Self-interacting asymmetric dark matter

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CosmoChart

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How to begin think about dark matter?

Motivation from high-energy physics (theory or exp)

- Hierarchy problem → WIMPs
- Strong CP problem → Axions
- Neutrino masses → Sterile neutrinos

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Dark-matter related observations

- Relic density: $\Omega_{DM} = 26\ \%$ → Asymmetric dark matter
- Patterns of gravitational clustering → Self-interacting dark matter

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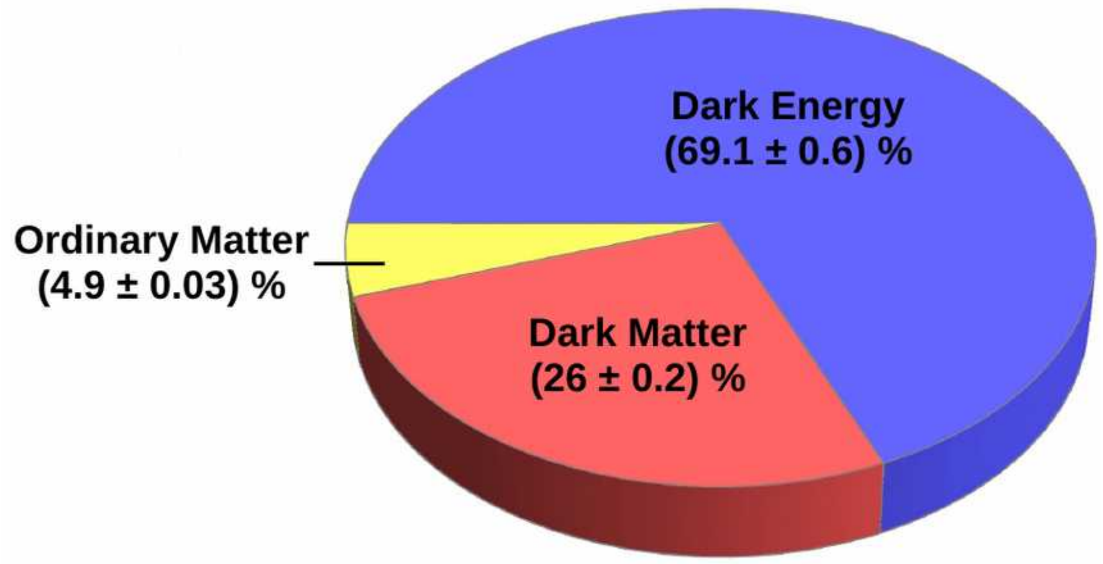
A cosmic coincidence

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



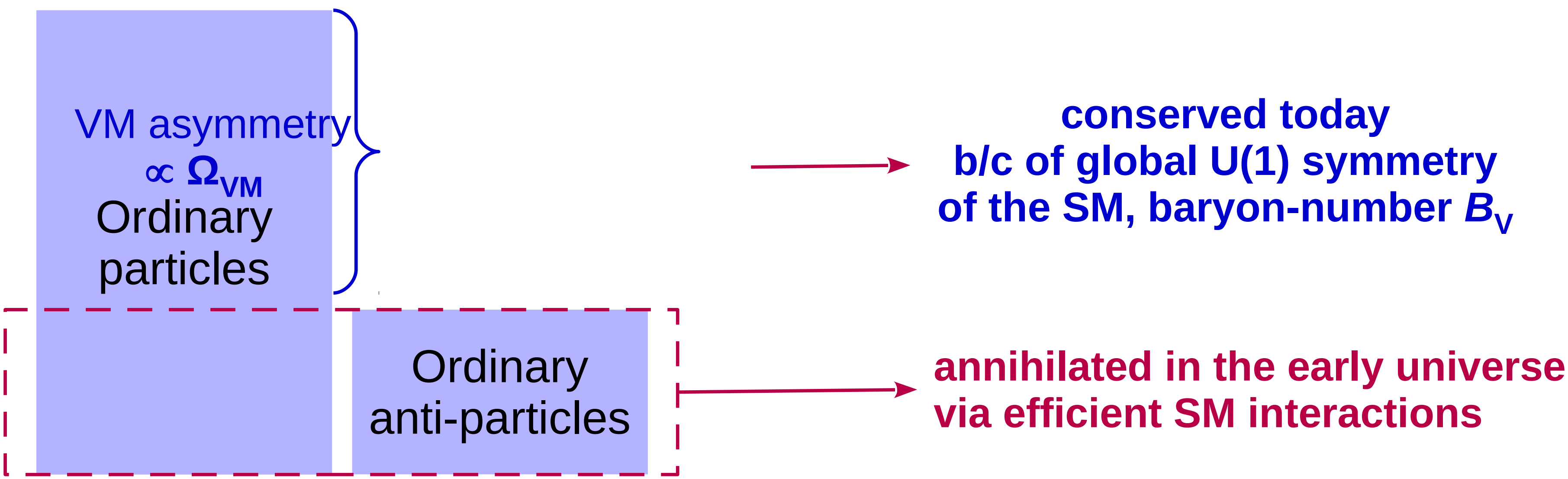
- Unrelated mechanisms → different parameters → result expected to differ by orders of magnitude.

- Similarity of abundances hints towards related physics for VM and DM production.

