Self-interacting asymmetric dark matter

Kallia Petraki

Oslo, 24 June 2015

How can we find dark matter?

First, we have to guess the answer!

… Need a strategy ...

Proposed strategy

Focus on DM-related observations:

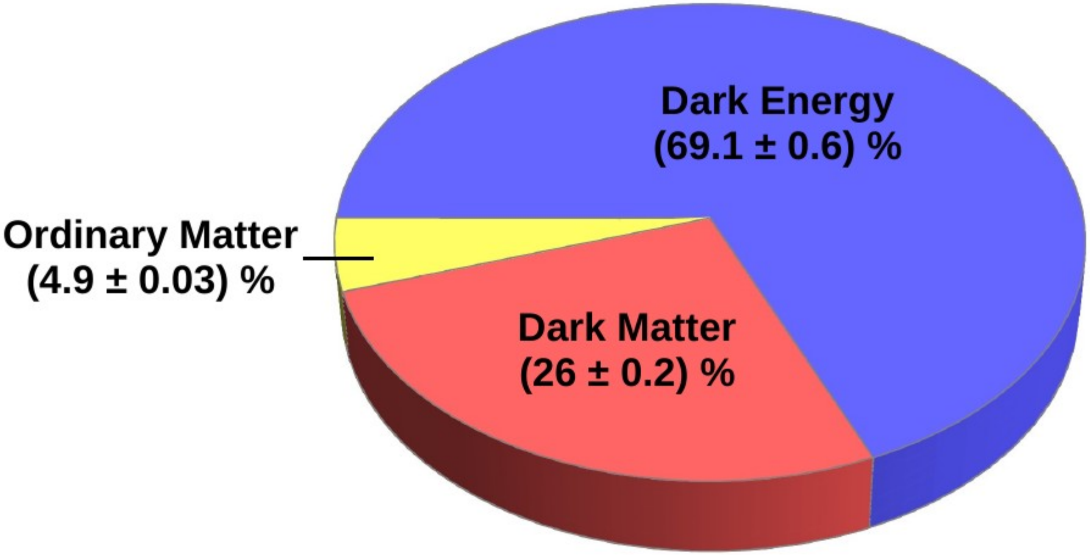
- DM density → Asymmetric DM
- Patterns of gravitational clustering → Self-interacting DM

Outline

- Asymmetric DM: general structure and features
- Self-interacting DM
- Self-interacting $\cap$ Asymmetric DM
- Case study: **atomic dark matter**

A cosmic coincidence

Why $\Omega_{DM} \sim \Omega_{OM}$?



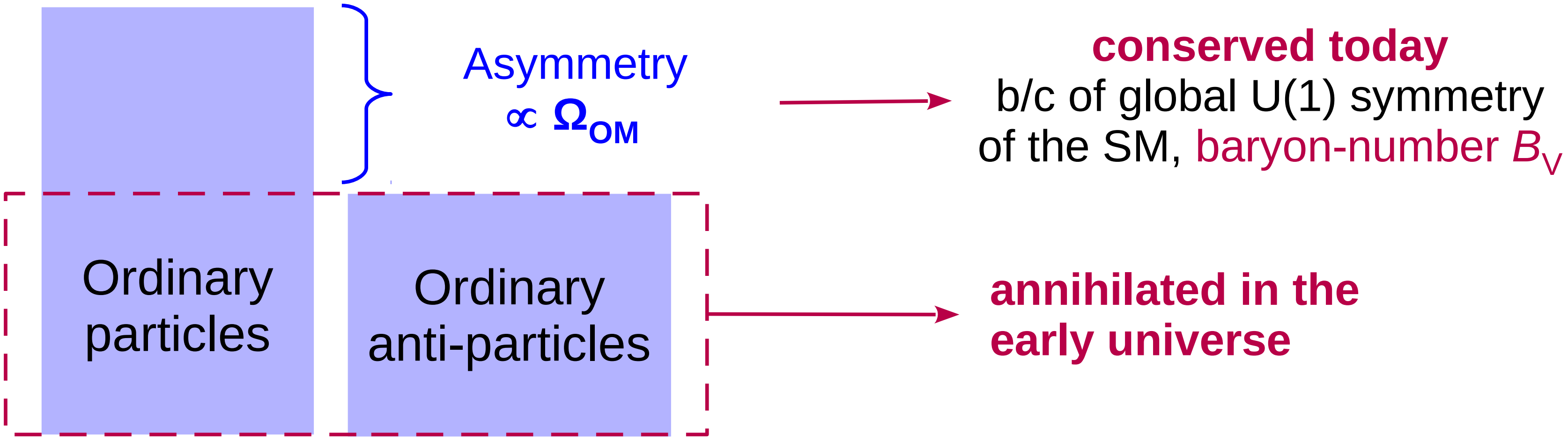
- Unrelated mechanisms → different parameters
  → result expected to differ by orders of magnitude.

- Similarity of abundances hints towards
  related physics for OM and DM production.

Ordinary matter

- Stable particles: p e γ ν
- p^+ make up most of ordinary matter in the universe.

  Only p^+, no p^- present today: matter-antimatter asymmetry



Asymmetry $\propto \Omega_{OM}$

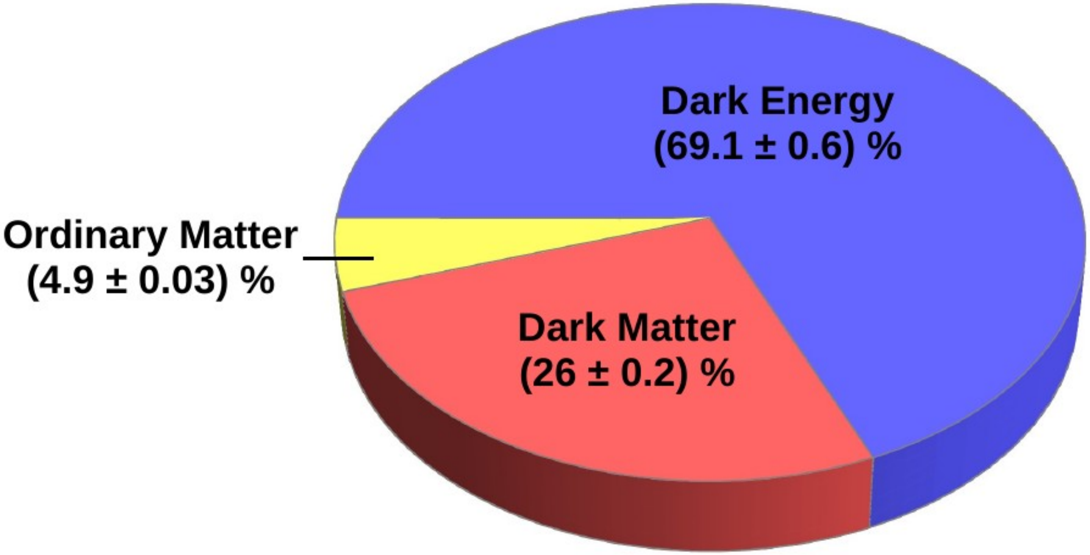
conserved today
b/c of global U(1) symmetry
of the SM, baryon-number B_V

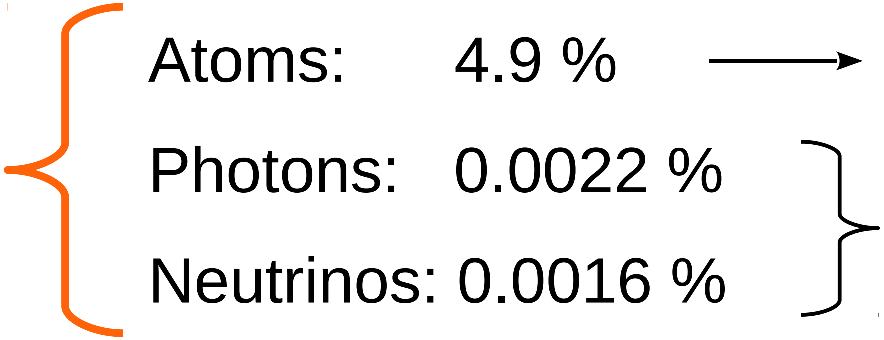
Ordinary particles

Ordinary anti-particles

annihilated in the early universe

A non-coincidence





Ordinary matter

Atoms: 4.9 % → Particle-antiparticle asymmetry

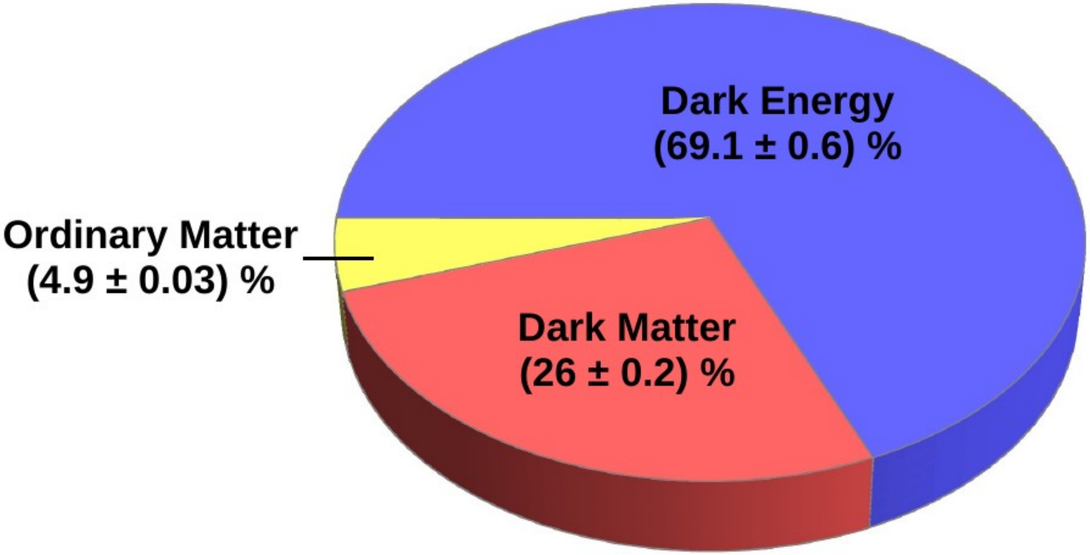
Photons: 0.0022 %

Neutrinos: 0.0016 %

Relativistic thermal relics

A cosmic coincidence

Why $\Omega_{DM} \sim \Omega_{OM}$?



