Bound states of symmetric and asymmetric dark matter

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Long-range interactions
mediated by
massless or light particles

Bound states

Long-range interactions

- Self-interacting DM
- DM explanations of galactic positrons
- DM explanations of IceCube PeV neutrinos
- Little hierarchy problem, e.g. twin Higgs models
- Sectors with stable particles in String Theory

Hidden sector DM

- WIMP DM with m_{DM} > few TeV ! [Hisano et al. 2002]

- Minimal DM [Cirelli et al.]
- LHC implications for SUSY
- Direct/Indirect detection bounds

Long-range interactions — Complications

- **Large logarithmic corrections:**

  $$\delta\sigma/\sigma \quad \sim \quad \alpha \ln \left(m_{DM} / m_{mediator} \right)$$

  → resummation techniques etc.

[In WIMP pheno:
Baumgart, Rothstein, Vaidya (2014)
Ovanesyan, Slatyer, Stewart (2014)
Bauer, Cohen, Hill, Solon (2014)]

- **Non-perturbative effects:**

  Sommerfeld enhancement in the non-relativistic regime.

  Usually invoked for DM annihilation into radiation, but in fact affects *all* processes with same initial state.

- **More processes:**
  Radiative formation of bound states [Sommerfeld enhanced]

Bound states — Phenomenological implications

- **Asymmetric DM → stable bound states**
  - Kinetic decoupling of DM from radiation, in the early universe
  - DM self-scattering in halos (screening)
  - Indirect detection signals (radiative level transitions)
  - Direct detection signals (screening, inelastic scattering)

- **Symmetric DM → unstable bound states**
  formation + decay = extra annihilation channel
  - Relic abundance [von Harling, KP (2014); Ellis et al. (2015)]
  - Indirect detection

A. **Confining theories**
Hadronic-like bound states ("non-perturbative non-perturbative bound states").

Cosmologically, they definitely form.
May leave a remnant weakly coupled long(-ish)-range interaction.

B. **Weakly coupled theories**
"Perturbative non-perturbative bound states", e.g. atoms.

Formation efficiency depends on the details:
(i) bound-state formation cross-section, and
(ii) thermodynamic environment
(early universe, DM halos, interior of stars)

Outline

- **Symmetric DM:** Relic density.
- **Asymmetric DM:** Self-scattering & indirect detection.

Toy model: Dark QED

Dirac fermions (χ, $\bar{\chi}$) of mass *m*, coupled to a massless dark photon γ, with dark fine-structure constant α.

Very important parameter: $\zeta = \alpha / v_{rel}$

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Annihilation

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

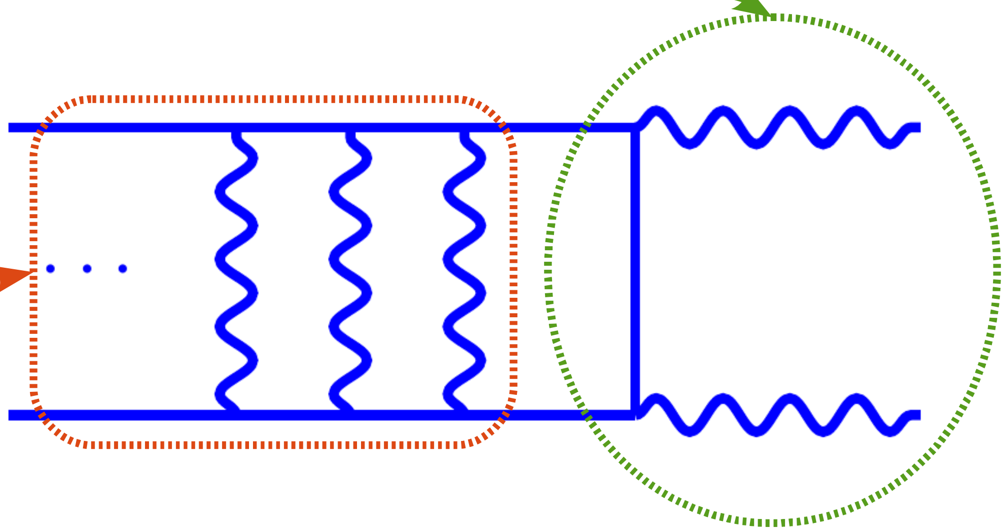
$$\sigma_{ann} v_{rel} = \sigma_0 \, S_{ann}(\zeta)$$

$$\sigma_0 = \pi \alpha^2 / m^2$$

$$S_{ann}(\zeta) = \frac{2\pi\zeta}{1 - e^{-2\pi\zeta}}$$

$$S_{ann}(\zeta \ll 1) \simeq 1$$

$$S_{ann}(\zeta \gtrsim 1) \simeq 2\pi\zeta$$



[Hisano et al. (2002);
Cirelli et al. (2005 … 2016);
Feng et al. (2009, 2010);
Slatyer et al. (2013);
Beneke et al. (2014 … 2016); ...]

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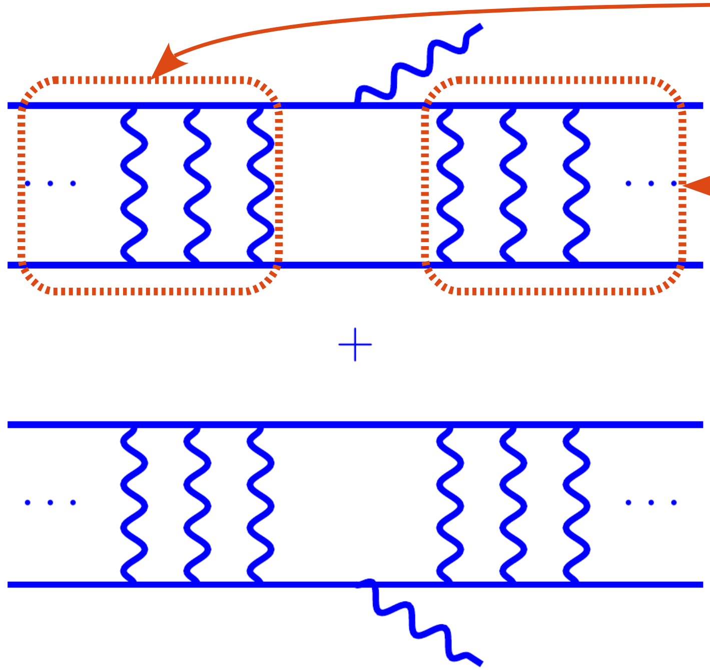

Bound state formation and decay

$$\boxed{\chi + \bar{\chi}} \rightarrow \boxed{(\chi\bar{\chi})_{bound}} + \gamma$$

$$(\chi\bar{\chi})_{bound} \rightarrow 2\gamma \quad or \quad 3\gamma$$

$$\sigma_{BSF} v_{rel} = \sigma_0 S_{BSF}(\zeta)$$

$$\sigma_0 = \pi \alpha^2 / m^2$$

$$S_{BSF}(\zeta) = \left[\frac{2^9}{3 e^{4\zeta \,\mathrm{arccot}(\zeta)}} \frac{\zeta^4}{(1+\zeta^2)^2} \right] \frac{2\pi\zeta}{1 - e^{-2\pi\zeta}}$$

$$S_{BSF}(\zeta \ll 1) \simeq \frac{2^9 \zeta^4}{3} \ll 1$$

$$S_{BSF}(\zeta \gtrsim 1) \simeq \frac{2^9}{3 e^4} \times 2\pi\zeta \simeq 3.13 \times S_{ann}$$

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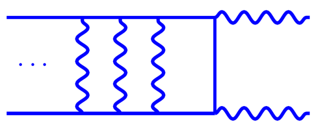

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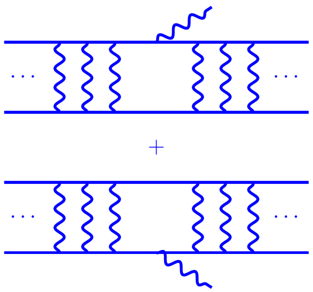

