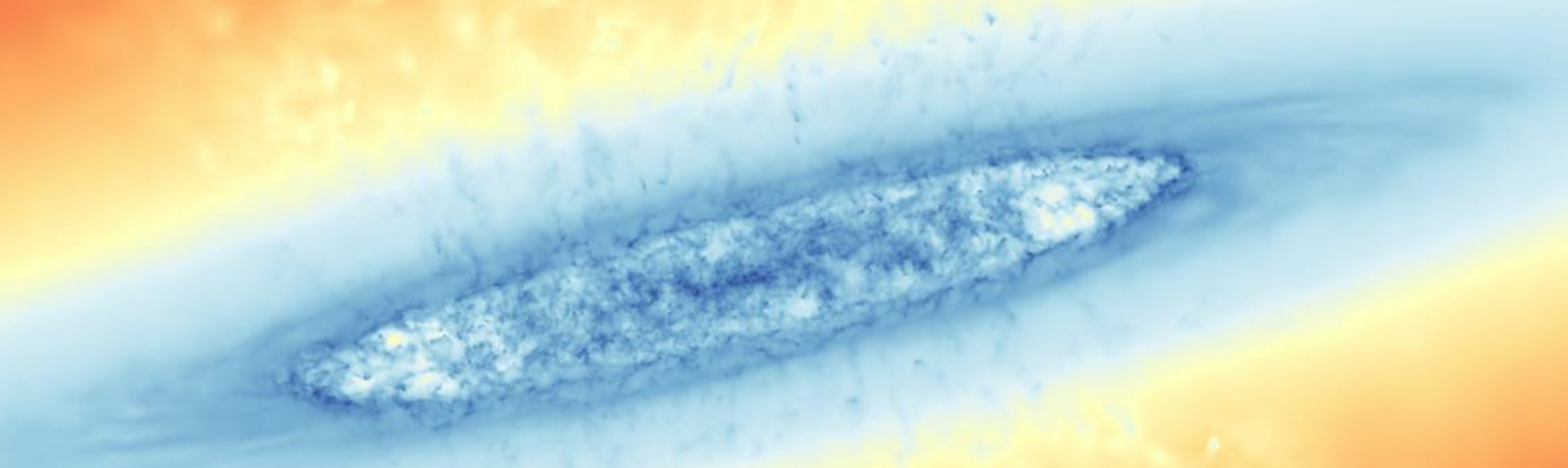
Superbubble Feedback in Galaxy Formation



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Paper: astro-ph/1405.2625 (Accepted MNRAS)
Keller, Wadsley, Benincasa & Couchman 2014

Background Image: High-resolution simulation of Milky Way like galaxy using superbubble feedback. Outflows with entrained cold clouds can be observed.

Stellar Feedback: Motivation

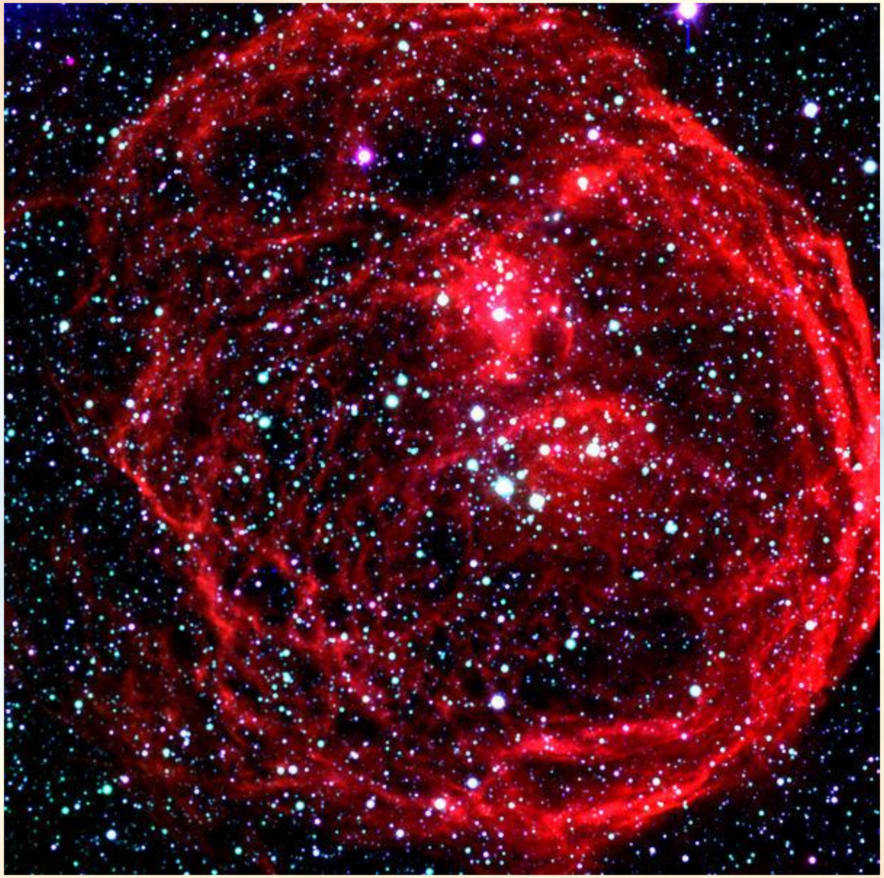
M82 Image: HST, NASA/ESA

- Feedback from Massive stars: *metals, energy, momentum* through Winds, UV, SN_{II}
- FB regulates star formation, ISM structure

FB-driven Galactic winds:

- Remove gas from disk, enrich IGM with metals
- Set final stellar mass

Superbubble Feedback: Motivation



N70 Superbubble LMC Image: ESO
D 100 pc Age: 5 Myr v ~ 70 km/s
Driver: OB assoc. 1000+ stars

- Massive star formation highly correlated in time and space
- Typical star cluster ~ 10,000 $M_\odot$ forms in ~10 pc over < 1 Myr

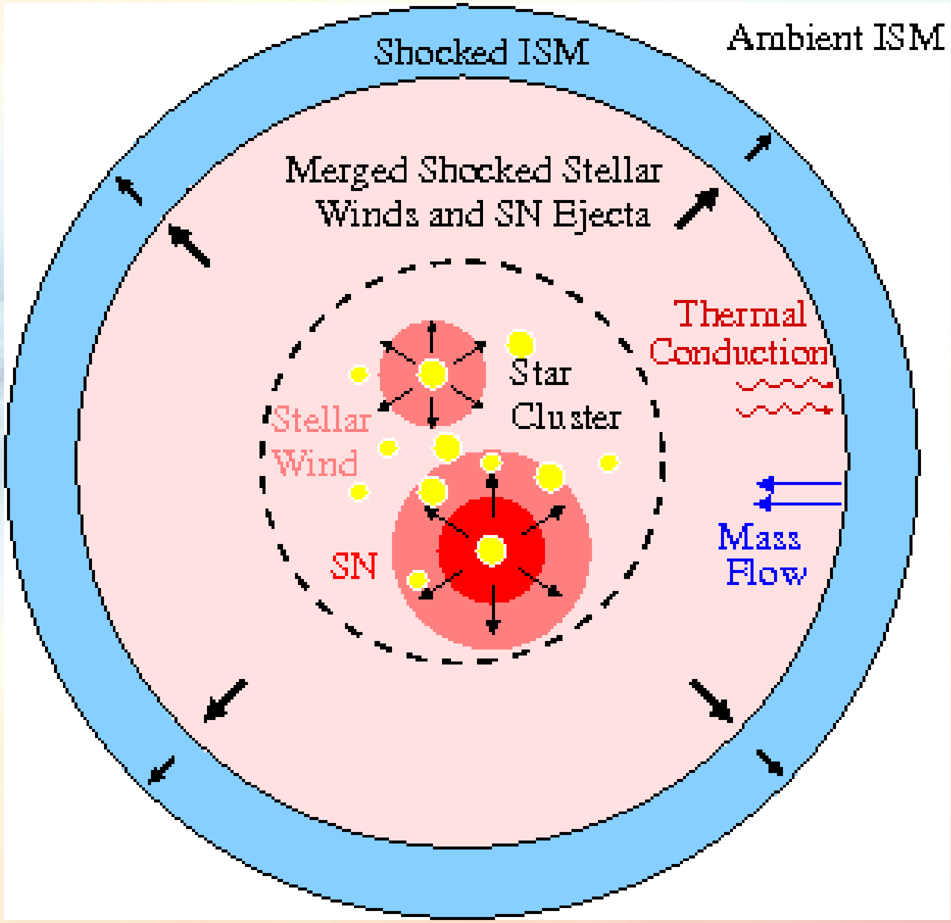
⇒ Stellar Feedback highly correlated

⇒ Natural unit of feedback is a superbubble combining feedback of 100+ massive stars

Super bubble features

Classic model:

- Stellar winds + supernovae shock and thermalize in bubble
- Negligible Sedov-phase
- Mechanical Luminosity $L=10^{34}$ erg/s/$M_{\odot}$
- Much more efficient than individual SN (e.g. Stinson 2006 Blastwave feedback model)