- Just a coincidence

  OR

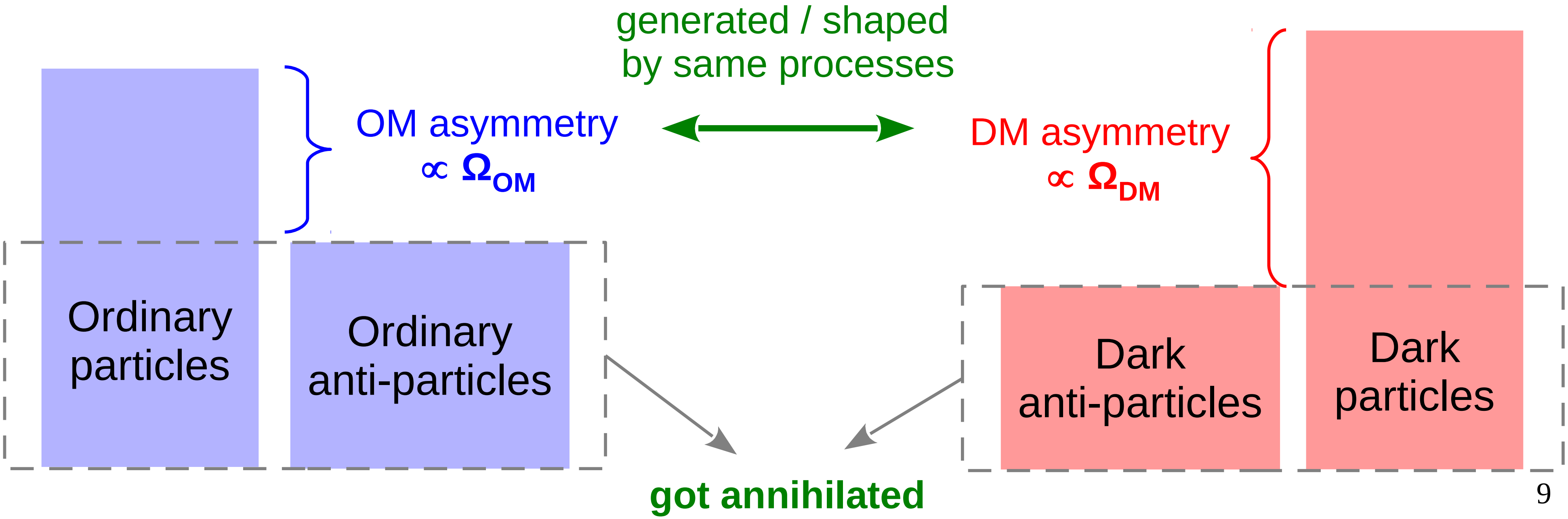
- Dynamical explanation:

  DM production related to ordinary matter-antimatter asymmetry → **asymmetric DM**

The asymmetric DM proposal

[Review of asymmetric dark matter; KP, Volkas (2013)]

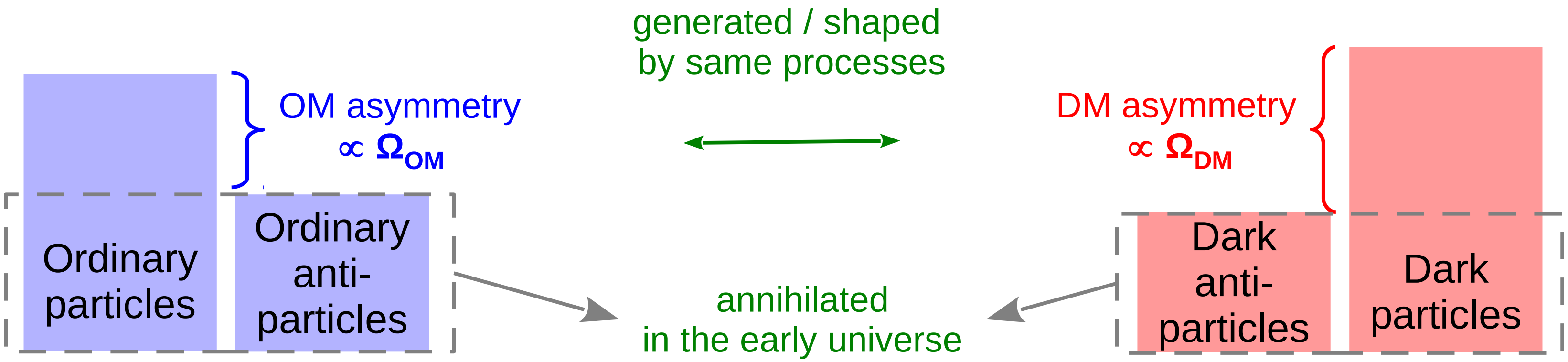
- DM density due to an excess of dark particles over antiparticles.
- DM – OM asymmetries related dynamically, by high-energy processes which occurred in the early universe.
- Dark and visible asymmetries conserved separately today.



Asymmetric DM

[Review of asymmetric dark matter;
KP, Volkas (2013)]

Ingredients



generated / shaped
by same processes

OM asymmetry
$\propto \Omega_{OM}$

DM asymmetry
$\propto \Omega_{DM}$

Ordinary particles

Ordinary anti-particles

annihilated
in the early universe

Dark anti-particles

Dark particles

- **Low-energy theory:**
  - Standard Model: Ordinary baryon number symmetry $\boldsymbol{B}_{O}$
    Dark sector: "Dark baryon number $\boldsymbol{B}_{D}$" [accidental global U(1) symmetry]
  - Interaction which annihilates dark antiparticles. How strong?
    → determines possibilities for DM couplings → low-energy pheno.
- **High-energy theory:**

$$\left.\begin{array}{l} \boldsymbol{B}_{O}\ \textbf{violation} \\ \boldsymbol{B}_{D}\ \textbf{violation} \end{array}\right\} \text{if correlated} \rightarrow \text{related asymmetries } \Delta B_{O}\ \&\ \Delta B_{D}$$

Asymmetric DM

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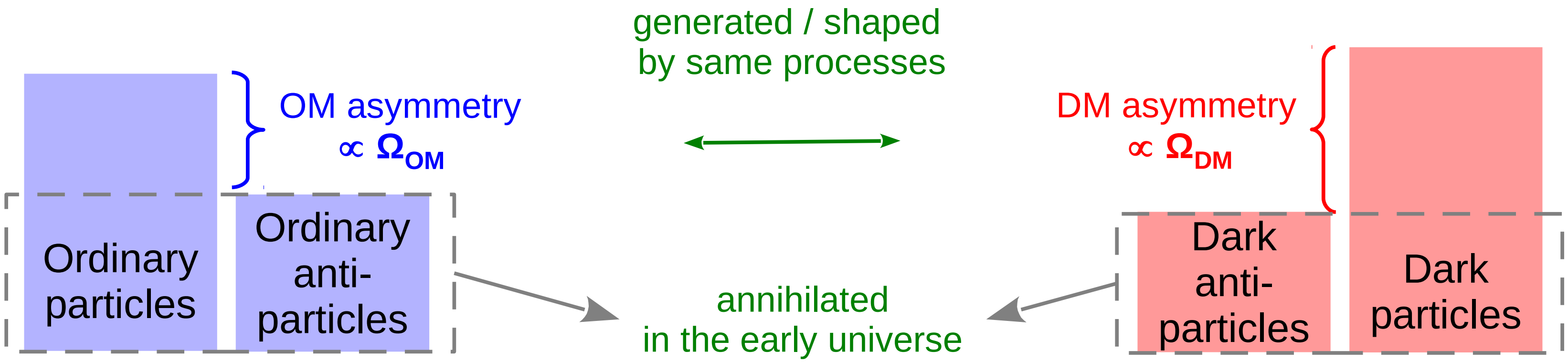

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OM asymmetry
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Ordinary particles

Ordinary anti-particles

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Relating ΔB_O & ΔB_D

Consider

$$B_{gen} \equiv B_O - B_D \qquad\qquad B_{gen} \equiv (B\text{-}L)_O - B_D$$
$$X \equiv B_O + B_D \quad \text{or} \quad X \equiv (B\text{-}L)_O + B_D$$

Need processes which

- violate **X** → $\Delta X \neq 0$
- preserve **B_{gen}** → $\Delta B_{gen} = 0$

$$\left.\begin{array}{l}\\ \\ \end{array}\right\} \boxed{\Delta(B\text{-}L)_O = \Delta B_D = \Delta X / 2}$$

