The Simba Simulation

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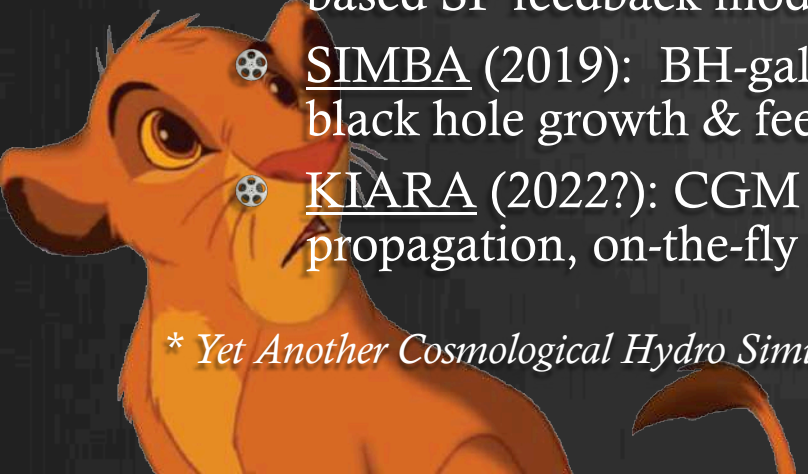
SIMBA: Does the world really need YACHS*?

- Illustris, Horizon-AGN, EAGLE, Sherwood, MassiveBlack, Mufasa, Blue Tides, Illustris-TNG, etc etc, and now … SIMBA! *Why?*

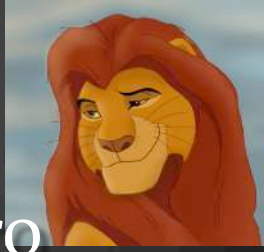
- SIMBA's main new features:
  - Subgrid models primarily based on high-res zoom results.
  - Novel black hole accretion & purely bimodal+kinetic AGN feedback.
  - On-the-fly dust production & destruction model.

- The Lineage:
  - MUFASA (2016): Growth of star-forming galaxies from z~6-0. FIRE-based SF feedback models, but heuristic halo-based model for quenching.
  - SIMBA (2019): BH-galaxy co-evolution. Replaces halo quenching with black hole growth & feedback modules. Includes passive dust.
  - KIARA (2022?): CGM evolution, baryon cycling. New wind propagation, on-the-fly radiation transport, active dust, and more.



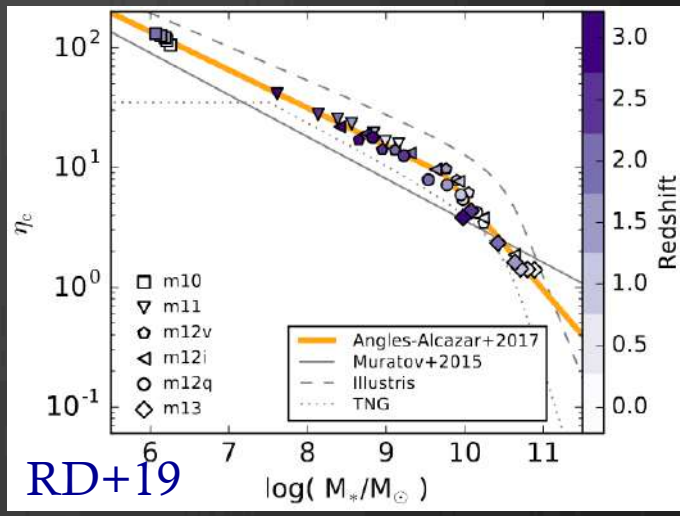
** Yet Another Cosmological Hydro Simulation*

GIZMO-Simba

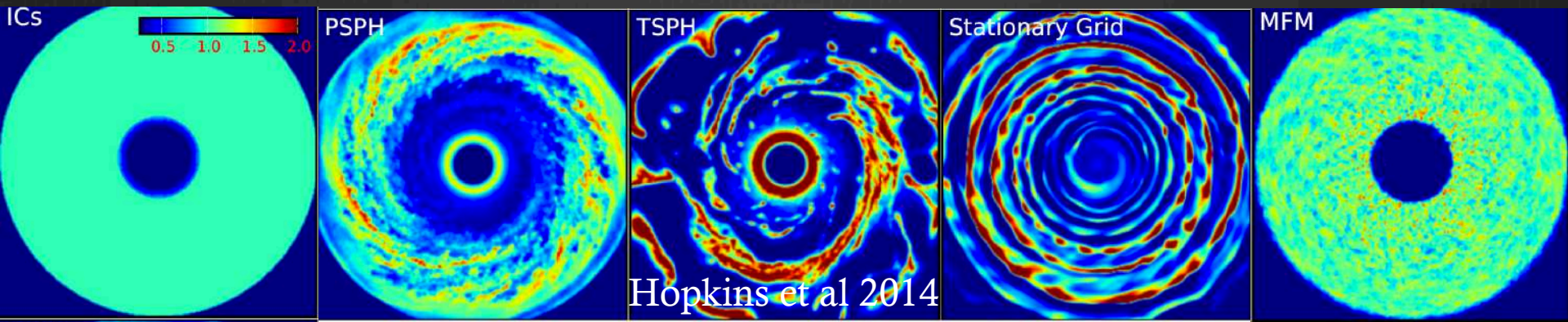


Cosmological simulations with meshless hydro

- GIZMO: Gravity + meshless finite mass hydro.
- H_2-based SF, Grackle (non-equil) cooling.
- 9 elements from Type II/Ia SN+AGB stars, metal cooling.
- Kinetic SF-driven decoupled winds, following FIRE scalings. Two-phase outflows.
- BH growth and feedback (next).
- Dust production & destruction.

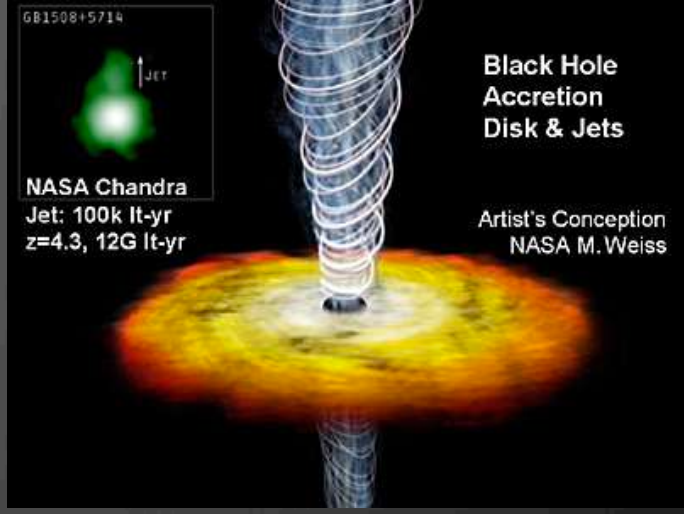


RD+19



Hopkins et al 2014

Bondi Accretion



Gravitational capture from a hot medium:

$$\dot{M}_{\rm Bondi} = \alpha \frac{4\pi G^2 M_{\rm BH}^2 \rho}{(c_s^2 + v^2)^{3/2}}$$