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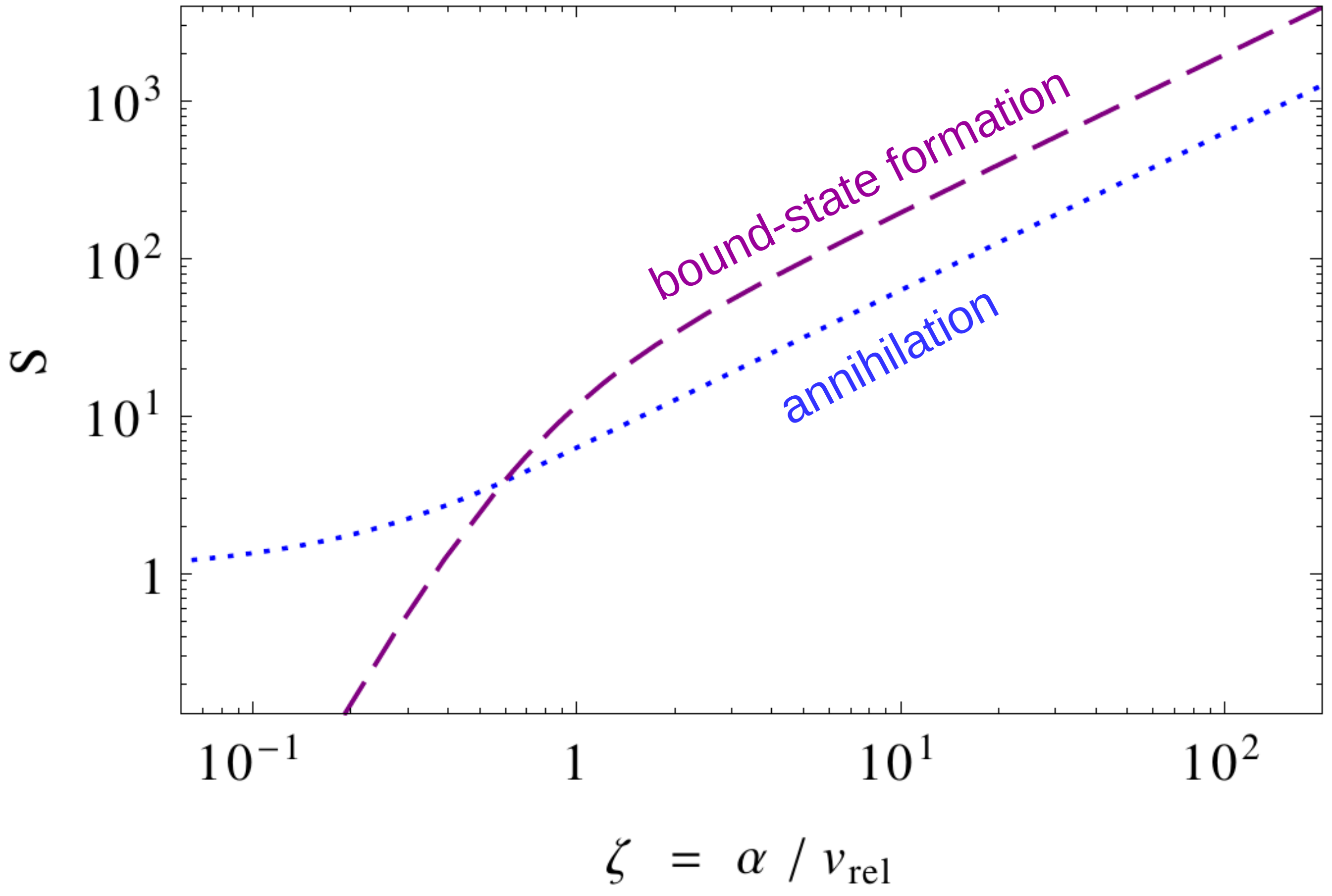


BSF dominates over annihilation everywhere the Sommerfeld effect is important (ζ > 1) !

Relic density of symmetric DM with long-range interactions

Boltzmann equations

$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\left(n_\chi^2 - n_\chi^{eq\ 2}\right)\langle\sigma_{ann} v_{rel}\rangle - n_\chi^2\langle\sigma_{BSF} v_{rel}\rangle + \left(n_{\uparrow\downarrow} + n_{\uparrow\uparrow}\right)\Gamma_{ion}$$

$$\frac{dn_{\uparrow\downarrow}}{dt} + 3Hn_{\uparrow\downarrow} = +\frac{1}{4}n_\chi^2\langle\sigma_{BSF} v_{rel}\rangle - n_{\uparrow\downarrow}\left(\Gamma_{ion} + \Gamma_{decay,\uparrow\downarrow}\right)$$

$$\frac{dn_{\uparrow\uparrow}}{dt} + 3Hn_{\uparrow\uparrow} = +\frac{3}{4}n_\chi^2\langle\sigma_{BSF} v_{rel}\rangle - n_{\uparrow\uparrow}\left(\Gamma_{ion} + \Gamma_{decay,\uparrow\uparrow}\right)$$

BSF important when $\Gamma_{decay} > \Gamma_{ion}$ (T)

$(\chi\bar{\chi})_{\uparrow\downarrow} \rightarrow 2\gamma$: $\Gamma_{decay,\uparrow\downarrow} = \alpha^5 (m/2)$

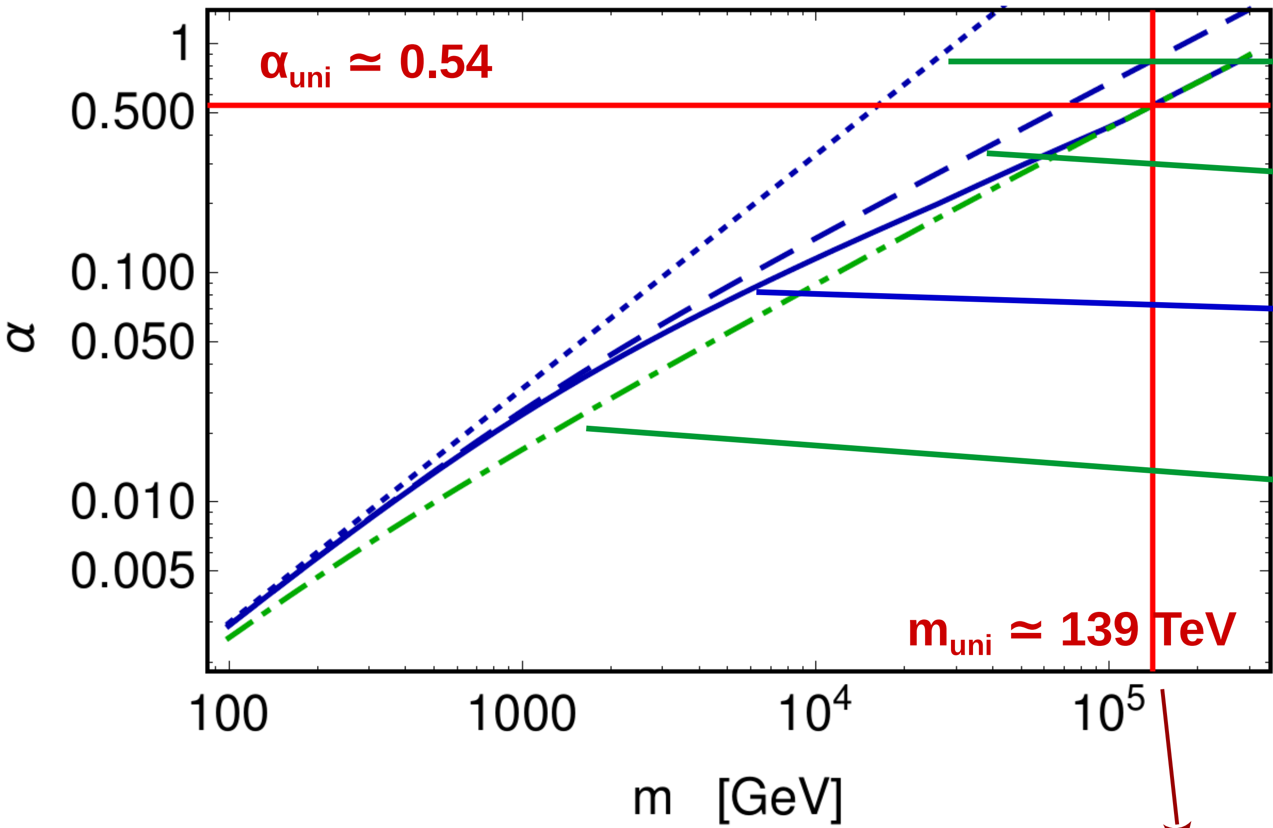
$(\chi\bar{\chi})_{\uparrow\uparrow} \rightarrow 3\gamma$: $\Gamma_{decay,\uparrow\uparrow} = \frac{4(\pi^2-9)}{9\pi}\alpha^6(m/2)$

