Tests of Thermal Relic Dark Matter

Ian M. Shoemaker

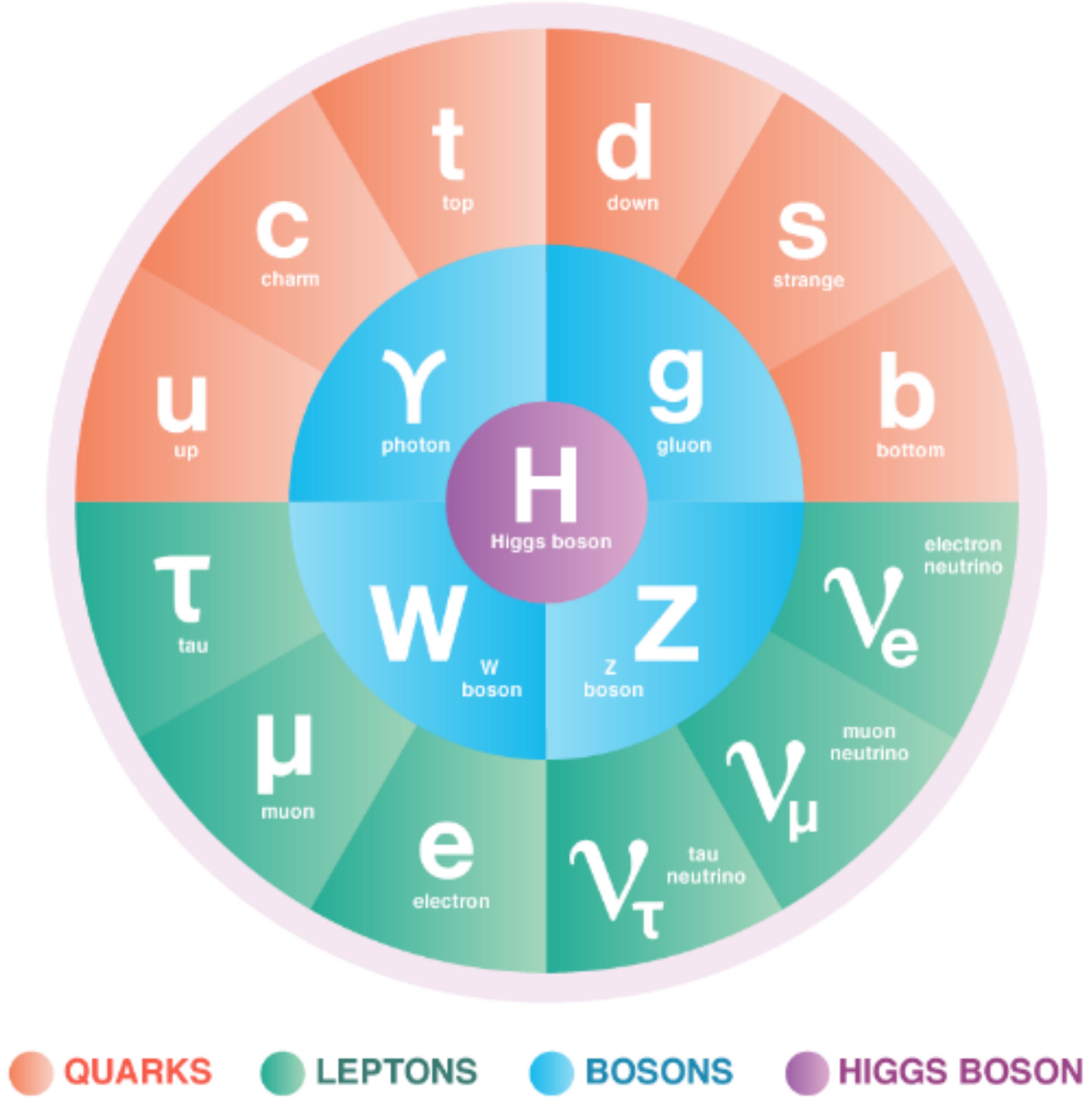
VIRGINIA TECH

2025 Belle-II Summer Workshop

Landscape of Physics…

Introducing the Standard Model

The Standard Model



Matter and Forces

The Standard Model is a theory of matter but also forces.

Representative example: Hydrogen Atom

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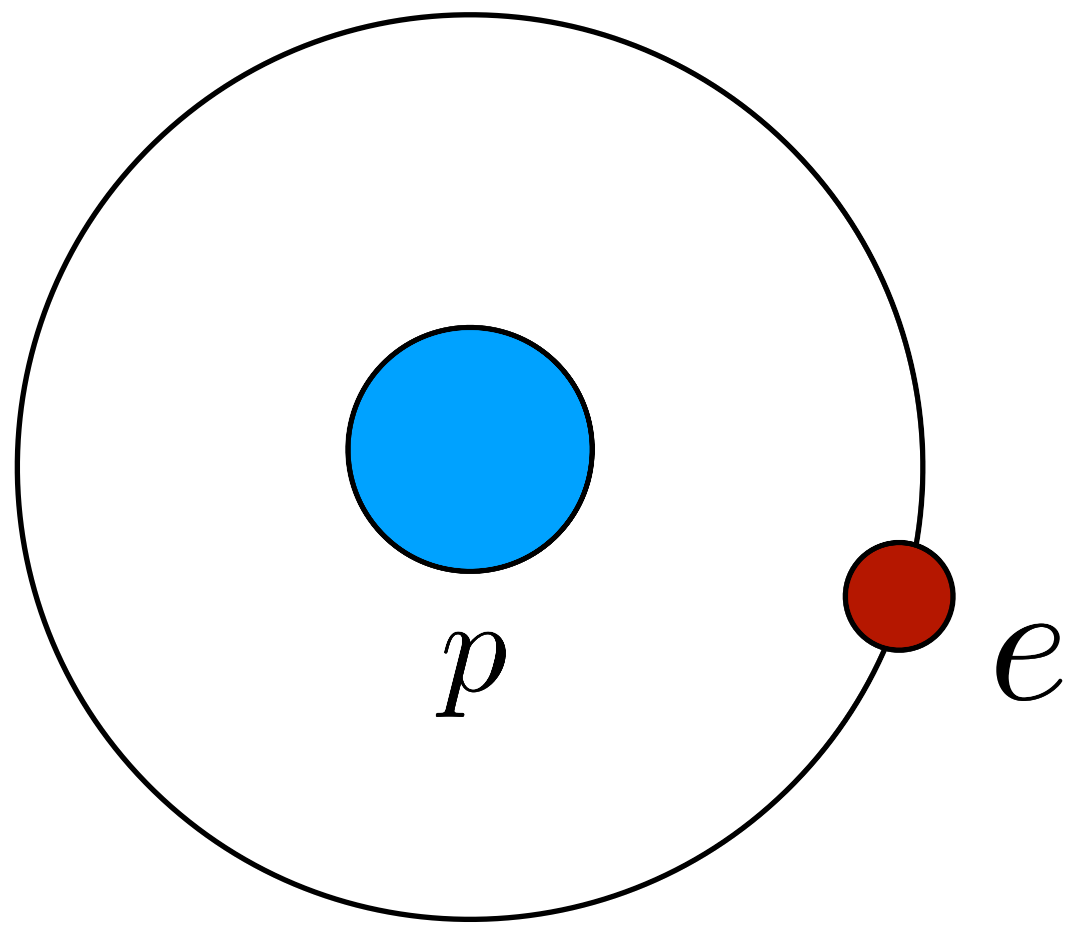

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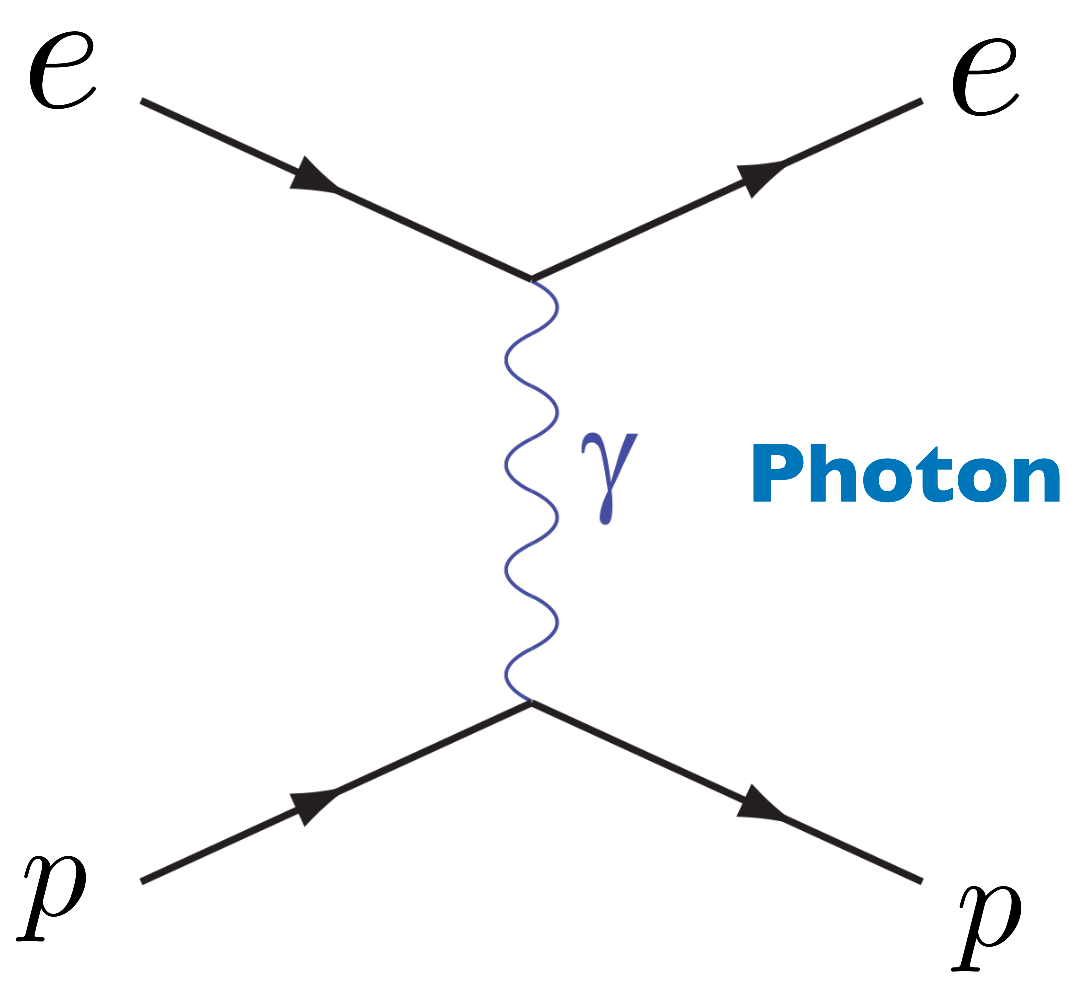

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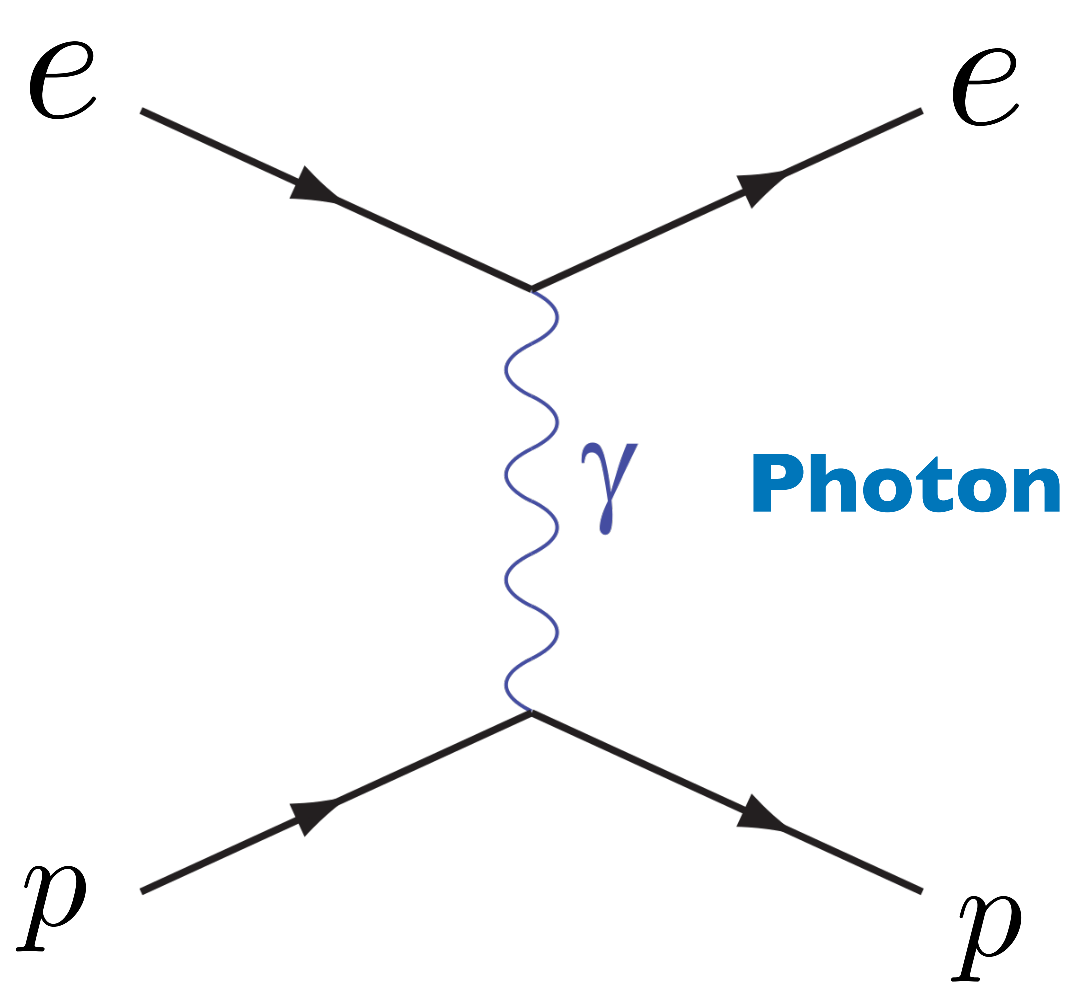
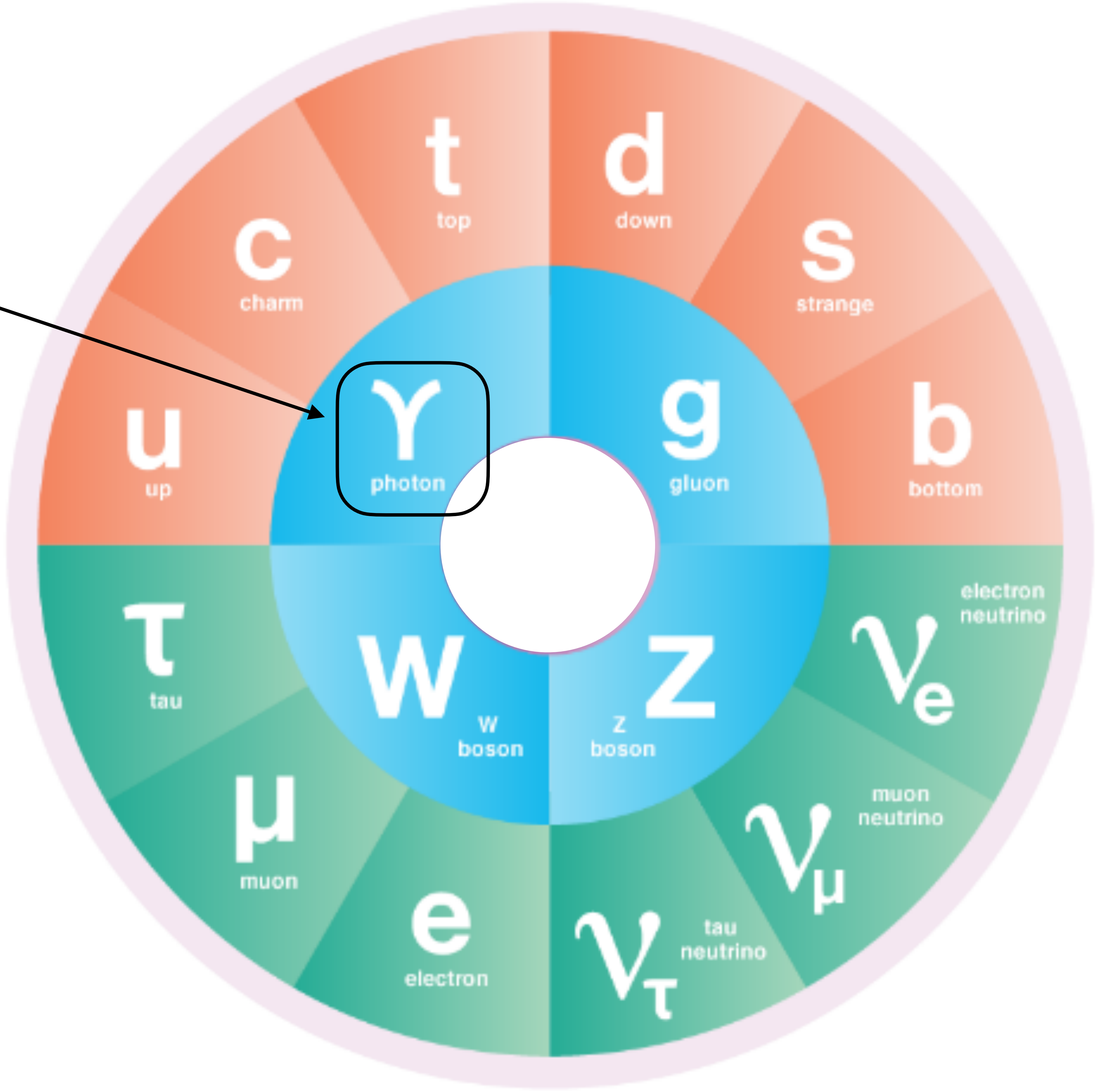


Electromagnetism is mediated via the exchange of photons.

The Standard Model

The Standard Model

Electromagnetic force



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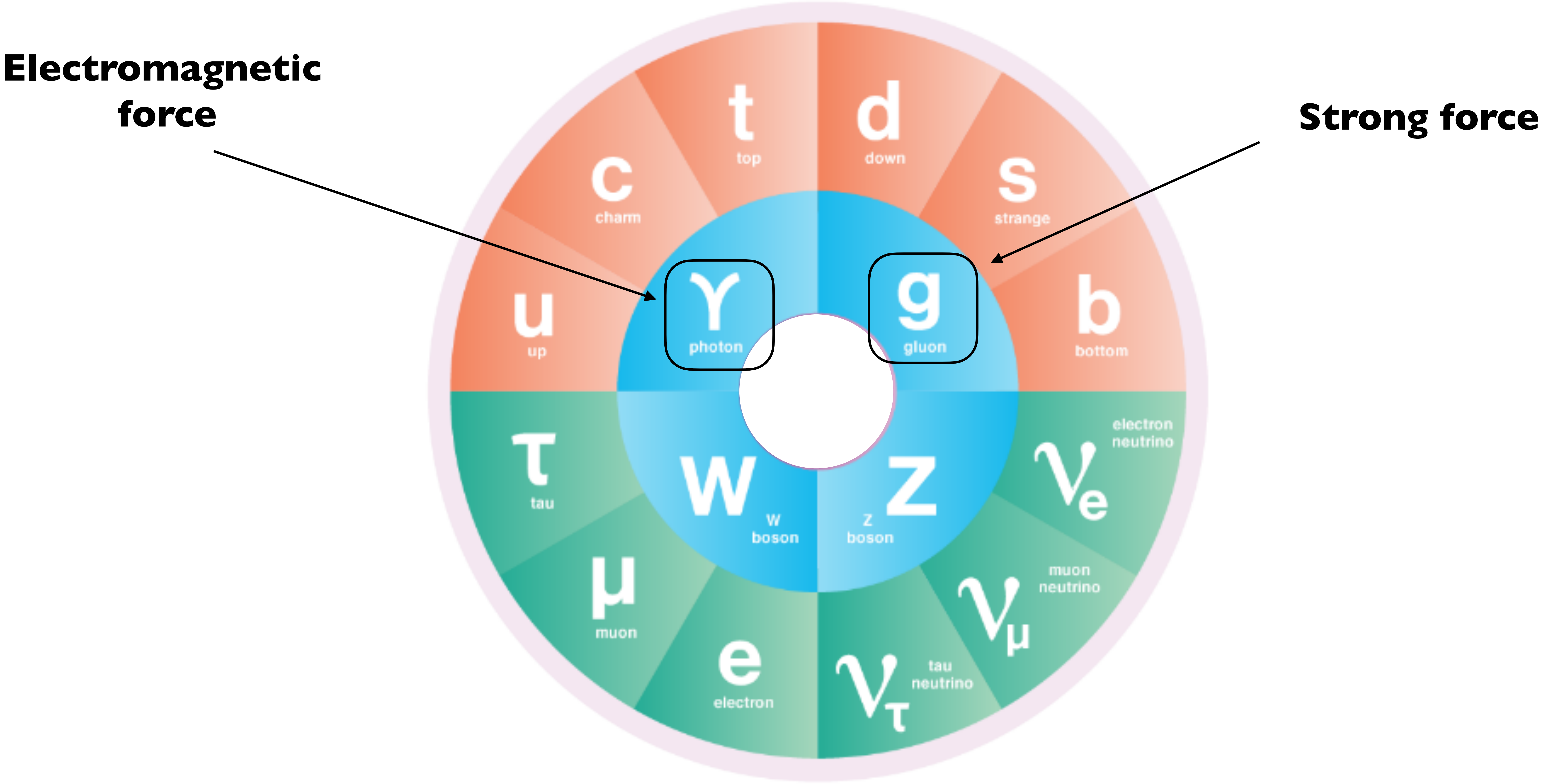

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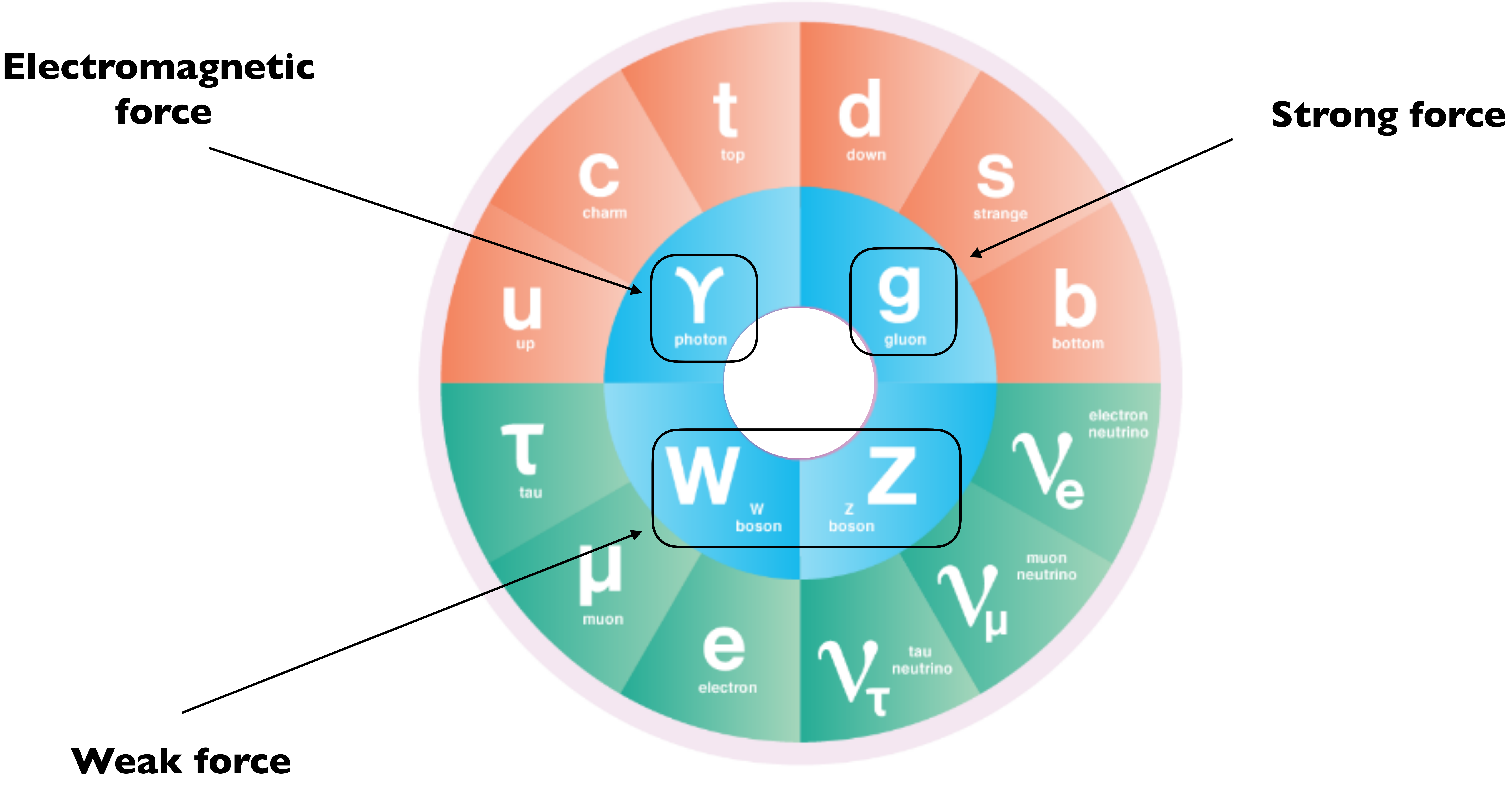
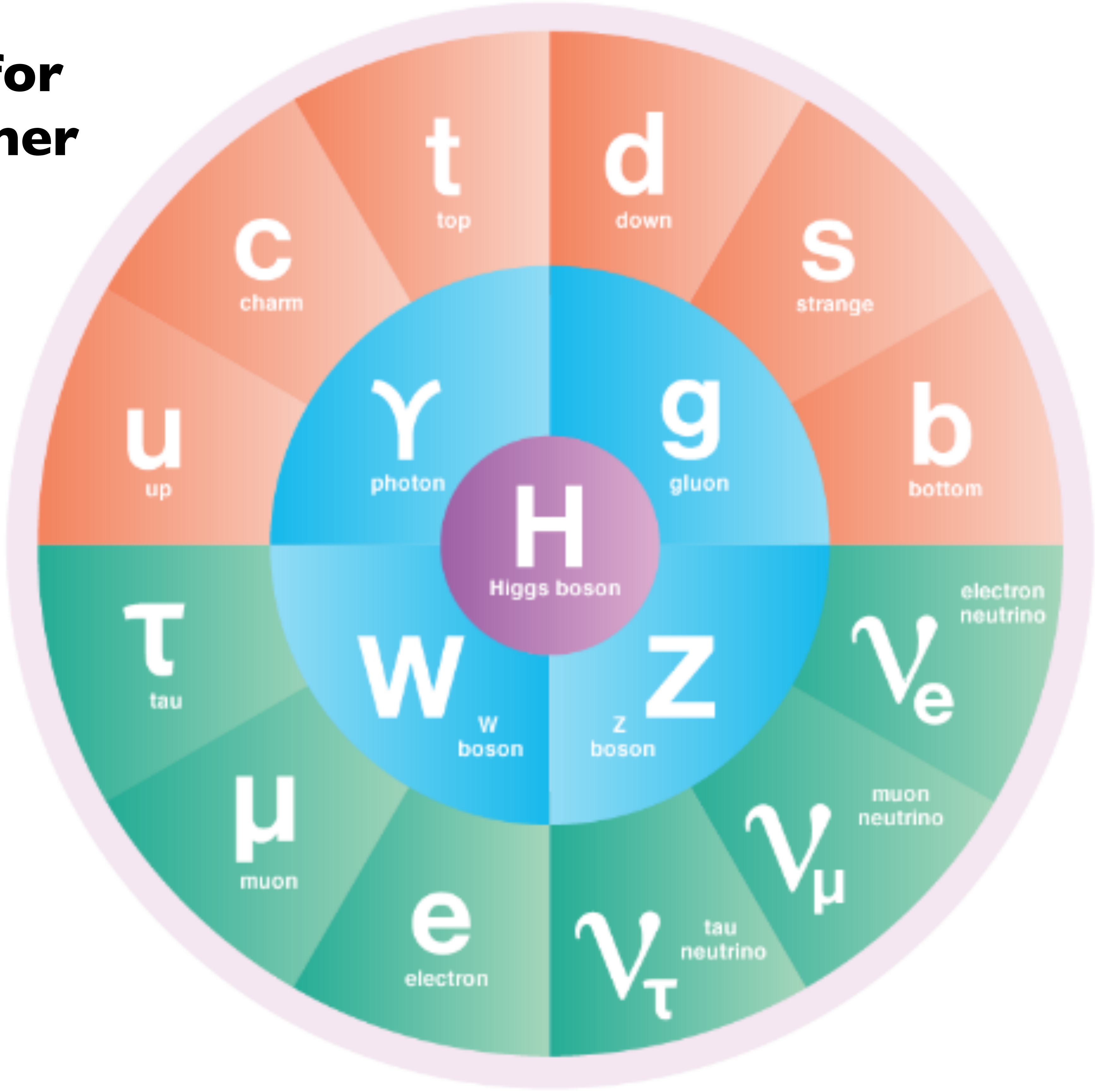


The Standard Model

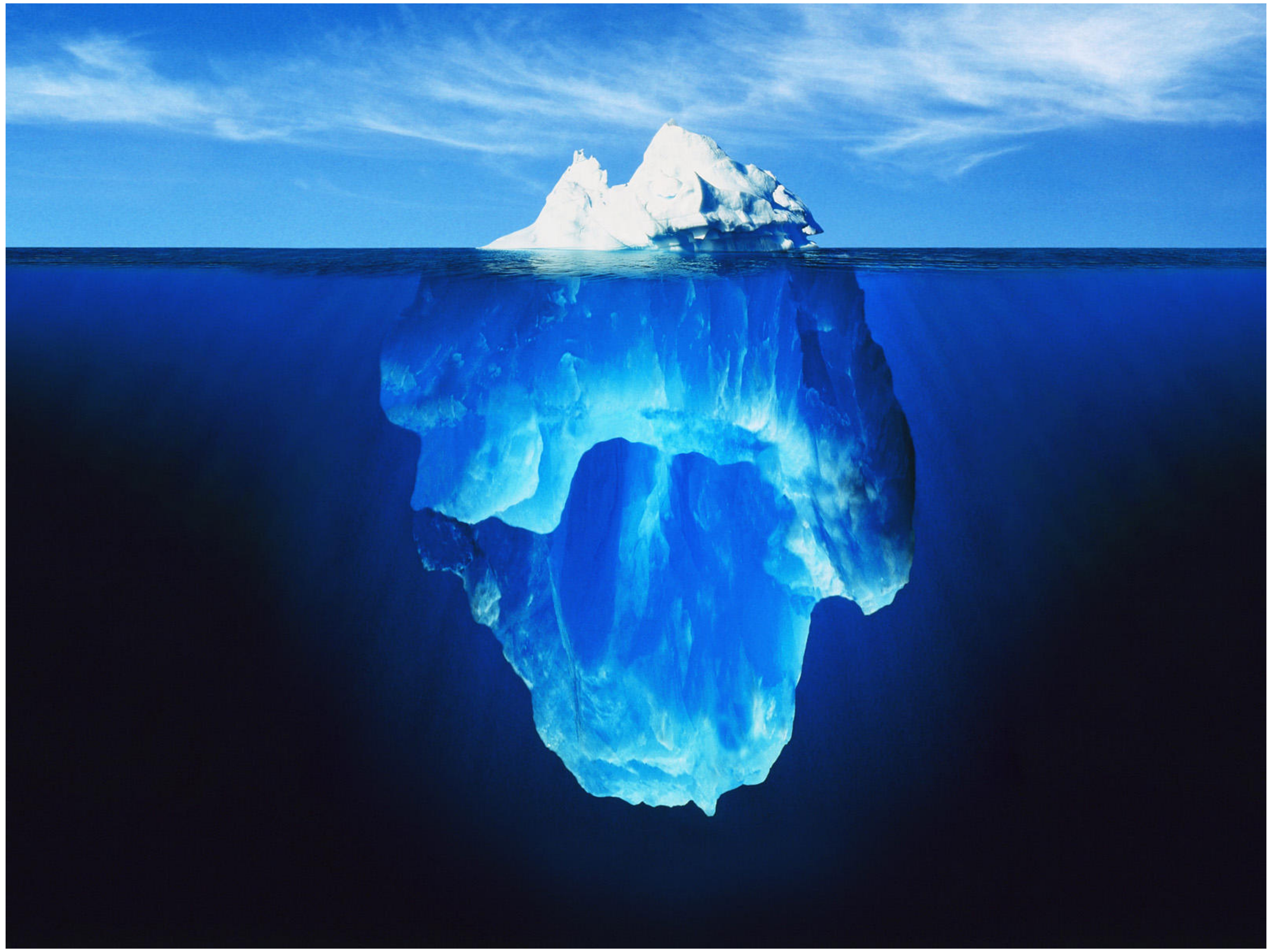
Higgs is responsible for giving mass to the other particles.



