INAF
ISTITUTO NAZIONALE
DI ASTROFISICA
OSSERVATORIO ASTRONOMICO
DI TRIESTE

ExaNeSt

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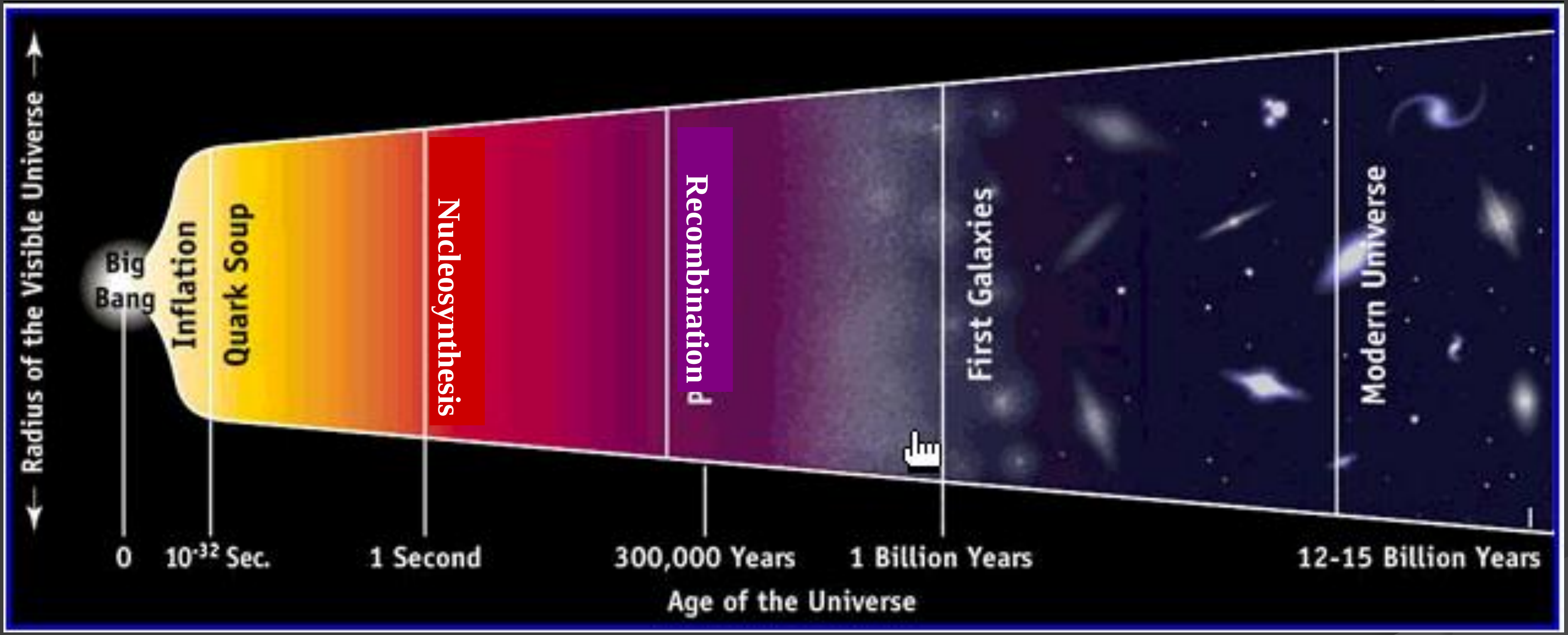
… and many others…

NUMERICAL SIMULATIONS OF GALAXY FORMATION

Cosmic Structure Formation



linear perturbation theory

nonlinear solutions of theory
AKA "simulations"

Scenario of structure formation

Primordial Fluctuations
Cosmological background

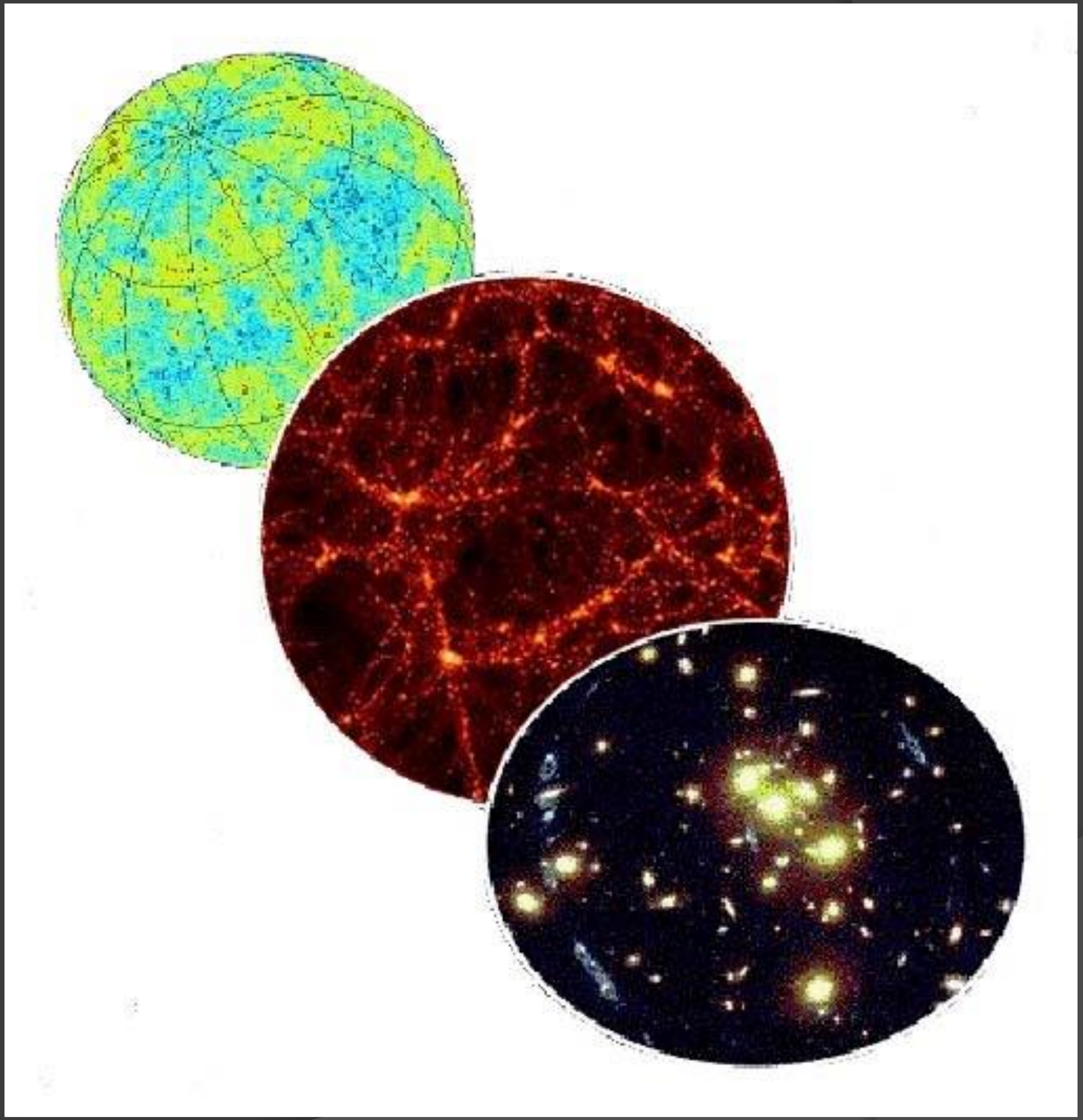
DM only! ⇩

Filamentary Structures – LSS - Cosmological simulations

⇩

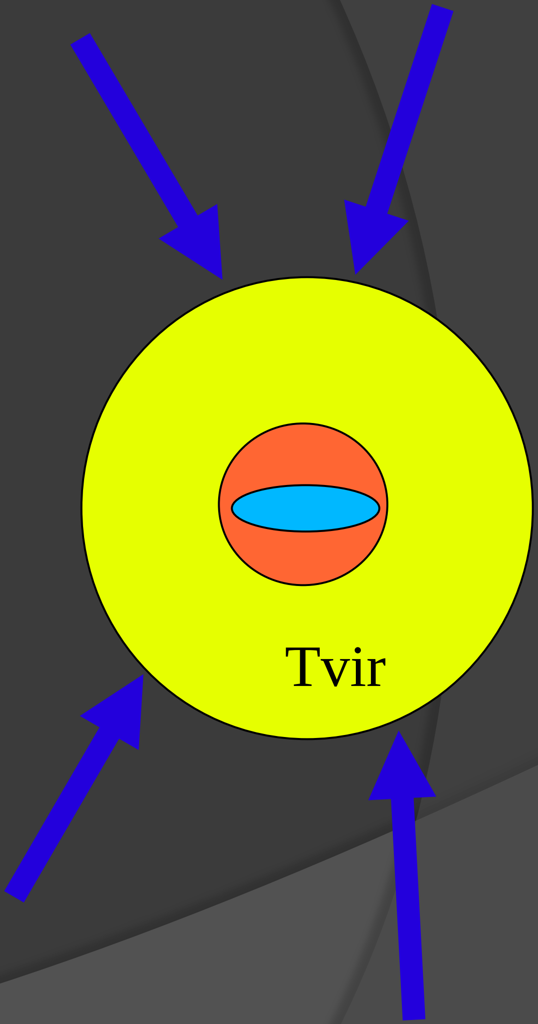
Gas dynamics
Star formation
Energy feedback
………………

Galaxies: baryons!
(theoretical predictions to be compared with observations)



Galaxy Formation: Standard Model

- E.g. White & Rees 1978
- Gas falling into a dark matter halo, shocks to the virial temperature T_{vir} at R_{vir}, and continuously forms quasi-hydrostatic equilibrium halo (but: cold flows).
- Hot, virialized gas cools, starting from the central parts, it loses its pressure support and settles into centrifugally supported disk –> the (spiral) galaxy.
- Mergers of disks can later produce spheroids.

