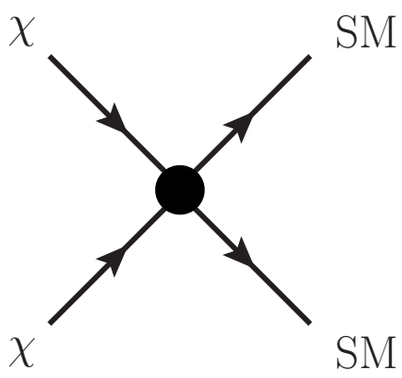
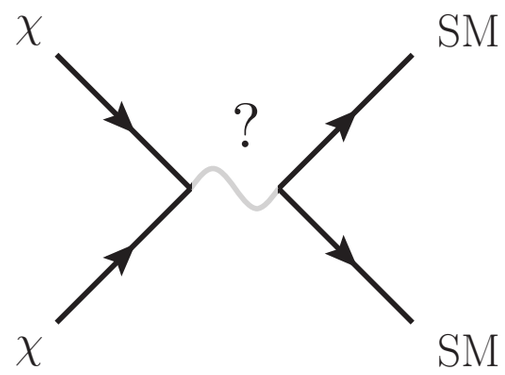
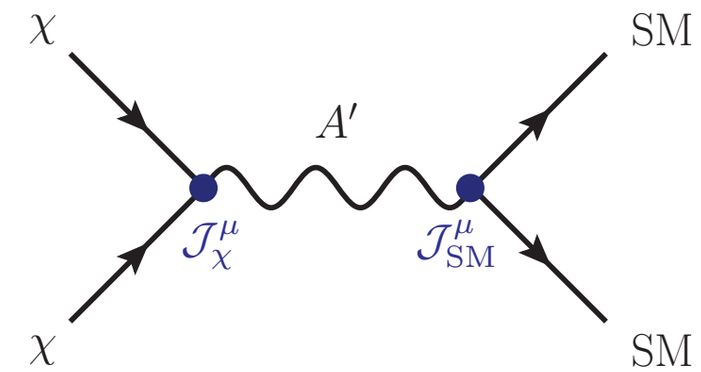




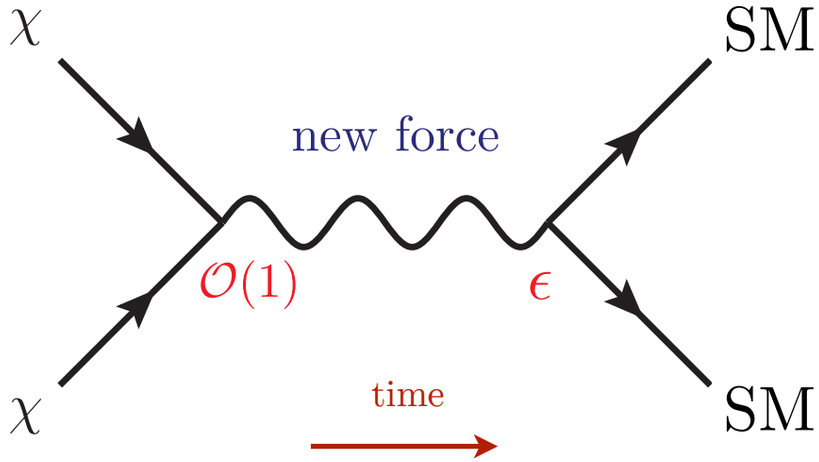


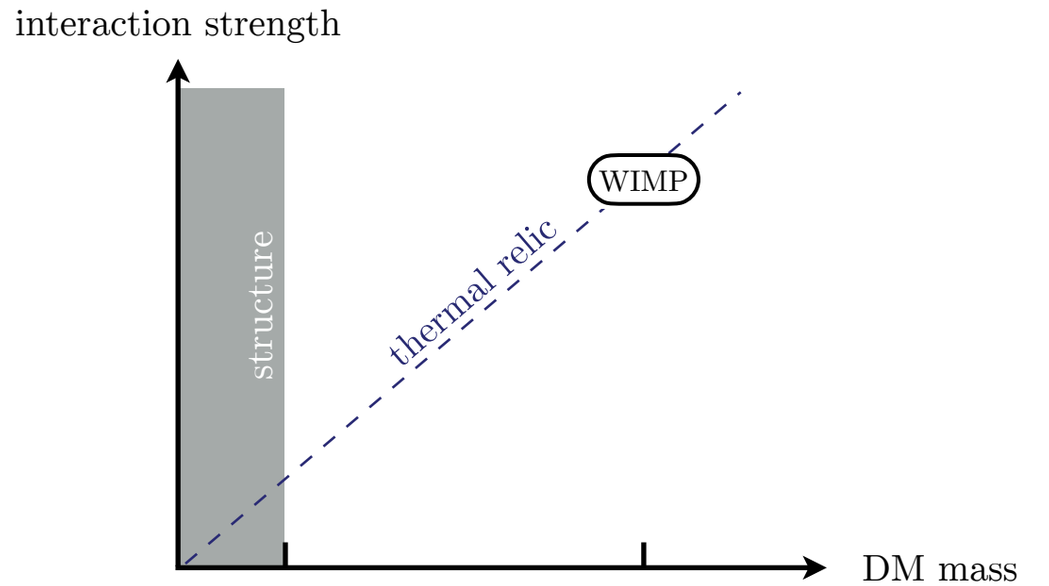
Thermal Targets in Minimal Dark Photon Models

Asher Berlin (NYU)

RF6 Dark Sector Theory Day 1
December 4, 2020

Light Mediators



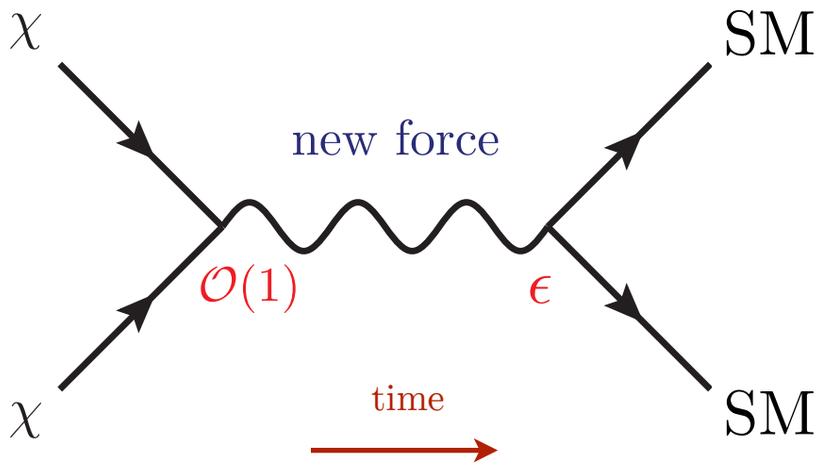


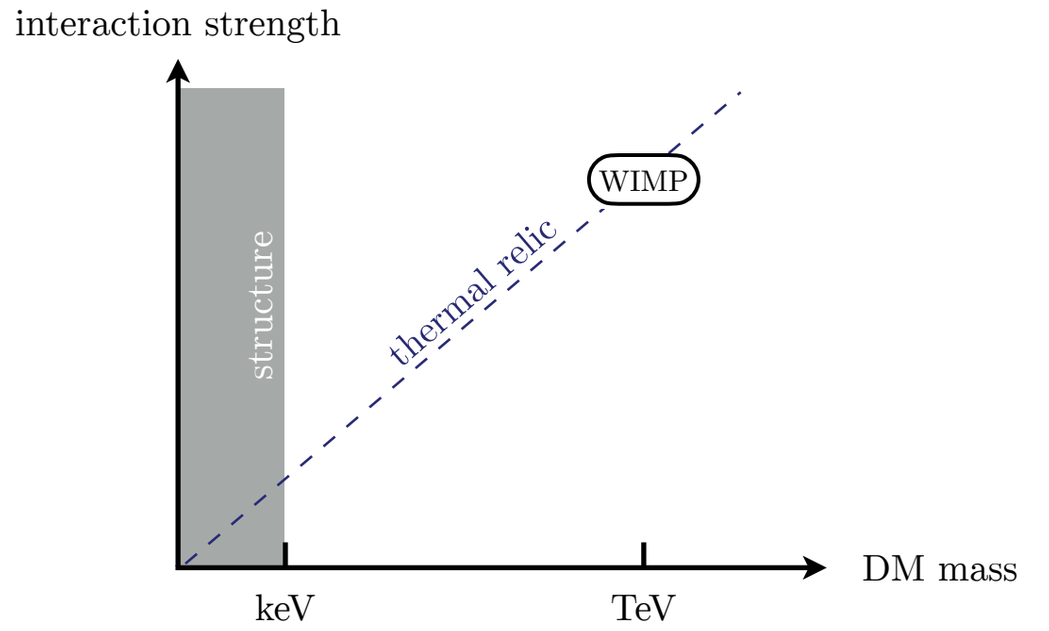
smaller couplings and smaller masses $\Longrightarrow$ same cross section

$$\sigma v(T \sim m_\chi) \sim \frac{\text{SM coupling}^2}{\text{mass}^2} \sim \frac{1}{(10\ \text{TeV})^2}$$

arXiv: hep-ph/0305261
Phys.Rev.Lett. 39 (1977) 165-168

Light Mediators





smaller couplings and smaller masses $\Longrightarrow$ same cross section

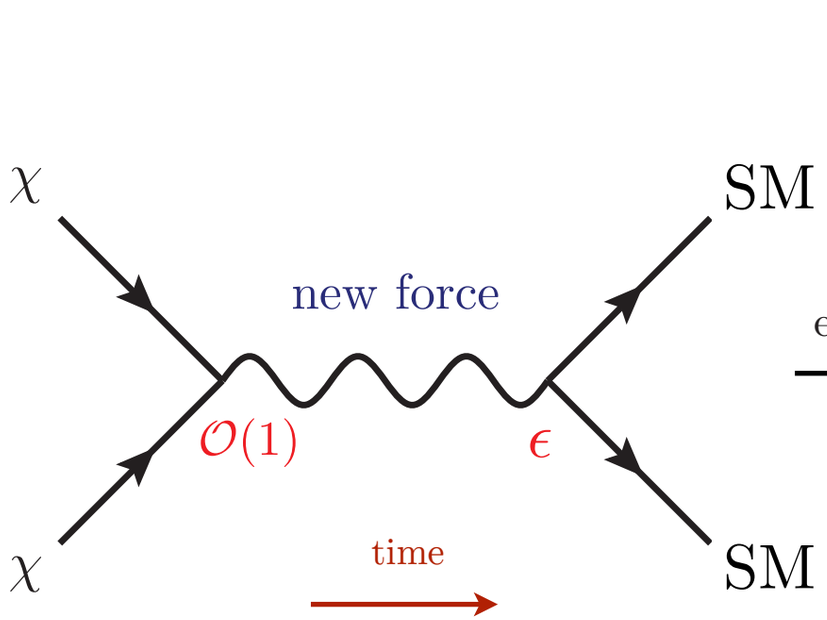
$$\sigma v(T \sim m_\chi) \sim \frac{\text{SM coupling}^2}{\text{mass}^2} \sim \frac{1}{(10\ \text{TeV})^2}$$

Why haven't we detected this force?

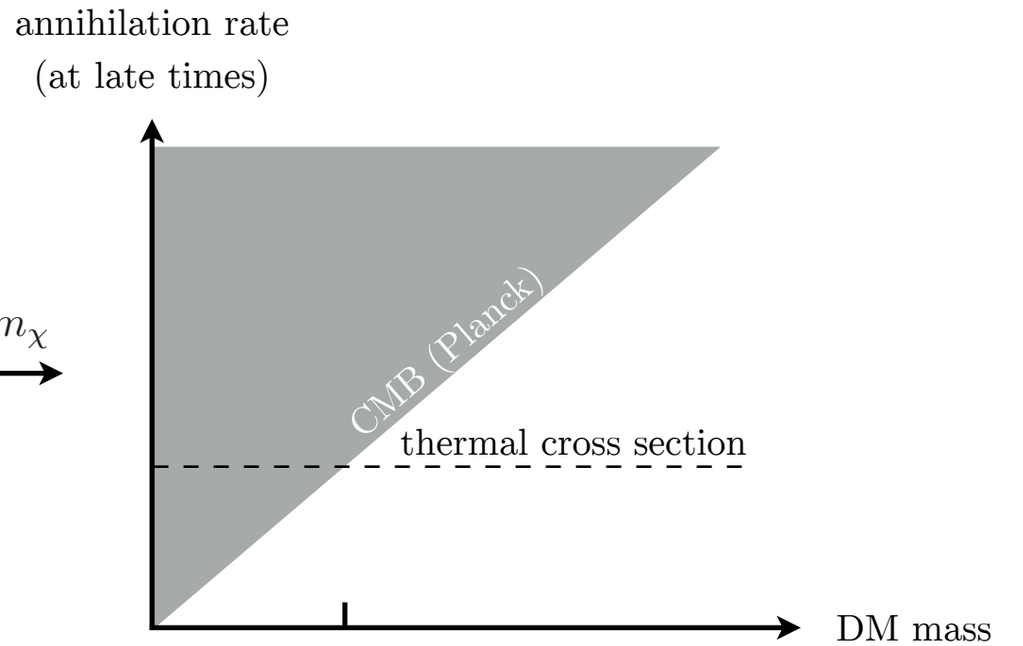
$$\epsilon \sim 10^{-5} \times \left(m_{\text{force}}/m_\chi\right)^2 \left(m_\chi/100\ \text{MeV}\right)$$

arXiv: hep-ph/0305261
Phys.Rev.Lett. 39 (1977) 165-168

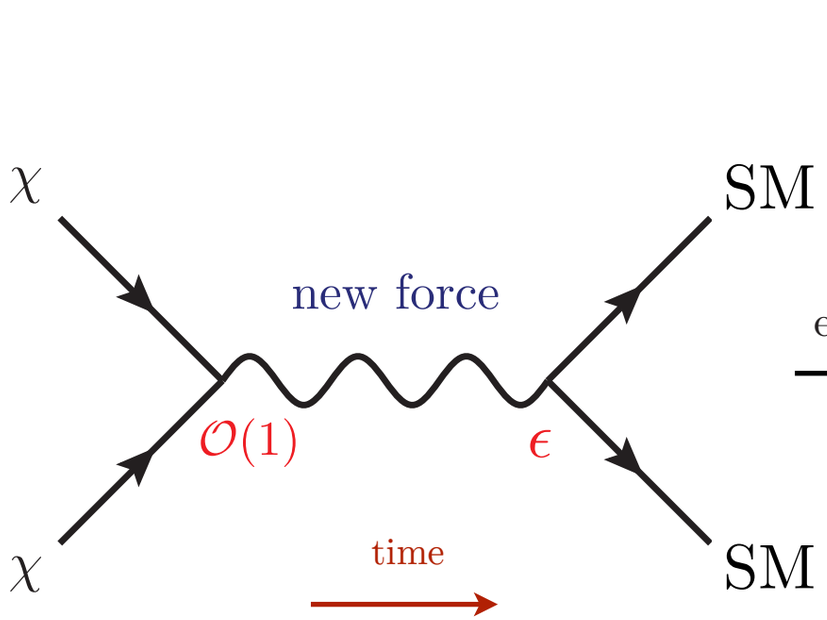
CMB



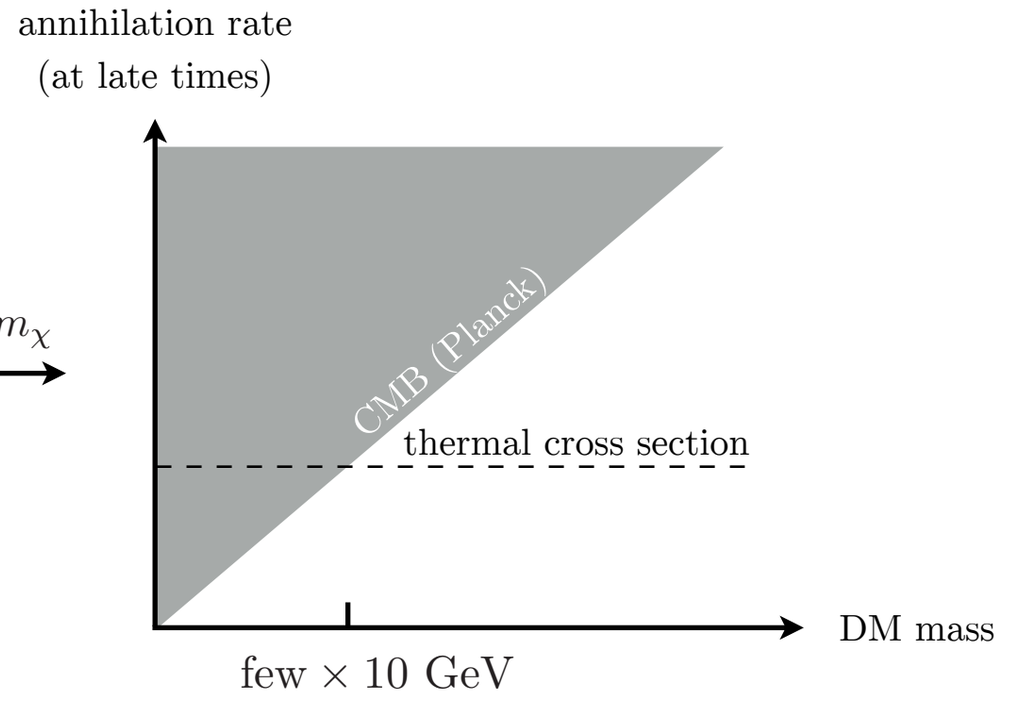
energy injection rate $\propto 1/m_\chi$



CMB



energy injection rate $\propto 1/m_\chi$



At times well after freeze-out, annihilations to visible final states should be suppressed for sub-GeV masses.

