Physics
UNIVERSITY OF TORONTO

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Fixed-Target Searches for Dark Sectors

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Canadian Association of Physicists
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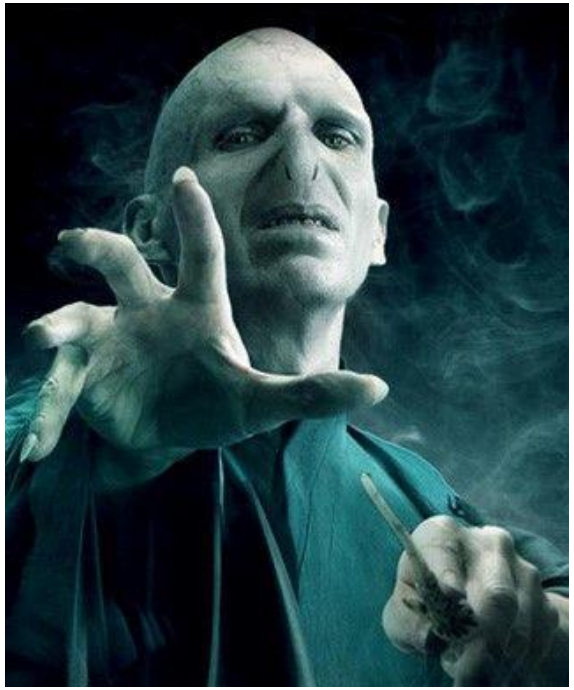
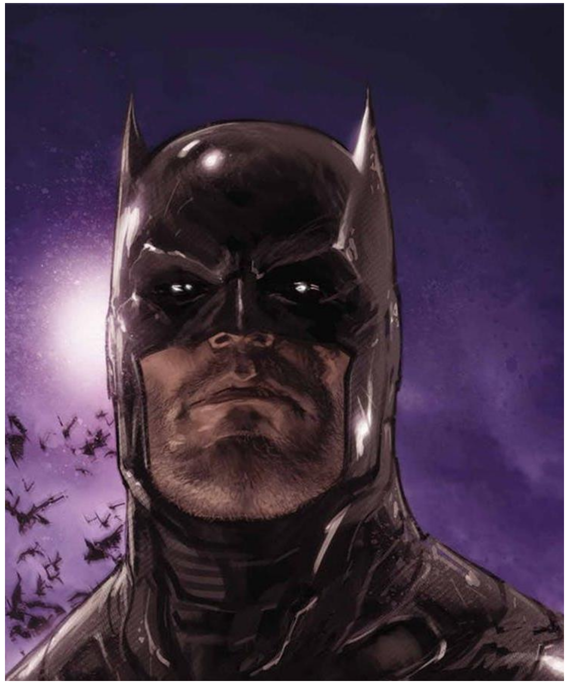
… or, Unlocking the Dark Side

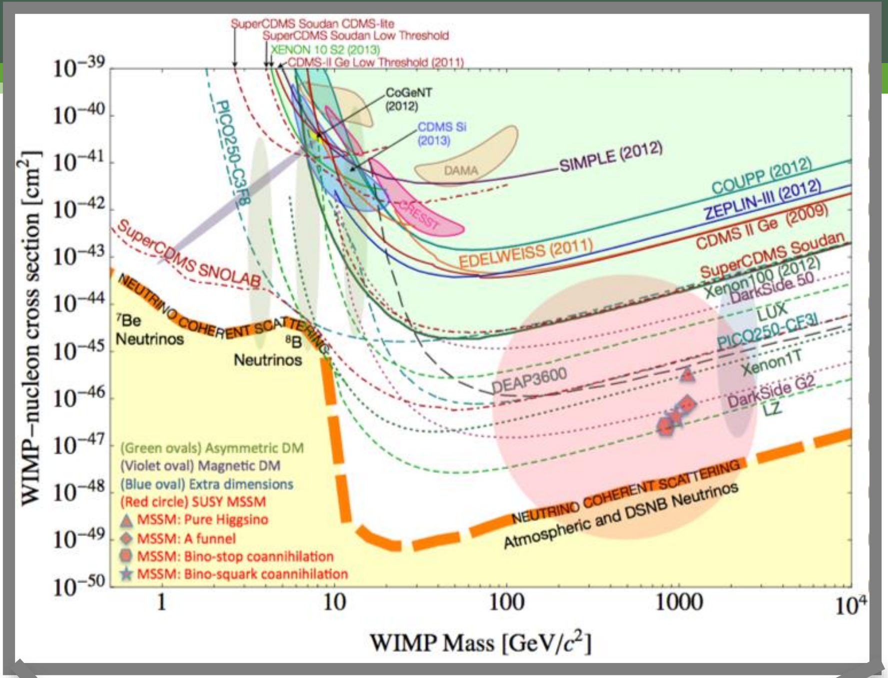


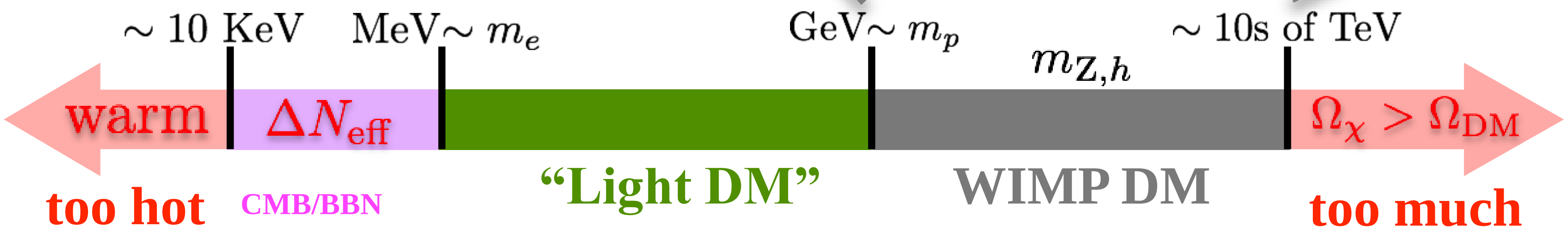
Outline

- Dark Photon Search Motivations
- Search Strategies
- Fixed Target Setups for Searches
  - Proton: e.g. NA48/2 & 62
  - Electron: e.g. HPS & LDMX
  - Positron: e.g. PADME
- Limits from Existing and Planned Fixed Target Searches

Dark Photon Search Motivations



- "Thermal Relic" WIMPs: seemingly the simplest scenario
- But haven't shown up in mass range where we most expected them!



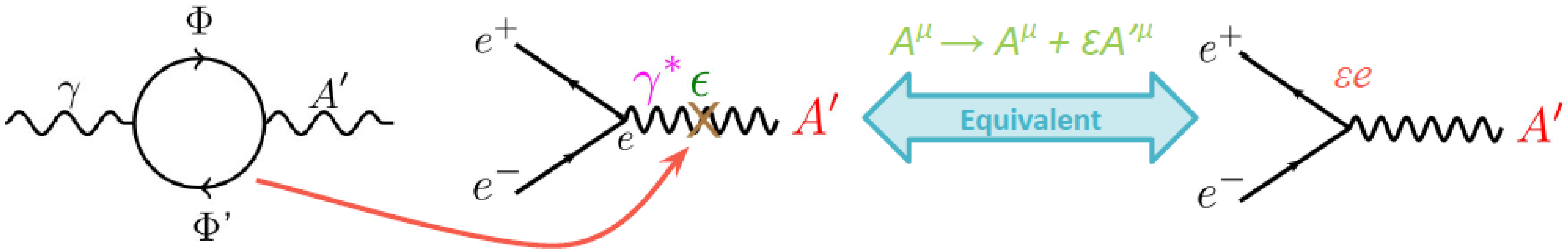
- Thermal Relic DM actually works fine at least down to $2m_e$
- But "light DM" requires new, comparably low-mass mediators to achieve required annihilation cross-section for thermal relics

Dark Photon Search Motivations

- Hidden Valley: dark sector weakly coupled to SM via “portal”
- Vector Portal: Add a U(1)’ , under which the dark sector is charged, whose massive “dark” gauge boson (A' / Z_D / γ_d) mixes kinetically with SM photon

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \boxed{\frac{\varepsilon}{2} F^{Y,\mu\nu} F'_{\mu\nu}} + \frac{1}{4} F'^{\mu\nu} F'_{\mu\nu} + m^2_{A'} A'^{\mu} A'_{\mu}$$

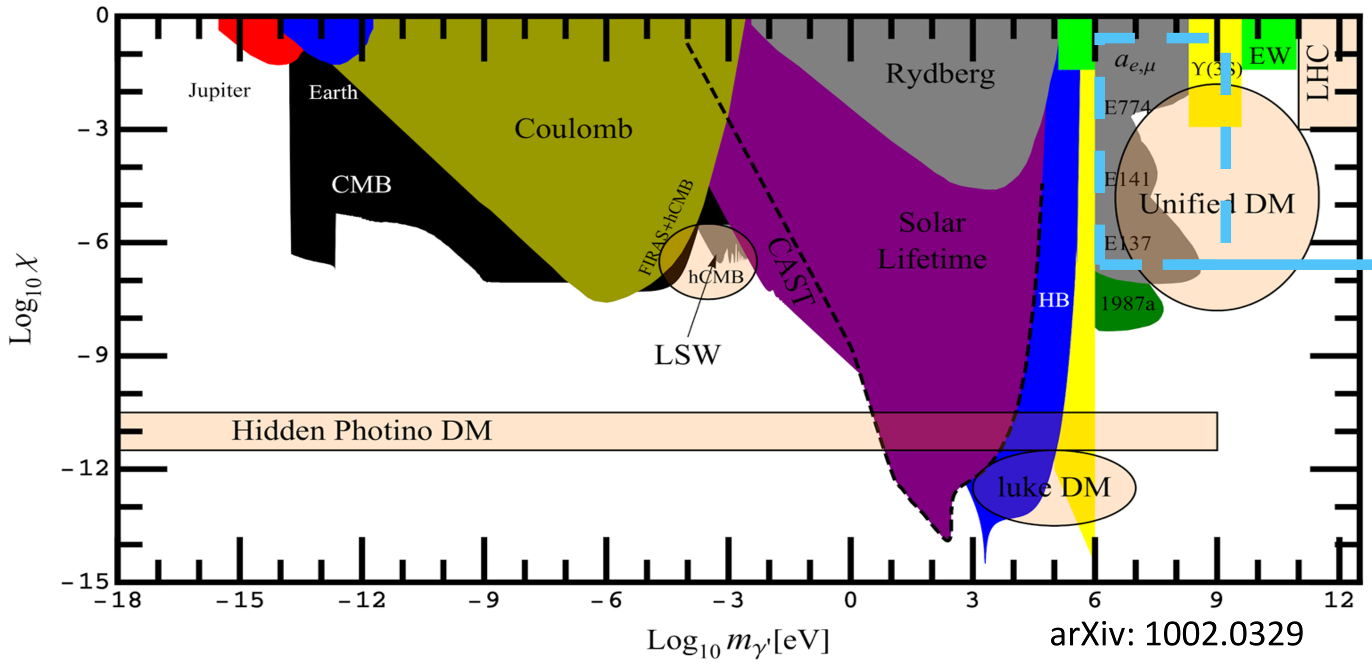
kinetic mixing $\longrightarrow$ induces weak coupling to electric charge



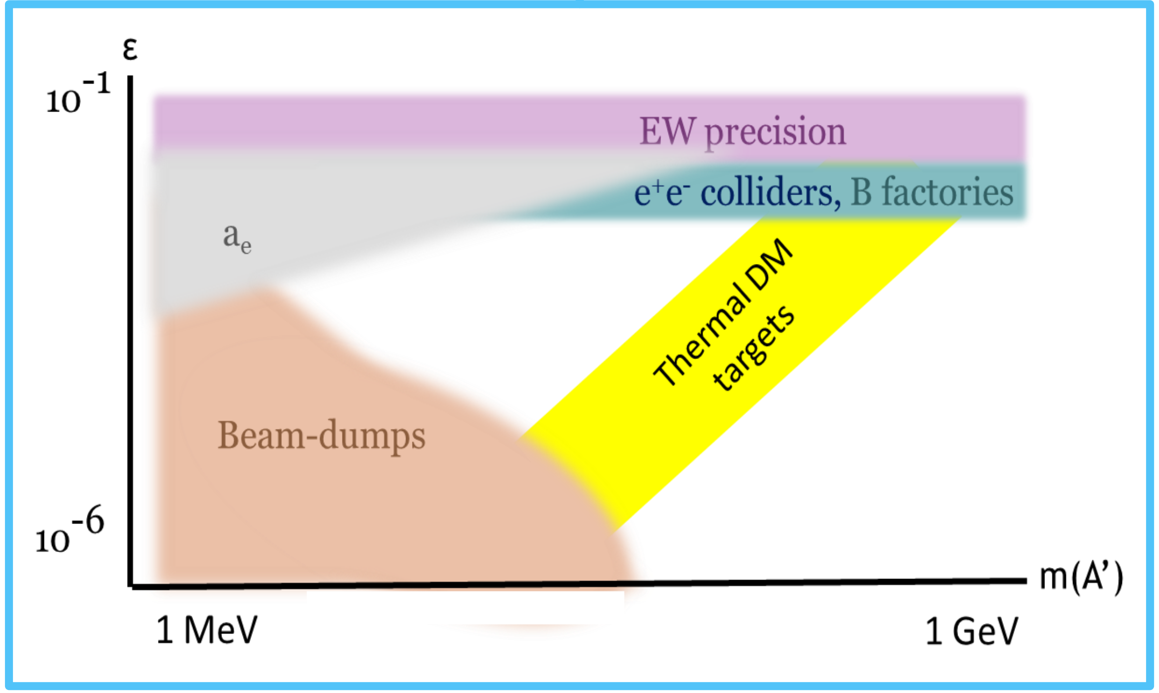
Dark Photon Search Motivations

Look for the Portal

Dark Photon Search Motivations

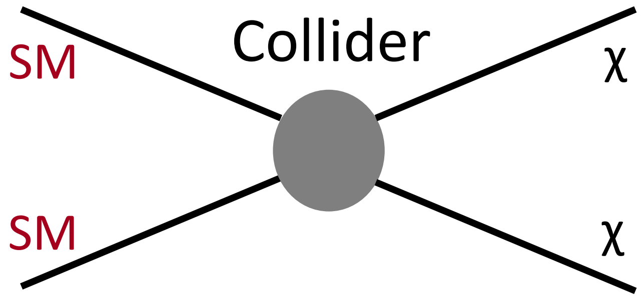


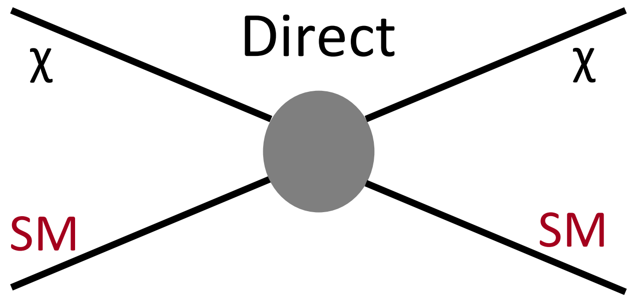
arXiv: 1002.0329

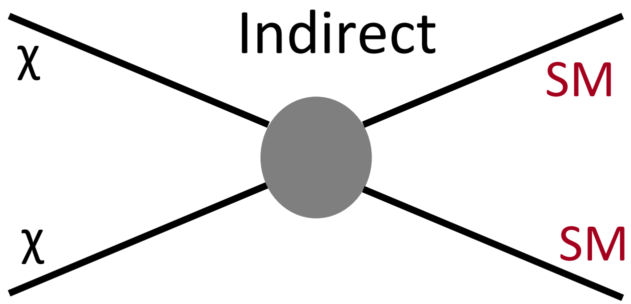


Dark Sector Search Strategies

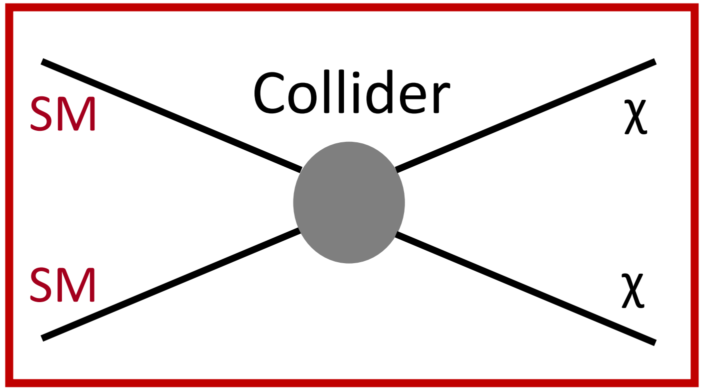
Complementarity between different types of experiments:

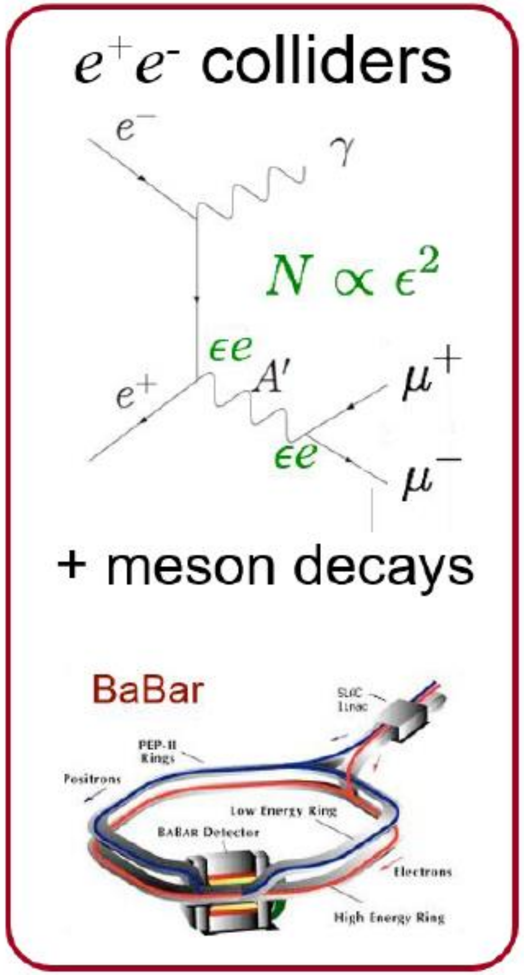


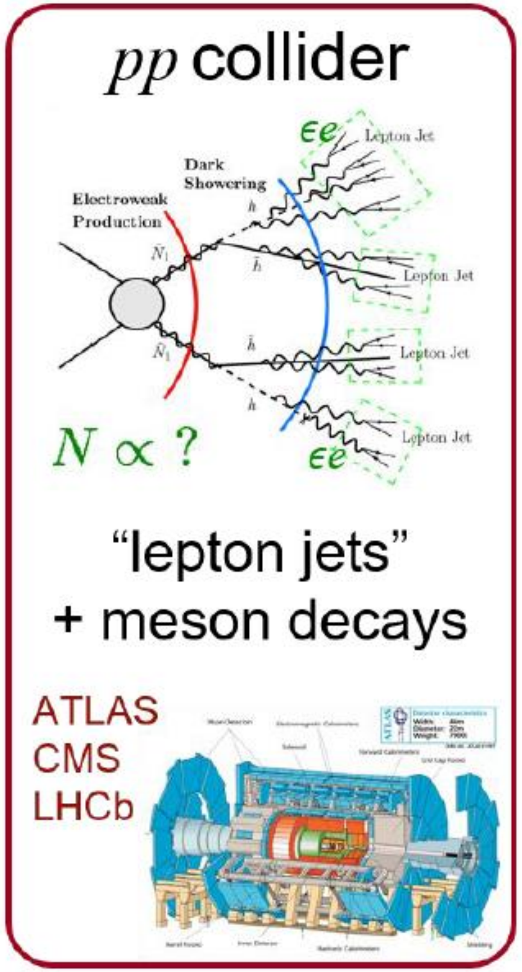




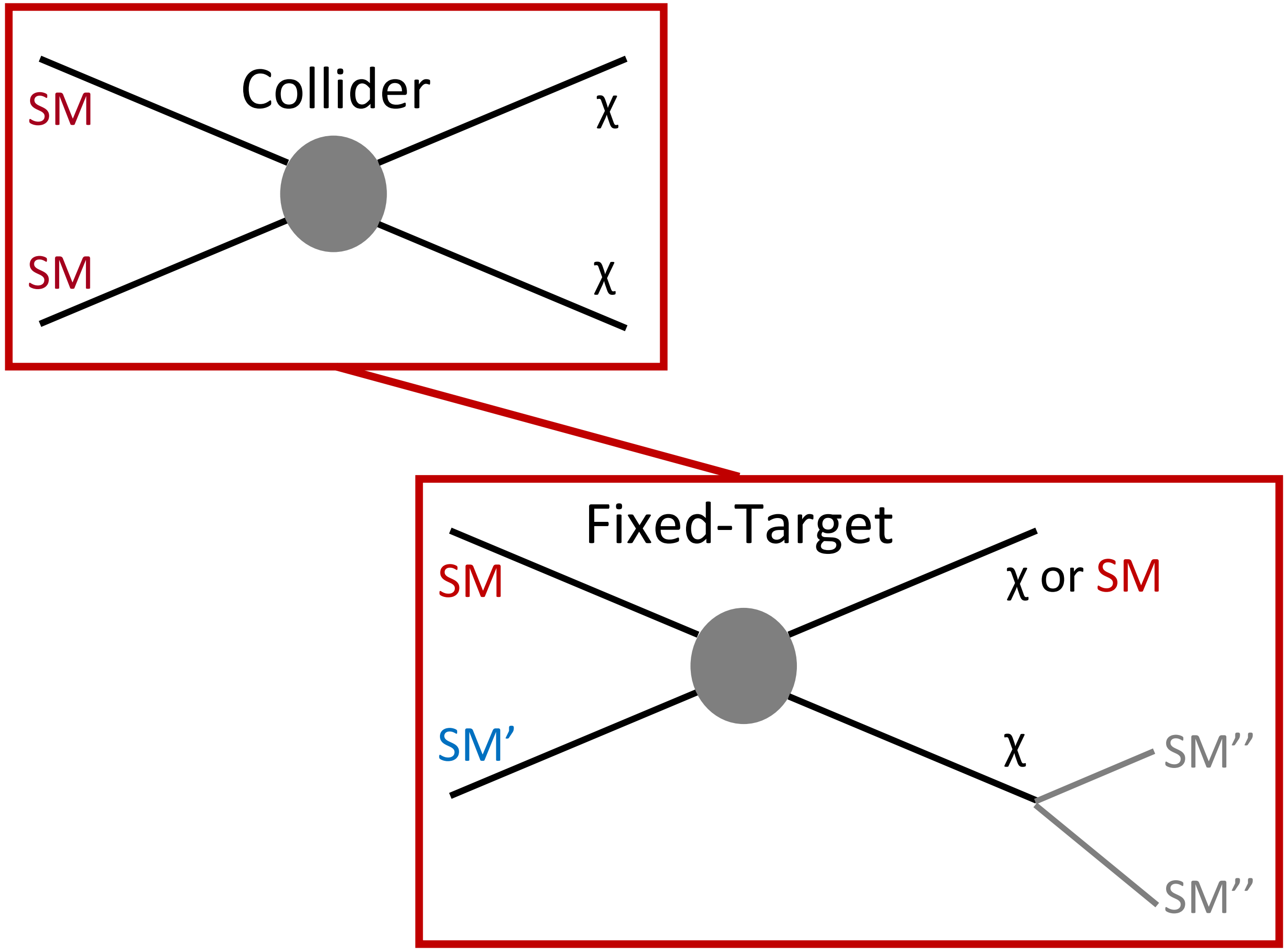
Dark Sector Search Strategies





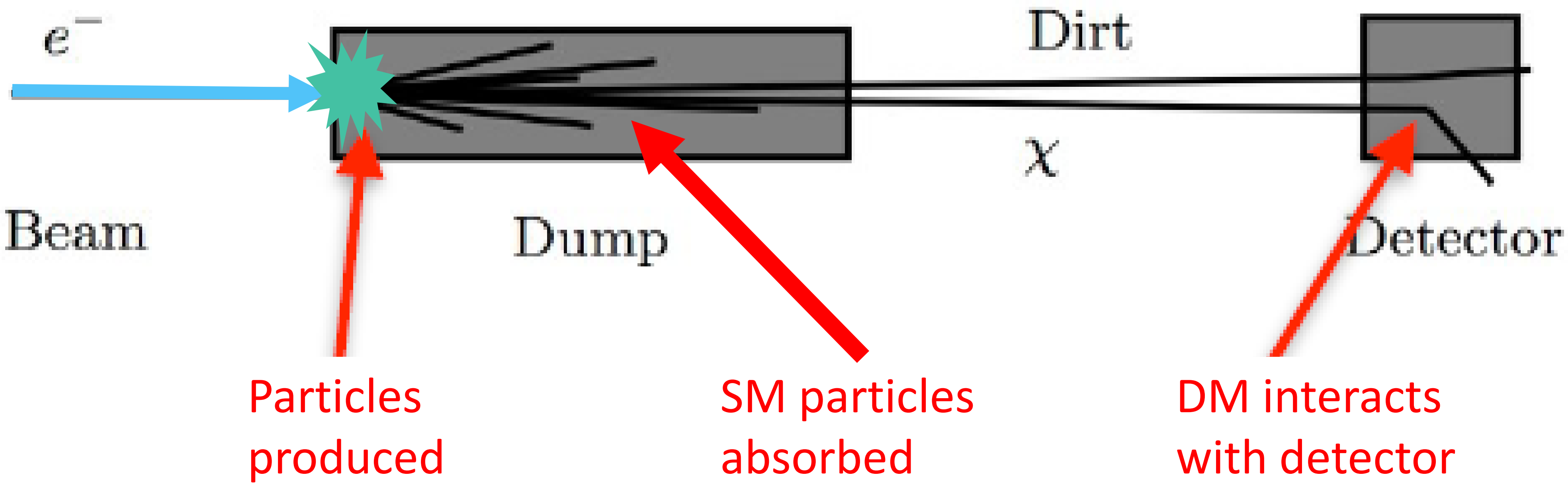


Dark Sector Search Strategies



Dark Sector Search Strategies

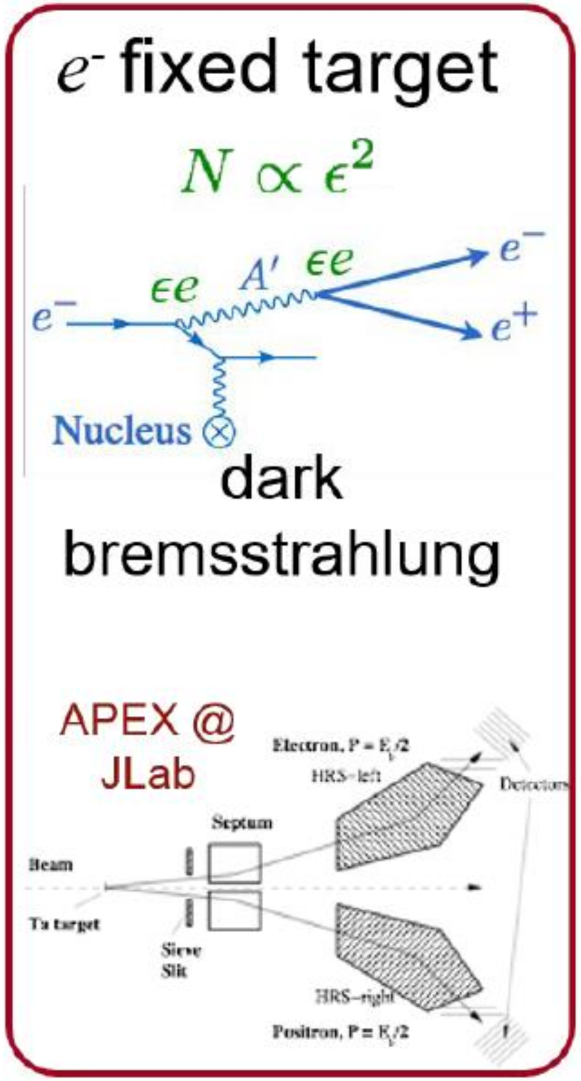
Simplest fixed-target experiment: “beam dump”

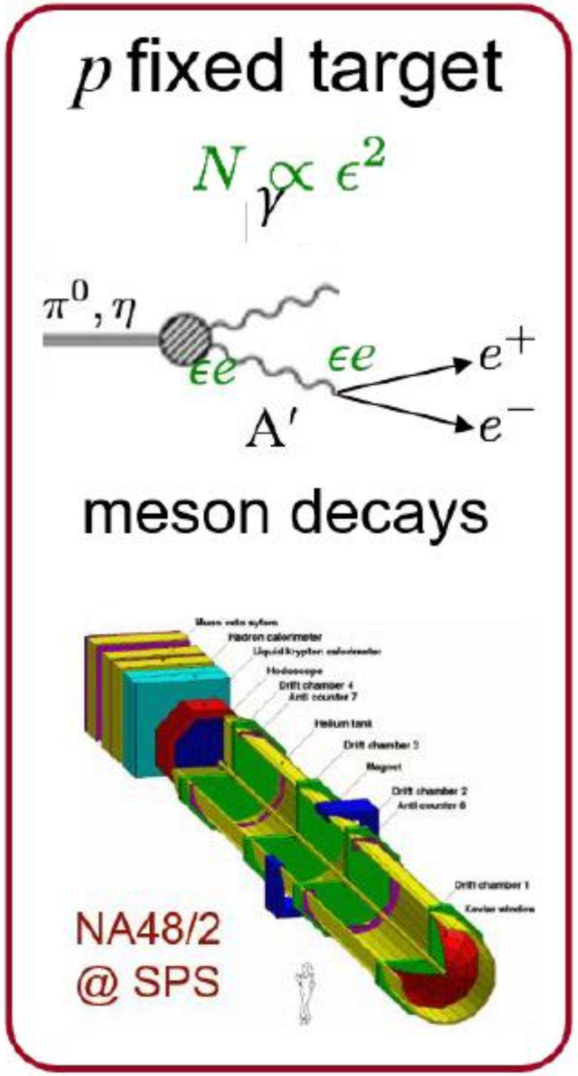


- When particle beam collides with fixed target, DM produced in association with visible SM particles
- Only the DM reaches detector behind “beam dump” and dirt

