Atomic dark matter

[Self-interacting and asymmetric dark matter]

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Outline

- Challenges of collision-less cold DM
- Self-interacting DM
- Self-interacting $\cap$ Asymmetric DM
- Asymmetric DM
- Case study: **atomic dark matter**

Collisionless ΛCDM and galactic structure

- Very successful in explaining large-scale structure.
- At galactic and subgalactic scales:
  discrepancies between simulations and observations.
  - **Cusps vs cores**: predicted galactic density profiles too steep; observations better fit with cores.
  - **Missing satellites:** Too many subhaloes predicted for a galaxy of the size of the Milky Way.
  - **"Too big to fail"** [Boylan-Kolchin, Bullock, Kaplinghat (2011)]

    The largest subhaloes formed in simulations are larger than the brightest satellites, i.e. they have no observed counterpart.

    This means that star formation must have failed where it is expected to be very successful.

Collisionless ΛCDM and galactic structure

Summary: collisionless ΛCDM predicts
too rich structure at small scales

↓

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:
possible resolutions

- **Baryonic physics**
- **Observations**
- **Shift in the DM paradigm**
    - Warm DM, e.g. keV sterile neutrinos
    - **Self-interacting DM**

Small-scale galactic structure:

shift in the DM paradigm

- **At large scales:**

  no difference from ΛCDM; retain its successes.

- **At smaller scales:**

  suppress structure, in agreement with observations

  → how warm, or how self-interacting can DM be?

Self-interacting DM

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 haloes

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

to retain ellipticity of large haloes

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

Self-interacting DM

to affect dynamics of small haloes

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

to retain ellipticity of large haloes

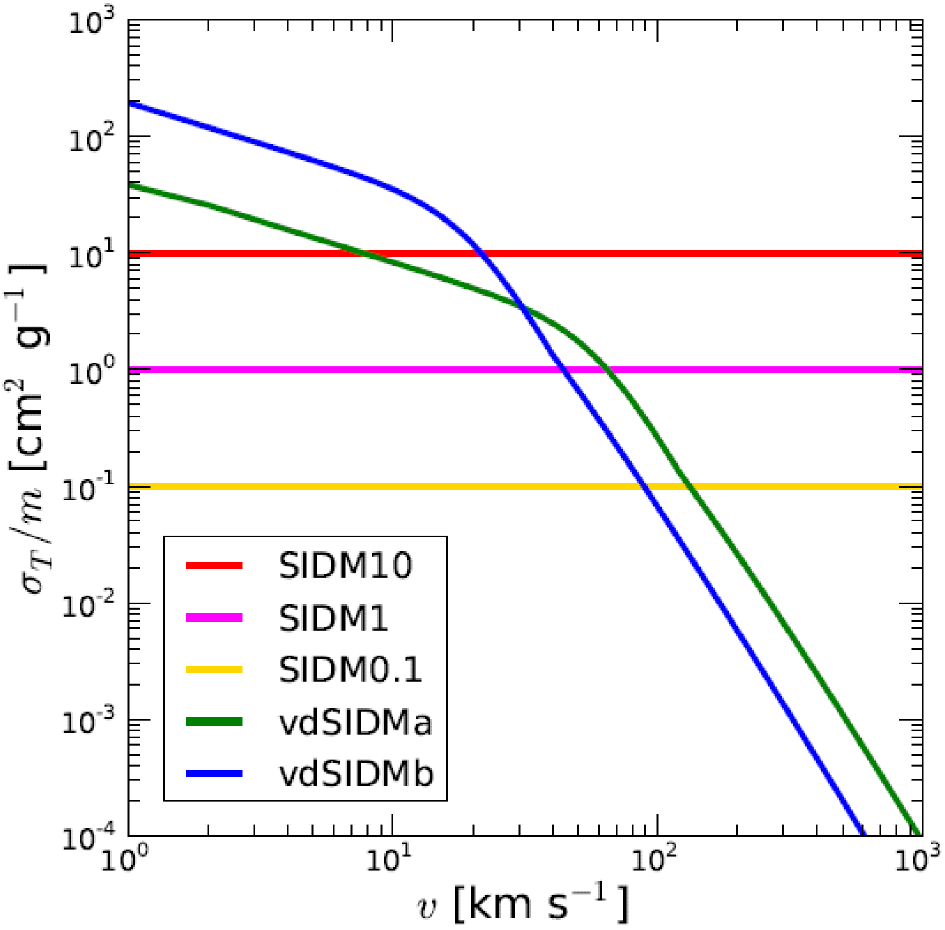
- Short-range interactions: σ_{scatt} is velocity independent; available range seems limited.
- Long-range interactions: $\boldsymbol{\sigma_{\text{scatt}} \sim 1 / v^n}$, n > 0; much larger range of possibilities
  - significant effect on small haloes (small velocity dispersion)
  - negligible effect on large haloes (large velocity dispersion)

→ Consider DM self-interactions mediated by light particles.

Self-interacting DM Simulations

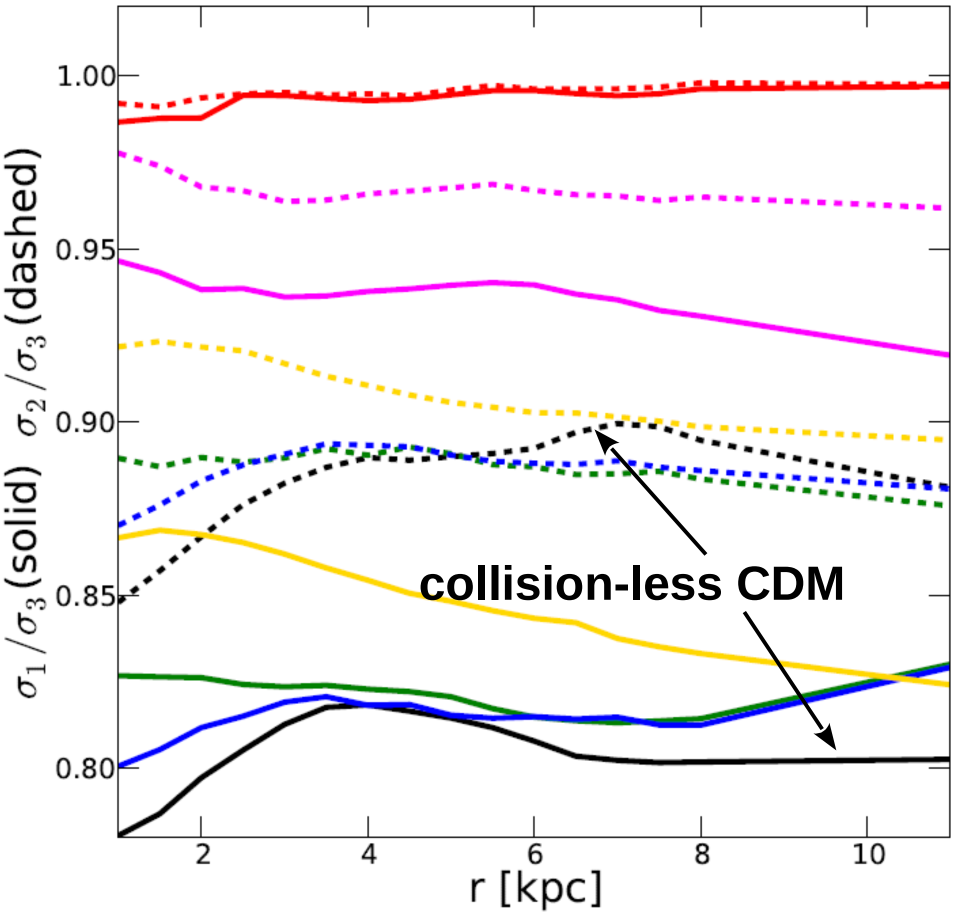
[Zavala, Vogelsberger, Walker (2012); Zavala, Vogelsberger (2012)]

Self-interaction cross-section



Ellipticity of haloes:

velocity dispersion (main halo)



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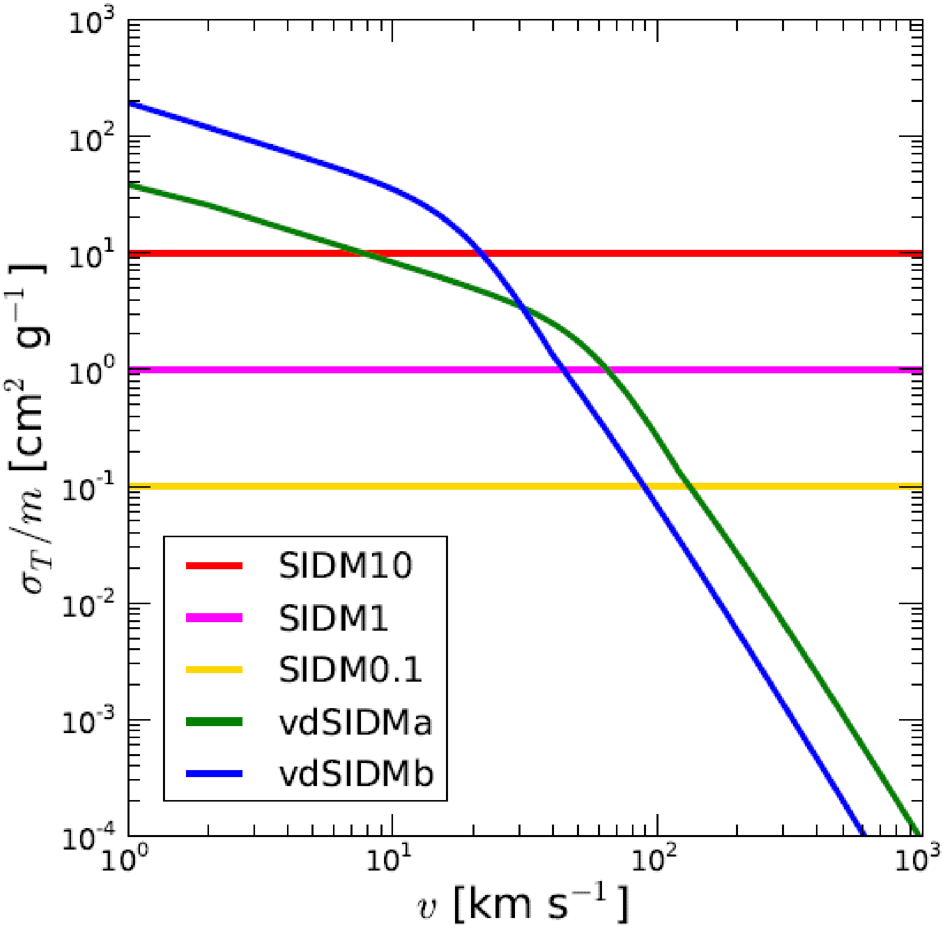
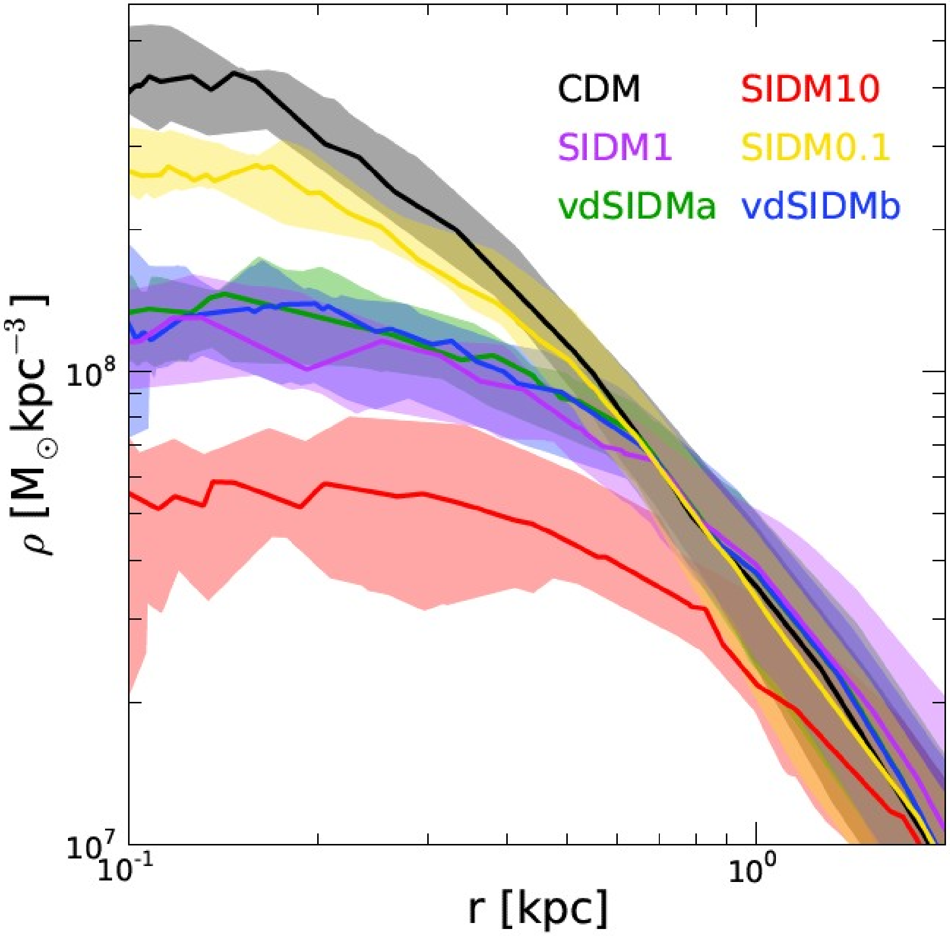


