Modeling the initial stages of star formation in AGN disks

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with Simona Pacuraru, Noah Kubli, Lucio Mayer

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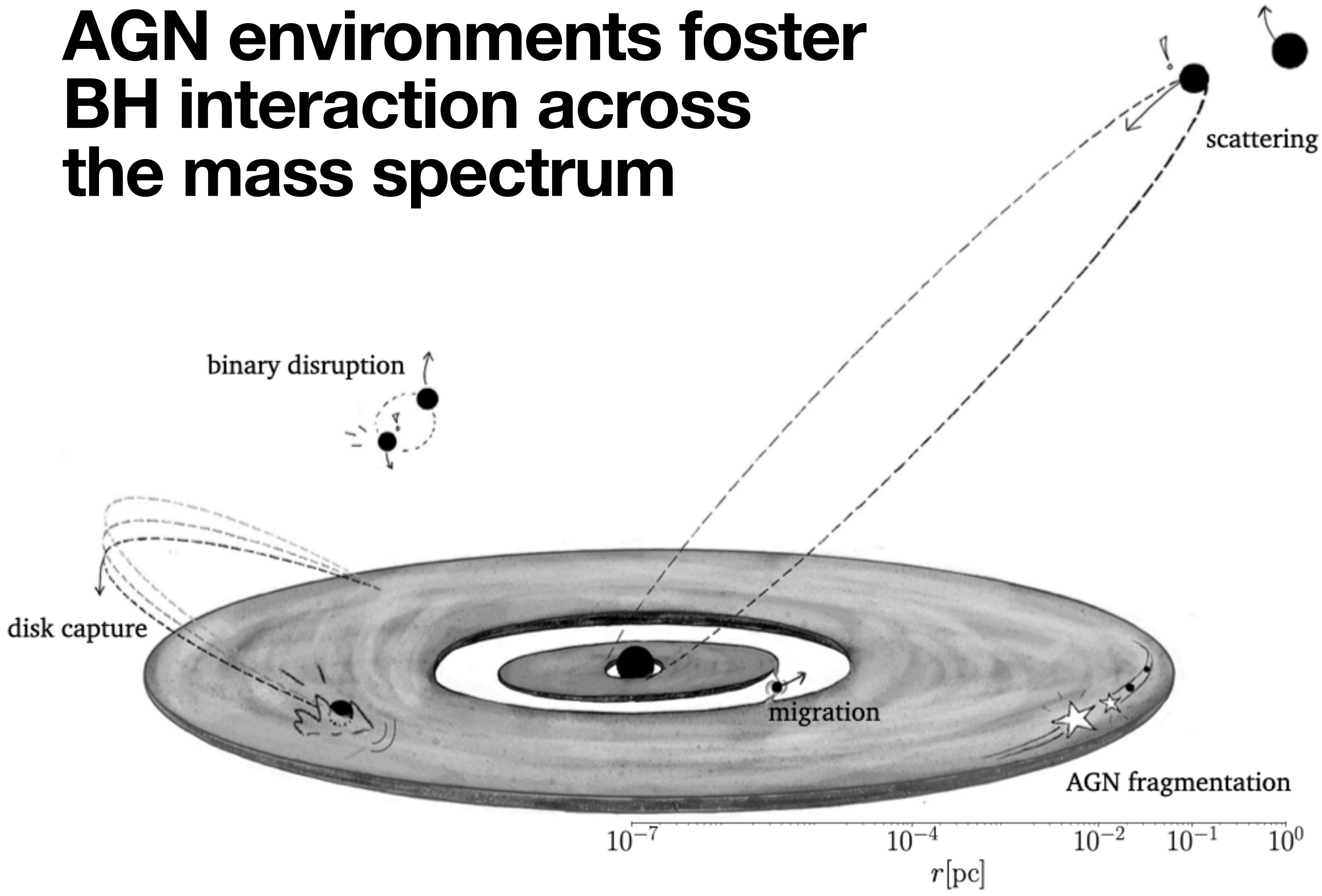
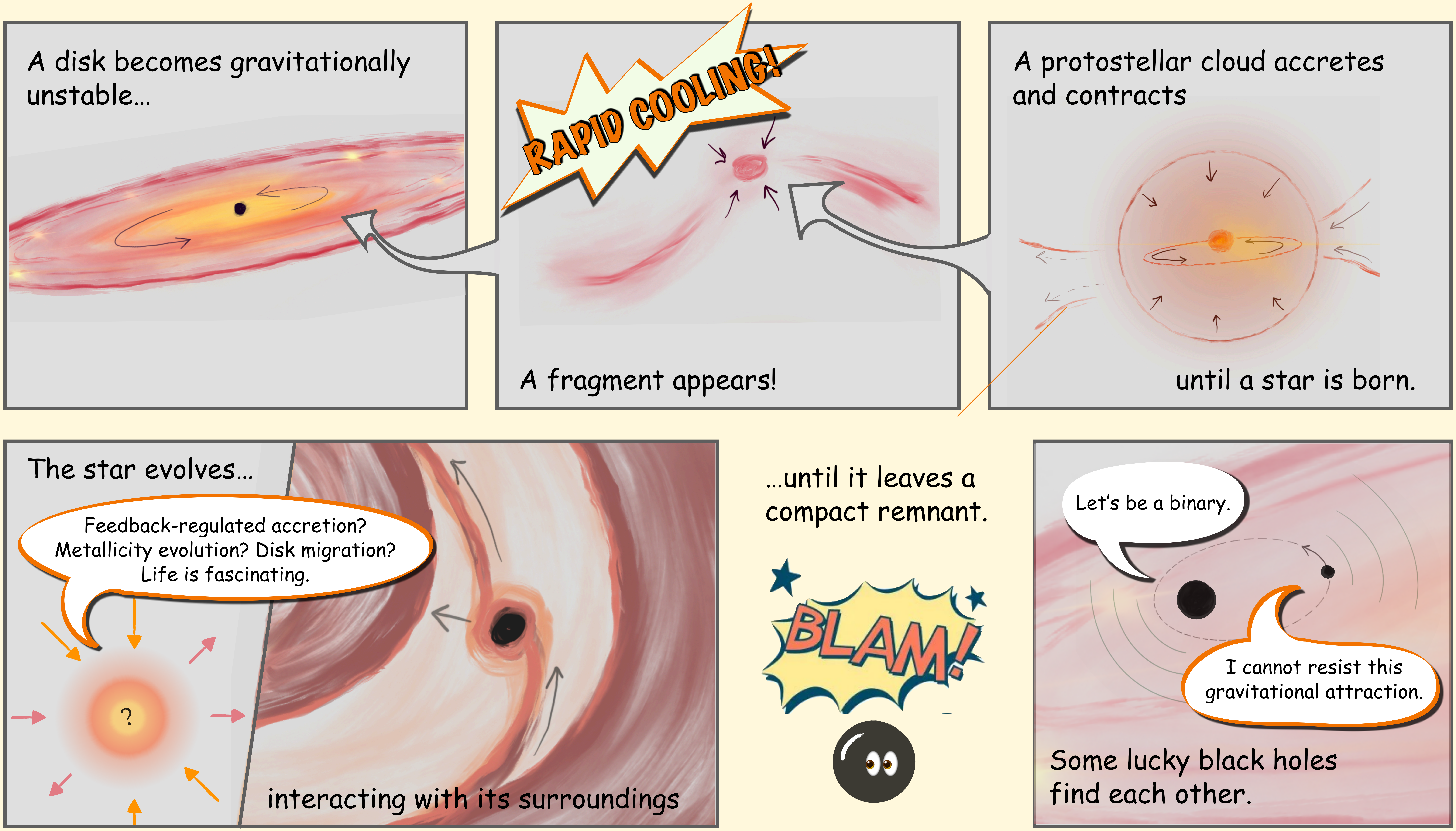
Establishing Multimessenger astronomy Inclusive Training

