Dark matter candidates

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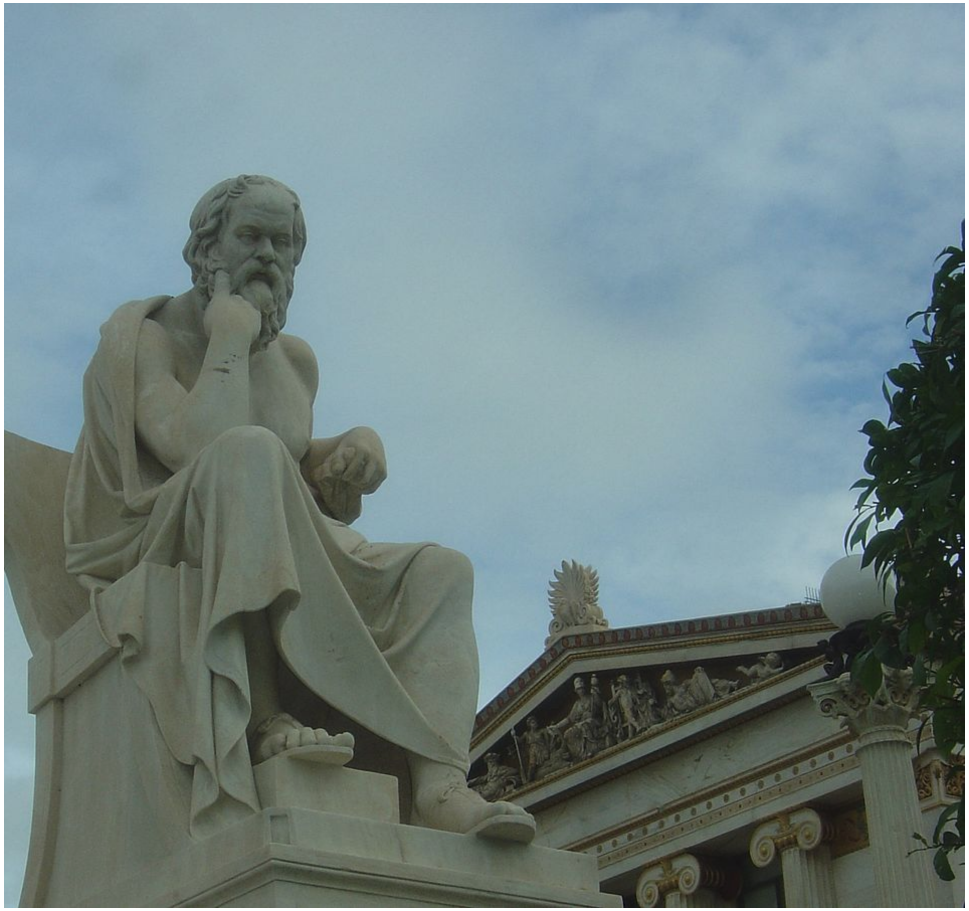
Dark matter properties

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

DM is not a known particle!

The Socratic moment

ἓν οἶδα ὅτι οὐδὲν οἶδα



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

We know
that we don't know.

But we also know that
we would like to know!

Dark matter candidates

Classification schemes

Dark matter candidates

Classification schemes

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 [Tim Tait's talk]

Dark matter candidates

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Interaction type

Long-range	Contact type
Self-interacting DM TeV-scale WIMPs	EFTs EW-scale WIMPs

Dark matter candidates

Classification schemes

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$\epsilon F_Y^{\mu\nu} F_{D\,\mu\nu}$ $(\mu\phi + \lambda\phi^2)\lvert H\rvert^2$ $yLHN$	WIMPs	EFTs [Tim Tait's talk]

Interaction type

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Self-interacting DM TeV-scale WIMPs	EFTs EW-scale WIMPs

Production mechanism

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

Dark matter candidates

Classification schemes

High-energy motivation

- Supersymmetry:
  WIMPs, Q-balls
- Neutrino masses:
  Sterile neutrinos
- Strong-CP problem:
  Axions

Observational motivation

- Neutrino masses:
  Sterile neutrinos
- DM density / BAU:
  Asymmetric DM
- Galactic structure:
  Self-interacting DM, warm DM
- Astrophysical anomalies:
  WIMP DM, sterile neutrinos,
  hidden sector models

In the following

I will discuss in a bit more detail

- WIMPs
- Self-interacting DM
- Asymmetric DM

} **with emphasis on long-range effects**

See dedicated talks on

- Primordial black holes **[Anne Green]**
- Axions **[Peter Graham]**
- Sterile neutrinos **[Kevork Abazajian]**

