Status of Dark Matter Theories

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Dark Matter $\Omega_{DM} \approx 23\%$
—The Known Unknown

- **Dark Matter:**
  85% of cosmic matter abundance!

Compelling evidence:
Dark Matter $\Omega_{DM} \approx 23\%$
—The Known Unknown

- What is it? Where does $\Omega_{DM}$ come from?

The Standard Model (SM)

- Beyond the Standard Model of Particle Physics!

New Physics !?
Towards Resolving the Mystery — What is dark matter?

• Clues about dark matter properties: very limited
  
  ‣ Must be stable \((\tau \gtrsim \tau_{\text{universe}})\)
  ‣ Must be produced in the early universe
  ‣ Must form cosmological structures consistent with astronomical observations: favors cold, collisionless DM, weakly interacting with the visible matter
  ‣ Must render observed relic abundance: \(\Omega_{\text{DM}} \approx 23\%\)

Mass? Non-gravitational interactions?
  Minimal, single particle specie or as complex as our visible matter sector?…?

☞ Deductive approach insufficient for resolving this big mystery!
Towards Resolving the Mystery
— What can dark matter be?

- Need additional inspiration/motivation as guideline, to nail down concrete theoretical models for investigations:
  - **Theoretical**: DM candidates connect to/solve other theoretical problems, philosophical appeals
    E.g. electroweak hierarchy problem (WIMP DM); strong CP problem (axion DM), WIMP miracle for $\Omega_{\text{DM}}$
  - **Observational**: experimental data that may be explained by certain type of DM
    E.g. cosmic ray excess unexplained by astrophysical sources (annihilating or decaying DM), $\Omega_{\text{DM}} \sim \Omega_{\text{Baryon}}$ (asymmetric DM)

- **Educated guesses/hypothesis** $\rightarrow$ testable predictions
  $\rightarrow$ experimental test/search $\rightarrow$ resolve the mystery
Vast Landscape of Theoretical Candidates for Dark Matter

Proposed DM models:

Ranges of mass, interaction strength with visible matter

Cross Section (Xenon for Reference)

- Axion
- Black Hole
- Gravitino
- Moduli
- Q–ball
- Sterile Neutrino
- Strangelet
- WIMP
- WIMPzlla
Classification of Dark Matter Candidates

- **Thermal dark matter:** once in thermal equilibrium in the early universe (with visible matter OR own sector)
  - Appreciable non-gravitational interaction(s)
    - Symmetric WIMP-type DM: $\Omega_{DM}$ set by thermal freezeout
      - Conventional WIMP, variations
    - Asymmetric DM: $\Omega_{DM}$ set by initial matter-antimatter asymmetry, analogous to $\Omega_{baryon}$

- **Non-thermal dark matter:** never in a thermal bath (*lone wolf*)
  - Super-weak or gravitational interactions
    - Axion DM
    - Sterile neutrino, SuperWIMP (produced from late decay) …

★ **Complex DM sector:** multiple-component? self-interactions?…
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(Conventional) WIMP Dark Matter

**WIMP**: Weakly Interacting Massive Particle

- Naturally expected new particle at new energy frontier of particle physics (Large Hadron Collider)!
  Motivated candidates by EW naturalness/hierarchy problem

- Could it be Dark Matter? 🎉?
(Conventional) WIMP Miracle DM — $\Omega_{DM}$ by weak scale new physics

- Cosmic Evolution of a stable WIMP $\chi$:

Universe expands, cools, $T \downarrow$

Thermal freezeout

Equilibrium

Annihilation

Time evolution of $\chi$ abundance:

$\Gamma_{\text{ann}} \sim n_{\chi}^{\text{eq}} \langle \sigma_{\text{ann}} v \rangle < H$

$n_{\chi}^{\text{eq}} \propto e^{-M_{\chi}/T}$
WIMP DM Miracle

- Neat prediction for the absolute amount of $\Omega_{DM}$:

$$\Omega_{\chi} \propto \langle \sigma_{\text{ann}} v \rangle^{-1}$$

$$\sim 0.1 \left( \frac{G_{\text{Fermi}}}{G_{\chi}} \right)^2 \left( \frac{M_{\text{weak}}}{m_{\chi}} \right)^2$$

With $m_{\chi} \sim M_{\text{weak}}, G_{\chi} \sim G_{\text{Fermi}}$, readily gives $\Omega_{DM} \approx 23%$

- Robust, insensitive to cosmic initial condition

- **Miracle**: Predicts the right location of a needle in a haystack!

