BLACK HOLE FUELING AND FEEDBACK: CHARACTERIZING SINGLE AND DUAL AGN DUTY CYCLES IN SMUGGLE SIMULATIONS

J. Motka, L. Blecha, A. Sivasankaran, P. Torrey, et al., in prep.

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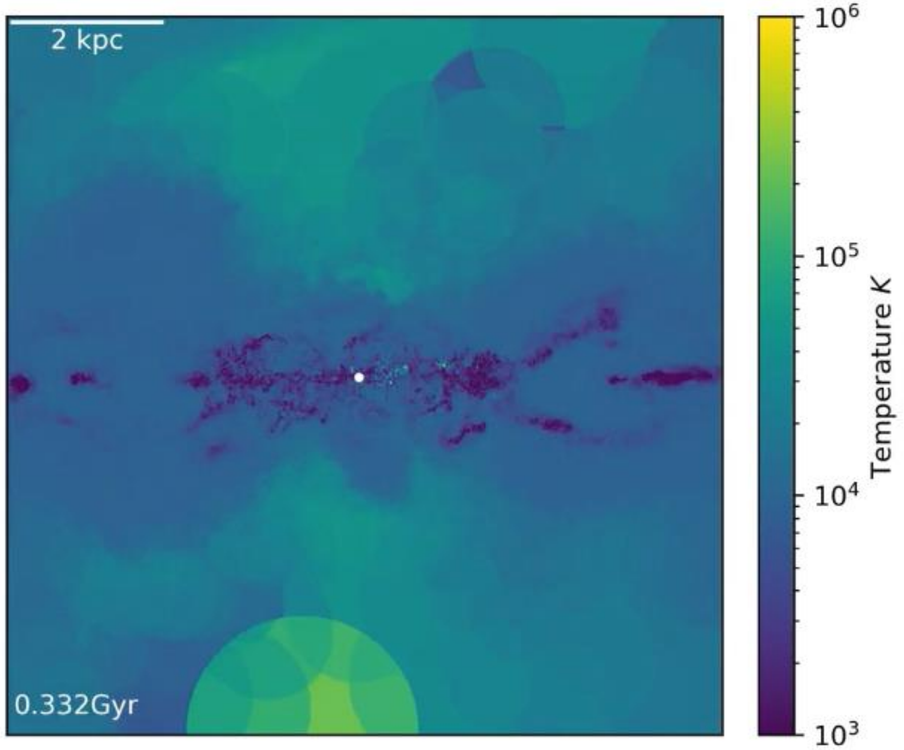
Sivasankaran et al. (2025)

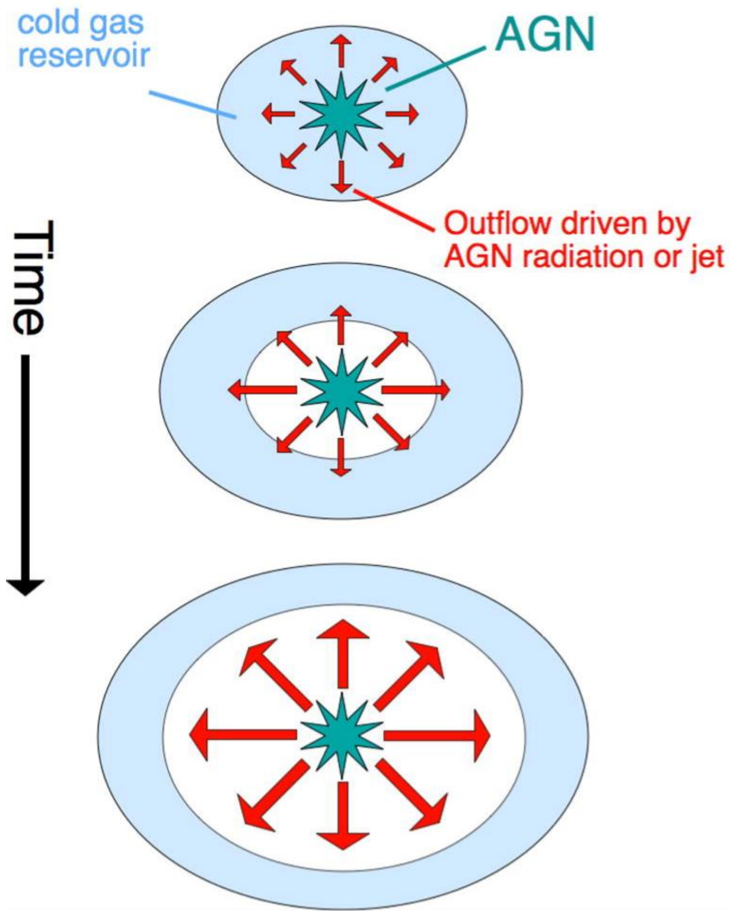


Supermassive black hole (SMBH) growth

SMBH merger

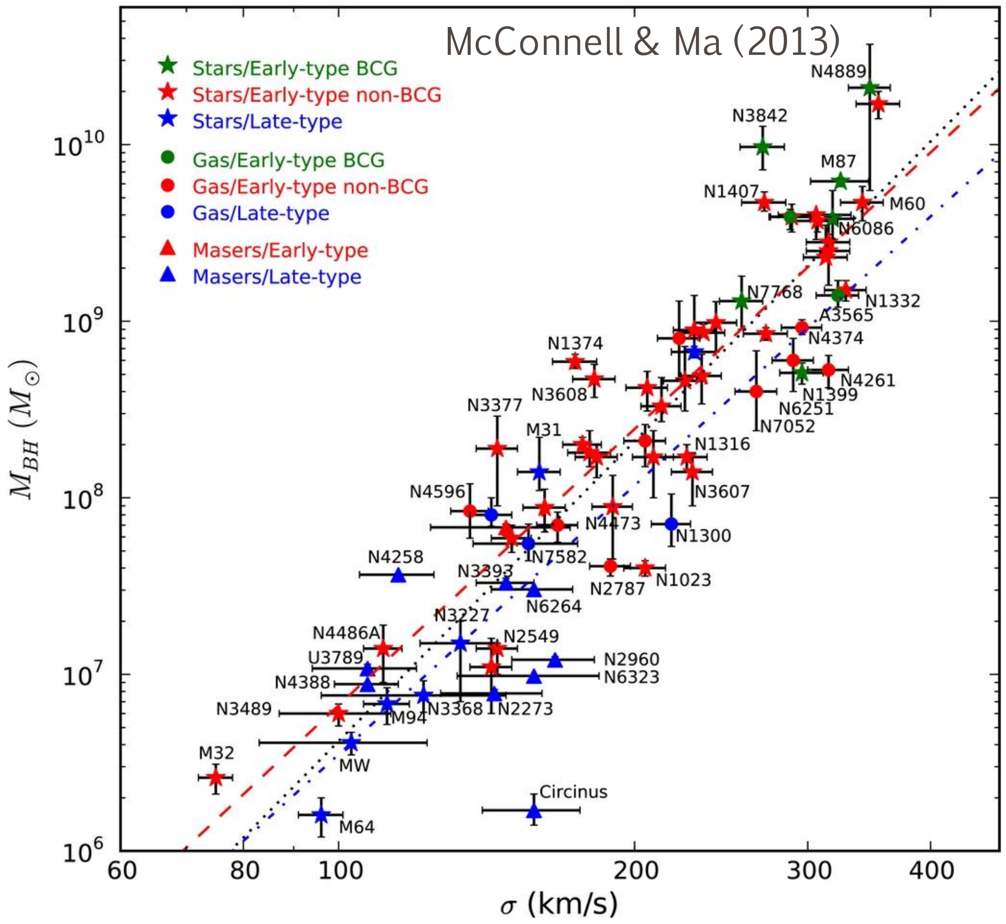
Credit: Pranav Satheesh

SMBH accretion

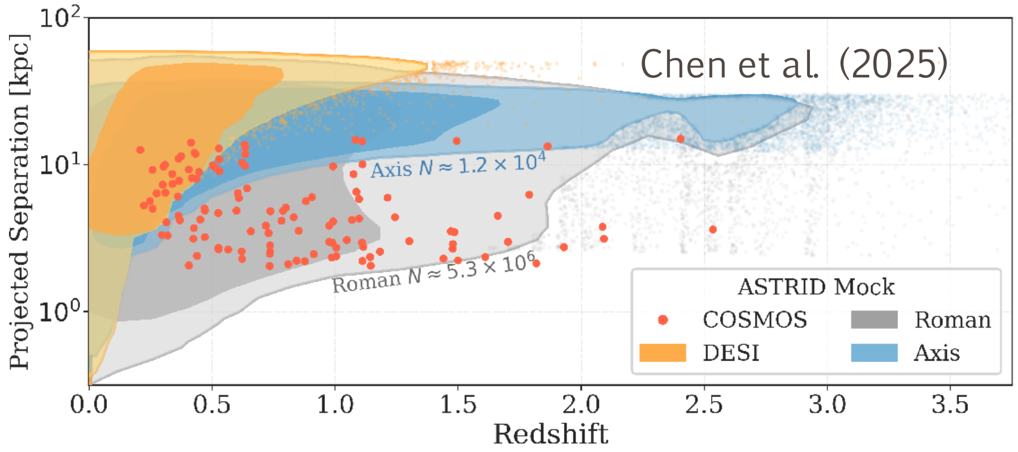


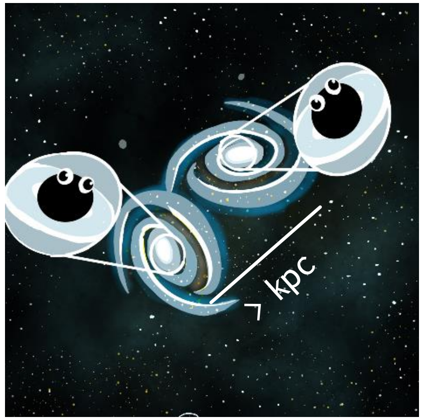
Alexander & Hickox (2012)