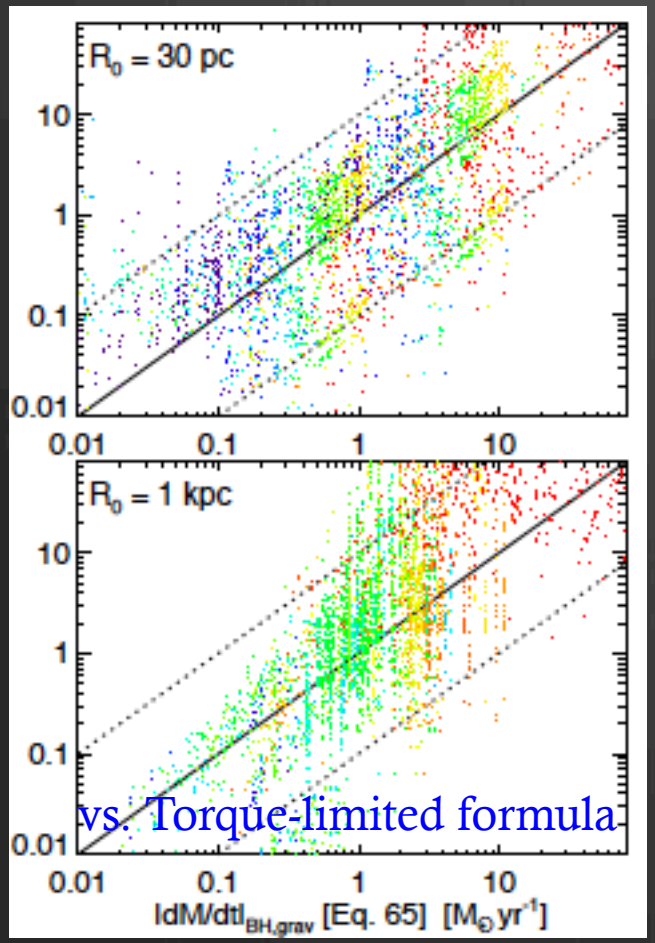
- Steep scaling w/BH mass requires *self-regulated growth*, hence locally sphericalized feedback.
- Key quantities (c_s, ρ) cannot be resolved in cosmological runs.
- Naturally connect BH growth to mergers, but unclear that mergers drive black hole growth.
- Detailed accretion simulations suggest that *angular momentum loss* limits BH accretion. Bondi accretion not seen in SMBHs.
- Successful! Every other YACHS uses Bondi.

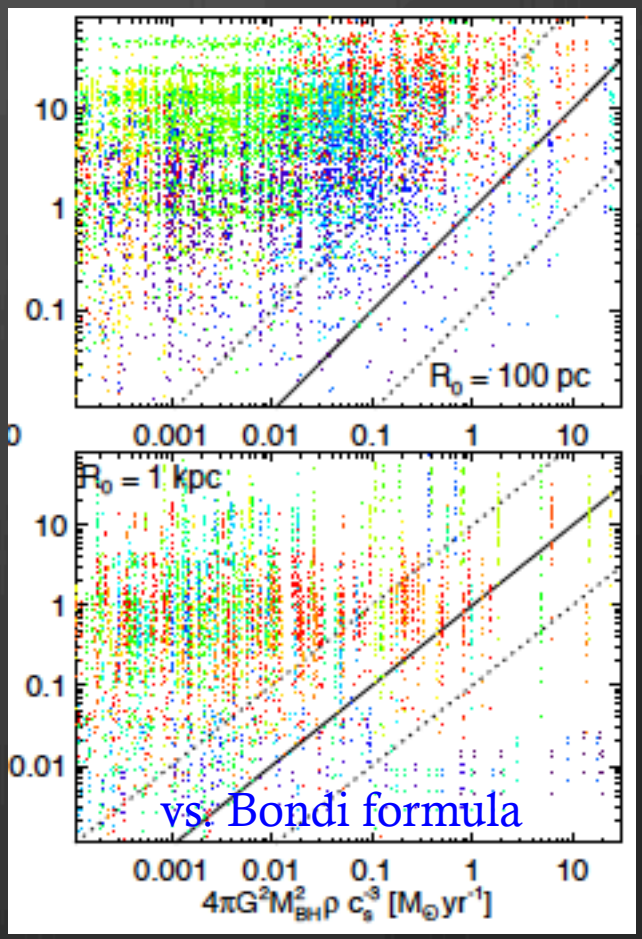
Torque-Limited Accretion

- Angular mom dissipated via disk instabilities (Hopkins&Quataert 2011):

$$\dot{M}_{\rm Torque} \approx \alpha_{\rm T}\, f_{\rm disk}^{5/2} \times \left(\frac{M_{\rm BH}}{10^8\,{\rm M}_\odot}\right)^{1/6} \left(\frac{M_{\rm disk}(R_0)}{10^9\,{\rm M}_\odot}\right)^{1} \times \left(\frac{R_0}{100\,{\rm pc}}\right)^{-3/2} \left(1+\frac{f_0}{f_{\rm gas}}\right)^{-1} {\rm M}_\odot\,{\rm yr}^{-1},$$

Directly Simulated accretion rate

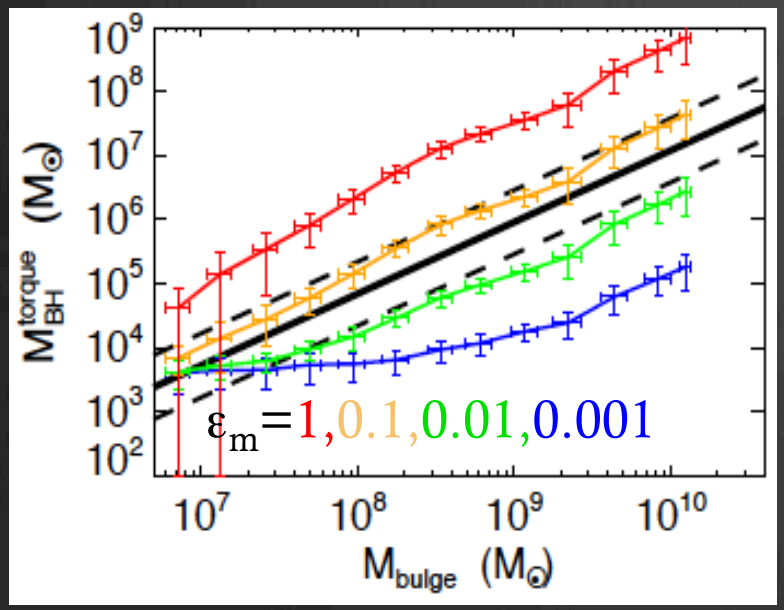


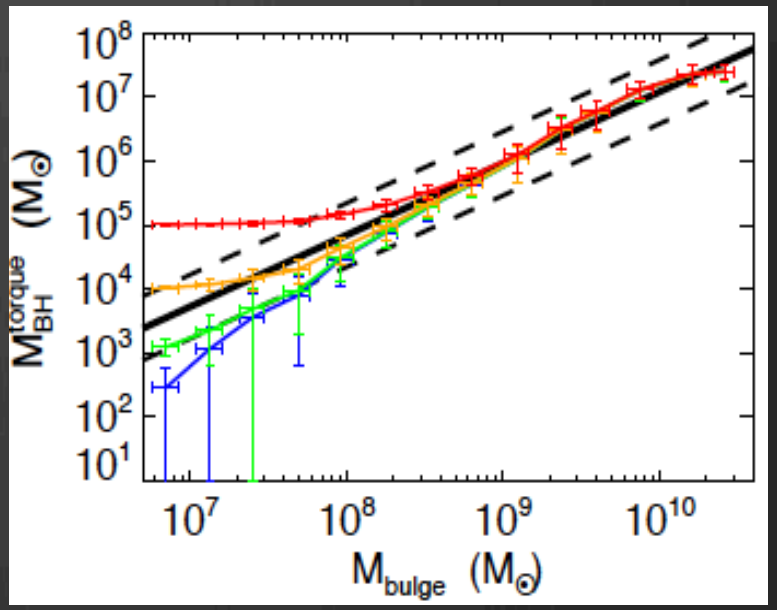


Hopkins & Quataert 11

Torque-Limited Accretion

- Galaxies evolve along M-σ – without self-regulating feedback!
- Free parameter ε_m: Fraction of mass falling into accretion disk that accretes onto BH (~5-10%). $dM_{\rm BH}/dt = \epsilon_{\rm m}\,\dot{M}_{\rm Torque}(t)$
- M-σ relation is an attractor solution, independent of M_{seed}.





