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
  - Not hot at the onset of gravitational collapse
  - Cold or warm?
  - Collisionless or self-interacting?

DM is not a known particle!
We know that we don't know.

But we also know that we would like to know!

Socrates
by Leonidas Drosis, Athens - Academy of Athens.
Image from Wikipedia.
Dark matter candidates
Classification schemes
Dark matter candidates

Classification schemes

Interaction with the SM

Portal operators

\[ \epsilon \, F_\gamma^{\mu \nu} F_{\rho \nu}^{\mu} \]
\[ (\mu \phi + \lambda \phi^2) |H|^2 \]
\[ y L H N \]

SM interactions

WIMPs

Heavy mediators

EFTs

[Tim Tait’s talk]
## Dark matter candidates

### Classification schemes

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# Dark matter candidates

## Classification schemes

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### Production mechanism

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

See dedicated talks on

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

with emphasis on long-range effects
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!

\[
\Omega \sim 0.26 \times \left( \frac{1 \text{pb} \cdot c}{\sigma_{\text{ann}} \nu_{\text{rel}}} \right)
\]
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

\[
\sigma_{\text{ann}}^{\text{eff}} = \left[ n_{\text{LSP}}^2 \sigma_{\text{ann}}^{\text{LSP}} + n_{\text{NLSP}}^2 \sigma_{\text{ann}}^{\text{NLSP}} + n_{\text{LSP}} n_{\text{NLSP}} \sigma_{\text{ann}}^{\text{LSP-NLSP}} \right] / n_{\text{tot}}^2
\]

- 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

\[ X + \bar{X} \rightarrow 2\gamma_D \]

\[ \sigma_{\text{ann}} \nu_{\text{rel}} = \frac{\pi \alpha_D^2}{m^2_x} \times S_{\text{ann}}(\alpha_D/\nu_{\text{rel}}) \]

Radiative bound-state formation

\[ X + \bar{X} \rightarrow \mathcal{B}(X \bar{X}) + \gamma_D \]

\[ \sigma_{\text{BSF}} \nu_{\text{rel}} = \frac{\pi \alpha_D^2}{m^2_x} \times S_{\text{BSF}}(\alpha_D/\nu_{\text{rel}}) \]
Bound-state formation and relic density

Dark U(1) model

Direct Annihilation \( X\bar{X} \rightarrow \gamma_D \gamma_D \)
Bound-state formation \( X\bar{X} \rightarrow B(X\bar{X}) + \gamma_D \)
and decay \( B(X\bar{X}) \rightarrow 2\gamma_D \) or \( 3\gamma_D \)

\[ \Omega_{SE\,ann} / \Omega_{DM} \approx 2 \]

Effect larger than the experimental uncertainty of 1% at 15 TeV

\[ \Omega_{SE\,ann} / \Omega_{DM} \]

Effect larger than experimental sensitivity

von Harling, KP: 1407.7874
Baldes, KP: 1703.00478
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]

DM co-annihilating with scalar color-triplet
DM co-annihilating with fermionic color-octet

SE annihilation + bound states
SE annihilation
Perturbative annihilation
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 potential influences how long-range the Higgs exchange manifests!

Higgs exchange, typically thought to be too contact-type

Gluon and Higgs exchange

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

Dashed bands: without Higgs enhancement
Solid bands: with Higgs enhancement

Range of \( \alpha_h \) occurs in MSSM

Effect on \( \Omega \) 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

  5-plet, $Y=0$
  Spin $\frac{1}{2}$
  $m_{DM} \sim 10 \text{ TeV}$

  Too heavy for LHC.
  Too weakly coupled (box diagram) and too heavy for direct detection.
  Best probe: Indirect detection

Constraints from diffuse Fermi data
Burkert profile, including background
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
  \[ \frac{\sigma_{\text{self-scatt}}}{m_{\text{DM}}} \sim \text{barn/GeV} \sim \text{cm}^2/\text{g} \]  
  at dwarf-galaxy scales, \( v_{\text{DM}} \sim 20 \text{ km/s} \).

- Upper limit from Clusters is of the same order, at \( v_{\text{DM}} \sim 1000 \text{ km/s} \).

- No tension between the two, if \( \sigma_{\text{self-scatt}} \) decreases with increasing \( v_{\text{DM}} \)
  \[ \Rightarrow \text{Light mediators, long-range interactions!} \]
  e.g. massless mediator: Rutherford scattering \( \sigma_{\text{self-scatt}} \sim 1/v^4 \).
A dark U(1) sector

\[ \mathcal{L} = \bar{X}(i\not \! \partial) - M_{DM} X - \frac{1}{4} F_{D\mu\nu} F_{D}^{\mu\nu} - \frac{1}{2} m_{V_{D}}^{2} V_{D\mu} V_{D}^{\mu} - \frac{\varepsilon}{2c_{w}} F_{D\mu\nu} F_{Y}^{\mu\nu} \]

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

Coupled, dark fine structure constant \( \alpha_{D} \)

Dark Photons \( V_{D} \), with mass \( m_{V_{D}} \)

Coupling between dark photons & ordinary photons “kinetic mixing” \( \varepsilon \)

\[ \alpha_{D} = \alpha_{D}(M_{DM}) \] fixed from relic density

Direct Annihilation \( X\bar{X} \rightarrow V_{D} V_{D} \)

Bound-state formation \( X\bar{X} \rightarrow \mathcal{B}(X\bar{X}) + V_{D} \)

and decay \( \mathcal{B}(X\bar{X}) \rightarrow 2V_{D} \) or \( 3V_{D} \)

Dark photon decay \( V_{D} \rightarrow f_{SM}^{+} f_{SM}^{-} \)
A dark U(1) sector
Constraints

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
  - Asymmetric dark matter

  [e.g. pure non-Abelian gauge theory Boddy, Feng, Kaplinghat, Tait (2014)]
Asymmetric dark matter
Asymmetric dark matter

Motivation

• 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.

Reviews:
KP, Volkas, 1305.4939
Zurek, 1308.0338
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

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

- **Non-Abelian gauge theory + fermions**
  
  Dark nucleons & nuclei

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

---


[KP, Pearce, Kusenko 2014]

[Detmold, McCullough, Pochinsky 2014]

[Wise, Zhang 2014]
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- **Scalar mediator**
  
  Attractive interaction between particles; multi-particle bound states may form.

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


Detmold, McCullough, Pochinsky 2014]

[KP, Pearce, Kusenko 2014]

Detmold, McCullough, Pochinsky 2014]

[Wise, Zhang 2014]
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.

\[ p_D + \bar{p}_D \rightarrow \gamma_D + \gamma_D \]
\[ \gamma_D \rightarrow f_{SM}^+ f_{SM}^- \]

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

\[ p_D + e_D \rightarrow H_D + \gamma_D \]
\[ \gamma_D \rightarrow f_{SM}^+ f_{SM}^- \]

[ 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

\[
\rho_\infty \equiv \frac{n_{\chi}}{n_X} \bigg|_{t \to \infty}
\]
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