Dark stars at the Galactic centre and the DARKSTARS public code

Pat Scott

Oskar Klein Centre for Cosmoparticle Physics (OKC) &
Department of Physics, Stockholm University

November 7–11 2009

Collaborators: Malcolm Fairbairn, Joakim Edsjö

Based on: PS, Edsjö & Fairbairn, arXiv:0904.2395
PS, Fairbairn & Edsjö, MNRAS **394**:82 (arXiv:0809.1871)
Fairbairn, PS & Edsjö, PRD 2008,**77**:047301 (arXiv:0710.3396)

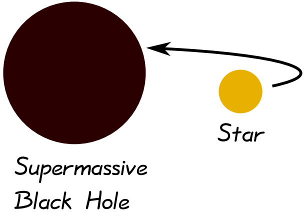
Outline

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

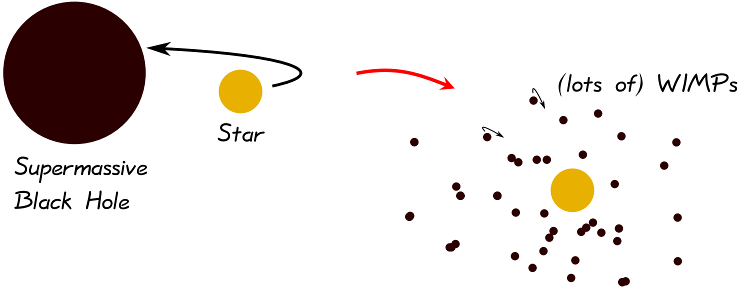
Stockholm University

The idea in a nutshell (cartoon version)

The idea in a nutshell (cartoon version)

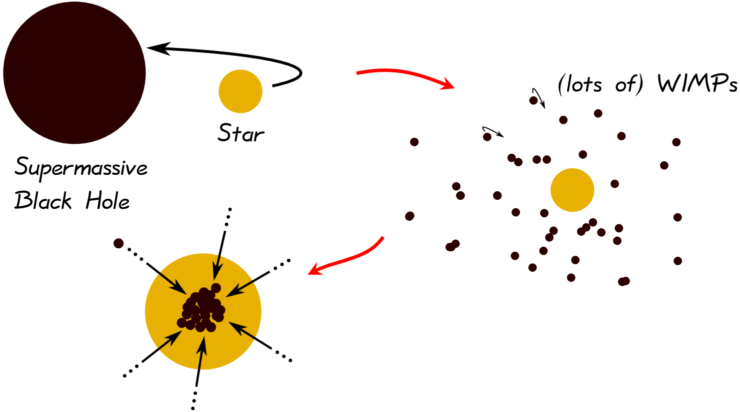


The idea in a nutshell (cartoon version)