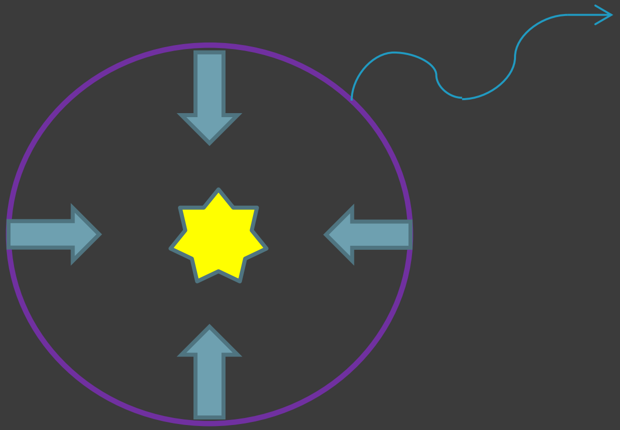


Star formation at «large» scales

...a problem of dynamical range…!

Katz+ 96: convert dense cold gas into stars

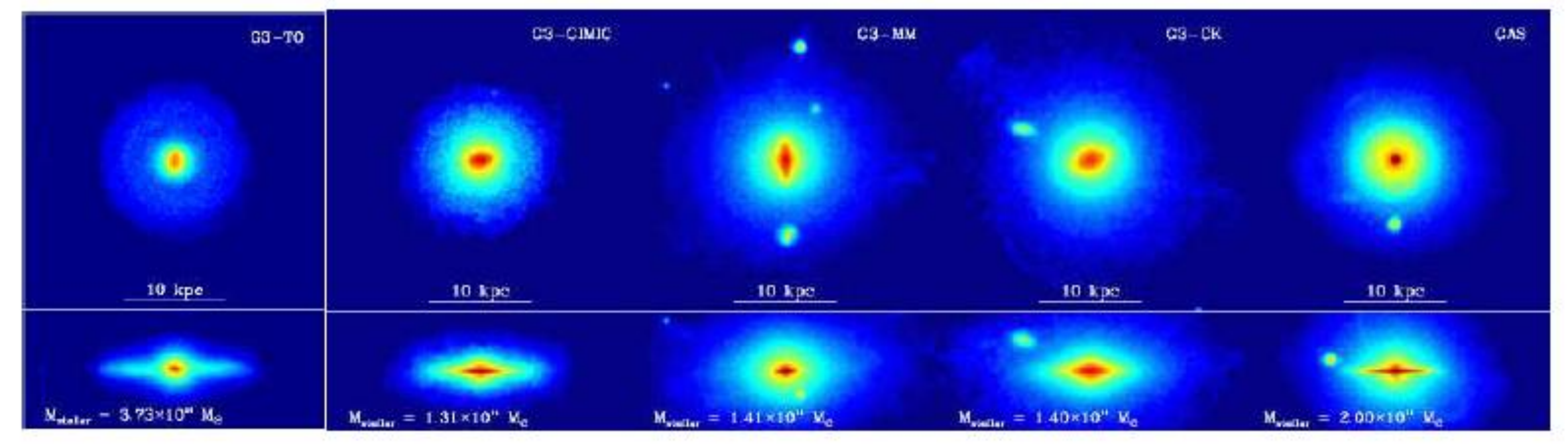
- ..SNe release thermal energy into gas

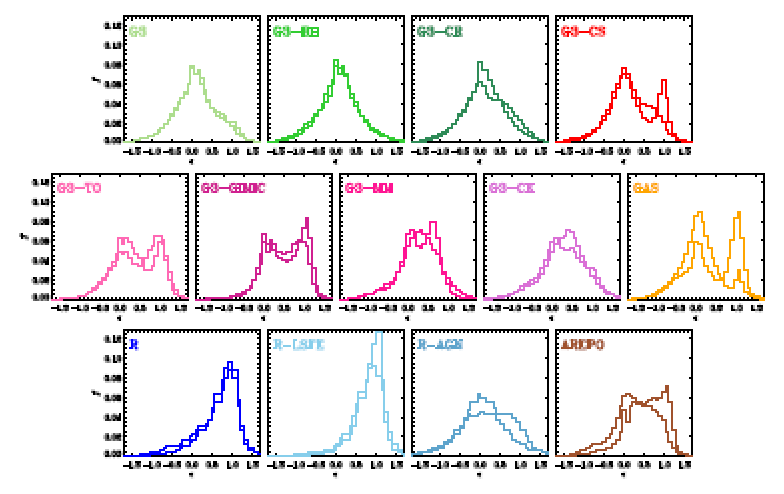


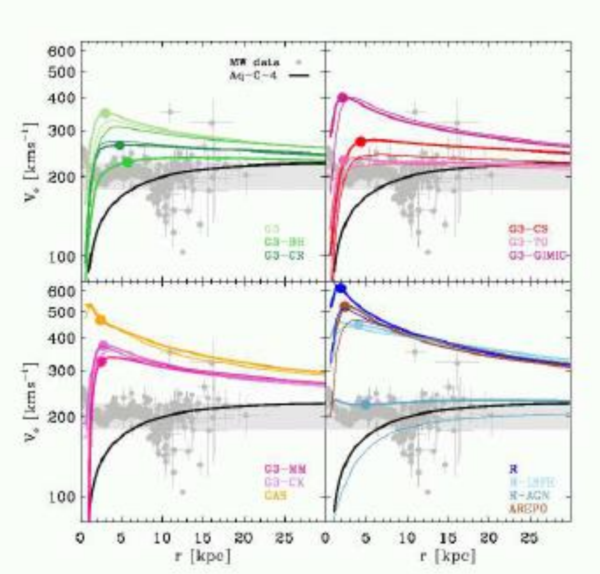
- energy radiated away..
  <<kinetic>> fb
  many other schemes
- subgrid

For many years, producing realitic disk galaxies in LCDM has been a problem

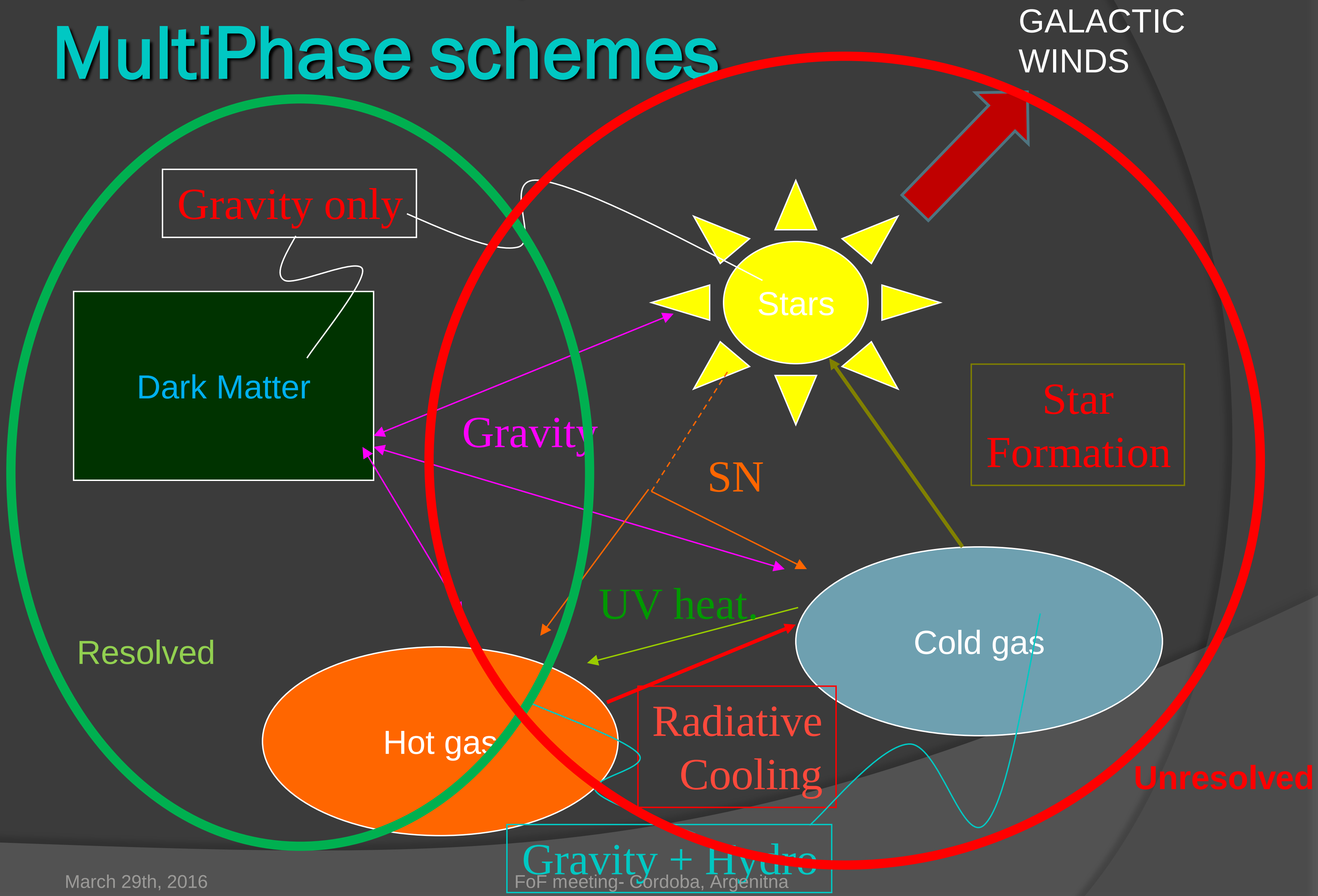
Aquila comparison project (Scannapieco+ 2012)







Star formation, feedback… MultiPhase schemes



GALACTIC WINDS (!= kinetic feedback…)

