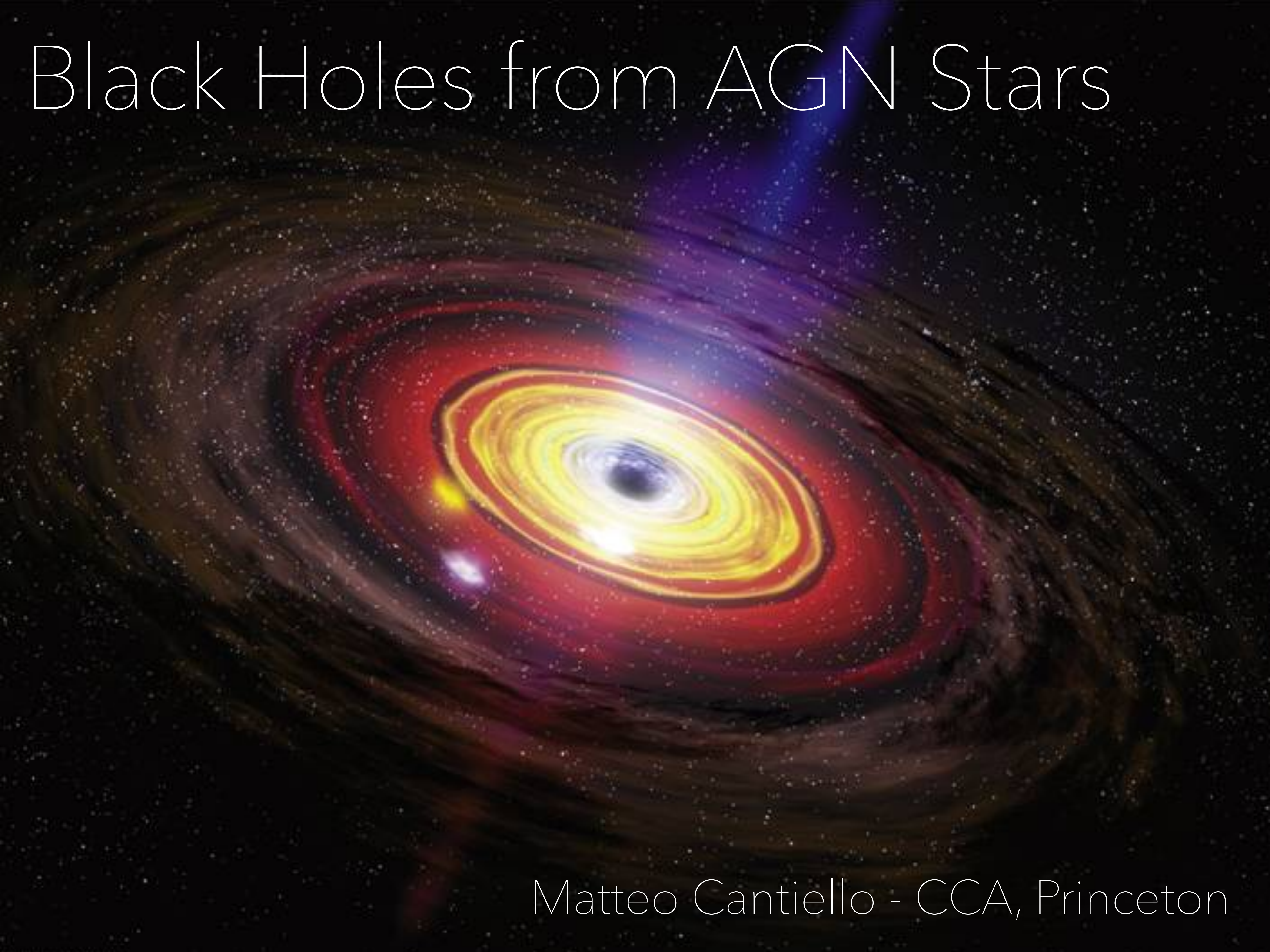
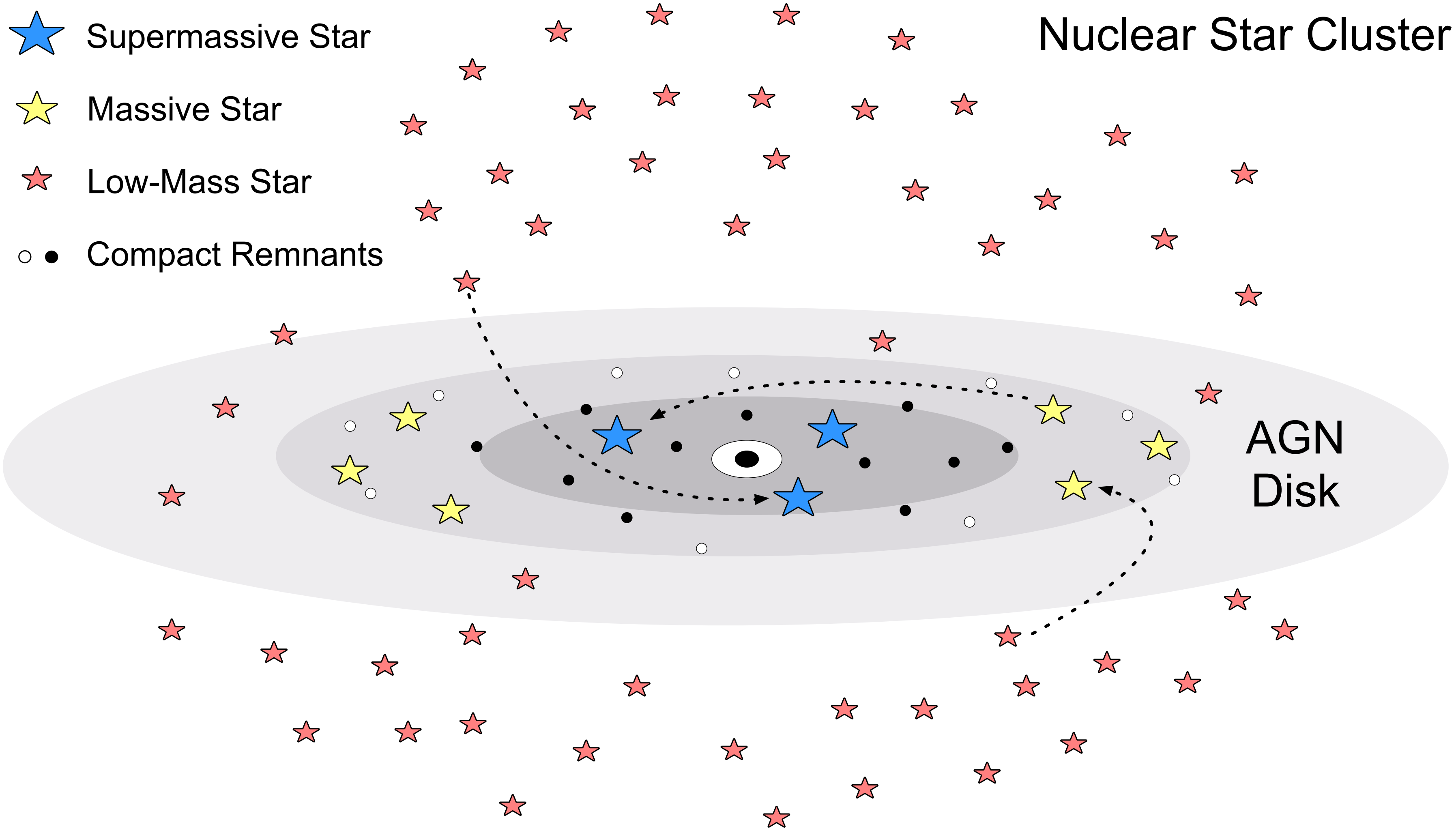
Black Holes from AGN Stars



Matteo Cantiello - CCA, Princeton

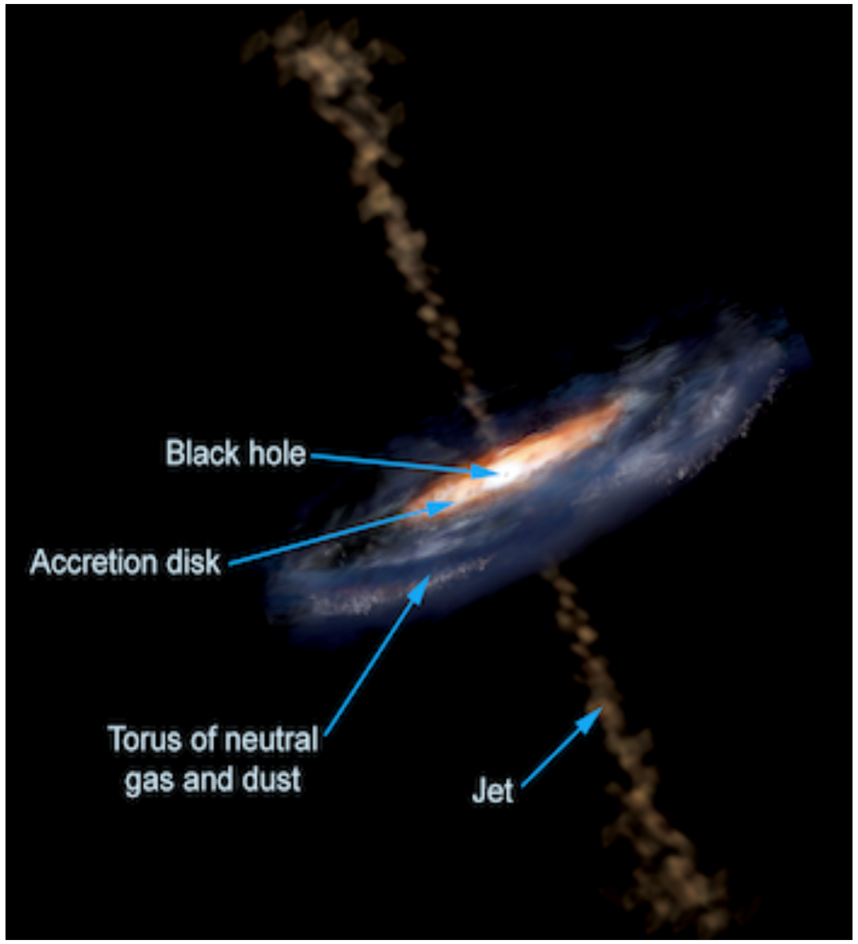
- Stars within ~10^5 R_g turned massive by AGN disk
- Up to ~10^4 BHs for AGN cycle

- ✶ Stars born or captured in AGN disks
- ✶ They undergo accretion-driven evolution
- ✶ Massive and Very Massive Stars Population
- ✶ Production of SNe, Long GRBs, BHs
- ✶ Impact on AGN disk properties



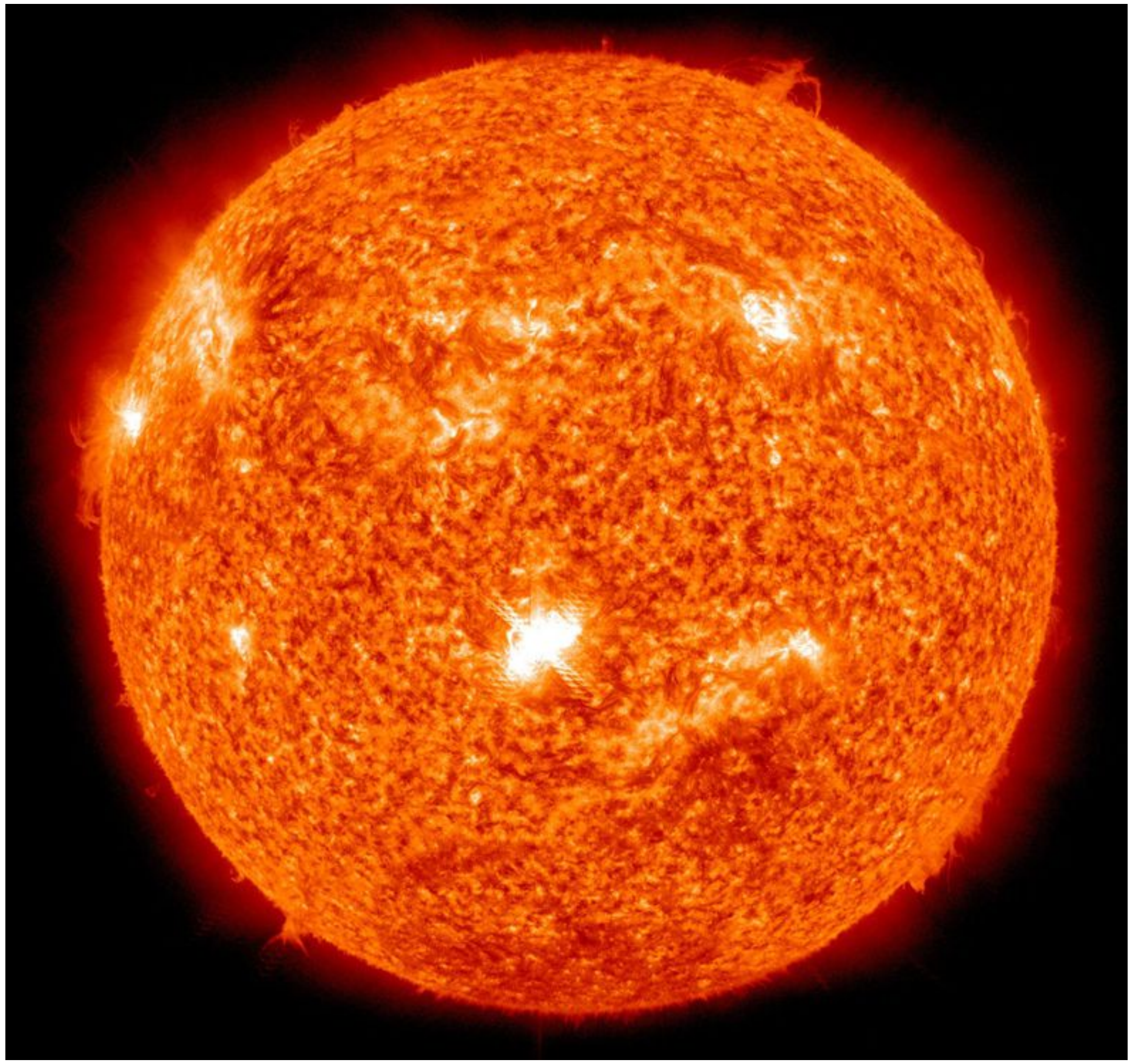
Why Studying Stars in AGNs?