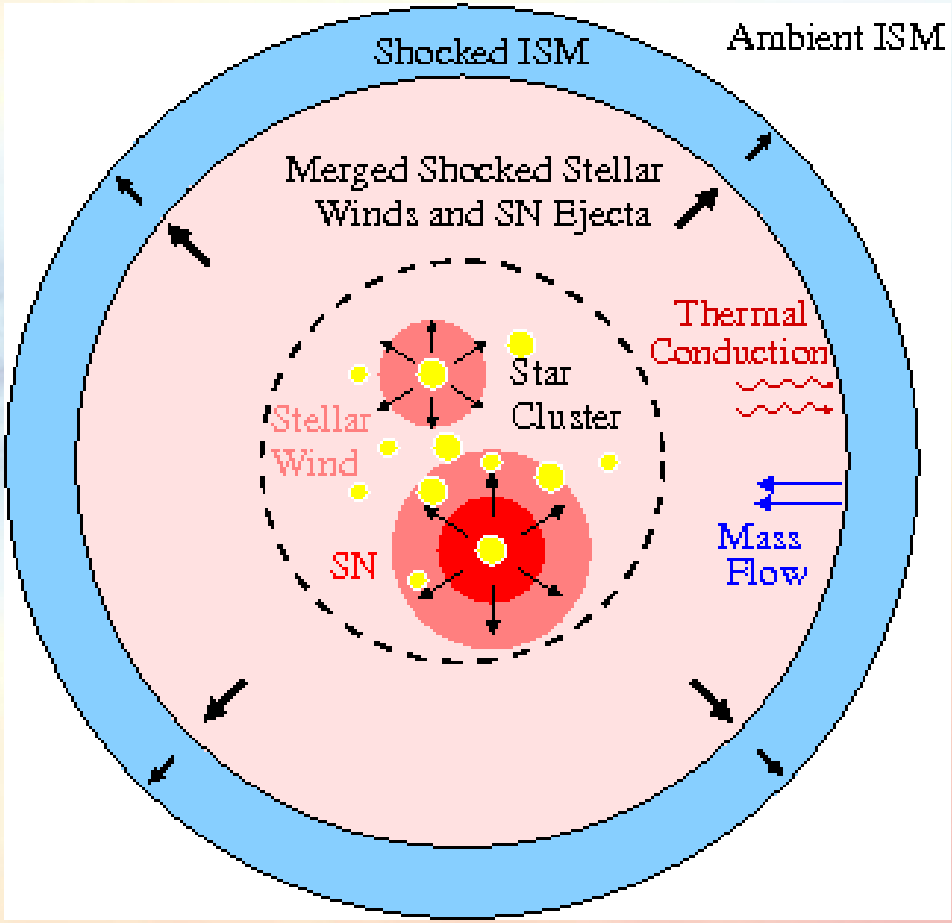
MacLow & McCray 1988, Weaver+ 1977, Silich+ 1996

Super bubble features

Limiting factor:

Radiative Cooling of bubble determined by bubble temperature ~ E_{th}/M_b and density M_b/R^3

Hot bubble mass (M_b) set by thermal conduction rate into bubble



MacLow & McCray 1988, Weaver+ 1977, Silich+ 1996

Modeling Superbubbles

1. Key physics: Thermal Conduction
   Without conduction bubble mass = ejecta mass
2. Evaporation resulting from conduction – hard to resolve directly
3. Low resolution, early bubble stages:

$M_b < M_{particle}$ – need to avoid overcooling

1. Thermal Conductivity

$$\frac{\partial E}{\partial t} = \nabla(\kappa_{Cond} \nabla T) \qquad \kappa_{Cond} = 6 \times 10^{-7} T^{5/2} \text{ (cgs)}$$

- Self regulating Energy flux ~ $T^{7/2}/R$ ($T > 10^5$ K)
- Flux limited by electron speeds (Cowie & McKee 1977)
- Note: κ reduced by 3-5 by Magnetic Fields
- For sharp temperature contrast, drives evaporative mass flux from cold into hot gas

2. Evaporation

- Evaporation front width < 0.1 pc !

Subgrid model:

- Based on MacLow & McCray 1988 rate estimate
- SPH implemention: Stochastically evaporate particles into hot bubble from cold shell
- Applied for $T > 10^5$ K particles
- Regulates bubble temperature

$$\frac{\partial M_b}{\partial t} = \frac{16 \pi\mu}{25 k_b} \kappa_0 T^{5/2}$$

3. Low Resolution : Subgrid Hot Phase

- For a poorly resolved bubble, $M_b < M_{particle}$ for the early stages
- Temporary 2-phase particle while injection/conduction grows mass of bubble phase
- No numerical/resolution related overcooling
- Feedback-heated particles briefly contain 2 phases in pressure equilibrium, with separate densities and temperatures
  - Each cools independently.

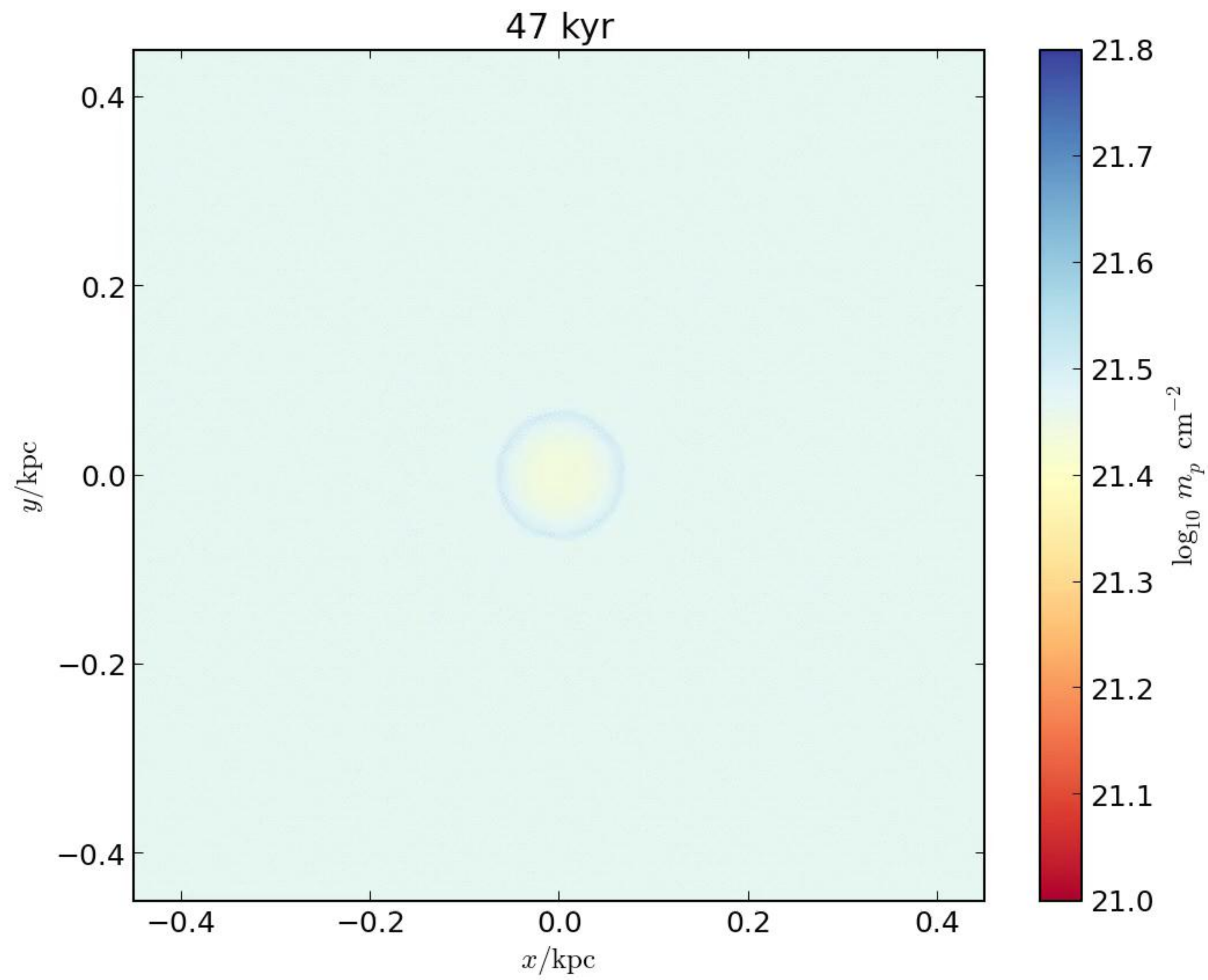
Implementation:

Gasoline

- N-body Solver (Tree Method) and Smoothed Particle Hydrodynamics
- Physics: Gravity, Hydrodynamics, Atomic Chemistry (Radiative Heating, Cooling), Radiative Transfer (Woods et al, in prep)
- Subgrid Physics: Star Formation, Turbulent Diffusion