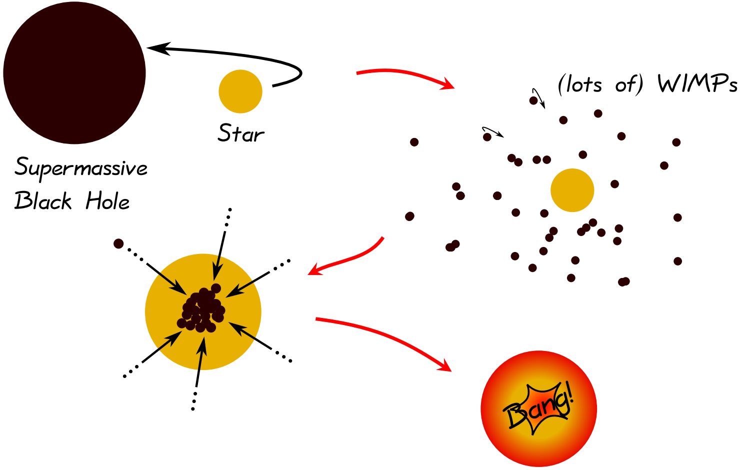


Stockholm University

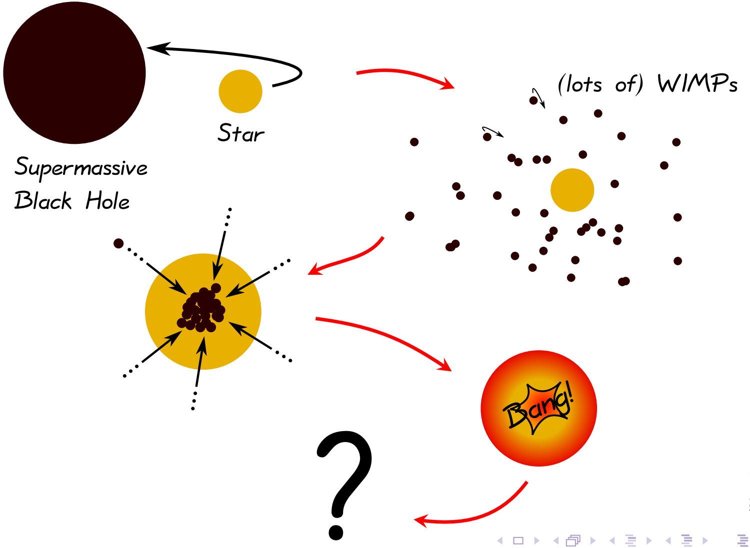
The idea in a nutshell (cartoon version)



The idea in a nutshell (cartoon version)



The idea in a nutshell (cartoon version)



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
- Previous efforts had 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 code
- Elliptical orbits, detailed treatment of dark matter density and velocity distributions at GC

Stockholm University

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
- Previous efforts had 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 code
- Elliptical orbits, detailed treatment of dark matter density and velocity distributions at GC

Stockholm University

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
- Previous efforts had 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 code
- Elliptical orbits, detailed treatment of dark matter density and velocity distributions at GC

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
- Previous efforts had 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 code
- Elliptical orbits, detailed treatment of dark matter density and velocity distributions at GC

Outline

Stellar structure and evolution

$$\frac{\mathrm{d}P}{\mathrm{d}m} = -\frac{Gm}{4\pi r^4} \quad (1)$$

$$\frac{\mathrm{d}r}{\mathrm{d}m} = \frac{1}{4\pi r^2 \rho} \quad (2)$$

$$\frac{\mathrm{d}L}{\mathrm{d}m} = \epsilon_{\mathrm{nuc}} - \epsilon_{\nu} + \epsilon_{\mathrm{grav}} + \epsilon_{\mathrm{WIMP}} \quad (3)$$

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

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

Plus:

- various boundary conditions
- constitutive relations (lookup tables) for nuclear reaction rates, equation of state $P(\rho, T)$ and opacities
- 4 additional equations for adaptive radial mesh

Stockholm University

Stellar structure and evolution

$$\frac{\mathrm{d}P}{\mathrm{d}m} = -\frac{Gm}{4\pi r^4} \quad (1)$$

$$\frac{\mathrm{d}r}{\mathrm{d}m} = \frac{1}{4\pi r^2 \rho} \quad (2)$$

$$\frac{\mathrm{d}L}{\mathrm{d}m} = \epsilon_{\mathrm{nuc}} - \epsilon_{\nu} + \epsilon_{\mathrm{grav}} + \epsilon_{\mathrm{WIMP}} \quad (3)$$

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

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

Plus:

- various boundary conditions
- constitutive relations (lookup tables) for nuclear reaction rates, equation of state $P(\rho, T)$ and opacities
- 4 additional equations for adaptive radial mesh

Stockholm University

WIMP capture and annihilation

$$\frac{\mathrm{d}N}{\mathrm{d}t} = C(t) - 2A(t) \qquad (5)$$

$$\epsilon_\mathrm{WIMP} \equiv \epsilon_\mathrm{ann} + \epsilon_\mathrm{trans} \qquad (6)$$

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

Capture: full expression for C is quite involved, but includes

- integration over radius, taking into account density profile
- integration over WIMP velocity distribution (numerical or analytical)
- summation over capture rates for 22 most important nuclei (including spin-dependant scattering)

Annihilation

Annihilation:

$$A(t) = 4\pi \int_0^{R_\star} r^2 a(r,t)\mathrm{d}r \qquad (7)$$

$$\epsilon_{\mathrm{ann}}(r,t) = \frac{2a(r,t)m_\chi c^2}{\rho(r,t)} - \nu_{\mathrm{loss}} \qquad (8)$$

$$a(r,t) = \frac{1}{2} < \sigma_{\mathrm{a}} v >_0 n_\chi(r,t)^2 \qquad (9)$$

a	local annihilation rate at radius r, per unit volume
$R_\star$	stellar radius
m_χ	WIMP mass
ν_{loss}	rate of energy loss into neutrino channels
$< \sigma_{\mathrm{a}} v >_0$	WIMP annihilation cross section
$n_\chi(r,t)$	local WIMP number density

