

Black hole-disk formation from rapidly rotating very massive star collapse

Paper in prep.

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6 Feb @ YITP long-term workstop 2026

In collaboration with: **Sho Fujibayashi, Masaru Shibata**



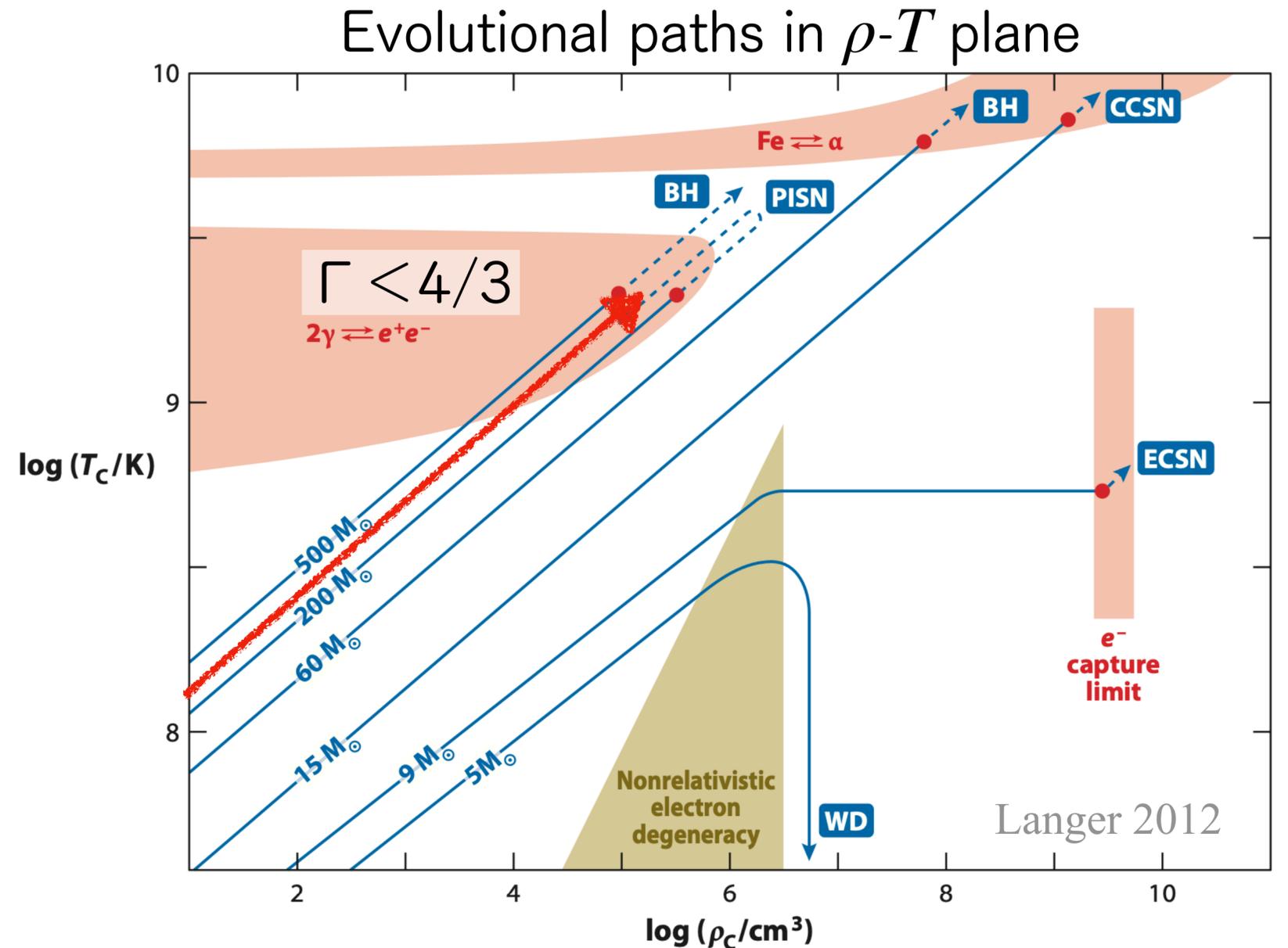
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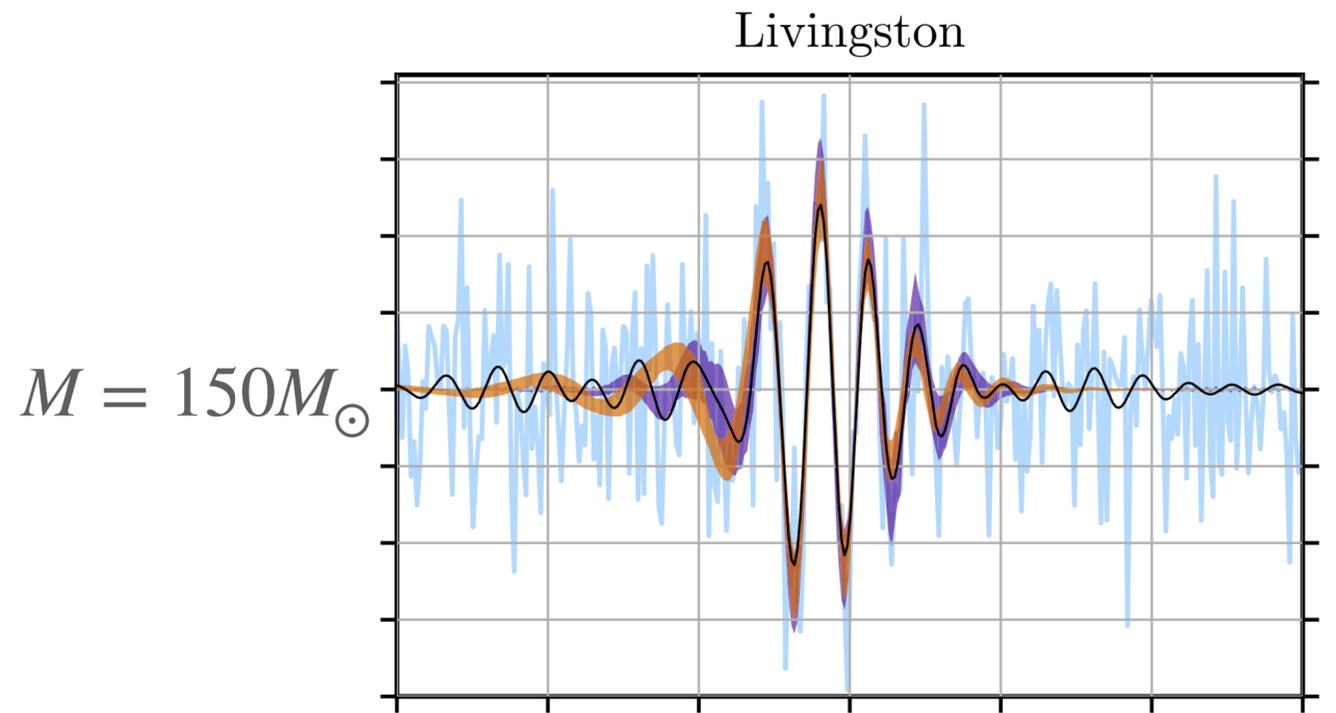
Very Massive Star (VMS)

- $M_{\text{ZAMS}} \gtrsim 130M_{\odot}$
 $e^{-}e^{+}$ pair production
 \Rightarrow **collapse to BH**
- Potential seed of high-z SMBH
- Possible formation of VMS
 with $M_{\star} \lesssim 2000M_{\odot}$
 + spin $J/M_{\star}^2 \lesssim 10$
 (talk from A. Tanikawa)

