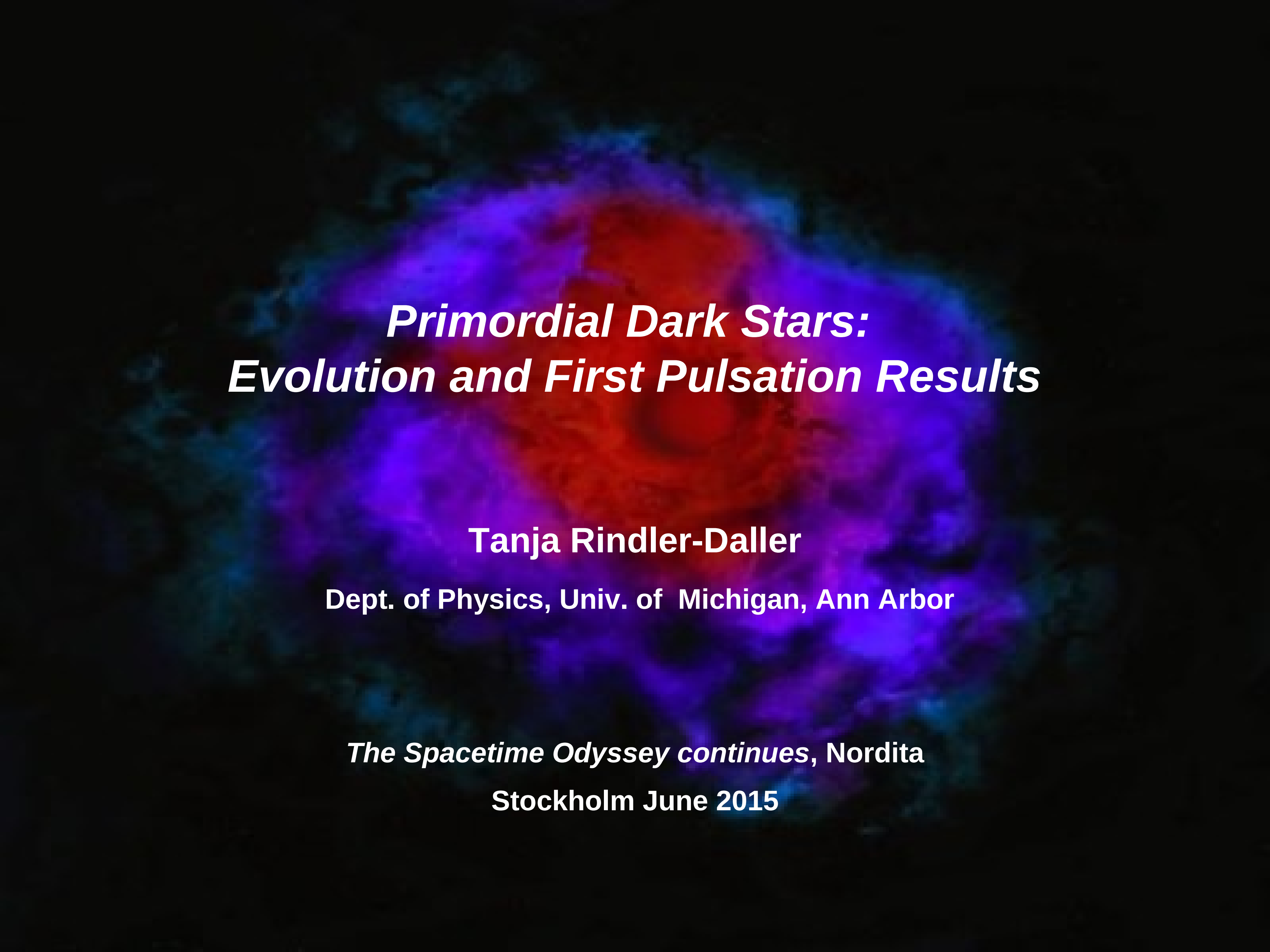

Primordial Dark Stars:
Evolution and First Pulsation Results

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***The Spacetime Odyssey continues*, Nordita**

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Structure formation with WIMP dark matter

- Earth-mass DM clumps merge to form bigger and bigger structures as overdense regions in the Universe assemble hierarchically

- Primordial minihalos with 10^5 -10^7 $M_\odot$ decouple from the Hubble flow at redshifts around z ~ 15-30

- Minihalos will merge to form ever larger halos, eventually up to galactic and cluster scales (e.g. today's Milky Way is made up of many smaller halos which merged in the past)

Baryons in DM potential wells

- Gas (baryonic matter) falls into the overdensity peaks

  provided by DM: when the gas cools, it will fall towards the minihalo center, collapse and lead to star formation

  → the *first stars* !

- molecular cooling prevails over atomic cooling in halos with

  $T_{vir} \lesssim 10^4$ K, i.e. minihalos of $10^6\ M_\odot$ (dep. on z)

→ the first stars are expected to form in those minihalos

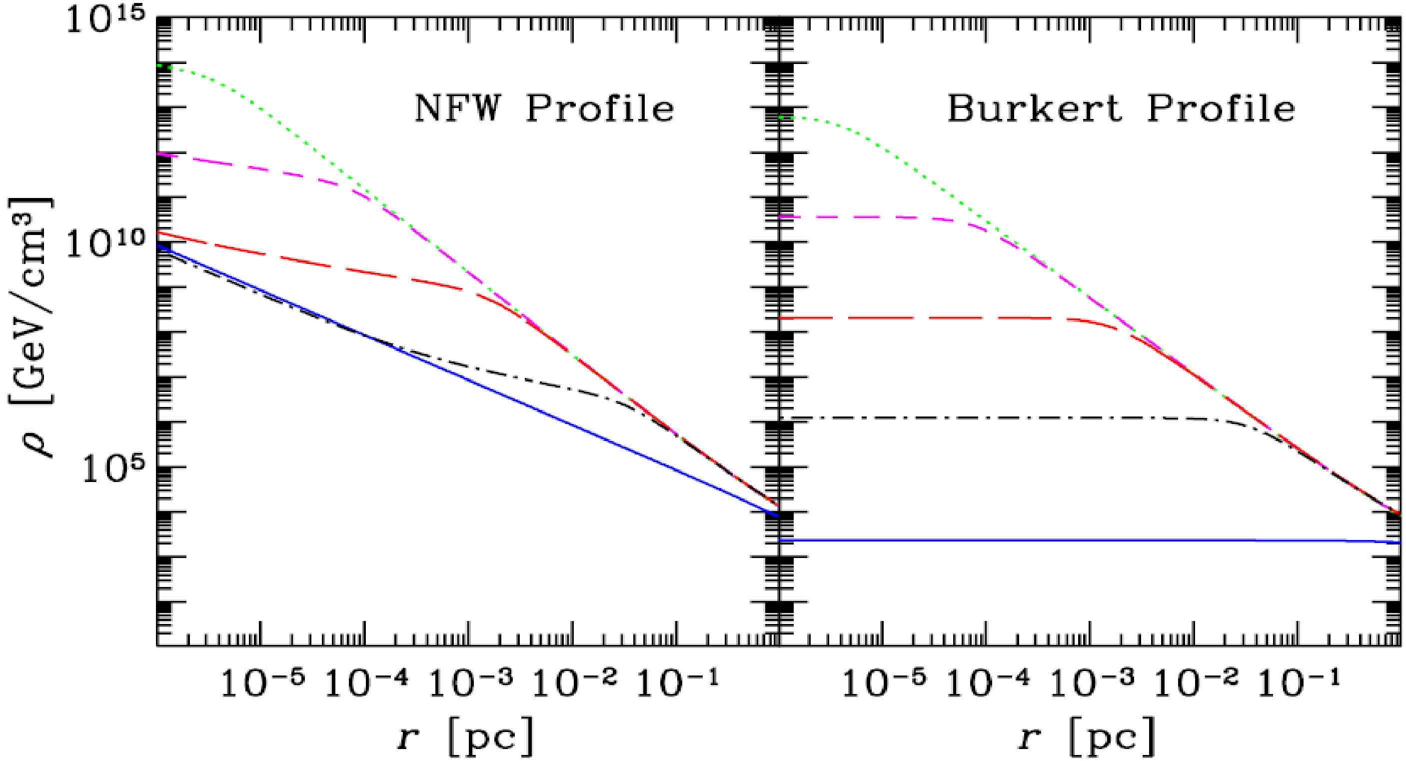
- While gas falls into the halo center, DM is gravitationally pulled in, as well → enhancing its central density !