$(\chi\bar{\chi})_{\uparrow\downarrow\text{ or }\uparrow\uparrow} + \gamma \rightarrow \chi + \bar{\chi}$: $\Gamma_{ion}(T) = \frac{2}{(2\pi)^3} 4\pi\int_0^\infty d\omega \frac{\omega^2}{e^{\omega/T}-1}\sigma_{ion}(\omega)$

related to σ_{BSF}

Determination of $\alpha(m)$ or $m(\alpha)$

To obtain the observed DM density, we need:



Perturbative annihilation.

Sommerfeld-enhanced annihilation.

Sommerfeld-enhanced annihilation and BSF.

Sommerfeld-enhanced annihilation and BSF, without ionisation.

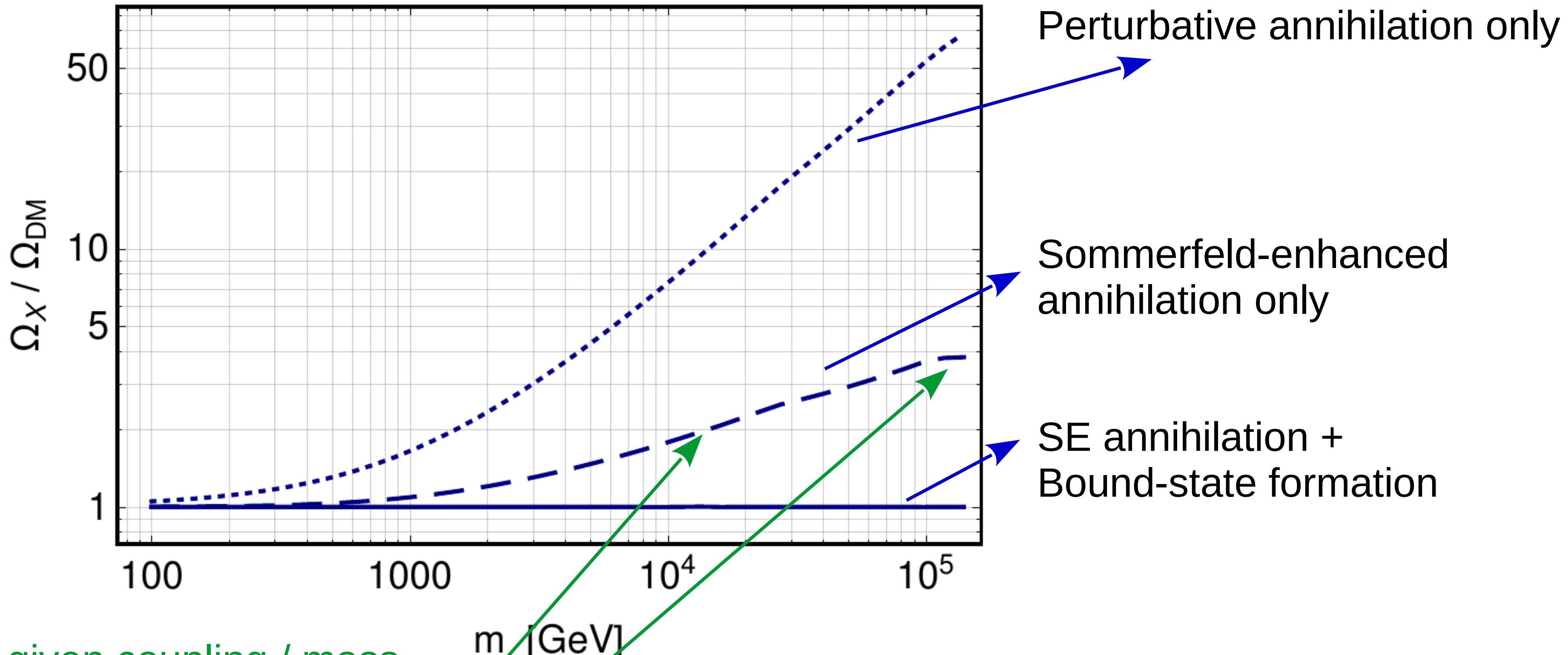
$$\sigma_{inel,J}\ v_{rel} \leqslant \frac{(2J+1)\,4\pi}{m^2\ v_{rel}}$$

[von Harling, KP (2014)]

Effect on DM relic density

Much larger than the experimental uncertainty of 1% !

α(m) determined from full analysis;
Effect of various processes on relic density



For a given coupling / mass,
SE annihilation alone results in

$\Omega_X / \Omega_{DM} \simeq 2$ @ 15 TeV

$\Omega_X / \Omega_{DM} \simeq 4$ @ 139 TeV

[von Harling, KP (2014)]

Bound states and symmetric DM
Generalisations needed

Massive mediators

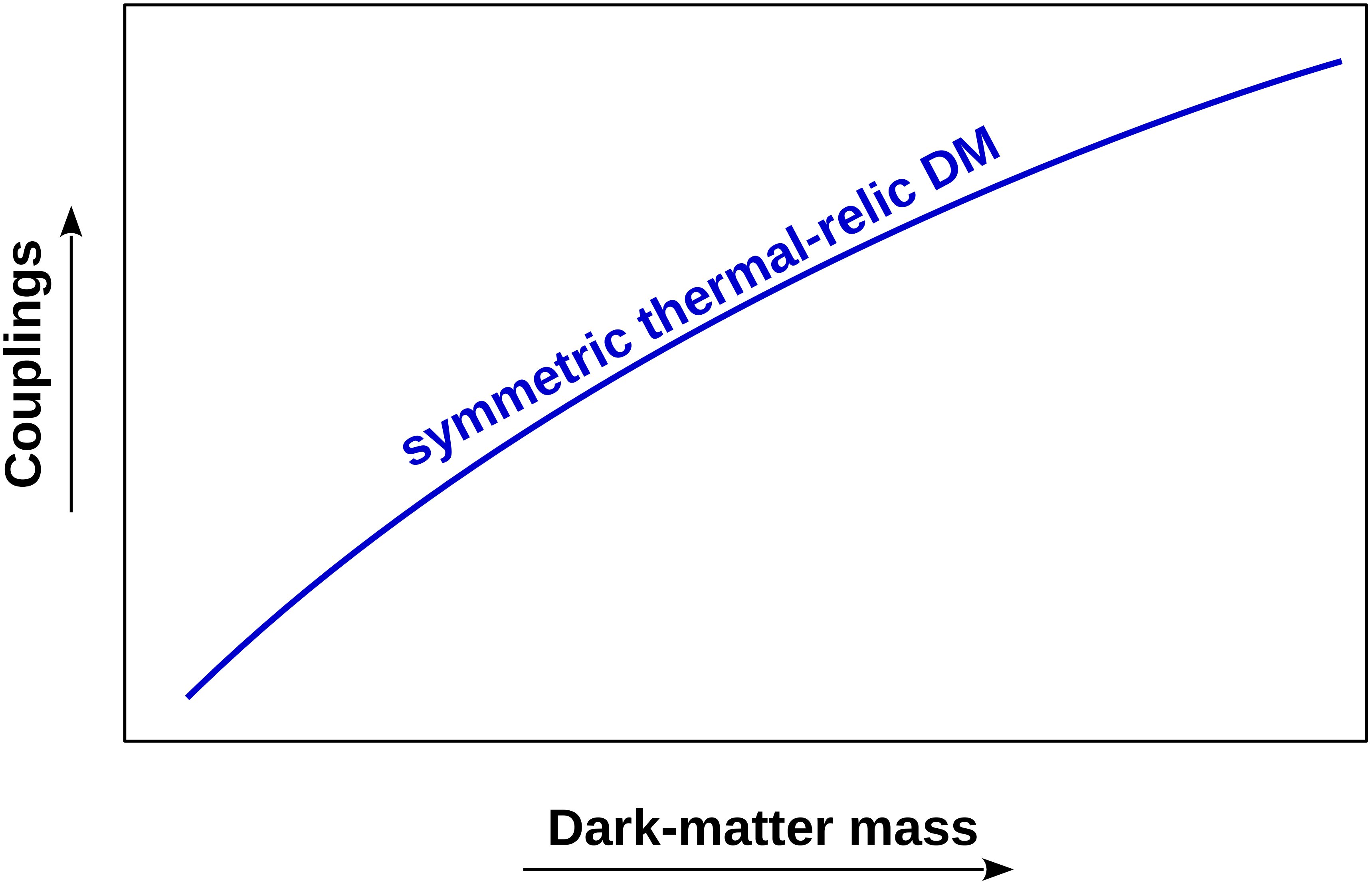
Different interactions, e.g. scalar mediator.