Final Keystone Piece: Higgs!

July 4, 2012 at CERN

And yet… there’s more.



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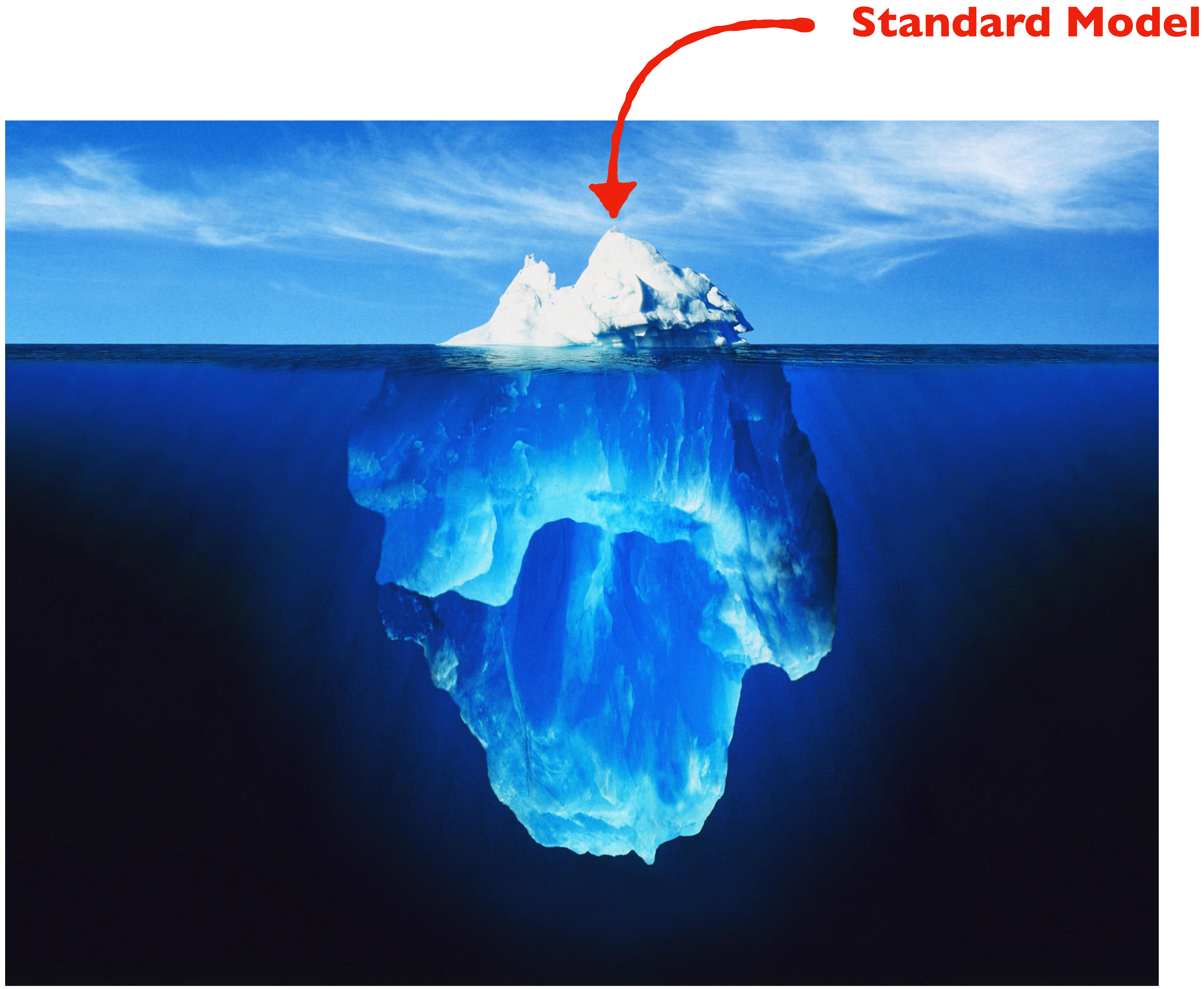
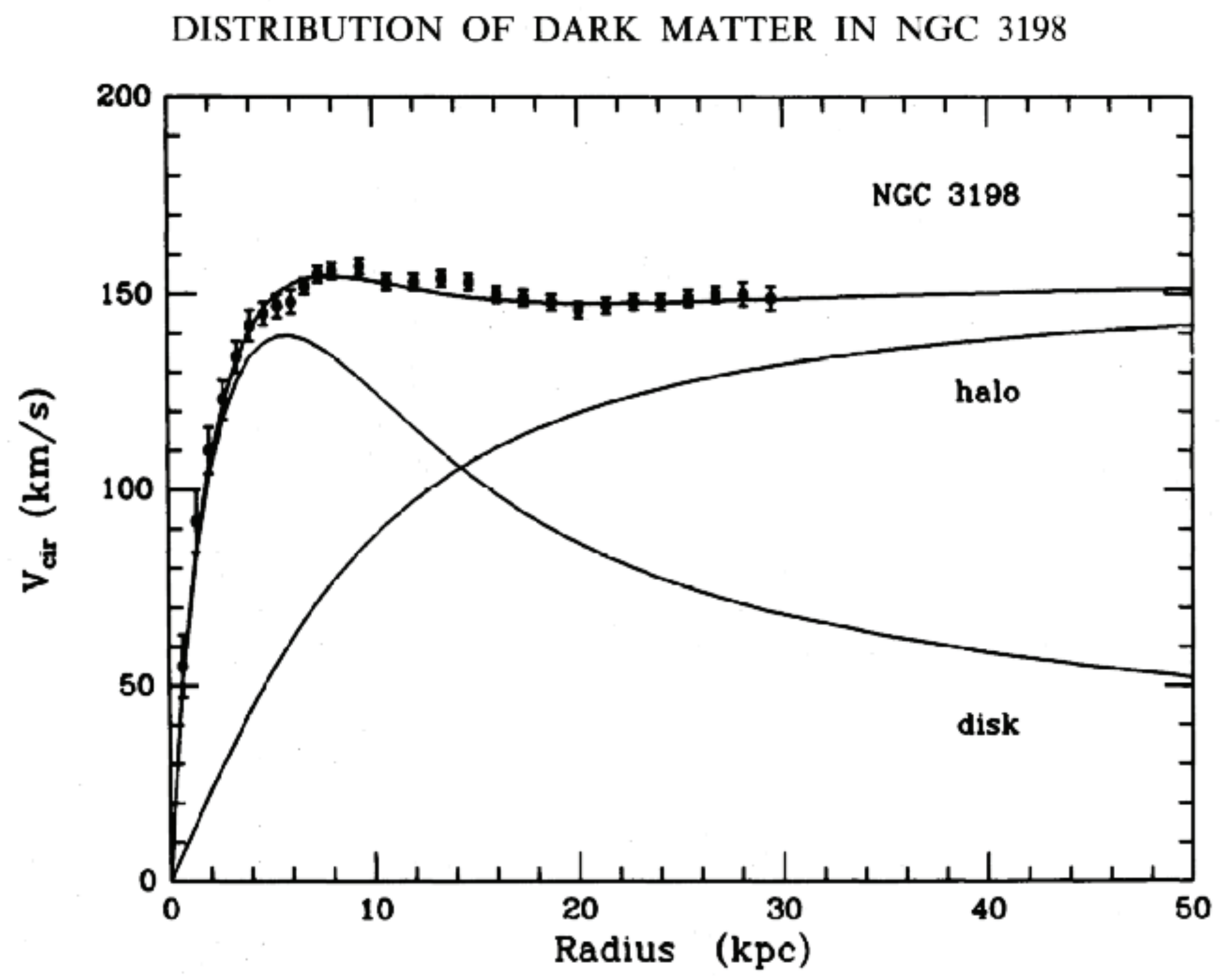
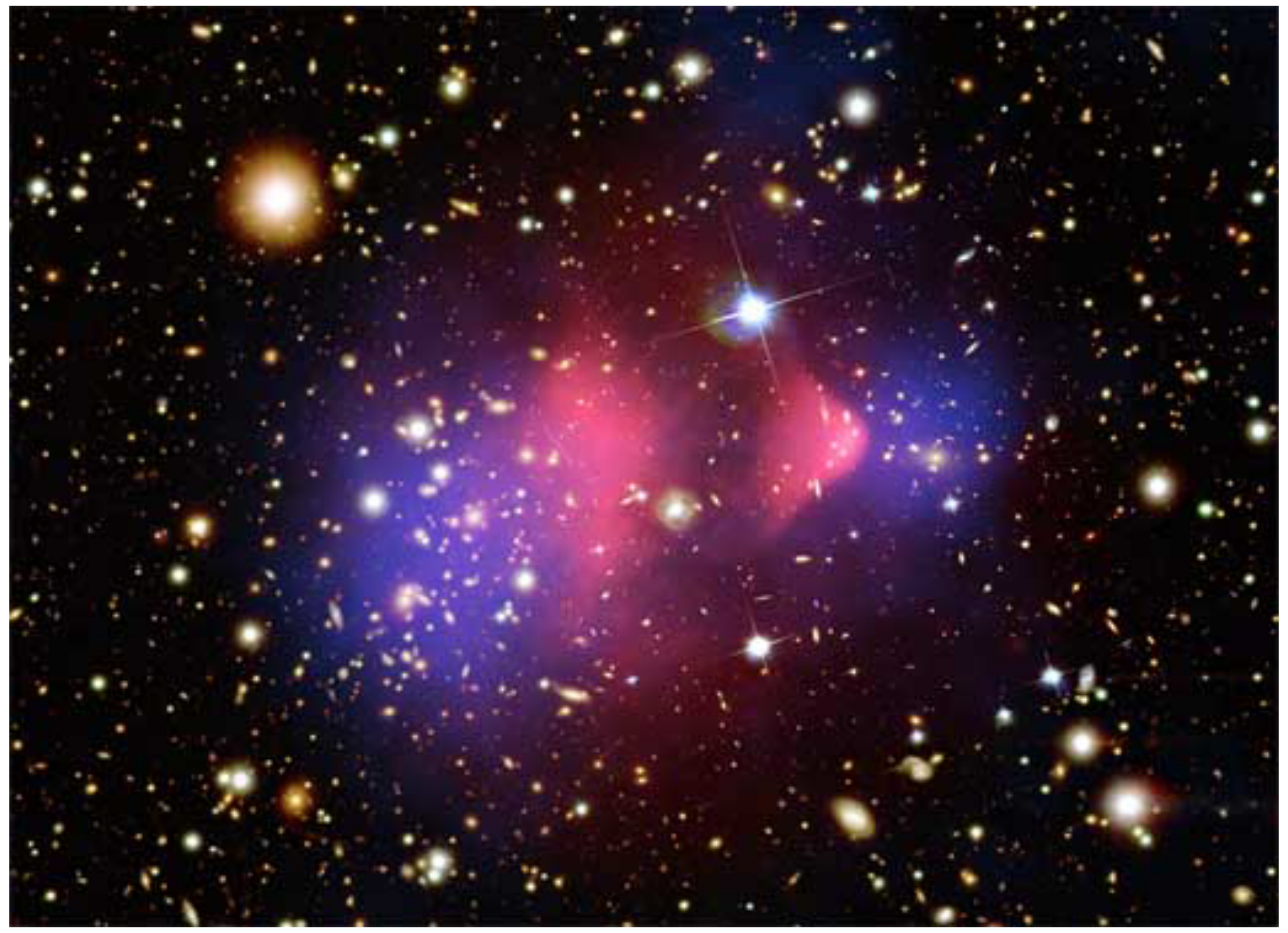
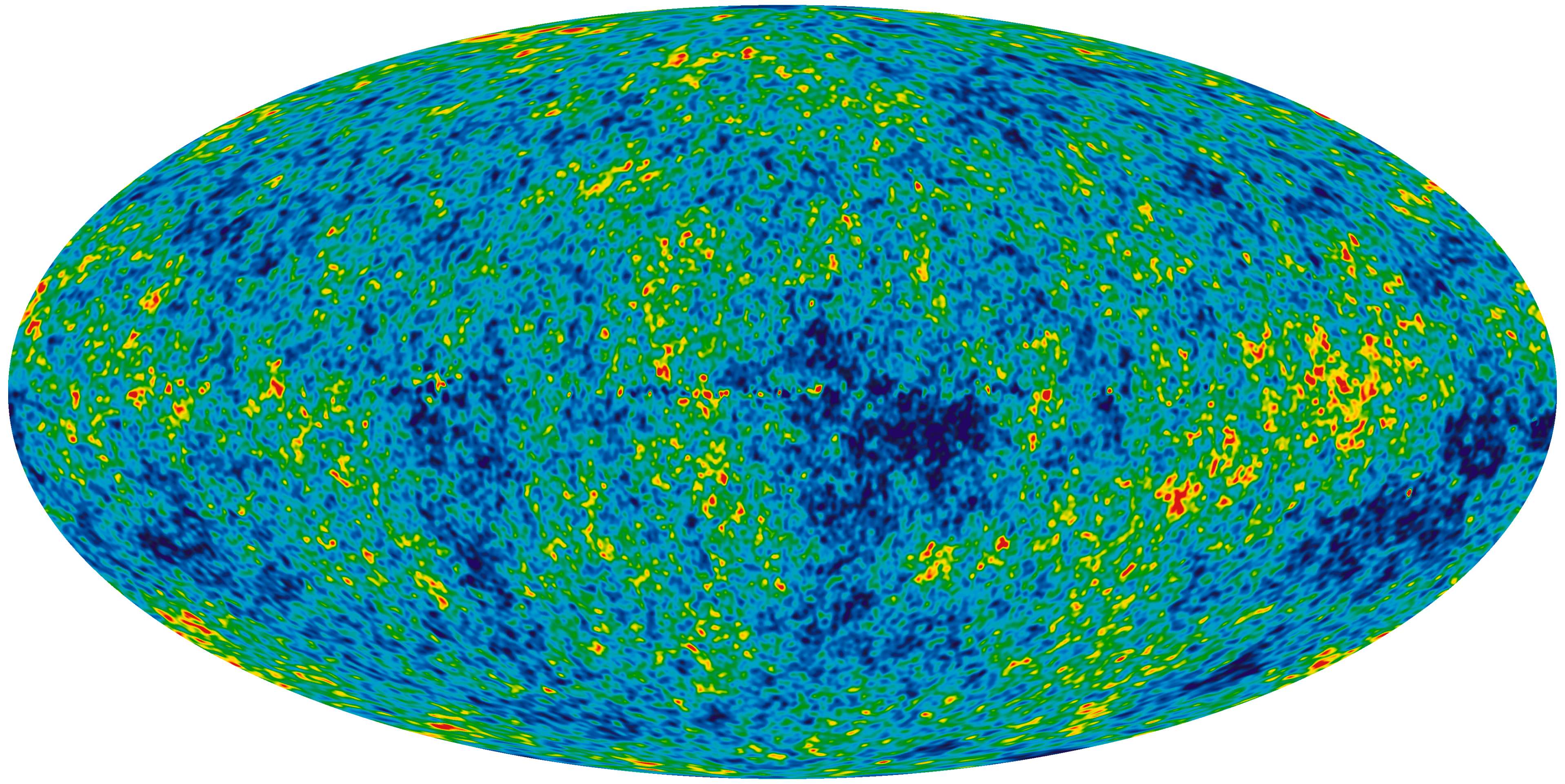
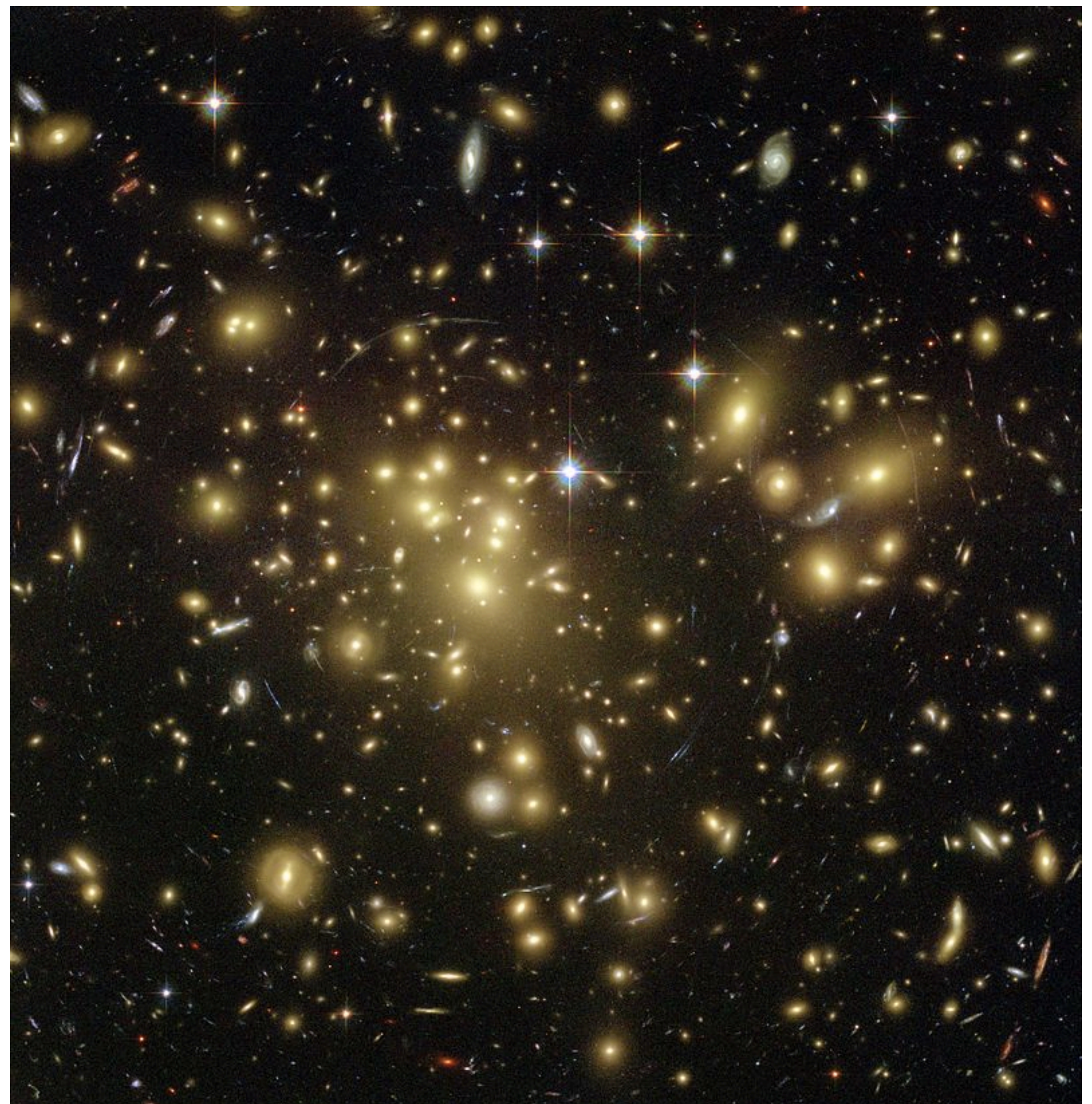


Most of the Universe's Matter is Invisible









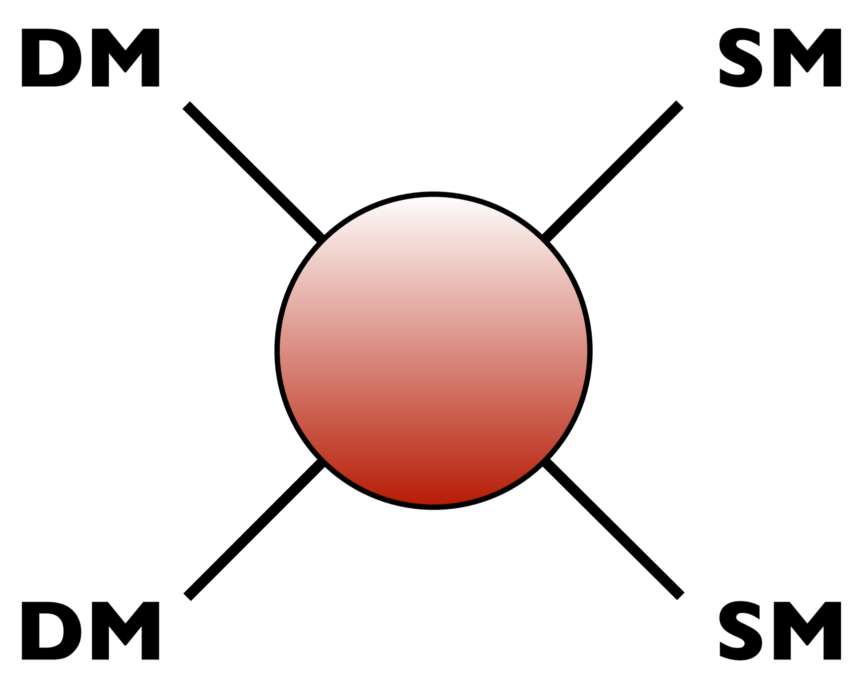
Non-Gravitational Searches for DM

“Break it” - Indirect Detection

Search for products of DM annihilation in regions of high DM density.

“Wait for it” Direct Detection

DM-SM scattering in detector



“Make it” - Colliders

Produce DM and find anomalous missing energy.

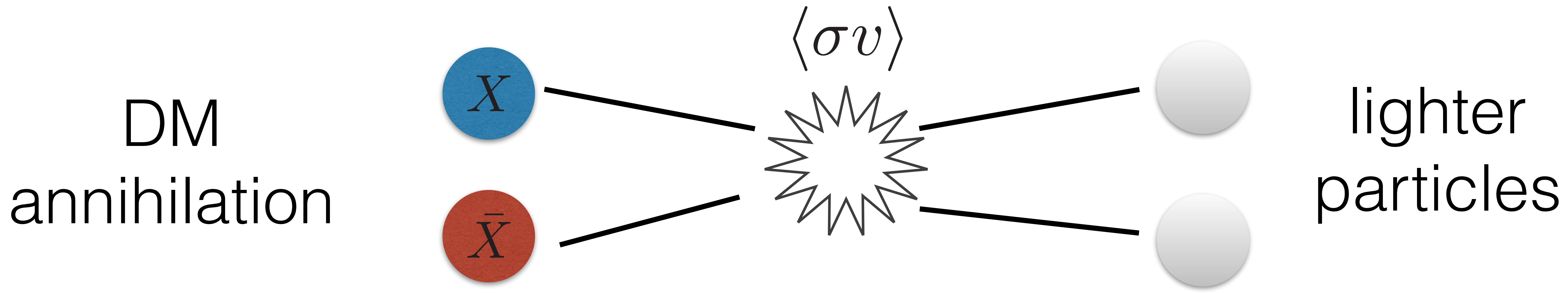
Outline

- **The Standard Model's successes & limitations.**
- **The Hunt for New Physics:**
  - **Thermal relic hypothesis for DM**
  - **Dark photons & kinetic mixing**
  - **Complementarity of Experimental Probes.**

Why should DM have non-gravitational interactions?

DM as a Thermal Relic

- The early Universe was a hot/dense place.



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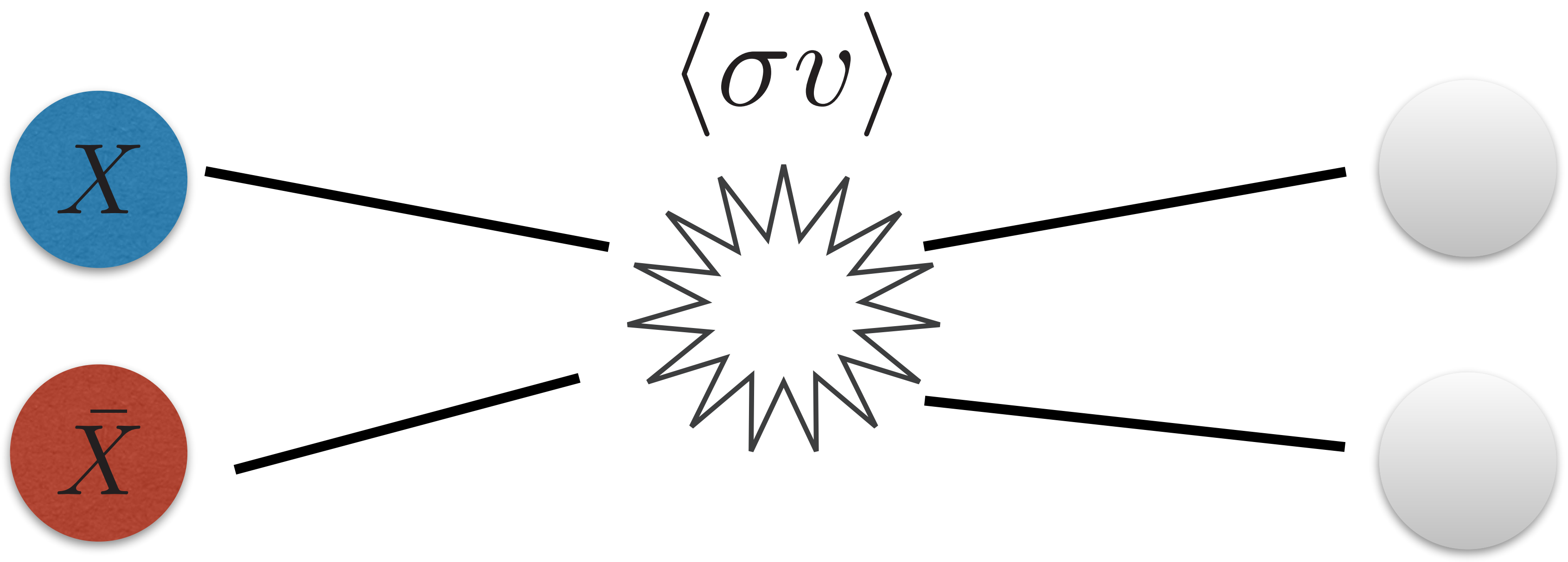
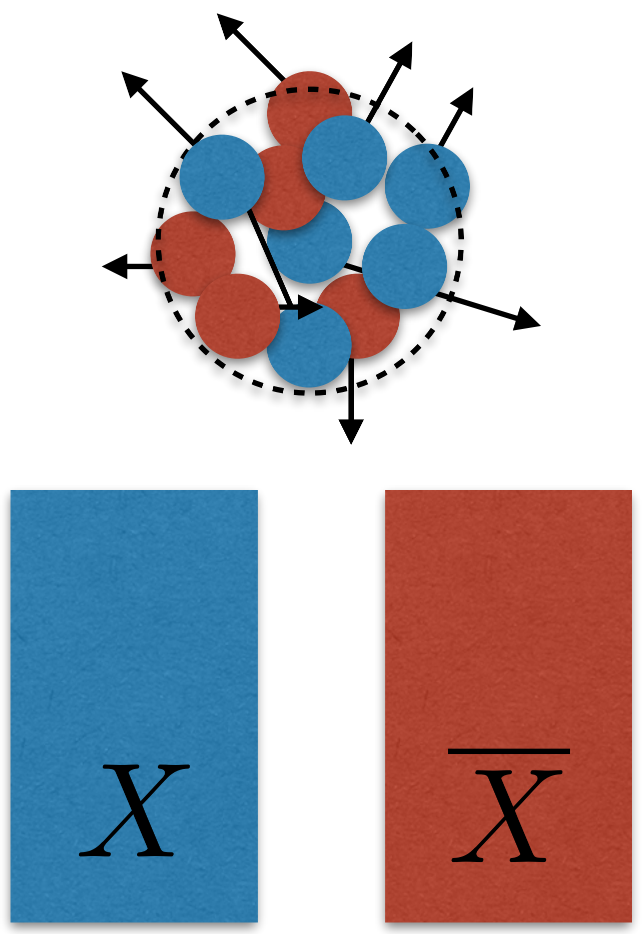


lighter
particles

early



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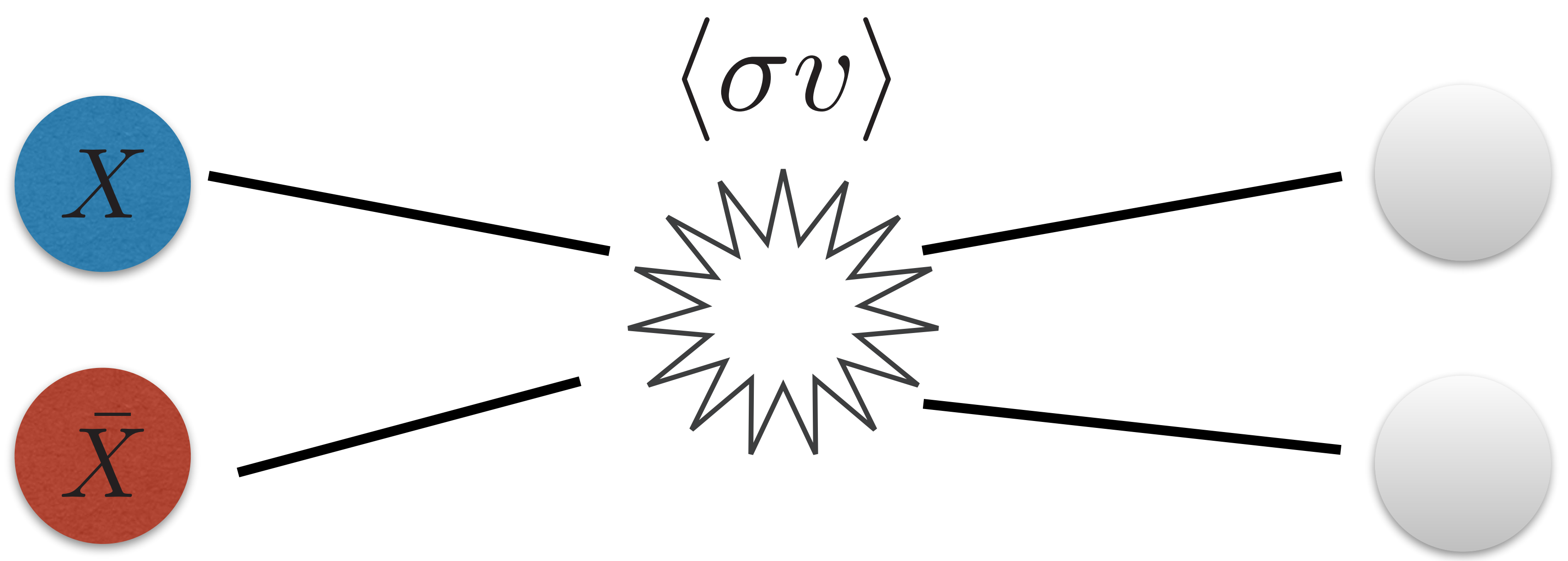

