Accretion, Buoyancy, and Chaos: ABCs of Galaxy Formation

Ben Keller
Universität Heidelberg

Diederik Kruijssen, James Wadsley, Samantha Benincasa, Hugh Couchman, Liang Wang

Outflows, Buoyancy, and Chaos: OBCs of Galaxy Formation

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UNIVERSITÄT HEIDELBERG
ZUKUNFT SEIT 1386

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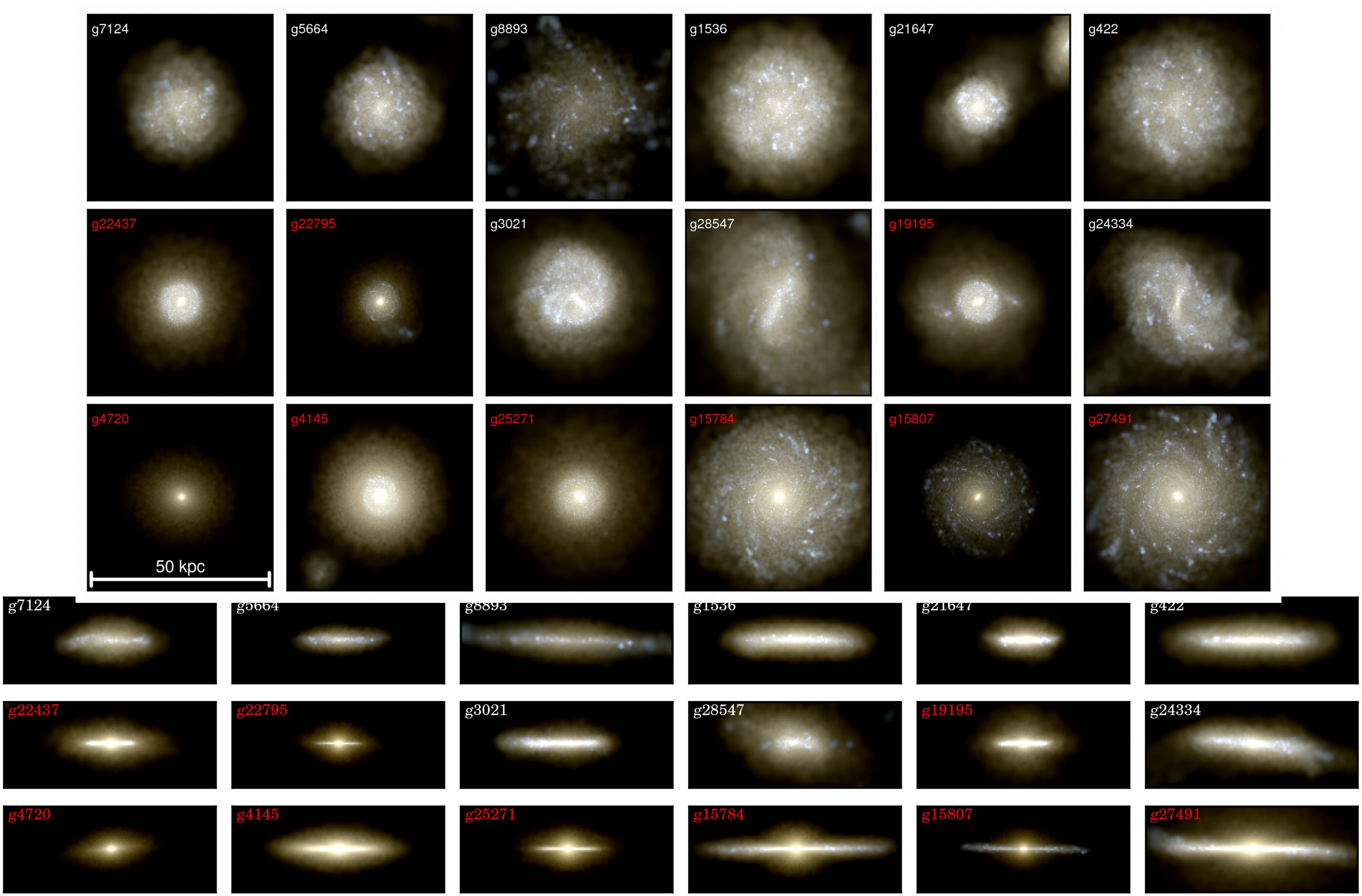
L* Galaxies are Neat

MUGS2: 18 L* Galaxies

- Cosmological zoom-in simulations, run using GASOLINE2 (Wadsley+ 2017), in a WMAP3 cosmology
- Initial conditions identical to MUGS (Stinson+ 2010), run with "classic" SPH and blast-wave feedback
- Virial Masses range from 3.7×10^{11} to $2.1 \times 10^{12} M_{sun}$
- Variety of merger histories, spin parameters
- 320pc softening, baryon mass resolution of $2.2 \times 10^{5} M_{sun}$

Keller+ 2016

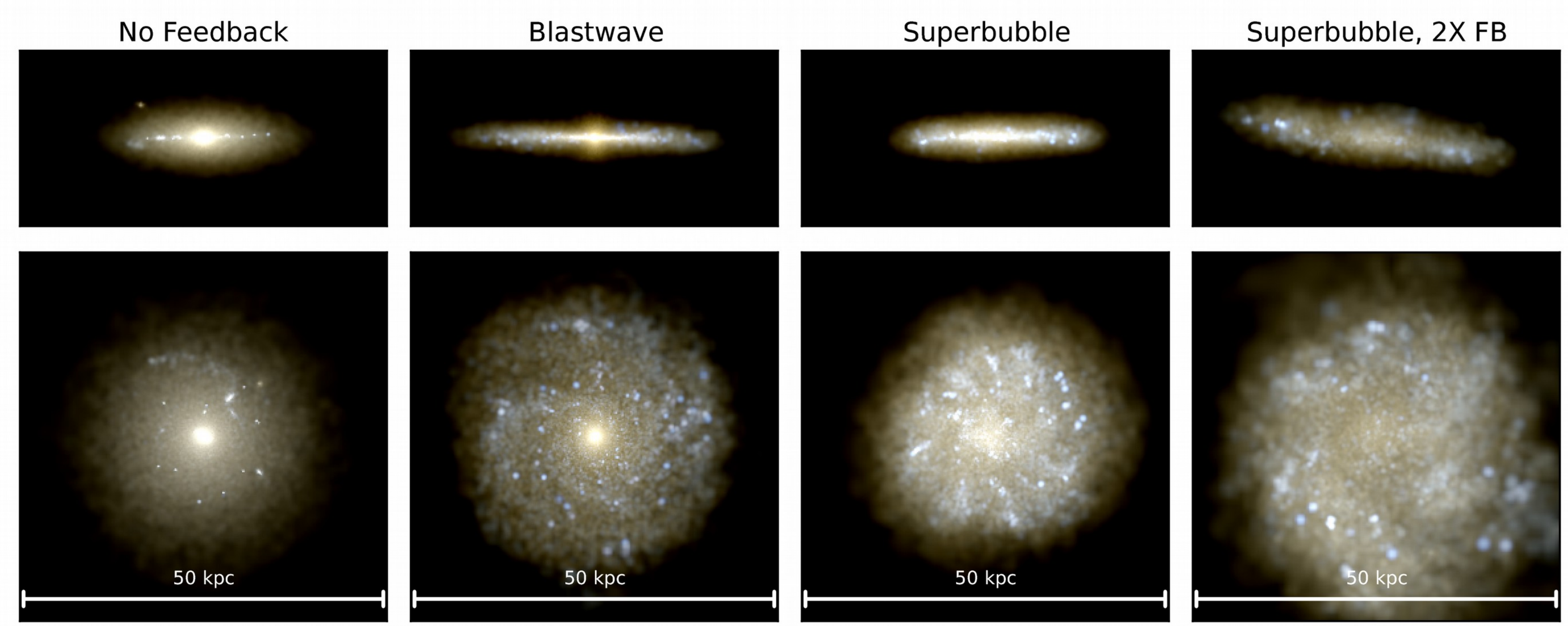
MUGS2: 18 L* Galaxies



Keller+ 2016

Feedback Models Matter!

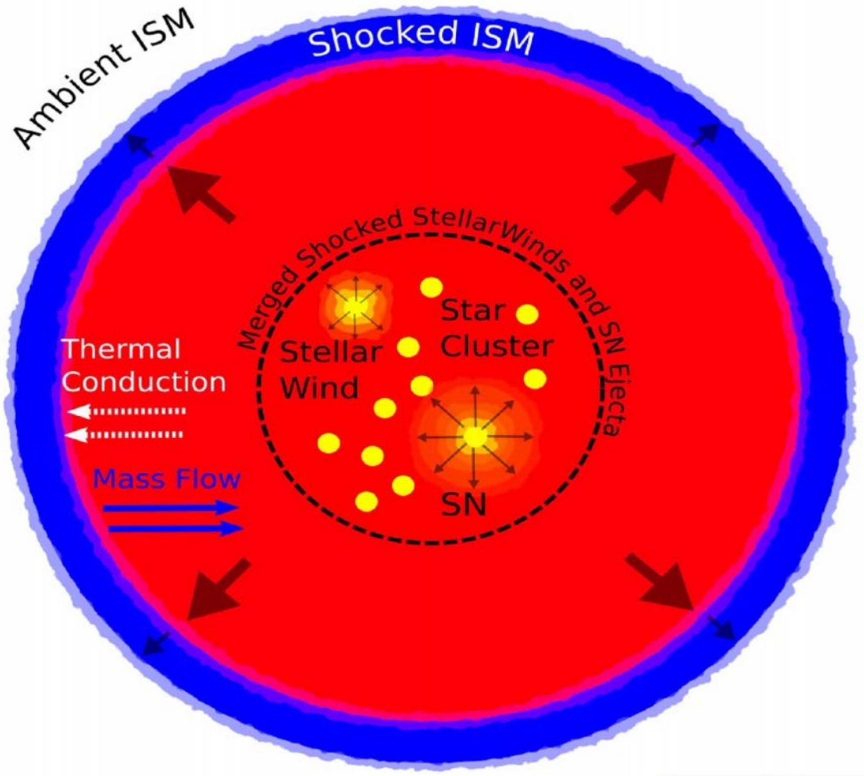
- 4 test cases:
  - No Feedback
  - Blastwave (Stinson+ 2006) feedback
  - Superbubble Feedback
  - Superbubble Feedback 2X Energy
- g1536
  - 8×10^{11} M_{sun} virial mass
  - Last major merger at z=4
  - Equal SN energy for Blastwave and Superbubble
  - Details in Keller+ 2015



Keller+ 2015

Superbubble Feedback

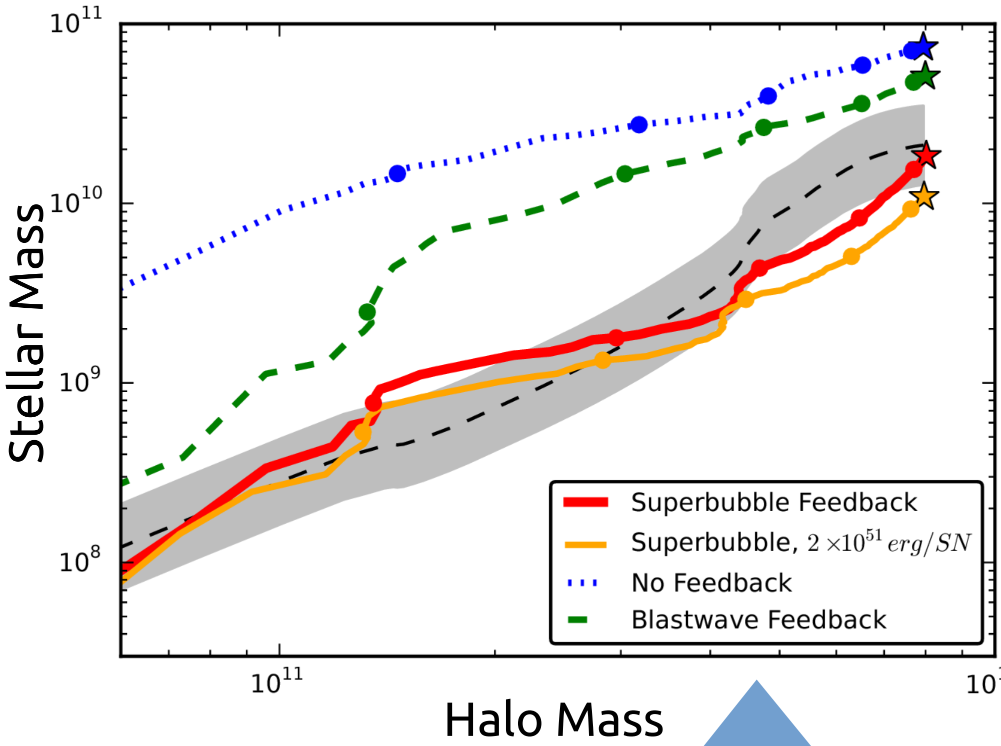
- Hot bubble is heated by multiple SN
- As bubble expands, forms a cold & radiative shell
- Shell is evaporated by thermal conduction

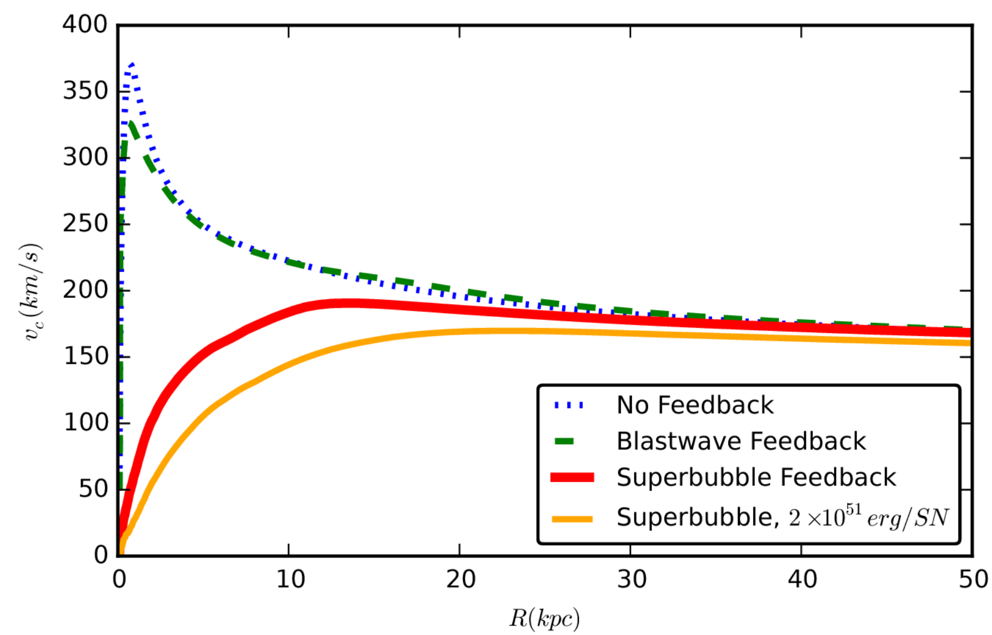


$$\frac{\partial M_B}{\partial t} = \frac{4\pi\mu}{25 k_B} \kappa_0 T^{5/2} A_B$$

