Dark stars: structure, evolution and impacts upon the high-redshift Universe

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Slides available from www.fysik.su.se/~pat
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Based on:

Dark star grids
PS, Fairbairn, Edsjö (arXiv:0904.2395, Proc DARK09)

Consequences of early-Universe dark stars
Venkatesan, PS, Gondolo, Pierpaoli, in prep.
Outline

1. Background
2. More Interesting Stuff
   - Dark star grids & the DARKSTARS code
   - Impacts of dark stars at high redshift
WIMPs at a glance

- Weakly-Interacting Massive Particles (one type of CDM)
- Dark because no electromagnetic interactions
- Cold because very massive ($\sim 10$ GeV to $\sim 10$ TeV) $\implies$ good for structure formation
- Non-baryonic and stable - no problems with BBN or CMB
- Weak-scale masses and annihilation cross-sections
  
  *naturally* lead to a relic abundance of the right order of magnitude
- Many theoretically well-motivated particle candidates (e.g. lightest neutralino in R-parity conserving supersymmetry, lightest Kaluza-Klein boson in extra-dimensional models)
- Weak interaction means scattering off nuclei $\implies$ direct detection experiments
- Almost all WIMPs are Majorana particles (own antiparticles) $\implies$ self-annihilation cross-section
(My preferred definition of) a ‘dark star’: any star whose structure or evolution has been effected by WIMP annihilation.

2 main ways to get the DM into the star:

- **gravitational contraction**: baryons collapse, change the gravitational potential, taking the DM along for the ride.
- **nuclear scattering**: WIMPy passers-by scatter off stellar nuclei and become gravitationally bound.
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⇒ There are many kinds of dark stars...

- Main sequence stars in the Milky Way - fed by scattering, maybe interesting (Salati, PS, Fairbairn, etc.)
- White dwarfs in the Milky Way - fed by scattering, maybe interesting (Moskalenko, Wai, Fairbairn, etc.)
- Neutron stars in the Milky Way - fed by scattering, not interesting (Bertone, Fairbairn, etc.)
- Pop III stars in the early Universe - fed by grav. contraction and *maybe* scattering, maybe interesting (Spolyar, Freese, Iocco, etc.)
Background
More Interesting Stuff

A Dark-Star Spotter’s Guide to the Universe

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- Pop III stars in the early Universe - fed by grav. contraction and *maybe* scattering, maybe interesting (Spolyar, Freese, Iocco, etc.)
However they got there, effects are similar

WIMPs congregate in the star and self-annihilate

⇒ standard model particles (= heat) are injected into the gas

What are the effects on stellar structure and evolution?
Stellar structure and evolution

\[ \frac{dP}{dm} = - \frac{Gm}{4\pi r^4} \]

\[ \frac{dr}{dm} = \frac{1}{4\pi r^2 \rho} \]

\[ \frac{dL}{dm} = \epsilon_{\text{nuc}} - \epsilon_\nu + \epsilon_{\text{grav}} + \epsilon_{\text{WIMP}} \]

\[ \frac{d\ln T}{dm} = - \nabla \frac{d\ln P}{dm} \]

\[ \epsilon_{\text{WIMP}} \equiv \epsilon_{\text{ann}} + \epsilon_{\text{trans}} \]

\[ \frac{dN}{dt} = C(t) - 2A(t) \]

- $r$: radius
- $m$: mass contained within radius $r$
- $P$: pressure
- $\rho$: density
- $L$: luminosity
- $\epsilon_{\text{nuc}}$: nuclear energy production rate per mass of baryonic matter
- $\epsilon_\nu$: rate of energy loss to neutrinos
- $\epsilon_{\text{grav}}$: energy production rate from gravitational contraction
- $\epsilon_{\text{WIMP}}$: energy production rate by WIMPs
- $N$: WIMP number
- $C$: capture rate
- $A$: annihilation rate
- $\epsilon_{\text{ann}}$: energy generation rate from WIMP annihilation
- $\epsilon_{\text{trans}}$: conductive energy transport rate by WIMPs
Stellar structure and evolution