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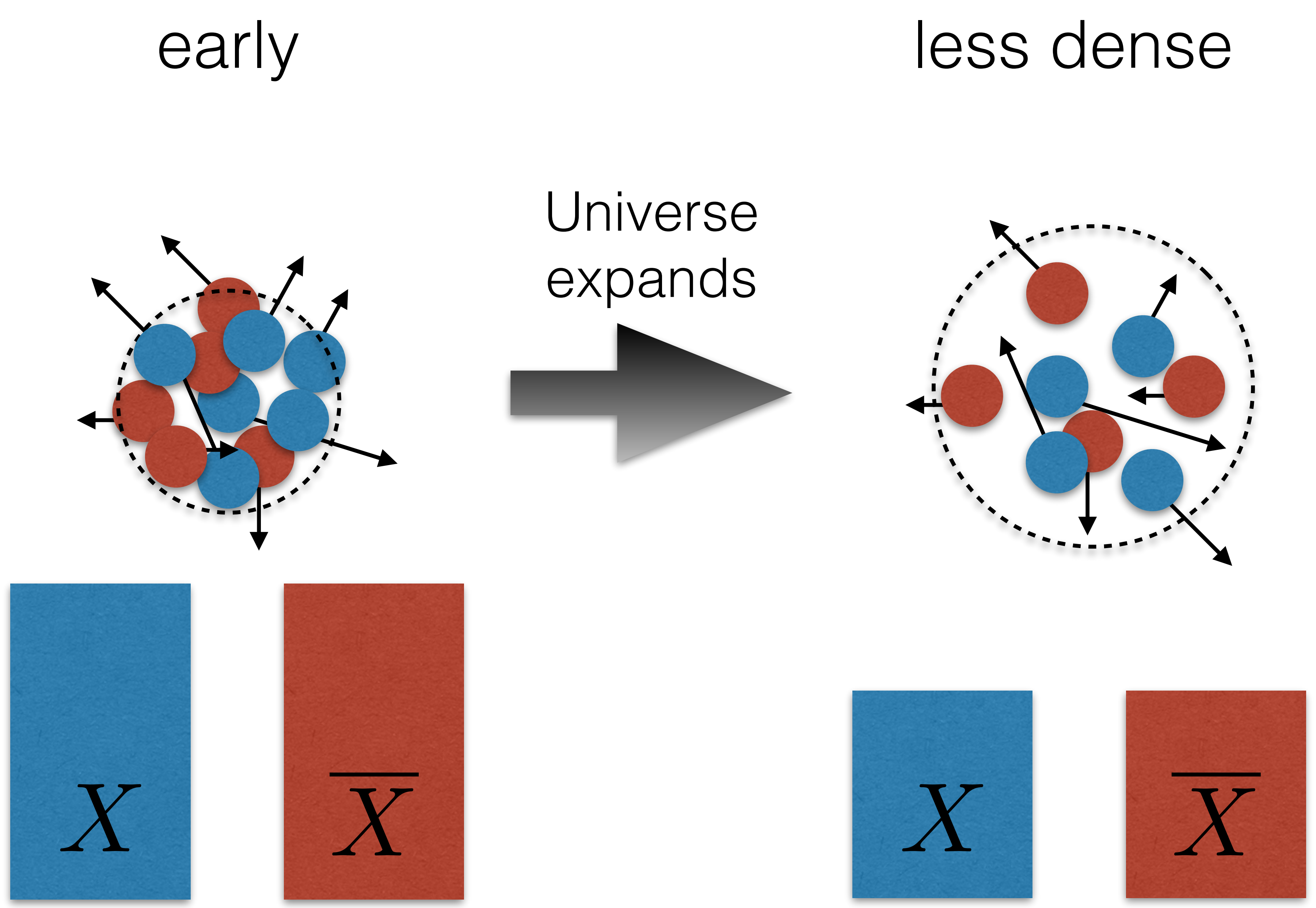

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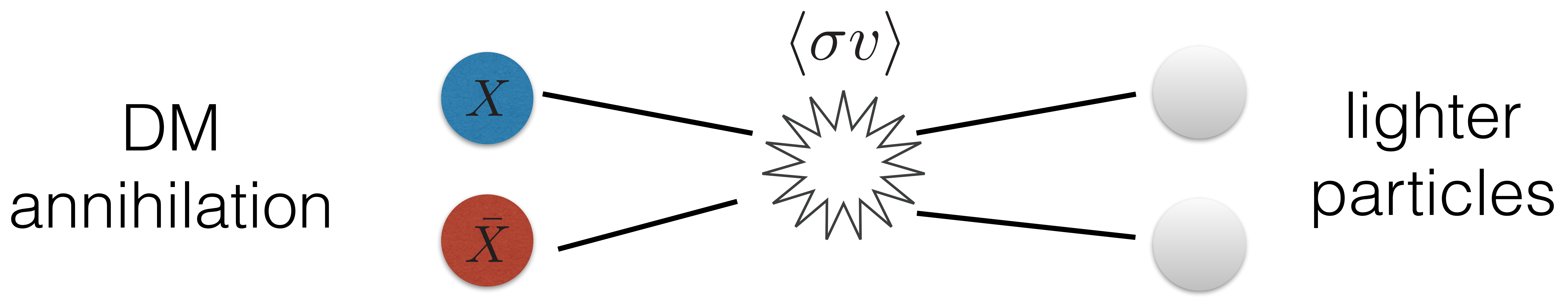

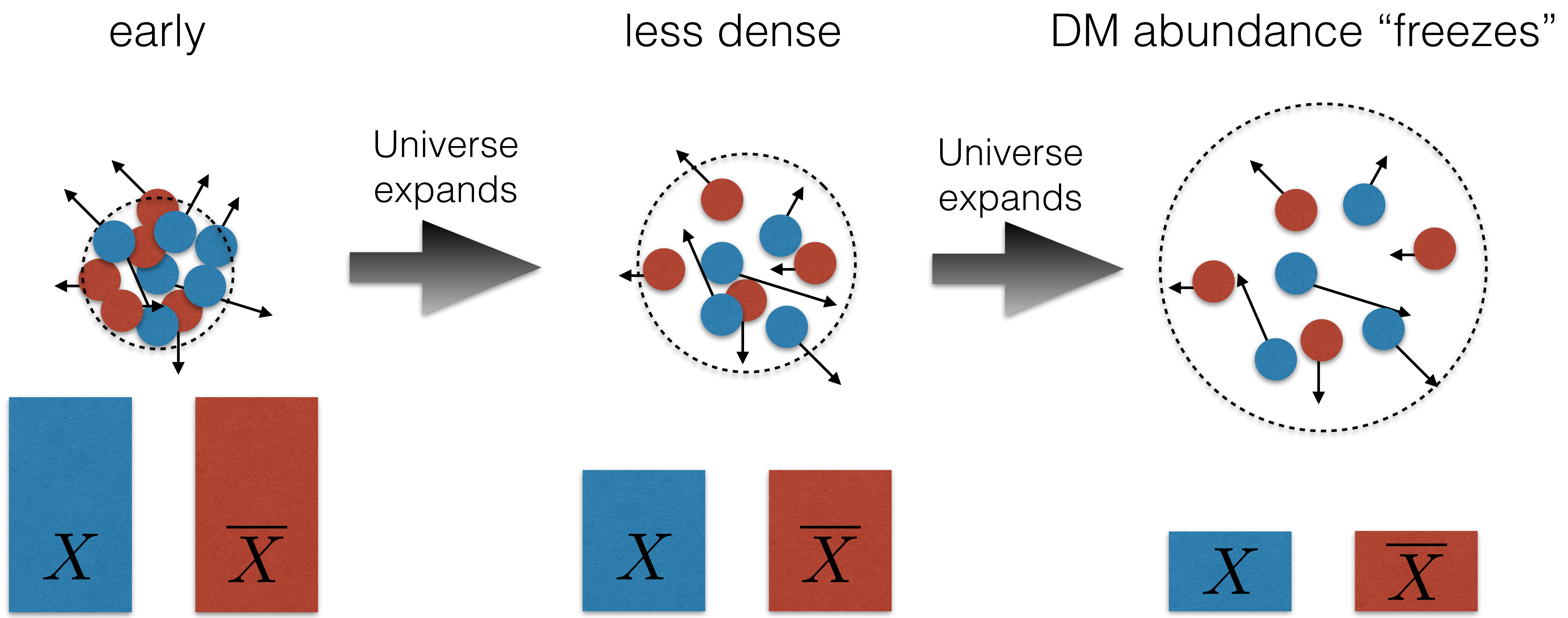

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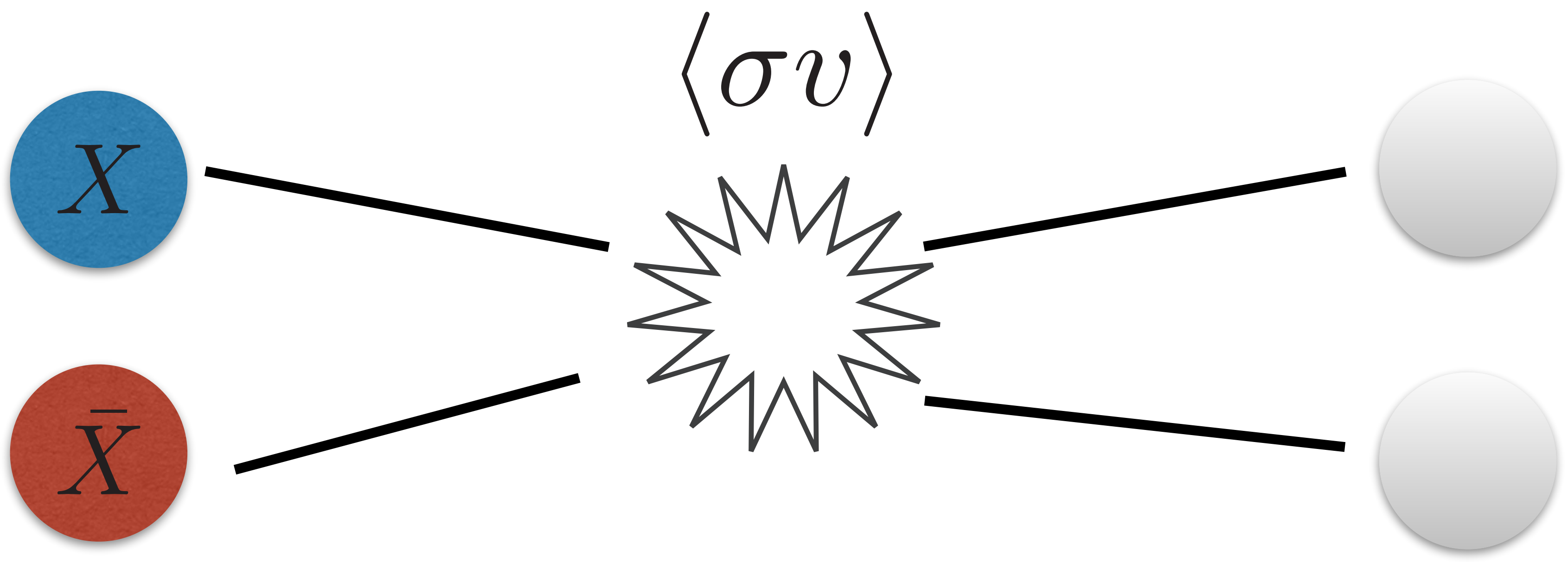
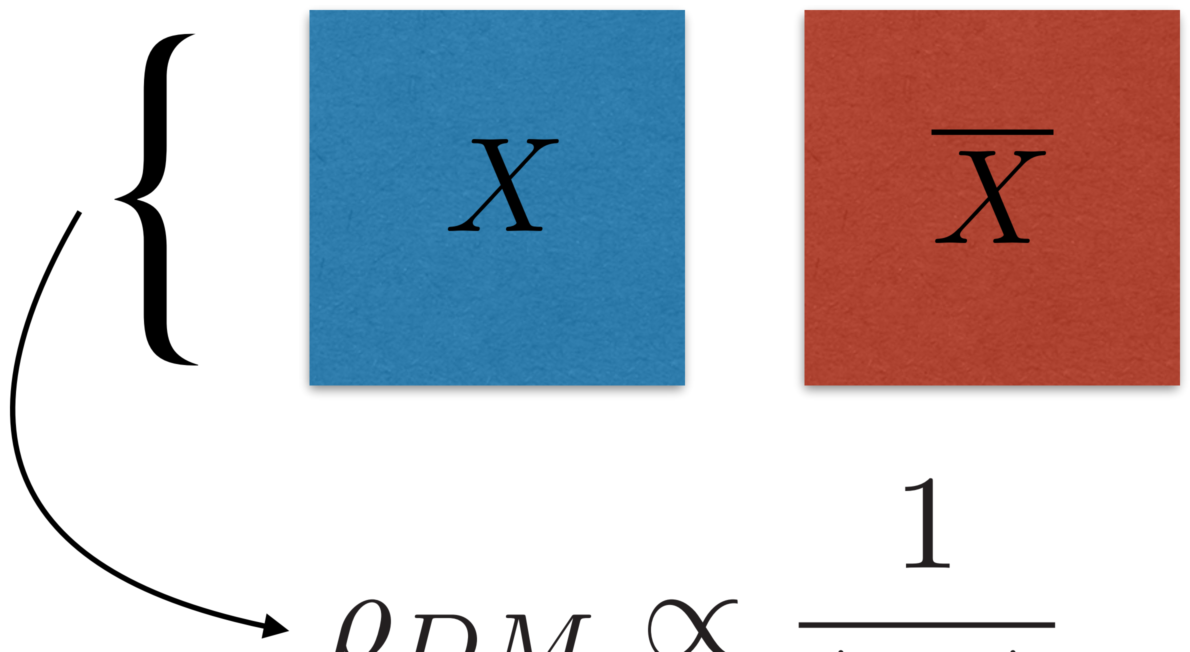


lighter particles

Final “freeze-out” abundance



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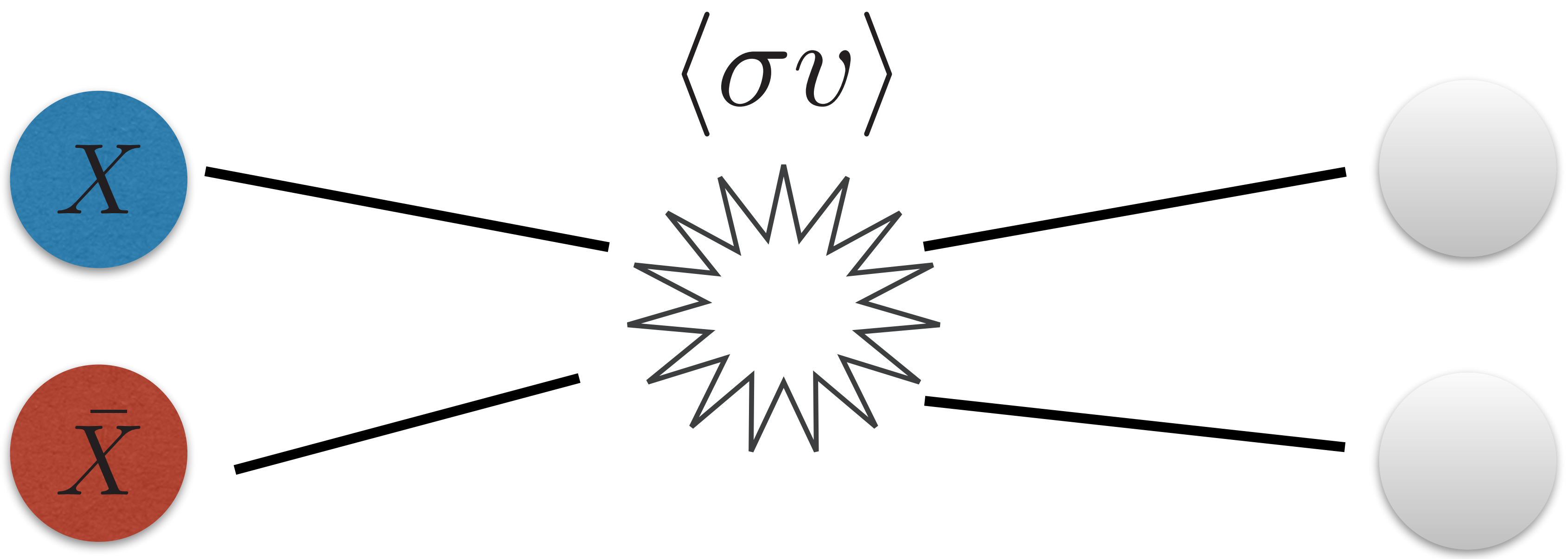

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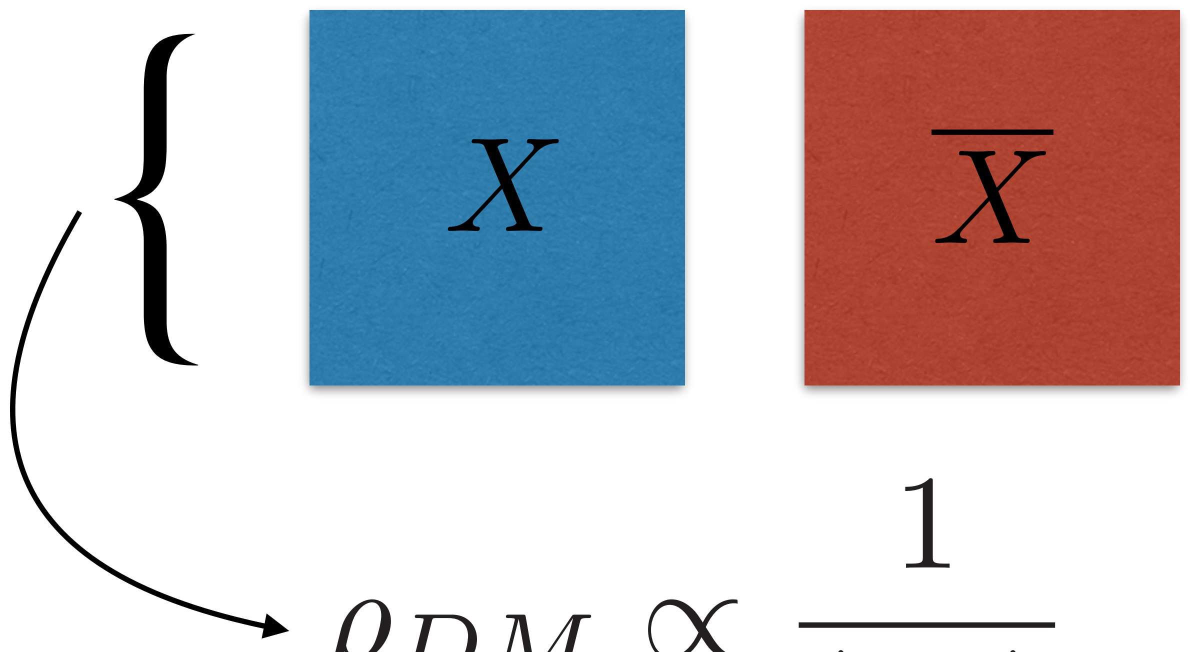

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A thermal relic has the observed DM abundance if:

$$\langle \sigma v \rangle = 3 \times 10^{-26}\ \mathrm{cm}^3\ \mathrm{s}^{-1}$$

"WIMP miracle"

WIMP = Weakly-Interacting Massive Particle

Elegant, compelling,
but not **unique.**

What about baryons?

- The amounts of dark and visible matter are **comparable**:

$$\frac{\Omega_{DM}}{\Omega_B} \simeq 5$$

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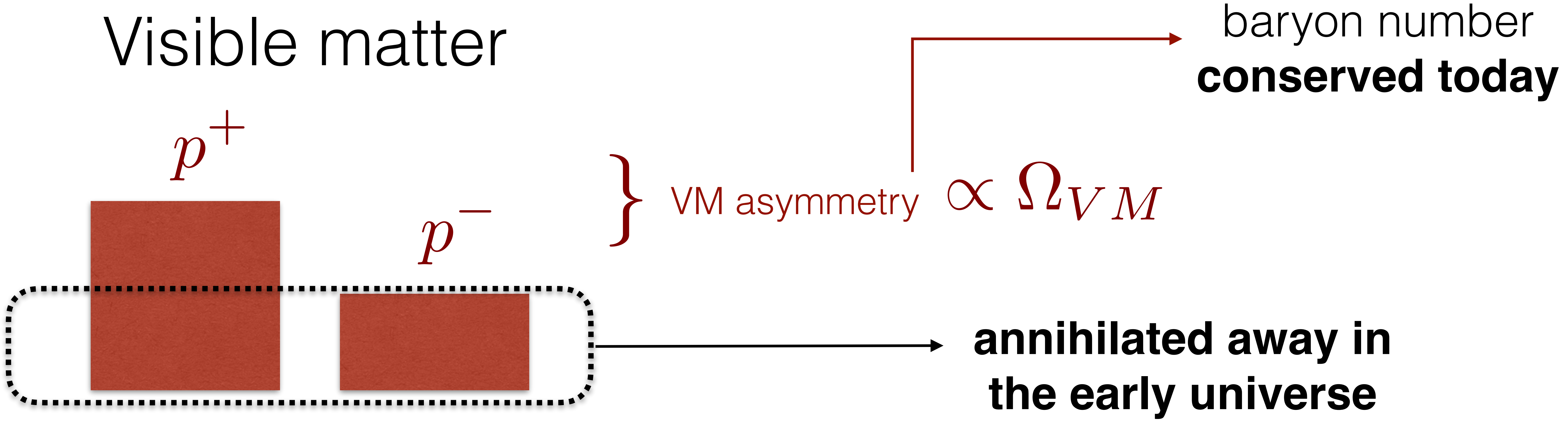
  - An anthropic selection effect? [Freivogel (2008)]
  - An indication of an underlying origin.

Ordinary matter & the baryon asymmetry

- In the Universe today, visible matter is mostly comprised of p^+ and very little p^- : **matter-antimatter asymmetry**.

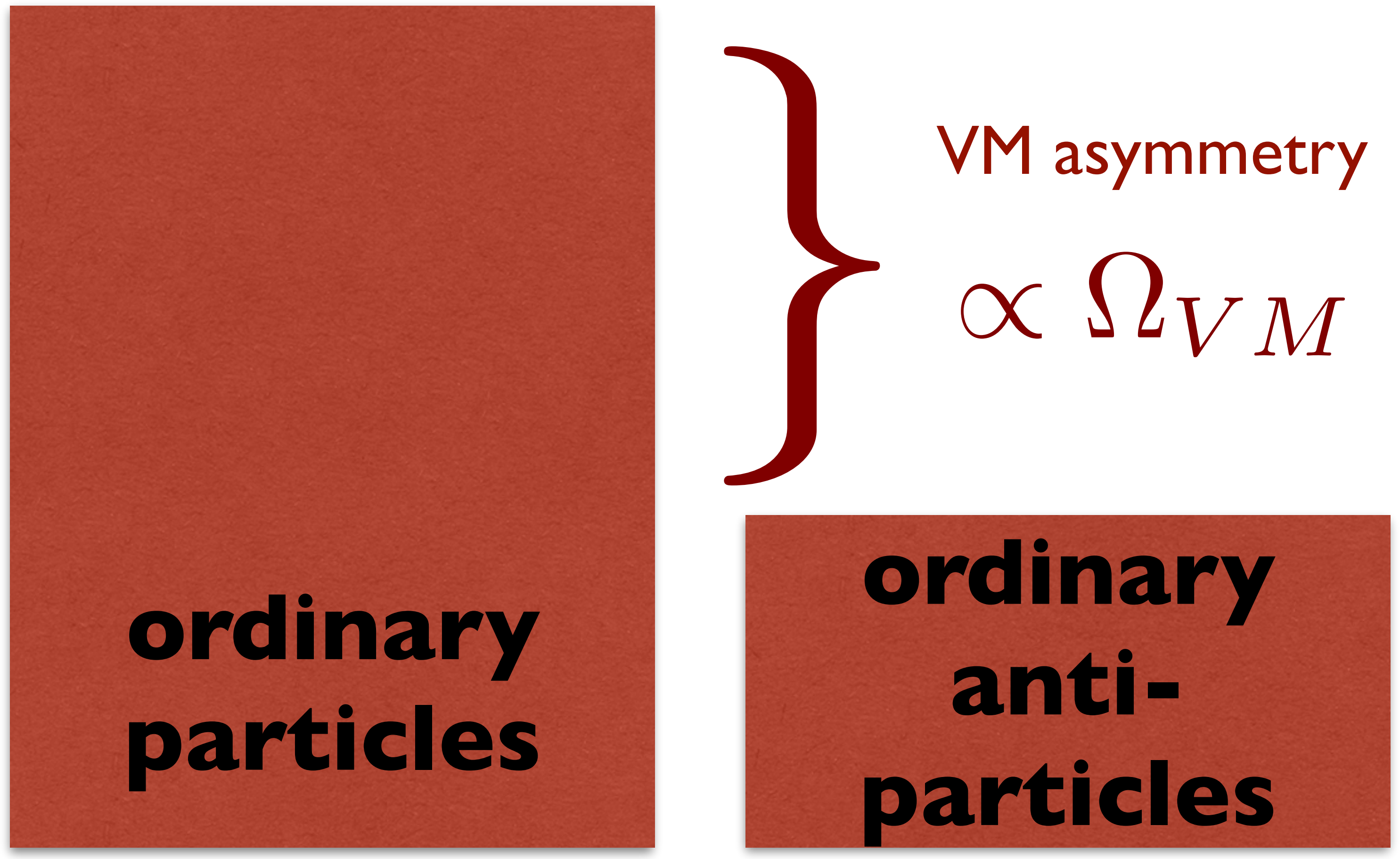
- Theoretically reasonable: $p^+ - p^-$ have large annihilation cross section.



