Dark matter in stars

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Overview

1. Dark matter in the Stars: results
2. Everything is wrong
3. The way forward?
Direct detection of dark matter

Most sensitive to heavy, fast particles $\rightarrow$ larger recoil signal

Signal $\propto$ detector mass (now $\sim$ 1000 kg)
The sun is a direct detection experiment

- M = 2 \times 10^{30} \text{ kg}
- 73\% \text{ Hydrogen}
- 25\% \text{ Helium}
- 2\% \text{ Heavier elements}
  (important since } \sigma_{SI} \propto A^2 \)
- DM scatters with nuclei, losing kinetic energy & becoming gravitationally bound
- Not supercooled: need to be clever about “readout”
Differences with earth-based detection

- More sensitive to lighter DM
- Different particle couplings
If DM annihilates: look for neutrinos
Spin-Independent

Spin-Dependent

See also poster by Neal Avis Kozar for more interesting models
Asymmetric DM in stars: no annihilation; DM accumulates

\[ \sigma \simeq \sigma_T \]
\[ \sigma \ll \sigma_T \]

\[ \lambda_{\text{nuc}} \ll r_{\text{core}} \]
\[ \lambda_{\chi} \gg \lambda_{\text{nuc}} \]

Heat can be transported, changing the stellar temperature, density and pressure profiles
Asymmetric DM in stars

**Dark Matter luminosity**

\[ \text{Dark matter luminosity (erg cm}^{-2} \text{s}^{-1}) \]

- 3 \times 10^{29}
- 2.5
- 2
- 1.5
- 1
- 0.5
- 0

Radius \( (R_{\odot}) \)

0
0.05
0.1
0.15

**transported energy**

\[ \frac{dL}{dR} \]

- 1 \times 10^{31}
- 0.5
- 0
- -0.5
- -1
- -1.5

\( R/R_{\odot} \)

0
0.05
0.1
0.15
0.2

\[ \sigma = 1 \times 10^{-35}, K = 0.64527 \]

- energy added to higher radii
- energy removed from core

*for \( n_{DM}/n_p = 10^{-15} \); recall \( L_{\odot} \sim 10^{33} \text{ erg s}^{-1} \)
Observable?

Change in radial heat transport

Change in temperature profile

Small changes in pp fusion chain: reduction in $^8\text{B}$ and $^7\text{Be}$ neutrino fluxes

Change in pressure and density: sound speed, Convective zone boundary

Helioseismology
Solar composition problem (since 2004)

\[ R_{CZ,\odot} = 0.713 \pm 0.001 \, R_\odot \]
\[ R_{CZ,SSM} = 0.722 \pm 0.004 \, R_\odot \]

Sound speed off by \( \sim 4 - 5\sigma \)?
Solar composition problem

Small frequency separations: a probe of the core

Asymmetric DM may be a solution to the solar composition problem

ACV, Pat Scott, Aldo Serenelli 1411.6626, 1504.04378, 1605.06502
Dark matter in other stars

Nearby stars $\gtrsim \ 1.3 \ M_\odot$:

**Convective cores** form in stars where the **temperature gradient** is too large to maintain hydrostatic equilibrium.

DM can erase these cores, affecting **asteroseismology**.
Convective core suppression

Constraint using $\alpha$ Cen B

Constraints are weak partly because the local DM density $\sim \text{GeV cm}^{-3}$ is small (and this is only one star)
Large amounts of dark matter?

Intro astronomy reminder

Main sequence stars are powered by Hydrogen fusion

Lifetime is limited by:
- How much fusion is needed to oppose gravitational pressure
- How much hydrogen ‘in the tank’ (in core above T required for fusion)
When a star exhausts its hydrogen it leaves the main sequence

Not visible in our lifetime, but we can look at populations of stars to test stellar evolution (like looking at populations of humans to understand aging)
Large amounts of DM: change trajectory on HR diagram erasure of convective ‘hook’ (because no convective cores)

No temperature inversions as previous studies had found (this was a numerical artefact)
Raen et al 2010.04184: Main sequence lifetime

Low mass stars: larger core — more available H to fuse, longer lifetime

High mass stars: suppression of convective core — no mixing = less available fuel. Shorter lifetime
Heat conduction in stars

