Long-range interactions in dark matter phenomenology

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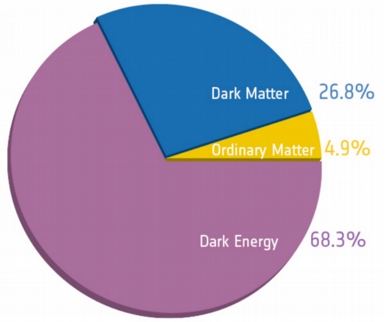
Dark matter properties

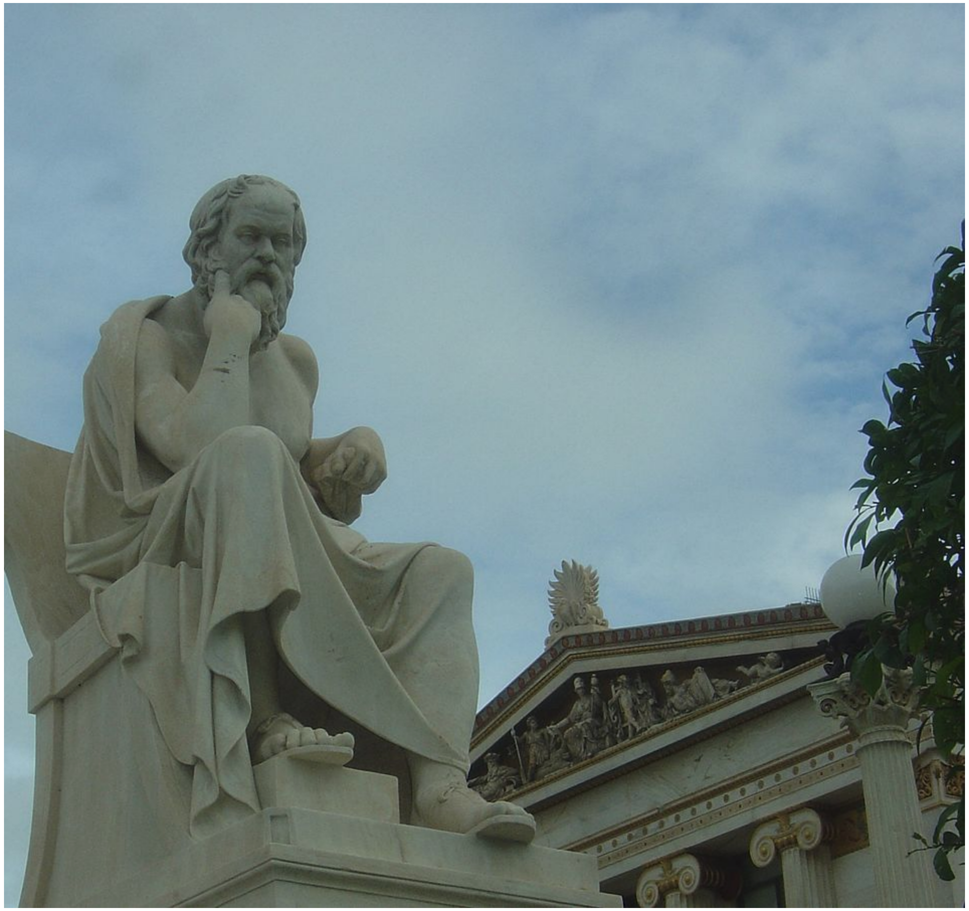


- Stable or very long-lived
- Dark
- Produced at the observed density in the early universe
- Consistent with observed galactic structure
  - Not hot at the onset of gravitational collapse
  - Cold or warm?
  - Collisionless or self-interacting?
- Compatible with existing experimental constraints (colliders, direct detection, indirect detection)

DM is not a known particle!

The Socratic epoch of DM physics

ἓν οἶδα ὅτι οὐδὲν οἶδα
ipse se nihil scire id unum sciat



Socrates
by Leonidas Drosis, Athens - Academy of Athens.
Image from Wikipedia.

We know
that we don't know.

Classification schemes

of dark matter candidates

Classification schemes
of dark matter candidates

Interaction with the SM

Portal operators	**SM interactions**	**Heavy mediators**
$\epsilon F_Y^{\mu\nu} F_{D\,\mu\nu}$ $(\mu\phi + \lambda\phi^2)\|H\|^2$ $yLHN$	WIMPs	EFTs

Classification schemes
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(Self-) interaction type

Long-range	Contact type
Light mediators $m_{med} << m_{DM}$	Heavy mediators $m_{med} \gtrsim m_{DM}$

Classification schemes
of dark matter candidates

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(Self-) interaction type

Long-range	Contact type
Light mediators $m_{med} \ll m_{DM}$	Heavy mediators $m_{med} \gtrsim m_{DM}$

Production mechanism

Scalar condensates	Collapse of density perturbations	Freeze-in	Asymmetric freeze-out	Symmetric freeze-out
Q-balls Axions	Primordial black holes	Sterile neutrinos Gravitinos	Hidden sector models, e.g. dark U(1), dark QCD	WIMPs Heavy meds Light meds

Classification schemes

of dark matter candidates

most of DM research

Interaction with the SM

Portal operators

$\epsilon F_Y^{\mu\nu} F_{D\,\mu\nu}$

$(\mu\phi + \lambda\phi^2)|H|^2$

$yLHN$

SM interactions

WIMPs

Heavy mediators

EFTs

(Self-) interaction type

Long-range

Light mediators

$m_{med} << m_{DM}$

Contact type

Heavy mediators

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Classification schemes

of dark matter candidates

this talk

Interaction with the SM

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Long-range interactions
Motivation

- **Iconoclastic-ism:**

  Most DM research has focused on contact interactions.
  Prototypical WIMP scenario: $m_{DM} \sim m_{mediators} \sim 100$ GeV.

