FIZINIŲ IR TECHNOLOGIJOS MOKSLŲ CENTRAS

Cold gas feels the shove, not the heat: how the *M-σ* relation emerges in multiphase bulges

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Turku | 2026

SMBH – galaxy connection

- Most massive galaxies host a central supermassive black hole
- Gravitational influence is confined to a tiny volume compared to the galactic scales:

$$r_{\rm inf} \approx 10\,{\rm pc}\left(\frac{M_{\rm BH}}{10^8\,M_\odot}\right)\left(\frac{200\,{\rm km\,s^{-1}}}{\sigma}\right)^2$$

- Evidence for host-SMBH connection:
  - Observed scaling relations ($M_{\rm BH}$-σ, $M_{\rm BH}$-$M_{\rm b}$, $M_{\rm BH}$-$L_{\rm b}$) (e.g. Kormendy & Ho 2013)
  - Regulation of various properties in cosmological simulations (e.g. Harrison & Ramos Almeida 2024)

How is there a causal connection?

AGN Feedback*

* We are fairly confident AGN feedback regulates galaxies. We are somewhat less confident about the exact terms and conditions under which the ISM agrees.

Momentum- vs Energy-driving

A fast AGN wind (v_w~0.1c) shocks against the ISM

$$T_{\rm sh} \approx 1.2 \times 10^{10}\,{\rm K} \left(\frac{v_{\rm w}}{0.1c}\right)^2$$

If: $t_{\rm cool} < t_{\rm flow}$

Thermal energy is radiated away:

$$\dot{p}_{\rm out} \sim \dot{p}_{\rm w} \sim \frac{L_{\rm AGN}}{c}$$

With $L_{\rm AGN} = L_{\rm Edd}$, $M_{\rm crit}$ becomes:

$$M_{\rm crit} = \frac{f_g \kappa}{\pi G^2} \sigma^4$$

King (2003); King & Pounds (2015)

If: $t_{\rm cool} > t_{\rm flow}$

Thermal energy is retained and contributes:

$$\dot{p}_{\rm out} \sim \frac{v_{\rm w}}{v_{\rm out}} \frac{L_{\rm AGN}}{c} \sim 10{-}20 \frac{L_{\rm AGN}}{c}$$

With $L_{\rm AGN} = L_{\rm Edd}$, $M_{\rm crit}$ becomes:

$$M_{\rm crit} \approx \frac{11 f_g \kappa}{0.5\,\eta\,\pi G^2 c} \sigma^5$$

Faucher-Giguère & Quataert (2012); Zubovas & King (2012); Costa et al. (2014)

