Opportunities for Missing Momentum Experiments

Nikita Blinov

November 5, 2020

DND 2020, TRIUMF

Dark Matter

Well-established ingredient of standard cosmology, but we only know that

1) It does not interact much with SM

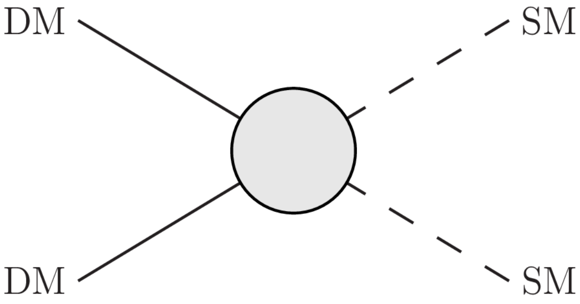
2) It behaves like a stable, non-relativistic particle in the cosmos

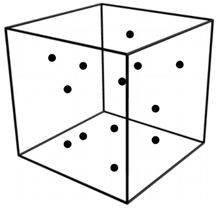
3) It makes up $\sim 1/6$ of the energy budget of the universe

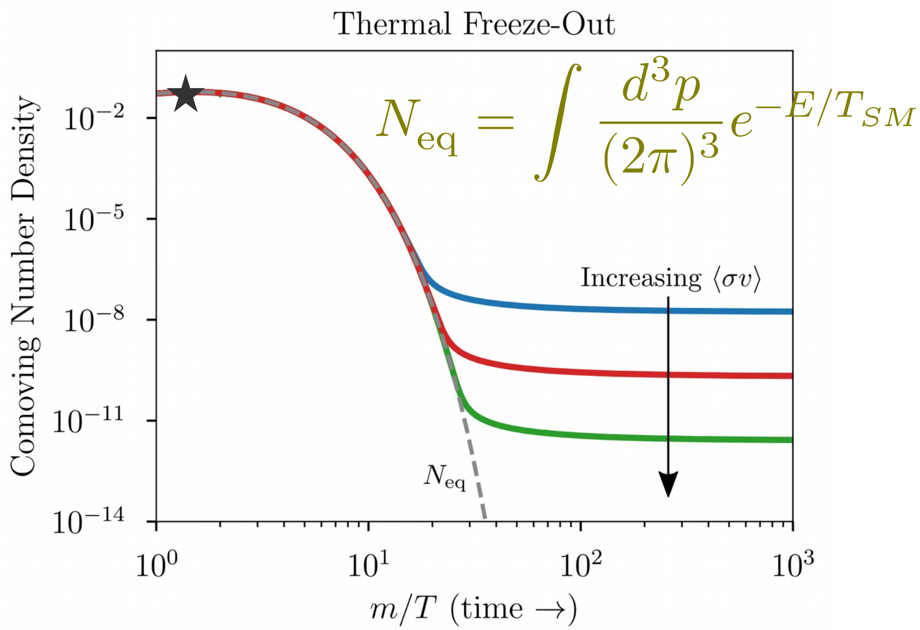
Thinking about achieving this relic abundance identifies search techniques and testable milestones

Thermal Origin of Dark Matter

Suppose DM interacts with SM particles







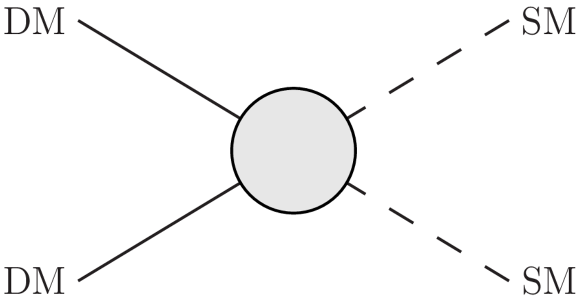
Correct abundance if

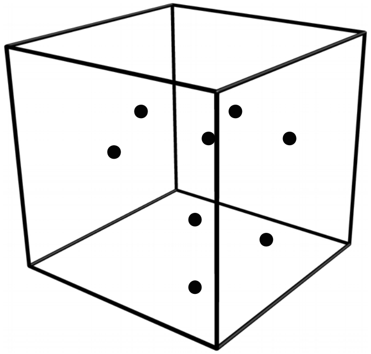
$$\langle \sigma v \rangle \approx \left(\frac{1}{20\ \text{TeV}} \right)^2$$

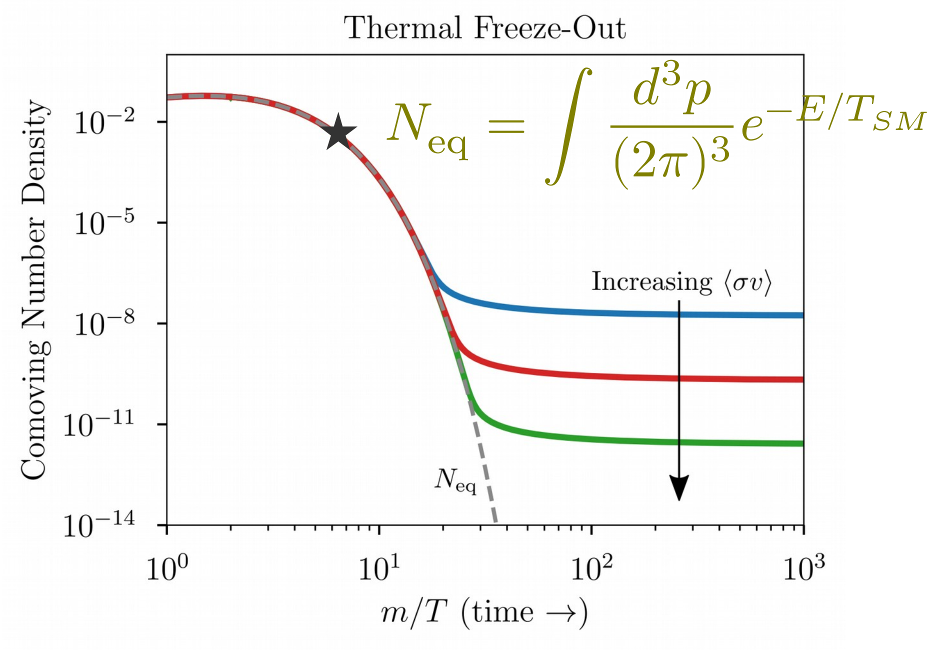
similar to Higgs production @ LHC

Thermal Origin of Dark Matter

Suppose DM interacts with SM particles







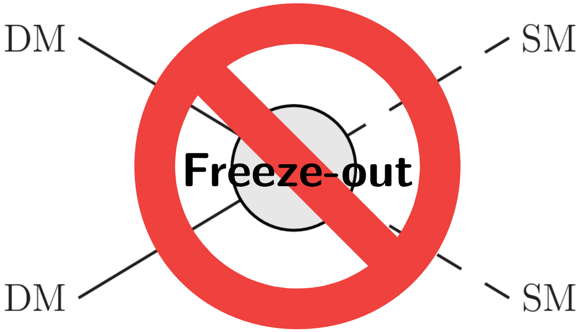
Correct abundance if

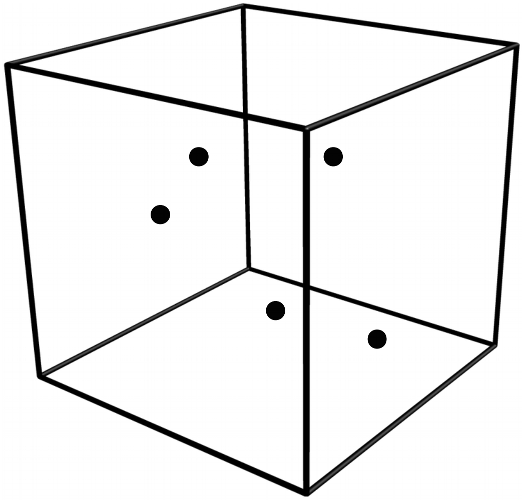
$$\langle \sigma v \rangle \approx \left(\frac{1}{20\ \mathrm{TeV}} \right)^2$$

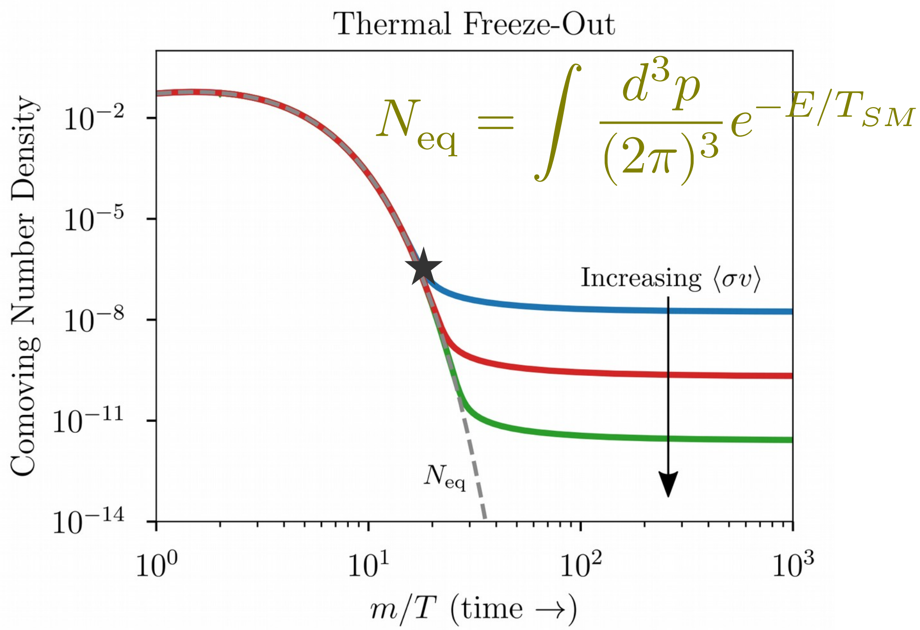
similar to Higgs production @ LHC

Thermal Origin of Dark Matter

Suppose DM interacts with SM particles





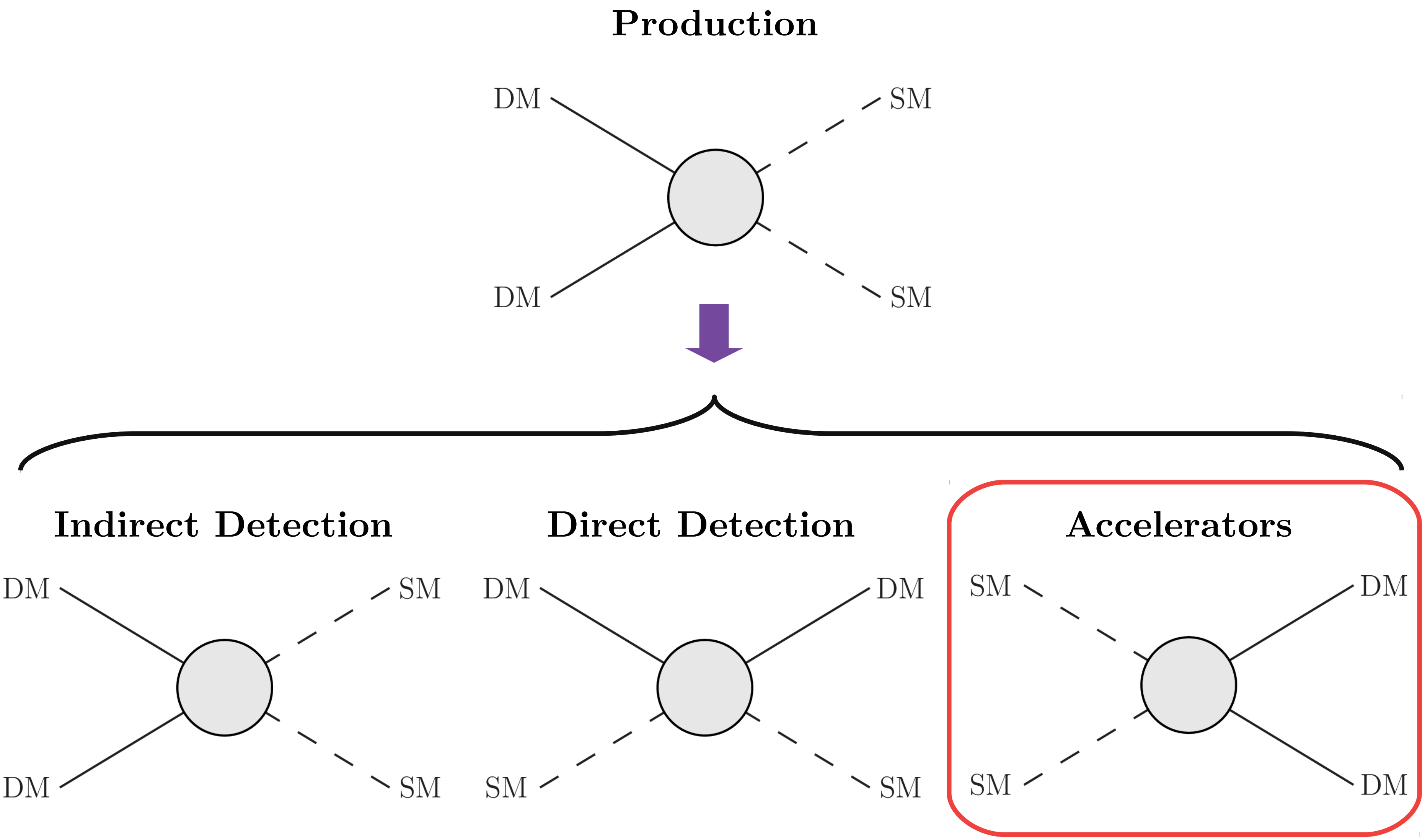


Correct abundance if

$$\langle\sigma v\rangle \approx \left(\frac{1}{20\ \text{TeV}}\right)^2$$

similar to Higgs production @ LHC

Advantage 1: Predictions for Experiments



Production

Indirect Detection

Direct Detection

Accelerators

Advantage 2: Reduced Parameter Range

Significantly smaller mass range for viable models

Big Bang Nucleosynthesis modified: wrong predictions for He, D

Theory non-perturbatve: can't compute anything

Advantage 2: Reduced Parameter Range

Significantly smaller mass range for viable models

Big Bang Nucleosynthesis modified: wrong predictions for He, D

Theory non-perturbatve: can't compute anything

Familiar energy scales, independence of initial conditions

$$\langle \sigma v \rangle \approx \left(\frac{1}{20\ \mathrm{TeV}} \right)^2 \sim \frac{y}{m_\chi^2}$$

Dimensionless product of coupling constants

DM mass

This talk: focus on DM lighter than a GeV

Dark Sectors

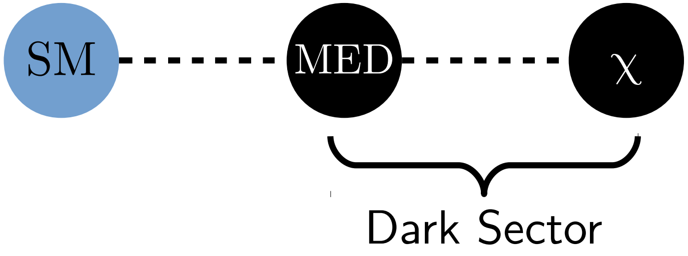
For light DM ($<$ GeV), SM interactions insufficient

$$\langle \sigma v \rangle_{\text{SM}} \sim \frac{\alpha^2 m_\chi^2}{m_Z^4} < \left(\frac{1}{20 \text{ TeV}} \right)^2$$

Lee & Weinberg '77

Boehm & Fayet '04

$$y \sim \alpha^2 \left(\frac{m_\chi}{m_Z} \right)^4$$



Dark Sector

Light thermal DM must be SM-neutral, requires a new mediator

How can such particles interact with familiar matter?

