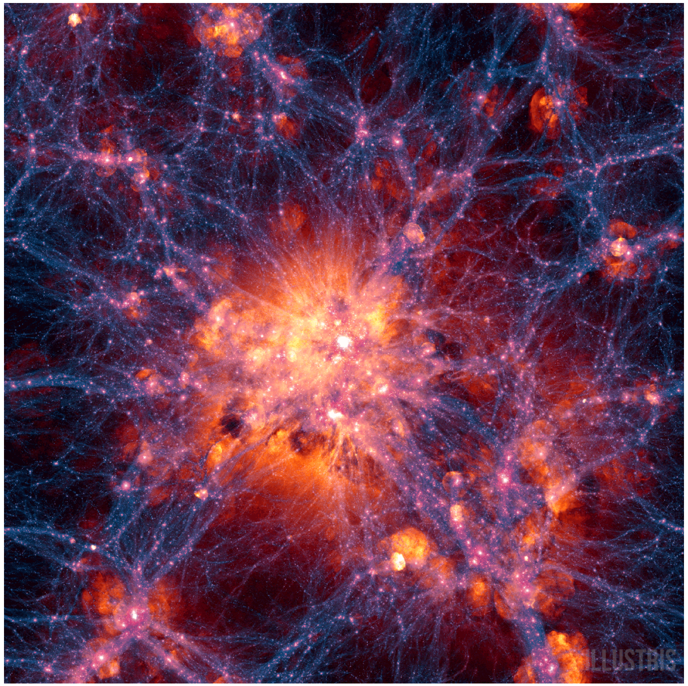
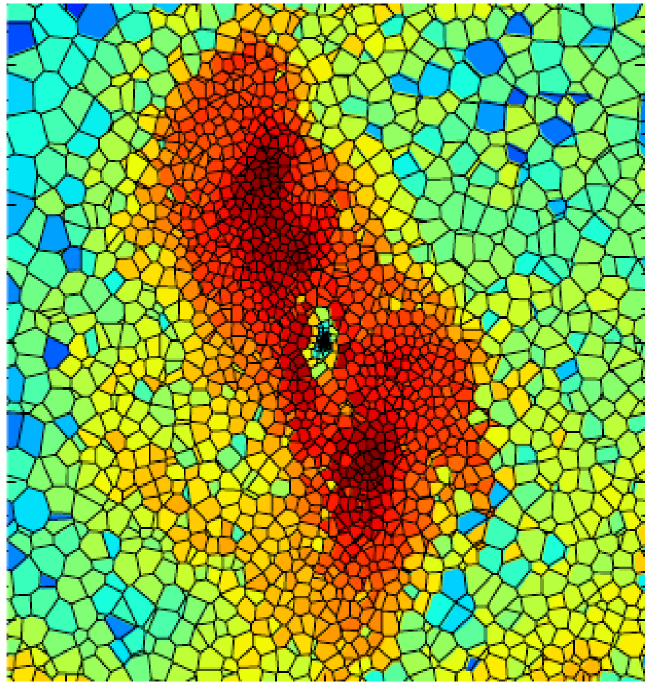
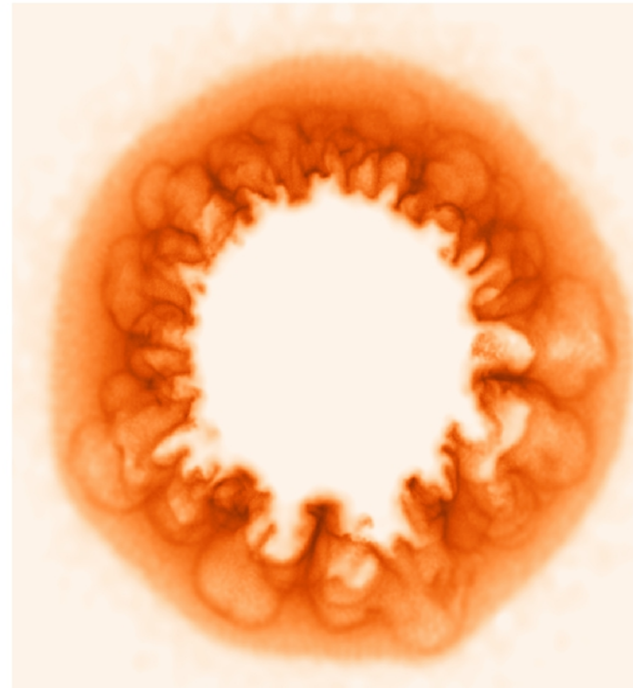
Black hole Growth and Feedback in AREPO







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Black holes in AREPO

- **BHs: collisionless sink particles**

  - BH seeding with FOF finder on the fly.

  - BH growth: via **mergers** with other BHs (within HSML and if $v<c_s$) or via gas **accretion** (Bondi-like) limited to the Eddington rate (Springel et al. 2005, Di Matteo et al. 2005).

$$\dot{M}_{\rm BH} = \frac{4\pi\alpha G^2 M_{\rm BH}^2 \rho}{\left(c_{\rm s}^2 + v^2\right)^{3/2}} \qquad \dot{M}_{\rm Edd} = \frac{4\pi G M_{\rm BH} m_{\rm p}}{\epsilon_{\rm r}\, \sigma_{\rm T}\, c}$$

with $\alpha = 100$ x volume averaged Bondi rate for hot and cold ISM.

- BH feedback in **two modes** (analogous with X-ray binaries):
  1. **Quasar feedback** if BHAR > (0.01 – 0.05) x Eddington rate

     - small fraction of bolometric luminosity couples THERMALLY to the surrounding gas. $$\dot{E}_{\rm feed} = \epsilon_{\rm f} L_{\rm r} = \epsilon_{\rm f}\epsilon_{\rm r}\dot{M}_{\rm BH}c^2$$

  2. **Radio feedback** if BHAR < (0.01 – 0.05) x Eddington rate.