Density profiles

(15 subhaloes with largest v_{max})



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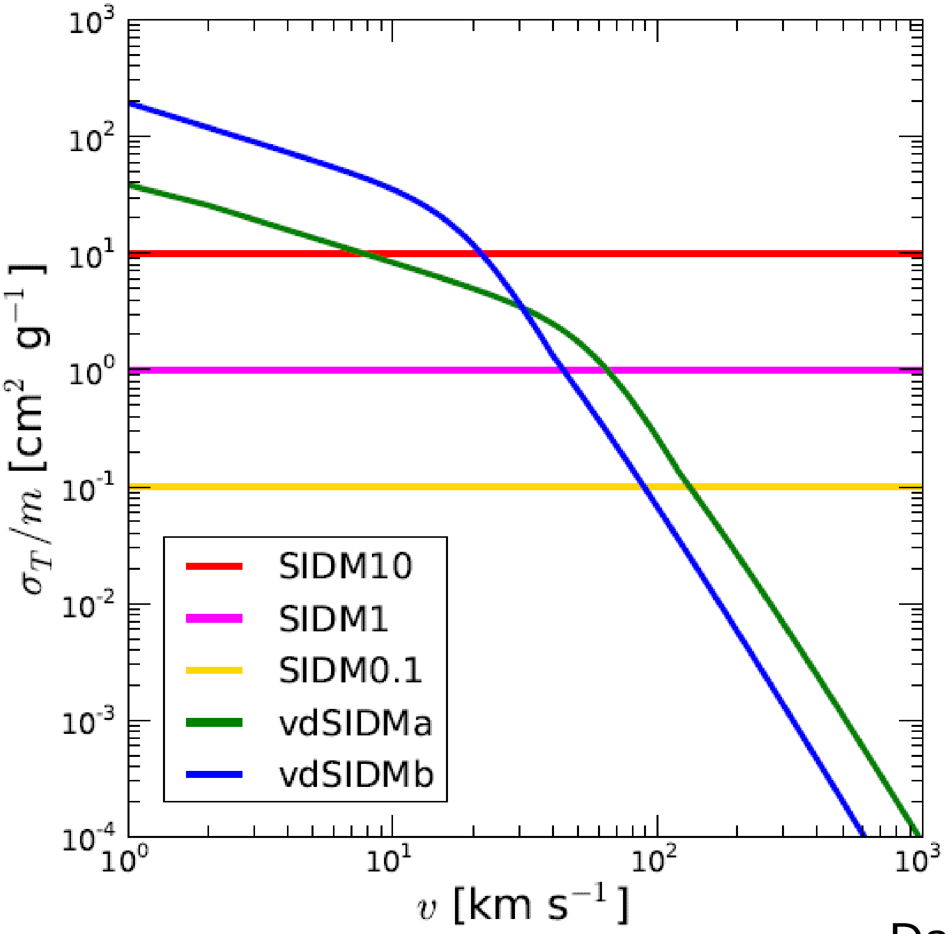
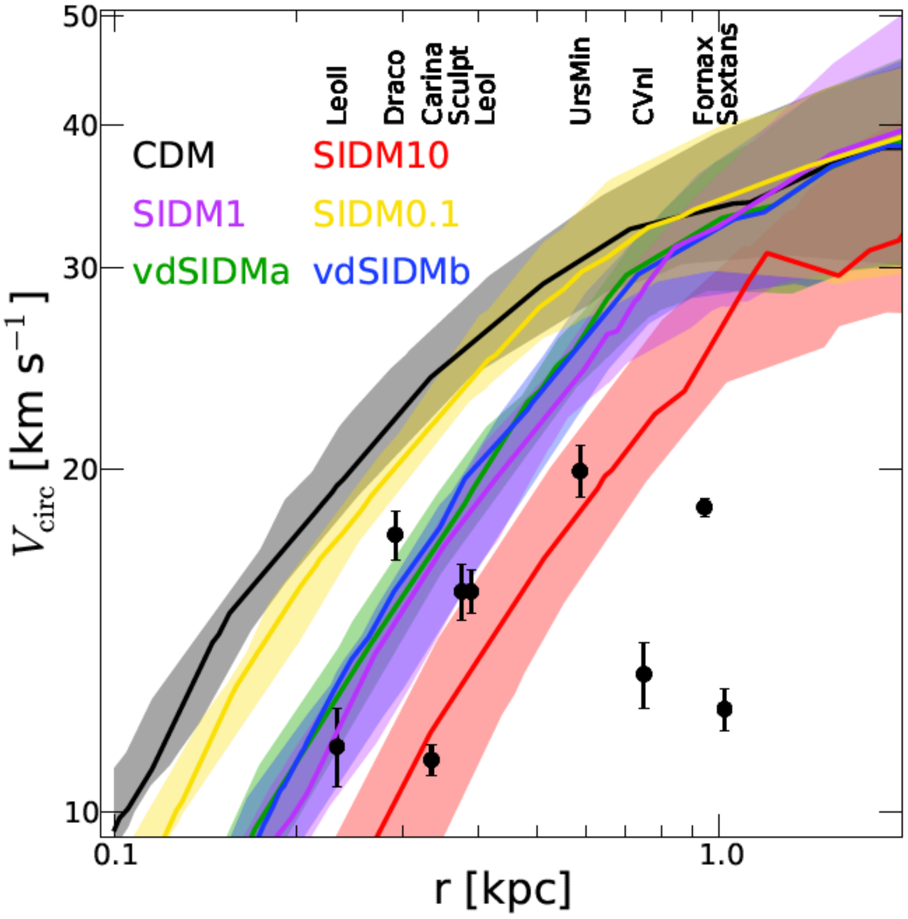


Circular velocity profiles

(15 subhaloes with largest v_{max})



Data: v_{circ} within the half-light radii for 9 MW dSphs.

Bottom right: can be fitted by lower mass subhaloes.

Self-interacting DM Simulations

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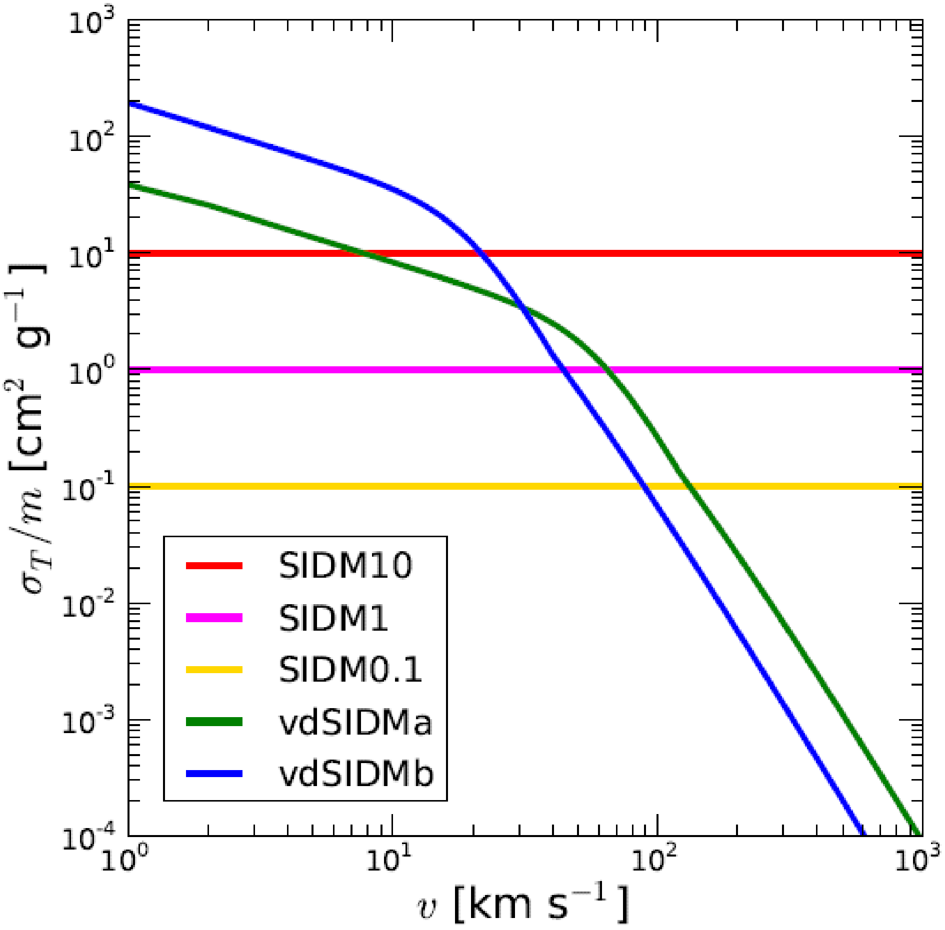
Self-interaction cross-section



Conclusion

Constant cross-section:

some tension between ellipticity constraints and cross-section required to change subhalo kinematics. Nevertheless

$$\sigma_{scatt} / m_{DM} \sim 1 \text{ barn / GeV}$$

could work (narrow range).

Velocity-dep cross-section:

satisfies ellipticity constraints and fits subhalo kinematics.