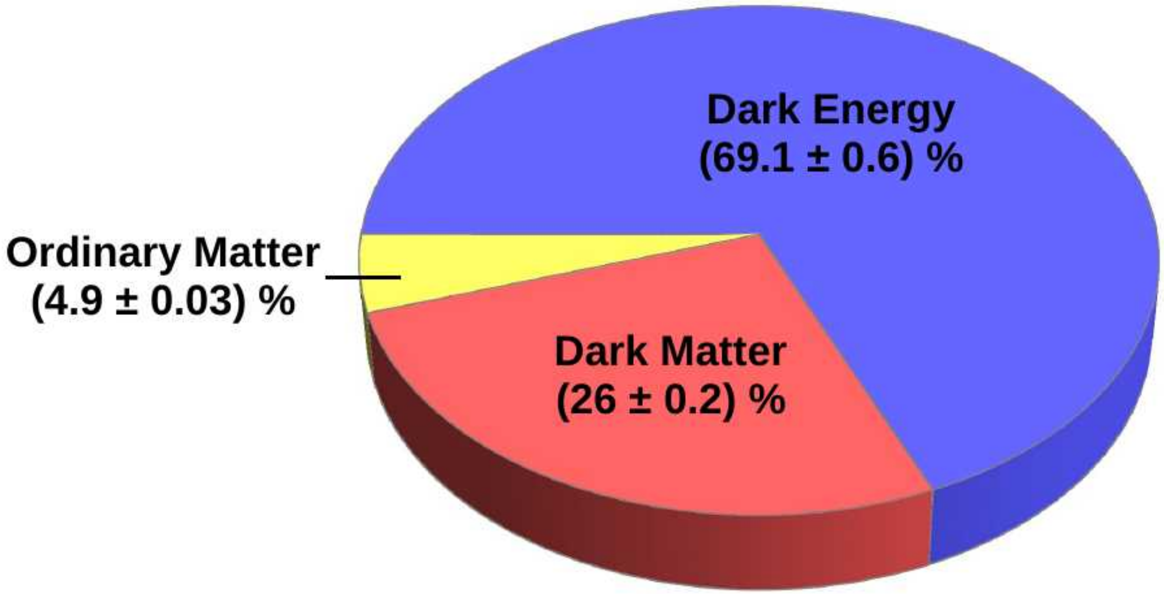
Ordinary matter

Stable particles: p e γ ν

- ***Protons*** make up most of ordinary matter in the universe
- ***Only p, no*** $\bar{p}$ present today: matter-antimatter asymmetry
  - Observational evidence: negligible antimatter in cosmic rays
  - Theoretical consistency: $p - \bar{p}$ annihilation cross-section too large



A non-coincidence



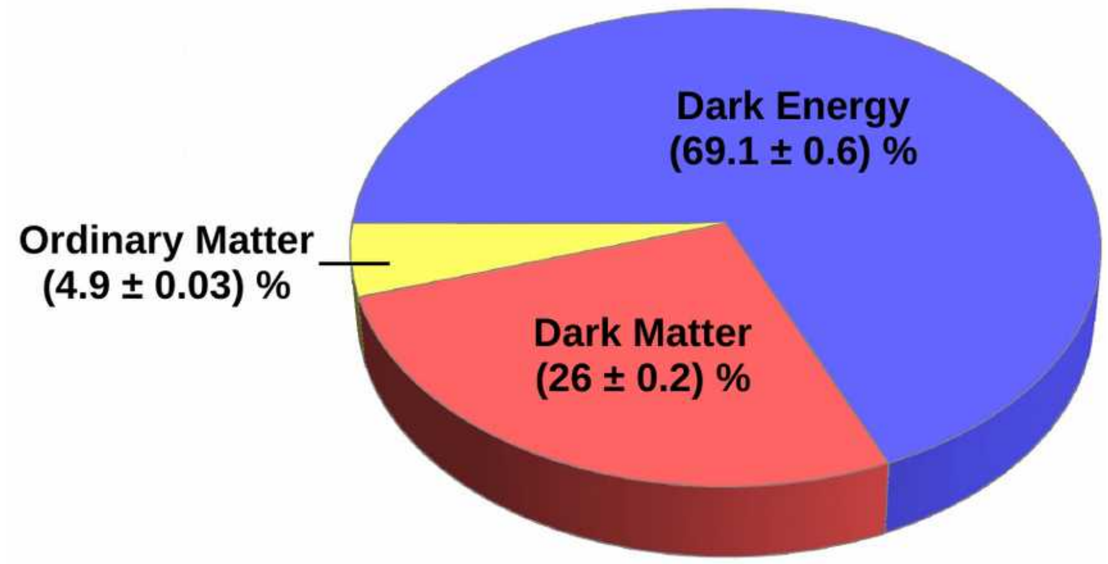
Ordinary matter

- Atoms: 4.9 % → Particle-antiparticle asymmetry
- Photons: 0.0022 %
- Neutrinos: 0.0016 %

(Photons and neutrinos: Relativistic thermal relics)

A cosmic coincidence

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



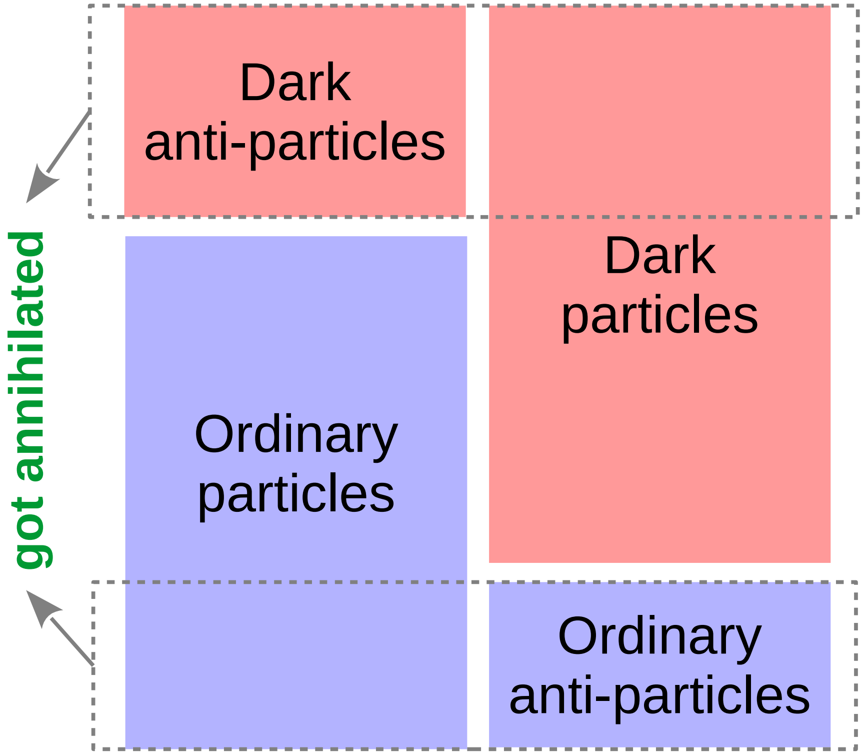
- Just a coincidence

  OR

- Dynamical explanation:

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

The asymmetric DM proposal



- DM density due to an excess of dark particles over antiparticles (asymmetry).
- Dark-ordinary asymmetries related dynamically in the early universe.
- Dark and visible asymmetries conserved separately today.

Ingredients of low-energy theory:

- Global U(1) symmetries: Ordinary and dark baryon numbers
- Dark interaction that annihilates efficiently the dark antiparticles.
  Cross-section needed: $\sigma_{ann} > (\sigma_{ann})_{symmetric\ DM}$ [no upper limit]

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Collisionless Cold Dark Matter and galactic structure

N-body simulations of Collisionless Cold DM

- Reproduce the observed clustering at large scales (> Mpc).
- Predict a lot of substructure also at smaller (galactic and subgalactic) scales. Discrepancies with observations:
  - "missing satellites"
  - "too big to fail"
  - "cusps vs cores"

