Towards Understanding Simulations of Galaxy Formation

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On the Origin of Cores in Simulated Galaxy Clusters

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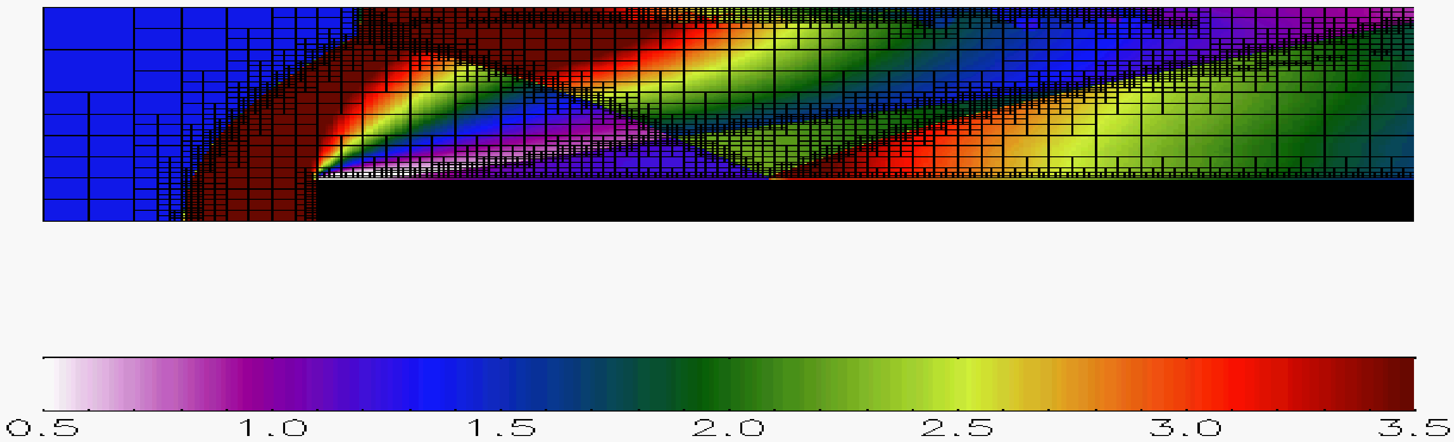
The importance of simulations

- The Universe is a very complex place with many competing physical processes including:
- Gravitational heating
- Ram pressure stripping and turbulent mixing
- Chemical dependant radiative cooling
- Star formation and black hole growth
- Supernova feedback

AMR (Adaptive Mesh Refinement)

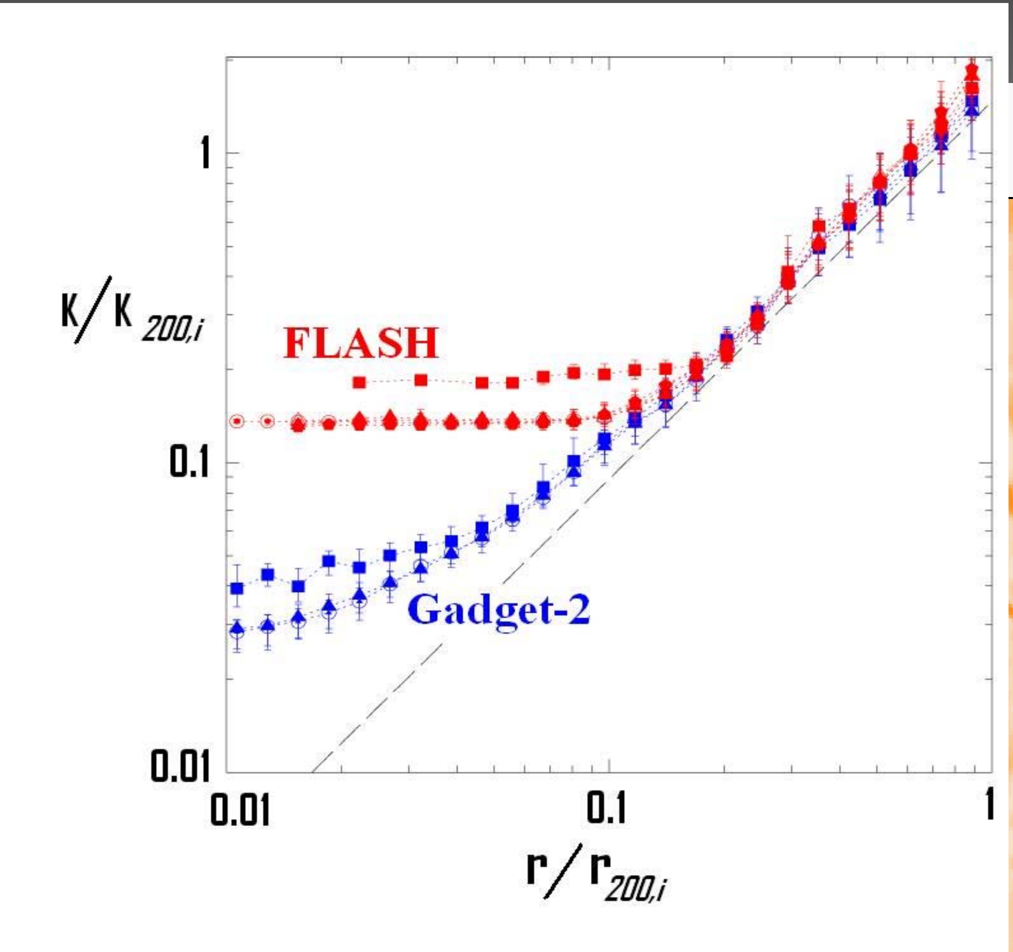
- **Eulerian Mesh based code**
- **Mesh can actively refine and de-refine**
- **Each cell has a given density, internal energy, pressure and temperature.**
- **Uses a “Riemann” solver to determine the flux through the cell faces. Enables shocks and contact discontinuities to accurately modelled**

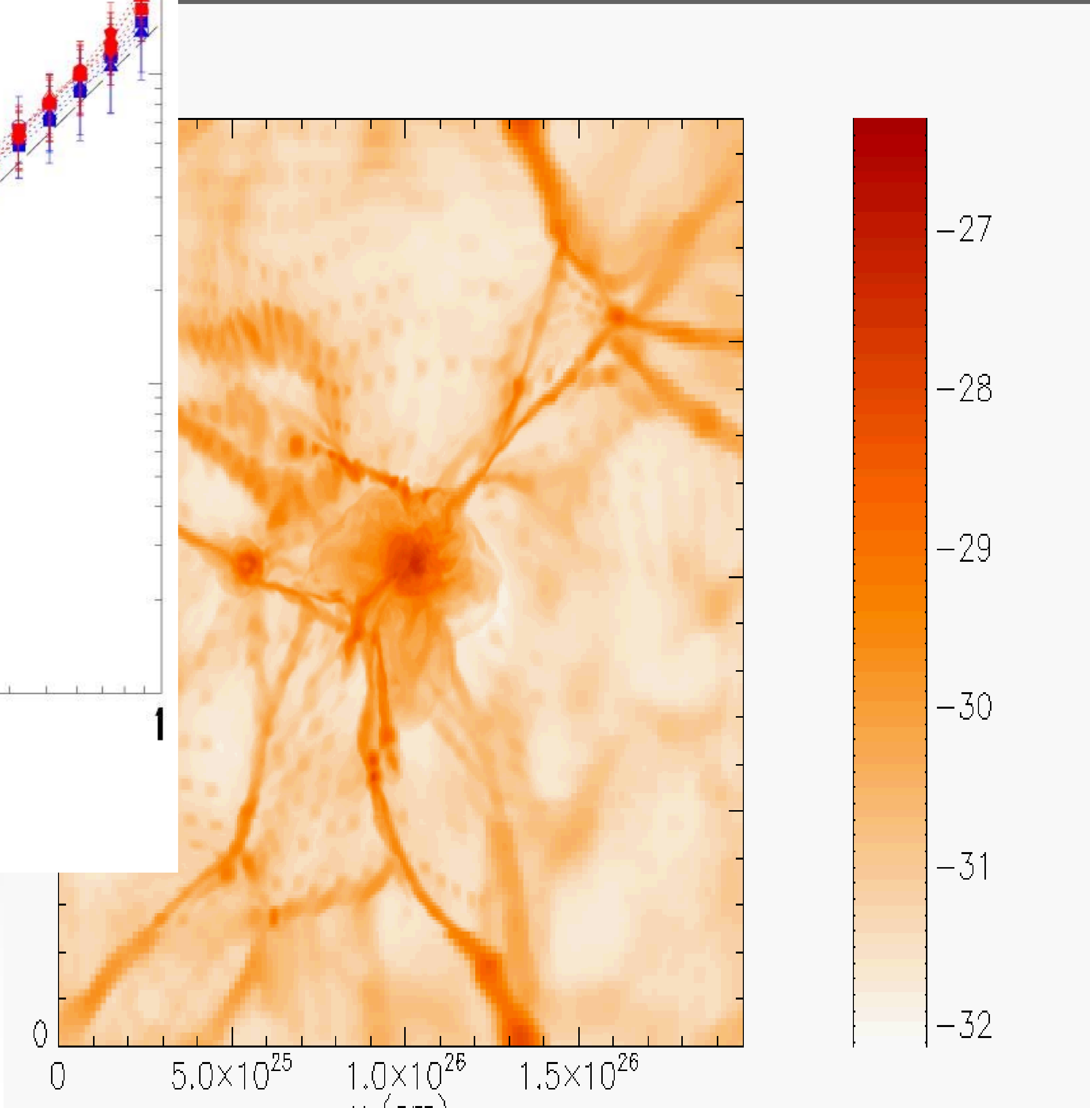


SPH (Smooth Particle Hydrodynamics)

- **Particle based hydrodynamics code**
- **Determine properties such as density by smoothing over neighbouring particles**
- **Very memory efficient and widely adopted**
- **Much faster than AMR codes**
- **Requires the use of an “artificial viscosity” to generate the energy released in shocks when particles approach each other**
- **Tends to smooth over shocks and contact discontinuities**
- **Confined to only refine on the density – lacks the flexible refinement schemes which AMR codes have**

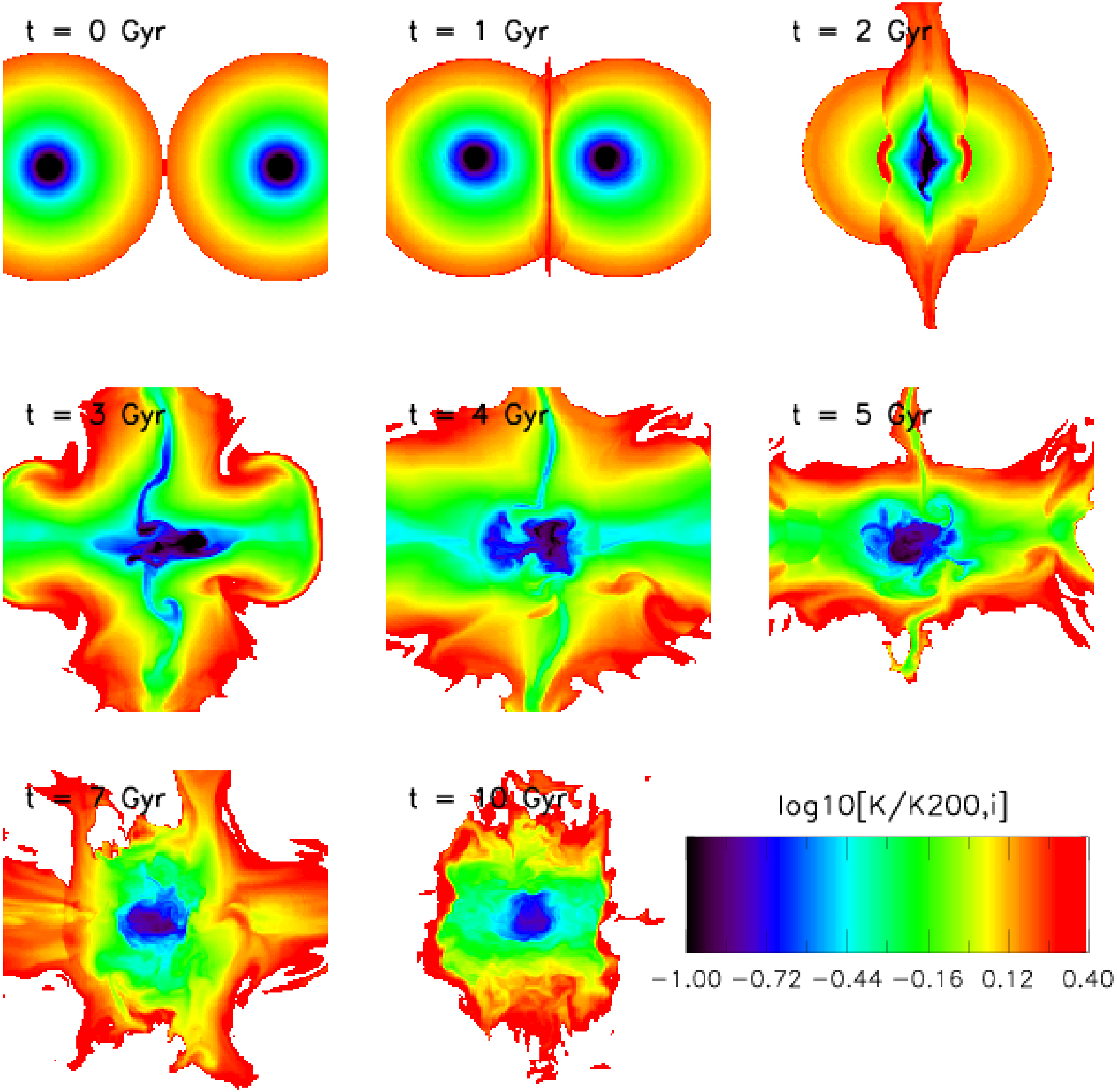
Santa Barbara code comparison highlights a strong difference between SPH and AMR codes