Asymmetric Dark Matter (ADM)

[see reviews: Petraki, Volkas (2013); Zurek (2013)]

Visible matter



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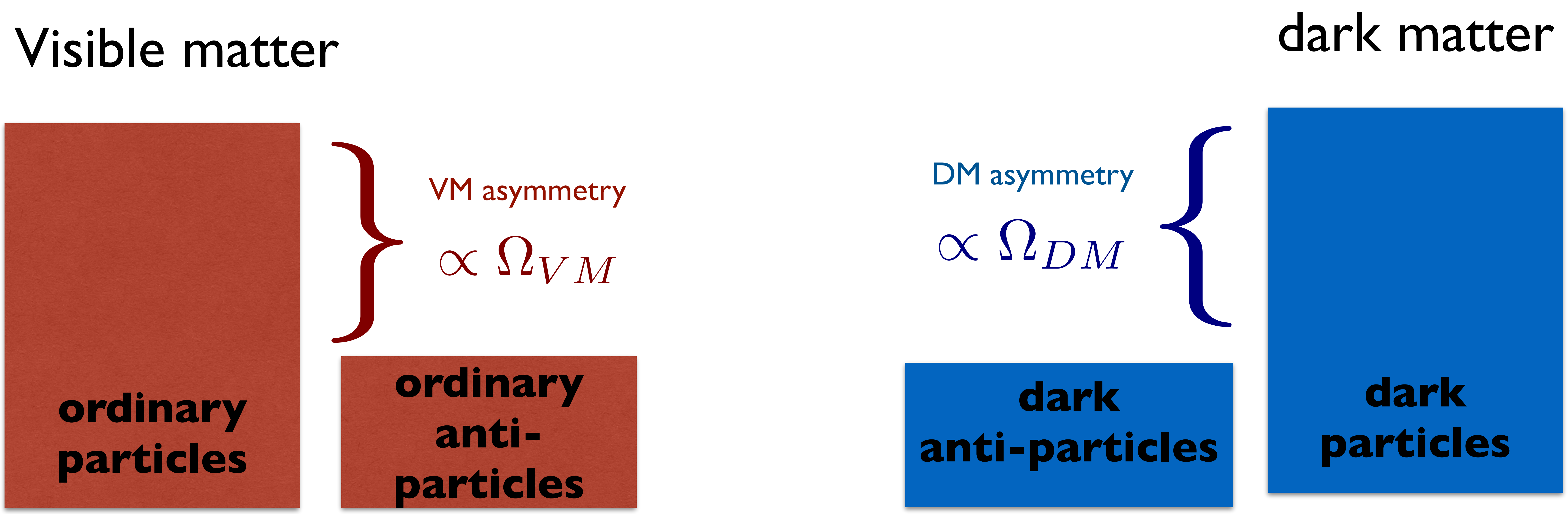

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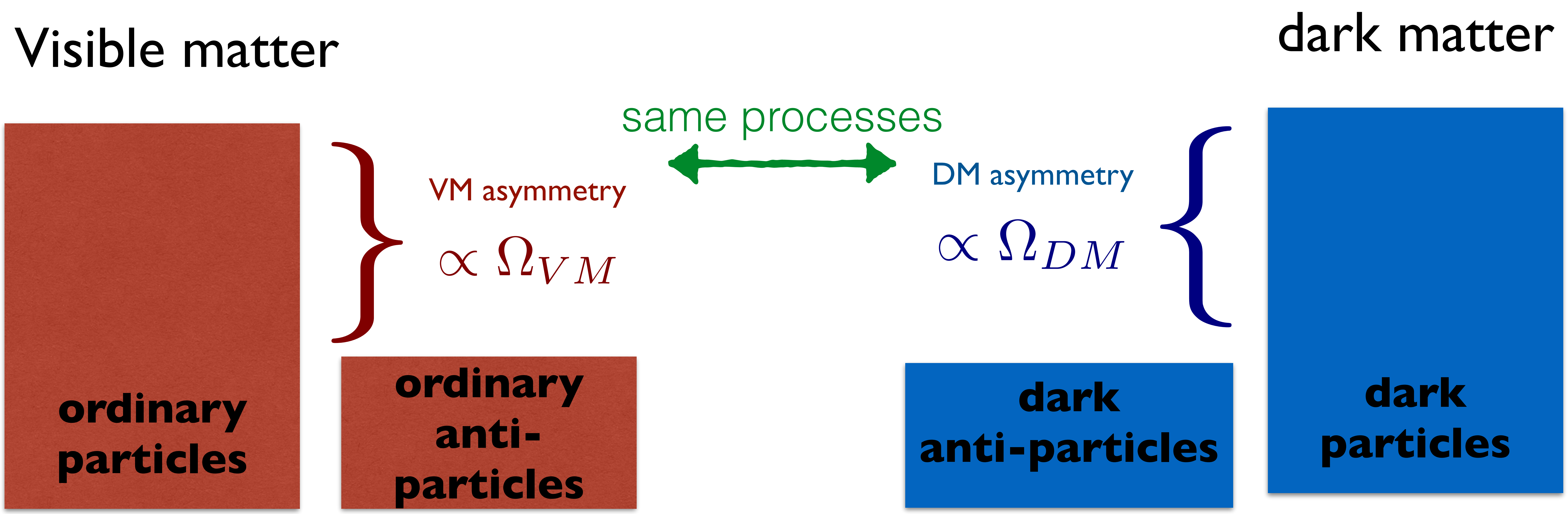

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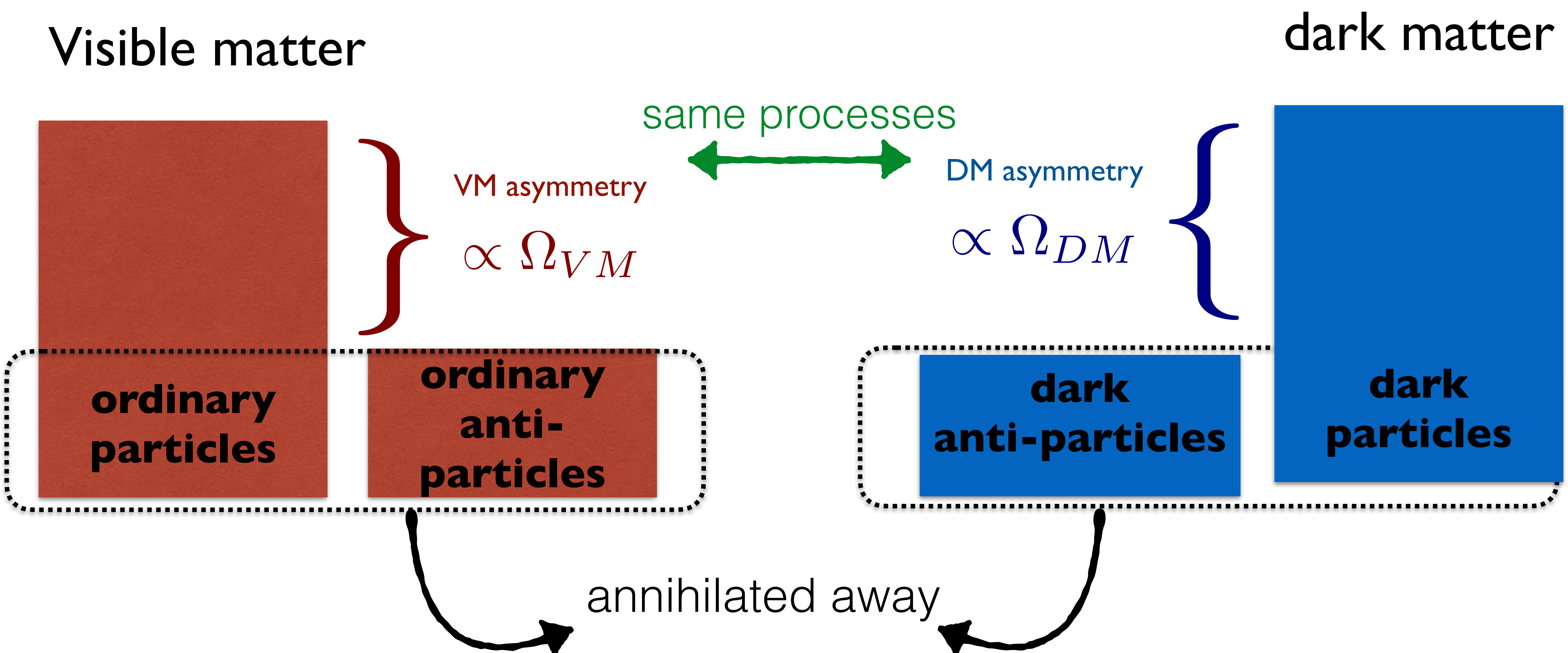

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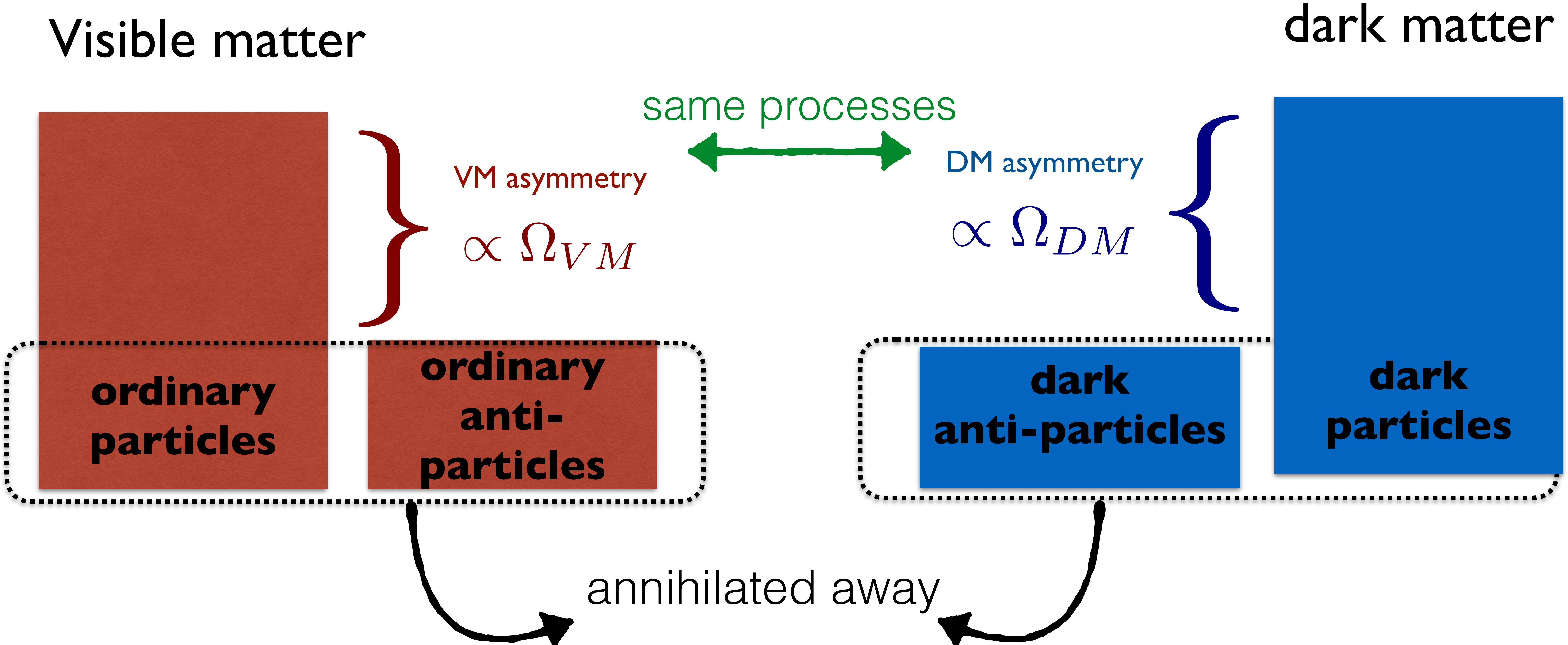

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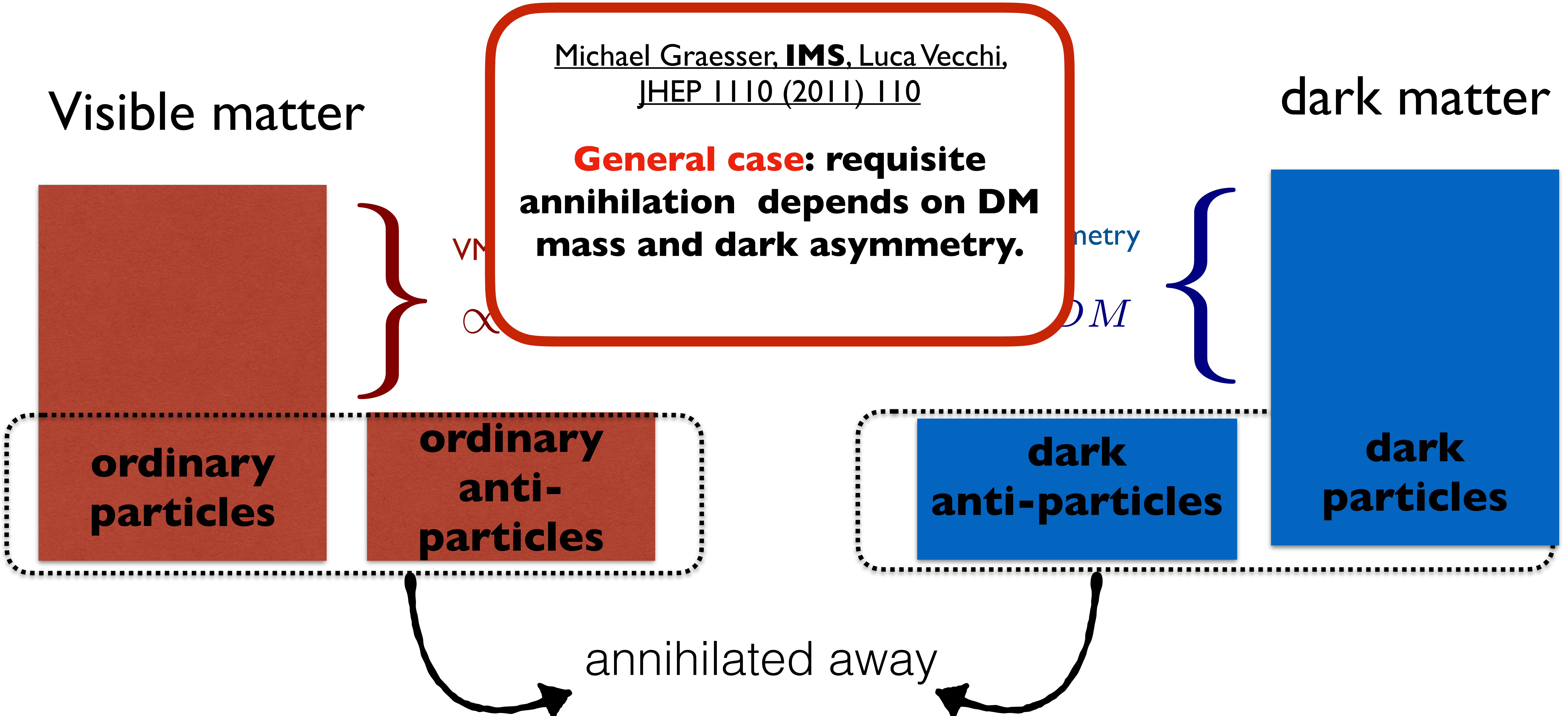

ADM Miracle Cross Sections

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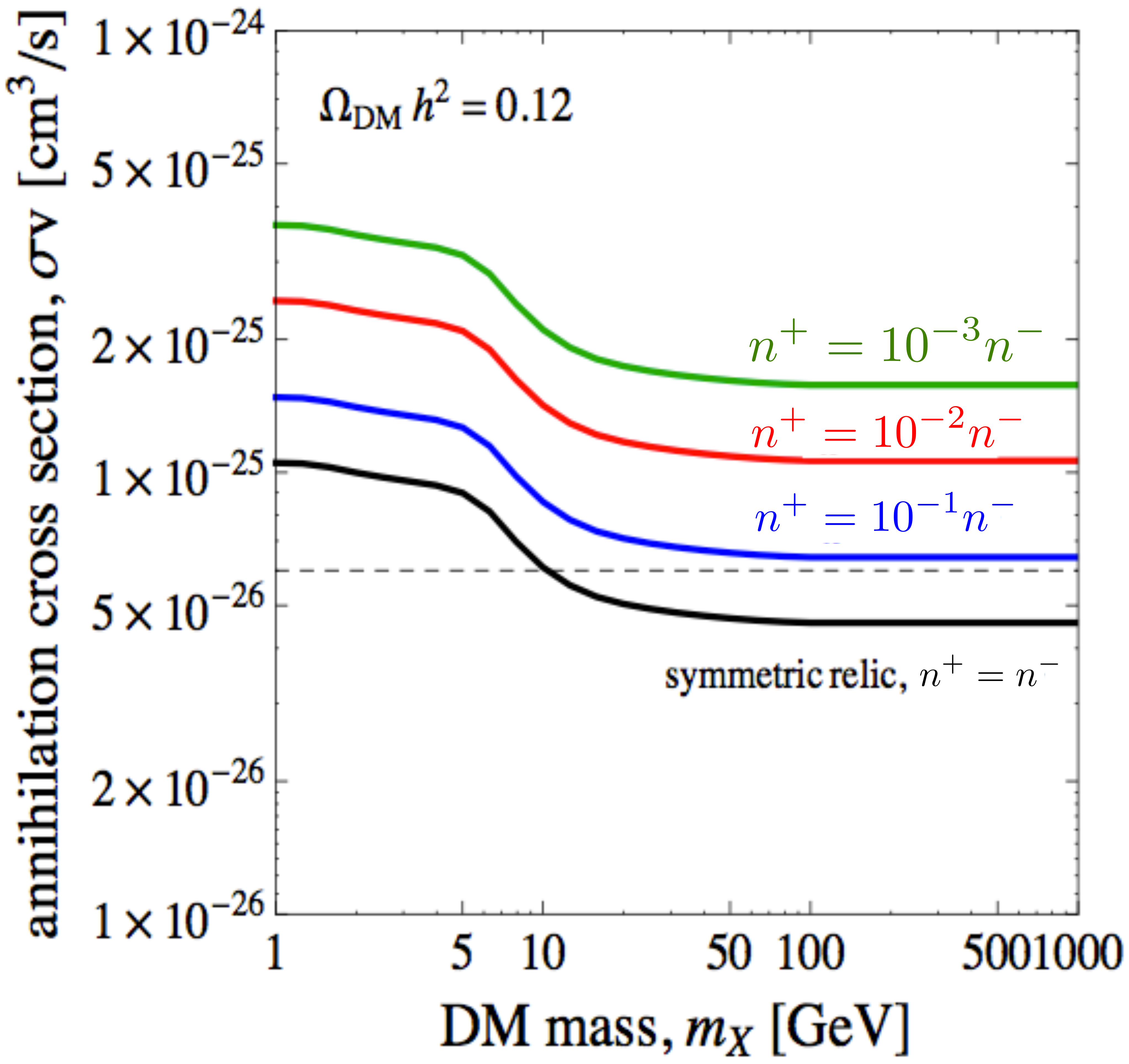

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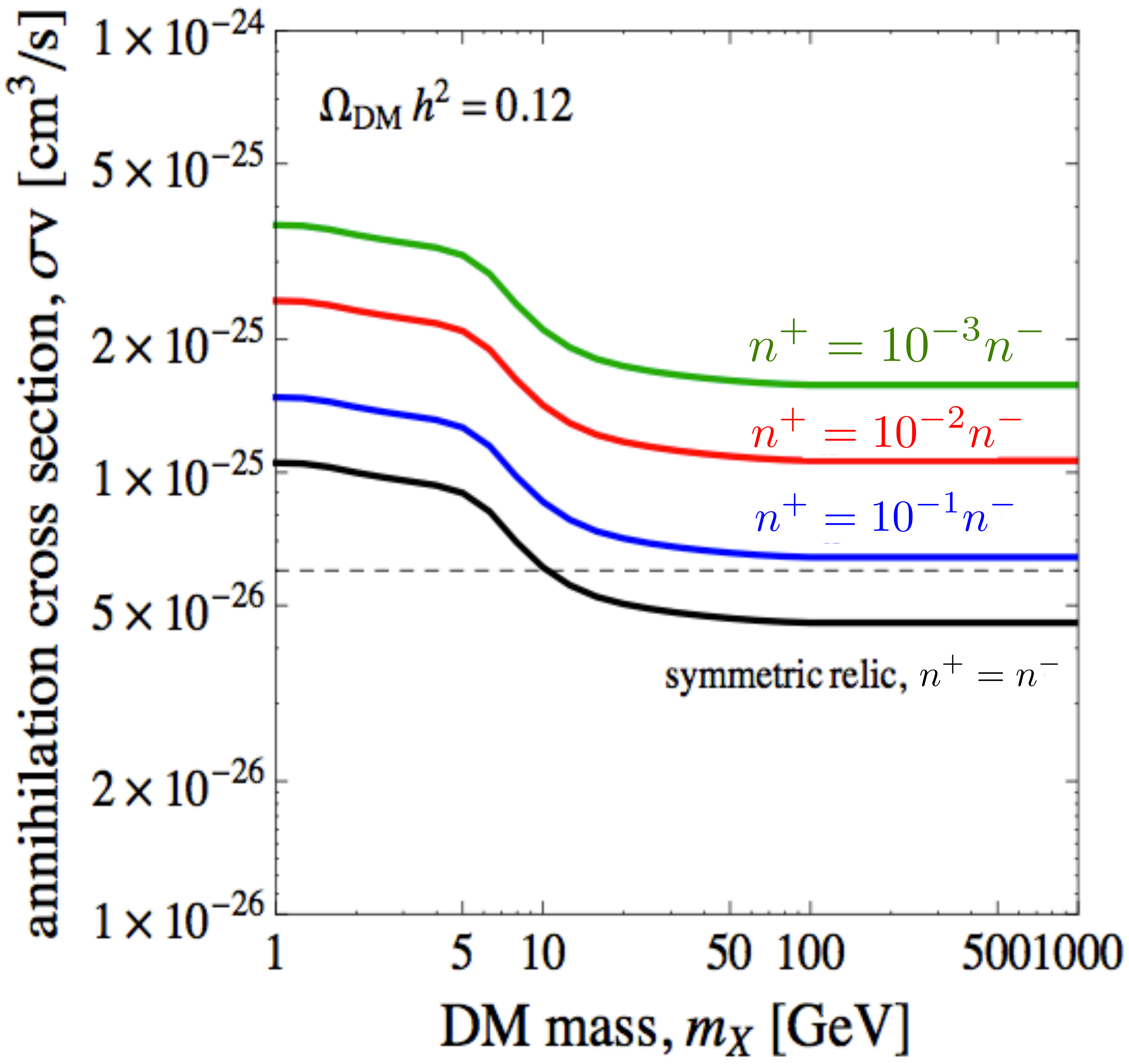

-Suppressed but **detectable** indirect signals.

-Given indirect detection bounds, ADM has non-trivial bounds on annihilation.

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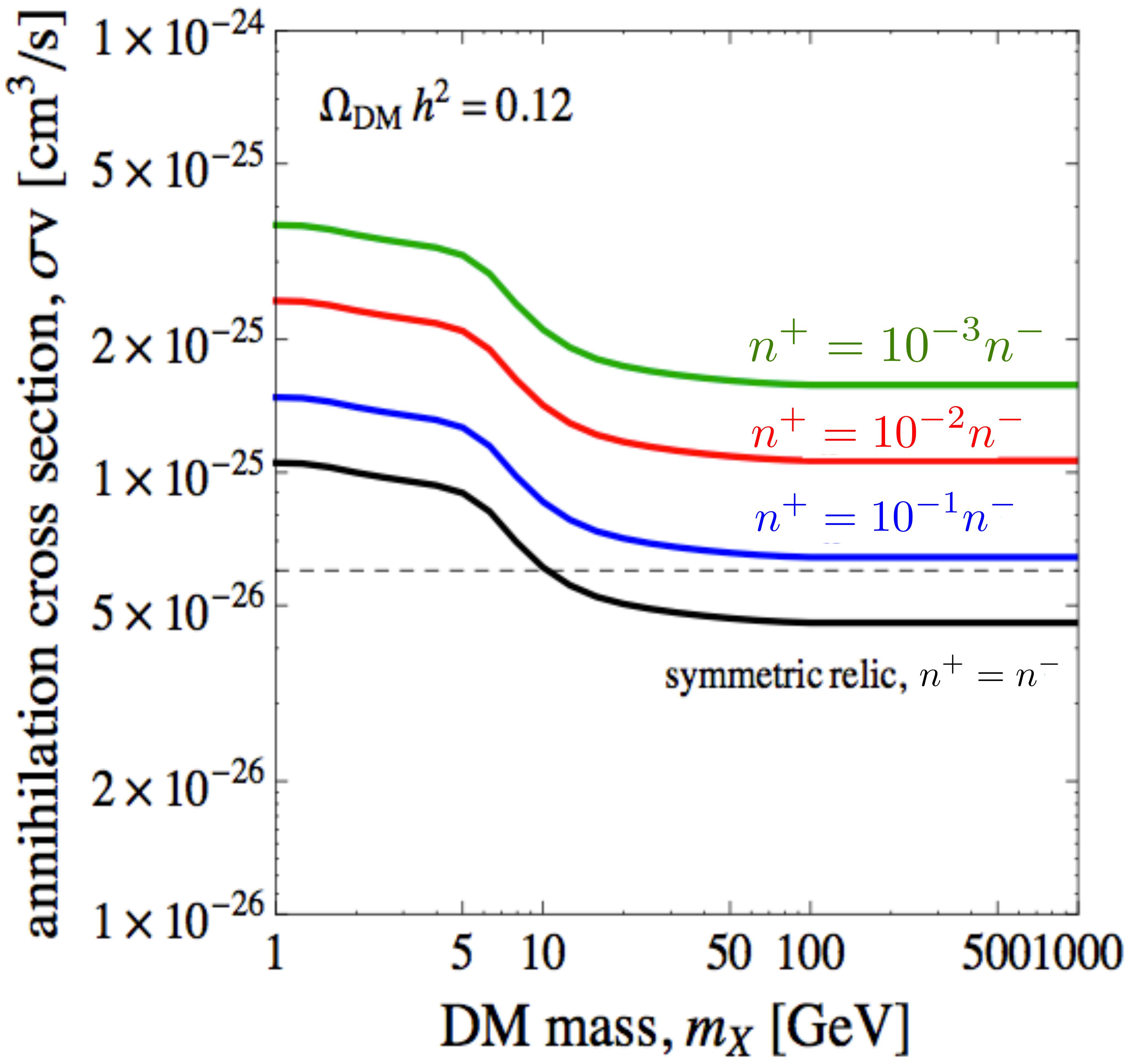

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-What models are consistent with thermal relic?

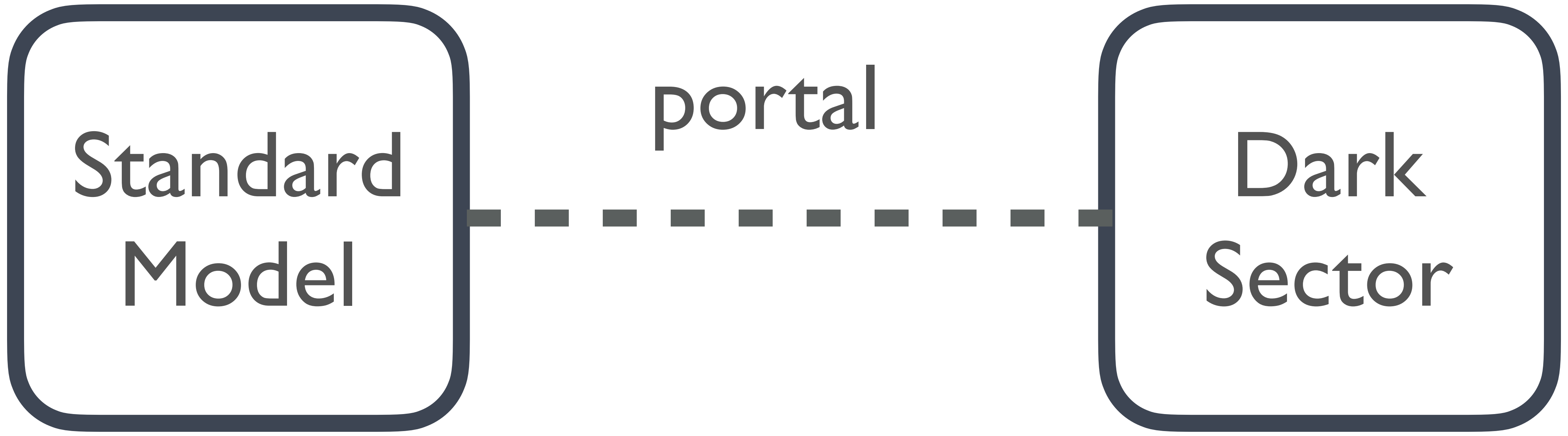
Lee-Weinberg Bound

- One of the few remaining options for thermal DM is < GeV.
- The Lee-Weinberg bound (1977), tells us that if **sub-GeV** DM annihilates via weak force the DM, annihilation rate is small and a thermal relic is overproduced:

$$\frac{\Omega_{DM}}{\Omega_{matter}} > 1$$

- Can be circumvented with new **light mediators.**
- **Dark Matter may require more than one new state.**

Dark Sectors



A dark sector hiding alongside ours only connected through a "portal" interaction (and gravity).

Possible Portals to a Dark World

Vector portal	$\mathcal{O}_{\text{vector}} = B_{\mu\nu}V^{\mu\nu}$	[Holdom '86]
Higgs portals	$\mathcal{O}^{(1)}_{\text{Higgs}} = SH^\dagger H$ $\mathcal{O}^{(2)}_{\text{Higgs}} = \phi^\dagger\phi H^\dagger H$	[Silveira,Zee '85]
Neutrino portal	$\mathcal{O}_{\text{Neutrino}} = LHN$	[Minkowski '77]

Only 4 renormalizable portals!
Let's test them!

DM coupled to a Dark Photon

•In ordinary EM, the photon is associated with a **$U_{EM}(1)$** gauge symmetry.

→As a result, the photon couples to anything with **$U_{EM}(1)$** charge (electrons, protons, etc.)

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$$\mathscr{L}_{\rm int} = -A'_\mu (g_D J^\mu_D + \epsilon e J^\mu_{\rm EM}),$$

ϵ = dimensionless kinetic mixing parameter

- As a result of **kinetic mixing** with the ordinary SM photon, it will have a **suppressed** coupling to anything with **U_{EM}** charge.

DM coupled to a Dark Photon

$$\mathscr{L}_{\text{int}} = -A'_\mu(g_D J^\mu_D + \epsilon e J^\mu_{\text{EM}}),$$

Then we just ask: what's Dark Matter made of? Answer to this question dictates the form of the dark current (assuming gauge/Lorentz invariance).

$$J^\mu_D = \begin{cases} i\chi^*\partial^\mu\chi + c.c. & \text{Scalar} \\ \frac{1}{2}\overline{\chi}\gamma^\mu\gamma^5\chi & \text{Majorana} \\ i\overline{\chi}_1\gamma^\mu\chi_2 & \text{Pseudo-Dirac} \\ \overline{\chi}\gamma^\mu\chi & \text{Dirac (Asymmetric)} \end{cases}$$

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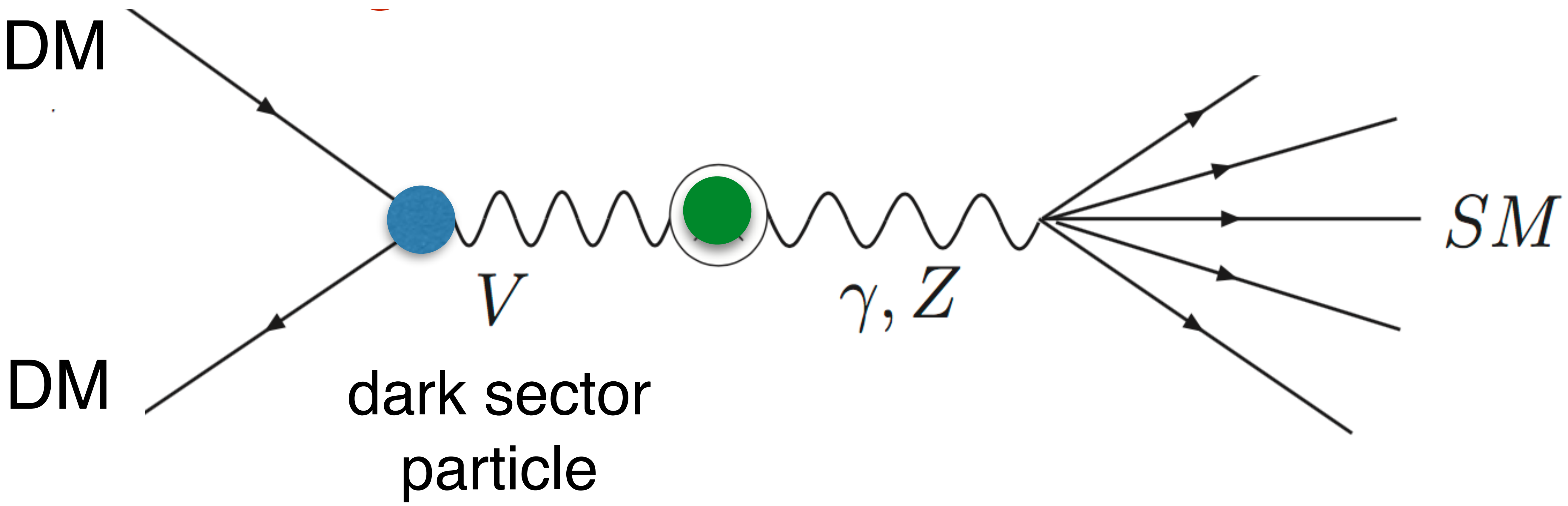
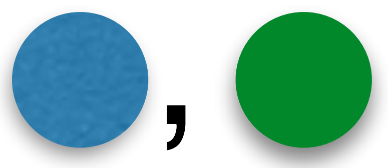
➡ Upshot: each of these have different requirements to be a thermal relic & predict different phenomenology!