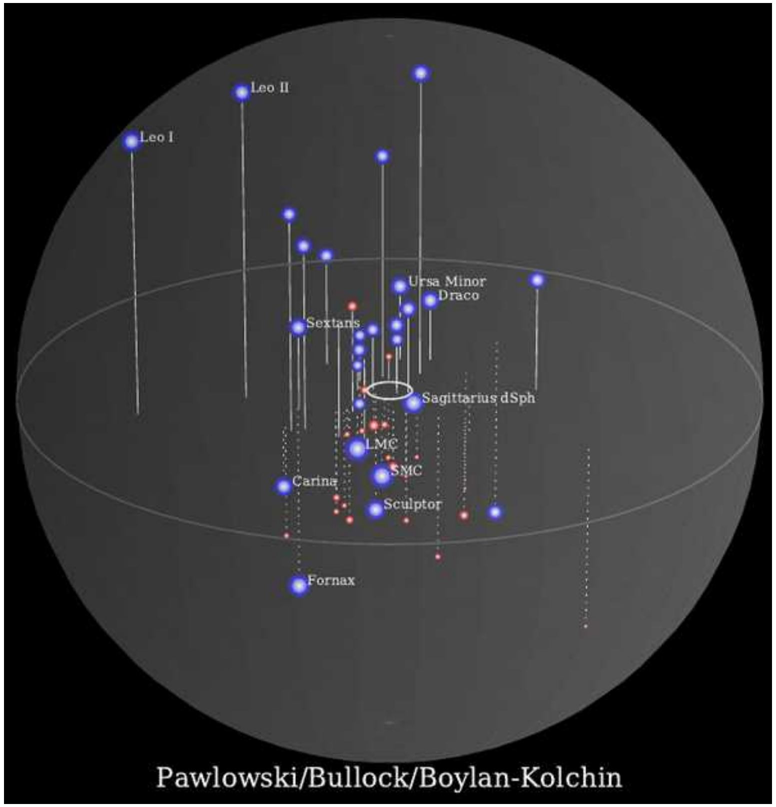
Collisionless Cold Dark Matter and galactic structure

"Missing Satellites"

- For a galaxy of the size of the Milky Way, there are many smaller subhalos
- CCDM simulations predict thousands more than observed

… but ...

- Recent sky surveys have discovered many faint objects. Future surveys expected to discover more.
- **Only the biggest clumps have enough stars to see?**



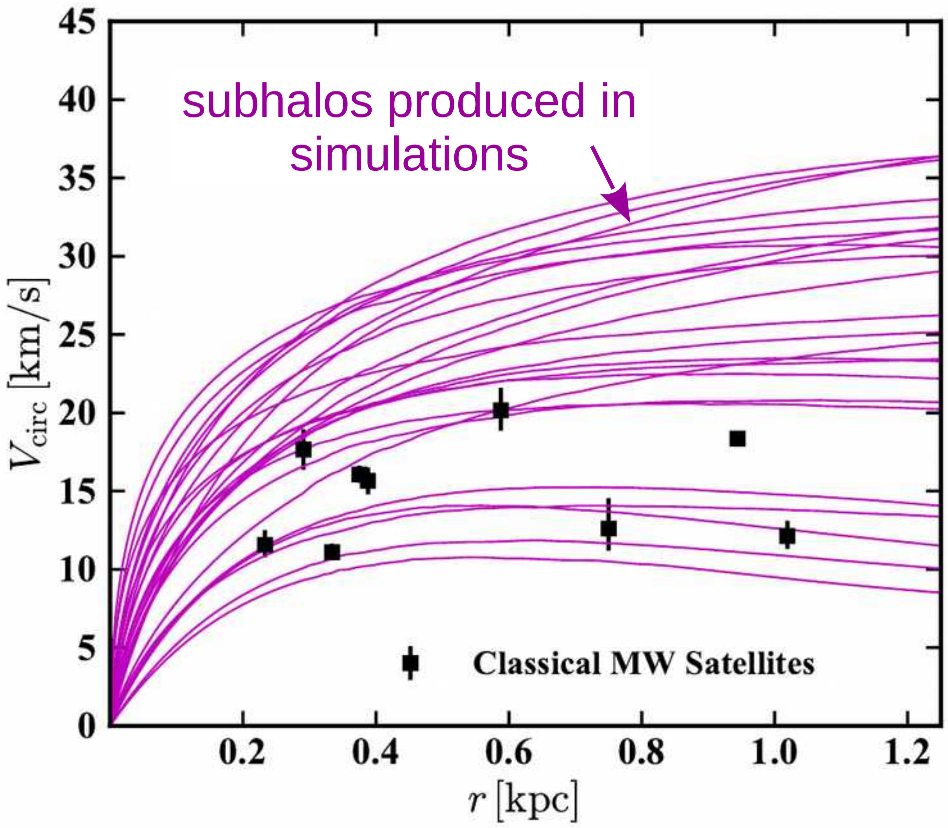
Bullock, Boylan-Kolchin, arXiv:1707.04256

Collisionless Cold Dark Matter and galactic structure

"Too big to fail"

- Focus on larger subhalos
- The massive subhalos produced in simulations are too dense to correspond to the brightest satellites observed.

Star formation could not have failed in largest subhalos



Boylan-Kolchin, Bullock, Kaplinghat, arXiv:1103.0007, 1111.2048

Collisionless Cold Dark Matter and galactic structure

“Cusps vs Cores”

The central regions of DM dominated galaxies are less dense and less cuspy (as inferred from rotation curves), than predicted in standard ΛCDM simulations.

Collisionless Cold Dark Matter and galactic structure

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Collisionless cold DM appears to cluster too efficiently.

Possible resolutions

- **Baryonic physics**

  Hydrodynamic simulations

  - Contraction due to dissipation → problem worsens
  - Supernovae explosions → gas outflow → weakened gravitational pull → DM escapes to larger radii

  Some simulations successful, others less successful. Very active field.

Possible resolutions

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- **Shift in the DM paradigm**

  Retain success at large scales, suppress structure at small scales

  - **Warm DM**
    Suppresses structure below a scale (free-streaming length).

  - **Self-interacting DM**

    Self-scatterings inside halos redistribute energy and momentum and heat up low-entropy material → overdensities get smoothed out, star-formation rate is suppressed.

Self-interacting dark matter

- Cross-section needed to affect galactic structure

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

large!

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

- Upper limit from clusters of galaxies is similar, 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. Rutherford scattering: $\sigma_{\text{self-scatt}} \propto 1 / \text{velocity}^4$

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

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

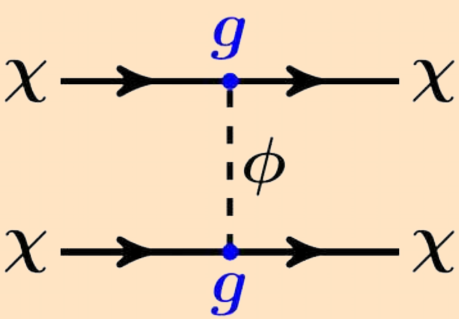
Self-interacting *and* asymmetric?

