Supermassive Dark Stars:

improved models and first pulsation results

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Prerequisite:
self-annihilating dark matter

- Self-annihilating dark matter (DM):

  if DM particle is its own anti-particle

  -) WIMPs (lightest SUSY particles; Kaluza-Klein particles, sterile neutrinos)

  → self-annihilation gives correct relic density of DM

  → possibly already indirect detection signatures
  (FERMI-LAT, AMS)

- Self-annihilation produces heat

  → affecting stellar evolution

  .) present-day stars: constrained by observations

  .) first stars: yet unconstrained

  → 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

First Stars

- First stars form in the high-DM density peaks of primordial (mini-)halos with $10^{5\text{-}6}$ M_{sun} at high redshift

  z ~ 15-25
- Those halos arose from the merging of smaller structures as overdense regions in the Universe assemble hierarchically into ever larger halos
- Pristine atomic gas of hydrogen and helium
- Baryonic matter cools and collapses via molecular hydrogen cooling into a single small protostar at the center of the halo

The Dark Star Proposal:

Spolyar, Freese & Gondolo (2008)

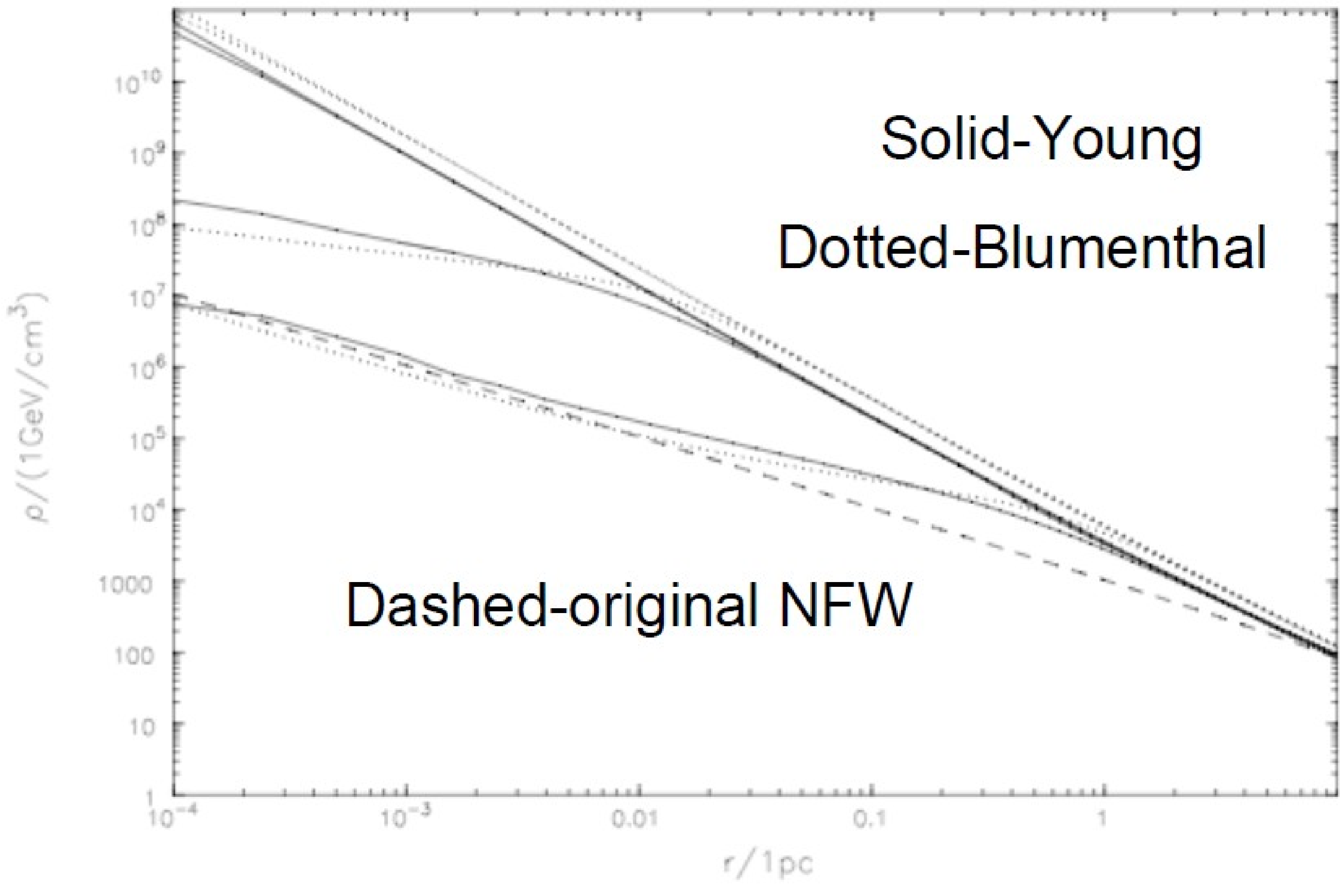
The effect of DM heating is more pronounced at the time when first stars form:

- DM density scales as $(1+z)^3$
- Protostar forms in the center of minihalo

Supply for DM “fuel”:

- upon collapse, baryons pull in more DM via extended, adiabatic contraction
- at high enough densities, DM replenished by capture from the surroundings, as DM scatters elastically off of nuclei in the star

Enhanced DM density due to adiabatic contraction



Solid-Young

Dotted-Blumenthal

Dashed-original NFW

DM heating

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

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

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

and we take the 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

Typical annih.products: e$^-$, **γ, ν**

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

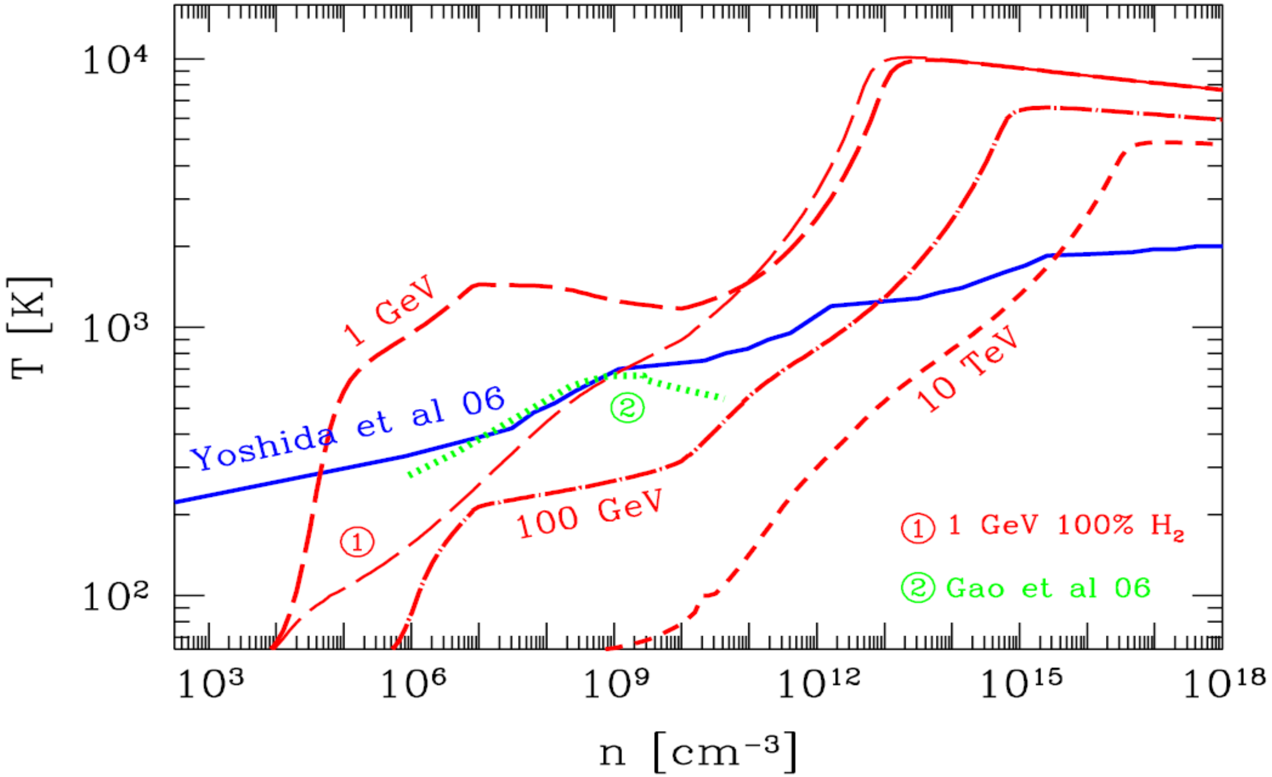
f_Q fraction of annh.energy deposited in the star; we take f_Q = 2/3, as is typical for WIMPs

(i.e. DM heating is 67% efficient; compared to 0.07% 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 mechanism (H_2 cooling, H line cooling, Compton cooling) at a given gas density n of the molecular cloud core



The Dark Star Proposal:

Spolyar, Freese & Gondolo (2008)

- At sufficiently high densities, most of the annihilation energy is trapped inside the core and heats it up
- When:

$$m_\chi \approx 1\ \mathrm{GeV} \rightarrow n \approx 10^{9}/\mathrm{cm}^{3}$$

$$m_\chi \approx 100\ \mathrm{GeV} \rightarrow n \approx 10^{13}/\mathrm{cm}^{3}$$

$$m_\chi \approx 10\ \mathrm{TeV} \rightarrow n \approx 10^{15-16}/\mathrm{cm}^{3}$$

- The DM heating dominates over all cooling mechanisms, impeding the further collapse of the core

How does this affect the subsequent evolution of the star ?

What equilibrium structure results ?