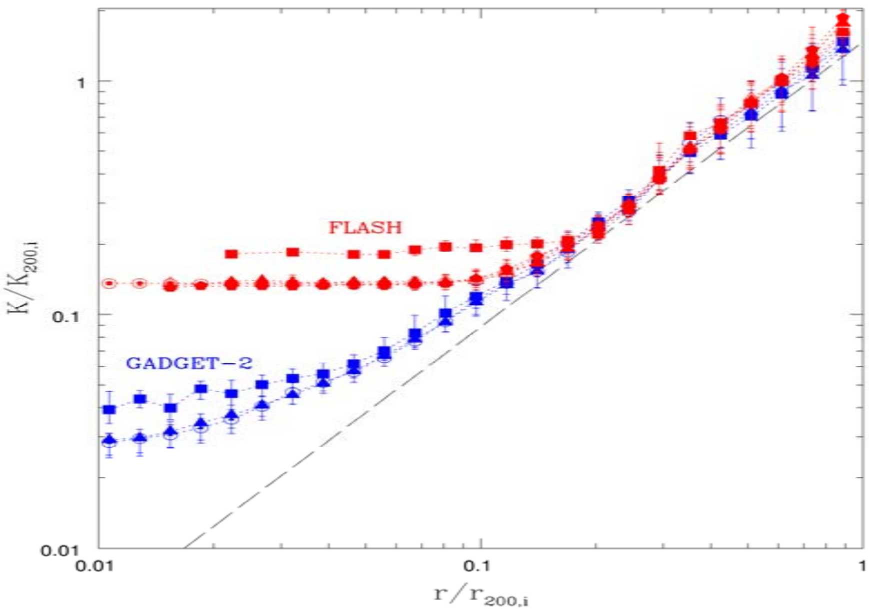


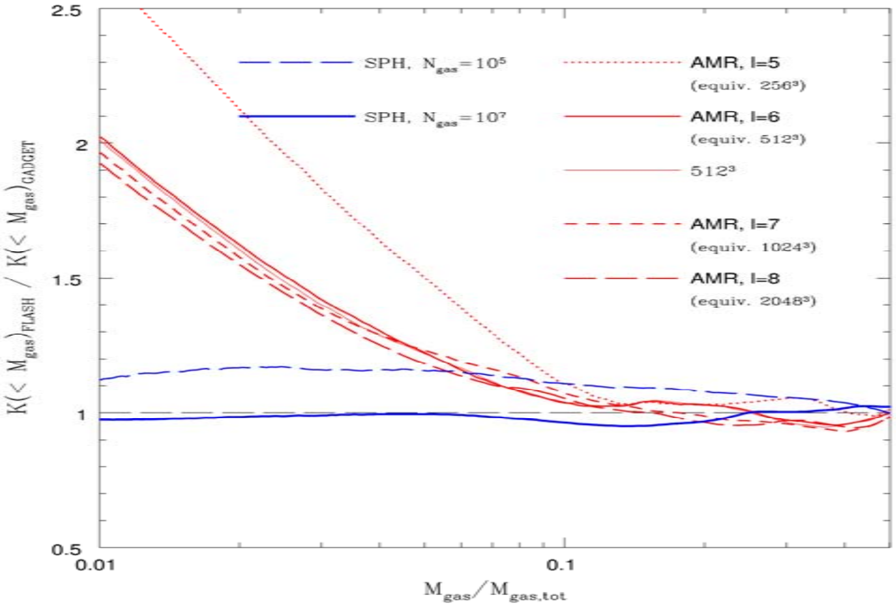
A new innovative approach using mergers between model clusters

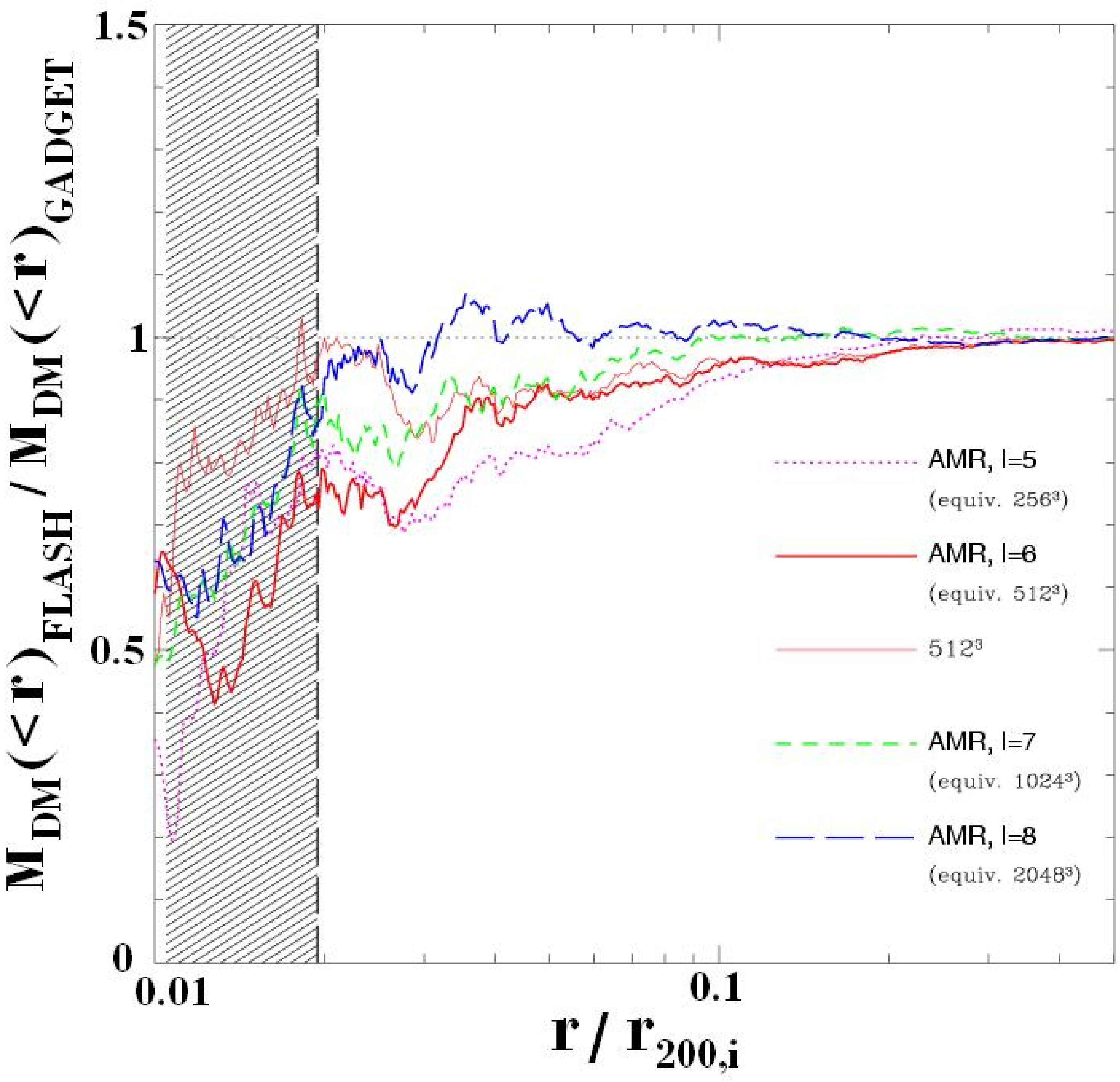
- **Adopt a simplified cluster model with an analytic NFW dark matter halo and a power law entropy profile.**
- **Model clusters lack complexity of large cosmological simulations**
- **Significantly less computationally demanding allowing large suites of simulations to be run**
- **Easy to adjust initial configuration allowing us to systematically explore different physical effects**



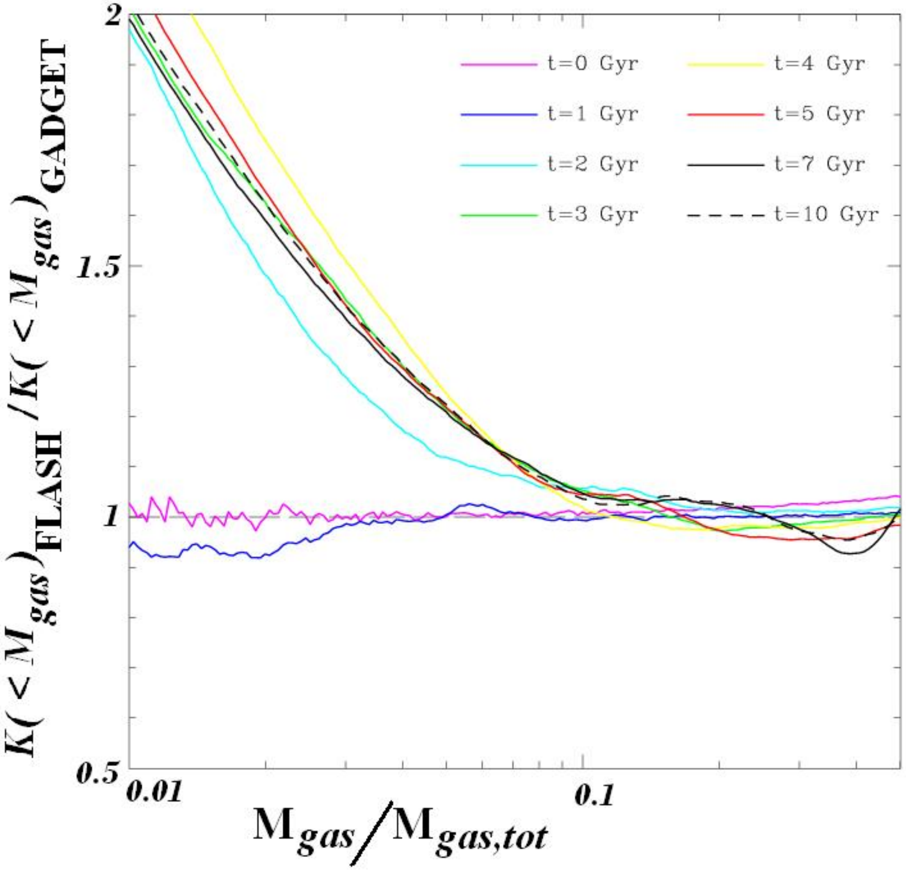
Logarithmic entropy slices through the centre of the default FLASH simulation over time.

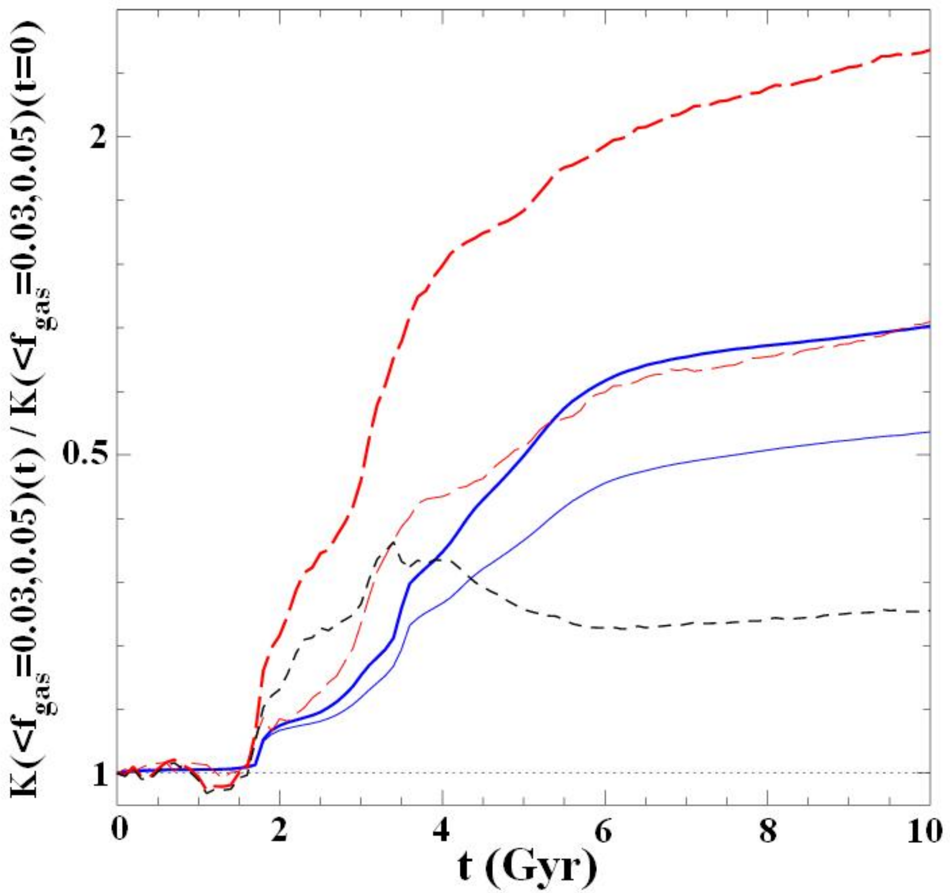

FLASH
GADGET−2
K/K$_{200,i}$
r/r$_{200,i}$
1
0.1
0.01
0.01
0.1
1


SPH, $N_{gas}=10^5$
SPH, $N_{gas}=10^7$
AMR, l=5
(equiv. 256^3)
AMR, l=6
(equiv. 512^3)
512^3
AMR, l=7
(equiv. 1024^3)
AMR, l=8
(equiv. 2048^3)
K(< M$_{gas}$)$_{FLASH}$ / K(< M$_{gas}$)$_{GADGET}$
M$_{gas}$/M$_{gas,tot}$
2.5
2
1.5
1
0.5
0.01
0.1