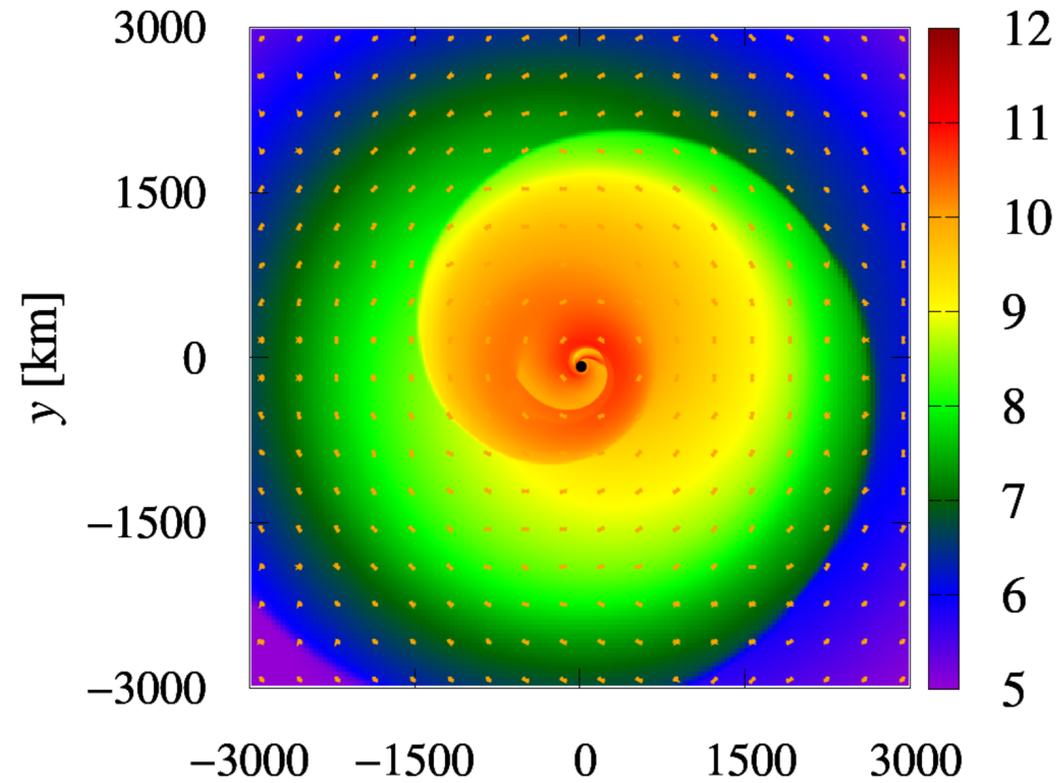


(talk from S. Fujibayashi)

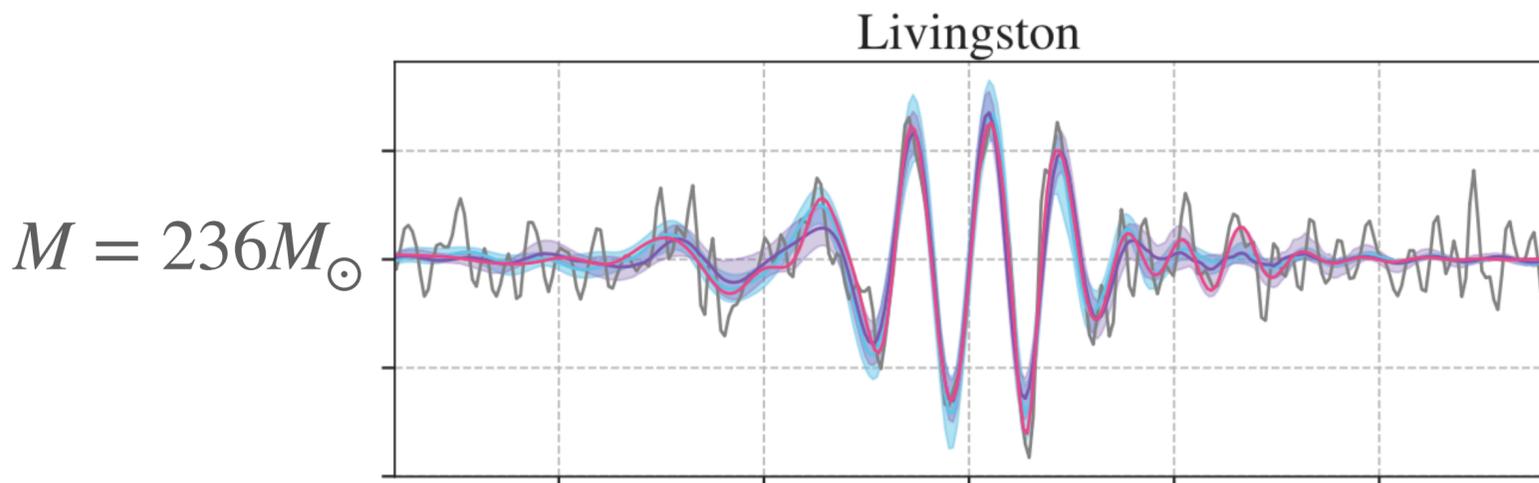
Alternative model for GW



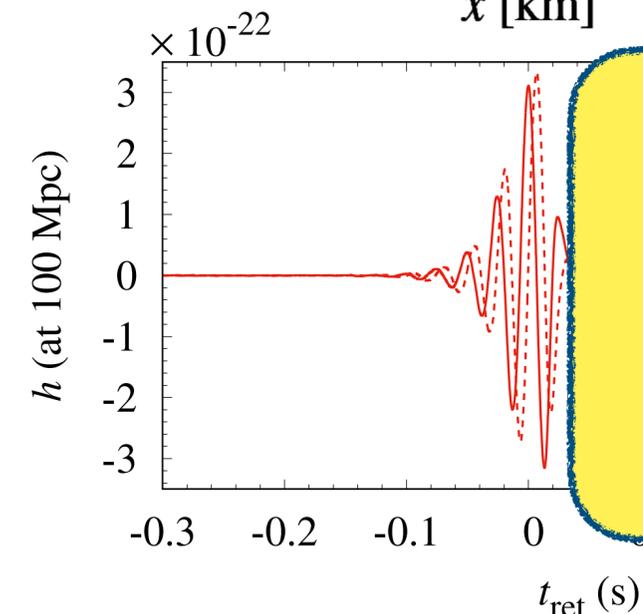
GW190521 (LIGO PRL. 125 (2020) 10, 101102)



x [km]



GW231123 (LIGO *Astrophys.J.Lett.* 993 (2025) 1, L25)

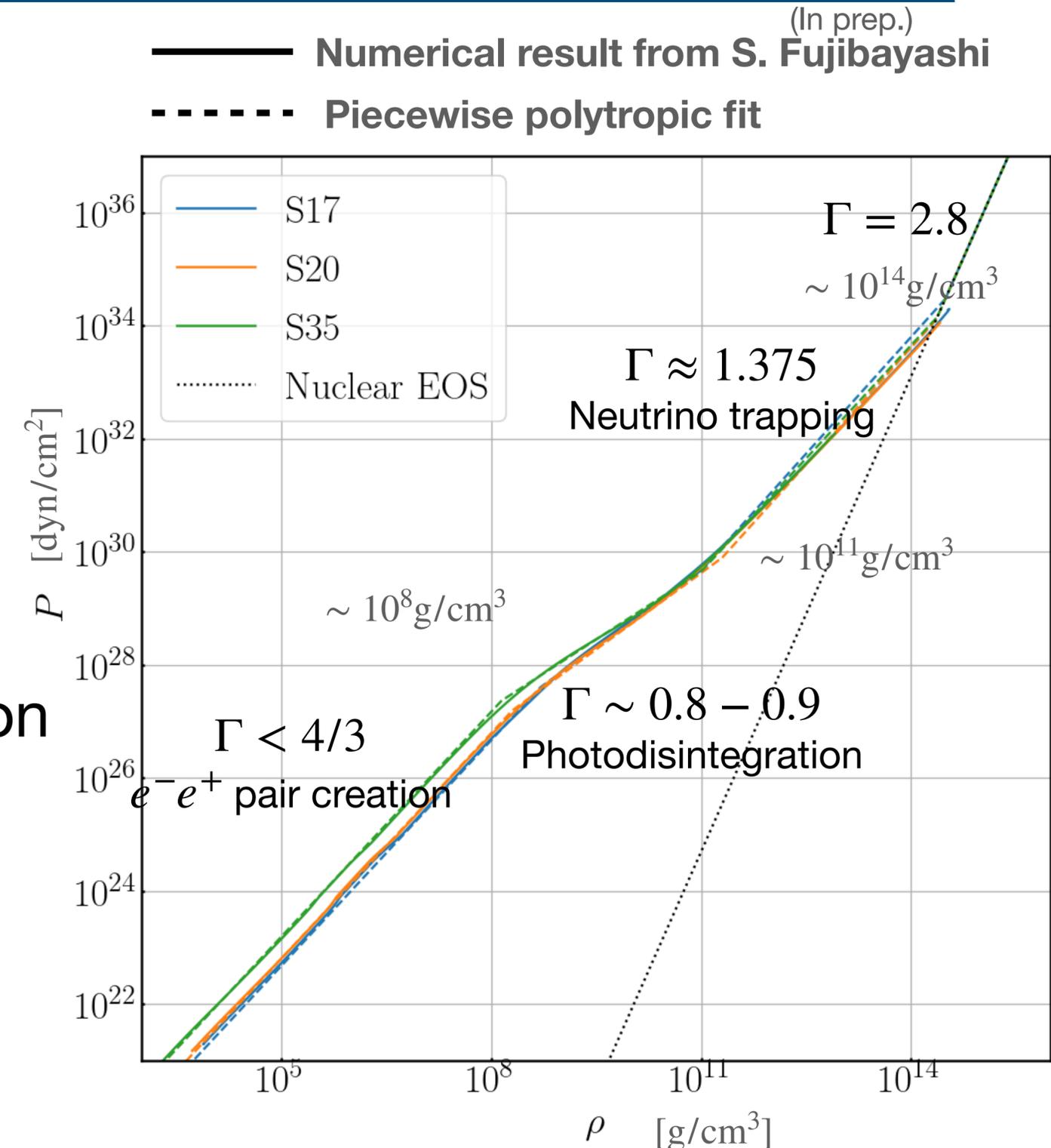


(M. Shibata, et al. PRD 103 (2021) 6, 063037)

