A Novel Physically Motivated Sub-Grid Model for Gas Accretion onto Massive Black Holes

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Building Galaxies from Scratch
Vienna, February 20, 2024

GALSPEC

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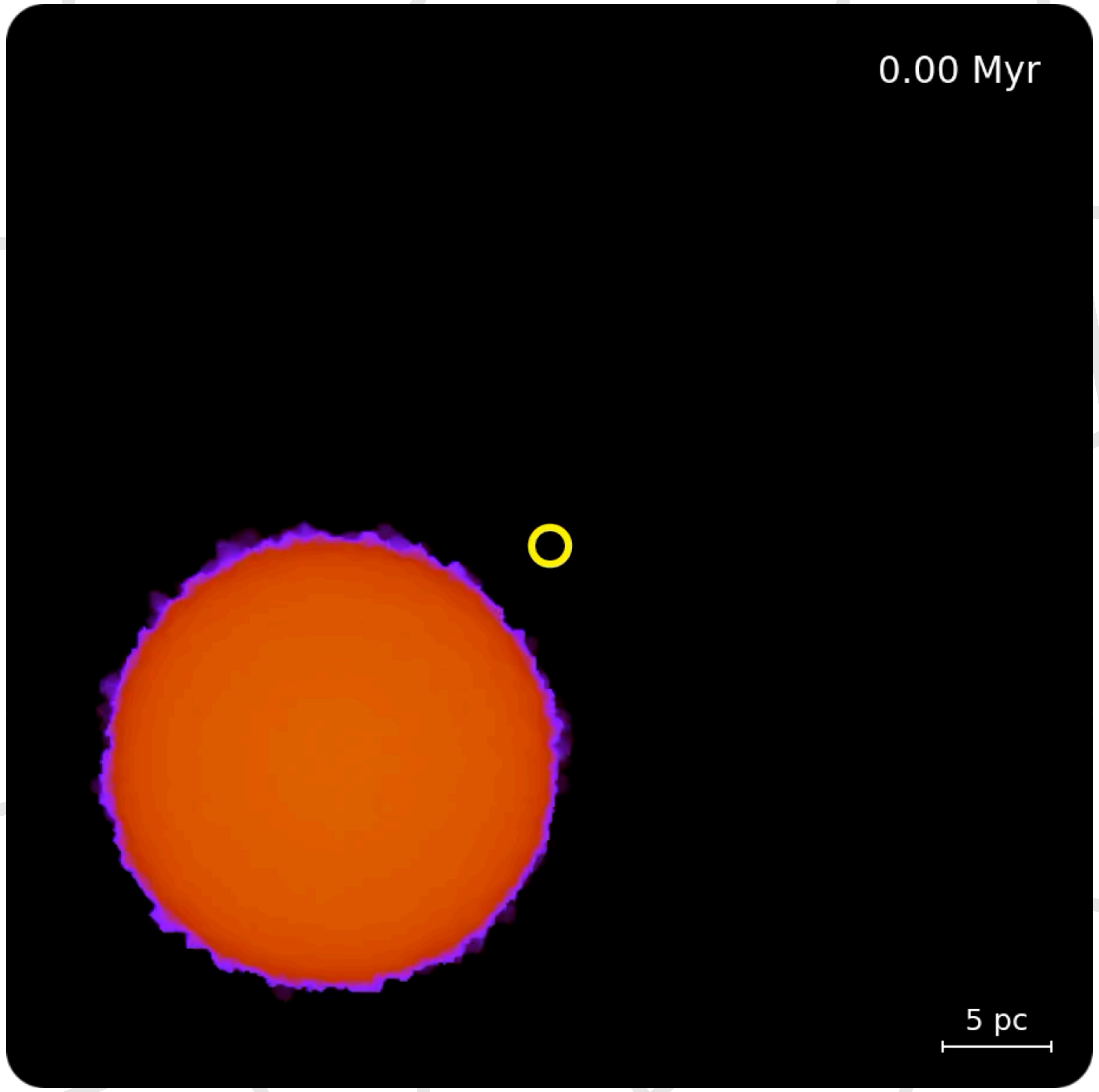
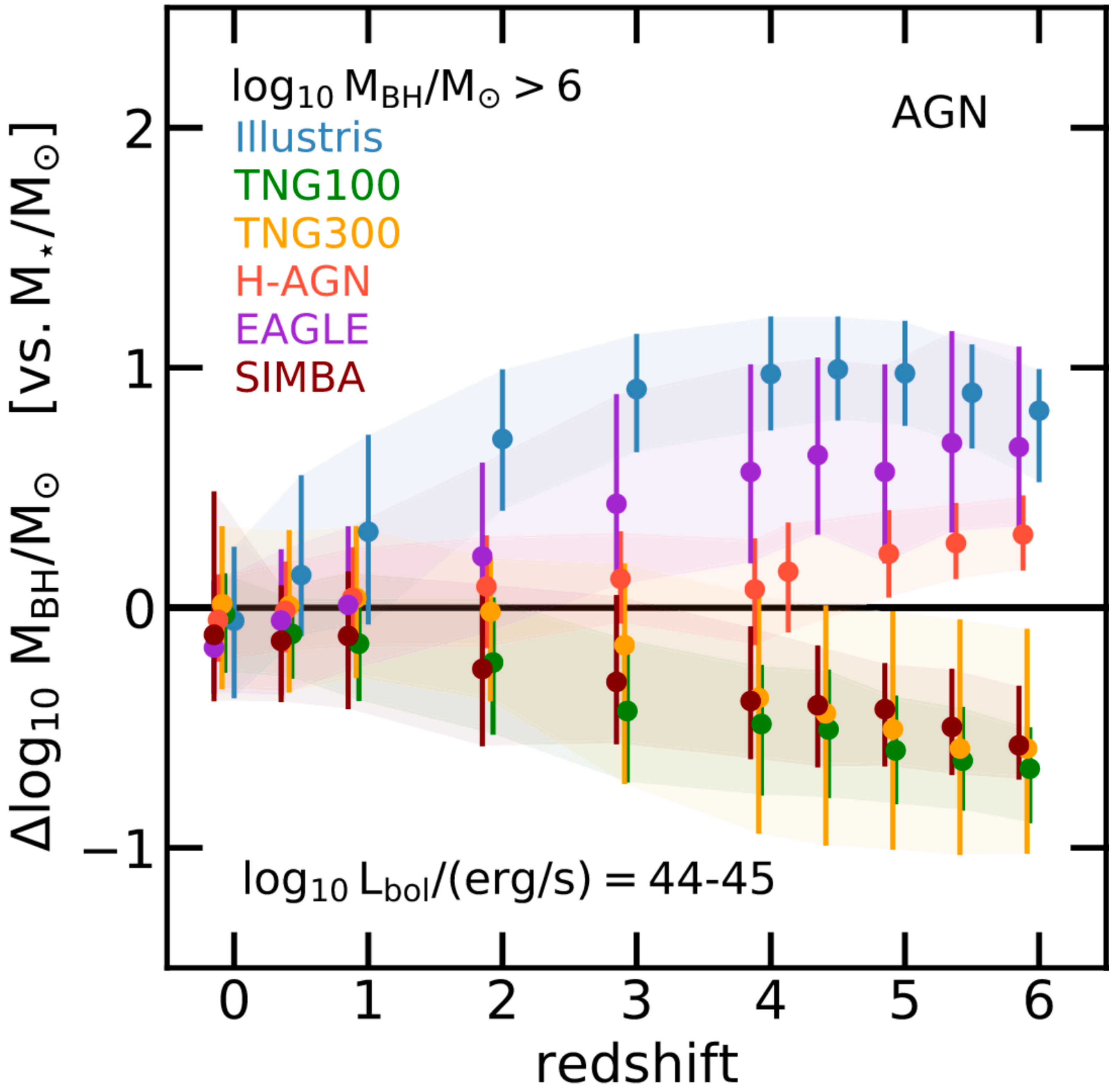


