Dark Stars, or How Dark Matter Can Make a Star Shine

Dark Stars are made of ordinary matter and shine thanks to the annihilation of dark matter.

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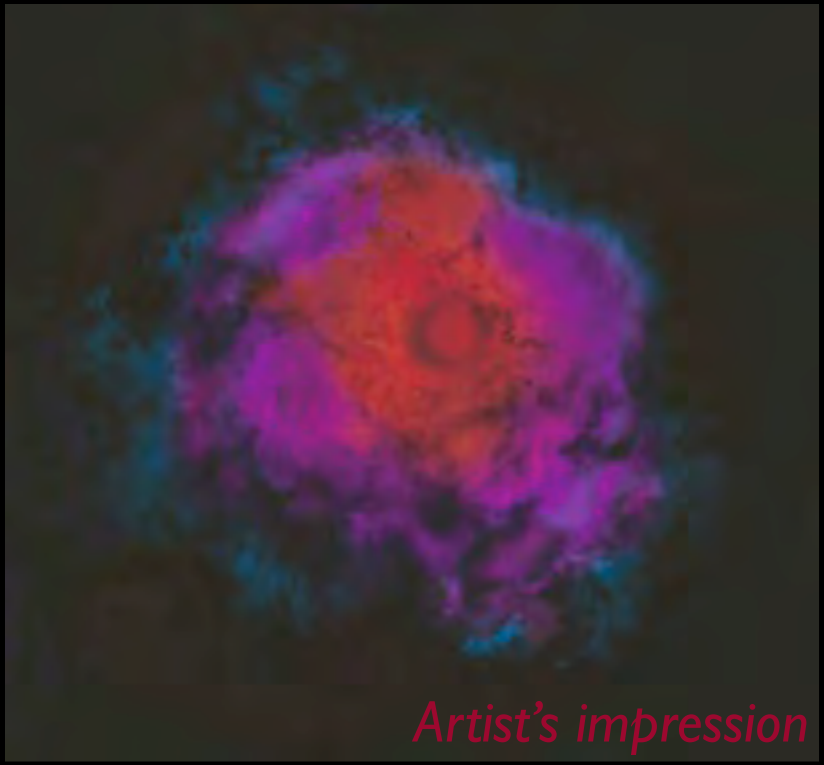
Oskar Klein Centre (Stockholm)

Dark Stars

The first stars to form in the universe may have been powered by dark matter annihilation instead of nuclear fusion.

They were *dark-matter powered stars* or for short *Dark Stars*



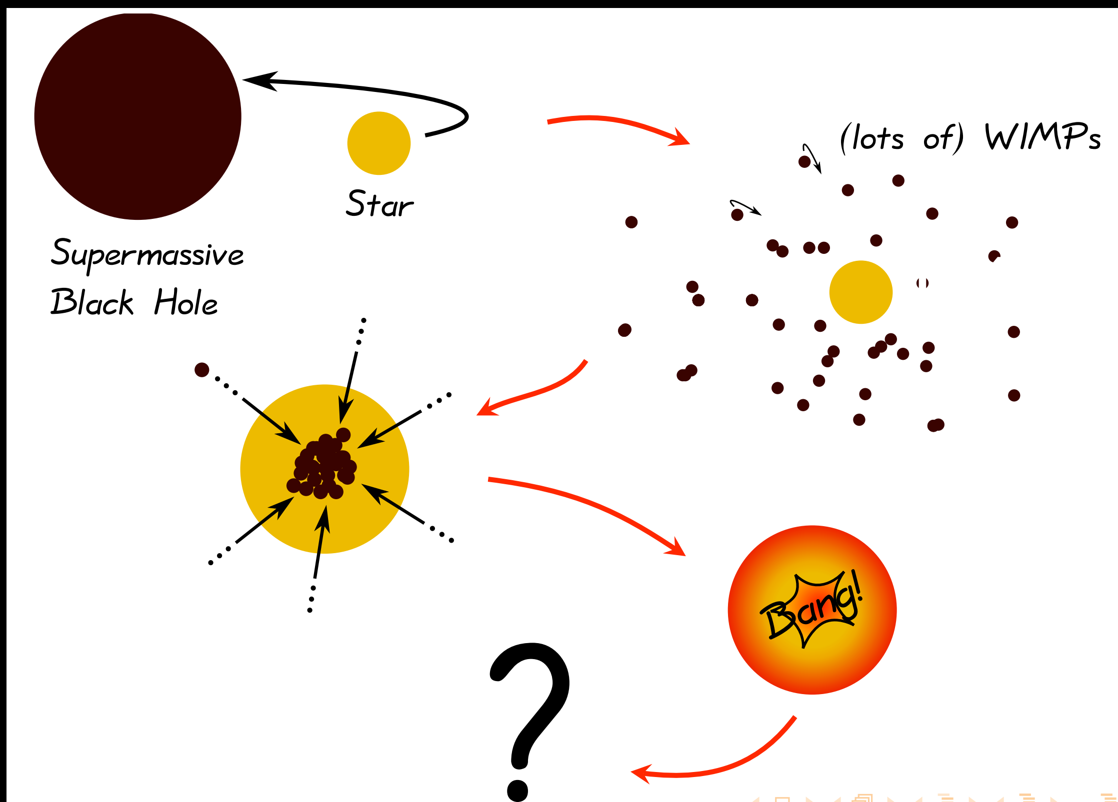
- Explain chemical elements in old halo stars
- Explain origin of supermassive black holes in early quasars

Spolyar, Freese, Gondolo 2008
Freese, Gondolo, Sellwood, Spolyar 2008
Freese, Spolyar, Aguirre 2008
Freese, Bodenheimer, Spolyar, Gondolo 2008
Natarajan, Tan, O'Shea 2009
Spolyar, Bodenheimer, Freese, Gondolo 2009

~~Dark Matter Burners~~ Dark Stars

Renamed in Fairbairn, Scott, Edsjö

Stars living in a dense dark matter environment may gather enough dark matter and become Dark Matter Burners

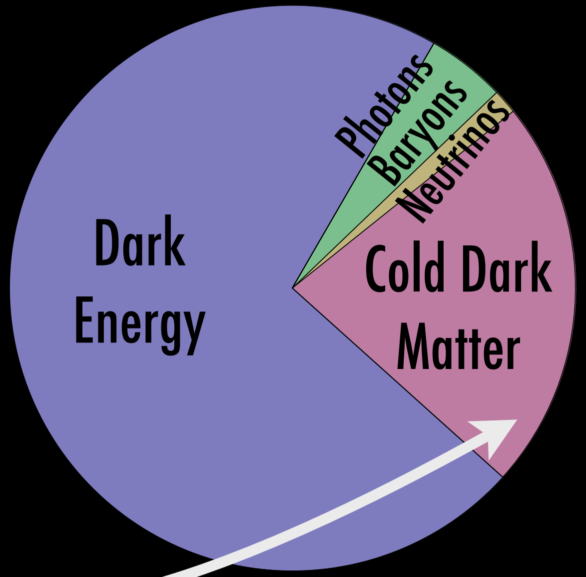


Galactic center example courtesy of Scott

- Explain young stars at galactic center?
- Prolong the life of Pop III Dark Stars?

Salati, Silk 1989
Moskalenko, Wai 2006
Fairbairn, Scott, Edsjö 2007
Spolyar, Freese, Aguirre 2008
Iocco 2008
Bertone, Fairbairn 2008
Yoon, Iocco, Akiyama 2008
Taoso et al 2008
Iocco et al 2008
Casanellas, Lopes 2009

Dark matter particles



Weakly Interacting Massive Particles (WIMPs)

- A WIMP in chemical equilibrium in the early universe naturally has the right density to be Cold Dark Matter

- One can experimentally test the WIMP hypothesis

  The same physical processes that produce the right amount of WIMPs make their detection possible

LHC

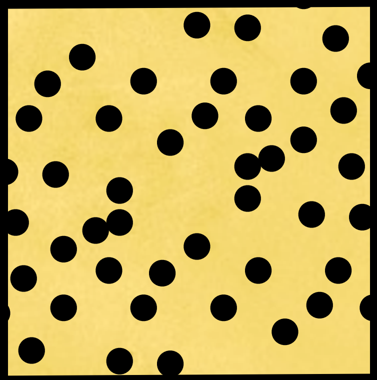
DAMA, XENON, etc

Fermi *IceCube* *PAMELA*

How do WIMPs get into stars?

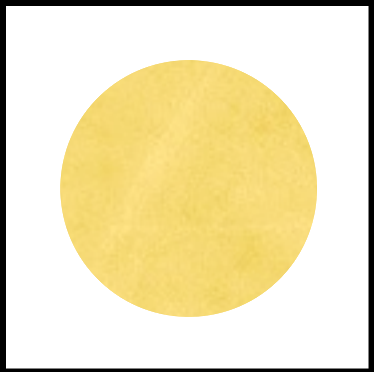
Some stars are born with WIMPs

First stars (Pop III)
~~Sun~~



Some stars capture them later

Stars living in dense dark matter clouds (main sequence stars, white dwarfs, neutron stars, Pop III stars)



How do WIMPs get into stars?

- *By gravitational contraction*: when object forms, dark matter is dragged in into deeper and deeper potential
  - adiabatic contraction of galactic halos due to baryons (Zeldovich et al 1980, Blumenthal et al 1986)
  - dark matter concentrations around black holes (Gondolo & Silk 1999)
  - dark matter contraction during formation of first stars (Spolyar, Freese, Gondolo 2007)
- *By capture through collisions*: dark matter scatters elastically off baryons and is eventually trapped
  - Sun and Earth, leading to indirect detection via neutrinos (Press & Spergel 1985, Freese 1986)
  - stars embedded in dense dark matter regions ("DM burners" of Moskalenko & Wai 2006, Fairbairn, Scott, Edsjo 2007-09)
  - dark matter in late stages of first stars (Freese, Spolyar, Aguirre; Iocco; Taoso et al 2008; Iocco et al 2009)

What do WIMPs do to stars?

Provide an extra energy source

Gravitational systems like stars have negative heat capacity.
Adding energy makes them bigger and cooler.

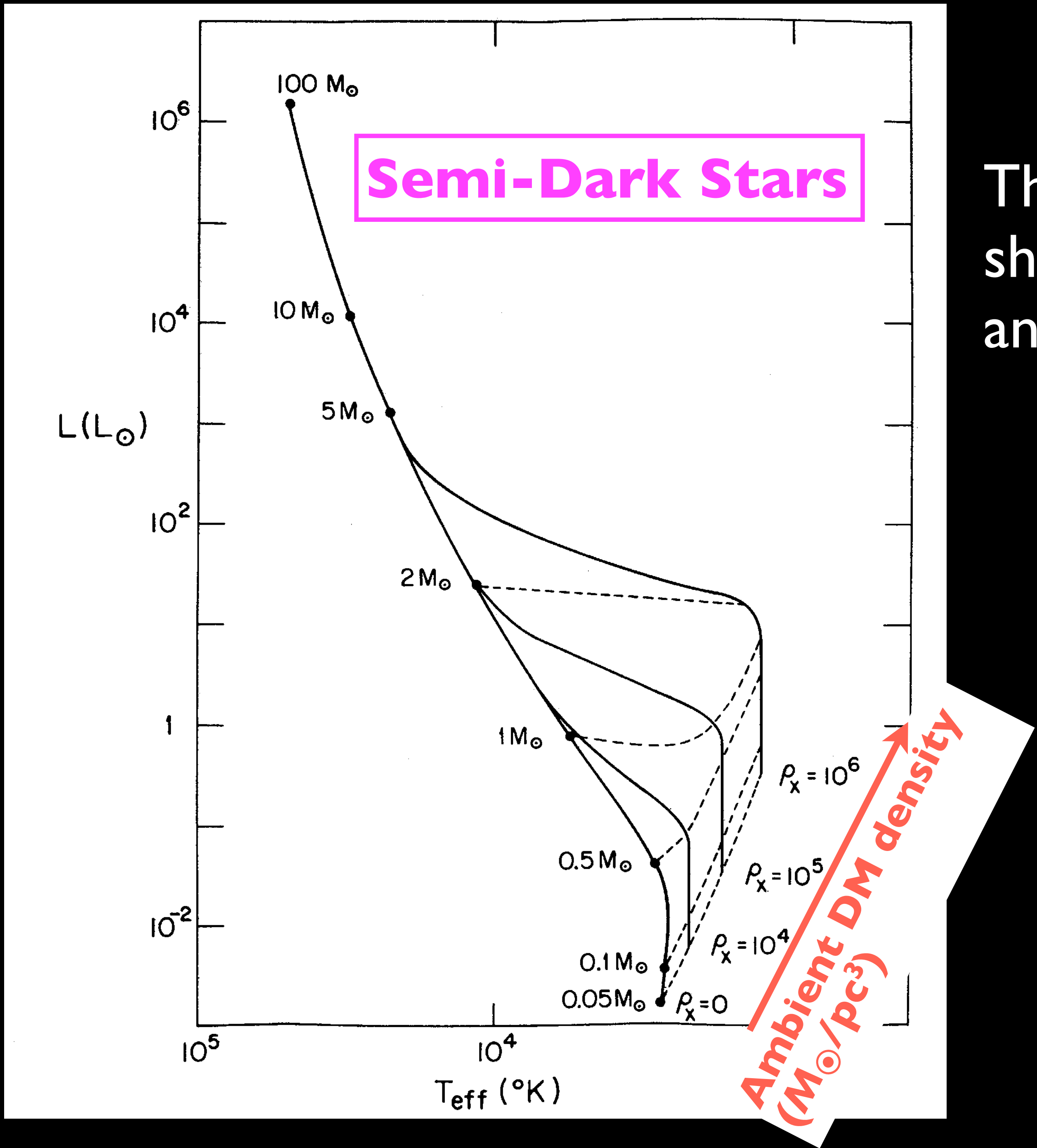
May provide a new way to transport energy

Ordinary stars transport energy outward by radiation and/or convection.
WIMPs with long mean free paths provides additional heat transport.

