Stellar Feedback and Galaxy Formation: Issues and Non-issues

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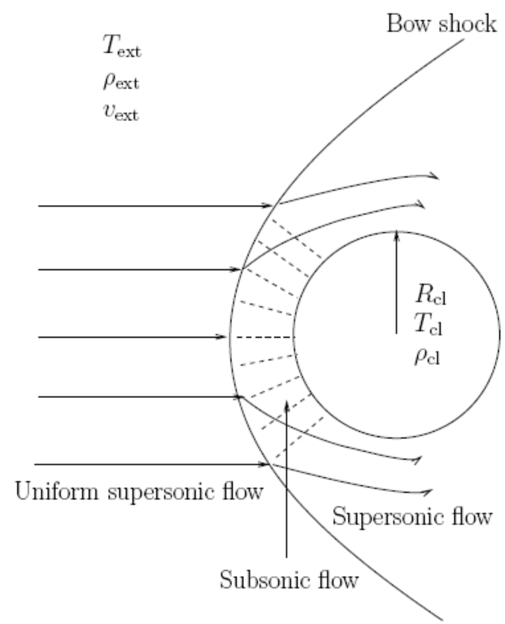
Ben Keller (McMaster), Tom Quinn (Washington)

Test

Agertz et al 2007

Code comparison paper from the proto AstroSim conference (2004)



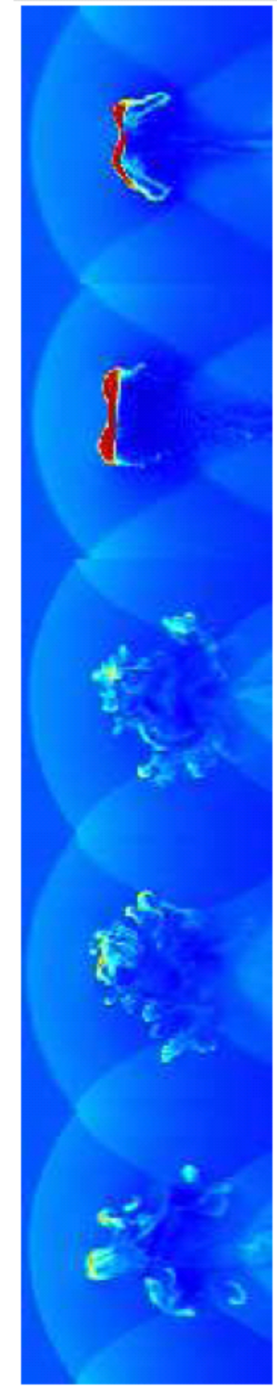
Gasoline (Wadsley, Stadel & Quinn 2004)

Gadget (Springel)

FLASH

ENZO

ART

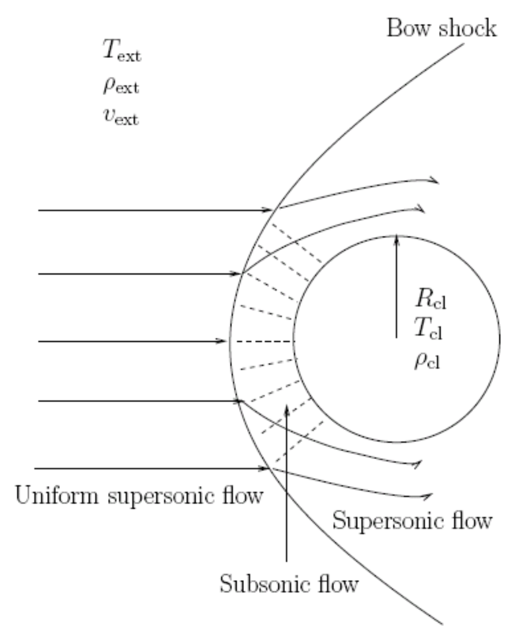


Test

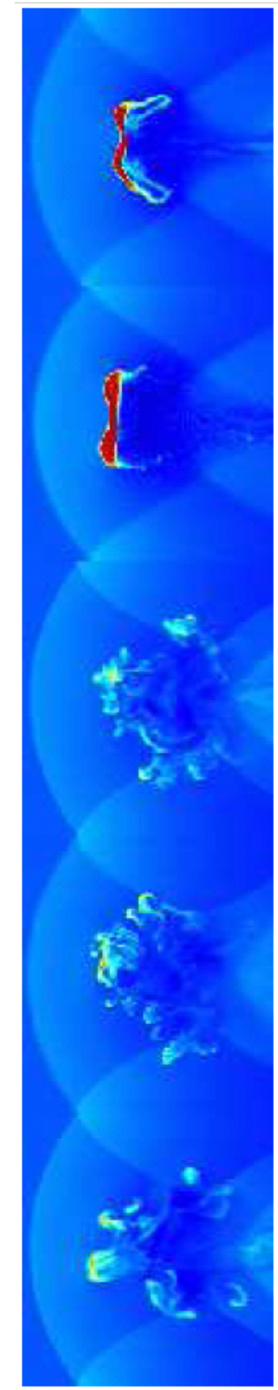
SPH
Smoothed Particle Hydrodynamics (Monaghan 1992, Springel & Hernquist 2002)

Agertz et al 2007

Code comparison paper from the proto AstroSim conference (2004)



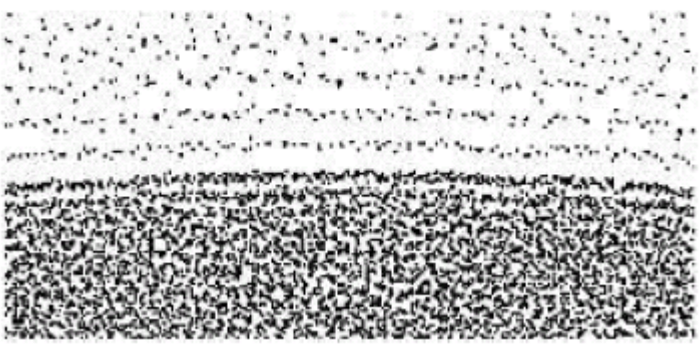
PPM
Piecewise Parabolic Method (Collela & Woodward 1987)



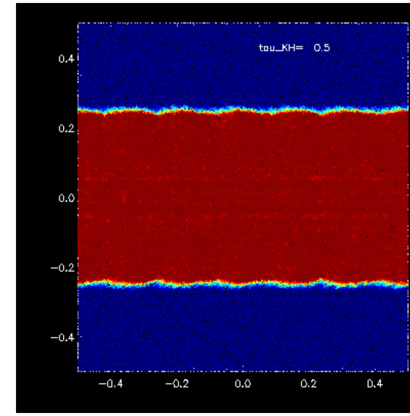
Agertz et al (2007) Basic Result: SPH blobs don't break up

Immediate SPH issue: Surface Tension present in arithmetic sum Pressure force (e.g. Monaghan 1992, Gadget 2, …)

Suppresses Kelvin Helmholtz instabilities

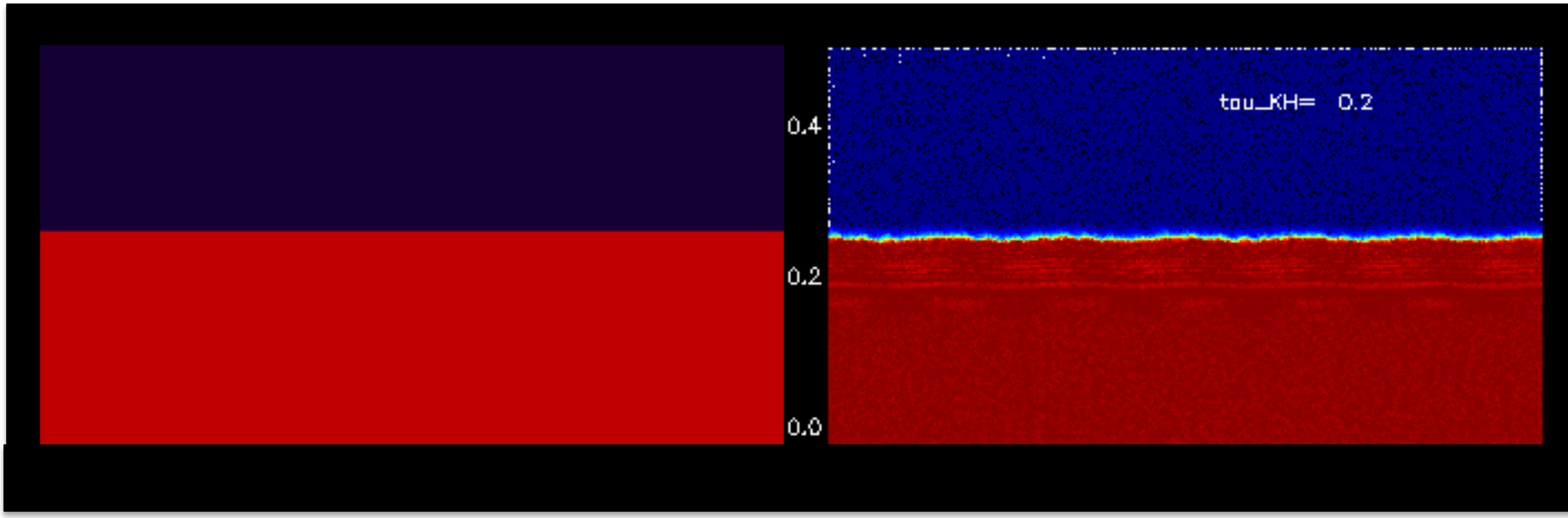


SPH Kelvin Helmholtz fixes



- Ritchie & Thomas (2001) – smooth pressure not density and Geometric Density Average in Force: remove surface tension (pressure errors at density jump)
- Price (2008) – smear density jumps
- Read, Hayfield & Agertz (2010), Read & Hayfield (2011), Abel (2011), Murante et al (2011) … modified SPH
- Pressure-Entropy SPH (Hopkins 2013)

1:10 Kelvin Helmholtz test



Athena 256^2

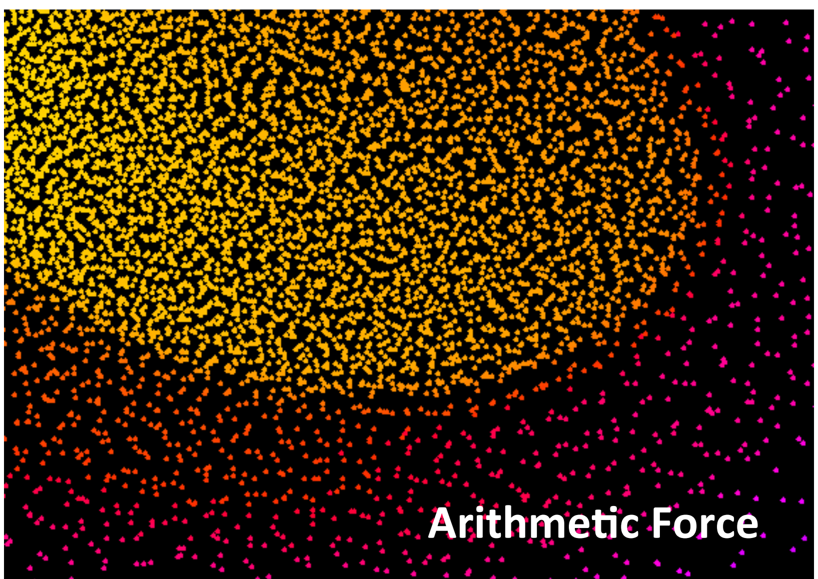
Gasoline 256x256x32

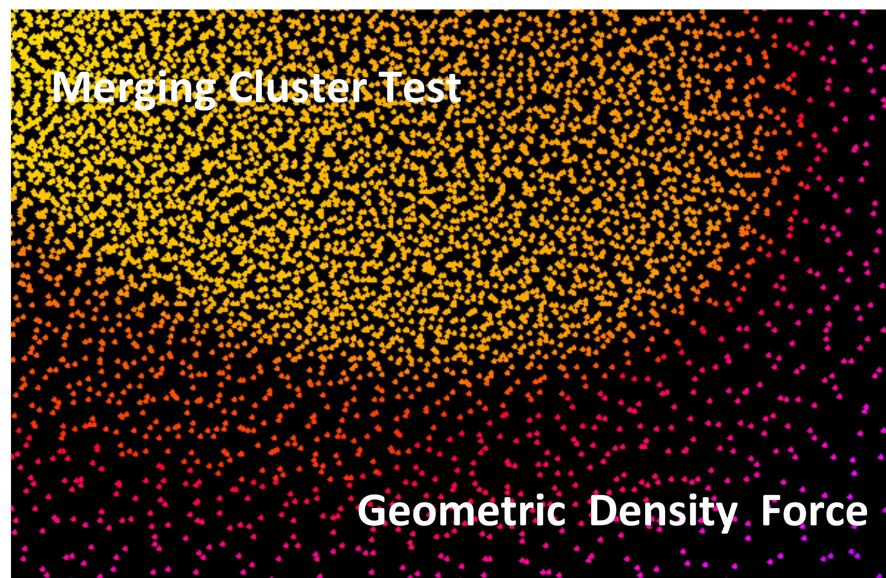
Common element in relieving SPH surface tension:

- Geometric Density Average in Force (GD Force):

$$\frac{dv_a}{dt} = -\sum_b m_b \left(\frac{P_a + P_b}{\rho_a \rho_b} \right) \nabla_a W_{ab}$$

Morris (1996), Monaghan (1992)
Ritchie and Thomas (2001),
Can be derived from a Lagrangian:
Monaghan & Rafiee (2012)
see also Abel (2011), Hopkins (2013)





Is removing surface tension enough?