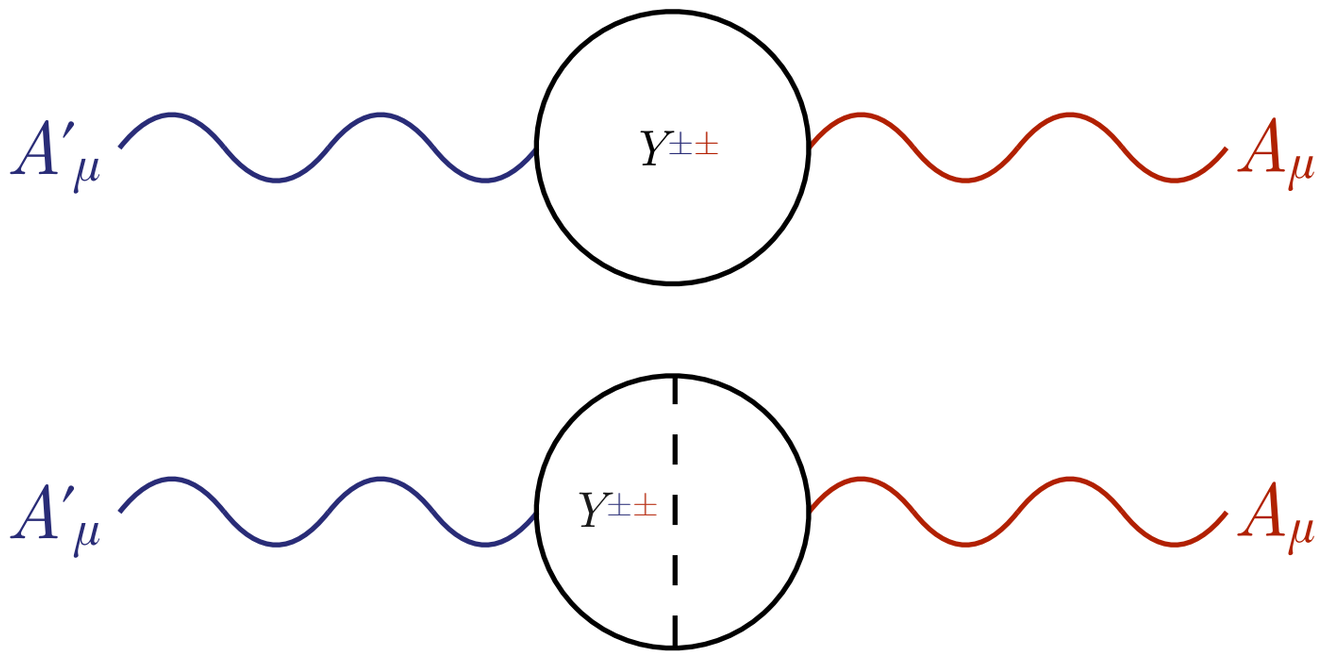
How generic is this?

$$\sigma v(T \sim \text{eV}) \ll \sigma v(T \sim m_\chi)$$

A Realistic and Simple Theory

$\epsilon\, A'_{\mu\nu}\, A^{\mu\nu}$

simple but not simplified...

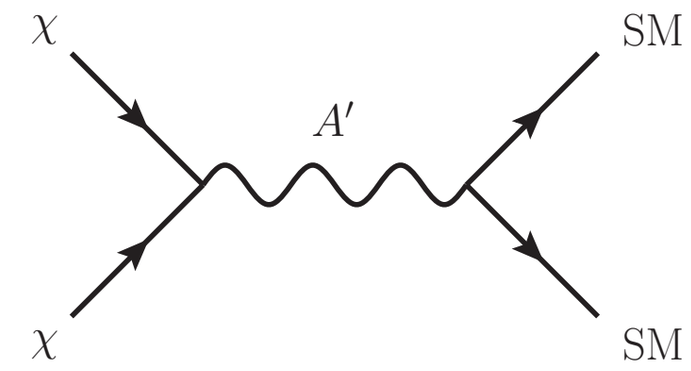
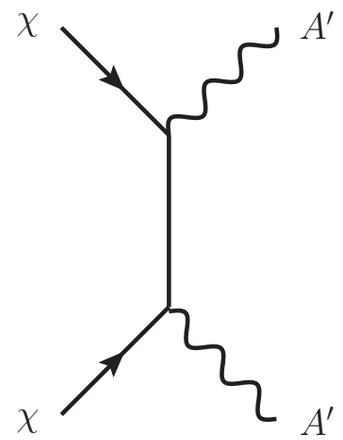
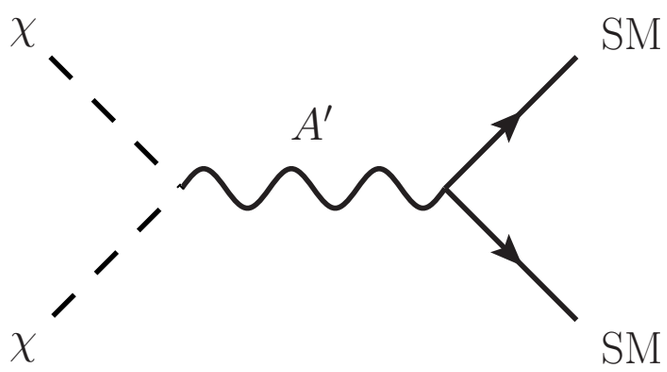
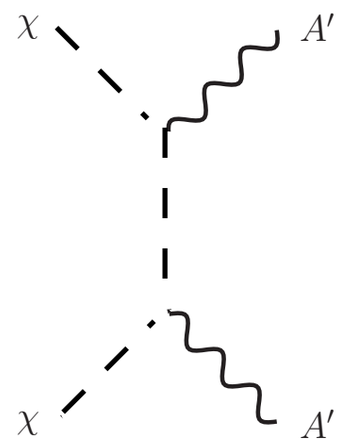


<u>small couplings</u> $\longleftrightarrow$ <u>small mass scales</u>

$\epsilon \sim 10^{-6} - 10^{-3}$ | $\epsilon\, m_{\rm weak} \sim m_e - m_p$

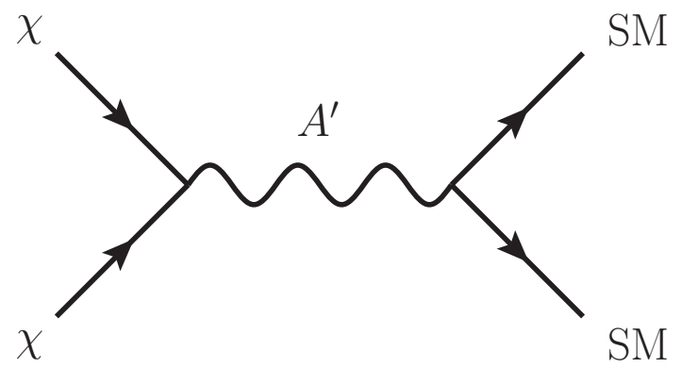
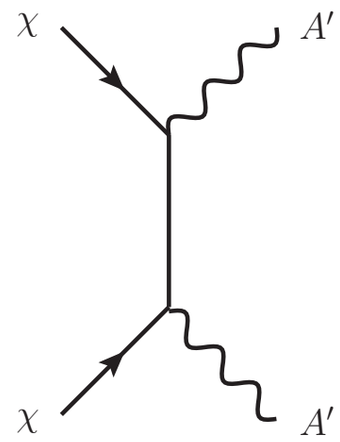
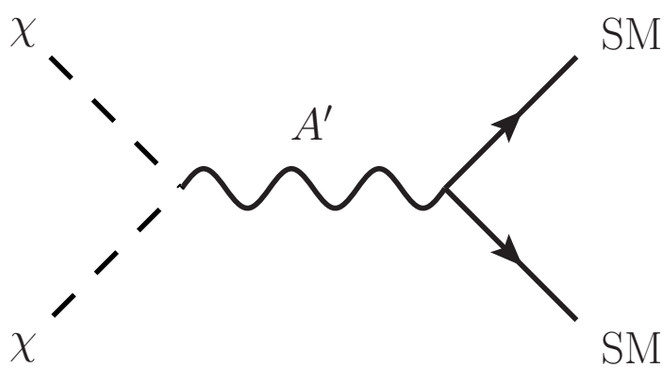
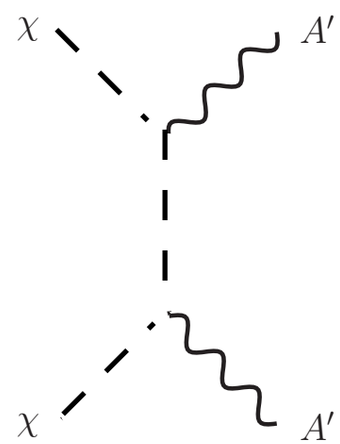
Phys.Lett.B 166 (1986)
arXiv:0902.3246

Minimal Thermal Dark Photon

	direct	indirect
fermion DM	 Dirac, pseudo-Dirac, Majorana	
scalar DM		

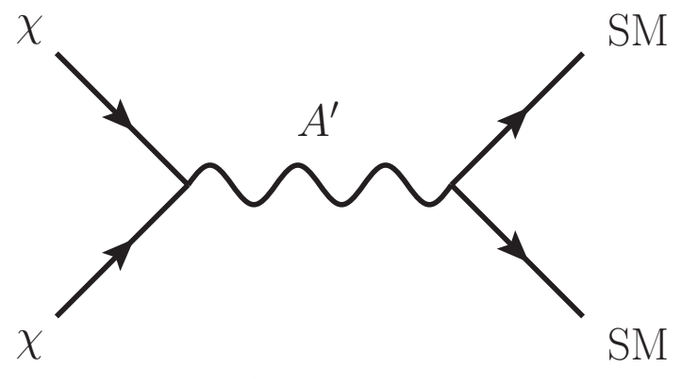
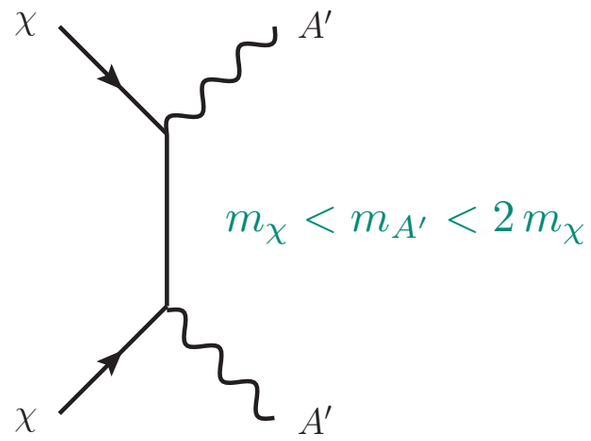
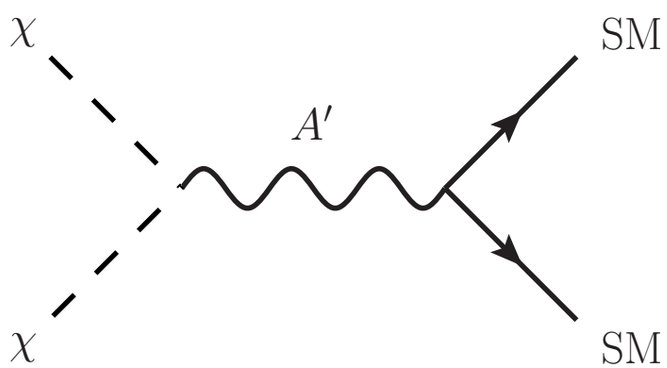
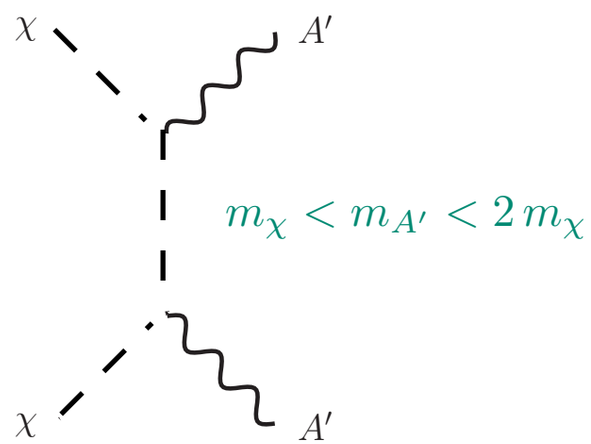
Minimal Thermal Dark Photon

forbidden $\sigma v \propto e^{-\delta m_\chi / T}$ *p*-wave $\sigma v \propto v^2$

