Dynamics of massive black holes in cosmological simulations

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R. Beckmann (University of Cambridge)
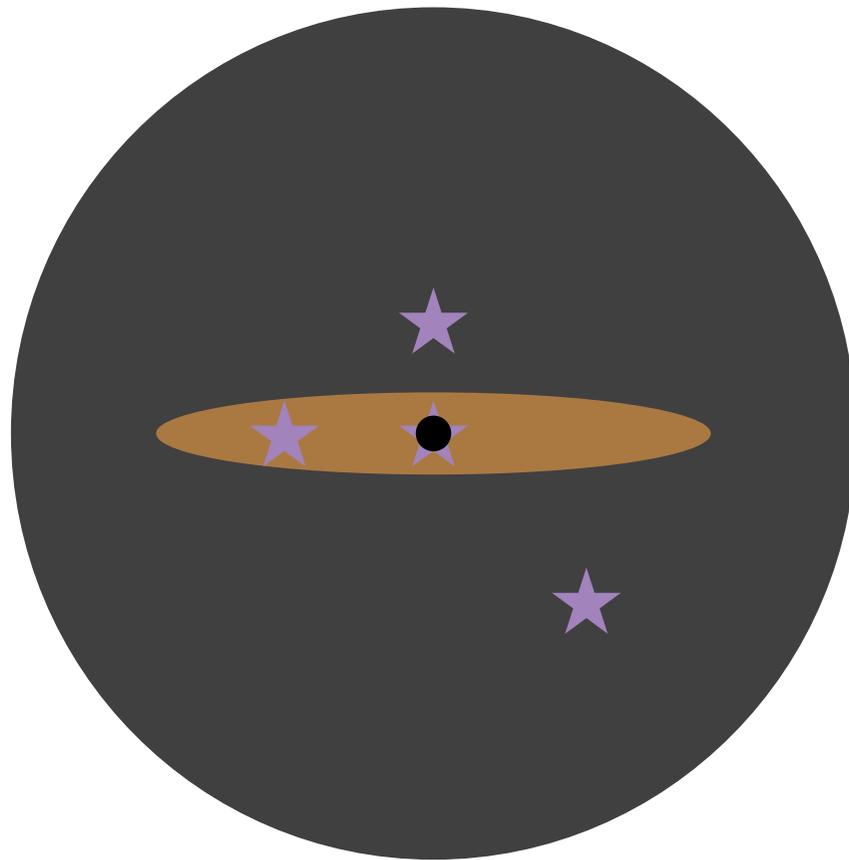Y. Dubois (IAP)
S. Lescaudron (IAP)
H. Pfister (Niels Bohr Institute/Hong Kong University)
M. Tremmel (Yale University)

Massive black holes in galaxies

$R_{bondi} \sim GM_{BH}/c_s^2$ PARSEC

$R_{inf} \sim GM_{BH}/\sigma^2$ PARSEC

$R_{sch} = 2GM_{BH}/c^2$ MICROPARSEC

100 kpc - 10^{12} solar masses

10 kpc - 10^{11} solar masses

MBH dynamics in cosmological simulations

Important for two main reasons:

- "Galaxy-centric": if one wants to have well-motivated AGN feedback to have the correct properties of galaxies (Booth&Schaye09, Dubois+12, Bahé+21)

