Quasar Feedback

In Theory and in Practice

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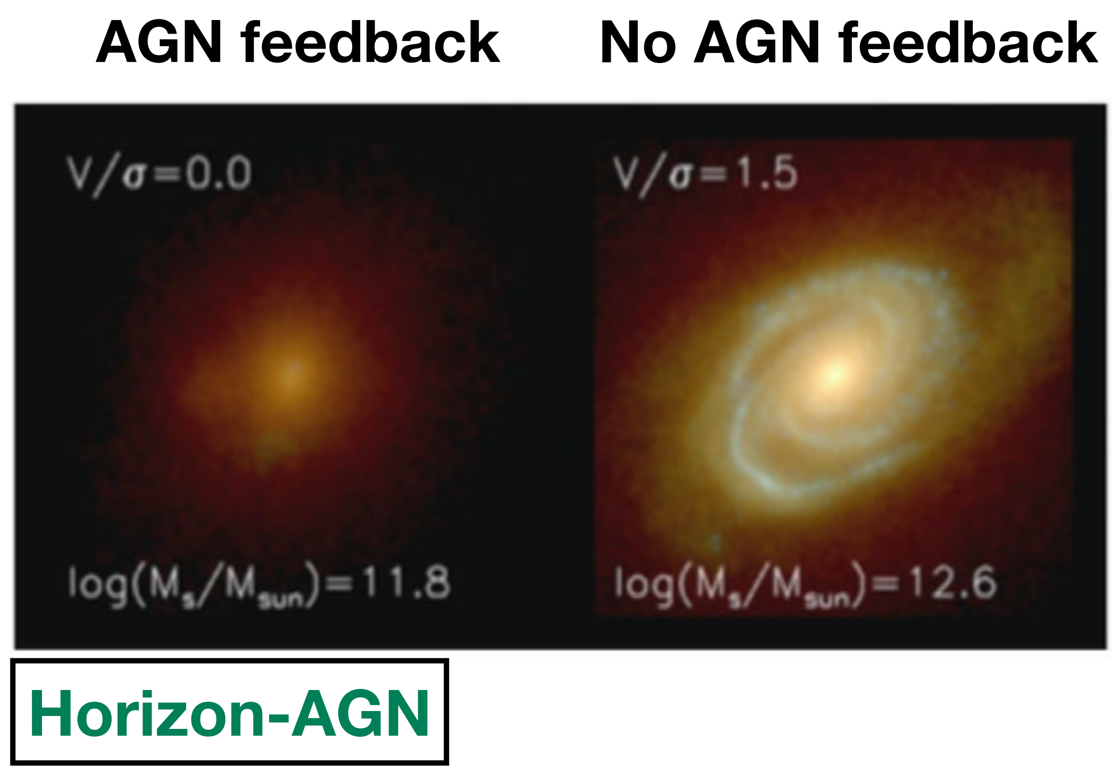
Newcastle University, UK

