The physics of AGN-driven outflows

Tiago Costa
Leiden Observatory, The Netherlands

Sterrewacht Leiden

Universiteit Leiden

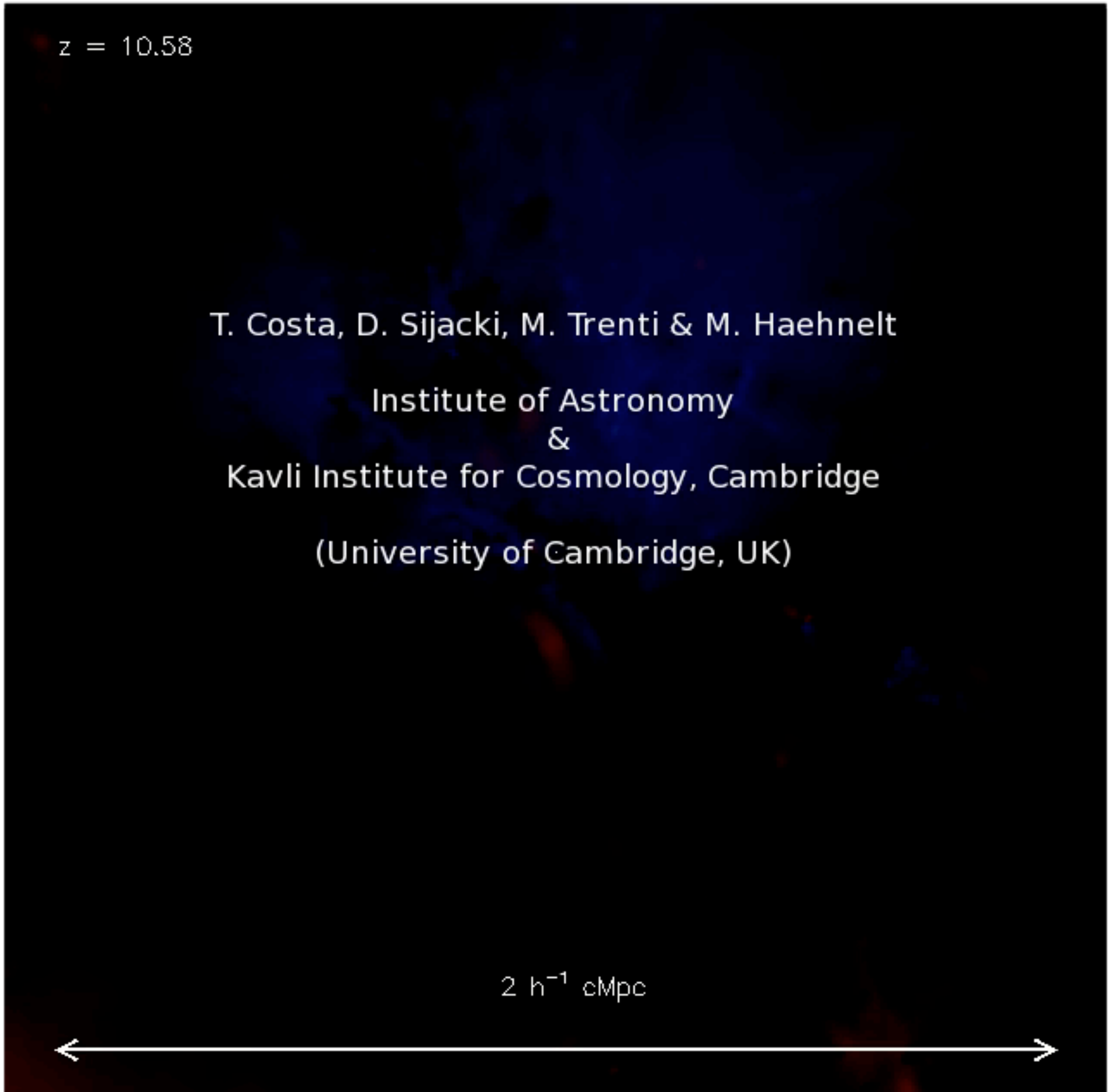
in collaboration with
Martin Haehnelt, **Debora Sijacki** (IoA@Cambridge),
Joakim Rosdahl & Joop Schaye (Leiden)

Quasar-mode feedback

Fundamental Models

- Radiation pressure on dust (Fabian 99, Murray+05, Thompson+15)
- Compton (X-ray) heating (Ciotti+01, Sazonov+05, Ostriker+10, Gan+14)
- **Interaction with nuclear AGN wind** (Silk & Rees 98, King 03, Roth+12, Zubovas & King 12, Faucher-Giguere & Quataert 12)

Simplifying assumptions:
Symmetry, homogeneity, static configuration


z = 10.58
T. Costa, D. Sijacki, M. Trenti & M. Haehnelt
Institute of Astronomy
&
Kavli Institute for Cosmology, Cambridge
(University of Cambridge, UK)
2 h⁻¹ cMpc

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Cosmological Simulations

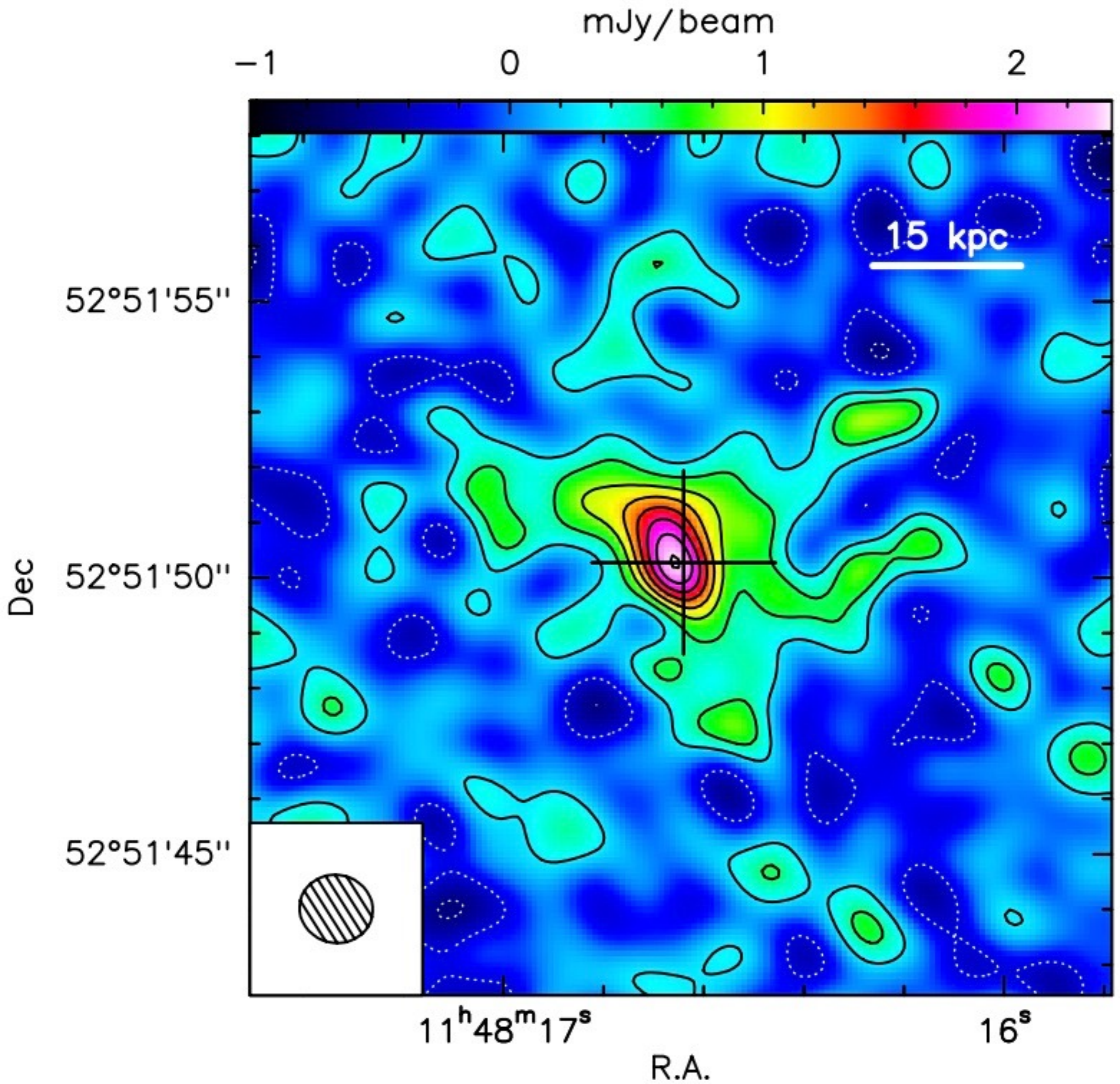
- AGN feedback is modelled through the injection of **thermal energy** (Springel+05, Di Matteo+05, Sijacki+07, Booth & Schaye 09, Dubois+12), **momentum** (Debuhr+11, Choi +12, Hopkins+15) or a **combination** thereof (Curtis & Sijacki 15).

How well posed are such “subgrid” models in view of the more robust analytical understanding?

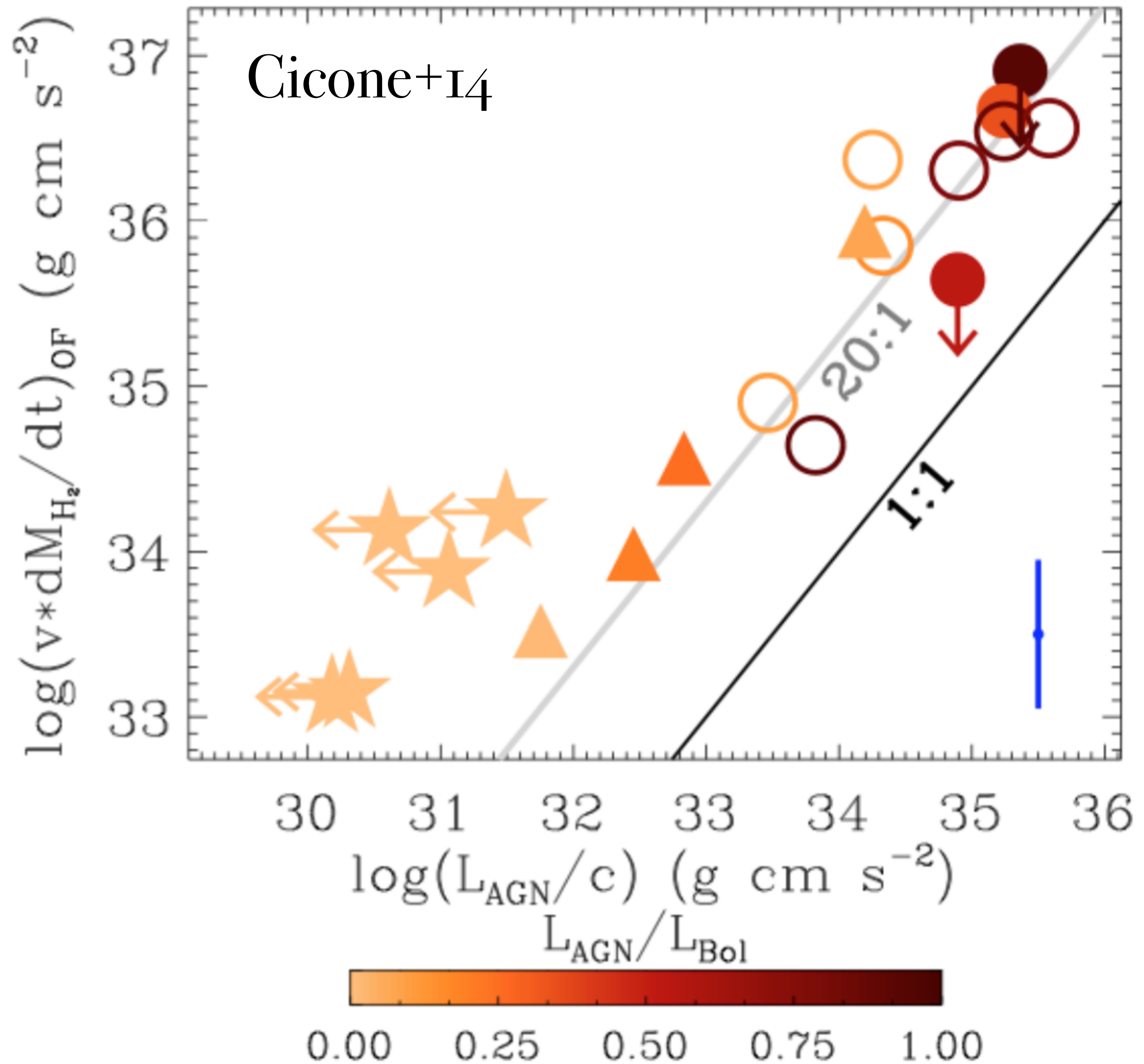
What is the impact of the cosmological environment?

How to bridge the gap with observations?

Observed outflows



CII emission from a z = 6.4 QSO

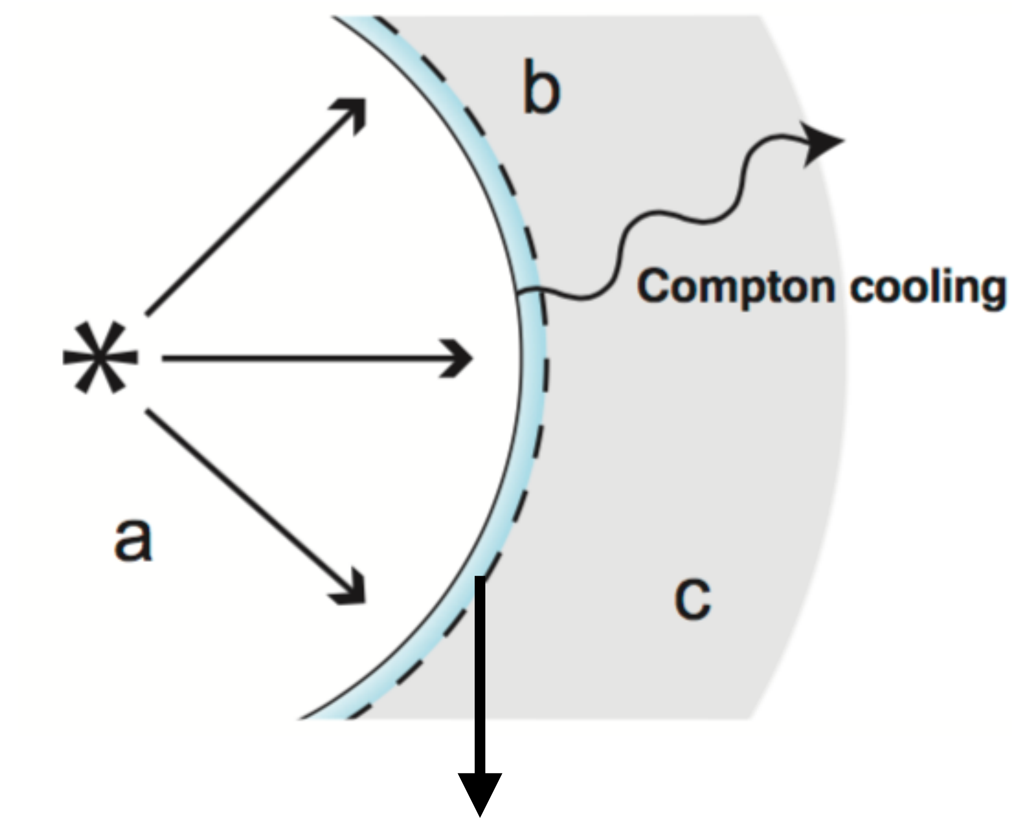


Observed AGN-driven outflows are often multi-phase, appear to have a momentum flux >> L/c and a kinetic luminosity of < 0.05 L.