Outflow fit with MAGNOFIT

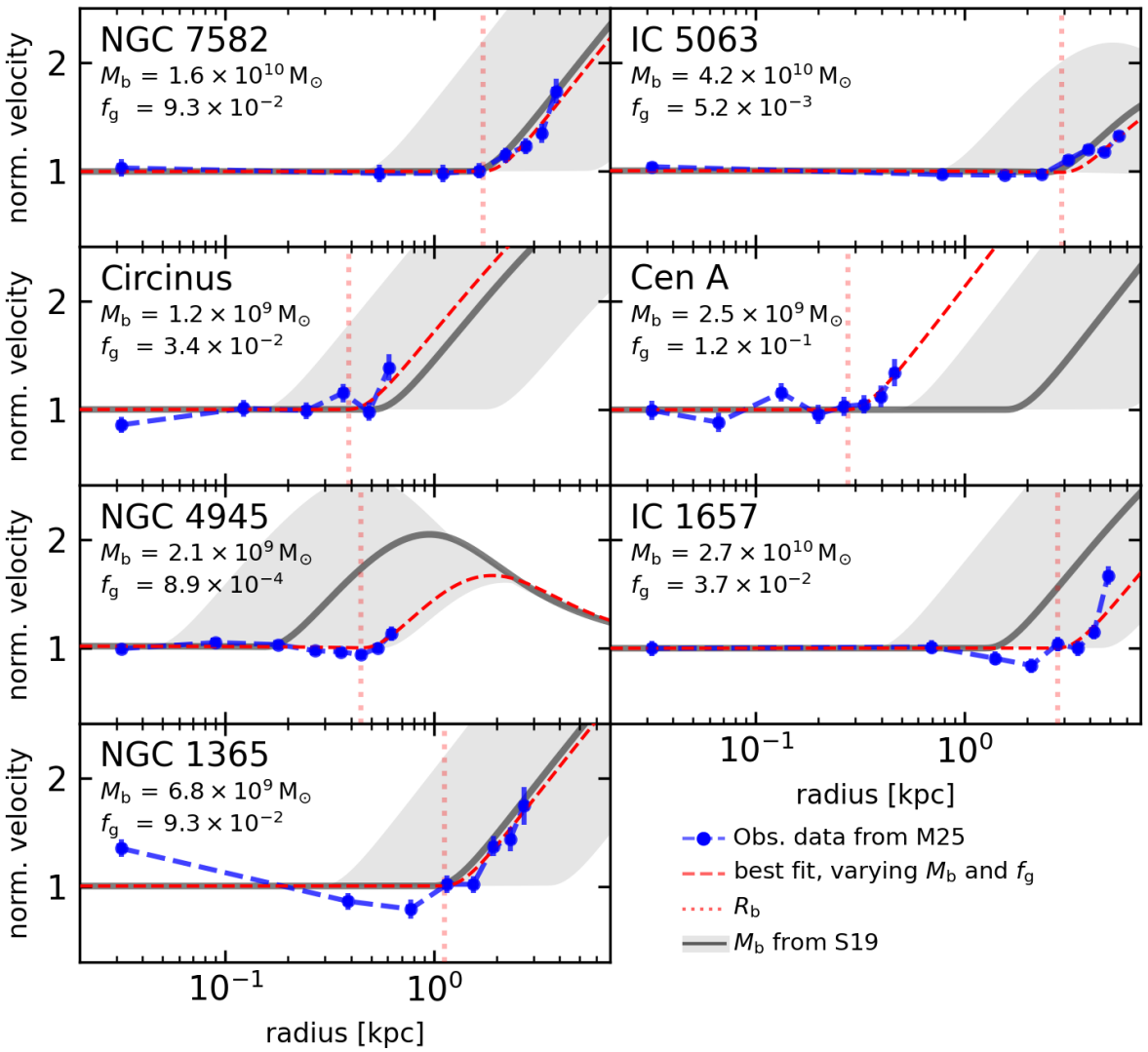
We took spatially resolved molecular outflow data from Marconcini et al. (2025)

- Outflow kinematics determined with MOKA^{3D}

We fit the data using a simple spherical wind shell propagation model from MAGNOFIT (Zubovas et al. 2022):

- Singular isothermal sphere
- Varying M_b and f_g

Outflows accelerate when they leave the bulge



Zubovas & Tartėnas (2025)

Model setup

We use a heavily modified Gadget-3 (Springel 2005) with SPHS flavor (Read & Hayfield 2012):

- Singular isothermal sphere profile external potential
- Radiative cooling/heating:
  - Below 10^4 K - cooling following Mashchenko et al. (2008)
  - Above 10^4 K - heating/cooling following Sazonov et al. (2005)
- No self-gravity*
  - We did test this :)
- Feedback injection using *gridWind*

We simulate an AGN outflow propagating in a clumpy multiphase galactic bulge to bridge the gap between the semi-analytical work and observations