WIMP dark matter

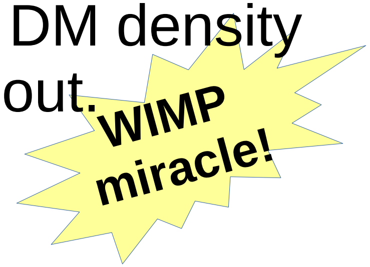
WIMP dark matter

Motivation

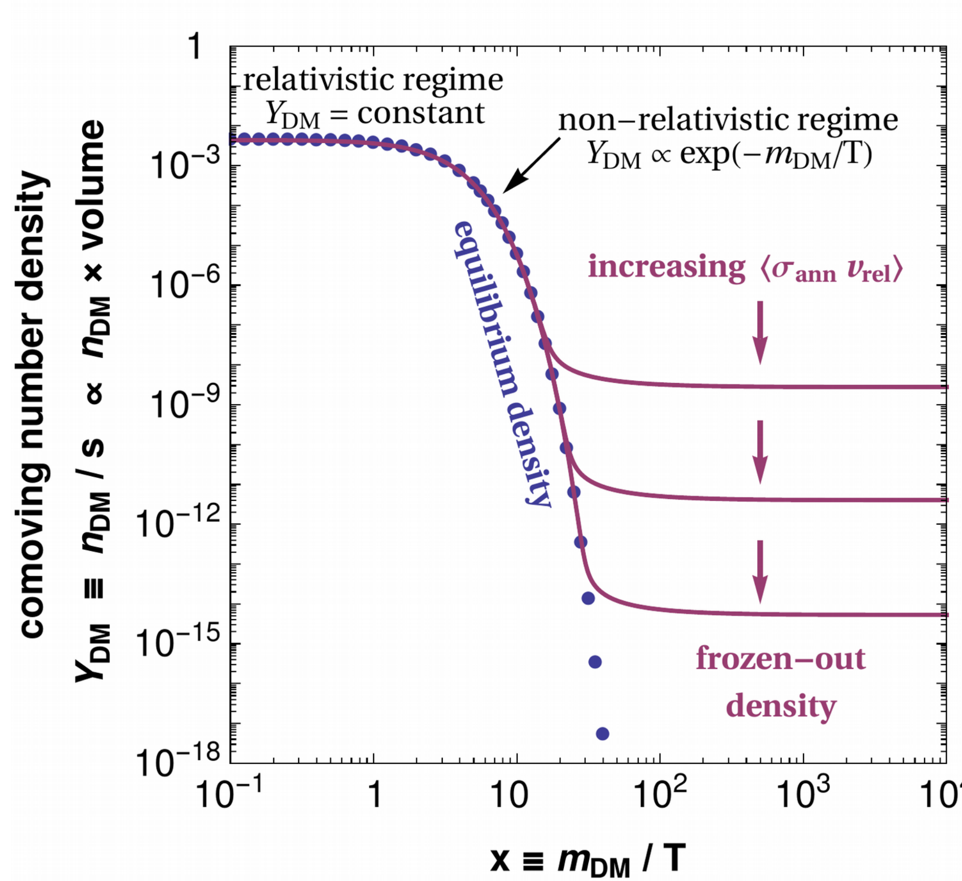
- New particles coupled to the Weak interactions of the SM are expected in theories that address the EW hierarchy problem.

  Caveat: Not all WIMP scenarios address the hierarchy problem.

- Weak-scale cross-sections can yield the observed DM density via thermal freeze-out.



- We know that the Weak interactions exist!



$$\Omega \simeq 0.26 \times \left(\frac{1pb \cdot c}{\sigma_{\rm ann} v_{\rm rel}} \right)$$

WIMP dark matter

Popular candidates

- **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

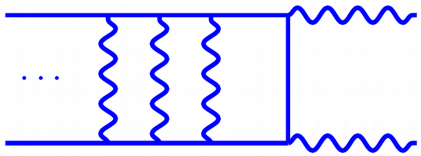
- Sommerfeld effect due to gluon exchange
- Formation and decay of unstable bound states
- Higgs enhancement

Bound-state formation and relic density

Dark U(1) model

Direct annihilation

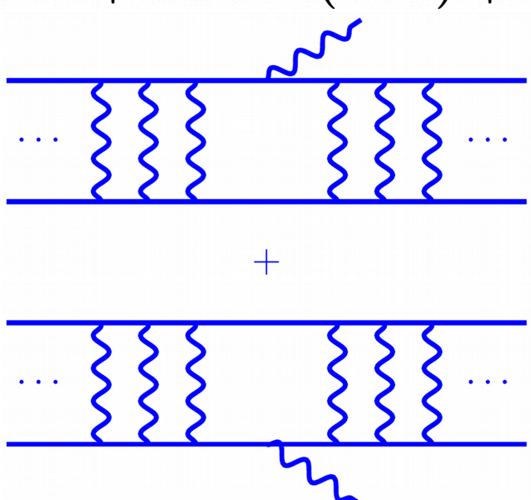
$$X + \bar{X} \to 2\gamma_D$$



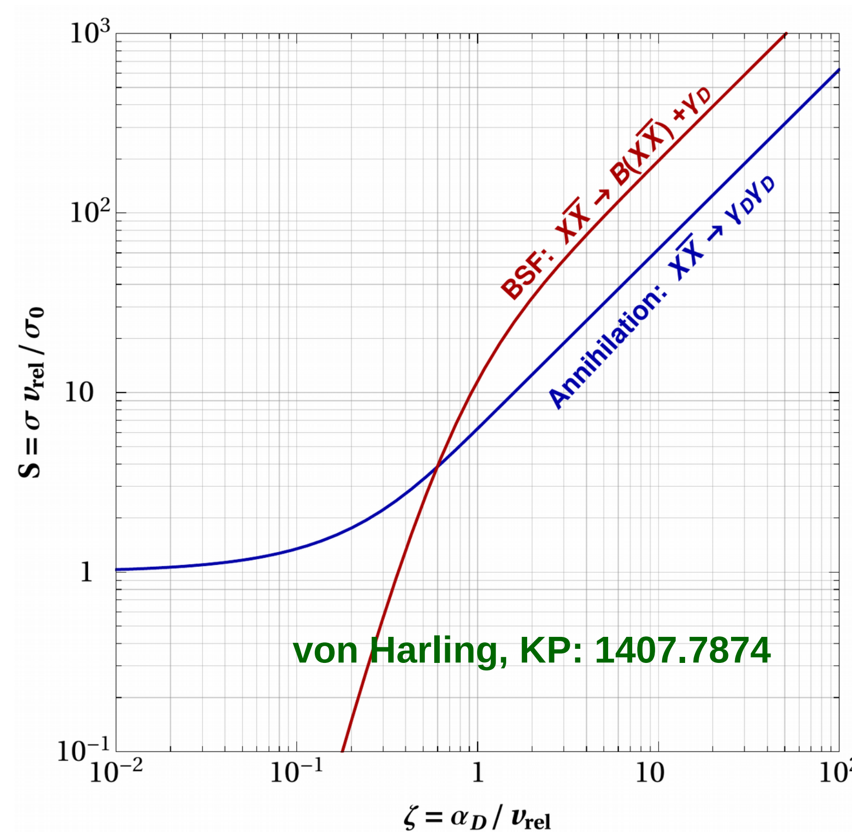
$$\sigma_{\rm ann} v_{\rm rel} = \frac{\pi \alpha_D^2}{m_X^2} \times S_{\rm ann}(\alpha_D / v_{\rm rel})$$