Dark Photon Search Strategies

- More complex setups target final-state dilepton signatures for *A′* as lowest-mass dark state
- *A′* lifetime varies with mass and ε



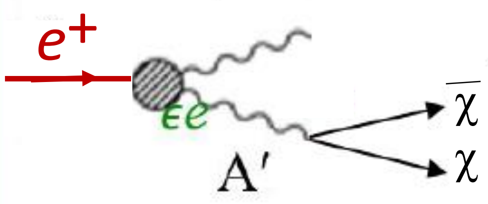


Dark Photon Search Strategies

Even more sophisticated: also look for signatures of invisible A' decay products in final state, where other dark sector particles are lighter than A'

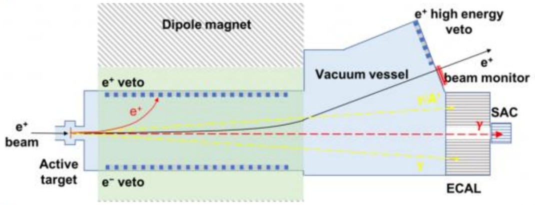
e^+ fixed target

Missing Energy



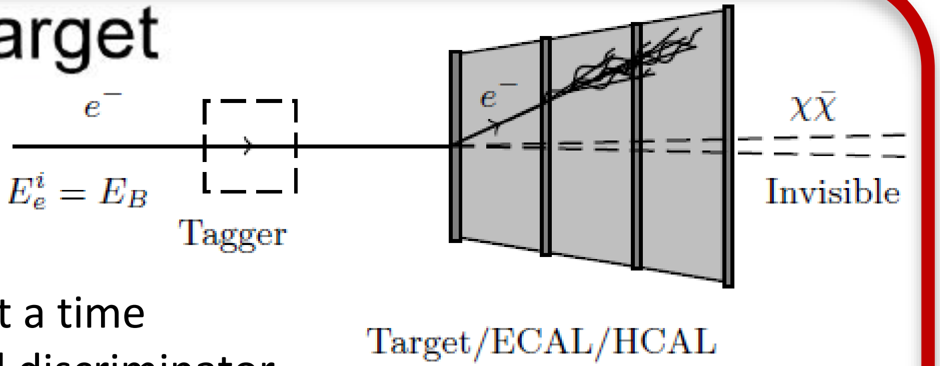
SM-dark photon pair production

PADME @ INFN



e^- fixed target

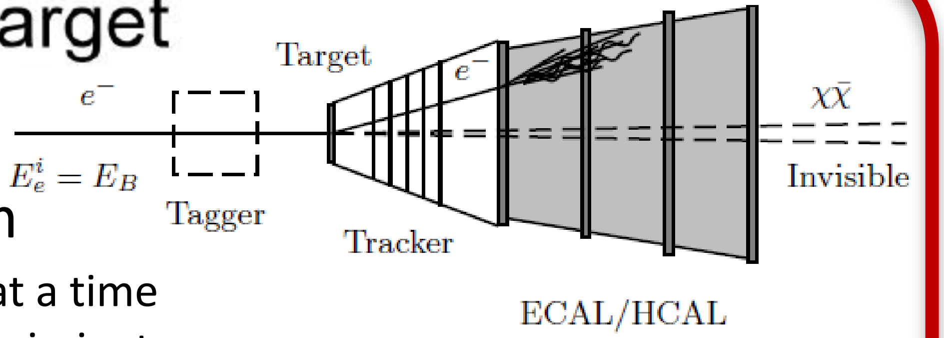
Missing Energy



One electron at a time
Only one signal discriminator
Insensitive to nature of interactions
Challenging backgrounds

e^- fixed target

Missing Momentum



One electron at a time
Two signal discriminators
Sensitive to A' mass
“Zero-background”

Fixed Target Dark Sector Search Experiments

- Re-interpreted electron beam-dump results
  - E141
  - E774
  - E137

- Proton
  - **NA48/2 & NA64**
  - TREK
  - SHIP
  - SBN
  - SeaQuest

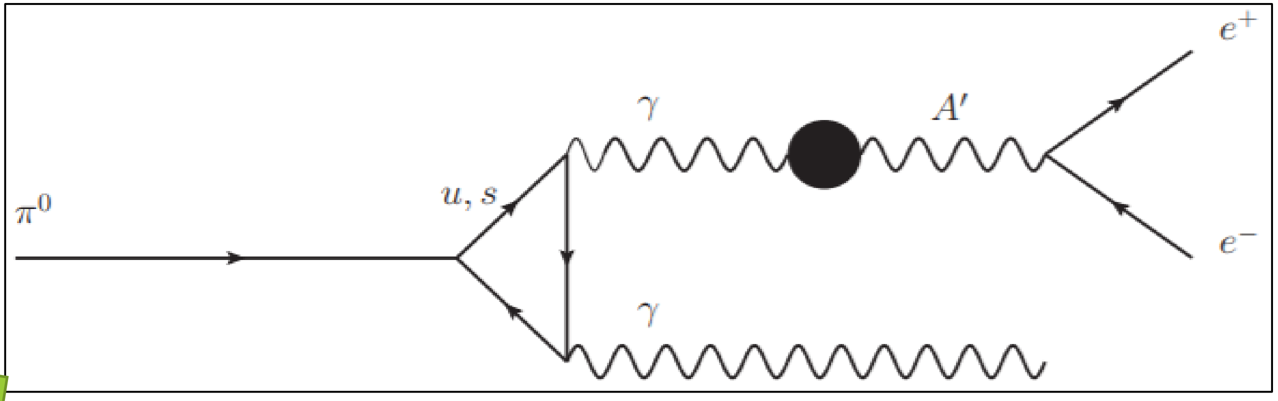
- Electron (specialized)
  - APEX
  - **Heavy Photon Search (HPS)**
  - **Light Dark Matter Search (LDMX)**
  - BDX
  - MAGIX
  - DarkLight

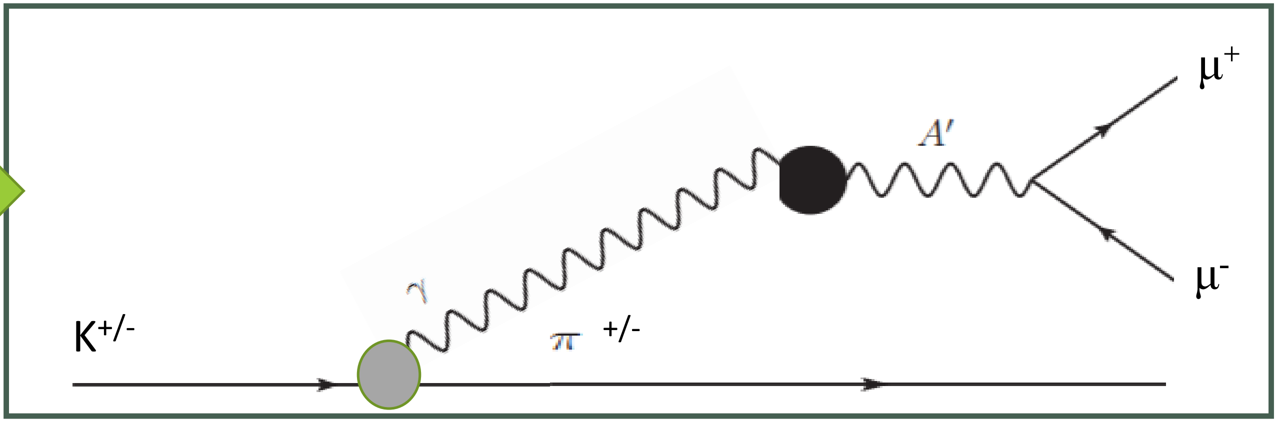
- Positron
  - **PADME**
  - VEPP3
  - MMAPS

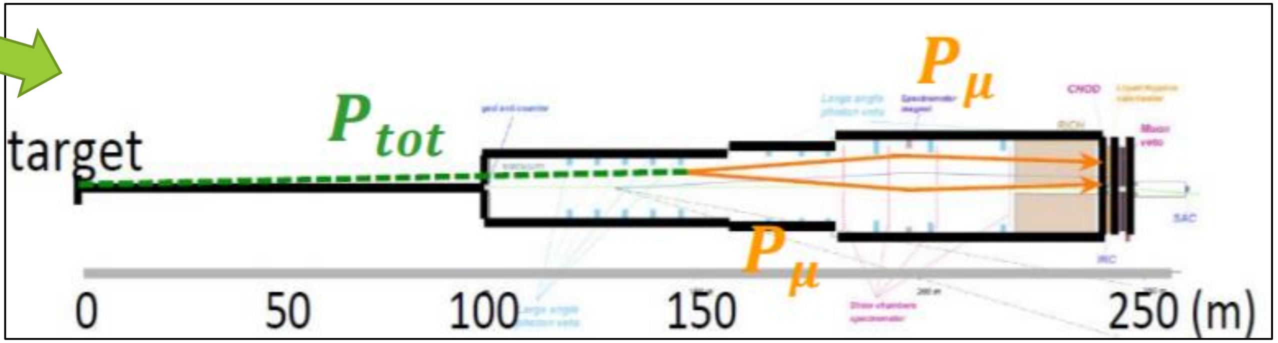
US Cosmic Visions: New Ideas in Dark Matter 2017
Community Report, arXiv:1707.04591

NA 48/2, NA62

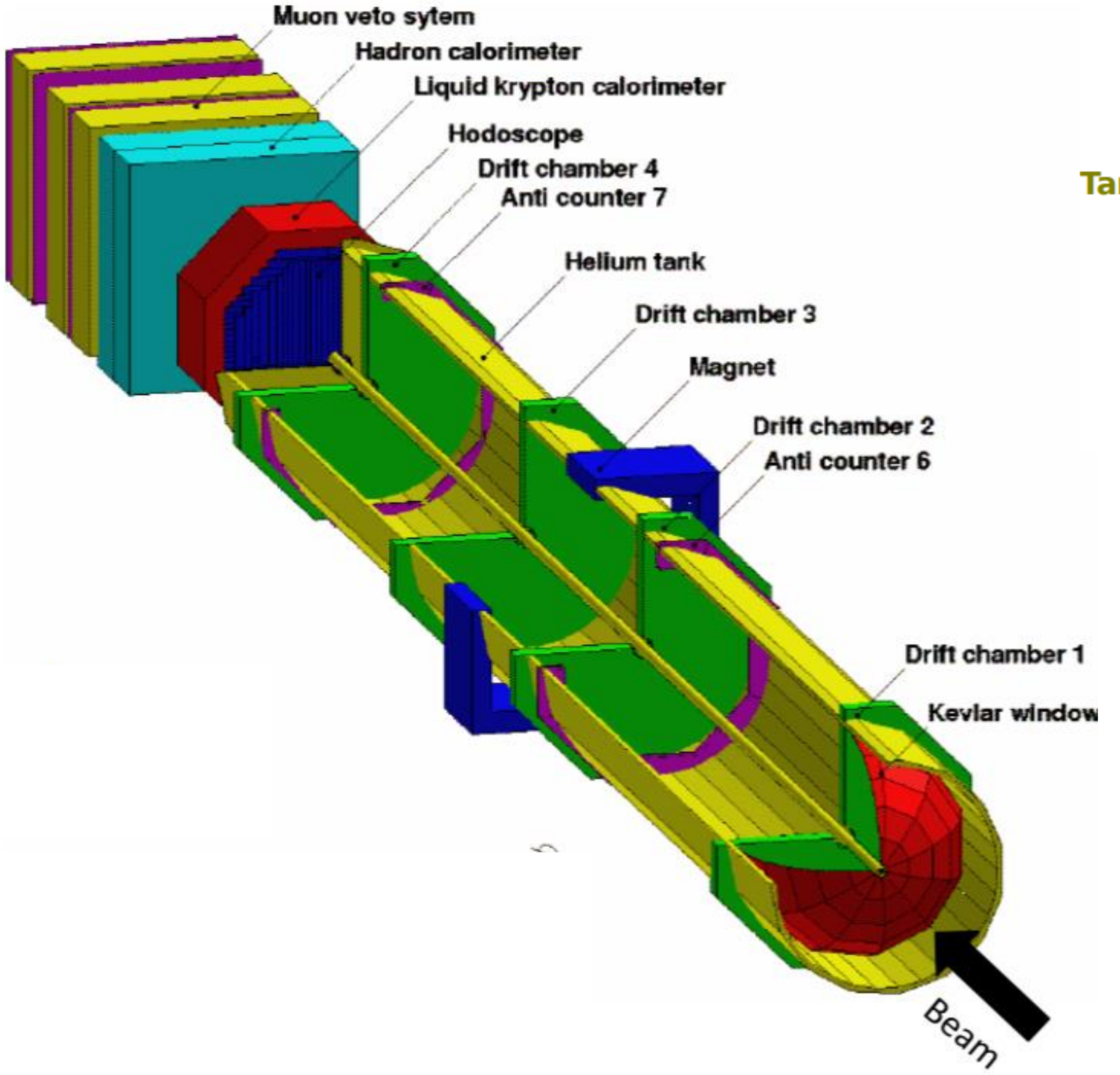
- Proton beam from SPS at CERN
- Protons on fixed target produce kaons
- Kaon decays (in-flight) produce pions
- NA48/2 :
  - Resonance: $\pi^0 \to \gamma\ (A' \to e^+ e^-)$
  - Resonance: $K^{+/-} \to \pi^{+/-}\ (A' \to \mu^+ \mu^-)$
- NA62 :
  - Resonance: $\pi^0 \to \gamma\ (A' \to e^+ e^-)$
  - Beam-dump: long-lived $A' \to \mu^+ \mu^-$





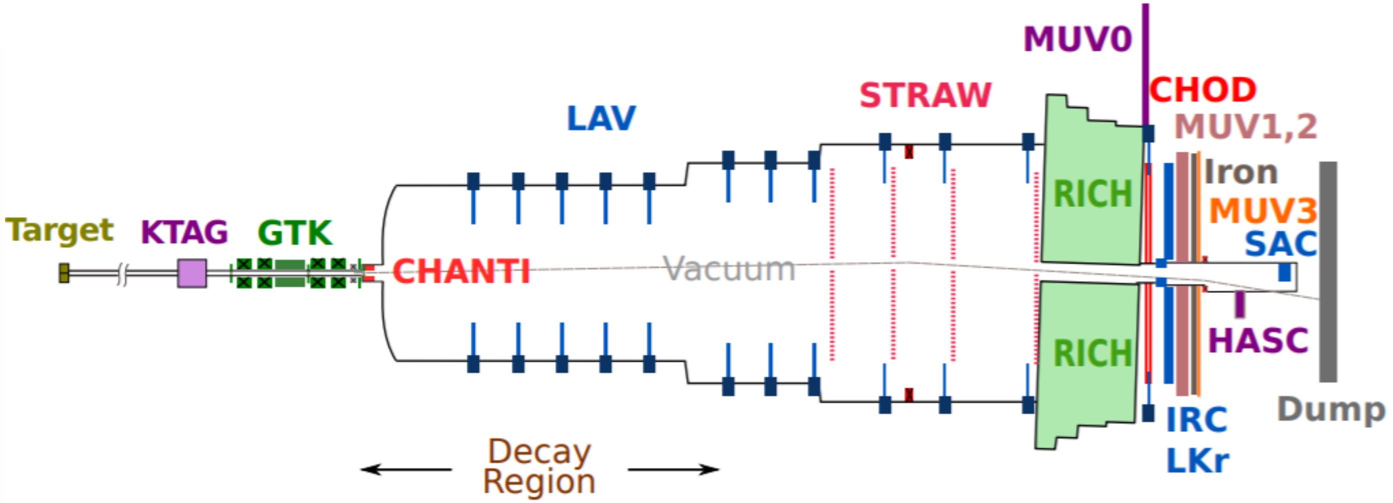


NA 48/2



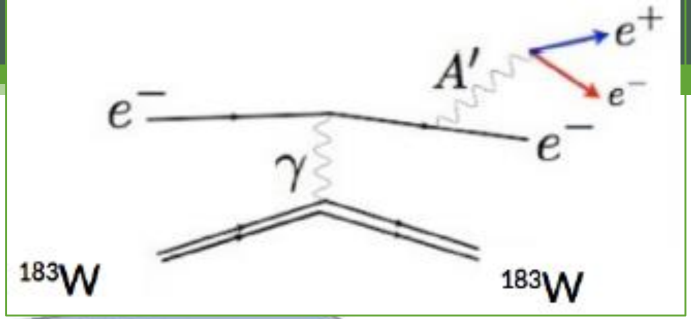
Muon veto sytem
Hadron calorimeter
Liquid krypton calorimeter
Hodoscope
Drift chamber 4
Anti counter 7
Helium tank
Drift chamber 3
Magnet
Drift chamber 2
Anti counter 6
Drift chamber 1
Kevlar window
Beam

