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

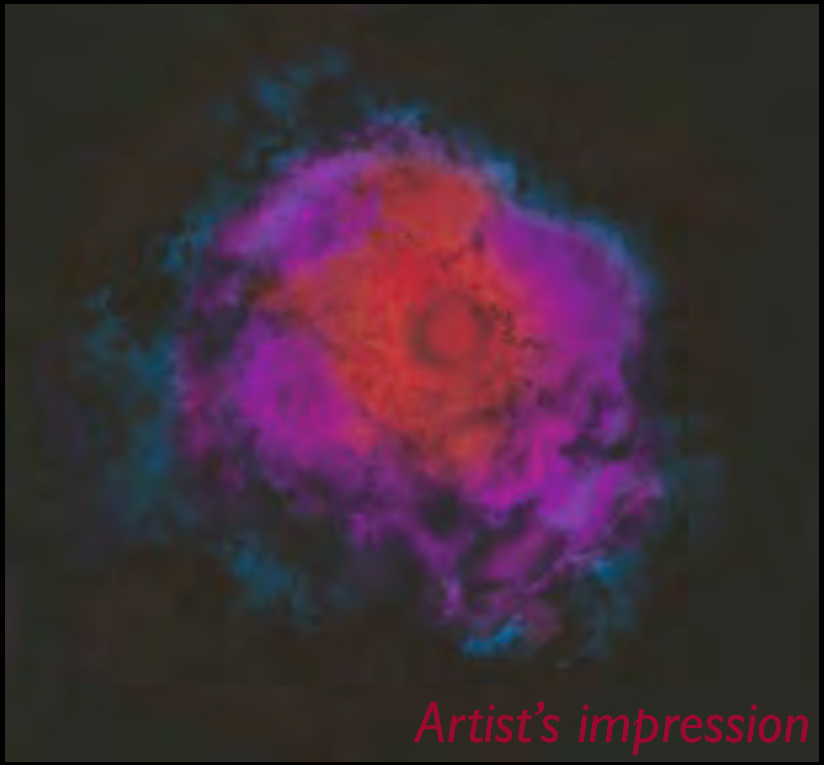
Dark Stars are stars made of ordinary matter that shine thanks to the annihilation of dark matter.

Paolo Gondolo
University of Utah

The original Pop III 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*

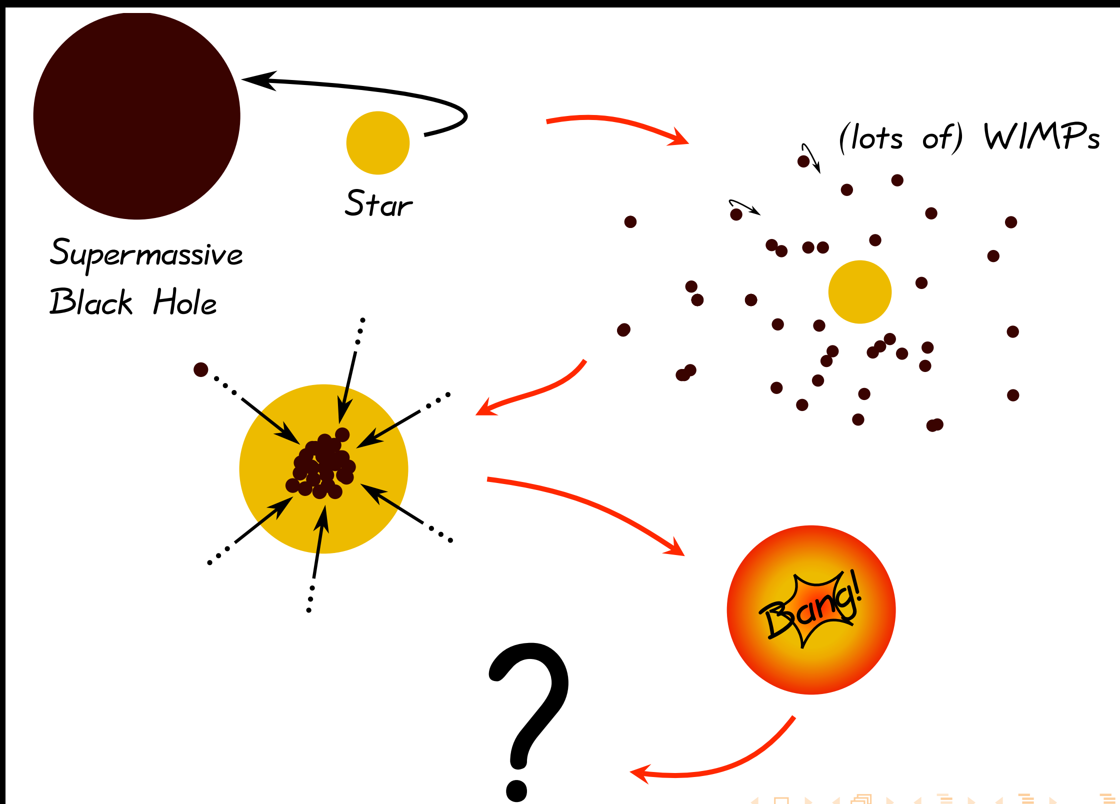


- Explain chemical elements in old halo stars
- Explain origin of supermassive black holes in early quasars

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

Stars living in a dense WIMP environment may gather enough WIMPs and become Dark Stars



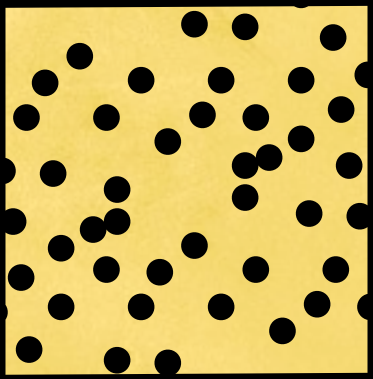
Galactic center example courtesy of Scott

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

Salati, Silk 1989
Moskalenko, Wai 2006
Fairbairn, Scott, Edsjo 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

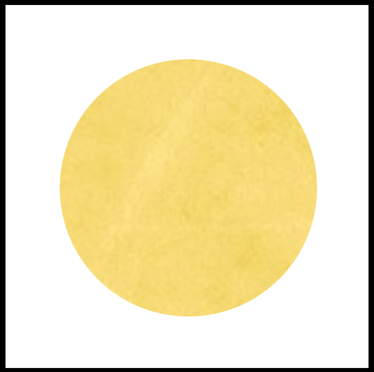
How do WIMPs get into stars?

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)

What do WIMPs do to stars?

"If heavy neutrinos exist, they would substantially affect stellar evolution. They could [...] provide an additional source of luminosity through annihilation, and increase the rate of energy transport."

Steigman, Sarazin, Quintana, Faulkner 1978

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.

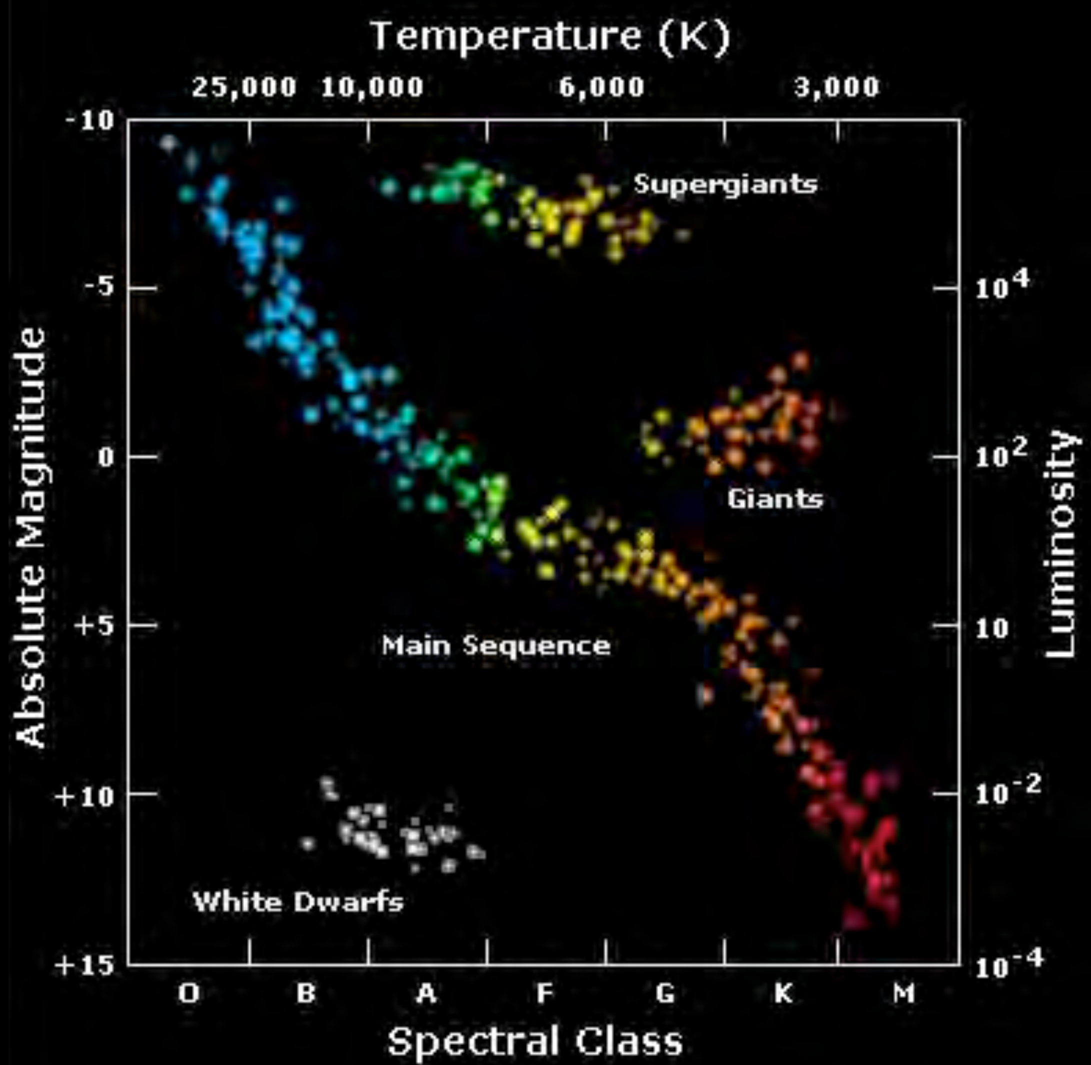
May provide a new way to transport energy