Radiative bound-state formation

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



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



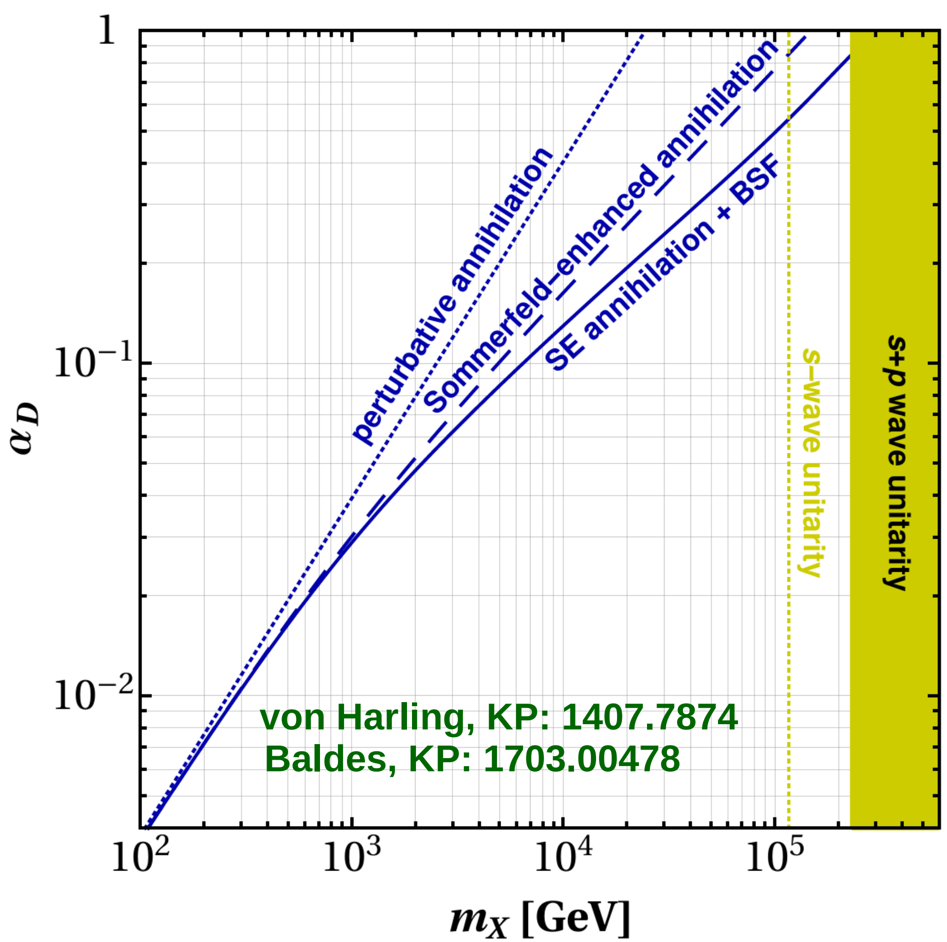
Bound-state formation and relic density

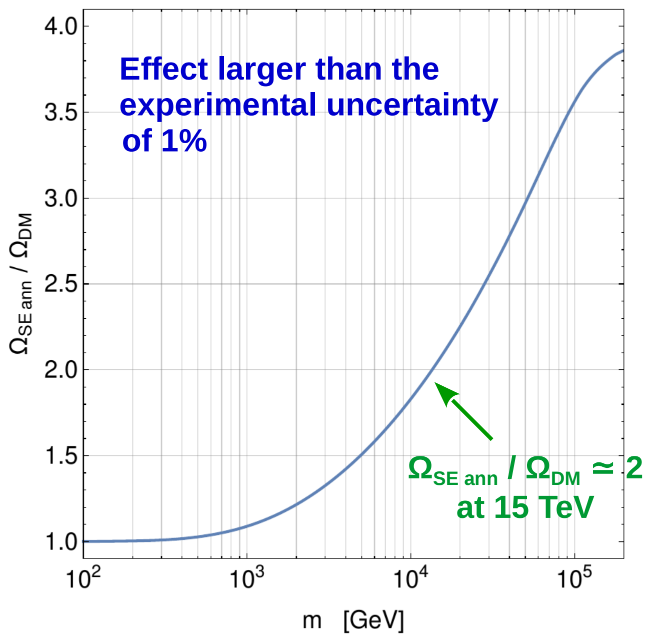
Dark U(1) model

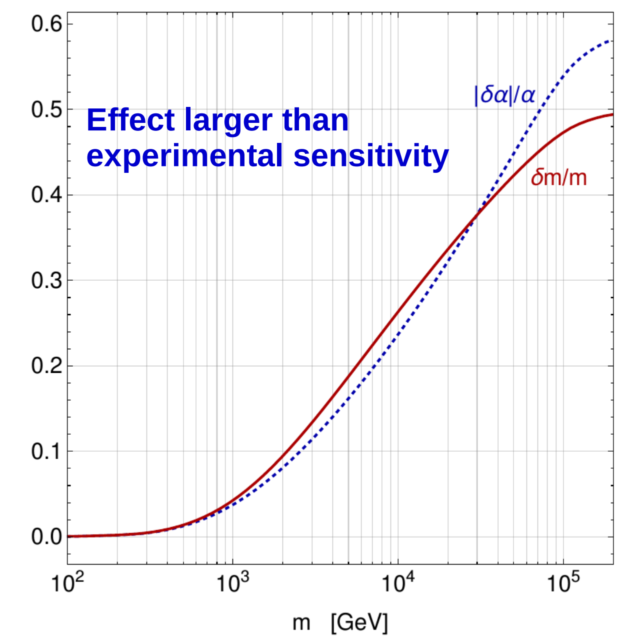
Direct Annihilation $X\bar{X} \to \gamma_D \gamma_D$