Blob Test in Entropy ($T^{3/2}/\rho$)

Hi-Res
ENZO

Hi-Res
Old
SPH

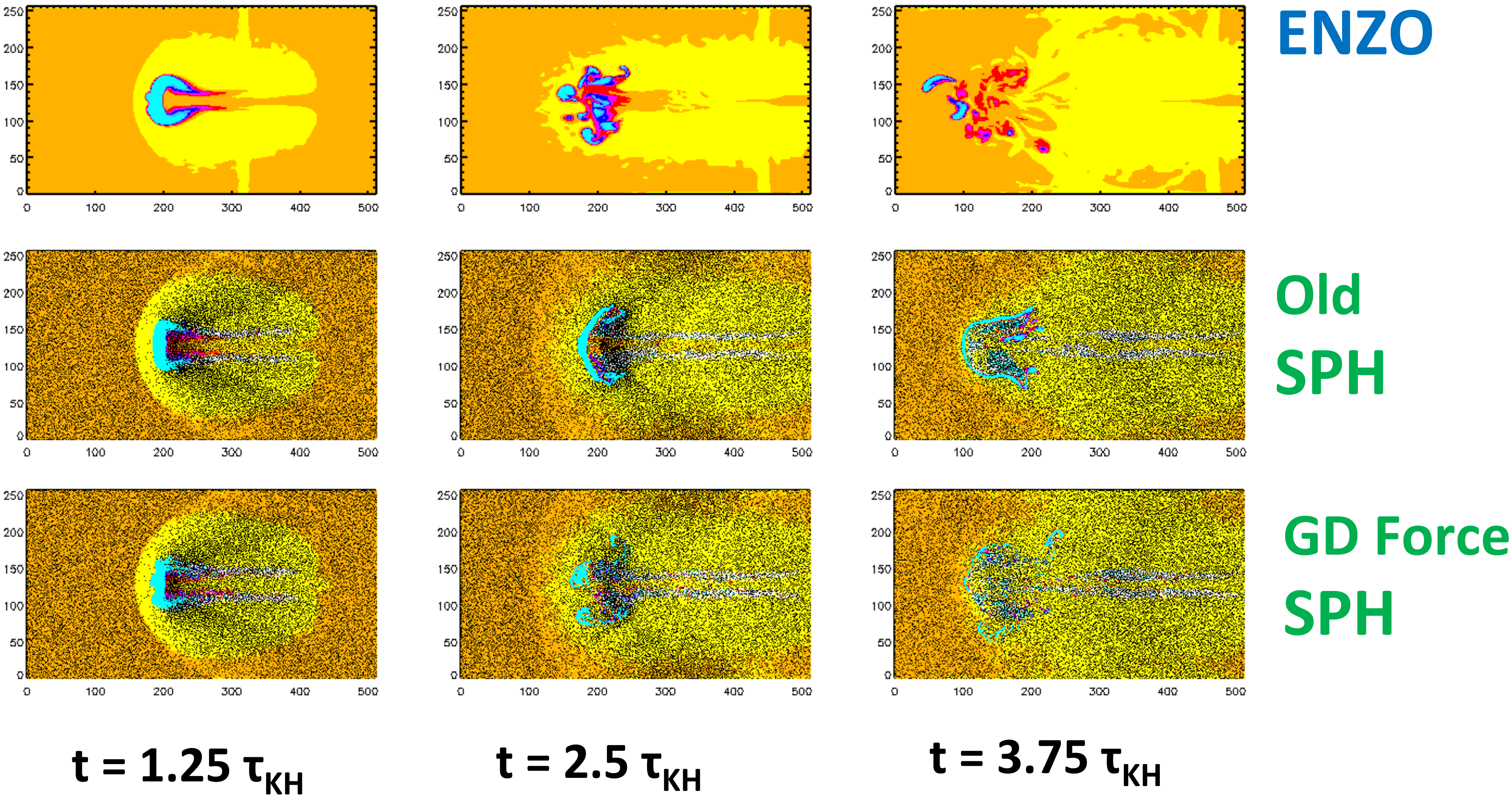
Is removing surface tension enough? No

Blob Test in Entropy ($T^{3/2}/\rho$)

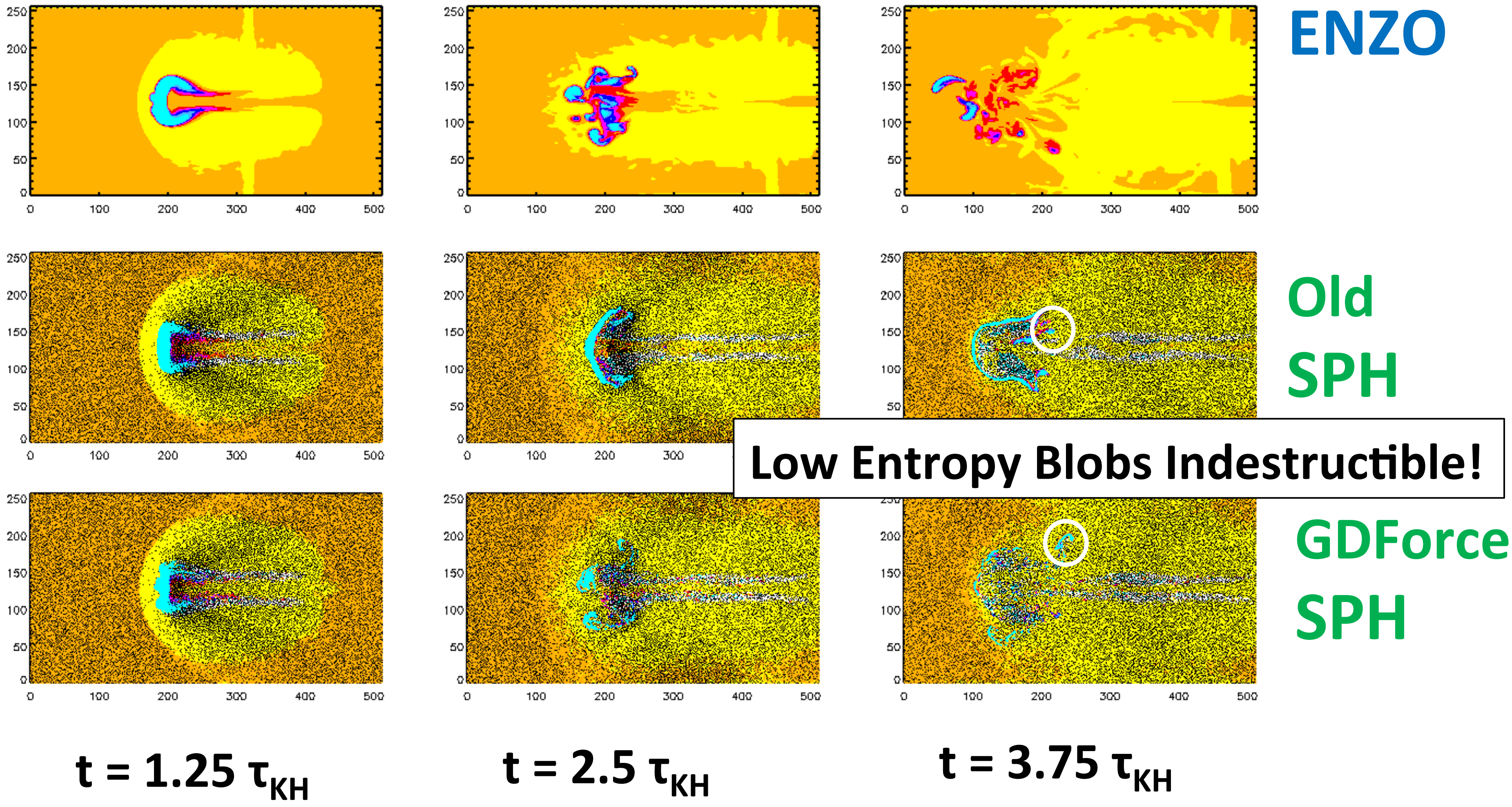
Hi-Res
ENZO

Hi-Res
GD Force
SPH

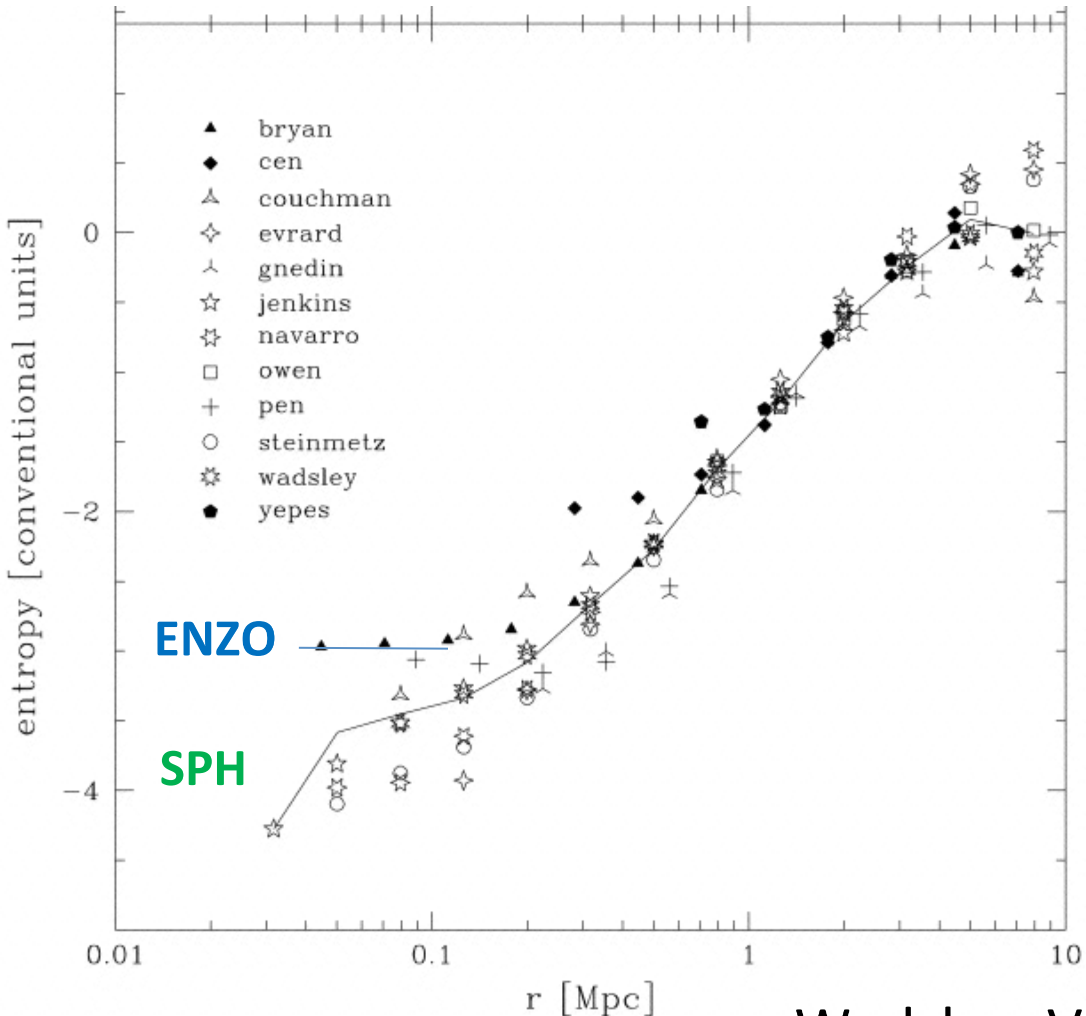
Blob Test in Entropy ($T^{3/2}/\rho$)



