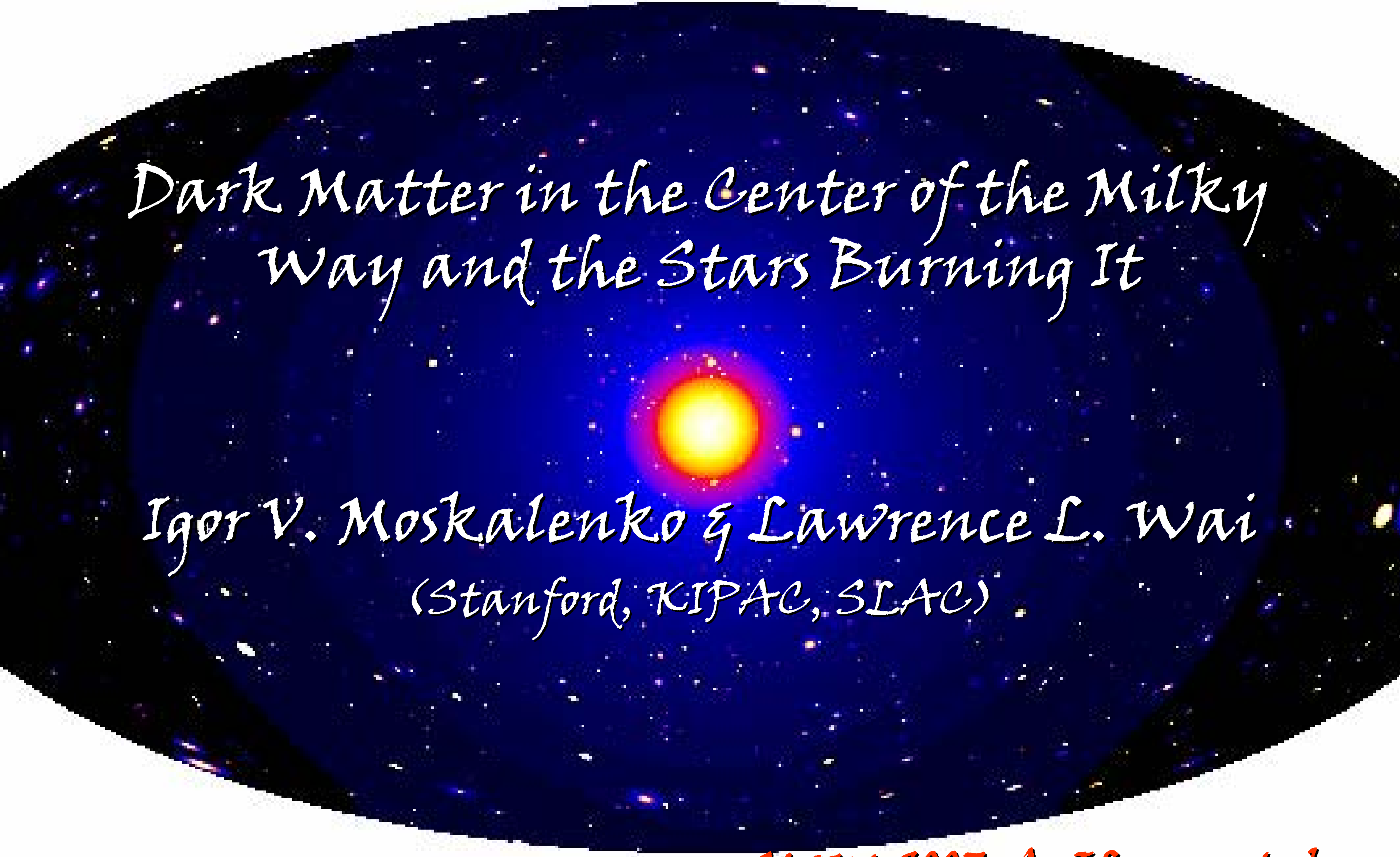
Dark Matter in the Center of the Milky Way and the Stars Burning It

Igor V. Moskalenko & Lawrence L. Wai

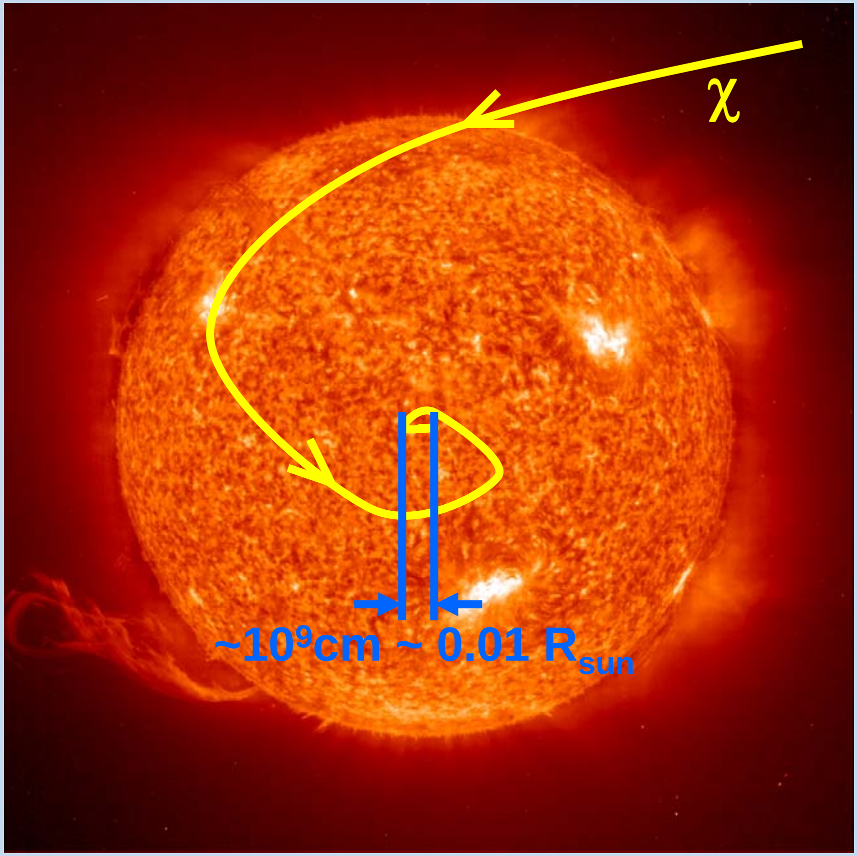
(Stanford, KIPAC, SLAC)



