

WIMPs and stellar evolution - dark stars at the Galactic centre

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Based on: PS, Fairbairn & Edsjö, [arXiv:0809.1871](https://arxiv.org/abs/0809.1871)

Outline

- 1 Preliminaries
 - Background
 - Theory
 - Simulations
- 2 Results
 - Benchmark evolutionary changes
 - Main-sequence stars at the Galactic Centre

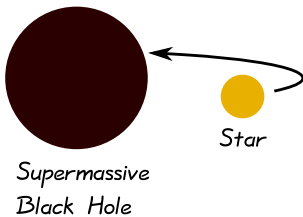
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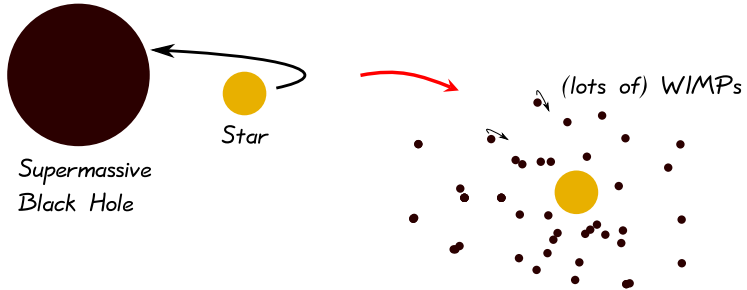
The idea in a nutshell (cartoon version)



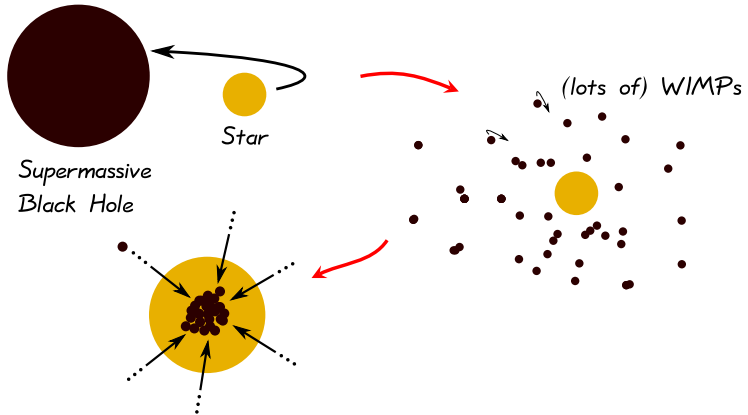
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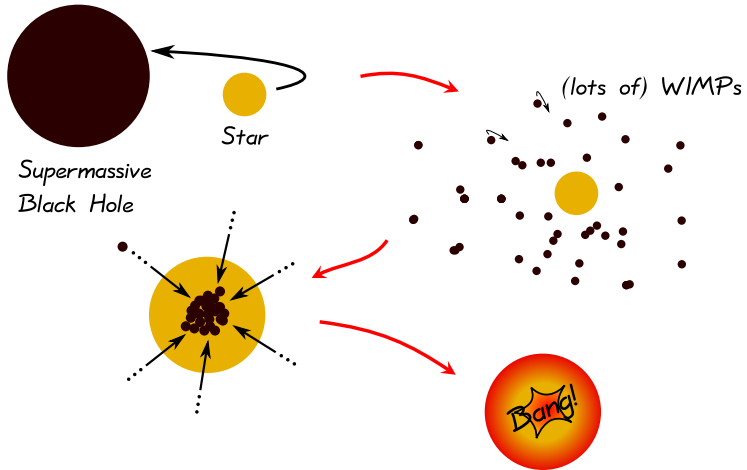
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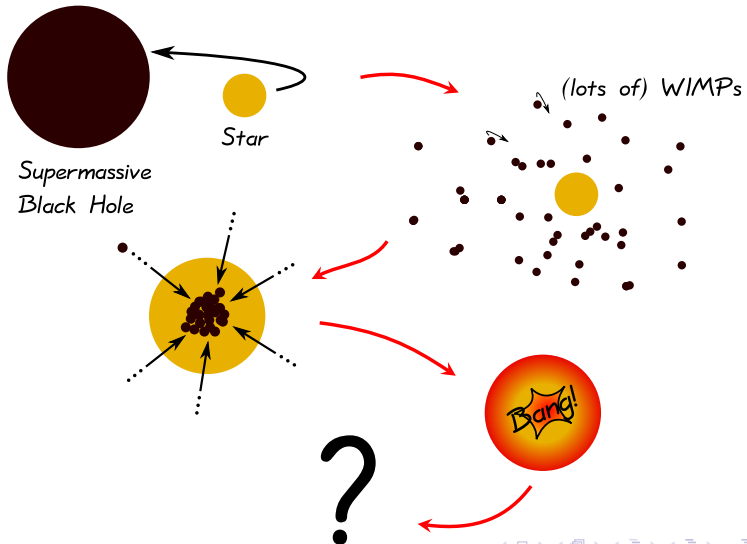
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Context

