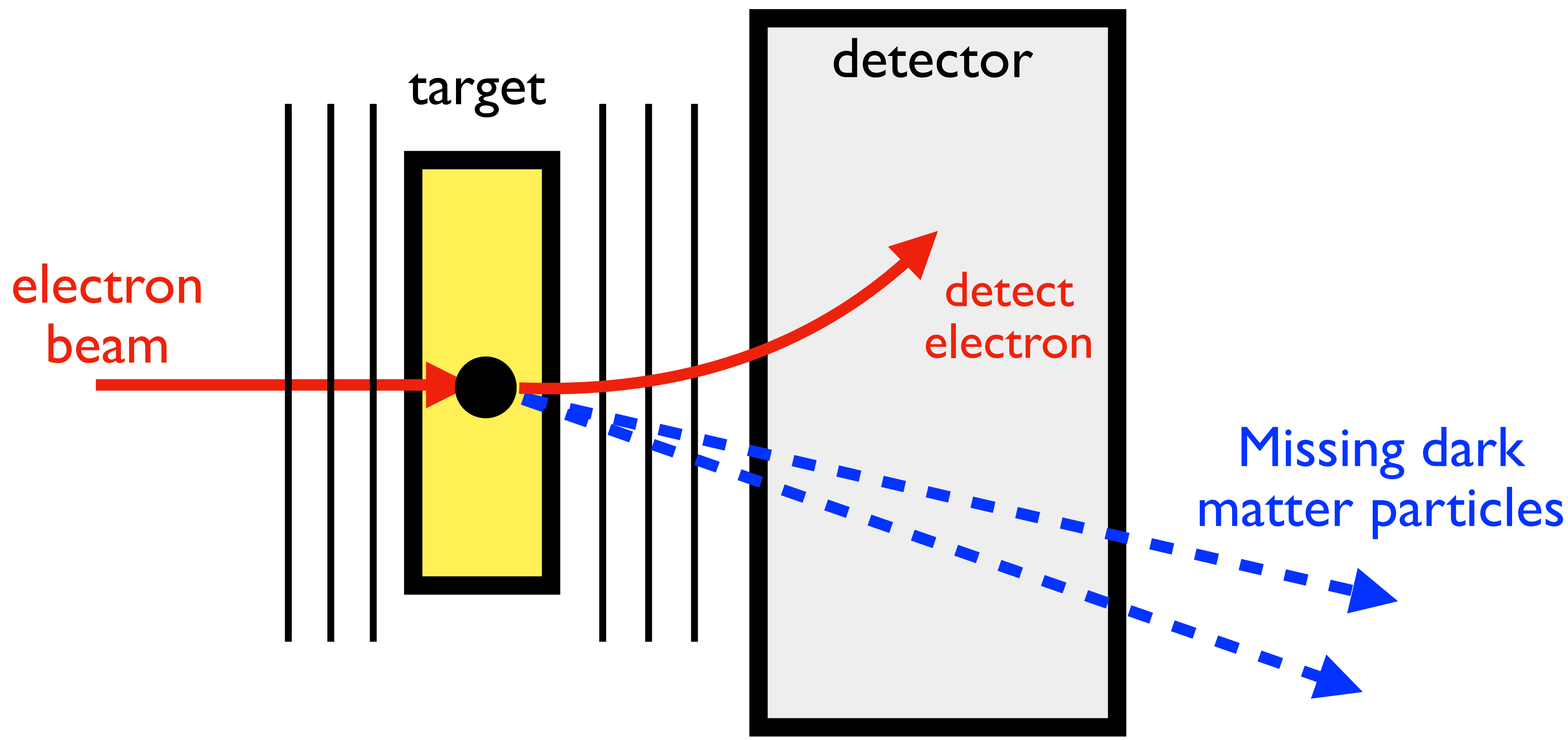






BDX proposal
1607.01390

Missing energy / momentum



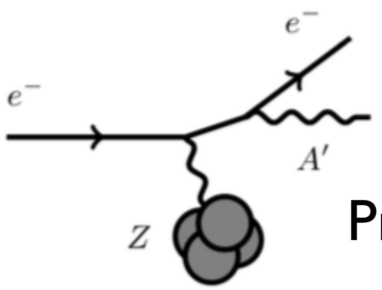
See talk by
N. Blinov

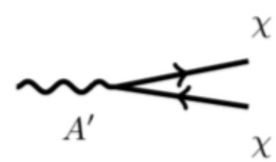
[Andreas. et al]