Blob Test in Entropy ($T^{3/2}/\rho$)



The second issue: Mixing

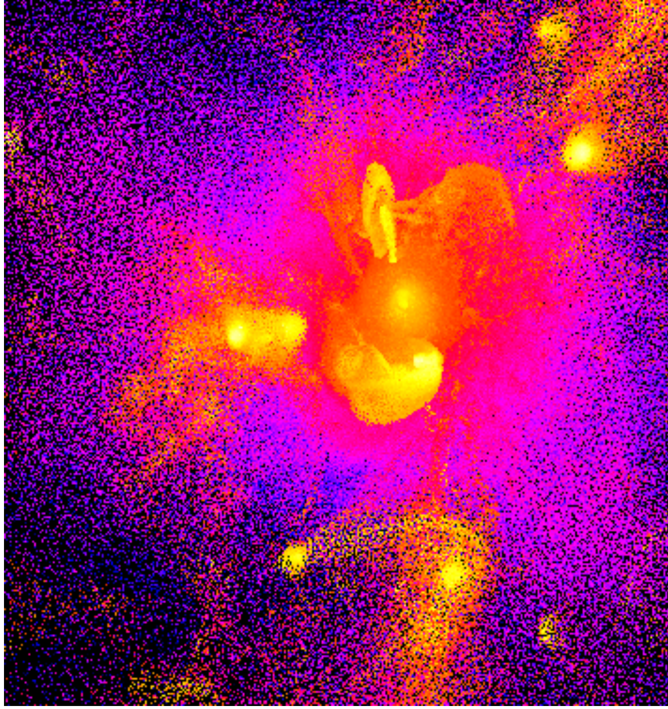


Cluster Comparison (Frenk et al 1999)

Grid codes have entropy cores, SPH codes didn't (because they didn't mix)

Wadsley, Veeravalli & Couchman (2008)

How to get entropy cores?



- Shocks (while c_s<v)
- Mix hot & cold cluster gas

SPH can't:

$$\frac{du}{dt} = -(\gamma - 1)\,u(\nabla.\mathrm{v}) \Rightarrow A(s) = \frac{P}{\rho^{\gamma}} = \begin{array}{c} const. \\ following\ flow \end{array}$$

Eulerian codes can (accidentally):

$$\frac{\partial u}{\partial t} + \mathrm{v}.\nabla u + \begin{array}{c} advection \\ errors \end{array} = -(\gamma - 1)\,u(\nabla.\mathrm{v})$$

Subgrid Turbulent Mixing

- Fluid elements on a fixed (resolved) physical scale do exchange energy/entropy due to unresolved (turbulent) motions

Turbulent diffusive heat flux

$$\frac{\partial u}{\partial t} + \mathrm{v}.\nabla u = -(\gamma - 1)\, u(\nabla.\mathrm{v}) \quad \text{goes to}$$

$$\frac{\partial \bar{u}}{\partial t} + \bar{\mathrm{v}}.\nabla \bar{u} + \overline{\delta\mathrm{v}.\nabla\,\delta u} = -(\gamma - 1)\left(\bar{u}(\nabla.\bar{\mathrm{v}}) + \overline{\delta u(\nabla.\delta\mathrm{v})}\right)$$

where $\bar{a}$ = resolved (filtered) part of field a,

δa = unresolved part, $\overline{\delta a} = 0$

Turbulent diffusion

- Lowest-order turbulent diffusion model:

$$\frac{\partial \bar{u}}{\partial t} + \bar{\mathrm{v}}.\nabla \bar{u} = -(\gamma - 1)\bar{u}(\nabla.\bar{\mathrm{v}}) + \nabla \kappa_{\mathrm{Turb}} \nabla \bar{u}$$

κ_{Turb} has units of velocity x length

Smagorinksy model (1963): $\kappa_{Turb} = l_S{}^2 S,\ S = \sqrt{S_{ij} S_{ij}}$

S_{ij} = strain tensor of resolved flow, l_S Smagorinsky length

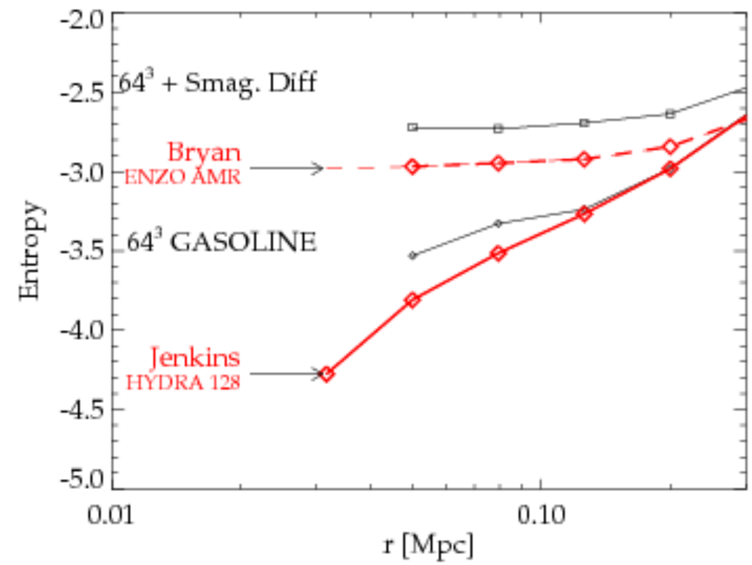
Incompressible grid models set $l_s{}^2 \sim 0.02\ \Delta x^2$ (Lilly 1967)

For SPH we can use $\kappa_{\mathrm{Turb}} = C\ h^2\ S$ $\quad C \sim 0.01\text{-}0.1$

Wadsley, Veeravalli & Couchman (2008)
Shen, Wadsley & Stinson (2010)

Turbulent diffusion

- Cluster Entropy Cores occur in SPH when thermal diffusion included
- Need: Galilean invariance, correct Prandtl numbers – see new paper: Power, Reid and Hobbs (2013)
- Not all diffusions are equal! Grid advection errors do not give correct solution!



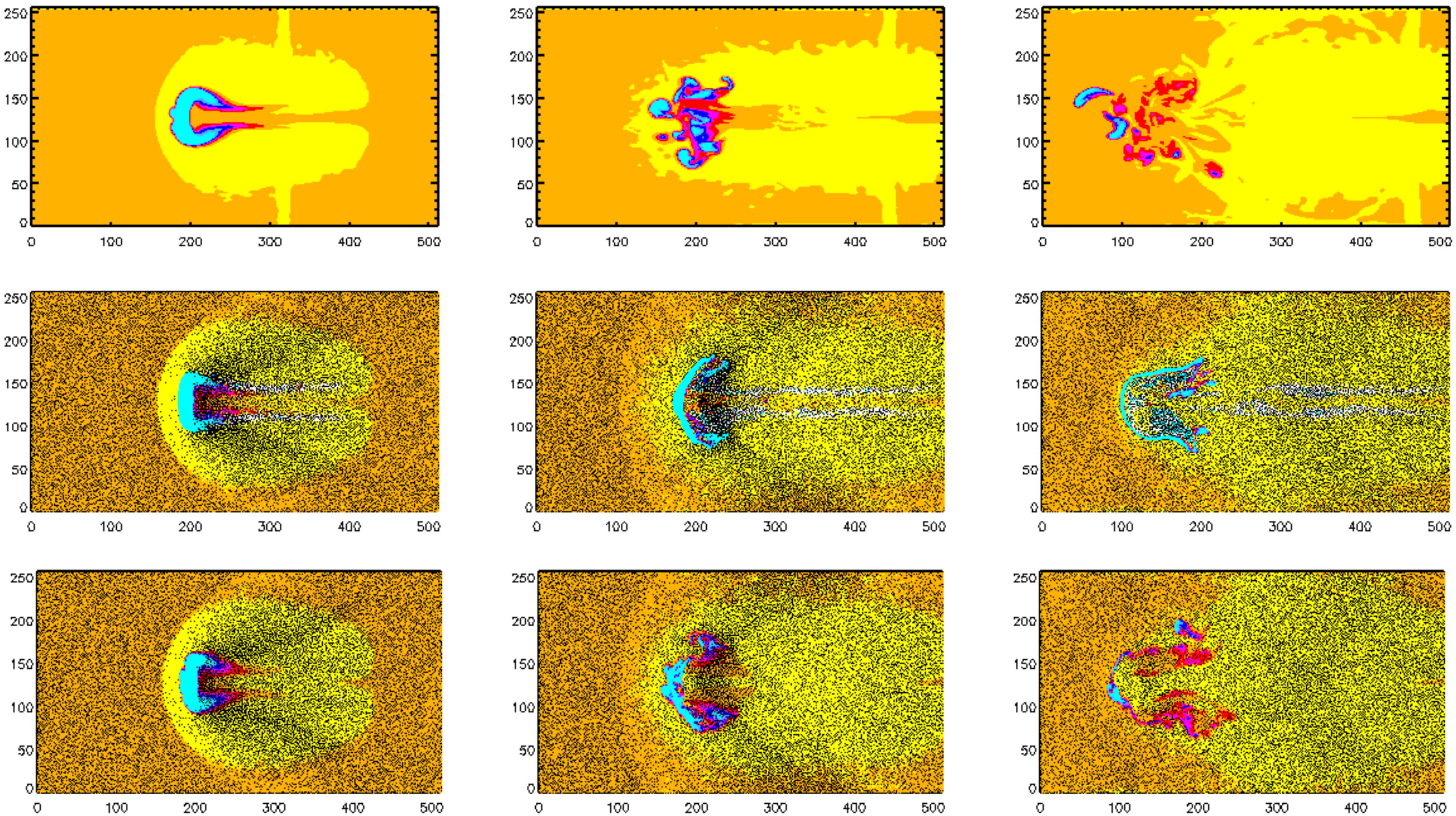
Wadsley, Veeravalli & Couchman (2008)
Shen, Wadsley & Stinson (2010)

Blob Test in Entropy ($T^{3/2}/\rho$)

Hi-Res ENZO

GD Force + Turbulent Diffusion SPH

Blob Test in Entropy ($T^{3/2}/\rho$)