- AGNs are relatively common (~1-10% of galaxies)
- The immediate surroundings of galactic centers are densely populated with stars (NSC). ~10^6 stars within 1 pc of our Galactic Center (Do et al. 2009, Genzel+2010)
- Stars can form in AGN disk (e.g. Goodman & Tan 2004, Dittmann & Miller 2020, Derdzinski & Mayer 2022)

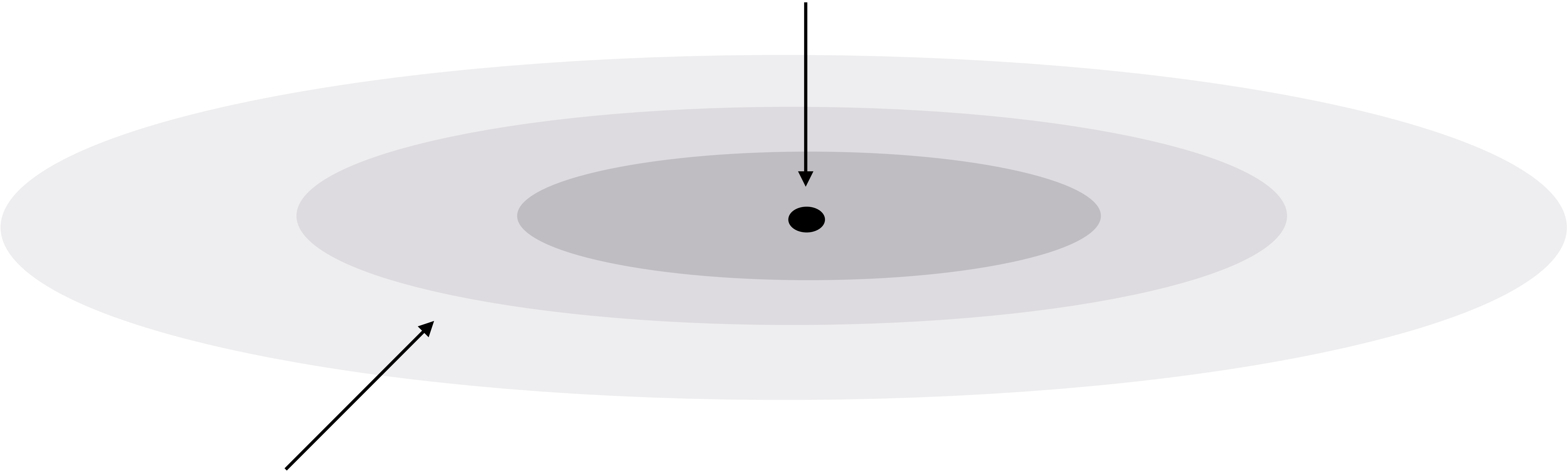


Canonical Stellar Evolution

- Stars are usually evolved in a relatively cold, ~empty ISM
- Surface boundary conditions account for low external temperature and pressure



AGN



Supermassive Black Hole (SMBH)
$M \sim 10^{6 \ldots 10} M_\odot$

Densities of $10^{-10 \ldots -20} g/cm^3$

Temperatures of $10^{2 \ldots 5} K$

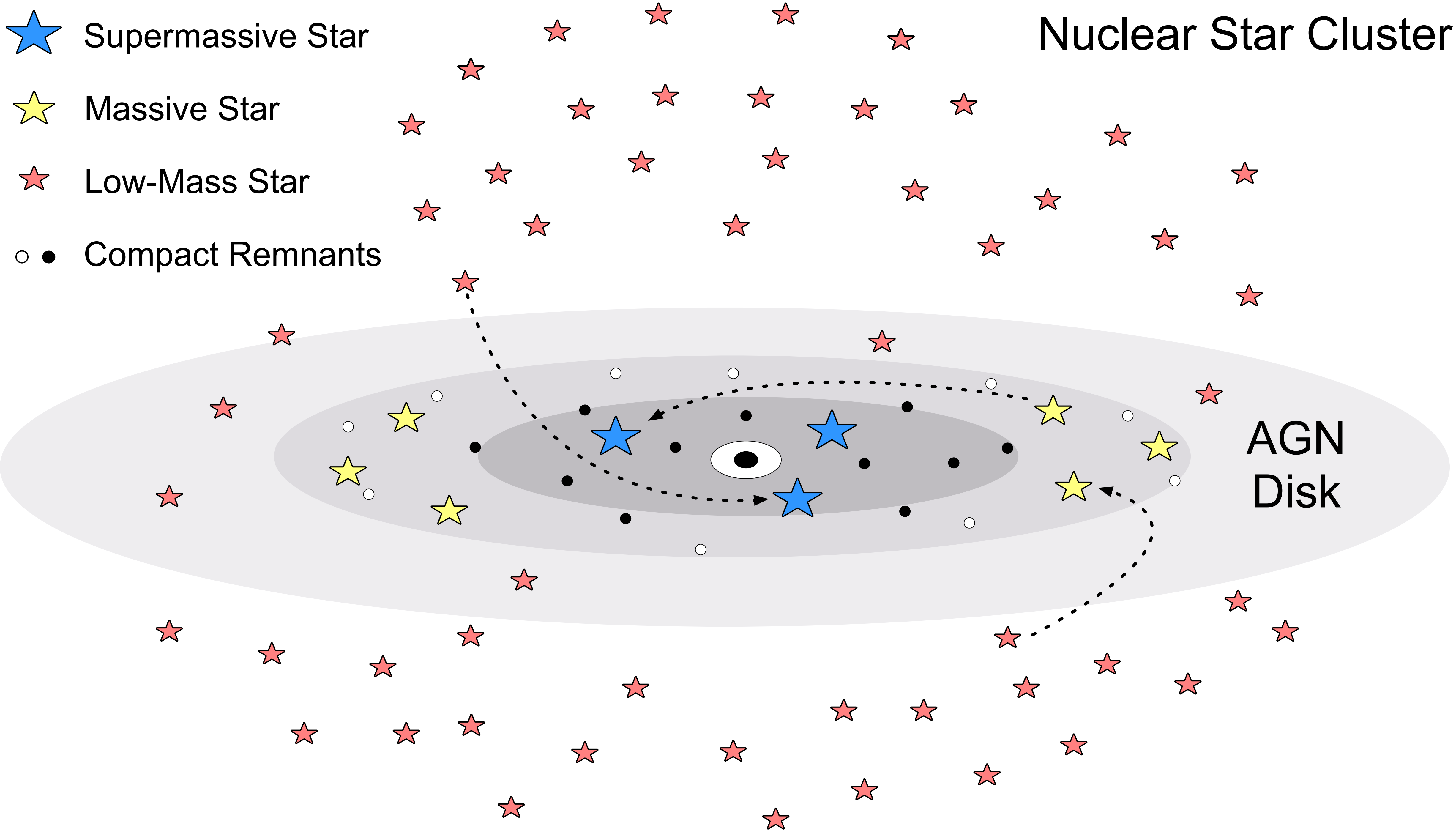
Sound speeds of $10^{0 \ldots 4} km/s$

Range over 100pc from SMBH

Centers of 1-10% of galaxies

Active phase ~$10^{6 \ldots 8} yr$
(e.g. King & Nixon 2015)

e.g. Thompson, Quataert & Murray 2005



- ★ Supermassive Star
- ☆ Massive Star
- ★ Low-Mass Star
- ○ ● Compact Remnants

Nuclear Star Cluster

AGN Disk

Stellar trapping relies on hydrodynamical drag, as well as the excitation of resonant density waves and bending waves

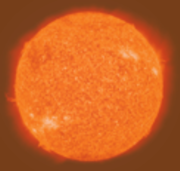
(Artymowicz+1993, MacLeod & Lin 2020, Fabj+2020)

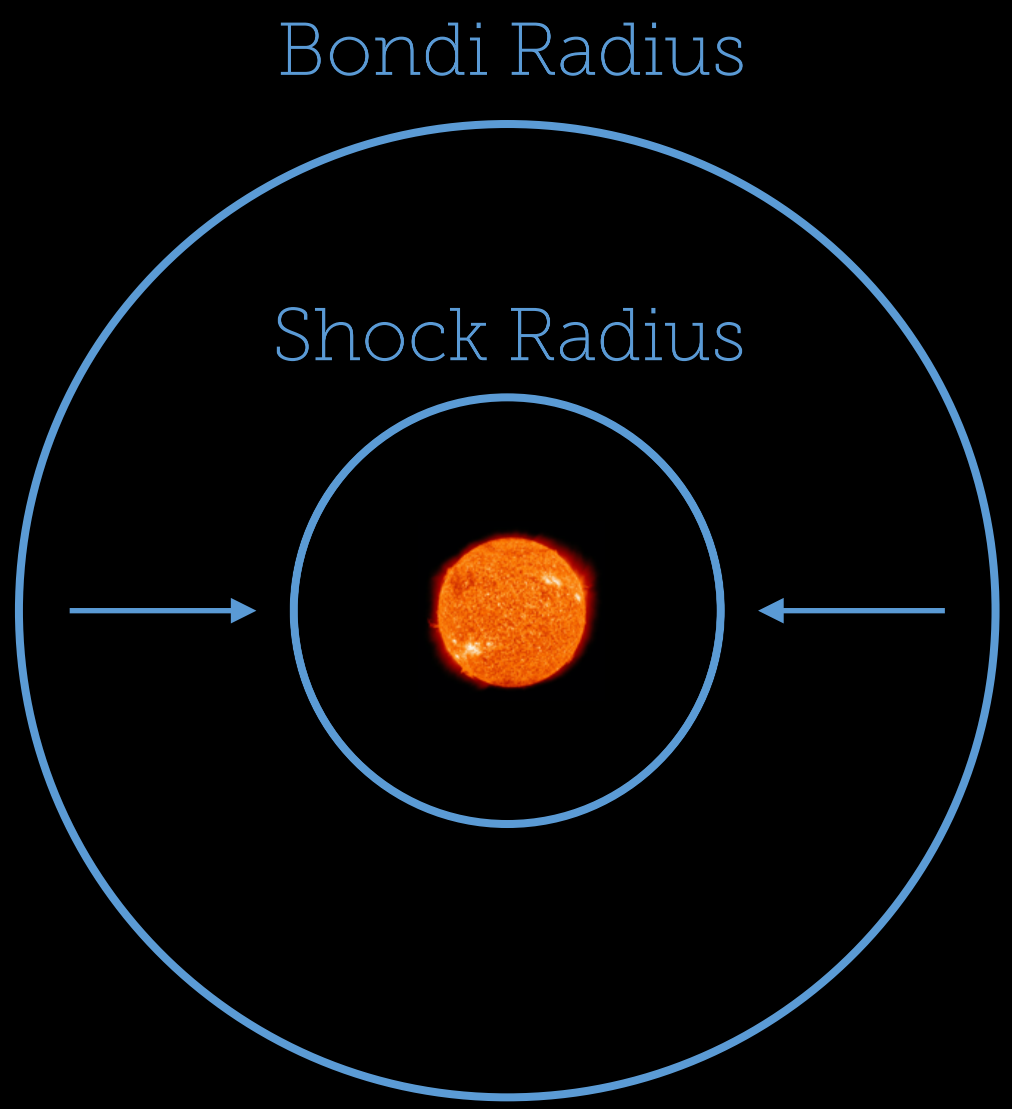
Gaia Fabj's talk

Modeling AGN Stars

AGN Stars - 3 main ingredients

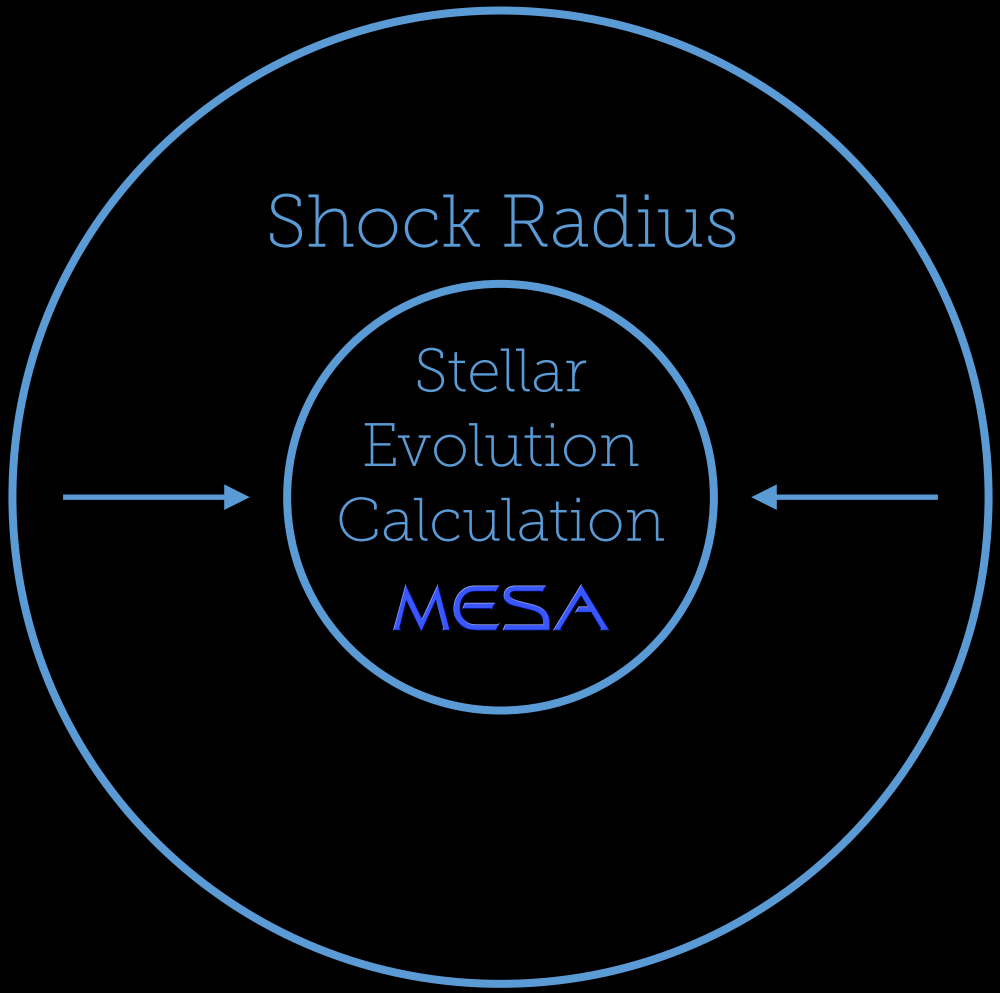
- Atmosphere Boundary Conditions
- Accretion
- Mass Loss