Classes of Thermal Relics

Case #1: DM is the lightest dark sector state ➡ Must annihilate to SM states



Annihilation cross section controlled by a product of couplings: 

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As long as we're far from resonance and

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

→ $$\boxed{\langle \sigma v \rangle \propto \frac{y}{m_X^2}}$$ $$y \equiv \epsilon^2 \alpha_D \left(\frac{m_X}{m_{A'}} \right)^4$$

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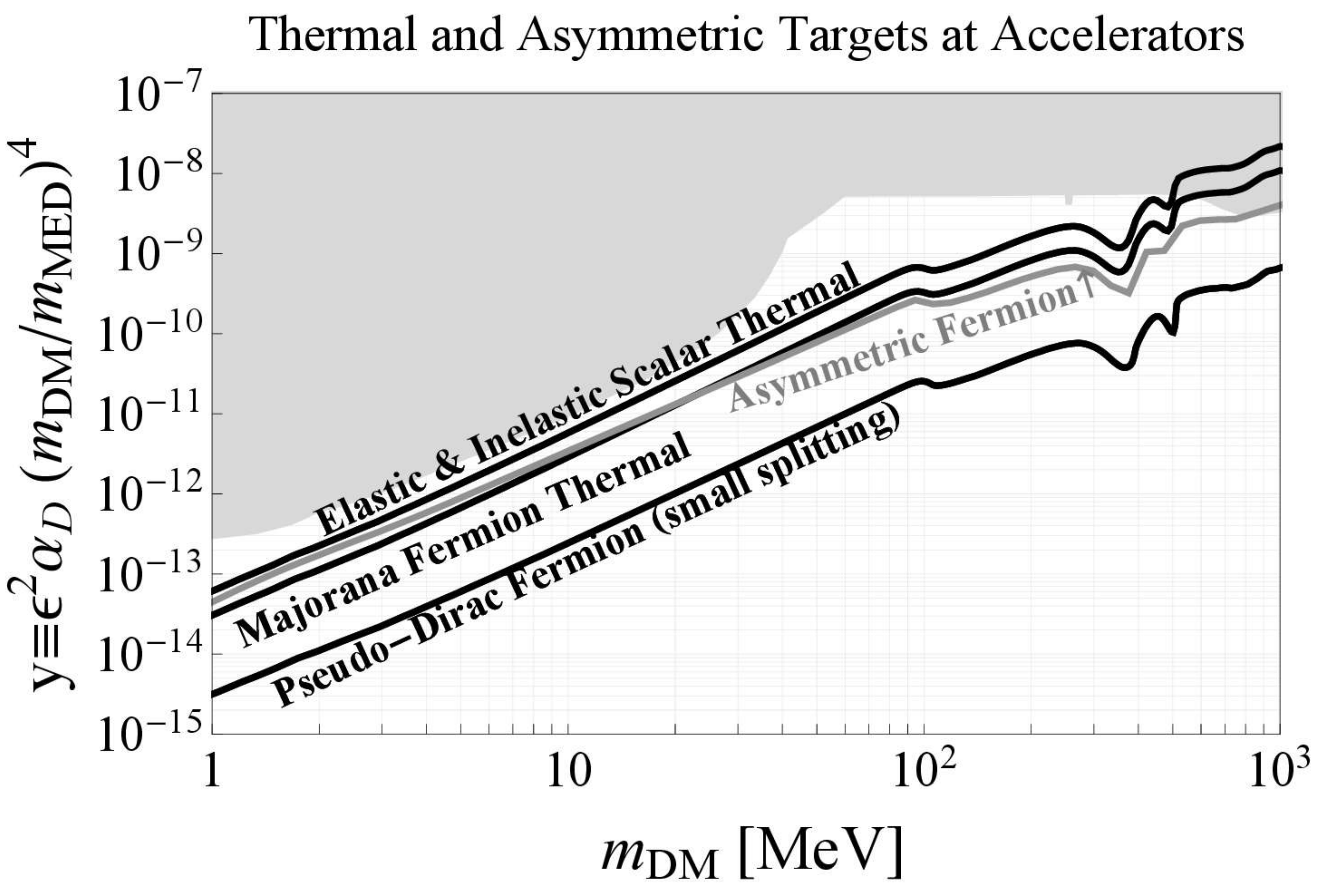

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US Cosmic Visions: New Ideas in Dark Matter [arXiv: 1707.04591]

DM coupled to a Dark Photon

$$\mathscr{L}_{\rm int} = -A'_\mu (g_D J^\mu_D + \epsilon e J^\mu_{\rm EM}),$$

NOTE: Despite this fairly minimal model, we still have **4 new parameters**:

{ 2 couplings: (ϵ, g_D)
2 masses: (m_X, $m_{A'}$)

Beware: different groups use different combinations of these to report results!

Typically fix 2 of them, and report a constraint in plane of the other 2 parameters.

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2 masses: (m_X, $m_{A'}$)

Common convention, fix g_D and mass ratio $R \equiv m_{A'} / m_X$

DM coupled to a Dark Photon

$$\mathscr{L}_{\rm int} = -A'_\mu (g_D J^\mu_D + \epsilon e J^\mu_{\rm EM}),$$

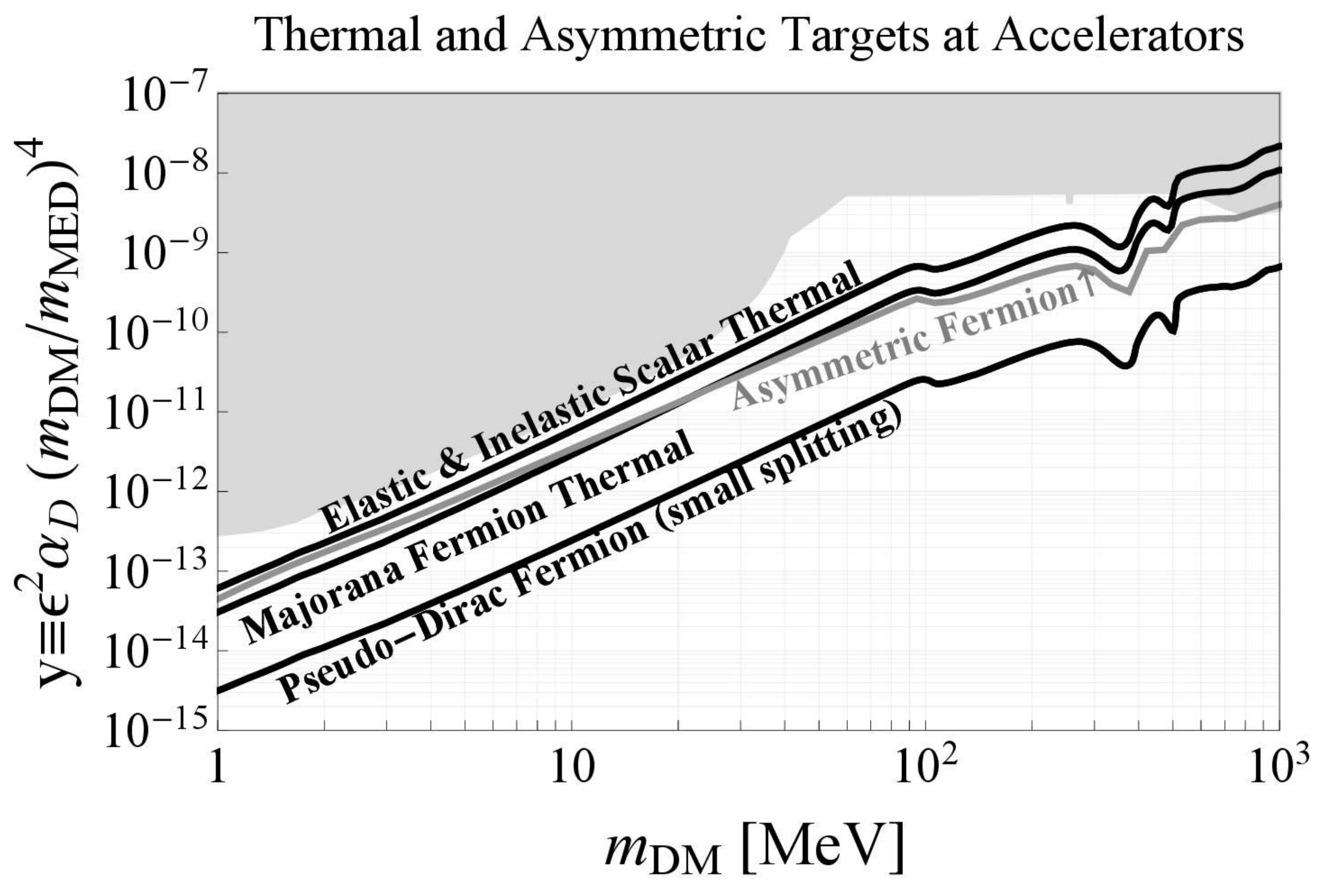
NOTE: Despite this fairly minimal model, we still have **4 new parameters**:

- 2 couplings: (ϵ, g_D)
- 2 masses: (m_X, $m_{A'}$)

Common convention, fix g_D and mass ratio $R \equiv m_{A'} / m_X$

→ Report constraints in the y-m_X plane.

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

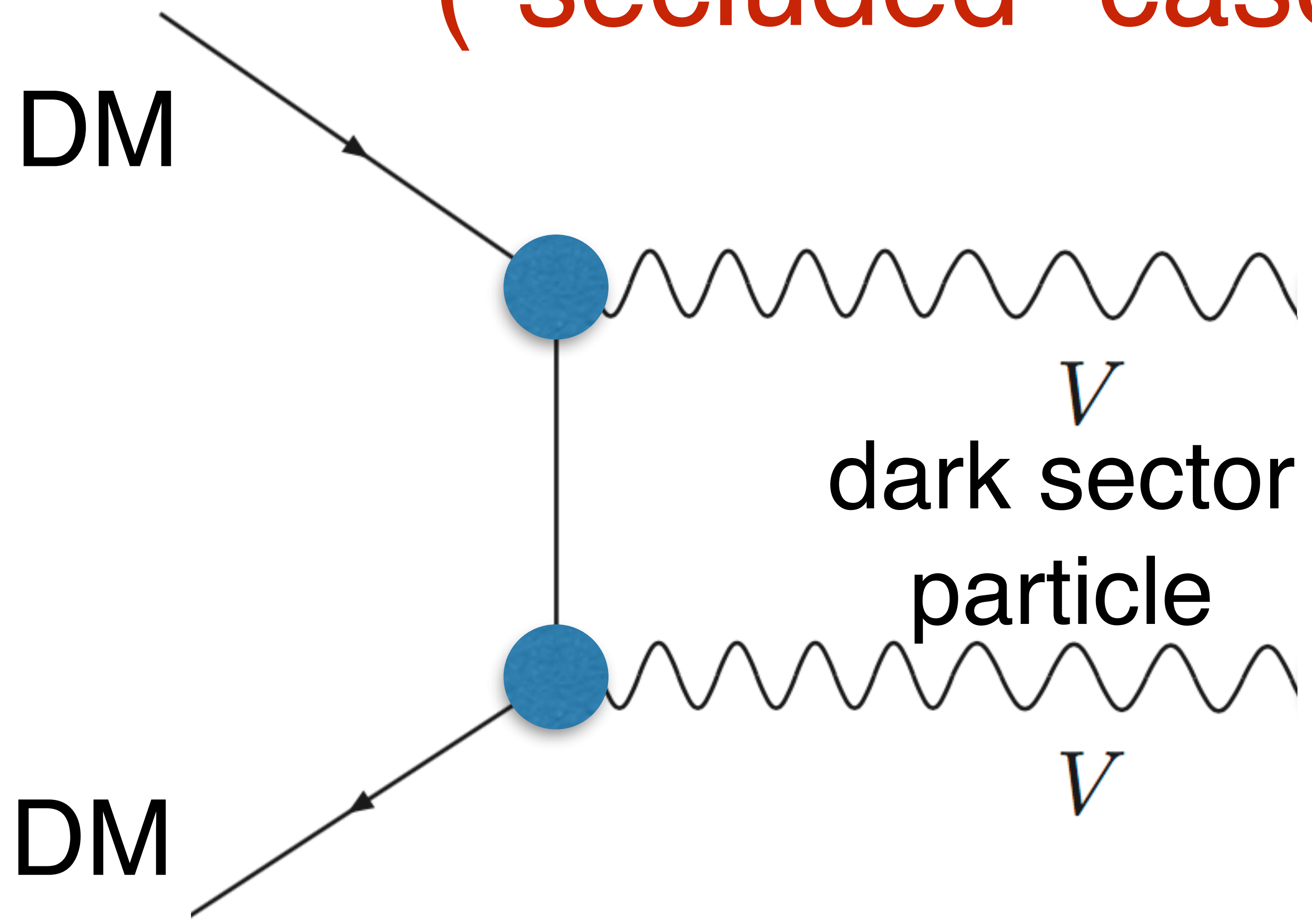


Classes of Thermal Relics

Case # 2: One or more particles in the dark sector are lighter than DM

DM can annihilate to dark sector states

("secluded" case)



Pospelov, Ritz, Voloshin, 0711.4866

$$\langle \sigma v \rangle \propto \frac{\alpha_D^2}{m_X^2}$$

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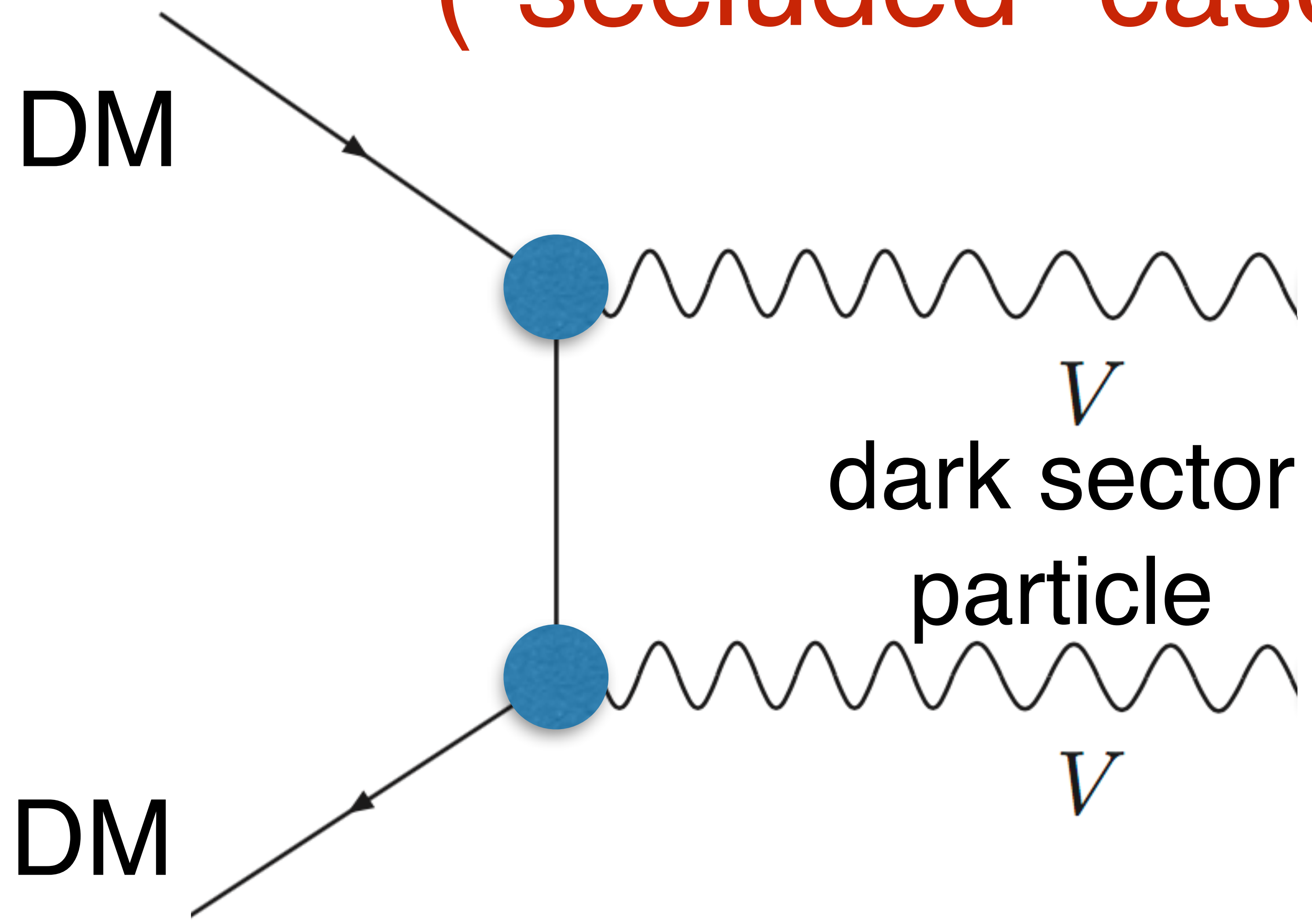

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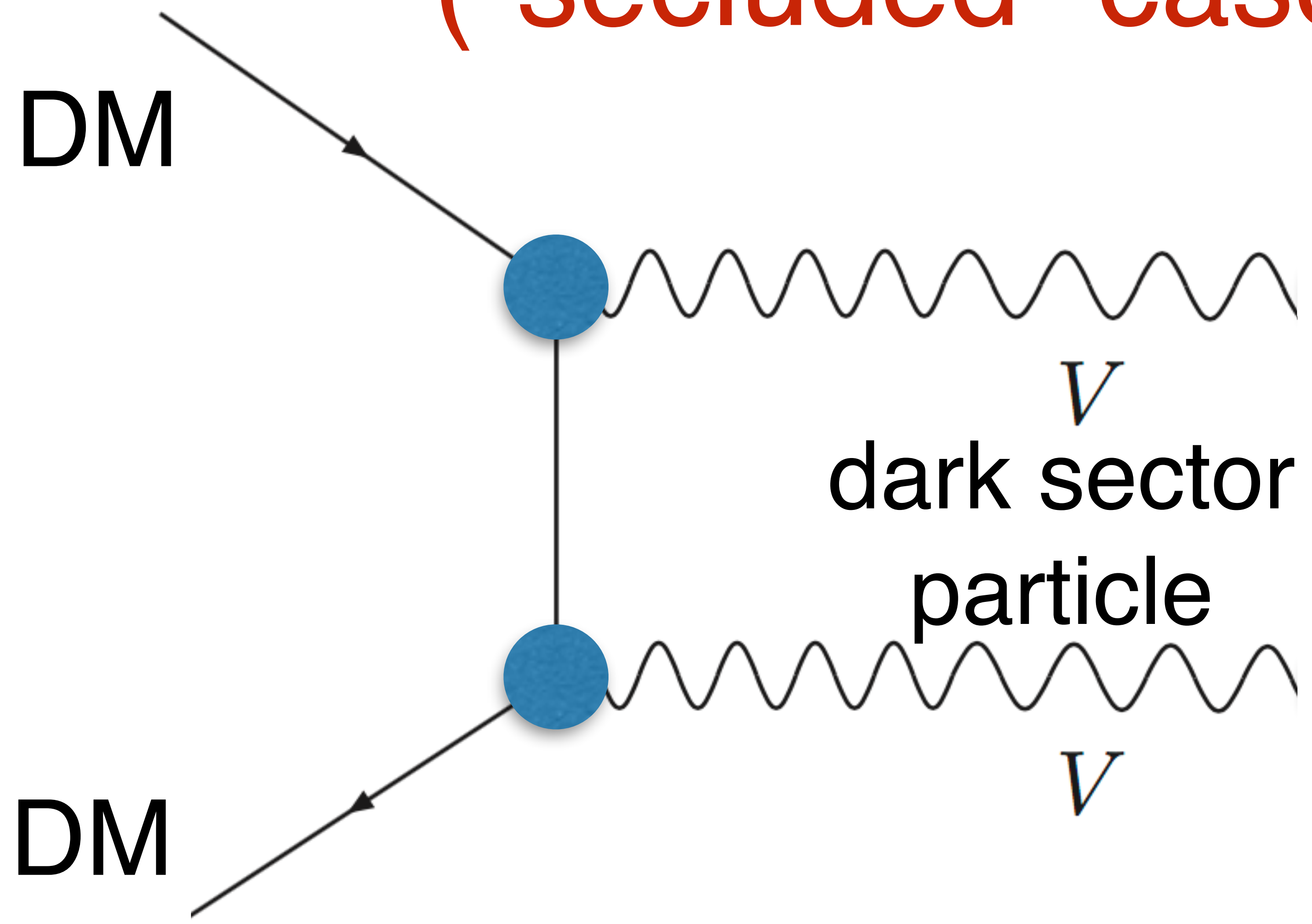

Pospelov, Ritz, Voloshin, 0711.4866

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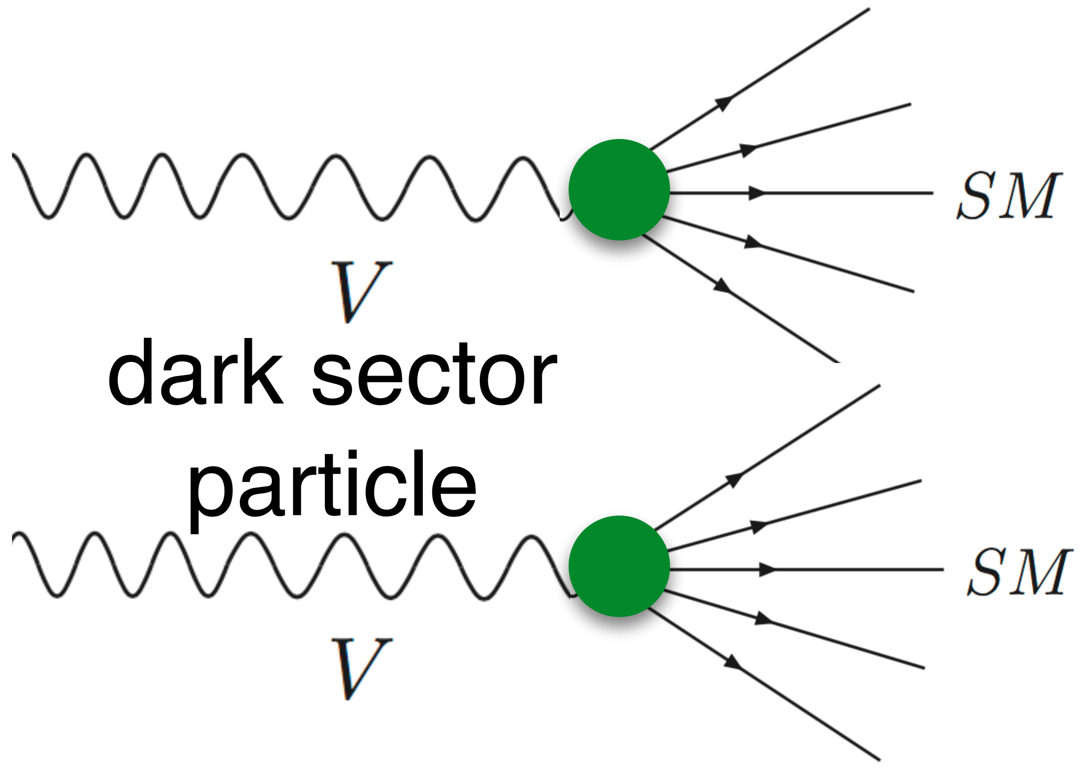


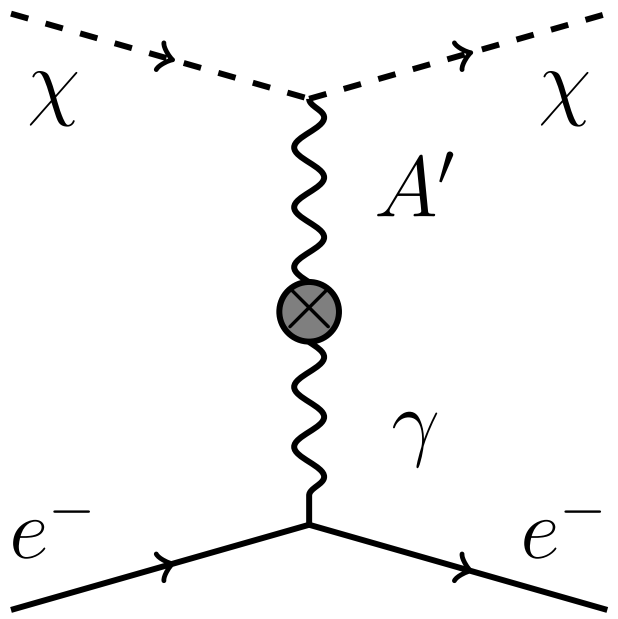
Certainly possible, but **less predictive** since dark coupling alone sets relic abundance

Signatures at experiments: Visible decay of Dark sector particles

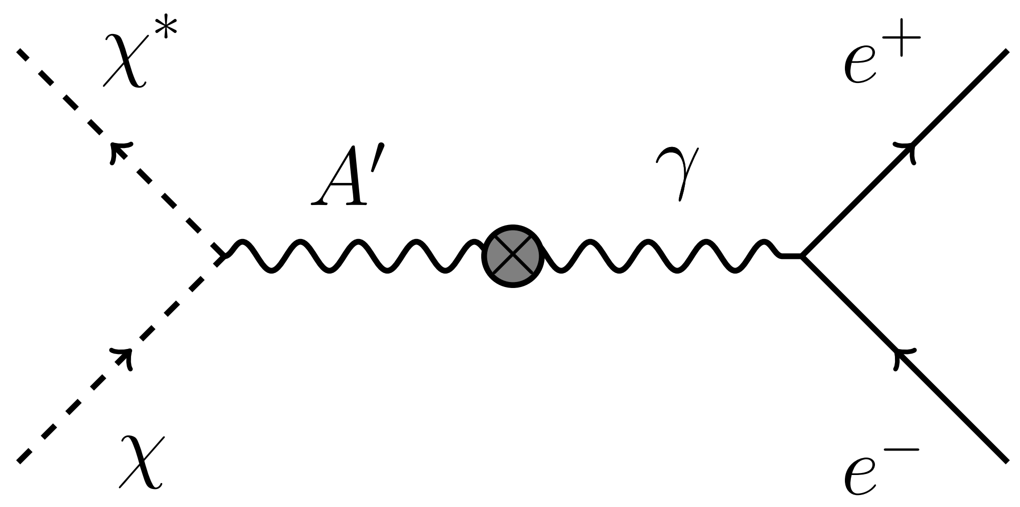
Phenomenological probes of DM through Dark Photon Portal

- Broad range of possible probes:

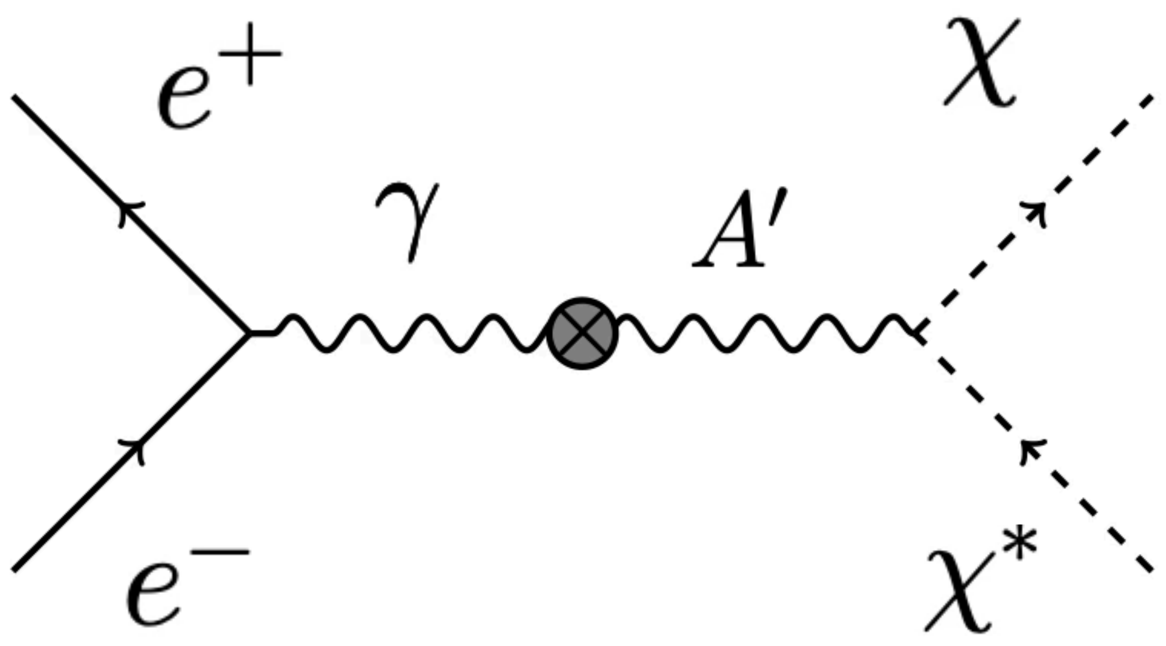
Direct Detection



Indirect detection



Collider production



...