     - THERMAL bubbles (determined by the BH properties)
     - Bubble radius derived from solutions for radio cocoon expansion

     (Sijacki et al. 2007) $$E_{\rm bub} = \epsilon_{\rm m}\epsilon_{\rm r}c^2\delta M_{\rm BH}$$

ADDITIONALLY:

3. Radiative feedback from AGNs:

   - Heats surrounding halo gas, modifies its ionisation state and the net cooling rate (Vogelsberger et al. 2013)

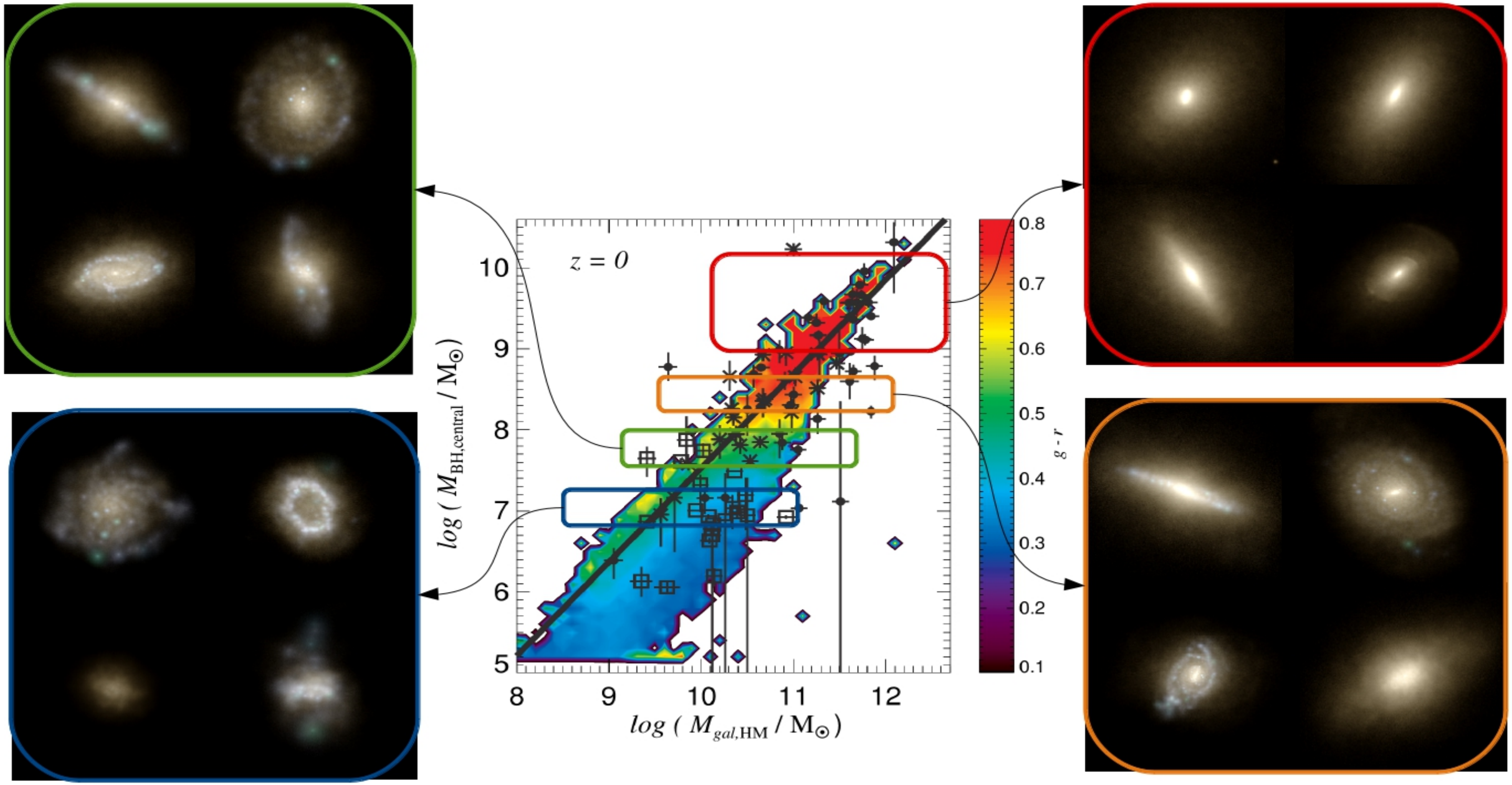
4. Momentum-driven outflows

   - Inject L/c into BH's neighbours rather than E_{th} (Costa et al. 2014).

Black holes in ILLUSTRIS

BH MASS – BULGE MASS RELATION

Sijacki et al. (in prep.)



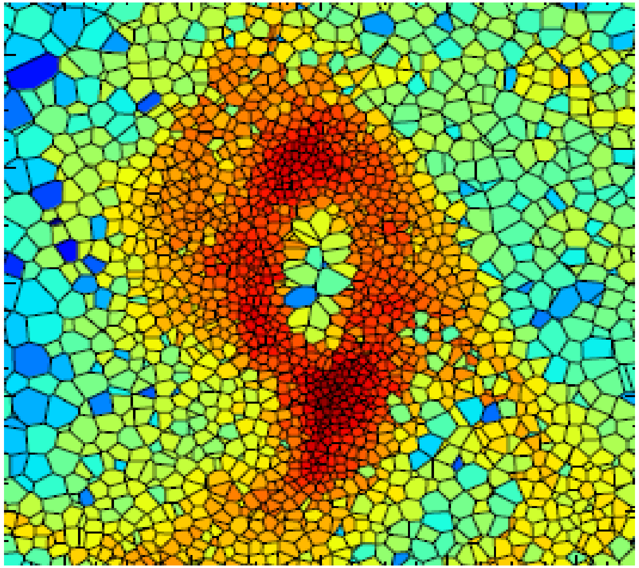
Kormendy & Ho 2013: circles: ellipticals, stars: spirals with bulges, squared: pseudo-bulges

GALAXY CATALOGUE:

Greg Snyder & Paul Torrey (g, r and I bands)

BLACK HOLE REFINEMENT IN AREPO

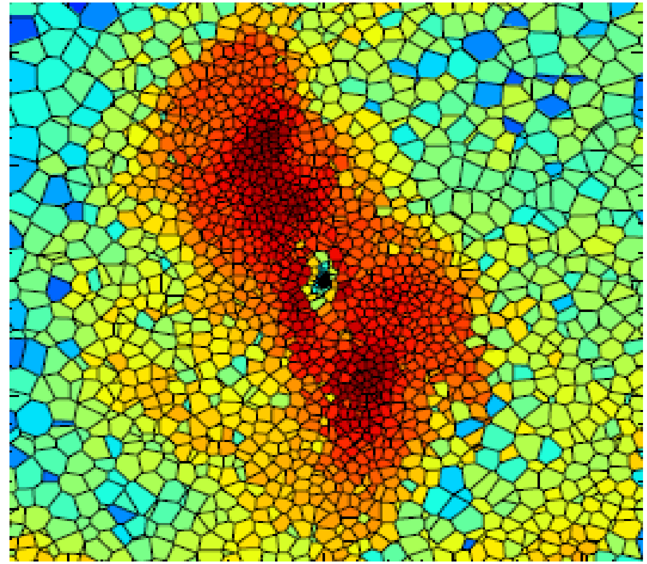
CURTIS & SIJACKI (IN PREP)