Equations of stellar structure in 1D

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

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

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

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

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

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

Equations of stellar structure in 1D

$$\epsilon = \epsilon[T(r), \rho(r), \mu(r)] \qquad \text{energy production}$$

$$\kappa = \kappa[T(r), \rho(r), \mu(r)] \qquad \text{radiative opacity}$$

$$\gamma = \gamma[T(r), \rho(r), \mu(r)] \qquad \text{adiabatic index}$$

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

Supermassive Dark Stars: stellar evolution using polytropes

(Freese, Ilie, Spolyar,Valluri,Bodenheimer, 2010)

Assume that DS can be described using polytropic law

$P = K\rho^{1+1/n}$ in hydrostatic equilibrium:

grow DS and calculate new equilibria iteratively during its evolution

→ established that DS can grow to ***supermassive size***

with masses $M \sim 10^4 - 10^7$ M_{sun}

having luminosities $L \sim 10^9 - 10^{11}$ L_{sun}

→ good prospects of observing them with JWST

Dark Star evolution: improved models

Use 1D 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

→ other features in stellar evolution ('flashes')

Halo environments

- DM: 85 %, baryons: 15 %
- H: 76 %, He: 24 %
- c = 3.5

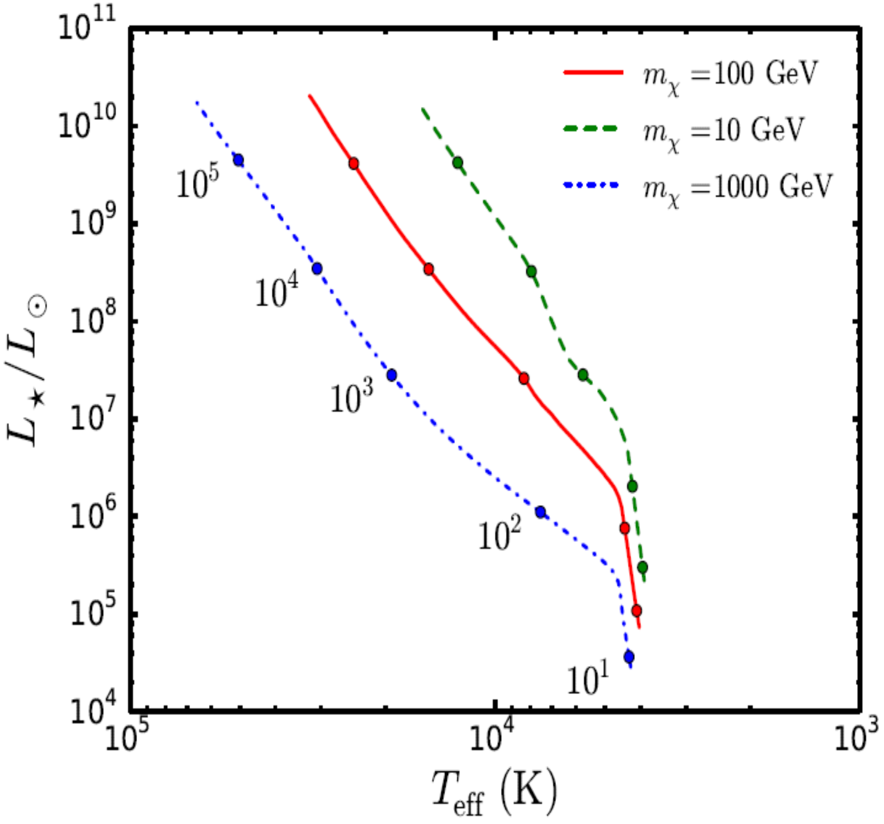
SMH: “small halo” : total mass 10^6 M_{sun} at z = 20, accretion rate dM/dt = 10^{-3} M_{sun} /yr

LMH: “large halo” : total mass 10^8 M_{sun} at z = 15, accretion rate dM/dt = 10^{-1} M_{sun} /yr