- Early work (late 80s, early 90s) by Salati, Dearborn, Bouquet, Raffelt and others
- Interest sprang up again in 2007
 - compact objects (Moskalenko & Wai, Bertone & Fairbairn)
 - Pop III formation from Spolyar, Freese, Gondolo, et al
 - PopI/II main sequence evolution from us
 - Pop III evolution from Iocco, Ripamonti et al, Yoon et al and Taoso, Bertone, et al
- Most efforts to date have been with simple semianalytical stellar structure models (polytropes), approximate capture expressions and simplified treatments of the WIMP physics within stars
- We wanted to do detailed numerical stellar structure and evolution investigations on main sequence stars at the Galactic Centre (GC) → DARKSTARS
- Elliptical orbits, detailed treatment of dark matter density and velocity distributions at GC

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Stellar structure and evolution + WIMPs

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

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

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

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

Plus:

$$\frac{dN}{dt} = C(t) - 2A(t) \quad (5)$$

$$\epsilon_{\text{WIMP}} \equiv \epsilon_{\text{ann}} + \epsilon_{\text{trans}} \quad (6)$$

r	radius
m	mass contained within radius r
P	pressure
ρ	density
L	luminosity
ϵ_{nuc}	nuclear energy production rate per mass of baryonic matter
ϵ_{ν}	rate of energy loss to neutrinos
ϵ_{grav}	energy production rate from gravitational contraction
ϵ_{WIMP}	energy production rate by WIMPs

N	WIMP number
C	capture rate
A	annihilation rate
ϵ_{ann}	energy generation rate from WIMP annihilation
ϵ_{trans}	conductive energy transport rate by WIMPs



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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 ϵ_{trans} **exists** (Gould & Raffelt, 1990)
- In the nonlocal regime, no exact solution - but an idea of how badly the LTE solution overestimates ϵ_{trans}