Self-interacting DM

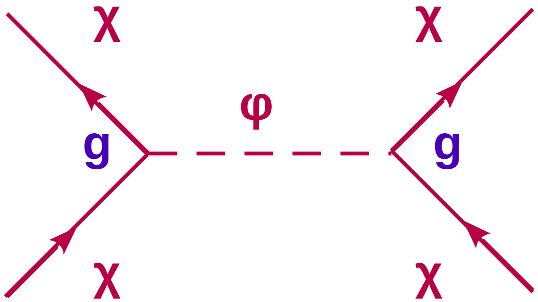
$$\mathcal{L} \supset g\, \varphi\, \bar{\chi}\, \chi$$

χ : dark matter

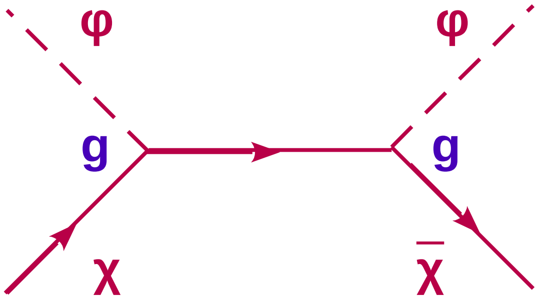
φ : mediator

$m_\varphi << m_\chi$

- **Self-interaction**



- **Annihilation**



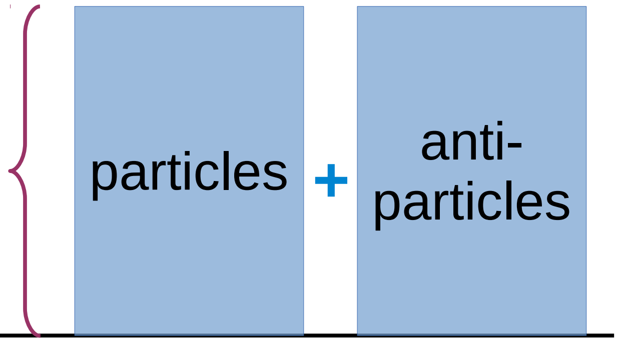
- Sizeable self-interactions via light mediators imply minimum contribution to DM annihilation; annihilation cross-section could exceed canonical value for symmetric thermal relic DM

→ consider **asymmetric DM**

Thermal relic DM

Symmetric DM

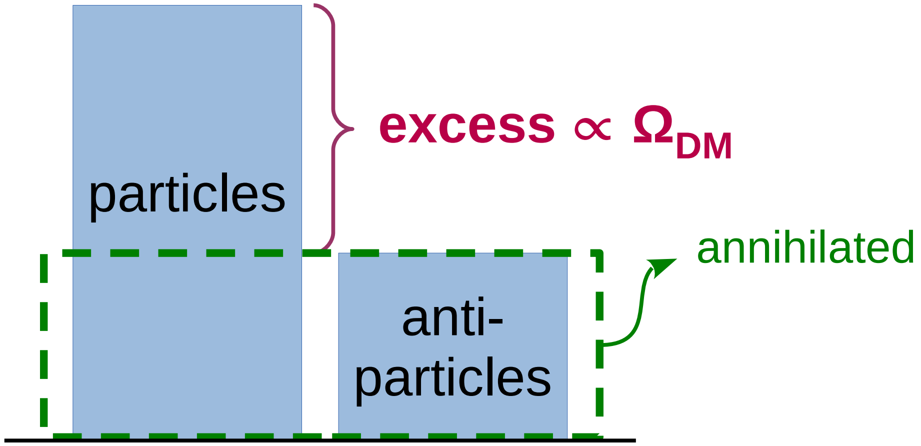
$\Omega_{DM} \propto 1 / (\sigma v)_{ann}$



$(\sigma v)_{ann} \approx 6 \times 10^{-26}\ \mathrm{cm^3/s}$

fixed value

Asymmetric DM



excess $\propto \Omega_{DM}$

$(\sigma v)_{ann} > 6 \times 10^{-26}\ \mathrm{cm^3/s}$

no upper limit

$$\text{For } \frac{(\sigma v)_{ann}}{6 \times 10^{-26}\ \mathrm{cm^3/s}} > 2 \rightarrow \frac{n(\bar{\chi})}{n(\chi)} < 5\%$$

[Graesser, Shoemaker, Vecchi (2011)]

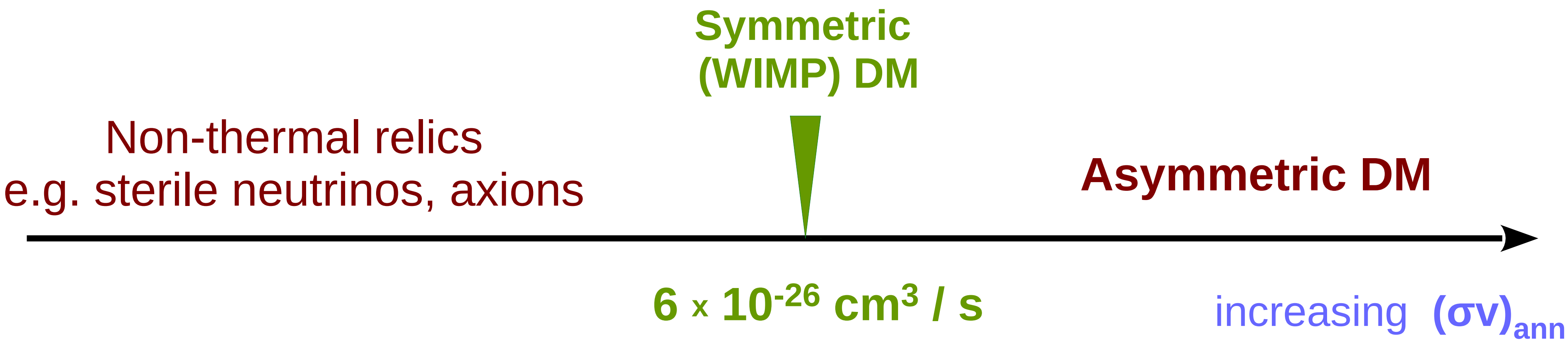
Asymmetric DM

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

(a little simplified)

Venn diagram of stable / long-lived relics

To get $\Omega_{DM} \sim 25\%$:



Symmetric (WIMP) DM

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

Asymmetric DM

$\mathbf{6 \times 10^{-26}\ cm^3 / s}$

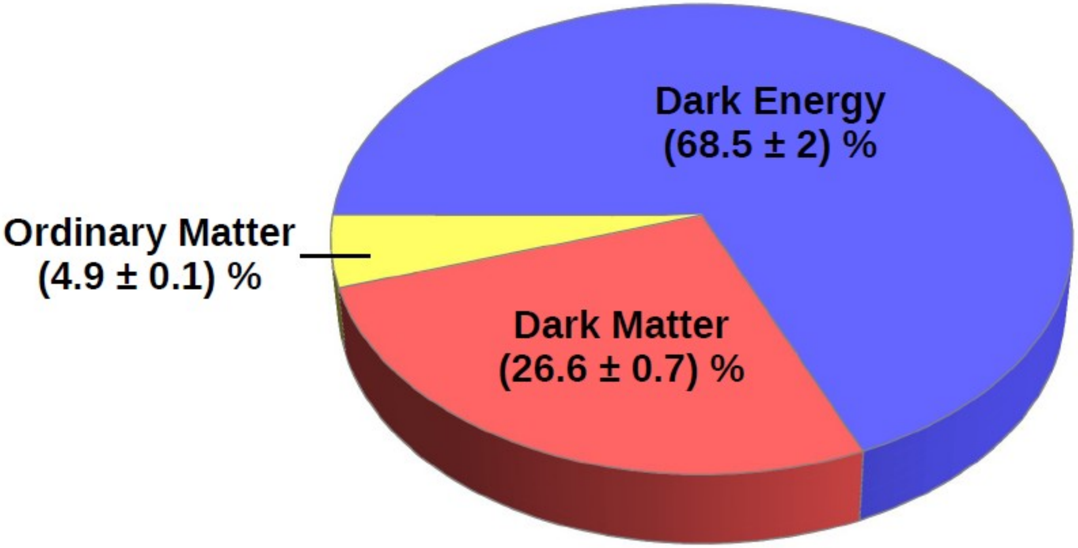
increasing $(\sigma v)_{ann}$

Asymmetric dark matter

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

a cosmic coincidence

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



- Unrelated mechanisms → different parameters → result expected to differ by orders of magnitude.
- Similarity of abundances hints towards related physics for VM and DM production.

Ordinary matter

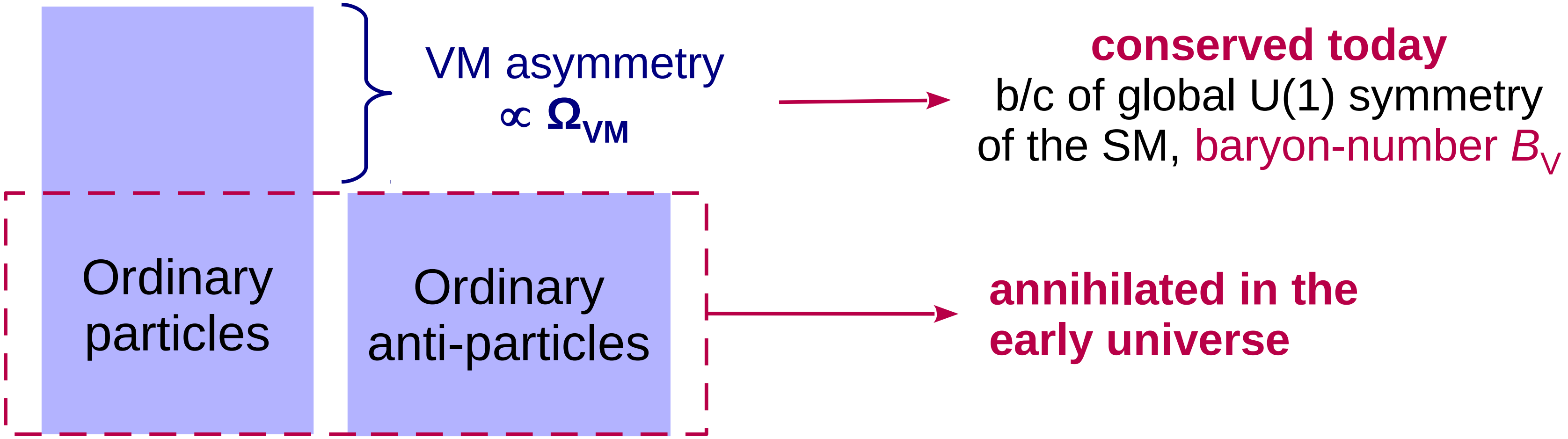
Stable particles: $p \quad e \quad \gamma \quad \nu$

- p^+ make up most of ordinary matter in the universe
- Only p^+, no p^- present today: matter-antimatter asymmetry
  - observational evidence: negligible antimatter in cosmic rays
  - theoretical consistency: $p^+ - p^-$ annihilation cross-section too large

⇒ they destroy each other too efficiently,

⇒ in an expanding universe, very few p^+ & p^- left over

⇒ deficit of antiparticles stops annihilations, excess of particles left.



VM asymmetry
$\propto \Omega_{VM}$

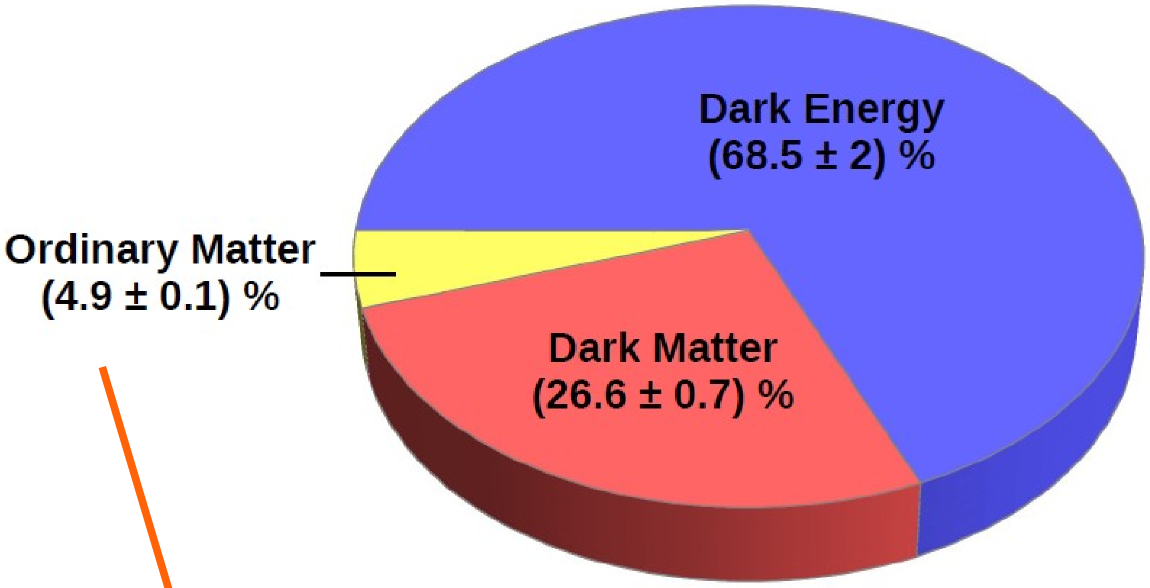
conserved today
b/c of global U(1) symmetry
of the SM, baryon-number B_V