NA62



MUV0
CHOD
MUV1,2
STRAW
LAV
Iron
MUV3
SAC
Target
KTAG
GTK
CHANTI
Vacuum
RICH
RICH
HASC
Dump
IRC
LKr
Decay
Region

Heavy Photon Search

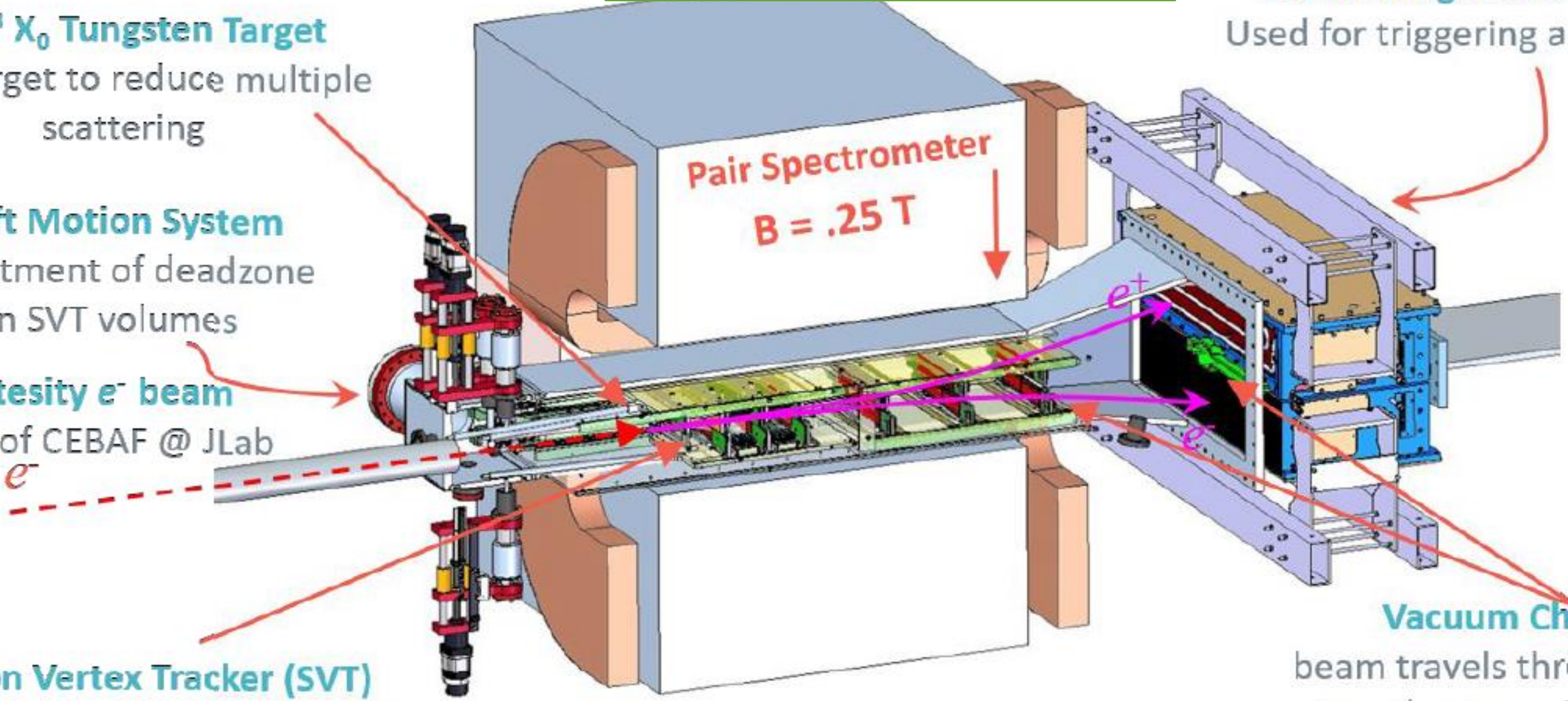


~10^{-3} X_0 Tungsten Target
Thin target to reduce multiple scattering

Linear Shift Motion System
Allows adjustment of deadzone between SVT volumes

High intesity e^- beam
Courtesy of CEBAF @ JLab

Silicon Vertex Tracker (SVT)
Split into two volumes to avoid intense flux of scattered beam electrons. Measures momentum and vertex precisely.



Electromagnetic Calorimeter
Used for triggering and particle ID

Vacuum Chambers
beam travels through vacuum in order to avoid beam-gas interactions

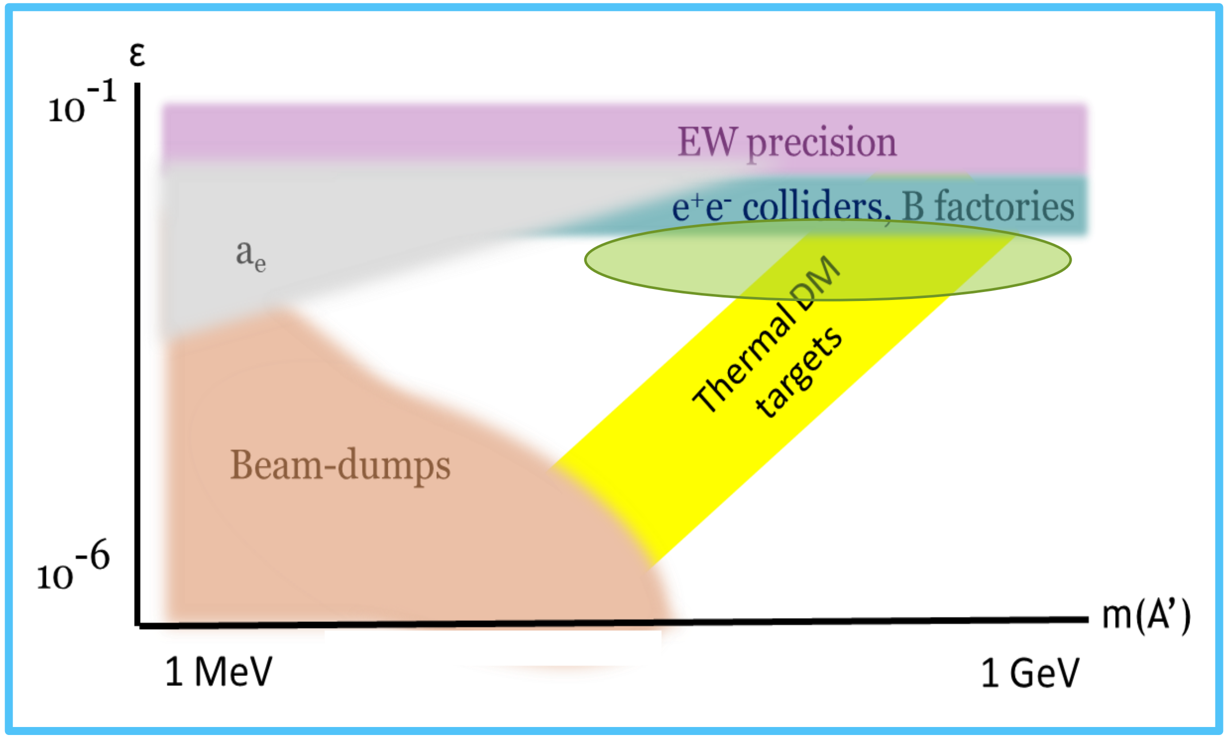
SVT + ECal DAQ capable of 50 kHz

Installed within the Hall B alcove at Jefferson Lab downstream of the CLAS12 detector

arXiv:1505.02025

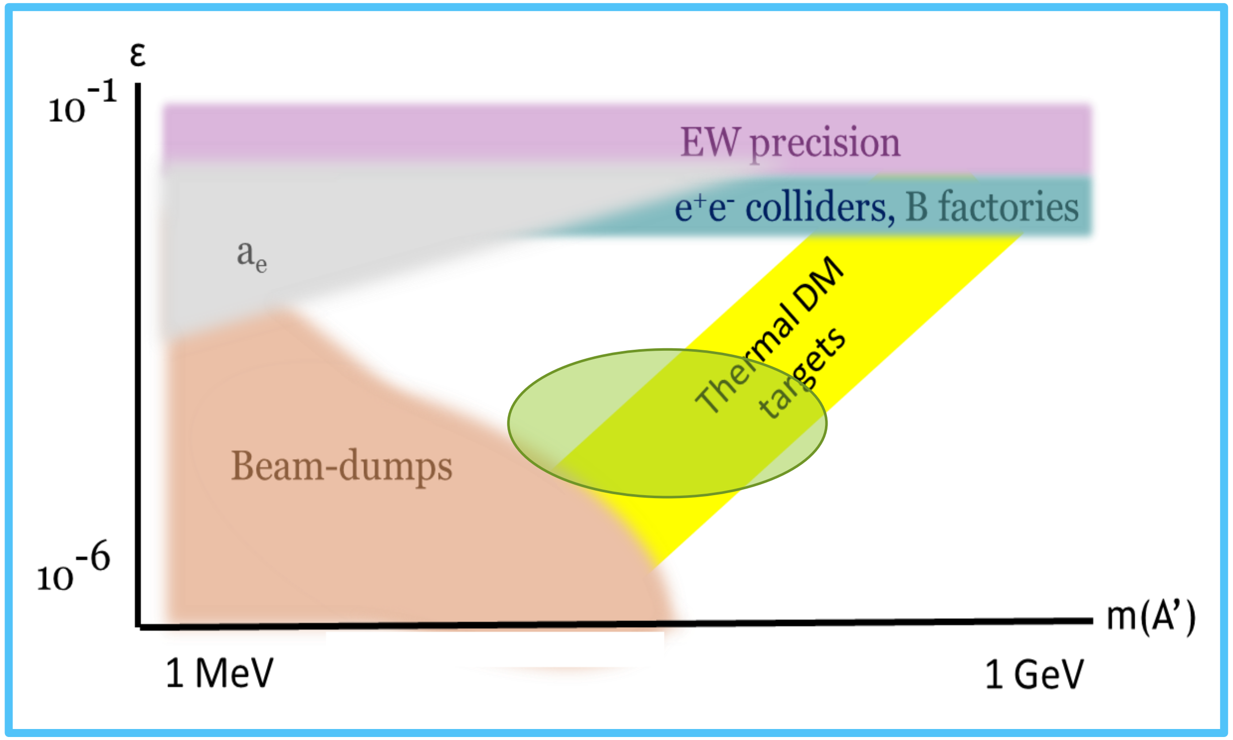
Heavy Photon Search

- Engineering Run (2015-2016) successful proof-of-concept; full run is starting this month!



Resonance Search

- Prompt *A'*
- Excess in $m(e^+e^-)$ above large QED bg



Displaced Vertex Search

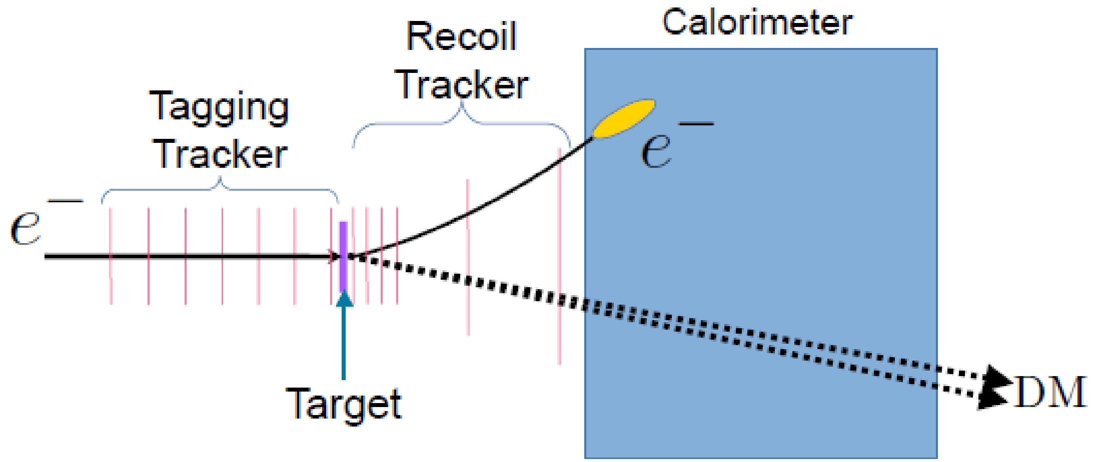
- Longer-lived *A'*
- Lower background, smaller signal