May produce a convective core (or become fully convective)

Very compact WIMP distributions generate steep temperature gradients that cannot be maintained by radiative transport.

What do WIMPs do to stars?



The main sequence shifts to lower temperatures and higher luminosities

Salati, Silk 1989

$\sigma = 4 \times 10^{-36}$ cm^2

$v = 300$ km/s

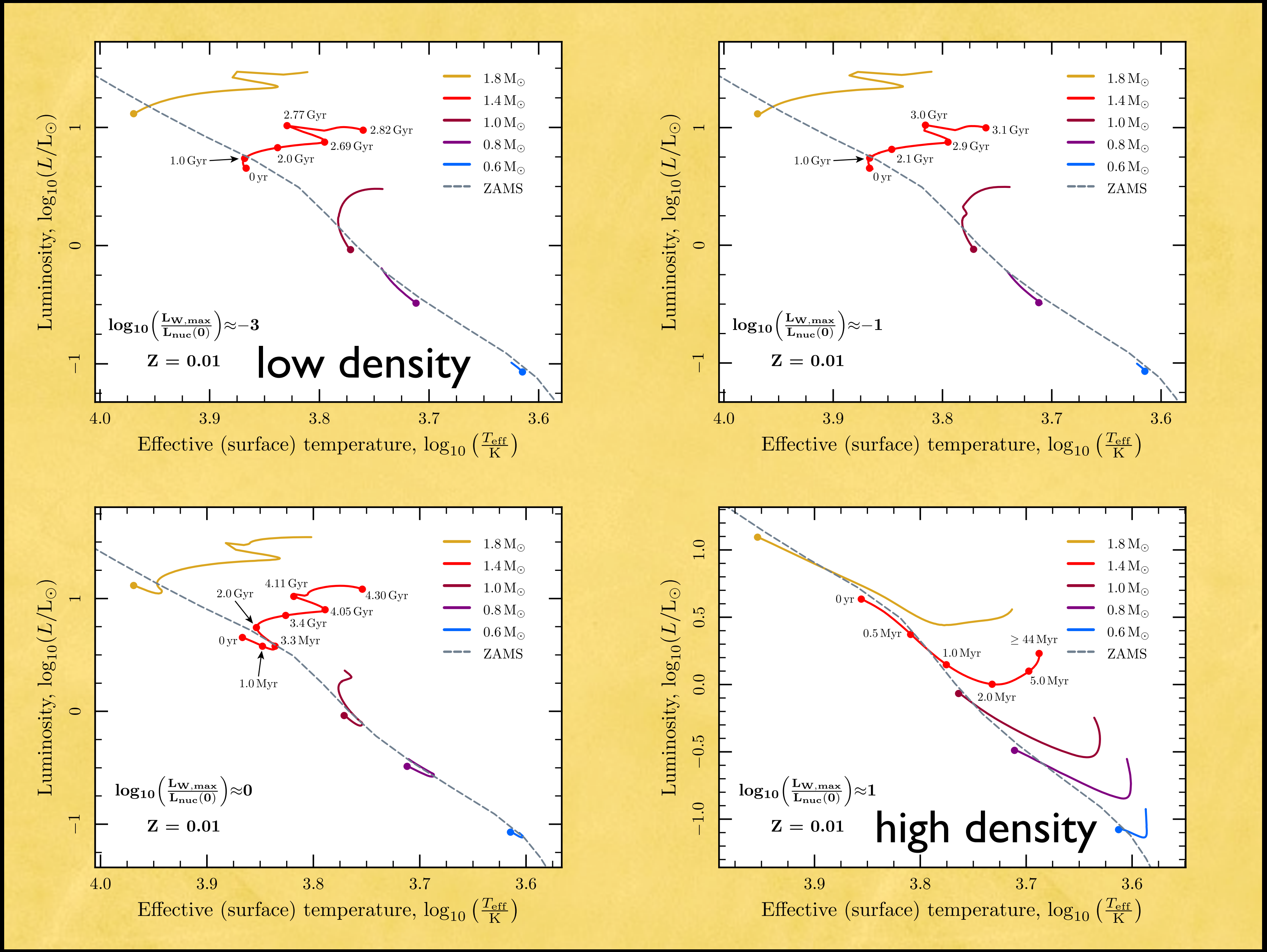
$\rho \leq 4 \times 10^7$ GeV/cm^3

1 $M_\odot$/pc^3 = 38 GeV/cm^3

What do WIMPs do to stars?

Semi-Dark Stars

Main sequence star entering a WIMP cloud

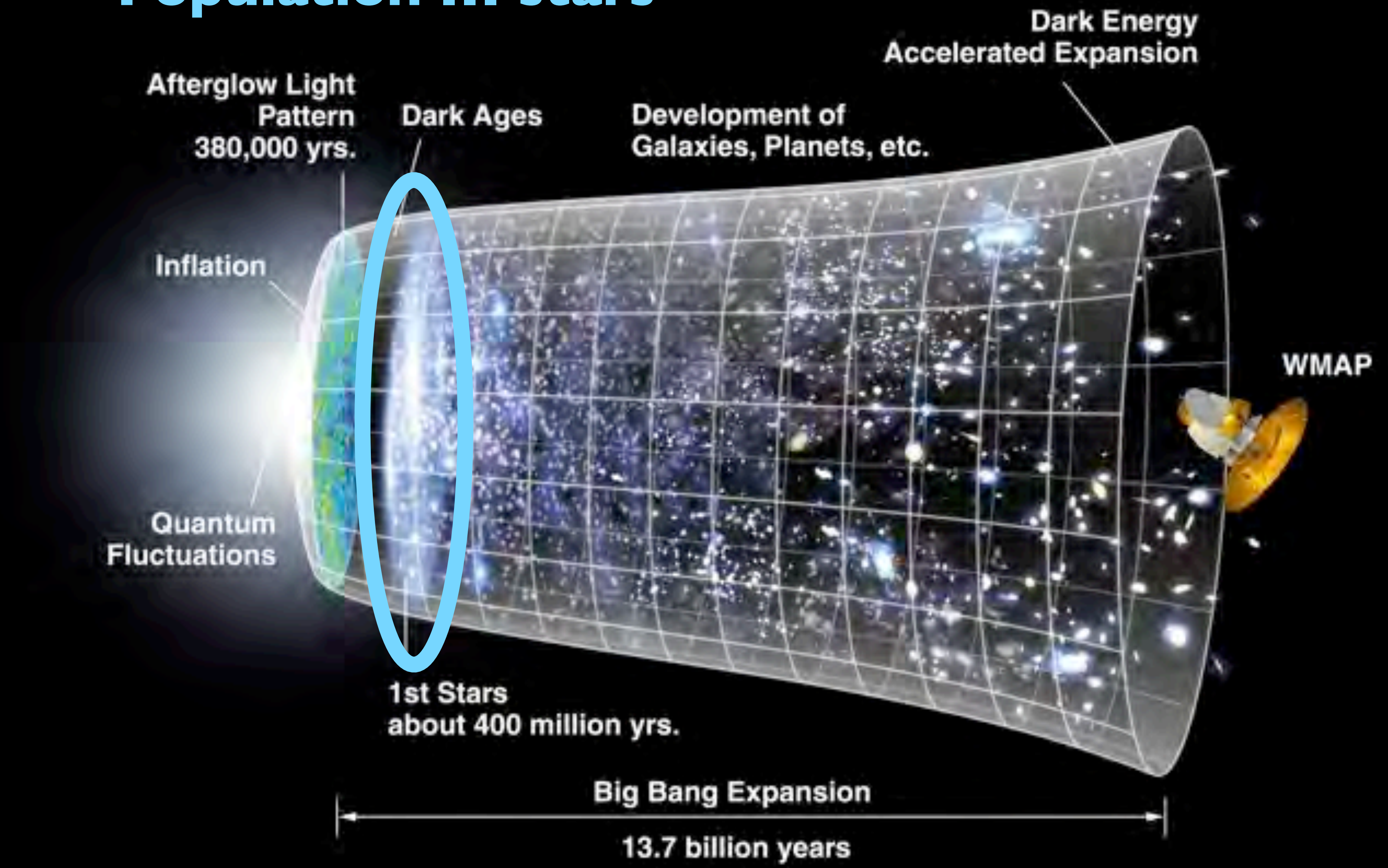


DarkStars evolution code (based on EZ)