Motivation



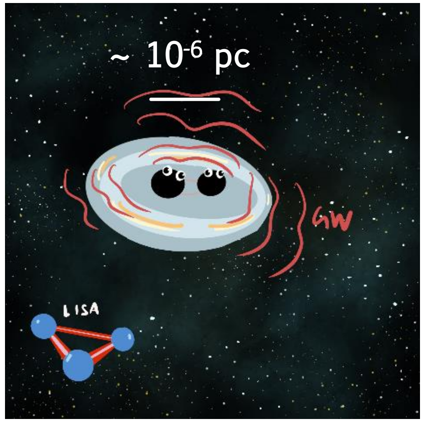
Other studies: Kormendy & Richstone (1995), Magorrian et al. (1998), Reines & Volonteri (2015), Savorgnan et al. (2016), etc.





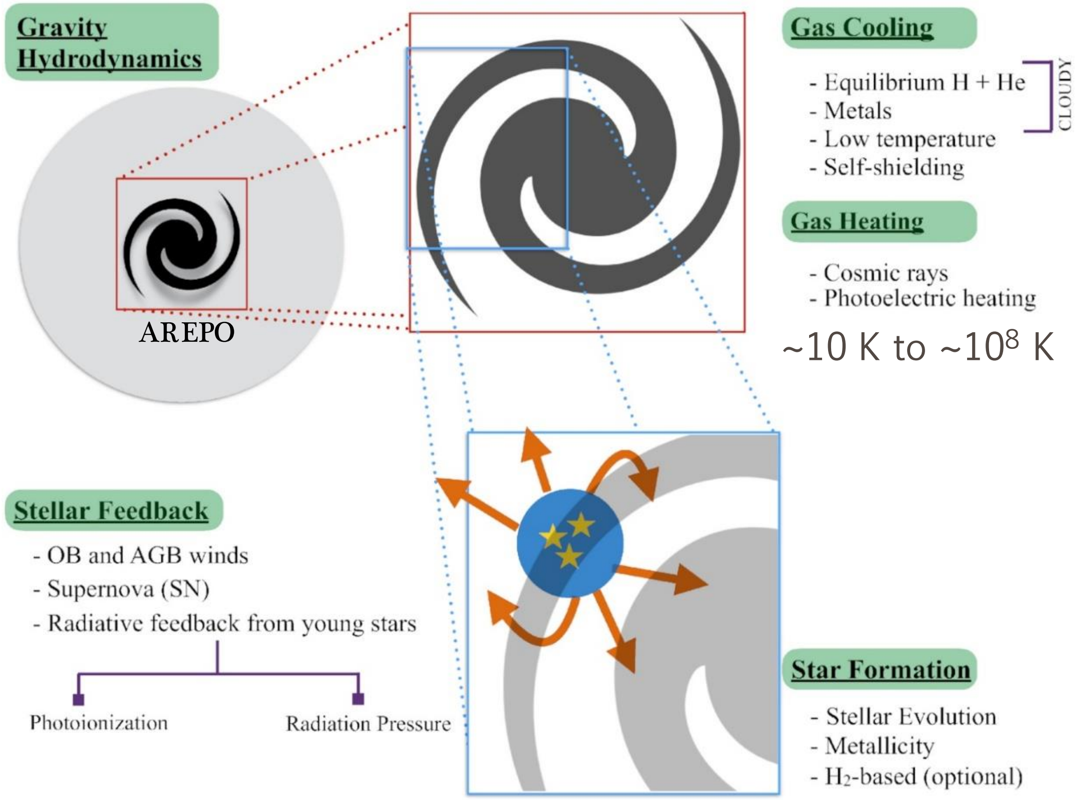
Delay Timescale

Credit: Pranav Satheesh

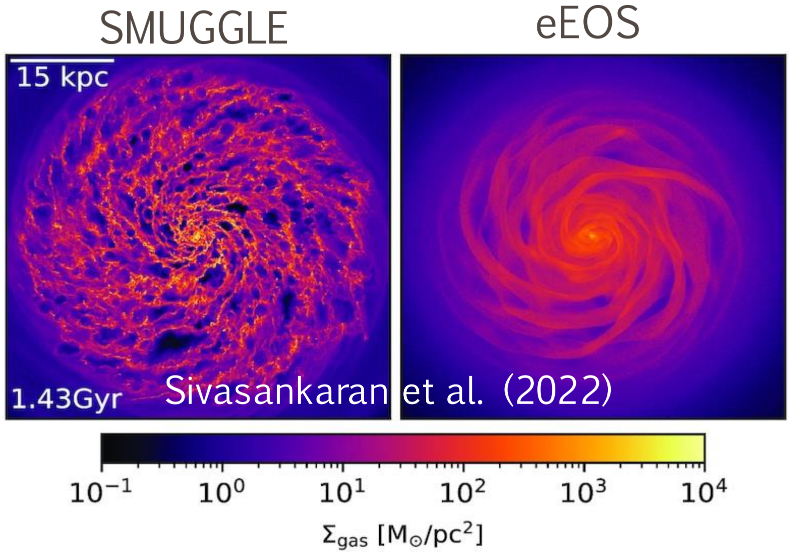


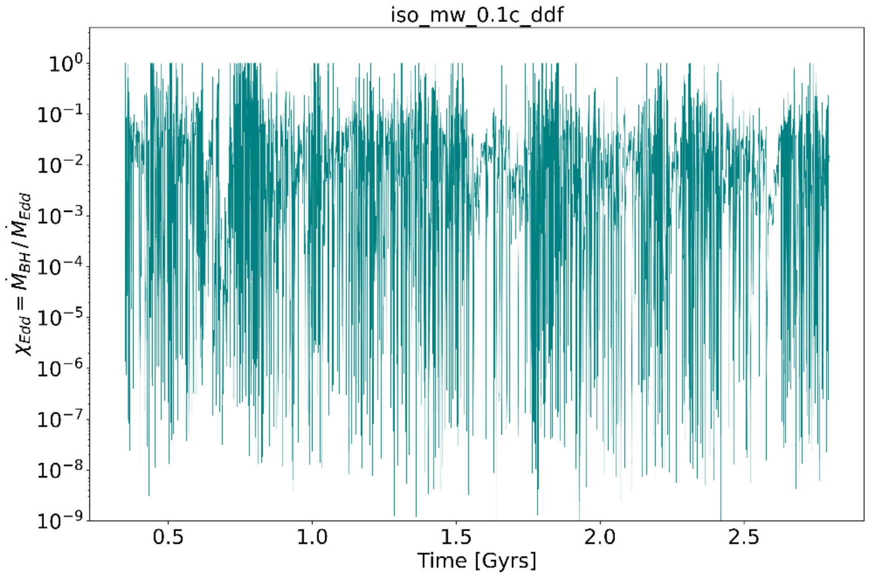
Goal: To characterize the episodic lifetimes of single & dual AGNs using high-resolution galaxy simulations.