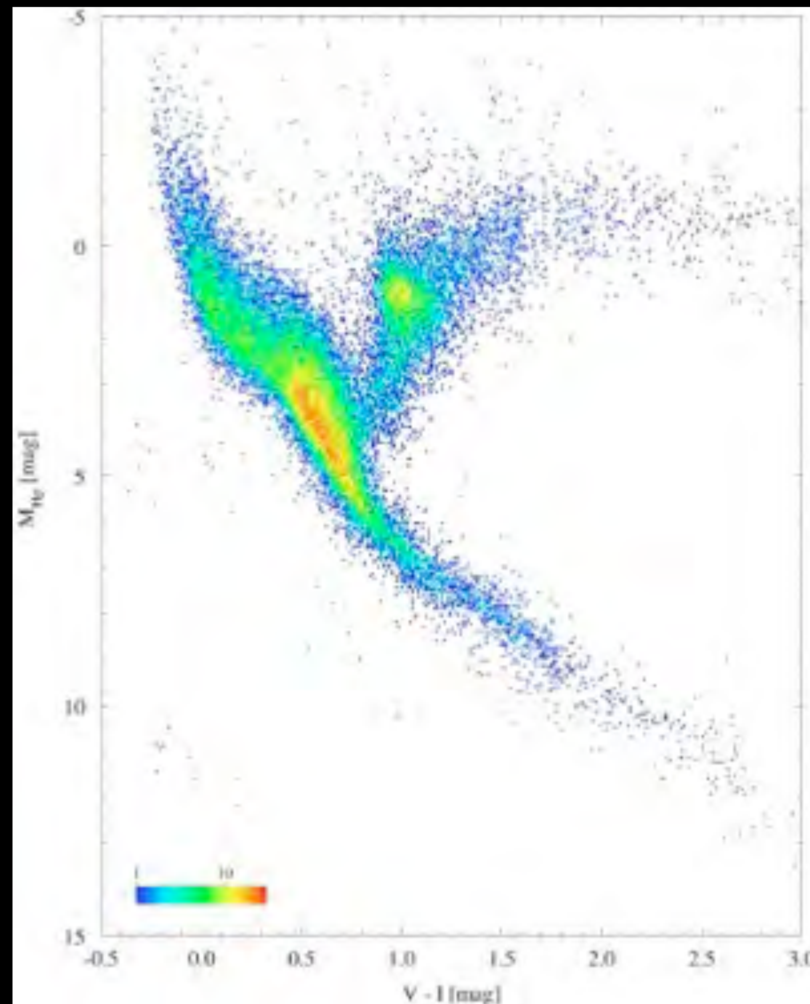
Ordinary stars transport energy outward by radiation and/or convection.
WIMPs with long mean free paths provides additional heat transport.

May produce a convective core (or become fully convective)