**GW from
spiral-arm instability of
rotating BH + compact disk
⇒ rapidly rotating VMS collapse?**

Parameter study - simplified toy model

- Simplified PWP EOS fitted from **S. Fujibayashi** with $\Gamma_{\text{th}} = 4/3$ for photon radiation
No microphysics, composition, nuclear burning
- Should be valid for direct collapse to BH
(take it with a pinch of salt for anything else)
- Main motivation:
 - Effect of rotation on final BH and disk formation
 - GW signature from BH disk instability

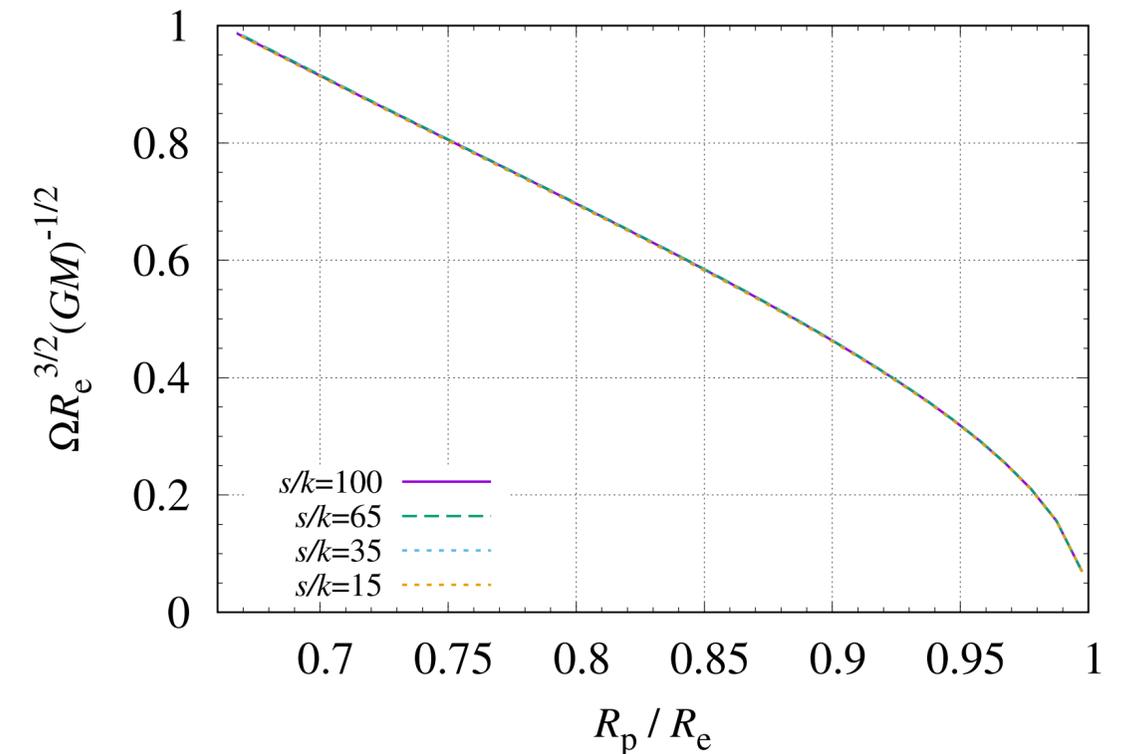


Numerical Setup

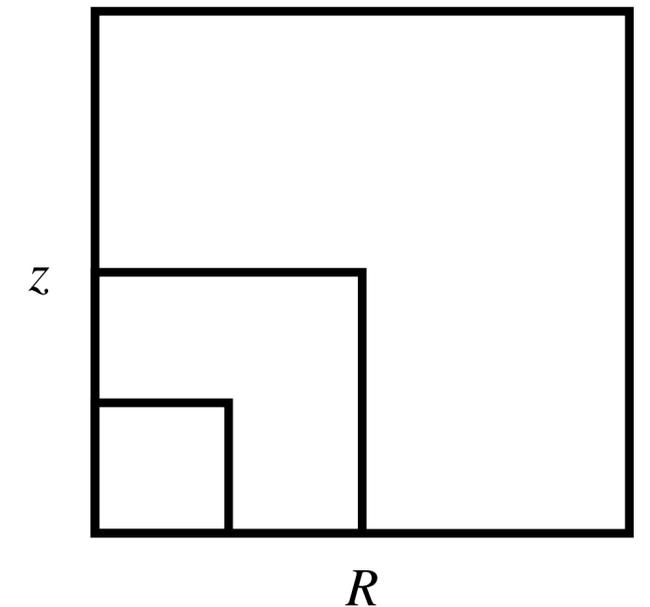
- **Initial Data:**

- Constant entropy $s/k = 17, 20, 35$
 $\Rightarrow M_{\star} = 200, 300, 1100 [M_{\odot}]$
 $r_{\text{eq}} = 8, 10, 25 [10^5 \text{km}]$
- Uniformly rotating characterised by $r_{\text{p}}/r_{\text{eq}}$ down to mass shredding limit [1, 0.67]

(M. Shibata, et al., *Astrophys.J.* 996 (2026) 1, 57)