SMUGGLE: Stars and MUltiphase Gas GaLaxiEs



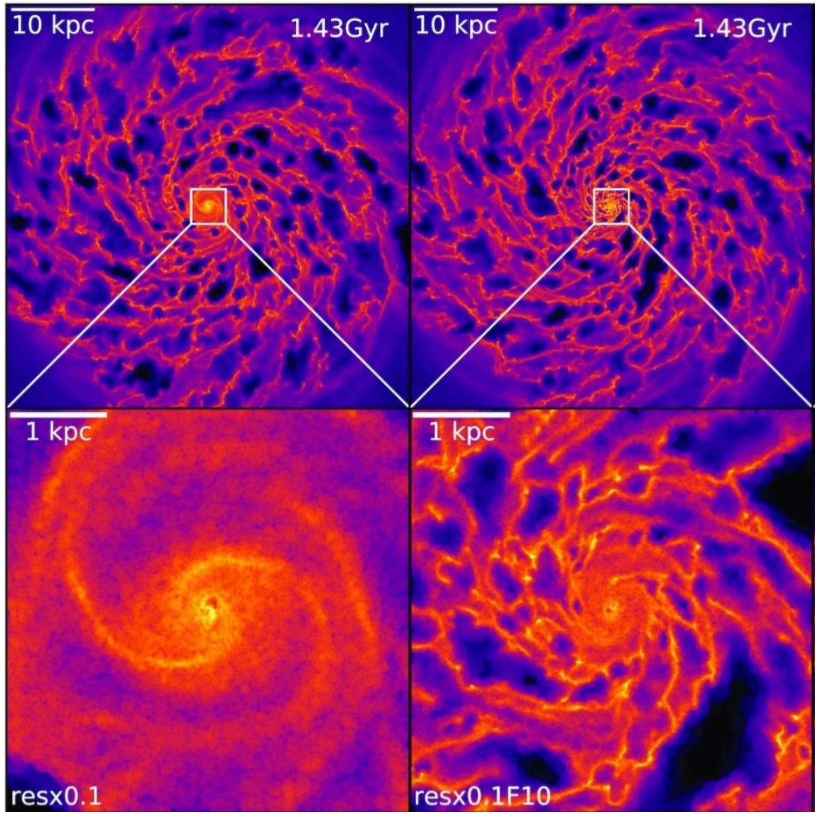
Marinacci et al. (2023)





BH physics

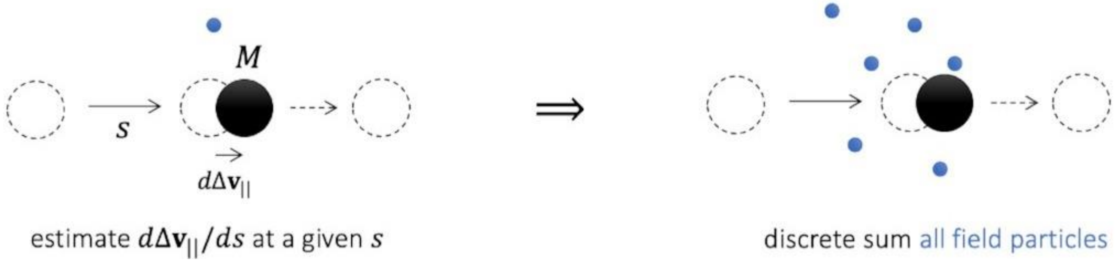
No refinement   With refinement



Sivasankaran et al. (2022)

The gas cell masses near the BHs are resolved in a radial kernel-weighted fashion.

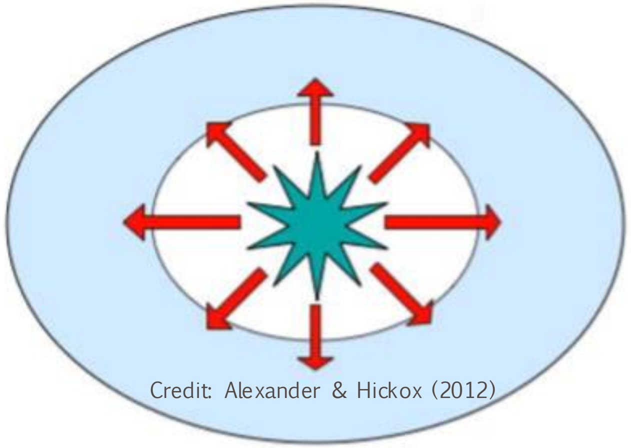
Discrete dynamical friction



Ma et al. (2023)

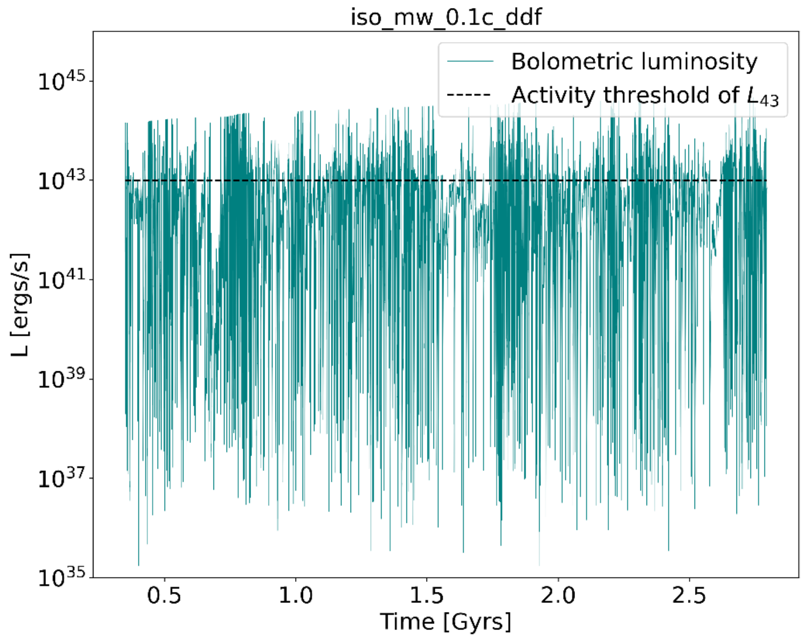
Eddington-limited Bondi-Hoyle accretion

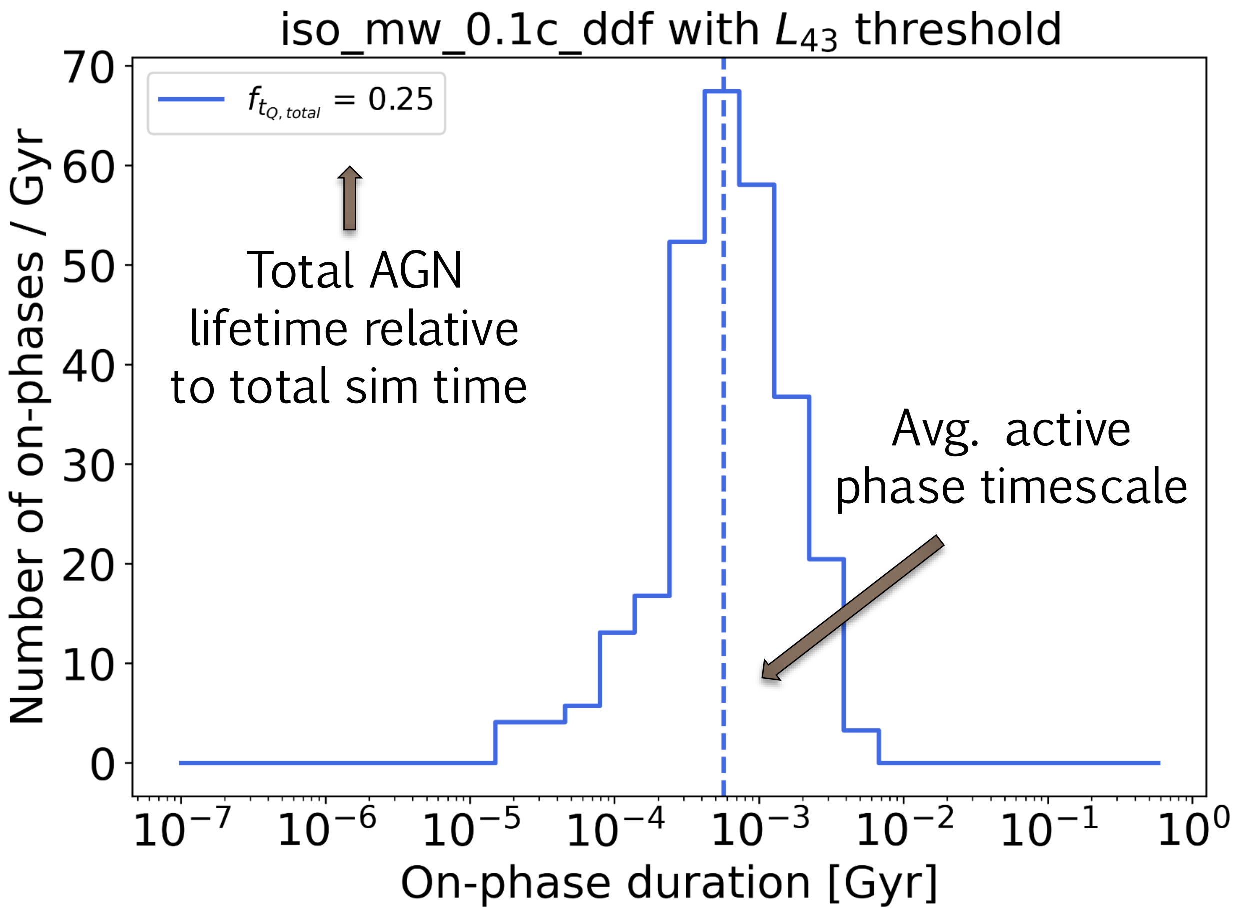
$L_{bol} \propto \dot{M}_{BH} \propto M_{BH}^2$