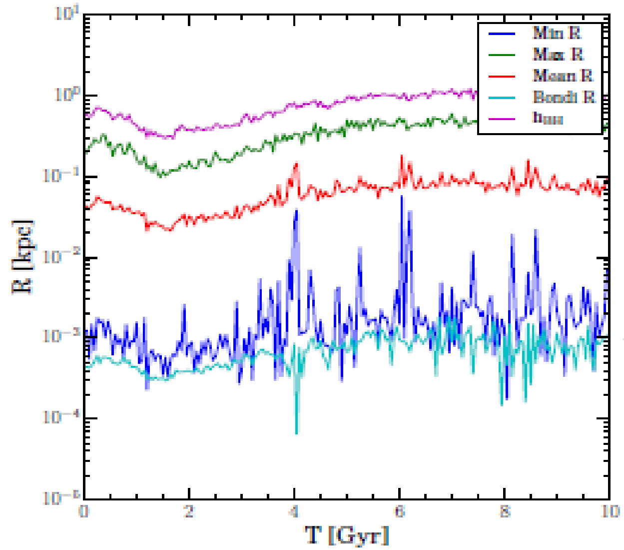


Force cells to split in the region of black holes

Cells scale linearly with distance to black hole

Big increase in resolution

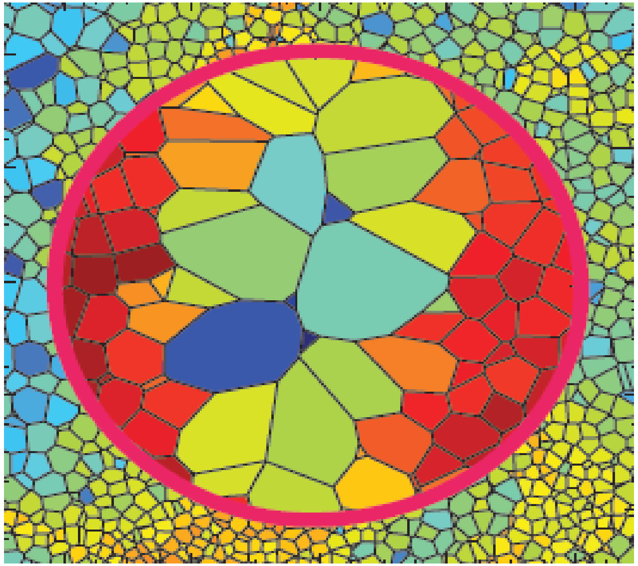




Smallest cells are a few factors of the Bondi Radius

BLACK HOLE REFINEMENT IN AREPO

CURTIS & SIJACKI (IN PREP)



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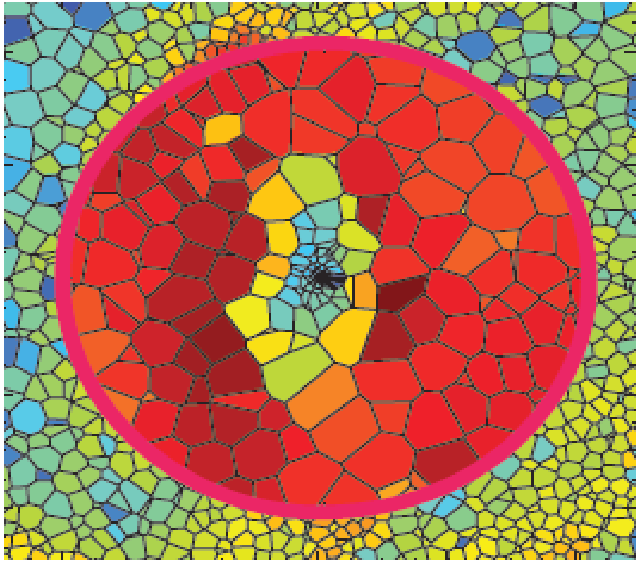
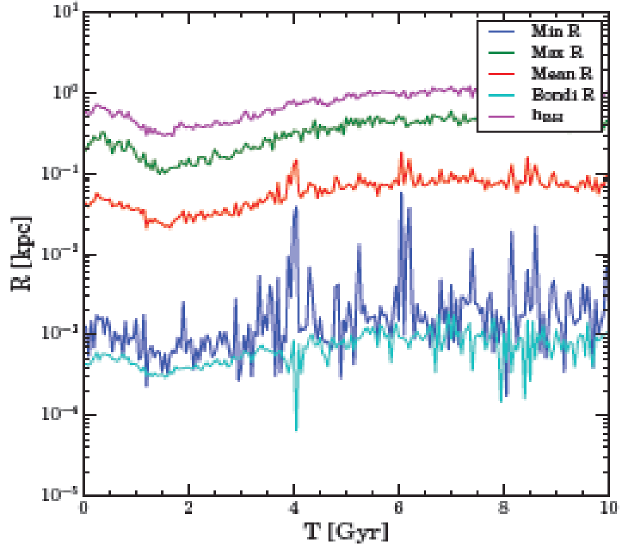
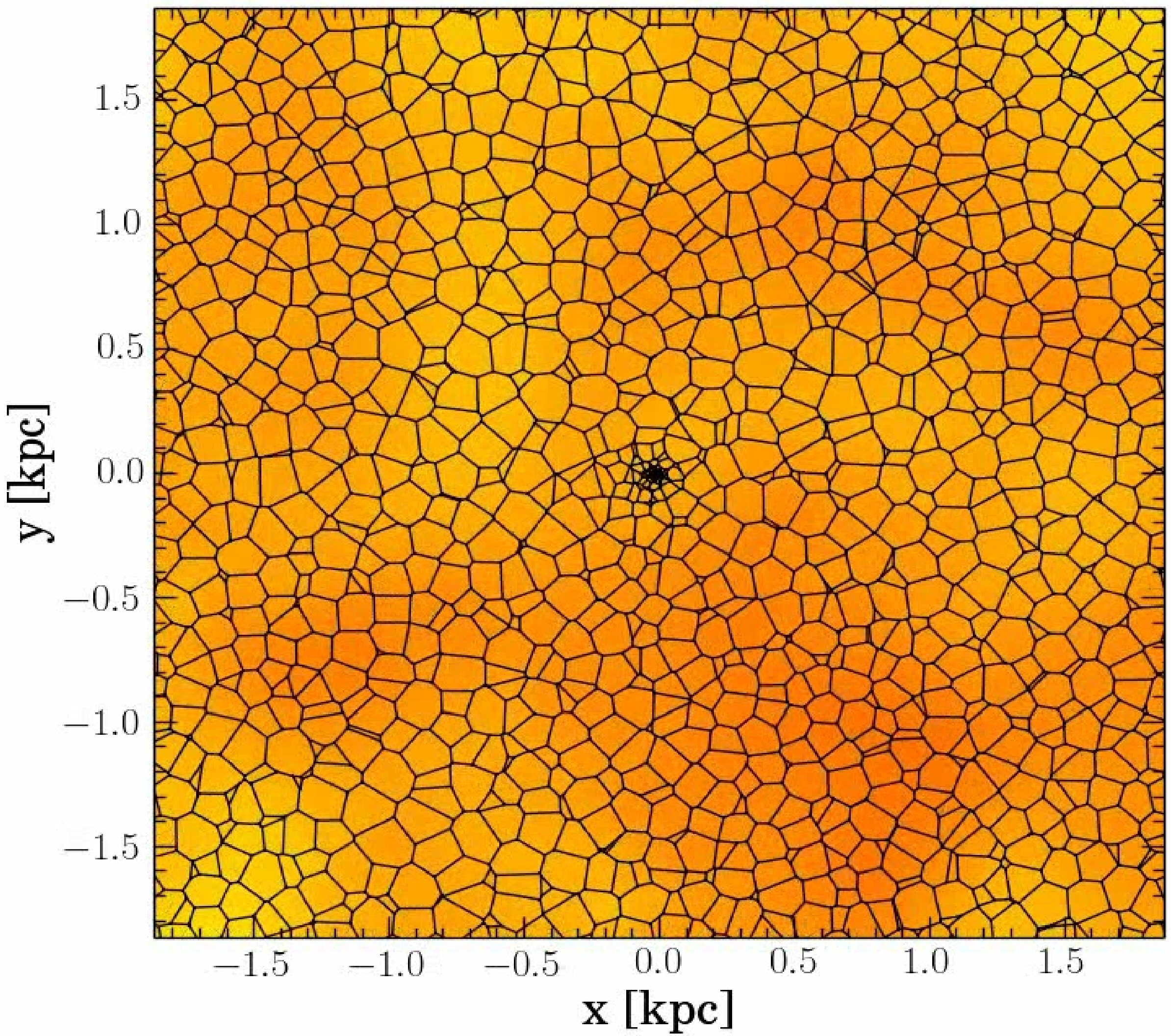




