Galaxy formation and evolution with a sub-resolution prescription

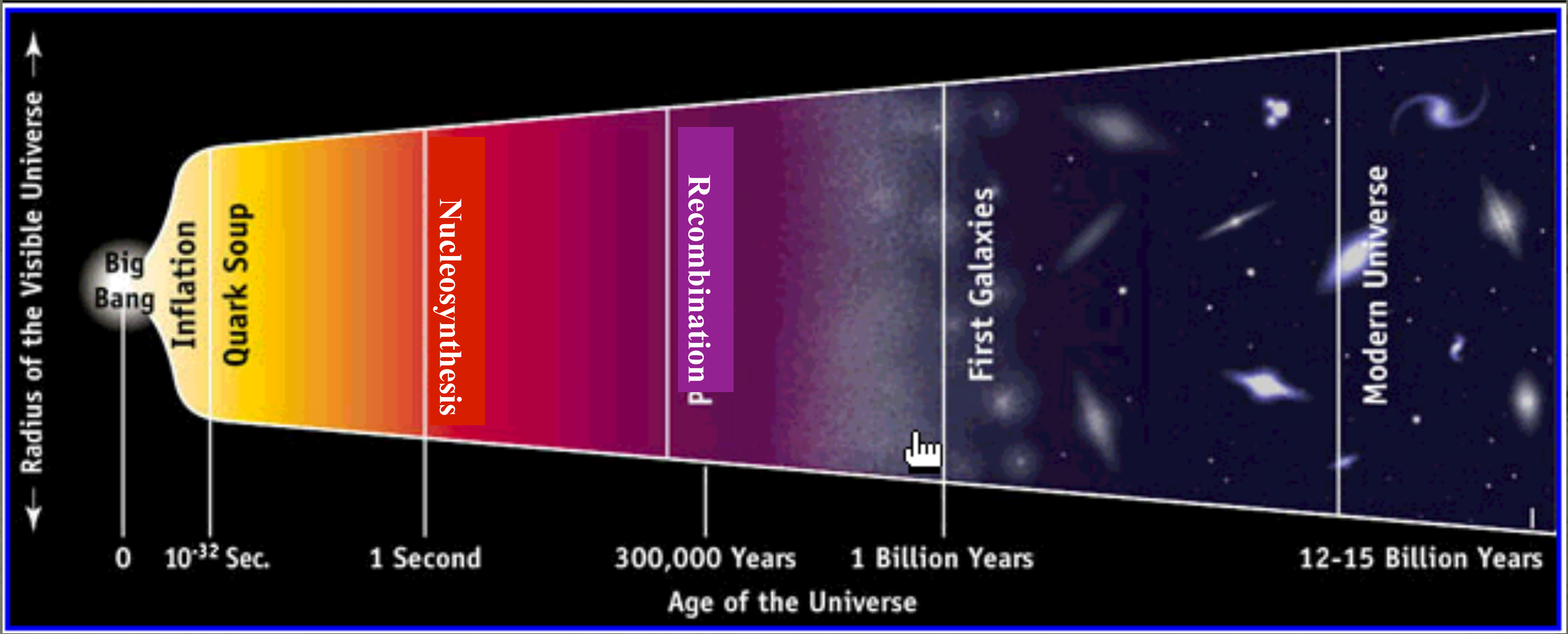
G. Murante, INAF-OATs

with: P. Monaco, S. Borgani, D. Goz, A. Ragagnin, L. Tornatore, G. De Lucia, S. Planelles, M. Viel, P. Barai, M. Hirshmann, G. Granato, C. Ragone, K. Dolag, M. Baldi, L. Moscardini, M. Roncarelli…

et al

MILANO, SAIT 2014

Cosmic Structure Formation



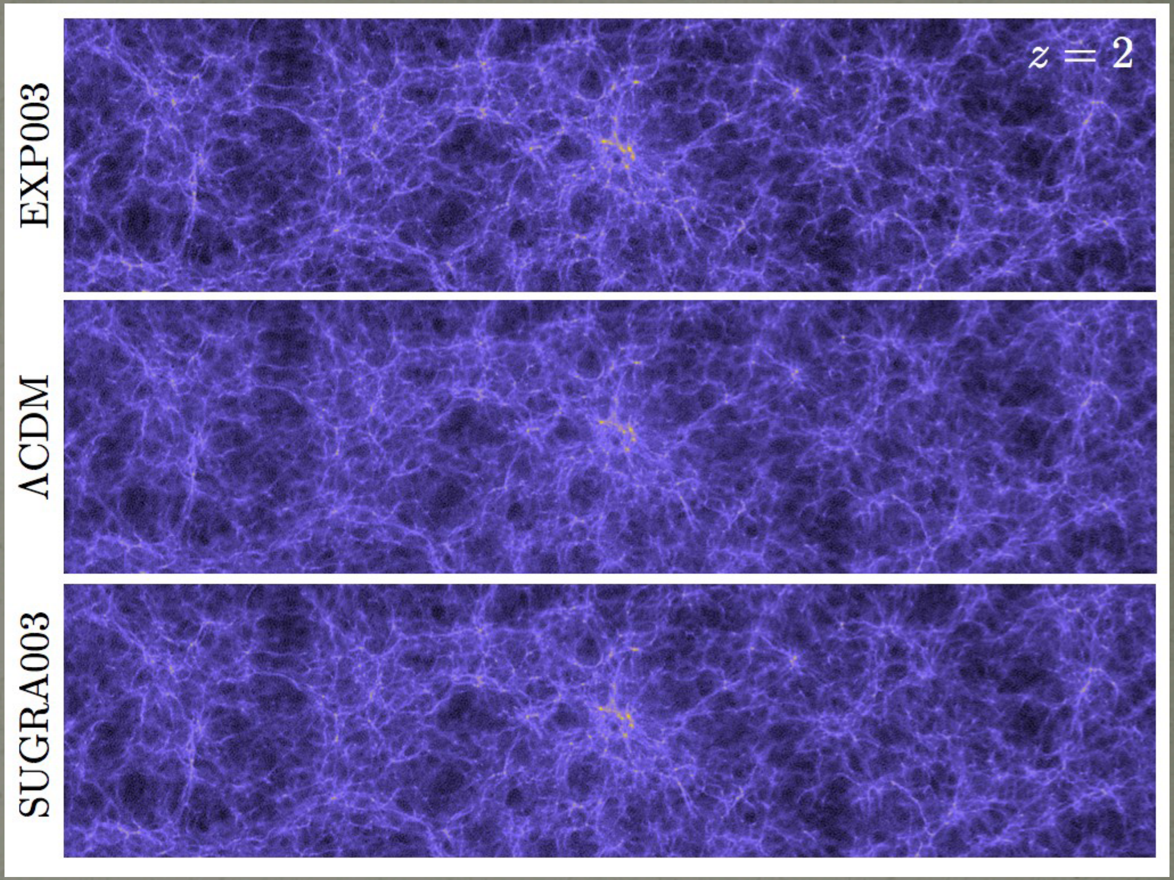
linear perturbation theory

nonlinear simulations

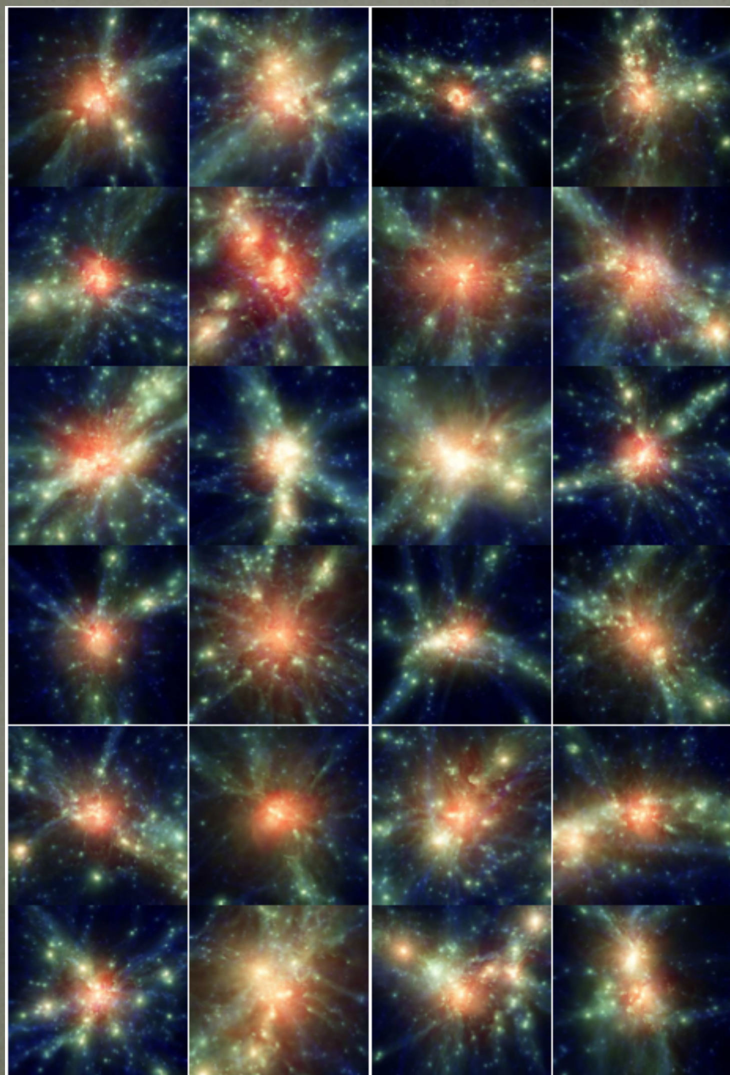
Forming structures with simulations

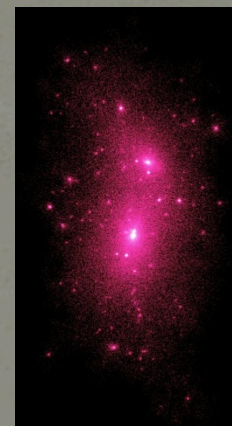
LARGE scale:
DM only, various cosmological models

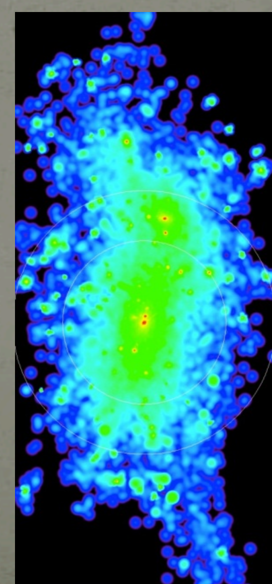
(E.G., Baldi+,2012)

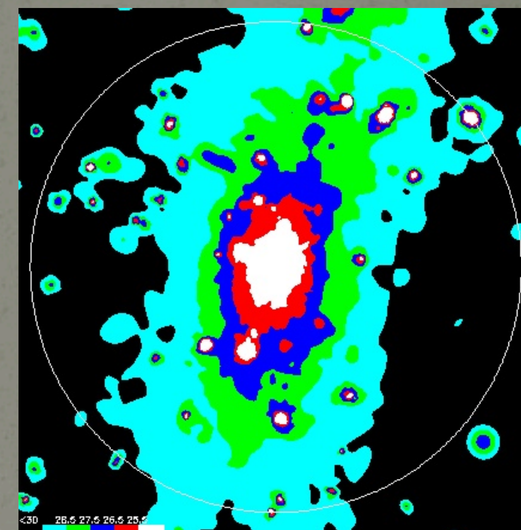


Galaxy cluster simulations









E.G.: Planelles+, 2014

Disk galaxy simulations

First reliable simulations only since a few years!