Keller+ 2014

Correct Stellar Mass, Small Bulge



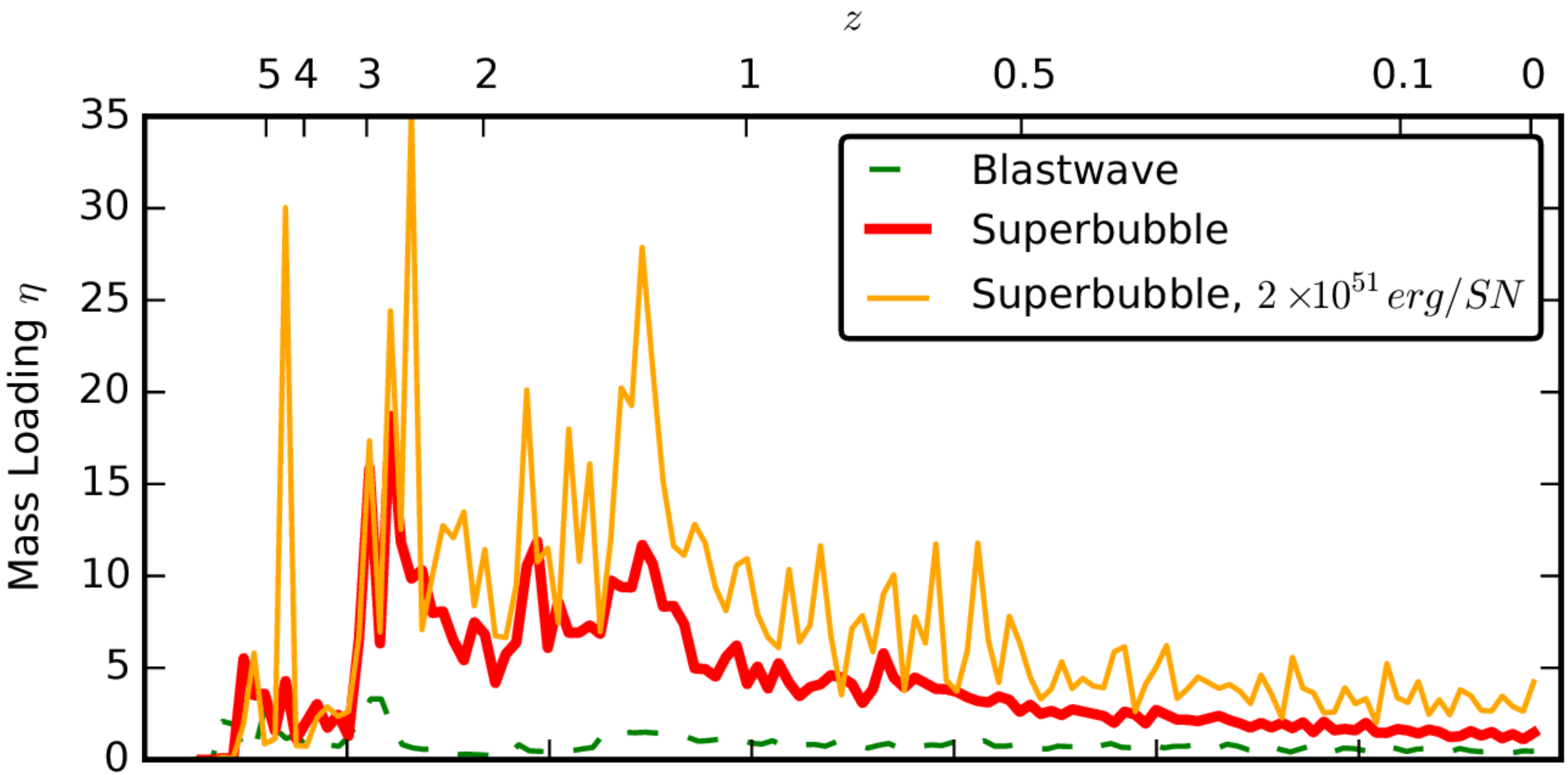


Stellar Mass Evolution Matches Behroozi+ 2012 abundance matching

Flat rotation curve == no major bulge component (B/T ratio of 0.09 vs. 0.46, MW B/T ~0.14)

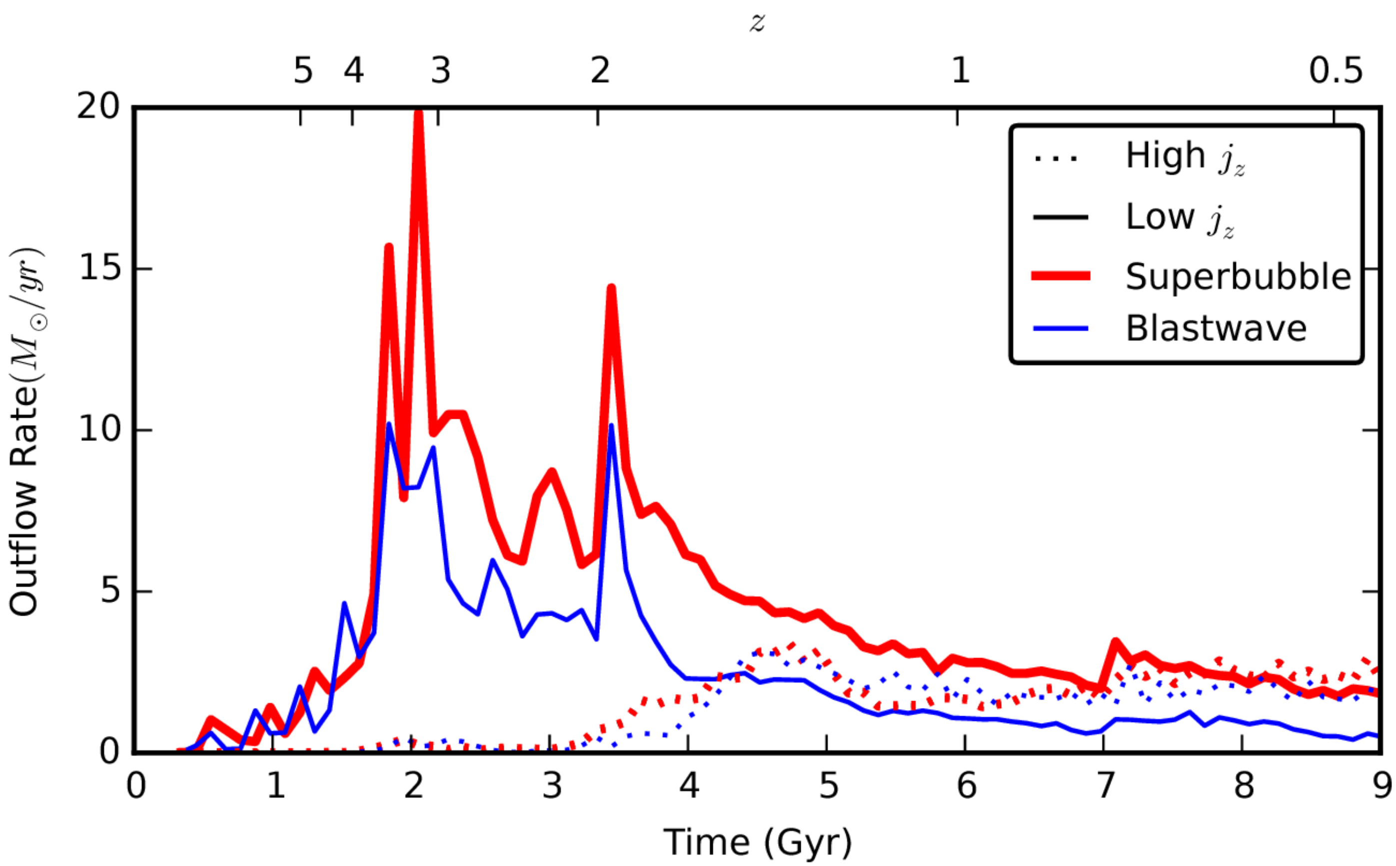
Keller+ 2015

Superbubbles drive outflows well



Keller+ 2015

High-z outflows prevent bulges, preserve disks



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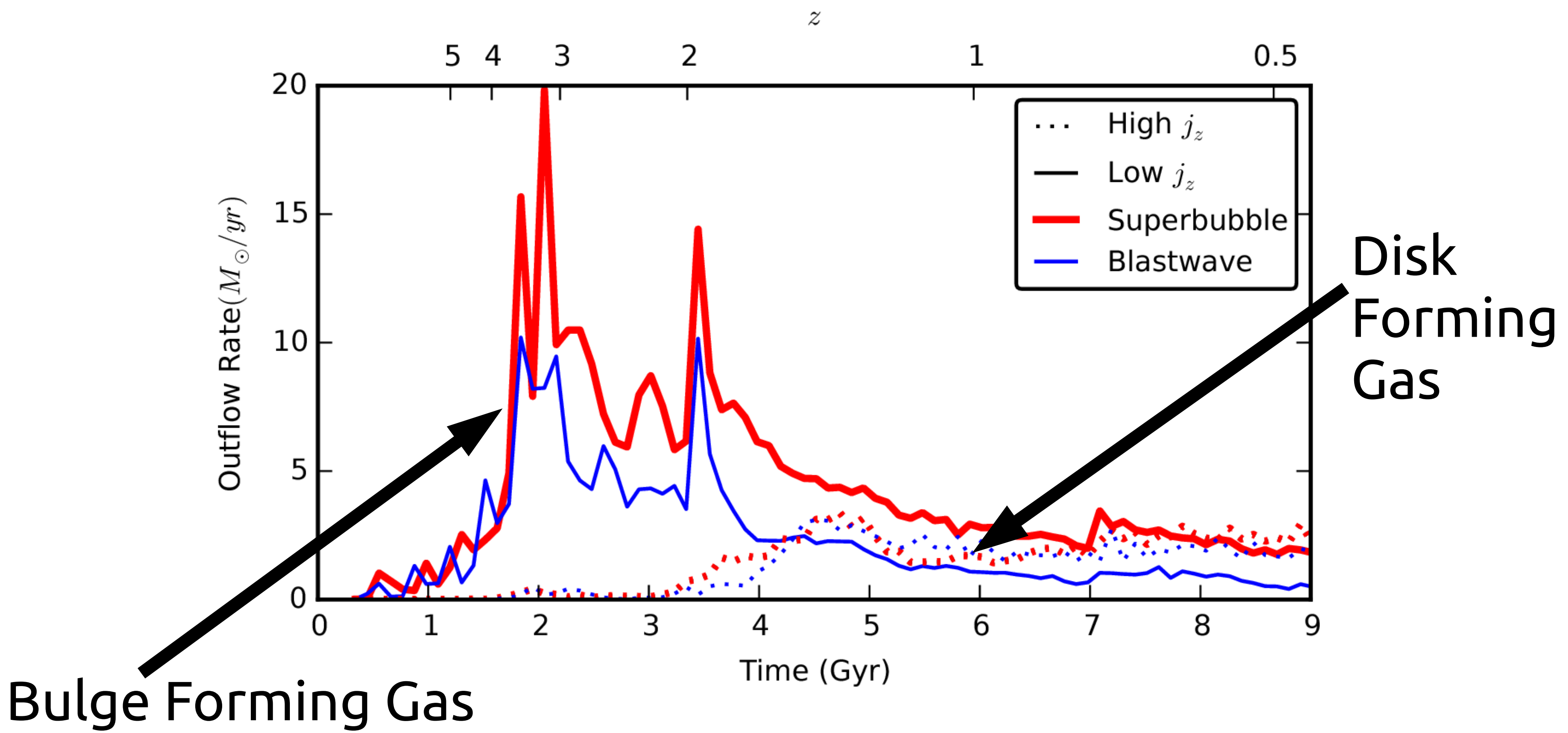
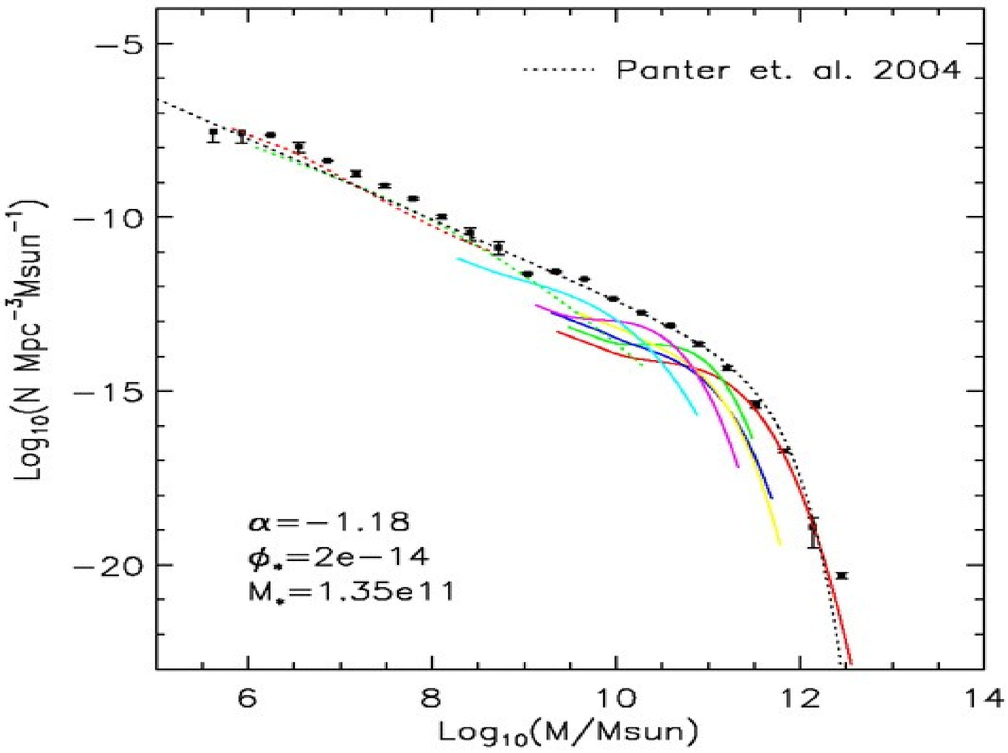
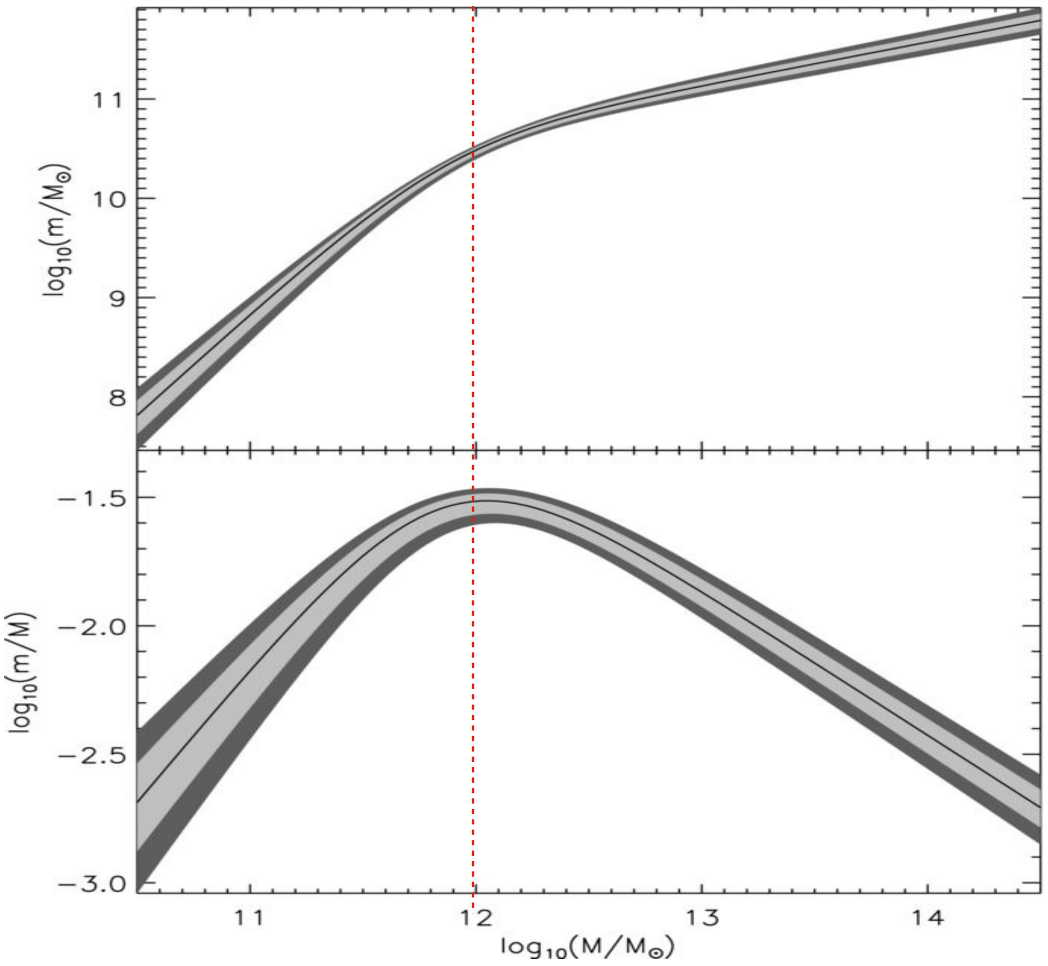


Keller+ 2015

Can Supernovae do it all?