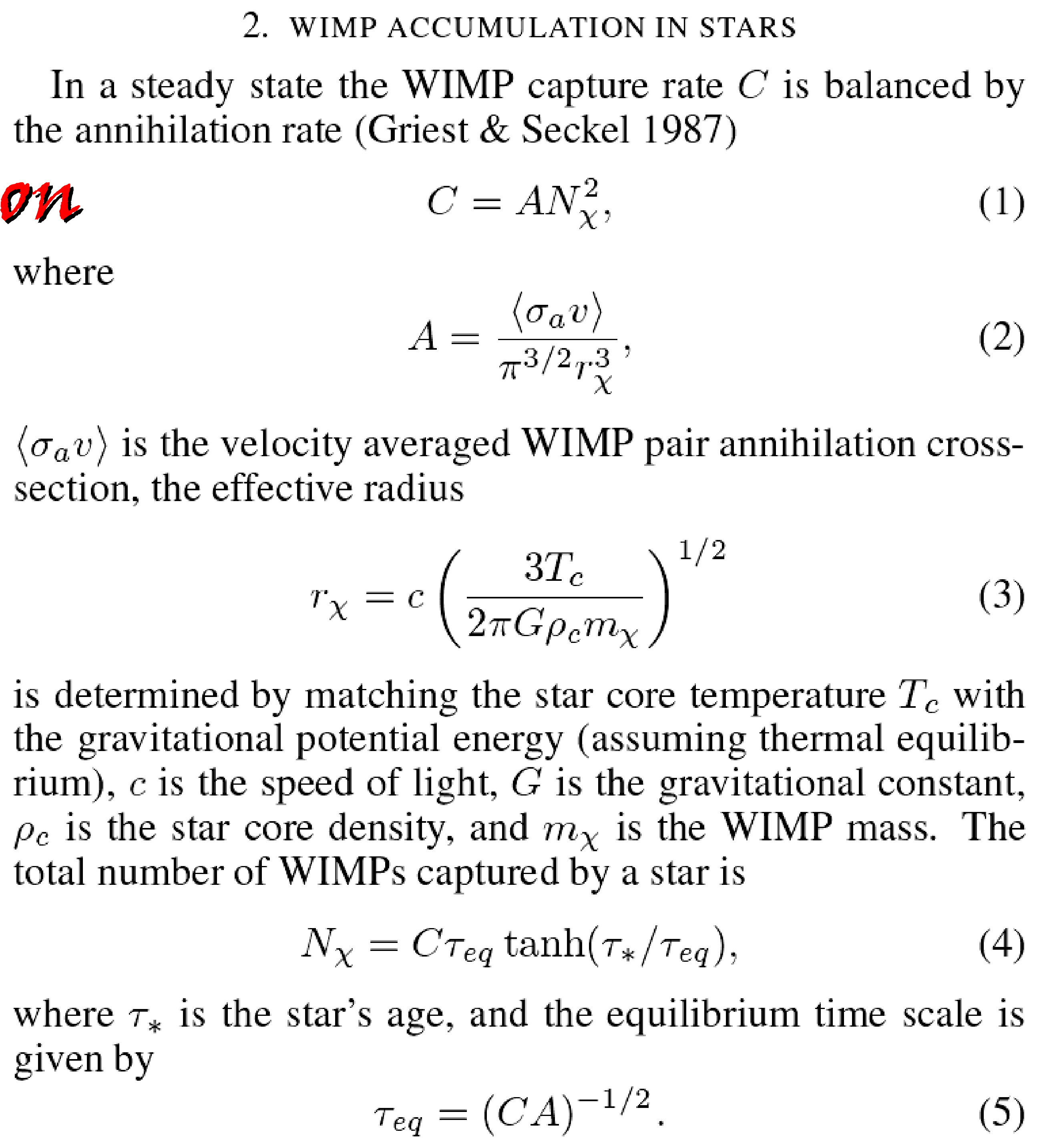
M&W 2007, ApJL accepted

Basic idea

- Extremely high dark matter density possibly exists near the supermassive black hole at the Galactic center
- WIMP-nucleon scattering leads to gravitational capture and the accumulation of WIMPs stars
- WIMP pair annihilation creates a new energy source in stars, i.e. the "burning" of dark matter
- Dark matter "burners" may appear as red giants (Salati & Silk 1989)
- Degenerate electron cores at the Galactic center can "burn" dark matter quickly enough to be observable (Moskalenko & Wai 2006)



WIMP accumulation in stars



2. WIMP ACCUMULATION IN STARS

In a steady state the WIMP capture rate C is balanced by the annihilation rate (Griest & Seckel 1987)

$$C = AN_{\chi}^{2}, \tag{1}$$

where

$$A = \frac{\langle\sigma_a v\rangle}{\pi^{3/2} r_{\chi}^{3}}, \tag{2}$$

$\langle\sigma_a v\rangle$ is the velocity averaged WIMP pair annihilation cross-section, the effective radius

$$r_{\chi} = c\left(\frac{3T_c}{2\pi G\rho_c m_{\chi}}\right)^{1/2} \tag{3}$$

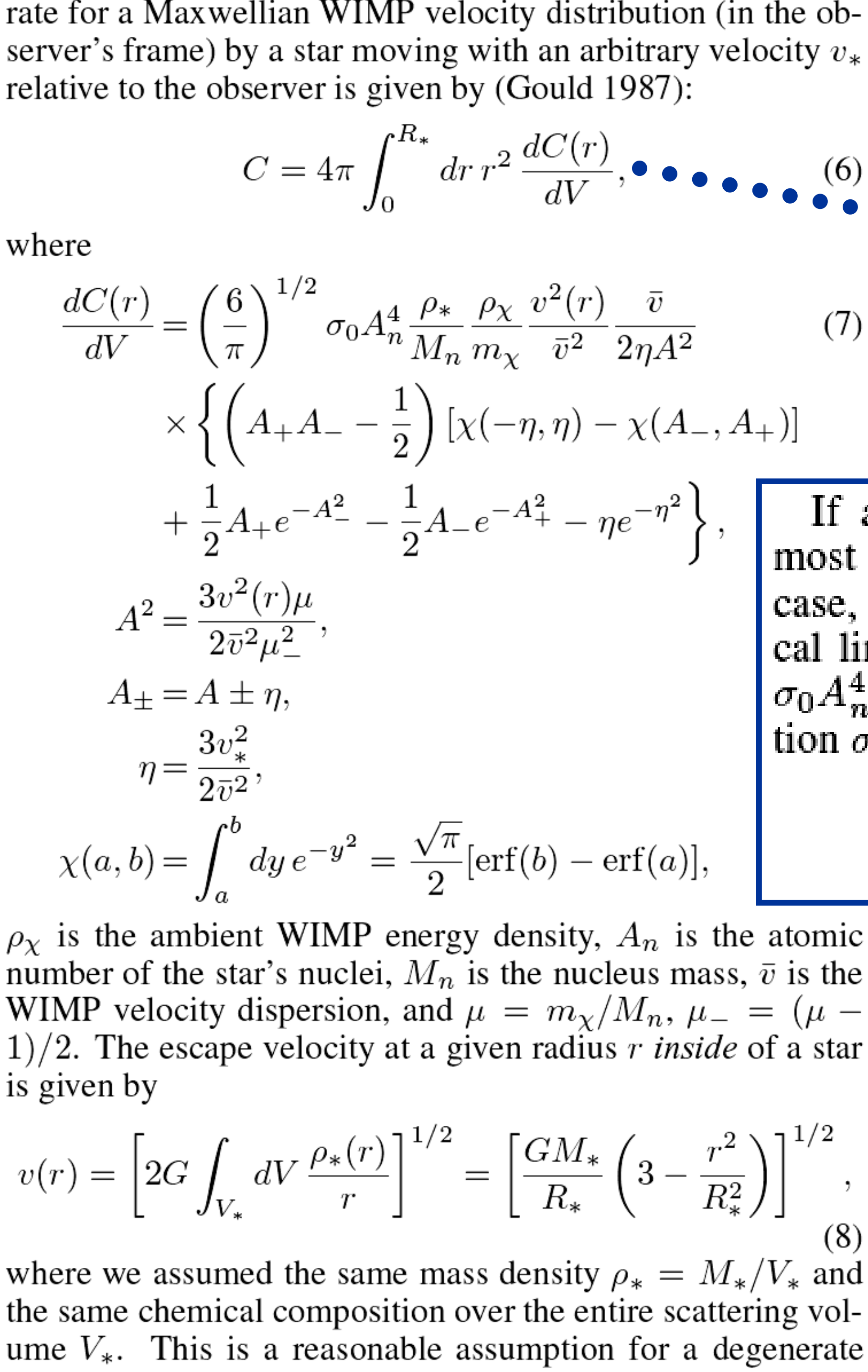
is determined by matching the star core temperature T_c with the gravitational potential energy (assuming thermal equilibrium), c is the speed of light, G is the gravitational constant, ρ_c is the star core density, and m_{χ} is the WIMP mass. The total number of WIMPs captured by a star is

$$N_{\chi} = C\tau_{eq}\tanh(\tau_{*}/\tau_{eq}), \tag{4}$$

where τ_{*} is the star's age, and the equilibrium time scale is given by

$$\tau_{eq} = (CA)^{-1/2}. \tag{5}$$

WIMP capture rate



rate for a Maxwellian WIMP velocity distribution (in the observer's frame) by a star moving with an arbitrary velocity v_* relative to the observer is given by (Gould 1987):

$$C = 4\pi \int_0^{R_*} dr\, r^2 \frac{dC(r)}{dV}, \tag{6}$$

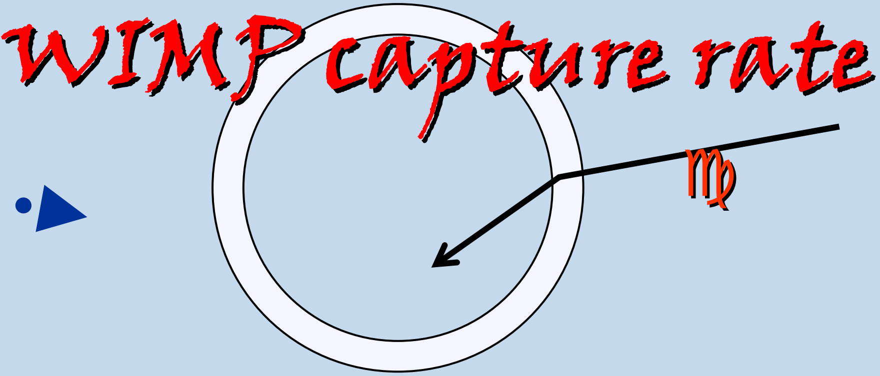
where

$$\begin{aligned}\frac{dC(r)}{dV} &= \left(\frac{6}{\pi}\right)^{1/2} \sigma_0 A_n^4 \frac{\rho_*}{M_n}\frac{\rho_\chi}{m_\chi}\frac{v^2(r)}{\bar{v}^2}\frac{\bar{v}}{2\eta A^2} \\ &\times \left\{\left(A_+A_- - \frac{1}{2}\right)[\chi(-\eta,\eta)-\chi(A_-,A_+)] \right. \\ &\left. + \frac{1}{2}A_+ e^{-A_-^2} - \frac{1}{2}A_- e^{-A_+^2} - \eta e^{-\eta^2}\right\}, \\ A^2 &= \frac{3v^2(r)\mu}{2\bar{v}^2\mu_-^2}, \\ A_\pm &= A \pm \eta, \\ \eta &= \frac{3v_*^2}{2\bar{v}^2}, \\ \chi(a,b) &= \int_a^b dy\, e^{-y^2} = \frac{\sqrt{\pi}}{2}[\mathrm{erf}(b)-\mathrm{erf}(a)],\end{aligned} \tag{7}$$