[Izaguirre, Krnjaic, Schuster, Toro]

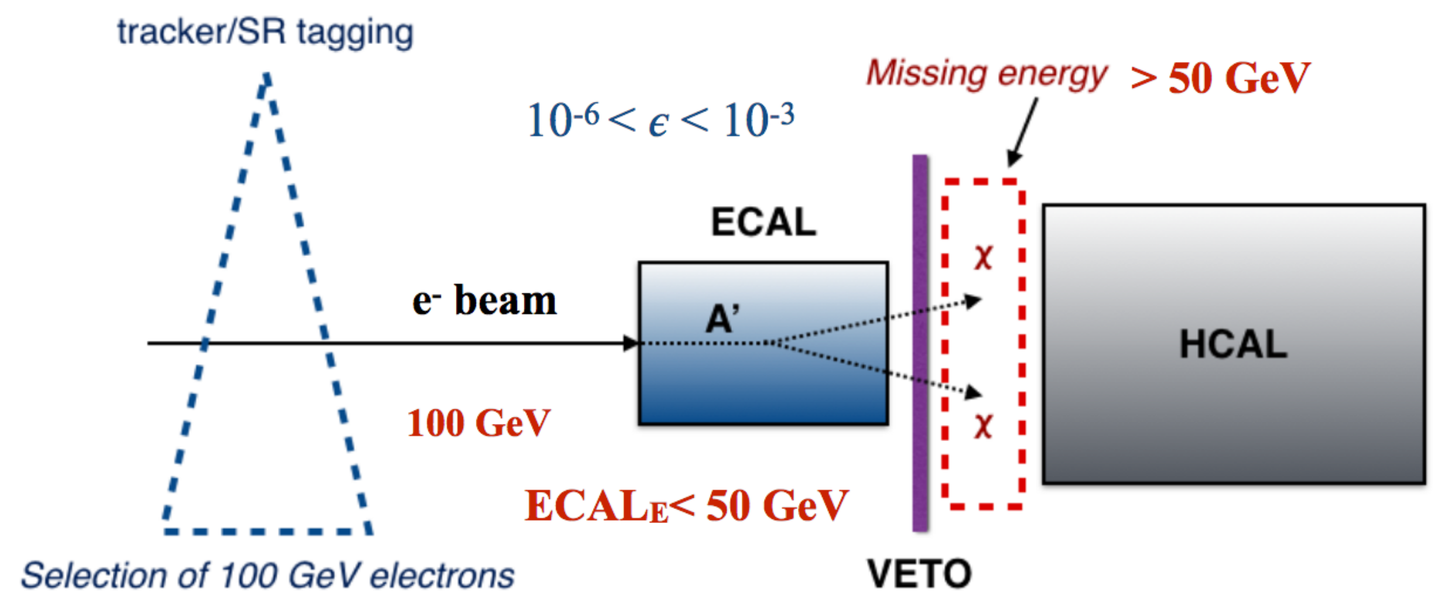
NA64 @ CERN

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

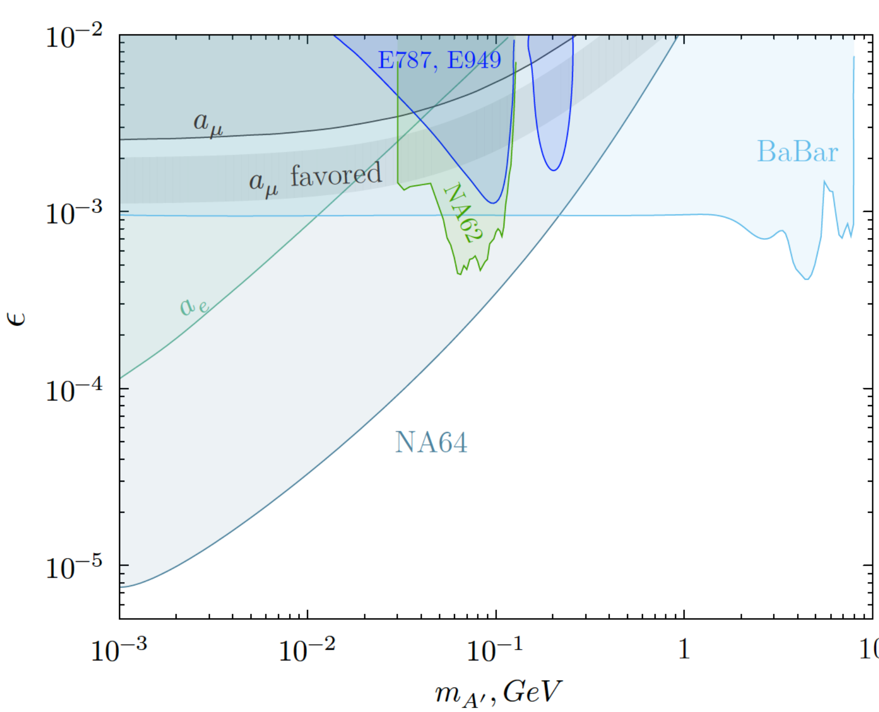


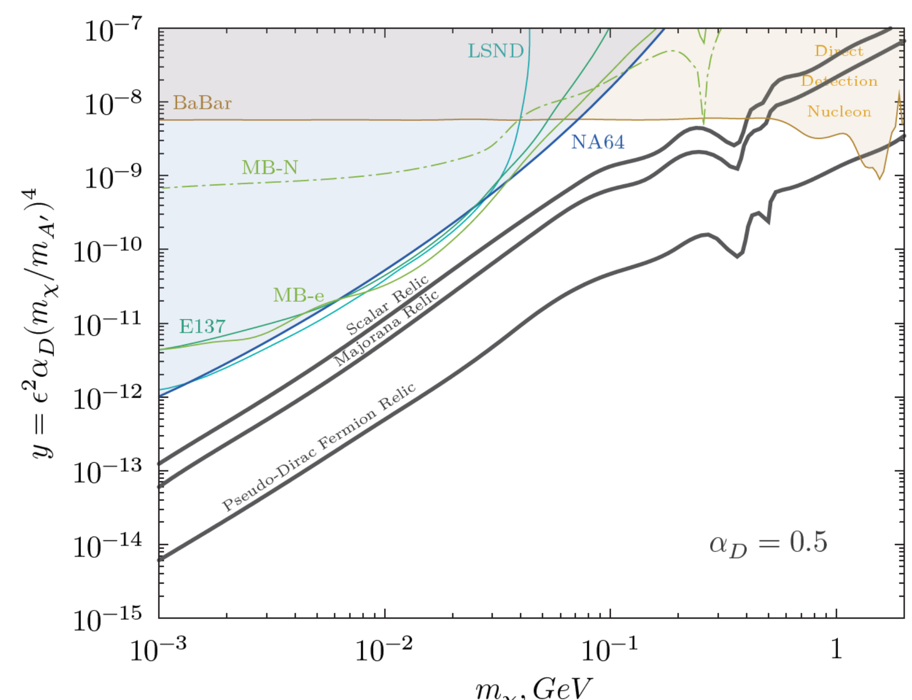


Production



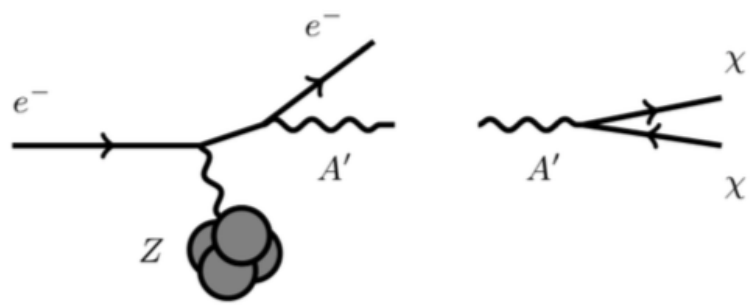
- Large missing energy signature (small energy deposition in ECAL, no energy deposition in HCAL)
- 2.84 x 10^{11} EOT - best limits on invisibly decaying dark photon below 300 MeV