Fast nuclear winds with wind velocities $v_w \sim 0.1c$

AGN lifetime distribution and fraction

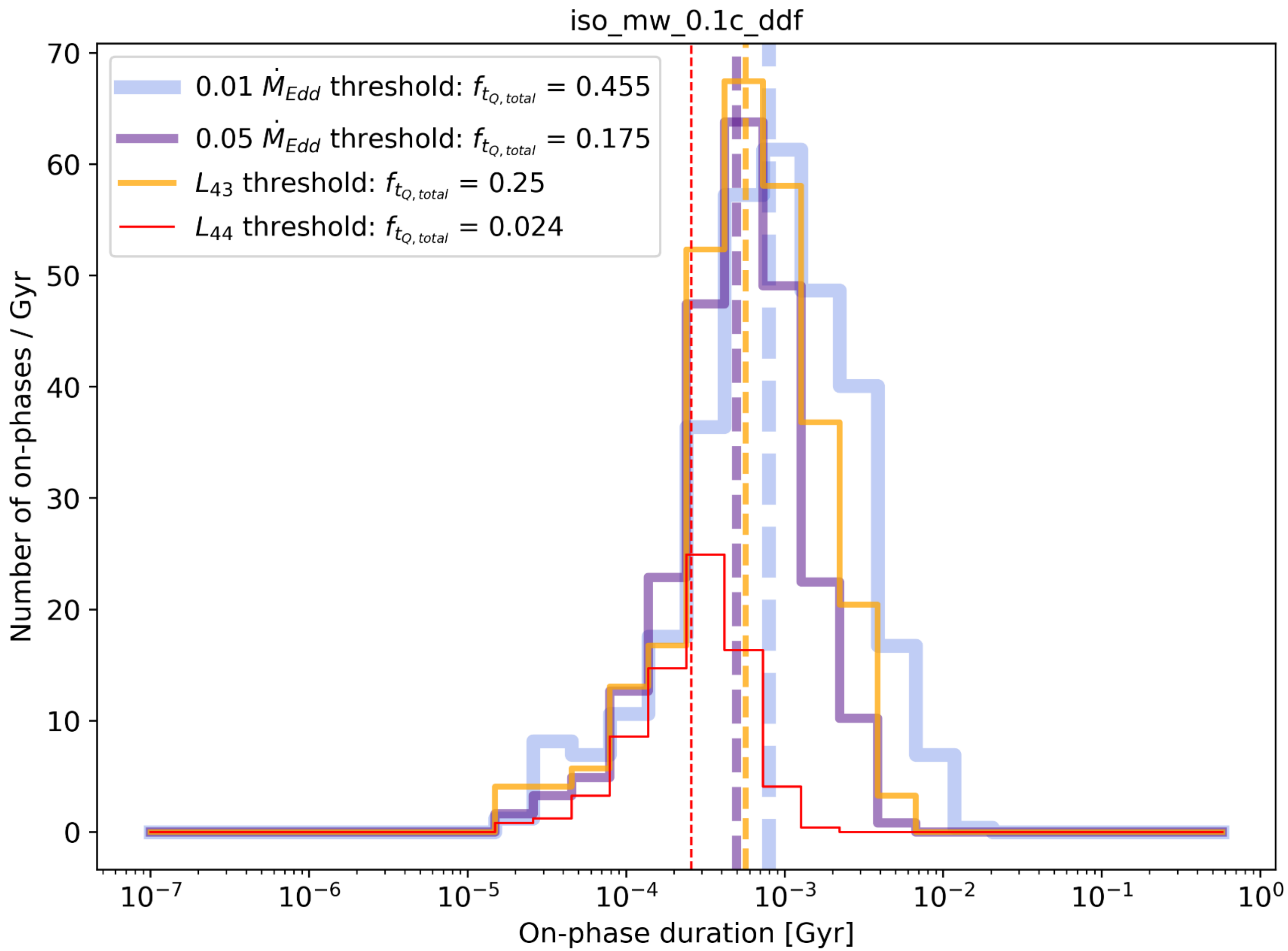




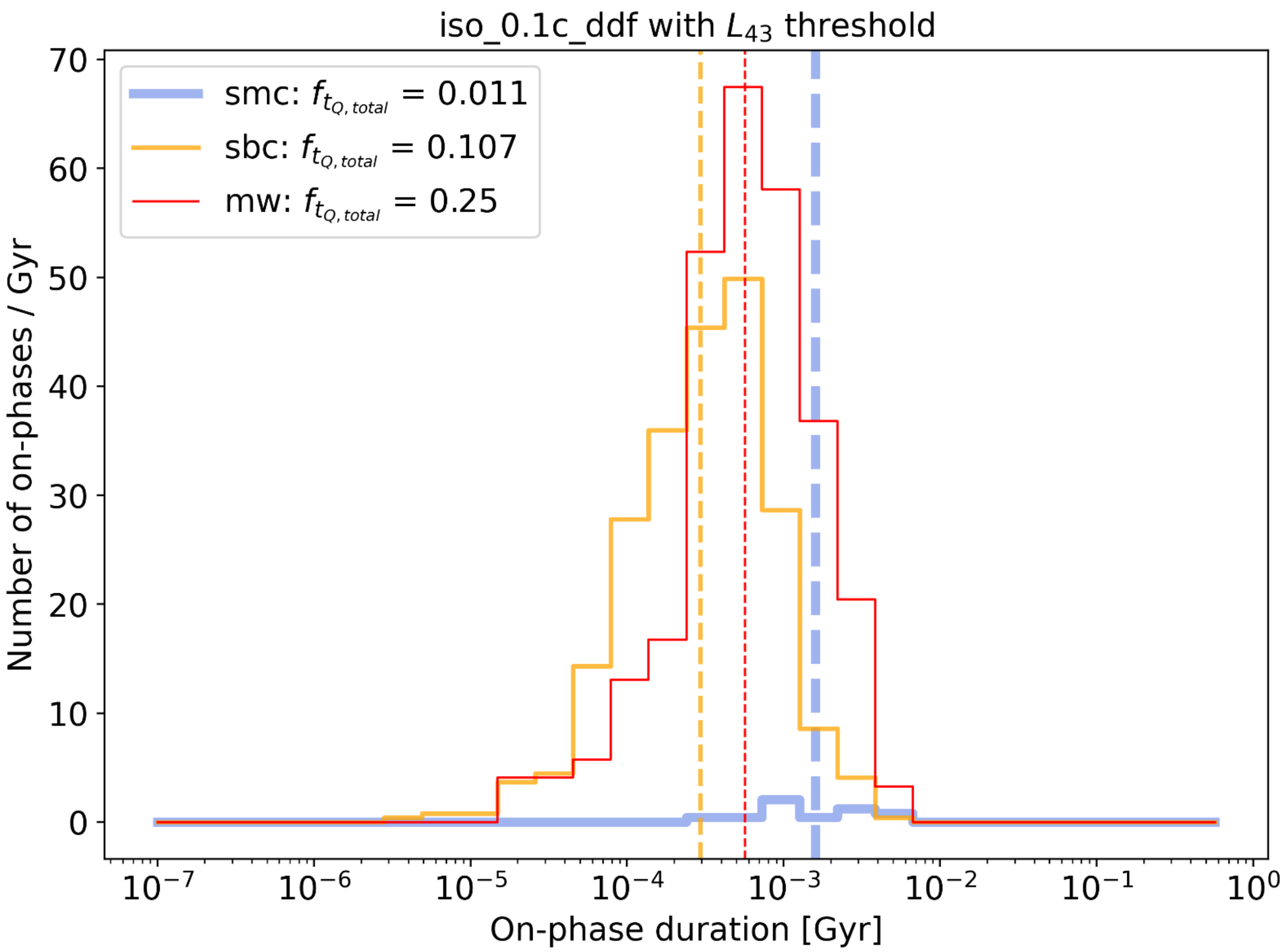
Results: spanning ~ 1000 – 10^7 yrs, on average ~0.1 – 1 Myr.

Well-matched with the constraints from the observations of ionized proximity regions and radio jet remnants.