Ordinary particles

Ordinary anti-particles

annihilated in the early universe

a non-coincidence

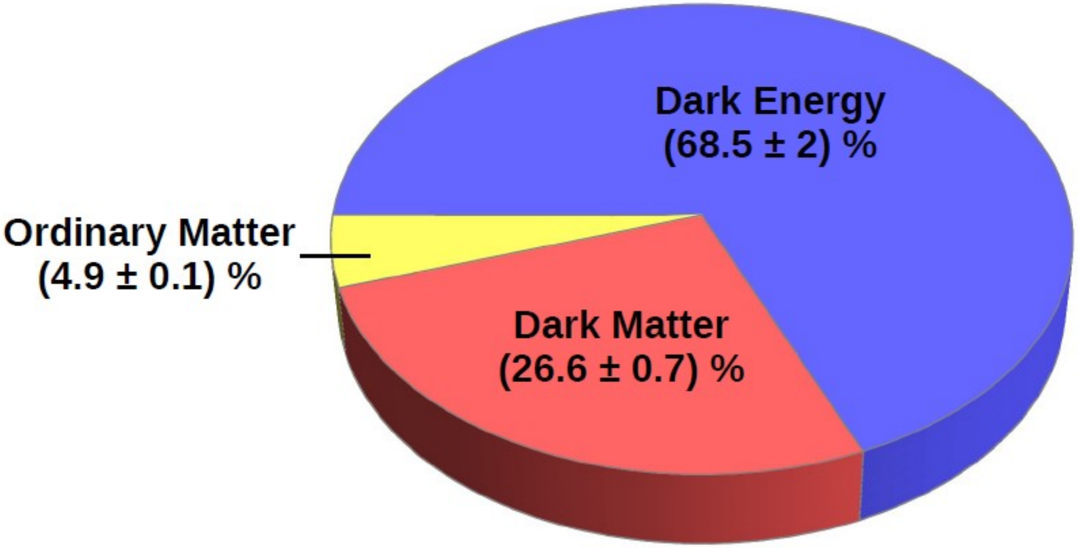


Atoms: 4.9 % → Particle-antiparticle asymmetry

Photons: 0.0022 %
Neutrinos: 0.0016 %
} Relativistic thermal relics

a cosmic coincidence

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



- Just a coincidence.

  OR

- Dynamical explanation:

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

a persisting coincidence

- Similar relic abundances $\Omega_{DM} \sim \Omega_{VM}$ → asymmetric DM

- Sub-galactic structure currently explained better by self-interacting DM with

  $$\sigma_{scatt} / m_{DM} \sim 1 \text{ barn /GeV} \sim \sigma_{nn} / m_n$$

  rather than by collisionless DM

- Tentative/unconfirmed direct-detection signal [DAMA], for DM mass

  $$m_{DM} \sim \text{few GeV} \sim m_n = \text{GeV}$$

a persisting coincidence

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connection between dark and ordinary matter microphysics ?

a persisting coincidence

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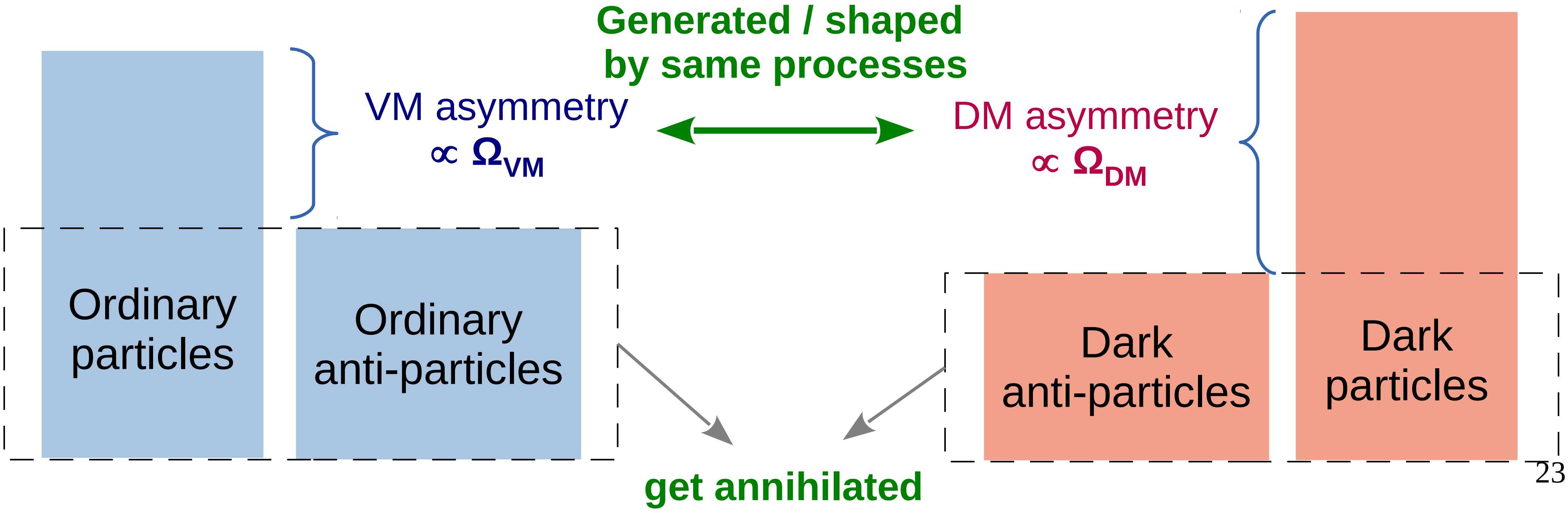
connection between dark and ordinary matter microphysics ?

Asymmetric DM

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

The hypothesis

- DM relic abundance due to an excess of dark particles over antiparticles (asymmetry).
- Dark asymmetry related to the BAU dynamically, by processes which occurred in the early universe.
- Dark and visible asymmetries conserved separately today.



Asymmetric DM

[Review of asymmetric dark matter;
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Ingredients

- Low-energy theory
  - (accidental) global U(1) symmetry, “dark baryon number, $\boldsymbol{B_D}$”, conserved independently of $\boldsymbol{B_V}$
  - Interaction which annihilates thermal symmetric population of DM: $(\sigma v)_{ann} > 6 \times 10^{-26}$ cm^3/s
- High-energy theory

  Joint violation of $\boldsymbol{(B\text{-}L)_V}$ and $\boldsymbol{B_D}$

[e.g. Nussinov (1985); Kaplan (1992); Foot, Volkas (2003); Farrar, Zaharijas (2004); Hooper, March-Russell, West (2005); Agashe, Servant (2005); Suematsu (2006); Gudnason, Kouvaris, Sannino (2006); Kitano, Low (2006); Kaplan, Luty, Zurek (2009); Davoudiasl et al. (2010); Buckley Randall, (2010); Kaplan, Krnjaic, Rehermann, Wells (2011); Bell, Shoemaker, KP, Volkas (2011); KP, Trodden, Volkas (2011); von Harling, KP, Volkas (2012); Servant, Tulin (2013); Baldes, Bell, KP, Volkas (2014)]

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Asymmetric DM

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DM annihilation

- Need $(\sigma v)_{ann} > 6 \times 10^{-26}\ cm^3/s$
- $\bar{\chi}\,\chi \rightarrow$ **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:

  - ✗ $\varphi\varphi \rightarrow$ SM SM : metastable mediators decaying into SM
  - ✗ φ stable light species: extra radiation

  e.g. dark photon (possibly massive with kinetic mixing to hypercharge), or a new light scalar.

Asymmetric DM

[Review of asymmetric dark matter;
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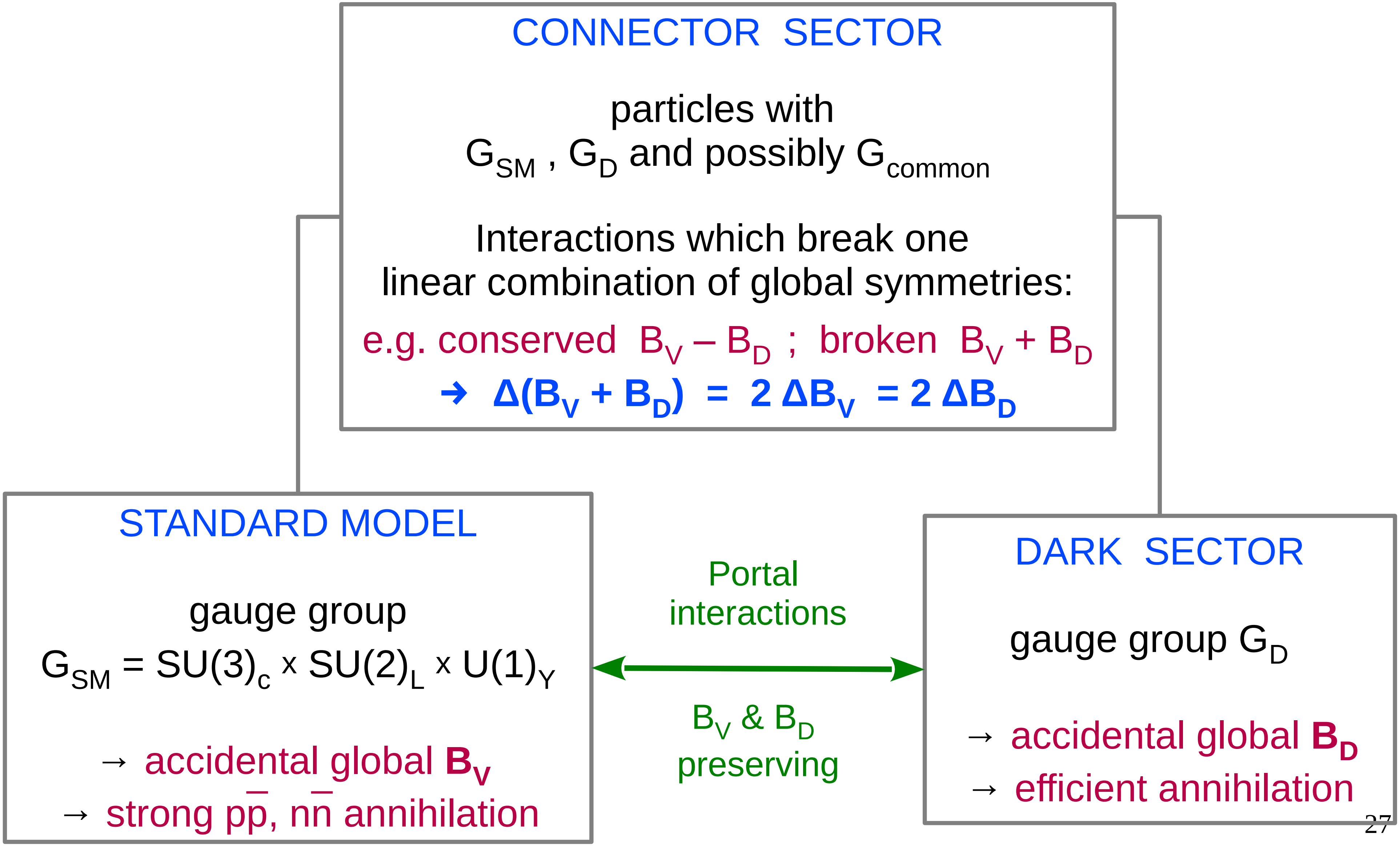
Structure



CONNECTOR SECTOR

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

Interactions which break one
linear combination of global symmetries:

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

→ $\Delta(B_V + B_D) = 2\,\Delta B_V = 2\,\Delta B_D$

STANDARD MODEL

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

→ accidental global **B_V**
→ strong $p\bar{p}$, $n\bar{n}$ annihilation

Portal
interactions

B_V & B_D
preserving

DARK SECTOR

gauge group G_D

→ accidental global **B_D**
→ efficient annihilation

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

Asymmetric dark matter with long-range self-interactions

- 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

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

- However, typically reality is more complicated for asymmetric DM with long-range interactions.