Massive Black Hole Growth

- Observations: strong scaling relations between $M_{\rm BH}$ & $M_{\rm bulge}/\sigma_{\rm bulge}/L_{\rm bulge}$
  (Silk and Rees, 1998; Magorrian et al., 1998; Häring and Rix, 2004; Gültekin et al., 2009)
  → co-evolution between SMBHs & their host galaxies (Fabian, 2012; Kormendy and Ho, 2013)

(Habouzit et al., 2022)



- Cosmological simulations: capable of recreating large-scale features and observed scaling relations
  (e.g. Di Matteo, Springel & Hernquist, 2005; Vogelsberger et al., 2014; Anglés-Alcázar et al., 2016)
- No consensus at high redshift: fundamentally different SMBH & AGN populations
  (e.g. Habouzit et al., 2022; Massonneau et al., 2023)
  - Various (often ad-hoc) sub-grid models for BH seeding, accretion and feedback due to limited resolution
- Contradicting MBH growth scenarios in the dwarf galaxy regime: the role of stellar & AGN feedback
  (Habouzit et al., 2017; Sharma et al., 2022; Koudmani et al., 2019/2021/2022)

Science Objective

Investigate how MBHs grow in mass in a well-resolved ISM together with high-fidelity models for ISM physics, star formation & stellar feedback, in the low-mass/ dwarf galaxy regime

- Under what conditions can stellar feedback regulate MBH growth?
- Do MBHs achieve (super-)Eddington accretion? If yes, over what timescale(s)?
- To what extent does AGN feedback regulate MBH growth?