- "MBH-centric": if one wants to have correct properties of MBHs and their mergers (Tremmel+15, Pfister+19, Volonteri+20)
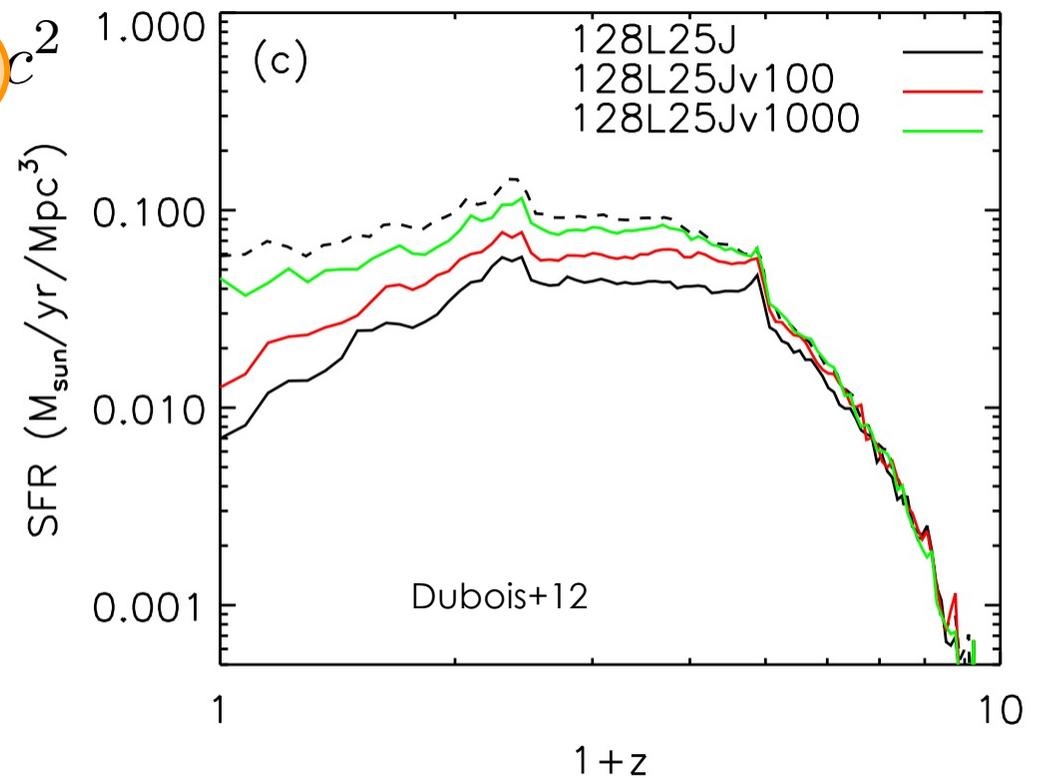
Note that one can have the "right amount" of AGN feedback to make galaxies look good, but have wrong AGN/MBH populations, like in TNG (Pillepich+18, Habouzit+19, Truong+21)
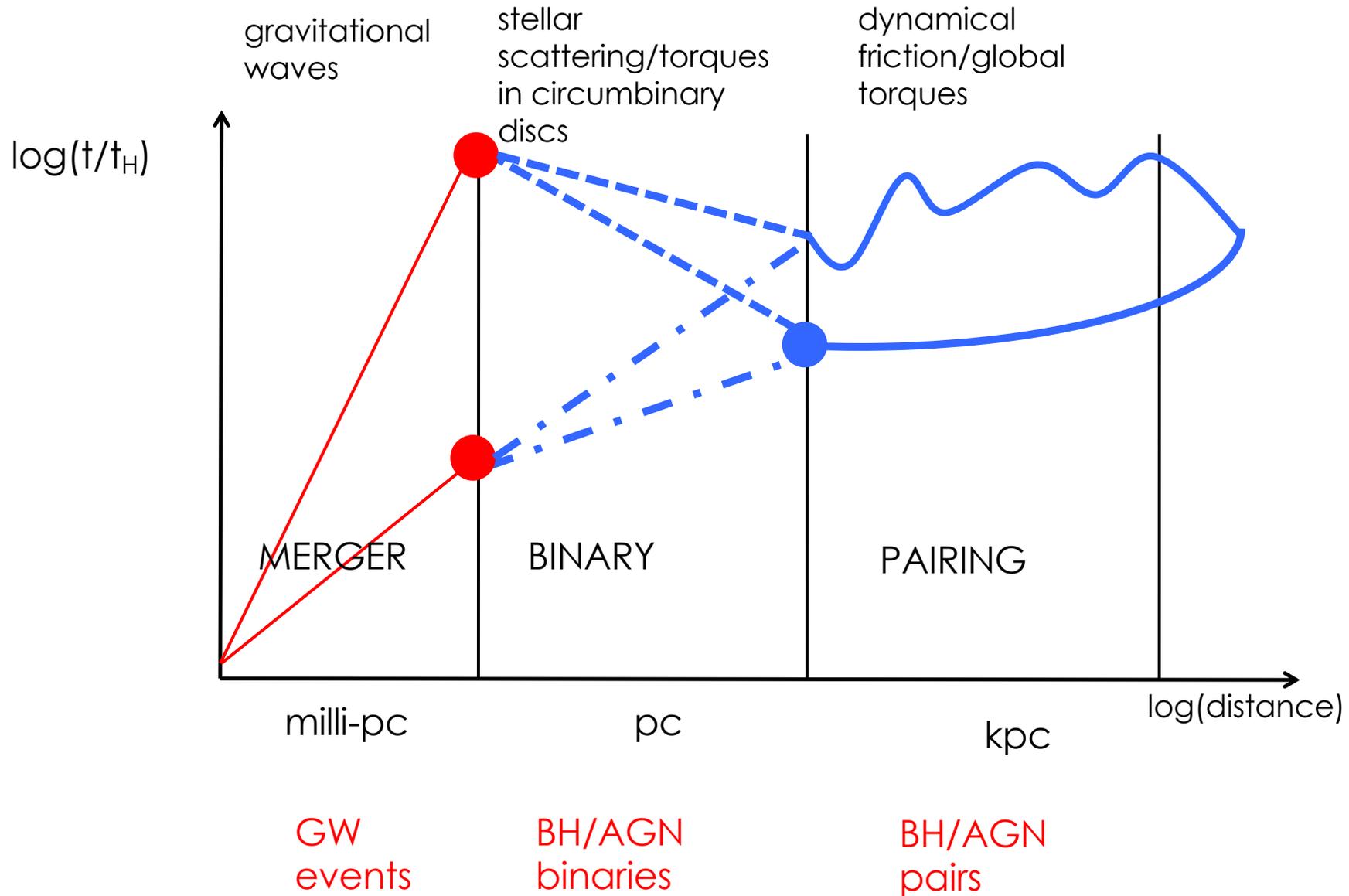
MBH dynamics and AGN feedback

