Self-interacting asymmetric dark matter

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Unraveling dark matter: Strategy

Focus on DM-related observations:

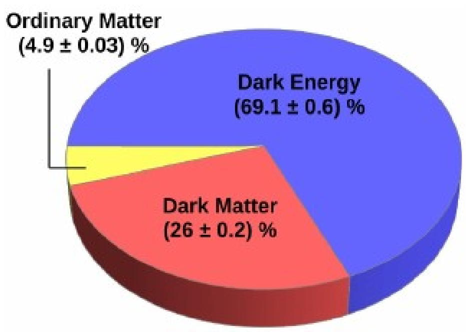
- DM density → Asymmetric DM
- Patterns of gravitational clustering → Self-interacting DM

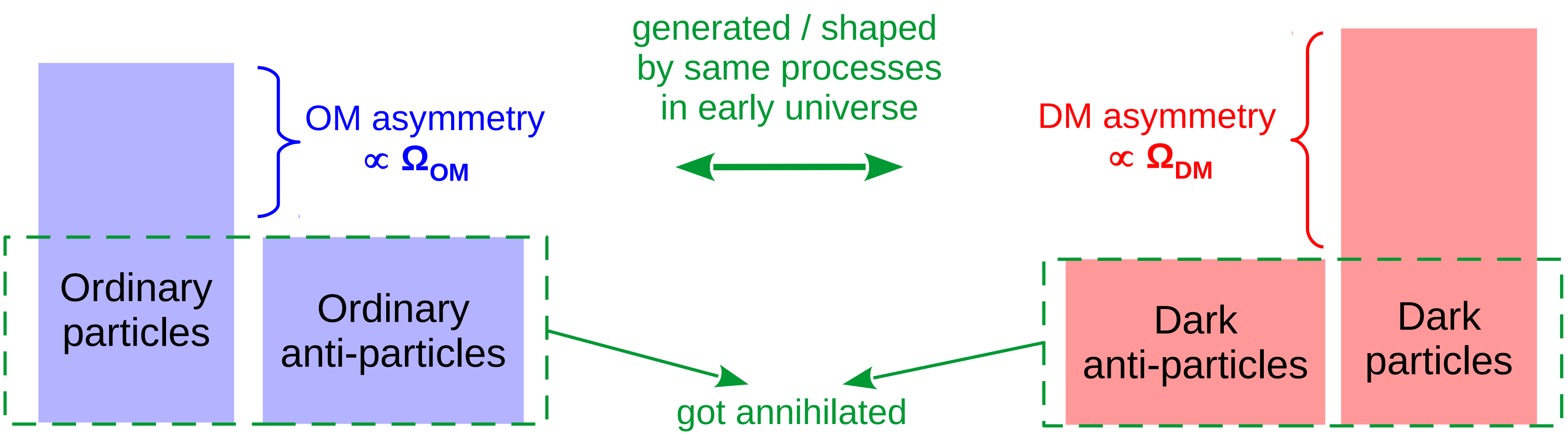
Asymmetric dark matter

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

Similarity of dark and ordinary matter densities suggests a **common origin.**

In contrast: different mechanisms → different parameters
→ densities expected to differ by many orders of magnitude,
e.g.   atoms ~ 5%   >> photons ~ 0.0022%, neutrinos ~ 0.0016%





Self-interacting dark matter

Structure at (sub)galactic scales
can be explained better by
DM with sizable self-interactions,
rather than collisionless DM.
Need:

$\sigma_{\text{self-scattering}} / m_{DM} \sim$ barn / GeV

Dark matter coupled to light force mediator:

$L \sim g\, \varphi\, \bar{\chi}\, \chi$

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

Many different kinds of interactions possible.

Self-interacting dark matter

Why *light* force mediator ?

- To ensure strong enough DM self-scattering
- Sufficiently light mediators

  → $\sigma_{\text{self-scattering}}$ decreases with velocity

  - significant effect on small halos (= small velocity dispersion), e.g. dwarf spheroidals
  - negligible effect on larger systems (= large velocity dispersion) → preserve ellipticity of Milky-Way-sized halos.