Methodology

- A novel physically motivated sub-grid model for MBH accretion in the moving mesh (magneto)hydrodynamic + *N*-body code AREPO (Springel, 2010) that follows high-fidelity 3D GRMHD simulation (e.g. Yuan et al., 2015) predictions of BH gas accretion disks
- Idealised simulations (bridge between smaller- & larger-scale simulations)

Accretion Model: Skimming Mass of Cells

Main idea: infalling gas will form an accretion disk at the circularisation radius[1] & fuel the MBH on a viscous timescale (inspired by Ciotti and Ostriker, 2012; Yuan et al., 2018)

[1]Radius of a circular orbit given some angular momentum

Infalling gas accretion rate:

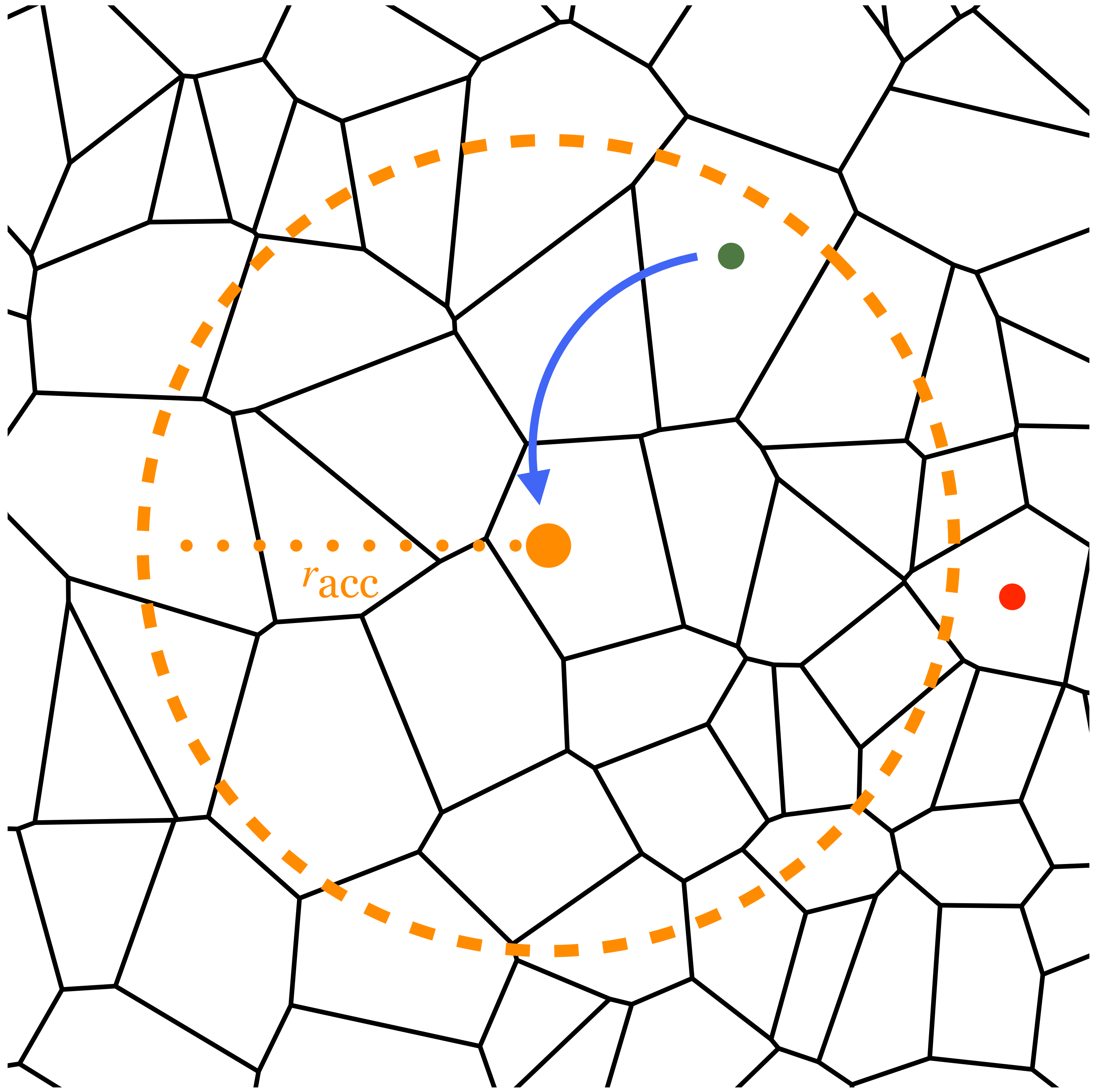
$$\dot{M}_{\rm in}(r_{\rm acc}) = 4\pi r_{\rm acc}^2 \langle\rho\rangle\langle v_r\rangle,$$

$\langle\rho\rangle$ and $\langle v_r\rangle$: mean density and mass-weighted mean radial velocity of gas cells fulfilling the accretion criteria

