Dark Matter, Phase Transitions and Capture onto Stars

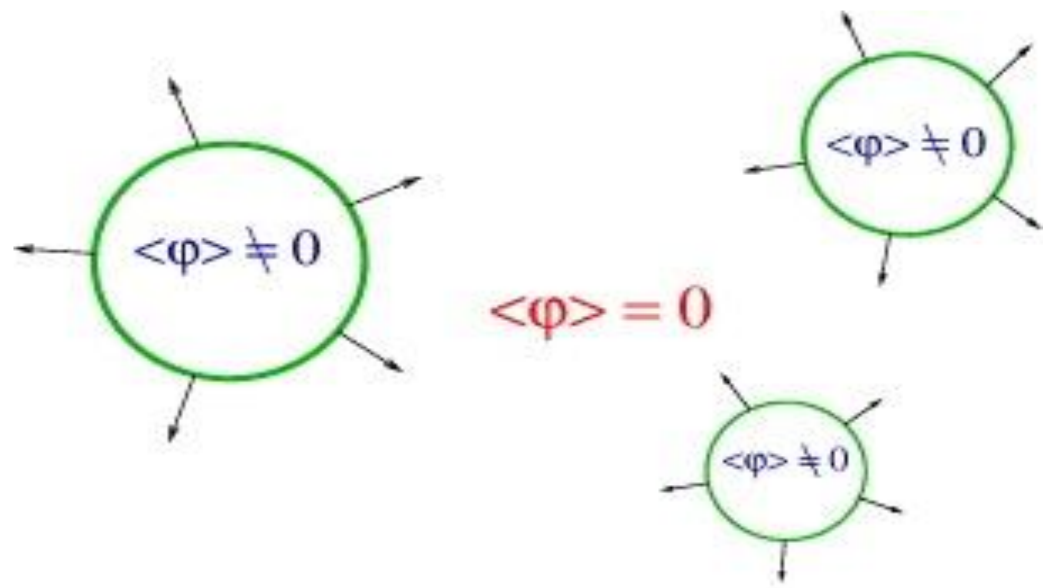
Malcolm Fairbairn

Program

- First order Phase Transitions (for Baryogenesis?) in a bottom up Dark Matter models

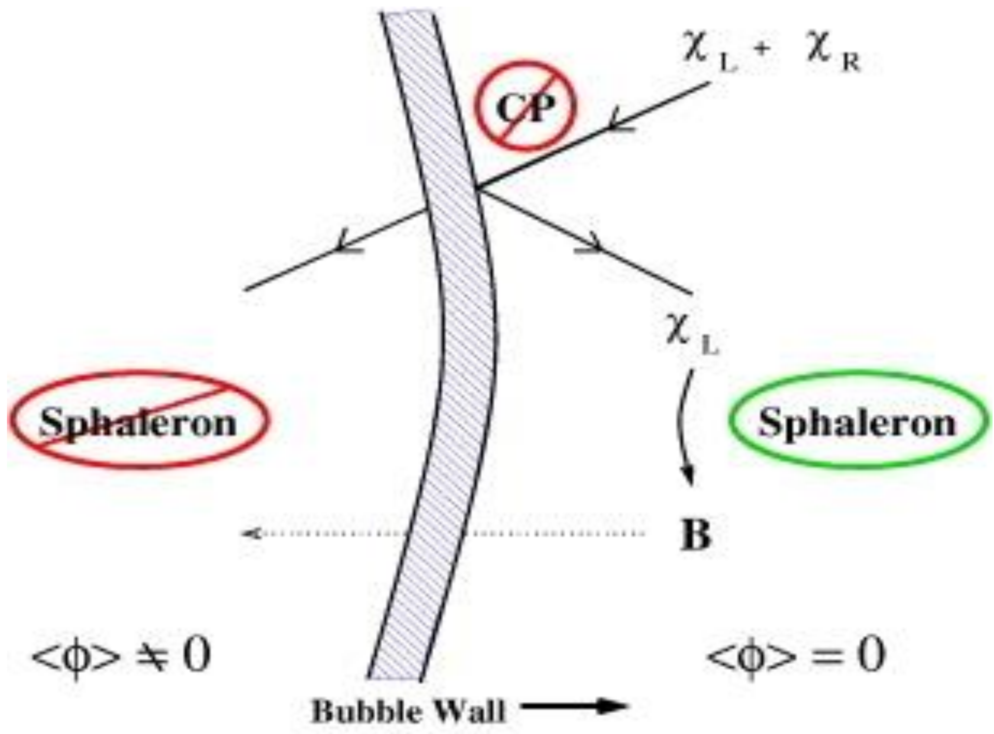
- Dark Matter Accretion onto Stars

Electroweak Baryogenesis



Figures from “Electroweak baryogenesis”
David E Morrissey and Michael J Ramsey-Musolf 2012 New J. Phys. 14

Electroweak Baryogenesis



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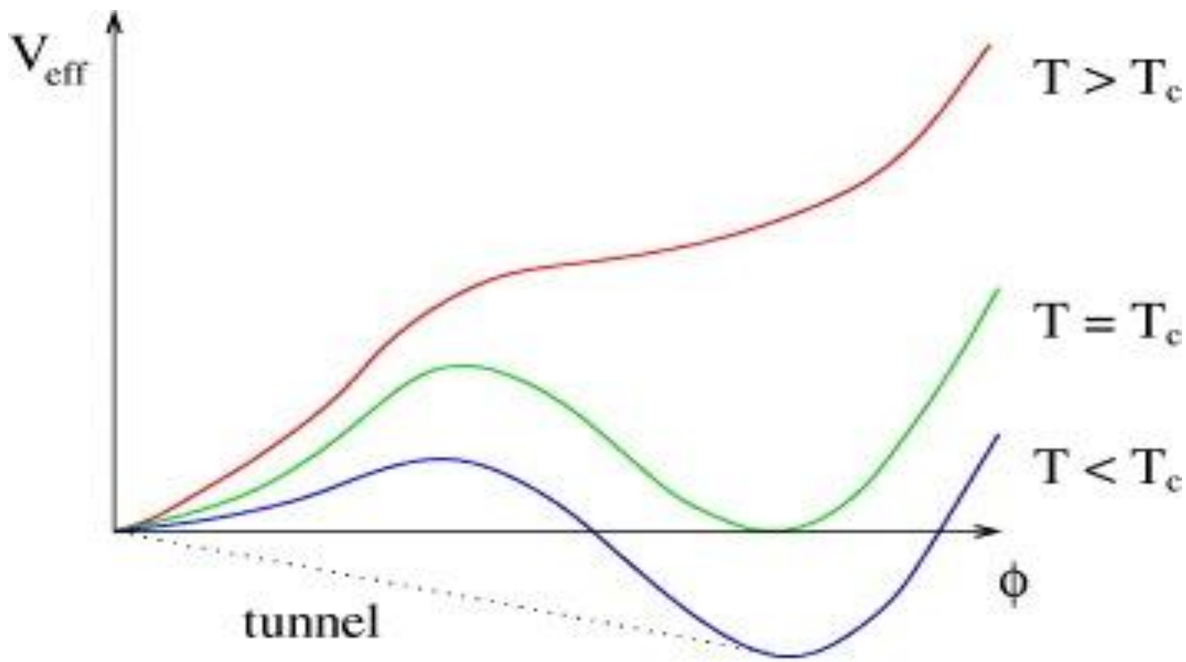
Electroweak Baryogenesis



Figures from “Electroweak baryogenesis”
David E Morrissey and Michael J Ramsey-Musolf 2012 New J. Phys. 14

Higgs Portal Dark Matter

Simply another particle which couples to the Standard model through the Higgs

$$\Delta\mathcal{L}_S = -\frac{1}{2}m_S^2 S^2 - \frac{1}{4}\lambda_S S^4 - \frac{1}{4}\lambda_{hSS} H^\dagger H S^2$$

Scalar dark matter

Standard model Higgs Field

V. Silveira, A. Zee, Phys. Lett. B161, 136 (1985);
J. McDonald, Phys. Rev. D50 (1994) 3637-3649;
C. P. Burgess, M. Pospelov, T. ter Veldhuis, Nucl. Phys. B619 (2001) 709-728 [hep-ph/0011335]

Higgs Portal Dark Matter

In fact you can look at scalar, vectorial and fermionic partners also.

$$\Delta\mathcal{L}_S = -\frac{1}{2}m_S^2 S^2 - \frac{1}{4}\lambda_S S^4 - \frac{1}{4}\lambda_{hSS} H^\dagger H S^2 \ ,$$

$$\Delta\mathcal{L}_V = \frac{1}{2}m_V^2 V_\mu V^\mu + \frac{1}{4}\lambda_V (V_\mu V^\mu)^2 + \frac{1}{4}\lambda_{hVV} H^\dagger H V_\mu V^\mu ,$$

$$\Delta\mathcal{L}_f = -\frac{1}{2}m_f f f - \frac{1}{4}\frac{\lambda_{hff}}{\Lambda} H^\dagger H f f + \mathrm{h.c.} \ .$$

Example of Higgs Portal Model:- Singlet Fermionic Dark Matter

McDonald, (1994)
H. Davoudiasl, R. Kitano, T. Li, and H. Murayama, (2005)
Burgess, Pospelov, and ter Veldhuis,(2001)
Kim, Lee, and Shin,(2007/2008)
Qin, Wang, and Xiong, (2011)
Lopez-Honorez, Schwetz, and Zupan, (2012)
Baek, Ko, Park, and Senaha, (2012)

We heavily used
Espinosa, T. Konstandin, and F. Riva, (2012)

Lagrangian with extra Scalar Field s

$$V = -\frac{1}{2}u_h^2 h^2 + \frac{1}{4}\lambda_h h^4 + \frac{1}{2}u_s^2 s^2 + \frac{1}{4}\lambda_s s^4$$

$$+ \frac{1}{4}\lambda_{hs} s^2 h^2 + \mu_1^3 s + \frac{1}{3}\mu_3 s^3 + \frac{1}{4}\mu_m s h^2$$

These terms arise from not assuming field *s* = -*s*

dark matter couples to s field

$$\mathcal{L}_{DM} = \bar{\psi}(i\partial\!\!\!/ - m)\psi + g_s s\bar{\psi}\psi$$

has global U(1) charge to prevent mixing with SM

The Phenomenology of the Extra Scalar Field

Two mass eigenstates:-

$$h_1 = \sin\alpha \ s + \cos\alpha \ h$$
$$h_2 = \cos\alpha \ s - \sin\alpha \ h$$

Effective branching ratio of $h_1 \to 2h_2, \ \bar{\psi}\psi$ needs to be calculated. Introduce parameter

$$\mu = \cos^2\alpha \left(1 - BR^1_{BSM}\right)\mu_{SM} = a'^2 \mu_{SM}$$

Then current constraints are $a' > 0.9$

Likewise can look at coupling of h_2 decays to the standard model (non-discovery).

$$\mu = \sin^2\alpha (1 - BR^2_{BSM})\mu_{SM} = b'^2 \mu_{SM}$$

and $b'^2 \lesssim 0.1$ for $\lesssim 400 \text{ GeV}$, this latter constraint dropping rapidly as the mass increases

$$\tan\alpha = \frac{x}{1 + \sqrt{1 + x^2}}$$

$$x = \frac{2m^2_{sh}}{m^2_h - m^2_s}$$

$$m^2_{sh} = \left.\frac{\partial^2 V}{\partial h \partial s}\right|_{(v,w)}$$

For LHC constraints,
Ellis and You 2013
Falkowski, Riva and Urbano 2013
CMS 1304.0213

One Example of a working Higgs Portal model

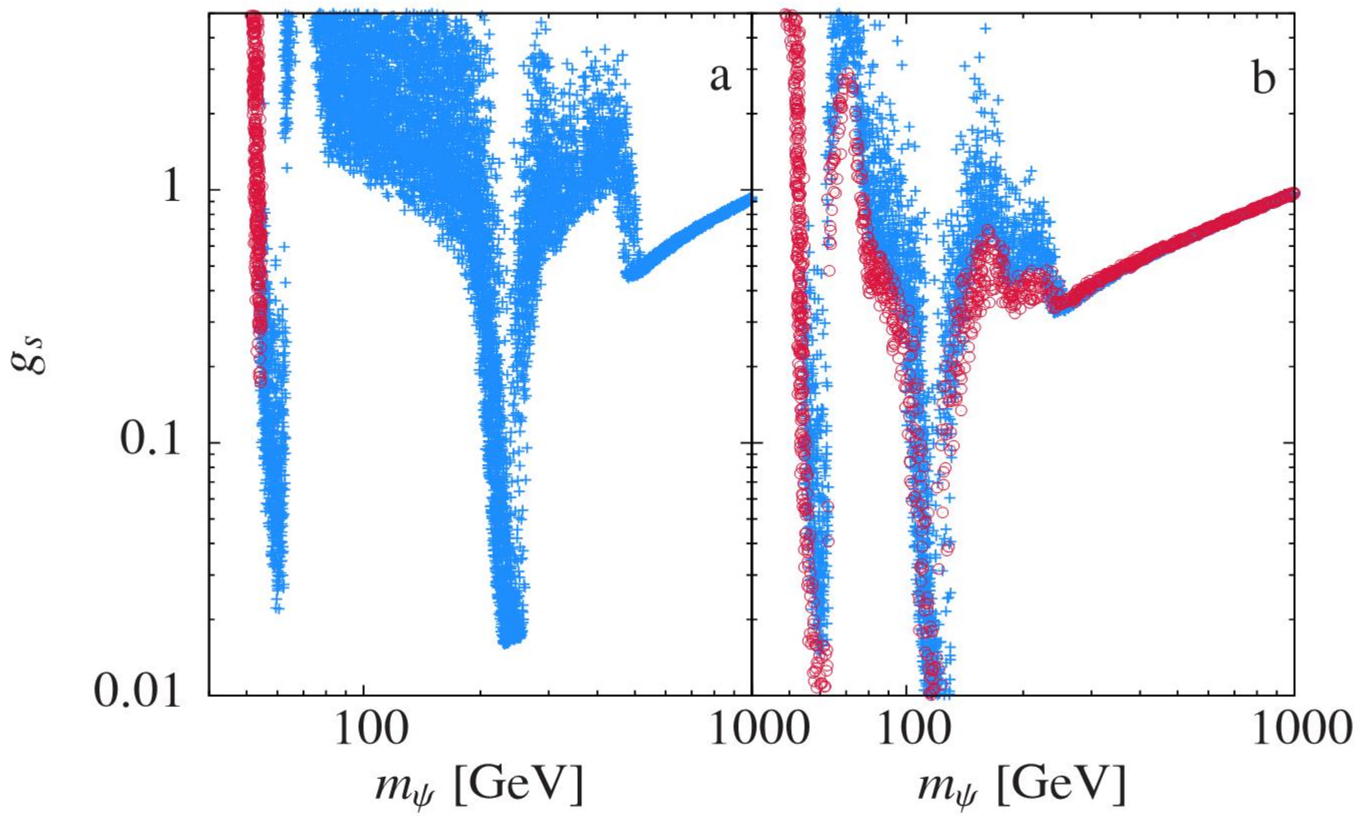
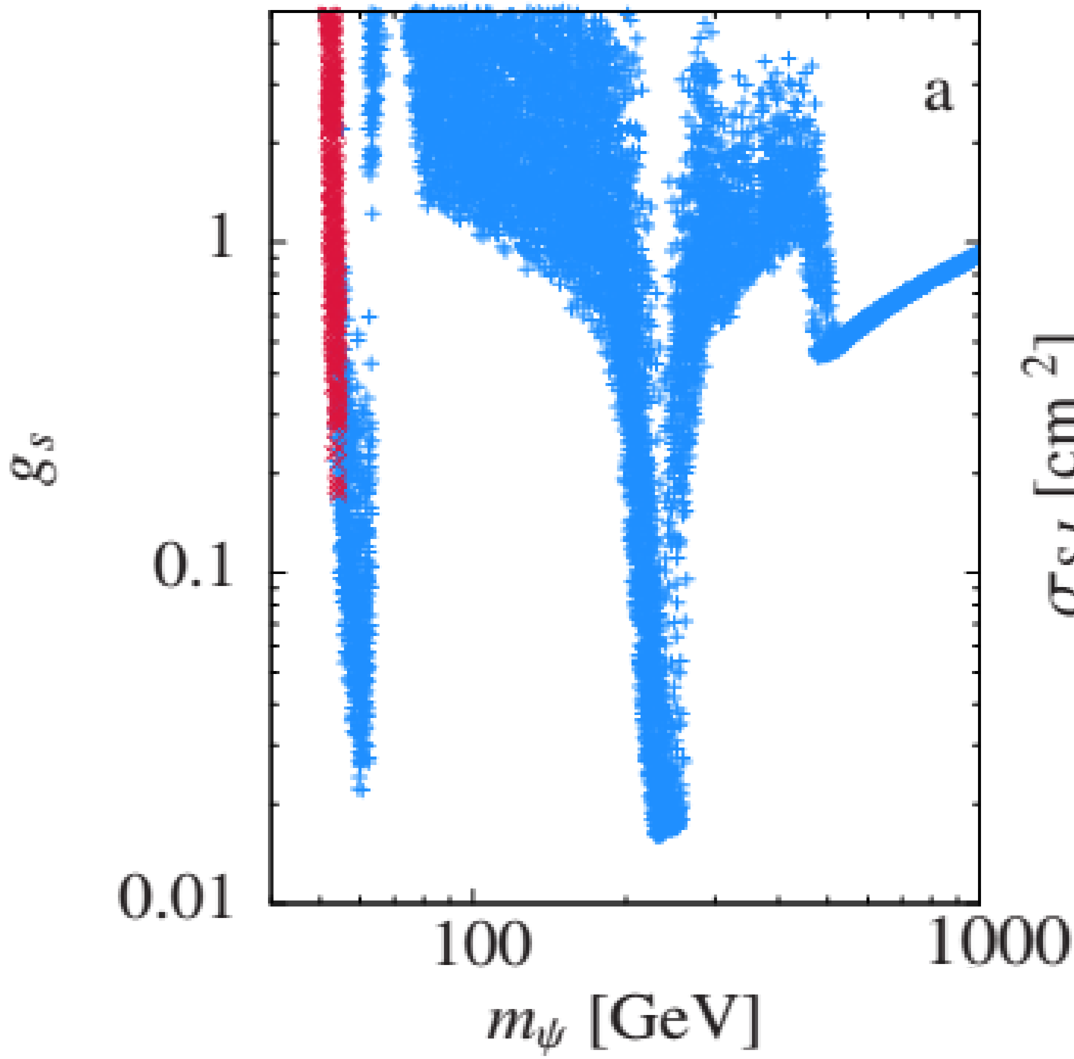


Figure 1: *Points in (g_s, m_ψ)-plane satisfying Planck relic density constraints for (a) $m_{h_2} = 500$ GeV ($\pm 5\%$), and (b) $m_{h_2} = 250$ GeV ($\pm 5\%$). The red points are ruled out by LHC Higgs physics.*

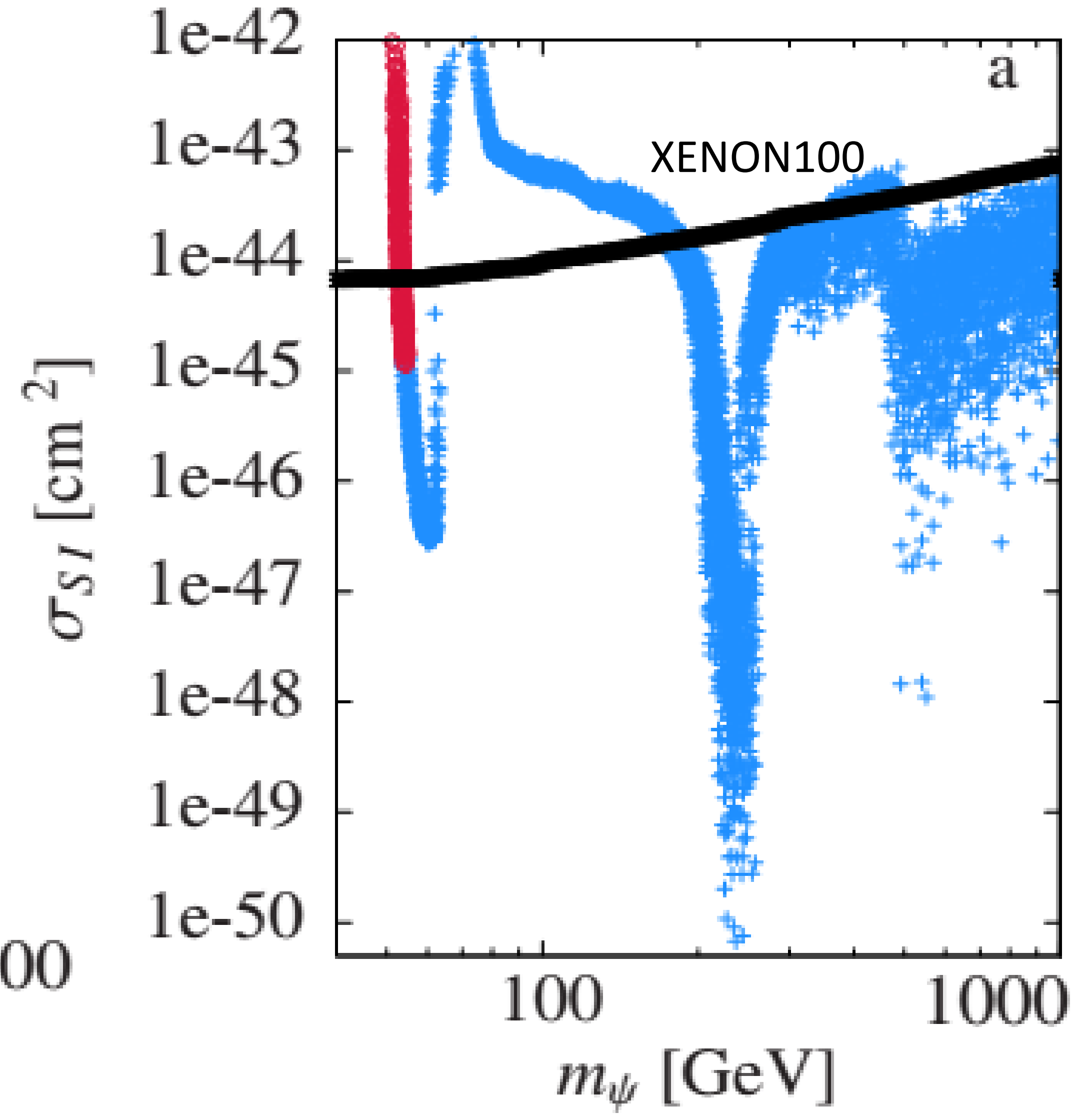
Fairbairn and Hogan 2013

$m_{h_2} = 500$

Relic abundance

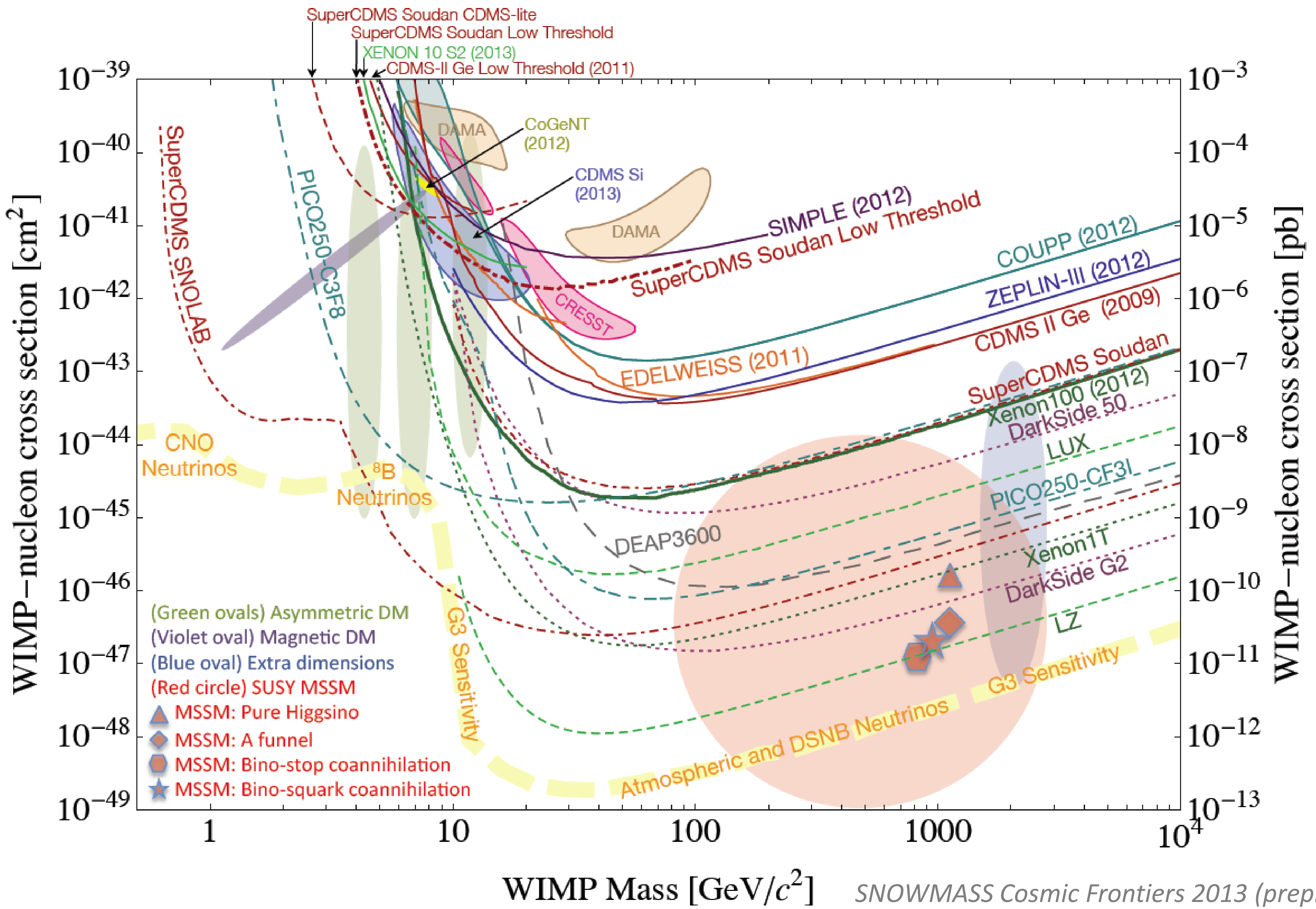


Direct Detection



$$\sigma \propto \left(\frac{g_s \cos\alpha \sin\alpha}{v}\right)^2 \left(\frac{1}{m_{h_1}^2} - \frac{1}{m_{h_2}^2}\right)^2$$

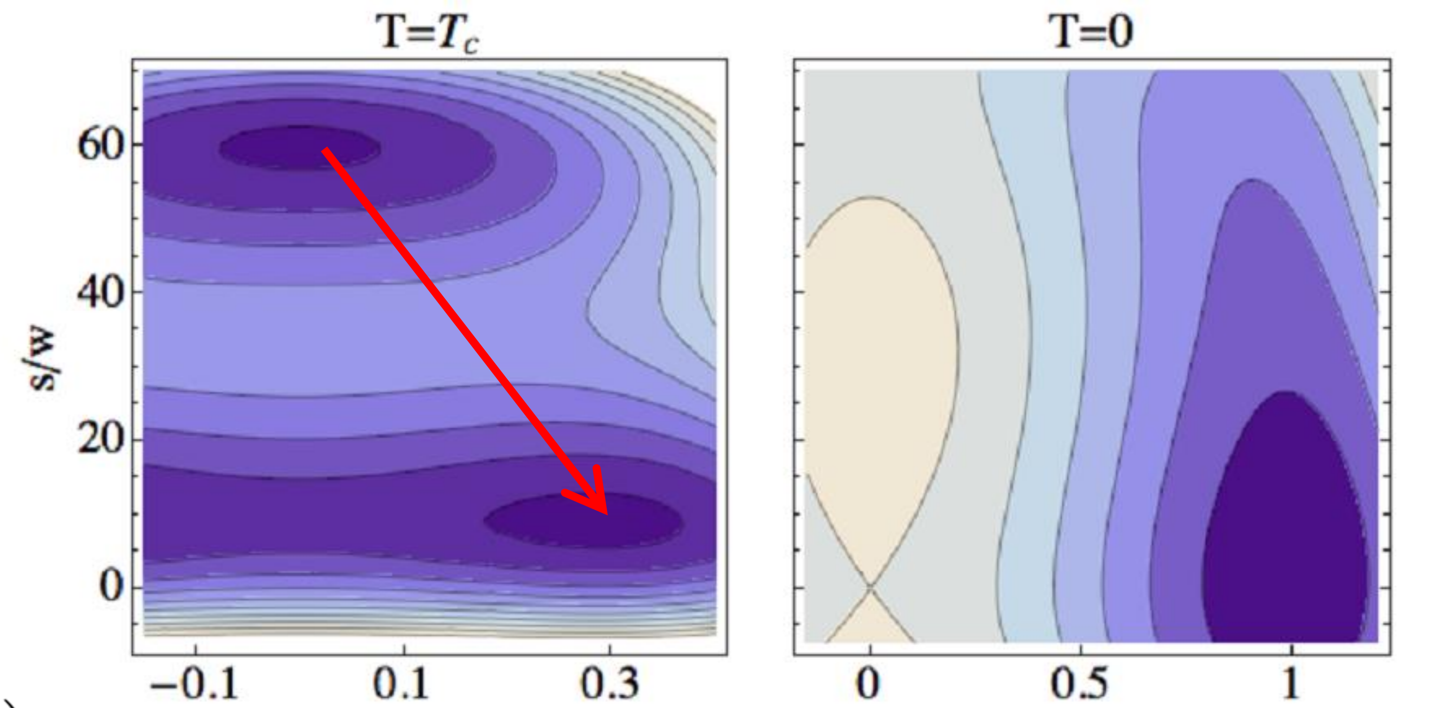
Science Reach



SNOWMASS Cosmic Frontiers 2013 (preprint)