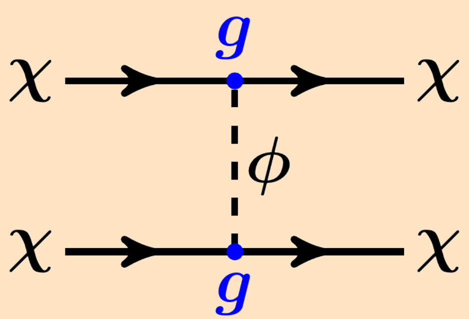
Why self-interacting *and* asymmetric?

$L \sim g\, \varphi\, \bar{\chi}\, \chi$

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

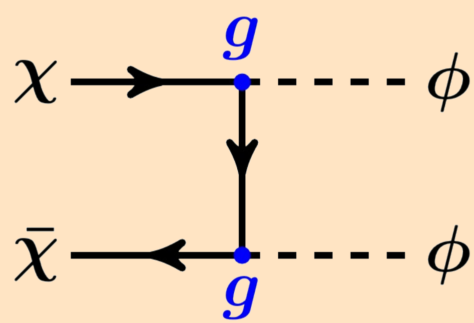
DM self-interaction

$\chi + \chi \rightarrow \chi + \chi$



DM annihilation

$\chi + \bar{\chi} \rightarrow \varphi + \varphi$



Too strong annihilation in the early universe leaves too little DM ...

… unless there is a particle-antiparticle asymmetry.

Asymmetric DM scenario: an excellent host of self-interacting DM

Self-interacting asymmetric dark matter

- How to go about studying it?
- Light force mediator → long-range interaction
- Many studies of long-range DM self-interactions (in either the symmetric or asymmetric regime) employ a Yukawa potential

$$V_{\chi\chi}(r) = \pm \alpha \exp(-m_\phi r)/r$$

- 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 radiative DM processes in haloes
  [bound-state formation, excitations+de-excitations of bound states]

  – Variety of DM-nucleon interactions
  [elastic, inelastic (excitation, break-up of bound states)]

- Delineate 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, e.g. KP, Trodden, Volkas (2011); von Harling, KP, Volkas (2012)]

Atomic DM

Minimal assumptions → rich dynamics

- DM relic density: dark particle-antiparticle asymmetry
- DM couples to a gauged $U(1)_D$ [dark electromagnetism]
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[specific models, e.g. KP, Trodden, Volkas (2011); von Harling, KP, Volkas (2012)]

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

fundamental

- 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)]

Atomic DM — Cosmology

Dark asymmetry generation via $U(1)_D$ – neutral op ($p_D e_D$)	$T_{asym} > m_{p_D} / 25$
Freeze-out of annihilations $\bar{p}_D p_D \to \gamma_D \gamma_D$ & $\bar{e}_D e_D \to \gamma_D \gamma_D$	$T_{FO} \approx m_{p_D, e_D} / 30$
Dark recombination, $p_D + e_D \to H_D + \gamma_D$	$T_{recomb} \lesssim$ 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	$T_{PT} \sim m_{\gamma_D} / (8\pi\alpha_D)^{1/2}$