Asymmetric dark matter with long-range self-interactions

- **Involved cosmology**
  - ⊃ Formation of bound states in the early universe
- **Rich phenomenology.** Could involve
  - Multi-component DM with a variety of intra- and inter-species interactions in haloes today.
  - Direct and indirect detection signals with rich structure.

  Necessitates studying the preceding cosmology
- Delineate possibilities (classes of models), study cosmo+pheno self-consistently

A minimal asymmetric
and self-interacting DM model:

atomic dark matter

A minimal asymmetric and self-interacting DM model

- Dark interaction: **gauged $U(1)_D$**
  - Efficient annihilation in the early universe, into “dark photons”
  - Dark photons mediate DM self-scattering in haloes today
  - Contributes to structural complexity in the dark sector
    → global $U(1)_{B_D}$ in the low-energy effective theory

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- Gauge invariance mandates DM be **multi-component**:
  - massless dark photon [analogous to ordinary matter]:

    $U(1)_D$ charge carried by **(dark) protons** must be compensated by opposite gauge charge carried by **(dark) electrons.**
  - 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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A minimal asymmetric and self-interacting DM model

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

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

$$\delta L_{\text{low}} = L_{SM} + \overbrace{\bar{p}_D\,(i\not{D} - m_p)\,p_D + \bar{e}_D\,(i\not{D} - m_e)\,e_D + (\varepsilon/2)\,F_{Y\,\mu\nu}\,F_D^{\mu\nu}}^{\text{accidental global } \mathbf{(B\text{-}L)_V} \;\&\; \mathbf{B_D}}$$

Direct / Indirect detection

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

preserves $B_{gen} = (B\text{-}L)_V - B_D$
breaks $X = (B\text{-}L)_V + B_D$

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)]

A minimal asymmetric and self-interacting DM model

Dark relic constituents

- Dark protons $\boldsymbol{p_D}$ (no $\bar{p}_D$), with mass $\boldsymbol{m_p}$
- Equal number of dark electrons $\boldsymbol{e_D}$ (no $\bar{e}_D$), with mass $\boldsymbol{m_e}$
- Dark Hydrogen atoms $\boldsymbol{H_D}$ = bound states of $\boldsymbol{p_D}$ & $\boldsymbol{e_D}$, with mass $\boldsymbol{m_H = m_p + m_e - \Delta}$, where $\Delta = \alpha_D^2 \mu_D /2$ = binding energy, and $\mu_D = m_p m_e /(m_p + m_e)$.

A minimal asymmetric and self-interacting DM model

Cosmology

Dark asymmetry generation	$T_{asym} > m_p / 25$
Freeze-out of annihilations $\bar{p}_D\, p_D \to \gamma_D\, \gamma_D$ & $\bar{e}_D\, e_D \to \gamma_D\, \gamma_D$	$T_{FO} \approx m_{p,e} / 30$
Dark recombination, $p_D + e_D \to H_D + \gamma_D$	$\Delta / 50 < T_{recomb} < \Delta$, Δ = binding energy = $\alpha_D^2\, \mu_D / 2$
Residual ionisation fraction	$x_{ion} \equiv \frac{n_p}{n_p + n_H} \sim min\left[1, 10^{-10} \frac{m_p m_e}{\alpha_D^4\, GeV^2}\right]$
[If dark photon massive] Dark phase transition	$T_{PT} \sim m_\gamma / (8\pi\alpha_D)^{1/2}$

t

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

Atomic DM with a light massive dark photon

- Asymmetry generation in both $\boldsymbol{p_D}$ and $\boldsymbol{e_D}$ if $T_{\mathrm{asym}} > T_{\mathrm{PT}}$

$$m_\gamma < (8\pi\alpha_D)^{1/2}\ m_p / 25$$

- $\boldsymbol{p_D}$ and $\boldsymbol{e_D}$ interact via an attractive Yukawa potential.

  Bound states exist if $m_\gamma < 1 / a_B = \mu_D\, \alpha_D$.

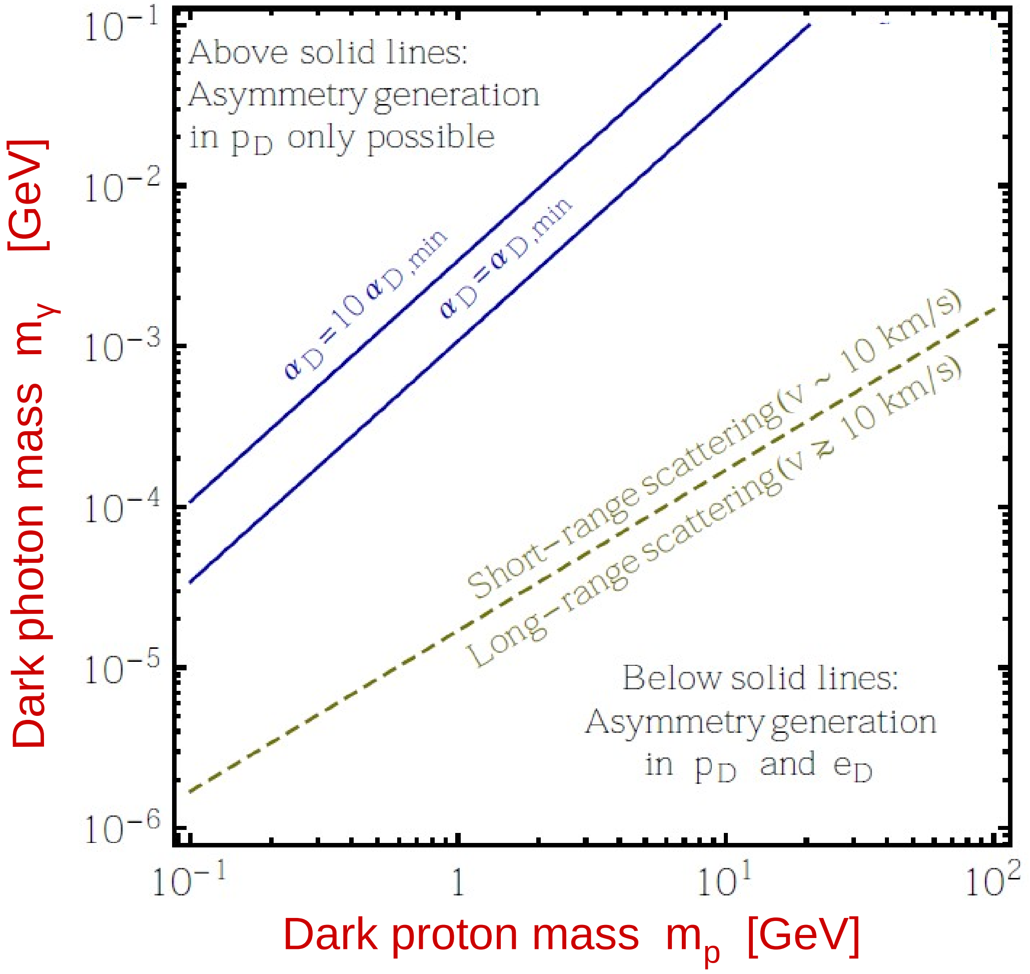
  Bound states can form radiatively, $p_D + e_D \rightarrow H_D + \gamma_D$, if

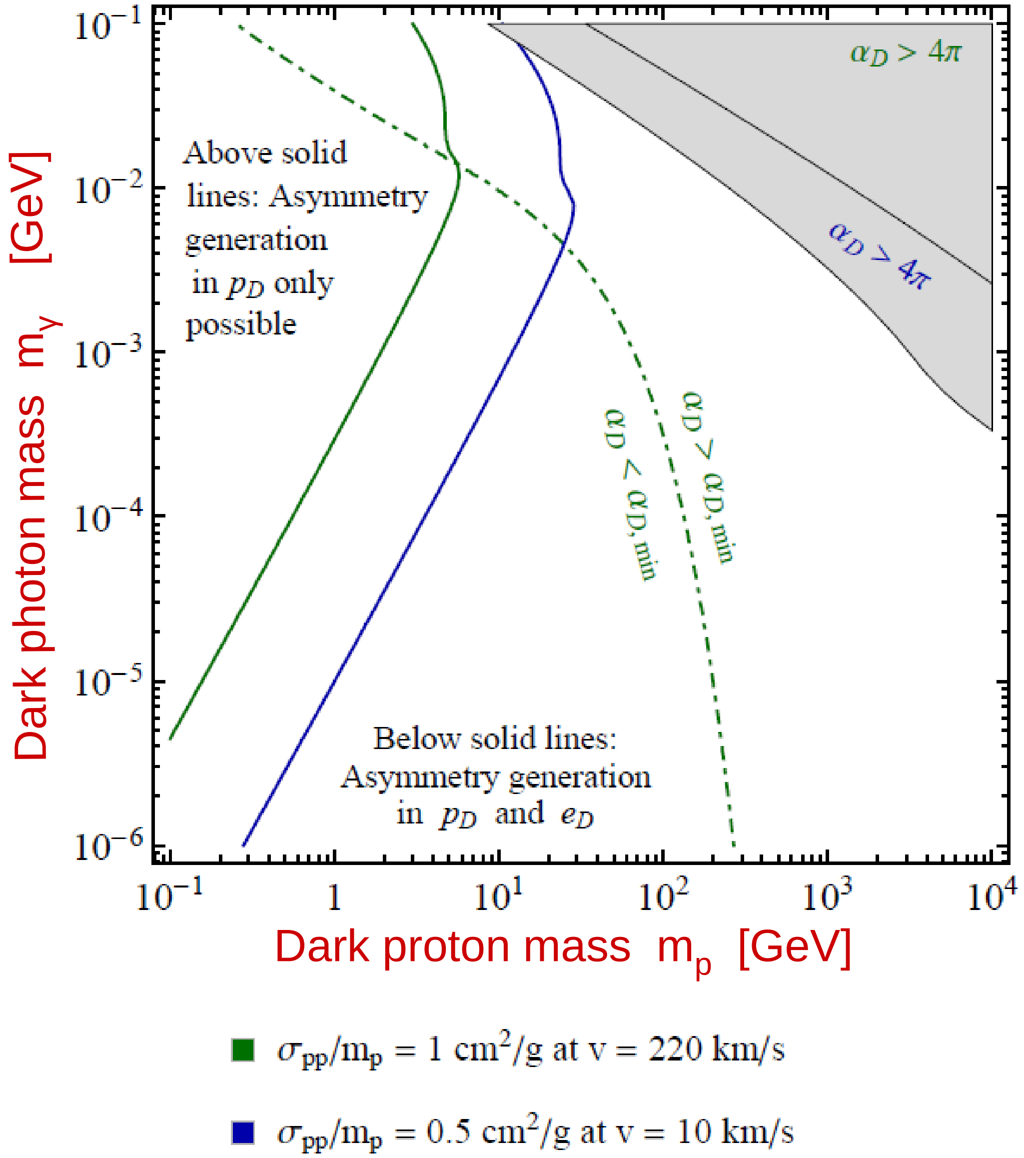
$$m_\gamma < \Delta = (1/2)\ \mu_D\ \alpha_D^2$$

- Dark recombination happens as for $m_\gamma = 0$, if $T_{\mathrm{end\ rec}} > T_{\mathrm{PT}}$

$$m_\gamma < (8\pi\alpha_D)^{1/2}\ [\ (1/2)\ \mu_D\ \alpha_D^2 / 50]$$

[KP, Pearce, Kusenko (2014)]





[KP, Pearce, Kusenko (2014)]

Atomic DM with a light massive dark photon

Asymmetric DM coupled to a dark photon is **atomic** in much of the parameter space where the dark photon is light enough to mediate sizeable (long-range) DM self-interactions

(i.e. not easy to avoid bound state formation)

[KP, Pearce, Kusenko (2014)]