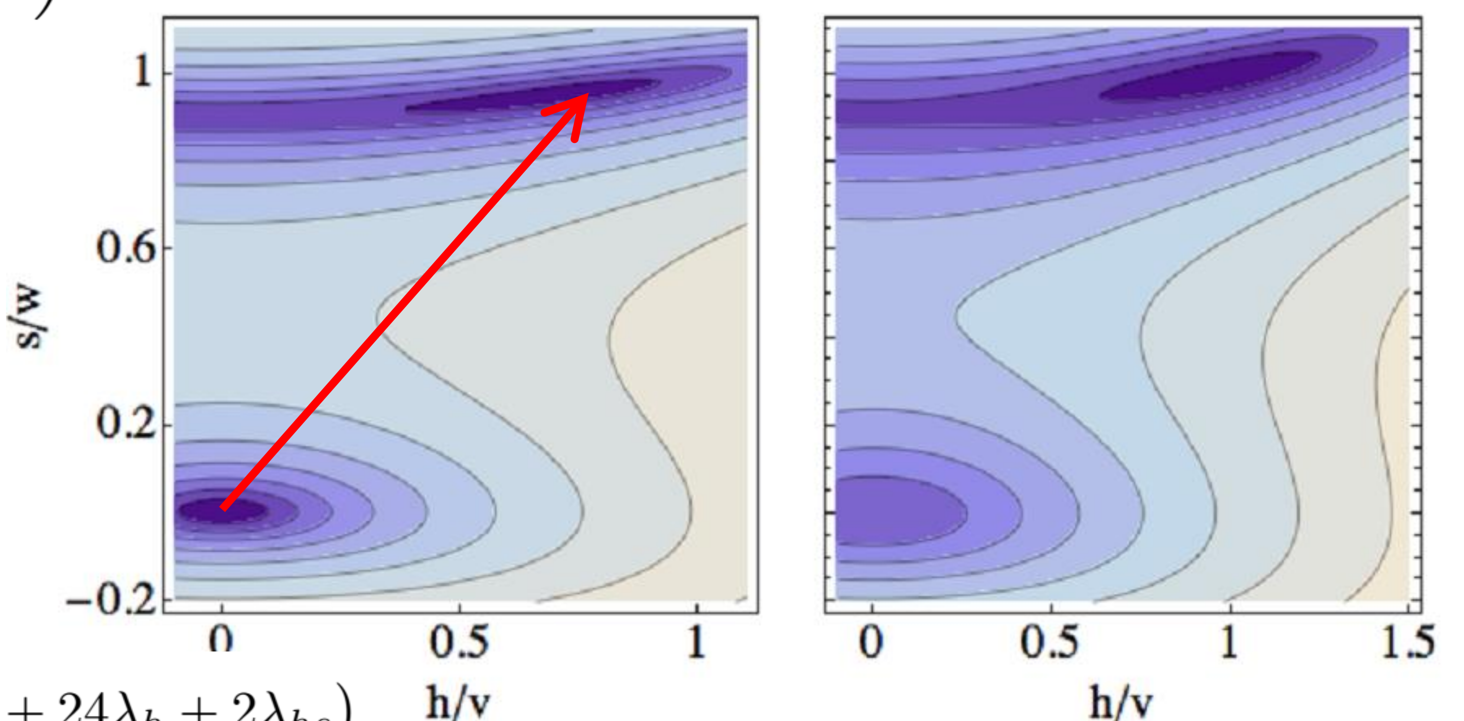
Electroweak Phase Transition with h and s

Fairbairn and Hogan 2013



The thermal correction to the tree level potential is given by

$$V_T = \left(\frac{1}{2}c_h h^2 + \frac{1}{2}c_s s^2 + m_3 s\right) T^2$$

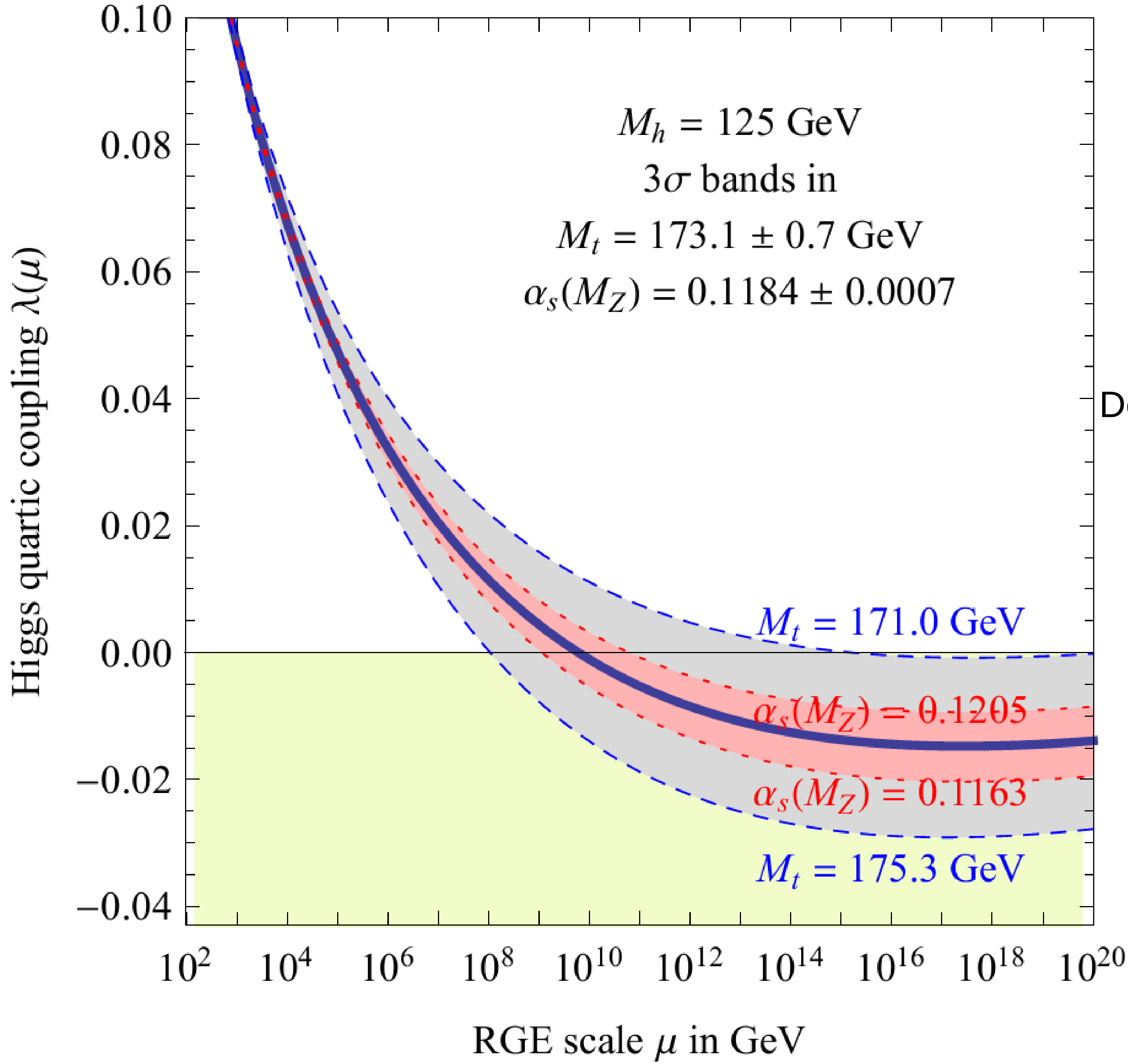


$$c_s = \frac{1}{12}\left(2\lambda_{hs} + 3\lambda_s + g_s^2\right)$$

$$m_3 = \frac{1}{12}\left(\mu_3 + \mu_m\right).$$

$$c_h = \frac{1}{48}\left(9g^2 + 3g'^2 + 12y_t^2 + 24\lambda_h + 2\lambda_{hs}\right)$$

Scalars help with Higgs Stablity



Degrassi et a;

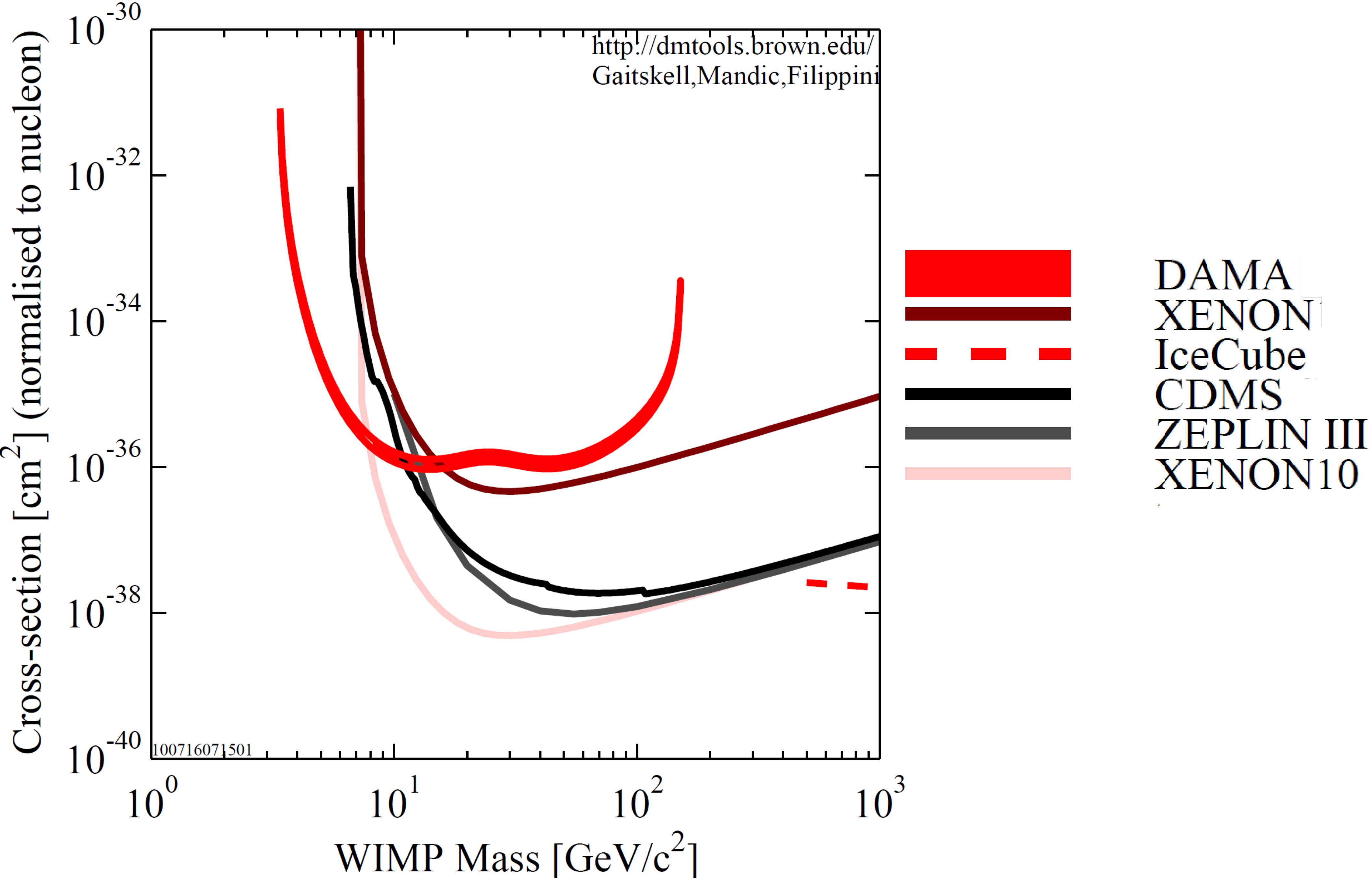
Part 1 Conclusions

- Singlet Fermionic Dark Matter through the Higgs sector is not ruled out by LHC and can be the missing mass in the Universe
- Allowing the mediating Higgs sector more freedom leads to exotic phase transition scenarios.
- The two effects are not tightly correlated parameter wise.
- Dark Matter direct detection predictions can be as low as 10^{-50} cm^2 at resonances, but are tightly constrained away from resonances

DARK MATTER BURNING STARS


Original Work:-
Salati, Bouquet, Raffelt, Krauss,
Nussinov and Silk 1980s

Limits on Spin Dependent WIMP-nucleon cross section



Capture of dark matter onto stars

$$\Gamma_c = \sum_i \left(\frac{6}{\pi}\right)^{1/2} \frac{\sigma_i \rho_\chi}{\bar{v} m_\chi} \int_0^R 4\pi r^2 \frac{\rho_i(r)}{m_i}$$

$$\times v_{esc}^2(r) \left[1 - \frac{1 - \mathrm{e}^{-A_i^2(r)}}{A_i^2(r)}\right] dr$$

where

$$A_i^2(r) = \frac{3 v_{esc}^2(r)}{2\bar{v}^2} \frac{2}{m_\chi/m_i + m_i/m_\chi - 2}$$

Steigman et al (1978), Press and Spergel (1985),
Gould (1987), Griest and Seckel (1987)

Capture of dark matter onto stars

Capture rate can be approximated by simple expression

$$\Gamma_c = \left(\frac{8}{3\pi}\right)^{1/2} \frac{\rho_{dm}\bar{v}}{m_{dm}} \left(\frac{3v_{esc}^2}{2\bar{v}^2}\right) \frac{M_*}{m_p} \sigma$$

1. Dark matter density
2. Dark matter velocity
3. Escape velocity of star
4. Number of targets in star (nucleons)
5. Cross section per target

Capture of dark matter onto stars

dark matter forms thermal core within the star of radius

$$r_{th} \sim \left[\frac{9kT}{8\pi G \rho_c m_\chi} \right]^{1/2}$$

for the sun and 100 GeV WIMP this is 9×10^8 cm

compare with solar radius $r = 7 \times 10^{10}$ cm

Capture of dark matter onto stars

annihilation rate inside the star given by

$$\Gamma_a = \frac{1}{2}\frac{N^2\langle\sigma v\rangle}{\frac{4}{3}\pi r_{th}^3}$$

# of DM particles in star

$$\frac{dN}{dt} = \Gamma_c - \Gamma_a$$

and equilibrium is reached when

$$\Gamma_c = \Gamma_a$$

N in sun is 10^{41} $\rightarrow$ 10^{43} GeV of DM in sun ~ 10^{13} tons

to be compared with Msun = 10^{57} GeV

Capture of dark matter onto stars

annihilation rate inside the star given by

$$\Gamma_a = \frac{1}{2}\frac{N^2\langle\sigma v\rangle}{\frac{4}{3}\pi r_{th}^3}$$

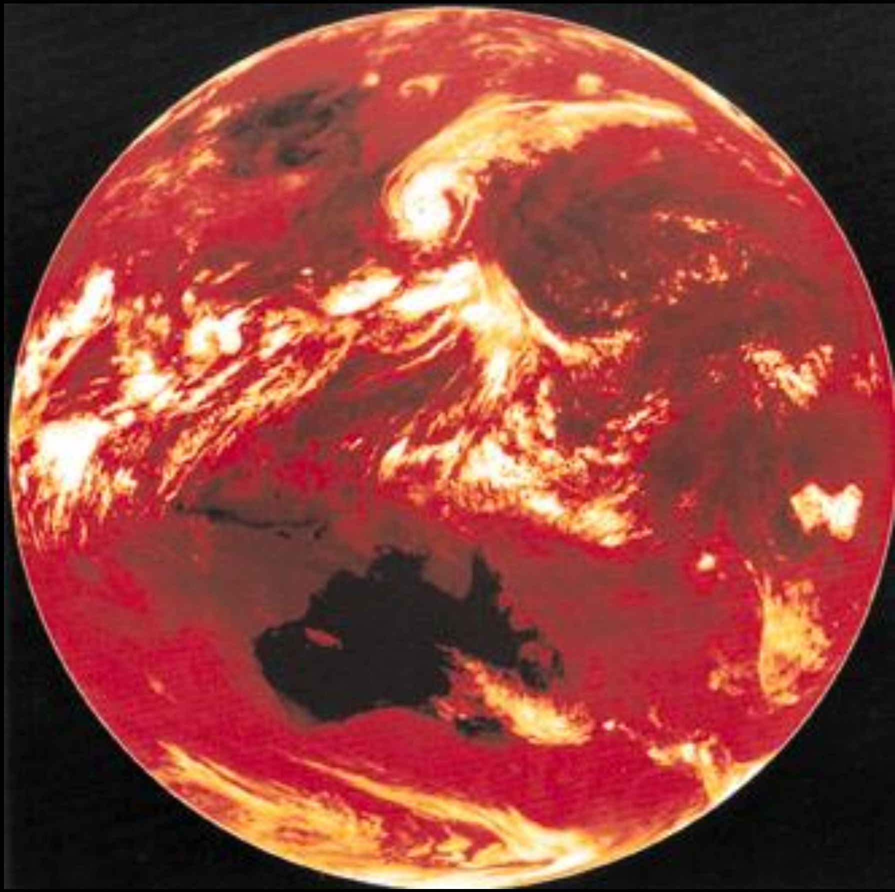
# of DM particles in star and equilibrium is reached when

$$\frac{dN}{dt} = \Gamma_c - \Gamma_a \qquad\qquad \Gamma_c = \Gamma_a$$

In the sun $\Gamma_c =$ 3 x 10^{24} s^{-1} so L_{DM}= 5 x 10^{23} erg s^{-1}

$L_{DM} = 10^{-10}\ L_{SUN}$

Luminosity of Sun due to WIMPs approximately 200 x Earth Luminosity



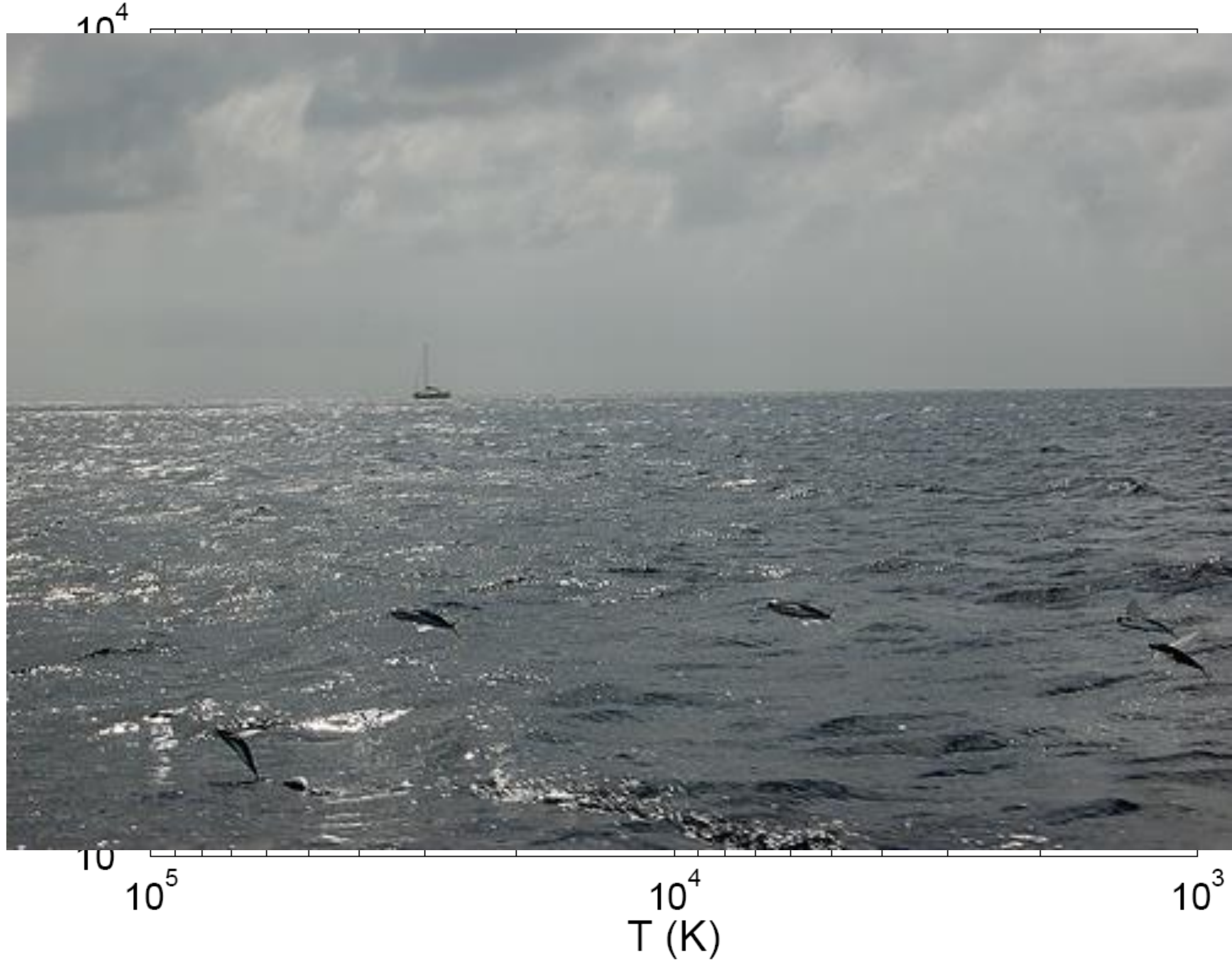
Equations of stellar structure have solutions which are stars

$$\frac{dM_r}{dr} = 4\pi r^2 \rho$$

$$\frac{dP}{dr} = -\frac{GM_r}{r^2}\rho$$

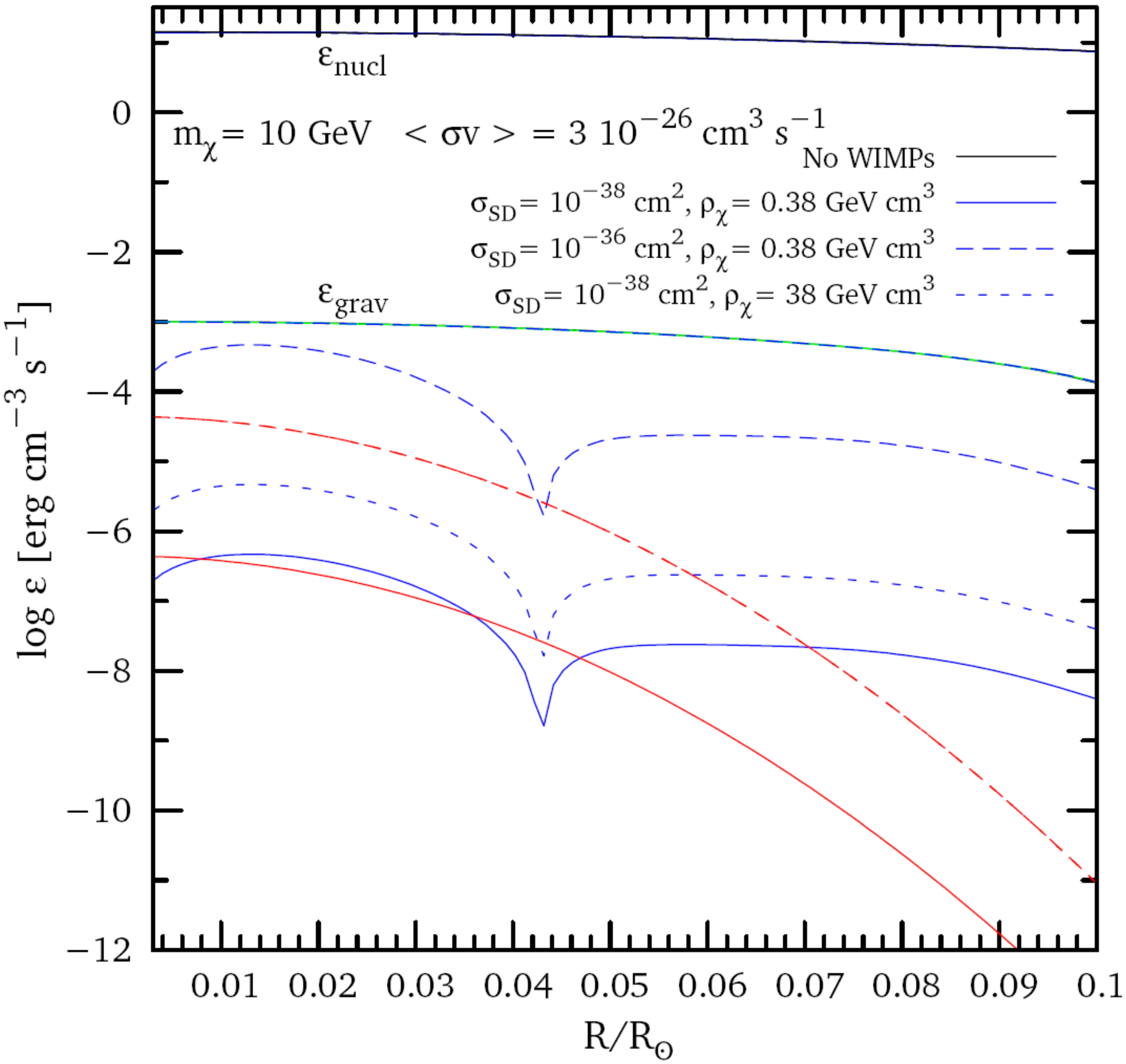
$$\frac{dL_r}{dr} = 4\pi r^2 \epsilon \rho$$

$$\frac{dT}{dr} = -\frac{1}{4\pi r^2 \lambda} L_r$$



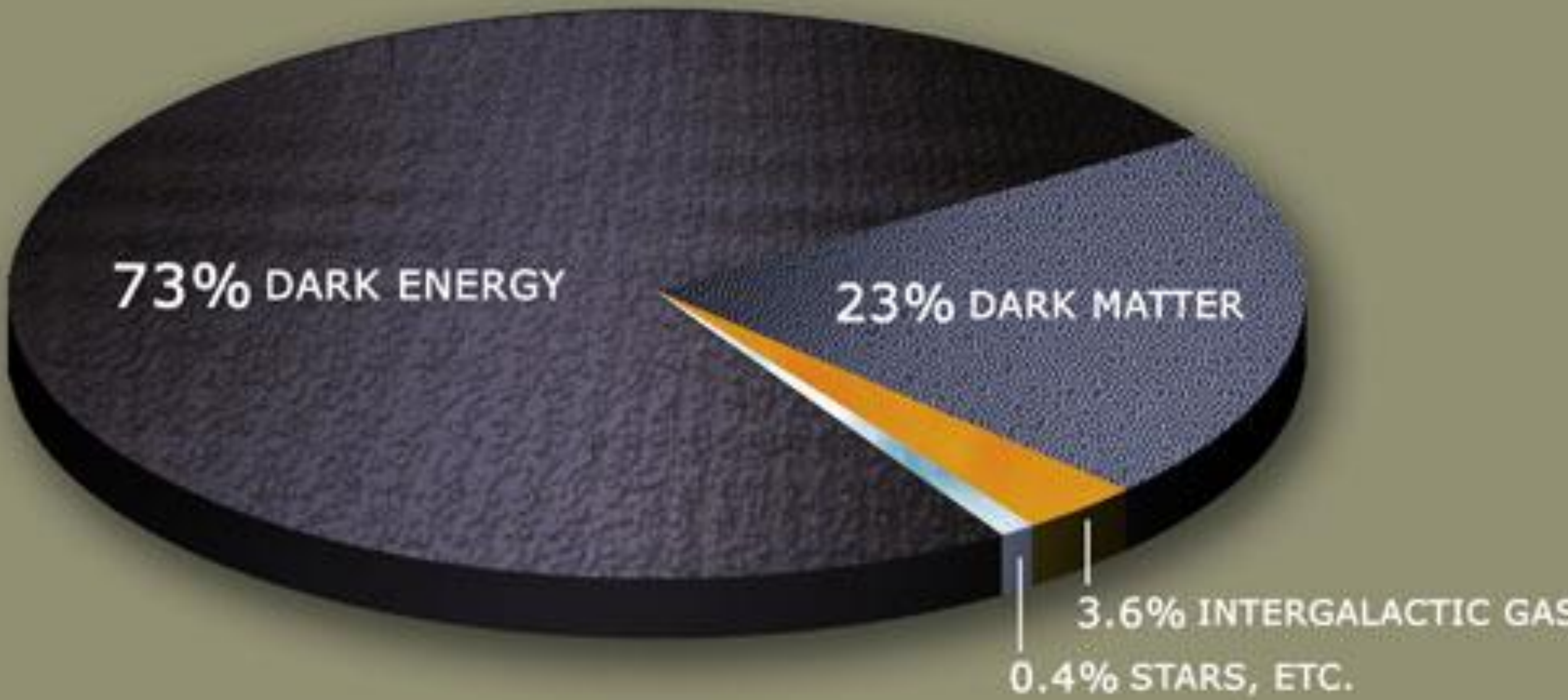
Scattering of WIMPs can reduce opacity

However, effect is very small for Annihilating dark matter

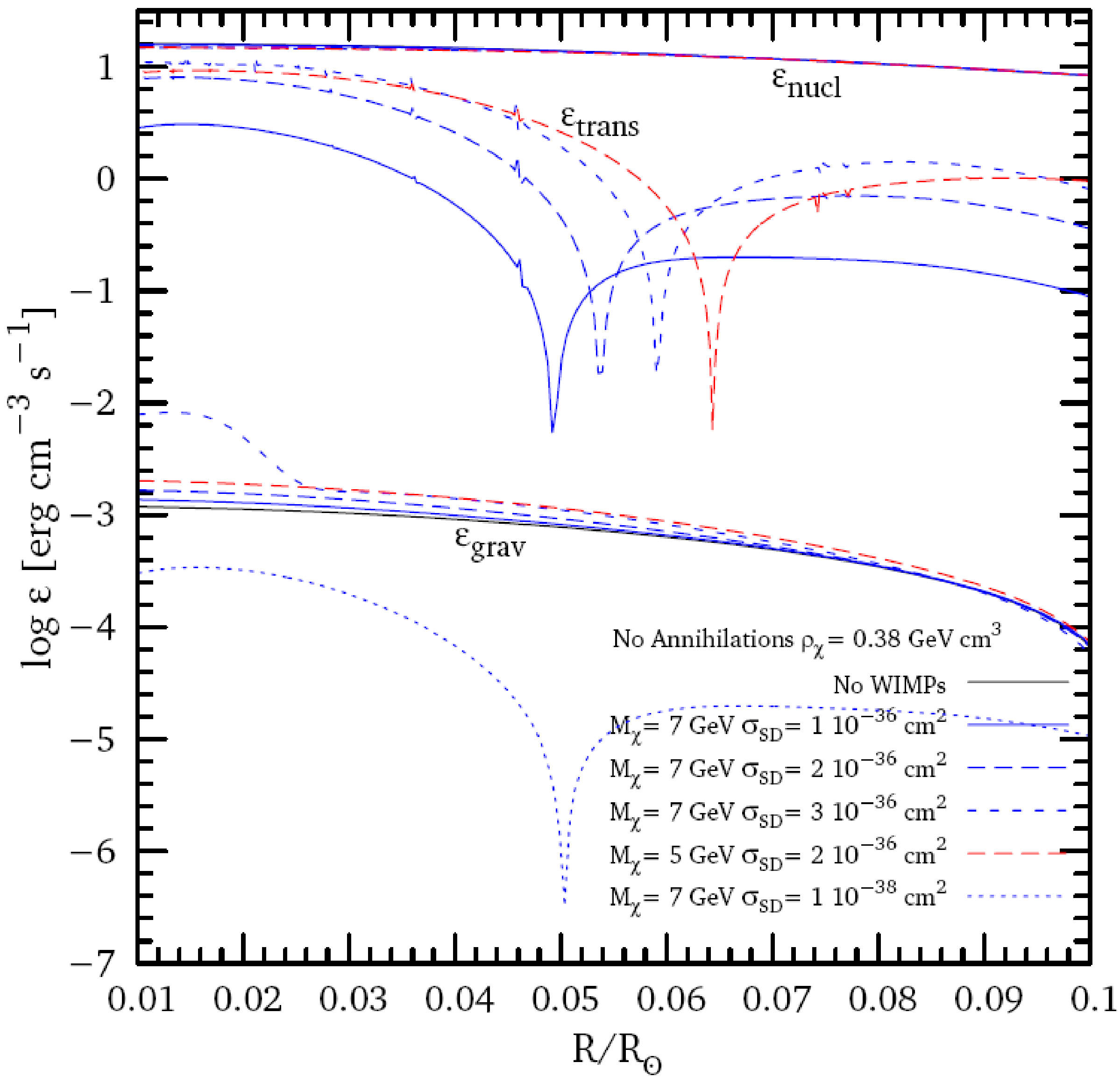


Taoso et al arXiv:1005.5711

Would be nice if it was about 7 GeV!