- Assume that DM follows adiabatically: **“adiabatic contraction”**

  (Blumenthal et al 1986, and many others since)

Adiabatically contracted DM density profiles

Minihalo with $M_{vir} = 10^6 M_\odot$ at z =19 (Spolyar et al 2008)



DM plays a *passive role* in the standard picture of first star formation.

What about the effect of **DM self-annihilation** on the formation and subsequent evolution of the

first stars ? (*active role*)

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What about the effect of **DM self-annihilation** on the formation and subsequent evolution of the first stars ? *(active role)*

- Self-annihilating dark matter (DM):

  DM particle is its own anti-particle in many theories

  -) WIMPs (lightest SUSY particles; Kaluza-Klein particles)

→ self-annihilation responsible for relic density of DM

→ indirect detection signatures are looked for

(Pamela, FERMI-LAT, AMS-02)

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- DM self-annihilation produces heat

  → affecting stellar evolution

  .) present-day stars: less potent and constrained by observations

  .) first stars: much more potent, and yet unconstrained observationally

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→ **DM may give rise to an entirely new class of stellar object:**

“Dark star”: star of primordial composition, but powered by the heat released due to DM self-annihilation

The Dark Star Proposal:

Spolyar, Freese & Gondolo (2008)

The effect of DM heating is more pronounced at the time when first stars form:

- DM density scales as $(1+z)^3$
- First stars form in the central DM peaks of minihalos

Supply for DM "fuel":

- upon collapse, baryons pull in more DM via extended, adiabatic contraction (AC)
- DM on centrophilic orbits pass through center and replenish fuel,

  i.e. refill the loss-cone

  → *these two are pure gravitational effects !*

- at high enough densities, DM replenished by capture from the surroundings, as DM scatters elastically off of nuclei in the star:

  → *this is subject to bounds from WIMP direct detection searches !*

DM heating

DM annihilation rate: $n_\chi^2 \langle \sigma v \rangle$

DM **annihilation** produces **energy** at a rate per unit volume

$$\hat{Q}_{DM} = n_\chi^2 \langle \sigma v \rangle m_\chi = \langle \sigma v \rangle \rho_\chi^2 / m_\chi$$

standard annihilation cross section: $\langle \sigma v \rangle = 3 \times 10^{-26} \mathrm{cm}^3/\mathrm{s}$

Studying a wide range of DM masses is comparable to studying a range of annihilation cross sections

Annihilation products and energy spectrum depend on WIMP model;

for neutralino DM: ~ 1/3 (e- , e+), 1/3 γ, 1/3 ν

Luminosity from DM heating: $L \sim f_Q \int \hat{Q}_{DM} dV$

Once gas density of collapsing cloud is high enough, fraction f_Q of annh.energy deposited into gas → heats it up and slows down collapse; f_Q = 2/3 is typical for WIMPs

(i.e. DM heating is 67 % efficient; compared to 0.7 % efficiency for hydrogen fusion)

The Dark Star Proposal:

Spolyar, Freese & Gondolo (2008)

Critical temperature $T_c(n)$ below which DM heating dominates over all cooling mechanisms: H_2 cooling (dominant), H line cooling, Compton cooling,

at a given gas density n of the molecular cloud core

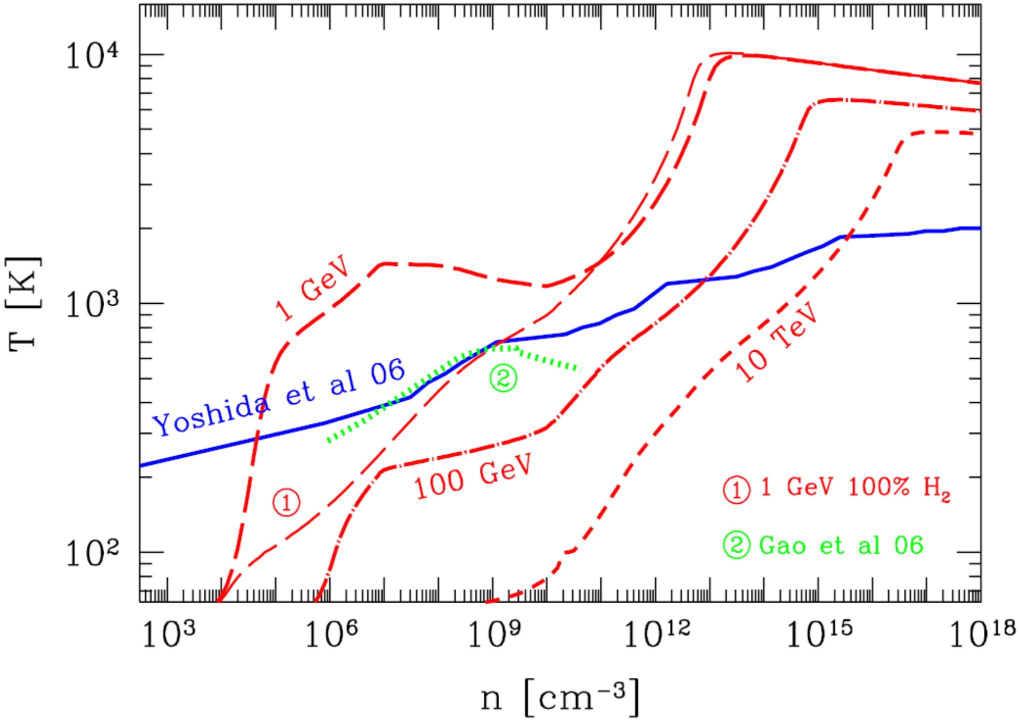
key result:

the evolution tracks and

the critical T-lines always

cross, regardless of

WIMP mass or H_2 fraction



3 criteria for the formation of a dark star

1. High DM density inside the protostar

2. DM annihilation products become trapped inside the protostar

3. DM heating is the dominant heating mechanism in the (proto)star

→ upon further collapse, need to find a regime of hydrostatic equilibrium, provided by DM heating

What **hydrostatic equilibrium** structure results ?