Annihilation Channels

A large but finite set of freeze-out channels possible

Available final states: ν, γ, ℓ, q

Theoretical Considerations: Only a few *low-dimensional*, *gauge-invariant* connections to BSM

Annihilation Channels

A large but finite set of freeze-out channels possible

Available final states: ν, γ, ℓ, q

Theoretical Considerations: Only a few *low-dimensional*, *gauge-invariant* connections to BSM

$A'_\mu J^\mu_{\rm SM}$	Dark vectors $\Rightarrow$	Coupling to conserved currents
$\|H\|^2\phi^2$	Higgs portal scalar $\Rightarrow$	Coupling to fermions
LHN_R	Right-handed neutrino$\Rightarrow$	Coupling to neutrinos
$aF_{\mu\nu}\widetilde{F}^{\mu\nu}$	Pseudo-scalar $\Rightarrow$	Coupling to electromagnetism
$\vdots$		

Pospelov, Ritz and Voloshin '07++

Annihilation Channels

A large but finite set of freeze-out channels possible

Available final states: ν, γ, ℓ, q

Theoretical Considerations: Only a few *low-dimensional*, *gauge-invariant* connections to BSM

$A'_\mu J^\mu_{\text{SM}}$ Dark vectors ⇒ Coupling to conserved currents

$|H|^2\phi^2$ Higgs portal scalar ⇒ Coupling to fermions

LHN_R Right-handed neutrino ⇒ Coupling to neutrinos

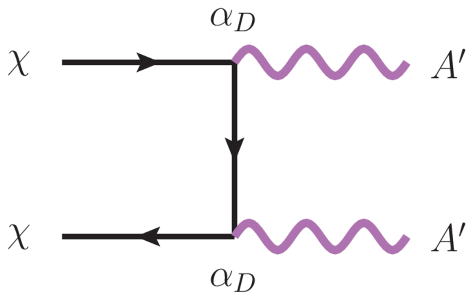
$aF_{\mu\nu}\widetilde{F}^{\mu\nu}$ Pseudo-scalar ⇒ Coupling to electromagnetism

$\vdots$

Pospelov, Ritz and Voloshin '07++

DM/Mediator Mass Hierarchy

For a specific model available annihilation channels depend on DM-mediator mass ordering



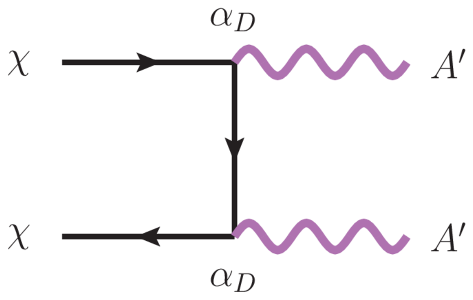
$$m_{A'} < m_\chi$$

Secluded Annihilation

Only depends on “dark” couplings

DM/Mediator Mass Hierarchy

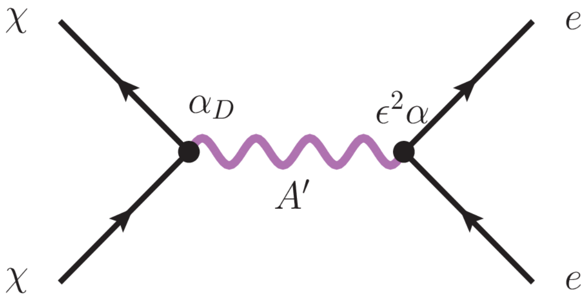
For a specific model available annihilation channels depend on DM-mediator mass ordering



$$m_{A'} < m_\chi$$

Secluded Annihilation

Only depends on "dark" couplings



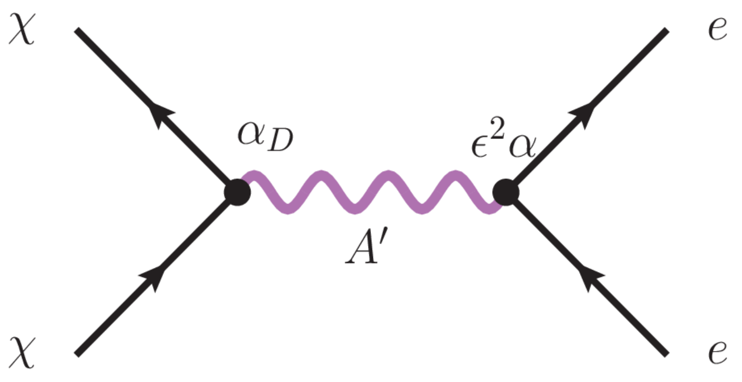
$$m_{A'} > m_\chi$$

Direct Annihilation

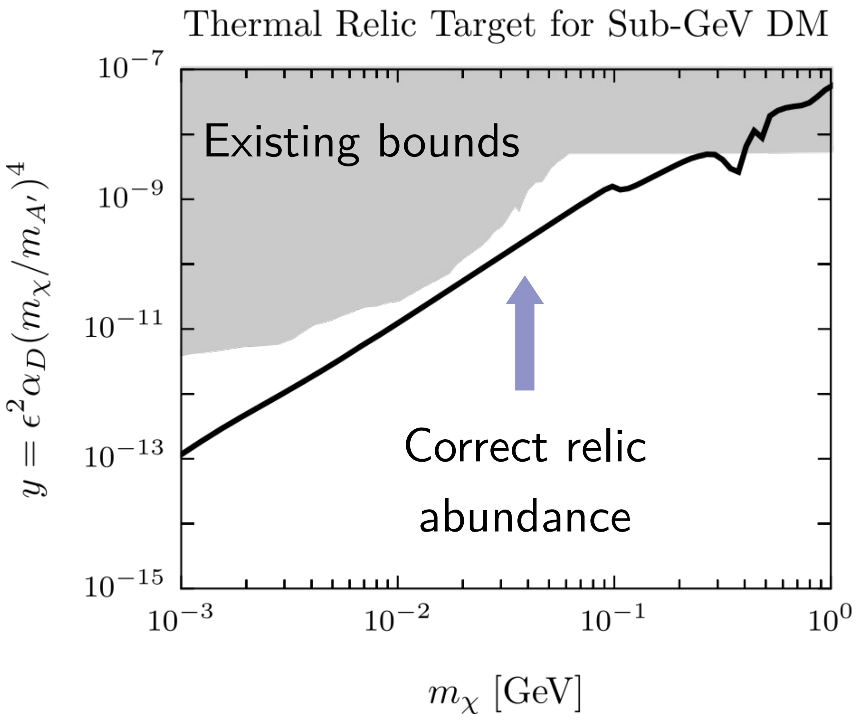
Depends on coupling to SM!

Dark Photon Example

Dark matter coupled to the dark photon can annihilate directly into SM particles

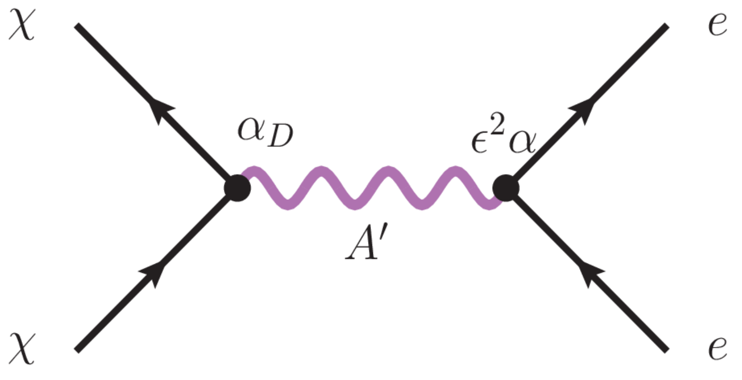


$$\langle \sigma v \rangle \propto \frac{\epsilon^2 \alpha \alpha_D m_\chi^2}{m_{A'}^4} \equiv \frac{y}{m_\chi^2}$$

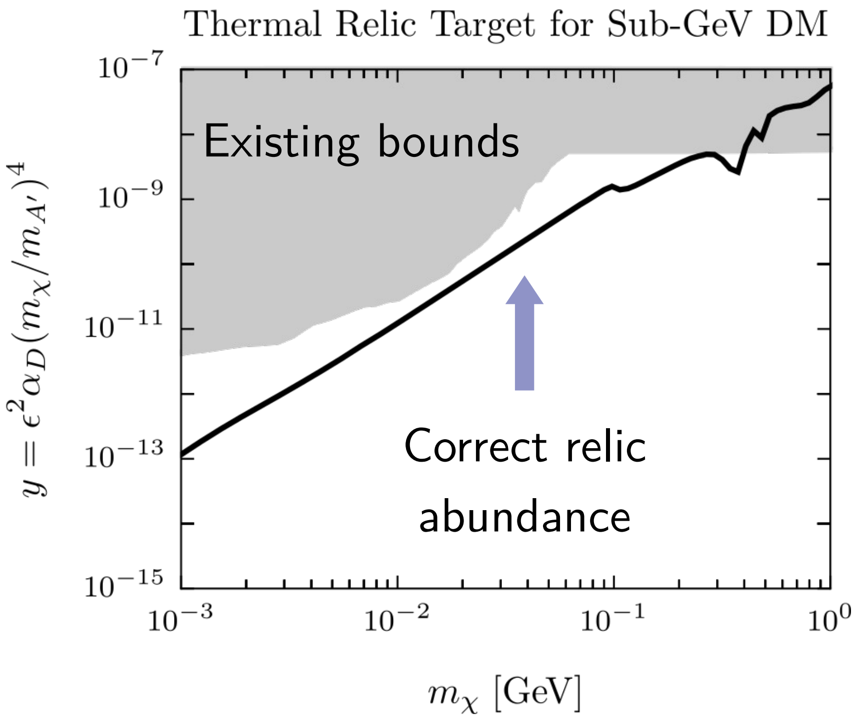


Dark Photon Example

Dark matter coupled to the dark photon can annihilate directly into SM particles



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



Thermal freeze-out identifies specific, within-reach target

Variations on a Theme

- Other DM options:

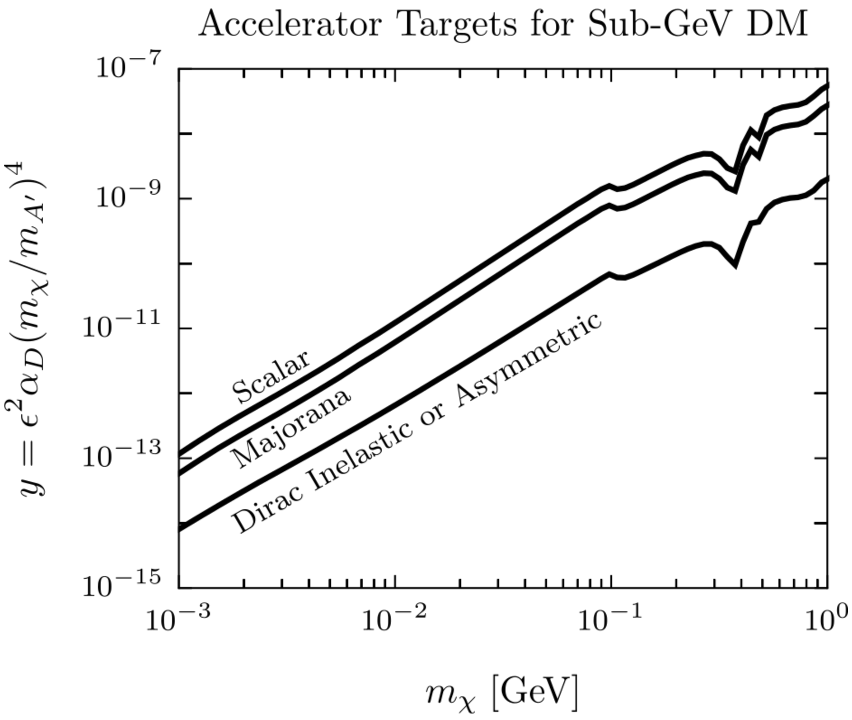
  Scalar, Majorana or Dirac

  Asymmetric, inelastic, SIMPs,..

- Other mediators

  B-L, L_e-L_{mu},...

  Scalar, pseudoscalar, ...



Berlin, NB, Gori, Schuster & Toro '18

Berlin, NB, Krnjaic, Schuster & Toro '19

Qualitatively similar targets in a wide variety of other models

Variations on a Theme

- Other DM options:

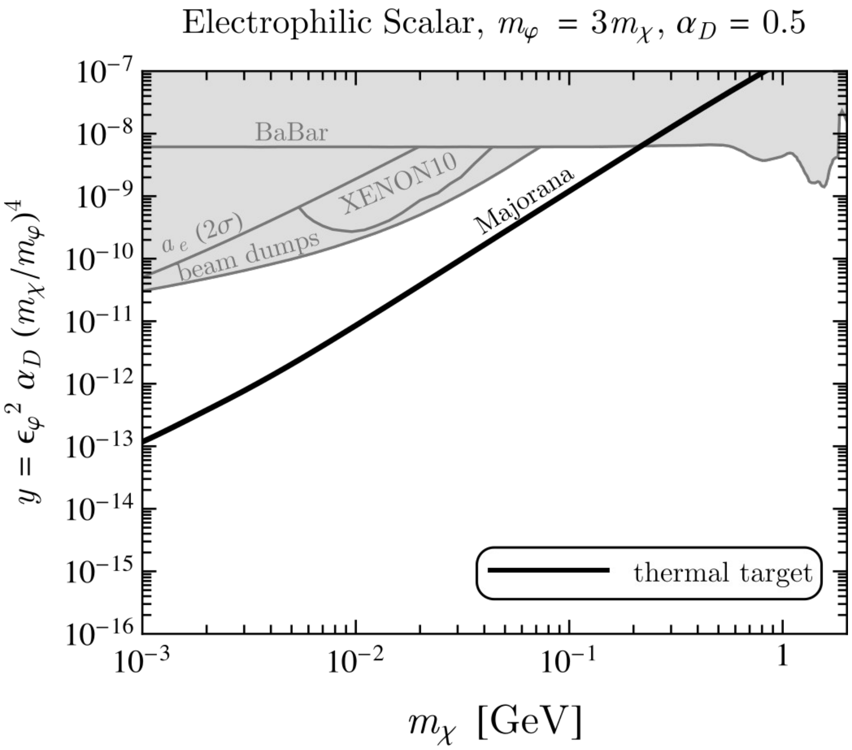
  Scalar, Majorana or Dirac

  Asymmetric, inelastic, SIMPs,..

- Other mediators

  B-L, L_e-L_{mu},…

  Scalar, pseudoscalar, …



Berlin, NB, Gori, Schuster & Toro ‘18
Berlin, NB, Krnjaic, Schuster & Toro ‘19

Qualitatively similar targets in a wide variety of other models

A Search Strategy

1) Relic abundance fixes y as a function of m_χ

$$y = \frac{\epsilon^2 \alpha \alpha_D m_\chi^4}{m_{A'}^4} \sim 10^{-13} \left(\frac{\text{MeV}}{m_\chi} \right)^2$$

2) Experimental constraints suggest $\epsilon^2 \alpha \ll \alpha_D$

∴ For $m_{\text{A'}} > 2 m_\chi$

$$\Gamma(A' \to \chi\chi) \gg \Gamma(A' \to \text{SM SM})$$

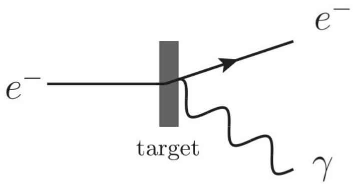
Mediator decays invisibly in predictive thermal models

Look for missing energy/momentum!

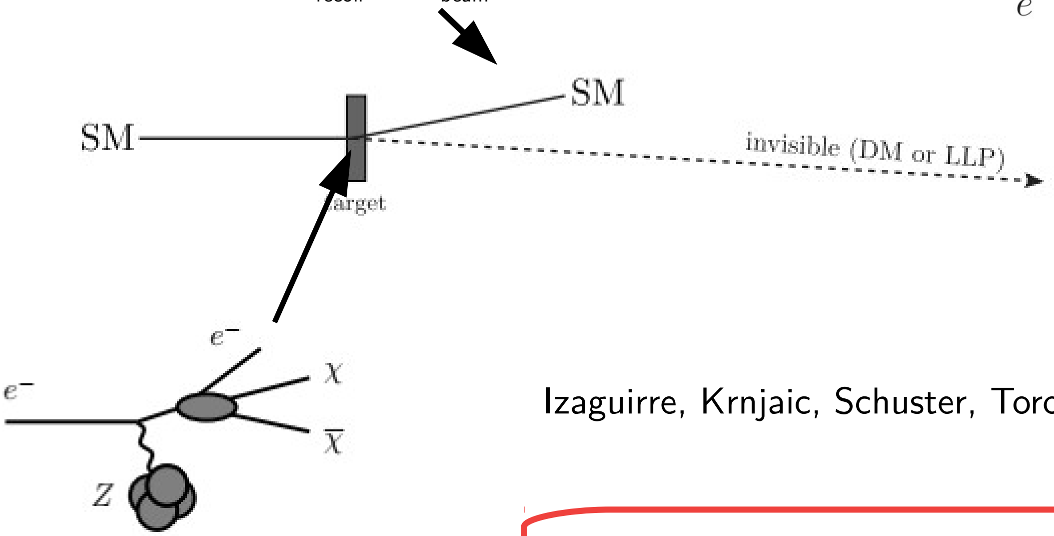
Missing Energy/Momentum

Detect DM indirectly by observing recoiling SM particle.