Smallest cells are a few factors of the Bondi Radius

WHY REFINE?



Better resolve the fluid parameters

Estimate accretion rate better

Robustly resolve the velocity structure around black holes

Include angular momentum effects in the accretion rate

More realistic feedback implementations

Exploring different feedback models in AREPO

- Hernquist (static) potential with:

$$M = 10^{12}\,\mathrm{M}_\odot$$

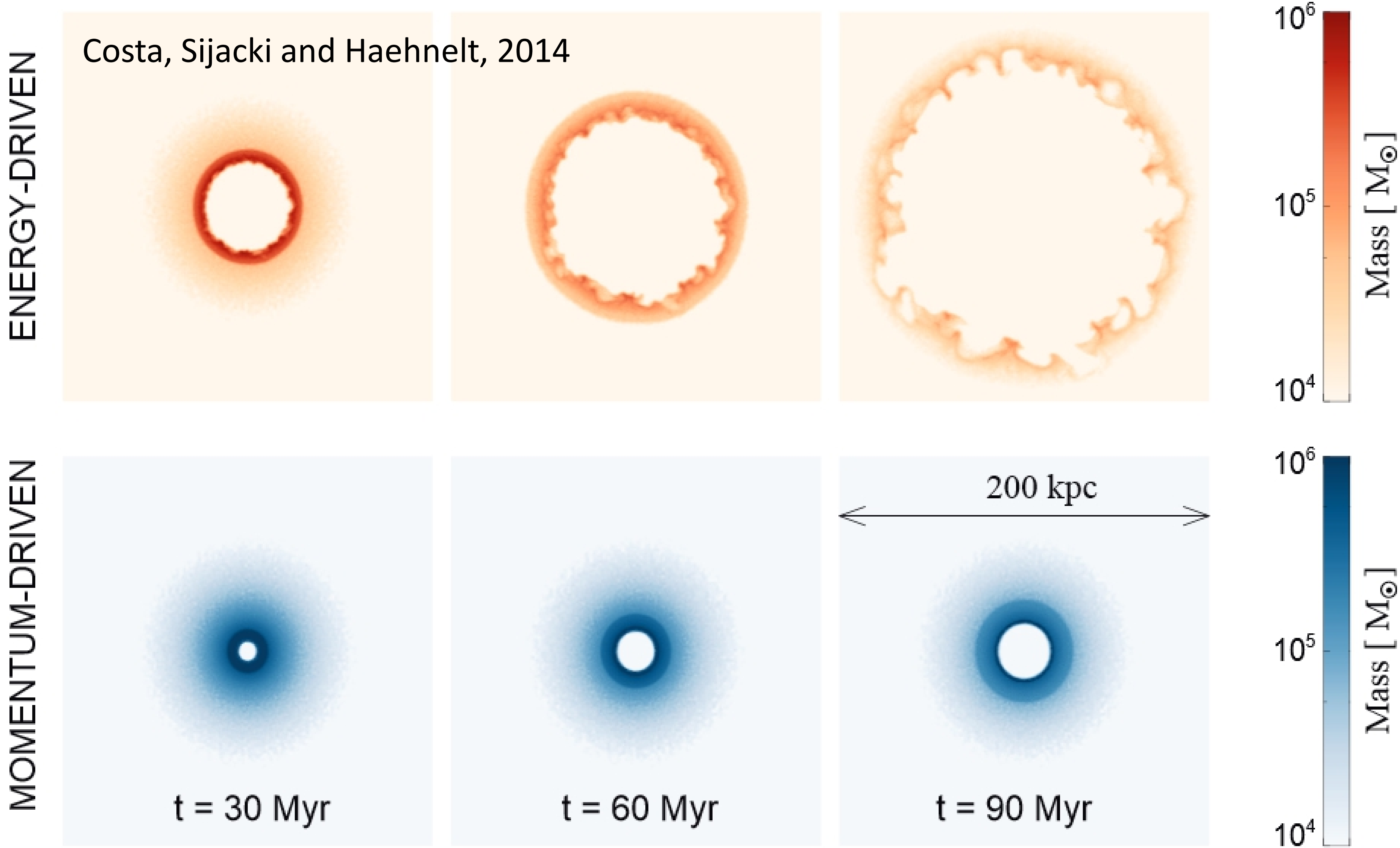
$$f_{\rm gas} = 0.17$$

- Minimum cell size: ~ 7 pc
- Gas at hydrostatic equilibrium
- Explore range of BH masses:

$$5 \times 10^{7}\,\mathrm{M}_\odot \ \text{to}\ 3 \times 10^{8}\,\mathrm{M}_\odot$$