18 Jul 2025, “18th Potsdam Thinkshop”, Potsdam, Germany

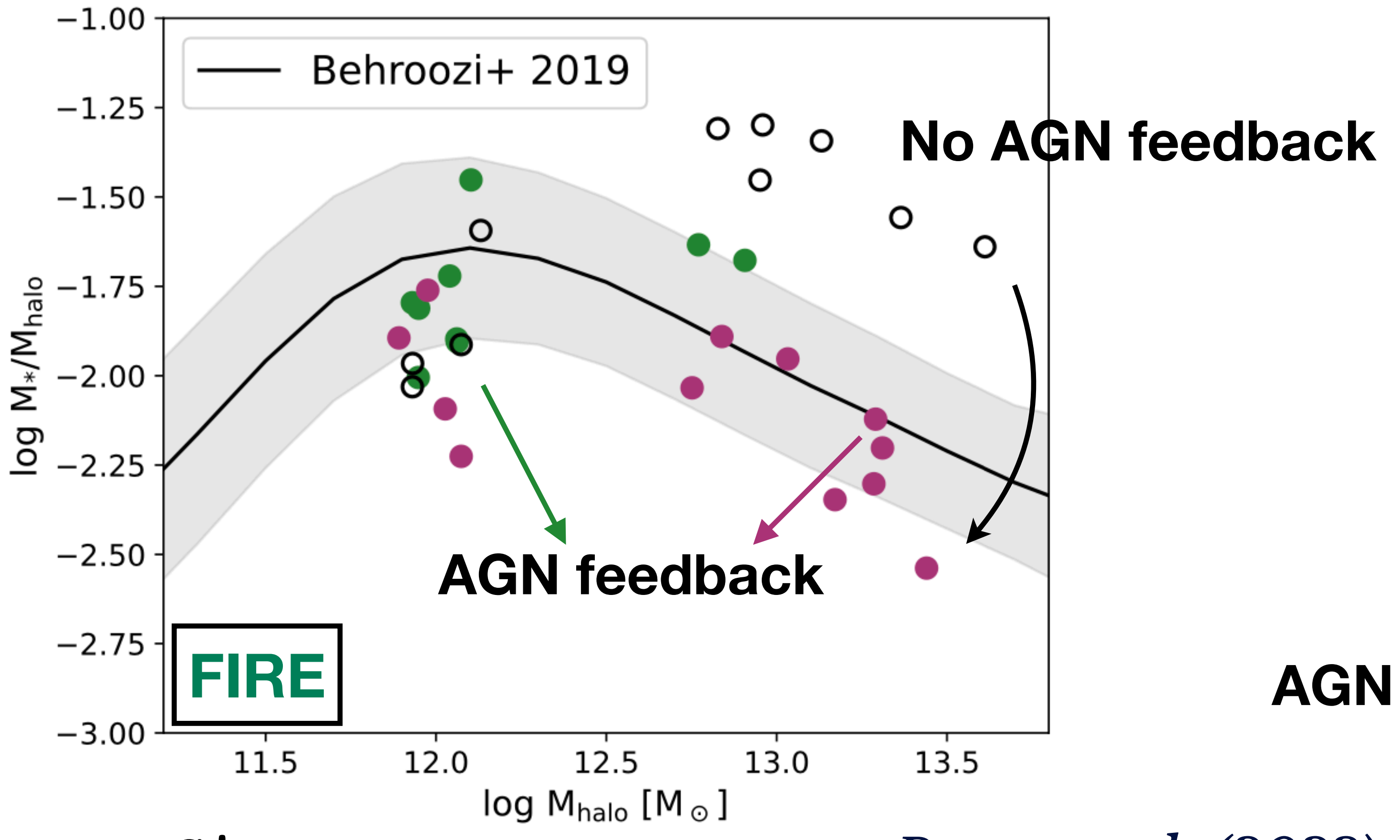
The Universe without AGN

Galaxy morphology & colours



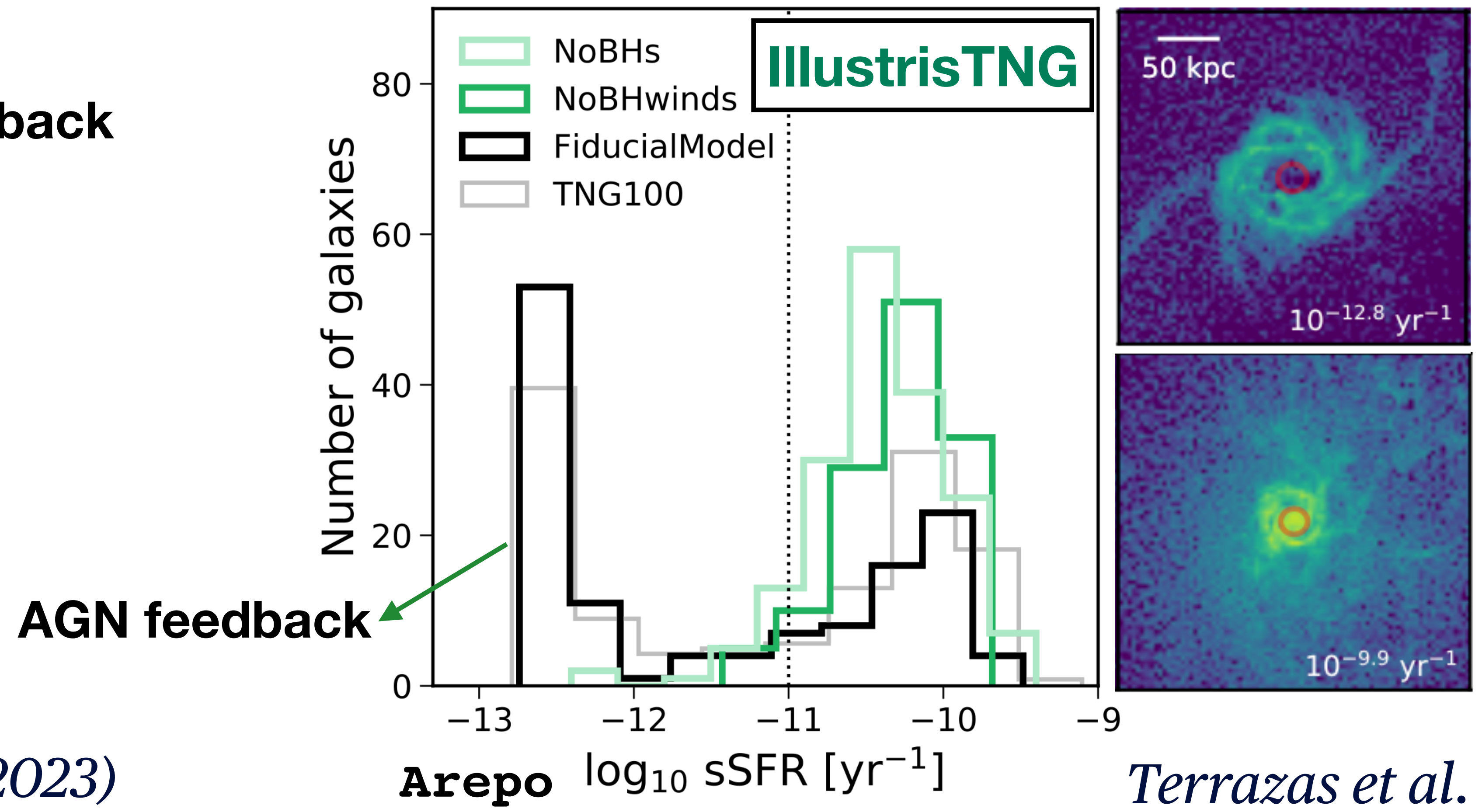
`Ramses` *Dubois et al. (2016)*

Star formation efficiency



`Gizmo` *Byrne et al. (2023)*

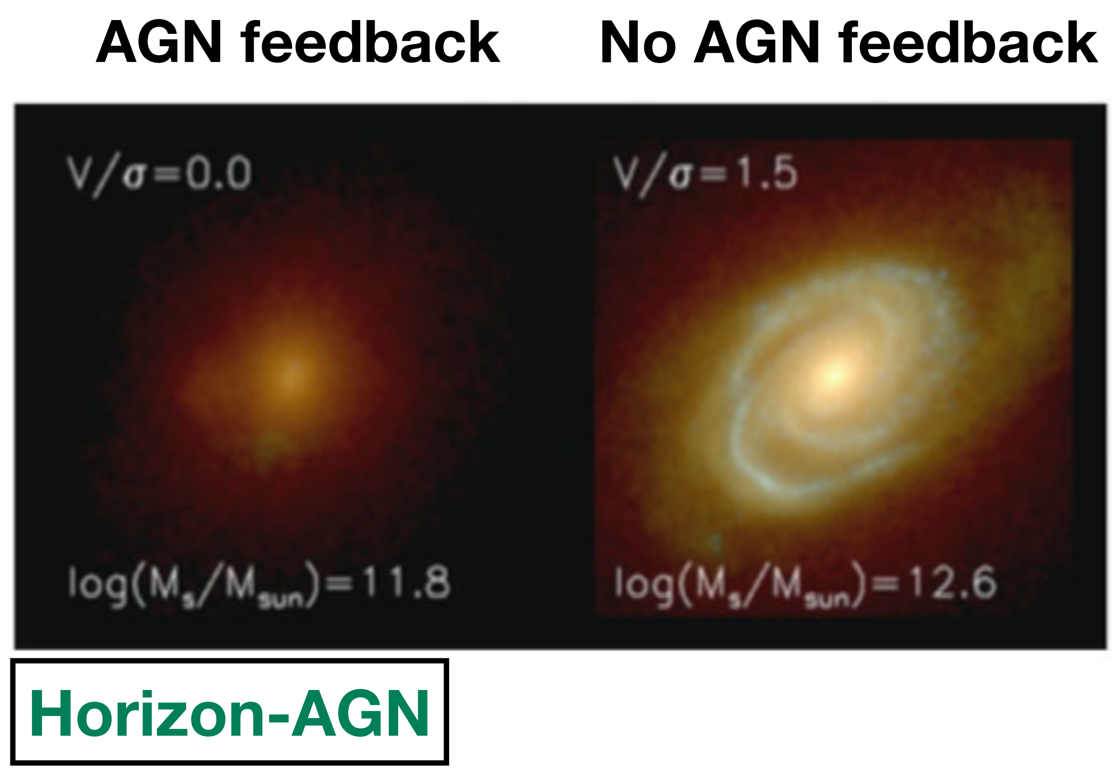
Quenched galaxies



`Arepo` *Terrazas et al. (2020)*

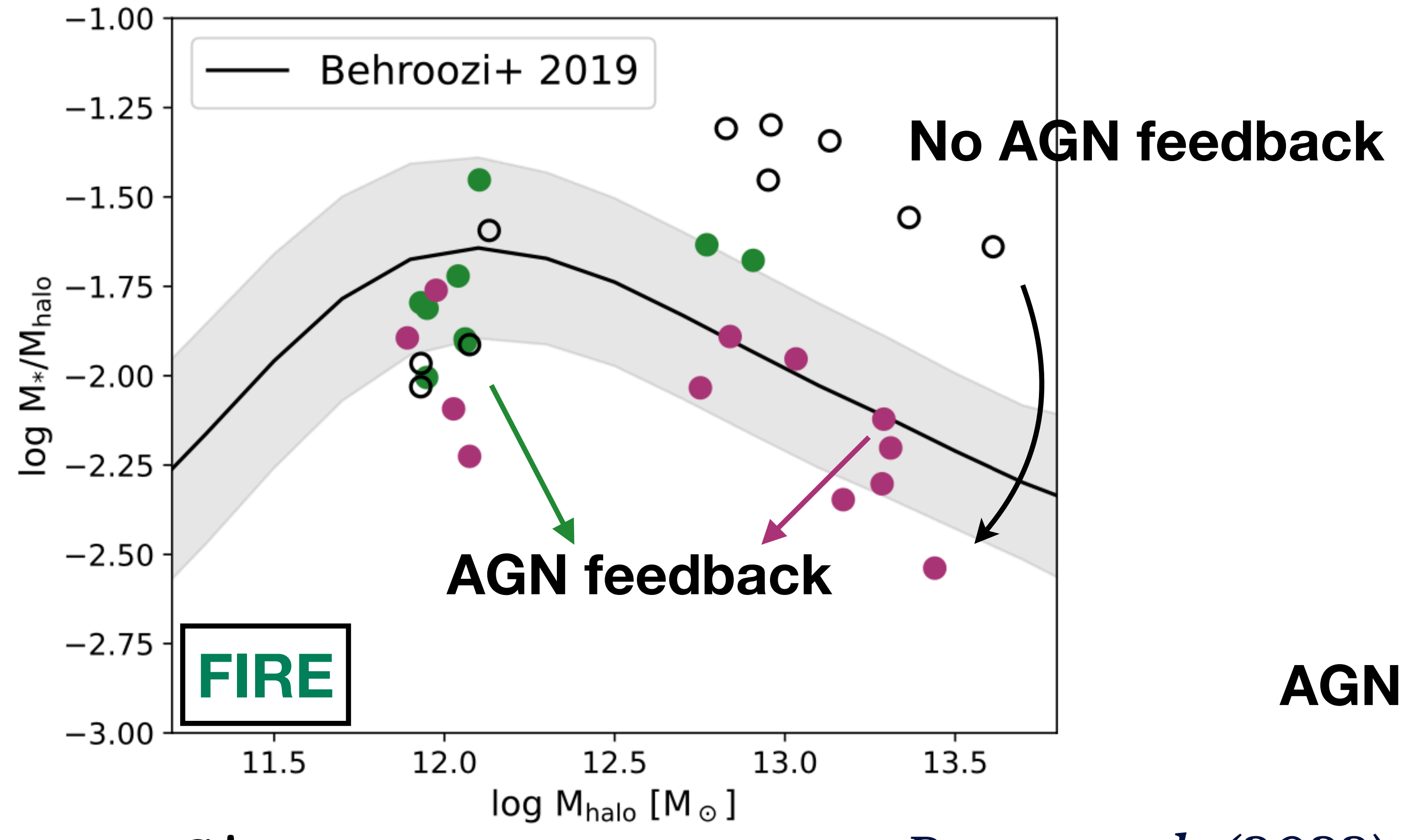
The Universe without AGN

Galaxy morphology & colours



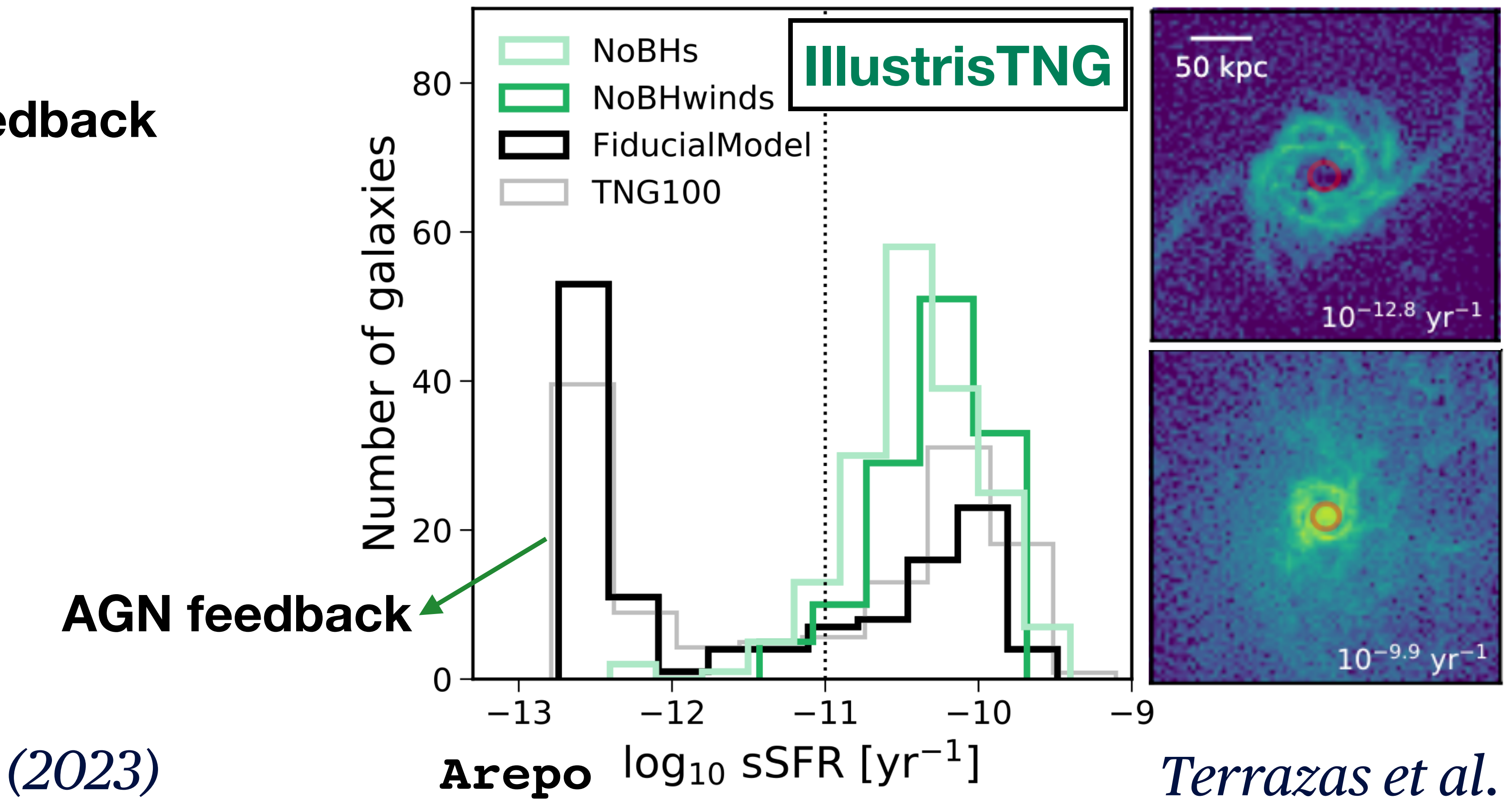
Ramses *Dubois et al. (2016)*

Star formation efficiency



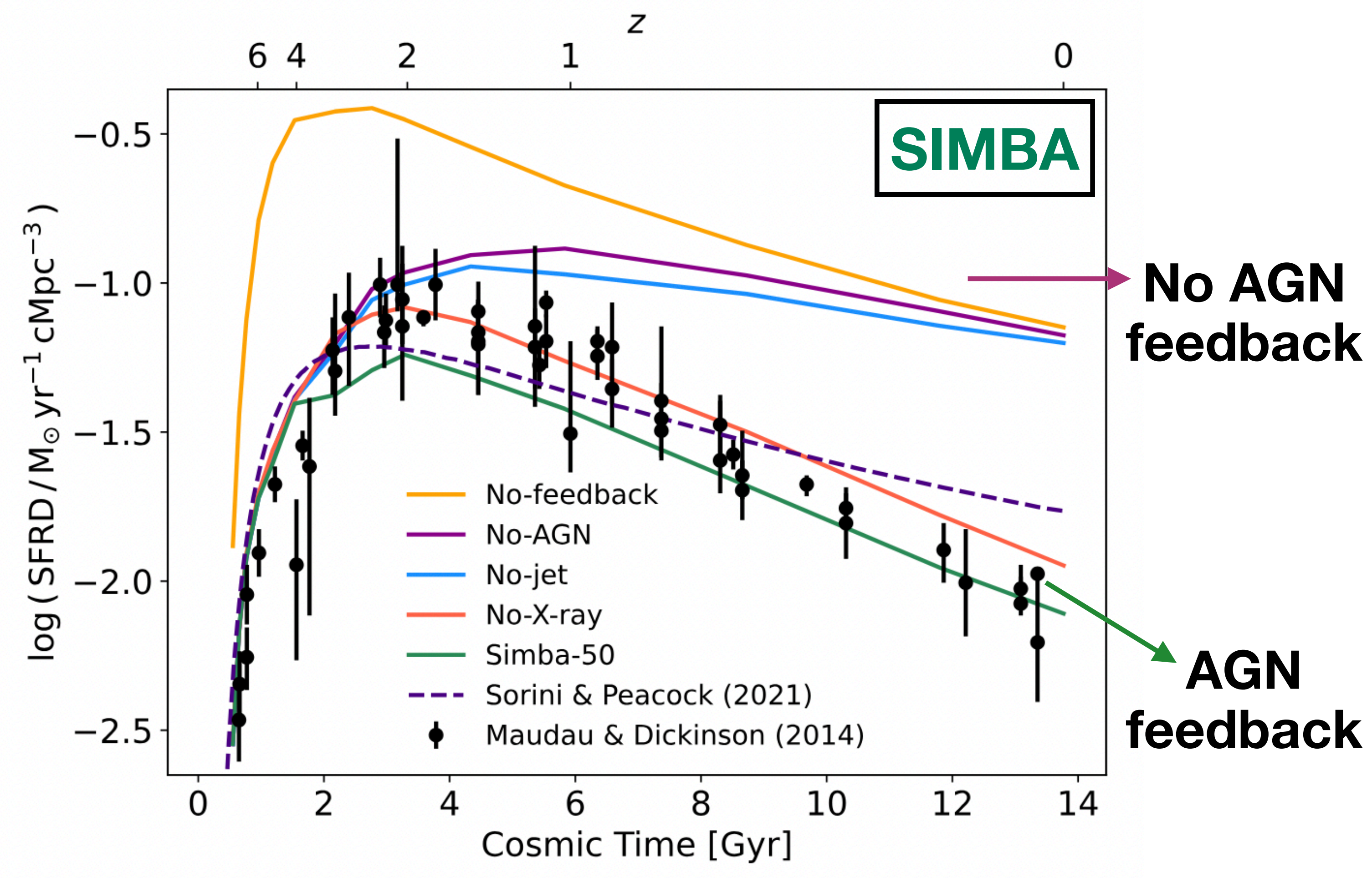
Gizmo *Byrne et al. (2023)*

Quenched galaxies



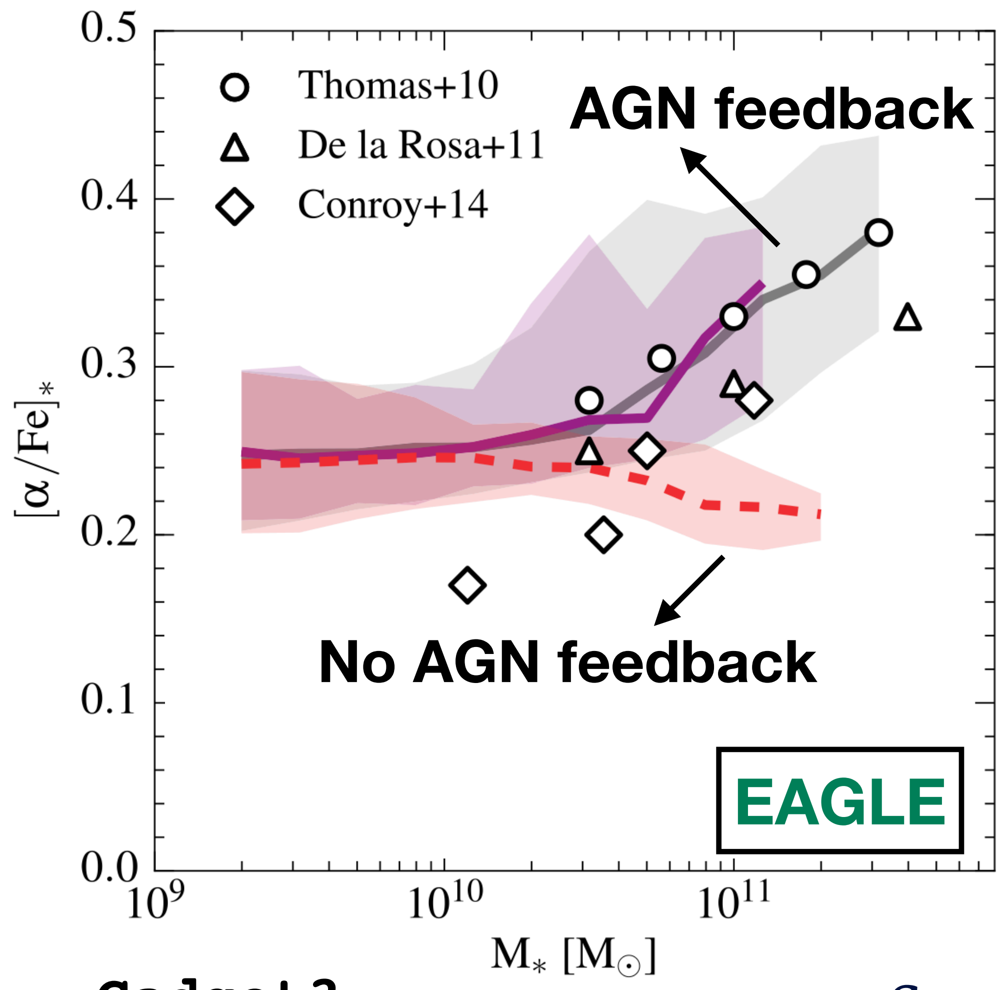
Arepo *Terrazas et al. (2020)*

Cosmic Star Formation History



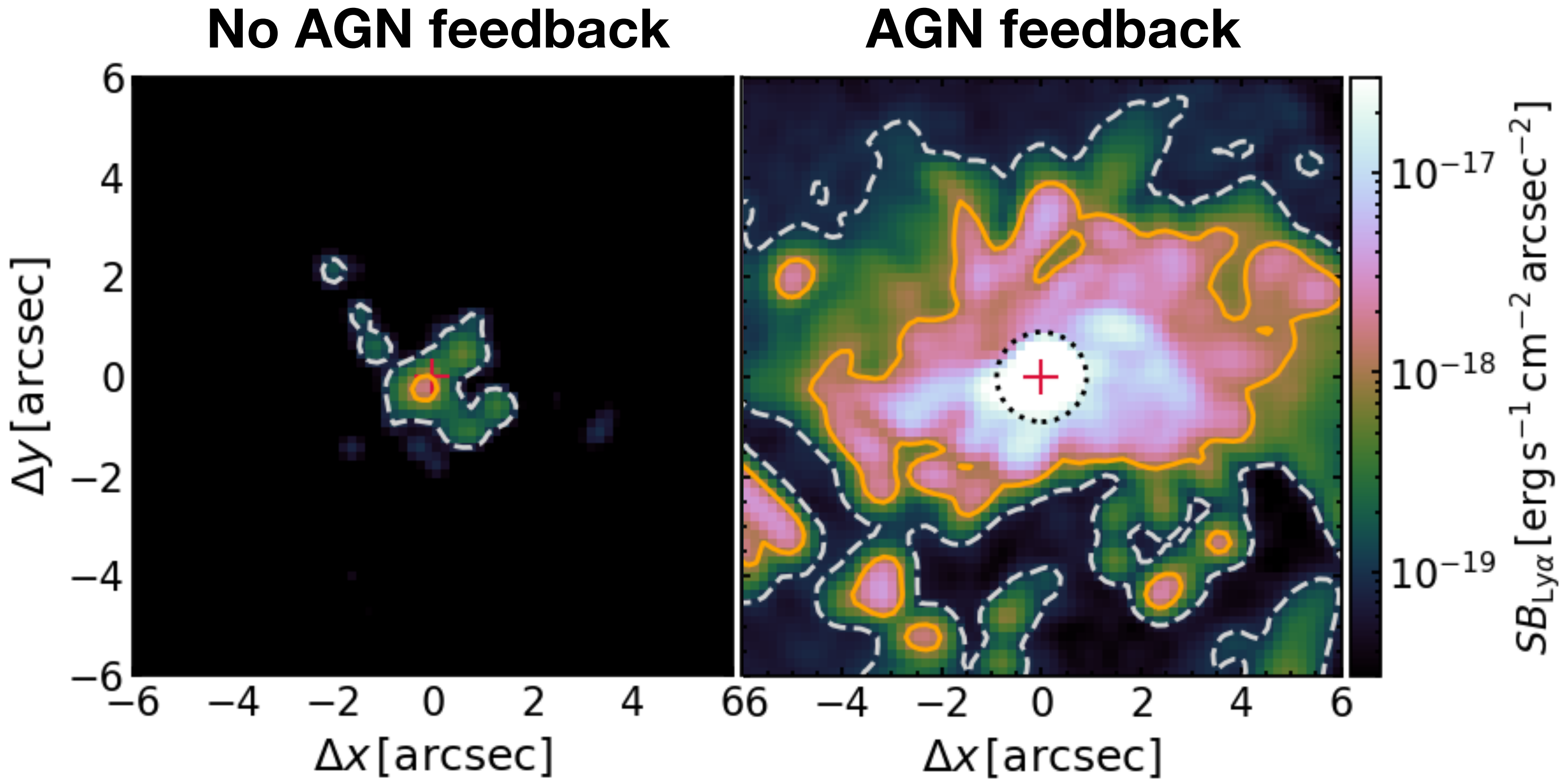
Gizmo *Scharré et al. (2024)*

Chemical enrichment of stellar populations



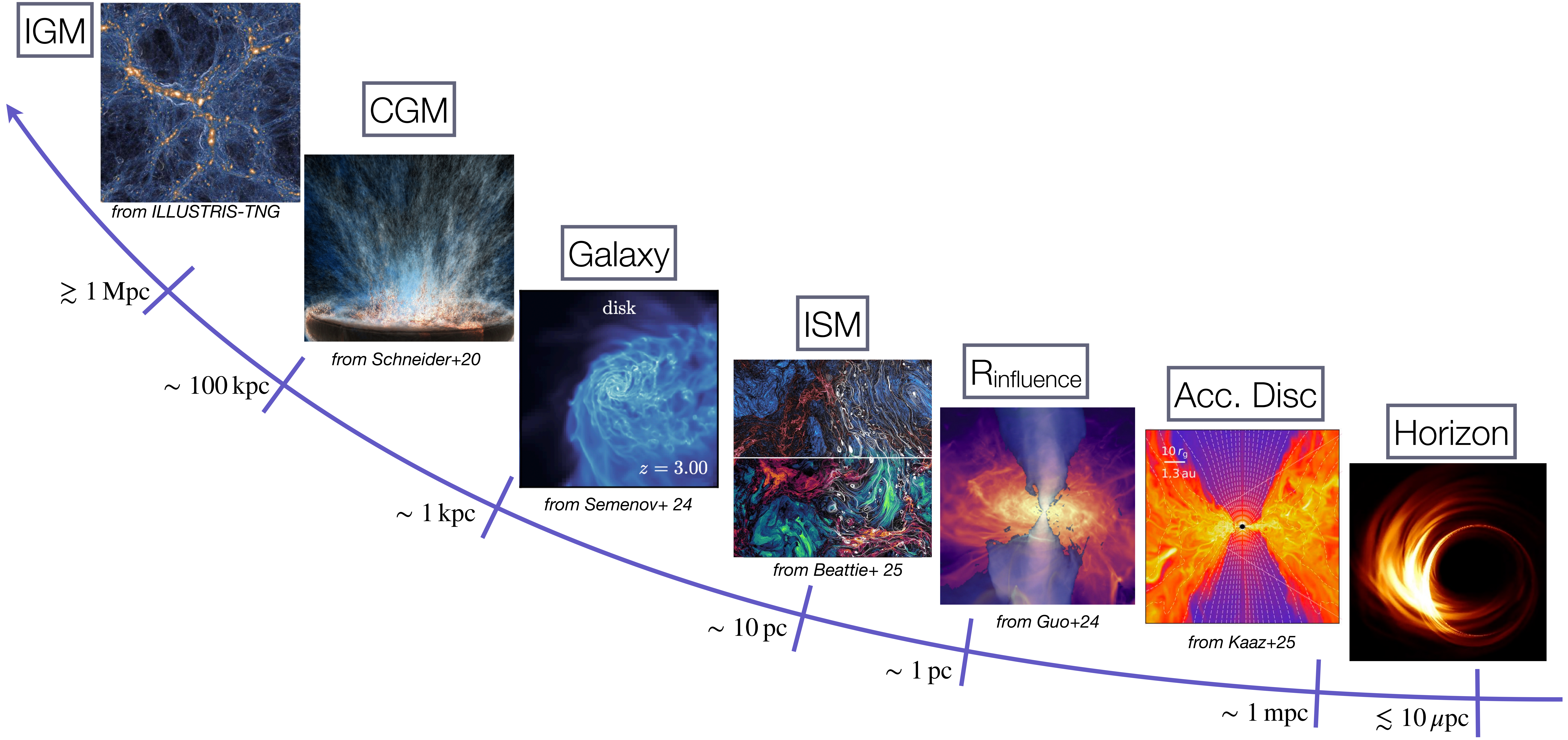
Gadget3 *Segers et al. (2017)*

CGM properties

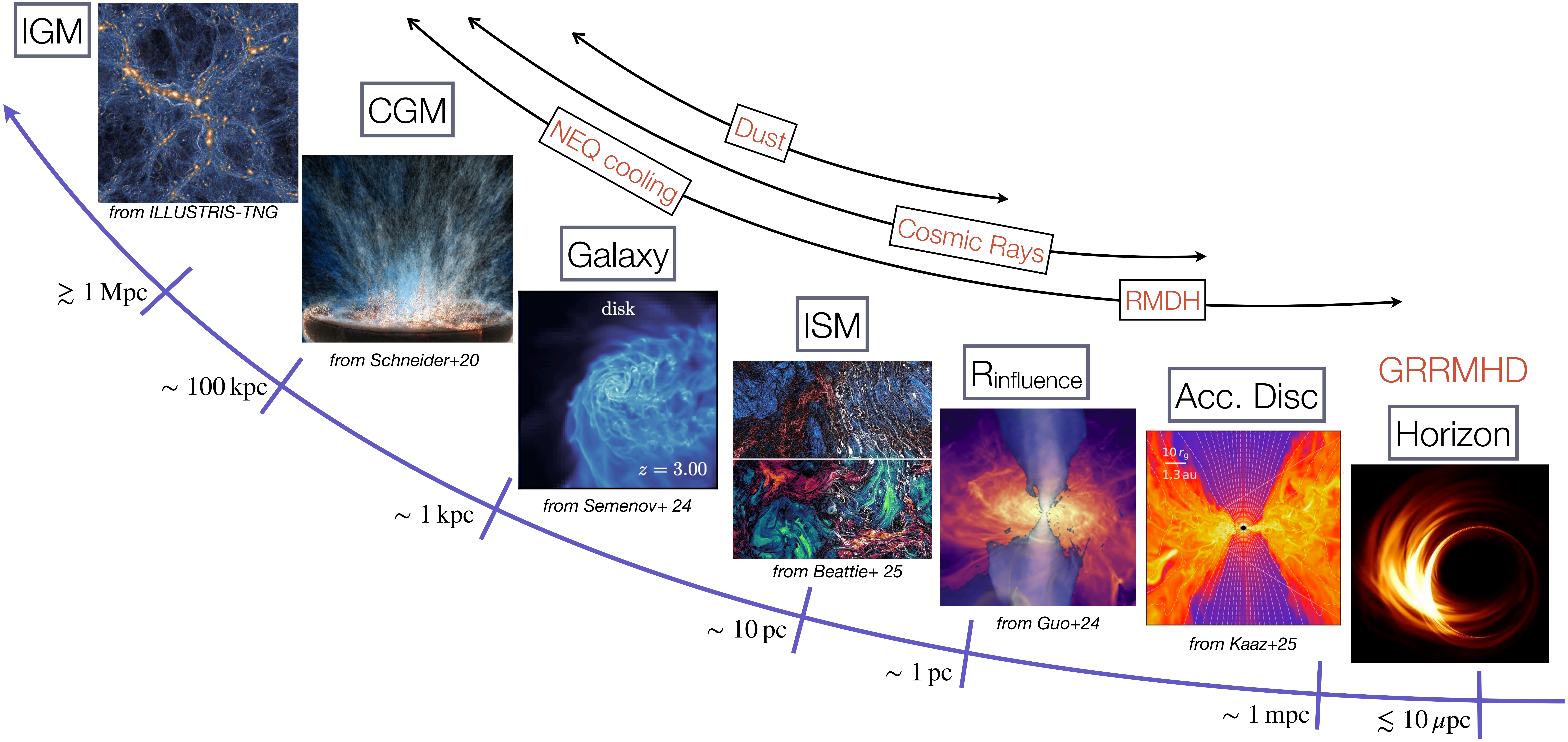


Ramses-RT *Costa et al. (2022)*

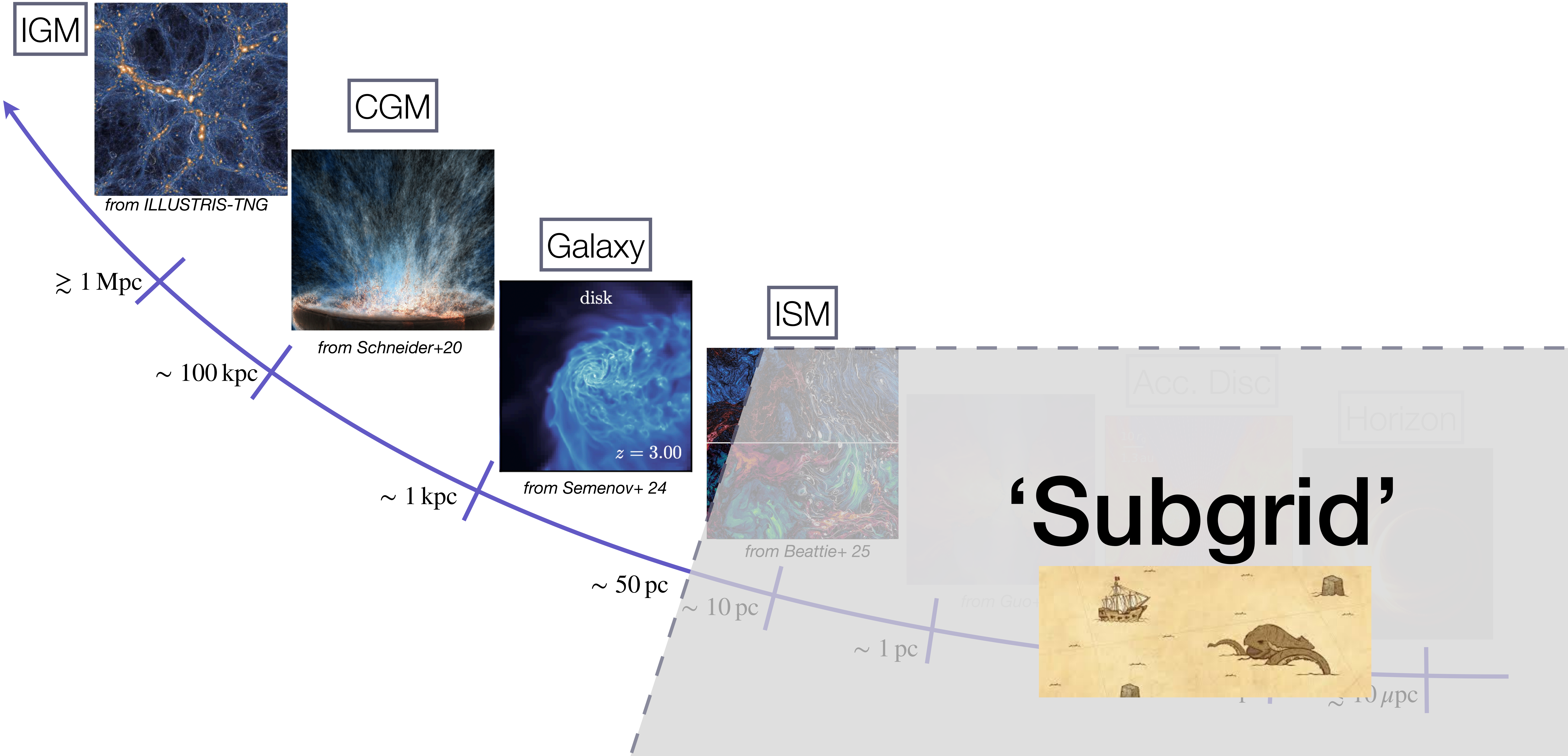
A multi-scale, multi-physics problem



A multi-scale, multi-physics problem

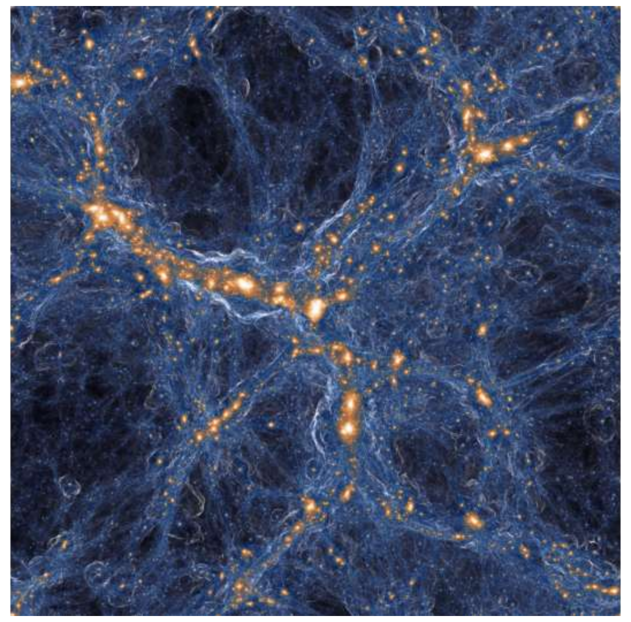


A multi-scale, multi-physics problem



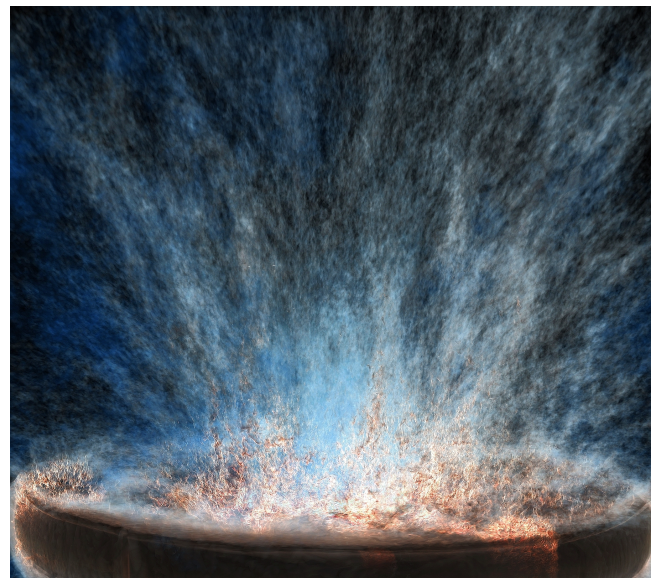
A multi-scale, multi-physics problem

IGM



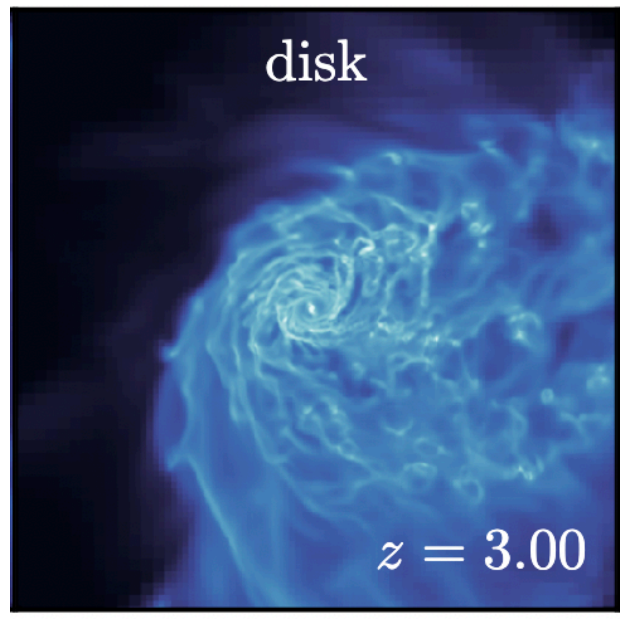
from ILLUSTRIS-TNG

CGM



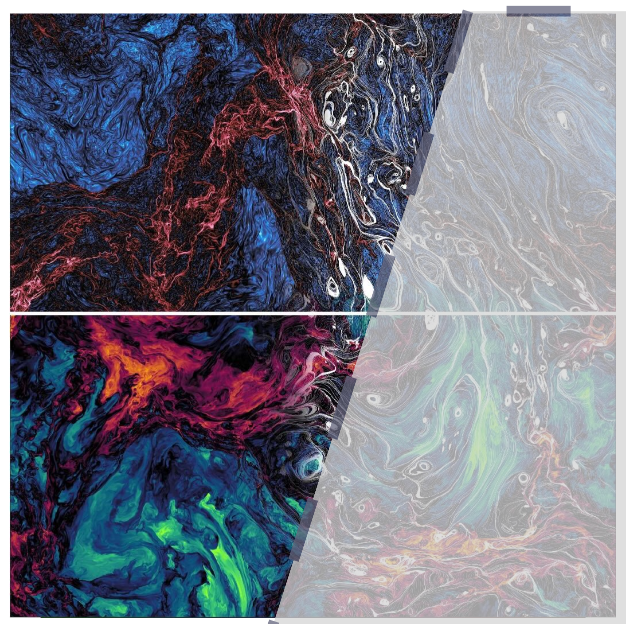
from Schneider+20

Galaxy



from Semenov+ 24

ISM



from Beattie+ 25

$\gtrsim 1\,\mathrm{Mpc}$

$\sim 100\,\mathrm{kpc}$

$\sim 1\,\mathrm{kpc}$

$\sim 10\,\mathrm{pc}$

$\sim 1\,\mathrm{pc}$

Acc. Disc

Horizon

In 10 years of **business as usual**:

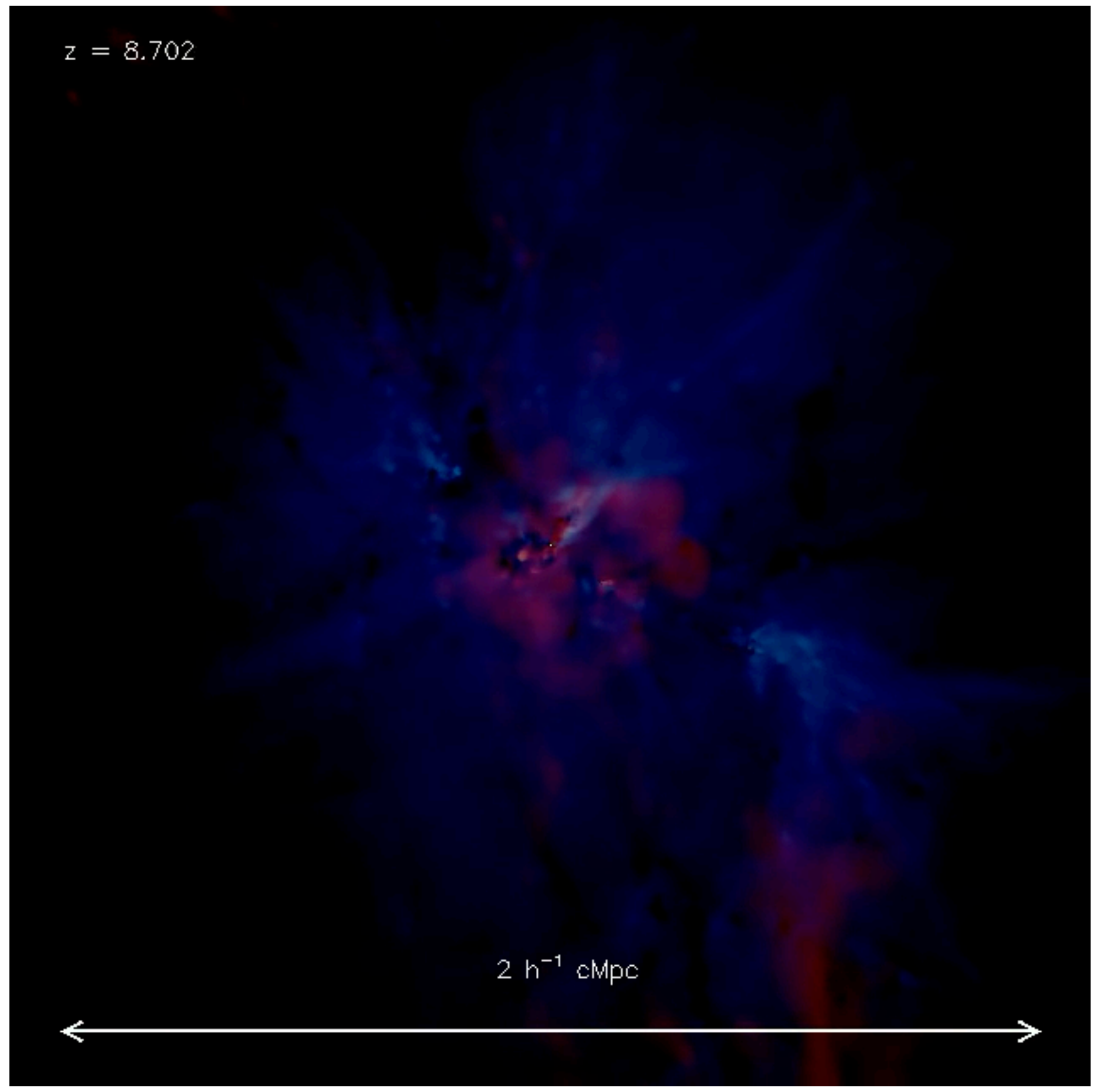
~16x cost with 2x increase in resolution

< 2x computing power increase every 18 months

Factor ~4 gain resolution in 10 years!