ρ_χ is the ambient WIMP energy density, A_n is the atomic number of the star's nuclei, M_n is the nucleus mass, $\bar{v}$ is the WIMP velocity dispersion, and $\mu = m_\chi/M_n$, $\mu_- = (\mu - 1)/2$. The escape velocity at a given radius r *inside* of a star is given by

$$v(r) = \left[2G\int_{V_*} dV\, \frac{\rho_*(r)}{r}\right]^{1/2} = \left[\frac{GM_*}{R_*}\left(3 - \frac{r^2}{R_*^2}\right)\right]^{1/2}, \tag{8}$$

where we assumed the same mass density $\rho_* = M_*/V_*$ and the same chemical composition over the entire scattering volume V_*. This is a reasonable assumption for a degenerate

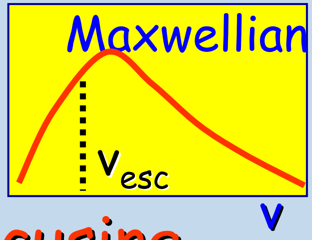


- Geometrical limit:

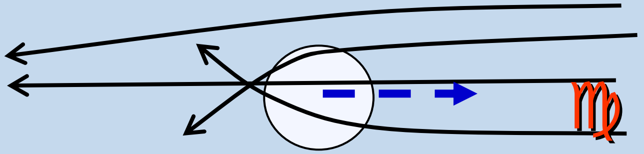
If a WD is heavy ($M \gtrsim M_\odot$) and/or $A_n \gg 1$, almost all WIMPs crossing the star will be captured. In this case, the WIMP capture rate is determined by the geometrical limit πR_*^2 rather than the total interaction cross section $\sigma_0 A_n^4 M_*/M_n$. We thus use a modified interaction cross section σ_0' defined as

$$\sigma_0' A_n^4 \frac{M_*}{M_n} = \min\left(\sigma_0 A_n^4 \frac{M_*}{M_n}, \pi R_*^2\right). \tag{9}$$

- Escape velocity



- Gravitational focusing



Effect of high WIMP density on stellar interiors

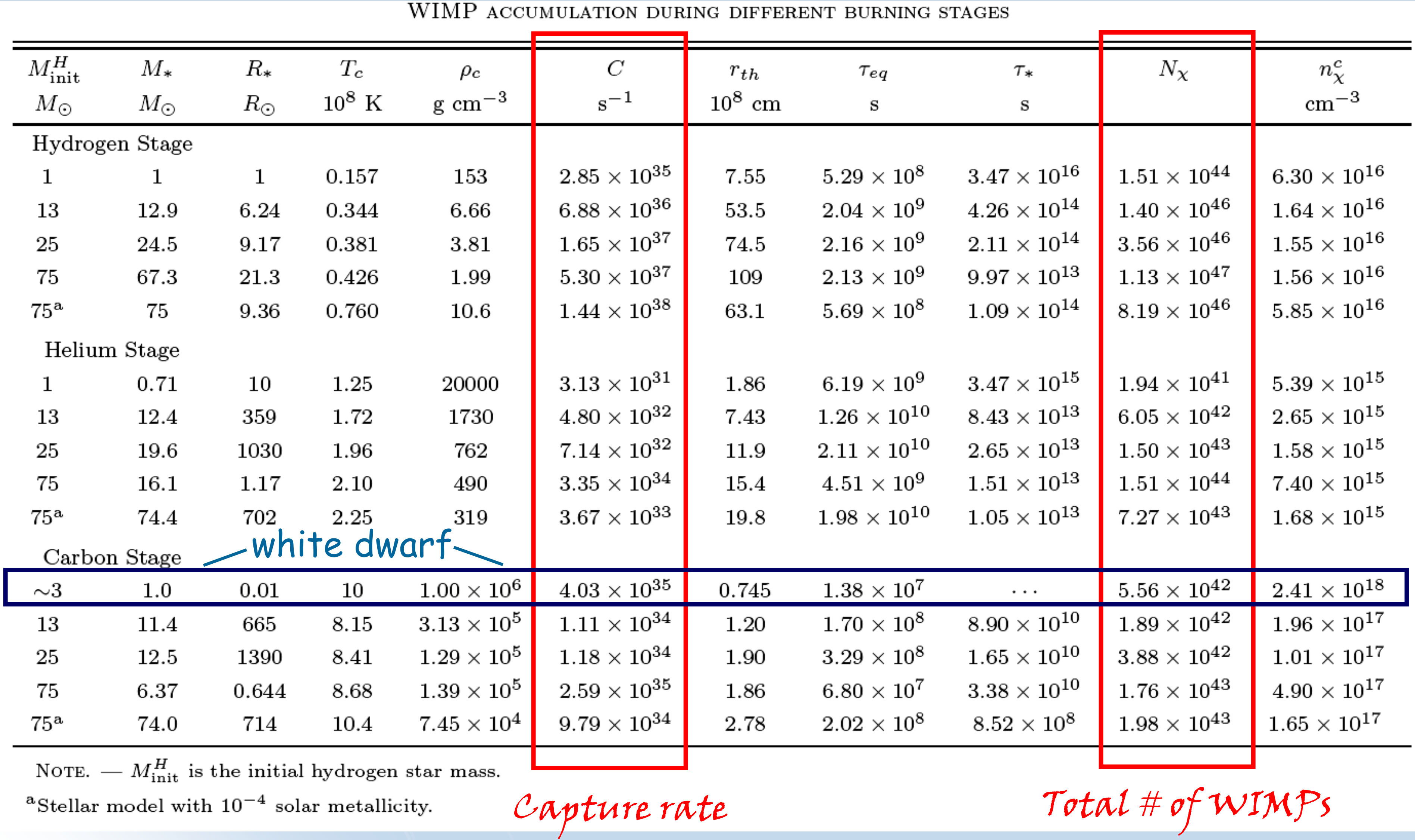
- Can change the evolution & appearance of low-mass stars
  - Additional source of energy comparable to the energy supply due to the thermonuclear reactions
    - The additional energy may require the convective energy transport since the radiative energy transport is not effective enough
    - The convective energy transfer may inflate the stellar radius
  - WIMPs may provide the effective energy transport suppressing the convection in the stellar core
    - Reduce the replenishment of the burning region with fresh fuel decreasing the stellar lifetime
- Does not change the appearance of massive stars and white dwarfs
  - Massive stars are too luminous, $L \sim M^4$
  - Energy transport in (bare) white dwarfs is dominated by degenerate electrons (isothermal interior)

Experimental inputs

- Spin-independent scattering limits
  - CDMS II: $\sigma_{SI}<10^{-43}\mathrm{cm}^2$
- Spin-dependent scattering limits
  - SuperK: $\sigma_{SD}<10^{-38}\mathrm{cm}^2$
- Annihilation cross-section estimate (actual value not important for results!)
  - $<\sigma v>\sim 3\times10^{-26}\mathrm{cm}^3\mathrm{s}^{-1}$
- Recent infrared (K-band) observations of Galactic center stars
- EGRET upper limit on gamma-ray flux at the Galactic center

WIMP accumulation

$L_{♍}$~0.16 C($m_{♍}$/100 GeV) erg/s　　L. ~$4x10^{33}$ erg/s



WIMP ACCUMULATION DURING DIFFERENT BURNING STAGES

$M^H_{\rm init}$ $M_\odot$	M_* $M_\odot$	R_* $R_\odot$	T_c 10^8 K	ρ_c g cm^{-3}	C s^{-1}	r_{th} 10^8 cm	τ_{eq} s	τ_* s	N_χ	n^c_χ cm^{-3}
Hydrogen Stage										
1	1	1	0.157	153	2.85×10^{35}	7.55	5.29×10^8	3.47×10^{16}	1.51×10^{44}	6.30×10^{16}
13	12.9	6.24	0.344	6.66	6.88×10^{36}	53.5	2.04×10^9	4.26×10^{14}	1.40×10^{46}	1.64×10^{16}
25	24.5	9.17	0.381	3.81	1.65×10^{37}	74.5	2.16×10^9	2.11×10^{14}	3.56×10^{46}	1.55×10^{16}
75	67.3	21.3	0.426	1.99	5.30×10^{37}	109	2.13×10^9	9.97×10^{13}	1.13×10^{47}	1.56×10^{16}
75[a]	75	9.36	0.760	10.6	1.44×10^{38}	63.1	5.69×10^8	1.09×10^{14}	8.19×10^{46}	5.85×10^{16}
Helium Stage										
1	0.71	10	1.25	20000	3.13×10^{31}	1.86	6.19×10^9	3.47×10^{15}	1.94×10^{41}	5.39×10^{15}
13	12.4	359	1.72	1730	4.80×10^{32}	7.43	1.26×10^{10}	8.43×10^{13}	6.05×10^{42}	2.65×10^{15}
25	19.6	1030	1.96	762	7.14×10^{32}	11.9	2.11×10^{10}	2.65×10^{13}	1.50×10^{43}	1.58×10^{15}
75	16.1	1.17	2.10	490	3.35×10^{34}	15.4	4.51×10^9	1.51×10^{13}	1.51×10^{44}	7.40×10^{15}
75[a]	74.4	702	2.25	319	3.67×10^{33}	19.8	1.98×10^{10}	1.05×10^{13}	7.27×10^{43}	1.68×10^{15}
Carbon Stage	white dwarf									
~3	1.0	0.01	10	1.00×10^6	4.03×10^{35}	0.745	1.38×10^7	...	5.56×10^{42}	2.41×10^{18}
13	11.4	665	8.15	3.13×10^5	1.11×10^{34}	1.20	1.70×10^8	8.90×10^{10}	1.89×10^{42}	1.96×10^{17}
25	12.5	1390	8.41	1.29×10^5	1.18×10^{34}	1.90	3.29×10^8	1.65×10^{10}	3.88×10^{42}	1.01×10^{17}
75	6.37	0.644	8.68	1.39×10^5	2.59×10^{35}	1.86	6.80×10^7	3.38×10^{10}	1.76×10^{43}	4.90×10^{17}
75[a]	74.0	714	10.4	7.45×10^4	9.79×10^{34}	2.78	2.02×10^8	8.52×10^8	1.98×10^{43}	1.65×10^{17}

NOTE. — $M^H_{\rm init}$ is the initial hydrogen star mass.