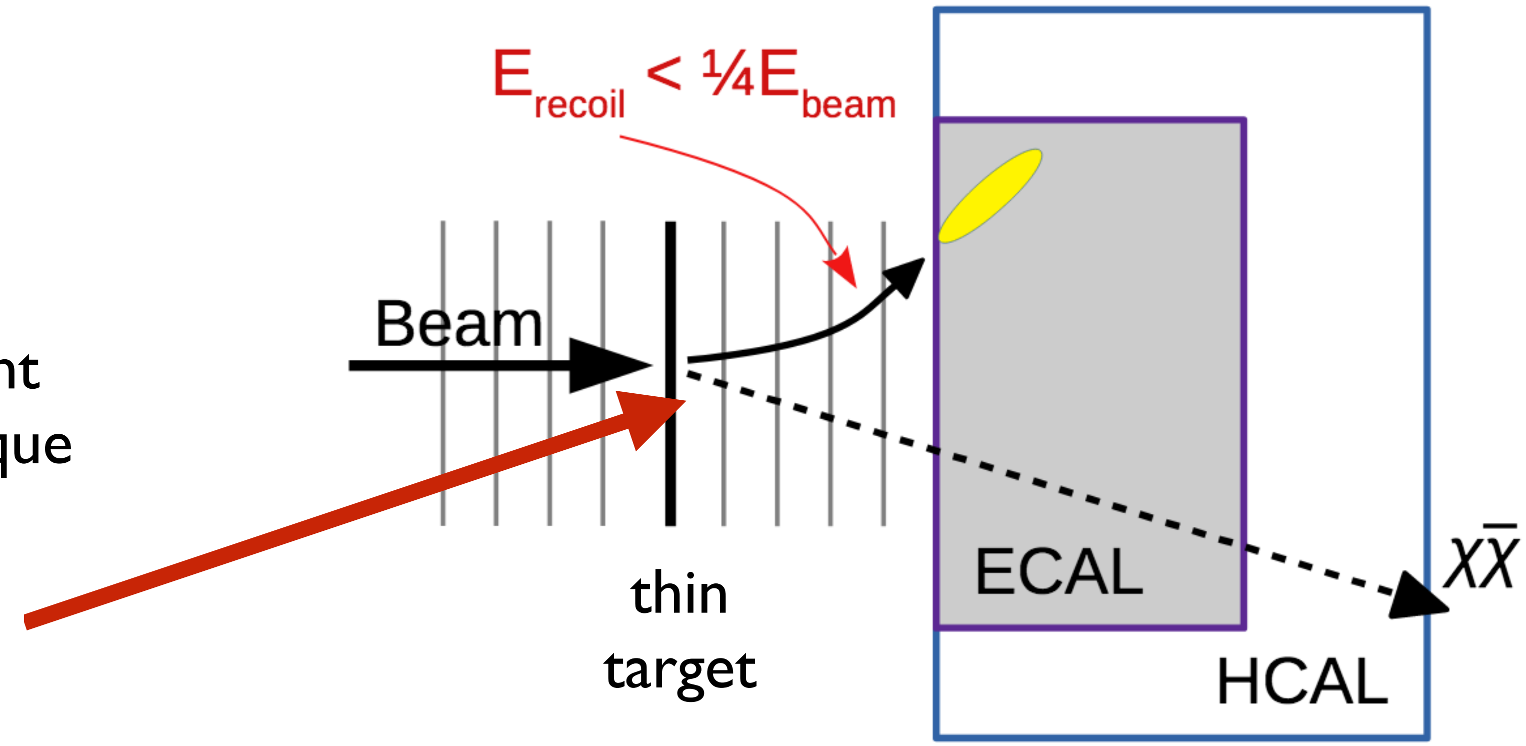




LDMX @ SLAC

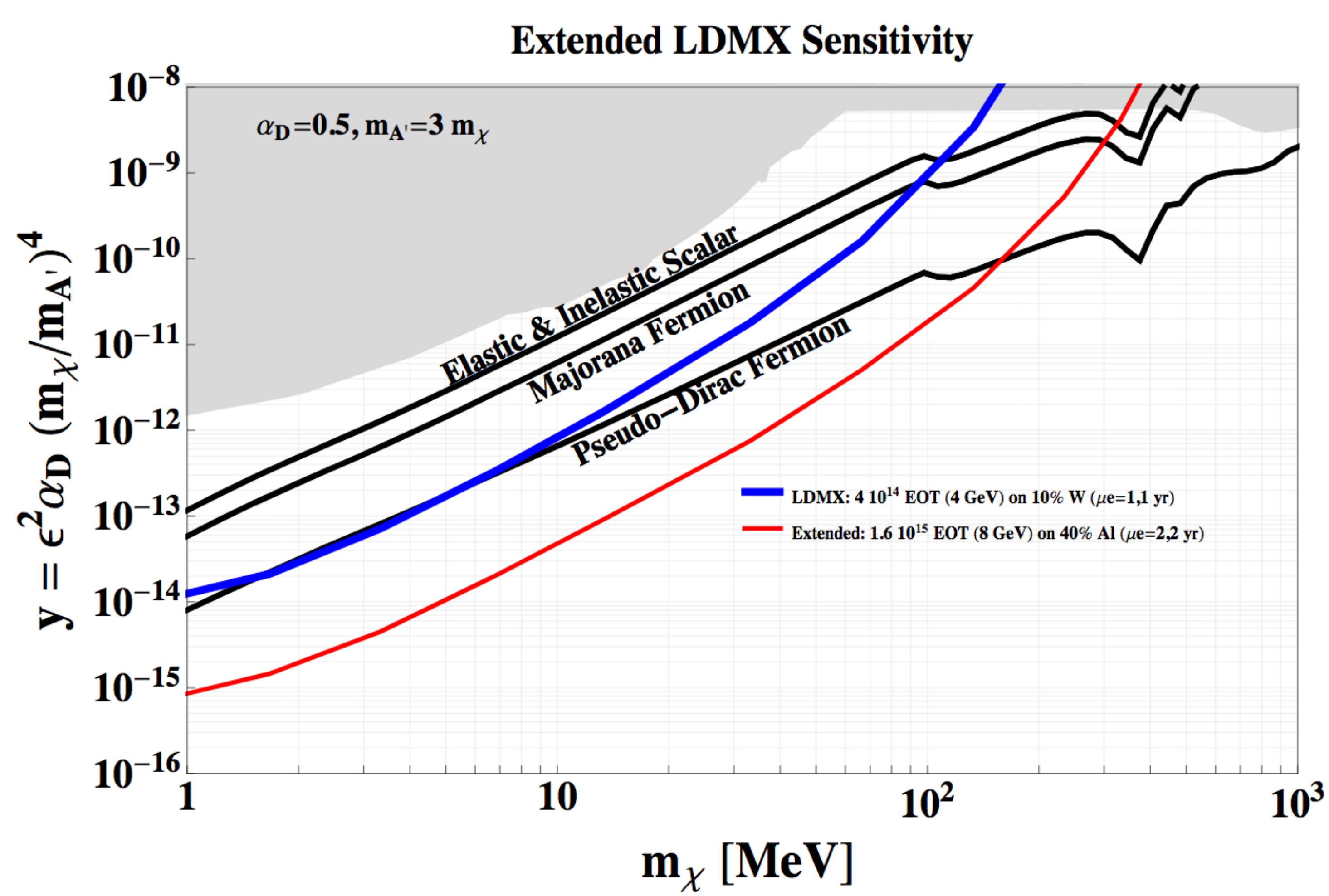
- Proposed electron beam experiment utilizing missing momentum technique