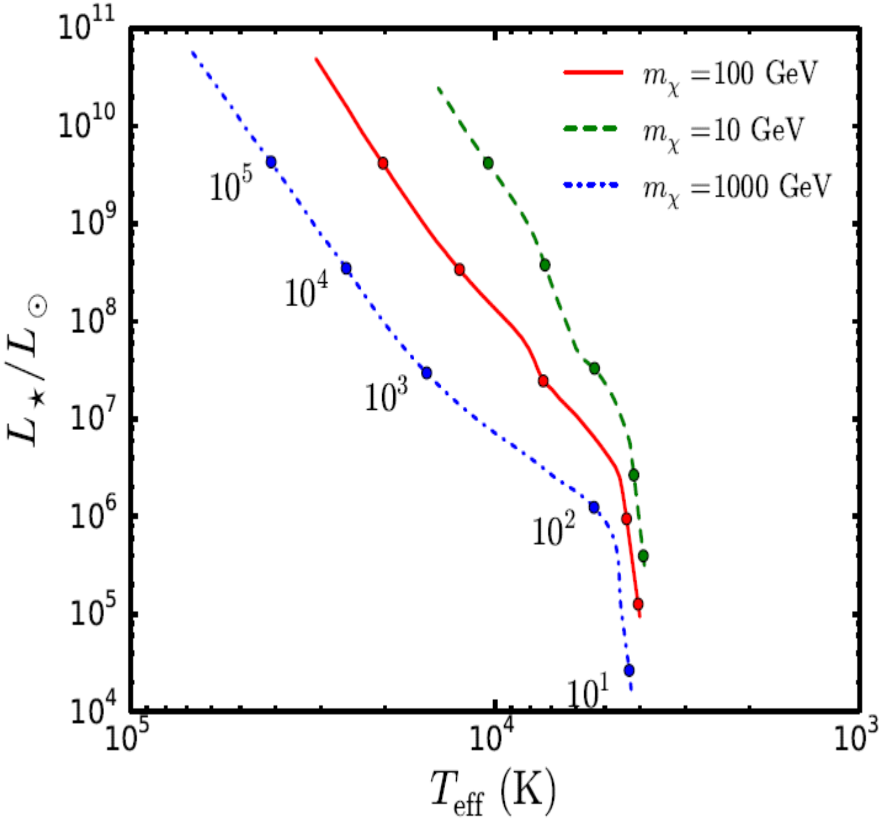
for m_χ = 10, 100, 1000 GeV

Tracks in the Hertzsprung-Russell Diagram

SMH



LMH



Main stellar characteristics

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

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

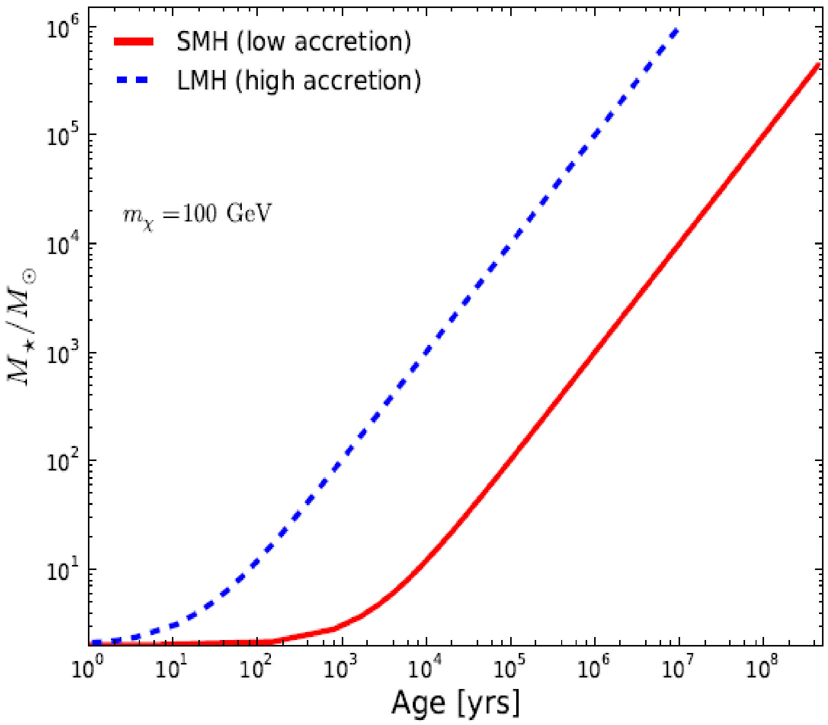
than polytropic DS models of Freese et al (2010)

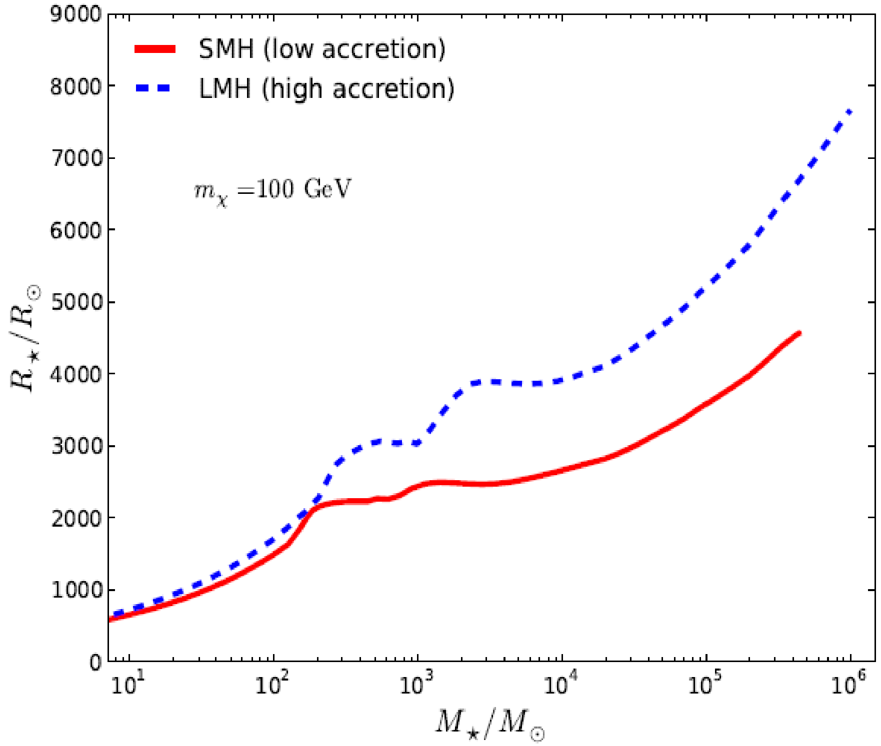
Focus on 100 GeV case:
Main stellar characteristics