(see: Aquila comparison project)

E.G. Murante+, Goz+, submitted

Baryon physics needed for comparing theory and observations in the «precision cosmology» era:

Cui+ 2013, 2014; Vogelsberger+ 2014; Vellisigh+ 2014

Italian collaborations

- «**Towards an Italian network for computational cosmology**», PRIN INAF 2010, PI M. Viel, OATS, OATO, IRABO, UNIBO, focus:
  - Imprint of feedback on IGM/ICM
  - Galaxy formation
  - Non-thermal phenomena in galaxy clusters
  - Simulations on non-standard cosmologies
- «**The Universe in a Box: Multi-scale Simulations of Cosmic Structures**», PRIN INAF 2012, PI G. Murante, OATS, UNIBO
  - Galaxy formation
  - Galaxy clusters
  - Analysis of non-standard cosmologies simulations
  - Resimulations of single objects from them

Galaxy formation with numerical simulation

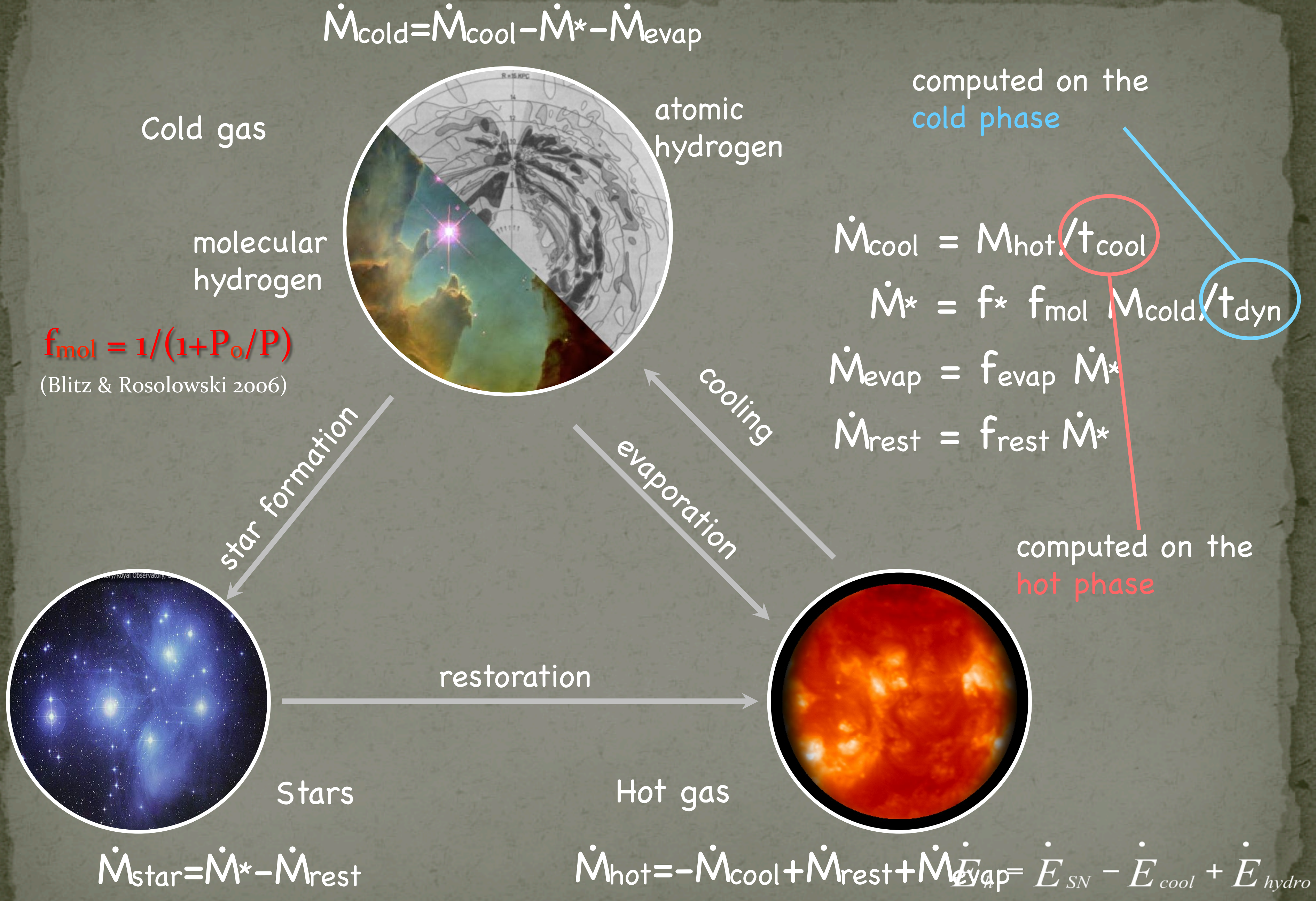
- (Most) multiscale problem, *needs* HPC!! Is first principle approach possible? Will be with future facilities?
- Code we used: GADGET-3 (Non-public TreePM+SPH evolution of the public code GADGET-2)
- Parallelized with MPI+OpenMP
- PM (density field sampled by particles and used to calculate gravitational potential, used to evolve particles) at large scale
- Tree code (direct particle interactions at small scales, interaction with center of mass of cells at larger ones)
- SPH: thermodynamical quantities smoothed on gas particles using a kernel
- Galaxy formation: need to treat astrophysical processes like cooling, star formation, UV heating…

MUlti-Phase Particle Integrator (MUPPI):

a new sub-resolution model for star formation and feedback in SPH simulations within Gadget-3

Murante, et al (2012); loosely following Monaco (2004, MNRAS 352, 181)

- gas in multi-phase particles is composed by two phases in thermal pressure equilibrium, plus a stellar component;
- gas molecular fraction is scaled with pressure;
- the evolution of the multi-phase ISM is described by a system of ODEs;
- the system of ODEs is numerically integrated within the SPH time-step (NO equilibrium solutions);
- energy from SNe is injected into the hot diluted phase; SPH hydro is done on this phase
  - ...entrainment of the cold phase...
- particles respond immediately to energy injection



$\dot{M}_{cold}=\dot{M}_{cool}-\dot{M}_{*}-\dot{M}_{evap}$
Cold gas
atomic hydrogen
molecular hydrogen
computed on the cold phase
$\dot{M}_{cool} = M_{hot}/t_{cool}$
$\dot{M}_{*} = f_{*}\ f_{mol}\ M_{cold}/t_{dyn}$
$\dot{M}_{evap} = f_{evap}\ \dot{M}_{*}$
$\dot{M}_{rest} = f_{rest}\ \dot{M}_{*}$
$f_{mol} = 1/(1+P_0/P)$
(Blitz & Rosolowski 2006)
star formation
evaporation
cooling
computed on the hot phase
restoration
Stars
Hot gas
$\dot{M}_{star}=\dot{M}_{*}-\dot{M}_{rest}$
$\dot{M}_{hot}=-\dot{M}_{cool}+\dot{M}_{rest}+\dot{M}_{evap}$
$\dot{E}_{h} = \dot{E}_{SN} - \dot{E}_{cool} + \dot{E}_{hydro}$

Relevant features

- Continuos interaction between hydro (SPH) and ISM characteristics. Determines SF regulation-
- Thermal and kinetic feedback: energy given to neighbours in a directional way
- Destruction of molecular clouds: MP ends after 1-2 dynamical times
- Chemical evolution and metal cooling (Tornatore et al. 2007)
- SK relation is predicted, not imposed
- UV background (Haardt & Madau 1996)
- Low density threshold for multi-phase, $n \sim 0.01\ cm^{-3}$
- ***star formation is significant for (sub-grid) densities of $n_c > P_0 / T_c \sim 70\ cm^{-3}$***
- No early radiative feedback
- The algorithm works at moderate resolution

Cosmological disk galaxy simulations

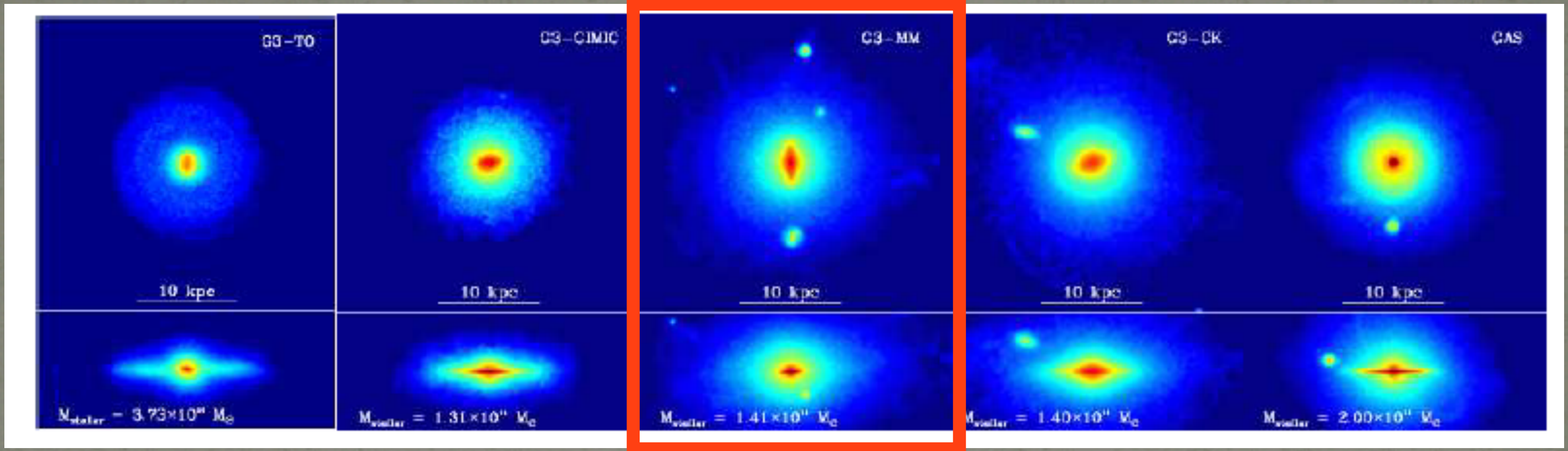
Simulation	M_{DM}	M_{gas}	ϵ_{Pl}	M_{Vir}	R_{Vir}	N_{DM}	N_{gas}	N_{star}
GA0	$1.4 \cdot 10^8$	$2.6 \cdot 10^7$	1.4	$2.69 \cdot 10^{12}$	212.17	13748	6907	26612
GA1	$1.5 \cdot 10^7$	$2.8 \cdot 10^6$	0.65	$2.72 \cdot 10^{12}$	214.74	133164	63232	281685
GA2 (R1)	$1.6 \cdot 10^6$	$3.0 \cdot 10^5$	0.325	$2.70 \cdot 10^{12}$	211.37	1201310	628632	2543495
GA3 (R2)	$1.7 \cdot 10^5$	$3.2 \cdot 10^4$	0.155	-	-	$\simeq$11000000	-	-
Aq-C-6	$1.3 \cdot 10^7$	$4.8 \cdot 10^6$	1.0	$2.21 \cdot 10^{12}$	169.80	87340	43605	187823
Aq-C-5	$1.6 \cdot 10^6$	$3.0 \cdot 10^5$	1.0	$2.26 \cdot 10^{12}$	171.51	694617	355056	1585276

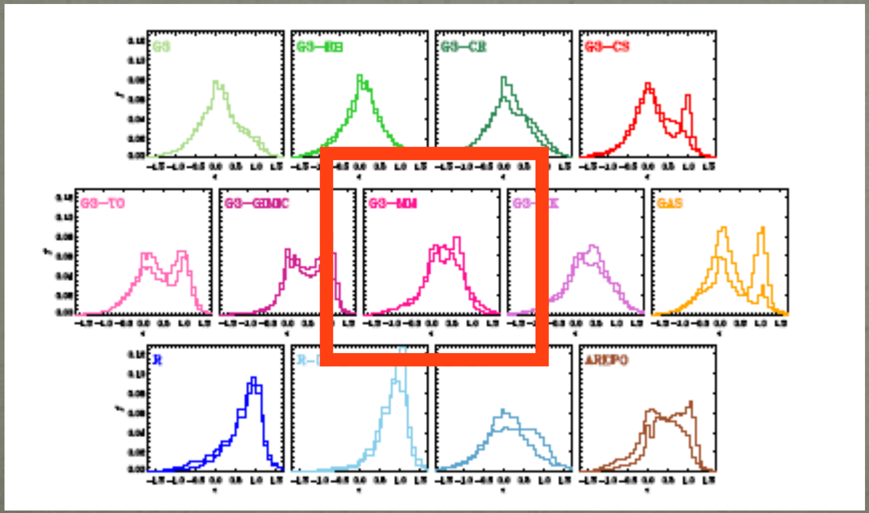
- (Stoehr+, 2002, MNRAS, 355, 84)
- (See *The Aquila comparison project*, Scannapieco+, 2012, MNRAS, in press)

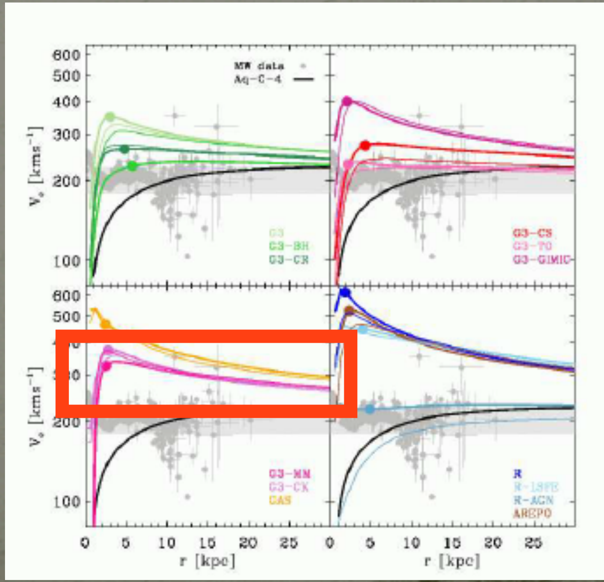
Resimulations of ~1e12 Msun halos with Vc~220 km/s and quiet merging history since z~2

Aquila comparison project

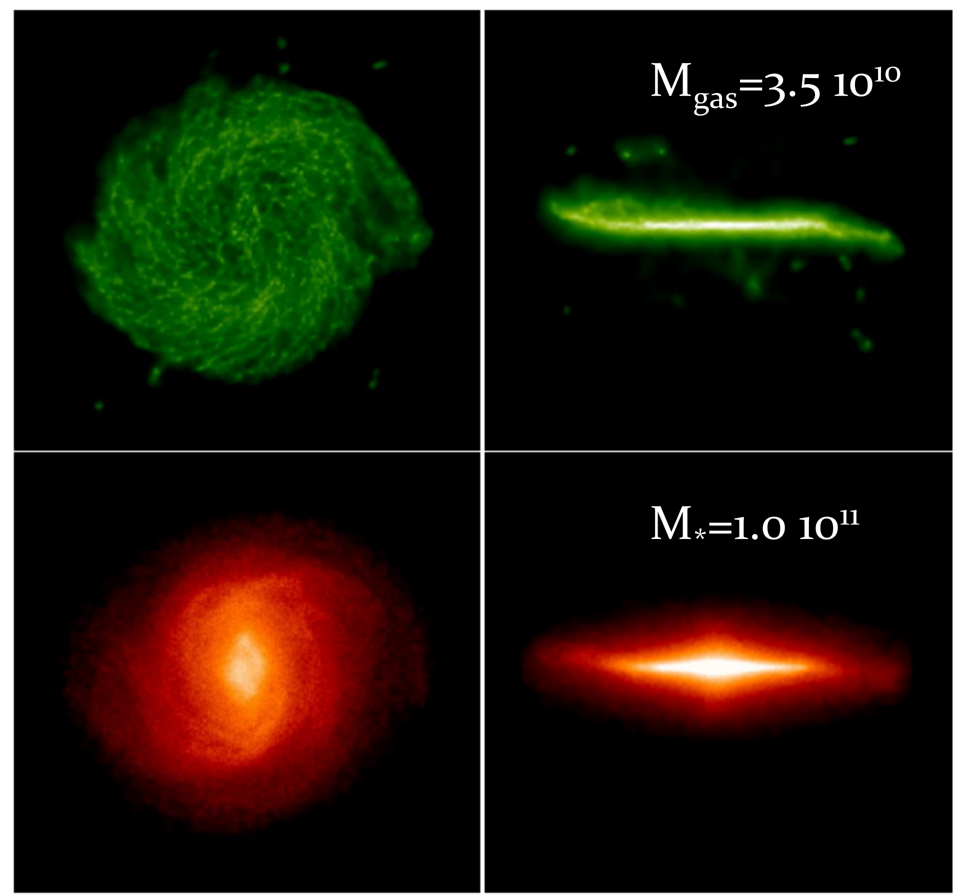
(Scannapieco et al. 2012)