‘Subgrid’

The ‘Subgrid Model’ Family Tree



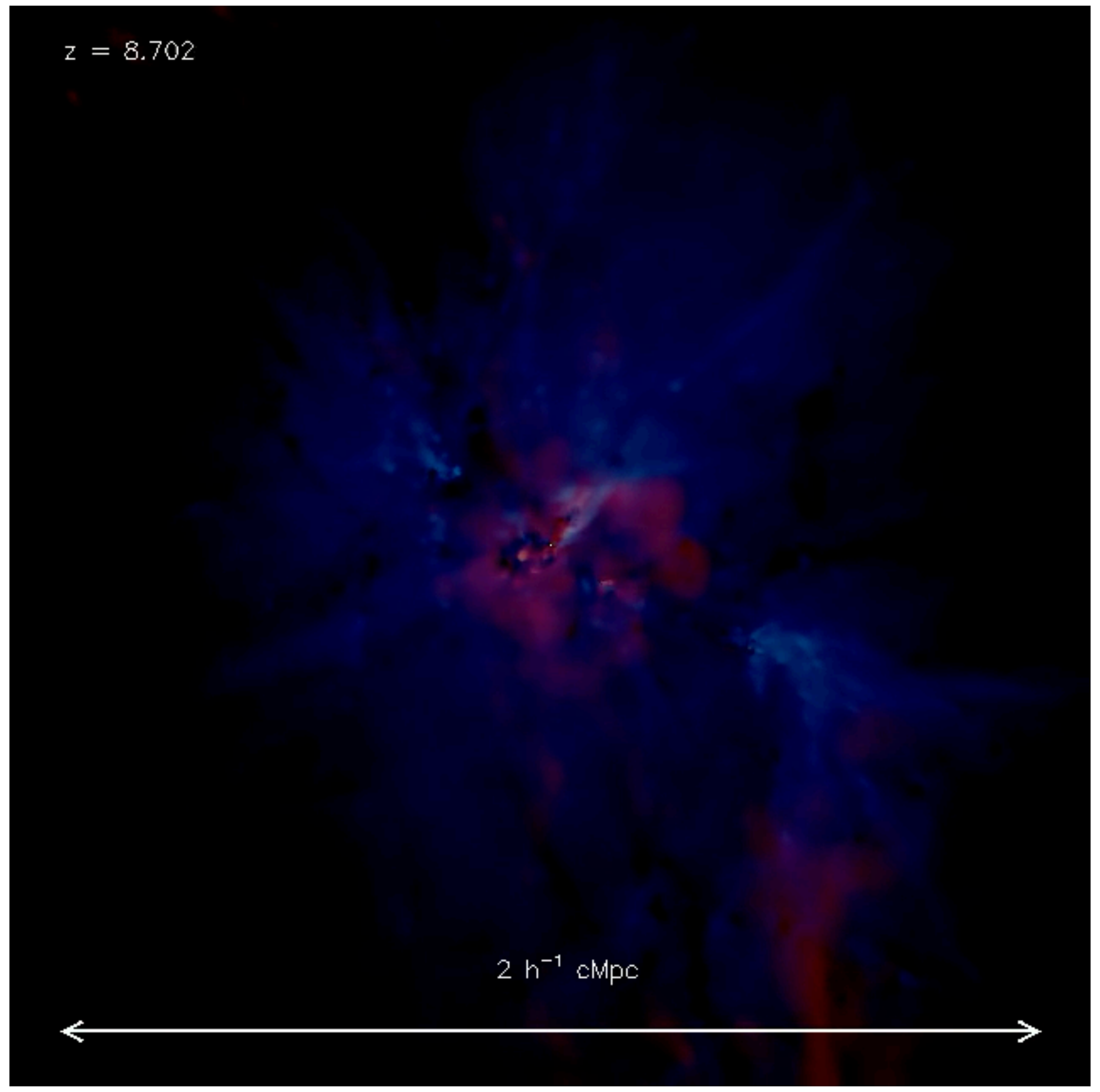
Thermal feedback in a z > 6 QSO (Costa+14)

$$\dot{E}_{\mathrm{fdb}} = \epsilon_{fdb} \eta_r \dot{M}_{\mathrm{acc}} c^2$$

Feedback efficiency

$$\epsilon_{fdb} = 0.05 - 0.15$$

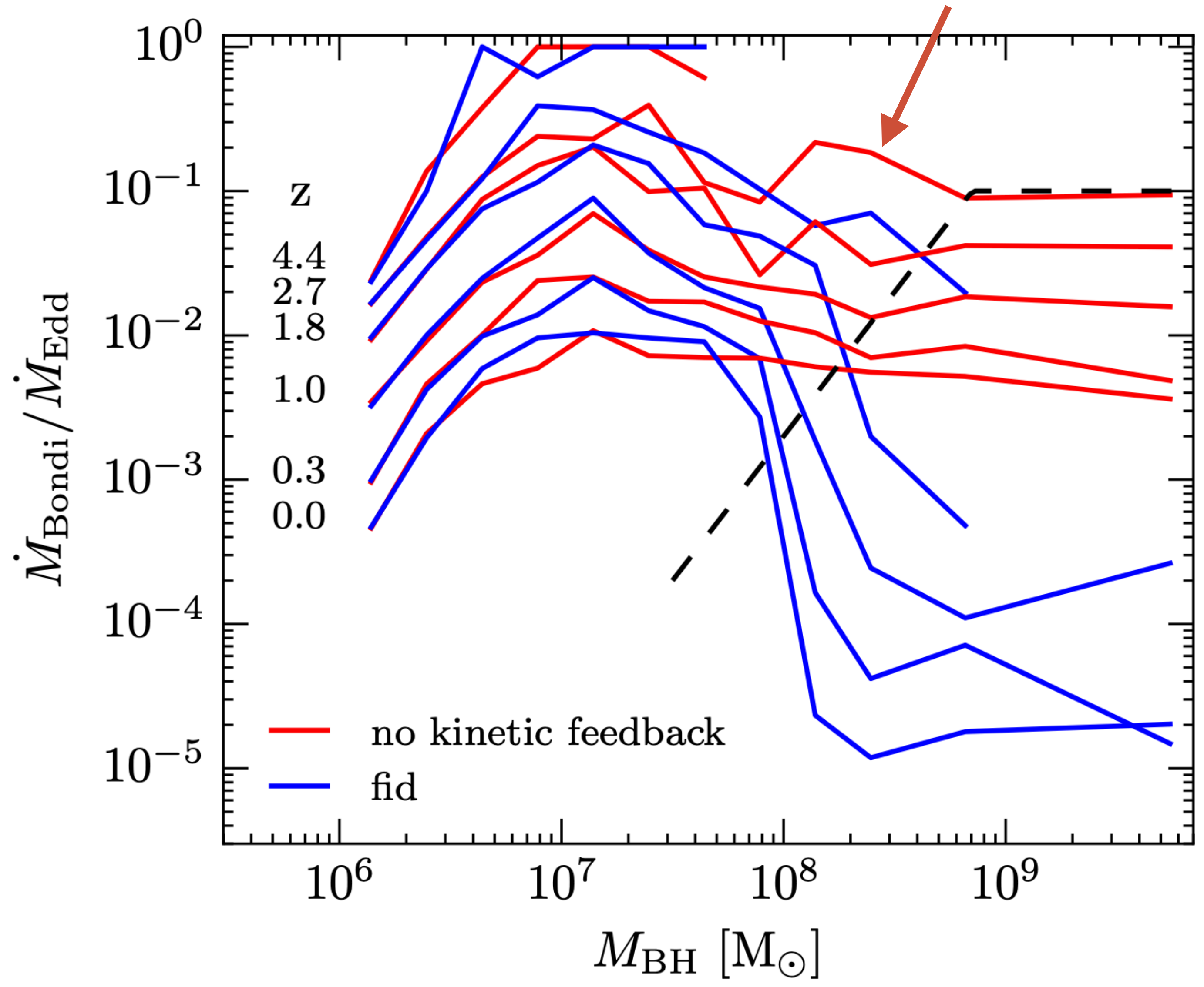
The ‘Subgrid Model’ Family Tree



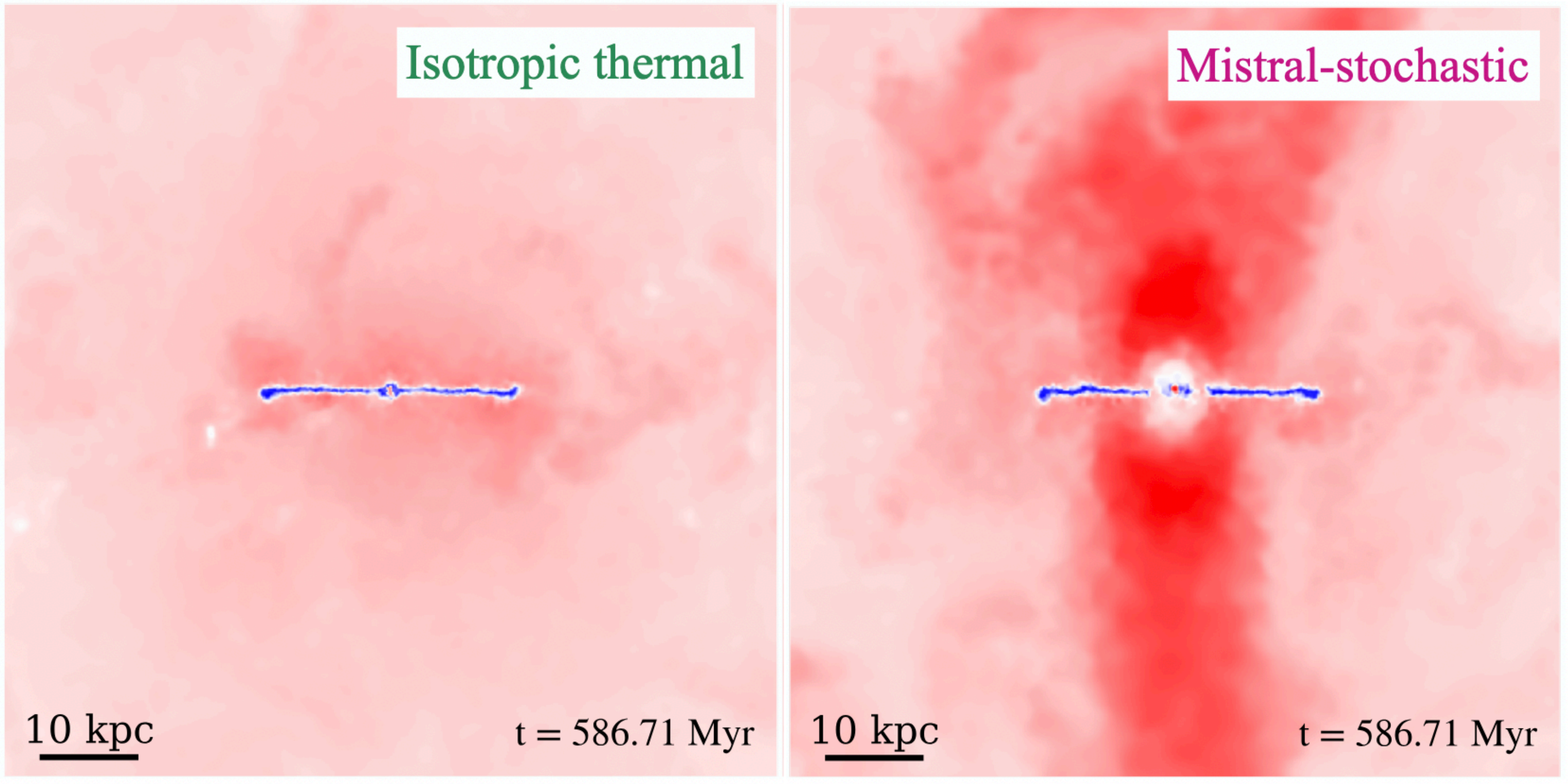
Thermal feedback in a z > 6 QSO (Costa+14)

Weinberger et al. (2017)

Vanilla thermal feedback



Farcy et al. (2025)



Vanilla thermal feedback

Kinetic feedback (quasar-mode)

The 'Subgrid Model' Family Tree

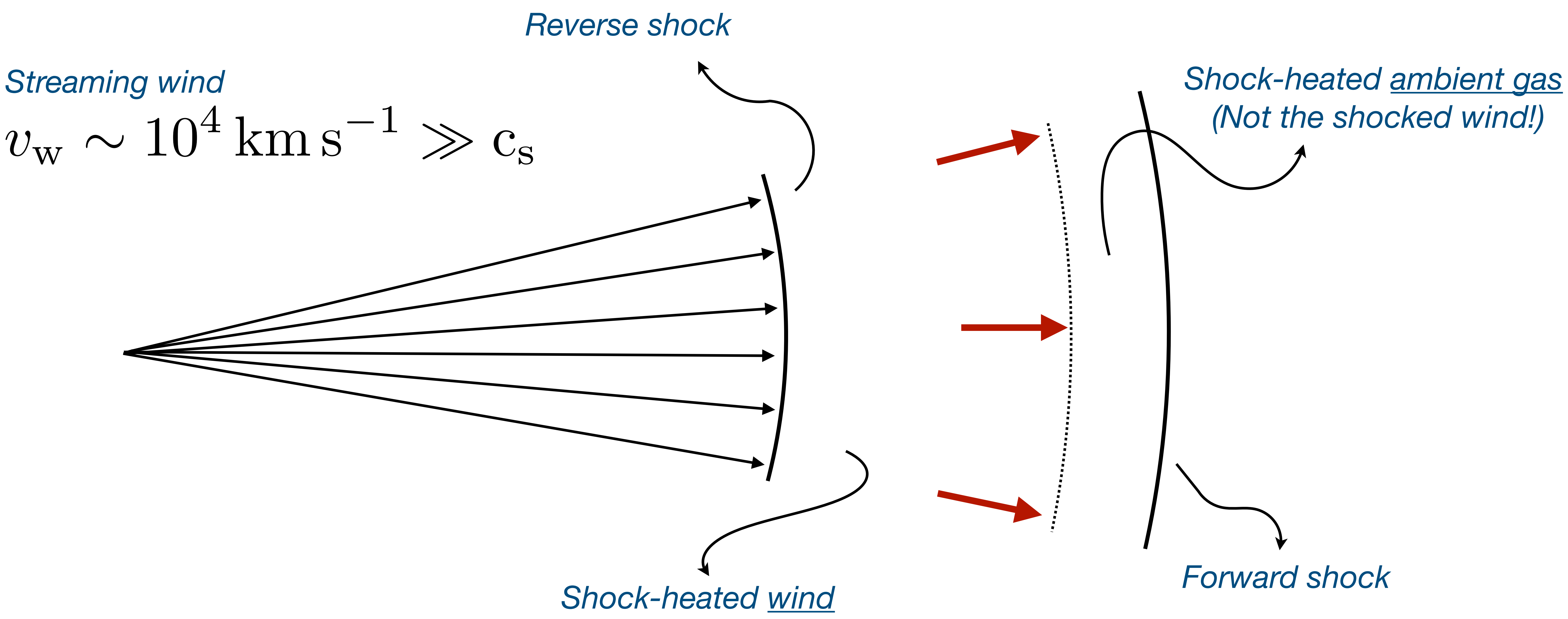
The ‘Subgrid Model’ Family Tree


2005
Springel et al, di Matteo et al. introduce thermal fdb.
2007
Sijacki et al. models two-mode feedback model (thermal & bubbles)
2009
Booth & Schaye modify thermal feedback to make it **efficient**
2012
Dubois et al. implement dual-mode AGN feedback
2012
Choi et al. Introduce momentum-injection-based feedback model for BAL winds
2017
Tremmel et al. Delayed-cooling thermal feedback
2017
Weinberger et al. replace “radio mode” with central kinetic energy injection
2019
Davé et al. Introduce new models for jets and winds using observations as motivation


2005
Springel et al, di Matteo et al. introduce thermal fdb.
2007
Sijacki et al. models two-mode feedback model (thermal & bubbles)
2008
Okamoto et al. model jets with thermal energy injection
2012
Faucher-Giguère & Quataert, Zubovas & King, analytic models for fast winds
2012
Dubois et al. implement dual-mode AGN feedback
2014
Dubois et al. model spin evolution
2014
Costa et al. models calibrated against analytical solutions (momentum-, energy-driven)
2017
Tremmel et al. Delayed-cooling thermal feedback
2017
Weinberger et al. replace “radio mode” with central kinetic energy injection
2017
Bourne et al. and Weinberger et al. jet models
2018
Costa et al. constrain radiation pressure on dust in RHD simulations
2019
Beckmann et al. couple spin evolution with jet efficiency
2021
Talbot et al. model Blandford-Znajek jets
2024
Lupi et al. (2024) super-Eddington feedback
2022, 2023
Huško et al. model spin-driven jets in Swift
2024
Bollatti et al. Spin-induced anisotropic UFO
2009
Booth & Schaye modify thermal feedback to make it efficient
2010
Debuhr et al. investigate subgrid model for radiation pressure
2011
Teyssier et al. implement modified thermal feedback into RAMSES
2012
Choi et al. Introduce momentum-injection-based feedback model for BAL winds
2014
Barai et al. introduce new models for kinetic feedback
2013
Anglés-Alcázar et al. Implement ‘torque-limited’ accretion
2015
Steinborn et al. models dual feedback with Gadget3
2016
Hopkins et al. inject kinetic energy to model BAL wind
2017
Anglés-Alcázar et al. Apply new wind model to cosmological sims.
2019
Davé et al. Introduce new models for jets and winds using observations as motivation
2020
Costa et al. BOLA
2020
Torrey et al. Particle spawning to launch wind.
2021
Trebitsch et al. photo-ionisation/heating from AGN with RHD
2024
Rennehan et al. (2023) 3-stage feedback

Energy- vs. momentum-driving

Talk by K. Zubovas



$$T \approx 1.2 \times 10^{10} \left(\frac{v_w}{3 \times 10^4\,\mathrm{km\,s^{-1}}}\right)\,\mathrm{K}$$

Shocked wind does not cool:
"Energy-driven"

$$\dot{P}_{out}/\dot{P}_w \approx 30 \left(\frac{v_w}{0.1c}\right)\left(\frac{v_{out}}{1000\,\mathrm{km\,s^{-1}}}\right)^{-1}$$

King (2005), Zubovas & King (2012), Faucher-Giguère & Quataert (2012), Zubovas & Nayakshin (2014), Costa et al. (2014, 2020)

Shocked wind cools:
"Momentum-driven"

$$\dot{P}_{out}/\dot{P}_w \approx 1$$

King (2003)

Theoretical expectation is that shocked wind component does not cool radiatively and outflows should be predominantly energy-driven on large-scales.

Schiano (1985), Silk & Rees (1998), Haehnelt, Natarajan & Rees (1998), King (2003, 2005), Zubovas & King (2012), Faucher-Giguère & Quataert (2012), Costa et al. (2014, 2020), King & Pounds (2015), Richings & Faucher-Giguère (2018a,b), Zubovas et al. (2024), Ward et al. (2024)

A side observation

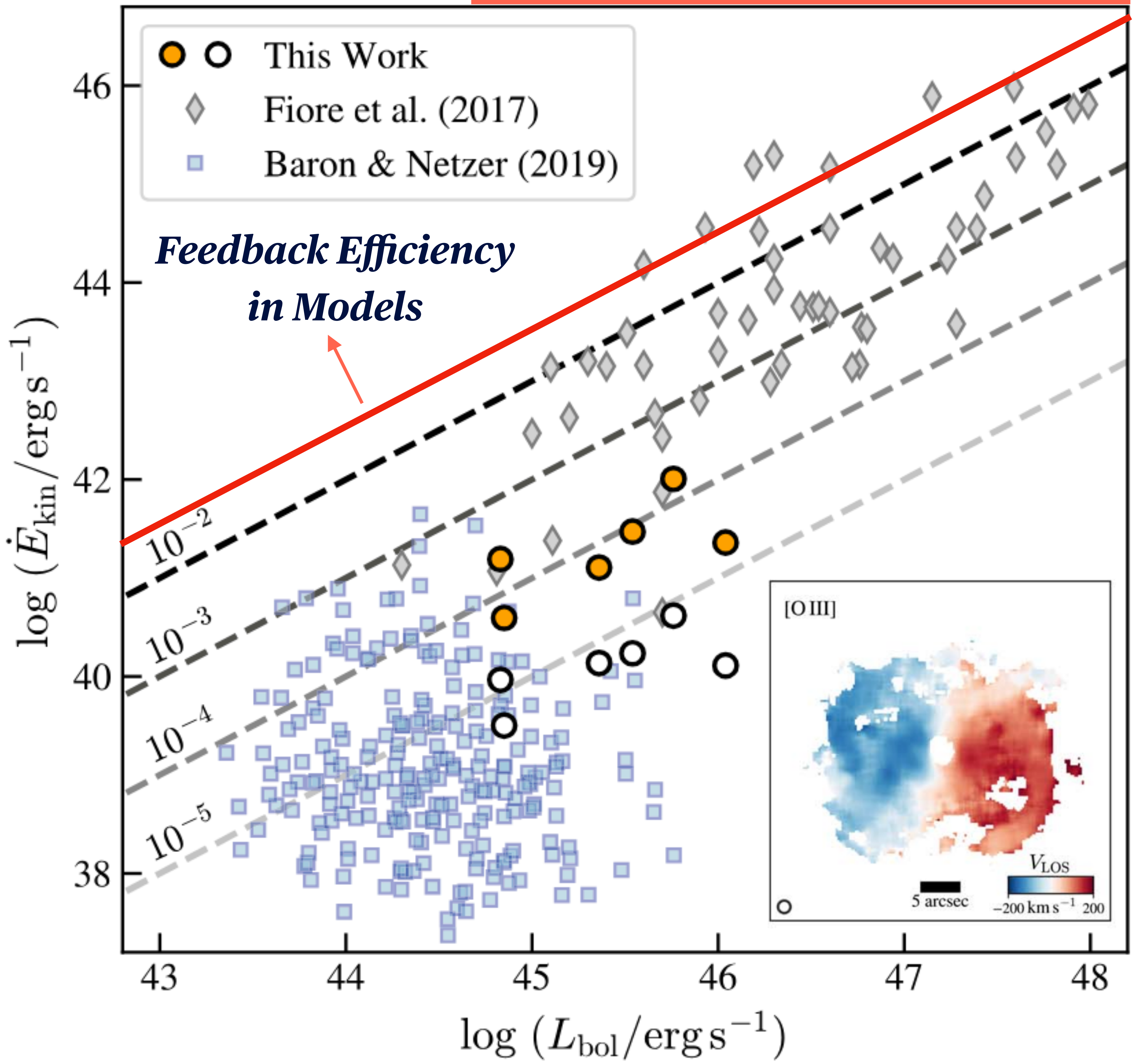
Kinetic Power

$$\dot{E}_{out} = \dot{M}_{out} v_{out}^2 / 2$$

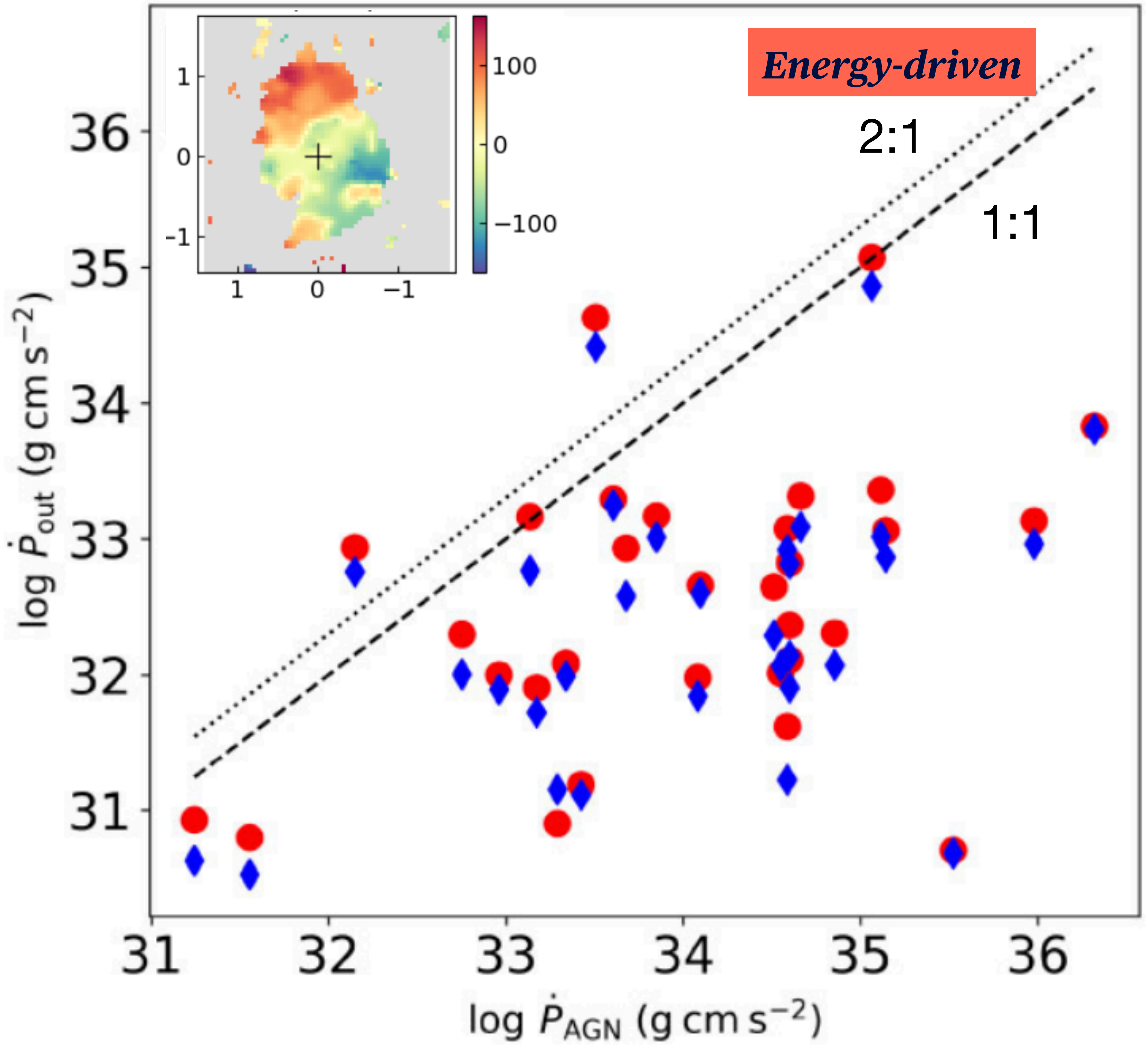
Momentum Flux

$$\dot{P}_{out} = \dot{M}_{out} v_{out}$$

Molina et al. (2022) **Talk by C. Ramos Almeida**



Riffel et al. (2024)

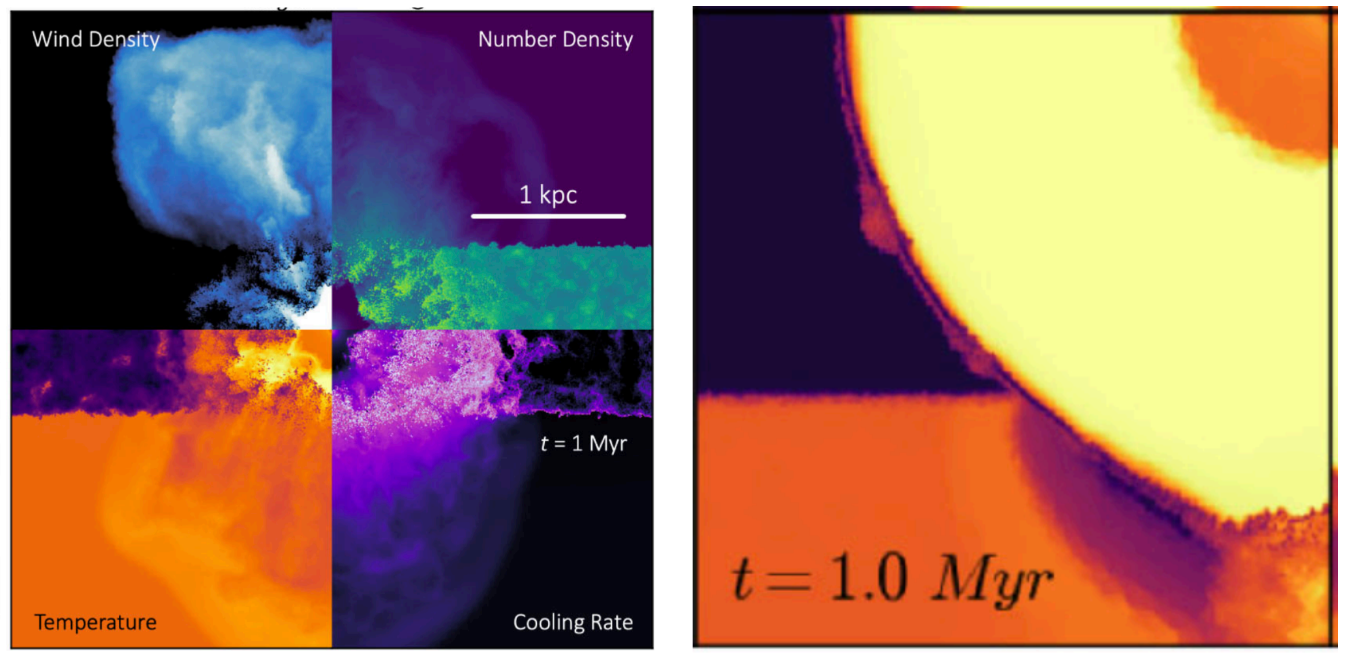


Measurements of kinetic power and momentum flux commonly used to constrain AGN feedback mechanism and estimate its impact.