  What happens if $m_{DM} \gg m_{mediators}$?

- **Long-range interactions appear in a variety of DM theories:**
  - Self-interacting DM
  - DM explanations of astrophysical anomalies, e.g. galactic positrons, IceCube PeV neutrinos
  - Sectors with stable particles in String Theory

  Hidden sector DM

  - WIMP DM with m_{DM} > few TeV. [Hisano et al. 2002]
  - WIMP DM with m_{DM} < TeV, in co-annihilation scenarios of DM with coloured/charged partners.

Self-interacting dark matter

ΛCDM: Successful at > Mpc, too rich structure at smaller scales

SIDM: Plausible solution to the apparent discrepancies between predictions of collisionless cold DM and observations

[Spergel, Steinhardt (2000)]

- Cross-section needed to affect galactic structure

$$\boldsymbol{\sigma_{\mathrm{self-scatt}}/m_{\mathrm{DM}} \sim \mathrm{barn/GeV} \sim \mathrm{cm^2/g}}$$

at dwarf-galaxy scales, v_{DM} ~ 20 km/s.

- Upper limit from Clusters is of the same order, but at v_{DM} ~ 1000 km/s.

- No tension between the two, if $\sigma_{\text{self-scatt}}$ decreases with increasing v_{DM}

⇒ Light mediators, long-range interactions!

e.g. massless mediator: Rutherford scattering $\sigma_{\text{self-scatt}} \sim 1/v^4$.

Long-range interactions
Complications

- **Large logarithmic corrections:**

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

- **Non-perturbative effects:**

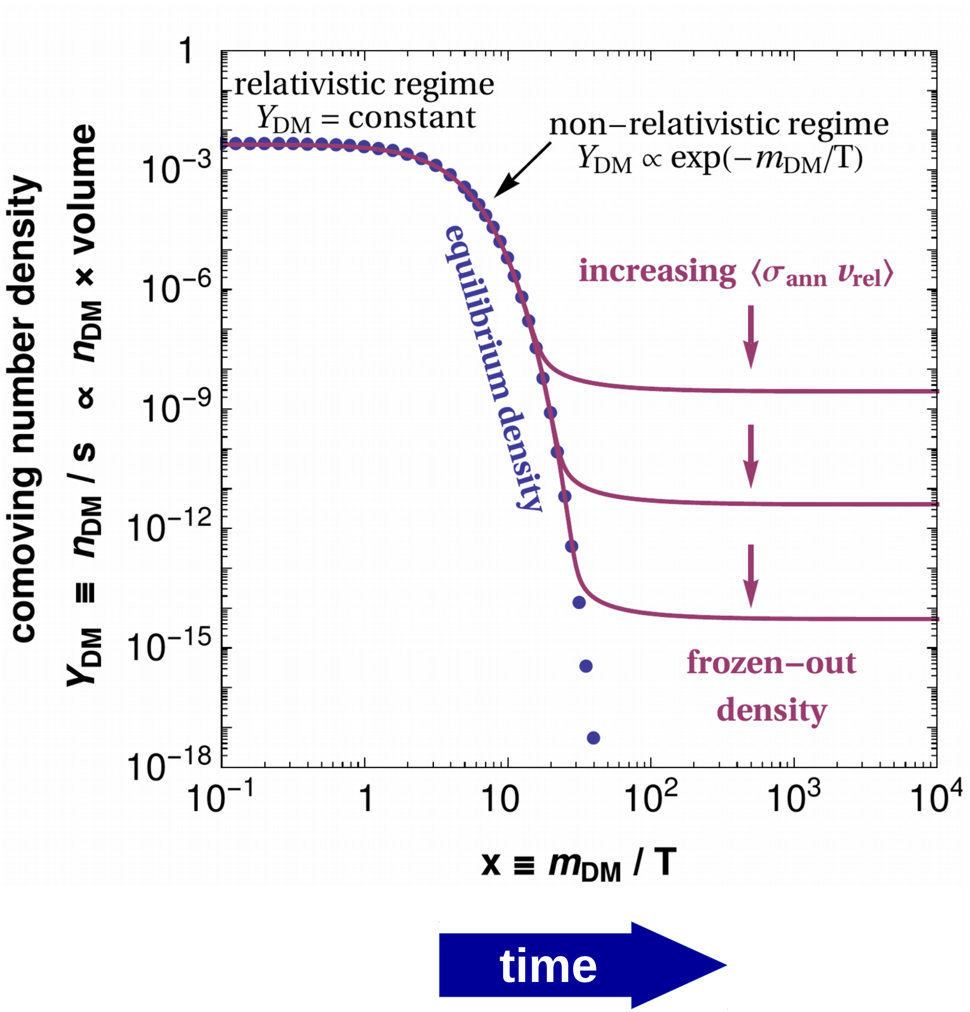
  Sommerfeld enhancement in the non-relativistic regime.