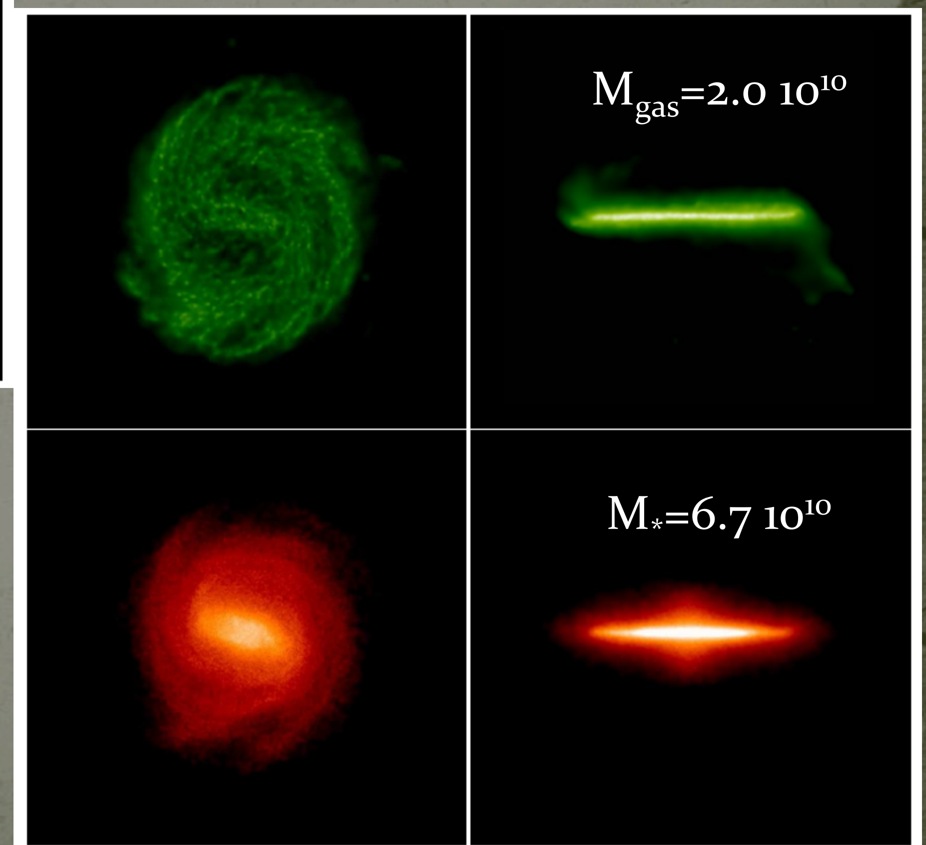




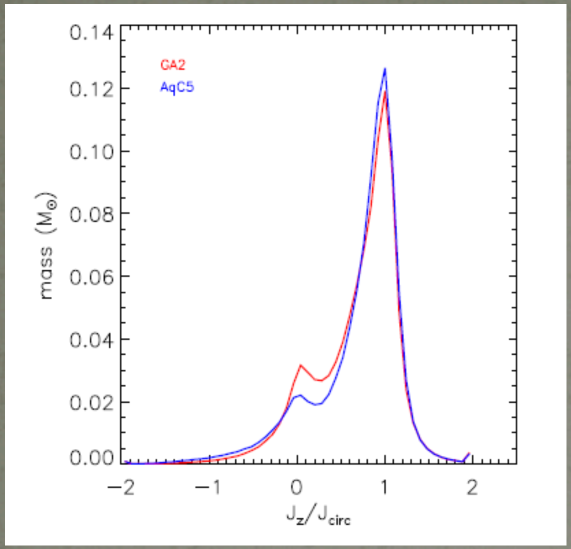
GA2

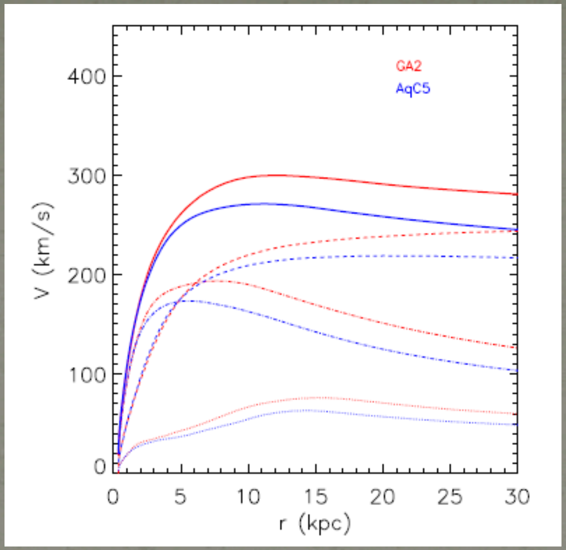


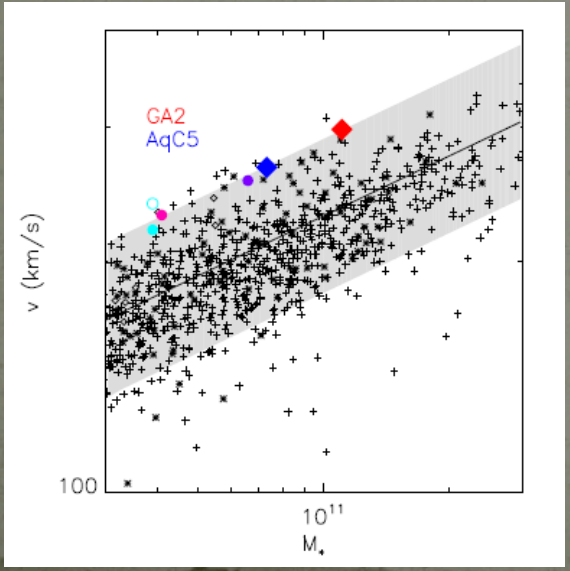
AqC5

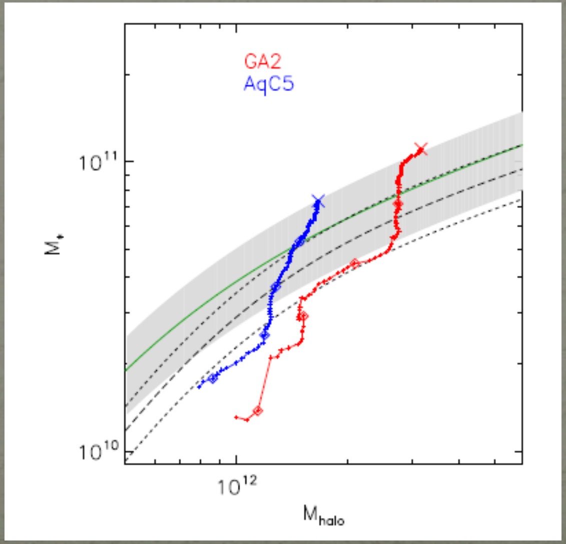


«Realistic» simulated galaxies



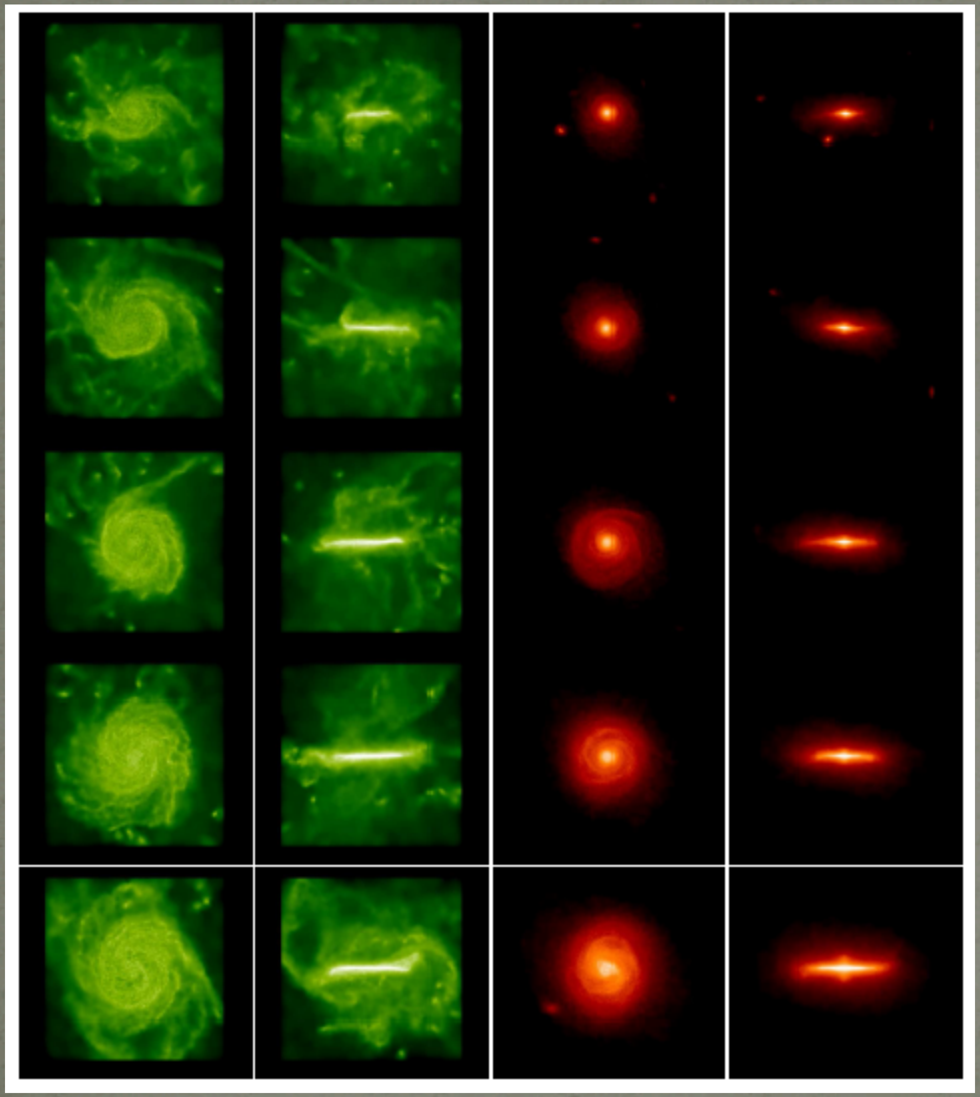


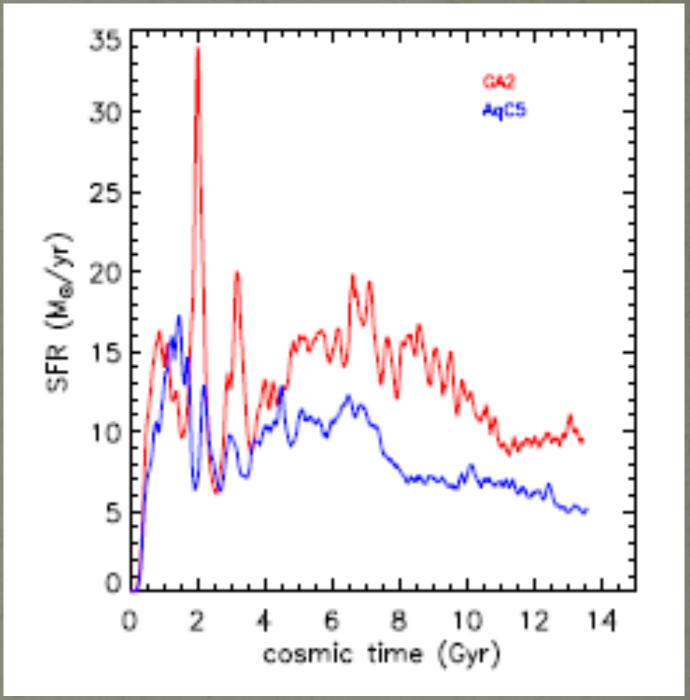




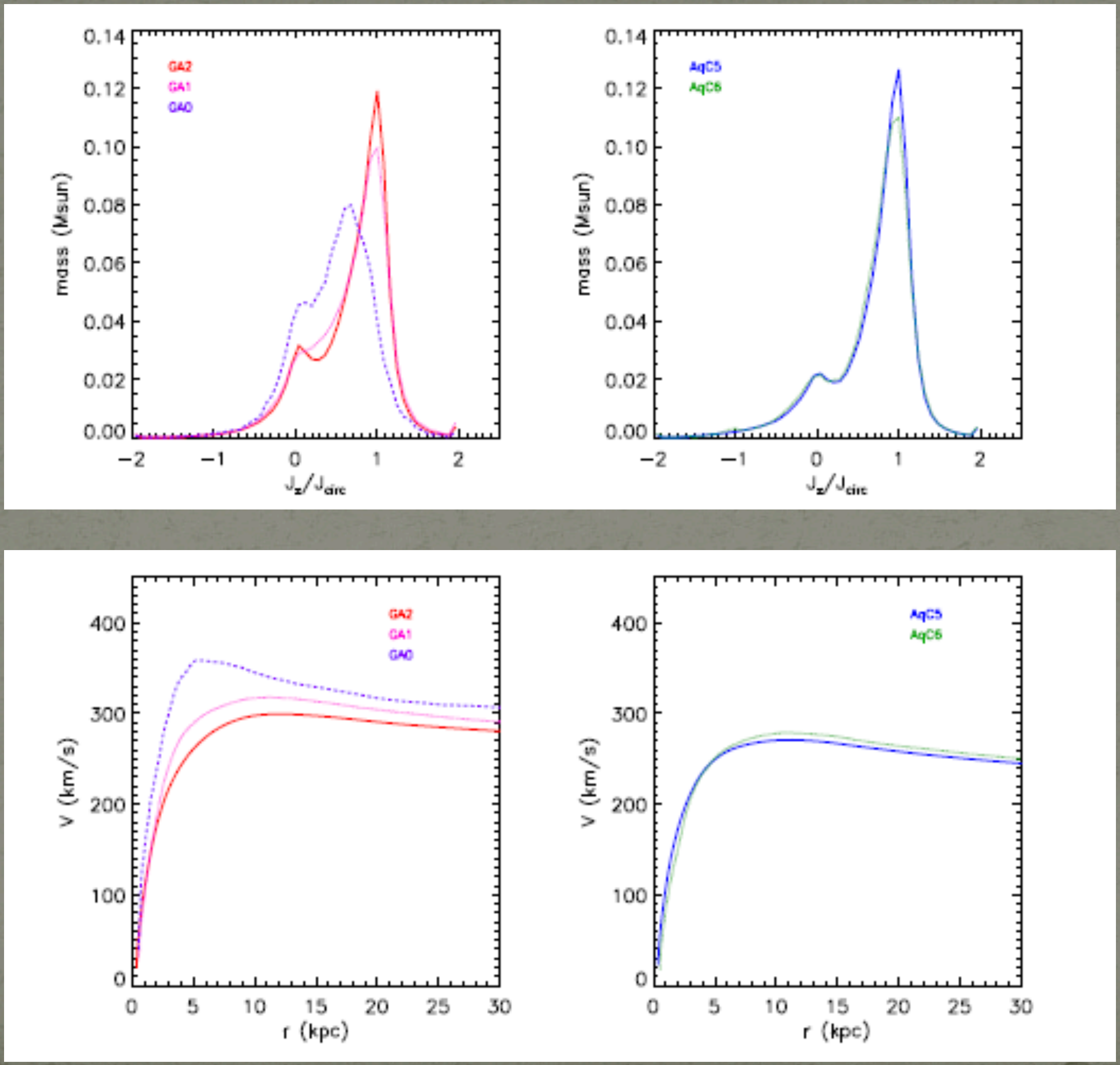
- Flat rotation curves
- «Dynamical» B/T: 0.14, 0.15
- On the (high end of) TF
- On the (high end of) baryon conversion efficiency plot
- Same object simulated by other groups shows very similar properties!