Theory vs. Observations

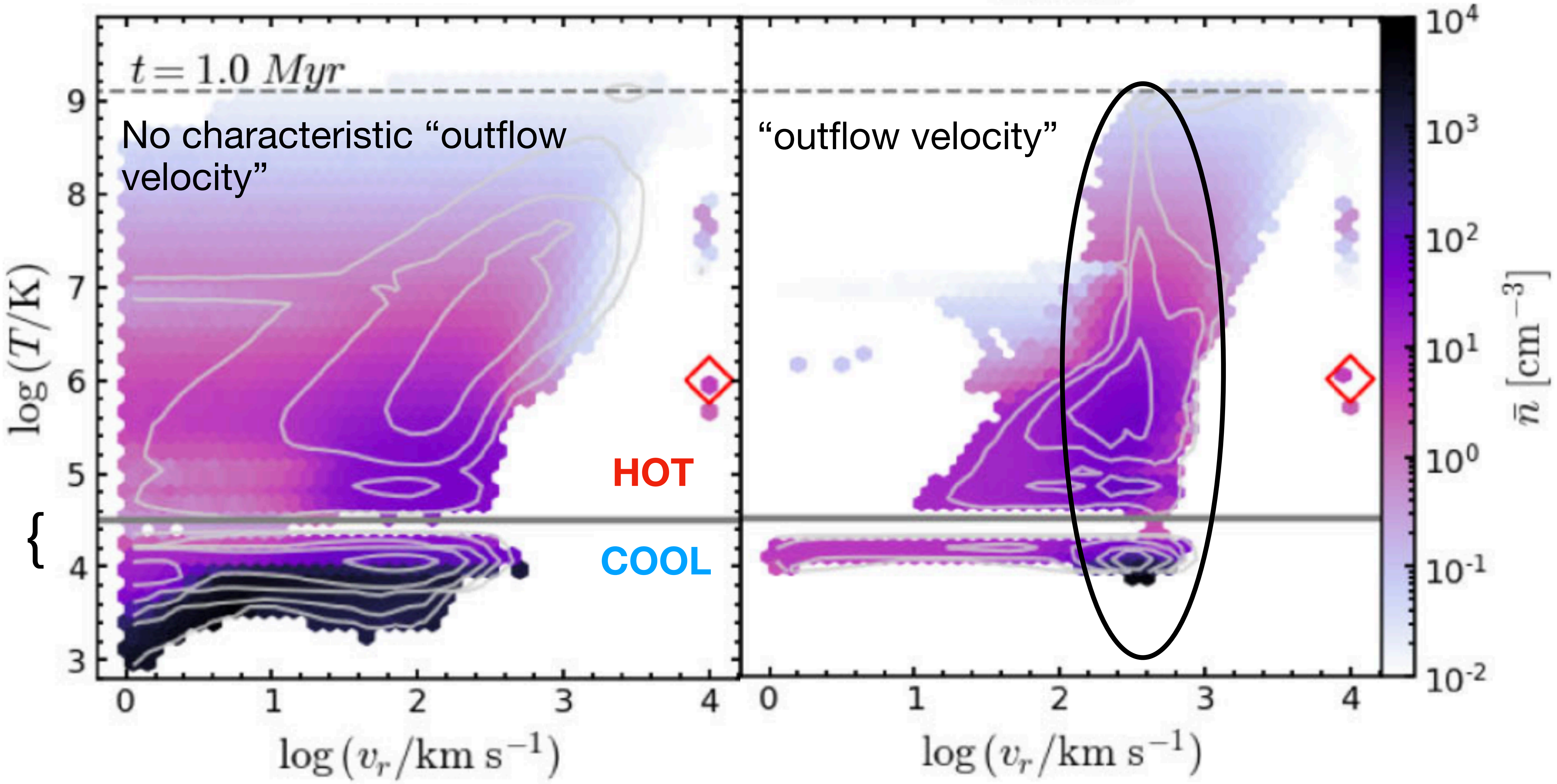
Ward, Costa et al. (2024)

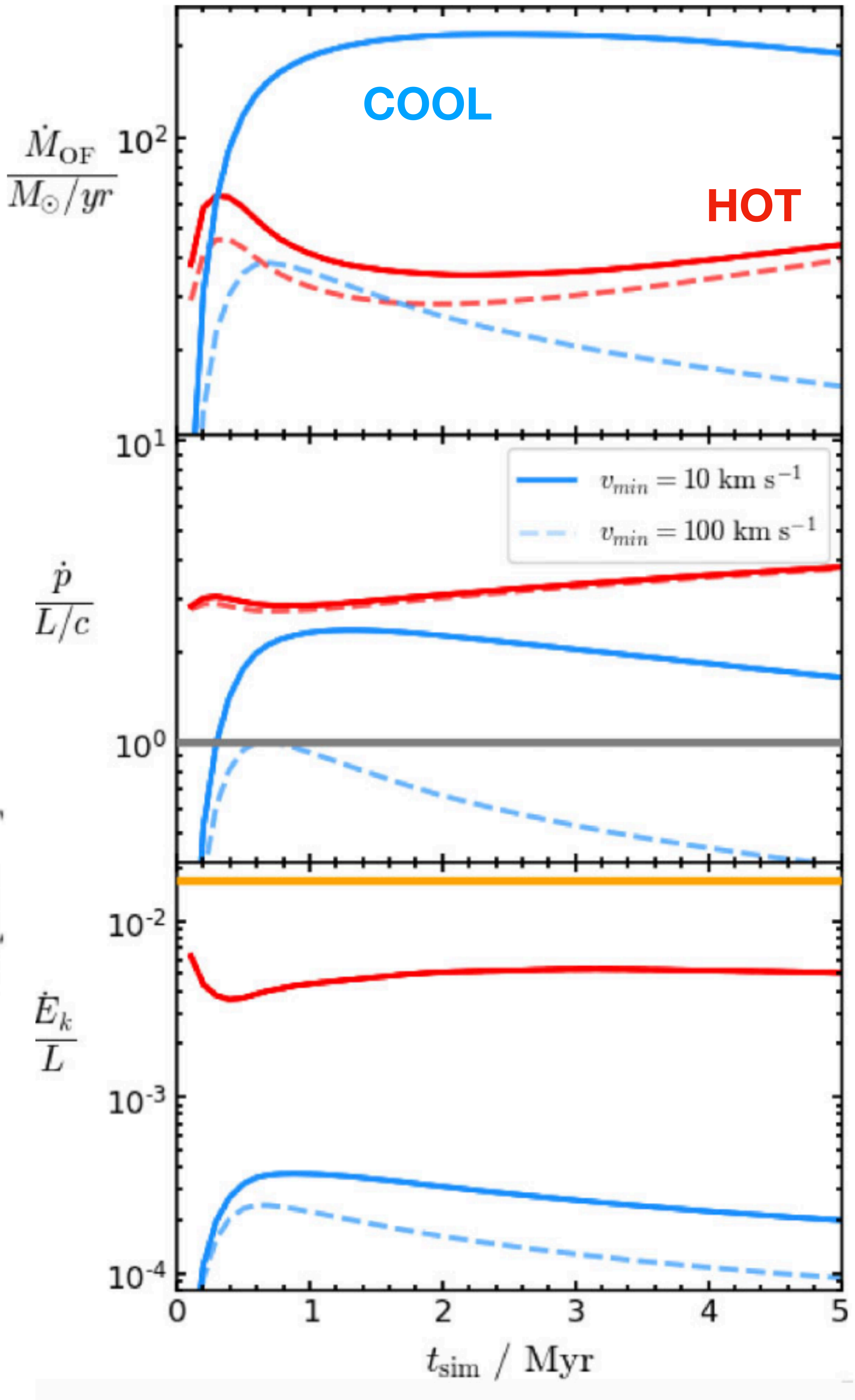
Clumpy Galaxy



Classic model

Optical Emission line {





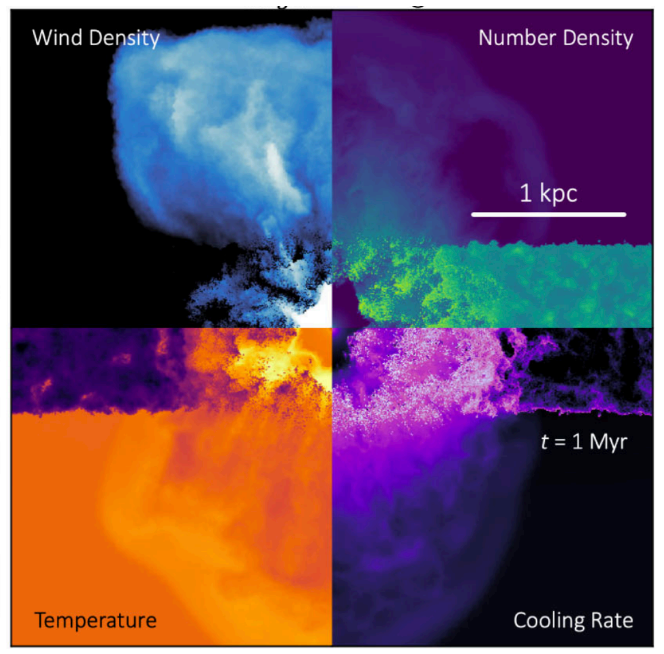
Very Sensitive to Outflow Definition

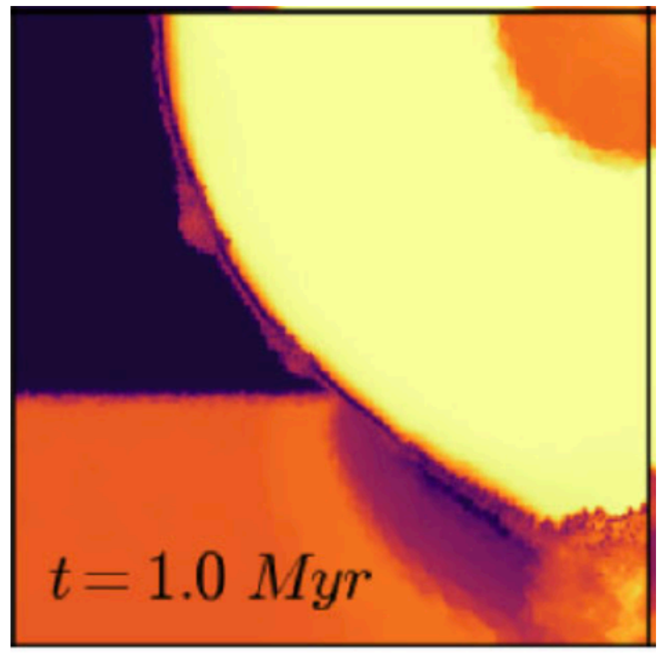
Mass outflow rate is extremely sensitive to any velocity cut.

Theory vs. Observations

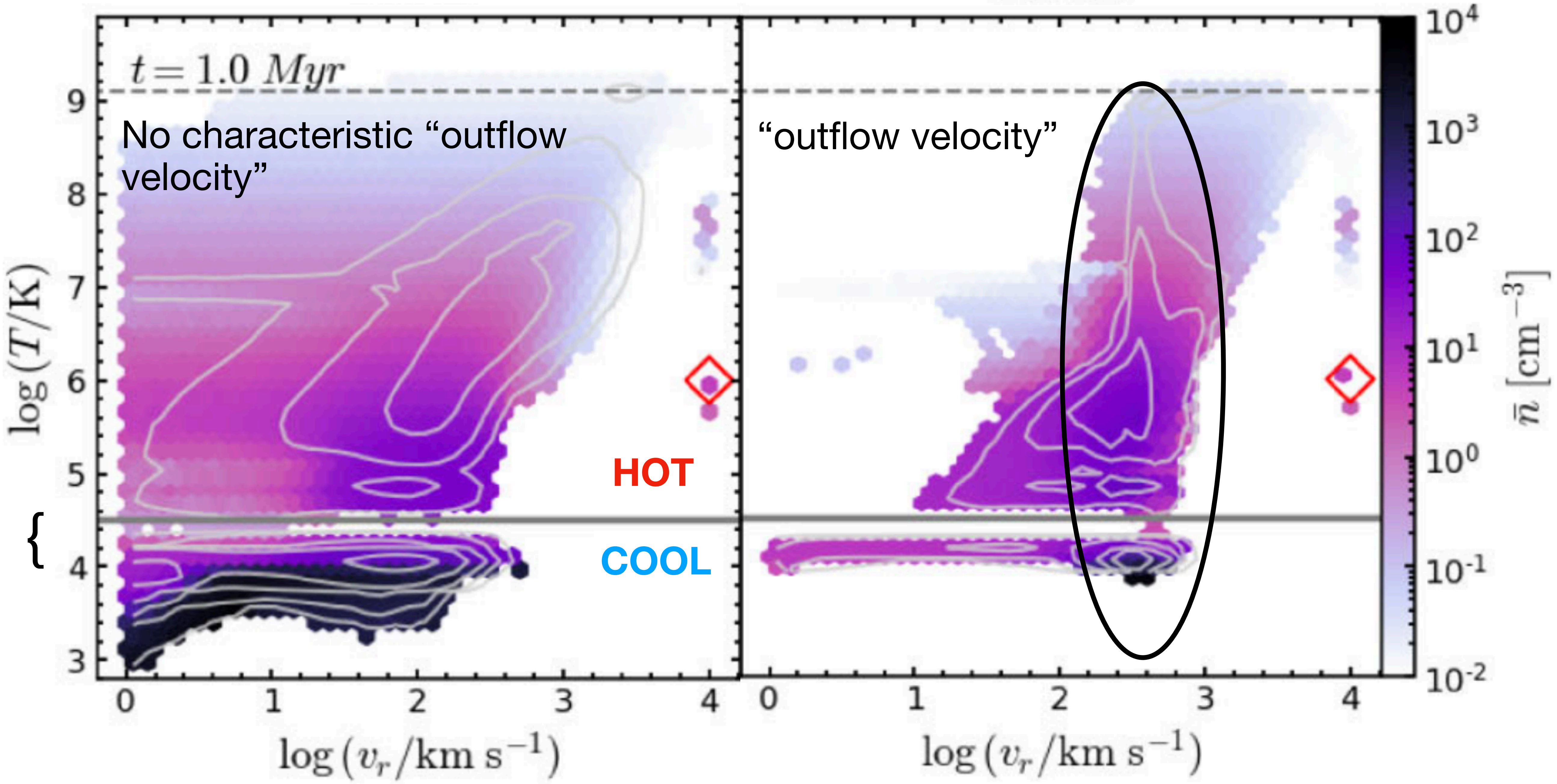
Ward, Costa et al. (2024)

Clumpy Galaxy

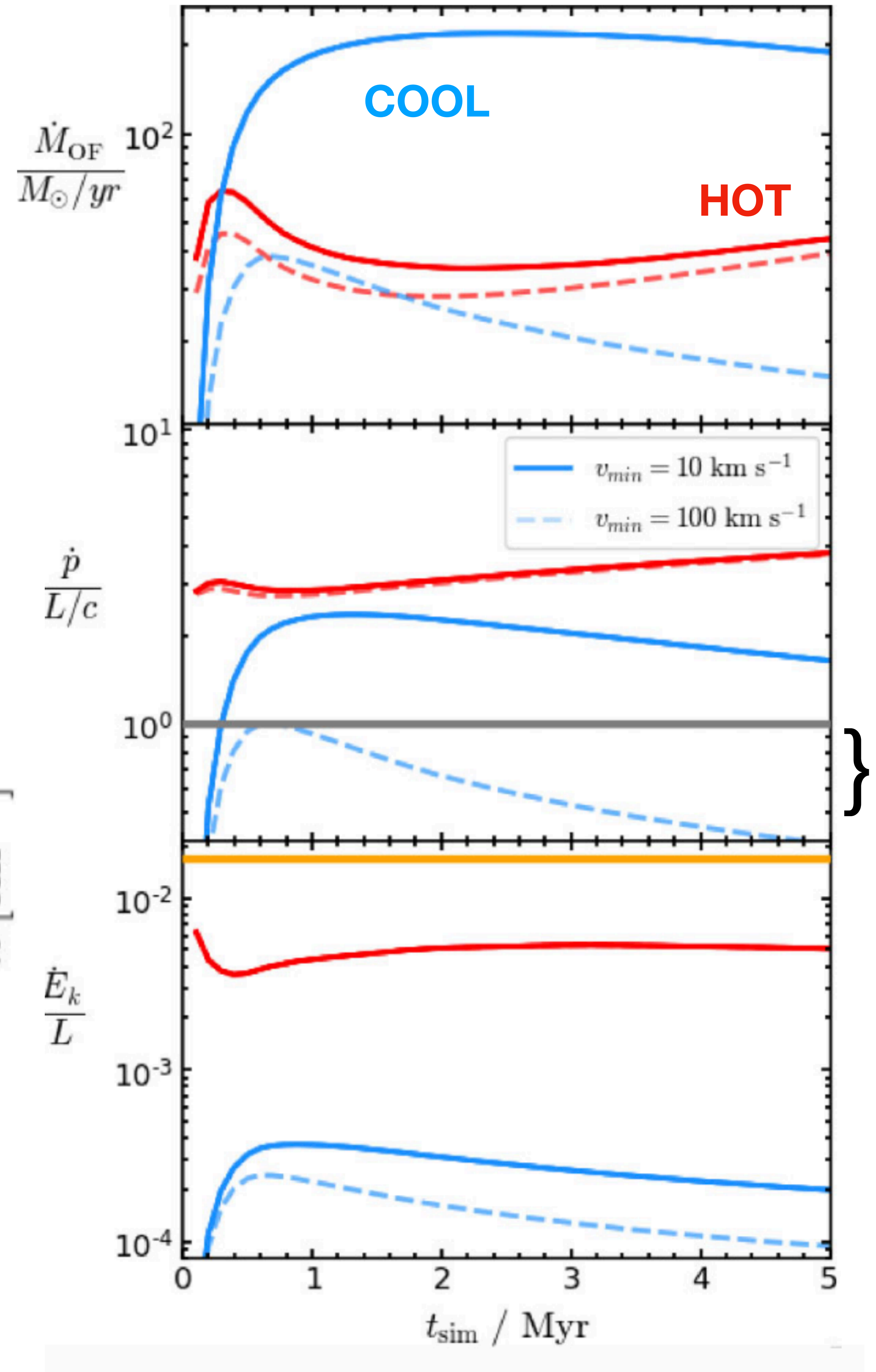




Classic model



Optical Emission line {



Very Sensitive to Outflow Definition

"Energy-Driven"

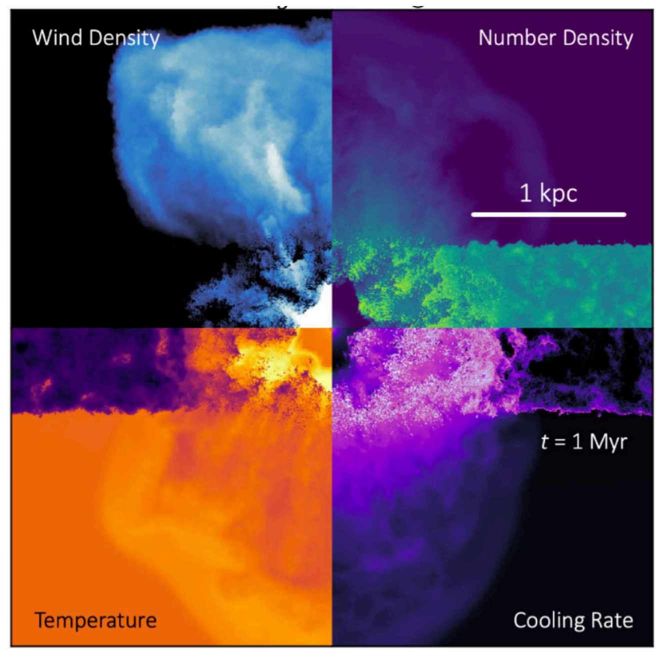
} "Momentum-Driven"

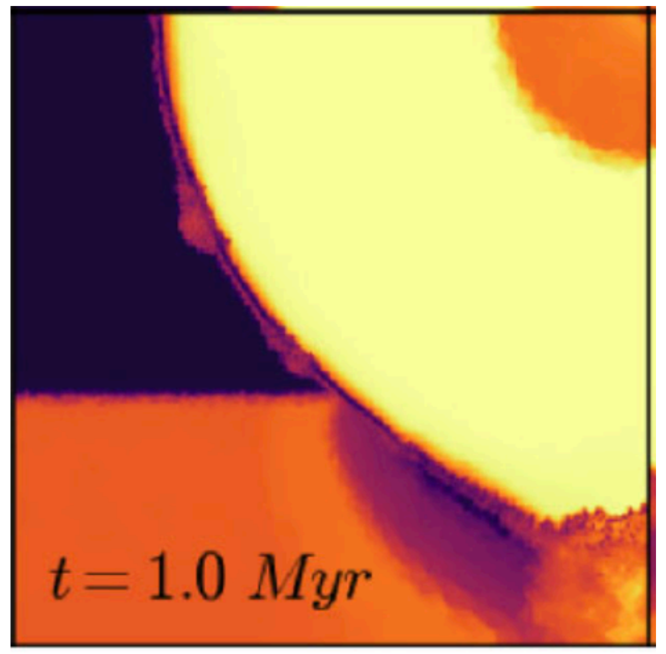
Momentum flux is low for cool phase, often < L/c even though outflow is energy-driven.

Theory vs. Observations

Ward, Costa et al. (2024)

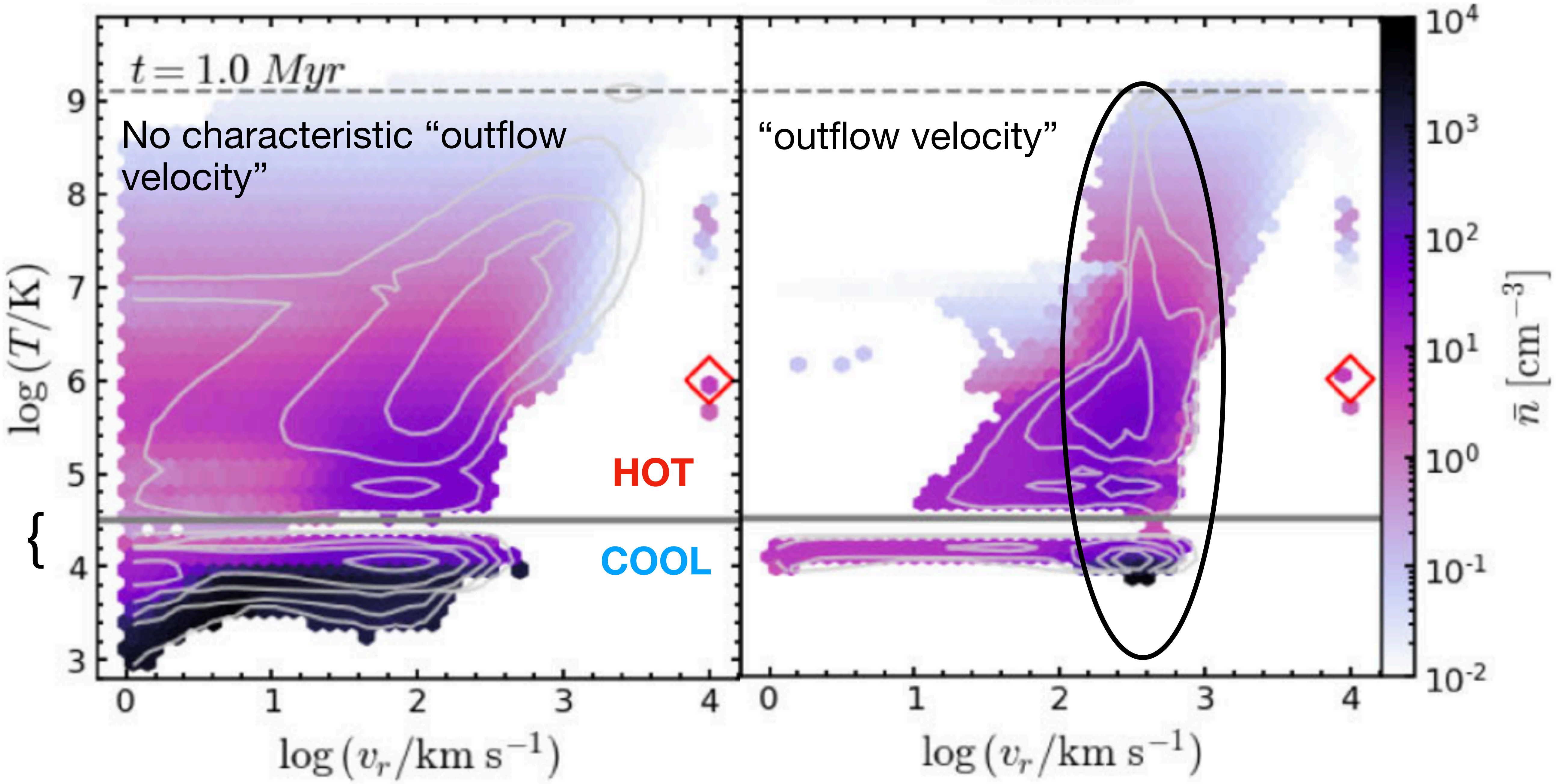
Clumpy Galaxy

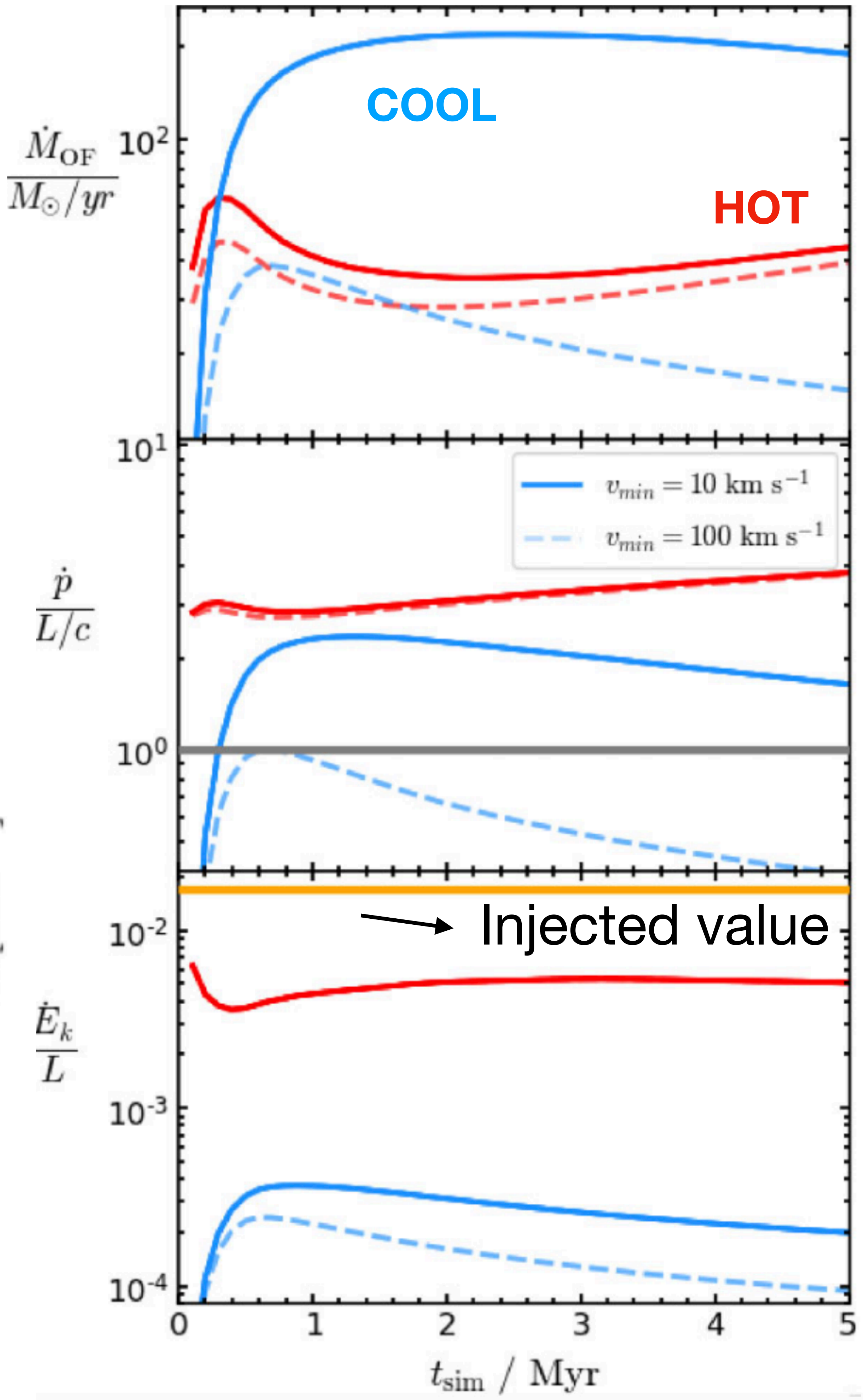




Classic model

Optical Emission line {





Very Sensitive to Outflow Definition

"Energy-Driven"

} "Momentum-Driven"

Dominant Hot Phase

Hot (> 10^7 K) phase is energetically dominant and closest to feedback power.