Light Dark Matter Experiment

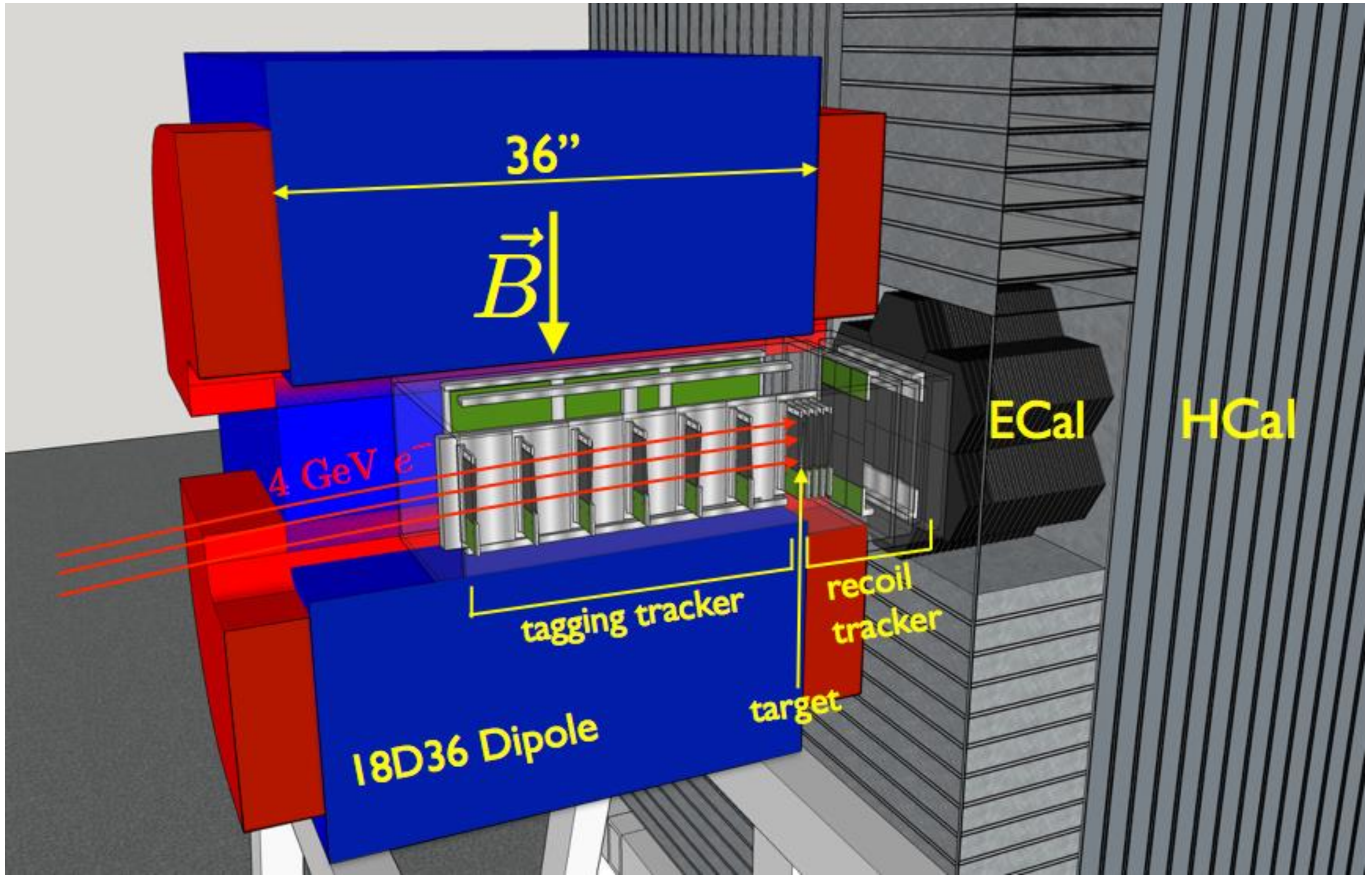
So far, have only looked for the visible A' decay products. What about the invisibles?

Light Dark Matter Experiment (LDMX): Proposal for "zero-background" missing momentum experiment

Could be hosted at SLAC, Jefferson Lab, or CERN

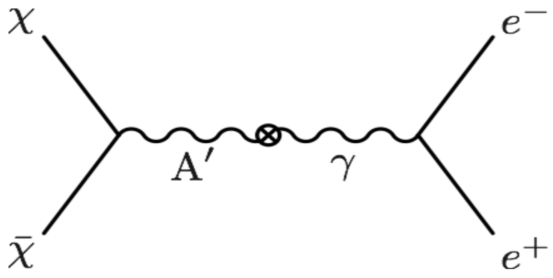


arXiv:1808.05219



Light Dark Matter Experiment

Parameterize limits in terms of y:

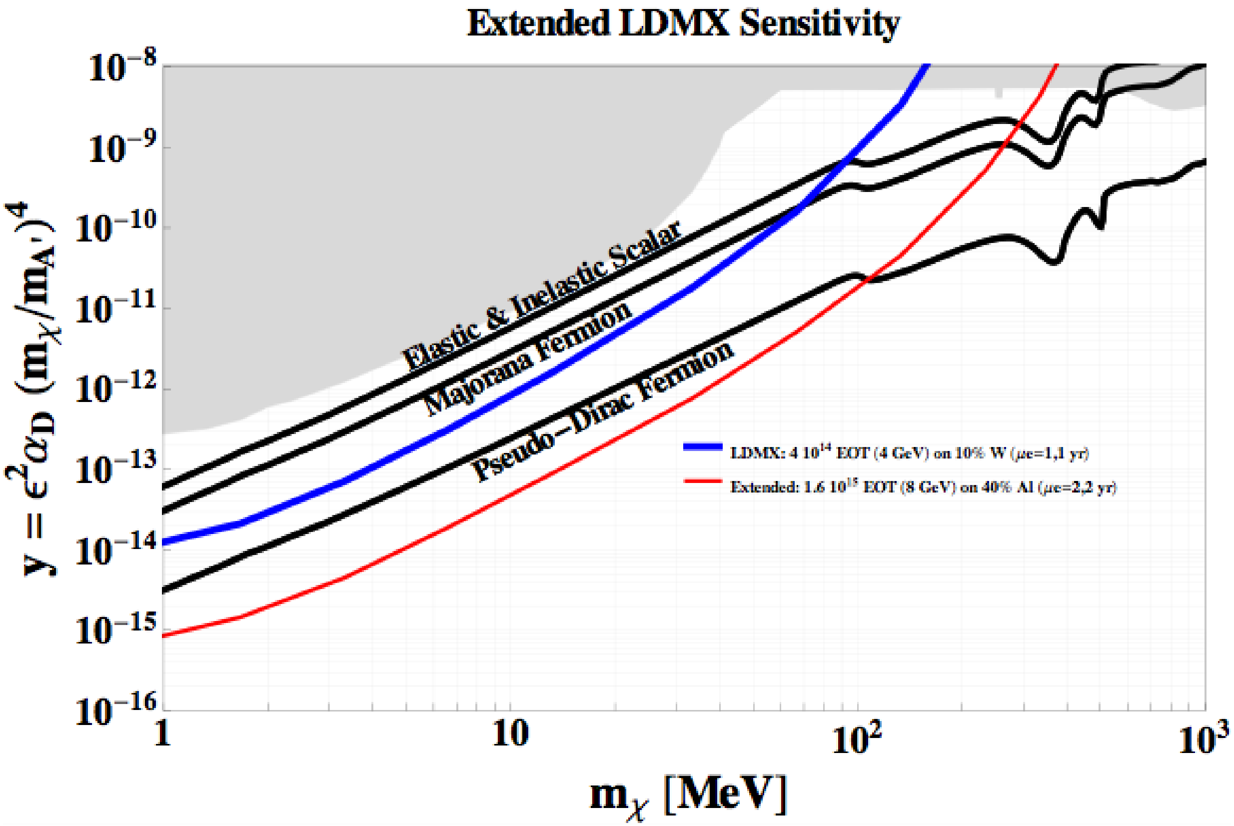


$$\sigma v \propto \epsilon^2 \alpha_D \frac{m_\chi^2}{m_{A'}^4} \equiv \frac{y}{m_\chi^2}$$

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

"Thermal limits" depend upon nature of χ

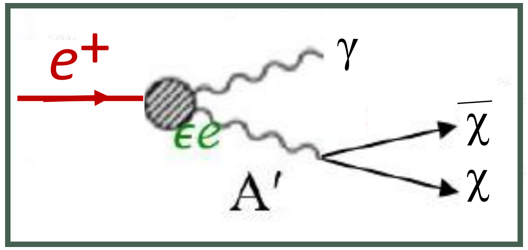
- Scalar (elastic, inelastic)
- Fermion (Majorana, pseudo-Dirac, Dirac)

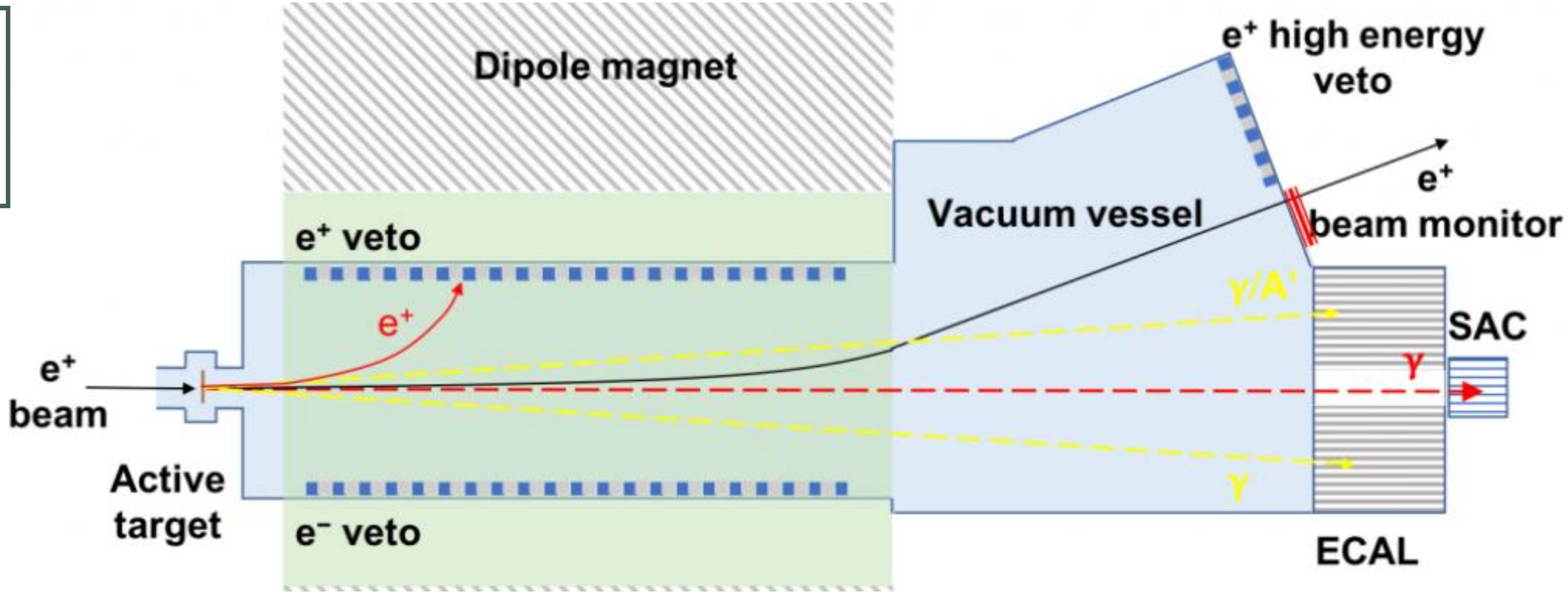


arXiv:1808.05219

Positron Annihilation into Dark Matter Experiment

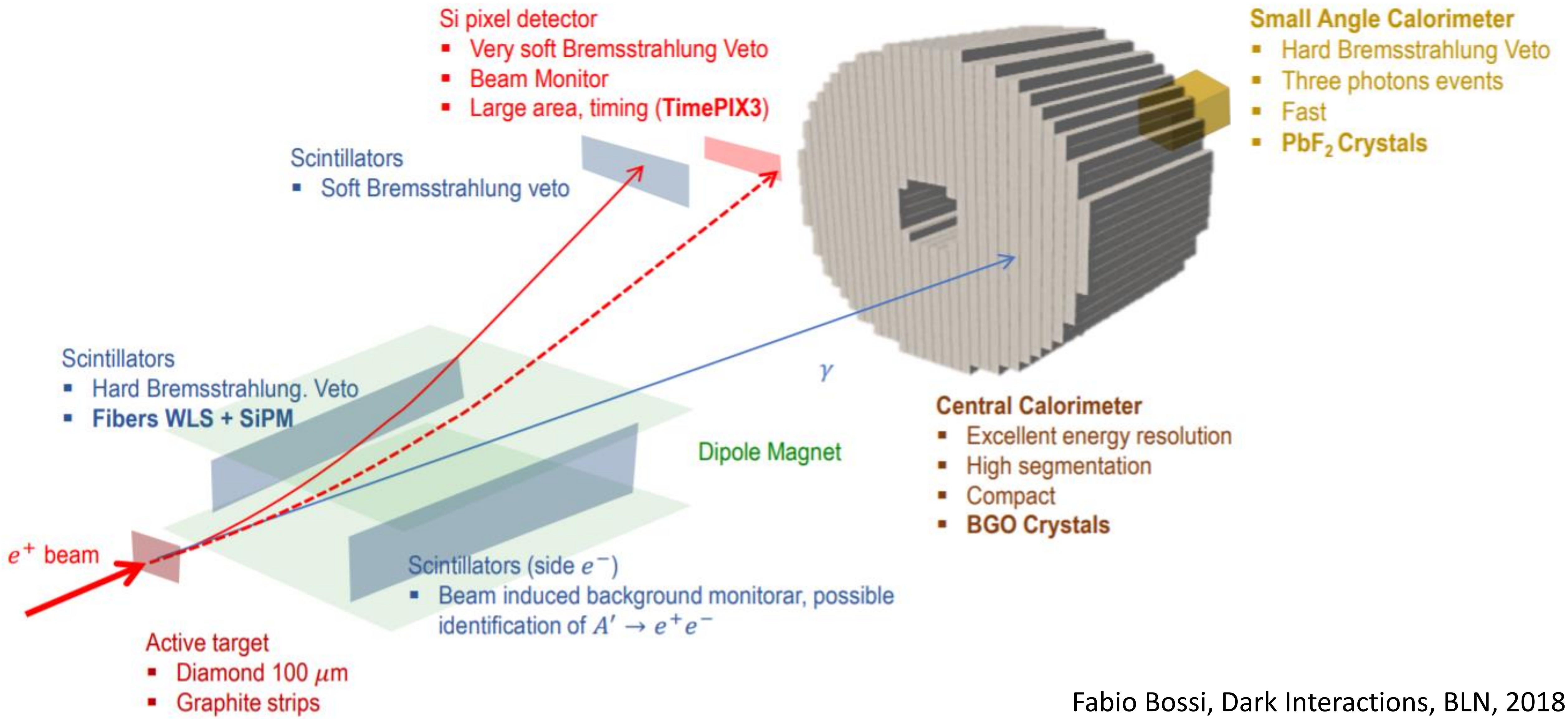
PADME @ Laboratori Nazionali di Frascati of INFN: positron-on-target collisions at DAΦNE Beam Test Facility