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

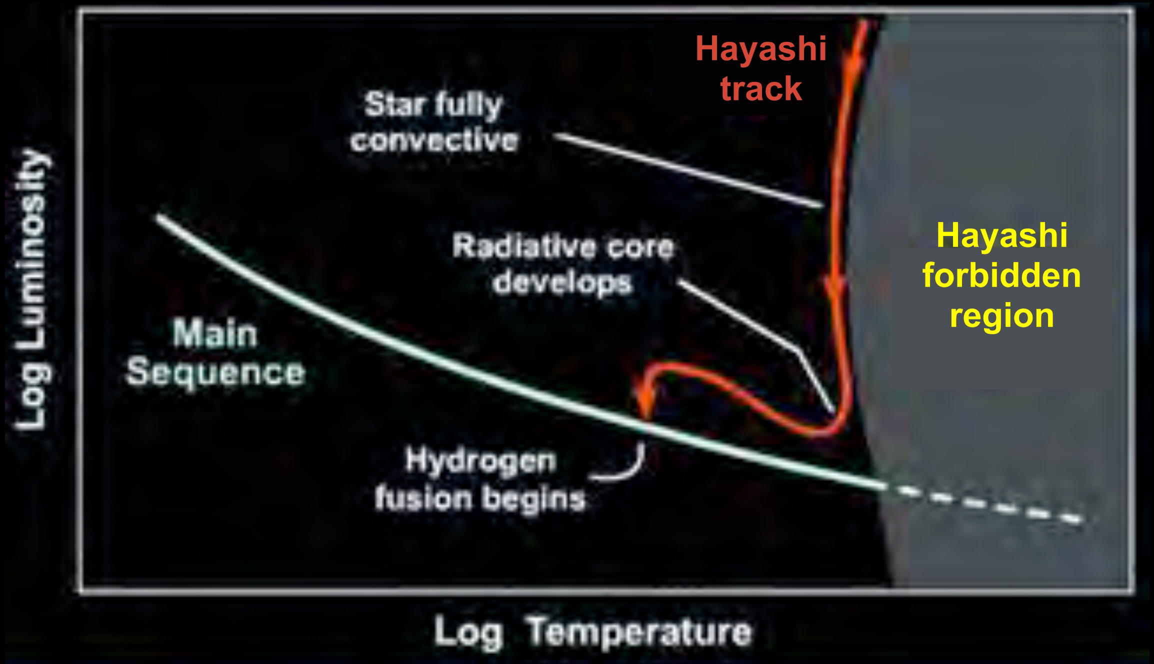
The Hertzsprung-Russell diagram

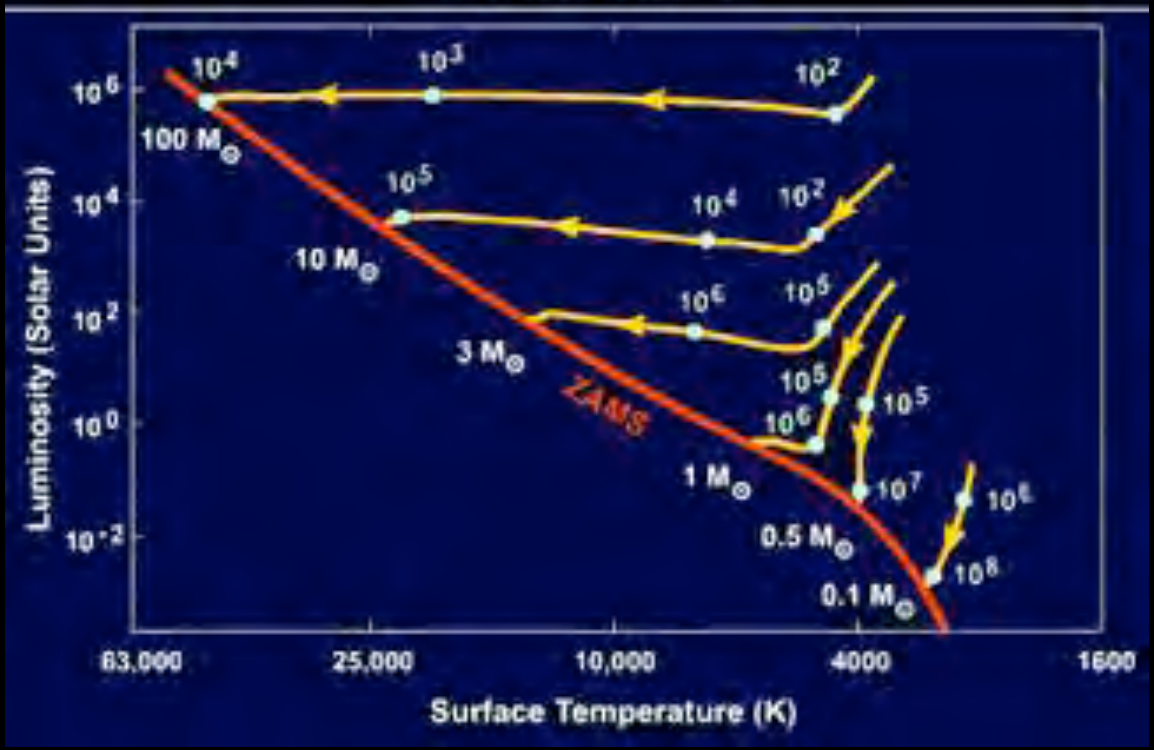




HIPPARCOS

Formation of ordinary stars





Two ways of gathering dark matter

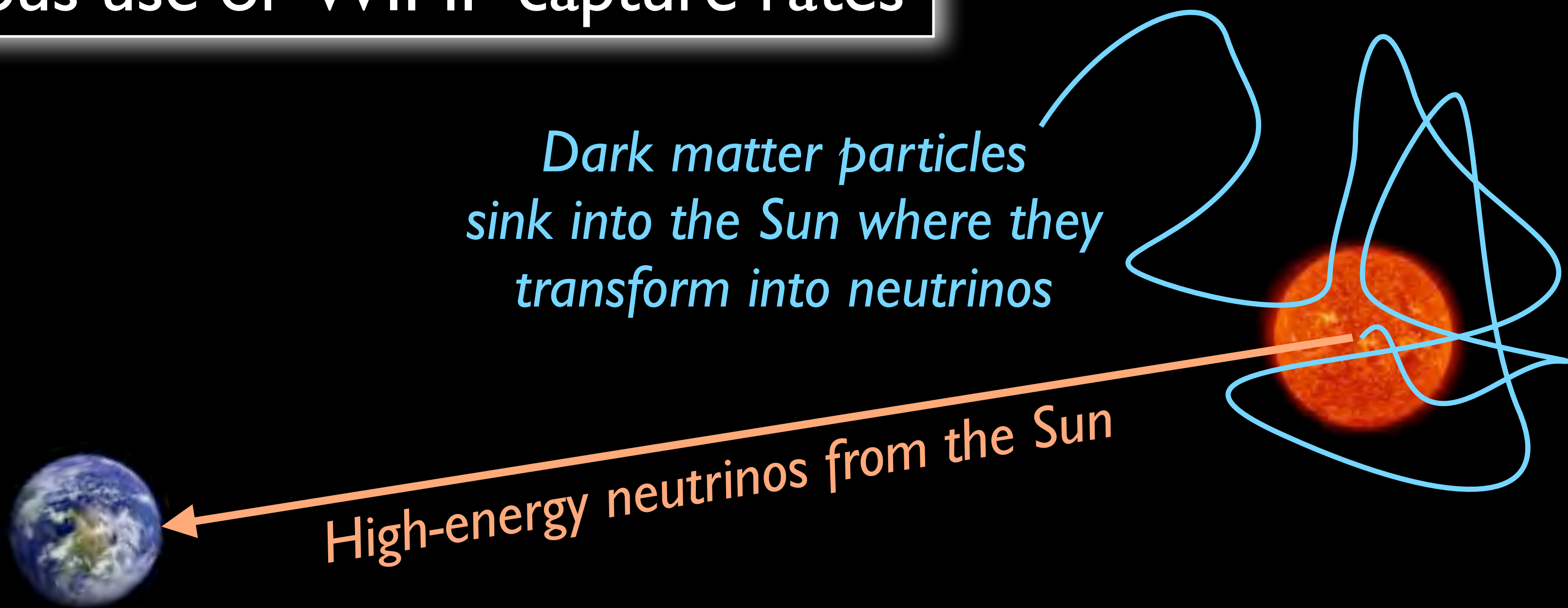
- *By gravitational contraction*: when object forms, dark matter is dragged in into deeper and deeper potential
  - adiabatic contraction of galactic halos due to baryons
    (Zeldovich et al 1980, Blumenthal et al 1986)
  - dark matter concentrations around black holes
    (Gondolo & Silk 1999)
  - 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)

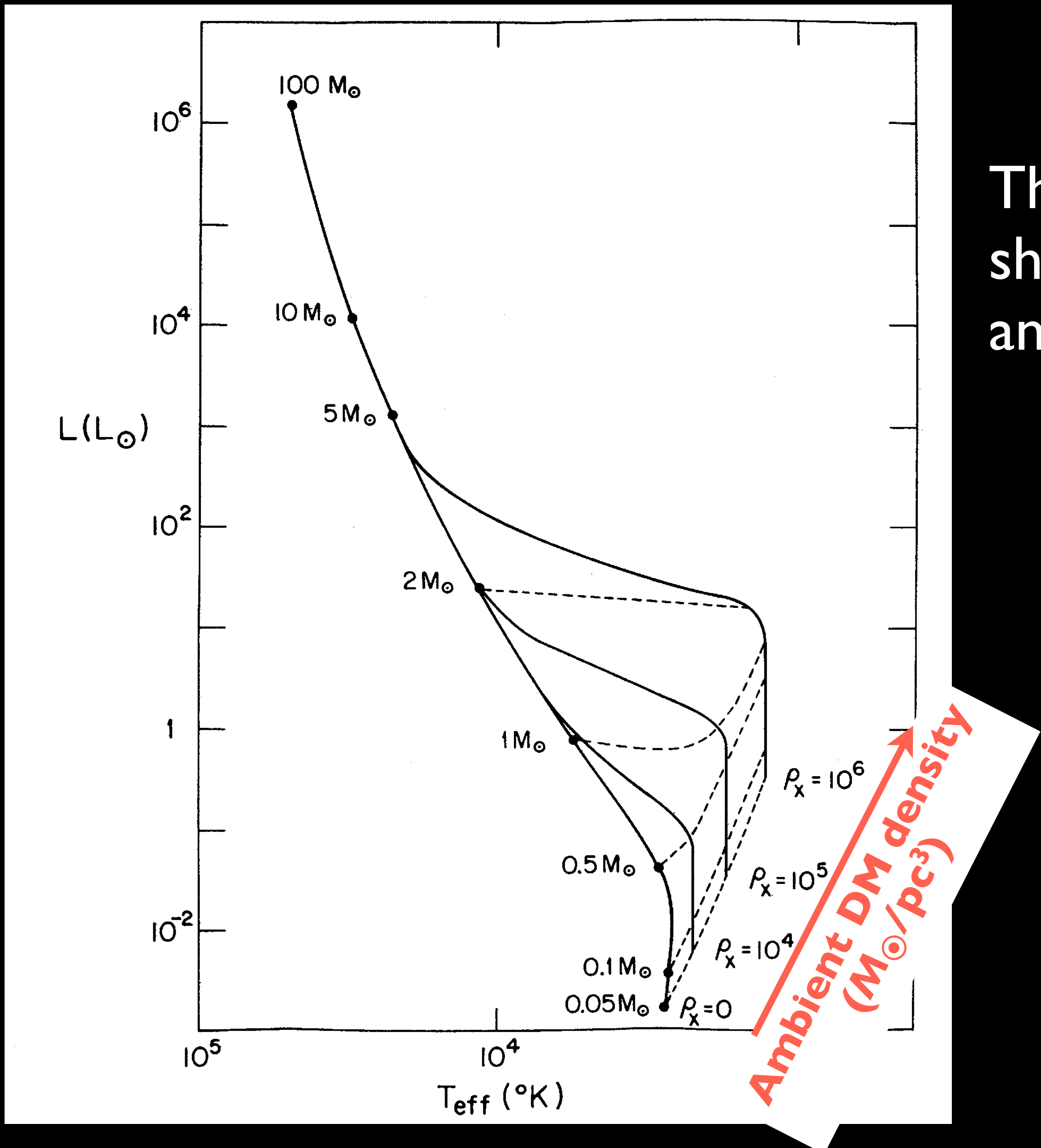
Dark Stars by capture

In equilibrium, the annihilation rate equals the capture rate, so the total WIMP luminosity equals mass x capture rate