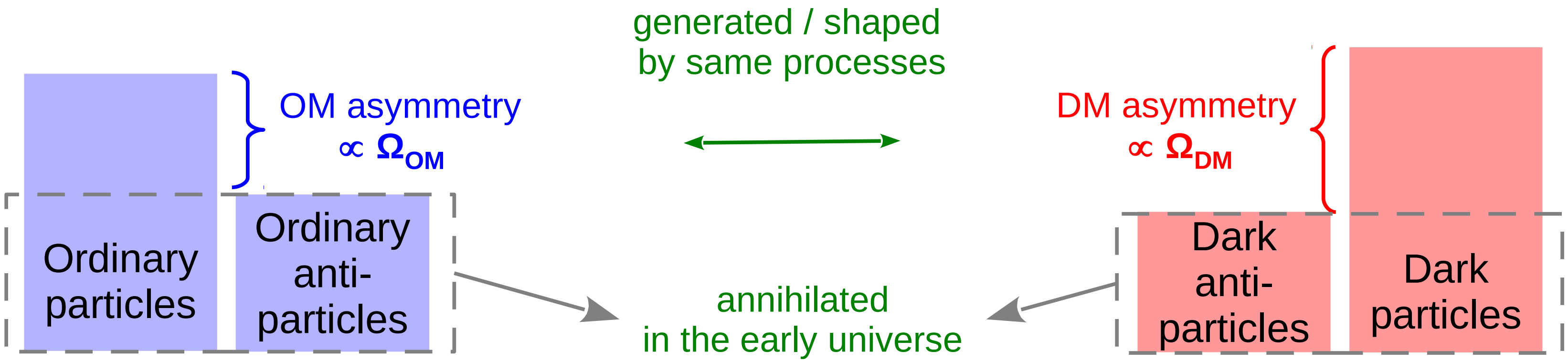
[e.g. Bell, KP, Shoemaker, Volkas (2011);
KP, Trodden, Volkas (2011);
von Harling, KP, Volkas (2012)]

Side point: B_{gen} remains always conserved → could originate from a gauge symmetry, a generalization of the B-L symmetry of the SM, coupled to a dark sector → **$Z'_{B\text{-}L}$** with invisible decay width in colliders

Asymmetric DM

[Review of asymmetric dark matter;
KP, Volkas (2013)]

Ingredients



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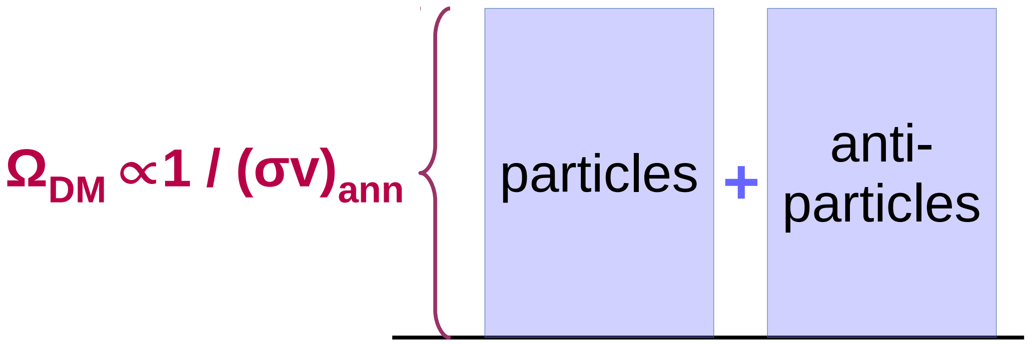
Non-relativistic thermal relic DM

Symmetric DM



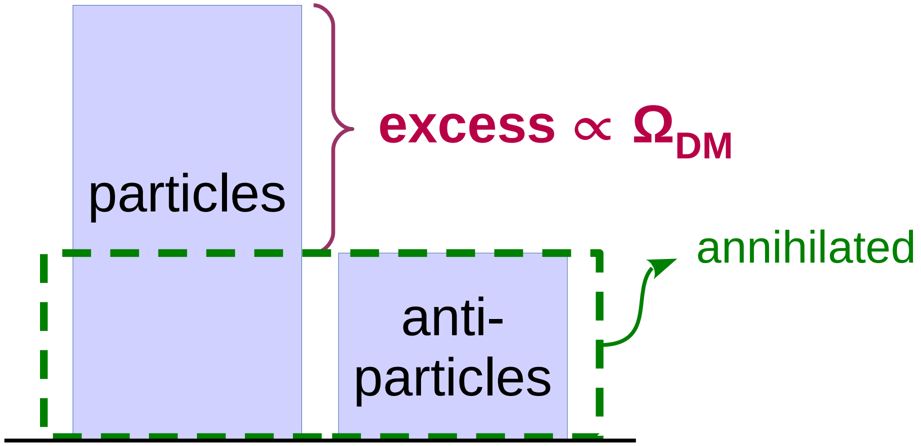
$\Omega_{DM} \propto 1 / (\sigma v)_{ann}$

particles + anti-particles

$\sigma_{ann} v_{rel} \approx 4.4 \times 10^{-26}\ \mathrm{cm}^3/\mathrm{s}$

fixed value

Asymmetric DM



particles

excess $\propto \Omega_{DM}$

annihilated

anti-particles

$\sigma_{ann} v_{rel} > \ 4.4 \times 10^{-26}\ \mathrm{cm}^3/\mathrm{s}$

no upper limit

$$\text{For } \frac{(\sigma v)_{ann}}{4.4 \times 10^{-26}\ \mathrm{cm}^3/\mathrm{s}} > 2 \rightarrow \frac{n(\bar{\chi})}{n(\chi)} < 5\%$$

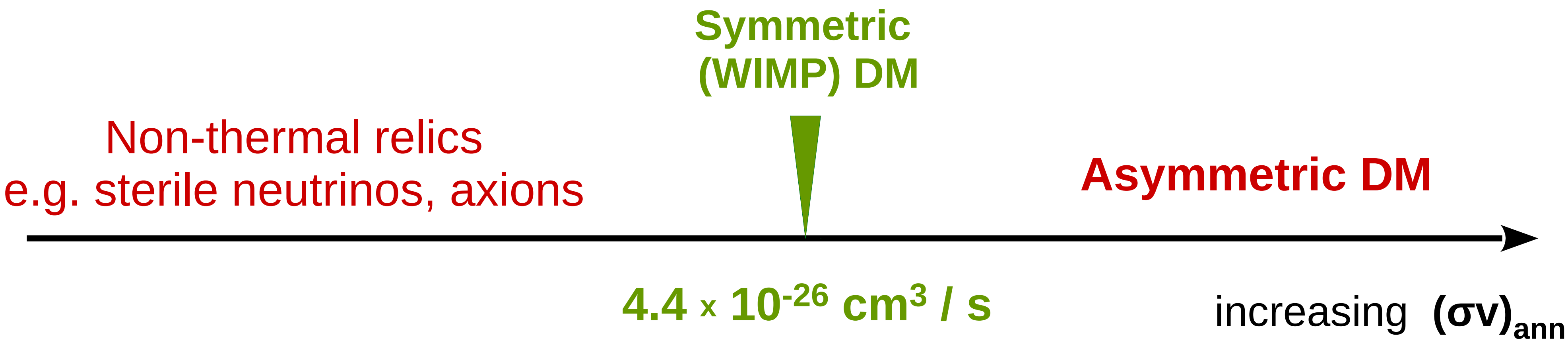
[Graesser, Shoemaker, Vecchi (2011)]

Asymmetric DM

[Review of asymmetric dark matter;
KP, Volkas (2013)]

Phase space of stable / long-lived relics

To get **$\Omega_{DM} \sim 26\%$:**



Symmetric (WIMP) DM

Non-thermal relics
e.g. sterile neutrinos, axions

Asymmetric DM

4.4×10^{-26} cm^3 / s

increasing **$(\sigma v)_{ann}$**

Asymmetric dark matter

- Encompasses most of the low-energy parameter space of thermal relic DM → study models and low-energy pheno.
- Provides a suitable host for DM self-interacting via light species.

Asymmetric DM

[Review of asymmetric dark matter;
KP, Volkas (2013)]

DM annihilation

Need $(\sigma v)_{ann} > 4.4 \times 10^{-26}\ \mathrm{cm}^3 / \mathrm{s}$.

What interaction can do the job?

- $\bar{\chi}\,\chi \rightarrow$ **SM SM**

  Annihilation directly into SM particles highly constrained via colliders and direct detection (see bounds on symmetric WIMP DM)

- $\bar{\chi}\,\chi \rightarrow \varphi\,\varphi$

  Annihilation into new light states:

  - ✗ $\varphi \rightarrow$ **SM SM** : metastable mediators decaying into SM
  - ✗ φ **stable light species**, e.g. dark photon (possibly massive, with kinetic mixing to hypercharge), or a new light scalar.