Non-Abelian non-confining theories, e.g. EW interactions.

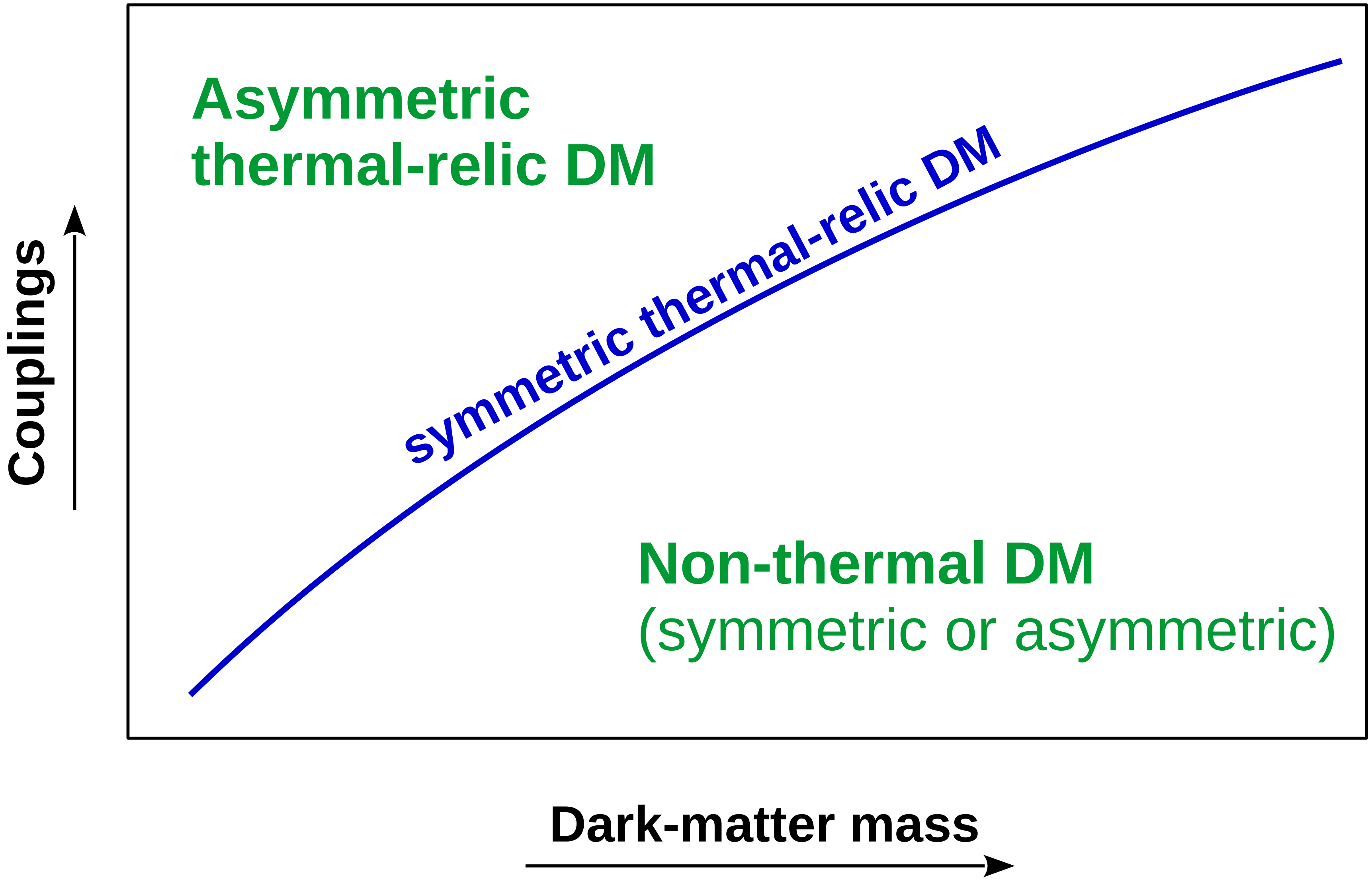
Relic density

Indirect detection

Beyond symmetric thermal-relic DM



Beyond symmetric thermal-relic DM



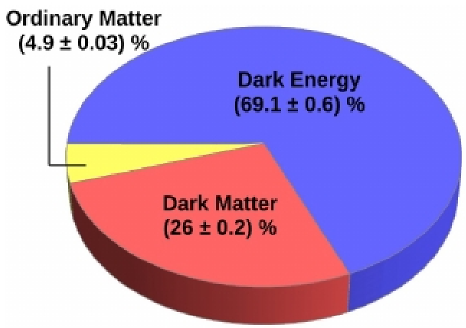
Asymmetric dark matter

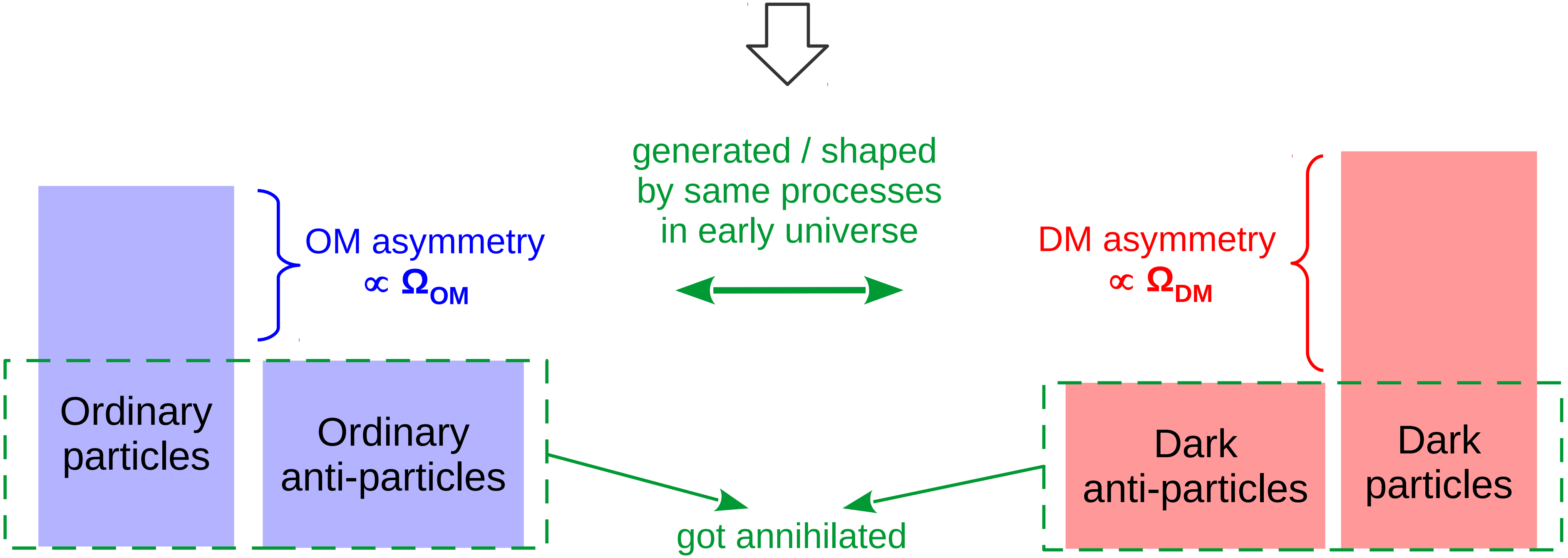
Similarity of dark and ordinary matter densities suggests a **common origin.**