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 $3\gamma_D$





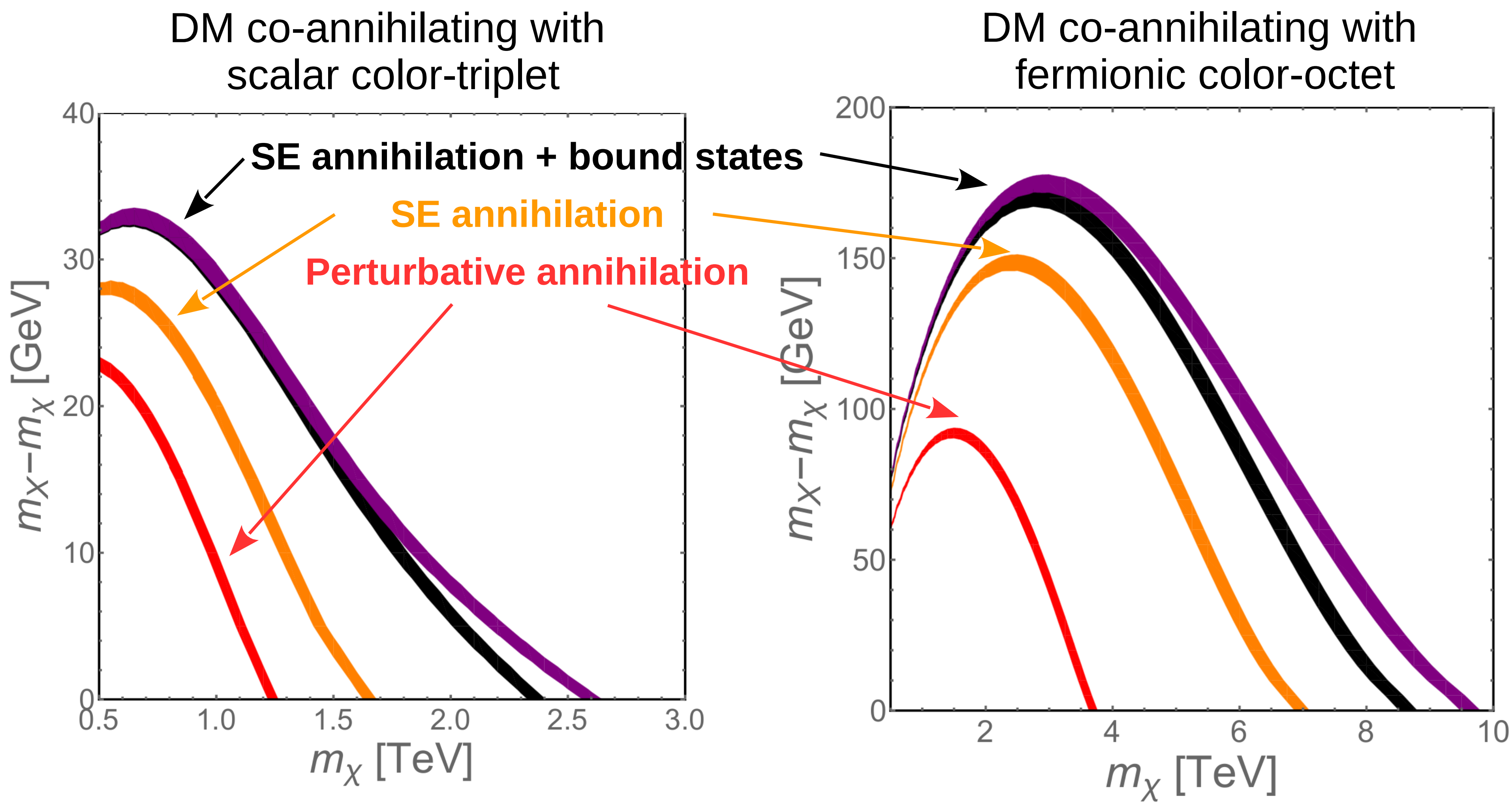


WIMP dark matter

Gluon-mediated bound states in co-annihilation scenarios

MSSM-inspired toy models

[Liew and Luo, 1611.08133; see also El Hedri+, 1703.00452]