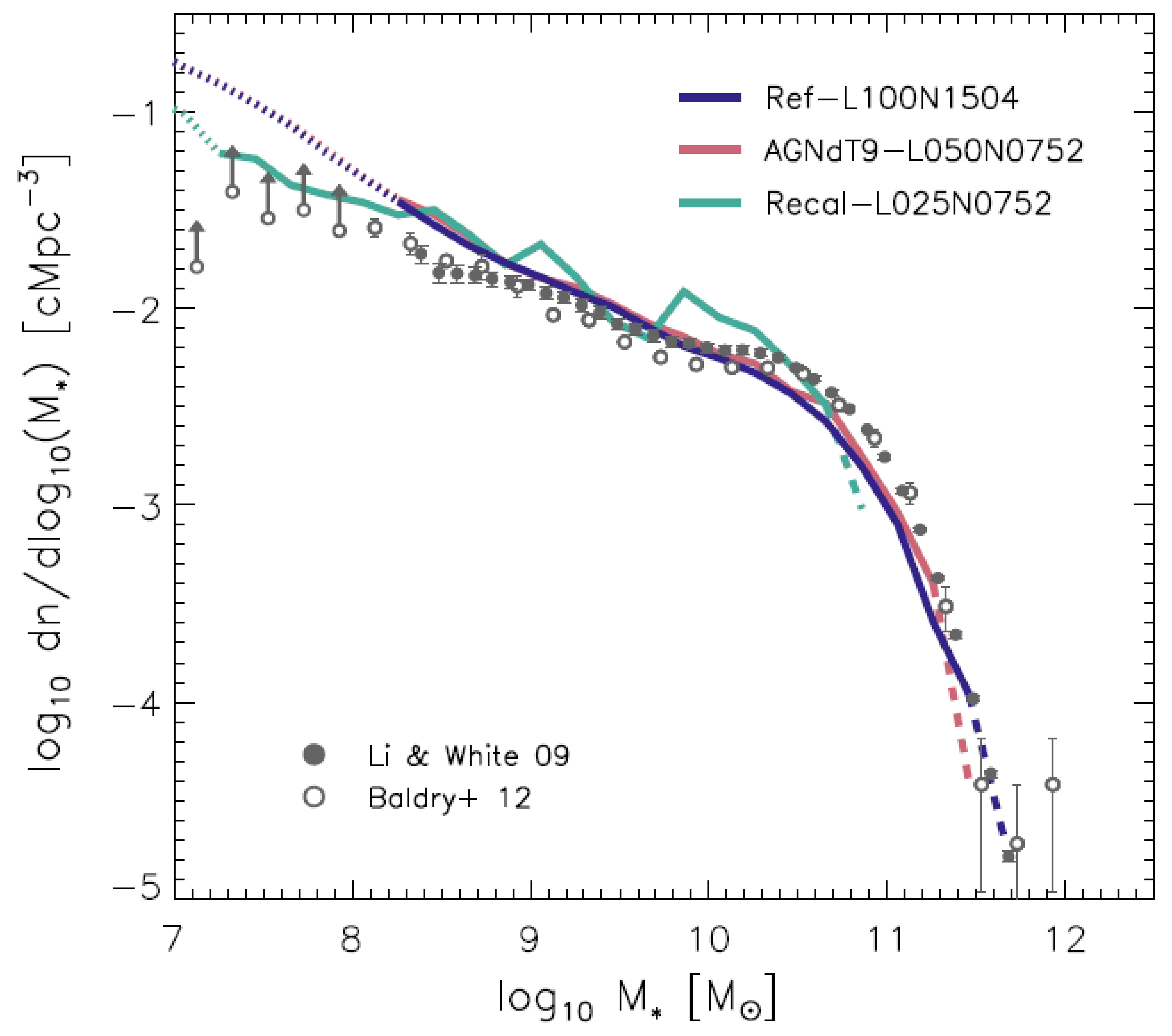
Needed to give **effective, high-z feedback**.

→ Stellar feedback is essential
for understanding galaxy formation!

→ Nonlinear calculations must produce them.

- Mass/Momentum driven
- Decoupled, not decoupled
- Local/Halo-based
- Kinetic/Thermal
- ……..

Several astrophysical processes invoked


Ref−L100N1504
AGNdT9−L050N0752
Recal−L025N0752
Li & White 09
Baldry+ 12
log₁₀ dn/dlog₁₀(M*) [cMpc⁻³]
−1
−2
−3
−4
−5
log₁₀ M* [M⊙]
7
8
9
10
11
12

re

enent,

)

Cosmological sets (II)

MAGNETICUM (Dolag+, in prep.); GADGET, improved SPH

- SH03, energy driven kinetic feedback
- AGN FB: quasar (thermal) + radio (thermal) Steinborn+ 2015 model
- Huge set of boxes, from 1560 Mpc/h to 18 Mpc/h
- Resolution: variable (MUPPI resolution available for the smaller boxes)

FIRE (Hopkins+ 2014) P-SPH/GIZMO, GADGET-based

- Katz+96 SF, high threshold (n>100 cm^{-3}); requires extreme resolution
- Molecular H followed; Krumholtz&Gnedin 2011
- Radiation pressure, Sne rates, mechanical luminosities and ejecta momentum, stellar winds, photo-ionization and photo-electrical heating: tabulated from stellar population models.
- FB as thermal energy/radial momentum. Thermal energy converted in momentum when cooling radius not resolved
- Resolution: 0.02-0.15 kpc/h, 1.8 10^2 – 2.7 10^4 M_{sun}/h
- Follow-up: LATTE (local group VHR resimulations)

Note: this is not a set of cosmological runs

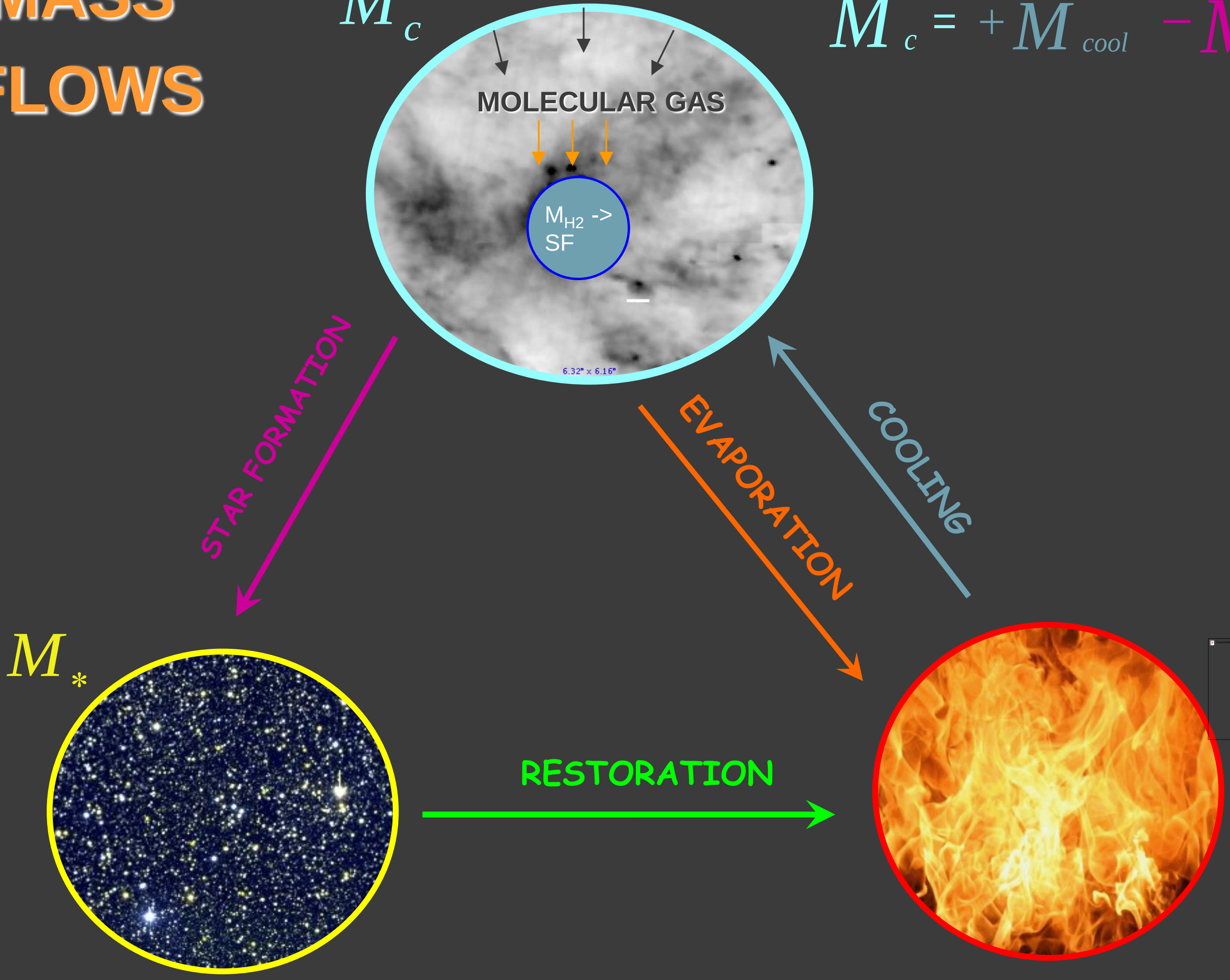
MUPPI: MUlti Phase Particle Integrator

Murante, Monaco, Giovalli, Borgani, Diaferio, 2010, MNRAS, 405, 1491

- Star formation & feedback algorithm
- Implemented in GADGET-3
- Integrates ISM equations for **each** particle at each SPH time step
- Effective thermal feedback
- Obtains SK relation without imposing it

  (See Monaco, Murante, Borgani, Dolag, 2012, MNRAS, 421, 2485)
- Gives ISM characteristics

MASS FLOWS



$$\dot{M}_c = +\dot{M}_{cool} - \dot{M}_{sf} - \dot{M}_{evap}$$

$$\dot{M}_{cool} = \frac{M_h}{t_{cool}}$$

$$\dot{M}_{sf} = f_{star} \cdot \frac{M_{H2}}{t_{dyn}}$$

$$\dot{M}_{rest} = f_{rest} \cdot \dot{M}_{sf}$$

$$\dot{M}_{evap} = f_{evap} \cdot \frac{M_{H2}}{t_{dyn}}$$

On **hot** **phase!**

On **cold** phase!

$$\dot{M}_* = +\dot{M}_{sf} - \dot{M}_{rest}$$

$$\dot{M}_h = -\dot{M}_{cool} + \dot{M}_{rest} + \dot{M}_{evap}$$

ENERGY FLOW(S..)