Moster+ 2010

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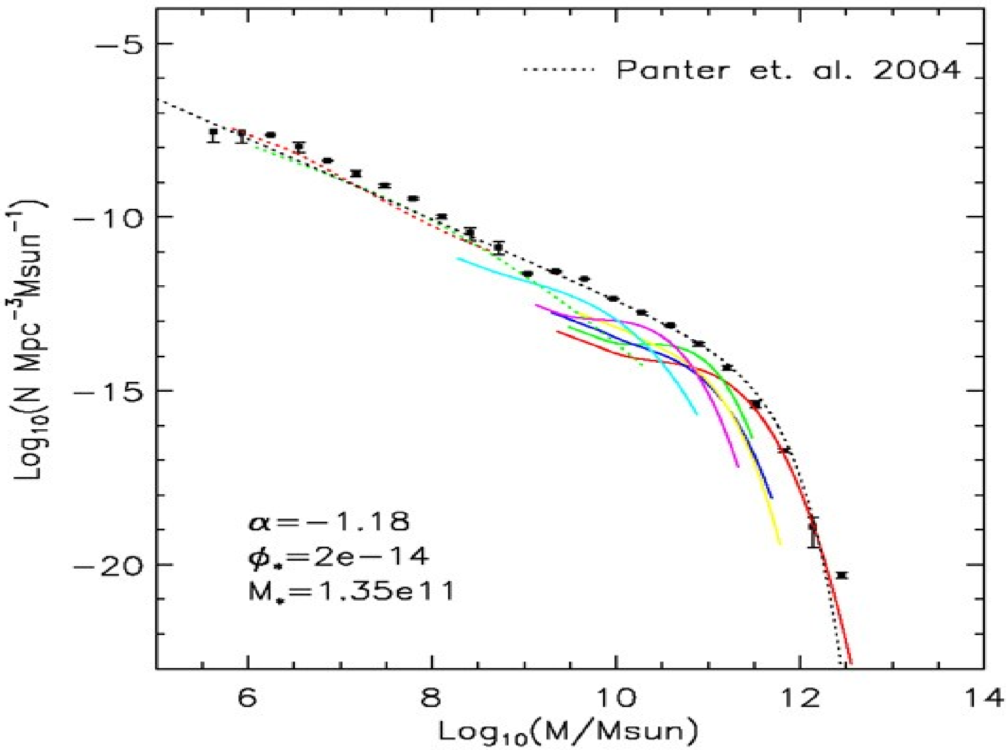

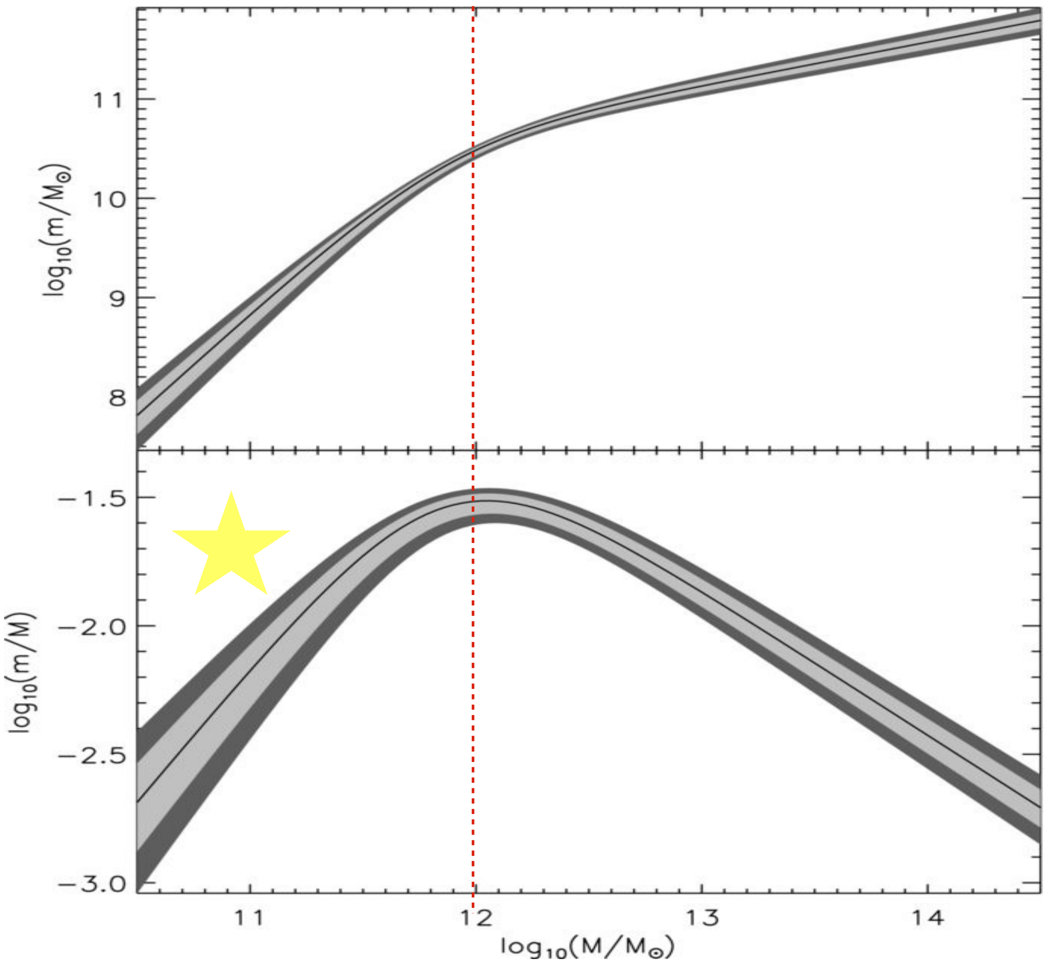

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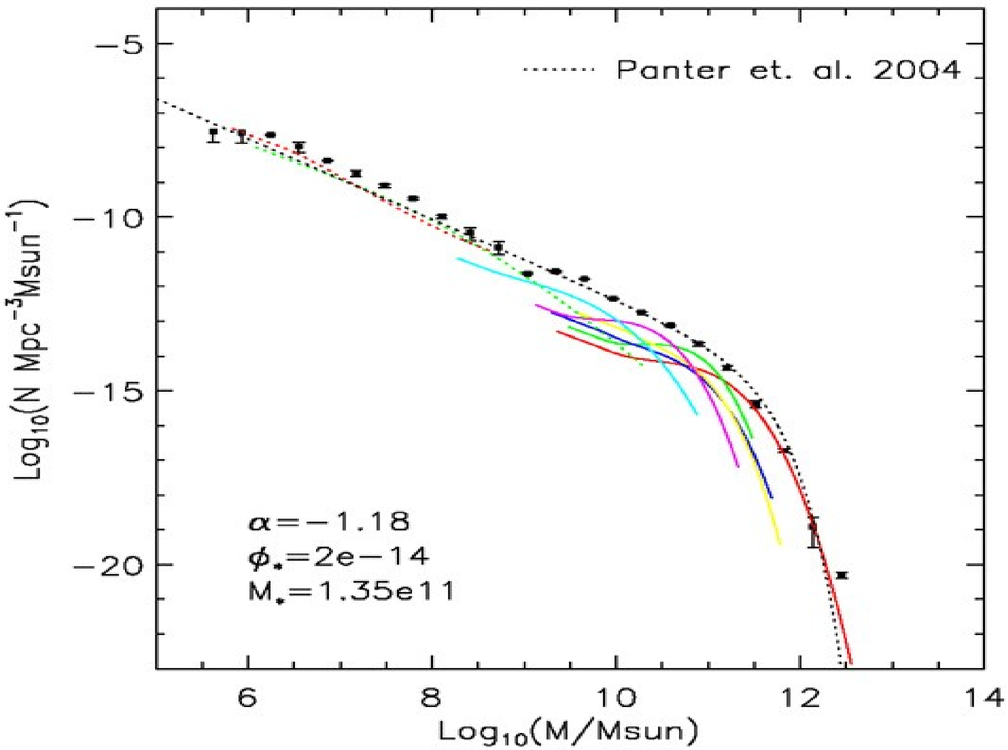

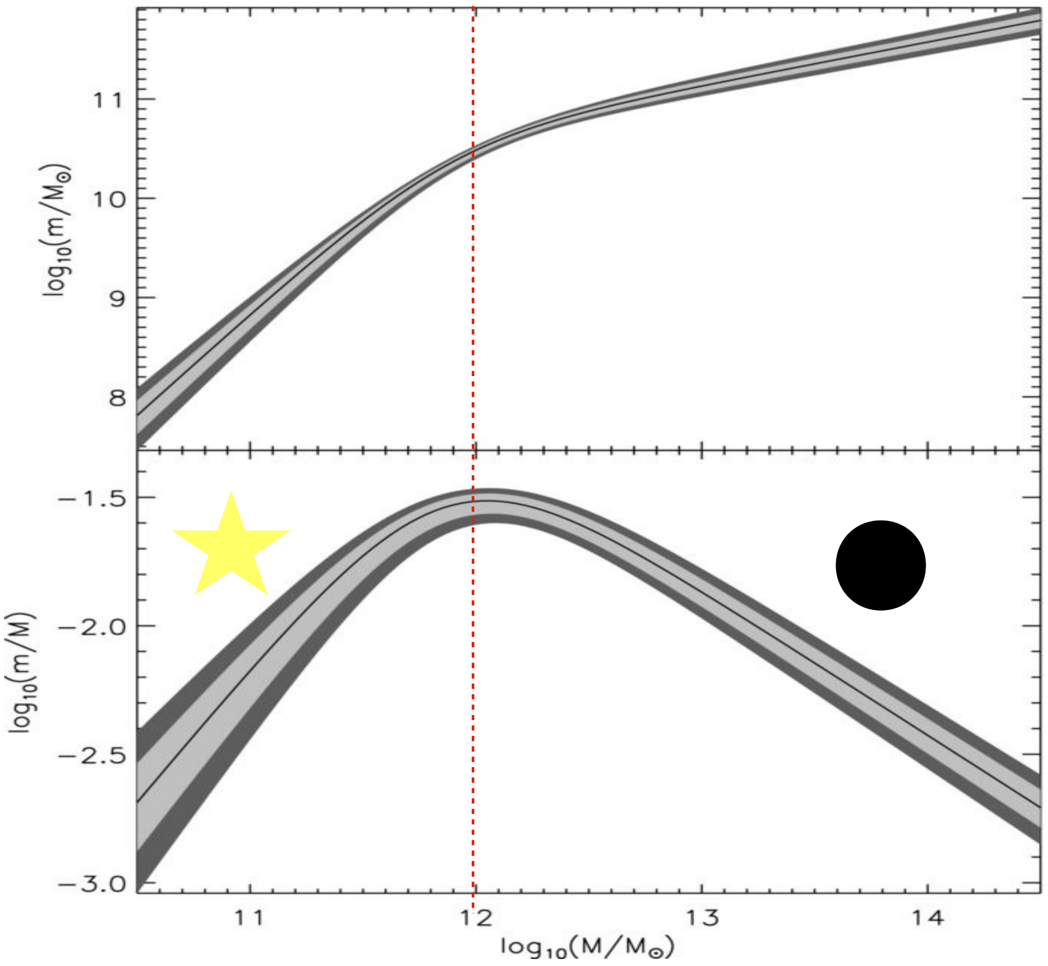

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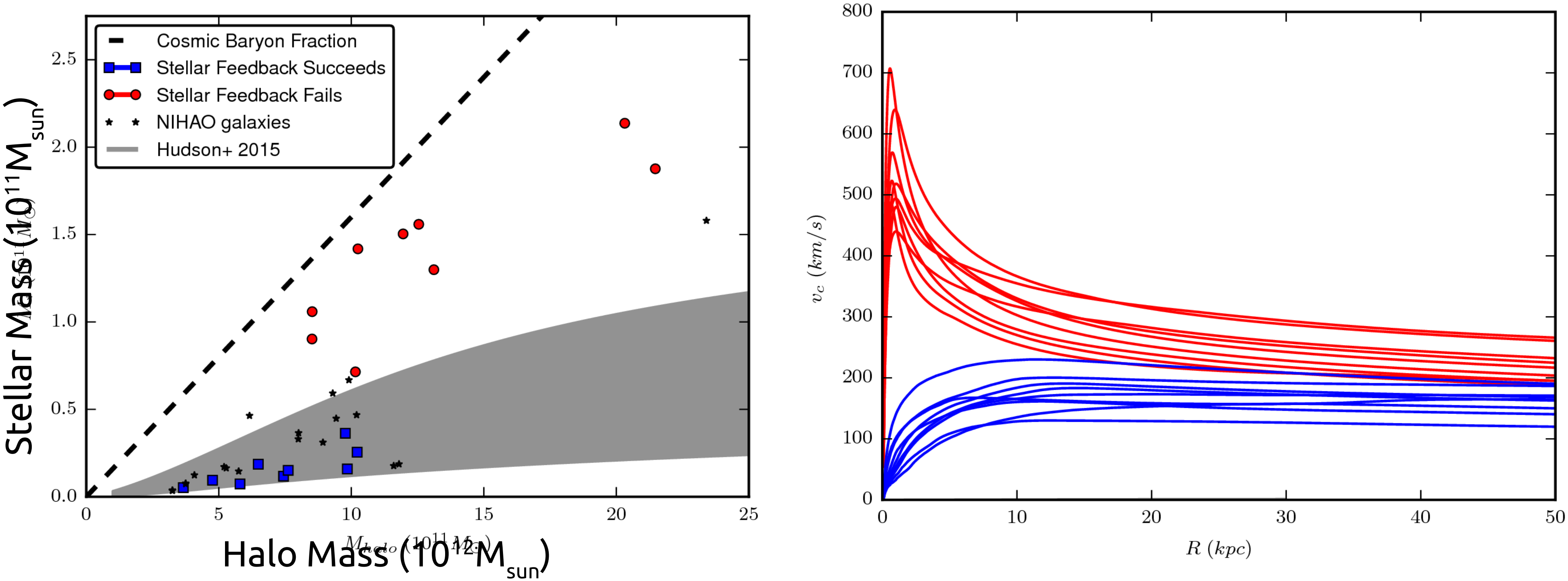
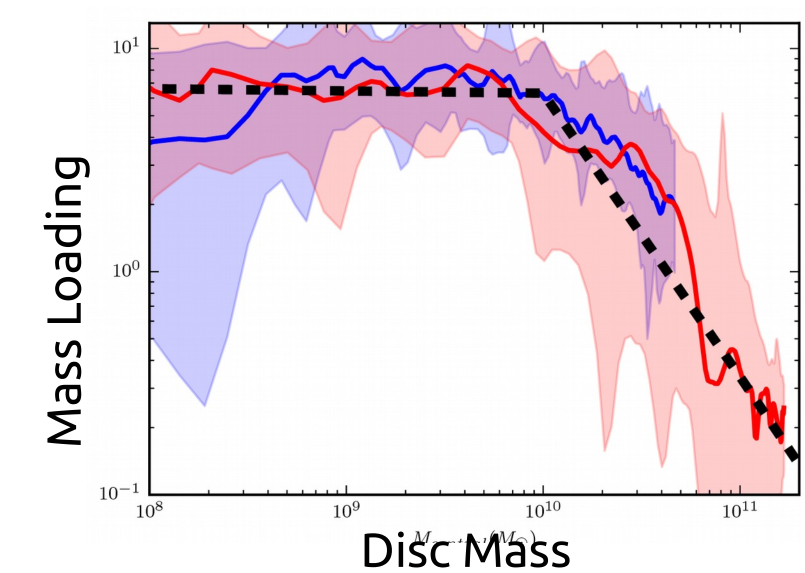
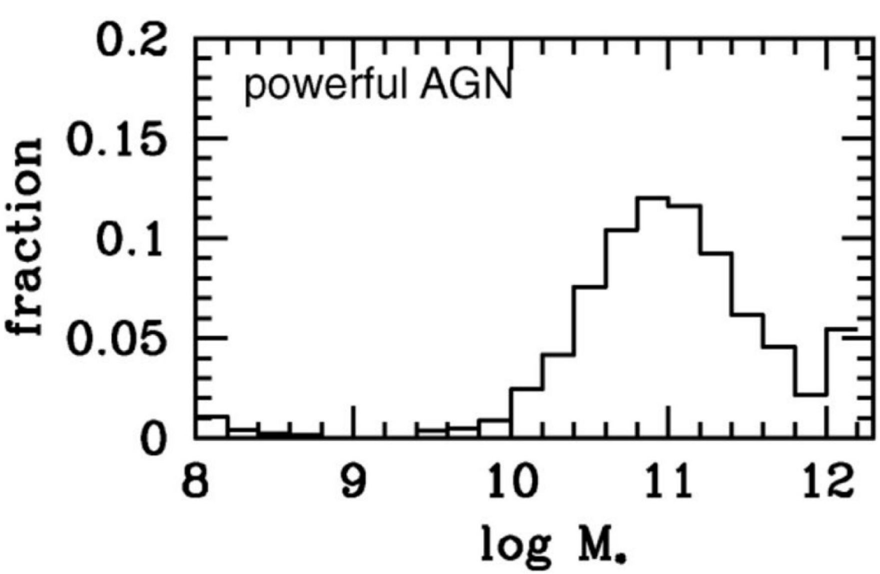


Answer: No!