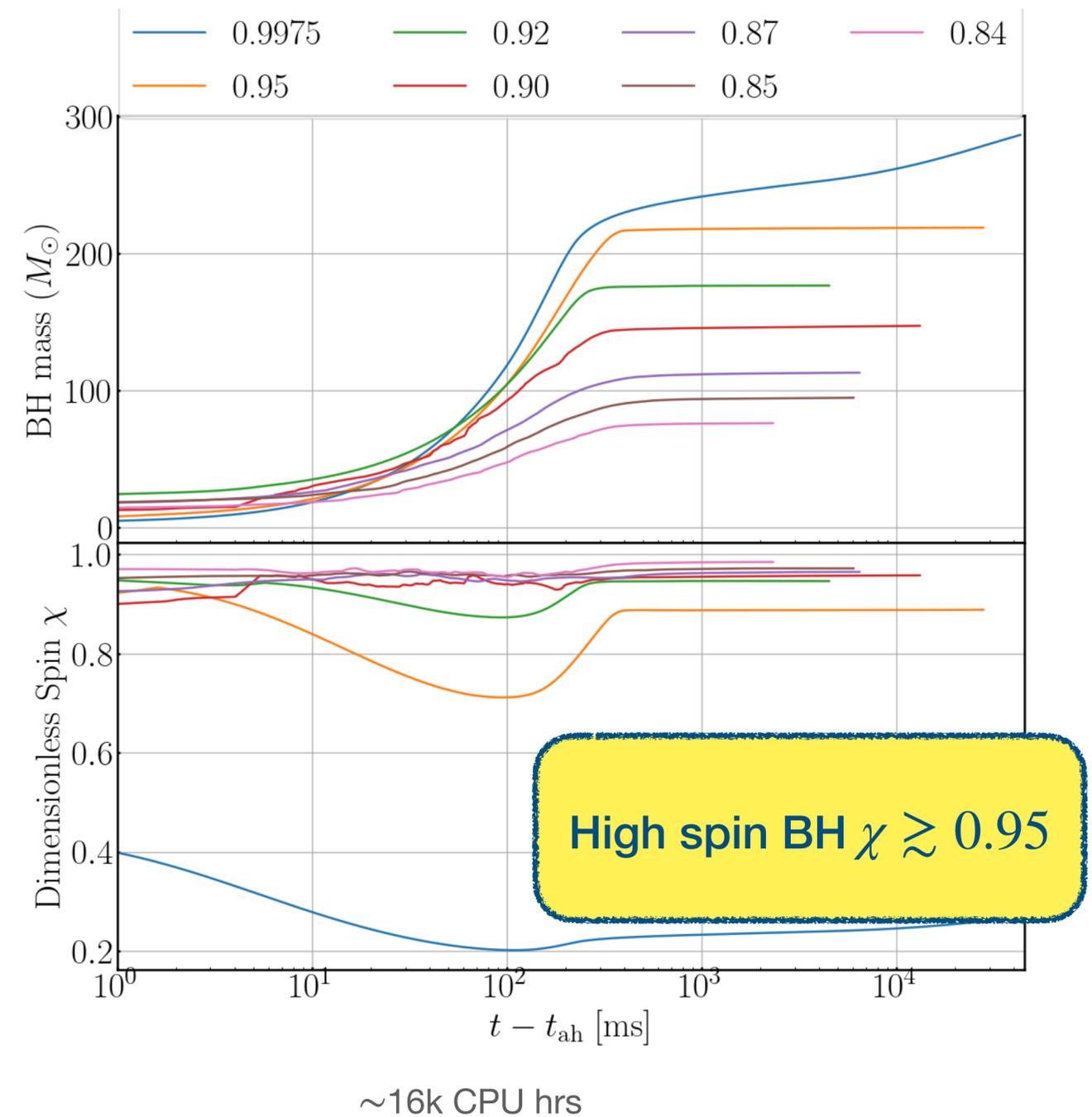
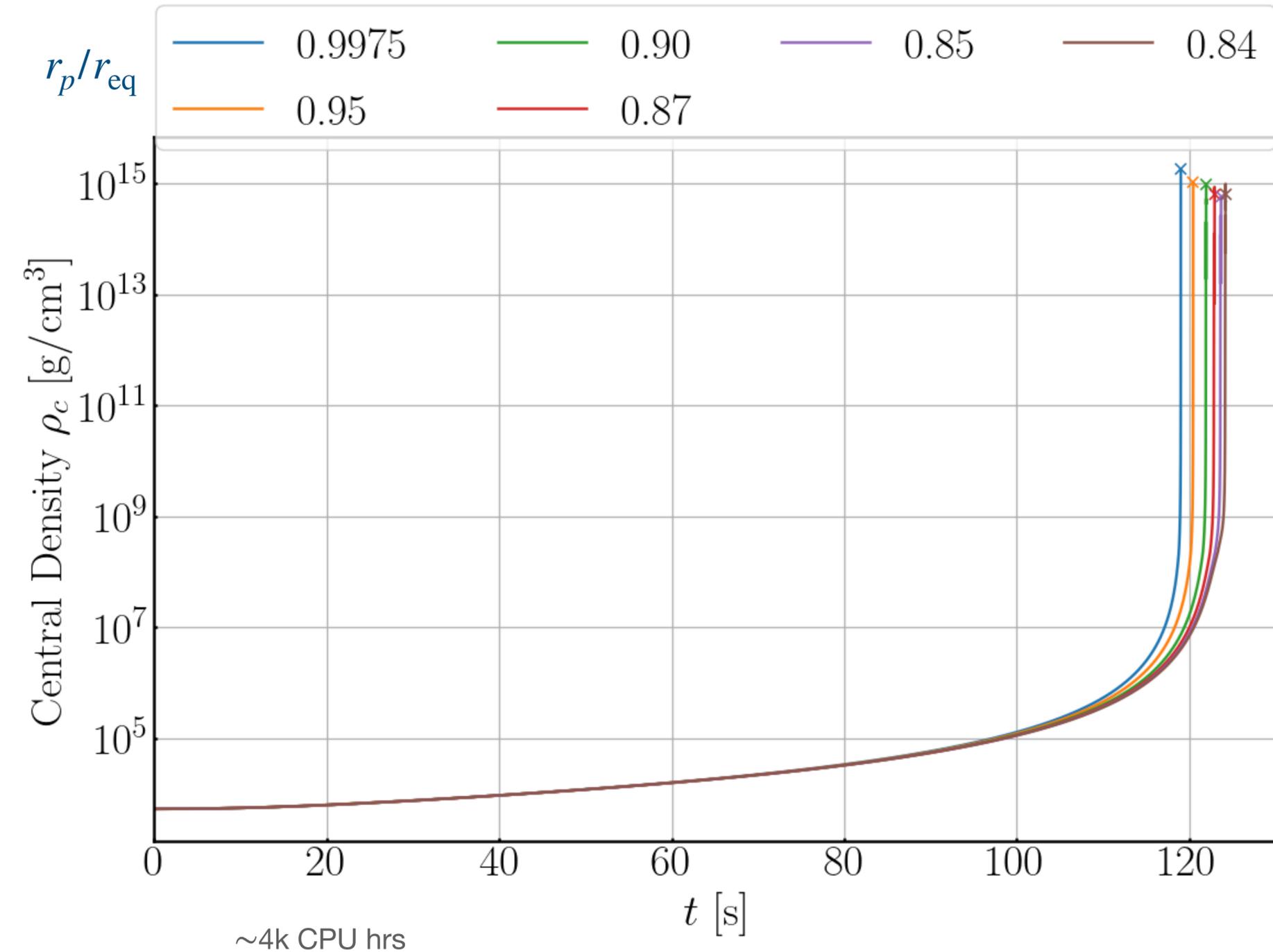


- **SACRA-2D:** Axisymmetric numerical relativity code
 Cartoon method for Z4c
 + GRHD (HLLC Riemann solver) in cylindrical
 + (**adaptive**) mesh refinement within timestep sub-cycling