How we skim mass of gas cells:

$$\dot{M}_{\rm cell} = \dot{M}_{\rm in} f_{\rm cell}, \quad \text{where} \quad f_{\rm cell} = M_{\rm cell} \Big/ \sum_{n=0}^{N} M_n$$

Optional: density smoothing of skimmed gas cells



Accretion criteria:

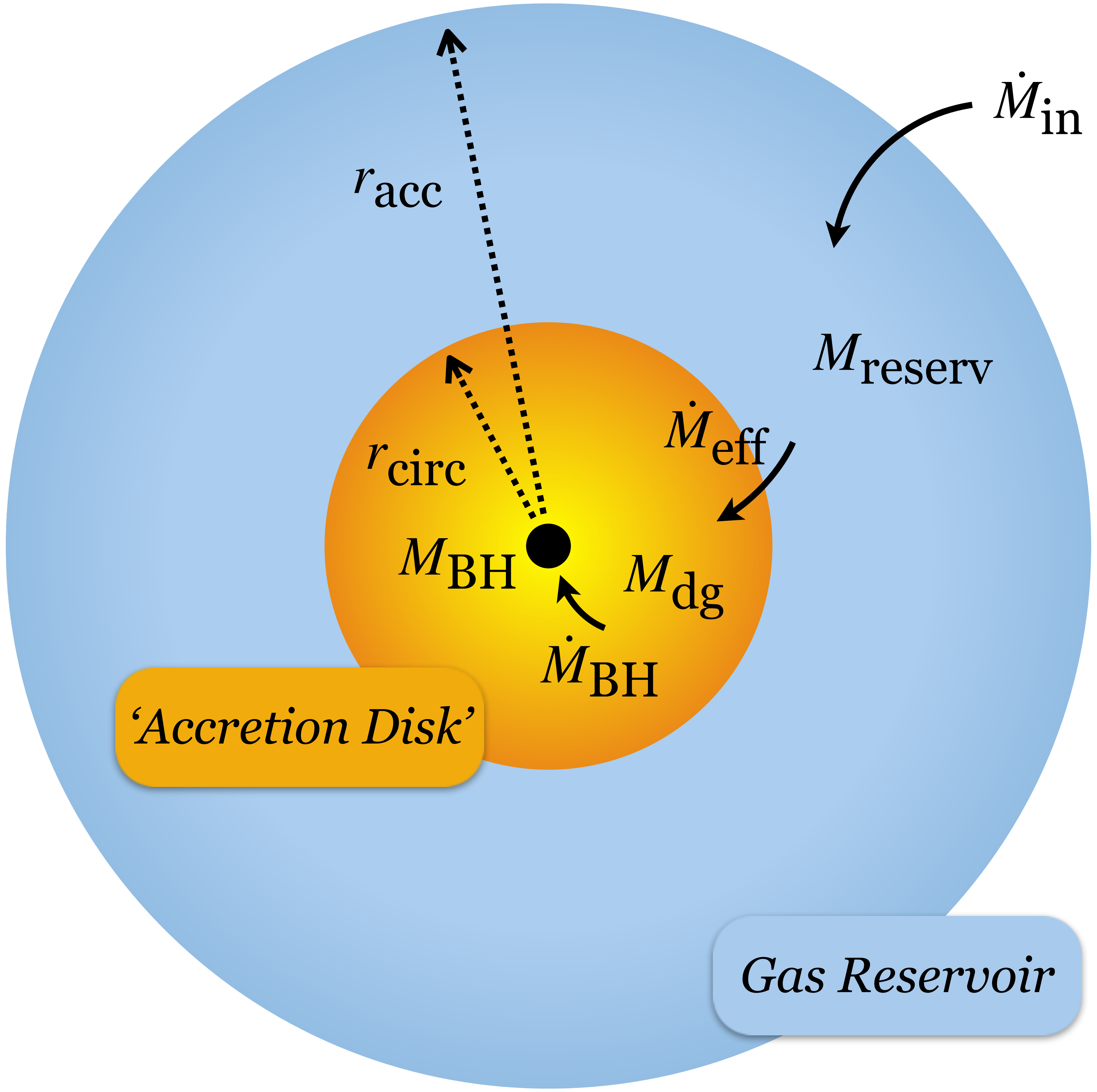
(1) Cell distance $< r_{\rm acc}$

(2) Gravitationally bound

(3) Converging flow: $\nabla \cdot v < 0$, $\nabla \cdot a < 0$

Gas cell not fulfilling the accretion criteria

Accretion Model: Sub-grid Recipe



- Infalling gas fuel the accretion disk on a free-fall timescale:

$$\frac{\mathrm{d}\dot{M}_{\rm eff}}{\mathrm{d}t} = \frac{\dot{M}_{\rm in} - \dot{M}_{\rm eff}}{\tau_{\rm ff}}, \quad \text{where} \quad \tau_{\rm ff} = \frac{r_{\rm acc}}{v_{\rm ff}}, \quad v_{\rm ff} = \left(\frac{2GM_{\rm BH}}{r_{\rm acc}}\right)^{1/2}$$