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

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

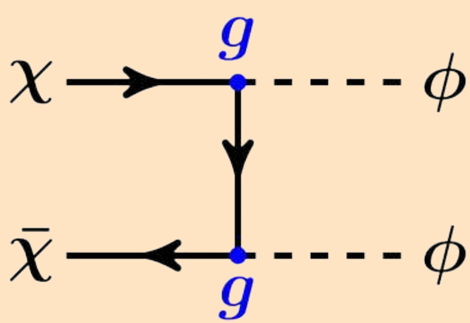
DM self-interaction

$\chi + \chi \to \chi + \chi$



DM annihilation

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



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

Dark U(1) sector:
Symmetric thermal-relic DM

Dark U(1) sector

Everybody's model for

- **astro anomalies**
- **self-interacting DM**
- **...**

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

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

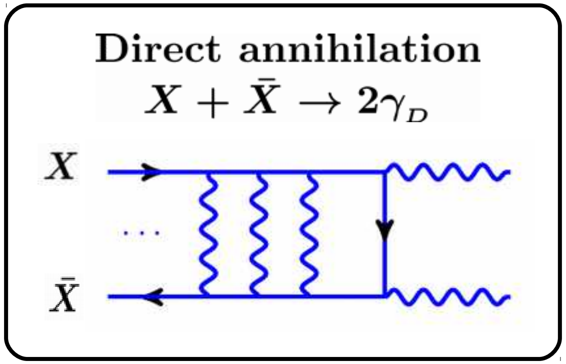
Coupled,

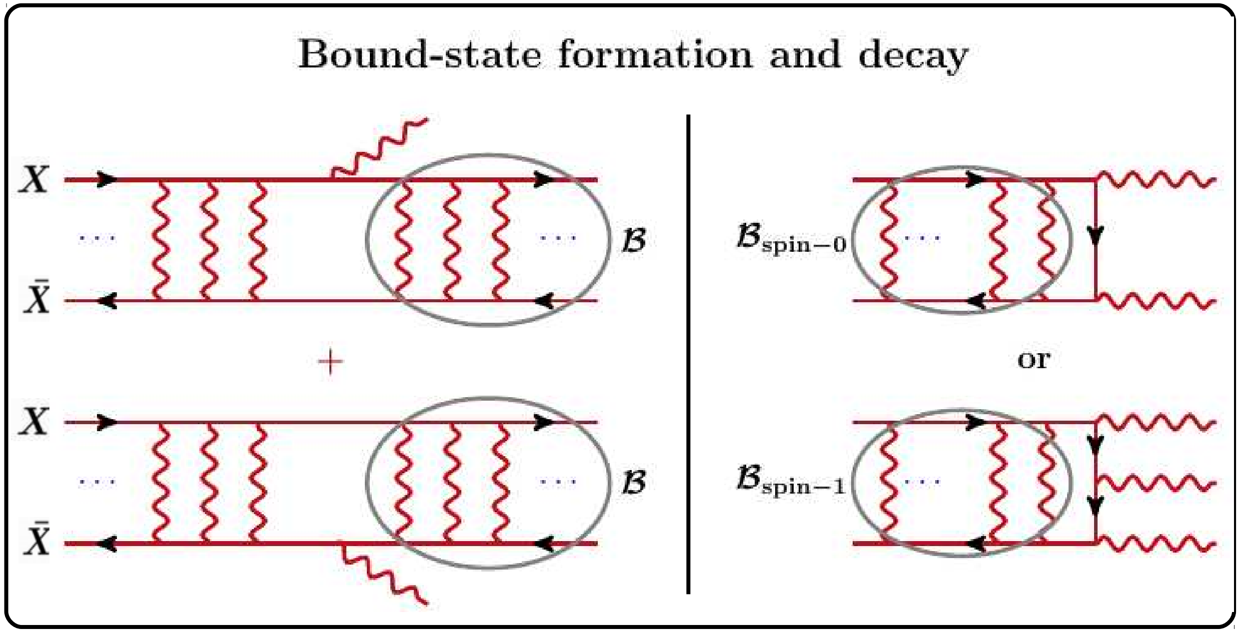
dark fine structure constant α_D

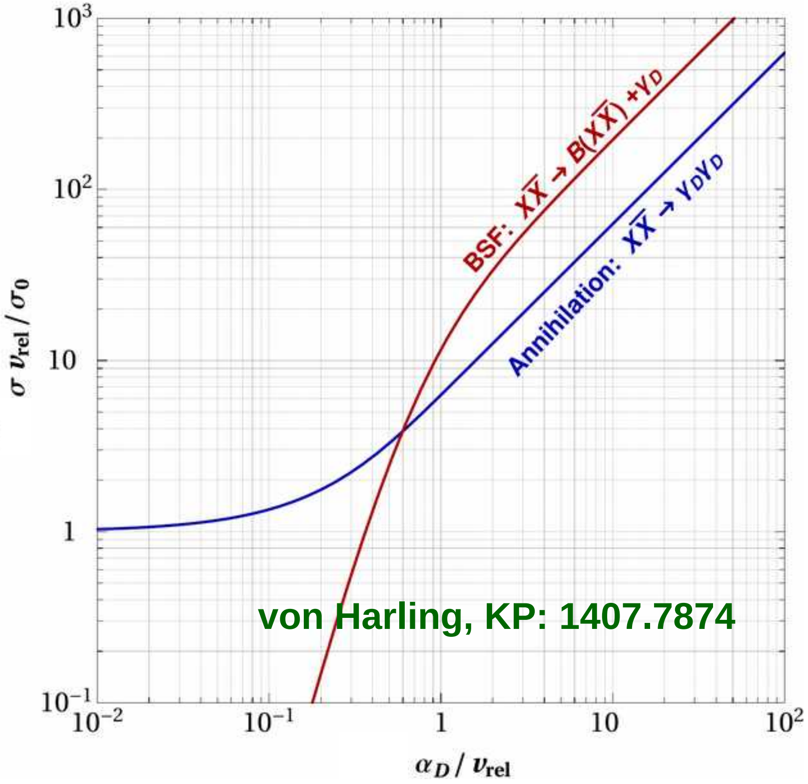
Dark Photons V_D (or γ_D),
with mass m_{V_D} (or m_{γ_D})

