Dark Matter Theory

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Evidence for Dark Matter

Dark Matter (DM): matter \textit{(which gravitates)} \textit{which neither emits nor absorbs light.} Hence is really transparent rather than dark.
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Dark Matter (DM): matter (which gravitates) which neither emits nor absorbs light. Hence is really transparent rather than dark.

(a) Galactic Scales: Rotation curves! (Vera Rubin . . .)

Measure rotation velocity as fct of distance from center. If mass tracks light: expect \( v(r) \propto 1/\sqrt{r} \) (true in solar system!)

observe \( v(r) \simeq \text{const!} \)

\( \Rightarrow \) Most galactic mass not in baryons!
Rotation Curve of the Milky Way

Bhattacharjee et al., Astrophys.J. 785 (2014) 63
A typical galaxy cluster
(b) Clusters of Galaxies

- Virial theorem: \[ \langle E_{\text{kin}} \rangle = -\frac{1}{2} \langle E_{\text{pot}} \rangle \propto M_{\text{cluster}} \] Zwicky 1933

- Similar argument holds for single atoms:
  Temperature of gas in cluster \( \propto M_{\text{cluster}} \)
  Gives consistent result.

- Gravitational lensing: Mass deflects light, by angle \( \propto \) mass: Most direct way to measure \( M_{\text{cluster}} \)

  \[ \sim 80\% \text{ of mass of cluster is } \textit{not} \text{ baryonic!} \]
(c) Cosmology: CMB

Pattern of CMB anisotropies requires most mass to be non–baryonic (does not feel radiation pressure)

PLANCK collab. 2015
Big Bang Nucleosynthesis (BBN): confirms CMB determination of total baryon density; not sensitive to DM density
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Evidence for DM: Summary

Many independent observations at distance scales between (few) kpc to Gpc (Hubble radius) can be explained consistently iff cold Dark Matter exists!
Alternatives to Particle DM: Modified Gravity?

All evidence for DM assumes standard GR (in fact, mostly Newtonian gravity sufficient); what if gravity is stronger at weak accelerations? (MOND: Milgrom)
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Looks very implausible to me!
Bullet cluster
Alternatives to Particle DM: Primordial Black Holes?

Must have formed before on–set of BBN, i.e. in first second after Big Bang.

Arguments in favor:

- First black holes mergers detected by LIGO indicate surprisingly large BH masses
- Might seed supermassive BHs found in center of galaxies, incl. AGNs
PBHs: Cons

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- Power spectrum must then quickly cut off again, to avoid overproduction of light, unstable BHs: \textit{needs finetuning}!
**PBHs: Cons**

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- Need primordial density perturbation at BH scale at least 7 orders of magnitude larger than at CMB scales; spectral power \( n < 1 \) goes in *wrong* direction.

- Power spectrum must then quickly cut off again, to avoid overproduction of light, unstable BHs: *needs* finetuning!

Looks almost as implausible as MOND to me.
Constraints on Primordial Black Holes

Carr et al., arXiv:1705.05567
Particle Physics Candidates: Properties

Mass range:

**Bosons:**
\[ \frac{1}{r_{\text{galaxy}}} \sim 10^{-22} \text{ eV} \lesssim m_{\text{DM}} \lesssim M_{\text{Pl}}: \text{50 orders of magnitude} \]

**Fermions** (or thermally produced bosons):
\[ 1 \text{ keV} \lesssim m_{\text{DM}} \lesssim M_{\text{Pl}}: \text{25 orders of magnitude} \]
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Lifetime:

$\tau_{\text{DM}} \gtrsim \tau_U \simeq 5 \cdot 10^{17} \text{ s} \text{ (all masses)}$

$\gtrsim 10^{25} \text{ s (}m_{\text{DM}} \gtrsim 1 \text{ GeV : search for decay products)}$
Self interactions:

\[ \sigma \lesssim 1 \text{ b} \cdot \frac{1 \text{ GeV}}{m_{DM}} \]  
for short–range interaction (bullet cluster): protons are factor ~ 30 below this bound
DM Properties (cont’d)

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DM should be significantly less dissipative than baryonic matter. Note: ordinary matter dissipates energy and angular momentum through emission of photons, mostly off electrons.
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DM should be **significantly less dissipative** than baryonic matter. Note: ordinary matter dissipates energy and angular momentum through emission of photons, mostly off electrons.