Scott, Fairbairn, Edsjo 2009

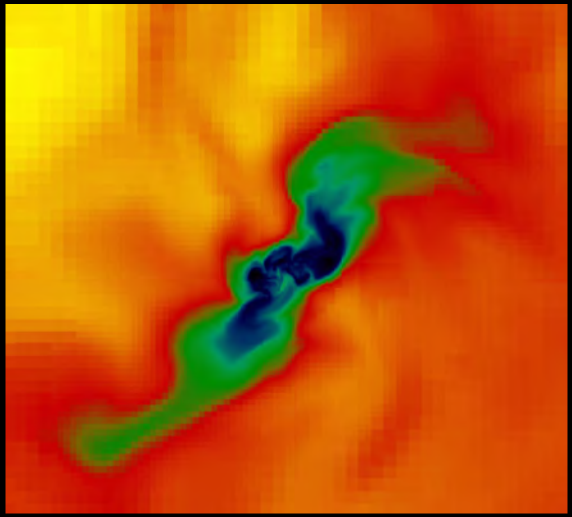
Dark Stars

Population III stars



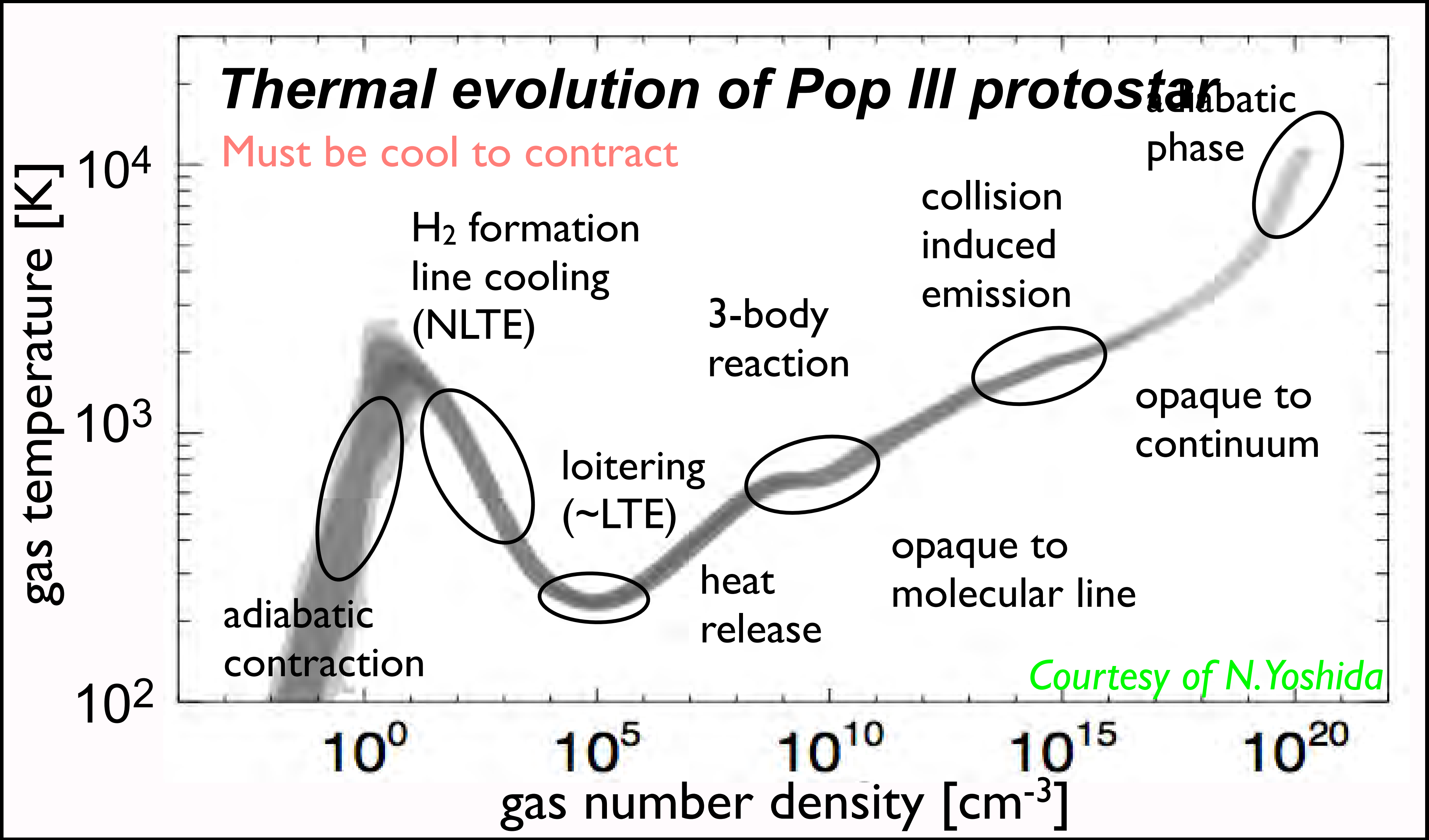
First stars: standard picture

- Formation Basics
  - first luminous objects ever
  - made only of H/He
  - form inside DM halos of 10^5-10^6 $M_\odot$
  - at redshift z=10-50
  - baryons initially only 15%
  - formation is a gentle process



- Dominant cooling mechanism to allow collapse into star is H_2 cooling (Peebles & Dicke 1968)

First stars: standard picture



First stars: three conditions for a dark star

Spolyar, Freese, Gondolo, arxiv:0705.0521, Phys. Rev. Lett. 100, 051101 (2008)

(1) Sufficiently high dark matter density to get large annihilation rate

(2) Annihilation products get stuck in star

(3) Dark matter heating beats H_2 cooling

Leads to new stellar phase

(1) Adiabatic contraction of dark matter

From cosmology. No extra free parameter.

(a) using cosmo-hydrodynamical simulations
Abel, Bryan, Norman 2002

(b) using prescription from Blumenthal, Faber, Flores & Primack 1986 (circular orbits only)
Spolyar, Freese, Gondolo 2008 $r\,M(r) = \text{constant}$

(c) using full phase-space a la Young 1991
Freese, Gondolo, Sellwood, Spolyar 2009

(d) using cosmo-hydrodynamical simulations
Natarajan, Tan, O'Shea 2009

(1) Adiabatic contraction of dark matter

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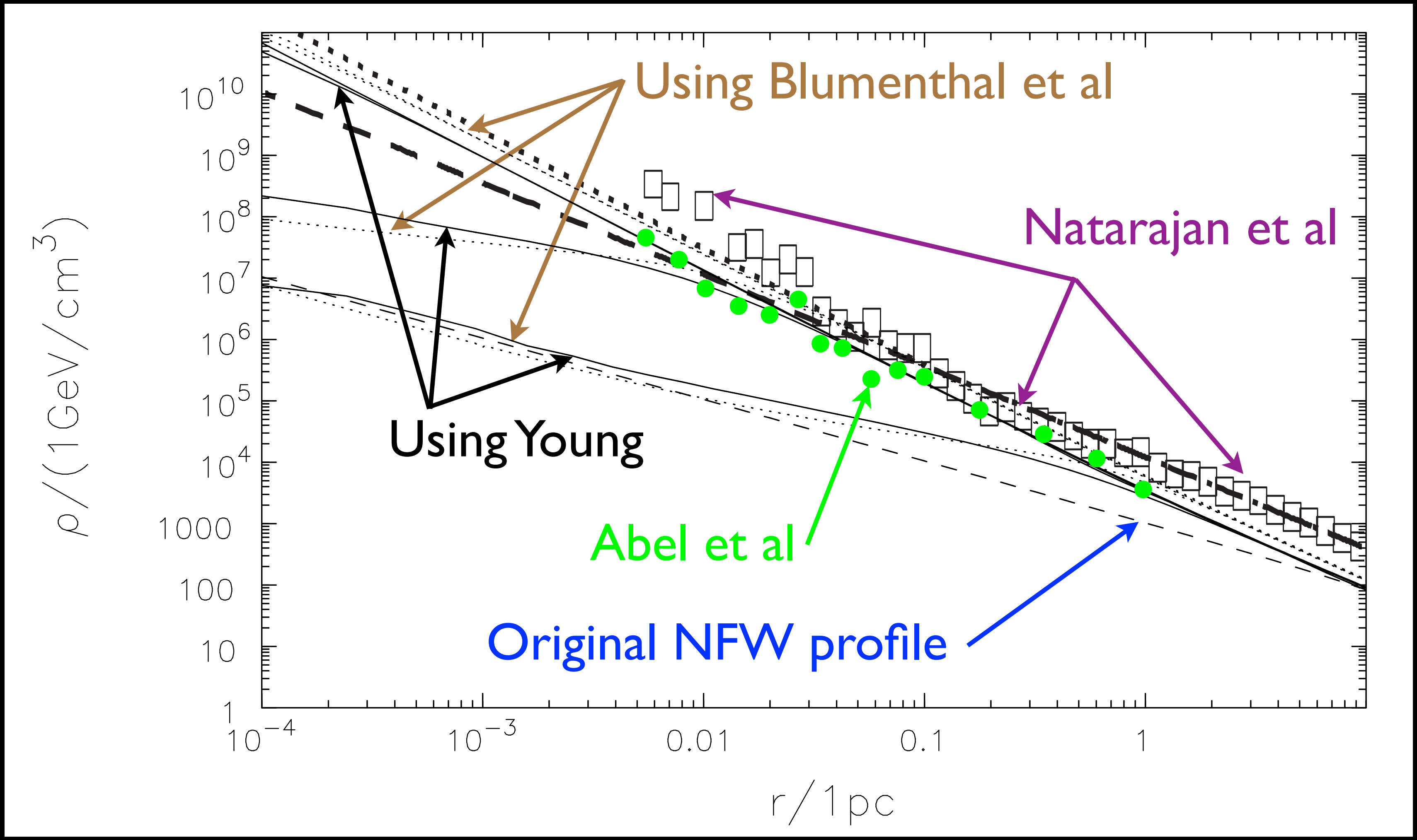


Spolyar, Freese, Gondolo 2008; Freese, Gondolo, Sellwood, Spolyar 2008

(2) Dark matter heating

Heating rate = $Q_{\mathrm{ann}} f_Q$

$\boldsymbol{Q}_{\mathbf{ann}}$: Rate of energy production from annihilation (per unit volume)

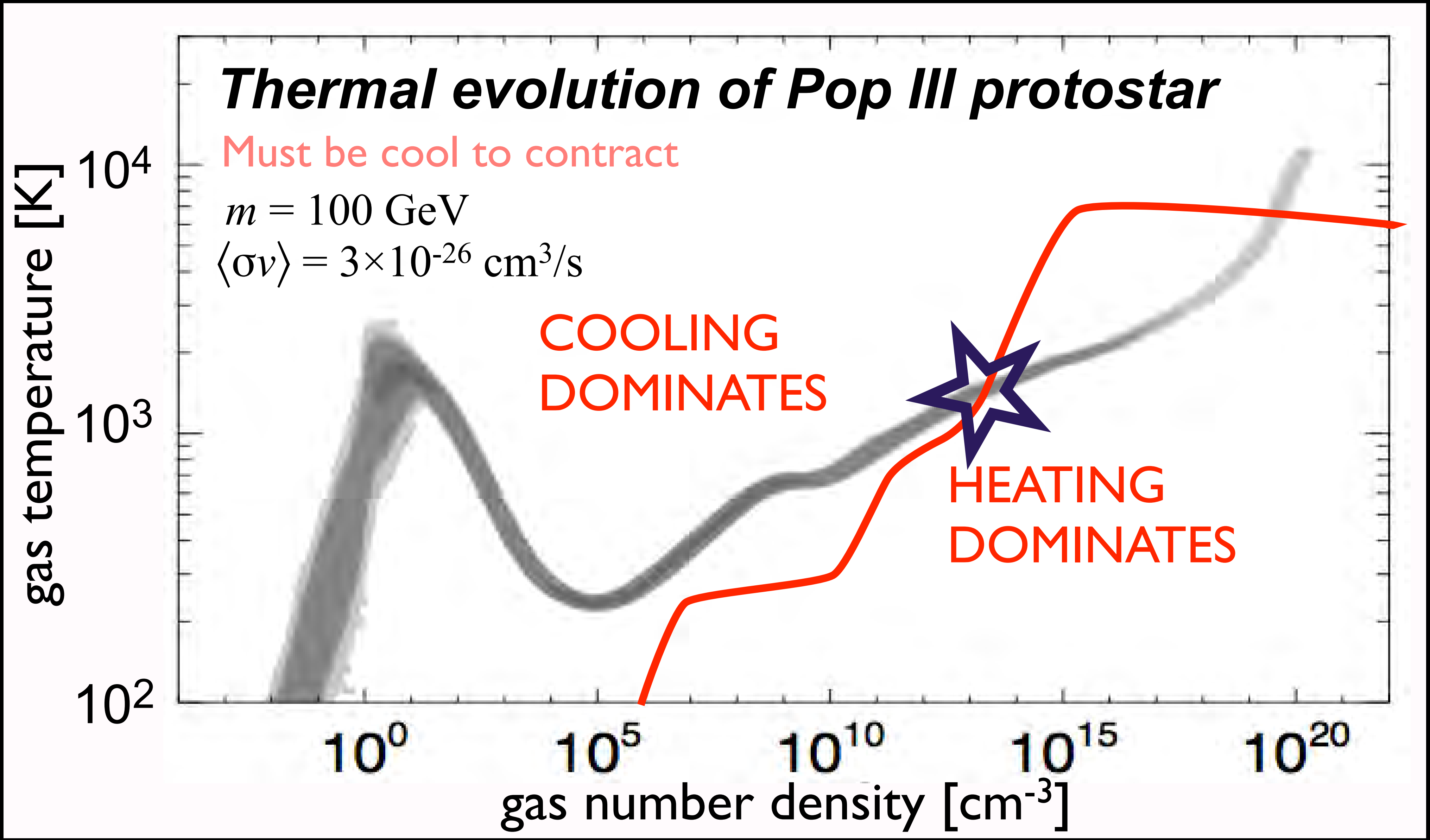
$$Q_{\mathrm{ann}} = n_\chi^2 \langle\sigma v\rangle m_\chi c^2 = c^2 \rho_\chi^2 \frac{\langle\sigma v\rangle}{m_\chi}$$