CMB Constraints on DM Annihilation

- Although any viable thermal DM candidate is frozen out well before recombination, out of equilibrium annihilation around z ~ 1100 can still reionize hydrogen at the surface of last scattering and thereby modify the CMB power spectrum

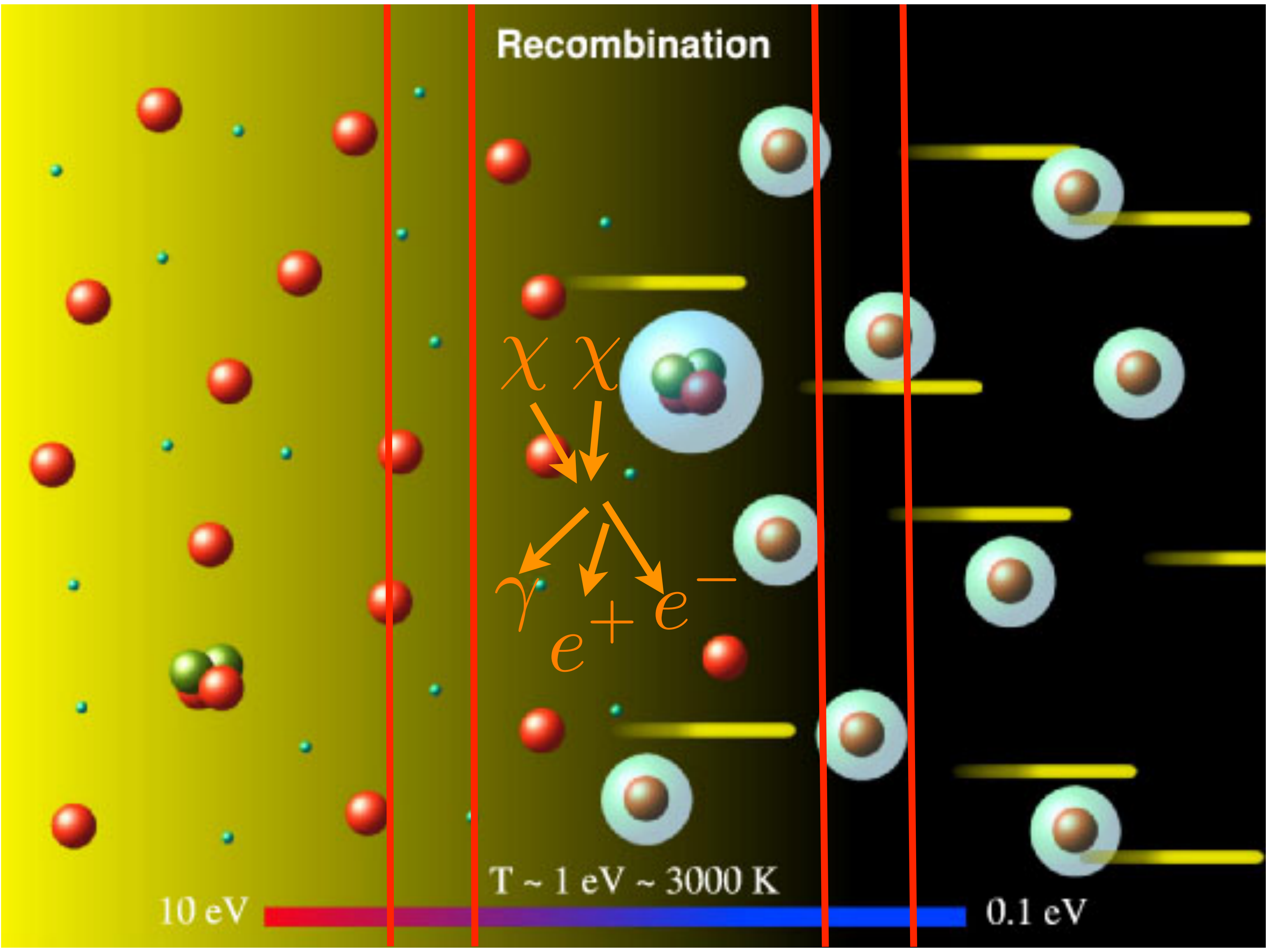


Image credit: William Kinney

Current Planck data [1807.06209] rule out thermal relic DM with mass < 10 GeV.

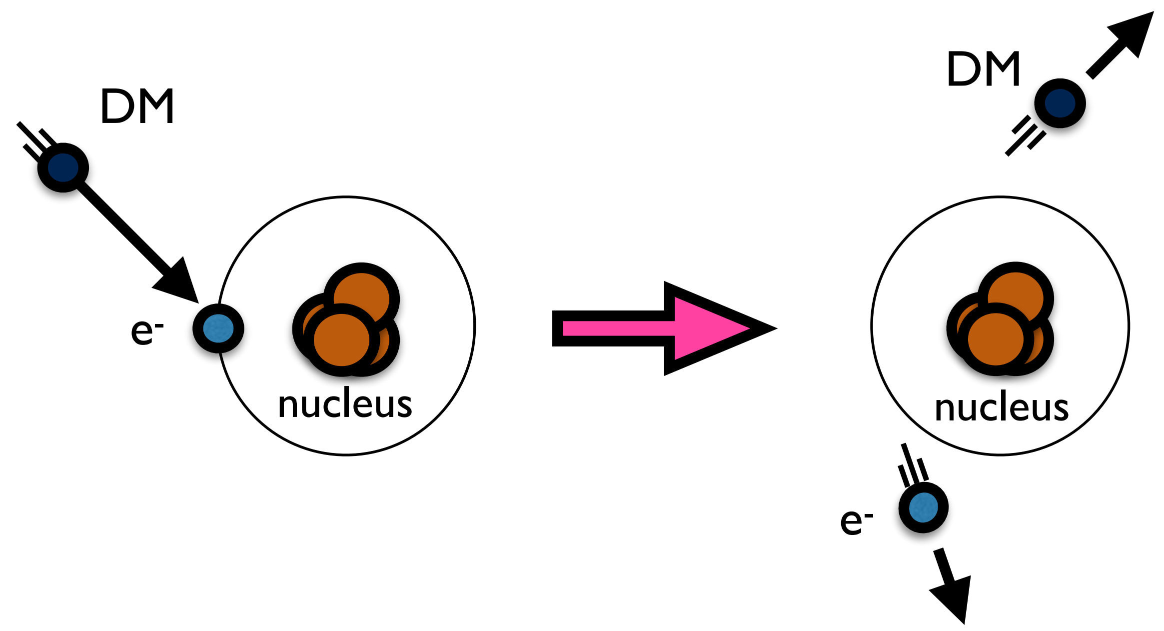
Key assumption:

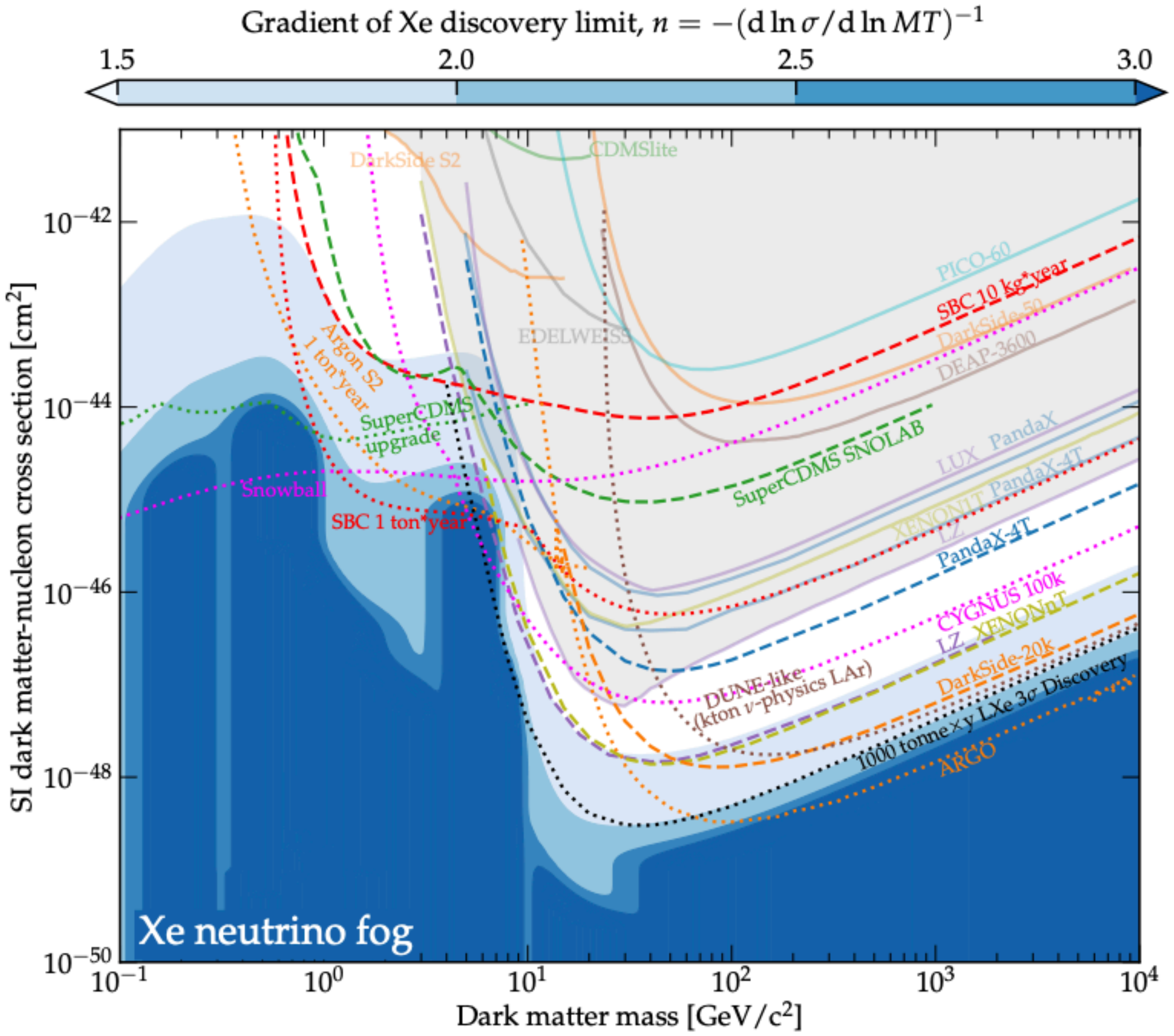
annihilation rate @ thermal freeze-out = annihilation rate @ recombination

Direct Detection of DM

- Notice that sub-GeV bounds get weak very quickly (like trying to move a boulder by throwing pebbles at it).

- Simple idea for light DM: look for ***electron scattering*** instead

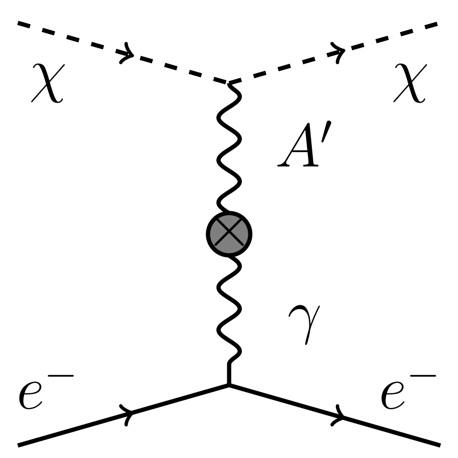




Current status thermal DM

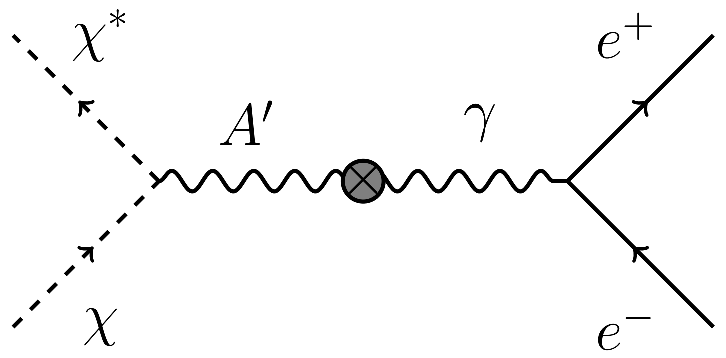
- First, let's just look at implications of **direct detection** bounds for MeV-GeV thermal relic DM.

Electron Scattering



$\sigma_e \propto \alpha_D \epsilon^2$

Direct Annihilation



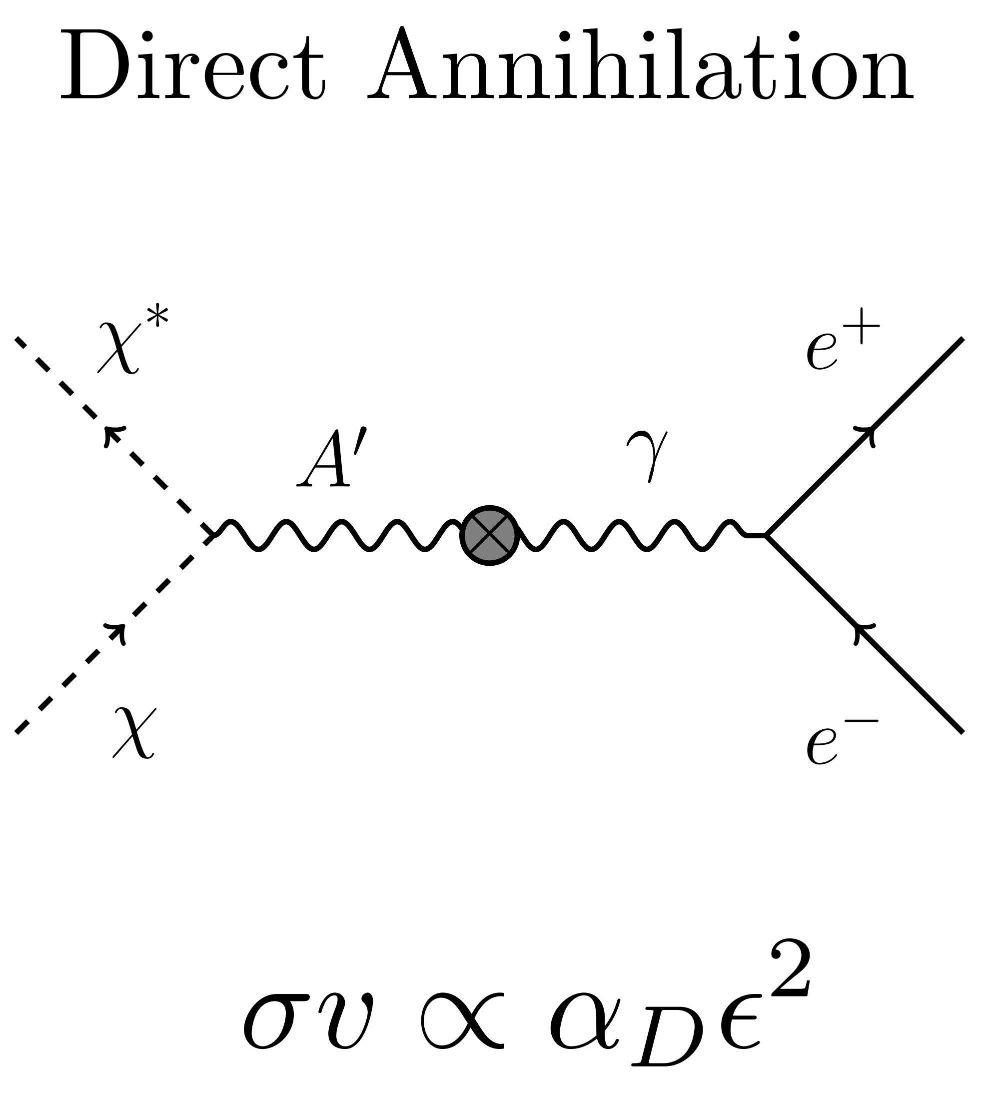
$\sigma v \propto \alpha_D \epsilon^2$

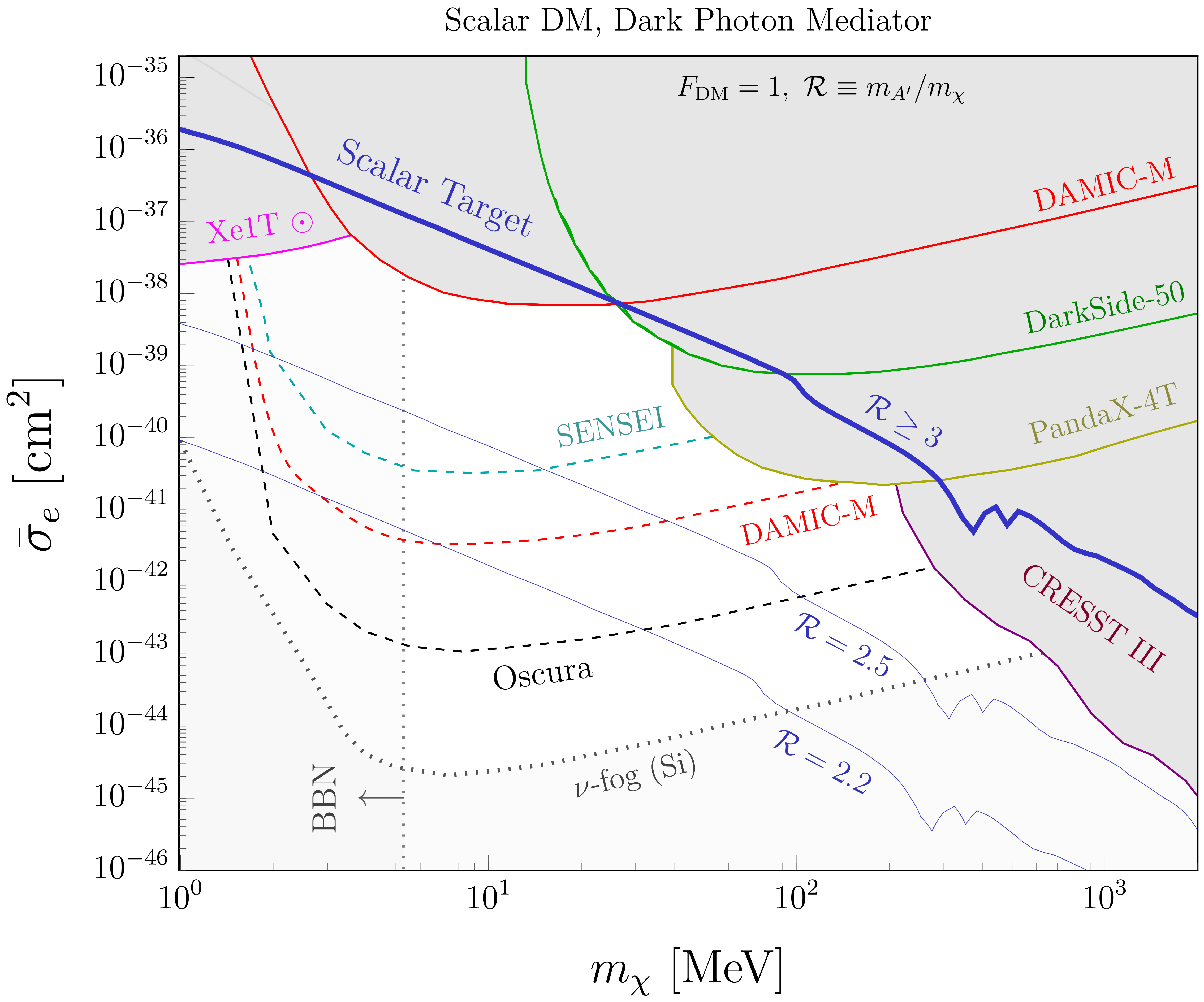
$J_D^\mu =$		Direct Detection Cross Section	Why is thermal relic CMB safe?
$i\chi^* \partial^\mu \chi + c.c.$	Scalar	$\sigma_e \sim v^0$	$(\sigma v) \sim v^2$
$\frac{1}{2}\overline{\chi}\gamma^\mu\gamma^5\chi$	Majorana	$\sigma_e \sim v^2$	$(\sigma v) \sim v^2$
$i\overline{\chi}_1\gamma^\mu\chi_2$	Pseudo-Dirac	Loop-suppressed	No Excited DM
$\overline{\chi}\gamma^\mu\chi$	Dirac (Asymmetric)	$\sigma_e \sim v^0$	No anti-DM

2505.04626

Current status thermal DM

- For **scalar DM**, the CMB bounds on thermal relics are satisfied since annihilation cross section ~ v^2.





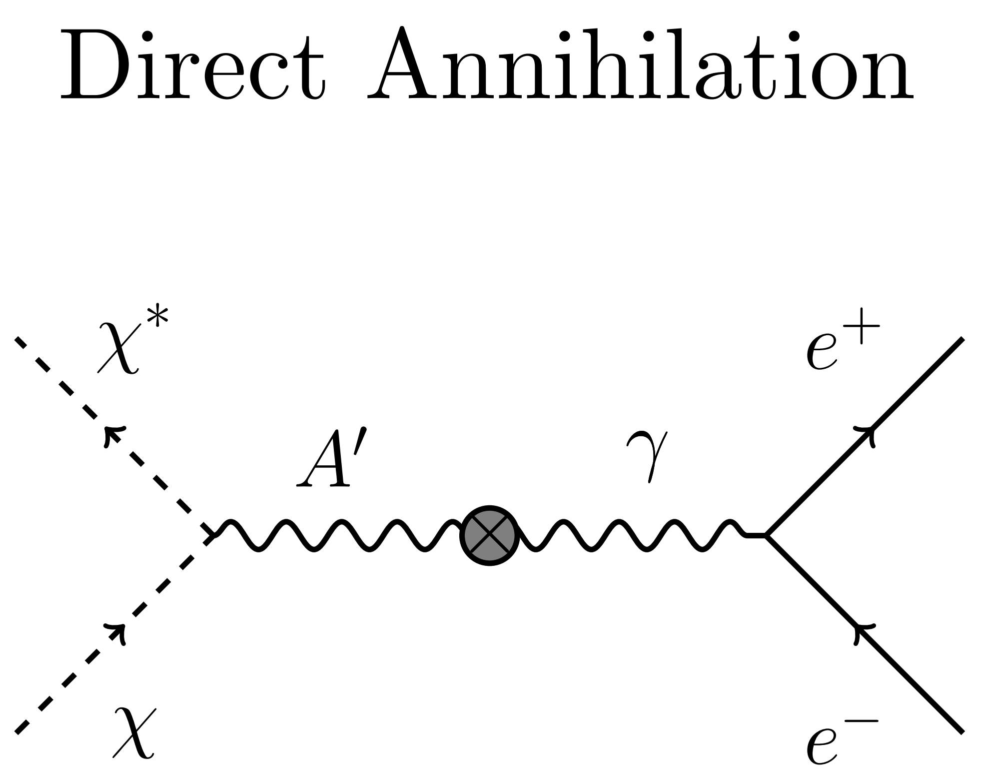
Even with only these DD bounds, all ratios R>3 thermal relics are now ruled out.

Fine-tuned region near resonance is still viable.

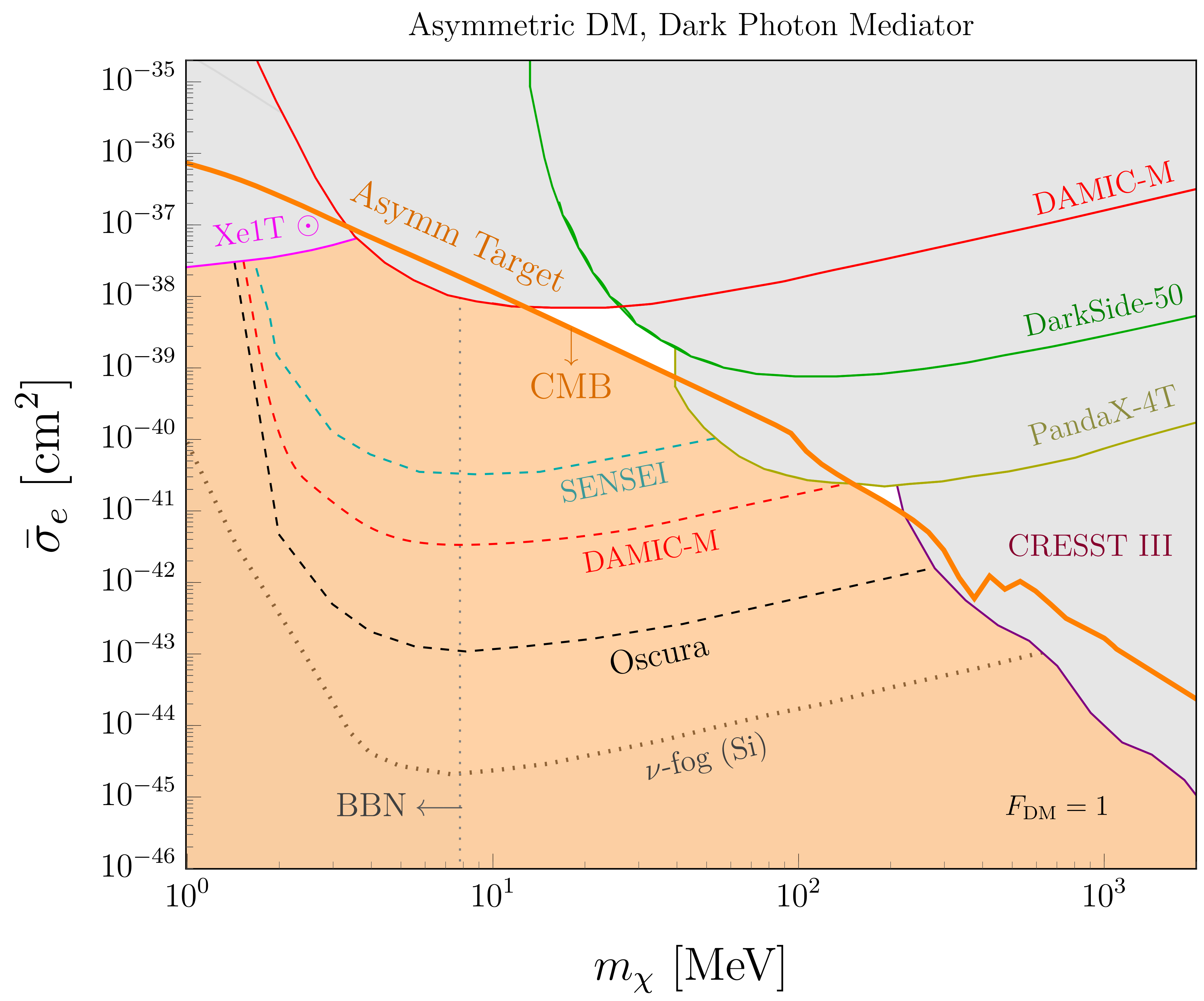
2505.04626

Current status thermal DM

- For **Dirac DM**, the CMB bounds on thermal relics are only satisfied in presence of an asymmetry.



$$\sigma v \propto \alpha_D \epsilon^2$$

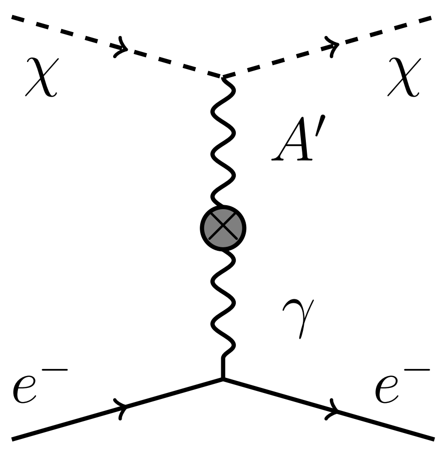


Nearly excluded for parameter space off resonance.

Current status thermal DM

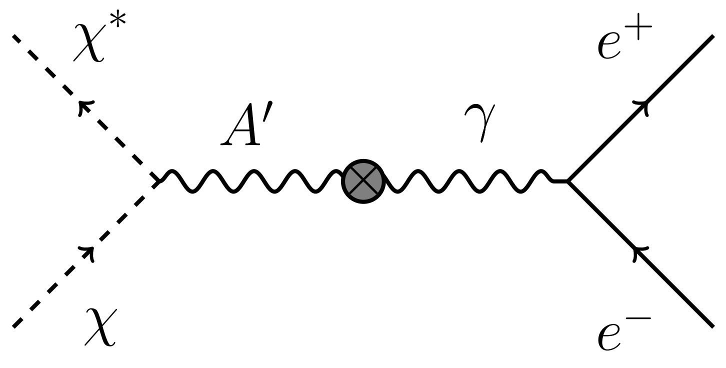
- First, let's just look at implications of direct detection bounds for MeV-GeV thermal relic DM.

Electron Scattering



$$\sigma_e \propto \alpha_D \epsilon^2$$

Direct Annihilation



$$\sigma v \propto \alpha_D \epsilon^2$$

$J_D^\mu =$		Direct detection of thermal relic?
$i\chi^* \partial^\mu \chi + c.c.$	Scalar	Dead as of 2025
$\frac{1}{2}\overline{\chi}\gamma^\mu\gamma^5\chi$	Majorana	**Orders of magnitude away**
$i\overline{\chi}_1\gamma^\mu\chi_2$	Pseudo-Dirac	**Orders of magnitude away**
$\overline{\chi}\gamma^\mu\chi$	Dirac (Asymmetric)	Verge of death: narrow ranges still allowed [~15-30 MeV, or ~200 MeV]

Need another strategy to test remaining thermal targets!

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↓

Produce it!