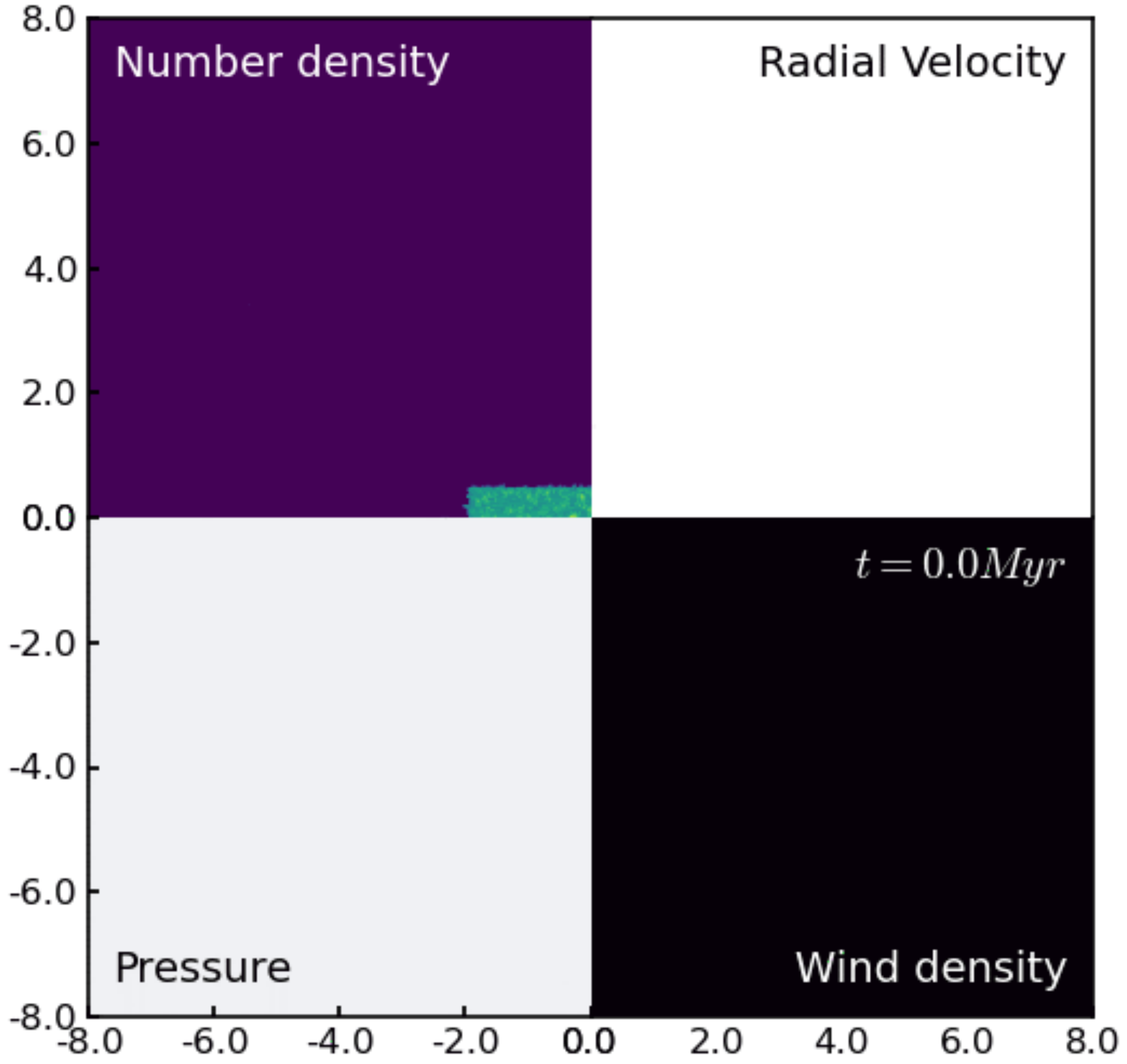
What this means

Energy Losses

Missing Phases

Missing Velocities

Ward, Costa, Harrison & Mainieri (2024)

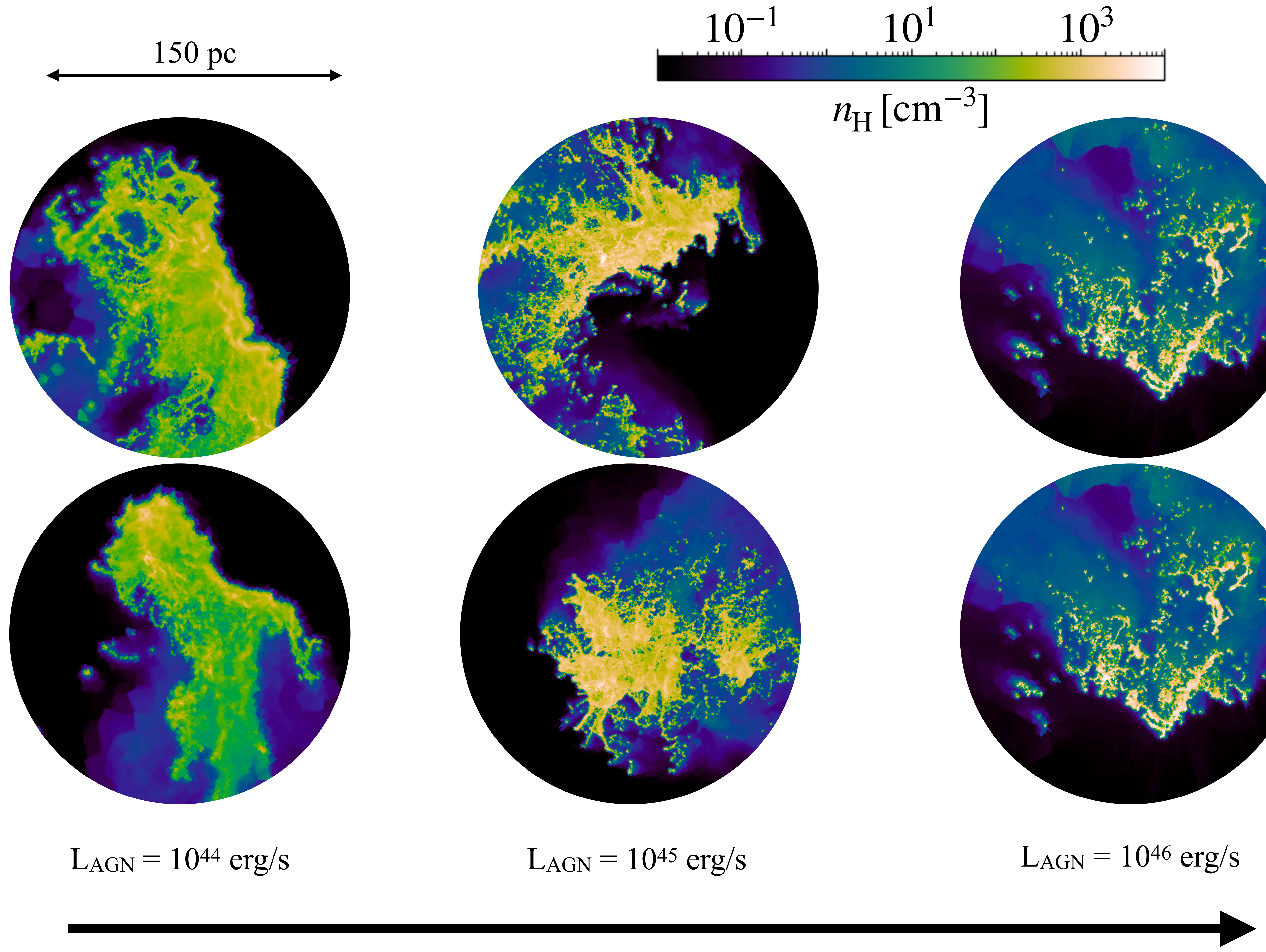


Outflow kinetic power ≠ Feedback power!

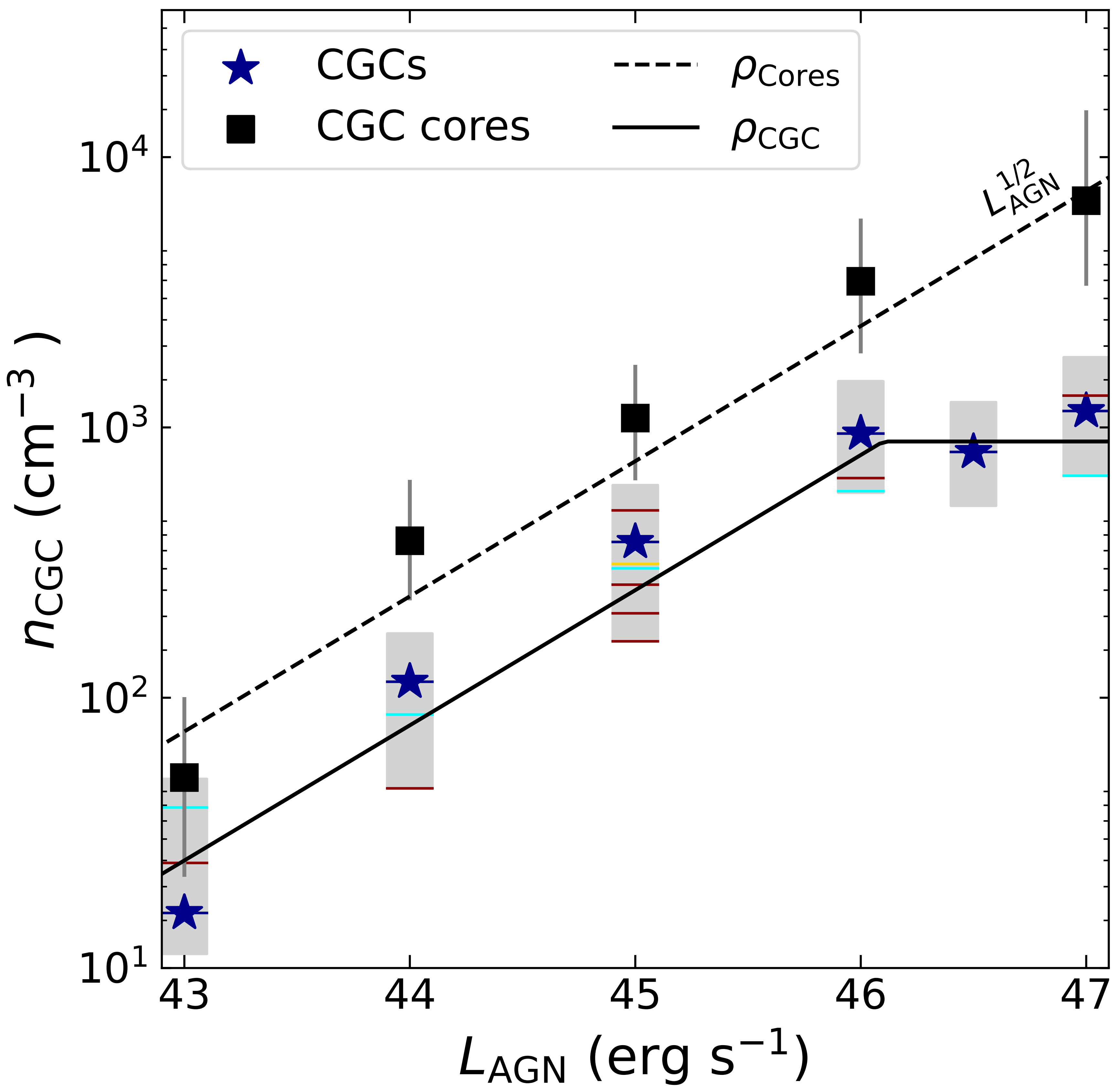
Lowish momentum flux ≠ Momentum-driven!

Lowish kinetic flux ≠ Weak Feedback!

Tracing the Hot Bubble



Almeida, Costa et al. (to be sub.)

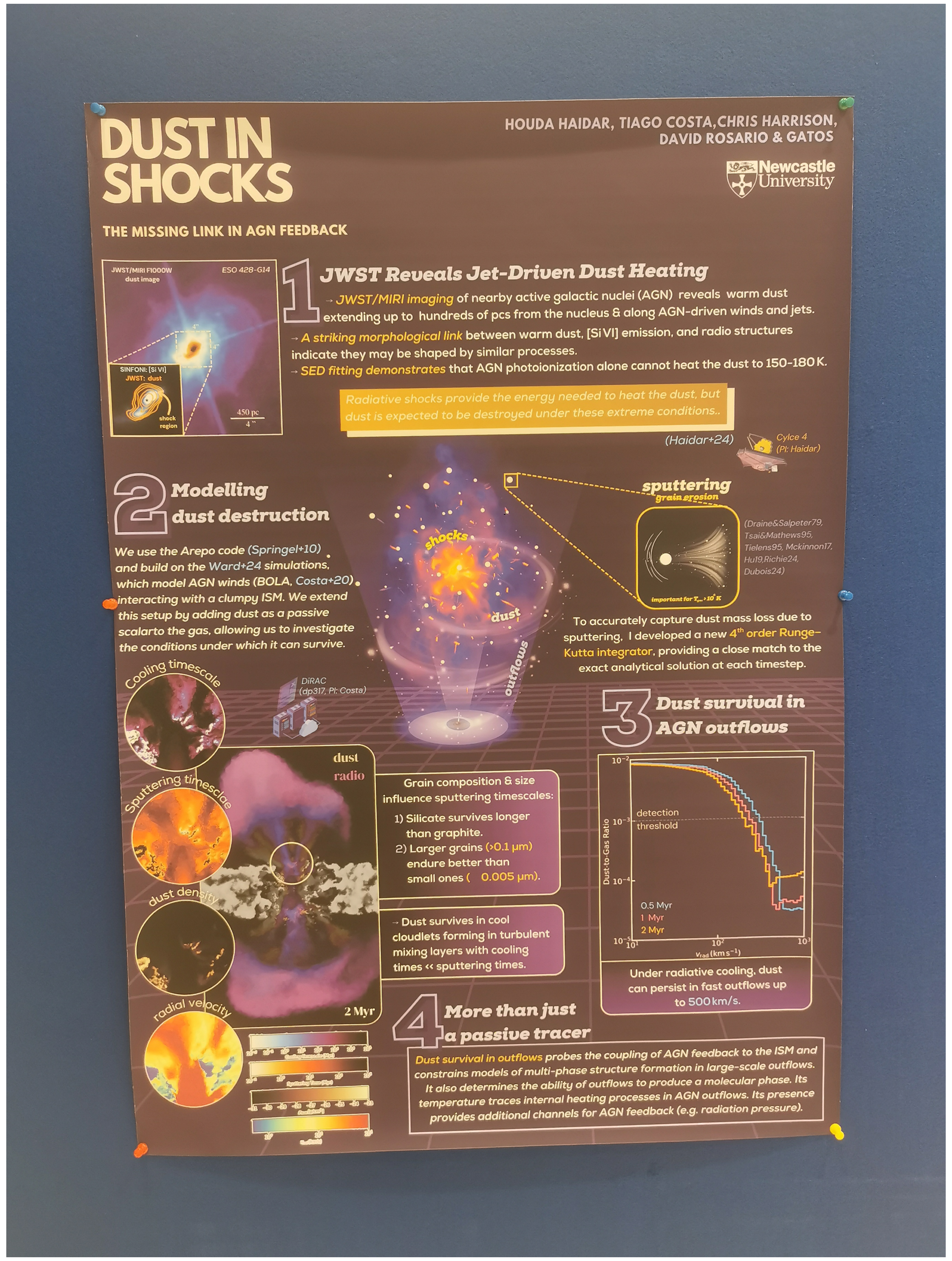


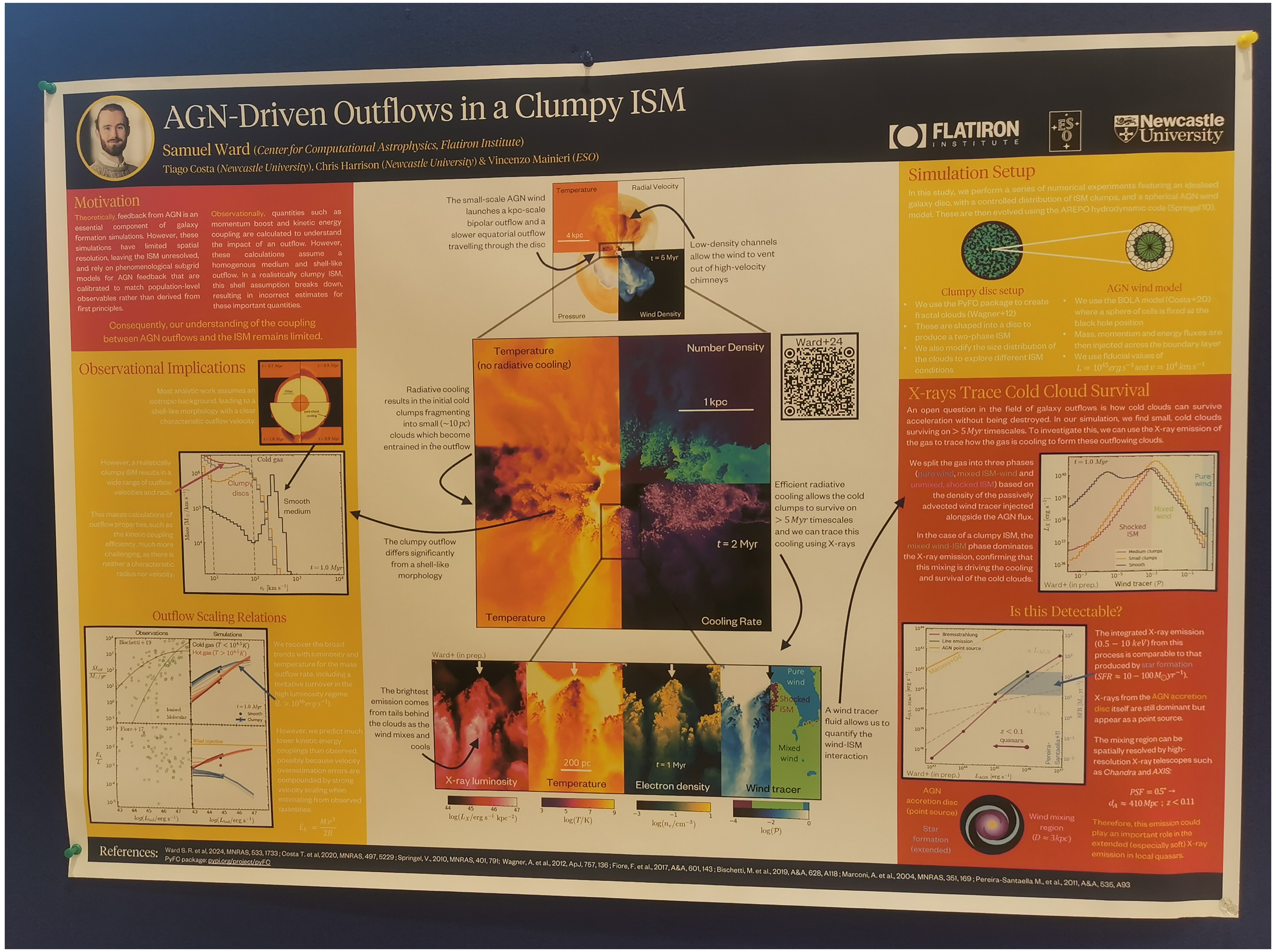
Cool gas phase "knows" about invisible hot bubble pressure:

<u>scaling relation between cool outflow density and outflow power</u>

Poster by Houda Haidar

Poster by Samuel Ward



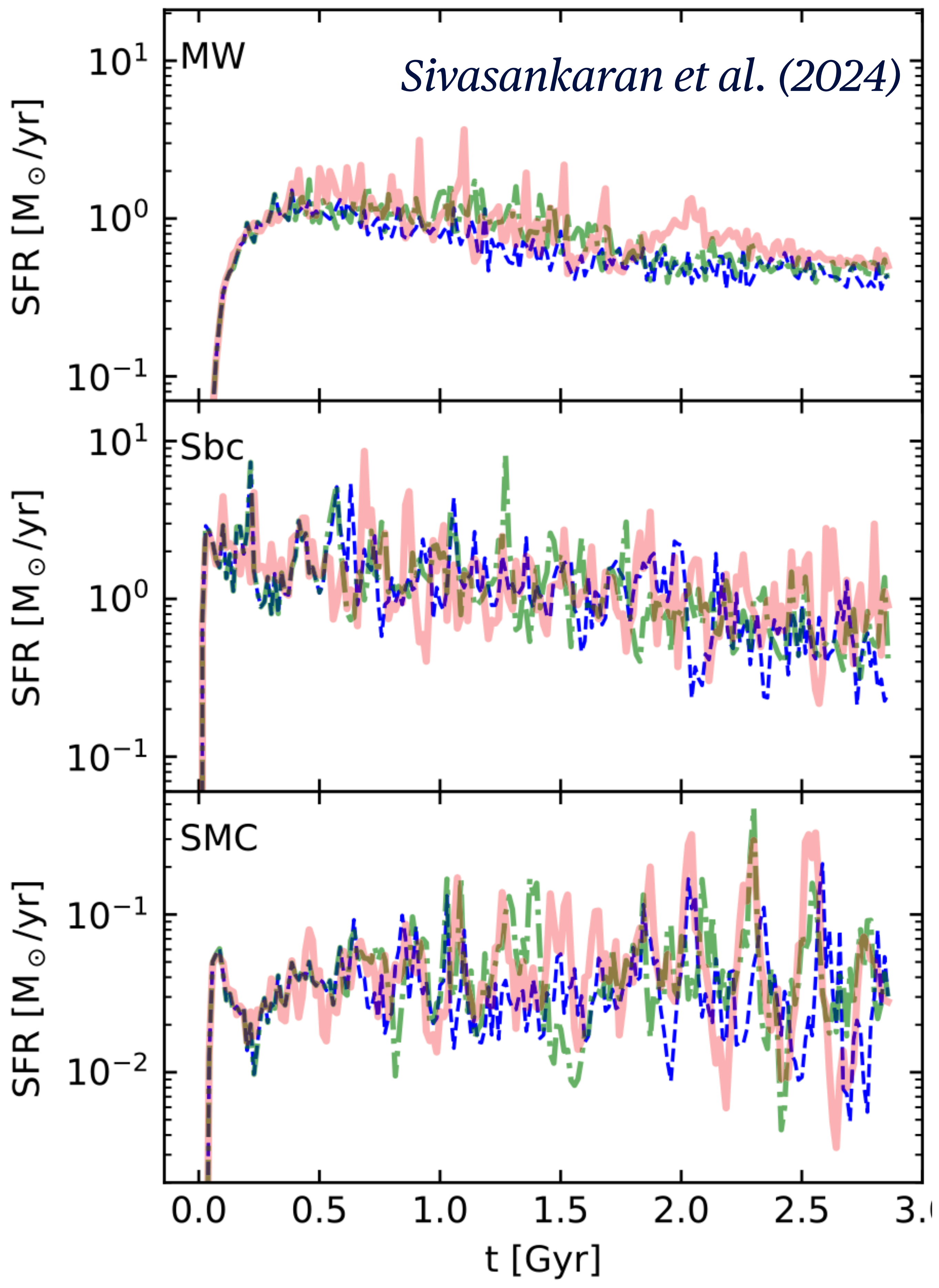


Dust Survival

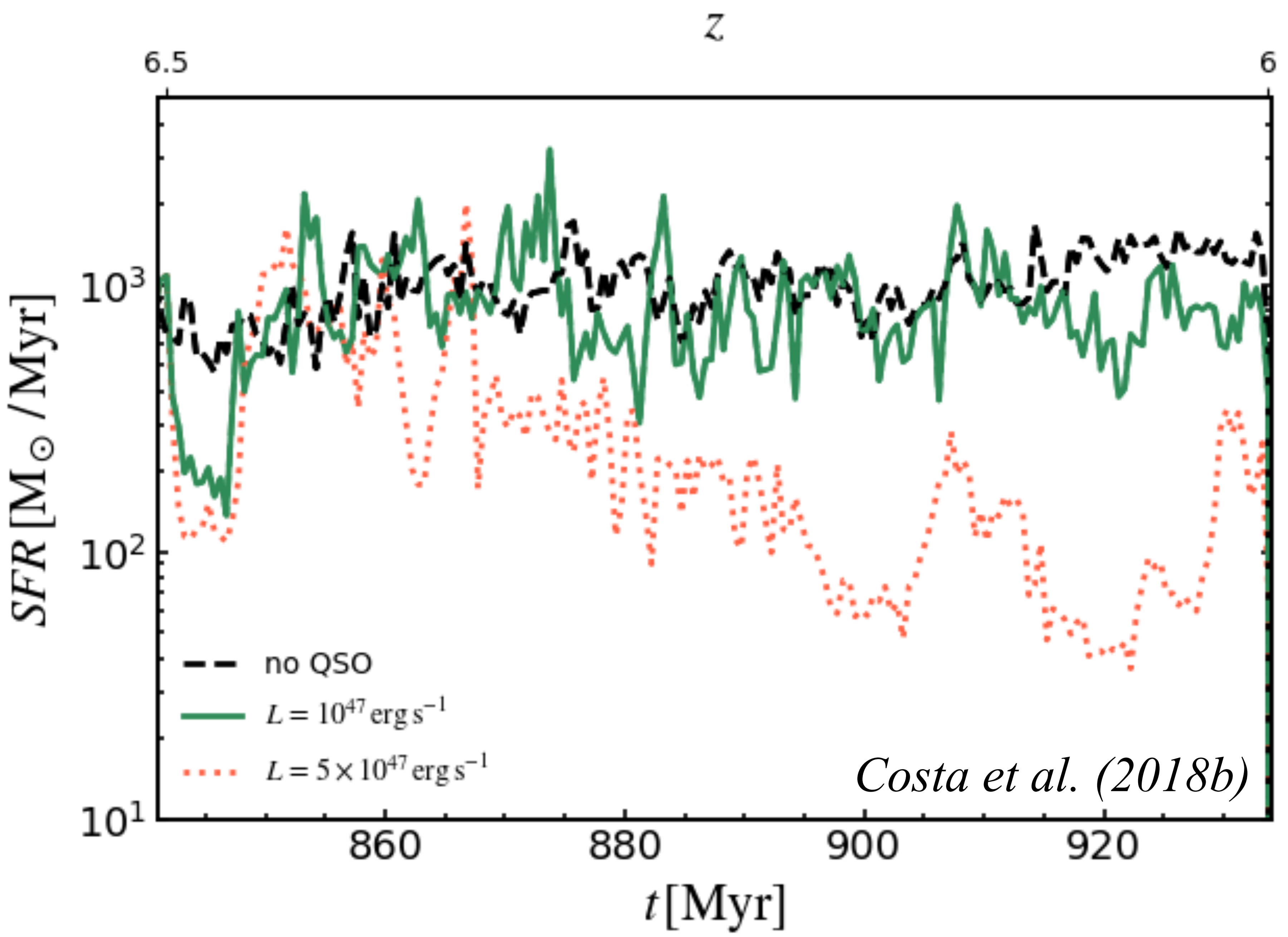
X-ray emission and high-ionisation lines

