Dark matter: new searches for ancient particles

PHENO 2021
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What do we know about dark matter?

mass in GeV

- fermi pressure vs small scale
- de Broglie vs small scale
- Planck mass
- composite: boson star, nuclearite, q ball, dark nucleus, black holes

- wide binaries
- smallest galaxies
What do we know about dark matter?

mass in GeV

- Fermi pressure vs small scale
- Planck mass
- boson
- composite: boson star, nuclearite, q ball, dark nucleus, black holes

production $T$ (or $\rho^{1/4}$) in GeV

- de Sitter fluctuation (wimpzilla)
- Classic freezeout (wimp)
- or freezeout variant (wimpish)

- BBN
- Matter=rad
- Tensor limit
What do we know about dark matter?

mass in GeV

- fermion
- boson
- composite: boson star, nuclearite, q ball, dark nucleus, black holes

Planck mass

de Broglie vs small scale

production $T$ (or $\rho^{1/4}$) in GeV

- others:
  - $\phi$ decay
  - oscillating scalar
  - collapse to pbh
  - freeze-in
  - asymmetric
  - dilution
  - misalignment
  - de Sitter fluctuation (wimpzilla)

- matter, radiation, inflation?

- BBN

- CMB, LSS measurements

- wide binaries

- smallest galaxies

- matter=rad
What do we know about dark matter?

Inflaton-oscillon gravitational wave probes of the early universe, Simran Nerval’s parallel

mass in GeV

production $T$ (or $\rho^{1/4}$) in GeV

de Sitter fluctuation (wimpzilla)
matter, radiation, inflation?

mass in GeV

fermi pressure vs small scale

fermion

boson

degree Broglie vs small scale

Planck mass

composite: boson star nuclearite q ball dark nucleus black holes

collapse to pbh

freeze-in

asymmetric

dilution

misalignment

classic freezeout (wimp)
or freezeout variant (wimpish)

matter = rad

CMB, BBN, LSS measurements
Dark Matter Models: SM Coupling and Detection

**dark matter**
- fundamental
- composite

**spin**
- \( \frac{1}{2} \)
- \( 1 \)
- \( \frac{3}{2} \)
- \( 2 \)
- \( \frac{5}{2} \)
- \( 3 \)
- ...

**direct coupling**
- Quarks
- Leptons
- Hypercharge Boson
- Weak Boson
- Higgs Boson
- Gluons...

**mixing**
- Dark Photon / Vector Portal
- Higgs Portal
- (Sterile) Neutrino Mixing...

**new intermediate field**
- Scalar
- Fermion
- Vector...
Dark Matter Models: SM Coupling and Detection

**Direct Coupling**
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**Mixing**
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**New Intermediate Field**
- Scalar
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**Interactions**
- annihilation
- scattering
- DM production

**Detector**
- interstellar gas
- stars
- planets
- Super-K, IceCube (neutrinos)
- HAWC, Fermi (gamma rays)
- XENON1T, LZ, PandaX, SuperCDMS, PICO, SENSEI
- ADMX, HAYSTAC
- collider, beam dump

**Mass of Interacting SM Particles in GeV**
- $\sim 10^{60}$
- $\sim 10^{50}$
- $\sim 10^{35}$
- $\sim 10^{30}$
- $\sim 10^{15}$
Dark matter near us

$baryonic$ mass
$DM$ mass

$0.3 \text{ GeV/cm}^3$ by Earth
Dark matter near us

**global (~0.001c)**

- Sofue 1307.8241
- White Dwarf ~0.05 c
- Neutron Star ~0.7 c
- Main Sequence ~0.002 c

**local structure**

- Neutron Star ~0.7 c

**local fine structure**

- minimum DM speed > 11 km/s
- 0.3 GeV/cm³ by Earth

**Equation:**

\[ f_s(v) \]

**Graph:**

- V (km/s) vs. R (kpc)
- \( \rho_{DM} (\text{GeV/cm}^3) \) vs. \( r (\text{kpc}) \)

**Legend:**

- Einasto
- NFW
- Burkert

**Note:**

- Dark matter near us
- 0.3 GeV/cm³ by Earth
As the universe cools, dark matter falls out of thermal equilibrium, some portion annihilates to SM particles:

$$\frac{m_x n_x}{n_H} \sim \frac{x_f}{m_{pl} \langle \sigma_a v \rangle} \quad x_f \sim \log[m_x^3 \langle \sigma_a v \rangle/H]$$

Observed DM relic abundance achieved for annihilation cross-section matching weak scale mass / couplings.