Bondi Radius

Shock Radius

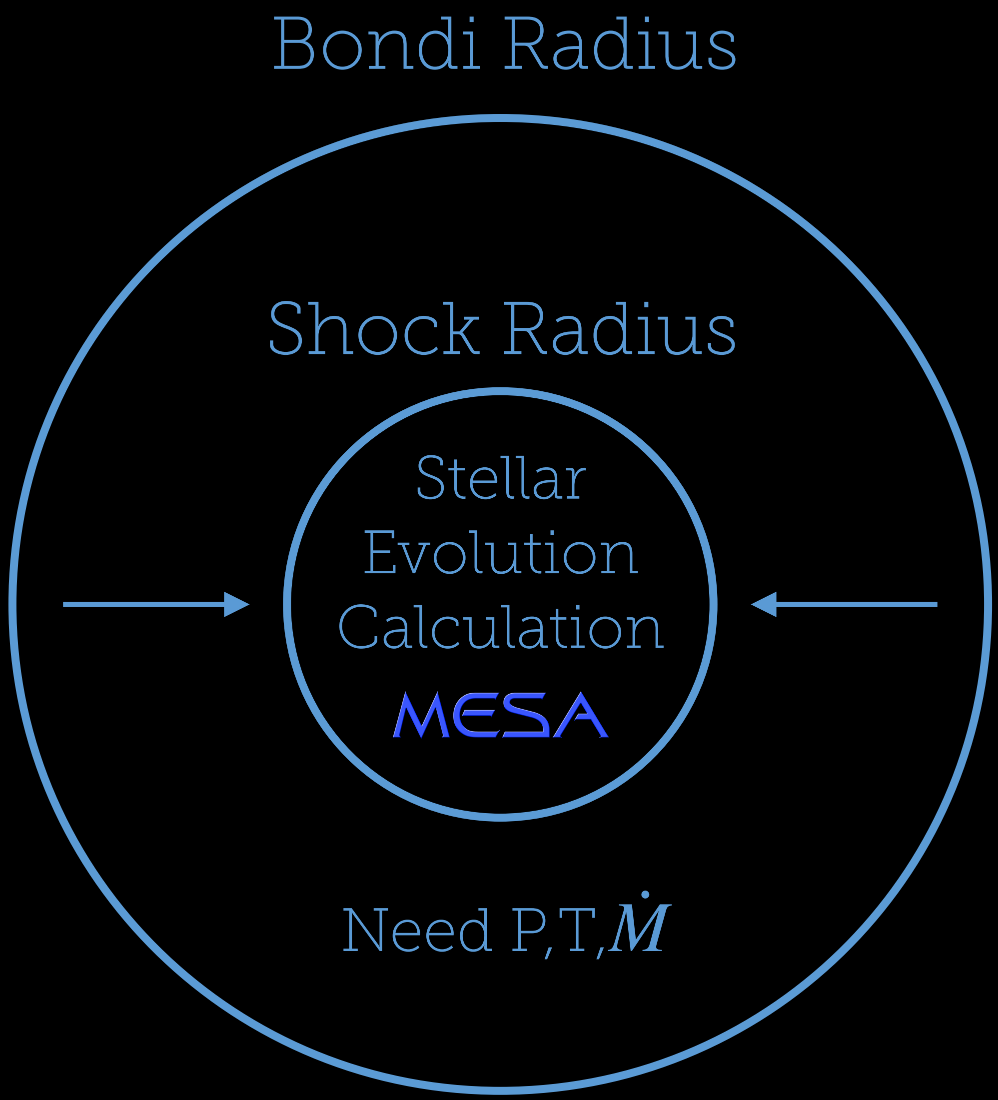


Bondi Radius

Shock Radius

Stellar
Evolution
Calculation

MESA



Bondi Radius

Shock Radius

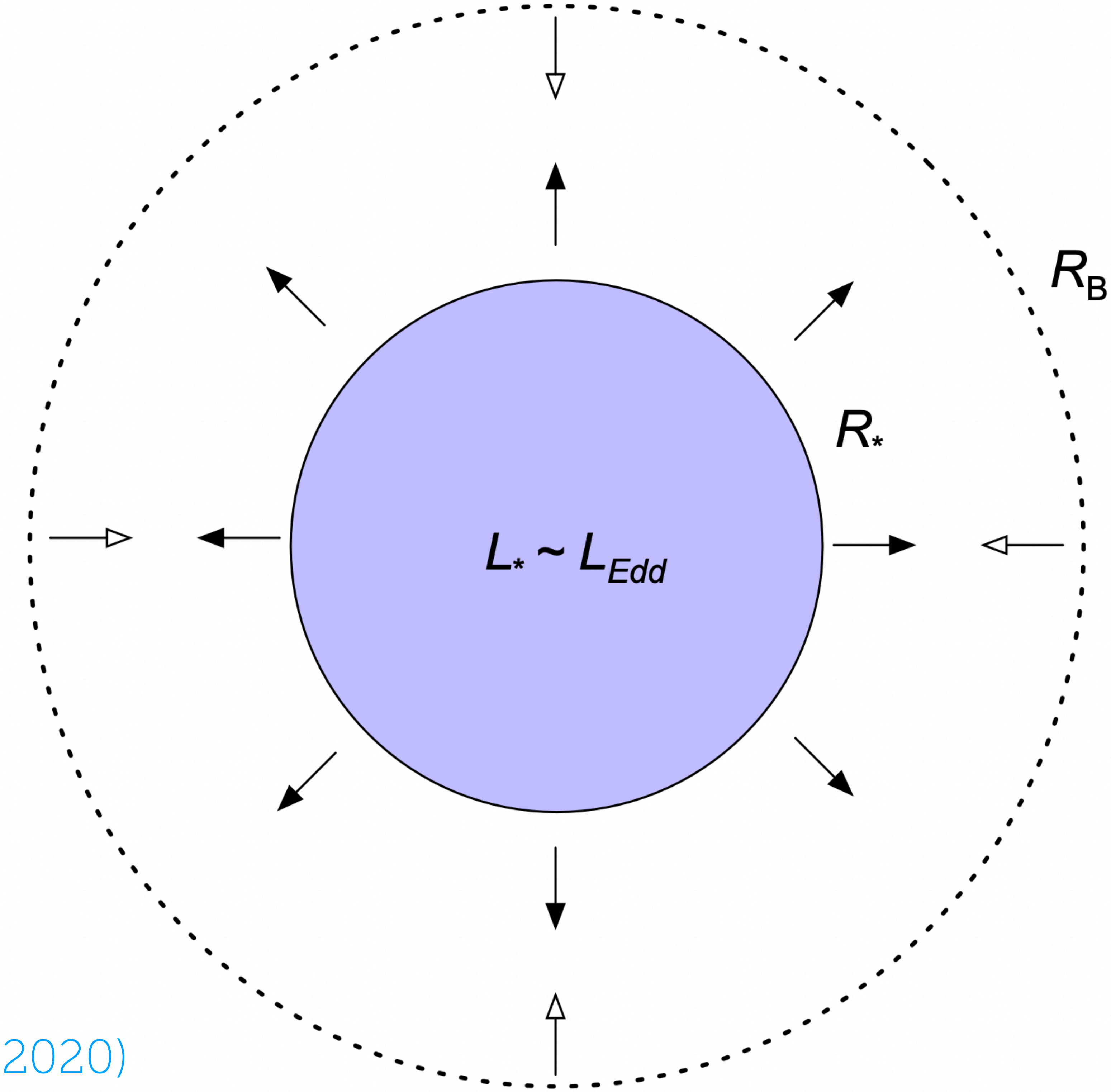
Stellar
Evolution
Calculation

MESA

Need P,T,$\dot{M}$

Eddington Luminosity

When $L_* \to L_{\rm Edd}$ both large accretion and mass loss expected. This is likely a complex multi-dimensional problem. We assume accretion is reduced



$$\dot{M}_{\rm B} = \eta\,\pi R_{\rm B}^2\,\rho_{\rm a}\,c_{s,\rm a}$$

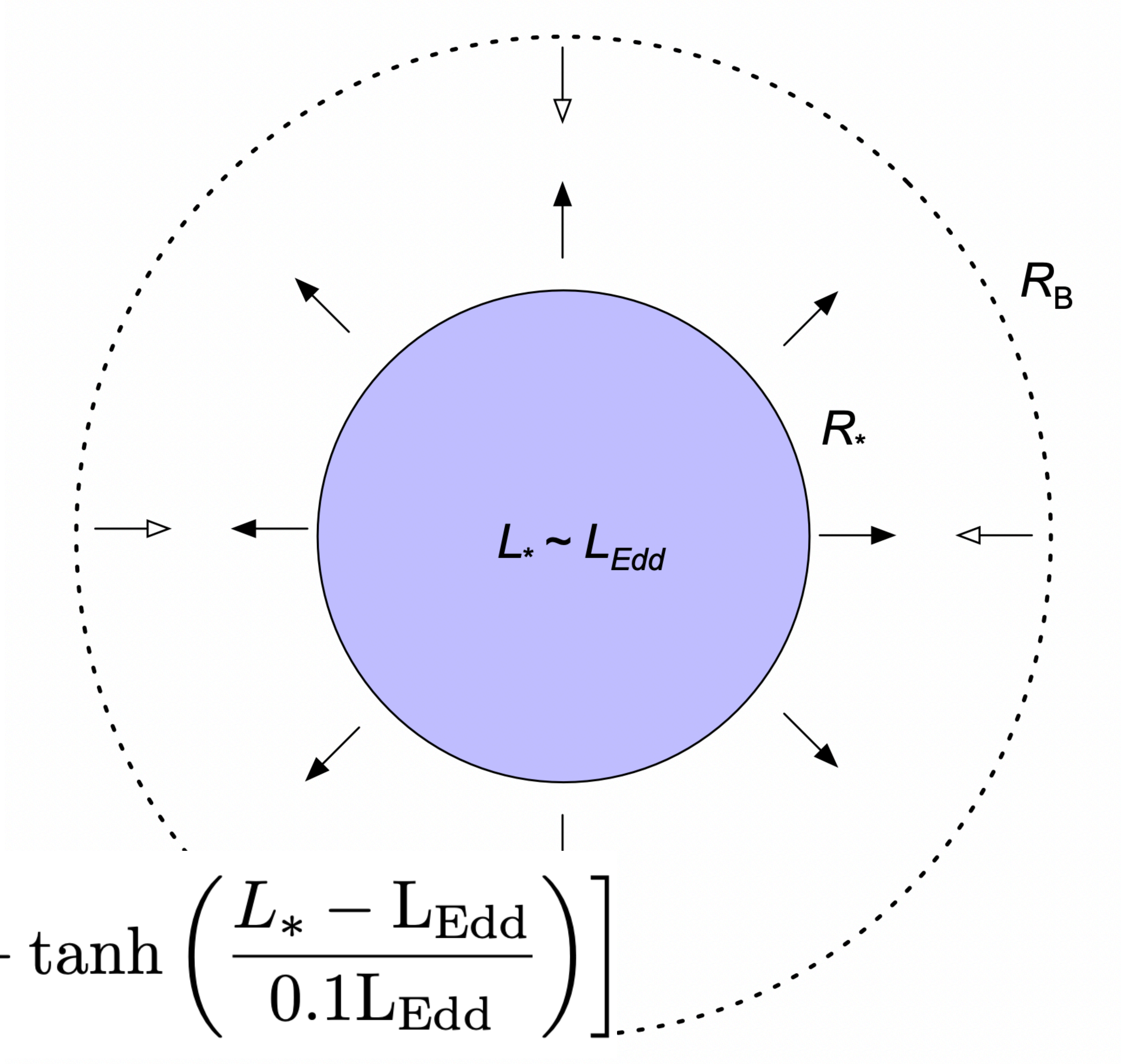
$$\dot{M}_{B,\Gamma} = \dot{M}_B \left(1 - \frac{L_*}{L_{\rm Edd}}\right)^2$$

Cantiello, Jermyn & Lin (CJL, 2020)
Dittmann, Cantiello & Jermyn (2021)

Eddington Luminosity

When $L_* \to L_{\rm Edd}$ both large accretion and mass loss expected. This is likely a complex multi-dimensional problem. We assume accretion is reduced.

We also assume mass loss is enhanced via a super-Eddington wind



$$\dot{M}_{\rm Edd} = -\frac{L_*}{v_{\rm esc}^2}\left[1 + \tanh\left(\frac{L_* - {\rm L_{Edd}}}{0.1{\rm L_{Edd}}}\right)\right]$$

AGN Stars - 3 main ingredients

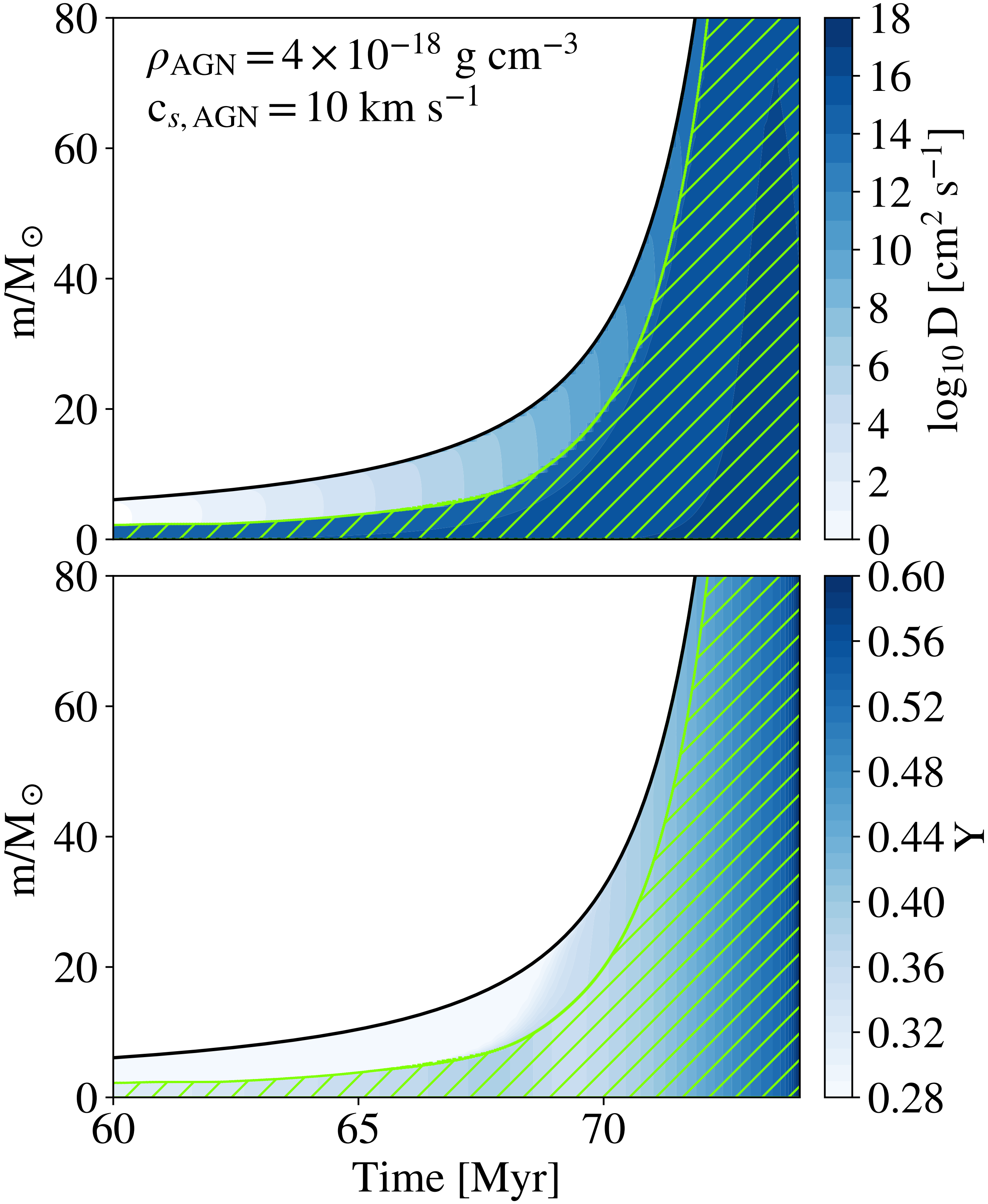
- Atmosphere Boundary Conditions
- Accretion $\dot{M}_{\mathrm{B}} = \eta\, \pi R_{\mathrm{B}}^2\, \rho_{\mathrm{a}}\, c_{s,\mathrm{a}}$
- Mass Loss $\dot{M}_{\mathrm{Edd}} = -\frac{L_*}{v_{\mathrm{esc}}^2}\left[1 + \tanh\left(\frac{L_* - \mathrm{L}_{\mathrm{Edd}}}{0.1\mathrm{L}_{\mathrm{Edd}}}\right)\right]$

Internal Mixing

Stars become massive and radiation dominated. They are marginally stable. Also likely rapidly rotating.

We model the effect of mixing by adding a compositional diffusivity D [cm^2/s] that increases with stellar luminosity. The form of this additional diffusivity is set to be of order the convective diffusivity were the region convectively unstable

$$D = H_\mathrm{p} \left(\frac{F}{\rho}\right)^{1/3} \tanh\left(\frac{L_*}{\mathrm{L_{Edd}}}\right)^{\xi}$$