- Assume all energy goes into heating gas (regardless of actual annihilation channel), except for some neutrino losses (10% – comes from detailed simulations of neutrino production in the solar core)

Stockholm University

Outline

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

The DARKSTARS modelling code

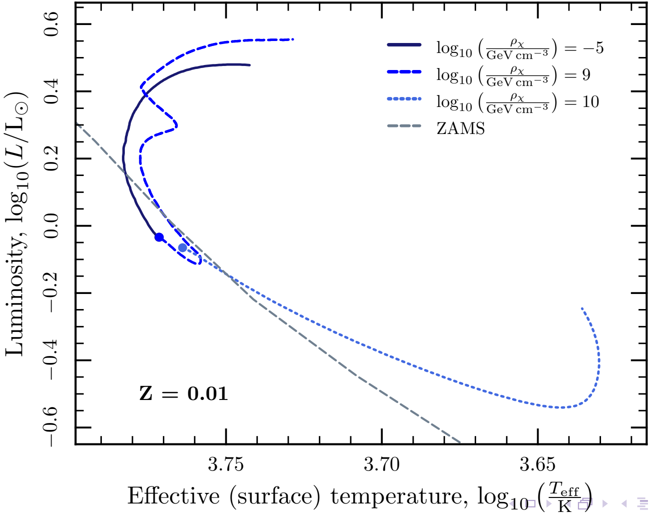
- Derived from the stellar evolution code EZ by Bill Paxton, itself derived from Peter Eggelton's STARS
- Solves the 4 stellar structure equations by relaxation
- Solution is over an adaptive grid of 200 points, introducing a further 4 grid equations
- Capture routines are derived from solar capture 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

The DARKSTARS modelling code

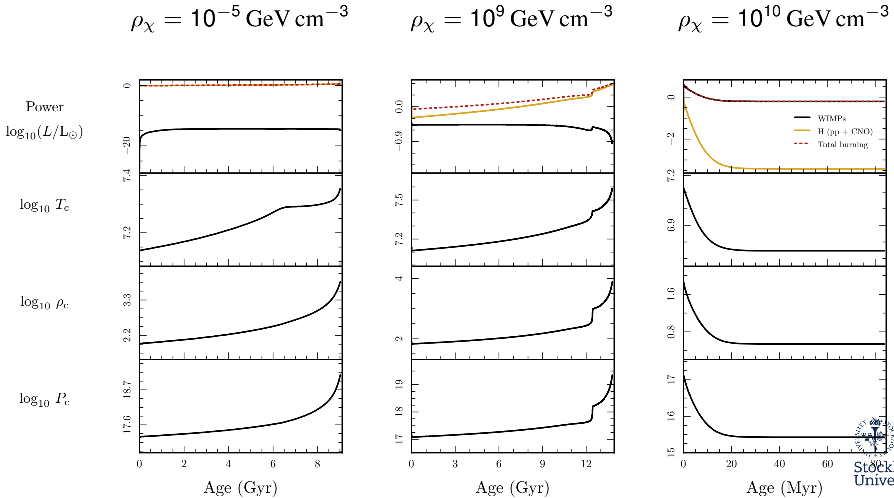
- Lots of options and switches: different velocity distributions, widths, stellar orbits, WIMP conductive transport / internal distribution schemes, particle data, stellar masses and metallicities, numerical options. . .
- Save and restart - good for evolving part-way then trying different late-stage scenarios
- DARKSTARS 2.0 coming soon: conversion to full $Z = 0$ (new opacities, equation of state) – DARKSTARS 1.01 can only do $Z = 0$ on pre-MS
- Future options for expansion to include alternative form factors and/or WIMP evaporation
- DARKSTARS 1.01 publicly available from http://www.fysik.su.se/~pat/darkstars