$$\dot{M}_{BHL} = 4\pi G \frac{M_{BH}^2 \rho}{(c_s^2 + v_{rel}^2)^{3/2}}$$

$$L_{feedback} = \epsilon_f \epsilon_{rad} \dot{M}_{BHL} c^2$$
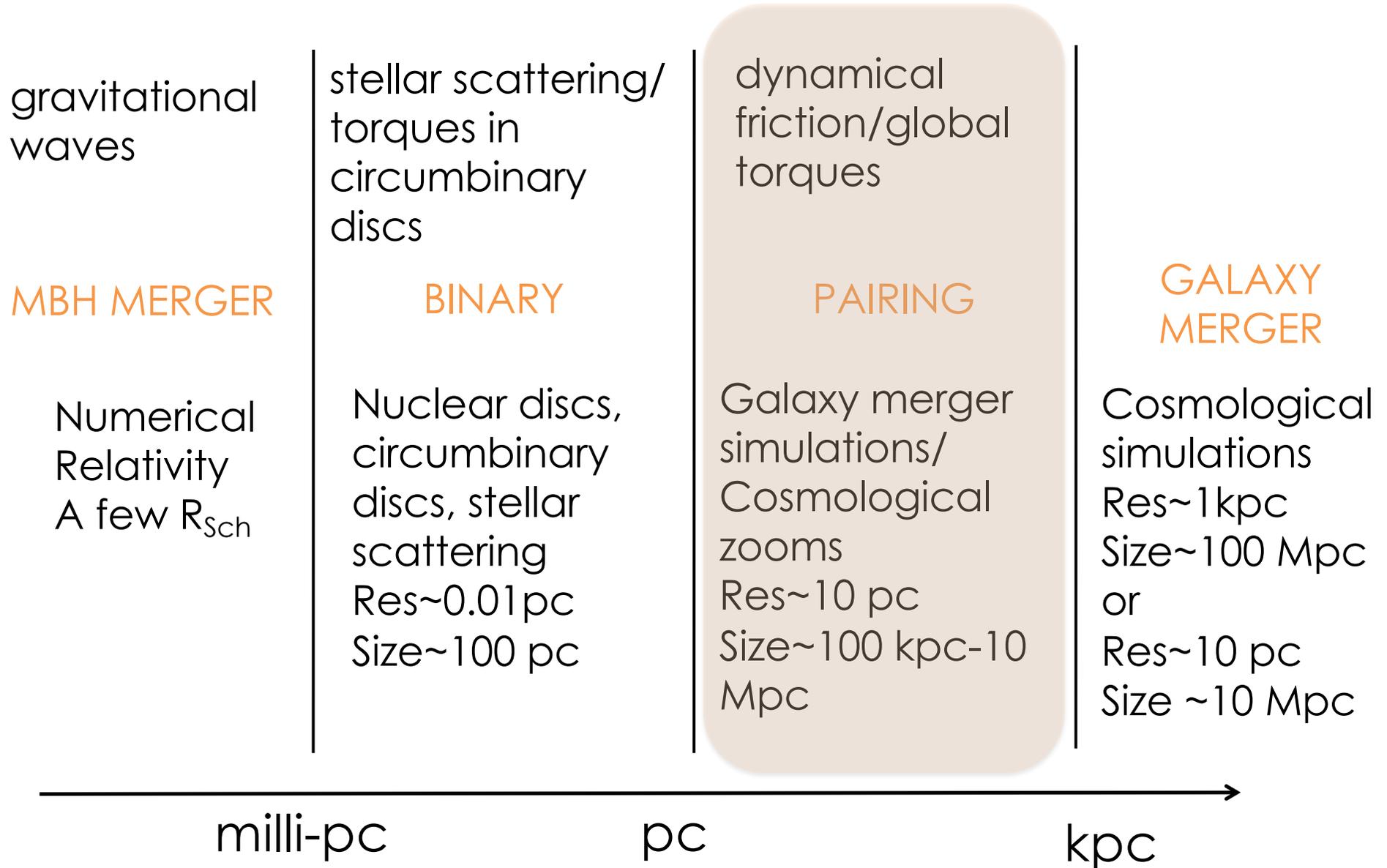
A high relative velocity between MBH and medium kills accretion and therefore AGN feedback
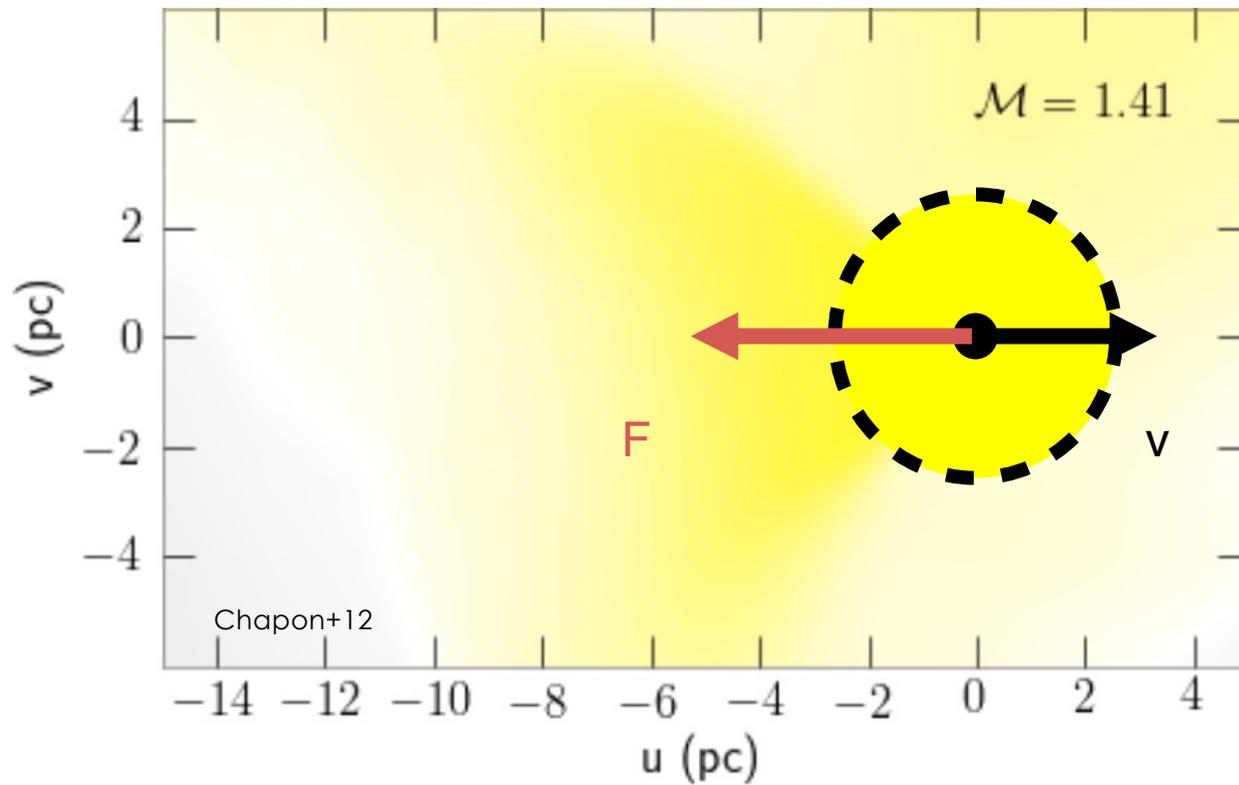

128L25J
128L25Jv100
128L25Jv1000

(c)

SFR (M$_{sun}$/yr/Mpc^3)