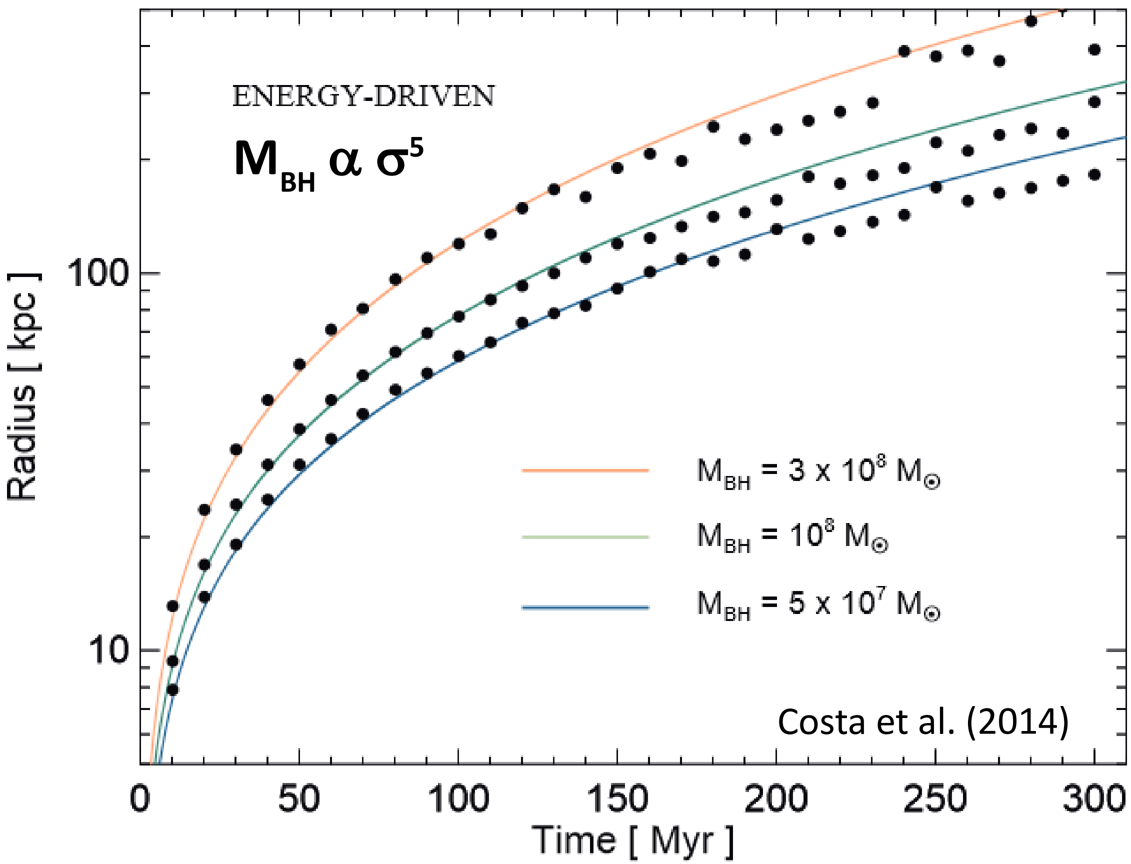
- Assume AGN is **constantly** emitting at its Eddington limit.

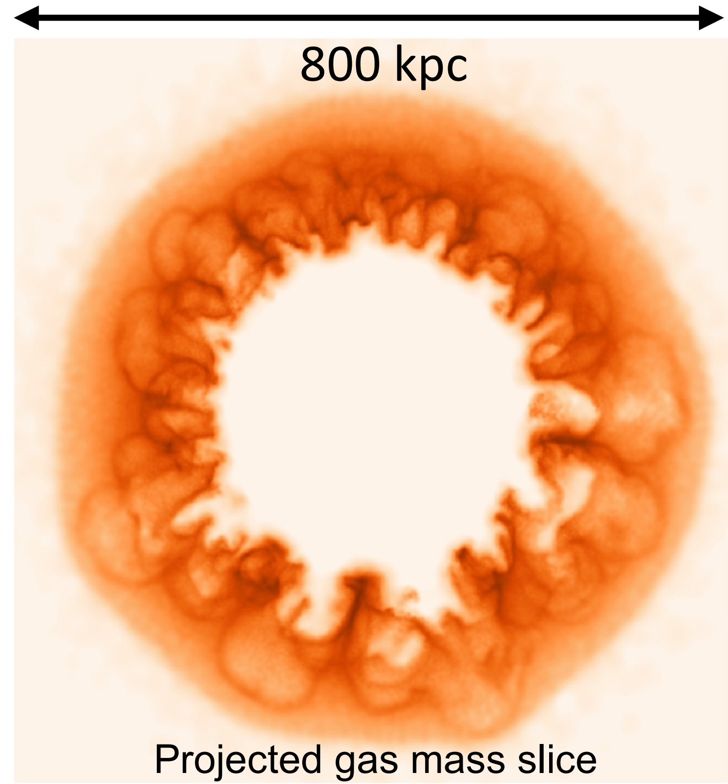
Dirac allocation, PI: Sijacki



Shell of shocked gas expands outwards as envisaged in models of spherical models of isolated haloes (Silk & Rees 1998, Fabian 1999, King 2003)