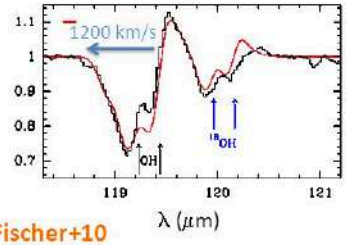
Anglés-Alcázar+14

AGN Feedback: Radiative Winds, Jets, X-ray heating

- HB14: HERGs ('cold') at f_{Edd}<~0.02, LERG ('hot') f_{Edd}>~0.02
- *Jet mode:* Red & dead, v~10^4 km/s, p>~few L/c
- *Radiative mode:* ULIRGs, v~10^3 km/s, p~20L/c
- *X-ray feedback:* High energy photons add outward momentum

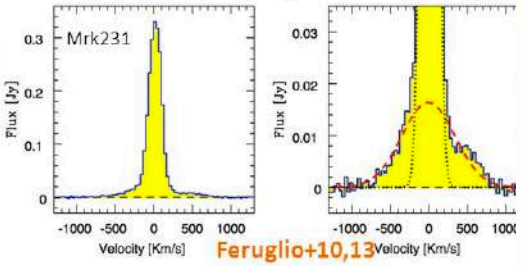
Evidence for massive quasar-driven molecular outflows

OH P-Cygni profiles



Fischer+10
Sturm+11

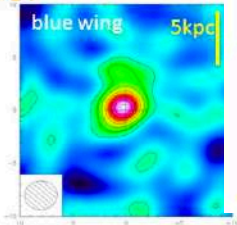
CO(1-0) high velocity wings



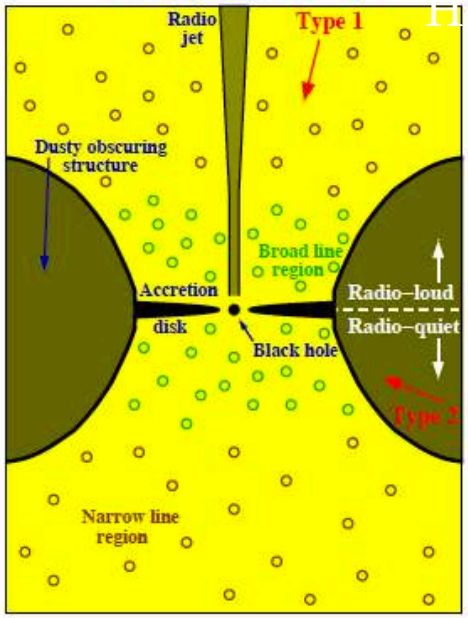
Feruglio+10,13
Cicone+14

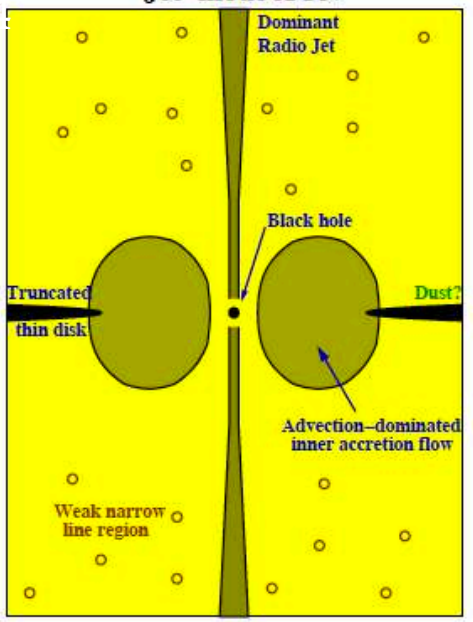
Massive molecular outflows (~1000 $M_\odot$/yr)
Extended on kpc scales
P_K ~ 0.05 L_{AGN}
Momentum rate ~ 20 L_{AGN}/c