AGN environments foster BH interaction across the mass spectrum

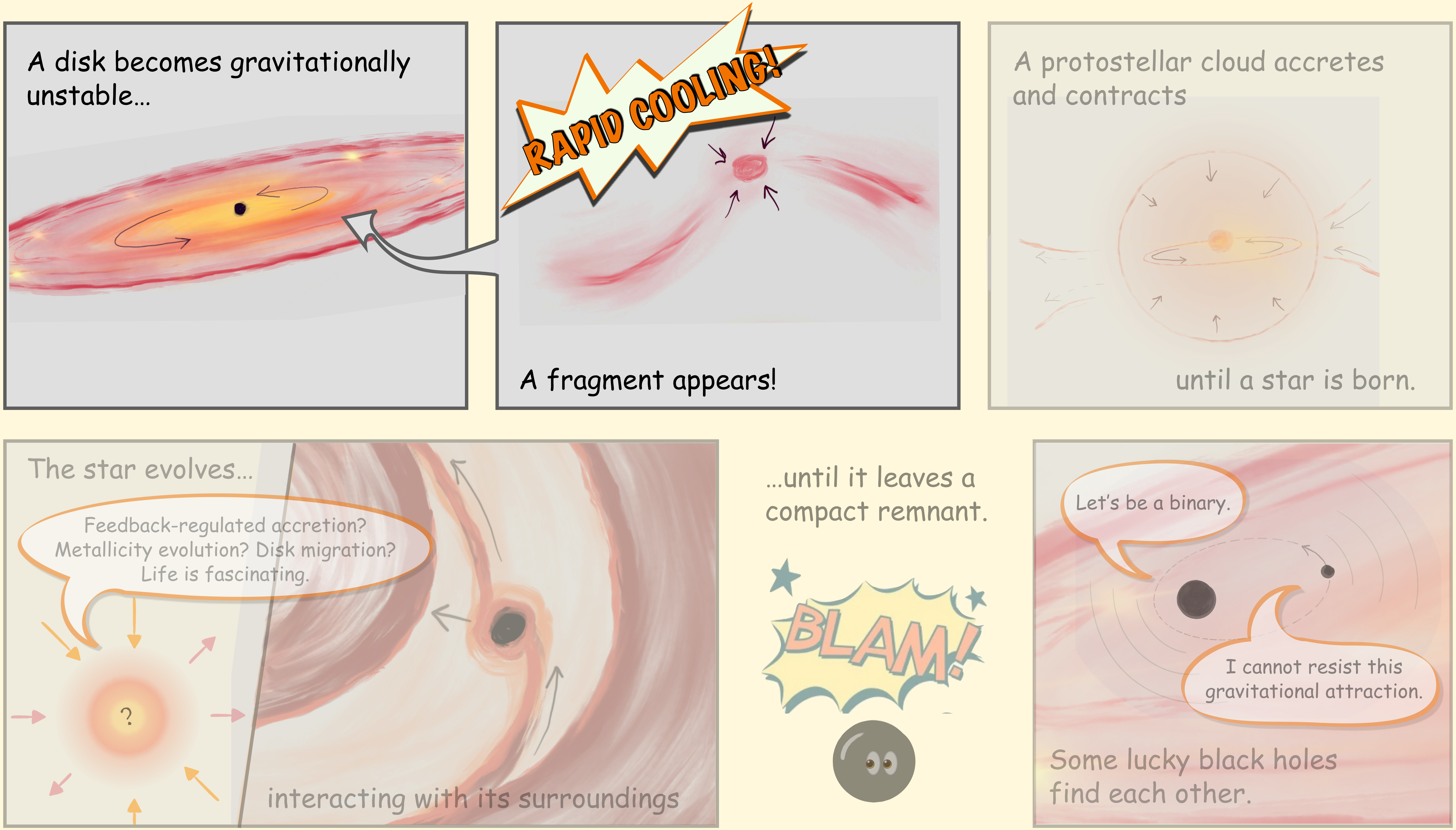


see:
Syer, Clarke & Rees 1991
Goodman & Tan 2004
Levin 1997
McKernan+2008
Bellovary+2016
Stone+2017
Secunda+2019
Dittmann & Miller 2019
Fabj+ 2020
Tagawa+2020, 2021
Pan & Yang 2021
Derdzinski & Mayer 2023
Rowan+ 2023
Peng & Chen 2023
Hopkins+ 2023
Grishin, Gilbaum, Stone 2023
Chen & Lin 2024
Wang+ 2024
Whitehead+ 2024
Epstein-Martin+ 2024
+ more…

From fragmentation to gravitational waves



From fragmentation to gravitational waves



AGN fragmentation questions

- How massive are the fragments? How fast do they collapse and grow?
  What's the stellar population?

- How do they migrate?
  Where are the stars/BHs born?
  Do they interact?

(initial) fragment masses $\sim 10^{-1} - 10^{2} M_{\rm sun}$

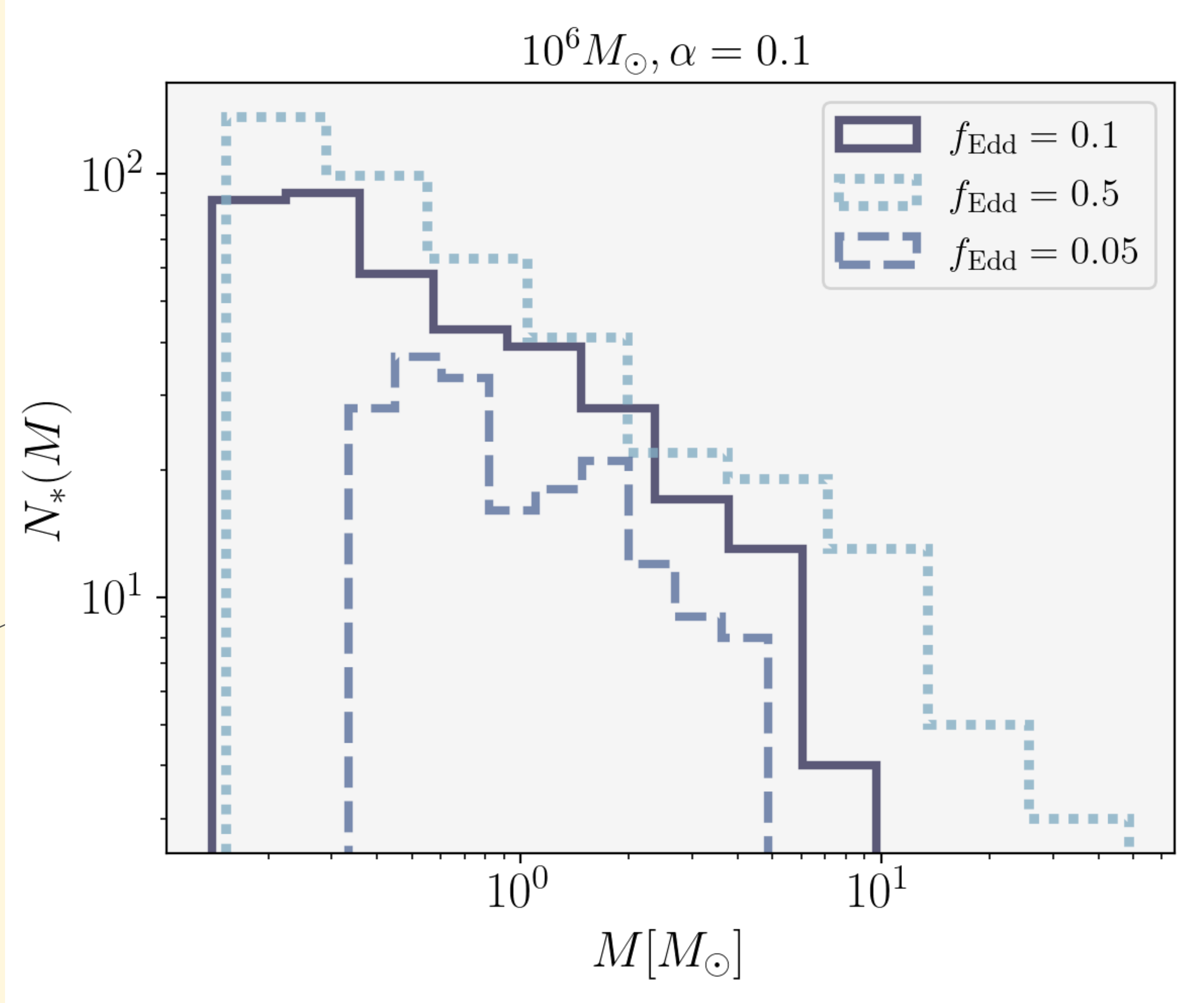
Sound speed

Toomre 1964:

$$M_{\rm fragment} \sim \frac{\pi c_s^4}{G^2 \Sigma}$$

Surface density

See also
Lin & Pringle 1987,
Gammie 2001,
Goodman 2003,
Matzner & Levin 2005,
Rafikov 2009,
Boley+2010, Mapelli+2012,
Genzel+2010,
Nayakshin & Sunyaev 2005,
Boss 1997,
Helled+2014