Interaction with a nuclear AGN wind

Momentum-driven

$$\dot{p}_{\rm sh} = \dot{p}_{\rm w} = \frac{L}{c}$$



$$T_{\rm r} = \frac{3}{16}\frac{\mu m_{\rm p}}{k}v_{\rm w}^2$$
$$\approx 1.2\times 10^{10}\left(\frac{\mu}{0.59}\right)\left(\frac{v_{\rm w}}{0.1c}\right)^2 \,{\rm K}$$

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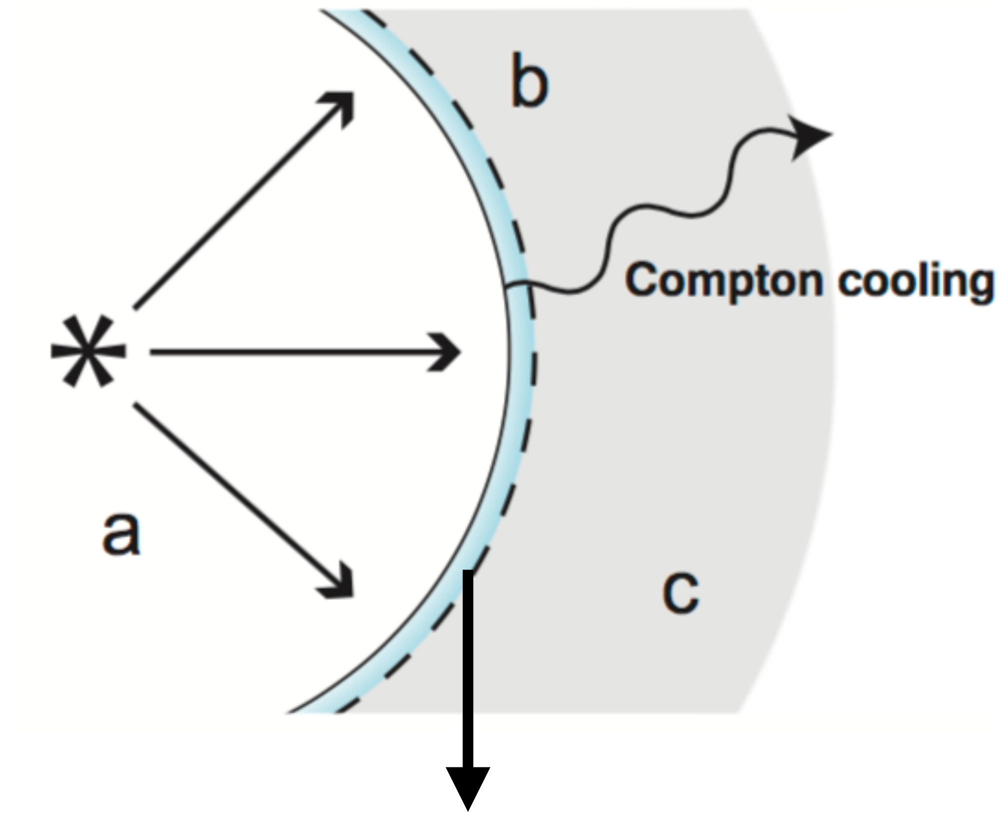

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King & Pounds 15

$$\boxed{\frac{d\left[R\dot{R}\right]}{dt} = -2\sigma^2\left(1-\frac{M_{\rm BH}}{M_\sigma}\right)}$$

$$M_\sigma = \frac{f_g\kappa}{\pi G^2}\sigma^4 \simeq 3.2\times10^8 {\rm M}_\odot \sigma_{200}^4$$

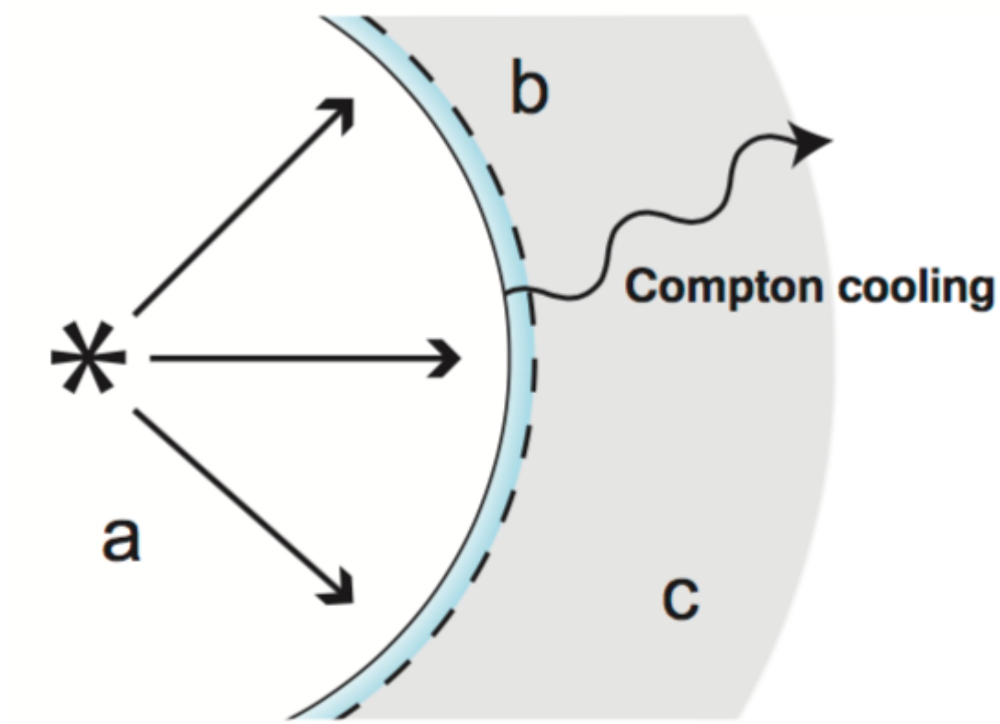
Observed:

$$\boxed{M \simeq 3\times10^8 {\rm M}_\odot \sigma_{200}^\alpha}$$

Momentum-driven flows have a momentum flux of L/c.
They have been claimed to lead to the observed scaling relations (King 03, Murray 05).

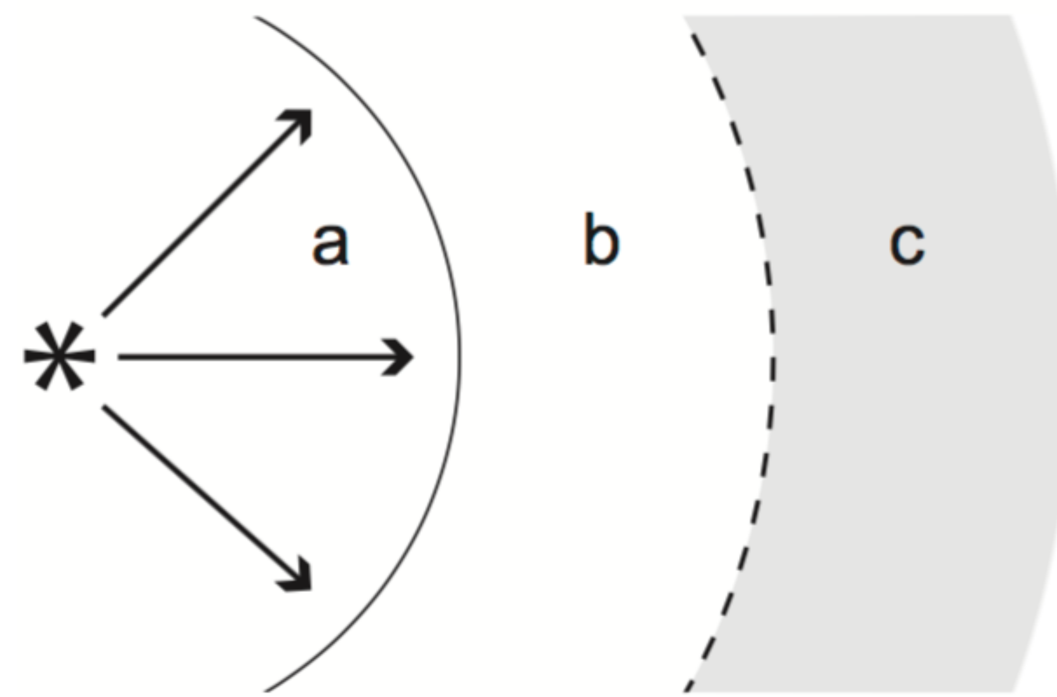
Interaction with a nuclear AGN wind

Momentum-driven



$$\dot{p}_{\rm sh} = \dot{p}_{\rm w} = \frac{L}{c}$$

Energy-driven

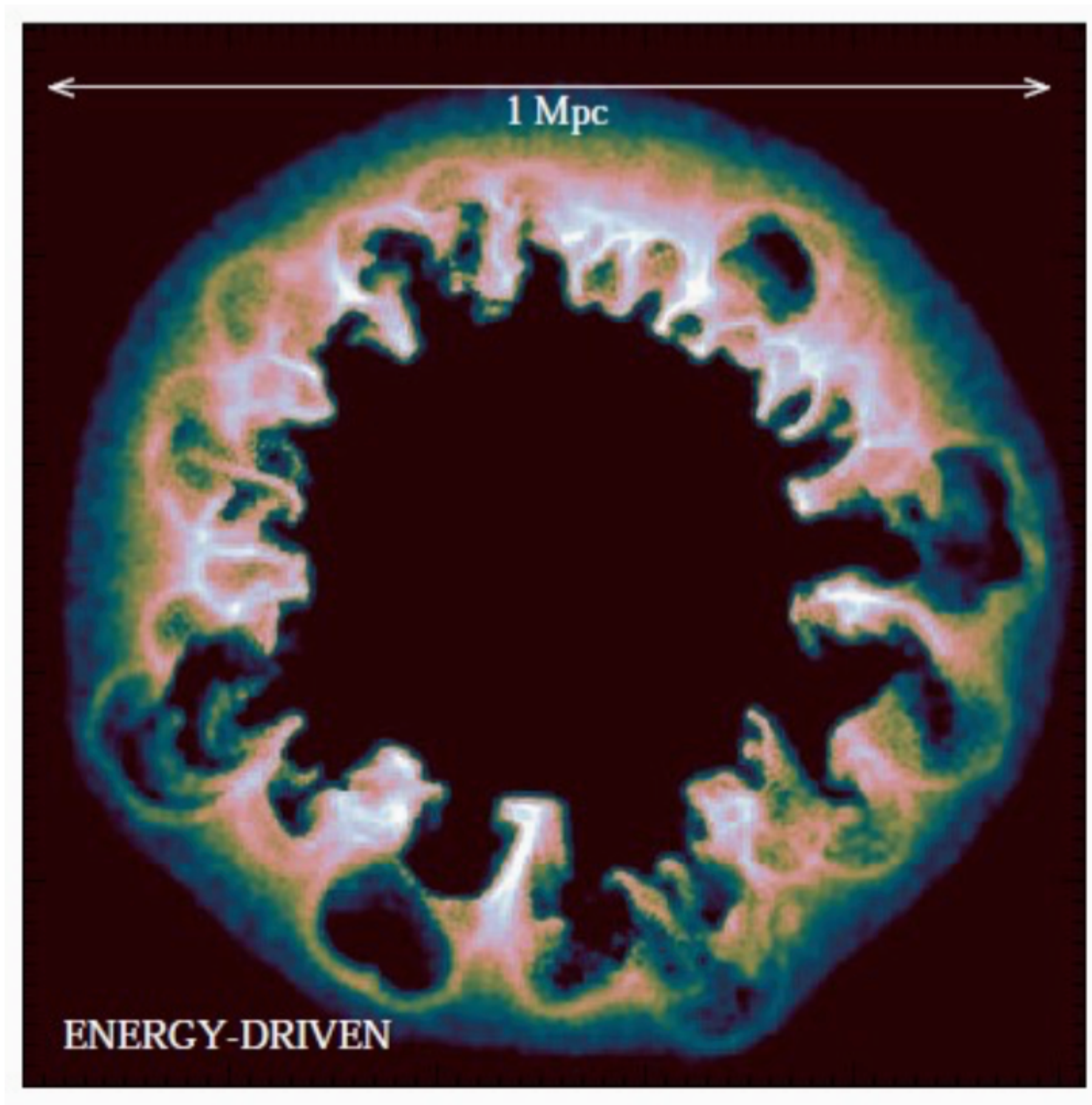


$$\left.\frac{\dot{p}_{\rm sh}}{\dot{p}_{\rm w}}\right|^{\rm e} = 2\epsilon^{\rm e}_{\rm kin}\frac{c}{v_{\rm sh}} = 30\epsilon_{\rm th-kin}\left(\frac{\epsilon}{0.05}\right)\left(\frac{v_{\rm sh}}{1000{\rm km\,s^{-1}}}\right)^{-1}$$

Whether outflow is momentum- or energy-driven depends on whether the shocked wind **(not the shocked ambient medium)** can radiate away its thermal energy.
(Weaver+77 [stellar winds], King 03, Zubovas & King 12, Faucher-Giguere & Quataert 12)

I.
Idealised simulations

Costa+14 (II)



Numerical Simulations

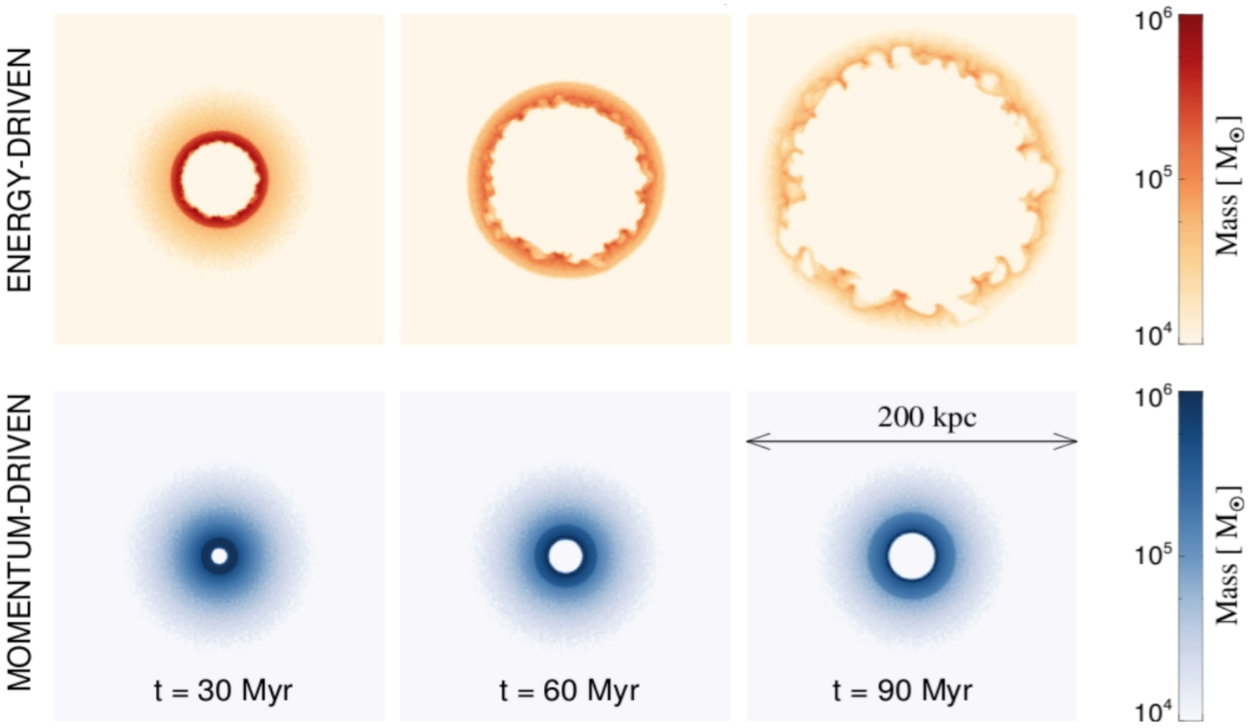
Address a deliberately simplified setup in order to mimic *the same* assumptions as taken in the analytic models:

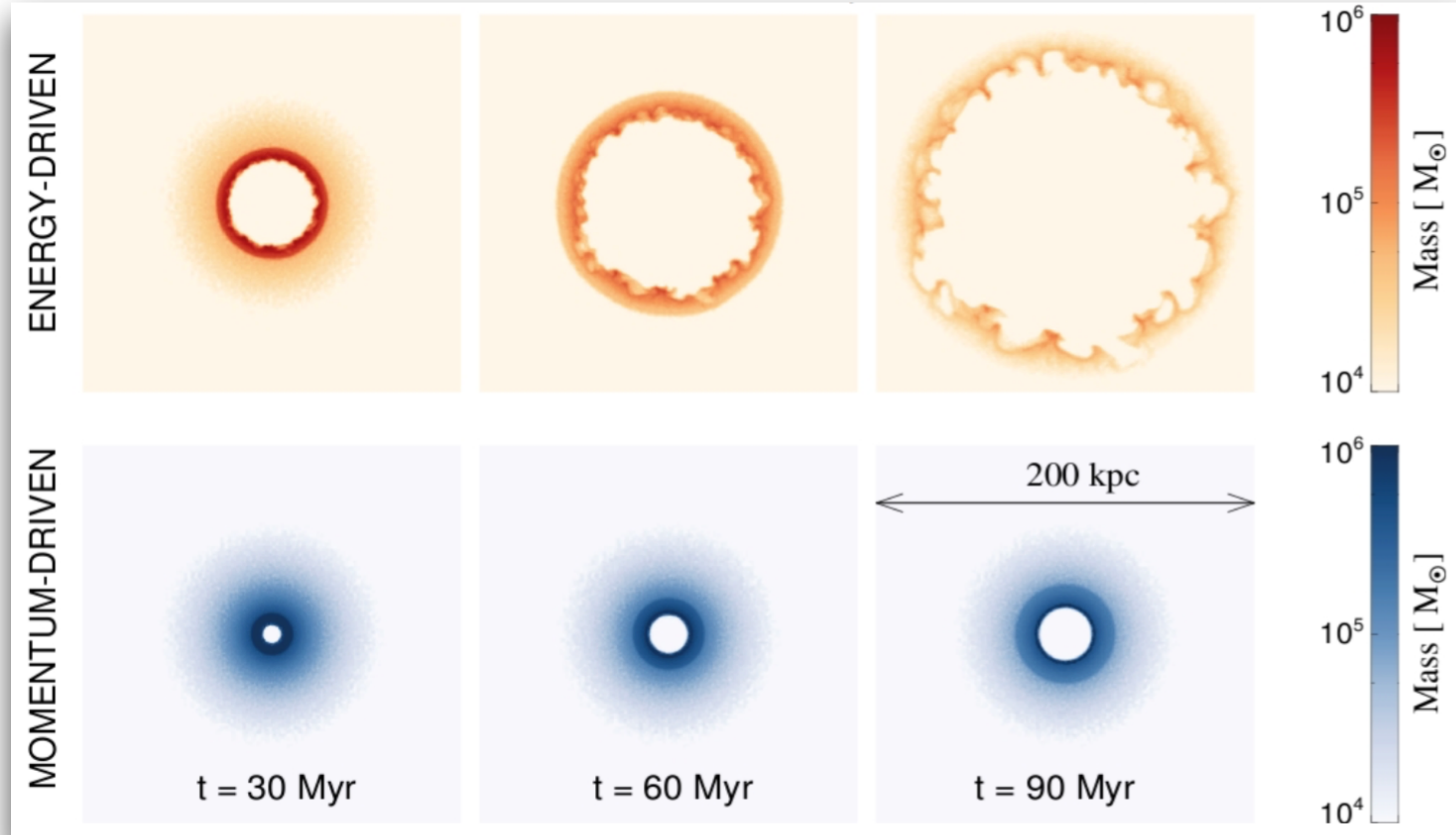
1. Isolated Hernquist potential (10^{12} M_{SUN}) populated by gas at hydrostatic equilibrium.
2. AGN located at the centre emitting at its Eddington limit (or following a specific light curve).
3. Aim at reproducing momentum- and energy-driven limits (as in King 03, 05) taking the same assumptions.