\[
\frac{dP}{dm} = -\frac{Gm}{4\pi r^4} \quad (1)
\]

\[
\frac{dr}{dm} = \frac{1}{4\pi r^2 \rho} \quad (2)
\]

\[
\frac{dL}{dm} = \epsilon_{\text{nuc}} - \epsilon_{\nu} + \epsilon_{\text{grav}} + \epsilon_{\text{WIMP}} \quad (3)
\]

\[
\frac{d\ln T}{dm} = -\nabla \frac{d\ln P}{dm} \quad (4)
\]

\[
\epsilon_{\text{WIMP}} \equiv \epsilon_{\text{ann}} + \epsilon_{\text{trans}} \quad (5)
\]

\[
\frac{dN}{dt} = C(t) - 2A(t) \quad (6)
\]
Annihilation:

\[ A(t) = 4\pi \int_0^{R_*} r^2 a(r, t) \, dr \]  
(7)

\[ \epsilon_{\text{ann}}(r, t) = \frac{2a(r, t)m_\chi c^2}{\rho(r, t)} - \nu_{\text{loss}} \]  
(8)

\[ a(r, t) = \frac{1}{2} < \sigma_a \nu >_0 n_\chi(r, t)^2 \]  
(9)

- Assume all energy goes into heating gas (regardless of actual annihilation channel), except for some neutrino losses (10%)
The DARKSTARS dark evolution code

- Derived from the stellar evolution code EZ by Bill Paxton, itself derived from Peter Egeland's STARS
- Solves the 4 stellar structure equations by relaxation
- Solution is over an adaptive grid of 200 points, introducing a further 4 grid equations
- Also includes full treatment of conductive energy transport by WIMPs
- WIMP population solved for explicitly at each timestep, annihilation and energy transport calculated at each gridpoint and fed into the structure equations
- Many, many options - new version will have highly-configurable DM velocity structure and $Z = 0$ mode
- Public - get it from http://www.fysik.su.se/~pat/darkstars
Grid input parameters (or at least the ones people will care about)

- Nuclear-scattering cross-sections: $\sigma_{SI} = 10^{-44} \text{ cm}^2$, $\sigma_{SD} = 10^{-38} \text{ cm}^2$
- Annihilation cross-section: $<\sigma_v> = 3 \times 10^{-26} \text{ cm}^3/\text{s}$
- Stellar masses: $0.3-2.0 \, M_\odot$, metallicities: $Z = 0.0003 - 0.02$
- Behaviour is qualitatively very similar at higher masses and $Z = 0$
Evolutionary tracks - HR diagram

\[ \log_{10}\left( \frac{L_{\text{W, max}}}{L_{\text{nuc}(0)}} \right) \approx 1 \]

\[ Z = 0.01 \]

- Luminosity, \( \log_{10}(L/L_\odot) \)
- Effective (surface) temperature, \( \log_{10}\left( T_{\text{eff}}/K \right) \)

- 1.8 M\(_\odot\)
- 1.4 M\(_\odot\)
- 1.0 M\(_\odot\)
- 0.8 M\(_\odot\)
- 0.6 M\(_\odot\)
- ZAMS

- 0 yr
- 0.5 Myr
- 1.0 Myr
- ≥ 44 Myr
- 2.0 Myr
- 5.0 Myr

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Dark stars: structure, evolution and high-redshift effects
Evolutionary tracks - HR diagram

- **Background**
  - More Interesting Stuff

- **Dark star grids & the DARKSTARS code**
  - Impacts of dark stars at high redshift

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**Effective (surface) temperature, log_{10}(T_{eff}/\text{K})**

**Luminosity, log_{10}(L/L_\odot)**

<table>
<thead>
<tr>
<th>Mass (M_\odot)</th>
<th>ZAMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.8</td>
<td></td>
</tr>
<tr>
<td>1.4</td>
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<tr>
<td>1.0</td>
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<td>0.8</td>
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<tr>
<td>0.6</td>
<td></td>
</tr>
</tbody>
</table>