ENZO

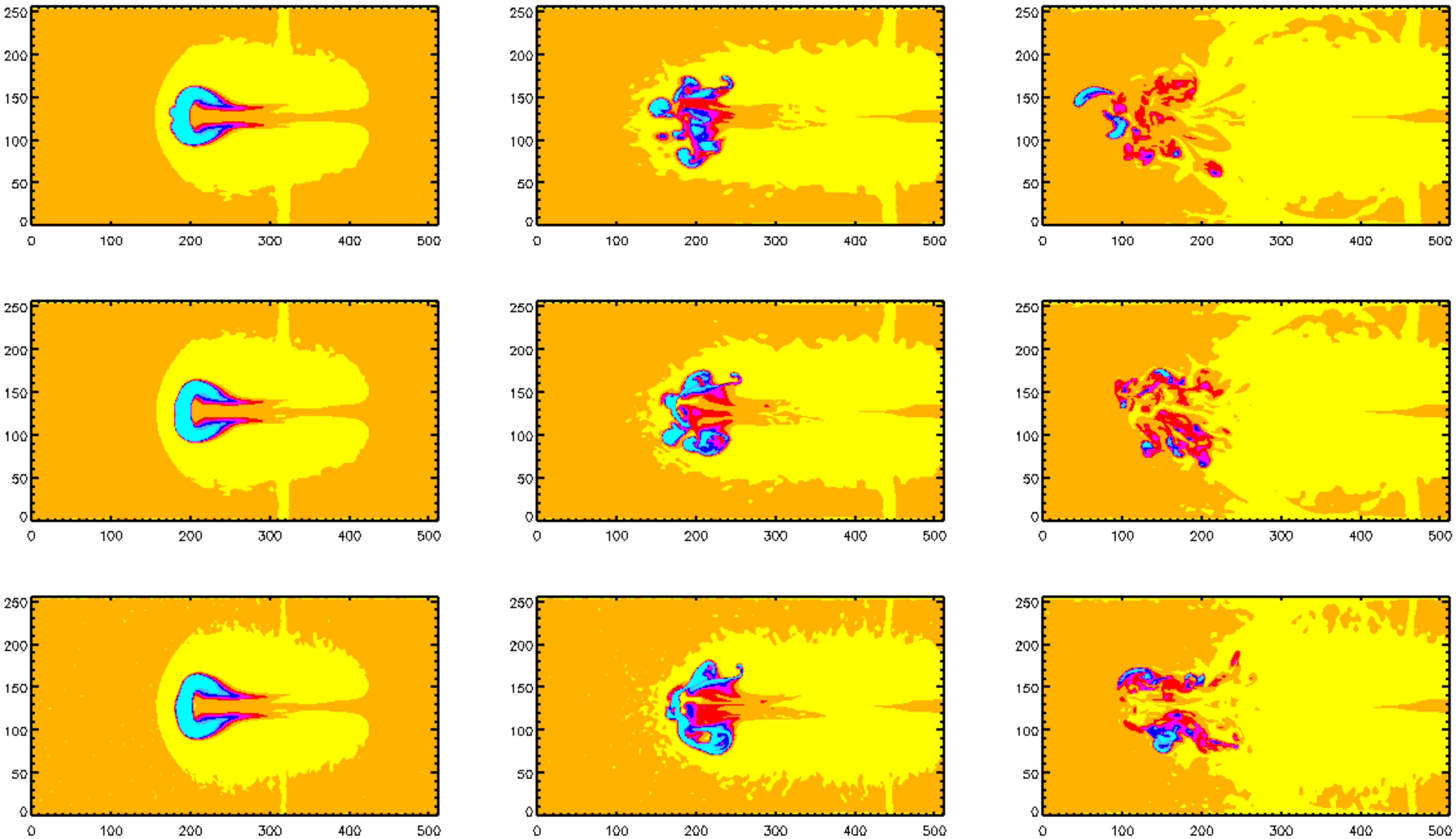
Old SPH

GD Force Turbulent Diffusion SPH

$t = 1.25\ \tau_{KH}$ **$t = 2.5\ \tau_{KH}$** **$t = 3.75\ \tau_{KH}$**

Is grid (PPM) the right answer?

No: Numerical Diffusion Approximate, e.g. is not Galilean Invariant



ENZO Moving flow

ENZO 1/2 – 1/2

ENZO Moving blob

t = 1.25 τ_{KH}   **t = 2.5 τ_{KH}**   **t = 3.75 τ_{KH}**

Aside:

Reducing numerical diffusion in grid codes

Galaxy disk
200 km/s rotation
Gives large advection errors unless you work in a rotating frame

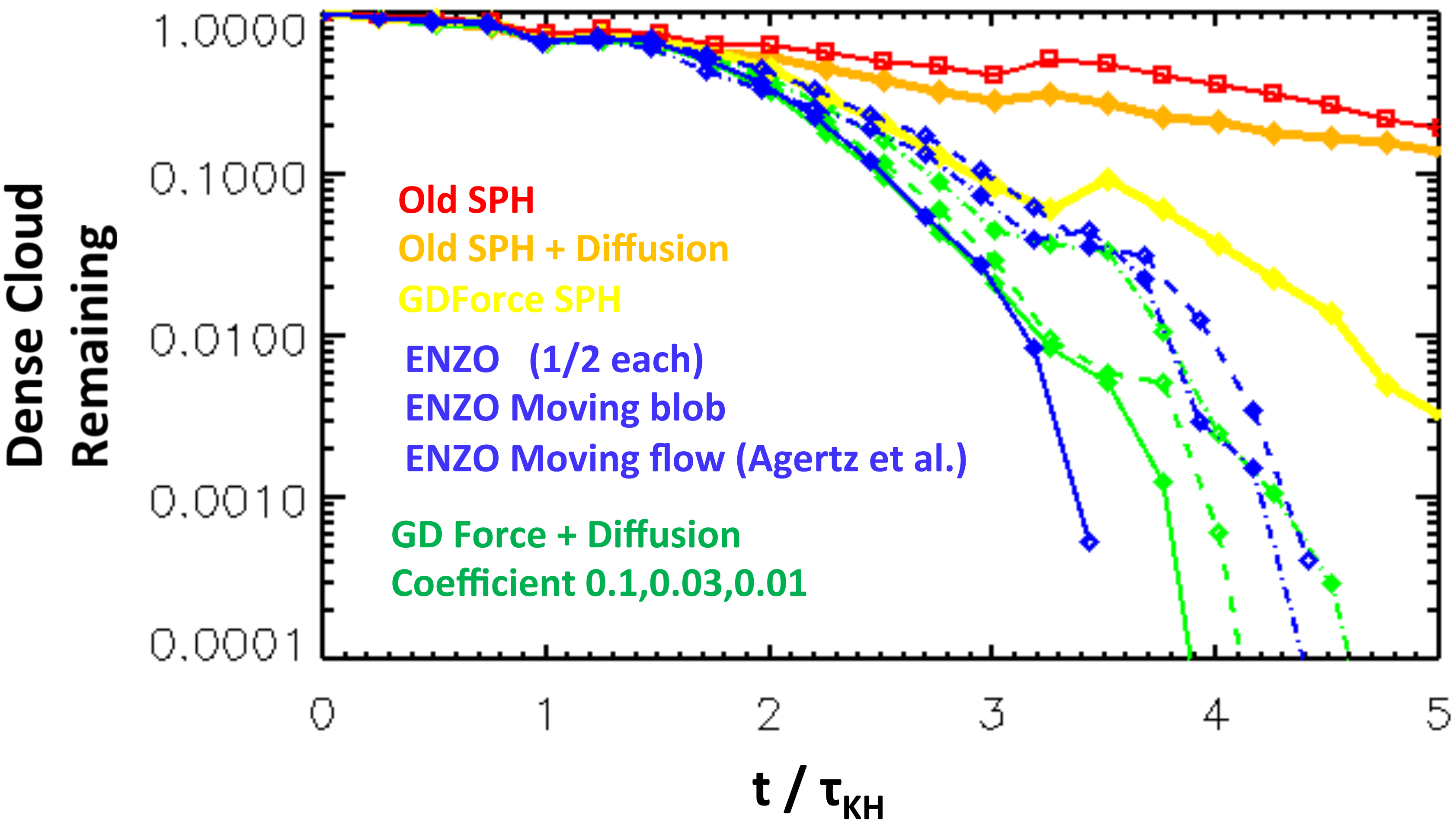
500 pc subregion in model MW galaxy ENZO simulation, both 30 pc resolution

- Pick a rotation rate: radii near co-rotation see large benefit
- Need to add coriolis force
- Effective resolution 4x better
- Faster: Courant timesteps much shorter dt ~ dx/10 km/s vs. dx/200 km/s

Lagrangian methods (e.g. SPH, AREPO) automatically get this benefit

Benincasa, Tasker, Wadsley & Pudritz (2013)

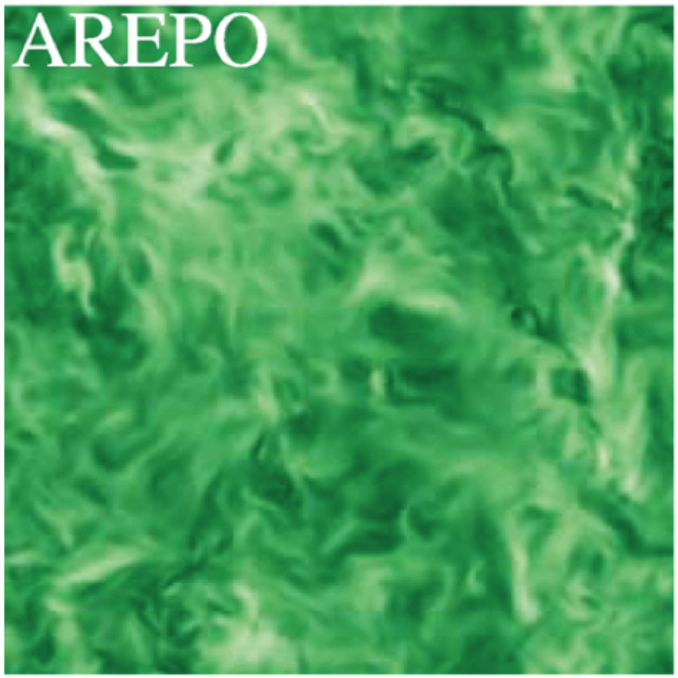
Blob's falling apart… (Log)



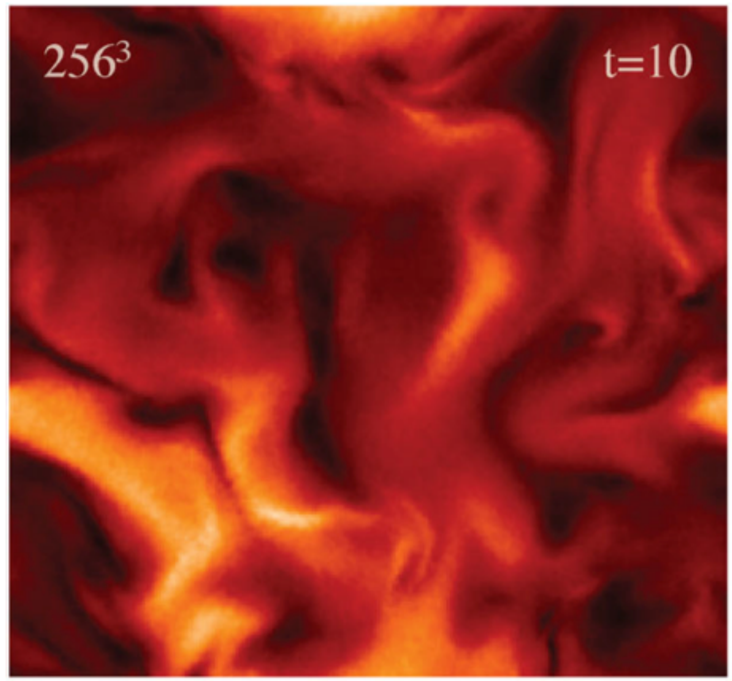
Outstanding issue?