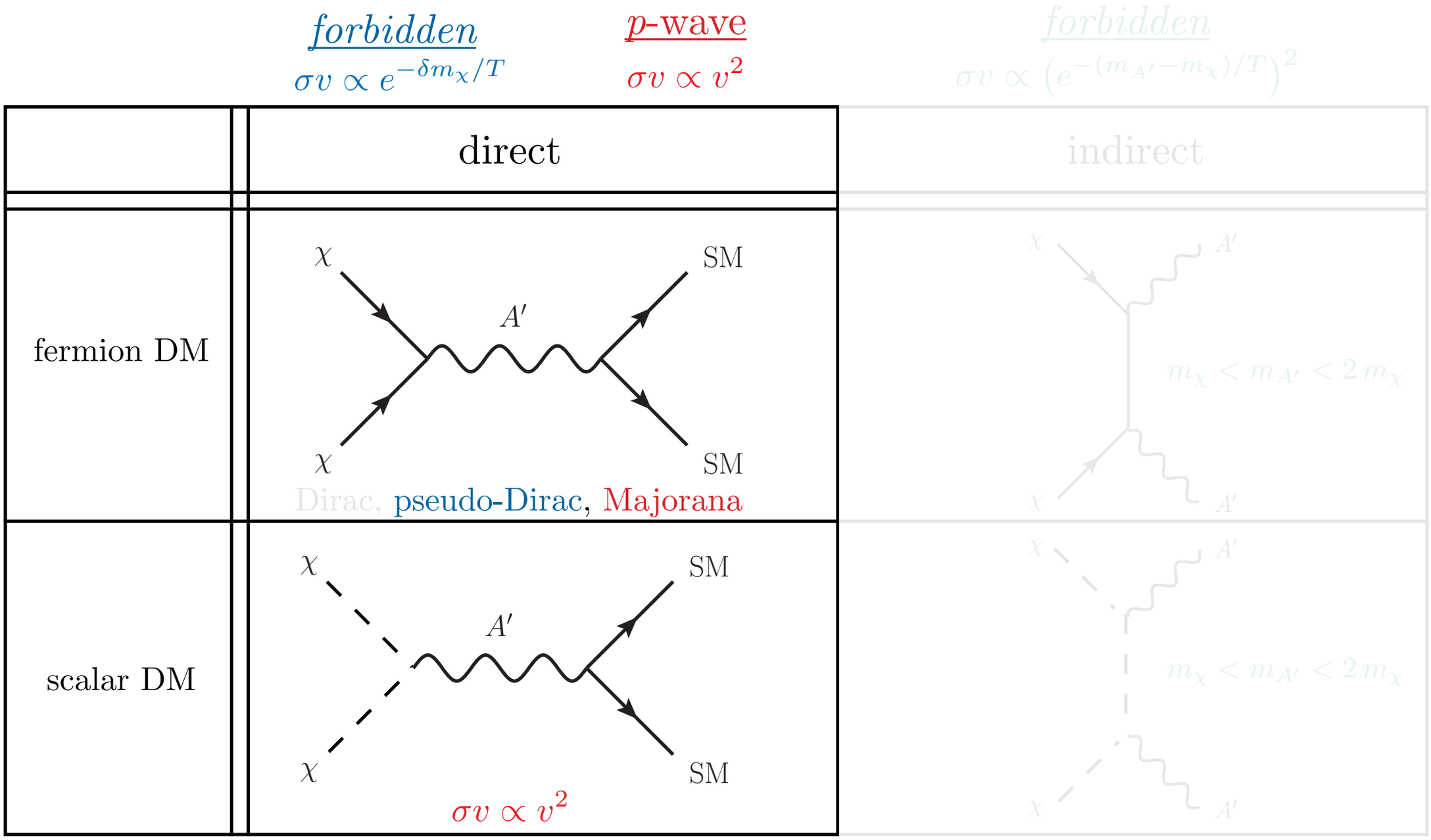
	direct	indirect
fermion DM	 Dirac, pseudo-Dirac, Majorana	
scalar DM	 $\sigma v \propto v^2$	

Minimal Thermal Dark Photon

<u>*forbidden*</u> $\sigma v \propto e^{-\delta m_\chi / T}$ | <u>*p*-wave</u> $\sigma v \propto v^2$ | <u>*forbidden*</u> $\sigma v \propto \left(e^{-(m_{A'}-m_\chi)/T}\right)^2$

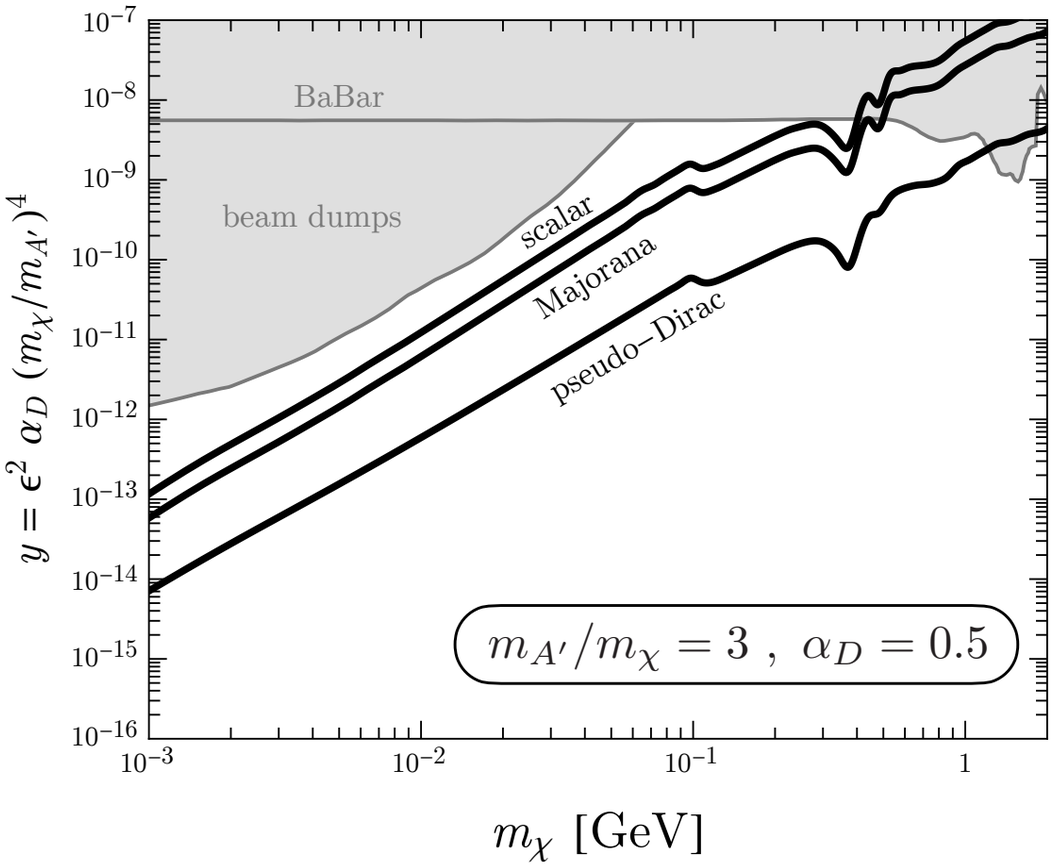
	direct	indirect
fermion DM	 Dirac, pseudo-Dirac, Majorana	
scalar DM	 $\sigma v \propto v^2$	

Minimal Thermal Dark Photon



I. Direct Annihilations

Direct Annihilations: y-m_χ plane



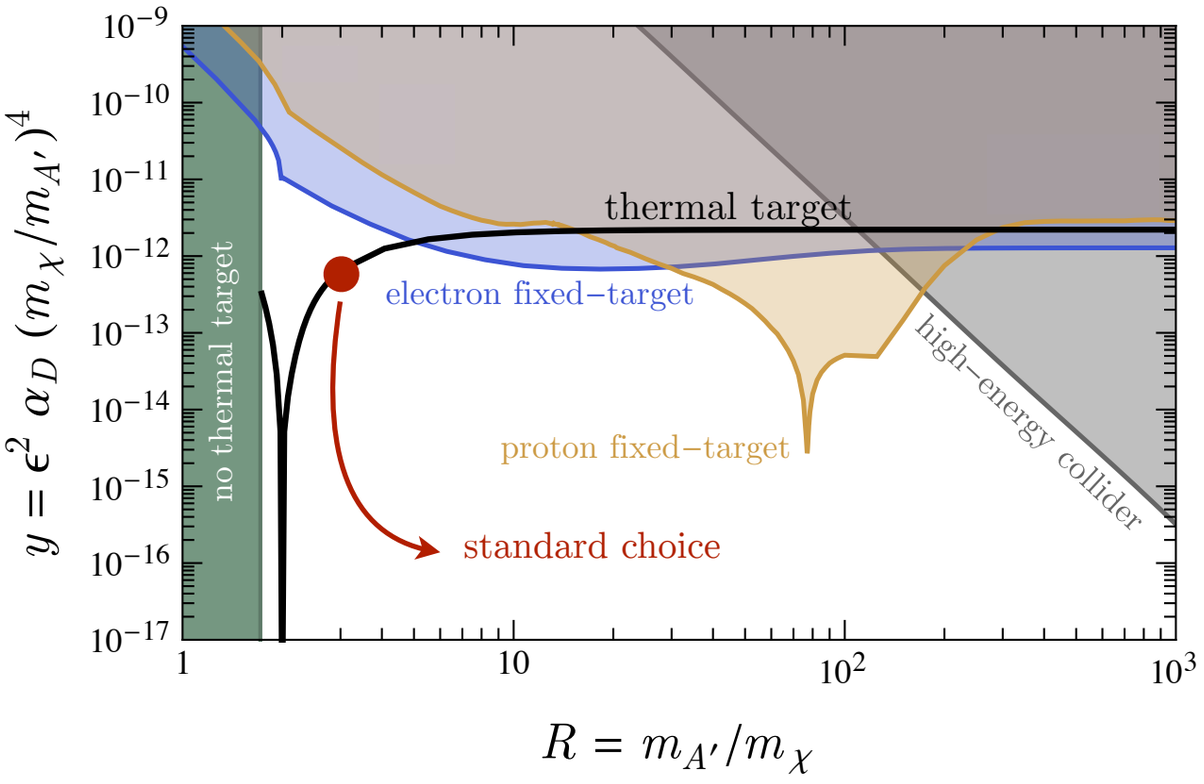
- $\sigma v \propto \alpha_{\rm em}\, y/m_\chi^2$
- y-target is fixed for $m_{A'}/m_\chi \gtrsim$ several

- fix dark sector coupling
- fix mediator-to-DM mass ratio
- vary DM mass

Similar story for other mediators, e.g., $U(1)_{B\text{-}L}$, $U(1)_{e\text{-}\mu}$, $U(1)_{\mu\text{-}\tau}$, etc.

see Berlin et al. arXiv:1807.01730

Direct Annihilations: y-R plane

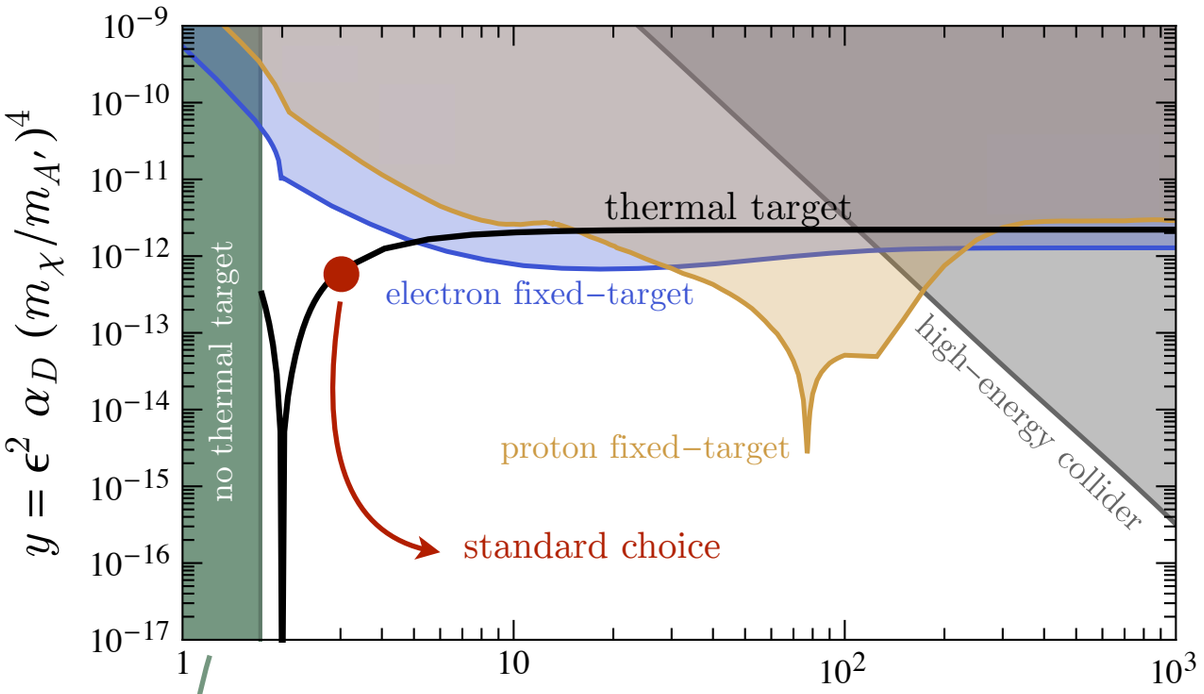


- $\sigma v \propto \alpha_{\rm em}\, y/m_\chi^2$
- y-target is fixed for $m_{A'}/m_\chi \gtrsim$ several

- fix dark sector coupling
- fix DM mass
- vary mediator-to-DM mass ratio

arXiv:2003.03379

Direct Annihilations: y-R plane



$\chi\chi \to A'A' + \chi\chi\chi \to \chi A'$ relevant

target → floor

(will come back to this later)

- $\sigma v \propto \alpha_{\rm em}\, y/m_\chi^2$
- y-target is fixed for $m_{A'}/m_\chi \gtrsim$ several

- fix dark sector coupling
- fix DM mass
- vary mediator-to-DM mass ratio

arXiv:2003.03379

Range of Momentum Scales

To meaningfully compare different avenues towards discovery:

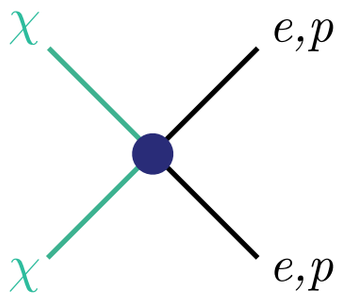
What momentum scales do experiments probe compared to the early universe?

Range of Momentum Scales

time →

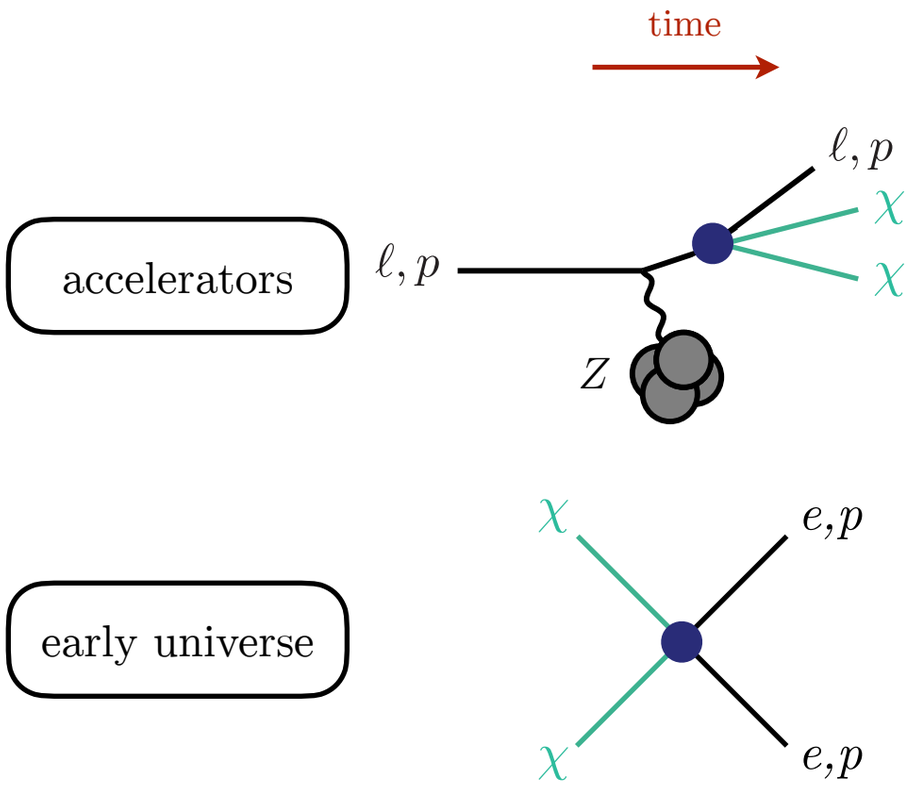
momentum transfer $\sim q$

early universe



$q \sim m_\chi$

Range of Momentum Scales



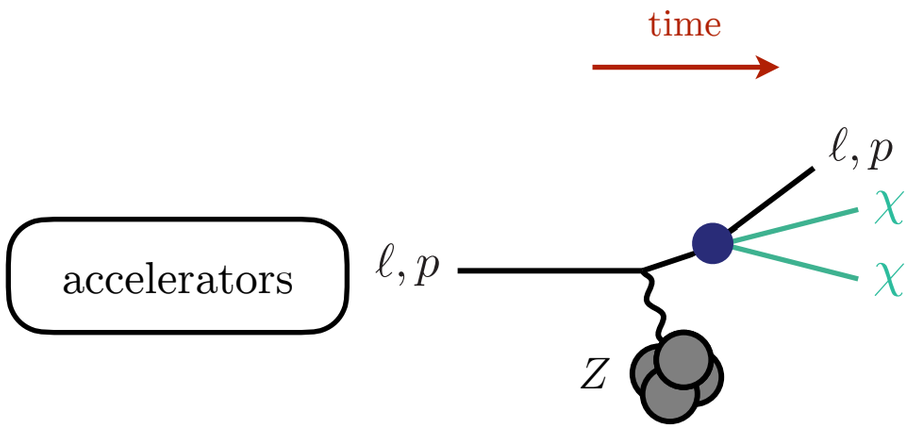
momentum transfer $\sim q$

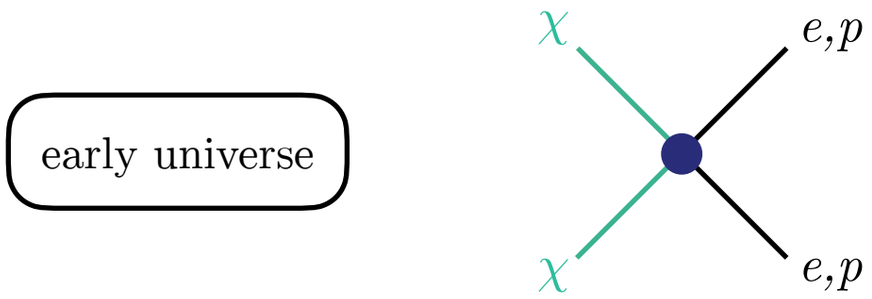
$q \gtrsim m_\chi$ (robust)