$$\Omega x h^2 \sim 0.1 \left( \frac{m_v}{100 \text{ GeV}} \right)^2 \left( \frac{0.03}{\alpha_w} \right)^2$$

Some symmetry arguments imply interactions at dark matter experiments.
As the universe cools, dark matter falls out of thermal equilibrium, some portion annihilates to SM particles.

\[
\frac{m_x n_x}{n_\gamma} \sim \frac{x_f}{m_{pl} \left\langle \sigma_a v \right\rangle} \quad x_f \sim \log[m_x^3 \left\langle \sigma_a v \right\rangle/H]
\]

\[
\Omega_x h^2 \sim 0.1 \left( \frac{m_v}{100 \text{ GeV}} \right)^2 \left( \frac{0.03}{\alpha_w} \right)^2
\]

Observed DM relic abundance achieved for annihilation cross-section matching weak scale mass / couplings.

Caveat: symmetry arguments require symmetry, and (for example) electroweak symmetry is broken.

Some symmetry arguments imply interactions at dark matter experiments.
Spin independent dark matter detection

\[ \sigma_n \approx \frac{\alpha_W^2 \mu_{nX}^2}{M_Z^4} \]

Dirac fermion coupled through Z boson
Spin independent dark matter detection

\[ \sigma_n \approx \frac{\alpha_W^2 \mu_{nX}^2}{M_Z^4} \]

Dirac fermion coupled through Z boson

Plenty of WIMP(ish) models waiting to be found!
The Higgsino: Broken Symmetry for Dirac WIMP

Standard Model of Elementary Particles

<table>
<thead>
<tr>
<th>Quarks</th>
<th>Leptons</th>
</tr>
</thead>
<tbody>
<tr>
<td>up, c, t</td>
<td>(e, \mu, \tau, \nu_e, \nu_\mu, \nu_\tau, \bar{e}, \bar{\mu}, \bar{\tau}, \bar{\nu}<em>e, \bar{\nu}</em>\mu, \bar{\nu}_\tau)</td>
</tr>
<tr>
<td>d, s, b</td>
<td>(\text{electrons}, \text{muons}, \text{taus}, \text{neutrinos})</td>
</tr>
<tr>
<td>u, c, t</td>
<td>(\text{charm, top, gluon, Higgs})</td>
</tr>
</tbody>
</table>

SUSY DM

Higgsino

Wino

Bino

EW Symmetry Breaking

\[ \begin{pmatrix} M_1 & -\mu \\ -\mu & M_2 \end{pmatrix} \]

neutral components mix

\[ \delta \]

e.g.

\[ \delta \sim \text{GeV} \left( \frac{\text{TeV}}{M_1} \right) \]

\[ X_1 \quad X_2 \]

Higgsino neutral states

split after EWSB
Underground dark matter detection, Higgsinos

Interaction forbidden at $v \sim 0.001c$ by $X_1 \leftrightarrow X_2$

mass gap $\rightarrow \delta \sim \text{GeV} \left( \frac{\text{TeV}}{M_1} \right)$

Loop suppressed scattering

Higgsino Dark Matter

Hisano et. al. 2013
Hill and Solon 2013
**Underground dark matter detection, Higgsinos**

Interaction forbidden at $v \sim 0.001c$ by $X_1 \leftrightarrow X_2$

mass gap $\rightarrow$ $\delta \sim \text{GeV} \left(\frac{\text{TeV}}{M_1}\right)$

- Motivates High Recoil Inelastic Searches
- Also neutron stars

JB Fox Kribs Martin 1608.02662

See also Ningqiang Song parallel
Diluted WIMP Dark Matter: heavier

Overabundant freeze-out

Then dilution from decay →

\[ \Omega_x h^2 \sim 0.1 \left( \frac{m_V}{\text{PeV}} \right)^2 \left( \frac{0.03}{a_D} \right)^2 \left( \frac{\zeta}{10^{-8}} \right) \]

Motivation

- Matter dominated epoch
- Decay of asymmetry field (Affleck-Dine)
- Decay of inflaton
- Decay of modulus / gravitino
- Field associated with ~PeV dark sector

\[ \zeta \equiv \frac{S_{ini}}{S_{fin}} = n_x \text{ dilution} \]

JB Unwin 1701.05859

see also e.g.
Allahverdi Dutta Sinha '11
Kane Shao Watson '11
Davoudiasl Hooper McDermott '15
Berlin Hooper Krnjaic '16
Consider a simple model of fermionic DM coupled by a scalar field

$$\mathcal{L} = \frac{1}{2}(\partial \phi)^2 + \bar{X}(i\gamma^\mu \partial_\mu - m_X)X + g_X \bar{X} \phi X - \frac{1}{2} m_\phi^2 \phi^2 + g_n \bar{n} \phi n + \mathcal{L}_{SM},$$