Coupling between
dark photons & ordinary photons
kinetic mixing ε

Dark U(1) sector
Annihilation and bound-state formation







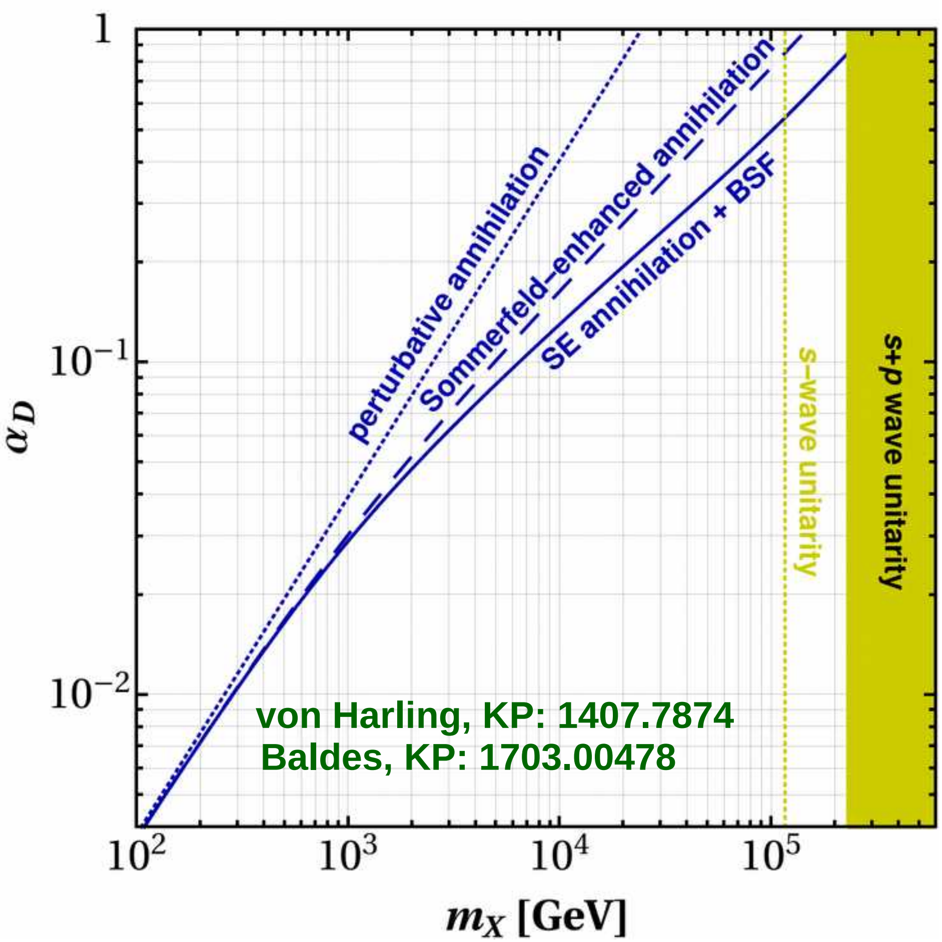
Dark U(1) sector

Freeze-out of symmetric DM

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** $3\gamma_D$



von Harling, KP: 1407.7874
Baldes, KP: 1703.00478

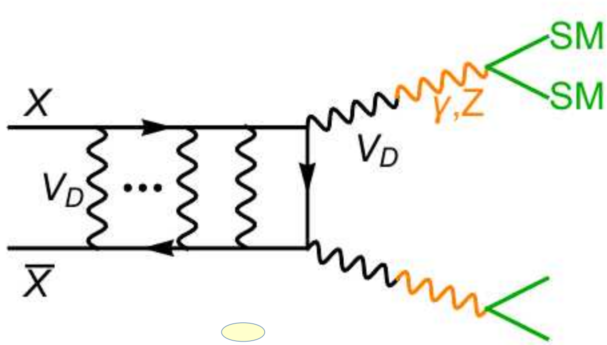
Dark U(1) sector

Indirect detection

Cirelli, Panci, KP, Sala, Taoso, 1612.07295

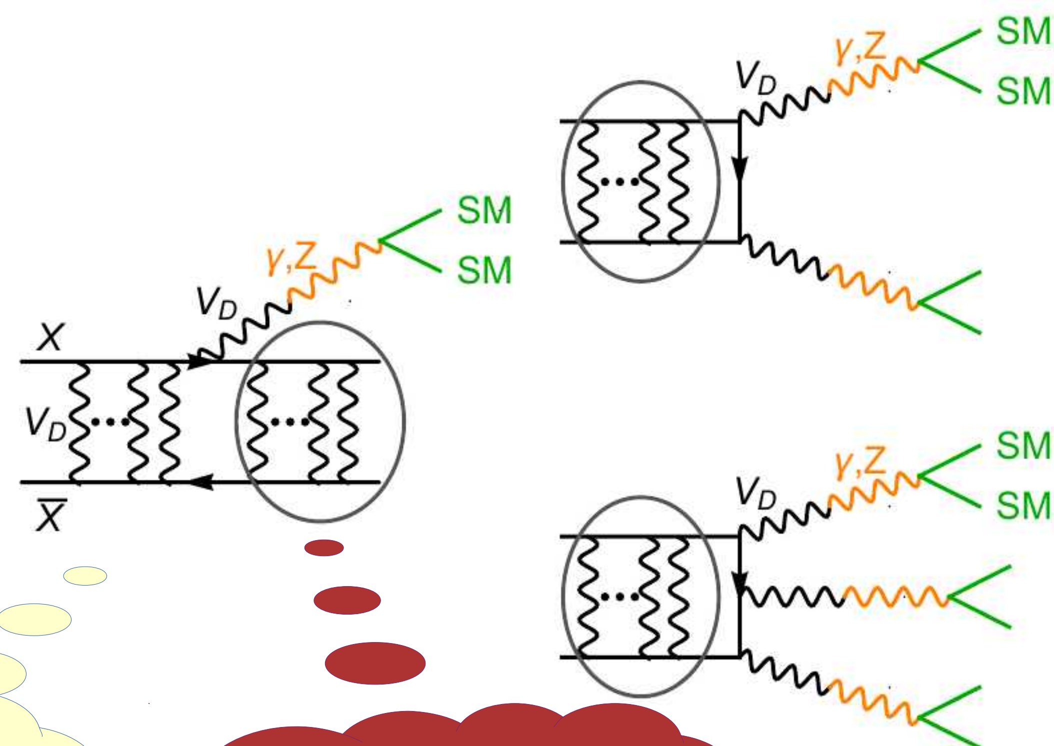