  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]

Phenomenological implications

Thermal freeze-out with contact interactions



- **At $T > m_{DM}/3$:**
  DM is kept in chemical & kinetic equilibrium with the plasma, via
  $$X + \bar{X} \leftrightarrow f + \bar{f}$$
  $n_{DM} \sim T^3$ or Y_{DM} = const.

- **At $T < m_{DM}/3$:** $Y_{DM} \propto \exp(-m_{DM}/T)$, while still in equilibrium

- **At $T < m_{DM}/25$:** Density too small, annihilations stall ⇒ **Freeze-out!**
  $$\Omega \simeq 0.26 \times \left(\frac{1pb \cdot c}{\sigma_{ann} v_{rel}} \right)$$

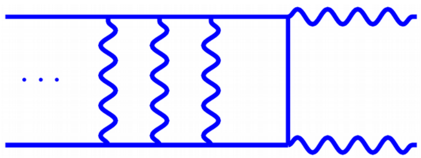
"canonical" annihilation cross-section – assumes contact interactions

Thermal freeze-out with long-range interactions

Dark U(1) model

Direct annihilation

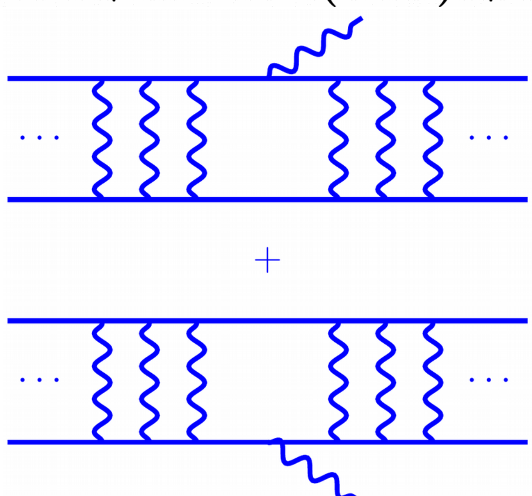
$$X + \bar{X} \to 2\gamma_D$$



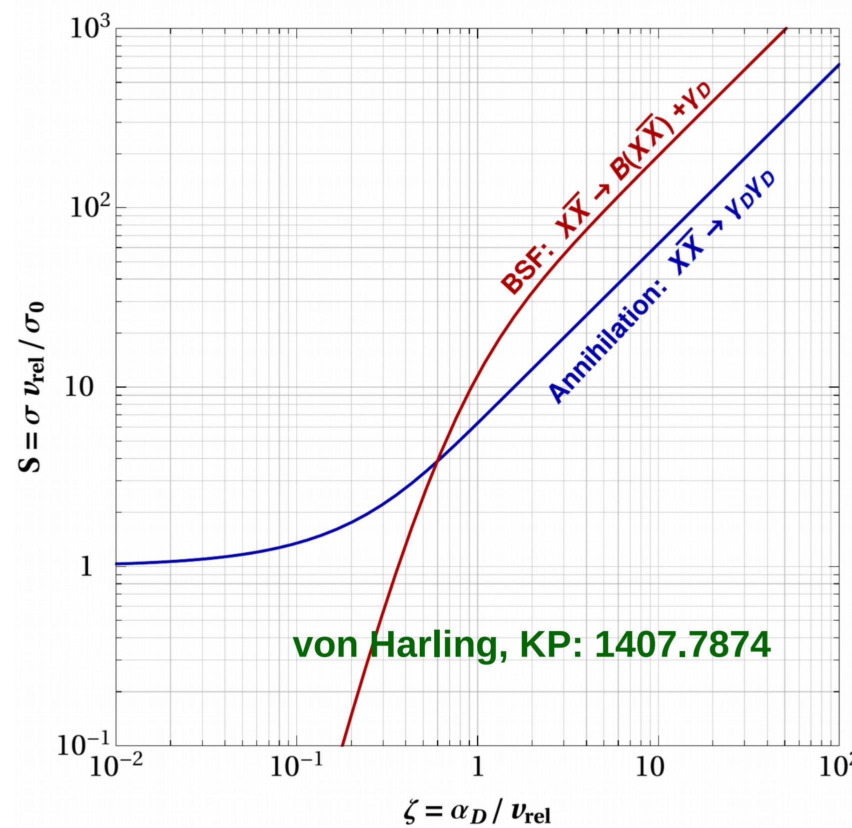
$$\sigma_{\rm ann} v_{\rm rel} = \frac{\pi \alpha_D^2}{m_X^2} \times S_{\rm ann}(\alpha_D / v_{\rm rel})$$

Radiative bound-state formation

$$X + \bar{X} \to \mathcal{B}(X\bar{X}) + \gamma_D$$



$$\sigma_{\rm BSF} v_{\rm rel} = \frac{\pi \alpha_D^2}{m_X^2} \times S_{\rm BSF}(\alpha_D / v_{\rm rel})$$