Self-interactions of atomic DM

- Multicomponent 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

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

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

(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 in haloes

Find the parameter space where DM self-scattering

- preserves ellipticity of large haloes; for single-component DM:

  σ/m_{DM} < 2 barn / GeV @ v > 200 km/s

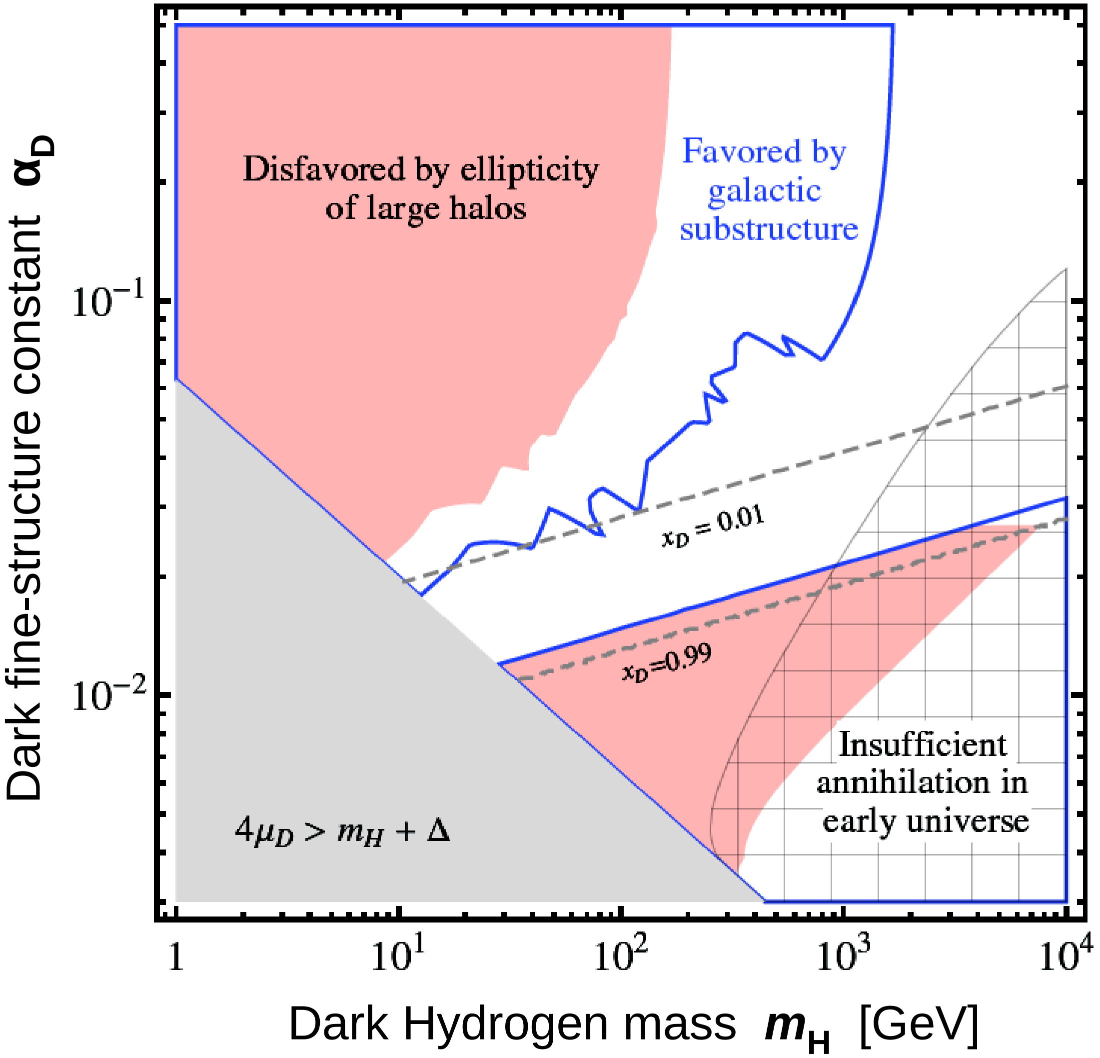
- affects smaller halo dynamics; for single-component DM:

  σ/m_{DM} > 1 barn / GeV @ v ~ 10 km/s

- Atomic DM is multi-component, bounds not directly applicable
  → appropriate average over various components

Binding energy **Δ = 0.5 MeV**

Dark photon mass **m_γ = 1eV**

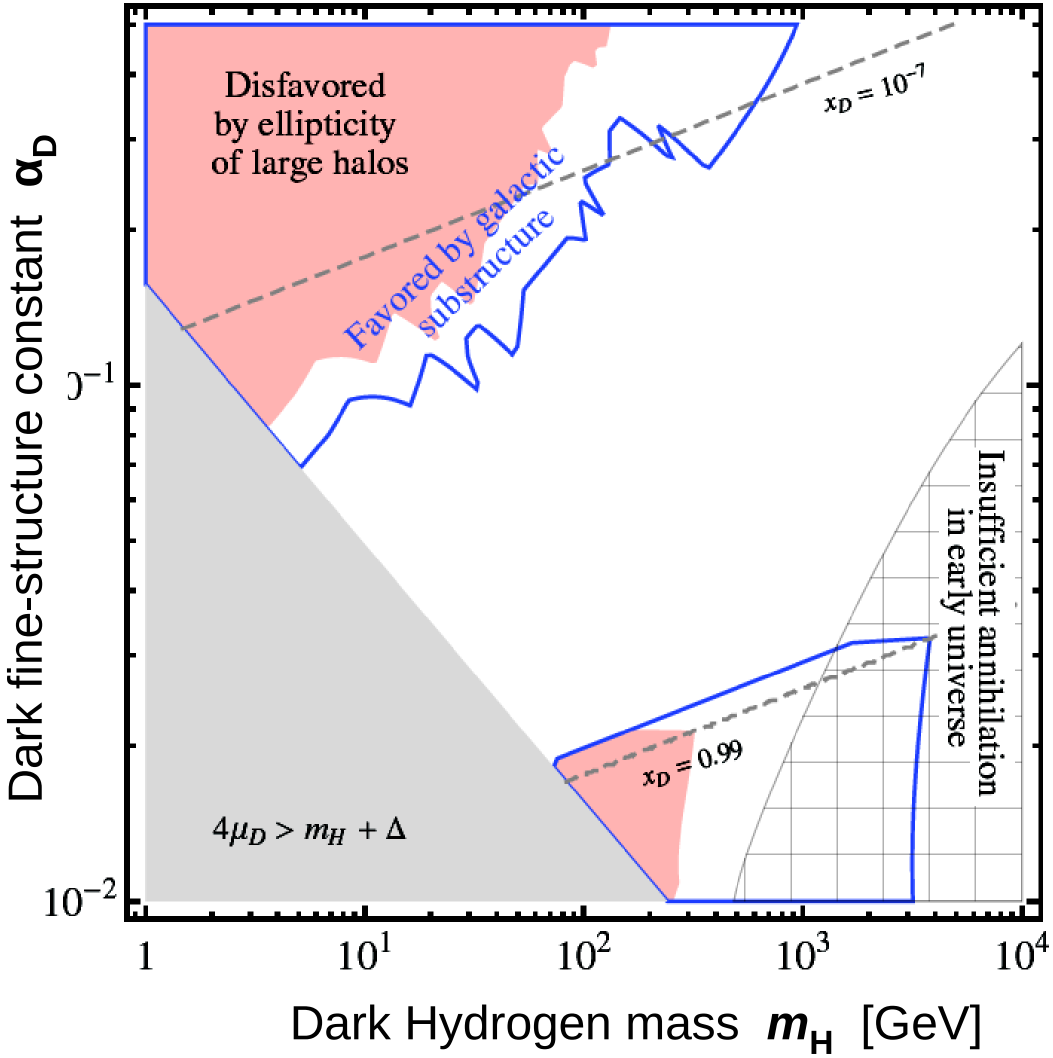


[KP, Pearce, Kusenko (2014)]

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

Binding energy **Δ = 3 MeV**

Dark photon mass **m_γ = 1 MeV**



[KP, Pearce, Kusenko (2014)]

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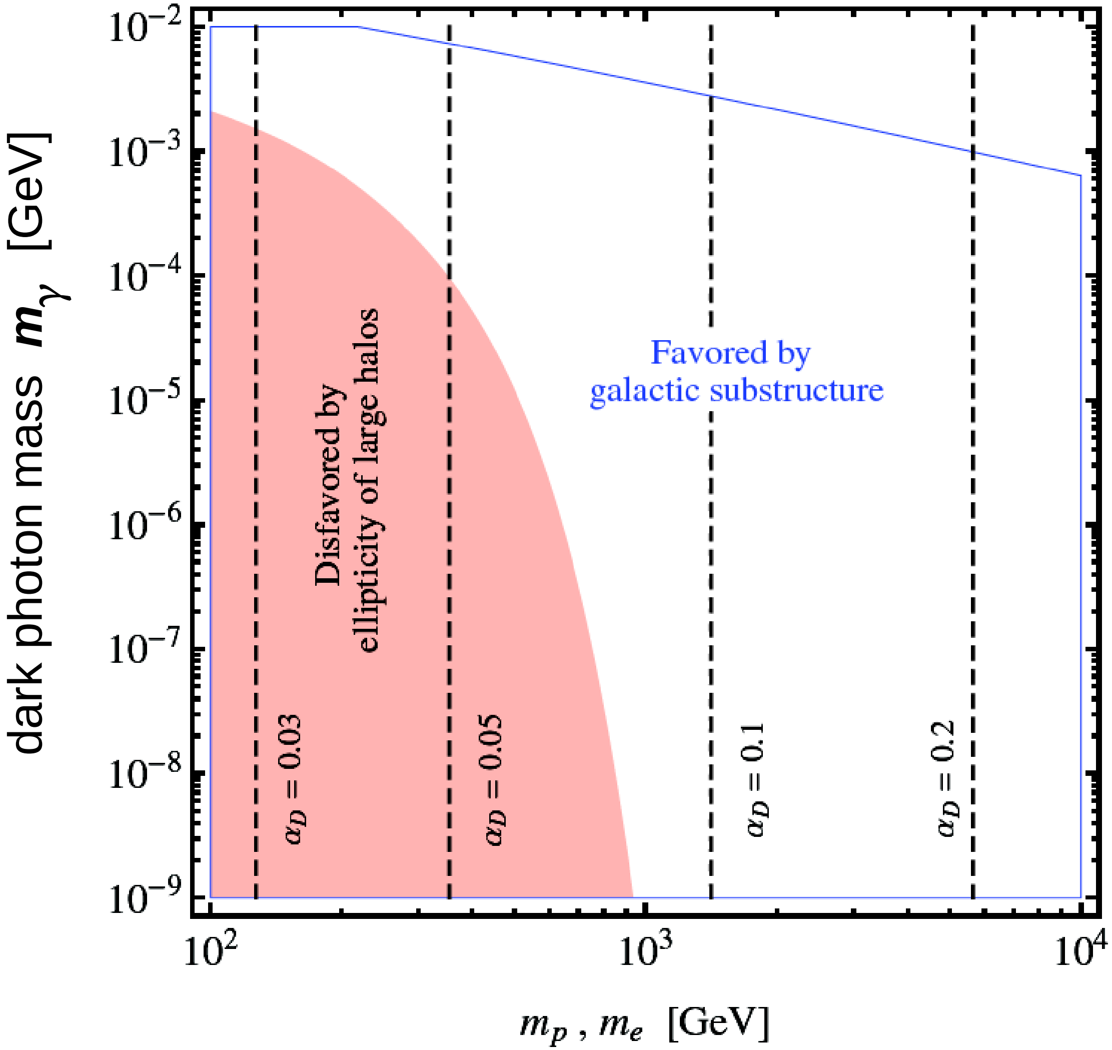
ionisation fraction **x_{ion} = 0.6**

dark proton mass m_p = dark electron mass m_e



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

[KP, Pearce, Kusenko (2014)]

Extensions

1) Detection prospects of atomic DM: $\delta\mathcal{L} = (\varepsilon/2)\, F_Y\, F_D$

- Indirect detection signals with rich structure, e.g.
  - bound-state formation in the galaxy today from ionised component

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

$$\gamma_D \rightarrow e^+ e^- \qquad \text{(for } m_\gamma > 1 \text{ MeV)}$$

[KP, Pearce, Kusenko (in preparation)]

  - level transitions (dark Hydrogen excitations)

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

[Along similar lines: Frandsen et al. (2014) , Cline et al. (2014)]

Extensions

1) Detection prospects of atomic DM: $\delta\mathcal{L} = (\varepsilon/2)\, F_Y\, F_D$

- Direct detection involving processes with different kinematics
  - ✗ elastic scattering of p_D, e_D, H_D on the target,

    and inelastic scattering of H_D (excitation or break-up)
  - ✗ contact-type and long-range DM-nucleon interactions,

    depending on the incident DM particle, screening scale (dark photon mass / Bohr radius), recoil energy.