Choice of activity threshold



Comparing morphologies



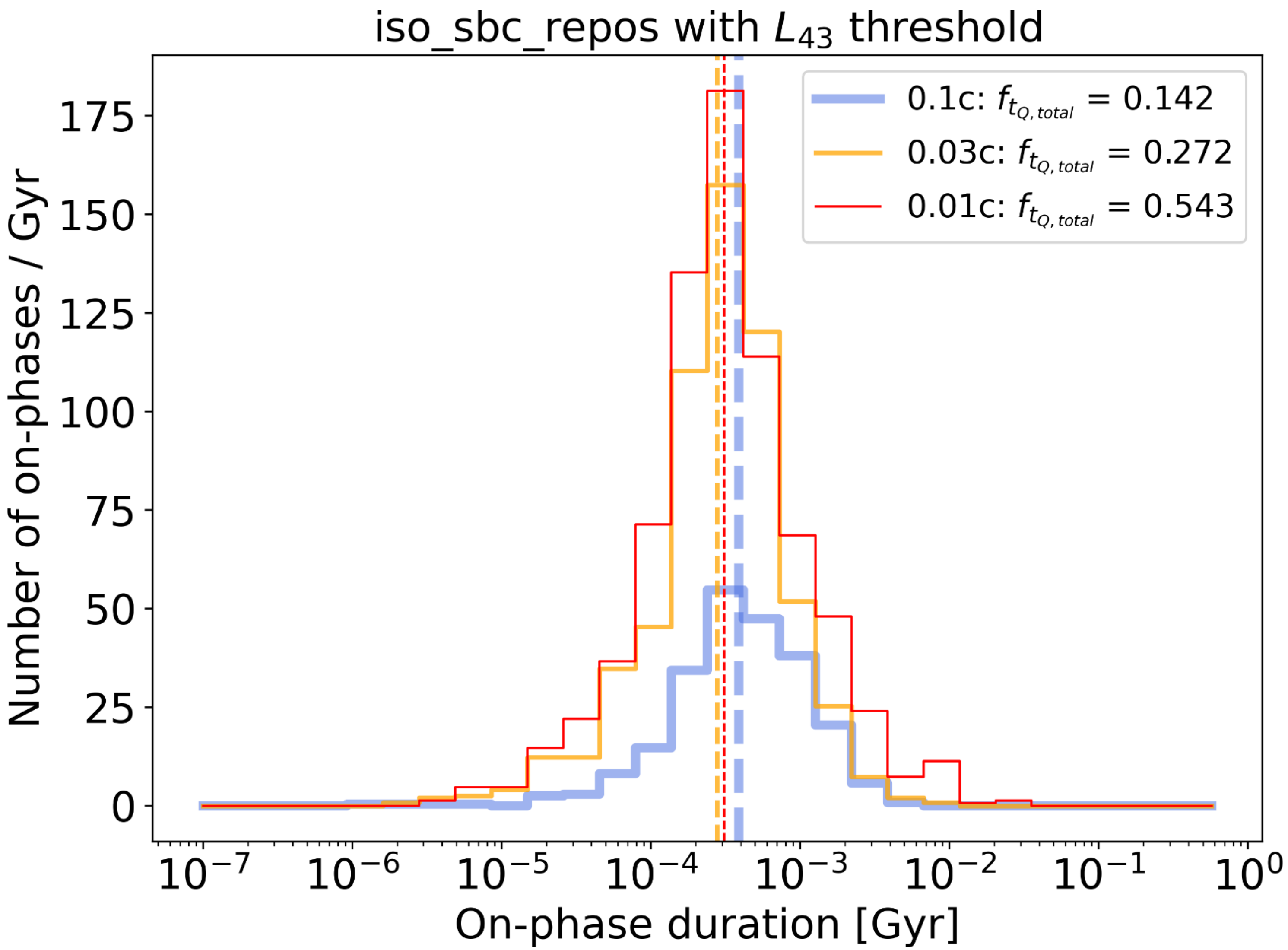
MW:

- Larger grav. potential
- Larger BH mass
- Smaller stellar feedback
- Smaller feedback-to-ISM coupling

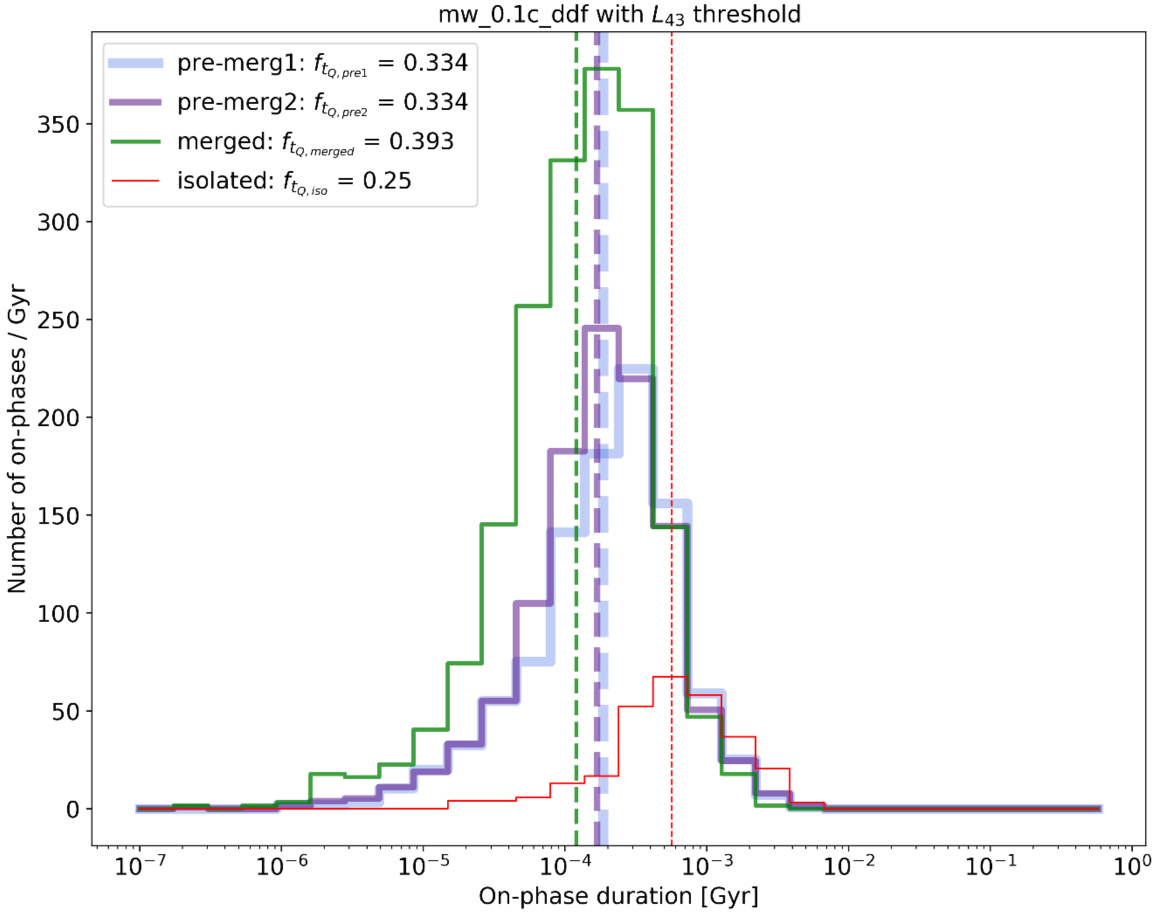
SMC:

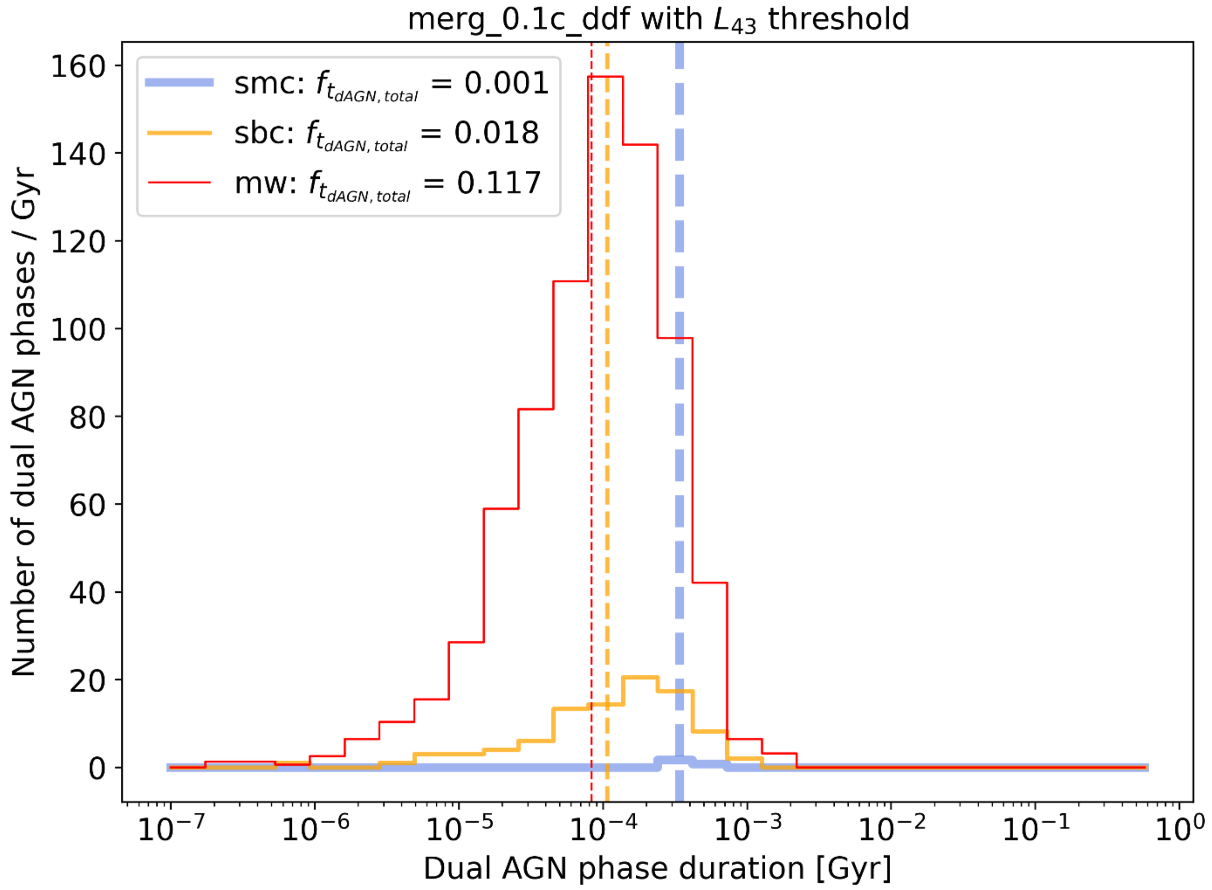
- Smaller grav. potential
- Smaller BH mass
- Higher stellar feedback
- Higher feedback-to-ISM coupling