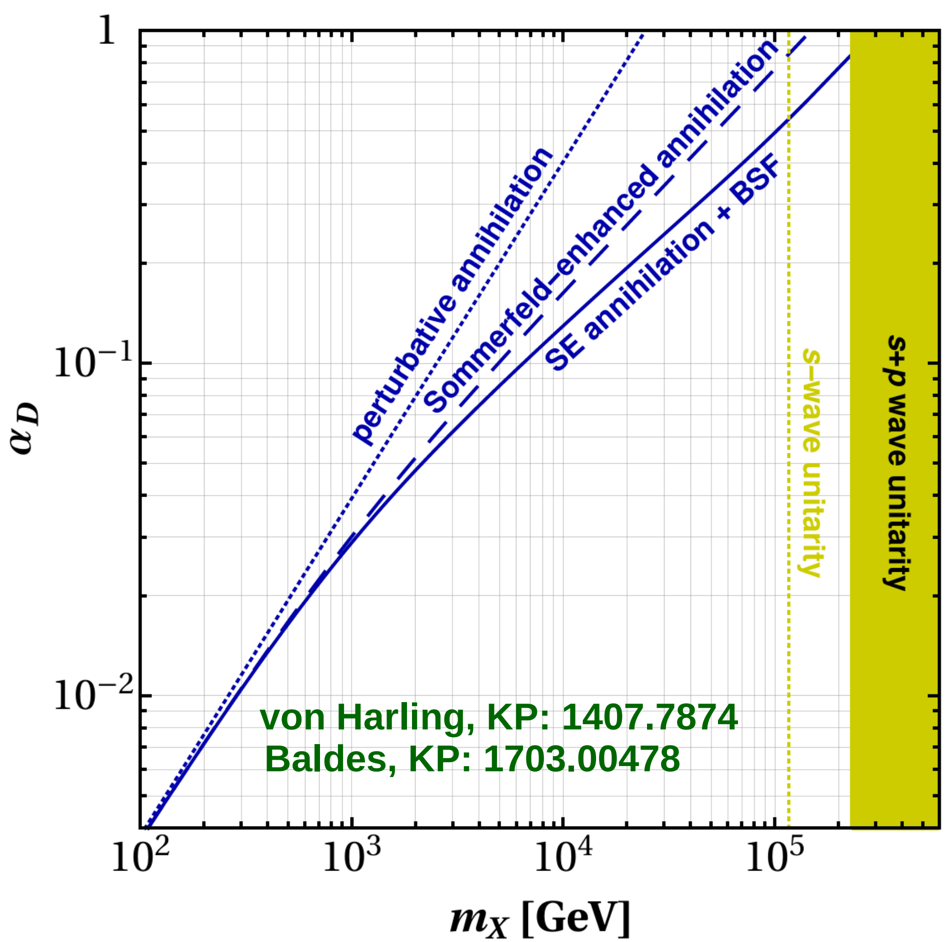
Thermal freeze-out with long-range interactions

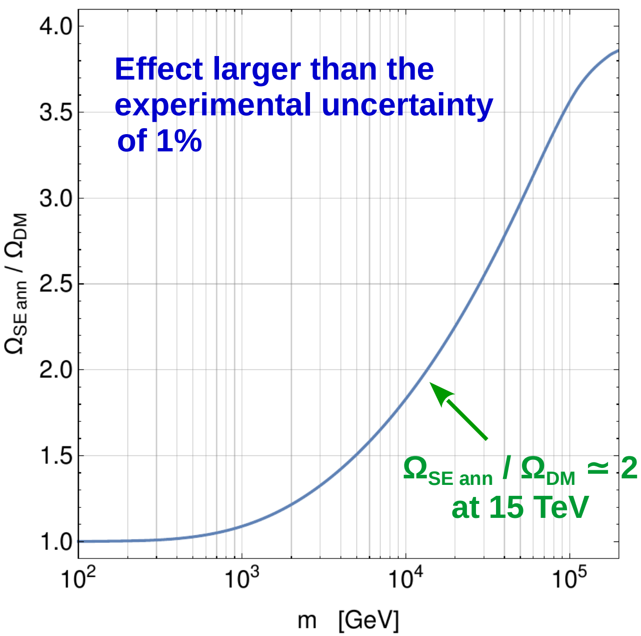
Dark U(1) model

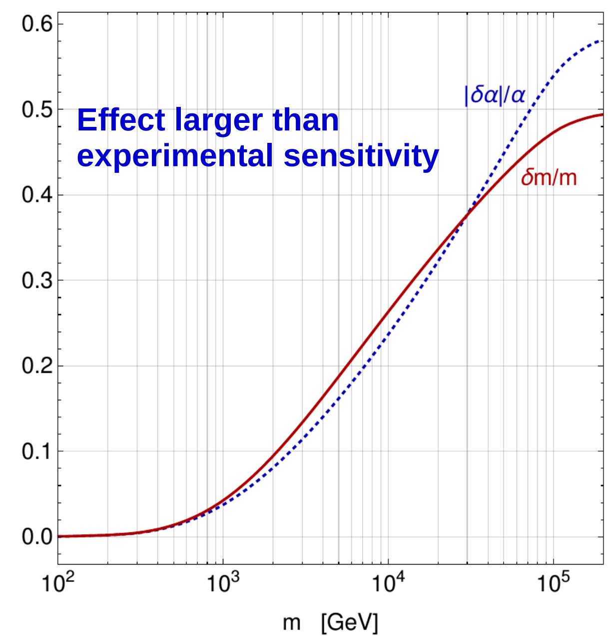
Direct Annihilation $X\bar{X} \to \gamma_D \gamma_D$