Keller+ 2016

Mass loading has universal scaling



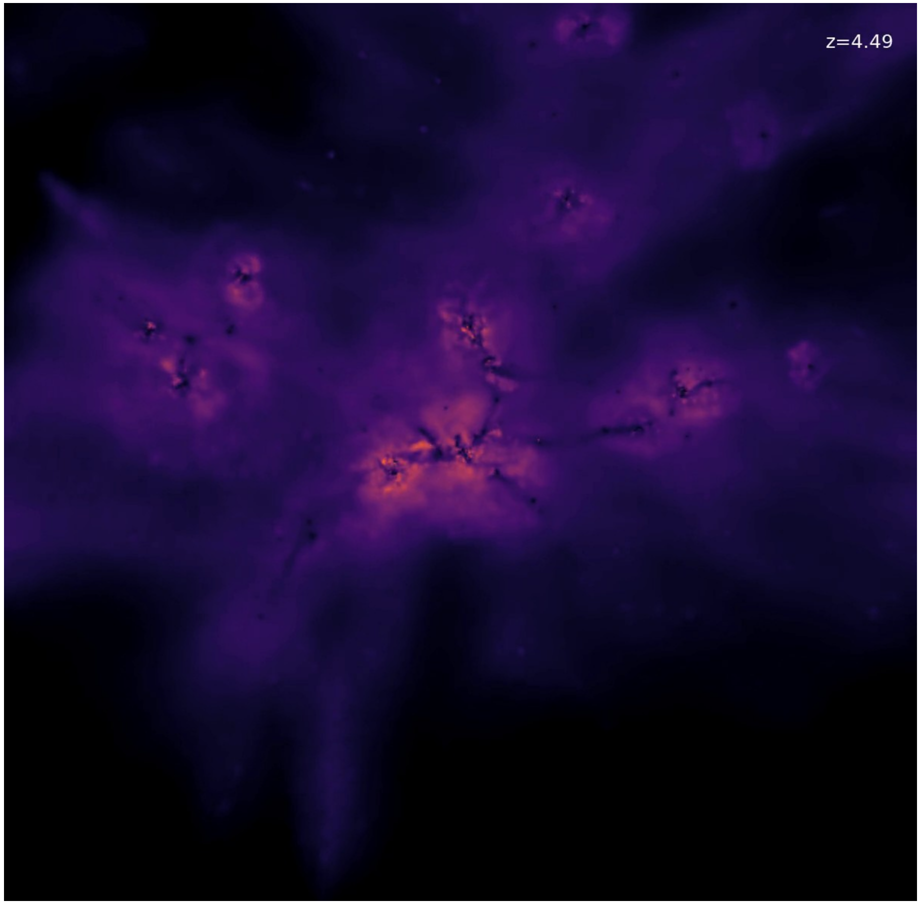


- Mass-loading begins to fall from ~10 when disc is ~$10^{10}M_{sun}$, halo is ~$2x10^{11}M_{sun}$ to << 1 in halos above ~$10^{12}M_{sun}$
- SDSS observations find powerful AGN kick in here!
- Dubois+ 2015 simulations found AGN regulation began at 280 km/s bulge v_{esc} at high z

Keller+ 2016

How Gas Moves Through the CGM

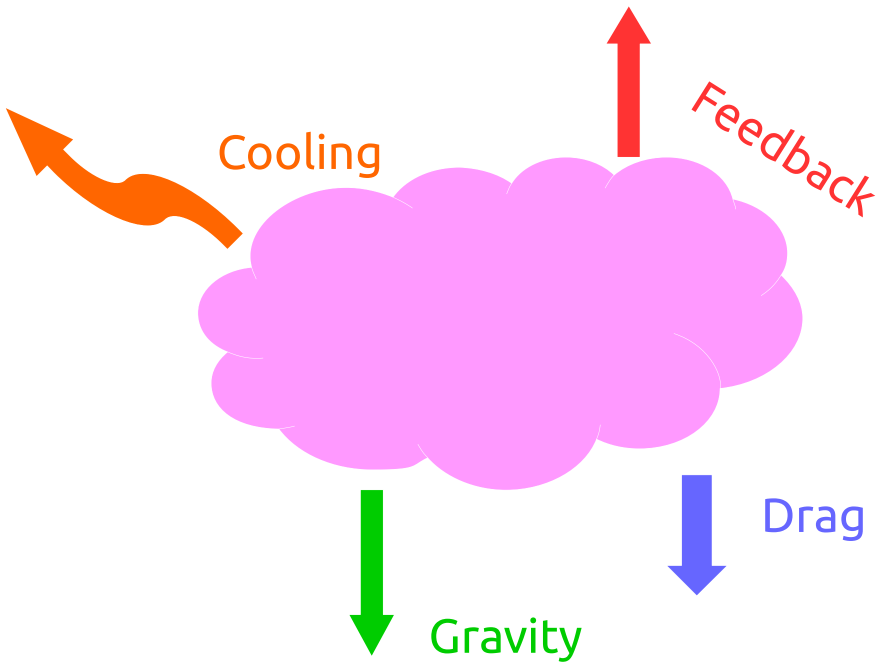
- Do outflows escape the halo?
  - Wind vs. Fountain
- Are they driven by energy, momentum, or something else?
- How does accreted material interact with outflowing material?



What Governs CGM Flow?

- Physics at work
  - Energy/Momentum injected by FB
  - Gravity/Accretion Shock
  - Hydrodynamic Drag
  - Radiative Cooling
  - *Buoyancy*
- **Buoyancy can add OR remove radial momentum!**

- Critical Timescales
  - Cooling t_{cool}
  - Gravitational Freefall t_{ff}
  - Brunt-Väisälä t_{buouy}



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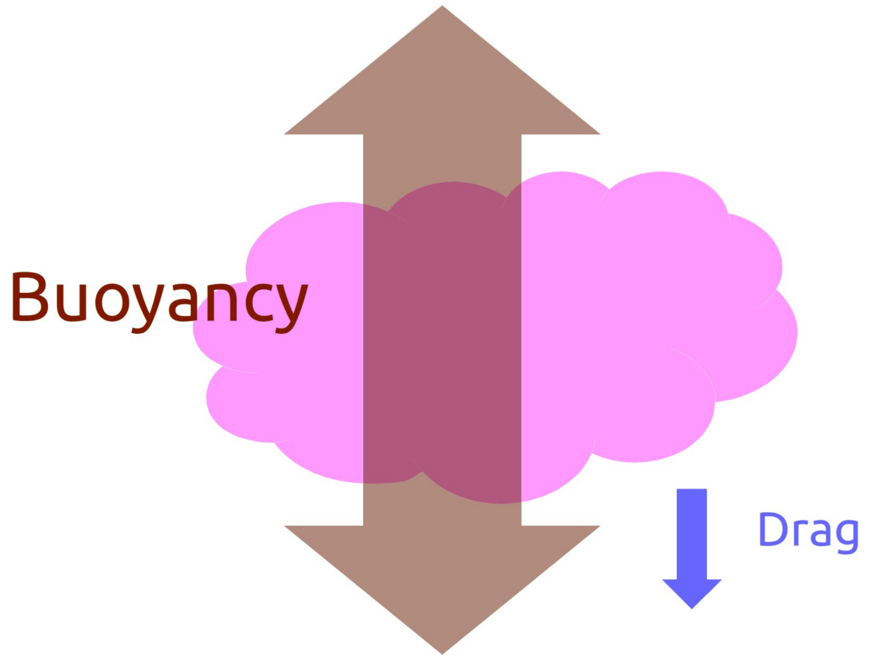


Buoyancy is all about Entropy!

"Entropy"

$$K = k_B T n^{-2/3}$$

Entropy

$$\Delta S = \Delta \ln(K)$$

Schwarzchild Criterion

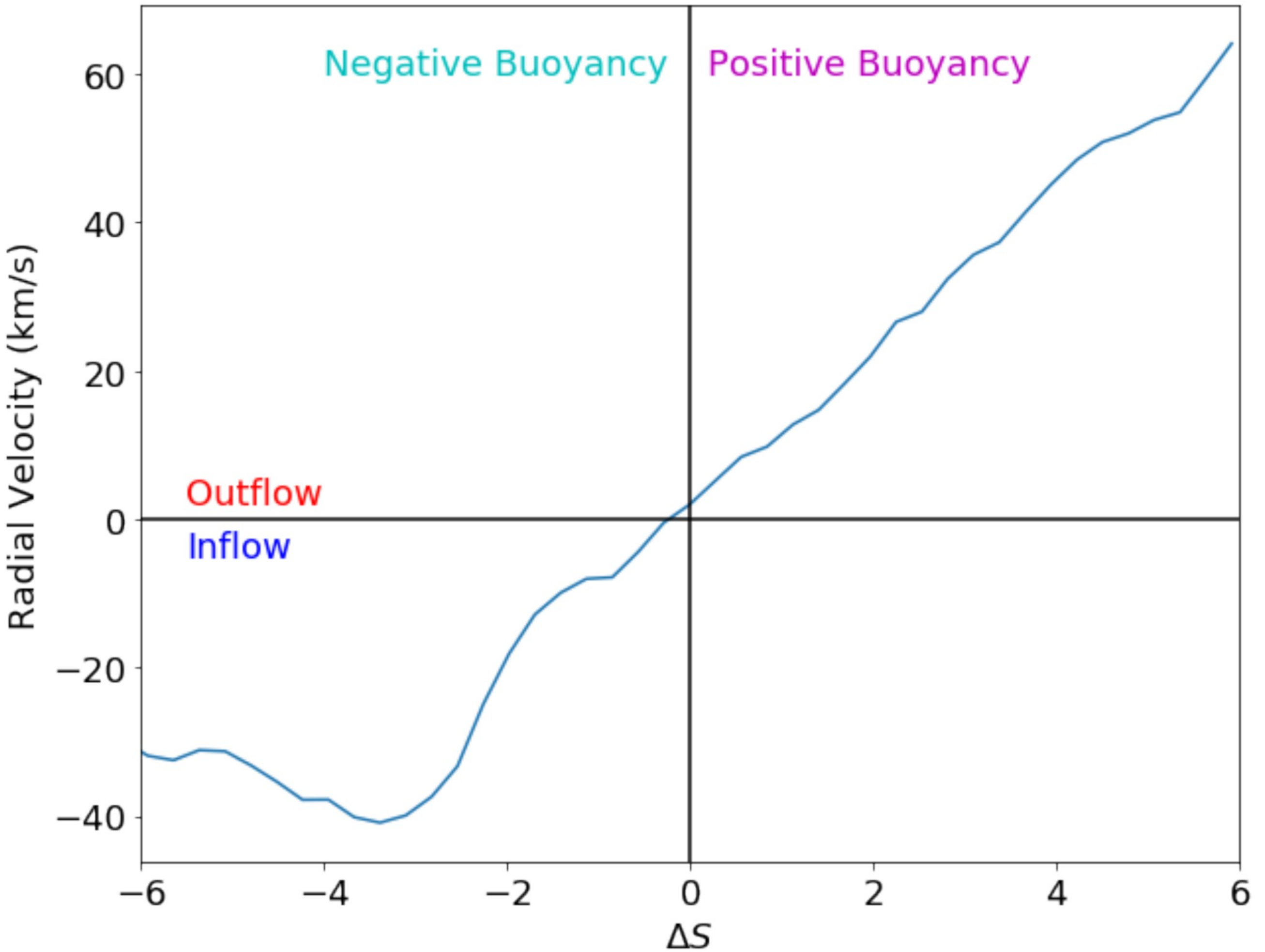
$$\frac{\partial S}{\partial r} > 0$$

Brünt-Väisälä Frequency

$$\omega = \sqrt{\frac{3}{5} \nabla \phi \nabla S}$$

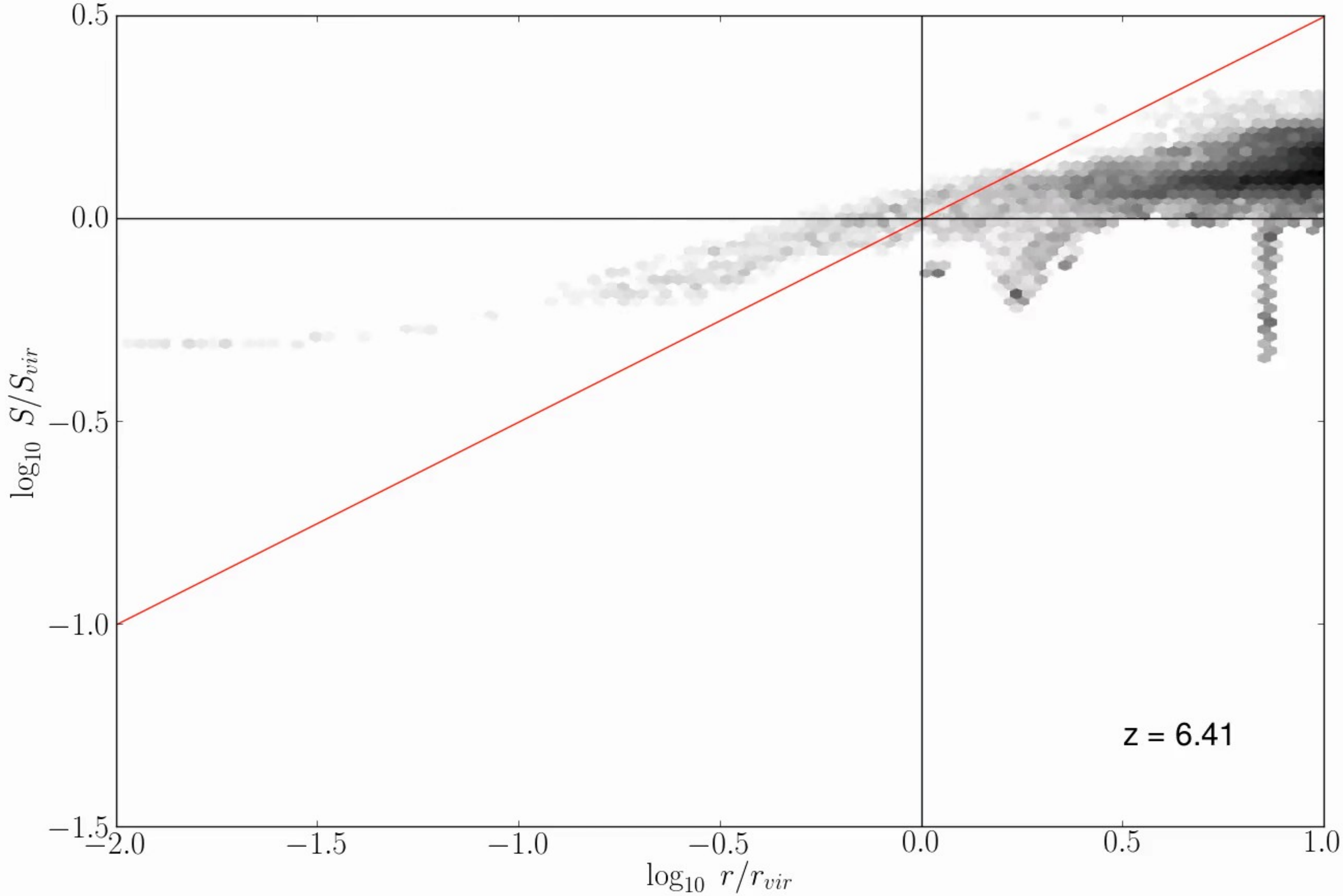
Keller+ 2018b, in prep

Buoyancy determines flow direction



Keller+ 2018b, in prep

Entropy-Driven Fountains



Keller+ 2018b, in prep

EoM for Entropy-Driven Fountains

$$\ddot{r} = \nabla\phi\left[\overbrace{\left(\frac{K_{SB}}{K(r)}\right)^{3/5} r^{-3\alpha/5}}^{\text{Buoyancy}} \underbrace{-1}_{\text{Gravity}}\right] \overbrace{-\gamma\rho(r)\frac{\dot{r}^{3}}{|\dot{r}|}}^{\text{Drag}}$$

Keller+ 2018b, in prep

Can We Derive the Entropy of a SB?