- The accretion disk fuels the BH on a viscous timescale[1]:

$$\dot{M}_{\rm BH} = \frac{M_{\rm dg}}{\tau_{\rm vis}}, \quad \text{where}$$

$$\tau_{\rm vis} \approx 1.2 \times 10^6 \text{ yr} \left(\frac{\alpha}{0.1}\right)^{-1} \left(\frac{R_{\rm circ}}{100 r_s}\right)^{7/2} \left(\frac{M_{\rm BH}}{10^9 \text{ M}_\odot}\right),$$

α is the viscosity parameter[2], and $R_{\rm circ}$ is the circularisation radius (fixed at $100r_s$)

- To better take into account the angular momentum of infalling gas → option for a variable $R_{\rm circ}$ at $\dot{M}_{\rm BH} > 0.02\dot{M}_{\rm Edd}$

[1]Kato et al., (2008), [2]Shakura and Sunyaev (1973)

- Test of the accretion model: small-scale collapsing gas cloud simulations (happy to provide more details if interested)

Dwarf Galaxy Simulations

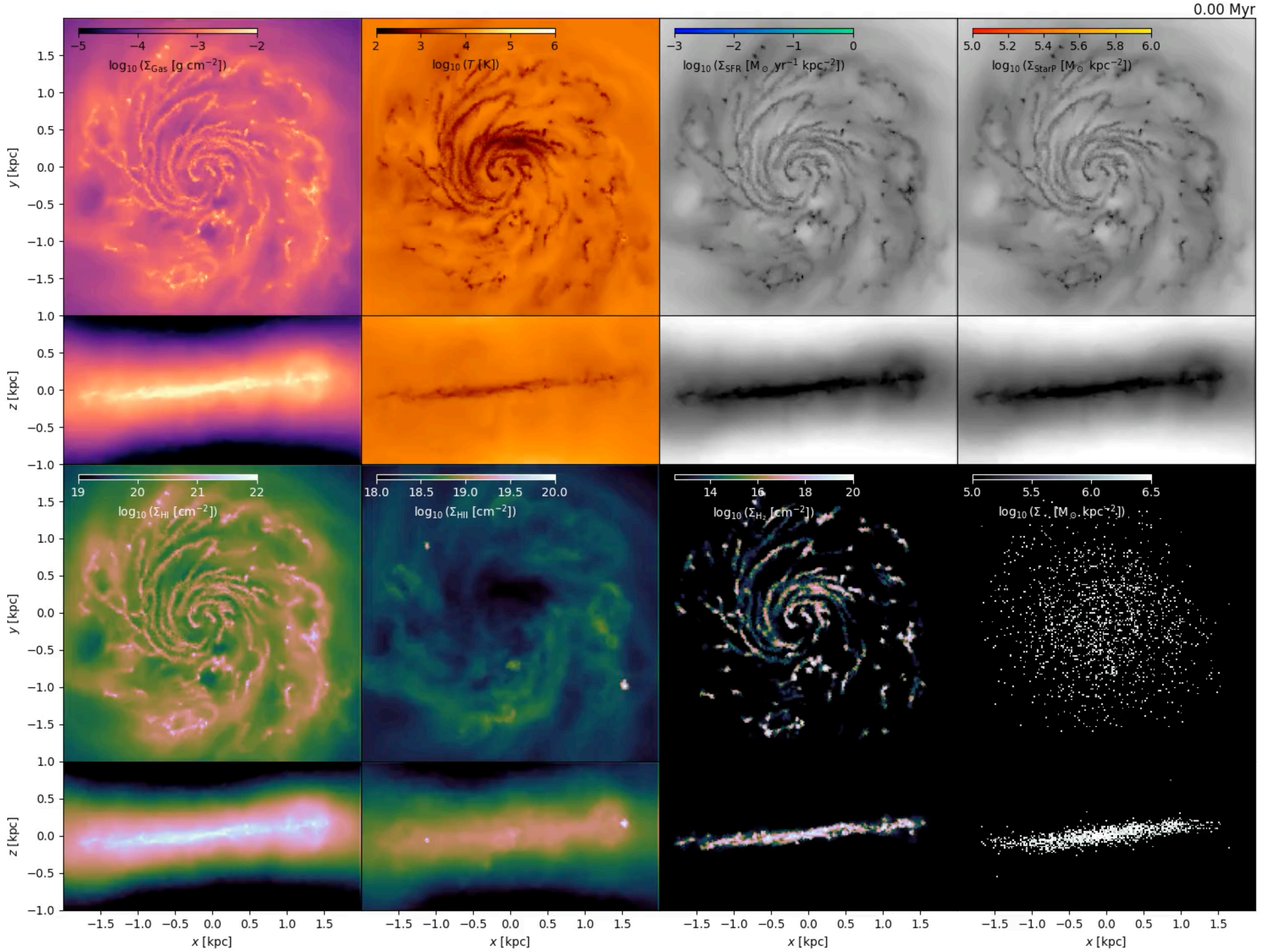
- 5.3×10^7 $M_\odot$ gaseous disk with $0.1 \times Z_\odot$ in a 2×10^{10} $M_\odot$ DM halo
  (similar as in Whitworth et al., 2021; Hu et al., 2016, generated using the method & software developed by Springel, Di Matteo & Hernquist, 2005)