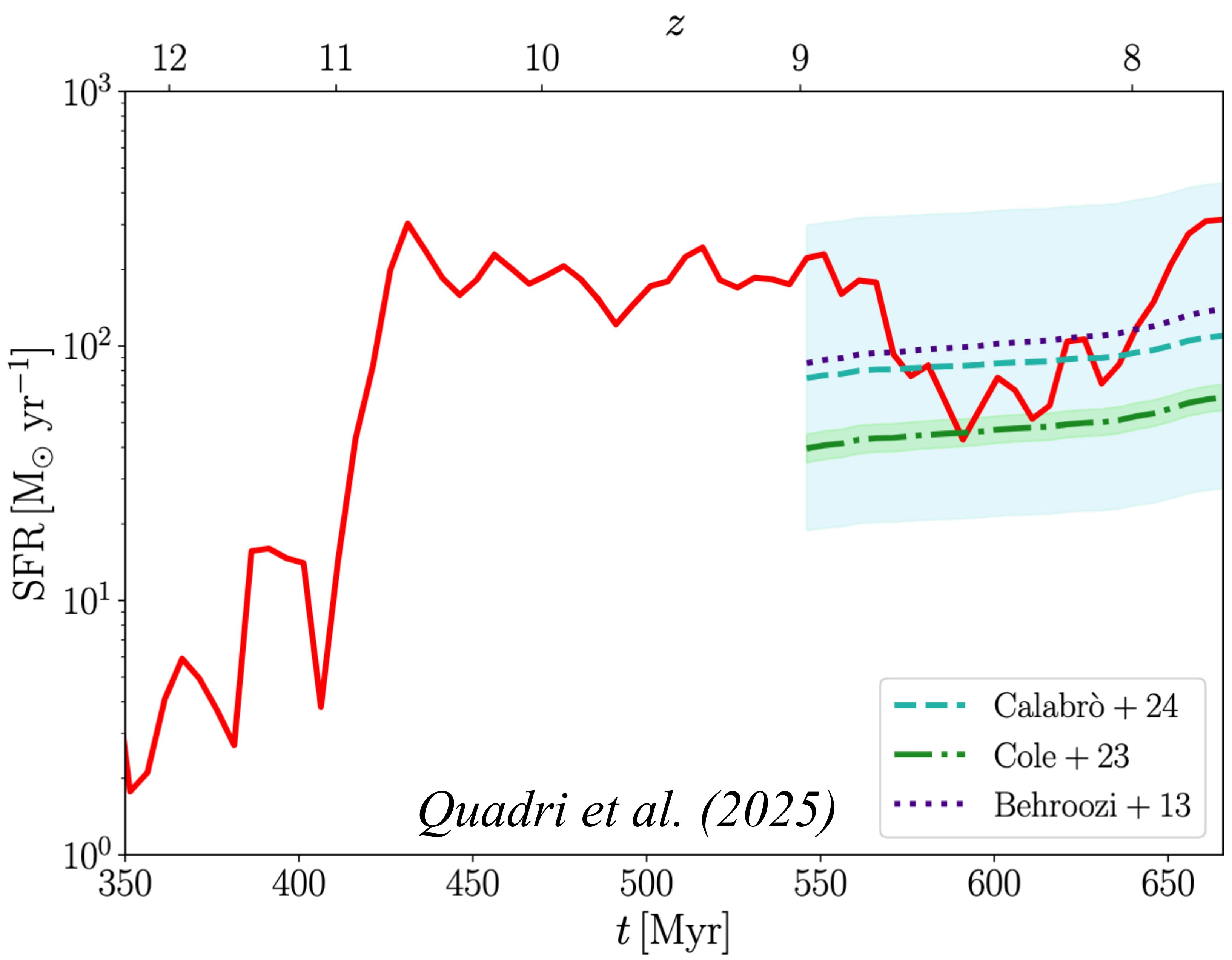
Feedback via ejection

Disc Galaxies



High-z Quasars

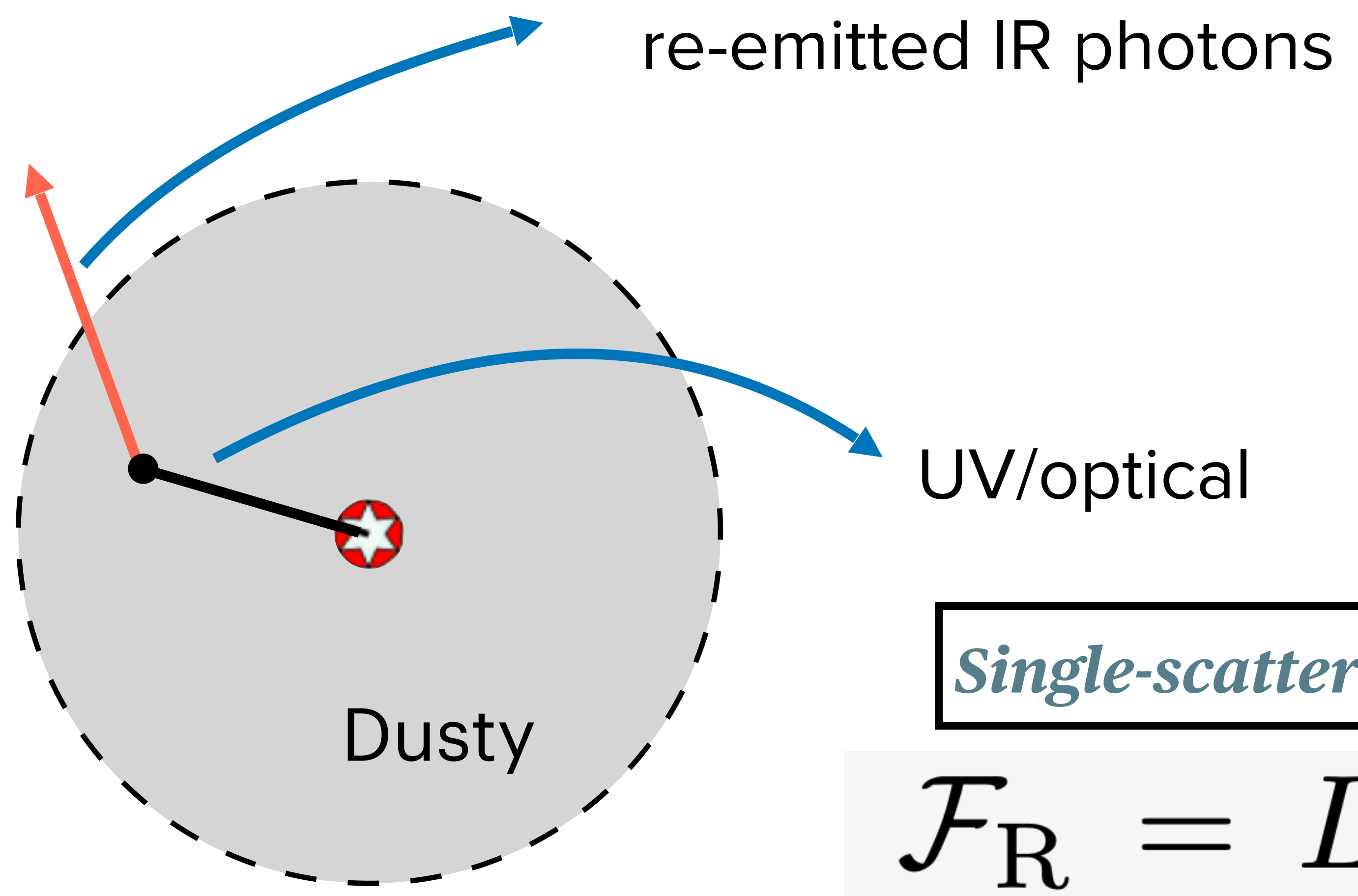




Profound, long-term quenching is difficult, particularly in high-z massive galaxies

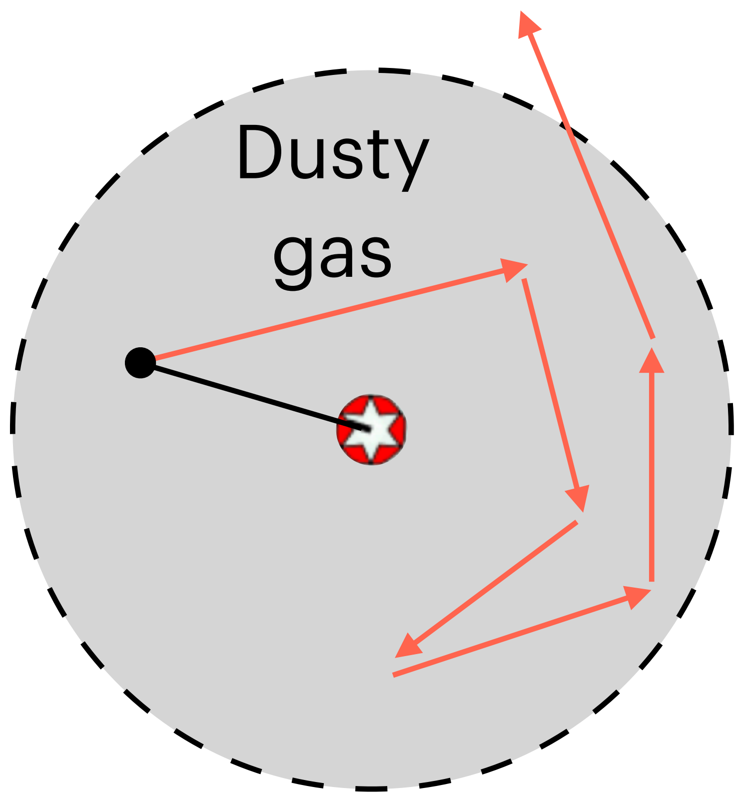
Sutherland & Bicknell (2007), Zubovas & Nayakshin (2012), Wagner et al. (2013), Silk (2013), Gabor & Bournaud (2014), Costa et al. (2014b, 2018b, 2020), Bieri et al. (2015, 2016), Hopkins et al. (2016), Zubovas & Bourne (2017), Nelson et al. (2019), Torrey et al. (2020), Mercedes-Feliz et al. (2023a, b), Sivasankaran et al. (2024)

Radiation pressure-driving



Single-scattering

$$\mathcal{F}_{\rm R} = L/c$$

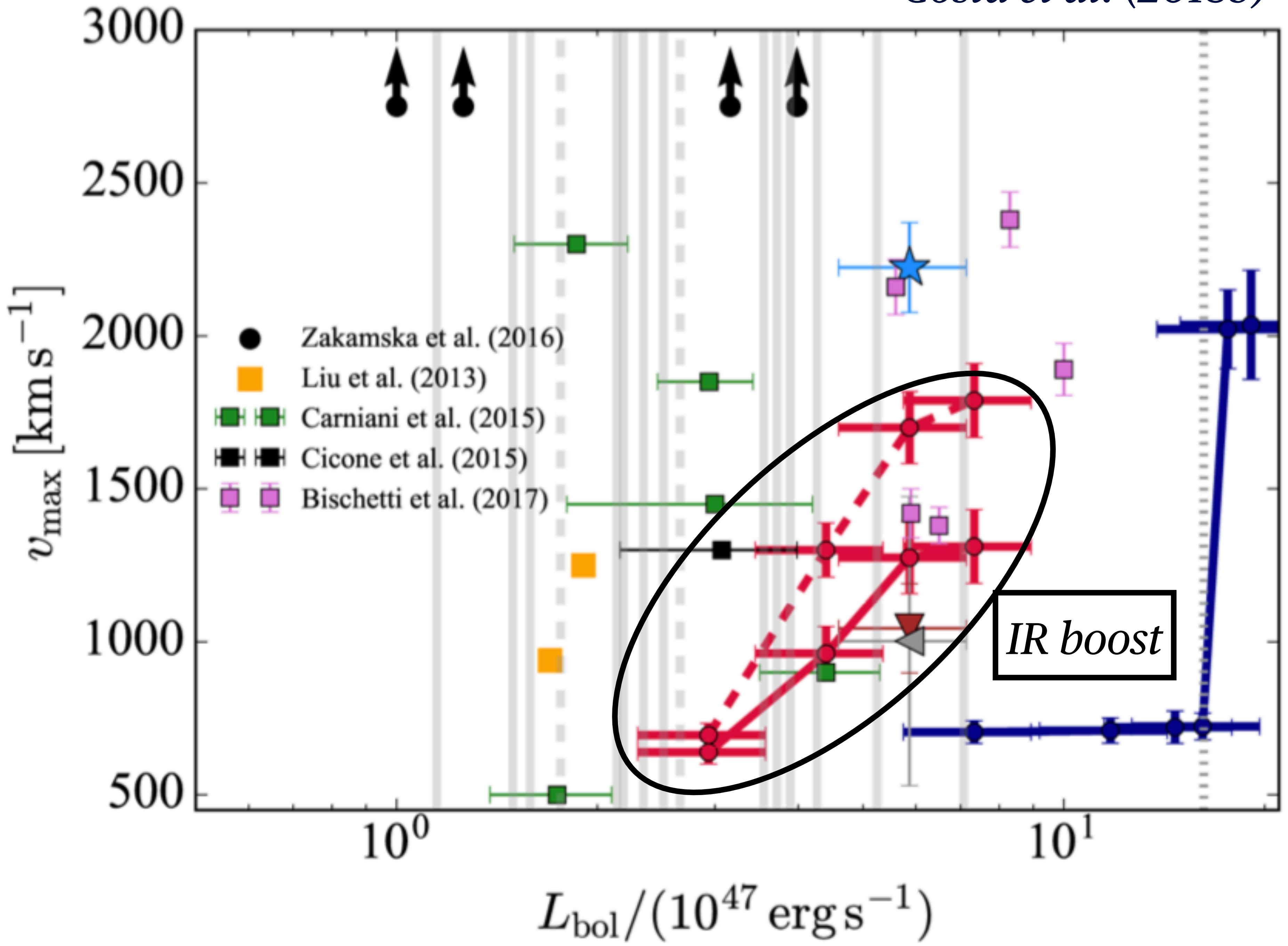


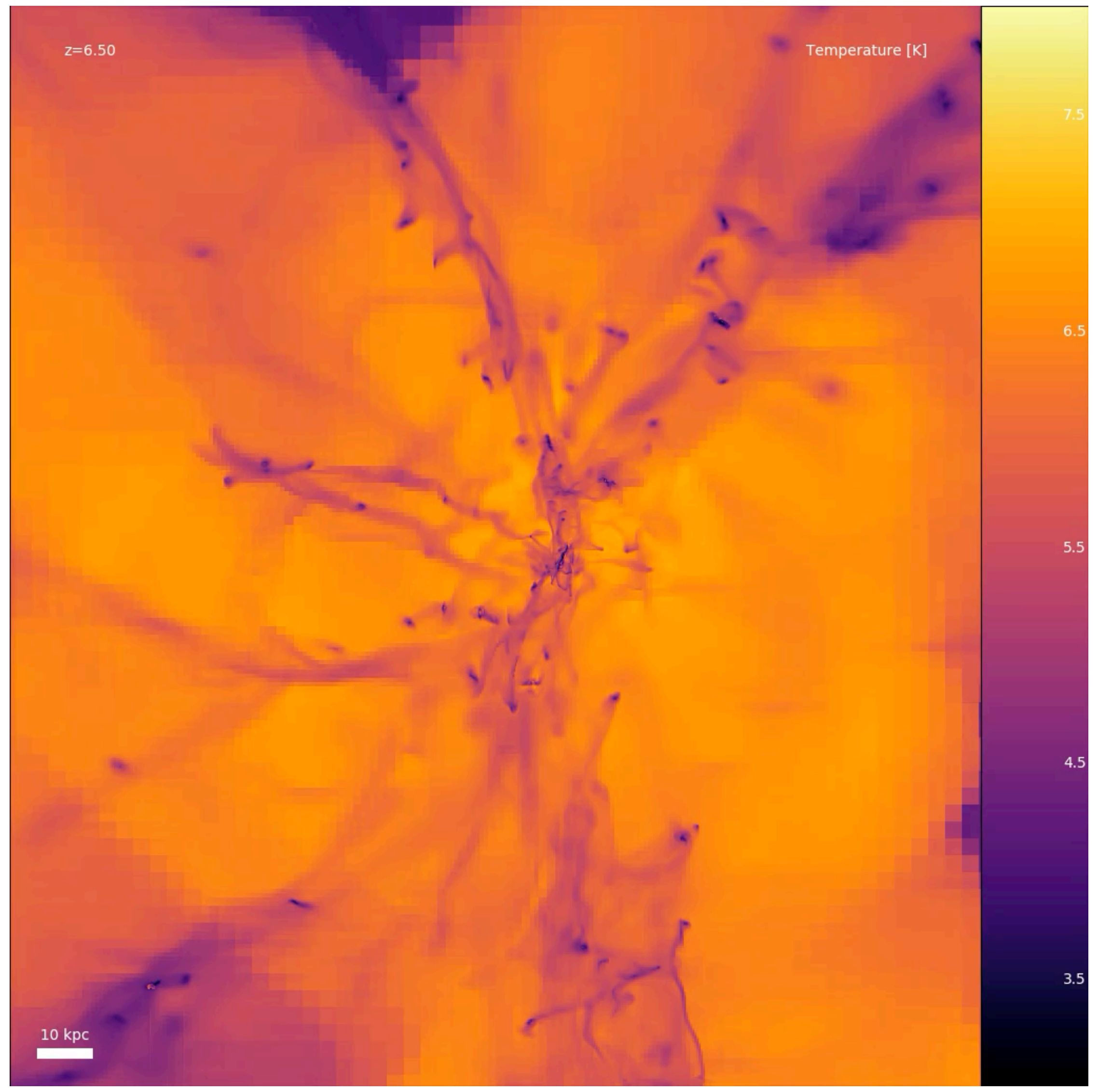
Multi-scattering

$$\mathcal{F}_{\rm R} = \tau_{\rm IR} L/c$$

re-emitted IR flux
trapped

Costa et al. (2018b)

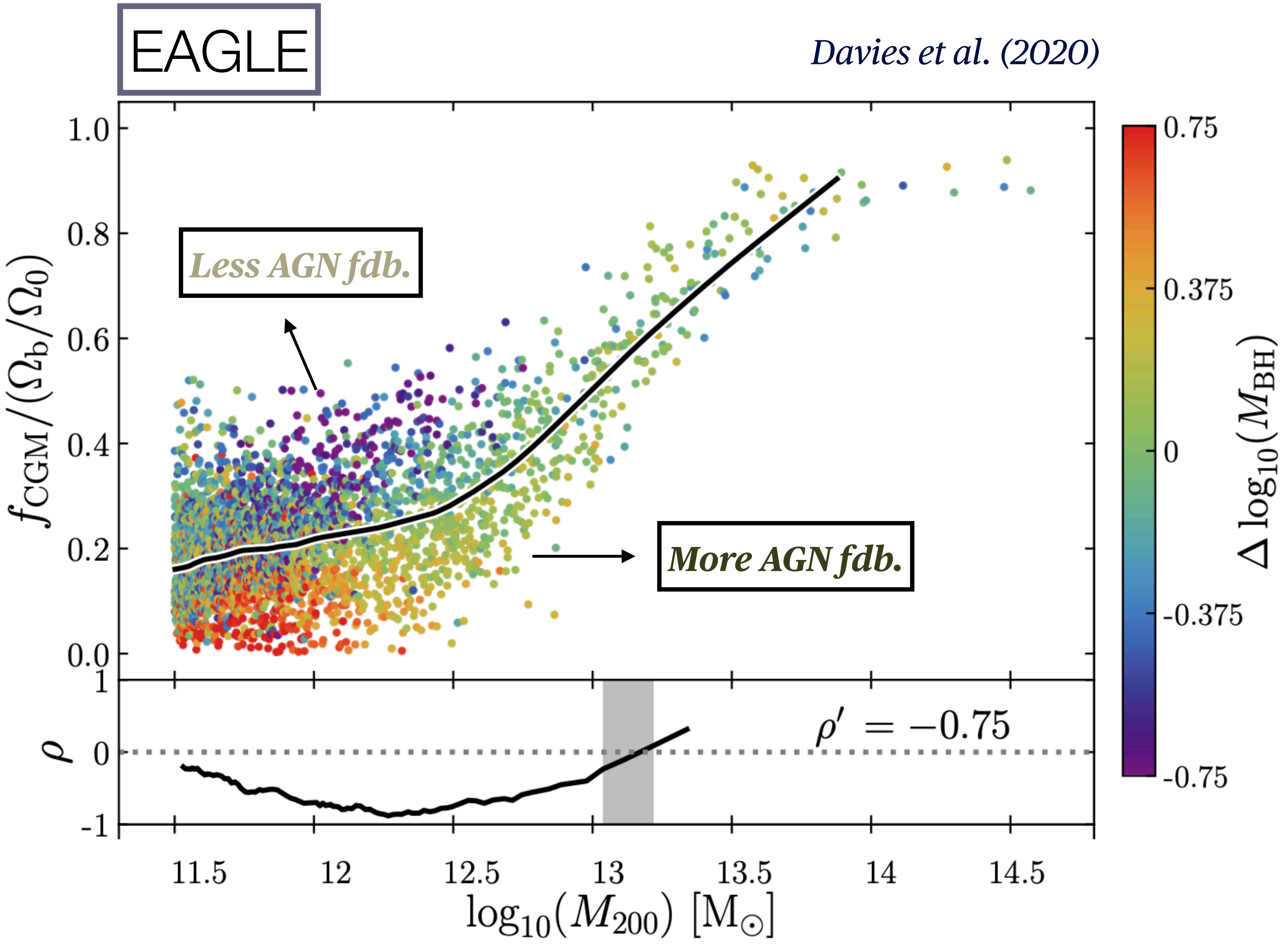


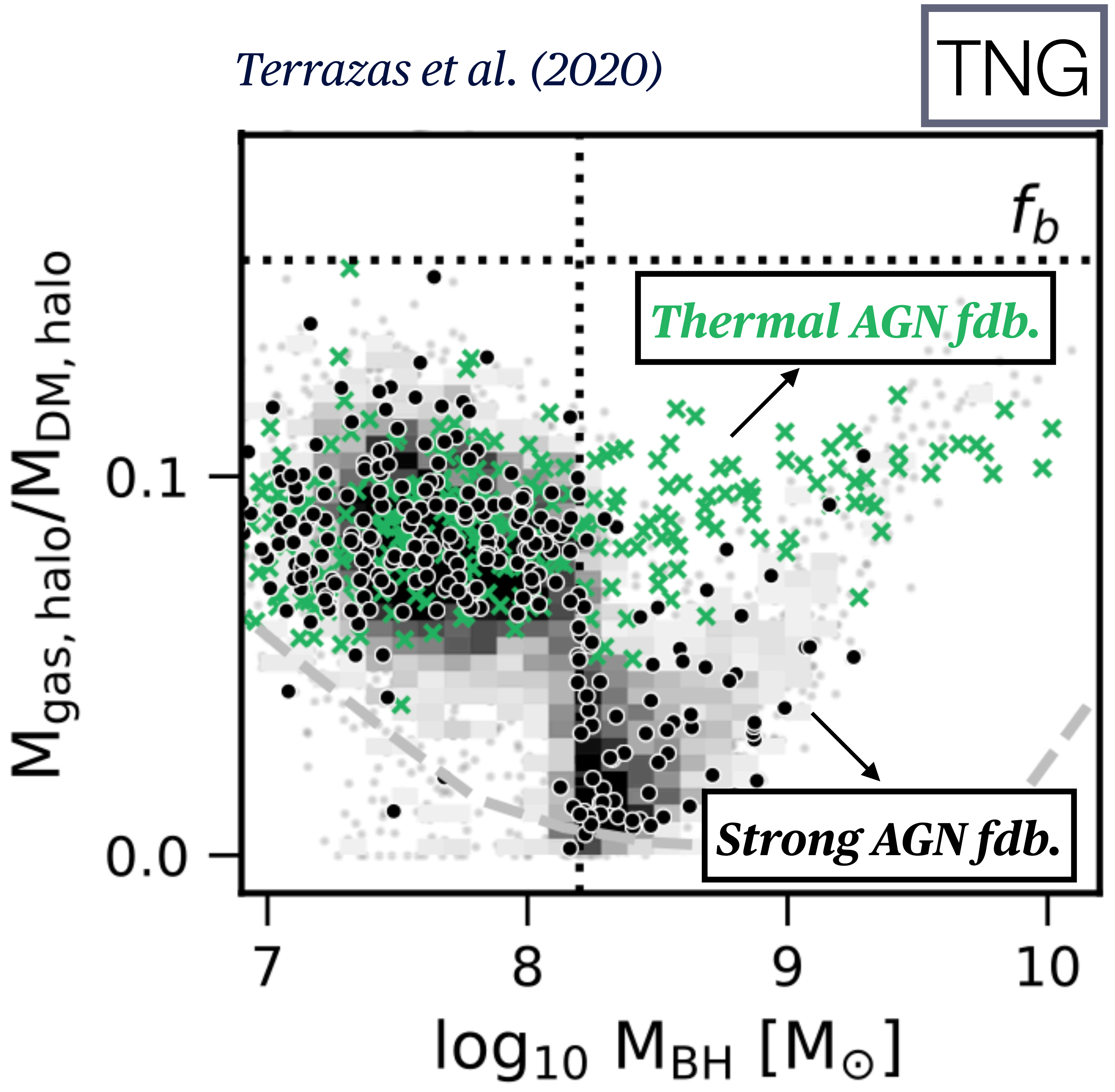


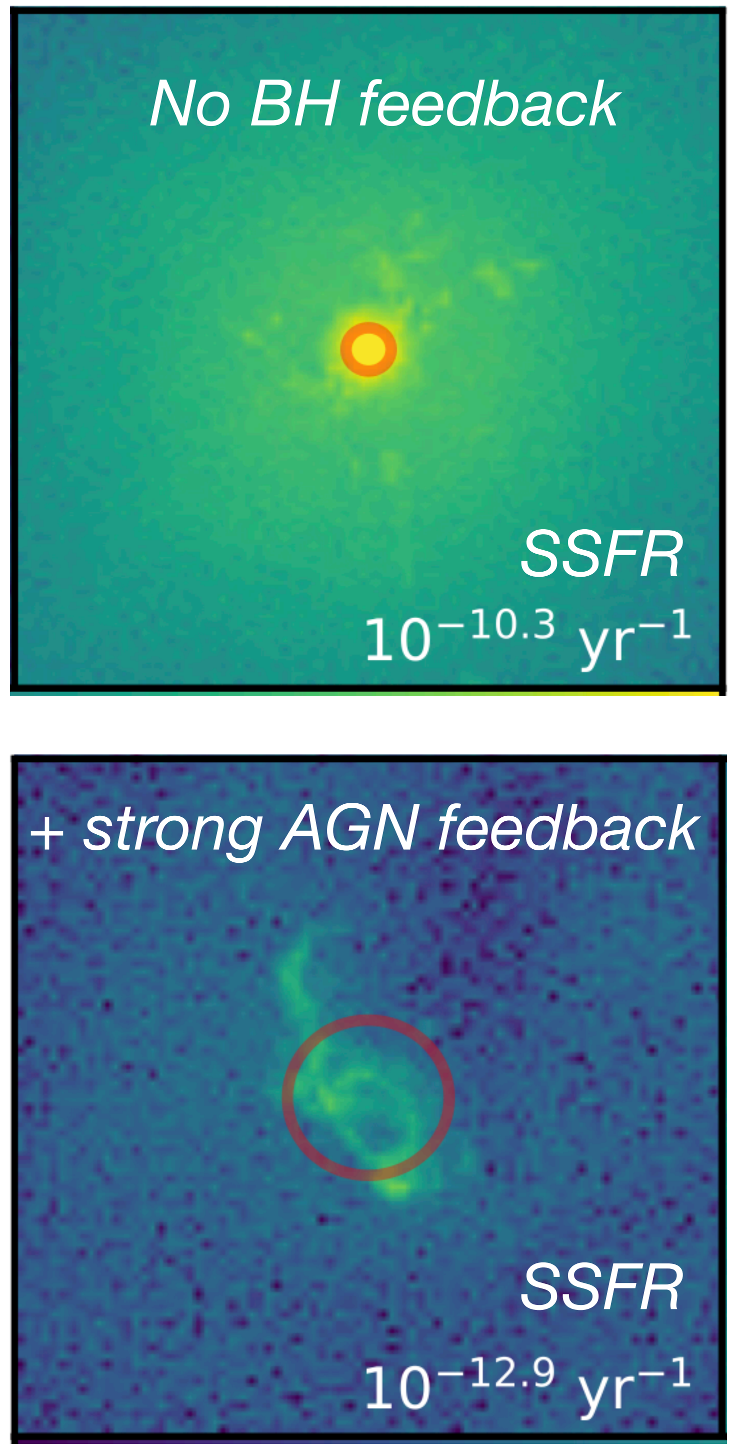
Radiation pressure on dust boosts outflows in obscured AGN in compact galaxies. A great, understudied high-z AGN feedback mechanism.