Wind speed comparison

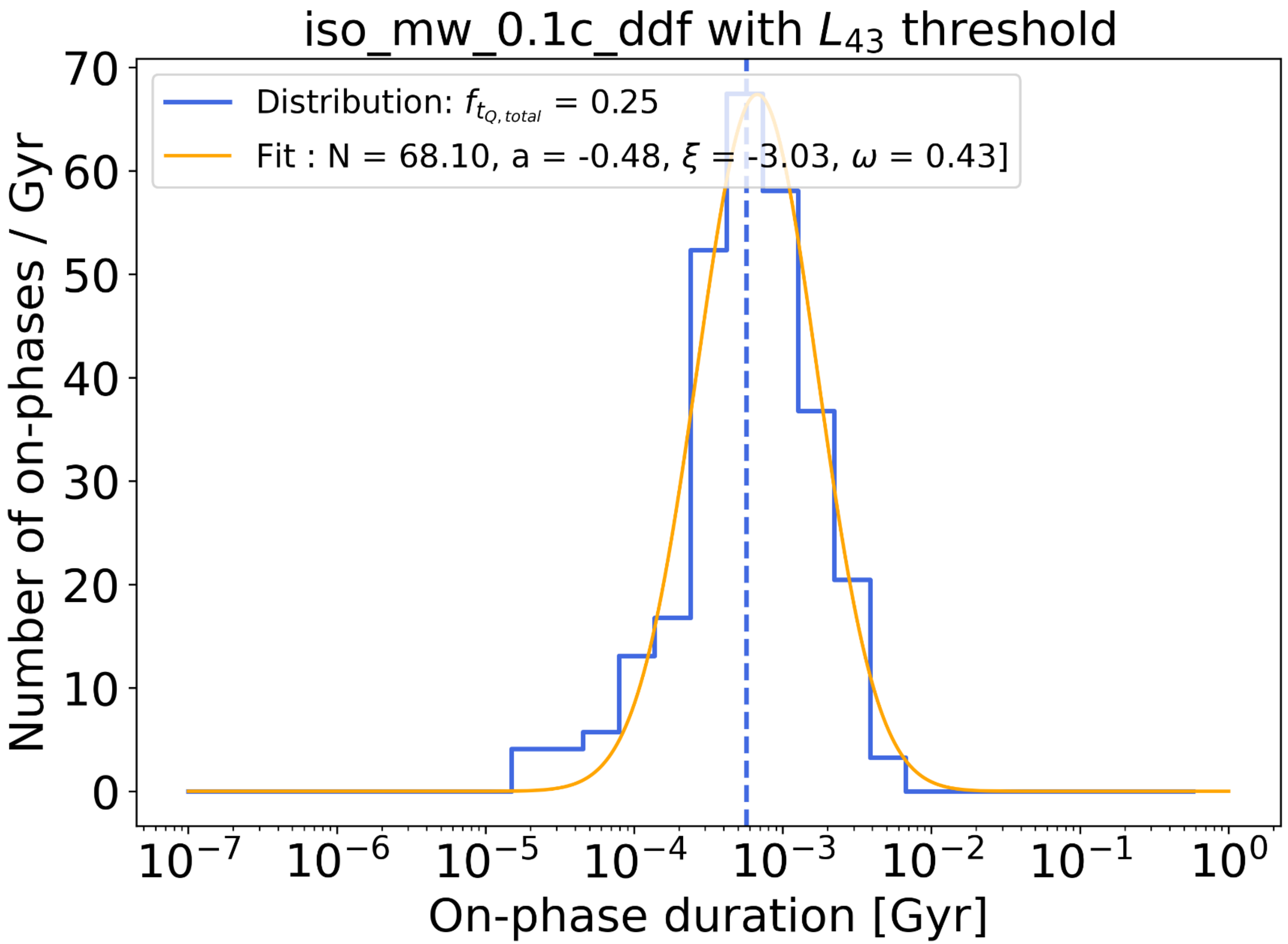


Merger enhancement and dual AGN lifetimes





Function fitting: current work



Future work

- Running a more diverse set of idealized isolated galaxies and mergers.
- Developing a subgrid method to semi-analytically model episodic AGN lifetimes in cosmological frameworks.
- Simulation-based inference based on observed AGN statistics to constrain the subgrid method.

Summary

- The average AGN lifetimes are of the order of $\sim 0.1 - 1$ Myr. However, the AGN lifetimes can span $\sim 100 - 10^7$ yrs.
- Higher feedback wind speeds are more efficient in suppressing BH activity. Stellar feedback can regulate enhancement in mergers.
- The dual AGNs are active for $\sim 0.1 - 12$ % of the pre-merger times. We do not observe a strong correlation between dual AGNs and radial separation.
- Parameters influencing the SMBH activity:
  - strengths of BH accretion and feedback
  - strength of stellar feedback
  - gravitational potential
  - feedback-to-ISM coupling
  - different merging scenarios

THANK YOU!

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Initial conditions

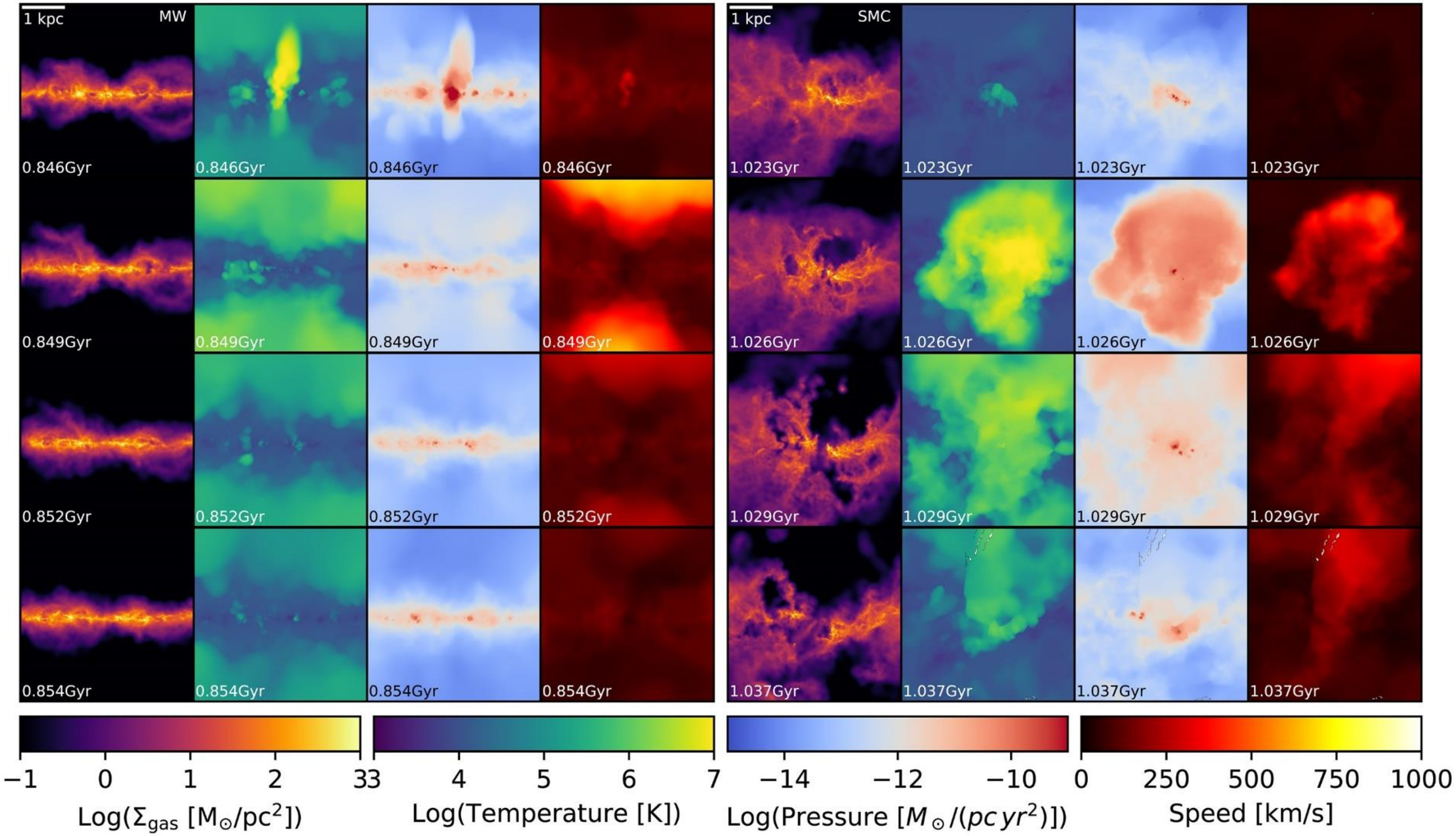
Isolated single galaxy & major mergers of the same type and mass:

- Milky Way-like gas-poor galaxy (MW),
- Luminous infrared-like galaxy (Sbc),
- Small Magellanic Cloud-like dwarf galaxy (SMC).

Name	M_{200} ($M_\odot$)	M_{BH} ($M_\odot$)	Gas Fraction	h_0/r_0
MW	1.43×10^{12}	1.14×10^{6}	0.16	0.015
Sbc	2.14×10^{11}	1.14×10^{6}	0.59	0.156
SMC	2.86×10^{10}	5.00×10^{4}	0.86	0.155

Sivasankaran et al. (2025)

Feedback-to-ISM coupling



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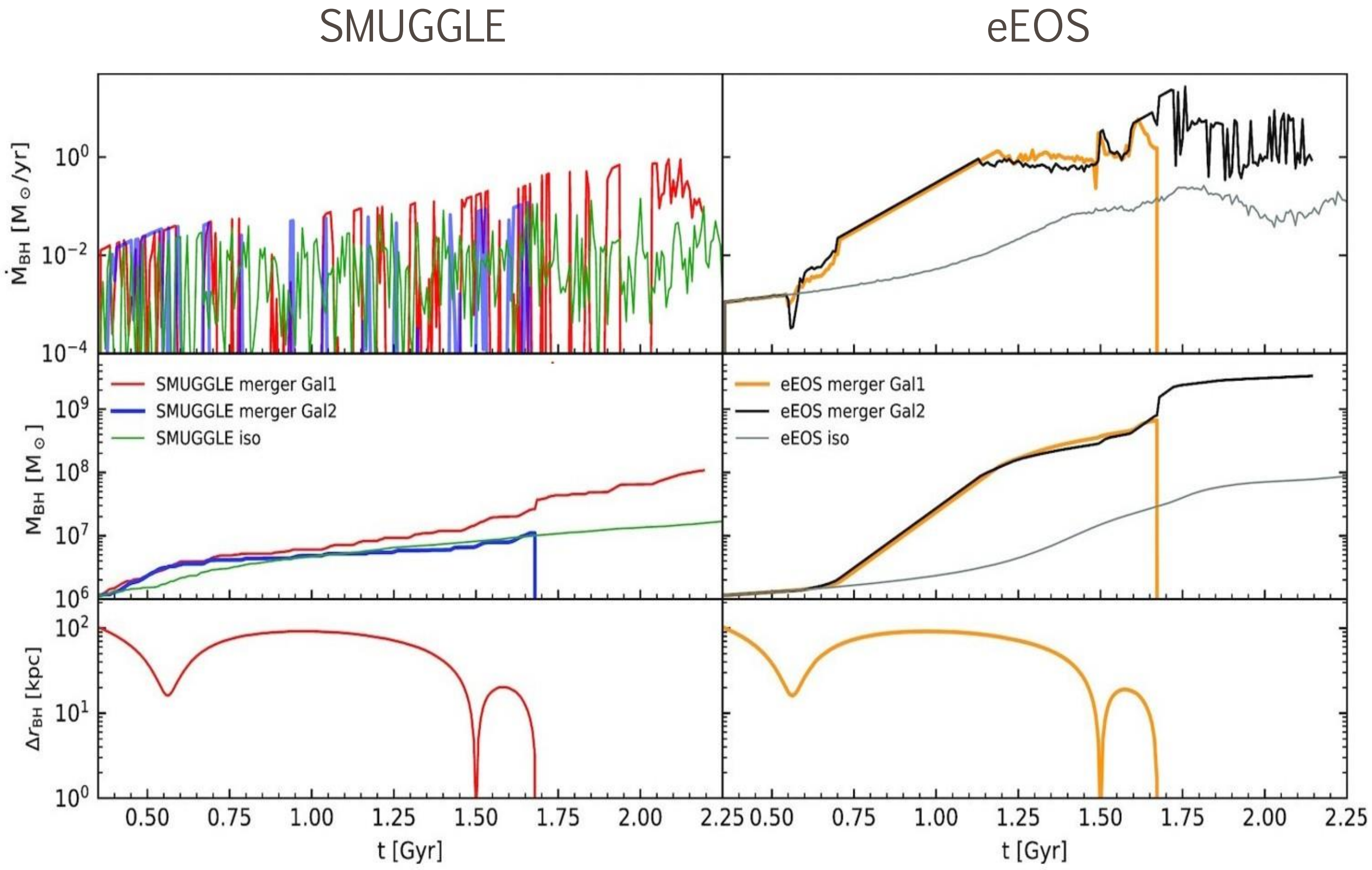
Multiphase gas vs effective equation of state (eEOS)



Sivasankaran et al. (2022)

AGN lifetime observations

Observationally constraining AGN lifetimes:

- Demographic argument: $\sim 10^6 - 10^9$ yrs (e-folding lifetimes)
- Ionized proximity regions: $\sim 10^3 - 10^7$ yrs
- AGN radio remnants: $\sim 10^4 - 10^8$ yrs.