Previous use of WIMP capture rates



Dark Stars by capture



The main sequence shifts to lower temperatures and higher luminosities

Salati, Silk 1989

$\sigma = 4\times10^{-36}$ cm^2

v=300 km/s

$\rho \leq 4\times10^7$ GeV/cm^3

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

Dark Stars by capture

Main sequence star inside a WIMP cloud

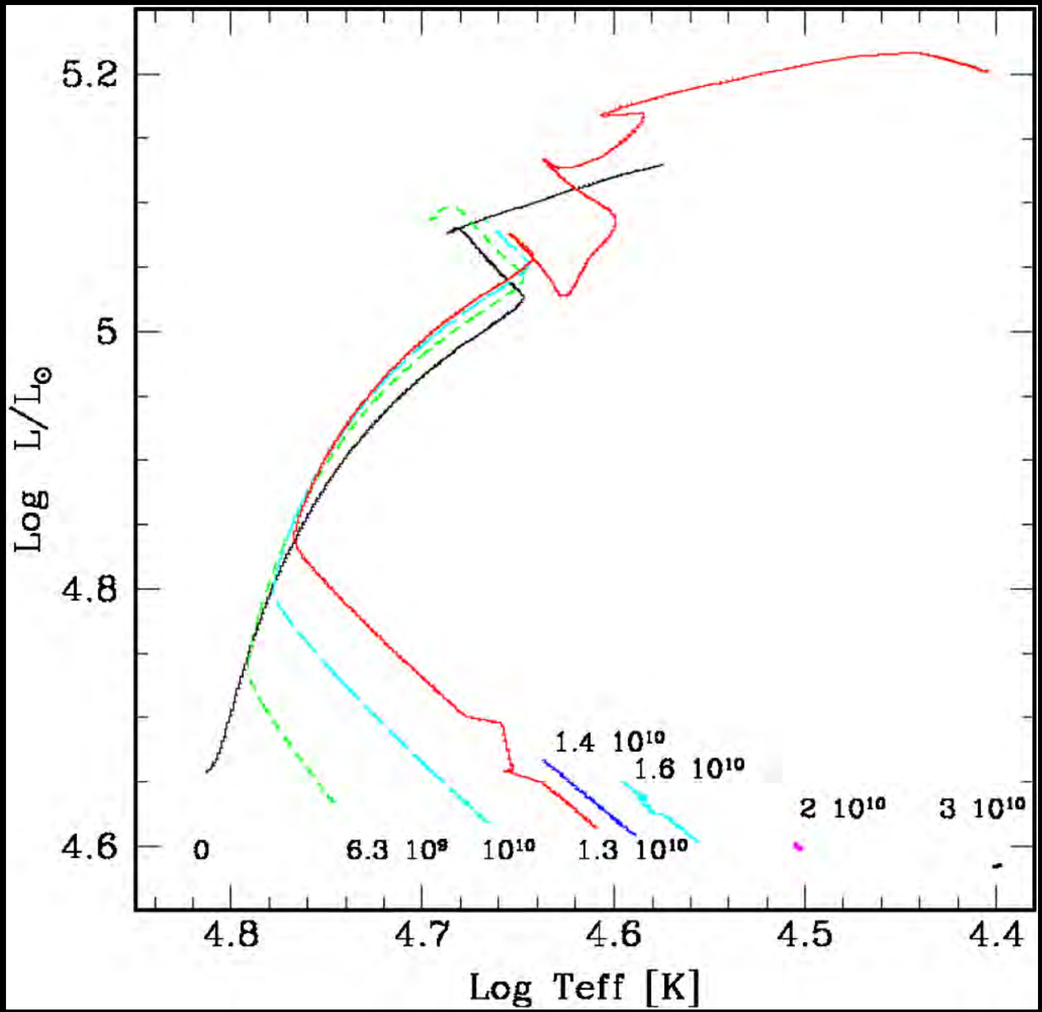
Geneva evolution code

$\sigma_{SD}=10^{-38}$ cm^2

v=10 km/s

10^8 GeV/cm^3 <ρ< 10^{11} GeV/cm^3

Lifetime longer than age of Universe for ρ≳5x10^{10} GeV/cm^3



Taoso, Bertone, Meynet, Ekstrom 2008

Dark Stars by capture

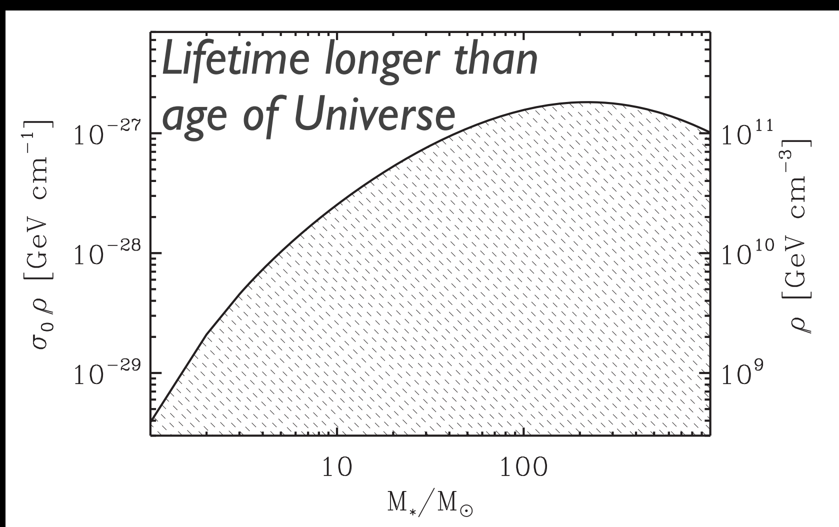
Zero metallicity star at redshift $z \approx 20$