1.000

0.100

0.010

0.001

Dubois+12

1   1+z   10

MBH dynamics and MBH mergers

Slide credit: Monica Colpi

Simulating MBH mergers

gravitational
waves

stellar scattering/
torques in
circumbinary
discs

dynamical
friction/global
torques

MBH MERGER

BINARY

PAIRING

GALAXY
MERGER

Numerical
Relativity
A few R_{Sch}

Nuclear discs,
circumbinary
discs, stellar
scattering
Res~0.01pc
Size~100 pc

Galaxy merger
simulations/
Cosmological
zooms
Res~10 pc
Size~100 kpc-10
Mpc

Cosmological
simulations
Res~1kpc
Size~100 Mpc
or
Res~10 pc
Size ~10 Mpc

milli-pc   pc   kpc

Dynamical friction

$M = 1.41$

Chapon+12

$$r_{\mathrm{def}} = 1 \text{ pc} \left(\frac{M_\bullet}{10^7 M_\odot} \right) \left(\frac{v}{200 \mathrm{km \ s^{-1}}} \right)^{-2}$$

Slide credit: Hugo Pfister

MBH dynamics in cosmological simulations

The *spatial resolution* needed is 0.1-10 pc
Most simulations have a resolution of 0.1-1 kpc

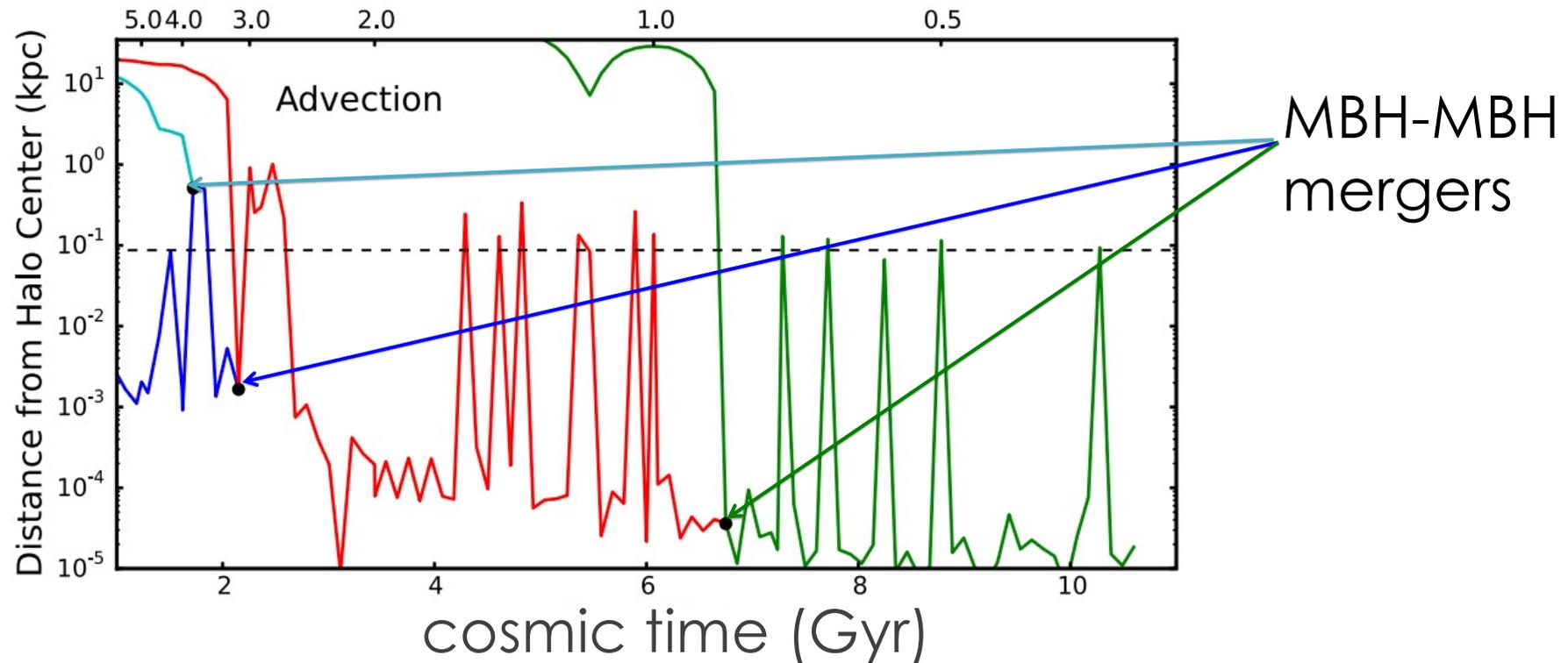The *mass resolution* needed is $M_{BH} > 10\, M_*$, with M_{BH} at birth $\sim 10^3$-10^4 Msun
Most simulations have $M_* \sim 10^3$-10^6 Msun

Two approaches:
- advect MBHs to the minimum of the local potential (Illustris, IllustrisTNG, Eagle, MassiveBlack, BlueTides)
- account for the "missing" force – dynamical friction (Horizon-AGN, NewHorizon, Romulus)

MBH dynamics – advection

Cosmological 'zoomed-in' simulation of dwarf galaxy with mass $\sim 10^{10}\,M_\odot$ at $z = 0$.

MBH mass $5\times10^5\,M_\odot$
dark matter particle mass $1.6 \times 10^4\,M_\odot$, gas particle mass $3.3 \times 10^3\,M_\odot$
gravitational softening 87 pc

Tremmel+ 2015

MBH dynamical friction

Calculate the momentum that should be removed due to unresolved force (dynamical friction) by gas, stars and dark matter
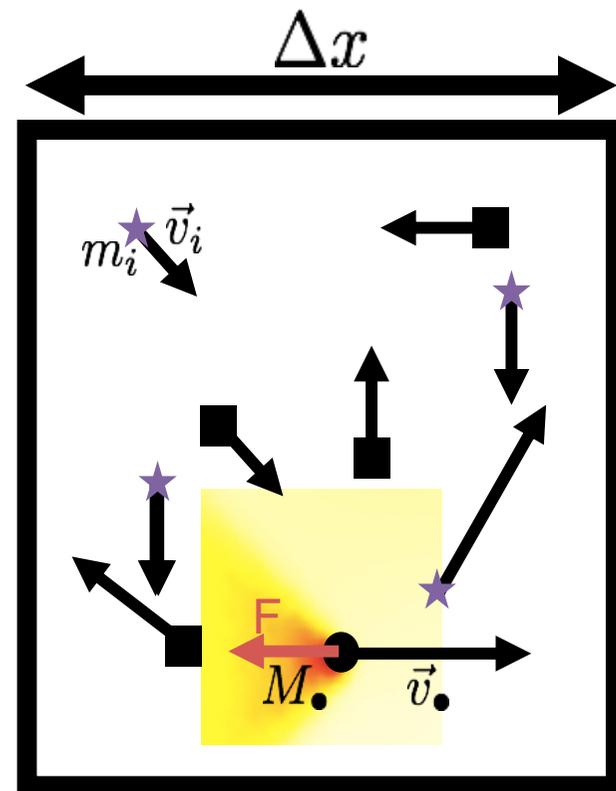
MBH orbits evolve naturally