Bound-state formation $X\bar{X} \to \mathcal{B}(X\bar{X}) + \gamma_D$

and decay $\mathcal{B}(X\bar{X}) \to 2\gamma_D$ or $3\gamma_D$







A dark U(1) sector
a closer look

Everybody's model for
- **astro anomalies**
- **self-interacting DM**
- **you name it...**

$$\mathcal{L} = \bar{X}(i\not{D} - M_{\rm DM})X \boxed{- \frac{1}{4}F_{D\mu\nu}F_D^{\mu\nu} - \frac{1}{2}m_{V_D}^2 V_{D\mu}V_D{}^{\mu}} - \frac{\epsilon}{2c_w}F_{D\mu\nu}F_Y^{\mu\nu}$$

Dark matter: Fermions X, $\bar{X}$, with mass M_{DM}

Coupled, dark fine structure constant α_D

Dark Photons V_D, with mass m_{V_D}

Coupling between dark photons & ordinary photons "kinetic mixing" ε

$\alpha_D = \alpha_D(M_{\rm DM})$ fixed from relic density

Direct Annihilation	$X\bar{X} \to V_D V_D$
Bound-state formation	$X\bar{X} \to \mathcal{B}(X\bar{X}) + V_D$
and decay	$\mathcal{B}(X\bar{X}) \to 2V_D$ or $3V_D$
Dark photon decay	$V_D \to f^+_{\rm SM} f^-_{\rm SM}$

A dark U(1) sector

Constraints

Everybody's model for
- astro anomalies
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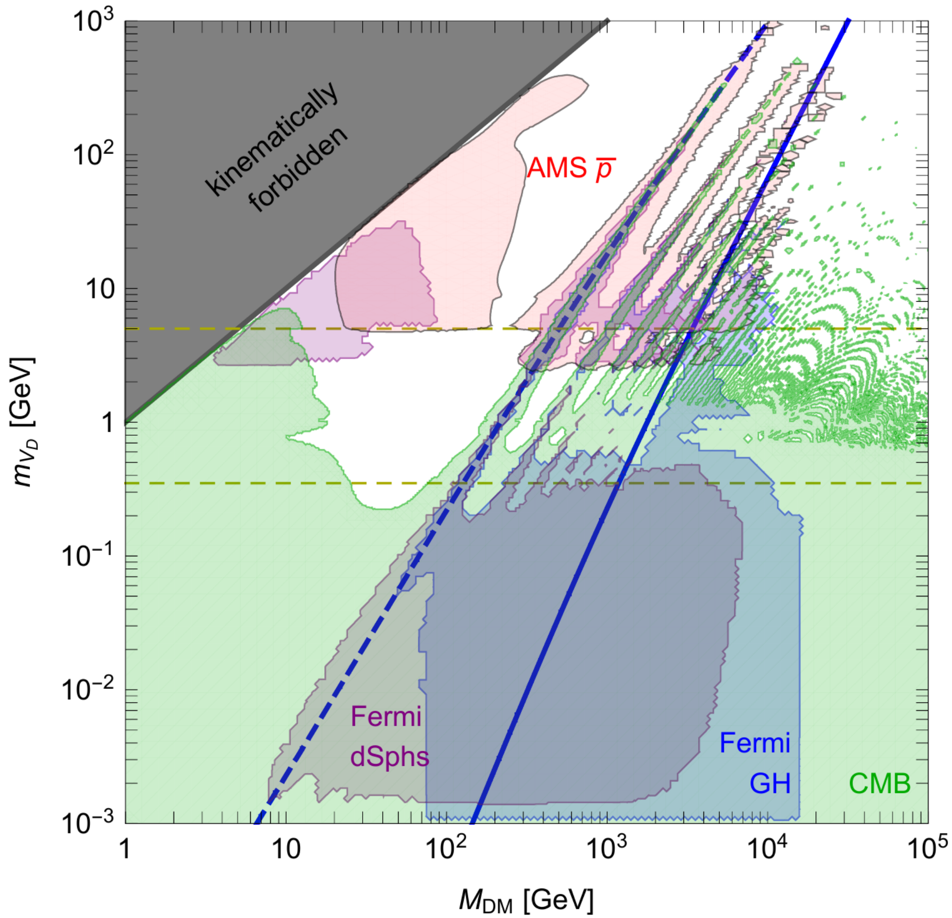
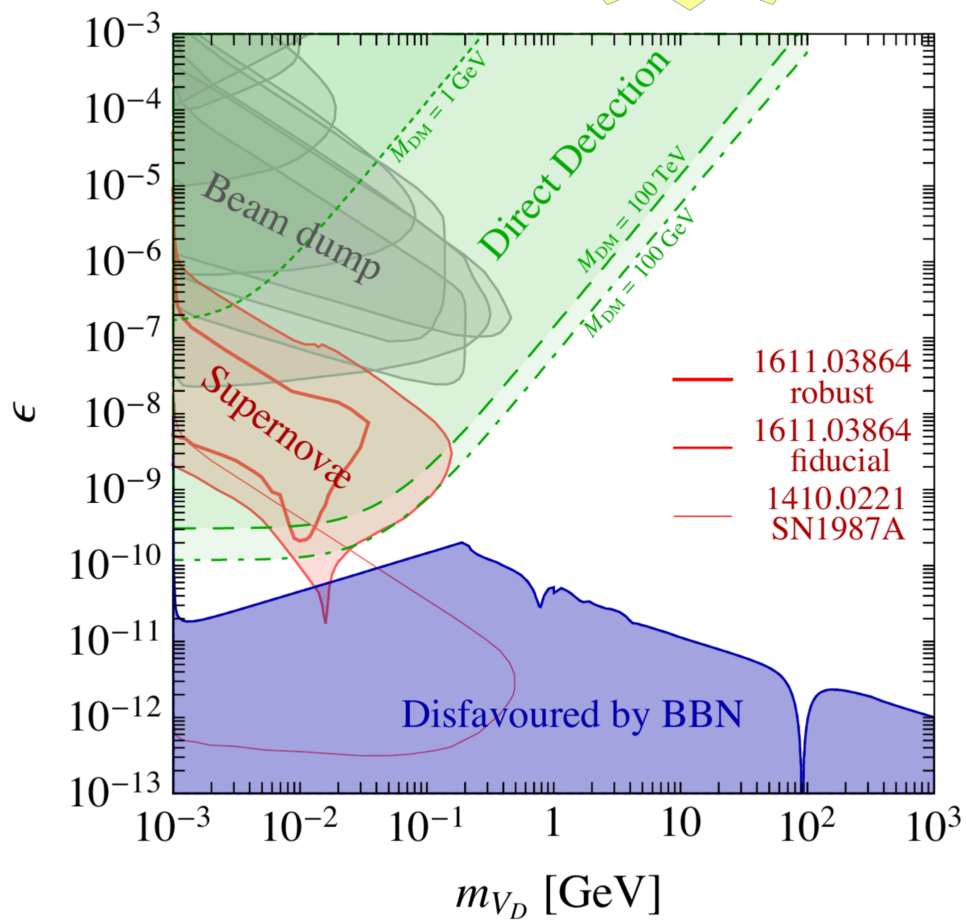
- you name it...