...as expected (and required) by models



from R. Maiolino



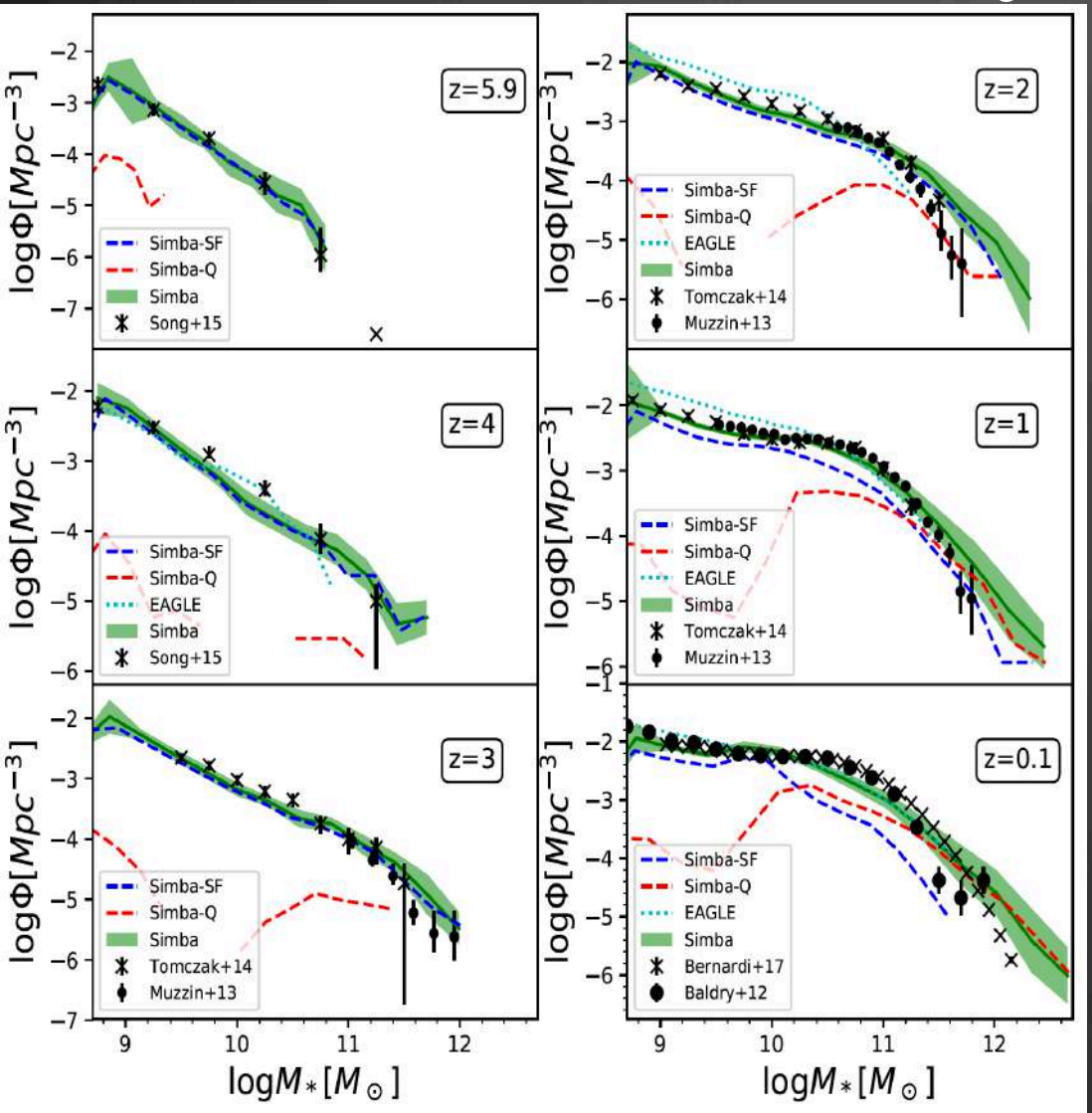


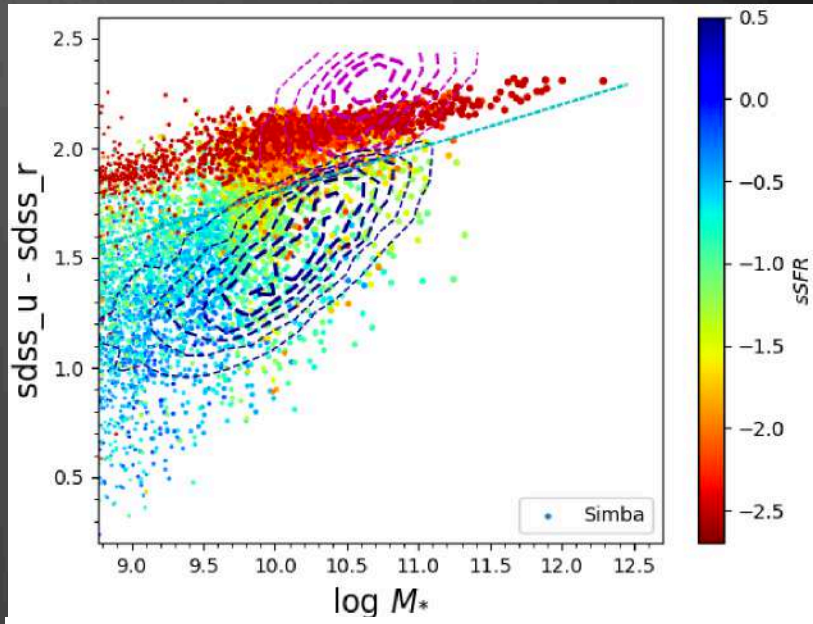
Simba: Mufasa + black hole accretion & feedback

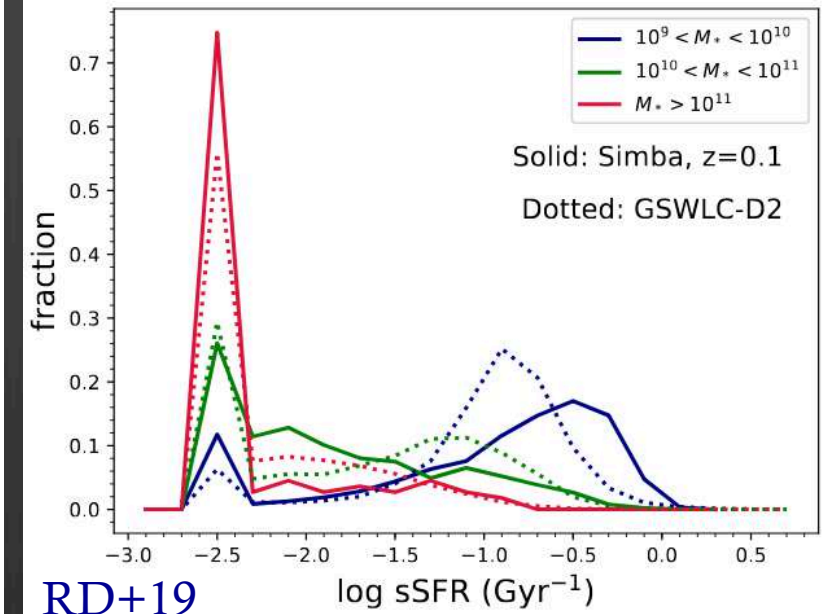
- BH accretion:
  - Torque-limited accretion for $T<10^5$K gas
  - Bondi accretion for $T>10^5$K gas
  - Torque mode dominates for all but largest BH at late times
- BH feedback:
  - Purely kinetic & *bipolar*; eject $1-\varepsilon_m \sim 0.9$ of M_{torque}
  - Only when $M_* > 10^9$ to mimic early suppression via bursts
  - Two modes, depending on Eddington ratio λ:
    - BAL: $\lambda > \sim 0.1$: $v \sim 10^3$ km/s (Perna+17), or $M_\bullet < 10^{7.5}$
    - Jet: $\lambda < \sim 0.02$: $v \sim 10^4$ km/s
  - Constant momentum $p = 20\ L/c$ (e.g. Costa+17)
  - X-ray heating following Choi+13

Does Simba make realistic galaxies?

(100 Mpc/h)^3 volume, ~1 kpc resolution
2x1024^3 elements, res limit M_*~6x10^{9}M$_\odot$.