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

PRESSURE-DRIVEN SF

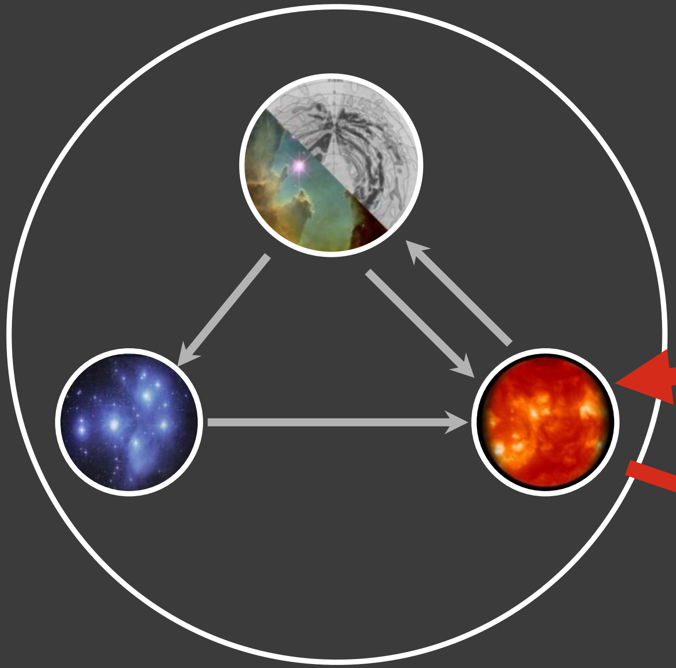
$$M_{H2} = f_{coll} \bullet M_c$$

$$f_{coll} = \frac{1}{1 + 4\left(\frac{P_0}{P_{ext}}\right)}$$

Phenomenological
(Blitz & Rosolowsky 2006)
$P_{ext} \approx P_{therm}$ with $P_0 = 35000$

Energy exchanges

Multi-Phase particle



SPH

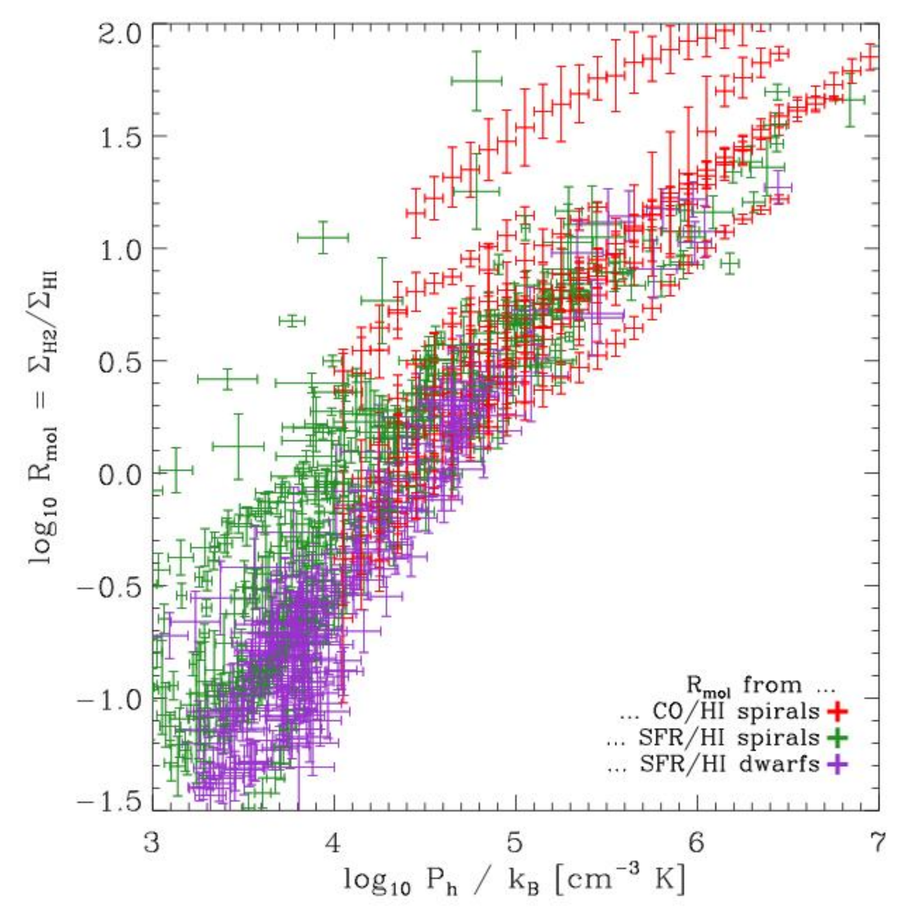
Δt, ΔS

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

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

new ΔS

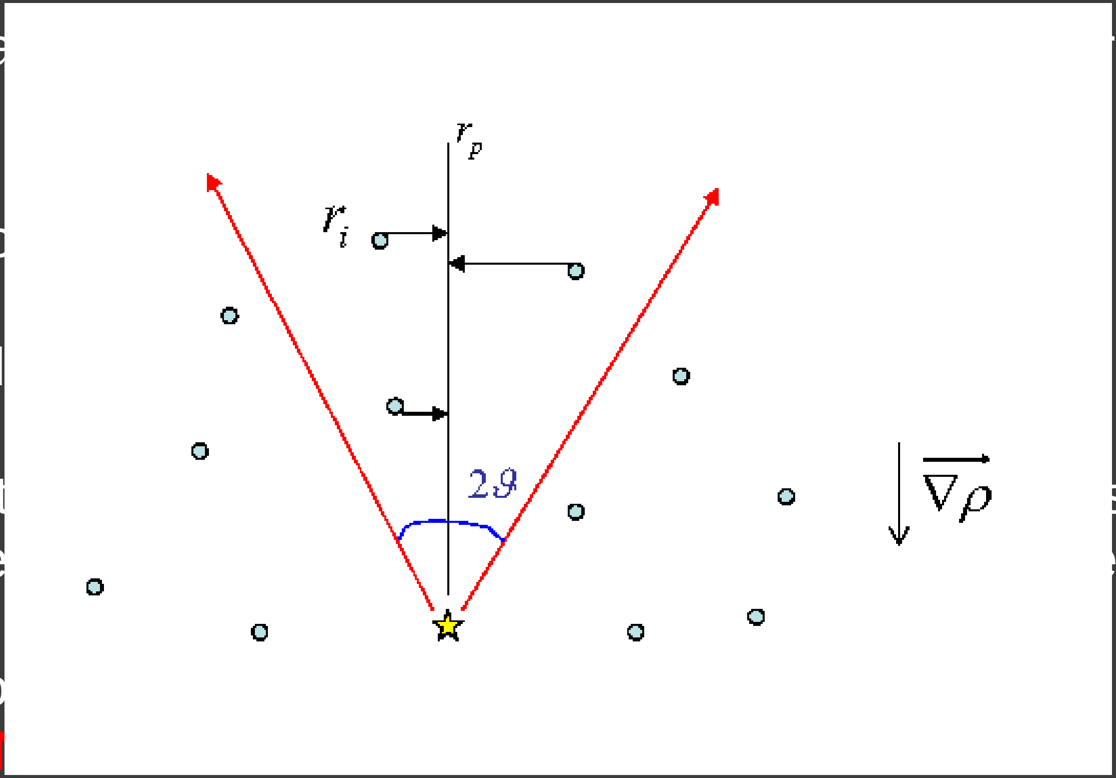
etc...



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

Note. This phenomenomenologically includes a number of astrophysic processes and feedbacks (turbulence, magnetic fields, cosmic rays, early Stellar feedback…) PROS: it’s the reality. CONS: local, kpc-averaged (…but… resolution…)

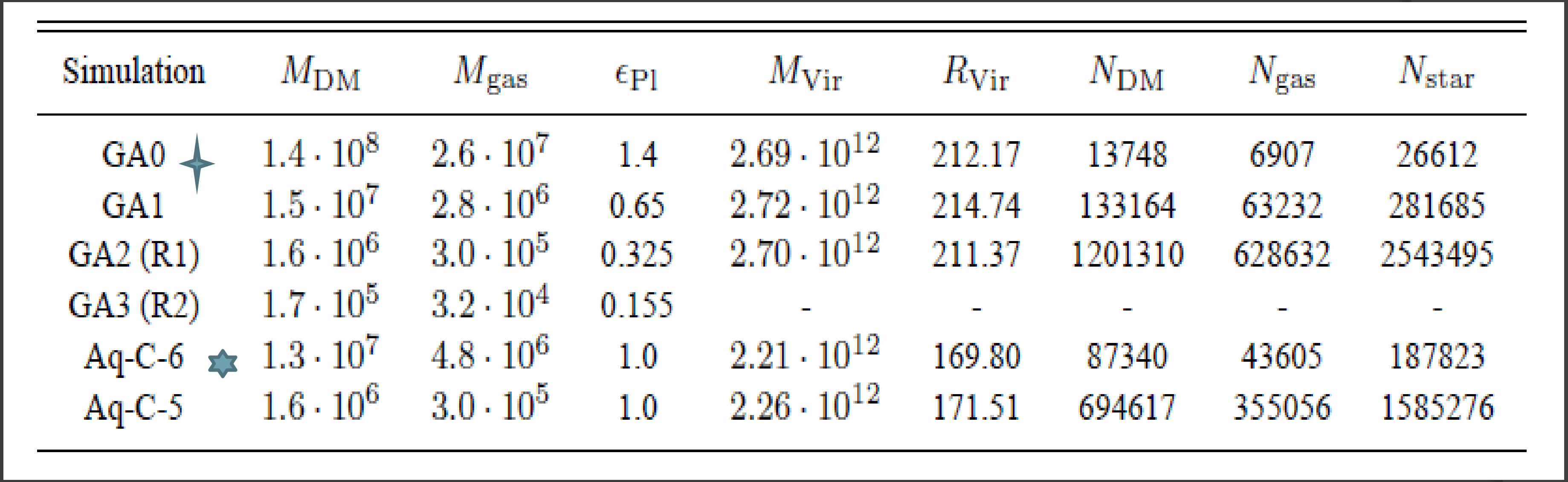
More characteristics



- Therma ectional way
- Chemic
- Metal d
- Stocast sly receive also kine ecouple from the ological simulatio

WORK I

Cosmological disk galaxy simulations



Simulation	$M_{\rm DM}$	$M_{\rm gas}$	$\epsilon_{\rm Pl}$	$M_{\rm Vir}$	$R_{\rm Vir}$	$N_{\rm DM}$	$N_{\rm gas}$	$N_{\rm star}$
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	-	-	-	-	-
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