Hydrodynamics followed using the moving-mesh code AREPO (Springel 2010).

Resolution: 10^6, 10^7, 10^8 cells.

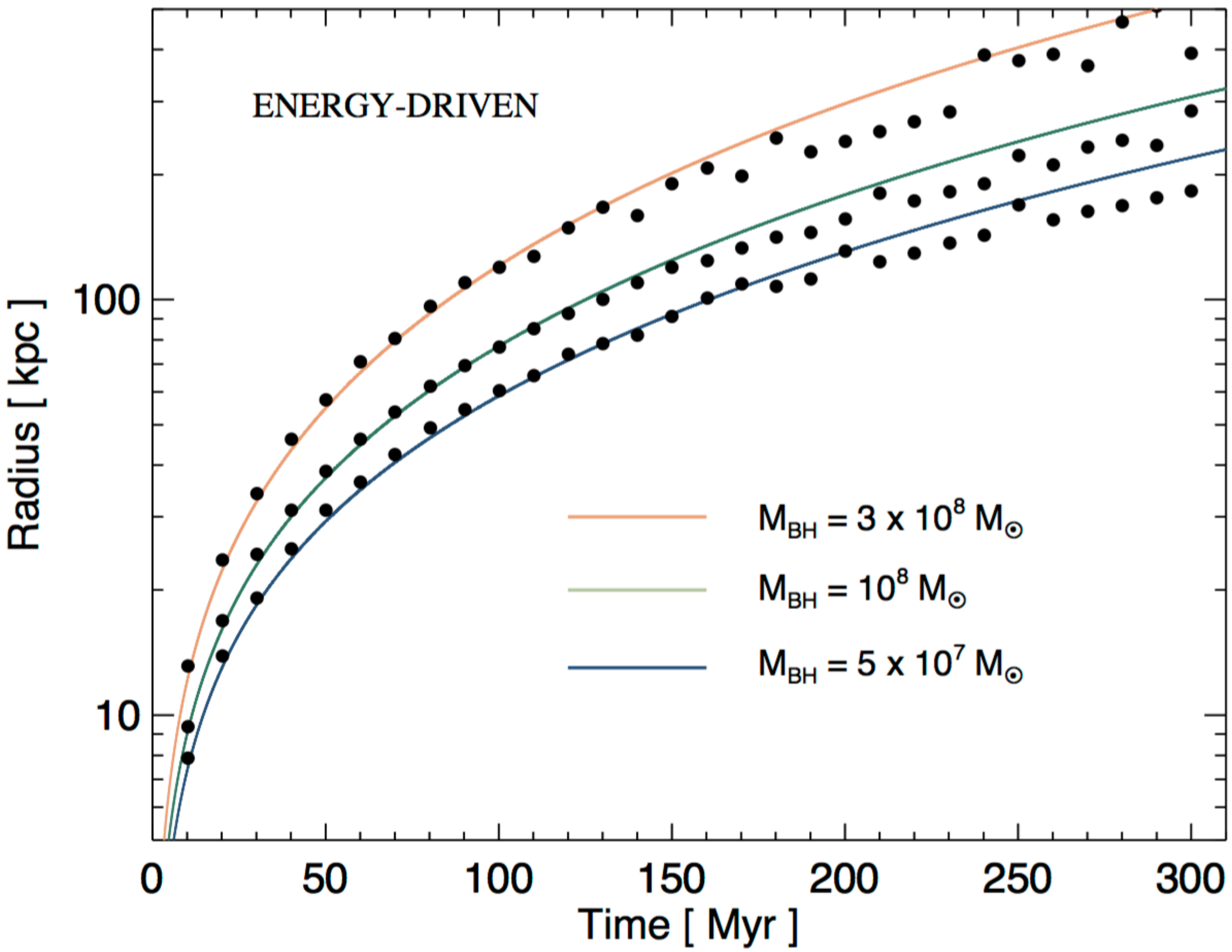
Black hole masses in the range of 5×10^7 M_{SUN} to 10^9 M_{SUN}.

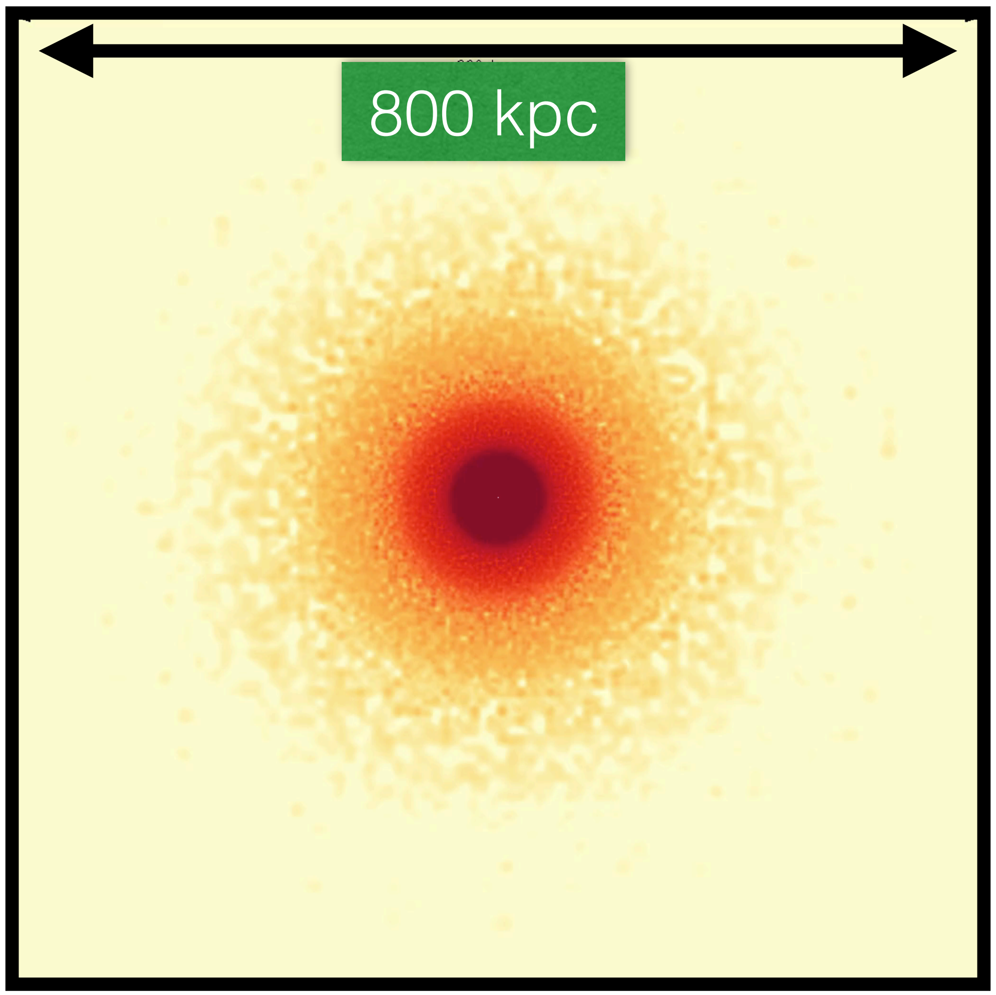




At any given time and given an AGN luminosity, energy-driven shells expand more quickly through the halo.

The energy-driven limit

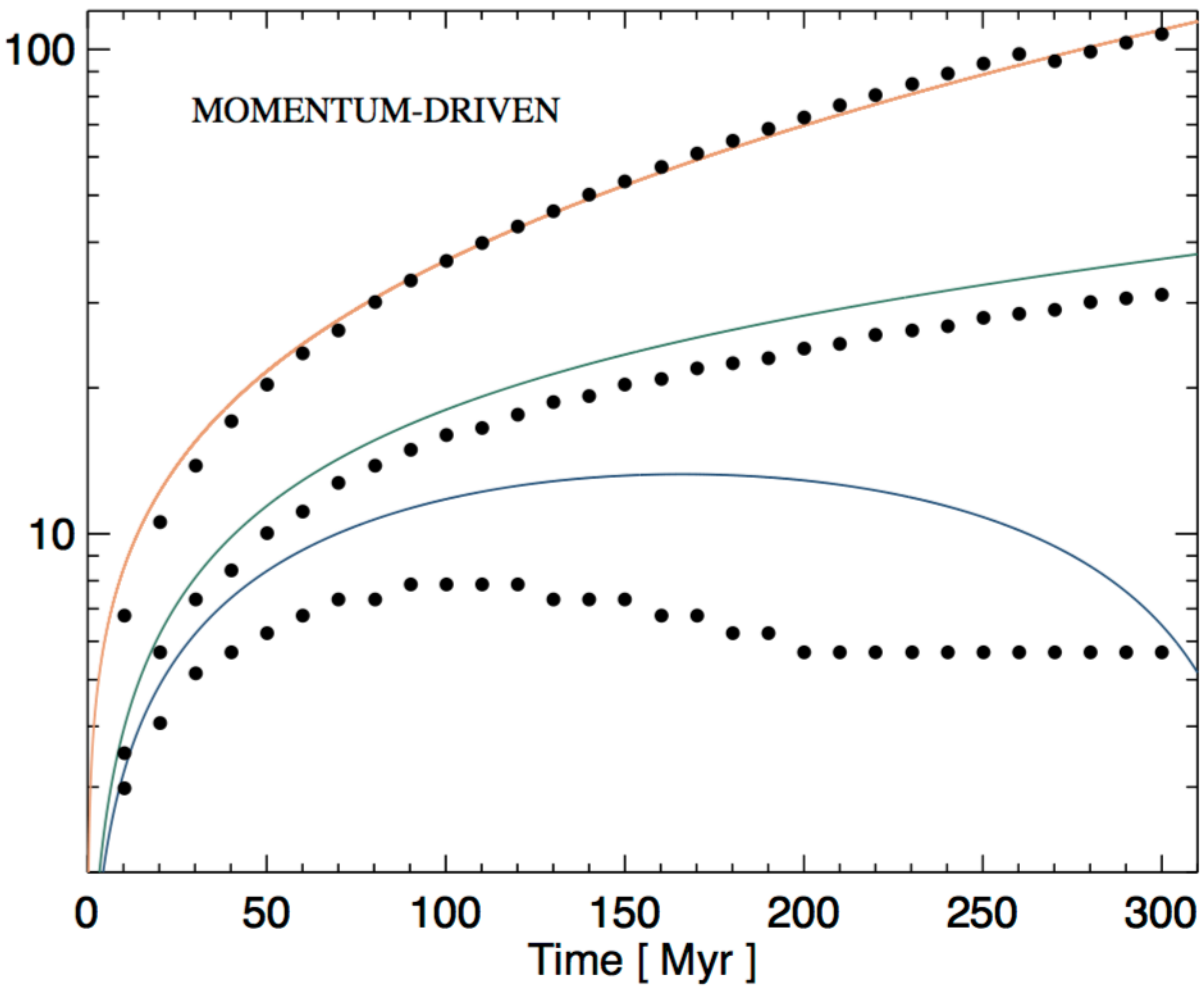


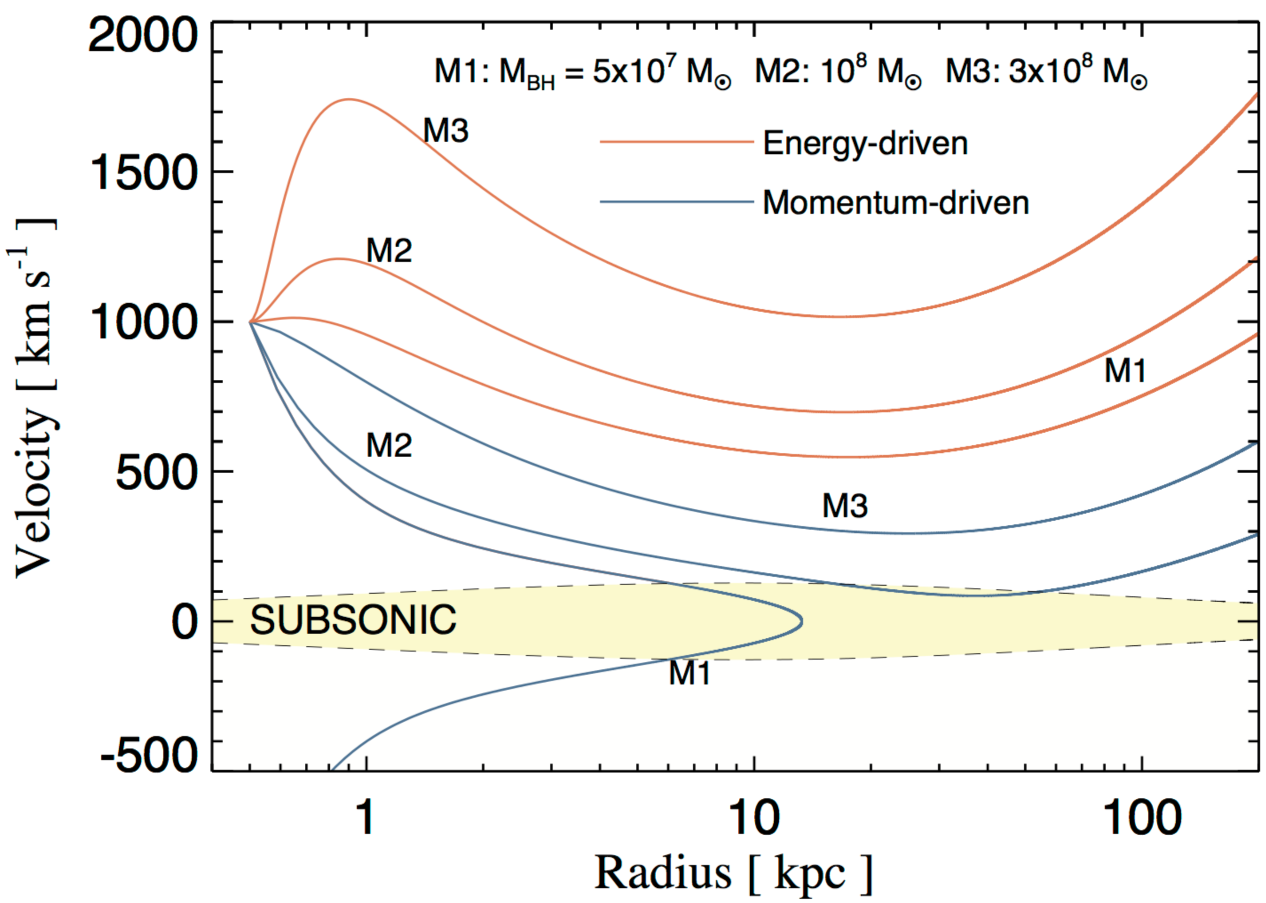


R-T instabilities develop

Can be modelled accurately in state-of-the-art simulations.
Rayleigh-Taylor instabilities lead to the breakdown of the “thin shell” assumption.