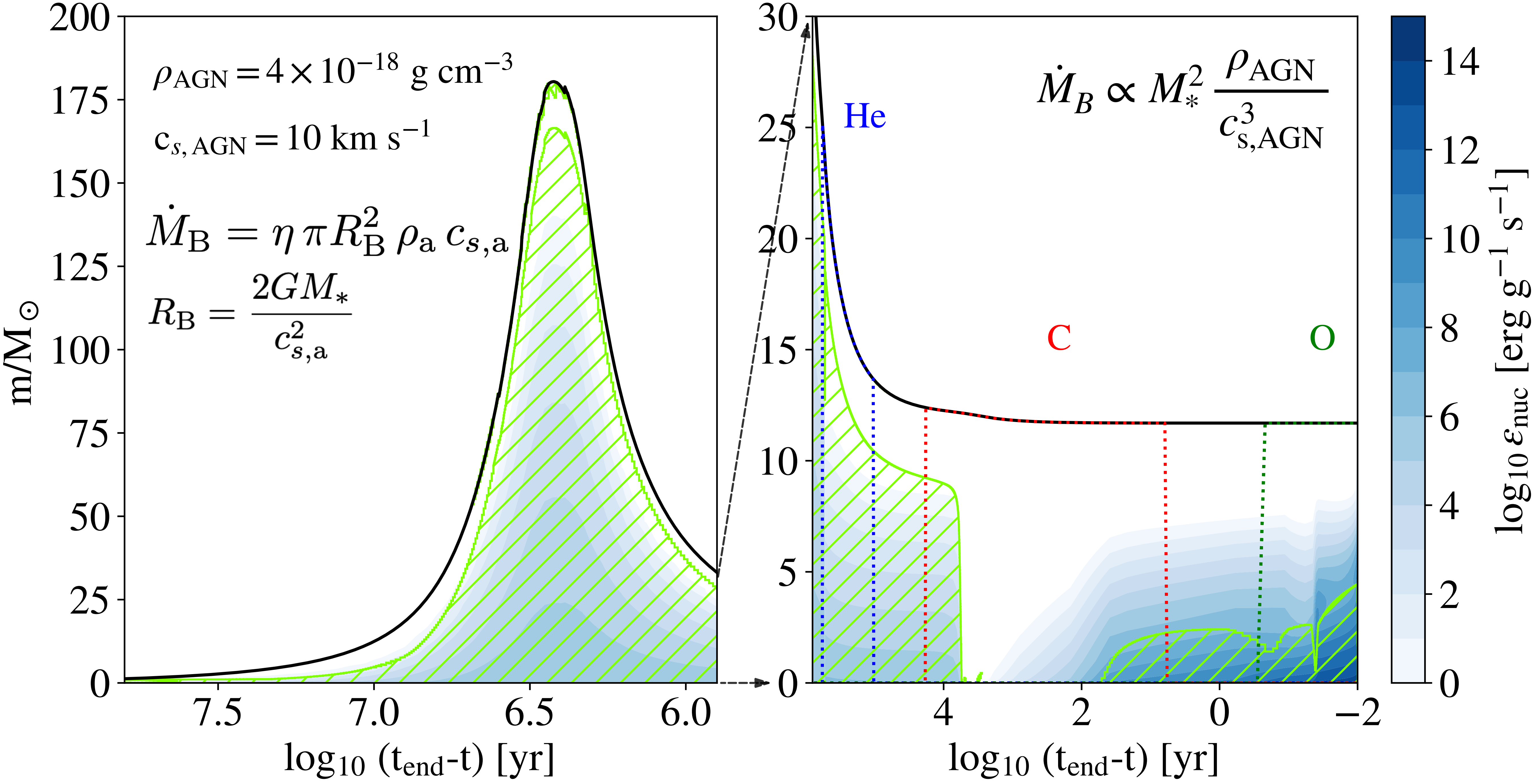


AGN Stars Evolution

Initial Conditions

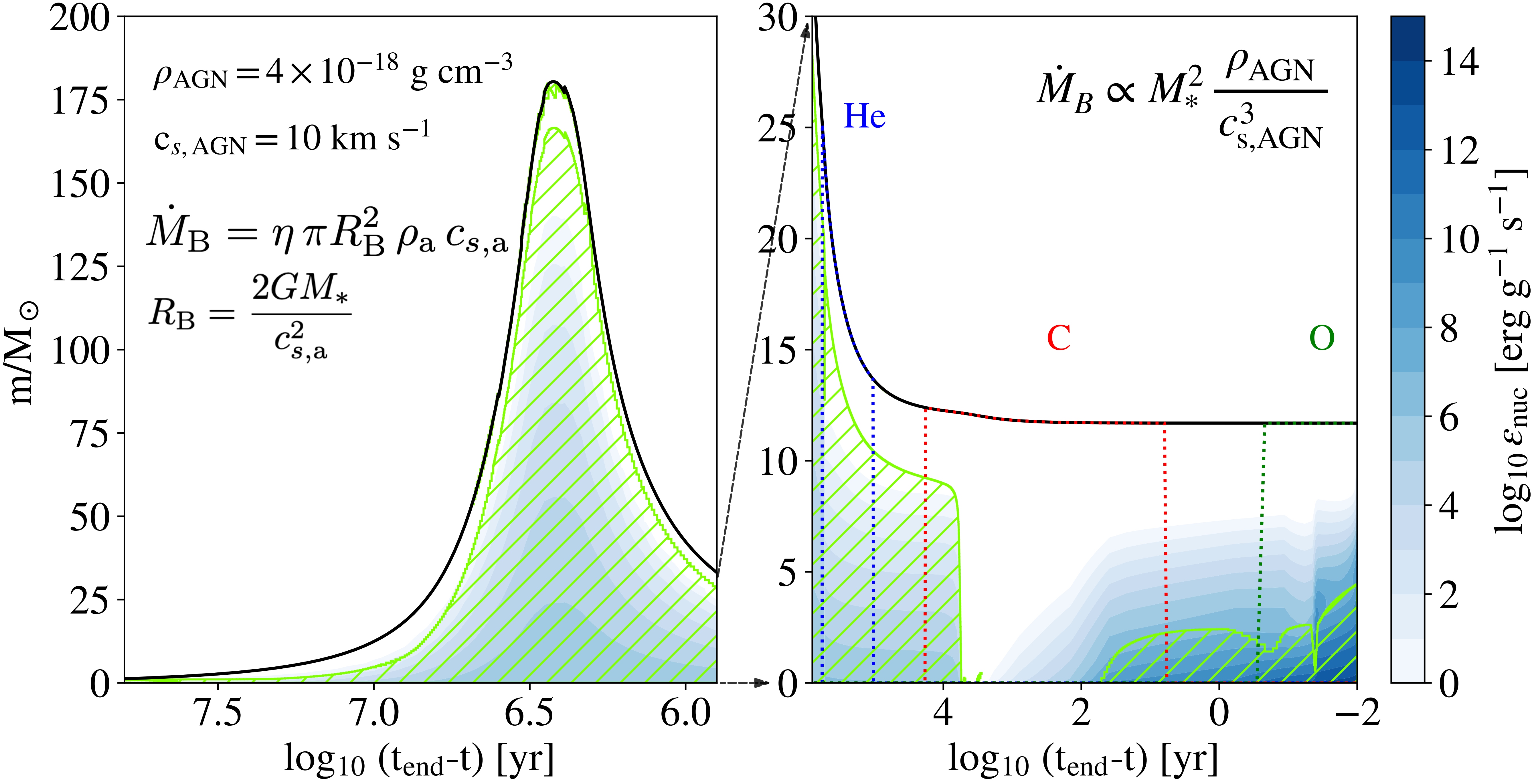
- We use MESA to include the extra physics required to simulate AGN stars (modified boundary conditions, Bondi Accretion, super-Eddington Massloss, extra mixing)
- We take a solar metallicity $1M_{\mathrm{Sun}}$ model and embed it in an AGN with $(\rho_a, c_{s,a})$
- We assume constant composition of accreted material
- For now we neglect rotation
  (but see Adam Jermyn's follow-up work)

AGN Stars Evolution



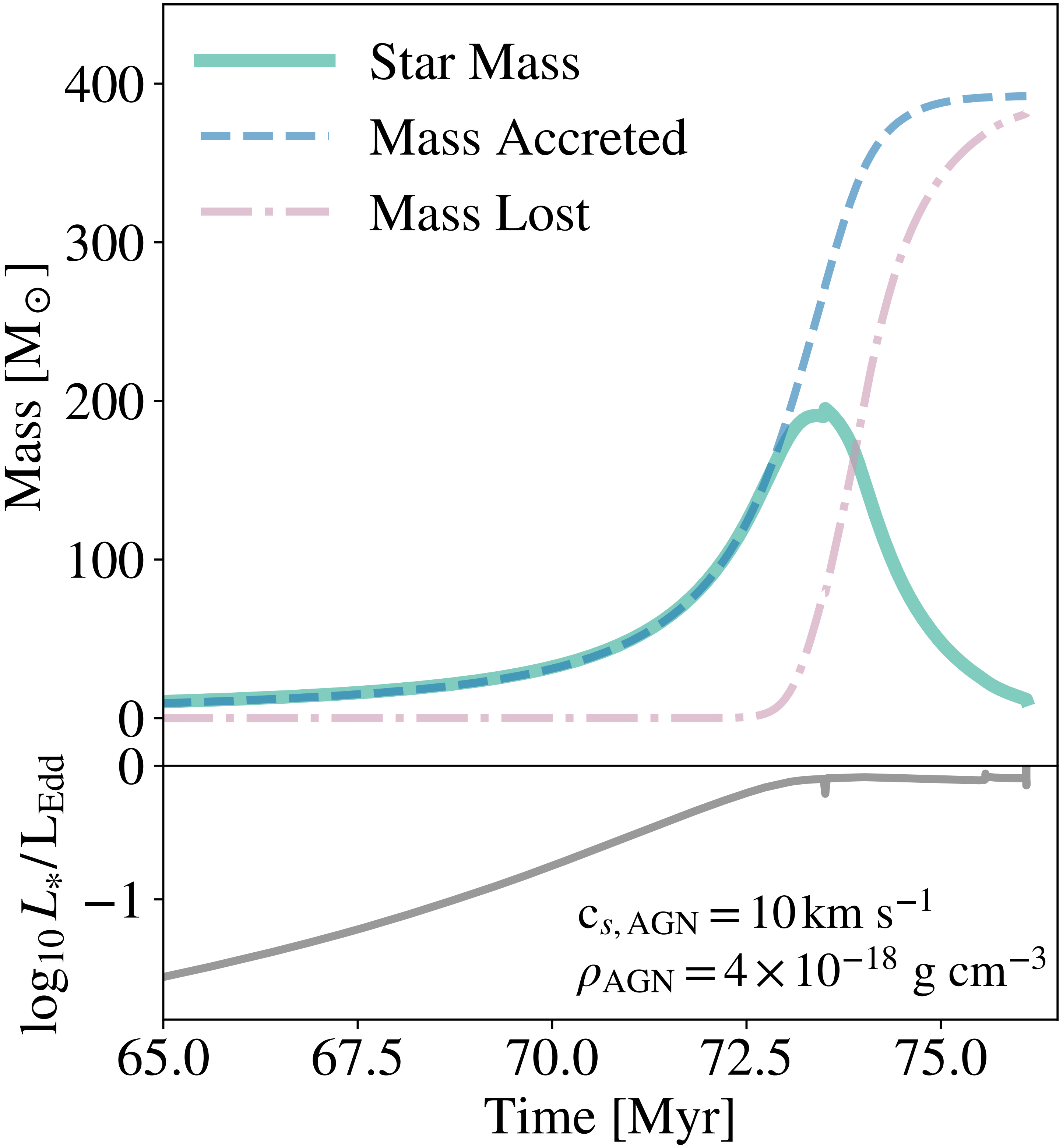
Cantiello, Jermyn & Lin (CJL 2020)

AGN Stars Evolution

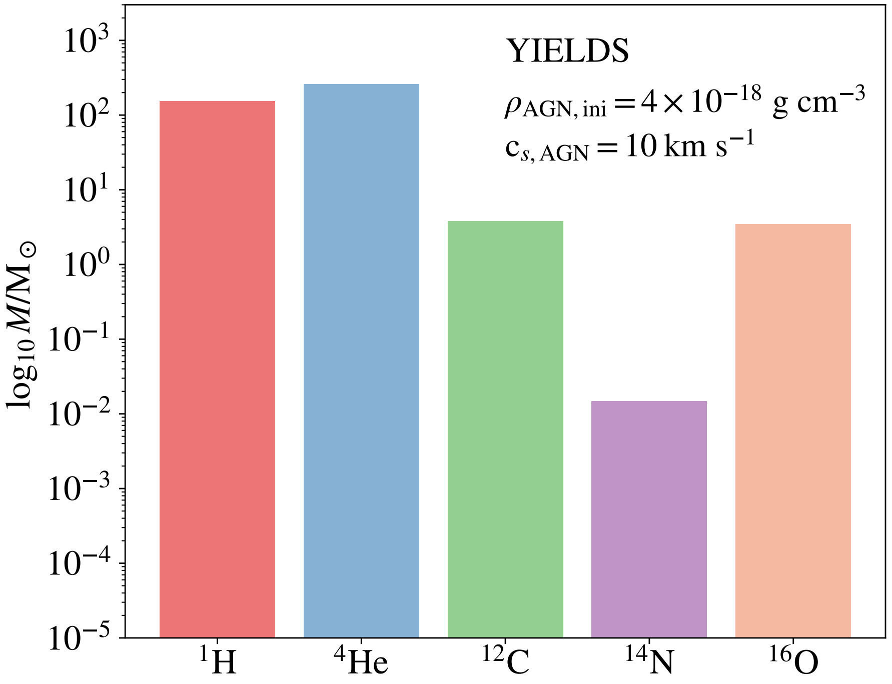


- Likely final outcome: BH with ~10$M_{\rm sun}$

Mass Budget

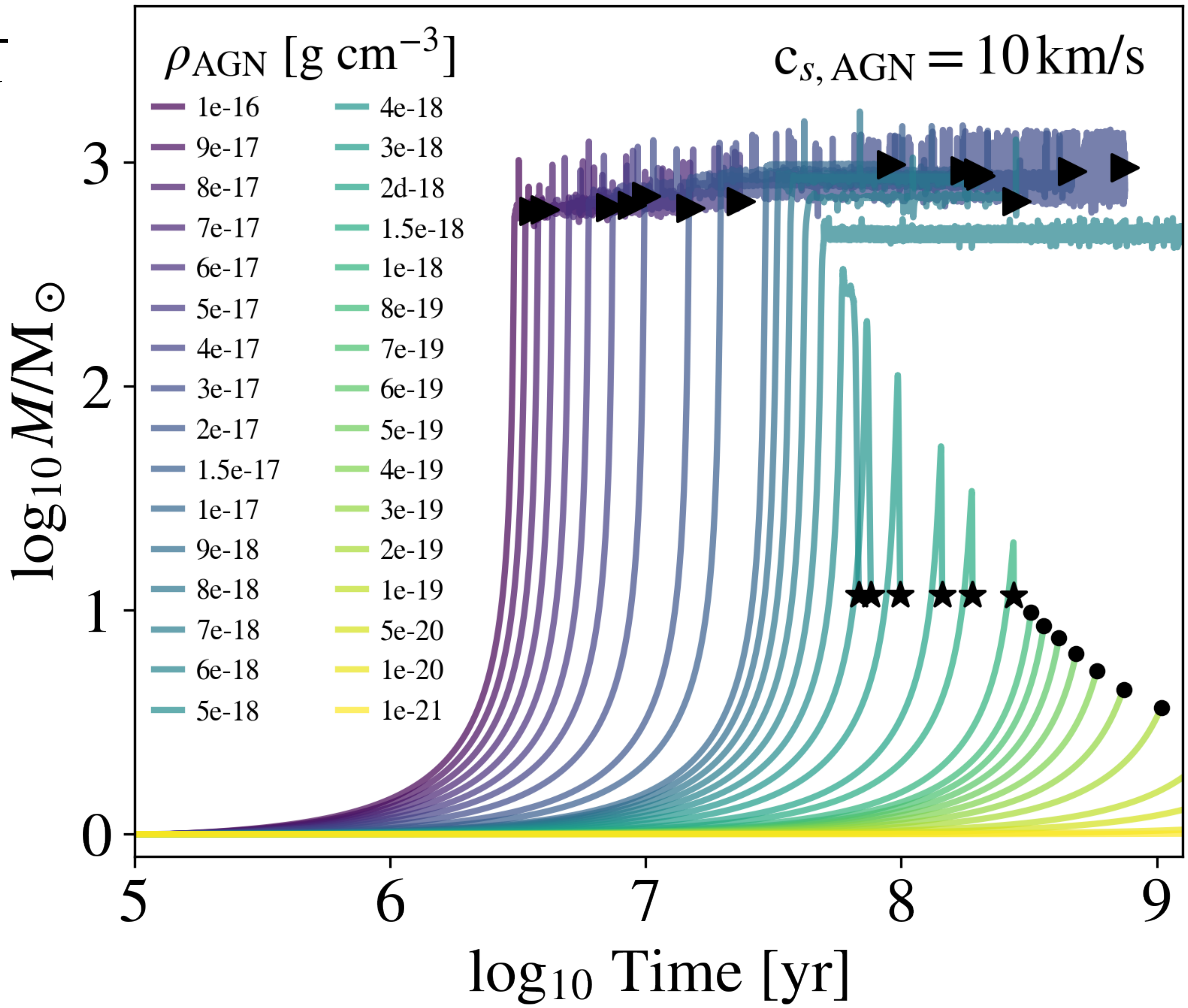


Started as a 1Msun, evolves to ~200M_{Sun} in 73Myr, loses ~400M_{Sun} of He-rich, CNO-processed material, leaves behind ~10M_{Sun} BH