Particle physics factor

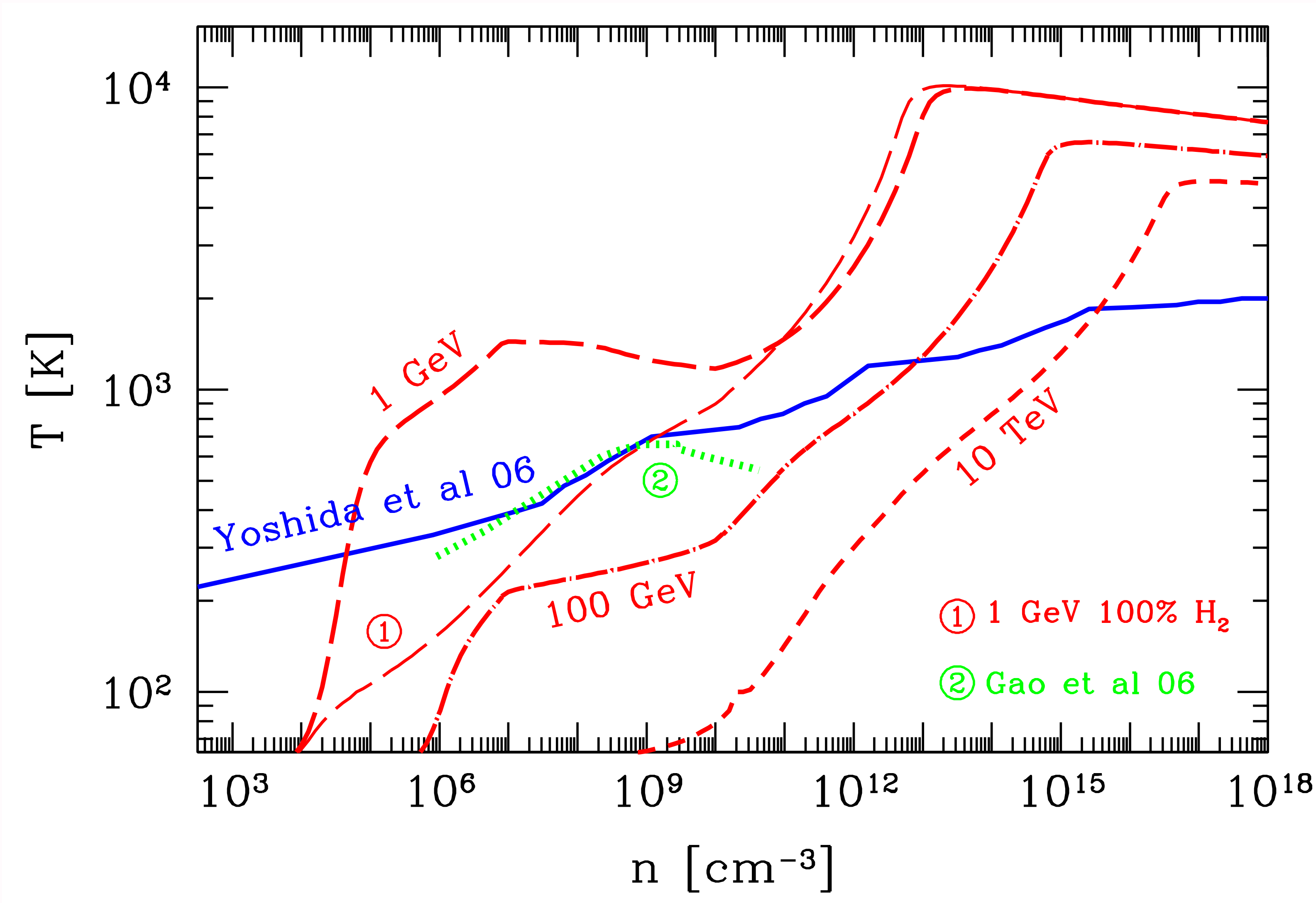
f_{Q}: Fraction of annihilation energy deposited inside star

- 1/3 neutrinos, 1/3 photons, 1/3 electrons/positrons
- Neutrinos escape
- Electrons $\gtrsim E_c \approx 280$ MeV $\rightarrow$ electromagnetic cascades
  $\lesssim E_c \approx 280$ MeV $\rightarrow$ ionization
- Photons $\gtrsim 100$ MeV $\rightarrow$ electromagnetic cascades
  $\lesssim 100$ MeV $\rightarrow$ Compton/Thomson scattering

(3) Birth of a dark star



(3) Birth of a dark star

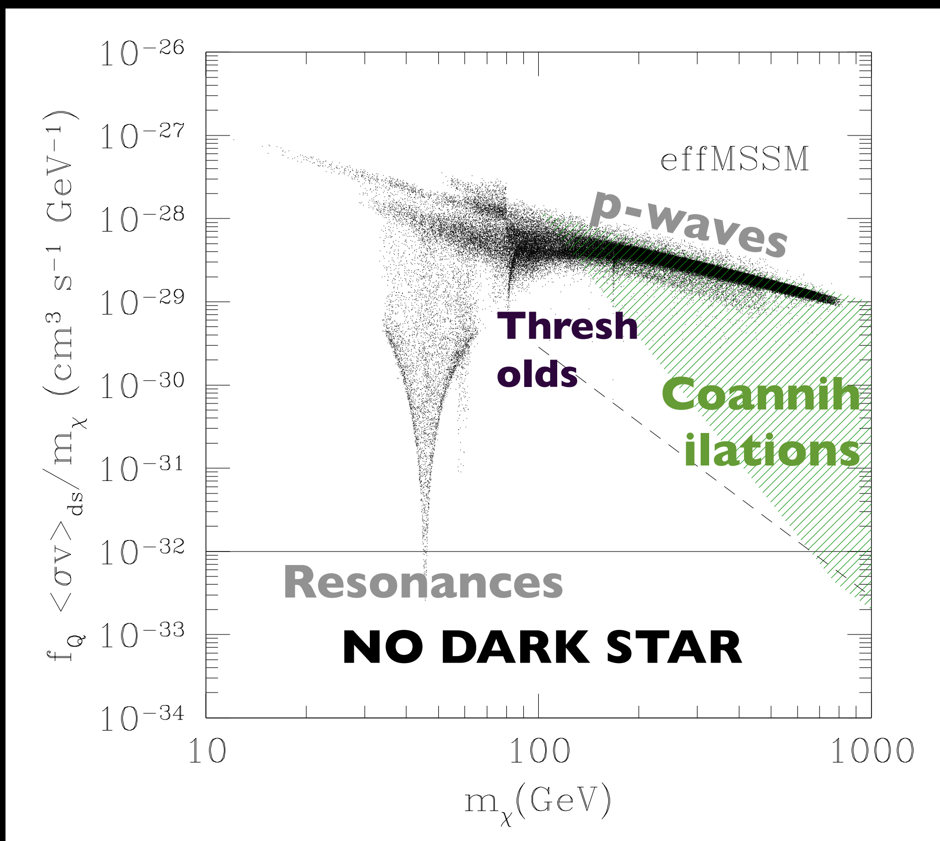


Spolyar, Freese, Gondolo 2008

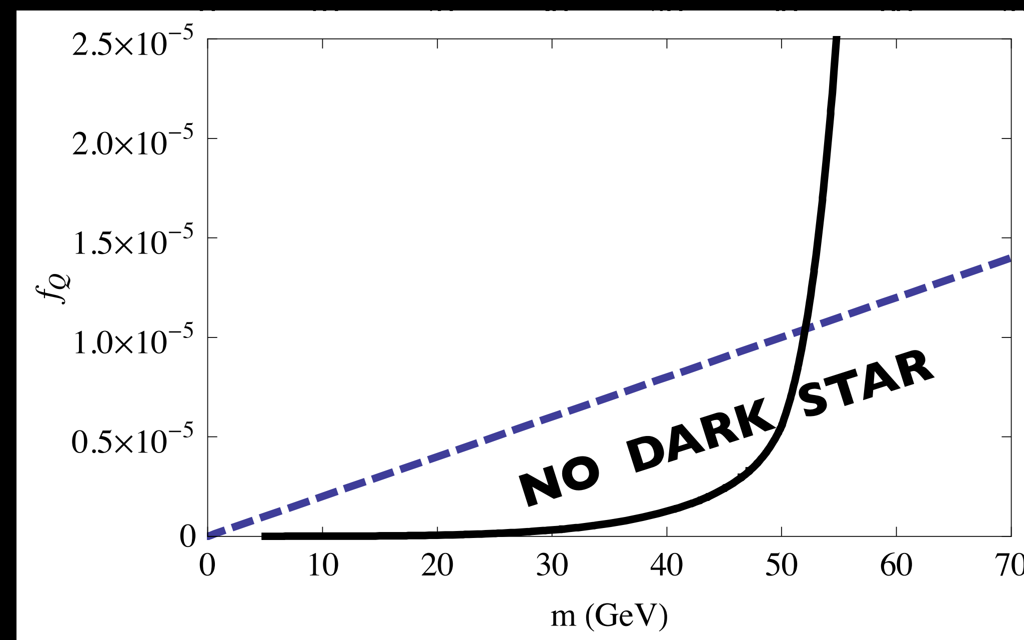
Dark matter that can form dark stars

Almost all thermal dark matter particles *Gondolo, Huh, Kim, Scopel 2010*

Exceptions: resonant annihilation, co-annihilation, neutrinophilic dark matter below ~50 GeV



Neutralino

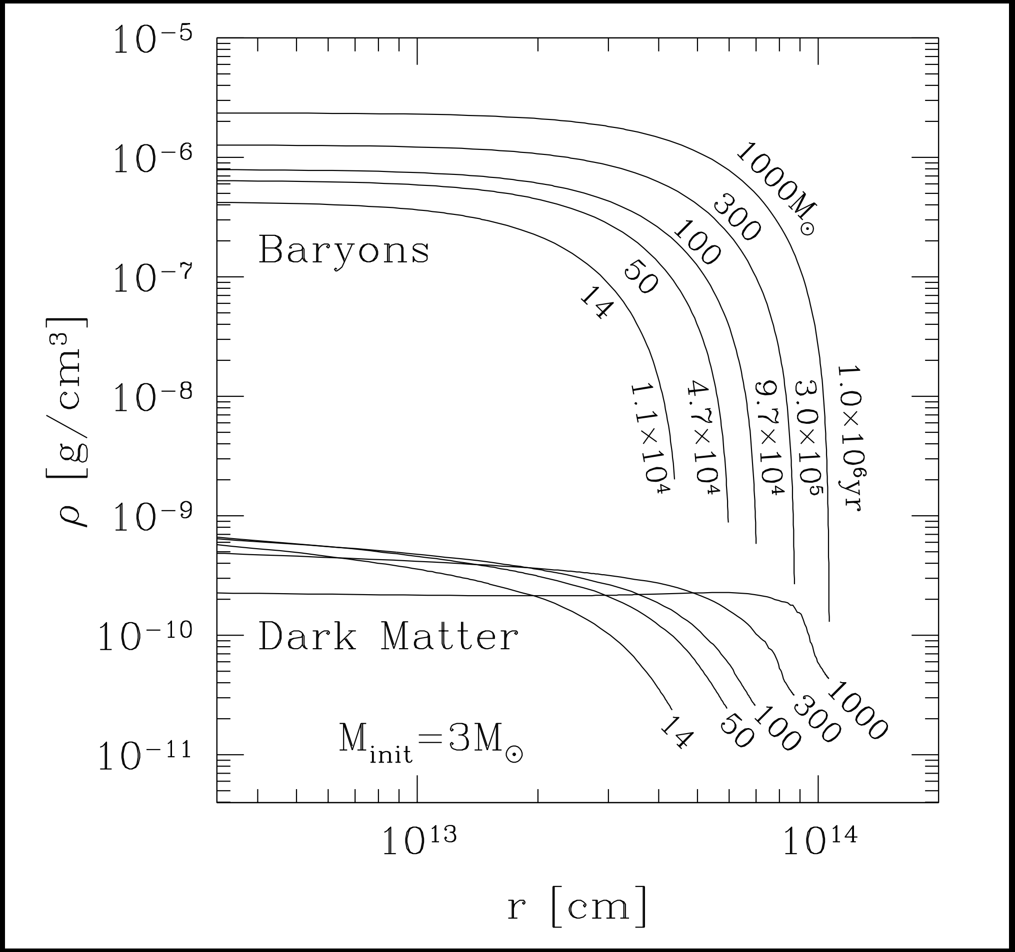


$$\chi\chi \to \nu\bar{\nu}, \nu\bar{\nu}W, \nu\bar{\nu}Z$$

Neutrinophilic

Structure of a dark star

- Polytropes ($p=K\rho^{1+1/n}$) supported by dark matter annihilation rather than fusion
- Dark matter is less than 2% of the mass of the star but provides the heat source (The Power of Darkness)