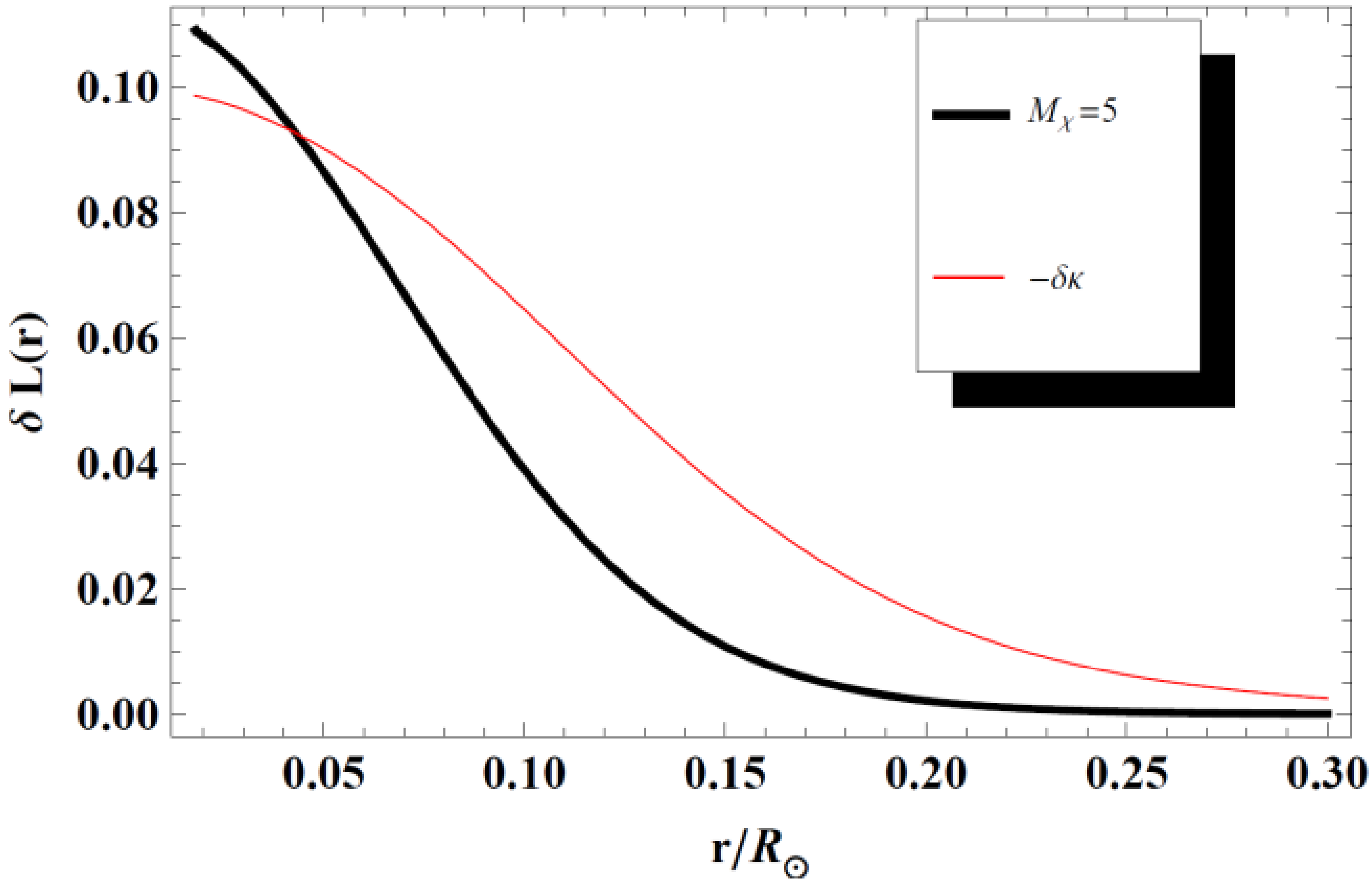


Energy transport for non-annihilating dark matter



Taoso et al arXiv:1005.5711

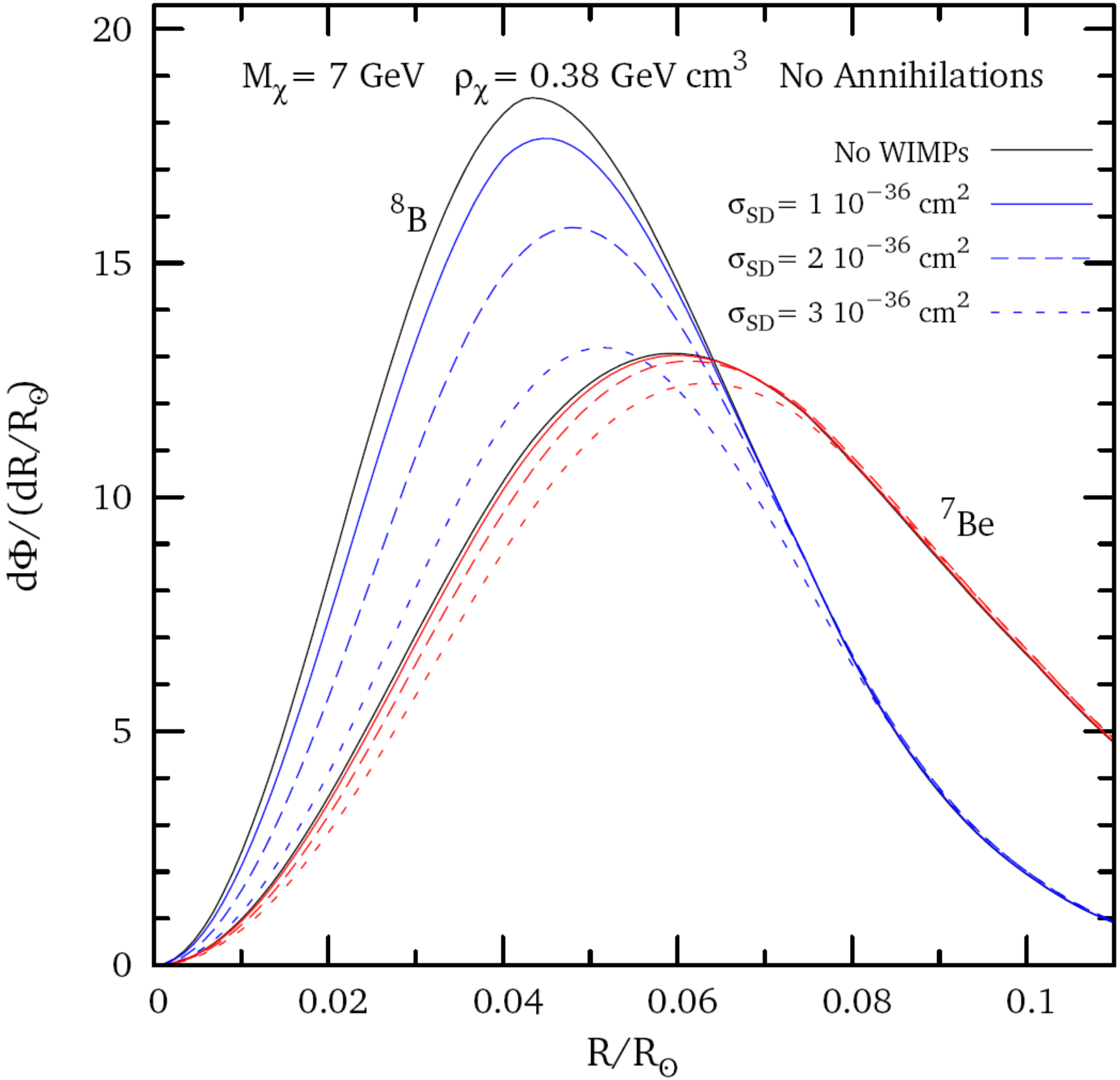
Fractional change in Luminosity as function of r



$$\delta L(r) \equiv L_\chi(r)/L_\odot(r) - 1$$

Frandsen and Sarkar arXiv:1003.4505

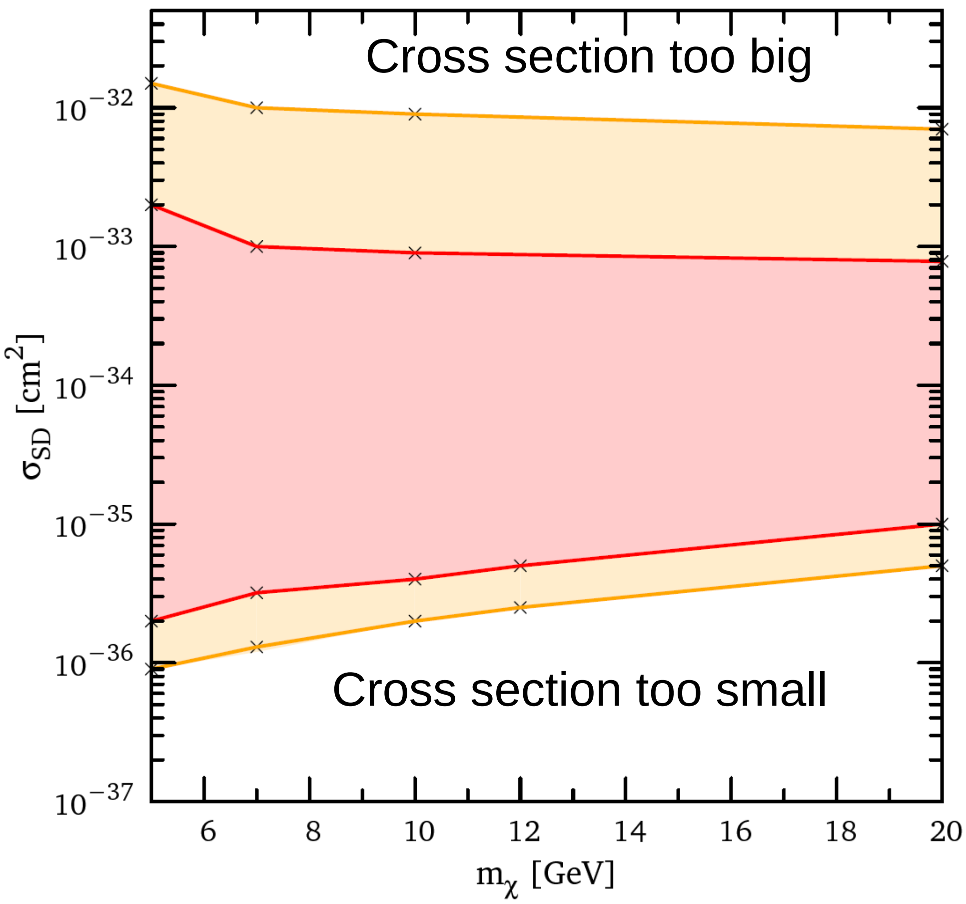
Change in Neutrino Flux due to Presence of Dark Matter

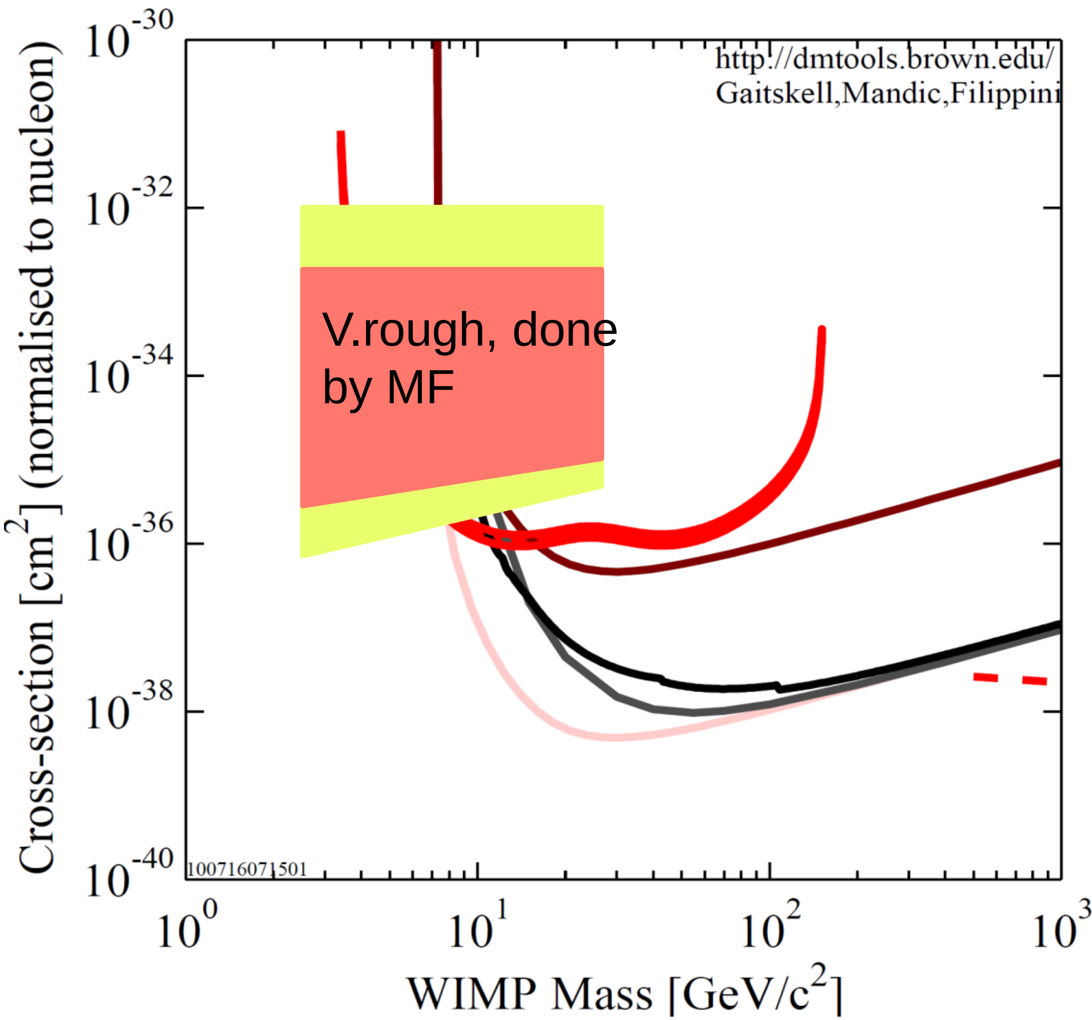


Taoso et al arXiv:1005.5711

^{8}B flux of neutrinos measured with 5% error
^{7}Be within 10%, means that one can put constraints...

... INTERESTING CONSTRAINTS !!



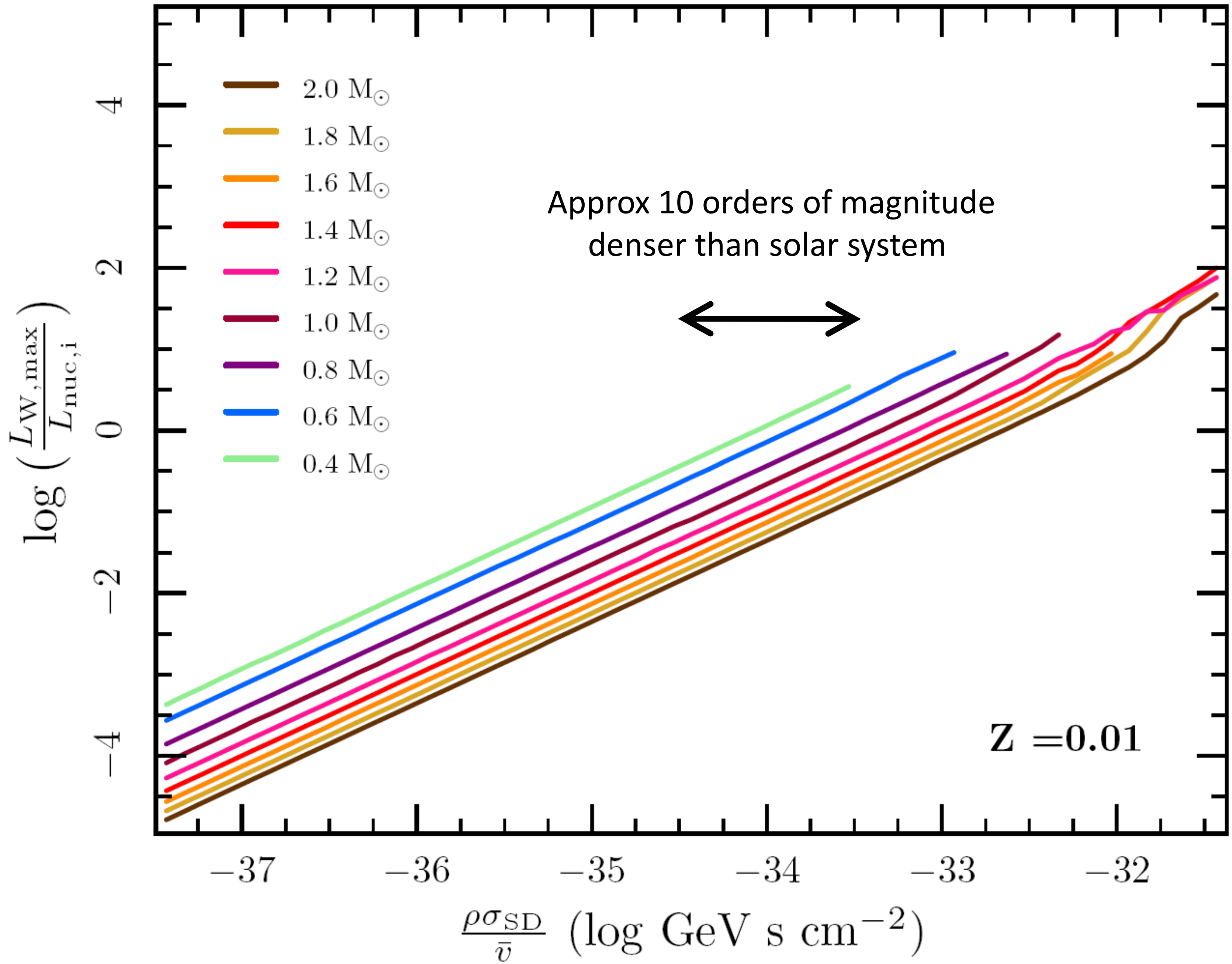


Pink region 25% change
Yellow region 5% change

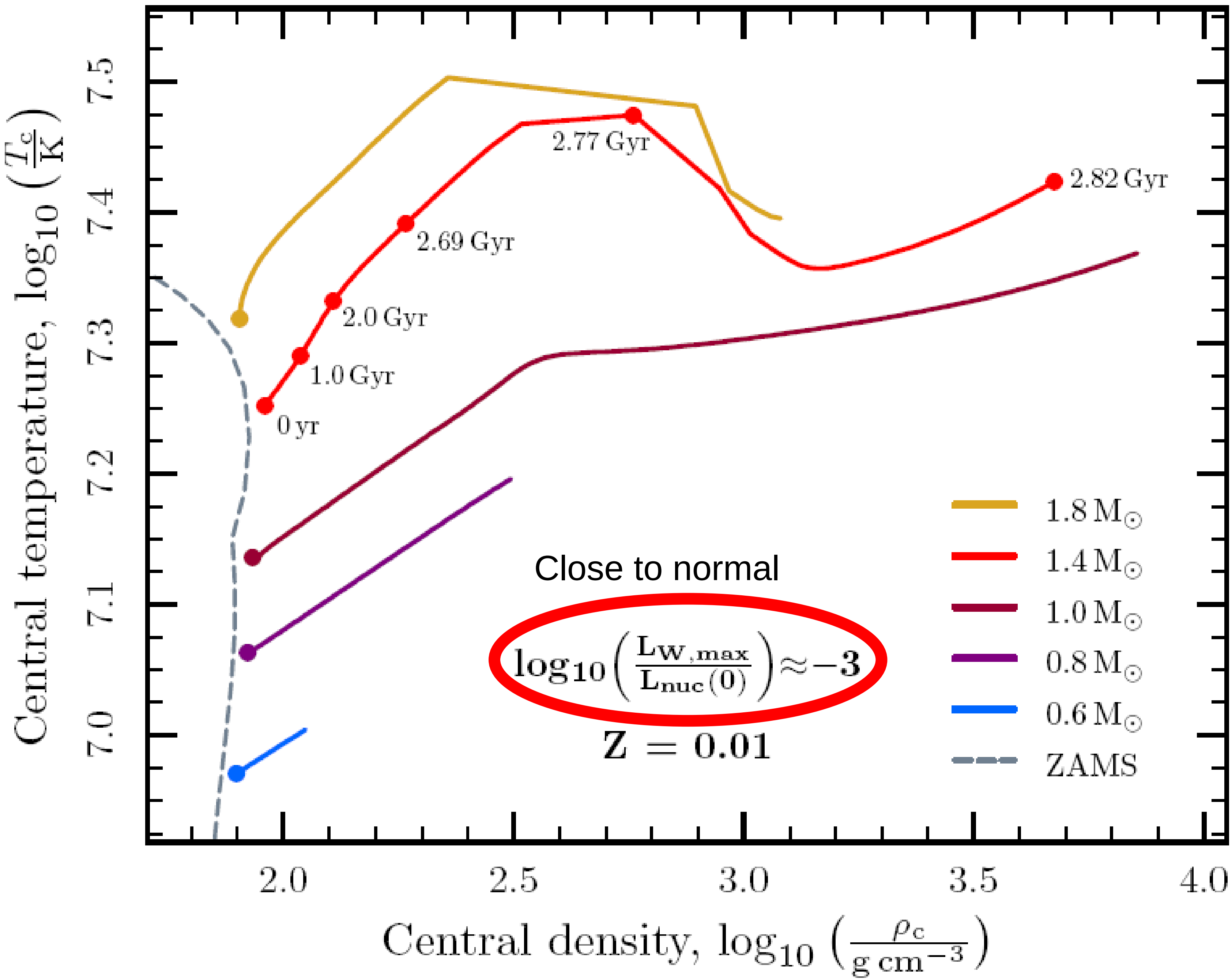
Taoso et al arXiv:1005.5711

How much *annihilating* dark matter needed to change a star?