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%





Asymmetric DM

DM annihilation

Need $\sigma_{ann} v_{rel} > (\sigma_{ann} v_{rel})_{\text{symmetric DM}}$

What interaction can do the job?

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

  Annihilation directly into SM particles highly constrained by colliders and direct detection.

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

Asymmetric dark matter coupled directly to light force mediators

- Efficient annihilation.
- Generic possibility.
  No conviction about dynamics of hidden sectors.
- High-energy theories.
  E.g. hidden sectors in string theory, twin Higgs models.
- Self-interacting DM.
  Motivated by observed galactic structure.

Self-interacting DM — What interaction?

$$\sigma_{\text{self-scattering}} \,/\, m_{DM} \;\sim\; \text{barn / GeV} \;\sim\; \text{cm}^2/\text{gr}$$

large!

DM coupled directly to a light or massless force mediator:

Many different kinds of interactions possible.

$$\mathcal{L} \supset g\, \varphi\, \bar{\chi}\, \chi \quad \begin{cases} \chi : \text{dark matter} \\ \varphi : \text{mediator} \\ m_\varphi \ll m_\chi \end{cases}$$

- Ensures strong enough DM self-scattering
- If mediator sufficiently light: $\sigma_{\text{self-scattering}}$ decreases with velocity [e.g. Rutherford scattering: $\sigma_{\text{self-scattering}} \propto 1/v^4$]
  - Significant effect on small halos (small velocity dispersion)
  - Negligible effect on large halos (large velocity dispersion)

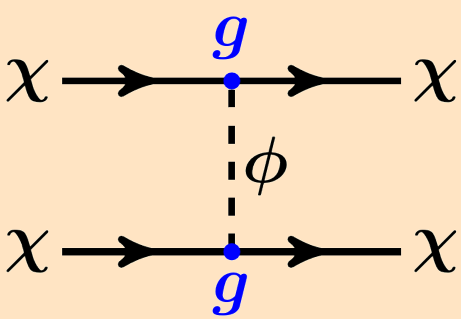
Why self-interacting *and* asymmetric?

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

$\left\{ \begin{array}{l} \chi \text{ : dark matter} \\ \varphi \text{ : force mediator} \\ m_\varphi \ll m_\chi \end{array} \right.$

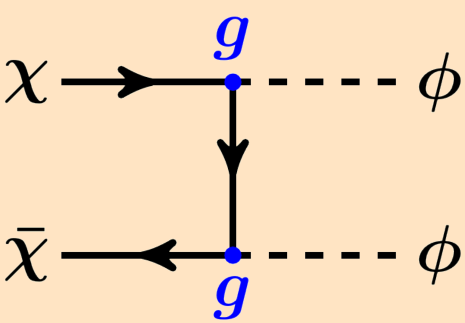
DM self-interaction

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



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 framework for self-interacting DM

Self-interacting asymmetric DM

- 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 DM

- **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.

    Bound-state formation determines decoupling of DM from dark radiation.

    Affect galactic structure.

  - 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)]

- **Calculate cosmology + phenomenology self-consistently.**

Self-interacting asymmetric DM

A minimal scenario:

Asymmetric DM coupled to a dark gauged U(1)

Vector mediator

Minimal assumptions

(i) Relic density: Particle-antiparticle asymmetry

(ii) DM couples to a gauged $U(1)_D$ [dark electromagnetism]: annihilation, self-scattering

[specific models, e.g.
KP, Trodden, Volkas 2011;
von Harling, KP, Volkas 2012;
Choquette, Cline 2015]

Vector mediator

Minimal assumptions ⇒ rich dynamics

(i) Relic density: Particle-antiparticle asymmetry

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

- Massless dark photon:
  Dark electric charge of dark protons p_D^+ compensated by dark electrons e_D^-. They can bind in dark Hydrogen atoms H_D.
- Mildly broken $U(1)_D$, light dark photon: [KP, Pearce, Kusenko (2014)]
  Similar conclusion in most of the parameter space of interest.

Vector mediator — Cosmology

Dark asymmetry generation via interactions neutral under $U(1)_D$ $\Rightarrow$ **p_D and e_D asymmetries**	$T_{asym} > m_{p_D} / 25$
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	$f_{ion} \equiv \frac{n_{p_D}}{n_{p_D} + n_{H_D}} \sim \min\left[1, \frac{10^{-10}}{\alpha_D^4} \frac{m_{p_D} m_{e_D}}{GeV^2}\right]$
[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)]

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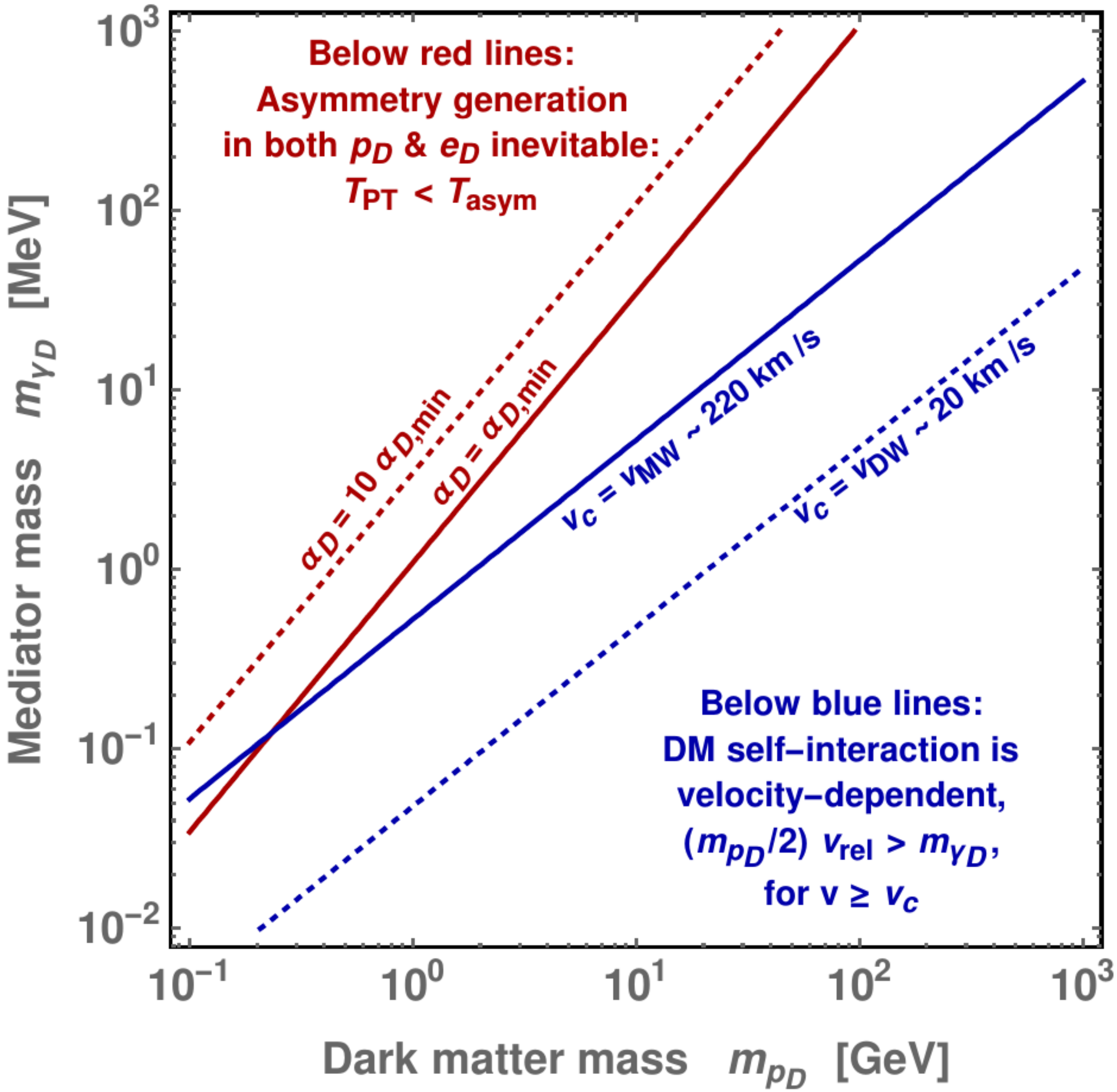
Asymmetric DM coupled to a dark photon is multicomponent (p_D , e_D), and possibly atomic (H_D) in much of the parameter space where the dark photon is light enough to mediate sizable (long-range) DM self-interactions.