Fabian (1999), Murray et al. (2005), Roth et al. (2012), Novak et al. (2012), Thompson et al. (2015), Ishibashi & Fabian (2015), Bieri et al. (2017), Costa et al. (2018a, b), Barnes et al. (2020)

Quenching & Impact on CGM







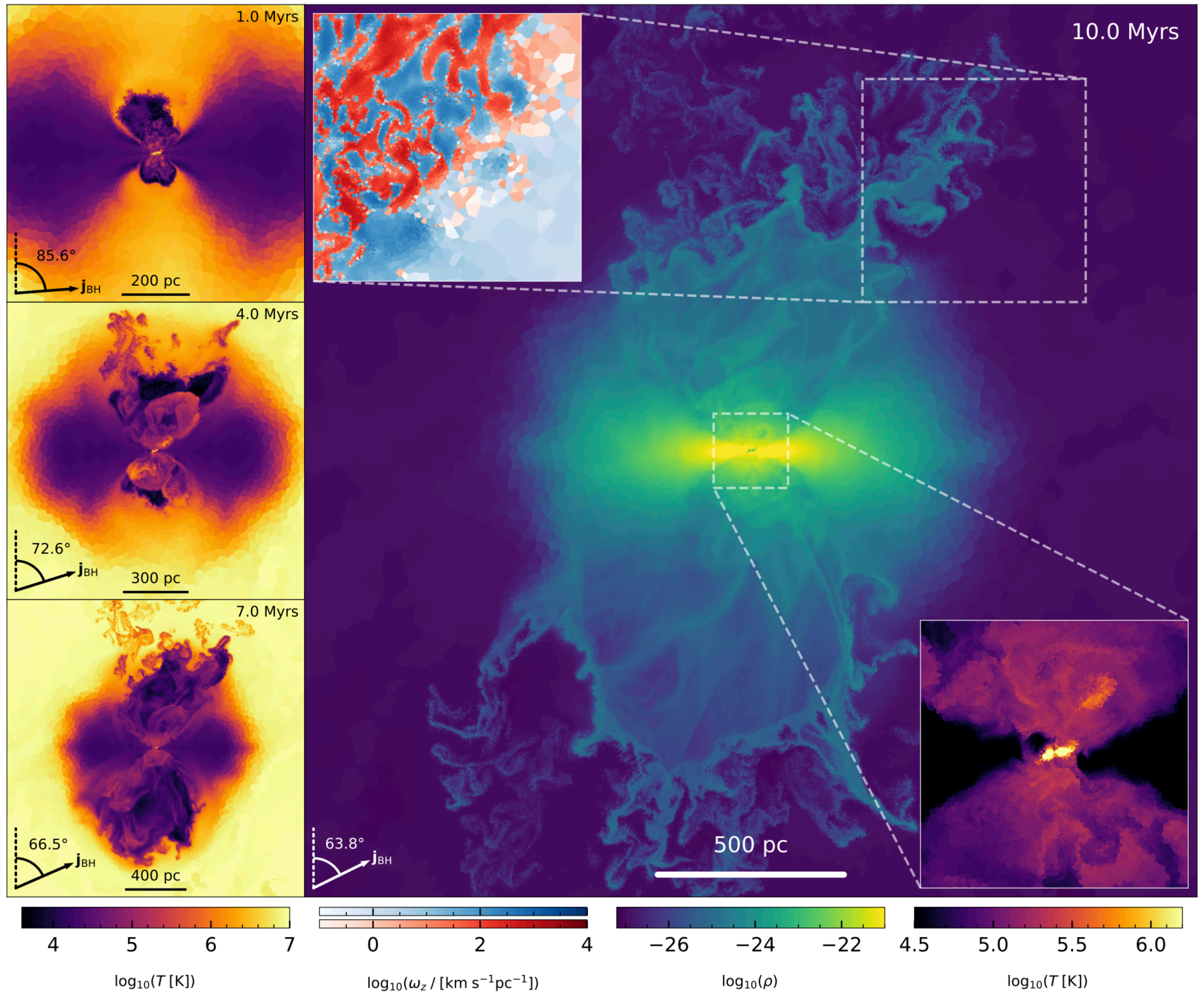
Massive galaxy quenching goes hand-in-hand with a suppression of the CGM density:
“Preventive feedback” required for long-term quenching.

Choi et al. (2014), Bower et al. (2017), Davies et al. (2019, 2020), Terrazas et al. (2020), Zinger et al. (2020), Oppenheimer et al. (2020), Ramesh et al, (2023), Voit et al. (2024)

Jets: not just "maintenance"

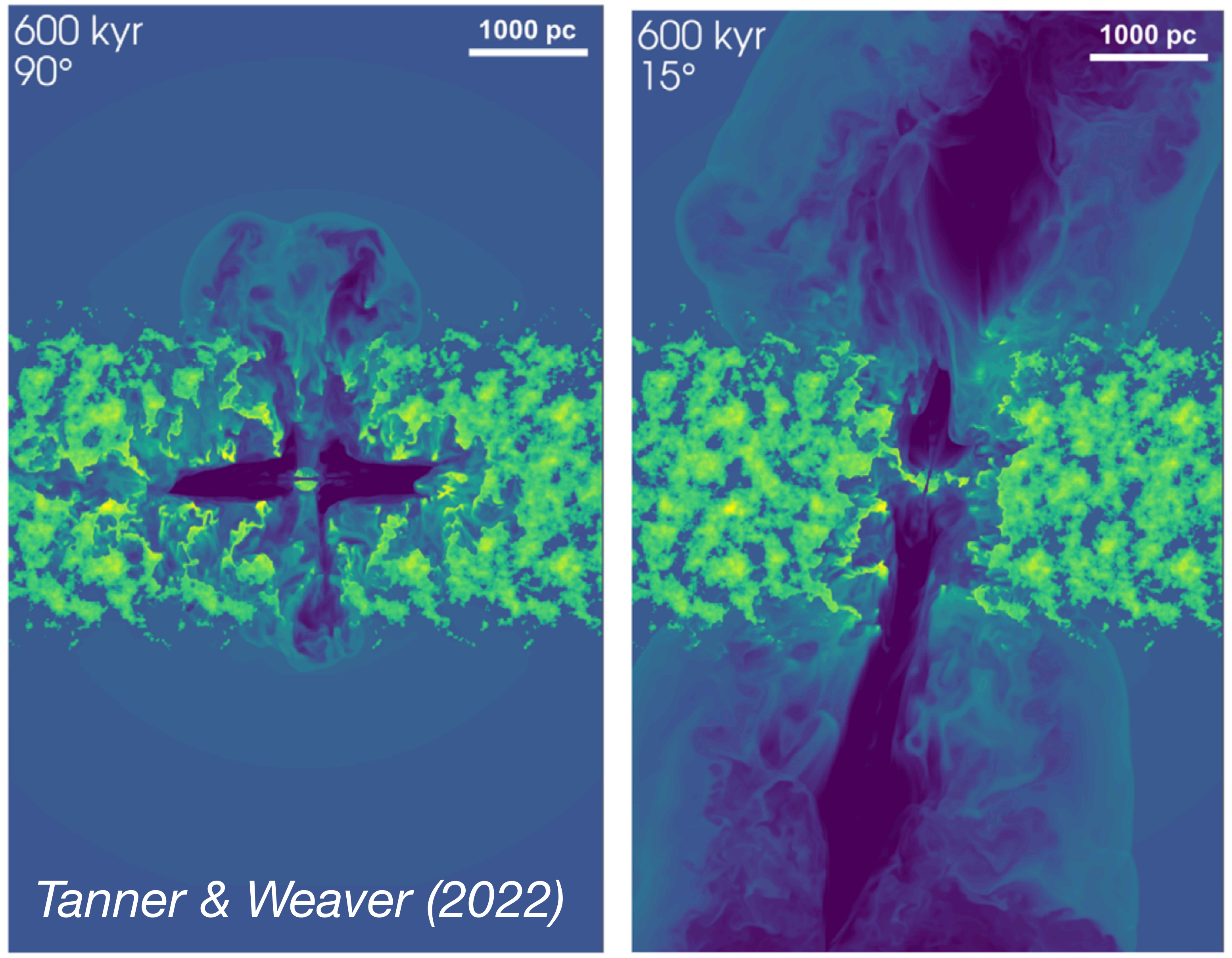
Poster by M. Meenakshi

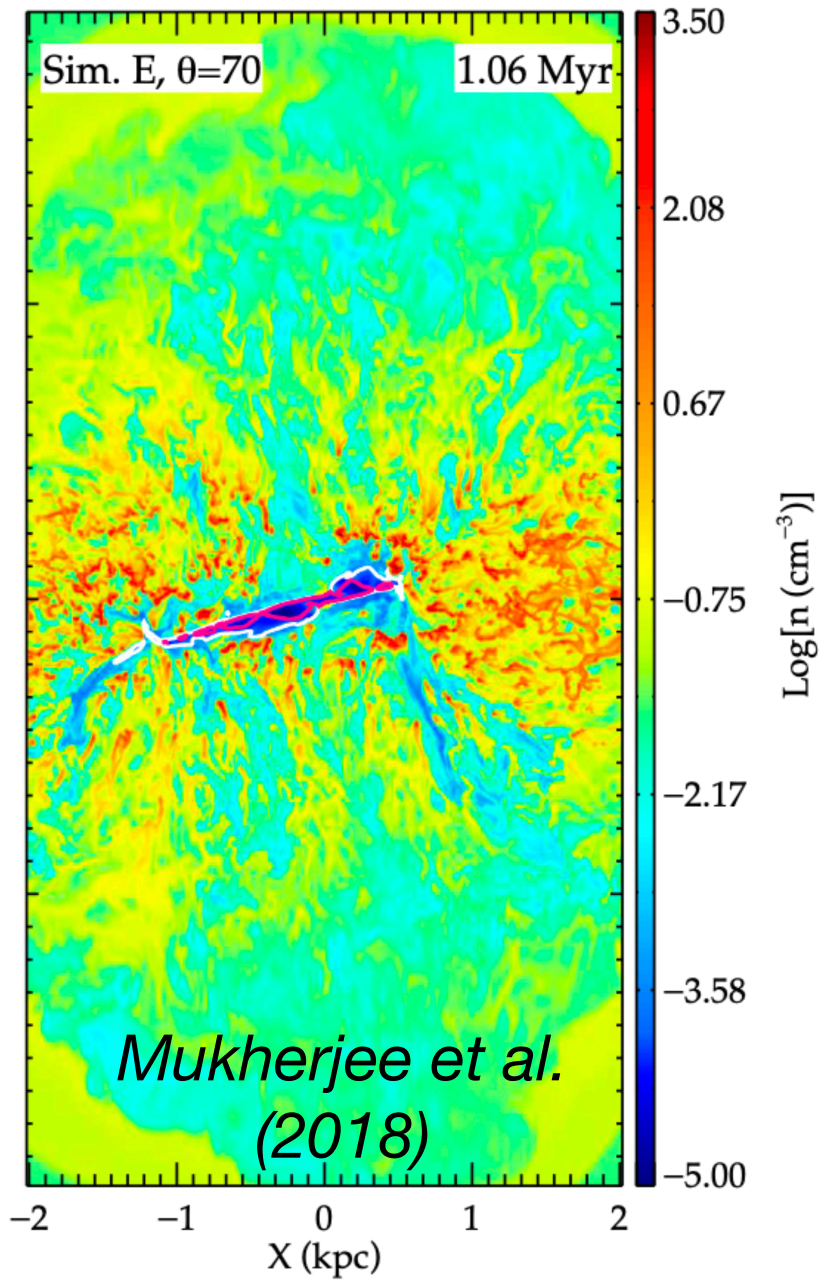
Talbot et al. (2021)



Wagner et al. (2016)

back most relevant to compact radio sources: The interaction of young jets in a radio galaxy with the ISM leads to quasar-mode, energy-driven, mechanical, negative or positive feedback.



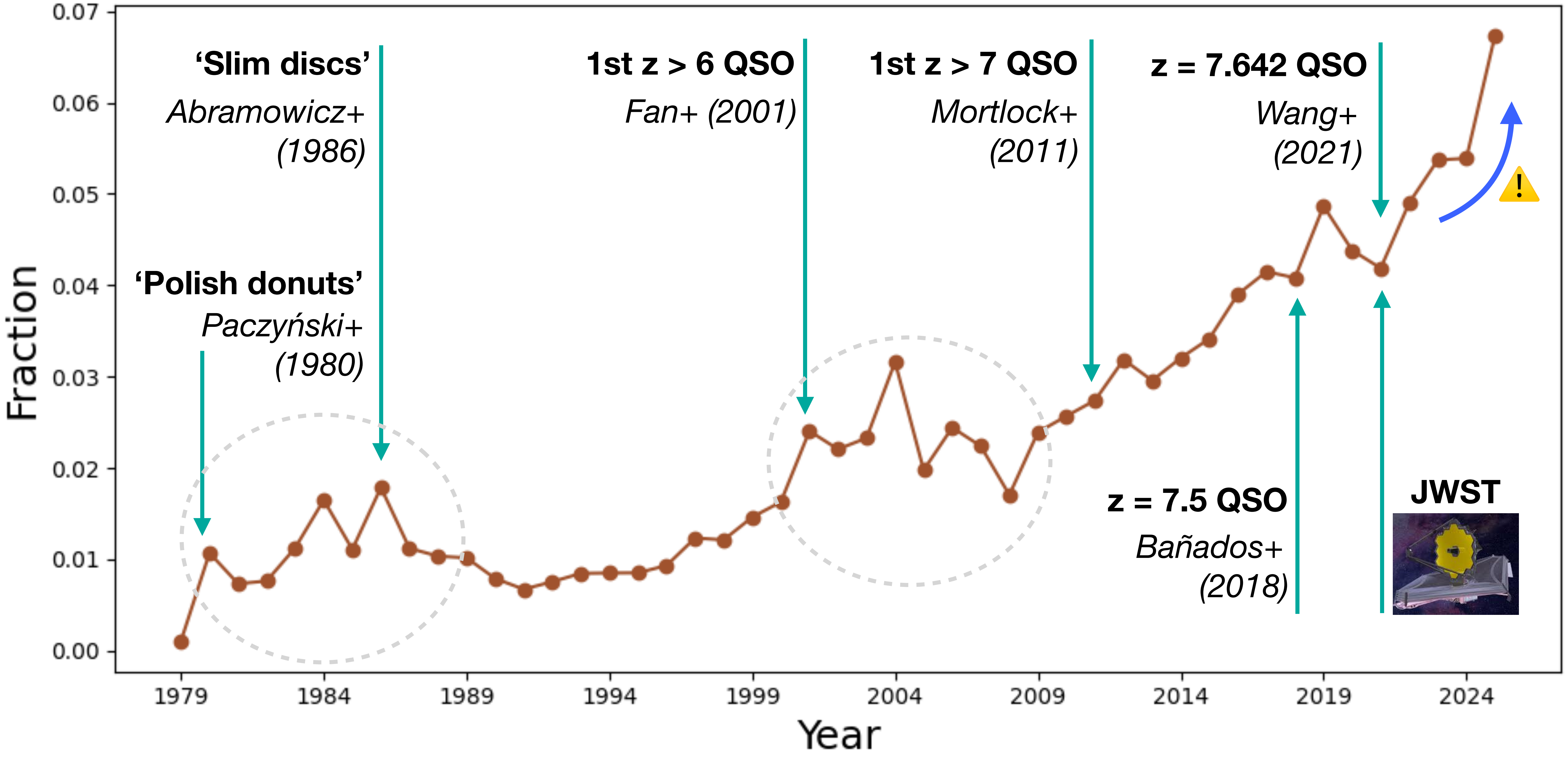


Jets, in fact, can interact significantly with host galaxy, causing a combination of ejection and positive feedback (like in "quasar mode") in addition to regulating cooling.

Wagner et al. (2011, 2012, 2016), Mukherjee et al. (2016, 2018, 2021), Cielo et al. (2008), Mandal et al. (2021), Tanner & Weaver (2022), Talbot et al. (2021, 2022, 2023), Sala et al. (2021), Huško et al. (2024), Borodina et al. (2025)

Super-Eddington

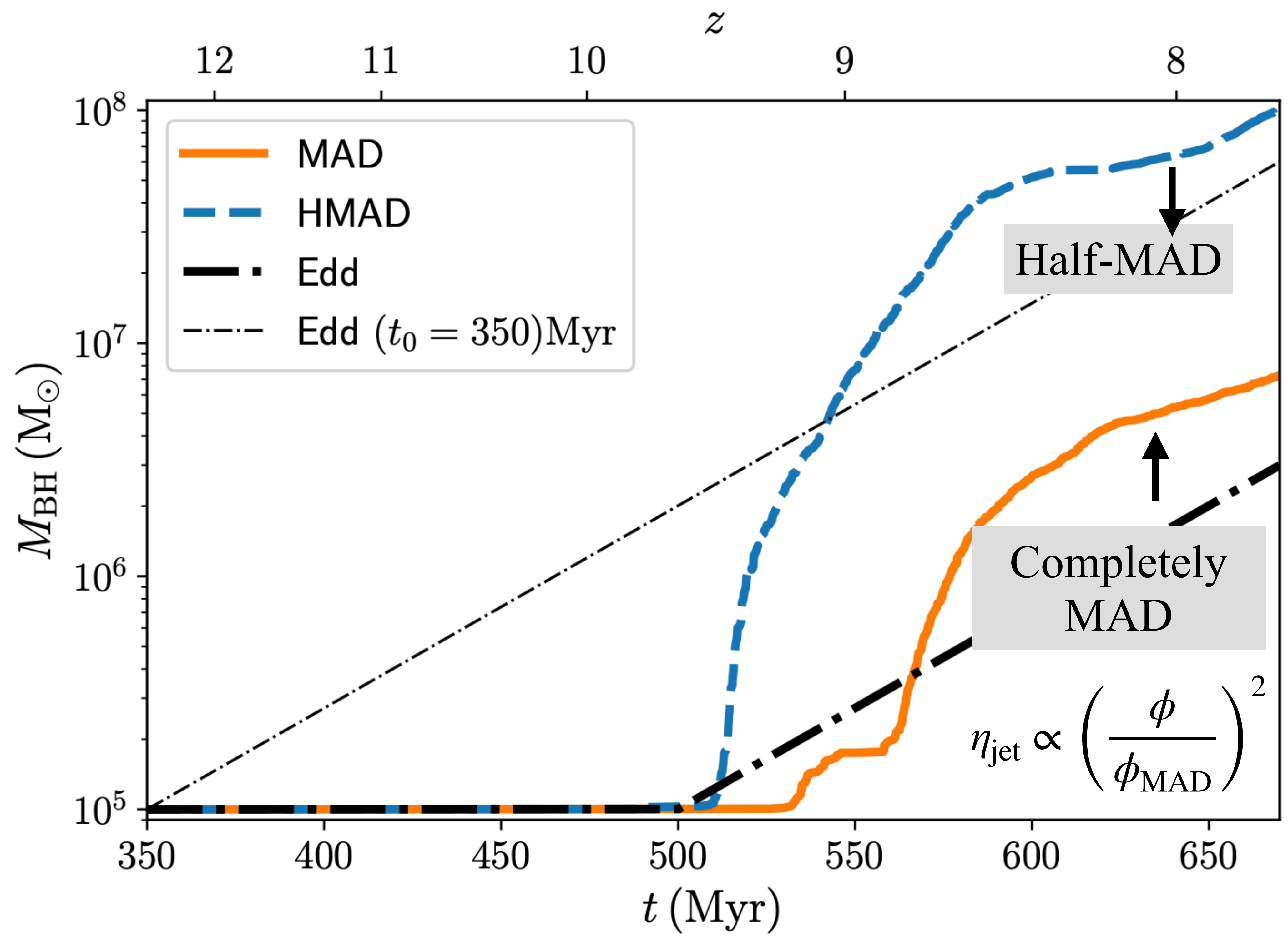
Ratio of publications mentioning “super-Eddington” AND either “quasar” or “supermassive black holes” to publications mentioning either “quasar” or “supermassive black holes” (from ads)



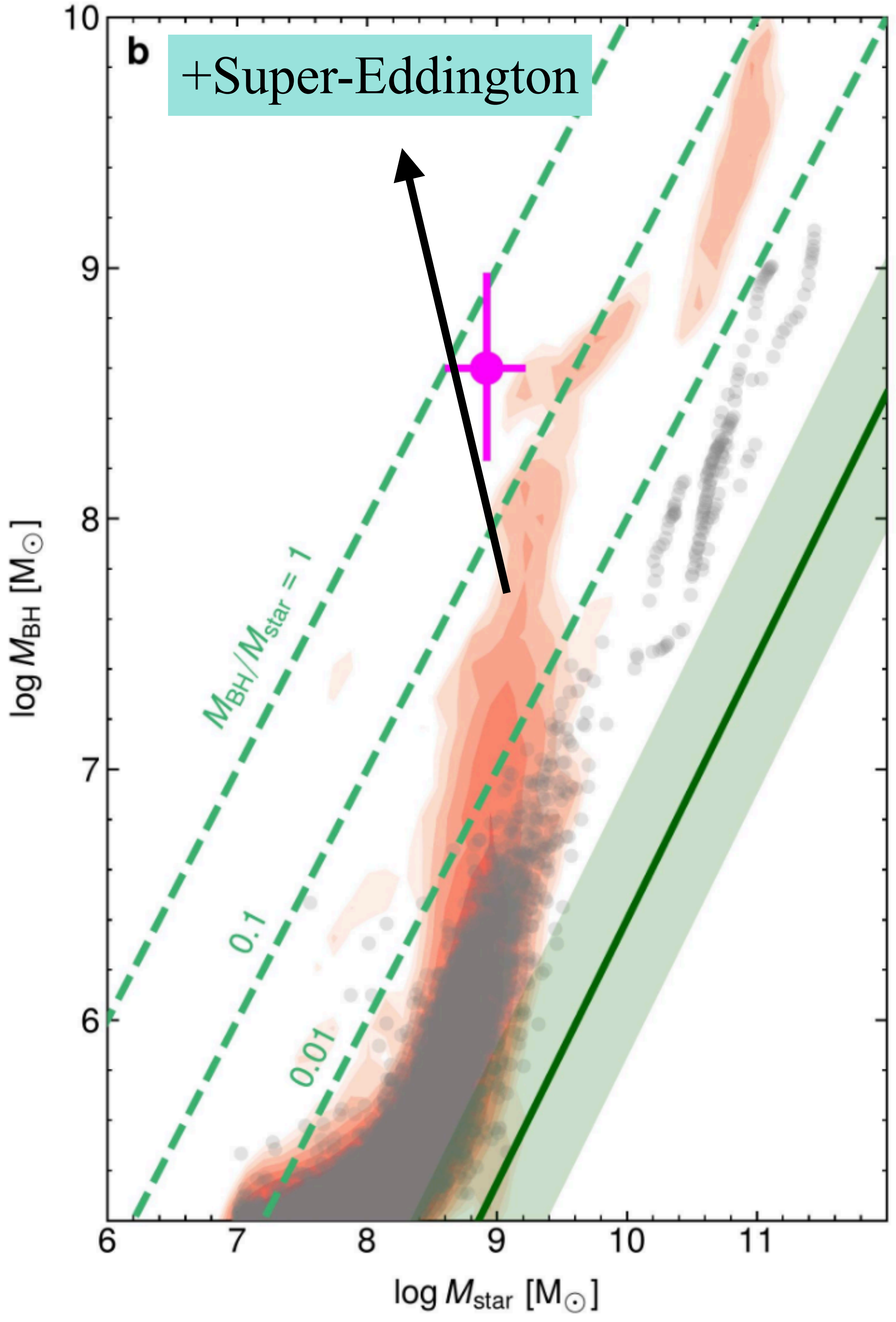
High-z quasars and AGN have generated growing interest in super-Eddington accretion.

Super-Eddington

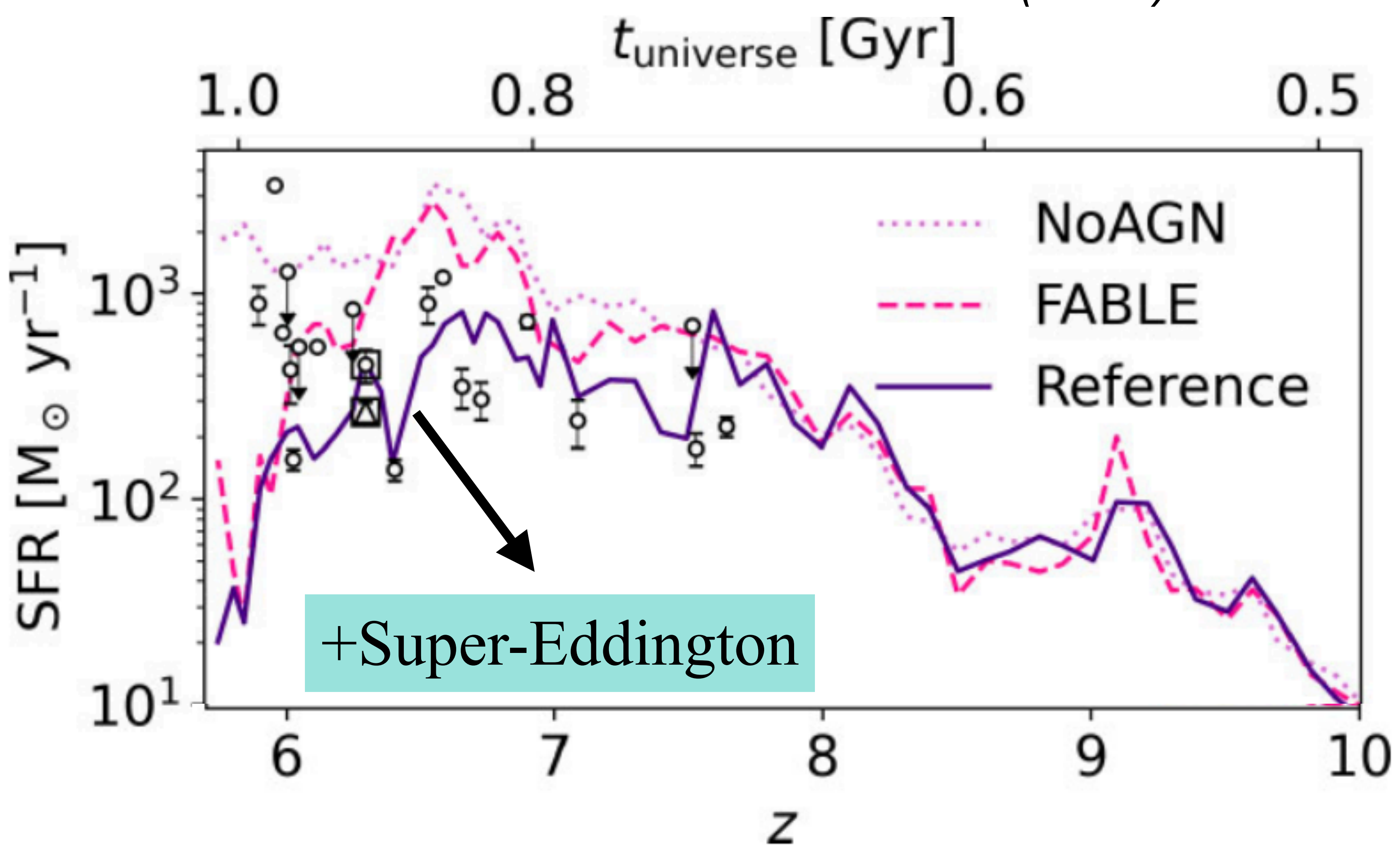
Lupi et al. (2024)