Stockholm University

The DarkStars code – examples



The DARKSTARS code – examples



Galactic centre: input parameters

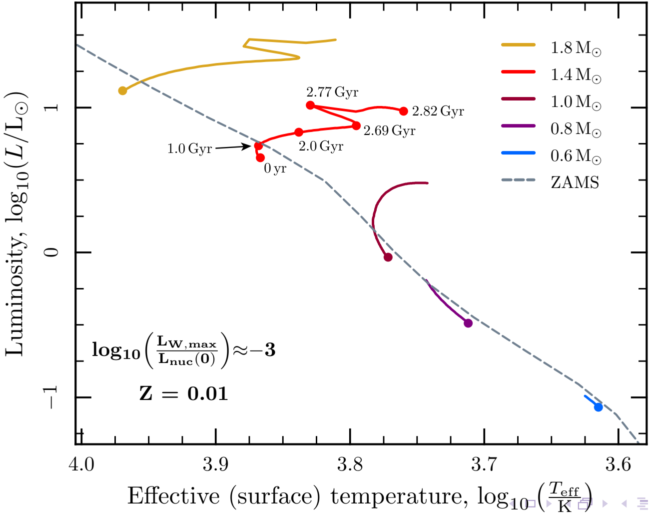
- Nuclear-scattering cross-sections: $\sigma_{\mathrm{SI}} = 10^{-44}\,\mathrm{cm}^2$, $\sigma_{\mathrm{SD}} = 10^{-38}\,\mathrm{cm}^2$
- Annihilation cross-section: $< \sigma_{\mathrm{a}} v >_0 = 3 \times 10^{-26}\,\mathrm{cm}^3/\mathrm{s}$
- WIMP halo densities: adiabatically contracted NFW profile 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: 0.3–2.0 $M_{\odot}$, metallicities: Z = 0.0003 – 0.02