Energy-driven outflow



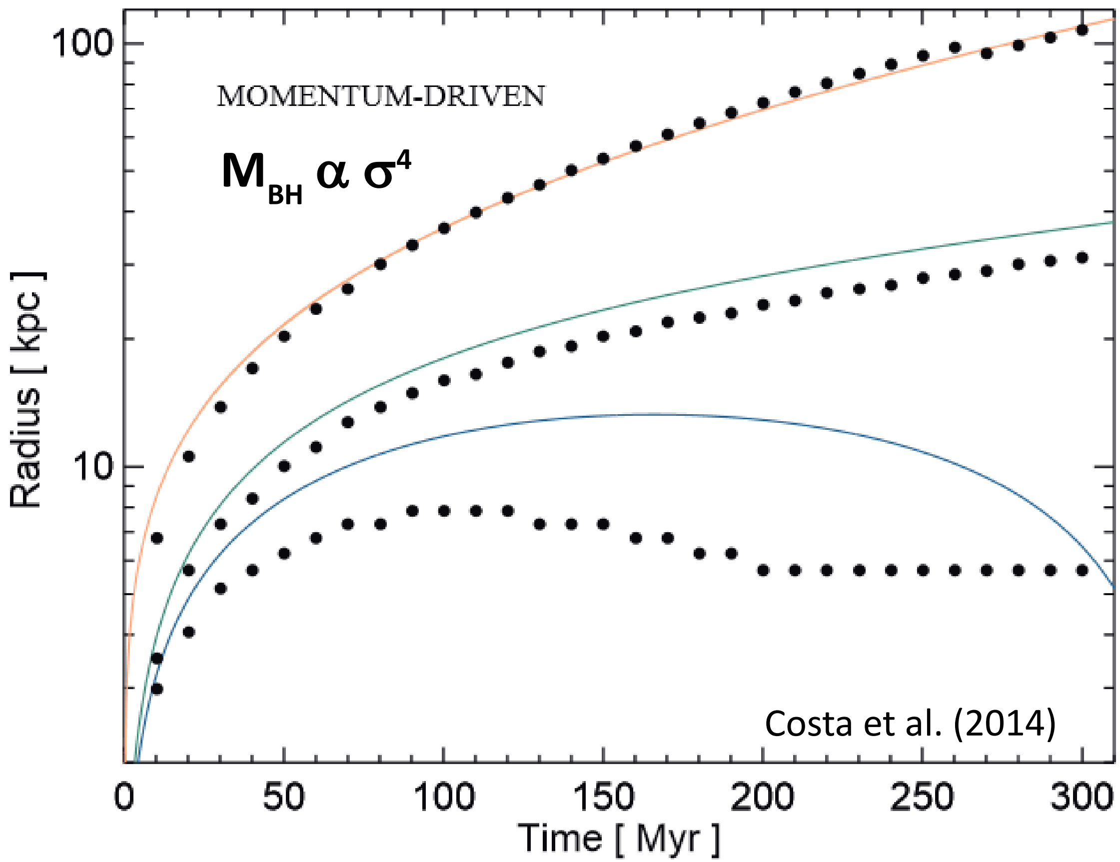


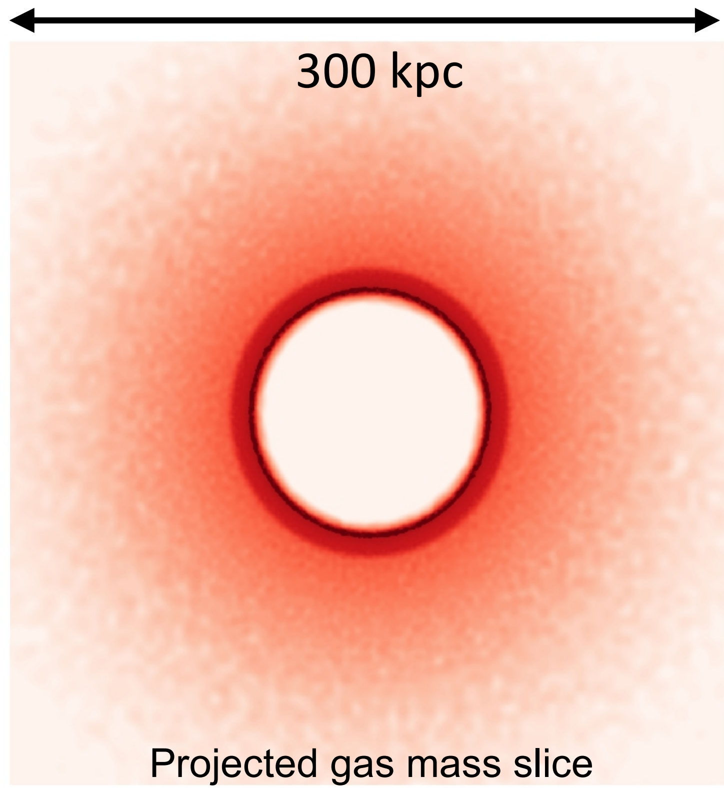
Costa, Sijacki and Haehnelt, 2014

cf. King's talk

Numerical and analytical wind solutions are in close agreement.
At late times, R-T instabilities develop and lead to disruption of the shell.