[KP, Pearce, Kusenko (2014)]

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



[KP, Pearce, Kusenko (2014)]

Atomic DM Self-scattering in halos

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

$$H_D - H_D\,,\quad H_D - p_D\,,\quad H_D - e_D\,,\quad p_D - p_D\,,\quad e_D - e_D,\quad p_D - e_D$$

- Strong velocity dependence of scattering cross-sections

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

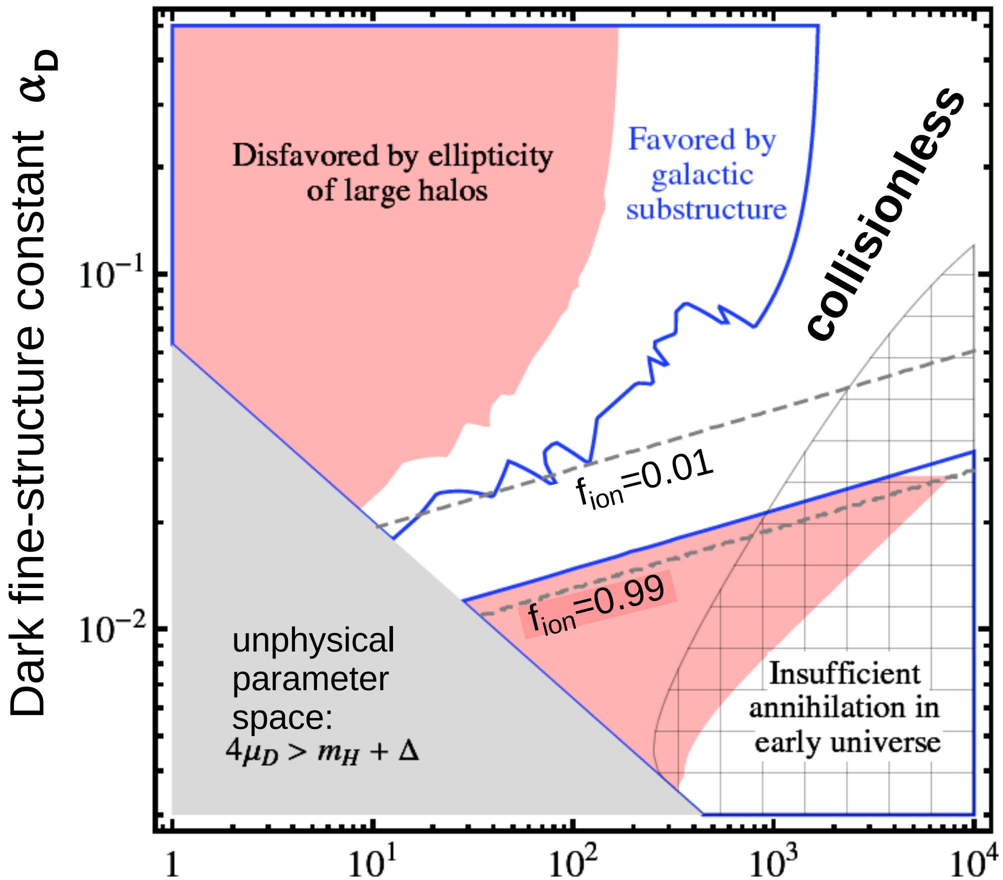
$$\sigma_{H_D-H_D} \approx (\alpha_D \mu_D)^{-2} \left[b_0 + b_1 \left(\frac{m_{H_D} v^2}{4\mu_D \alpha_D^2} \right) + b_2 \left(\frac{m_{H_D} v^2}{4\mu_D \alpha_D^2} \right)^2 \right]^{-1}$$

(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 **Δ = 0.5 MeV**
Dark photon mass $\mathbf{m_{\gamma_D}}$ **= 1 eV**



- Non-monotonic behavior in α_D, because of the formation of bound states
  ⇒No upper limit on α_D, no lower limit on m_{γ_D}
- Strong velocity dependence of scattering cross-sections allows for ellipticity constraints to be satisfied, while having a sizeable effect on small scales.
- Many 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)]

Asymmetric DM and indirect detection

The myth

No radiative signals expected,
since there are no antiparticles for DM to annihilate with.

In fact

because asymmetric DM may have
complex structure and sizable couplings to light force mediators,
radiative signals can be expected!

Level transitions invariably occur with dissipation of energy.

Pearce, Kusenko (2013); Cline et al. (2014);
Detmold, McCullough, Pochinsky (2014); Pearce, KP, Kusenko (2015)

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

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

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

[Pearce, KP, Kusenko (2015)]

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

$$H_D + H_D \rightarrow H_D + H_D^*$$

$$H_D^* \rightarrow H_D + \gamma_D$$

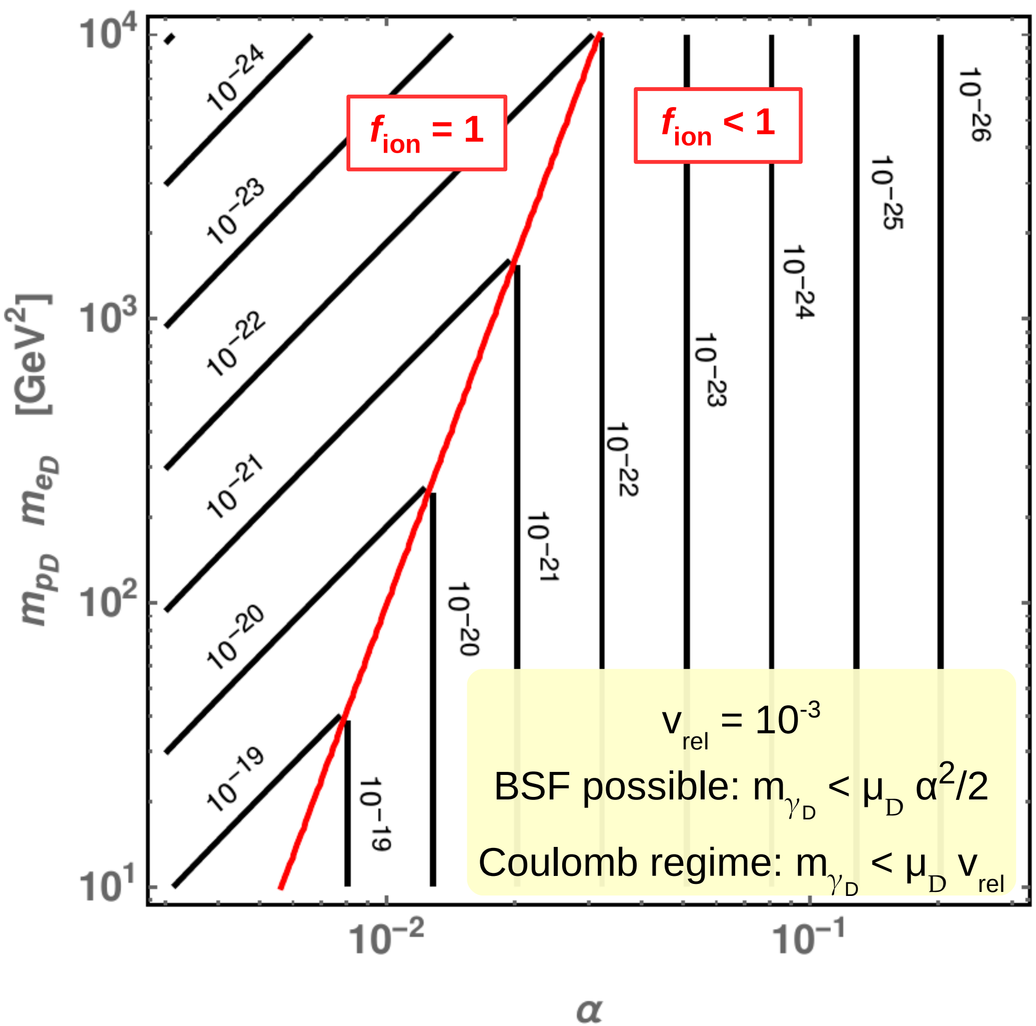
$$\gamma_D \rightarrow f_{SM}^+ \, f_{SM}^-$$