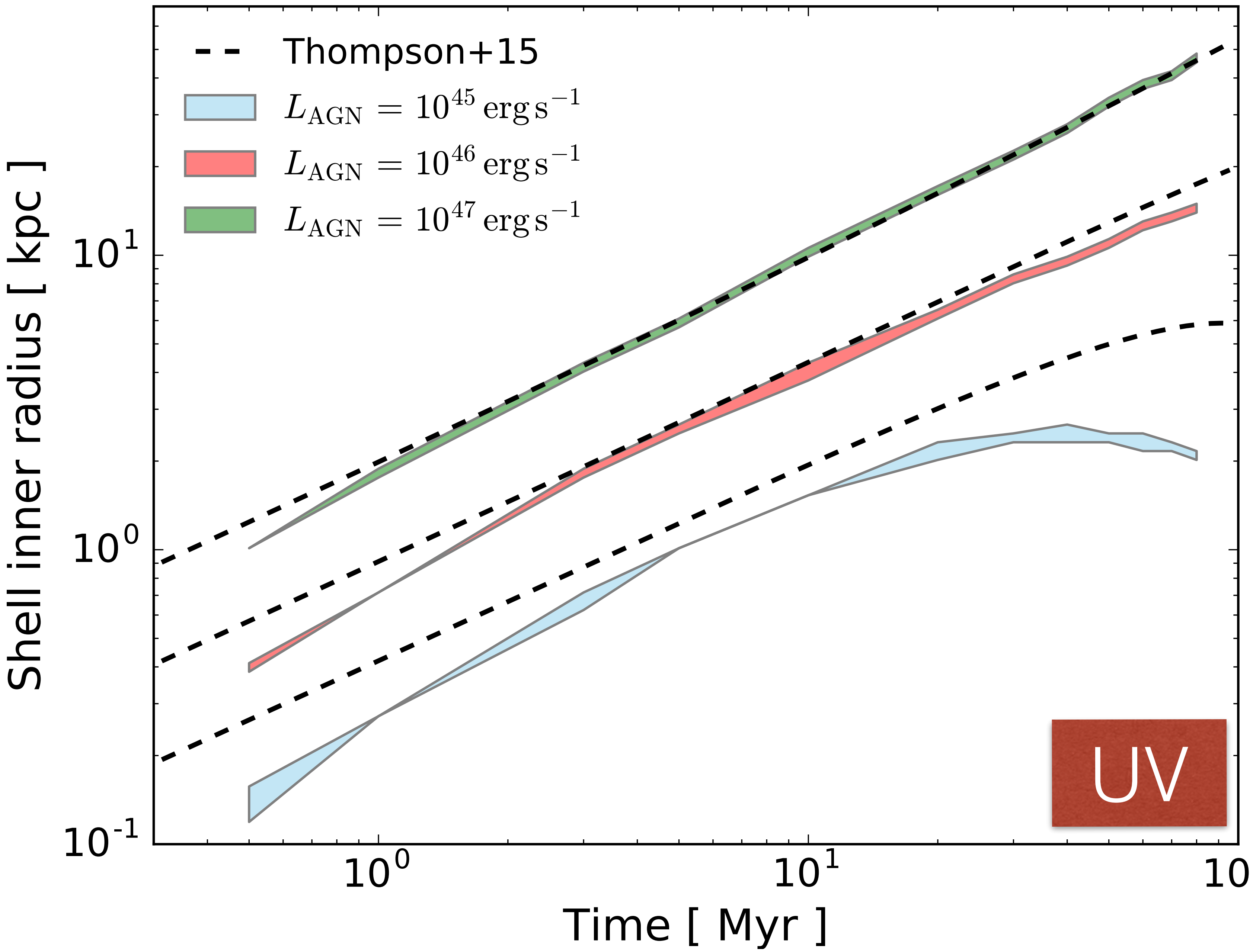
The momentum-driven limit



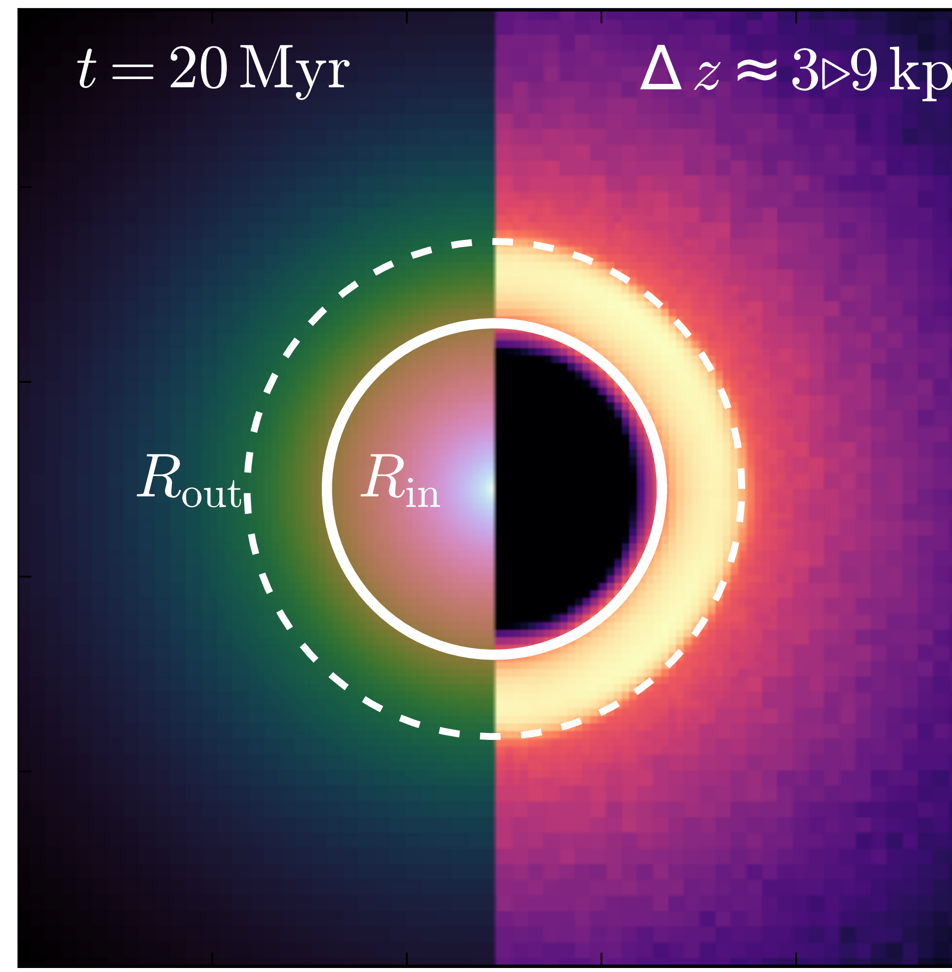


King's momentum-driven solution can be well reproduced in the supersonic regime.
We confirm that:
There is a limiting luminosity above which outflows are gravitationally unbound.

Radiation pressure on dust



PRELIMINARY

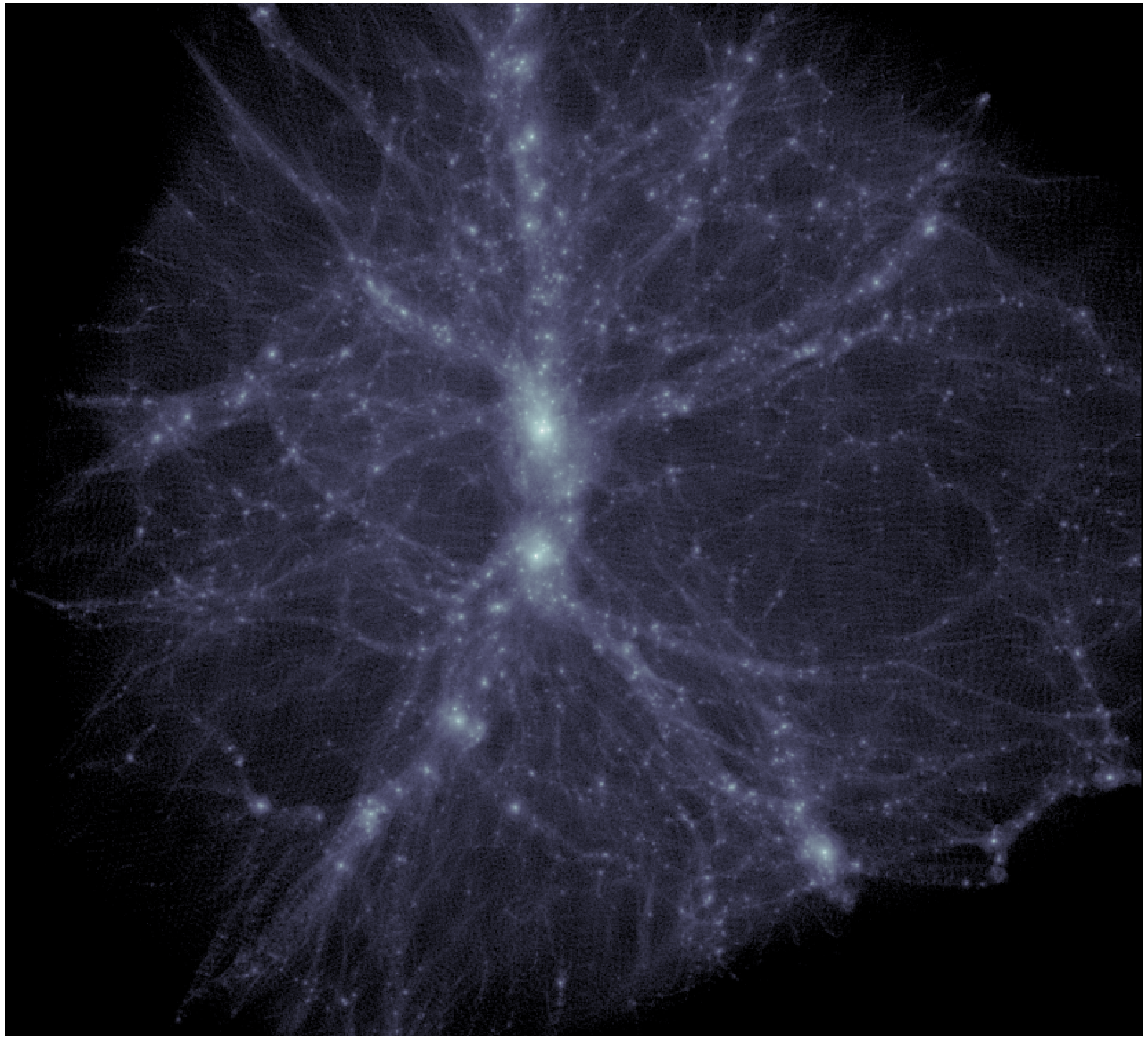


Can reproduce radiation pressure-driven shells in RAMSES-RT (Rosdahl & Teyssier 2012) with remarkable accuracy too.

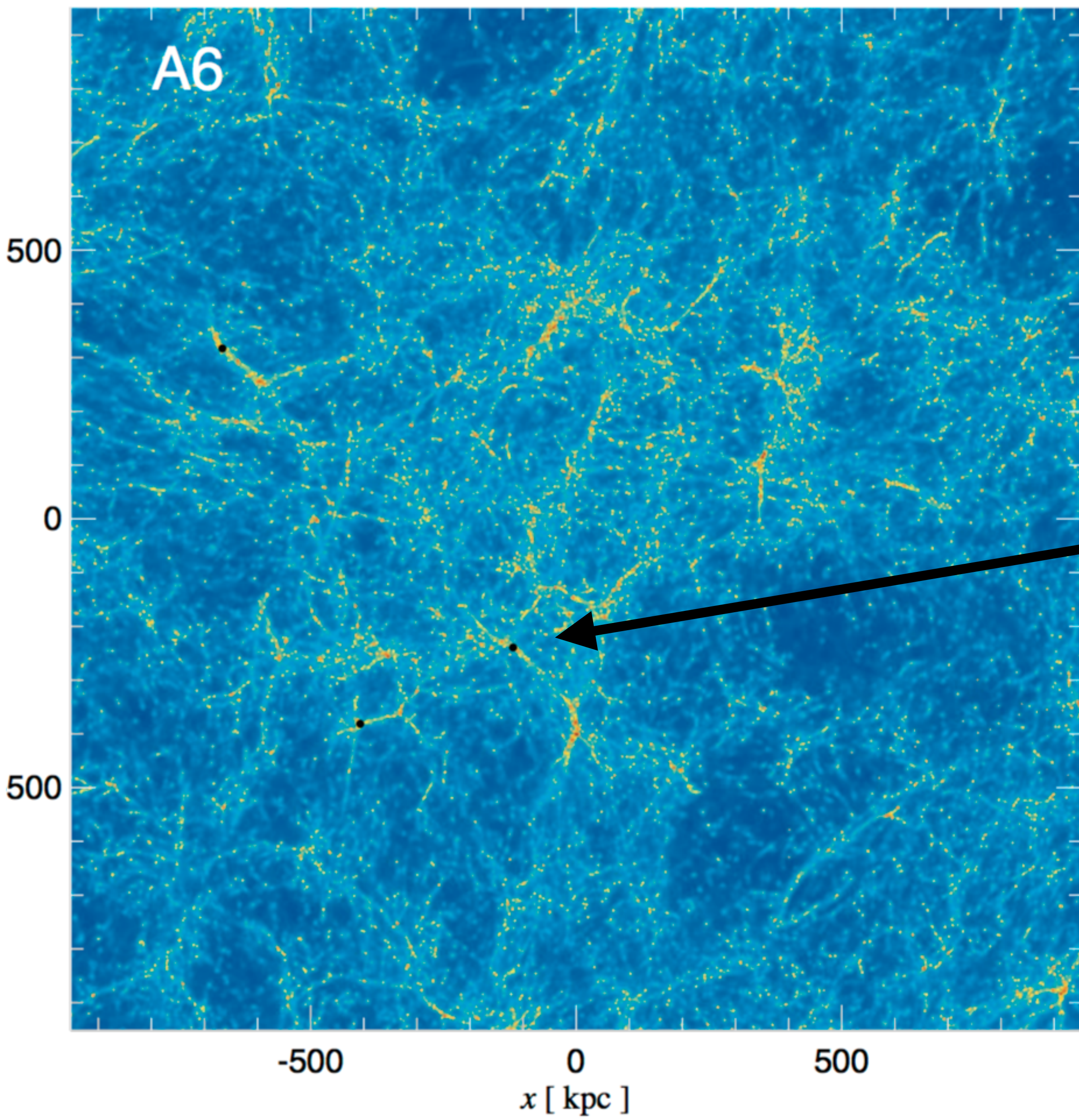
Costa, Rosdahl, Sijacki+ (in prep.)

II.
The cosmological environment

Costa+14 (II)

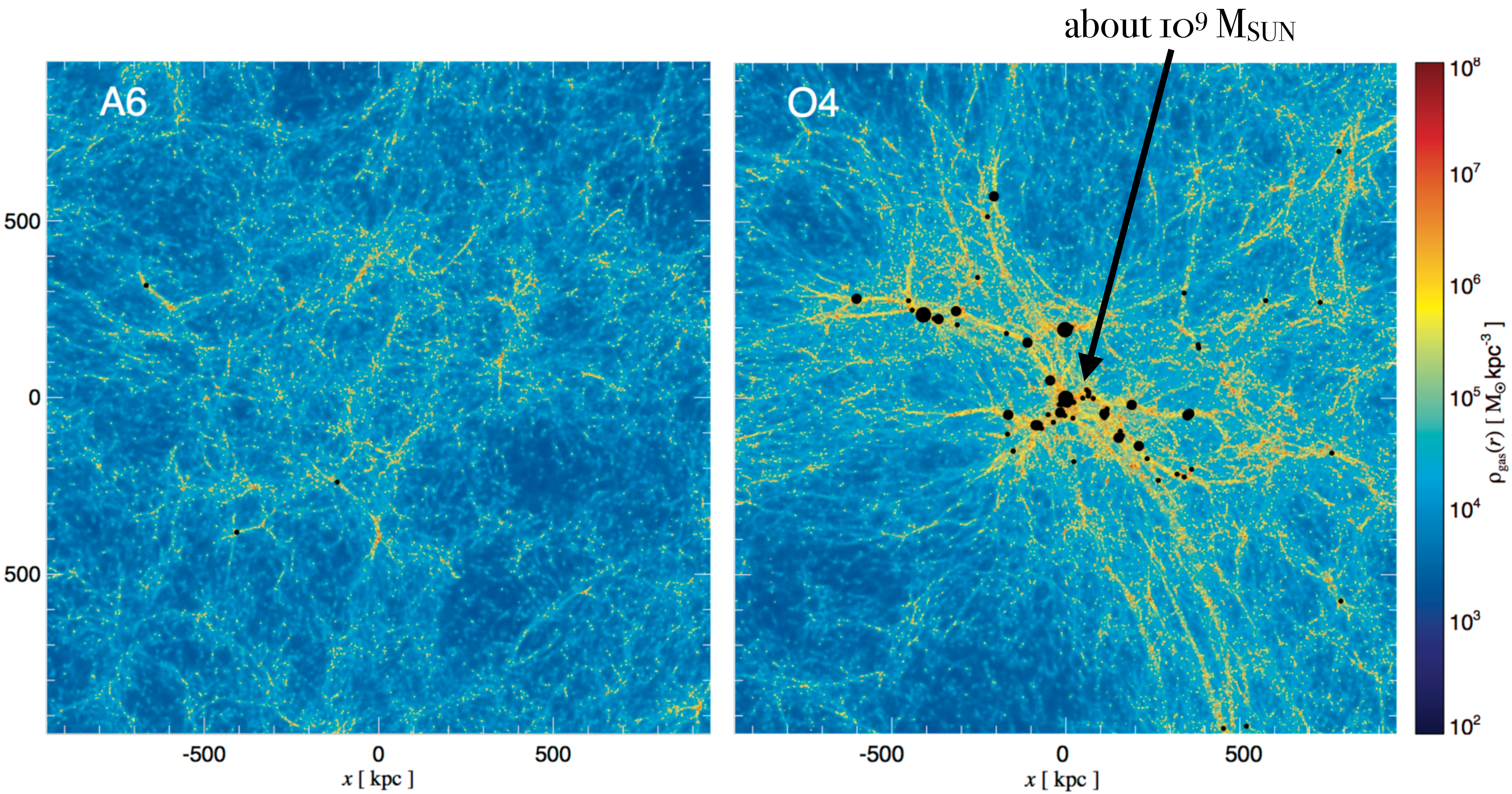


The host haloes of z = 6 quasars I



about 10^6 M_{SUN}

The host haloes of z = 6 quasars II



High-redshift quasars *probably* lie in extremely deep potential wells fed by multiple filaments.