Momentum-driven outflow

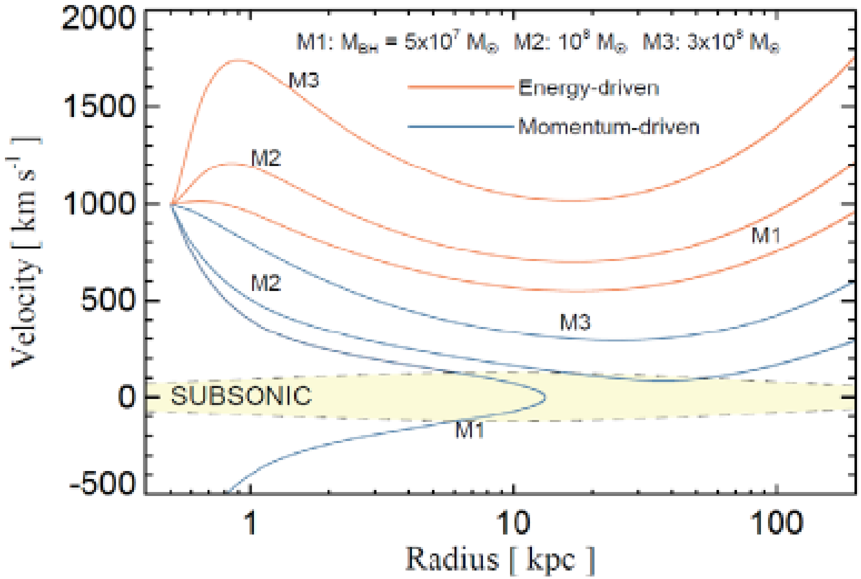


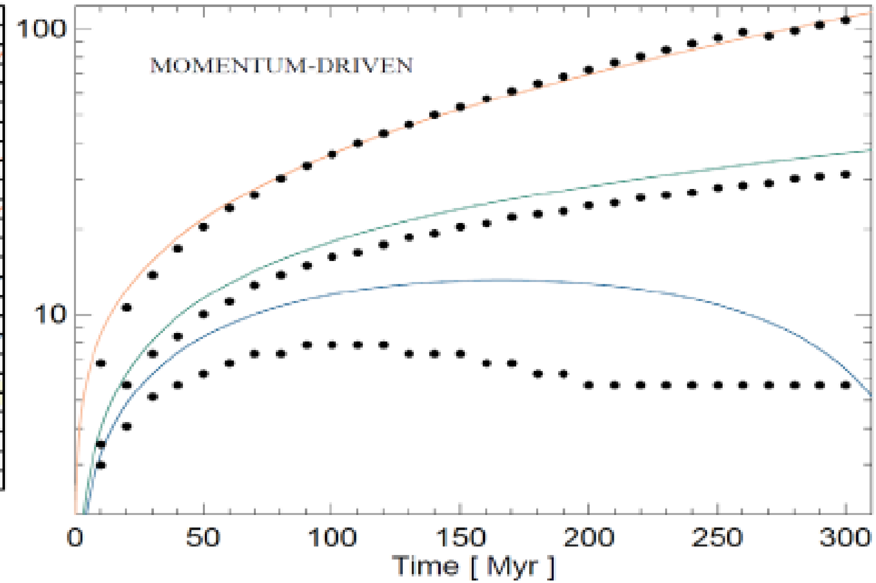


Costa, Sijacki and Haehnelt, 2014

Numerical and analytical solutions agree at **high black hole masses**.

Costa, Sijacki & Haehnelt, 2014



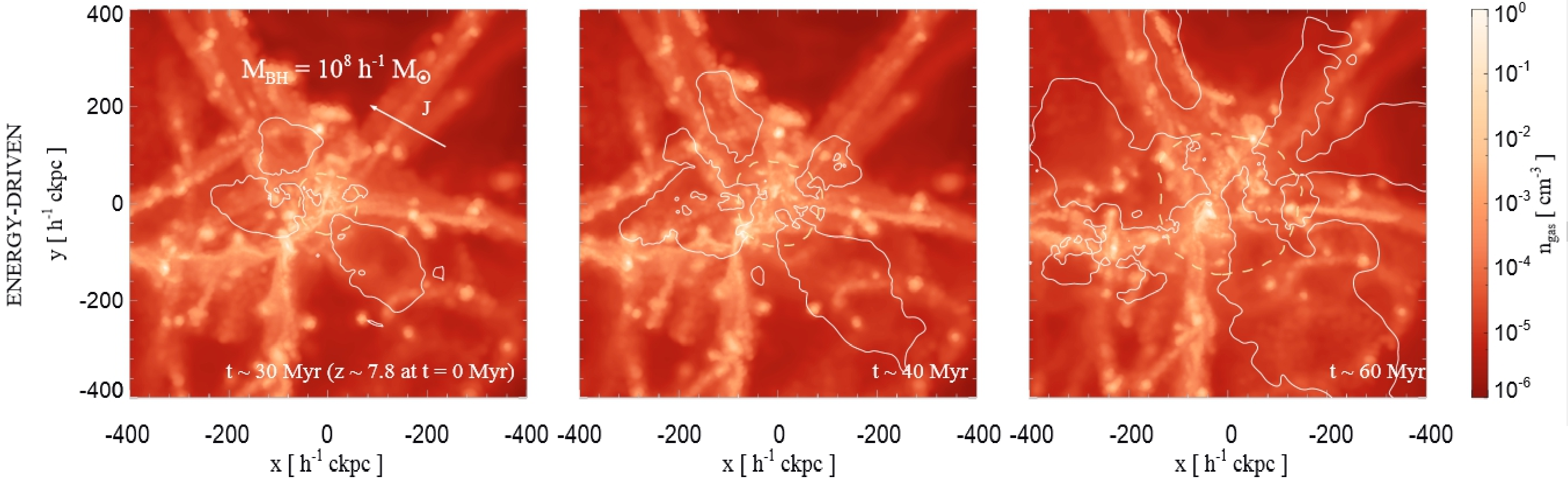


Cause of disagreement at lower black hole masses is confining pressure of halo gas in the subsonic regime.

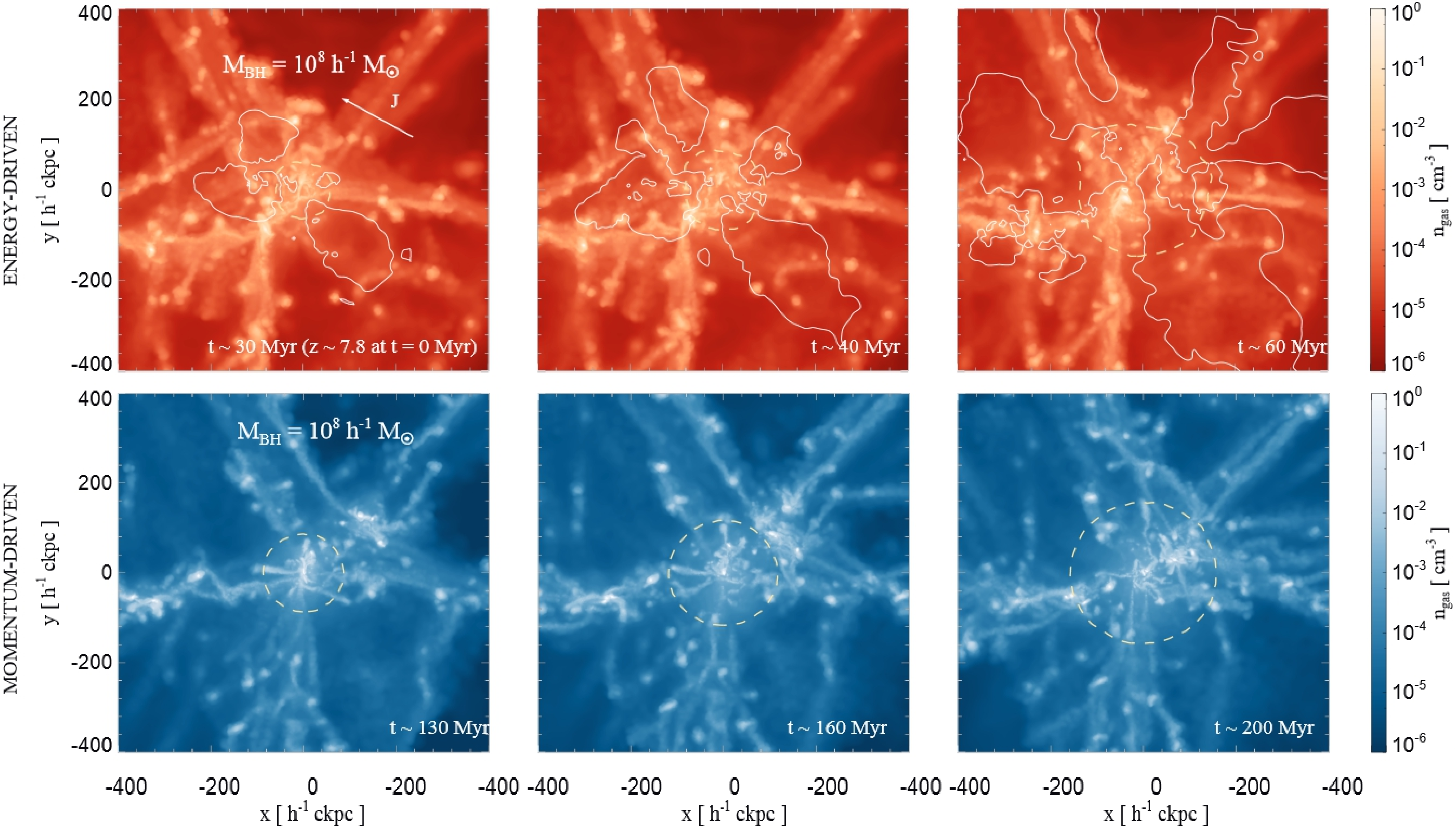
There is however a critical mass below which outflow solutions are bound.