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

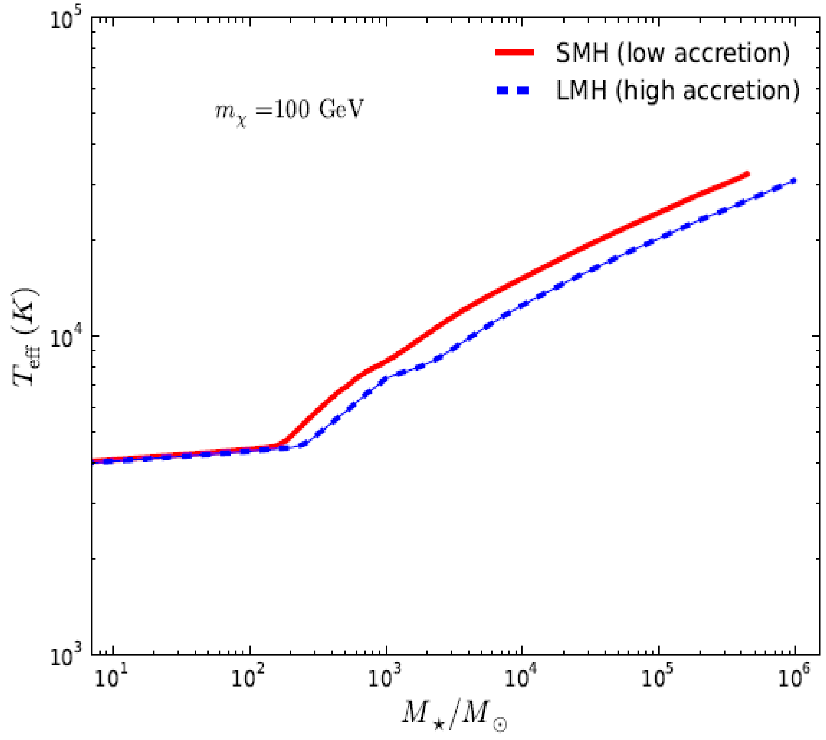
	$M_\star$ $[M_\odot]$	$L_\star$ $[10^6\ L_\odot]$	$R_\star$ $[R_\odot]$	$T_{\rm eff}$ $[10^3\ {\rm K}]$	T_c $[10^5\ {\rm K}]$	ρ_c $[{\rm g\ cm^{-3}}]$
SMH:	10^4	341.21	2659.2	15.2	30.6	3.9×10^{-5}
	10^5	4121.02	3578.6	24.4	69.5	1.4×10^{-4}
LMH:	10^4	338.41	3916.5	12.5	20.7	1.2×10^{-5}
	10^5	4149.34	5205.5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