- **Z = 0.01**

- **Effective (surface) temperature, log_{10}(T_{eff}/\text{K})**

- **Luminosity, log_{10}(L/L_\odot)**

- **ZAMS**

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Dark stars: structure, evolution and high-redshift effects
Evolutionary tracks - central equation of state

Central temperature, log$10$ $T$

Central density, log$10$ $\rho_c$

$\approx -3$

$\approx -1$

$Z = 0.01$

$Z = 0.01$

$1.8 M_\odot$

$1.4 M_\odot$

$1.0 M_\odot$

$0.8 M_\odot$

$0.6 M_\odot$

$\geq 44$  Myr

$ZAMS$

$1.8 M_\odot$

$1.4 M_\odot$

$1.0 M_\odot$

$0.8 M_\odot$

$0.6 M_\odot$

$\approx -1$

$\approx 1$
**Convection**

- **Enclosed mass (M/M_☉)**
  - **M = 0.4 M_☉**, **Z = 0.01**
  - **M = 1.0 M_☉**, **Z = 0.01**
  - **M = 1.6 M_☉**, **Z = 0.01**

- **WIMP luminosity, log_{10} L_{W,max} / L_{nuc(0)}**
  - **M = 0.6 M_☉**, **Z = 0.01**
  - **M = 1.2 M_☉**, **Z = 0.01**
  - **M = 1.8 M_☉**, **Z = 0.01**

- **More Interesting Stuff**
  - Background
  - Impacts of dark stars at high redshift

- **Dark star grids & the DARKSTARS code**
Main-sequence lifetimes

Main-sequence lifetime (Gyr) vs. WIMP luminosity, log_{10} \left[ \frac{L_{\text{WIMPMAX}}}{L_{\text{NUC}(0)}} \right]

- Z = 0.0003
- Z = 0.004
- Z = 0.01
- Z = 0.02

Masses: 2.0 M_\odot, 1.8 M_\odot, 1.6 M_\odot, 1.4 M_\odot, 1.2 M_\odot, 1.0 M_\odot, 0.9 M_\odot

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Dark stars: structure, evolution and high-redshift effects
Detecting Population III dark stars with JWST

- Individual dark stars not detectable with JWST unless viewed through a gravitational lens, e.g. cluster MACS J0717.5+3745 ($\mu = 160$)
- Very red spectra $\Rightarrow$ distinguishable from other objects
- Creates unique signature in integrated galaxy spectra
Freese et al. proposed that Pop III dark stars could grow to $10^7 M_\odot$.

Extreme scenario $\implies$ severely limited even by existing observations.

Limits on *supermassive* dark stars with HST

![Log-log plot showing the relationship between mass and lifetime](image-url)
Impacts of dark stars on reionization

- Reionization history of the Universe would have looked very different with dark stars
- Proto-Pop III (PP3) which was huge ($\sim 1000 \, M_\odot$), cool and long-lived
- (Based on real dark star model atmospheres)

Example star-formation histories with dark stars:

- $t_{DS} = 10$ Myr PP3 $\rightarrow$ 10 Myr Pop III $\rightarrow$ Pop II
- $t_{DS} = 10$ Myr PP3 $\rightarrow$ Pop II
- $t_{DS} = 100$ Myr PP3 $\rightarrow$ 10 Myr Pop III $\rightarrow$ Pop II
- $t_{DS} = 100$ Myr PP3 $\rightarrow$ Pop II

Figure courtesy of Aparna Venkatesan. Semianalytical (Press-Schechter-based) reionization models of Venkatesan, Tumlinson & Shull (2003), Venkatesan (2000)
Optical depths to the last scattering surface

WMAP & Planck can distinguish different dark star scenarios
Summary

- Dark stars form when DM annihilates in stellar cores
- They don’t look like the stars we know & love
- They might just be detectable with JWST
- They should impact reionization
- The CMB can be used to put limits on their formation and lifetimes
- The DARKSTARS evolution code is publicly available for doing dark stellar evolution, and you are encouraged to use it.

http://www.fysik.su.se/~pat/darkstars
Extras 1: WIMP conductive energy transport

WIMP distribution:
- $n_\chi(r, t)$ can be given by either an isothermal (nonlocal) approximation or an LTE approximation (completely local).