How does this affect the **subsequent evolution** of the star ?

→ need to **study the stellar properties of stars which are powered by DM heating**, instead of nuclear fusion !

→ make quantitative **predictions for observability** to test the dark star scenario

Equations of stellar structure in 1D

$$\frac{dM(r)}{dr} = 4\pi r^2 \rho(r) \qquad \text{conservation of mass}$$

$$\frac{dL(r)}{dr} = 4\pi r^2 \rho(r) \epsilon(r) \qquad \text{conservation of energy}$$

$$\frac{dP(r)}{dr} = -\frac{GM(r)\rho(r)}{r^2} \qquad \text{conservation of momentum (=hydrostatic equilibrium)}$$

$$\frac{dT(r)}{dr} = -\frac{3\kappa(r)\rho(r)L(r)}{16\pi acT^3(r)r^2} \qquad \text{radiative transport}$$

$$\left(\frac{dT(r)}{dr}\right)_{ad} = \frac{\mu m_h GM(r)}{(n+1)kr^2} \qquad \text{convective transport}$$

$$(\Delta\nabla T) = \left[\frac{L^2(r)T(r)}{C_p^2 \rho^2(r) GM(r) \pi^2 l^4 r^2}\right]^{1/3}$$

Microscopic input

$\epsilon = \epsilon[T(r), \rho(r), \mu(r)]$ energy production

$\kappa = \kappa[T(r), \rho(r), \mu(r)]$ radiative opacity

$\gamma = \gamma[T(r), \rho(r), \mu(r)]$ adiabatic index

$P = P[T(r), \rho(r), \mu(r)]$ equation of state

Previous work: polytropic dark star models

Spolyar et al, 2009; Freese et al, 2010

Polytropic EOS: $P = K \rho^{1+1/n}$, n=0,..,4

Key result: while hydrostatic EQ is provided by DM heating due to DM annihilation, *the dark star remains cool enough to continue accreting matter from its surrounding !*

Depending on halo environment, DS can grow to ***supermassive size***

with $M_* \sim 10^4 - 10^7\ M_\odot$, $L_* \sim 10^9 - 10^{11}\ L_\odot$ (Freese et al,2010)

Energy transport in DS with $M_* > 10^3\ M_\odot$ is radiation-dominated

Supermassive DS are described by (n=3)-polytropes

Dark Star evolution:
improved models and first pulsation results

TRD, Montgomery, Freese, Winget, Paxton

arXiv:1408.2082, ApJ 799, 210 (2015)

Use fully-fledged stellar evolution code

MESA

(**M**odules for **E**xperiments in **S**tellar **A**strophysics)

http://mesa.sourceforge.net/

→ improve upon polytropic models

→ study pulsations of dark stars

(i.e. deviations from hydrostatic equlibrium)

Halo environments

- DM: 85 %, baryons: 15 %
- H: 76 %, He: 24 %
- NFW density profile with c = 3.5

SMH: "small halo" : total mass 10^6 M_{sun} at $z = 20$,

accretion rate 10^{-3} M_{sun}/yr

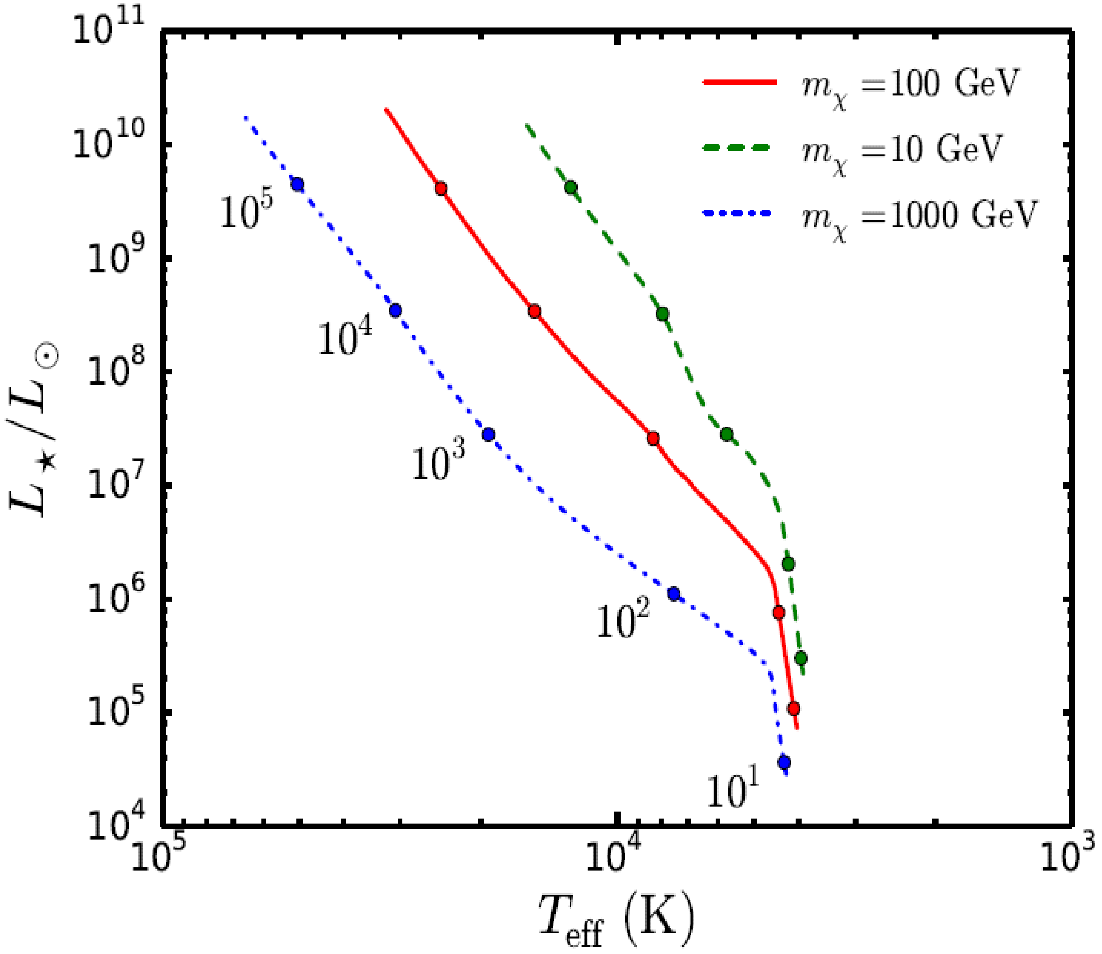
LMH: "large halo" : total mass 10^8 M_{sun} at $z = 15$,