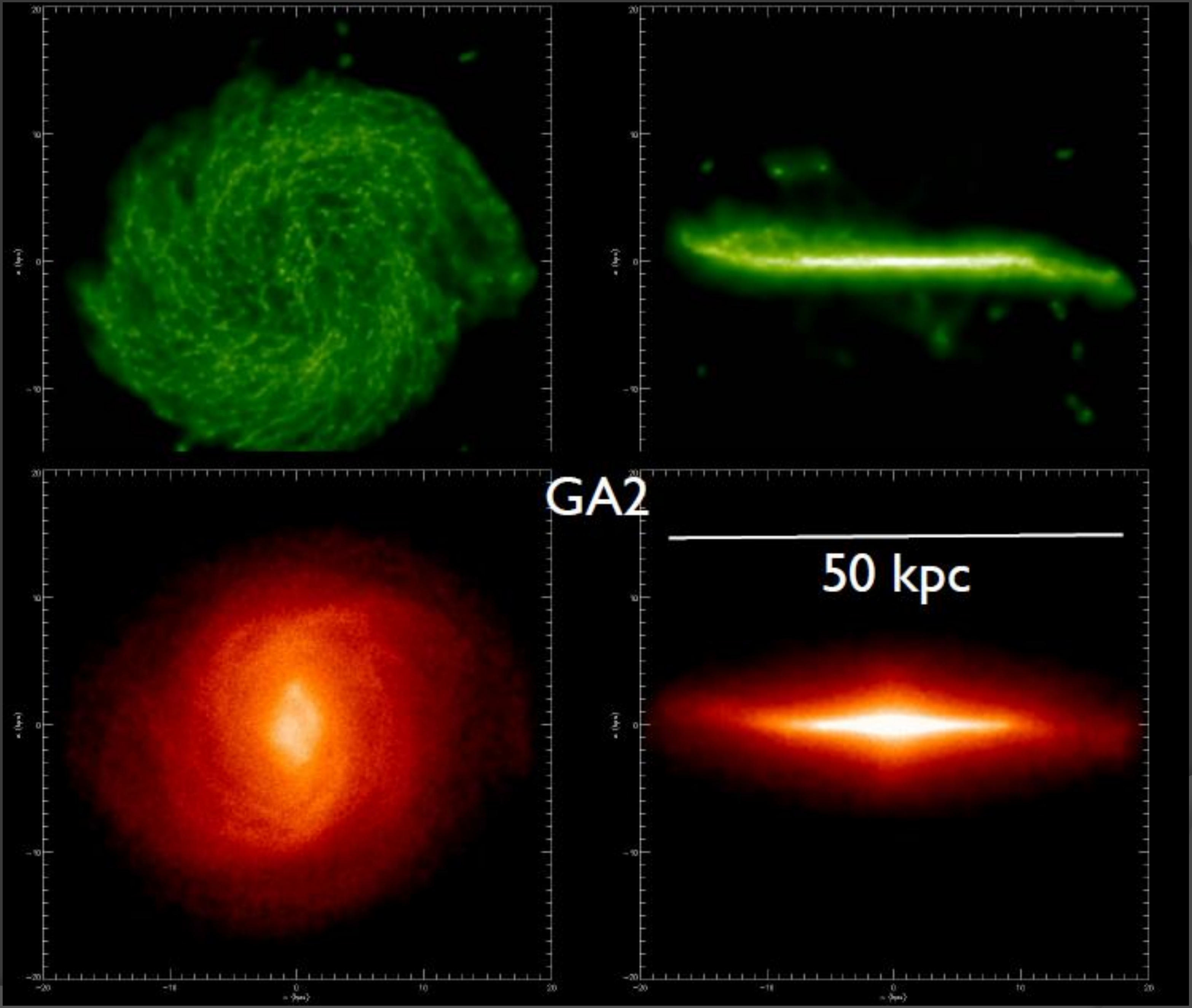
✦ (Stoehr+, 2002, MNRAS, 355, 84)

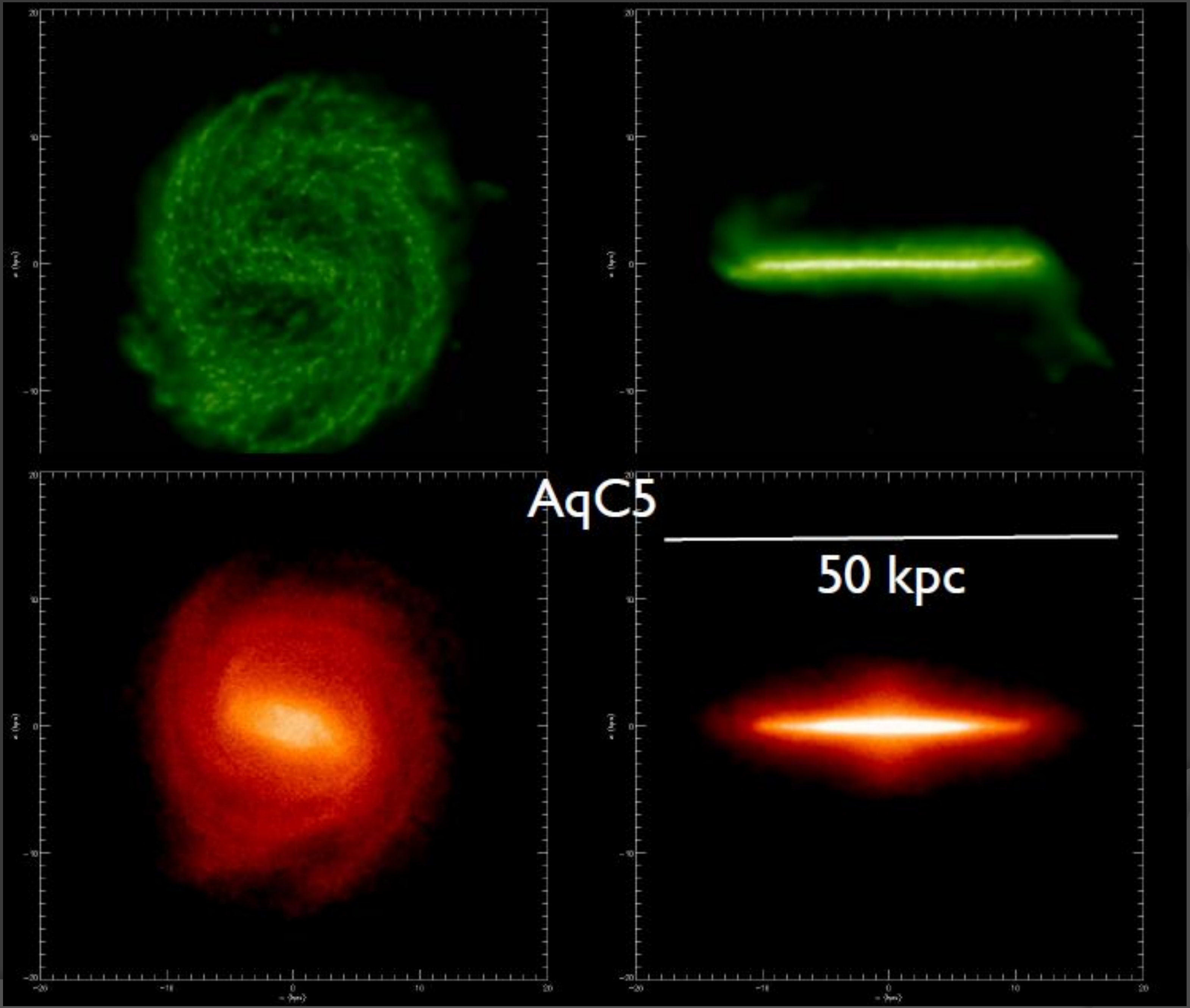
✶ (See *The Aquila comparison project*, Scannapieco+, 2012, MNRAS, 423, 1726)