Boltzmann equation

\[ DF(v, r, t) = \frac{1}{\ell_{\chi}} CF(v, r, t) \]

\( D \): Liouville operator (covariant derivatives)

\( F(v, r, t) \): Dark matter phase space density

\( C \): Collision operator (a bunch of integrals)

\[ \ell_{\chi} \propto \sigma_{\chi N} \]: Mean free path

\[ = 6 \text{-dimensional integro-differential equation} \]

Must be solved consistently \textbf{at every time step} in stellar evolution
Only exact(ish) solution is Monte Carlo (random walk)

Let a particle bounce around for many iterations, histogram distribution, average heat transferred vs $r$ using **ergodicity**

Cannot possibly do this for every simulated time step. Need some **approximations**
Solution method 1: isothermal (Spergel & Press)

\[ DF(v, r, t) \simeq 0 \quad \rightarrow \quad F \sim \exp \left( -\frac{1}{2}mv^2 + m\phi(r) \right) / kT_\chi \]

DM is at a single ‘average’ temperature \( T_\chi \)

Conduction treated as contact between two weakly coupled heat baths

\[ \epsilon \propto \sigma[T_\star(r) - T_\chi] \]

\[ \{ \begin{align*} 
\text{Heat removed from star where } & T_\star(r) > T_\chi \\
\text{Heat deposited in star where } & T_\star(r) < T_\chi 
\end{align*} \]
Solution method 1: isothermal (Spergel & Press)

\[ \epsilon \propto \sigma [T_\star(r) - T_\chi] \]

This has been known to be incorrect since 1990, but is still most widely used because it is numerically stable.

Gould & Raffelt 1990 Monte Carlo simulation

Isothermal assumption \( T_\chi \)
Actual DM temperature

\( \Delta T \) overestimated \( \rightarrow \) heat transfer overestimated
Solution method 2: corrected LTE (Gould & Raffelt)

If $\ell \ll r_\chi$, conduction is local ($T_\chi(r) \simeq T_\star(r)$)

Expand

$$DF(v, r, t) = \frac{1}{\ell_\chi} CF(v, r, t)$$

in a series in $\ell_\chi |\nabla \ln T_\star|$

Solve first order dipole (only care about radial part)

$$\text{Luminosity } \propto \kappa(m_\chi) n_\chi(r) \ell_\chi \frac{dT_\star}{dr}$$

$\kappa(m_\chi)$: thermal conduction coefficient computed from $C$
Solution method 2: corrected LTE (Gould & Raffelt)

Two corrections still needed:

- **Knudsen suppression:** condition
  \[ \ell \chi \ll |\nabla \ln T|^{-1} \]
  breaks down.

- **Radial suppression:** isotropy assumption
  breaks down at low radii

All “correct” results in the past 30 years use a fit to this graph to fix the LTE prediction

Additional technical issue: numerically unstable (reason method 1 still used)
Monte Carlo: A few thousand CPU hours

Hannah Banks (Cambridge)

Angular momentum: distribution not fully specified by
\[ E = \frac{1}{2}mv^2 + m\phi \]

Anisotropy ↔ departure from Maxwell-Boltzmann

Interesting results from non-constant cross sections to come
Heat transport: theory vs Monte Carlo

Dark Matter luminosity

transported energy

Currently working on a robust parametrization + next-gen simulations — stay tuned!
Summary

• Dark matter in the ‘traditional’ mass range ~ GeV-TeV can affect the Sun in observable ways

• Low-mass Asymmetric dark matter can do very interesting things to main sequence stars

• Current results are built on a theoretical framework that relies on some inconsistent assumptions

• The true effect of ADM in stars remains to be elucidated. Stay tuned!
Please check out

**Ningqiang Song**
*Closing the window for WIMPy inelastic dark matter with heavy nuclei*
Particle physics session 17:15 Jun 9

**Avi Friedlander**
*Signatures of Primordial Black Holes in theories of Large Extra Dimensions* (← link to video)

**Neal Avis Kozar**
*Exploring dark matter detection using Solar capture and the Non-Relativistic Effective Operator formalism* (← link to poster)
GatherTown Room 5, poster J83