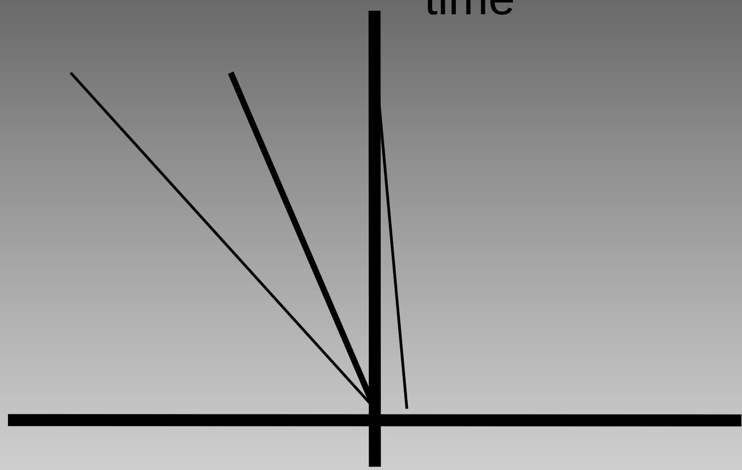
1.5
1
0.5
0
0.01
0.1
r / r200,i
MDM(<r)FLASH / MDM(<r)GADGET
AMR, l=5
(equiv. 256³)
AMR, l=6
(equiv. 512³)
512³
AMR, l=7
(equiv. 1024³)
AMR, l=8
(equiv. 2048³)

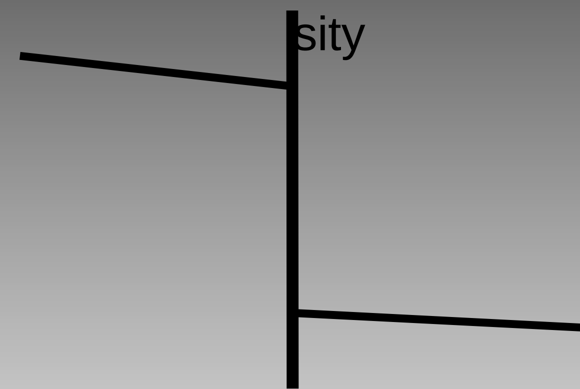




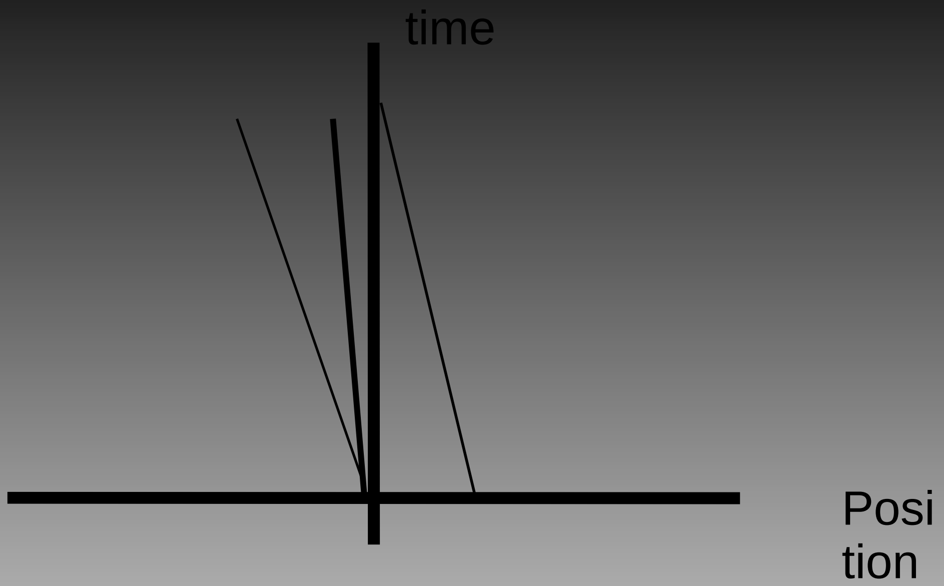
The difference in the core entropy between the two simulations is generated at the time of core collision at ~1.8 Gyrs.

Is it due to Galilean non-invariance in mesh codes?

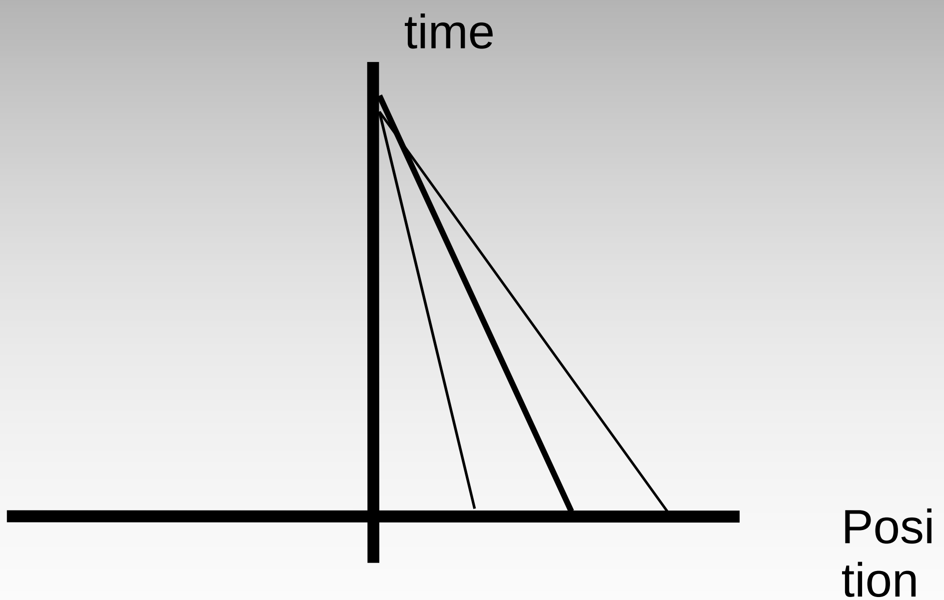




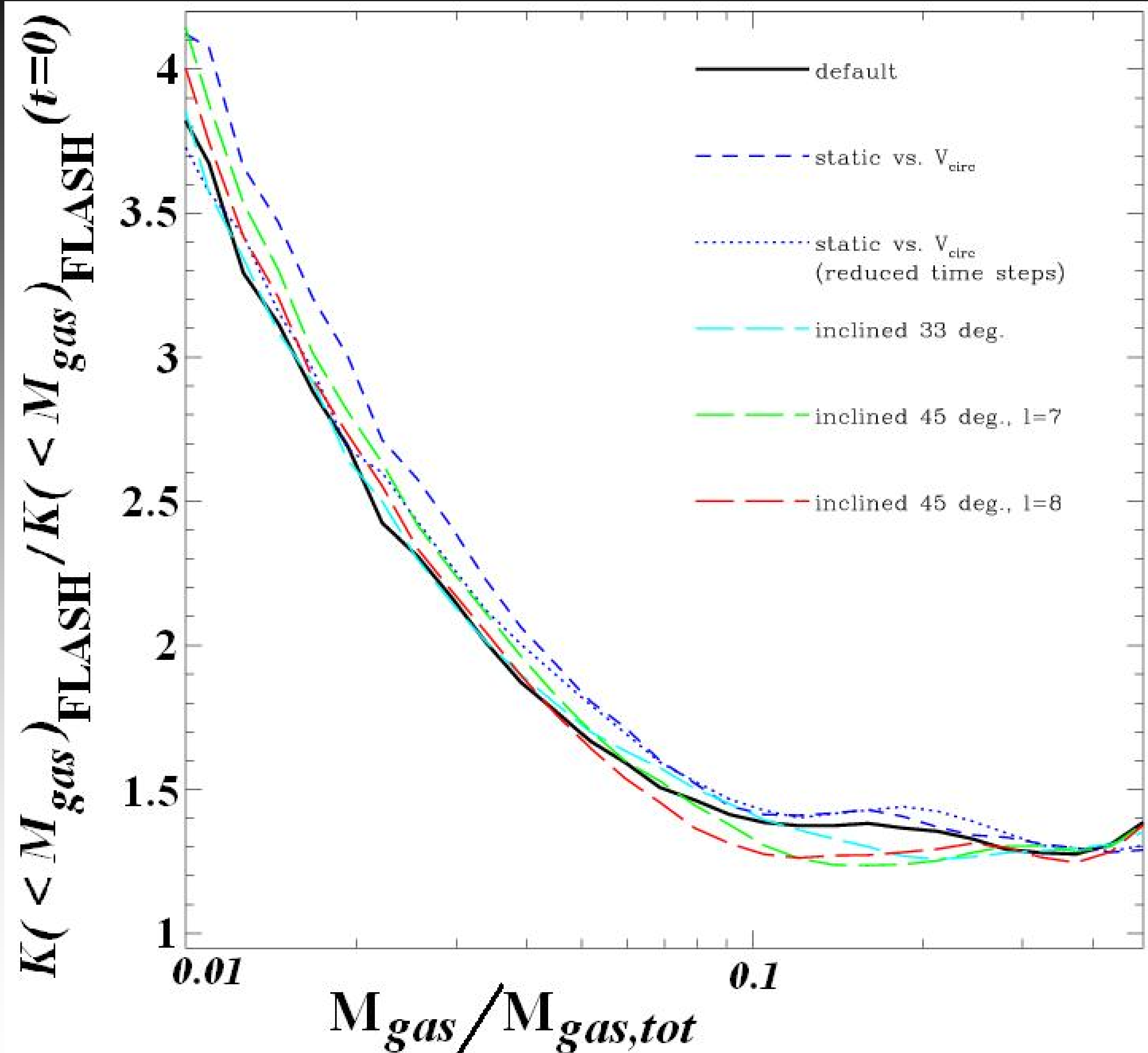
Riemann Solver constructs left and right states based on sound speed and fluid velocity in the left and right states.
Given that the reference frame of the boundary is fixed, we can work out how much material can interact at the interface based on the sound speed relative to the fluid velocity within a given time step.



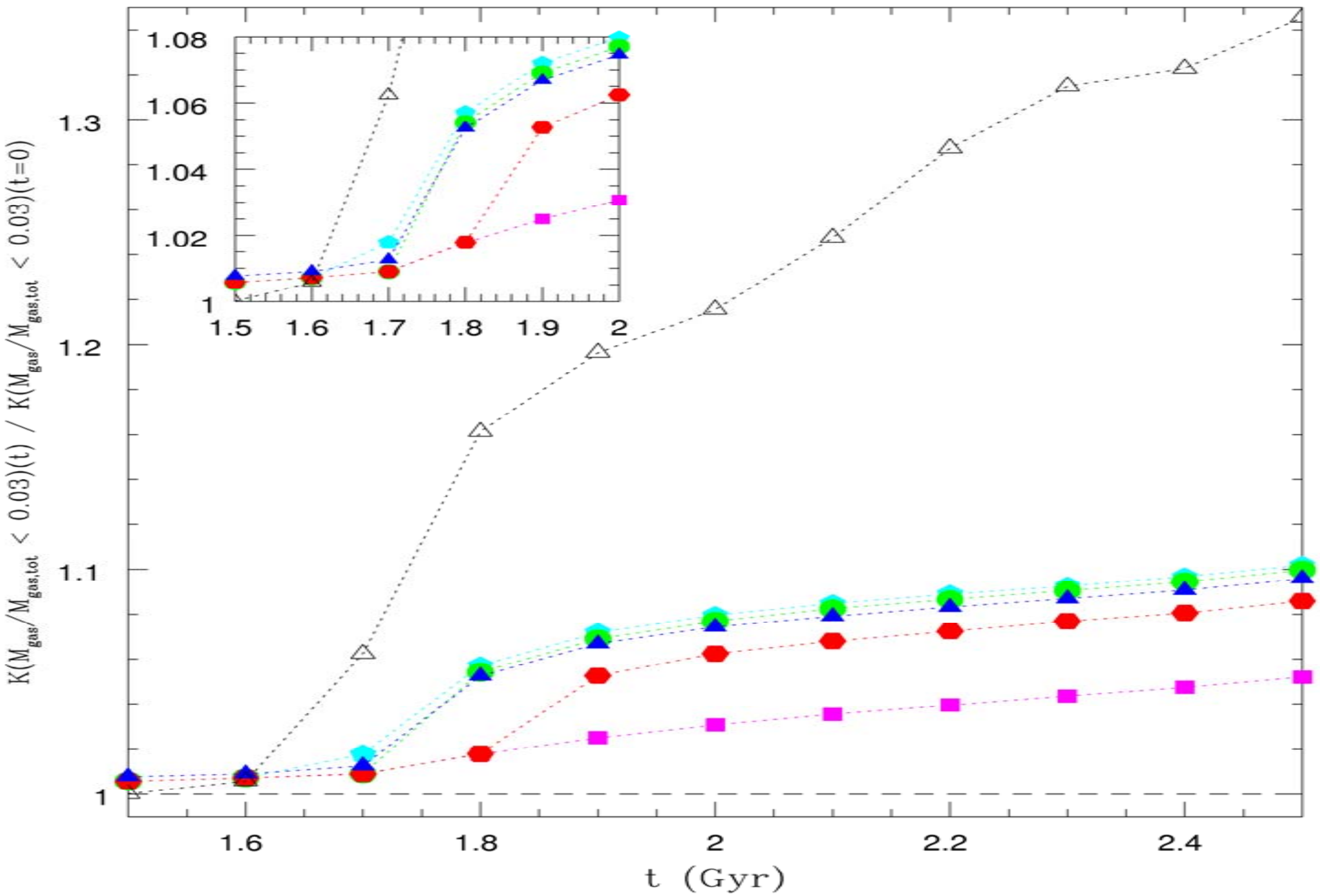
Application of a sub-sonic bulk flow changes the amount of material which will be able to interact at the cell boundary