Bound state formation and decay enhances signals, strengthens constraints from galaxy observations

[Cirelli, Panci, KP, Sala, Taoso, 1612.07295]

Dark photon masses
sub-eV < m_{V_D}< GeV excluded !
Important for SIDM.

Self-interacting dark matter

- Strong constraints on minimal SIDM models from the combination of CMB & indirect detection, direct detection and cosmological considerations

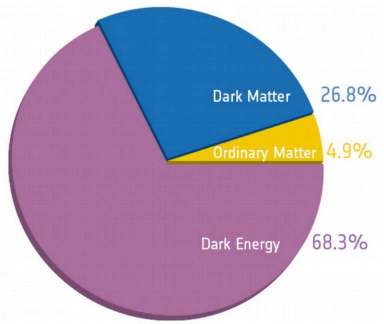
  [Constraints on light scalar mediators: Kahlhoefer+ 1704.02149]

- Viable SIDM scenarios
  - Entirely massless mediators
  - More complex sectors with symmetric DM **[e.g. pure non-Abelian gauge theory Boddy, Feng, Kaplinghat, Tait (2014)]**
  - **Asymmetric dark matter**

Asymmetric dark matter

Motivation

Review of Asymmetric DM:
KP, Volkas, 1305.4939



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

  Proposal: DM density due to a excess of particles over antiparticles related dynamically to the BAU in the early universe and conserved separately today.

- Very suitable host of self-interacting dark matter:

  No upper limit on the annihilation cross-section → allows for large couplings to light mediators.

  Dark and ordinary asymmetries need not be related → ADM may have a wide range of masses.

Asymmetric and self-interacting dark matter?

DM coupled to light mediators

The effect of bound states

- **Symmetric DM → unstable bound states**
  Formation + decay = extra annihilation channel
  - Relic abundance
  - Indirect detection
- **Asymmetric DM → stable bound states**
  - DM self-scattering in halos (screening)
  - Indirect detection signals (radiative level transitions)
  - Direct detection signals (screening, inelastic scattering)

Asymmetric DM coupled to light mediators

- Dark gauge U(1) sector

  Gauge invariance implies at least two asymmetric dark species, oppositely charged: dark protons & dark electrons → dark atoms

  [Kaplan+ 2009; KP, Trodden, Volkas 2011 von Harling, KP, Volkas 2012 Cyr-Racine, Sigurdson 2013 Cline+ 2014 KP, Pearce, Kusenko 2014 Choquette, Cline 2015 ....]

  Same conclusion if dark U(1) mildly broken and dark photon light enough to yield SIDM.

  [KP, Pearce, Kusenko 2014]

- Non-Abelian gauge theory + fermions

  [Detmold, McCullough, Pochinsky 2014]

  Dark nucleons & nuclei

- Scalar mediator

  [Wise, Zhang 2014]

  Attractive interaction between particles; multi-particle bound states may form.