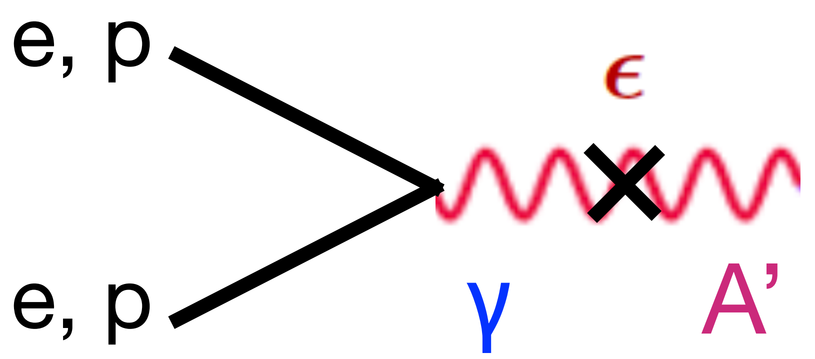
Recipes for Making Dark Photons from Scratch

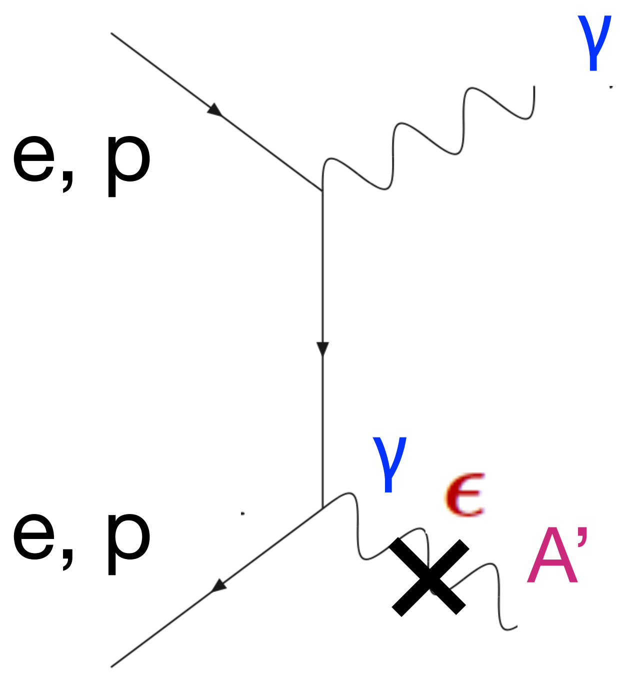
$$\mathscr{L}_{\rm int} = -A'_\mu (g_D J^\mu_D + \epsilon e J^\mu_{\rm EM}),$$

Couples to electric charge

Collider experiments

Drell-Yan production:

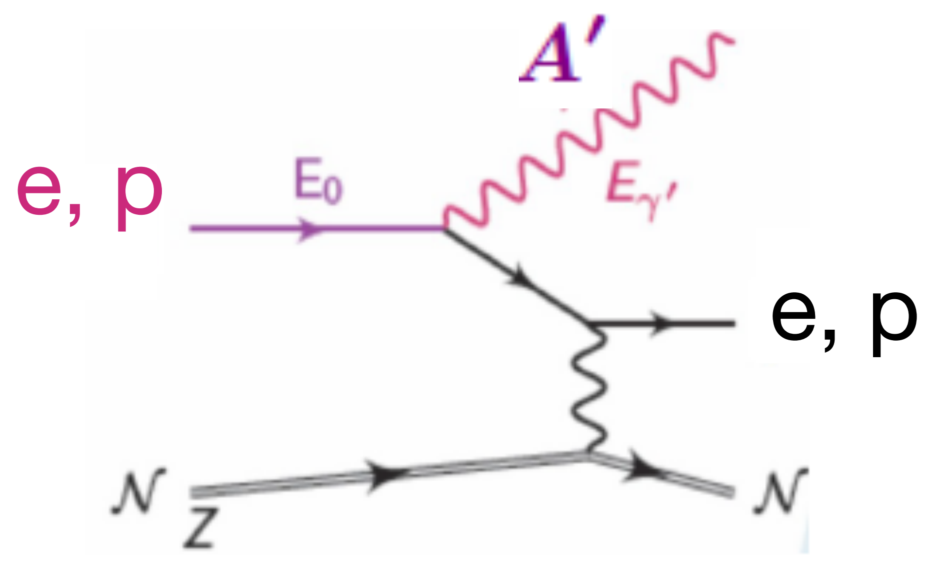




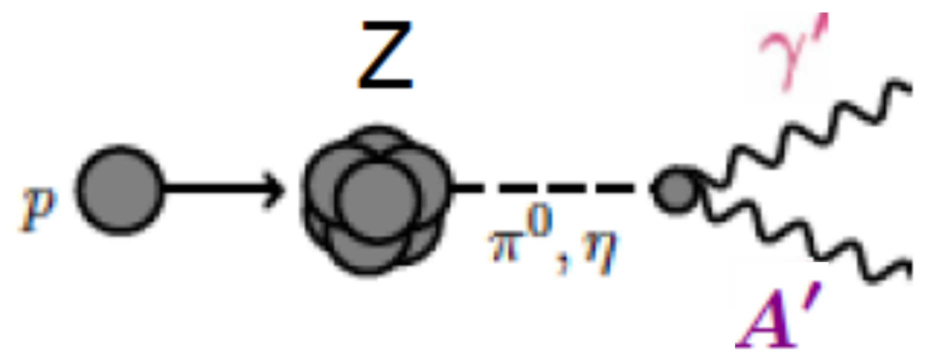
$$\sigma \propto \frac{\varepsilon^2 \alpha^2_{\rm em}}{E^2}$$

1/fb at 1GeV (KLOE) competes with 1/ab at 10 GeV (B-factories)

Fixed target experiments



brems-strahlung



meson decay

Also @ Neutrino experiments like COHERENT & DUNE

Decaying Dark Photons

$$\mathscr{L}_{\text{int}} = -A'_\mu (g_D J^\mu_D + \epsilon e J^\mu_{\text{EM}}),$$

First, assume DM isn't kinematically accessible: $M_{A'} < 2m_\chi$

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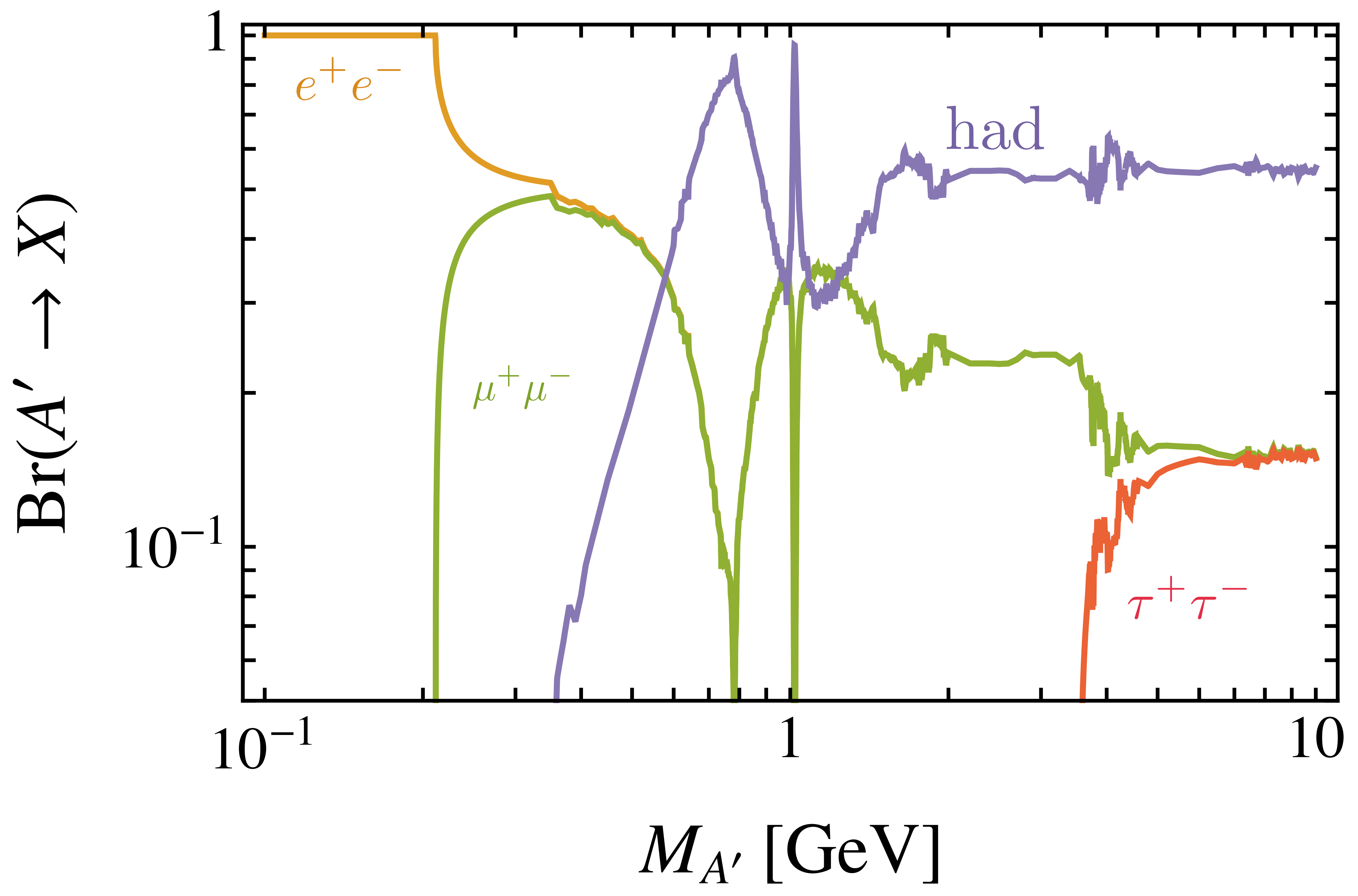

- Visible dark photon: decays 100% to SM states
- Couples to everything the photon does but reduced strength.
- Depending on ϵ, decay length scales can be macroscopic:

$$L_D \sim 1/(\epsilon^2\, m_{A'})$$

Decaying Dark Photons

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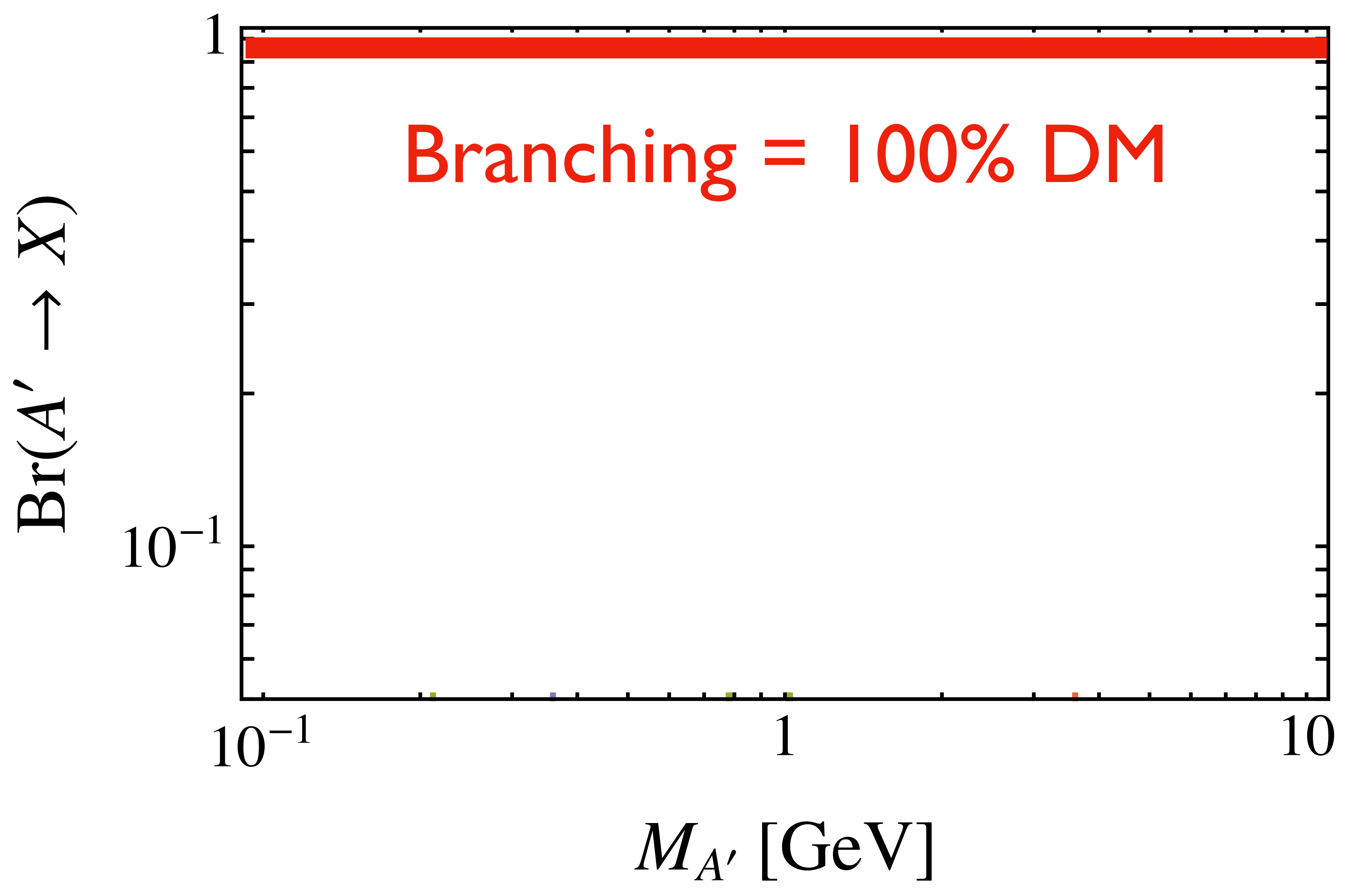
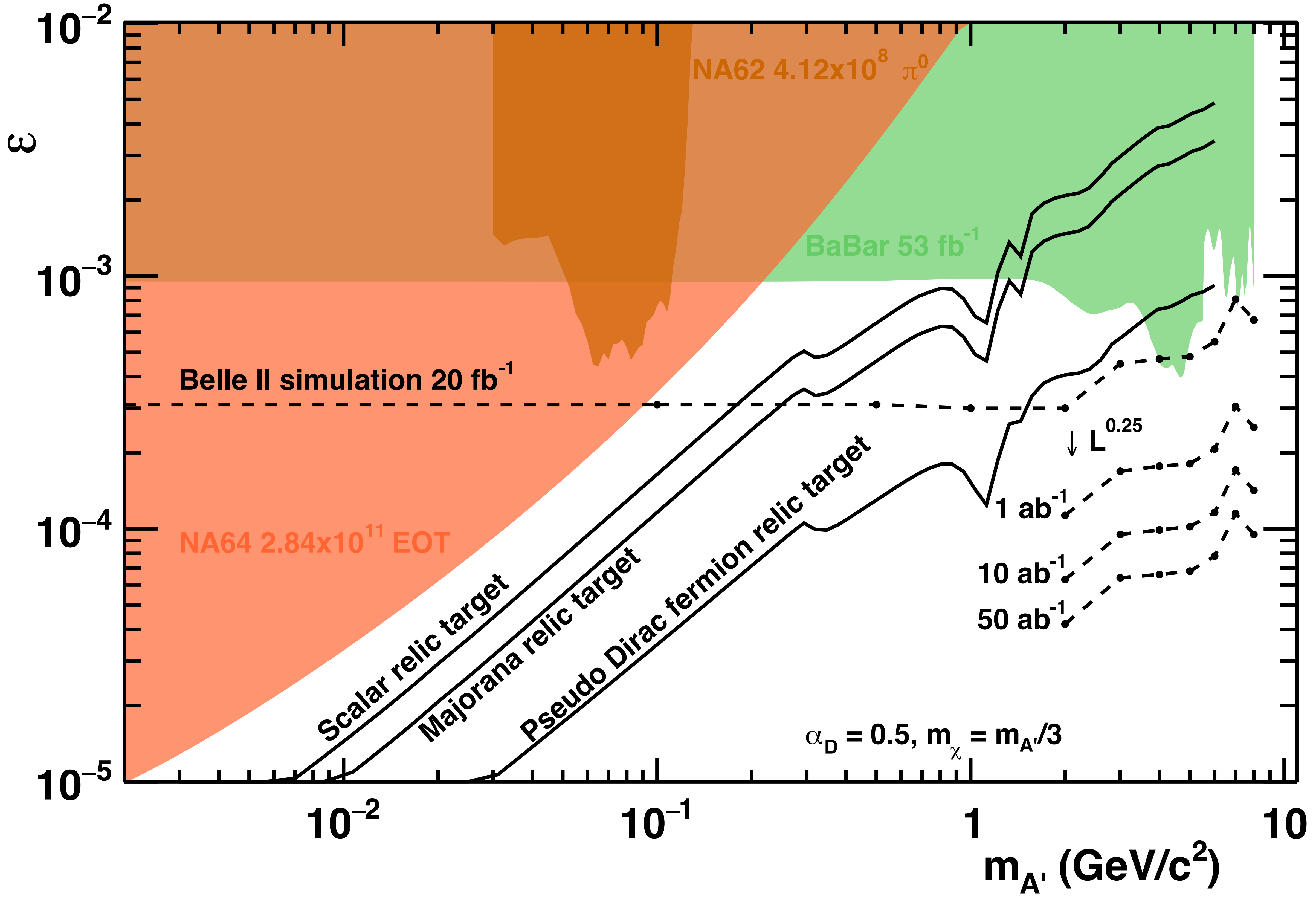
Now, assume DM is kinematically accessible: $M_{A'} > 2m_\chi$



- Invisible dark photon: decays 100% to DM
- Why? Experimental bounds constrain ϵ to be small, need α_D large for thermal relic DM:

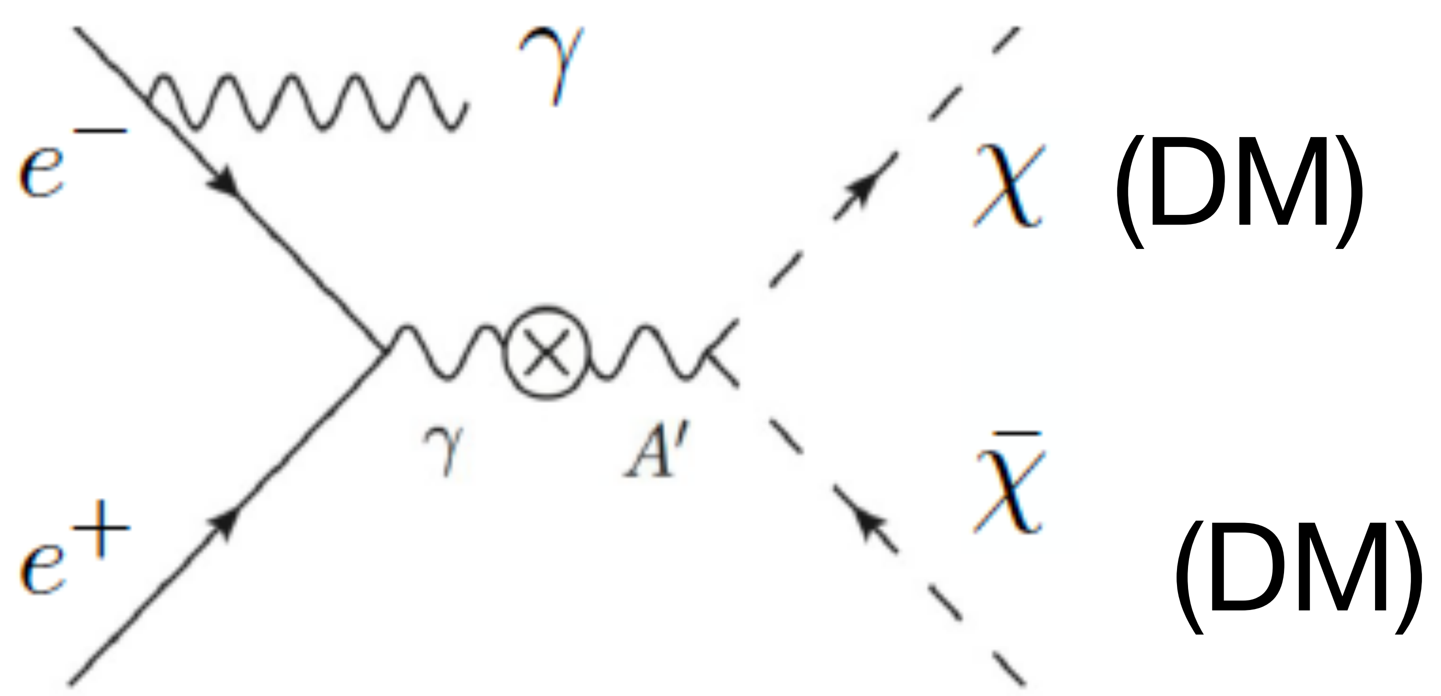
$$\langle \sigma v \rangle \simeq \epsilon^2 \alpha_D \frac{m_X^2}{m_{Z'}^4}$$

Invisible Dark Photons @ Belle II



Snowmass White Paper: Belle II physics reach and plans for the next decade and beyond, ***arXiv: 2207.06307***

mono-photon + invisible



See talk this afternoon for details!

Inelastic DM

- In scenarios of "Pseudo-Dirac" ($m_D >> M$) DM, dominant coupling to the dark photon is off-diagonal:

$$\mathcal{L} \supset A'_\mu \left(\bar{\chi}_1 \gamma^\mu \chi_2 - \bar{\chi}_2 \gamma^\mu \chi_1\right)$$

Tucker-Smith, Weiner (hep-ph/0101138).

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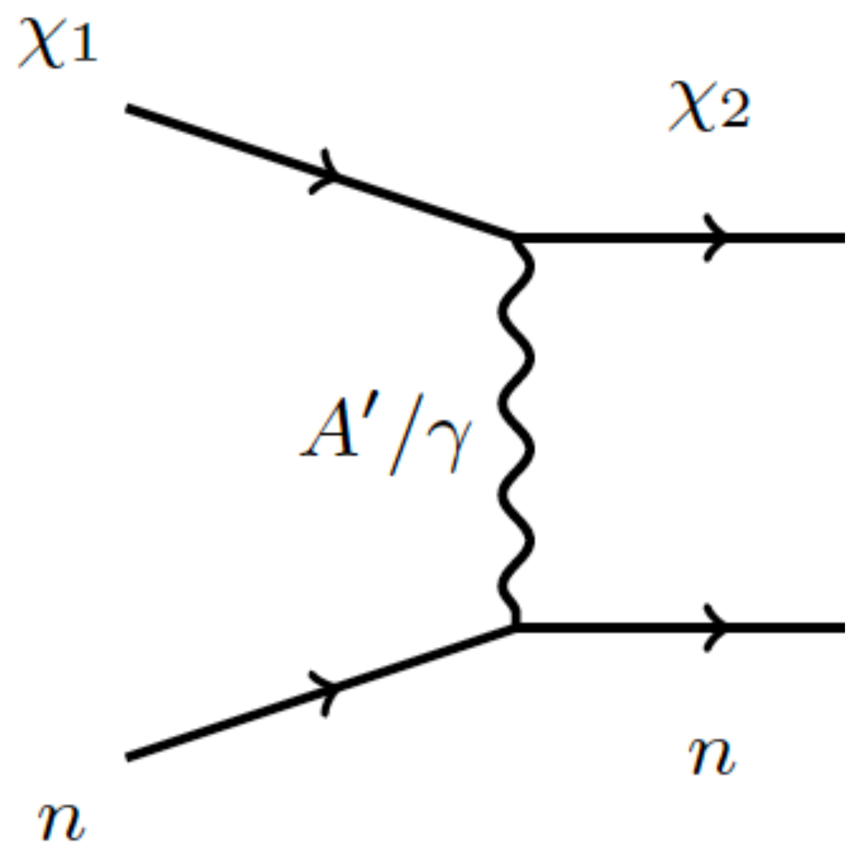

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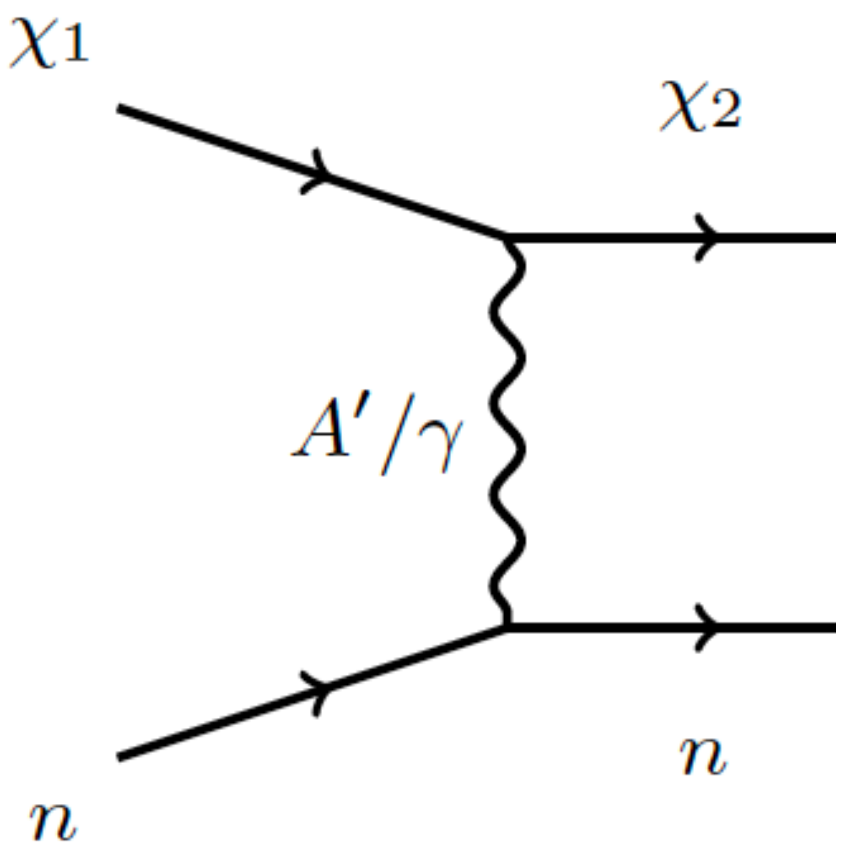

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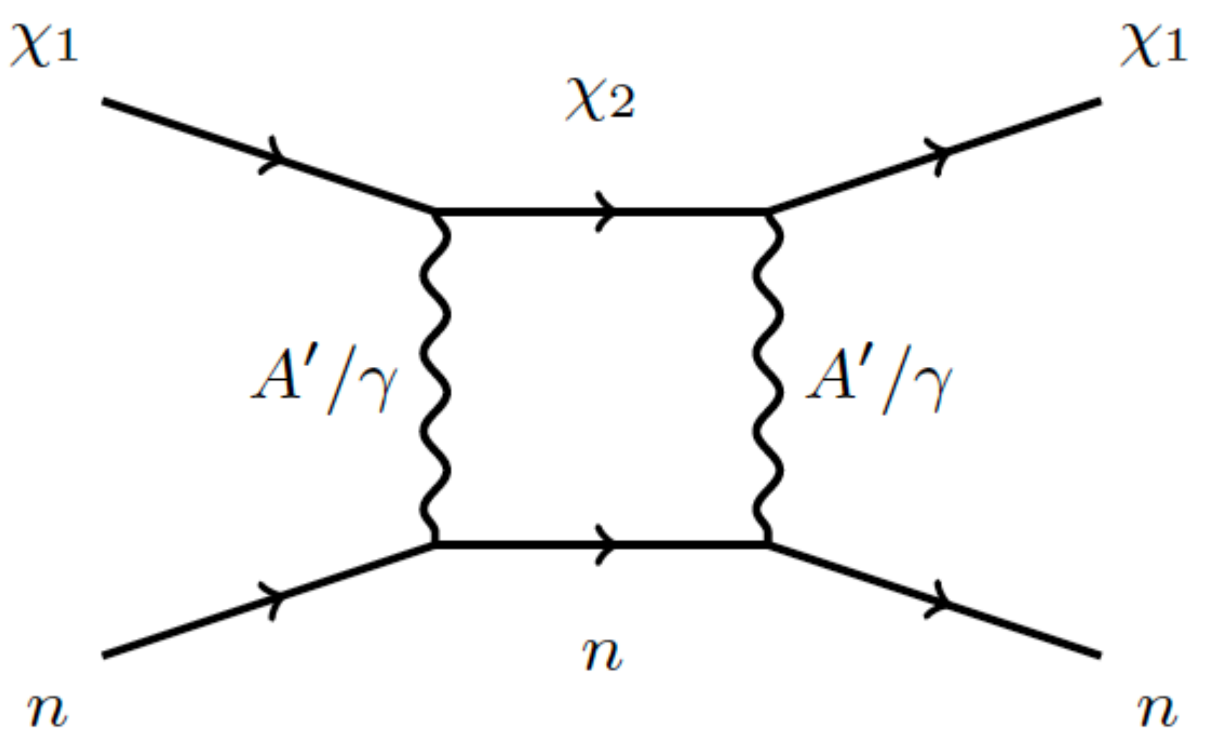


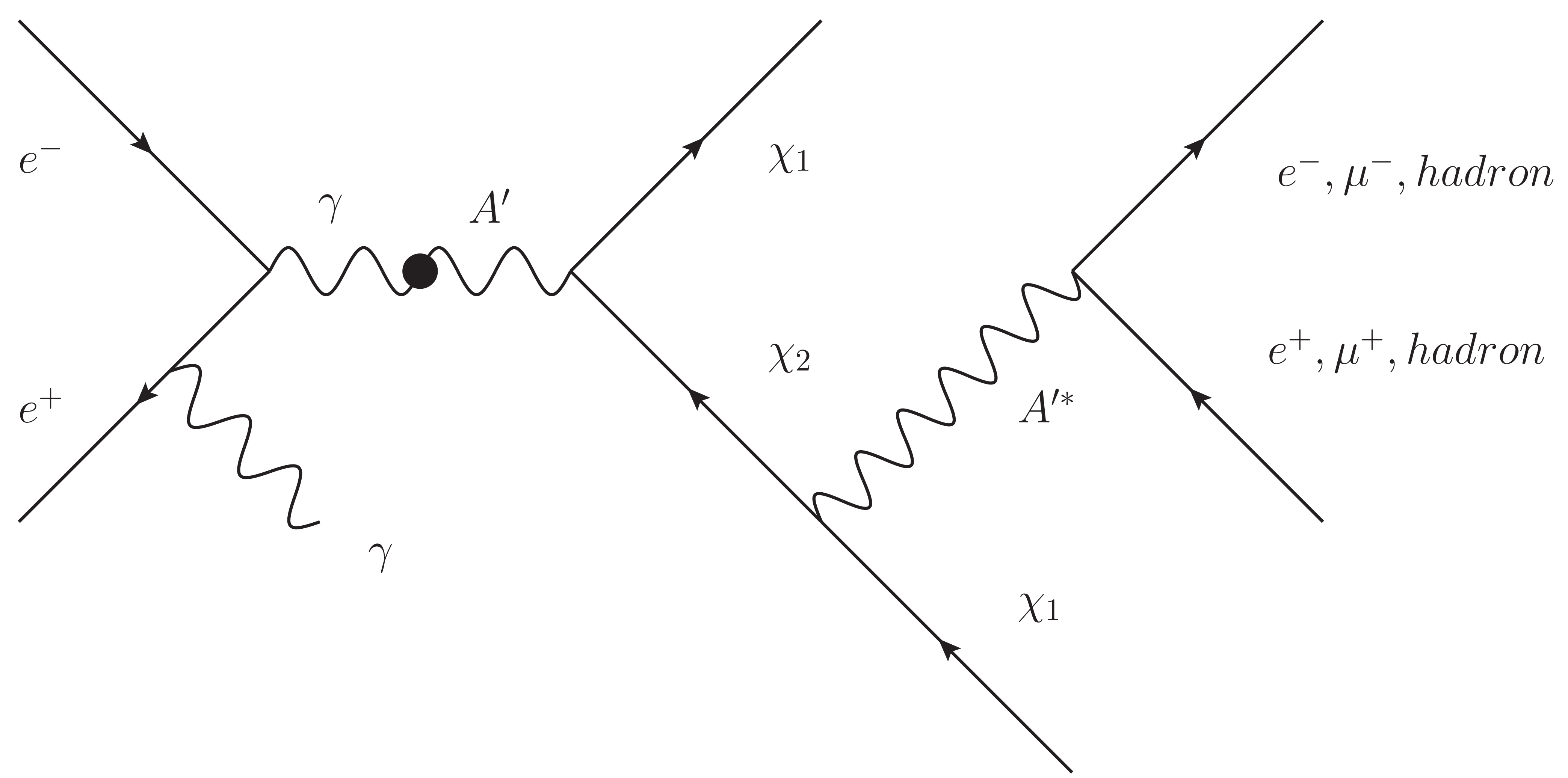
Dominant direct detection cross section is loop-suppressed

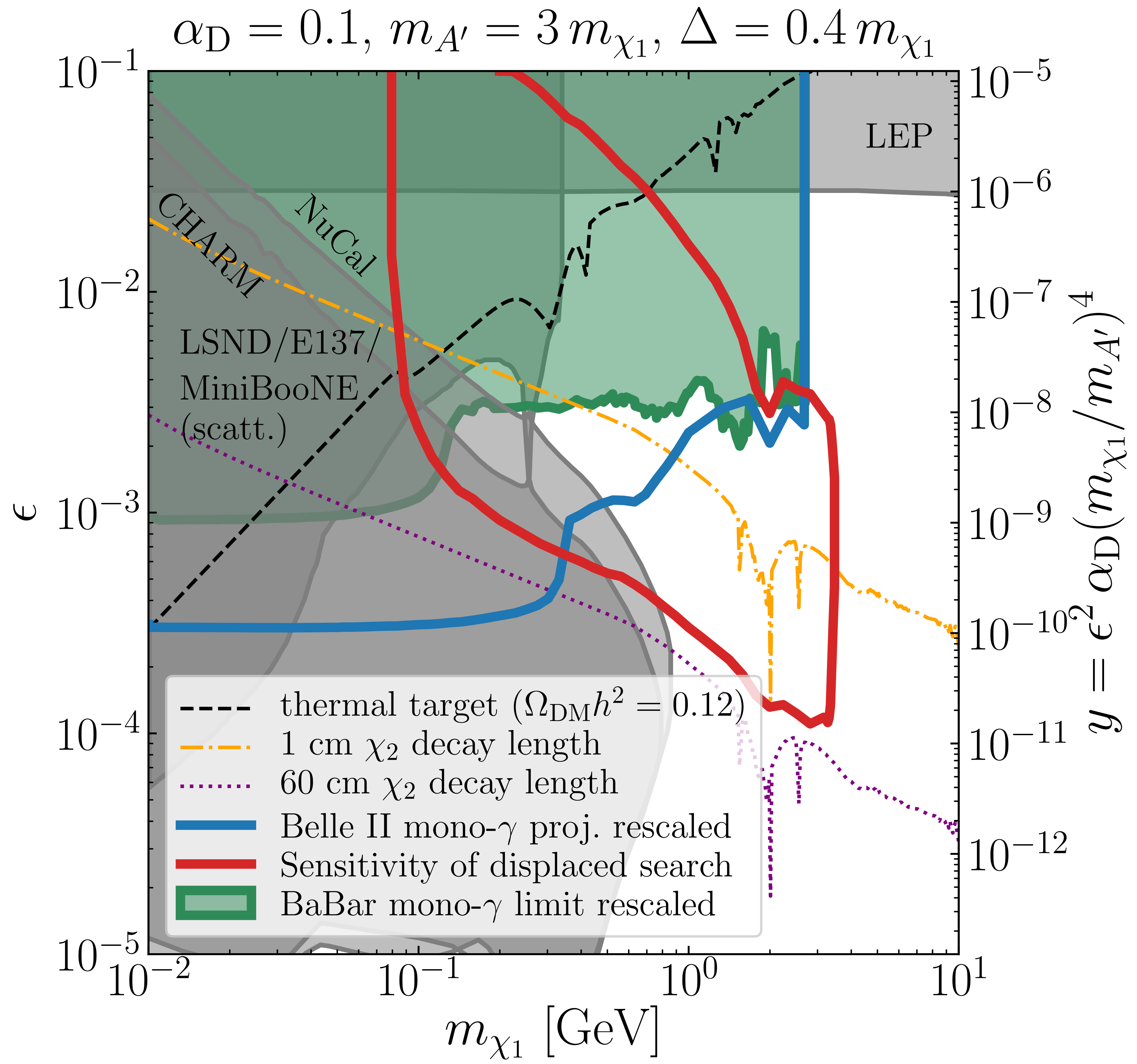
Tucker-Smith, Weiner (hep-ph/0101138).