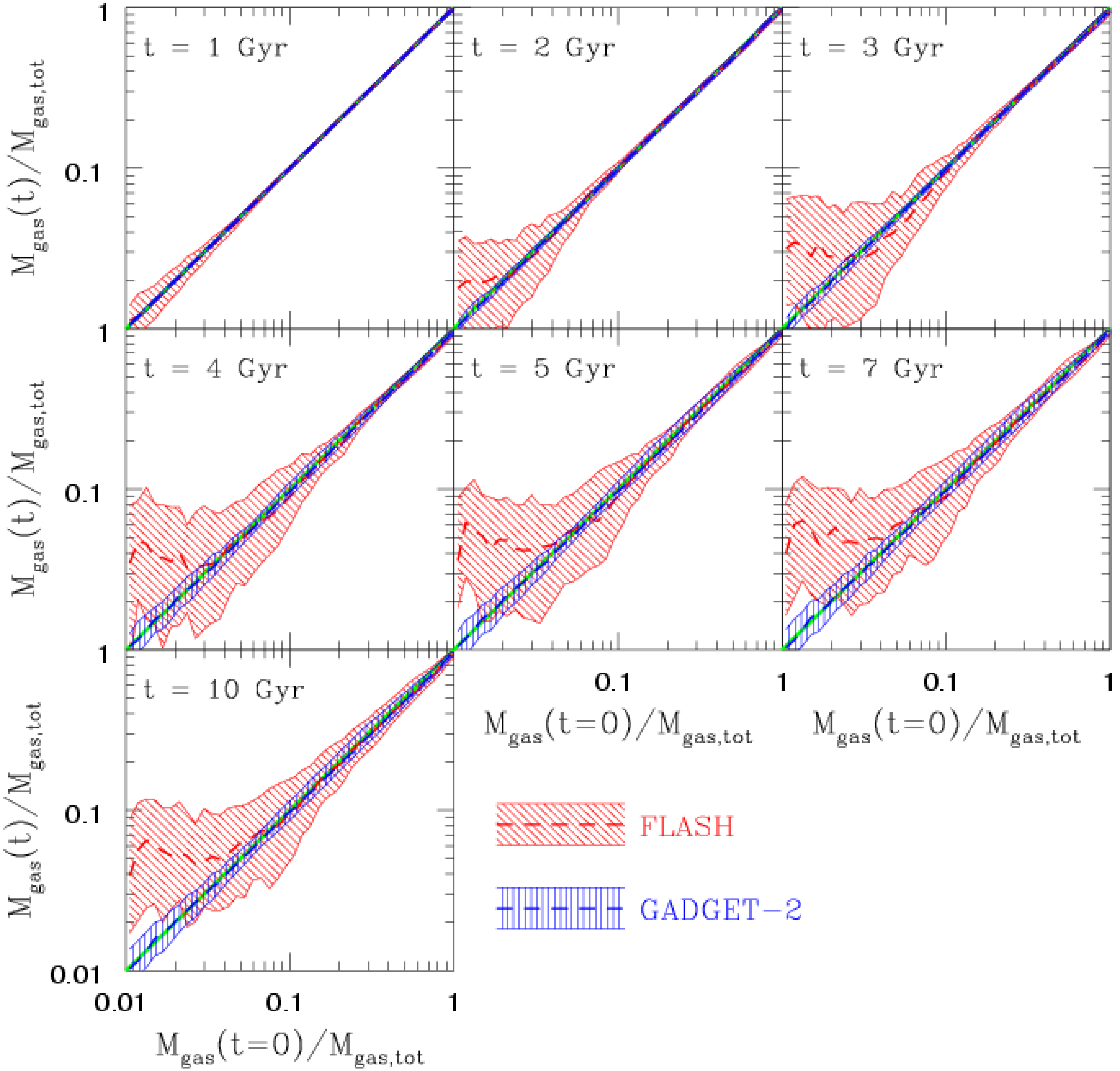
Application of a super-sonic bulk flow drastically alters the Riemann problem conditions



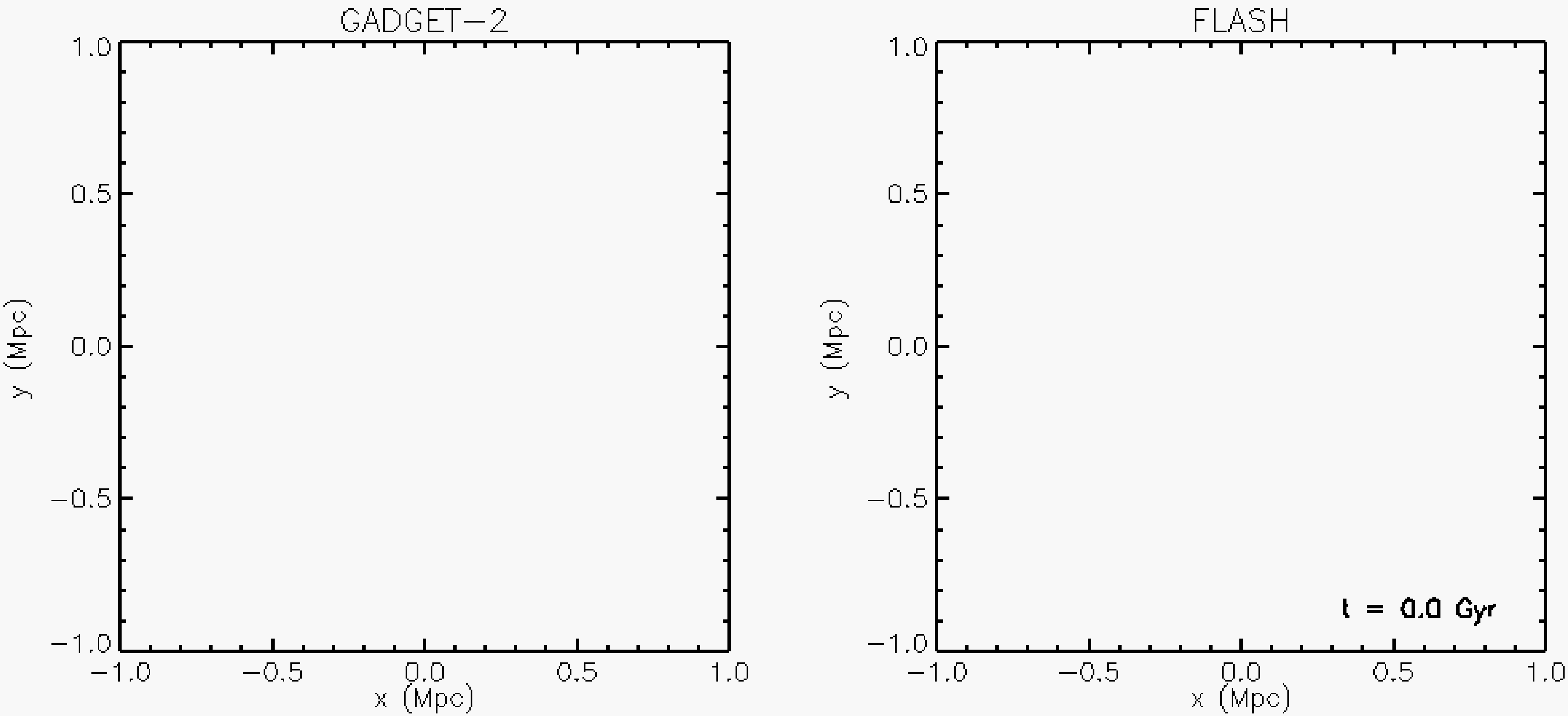
default
static vs. V_circ
static vs. V_circ
(reduced time steps)
inclined 33 deg.
inclined 45 deg., l=7
inclined 45 deg., l=8
4
3.5
3
2.5
2
1.5
1
0.01
0.1
K(<M_gas)_FLASH / K(<M_gas)_FLASH(t=0)
M_gas/M_gas,tot



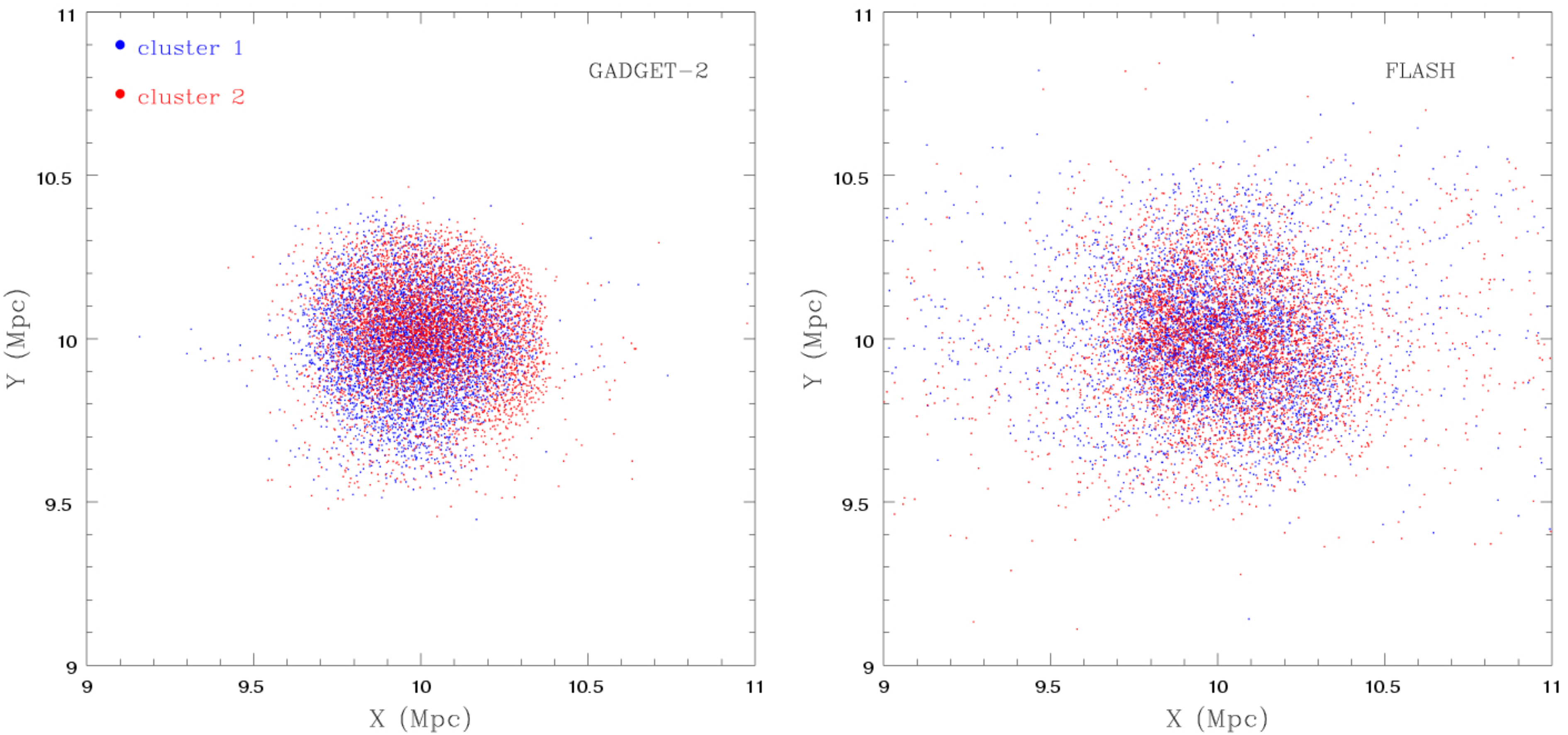
K(M_gas/M_gas,tot < 0.03)(t) / K(M_gas/M_gas,tot < 0.03)(t=0)
t (Gyr)
1.6
1.8
2
2.2
2.4
1
1.1
1.2
1.3
1.5
1.6
1.7
1.8
1.9
2
1
1.02
1.04
1.06
1.08



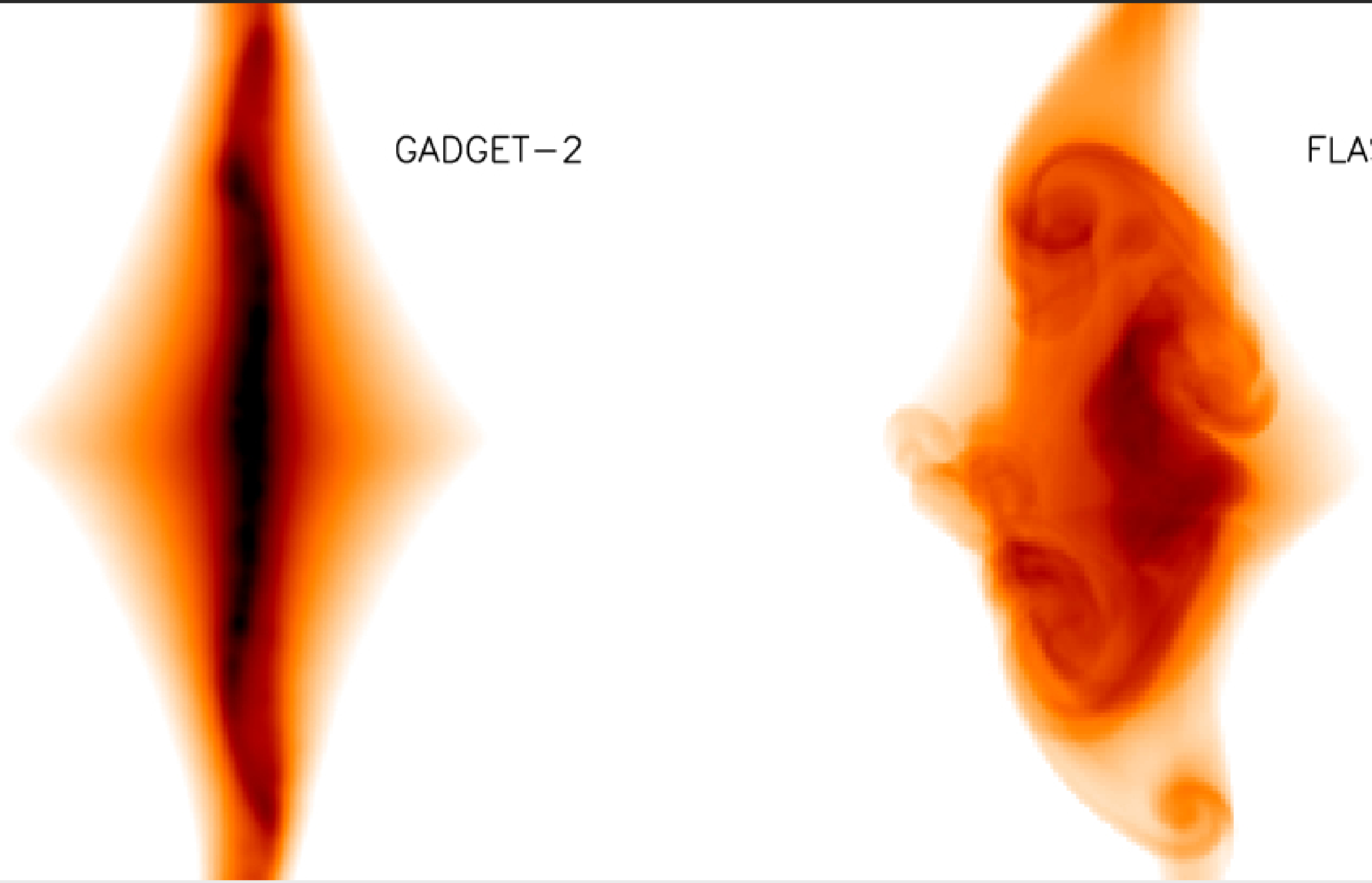
t = 1 Gyr
t = 2 Gyr
t = 3 Gyr
t = 4 Gyr
t = 5 Gyr
t = 7 Gyr
t = 10 Gyr
$M_{gas}(t)/M_{gas,tot}$
$M_{gas}(t=0)/M_{gas,tot}$
0.01
0.1
1
FLASH
GADGET−2