Mass Accretion and Loss

$$\dot{M}_B \propto M_*^2 \frac{\rho_{\rm AGN}}{c_{\rm s,AGN}^3}$$



CJL 2020

Results: three regimes

- Slow Accretion: $\tau_{Acc} > \tau_{Nuc}$ or $\tau_{Acc} > \tau_{AGN}$
- Intermediate Accretion: $\tau_{Nuc} \lesssim \tau_{Acc} < \tau_{AGN}$
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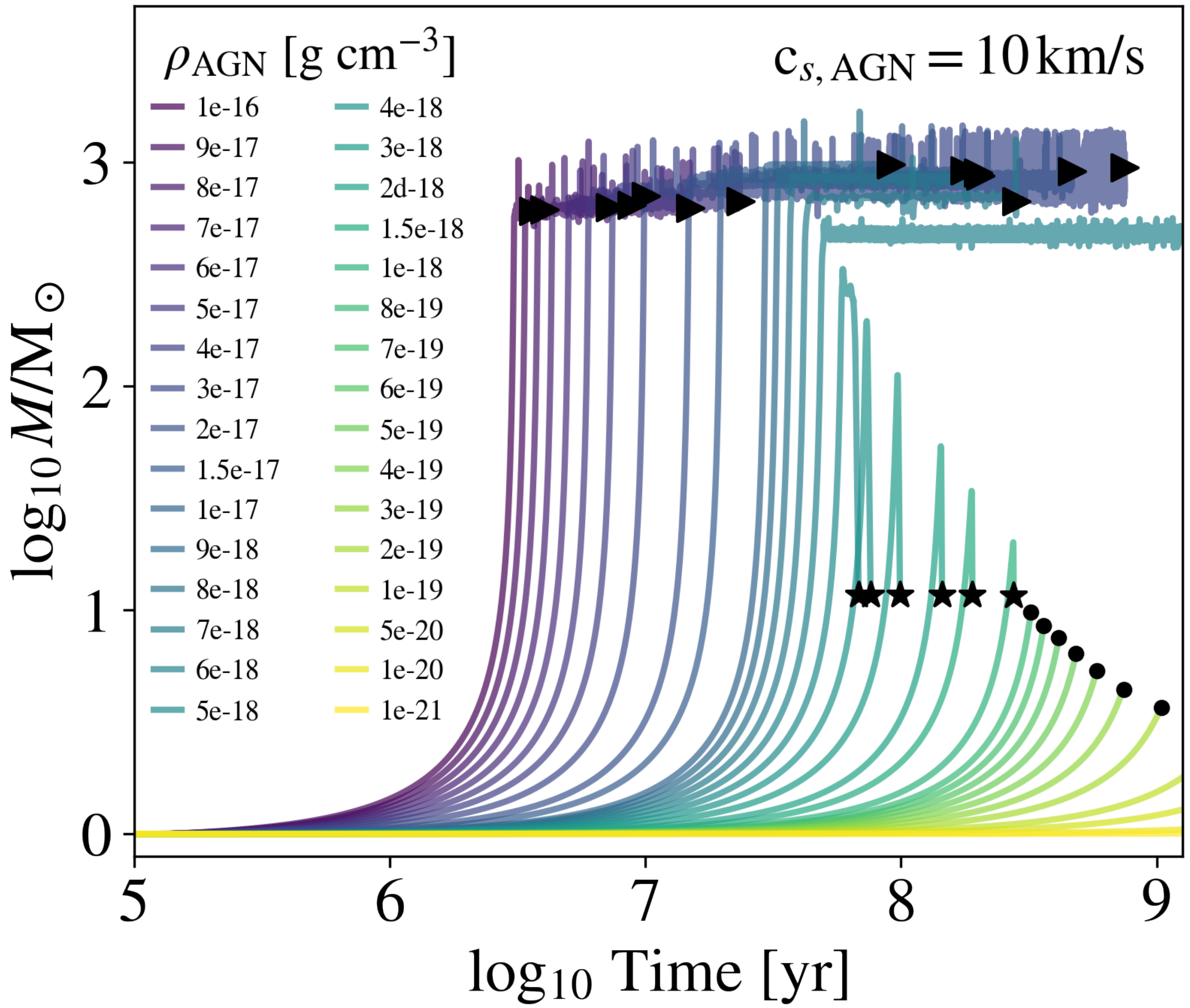
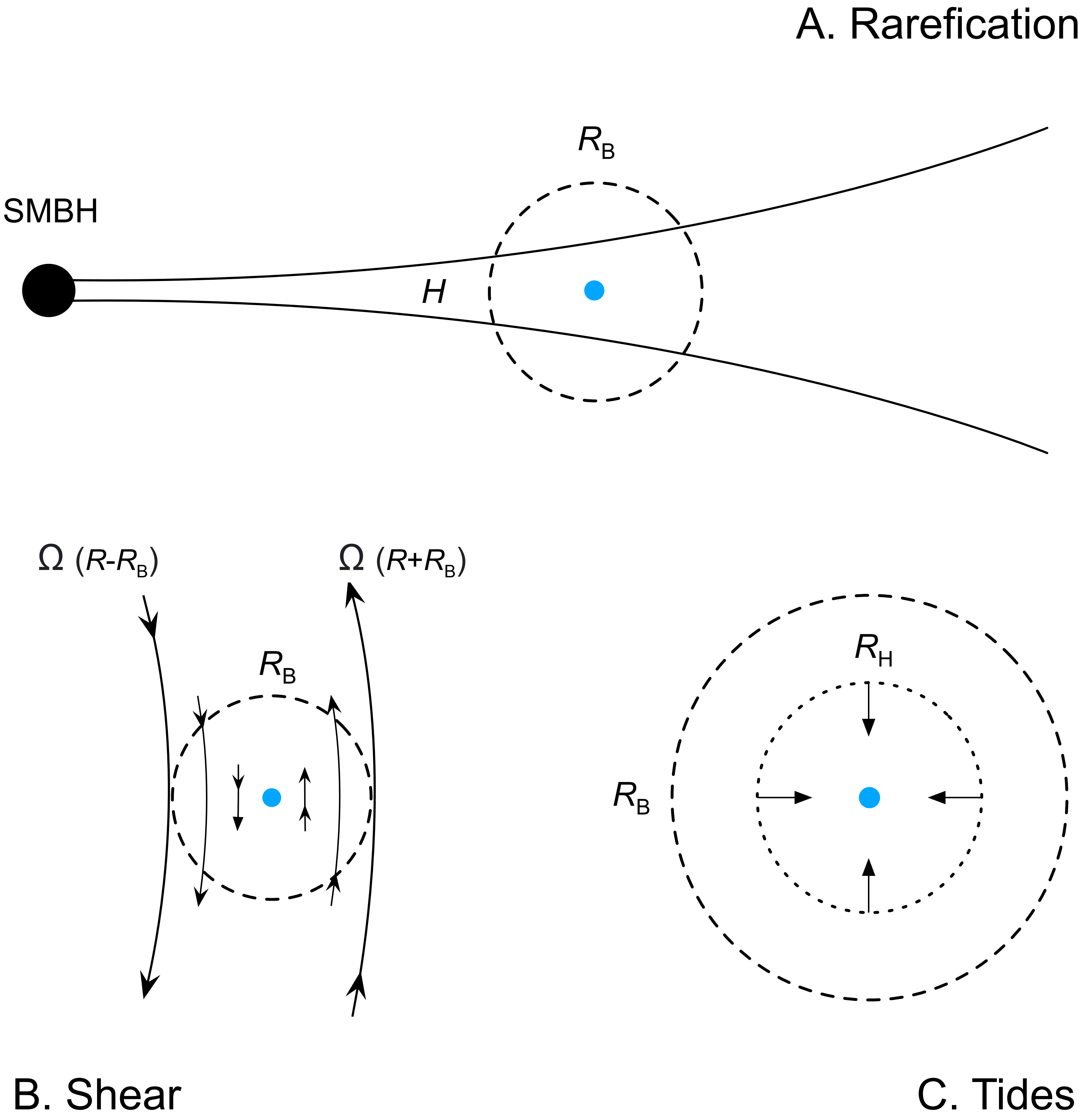


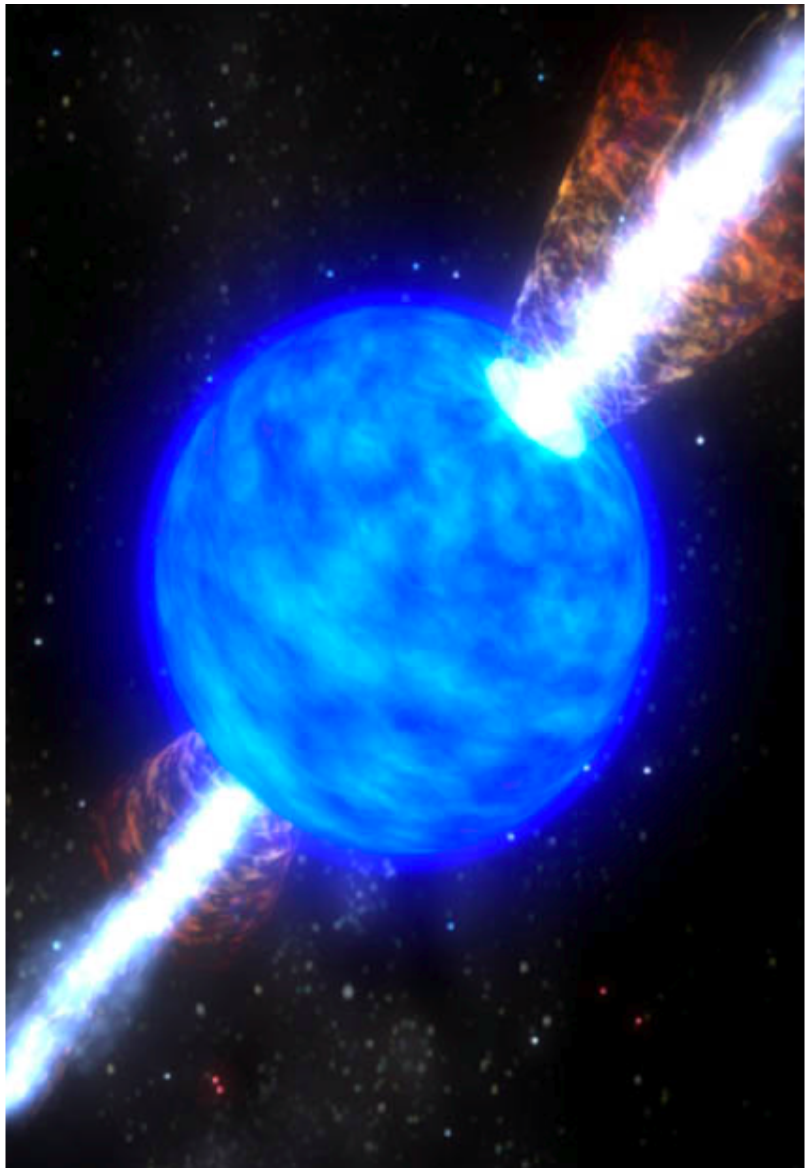
Modifications to Bondi Accretion



Reduction of Bondi accretion in AGN disks. Better mapping of evolutionary outcomes in realistic disk conditions

Dittmann, Cantiello & Jermyn 2021

AGN Stars Rotational Evolution

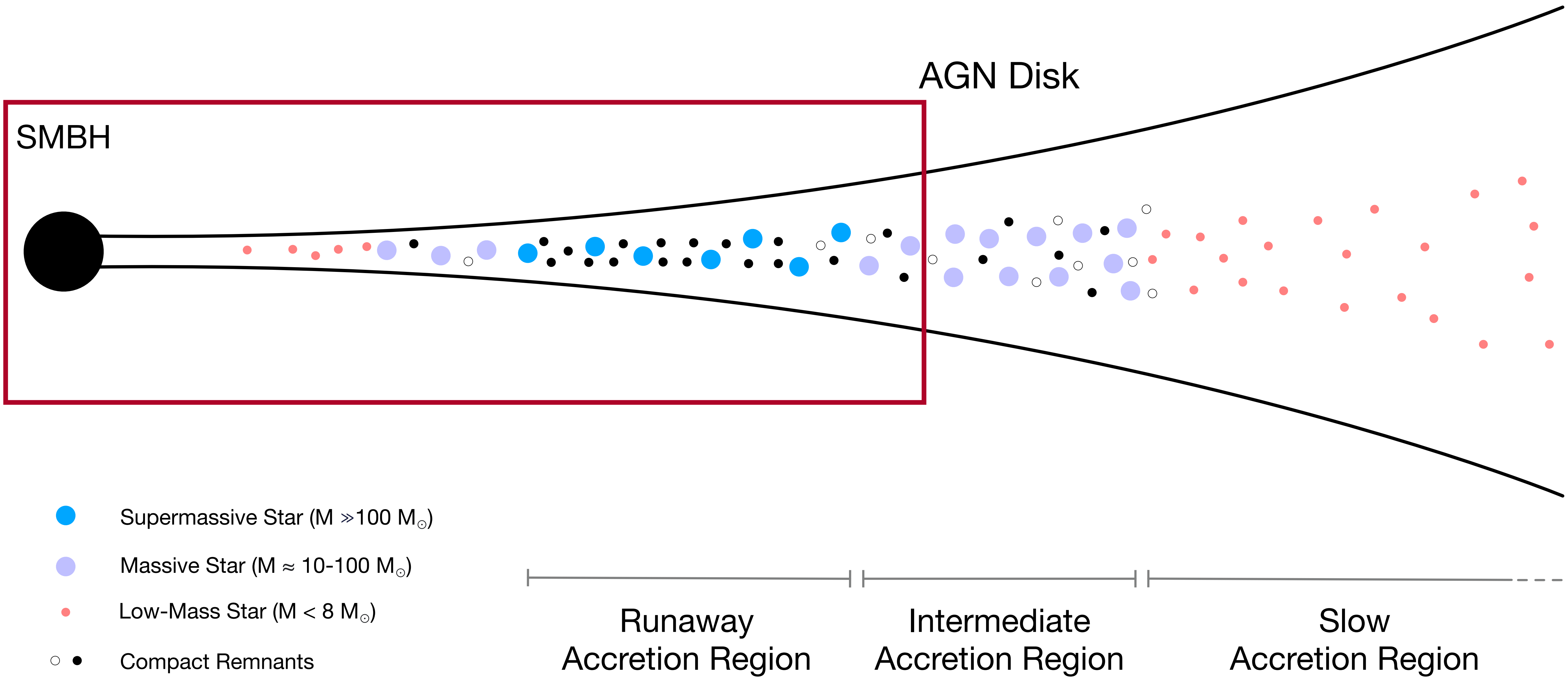


Stars accrete mass but also angular momentum. They rotate very rapidly by the end of their lives.