WIMP energy transport:
- WIMPs can transport energy by conduction only (Weakly-Interacting Mas...)
- In the LTE regime, an exact solution for $\epsilon_{\text{trans}}$ exists (Gould & Raffelt, 1990)
- In the nonlocal regime, no exact solution - but an idea of how badly the LTE solution overestimates $\epsilon_{\text{trans}}$

Degree of nonlocality of WIMP energy transport and distribution can be given by the Knudsen parameter $K$:

$$K \equiv l(0, t)/r_\chi(t),$$  \hspace{1cm} (10)

$\begin{align*}
\frac{l}{r_\chi} & \text{ WIMP mean free path} \\
\text{Approximate WIMP scale height}
\end{align*}$

used to interpolate between densities and scale LTE energy transport.
$\epsilon_{\text{trans}}$ & $\mathcal{E}(t)$

$\epsilon_{\text{trans}} (\text{erg g}^{-1} \text{s}^{-1})$

Height in star, $\log_{10}(r/\text{R}^{\star})$

$-1.7$ $-1.6$ $-1.5$ $-1.4$ $-1.3$ $-1.2$ $-1.1$ $-1.0$

$-4$ $-2$ $0$ $2$ $4 \times 10^{-5}$

$\mathcal{E}(t) \equiv \frac{\int_{0}^{R^{\star}} r^2 \frac{\rho^{\star}(r, t)}{\mu^{\star}(r, t)} \left| \frac{\epsilon_{\text{trans}}}{\epsilon_{\text{other}}} \right| \, dr}{\int_{0}^{R^{\star}} r^2 \frac{\rho^{\star}(r, t)}{\mu^{\star}(r, t)} \, dr}$

Eq. (11)
Extras 2 (cont.): WIMP conductive energy transport

WIMP conductive effectiveness, $\log_{10}(E(t_{\text{adjust}}))$

WIMP luminosity, $\log_{10}(L_{W,\text{max}}/L_{\text{nuc}}(0))$

$Z = 0.01$

2.0 $M_\odot$
1.8 $M_\odot$
1.6 $M_\odot$
1.4 $M_\odot$
1.2 $M_\odot$
1.0 $M_\odot$
0.8 $M_\odot$
0.6 $M_\odot$
0.4 $M_\odot$
Extra 3: energy production

- Central temperature, $T_{c}(t_{\text{adjust}})$ (K)
- WIMP luminosity, $L_{W,\text{max}}$ (log)
- $Z = 0.01$

- pp–chain luminosity, $L_{\text{pp}}(t_{\text{adjust}}) / L_{\text{pp}}(0)$
- WIMP luminosity, $L_{W,\text{max}}$ (log)
- CNO–process luminosity, $L_{\text{CNO}}(t_{\text{adjust}}) / L_{\text{CNO}}(0)$
- $Z = 0.01$

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Extras 4: Stars on elliptical orbits at the Galactic centre

$P = 10 \text{ yr}$

$Z = 0.02$

WIMP luminosity, log

$\log_{10}\left( \frac{L_{W,\text{max}}}{L_{\text{nuc}}(0)} \right)$

Modified orbital ellipticity, log

$\log_{10}(1 - e)$

0.6 $M_{\odot}$, AC+spike
1.0 $M_{\odot}$, AC+spike
1.5 $M_{\odot}$, AC+spike
0.6 $M_{\odot}$, NFW+spike
1.0 $M_{\odot}$, NFW+spike
1.5 $M_{\odot}$, NFW+spike