Subsonic turbulence (cf. Bauer & Springel 2012)

- Test Problem: Driven Mach 0.3 turbulence

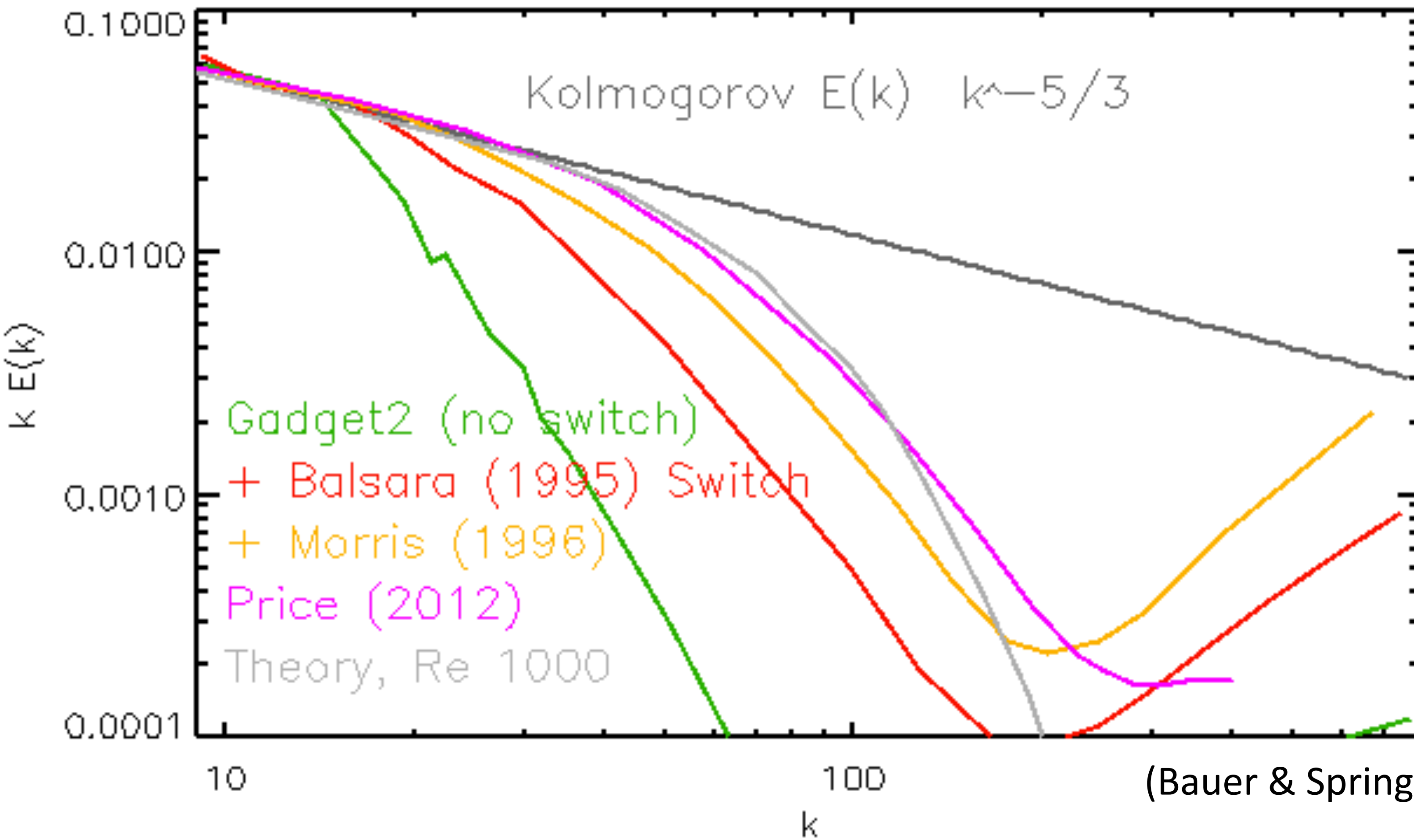


AREPO velocity field
(Bauer & Springel 2012)



SPH velocity field
(Phantom – Price 2012)

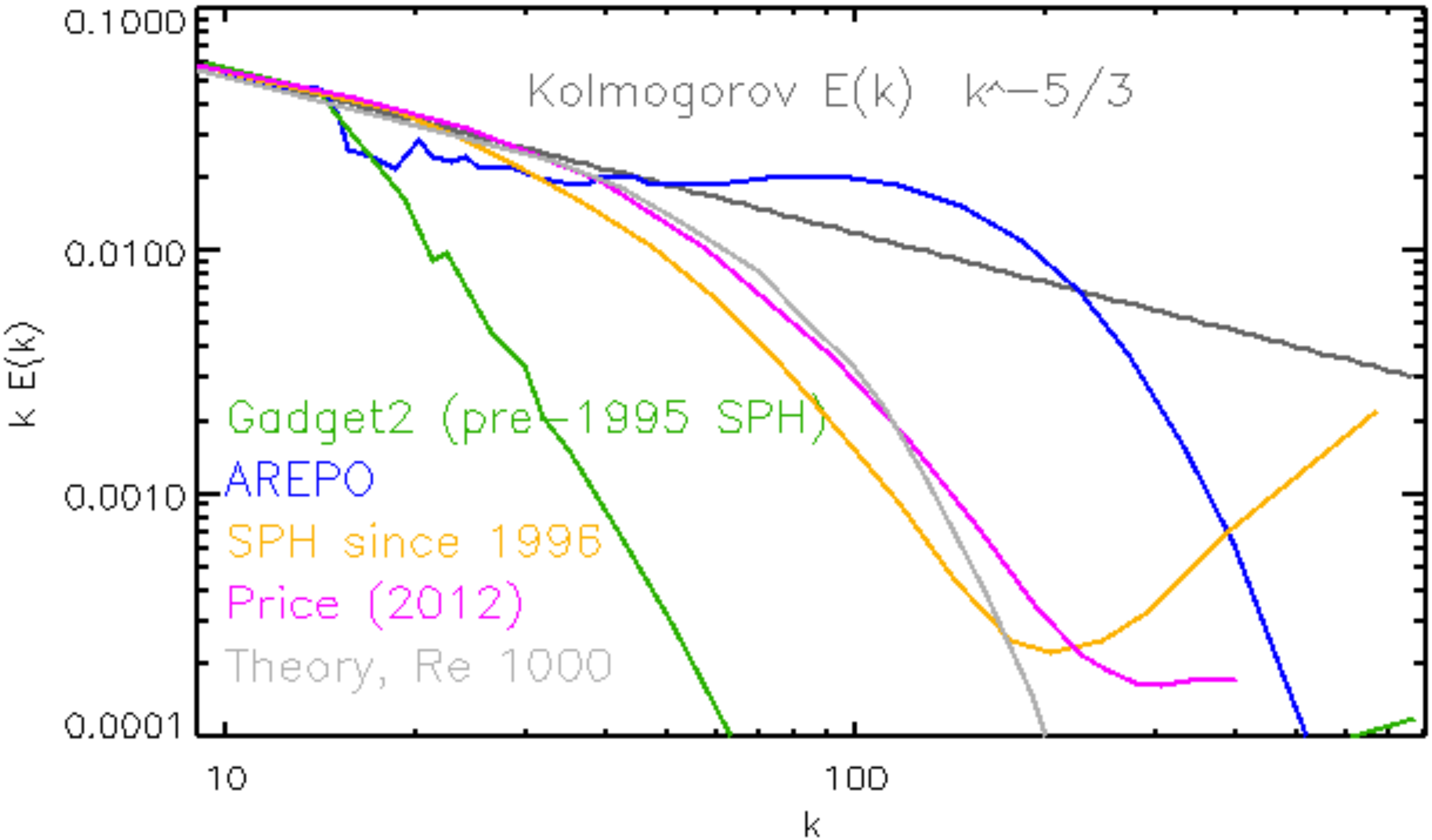
Subsonic Turbulence



(Bauer & Springel 2012)

SPH dissipation limits the effective Reynolds number
All SPH variants good except non-standard, switch-free Gadget2

Subsonic Turbulence



AREPO & grid codes suffer from bottleneck of excess KE
All codes deviate from Kolmogorov at high k

Subsonic Turbulence

- Turbulence provides effective pressure

$$P_{Eff} = P_{Thermal}(1 + M^2)$$

- Mach No. M=0.3 gives < 10% Effect
- Most power in large modes (similar in all codes)
- Grid (incl. AREPO) few % high, SPH few % low

- Note: Engineers/fluid dynamicists would never use finite volume (e.g. PPM, AREPO) for turbulence
  - Use high order (Spectral methods) with controlled dissipation but poor shock capturing

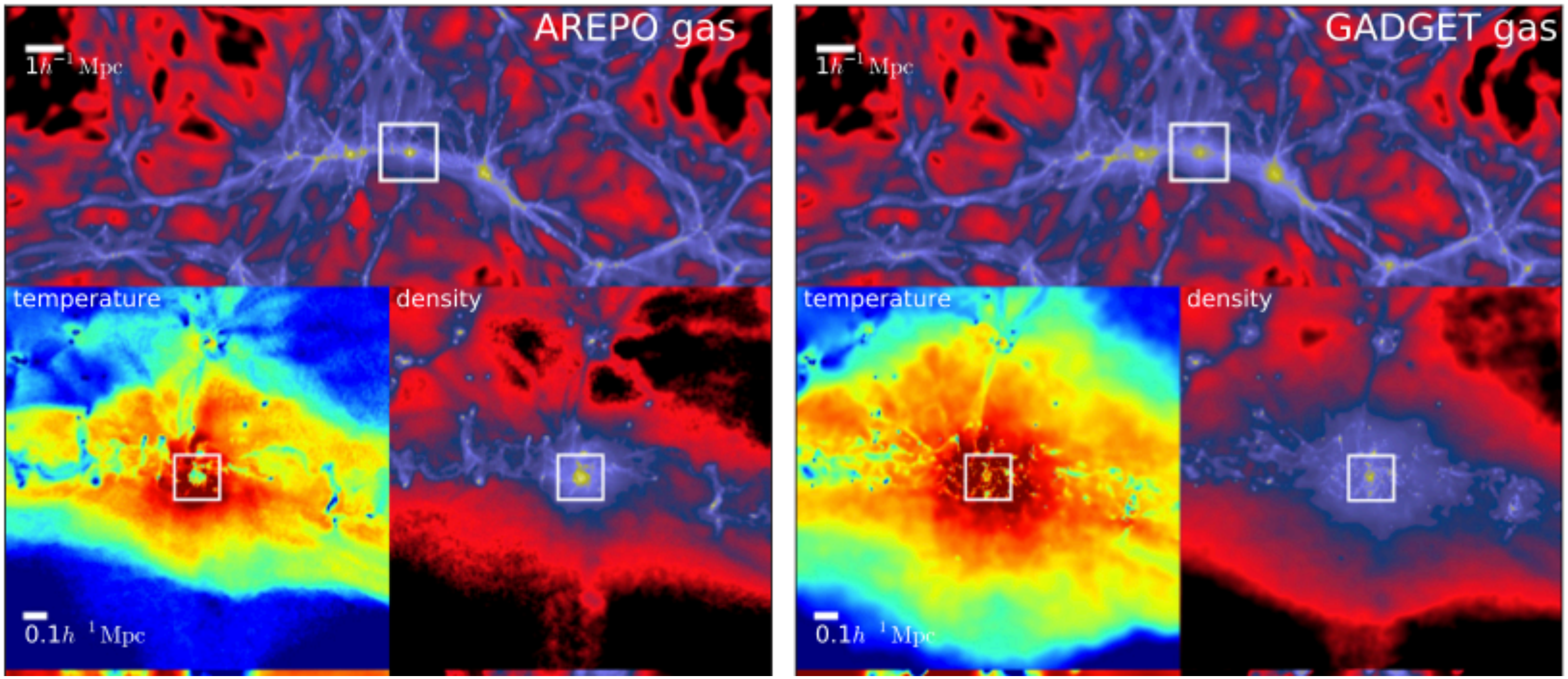
Subsonic Turbulence in galaxy formation

- Post Virial shock, halo gas becomes subsonic
- Grid/SPH bracket reality by few percent up/down

NB: "Excess dissipation" of turbulence into thermal energy would allow it to cool. This implies SPH should be under pressured opposite to claims in Vogelsberger + 2012 / Bauer & Springel 2012

Suspect Vogelsberger+ 2012 result is related to lack of modern switch in Gadget2 for shock heating