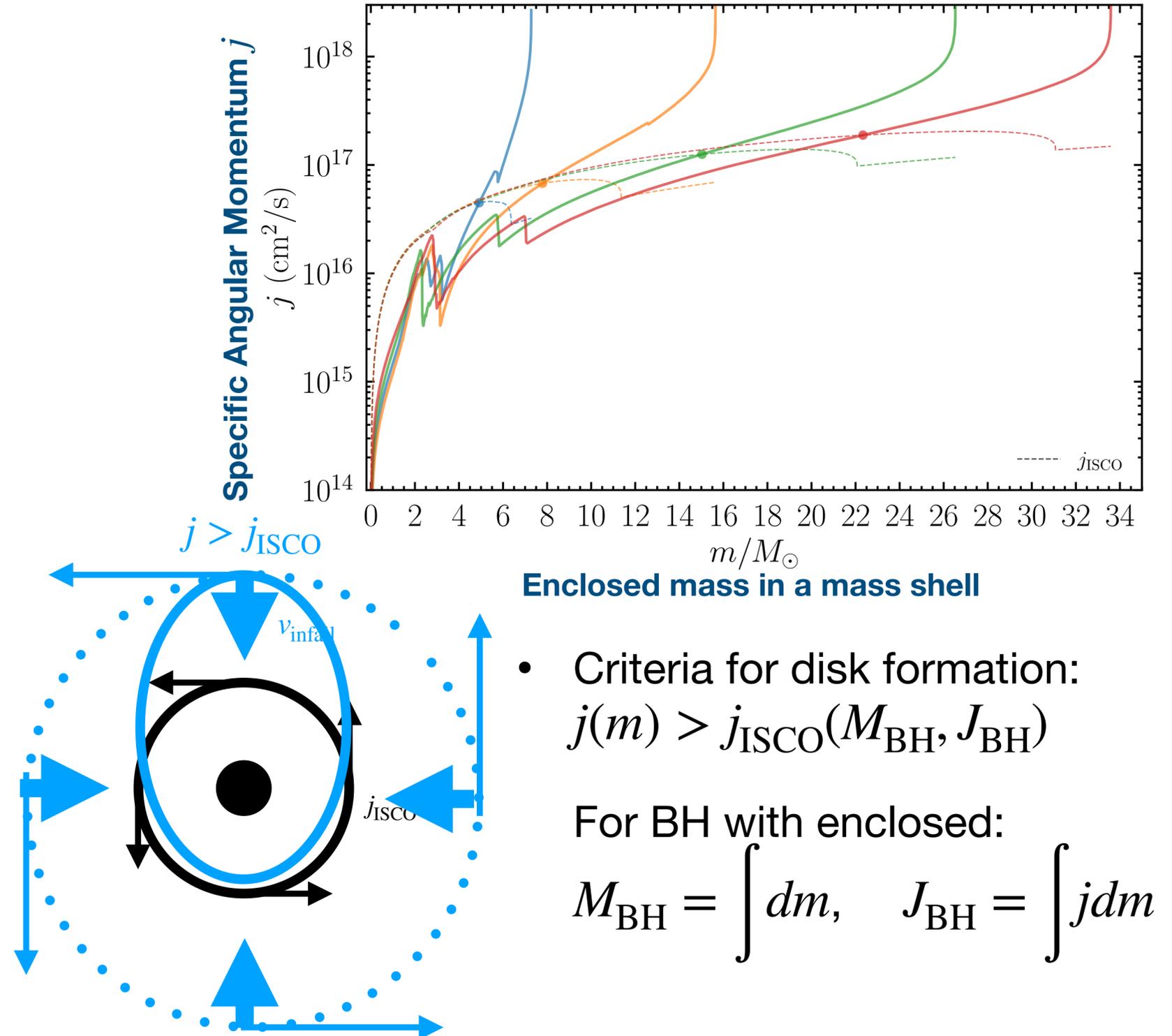
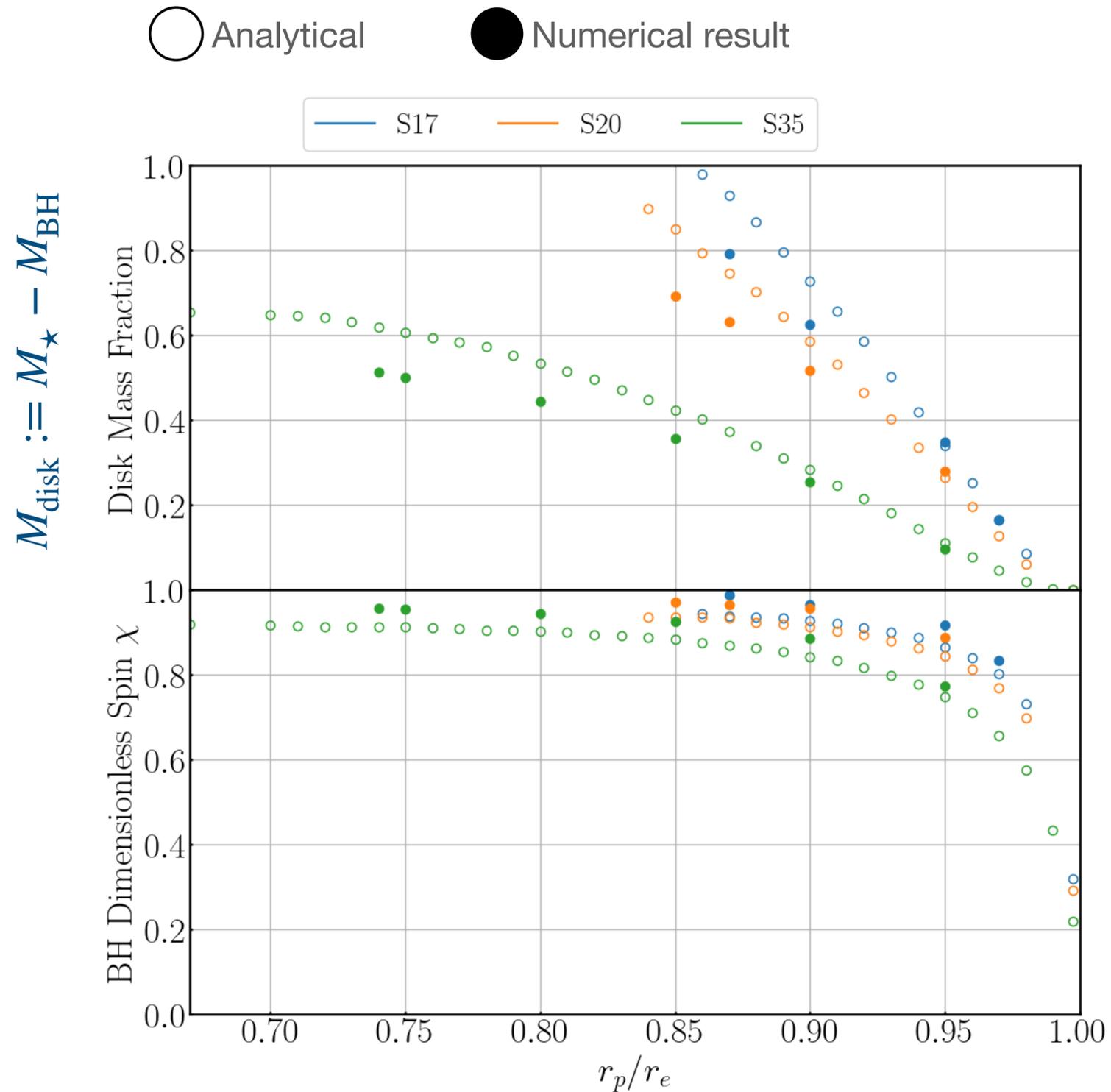


$R_{\star} \approx 10^6 \text{ km} \Leftrightarrow$ Initial rapidly spinning BH $\sim 10M_{\odot}$