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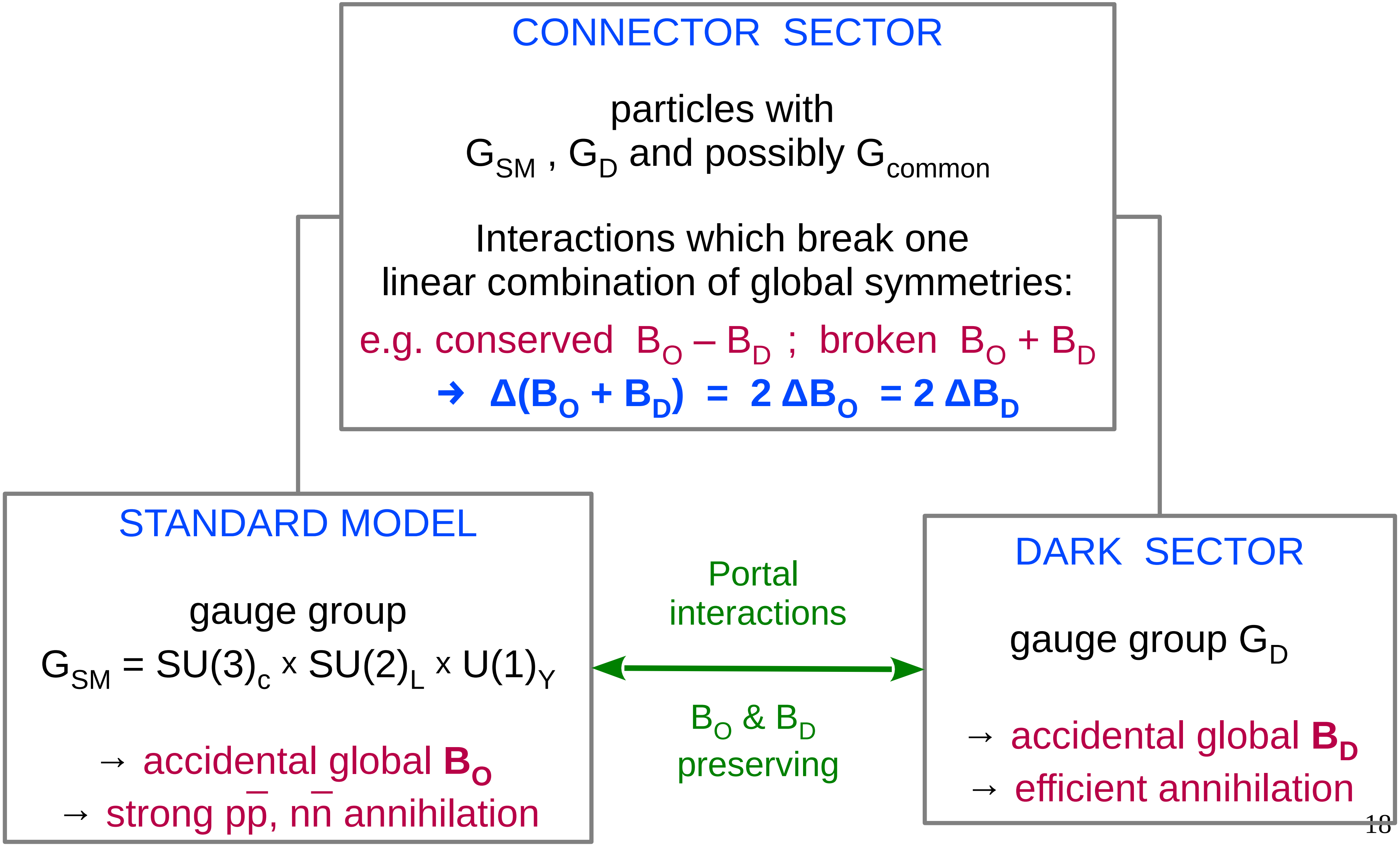
Structure



CONNECTOR SECTOR

particles with
G_{SM} , G_D and possibly G_{common}

Interactions which break one
linear combination of global symmetries:

e.g. conserved $B_O - B_D$; broken $B_O + B_D$

➜ $\Delta(B_O + B_D) = 2\,\Delta B_O = 2\,\Delta B_D$

STANDARD MODEL

gauge group
$G_{SM} = SU(3)_c \times SU(2)_L \times U(1)_Y$

→ accidental global $\mathbf{B_O}$
→ strong $p\bar{p}$, $n\bar{n}$ annihilation

Portal
interactions

B_O & B_D
preserving

DARK SECTOR

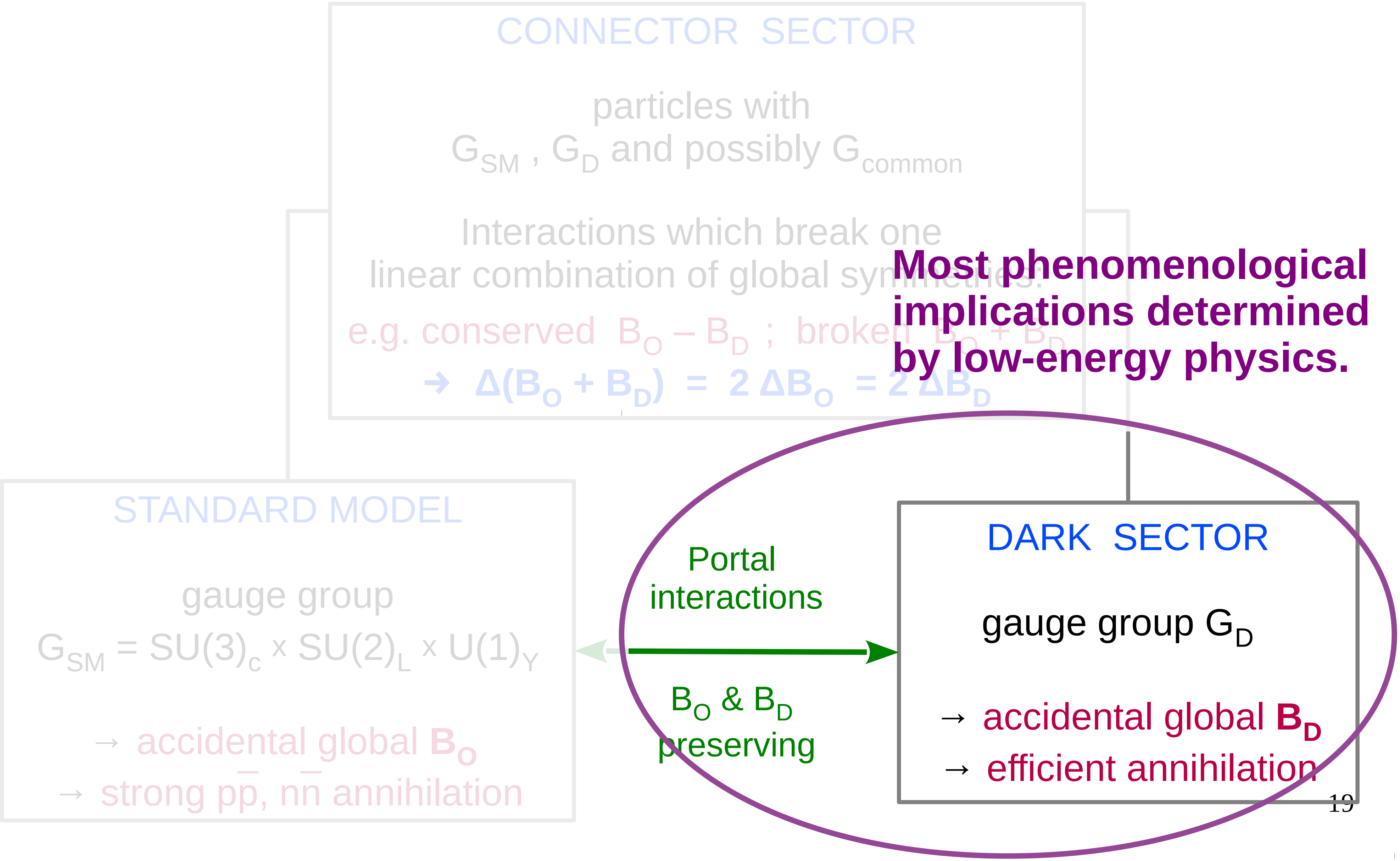
gauge group G_D

→ accidental global $\mathbf{B_D}$
→ efficient annihilation

Asymmetric DM

[Review of asymmetric dark matter;
KP, Volkas (2013)]

Structure



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Most phenomenological implications determined by low-energy physics.

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Asymmetric DM

[Review of asymmetric dark matter;
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Phenomenology: zoo of possibilities

- Does asymmetric DM pheno have to be unconventional ? ***No.***
    - Many regimes where it behaves as collisionless CDM.
    - Could have weak-scale interactions with ordinary matter.
    - Main difference in (sufficiently) high-energy physics.
    - Scenario still motivated by cosmic coincidence.
- Is it interesting to consider regimes with unconventional pheno? ***Yes!***
    - Disagreement between collisionless CDM predictions and observations of galactic structure: May be telling us something non-trivial about DM.
    - Potential for interesting signatures (not yet fully explored).

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Collisionless ΛCDM and galactic structure

- Very successful in explaining large-scale structure.
- At galactic and subgalactic scales: simulations predict too rich structure. Various problems identified: “cusps vs cores”, “missing satellites”, “too big to fail”.

↓

too much matter
in central few kpc of typical galaxies.

[an overview: Weinberg, Bullock, Governato, Kuzio de Naray, Peter; arXiv: 1306.0913]

Small-scale galactic structure: How to suppress it

- **Baryonic physics**
- **Shift in the DM paradigm:**
  Retain success of collisionless ΛCDM at large scales, suppress structure at small scales
  - Warm DM, e.g. keV sterile neutrinos
  - Self-interacting DM

Continuum of possibilities:

How warm or how self-interacting can / should DM be?

Self-interacting DM

What is it good for?