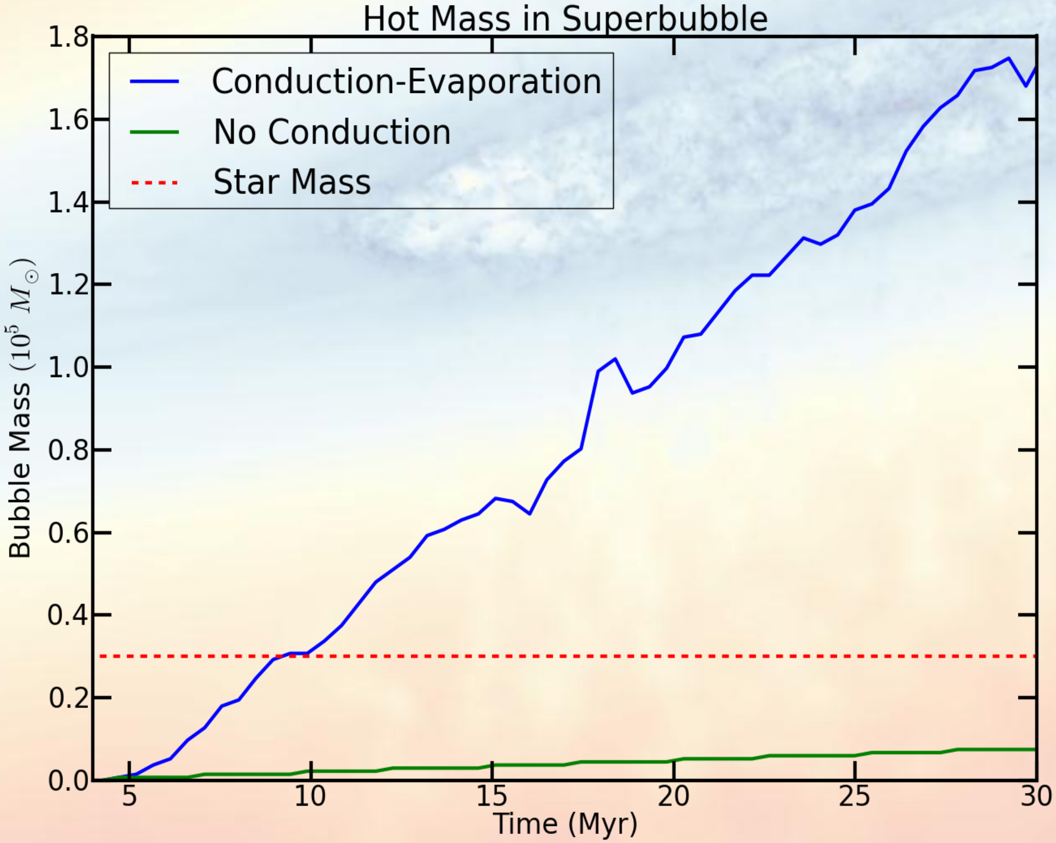
Wadsley+ 2004

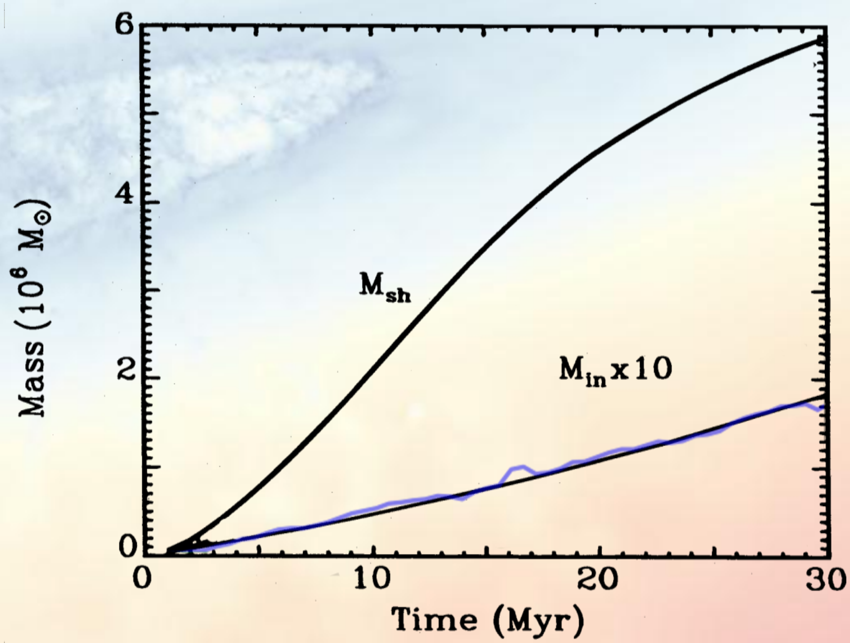
High Resolution Superbubble Simulation



Mass loading

- Bubble mass, temperature regulated:



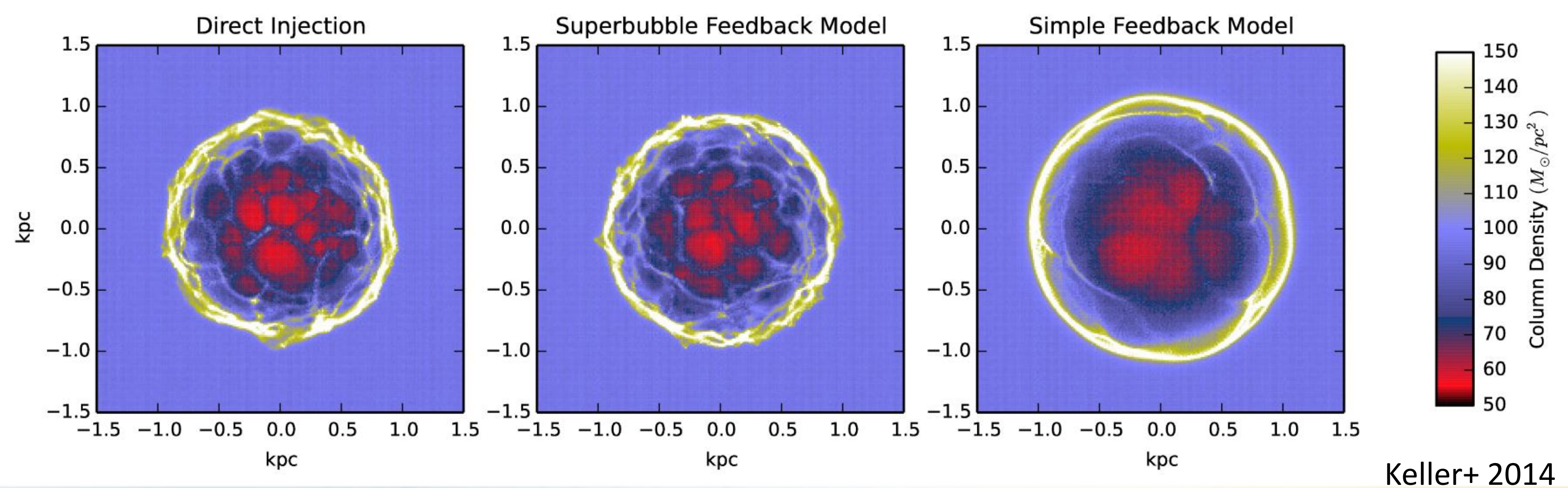


Match Silich+ 1996

Mass loading

For 3×10^{38} erg/s Feedback

Test 30,000 $M_\odot$ cluster: 3 cases



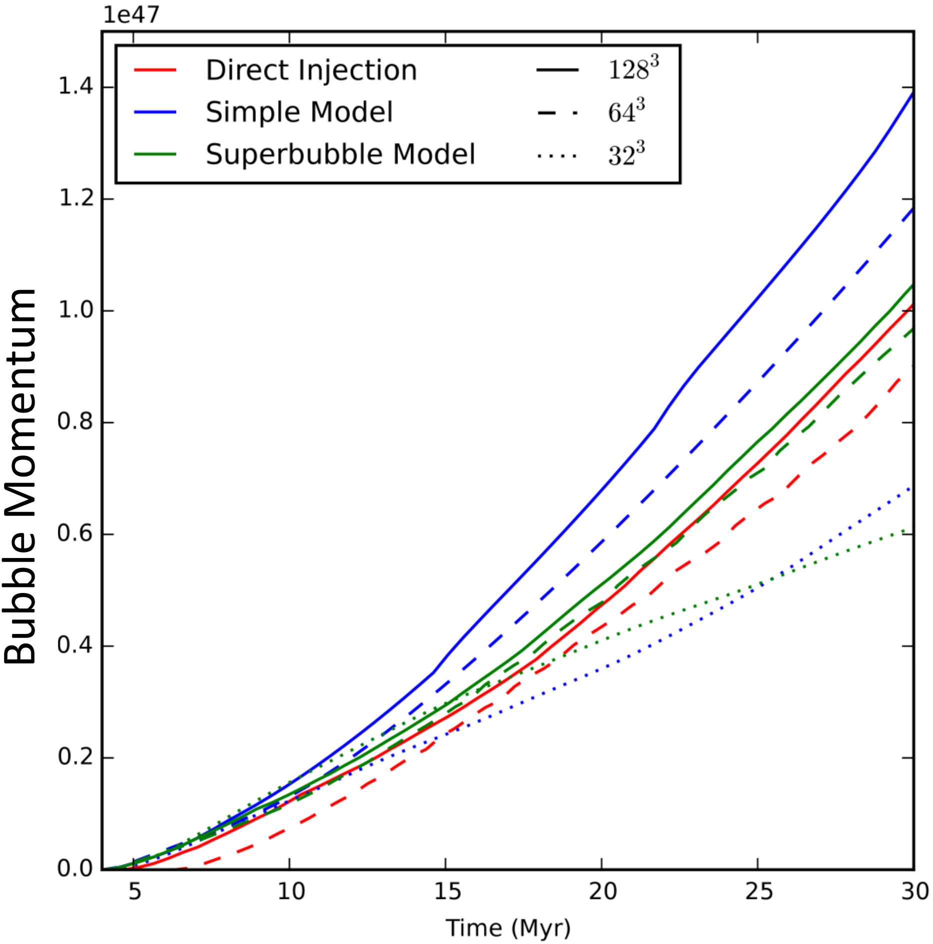
Keller+ 2014

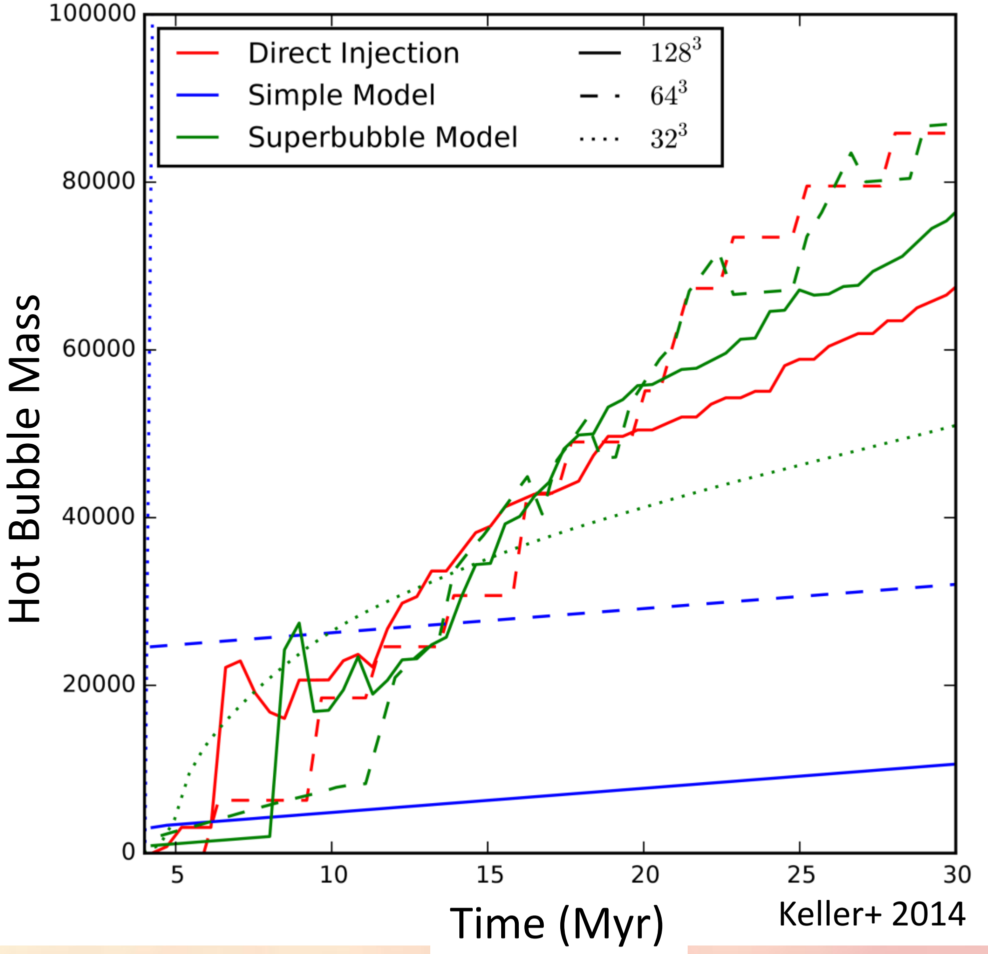
Direct Injection: Resolved stellar ejecta mass, no subgrid required ($M_{particle}$=760 $M_\odot$ at 128^3), conduction + evaporation