$$\vec{F}_{\star} = -4\pi G^2 M_{\bullet}^2 \frac{\vec{v_{\bullet}}}{v_{\bullet}^3} \left\{ \ln\Lambda \int_0^{v_{\bullet}} 4\pi v^2 f(v) dv + ... \right.$$

$$\left. ... \int_{v_{\bullet}}^{\infty} 4\pi v^2 f(v) \left[\ln\left(\frac{v + v_{\bullet}}{v - v_{\bullet}} \right) - 2\frac{v_{\bullet}}{v} \right] dv \right\}$$

with:
$$\ln\Lambda = \ln(4\Delta x/r_{\text{def}})$$
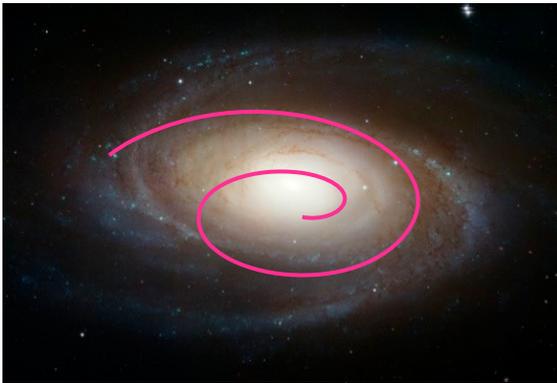$$4\pi v^2 f(v) = \frac{3}{256\pi\Delta x^3} \sum_{i \in \mathcal{S}} m_i \delta(v_i - v)$$

Tremmel+15, Pfister+19; slide credit: Hugo Pfister

MBH dynamics – adding the missing friction
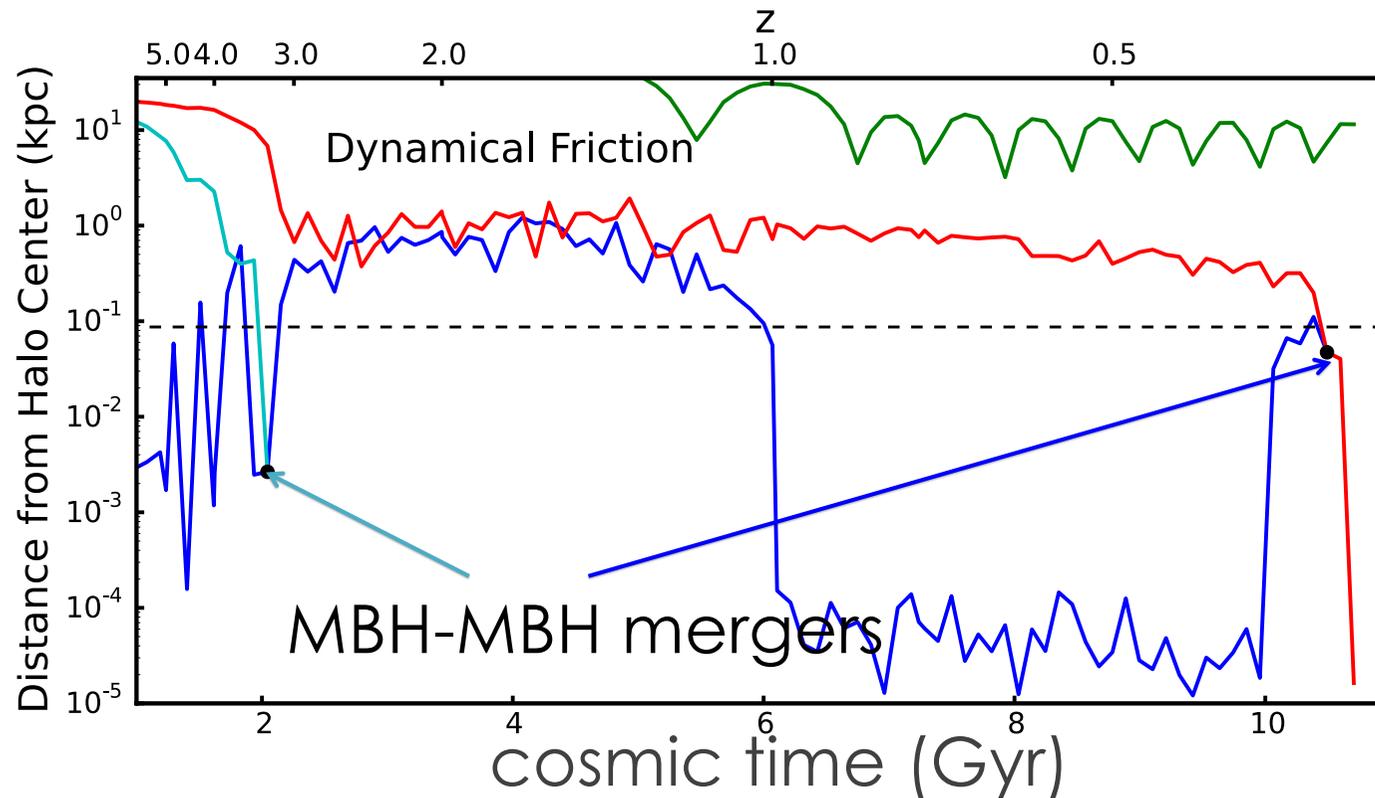
Cosmological 'zoomed-in' simulation of dwarf galaxy with mass ~ $10^{10}\,M_\odot$ at z = 0.