$$M_\sigma \approx \left(\frac{f}{0.17}\right)\left(\frac{v_c}{200\,\mathrm{km\,s^{-1}}}\right)^4 10^8\,\mathrm{M}_\odot$$

cf. Fabian 1999, King 2003



Anisotropic outflow escapes along paths of least resistance.



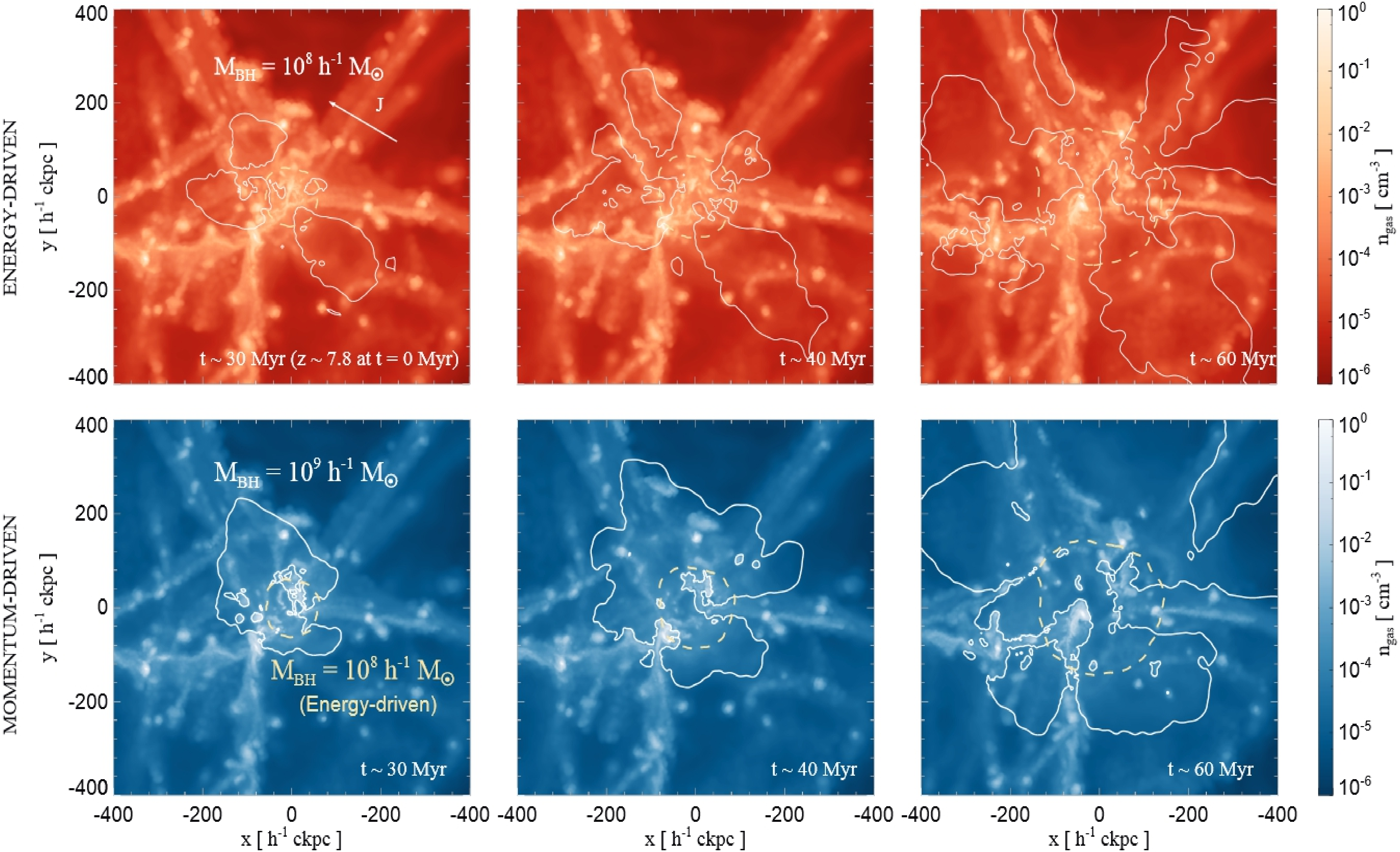
No significant momentum-driven outflow for $M = M_\sigma$.

Conclusions

- In isolated potentials, we verify that a momentum flux of L/c is sufficient to lead to a relation:

$$M_\sigma \approx \left(\frac{f}{0.17}\right)\left(\frac{v_c}{200\,\mathrm{km\,s^{-1}}}\right)^4 10^8\,\mathrm{M}_\odot$$

- A momentum flux >> L/c is however required to revert inflows of gas as predicted by cosmological simulations of BH growth.
- Energy-driven outflows provide the required momentum input.
- New implementation methods, such as super-Lagrangian refinement are a promising tool to study BH growth and feedback in the next generation of cosmological simulations.



ENERGY-DRIVEN
MOMENTUM-DRIVEN
$M_{BH} = 10^8\ h^{-1}\ M_\odot$
J
t ~ 30 Myr (z ~ 7.8 at t = 0 Myr)
t ~ 40 Myr
t ~ 60 Myr
$M_{BH} = 10^9\ h^{-1}\ M_\odot$
$M_{BH} = 10^8\ h^{-1}\ M_\odot$
(Energy-driven)
t ~ 30 Myr
t ~ 40 Myr
t ~ 60 Myr
y [h^{-1} ckpc]
x [h^{-1} ckpc]
n_{gas} [cm^{-3}]
400
200
0
-200
-400
-400
-200
0
-200
-400
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}