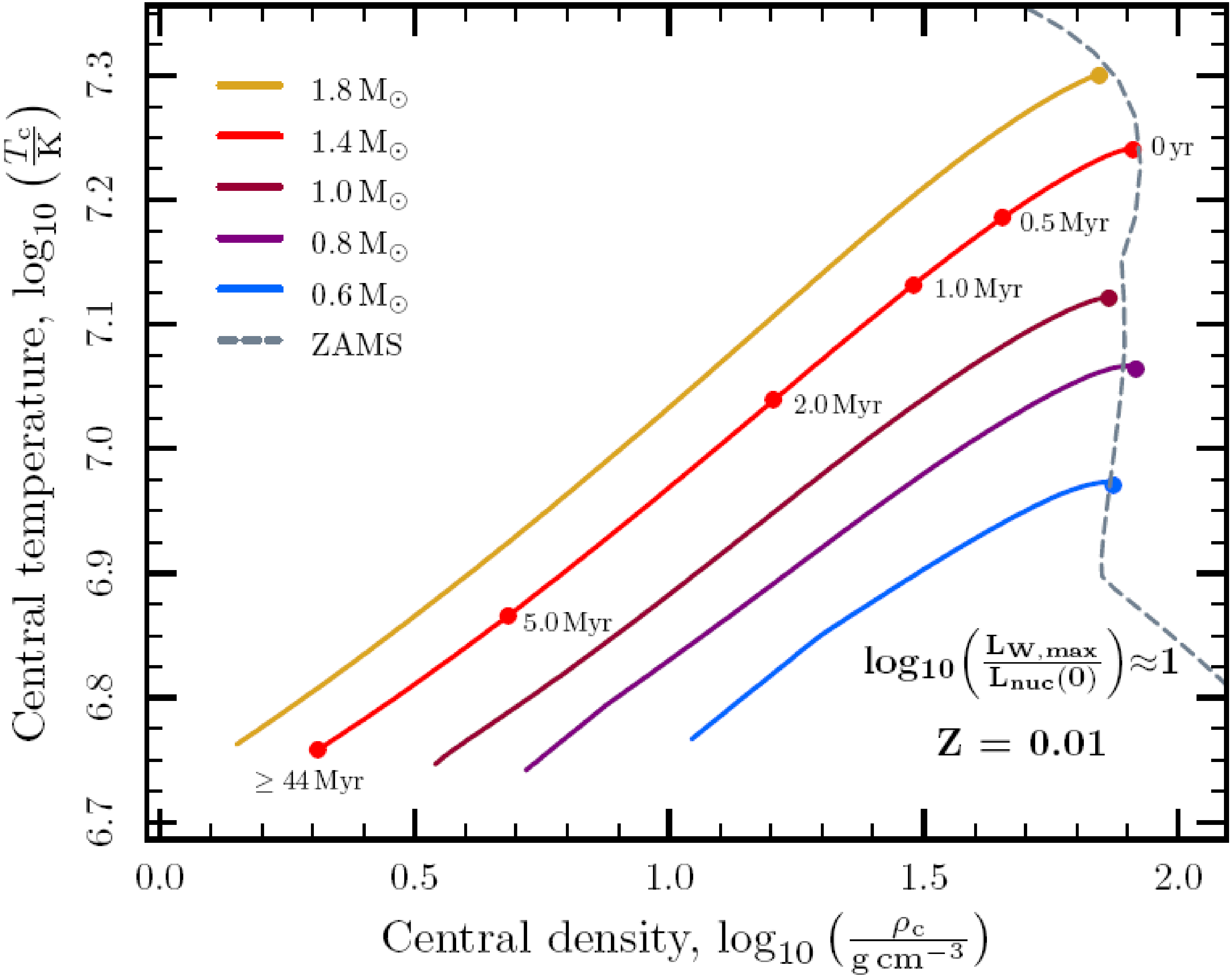
Simulations over next few slides from Scott, Fairbairn and Edsjo arXiv:0809.1871



Central Equation of state

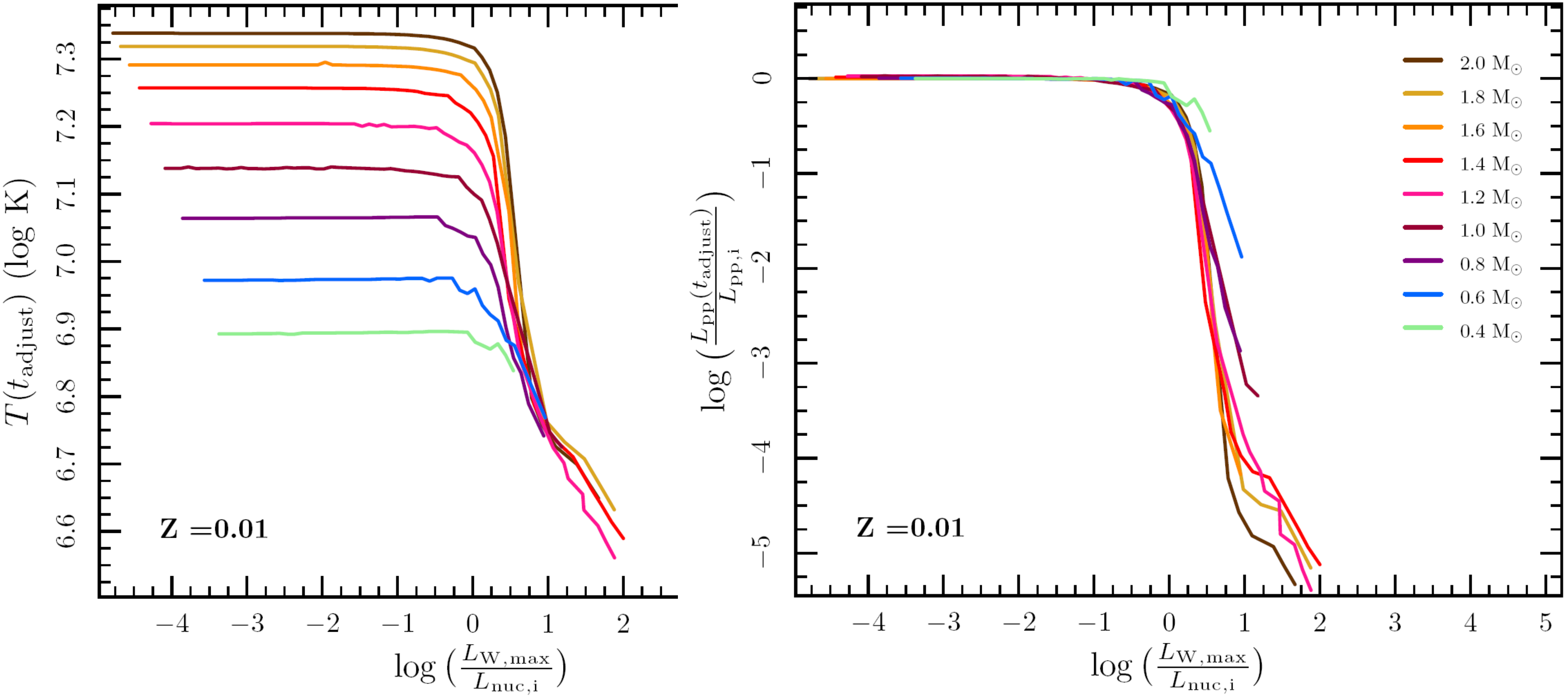


Central Equation of state



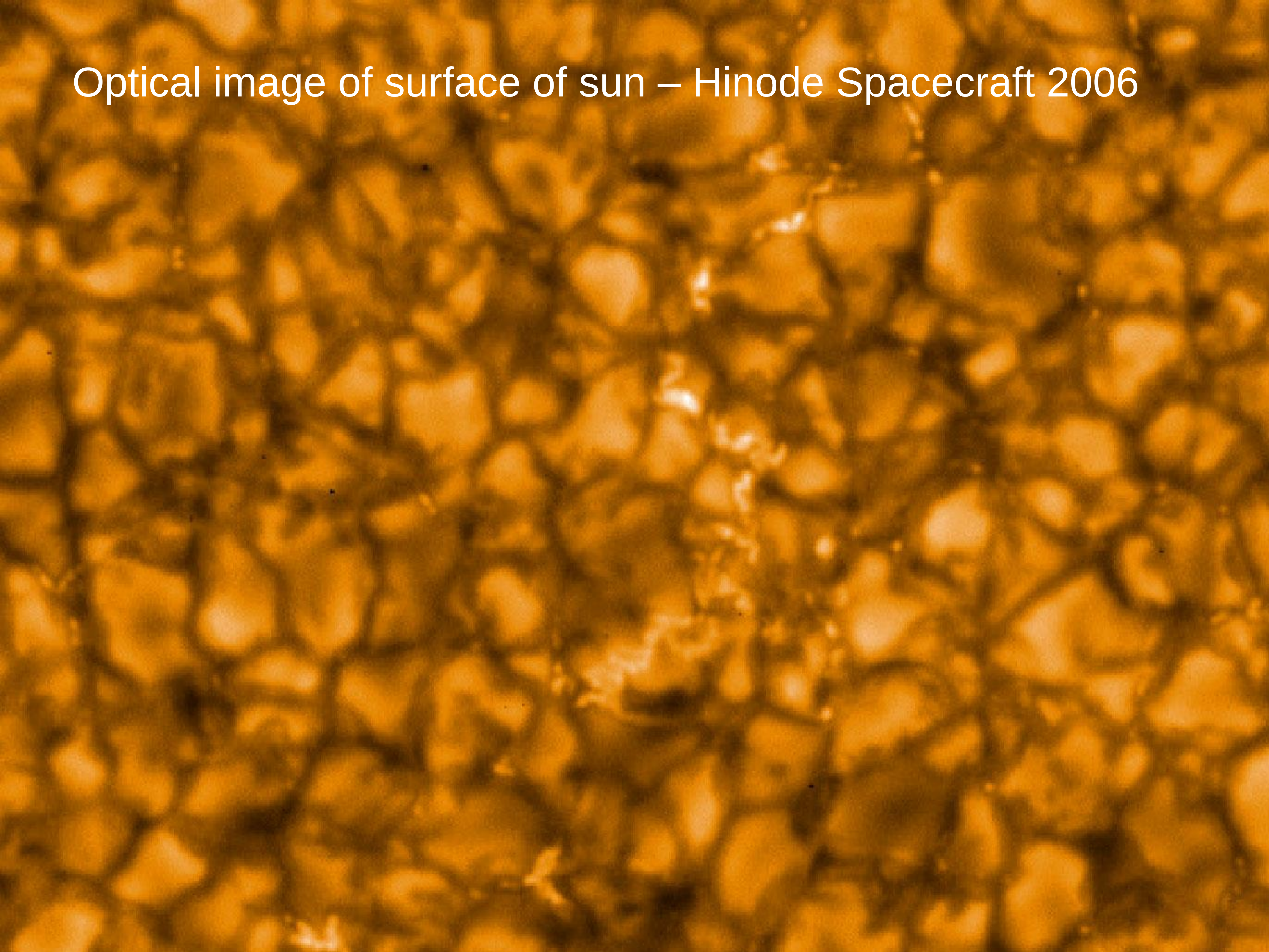
Reduction in temperature
by less than order of mag....

switches off nuclear burning
almost completely



the stars become WIMP burning stars

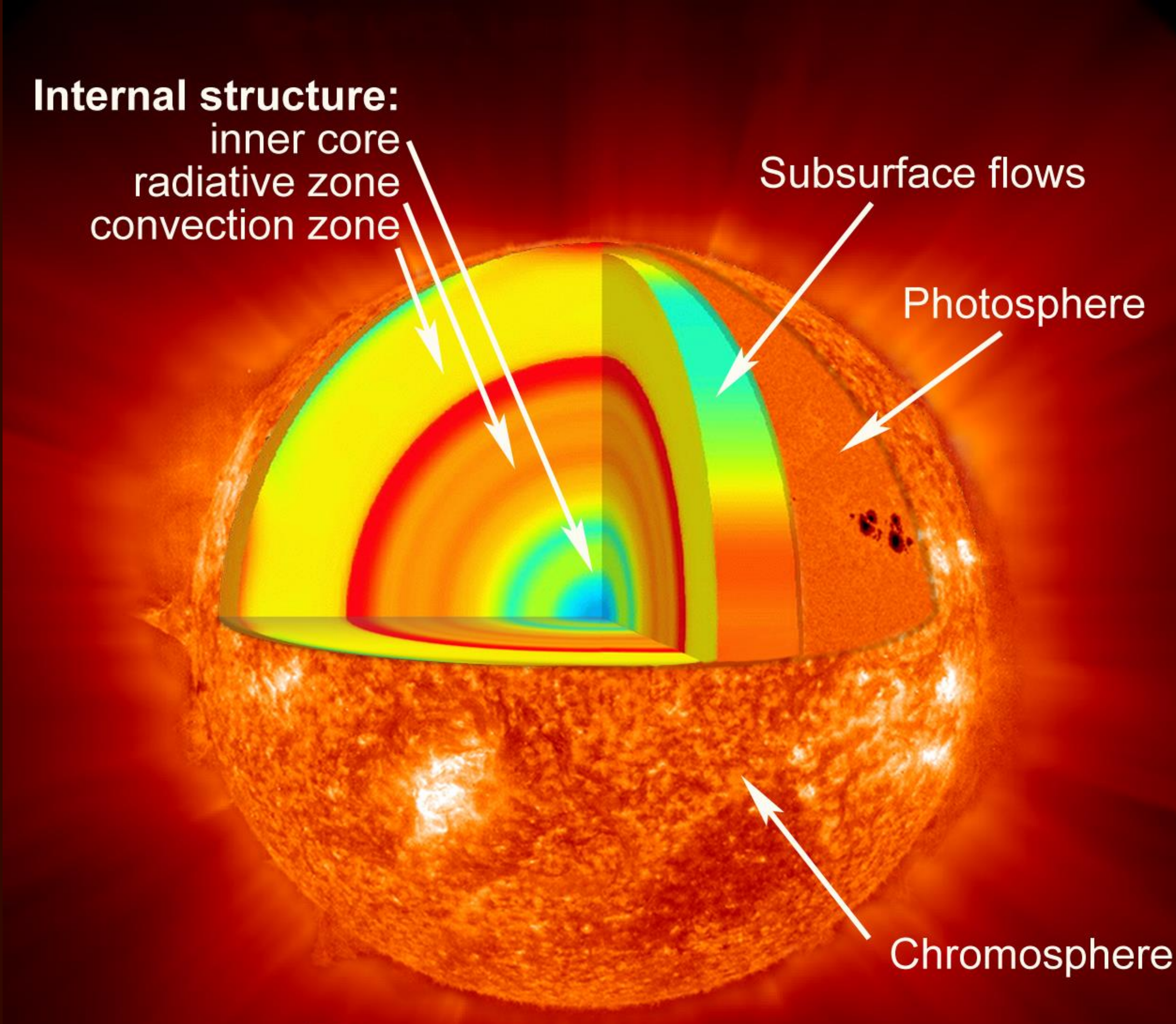
Optical image of surface of sun – Hinode Spacecraft 2006



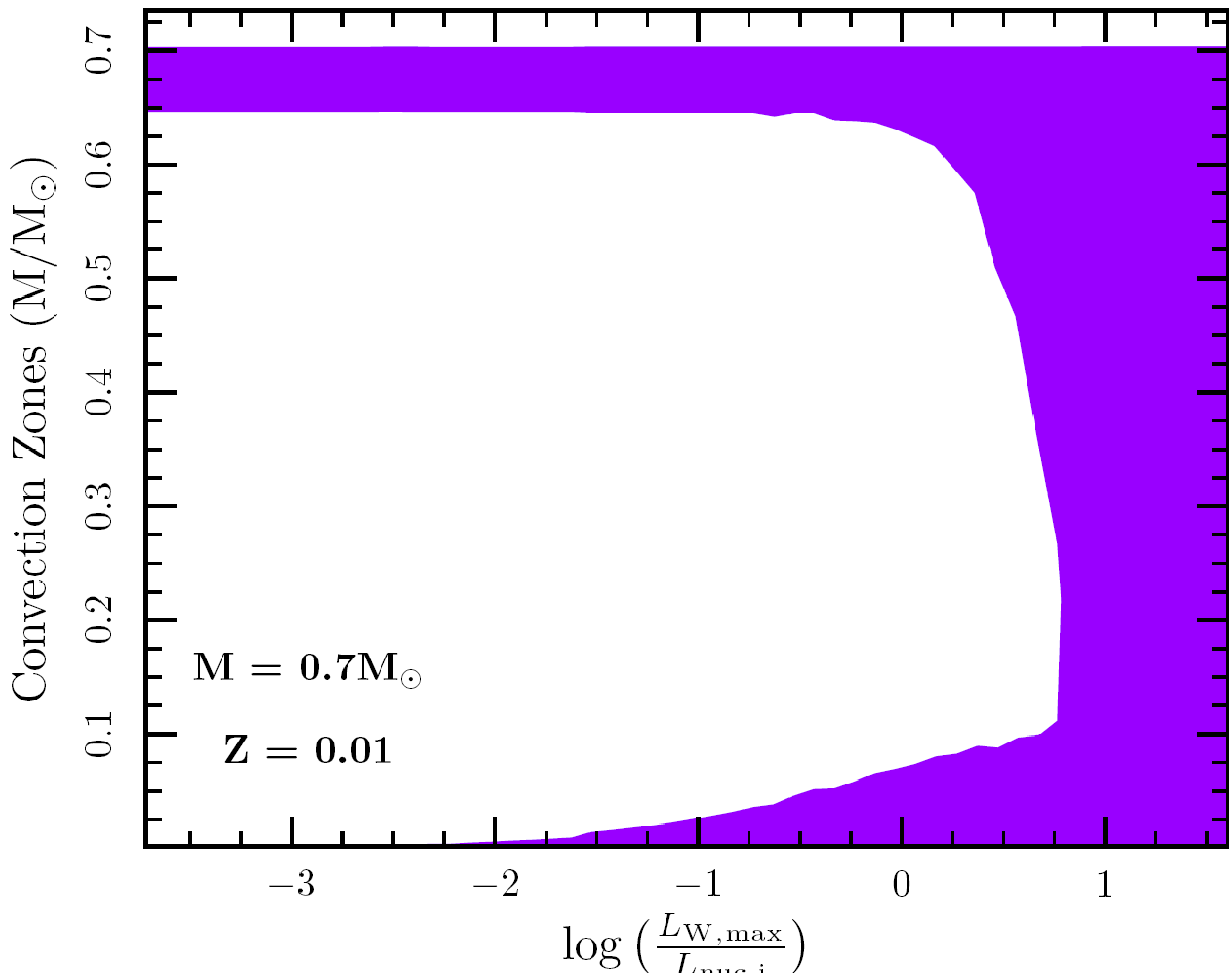
- cells heat up, density goes down and they become more buoyant

- convective energy transport dominant so long as cells cannot lose energy via radiative processes quicker than they rise

- occurs when net energy flow is very high

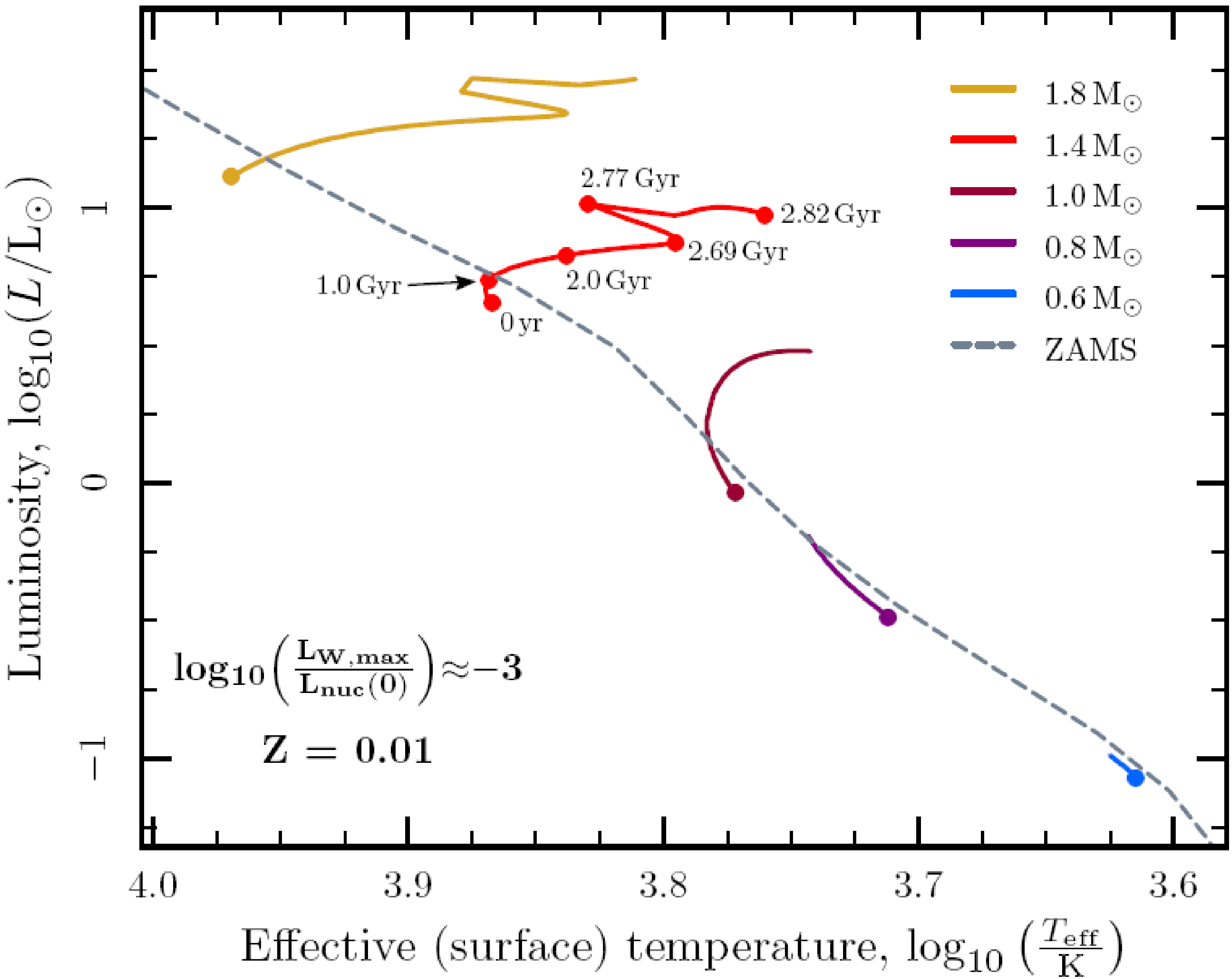


Internal structure:
inner core
radiative zone
convection zone
Subsurface flows
Photosphere
Chromosphere

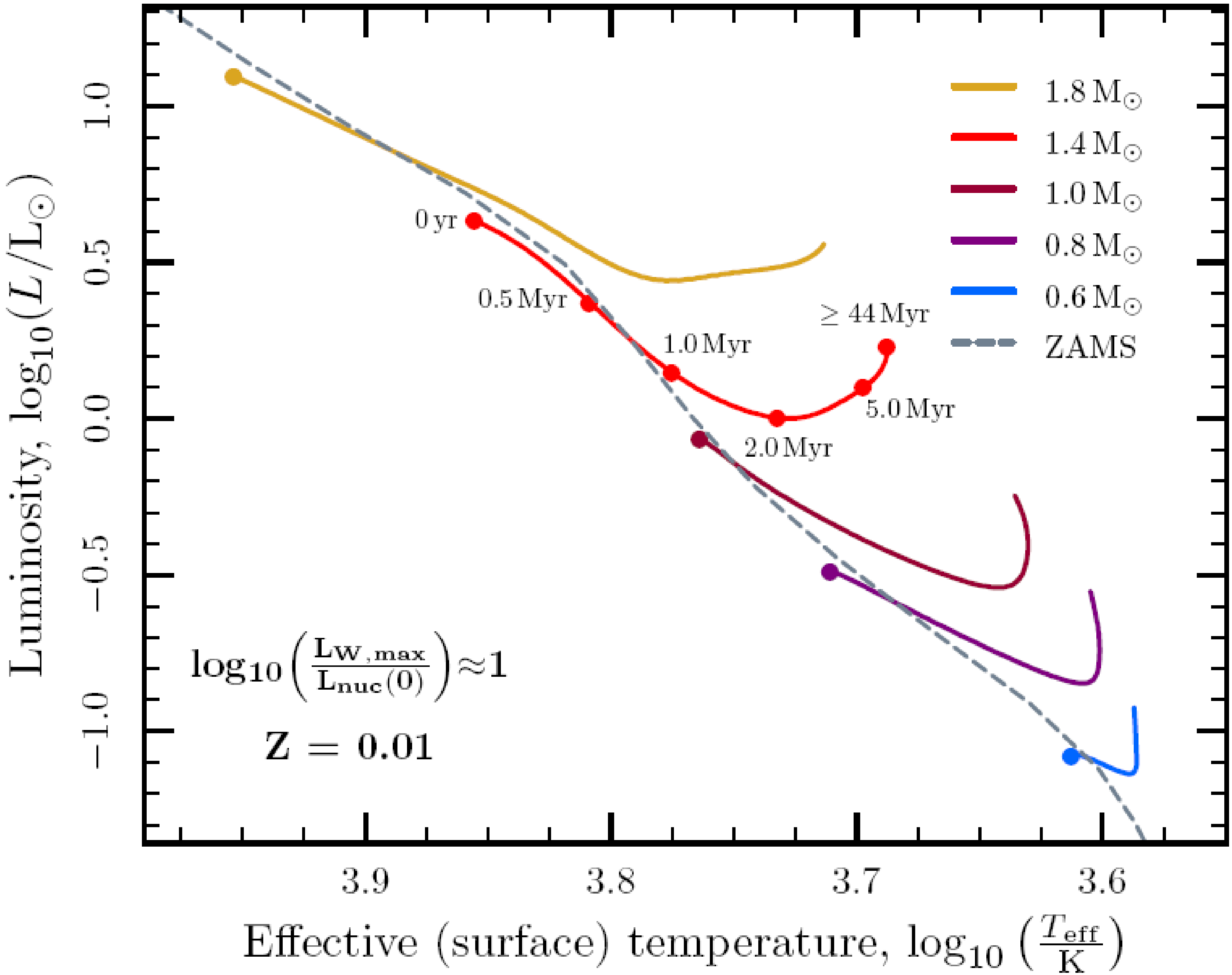


Convection Zones $(\mathrm{M}/\mathrm{M}_\odot)$
0.1
0.2
0.3
0.4
0.5
0.6
0.7
$\mathbf{M = 0.7M_\odot}$
$\mathbf{Z = 0.01}$
−3
−2
−1
0
1
$\log\left(\frac{L_{\mathrm{W,max}}}{L_{\mathrm{nuc,i}}}\right)$

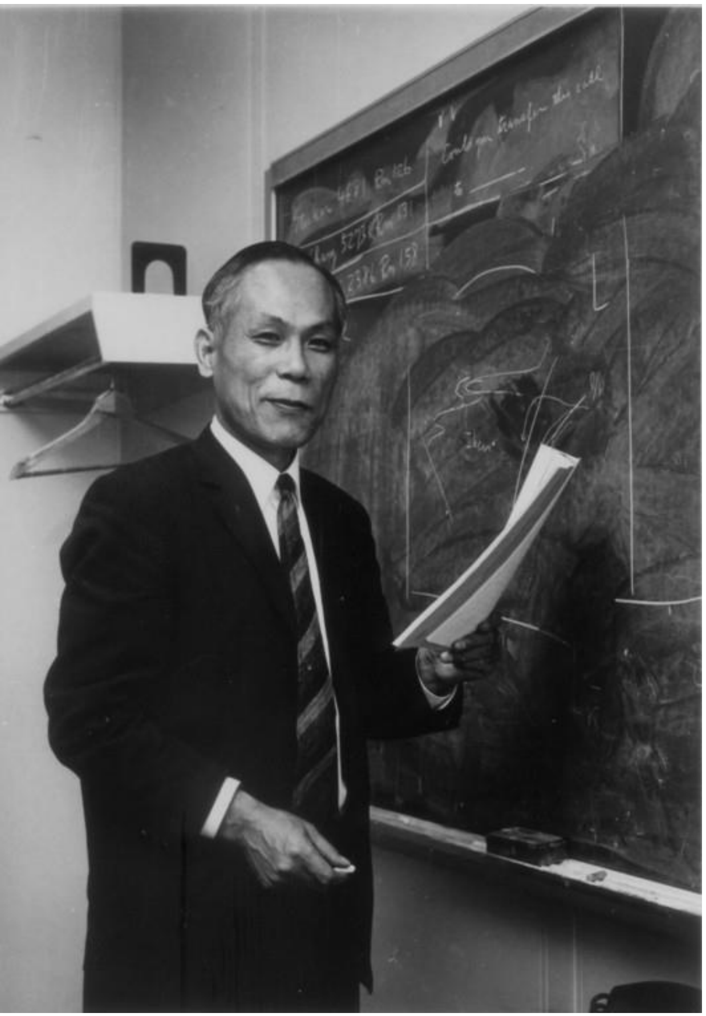
Herzsprung Russell Diagrams

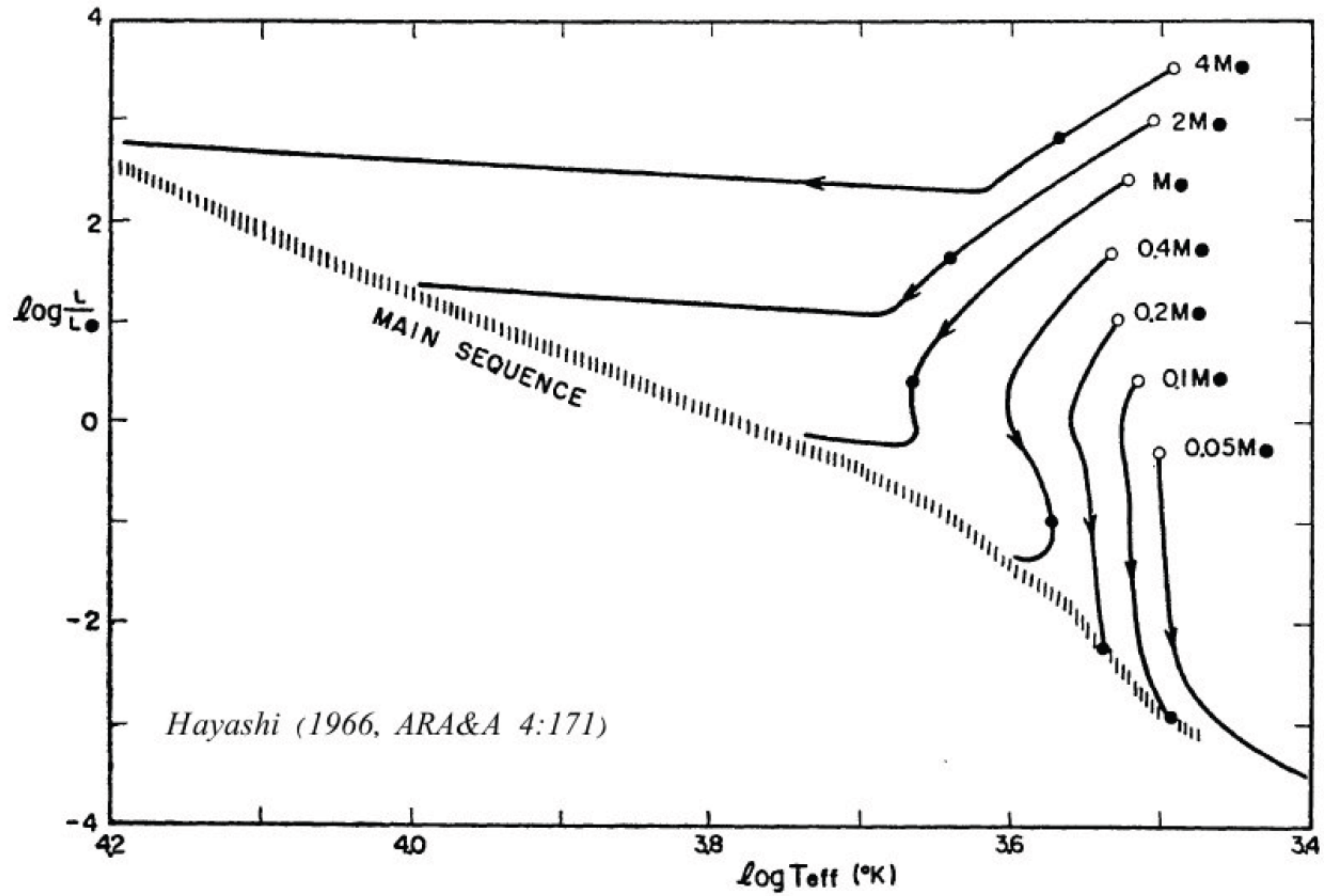


Herzsprung Russell Diagrams



Compare with Hayashi Track of Protostars...