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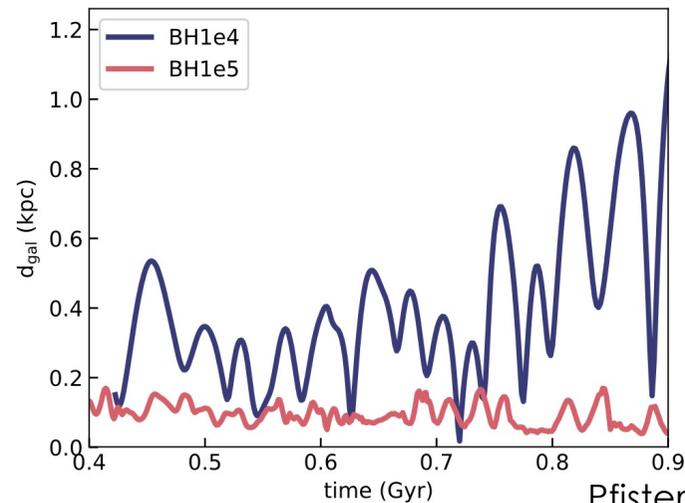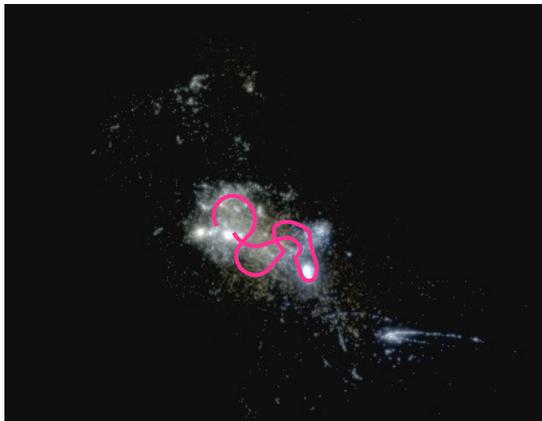gravitational softening 87 pc

Tremmel+ 2015

MBH dynamics - dynamical friction

In a smooth potential, e.g., isothermal sphere, dynamical friction causes orbital decay towards the center (Binney & Tremaine) on :
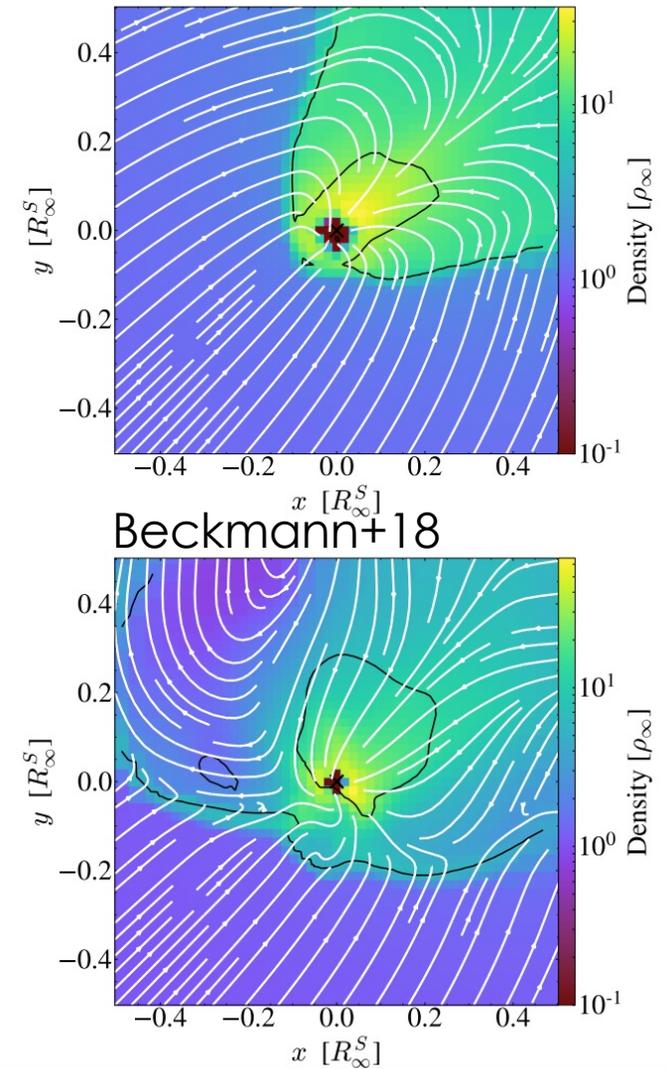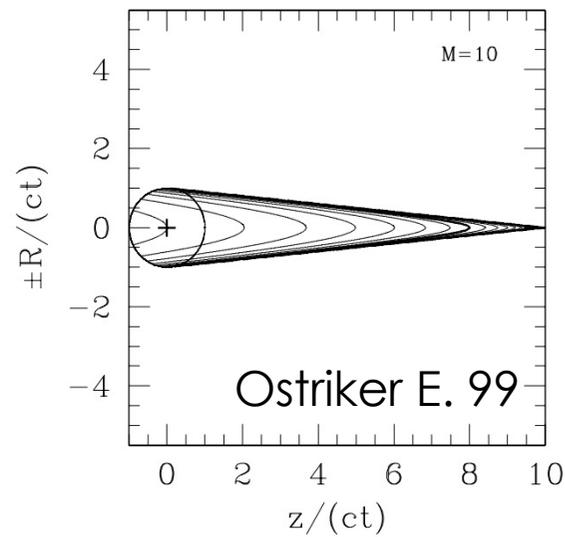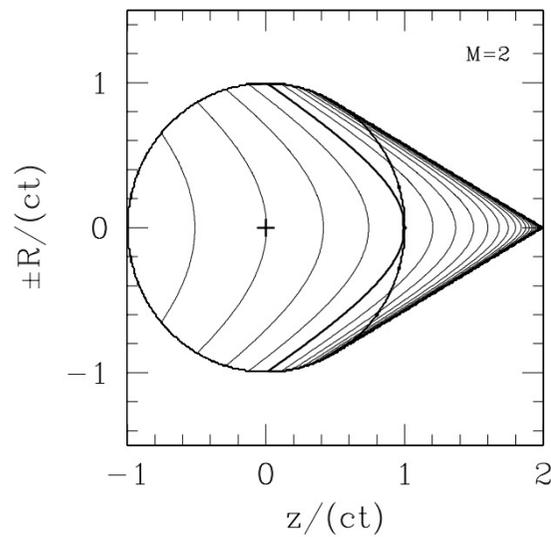
$$t_{\mathrm{df}} = 0.67 \, \mathrm{Gyr} \left(\frac{a}{4 \, \mathrm{kpc}} \right)^2 \left(\frac{\sigma}{100 \, \mathrm{km \, s^{-1}}} \right) \left(\frac{M_{\mathrm{BH}}}{10^8 \, M_\odot} \right)^{-1} \frac{1}{\Lambda}$$