Inelastic DM @ Belle II

$$\Delta = m_{\chi_2} - m_{\chi_1}$$

Prompt mono-photon & possibly displaced dilepton

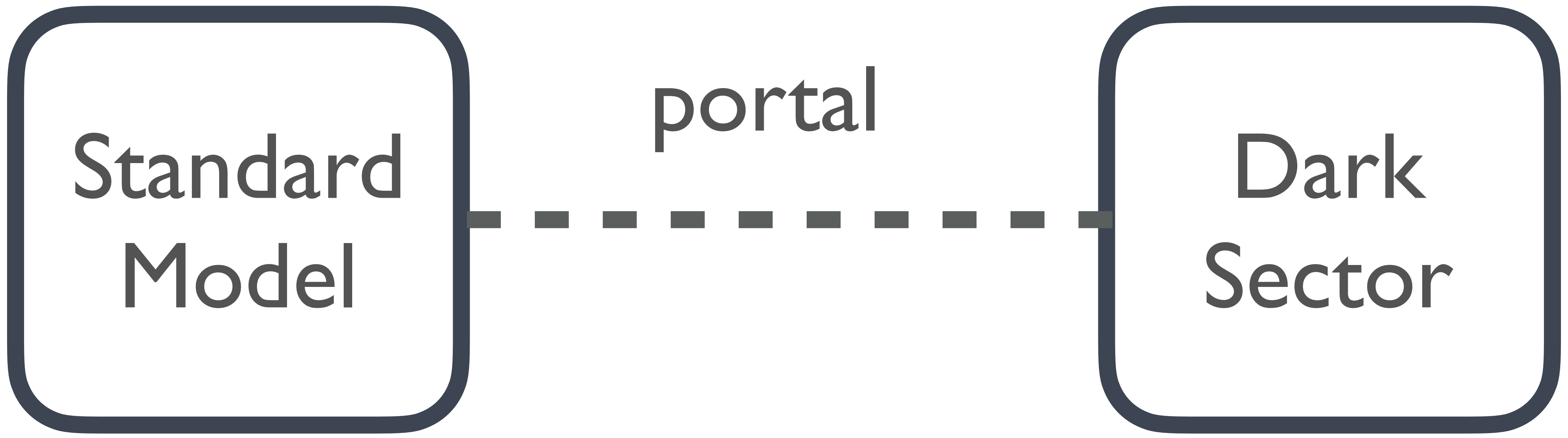




Duerr et al. 1911.03176

Displaced search is better at large Δ & opposite for monophoton

Many other possibilities



- We looked at one of the renormalizable portals.
- Can be non-renormalizable portals: e.g. **axion-like particles**.
- Anomaly free gauge bosons: **(B - L), ($L_\mu - L_\tau$)**, etc.
- In some cases, can have additional motivation: connect to models of neutrino masses, Strong CP problem, experimental anomalies, etc.
- Can also consider non-thermal mechanisms for DM abundance.

Outlook

- The landscape for DM is vast, but **thermal relic hypothesis** can offer compelling experimental target.

- **Dark photons** are a well-motivated portal to dark sector physics.

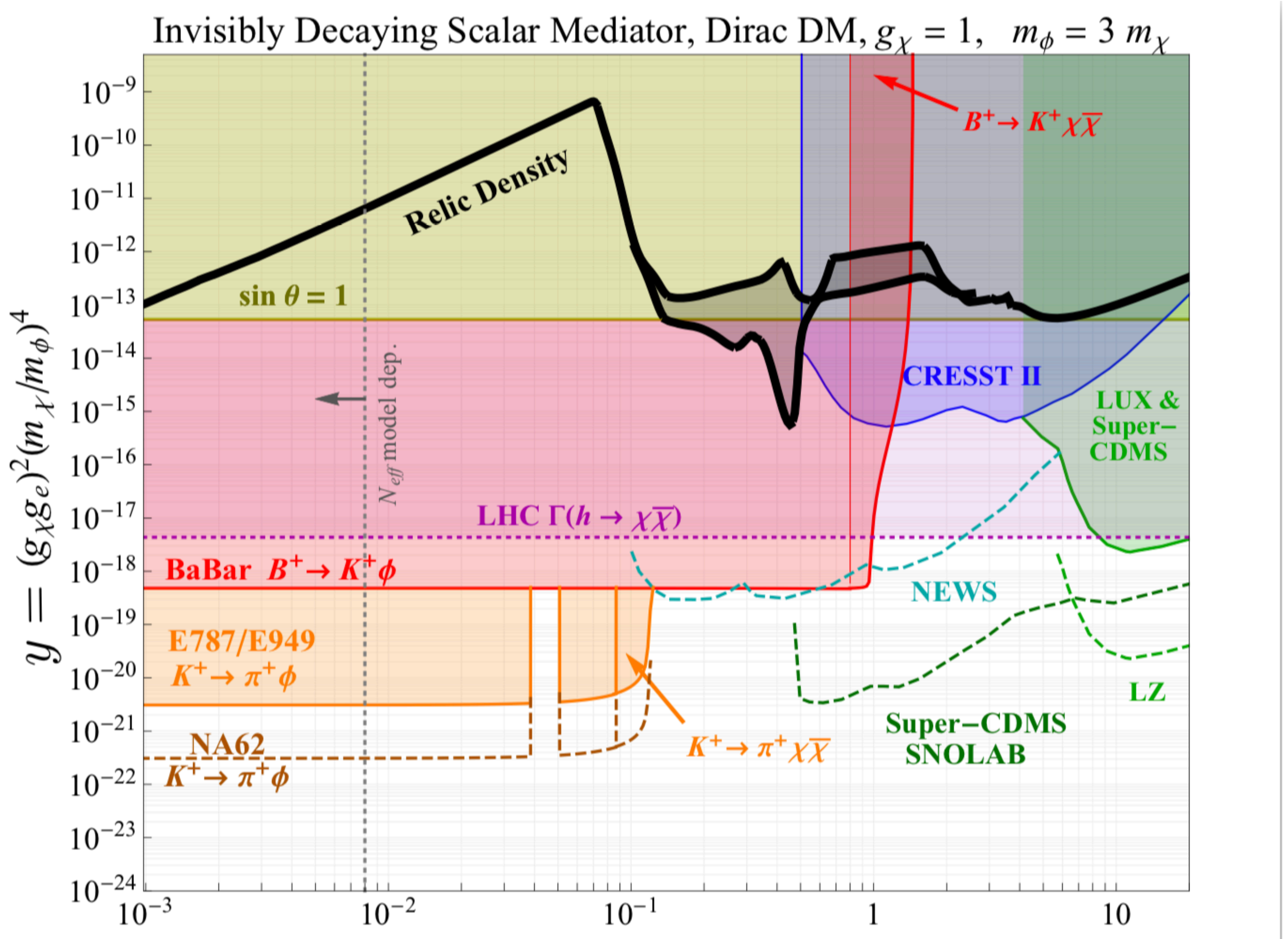
    - Different dark sector states can drastically impact phenomenology.

    - Need an array of **complementary experimental** probes: CMB, direct detection, colliders, beam-dumps.

    - Belle-II will be crucial in probing remanning territory for thermal DM via dark photon mediator.

See upcoming DM talks this afternoon: Savino Longo, Tommy Lam, and Haurki Kindo

Higgs Portal example

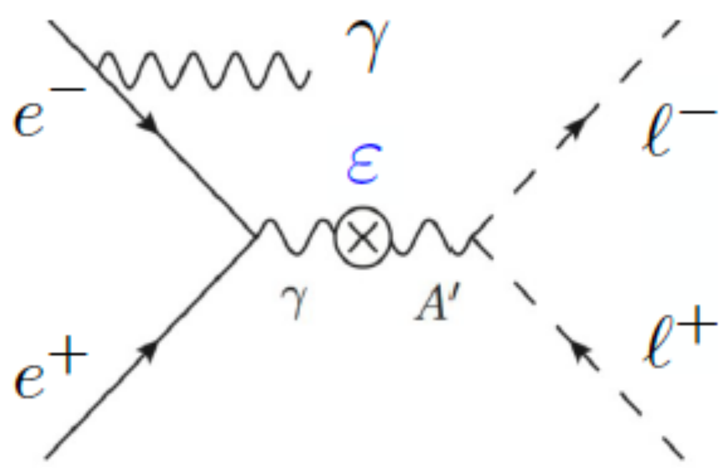


($m_s = 3m_\chi$)

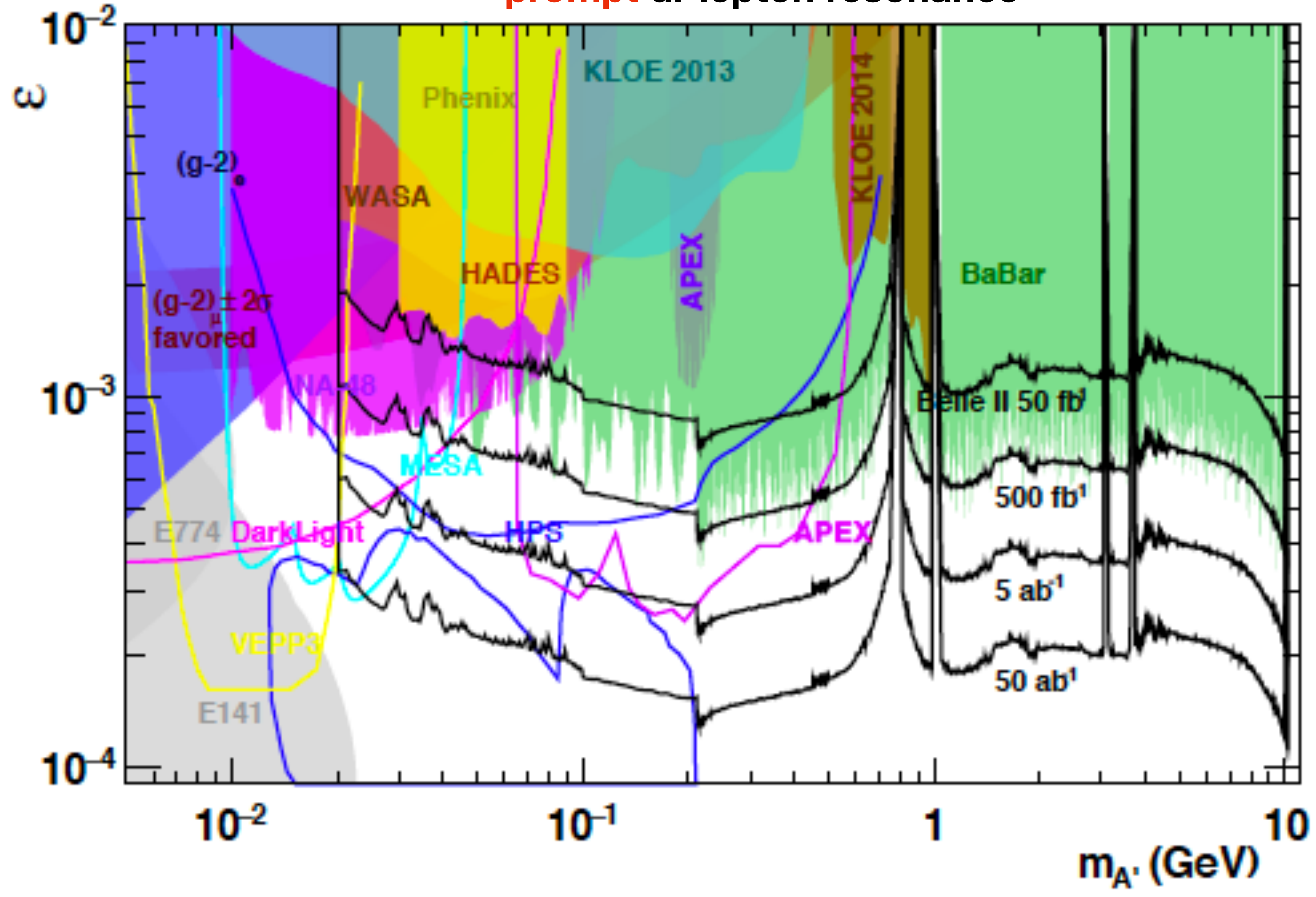
Krnjaic, 1512.04119

Already **ruled out** by combination of LHC invisible Higgs decays, meson decays, and Direct detection.

Visible Dark Photons @ Belle II

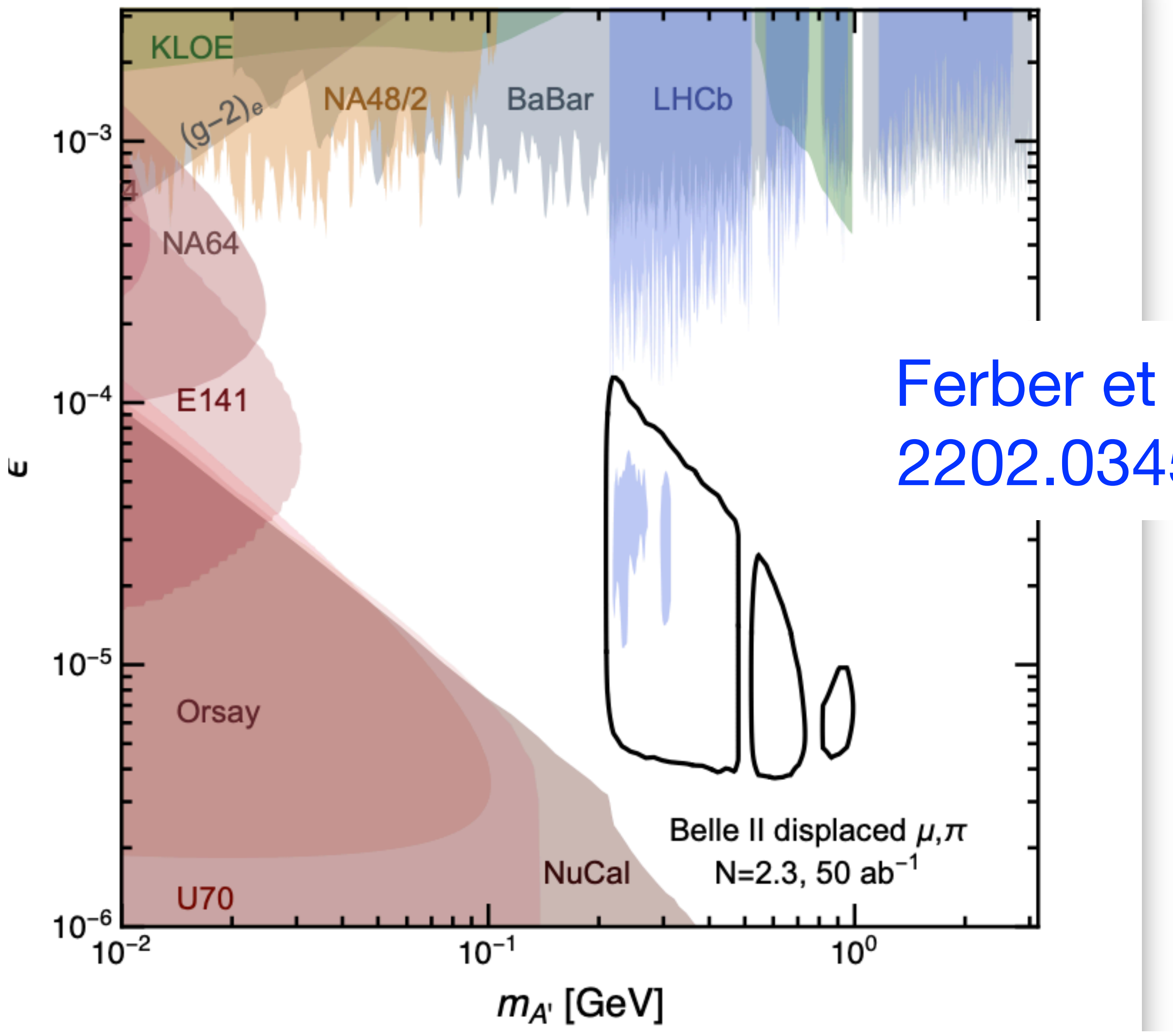


photon +
prompt di-lepton resonance



The Belle II physics book, 1808.10567

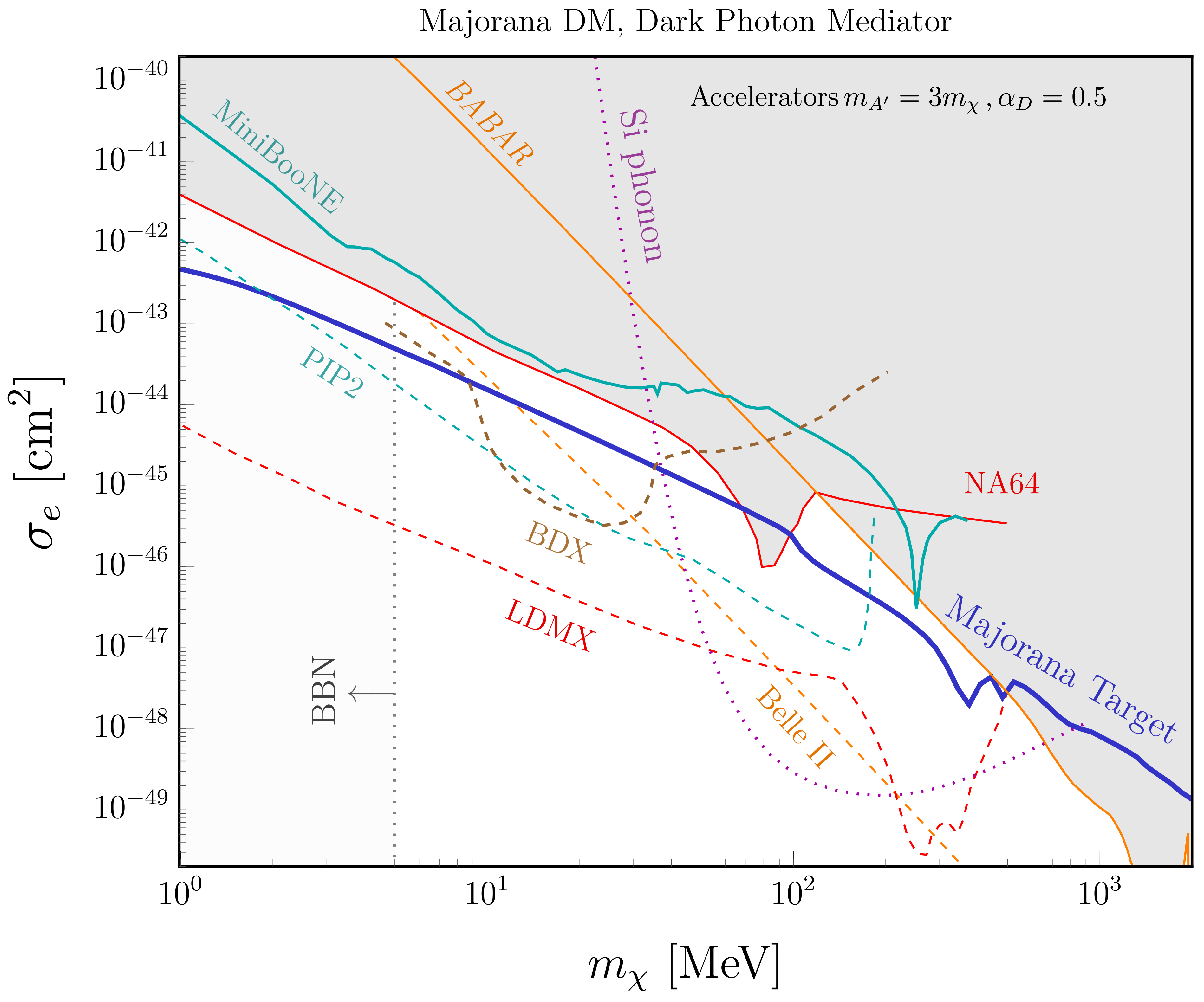
photon +
displaced di-lepton resonance

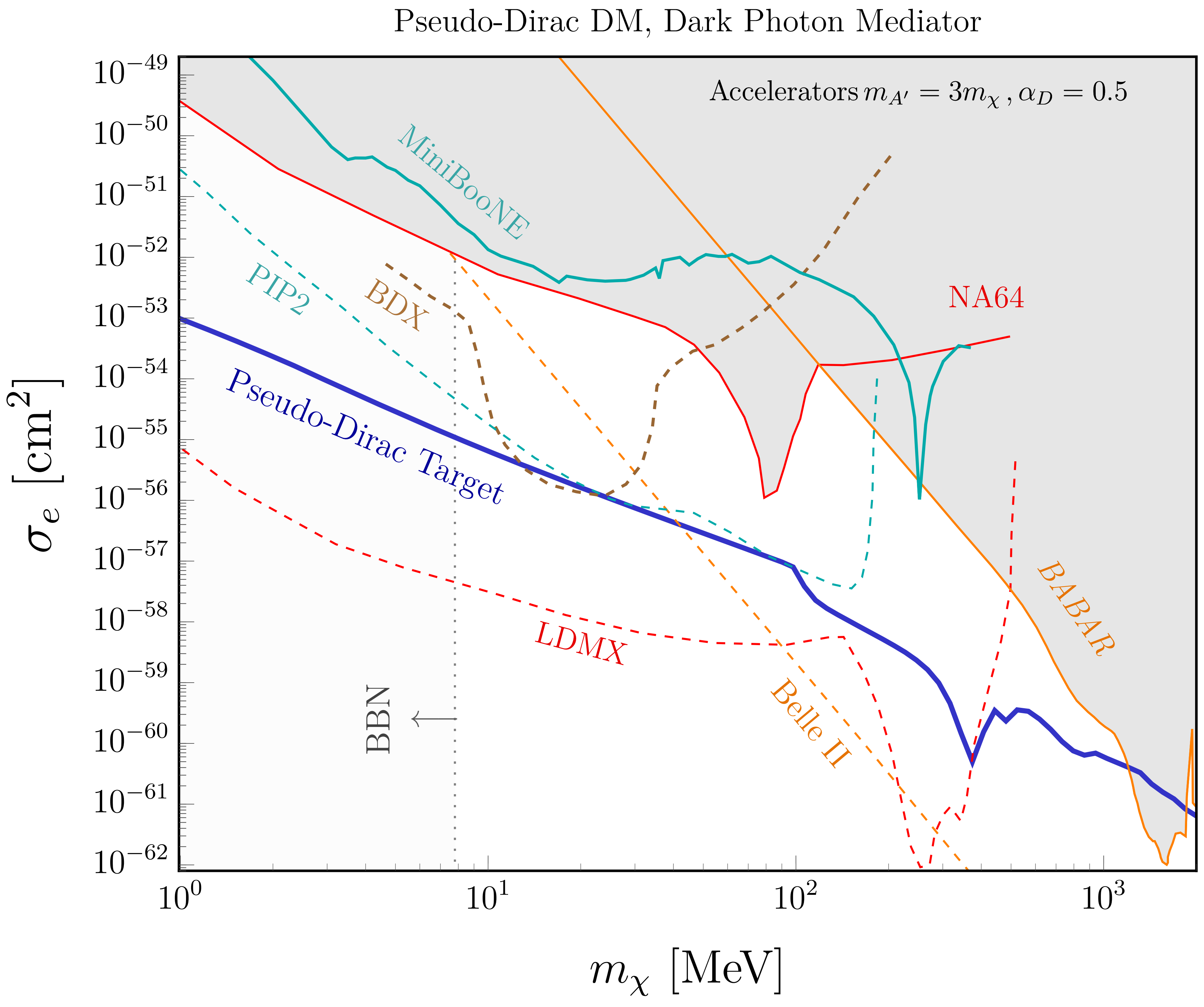


Ferber et al,
2202.03452

2505.04626

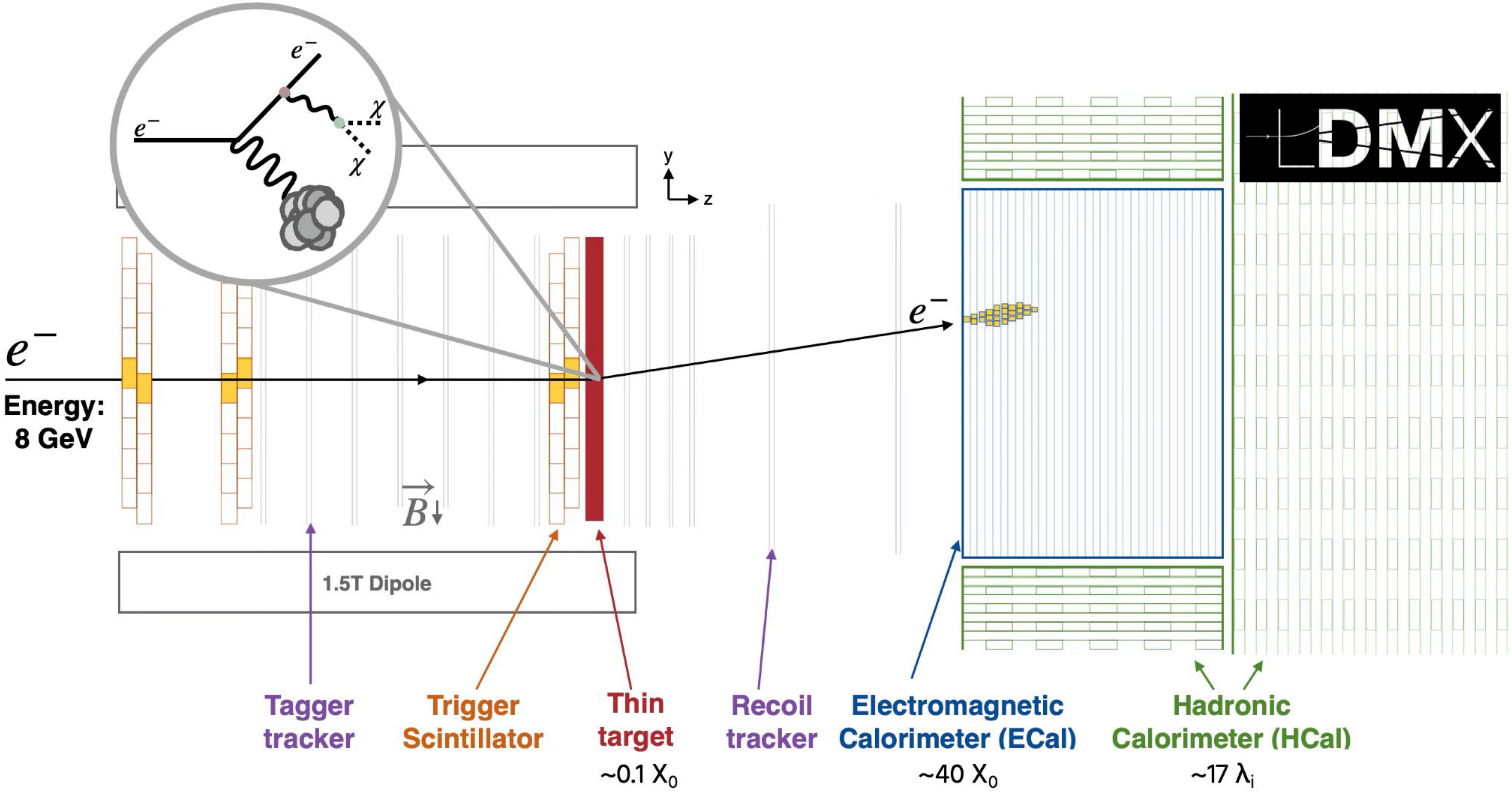
Future status thermal DM





In Majorana and Pseudo-Dirac cases, need to produce DM in the lab to test thermal relic hypothesis .

LDMX: missing momentum



This missing momentum *and* missing energy signature drives the design of LDMX.

[Slide credit: Erik Wallen, Light Dark Matter @ Accelerators 2025]