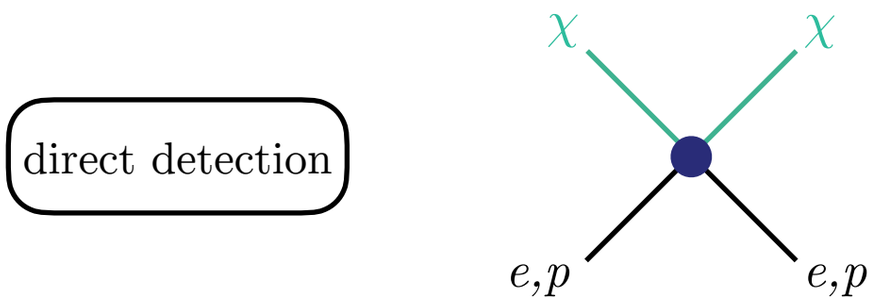
less sensitive to interaction structure

$q \sim m_\chi$

Range of Momentum Scales







momentum transfer $\sim q$

$q \gtrsim m_\chi$ (robust)

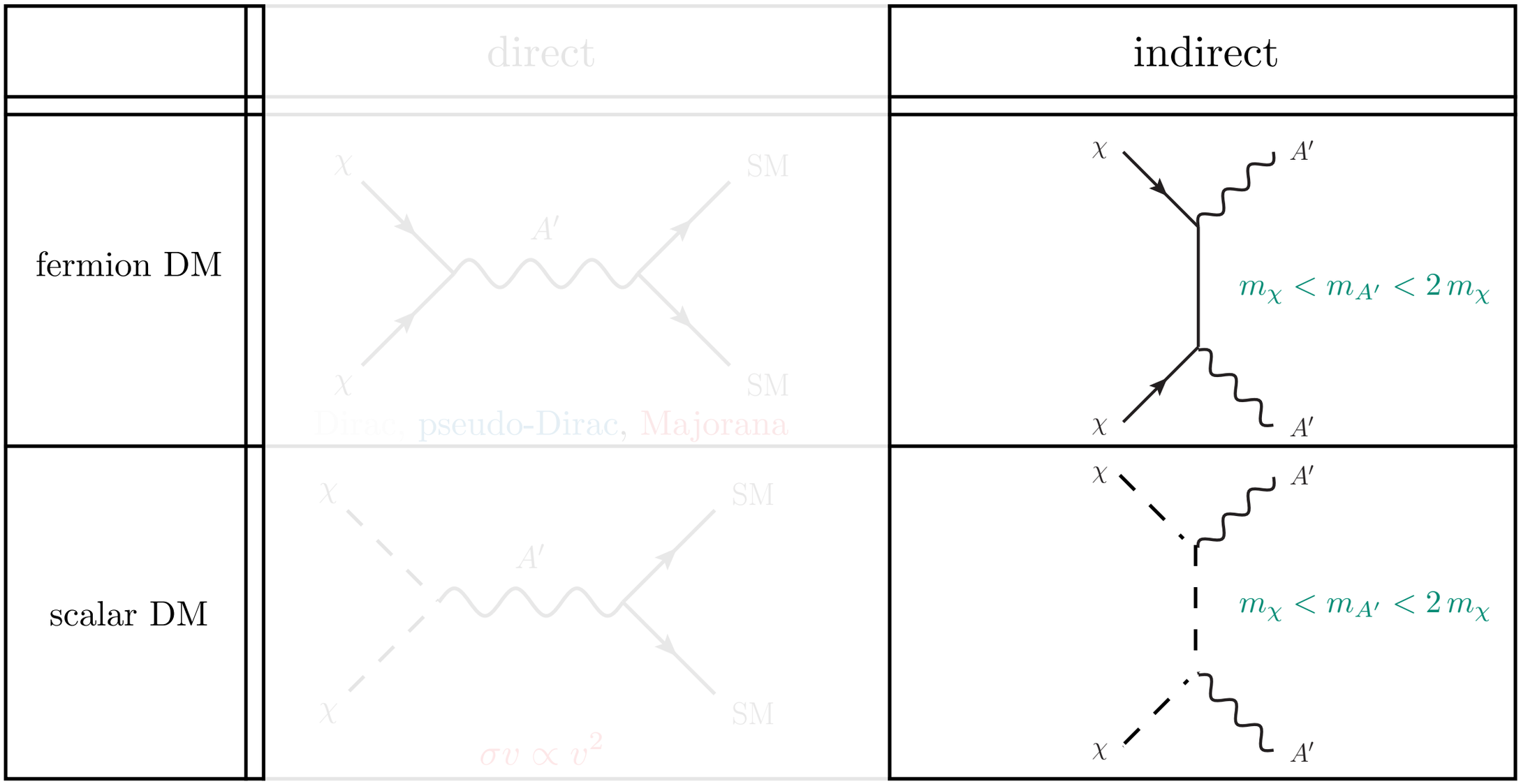
less sensitive to interaction structure

$q \sim m_\chi$

more sensitive to interaction structure

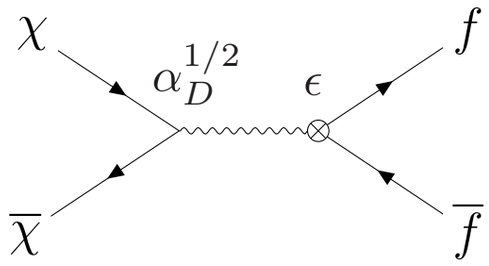
$q \ll m_\chi$ (suppressions/enhancements)

Minimal Thermal Dark Photon



II. Indirect Annihilations

Dark Sector Dynamics



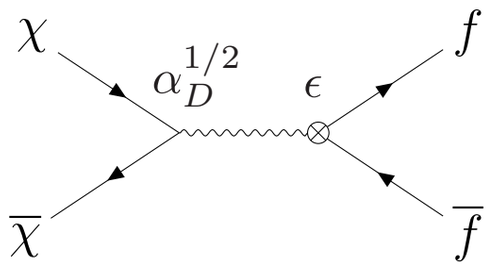
$\text{rate} \propto \alpha_D \, \alpha_{\text{em}} \, \epsilon^2 \propto y$

- For Dirac fermion, CMB constrains late-time annihilations:

$$y/y_{\text{target}} \lesssim 10^{-3} \times (m_\chi/100 \text{ MeV})$$

PRD 43 (1991)
arXiv:1505.07107
arXiv:1702.07716
arXiv:2011.01240

Dark Sector Dynamics



rate $\propto \alpha_D\, \alpha_{\rm em}\, \epsilon^2 \propto y$

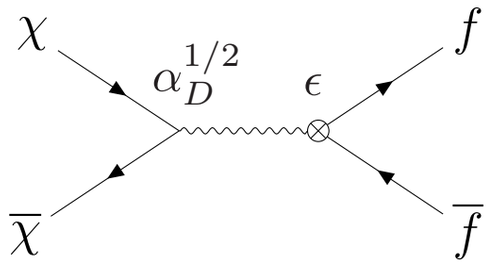
- For Dirac fermion, CMB constrains late-time annihilations:

$$y/y_{\rm target} \lesssim 10^{-3} \times (m_\chi/100\ {\rm MeV})$$

- For smaller ϵ and large α_D, hidden sectors processes dominate.

PRD 43 (1991)
arXiv:1505.07107
arXiv:1702.07716
arXiv:2011.01240

Dark Sector Dynamics

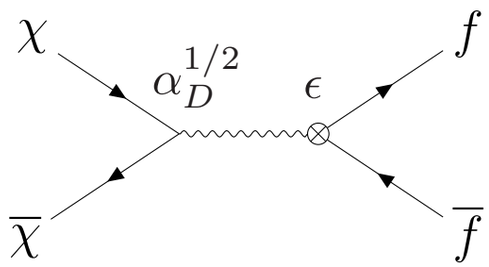


rate $\propto \alpha_D\, \alpha_{\rm em}\, \epsilon^2 \propto y$

- For Dirac fermion, CMB constrains late-time annihilations:
$$y/y_{\rm target} \lesssim 10^{-3} \times (m_\chi/100\ {\rm MeV})$$
- For smaller ϵ and large α_D, hidden sectors processes dominate.
- For $\epsilon \gtrsim 10^{-8} \times (m_{A'}/{\rm GeV})^{1/2}$, DM and SM equilibrate.

PRD 43 (1991)
arXiv:1505.07107
arXiv:1702.07716
arXiv:2011.01240

Dark Sector Dynamics



rate $\propto \alpha_D\, \alpha_{\rm em}\, \epsilon^2 \propto y$

- For Dirac fermion, CMB constrains late-time annihilations:

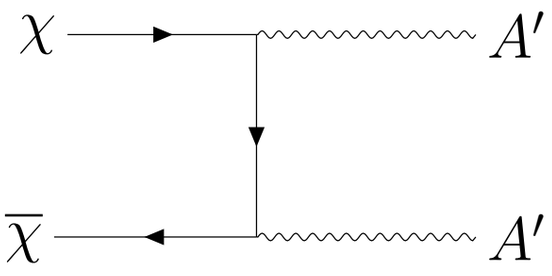
$$y/y_{\rm target} \lesssim 10^{-3} \times (m_\chi/100\ {\rm MeV})$$

- For smaller ϵ and large α_D, hidden sectors processes dominate.

- For $\epsilon \gtrsim 10^{-8} \times (m_{A'}/{\rm GeV})^{1/2}$, DM and SM equilibrate.

$$m_\chi < m_{A'} < 2\, m_\chi$$

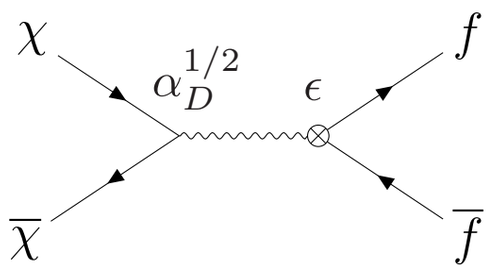
<u>kinematically forbidden channels</u>
(annihilation rates vanish at zero temperature)



rate $\propto \alpha_D^2 \left(e^{-(m_{A'}-m_\chi)/T}\right)^2$

PRD 43 (1991)
arXiv:1505.07107
arXiv:1702.07716
arXiv:2011.01240

Dark Sector Dynamics



rate $\propto \alpha_D\, \alpha_{\rm em}\, \epsilon^2 \propto y$

- For Dirac fermion, CMB constrains late-time annihilations:

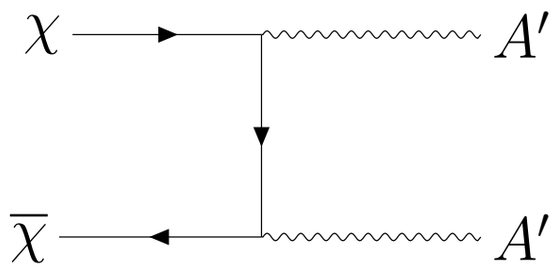
$$y/y_{\rm target} \lesssim 10^{-3} \times (m_\chi/100\ {\rm MeV})$$

- For smaller ϵ and large α_D, hidden sectors processes dominate.

- For $\epsilon \gtrsim 10^{-8} \times (m_{A'}/{\rm GeV})^{1/2}$, DM and SM equilibrate.

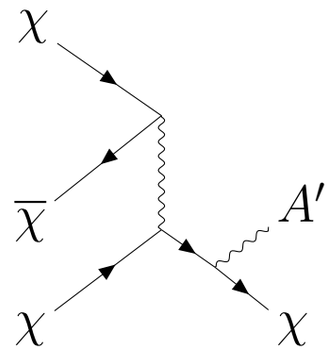
$$m_\chi < m_{A'} < 2\, m_\chi$$

<u>kinematically forbidden channels</u>
(annihilation rates vanish at zero temperature)



rate $\propto \alpha_D^2 \left(e^{-(m_{A'}-m_\chi)/T}\right)^2$

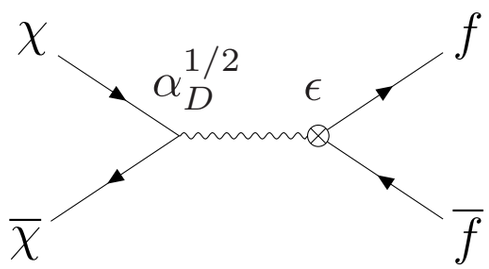
<u>additional dark sector channels</u>
(rate suppressed by additional initial state)



rate $\propto \alpha_D^3\, e^{-m_\chi/T}$

PRD 43 (1991)
arXiv:1505.07107
arXiv:1702.07716
arXiv:2011.01240

Dark Sector Dynamics



rate $\propto \alpha_D\, \alpha_{\rm em}\, \epsilon^2 \propto y$

- For Dirac fermion, CMB constrains late-time annihilations:

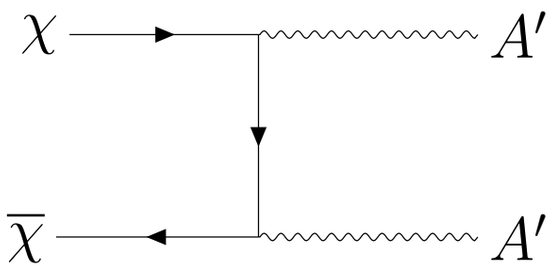
$$y/y_{\rm target} \lesssim 10^{-3} \times (m_\chi/100\ {\rm MeV})$$

- For smaller ϵ and large α_D, hidden sectors processes dominate.

- For $\epsilon \gtrsim 10^{-8} \times (m_{A'}/{\rm GeV})^{1/2}$, DM and SM equilibrate.