Background



$E_{\text{recoil}} < E_{\text{beam}}$



Izaguirre, Krnjaic, Schuster, Toro '15

$\text{production} \propto y$

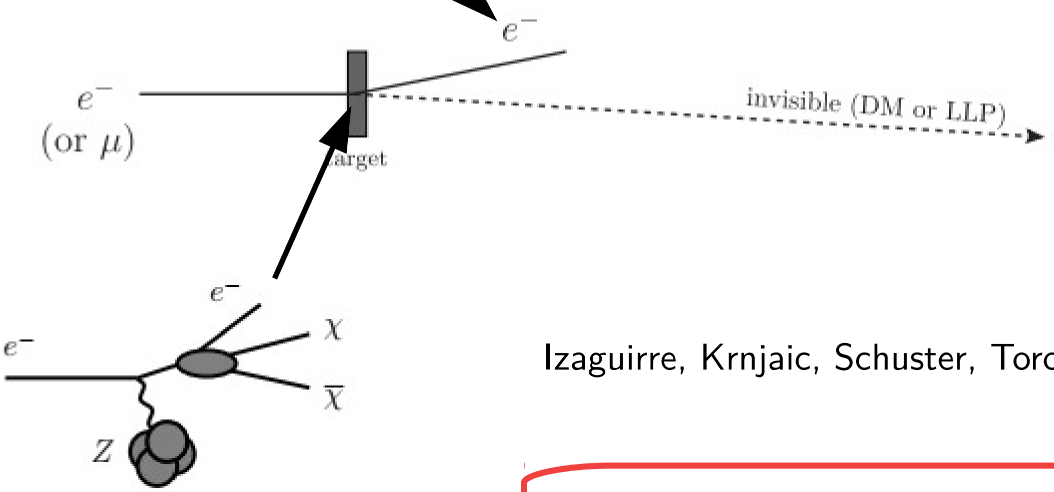
$$\boxed{\text{Signal Yield} \sim y \times N_{\text{EOT}}}$$

Every Mediator/DM particle produced is detected!

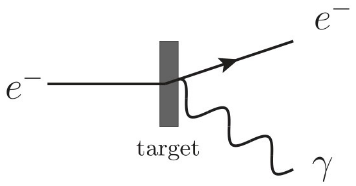
Missing Energy/Momentum

Detect DM indirectly by observing recoiling SM particle.

$E_{\text{recoil}} < E_{\text{beam}}$



Background



Izaguirre, Krnjaic, Schuster, Toro ‘15

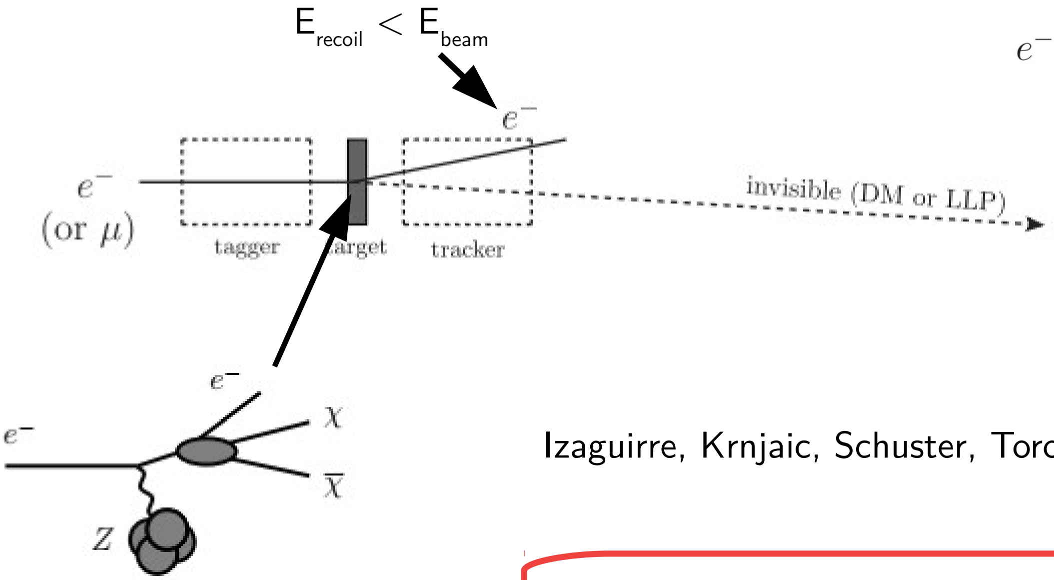
$\text{production} \propto y$

$$\boxed{\text{Signal Yield} \sim y \times N_{\text{EOT}}}$$

Every Mediator/DM particle produced is detected!

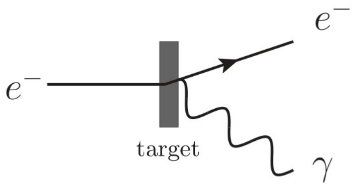
Missing Energy/Momentum

Detect DM indirectly by observing recoiling SM particle.



$E_{\text{recoil}} < E_{\text{beam}}$

Background



Izaguirre, Krnjaic, Schuster, Toro '15

$$\text{production} \propto y$$

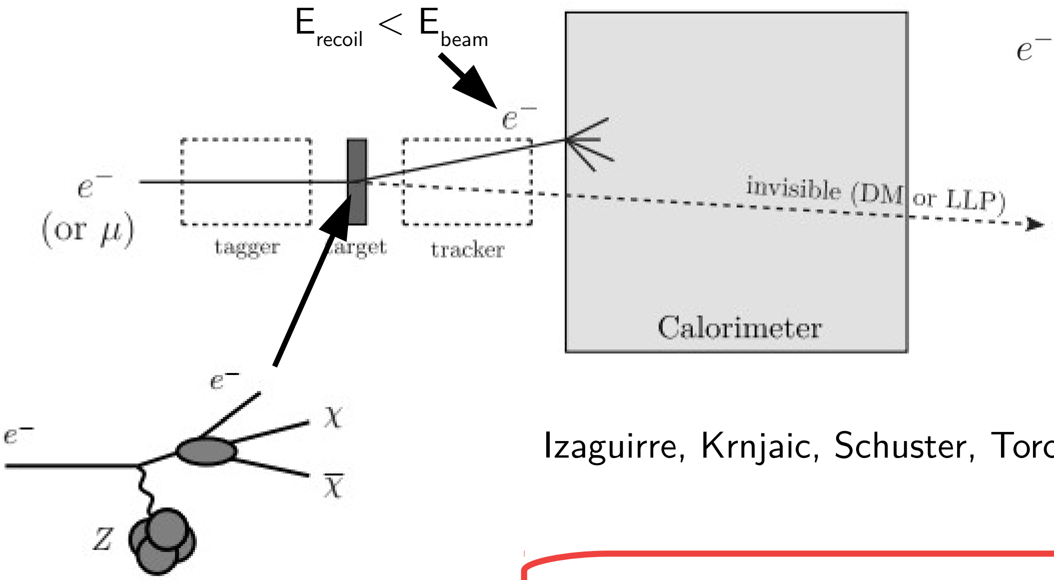
$$\boxed{\text{Signal Yield} \sim y \times N_{\text{EOT}}}$$

Every Mediator/DM particle produced is detected!

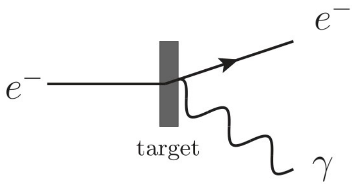
Missing Energy/Momentum

Detect DM indirectly by observing recoiling SM particle.

$E_{\text{recoil}} < E_{\text{beam}}$



Background



Izaguirre, Krnjaic, Schuster, Toro ‘15

production $\propto y$

$$\boxed{\text{Signal Yield} \sim y \times N_{\text{EOT}}}$$

Every Mediator/DM particle produced is detected!

Beam Requirements

1) Need to track each incident beam particle

low current

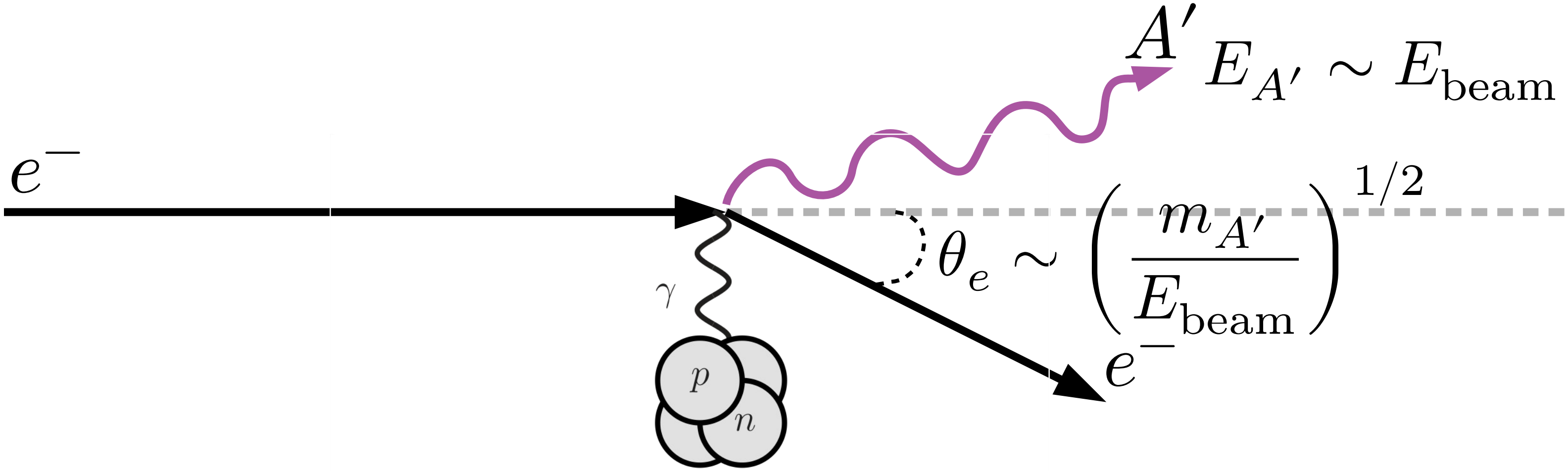
2) High statistics on a ~year time scale ($>10^{14}$ EOT)

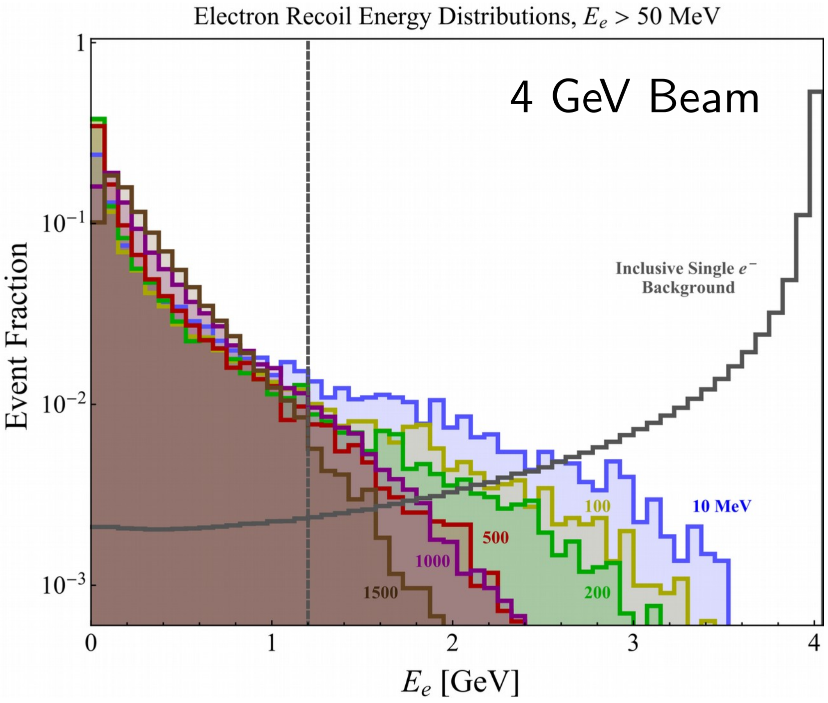
single/few electrons @ $>$ 30 MHz repetition rate

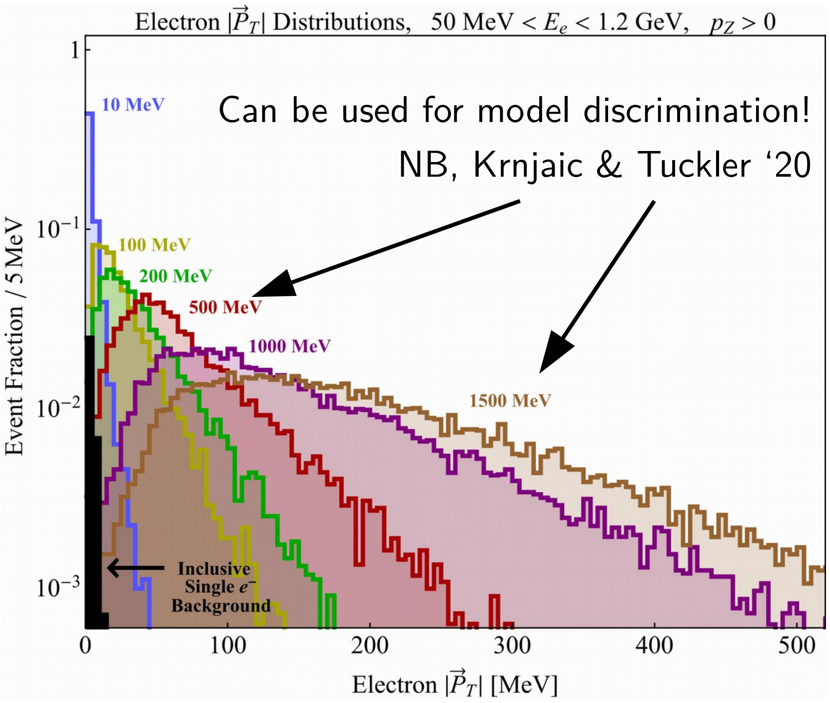
Candidate beams:

- S30XL@SLAC - SLAC-R-1147; must be parasitic to free-electron laser program
- CEBAF@JLAB – primarily a nuclear physics facility
- eSPS@CERN - CERN-SPSC-2018-023 - hypothetical

Signal Kinematics



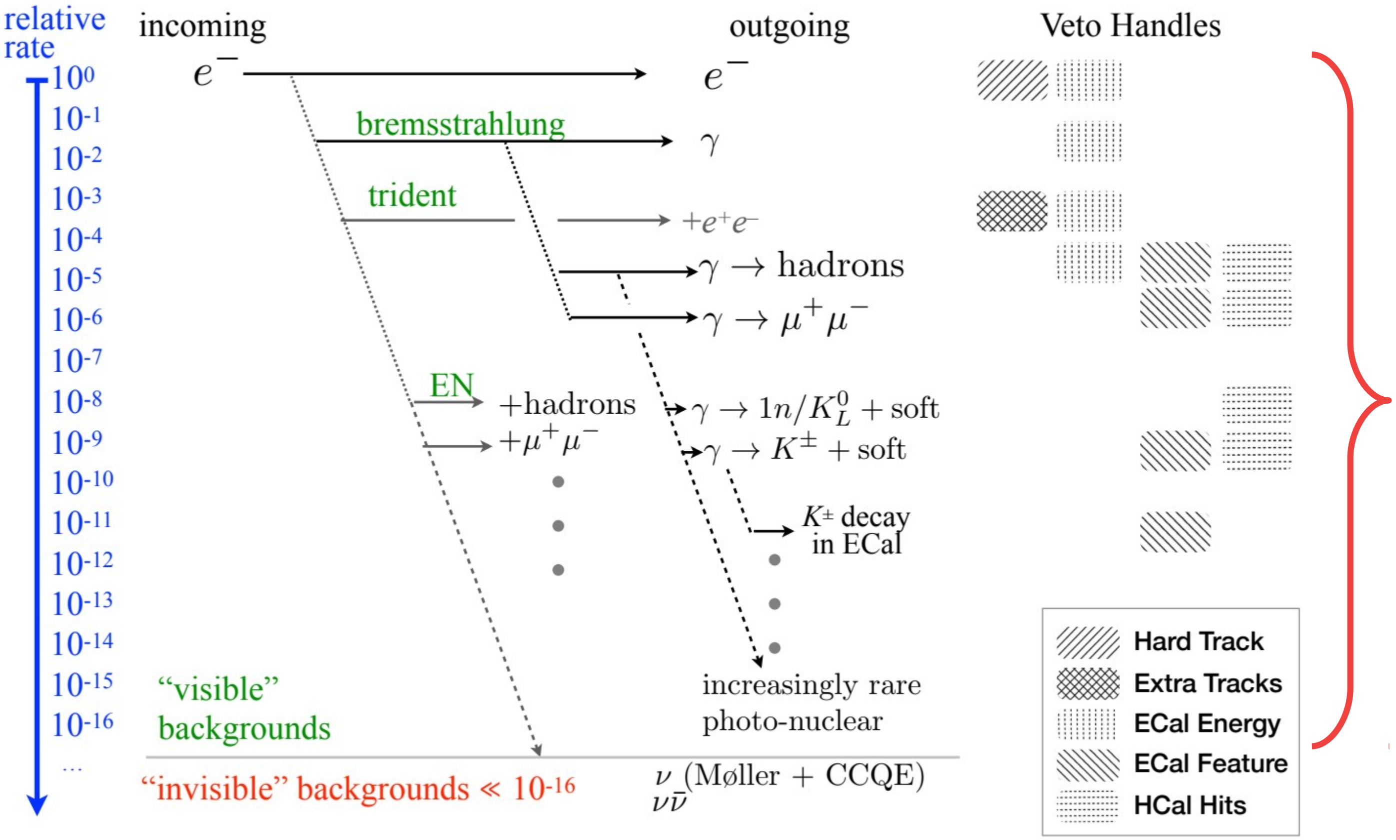

4 GeV Beam


Can be used for model discrimination!