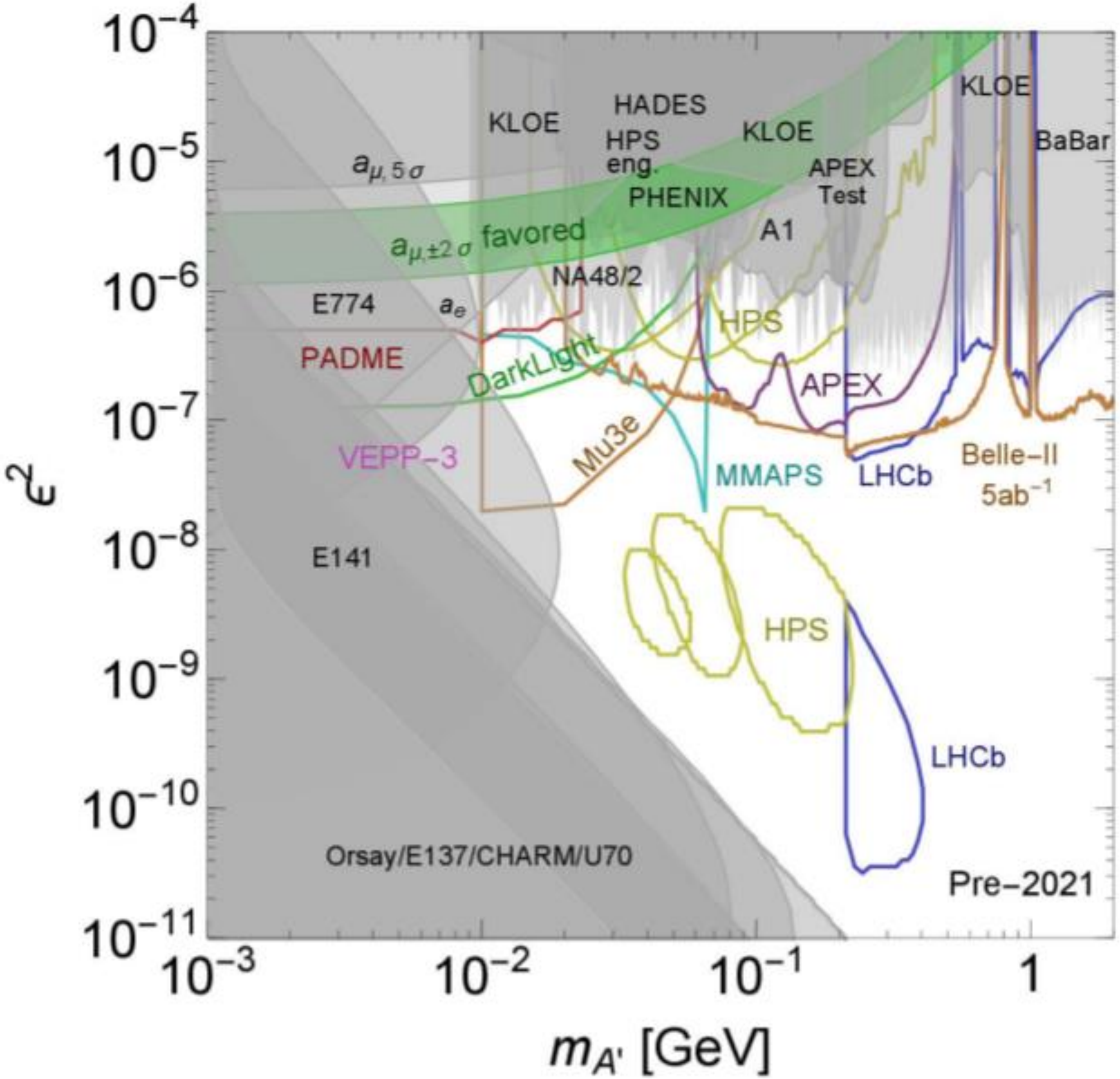


- Search for peak in the missing energy distribution of incoming e^+ vs outgoing γ
- Detector was fully installed in Sept

Positron Annihilation into Dark Matter Experiment



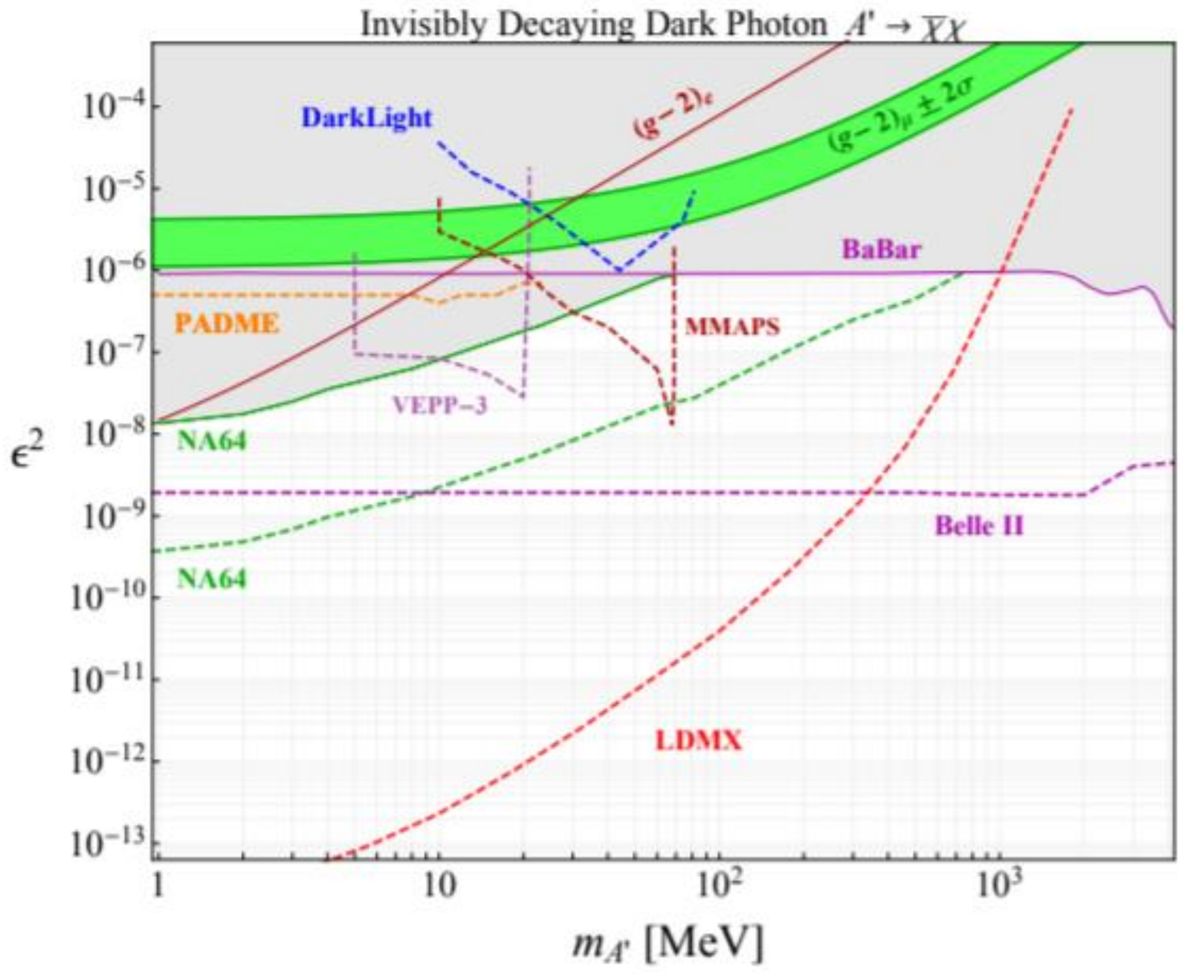
Constraints on Visible Decays of A’

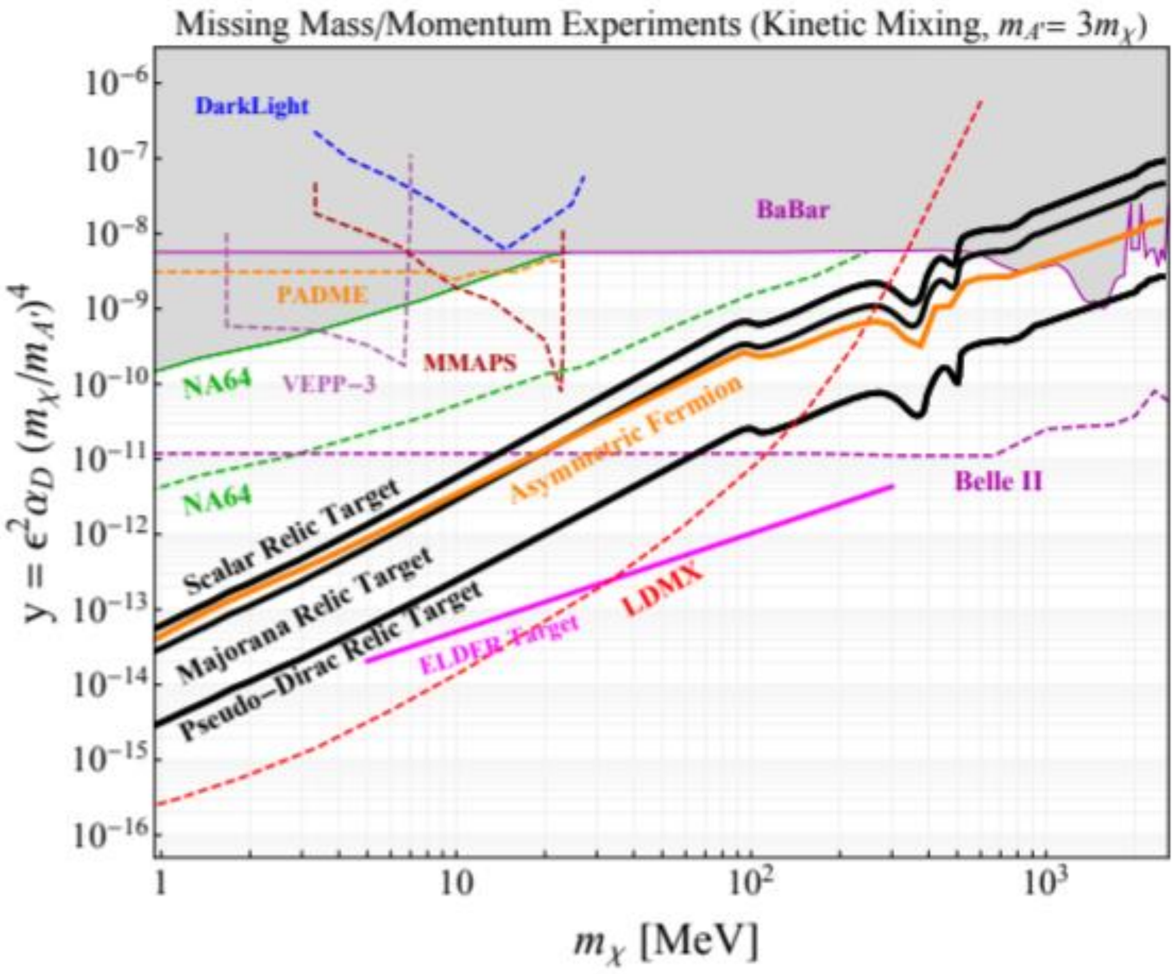


- Existing limits in gray
- Projected limits from experiments planned for before 2021 in color

US Cosmic Visions: New Ideas in Dark Matter 2017 Community Report, arXiv:1707.04591

Constraints on Invisible Decays of A'





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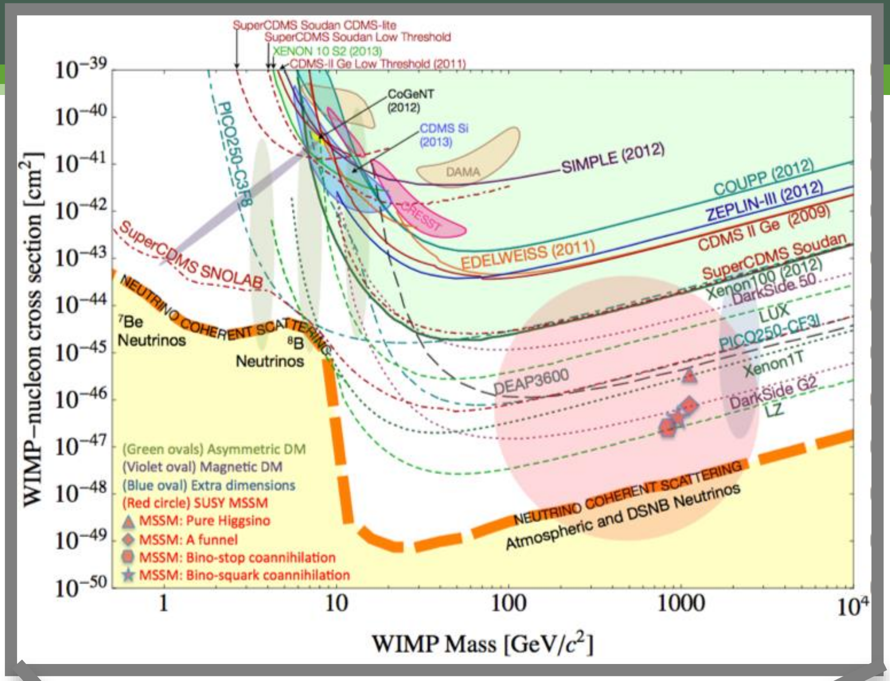
Conclusions

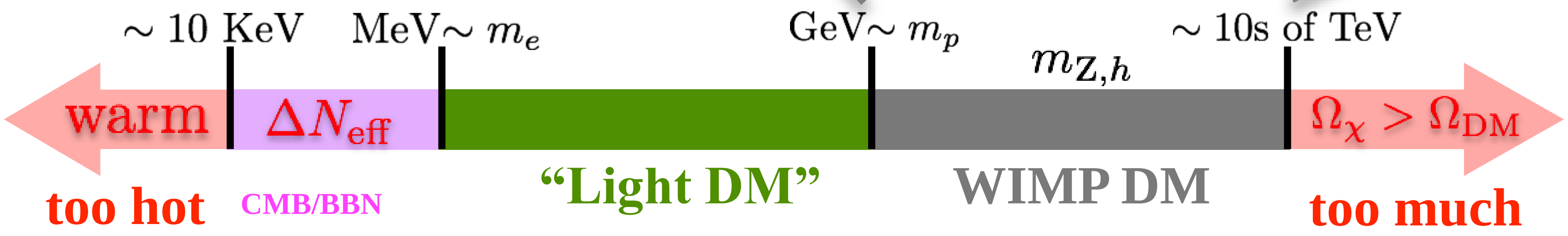
- Beyond WIMPs, light thermal relic DM is simple and well-motivated, requiring a new light mediator (~MeV-GeV)
- In both “visible” and “invisible” decay searches for dark photons, much of parameter space is still unconstrained
- Fixed-target experiments (proton, electron, and positron) play a key role now and in the future
- Diverse ongoing program of small-to-medium scale experiments

Additional Slides

Dark Sector Search Motivations

- "Thermal Relic" Weakly Interacting Massive Particles: seemingly the simplest scenario
- But haven't shown up in mass range where we most expected them!





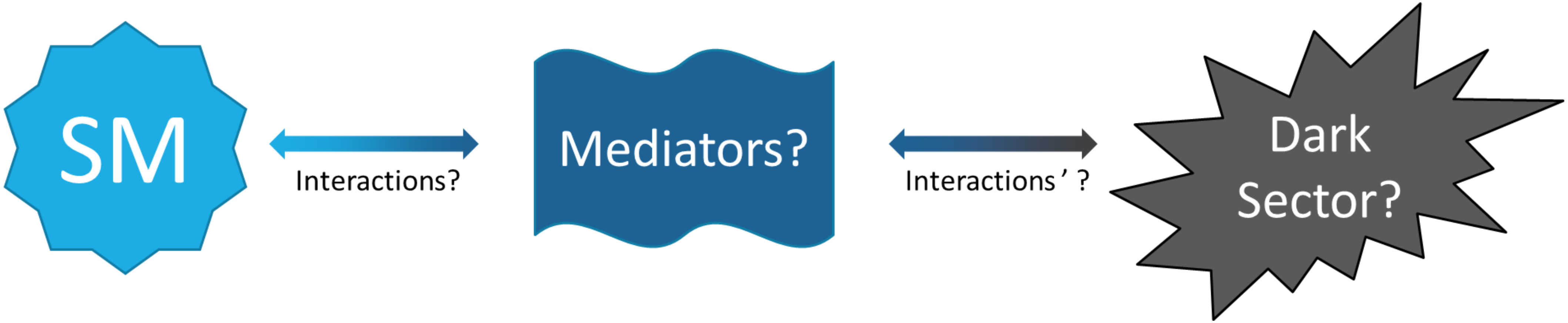
- Thermal Relic DM actually works fine at least down to $2m_e$
- But "light DM" requires new, comparably low-mass mediators to achieve required annihilation cross-section for thermal relics

Dark Sector Search Motivations

The Standard Model is only ~5% of the universe.
It includes 3 forces.