This is basically all we know about properties of DM particles!

No particle with these properties exists in the SM!
Particle DM Candidates

Many hypothetical particles satisfy these conditions:

- Extremely light bosons ("fuzzy DM") [Hu et al., astro-ph/0003365]
- Axions or ALPs ($10^{-12}$ eV $\lesssim m_a \lesssim 10^{-3}$ eV)
- keV–ish sterile neutrinos
- Dark photons ($m = ?$)
- Gravitinos ($m \gtrsim 1$ keV)
- Weakly Interacting Massive Particles (WIMPs)
- WIMPZILLAs ($m \sim 10^{10}$ GeV)
- …
My preference

- DM particle should have independent motivation! QCD axion, some WIMPs, gravitino
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- And it would be nice if it could be detected somehow: QCD axion, some WIMPs
- I’ve never worked on axions . . .
Some News on WIMPs

In standard cosmology: relic density of particle $\chi$ that once was in thermal equilibrium:

$$\Omega_{\chi} h^2 \propto \frac{1}{\langle \sigma_{\text{ann}} v \rangle |_{T \simeq T_F}}$$

$\Omega_{\chi} = \rho_{\chi}/\rho_{\text{crit}}$: scaled mass density

$\sigma_{\text{ann}}$: (effective) total annihilation cross section

$v$: relative velocity in cms frame;

$\langle \ldots \rangle$: thermal averaging

$T_F \simeq m_{\chi}/20$: freeze−out temperature
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Get correct relic density if $\langle \sigma_{\text{ann}} v \rangle \sim 1 \text{ pb} \cdot c$: points towards weak scale, connection to hierarchy/naturalness problem?
Searching for WIMPs

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- **Direct searches:** Look for elastic WIMP–nucleus scattering; signal: recoil energy of the nucleus. *(Probably) no signal found (DAMA??)*
Most recent direct search bound

XENON1T collab., arXiv:1805.12562
Most recent direct search bound

The bound is somewhat weaker than the expected sensitivity, i.e. there is a slight excess of events
Direct WIMP Searches

Kinematics:

\[ E_{\text{recoil}} \leq 2v^2m_N \left( \frac{m_\chi}{m_N + m_\chi} \right)^2 \rightarrow \begin{cases} 2v^2m_N, & m_\chi \gg m_N \\ 2v^2m_\chi^2/m_N, & m_\chi \ll m_N \end{cases} \]

Allows to understand shape of excluded parameter space:

- **Small** \( m_\chi \): recoil energy below threshold \( \Rightarrow \) complete loss of sensitivity

- **Large** \( m_\chi \): Kinematics saturates; rate \( \propto \) flux \( \propto 1/m_\chi \), hence bound on \( \sigma_{\chi p} \propto 1/m_\chi \)
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This drives a fair amount of recent model building!
Very Light WIMPs

In standard cosmology, need light mediator(s) (dark gauge boson, dark Higgs, ...) to get sufficiently large $\sigma_{\text{ann}}$:

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- New opportunities for low-$\sqrt{s}$ collider, fixed target experiments
- Need new techniques for direct detection
- Not clear what the smallest mass of a “WIMP” is (GeV? MeV? keV??)
Very Heavy WIMPs: Upper Bounds on Mass

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- **Co–annihilation:** e.g. $\tilde{B} - \tilde{t}$ Boehm, Djouadi, MD 1999
  - $m_{\tilde{B}} \leq 3.3$ TeV Harz & Petraki, 1805.01200
  - $m_{\tilde{B}} \lesssim 6$ TeV, if $\delta m/m < 0.5\%$: stoponium mass $< 2m_{\tilde{B}}$! Biondini & Laine, 1801.05821
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- How about resonant annihilation?
(Reasonably) well motivated model:
MSSM $+$ $\tilde{\nu}_R$ Superfield (SM singlet) $+$ $E(6)$ inspired $U(1)$, broken by SM singlet $N$
\( \tilde{\nu}_R \) in \( U(1) \) Extended MSSM

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LHC: \( m_{Z'} \gtrsim 4 \text{ TeV} \gg m_Z, m_h \)