accretion rate 10^{-1} M_{sun}/yr

for $m_\chi = 10, 100, 1000$ GeV

Tracks in the Hertzsprung-Russell Diagram

SMH



Main stellar characteristics

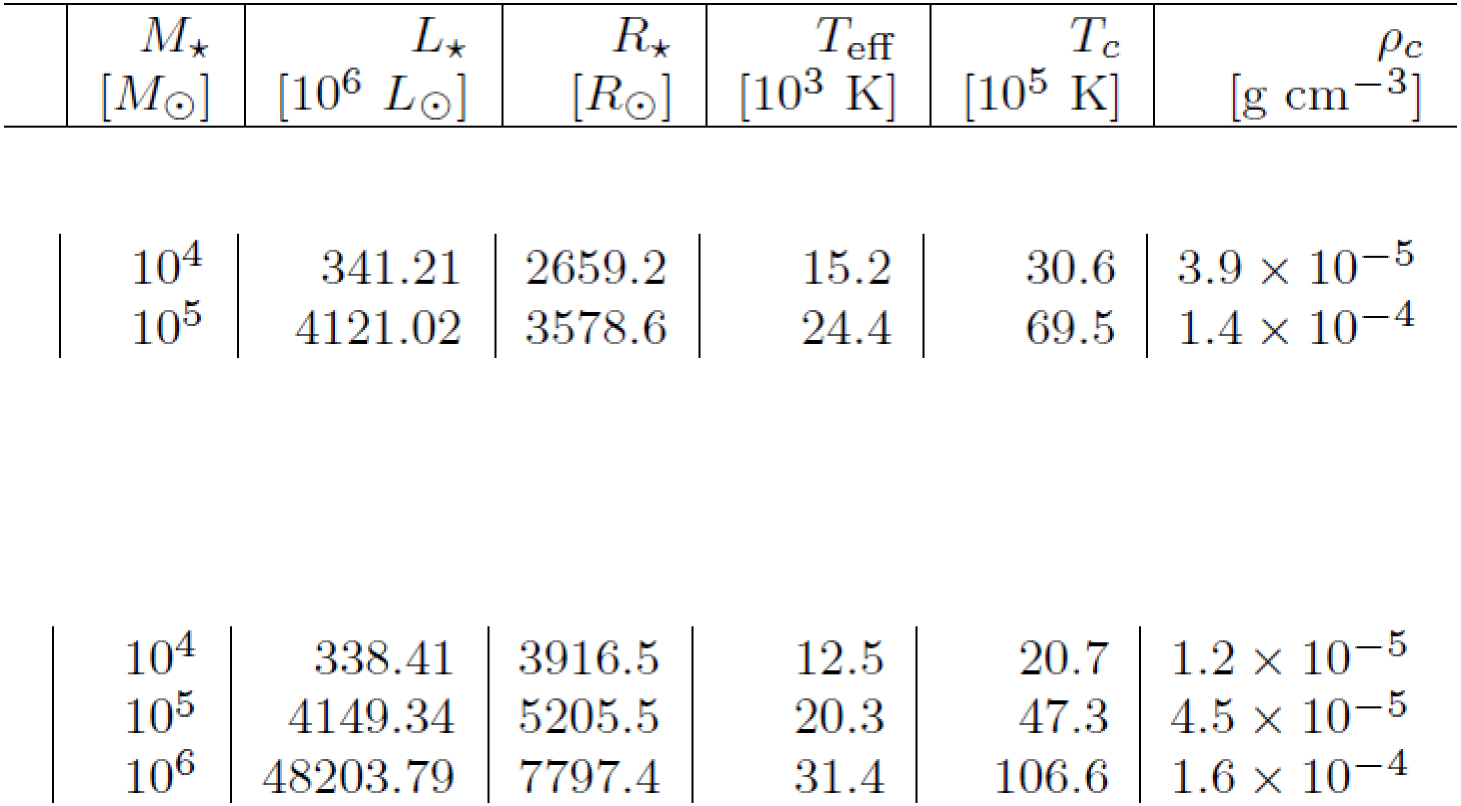
MESA dark stars with 10^4 -10^6 M_{sun} are

- brighter ~ 2x
- hotter ~ 1.5x (for T_{eff} and T_c)
- smaller ~ 0.6x
- denser ~ 3–4 x

than polytropic DS models of Freese et al (2010)

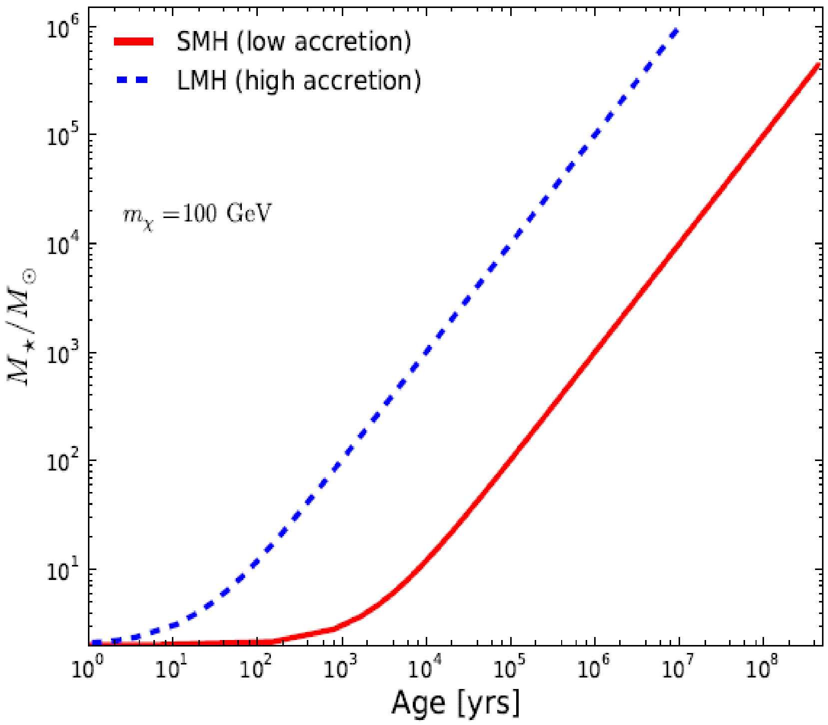
Focus on 100 GeV case:
Main stellar characteristics