[a] Stellar model with 10^{-4} solar metallicity.

Capture rate　　Total # of WIMPs

M&W 2006, astro-ph/0608535

Mass-Radius relationship for WDs

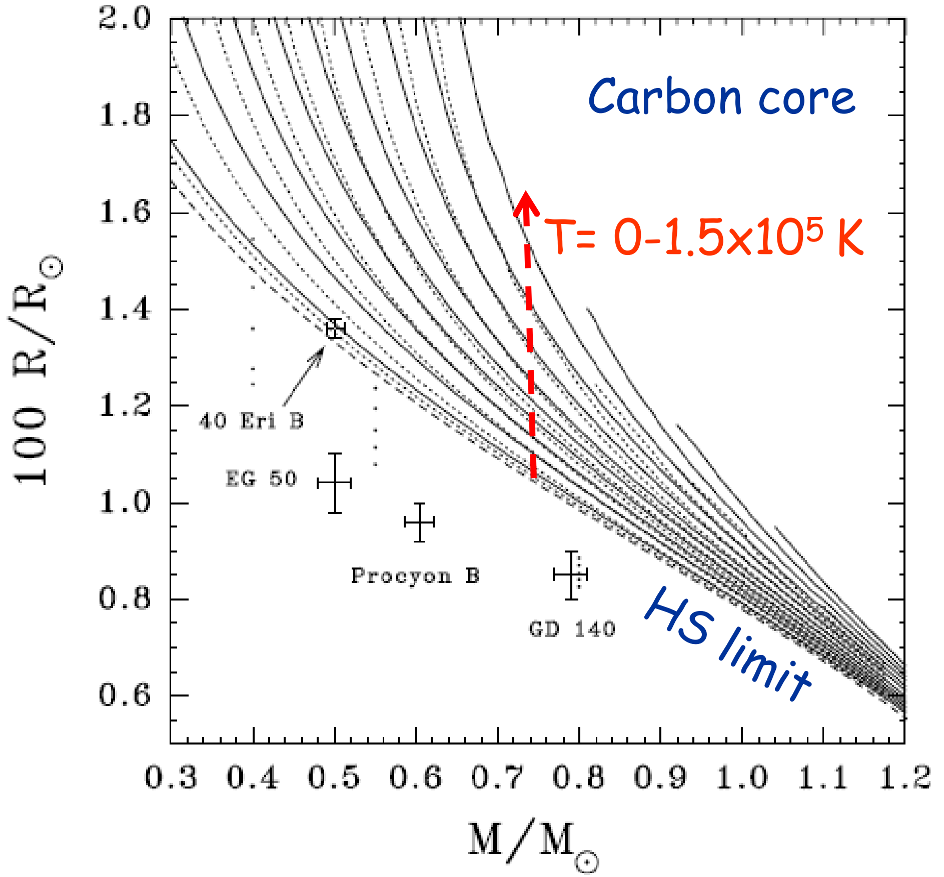


Fig. 4a. The mass-radius relation for WD stars with a carbon core surrounded by a helium layer with a thickness of 10^{-2} M_*. Solid and short dashed lines have the same meaning as in Fig. 3 but for case of the hydrogen envelope we assumed a mass of 10^{-5} M_*. Medium dashed line corresponds to the mass-radius relationship for homogeneous HS carbon models. We have included in this figure the values corresponding to $T_{\rm eff}$ (in 10^3 K) of 5, 15, 25, 35, 45, 55, 70, 85, 100, 115, 130 and 145. We have also included the data for strange dwarf models with $T_{\rm eff}$ (in 10^3 K) of 10, 20, 30, 40 and 50. Notice that they

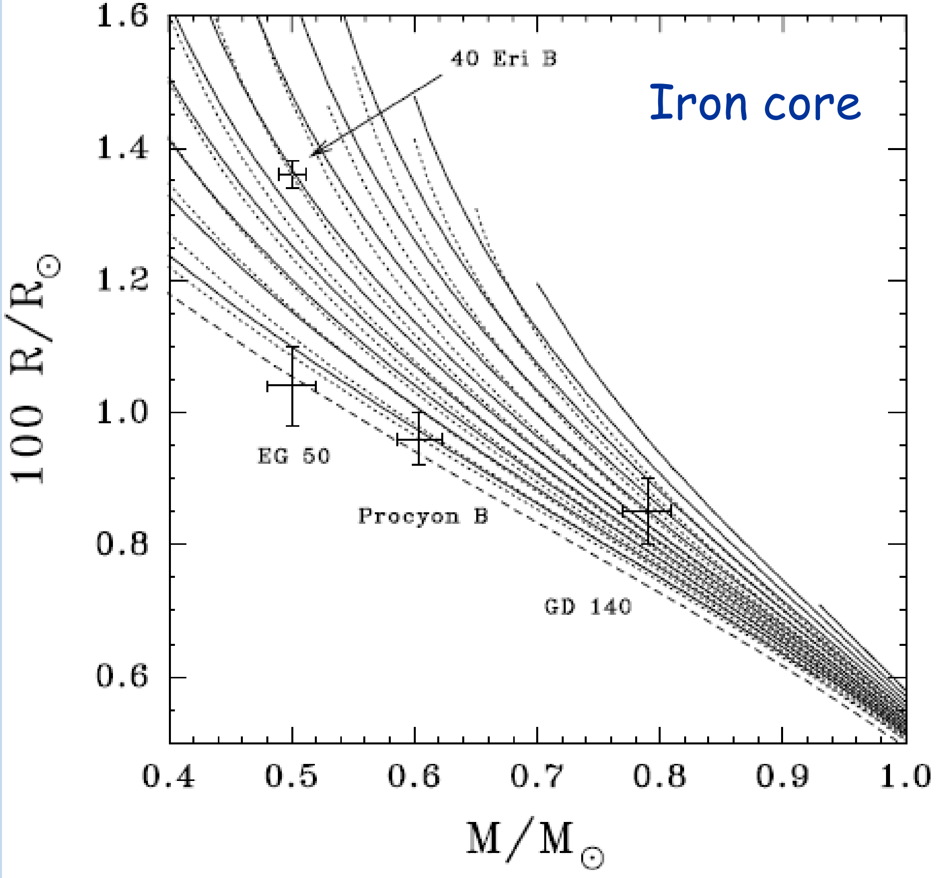
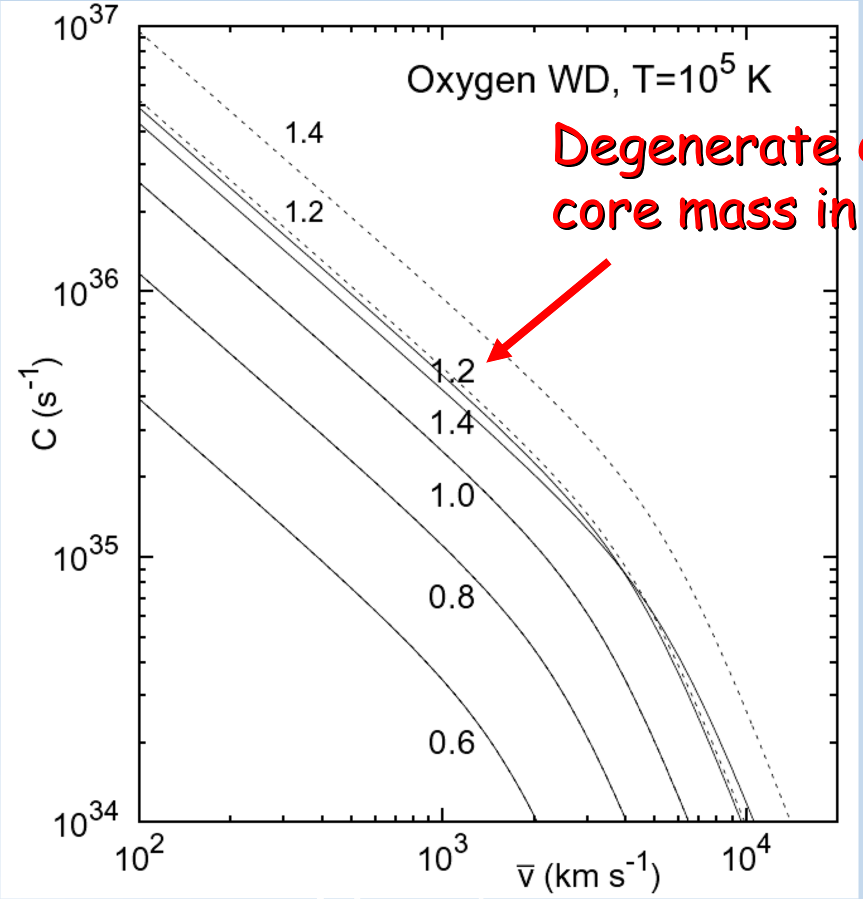