GADGET−2
FLASH
y (Mpc)
x (Mpc)
1.0
0.5
0.0
−0.5
−1.0
t = 0.0 Gyr

Gadget-2 FLASH



- The final spatial distribution of particles (tracer particles in the case of FLASH) with the lowest initial entropies (we select the central 5% of particles/tracer particles in both clusters). Red particles belong to one cluster and the blue to the other.



- Gadget-2 FLASH
- Logarithmic projected entropy maps of the default merger simulation at t=2.3 Gyr.

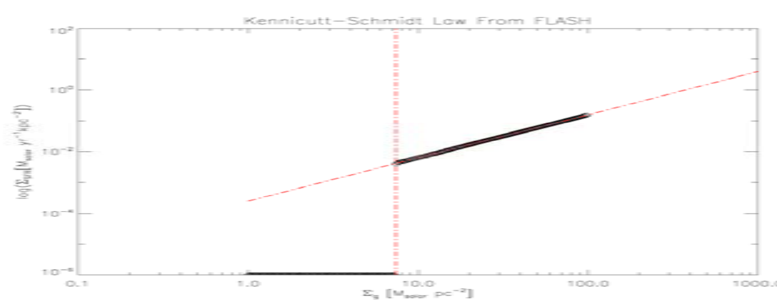
- ***GIMIC*** – Galaxies Intergalactic Medium Interaction Calculation.
- Includes metal dependant cooling, star formation and supernova feedback.
- Five spheres with radius *18-25 h-1 Mpc* chosen from the Millenium cosmological dark matter simulation
- Carefully selected to give a range of over and under densities relative to the critical density: *-2,-1,0,+1,+2 σ*
- *(see Crain et al., 2009,* arXiv:0906.4350)
- ***OWLS*** – Over Whelmingly Large Simulations project
- Suite of over 50 large cosmological simulations
- Same physics as in GIMIC
- Determines the effect of varying different sub-grid physics
- (see Schaye, 2009, arXiv:0909.5196)

Star formation

- **Recipe of Schaye & Dalla Vecchia (2008, arXiv:0709.0292)**
- **Derived from empirical relations. Relates surface densities to volume densities allowing any arbitrary Kennicutt-Schmidt star formation law to be reproduced.**

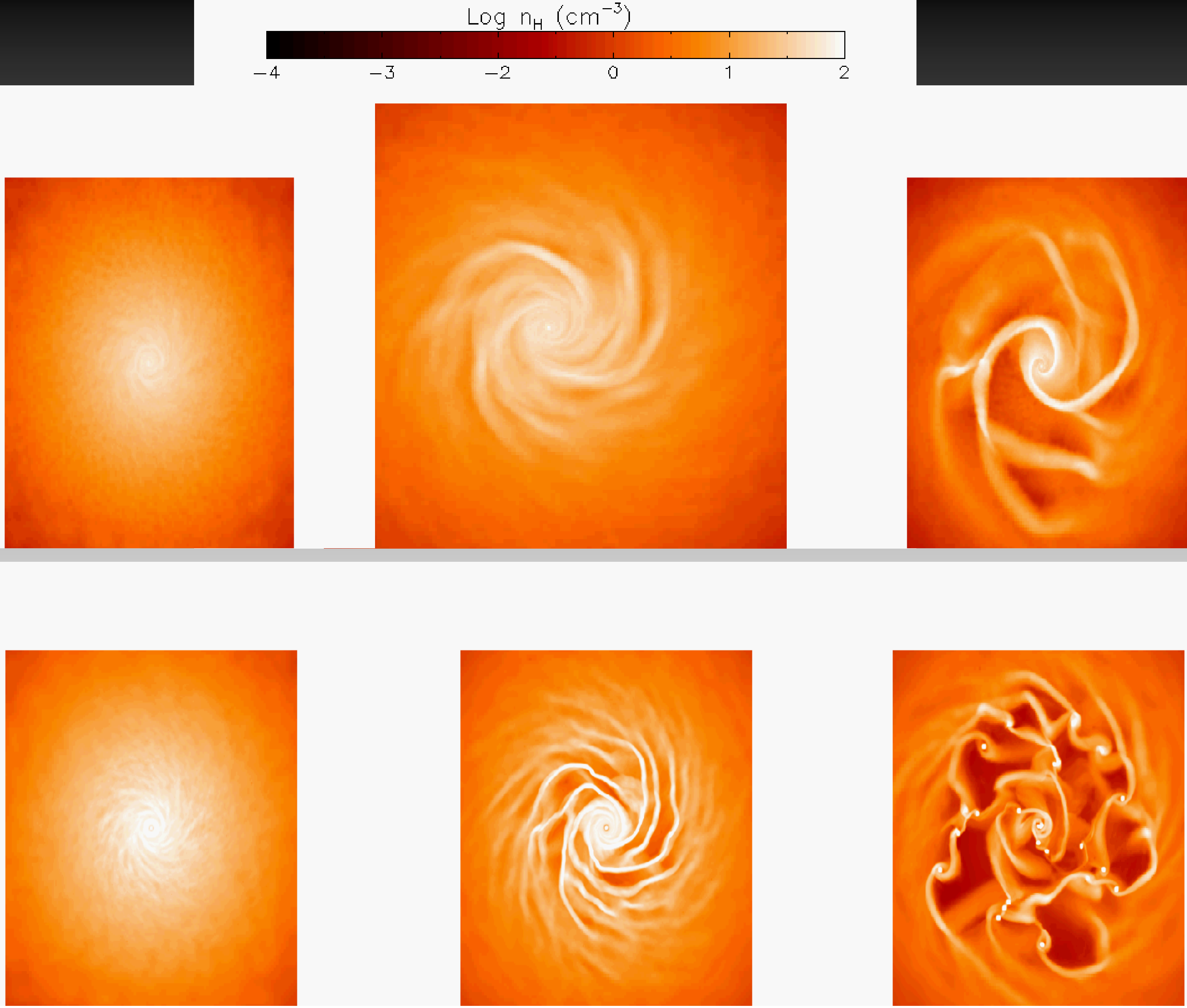
$$\dot{\Sigma}_* = (2.5\pm0.7)\times10^{-4}\,\mathrm{M_\odot\,yr^{-1}\,kpc^{-2}}\left(\frac{\Sigma_\mathrm{g}}{1\ \mathrm{M_\odot\,pc^{-2}}}\right)^{(1.4\pm0.15)}$$

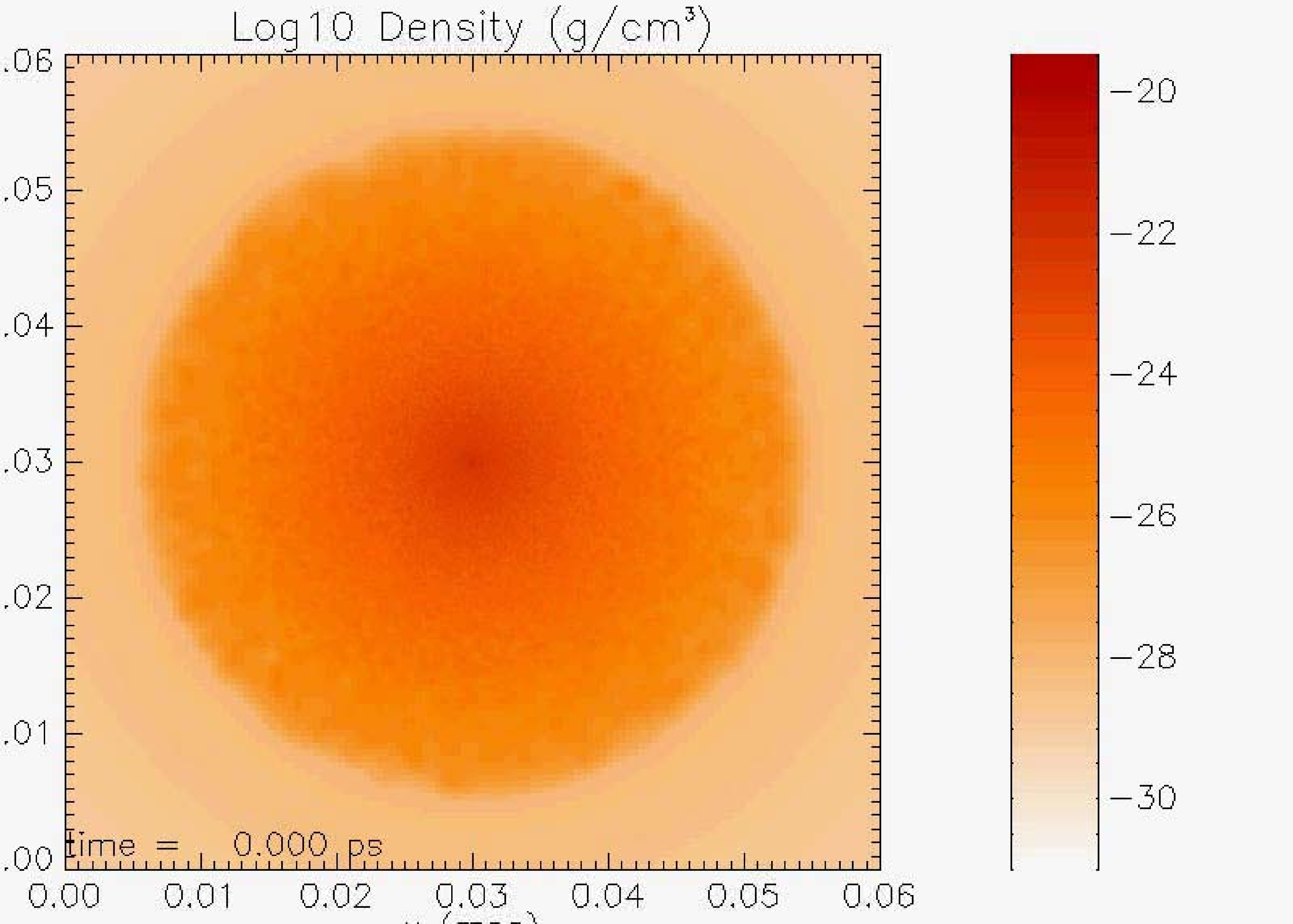
$$\dot{m}_* \;=\; A\left(1\ \mathrm{M_\odot\,pc^{-2}}\right)^{-n} m_\mathrm{g}\left(\frac{\gamma}{G}f_\mathrm{g}P_\mathrm{tot}\right)^{(n-1)/2}$$

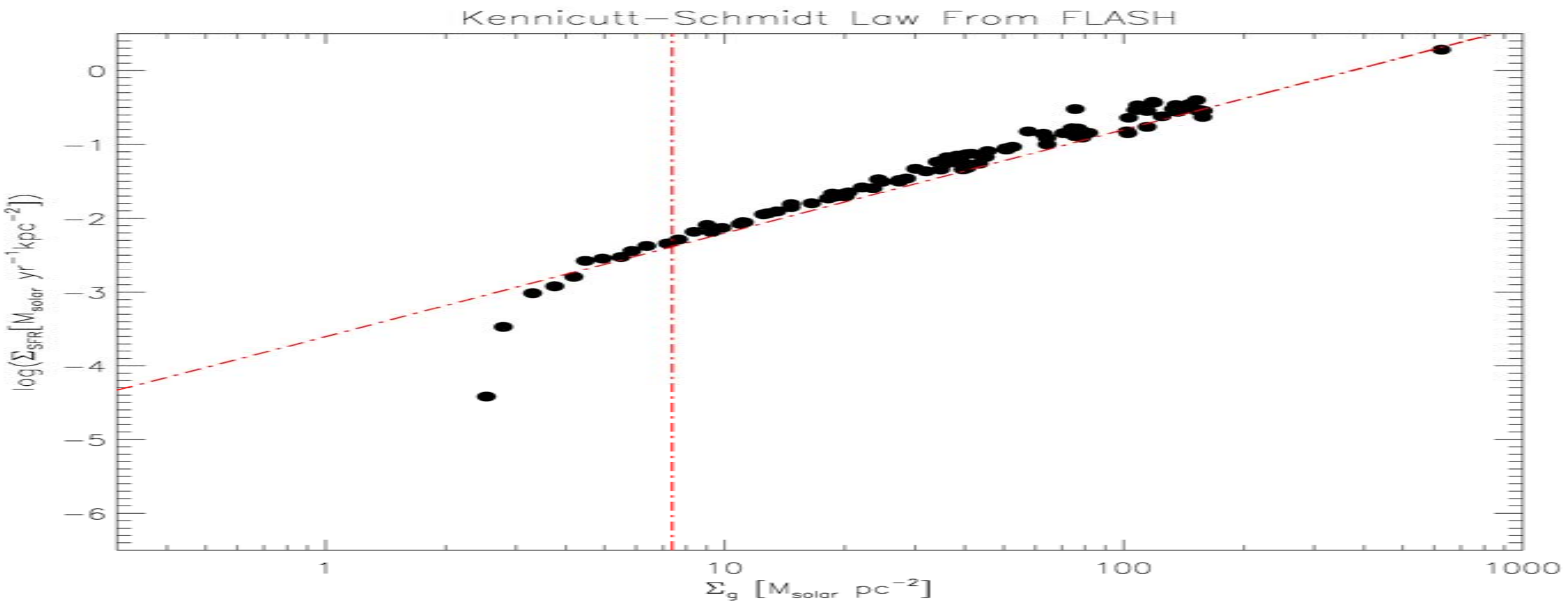


Need to adopt a Polytropic Equation of State to allow our single phase medium to represent the unresolved multi-phase ISM