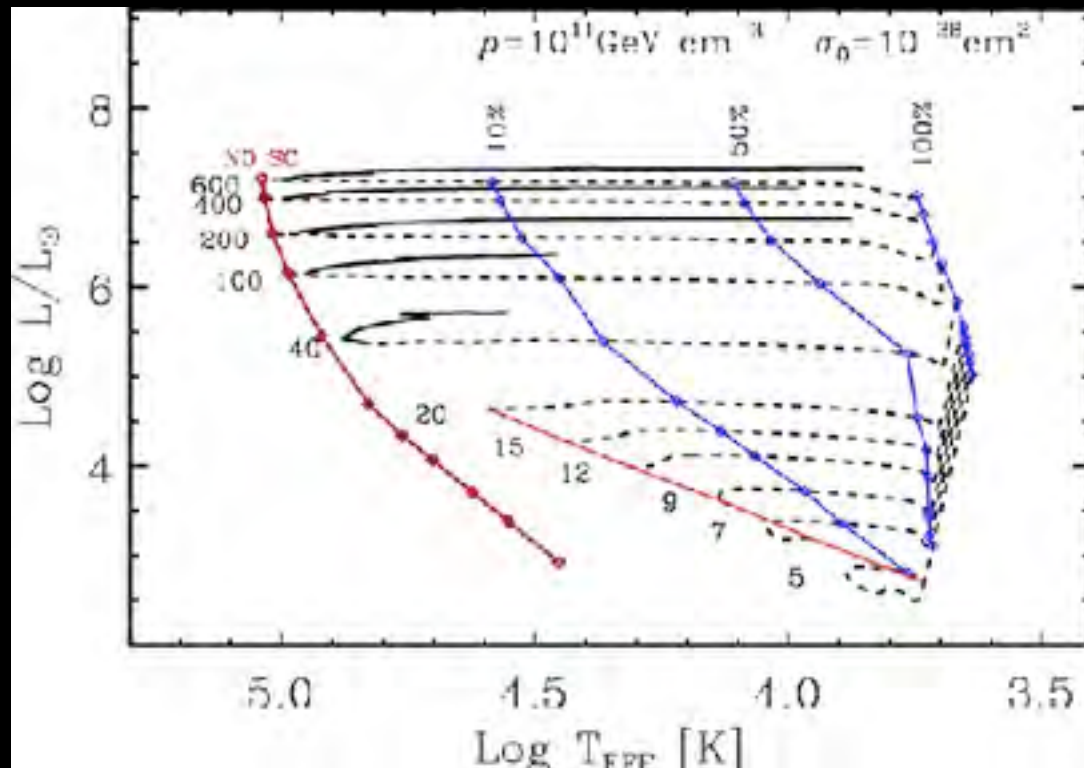
Modified Padova stellar code

$\sigma_{SD} = 10^{-38}$ cm^2

v=10 km/s

10^8 GeV/cm^3 $< \rho < 10^{12}$ GeV/cm^3

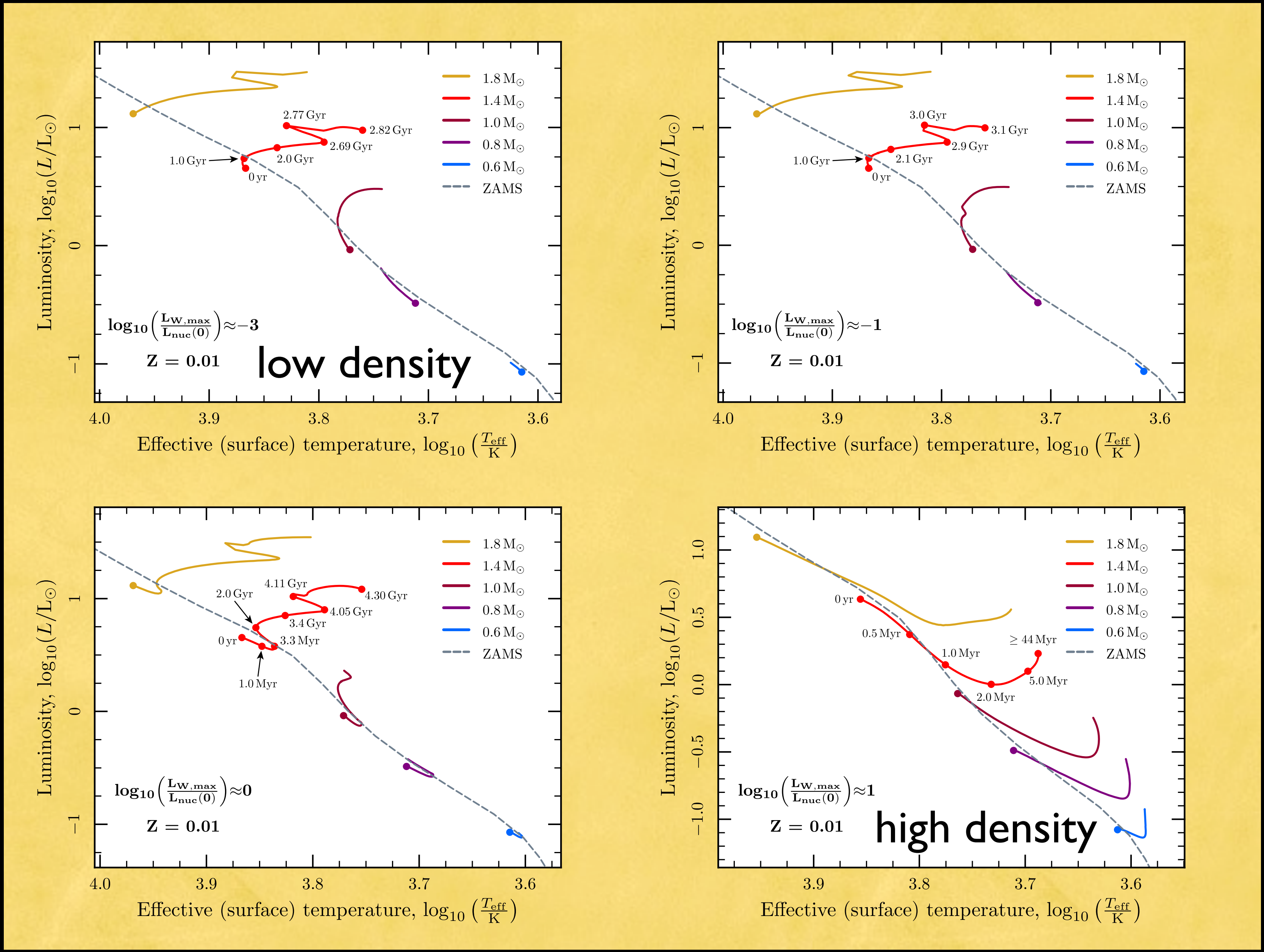




Iocco, Bressan, Ripamonti, Ferrara, Marigo 2008

Dark Stars by capture

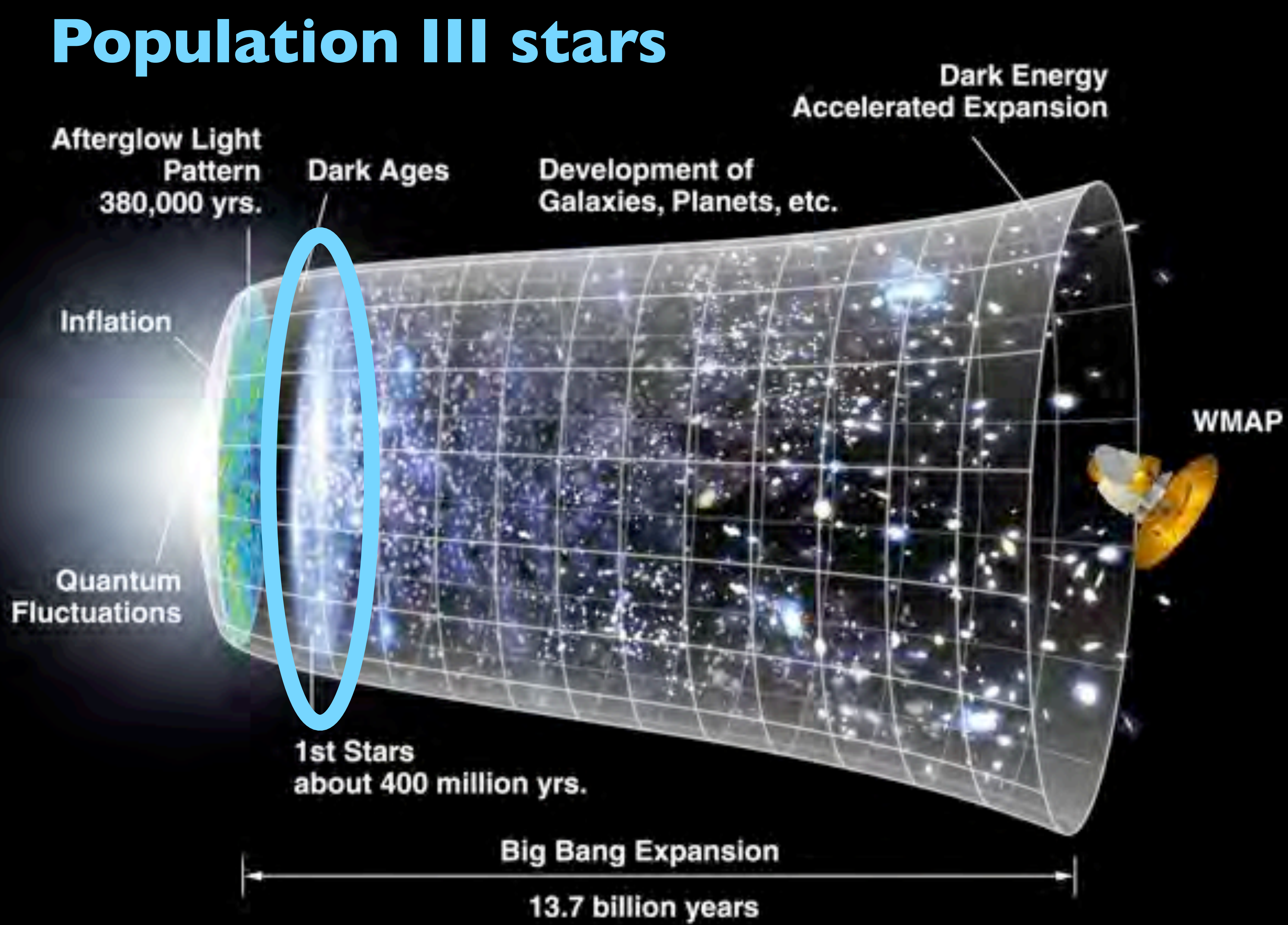
Main sequence star entering a WIMP cloud



DarkStars evolution code (based on EZ)

Scott, Fairbairn, Edsjo 2009

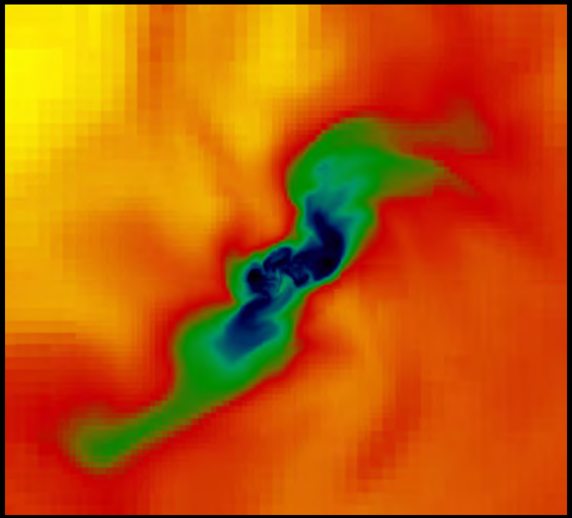
Dark Stars by contraction



Dark Stars by contraction

First Stars: Standard Picture

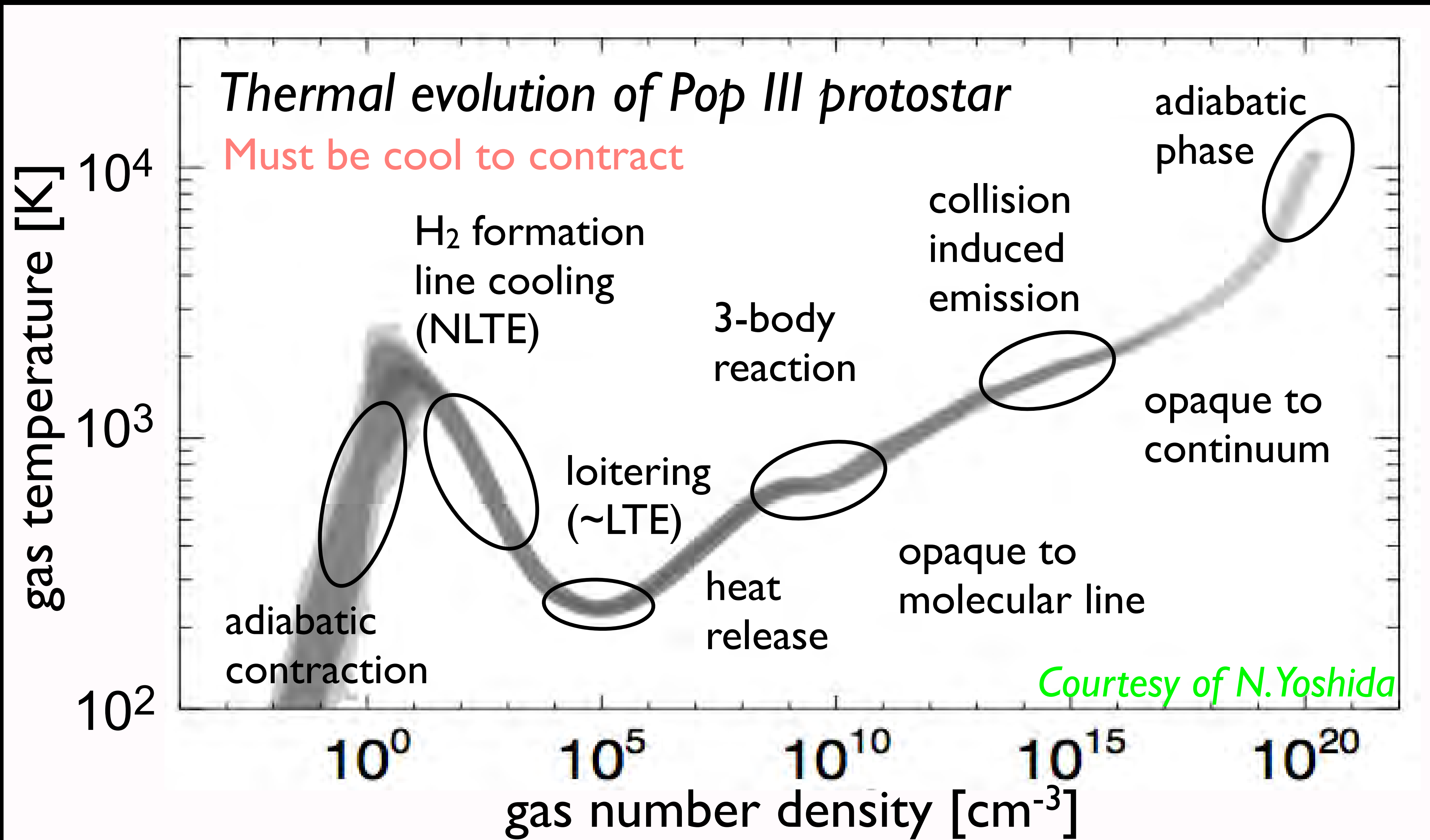
- Formation Basics
  - first luminous objects ever
  - made only of H/He
  - form inside DM halos of 10^5-10^6 $M_\odot$
  - at redshift z=10-50
  - baryons initially only 15%
  - formation is a gentle process



- Dominant cooling mechanism to allow collapse into star is H_2 cooling (Hollenbach & McKee 1979)