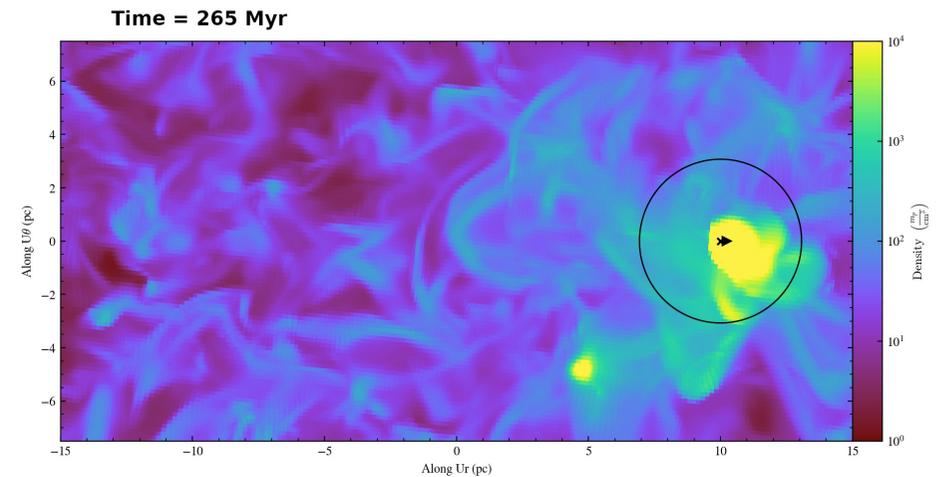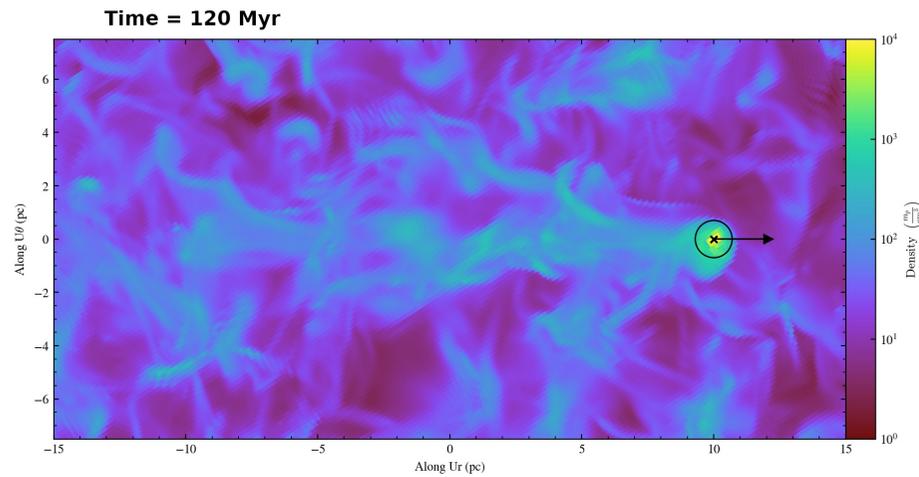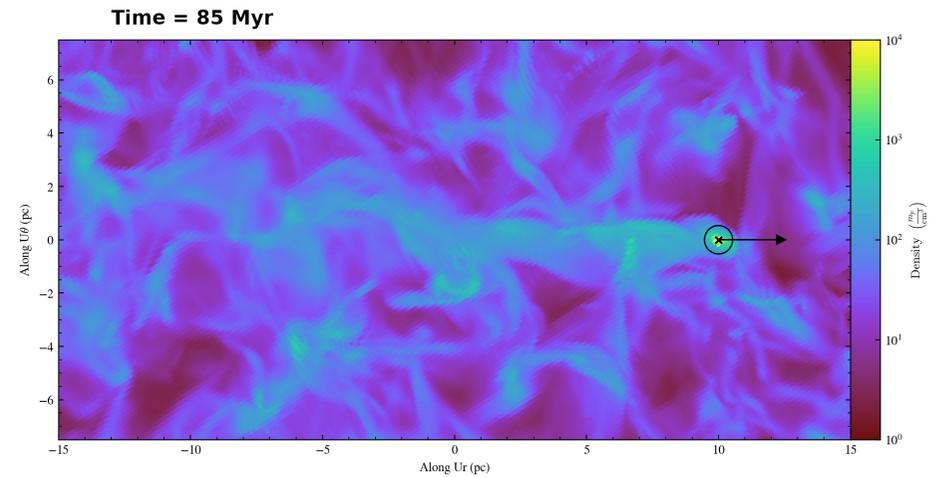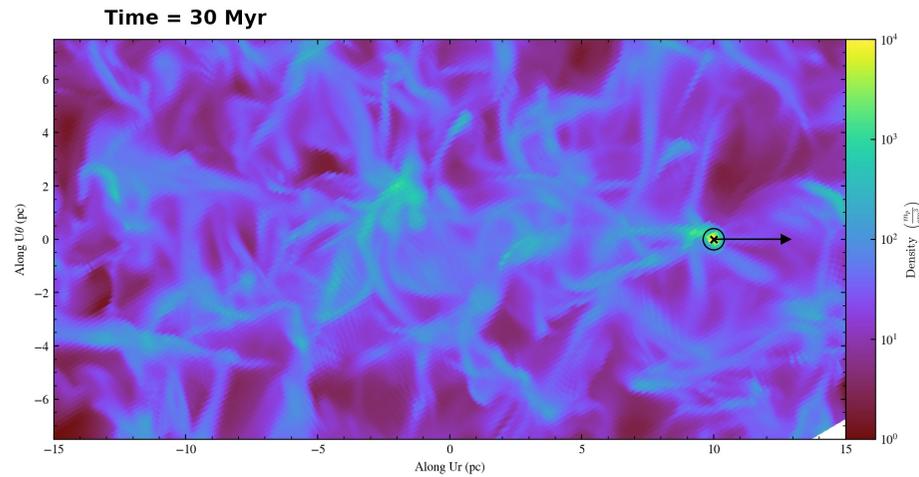High-z dwarf galaxies have messy, non smooth, time-variable potentials, and no real center:

Pfister+19; Bortolas+20

Dynamical friction: gas

Evolution in an infinite, homogeneous medium

Ostriker E. 99

Beckmann+18

Dynamical friction: gas

Evolution in a turbulent medium


Lescaudron+ in prep
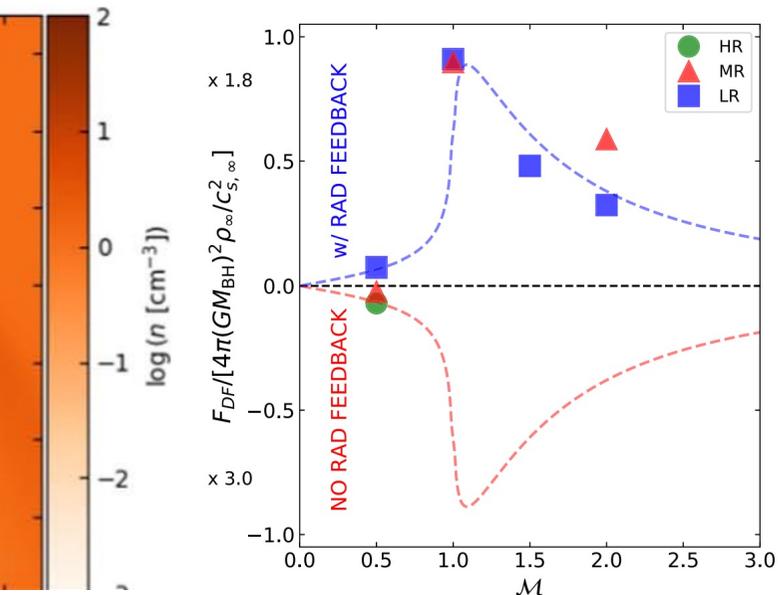
Gas dynamical friction and feedback
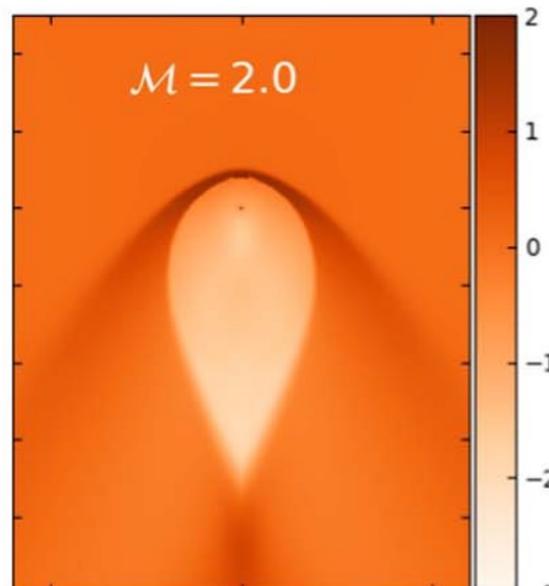
At fixed density gas dynamical friction can be stronger than the friction from stars if gas is slightly supersonic

However, the gas distribution is perturbed more easily by energy injection (turbulence, radiation, heat)

Removal of gas in the wake behind the MBH limits deceleration
Shell of gas in front of the MBH can instead cause *acceleration*
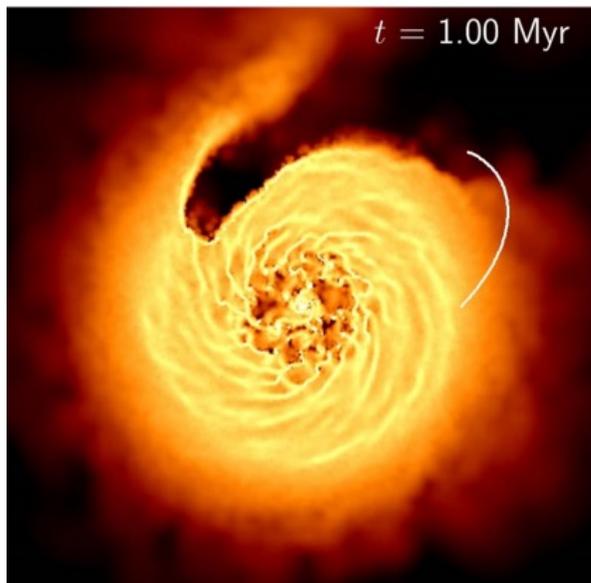
Souza Lima+2017

Park&Bogdanovic+2017

MBH dynamics in cosmological simulations

It's been difficult… and not all problems are solved yet

Even with sub-grid DF stellar mass resolution remains a problem, i.e., high resolution is needed

Gas dynamical friction requires adjusting to account for turbulence and to avoid interacting with feedback (aka "flying BHs")

The effect of feedback is still unclear

Global torques can be captured only at high resolution

Postdoctoral position at IAP

We are offering a postdoctoral position at the Institut d'Astrophysique de Paris (IAP) to work with Dr. Marta Volonteri and Dr. Yohan Dubois on numerical modeling of massive black hole dynamics, and the gravitational wave and electromagnetic properties of massive black hole binaries and mergers.

Applicants with interests and experience in the above fields, and with familiarity with hydrodynamical/N-body codes, ideally AMR codes, are particularly encouraged to apply.

We'll post an ad on the AAS job register soon, please contact martav@iap.fr or dubois@iap.fr if you wish to have additional information in the meanwhile.