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Observed $\Omega_{DM} \approx 23\%$

Vast possible range of a cosmological quantity: e.g. $\Omega_{DM}^{\text{theory}} \sim (10^{-7} - 10^{35})$
Detectability, Challenges of WIMP DM

- Multi-pronged detectability (w/DM-SM interactions)

\[ \Omega_{DM}, \text{Indirect detection} \]

Direct detection

Collider search

- No convincing signal so far, constraints getting strong

\[ \Omega_{DM} \]

- Could be right at the corner…
- Simple, natural variations?
  - Light thermal DM \((m_{DM} \approx O(\text{GeV}))\)
  - Thermal annihilation into dark states

\[ \sigma_{N} \]

\[ \sigma_{V} \]
Light Thermal Dark Matter

- **Motivations:**
  - Thermal DM doesn’t have to be $M_{\text{weak}} \sim 100$ GeV
    \[
    \Omega_\chi \propto \langle \sigma_{\text{ann}} v \rangle^{-1} \\
    \sim 0.1 \left( \frac{G_{\text{Fermi}}}{G_\chi} \right)^2 \left( \frac{M_{\text{weak}}}{m_\chi} \right)^2 \quad \text{weaker coupling, lighter mass ✔}
    \]
  - In part inspired by anomalies at experiments (DAMA, COGENT…)

- **Theoretical models:**
  Often involve light dark photon $A'$ ✔New force!

  Kinetic mixing with SM photon

  ![Kinetic Mixing Diagram](image)

- **New detection strategies needed!** (Essig, Schuster, Toro…)
  Low threshold DM experiments, dark photon search…
Thermal Annihilation into Stable Dark States — New Realization of WIMP Miracle

Simple, generic variation: ➔ new search strategies!

WIMP DM

Stable dark states

Massive: DM’ ➔ Boosted DM! (vs. cold/slow)

(Nearly) massless: Dark radiation ➔ affect CMB

Stable dark states
Thermal Annihilation into Stable Dark States
— New Realization of WIMP Miracle

Simple, generic variation: new search strategies!

- WIMP miracle intact: $\Omega_{\chi} \propto \langle \sigma_{\text{ann}} v \rangle^{-1}$ insensitive to final states
- Conventional search signals: absent or suppressed
- DM’: depleted by annihilation, subdominant DM, $\Omega_{\text{DM}'} < \Omega_{\text{DM}}$
  Dark radiation: $\Omega_{\text{DR}} < \Omega_{\text{DM}}$, w/ $m_{\text{DR}} \approx O(\text{eV})$
- Motivate non-minimal DM sector! (SM non-minimal! $p$, $e^-$ ...)

WIMP DM

Stable dark states

Massive: DM’ ➔ Boosted DM! (vs. cold/slow)
(Nearly) massless: Dark radiation ➔ affect CMB

WIMP DM

Stable dark states
Scenario #1: Boosted DM


E.g. Two-component DM sector

\[ m_A > m_B, \quad \Omega_A \approx \Omega_{\text{DM}} \]

\[ \gamma_B = m_A / m_B \]
Scenario #1: Boosted DM

(arxiv: 1405.7370, Agashe, YC, Necib, Thaler; arxiv: 1410.2246, Berger, YC and Zhao)

E.g. Two-component DM sector • **Where to look?** Galactic Center, Sun

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E.g. Two-component DM sector

- Where to look?
  - Galactic Center, Sun

- Detectable?

- DM A
  - DM B
  - $m_A > m_B$, $\Omega_A \approx \Omega_{DM}$
  - $\gamma_B = m_A/m_B$

- SM (e, p)
  - $T_{DS}^{f.o.} \sim T_{SM}^{f.o.}$ + detectability

- DM B depletion

- $n_{DM} = n_{DM}^{in}$

- $T_{DS}^{f.o.}$
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• Detectable?

• What experiment? (large volume, sensitive to energetic e\(^{-}\), p)

( Conventional dark matter direct detection 😞 )
**Scenario #1: Boosted DM**

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E.g. Two-component DM sector

- **Where to look?** Galactic Center, Sun
- **Detectable?**

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Existing experiments for neutrinos, re-purposed!

- Based on Cherenkov-radiation:
  - SuperK/HyperK, IceCube/PINGU(MICA)...
- Based on ionization: (future, planned)
  - DUNE, GLACIER… (liquid Argon/LArTpc)
Detecting Boosted Dark Matter

“Neutrinos”? How to discriminate?

- **Directional information:**
  Boosted DM from GC or Sun vs. isotropic $\nu_{\text{atm}}$

- **Distinct interactions:**

  Neutrinos:
  
  ![Leading charged-current scattering](image)
  
  ![Neutral-current scattering](image) + hadronic inelastic

  Boosted DM:

  ![Neutral-current scattering only](image)

  neutral-current scattering only, no correlated $\mu^-$
Scenario #2: CMB Signals of Dark Radiation from a Hidden DM Sector

(arXiv:1505.04192 Chacko, YC, Hong, Okui)

- Effect of DR on CMB: $\rho_{\text{rad}} \uparrow$, Hubble expansion rate $\uparrow$, Silk-damping… $\Rightarrow \Delta N_{\nu}^{\text{eff}}$
  - DR can generally be interacting, unlike free-streaming “neutrinos”!