Superbubble: conduction, evaporation + subgrid

Simple Feedback: A non-cooling phase with conversion time 5 Myr to cooling form (cf. Agertz+ 2013)

Bubble Momentum + Hot Mass





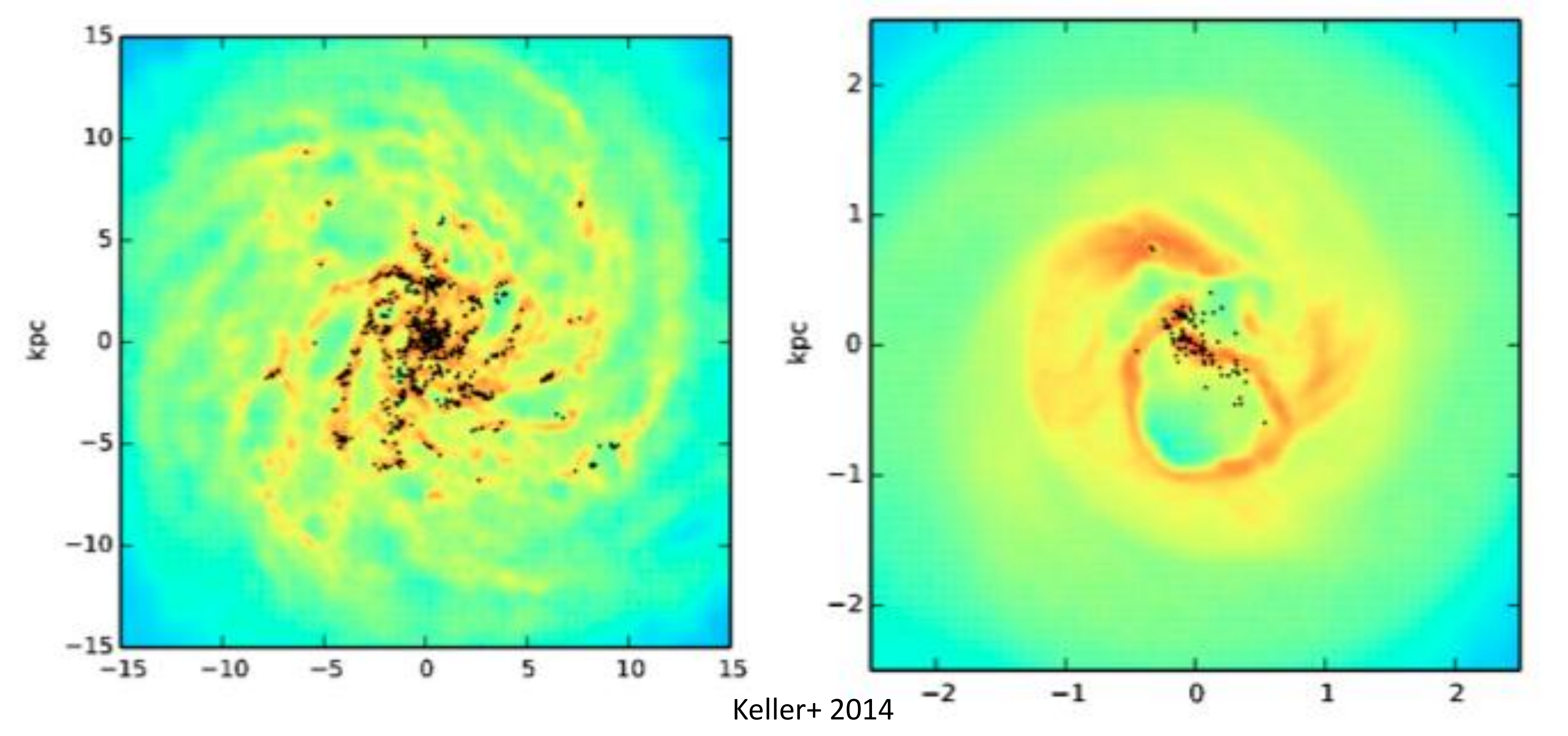
Keller+ 2014

- Simple Model resolution sensitive
- Superbubble Model still works with a 1 particle bubble (32^3 case)