(cf. Yohan Dubois's talk)

Numerical Simulations

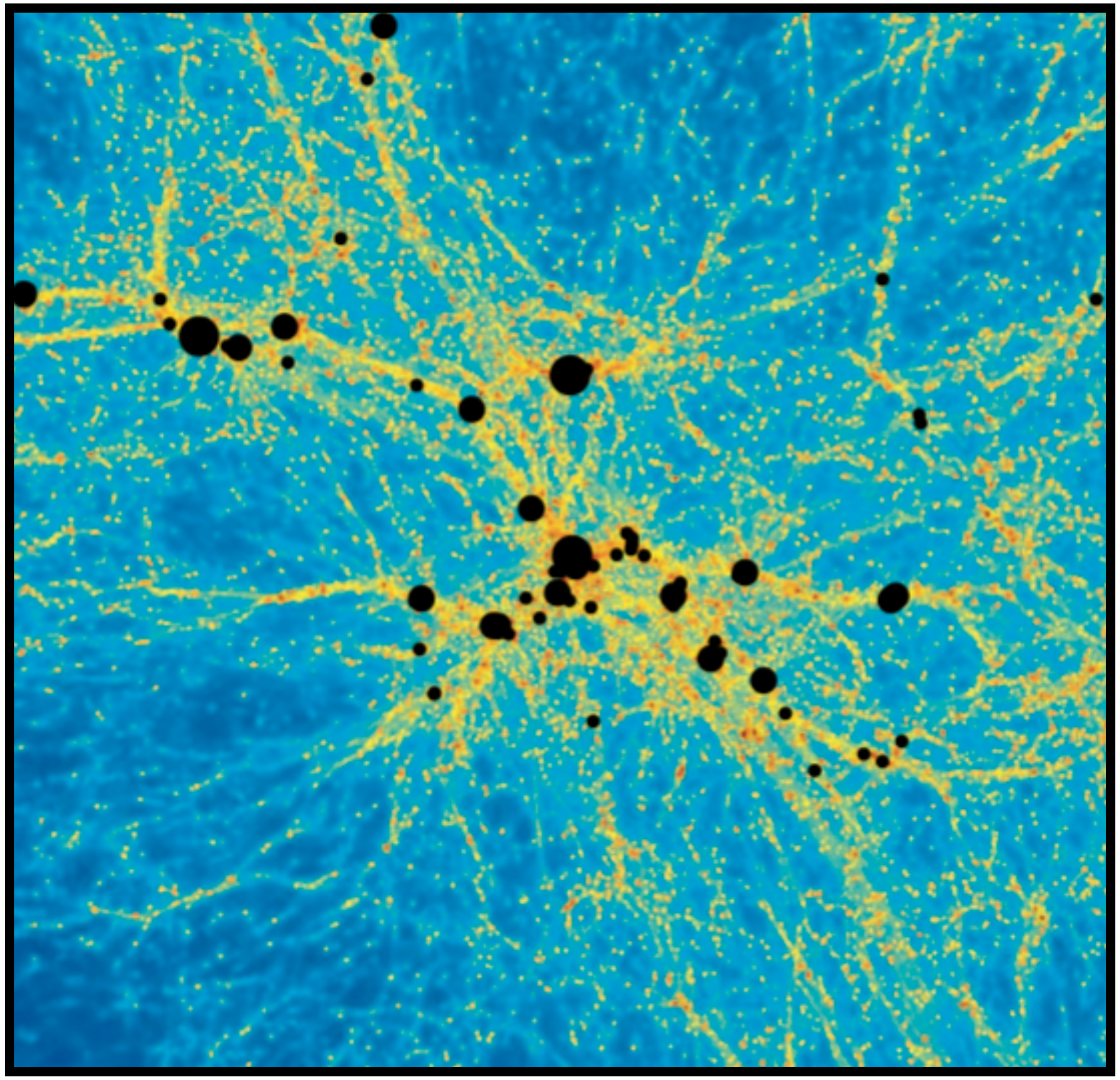
Include the *same* prescriptions for energy- and momentum-driven outflows into cosmological simulations of BH growth, including:

1. Radiative cooling & star formation

2. AGN at different constant luminosities (for the purpose of comparison with simple analytical models).

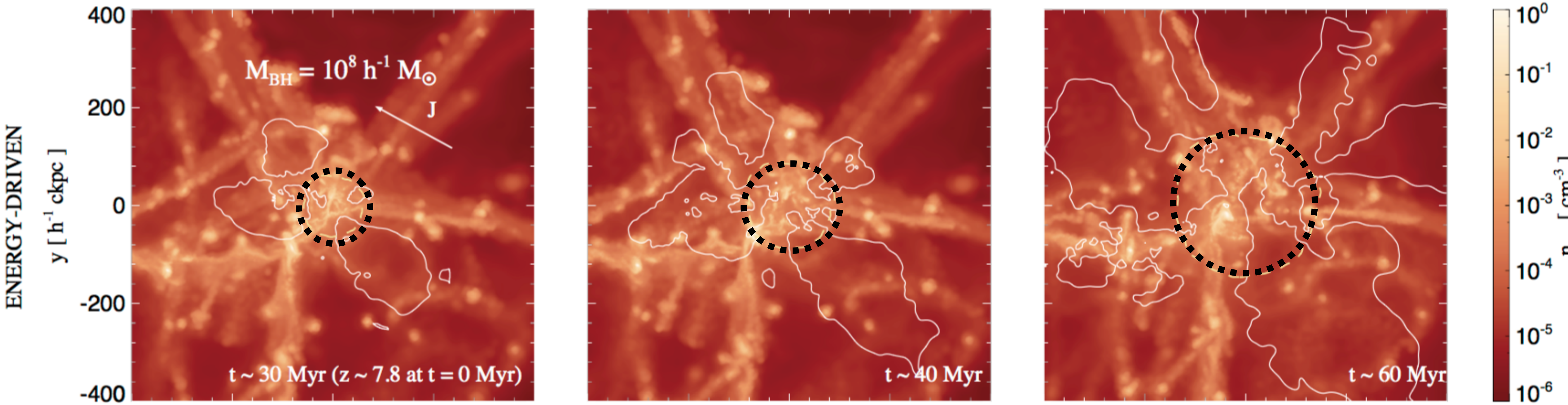
Perform simulations for an identical halo, but now addressed in isolation.

Maximum resolution: 70 pc.



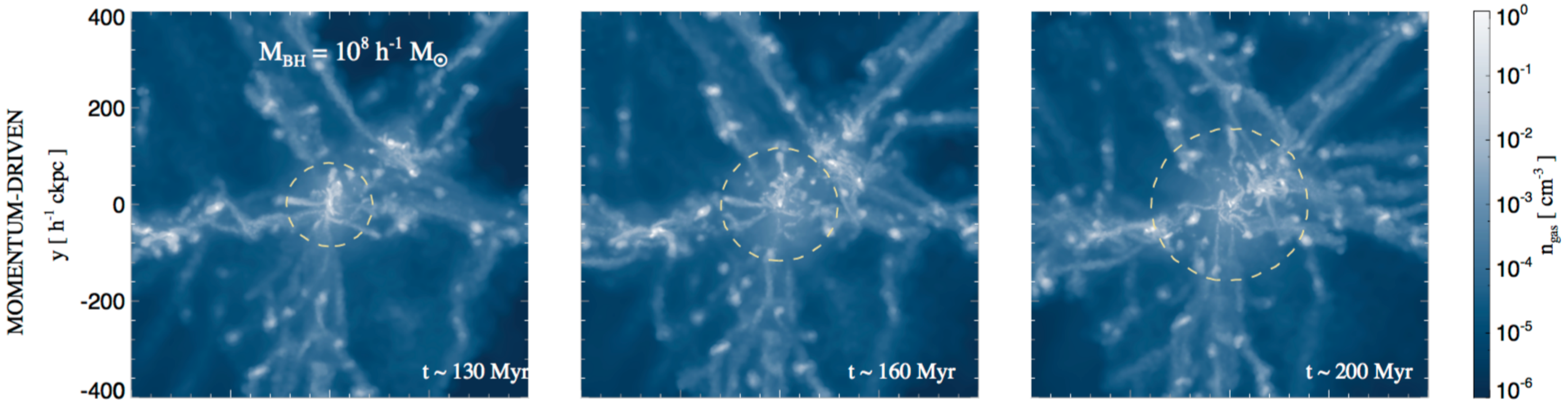
Goal: Given the same AGN-driving mechanism, how does its efficiency change by including a realistic treatment of the cosmological environment?

The energy-driven limit



Outflows take paths of least resistance.
While slightly less efficient, energy-driven outflows are sufficiently energetic to evacuate the quasar host potential.

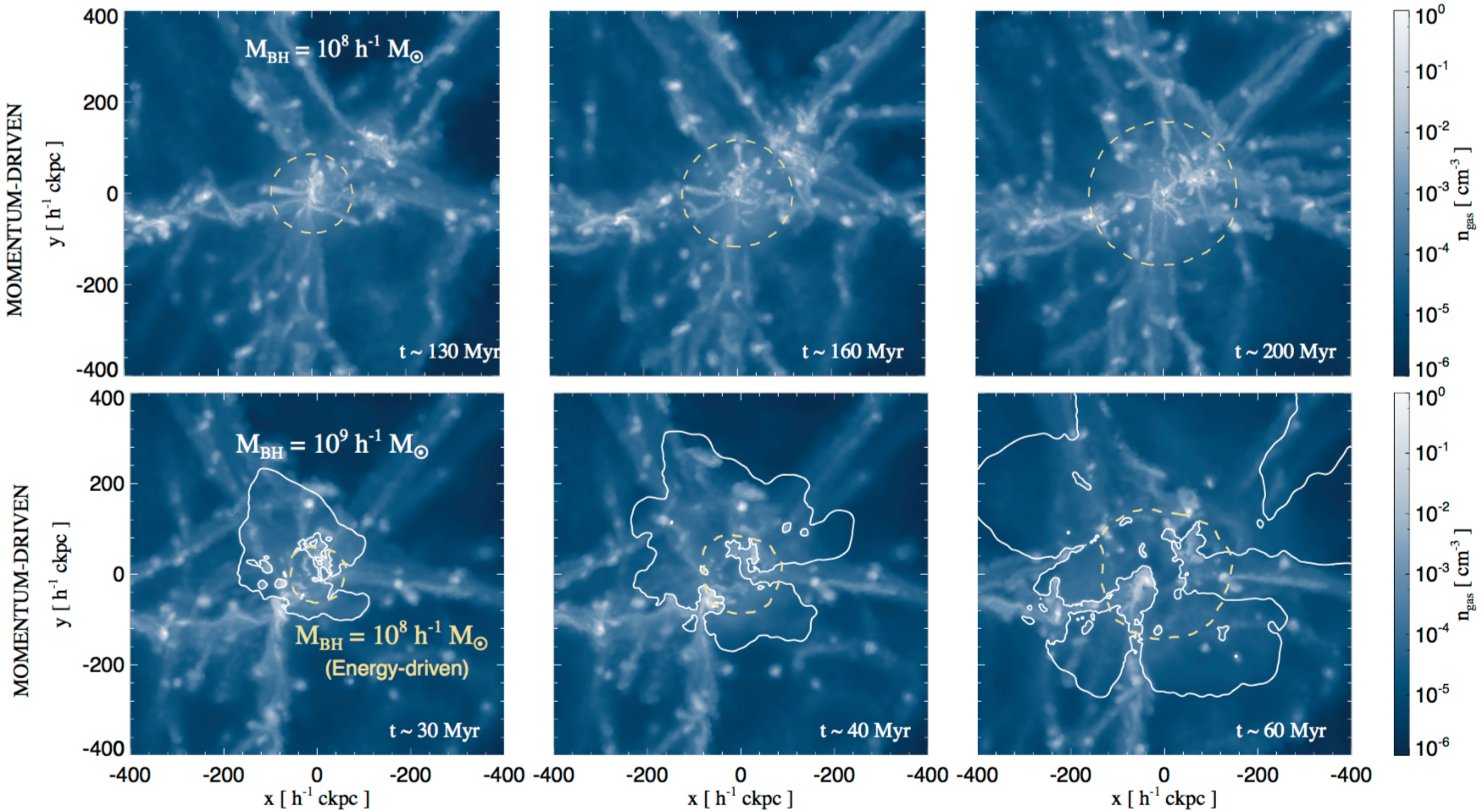
The momentum-driven limit



Momentum-driven outflows inefficient already at scales > 70 pc.

Crucially, a momentum flux of L/c is insufficient to prevent the innermost regions of the halo from being replenished.

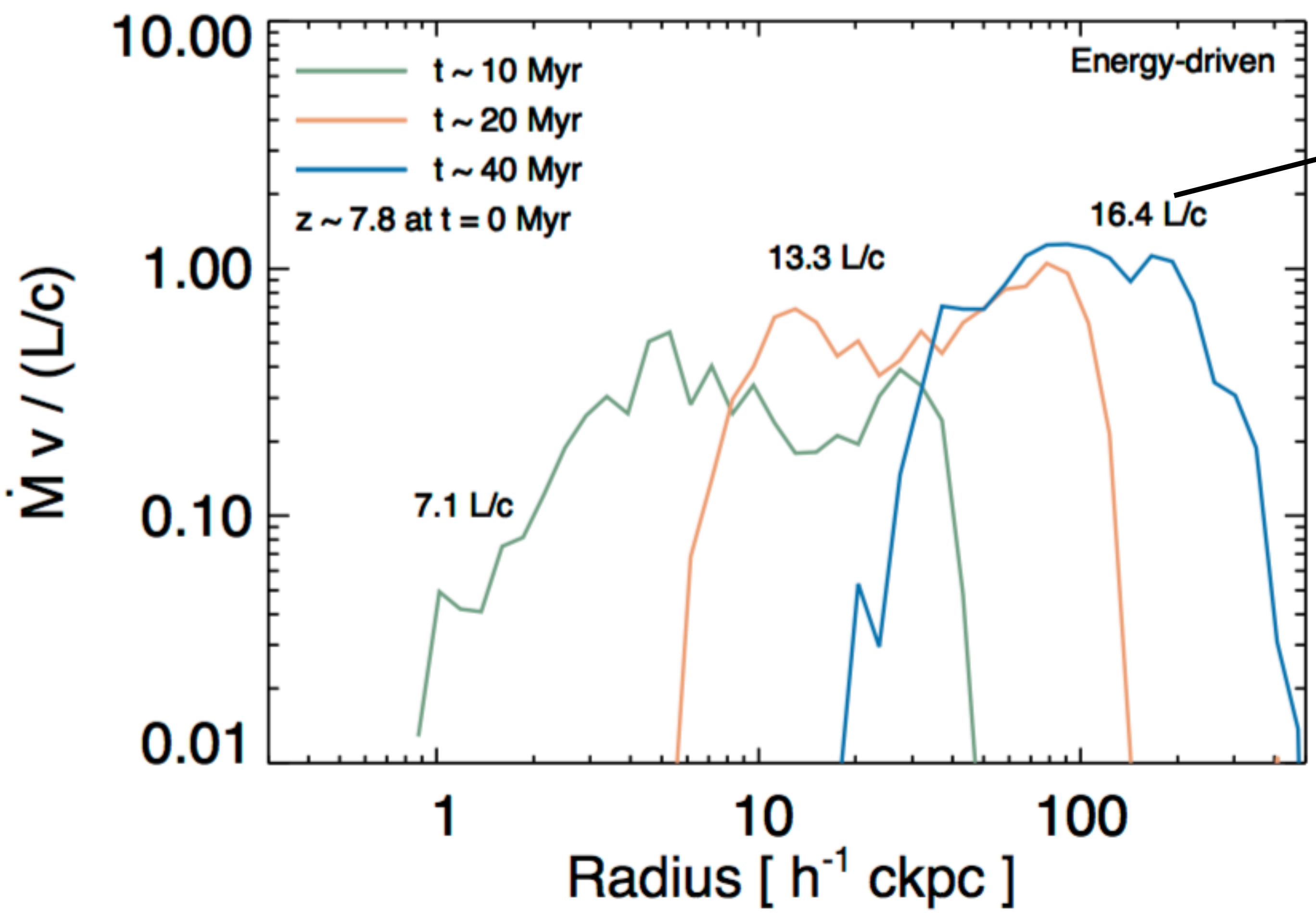
The momentum-driven limit

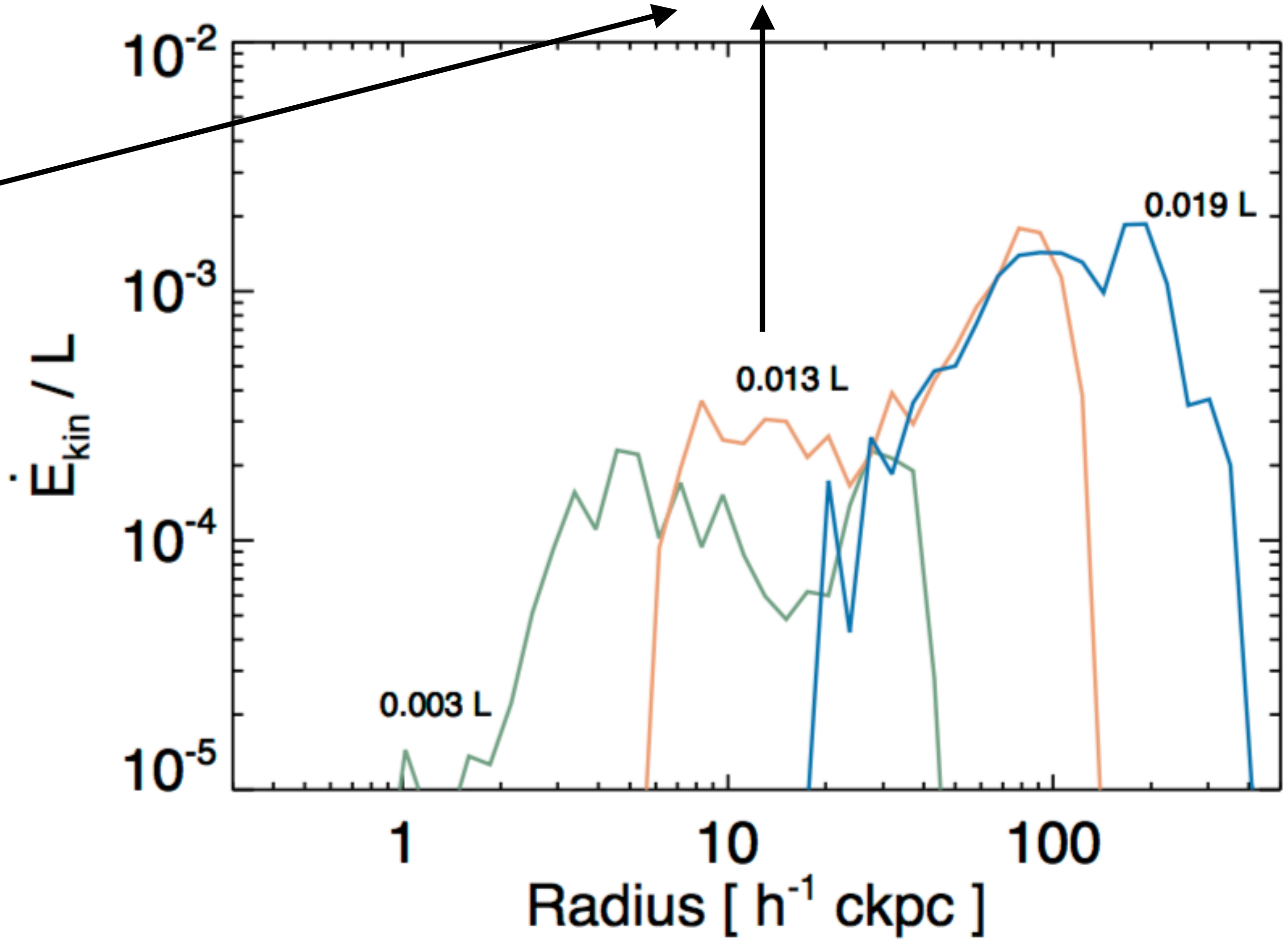


A momentum flux of10 L/c is about sufficient.