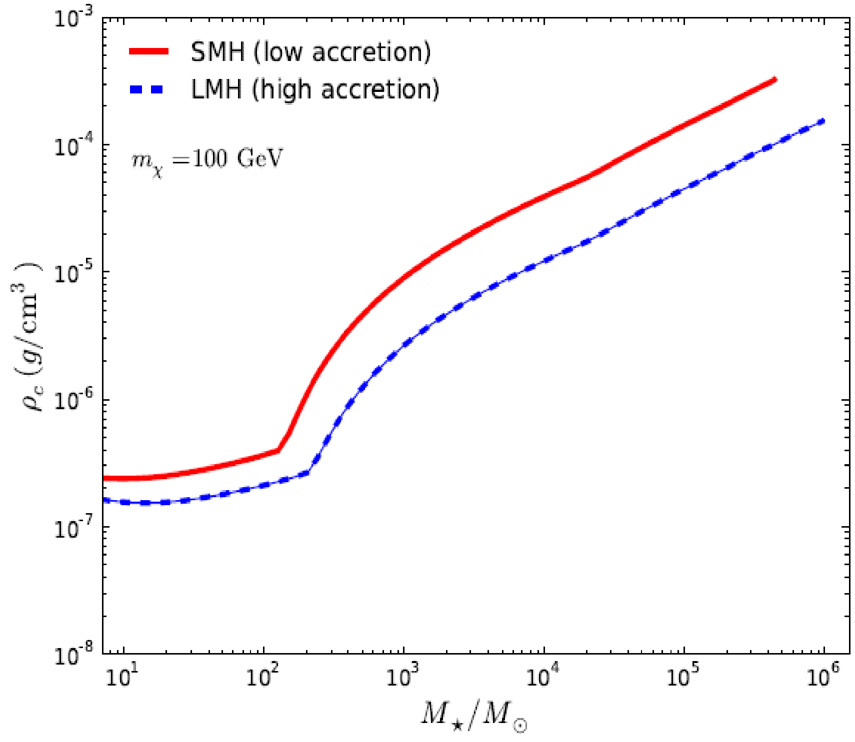
Evolution of DS



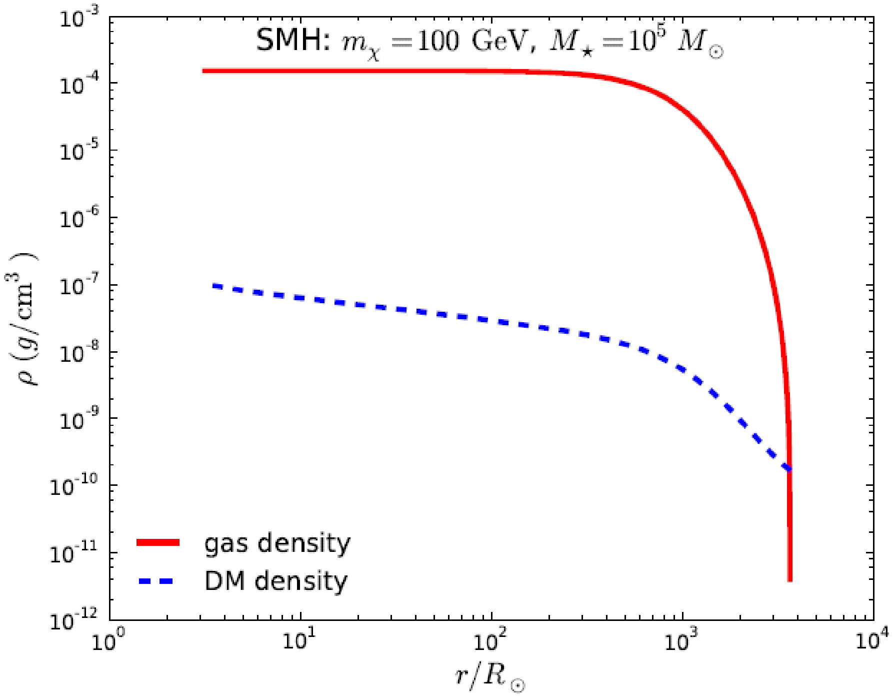


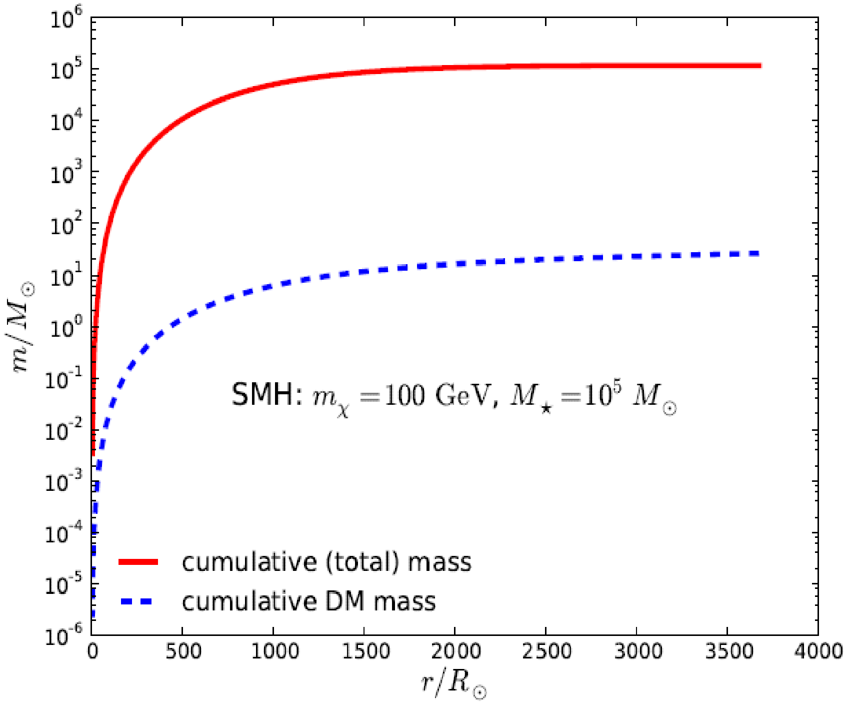
Evolution of DS (cont.)