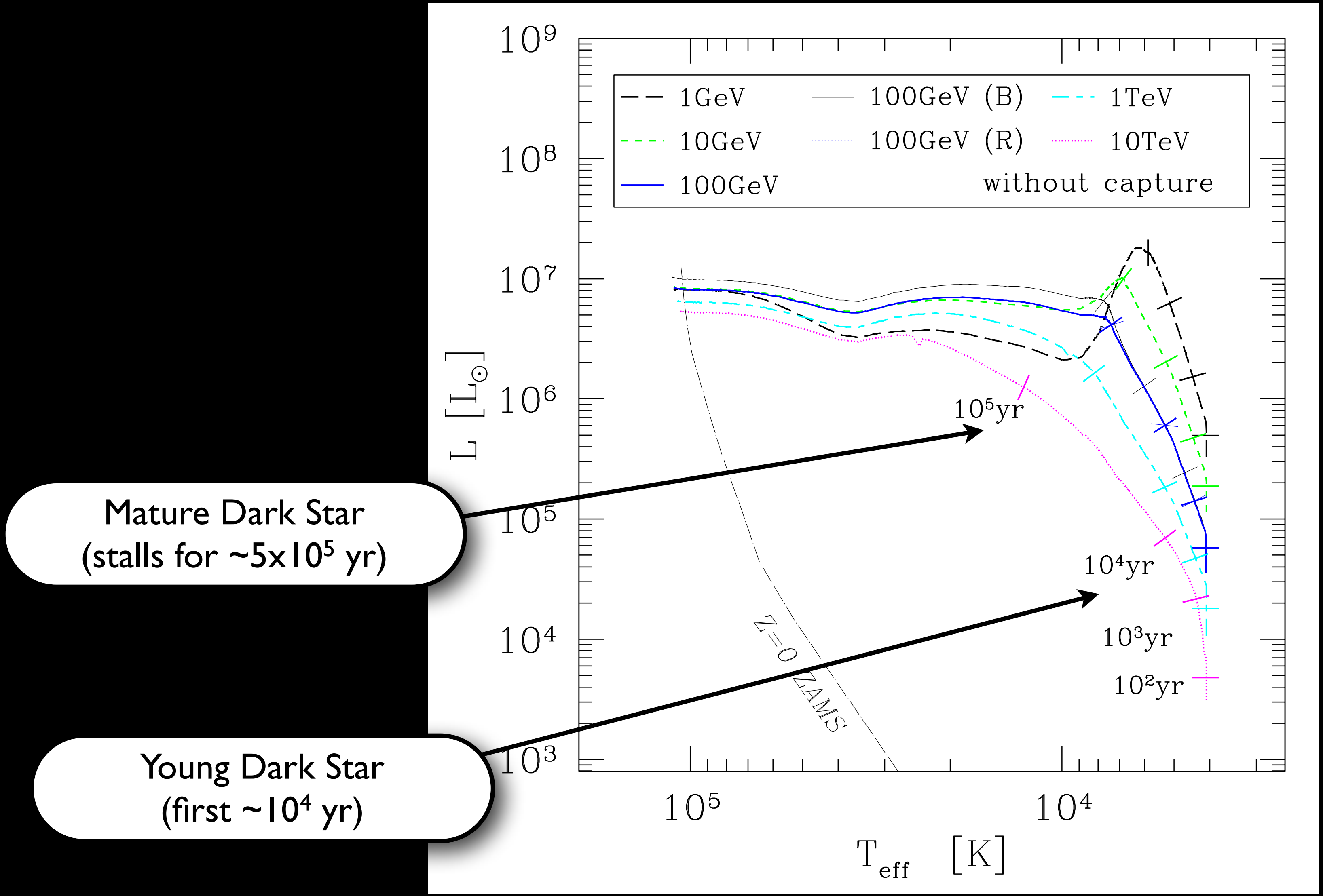


Freese, Bodenheimer, Spolyar, Gondolo 2008
Spolyar, Bodenheimer, Freese, Gondolo 2009

Life of a dark star

Sequence of polytropes with gas and dark matter accretion

Spolyar, Bodenheimer, Freese, Gondolo 2009



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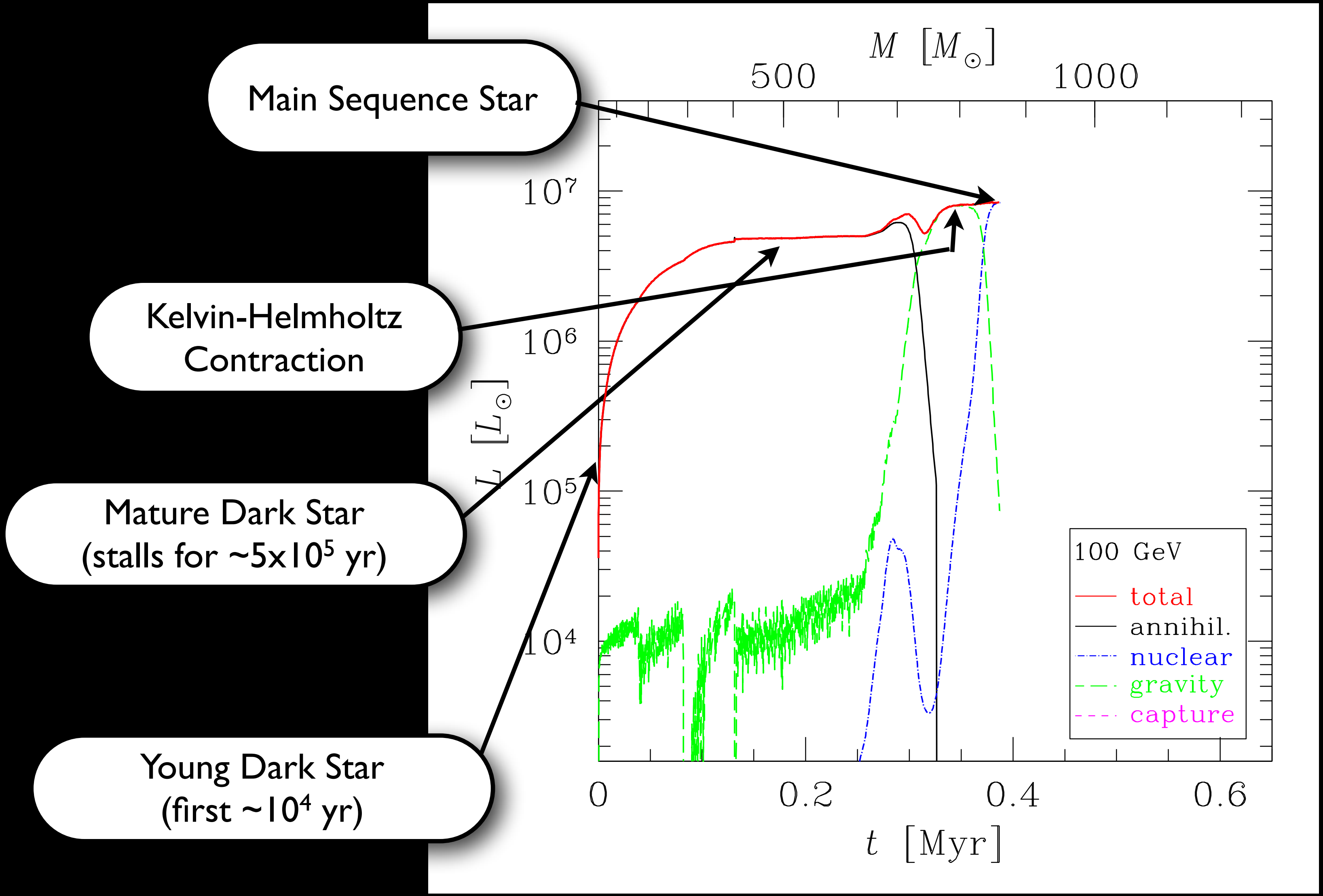

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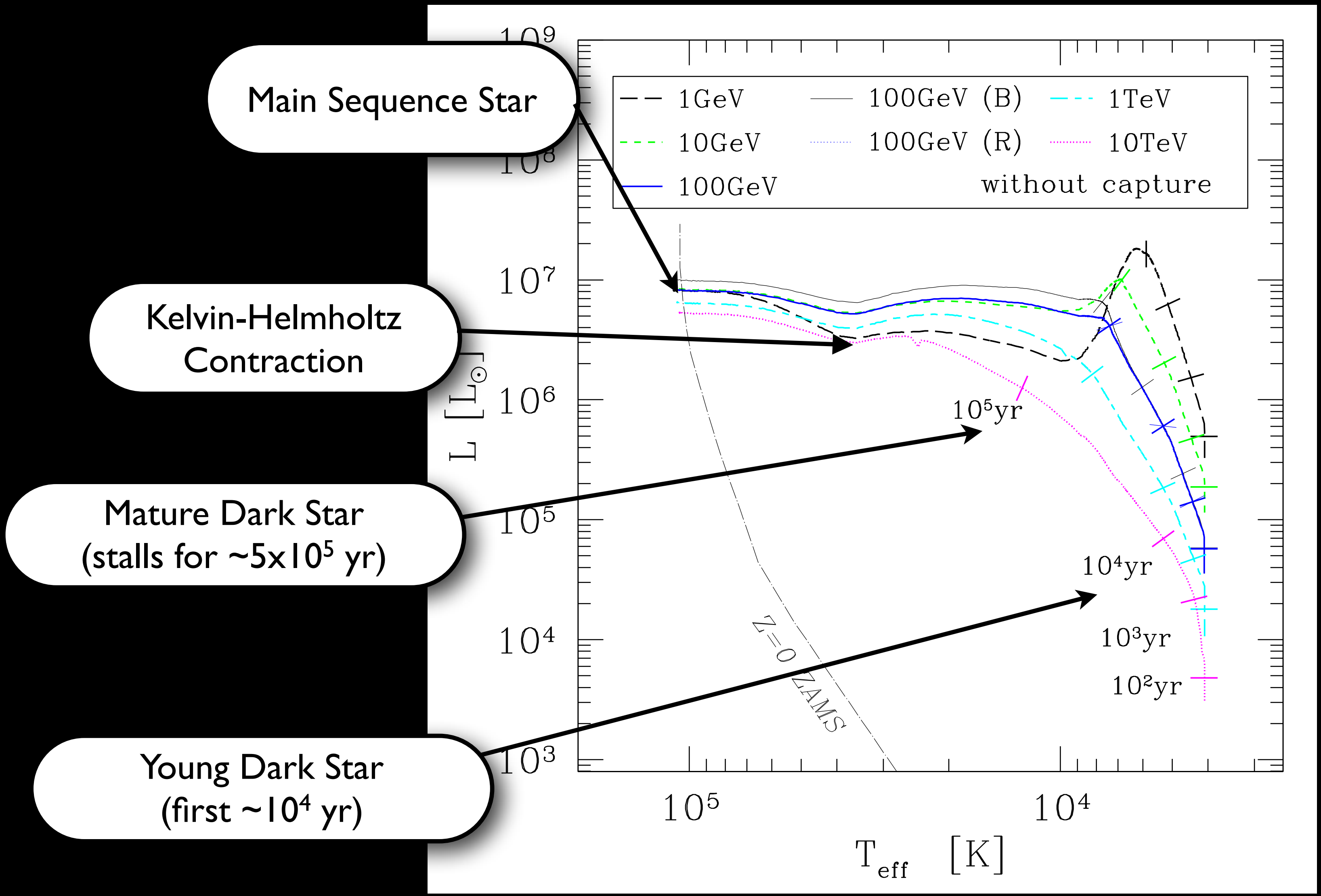


Life of a dark star

Spolyar, Bodenheimer, Freese, Gondolo 2009

For 0.2-1 Myr, dark stars are massive (200-1000 $M_\odot$), bright (10^6-10^7 $L_\odot$), and cold (T_{eff}~10^4K).