Evolution




GA2
AqC5
SFR ($M_\odot$/yr)
cosmic time (Gyr)
0
5
10
15
20
25
30
35
0
2
4
6
8
10
12
14

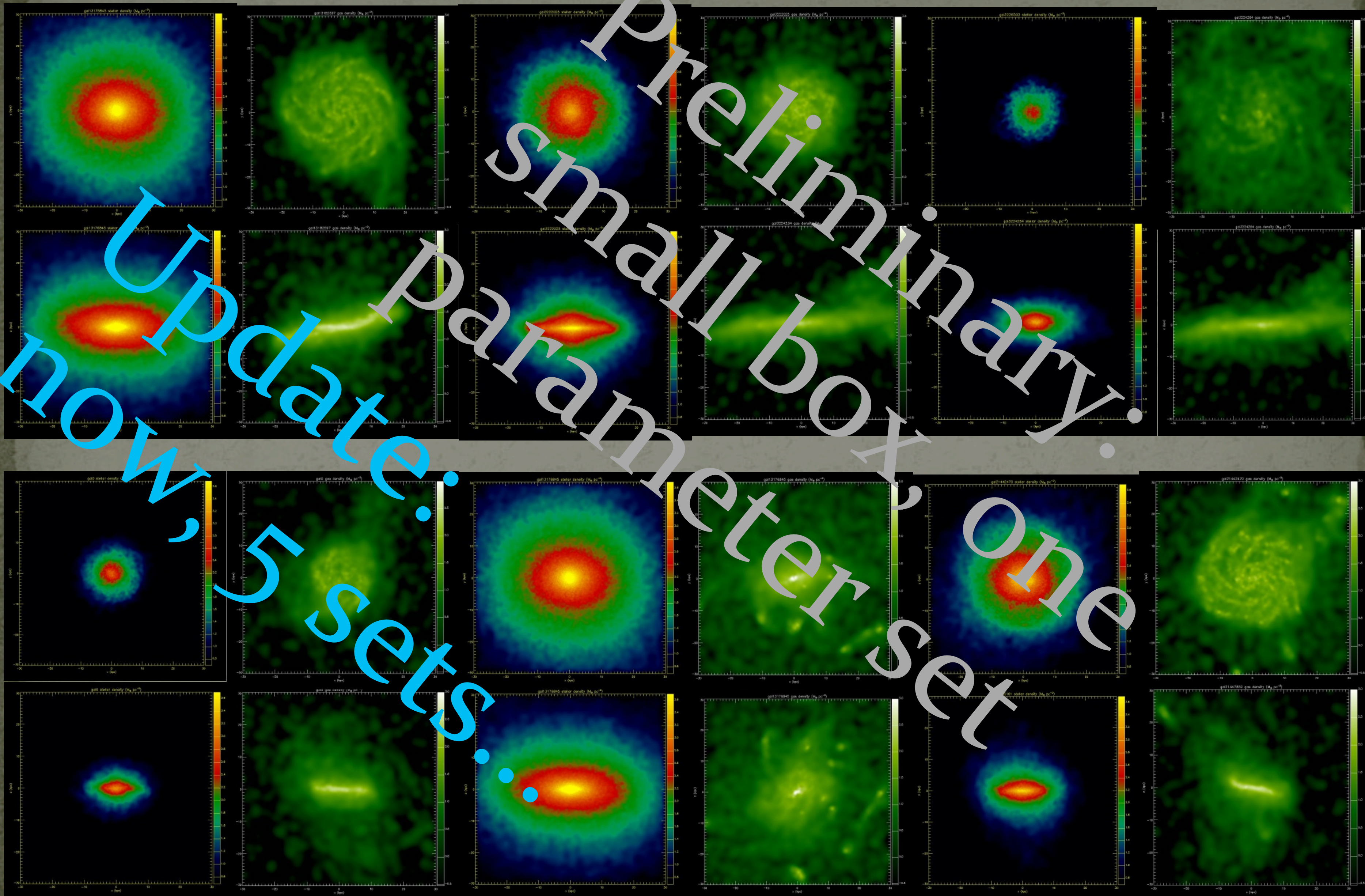
Resolution



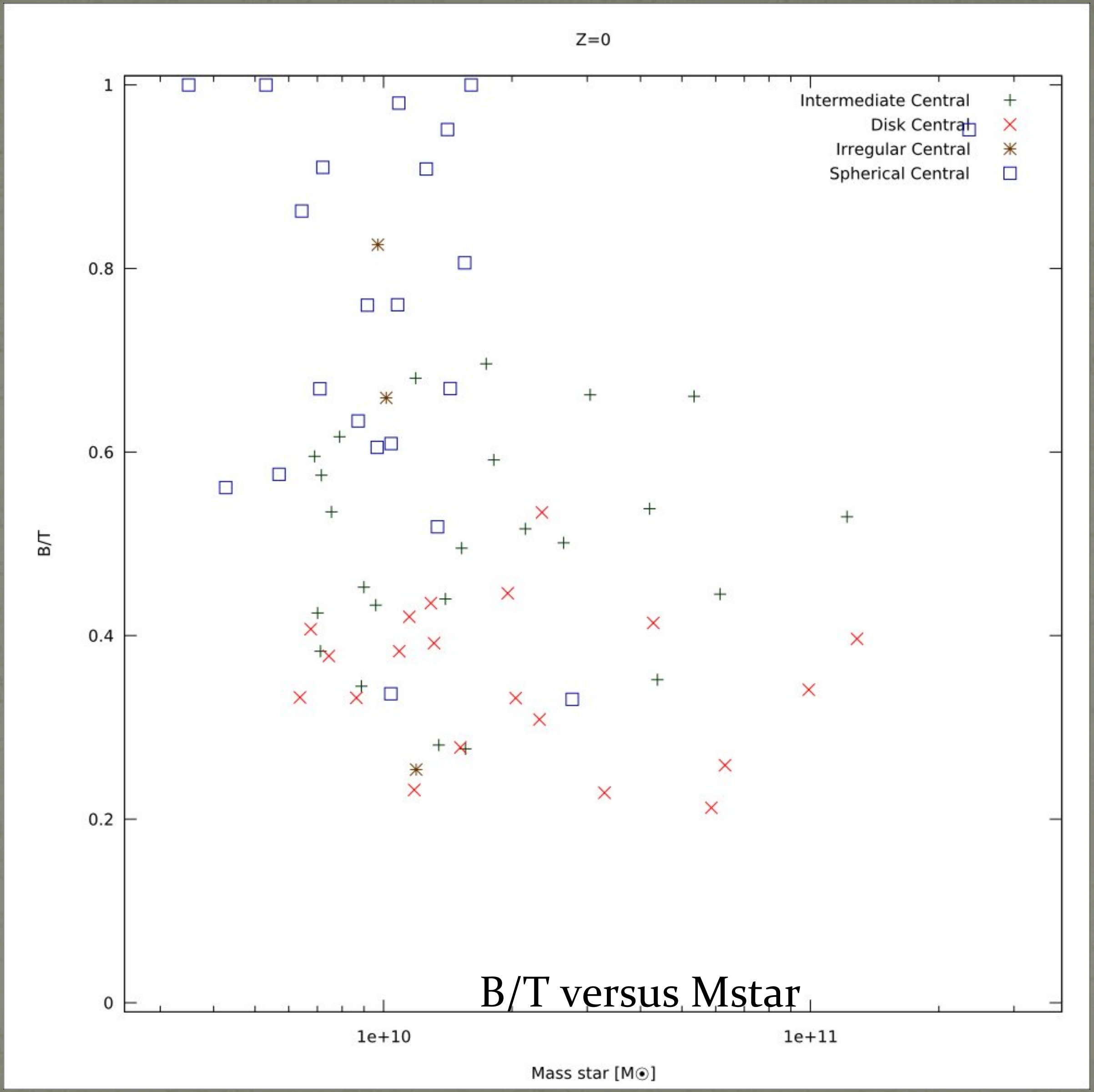
GA2
GA1
GA0
mass (Msun)
J_z/J_{circ}
AqC5
AqC6
mass (Msun)
J_z/J_{circ}
GA2
GA1
GA0
V (km/s)
r (kpc)
AqC5
AqC6
V (km/s)
r (kpc)

Cosmological boxes

- Box size: 25 and 50 Mpc (H_0=72 km/s/Mpc)
- N. particles: 2 x 256^3 and 2 x 512^3
- Mgas: 5.4×10^6 M_{sun}
- Mstar: 1.3×10^6 M_{sun}
- softening: 0.5 physical kpc (comoving for z>2)