Dark Stars by contraction

First Stars: Standard Picture



Dark Stars by contraction

First Stars: Adiabatic Contraction of Dark Matter

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

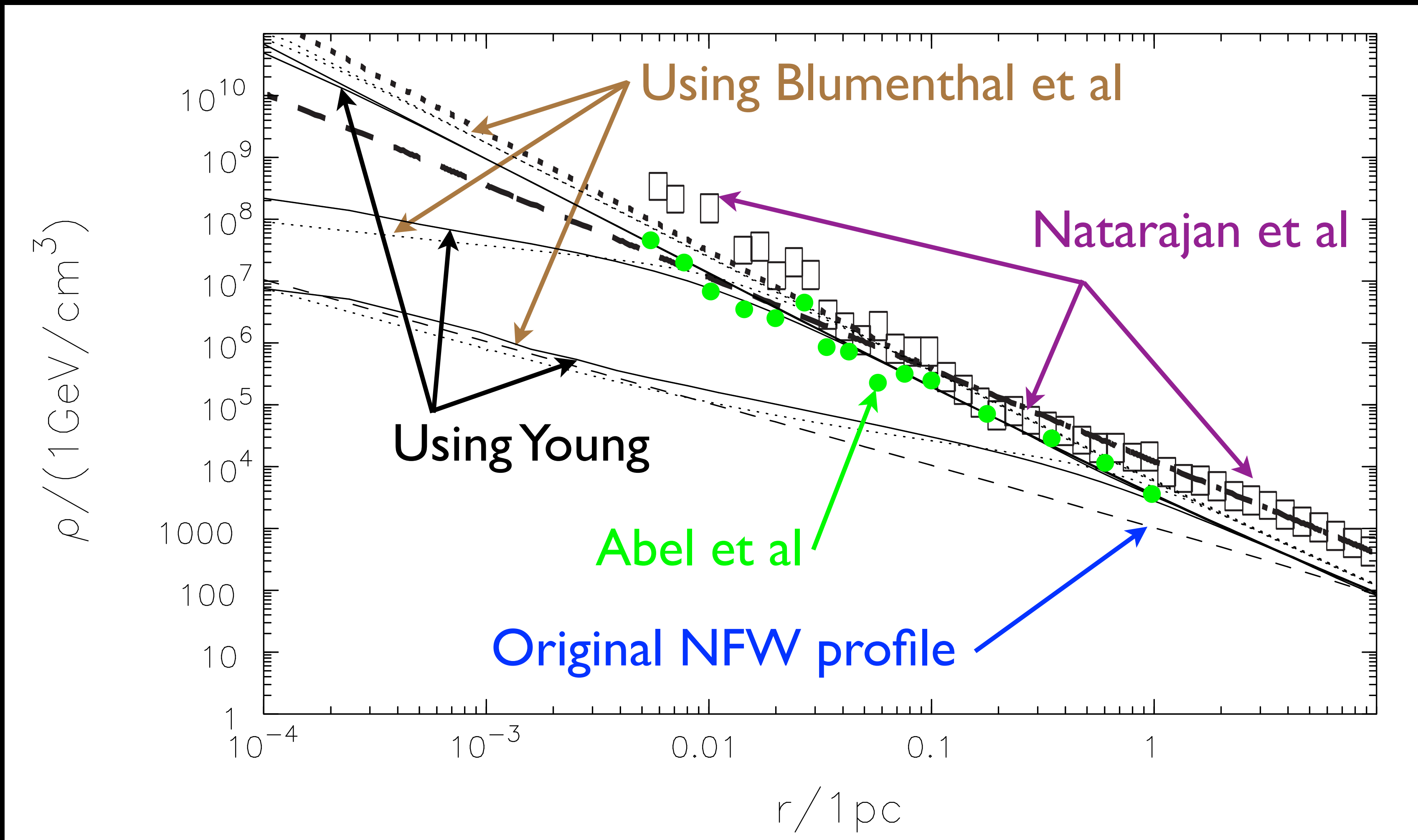
(b) using prescription from Blumenthal, Faber, Flores & Primack 1986 (circular orbits only)
Spolyar, Freese, Gondolo 2008 $r\,M(r) = \text{constant}$

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

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

Dark Stars by contraction

First Stars: Adiabatic Contraction of Dark Matter



Dark Stars by contraction

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

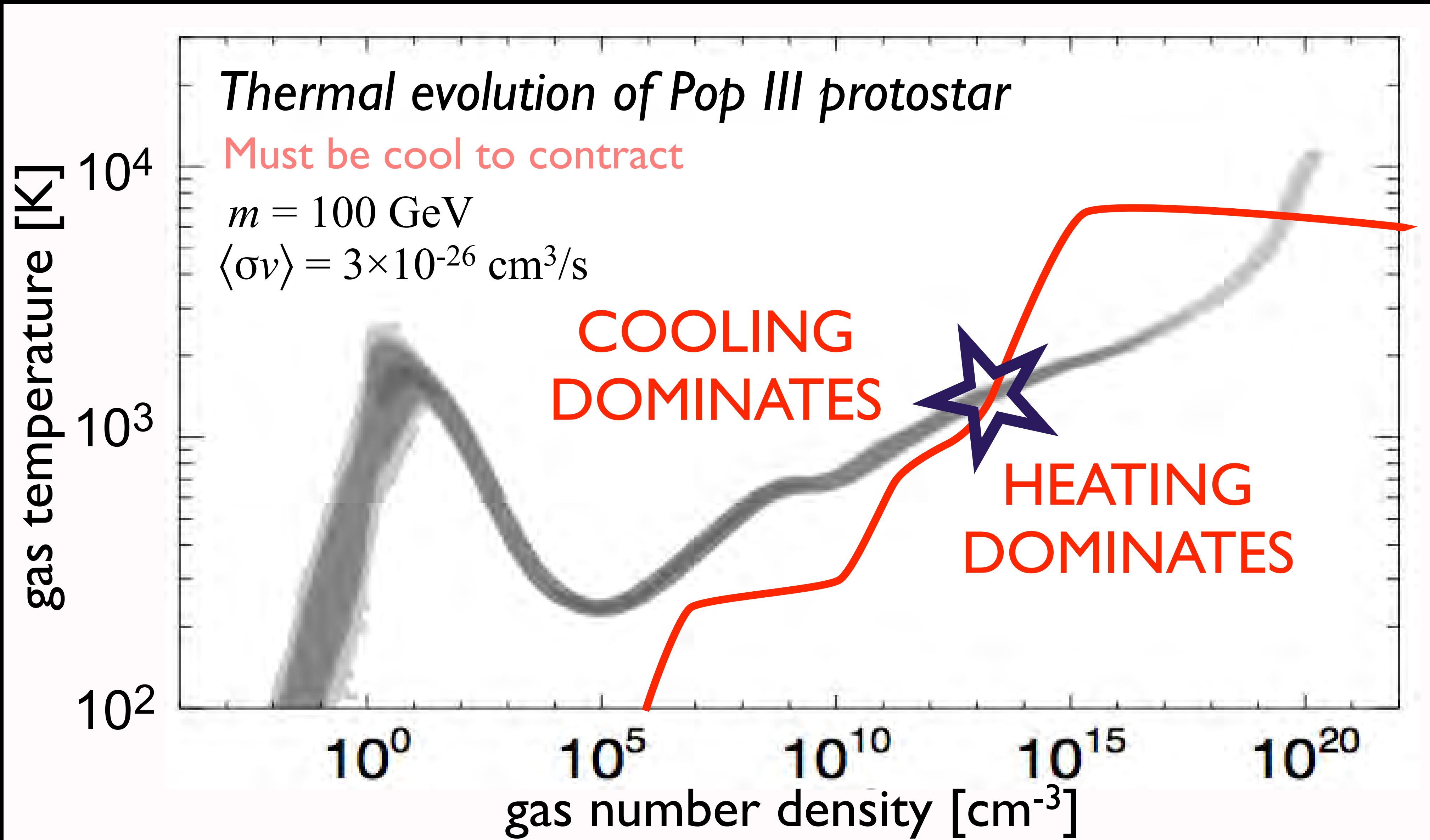
(2) Annihilation products get stuck in star