Energy-driven outflows

Integrated values

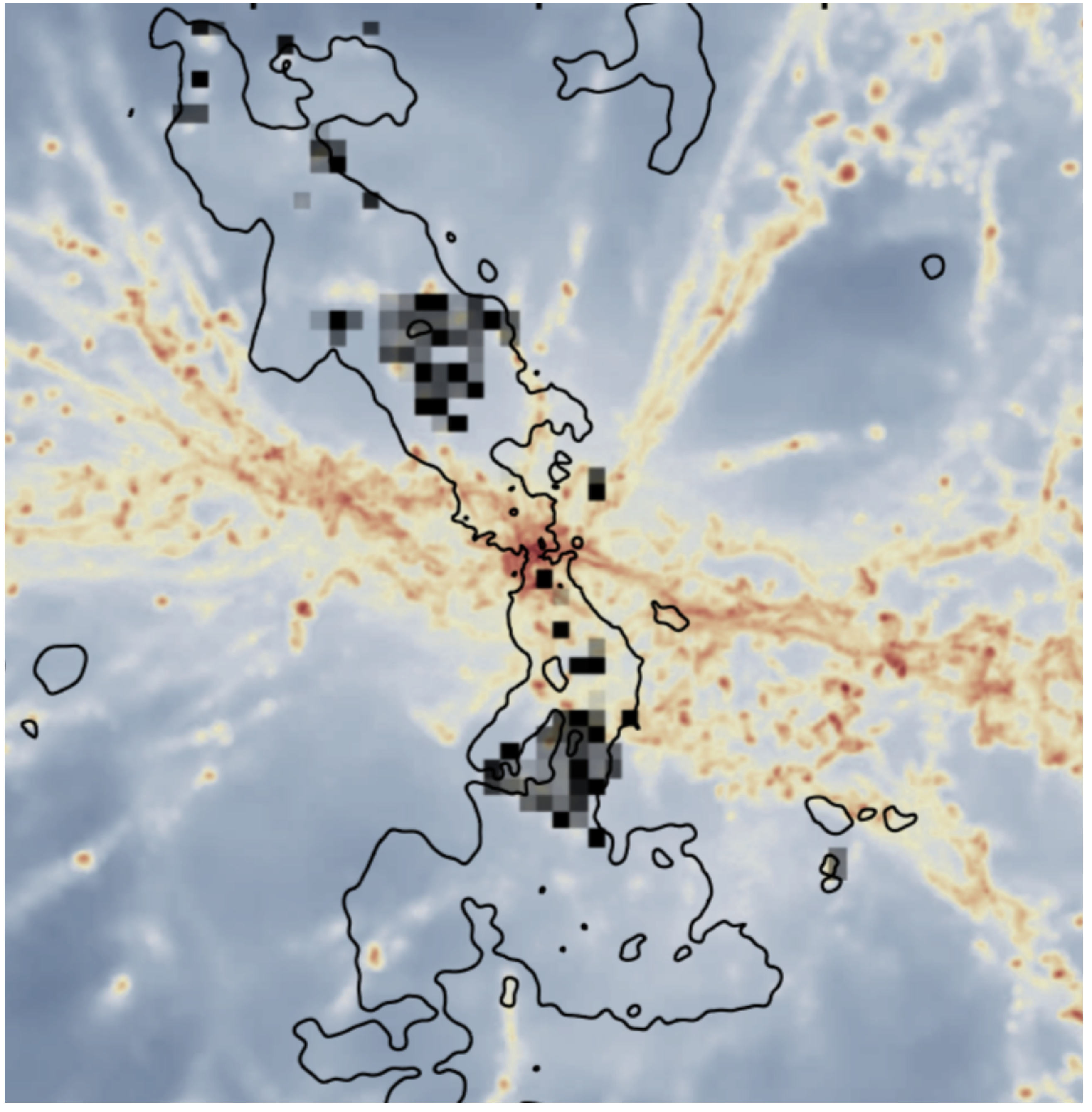




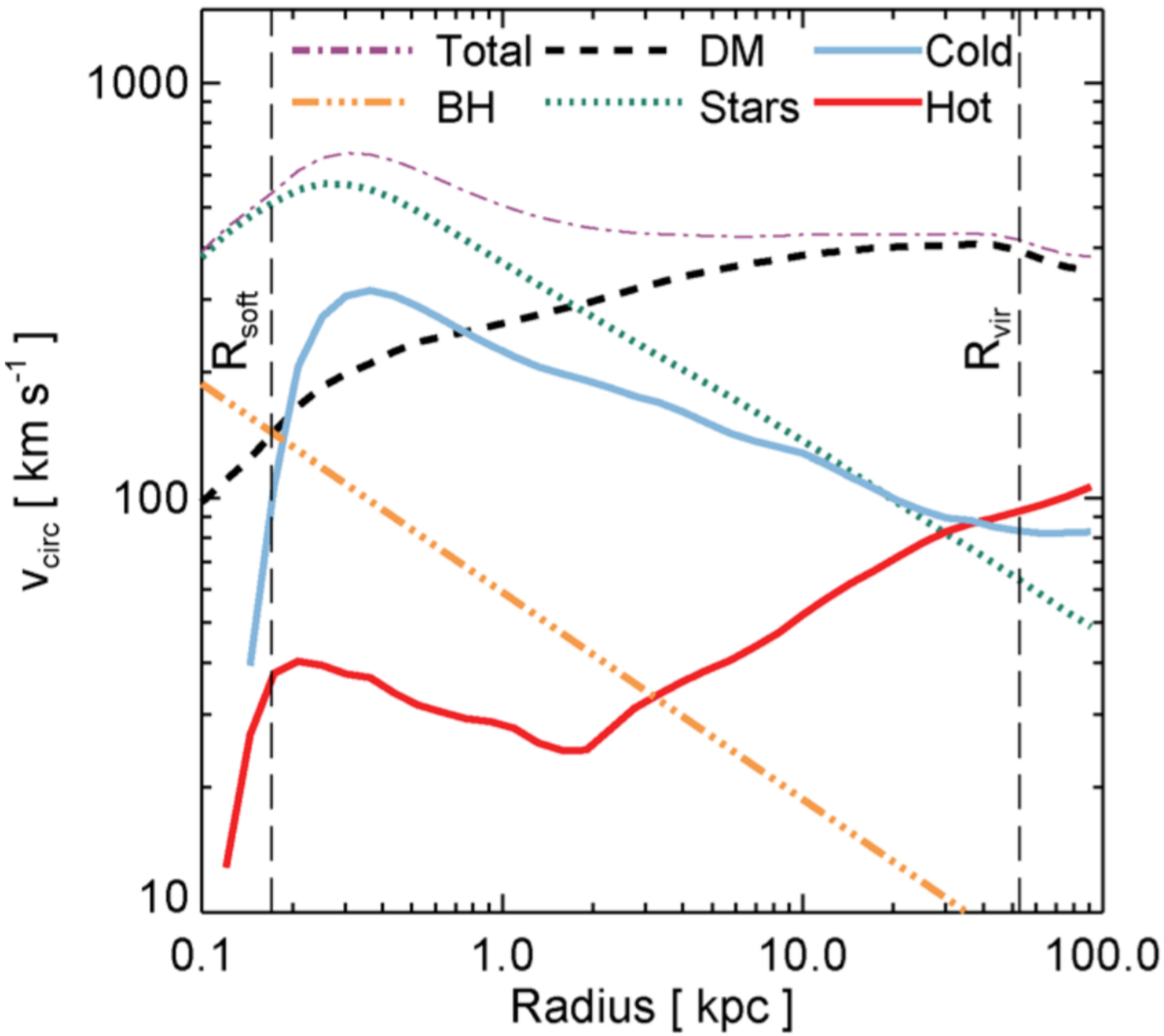
High momentum fluxes and kinetic luminosities reproducible in cosmological simulations as required by observational constrains.