1) Rapidly spinning compact remnants
2) Relativistic explosions (LGRBs)

Jermyn, Cantiello, Dittmann & Perna 2021, Perna et al. 2021

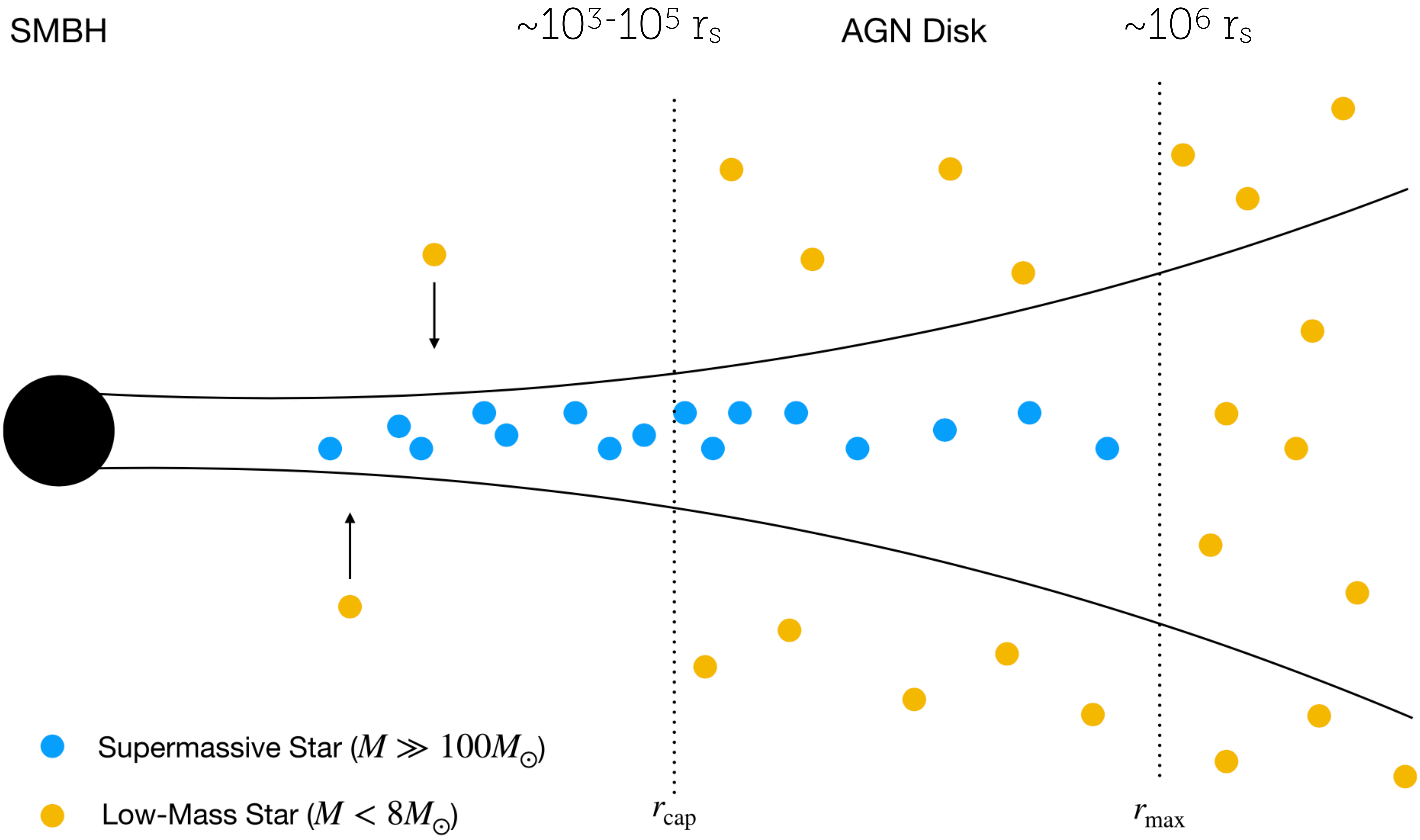
Massive & Very Massive Stars



More realistic mapping
to AGN models

Dittmann, Cantiello & Jermyn 2021

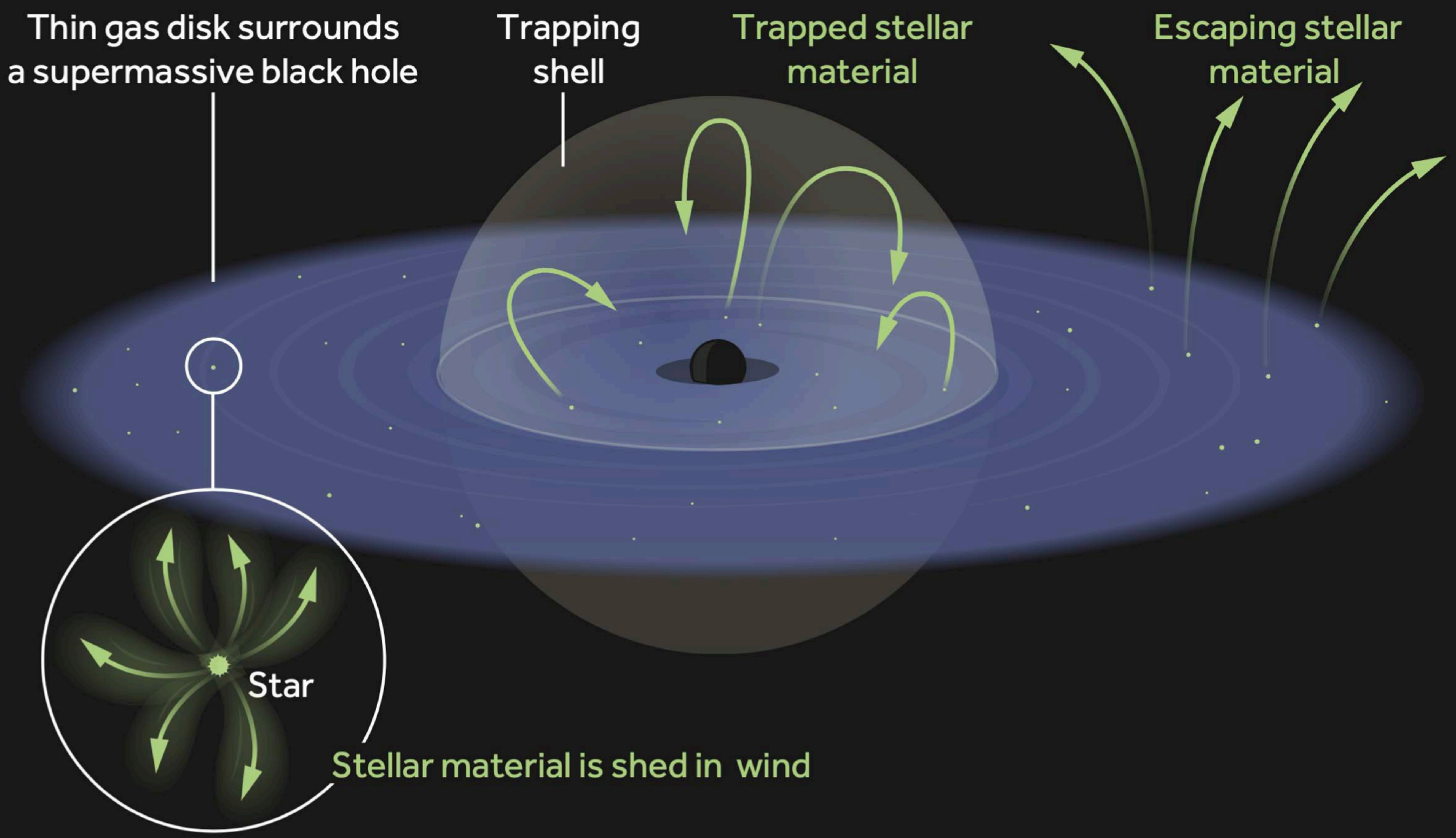
e.g. Fabj et al. 2020



Realm of Immortal Stars

Jermyn et al. 2022

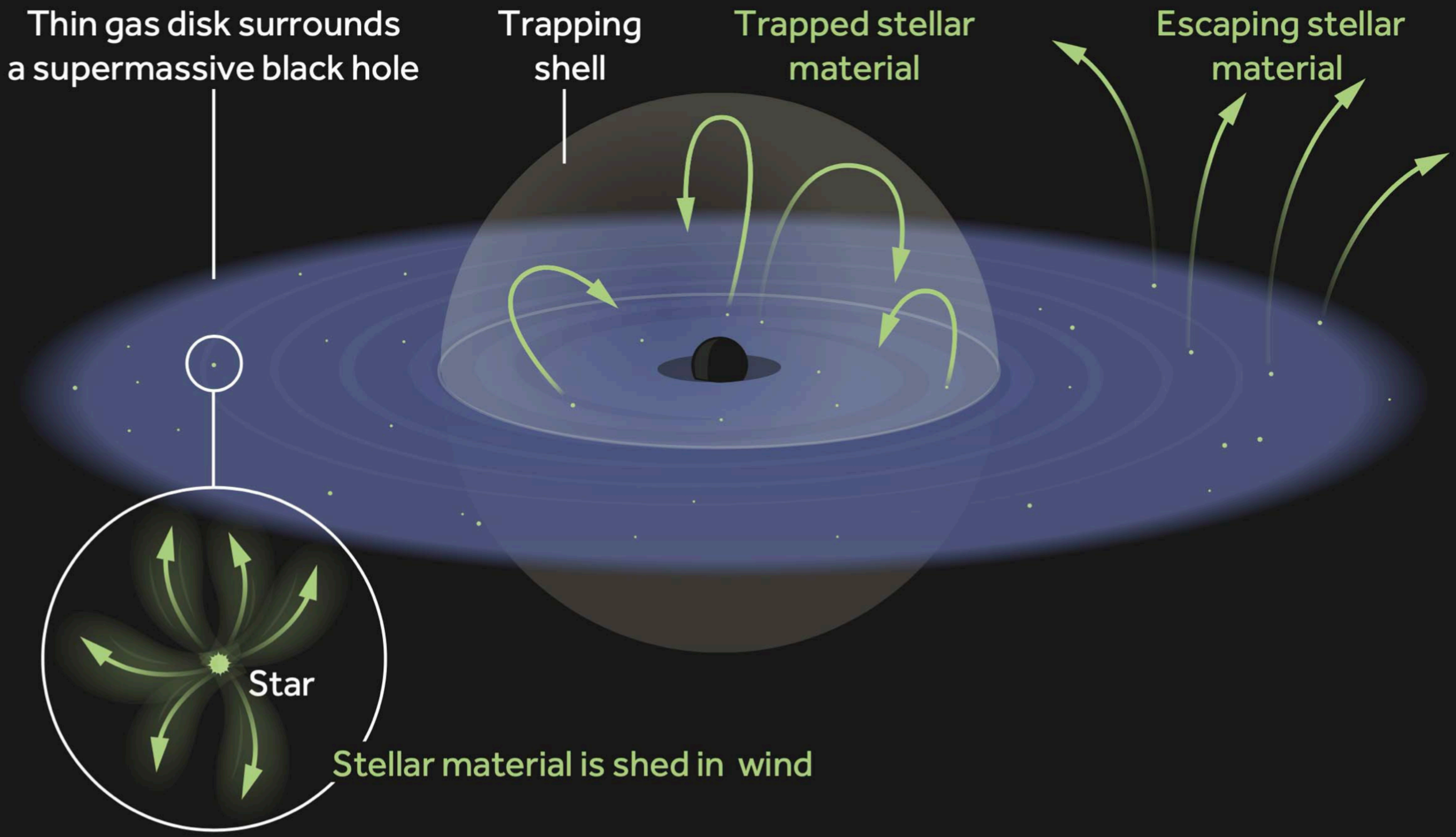
Impact of Immortal Stars on AGN Disks



~10^2 - 10^4 immortal stars per AGN

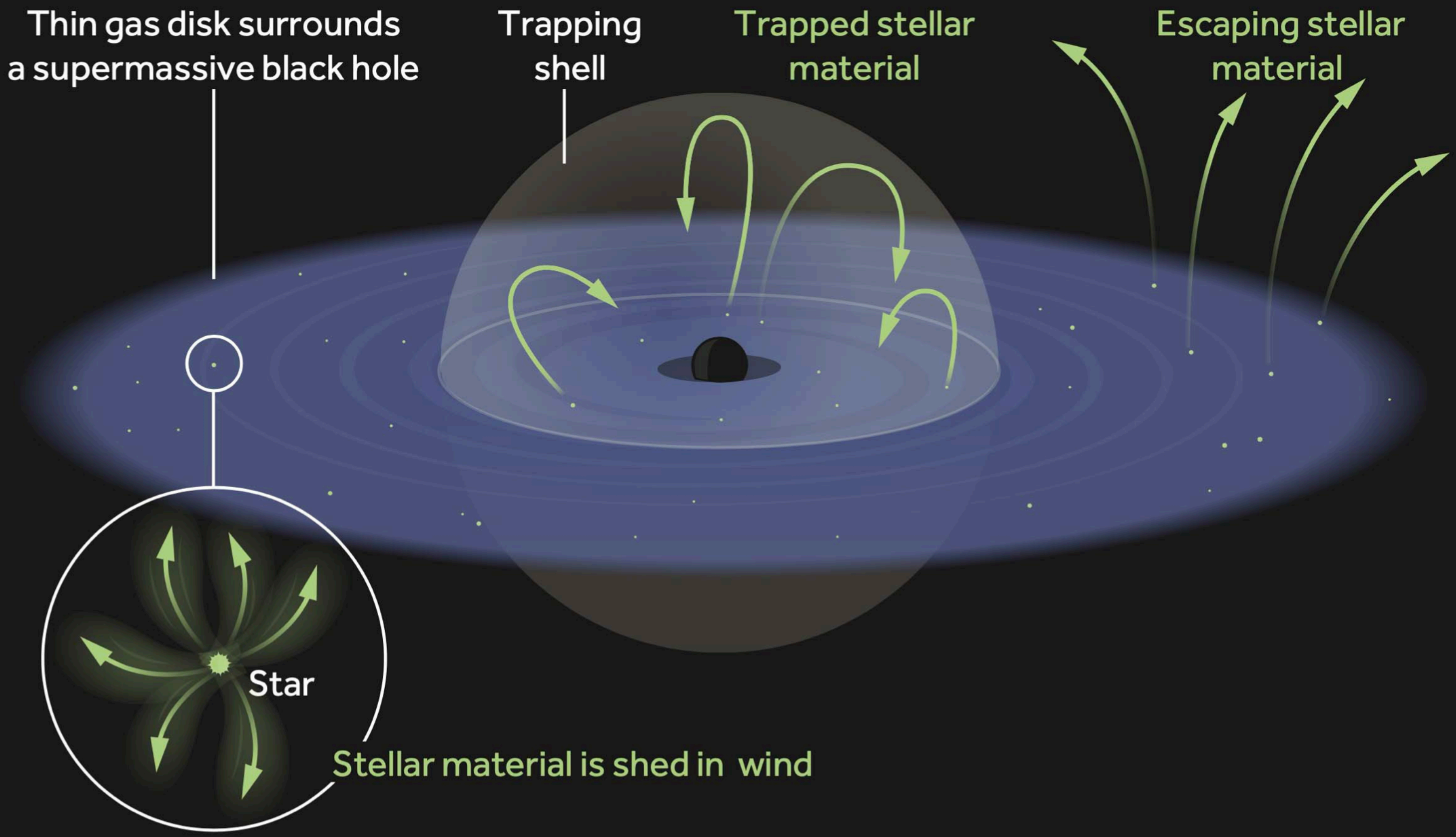
Jermyn et al. 2022

Impact of Immortal Stars on AGN Disks



~10^2 - 10^4 BHs + BHs from intermediate accretion

Impact of Immortal Stars on AGN Disks



Many possible dynamical interactions (see Jermyn+ 22)

Possible Implications / Predictions

- ✷ Population of massive & very massive * in AGN disks

  (e.g. Goodman & Tan 2004, Dittmann & Miller 2020)

- ✷ AGN Disk composition evolution

  (Cantiello, Jermyn, Lin 2020)

- ✷ AGN Feedback (from winds / SNe / GRBs …)

  (Perna, Lazzati & Cantiello 2020; Jermyn, Cantiello, Dittmann & Perna 2021 In Prep.)

- ✷ Mergers of Compact Objects (LIGO/Virgo, LISA)

  (McKernan et al. 2012, 2014; Bellovary et al. 2016, Bartos et al. 2017; Stone et al. 2017; Leigh et al. 2018, Fragione et al. 2019;Secunda et al. 2019; Tagawa et al. 2020; Yang et al. 2020; Gröbner et al. 2020; Ishibashi & Gröbner 2020; Graham et al. 2020, Abbott et al. 2020ab)

- ✷ Galactic Center stellar populations and abundances

  (e.g. Levin 2003, Levin & Beloborodov 2003, Davies & Lin 2020)

See M. Davies' talk

Uncertain Physics and Future Steps

- Bondi-Hoyle accretion around massive stars
- Mass Loss
- Effects of rotation
- Pairing Evolution + Dynamics
- Evolving composition of accreted matter
- Explore different metallicities

Current team: Adam Jermyn, Doug Lin, Alexander Dittmann, Yan-Fei Jiang, Rosalba Perna, Saavik Ford, Barry McKernan. Still a lot of possible projects and collaborations. Talk to us!