Superbubble Density

$$n_{SB} = 9.6 \circ 10^{-3}\, cm^{-3}\, L_{38}^{6/35}\, n_0^{19/35}\, t_7^{-22/35}$$

Superbubble Temperature

$$T_{SB} = \frac{10\,\mu\, m_p}{33\, k_B\, m_{SB}} L\, t$$

Superbubble Radius

$$R_{SB} = 267\, pc\, L_{38}^{1/5}\, n_0^{-1/5}\, t_7^{3/5}$$

Weaver+ 1977, Mac Low & McCray 1988

Superbubble Entropy

Entropy at breakout (R~h)

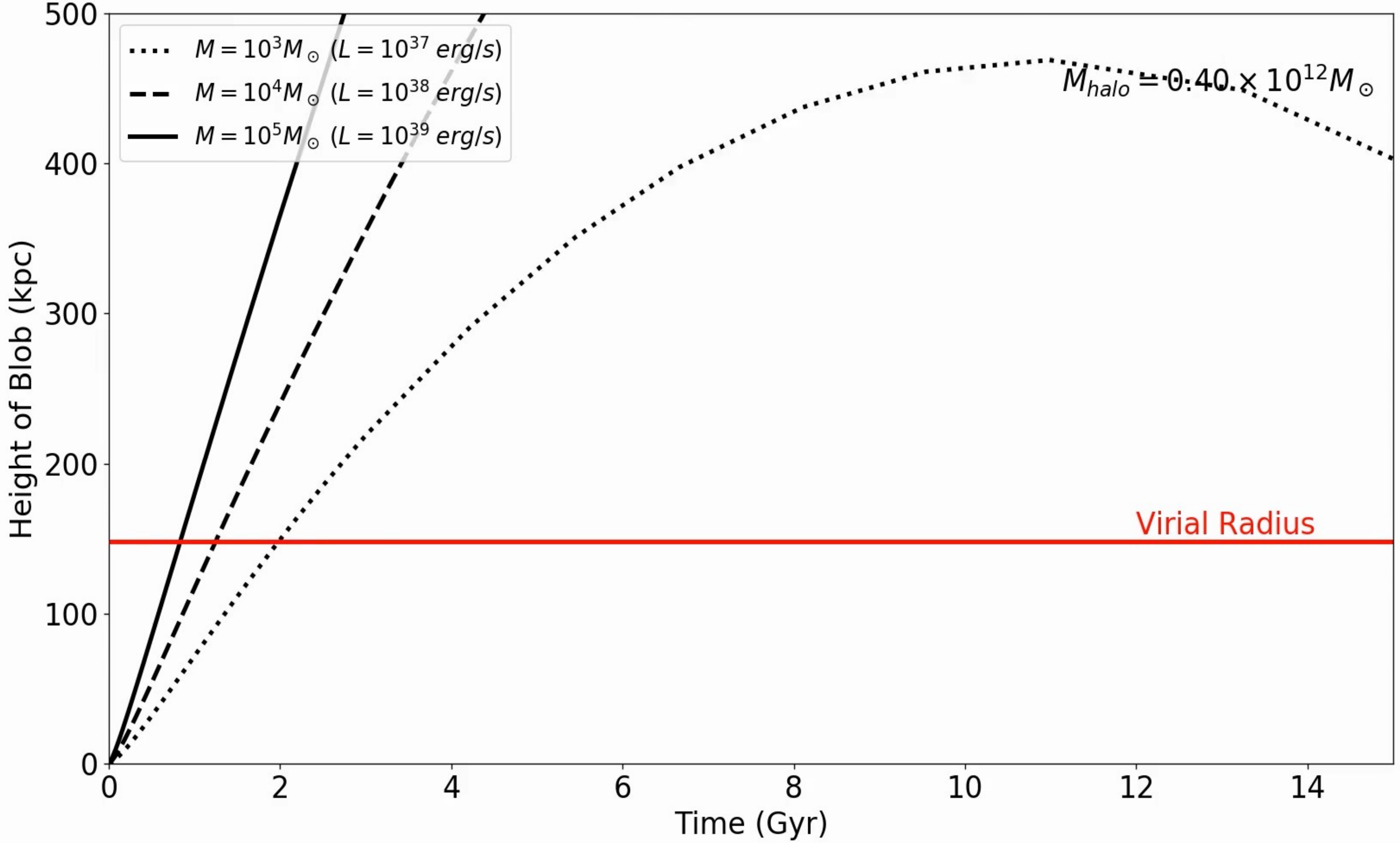
$$K_{SB} = 5.84\, keV\ cm^2 \left(\frac{h}{267\ pc}\right)^{26/36} L_{38}^{2/63}\, n_0^{-14/63}$$

Halo Entropy

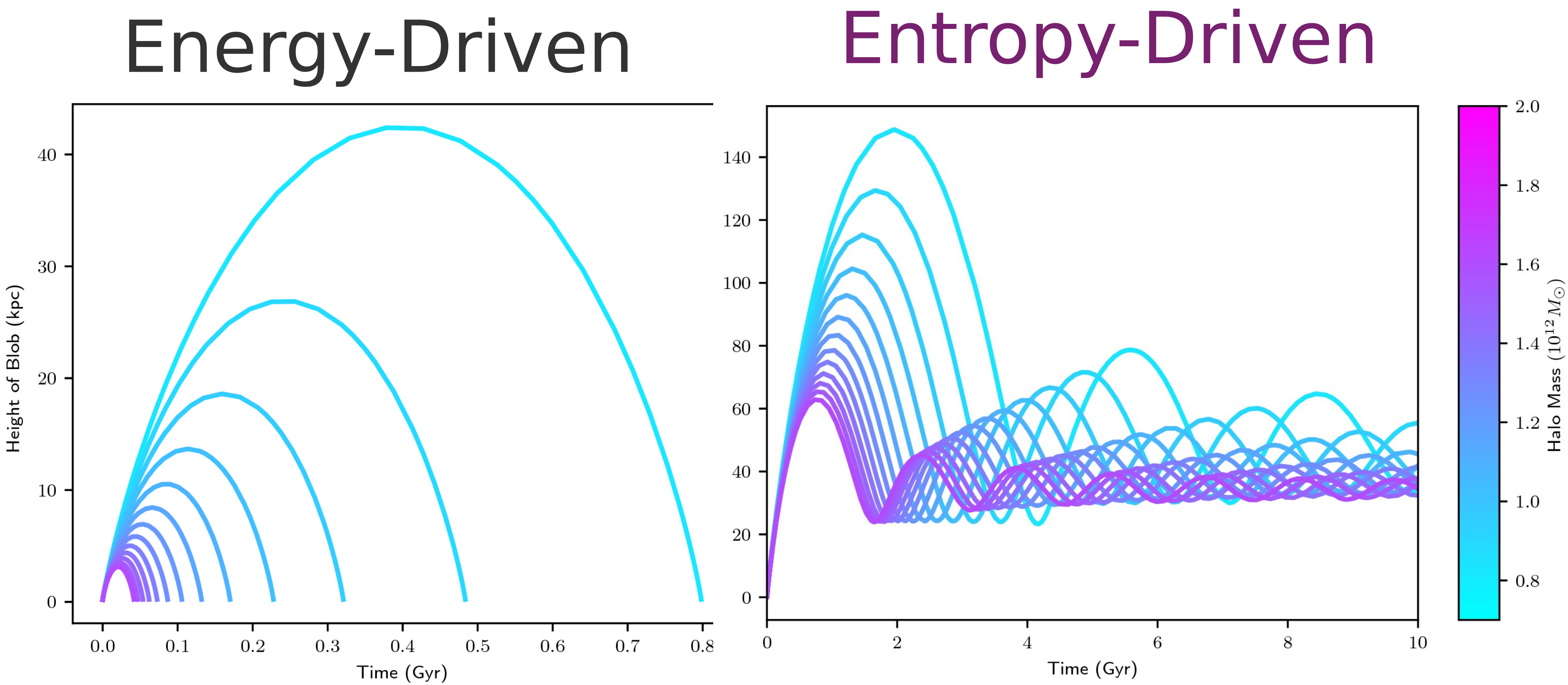
$$K_{vir} = 30.06\, keV\ cm^2 \left(\frac{M_{vir}}{10^{12}\, M_{sun}}\right)^{2/3}$$

Keller+ 2018b, in prep

Integrating the Buoyant EoM

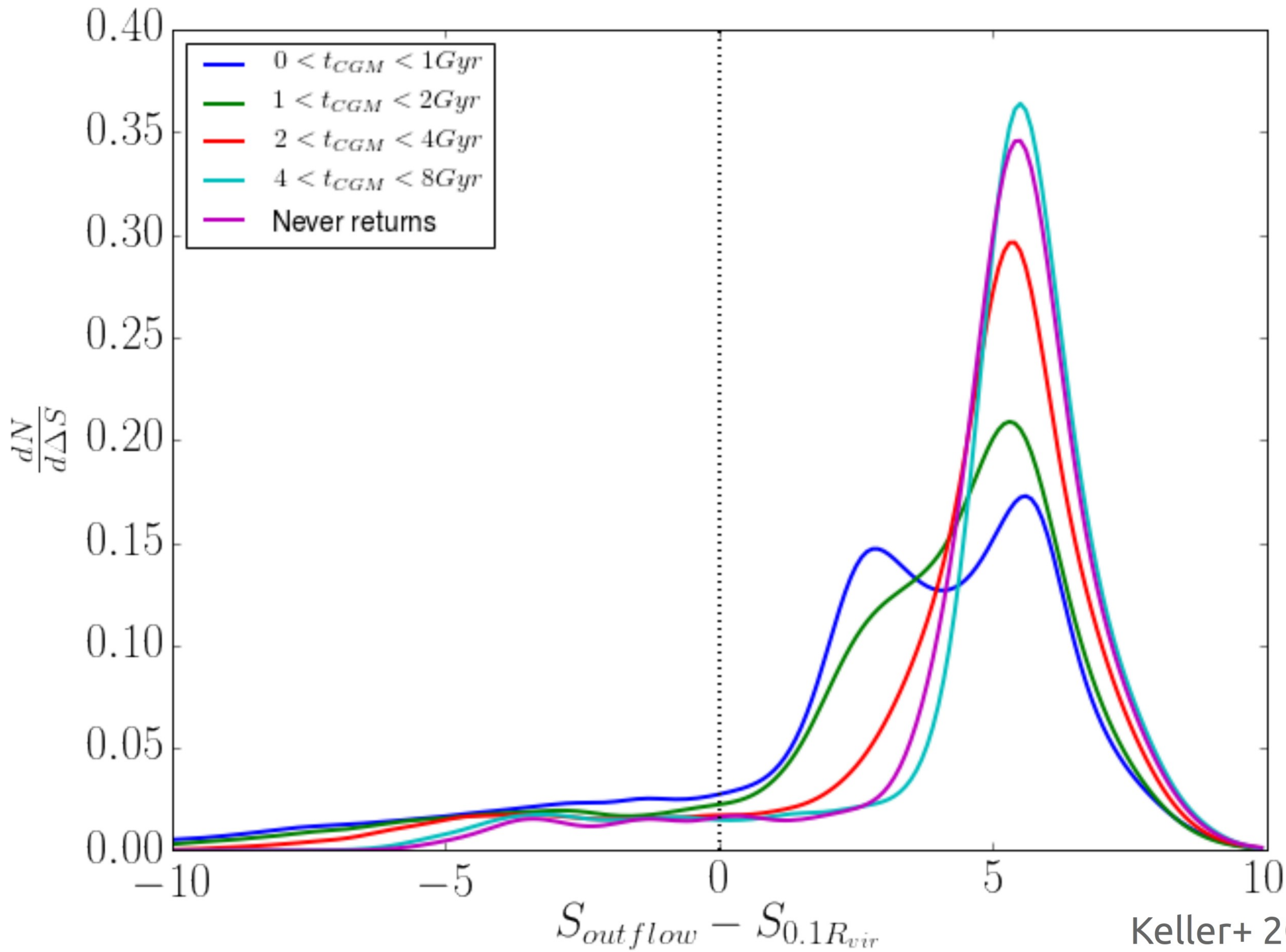


Buoyant Outflows Recycle Slowly!



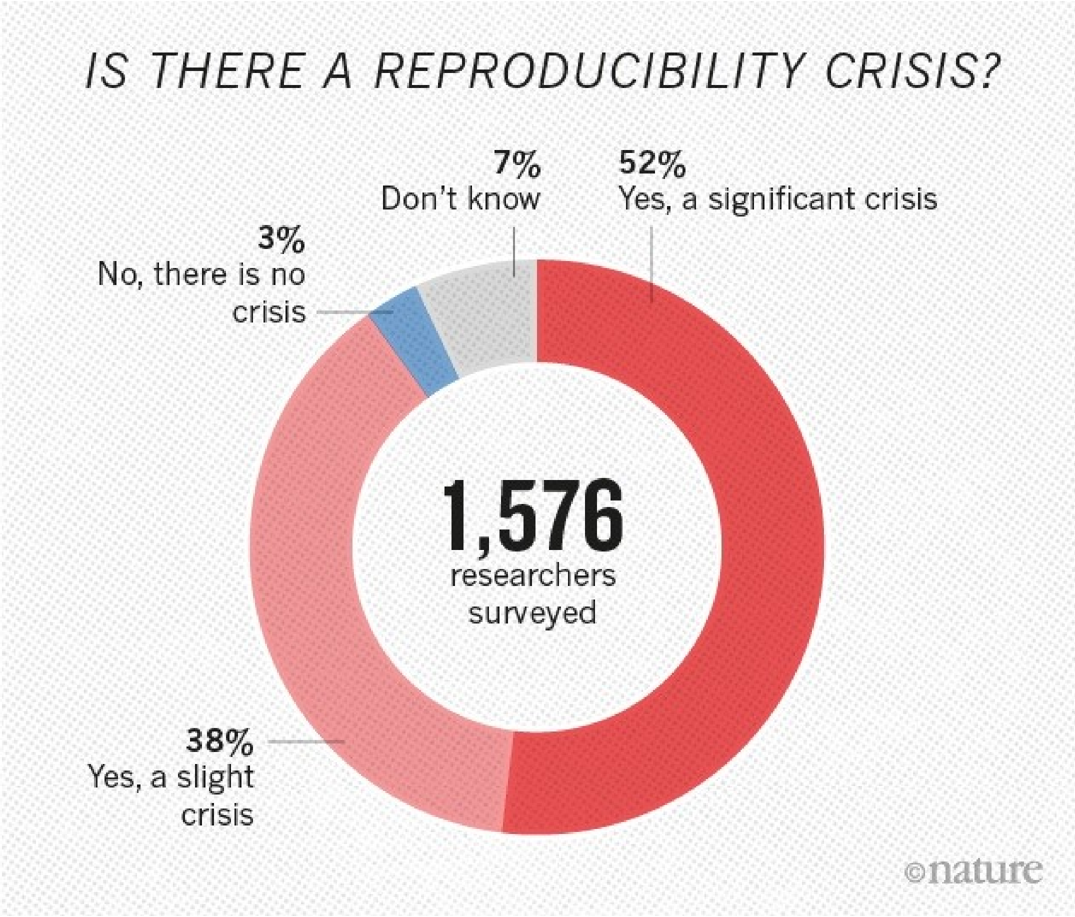
Keller+ 2018b, in prep

Buoyancy determines recycling time



Keller+ 2018b, in prep

A “Reproducibility Crisis” In Numerical Astrophysics?