Asymmetric DM coupled to light mediators

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Multicomponent DM is a generic feature of asymmetric DM coupled to light mediators

Self-interacting asymmetric DM

Indirect detection: U(1) sector + kinetic mixing

- **Annihilations of residual symmetric component,**

  Rate suppressed by asymmetry, but enhanced by Sommerfeld effect due to light dark photon.

$$p_D + \bar{p}_D \to \gamma_D + \gamma_D$$
$$\gamma_D \to f^+_{\rm SM} f^-_{\rm SM}$$

  Rate significant for antiparticle-to-particle ratio as low as $10^{-3} - 10^{-4}$.
  Caveat: Formation of dark atoms may deplete available p_D and suppress annihilation signals.

  **[Baldes, KP 1703.00478,
  Baldes, Cirelli, Panci, KP, Sala, Taoso 1712.07489]**

- **Radiative level transitions,** e.g. dark atom formation from residual ionized component

$$p_D + e_D \to H_D + \gamma_D$$
$$\gamma_D \to f^+_{\rm SM} f^-_{\rm SM}$$

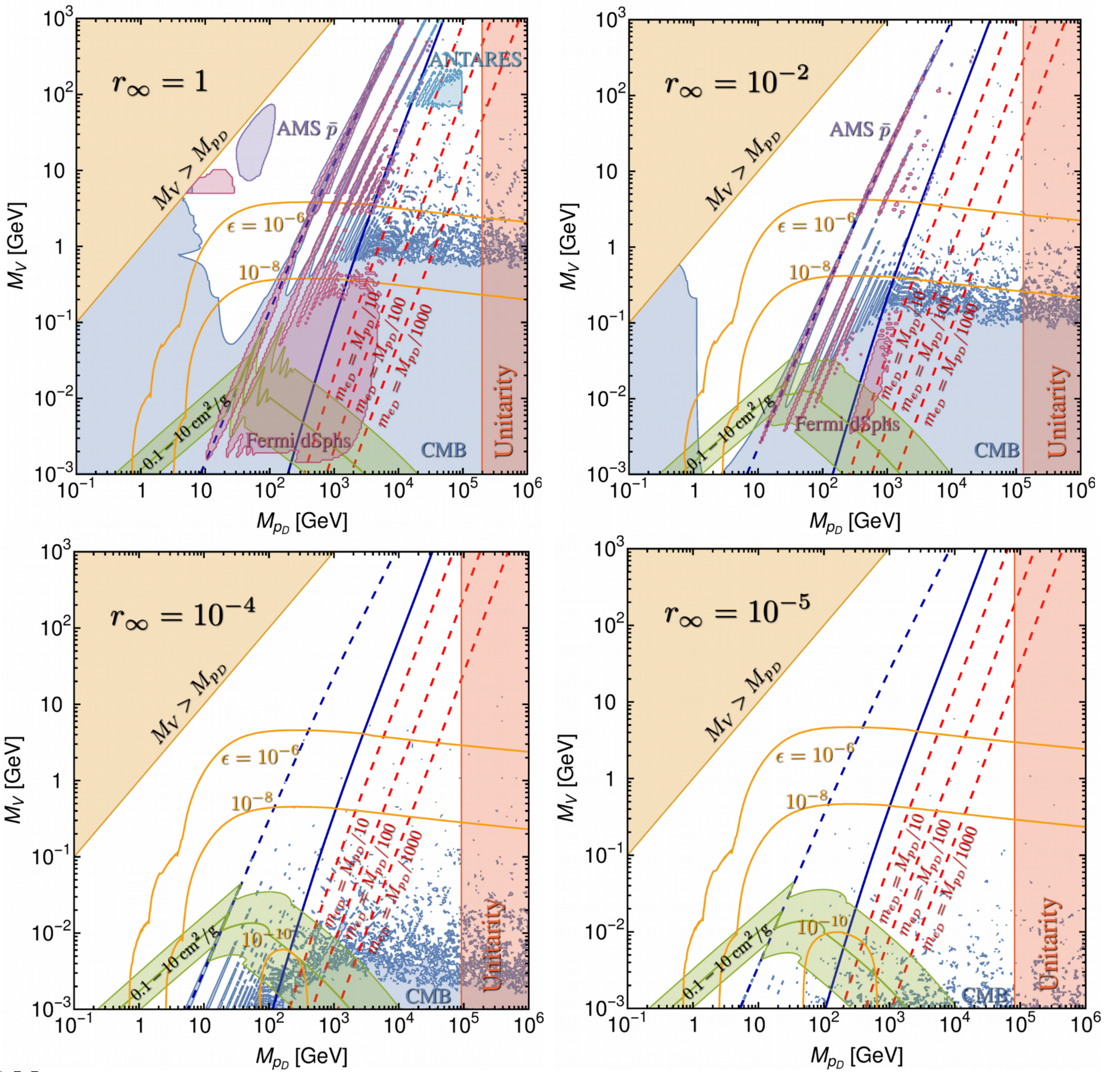
  [Pearce, KP, Petraki, 1502.01755

  **For other models:
  arXiv:1303.7294;
  arXiv:1404.3729;
  arXiv:1406.2276]**

(A)symmetric DM coupled to a dark photon: annihilation constraints

$$r_\infty \equiv \left.\frac{n_{\bar{X}}}{n_X}\right|_{t\to\infty}$$

Decreases with annihilation cross-section



dark photon mass

DM mass

Baldes, Cirelli, Panci, KP, Sala, Taoso, 1712.07489

Good old WIMP DM
and long-range interactions

Neutralino in SUSY models

- Constrained MSSM rather constrained
- Co-annihilation scenarios, for near mass-degenerate LSP-NLSP
  - Degenerate spectrum → soft jets → evade LHC constraints
  - Large stop-Higgs coupling reproduces measured Higgs mass and brings the lightest stop close in mass with the LSP.