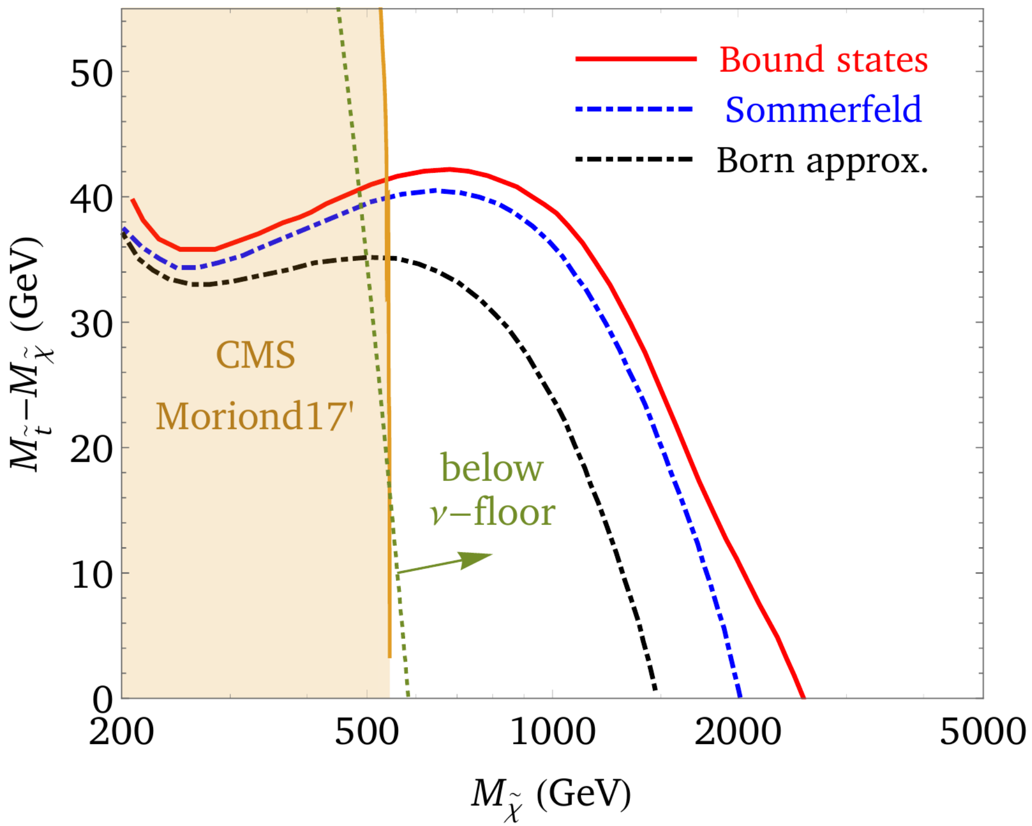
WIMP dark matter

Gluon-mediated bound states in co-annihilation scenarios

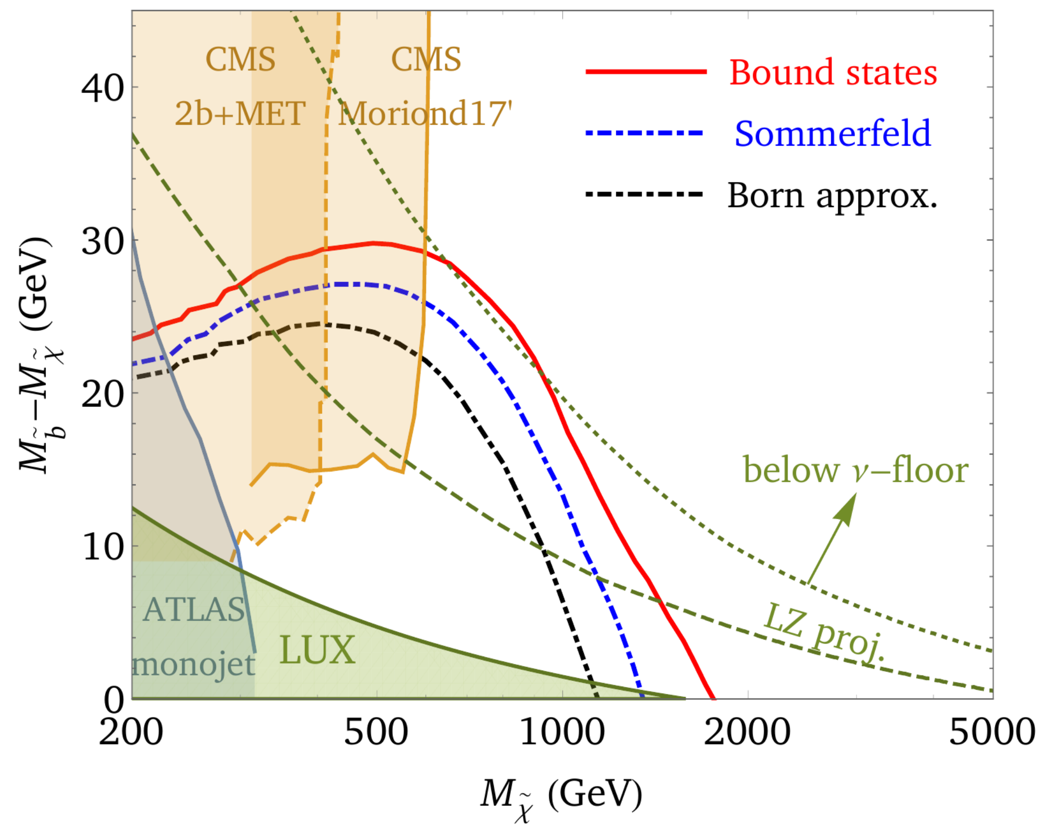
MSSM with near-degenerate NLSP-LSP

Keung, Low, Zhang, 1703.02977; see also Ellis, Luo, Olive, 1503.07142

Bino-Stop coannihilation



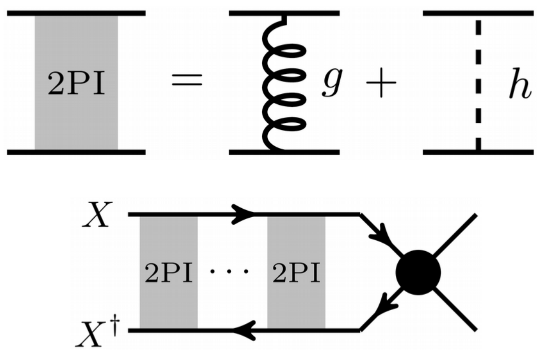
Bino-Sbottom coannihilation



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

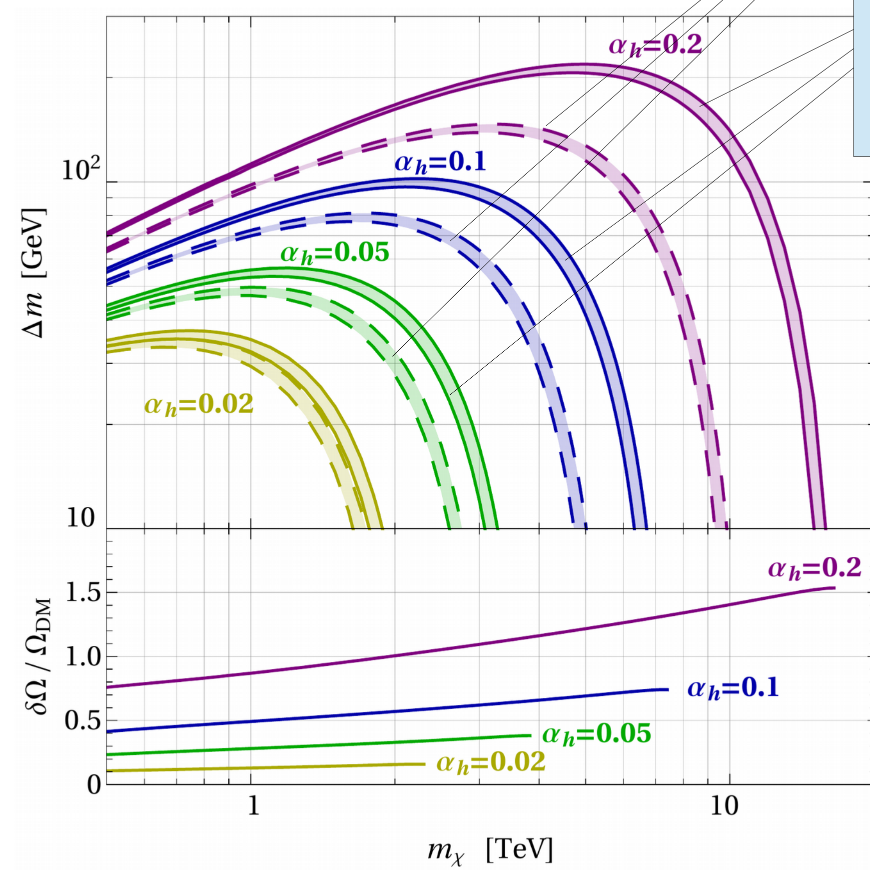
Higgs exchange, typically thought to be too contact-type

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