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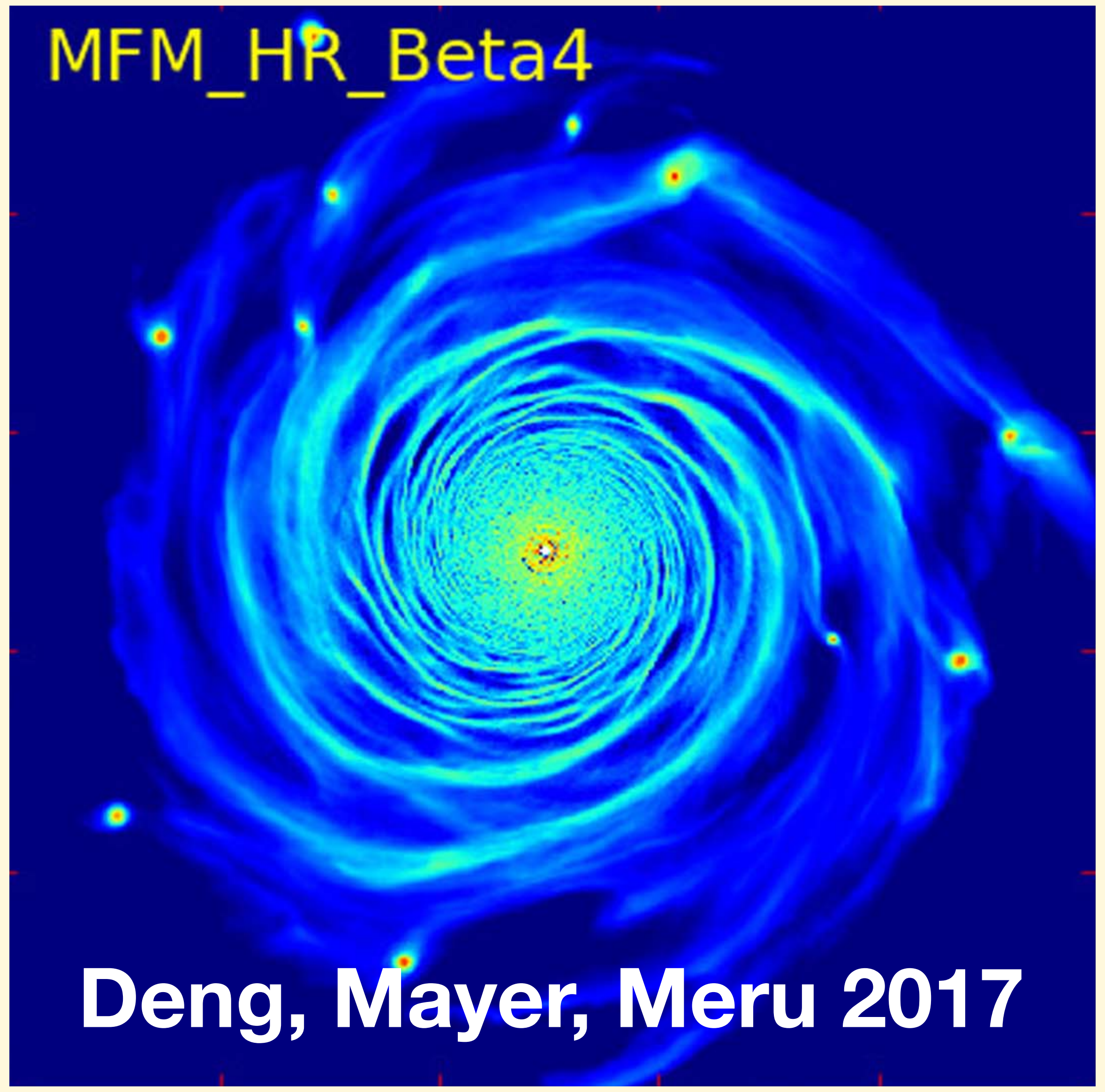
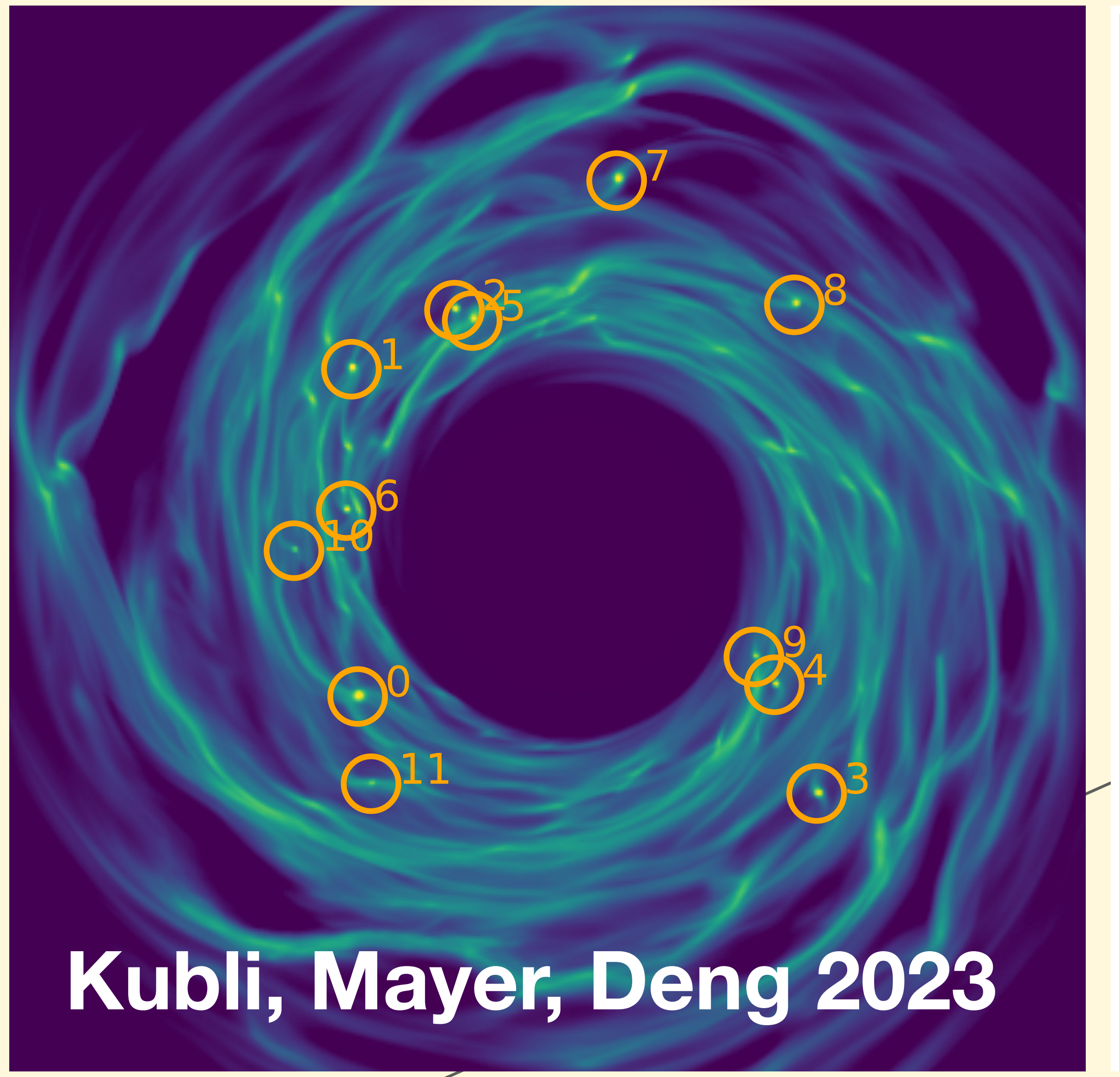