NB, Krnjaic & Tuckler '20

LDMX Collaboration (1808.05219) '18

Backgrounds



Visible energy deposition in ECAL/HCAL

LDMX Collaboration '19

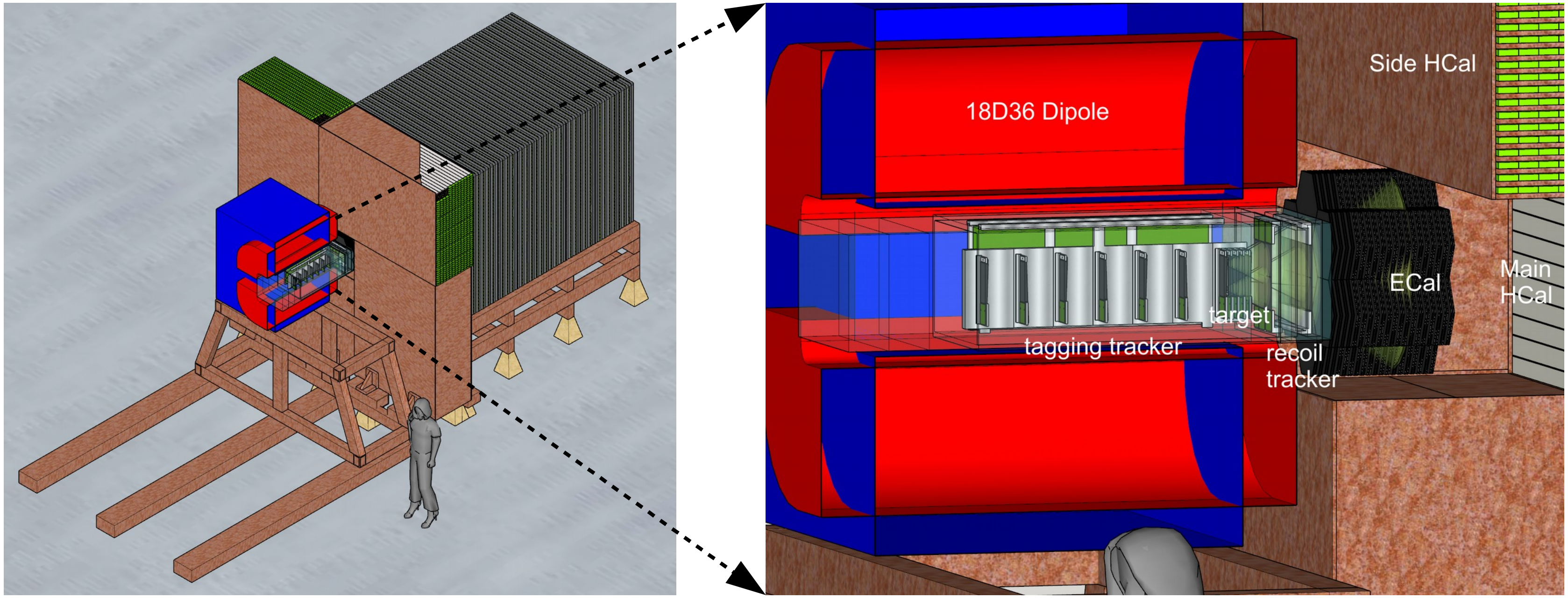
Light Dark Matter eXperiment

- Detector design developed by the LDMX collaboration, using technology from CMS, Mu2e and HPS experiments

LDMX Collaboration (1808.05219) ‘18

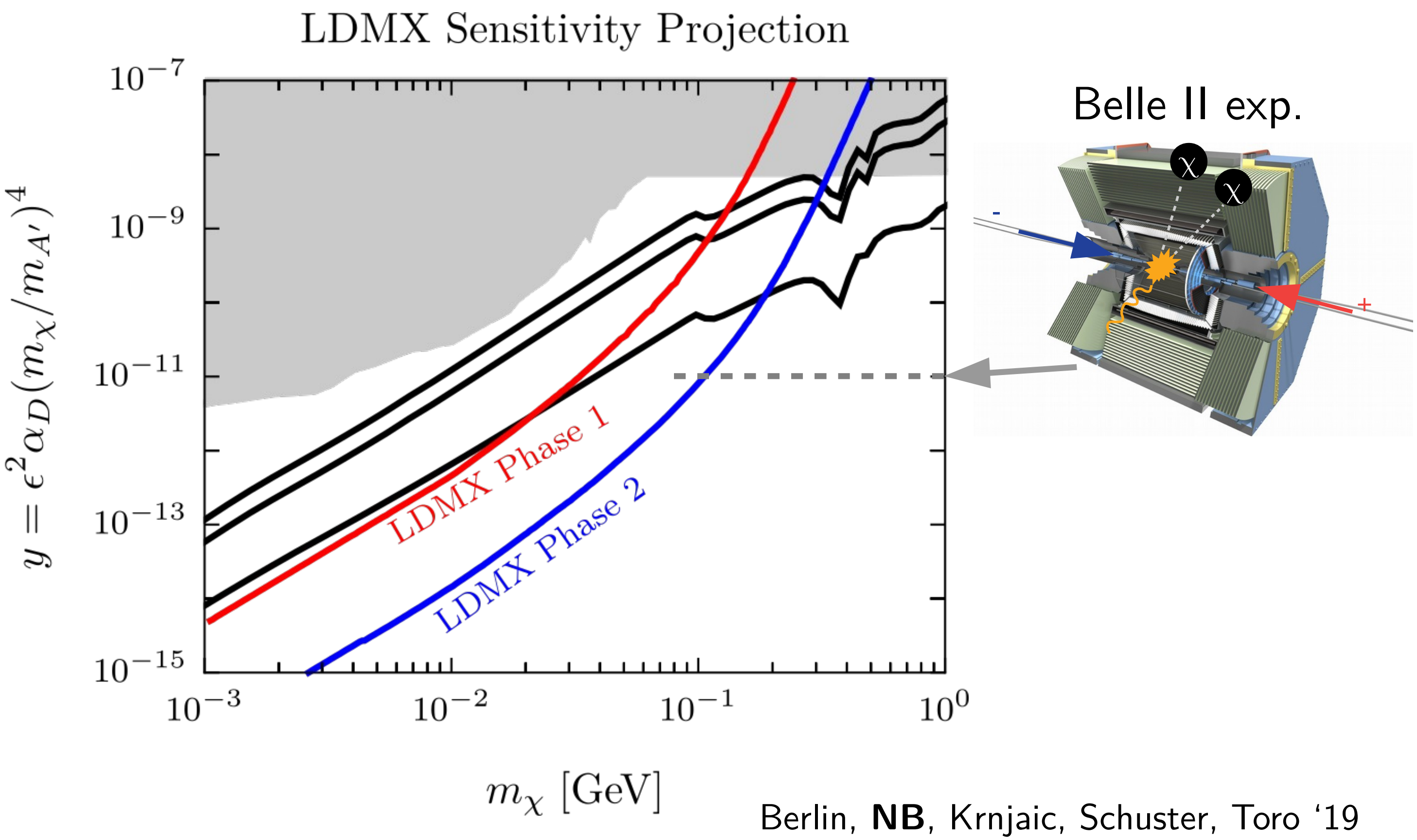
- Background studies using realistic detector simulation show the design achieves the necessary background rejection for 10^{14} EOT

LDMX Collaboration (1912.05535) ‘19



Fermilab SLAC UCSB University of Minnesota Caltech Lund University University of Virginia

LDMX Projections



Berlin, **NB**, Krnjaic, Schuster, Toro ‘19

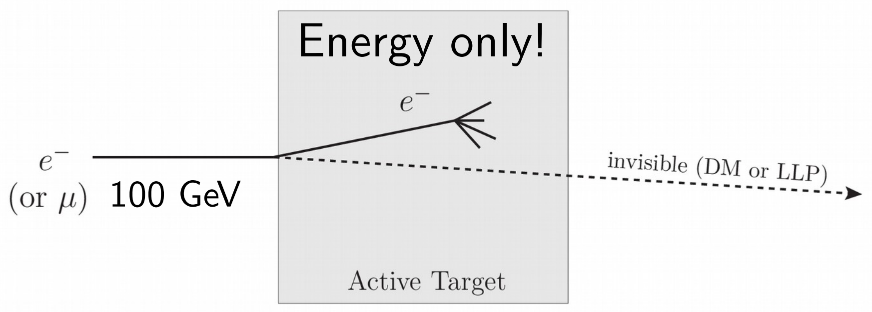
Phase 1: ~10^{14} EOT, 4 GeV e Beam
Phase 2: ~10^{16} EOT, 8 GeV e Beam

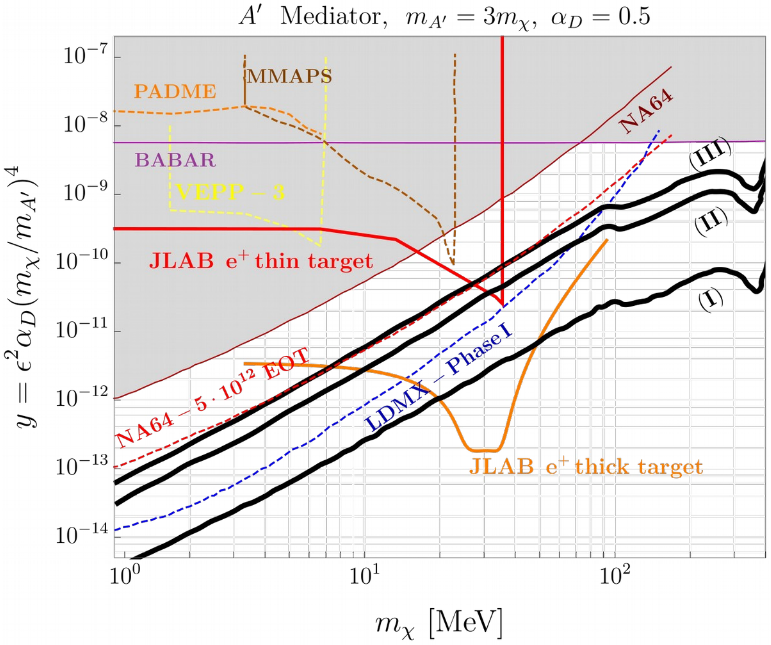
LDMX+Belle II can decisively test thermal DM below a GeV!

Missing Momentum/Energy/Mass

- NA64 – missing energy

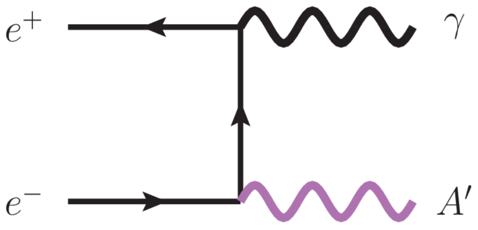
Andreas *et al* (1312.3309); Banerjee *et al* (1710.00971)





- JLAB/PADME e+ beam

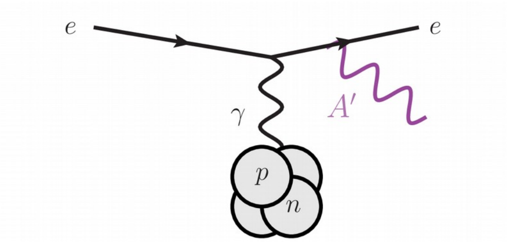
Accardi *et al* ‘20 (2007.15081)

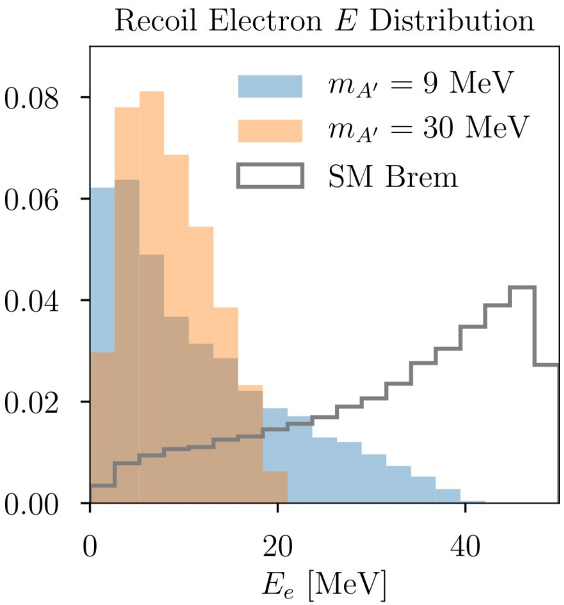


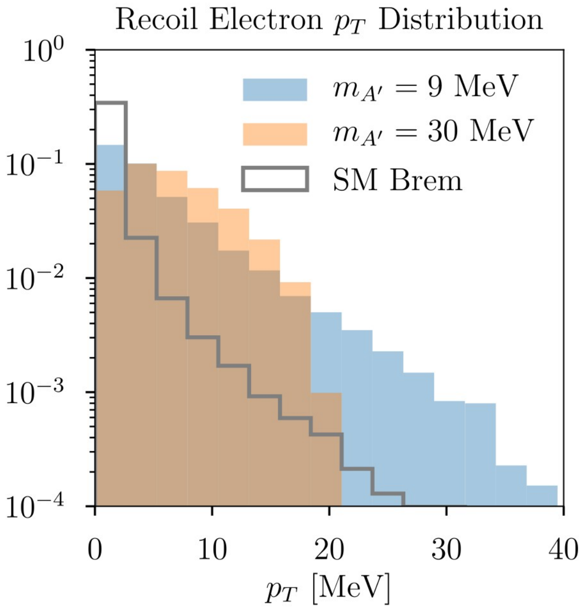
$$m_{A'}^2 = (p_{e^+} + p_{e^-} - p_\gamma)^2$$

ARIEL Beam

- Much of previous discussion translates to ~50 MeV electron beam

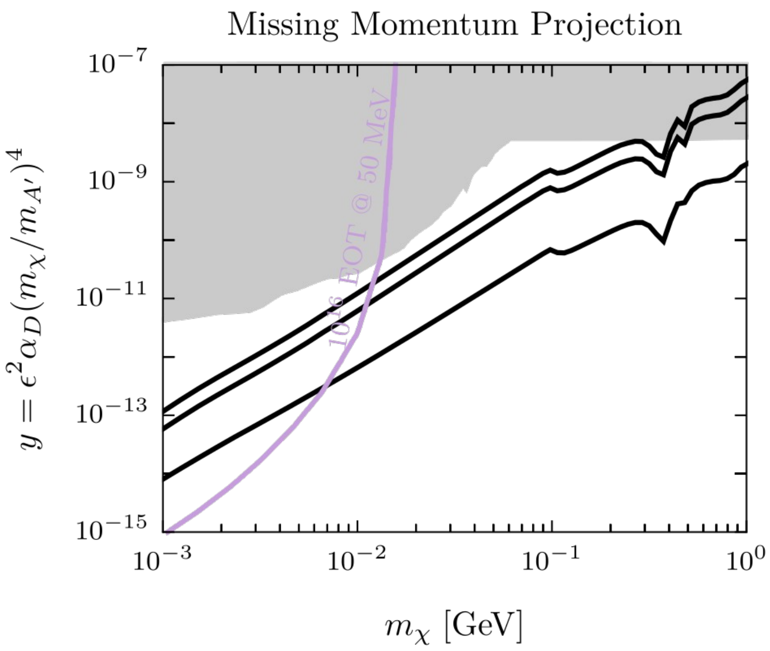


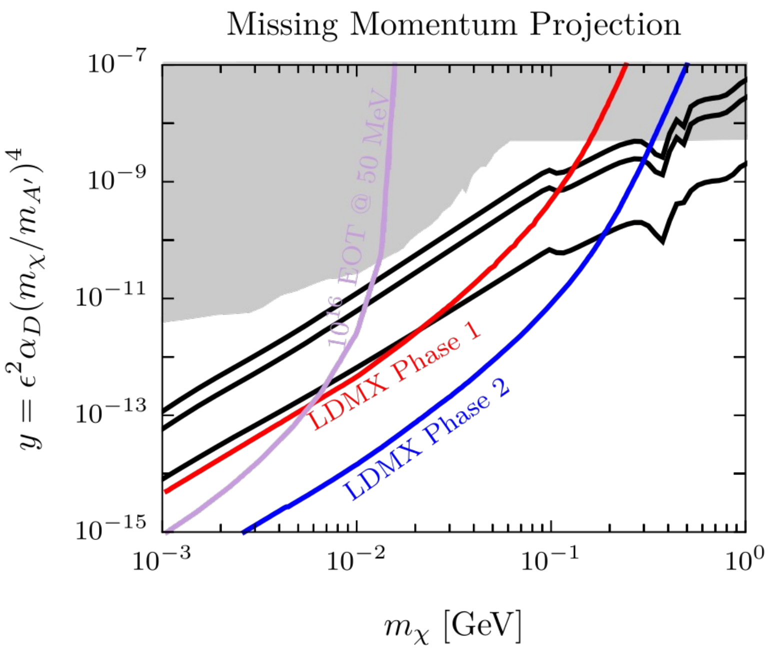




Possible Reach

50 MeV electron beam, 10^{16} EOT on $0.1X_0$ Tungsten





Challenge 1: nominal ARIEL current probably too high (pileup)

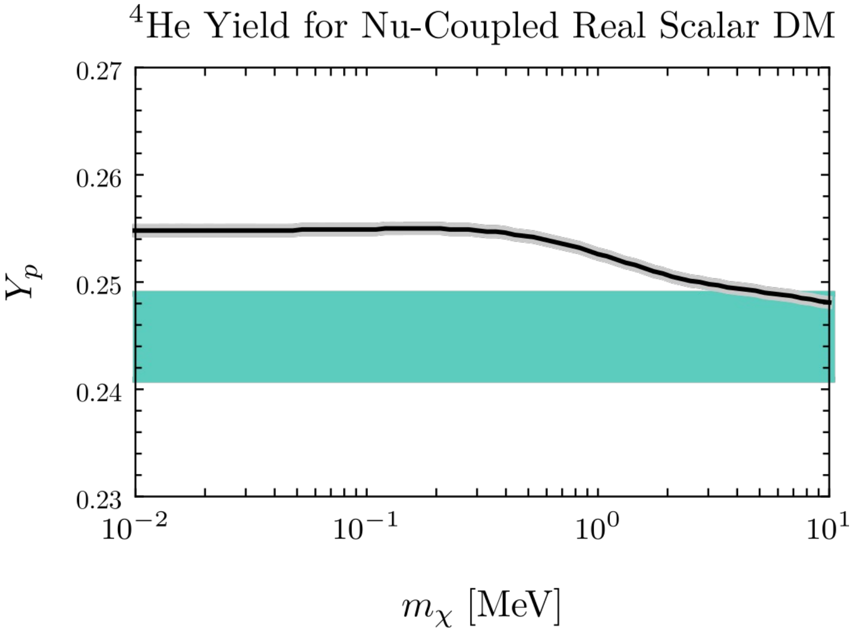
Challenge 2: lower energy, more wide-angle/lost emissions (background)?