Diluted dark matter has a freeze-out abundance that scales with $\zeta^{-1}$

This overabundance of dark matter leads to very large $\varphi - X$ composites

$$N_c = \left( \frac{2 \sigma_{\chi X} v_X}{3H} \right)^{6/5} = \left( \frac{20 \sqrt{g_*^c} T_c T_c^{3/2} M_{pl}}{m_X^{7/2} \zeta} \right)^{6/5} \approx 10^{27} \left( \frac{g_*^c}{10^2} \right)^{3/5} \left( \frac{T_c}{10^5 \text{GeV}} \right)^{9/5} \left( \frac{5 \text{ GeV}}{m_X} \right)^{21/5} \left( \frac{10^{-6}}{\zeta} \right)^{6/5}$$

Composite mass ranging from milligrams to thousands of tons
HIGH MASS ASYMMETRY, DILUTION, AND COMPOSITE DM

- Large internal composite potential has new consequences for detection.

- Fusion, Bremsstrahlung and the Migdal effect inside dark matter.

- Large cross-sections also make composites discoverable through multi scatter detection.

2012.10998, see Javier Acevedo parallel
Multiscatter dark matter detection

- Cross-section for DM to hit detector particle
- Mass of dark matter
- Overburden
- Flux limit (a few heavy particles)
- Threshold
- Sensitivity limit
Multiscatter dark matter detection

\[ n_a \sigma_{ax} L > 1 \]

\[ \tau = n_a \sigma_{ax} L = 1 \]

\[ n_a \sigma_{ax} L < 1 \]
Underground multiscatter prospects

Scintillating Neutrino Detectors

Underground Multiscatter Searches

Ongoing work at PICO, XENON1T

JB Broerman Kumar Lang Pospelov Raj 1812.09325
1803.08044 1910.05380

22
Ancient searches for new particles: mica and plastic

- Calibrated and etched mica samples from Price 1986, Snowden-Ifft 1995

- Reanalyzed mica data using overburden
  Acevedo, JB, Goodman 2105.06473
  Bhoonah, JB, Courtman Song 2012.13406
Ancient searches for new particles: mica and plastic

- Calibrated and etched mica samples from Price 1986, Snowden-IIft 1995
- Reanalyzed mica data using overburden

Amit Bhoonah's parallel on heavy dark matter and plastic etch searches
Stars and Planets As Dark Matter Detectors

Acevedo, JB, Goodman, Kopp, Opferkuch
2012.09176
1909.11683
1405.1031
1505.07464
1904.11993
Annihilating DM heats Earth

Or

Non-annihilating DM collapses to BH, then heats or eats earth

Scatter Capture $\rightarrow$ Slow Below Escape Velocity

First Thermalization

Second Thermalization

-These processes occur via a single low-velocity DM-SM cross-section
Scatter Capture
Non-annihilating DM collapses to $B_H$ (then heats or eats earth)

Same for the Sun
Scatter Capture

Non-annihilating DM collapses to B\text{H} (then heats or eats earth)

Same for the Sun

And White Dwarfs and Neutron stars
For high mass DM, need proper Earth frame DM distribution, since capture is often dominated by low-velocity DM.

\[ f_*(v) \sim \int_{-1}^{1} d \cos \phi \left( v^2 - v_e^2 \right)^{3/2} \exp \left( -\frac{\tilde{v}^2}{v_0^2} \right) \Theta(v - v_e) \Theta(v_{eg} - \tilde{v}) \]

DM is slower than galactic escape velocity \( v_{eg} \sim 550 \) km/s, but faster than Earth’s escape velocity.
Sphere of DM particles in the Earth settle at thermal radius:

\[ \langle E_k \rangle \approx -2 \langle V \rangle \quad \Rightarrow \quad r_{th} = \sqrt{\frac{9T_{\oplus}}{4\pi G \rho_{\oplus} m_\chi}} \lesssim \mathcal{O}(\text{km}) \]

If they annihilate: Earth/Martian heating!

---

JB, Buchanan, Goodman, Lodhi 1909.11683
see also Mack, Beacom, Bertone 0705.4298
If they don’t annihilate: collapse!