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

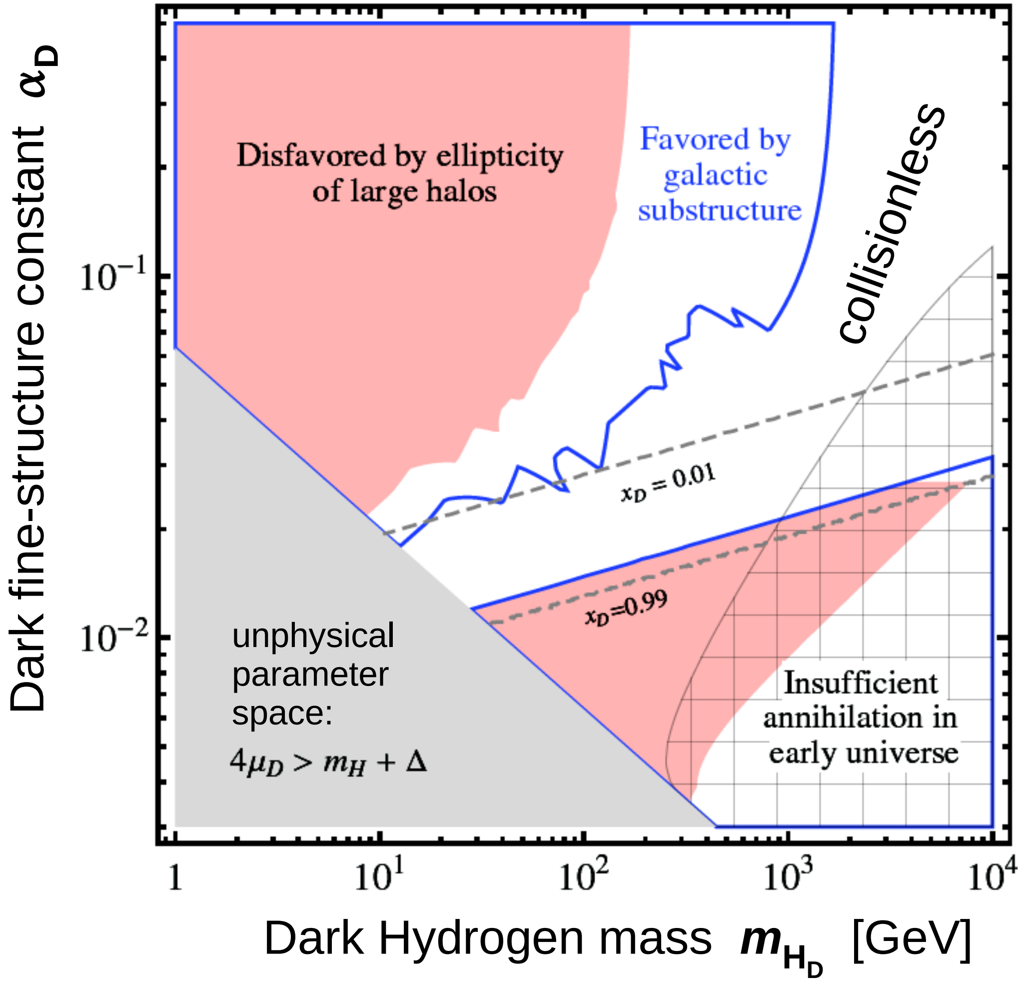
Asymmetric DM coupled to a dark photon is **multicomponent (p_D , e_D)**, and possibly **atomic** (H_D) in much of the parameter space where the dark photon is light enough to mediate sizable (long-range) DM self-interactions

[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-scattering in halos

Binding energy **Δ = 0.5 MeV**
Dark photon mass **m_{γ_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

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

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

- Bound-state formation in galaxies today from ionized component

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

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

[Pearce, KP, Kusenko (2015)]