Annihilation

$X + \bar{X} \leftrightarrow V_D + V_D$



Bound-state formation

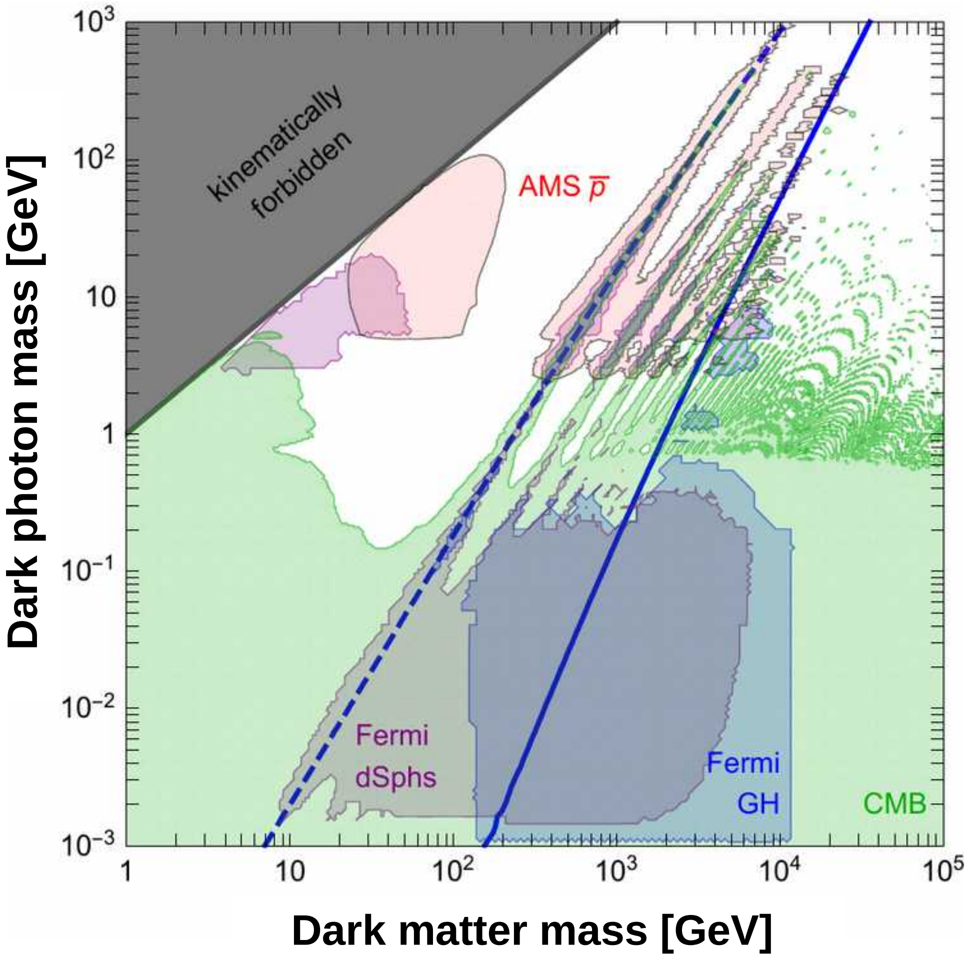
$X + \bar{X} \leftrightarrow (X\bar{X})_{bound} + V_D$



Sommerfeld effect: enhancement at low velocities if V_D light

"Dark positronium" bound states: exist if V_D light

Dark U(1) sector
Indirect detection



- Dark photon mass range MeV – GeV, suitable for self-interacting DM, highly constrained by γ-rays & CMB

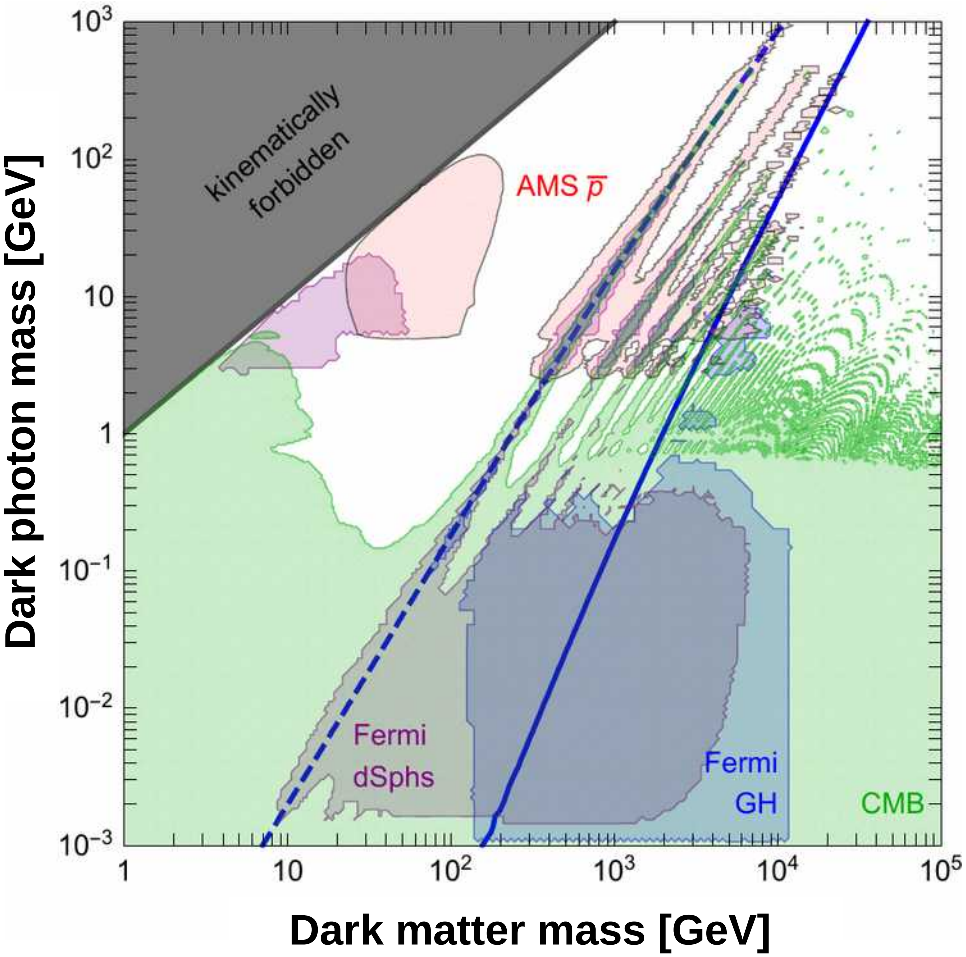
- Can bounds be evaded for small ε?