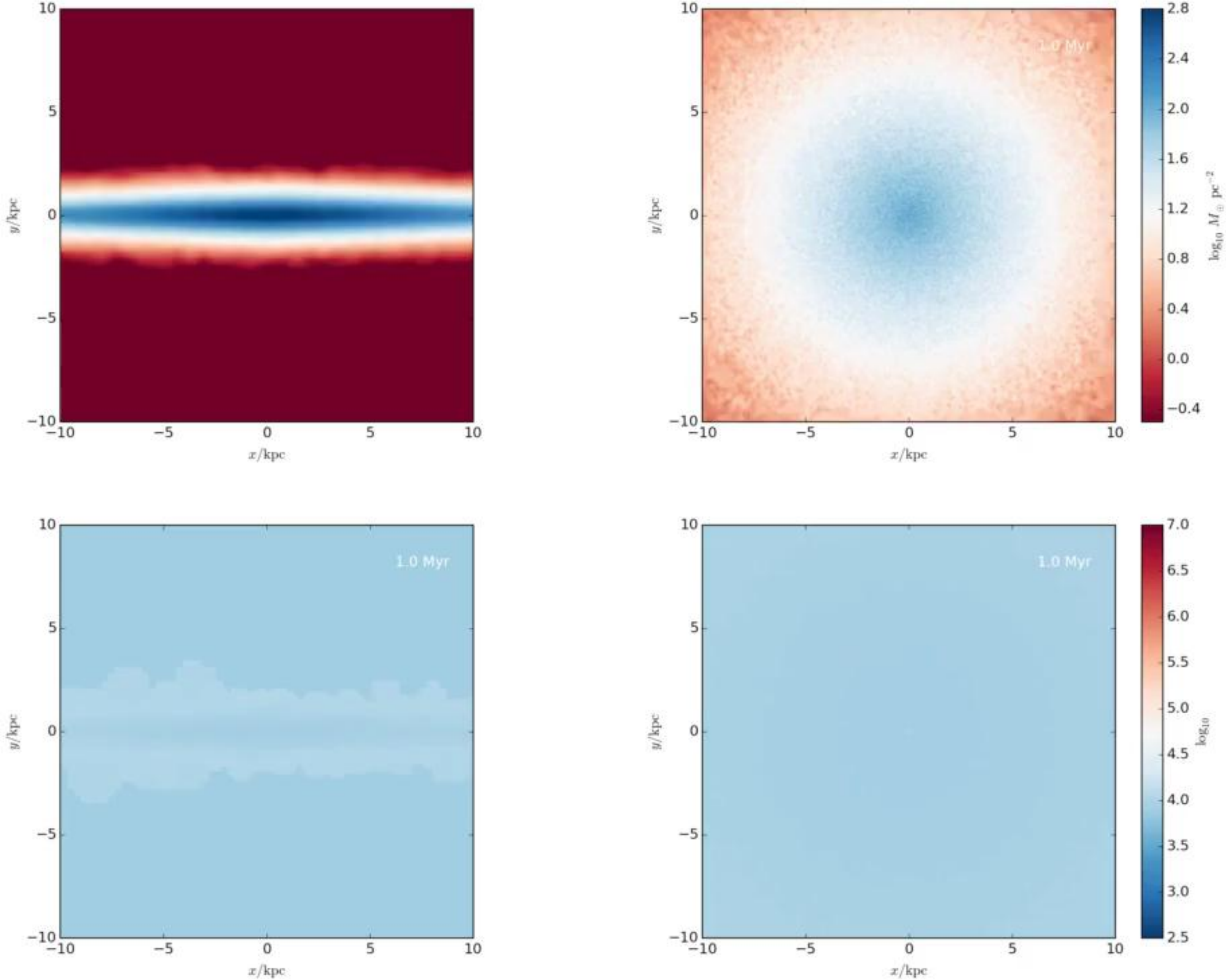
Galaxy Tests

Similar to Dalla Vecchia & Schaye (2012) --

MW analogue ($M_{gas} \sim 10^9\ M_\odot$ $N_{gas} = 10^5$) & Dwarf



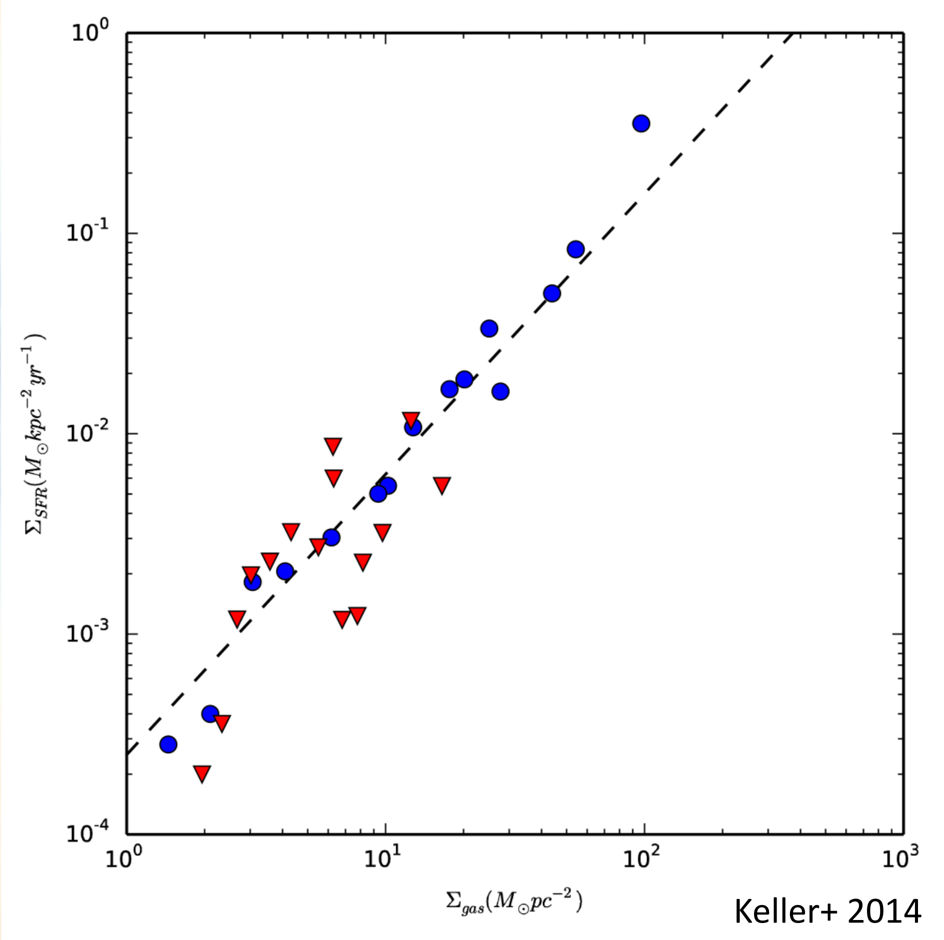
Keller+ 2014



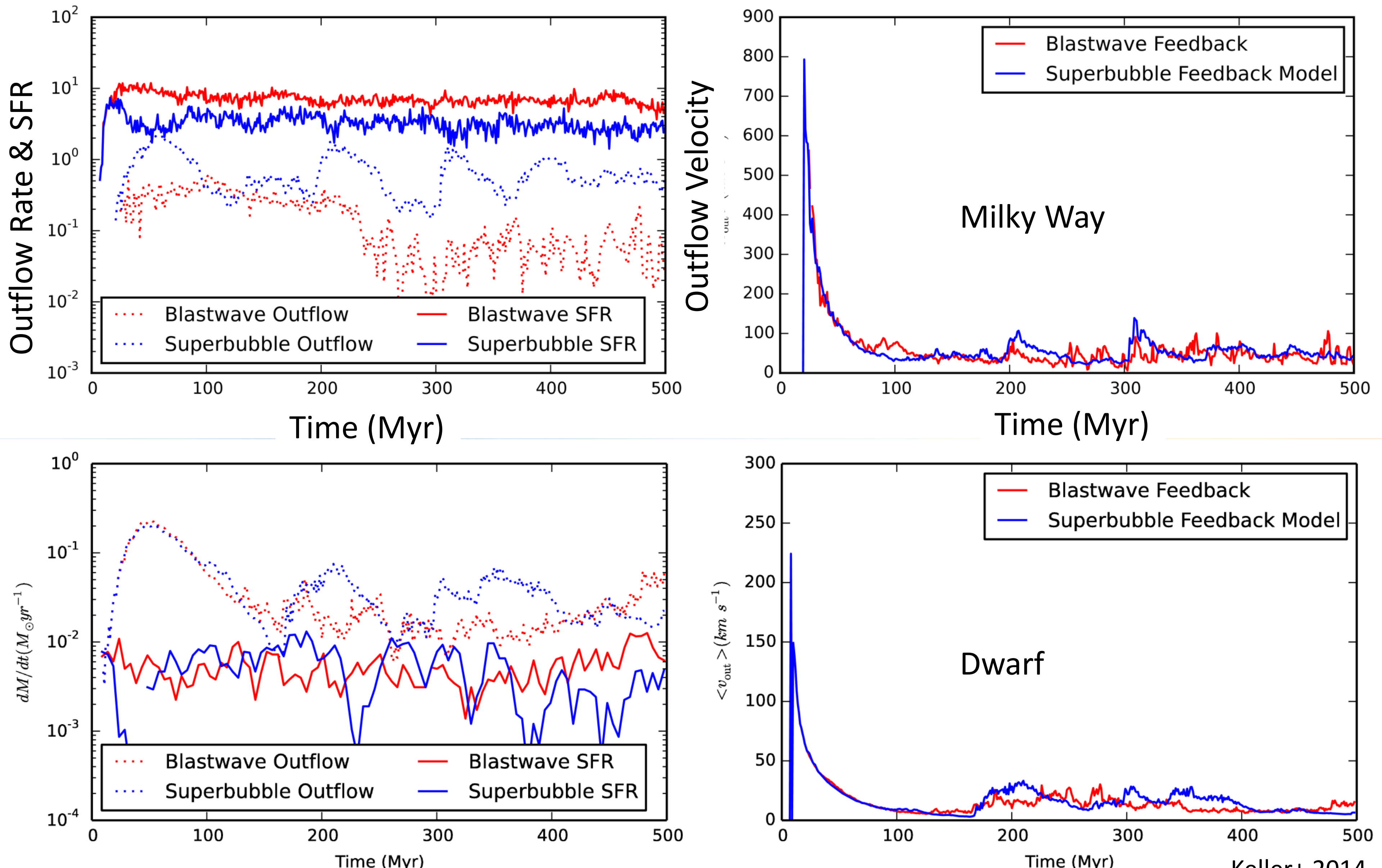
1.0 Myr
1.0 Myr
1.0 Myr
1.0 Myr
$\log_{10} M_\odot\ \mathrm{pc}^{-2}$
$\log_{10}$
x/kpc
y/kpc

MW & Dwarf Star Formation

- Star formation rates regulated. Bursty as expected in dwarf
- Higher mass loading
- Outflow evolution similar to Dalla Vecchia & Schaye 2012
- Note: dwarf has low surface density
- Kennicutt-Schmidt law matched

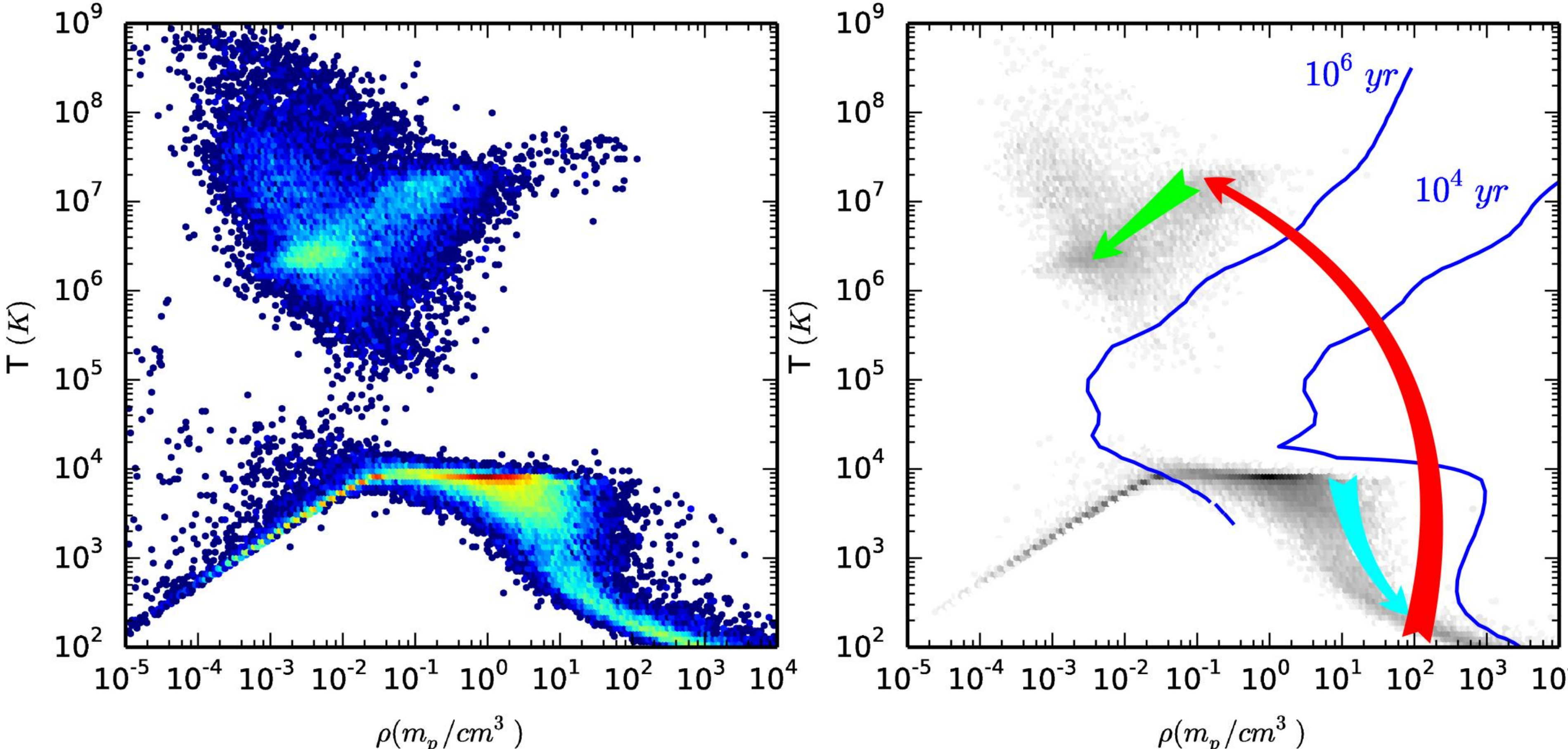


Galaxies: SFR & Outflows



Keller+ 2014

Temperature-Density Phase space



Keller+ 2014

Particles split into cold dense + hot rarefied phases

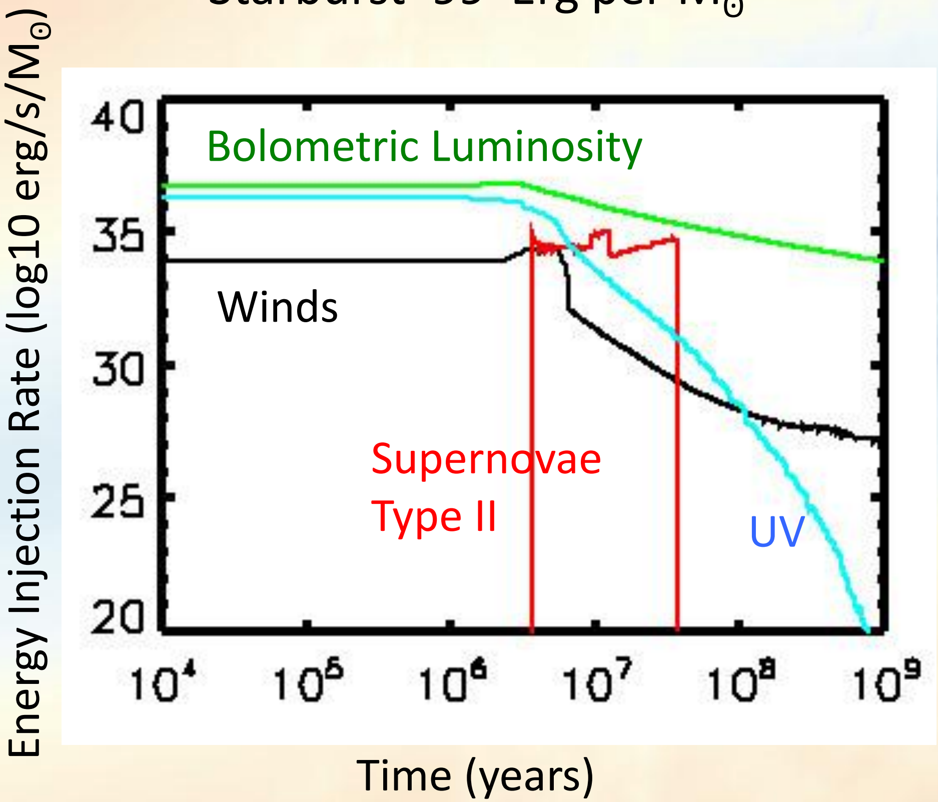
Rapidly become hot, single phase – evolve adiabatically