Subsonic Turbulence in galaxy formation



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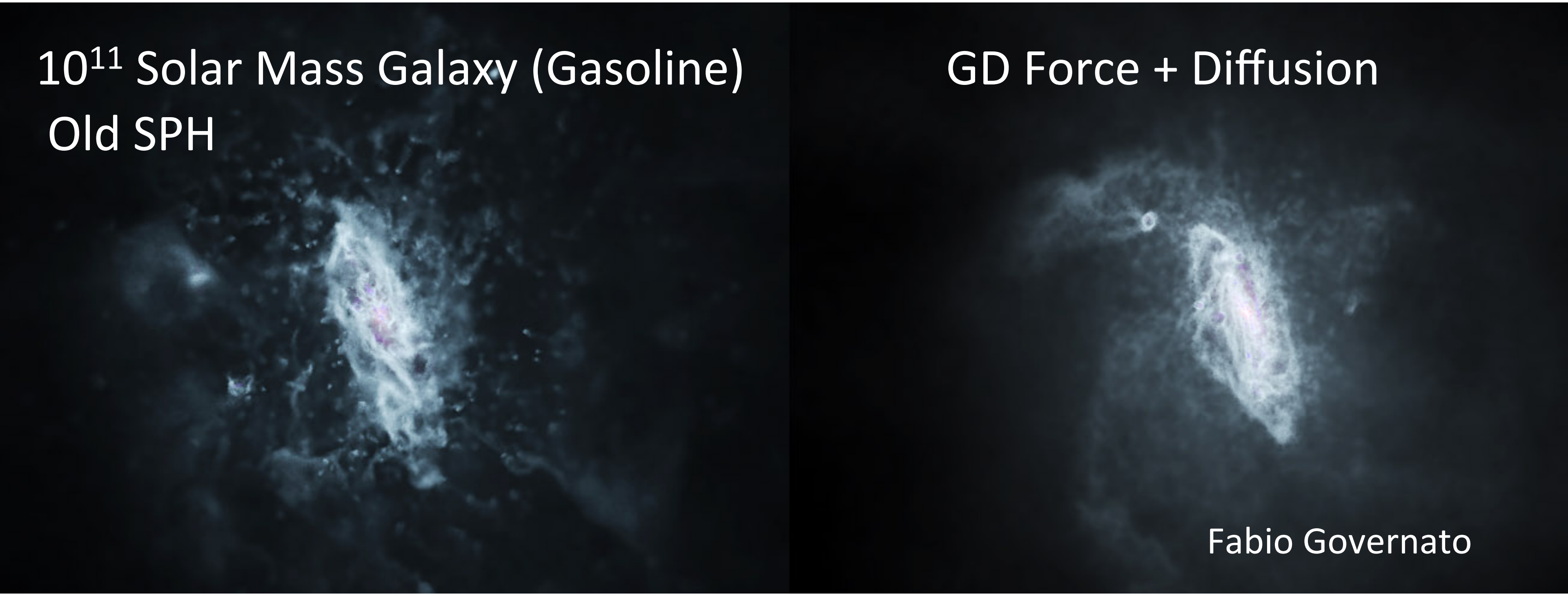
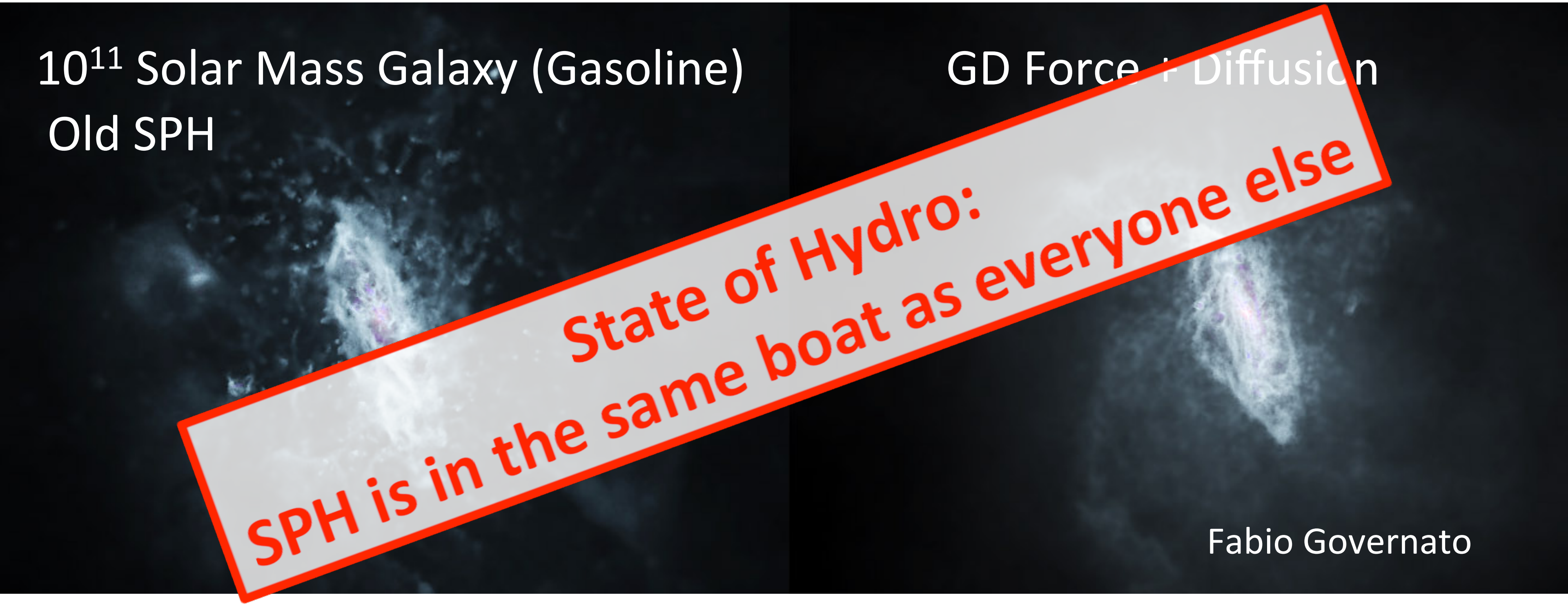
SPH Galaxies: No more blobs



- Large scale gas accretion similar, but overall star formation higher – feedback less effective
- Mixing → More gas at intermediate Temperatures → more cooling (cf. Eagle, Illustris, Teyssier – strong 300% SN FB)

SPH Galaxies: No more blobs



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Outstanding issue:

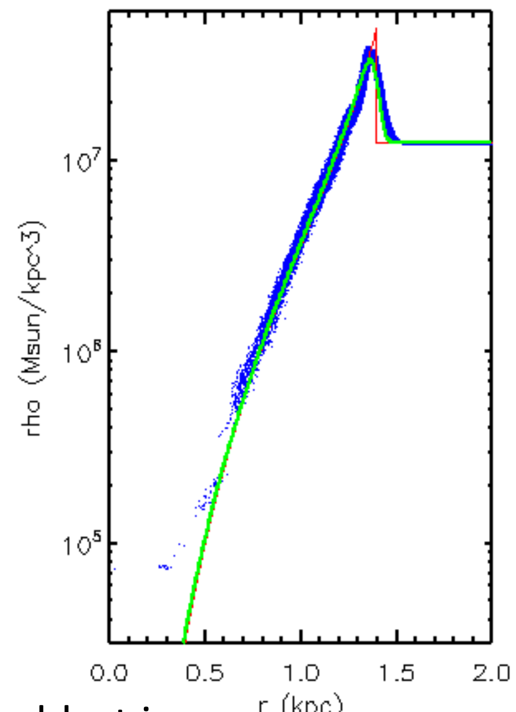
Feedback, Cooling & Mixing

- These processes involve thin layers/smalls scales no code currently resolves
- Makes feedback less effective, tends to overcool and overmix …. – not quantified!
- Tricks:
  - Turn Hydro off in winds (Springel & Hernquist 2003 + recent AREPO runs, e.g. Illustris)
  - Extreme "Multiphase" decouple hot & cold (Aumer+ 2013, Scannpieco+ 2006, Marri & White 2003)

Gasoline

Current Version (2013):

- Fixed number of neighbours (e.g. 64 for Wendland C_2 kernel, Dehnen & Aly 2012)
- Single SPH smooth (no iterations)
- Standard density, geometric density forces
- Turbulent Diffusion (Shen, Wadsley & Stinson 2010)
- f correction to PdV work
- Multistepping power of 2 KDK plus Saitoh & Makino (2009) timestep adjustment



good integrator test: Sedov-Taylor blast in T=0 K gas (128^3) 0.08 % Energy error

Stellar Feedback

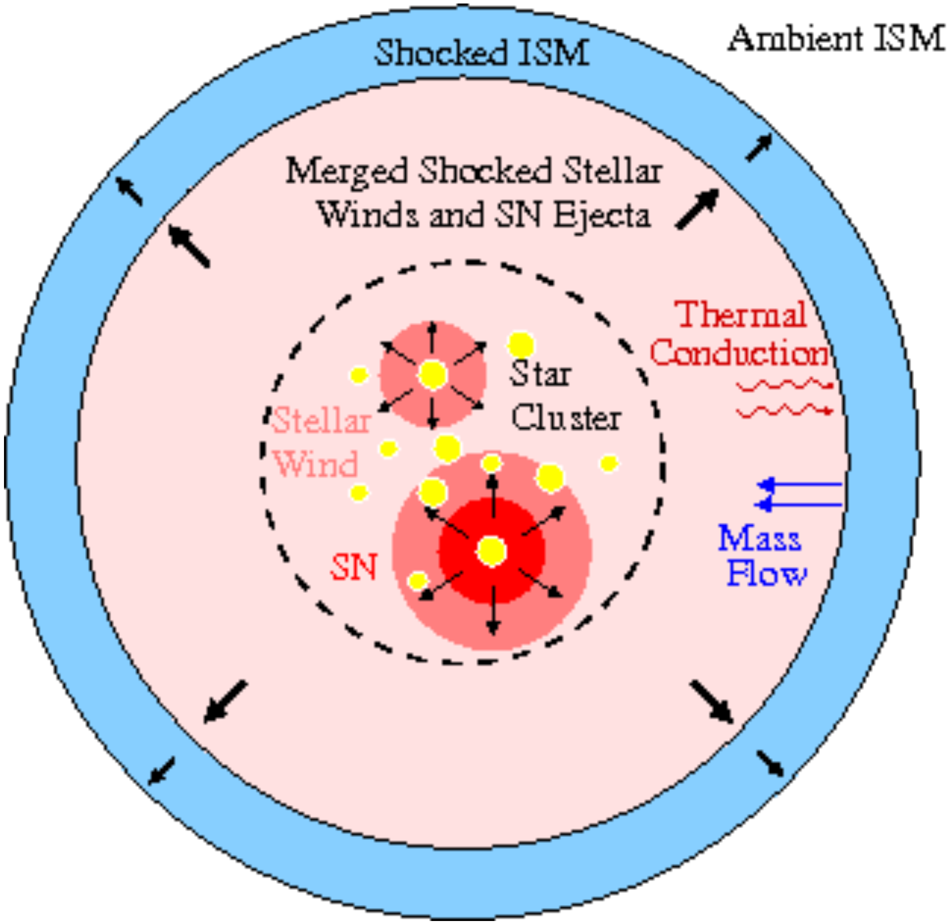
Efficient Stellar Feedback

Keller & Wadsley (in prep)

- Radiation pressure and UV feedback: pre-process medium around star cluster but self-limiting to roughly $v_{esc\ GMC}$ ~ 20 km/s (for normal galaxies)
- Many stellar feedback ideas based on single supernovae (e.g. Stinson et al. 2006, "blastwave"). Feedback from star clusters is qualitatively different …
- Stellar winds and supernovae combine into a super bubble that can drive outflows

Super bubble features

- Star cluster output: winds supernova, shock and thermalize in bubble
- Mechanical Luminosity $L=10^{38}$ erg/s/10^4 M_{SUN} cluster
- Thin shell forms quickly: immediately get pressure driven snowplough
- Mass loading of bubble due to evaporation by thermal conduction