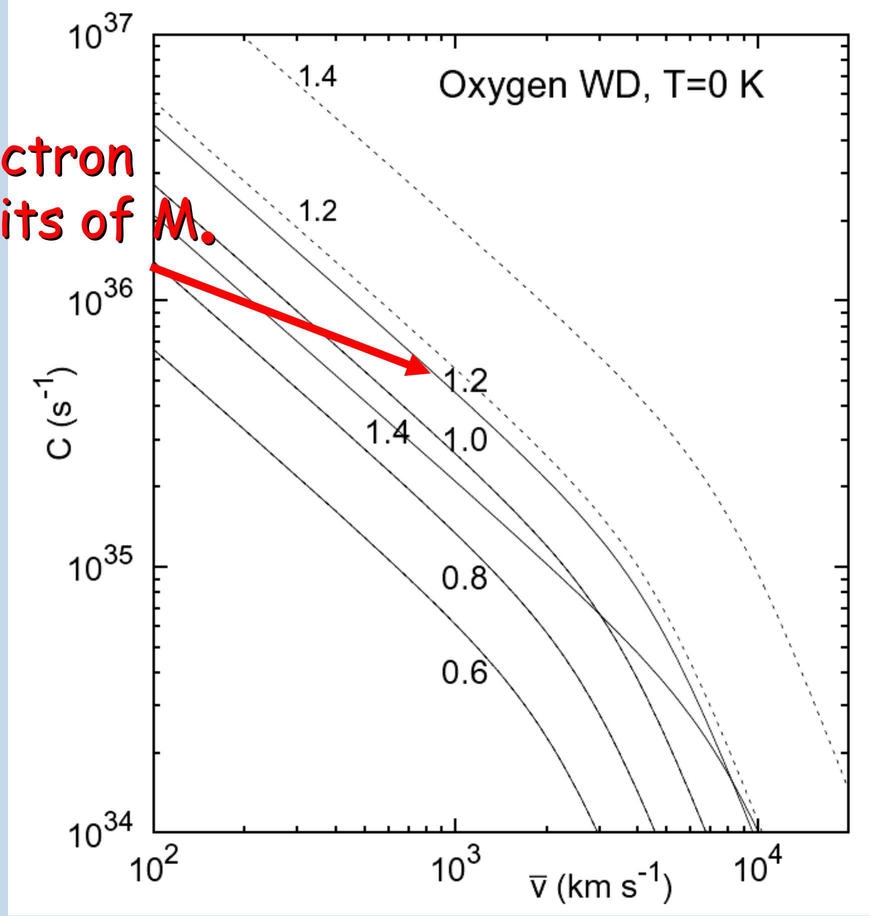
Fig. 7. Same as Fig. 4a, but for an iron core. We have also included the data corresponding to 40 Eri B, EG 50, Procyon B and GD 140 taken from Provencal et al. (1998). Note the change in the vertical scale compared to the previous figures. For further discussion, see text.

Panei+ 2000

WIMP capture rate vs velocity dispersion

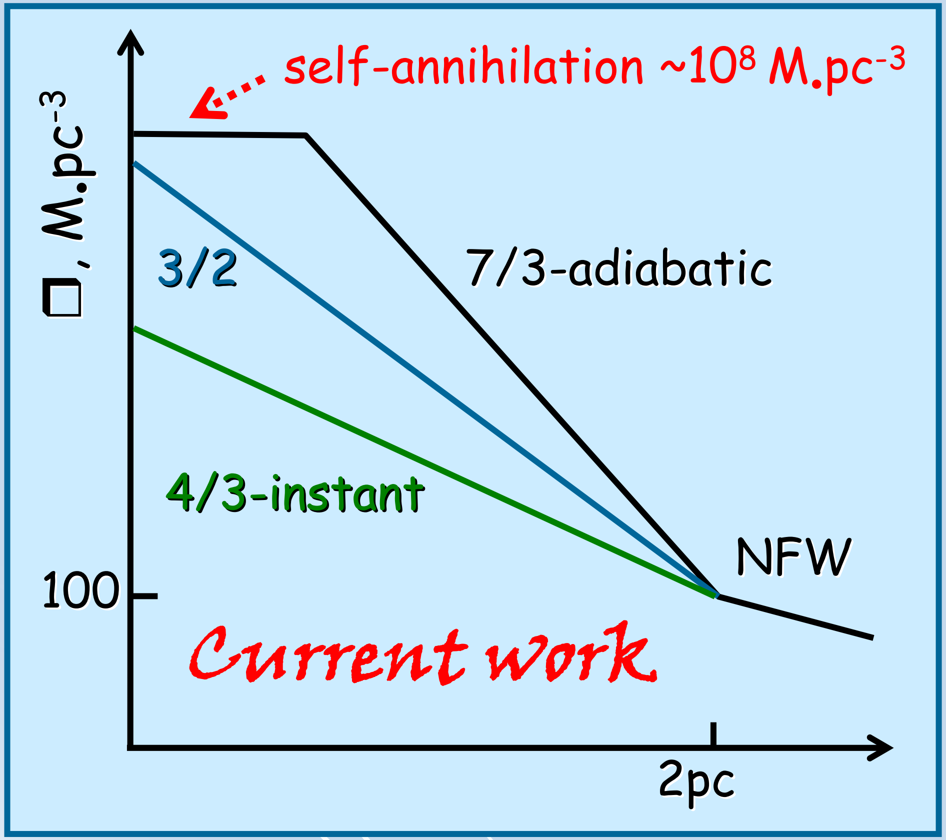


Degenerate electron core mass in units of M.

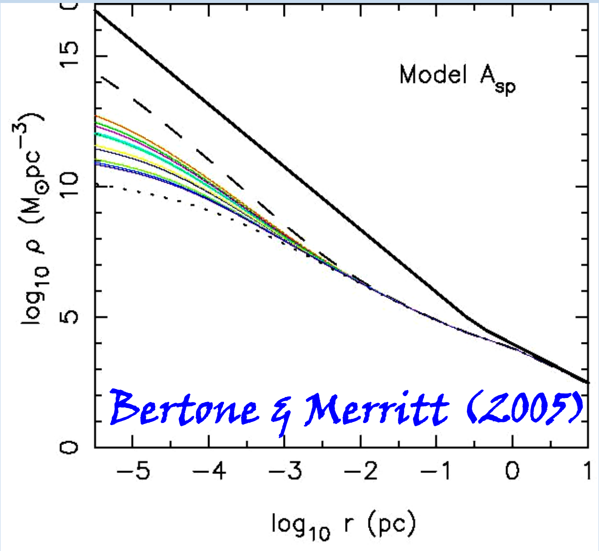


Solid lines are for the capture rate taking into account the geometrical limit; dotted lines without the geometrical limit

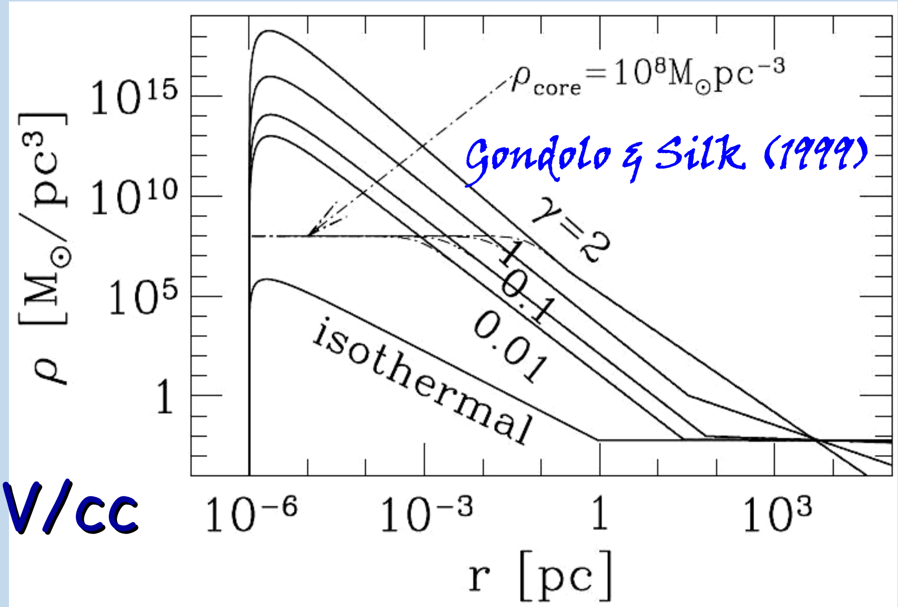
Computed dark matter densities near the supermassive black hole at the Galactic center