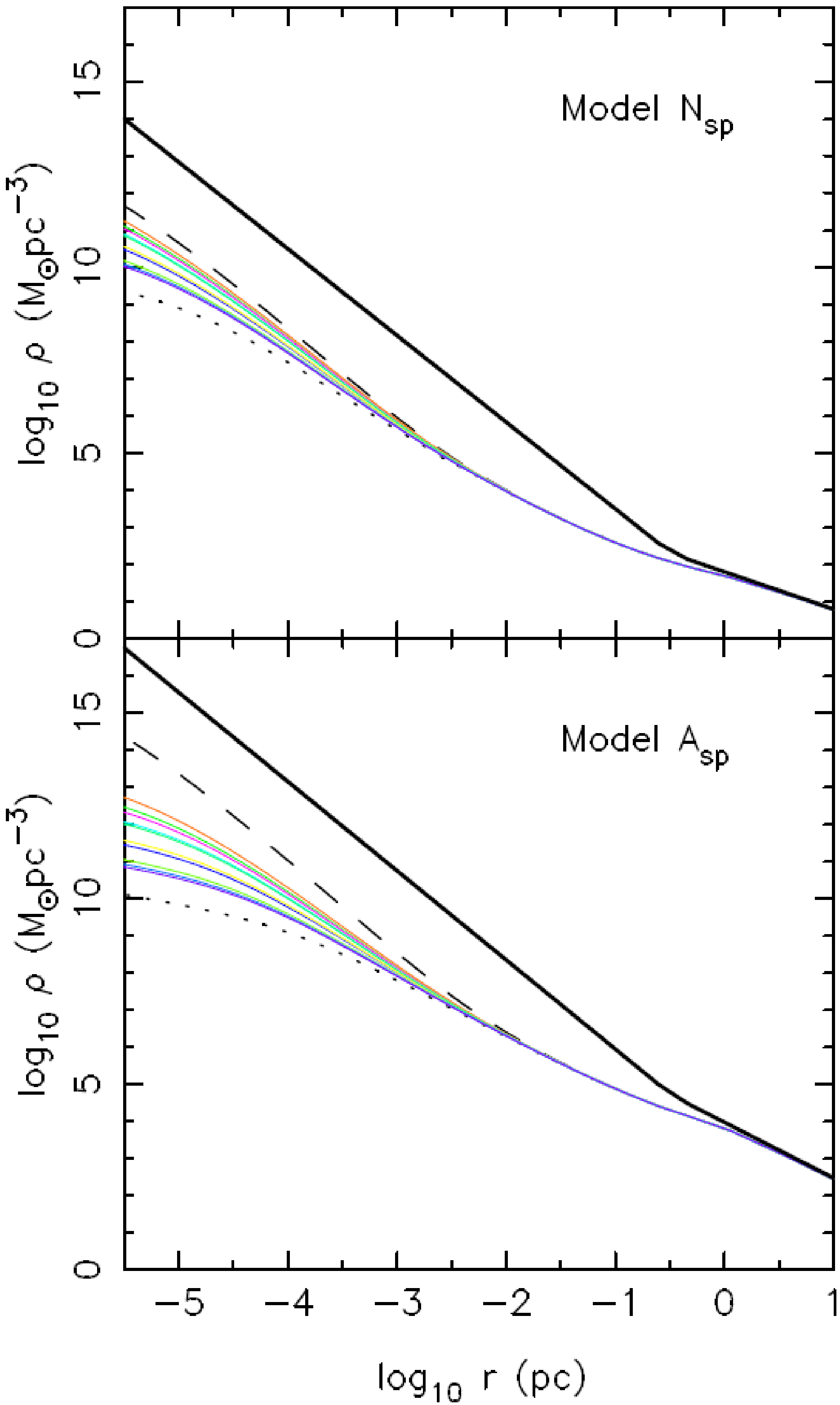




Protostars in the Orion Nebula (infrared image from Spitzer telescope)

Detailed dark matter simulation. Dark matter concentrated in core of halo

(Via Lactea simulation, Diemand et al 2005)



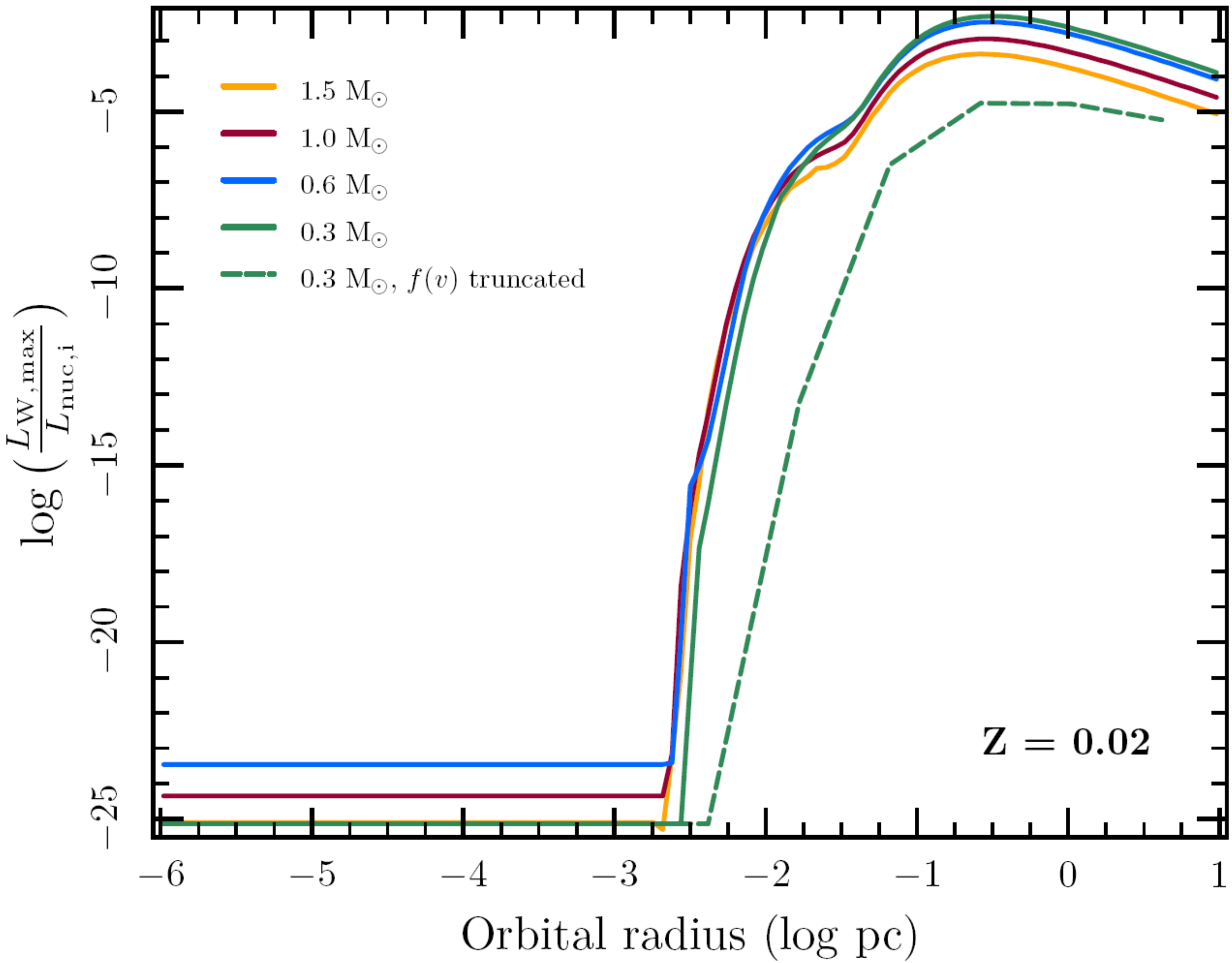
Most Optimistic Respectable Scenario

Bertone and Merritt 2005

Note 10^{10} $M_\odot$ pc^{-3} ~10^{11} GeV cm^{-3}

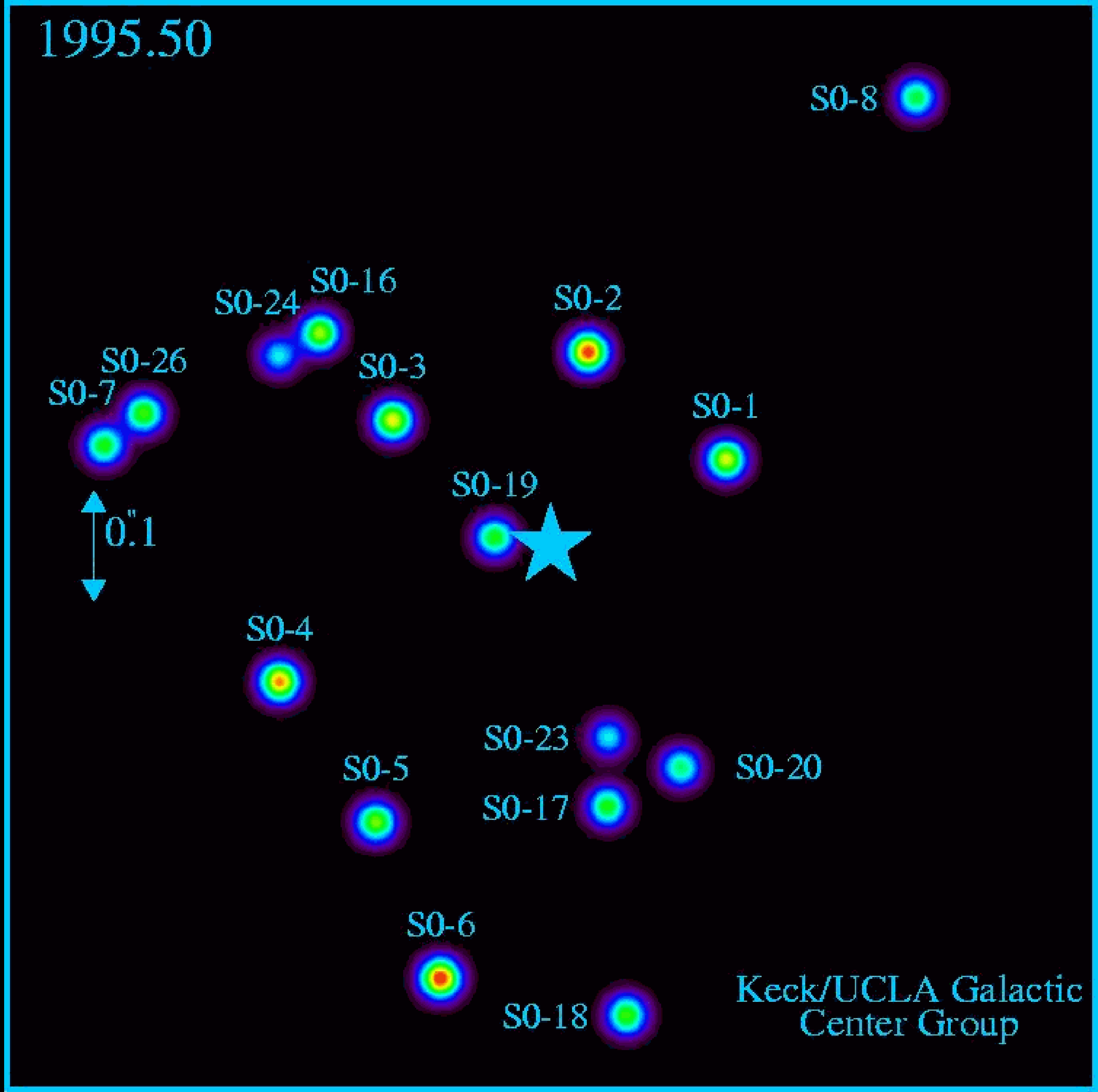
Solar system density ~ 0.3 GeV cm $^{-3}$

Not enough dark matter at Galactic Center?

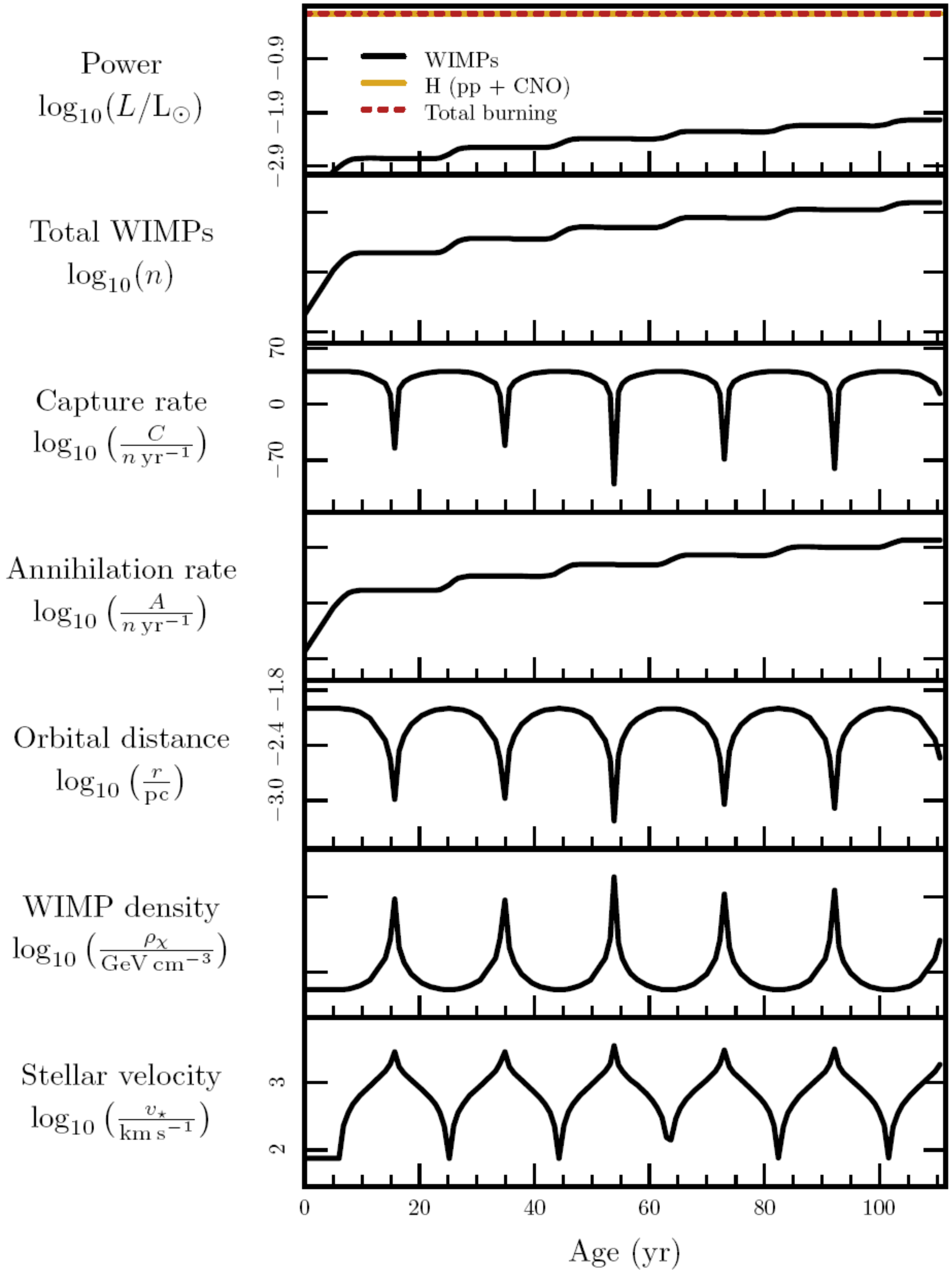


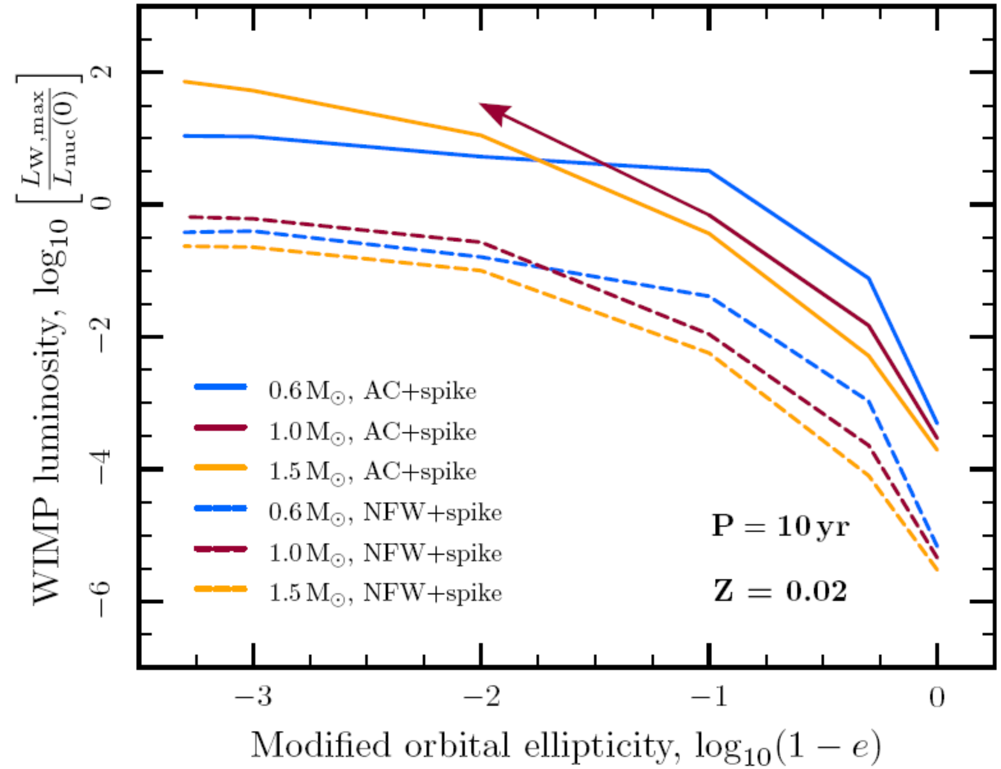
Closest approach of
SO-16 is
0.0002 pc
=45 AU
=600 Rsch

0.04 pc

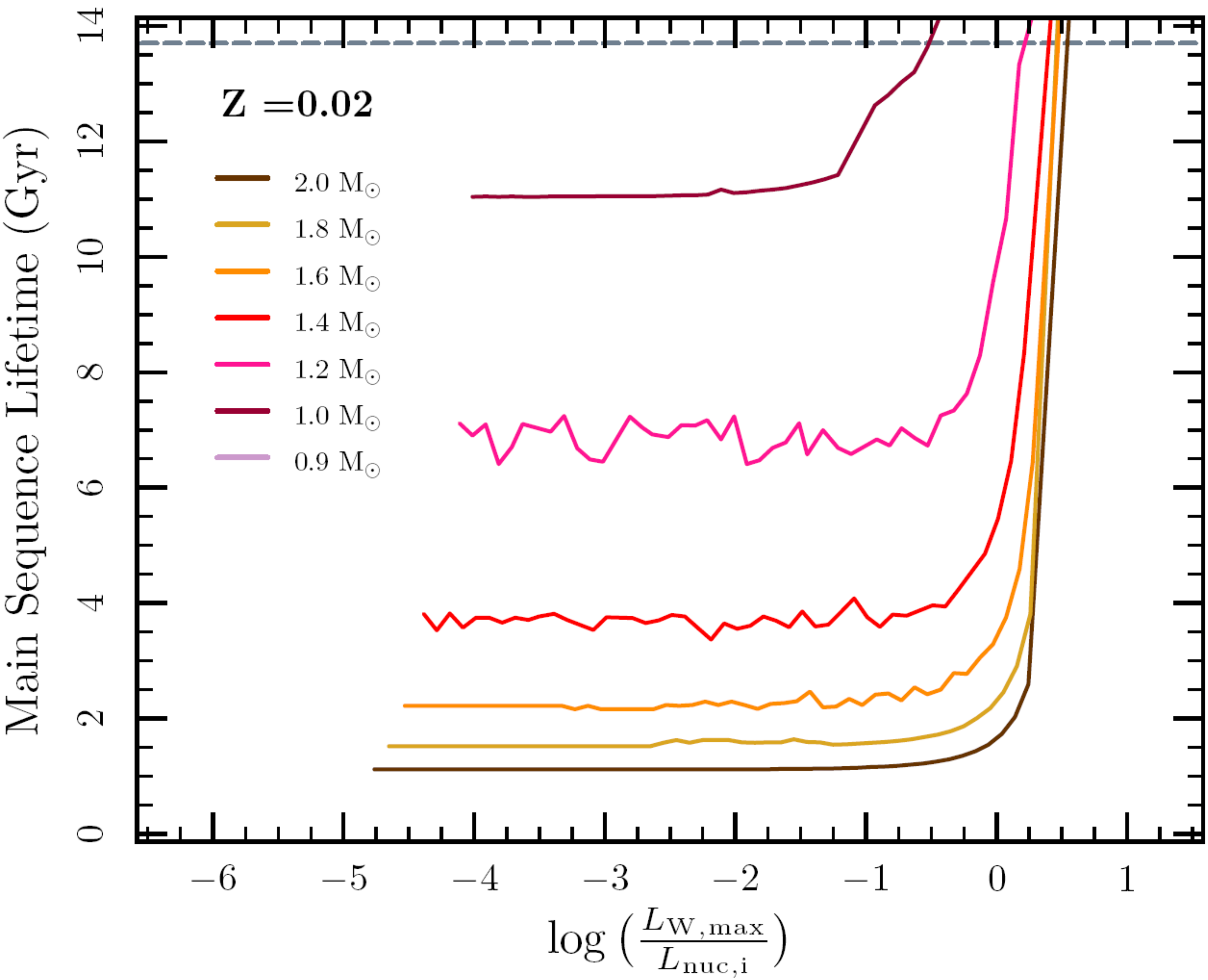


Capture rates for elliptical orbits



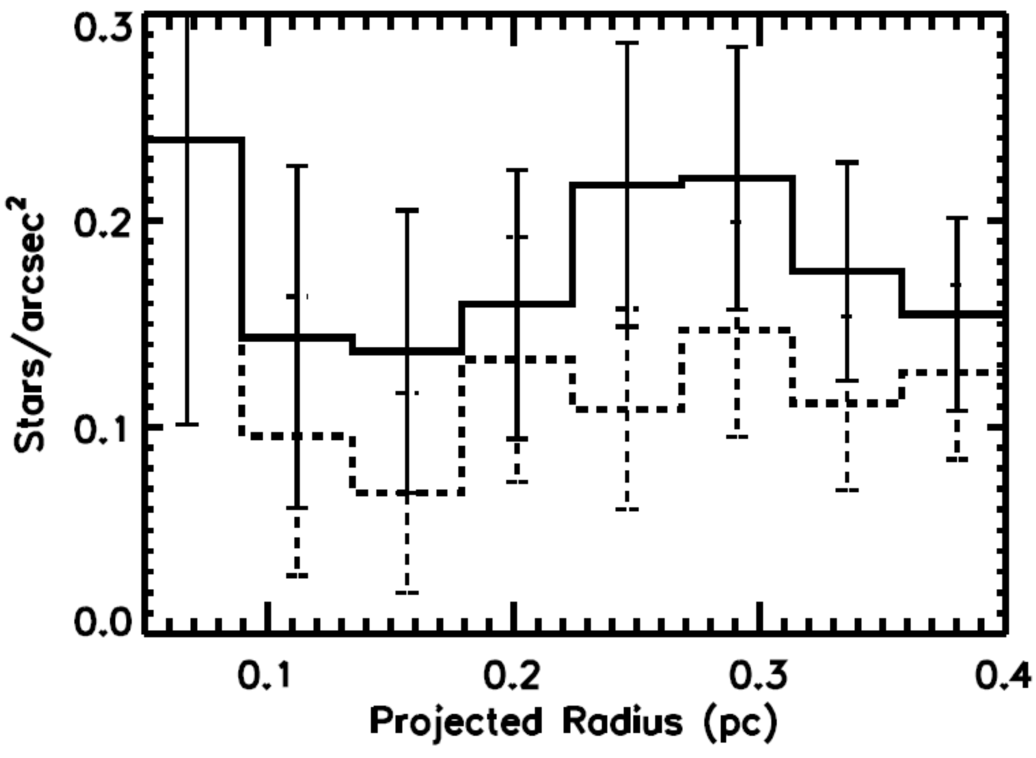


Main Sequence Lifetime of WIMP burners

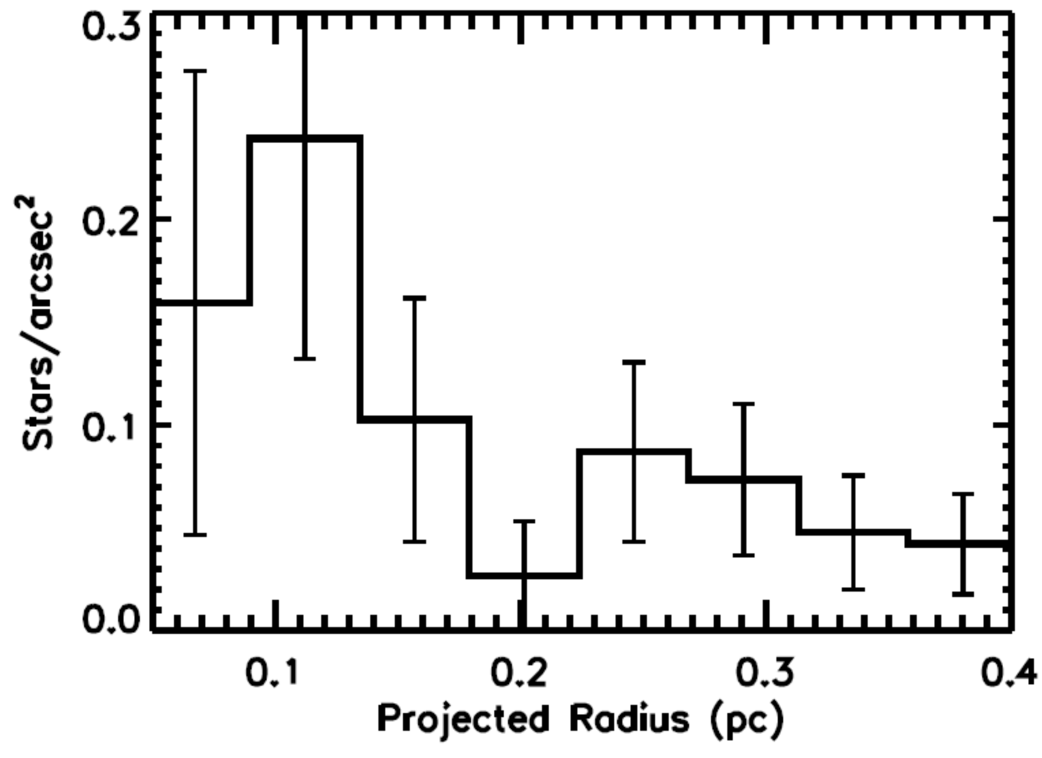


Probably can't explain 'Paradox of Youth'

Late type stars



Early type stars
(which shouldn't be there)



Zhu, Kudritzki, Figer, Francisco, Najarro and Merritt (2008)

Seems difficult to explain using WIMP burning stars

Cuspy No More: How Outflows Affect the Central Dark Matter and Baryon Distribution in ΛCDM Galaxies.

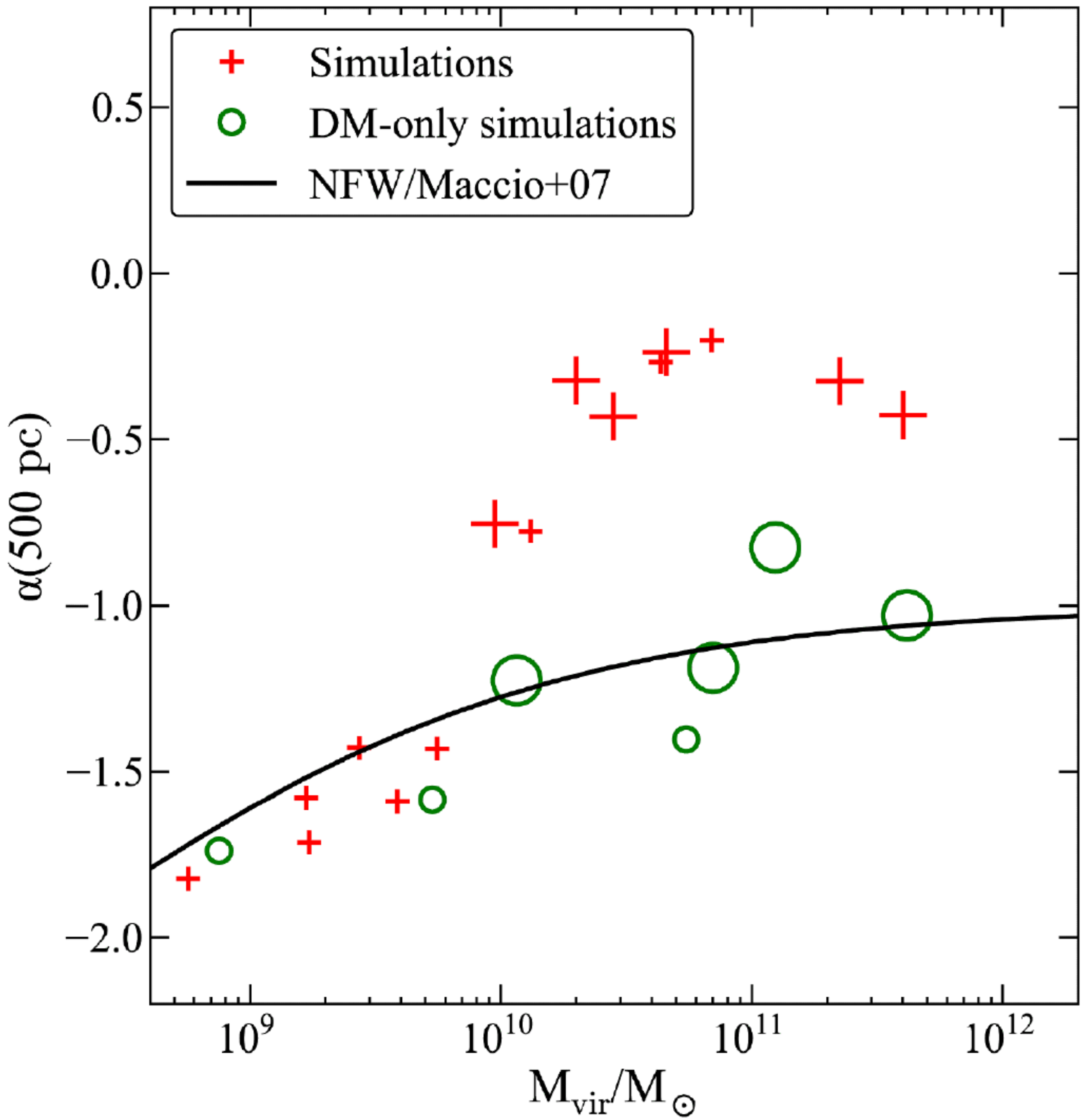
GENERAL NEW PROBLEM FOR INDIRECT SEARCHES?