MacLow & McCray 1988, Weaver et al 1977, Silich et al 1996

Super bubble features

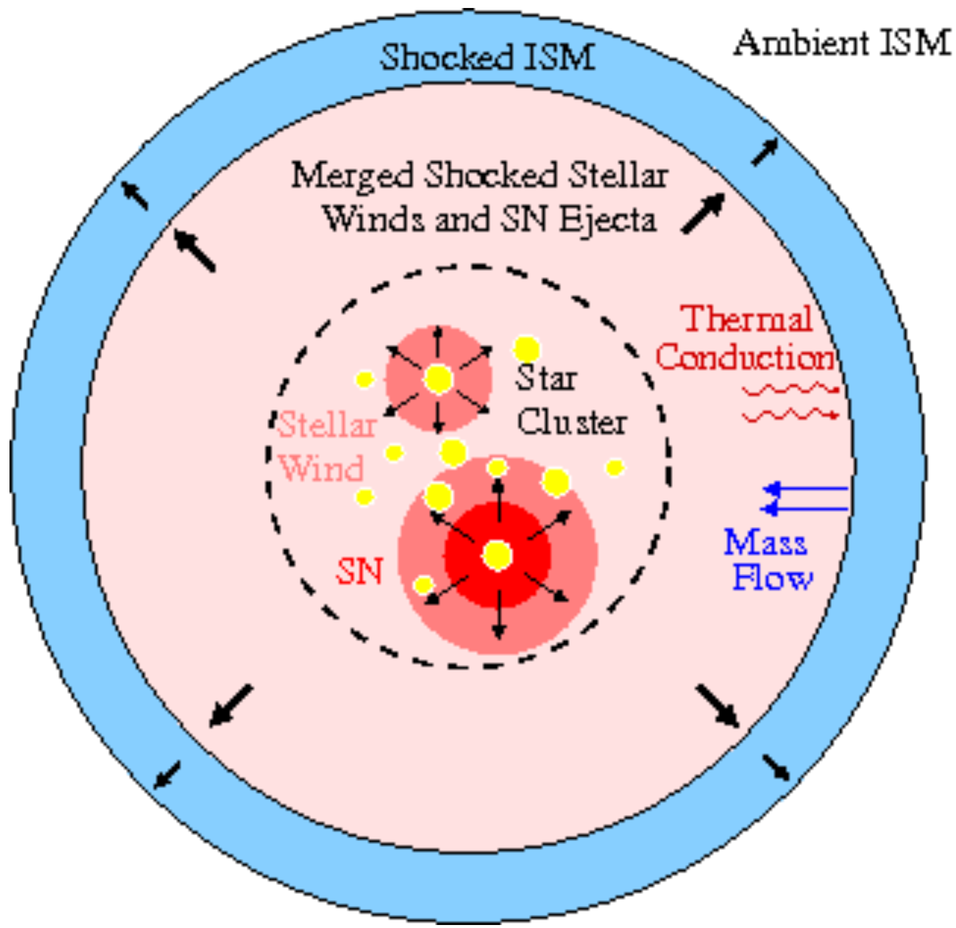
Superbubbles efficient

Ideal self-similar PDS solution

- Thermal Energy: Eth = 0.45 L t
- Kinetic Energy: Ek = 0.20 L t
- Shell radiative losses: 0.35 L t

Limiting factor: Radiative Cooling of bubble determined by bubble temperature ~ Eth/Mb and density Mb/R^3

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

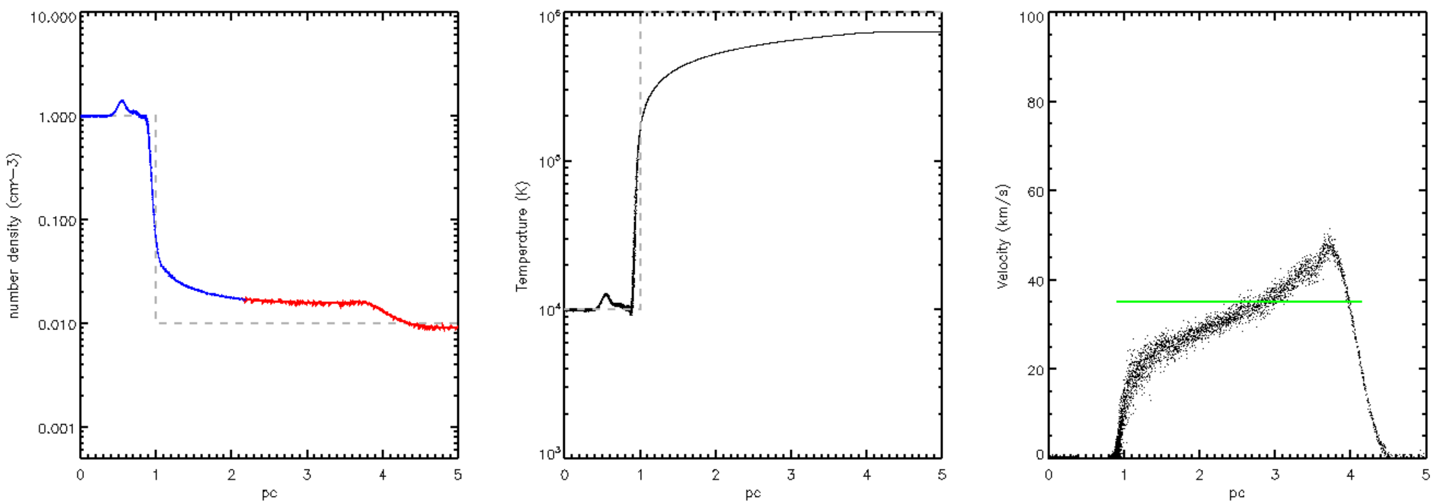


MacLow & McCray 1988, Weaver et al 1977, Silich et al 1996

Thermal Conductivity

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

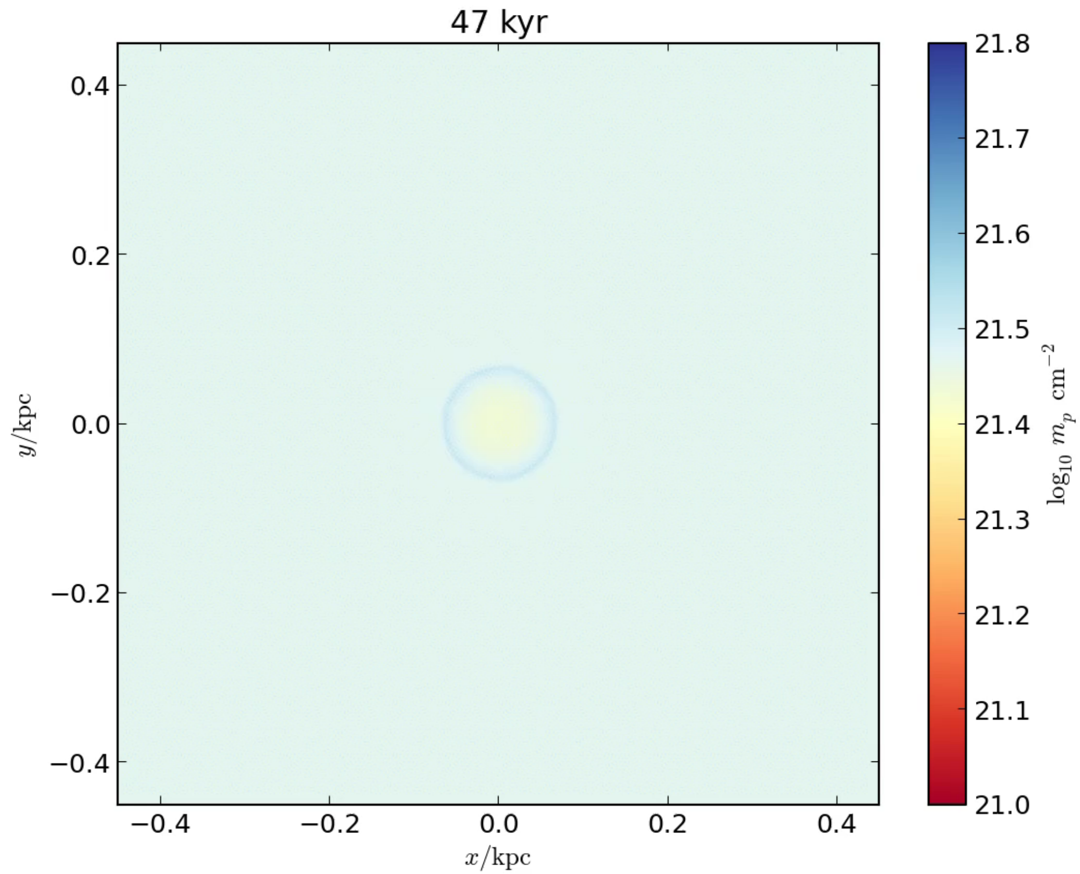
- Self regulating Energy flux ~ $T^{7/2}/L$
- Translates into mass flow from shell until bubble T is lowered to ~ few 10^6 K (Bubble energy, metals conserved)



High-Res SPH conductivity simulation

Gasoline (method similar to Jubelgas et al 2004)

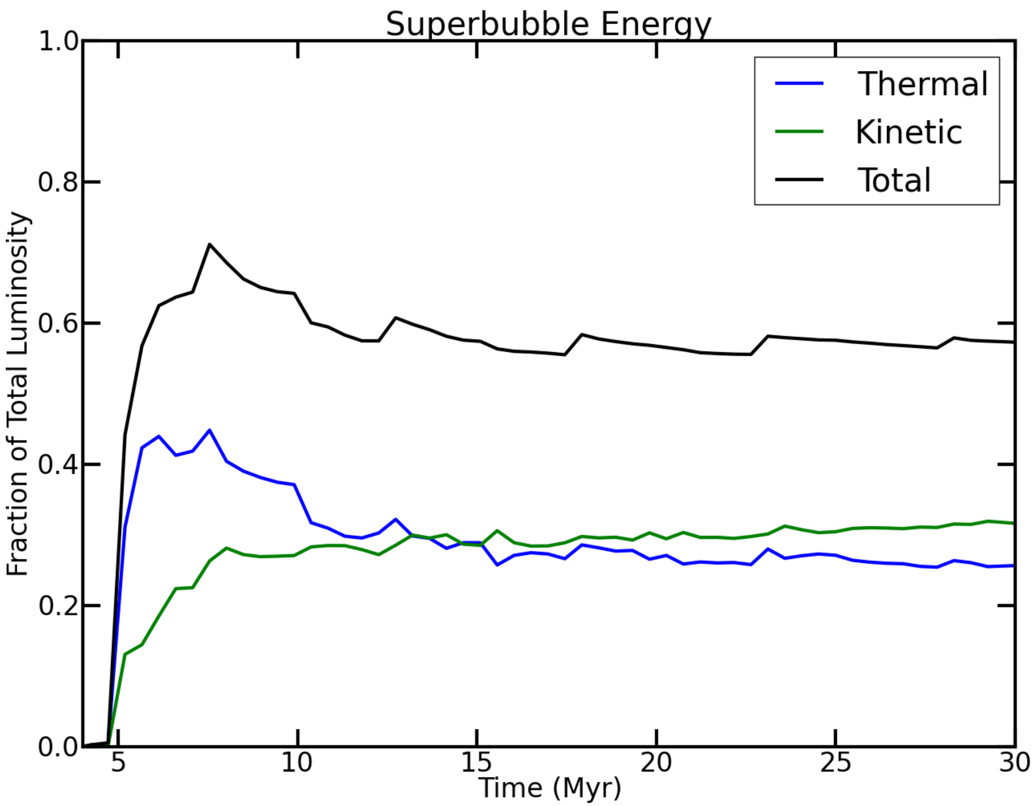
Super bubble Simulation



Super bubble Simulation

- SPH: 750 Msun/particle – similar to galaxy sim
- $3x10^4$ Msun star cluster in 1 H/cc,
  solar metallicity cooling
- 40 star particles
- 10 gas ejecta