(3) Dark matter heating beats H_2 cooling

Leads to new stellar phase

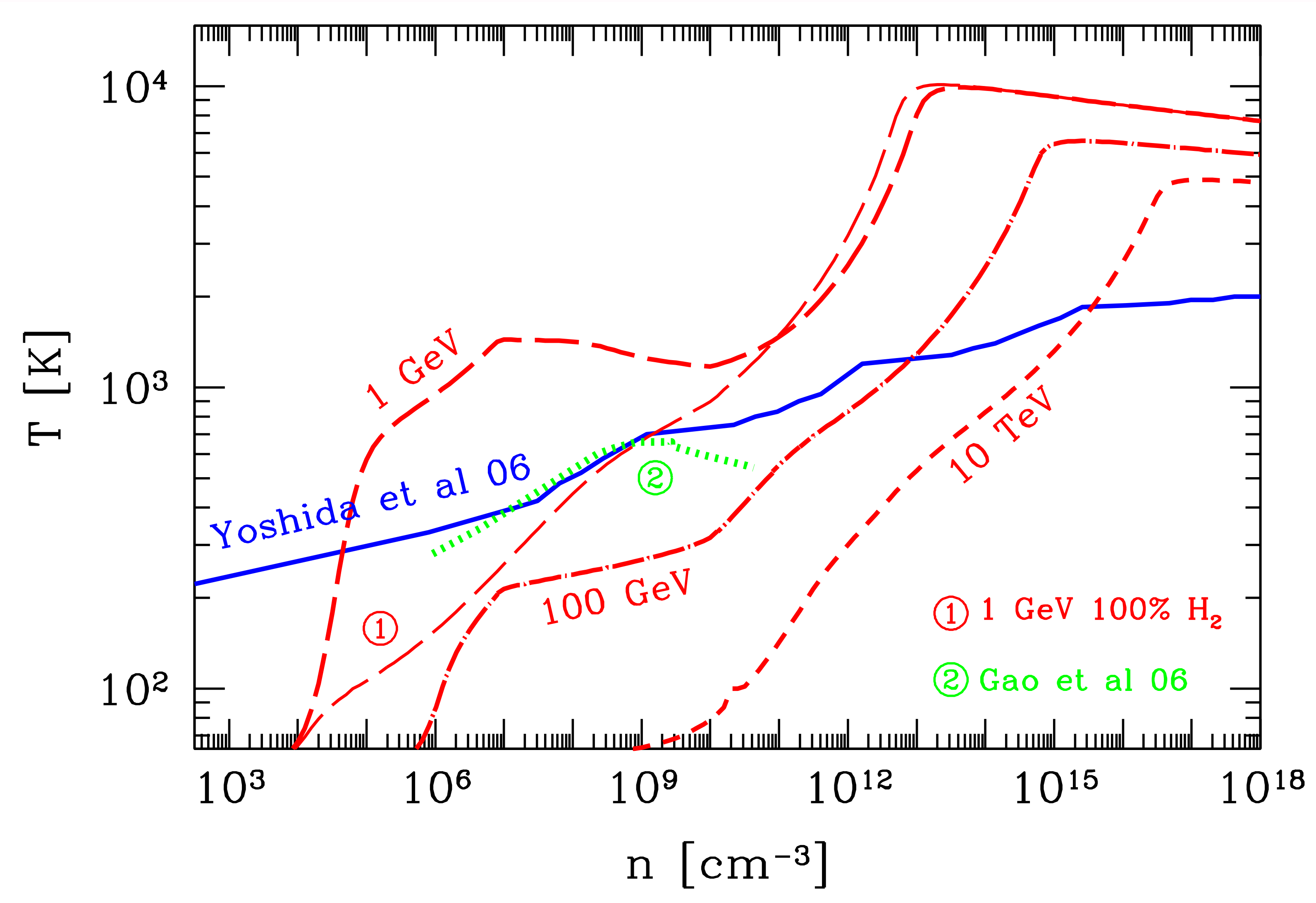
Dark Stars by contraction

First Stars: Birth of a Dark Star



Dark Stars by contraction

First Stars: Birth of a Dark Star



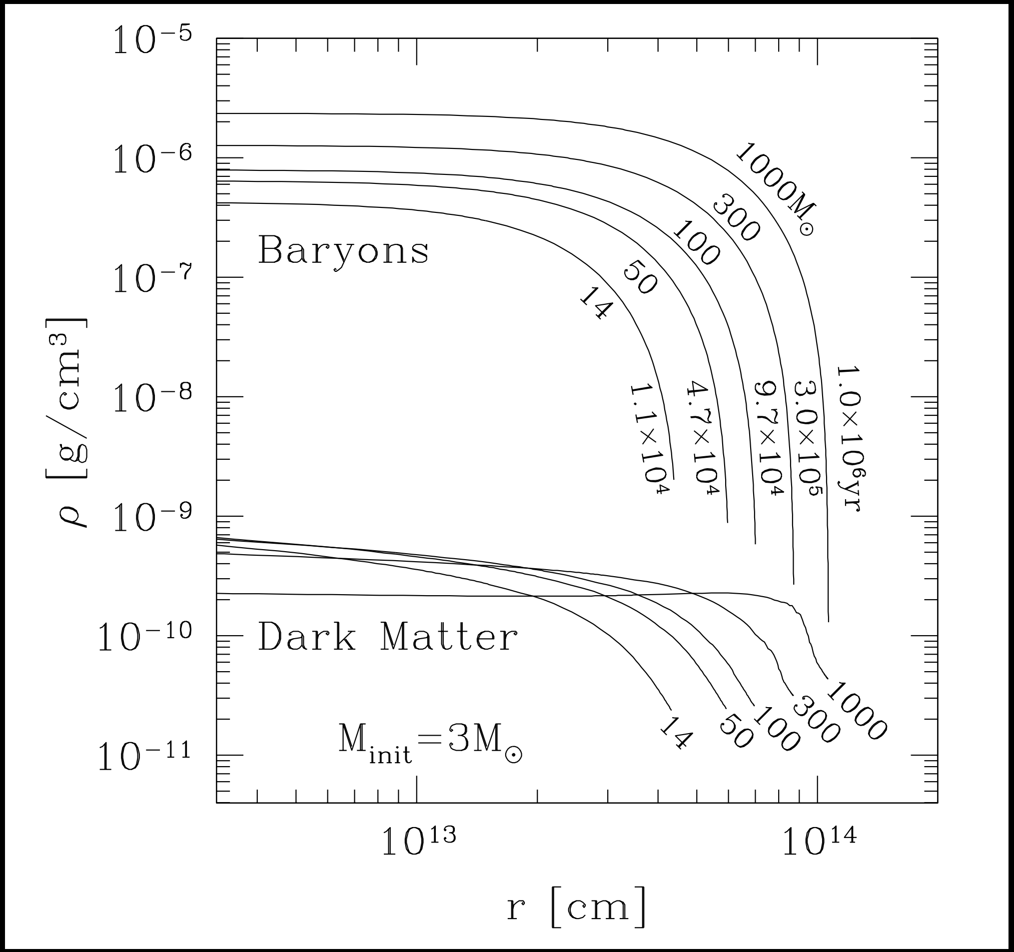
Spolyar, Freese, Gondolo 2008

Wednesday, December 9, 2009

Dark Stars by contraction

First Stars: Birth of a Dark Star

- Dark Star supported by DM annihilation rather than fusion
- DM is less than 2% of the mass of the star but provides the heat source
  (The Power of Darkness)



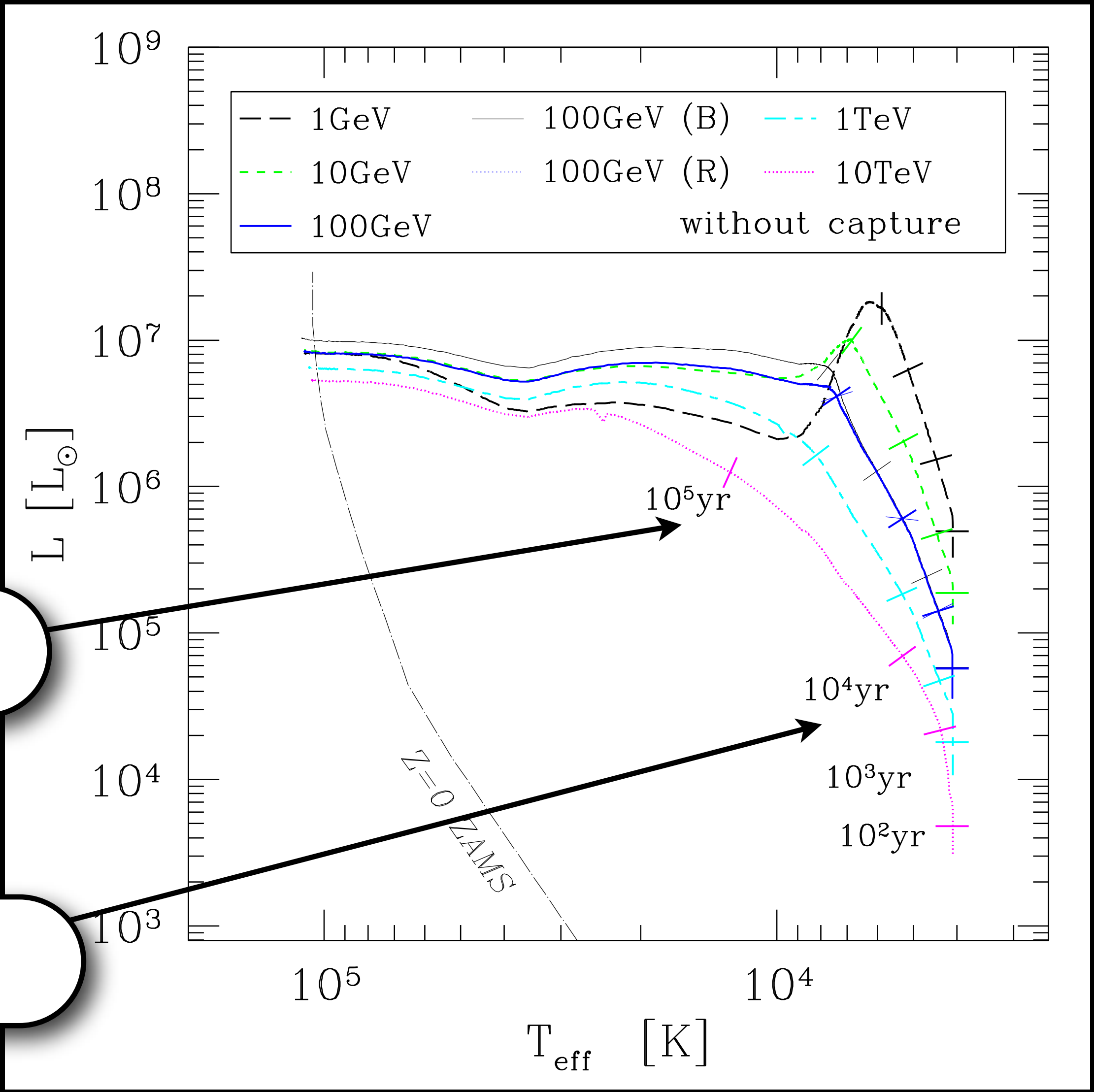
Freese, Bodenheimer, Spolyar, Gondolo 2008