Why should the ~25% that is Dark Matter be any simpler?
Dark Forces?

How would DM interact with the SM?
Mediator particles?



Dark Sector Search Motivations

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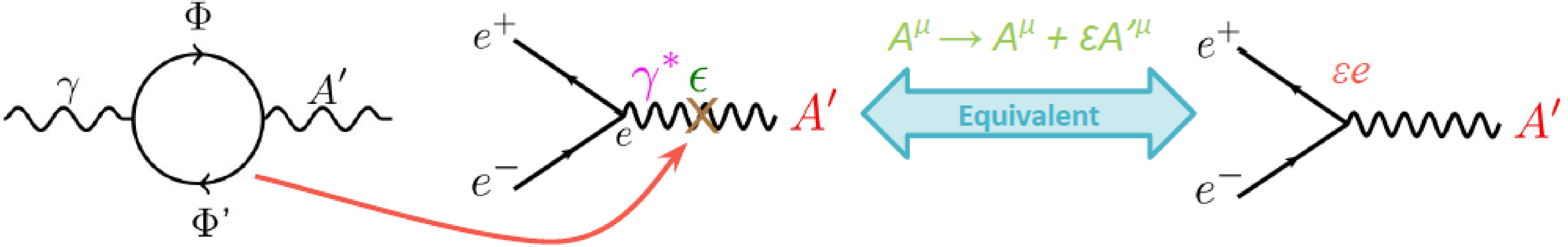
$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \boxed{\frac{\varepsilon}{2} F^{Y,\mu\nu} F'_{\mu\nu}} + \frac{1}{4} F'^{\mu\nu} F'_{\mu\nu} + m^2_{A'} A'^{\mu} A'_{\mu}$$

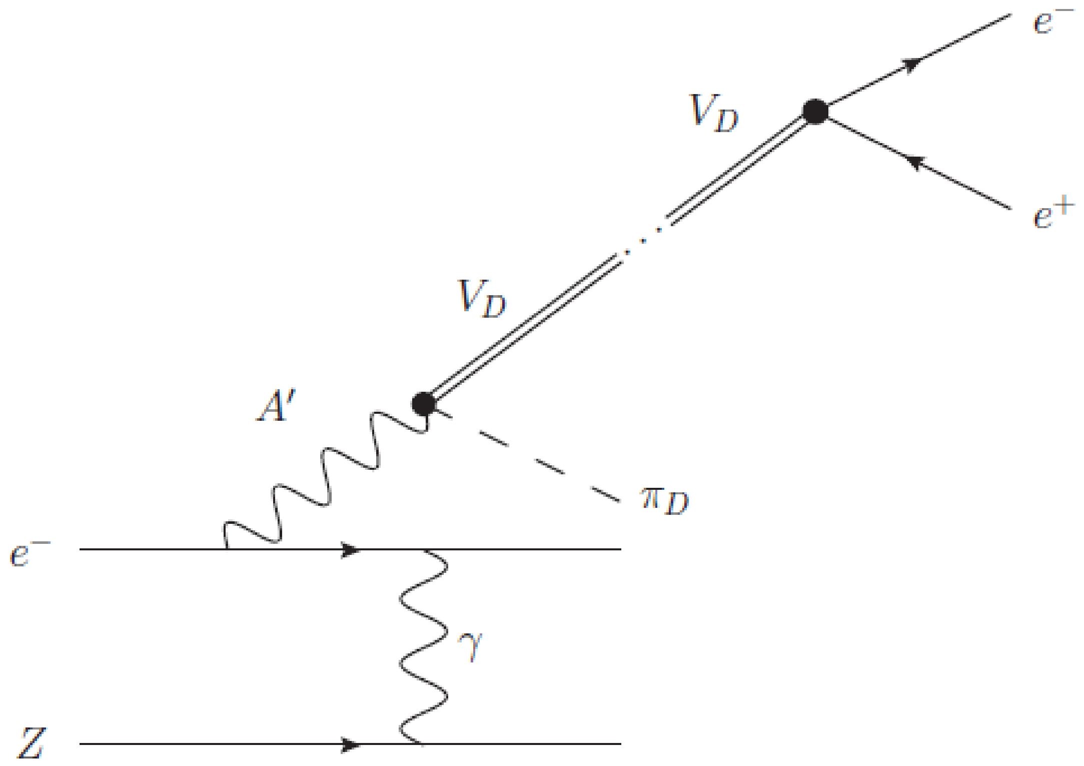
kinetic mixing $\longrightarrow$ induces weak coupling to electric charge



Dark Sector Search Motivations

- Hidden Valley: sector of dark particles, interacting amongst themselves, weakly coupled to SM through loops of TeV-scale particles or marginal operators
  - Lowest particle in Valley forced to decay to SM due to mass gap or symmetry
  - “Portal” couples both to SM and Valley operators

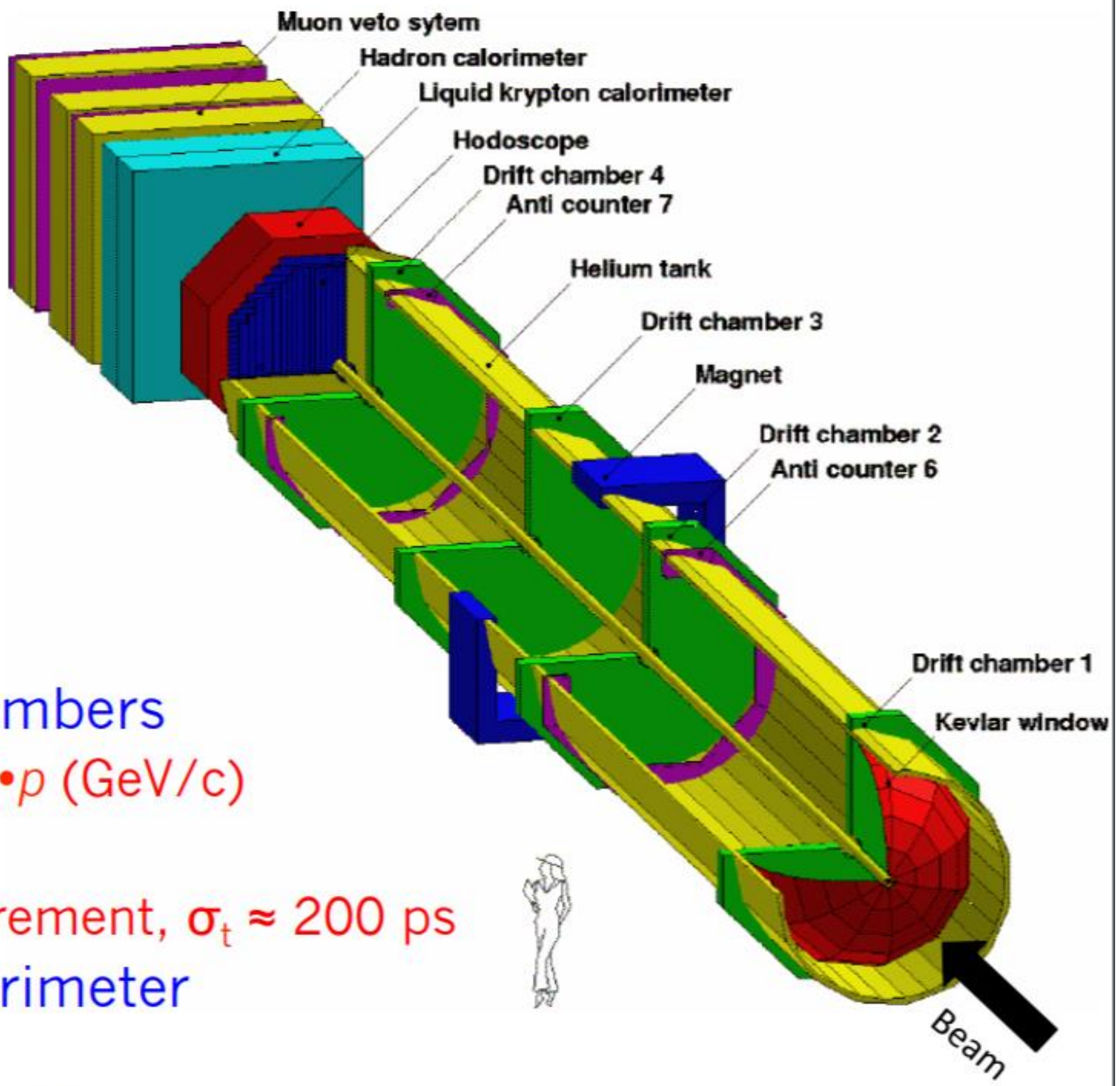
- “Bottom-up” astrophysics models with *A’*:
  - Inelastic DM
  - Exciting DM
  - Secluded DM
  - Self-Interacting Massive Particles



NA 48/2, NA62

NA48 setup:

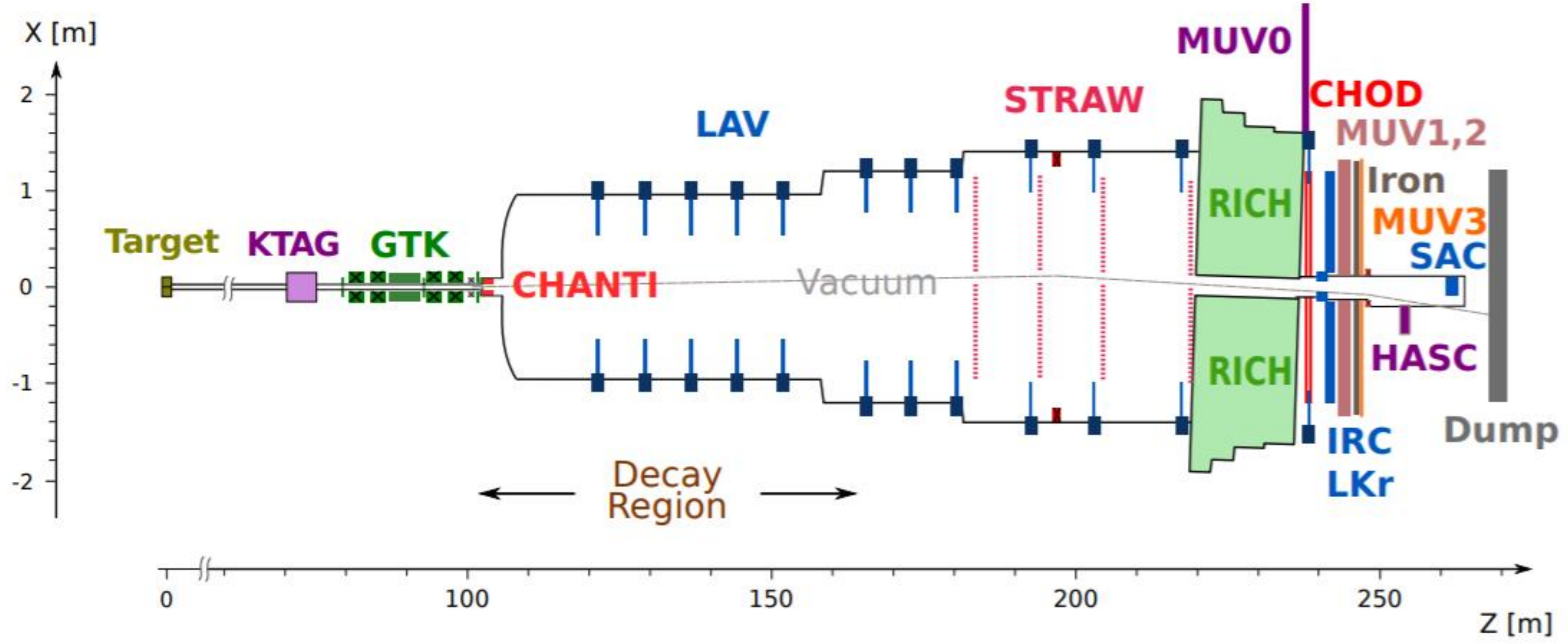
- Simultaneous $K^{\pm}$ beam
  - p_K=60 GeV/c
  - $\Delta p_K/p_K$=4%
  - Total $K^{\pm}$ decays: ~10^{11}
  - Main triggers:
    - Three-tracks
    - $K^{\pm} \rightarrow \pi^{\pm}\pi^0\pi^0$
- Major sub-detectors
  - Spectrometer, 4 drift chambers
    - σ_p/p = 1.02% + 0.044%•p (GeV/c)
  - Scintillator hodoscope
    - Fast trigger, time measurement, $\sigma_t \approx$ 200 ps
  - LKr electromagnetic calorimeter
    - σ_E/E = 1.4% @ 10 GeV
    - $\sigma_x = \sigma_y$ = 1.5mm @ 10 GeV



NA 48/2, NA62

NA62 setup:

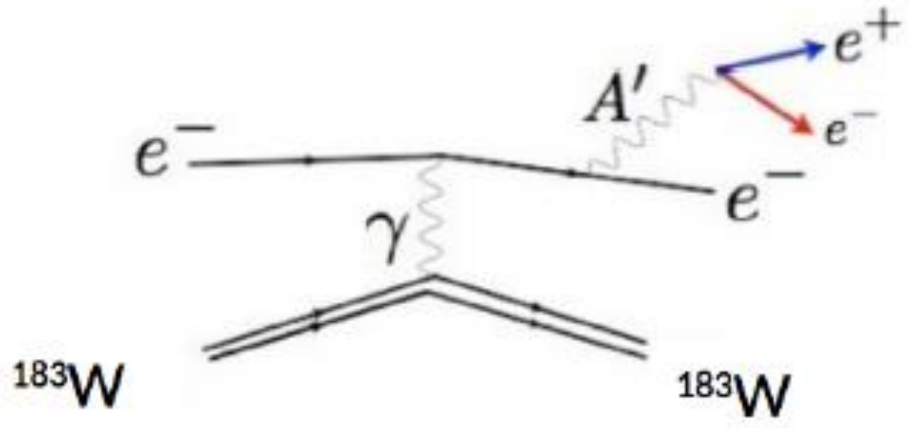
- K⁺ beam
  - 6% of the secondary beam
  - p_{Kaon} = 75 GeV/c
  - Δp_{K} = 1 GeV/c (RMS)
  - Total Kaon decays: ~10^{13}
- Many new sub-detectors compared to NA48
- Advanced trigger (FPGA based) and data acquisition systems