Murante, Monaco, Borgani, Tornatore, Dolag, Goz, 2015, MNRAS, 447, 178

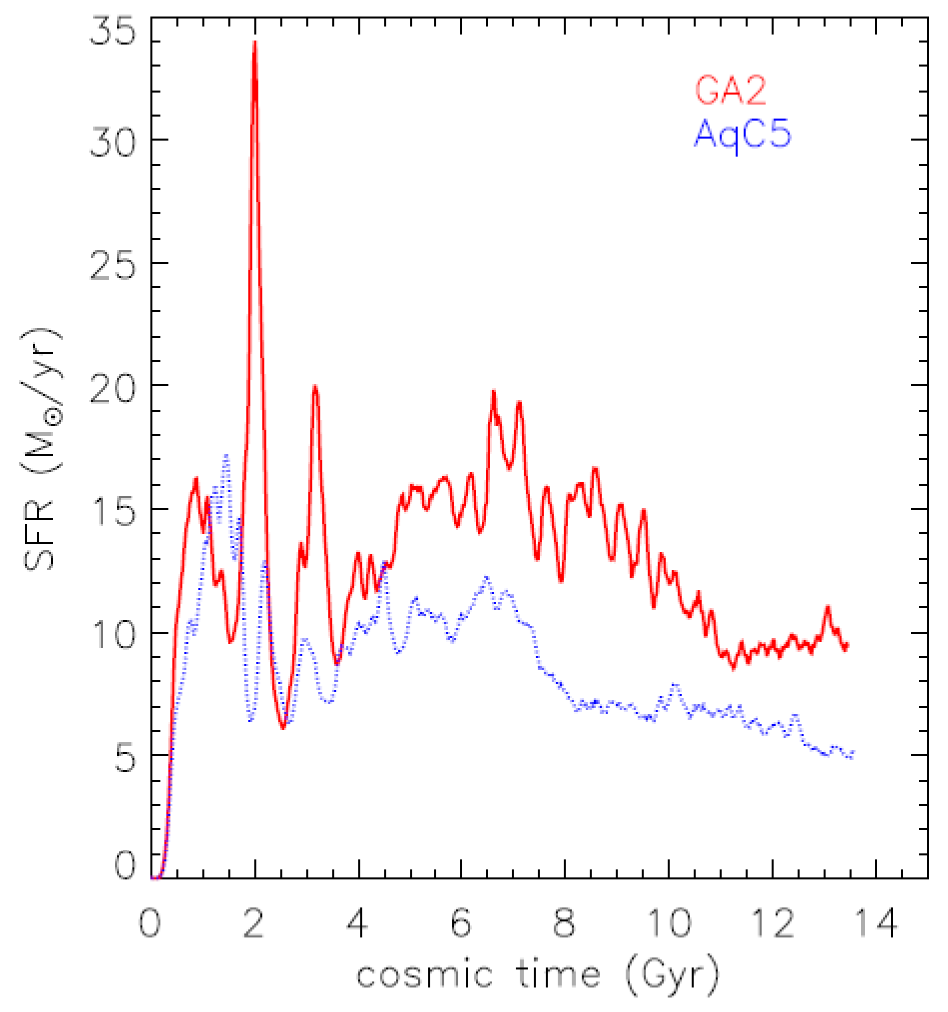
Goz+, 2015, MNRAS, 447, 1774

Monaco+, 2012, MNRAS, 447, 1774


GA2
50 kpc
20
10
0
−10
−20

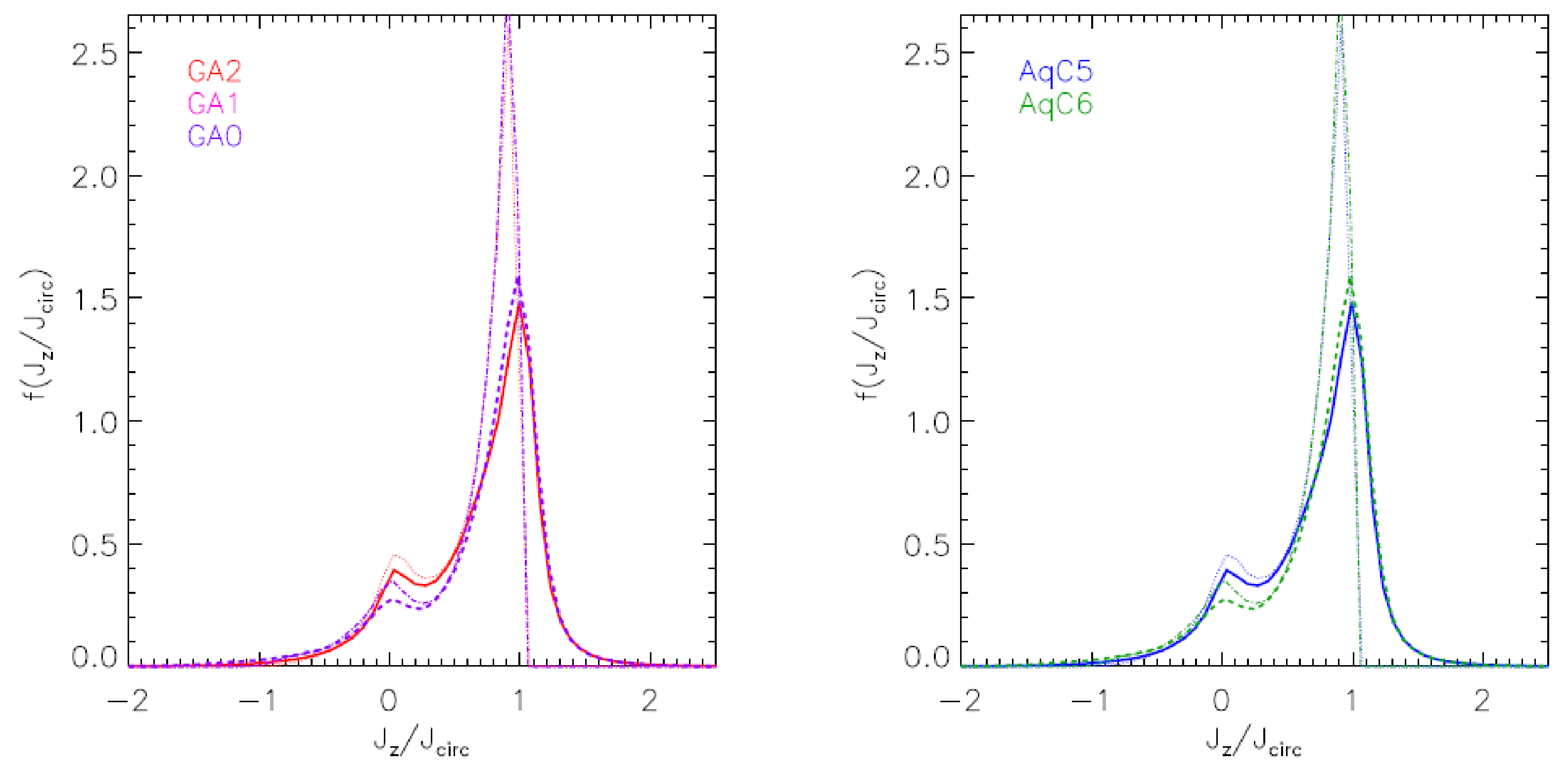

AqC5
50 kpc
20
10
0
-10
-20

Star Formation Rates

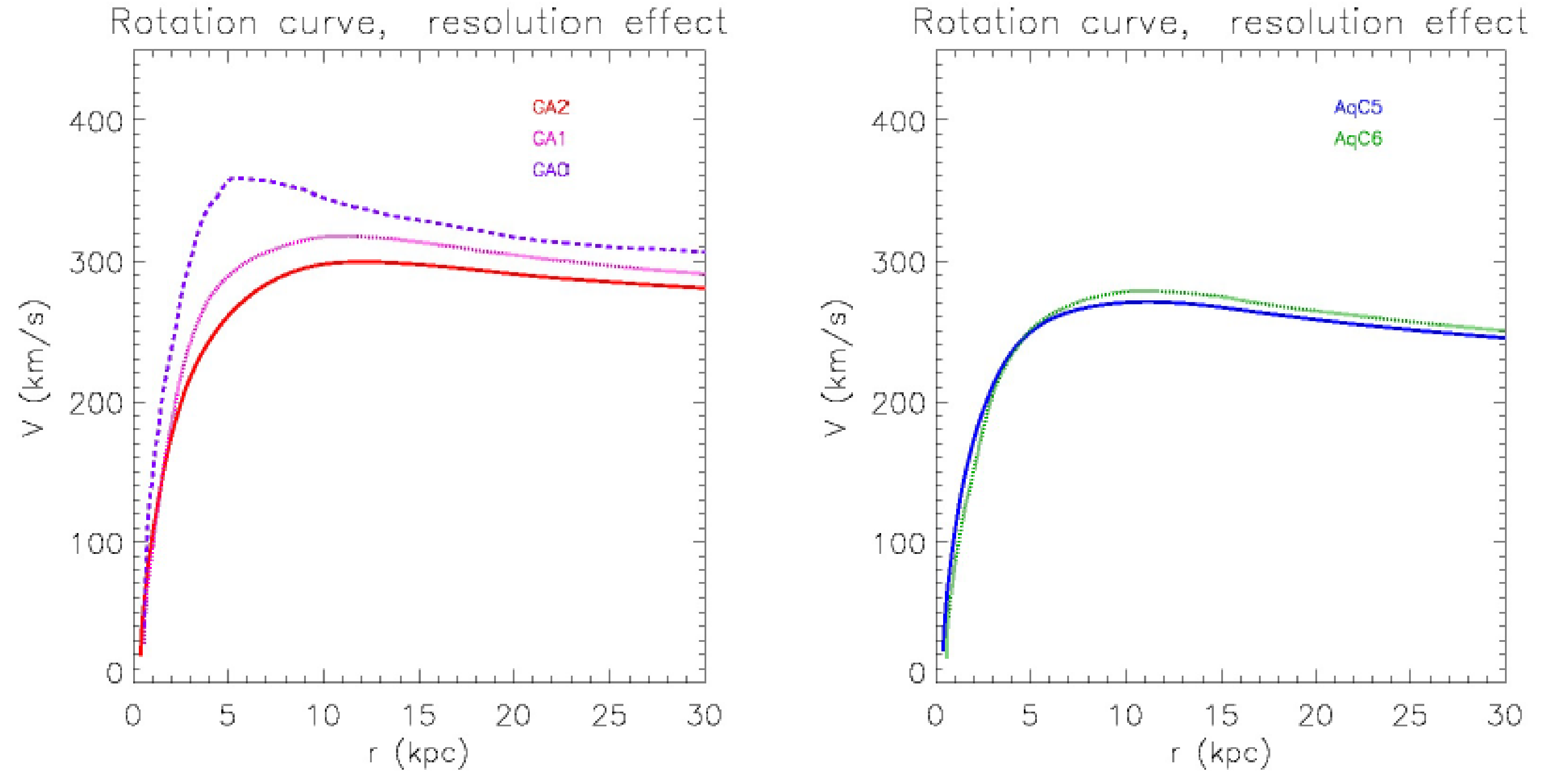