- 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

A global effort is emerging to study dark sectors

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

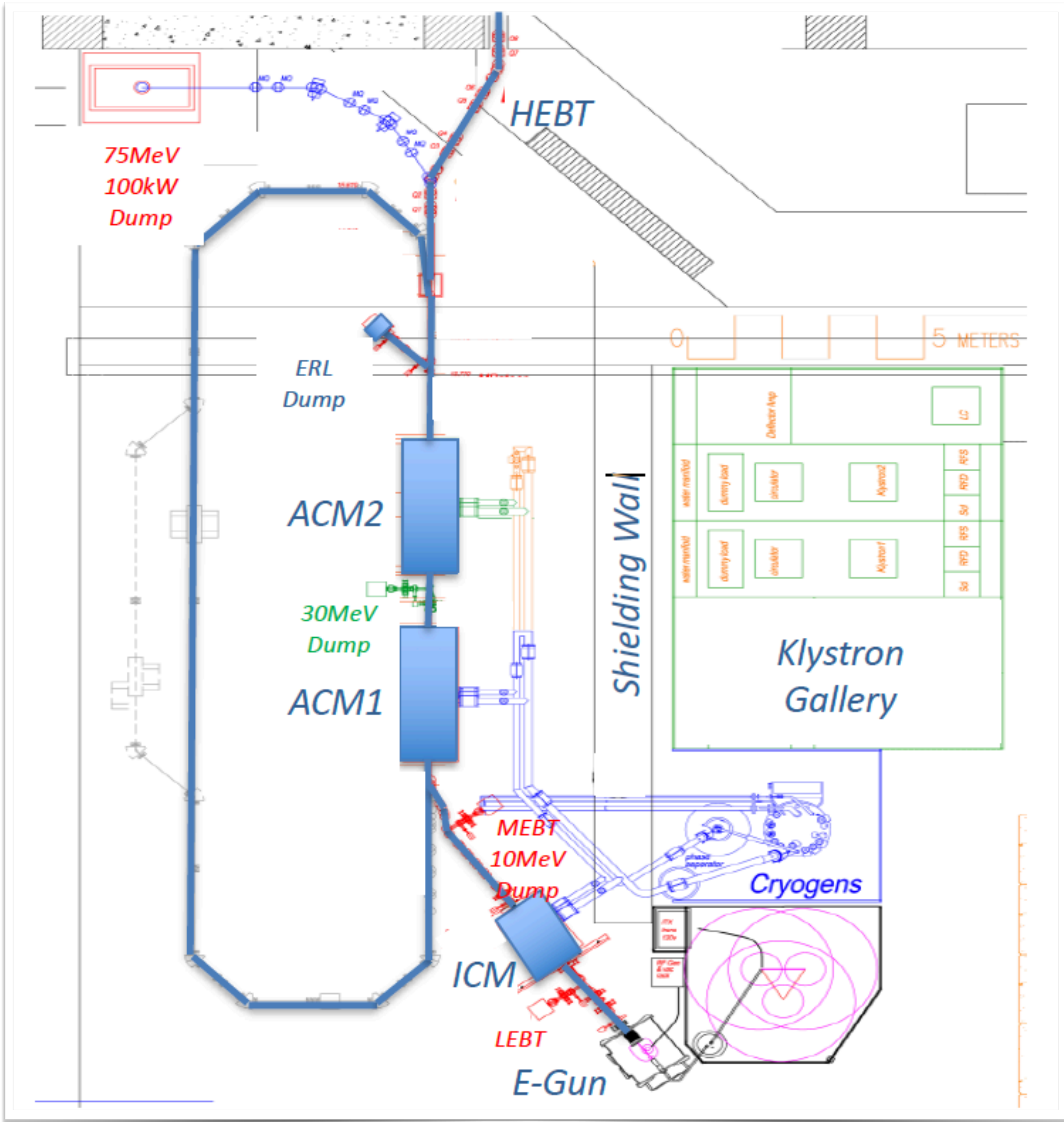
- Basic Research Needs for Dark Matter Small Projects New Initiatives

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

ARIEL e-Linac @ TRIUMF

- 35 MeV, 100 kW electron linac
- Upgradeable to 50 MeV
- Dedicated experiments could target new particles with masses in the1-10 MeV range
- It is worth exploring the potential opportunities for new physics searches at ARIEL
    - E.g., DarkLight @ TRIUMF

See talk by J. Bernauer



Outlook

- Light dark sectors and provide a novel framework for BSM physics
  - Dark matter, neutrino masses, axions, baryogenesis, experimental anomalies, …
- Electron beam fixed target experiments provide a powerful probe of dark sectors
  - Past experiments provide some of the best constraints
  - Current and near future experiments will cover well-motivated theory targets and explore large swaths of dark sector parameter space
- It would be very interesting to explore options for new experiments at TRIUMF to probe new light physics