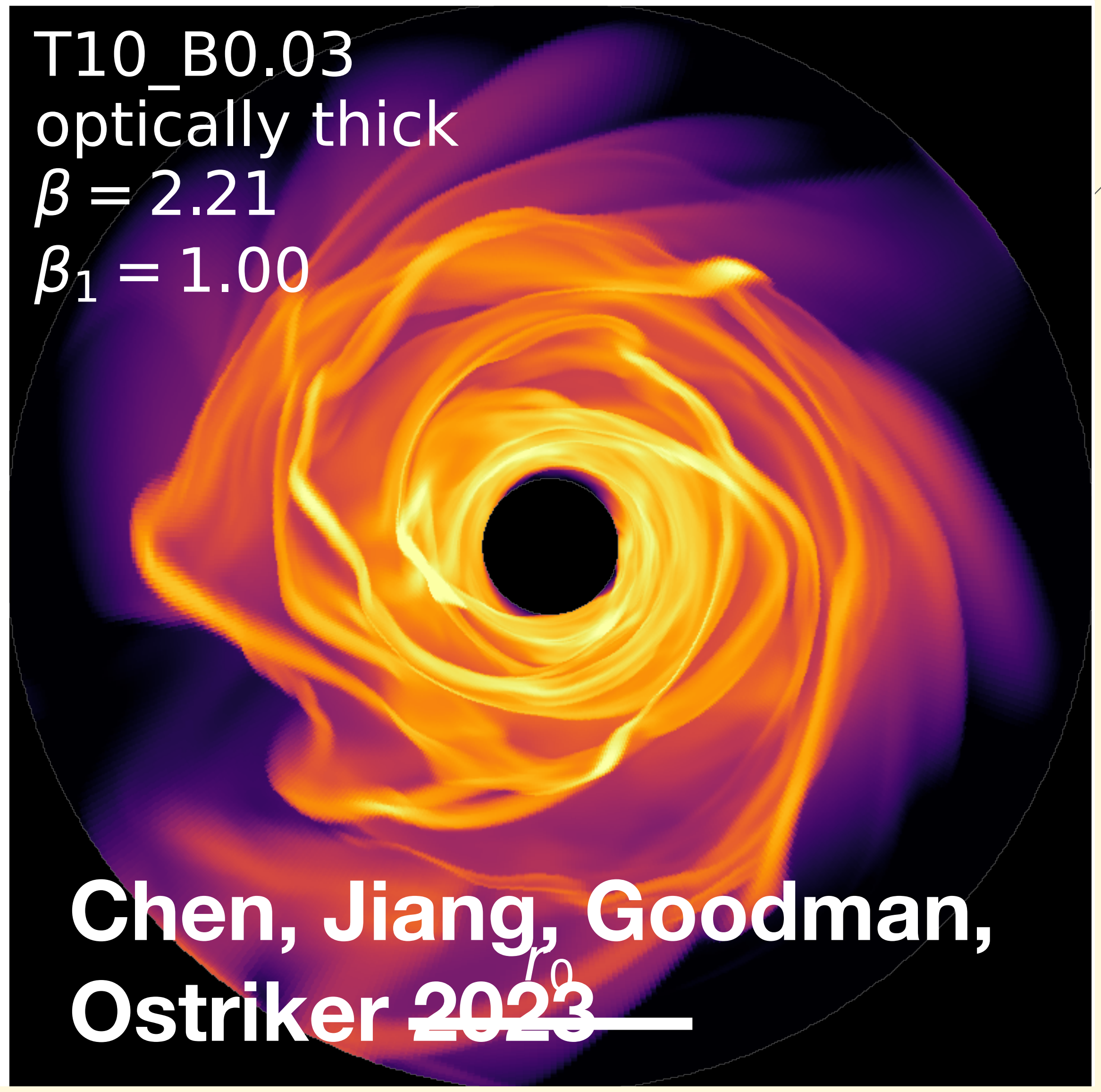
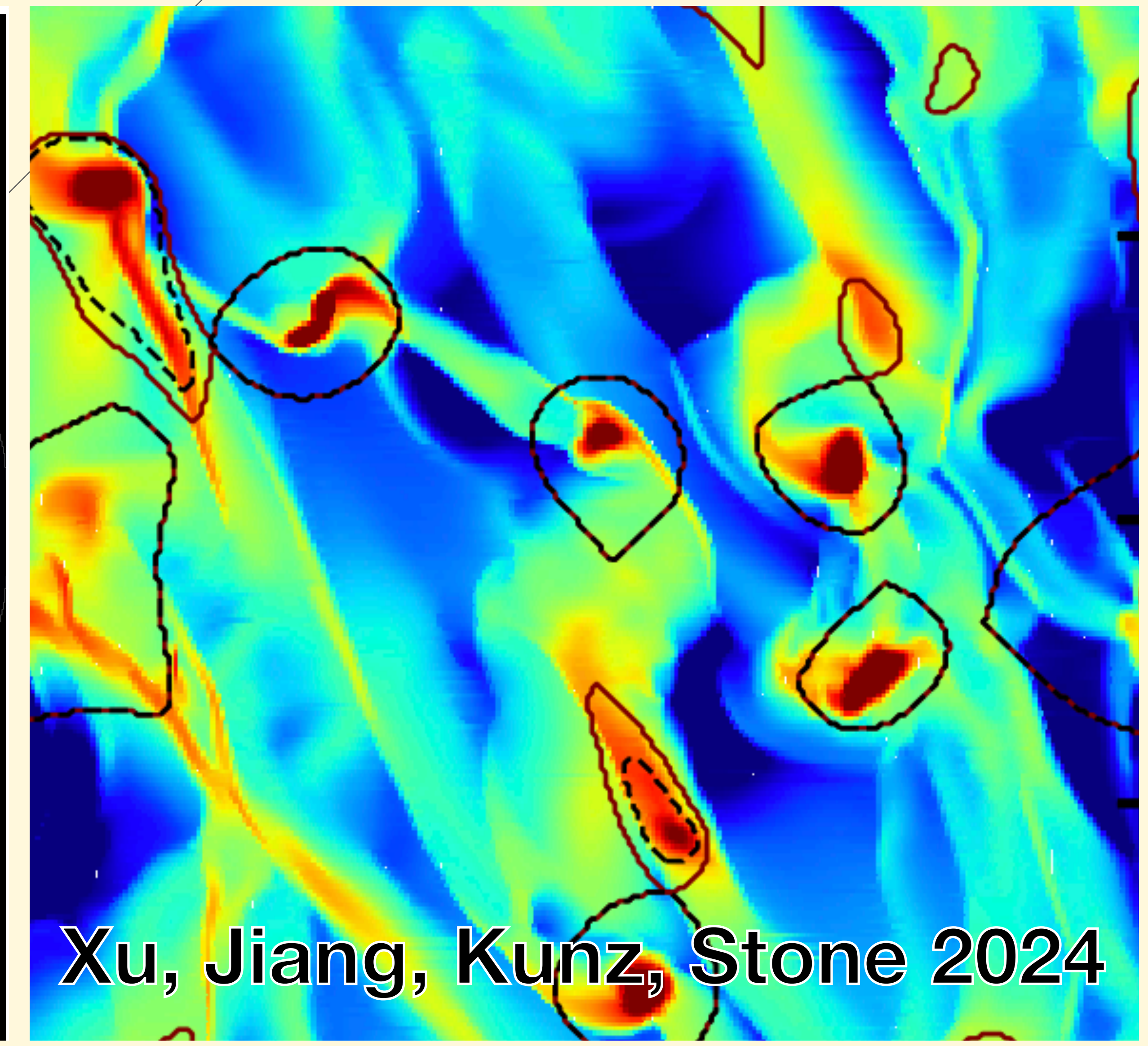
Nonlinear deviations