Atomic DM

Indirect detection: Dark-atom formation in halos

(1) $p_D^+ + e_D^- \rightarrow H_D + \gamma_D$ **(2)** $\gamma_D \rightarrow f_{SM} + \bar{f}_{SM}$

$$s_{BSF} \equiv \frac{x_{ion}^2 \left(\sigma_{BSF}\, v_{rel}\right)}{m_{H_D}^2} \quad \left[cm^3 \;\; s^{-1} \;\; TeV^{-2}\right]$$



[Pearce, KP, Kusenko (2015)]

Bound – state formation:

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

Annihilation of symmetric DM:

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

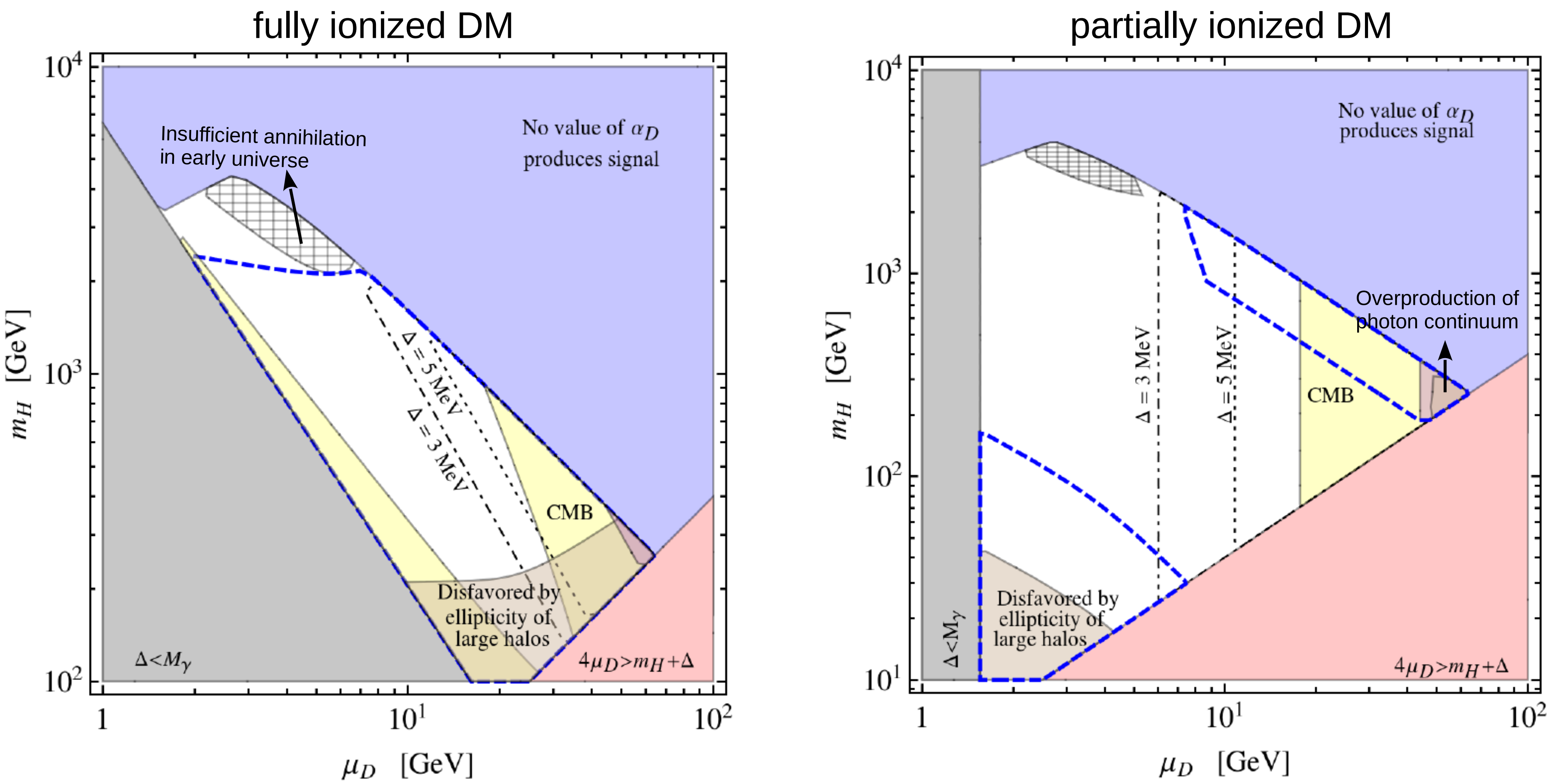
Interplay between early universe cosmology and strength of interaction →
min and max signal strength

Atomic DM

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

(1) $p_D^+ + e_D^- \rightarrow H_D + \gamma_D$ (2) $\gamma_D \rightarrow e^+ + e^-$ (3) $e^+ + e^- \rightarrow \gamma\gamma$

m_{γ_D} = 2 MeV; contracted NFW profile.



[Pearce, KP, Kusenko (2015)]

Conclusion

The early universe regulates the DM manifestations today.
For long-range interactions, the regulator is bound-state formation:

- ✗ Symmetric thermal relics:
  Reduced abundance / Lower predicted couplings.

- ✗ Asymmetric thermal relics:
  Neutralises / screens the interaction.

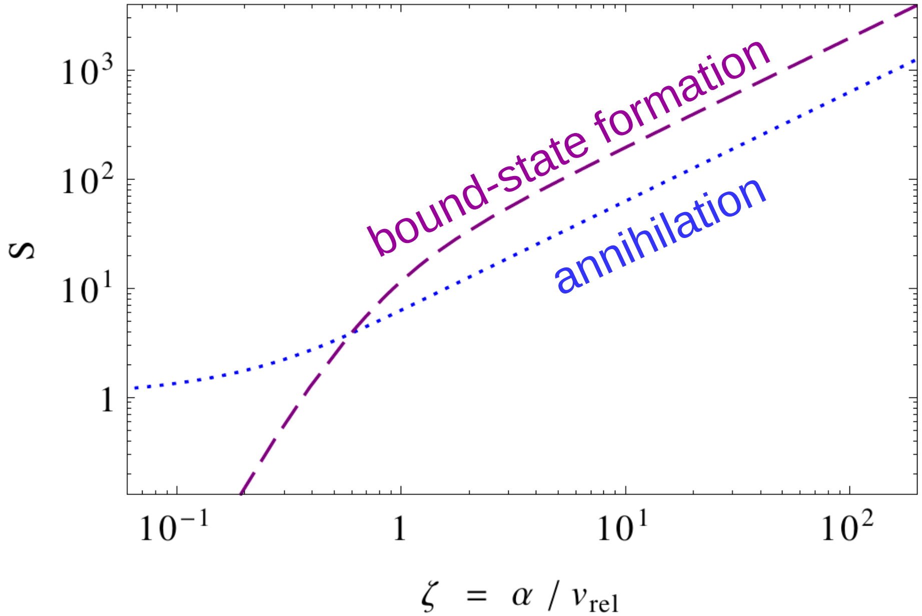
Bound-state formation ⇒ observational signatures,
e.g. indirect detection signals for symmetric and asymmetric DM.