\( \implies \) one physical Higgs \( \simeq N \), with \( m_N \simeq m_{Z'} \)!
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Relic density minimized, if \( N \) coupling to final state \( \simeq g_N \tilde{\nu}_R \tilde{\nu}_R^* \): achieved by tuning doublet Higgs masses.
Result

MD, F.A. Gomes Ferreira, to appear

Linear Fit:

\[ M_{y_R}^{\text{max}} = 208.76 + 41154.8 \mid Q_N' \mid \]
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Linear Fit:
\[ M_{\tilde{\nu}_R}^{\text{max}} = 208.76 + 41154.8 \ |Q'_N| \]

Allows \( m_{\tilde{\nu}_R} \) up to 26 TeV!
WIMPs from “Moduli”

In Supergravity / Superstrings: Often have particles $\Phi$ with $m_\Phi \gtrsim m_{\text{sparticle}}$, $1/M_{\text{Pl}}$ suppressed couplings (“Polonyi” fields, “moduli”)
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(Early matter dominated epoch: Coughlar et al. 1983, . . . )
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Need $m_\Phi > 10 \text{ TeV}$!

(Problem with hierarchy, if $m_\Phi \simeq m_{\text{sparticle}}$.)
Impact on WIMP Density

e.g. Acharya et al. 2009, Kane et al. 2015

Φ decays release a lot of entropy
⇒ dilute earlier WIMP density
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- $\chi$ production channels:
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  - From hot thermal background during $\Phi$ domination
  - From hot thermal background after $\Phi$ decays
    (standard contribution)
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Hence WIMP density can be smaller or larger than in standard cosmology! Gelmini et al., hep-ph/0605016
Three evolution equations:

\[
\frac{dn_\Phi}{dt} = -3Hn_\Phi - \Gamma_\Phi n_\Phi;
\]
\[
\frac{dn_\chi}{dt} = -3Hn_\chi - \langle \sigma_{\text{ann}} v \rangle \left[ n_\chi^2 - (n_{\chi}^{\text{eq}})^2 \right] + n_\Phi \Gamma_\Phi B(\Phi \rightarrow \chi);
\]
\[
\frac{dT}{dt} = \frac{1}{1 + \frac{T}{3h_*} \frac{dh_*}{dT}} \left\{ -HT + \frac{1}{3s} \left[ n_\Phi m_\Phi \Gamma_\Phi + 2m_\chi \langle \sigma_{\text{ann}} v \rangle \left[ n_\chi^2 - (n_{\chi}^{\text{eq}})^2 \right] \right] \right\}
\]

Here, entropy density \( s = \frac{2\pi^2}{45} h_* T^3 \).

Note:

- Entropy is \textit{not} conserved during \( \Phi \) decay!

- Still normalize DM density to \( s \Rightarrow \) need to keep track of \( s \) accurately, including \( T \) dependence of \( h_* \).
\[ m_\Phi = 5 \cdot 10^3 \text{ TeV}, \ T_{RH} = 850 \text{ MeV}, \ B(\Phi \rightarrow \chi) = 10^{-5} \]
WIMPs from Moduli: Results

If WIMP has overdensity in standard cosmology: Need:

- \( Br(\Phi \to \chi) \lesssim 10^{-4} \cdot \frac{100 \text{ GeV}}{m_\chi} \) and

- \( M_\Phi \lesssim 10^4 \text{ TeV} \cdot \left( \frac{m_\chi}{100 \text{ GeV}} \right)^{2/3} \)
**WIMPs from Moduli: Results**

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  and

  \[ M_\Phi \lesssim 10^4 \text{ TeV} \cdot \left( \frac{m_\chi}{100 \text{ GeV}} \right)^{2/3} \]

- Can (e.g.) find extended region with good bino–like WIMP
E.g. pMSSM scan with \( m_\Phi = 5 \cdot 10^4 \) TeV

\[
Br(\Phi \rightarrow \chi) = 10^{-5}
\]

\[
Br(\Phi \rightarrow \chi) = 10^{-7}
\]

MD, F. Hajkarim, to appear
Take–Home Messages

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- Most likely consists of new kind(s) of particle
- We don’t know much about these particles
- Most likely, no DM particle has been found yet
- Oldest/simplest candidates (axion, WIMPs, gravitinos) are *not* excluded
- WIMPs are getting squeezed $\Rightarrow$ theorists are extending WIMP parameter space