Cosmology and Dark Sectors Near MeV

- In thermal models at early times

$$\rho_{\mathrm{DS}} \sim \rho_\gamma \sim T^4$$

DM+associated particles



- If DS lighter than a few MeV

Faster expansion

Different baryon abun.

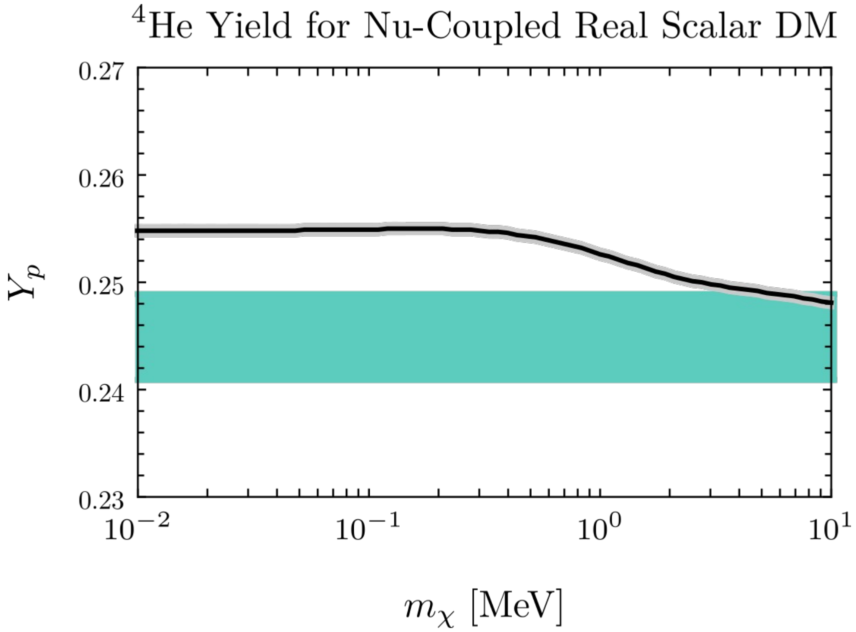
$$H(T) \propto \sqrt{\rho_{\mathrm{SM}} + \rho_{\mathrm{DS}}} \quad \eta_b = \frac{n_b}{n_\gamma}$$

Cosmology and Dark Sectors Near MeV

- In thermal models at early times

$$\rho_{\rm DS} \sim \rho_\gamma \sim T^4$$

DM+associated particles



- If DS lighter than a few MeV

Faster expansion

$$H(T) \propto \sqrt{\rho_{\rm SM} + \rho_{\rm DS}}$$

Different baryon abun.

$$\eta_b = \frac{n_b}{n_\gamma}$$

Wrong predictions for

$$^4\text{He},\ \text{D}$$

abundances, CMB!

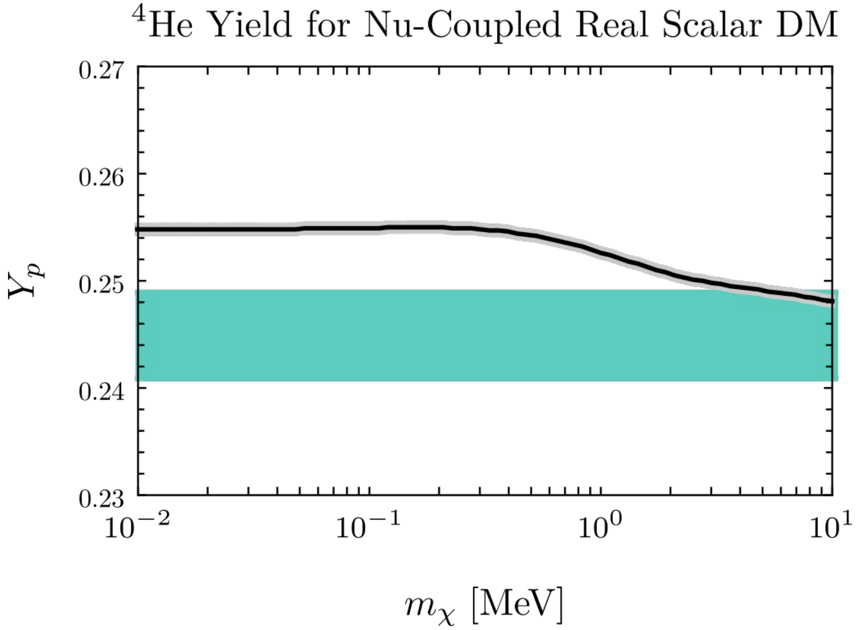
See, e.g., 1910.01649 (Sabti *et al* ‘19)

Cosmology and Dark Sectors Near MeV

- In thermal models at early times

$$\rho_{\mathrm{DS}} \sim \rho_\gamma \sim T^4$$

DM+associated particles



- If DS lighter than a few MeV

Faster expansion

Different baryon abun.

$$H(T) \propto \sqrt{\rho_{\mathrm{SM}} + \rho_{\mathrm{DS}}} \quad \eta_b = \frac{n_b}{n_\gamma}$$

Wrong predictions for

$${}^4\mathrm{He},\ \mathrm{D}$$

abundances, CMB!

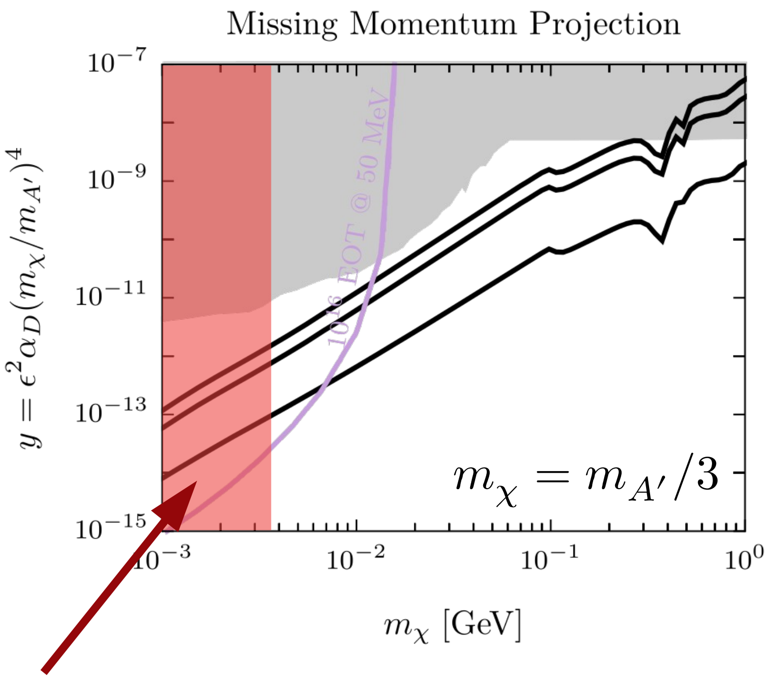
See, e.g., 1910.01649 (Sabti *et al* '19)

Cosmology constrains (BBN+CMB)

$$m_{A'} \gtrsim 10\ \mathrm{MeV} \qquad m_\chi \gtrsim 5\ \mathrm{MeV}$$

Viable Parameter Space

- **Challenge 3: Large range of accessible parameter space in tension with cosmology**



In conflict with BBN/CMB

Outlook

- Cosmological production of DM can identify “preferred” regions in DM mass and coupling

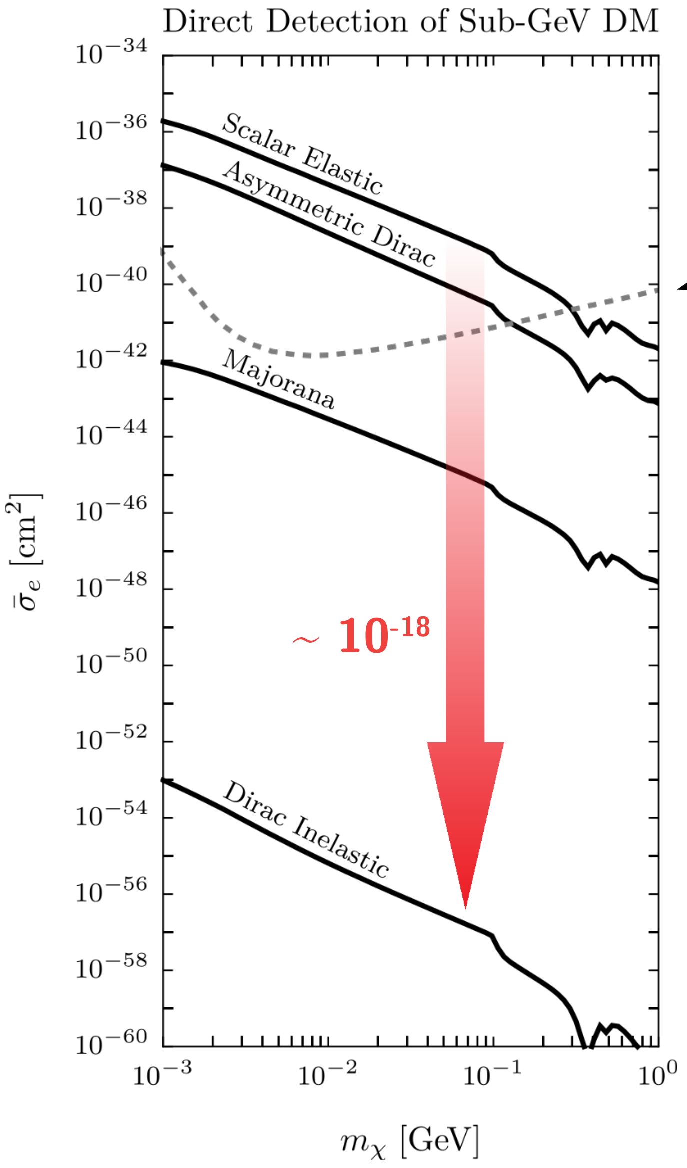
- Theoretical principles and SM spectrum further constrain possible interactions and signals

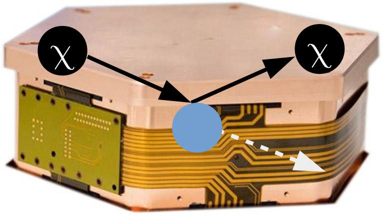
- Missing energy/mass/momentum experiments with few-GeV lepton beams poised to decisively test well-motivated models

Thank you!

Appendix

Advantages of Accelerator Searches



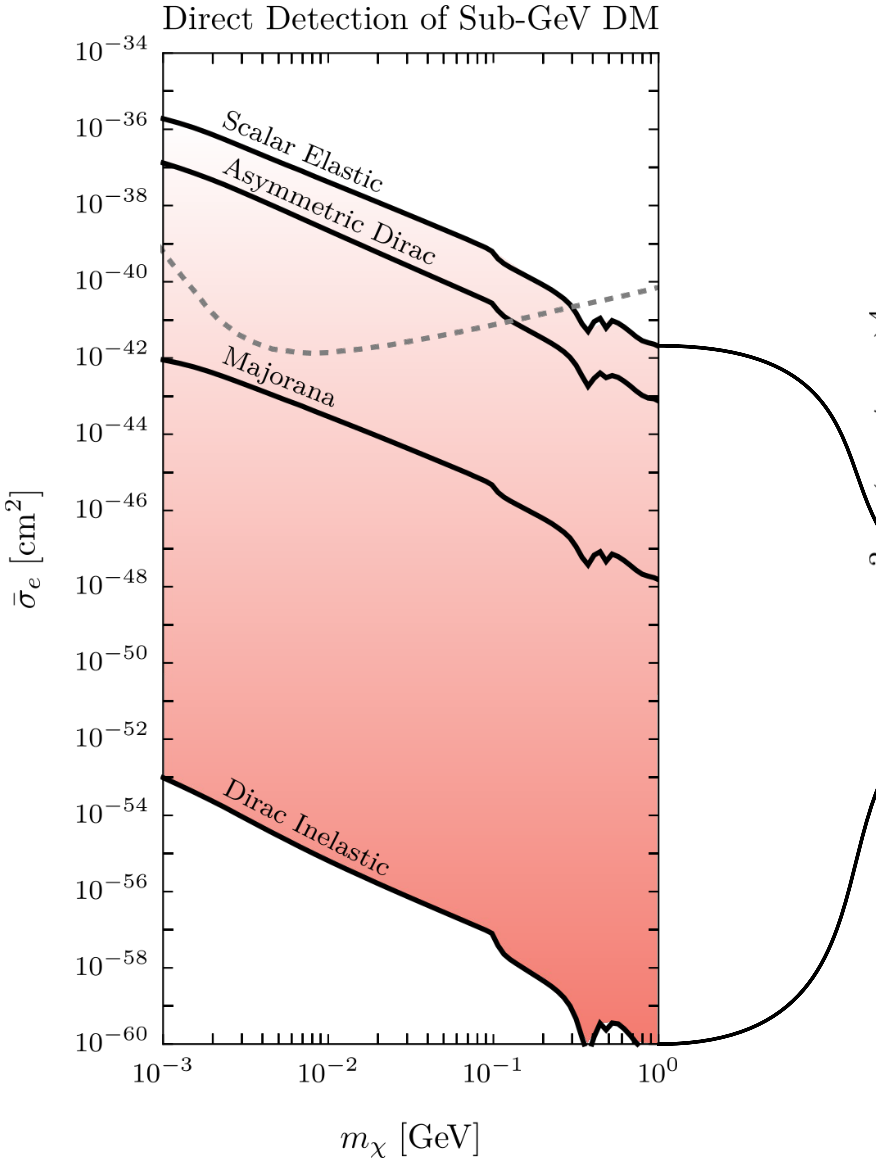


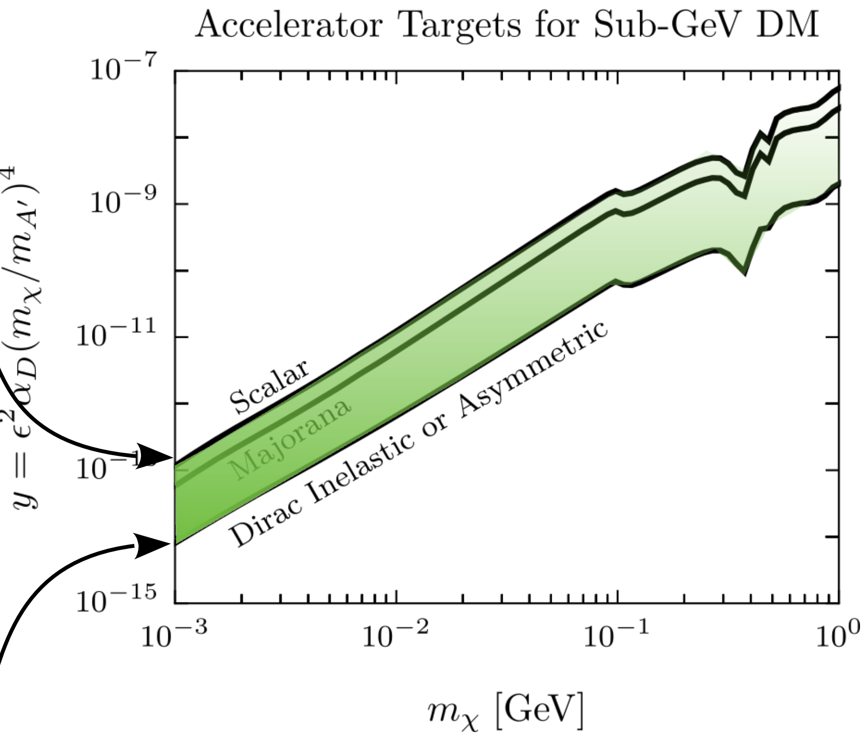
SuperCDMS SNOLAB

Direct detection strongly sensitive to possible DM velocity dependence in scattering rates:

Challenging to cover all thermal targets!