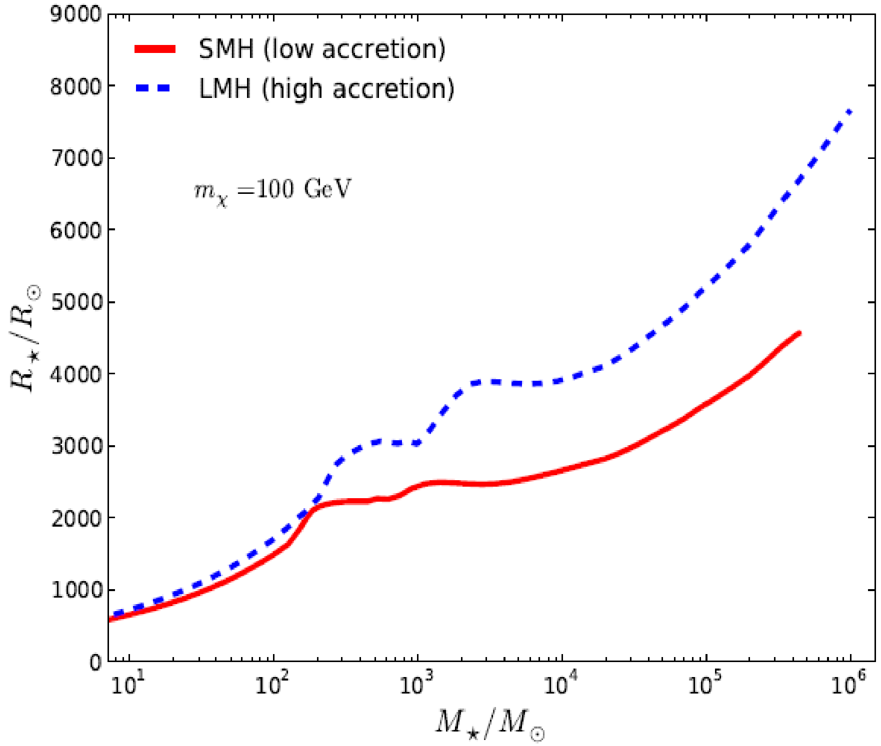
MESA dark stars with **10^4 -10^6 M_{sun}** :



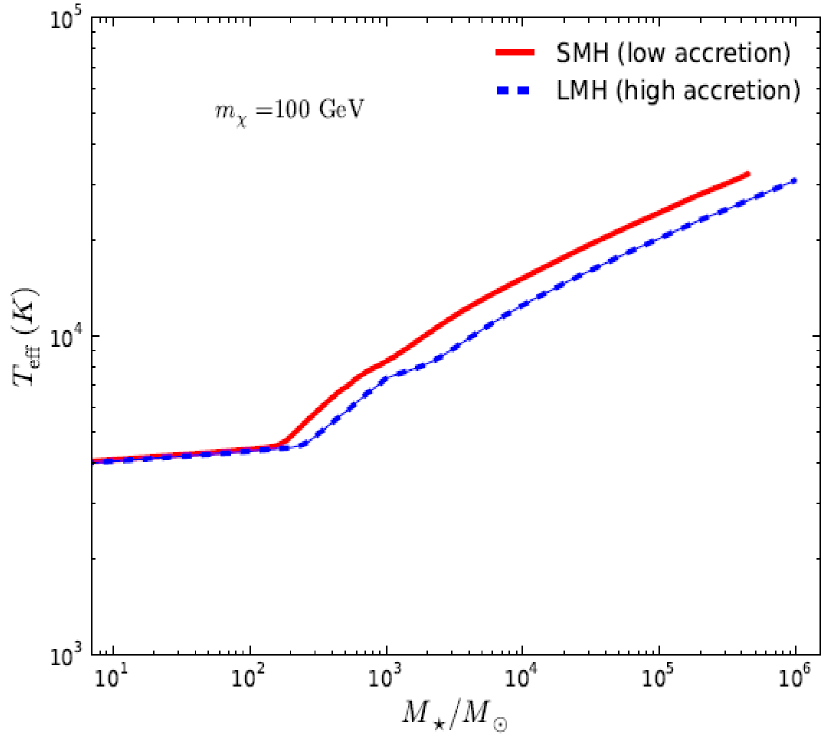
	$M_\star$ $[M_\odot]$	$L_\star$ $[10^6\ L_\odot]$	$R_\star$ $[R_\odot]$	$T_{\rm eff}$ $[10^3\ {\rm K}]$	T_c $[10^5\ {\rm K}]$	ρ_c $[{\rm g\ cm^{-3}}]$
SMH:	10^4	341.21	2659.2	15.2	30.6	3.9×10^{-5}
	10^5	4121.02	3578.6	24.4	69.5	1.4×10^{-4}
LMH:	10^4	338.41	3916.5	12.5	20.7	1.2×10^{-5}
	10^5	4149.34	5205.5	20.3	47.3	4.5×10^{-5}
	10^6	48203.79	7797.4	31.4	106.6	1.6×10^{-4}