Pair-instability region is avoided because core density is small (10^{-7}-10 g/cm^3).

Mass accretion is not stopped by feedback because ionizing UV radiation is negligible.

The dark star phase ends onto Zero Age Main Sequence stars that are massive (500-1000 $M_\odot$), bright (10^6-10^7 $L_\odot$), and hot (T_{eff}~10^5K).

These very massive stars undergo core-collapse into intermediate mass-black holes and may produce the chemical composition of extremely metal poor halo stars *Ohkubo et al 2006, 2009*

Quasars from dark stars?

An old problem: quasars form too early

Quasars have been observed at redshift 6 and beyond.

There is not enough time to form high-redshift quasars from standard Population III remnants of $\sim 100 M_\odot$

A suggested solution: direct collapse to seed black holes

But how does one get seed black holes that are massive enough?

e^+e^- *pair instability prevents the formation of massive stars.*

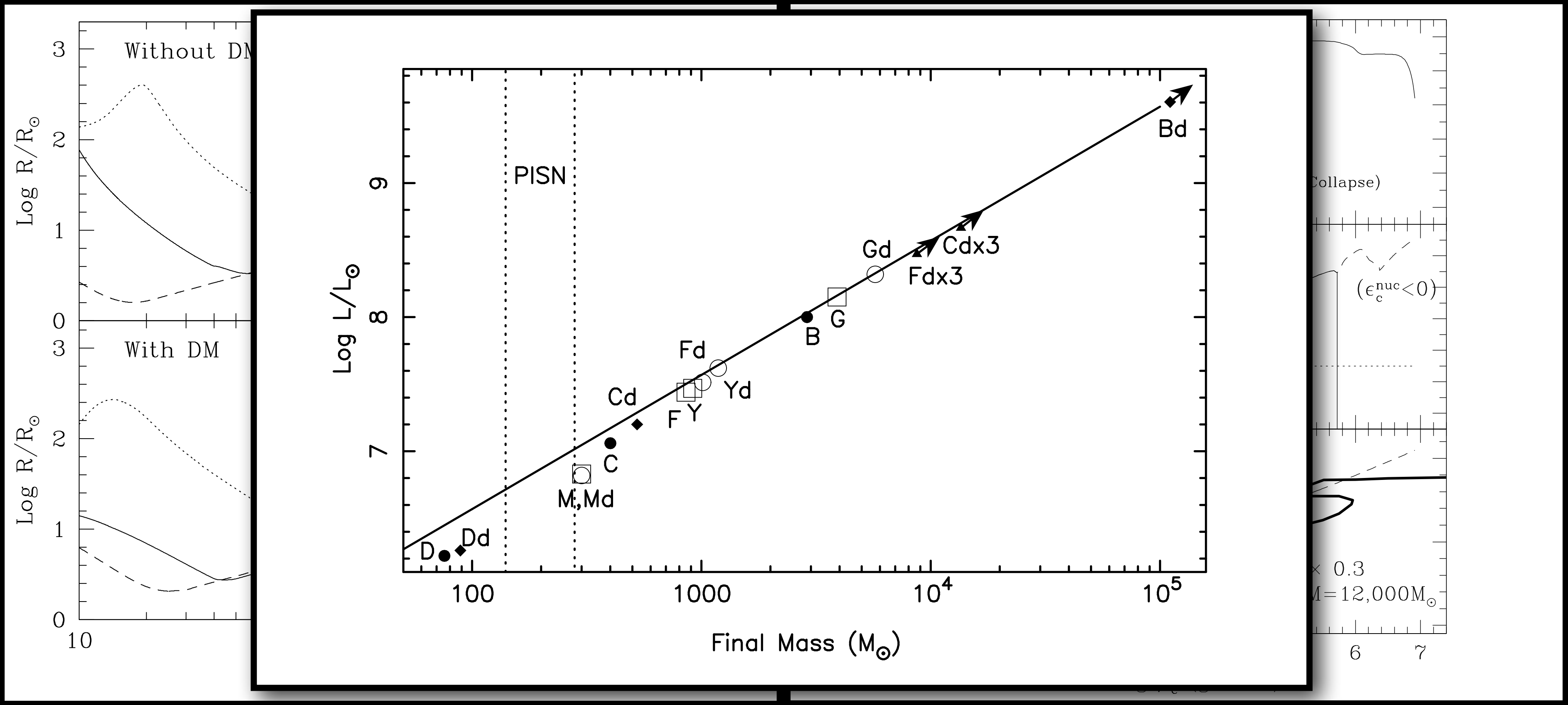
Bromm & Loeb (2003) suggest superfast gas accretion rates devoid of molecular hydrogen.

Dark stars provide another way.

Quasars from dark stars?

Extended capture and appropriate gas accretion rate give dark stars that can solve the high-redshift quasar formation problem.

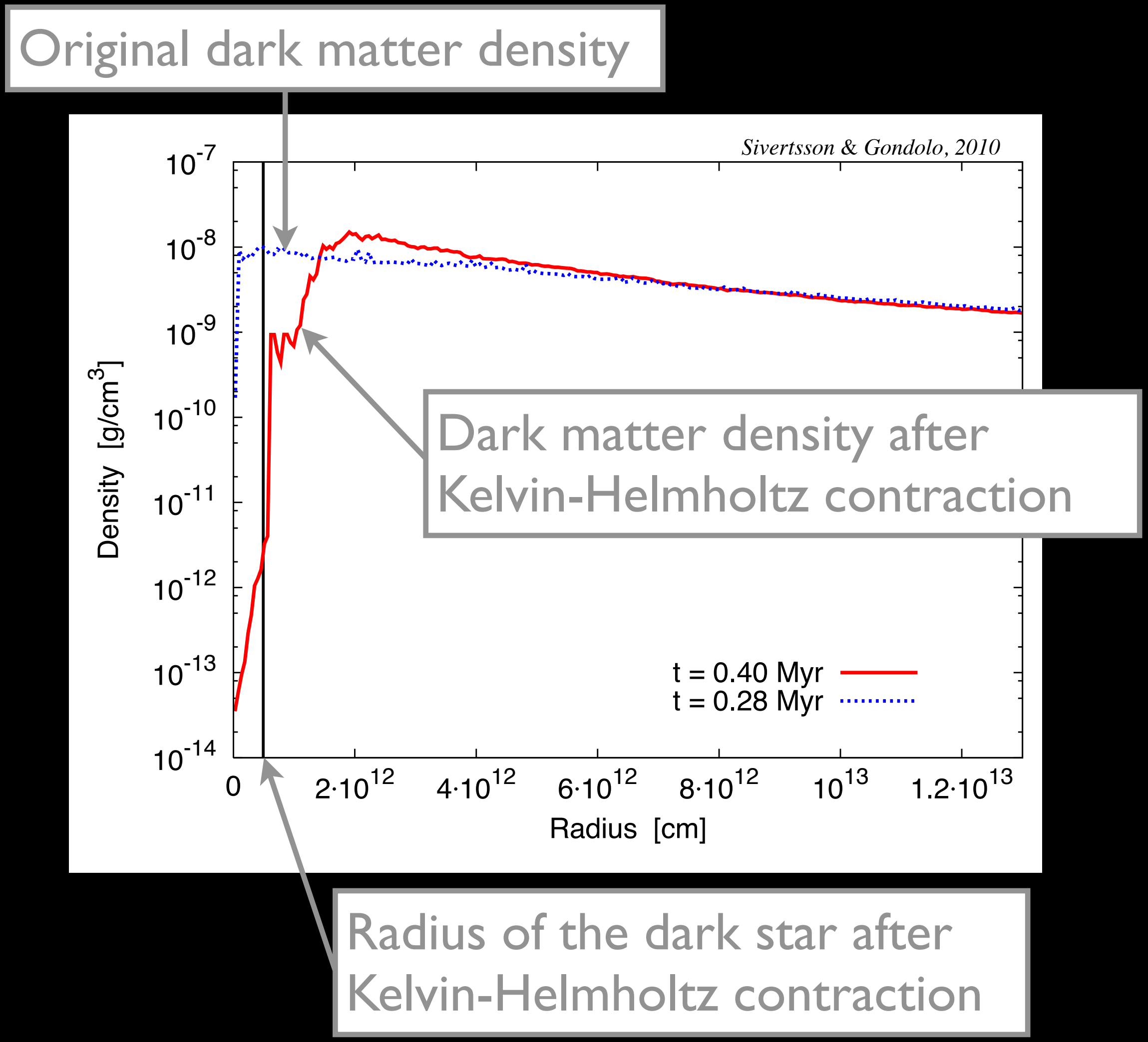
Umeda, Yoshida, Nomoto, Tsuruta, Sasaki, Ohkubo 2009



No extended capture

Once the dark star contracts to the Zero Age Main Sequence, the supply of dark matter ends.

Sivertsson, Gondolo 2010



On the throat of death , the dark star burns all of the dark matter it can get.

The rest of the dark matter stays in orbit out of reach of the dead dark star.

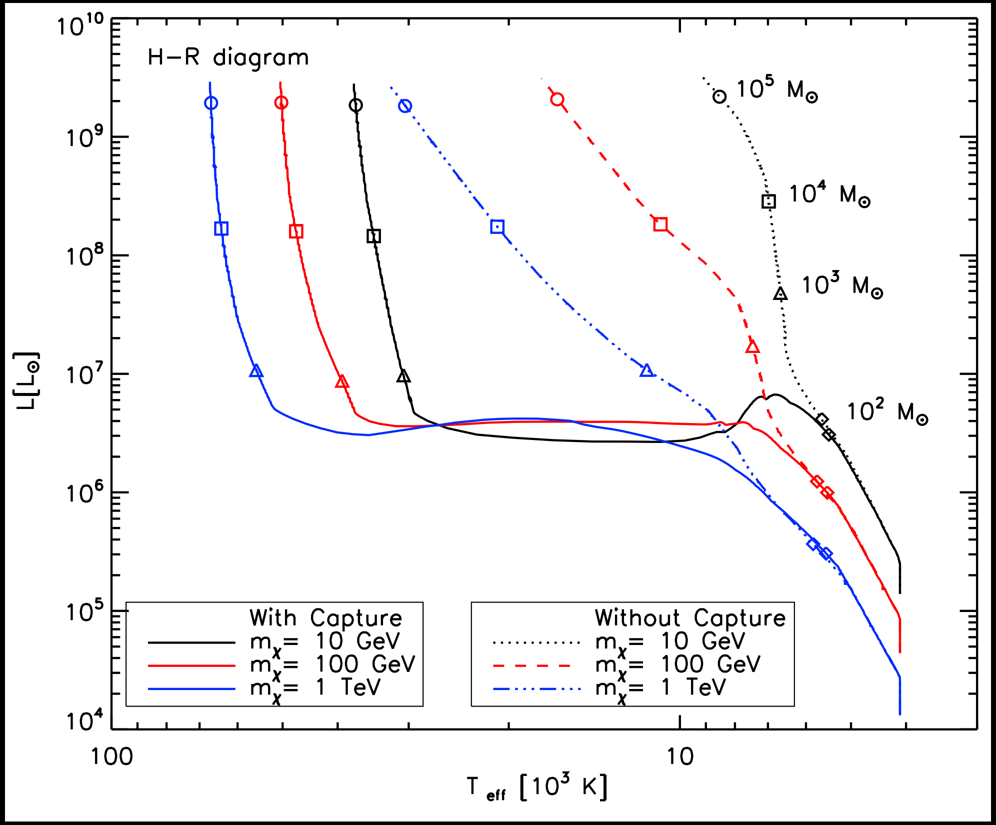
Supermassive dark stars?

Perhaps some dark stars become much more massive (10^7 vs 10^2 $M_\odot$) and much brighter (10^{11} vs 10^7 $L_\odot$)

Freese, Ilie, Spolyar, Valluri, Bodenheimer 2010

In triaxial dark matter halos, centrophillic orbits (box and chaotic) may extend the supply of dark matter to the dark star.

However, orbits in the dark star potential are not expected to be centrophillic (exception Valluri et al 2010).