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

$$K \equiv l(0, t)/r_\chi(t), \quad (7)$$

l

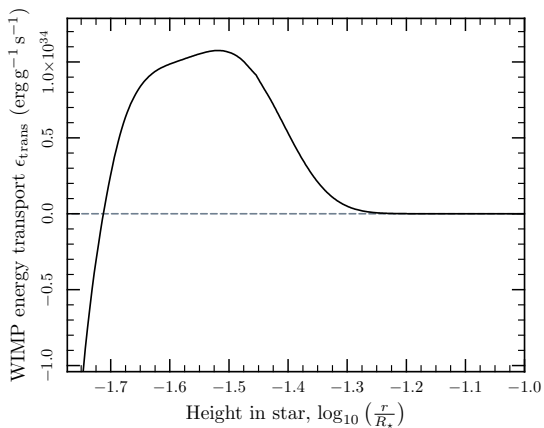
WIMP mean free path

r_χ

Approximate WIMP scale height

used to interpolate between densities and scale **LTE energy transport**



ϵ_{trans} 

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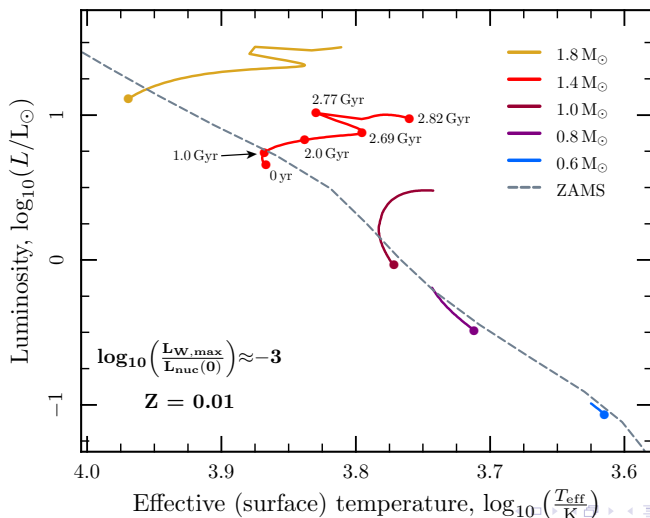
Input parameters

- Nuclear-scattering cross-sections: $\sigma_{\text{SI}} = 10^{-44} \text{ cm}^2$,
 $\sigma_{\text{SD}} = 10^{-38} \text{ cm}^2$
- Annihilation cross-section: $\langle \sigma_a v \rangle_0 = 3 \times 10^{-26} \text{ cm}^3/\text{s}$
- WIMP halo densities: adiabatically contracted NFW profile with a central spike (“AC+spike”), or without adiabatic contraction (“NFW+spike”).
- WIMP halo velocities: isothermal with dispersion 270 km/s, or non-Gaussian derived from Via Lactea simulation. Extending to infinity, or truncated at the local value of the Galactic escape velocity.
- Stellar masses: $0.3\text{--}2.0 M_{\odot}$, metallicities: $Z = 0.0003 - 0.02$

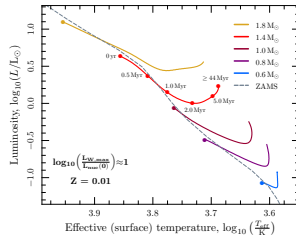
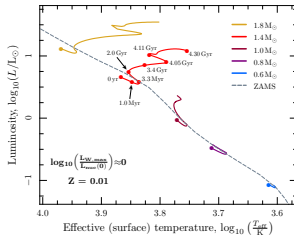
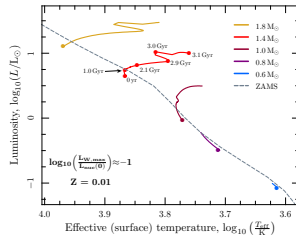
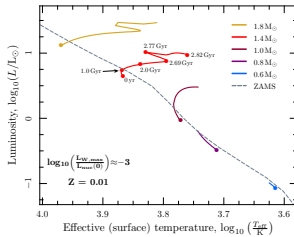
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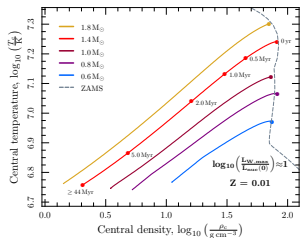
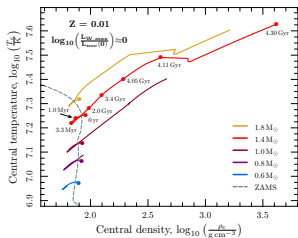
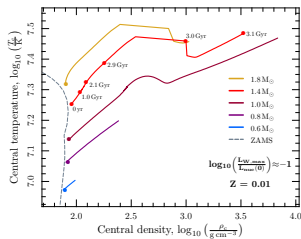
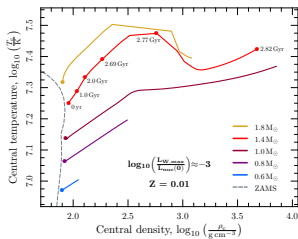
Evolutionary tracks - HR diagram