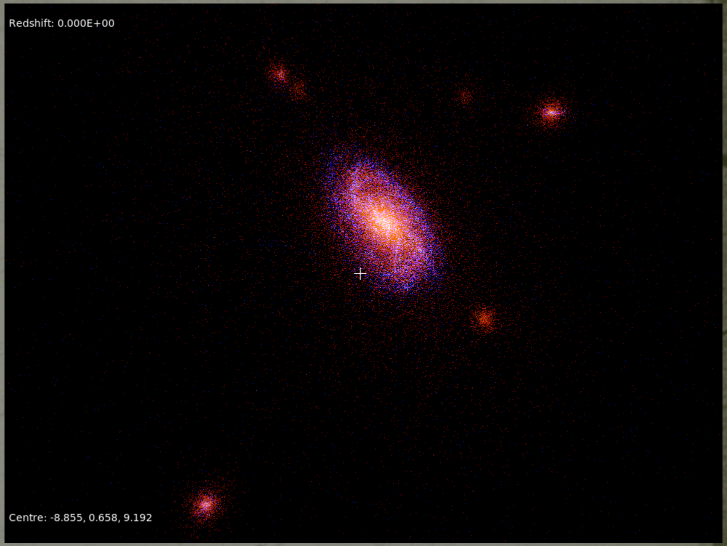

Preliminary:
small box, one
parameter set
Update:
now, 5 sets…

A. Ragagnin ì, in prep.; P. Barai+, in prep.

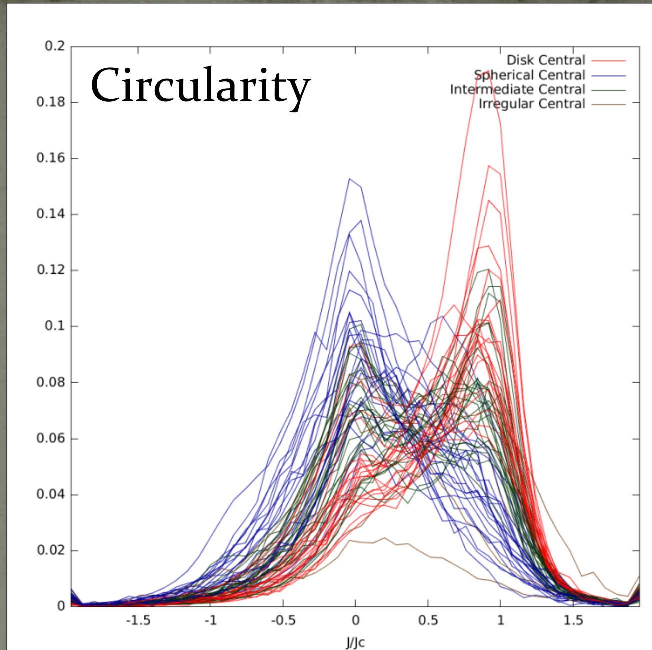


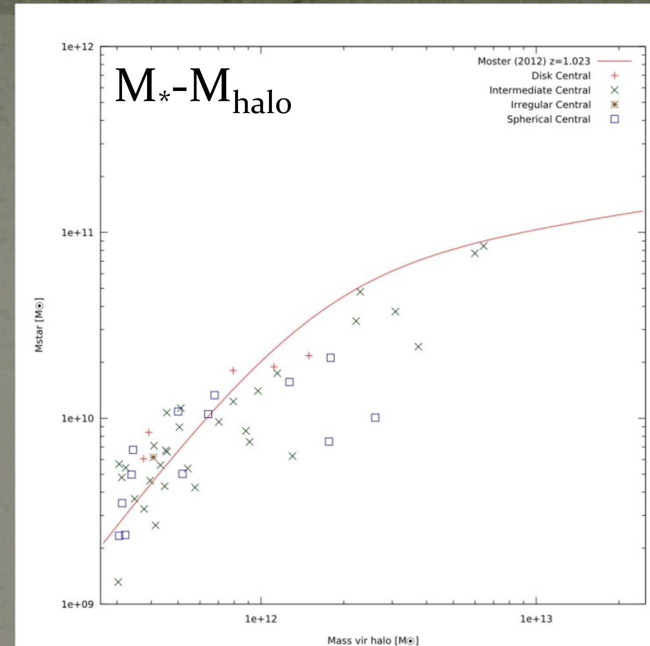
B/T versus Mstar

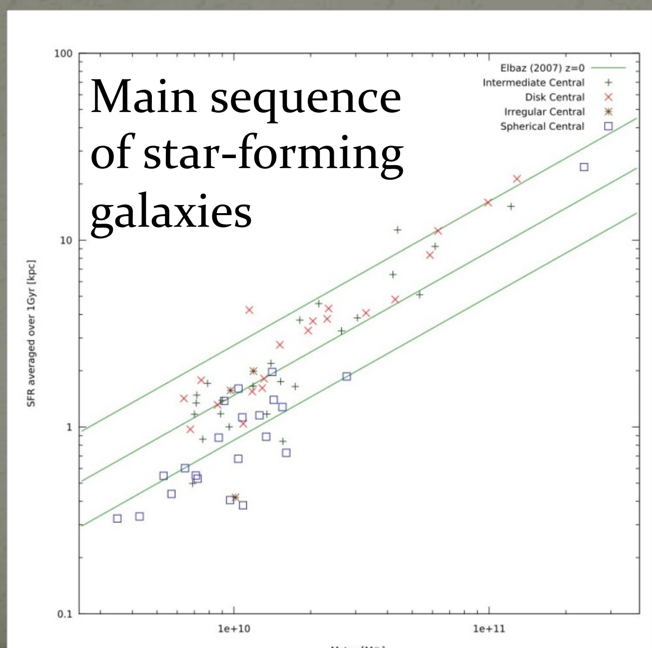
Best disk galaxy in the box

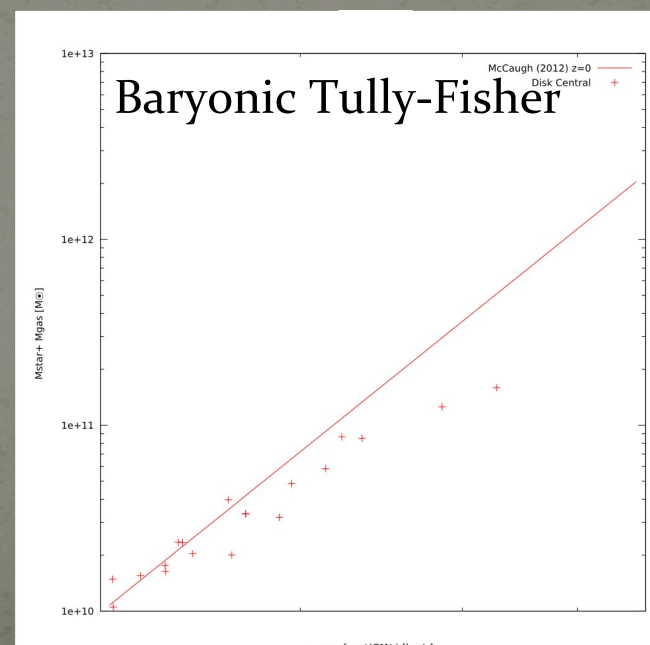


Mass: stars, 7.2×10^{10} Msun; gas, 3.4×10^{10}
f_{bar}: 0.075 (galaxy) 0.12 (halo)
B/T: 0.21; mass of stellar disk: 5.65×10^{10}
approx. 10^5 baryon particles in the galaxy


Circularity
Disk Central
Spherical Central
Intermediate Central
Irregular Central
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
-1.5
-1
-0.5
0
0.5
1
1.5
J/Jc

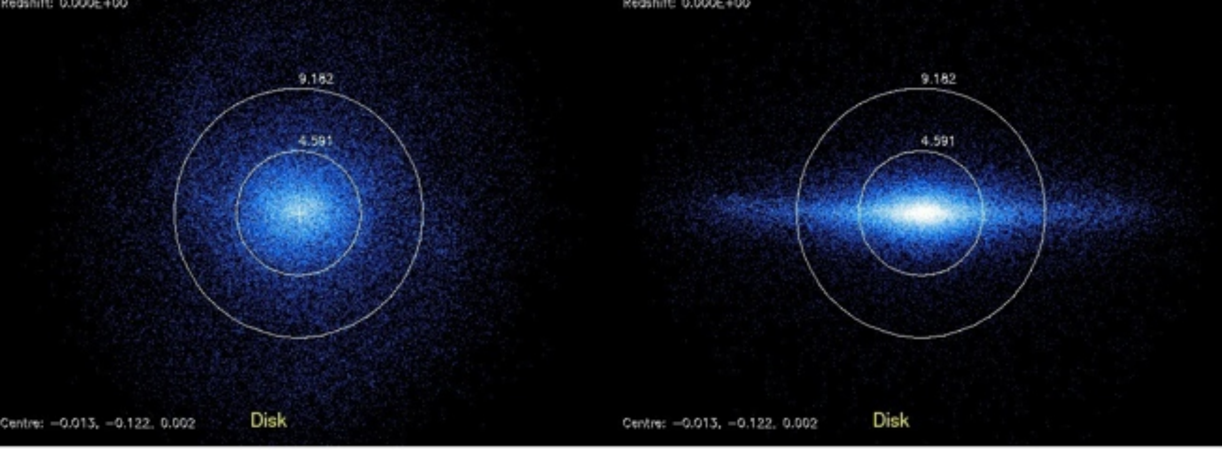

M*-Mhalo
Moster (2012) z=1.023
Disk Central
Intermediate Central
Irregular Central
Spherical Central
1e+12
1e+11
1e+10
1e+09
Mstar [M☉]
1e+12
1e+13
Mass vir halo [M☉]


Main sequence of star-forming galaxies
Elbaz (2007) z=0
Intermediate Central
Disk Central
Irregular Central
Spherical Central
100
10
1
0.1
SFR averaged over 1Gyr [kpc]
1e+10
1e+11
Mstar [M☉]

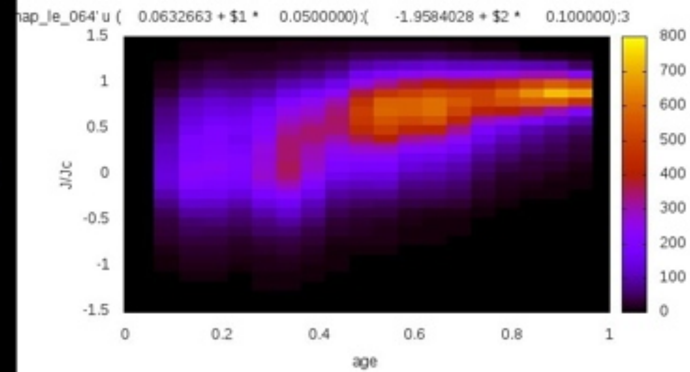

Baryonic Tully-Fisher
McCaugh (2012) z=0
Disk Central
1e+13
1e+12
1e+11
1e+10
Mstar+ Mgas [M☉]
max of sqrt(GM/r) [km/s]

Conclusions

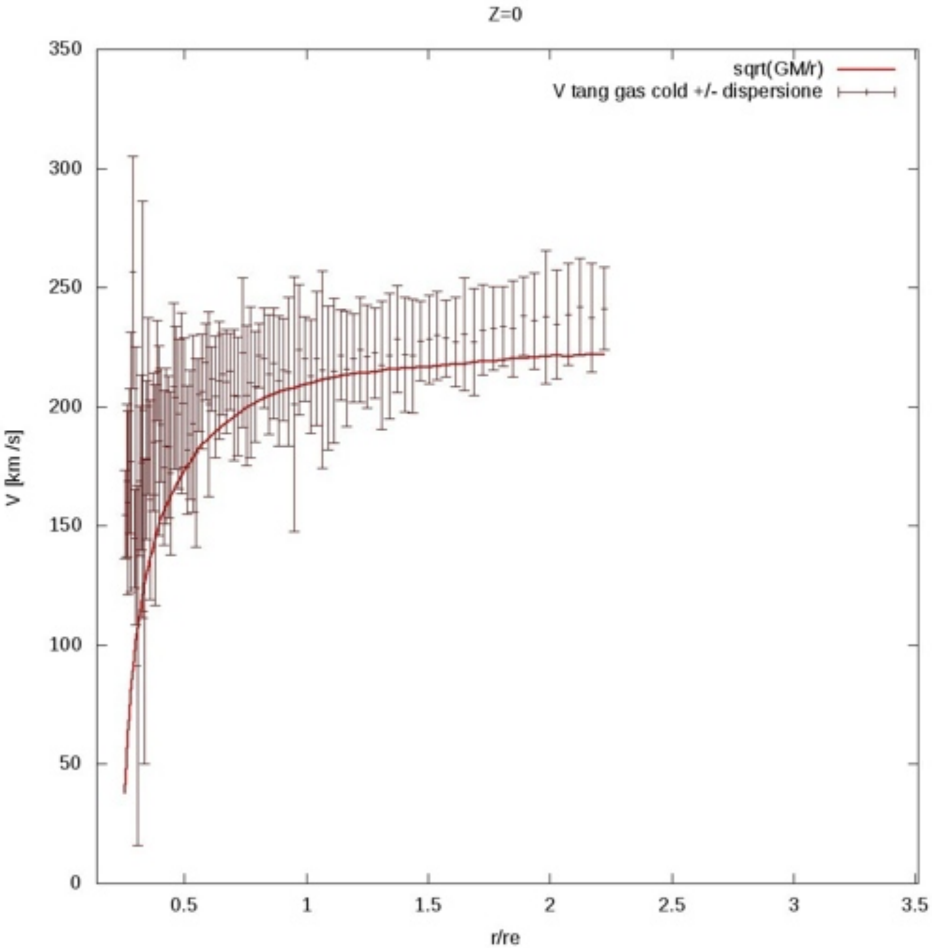
- We begin to be able to reliably compare theory predictions with observations, using numerical simulations as a tool
- (Disk) galaxy simulations now produce realistic objects....
- ...with similar properties when simulated by different groups...
- ...we have convergence at moderate resolutions...
- ...but *using different subgrid prescriptions!*
- *Italian numerical cosmology & structure formation research is currently state-of-the-art..*
- *...but suffer from lack of appropriate resources and lacks the possibility of long-term planning (fundamental in this field)*