Current work



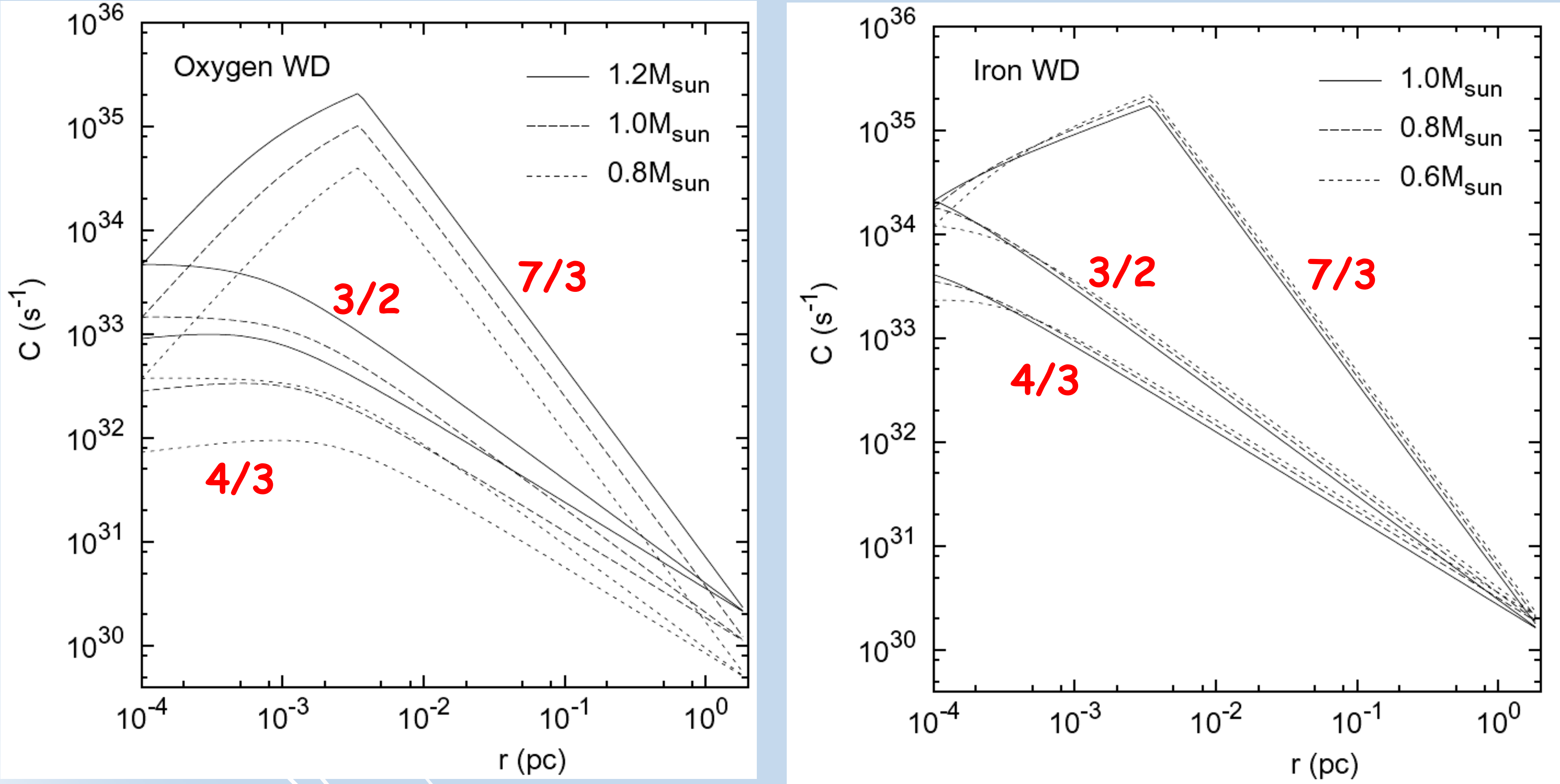
Bertone & Merritt (2005)



Gondolo & Silk (1999)

$\square_{♍}^{max} \sim m_{♍} / \langle ♦_{a} v \rangle\, ♦_{BH} \sim 10^{10}$ GeV/cc

WIMP capture rate vs distance from the SMBH

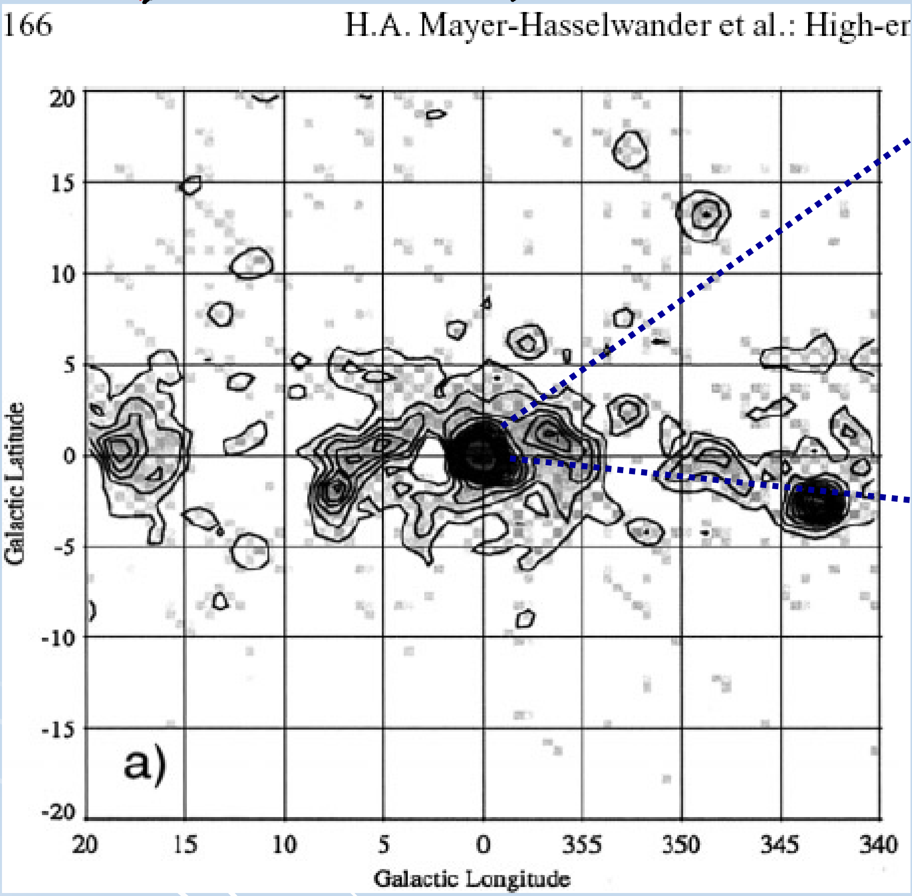


Capture rate vs distance from the central BH for Oxygen (left) and Iron (right) white dwarfs of T_{eff} =(1.0-1.5)x10^5 K. Numbers (7/3-adiabatic, 3/2, 4/3-instant) show power-law indices for the central spike profile.