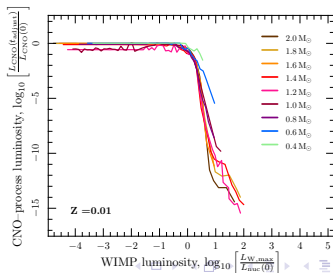
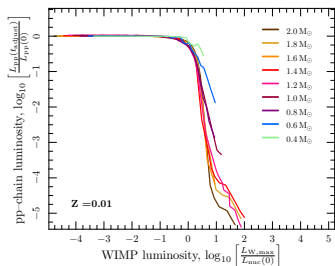
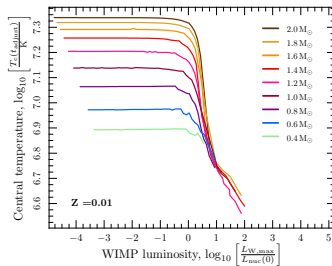
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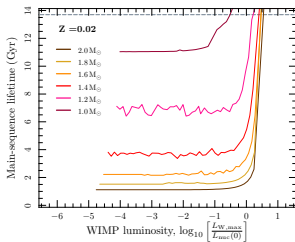
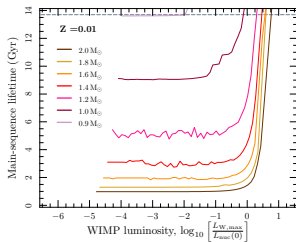
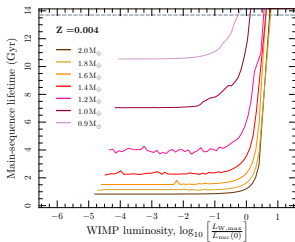
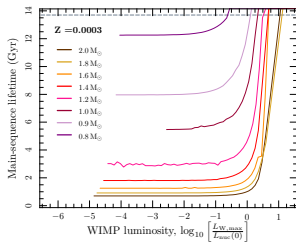
Evolutionary tracks - central equation of state



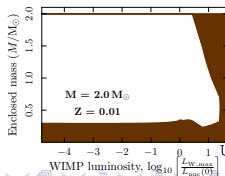
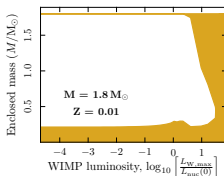
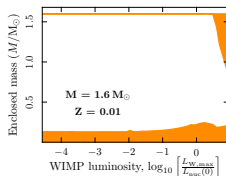
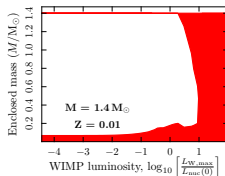
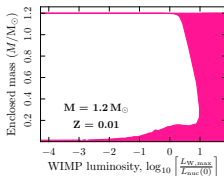
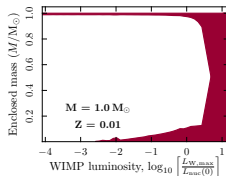
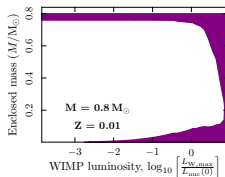
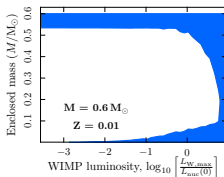
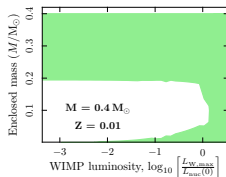
Energy production