Advantages of Accelerator Searches





DM produced with v~1 at accelerators:

Insensitive to model details

like spin or inelasticity

Thermal DM Caveats

Not all models of thermal DM predict SM coupling as a function of DM mass. Examples include

1) Secluded DM: DM mass $<$ mediator mass. No target SM coupling because abundance determined by DS interactions alone

Examples include 1812.05103 (Batell et al '18)

2) Resonant annihilation: if mediators mass close to twice the DM mass, tiny SM couplings can still lead to correct abundance

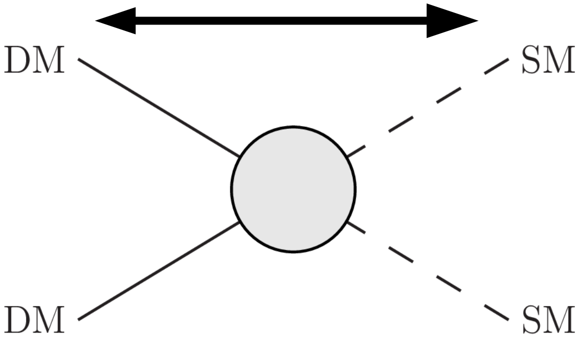
See, e.g., 1707.03835 (Feng and Smolinksy '17)

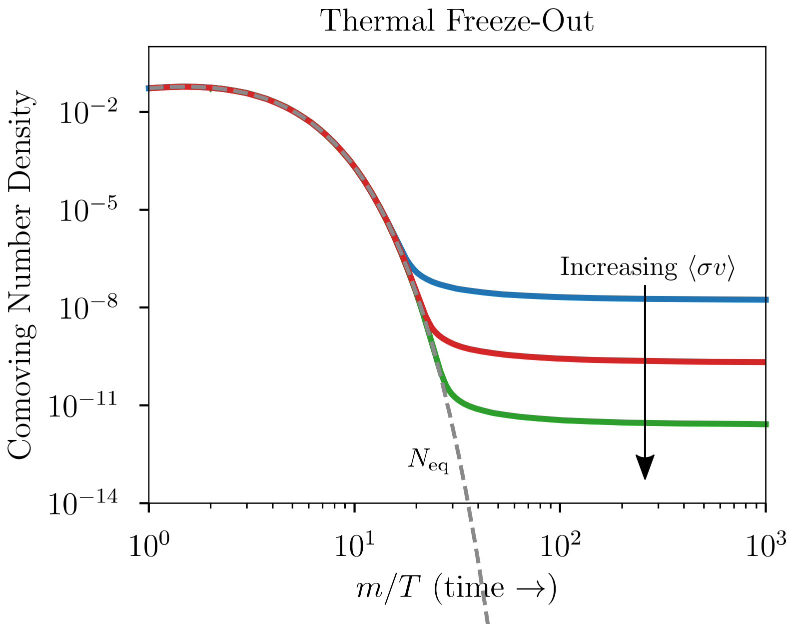
Thermal Dark Matter

DM particles were in kinetic and chemical equilibrium with the SM at early times:

$$T_\chi = T_{SM}$$

$$n_\chi = \int \frac{d^3p}{(2\pi)^3} e^{-(E-\cancelto{0}{\mu})/T_{SM}}$$



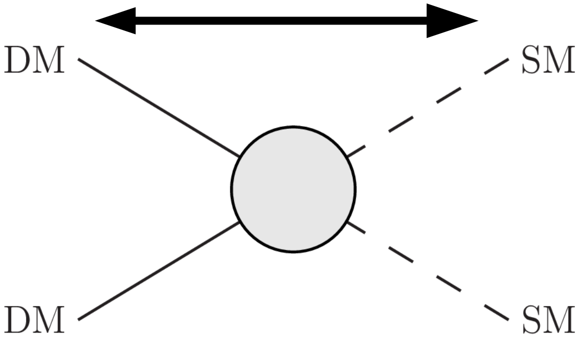


Thermal Dark Matter

DM particles were in kinetic and chemical equilibrium with the SM at early times:

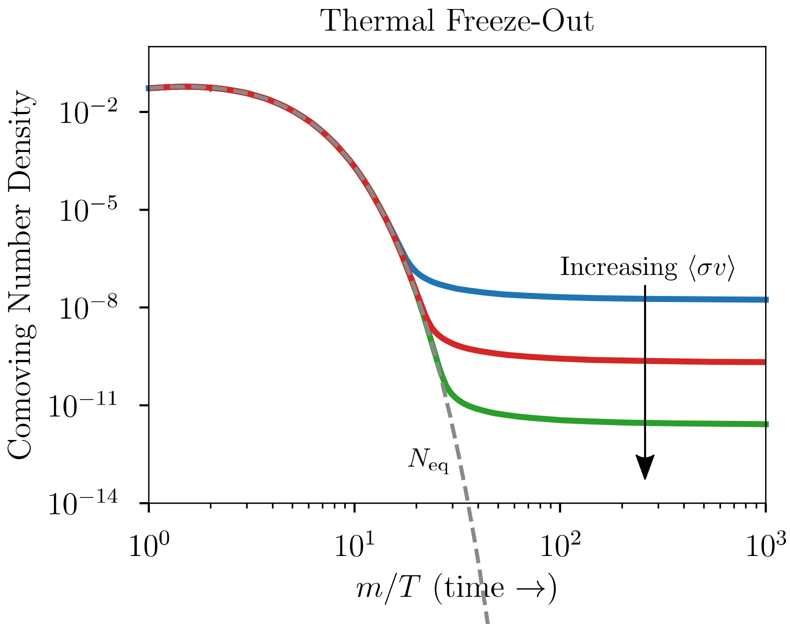
$$T_\chi = T_{SM}$$

$$n_\chi = \int \frac{d^3p}{(2\pi)^3} e^{-(E-\cancelto{0}{\mu})/T_{SM}}$$



$$n_\chi \langle \sigma v \rangle = H(T_{\mathrm{fo}})$$

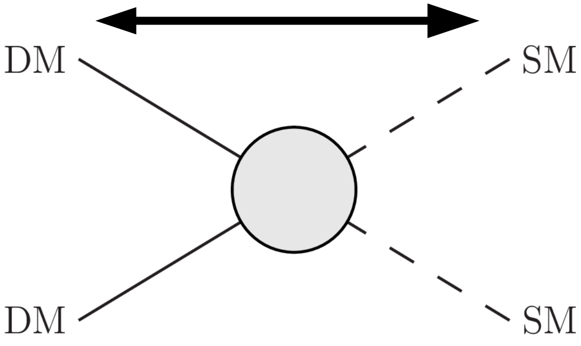
$$m_\chi \sim \alpha_{\mathrm{eff}} \underbrace{(T_{\mathrm{eq}} M_{\mathrm{Pl}})^{1/2}}_{\text{100 TeV}}$$



Thermal Dark Matter

DM particles were in kinetic and chemical equilibrium with the SM at early times:

$$T_\chi = T_{SM}$$



$$n_\chi = \int \frac{d^3p}{(2\pi)^3} e^{-(E-\cancelto{0}{\mu})/T_{SM}}$$

$$n_\chi \langle \sigma v \rangle = H(T_{\text{fo}})$$

$$m_\chi \sim \alpha_{\text{eff}} \underbrace{(T_{\text{eq}} M_{\text{Pl}})^{1/2}}_{\text{100 TeV}}$$

Advantages of thermal DM

1) Insensitive to UV/initial conditions

2) **Interactions with SM required**

3) Finite mass range

Thermal-ish Dark Matter

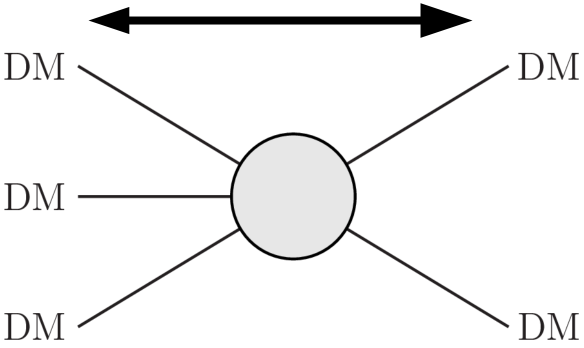
- DM particles were in kinetic but not chemical equilibrium with the SM

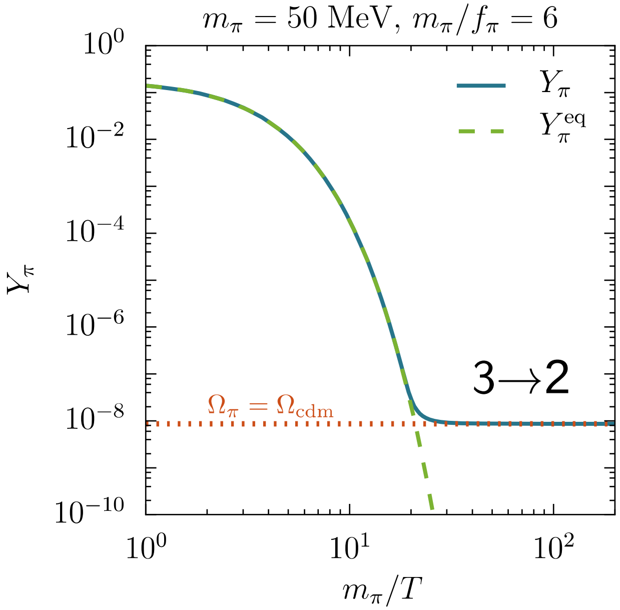
Hochberg *et al* ‘14

$$T_\chi = T_{SM}$$

$$n_\chi = \int \frac{d^3p}{(2\pi)^3} e^{-(E-\cancelto{0}{\mu})/T_{SM}}$$

Only DM-number-changing process





Thermal-ish Dark Matter

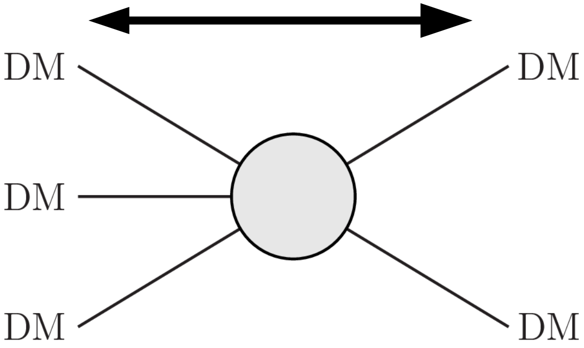
- DM particles were in kinetic but not chemical equilibrium with the SM

$$T_\chi = T_{SM}$$

Hochberg *et al* '14

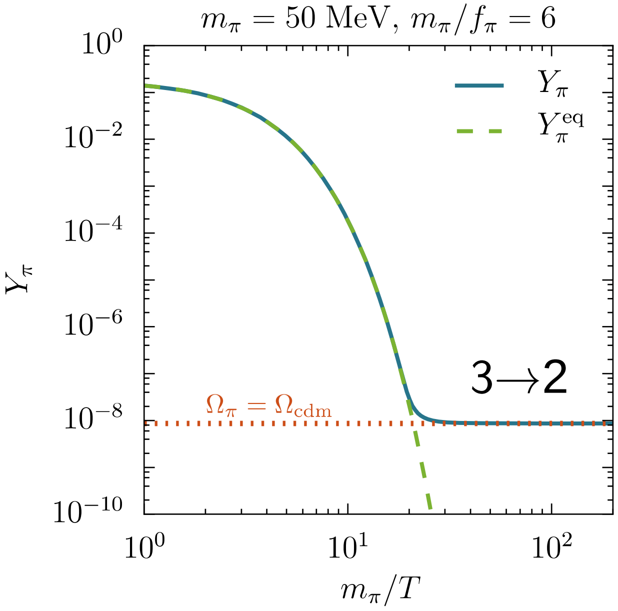
$$n_\chi = \int \frac{d^3p}{(2\pi)^3} e^{-(E-\cancelto{0}{\mu})/T_{SM}}$$

Only DM-number-changing process



$$n_\chi^2 \langle \sigma v^2 \rangle = H(T_{\rm fo})$$

$$m_\chi \sim \alpha_{\rm eff} \underbrace{(T_{\rm eq}^2 M_{\rm Pl})^{1/3}}_{\sim \text{GeV}}$$



Thermal-ish Dark Matter

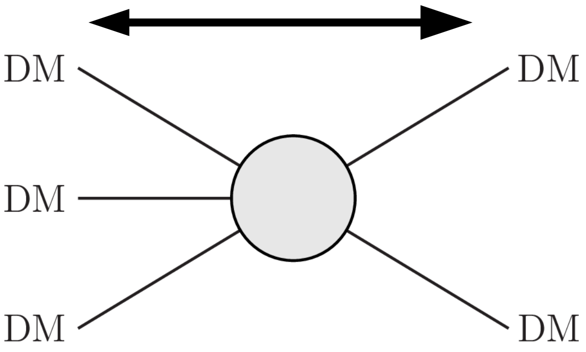
- DM particles were in kinetic but not chemical equilibrium with the SM

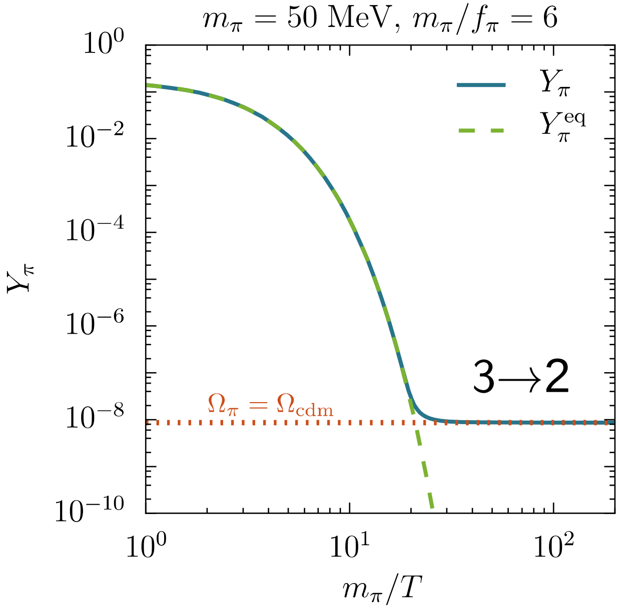
$$T_\chi = T_{SM}$$

Hochberg *et al* ‘14

$$n_\chi = \int \frac{d^3p}{(2\pi)^3} e^{-(E-\cancelto{0}{\mu})/T_{SM}}$$

Only DM-number-changing process



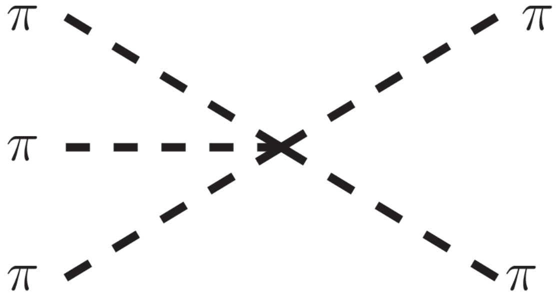


DM abundance determined by DS dynamics, but **requires** kinetic equilibrium with SM

Confining Dark Sectors

QCD-like models naturally realize 3→2 freeze-out via

$$\frac{N_c}{240\pi^2 f_\pi^5}\epsilon^{\mu\nu\rho\sigma}\mathrm{Tr}\left(\pi\partial_\mu\pi\partial_\nu\pi\partial_\rho\pi\partial_\sigma\pi\right)$$



1411.3727 (Hochberg *et al* '15)++

Kinetic equilibrium with SM required to avoid DM overproduction. Many ways (interactions) to do this:

dark photons, ALPs, Higgs portal,...