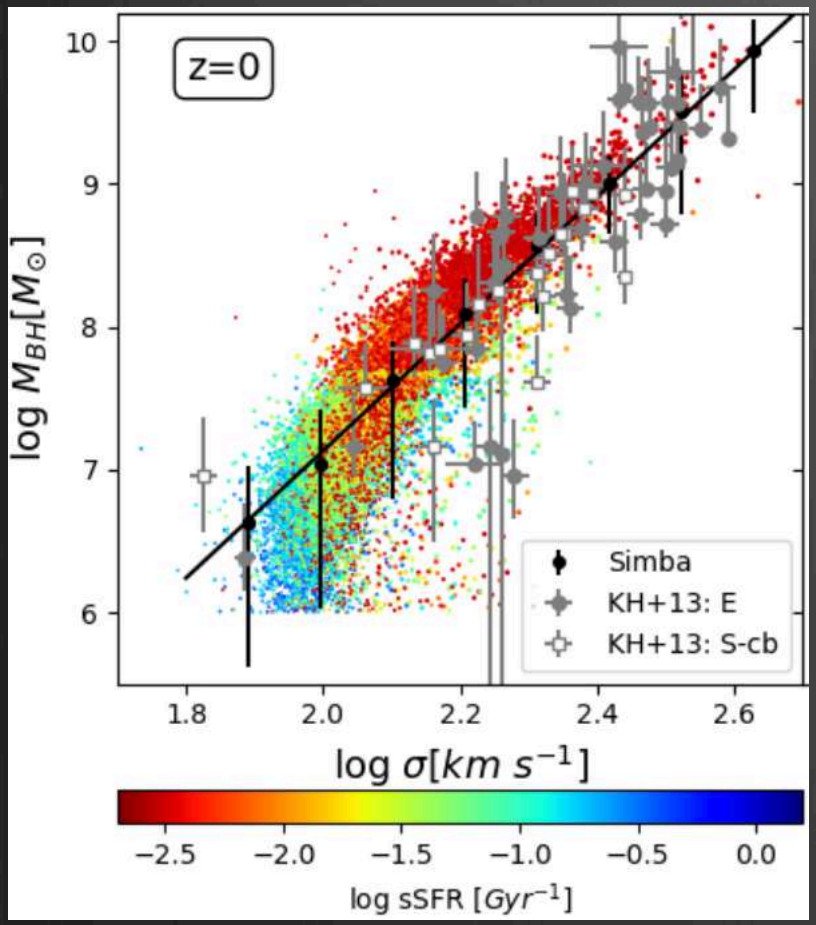


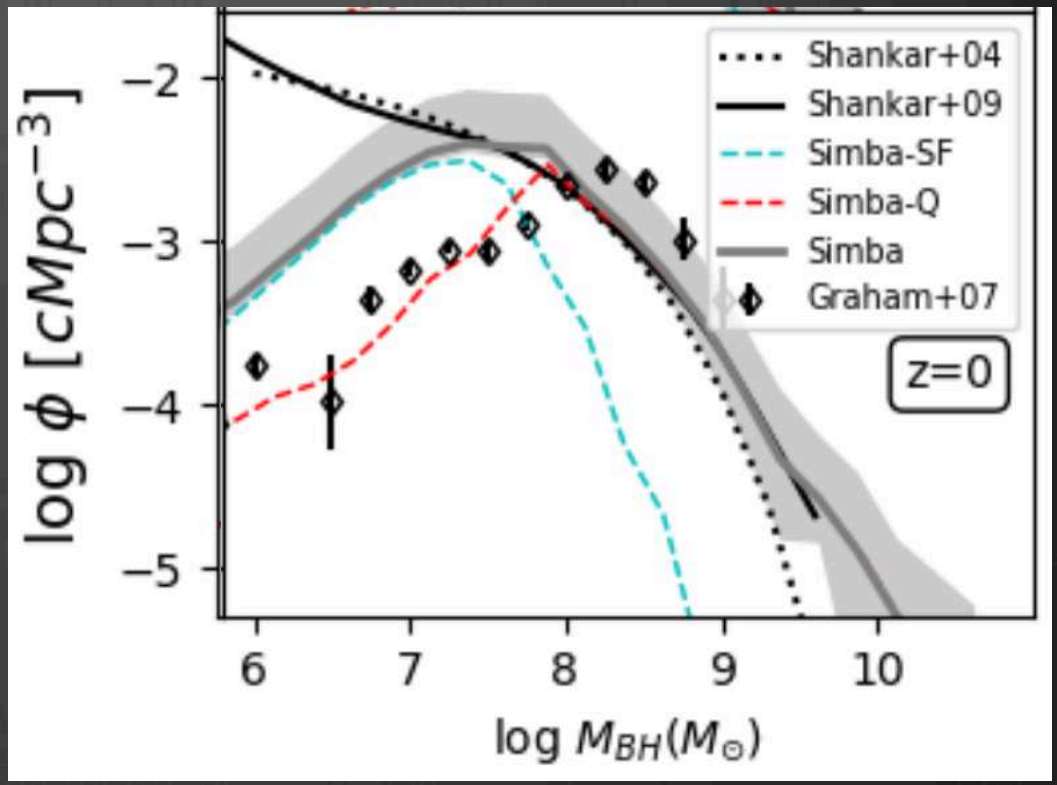




RD+19

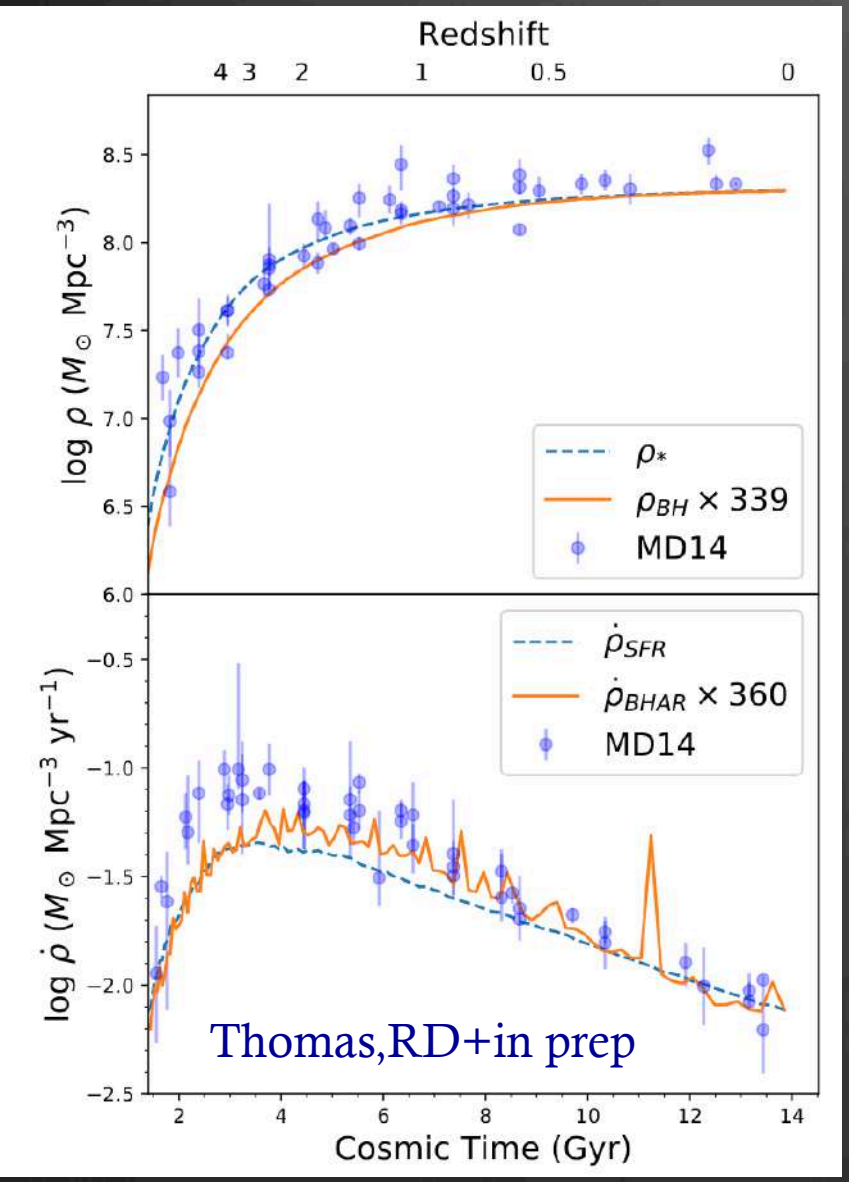
What about black holes?