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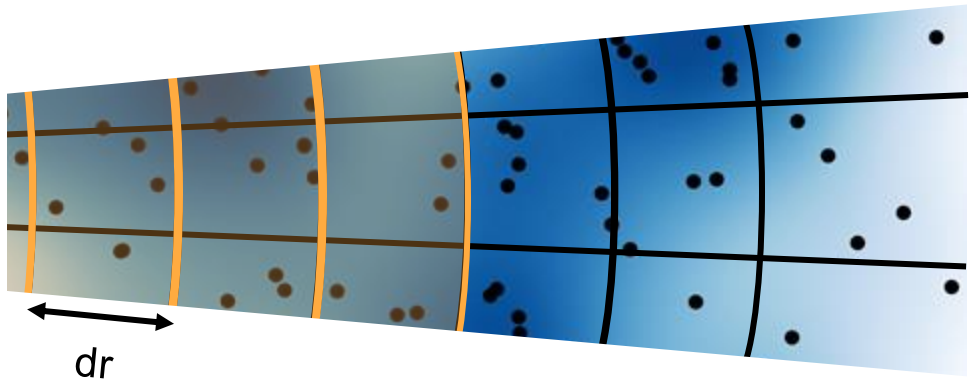
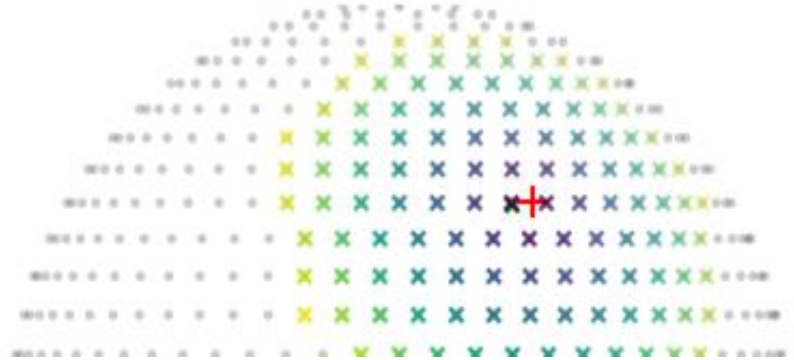




Model setup

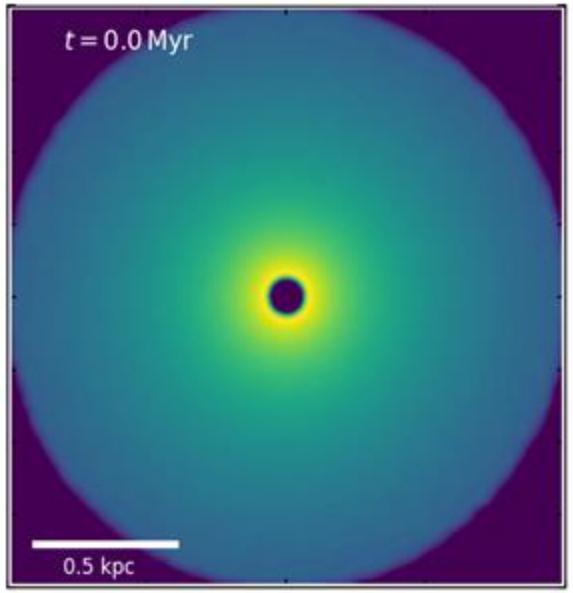
Initial conditions are defined by the *M-σ* relation:

- $M_{BH} = 10^8\ M_\odot$
- σ_b = 142 km / s
- $f_g = 0.1$; $M_{gas} = 9.4 \times 10^9\ M_\odot$
- N ~ 10^6
- t_{AGN} = 1 Myr

Clumpiness is generated via initially seeded turbulence

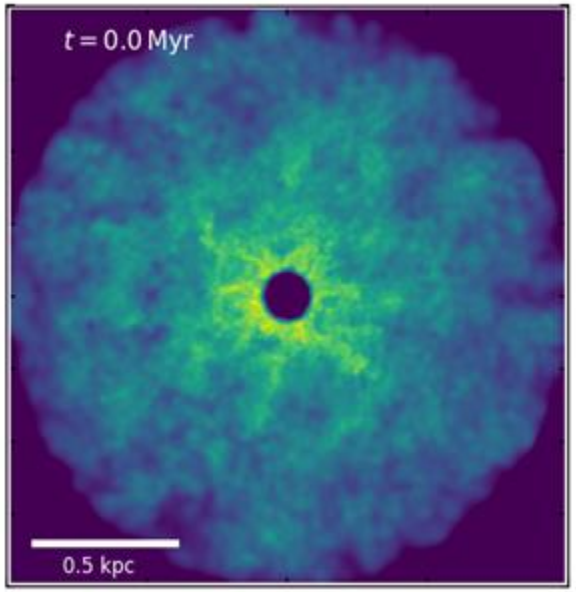
Main set of 13x4 simulations:

- 13 luminosities from 0 to $2.5 L_{Edd}$ with $L_{Edd} = 1.26 \times 10^{46}$ erg/s
- 4 turbulence/initial particle position realizations for each luminosity



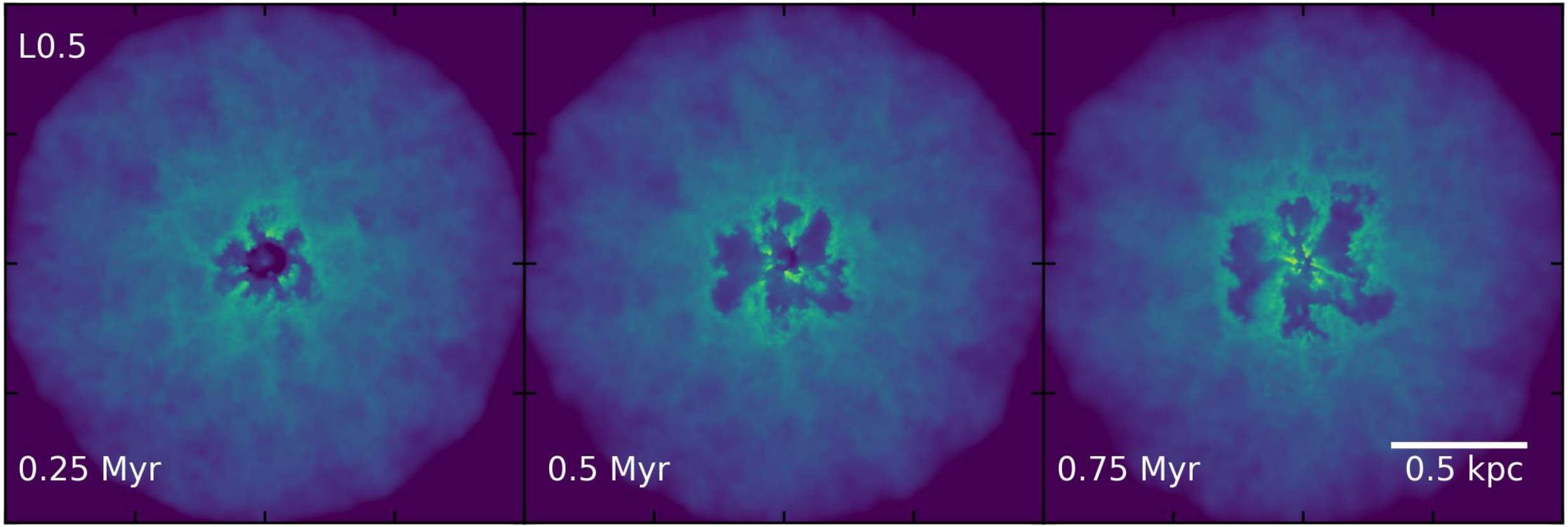
Smooth

1 Myr



Turbulent

Morphology



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