Stockholm University

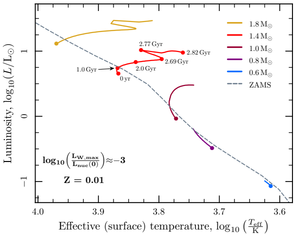
Outline

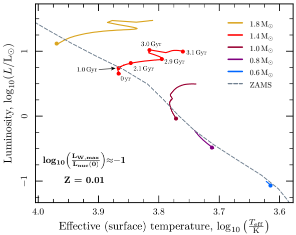
Stockholm University

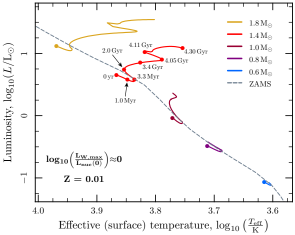
Evolutionary tracks - HR diagram

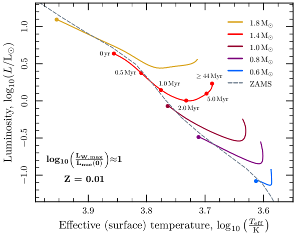


Evolutionary tracks - HR diagram



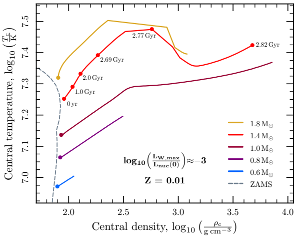


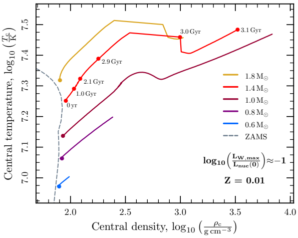


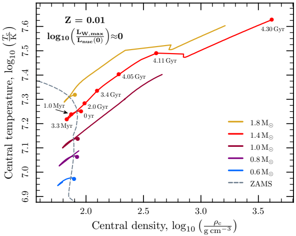


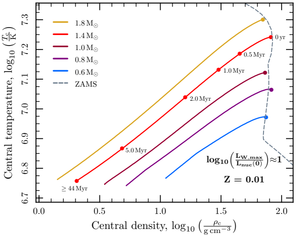
Stockholm University

Evolutionary tracks - central equation of state



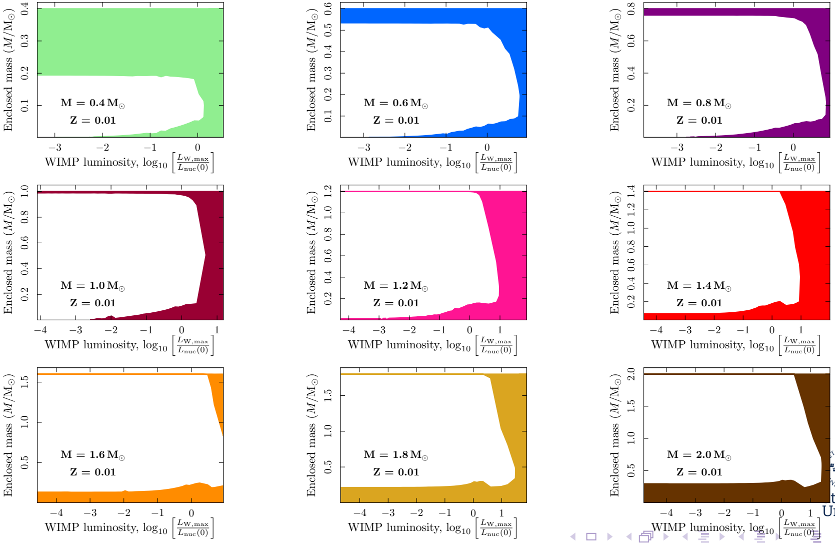




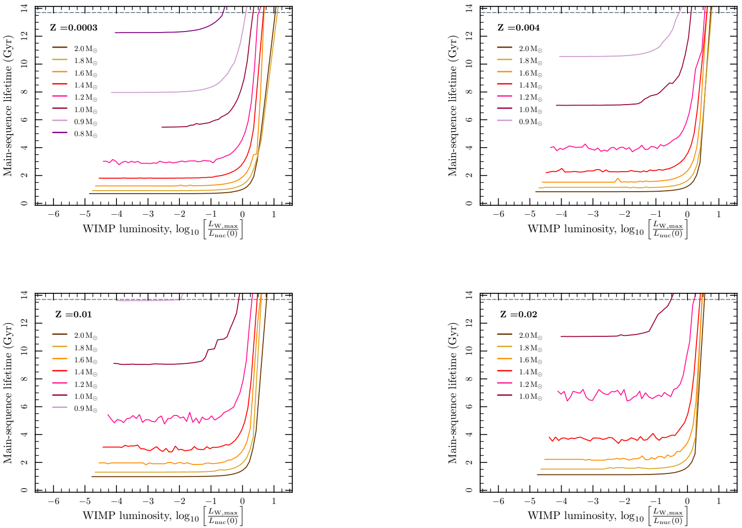


Stockholm University

Convection

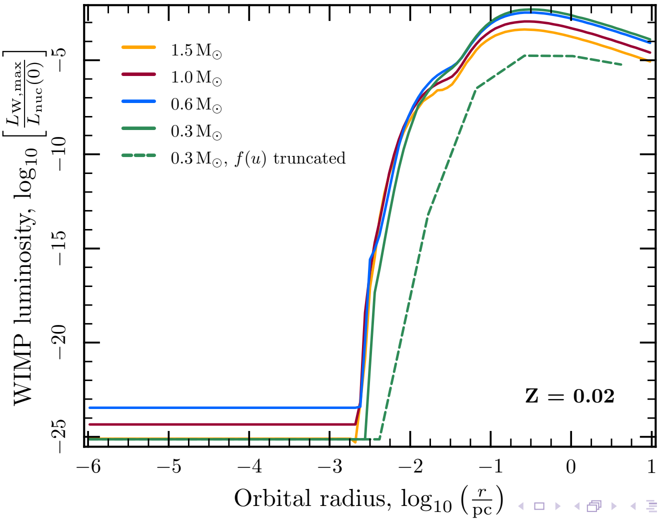

Enclosed mass $(M/M_\odot)$
WIMP luminosity, $\log_{10}\left[\frac{L_{W,max}}{L_{nuc}(0)}\right]$
$M = 0.4\,M_\odot$
$Z = 0.01$
$M = 0.6\,M_\odot$
$Z = 0.01$
$M = 0.8\,M_\odot$
$Z = 0.01$
$M = 1.0\,M_\odot$
$Z = 0.01$
$M = 1.2\,M_\odot$
$Z = 0.01$
$M = 1.4\,M_\odot$
$Z = 0.01$
$M = 1.6\,M_\odot$
$Z = 0.01$
$M = 1.8\,M_\odot$
$Z = 0.01$
$M = 2.0\,M_\odot$
$Z = 0.01$