Numerical Result - S20

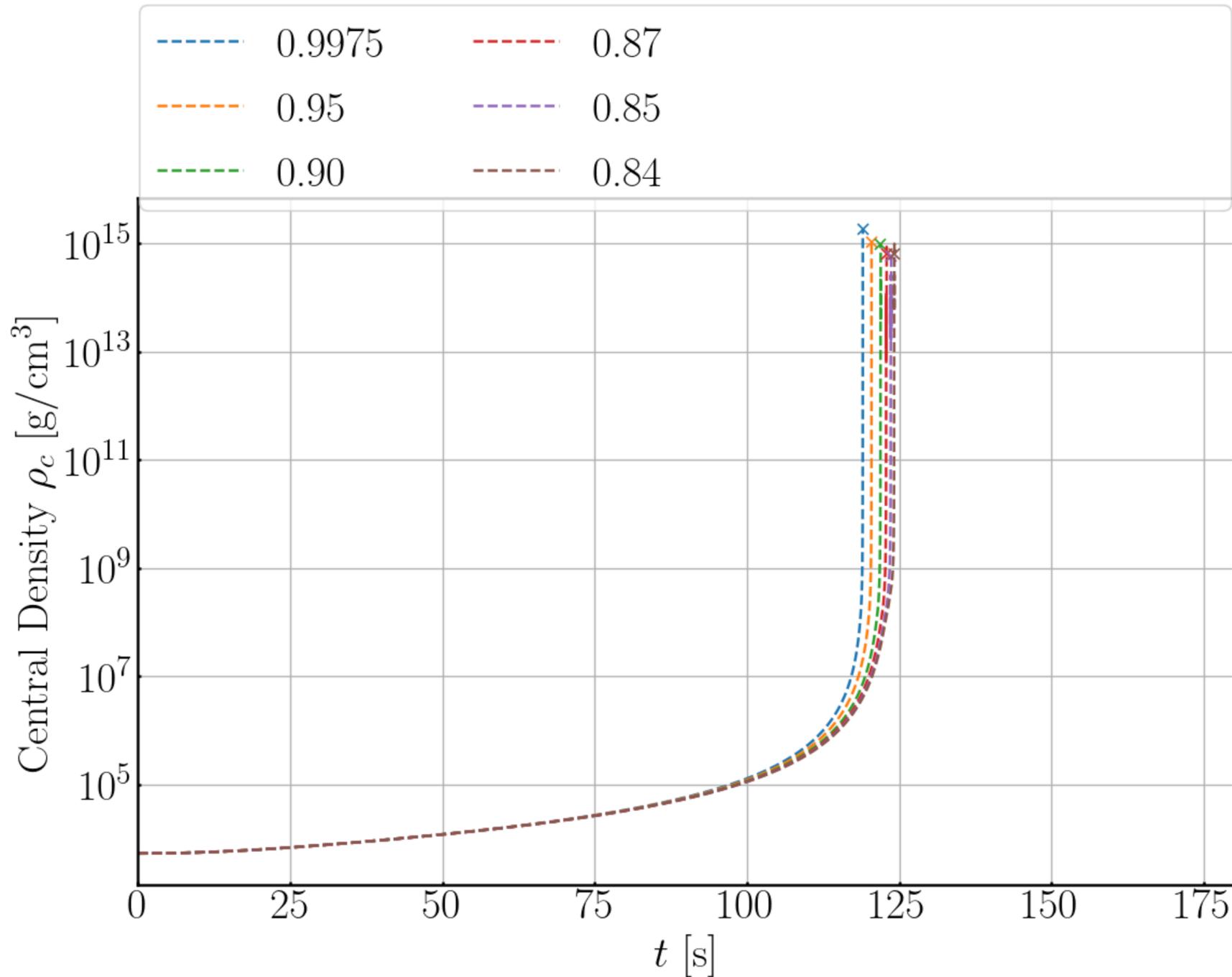


BH + disk formation

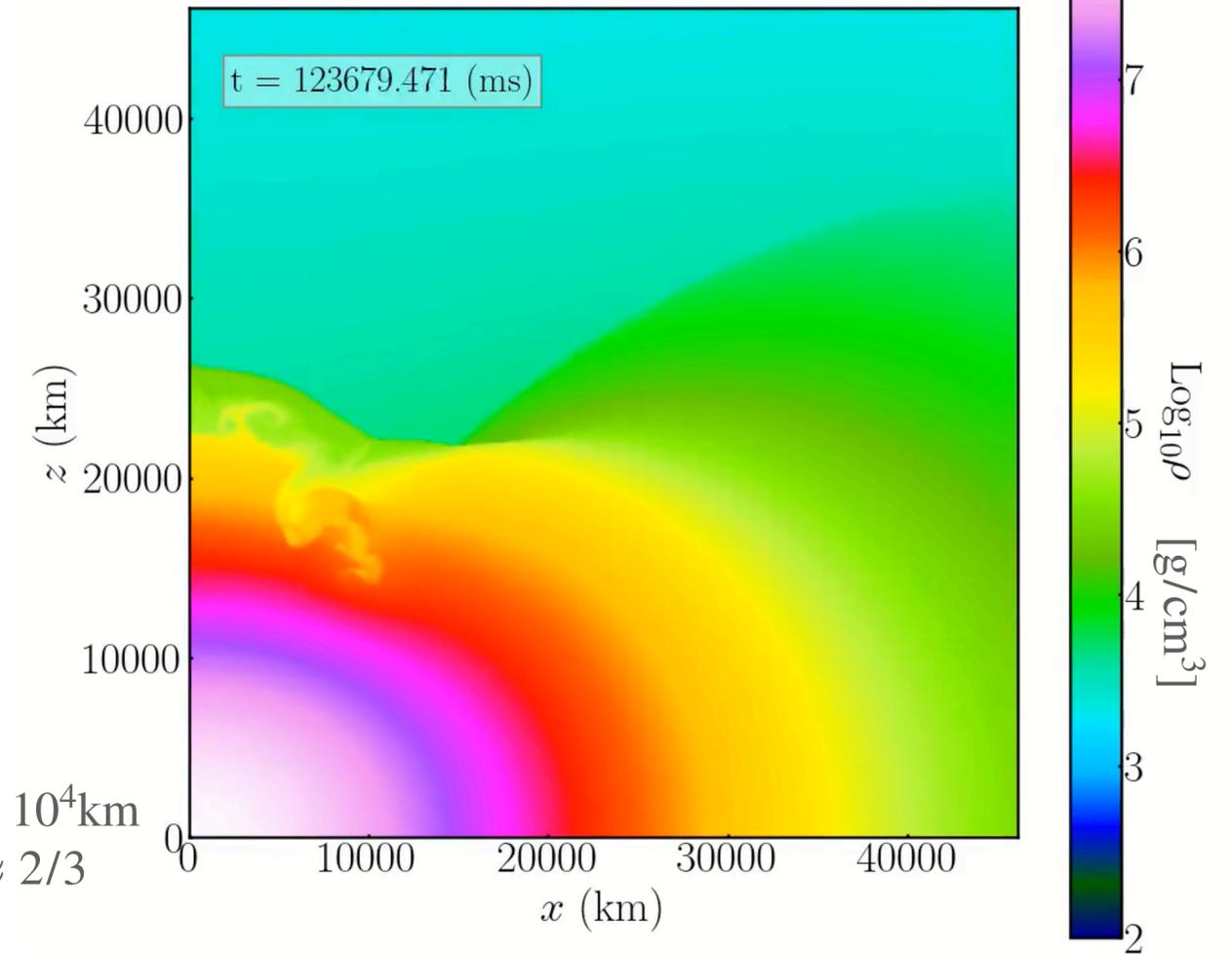


White dwarf bounce ?

S20



Core Radius $\sim 10^4$ km
with $r_p/r_{eq} \approx 2/3$



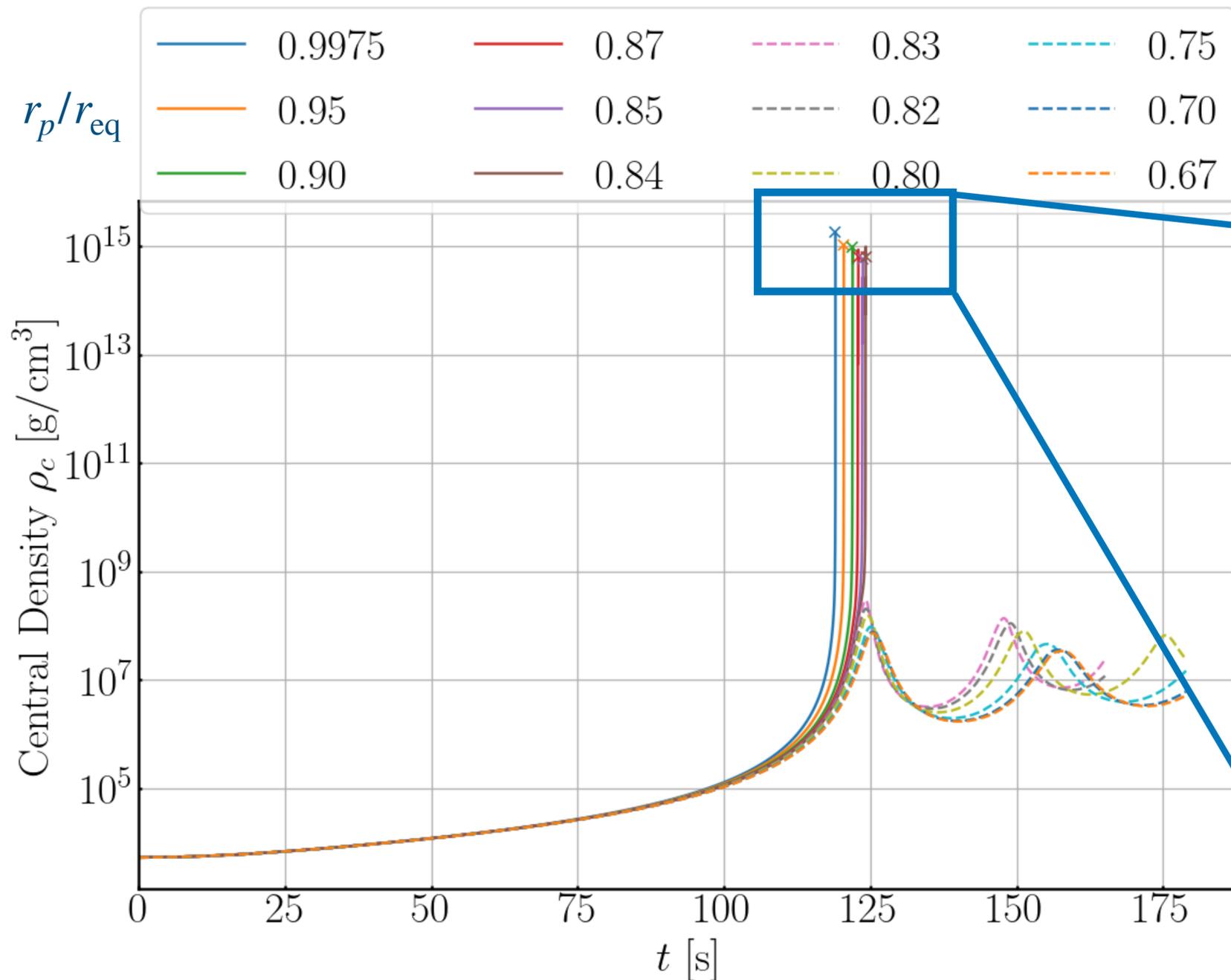
- Spin $\uparrow \Rightarrow$ Centrifugal support \uparrow large enough before $\rho_c \sim 10^8$ g/cm³

CAVEAT!!