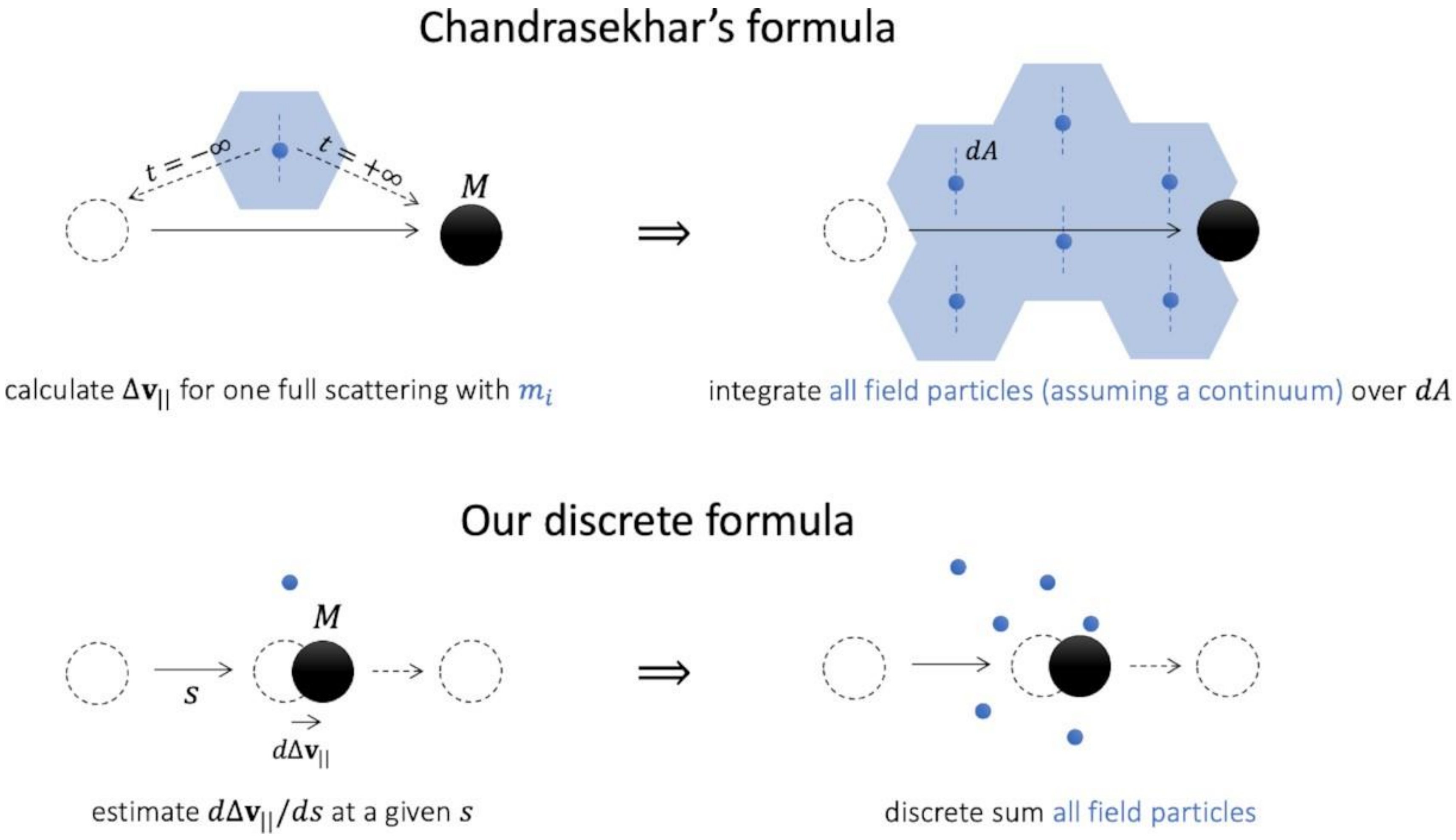
Super-Lagrangian refinement scheme

- The gas cell masses near the BHs are varied as a function of distance from the BH as follows:

$$m(r) = \begin{cases} \dfrac{m_0}{F} & ; r \leq r_{min} \\ \dfrac{m_0}{F}\left(1 + (F-1)\dfrac{r - r_{min}}{r_{max} - r_{min}}\right) & ; r_{min} < r \leq r_{max} \\ m_0 & ; r_{min} < r \end{cases}$$

- $r_{min} = 2.86\, kpc$, $r_{max} = 14.26\, kpc$, & $F = 10$.
- The gas cells in the refinement region of our simulations have a median size of $\sim$ 30 pc and a minimum softening length of 45 pc.

Discrete vs. Chandrasekhar dynamical friction



Ma et al. (2023)

BH accretion

- Eddington limited Bondi-Hoyle Accretion:

$$\dot{M}_{BH} = min(\dot{M}_{Bondi}, \dot{M}_{Edd}),$$

where $\dot{M}_{Bondi}$ is the Bondi-Hoyle accretion rate,

$$\dot{M}_{Bondi} = \frac{4\pi G^2 M_{BH}^2 \rho}{c_s^3},$$

and $\dot{M}_{Edd}$ is the Eddington limit,

$$\dot{M}_{Edd} = \frac{4\pi G M_{BH} m_p}{\epsilon_r \sigma_T c}.$$

- The BH's kernel is defined by 64 nearest gas cells.
- The kernel radius of the BHs with the weighted number of neighbors set to 64 is $\sim 100\,pc$.
- Note: Eddington Ratio is defined as,

$$\chi_{Edd} = \frac{\dot{M}_{BH}}{\dot{M}_{Edd}}.$$

BH feedback

- We implement fast nuclear winds with wind velocity of the order ($\sim 0.01c$ to $\sim 0.1c$).
- There are two free parameters that govern this feedback mechanism:
  - the wind velocity, v_w,
  - the wind mass loading factor, η_w, which is the ratio of the wind mass outflow rate ($\dot{M}_w$) and the black hole growth rate ($\dot{M}_{BH}$).
- Wind mass is calculated as $M_w = \eta_w \dot{M}_{BH} \Delta t$ at each timestep.
- $\eta_w = 1$ is fixed for the purpose of this study, given the interest of comparing models with varying wind velocity.

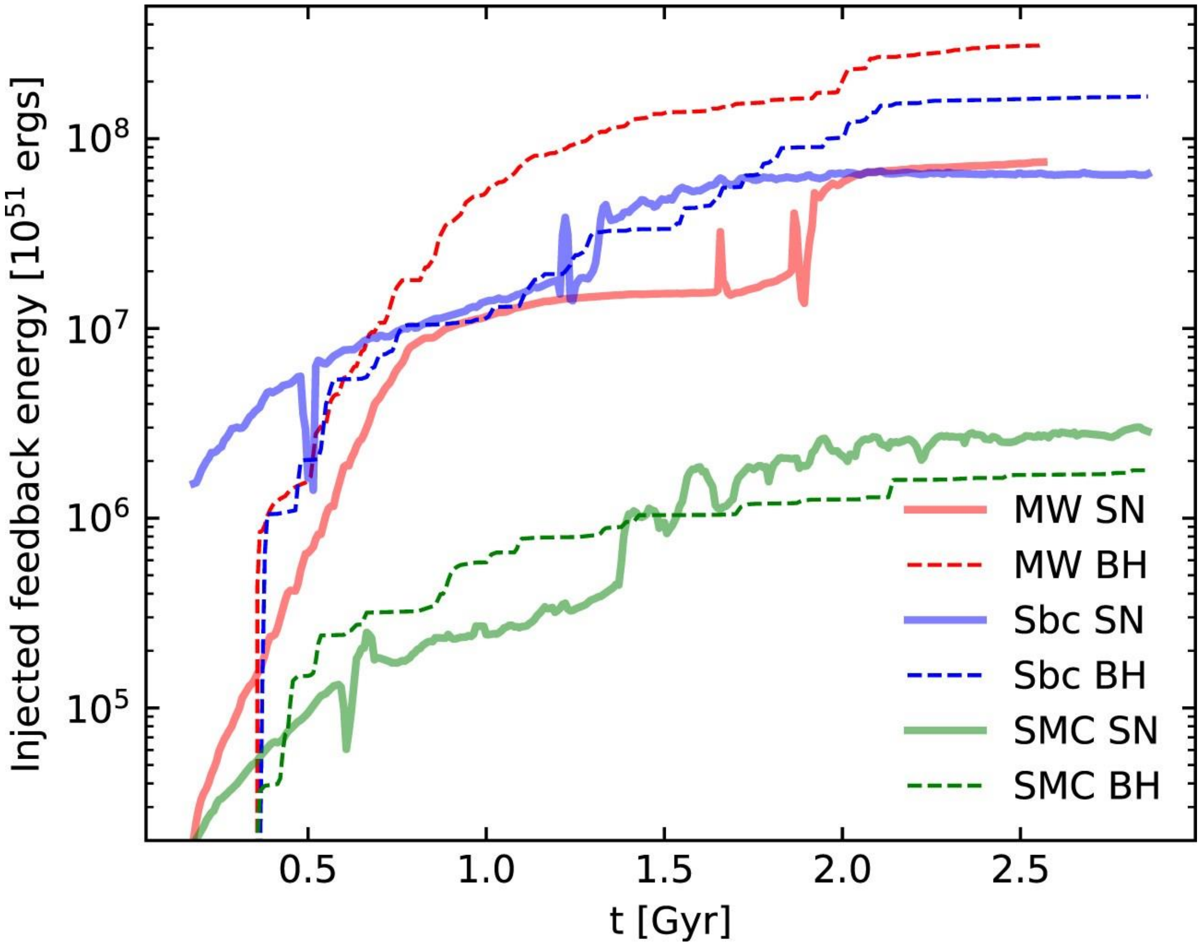
BH feedback

- The gas cells are kicked with velocity v_w in a random direction with probability $P = M_w/M_{kernel}$, where M_{kernel} is the total mass of all gas cells in the kernel.
- This ensures energy and momentum conservation in a time-averaged sense.
- We choose to inject the feedback only when $\chi_{Edd} \geq 0.05$.
- We allow the initial conditions to relax for a period of $0.36\,Gyr$ before we turn on BH accretion and feedback.

Initial conditions

- Density profiles:
  - Stellar bulge & dark matter halo: Hernquist (1990) profile,
  - Stellar & gaseous disk: exponential radial profile,
  - Vertical structure of gas disk: determined by hydrostatic equilibrium,
  - Vertical structure of stellar disk: $\mathrm{sech}^2(z)$ profile.
- Parabolic orbit with separation such that the first pericentric passage happens at $\sim$ 0.5 Gyr.
- The initial angular momenta of the two galaxies are chosen to be at$(30^\circ, 60^\circ)$ and $(-30^\circ, 45^\circ)$ with respect to the orbital angular momentum.
- Mass resolution:
  - Gas mass (unrefined): $2.5 \times 10^4\ M_\odot$,
  - Stellar bulge particle mass: $2.59 \times 10^4\ M_\odot$,
  - Stellar disk particle mass: $2.78 \times 10^4\ M_\odot$,
  - Dark matter particle mass: $2.64 \times 10^5\ M_\odot$.

Cumulative supernovae feedback



Sivasankaran et al. (2026)

BH dynamics comparison