Main-sequence lifetimes

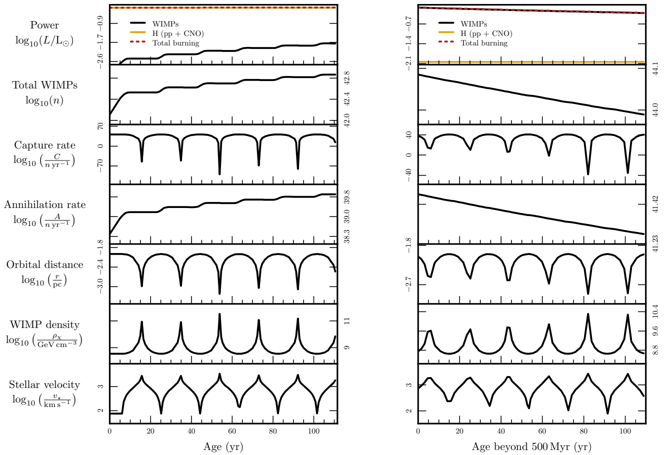


Outline

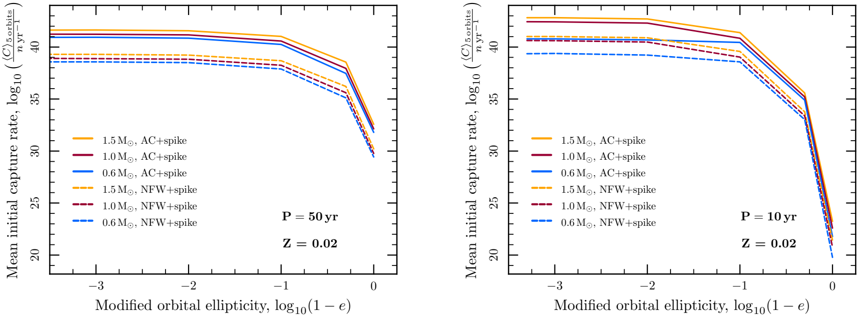
Circular orbits



Elliptical orbits - orbit by orbit evolution

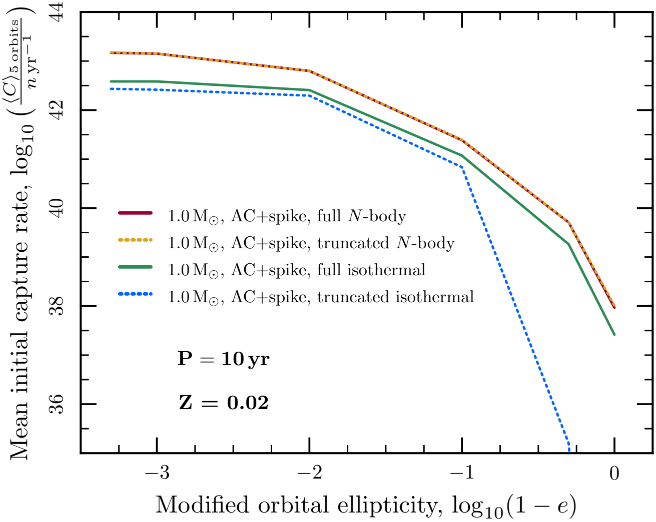


Elliptical orbits - mean capture rates



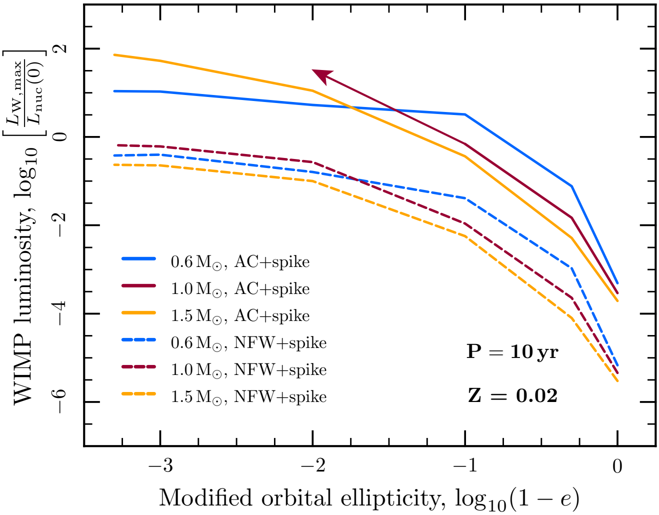
Stockholm University

Elliptical orbits - alternative velocity distribution



Stockholm University

Put them all together and you get...