Monya Baker, Nature News, 2016

How Sensitive Are Galaxy Properties to Small Perturbations?

- N-Body Chaos
- Infinitesimal Initial Condition Perturbations
- Random Number Generator seeds
- Poisson Noise
- Floating Point Roundoff

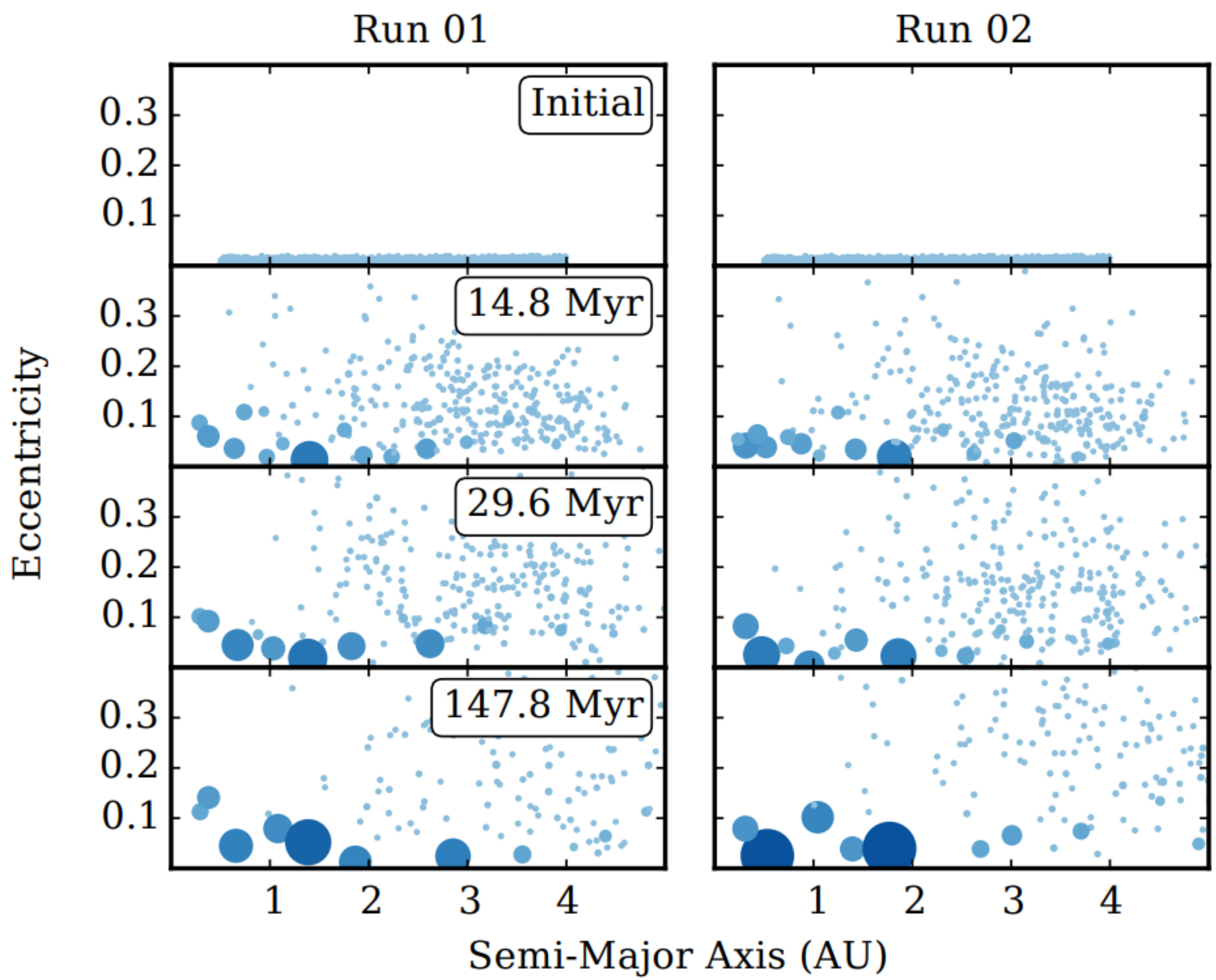
Chaos Rules Everything Around Me

the Sun. More surprisingly, in one of these high-eccentricity solutions, a subsequent decrease in Mercury's eccentricity induces a transfer of angular momentum from the giant planets that destabilizes all the terrestrial planets ~3.34 Gyr from now, with possible collisions of Mercury, Mars or Venus with the Earth.

Using the JADE supercomputer at the French National Computing Centre CINES, we integrated 2,501 orbital solutions, S_k, of the complete model over 5 Gyr, with the initial semi-major axis of Mercury differing by $0.38k$ mm ($k \in [-1{,}250, 1{,}250]$) from that in the nominal solution, S_0, which was adjusted to the planetary ephemeris INPOP06[17]. The results (Fig. 1b and Supplementary Table 1b) are comparable to those of the relativistic secular equations[2], with Mercury having a high eccentricity in about 1% of solutions.

Laskar & Gastineau 2009

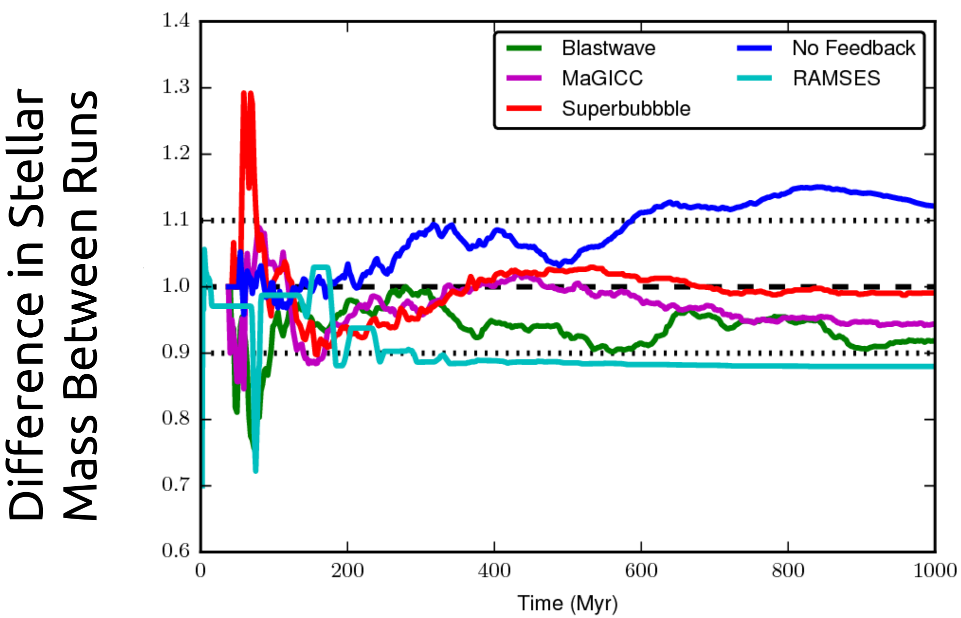
Chaos is Important in Protoplanetary Discs: Why Not Galactic Discs?



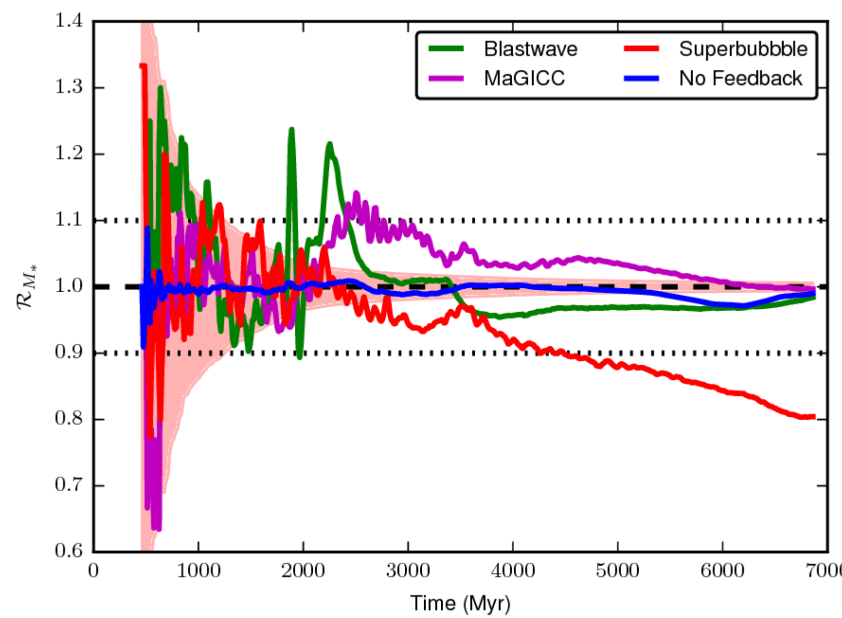
Hoffmann+ 2017

Chaos is Universal!

Isolated Dwarf Galaxy

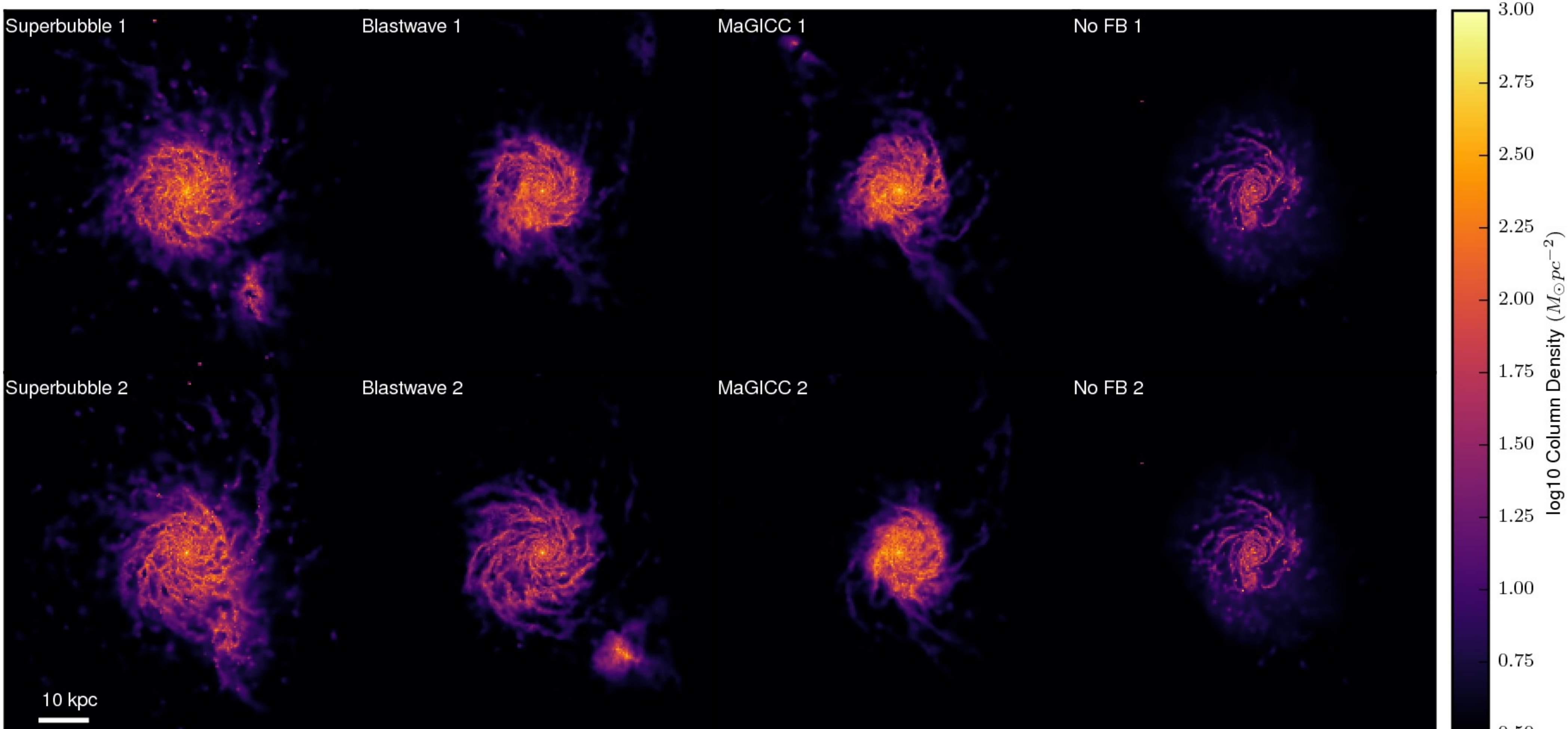


Cosmological MW Zoom

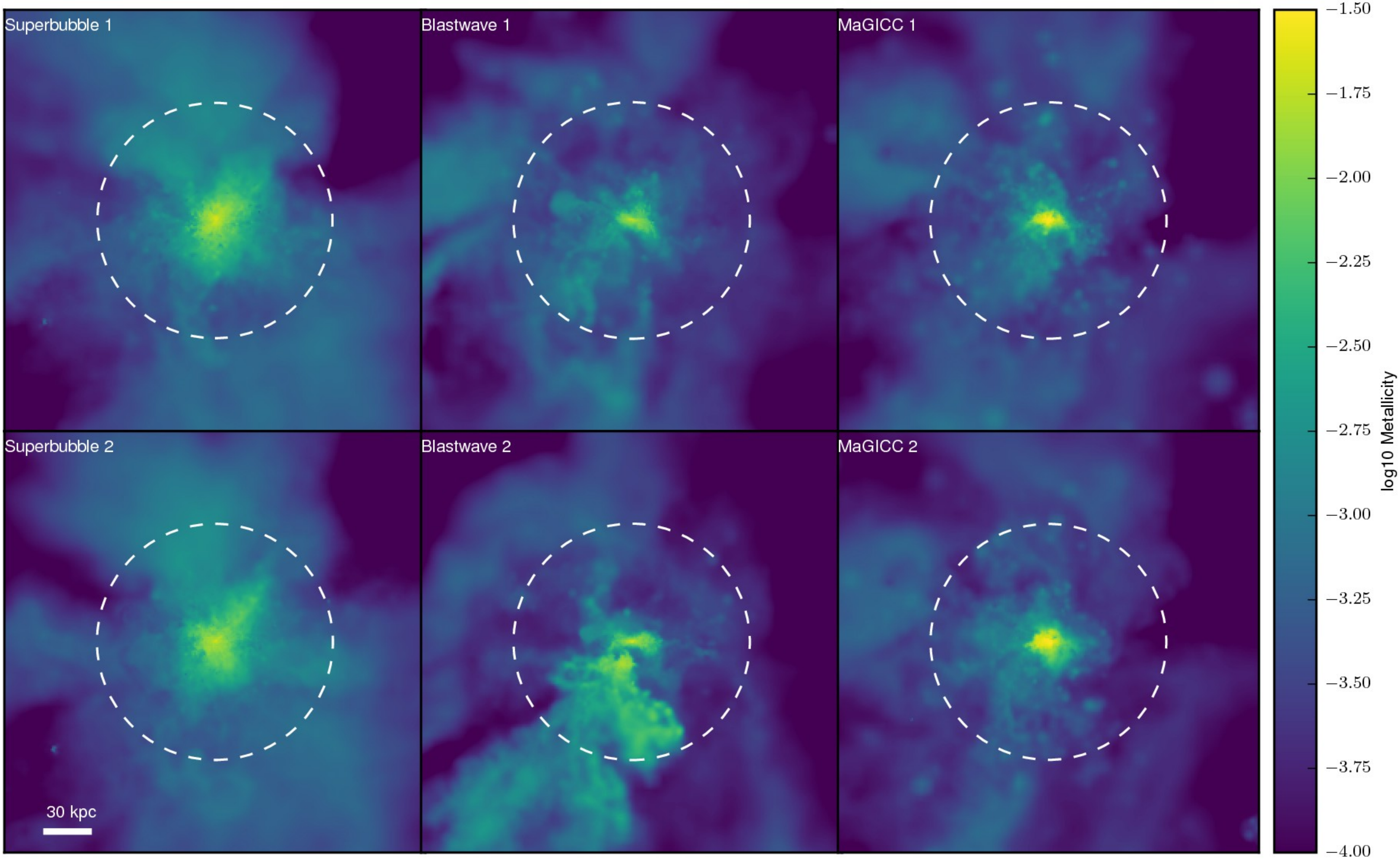


- All codes
- All subgrid feedback models
- All initial conditions
- See also Genel+ 2018