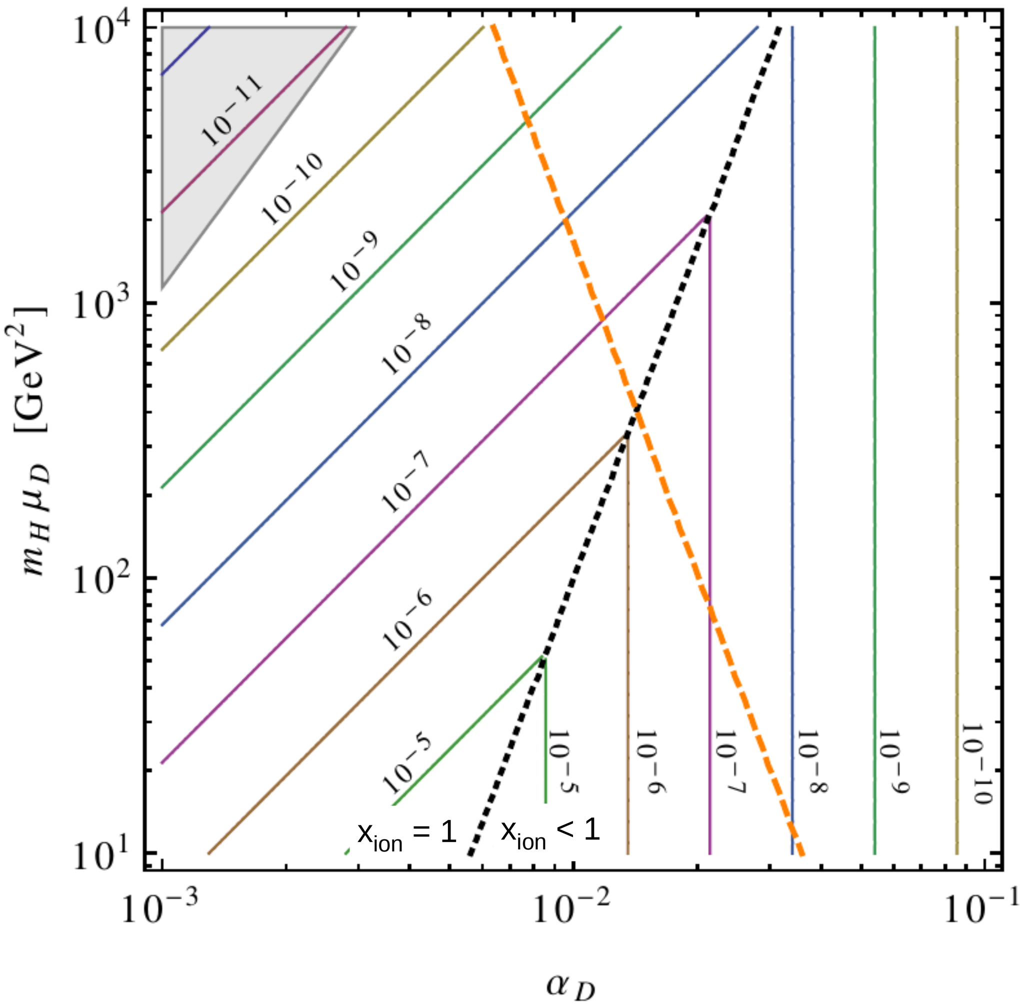
- Level transitions (dark Hydrogen excitations and de-excitations)