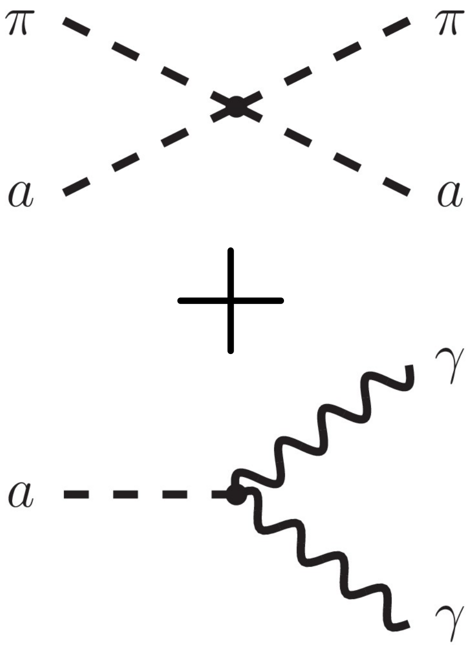
Hochberg, Kuflik & Murayama '15
Berlin, NB, Gori, Schuster & Toro '18
Katz, Salvioni & Shakya '20

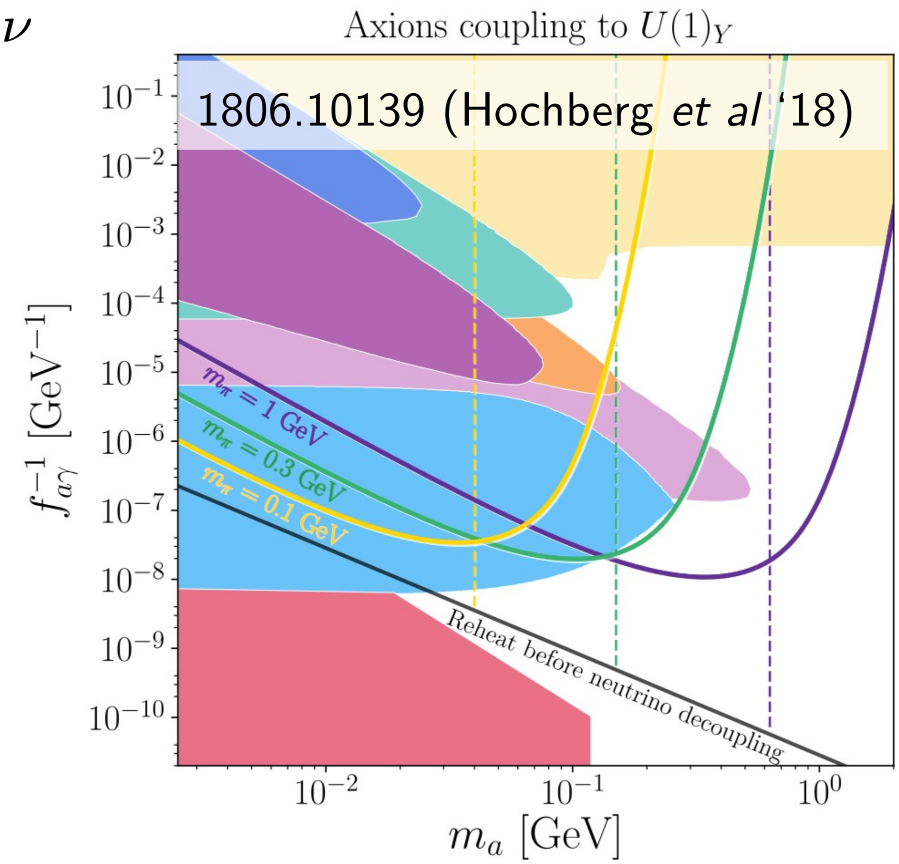
Choi *et al '17*

Hochberg *et al '18*

Kinetic Equilibrium With ALPs

$$\mathcal{L} \supset \kappa a^2 \pi^2 + \frac{a}{f_{a\gamma}} F_{\mu\nu} \widetilde{F}^{\mu\nu}$$

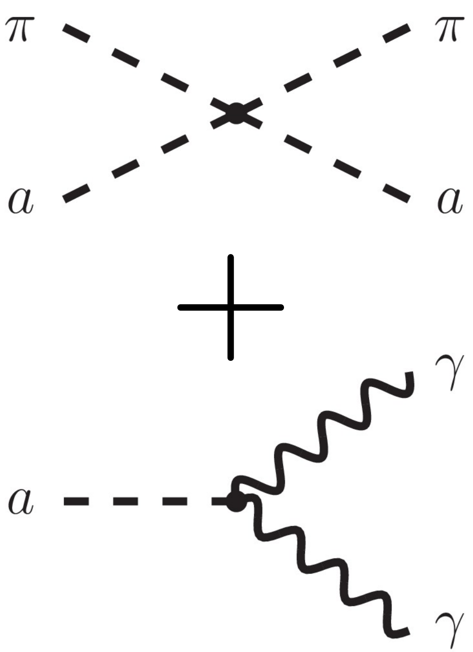


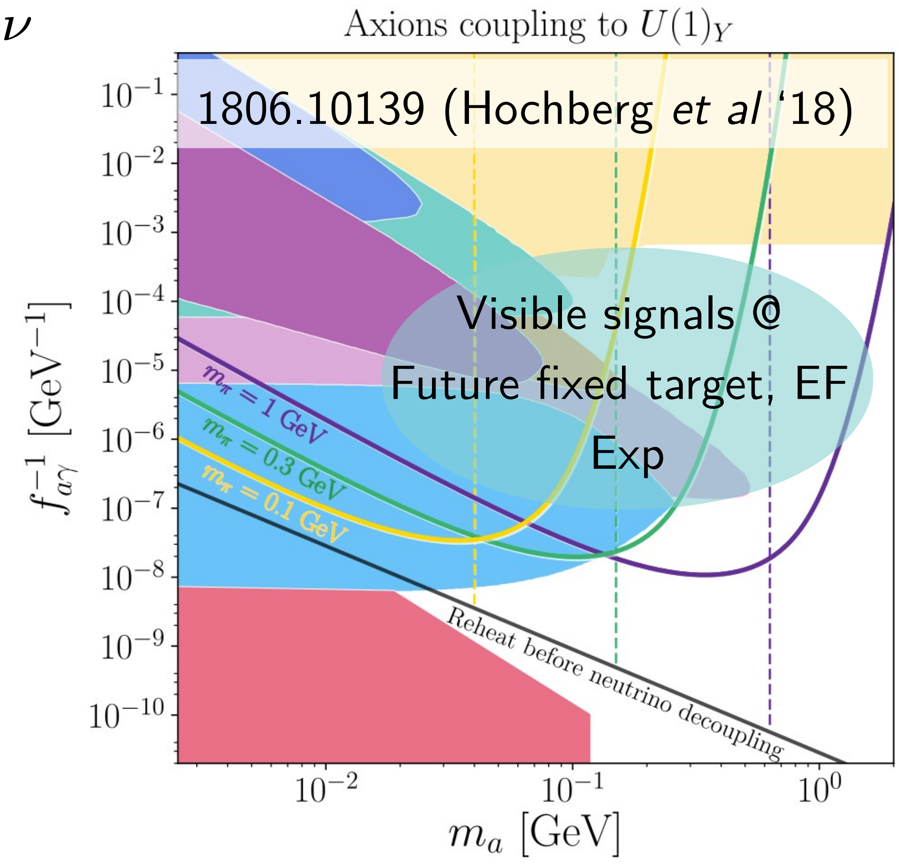

1806.10139 (Hochberg *et al* ‘18)

Requiring that this is rapid enough gives **lower** bound on $f_{a\gamma}^{-1}$

Kinetic Equilibrium With ALPs

$$\mathcal{L} \supset \kappa a^2 \pi^2 + \frac{a}{f_{a\gamma}} F_{\mu\nu} \widetilde{F}^{\mu\nu}$$





1806.10139 (Hochberg *et al* '18)

Visible signals @ Future fixed target, EF Exp

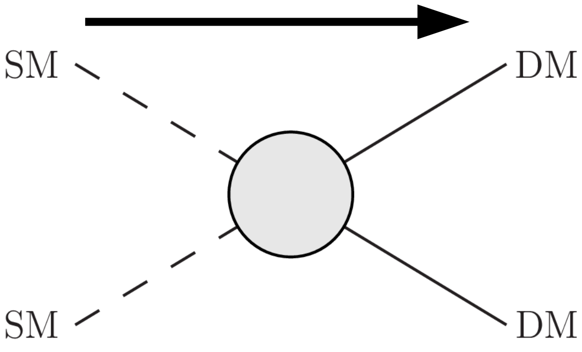
Requiring that this is rapid enough gives **lower** bound on $f_{a\gamma}^{-1}$

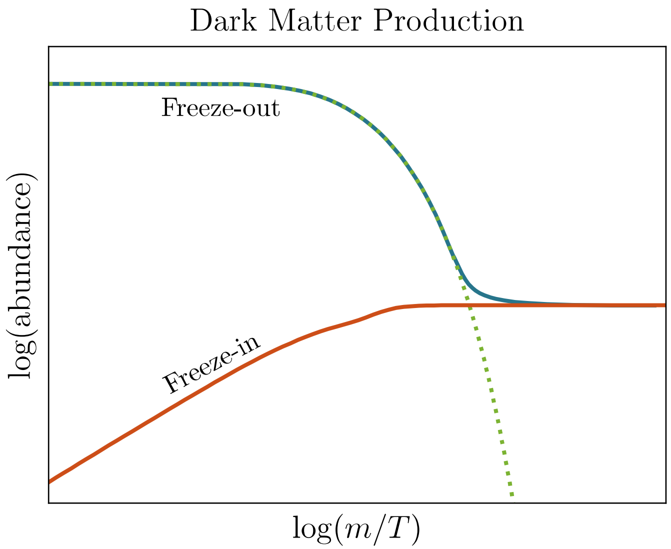
Non-Thermal Dark Matter

DM particles were *never* in kinetic or chemical equilibrium with the SM

$$T_\chi \neq T_{SM}$$

$$n_\chi = \int \frac{d^3p}{(2\pi)^3} f_\chi(E)$$





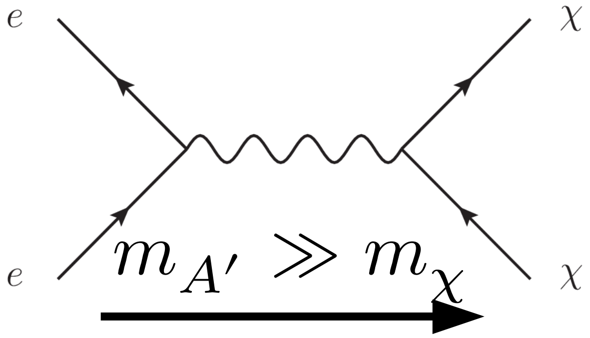
$$n_{\rm SM}\langle\sigma v\rangle \ll H(T)$$

$$\Omega_\chi \propto \int_{t_i} dt\, n_{\rm SM}\langle\sigma v\rangle$$

Dodelson & Widrow ‘93; Hall *et al* ‘09

Example 1: Freeze-in With a Massive A’

Freeze-in typically requires tiny couplings

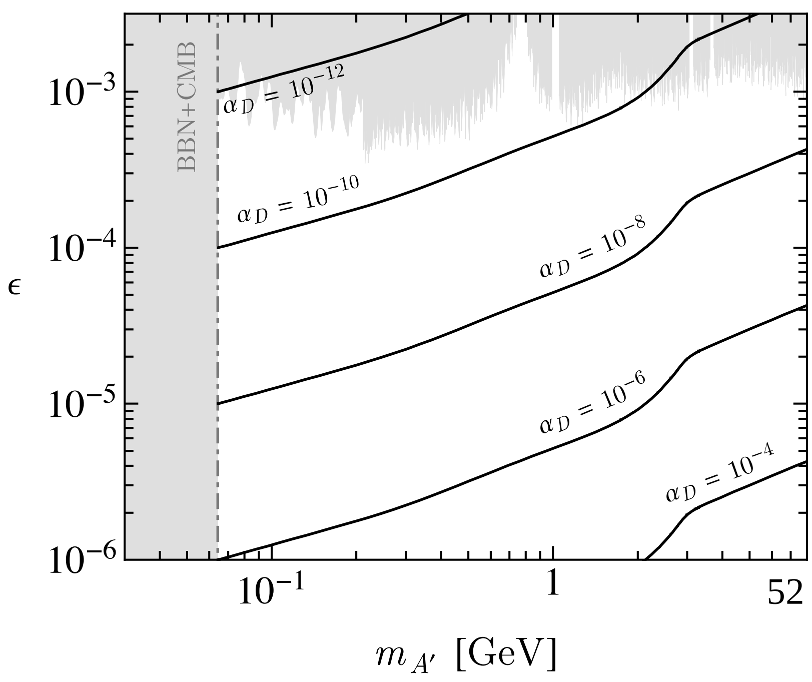


$$m_{A'} \gg m_\chi$$

$$\epsilon^2\alpha_D \sim 10^{-22}\left(\frac{m_{A'}}{m_\chi}\right)$$

Berlin, NB, Krnjaic, Schuster & Toro ‘18

Low−Reheat Freeze−In, $m_{A'} = 15\ T_{\rm RH}$, $m_\chi = 10$ keV



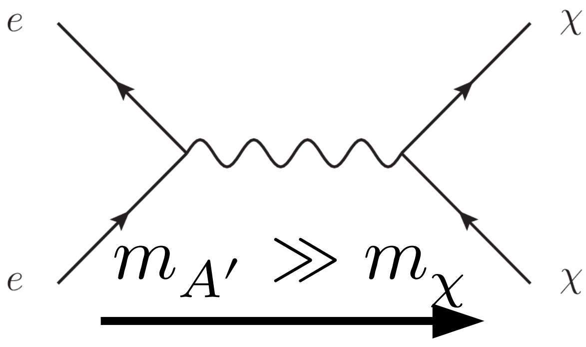
Accelerator-accessible signals possible if

$$\alpha_D \lll 1$$

Visible and invisible mediator decays

Example 1: Freeze-in With a Massive A'

Freeze-in typically requires tiny couplings



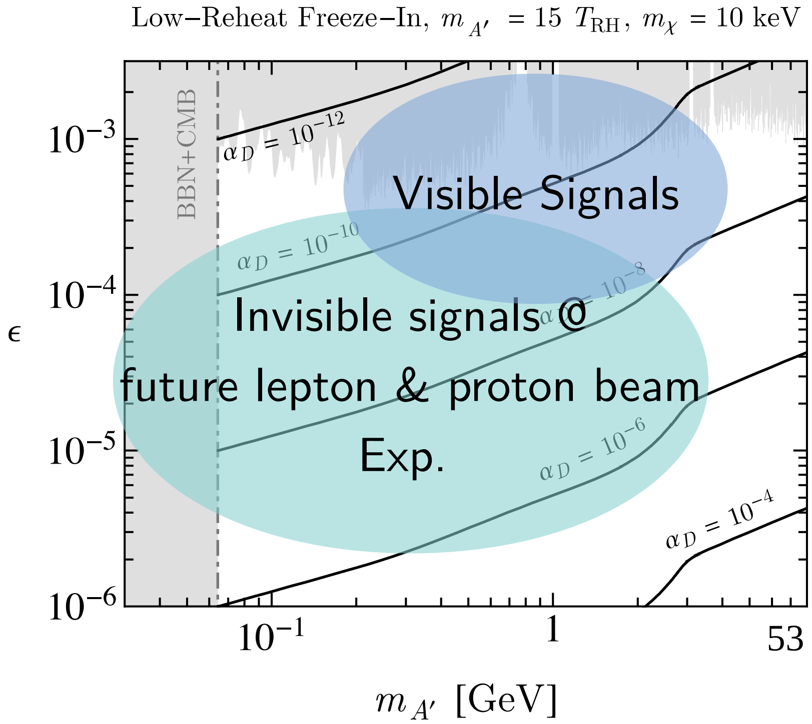
$$\epsilon^2 \alpha_D \sim 10^{-22} \left(\frac{m_{A'}}{m_\chi} \right)$$

Berlin, NB, Krnjaic, Schuster & Toro '18

Accelerator-accessible signals possible if

$$\alpha_D \lll 1$$

Visible and invisible mediator decays

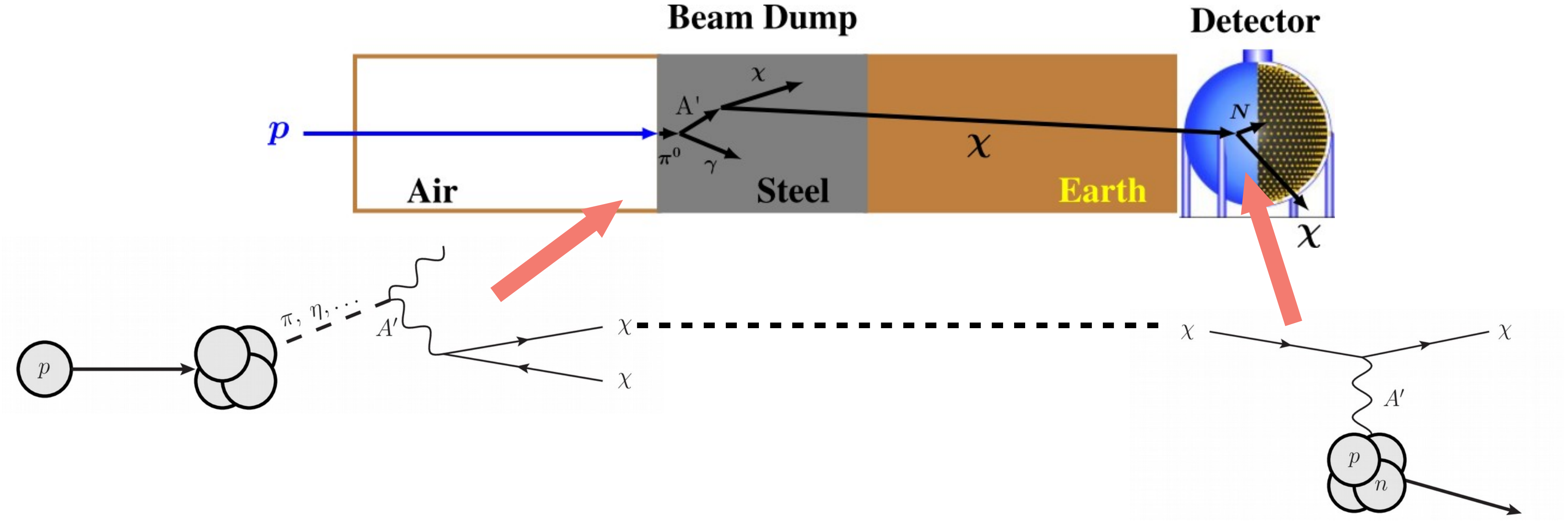


Visible Signals

Invisible signals @ future lepton & proton beam Exp.