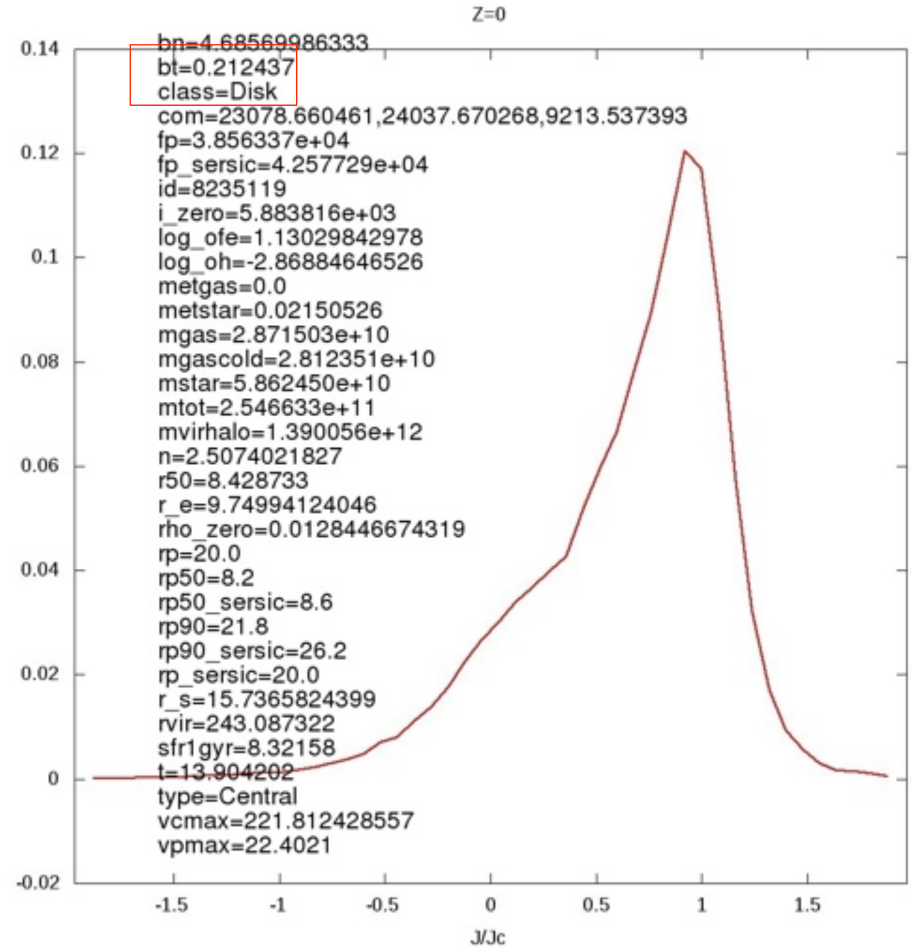
Redshift: 0.000E+00
9.182
4.591
Centre: −0.013, −0.122, 0.002
Disk
Redshift: 0.000E+00
9.182
4.591
Centre: −0.013, −0.122, 0.002
Disk



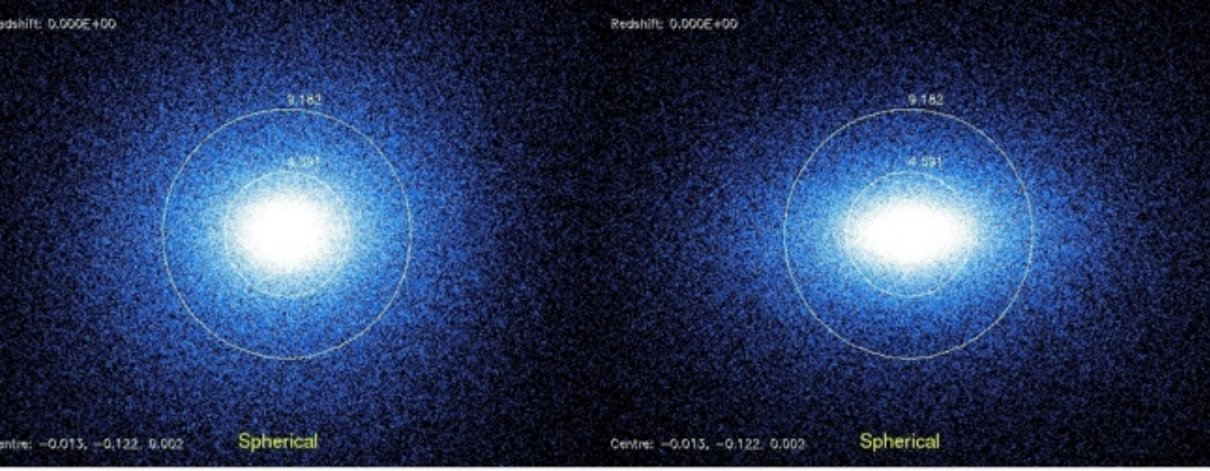
map_le_064' u (0.0632663 + $1 * 0.0500000):(-1.9584028 + $2 * 0.100000):3
J/Jc
age

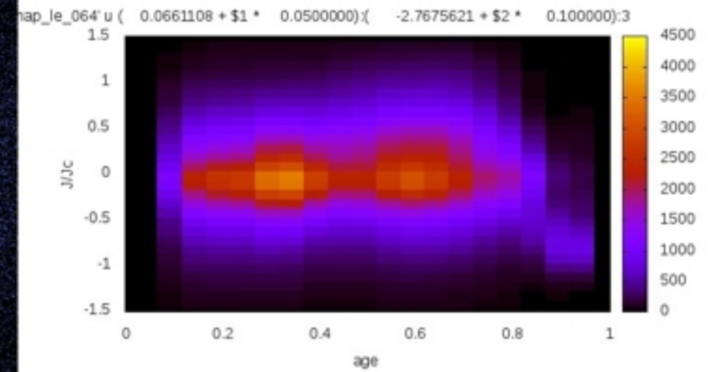


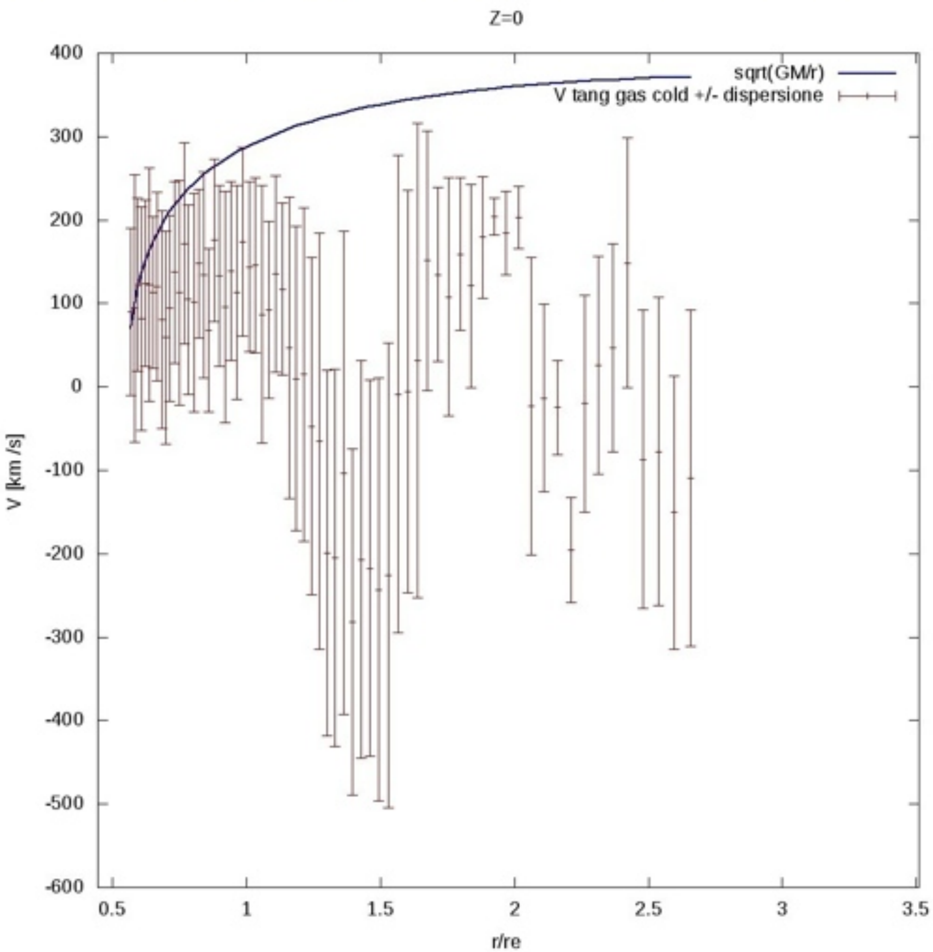
Z=0
sqrt(GM/r)
V tang gas cold +/- dispersione
V [km /s]
r/re

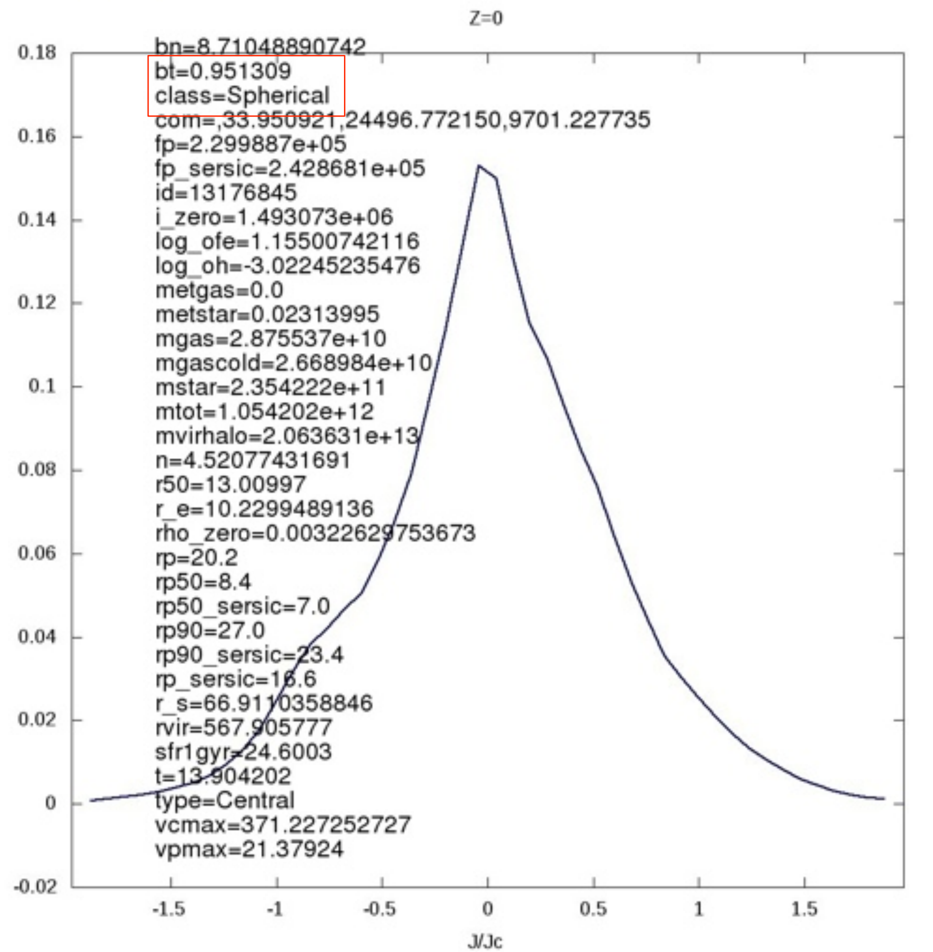


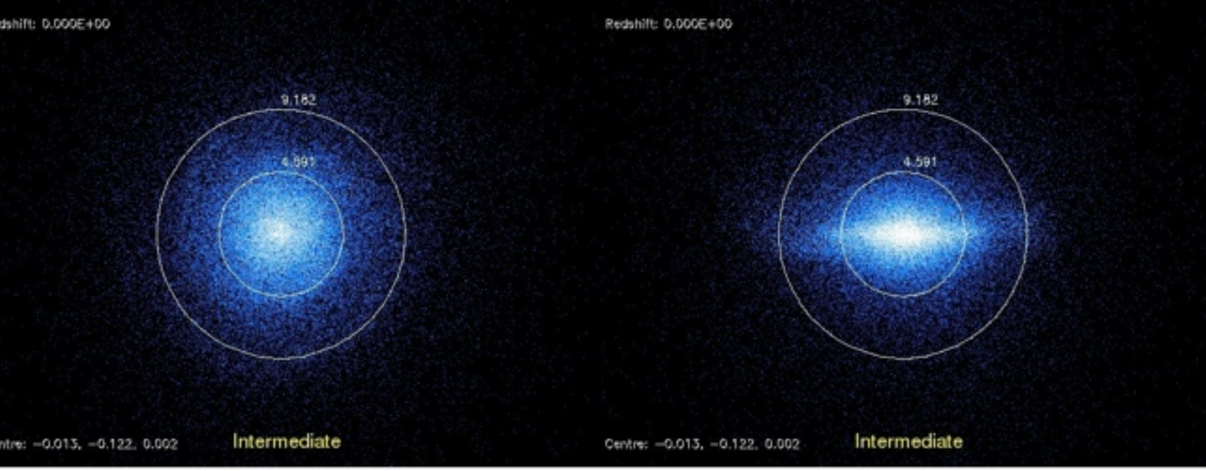
Z=0
bn=4.68569986333
bt=0.212437
class=Disk
com=23078.660461,24037.670268,9213.537393
fp=3.856337e+04
fp_sersic=4.257729e+04
id=8235119
i_zero=5.883816e+03
log_ofe=1.13029842978
log_oh=-2.86884646526
metgas=0.0
metstar=0.02150526
mgas=2.871503e+10
mgascold=2.812351e+10
mstar=5.862450e+10
mtot=2.546633e+11
mvirhalo=1.390056e+12
n=2.5074021827
r50=8.428733
r_e=9.74994124046
rho_zero=0.0128446674319
rp=20.0
rp50=8.2
rp50_sersic=8.6
rp90=21.8
rp90_sersic=26.2
rp_sersic=20.0
r_s=15.7365824399
rvir=243.087322
sfr1gyr=8.32158
t=13.904202
type=Central
vcmax=221.812428557
vpmax=22.4021
J/Jc