Some caution:
Computations are new, need to be checked and refined
results presented may change!

WIMP dark matter

Popular candidates

- **Minimal DM** **[Cirelli et al, 2005…]**

  Neutral component of a pure $SU(2)_L$ multiplet.

  Multiplicity & spin chosen to ensure stability.

  Mass determined by observed DM density from thermal freeze-out

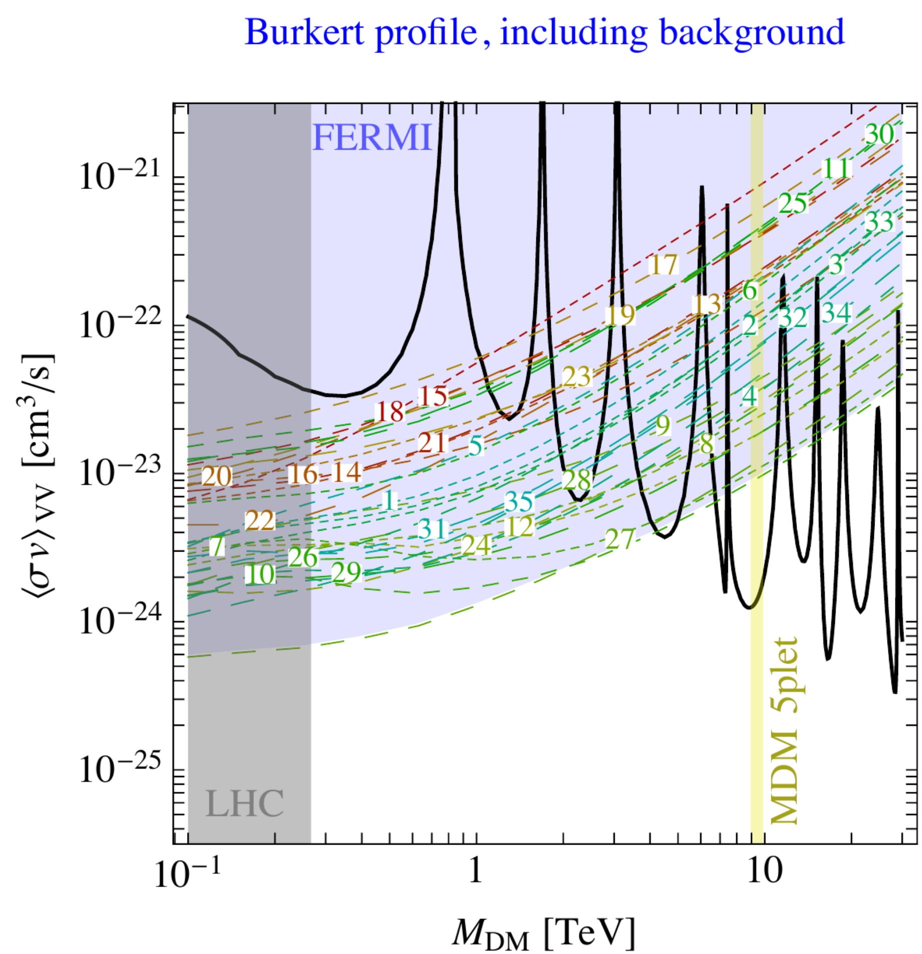
Sommerfeld and BSF important

5-plet, *Y*=0
Spin ½
m_{DM} ~ 10 TeV

Too heavy for LHC.
Too weakly coupled (box diagram) and too heavy for direct detection.