Circularity Histograms

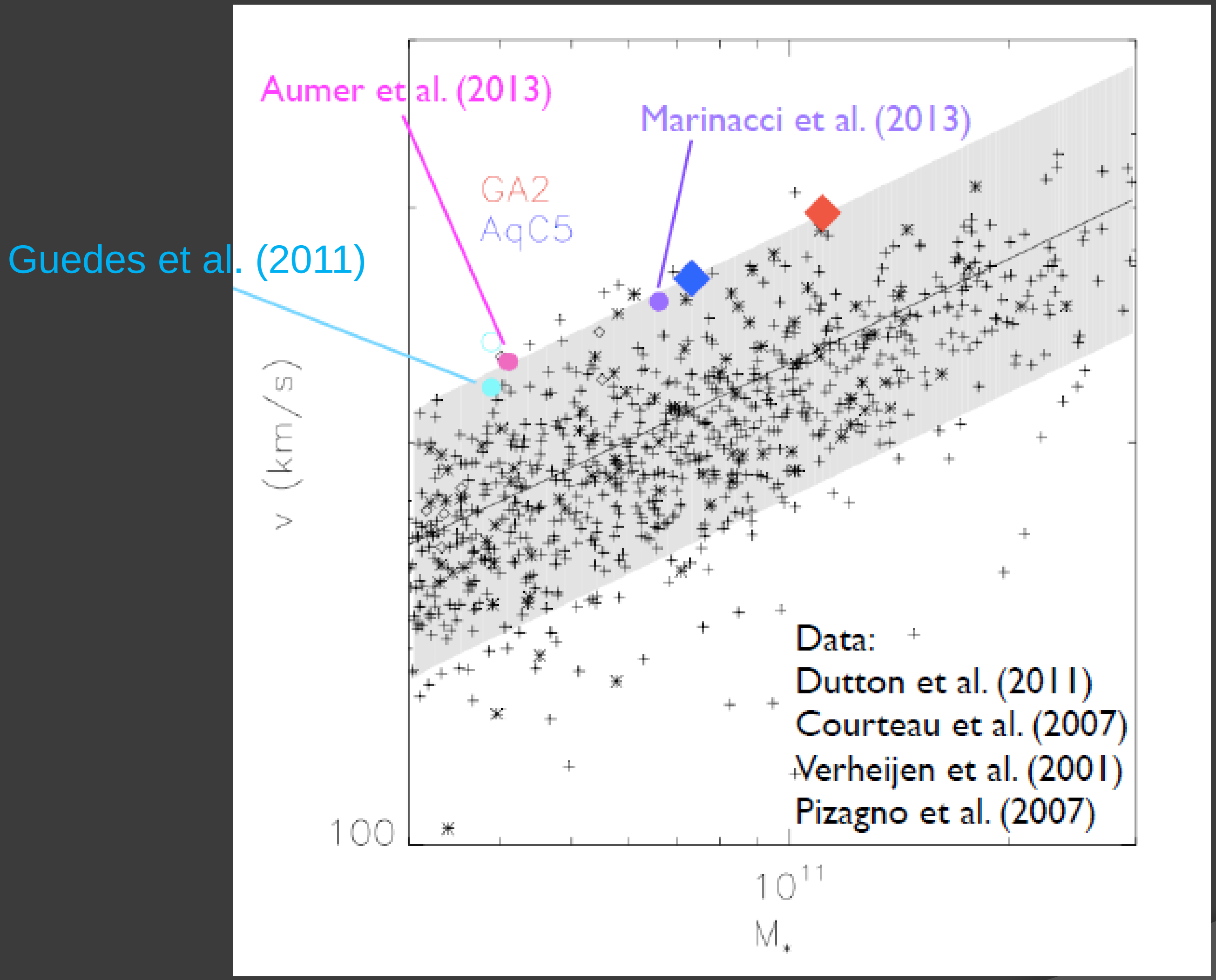
B/T=0.30 (GA0), 0.22 (GA1), 0.20 (GA2) B/T=0.24 (Aq-C5), 0.23 (Aq-C6)



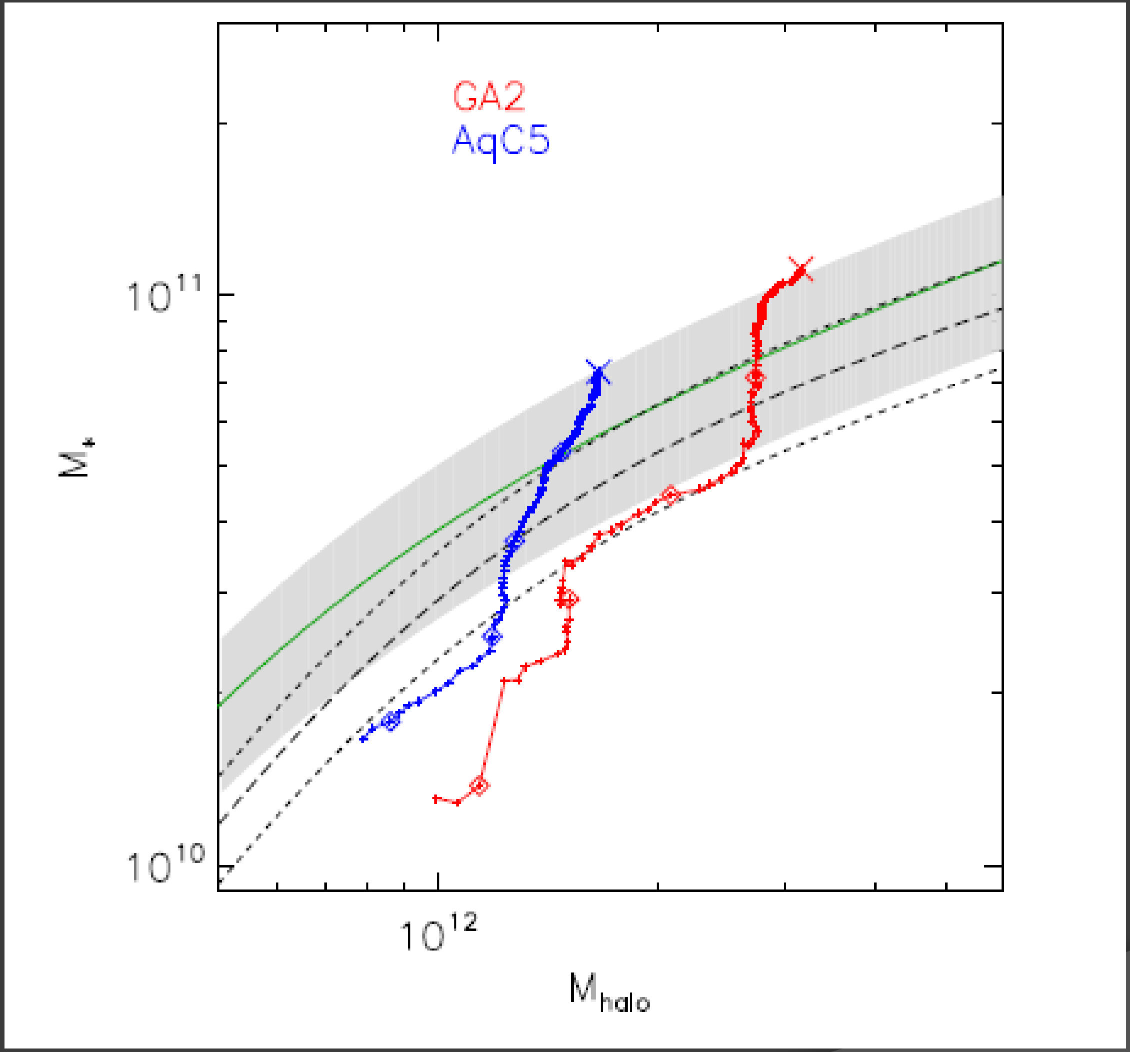
Circular Velocity Profiles



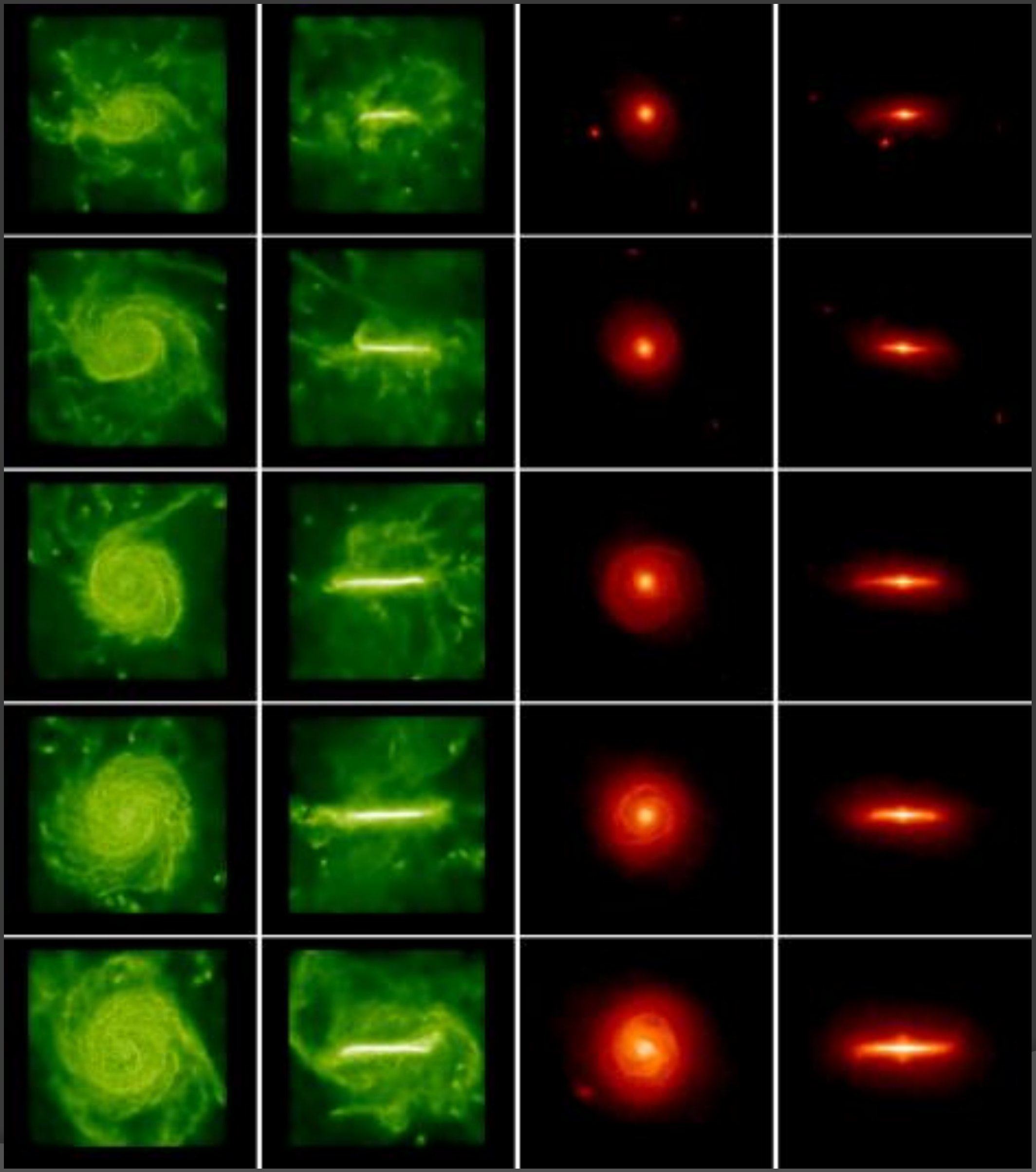
Tully-Fisher



Barion conversion efficiencies



Redshift evolution (AqC5)