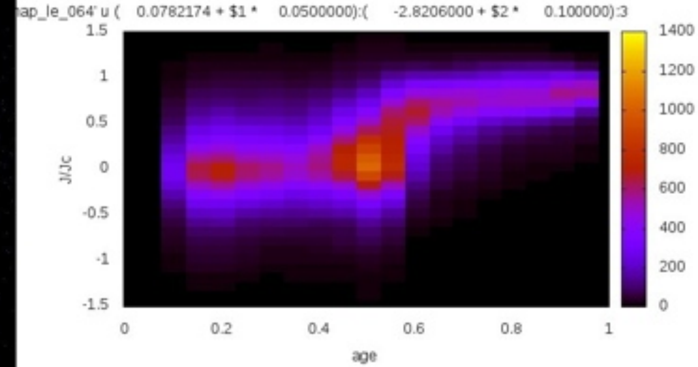

Redshift: 0.000E+00
9.182
4.591
Centre: −0.013, −0.122, 0.002
Spherical
Redshift: 0.000E+00
9.182
4.591
Centre: −0.013, −0.122, 0.002
Spherical

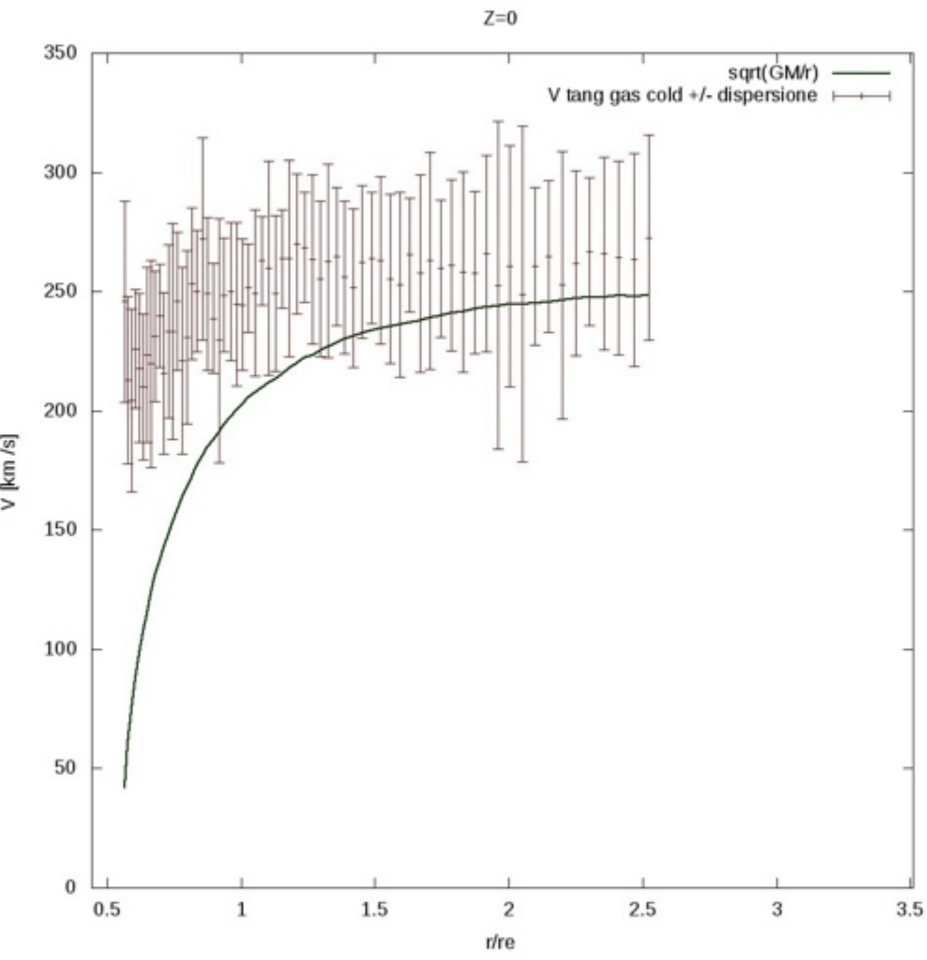

ap_le_064' u (0.0661108 + $1 * 0.0500000):(-2.7675621 + $2 * 0.100000):3
J/Jc
age

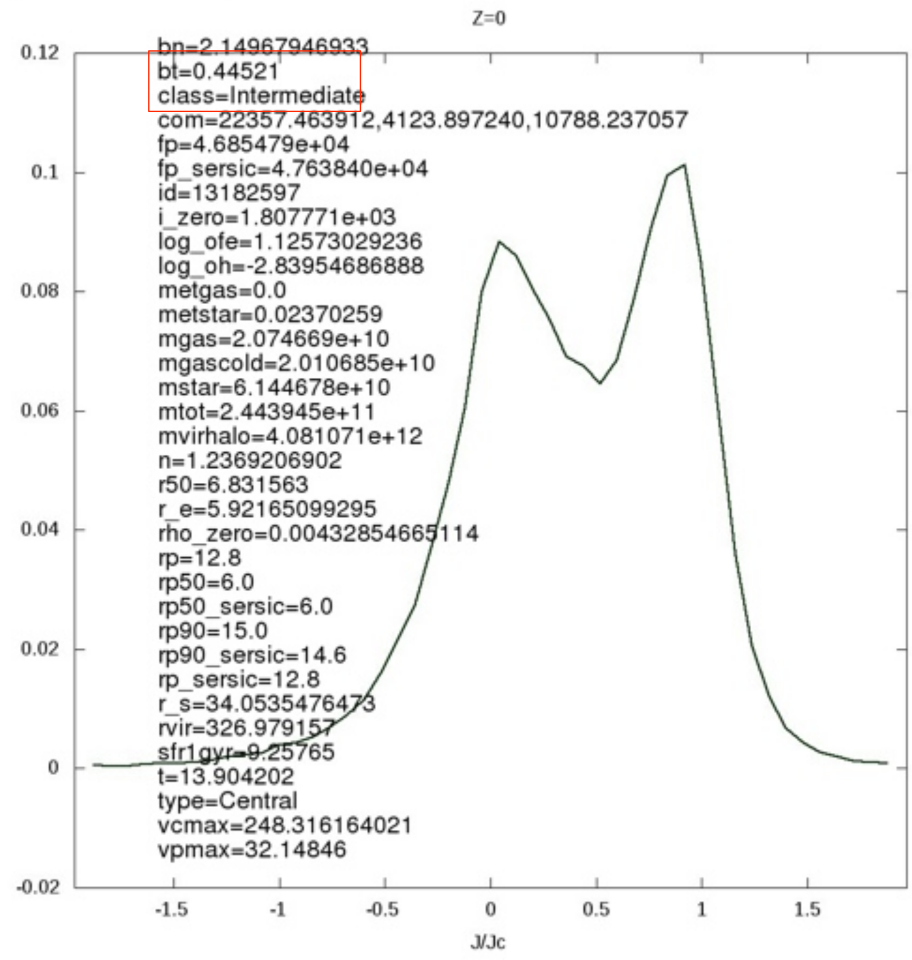

Z=0
sqrt(GM/r)
V tang gas cold +/- dispersione
V [km /s]
r/re


Z=0
bn=8.71048890742
bt=0.951309
class=Spherical
com=,33.950921,24496.772150,9701.227735
fp=2.299887e+05
fp_sersic=2.428681e+05
id=13176845
i_zero=1.493073e+06
log_ofe=1.15500742116
log_oh=-3.02245235476
metgas=0.0
metstar=0.02313995
mgas=2.875537e+10
mgascold=2.668984e+10
mstar=2.354222e+11
mtot=1.054202e+12
mvirhalo=2.063631e+13
n=4.52077431691
r50=13.00997
r_e=10.2299489136
rho_zero=0.00322629753673
rp=20.2
rp50=8.4
rp50_sersic=7.0
rp90=27.0
rp90_sersic=23.4
rp_sersic=16.6
r_s=66.9110358846
rvir=567.905777
sfr1gyr=24.6003
t=13.904202
type=Central
vcmax=371.227252727
vpmax=21.37924
J/Jc

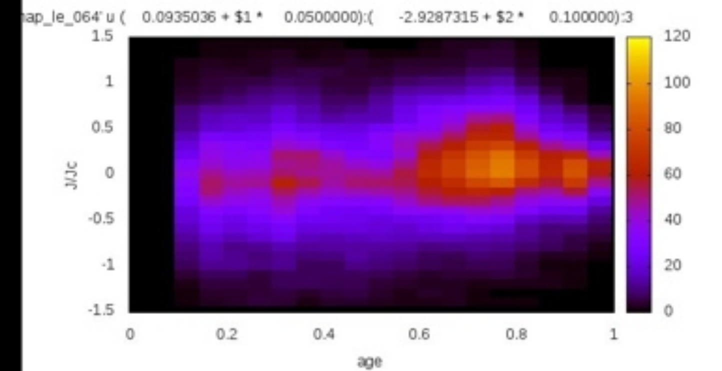

dshift: 0.000E+00
Redshift: 0.000E+00
9.182
4.591
9.182
4.591
ntre: −0.013, −0.122, 0.002
Intermediate
Centre: −0.013, −0.122, 0.002
Intermediate


nap_le_064' u (0.0782174 + $1 * 0.0500000):(-2.8206000 + $2 * 0.100000):3
J/Jc
age
1.5
1
0.5
0
-0.5
-1
-1.5
0
0.2
0.4
0.6
0.8
1
1400
1200
1000
800
600
400
200
0

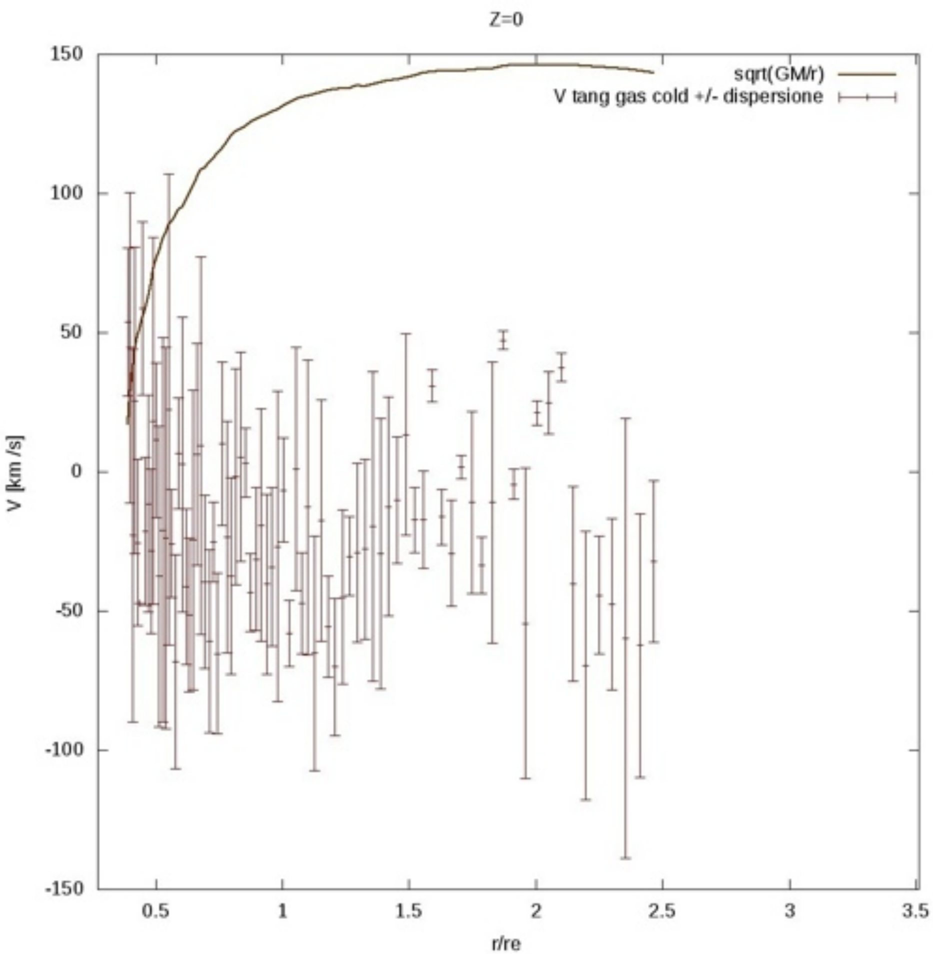

Z=0
sqrt(GM/r)
V tang gas cold +/- dispersione
V [km /s]
r/re
350
300
250
200
150
100
50
0
0.5
1
1.5
2
2.5
3
3.5


Z=0
bn=2.14967946933
bt=0.44521
class=Intermediate
com=22357.463912,4123.897240,10788.237057
fp=4.685479e+04
fp_sersic=4.763840e+04
id=13182597
i_zero=1.807771e+03
log_ofe=1.12573029236
log_oh=-2.83954686888
metgas=0.0
metstar=0.02370259
mgas=2.074669e+10
mgascold=2.010685e+10
mstar=6.144678e+10
mtot=2.443945e+11
mvirhalo=4.081071e+12
n=1.2369206902
r50=6.831563
r_e=5.92165099295
rho_zero=0.00432854665114
rp=12.8
rp50=6.0
rp50_sersic=6.0
rp90=15.0
rp90_sersic=14.6
rp_sersic=12.8
r_s=34.0535476473
rvir=326.979157
sfr1gyr=9.25765
t=13.904202
type=Central
vcmax=248.316164021
vpmax=32.14846
J/Jc
0.12
0.1
0.08
0.06
0.04
0.02
0
-0.02
-1.5
-1
-0.5
0
0.5
1
1.5