from protoplanetary disks to AGN scales









- Clumps have rotation, eccentricity, masses depend on EOS, magnetic fields…

A global simulation with GIZMO

$M_{\rm BH} = 10^6 M_{\rm sun}$

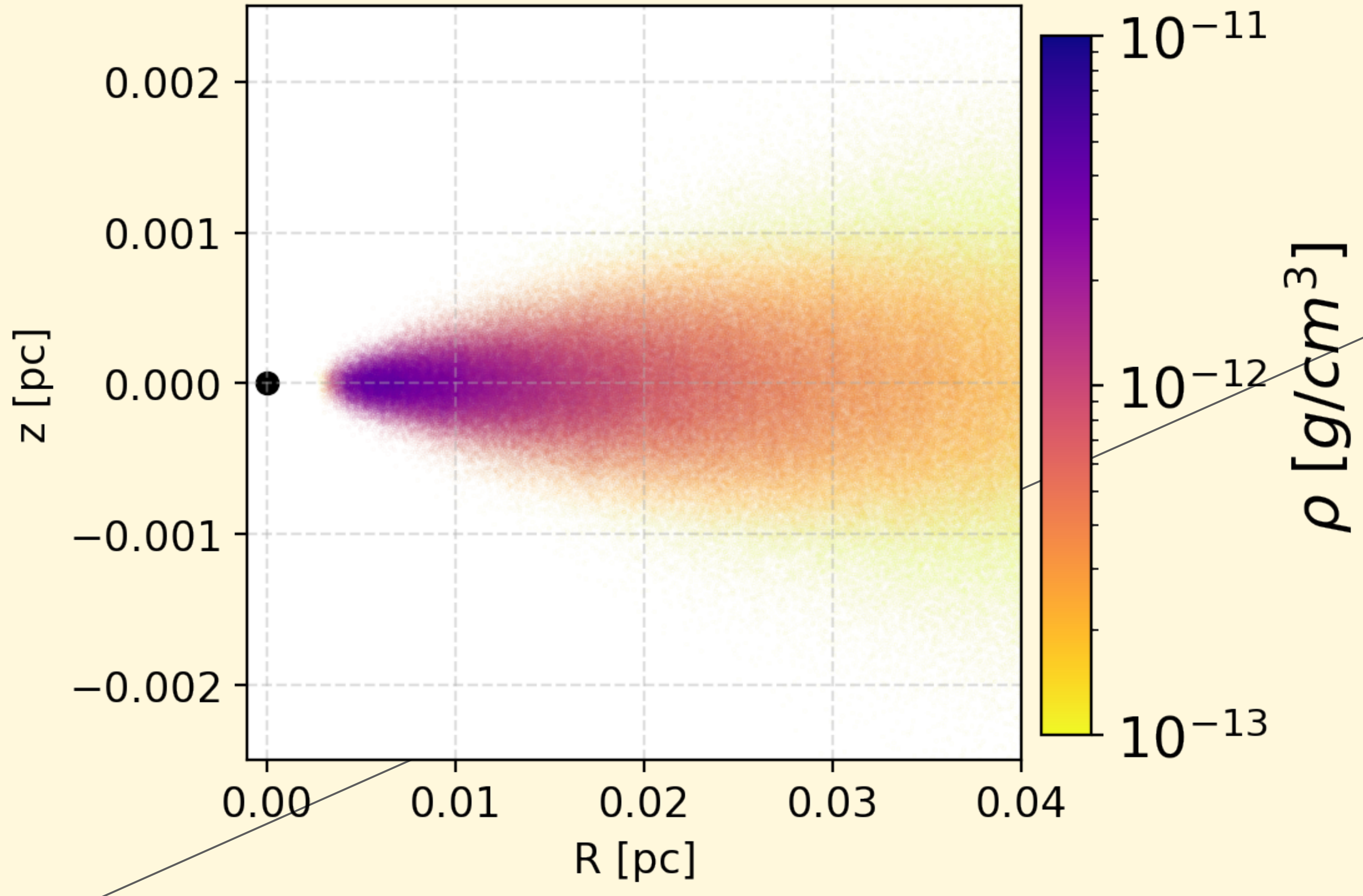
$M_{\rm bulge} = 10^6 M_{\rm sun}$

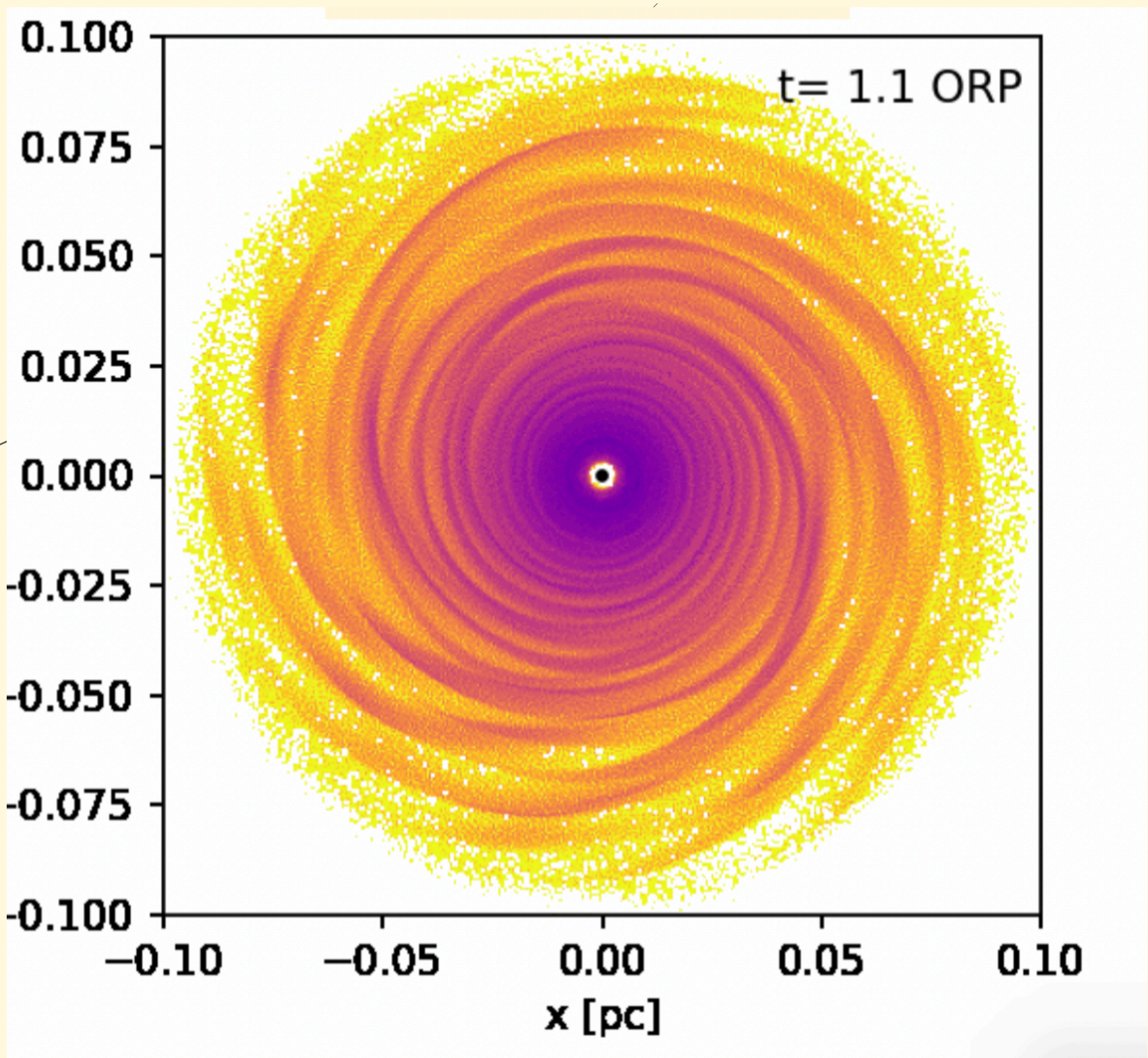
$M_{\rm disk} = 10^5 M_{\rm sun}$

Step 1: relax to gravitoturbulent state

Step 2: gradually reduce cooling time