The energy & momentum exchange between DM particles:

- **Heats up the low-entropy material**
  → suppresses overdensities [cusps vs cores]
  → suppresses star-formation rate [missing satellites, “too big to fail”]

- **Isotropises DM halos**
  → constrained by observed ellipticity of large haloes.

to affect dynamics of small halos

$$0.2\ \text{barn/GeV} < \sigma_{\text{scatt}} / m_{\text{DM}} < 2\ \text{barn/GeV}$$

to retain ellipticity of large halos

[Theory: Spergel, Steinhardt (2000). Simulations: Rocha et al. (2012); Peter et al. (2012); Zavala et al (2012)]

Self-interacting DM

What interaction?

$$\sigma_{\mathrm{scatt}} / m_{\mathrm{DM}} \sim \text{barn / GeV}$$

DM coupled to a light or massless force mediator (long-range interaction)

- $\sigma_{\mathrm{scatt}} / m_{\mathrm{DM}}$ ~ nuclear interaction strength
- If mediator sufficiently light: $\boldsymbol{\sigma_{\mathrm{scatt}} \sim 1 / v^n}$, $n > 0$:
    - Significant effect on small halos (small velocity dispersion)
    - Negligible effect on large halos (large velocity dispersion)

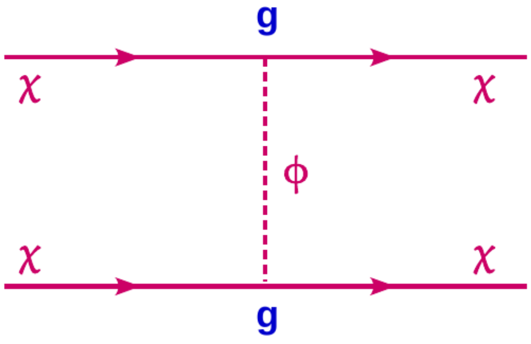
Self-interacting DM

Sketching a theory

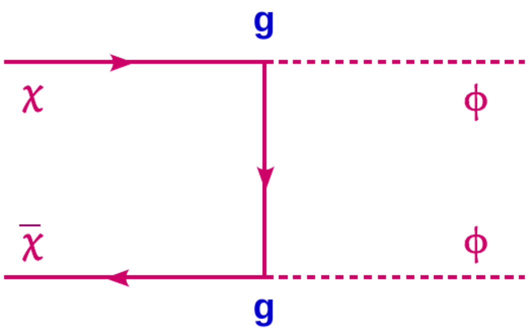
$$\mathcal{L} \supset g\,\varphi\,\bar{\chi}\,\chi$$

χ : dark matter
φ : mediator
$m_\varphi \ll m_\chi$

Self-interaction



Annihilation



Sizable self-interactions via light mediators imply minimum contribution to DM annihilation; annihilation cross-section could exceed canonical value for symmetric thermal relic DM

→ consider **asymmetric DM** (also motivated by $\Omega_{DM} \sim \Omega_{OM}$)

Asymmetric dark matter with (long-range) self-interactions

Self-interacting asymmetric dark matter

- How to go about studying it?

- Many studies of long-range DM self-interactions (in either the symmetric or asymmetric regime) employ a Yukawa potential

$$\mathbf{V_{\chi\chi}\,(r) \;=\; \pm\,\alpha\,\exp\,(-\,m_\varphi\,r)\,/\,r}$$

[upper bound on σ_{scatt} → lower bound on m_φ / upper bound on α]

- However, typically reality is often more complex for asymmetric DM with (long-range) self-interactions.

Self-interacting asymmetric dark matter

- **Complex early-universe dynamics**

  Formation of stable DM bound states → Multi-species DM, e.g. dark ions, dark atoms, dark nuclei.

- **Implications for detection**
  - Variety of DM self-interactions → affect kinematics of halos.
  - Variety of DM-nucleon interactions → direct detection.
  - Variety of radiative DM processes → indirect detection.

- Consider classes of models,
  calculate cosmology + phenomenology self-consistently

A minimal self-interacting asymmetric DM example:

atomic dark matter

Atomic DM

Minimal assumptions

- DM relic density: dark particle-antiparticle asymmetry
- DM couples to a gauged $U(1)_D$ [dark electromagnetism]
  - → DM self-scattering in halos today via dark photons.
  - → DM annihilation in the early universe into dark photons.

[specific models: Kaplan et al (2009, 2011); KP, Trodden, Volkas (2011); von Harling, KP, Volkas (2012)]

Atomic DM

Minimal assumptions → rich dynamics

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Gauge invariance mandates DM be **multi-component**:

- Massless dark photon:

  Dark electric charge carried by dark protons $\boldsymbol{p_D^+}$ compensated by opposite charge carried by dark electrons $\boldsymbol{e_D^-}$. They can bind in dark Hydrogen atoms $\boldsymbol{H_D}$.

- Mildly broken $U(1)_D$, light dark photon:

  Similar conclusion in most of the parameter space of interest.

[KP, Pearce, Kusenko (2014)]

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  fundamental

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[KP, Pearce, Kusenko (2014)]

Atomic DM

Model-building example

$$G = G_{SM} \times U(1)_{B_{gen}} \times \boxed{U(1)_D}$$

same as $(B\text{-}L)_V$
for SM particles

- Efficient annihilation
- DM self-scattering in halos

	gauged B_{gen}	gauged D	accidental global B_D
p_D	-2	1	2
e_D	0	-1	0

accidental global $(\boldsymbol{B\text{-}L})_V$ & $\boldsymbol{B}_D$

$$\delta\mathcal{L}_{\text{low}} = \overbrace{\mathcal{L}_{SM} + \bar{p}_D\,(i\cancel{D} - m_p)p_D + \bar{e}_D\,(i\cancel{D} - m_e)\,e_D + (\varepsilon/2)\,F_{Y\,\mu\nu}\,F_D^{\mu\nu}}$$

Direct / Indirect detection

$$\delta\mathcal{L}_{\text{high}} \supset \underbrace{(1/\Lambda^8)\,(\,\bar{u}^c d\,\bar{s}^c u\,\bar{d}^c s)\,\bar{e}_D{}^c\,p_D}$$

preserves $\boldsymbol{B}_{gen} = (\boldsymbol{B\text{-}L})_V - \boldsymbol{B}_D$
breaks $\boldsymbol{X} = (\boldsymbol{B\text{-}L})_V + \boldsymbol{B}_D$

***X* asymmetry generation: $\Delta\,(B\text{-}L)_V = \Delta B_D$**
[e.g. via Affleck-Dine mechanism in susy models; von Harling, KP, Volkas (2012)]

Atomic DM

Cosmology

Dark asymmetry generation in $U(1)_D$–neutral op ($\boldsymbol{p_D e_D}$)	$T_{\text{asym}} > m_{p_D} / 25$
Freeze-out of annihilations $\bar{\boldsymbol{p}}_D \boldsymbol{p}_D \to \gamma_D \gamma_D$ & $\bar{\boldsymbol{e}}_D \boldsymbol{e}_D \to \gamma_D \gamma_D$	$T_{\text{FO}} \approx m_{p_D, e_D} / 30$
Dark recombination, $\boldsymbol{p}_D + \boldsymbol{e}_D \to \boldsymbol{H}_D + \gamma_D$	$T_{\text{recomb}} \lesssim$ binding energy = $\alpha_D^2 \mu_D / 2$
Residual ionisation fraction	$x_{ion} \equiv \frac{n_{p_D}}{n_{p_D} + n_{H_D}} \sim \min\left[1,\ 10^{-10} \frac{m_{p_D} m_{e_D}}{\alpha_D^4 \ GeV^2}\right]$
[If dark photon massive] Dark phase transition	$T_{\text{PT}} \sim m_{\gamma_D} / (8\pi\alpha_D)^{1/2}$

t

[Kaplan, Krnjaic, Rehermann, Wells (2009); KP, Trodden, Volkas (2011); Cyr-Racine, Sigurdson (2012); KP, Pearce, Kusenko (2014)]

Atomic DM with a massive dark photon

Asymmetric DM coupled to a dark photon is **multicomponent (p_D , e_D)**, and possibly **atomic** (H_D)
in much of the parameter space where
the dark photon is light enough to mediate
sizable (long-range) DM self-interactions

[KP, Pearce, Kusenko (2014)]

- Bound-state formation cannot be ignored.
- The formation of atomic bound states screens the DM self-interaction.
- Force mediator need not be “sufficiently massive” to satisfy constraints.
- Interplay between cosmology and strength of the interactions.