Detecting a DM Beam: Beam Dump Searches

DeNiverville, Pospelov, Ritz ‘12; MiniBooNE-DM ‘18



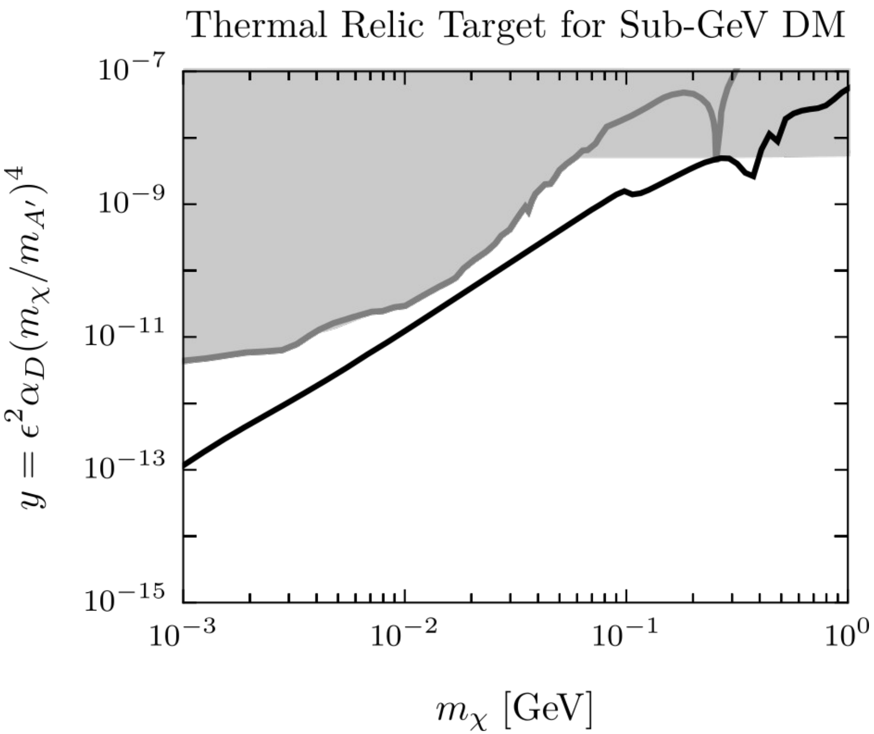
$$\text{production} \propto y \qquad\qquad \text{detection} \propto y$$

$$\text{Signal Yield} \sim y^2 \times N_{\rm POT}$$

Only a small fraction ∼ y of DM detected. Can we do better?

Detecting a DM Beam: Beam Dump Searches

DeNiverville, Pospelov, Ritz ‘12; MiniBooNE-DM ‘18



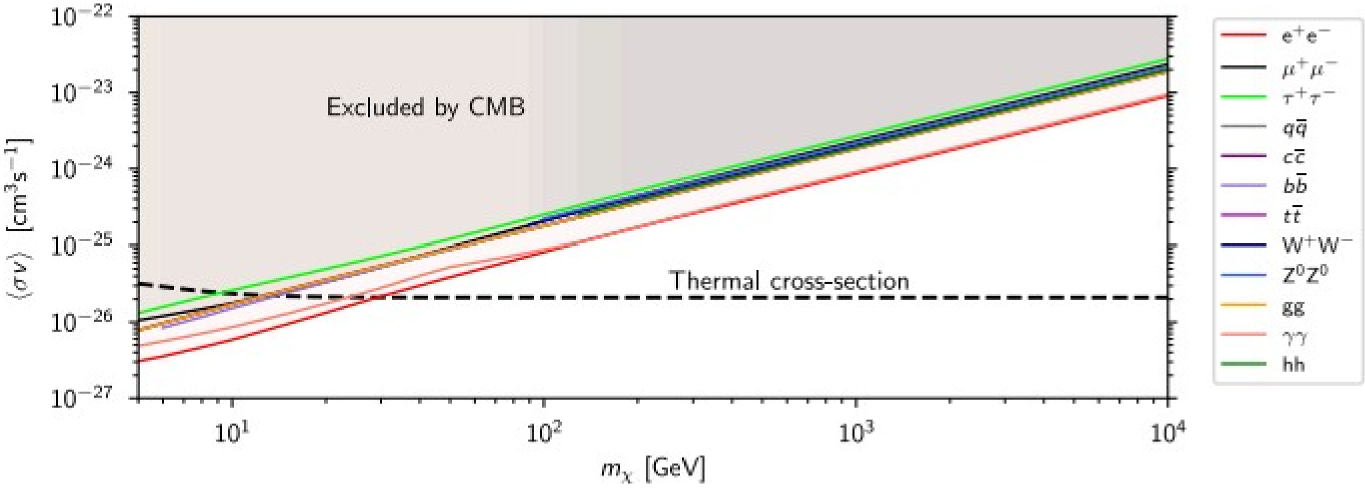
$$\text{Signal Yield} \sim y^2 \times N_{\text{POT}}$$

Only a small fraction ∼ y of DM detected. Can we do better?

Indirect Searches

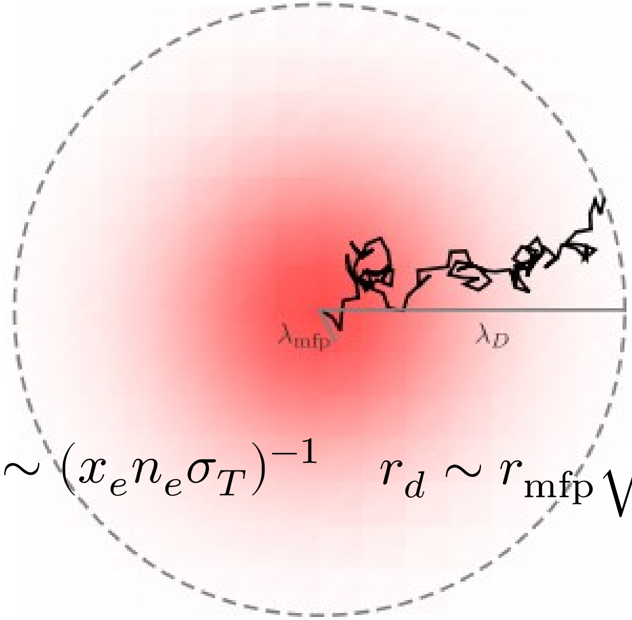
Look for annihilation products today: but CMB bounds preclude an indirect detection signal

If residual annihilation continue after recombination: ionize neutral hydrogen and distort the CMB!
E.g. 100 MeV DM particle annihilating to electrons has enough energy to dissociate 10^7 H atoms!



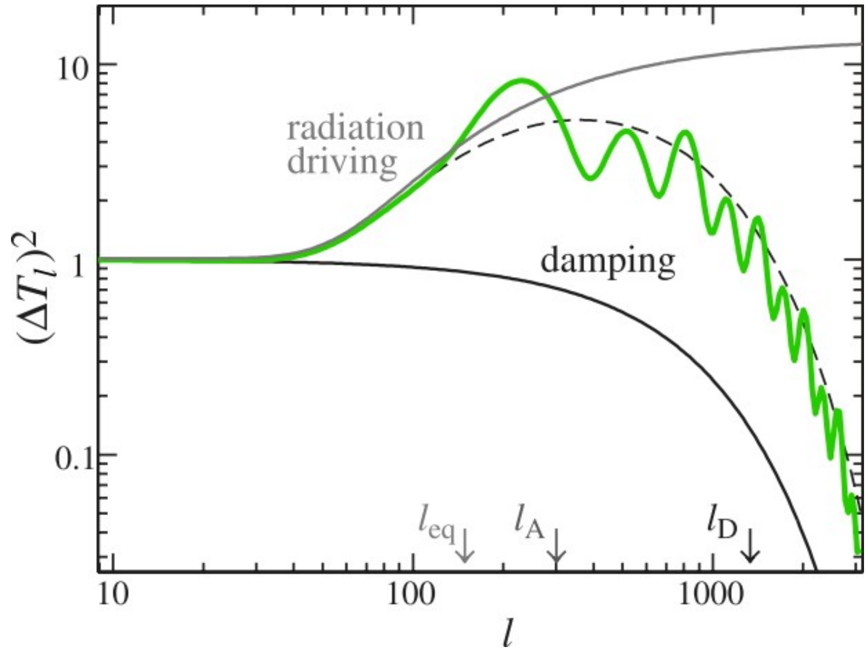
Late-time annihilations must be suppressed – no indirect detection signal

Photon Diffusion Damping



$r_{\rm mfp} \sim (x_e n_e \sigma_T)^{-1}$ $\quad r_d \sim r_{\rm mfp}\sqrt{t/r_{\rm mfp}}$

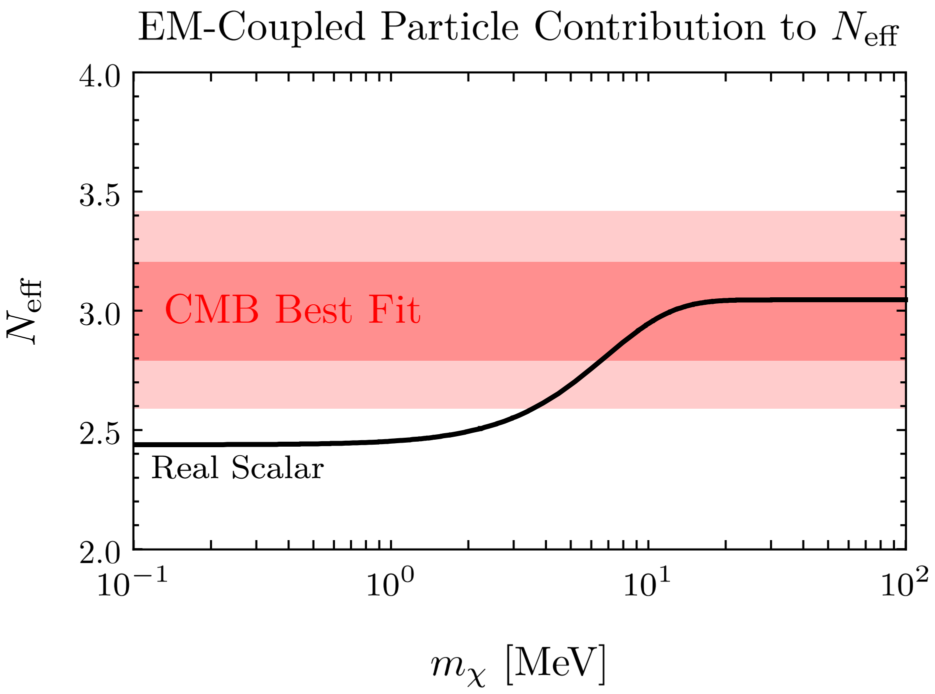
Hu, Fukugita, Zaldarriaga & Tegmark (2000)



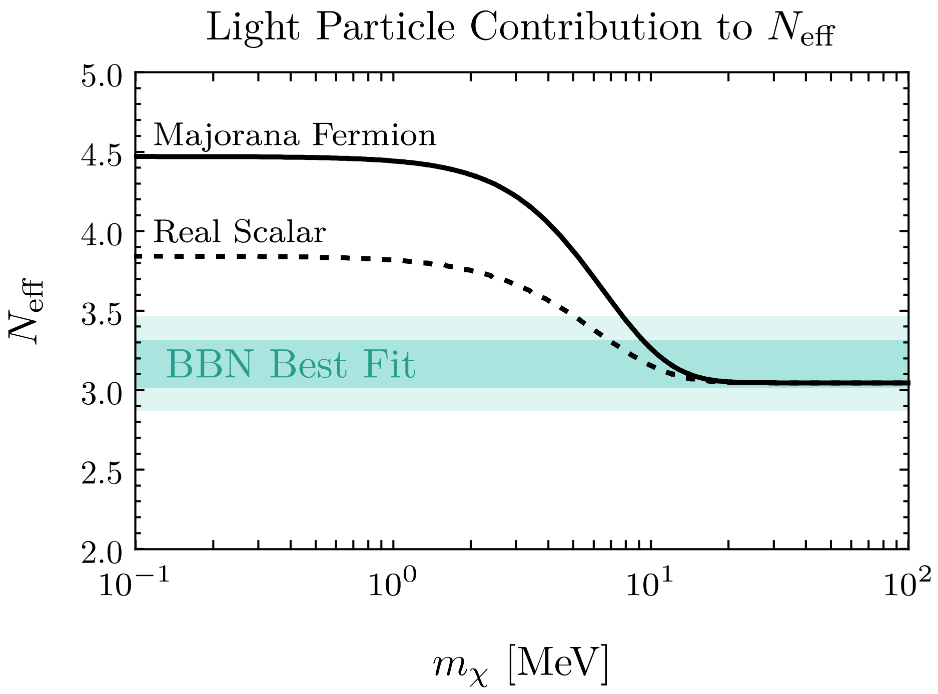
$$r_d^2 \sim \int_0^{a_d} \frac{da}{a^3 x_e n_e H(a) \sigma_T}$$

Precise measurements at large ℓ preclude large modifications to r_d relative to r_s

Light Dark Sectors and BBN



EM-Coupled Particle Contribution to $N_{\rm eff}$

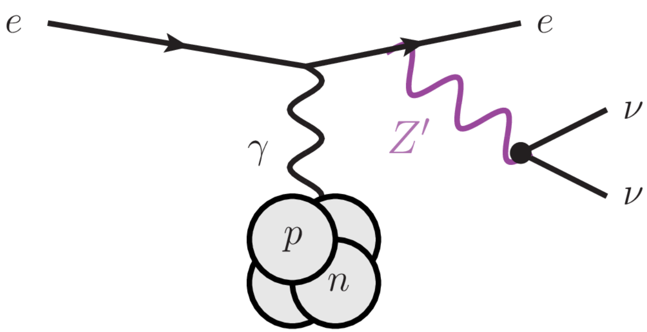


Light Particle Contribution to $N_{\rm eff}$

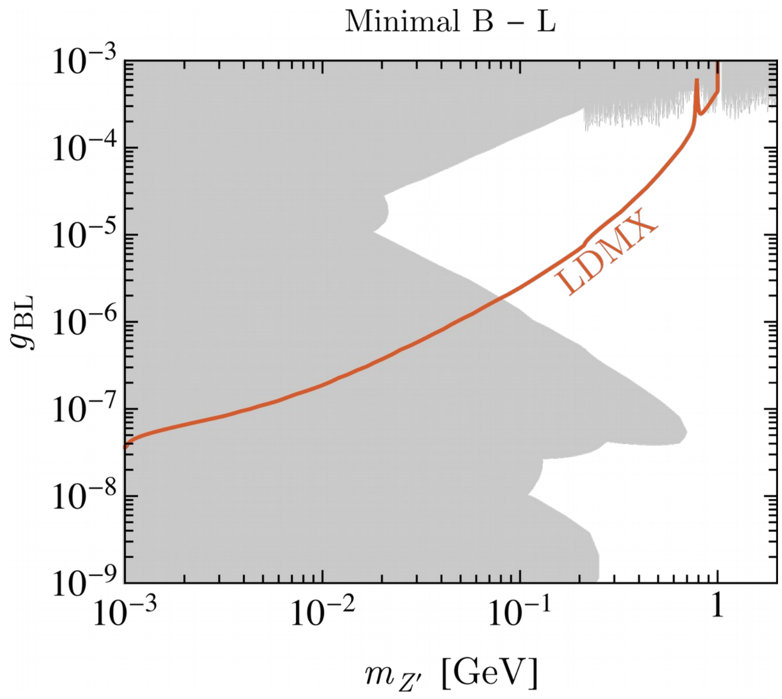
Beyond Dark Photons: New Gauge Bosons

Many theoretically consistent extensions of SM have couplings to **electrons** and **neutrinos**:

New force carriers Z' of $U(1)_{B-L}$, $U(1)_{B-3L_i}$, $U(1)_{L_i-L_j}, \ldots$



Missing Momentum w/o Dark Matter!



Berlin, **NB**, Krnjaic, Schuster, Toro ‘19