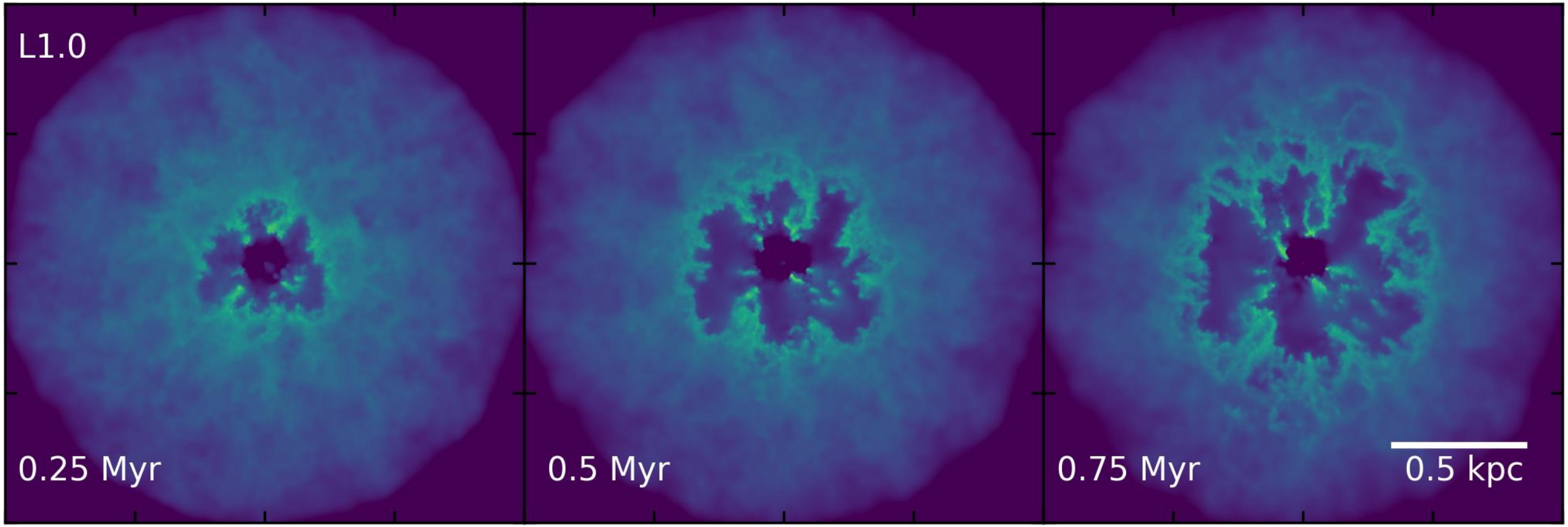
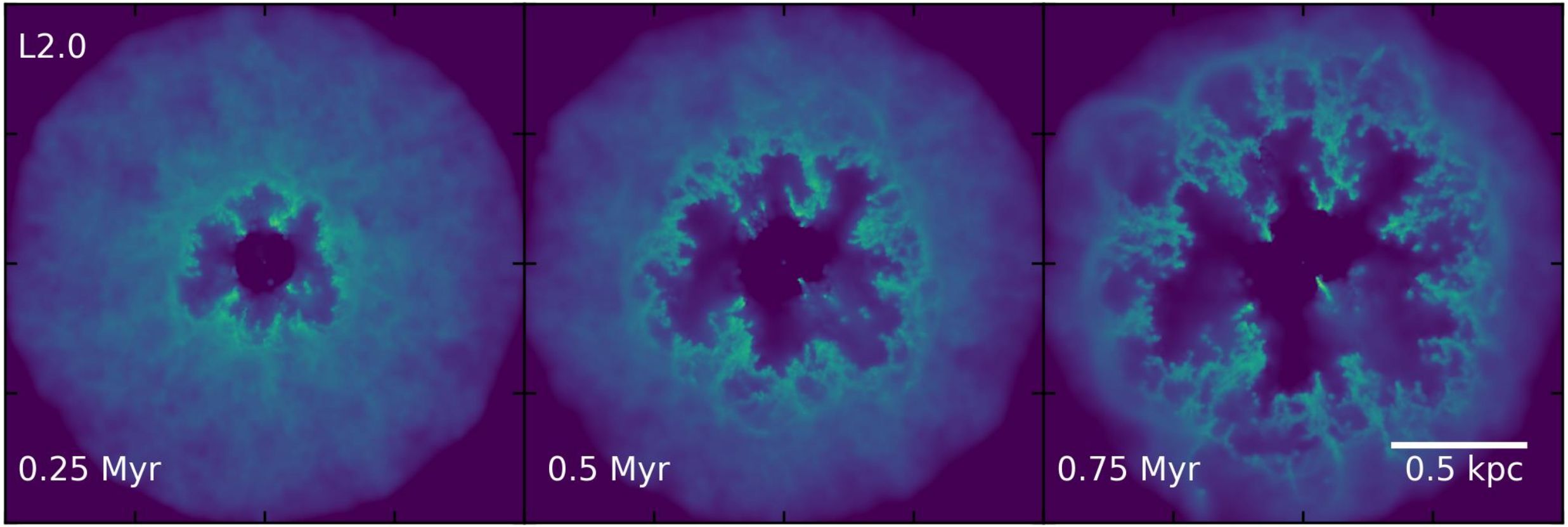
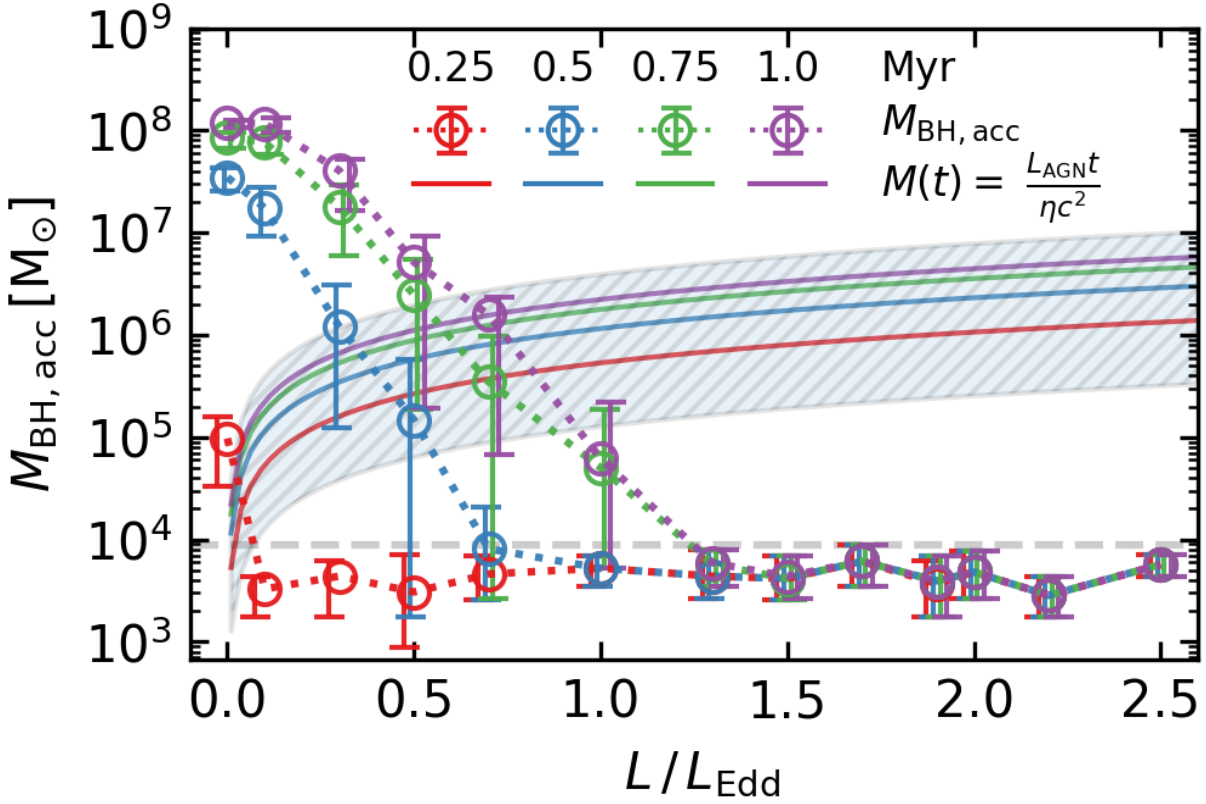