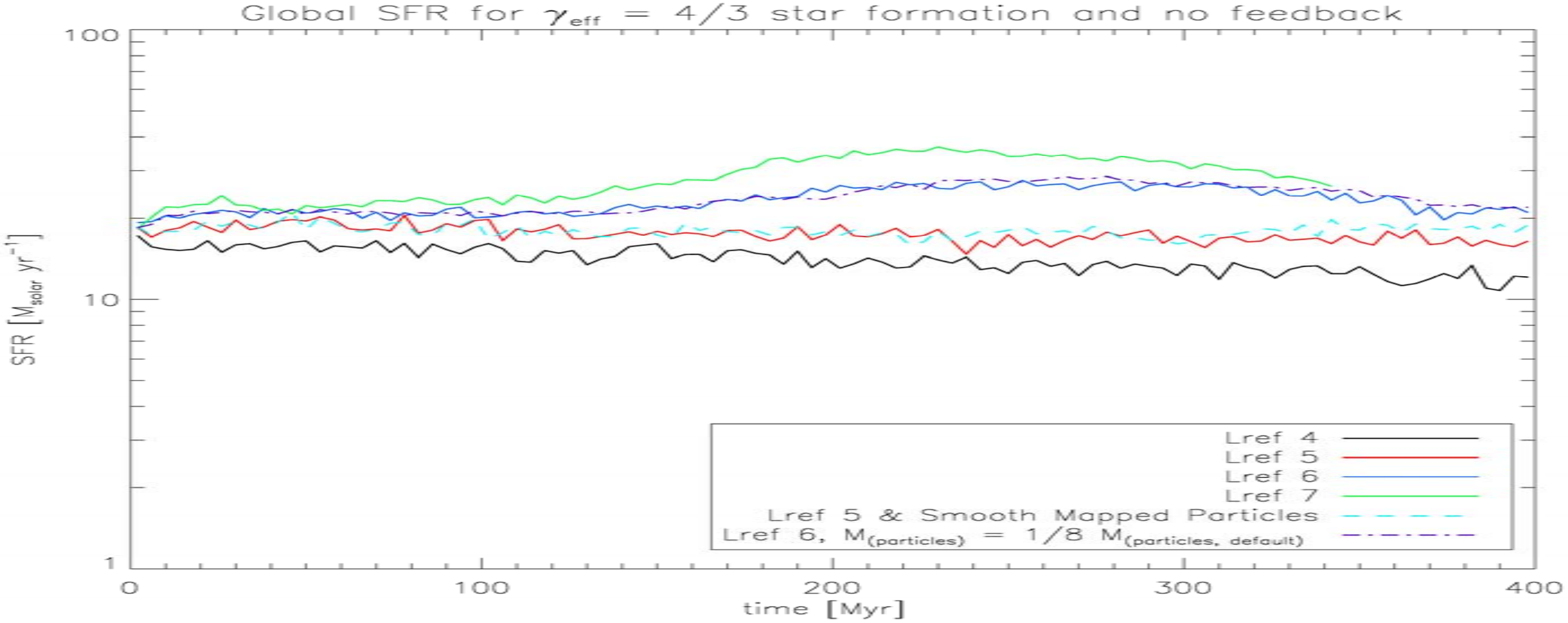
$$P_{\rm tot} = P_{\rm tot,c} \left(\frac{\rho_{\rm g}}{\rho_{\rm g,c}} \right)^{\gamma_{\rm eff}}$$


Log n_H (cm^-3)
−4
−3
−2
0
1
2

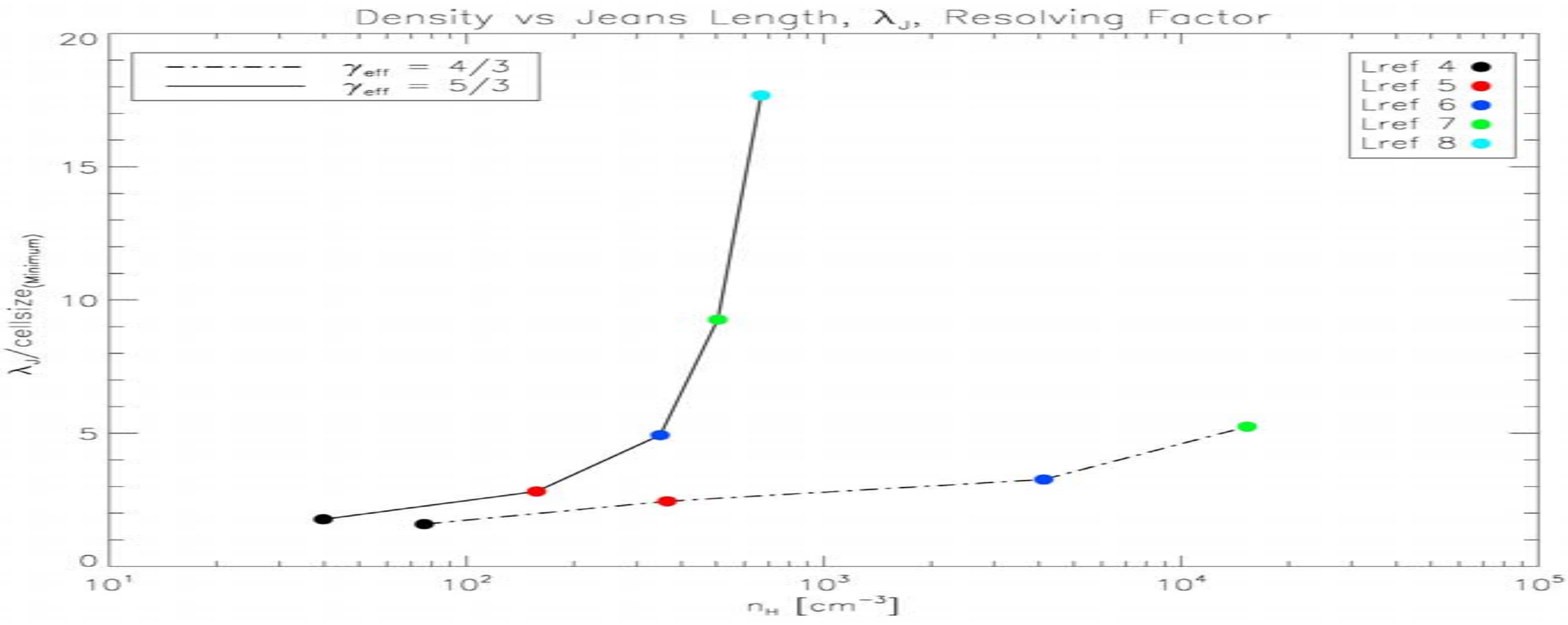

Log10 Density (g/cm³)
.06
.05
.04
.03
.02
.01
.00
0.00
0.01
0.02
0.03
0.04
0.05
0.06
time = 0.000 ps
−20
−22
−24
−26
−28
−30



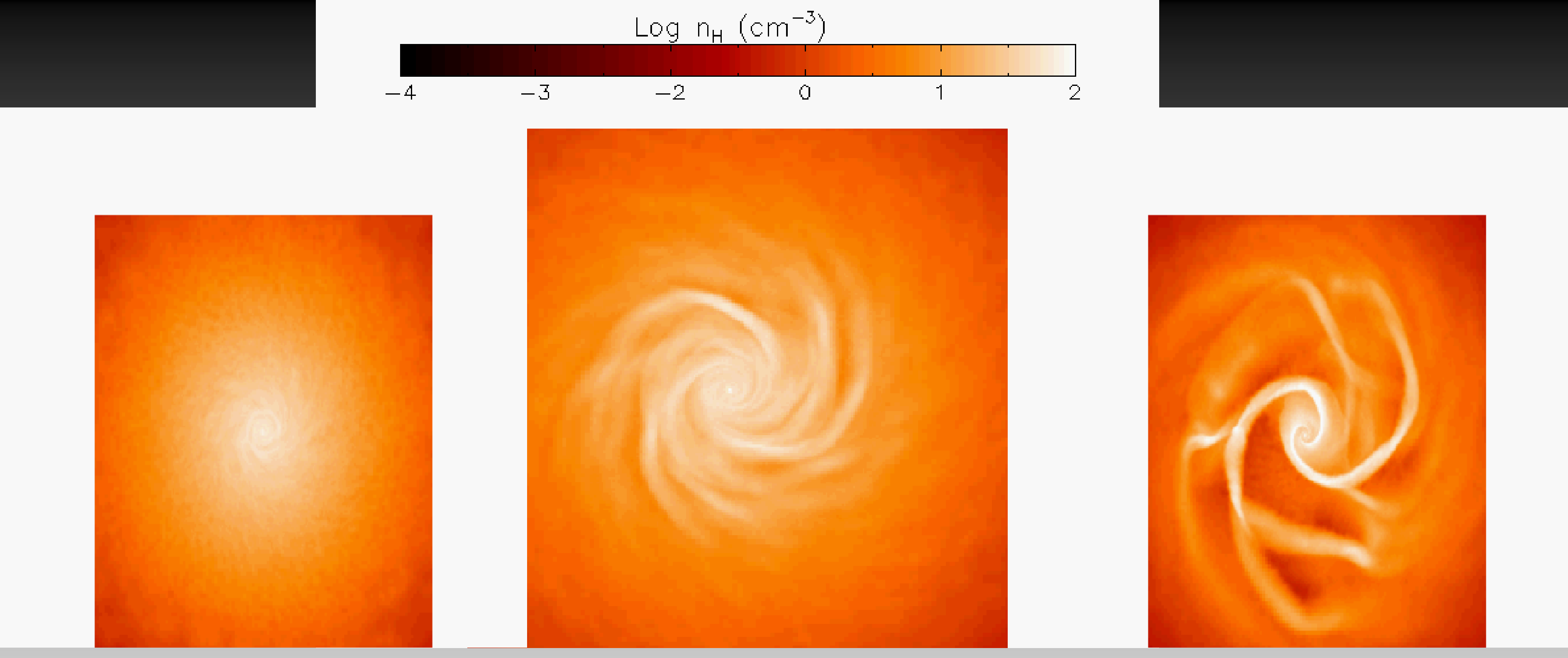
Kennicutt–Schmidt Law From FLASH
0
−1
−2
−3
−4
−5
−6
1
10
100
1000
$\log(\Sigma_{SFR}[M_{solar}\ yr^{-1} kpc^{-2}])$
$\Sigma_g\ [M_{solar}\ pc^{-2}]$