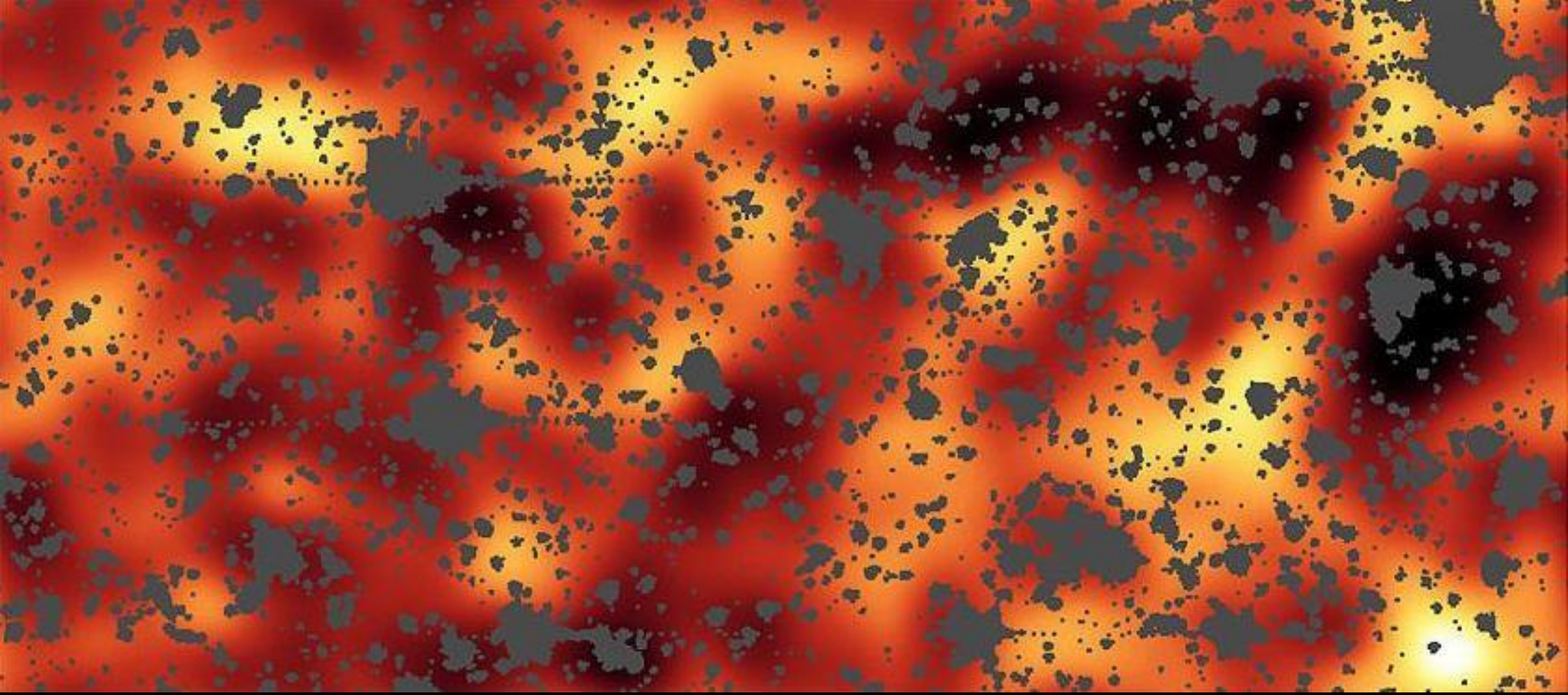
F.Governato[1⋆] A.Zolotov[2], A.Pontzen[3], C.Christensen[4], S.H.Oh[5,6], A. M.Brooks[7], T.Quinn[1], S.Shen[8], J.Wadsley[9]

$$\rho \propto r^{\alpha}$$

Repeated baryonic contraction and shocking reduces central density of dark matter.

If correct, bad for indirect detection signals.
arXiv:1202.0554



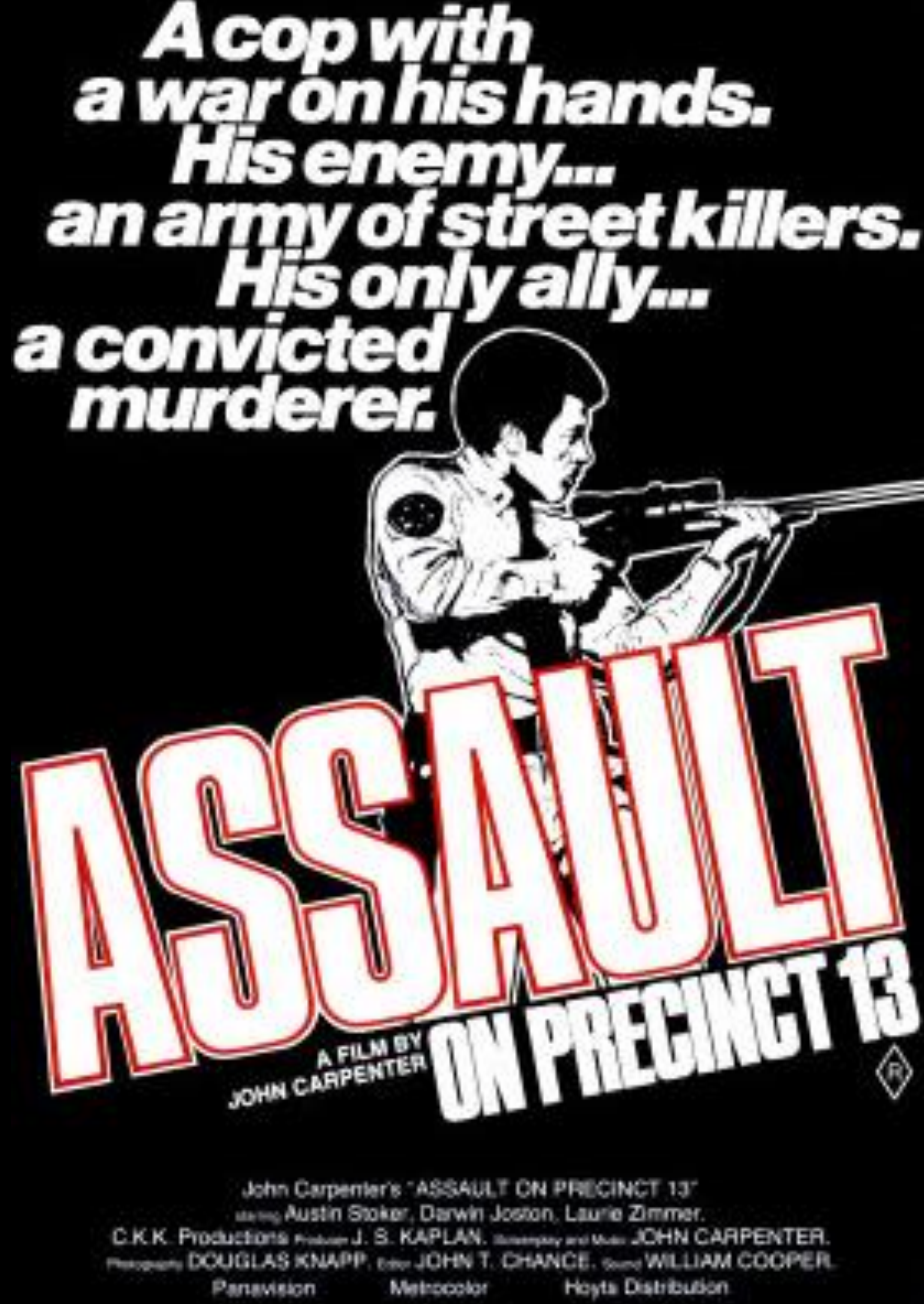


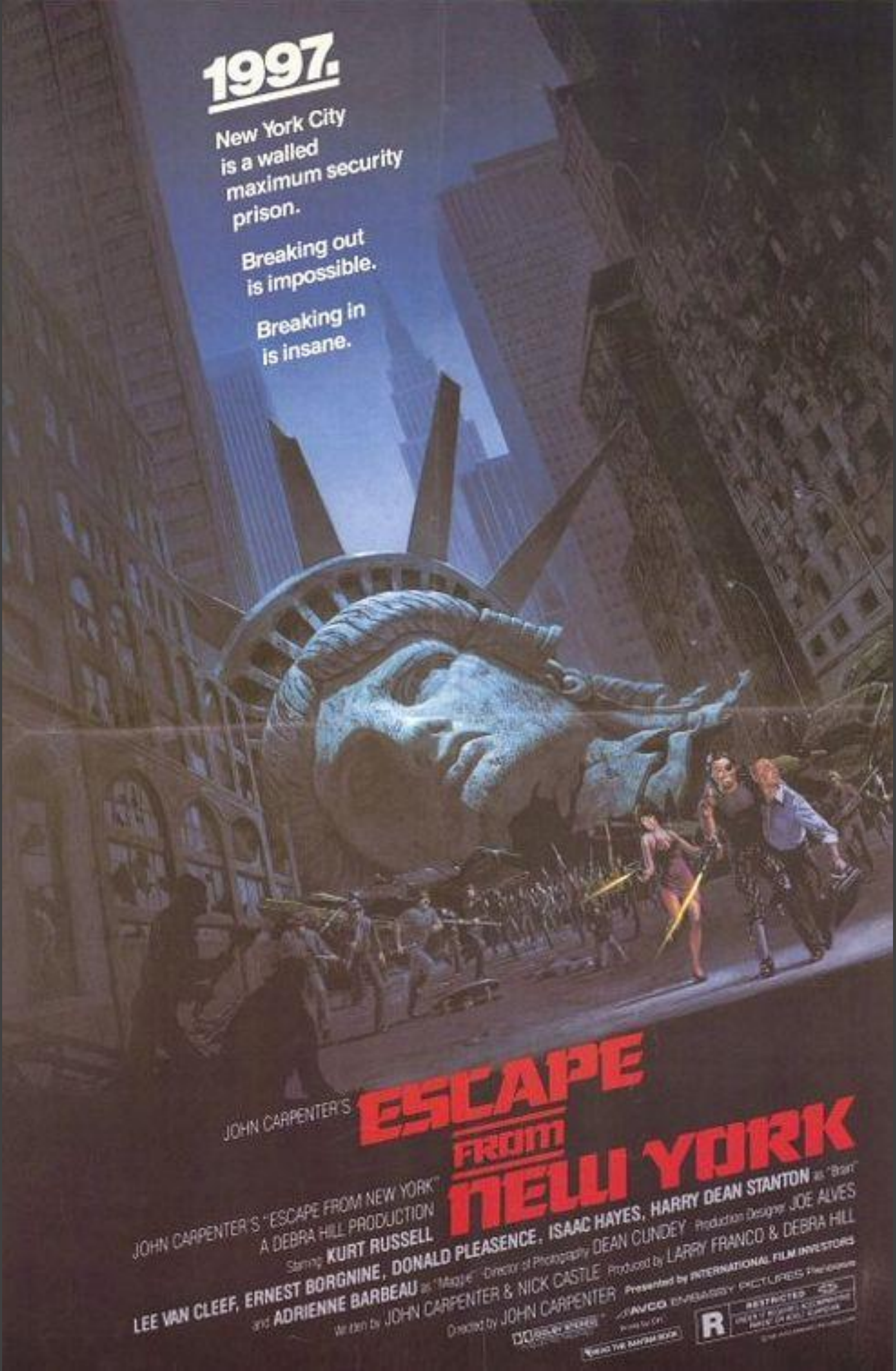
Population III stars viewed by Spitzer (probably, anyway)

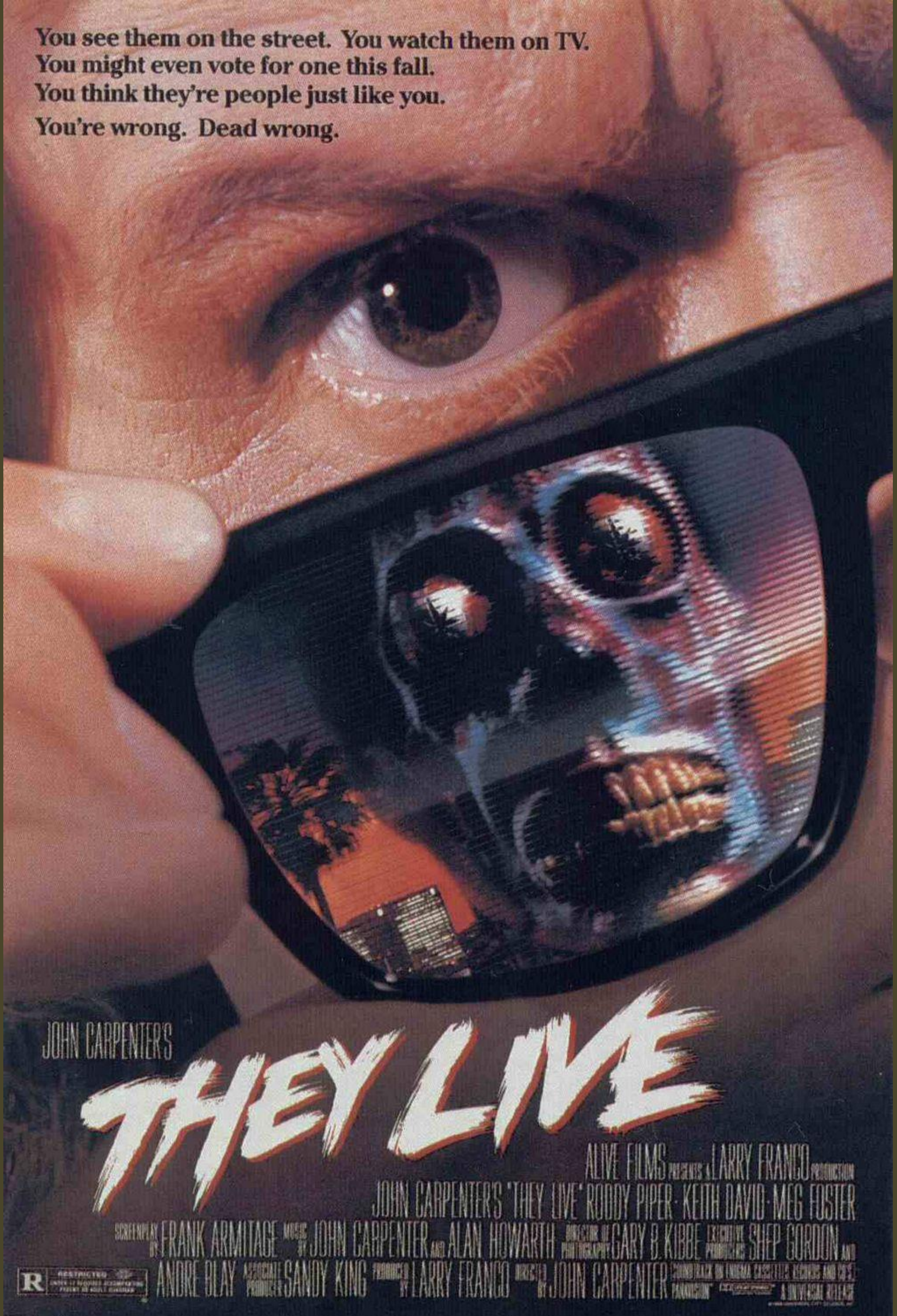
First stars to form at beginning of universe z~20 , 100 million yrs after big bang.

masses 10-100 M_{SUN}?

Dark matter much denser then - could play huge role in the lives of these stars...


A cop with
a war on his hands.
His enemy...
an army of street killers.
His only ally...
a convicted
murderer.
ASSAULT
ON PRECINCT 13
A FILM BY
JOHN CARPENTER
R
John Carpenter's "ASSAULT ON PRECINCT 13"
Austin Stoker, Darwin Joston, Laurie Zimmer.
C.K.K. Productions J. S. KAPLAN. JOHN CARPENTER.
DOUGLAS KNAPP. JOHN T. CHANCE. WILLIAM COOPER.
Panavision
Metrocolor
Hoyts Distribution

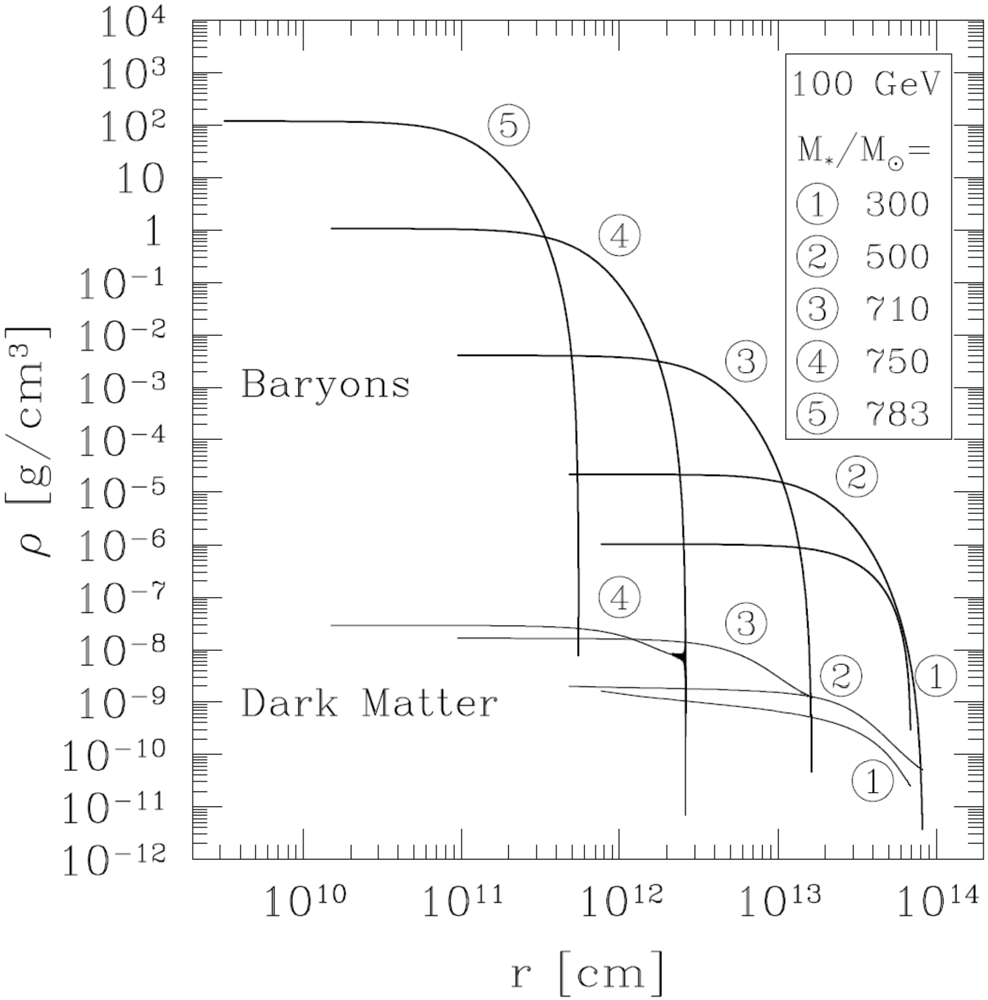

1997.
New York City is a walled maximum security prison.
Breaking out is impossible.
Breaking in is insane.
JOHN CARPENTER'S
ESCAPE FROM NEW YORK
JOHN CARPENTER'S "ESCAPE FROM NEW YORK"
A DEBRA HILL PRODUCTION
Starring KURT RUSSELL
LEE VAN CLEEF, ERNEST BORGNINE, DONALD PLEASENCE, ISAAC HAYES, HARRY DEAN STANTON as "Brain"
and ADRIENNE BARBEAU as "Maggie"
Director of Photography DEAN CUNDEY Production Designer JOE ALVES
Written by JOHN CARPENTER & NICK CASTLE
Produced by LARRY FRANCO & DEBRA HILL
Directed by JOHN CARPENTER
Presented by INTERNATIONAL FILM INVESTORS
AVCO EMBASSY PICTURES
R
RESTRICTED

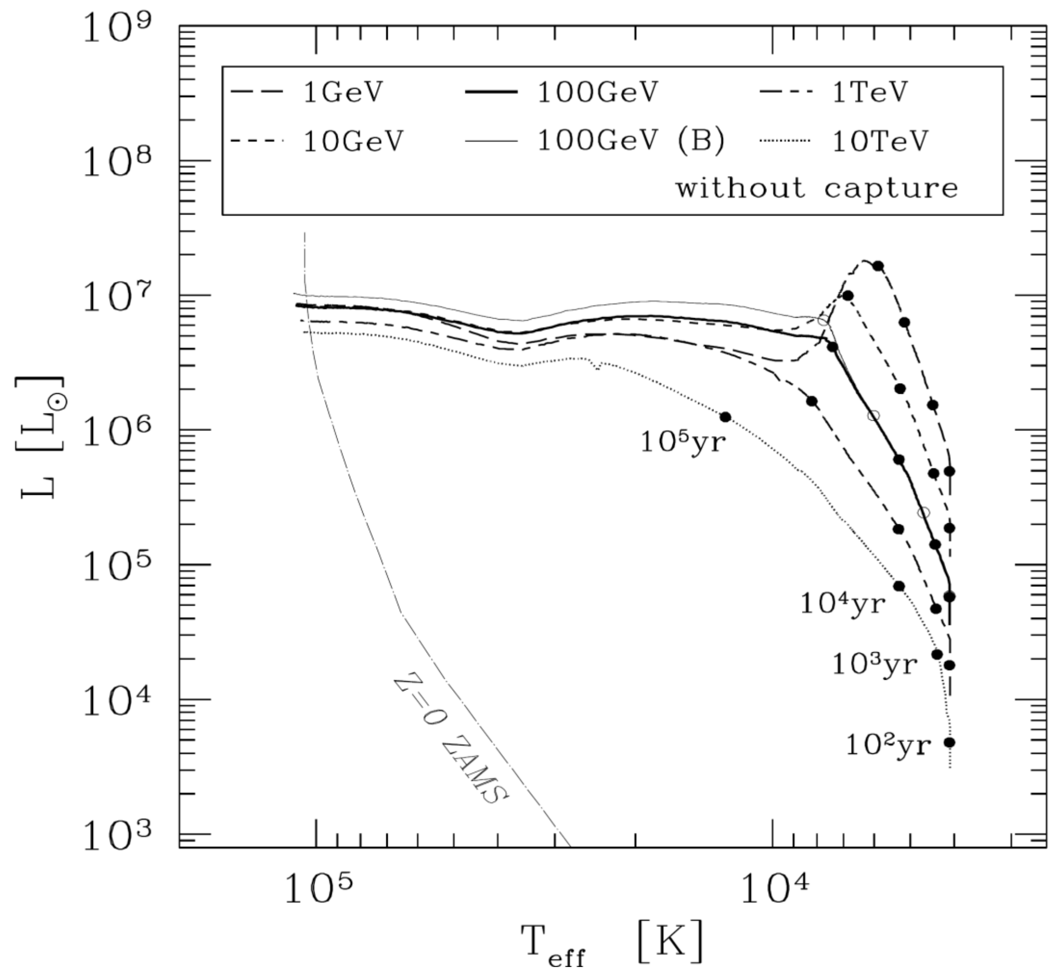

You see them on the street. You watch them on TV.
You might even vote for one this fall.
You think they're people just like you.
You're wrong. Dead wrong.
JOHN CARPENTER'S
THEY LIVE
ALIVE FILMS PRESENTS A LARRY FRANCO PRODUCTION
JOHN CARPENTER'S "THEY LIVE" RODDY PIPER · KEITH DAVID · MEG FOSTER
SCREENPLAY BY FRANK ARMITAGE MUSIC BY JOHN CARPENTER AND ALAN HOWARTH DIRECTOR OF PHOTOGRAPHY GARY B. KIBBE EXECUTIVE PRODUCERS SHEP GORDON AND
ANDRE BLAY ASSOCIATE PRODUCER SANDY KING PRODUCED BY LARRY FRANCO DIRECTED BY JOHN CARPENTER
R RESTRICTED
A UNIVERSAL RELEASE


DAVID GRANT presents
A JOHN CARPENTER film
From
ALAN DEAN FOSTER
FIRST
2001: A SPACE ODYSSEY
THEN
THE POSEIDON ADVENTURE
NOW
DARK STAR
A
DS-1
BOMB No 20
bombed out in space
with a spaced out bomb!
CHANTRELL
An OPPIDAN ENTERTAINMENTS Release of a JACK H. HARRIS Production · Starring DAN O'BANNON and BRIAN NARELLE · Produced & directed by JOHN CARPENTER