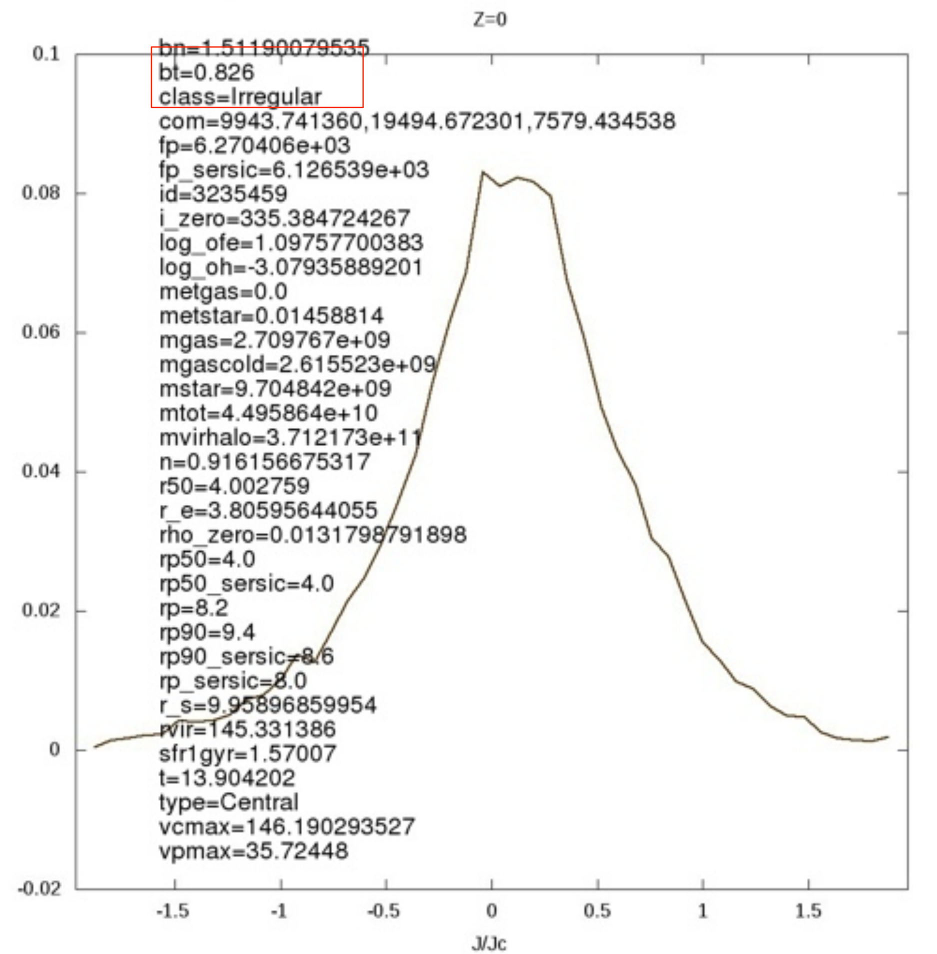
edshift: 0.000E+00
9.162
4.591
entre: −0.013, −0.122, 0.002
Irregular
Redshift: 0.000E+00
9.162
4.591
Centre: −0.013, −0.122, 0.002
Irregular



ap_le_064' u (0.0935036 + $1 * 0.0500000):(-2.9287315 + $2 * 0.100000):3
J/Jc
age

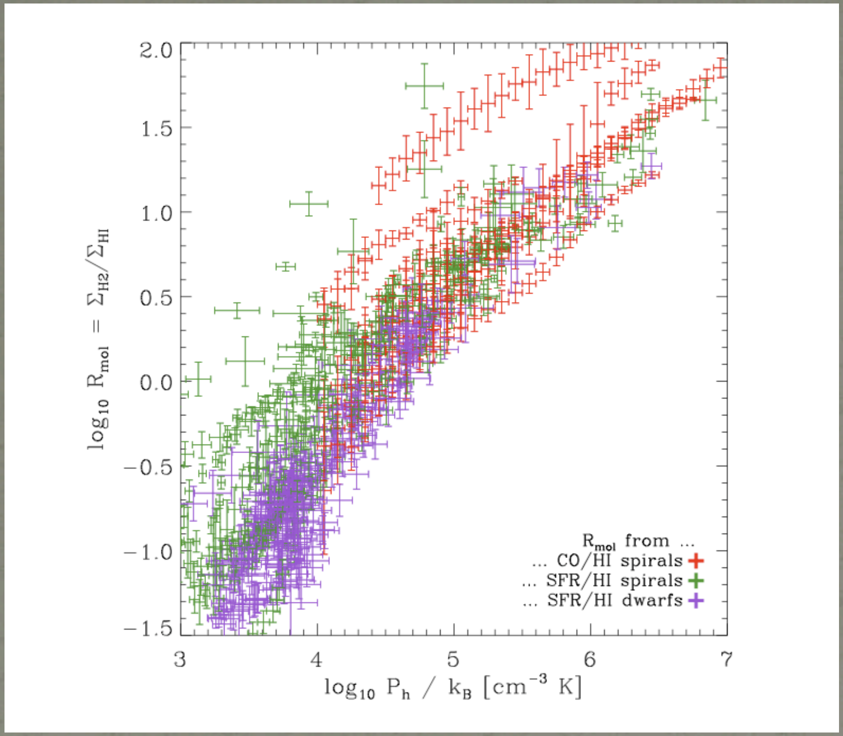


Z=0
sqrt(GM/r)
V tang gas cold +/- dispersione
V [km /s]
r/re



Z=0
bn=1.51190079535
bt=0.826
class=Irregular
com=9943.741360,19494.672301,7579.434538
fp=6.270406e+03
fp_sersic=6.126539e+03
id=3235459
i_zero=335.384724267
log_ofe=1.09757700383
log_oh=-3.07935889201
metgas=0.0
metstar=0.01458814
mgas=2.709767e+09
mgascold=2.615523e+09
mstar=9.704842e+09
mtot=4.495864e+10
mvirhalo=3.712173e+11
n=0.916156675317
r50=4.002759
r_e=3.80595644055
rho_zero=0.0131798791898
rp50=4.0
rp50_sersic=4.0
rp=8.2
rp90=9.4
rp90_sersic=8.6
rp_sersic=8.0
r_s=9.95896859954
rvir=145.331386
sfr1gyr=1.57007
t=13.904202
type=Central
vcmax=146.190293527
vpmax=35.72448
J/Jc

Molecular fraction f_{mol}



Leroy et al. (2009)

Inspired by Blitz & Rosolowsky, we scale the molecular fraction with SPH pressure - NOT the same quantity the observers use!

$$f_{mol} = 1/(1+P_o/P)$$

Energy from SNe increases pressure

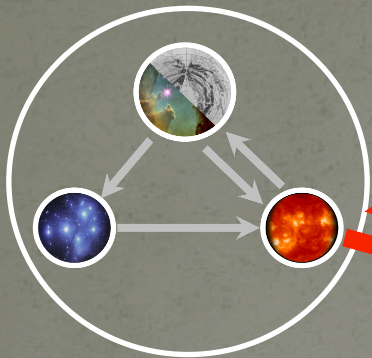
Pressure increases f_{mol}

f_{mol} increases star formation

star formation runaway, up to $f_{mol} \sim 1$

NO EQUILIBRIUM SOLUTIONS

Multi-Phase particle



SPH

$\Delta t, \Delta S, \Delta \rho$

$\dot{E}_{hydro} = \Delta[S/(\gamma-1)\rho^{(\gamma-1)}]/\Delta t$

$\dot{E}_{hot} = -\dot{E}_{cool}+\dot{E}_{sn}+\dot{E}_{hydro}$

new ΔS

To SPH again

- Star formation stars
- SNe energy increases pressure
- Molecular fraction increases
- SFR goes up

- Star formation runaway
  No equilibrium solutions

SPH interaction with surrounding particles halts the runaway

Hot phase energy

$$\dot{E}_h = \dot{E}_{SN} - \dot{E}_{cool} + \dot{E}_{hydro}$$

ENERGY RELEASED BY SNe

$$\dot{E}_{SN} = E_{51} \cdot f_{fb,in} \cdot \frac{\dot{M}_{sf}}{\beta_{sf}}$$

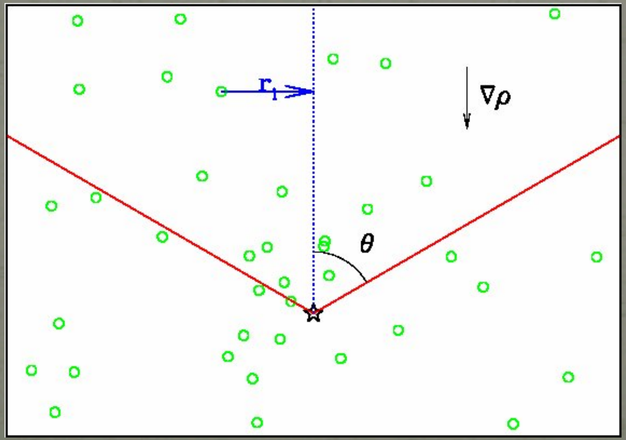
ENERGY LOSS DUE TO COOLING

$$\dot{E}_{cool} = \frac{E_h}{t_{cool}}$$

ENERGY CONTRIBUTION DUE TO HYDRODYNAMICS

$$\dot{E}_{hydro} = \frac{1}{dt} \frac{\Delta S_{SPH}}{(\gamma - 1)\rho^{\gamma - 1}}$$

this is the ENTROPY variation due to SPH hydrodynamics



A large fraction of thhermal & kinetic energy is given in a directional way to neighbours

Wind speed and mass loading are determined by energy fraction and probability

Other relevant features

destruction of molecular clouds

→

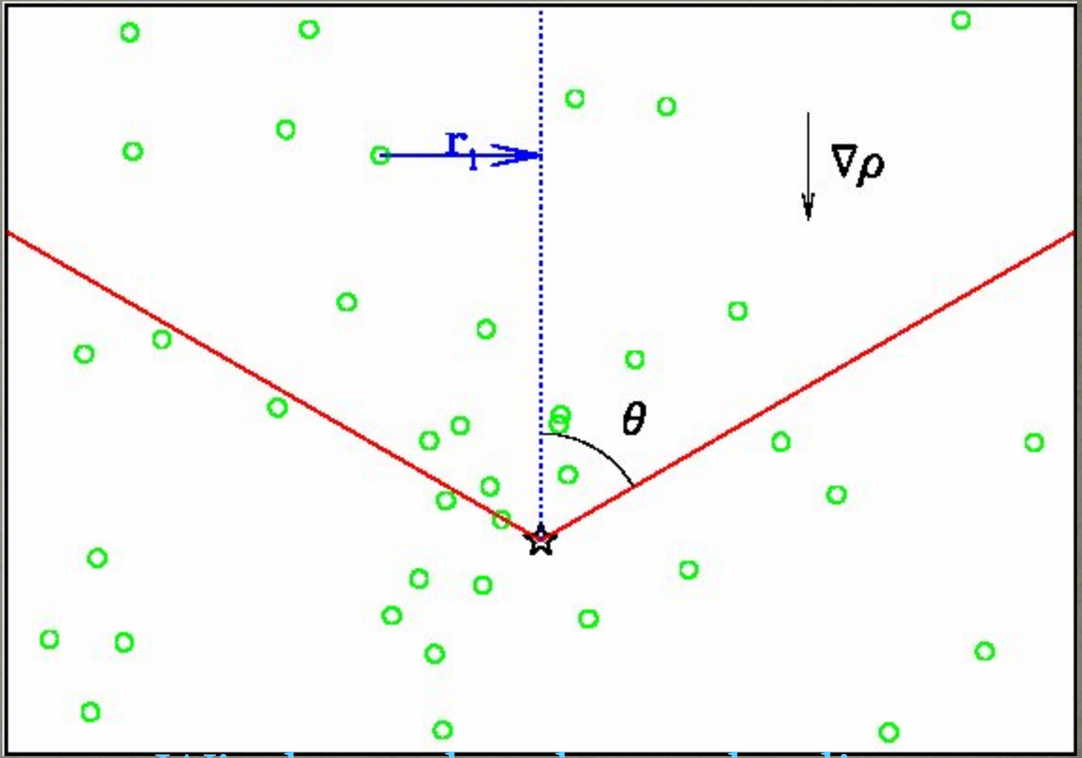
exit after 1-2 dynamical times

- Chemical evolution and metal cooling (Tornatore et al. 2007)
- UV background (Haardt & Madau 1996)
- Low density threshold for multi-phase, n~0.01 cm^{-3}
- ***star formation is significant for (sub-grid) densities of $n_c > P_0 / T_c$ ~ 70 cm^{-3}***
- No early radiative feedback
- The algorithm works at moderate resolution

Distribution of SN energy

The energy given to neighbours is assigned along the "least resistence path", i.e. along (minus) the density gradient

Only a small part (2%) of SN energy is given to the local hot phase, the rest is distributed to neighbours.



Thermal energy (20-30% of 10^{51} erg per SN) is weighted by distance from cone axis

Kinetic energy (40-60% of 10^{51} erg per SN) is weighted in the same way, but it is given only to 3% of particles that exit a multi-phase cycle; from other star-forming particles and for one dynamical time

Wind speed and mass loading are determined by energy fraction and probability

Wind particles are decoupled