Atomic DM

Self-interactions

- Multi-component DM with different inter- and intra-species interactions

$H_D - H_D$, $H_D - p_D$, $H_D - e_D$, $p_D - p_D$, $e_D - e_D$, $p_D - e_D$

- Strong velocity dependence of scattering cross-sections

$$\sigma_{ion-ion} \propto v^{-4}, \quad screened \quad at \quad \mu_{ion-ion} v < m_{\gamma_D}$$

$$\sigma_{H_D-H_D} \approx (\alpha_D \mu_D)^{-2} \left[b_0 + b_1 \left(\frac{m_{H_D} v^2}{4 \mu_D \alpha_D^2} \right) + b_2 \left(\frac{m_{H_D} v^2}{4 \mu_D \alpha_D^2} \right)^2 \right]^{-1}$$

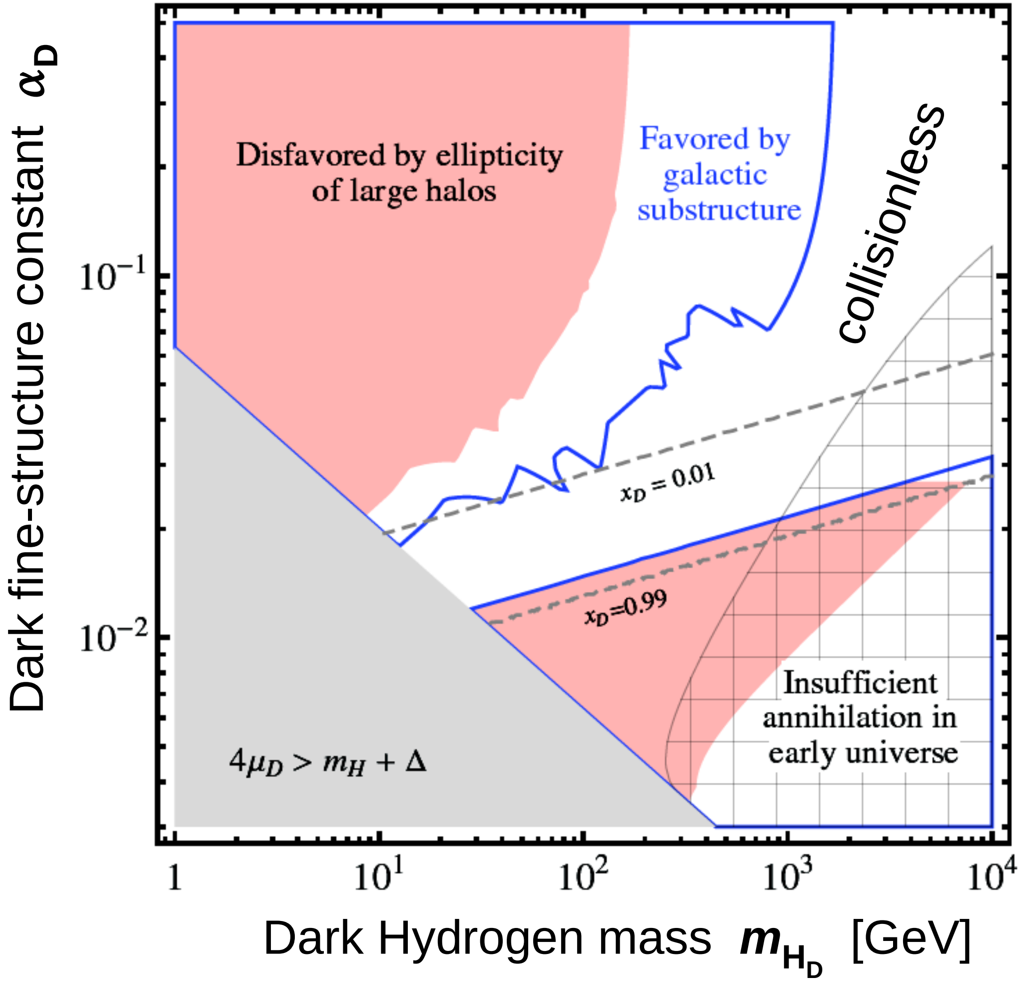
(valid away from resonances; b_0, b_1, b_2 : fitting parameters, depend mildly on m_p/m_e)
[Cline, Liu, Moore, Xue (2013)]

Atomic DM

Self-scattering in halos

Binding energy **$\Delta = 0.5$ MeV**

Dark photon mass **$m_{\gamma_D} = 1$ eV**



- Non-monotonic behavior in α_D, because of the formation of bound states (→ no upper limit on α_D, or lower limit on m_{γ_D}).
- Strong velocity dependence of scattering cross-sections allows for ellipticity constraints to be satisfied, while having a sizable effect on small scales.
- Collisionless CDM limits:
  large m_{H_D} → small number density
  large α_D → tightly bound atoms
  small α_D → small interaction
  small m_{γ_D} → atom formation
  large m_{γ_D} → no atoms, ion-ion screening

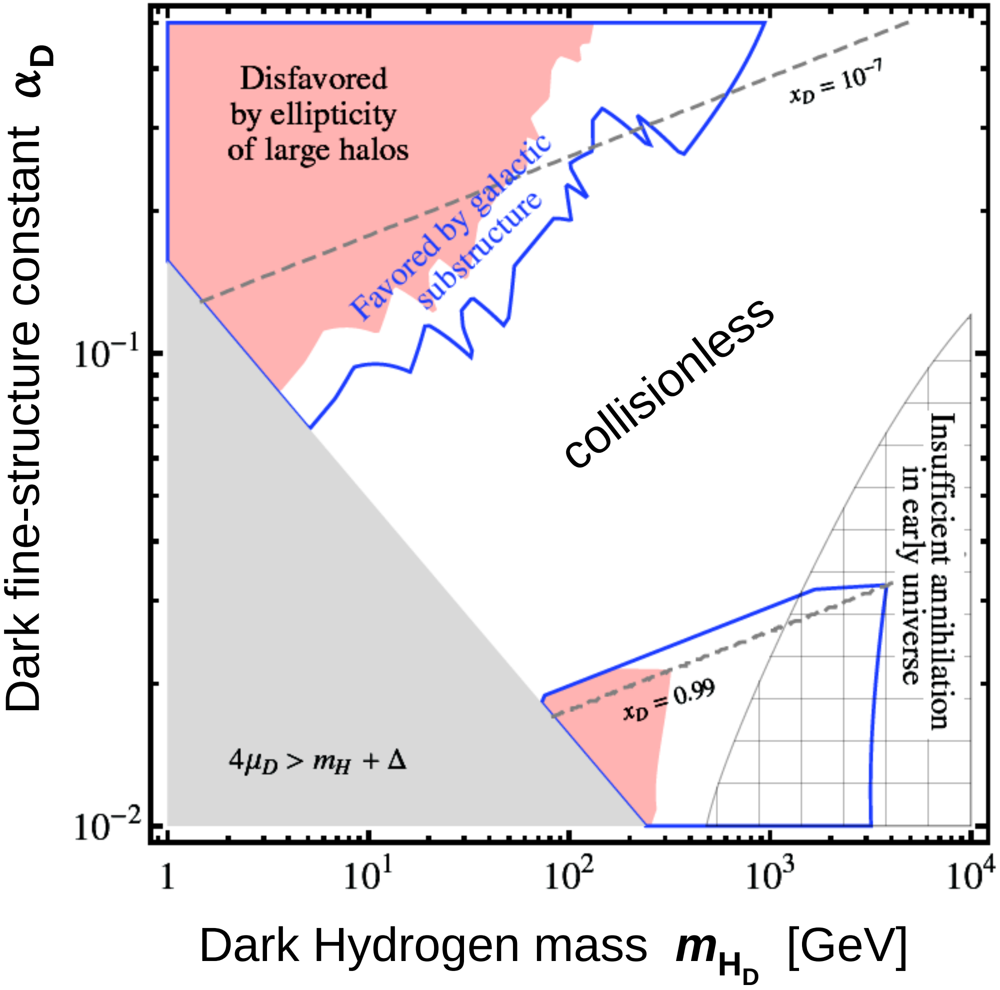
[KP, Pearce, Kusenko (2014)]

Atomic DM

Self-scattering in halos

Binding energy **Δ = 3 MeV**

Dark photon mass **m_{γ_D} = 1 MeV**



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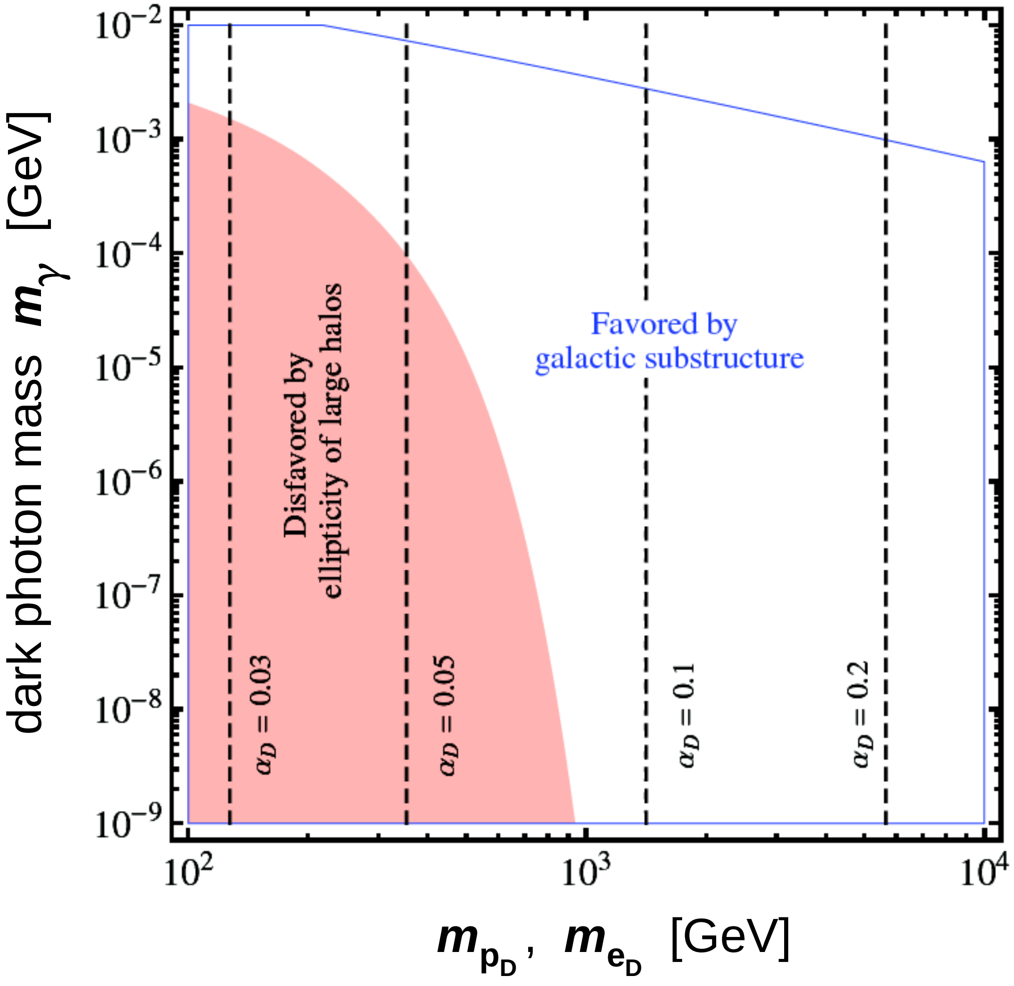
[KP, Pearce, Kusenko (2014)]