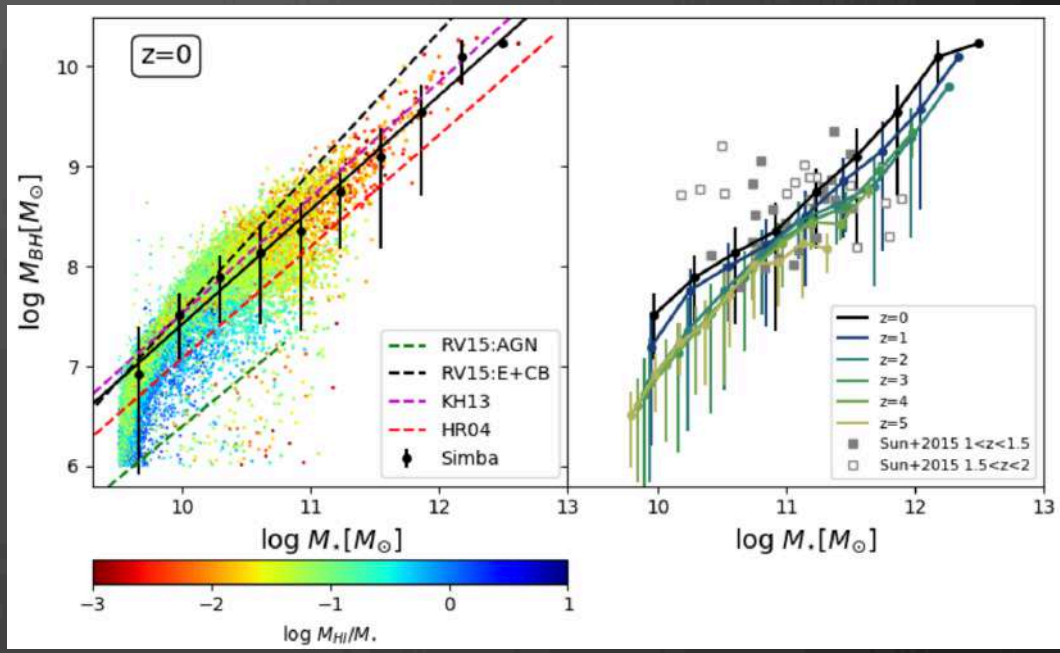


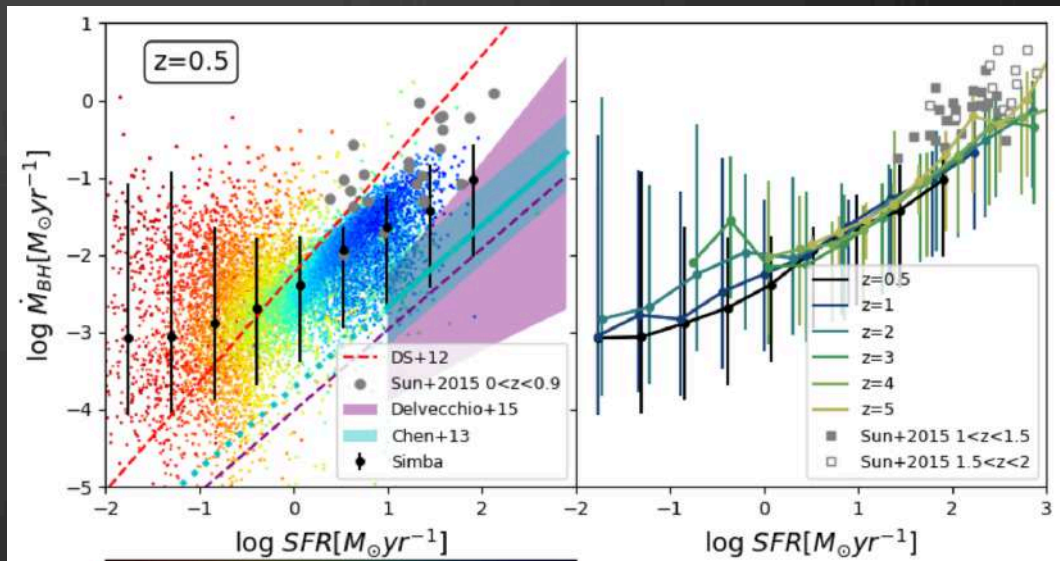


Thomas,RD+in prep

Black holes and galaxies co-grow

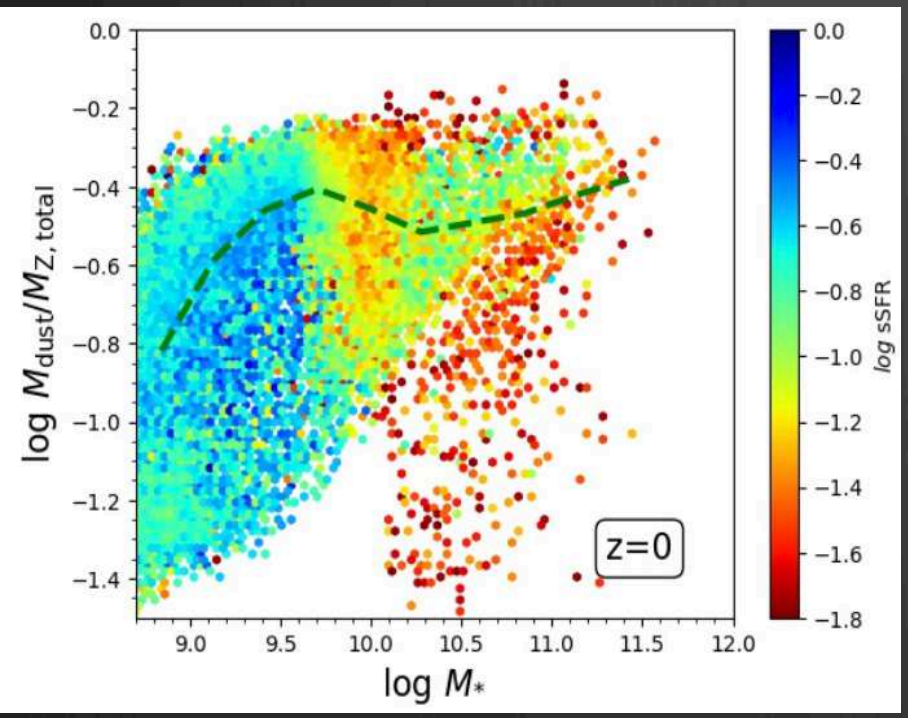


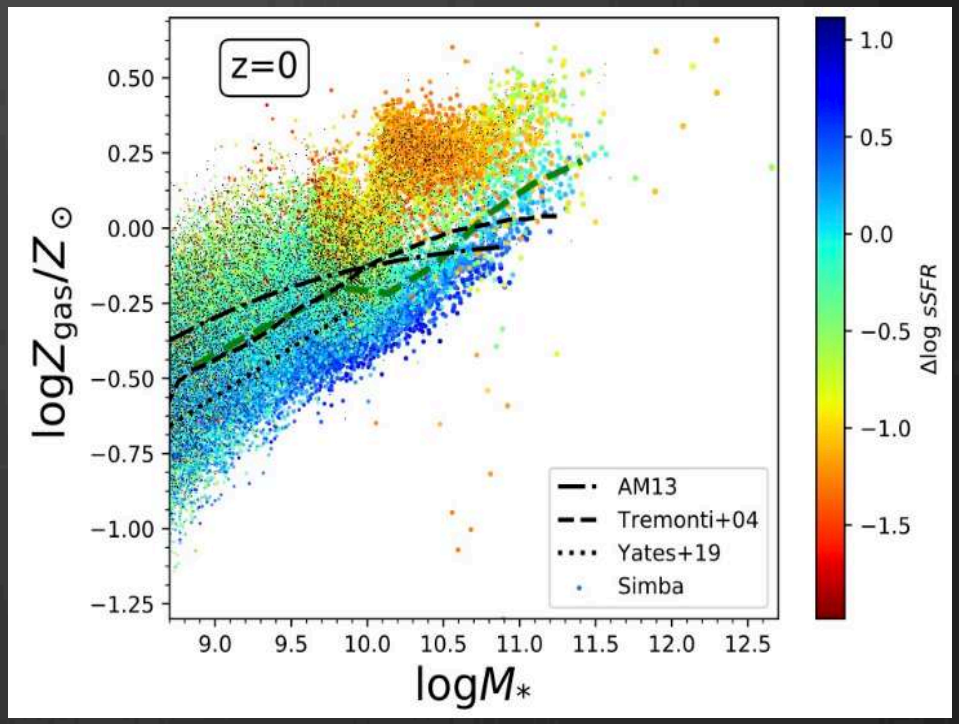




Bonus: Dust!