Morphology



Suppressed gas inflow

- To quantify the amount of gas falling to the center, we use the central SMBH sink particle
  - There is no "realistic" accretion description
- High luminosity runs do not accrete enough to sustain an AGN

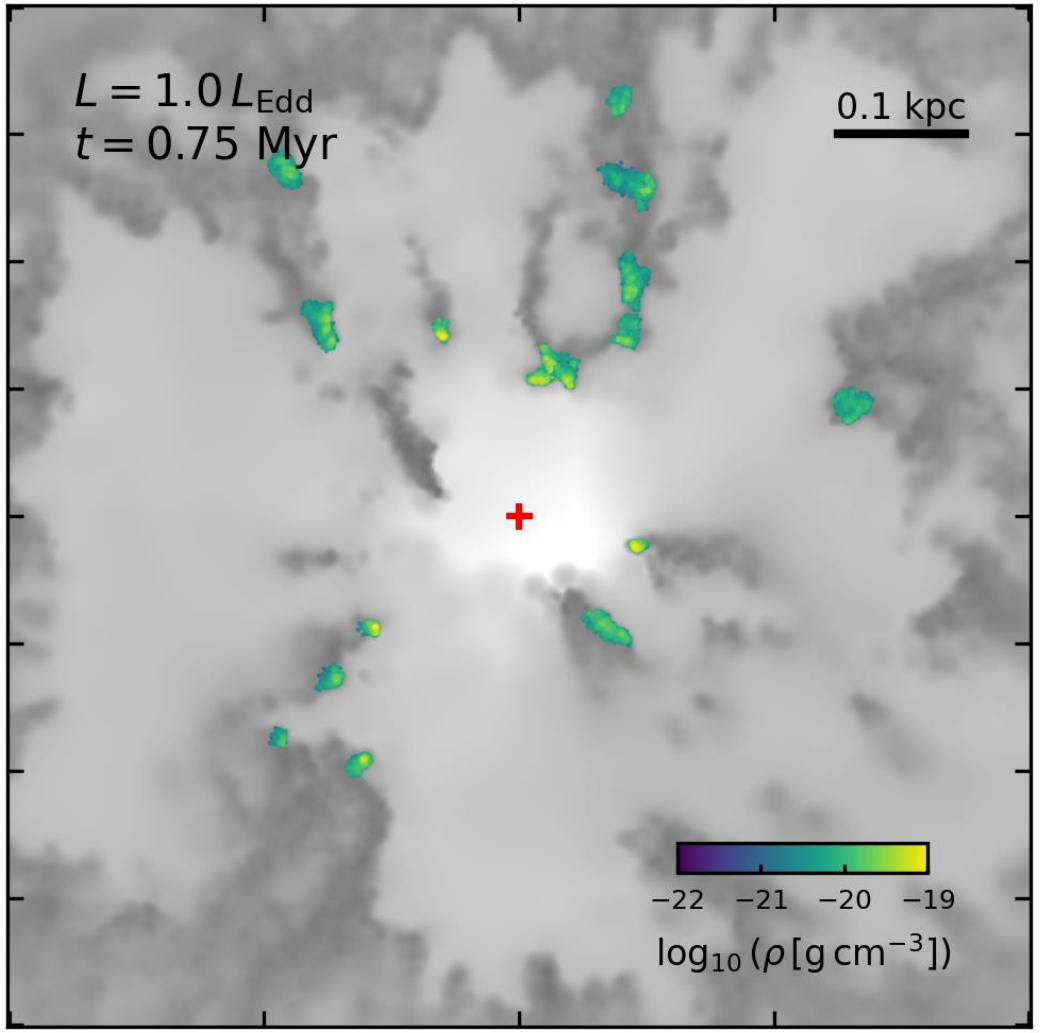


Feedback effect on dense ISM clumps

Can we quantify how strongly AGN feedback couples to cold dense gas?