Keller+ 2018a, submitted



Keller+ 2018a, submitted

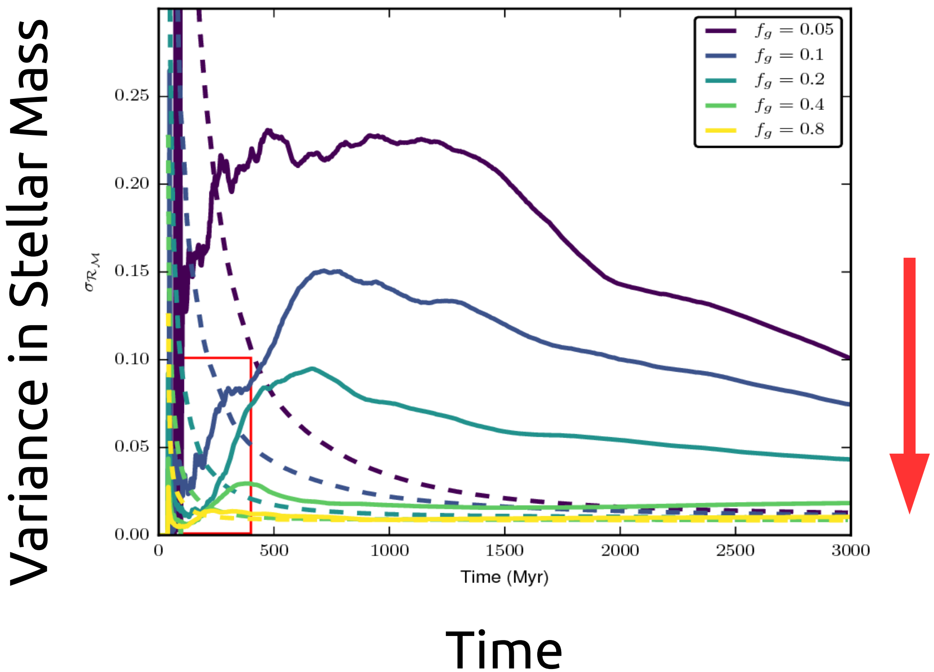


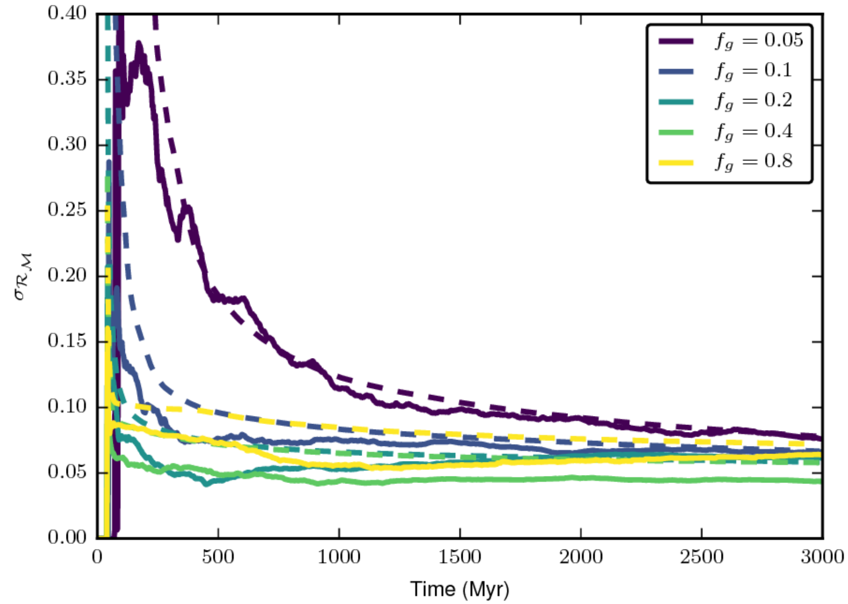
Keller+ 2018a, submitted

Feedback & Gas Exhaustion Constrain Stochasticity

No Feedback:
Gas Exhaustion

Feedback:
Self-Regulation

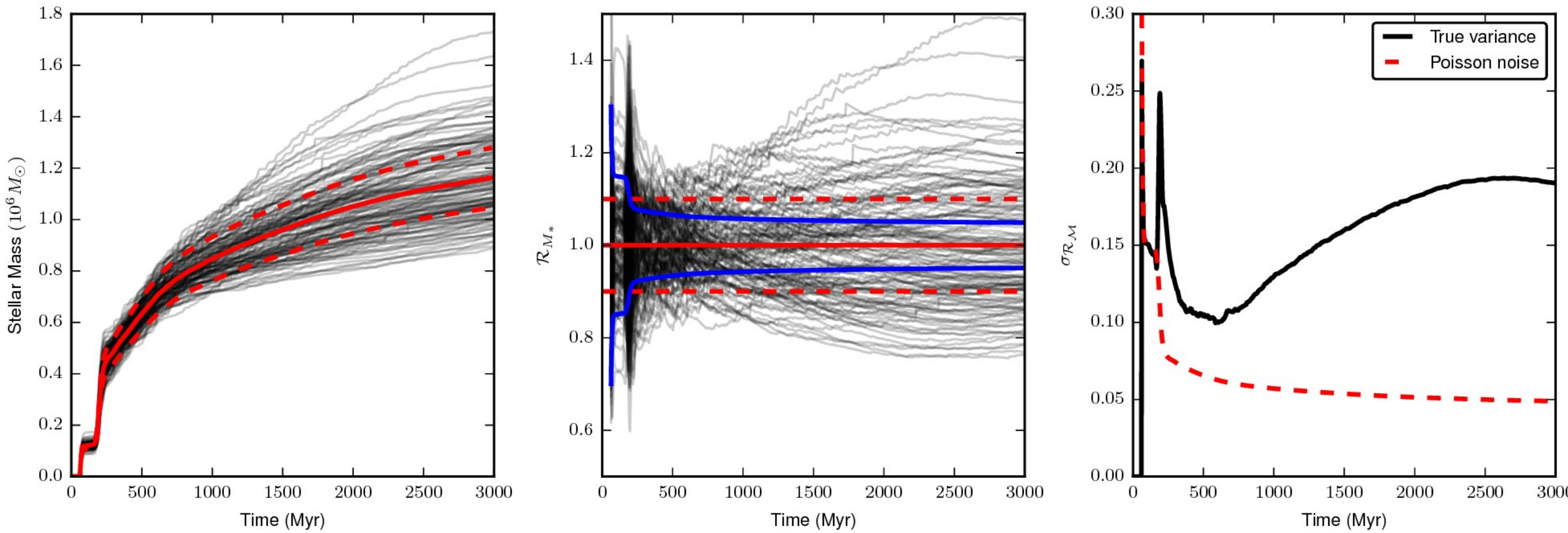




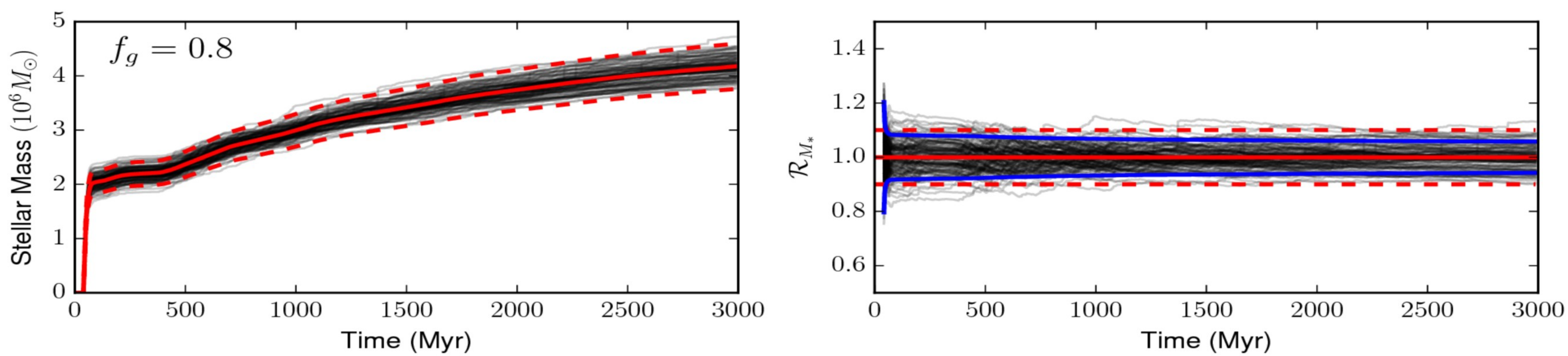
Keller+ 2018a, submitted

Starbursts & Mergers Pump Chaos

Merger



Isolated/



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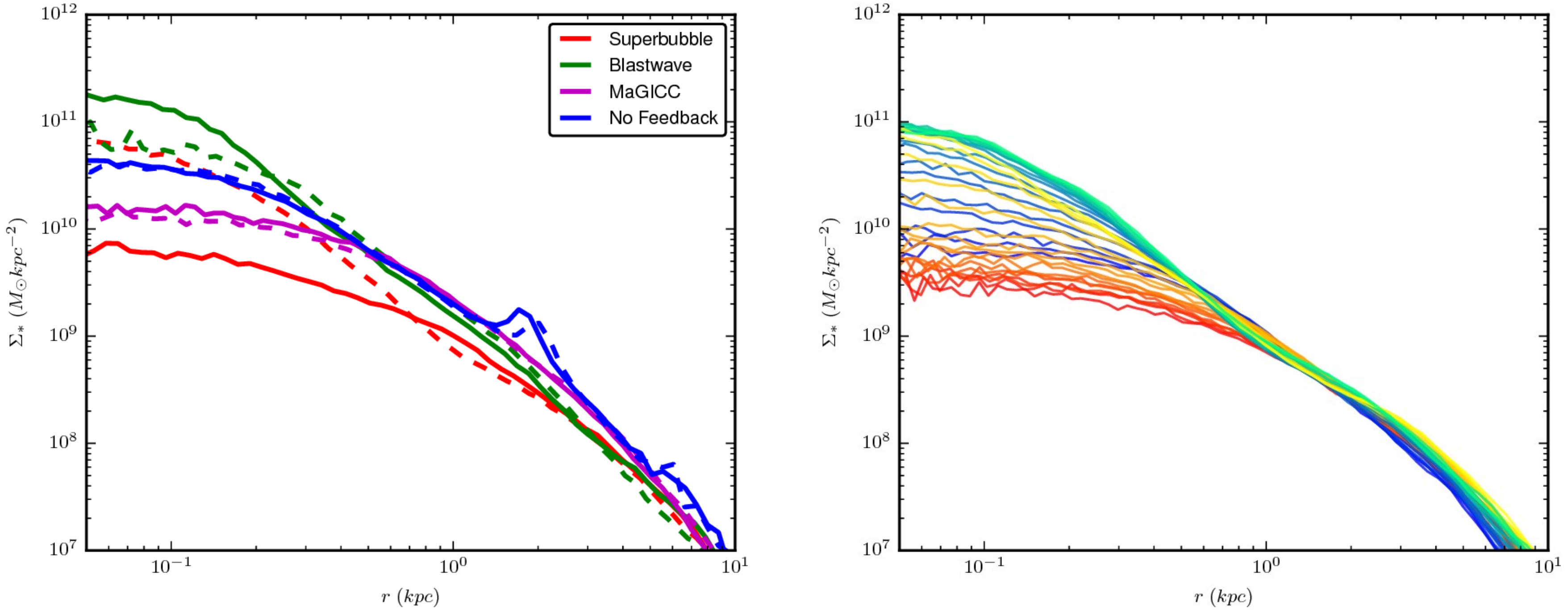
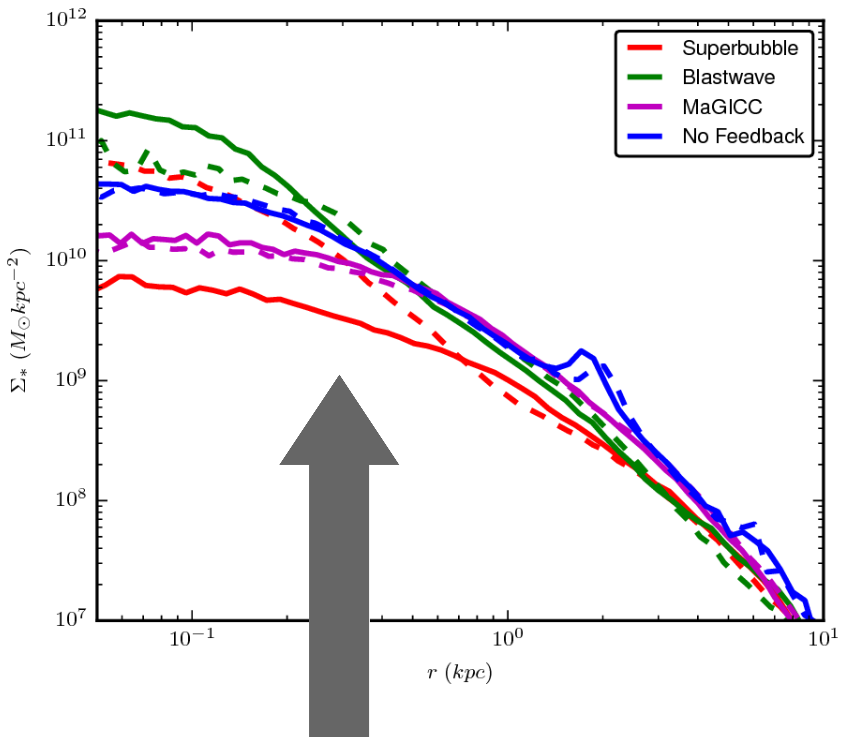
Temporal ~ Numerical Stochasticity