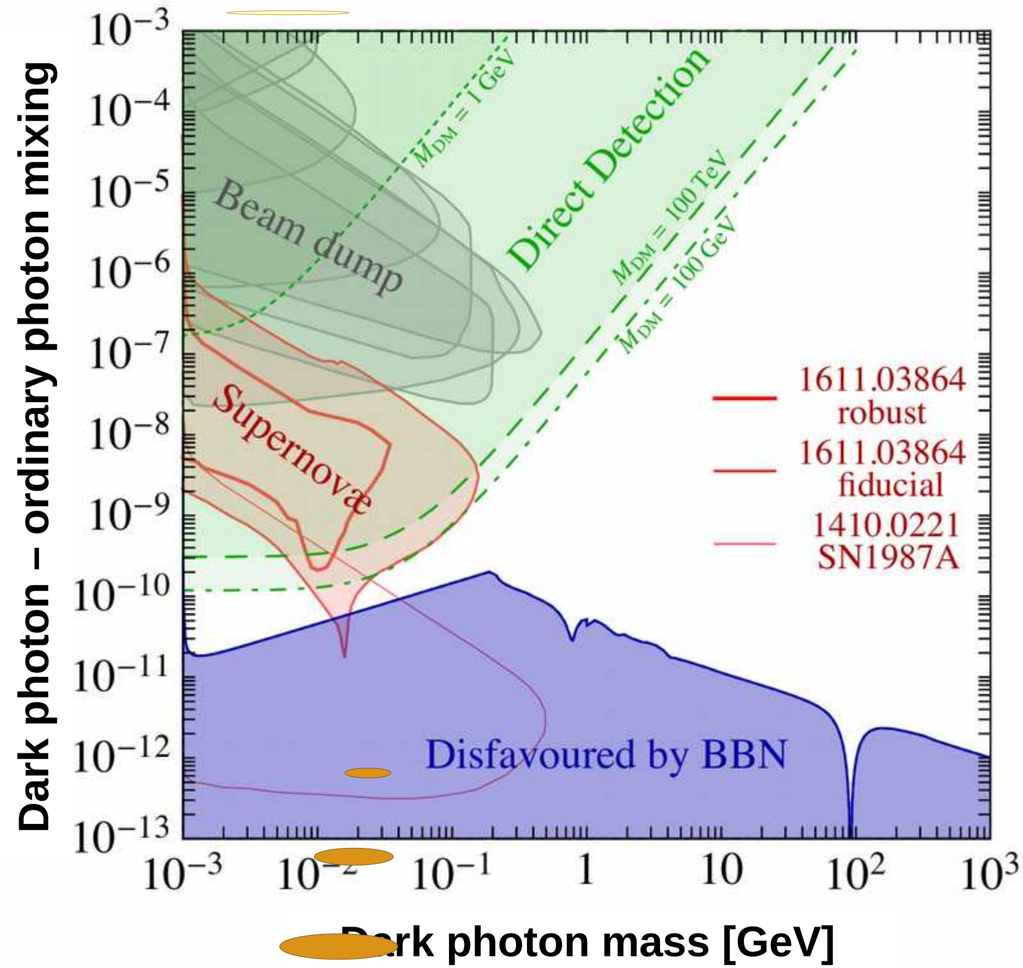
Cirelli, Panci, KP, Sala, Taoso 1612.07295

Dark U(1) sector

Indirect detection

Large mixing constrained by indirect & direct detection and other exps





Small ε constrained by cosmology

Cirelli, Panci, KP, Sala, Taoso 1612.07295

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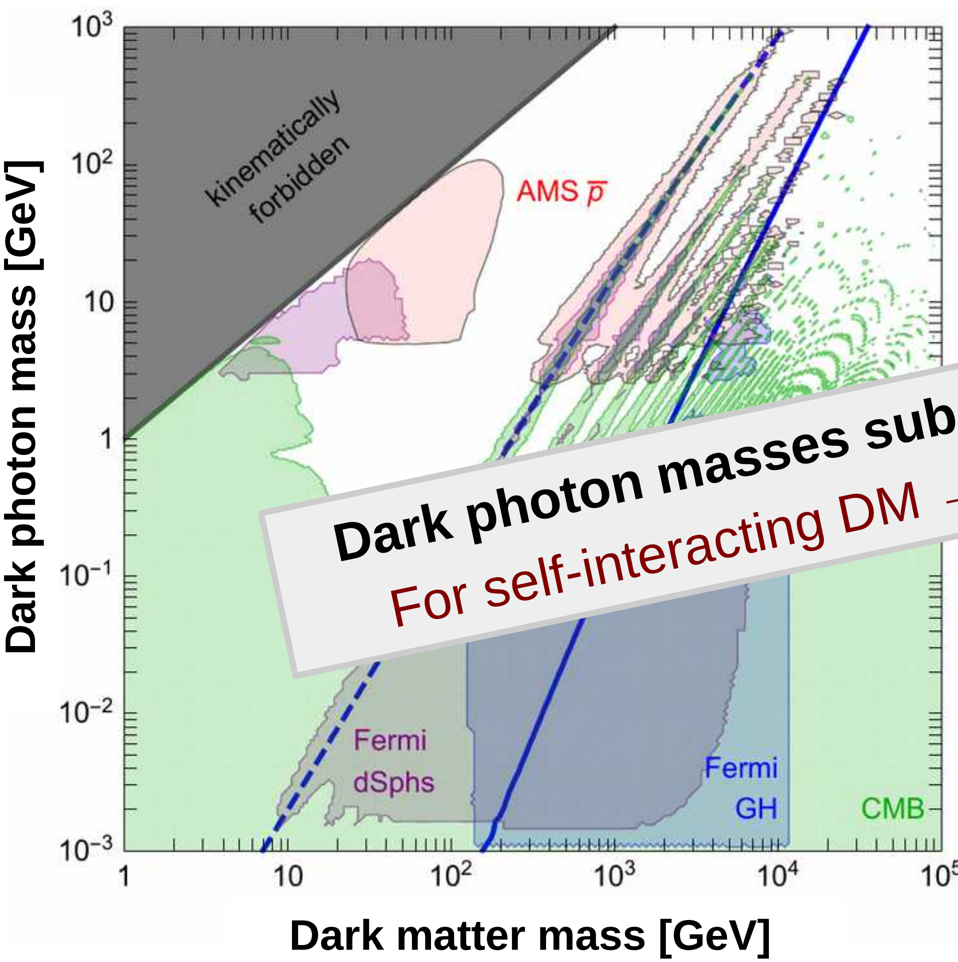
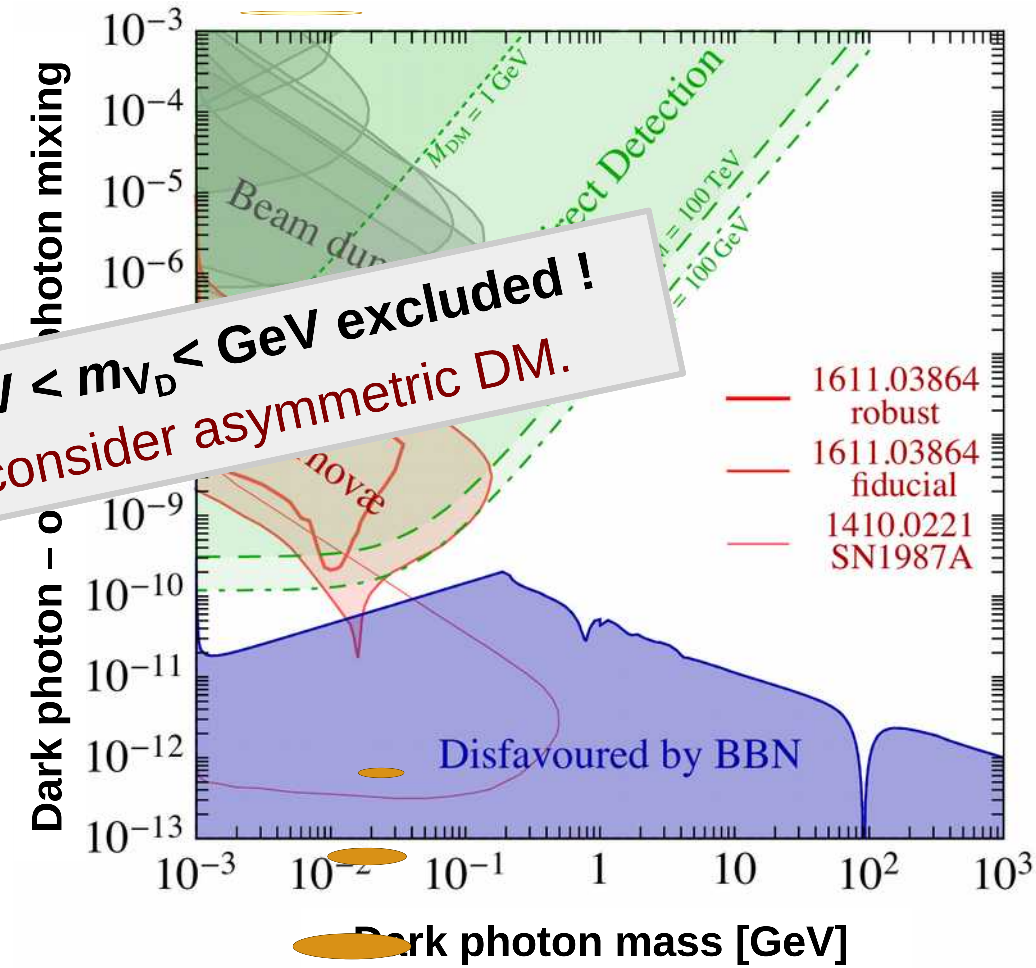