CMB observables: opposite effects from $\Delta N_{\nu,\text{eff}}^{\text{free}}$ and $\Delta N_{\nu,\text{eff}}^{\text{scatt}}$

Scaled $\theta$-parameter: universal phase shift;

Tensor mode: amplitude change
Scenario #2: CMB Signals of Dark Radiation from a Hidden DM Sector

- Analyze simple example model:

  \[ \text{DM} \rightarrow H \rightarrow \text{DM} \]

  \[ \text{SM} \rightarrow \text{SM} \]

  Maintain \( T_{\text{DM}} = T_{\text{SM}} \) at \( T_{\text{EW}} \) via Higgs-portal (related: invisible H decay at the LHC!)

- Model prediction on \( \Delta N_{\nu}^{\text{eff}} \) consistent with Planck data, better sensitivity at future CMBpol, CMB-S4!

- **Caveat:** bound from standard CMB analysis (assuming all free-streaming) may not directly apply, need dedicated study, e.g. 2-param fit: \( \Delta N_{\nu,\text{eff}}^{\text{free}} \) and \( \Delta N_{\nu,\text{eff}}^{\text{scatt}} \)
Asymmetric Dark Matter

• **Observation**: $\Omega_{\text{DM}} \sim \Omega_{\text{B}}$ — coincidence or connection?

• **Paradigm**: Asymmetric dark matter
  
  (Nussinov 1985; Kaplan 1992; Kaplan, Luty, Zurek 2009…)

Similar origin of $\Omega_{\text{DM}}$ and $\Omega_{\text{B}}$: asymmetric excess $\Omega_{\text{DM}} - \Omega_{\text{DM}}$, symmetric component depleted by thermal annihilation

  ‣ Co-generation of dark & baryon asymmetry
  ‣ Asymmetry transfer by DM-baryon interactions in early universe

★ Require additional input: asymmetry generation (baryogenesis)

• **Phenomenology**:

  ‣ DM mass range: $\mathcal{O}(\text{GeV})$ motivated, but wide range possible
  ‣ Indirect detection absent/suppressed, direct detection relevant
Axion Dark Matter

- Strong CP problem in the Standard Model:
  - Expected CP-violation in QCD: naively $\theta \sim 1$
  - But, neutron electric dipole moment measurement: $\theta \leq 10^{-10}$

  🐱 Why is $\theta$ so tiny?  SM can’t explain…

- Solution by a small modification to the SM: (Peccei, Quinn 1977)
  spontaneously broken $U_{\text{PQ}}(1) \rightarrow$ Goldstone boson $a$ (axion)

  $L = \ldots + \frac{a}{f_a} \frac{g^2}{32 \pi^2} G^a_{\mu\nu} \tilde{G}^{a\mu\nu} + \frac{1}{2} \partial_\mu a \partial^\mu a + \ldots \implies \theta = -\frac{a}{f_a}$ CPV relaxes to zero!

- Axion can be dark matter! Ultra-light, super-weakly interacting

  $f_{16} \equiv (f_a/N)/(10^{16} \text{ GeV}) \quad m_a \approx 6 \times 10^{-9} \text{ eV} \times f_{16}^{-1} \quad \Omega_a \simeq \Omega_c (N\theta_i)^2 \times \begin{cases} \frac{5 \times 10^5 f_{16}^{7/6}}{3 \times 10^4 f_{16}^{3/2}}, & f_{16} < 1/10 \\ 3 \times 10^4 f_{16}^{3/2}, & f_{16} > 10 \end{cases}$

- Axion interactions, detections
  Use axion-photon conversion in magnetic field (e.g. ADMX…)

\[\gamma \rightarrow a \rightarrow \gamma\]
Self-interacting Dark Matter

- Collisionless cold DM: fit large scale structure very well
- "Anomalies" at small scales: dwarf galaxies, sub-halos...

Core VS. Cusp

"Too big to fail"

- Strong DM self-interaction helps! (reduce central density)
  \[ \frac{\sigma}{m_X} \sim 0.1\text{–}10 \text{ cm}^2/\text{g} \]
  (Spergel, Steinhardt, 1999)

- Constraints: bullet cluster, halo ellipticity
- Viable model: velocity-dependent scattering via light mediator
  \[ \sigma \approx 5 \times 10^{-23} \text{ cm}^2 \left( \frac{\alpha_X}{0.01} \right)^2 \left( \frac{m_X}{10 \text{ GeV}} \right)^2 \left( \frac{10 \text{ MeV}}{m_\phi} \right)^4 \]
  (Kaplinghat, Tulin, Yu, Zurek,...)
Conclusion/Outlook

- What is dark matter?
  - a greatest puzzle for particle physics and cosmology
  - limited observational clues, many theoretical candidates
- Conventional focus: WIMP+ direct interaction w/SM states
  - increasing constraints from data, or right at corner…
- Recent trends: theoretical scope expanded
  - Non-minimal DM sector: rich particle contents/interactions
  - More weakly/indirect interaction with the visible sector (SM)
  - Wide mass range: (in particular) light mass
- Expanded experimental search programs on the way:
  - Existing experiments re-purposed: CMB, neutrino detectors
  - Proposals for new experiments (axion, light DM, dark force…).