Stellar Surface Density

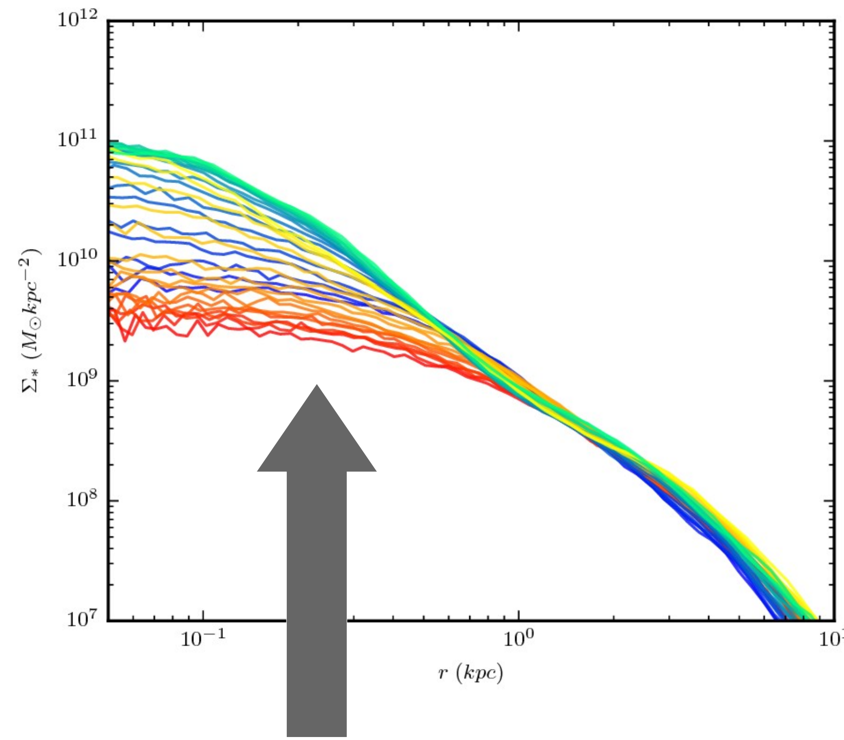


Keller+ 2018a, submitted

Temporal ~ Numerical Stochasticity



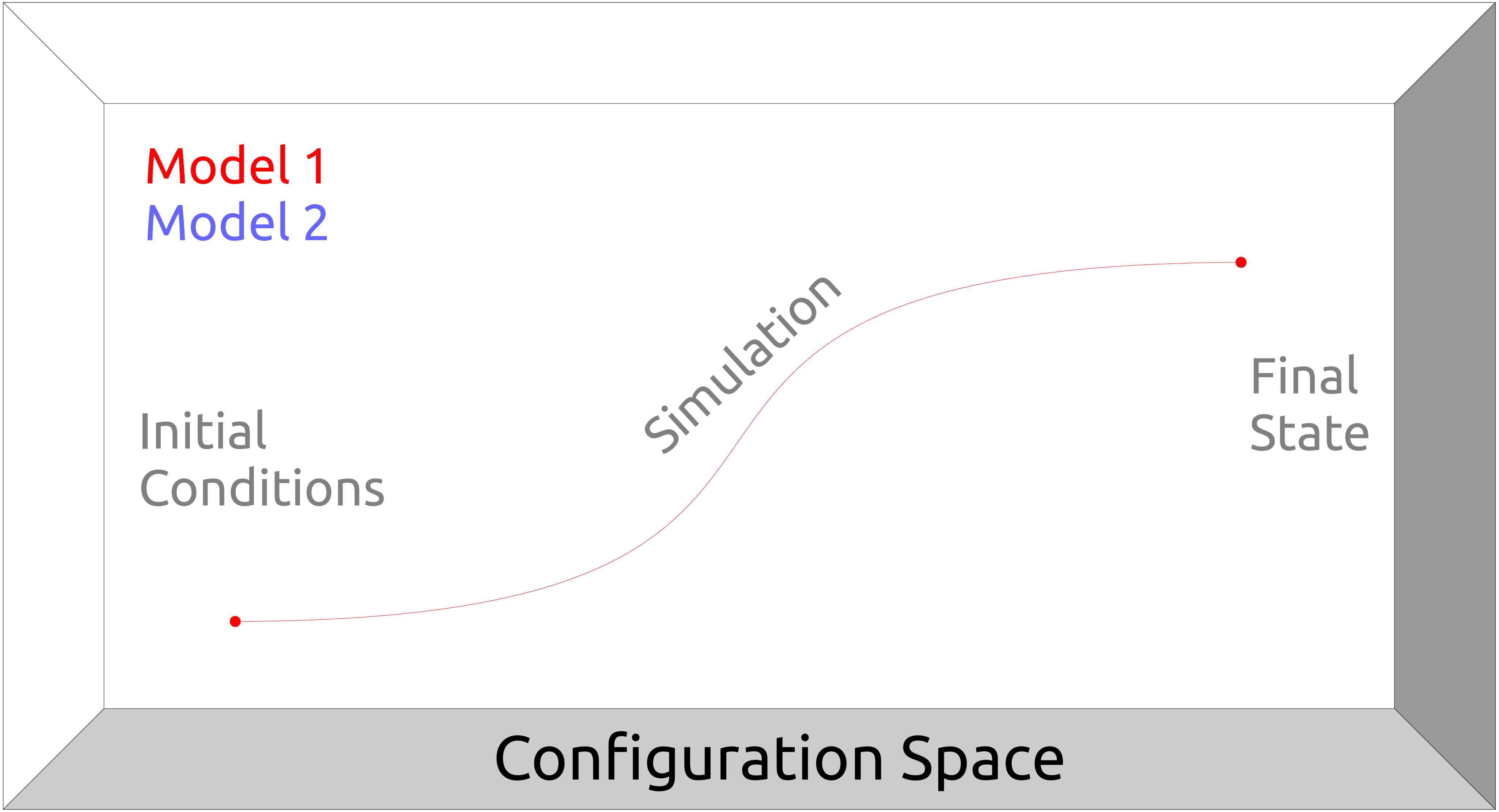
Run-to-Run Variation



Step-to-Step Variation

Keller+ 2018a, submitted

What does “simulation” mean?



Keller+ 2018a, submitted

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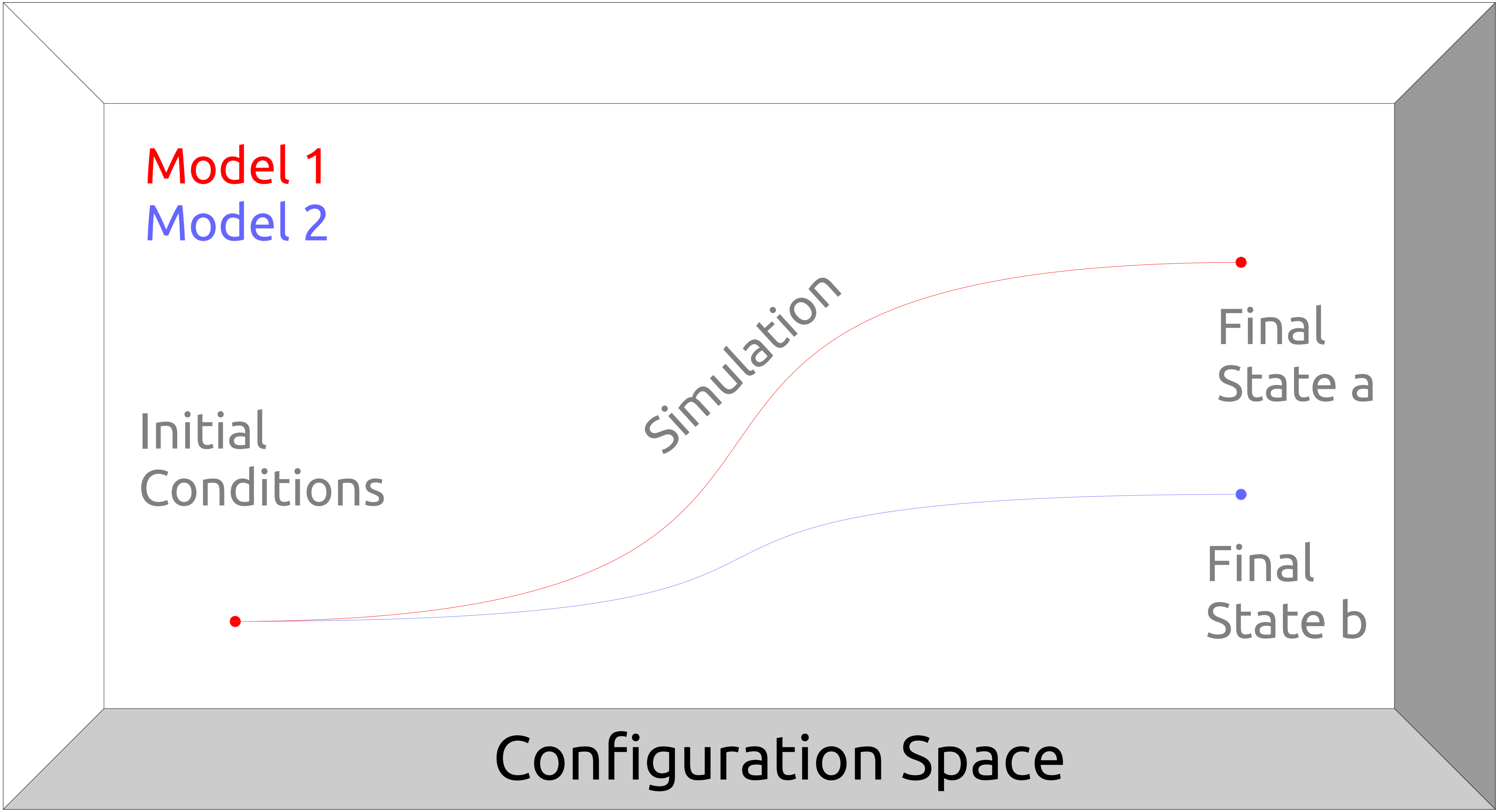

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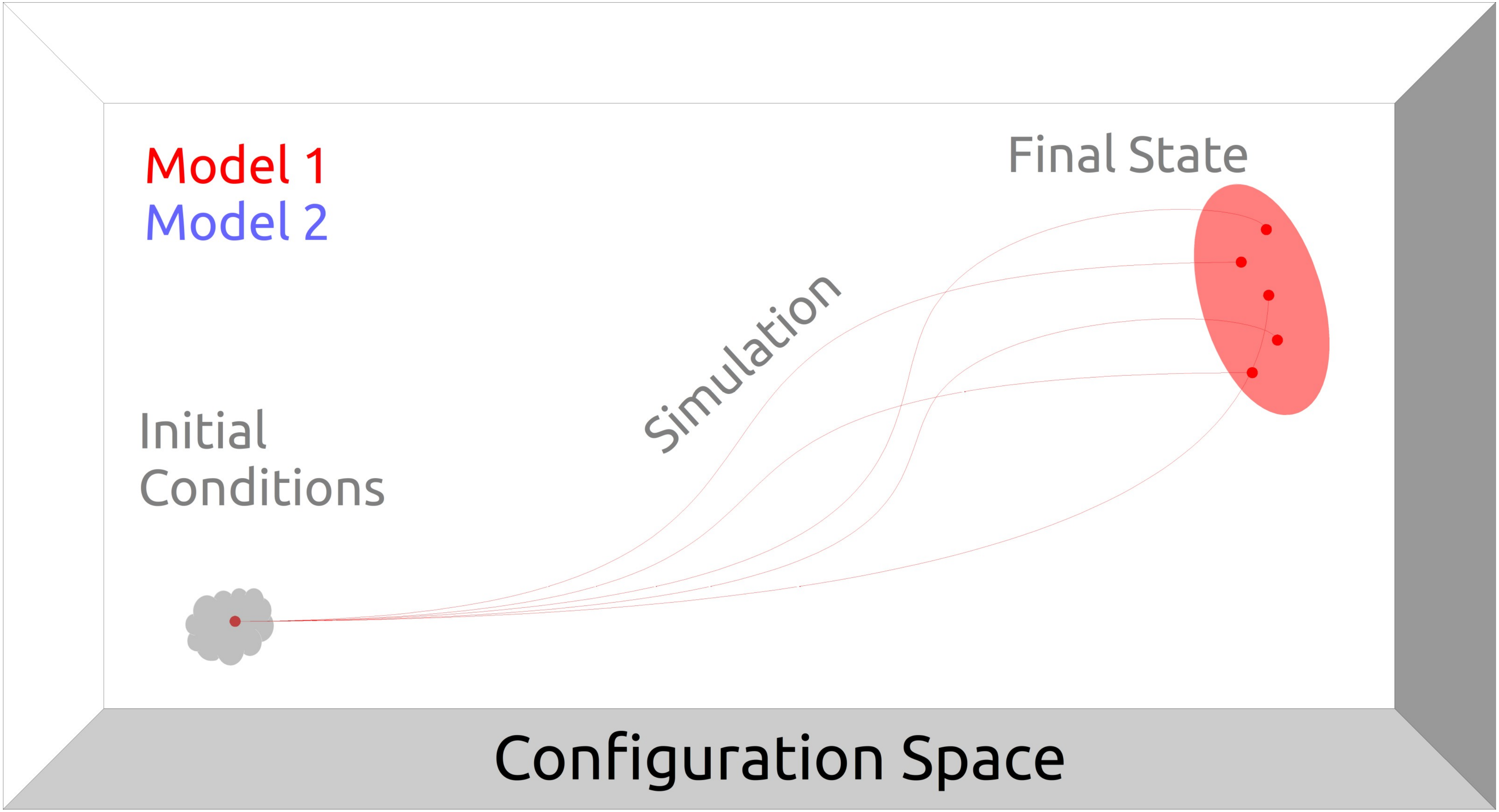

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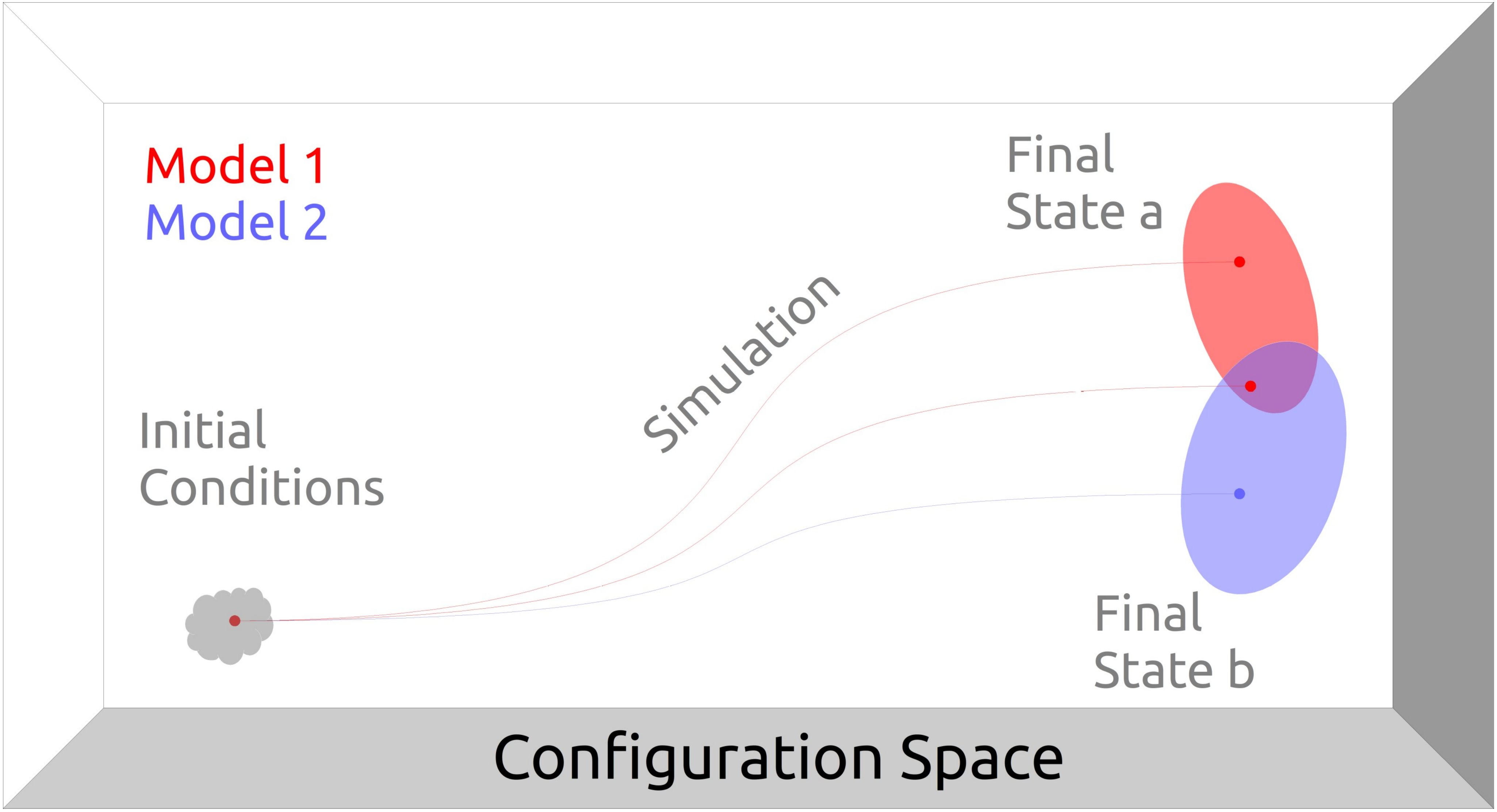

Keller+ 2018a, submitted

Read My Papers Here :)

Conclusions

- Highly mass-loaded outflows, especially at high-z, are *essential* to forming realistic L* galaxies
  - These outflows *cannot* be driven by SN alone in halos more massive than 10^{12} M_{sun}
- Entropy-driven winds, driven by buoyancy, behave quite differently than ballistic outflows
  - Gentle acceleration, low velocities
  - Long recycling times
  - Halo entropy exceeds superbubble entropy near 10^{12} M_{sun}, halting outflows
- Galaxy evolution involves chaotic physics: small-scale stochasticity can pump large-scale changes