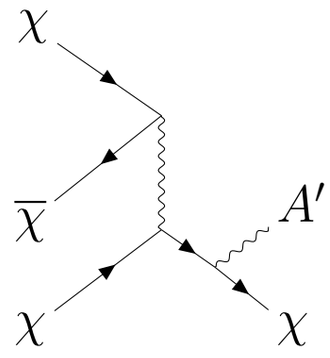
$$m_\chi < m_{A'} < 2\, m_\chi$$

<u>kinematically forbidden channels</u>
(annihilation rates vanish at zero temperature)



rate $\propto \alpha_D^2 \left(e^{-(m_{A'}-m_\chi)/T}\right)^2$

<u>additional dark sector channels</u>
(rate suppressed by additional initial state)



rate $\propto \alpha_D^3\, e^{-m_\chi/T}$

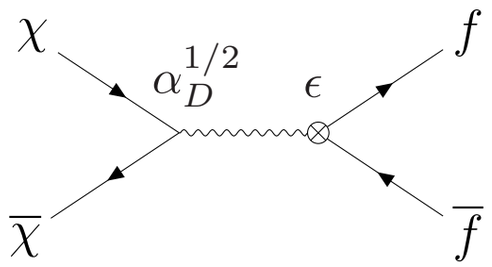
$1 \lesssim m_{A'}/m_\chi \lesssim 1.5$

$$\frac{3 \to 2}{2 \to 2} \propto \alpha_D\, e^{2m_\chi (m_{A'}/m_\chi - 3/2)/T}$$

$1.5 \lesssim m_{A'}/m_\chi \lesssim 2$

PRD 43 (1991)
arXiv:1505.07107
arXiv:1702.07716
arXiv:2011.01240

Dark Sector Dynamics



rate $\propto \alpha_D\, \alpha_{\rm em}\, \epsilon^2 \propto y$

- For Dirac fermion, CMB constrains late-time annihilations:
$$y/y_{\rm target} \lesssim 10^{-3} \times (m_\chi/100\ {\rm MeV})$$
- For smaller ϵ and large α_D, hidden sectors processes dominate.
- For $\epsilon \gtrsim 10^{-8} \times (m_{A'}/{\rm GeV})^{1/2}$, DM and SM equilibrate.

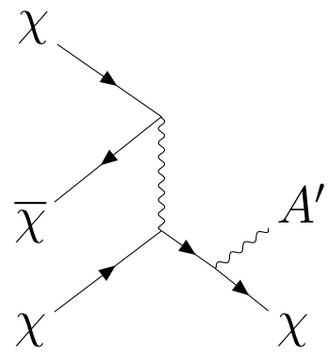
$$m_\chi < m_{A'} < 2\, m_\chi$$

kinematically forbidden channels
(annihilation rates vanish at zero temperature)

rate $\propto \alpha_D^2 \left(e^{-(m_{A'}-m_\chi)/T}\right)^2$

$1 \lesssim m_{A'}/m_\chi \lesssim 1.5$

additional dark sector channels
(rate suppressed by additional initial state)



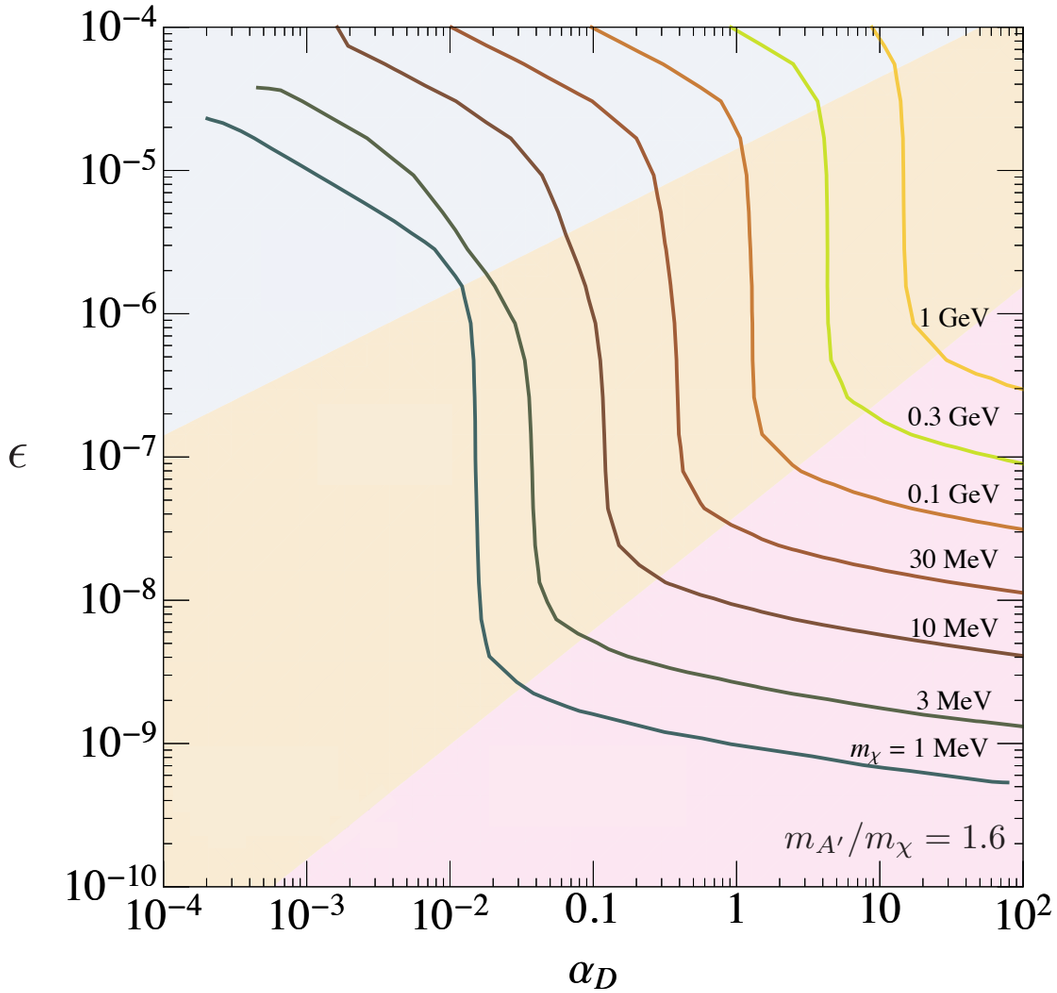
rate $\propto \alpha_D^3\, e^{-m_\chi/T}$

$1.5 \lesssim m_{A'}/m_\chi \lesssim 2$

$$\frac{3 \to 2}{2 \to 2} \propto \alpha_D\, e^{2m_\chi (m_{A'}/m_\chi - 3/2)/T}$$

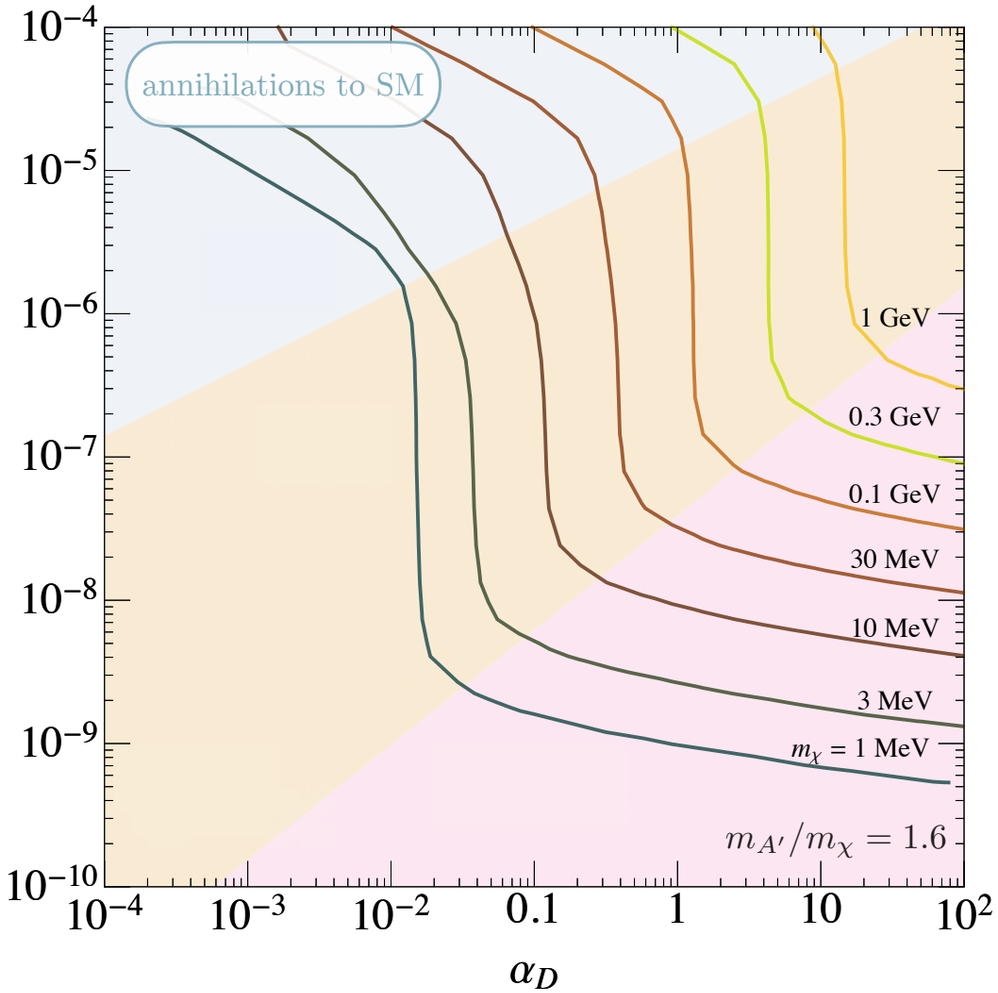
PRD 43 (1991)
arXiv:1505.07107
arXiv:1702.07716
arXiv:2011.01240

Dark Sector Dynamics



(decreasing ϵ)

Dark Sector Dynamics

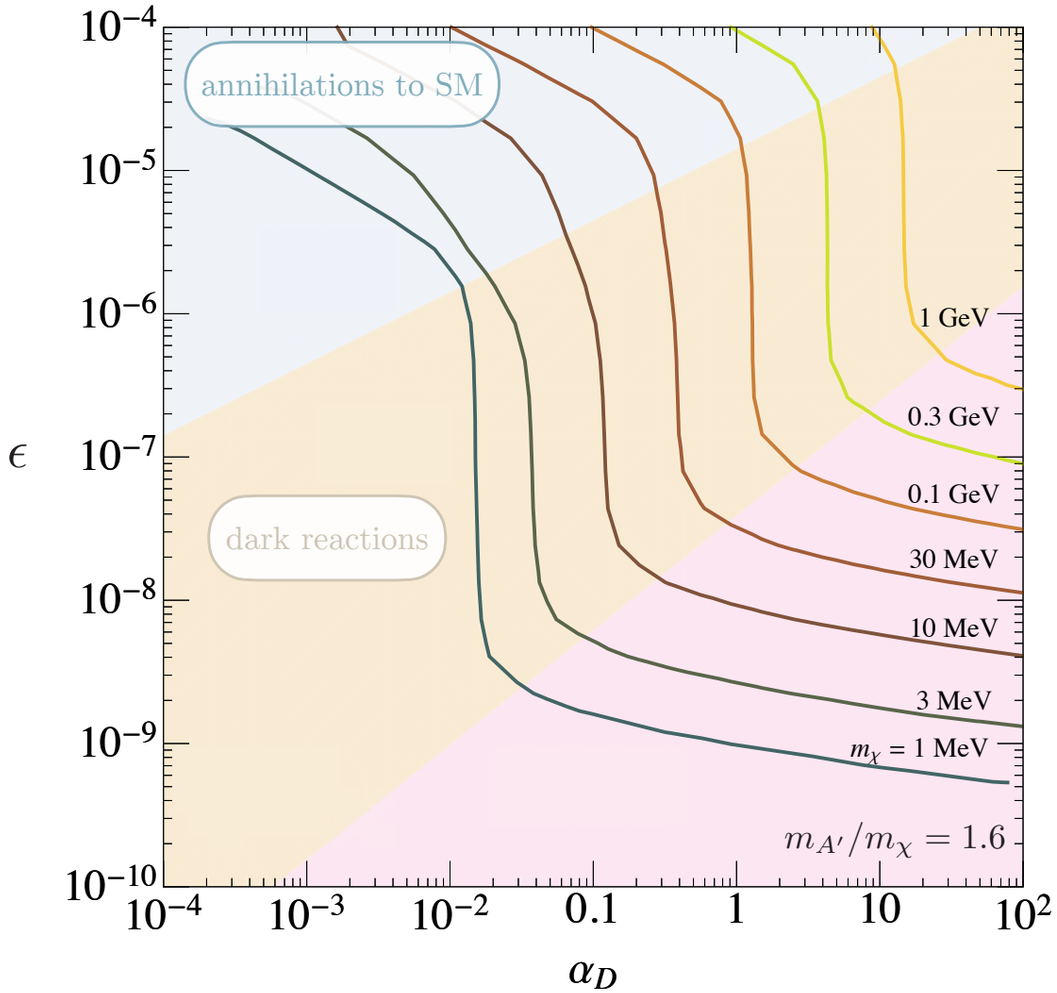


- annihilations to SM: $\epsilon^2\,\alpha_D = \text{const.}$

(decreasing ϵ)

arXiv:2011.01240

Dark Sector Dynamics



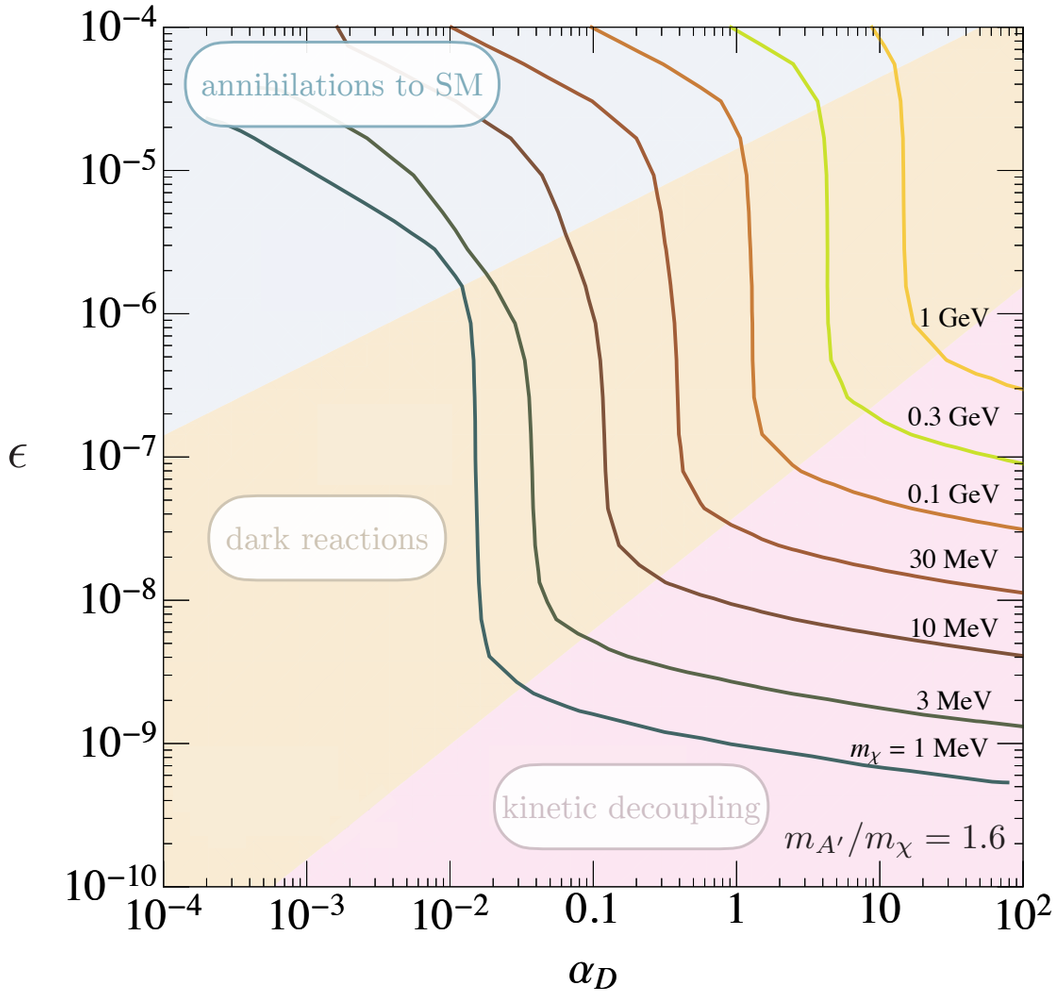
- annihilations to SM: $\epsilon^2\,\alpha_D = \text{const.}$