Dark photon masses sub-eV < m_{V_D} < GeV excluded !

For self-interacting DM → consider asymmetric DM.

Small ε constrained by cosmology

Cirelli, Panci, KP, Sala, Taoso 1612.07295

Asymmetric dark matter

- Dark antiparticles annihilate in the early universe with dark particles → mostly dark particles left today

- Yes, but not completely! A small amount of antiparticles is left.

  How much depends on annihilation cross-section.
  Strong annihilation → fewer antiparticles left.

- Due to long-range interaction, the annihilation cross-section inside galaxies (smaller velocities) is larger than in the early universe (larger velocities)

  → Annihilations signals of asymmetric DM can be significant!

Baldes, KP 1703.00478

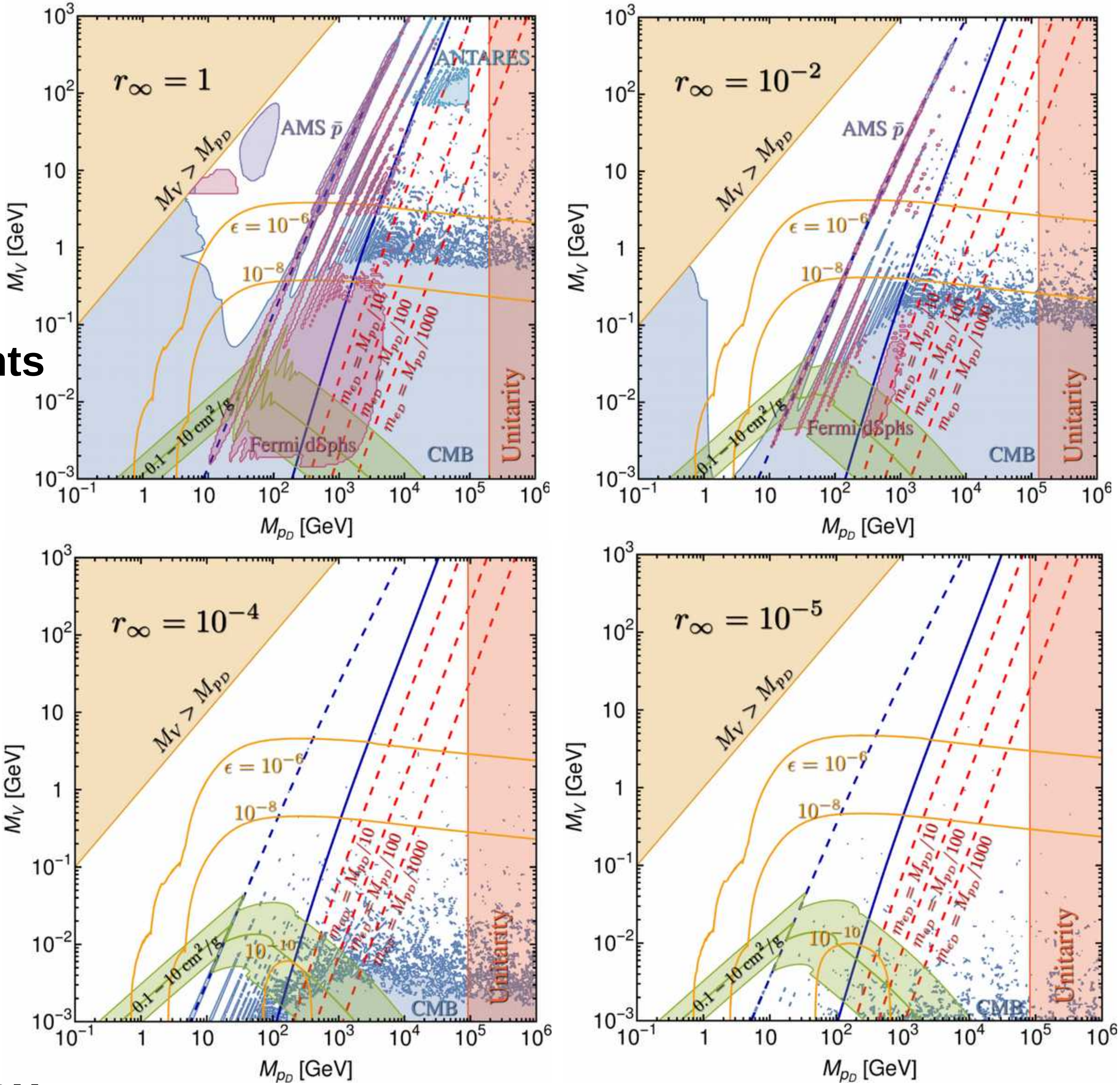
(A)symmetric DM coupled to a dark photon:

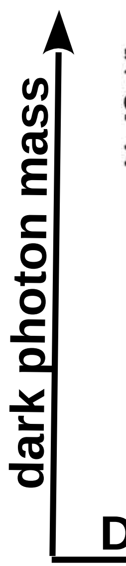
Self-interactions

and

indirect & direct detection constraints

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





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

Conclusion

- Small-scale galactic structure may be offering important hints on the nature of dark matter:

  compelling self-interacting DM paradigm

- Indirect detection, direct detection and cosmology offer complimentary probes.

  Direct detection particularly important for asymmetric DM