**Conditions**

Jeans instability:

\[ \rho_\chi \gtrsim \rho_\oplus \]

Self-gravitating:

\[ M_{\text{cap}} \gtrsim \sqrt{\frac{3T_\oplus^3}{\pi G^3 m_\chi^3 \rho_\oplus}} = M_{sg} \]

Fermi degeneracy:

\[ M_{\text{cap}} \gtrsim \frac{M_{pl}^3}{m_\chi^2} = M_f \]
Dark matter mass $m_{\chi}$ [GeV]

DM-nucleon cross-section $\sigma_{\chi N}$ [cm$^2$]

BH formation time

BH Evap time
**Max destructive** $m_\chi$

Hawking = Bondi + $m_\chi \Phi_\chi$

$2.7 \times 10^{10}$ GeV

**Min evaporative** $m_\chi$

Hawking = Bondi

$4.5 \times 10^{9}$ GeV

- Upshot: higher mass DM implies smaller black holes formed
- Two factors: fermi and thermalization
- Smaller black holes evaporate
Sun destroyed

Earth destroyed

Earth heating

Dark matter mass $m_\chi$ [GeV]

DM–nucleon cross-section $\sigma_{\chi N}$ [cm$^2$]

$M_{\text{crit}} = m_\chi \Phi_\chi \times \text{Gyr}$

$M_{\text{cap}} = 44$ TW

$M_{\text{cap}} = M_{\text{crit}}$

$\sigma_{\chi N} = \frac{\text{Sun destroyed}}{\text{Earth destroyed}} = \frac{\text{Earth heating}}{\text{Earth destroyed}}$

DM contact cross-section $\sigma_c$ [cm$^2$]

$M_{\text{crit}} = m_\chi \times \text{Gyr}$

$t_{\text{drift}} \geq 1 \text{ Gyr}$

$M_{\text{cap}} = 44$ TW

$M_{\text{cap}} = M_{\text{crit}}$

$\sigma_c = \frac{\text{Sun destroyed}}{\text{Earth destroyed}} = \frac{\text{Earth heating}}{\text{Earth destroyed}}$
Neutrinos From Black Holes in the Sun

Signal
- Flavour universal
- Blackbody (with gray body factors) \( T = \frac{1}{8\pi GM_{BH}} \)
- Transient, directional

Spectra
- Primary \( \nu_\alpha \bar{\nu}_\alpha \) pairs emitted at event horizon
- Secondary decays

BlackHawk (Hawking radiation) + PYTHIA (hadronization) + nuSQuIDS (propagation)
Dark matter mass $m_\chi \,[\text{GeV}]$

DM contact cross-section $\sigma_c \,[\text{cm}^2]$

DM-nucleon cross-section $\sigma \chi N \,[\text{cm}^2]$

$\sigma_f = m_\chi$

Neutrinos from BHs in sun

CMB gas heating

Neutrinos

Sun destroyed

Isotope-dependent

Isotope-independent

Acevedo, JB, Goodman, Kopp, Opferkuch 2012.09176
Neutron stars: nature’s dark matter accelerators

➤ Neutron stars accelerate dark matter to beyond freezeout speeds

\[ v_{esc} = \sqrt{\frac{2GM}{R}} \sim 0.7c \]

➤ Dense, accept a large DM flux

- fiducial mass of \( \sim 10^{57} \) GeV
- neutrons:protons:electrons \( \sim 10:1:1 \)
- flux of \( \sim 100 \) grams of DM/second
Neutron stars: broad reach for particle dark matter

1. EFT, Spin-Dependent, Spin-Independent, Strongly Interacting, Electroweakino, Inelastic
2. Leptophilic dark matter
3. Self-interacting dark matter
4. Heavy DM, baryon and lepton annihilating DM, compressed WIMPs, co-annihilating DM
5. Winos, Higgsinos, Precision Capture, Pasta Capture
6. Muonphilic
7. Asymmetric (converts NSs into black holes)

Kouvaris 2007
Bertone, Fairbairn 2007
JB Delgado, Martin 2017
Baryakhtar, JB, Li, Linden, Raj 2017
Raj, Tanedo, Yu 2017
Acevedo, JB, Leane, Raj 2019
Bell, Busoni, Robles 2019
Joglekar, Raj, Tanedo, Yu 2019
Chen, Lin 2018
Jin, Gao 2018
Hamaguchi, Nagata, Yanagi 2019
Garani, Genolini, Hambye 2018
Keung, Marfatia, Tseng 2020
Bai, Berger, Korwar, Orlofsky 2020
Camargo, Queiroz, Sturani 2019
Bell, Busoni, Robles 2020
Garani, Heeck 2019
Goldman, Nussinov 1989
Kouvaris, Tinyakov 2011
McDermott, Yu, Zurek 2011
JB, Fukushima, Kumar 2013
Bell, Melatos, Petraki 2013
Bertoni, Nelson, Reddy 2014
JB, Linden 2014
JB, Elahi 2015