    ⇒ DM density determined by "effective" Boltzmann equation for

$$n_{\rm tot} = n_{\rm LSP} + n_{\rm NLSP}$$

$$\sigma^{\rm eff}_{\rm ann} = [\, n^2_{\rm LSP}\, \sigma^{\rm LSP}_{\rm ann} + n^2_{\rm NLSP}\, \sigma^{\rm NLSP}_{\rm ann} + n_{\rm LSP}\, n_{\rm NLSP}\, \sigma^{\rm LSP-NLSP}_{\rm ann}\,]/n^2_{\rm tot}$$

- Extended models, e.g. NMSSM

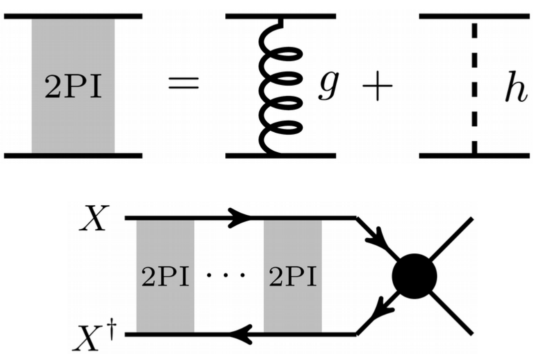
Long-range effects

- Sommerfeld effect due to gluon exchange
- Higgs enhancement

WIMP dark matter

Higgs enhancement in co-annihilation scenarios

[Harz and KP, arXiv:1711.03552]



$$V(r) = -\frac{\alpha_g}{r} - \frac{\alpha_h}{r}\, e^{-m_h r}$$

gluon exchange

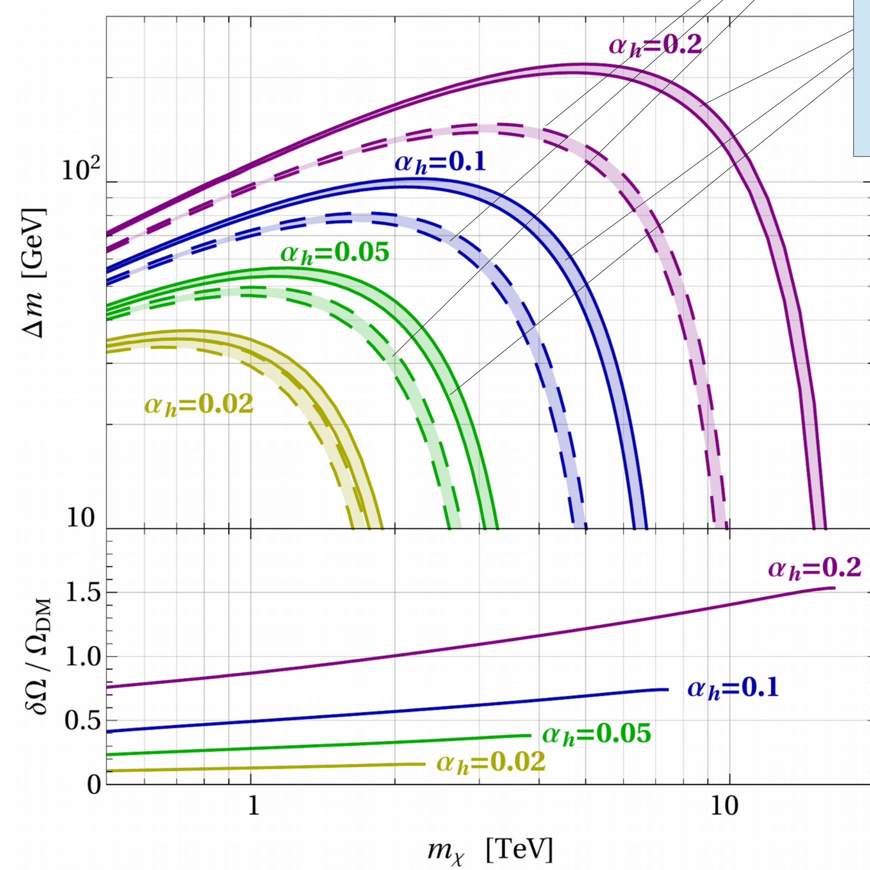
Higgs exchange, typically thought to be too contact-type

Gluon potential influences how long-range the Higgs exchange manifests!

DM co-annihilating with scalar color-triplet (e.g stops)

dashed bands: without Higgs enhancement

solid bands: with Higgs enhancement



Range of α_h occurs in MSSM

Effect on Ω large!

[No bound-state effects included, yet.]

WIMP dark matter

Implications of long-range effects in co-annihilation scenarios

- Alter the interpretation of experimental results
- Increase mass gap
  →improve detection prospects with multi-/mono-jet searches.
- DM can be heavier than anticipated
  → probe multi-TeV regime with indirect detection

Conclusion

- Dynamics of dark matter can be quite complex, there are many more frontiers to explore!
- Interplay between cosmology and fundamental interactions tames manifestations of DM today.