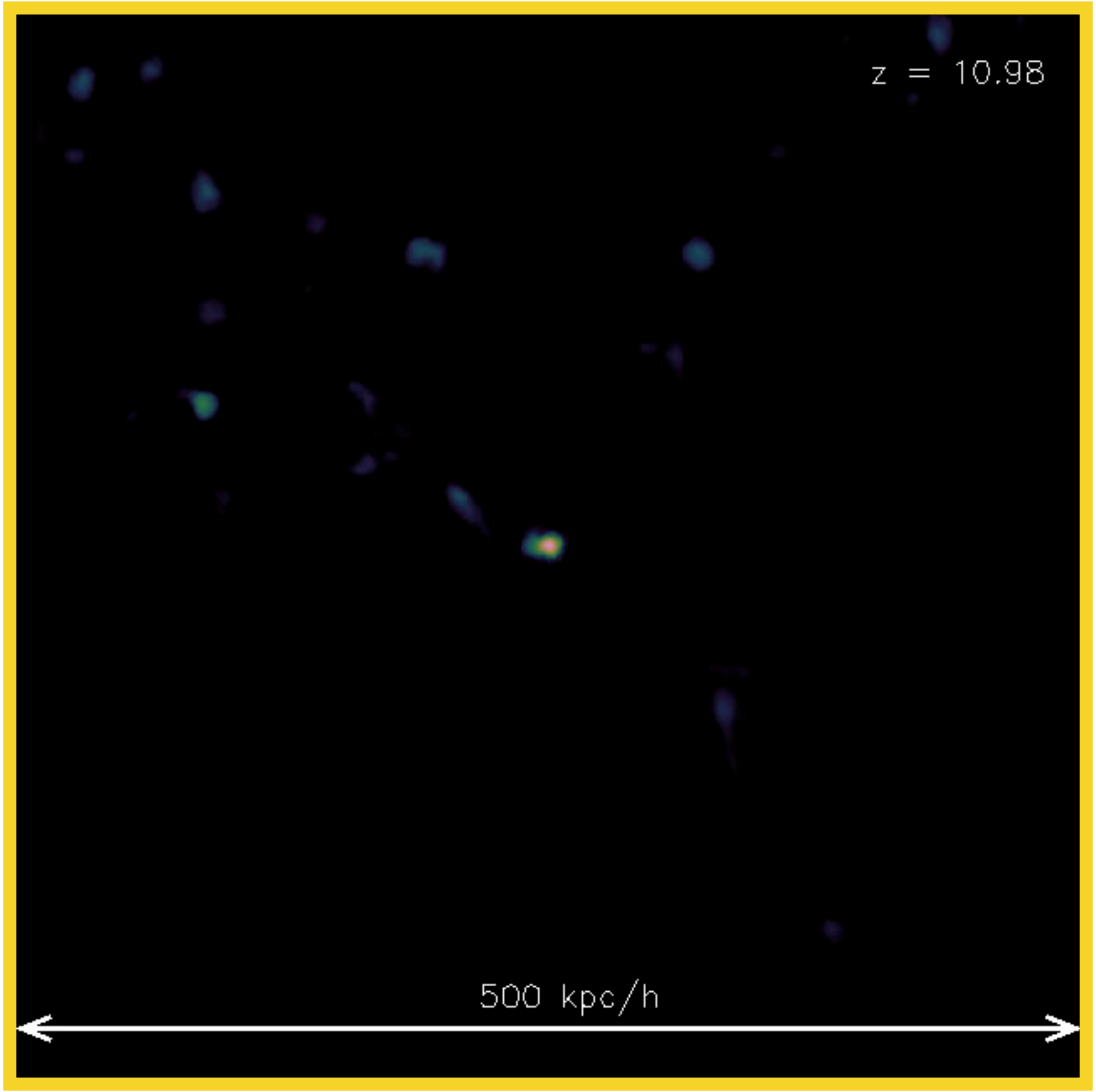
III.
The origin of cold outflowing gas

Costa+15



The host haloes of z = 6 quasars III



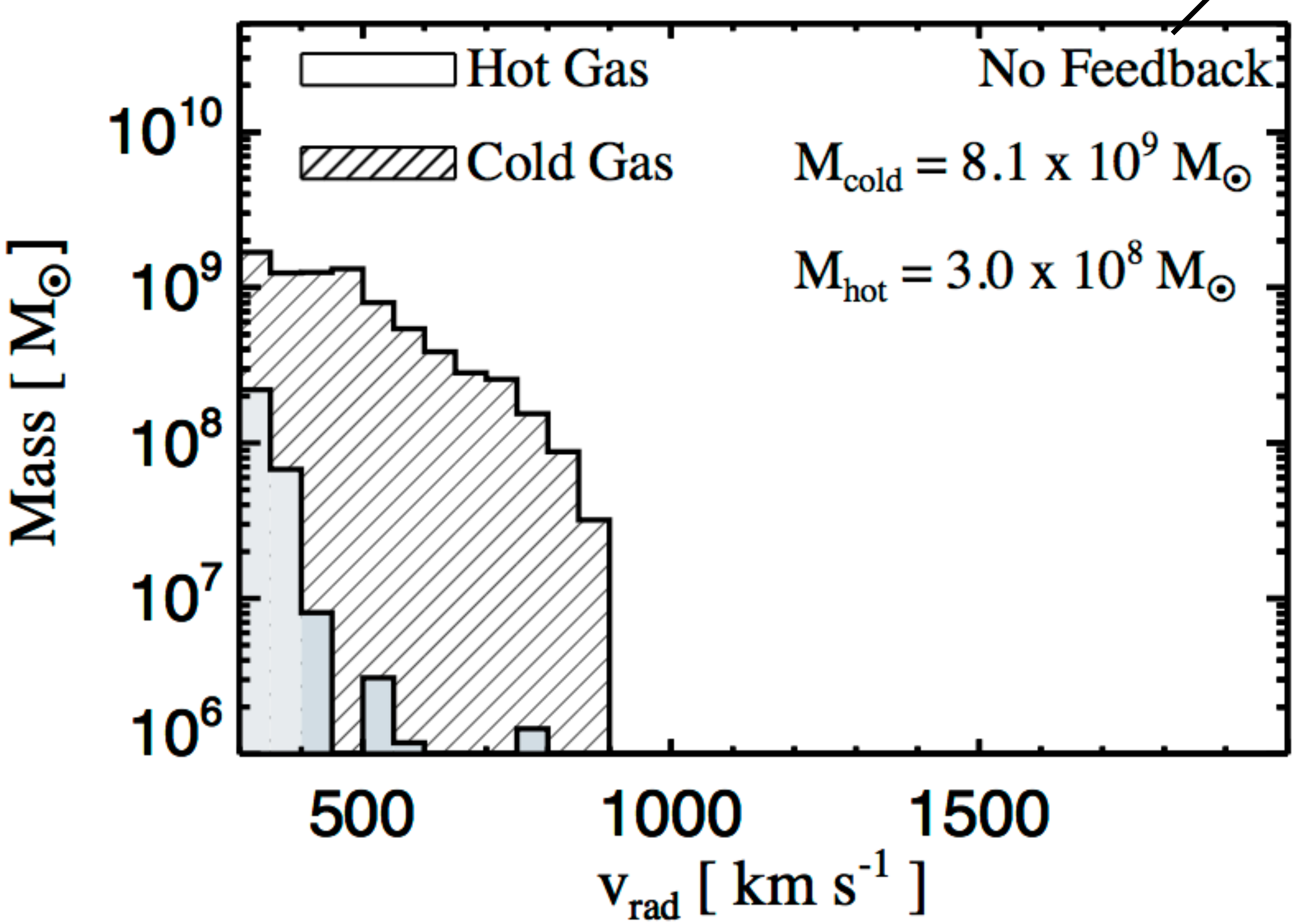


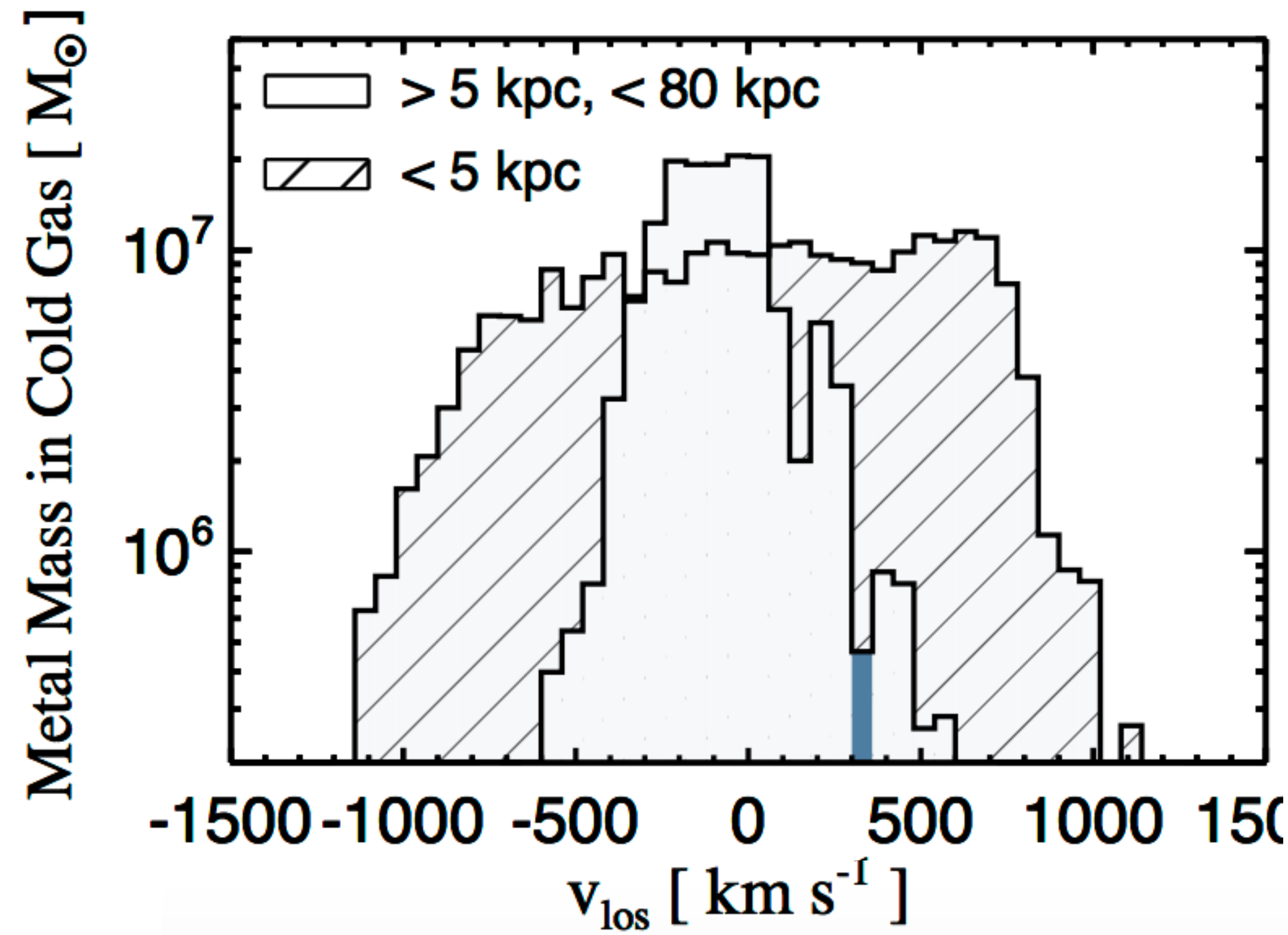
High-redshift quasars *probably* lie in extremely deep potential wells.
Circular velocity can exceed 500 km/s even in the presence of strong feedback.

Costa+15

In-situ cold gas formation I

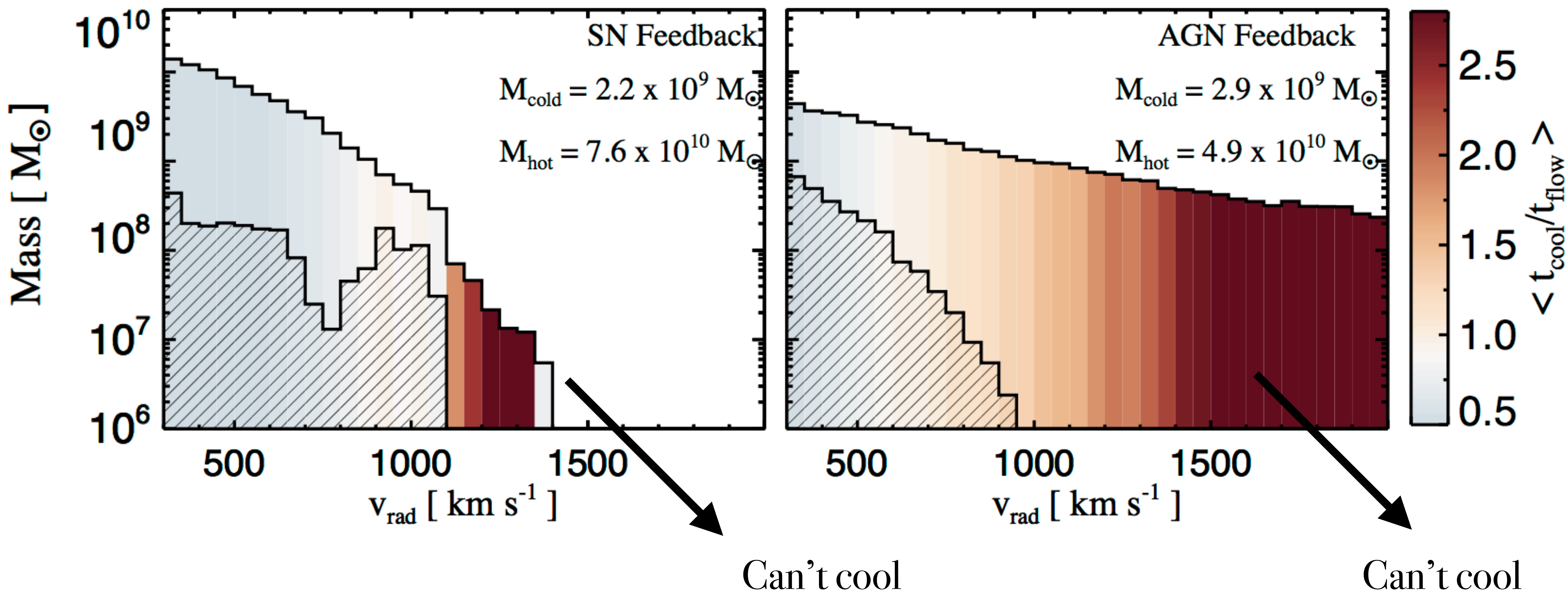
Potential well unrealistically deep in this case.





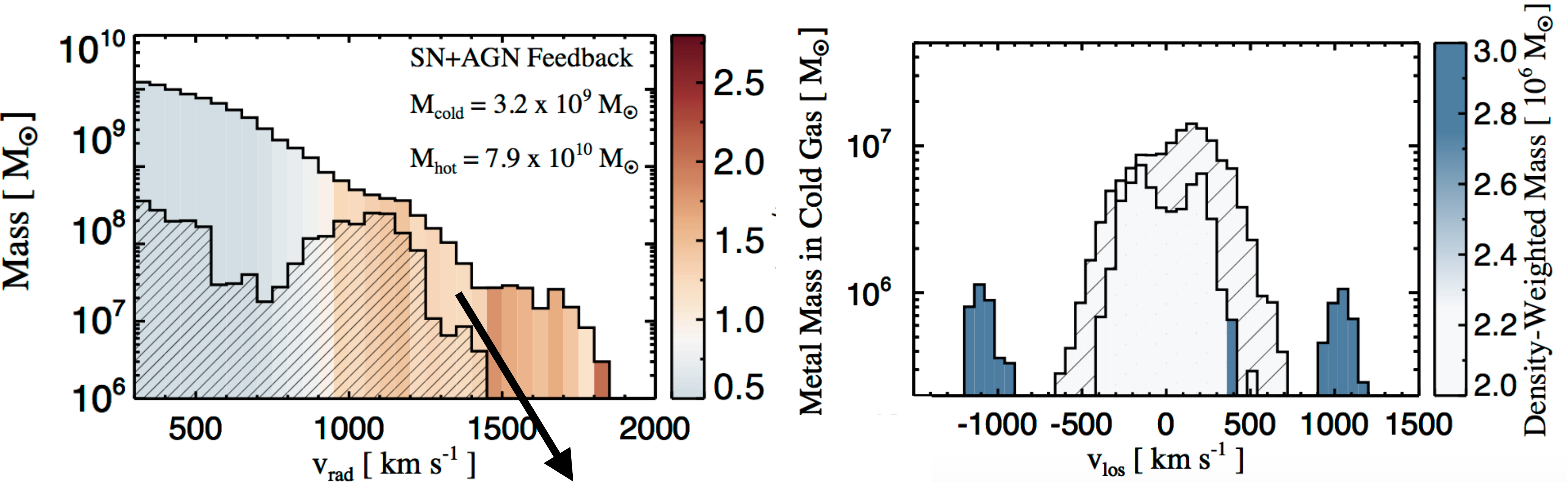
High-redshift quasars *probably* lie in extremely deep potential wells.
Gas can be accelerated to speeds > 500 km/s due to gravity alone.

In-situ cold gas formation II



Hard to cool in-situ at > 5 kpc in cosmological simulations, since outflows quickly expand into low density regions, where cooling times are long.

In-situ cold gas formation III



This gas **must** leave the halo and it also cools.

Radiative cooling of hot outflowing gas can lead to in-situ cold gas formation provided that IGM is clumpy and metal-enriched.

Important physics most likely missing: radiation pressure on dust, low T cooling and non-equilibrium chemistry, MHD, conduction, …

(Zubovas & King 14, Thompson+15)

Conclusions

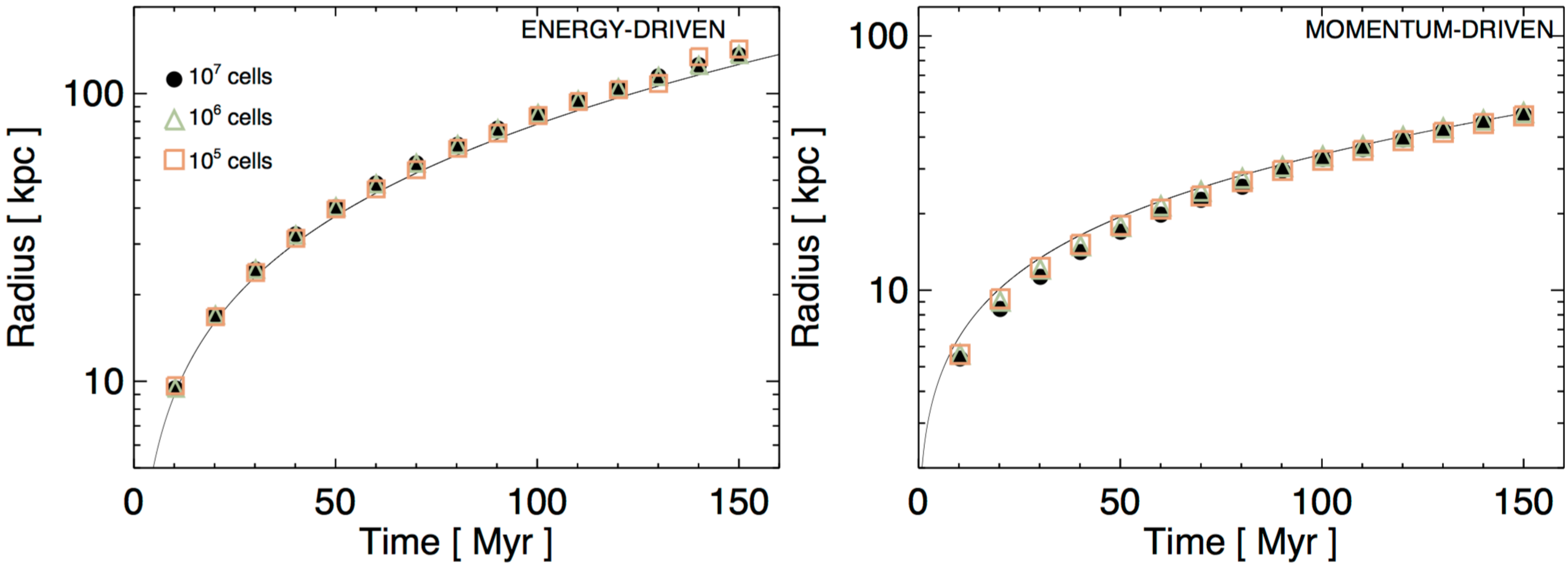
- Outflows require momentum fluxes >> L/c in order to revert inflows and eject large masses of gas out of massive quasar host haloes.

- Momentum-driven outflows (or any outflow carrying a momentum flux of about L/c) fall short already at scales < 100 pc.

- Energy-driven outflows are sufficiently energetic, but "quenching" occurs only temporarily in the rapid cooling phase.

- Cold outflowing gas extended over scales > 10 kpc can form in-situ via radiative cooling, provided the IGM is pre-enriched with metals and dense clumps.

Numerical convergence



Numerical models are well converged.