$t_{\rm cool} \propto t_{\rm orb}$

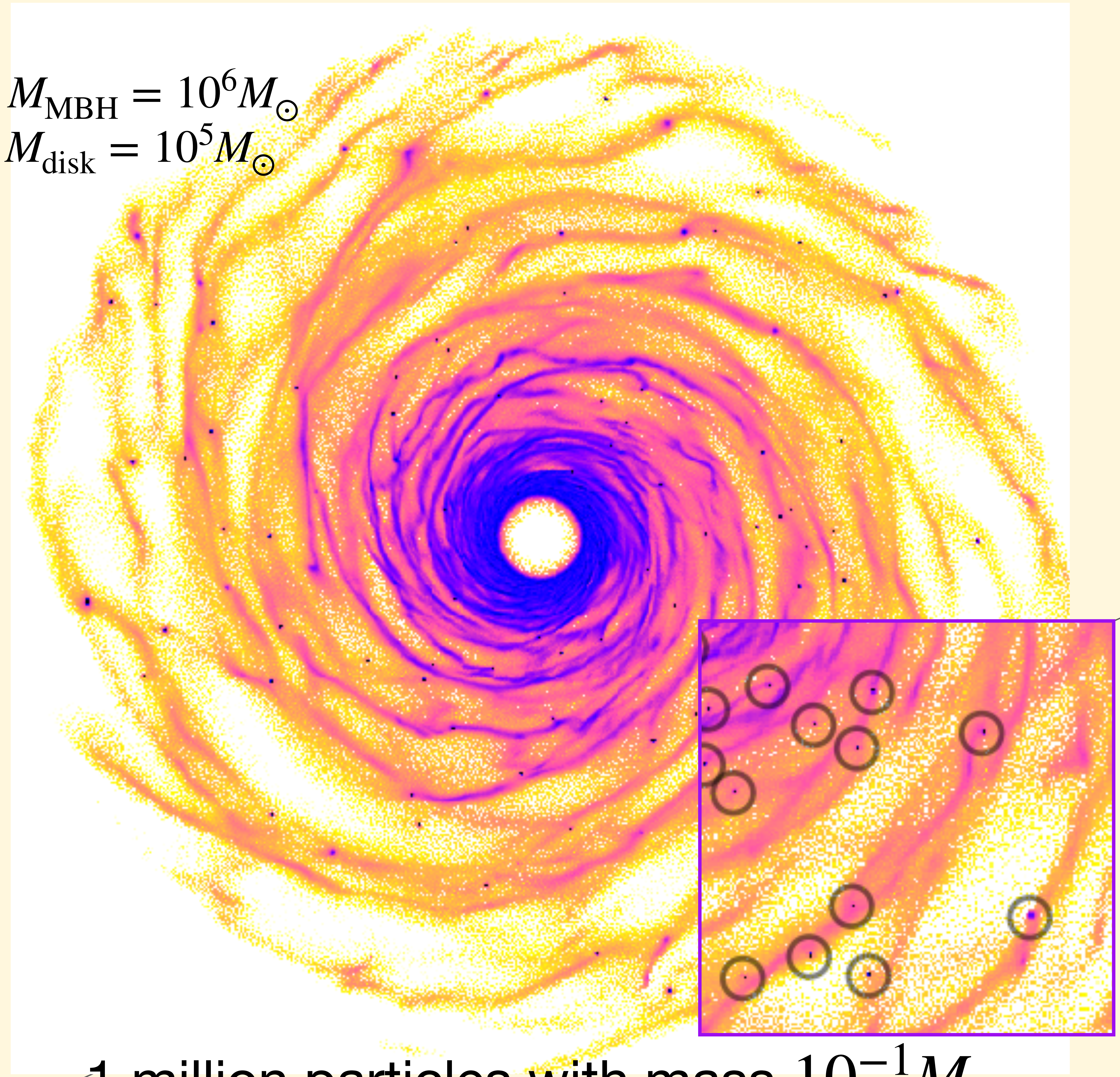


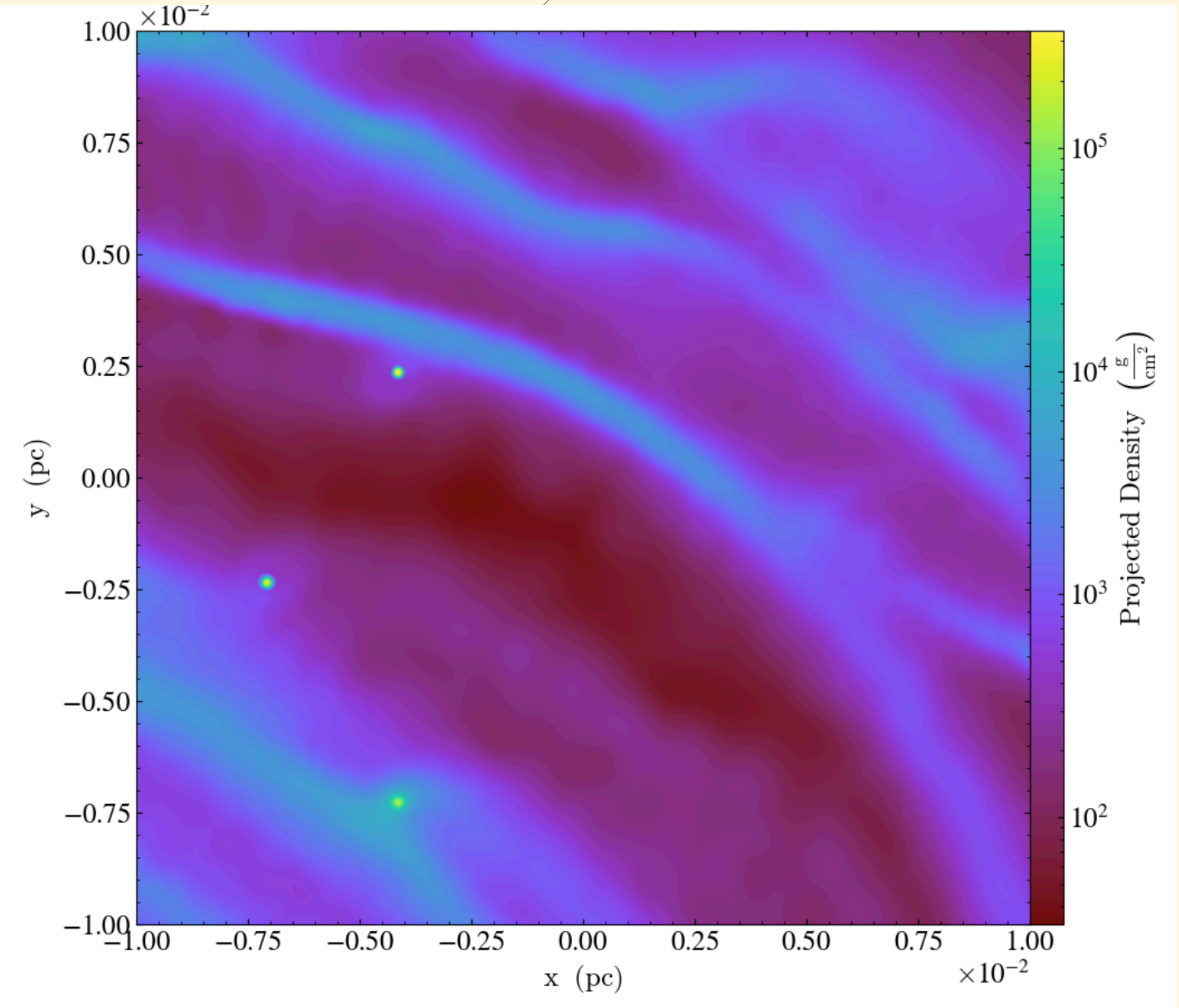


Simulations by Simona Pacuraru (Birmingham)

Beta cooling gradual reduction to

$$\beta = \frac{t_{\mathrm{cool}}}{t_{\mathrm{orb}}} = 3$$

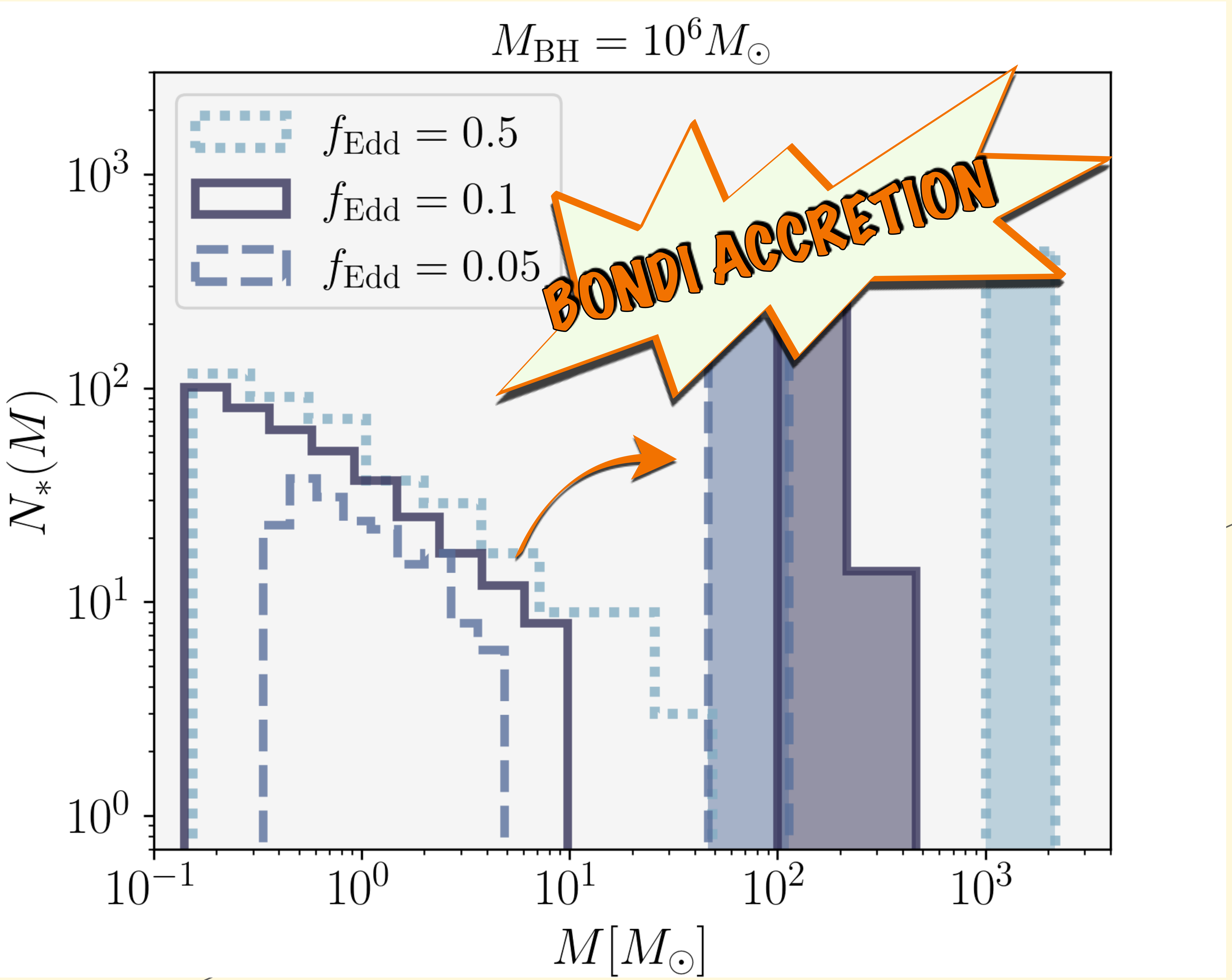




1 million particles with mass $10^{-1} M_{\mathrm{sun}}$

Fragment mass evolution

Prediction:



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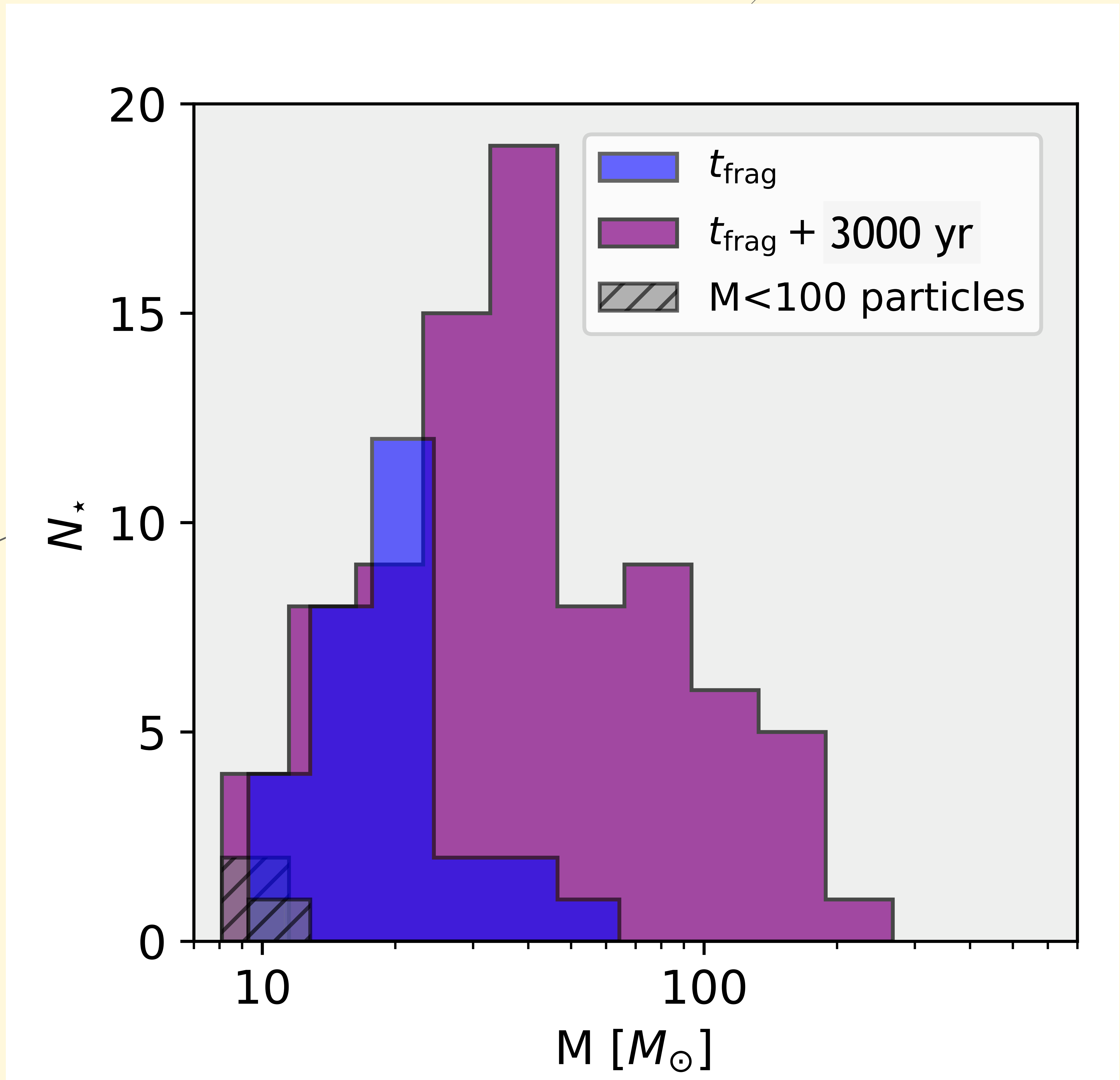
Simulation:



This work:

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~ 100* protostellar clumps within 0.1 pc
ranging from 10s to 100s solar masses
*dependence on MBH, cooling rate

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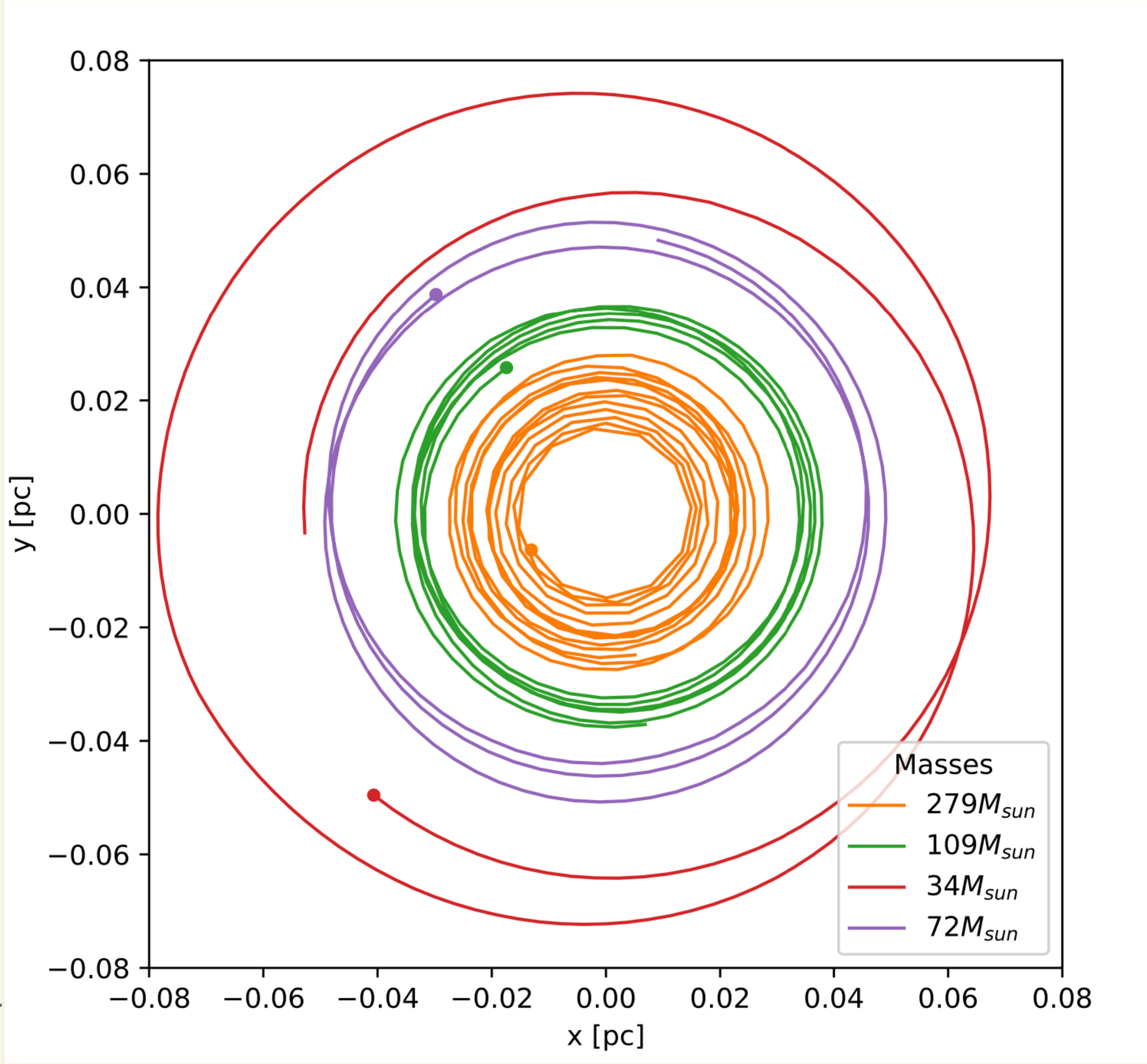
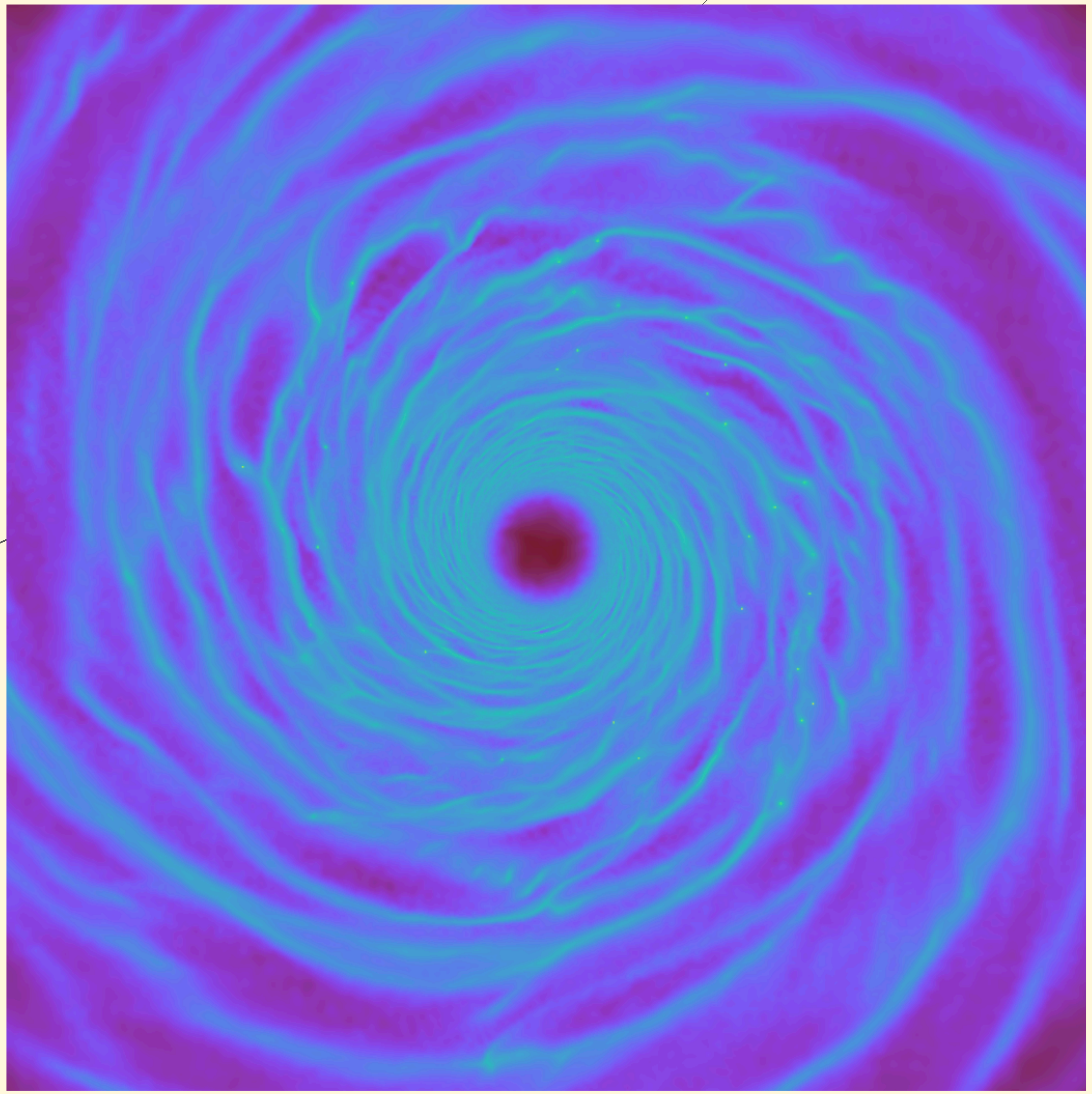


protostar trajectories and concurrent accretion rates suggest rapid collapse to massive stars