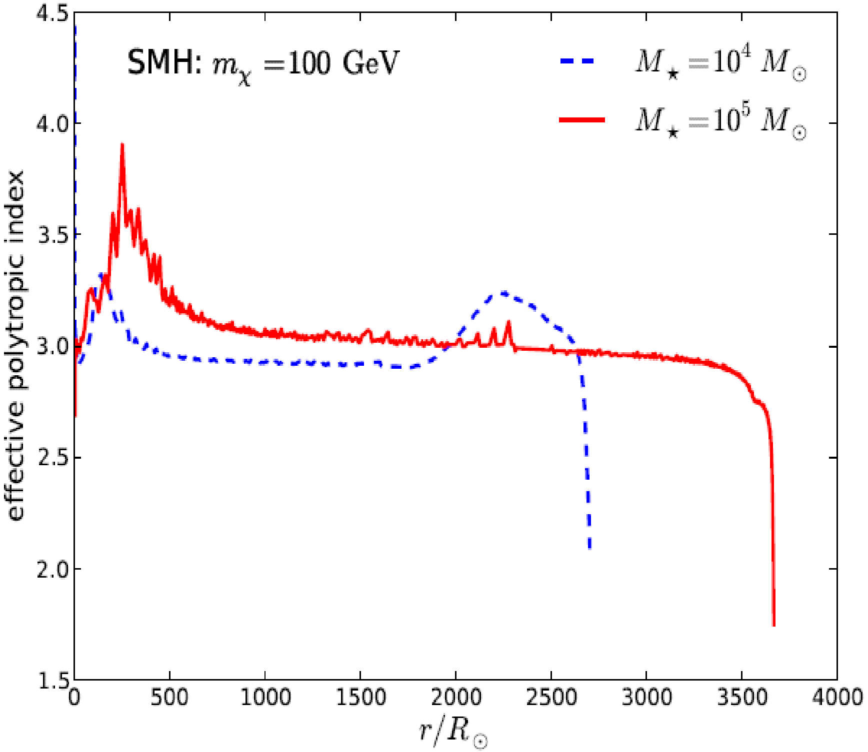


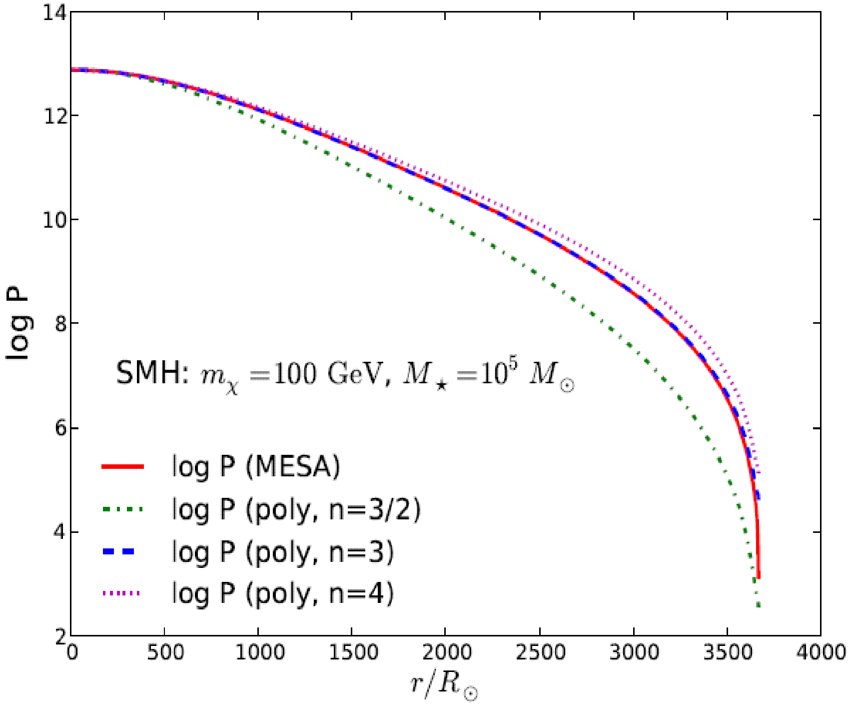
Focus on SMH: density profiles





Pressure distribution





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

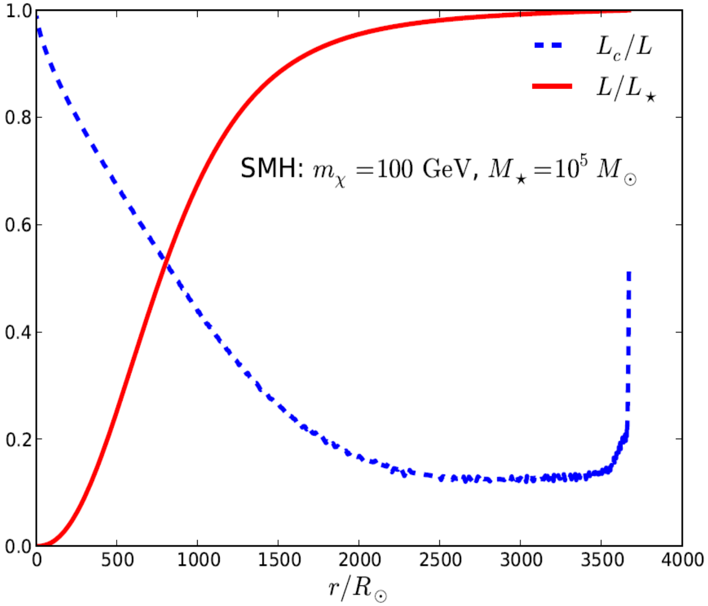
Supermassive DS can be very well approximated by **(n=3)-polytropes**