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

Atomic DM

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*:**

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

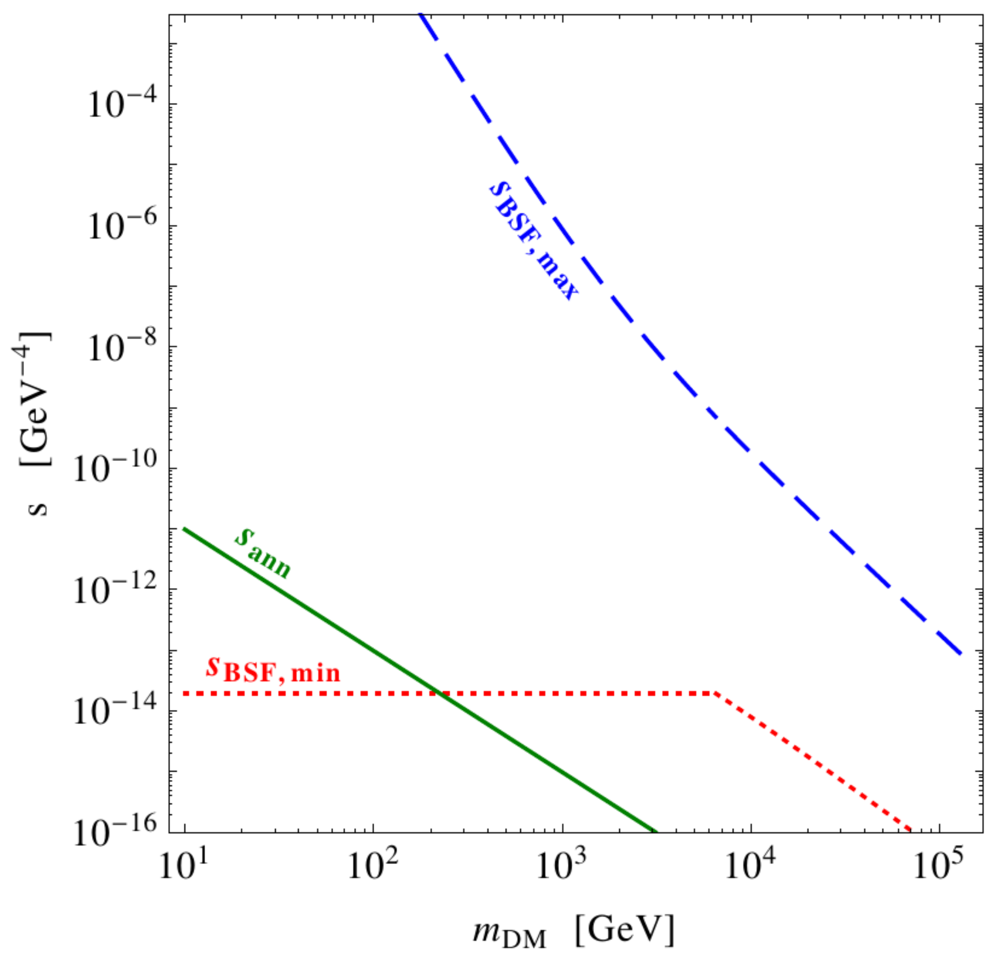
***Annihilation of symmetric DM*:**

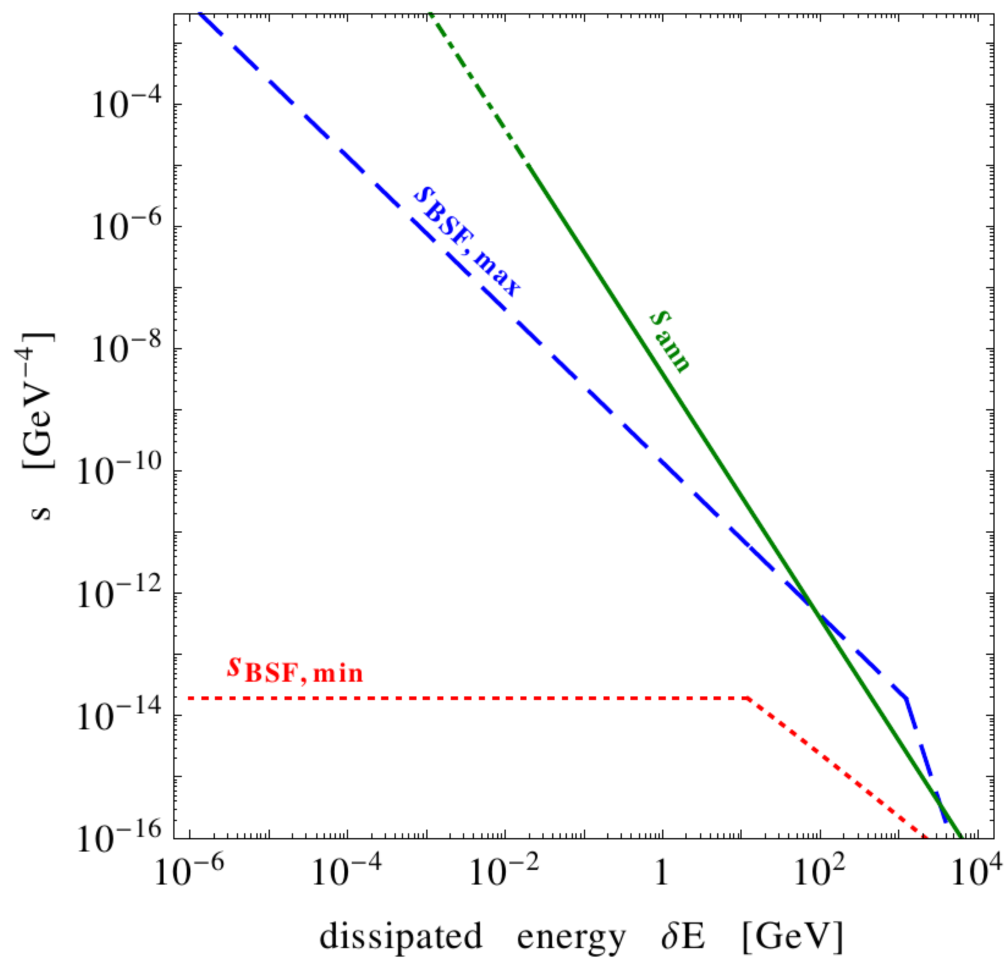
$$\frac{d\Gamma_{ann}}{dV} = \left(\sigma_{ann} v_{rel}\right) \frac{\rho_{DM}^2}{m_{DM}^2}$$