- We looked for dense clumps:
  - $\rho > 10^{-22}$ g cm^{-3} and $T < 10^4$ K thresholds
  - DBSCAN clustering with $\Delta d < 10$ pc $\Delta v < 0.5\ \sigma$
- We measure the line-of-sight size of each clump and look how far it moved over a period of $\Delta t = 0.05$ Myr
- This allows to determine how much of a boost it received compared to pure momentum driving:

$$f_p = \frac{\Delta\left(M_{\rm cl} v_{\rm rad,cl}\right)/\Delta t + G M_{\rm cl} M_{\rm pot}(<d_{\rm cl})/d_{\rm cl}^2}{(L_{\rm AGN}/c)\times \Omega_{\rm cl}/4\pi}$$



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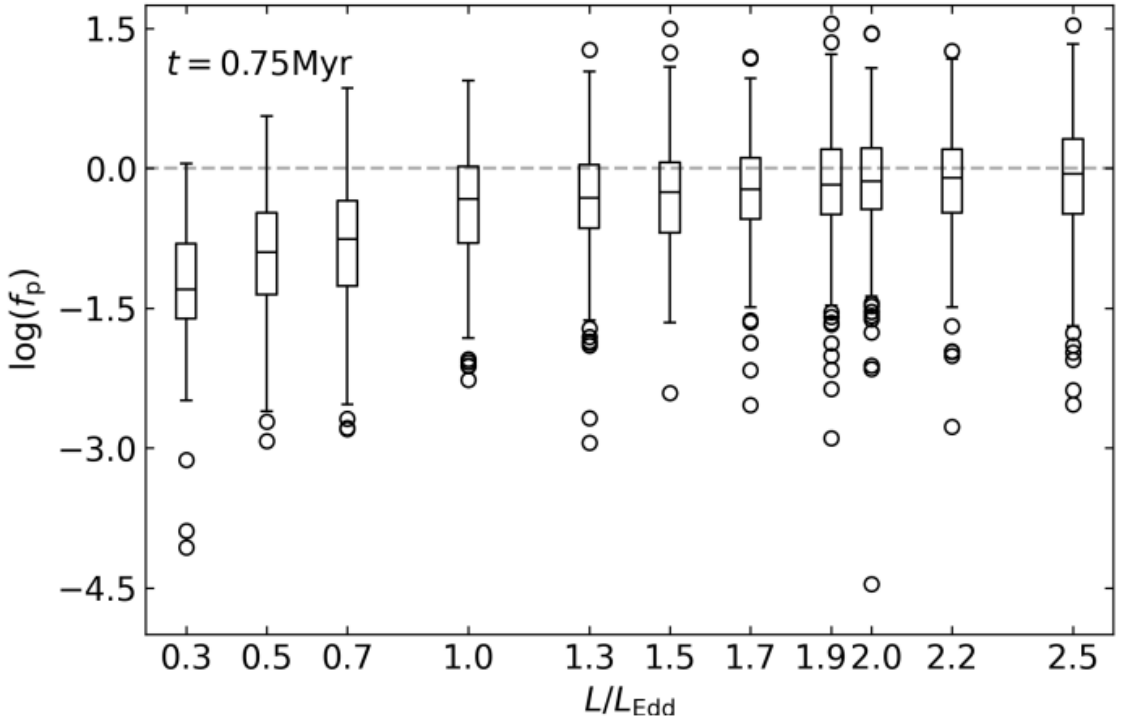

New and improved setup

Want to have a robust bulge model setup, not for singular experiments, but as a clear physical reference.

1. On-the-fly turbulence driver (Federrath et al. 2010)
   - Artificial structure
   - Collapse due to cooling

2. External pressure
   - Secures the external boundary during a long (>10 Myr) run
3. …?

Aspirational goal:
Episodic AGN - either predetermined or based on a realistic on-the-fly accretion prescription