Dark Stars

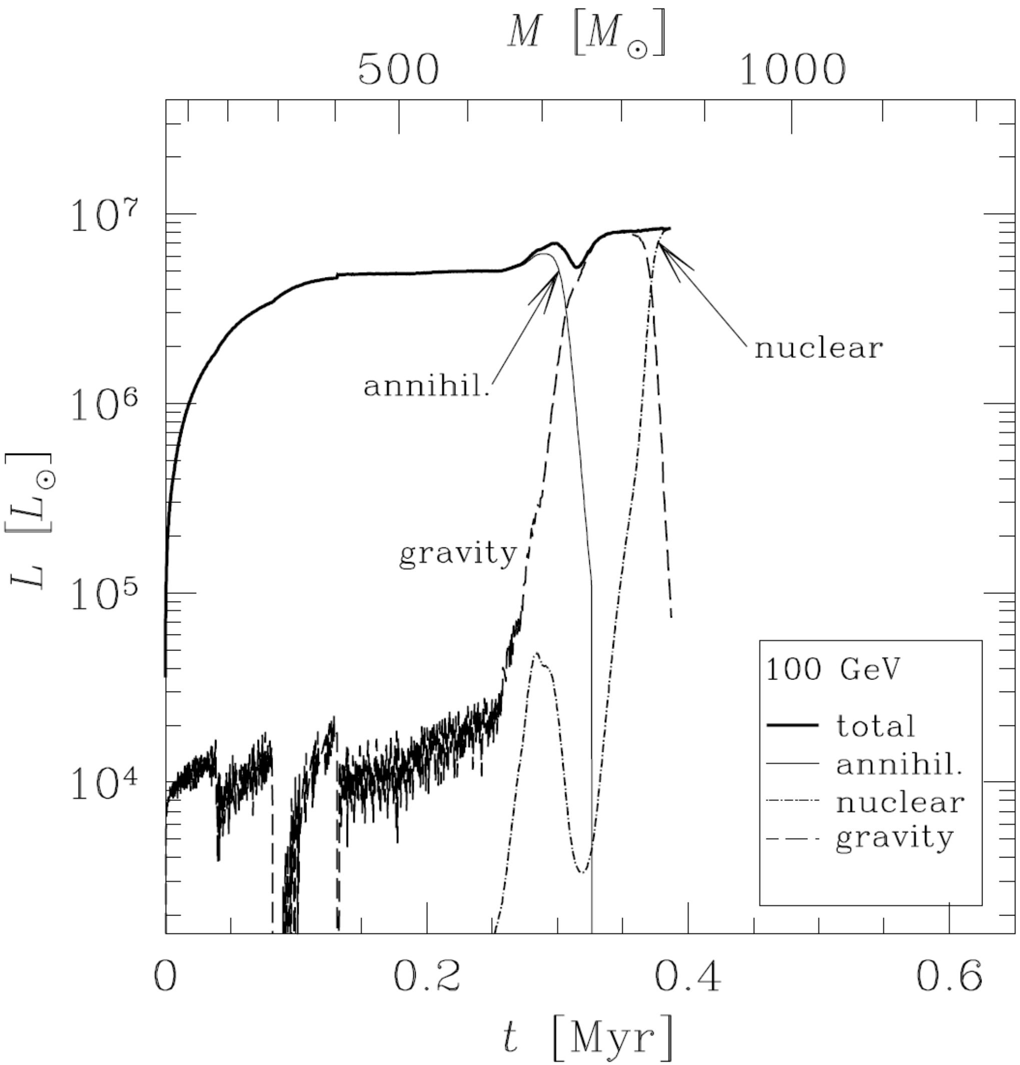
Spolyar, Freese and Gondolo 2008

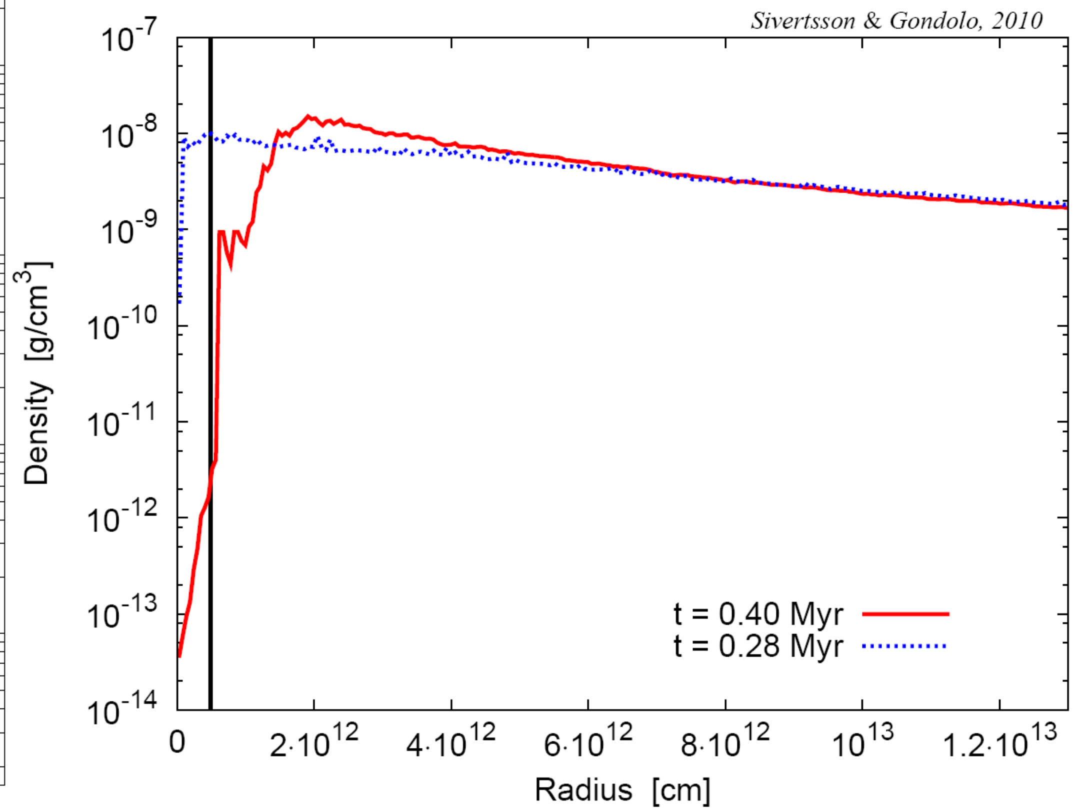




Spolyar et al arXiv:0903.3070

Exhaustion of WIMP fuel in Dark Stars





Spolyar et al arXiv:0903.3070

Sivertsson and Gondolo
arXiv:1006.0025

Dark Stars

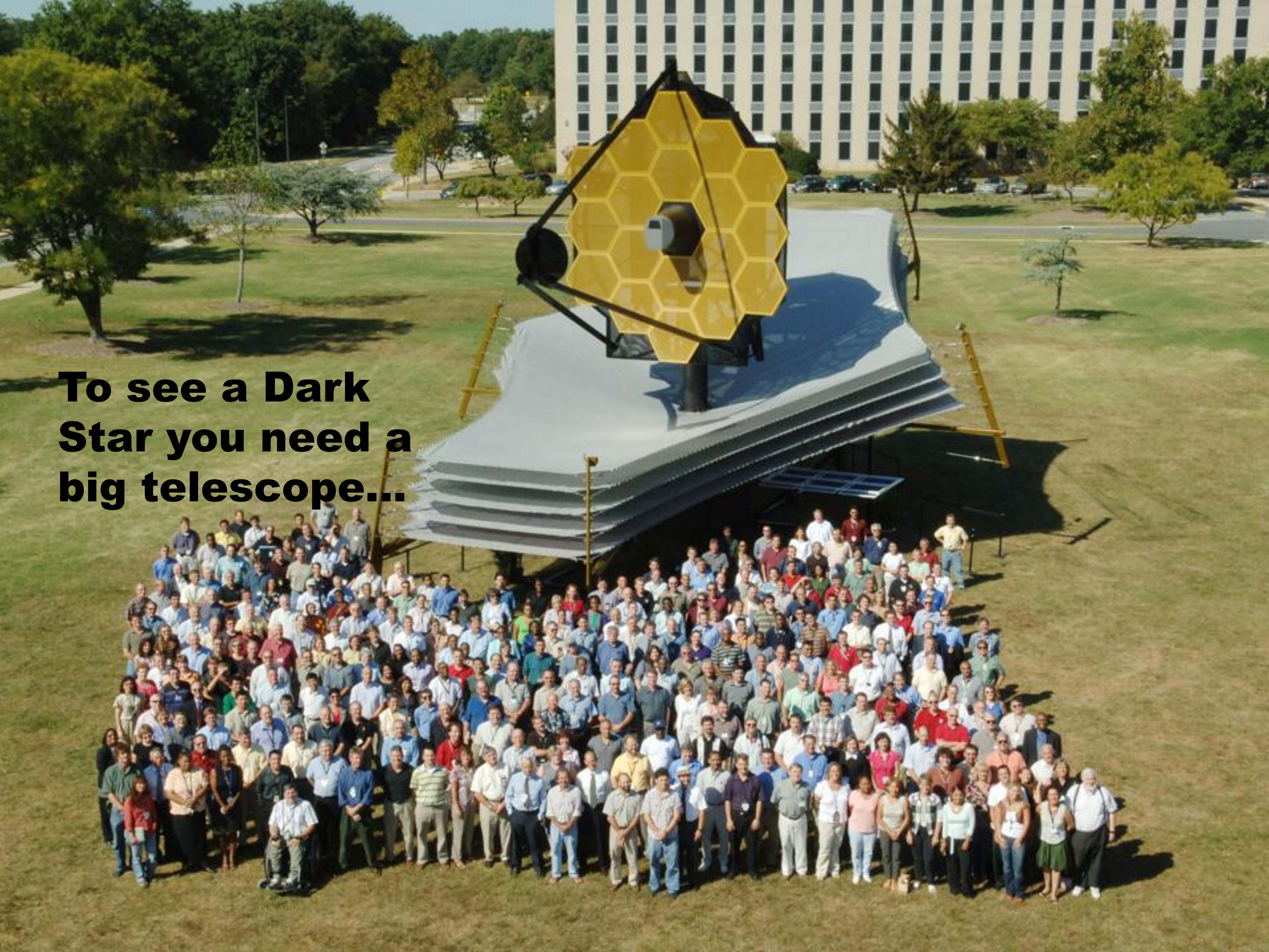
Implications:-

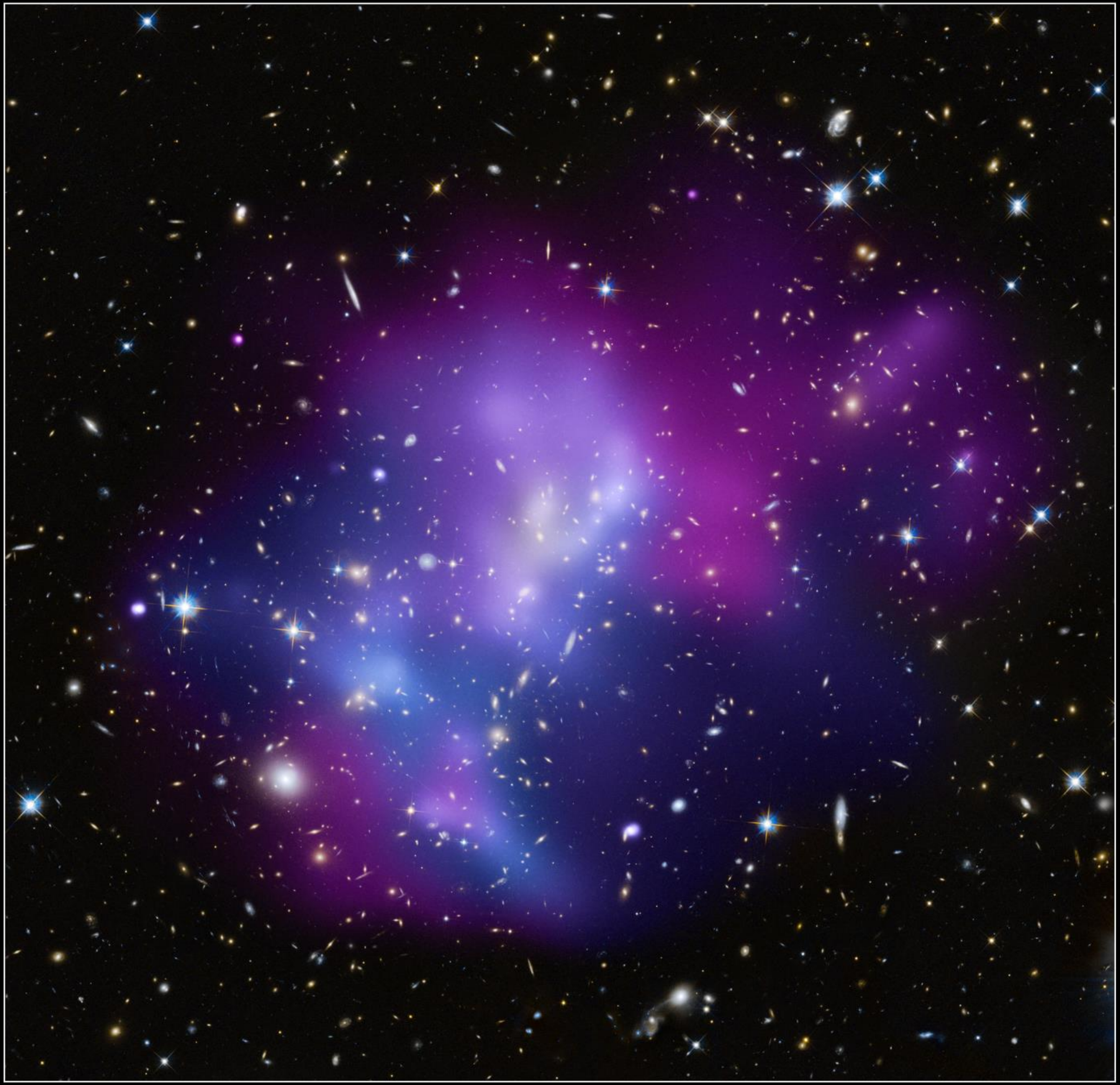
1. Population III stars grow much larger

2. Such large stars may be observable

3. Will leave larger black holes behind

4. Change chemical evolution of Universe


To see a Dark Star you need a big telescope...

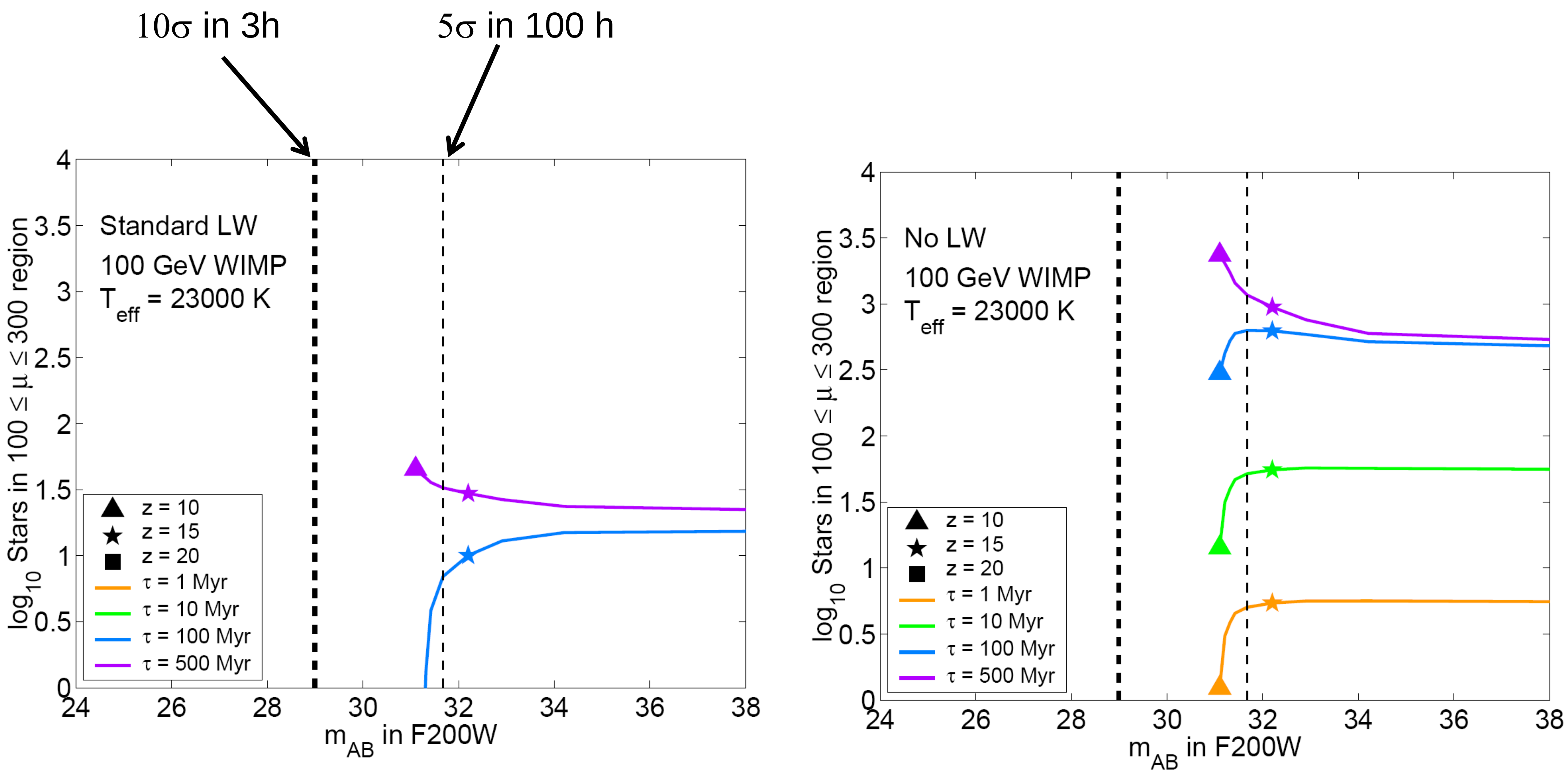


Galaxy Cluster MACS J0717.5+3745
Hubble Space Telescope ▪ ACS/WFC
Chandra X-ray Observatory ▪ ACIS

NASA, ESA, CXC, C. Ma (University of Hawaii), and STScI STScI-PRC09-17

...and a big gravitational lens

Detectability of Dark Stars



Detectability with JWST when lensed through J0717.5+3745
Zackrisson arXiv:1002.3368

Accretion onto Compact Objects

$$\Gamma_c = \left(\frac{8}{3\pi}\right)^{1/2} \frac{\rho_{dm}\bar{v}}{m_{dm}} \left(\frac{3v_{esc}^2}{2\bar{v}^2}\right) \sigma_{eff}$$

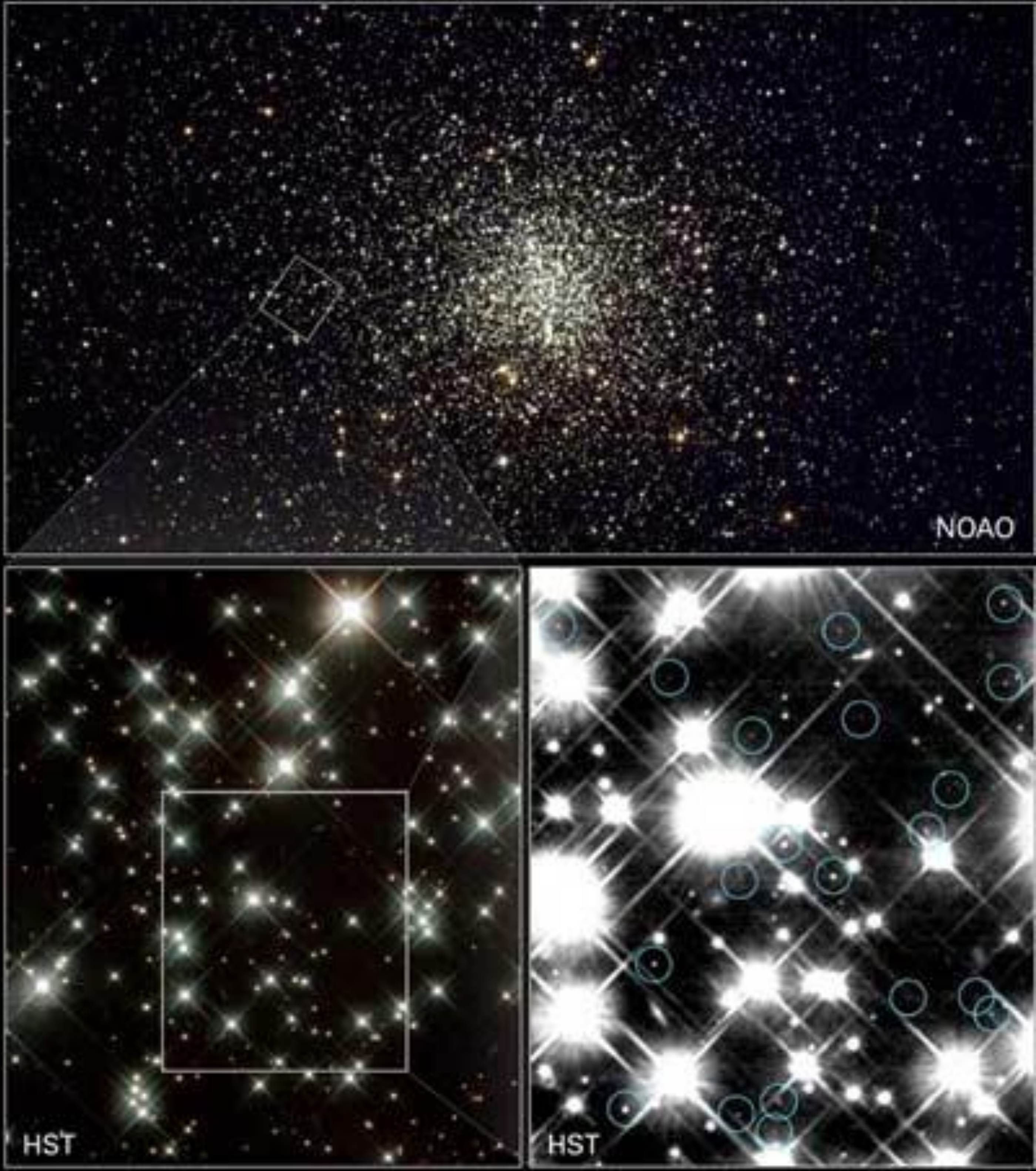
What about increasing escape velocity?

White dwarves - high escape velocity 

- born hot 

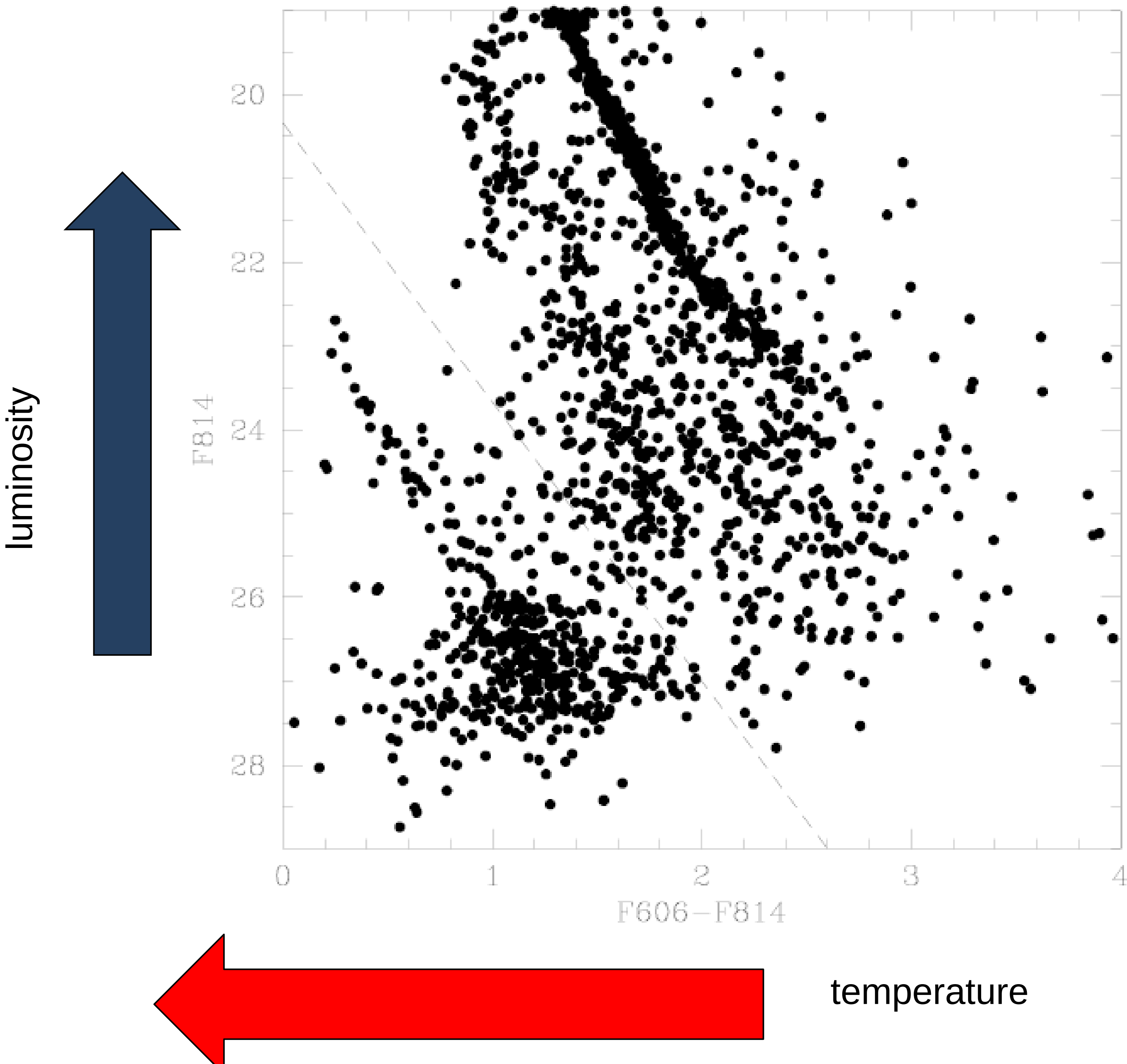
NEED TO FIND SOME OLD ONES

White Dwarves in Globular Cluster M4

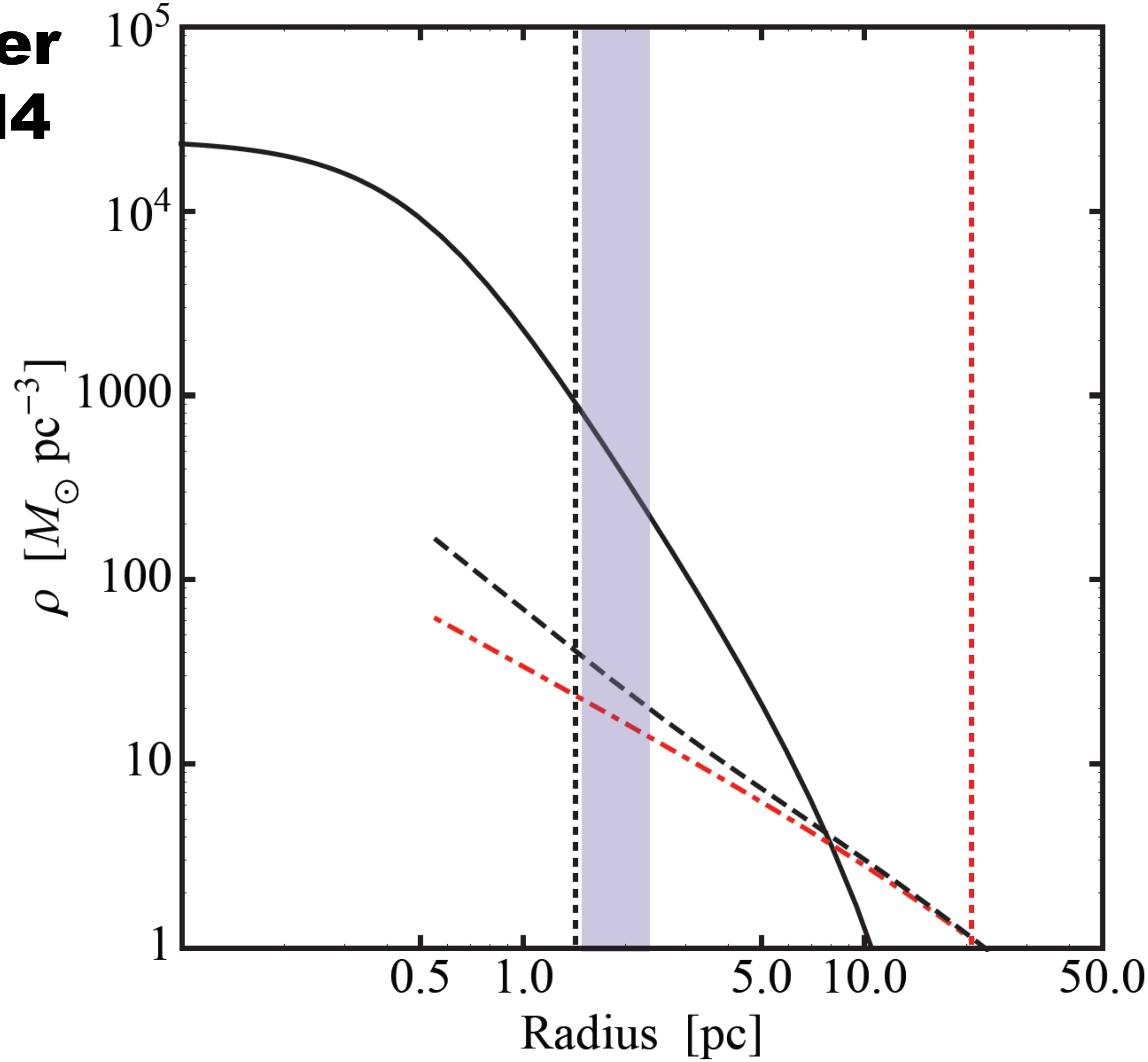


Richer et al. 2004

Bottom of HR diagram in Globular Cluster M4



Density of dark matter in globular cluster M4



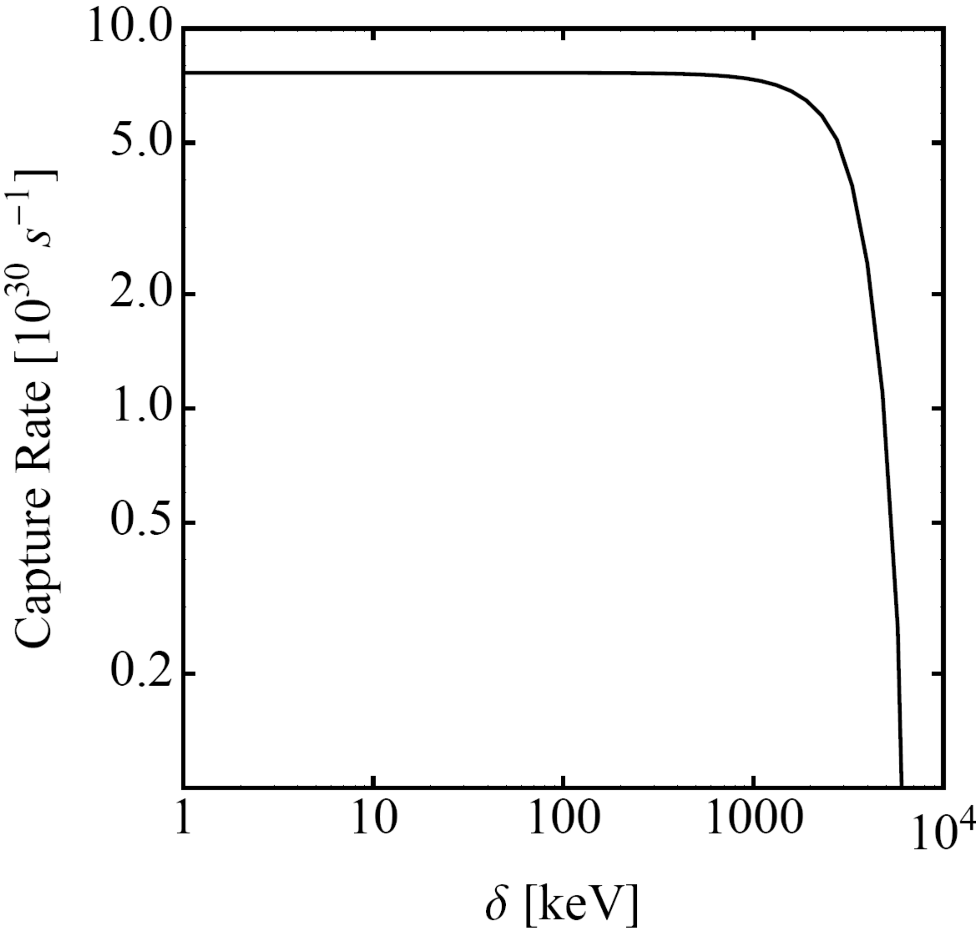
Bertone and Fairbairn
arXiv:0709.1485
McCullough and Fairbairn
arXiv:1001.2737