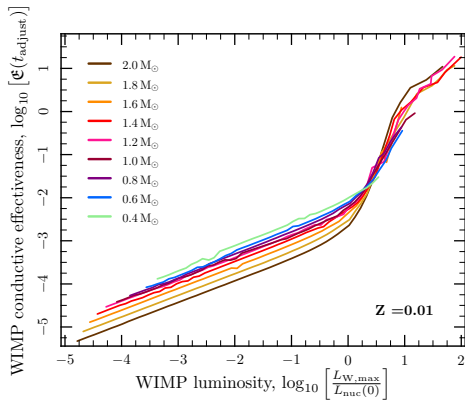
Main-sequence lifetimes



Convection



Conductive transport

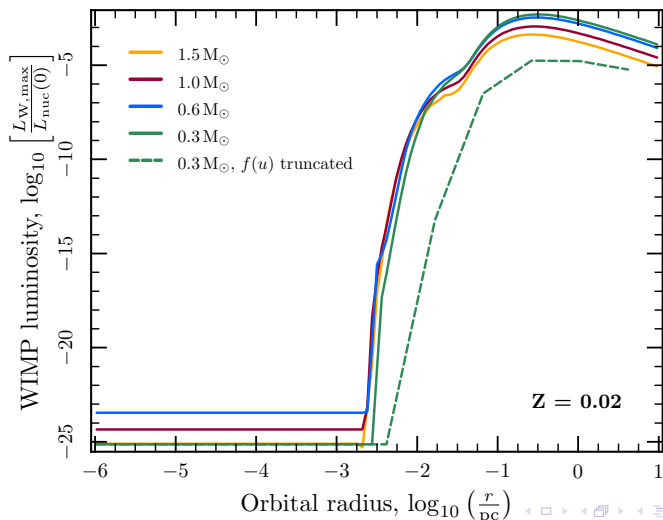


$$\epsilon(t) \equiv \frac{\int_0^{R_*} r^2 \frac{\rho_*(r, t)}{\mu_*(r, t)} \left| \frac{\epsilon_{\text{trans}}}{\epsilon_{\text{other}}} \right| dr}{\int_0^{R_*} r^2 \frac{\rho_*(r, t)}{\mu_*(r, t)} dr} \quad (8)$$

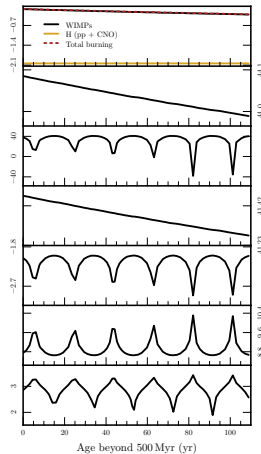
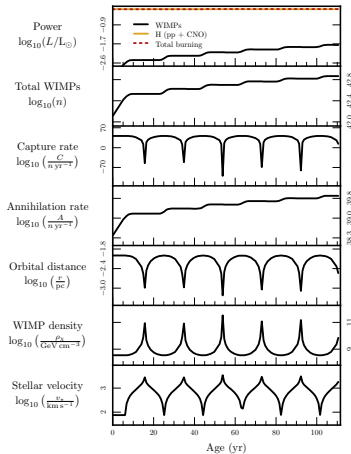
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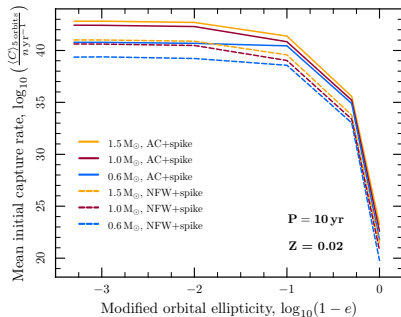
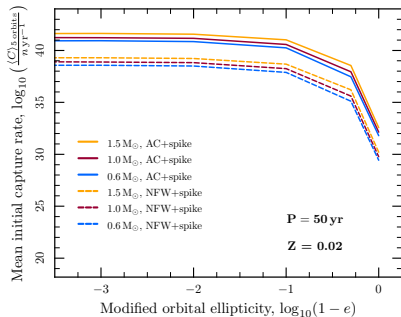
Circular orbits