Summary

- Superbubble is relevant scale for stellar feedback in galaxies
- Thermal conduction is dominant physical process in superbubble evolution
- Taking this into account gives you a powerful model for feedback:
  - Separating Cold & Hot phases in unresolved superbubble prevents overcooling
  - Feedback can be continuous, multi-source
  - Feedback gas doesn't persist in unphysical phases
  - Star formation is strongly regulated, winds are driven with realistic mass loadings
- Read the Paper:
  - astro-ph/1405.2625 (Accepted MNRAS)
  - Keller, Wadsley, Benincasa & Couchman 2014

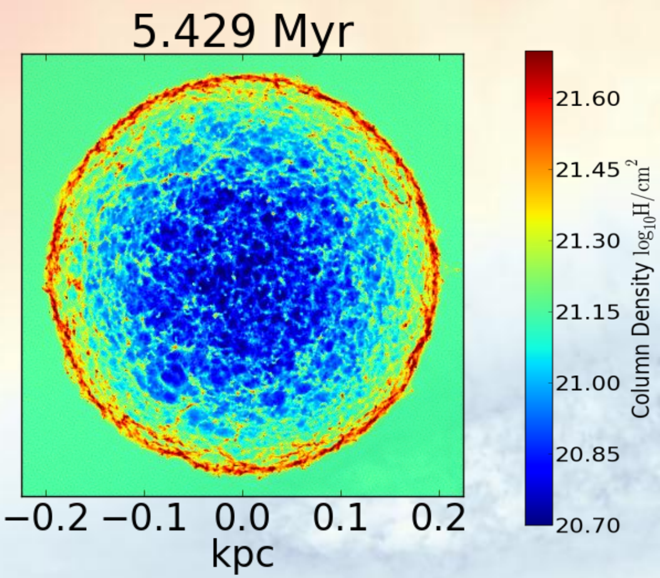
Stellar Feedback Budget

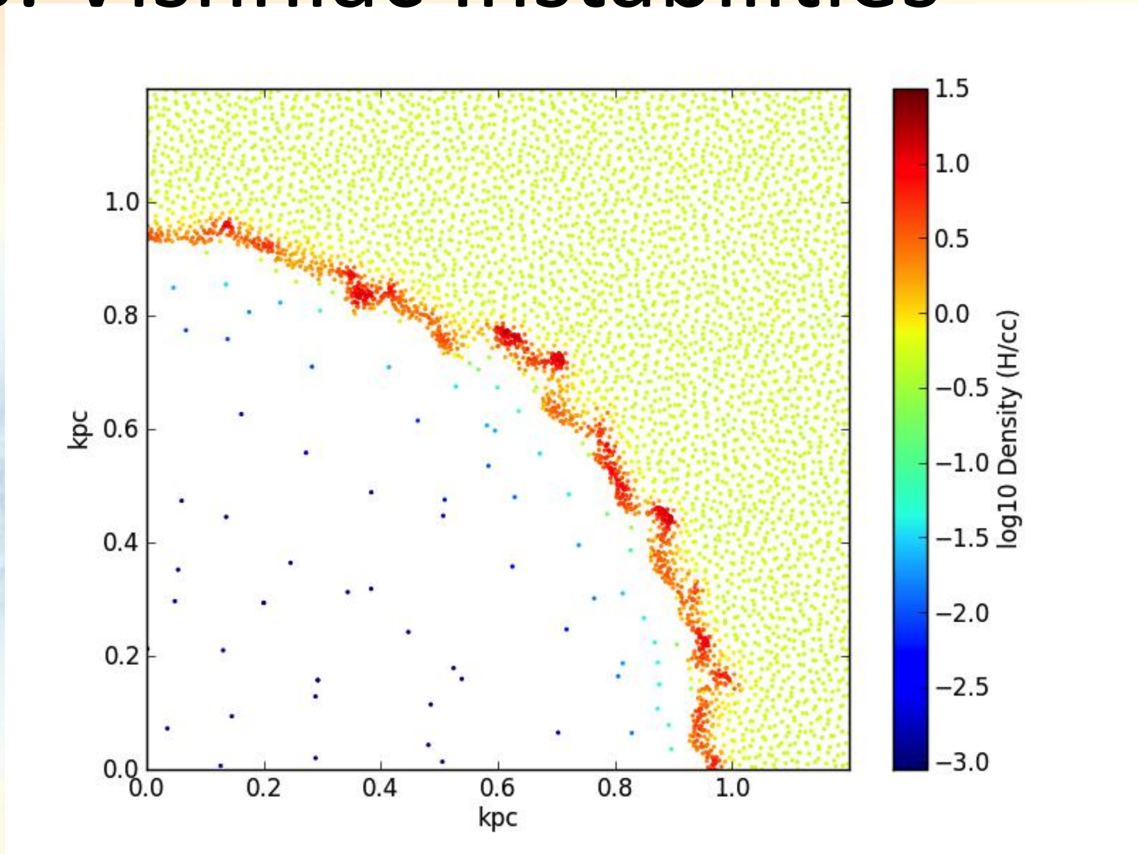
Starburst '99 Erg per $M_{\odot}$

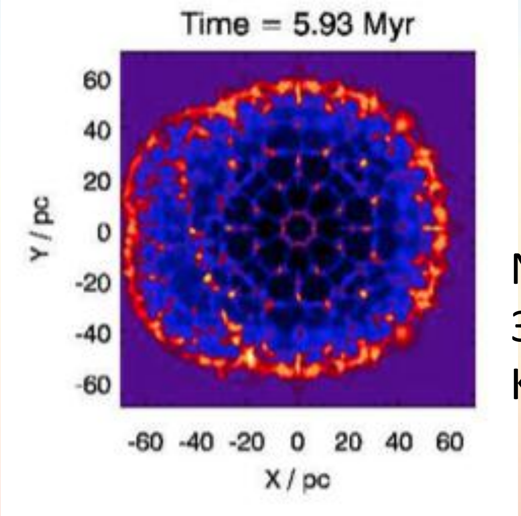


- UV & Radiation pressure disrupt dense clouds
  - Denser gas (>10^4 H/cc) dispersed, star formation cut off
- SN_{II} and stellar winds
  Steady 10^{34} erg/s/$M_{\odot}$
  for ~ 40 Myr

Super bubbles: Vishniac Instabilities







Nirvana simulations
3 star bubble
Krause et al 2013

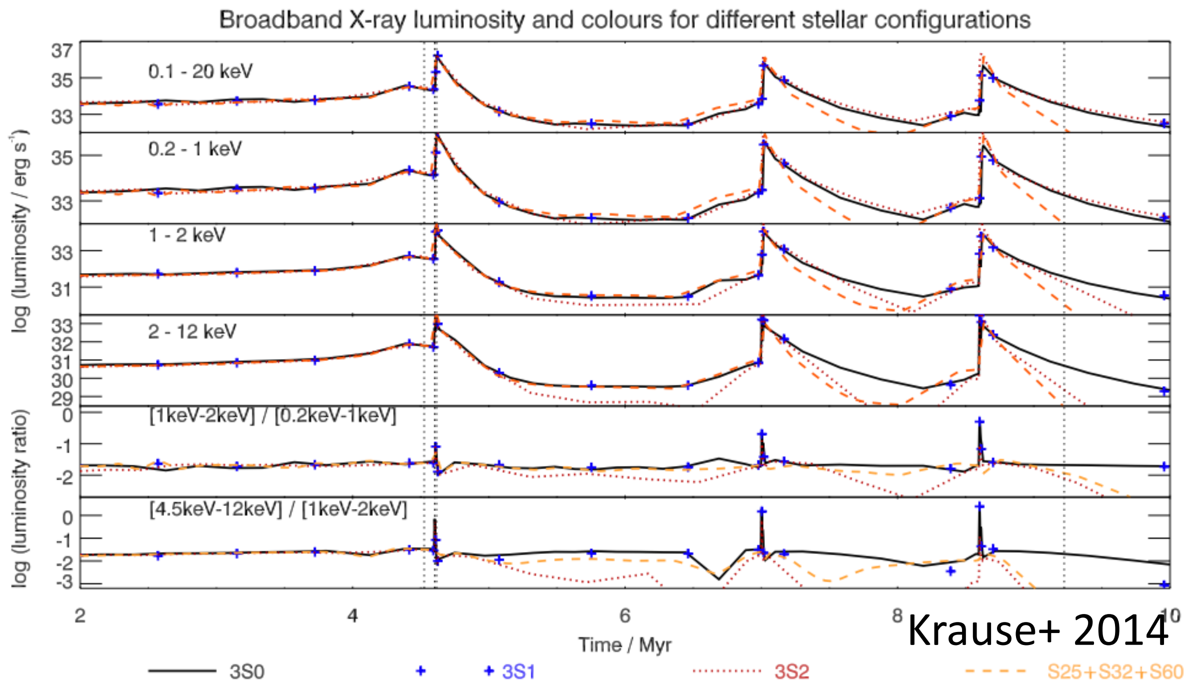
Theory: Vishniac 1983
Sims: McLeod & Whitworth 2013,
Nayakshin+ 2012 (AGN)