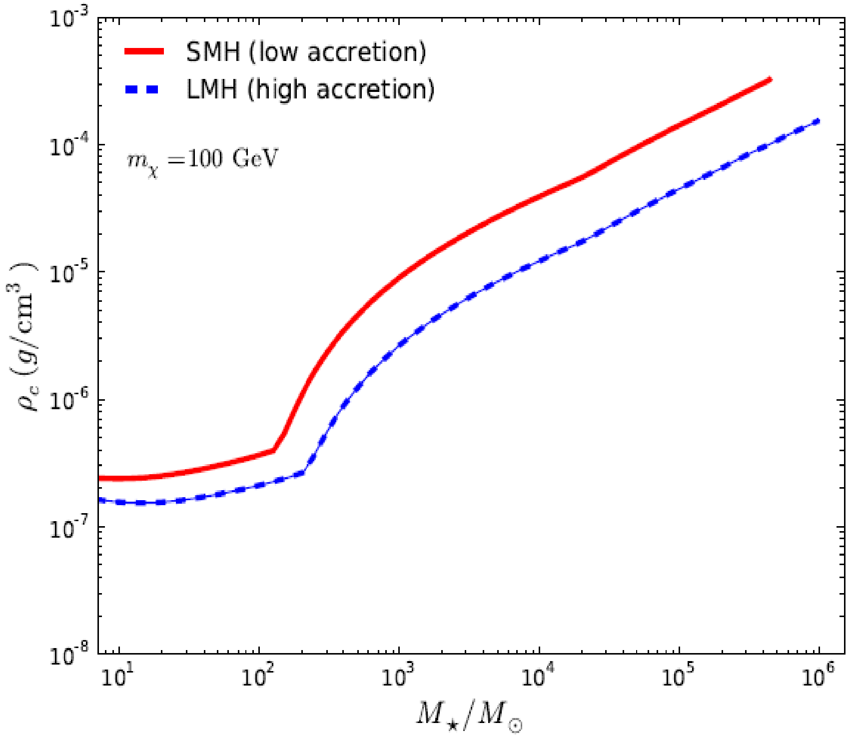
Evolution of DS



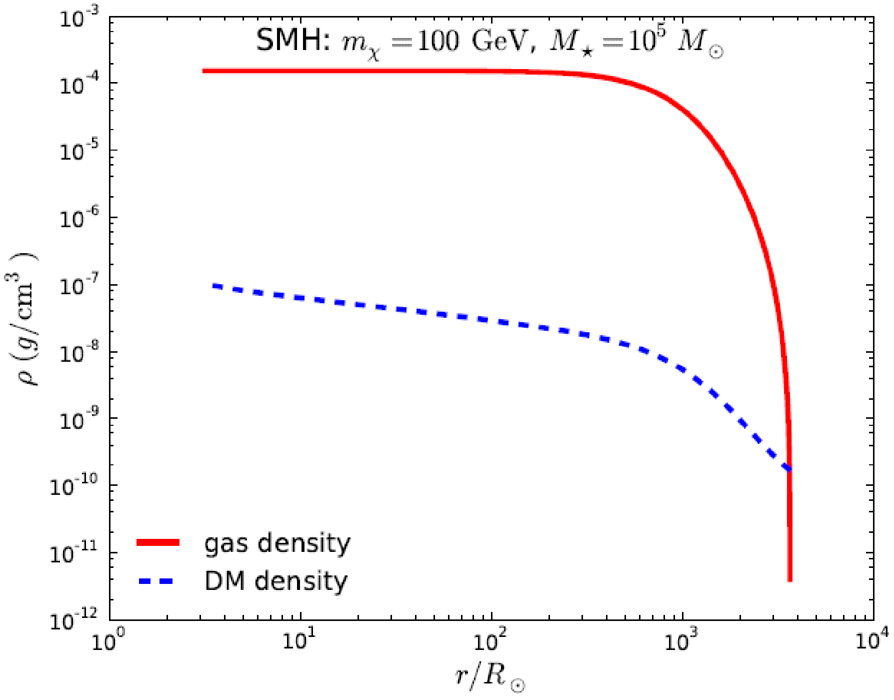


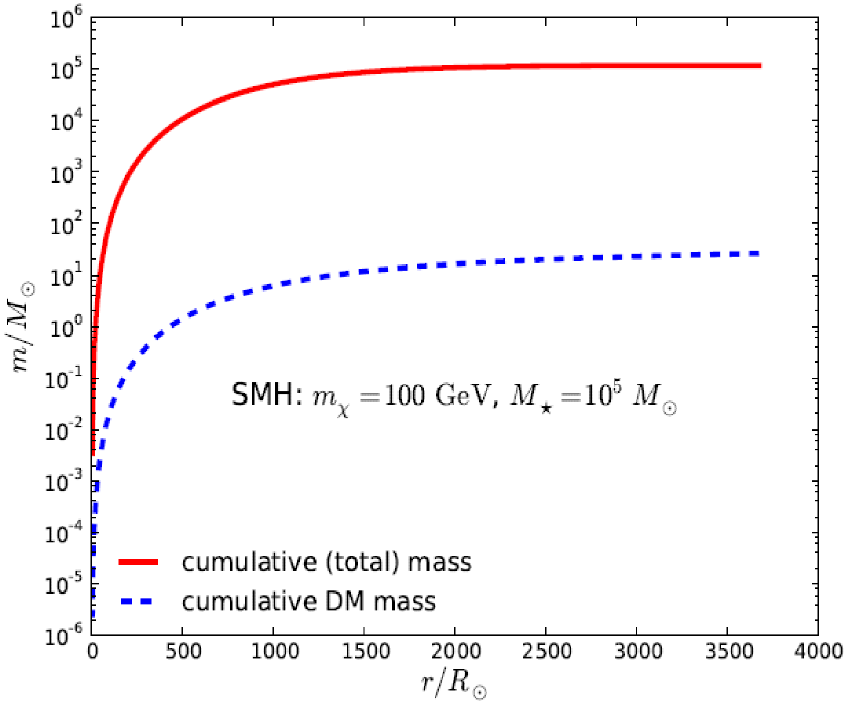
Evolution of DS (cont.)



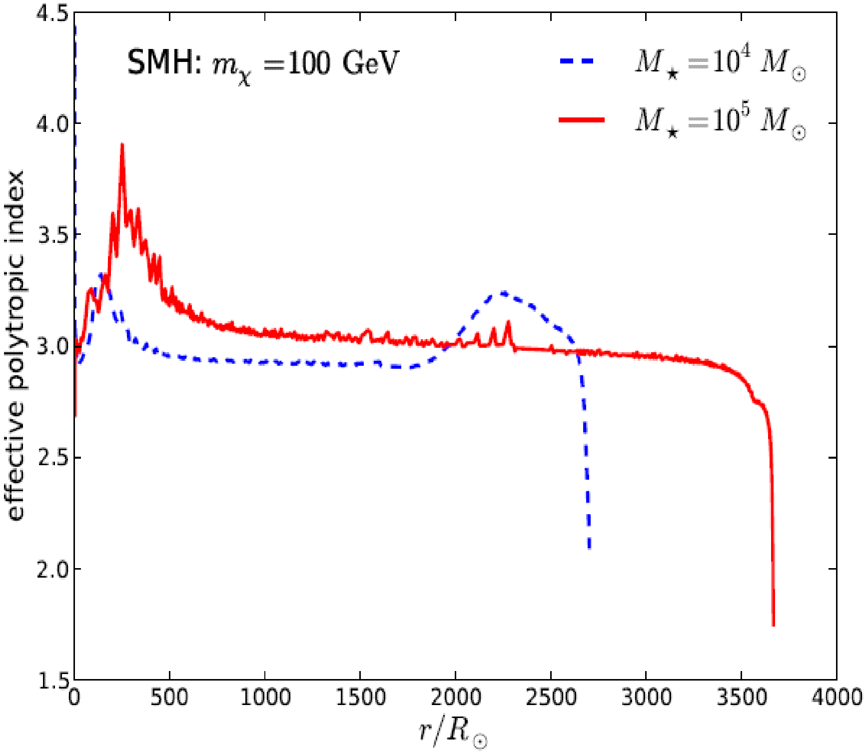


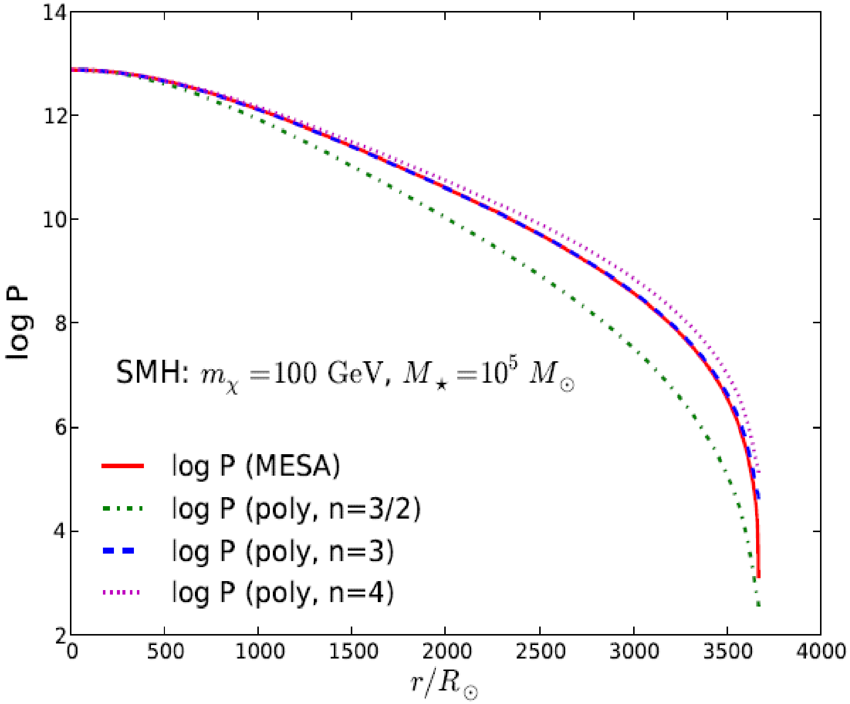
Focus on SMH: density profiles...