Extra slides

Relic density of symmetric DM with long-range interactions

[von Harling, KP (2014)]

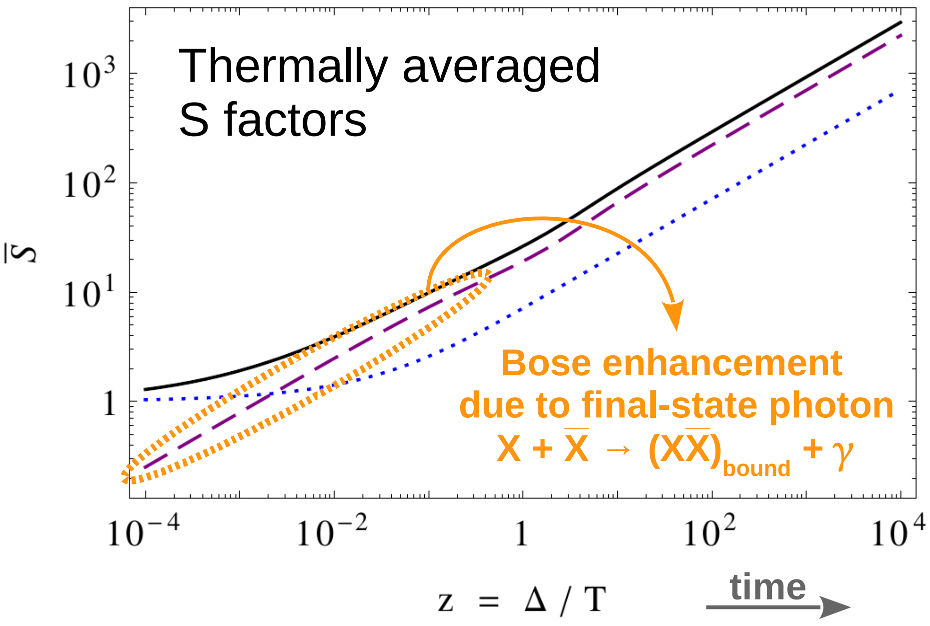
Rates



$$\zeta \equiv \frac{\textit{Bohr momentum}}{\textit{relative momentum}} = \frac{\mu\,\alpha}{\mu\, v_{rel}}$$

(reduced mass μ = m/2)

$\sigma_{BSF}\, v_{rel} > \sigma_{ann}\, v_{rel}$
everywhere the Sommerfeld effect is important (ζ > 1).



Time parameter :

$$z \equiv \frac{\textit{binding energy}\,[\Delta]}{T} \sim \frac{(1/2)\,\mu\,\alpha^2}{(1/6)\,\mu\,\langle v_{rel}^2\rangle} \sim \langle \zeta^2 \rangle$$

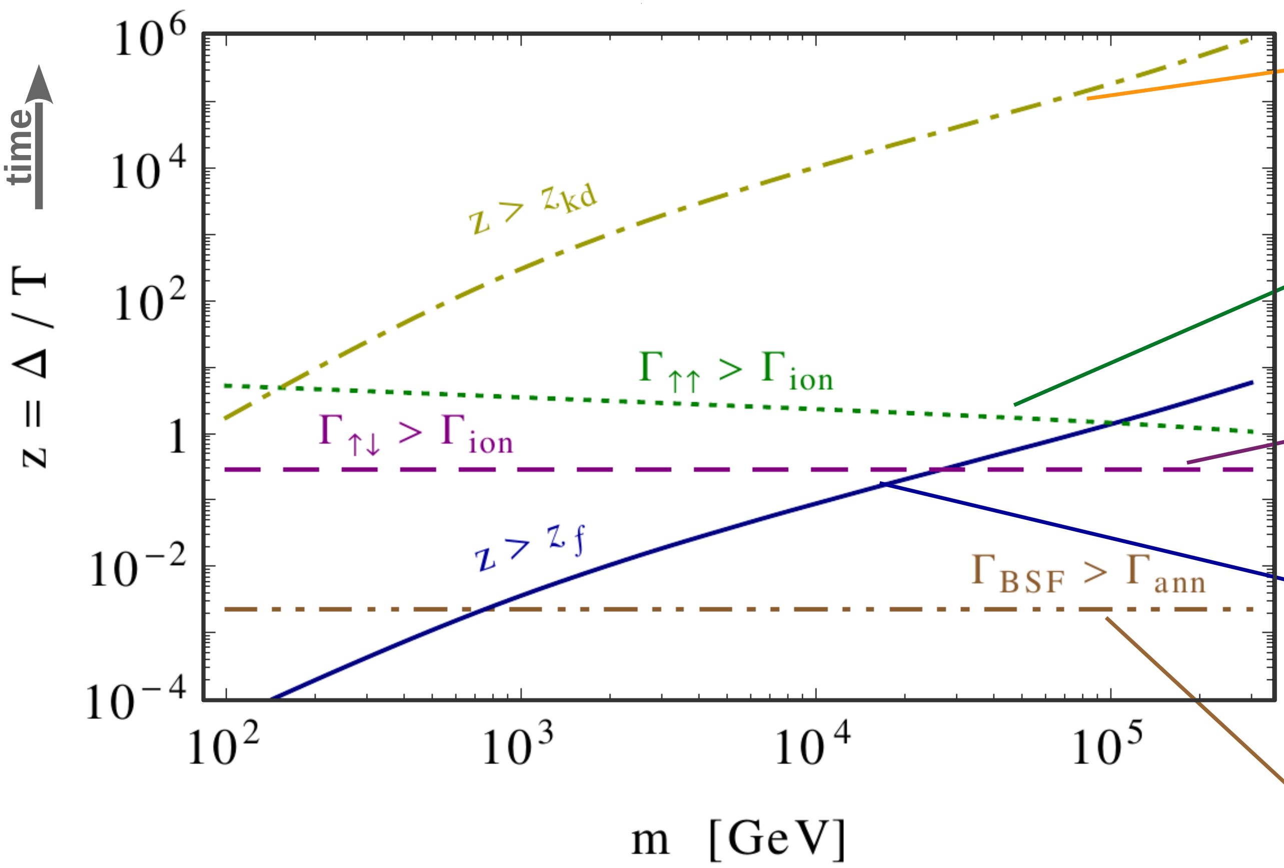
$\langle\sigma_{BSF}\, v_{rel}\rangle > \langle\sigma_{ann}\, v_{rel}\rangle$ even at $z \ll 1$,
but

BSF can deplete DM only at $z \gtrsim 1$, when disassociation of bound states becomes unimportant.

Relic density of symmetric DM with long-range interactions
[von Harling, KP (2014)]

Timeline

$\alpha = \alpha(m)$ fixed from relic abundance [see results]



Kinetic decoupling

Ortho-positronium decay faster than ionisation (z ~ 1-10, depending on m)

Para-positronium decay faster than ionisation (z=0.28)

Freeze-out:
DM density has departed from equilibrium value by O(1) factor [standard definition]

BSF becomes faster than annihilation: $z = 2.2 \times 10^{-3}$

Relic density of symmetric DM with long-range interactions

[von Harling, KP (2014)]

"Effective" enhancement