- dark reactions: ϵ independent

(decreasing ϵ)

arXiv:2011.01240

Dark Sector Dynamics

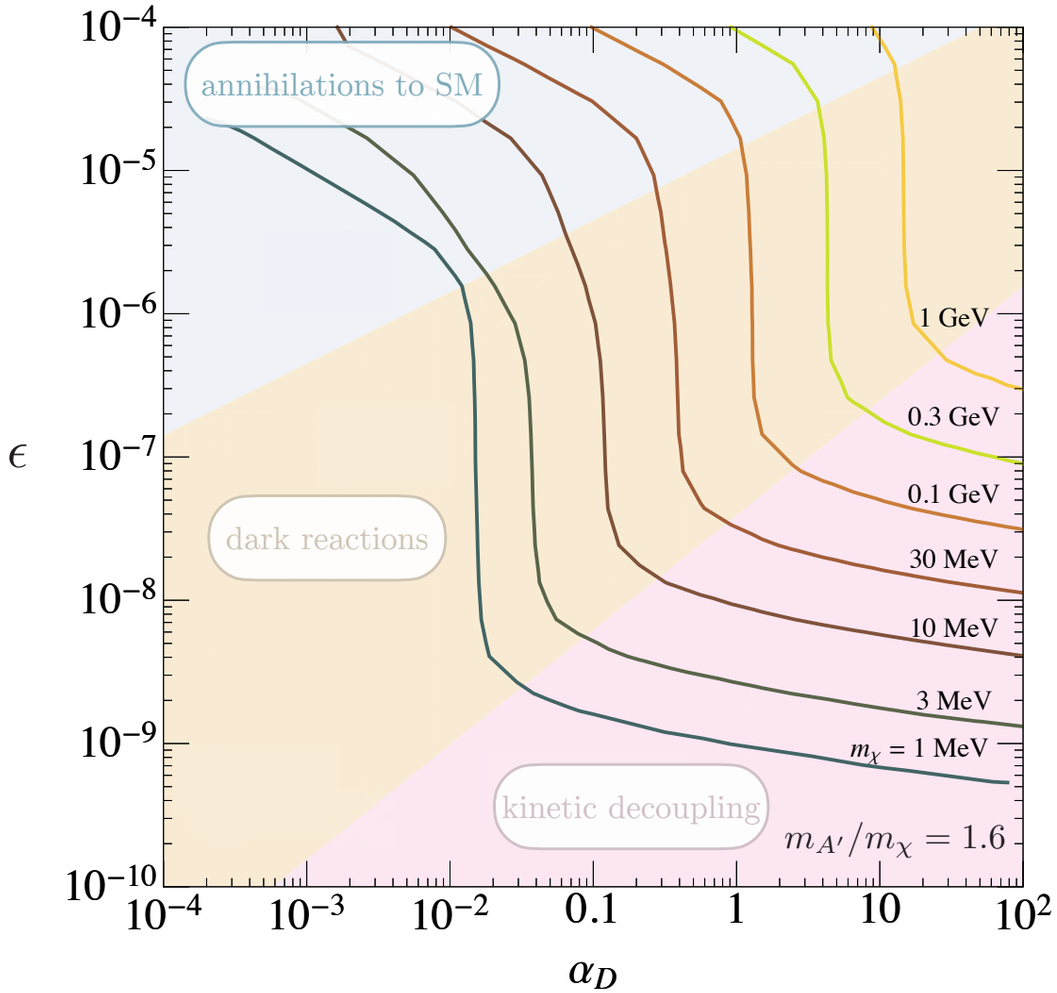


(decreasing ϵ)

- annihilations to SM: $\epsilon^2\,\alpha_D = \text{const.}$
- dark reactions: ϵ independent
- early kinetic decoupling: $\sim \alpha_D$ independent

arXiv:2011.01240

Dark Sector Dynamics



(decreasing ϵ)

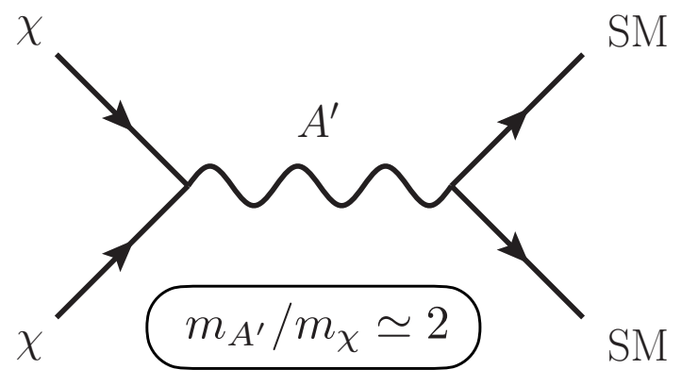
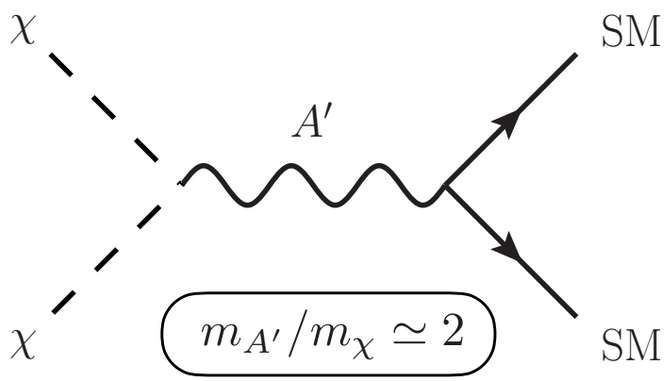
- annihilations to SM: $\epsilon^2\,\alpha_D = \text{const.}$
- dark reactions: ϵ independent
- early kinetic decoupling: $\sim \alpha_D$ independent

Terrestrial Tests:

Upcoming visible accelerator searches and low-threshold direct detection experiments.