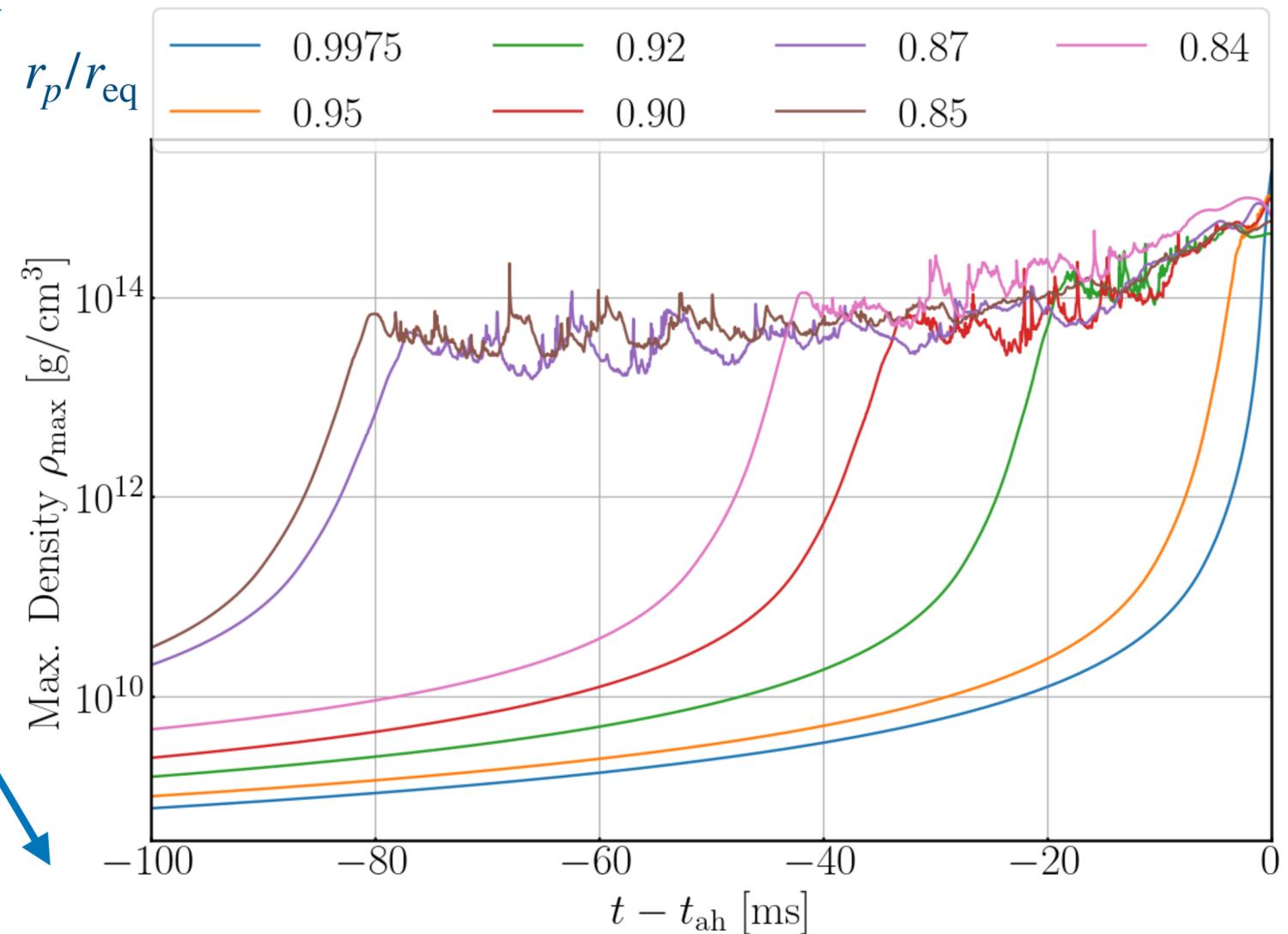
Neutrino cooling reduce P at $\rho \sim 10^7$ g/cm³
Numerical artifact from PWP fitting \Rightarrow over estimated P .

Centrifugal bounce

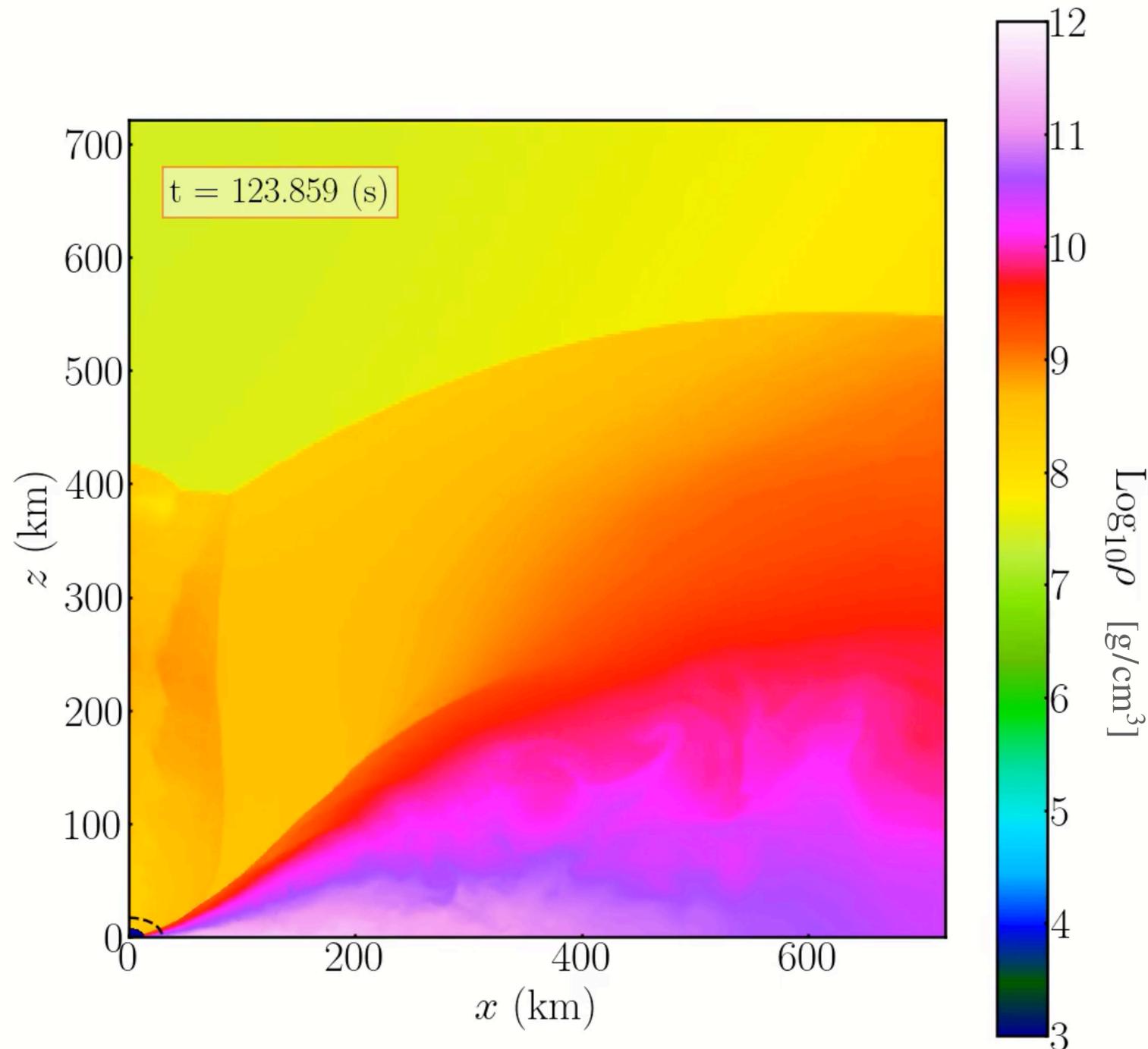
S20



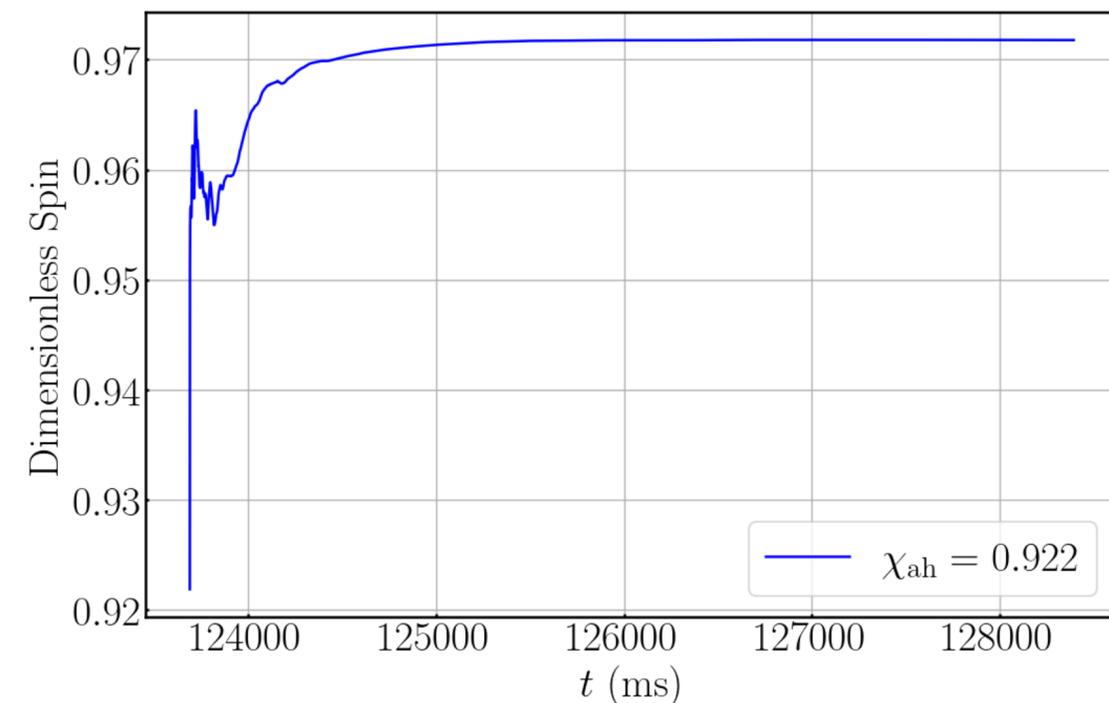
- Centrifugal bounce happens at $\rho \lesssim 10^{14}$ g/cm³
- Lifetime: 10-100 ms