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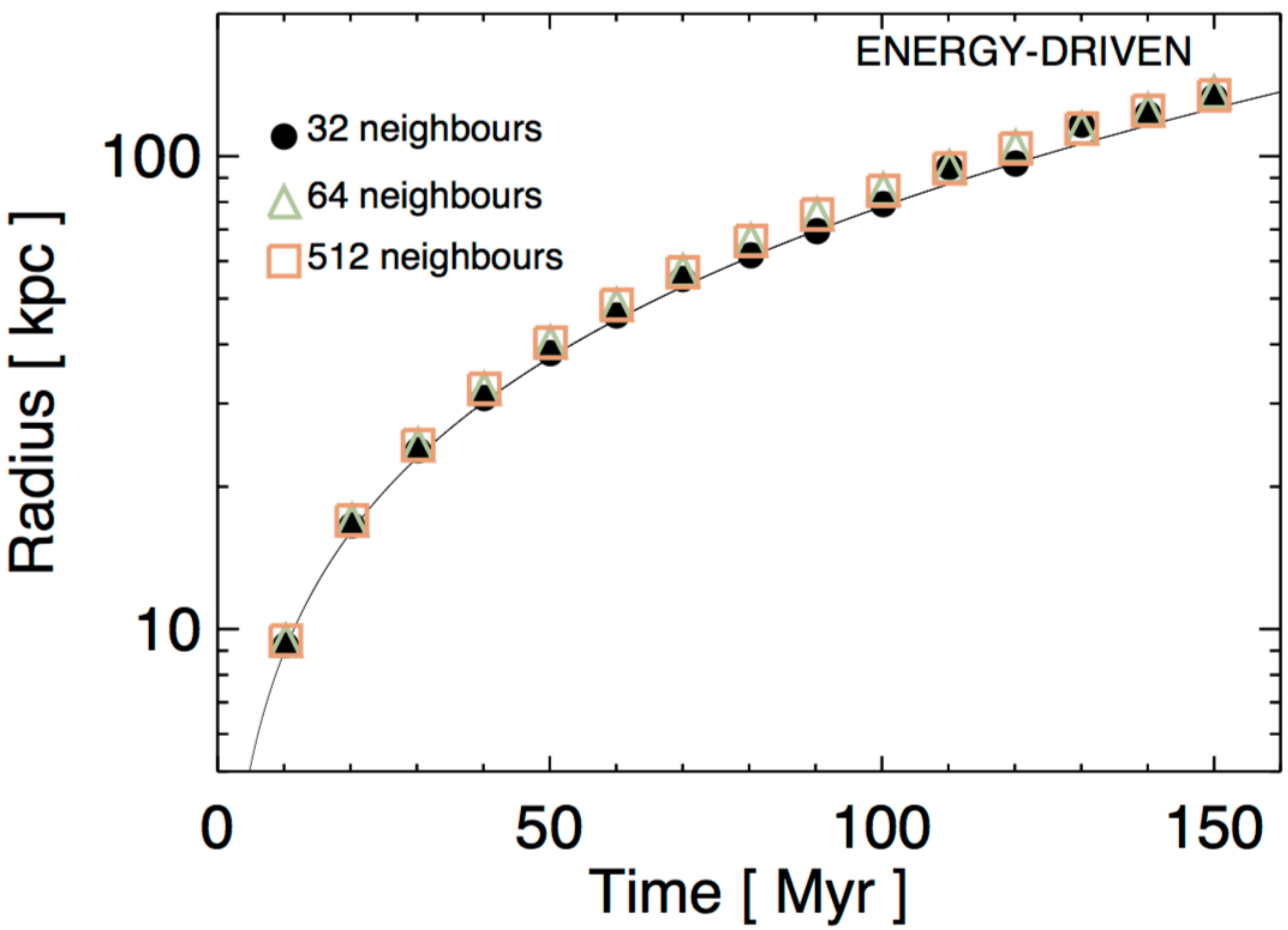
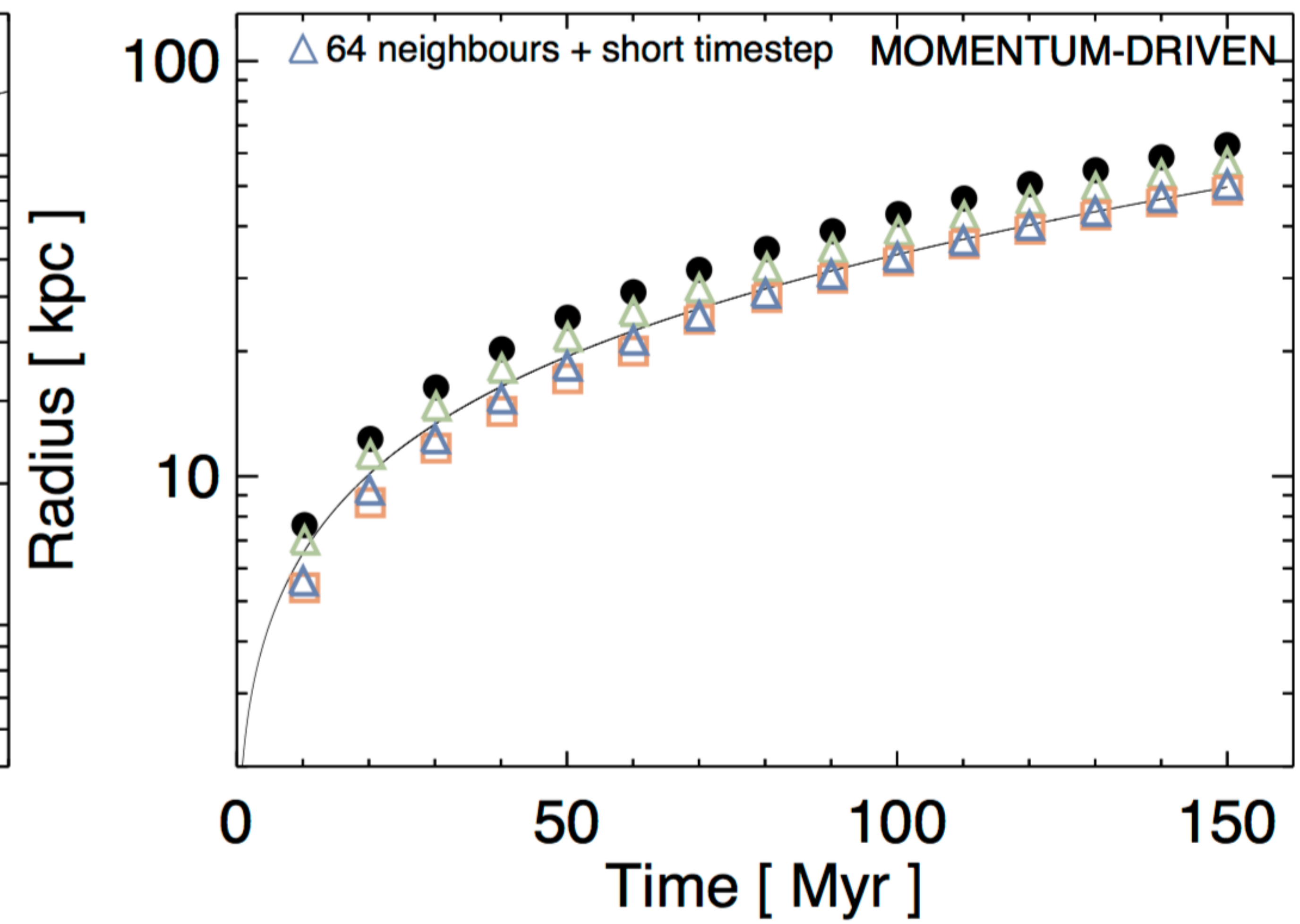
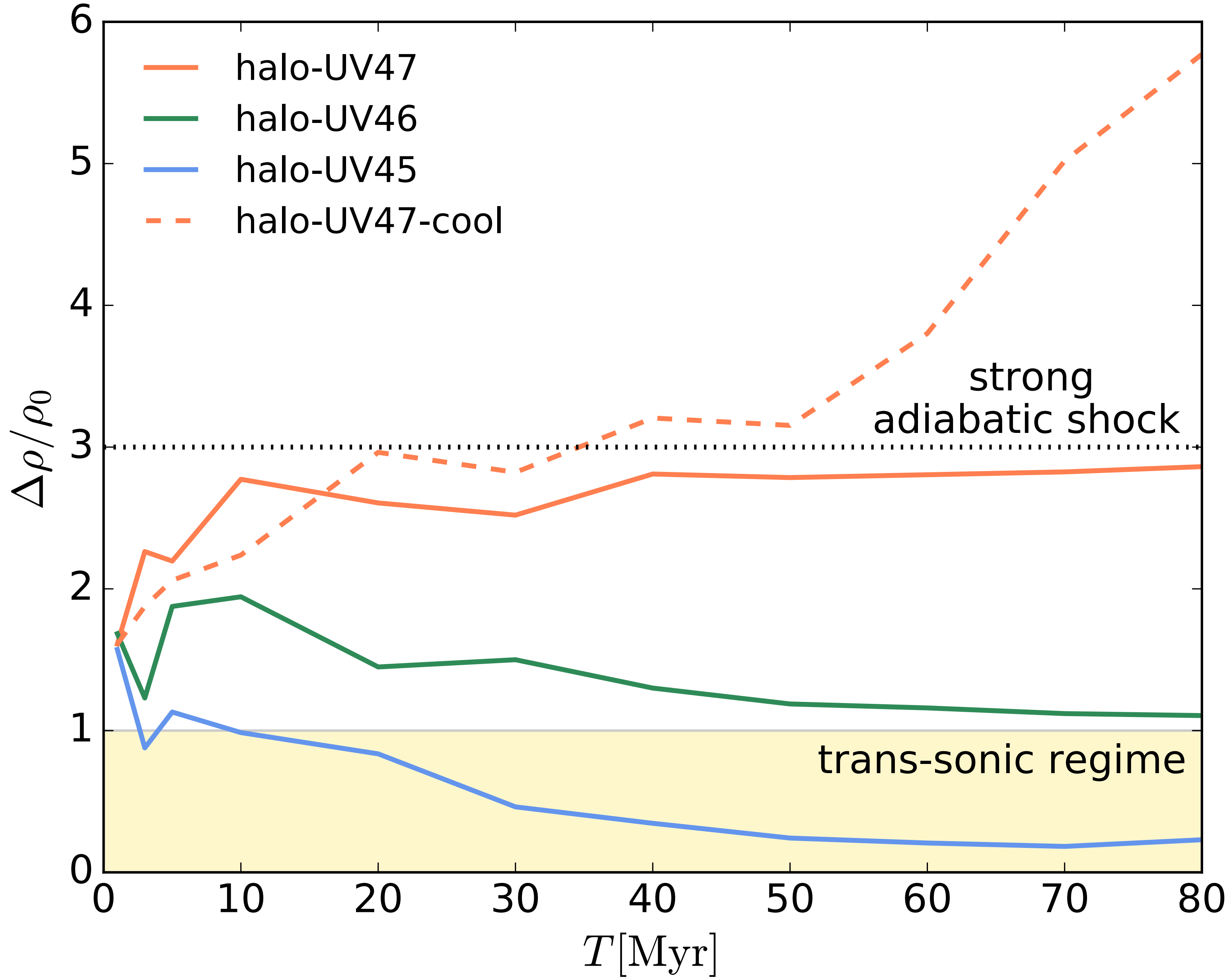




Radiation pressure on dust

PRELIMINARY



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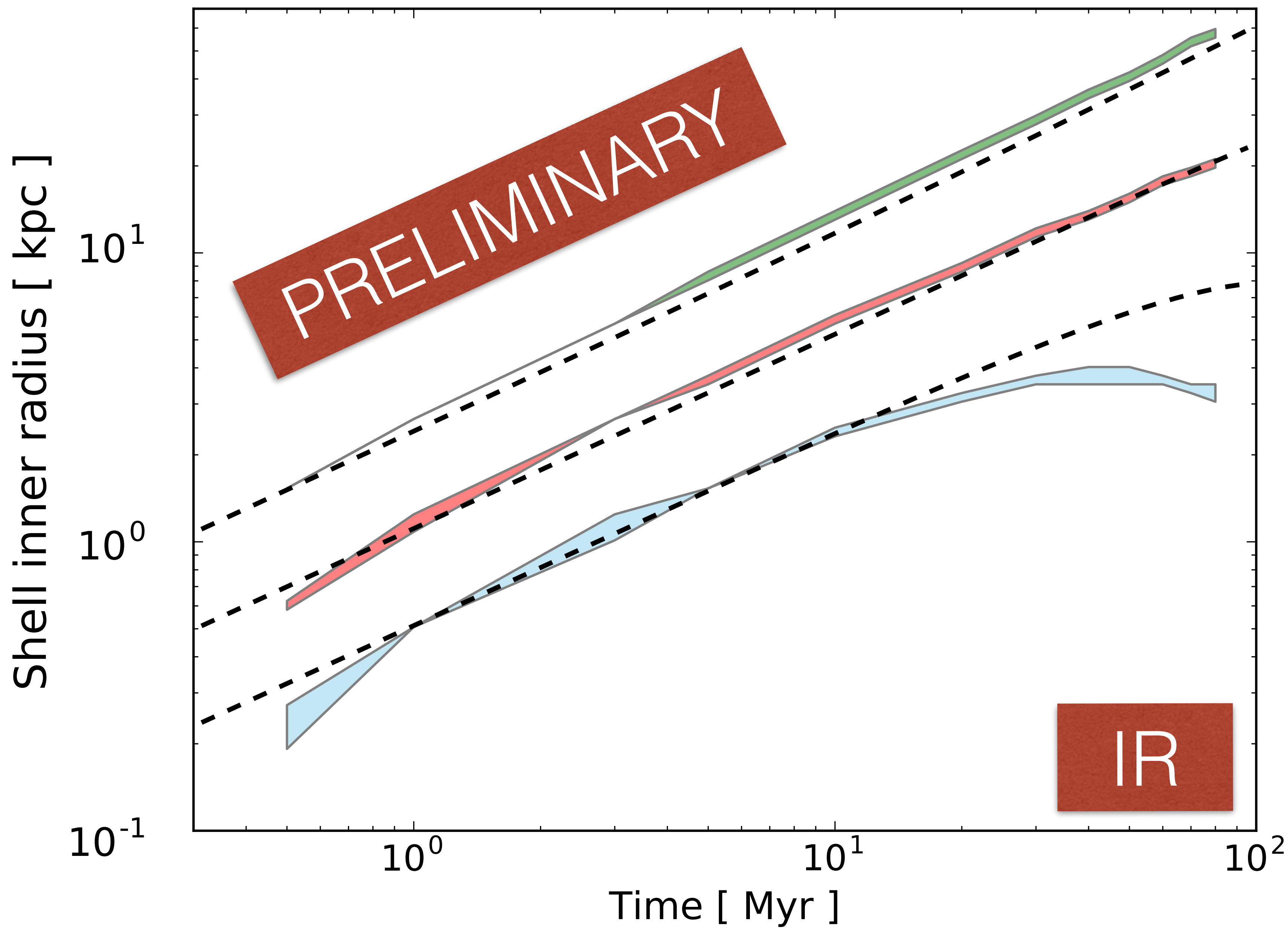

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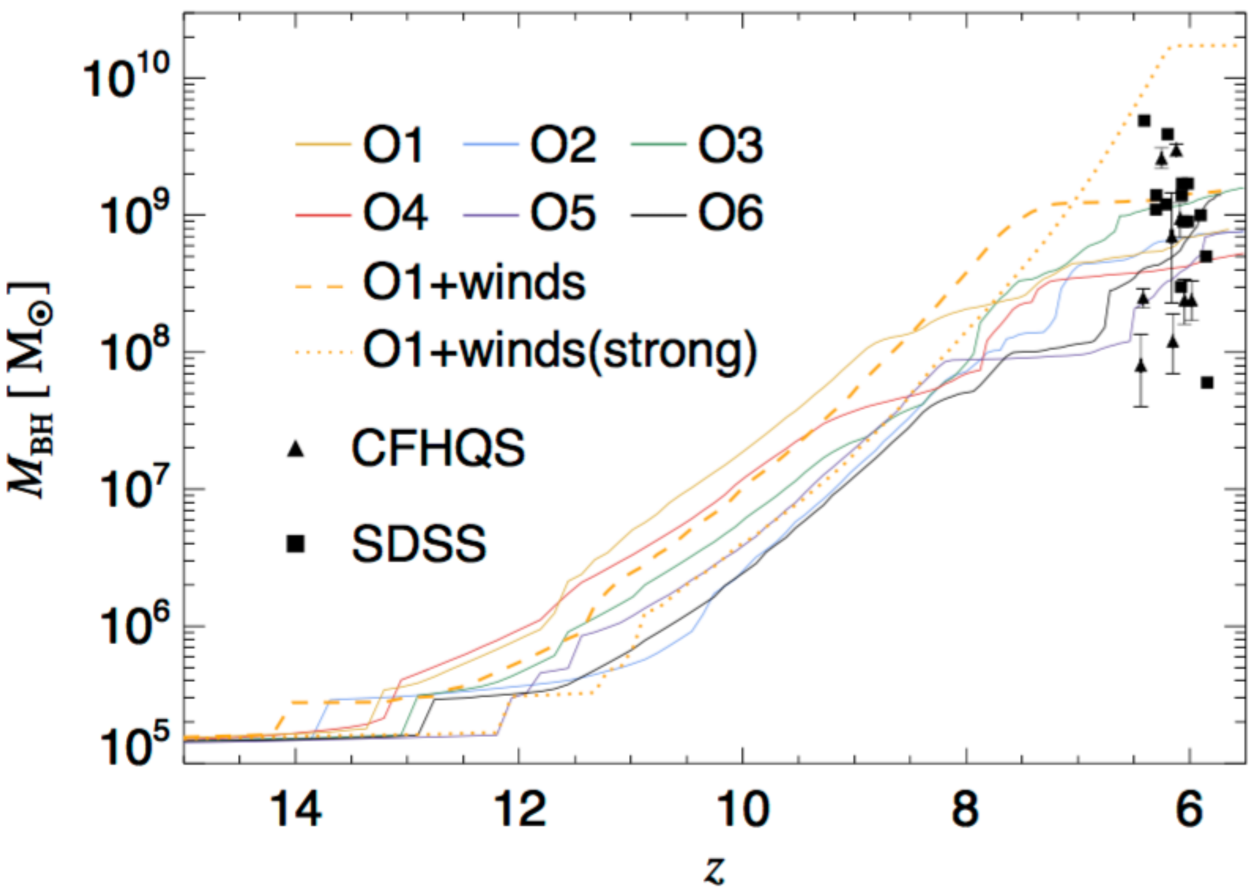
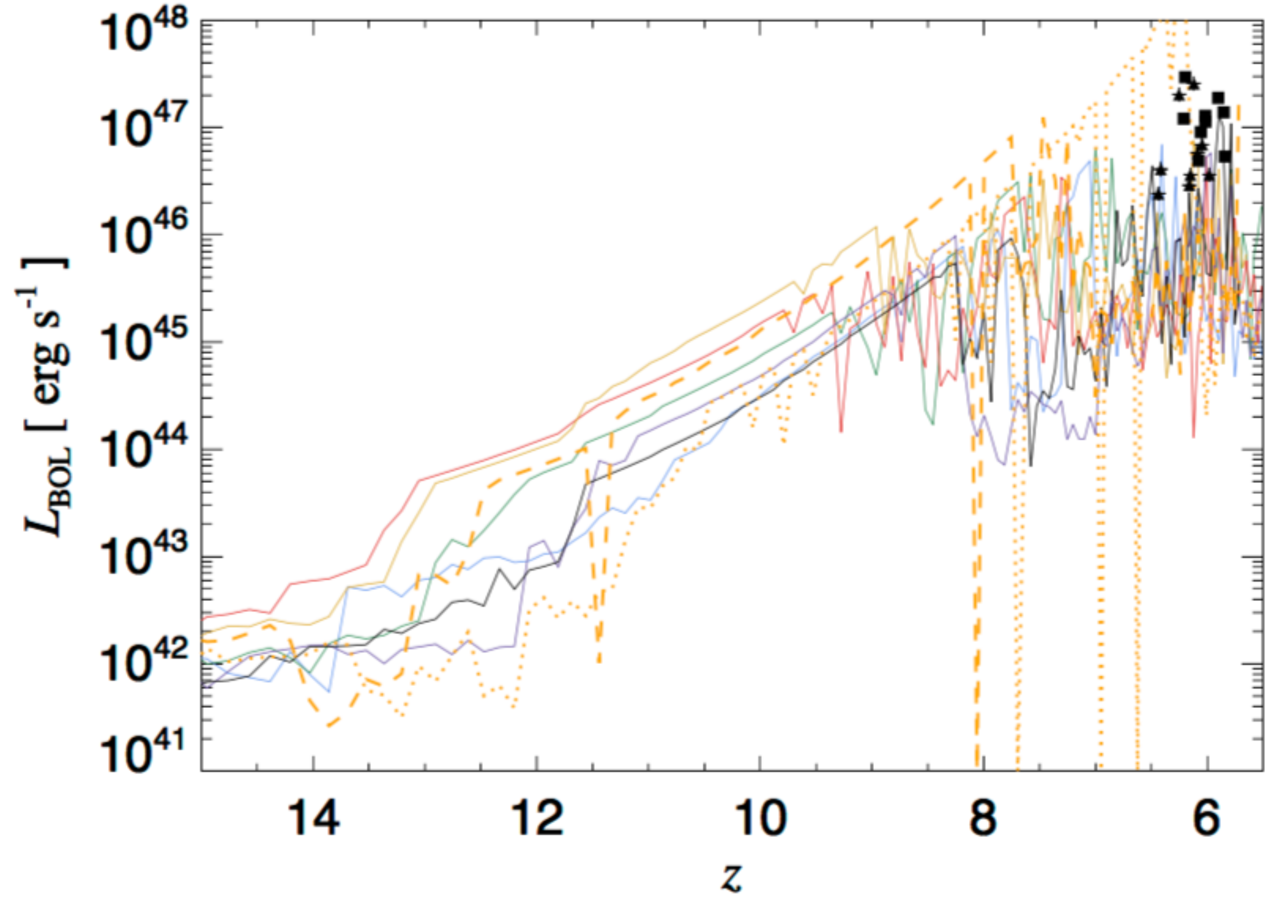
The host haloes of z = 6 quasars





In order to grow to masses > 10^9 M_{SUN} by z = 6, high-redshift quasars must be hosted by massive (> 5×10^{12} M_{SUN}) and rare dark matter haloes.