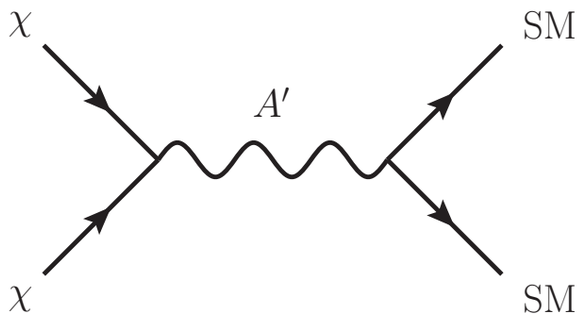
arXiv:2011.01240

Minimal Thermal Dark Photon

	direct	indirect
fermion DM		
scalar DM		

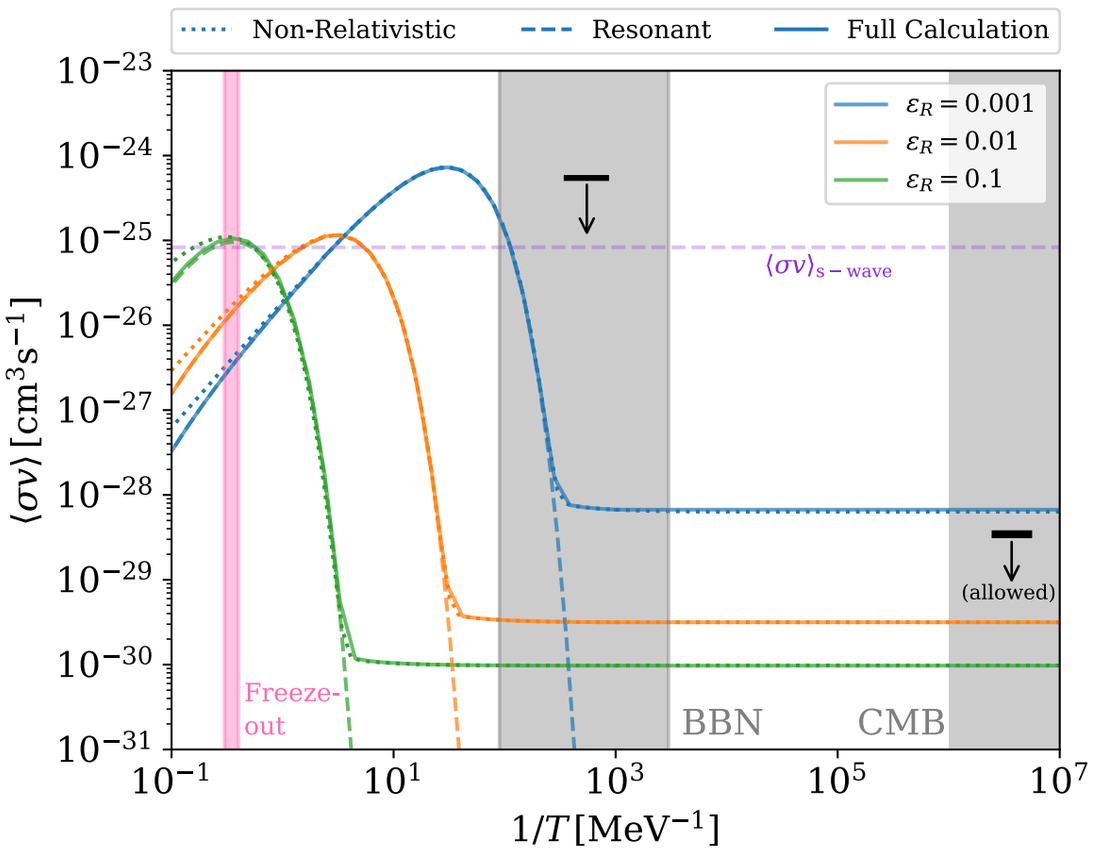
III. Resonant Annihilations

Resonant Annihilations



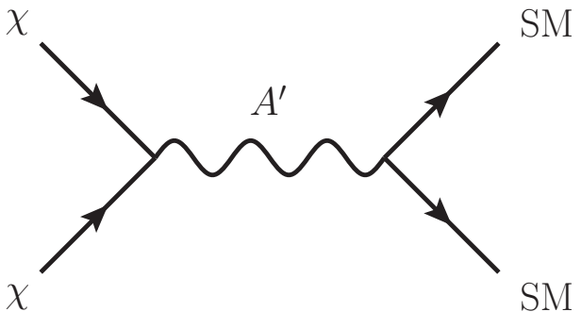
$$\epsilon_R \simeq m_{A'}/m_\chi - 2$$

$$(0 < \epsilon_R \ll 1)$$



PRD 43 (1991)
arXiv:1707.03835
arXiv:2010.14522

Resonant Annihilations

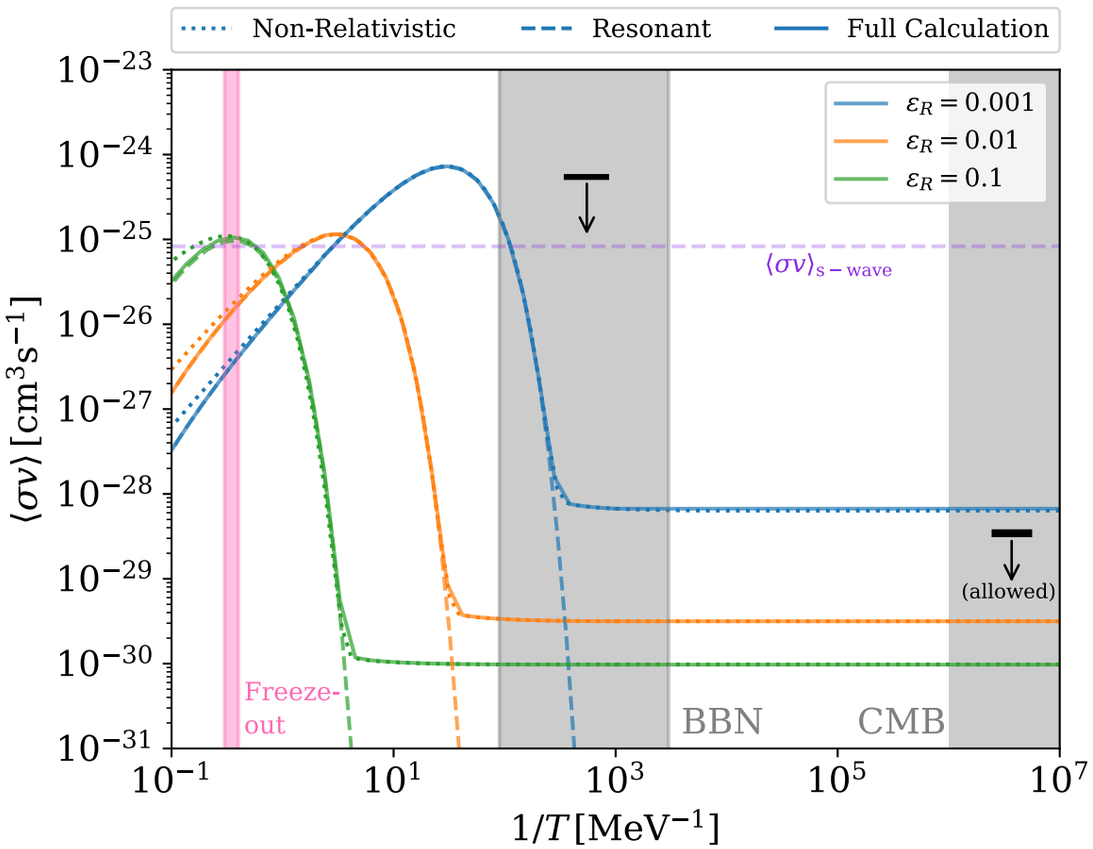


$$\epsilon_R \simeq m_{A'}/m_\chi - 2$$

$$(0 < \epsilon_R \ll 1)$$

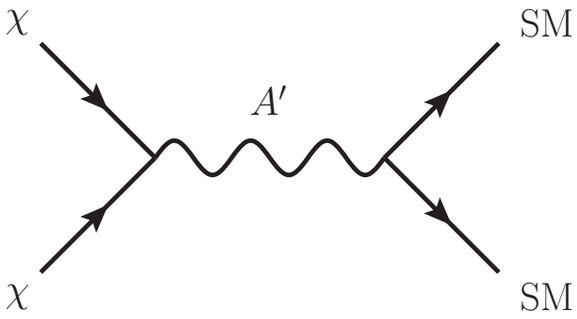
closer to resonance at freeze-out

resonance significant when non-relativistic



PRD 43 (1991)
arXiv:1707.03835
arXiv:2010.14522

Resonant Annihilations

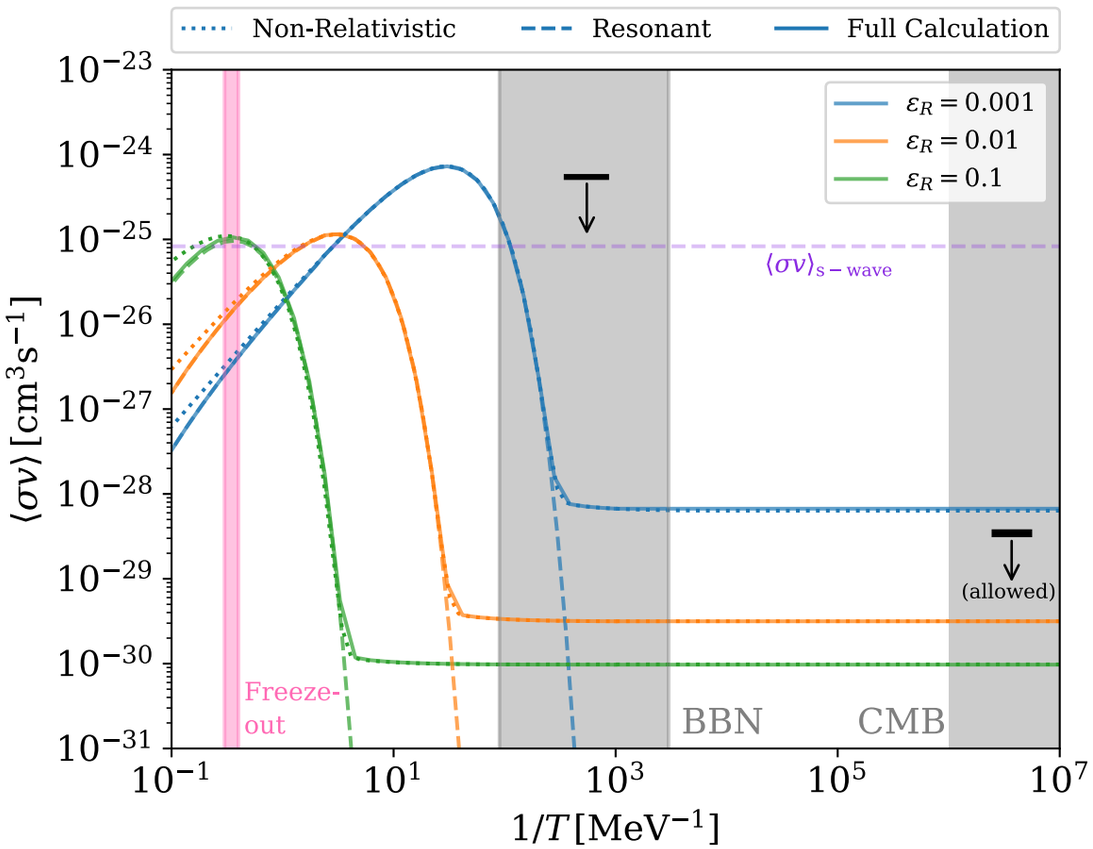


$$\epsilon_R \simeq m_{A'}/m_\chi - 2$$

$$(0 < \epsilon_R \ll 1)$$

closer to resonance at freeze-out

resonance significant when non-relativistic



$$\sqrt{s} \simeq 2m_\chi + \mathcal{O}(T)$$

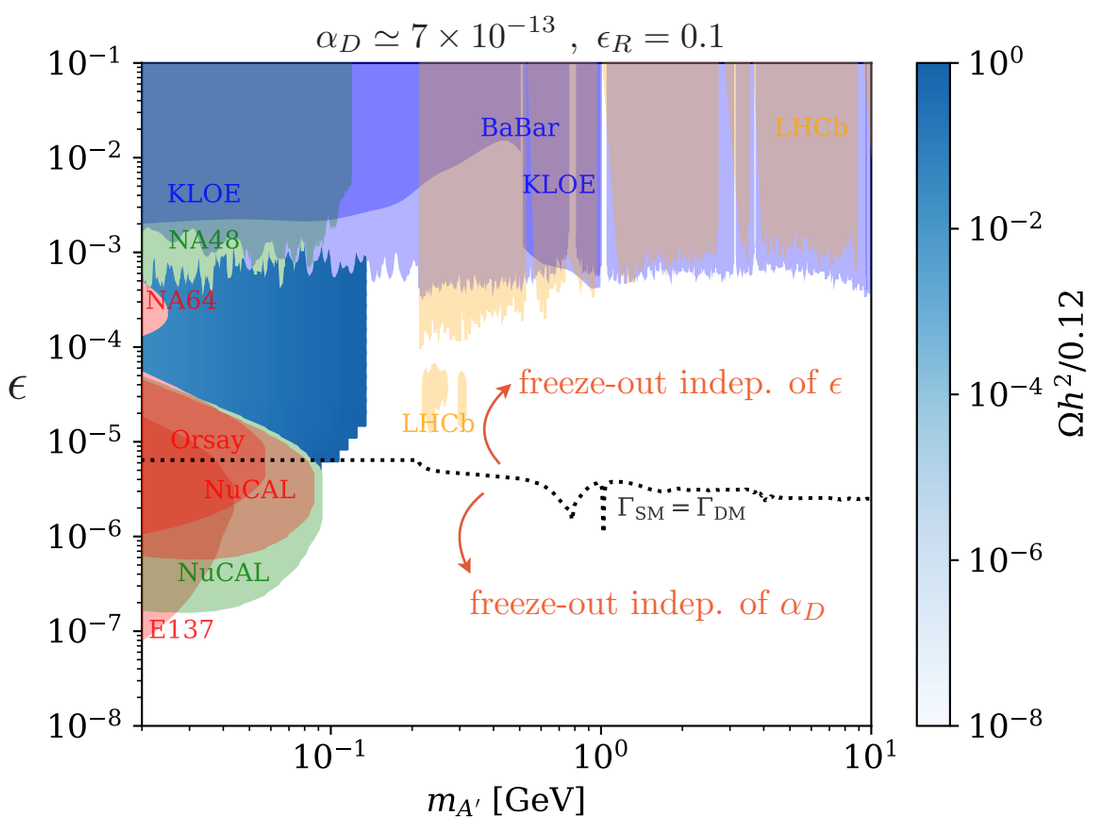
$\sqrt{s} \simeq m_{A'}$ freeze-out (larger T)

$\sqrt{s} \simeq 2m_\chi$ recombination (smaller T)

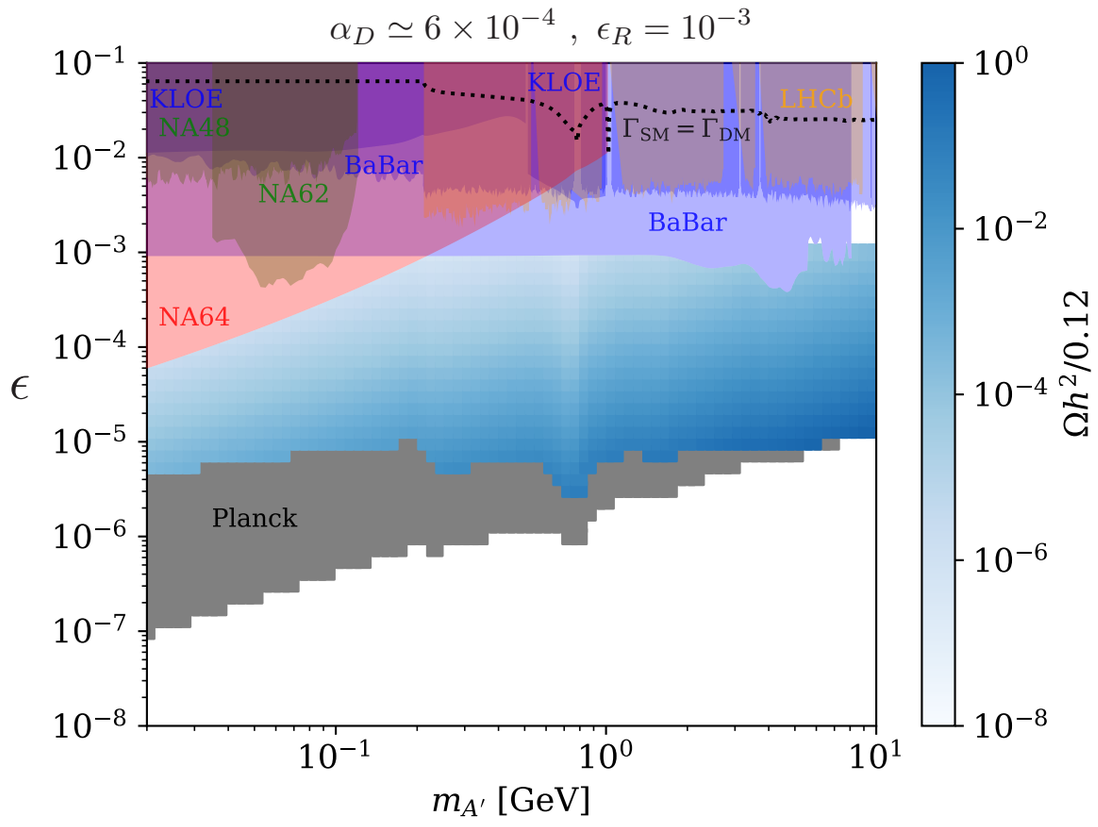
PRD 43 (1991)
arXiv:1707.03835
arXiv:2010.14522

Resonant Annihilations

visible signals



invisible signals



abundance of $\chi \propto \dfrac{\Gamma_{A'}}{\alpha_D\, \epsilon^2}$ (narrow width)

at small ϵ: $n_\chi^2 \langle \sigma v \rangle_{\rm CMB} \propto \dfrac{1}{\epsilon^4} \times \alpha_D\, \epsilon^2 = \dfrac{\alpha_D}{\epsilon^2}$ (CMB)

arXiv:2010.14522

Take Away

Take Away

theory space

- Cosmological organization $\Longrightarrow$ identify motivated, economical, predictive models.

- There exist such models that are simple and realistic.

Take Away

theory space

- Cosmological organization $\Longrightarrow$ identify motivated, economical, predictive models.
- There exist such models that are simple and realistic.

direct annihilations to SM states

- For accelerators, momentum transfer comparable to early universe leads to robust production rates, insensitive to many model details.
- Direct detection sensitive to some cases.

Take Away

theory space

- Cosmological organization $\Longrightarrow$ identify motivated, economical, predictive models.
- There exist such models that are simple and realistic.

direct annihilations to SM states

- For accelerators, momentum transfer comparable to early universe leads to robust production rates, insensitive to many model details.
- Direct detection sensitive to some cases.

dark sector dynamics and resonances

- Thermal freeze-out viable with smaller couplings.
- Portal coupling bounded from below if dark sector is to maintain equilibrium with the SM.

Take Away

theory space

- Cosmological organization $\Longrightarrow$ identify motivated, economical, predictive models.
- There exist such models that are simple and realistic.

direct annihilations to SM states

- For accelerators, momentum transfer comparable to early universe leads to robust production rates, insensitive to many model details.
- Direct detection sensitive to some cases.

dark sector dynamics and resonances

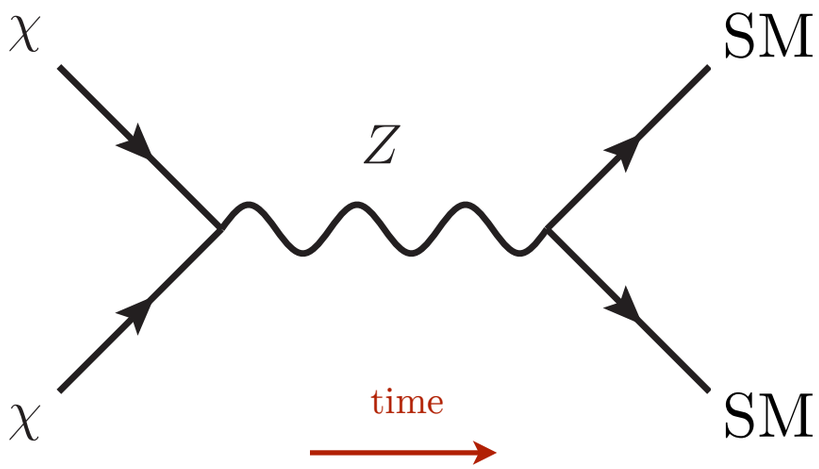
- Thermal freeze-out viable with smaller couplings.
- Portal coupling bounded from below if dark sector is to maintain equilibrium with the SM.

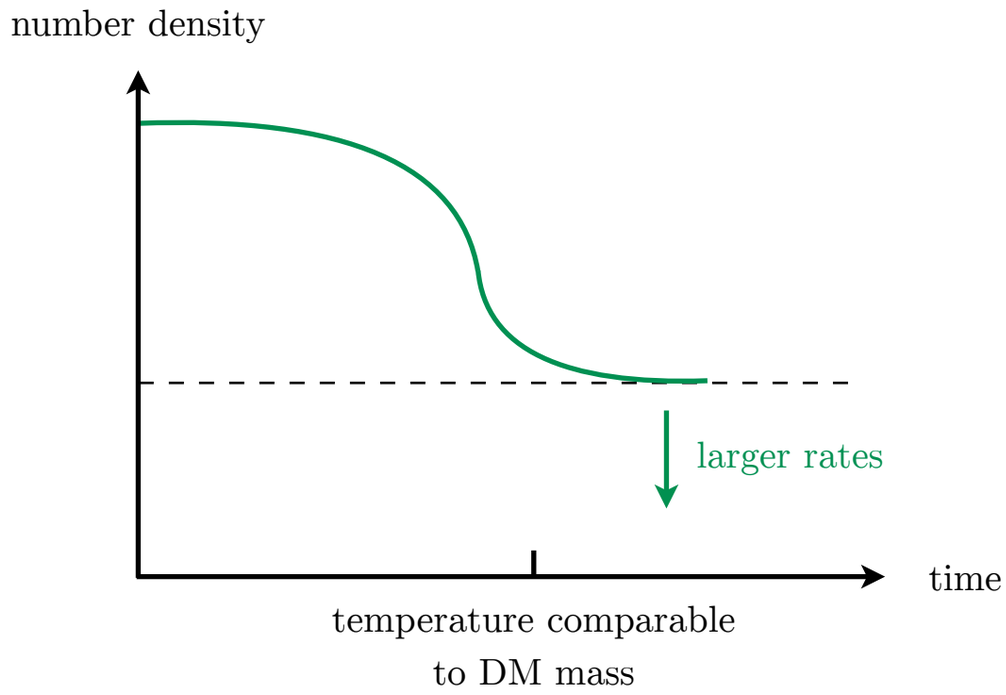
experimental signatures

- Signatures are largely unchanged compared to standard visible and invisible searches.
- Minimal extensions upon standard targets motivate further exploration to smaller couplings.
- Upcoming experiments will explore broad paradigms for DM.

Backup

Light Mediators





(perturbative) $$\sigma v \lesssim \frac{m_\chi^2}{m_Z^4} \implies m_\chi \gtrsim \frac{m_Z^2}{(T_{\rm eq}\, m_{\rm pl})^{1/2}} \sim \text{GeV}$$

thermal WIMP interacting solely through the electroweak force must be heavier than a GeV

sub-GeV thermal DM motivates light mediators

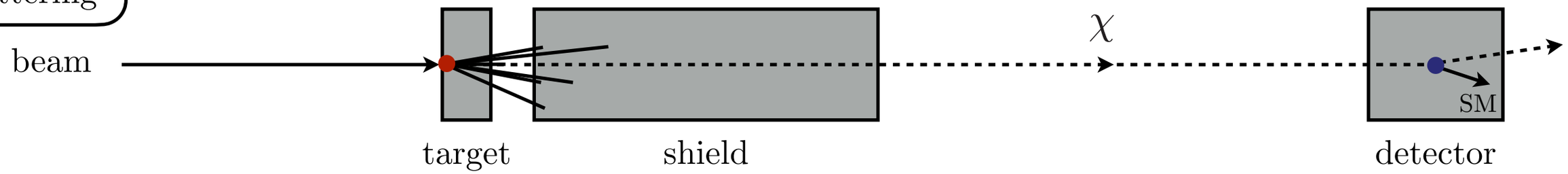
arXiv: hep-ph/0305261
Phys.Rev.Lett. 39 (1977) 165-168

Accelerator Signatures

e.g., fixed-target:

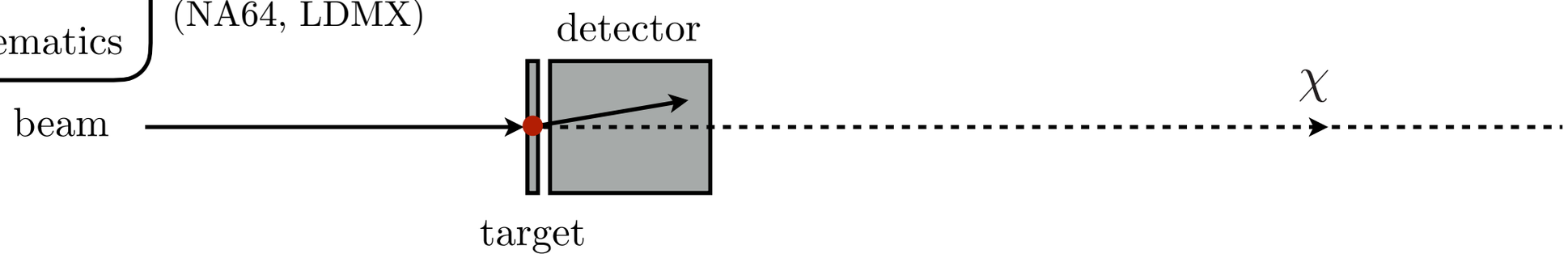
subsequent scattering

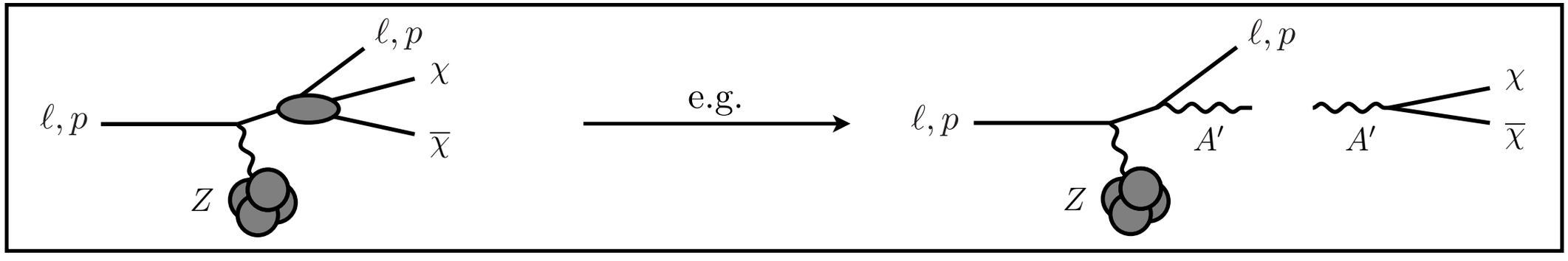
(E137, LSND, MiniBooNE, BDX)



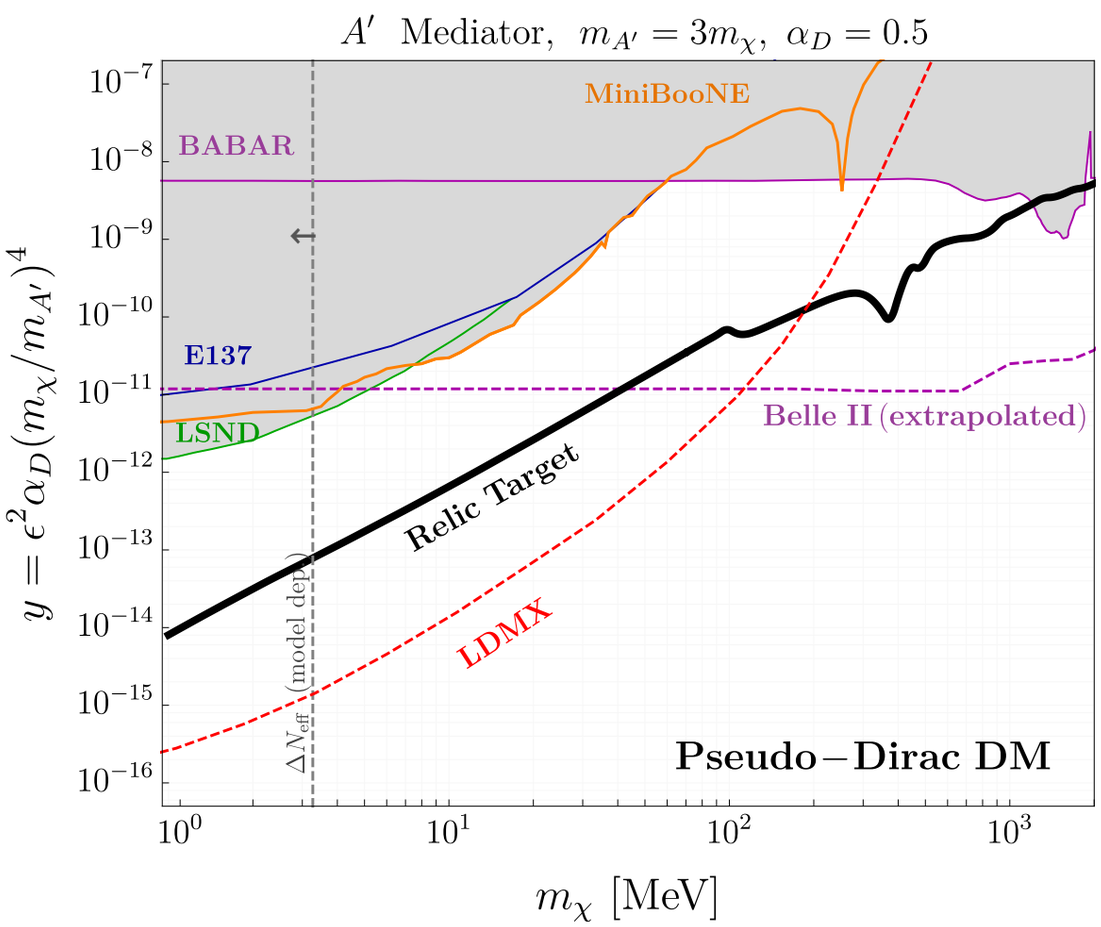
production kinematics

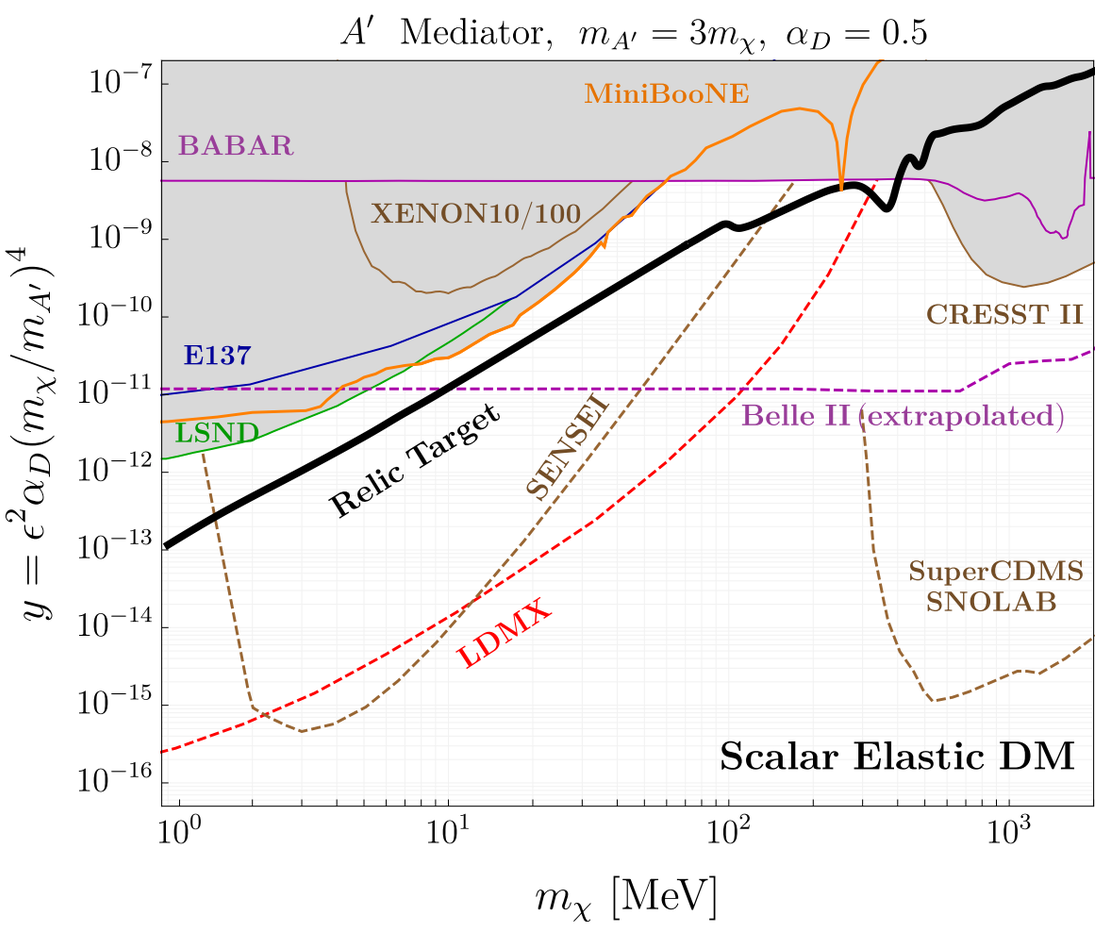
(NA64, LDMX)





Accelerator Signatures



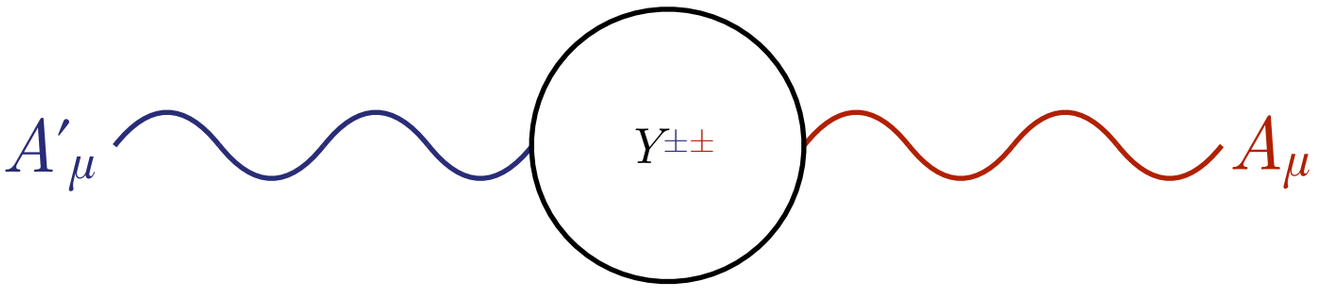


In the predictive case of direct DM annihilation to electrons, sub-GeV thermal target is accessible to next-generation experiments for many (if not all) DM spins and interaction structures.

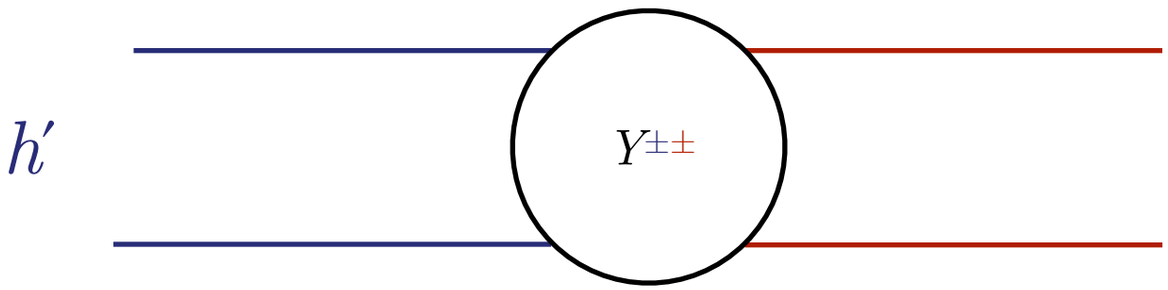
Upcoming low-threshold direct detection experiments will be sensitive to certain cases, e.g., scalar DM.

see, e.g., Berlin et al. 1807.01730, 2003.03379

Small Scales from Small Couplings



$$\epsilon \sim \frac{g_D\, g_Y}{16\,\pi^2} \sim 10^{-3}$$



$$\mathcal{L} \sim \frac{y_D^2\, y^2}{16\,\pi^2}\; |\, h'\,|^2\; |H|^2$$

$$\mu_D^2 \sim \frac{y_D^2\, y^2}{16\,\pi^2}\; v^2 \quad \Longrightarrow \quad m_{A'} \sim g_D \left(\frac{\mu_D^2}{\lambda_D}\right)^{1/2} \sim 4\pi\,\epsilon\, v \times \frac{y_D\, y}{\lambda_D^{1/2}\, g_Y}$$

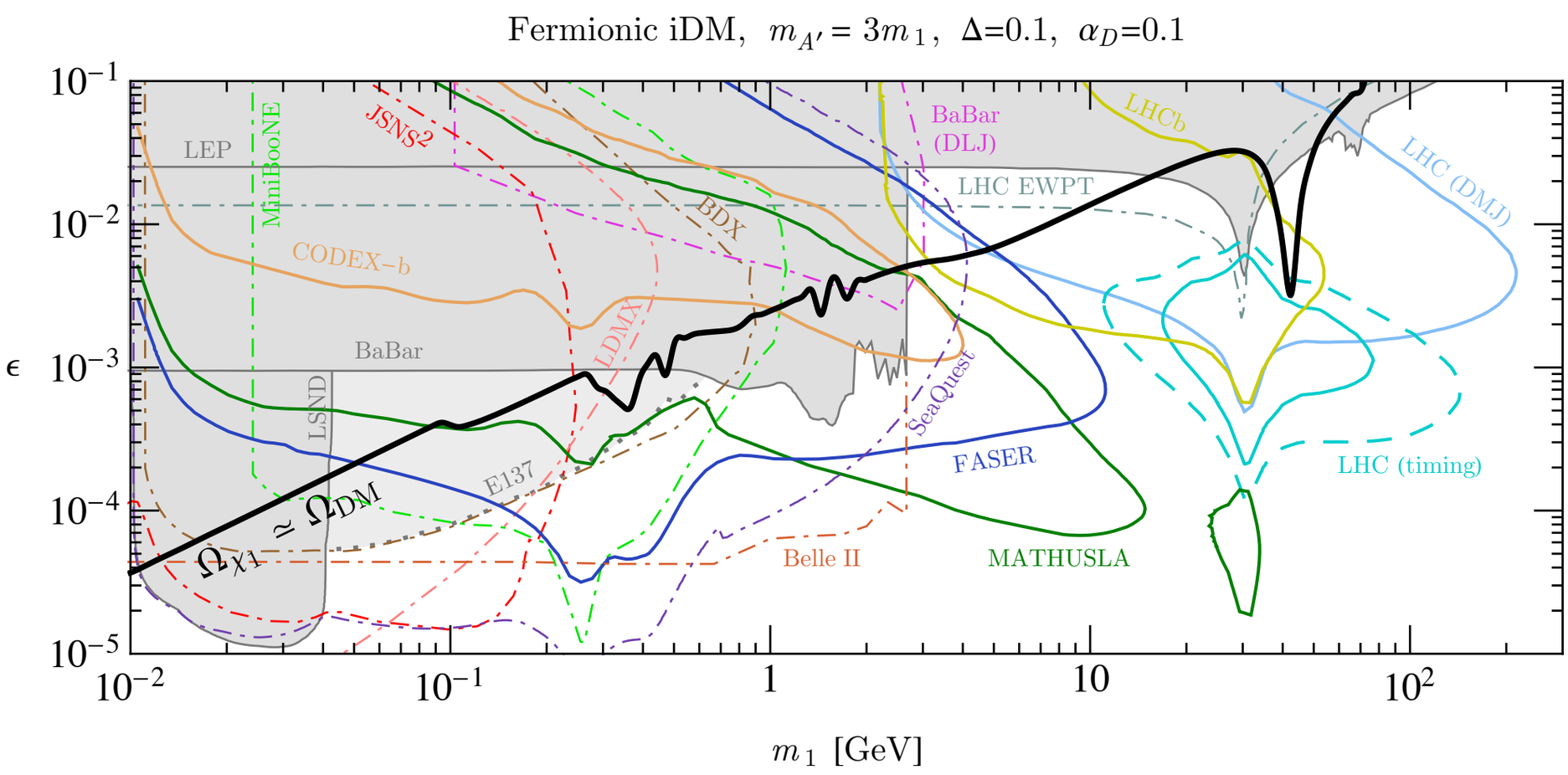
$$\boxed{m_{A'} \sim 4\pi\,\epsilon\, v \sim \mathcal{O}(1)\ \text{GeV} \times \frac{\epsilon}{10^{-3}}}$$

Phys.Lett.B 166 (1986)

arXiv:0902.3246

Inelastic Dark Matter

similar signatures from 10 MeV → 100 GeV



also relevant for e^+e^- machines (Belle II)

see, e.g., arXiv: 1911.03176