[Frandsen, Kouvaris, KP, Shoemaker (in progress)]

Extensions

2) Consider other types of long-range interactions.

- DM interactions mediated by a scalar boson:
  always attractive → large bound states.

- Non-Abelian confining theories

DM bound states and cosmology
– the symmetric DM case

DM bound states and cosmology – the symmetric DM case

- Non-relativistic freeze-out of symmetric thermal relics:

$$\sigma_{ann}\, v_{rel} = \sigma_0 = 6 \times 10^{-26}\ cm^3/s$$

- If DM is heavy or mediator is light

$$(m_{DM} / 2)\, v_{rel} > m_{mediator}$$

→ Sommerfeld effect:

$$\sigma_{ann}\, v_{rel} = \sigma_0 \frac{2\pi\alpha / v_{rel}}{1 - \mathrm{Exp}[-2\pi\alpha/v_{rel}]} \longrightarrow \sim \alpha/v_{rel} \ @ \ \text{large } \alpha/v_{rel}$$

→ Can affect freeze-out, indirect detection [see explanations of Pamela/AMS positrons]

DM bound states and cosmology – the symmetric DM case

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- If DM is heavy or mediator is light

$$(m_{DM} / 2)\, v_{rel} > m_{mediator}$$

At freeze-out $v_{rel} \sim 0.3$;
Holds for $m_{WIMP} > 1$ TeV

→ Sommerfeld effect:

$$\sigma_{ann}\, v_{rel} = \sigma_0 \frac{2\pi\alpha / v_{rel}}{1 - \mathrm{Exp}[-2\pi\alpha/v_{rel}]} \longrightarrow \sim \alpha/v_{rel} \quad @ \quad \text{large } \alpha/v_{rel}$$

→ Can affect freeze-out, indirect detection [see explanations of Pamela/AMS positrons]

DM bound states and cosmology – the symmetric DM case

- Long-range attractive interactions → bound states.

Consider e.g. Dirac fermions **X**, coupled to *massless* dark photons $\gamma_{\mathbf{D}}$

annihilation: $\mathbf{X} + \bar{\mathbf{X}} \rightarrow \gamma_{\mathbf{D}}\ \gamma_{\mathbf{D}}$

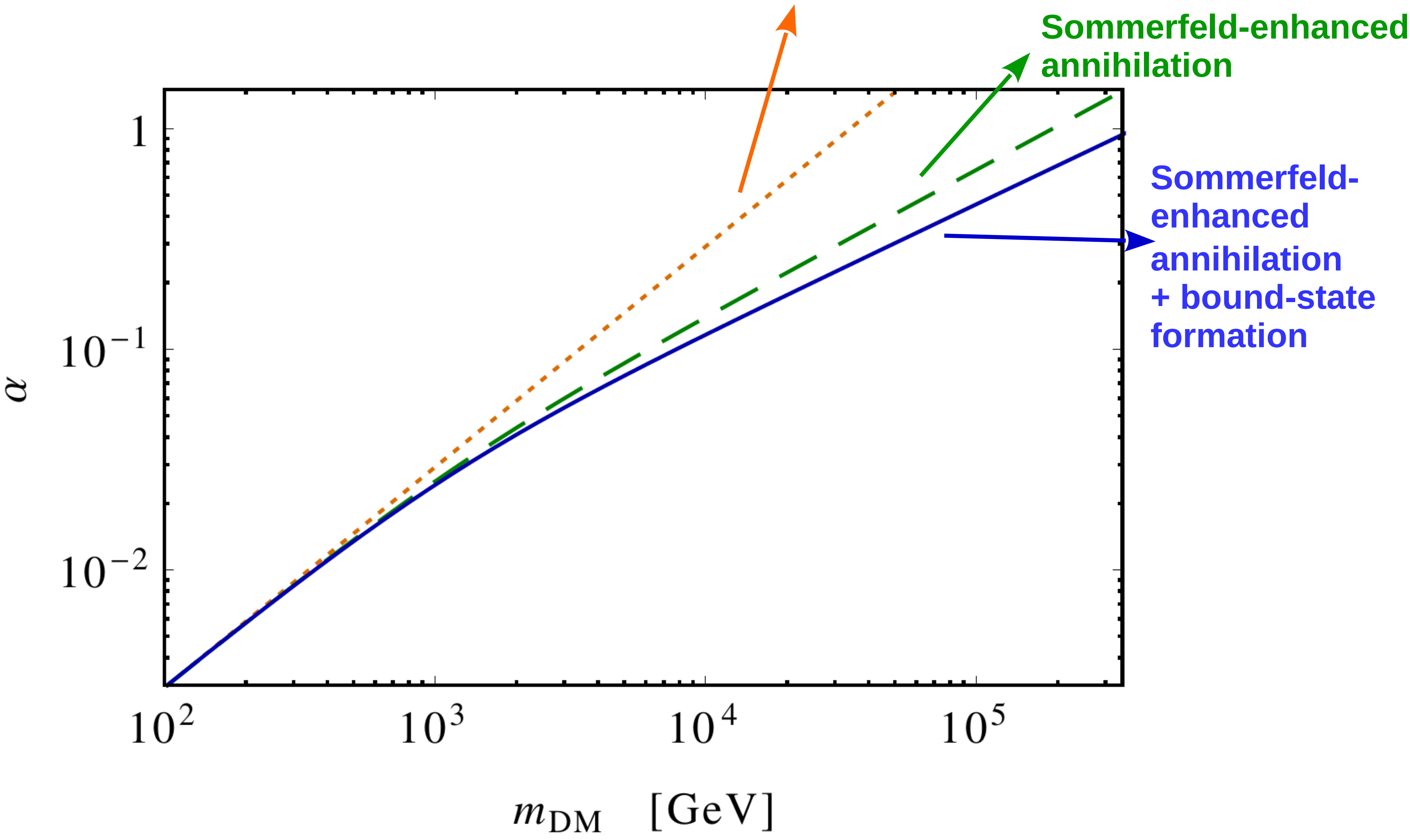
Bound-state formation and decay

$$\left\{ \begin{array}{l} \mathbf{X} + \bar{\mathbf{X}} \rightarrow (\mathbf{X}\bar{\mathbf{X}})_{\mathbf{bound}} + \gamma_{\mathbf{D}} \\ (\mathbf{X}\bar{\mathbf{X}})_{\mathbf{bound}} \rightarrow 2\gamma_{\mathbf{D}} \ \text{ or } \ 3\gamma_{\mathbf{D}} \end{array} \right.$$

- Bound-state formation is also Sommerfeld-enhanced, becomes dominant inelastic process at $\alpha / v_{rel} > 0.6$

→ Implications for freeze-out, indirect detection;
hidden-sector and possibly heavy WIMP DM

Freeze-out



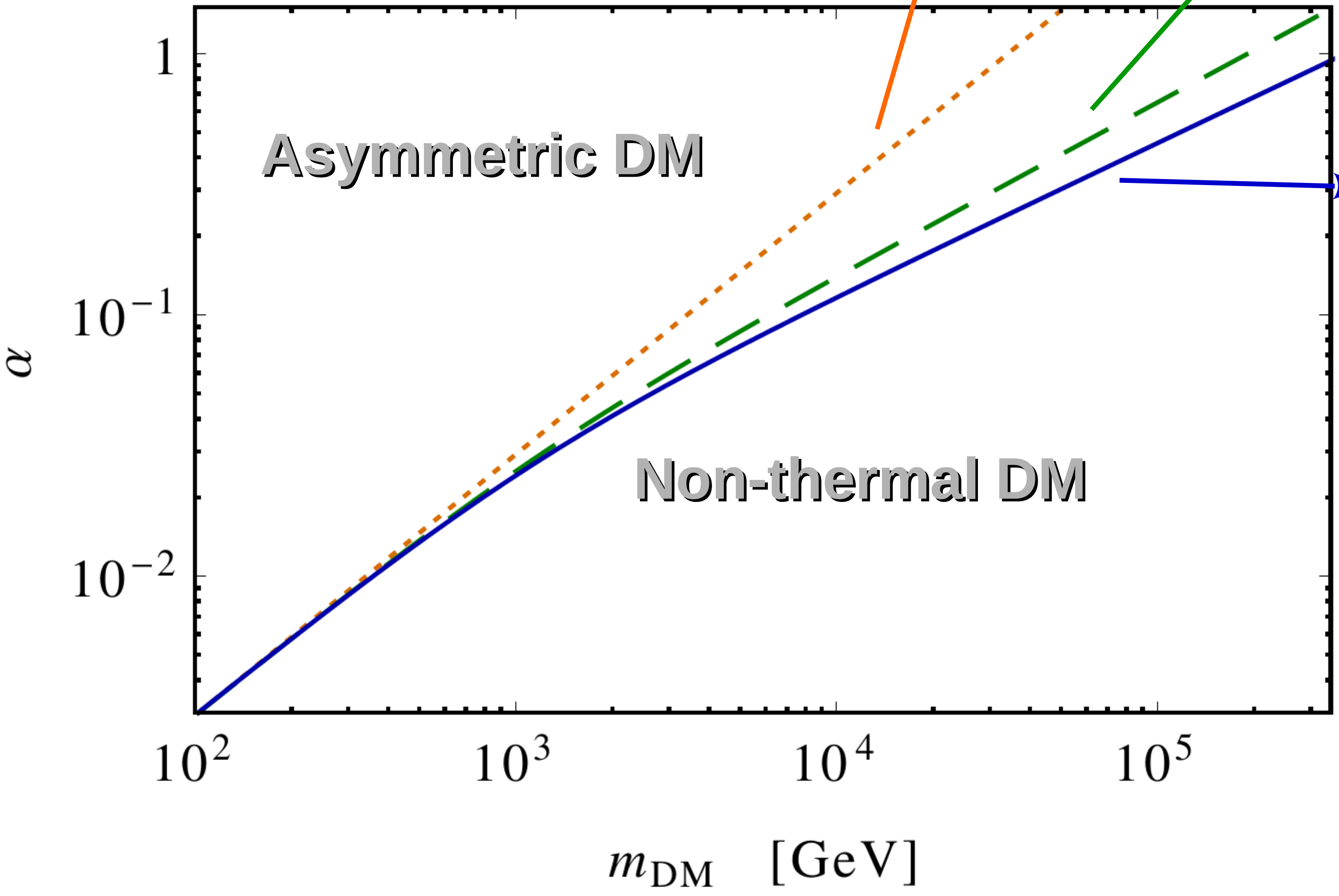
[von Harling, KP (2014)]

Why is this important?