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 : δE = *binding energy* $\ll m_{H_D}$

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

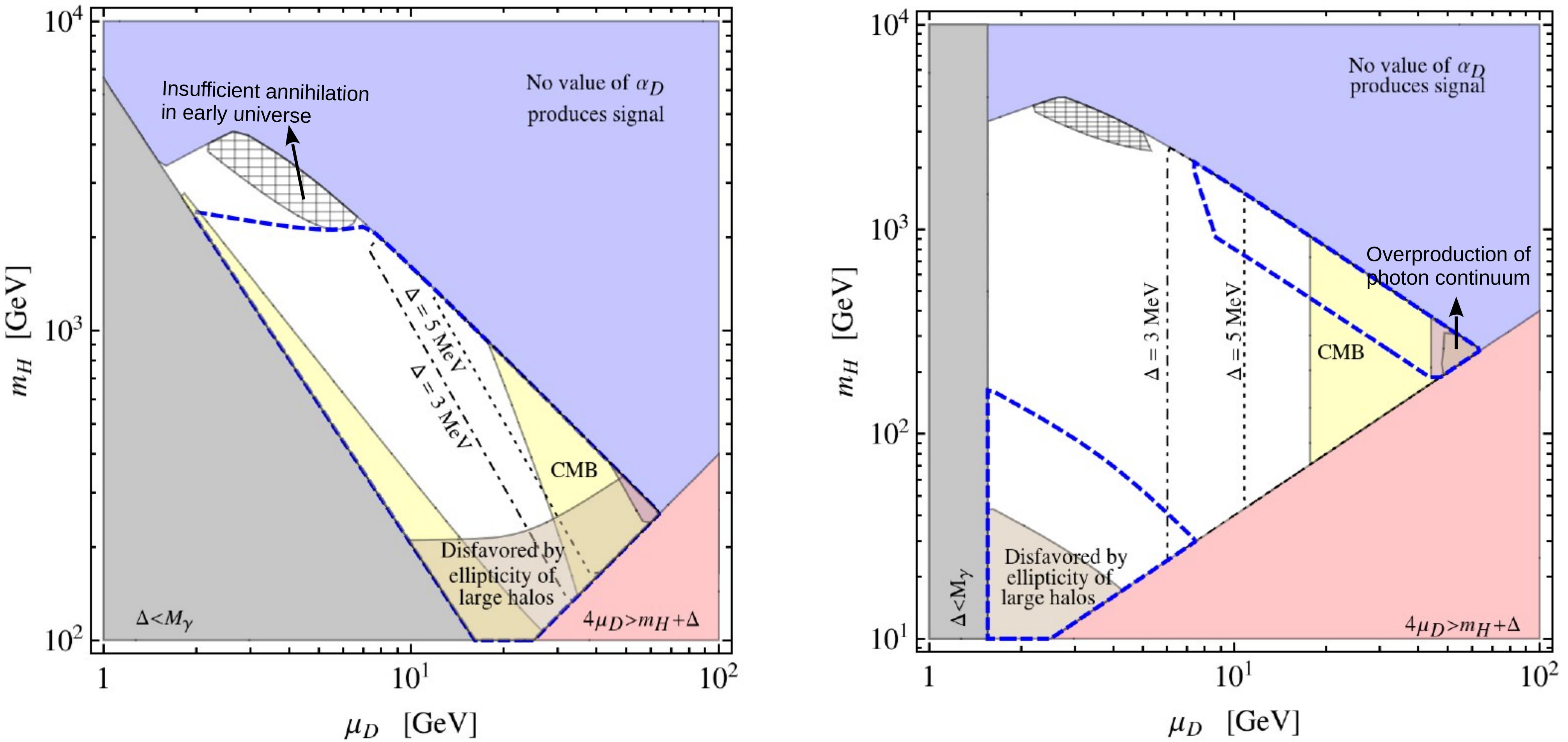
[Pearce, KP, Kusenko (2015)]

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

- Dark-sector dynamics can be complex.

  Interplay between cosmology and fundamental interactions determines low-energy phenomenology. Details are model-dependent, general picture is similar:

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

- Detectable signals via portal operators:
  Higgs portal, dark-ordinary photon kinetic mixing.