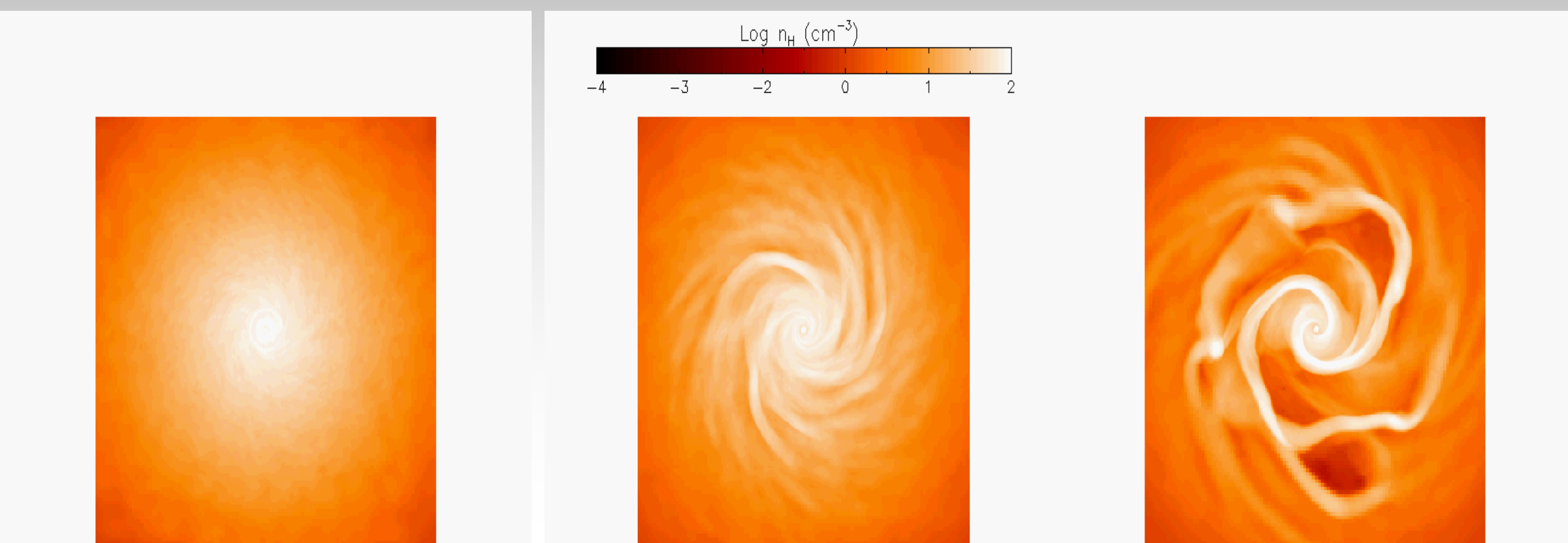


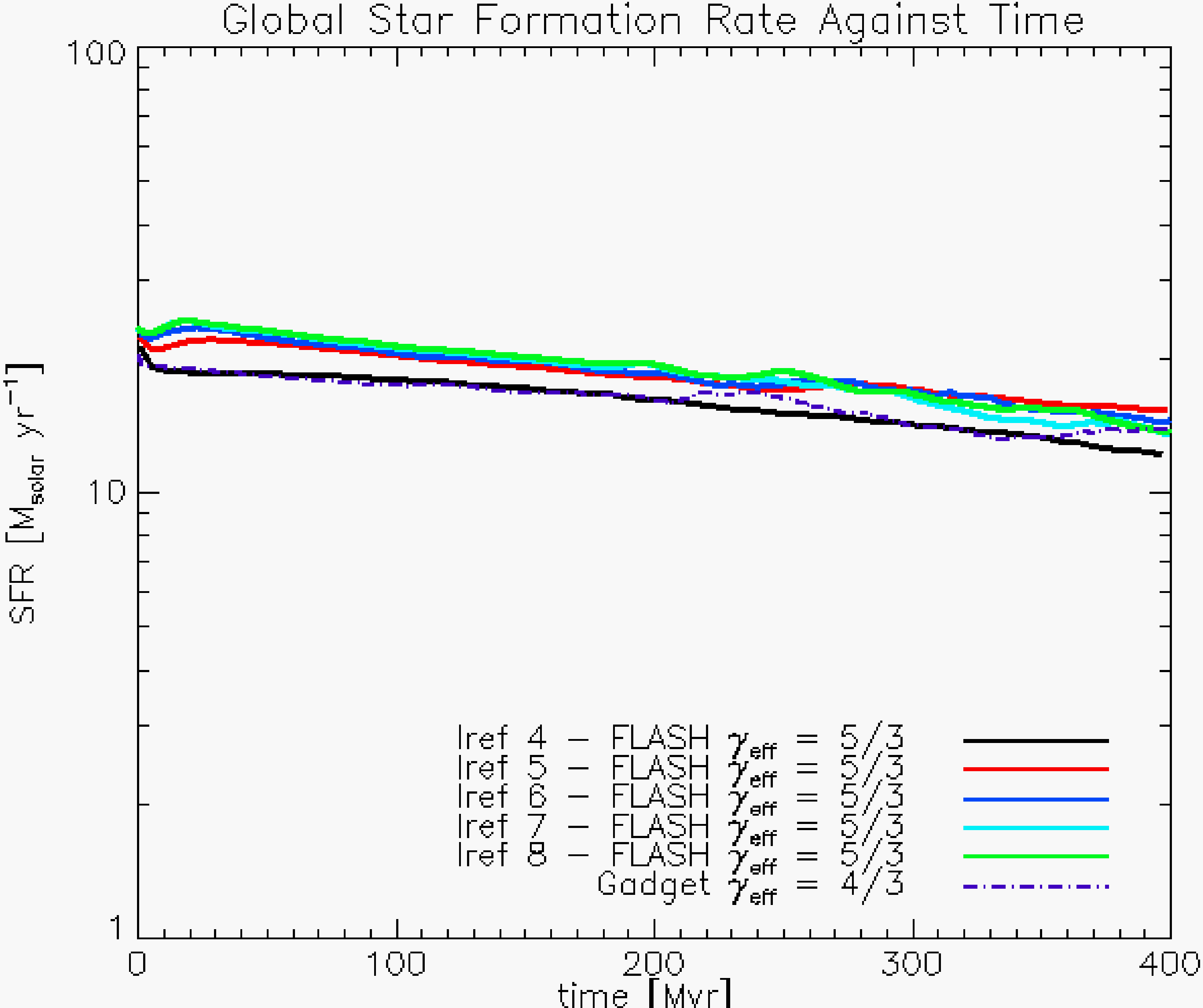
Global SFR for γ_{eff} = 4/3 star formation and no feedback
100
10
1
SFR [M_{solar} yr^{-1}]
0
100
200
300
400
time [Myr]
Lref 4
Lref 5
Lref 6
Lref 7
Lref 5 & Smooth Mapped Particles
Lref 6, $M_{(particles)}$ = 1/8 $M_{(particles, default)}$



Density vs Jeans Length, λ_J, Resolving Factor
γ_{eff} = 4/3
γ_{eff} = 5/3
Lref 4
Lref 5
Lref 6
Lref 7
Lref 8
λ_J/cellsize$_{(Minimum)}$
n_H [cm^{-3}]
0
5
10
15
20
10^1
10^2
10^3
10^4
10^5


Log nH (cm−3)
−4
−3
−2
0
1
2


Log nH (cm−3)
−4
−3
−2
0
1
2


Global Star Formation Rate Against Time
100
10
1
SFR [M_{solar} yr^{-1}]
0
100
200
300
400
time [Myr]
lref 4 – FLASH γ_{eff} = 5/3
lref 5 – FLASH γ_{eff} = 5/3
lref 6 – FLASH γ_{eff} = 5/3
lref 7 – FLASH γ_{eff} = 5/3
lref 8 – FLASH γ_{eff} = 5/3
Gadget γ_{eff} = 4/3

Assume a fraction of energy from supernova is carried by the wind

Remaining energy corresponds to the energy needed to maintain the polytropic EOS.

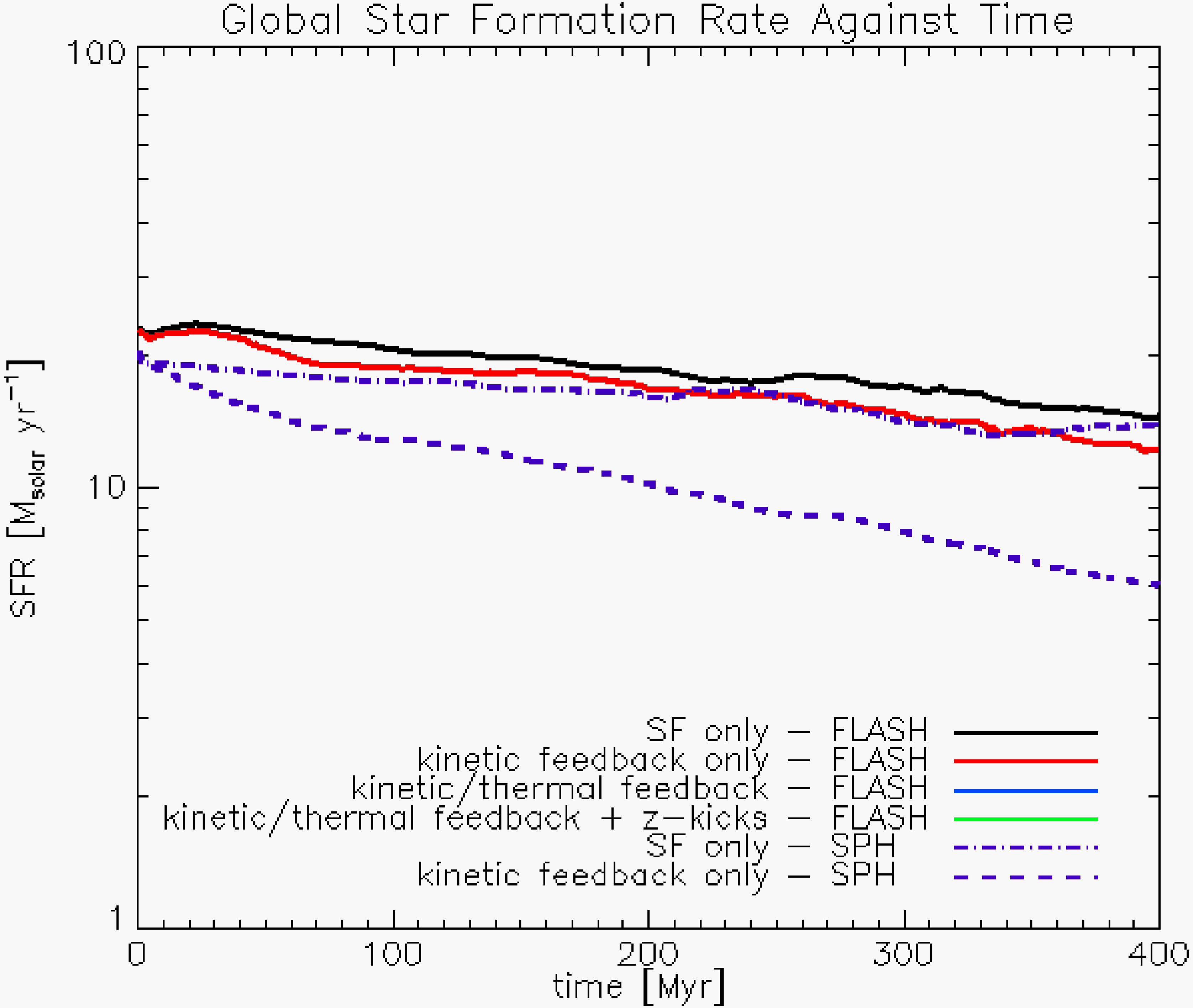
Kicks cells stochastically with a given probability

- Adopt a kinetic feedback prescription as described in Dalla Vecchia & Schaye (2008).

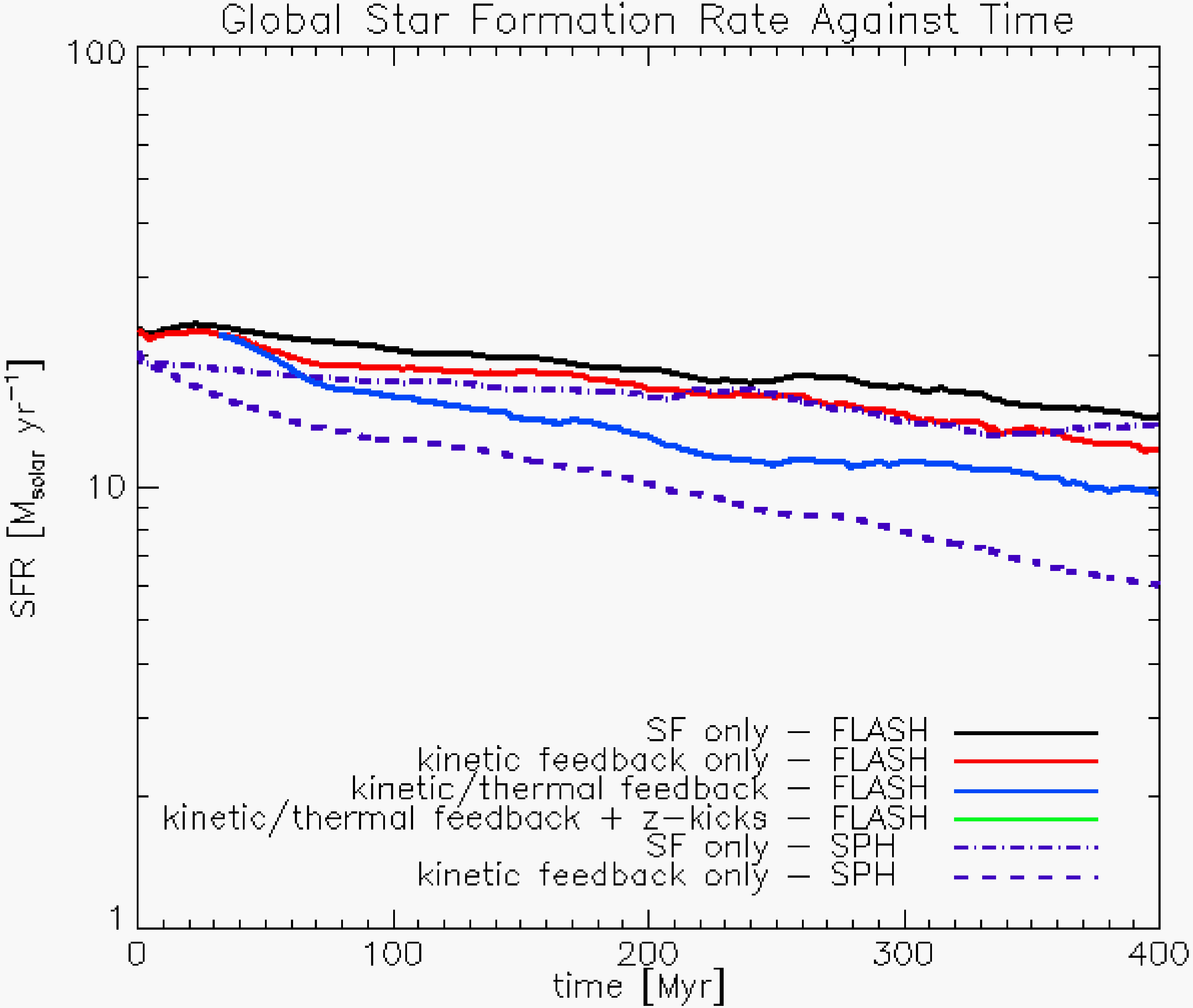
- Assume a fraction of energy from supernova is carried by the wind
- Rem… sponds to the energy needed to mainta… S.
- Kick… y with a given probability