Best probe: Indirect detection

Constraints from diffuse Fermi data



[Cirelli et al, 1507.05519]

resonances imply sensitivity to higher-order corrections & other radiative transitions

Self-interacting dark matter

Self-interacting dark matter

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

[Spergel, Steinhardt (2000)]

- Cross-section needed to affect galactic structure

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

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

- Upper limit from Clusters is of the same order, 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 $\sigma_{\text{self-scatt}} \sim 1/v^4$.

A dark U(1) sector

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

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}

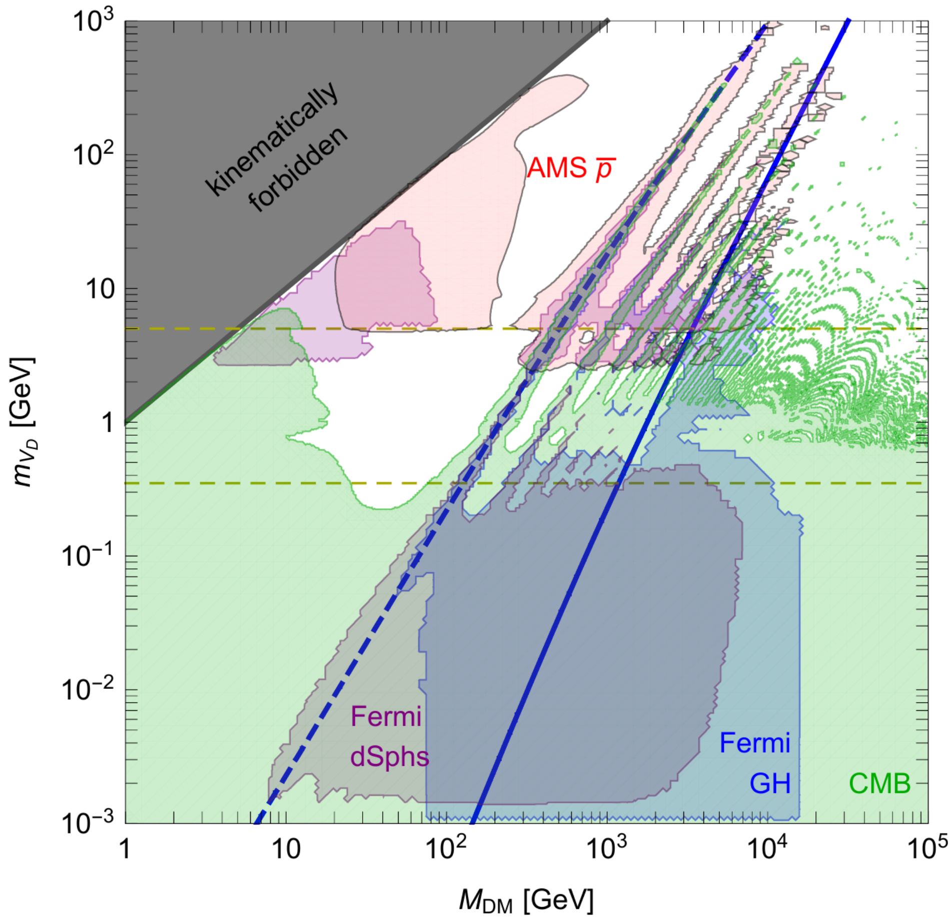
Coupling between
dark photons & ordinary photons
"kinetic mixing" ε

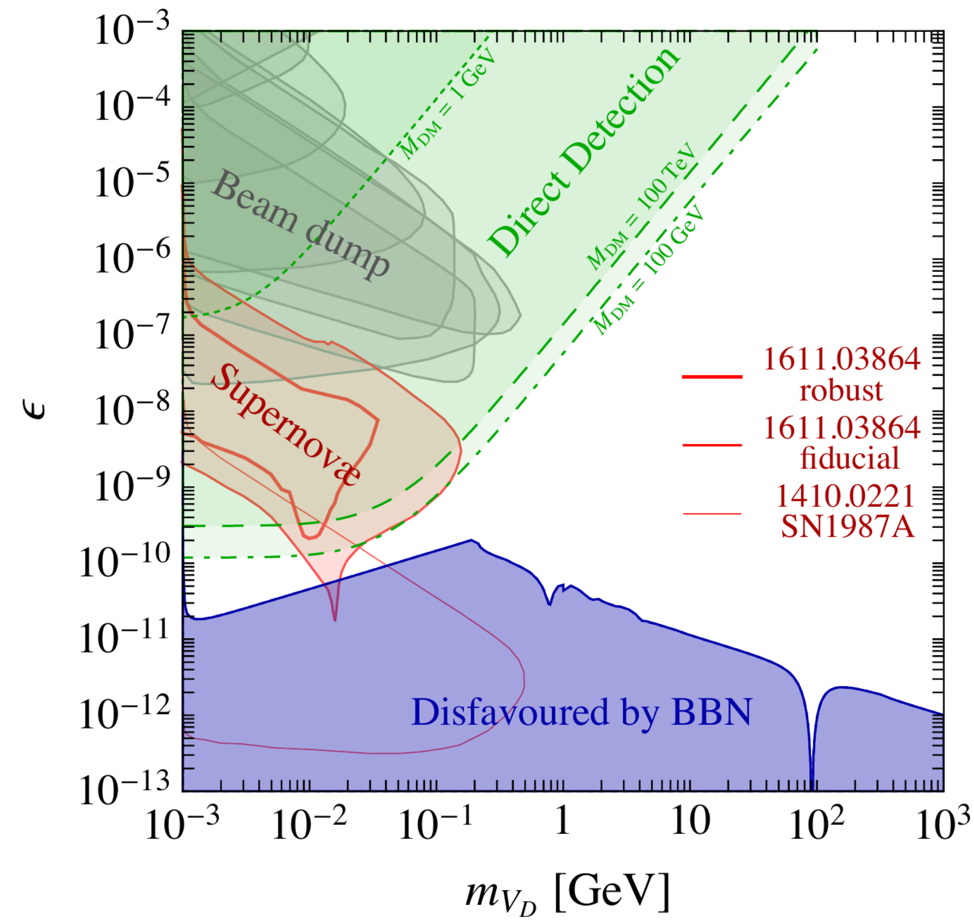
$\alpha_D = \alpha_D(M_{\rm DM})$ **fixed from relic density**

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





Cirelli, Panci, KP, Sala, Taoso, 1612.07295; (see also Bringmann+ 1612.00845)

Dark photon masses sub-eV < m_{V_D} < GeV, excluded !