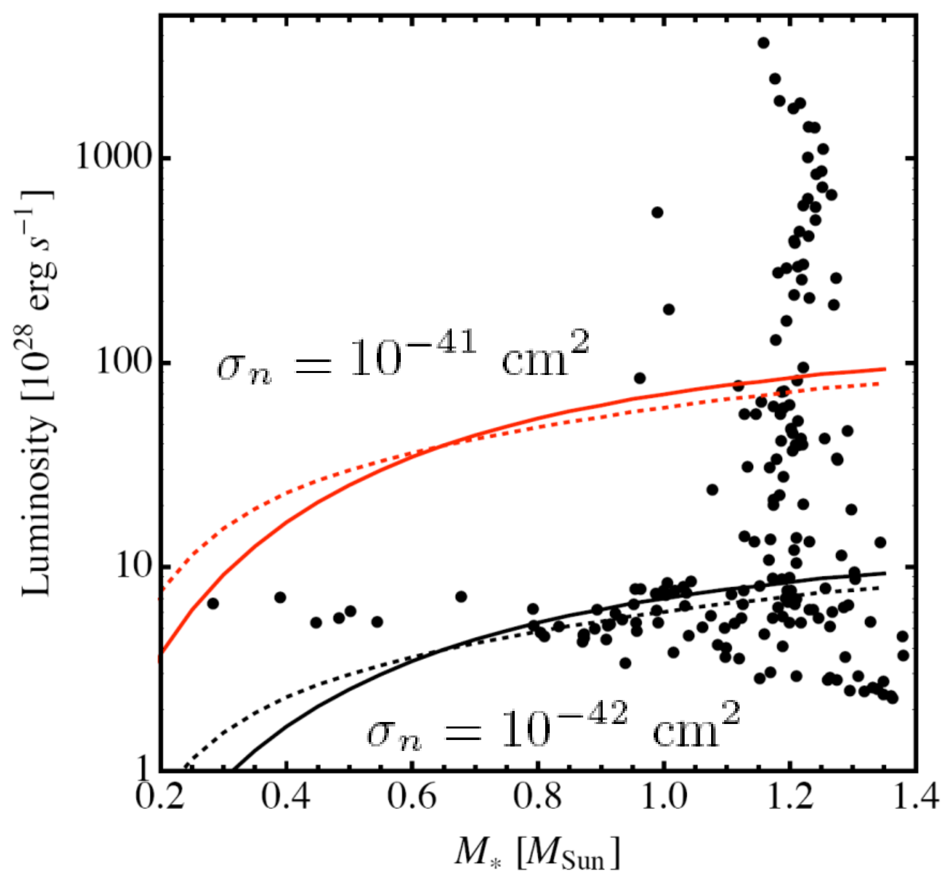
Heating timescale of dark matter via gravitational interactions with stars

$$T_{heat} \equiv \left| \frac{1}{\epsilon} \frac{d\epsilon}{dt} \right|^{-1} = \frac{0.814 v_{rms}^3}{G^2 m_* \rho_* \ln \Lambda}$$

Constraints on Dark Matter (Elastic and Inelastic) through accretion onto WDs

SEE ALSO Hooper et al **arXiv:1002.0005**



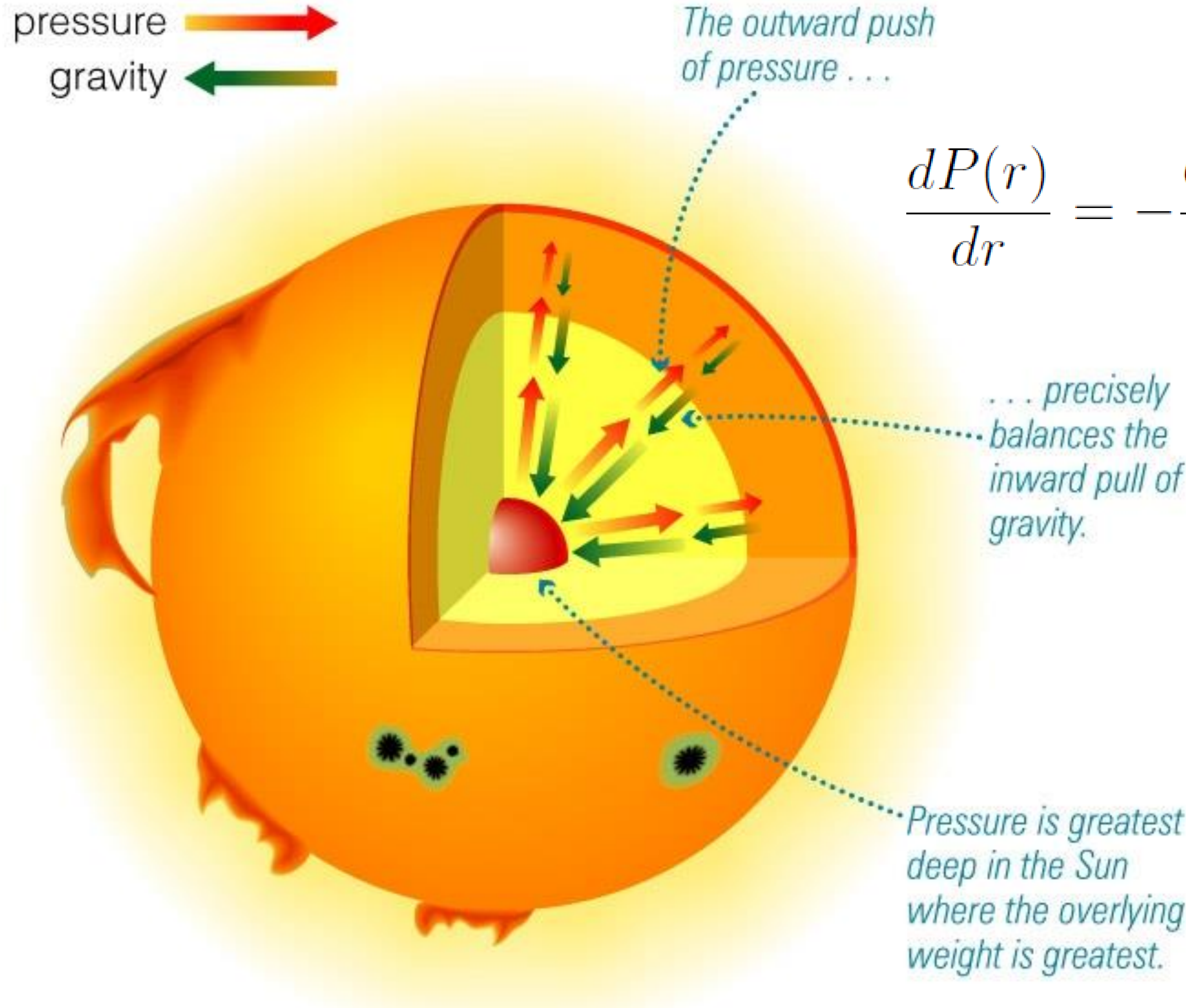


High escape velocity means no effect for
Splittings used to explain DAMA result

McCullough and Fairbairn
arXiv:1001.2737

Effect of GR on stars

$$\frac{dP(r)}{dr} = -\frac{GM(r)\rho(r)}{r^2}$$



Equation of hydrostatic equilibrium

Newtonian Version

1. Doesn't include gravitational effect of pressure.
2. Doesn't include space-time curvature.

$$\frac{dP(r)}{dr} = -\frac{GM(r)\rho(r)}{r^2}$$

Pressure in star gravitates

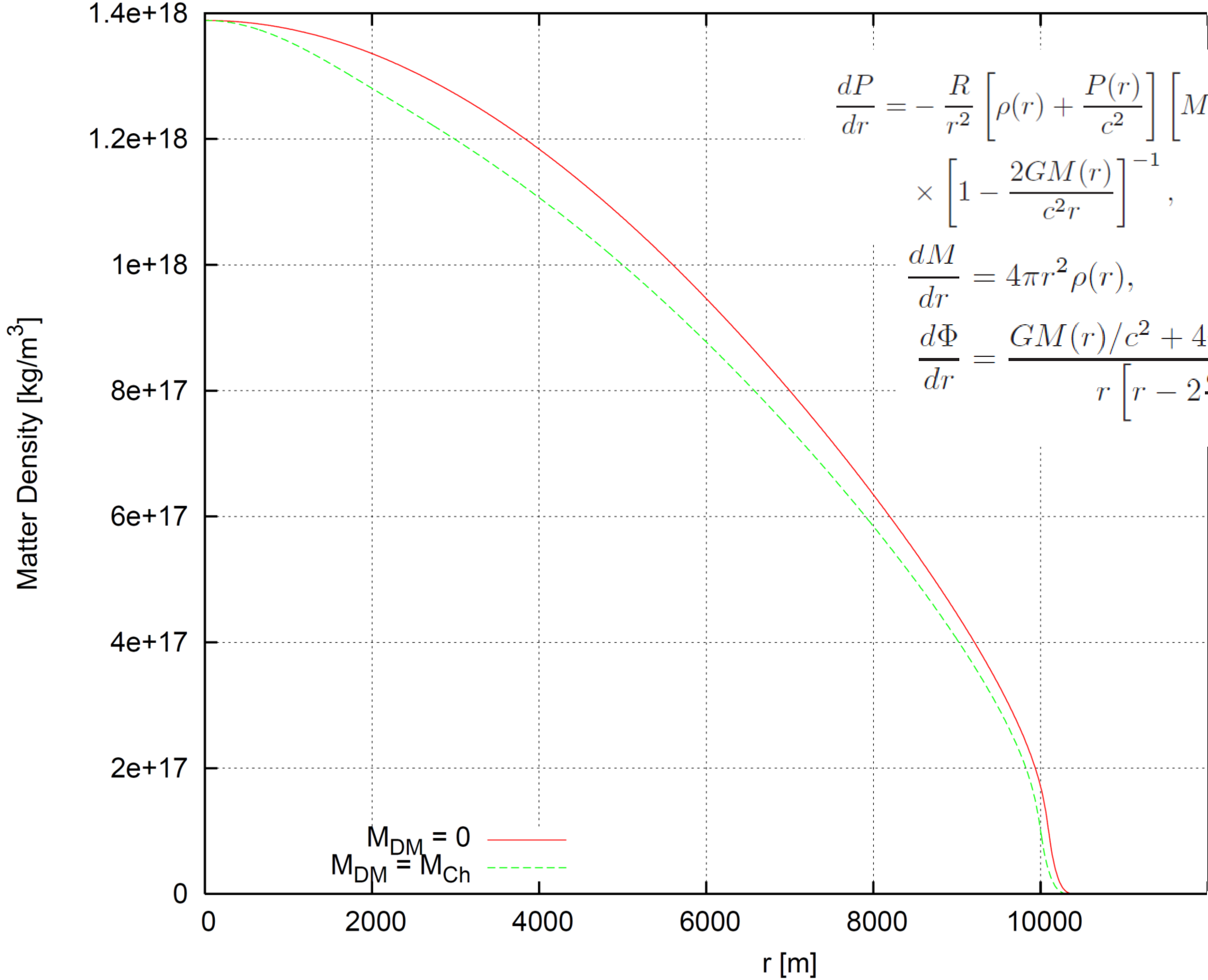
Pressure in shell gravitates

$$\frac{dP(r)}{dr} = -\frac{G\left[M(r) + \boxed{4\pi r^3 \frac{P(r)}{c^2}}\right]\left[\rho(r) + \boxed{\frac{P(r)}{c^2}}\right]}{r^2\left[\boxed{1 - \frac{2GM(r)}{c^2 r}}\right]}$$

Space-time is curved...

Oppenheimer-Volkoff Equation

Presence of Dark Matter changes structure of Neutron Stars.

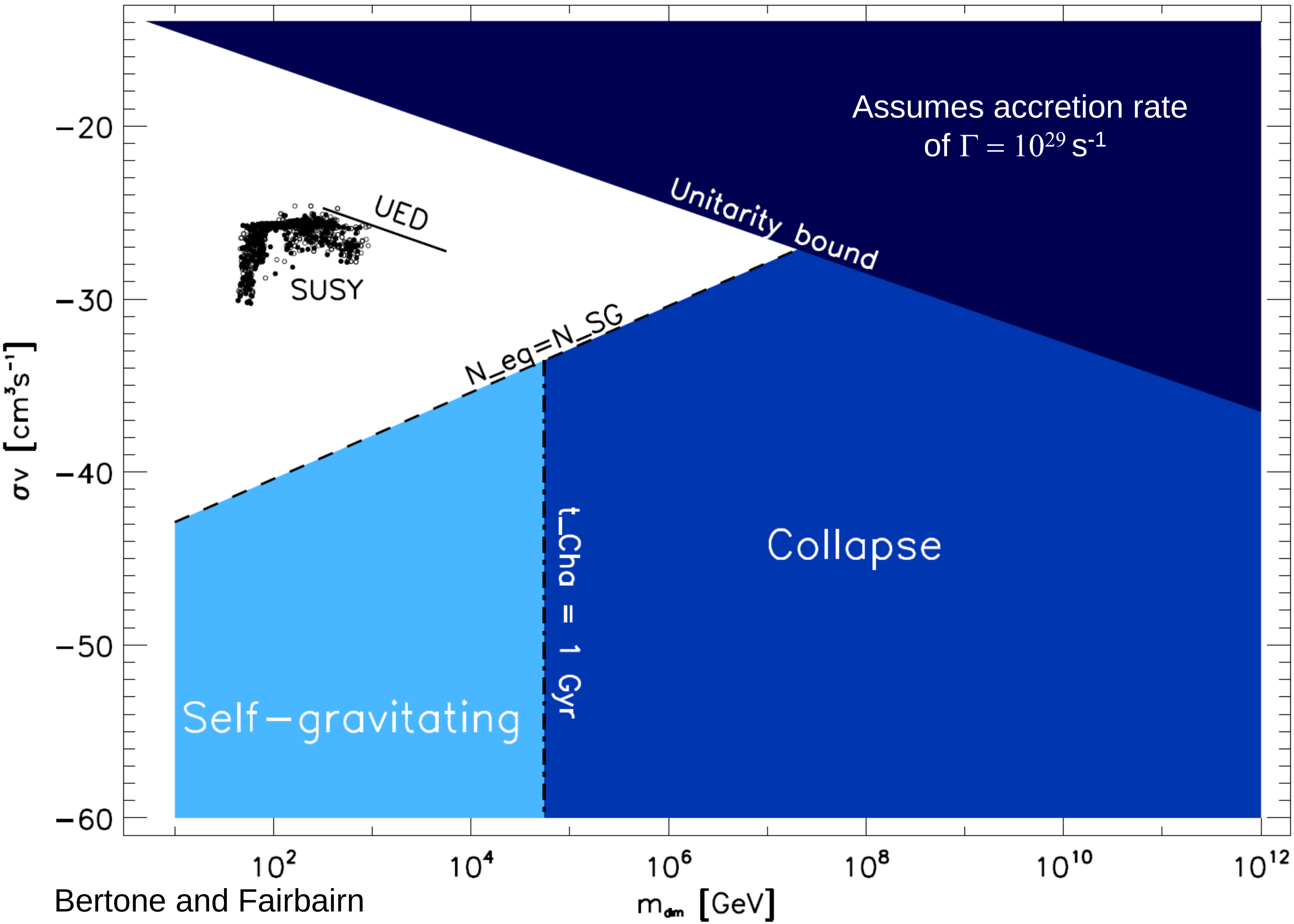


$$\frac{dP}{dr} = -\frac{R}{r^2}\left[\rho(r) + \frac{P(r)}{c^2}\right]\left[M(r) + 4\pi r^3 \frac{P(r)}{c^2}\right] \times \left[1 - \frac{2GM(r)}{c^2 r}\right]^{-1},$$

$$\frac{dM}{dr} = 4\pi r^2 \rho(r),$$

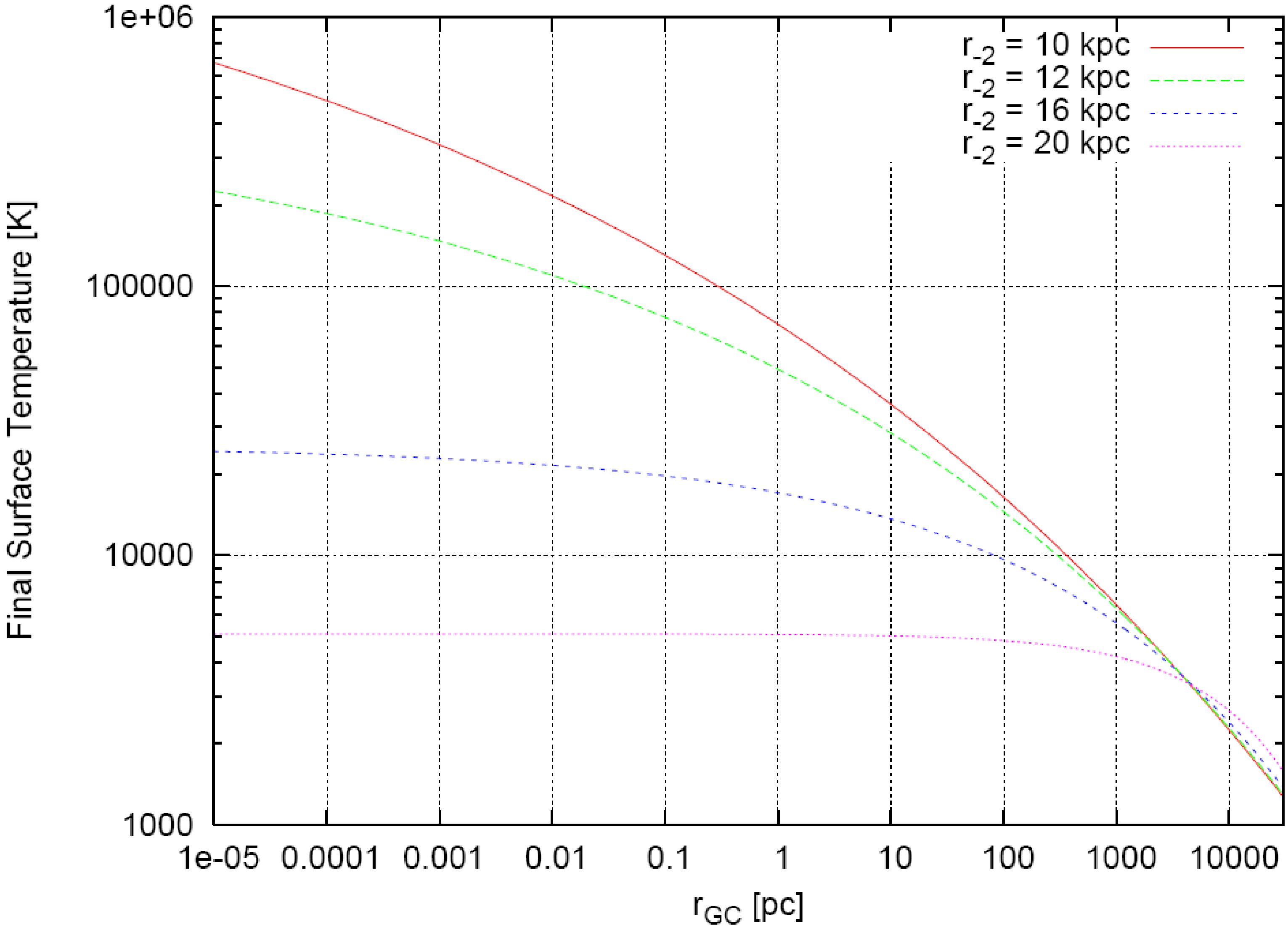
$$\frac{d\Phi}{dr} = \frac{GM(r)/c^2 + 4\pi G r^3 P(r)/c^4}{r\left[r - 2\frac{GM(r)}{c^2}\right]}$$

Interesting fates for neutron stars with Non-WIMP dark matter

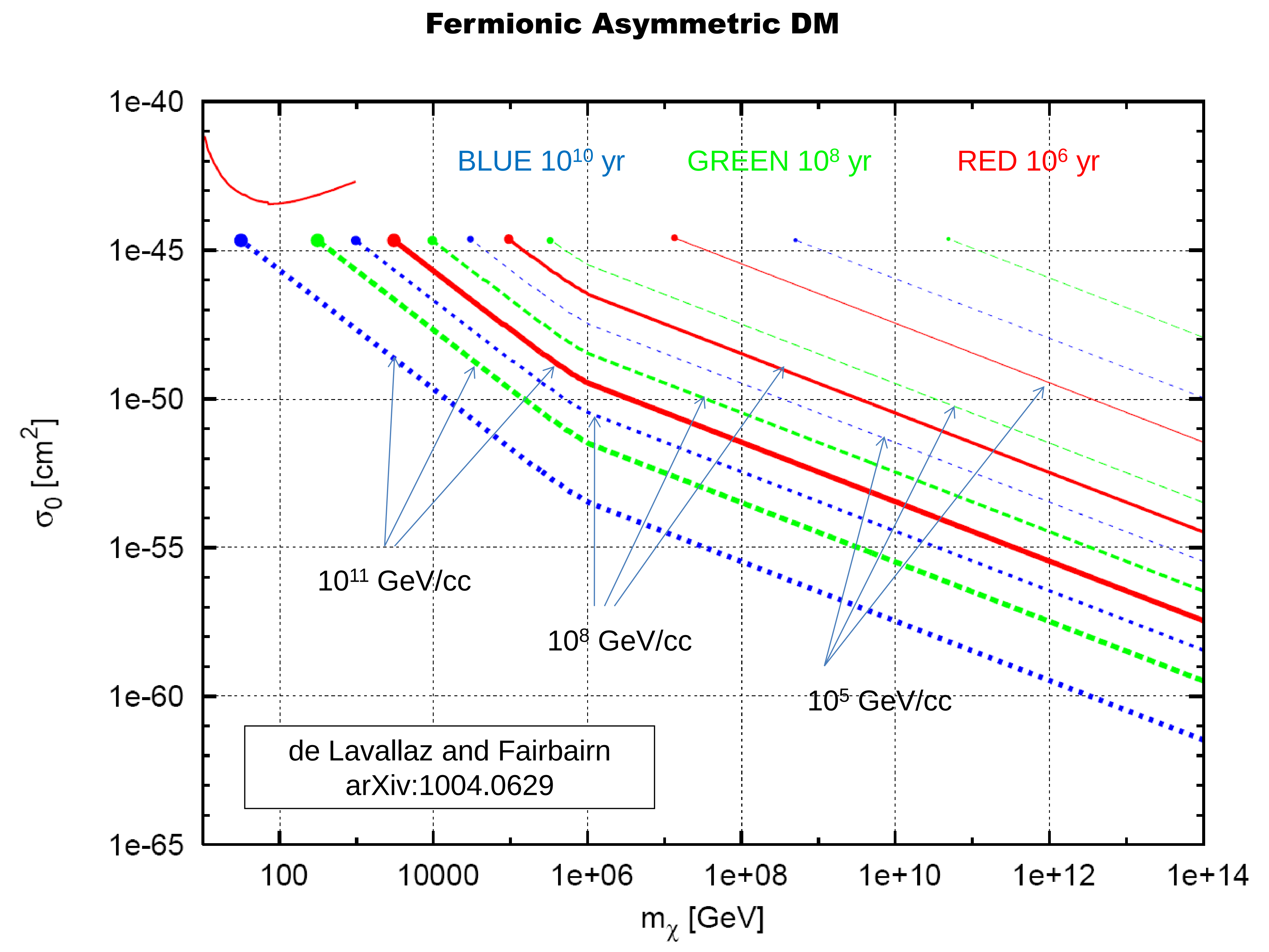


Bertone and Fairbairn
arXiv:0709.1485

Annihilating Dark Matter can heat Neutron Stars



de Lavallaz and Fairbairn
arXiv:1004.0629



Fermionic Asymmetric DM
BLUE 10^{10} yr
GREEN 10^{8} yr
RED 10^{6} yr
10^{11} GeV/cc
10^{8} GeV/cc
10^{5} GeV/cc
de Lavallaz and Fairbairn
arXiv:1004.0629
1e-40
1e-45
1e-50
1e-55
1e-60
1e-65
σ_0 [cm^2]
100
10000
1e+06
1e+08
1e+10
1e+12
1e+14
m_χ [GeV]

Bosonic Asymmetric Dark Matter

Bose Einstein condensate collapses if Gravity beats H.U.P.

$$\frac{\hbar}{r} < \frac{GMm}{r} \Leftrightarrow M > \frac{M_{pl}^2}{m}$$

When do they become self gravitating?

$$r_{\rm th} = \left(\frac{9kT_c}{8\pi G\rho_c m}\right)^{1/2} = 220{\rm cm}\left(\frac{\rm GeV}{m}\right)^{1/2}\left(\frac{T_c}{10^5 K}\right)^{1/2}$$

Should be replaced by

$$r_{\rm BEC} = \left(\frac{8\pi}{3}G\rho_c m^2\right)^{-1/4} \simeq 1.6\times 10^{-4}\left(\frac{\rm GeV}{m}\right)^{1/2}\,{\rm cm}.$$

Which will happen if the mass of dark matter reaches a mass

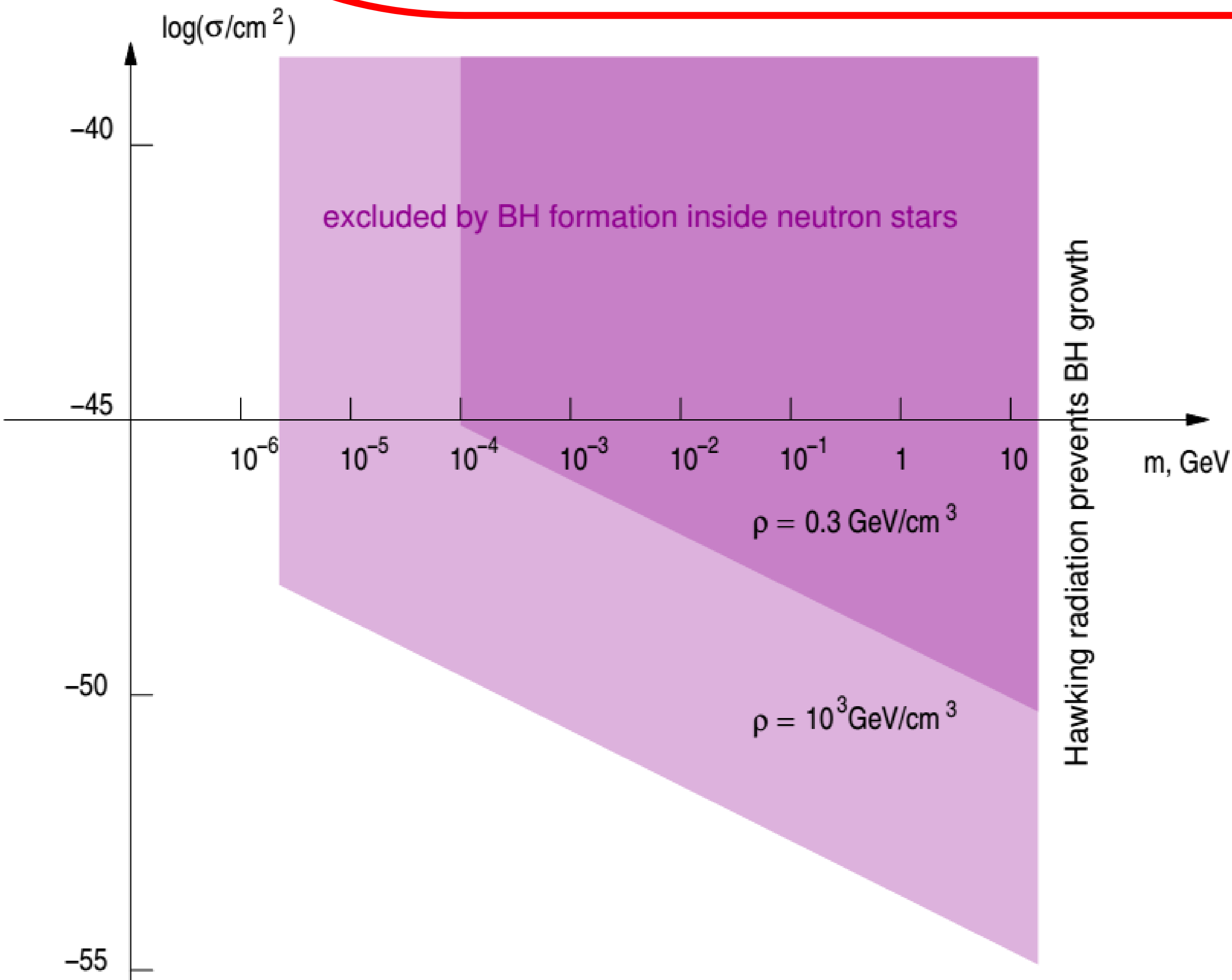
$$M > 8\times 10^{27}\ {\rm GeV}\left(\frac{m}{\rm GeV}\right)^{-3/2}$$

Kouvaris and Tinyakov (2010)

Bosonic Asymmetric Dark Matter

Mass evolution of BH then depends upon Hawking Radiation and Accretion

$$\frac{dM}{dt} = \frac{4\pi\rho_c G^2 M^2}{c_s^3} - \frac{f}{G^2 M^2}$$



Kouvaris and Tinyakov (2010)

Conclusions

• It is possible that some stars sometimes accrete large amounts of dark matter

• If they do, this dark matter can change the outward appearance of the star

• stars can burn for longer – interesting effects can arise for population III stars and at centre of galaxy

• white dwarfs can also be heated, maybe a powerful probe

• neutron stars place constraints on exotic dark matter scenarios