$$f_{\rm w} = \frac{\eta v_{\rm w}^2}{2\epsilon_{\rm SN}}$$

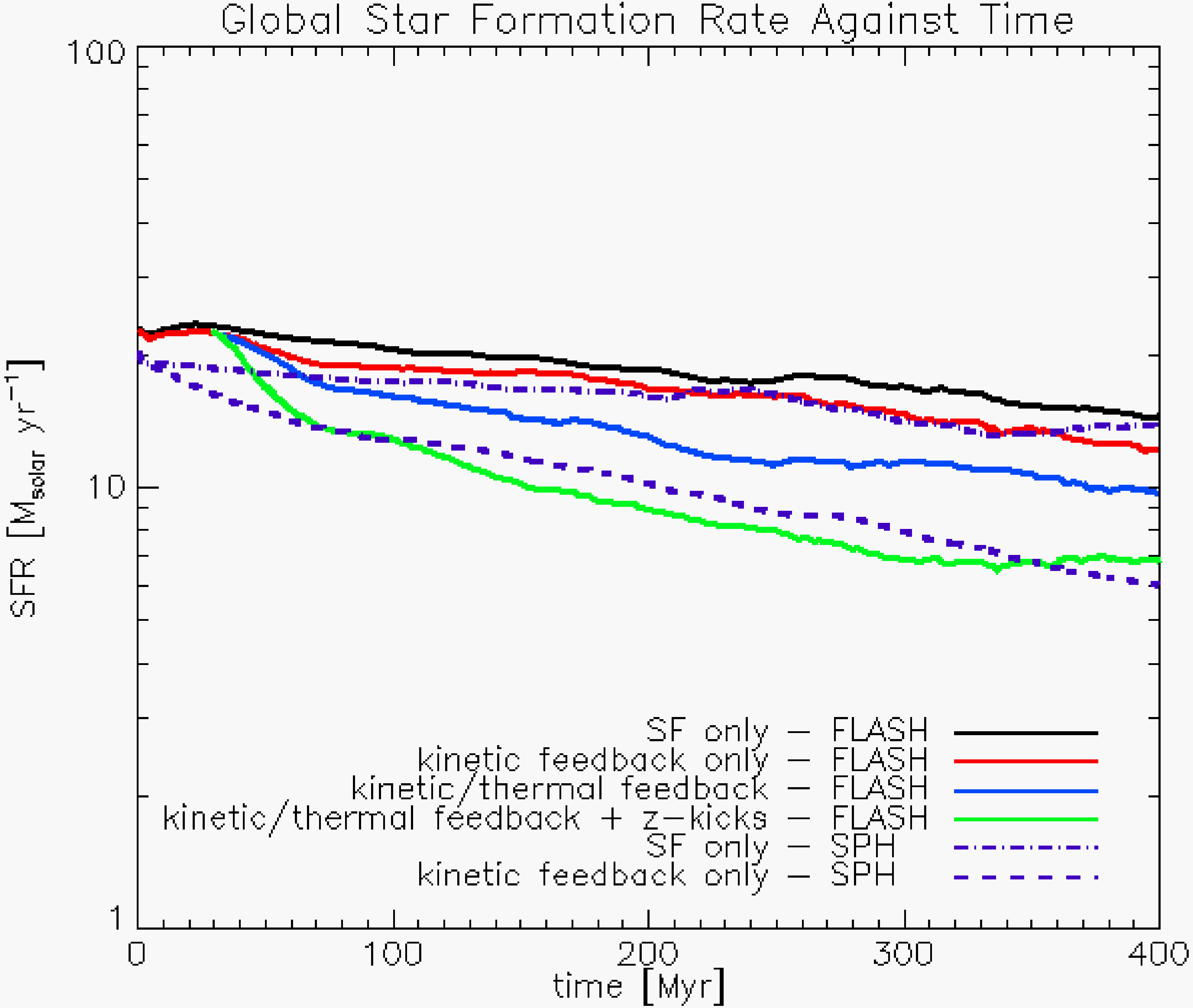
$$Prob = \eta \frac{m_*}{\sum_{i=1}^{N_{\rm ngb}} m_{g,i}}$$

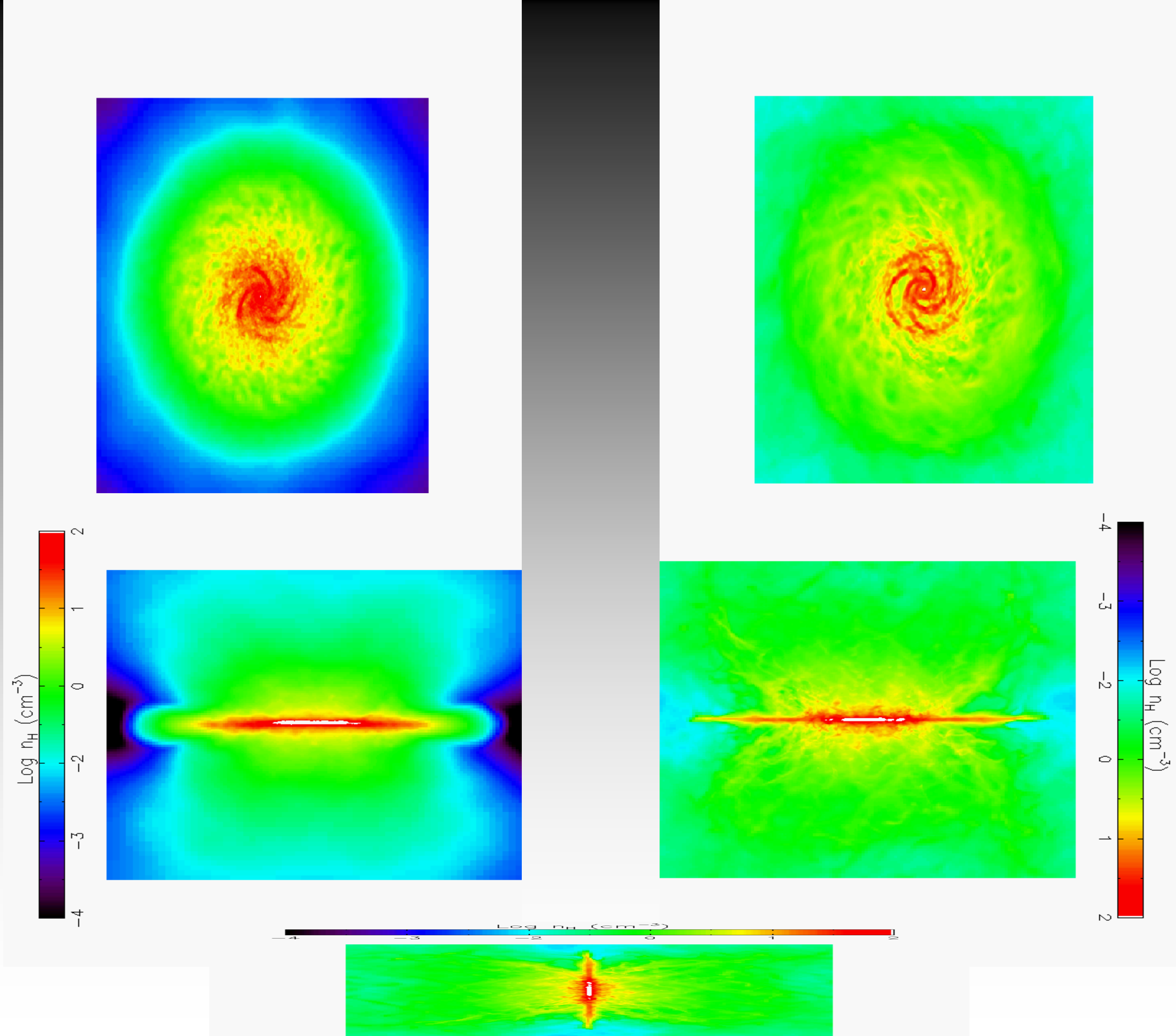


Global Star Formation Rate Against Time
100
10
1
SFR [M_{solar} yr^{-1}]
0
100
200
300
400
time [Myr]
SF only – FLASH
kinetic feedback only – FLASH
kinetic/thermal feedback – FLASH
kinetic/thermal feedback + z-kicks – FLASH
SF only – SPH
kinetic feedback only – SPH



Global Star Formation Rate Against Time
100
10
1
SFR [M_solar yr^-1]
0
100
200
300
400
time [Myr]
SF only – FLASH
kinetic feedback only – FLASH
kinetic/thermal feedback – FLASH
kinetic/thermal feedback + z-kicks – FLASH
SF only – SPH
kinetic feedback only – SPH


Global Star Formation Rate Against Time
100
10
1
SFR [M$_{solar}$ yr^{-1}]
0
100
200
300
400
time [Myr]
SF only – FLASH
kinetic feedback only – FLASH
kinetic/thermal feedback – FLASH
kinetic/thermal feedback + z–kicks – FLASH
SF only – SPH
kinetic feedback only – SPH


Log n_H (cm^-3)
2
1
0
-2
-3
-4
Log n_H (cm^-3)
-4
-3
-2
0
1
2

Conclusions

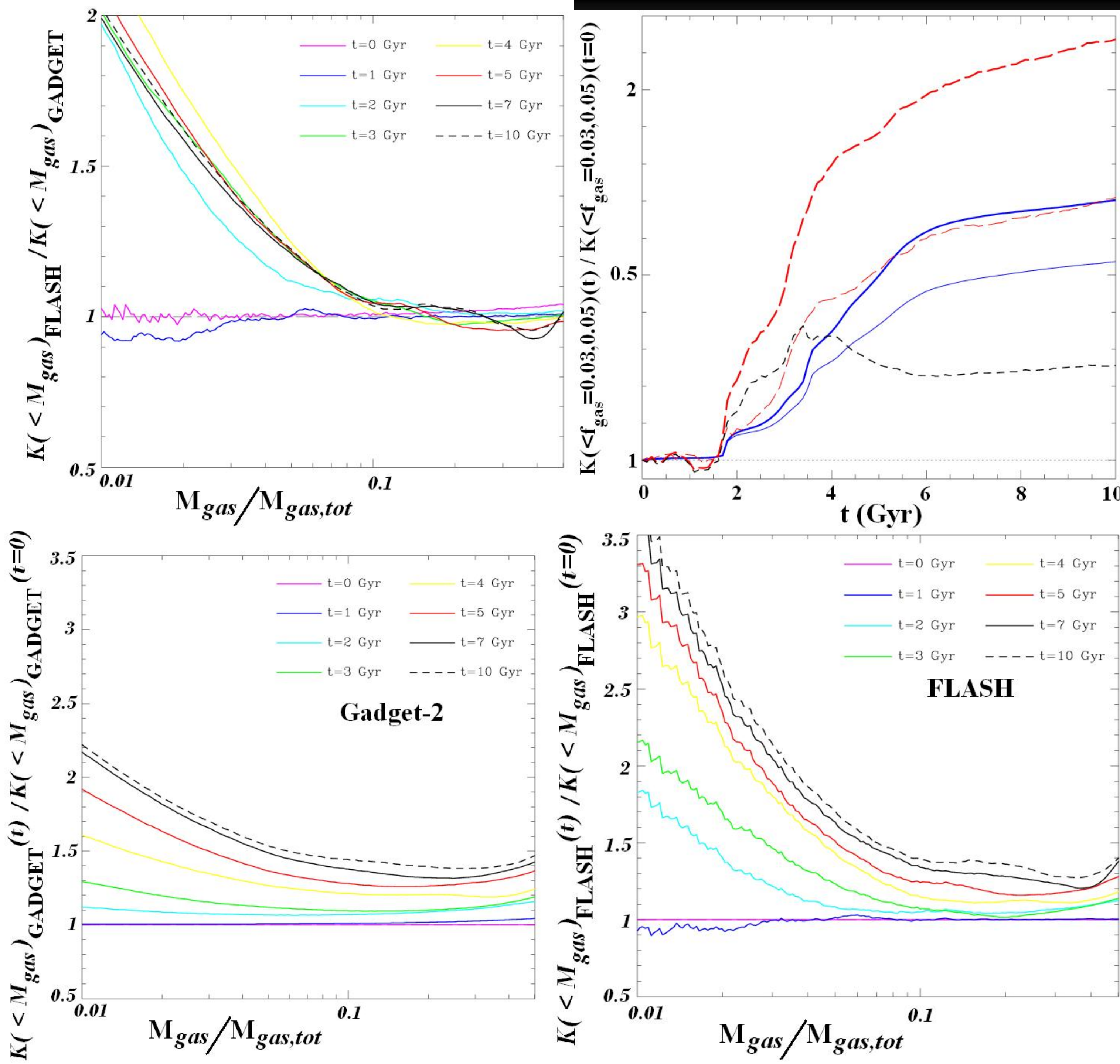
- Fundamental differences in the two hydrodynamic implementations adopted by AMR and SPH codes lead to startling differences between numerical simulations.
- SPH codes suppress turbulent instabilities which in AMR codes generate higher entropy cores during mergers.
- Turbulent mixing could reduce the need for pre-heating and feedback during the creation of non-cool core clusters which SPH codes have problems dealing with.
- The behaviour of identically implemented sub-grid techniques shows distinct differences between the two codes.
- AMR codes demonstrate a much higher effective mass loading than in SPH codes which seem to allow particles to free stream out of the galaxy much easier.
- Identical star formation rates can be obtained but the resulting galaxy physiology shows substantial differences.

Thank you for listening, any Questions?

GADGET-2

FLASH

t = 0.0 Gyr


t=0 Gyr
t=1 Gyr
t=2 Gyr
t=3 Gyr
t=4 Gyr
t=5 Gyr
t=7 Gyr
t=10 Gyr
$K(<M_{gas})_{FLASH}/K(<M_{gas})_{GADGET}$
$M_{gas}/M_{gas,tot}$
$K(<f_{gas}=0.03,0.05)(t) / K(<f_{gas}=0.03,0.05)(t=0)$
t (Gyr)
Gadget-2
$K(<M_{gas})_{GADGET}(t) / K(<M_{gas})_{GADGET}(t=0)$
FLASH
$K(<M_{gas})_{FLASH}(t) / K(<M_{gas})_{FLASH}(t=0)$