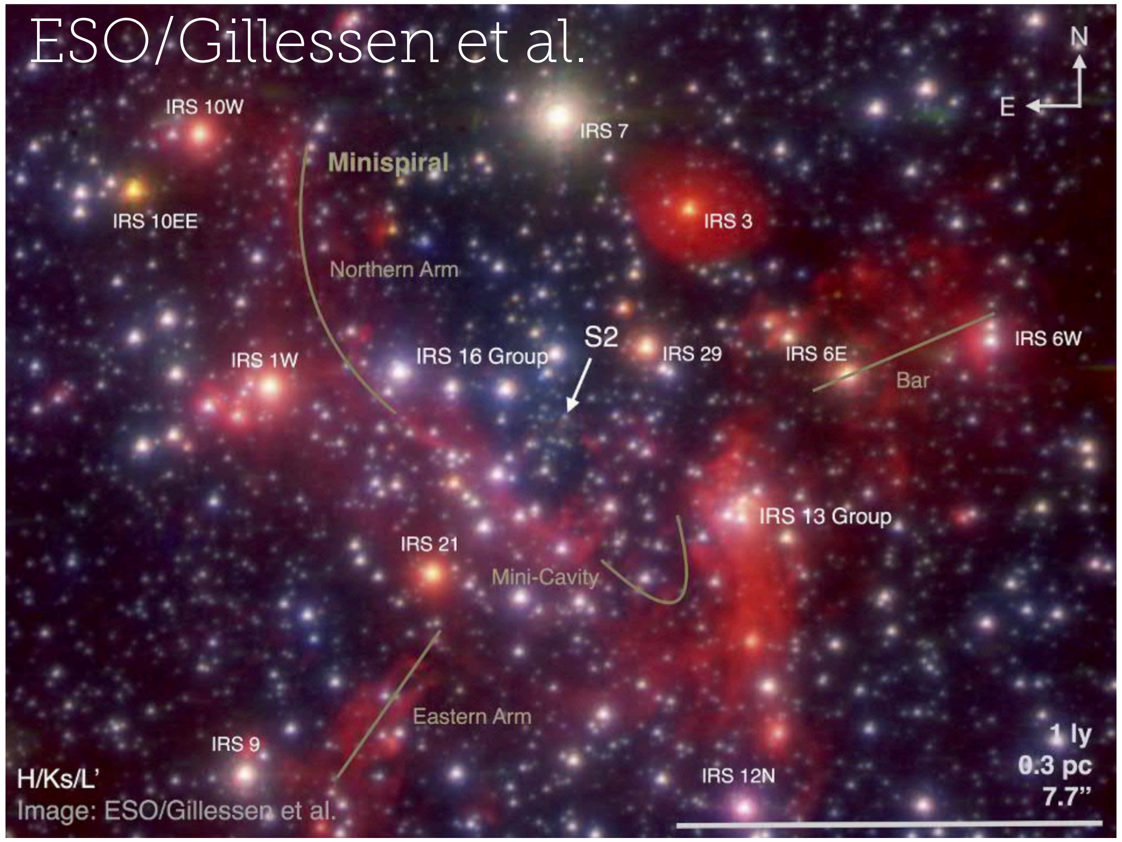
Thanks!

Backup Slides

Observational Constraints

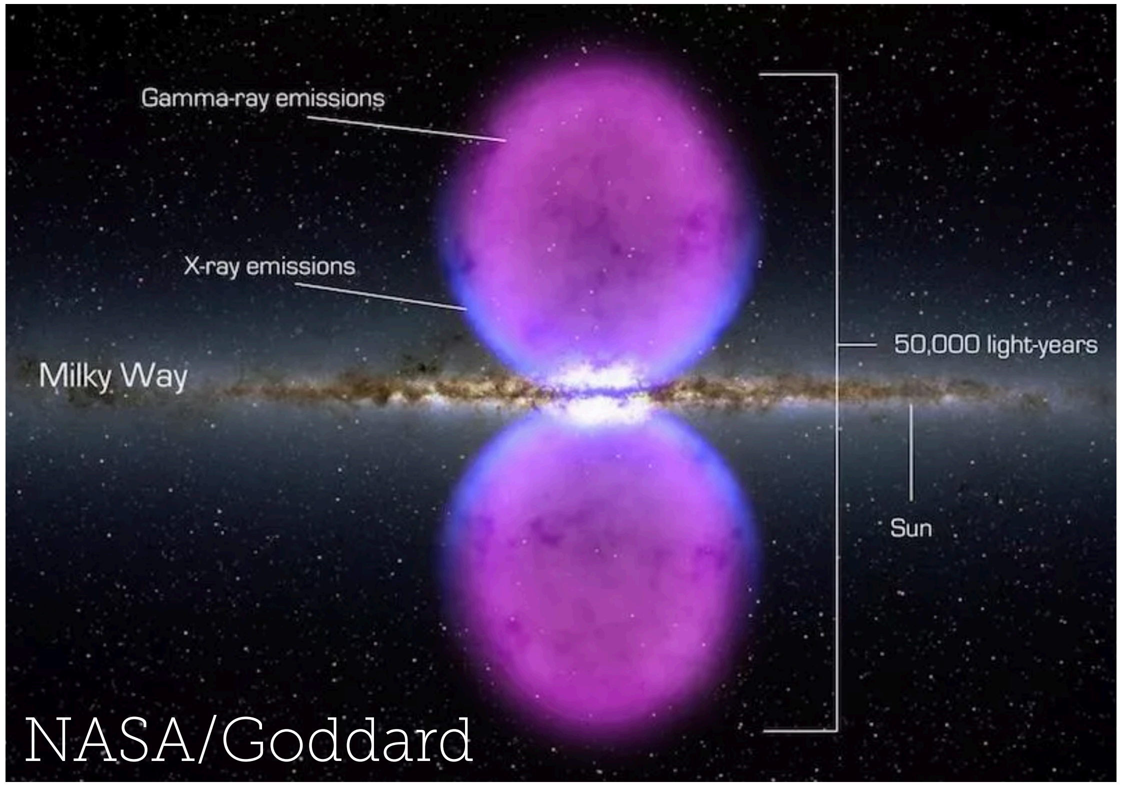
The Galactic Center

- Observations of stellar populations and stellar remnants are directly available



ESO/Gillessen et al.

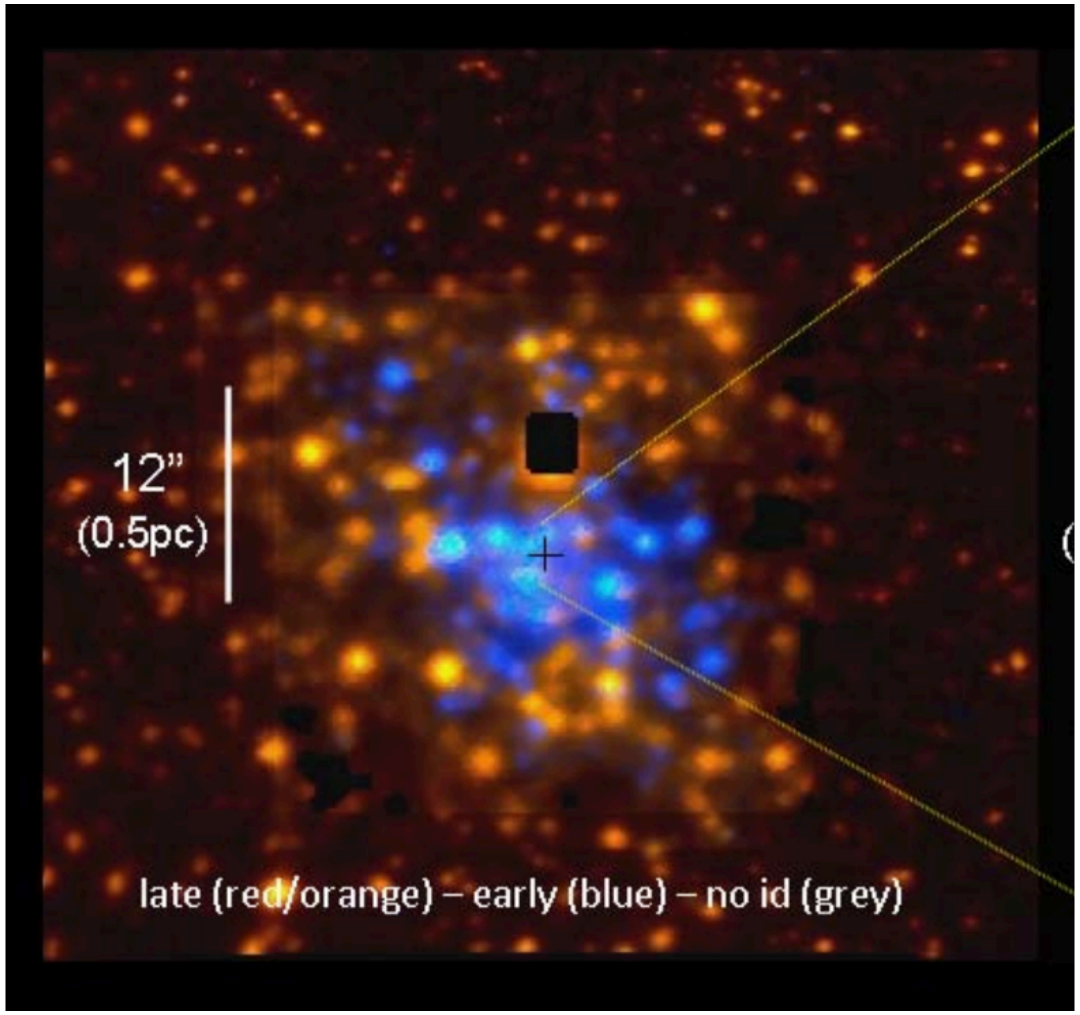
- Might have experienced AGN-like phase ~6-7Myr ago



NASA/Goddard

The Galactic Center

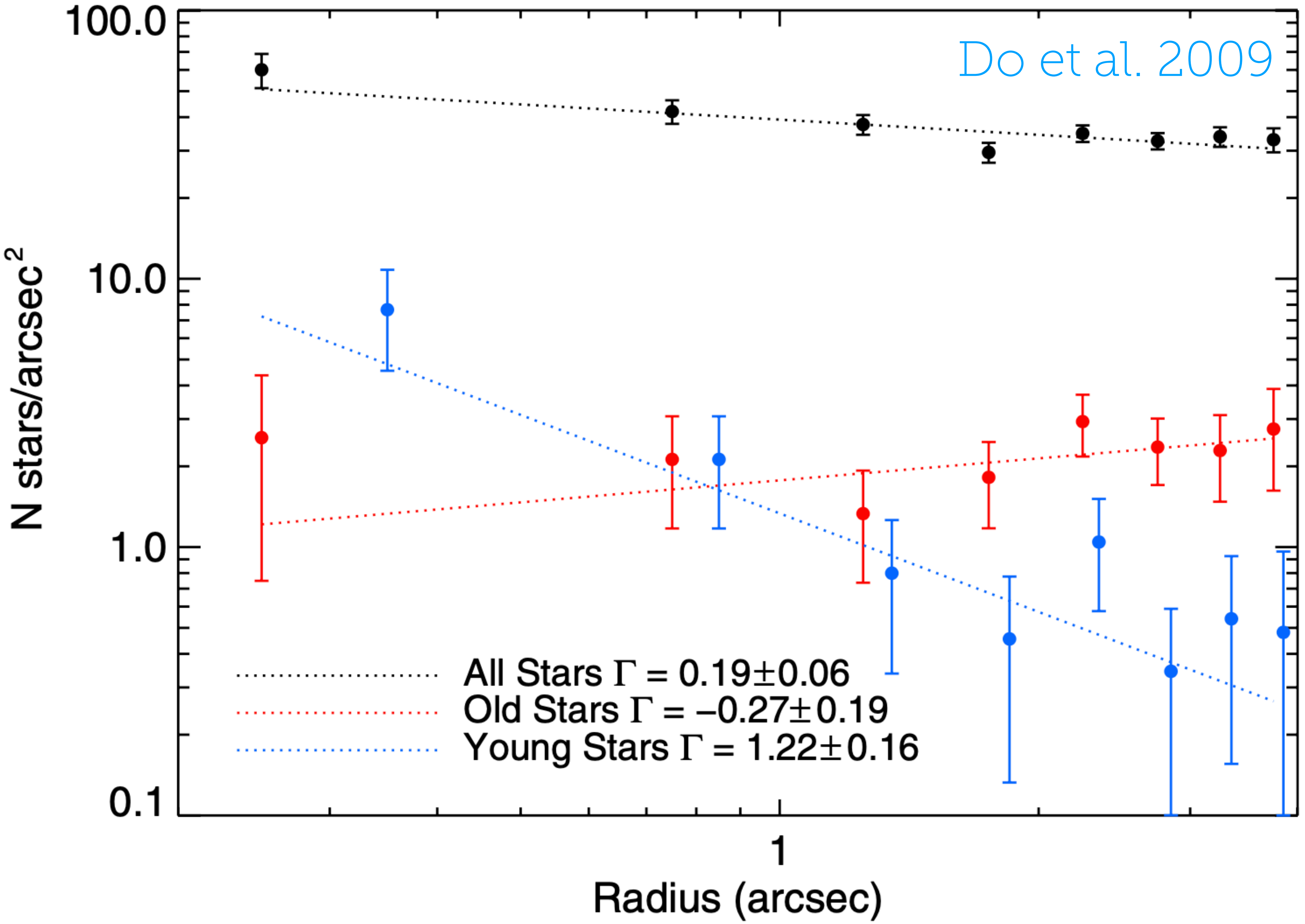
- ~200 young massive stars within ~1pc. Presence of so many young stars in the immediate vicinity of the central BH unexpected (Ghez et al. 2003b; Alexander 2005)
- Density of massive O/WR stars in the inner 1pc region raises steeply within ~0.5pc. No O/WR stars beyond 0.5pc (Paumard et al. 2006; Bartko et al. 2010)
- Top-heavy present day mass function within 0.5pc (Genzel 2010)
- Stellar spectroscopy shows that some of these stars might be He-rich (Martins et al. 2008; Habibi et al. 2017; Do et al. 2018)