Dark Stars by contraction

First Stars: Life of a Dark Star

Spolyar, Bodenheimer, Freese, Gondolo 2009

Sequence of polytropes with mass and dark matter accretion



Mature Dark Star (stalls for ~5x10^5 yr)

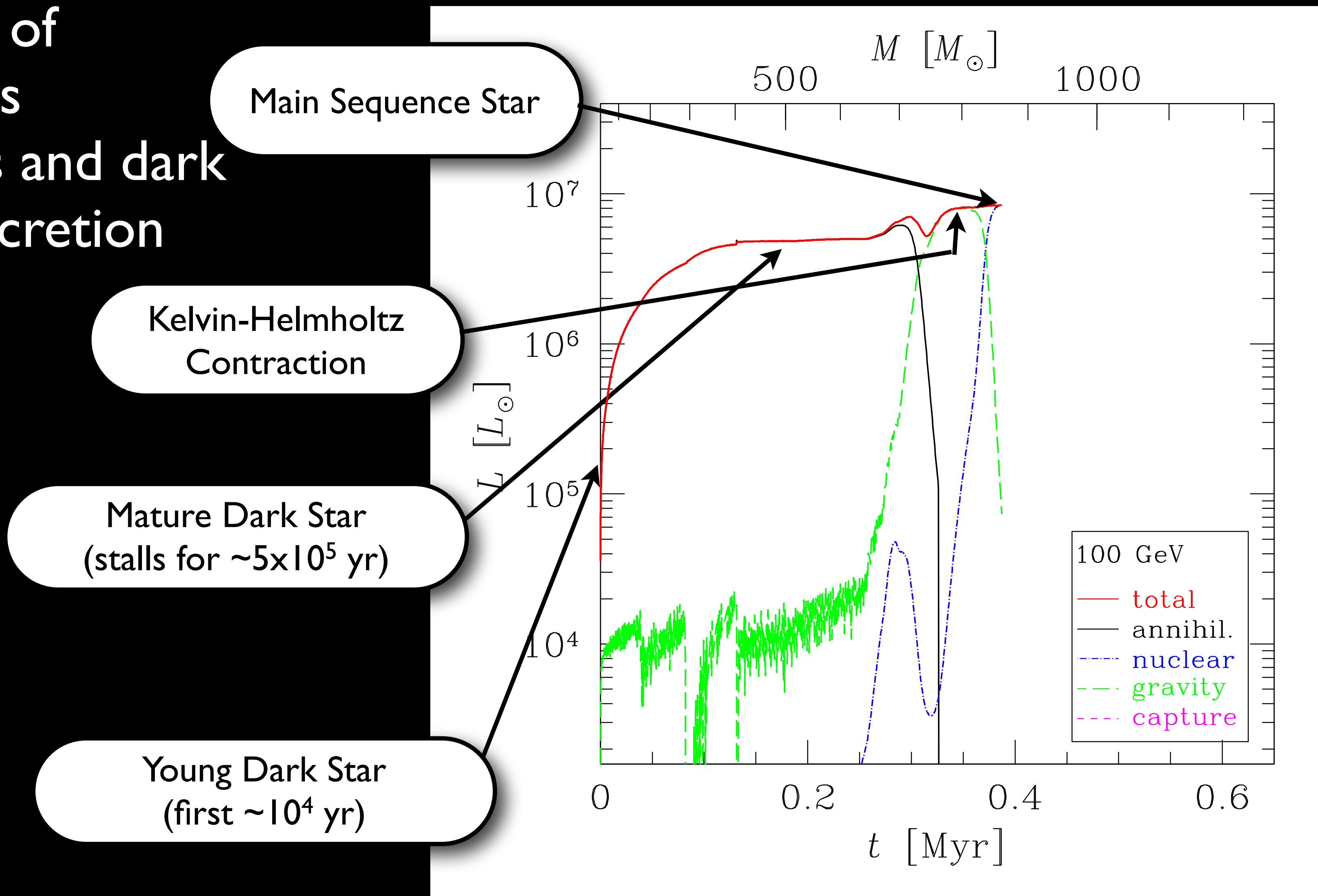
Young Dark Star (first ~10^4 yr)

Dark Stars by contraction

First Stars: Life of a Dark Star

Spolyar, Bodenheimer, Freese, Gondolo 2009

Sequence of polytropes with mass and dark matter accretion



Dark Stars by contraction

First Stars: Life of a Dark Star

Spolyar, Bodenheimer, Freese, Gondolo 2009

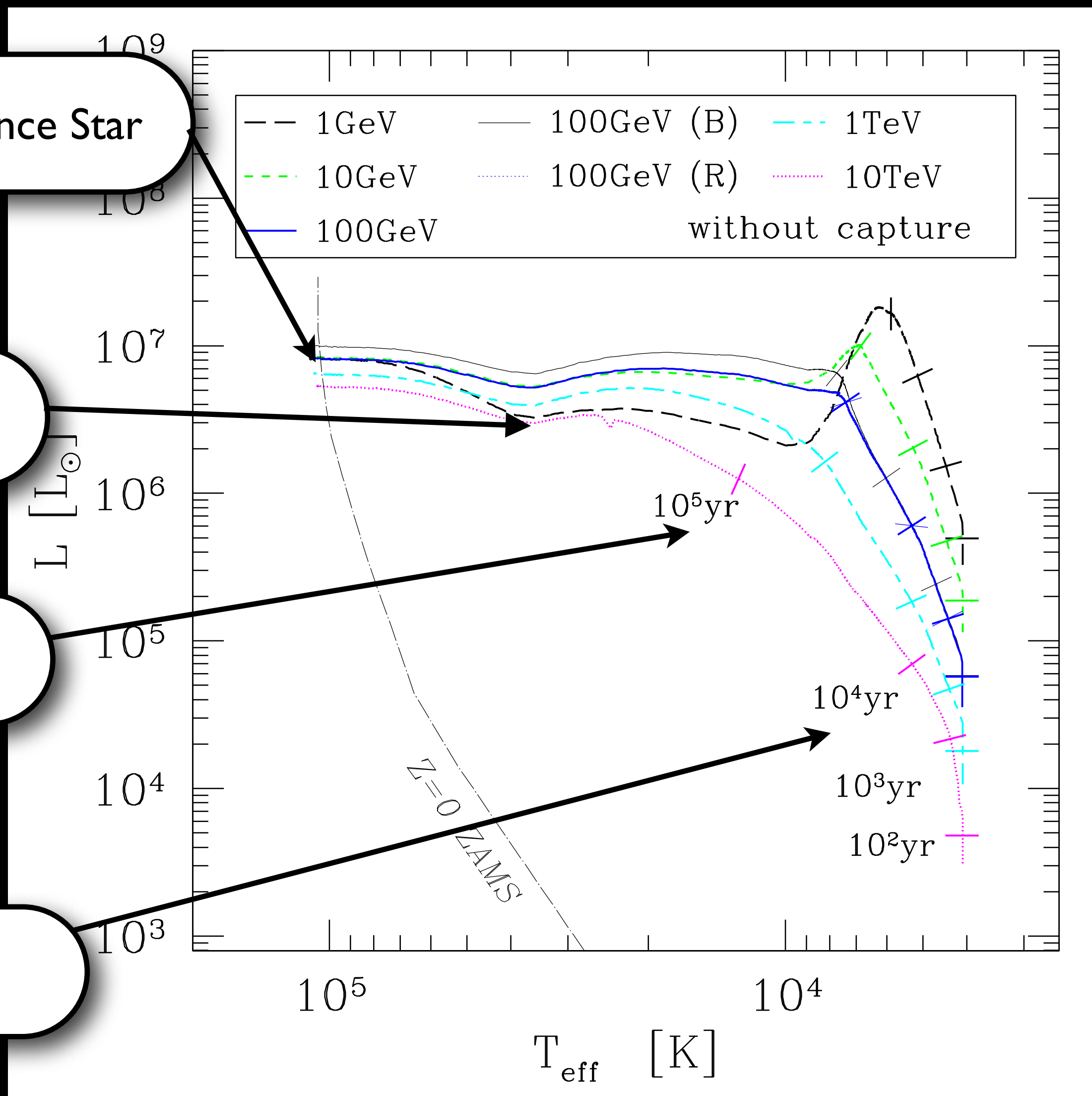
Sequence of polytropes with mass and dark matter accretion

Main Sequence Star

Kelvin-Helmholtz Contraction

Mature Dark Star (stalls for ~5x10^5 yr)

Young Dark Star (first ~10^4 yr)



Dark Stars by contraction

First Stars: 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*

Current questions

- What is the *detailed structure and evolution* of a Dark Star?
- *How long* can a Dark Star capture dark matter?
- How do Dark Stars modify the *reionization history of the universe*?
- How do Dark Stars change the production of heavy elements and the *chemical abundances of the oldest stars*?
- Do Dark Stars evolve into *intermediate-mass or supermassive black holes* that grow into high-redshift quasars?
- Can Dark Stars power *gamma-ray bursts* at high redshift?
- How can we *observe* Dark Stars? JWST, neutrinos, gamma-rays?
- What about *non-WIMP dark matter*?