Atomic DM

Self-scattering in halos

ionisation fraction **$x_{ion} = 0.6$**

dark proton mass m_{p_D} = dark electron mass m_{e_D}



- DM in bound states: even massless mediators viable (and very interesting: v-dependent scattering)
- If DM mostly ionized, and $m_{DM} < 500$ GeV → sizable mediator mass needed
- Even if DM mostly ionized, very light / massless mediators still good, if $m_{DM} > 500$ GeV

[KP, Pearce, Kusenko (2014)]

Atomic DM

Indirect detection: $\delta\mathcal{L} = (\varepsilon/2)\, F_Y\, F_D$

- Bound-state formation in galaxies today from ionized component

$$p_D^+ + e_D^- \rightarrow H_D + \gamma_D$$

$$\gamma_D \rightarrow e^+\, e^- \qquad \text{(for } m_\gamma > 1.022 \text{ MeV)}$$

[Pearce, KP, Kusenko (2015)]

- Level transitions (dark Hydrogen excitations and de-excitations)

$$H_D + H_D \rightarrow H_D + H_D^*, \quad H_D^* \rightarrow H_D + \gamma_D, \quad \gamma_D \rightarrow e^+\, e^-$$

Atomic DM

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Sommerfeld-enhanced process:
efficient in non-relativistic
environment of halos

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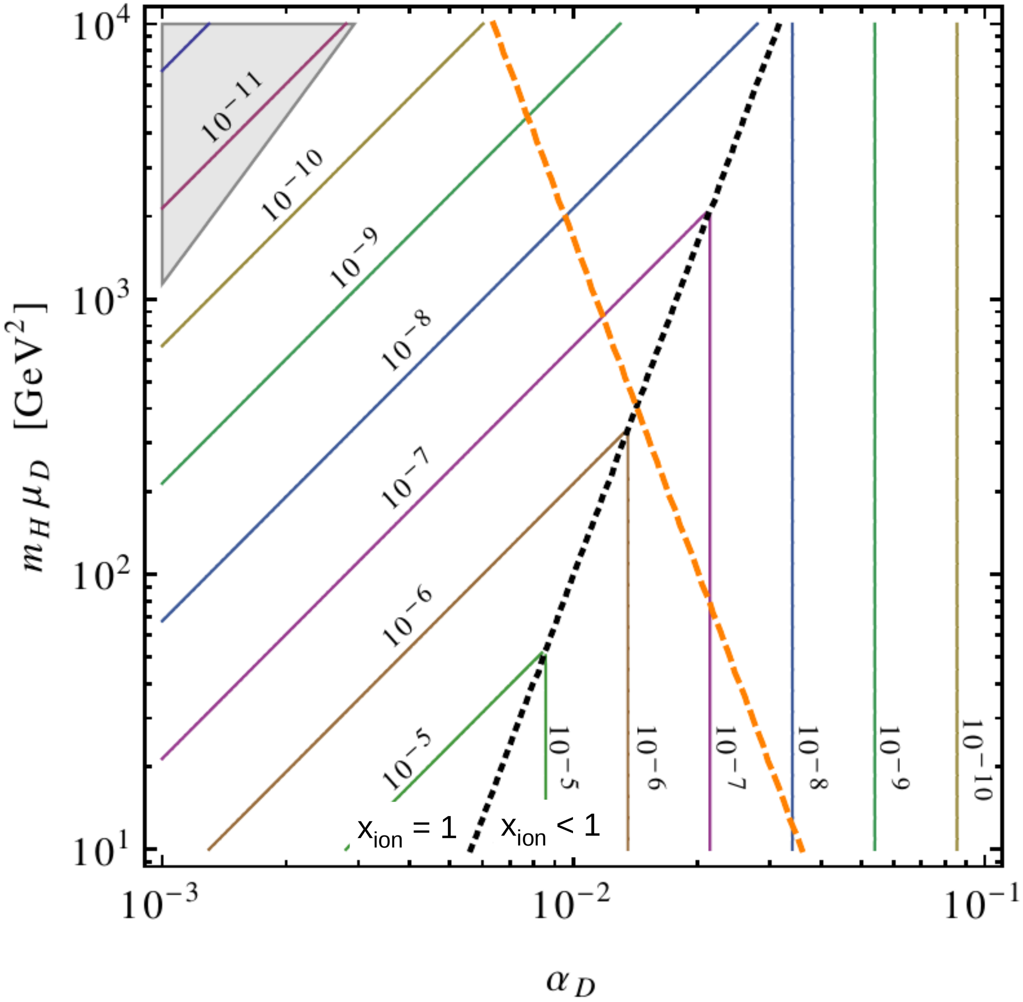
Atomic DM

Indirect detection: dark-atom formation in halos

$$s_{BSF} \equiv \frac{x_{ion}^2 \left(\sigma_{BSF} v_{rel}\right)}{m_{H_D}^2} \quad \left[GeV^{-4}\right]$$



[Pearce, KP, Kusenko (2015)]

***Bound – state formation*:**

$$\frac{d\Gamma_{BSF}}{dV} = \left(\sigma_{BSF} v_{rel}\right) x_{ion}^2 \frac{\rho_{DM}^2}{m_{H_D}^2}$$