… and pressure distribution





$$n_{\rm eff} = \left[\frac{\log(P/P_c)}{\log(\rho/\rho_c)} - 1 \right]^{-1}$$

Supermassive DS can be very well approximated by **(n=3)-polytropes**

Stellar structure

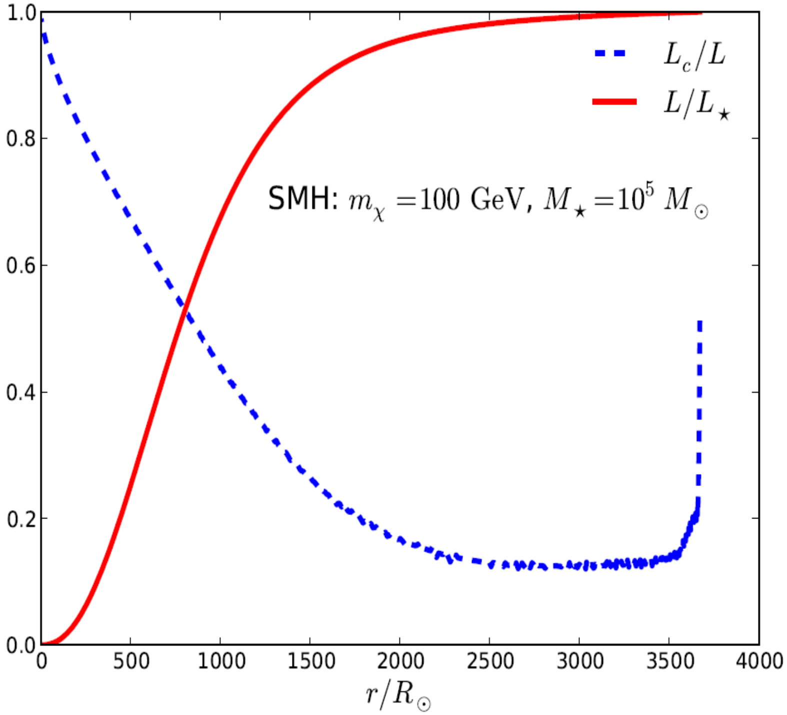
- We confirm that the transition from convection to radiation-domination happens earlier, i.e. at lower M_*, for higher WIMP mass
- around that transition when $L_c \sim L_{rad}$, very inefficient convection

  ("weak convection") with large superadiabaticity gradients develop in the envelopes
- 10 – 20 $M_\odot$: $n_{eff} \approx 3/2$
- $> 100\ M_\odot$: $n_{eff} > 2$
- $\gg 100\ M_\odot$: $n_{eff} \approx 3$
- L_{rad} becomes increasingly important

  for increasing M_*

  → energy transport in supermassive DS

  is dominated by radiation transfer



Implications of (super)massive dark stars

- **Seeds for supermassive BHs at high redshift**

  when DM fuel runs out

  → DS collapses to find new EQ in a huge fusion-powered Pop III star →

  in turn collapses and creates a BH of order 10^4-10^6 $M_\odot$ at redshift 12-15

  → helps explain SMBH in quasars at z ~ 6-10

- **Reionization, 21cm and cosmic IR and MW background:**

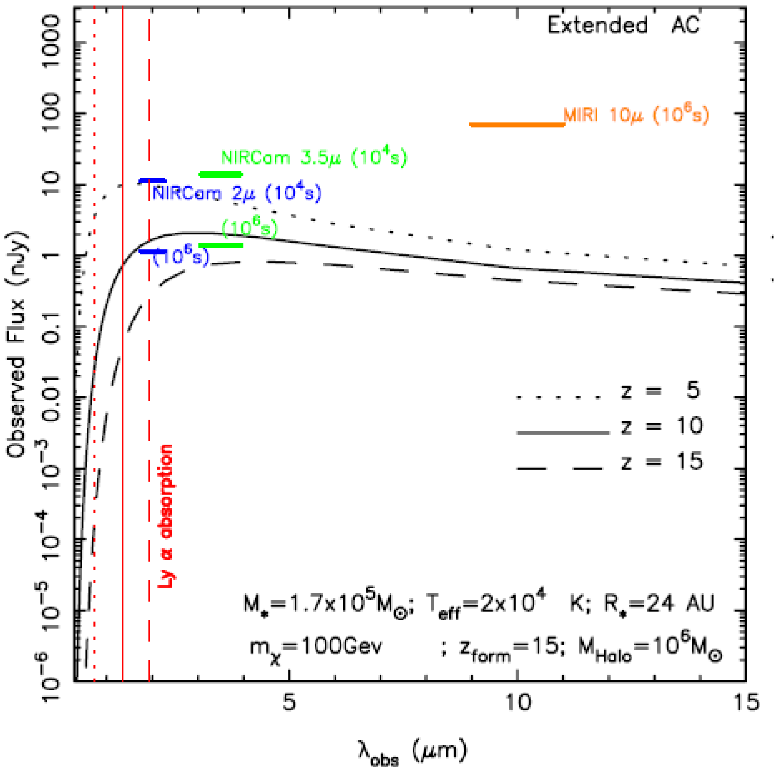
  DS with ~1000 $M_\odot$, undergoing transition to Pop III could be producing too many UV photons (Schleicher et al 2009)

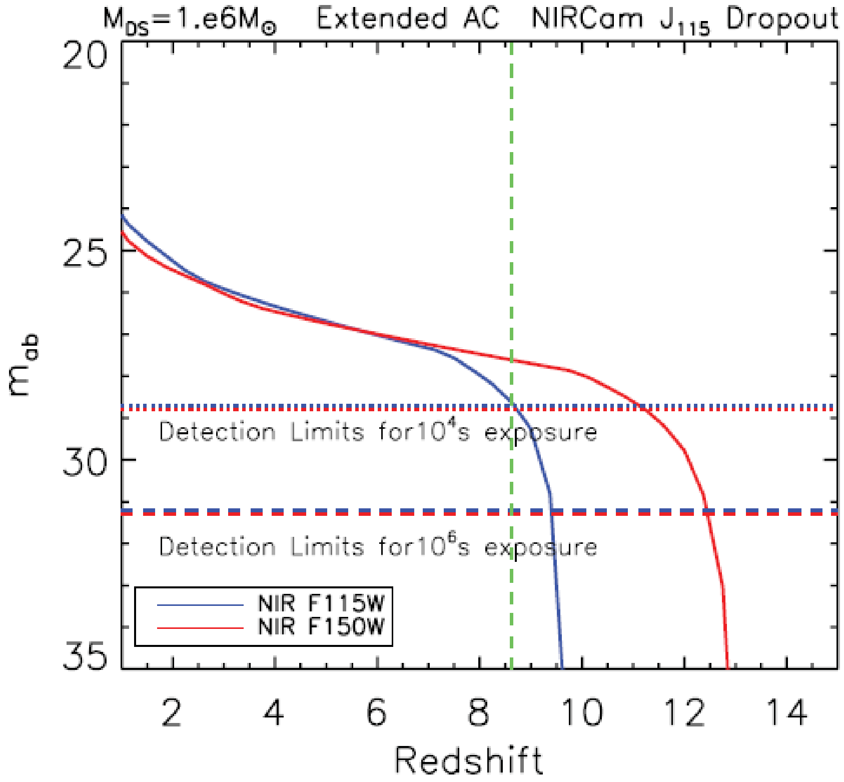
  Reionization delayed or slightly sped up, depending on amount of DM capture (Scott et al 2011)

- **Gamma-rays from DM spikes around BH remnants** (Sandick et al 2011)

Detectability of Dark Stars with JWST

Freese et al, 2010; Ilie et al (2012)





Deviations from equilibrium: pulsations

What about pulsational (in)stability of supermassive dark stars ?