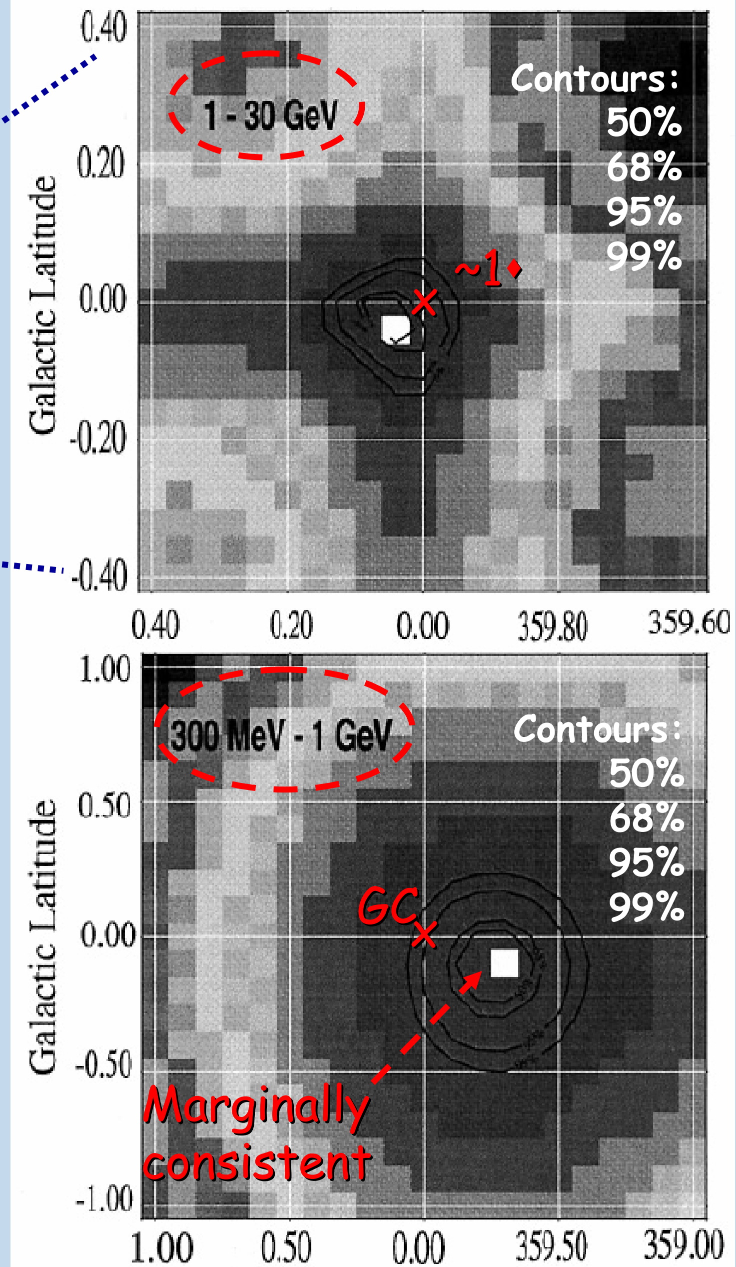
Confirmed hot bare WDs

- DM burners (bare WD): T~1.5×10^5 K
- Sloan Digital Sky Survey (Eisenstein+2006):
  - 9316 confirmed WDs
  - 12 WDs have T~ 10^5 K
- H1504+65: T=$(1.7-2.0) \times 10^5$ K (Werner & Wolff 1999)

HE gammas from the GC



166 H.A. Mayer-Hasselwander et al.: High-er

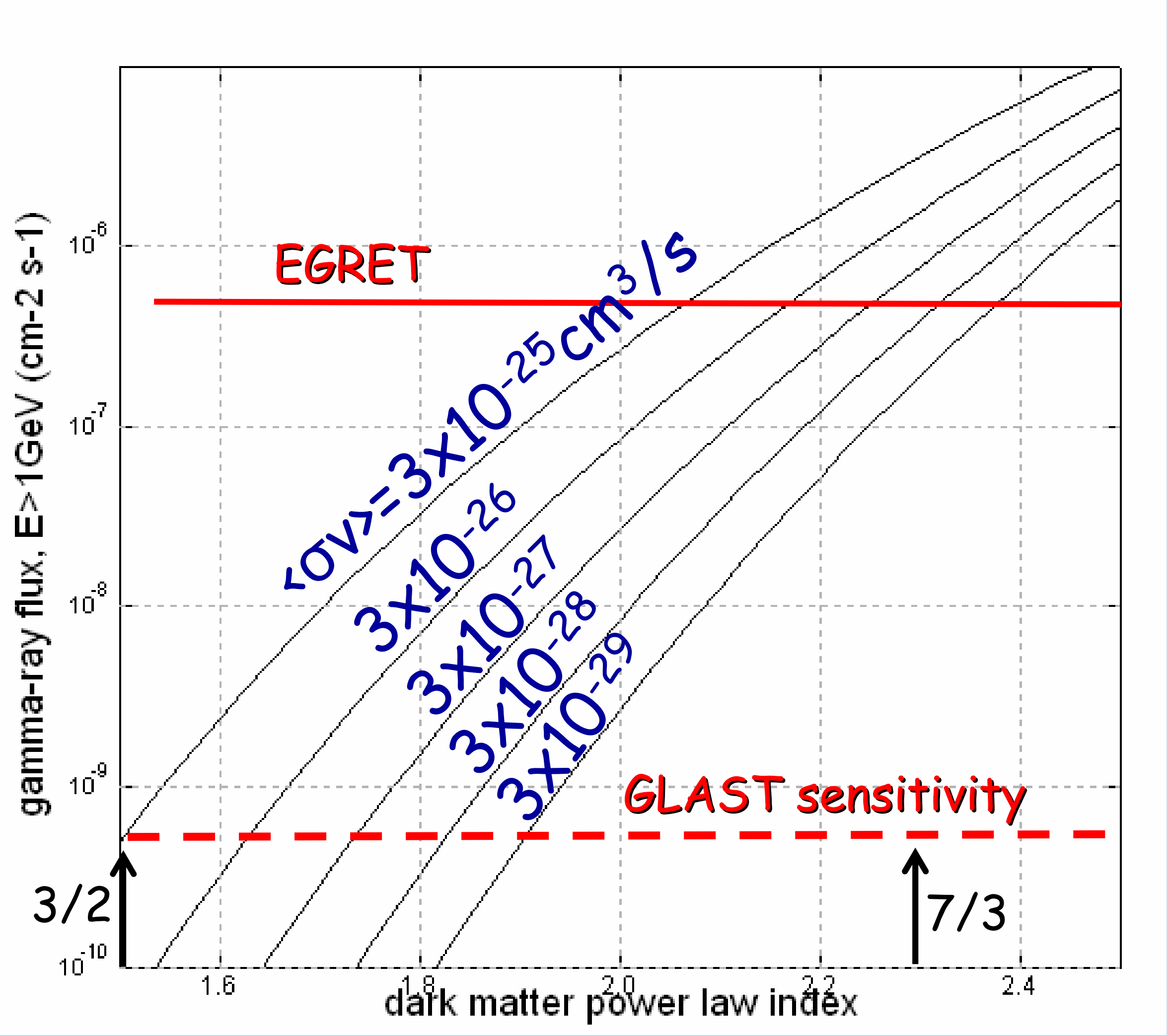


$F_{GC}(>1\ \text{GeV})=(49\pm3)\times10^{-8}\ \text{cm}^{-2}\ \text{s}^{-1}$

γ-ray flux vs DM spike power-law index

The DM annihilation γ-ray flux from the central spike vs DM matter density power-law index assuming ♍♍✹10♑ (>1 GeV) for $M_{\text{♍}}$=100 GeV

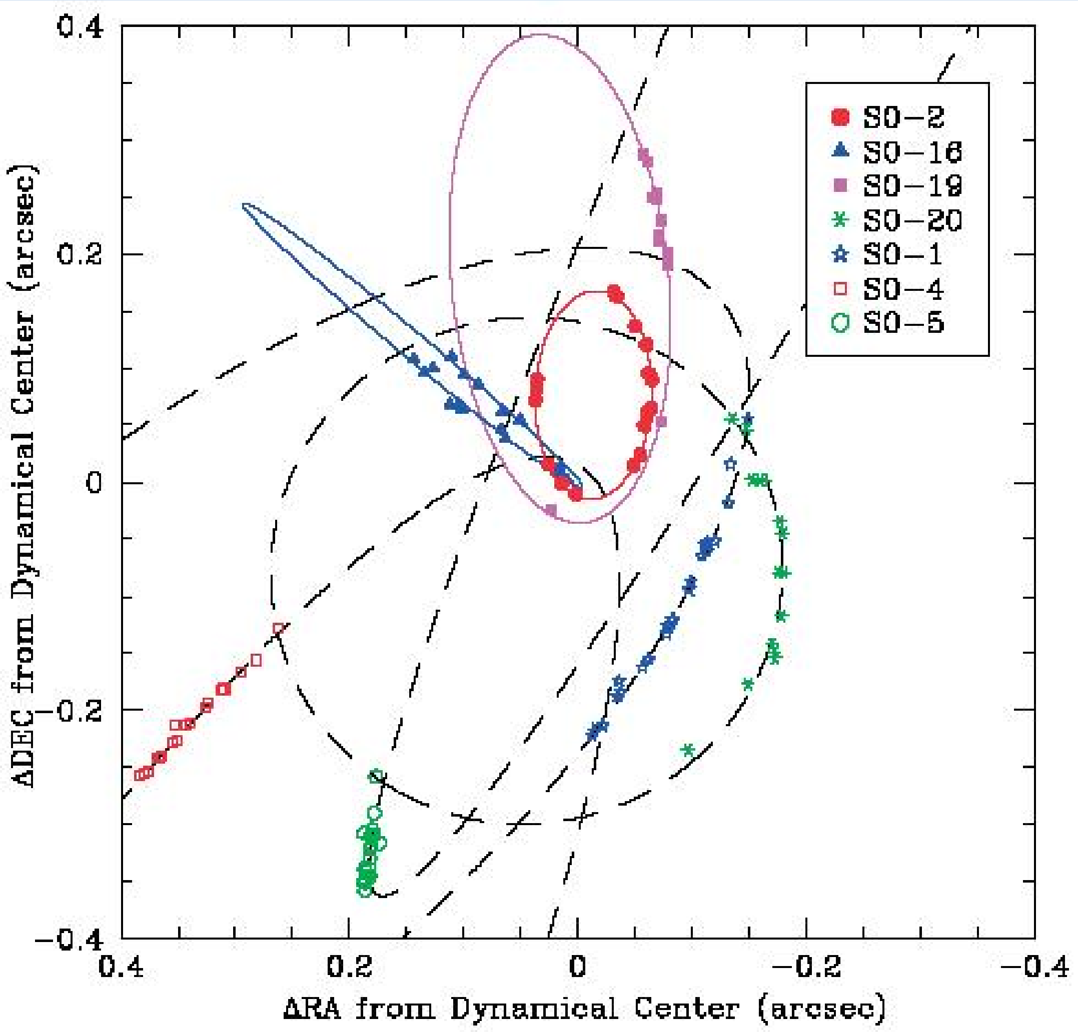
The EGRET upper limit on gamma-ray flux from the Galactic center F(>1 GeV) = 5×10^{-7} cm^{-2} s^{-1} (Mayer-Hasselwander, et.al. 1998)