(more...)
Dark matter kinetic and annihilation heating of neutron stars

1. Dark matter accelerated to $\sim 0.7c$ by neutron star

2. DM deposits kinetic energy by scattering and re-scattering in the neutron star (may also annihilate in the NS)

3. Heats NS to $T \sim 1750$ K if all DM captured ($\sim 2500$ K with annihilation)

$T \sim 1750$ / $2500$ K, for NS near Earth
Dark matter kinetic and annihilation heating of neutron stars

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2. DM deposits kinetic energy by scattering and re-scattering in the neutron star (may also annihilate in the NS)

3. Heats NS to $T \sim 1750$ K if all DM captured ($\sim 2500$ K with annihilation)

0. Compare to NS without DM heating

$$T_{\text{eff}} \sim 100 \text{ K} \left( \frac{\text{Gyr}}{t} \right)^{1/2}$$

3. $T \sim 1750 / 2500$ K, for NS near Earth

\[ \text{e.g. Yakovlev Pethick astro-ph/0402143} \]
\[ \text{Page Lattimer et al. astro-ph/0403657} \]
Neutron Star Dark Matter Heating Sensitivity

all incoming DM captured (ann. T~2500 K)

10% incoming DM captured (ann. T~1400 K)

Baryakhtar, JB, Li, Linden, Raj 2017
Neutron Star Dark Matter Heating Sensitivity

Does the Higgsino annihilate in a NS?

Higgsino DM in a NS, 0.7c

Higgsino DM at 0.001c

all incoming DM captured (ann. T~2500 K)

10% incoming DM captured (ann. T~1400 K)
Neutron Star Pasta Cooker: Higgsinos (and WIMPS) annihilate in NS

- Standard NS heating calculation uses DM annihilation at low velocities, settling in NS core
- DM-neutron cross-section is unbounded for DM that settles into NS core because of accidental loop-level nucleon coupling cancellation and pdf uncertainties
- The timescale for DM settling in NS core can’t be computed without \((v << c)\) cross-section

Higgsino DM at \(v << c\)
Neutron Star Pasta Cooker: Higgsinos (and WIMPS) annihilate in NS

Solution: annihilation in “pasta” region as limiting case

\[ \tau_{eq} \propto R_{ann}^{(3-2\ell)/2} \]

- DM annihilates at \(~0.1c\) much like in the early universe
- keV-PeV mass WIMPs annihilate, for s-wave (\(l=0\)), p-wave (\(l=1\)), \(\langle \sigma v \rangle = 3 \times 10^{-26} \text{ cm}^3/\text{s} \), with

\[ \tau_{eq} \lesssim 10^4 \text{ yrs} \left( \frac{m_x}{\text{TeV}} \right)^{1/2} \]

\( \tau_{eq} \) - annihilation-capture equilibrium
Looking for Higgsinos with 30+ meter telescopes

**ELT 2σ sensitivity estimates**

Annihilation of WIMPs, Higgsinos

\[ t \sim 3 \times 10^6 \text{ sec} \left( \frac{d}{100 \text{ pc}} \right)^4 \] (Y band)

Kinetic only

\[ t \sim 10^6 \text{ sec} \left( \frac{d}{30 \text{ pc}} \right)^4 \] (K band)

**Radio observations of nearby pulsars**

<table>
<thead>
<tr>
<th>Pulsar</th>
<th>Distance (pc)</th>
<th>Period (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>J1057-5226</td>
<td>90</td>
<td>0.19</td>
</tr>
<tr>
<td>J0736-6304</td>
<td>95</td>
<td>4.86</td>
</tr>
<tr>
<td>J0834-60</td>
<td>100</td>
<td>0.38</td>
</tr>
<tr>
<td>J0711-6830</td>
<td>110</td>
<td>0.005</td>
</tr>
<tr>
<td>J0749-68</td>
<td>110</td>
<td>0.91</td>
</tr>
<tr>
<td>J0924-5814</td>
<td>110</td>
<td>0.71</td>
</tr>
</tbody>
</table>

- YMW16 dispersion measure distances
Dark Matter: New Searches For Ancient Particles

- Higgsino dark matter at high recoil and in neutron stars

- Heavy composite formation, multi scatter detection

- Dark matter forming black holes in the Sun and Earth

- Thermal neutron star searches for dark matter

Thanks!