Deviations from equilibrium: pulsations

Energy transport in supermassive DS is dominated by radiation transfer; weak convection

→ expect **no gravity modes**

(or g-modes)



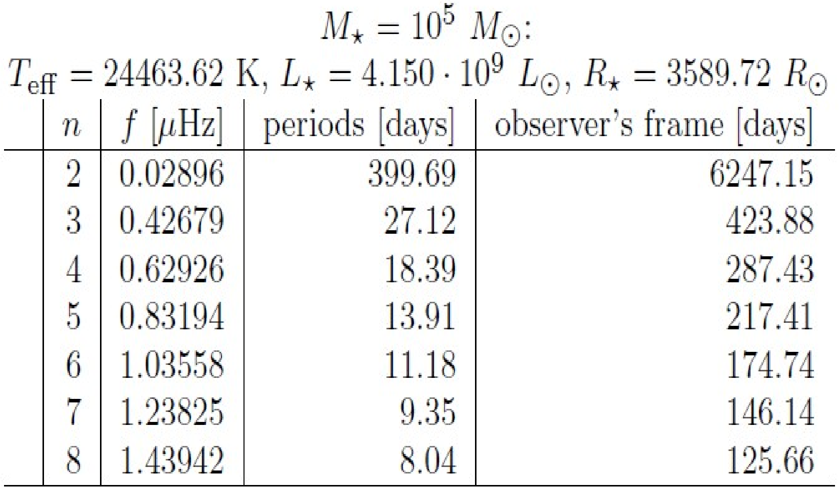
But **acoustic modes (or p-modes) are permitted**

→ calculate adiabatic pulsation periods of radial modes (l=0)

with different overtone number n:

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

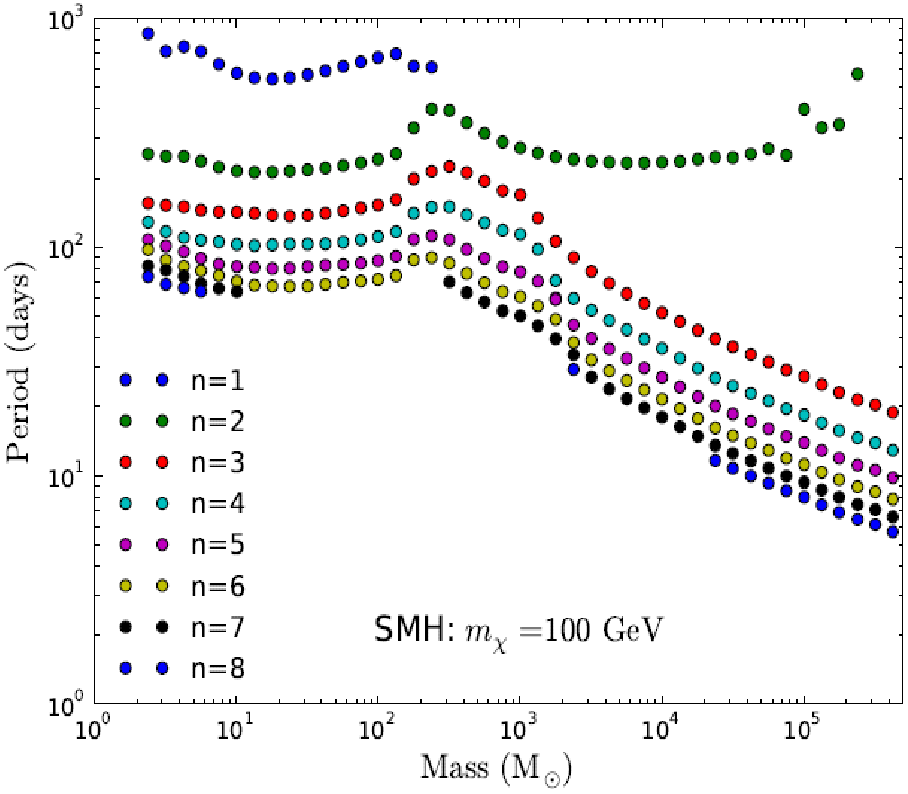
Pulsation periods of acoustic, or p-modes



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

$T_{\rm eff} = 24463.62$ 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



- the periods are much shorter for higher n
- more modes with high n for larger DM mass
- periods are shorter for larger DM mass

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

  in the rest frame
- shortest periods expected in the observer's frame:

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

Summary

DM may be responsible for an entirely new class of stellar object: “Dark Star”, its luminosity powered by heat released due to DM self-annihilation

→ alter the standard picture of first star formation with implications for reionization, supermassive BH formation, galaxy evolution

→ detectable by JWST

→ if pulsations can be driven, DS might someday serve as novel standard candles for cosmological studies

Next steps

- study driving mechanisms of pulsation modes of dark stars in more detail
- implement DM capture via nuclei within the DS
- study dark star 'flash'

  in luminosity when

  DM runs out