Stockholm University

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 is publicly available from `http://www.fysik.su.se/~pat/darkstars`

Stockholm University

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 is publicly available from `http://www.fysik.su.se/~pat/darkstars`

Stockholm University

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 is publicly available from `http://www.fysik.su.se/~pat/darkstars`

Stockholm University

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 is publicly available from http://www.fysik.su.se/~pat/darkstars

Stockholm University

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 is publicly available from http://www.fysik.su.se/~pat/darkstars

Stockholm University

Extra: 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 (*W*eakly-*I*nteracting *M*as...)
- In the LTE regime, an exact solution for $\epsilon_{\mathrm{trans}}$ exists (Gould & Raffelt, 1990)
- In the nonlocal regime, no exact solution - but an idea of how badly the LTE solution overestimates $\epsilon_{\mathrm{trans}}$

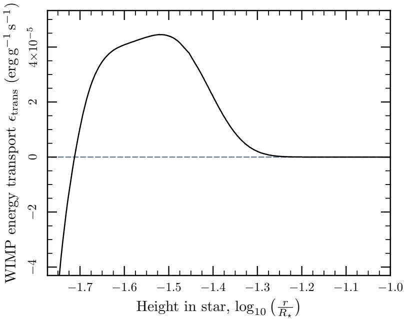
Degree of nonlocality of WIMP energy transport and distribution can be given by the Knudsen parameter K:

$$K \equiv l(0,t)/r_\chi(t), \qquad (10)$$

l	WIMP mean free path
r_χ	Approximate WIMP scale height

used to interpolate between densities and scale LTE energy transport

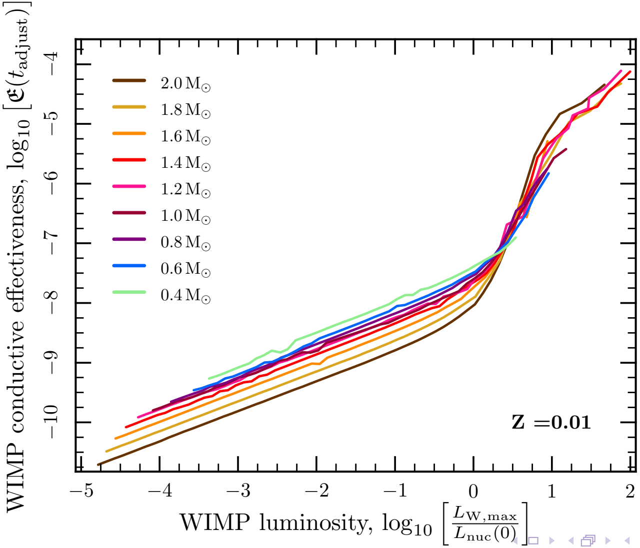
Extras (cont.): $\epsilon_{\rm trans}$ & $\mathfrak{E}(t)$



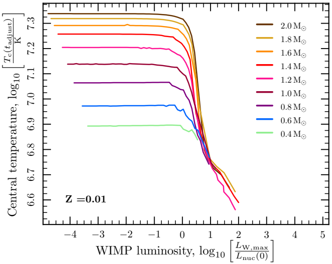
$$\mathfrak{E}(t) \equiv \frac{\int_0^{R_\star} r^2 \frac{\rho_\star(r,t)}{\mu_\star(r,t)} \left| \frac{\epsilon_{\rm trans}}{\epsilon_{\rm other}} \right| \mathrm{d}r}{\int_0^{R_\star} r^2 \frac{\rho_\star(r,t)}{\mu_\star(r,t)} \mathrm{d}r} \quad (11)$$

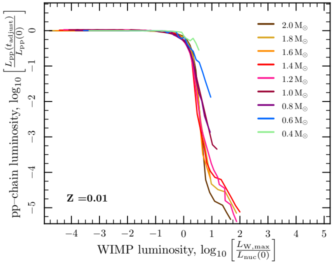
Stockholm University

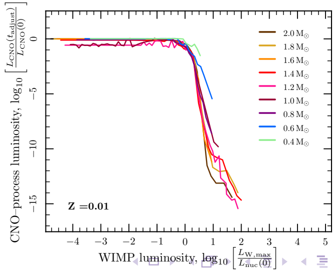
Extras (cont.): WIMP conductive energy transport



Extras 2: energy production







Stockholm University