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

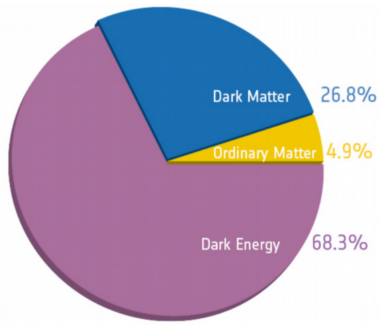
Asymmetric dark matter

Asymmetric dark matter

Motivation

Reviews:
KP, Volkas, 1305.4939
Zurek, 1308.0338

- 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**
  - 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)

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.

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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

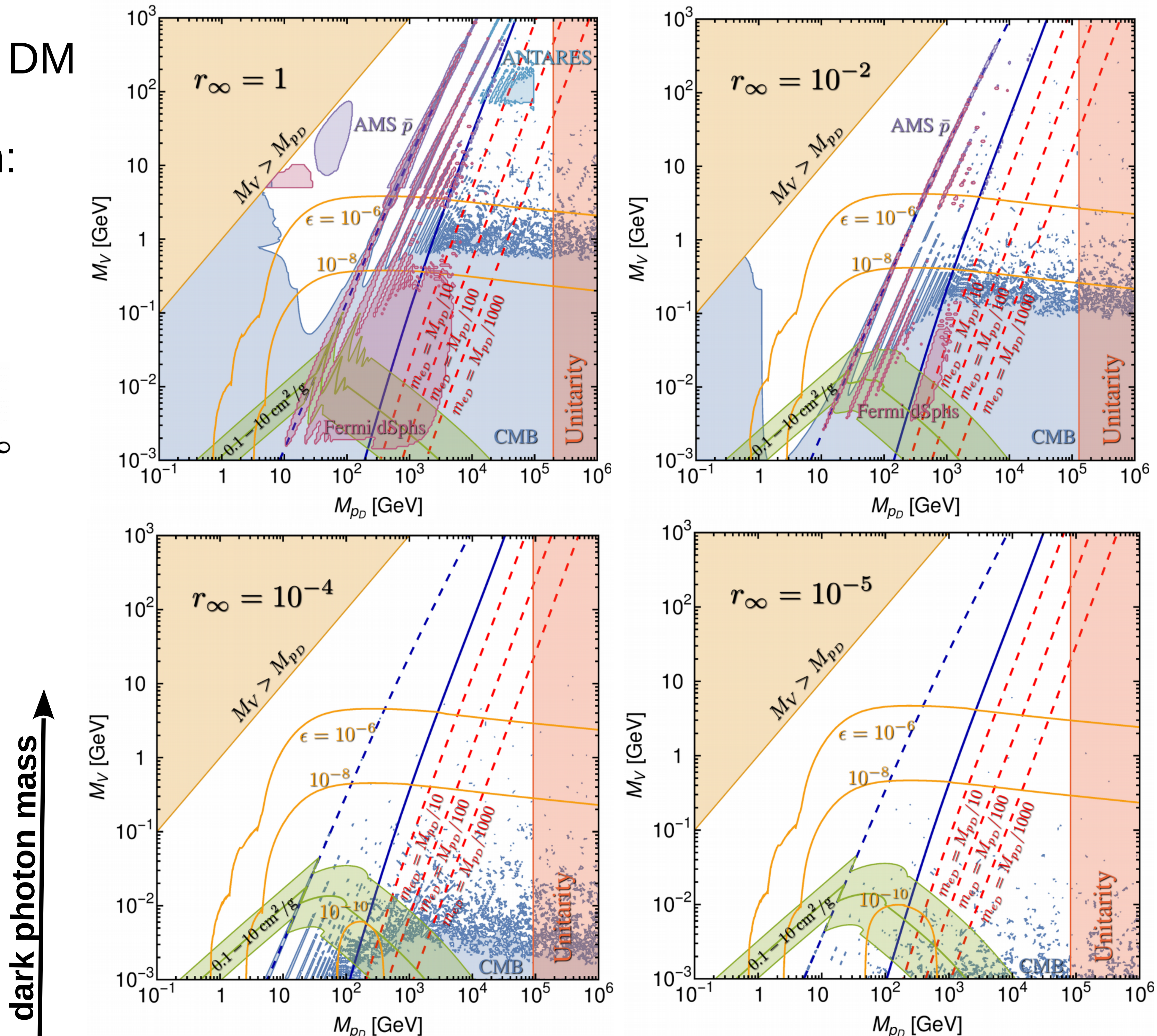
$$p_D + e_D \to H_D + \gamma_D$$
$$\gamma_D \to f^+_{\rm SM} f^-_{\rm SM}$$

[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

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



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

Conclusion

Dynamics of dark matter can be quite complex,
and there are many more frontiers to explore!

- Multicomponent self-interacting DM – effect on galactic structure
- Indirect detection signals from radiative level transitions of symmetric and asymmetric DM
- Signatures in direct detection experiments