Identifying DM burners

- UV, X-ray observations of concentration of the bare hot WDs in the Galactic center
- Peculiar chemical composition of the stellar atmospheres as the result of unusual evolution path
- Indirect identification
  - GLAST ♑-ray flux measurements from the Galactic center ✹ fixes the central spike profile & the annihilation cross section
  - Direct WIMP-nucleon scattering cross section measurements ✹ fixes WIMP capture rate
  - Observation of the particular star orbits ✹ calculation of the WIMP burning rate and the WIMP luminosity
  - Additionally: LHC detection of WIMPs may provide info about annihilation cross section

Galactic center stars in near-infrared (K-band)



Ghez et al. 2005

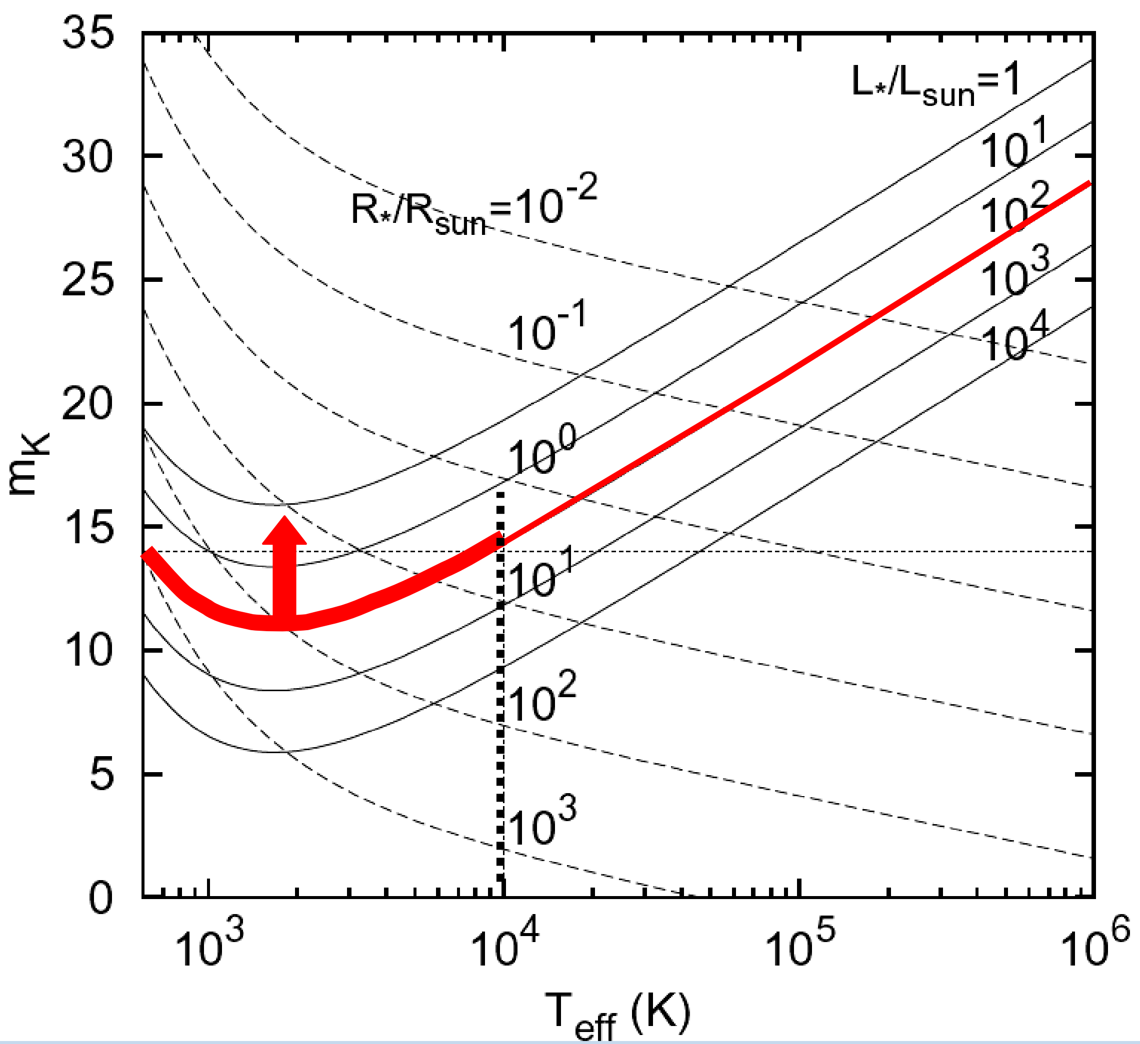
The "paradox of youth" for Sgr A* stars (e.g. Ghez, et.al. 2005)

- K-band measurements of Sgr A* stars indicate that they are hot (m_K=14-17 mag, extinction ~3.3 mag)
  - imply that they are young stars (O9) or old stars (K5)
- Difficult to see how they could have formed in situ:
  - given the lack / low density of gas
  - extreme gravitational forces near the supermassive BH
- Difficult to see how they could have efficiently migrated in given the short time since birth
- Conventional hypotheses discussed are:
  - "old stars masquerading as young" or
  - "hot dwarfs – stripped cores of red giants"

K-band magnitude vs. effective temperature

K-band magnitude m_K vs effective temperature T_{eff} without extinction.

A degenerate core with H or He envelope can be brighter than 14 mag if T_{eff} = 600-10000K and R>5 R..



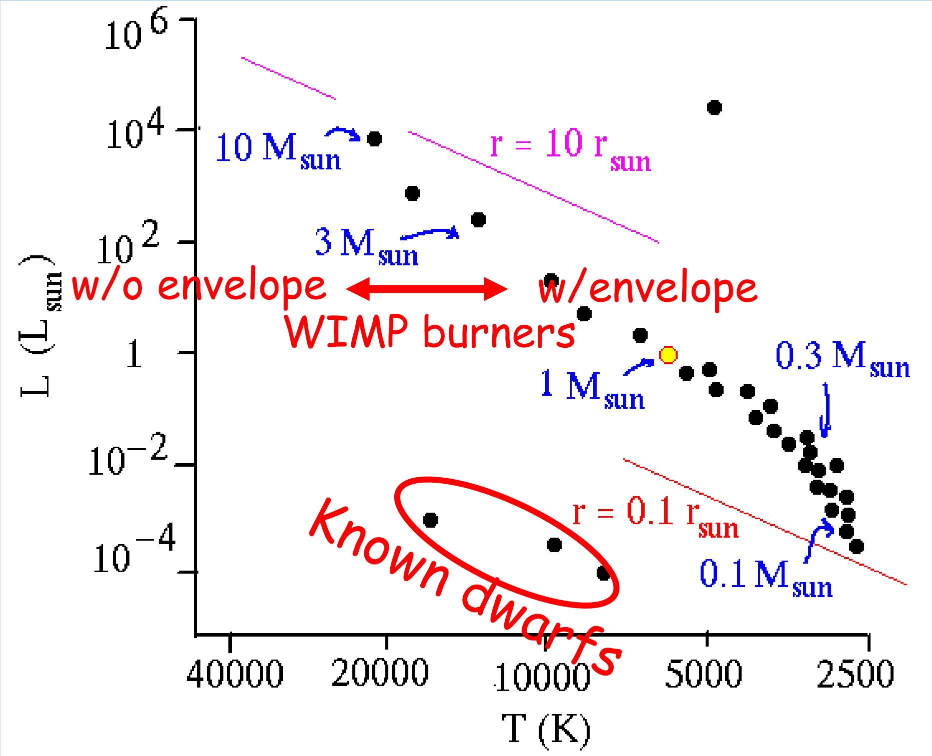
The degenerate core WIMP burner hypothesis

- **Stars with degenerate electron cores are everywhere!**

  Some just happen to fall into the high density dark matter region near the black hole where they appear as WIMP burners

- **Compact structure: more stable against extreme gravitational conditions near the supermassive black hole**
- **What are the spectral or other signatures?**

Hertzsprung-Russell diagram



Summary

- If the supermassive black hole at the Galactic center has a dark matter spike with a profile ~7/3, unusual stars – “WIMP burners” - may be observed in the K-band (m_K<14 mag)
- If found, a luminosity distribution of dark matter burners near Sgr A* would trace the dark matter distribution
- Another consequence of the dark matter spike is a gamma-ray WIMP annihilation flux above 1 GeV coincident with Sgr A*; this prediction is consistent with EGRET measurements
- GLAST should be able to provide crucial measurements of the Galactic center gamma-ray source and thereby confirm or set stringent limits on this scenario