Freeze-out

annihilation only:
$\sigma_0 = \pi \alpha^2 / m_{DM}^2$ = canonical

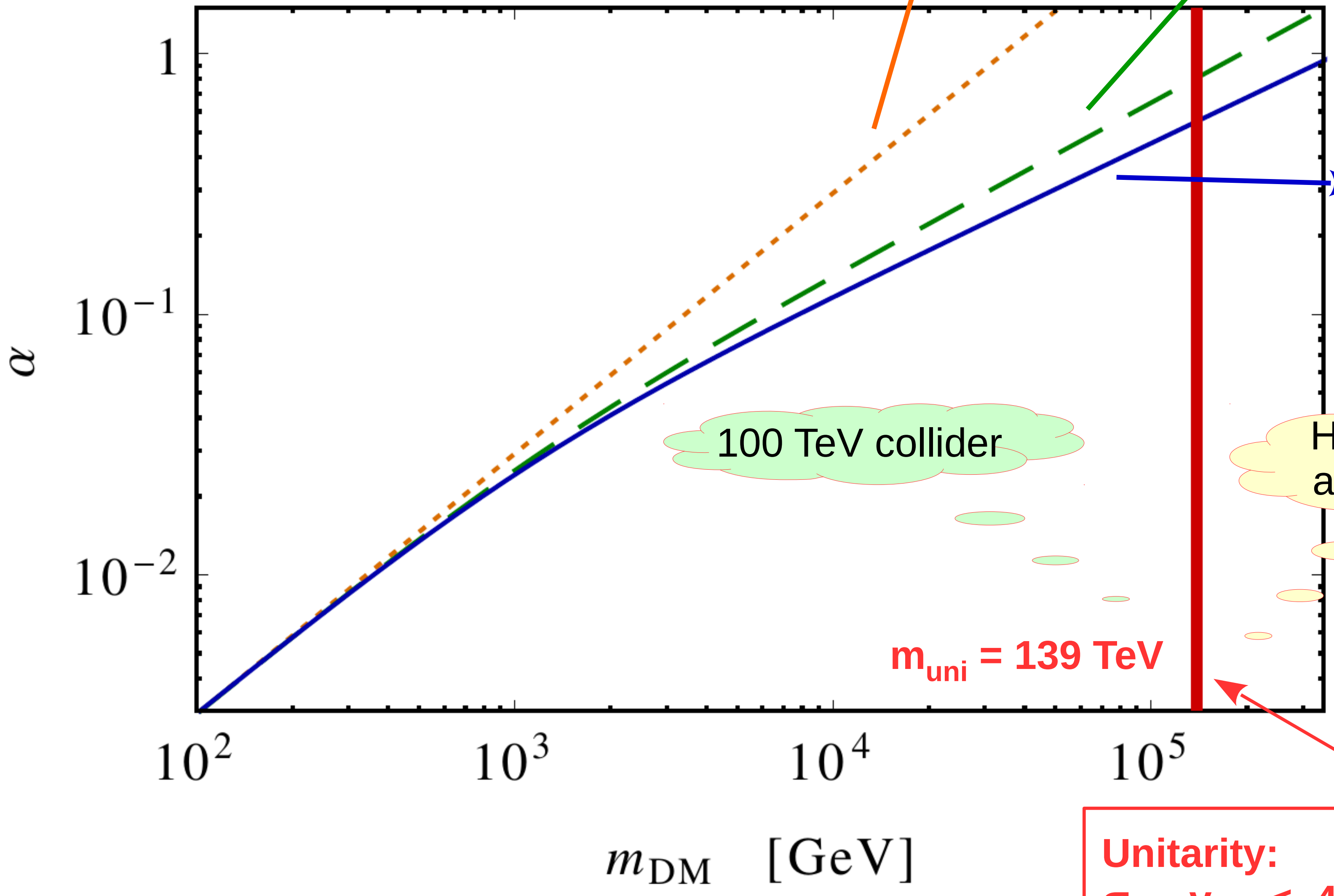
Sommerfeld-enhanced
annihilation



Sommerfeld-enhanced
annihilation
+ bound-state
formation

[von Harling, KP (2014)]

Freeze-out



annihilation only:
$\sigma_0 = \pi\, \alpha^2 / m_{DM}^{\;2}$ = canonical

Sommerfeld-enhanced annihilation

Sommerfeld-enhanced annihilation + bound-state formation

100 TeV collider

High-energy astro signals

m_{uni} = 139 TeV

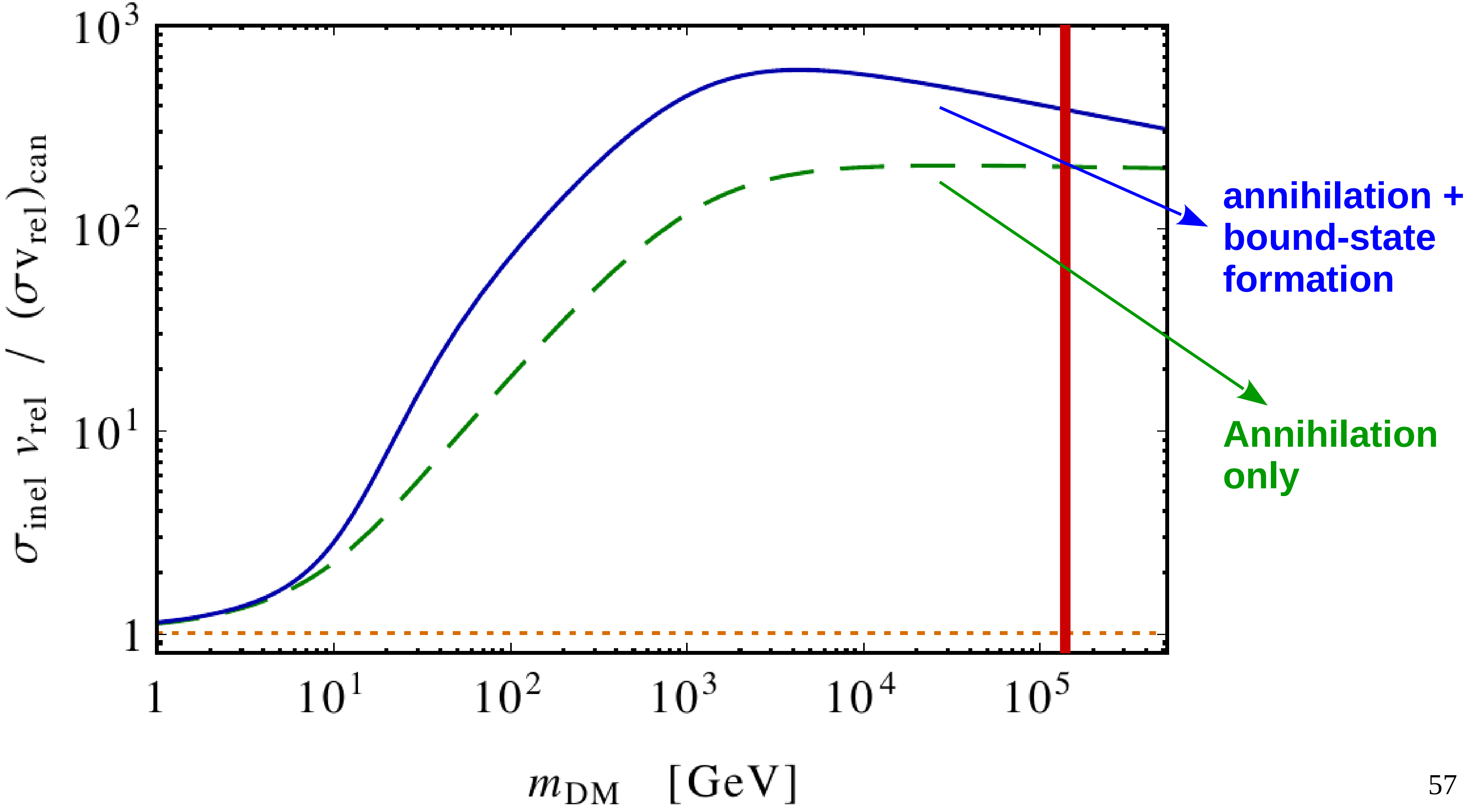
Unitarity:
$\sigma_{inel}\, v_{rel} < 4\pi / (m^2\, v_{rel})$

[von Harling, KP (2014)]

Implications for indirect detection

Milky Way: **v_{rel} ~ 10^{-3}**

→ large Sommerfeld enhancement



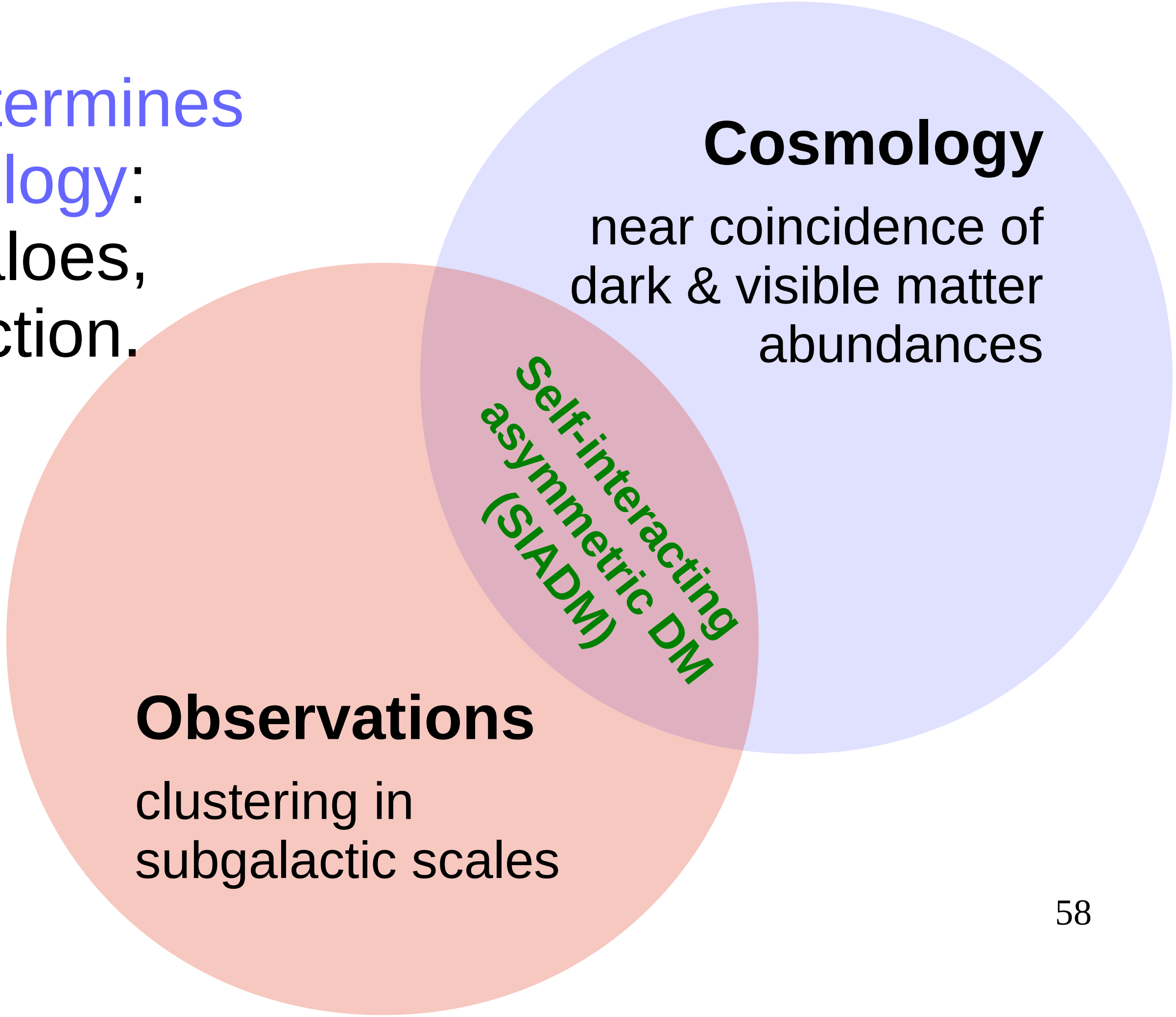
annihilation + bound-state formation

Annihilation only

Conclusion

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

- Involved cosmology determines low-energy phenomenology: DM self-scattering in haloes, direct and indirect detection.



Cosmology

near coincidence of
dark & visible matter
abundances

Self-interacting asymmetric DM (SIADM)

Observations

clustering in
subgalactic scales