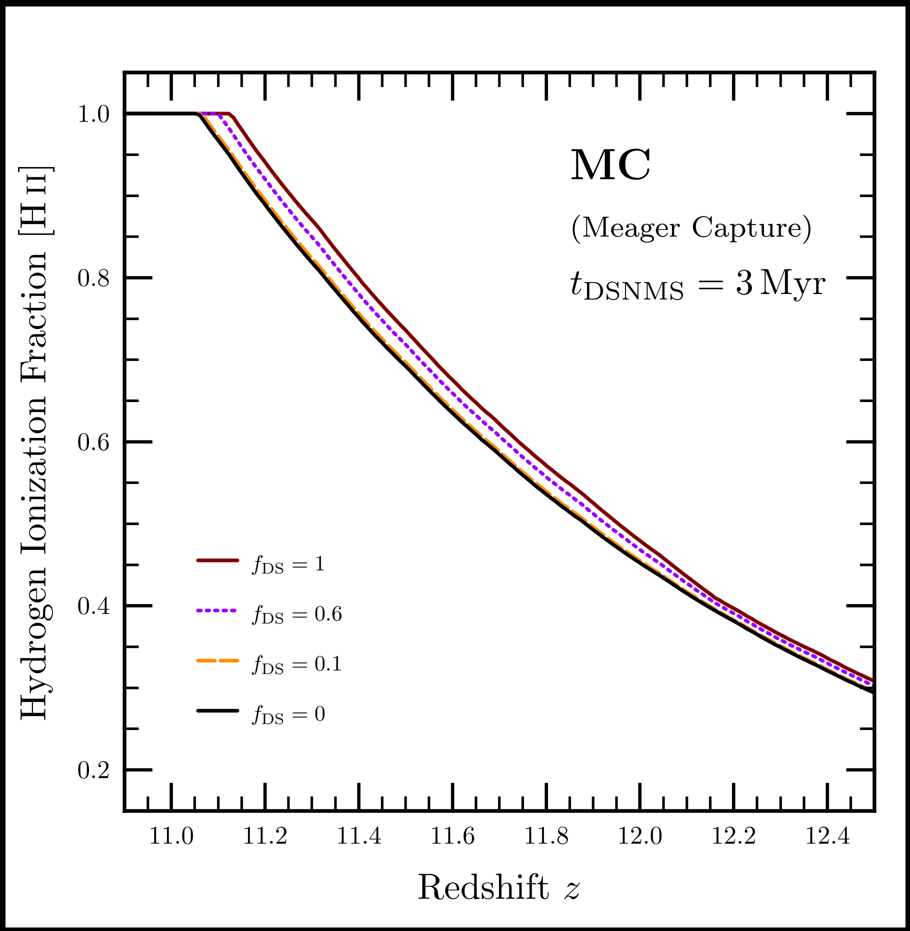


Dark stars and reionization

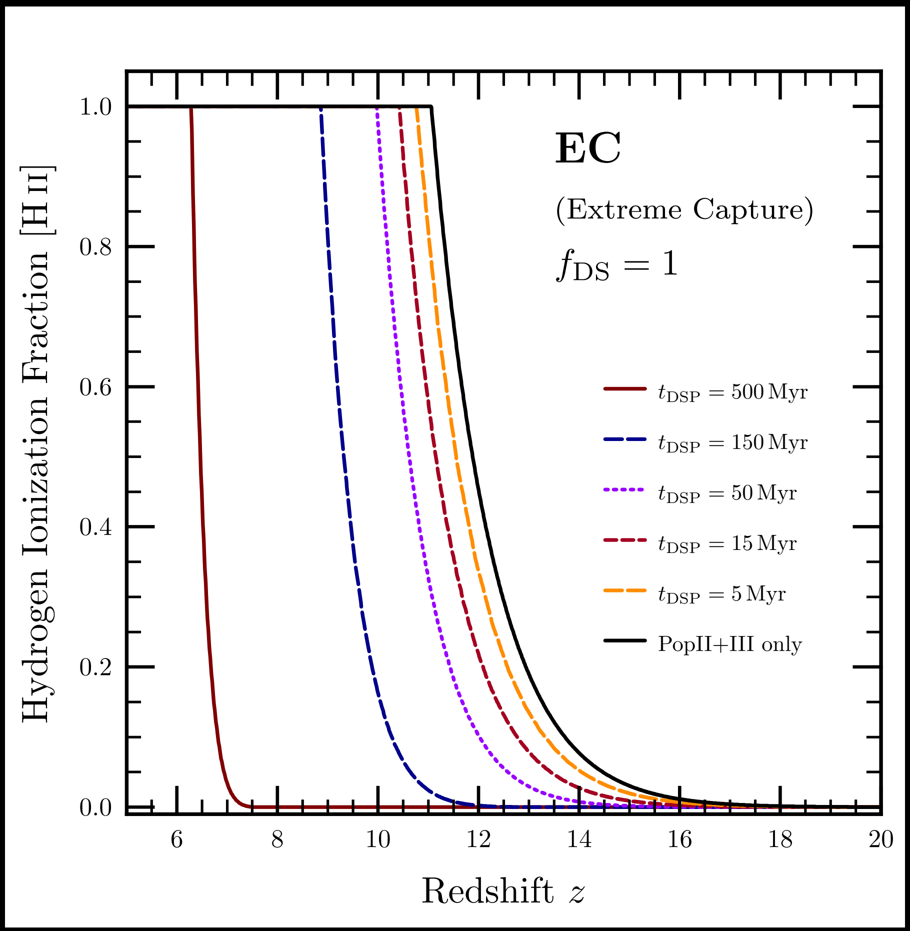
A dark star phase can delay reionization

Scott, Venkatesan, Roebber, Gondolo, Pierpaoli, Holder 2011

With capture



With extended capture



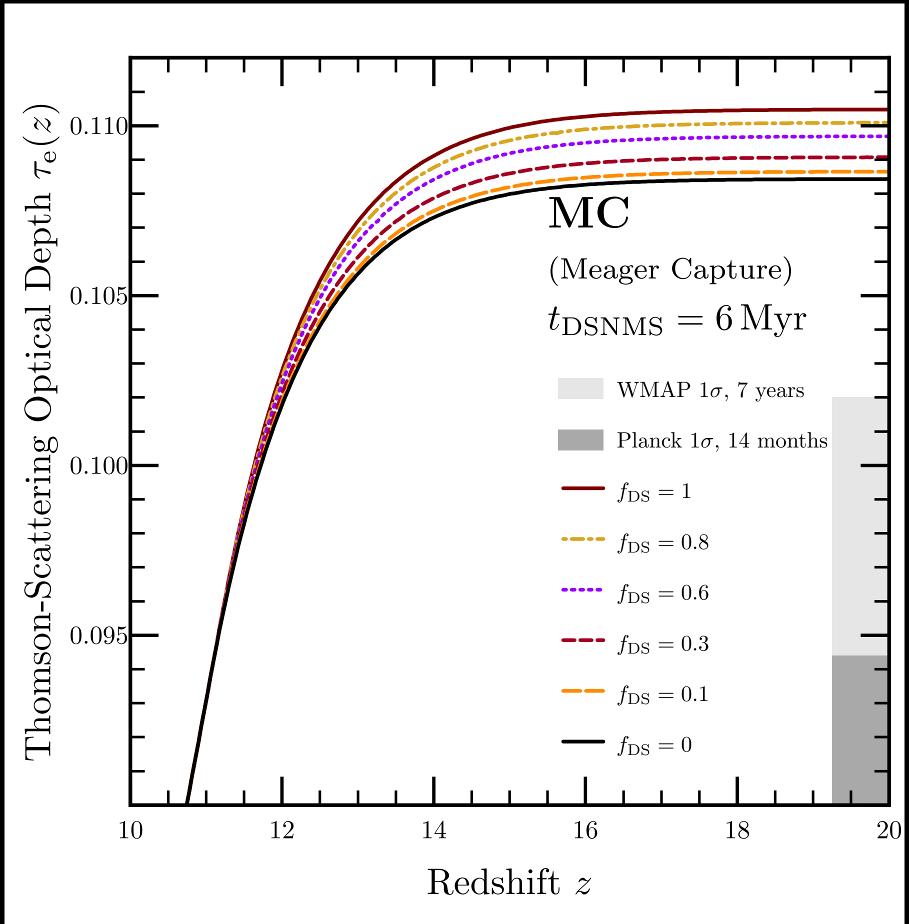
Without capture, no effect on reionization.

Dark stars and the CMB

A dark star phase can affect the cosmic microwave background

Scott, Venkatesan, Roebber, Gondolo, Pierpaoli, Holder 2011

With capture



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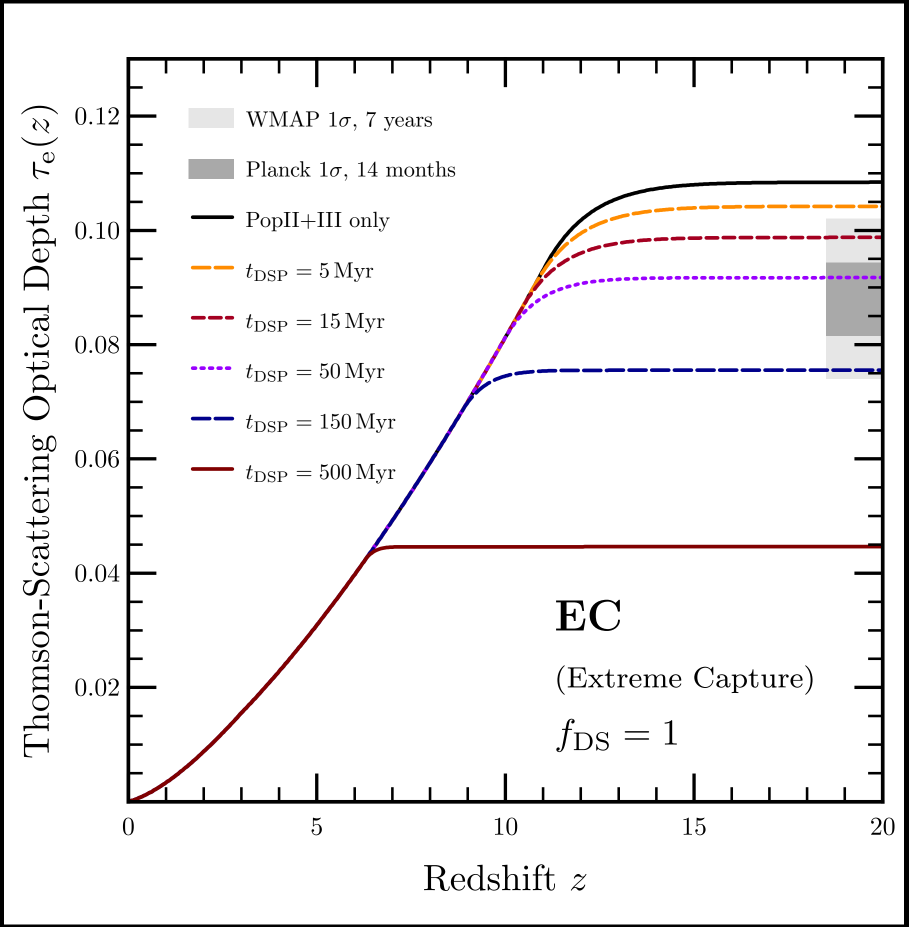


Without capture, no effect on the CMB.