- Chemical network for H, He & CO
  (Glover and Clark, 2012)

- Dust shielding & H_2/CO self-shielding
  (TreeCol algorithm in Clark et al., 2012)

- Radiative heating & cooling of gas
  (Clark et al., 2019; Gnat and Ferland, 2012)

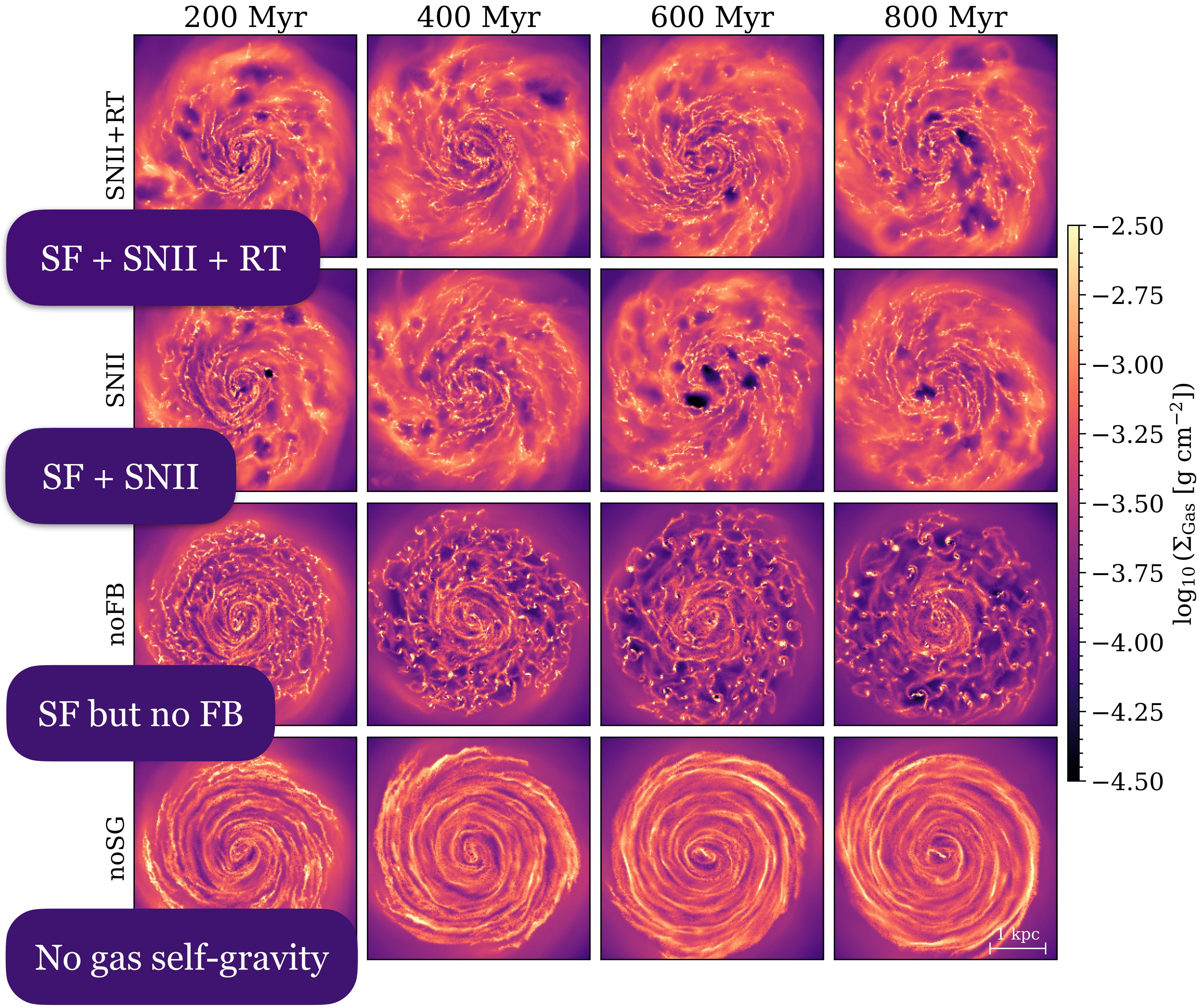
- Star formation & stellar feedback
  (Goeller et al., in prep; Smith et al., 2021)
  - SN type II + radiative feedback via RT on-the-fly (SWEEP) (Peter et al., 2022)
    (for more details on SWEEP, see Robin Tress' talk on Friday)



Preliminary results!