Dark stars: extended, fluffy, cool, but in contrast to “normal” RGB stars,
their low-density 'envelopes' do not host an ultra-dense core;
much larger radii and lower temperatures than fusion-powered stars
→ GR corrections ~GM_*/R_* much smaller
→ upper limit on allowed stellar mass larger !
→ stability to radial pulsations easier to achieve (?)

Stellar pulsation types:

- **p**(ressure) **– modes**: restoring force is pressure (e.g. sound waves)
- **g**(ravity) **– modes**: restoring force is buoyancy

Pulsations: results

- Energy transport in supermassive DS is dominated by radiation transfer and weak convection: Brunt-Väisälä frequency < 0 throughout most of the interior

$$N^2 = \frac{g}{r}\left[\frac{1}{\Gamma_1}\frac{d\ln P}{d\ln r} - \frac{d\ln\rho}{d\ln r}\right]$$

→ expect **no gravity modes** (or g-modes)

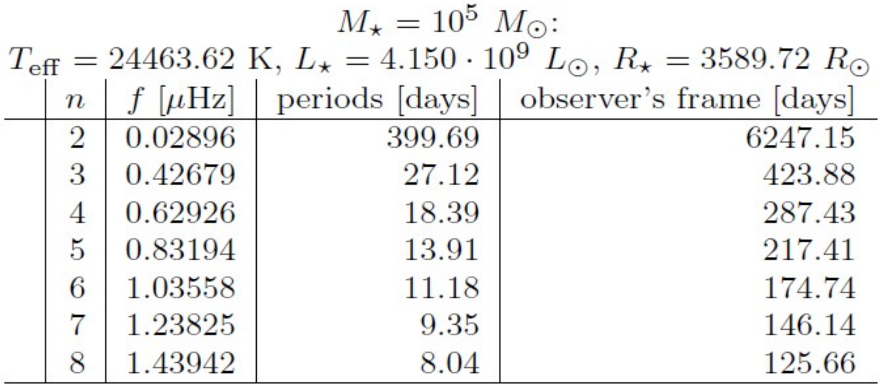
- But **acoustic modes (or p-modes) are permitted:**

  Calculate adiabatic pulsation periods of radial modes (l=0)

  with different overtone number n:

  n=1 fundamental mode; n > 1 higher overtone modes

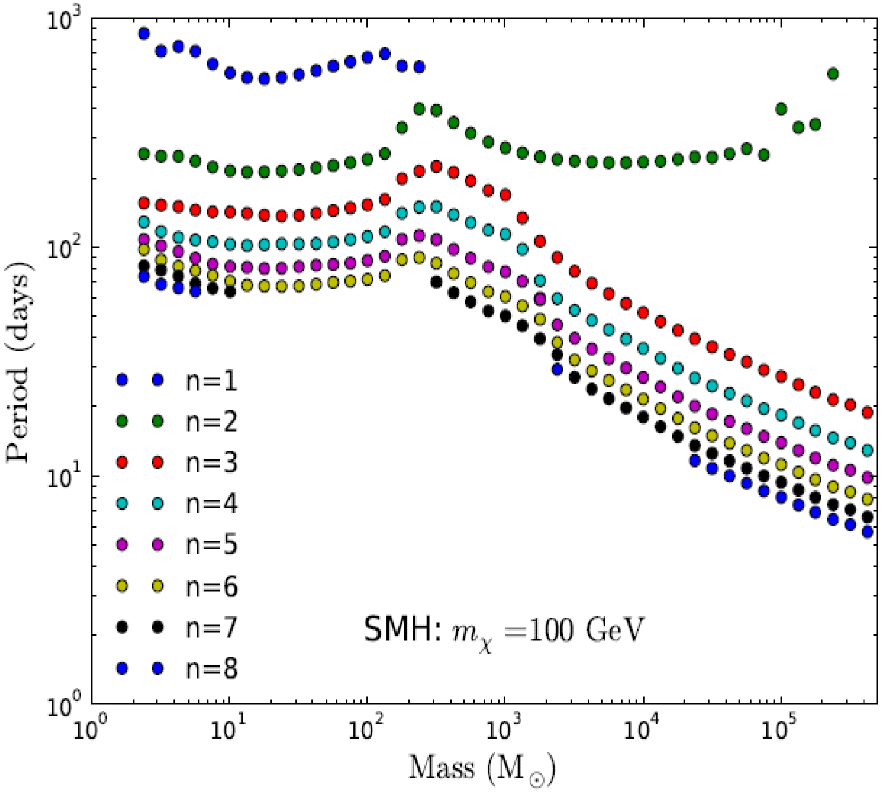
Pulsation periods of p-modes



$M_\star = 10^5\ M_\odot$:

$T_{\mathrm{eff}} = 24463.62$ K, $L_\star = 4.150 \cdot 10^9\ L_\odot$, $R_\star = 3589.72\ R_\odot$

n	f [μHz]	periods [days]	observer's frame [days]
2	0.02896	399.69	6247.15
3	0.42679	27.12	423.88
4	0.62926	18.39	287.43
5	0.83194	13.91	217.41
6	1.03558	11.18	174.74
7	1.23825	9.35	146.14
8	1.43942	8.04	125.66



- periods shorter for dark stars of higher mass
- periods shorter for higher overtone number n
- more high-n modes for higher WIMP mass
- periods shorter for higher WIMP mass

  10 GeV: 60-400 days; 1000 GeV: <~O(days)

  in the rest frame z = 14.82
- shortest periods we expect in the observer's frame:

  1000 GeV: < 50 days for modes with n > 6

Conclusions

- WIMP or other self-annihilating dark matter can affect the power generation and evolution of stars, particularly of the *first stars*

  → if energy generation is entirely due to DM → ***„Dark Stars"***

- Dark stars remain cool enough to accrete matter onto them, such that they grow to sizes unattainable to fusion-powered stars; they may grow to **$M > 10^5 - 10^6\ M_{sun}$**

- These supermassive stars have enormous luminosities, **$L > 10^9 - 10^{10}\ L_{sun}$**

  → prospects are good to **observe** such objects at a redshift of **$z \sim 15$** with the new generation of telescopes (esp. the James Webb Space Telescope)

- **Pulsations** of dark stars are **possible**: the expected pulsation periods depend on the mass of the dark matter particle and the overtone number of the pulsation mode

  → these pulsations could provide a means to **distinguish dark stars from early galaxies** at high redshift

  → potentially a **new standard candle** to measure cosmological distances at high redshift