Centrifugal bounce - S20 $r_p/r_{eq} = 0.85$



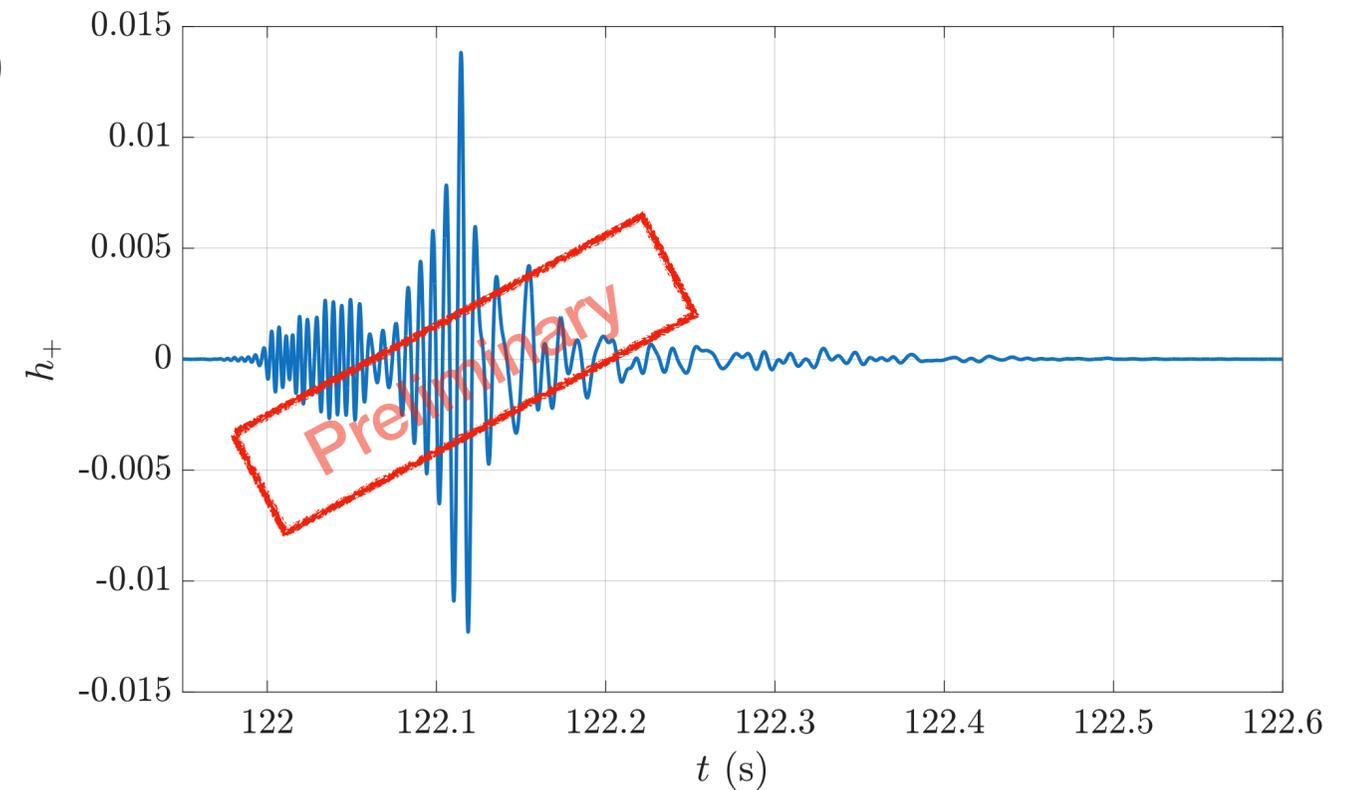
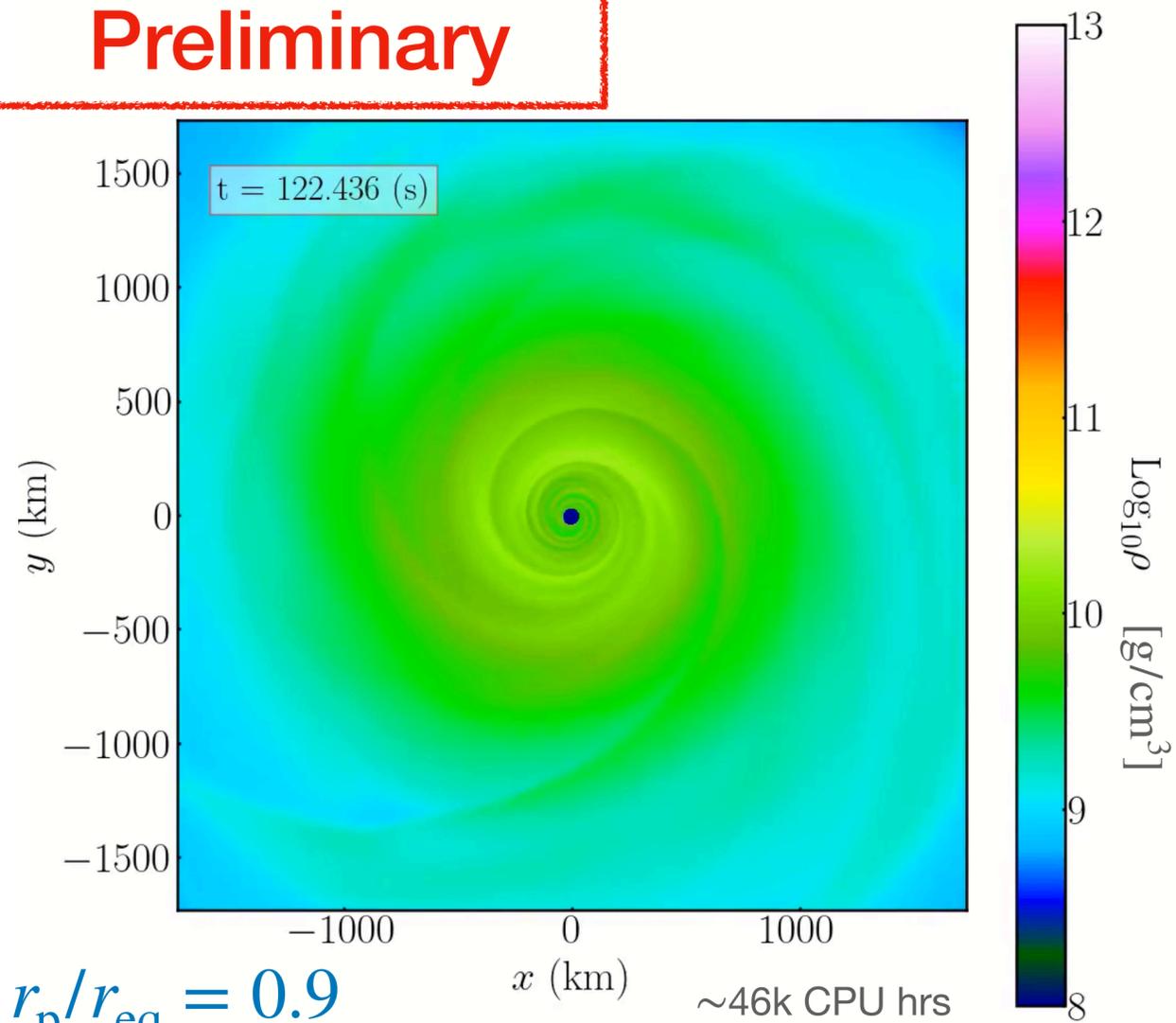
- Oblate core $R_{eq} \approx 60$ km with lifetime: ~ 100 ms
- Such oblate core should be **bar-mode** unstable in 3D
- 2D: BH Mass $15M_{\odot} \rightarrow 90M_{\odot}$ with spin ~ 0.97



GW from VMS collapse

- After BH formation in 2D simulation \Rightarrow 3D simulation for disk instability/GW
- **SACRA-3D**: 1+D extension from **SACRA-2D**

Preliminary



GW produced by spiral-arm instability
in VMS collapse

Summary

- Simplified picture of collapse of rotating VMS to BH
- Rapidly spinning BH + compact massive disk can form $\chi_{\text{BH}} \gtrsim 0.95$
- Centrifugal force could be important for $\rho \sim 10^8 \text{ g/cm}^3$ and $\rho \sim 10^{14} \text{ g/cm}^3$
- Spiral-arm instability found in 3D
VMS collapse: potential alternative source of GW
- Microphysics & Nuclear burning is necessary.....

AthenaK Summer School 2026
July 7 - 17 @Penn State
Application Deadline: 15 Feb