Super bubbles: X-Ray Observations

Table 1. Physical Properties of Hot Gas in Bubble Interiors

Bubble Type	T_e [10^6 K]	N_e [cm^{-3}]	L_X [erg s^{-1}]
Orion Bubble	2	0.2–0.5	5×10^{31}
WR Bubble	1–2	1	$10^{33} - 10^{34}$
M17 Superbubble	1.5, 7	0.3	3.4×10^{33}
Planetary Nebula	2–3	100	$10^{31} - 10^{32}$

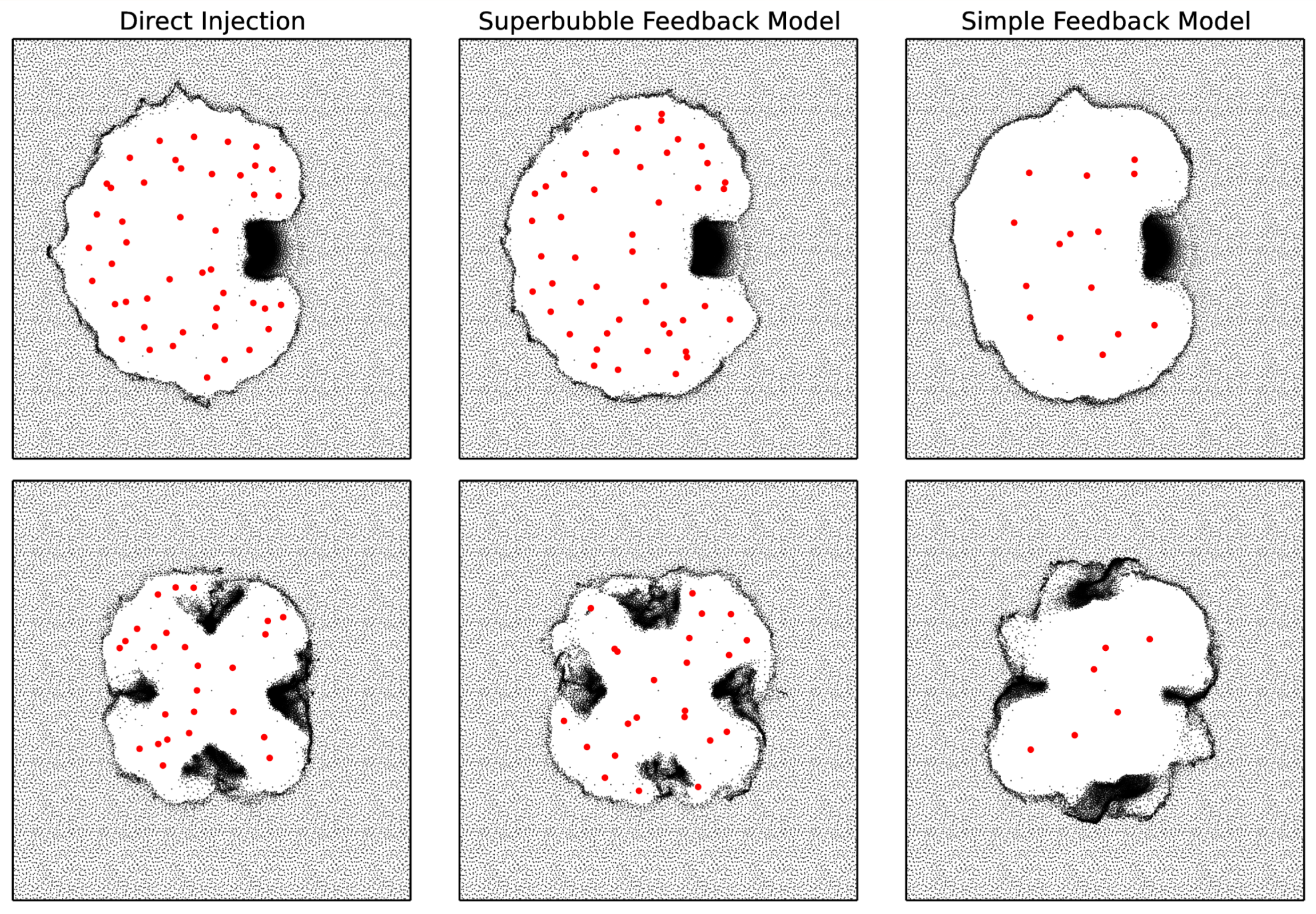
Chu 2008



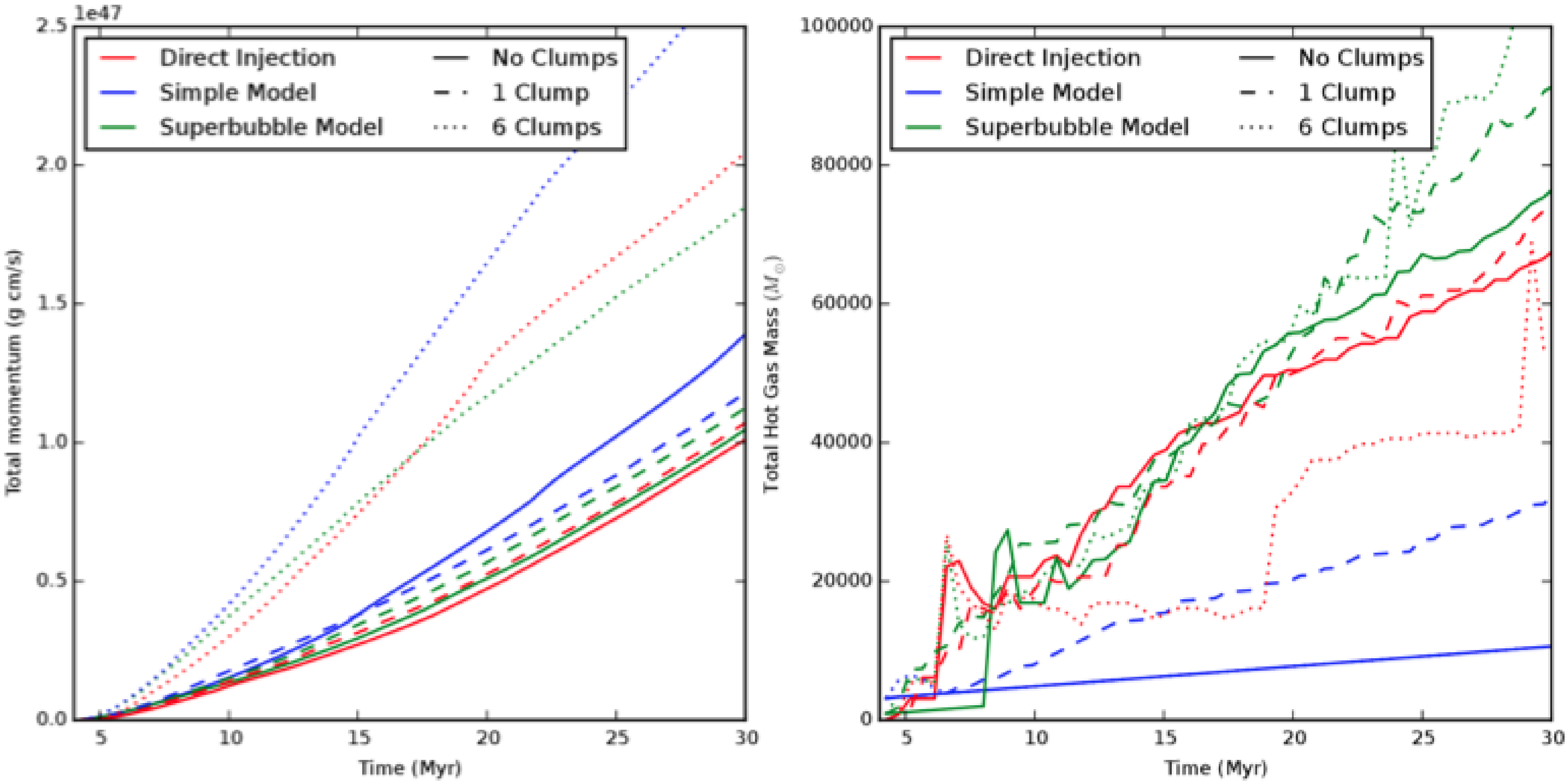
Krause+ 2014

- X-Ray luminosity highly variable over space, time
- Very few observations, large scatter in observed L_X
- Leaking of interior, B-field amplification in shell may explain some reduced luminosities (see Rosen+ 2014)