Genzel 2010

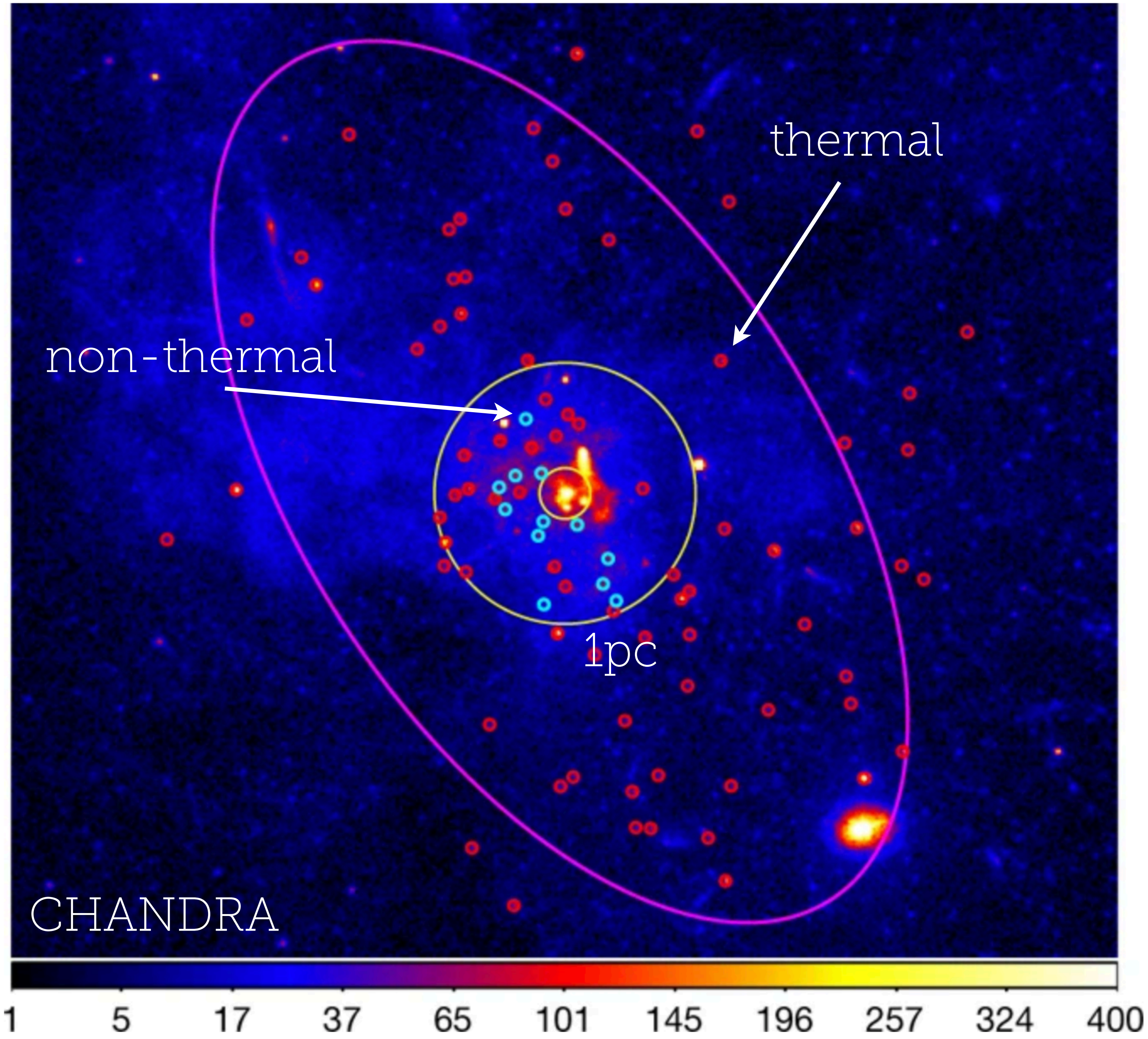
See also M. Davies' talk

The Galactic Center



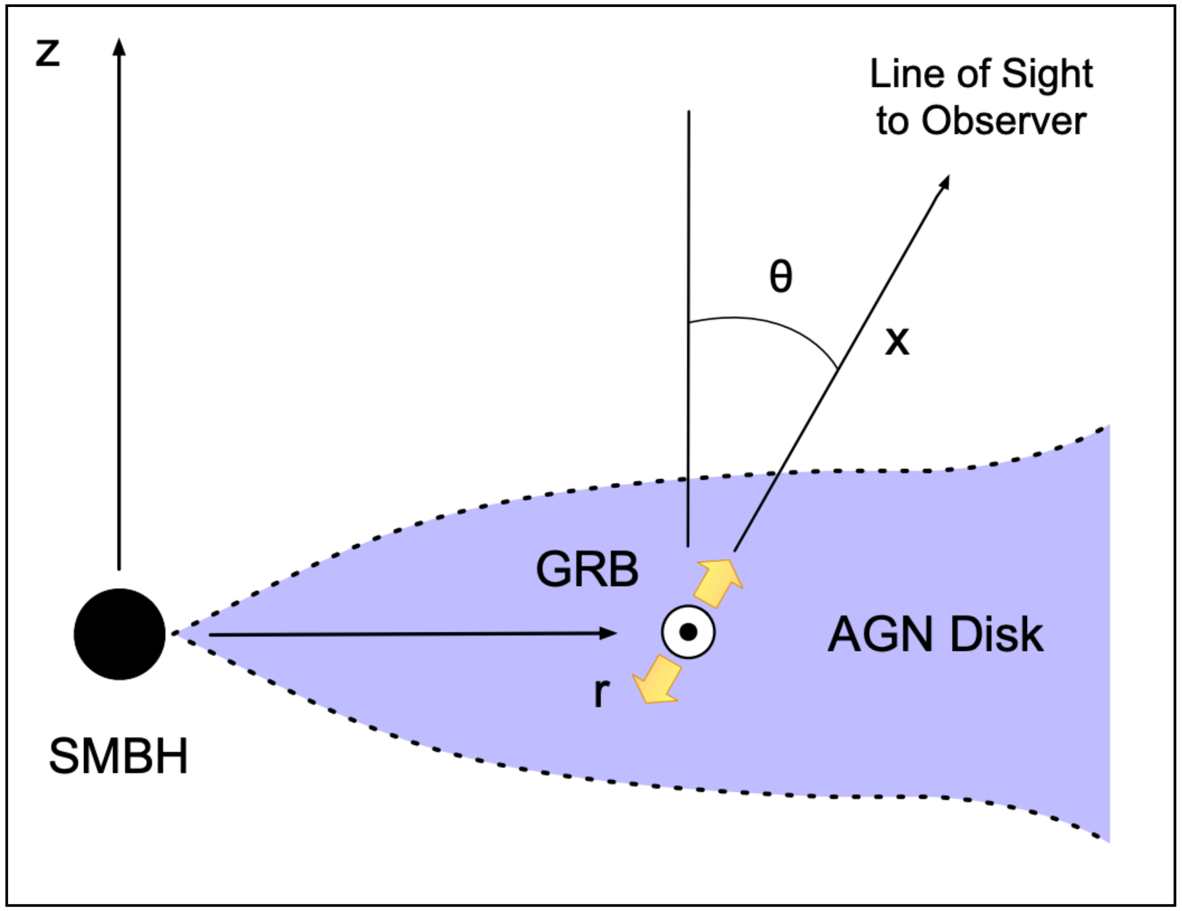
Missing stellar cusp (Bahcall&Wolf 1976). Possible depletion of low-mass stars in the inner regions

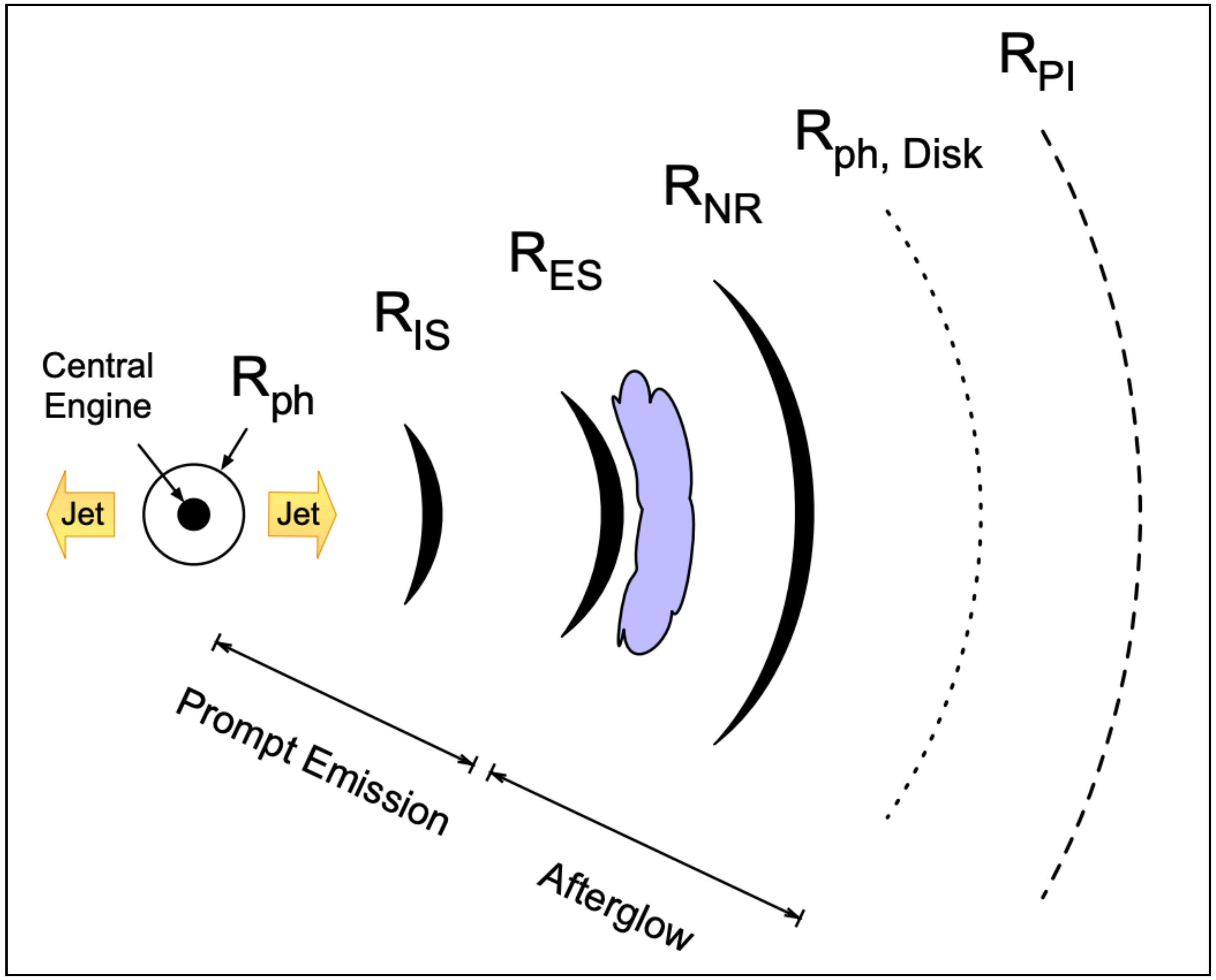
The Galactic Center



LMXB candidates identified by Hailey+ 2018 are found only within ≈ 1 pc.

(Embedded) Relativistic Explosions?



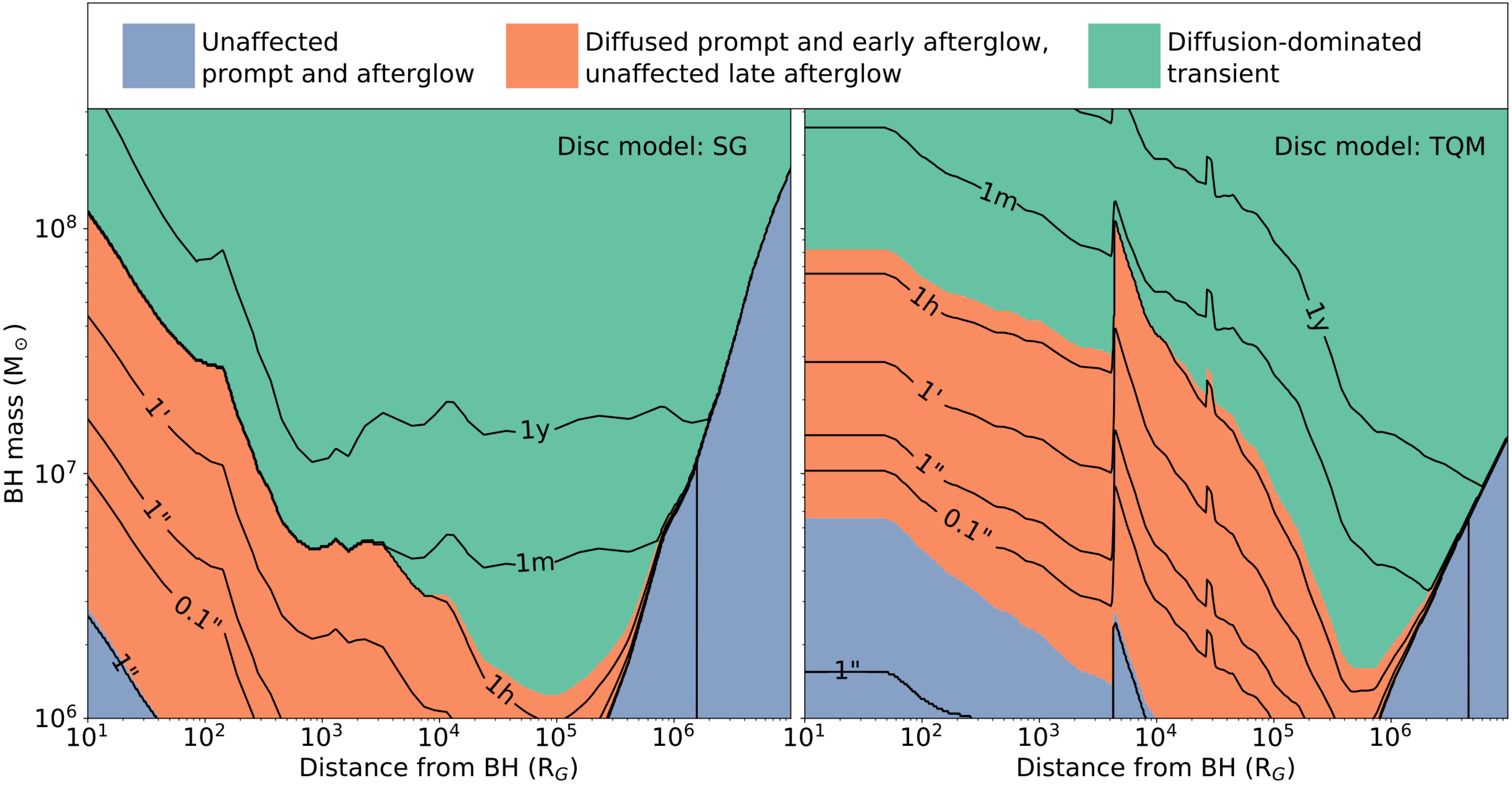


AGN Stars evolve chemically homogeneously. They also spin rapidly (Jermyn, Cantiello, Dittmann, Perna In prep.)

-> Relativistic explosions in AGNs (Long and short GRBs)

Perna, Lazzati & Cantiello 2021

(Embedded) Relativistic Explosions?

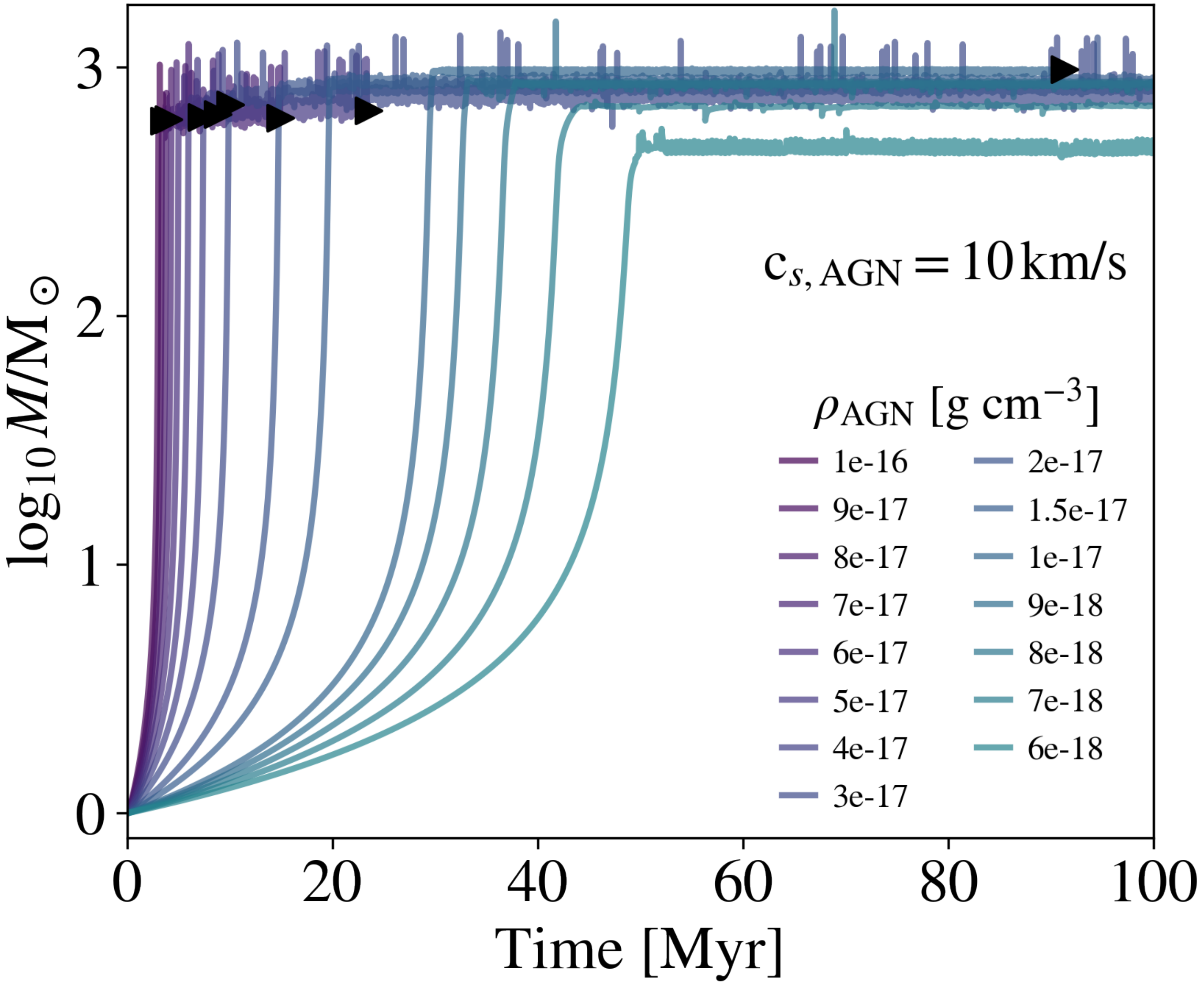


Possible impact on feedback
and AGN variability
e.g. Graham+2017

Perna, Lazzati & Cantiello 2021

"Immortal" Massive Stars

Because $\tau_{Acc} \ll \tau_{Nuc}$ and since the star is well-mixed, the star is constantly fed fresh fuel from the disk. Massive stars can stay on the main sequence burning H as long as accretion proceeds



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