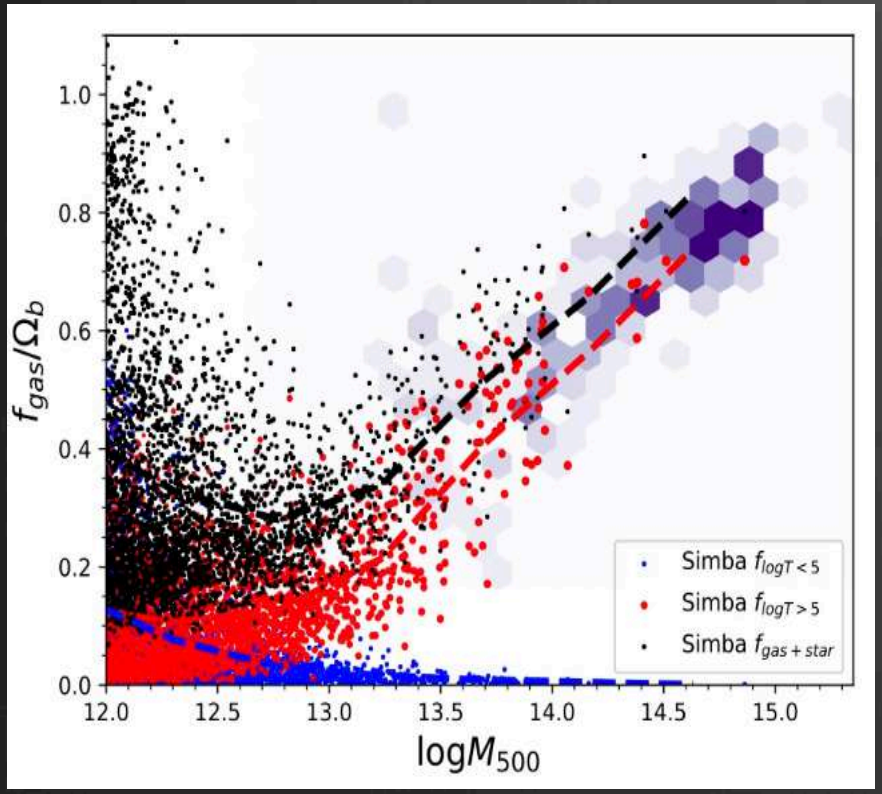
- Simba also includes an on-the-fly dust production and destruction model (led by Q. Li and D. Narayanan).
- Typically third to half of metals in dust. This gives rise to a good mass-metallicity relation out of the box (unlike Mufasa).



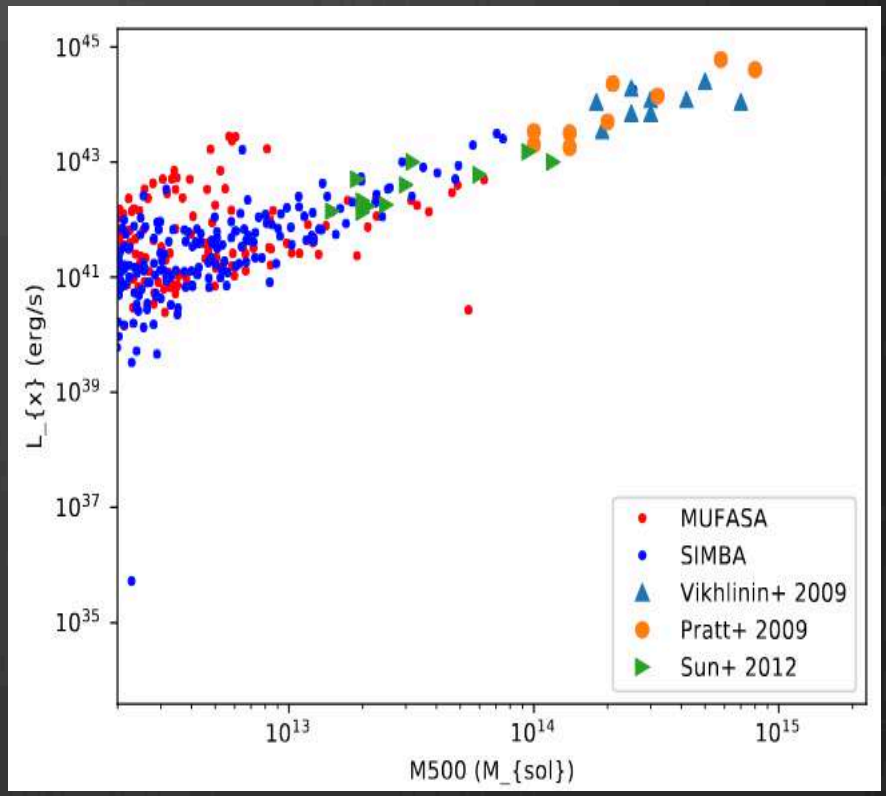


Hot Halo Gas

- Hot gas fractions in big halos is hard for models to match. EAGLE, Illustris, TNG all fail. Simba works!
- ICM X-rays provide a key test. Preliminarily it looks ok.