Super bubble Simulation



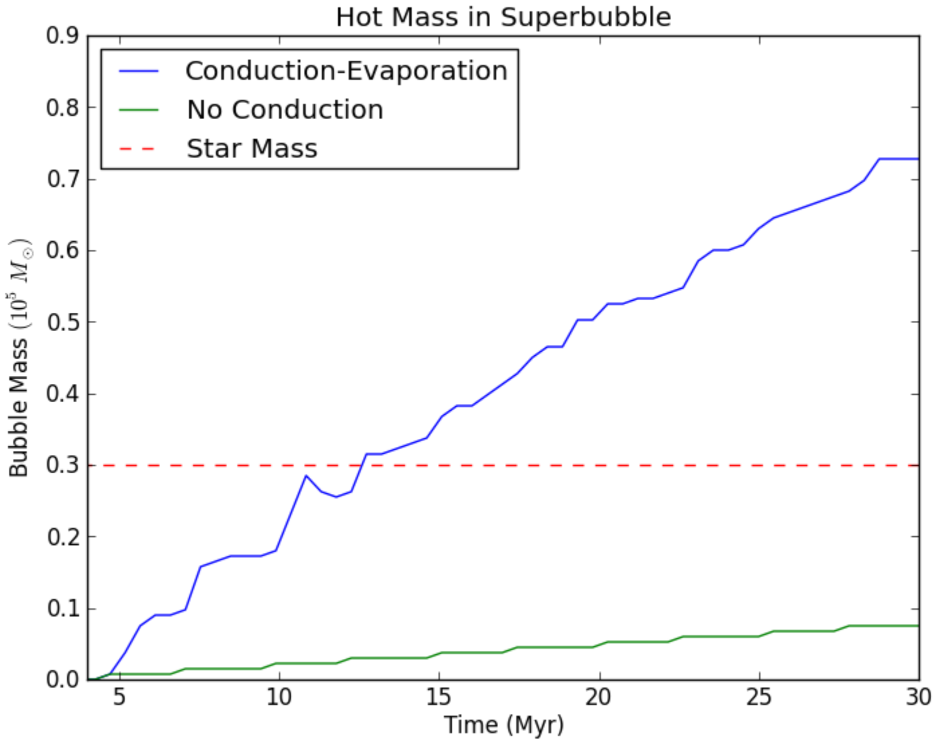
> 50% Feedback efficiency
After 30 Myr !

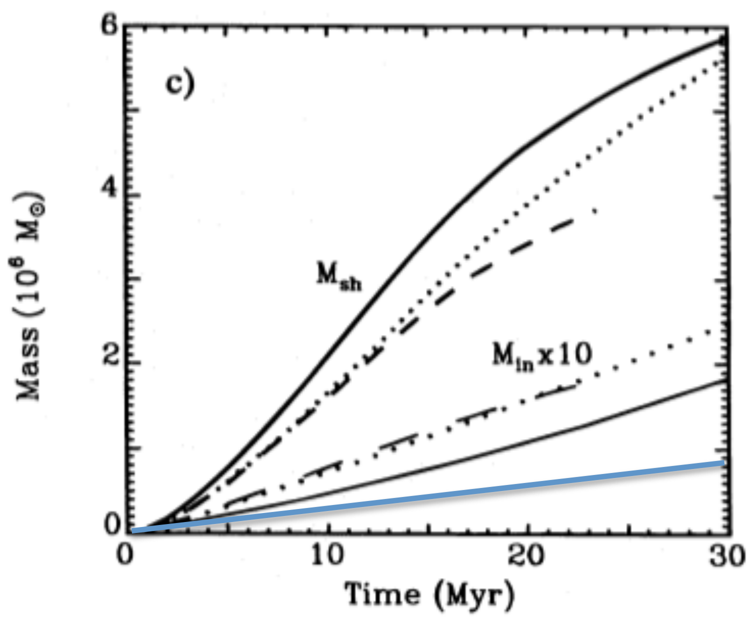
Compare: < 10% for one SN, e.g. Chevalier '74

Note: Thermal Energy of bubble, KE of shell + bubble

Mass loading

- ~ 100 shell particles evaporated into bubble
- Mass loading 3-6 M_*



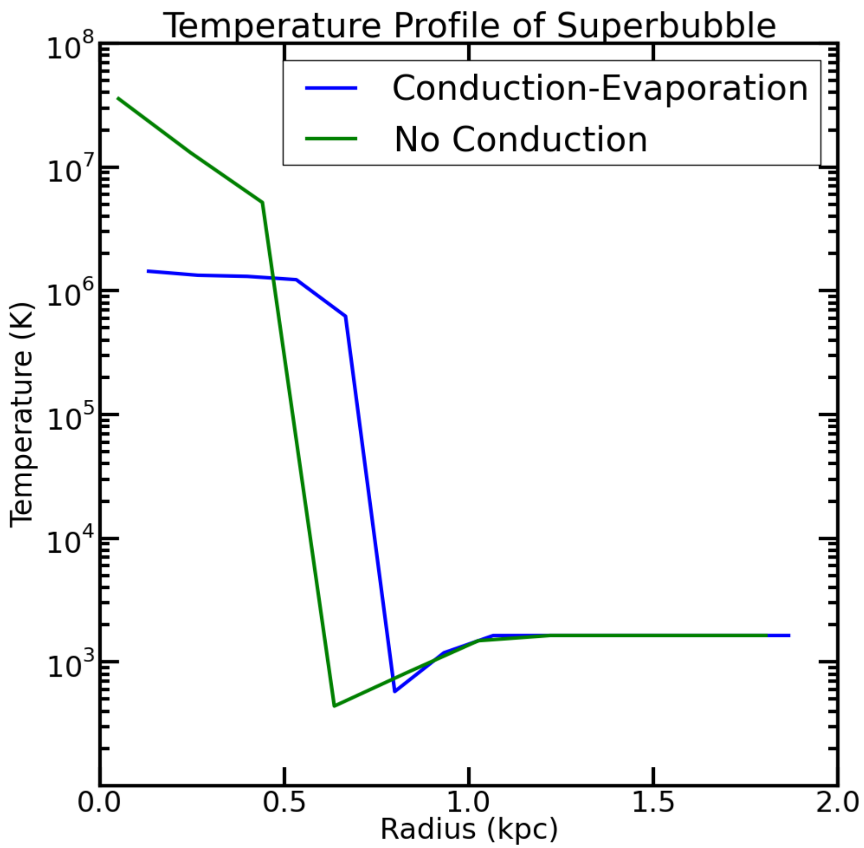


Silich et al 1996

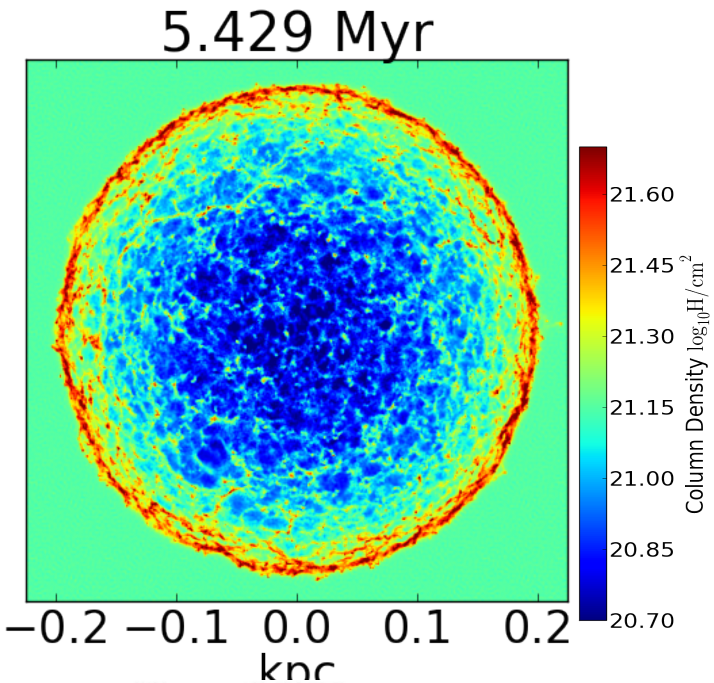
Mass loading

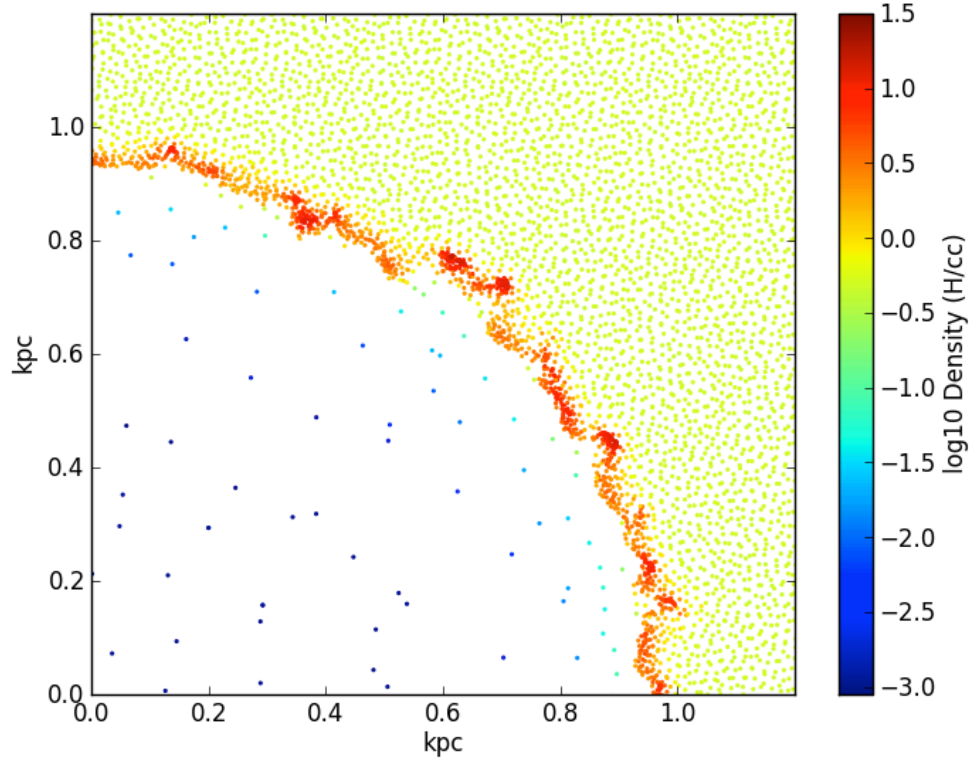
- Bubble temperature regulated at ~2 x 10^6 K

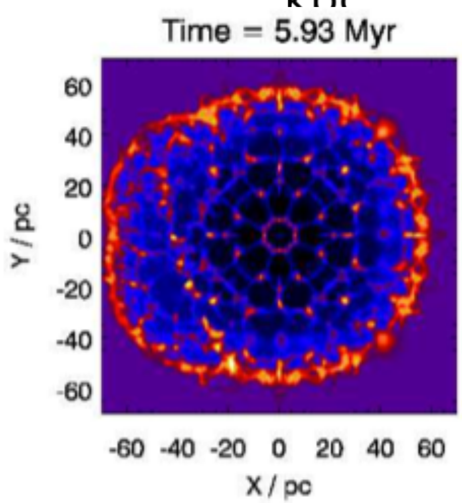
  (cf. Dalla Vecchia & Schaye 2012)



Super bubbles: Vishniac Instabilities







Nirvana simulations
3 star bubble
Krause et al 2013

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

Summary:

Super bubble Feedback

- Dalla Vecchia & Schaye (2012) showed the importance of moderate feedback mass ($T_{feedback} > 10^{6.5}$ K) for effective feedback
  - but what sets $T_{feedback}$?
- Can use physical models (conduction) to determine mass loading and $T_{feedback}$
- No cooling shutoff
- Much more efficient than individual SN
- Future work: Combined feedback, lumpy ISM