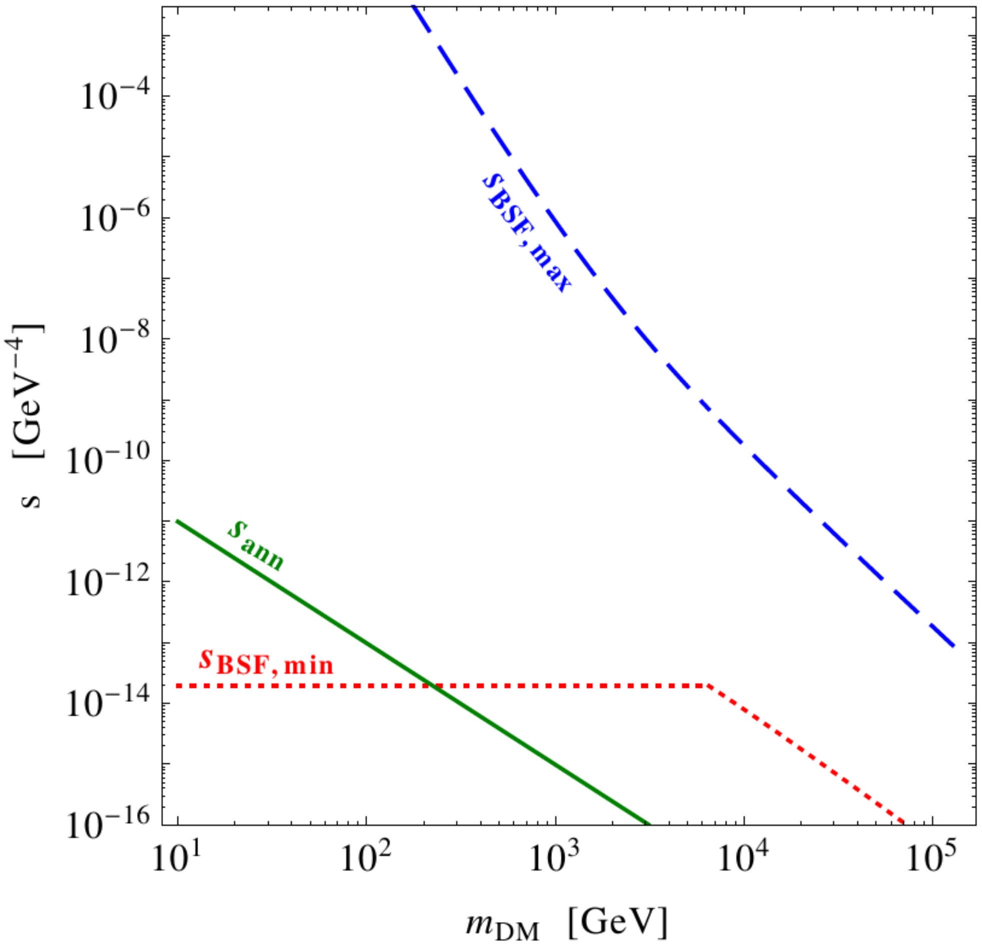
***Annihilation of symmetric DM*:**

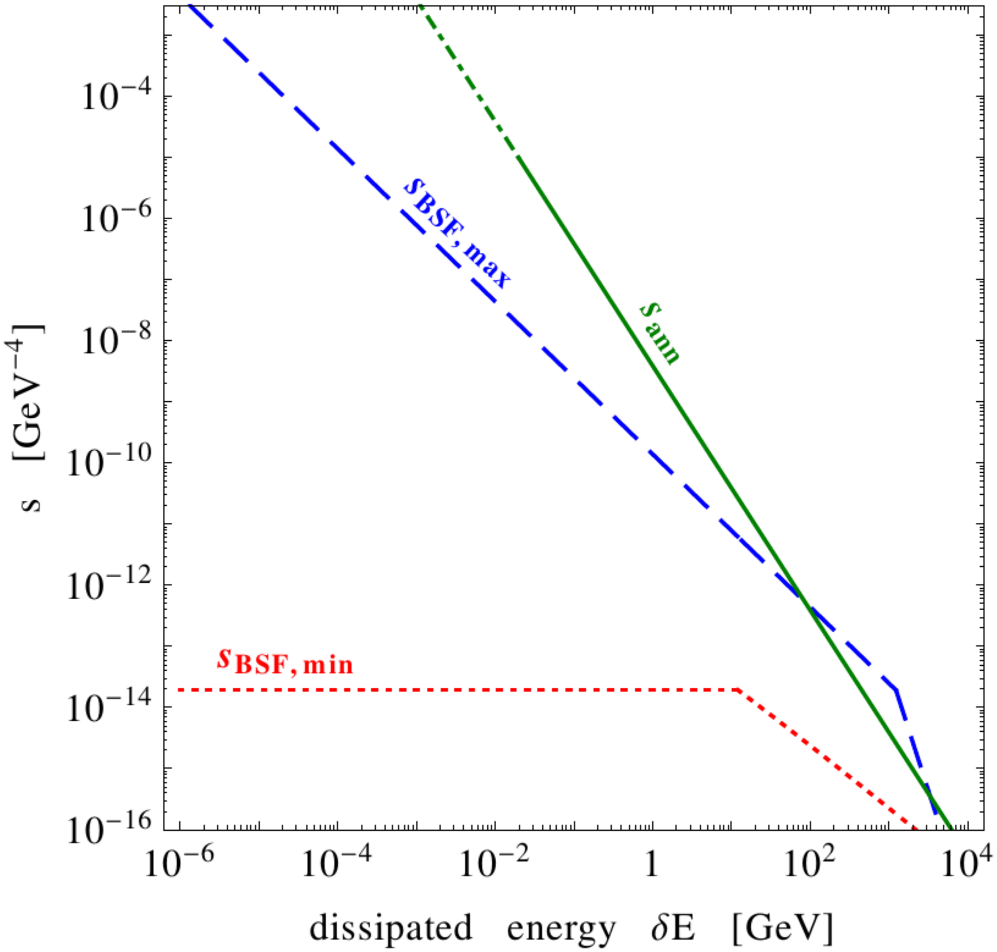
$$\frac{d\Gamma_{ann}}{dV} = \left(\sigma_{ann} v_{rel}\right) \frac{\rho_{DM}^2}{m_{DM}^2}$$

Interplay between early universe cosmology and strength of interaction →
min and max signal strength

Atomic DM

Indirect detection: atomic DM vs annihilating DM





atomic DM : $\delta E = \textit{binding energy} \ll m_{H_D}$

annihilating DM : $\delta E = 2\, m_{DM}$

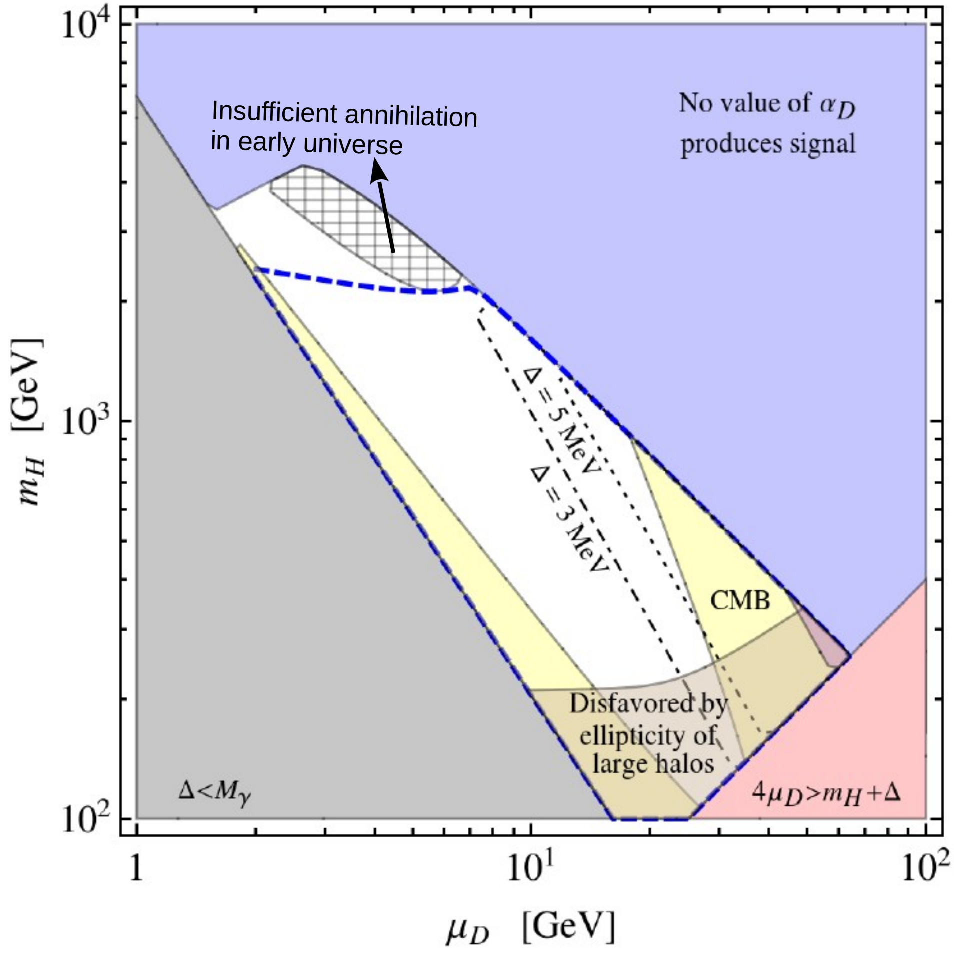
[Pearce, KP, Kusenko (2015)]

Atomic DM

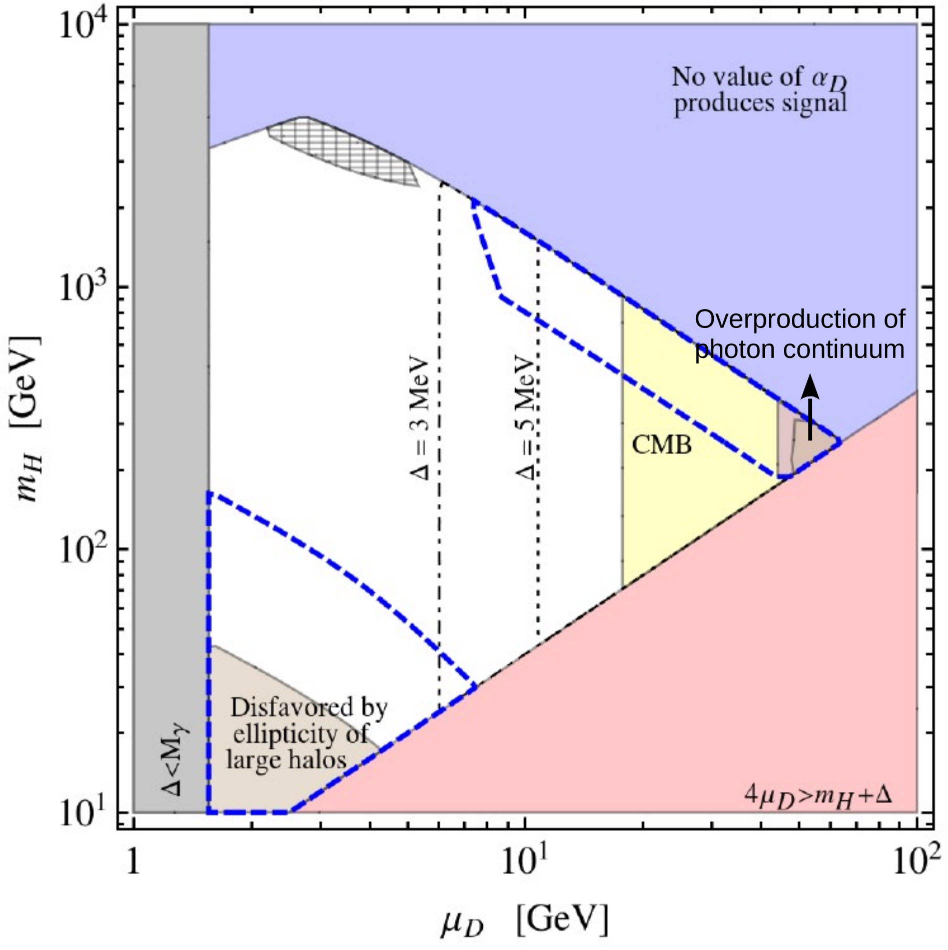
511 keV line in the Milky Way from dark-atom formation

m_{γ_D} = 2 MeV; contracted NFW profile (γ = 1.4)

fully ionized DM



partially ionized DM



[Pearce, KP, Kusenko (2015)]

Conclusion

- Symmetric thermal-relic WIMP DM ↔ collisionless CDM
  Asymmetric (thermal relic) DM ↔ self-interacting DM

  independently motivated

- Dark-sector dynamics can be complex. Interplay between cosmology and strength of fundamental interactions determines low-energy phenomenology:

  The early universe regulates any manifestation of DM we may hope to detect today.

- Lots more to think about and to calculate!