+ initial conditions for what happens next

- A stellar population is naturally seeded within a typical (moderately accreting) AGN accretion disk
- Variations of this process occur based on MBH mass, accretion rate, cooling
- Simulations provide insights into formation, collapse, morphology and orbits of embedded protostars
- + tools to calibrate subsequent EMRI rates



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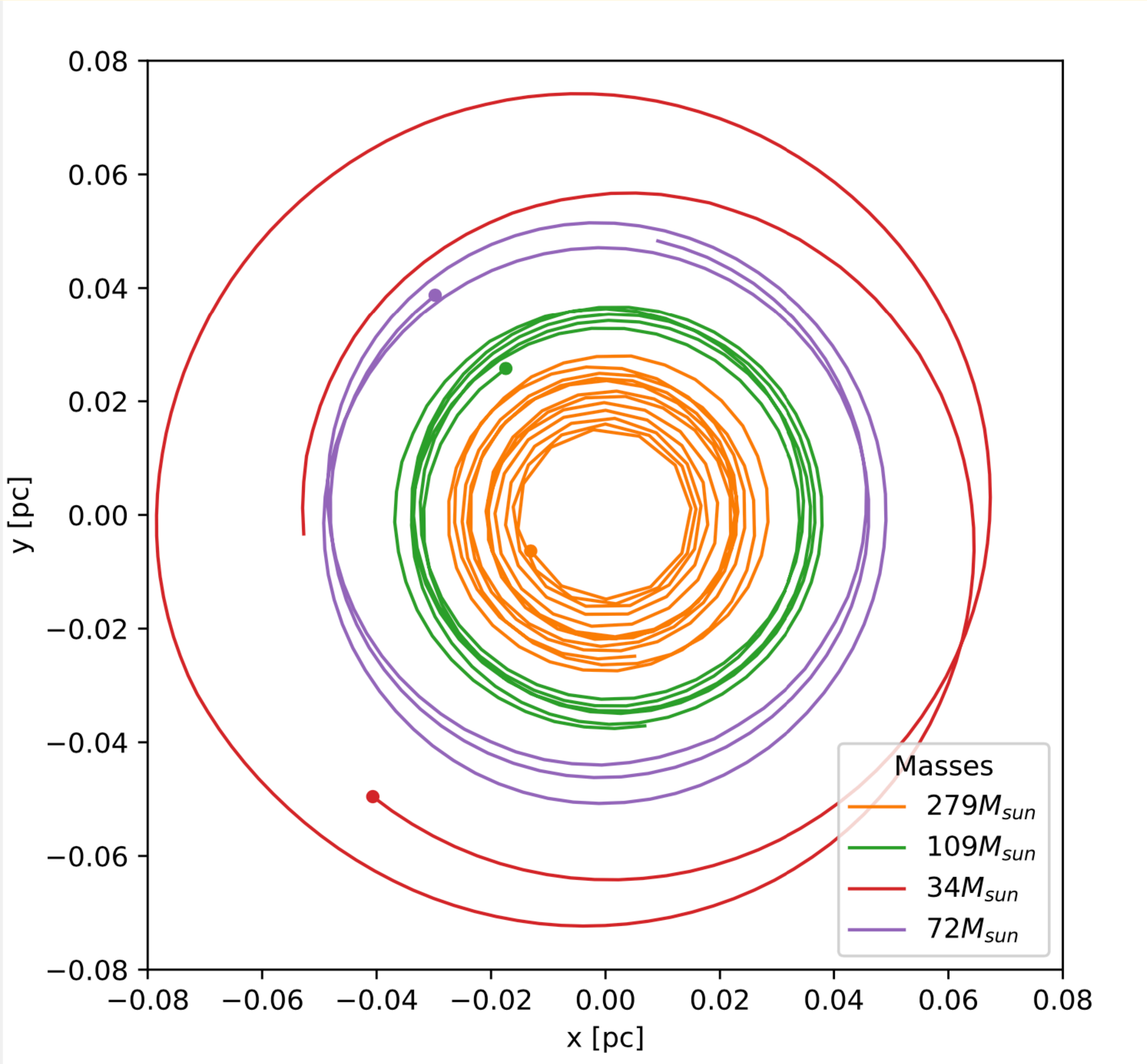
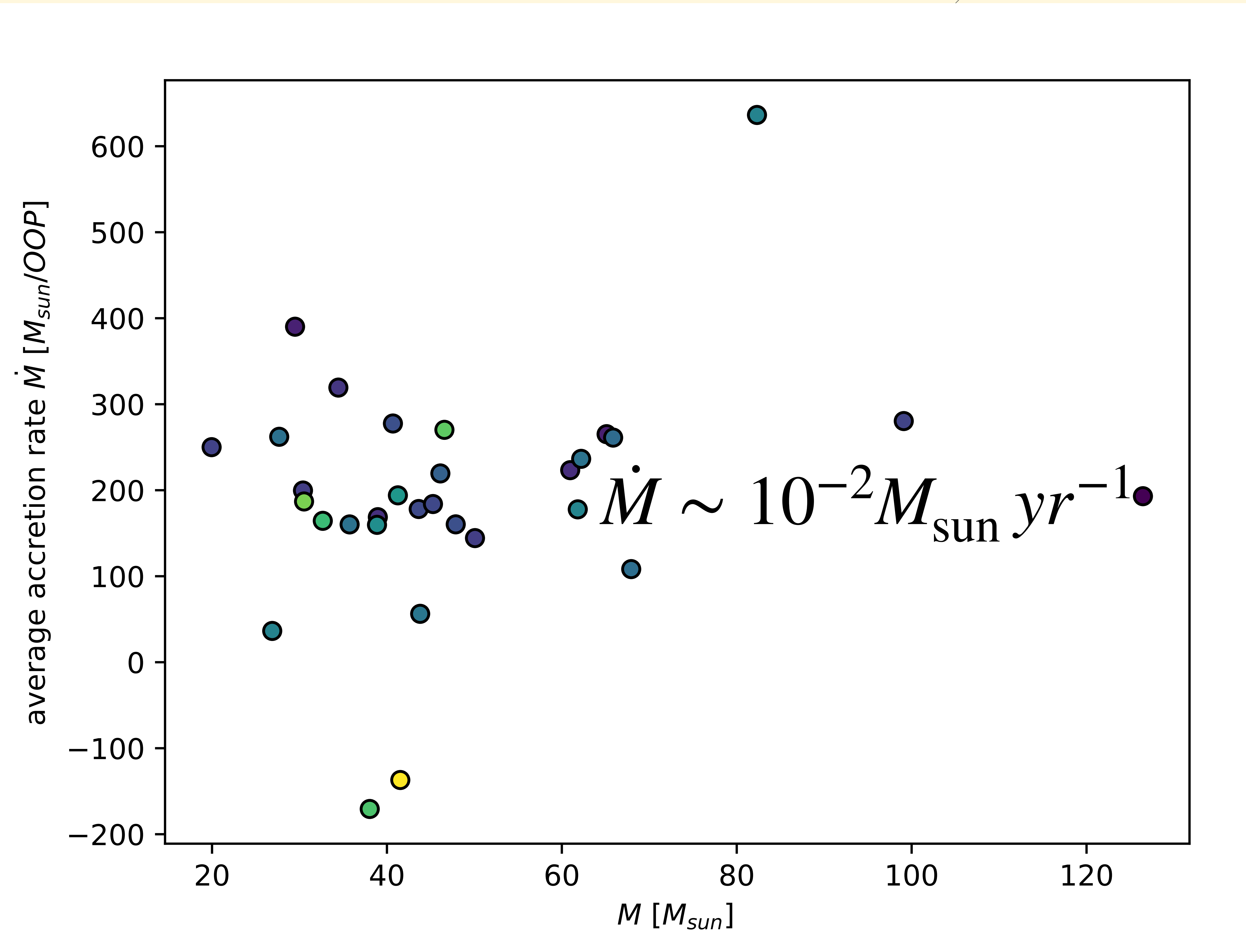
Average accretion rate vs. clump mass





Figures by Noah Kubli (UZH)