Dark stars and the CMB

A dark star phase can affect the cosmic microwave background

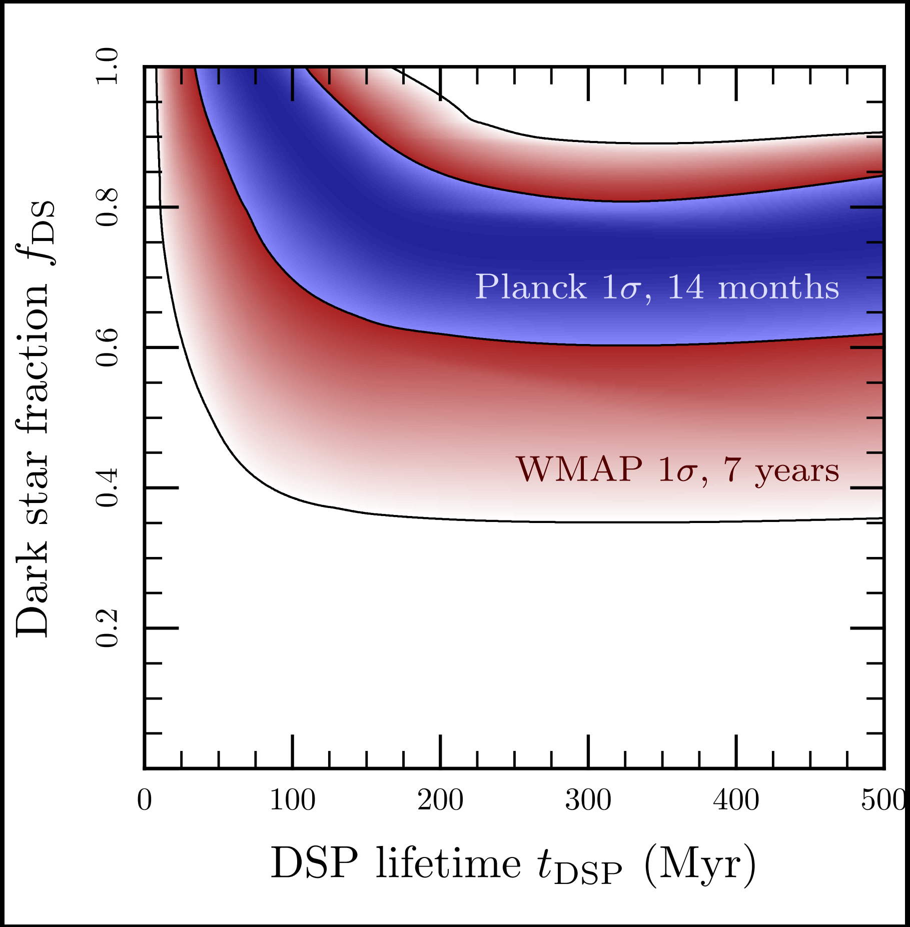
Scott, Venkatesan, Roebber, Gondolo, Pierpaoli, Holder 2011

WMAP7 excludes the region outside the red band

Planck will probe the blue band

Star formation efficiency and UV photon escape rate shift these regions substantially.

With extended capture

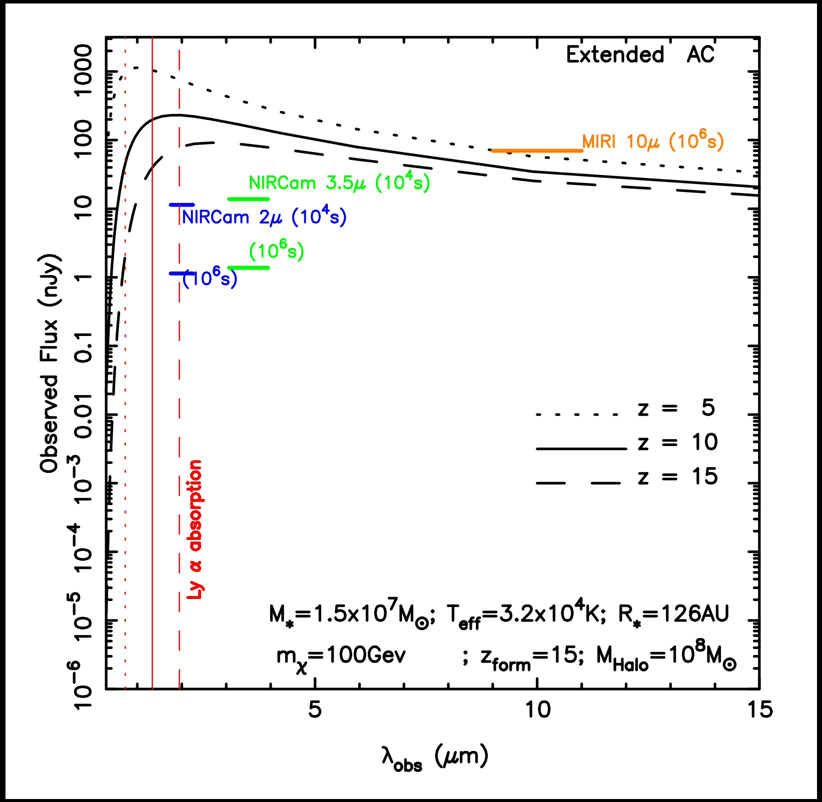


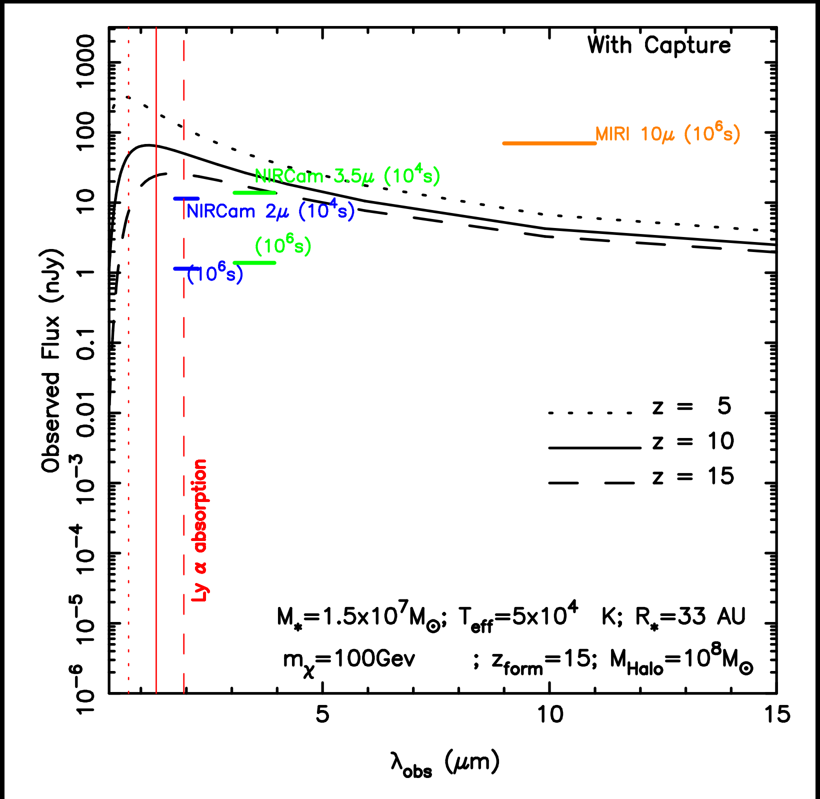
Finding dark stars with JWST

Dark stars at redshift z~6-15 are too dim to be detected, but....

Idea: Dark stars may become supermassive

Freese et al 2010





Finding dark stars with JWST

Dark stars at redshift z~6-15 are too dim to be detected, but....

Idea: Use a magnifying lens

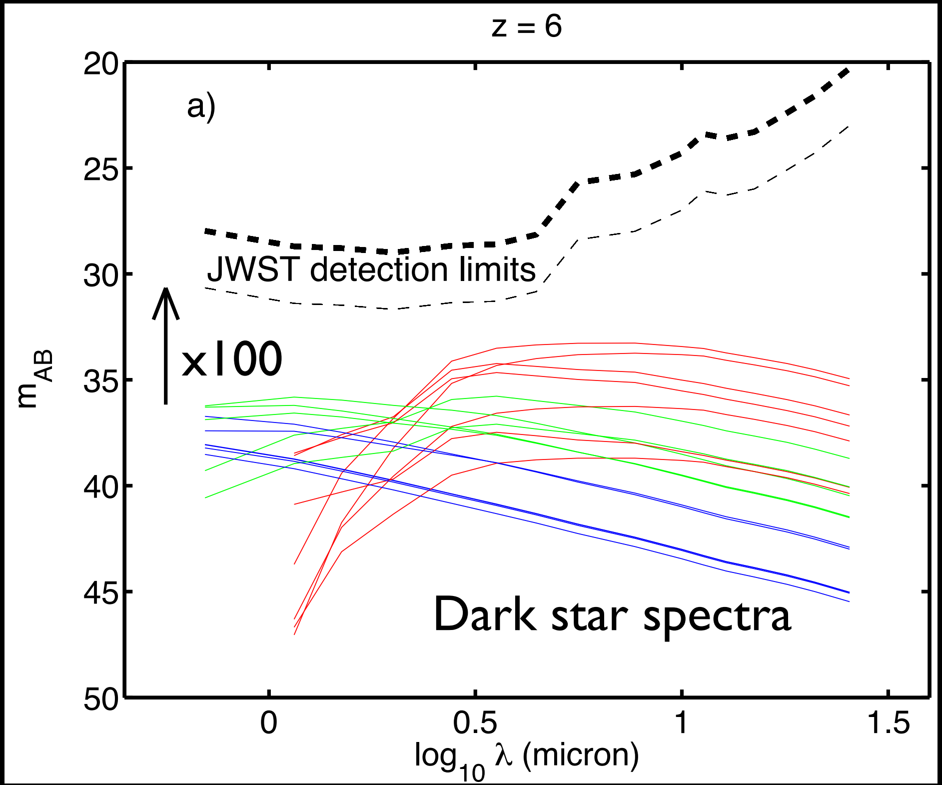
Zackrisson et al 2010

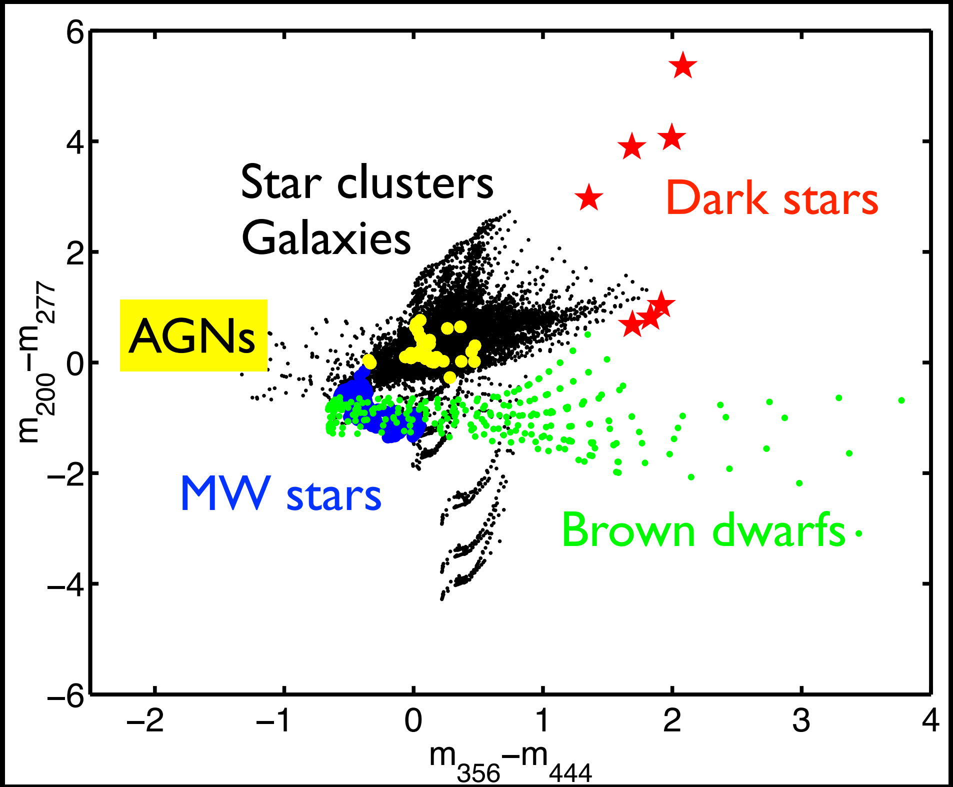
Finding dark stars with JWST

Dark stars at redshift z~6-15 are too dim to be detected, but....

Idea: Use a magnifying lens *Zackrisson et al 2010*

Detectable with JWST via gravitational lens magnification ~100





Conclusions

Dark Stars are stars made of ordinary matter that shine thanks to the annihilation of dark matter.

The first stars to form in the universe may have been powered by dark matter annihilation instead of nuclear fusion.

- Explain chemical elements in old halo stars
- Explain origin of supermassive black holes in early quasars