Early Suite of Simulations

- 10^4 $M_\odot$ MBH with $r_{acc} = 10$ pc
- Geometrical (de-)refinement around the MBH to ensure a certain number of cells in the accretion region
- 100 $M_\odot$ resolution (sub-parsec maximum physical resolution)
- Gradually add star formation & stellar feedback processes

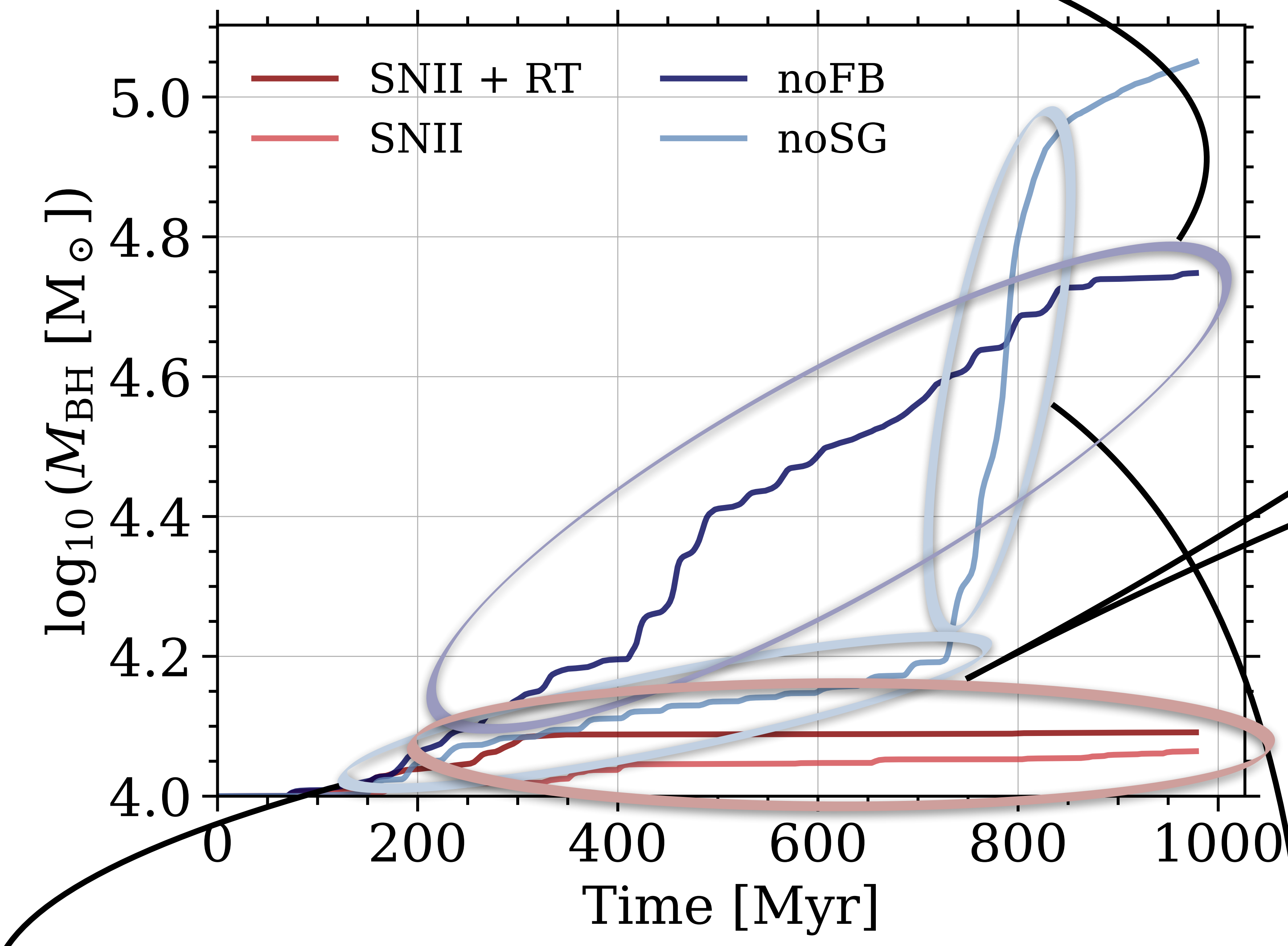


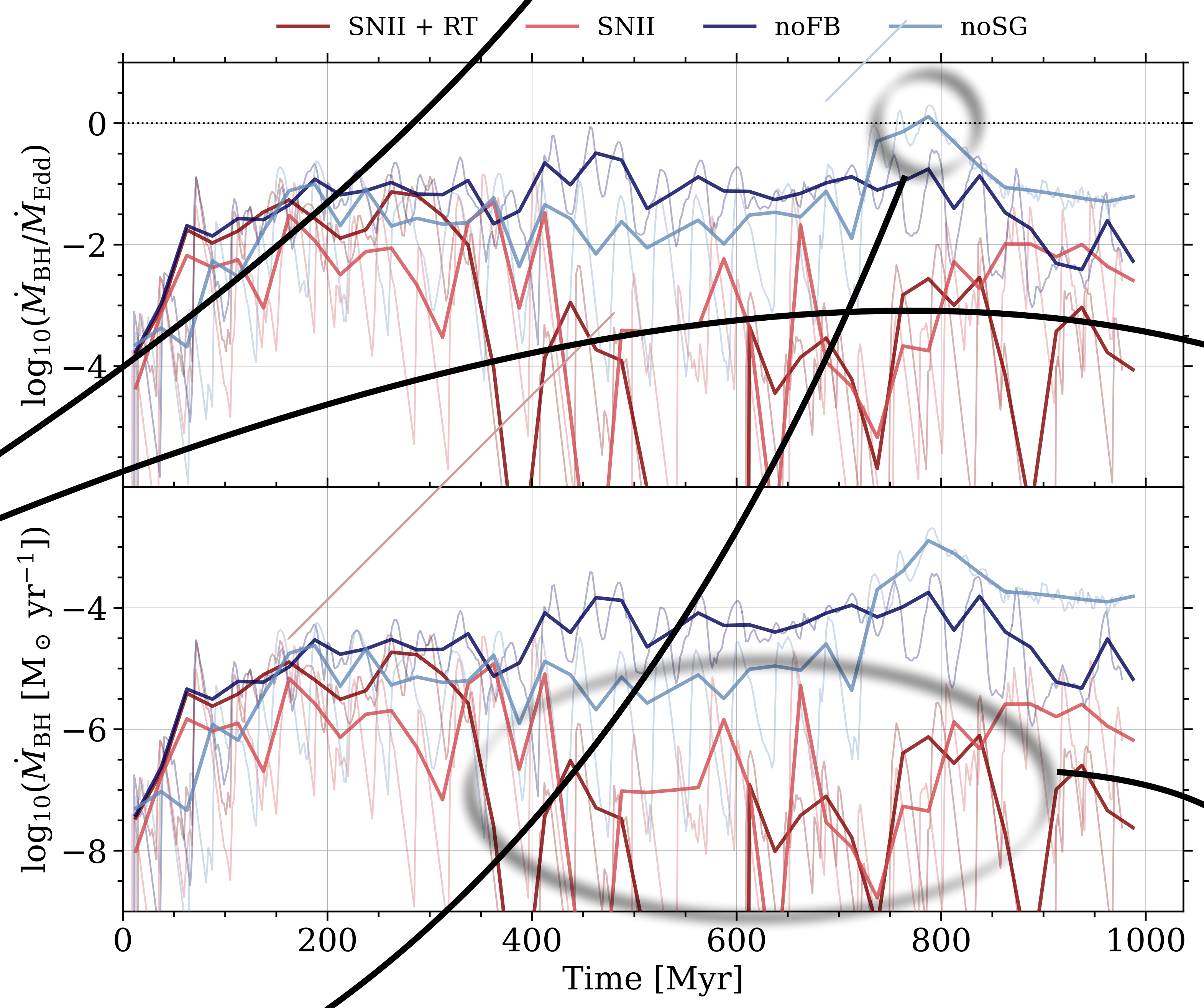
Black Hole Growth

Preliminary results!

Initially higher BH growth with SF, but eventually lower due to depletion of gas

Suppression of BH growth due to SN feedback





No distinct difference with RT

Steady increase in $M_{\rm BH}$ as the gas cools

Eddington accretion from a nearby molecular cloud

Episodes of close-to or no accretion (100s Myr)

Summary

- Now available: a novel physically motivated sub-grid model for MBH accretion that follows high-fidelity predictions of gas accretion disks surrounding BHs
- SN feedback can suppress MBH growth by close-to an order of magnitude within 1 Gyr and prevent gas to be accreted onto the SMBH for 100s Myr

Future Work

- Continue to investigate under what conditions stellar feedback can regulate MBH growth & further explore the parameter space (M_{BH}, α, Z_{Gas}, resolution, etc)
- Implementation of AGN feedback: radiation via RT on-the-fly (SWEEP) & winds via hot & cold mode accretion/feedback (e.g. Yuan et al., 2018)
- High-resolution cosmological zoom-in simulations at high redshift