Clumpy medium



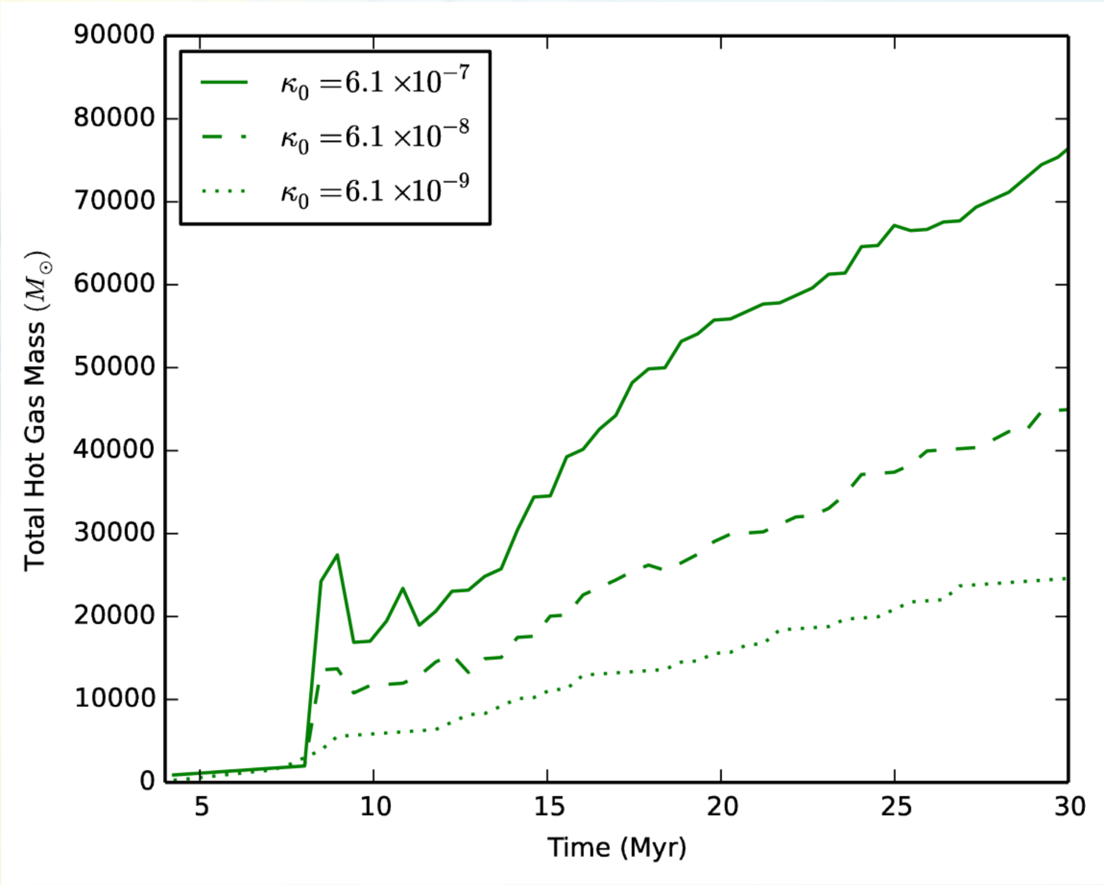
Clumpy Medium



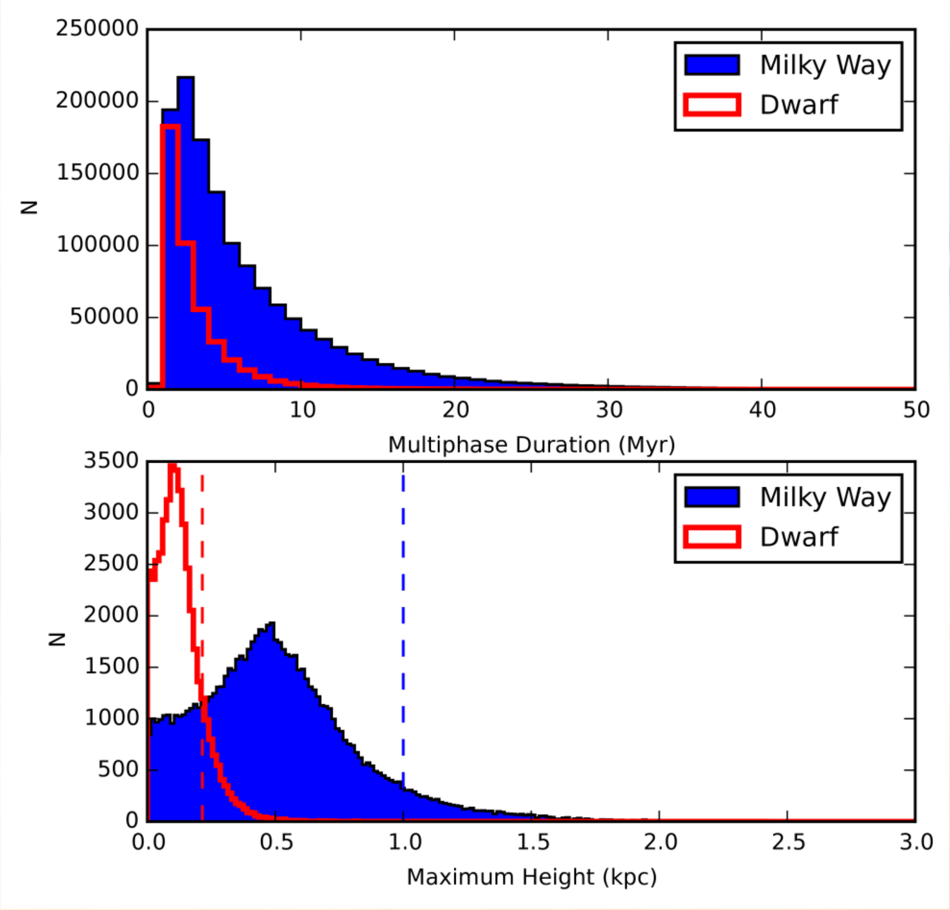
- Some changes in bubble mass/momentum
- Agreement with direct model still good

Reduced Conduction & Magnetic Fields

- Conduction suppressed across magnetic field lines
- 100x reduction in conduction rate κ_0 results in only factor of ~2 reduction in M_b



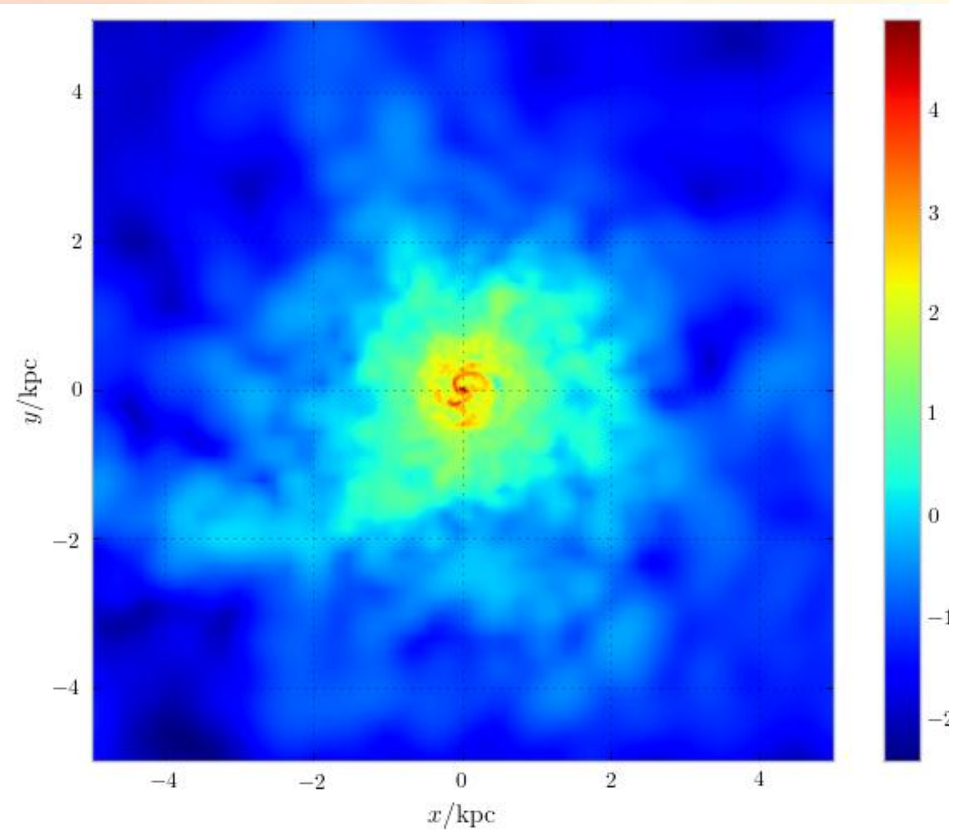
Multiphase Properties

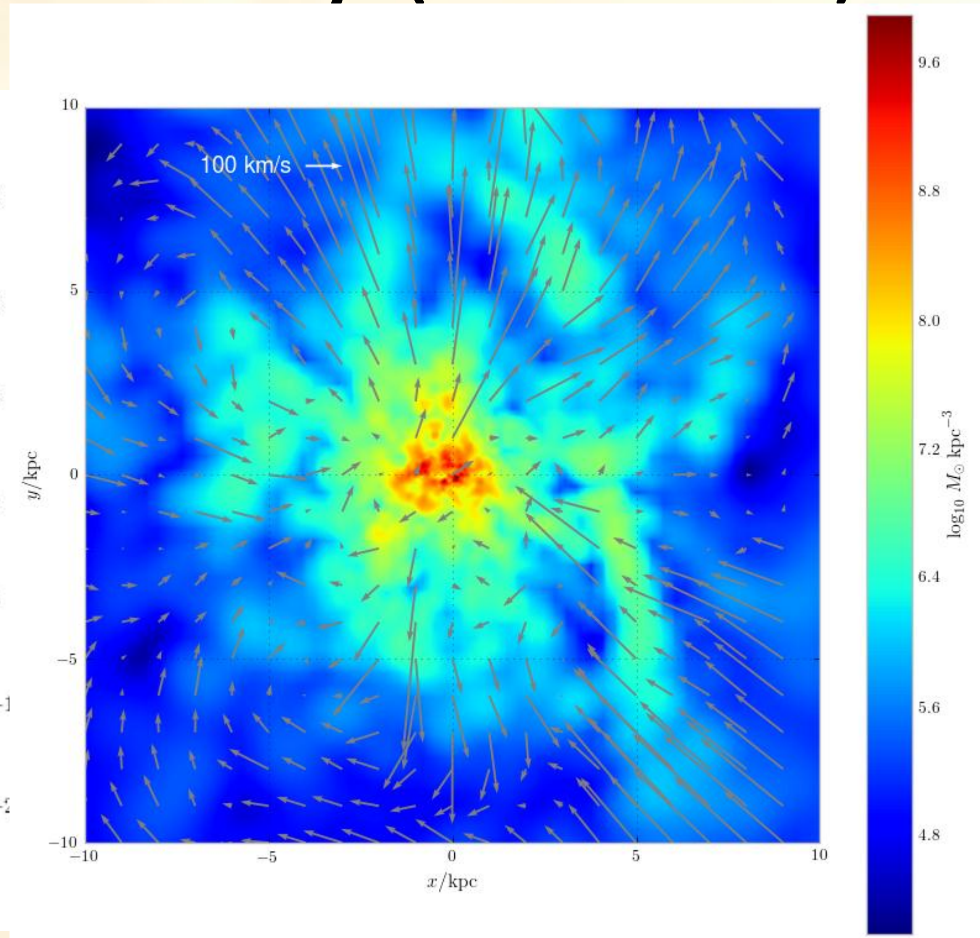


- Median time as mixed-phase particle < 5 Myr

Coming
Soon…

Cosmological Galaxy (now z=2)





- ~ 10^{11} Msun halo
- So far on track for reasonable M_*