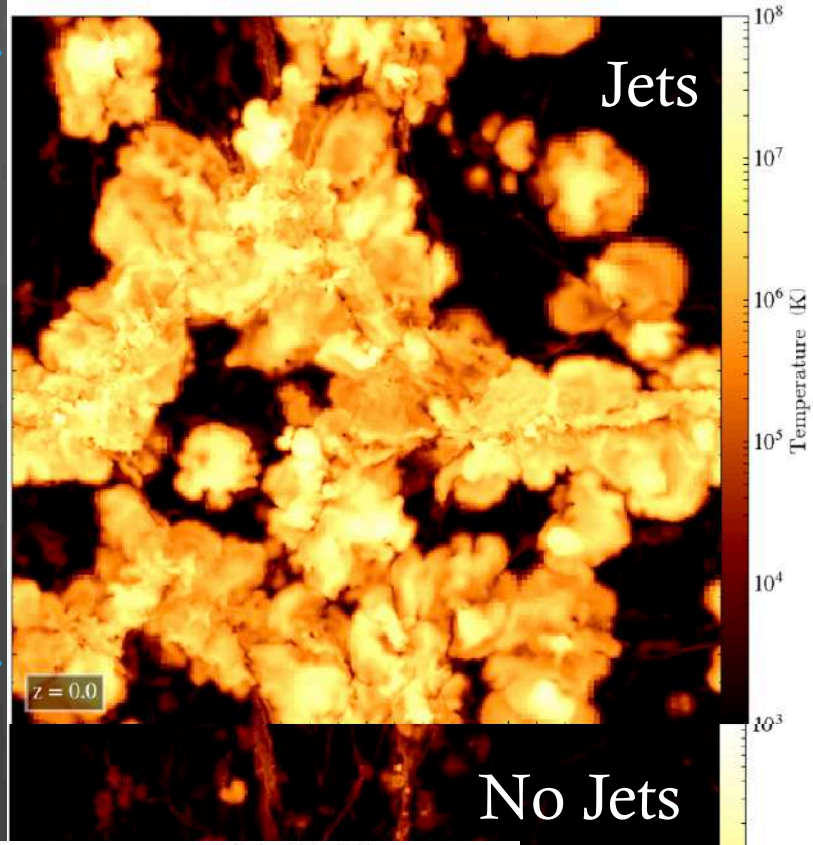
RD+19

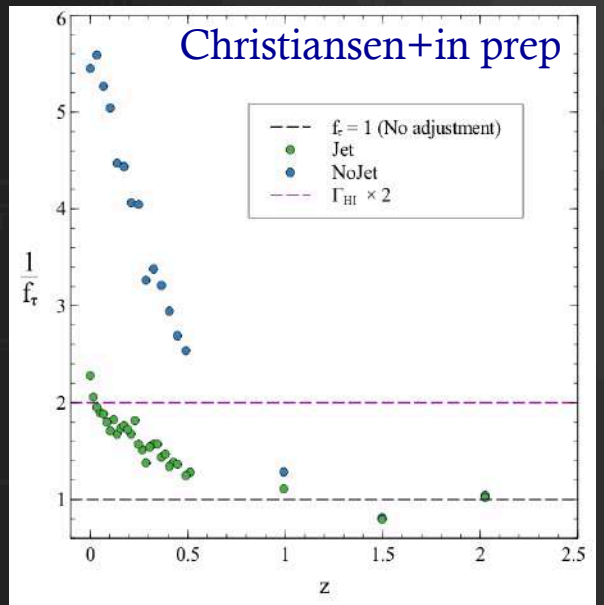


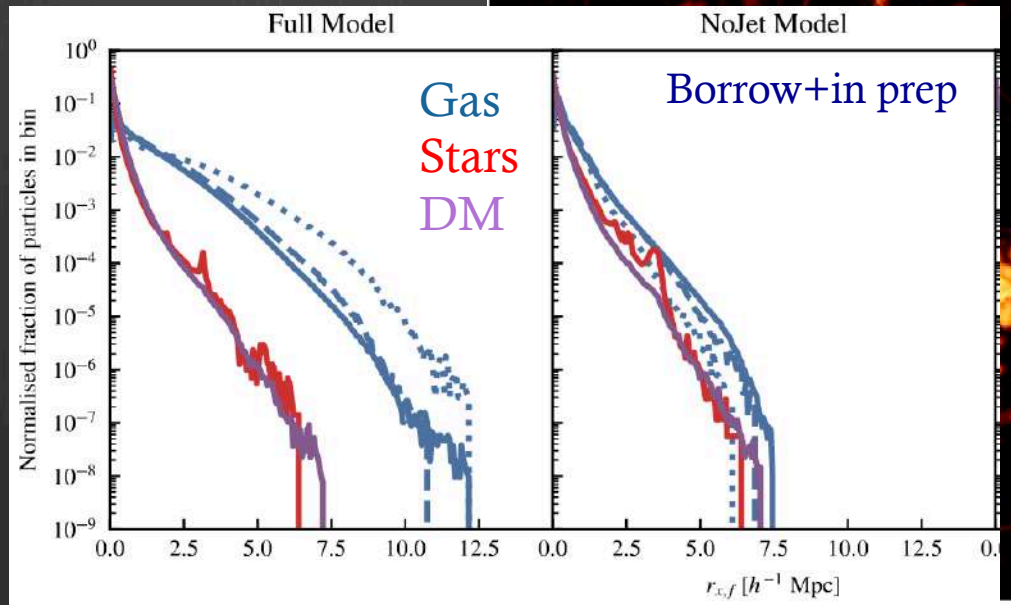
Robson+in prep

J-E-T-S Jets!

- By z=0, heats significant fraction of cosmic volume.
- Mostly solves the Photon Underproduction Crisis
- Moves substantial material outside of Lagrangian regions (Inter-Lagrangian Transfer)

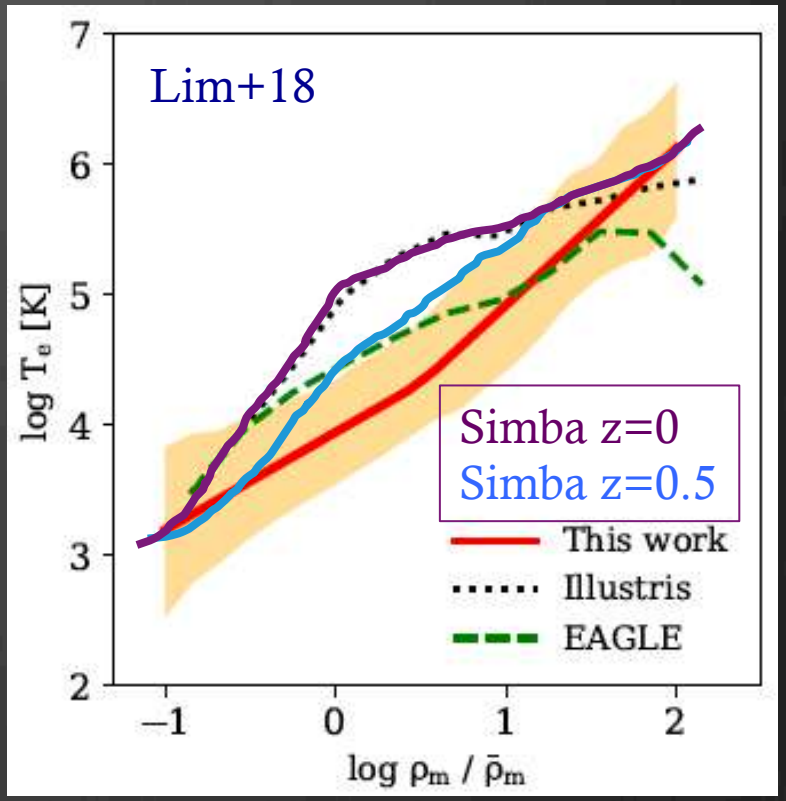






Impact of BH feedback on IGM

- Planck SZ cross-corr with SDSS to measure IGM equation of state: *Simba fails!* (at first glance)
- Rapid effect at z<~0.5
- To reconcile, jets must inject energy on halo scales, but abruptly stop beyond halos.



- SIMBA's novel black hole accretion and feedback models produce galaxies and black holes in good agreement with data.
- Simba includes on-the-fly dust for more detailed extinction modeling.
- Black hole jet feedback has a large-scale impact on baryons

Why does Bondi need self-regulation while torque model doesn't?

- Given 2 BH's of mass $M_a > M_b$, and $dM_\bullet/dt = D(t) M_\bullet^p$: (Bondi: p=2. Torque: p=1/6)

$$\frac{d}{dt}\left(\frac{M_a}{M_b}\right) = D(t)\,\frac{M_a^p}{M_b}\left[1-\left(\frac{M_a}{M_b}\right)^{1-p}\right]$$

- If p>1, BH masses diverge, need self-regulation: D(t,M•)
- If p<1, BH masses converge onto relation set by D(t)
- *All trends of torque-limited model will be similar in any model with p<<1.*

Black Hole Growth

Bondi

Bondi, Hoyle, Littleton 1954

$$\dot{M}_{\rm Bondi} = \alpha \frac{4\pi G^2 M_{\rm BH}^2 \rho}{(c_s^2 + v^2)^{3/2}}$$

- Steep scaling w/M_{BH} requires BHs to *self-regulate*.
- Key quantities (c_s, ρ) cannot be resolved directly
- Naturally connect BH growth to mergers.
- Successful! Every other YACHS uses Bondi.

Torque-limited

Hopkins& Quataert 2011

$$\dot{M}_{\rm Torque} \approx \alpha_{\rm T} f_{\rm disk}^{5/2} \times \left(\frac{M_{\rm BH}}{10^8\,{\rm M}_\odot}\right)^{1/6} \left(\frac{M_{\rm disk}(R_0)}{10^9\,{\rm M}_\odot}\right)^{1} \times \left(\frac{R_0}{100\,{\rm pc}}\right)^{-3/2} \left(1+\frac{f_0}{f_{\rm gas}}\right)^{-1} {\rm M}_\odot\,{\rm yr}^{-1},$$

- BH co-grows with disk, self-regulation not needed
- Sub-grid model works on resolvable (~1kpc) scales.
- Weak connection with mergers for most AGN.
- Appropriate when angular momentum loss limits growth.

Anglés-Alcázar et al. 2013, 2015, 2017