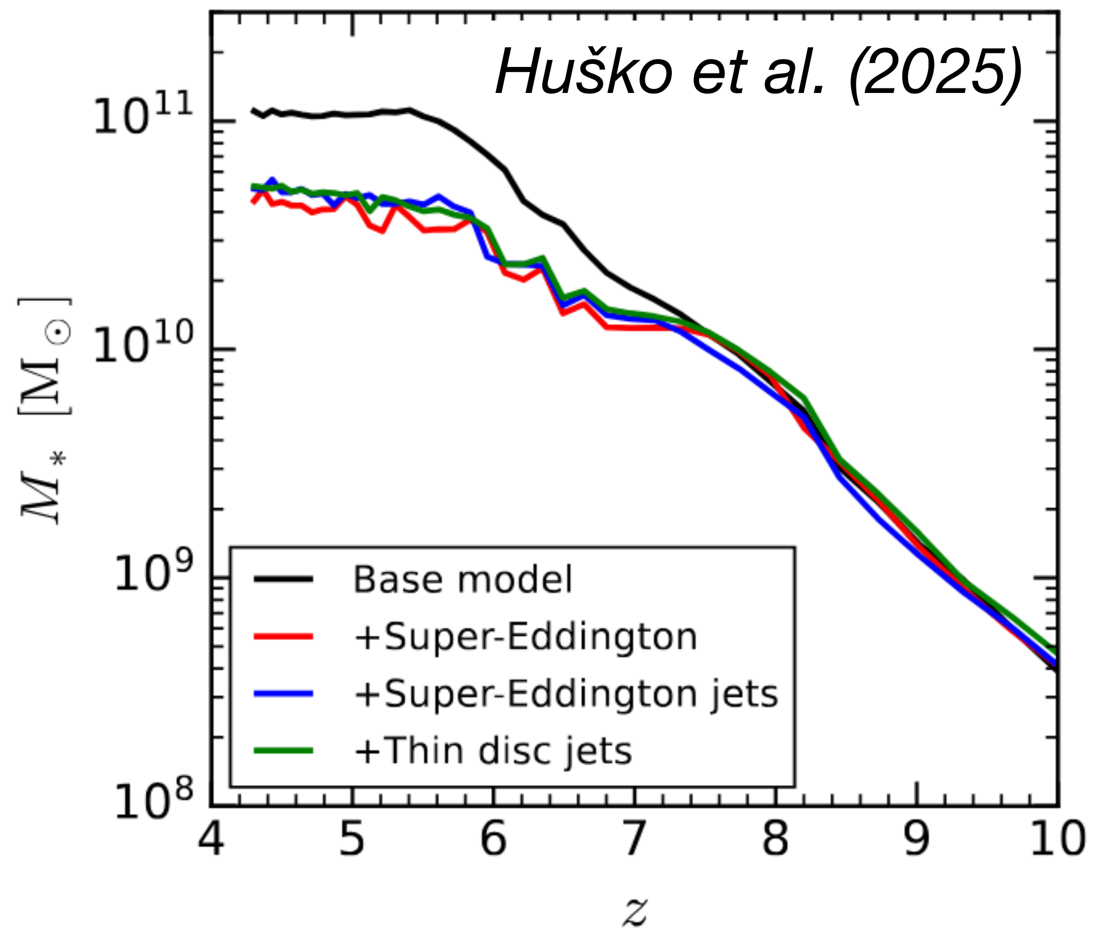


Juodžbalis et al. (2024)



Bennett et al. (2024)





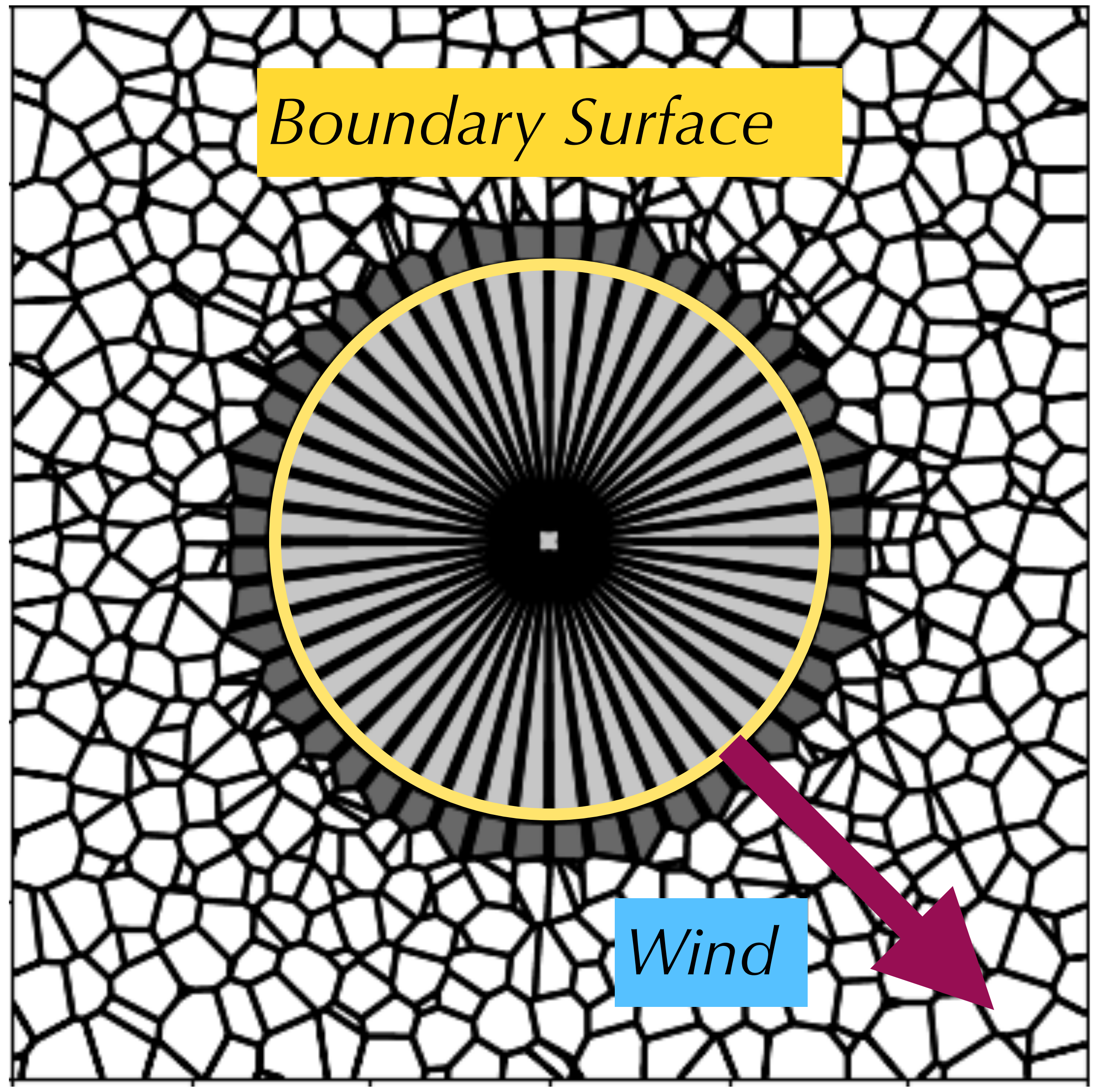
Super-Eddington growth helps not just with producing more massive (even overmassive) black holes: it helps with suppressing star formation earlier on.

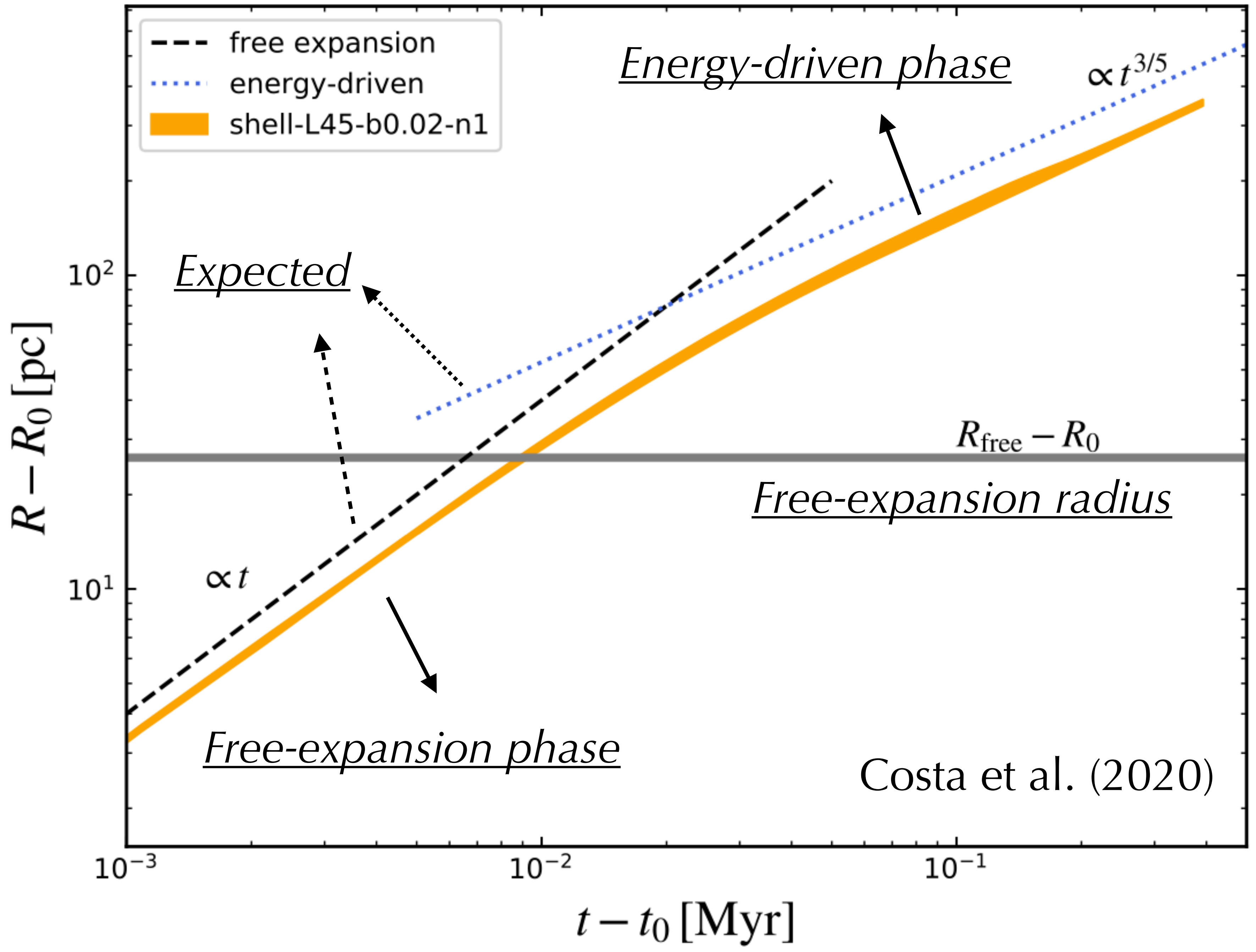
Massonneau et al. (2023), Rennehan et al. (2024), Bennett et al. (2024), Lupi et al. (2024), Juodžbalis et al. (2024), Huško et al. (2025), Quadri et al. (2025),

BOLA

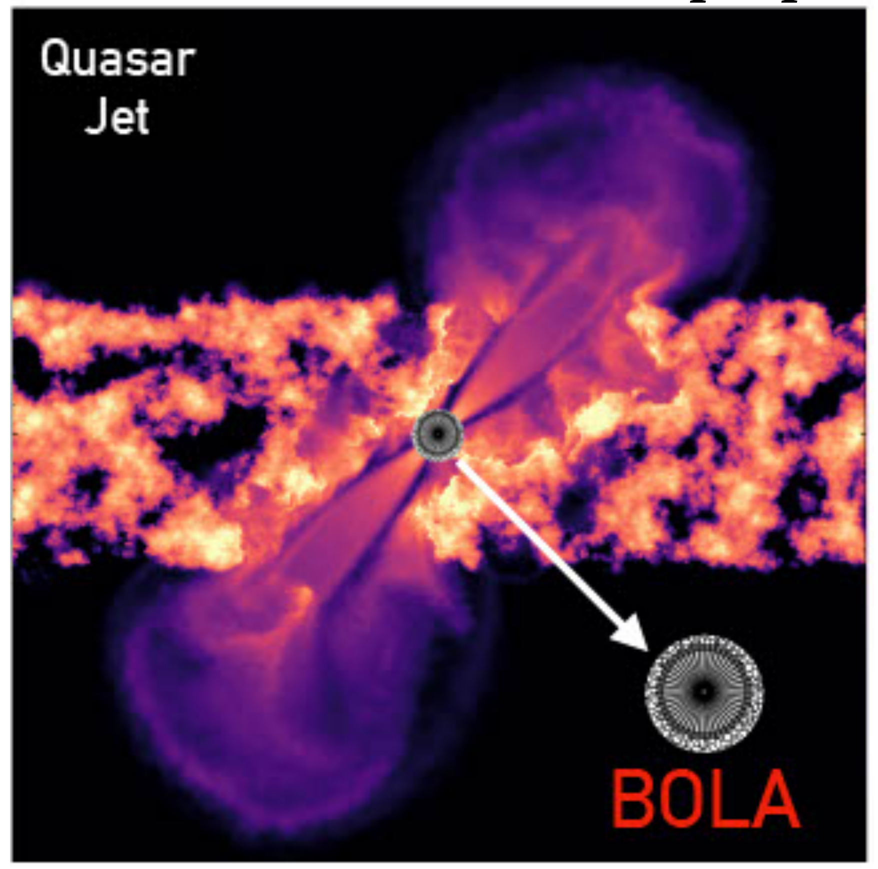
Add a boundary surface & model a wind/jet through appropriate boundary conditions.

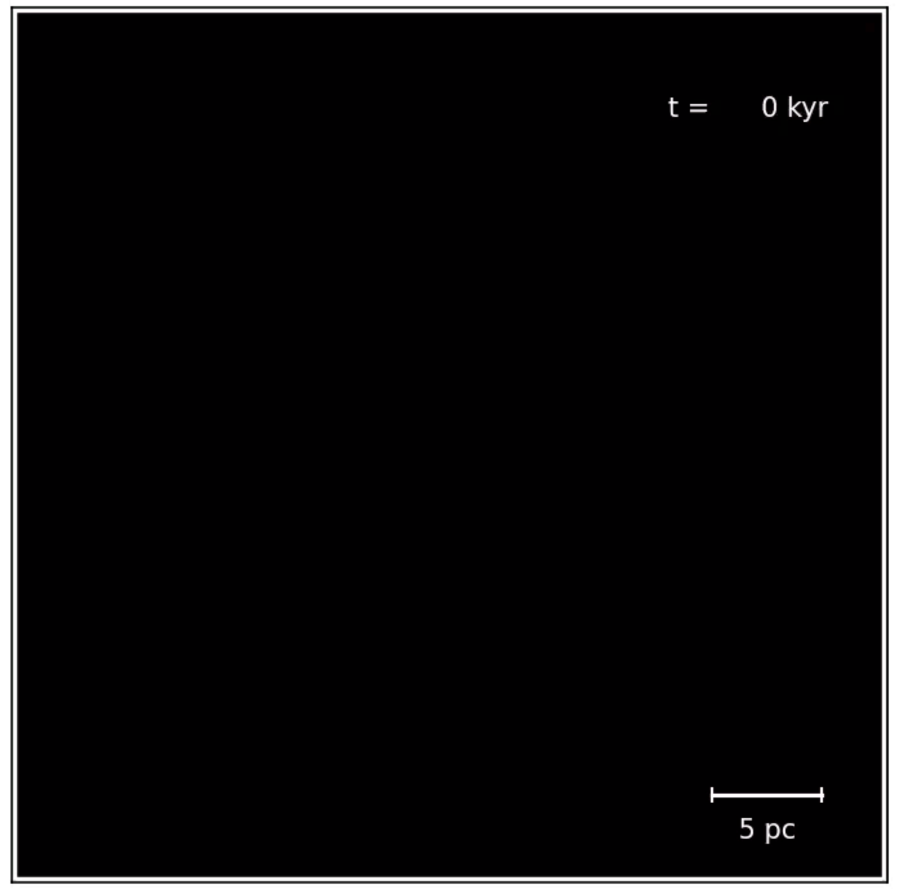
Winds: Costa, Pakmor & Springel (2020), **Accretion:** Costa, Pakmor & Springel (in prep.)
https://www.mas.ncl.ac.uk/tiago.costa/BOLA_documentation.pdf





Almeida, Costa et al. (in prep.)





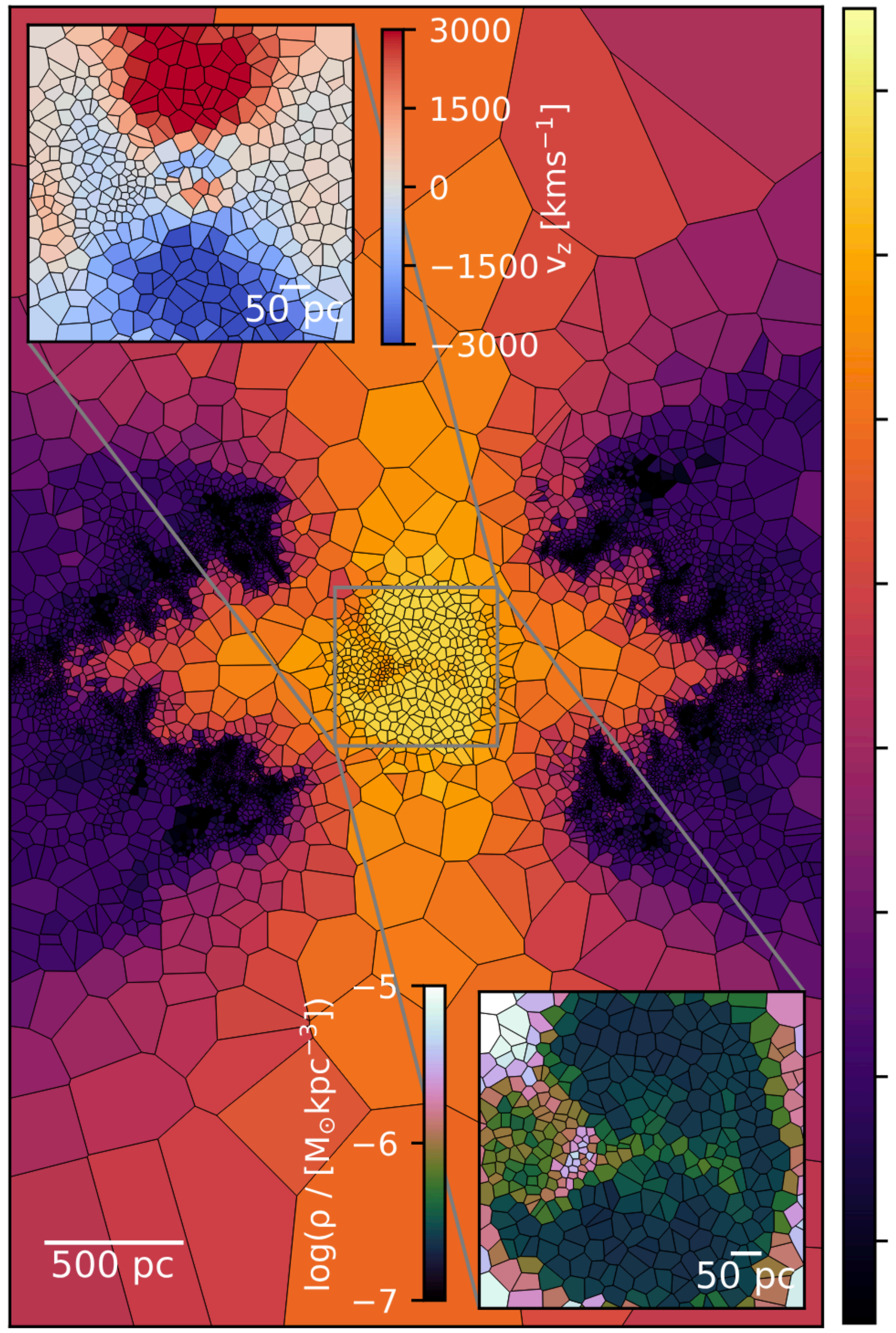
Tartènas, Costa et al. (in prep.)

- Mass, momentum and energy fluxes for small-scale wind.
- Large-scale outflow dynamics, energetics and phase structure predicted with high level of physical detail. Momentum- and energy-driven outflows predicted based on any small-scale wind/jet.

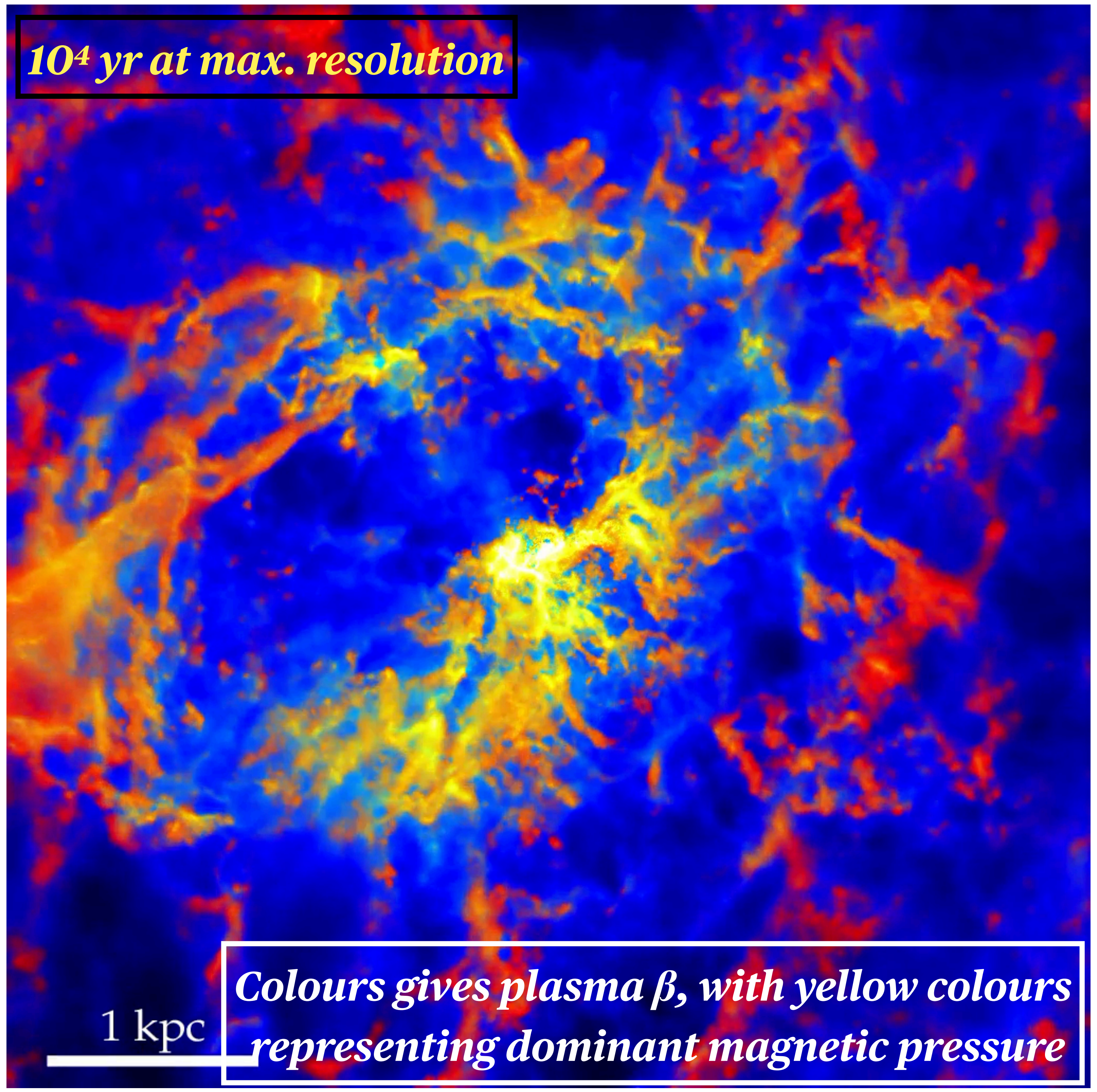
Bridging scales

Talk by M. Cernetic

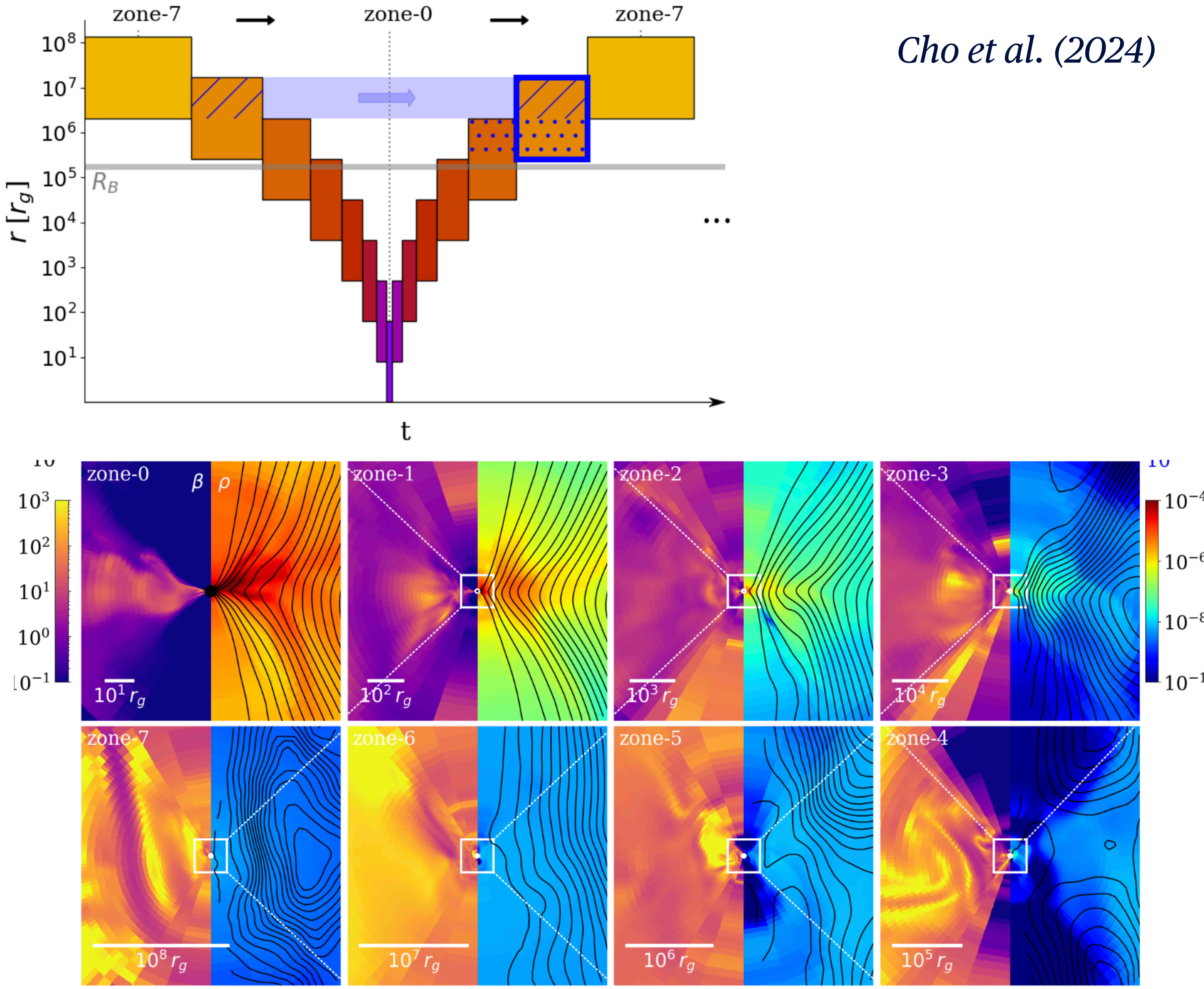
Koudmani et al. (2019)



Hopkins et al. (2024a, b, c)



Cho et al. (2024)



Improvements, e.g. hyper-refinement, now probe >8 orders of magnitude in physical scale. But restricted to short time-scales or to steady-state solutions.

Curtis & Sijacki (2015, 2016), Prieto & Escala (2016), Costa et al. (2020), Anglés-Alcázar et al. (2021), Talbot et al. (2021, 2022), Franchini et al. (2022), Hopkins et al. (2024a, b, c), Cho et al (2023, 2024), Guo et al (2024, 2025)

Main Lessons

A personal take

Effective AGN feedback has to proceed via energy-conserving outflows.

A single feedback *mechanism* operates through multiple *channels*. Line between “quasar” and “kinetic/maintenance” modes is blurry.

The driving force behind AGN outflows is a tenuous, volume-filling extremely hot **and invisible phase**.

Long-term quenching requires clearing out the CGM -> **need preventive feedback**. Quenching via ejection only possible with high covering factor for cold gas and is short-lived unless CGM is also ejected.