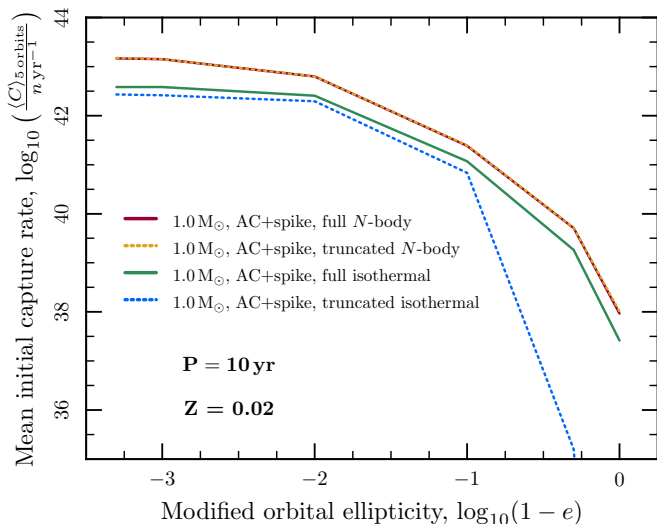
Elliptical orbits - orbit by orbit evolution



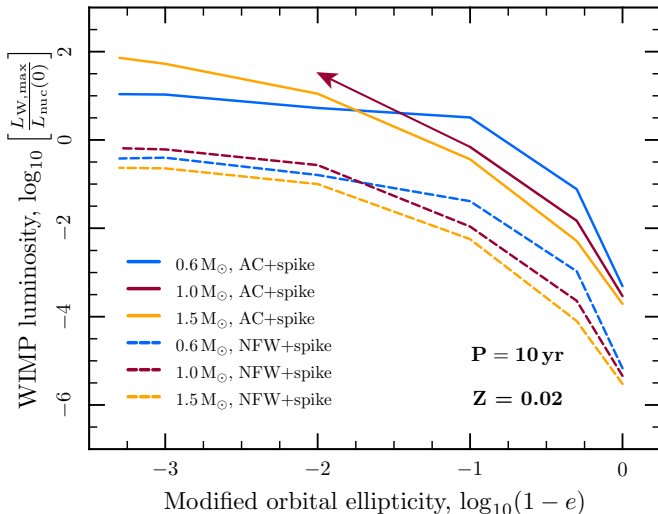
Elliptical orbits - mean capture rates



Elliptical orbits - alternative velocity distribution



Put them all together and you get...



Conclusions

- Finding dark stars near the Galactic Centre seems quite possible - not S stars, but low-mass counterparts
- Assuming adiabatic contraction, $1 M_{\odot}$ stars with orbital periods $\lesssim 50$ years and eccentricities $\gtrsim 0.9$
- Without adiabatic contraction, $1 M_{\odot}$ stars require orbits with periods $\lesssim 10$ years and eccentricities $\gtrsim 0.99$
- Any observation of *normal* stars on these orbits, of a solar mass or below, would provide constraints upon
 - the dark matter density profile at the GC
 - the WIMP mass and spin-dependent nuclear-scattering cross-section - **competitive with current direct detection sensitivities**
- DARKSTARS code will be publicly available in the near future
- ... as will results with red giants and metal-free stars

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Extra: the DARKSTARS modelling code

- Derived from the stellar evolution code EZ by Bill Paxton, itself derived from Peter Eggelton'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
- Capture routines are derived from solar capture routines in the DarkSUSY package
- WIMP population solved for explicitly at each timestep, annihilation and energy transport calculated at each gridpoint and fed into the structure equations
- Most extensive 'dark' evolution code on the market (in terms of capture rates, annihilation, conductive energy transport, internal WIMP distribution, neutrino losses)