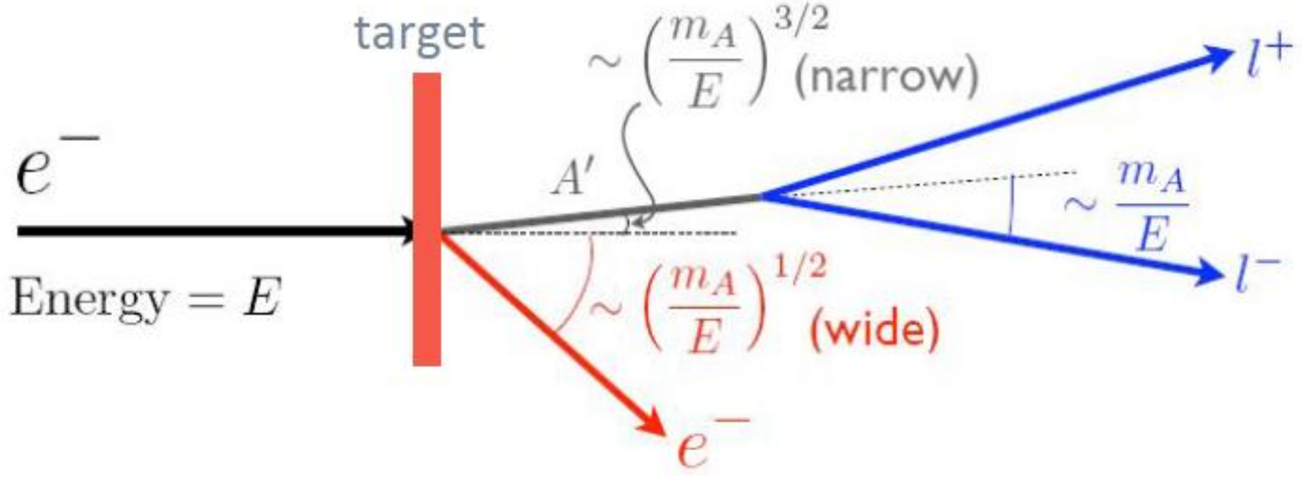
Heavy Photon Search

arXiv:1505.02025

- *A'* takes most of beam energy
- e^+e^- opening angle ~ $m_{A'}$ / E_{beam}



- Keys:
  - High intensity (luminosity)
  - Beam: use timing for background mitigation
  - Thin target: minimize scattering
  - Vacuum: eliminate secondaries
  - Magnetic field: spread e^+e^- pairs
  - Tracker: narrow displaced vertices
  - Electromagnetic Calorimeter: fast, high-rate e^+e^- triggering



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arXiv:1808.05219

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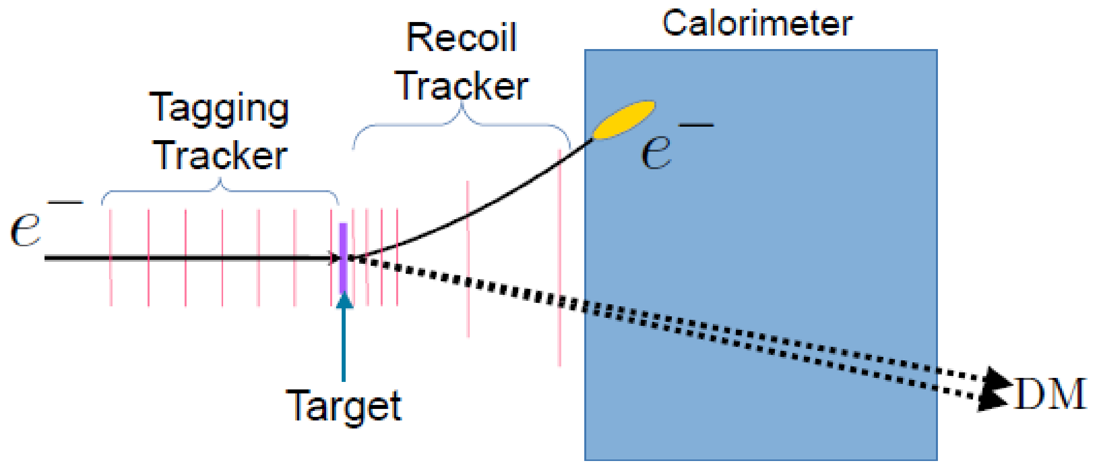
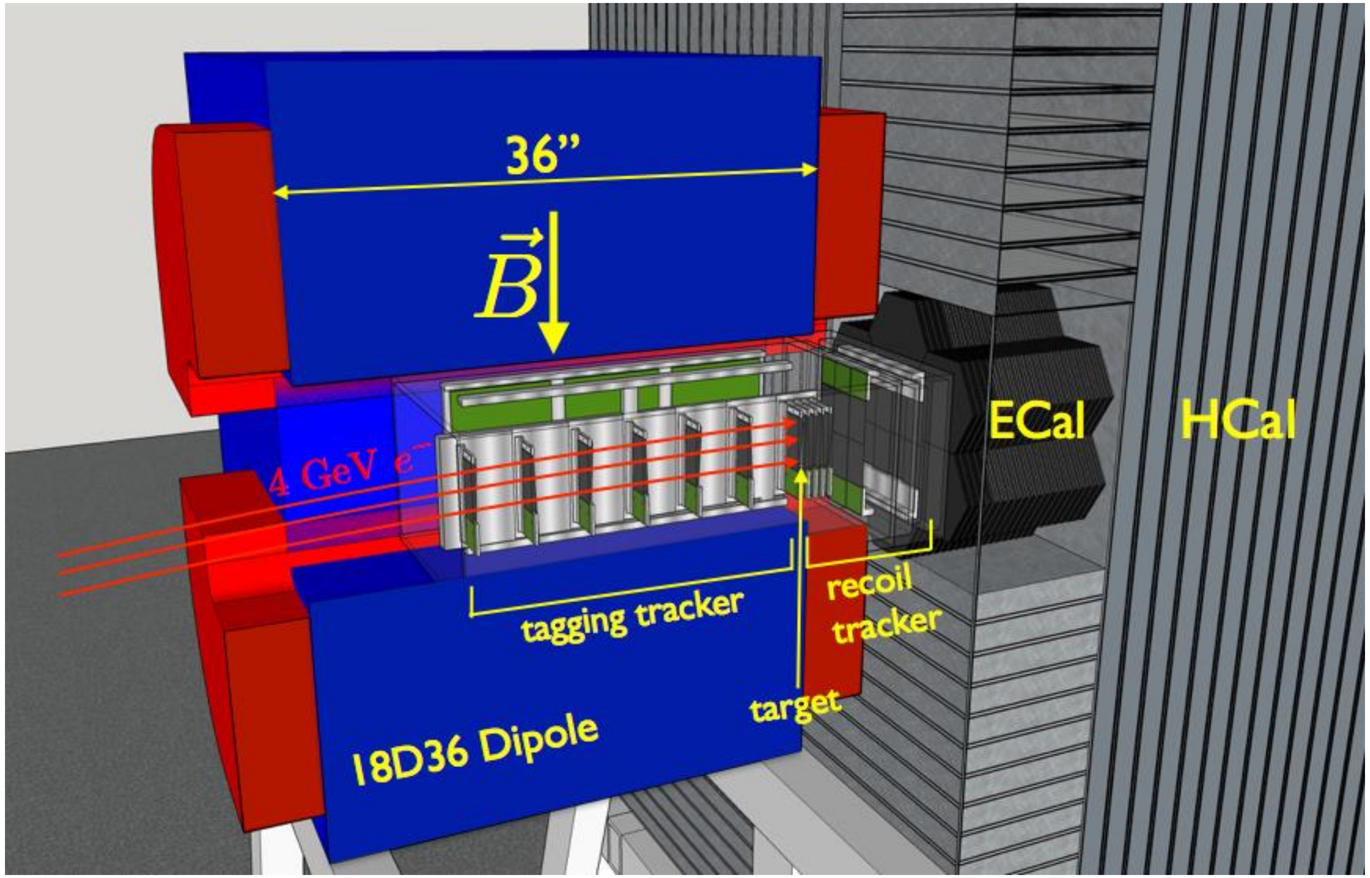
Light Dark Matter Experiment (LDMX): Proposal for "zero-background" missing momentum experiment

Could be hosted at SLAC, Jefferson Lab, or CERN

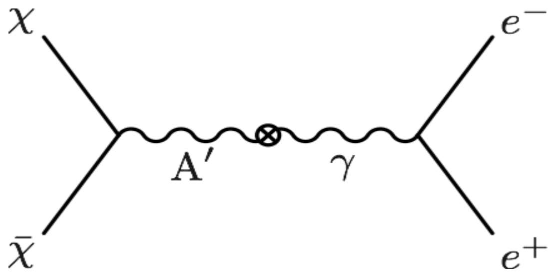


- Tagging tracker: track carrying beam energy, on expected trajectory
- Recoil tracker: single low-momentum track pointing back to tag
- Calorimeter: shower consistent with recoil track and no other activity



Light Dark Matter Experiment

Parameterize limits in terms of y:

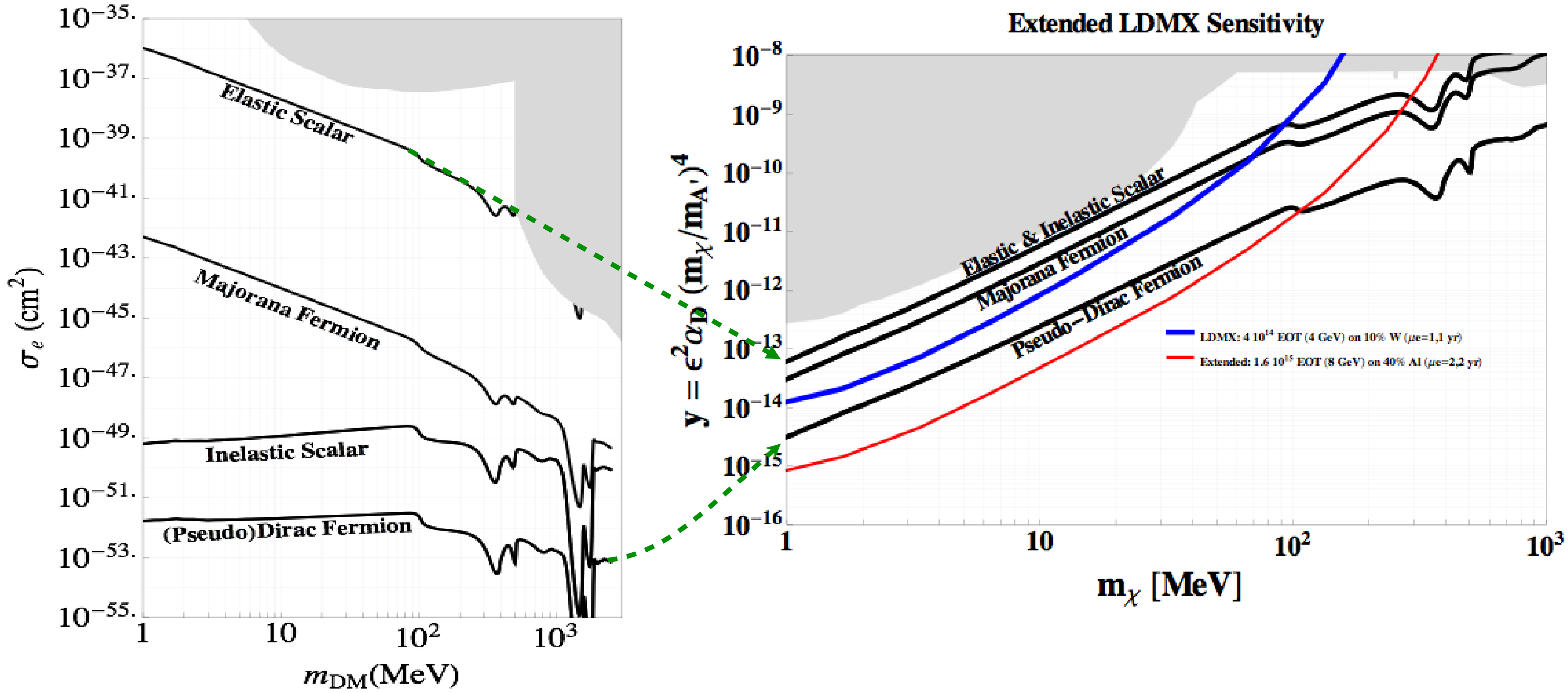


$$\sigma v \propto \epsilon^2 \alpha_D \frac{m_\chi^2}{m_{A'}^4} \equiv \frac{y}{m_\chi^2}$$

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

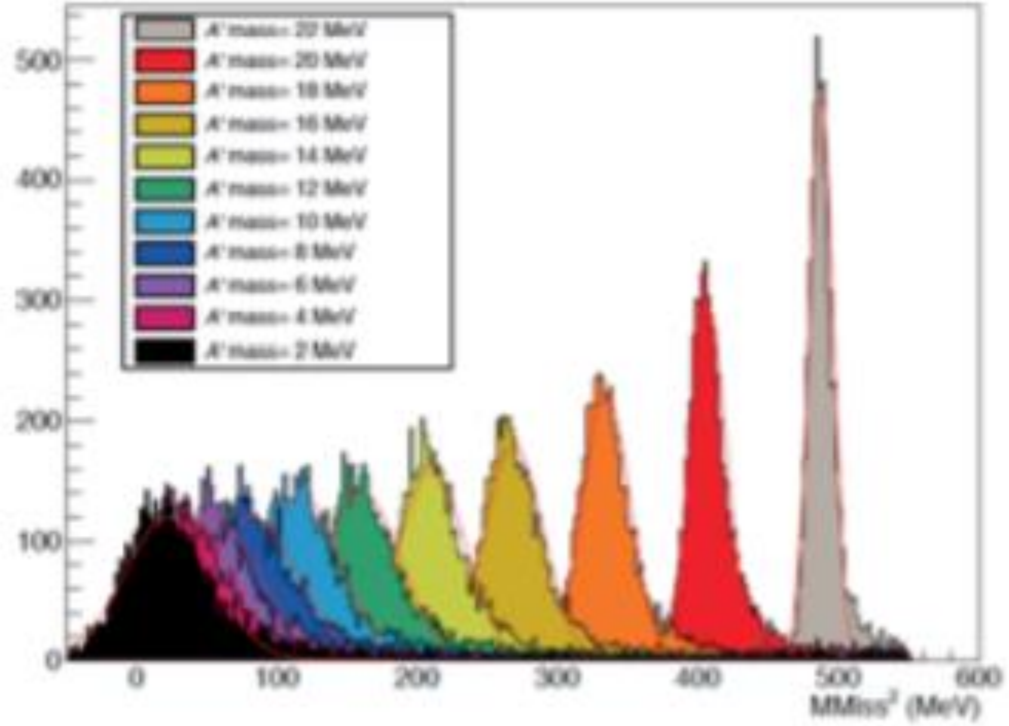
"Thermal limits" depend upon nature of χ

- Scalar (elastic, inelastic)
- Fermion (Majorana, pseudo-Dirac, Dirac)



Positron Annihilation into Dark Matter Experiment

- Search for peak in the missing energy distribution of incoming e^{+} vs outgoing γ
- Keys:
  - Target thickness & beam intensity determined by maximum sustainable pile-up
    - Distribution and rate of photons
    - Detector timing resolution
  - M_{miss} resolution given by
    - Spatial resolution (Moliére radius)
    - Energy resolution
    - Distance target-to-calorimeter
  - Acceptance determined by magnet configuration
  - Hole in central calorimeter because of SM bremsstrahlung limitation
  - Everything in vacuum to limit e^{+} interactions outside target



- Detector was fully installed in Sept