Z=2.48

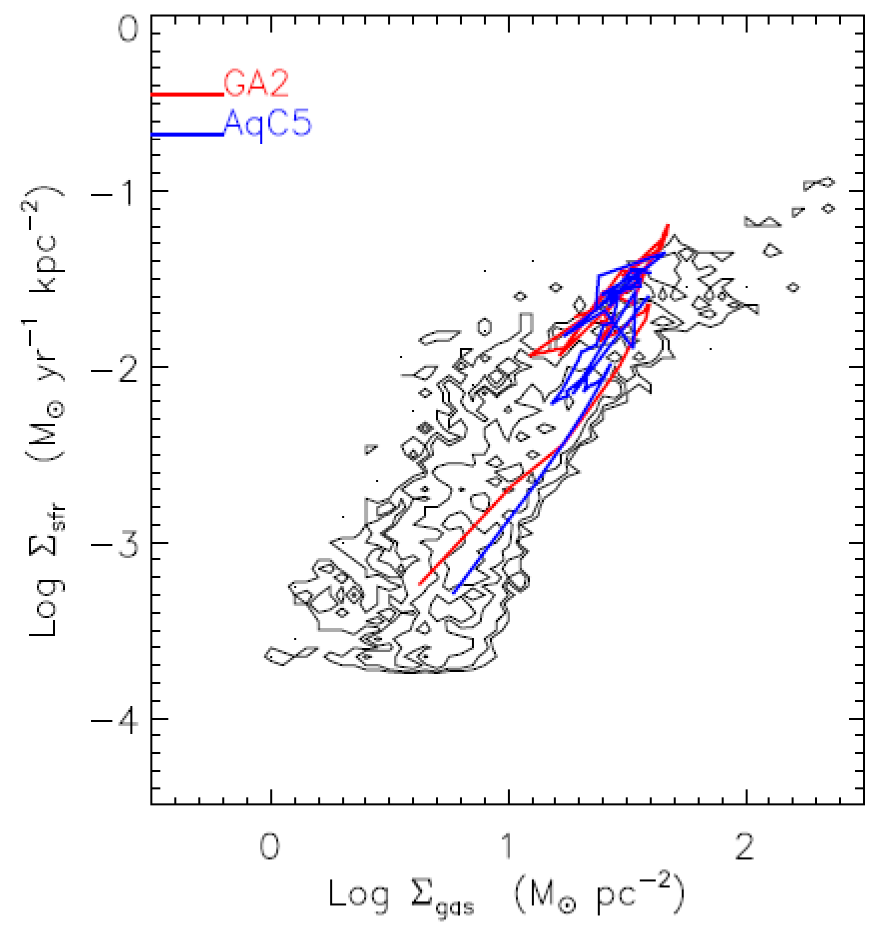
Z=2.02

Z=1.50

Z=1.01

Z=0.49

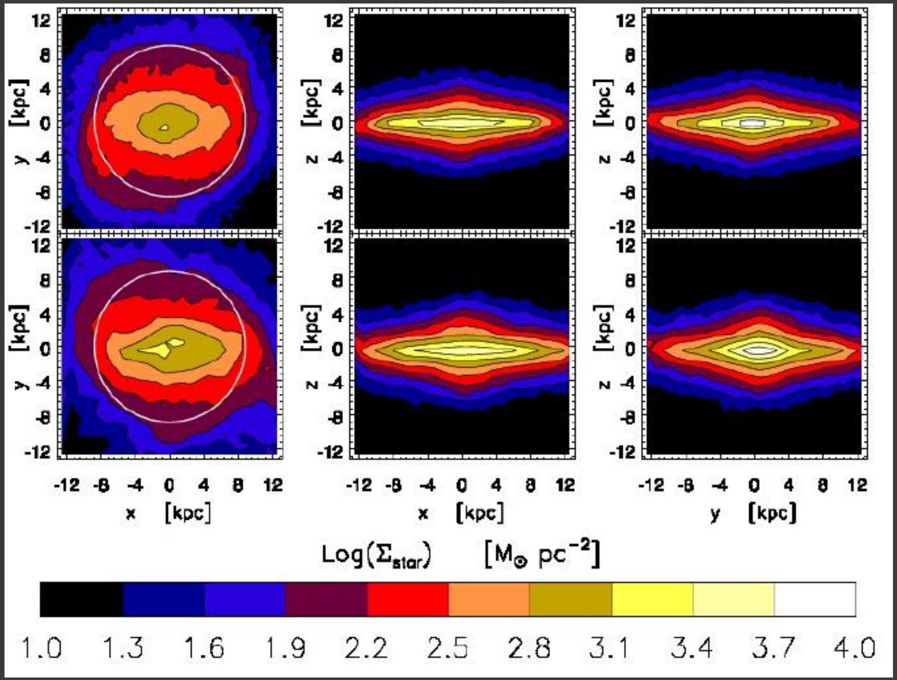
Schmidt-Kennicutt relation

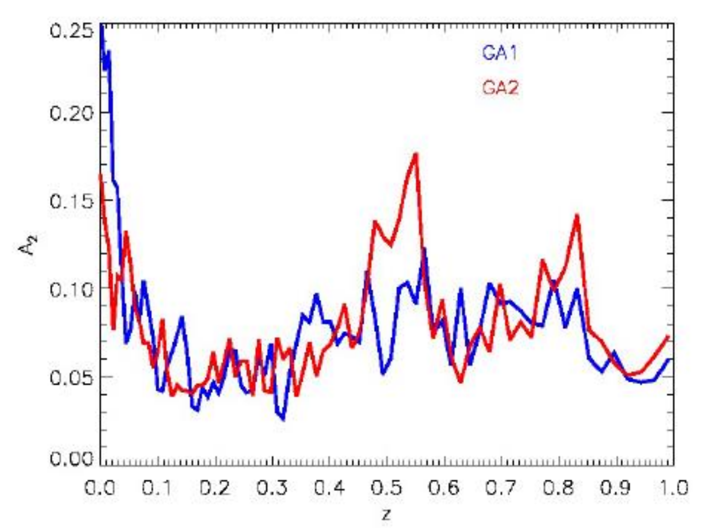


Bars! (Goz+, 2015, MNRAS, 447, 1774)

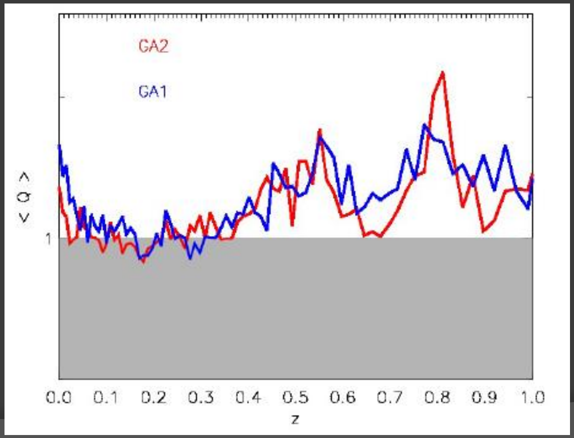
GA2

GA1





Bar strenght



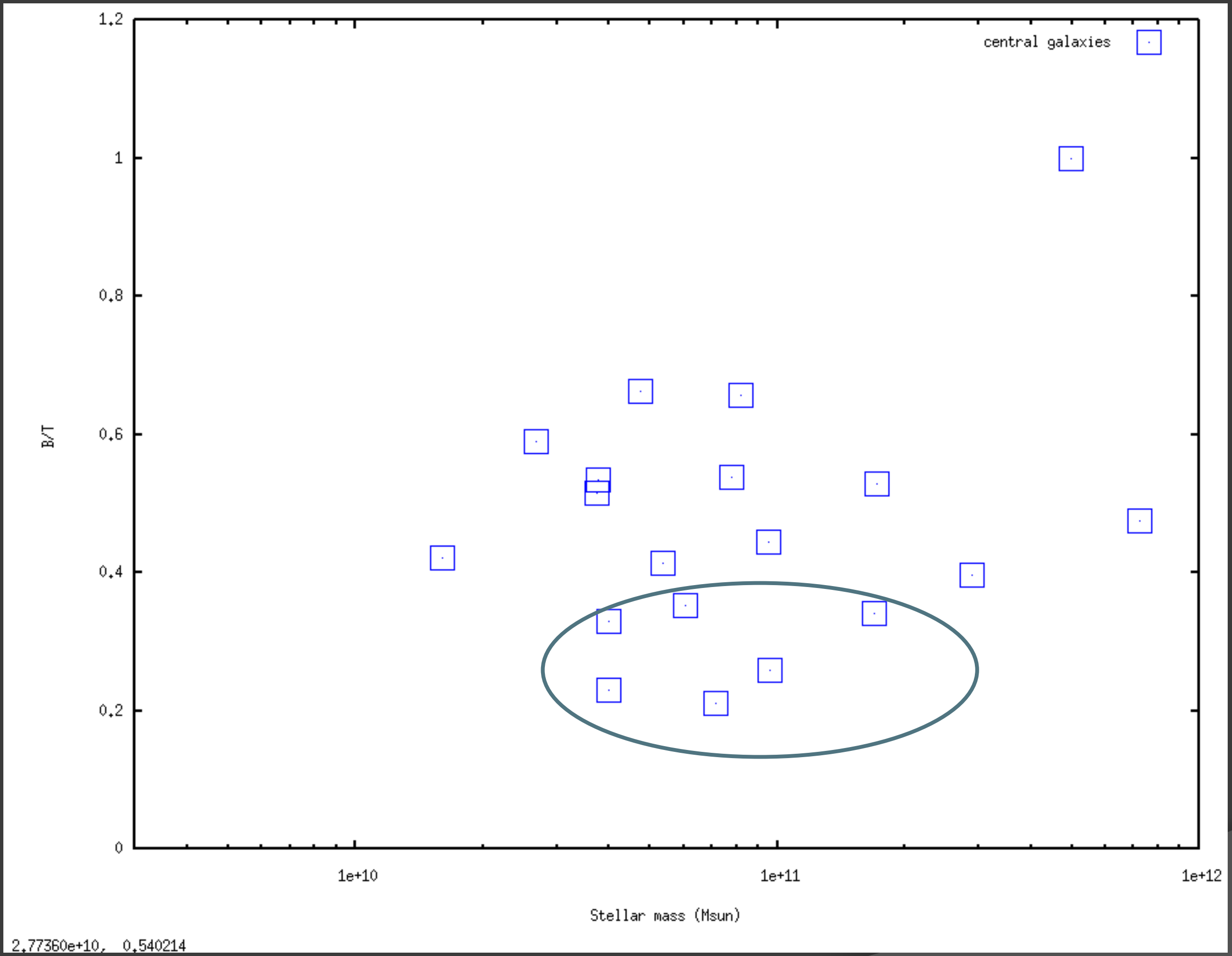
Disk stability (Toomre) criterion

MUPPI Boxes

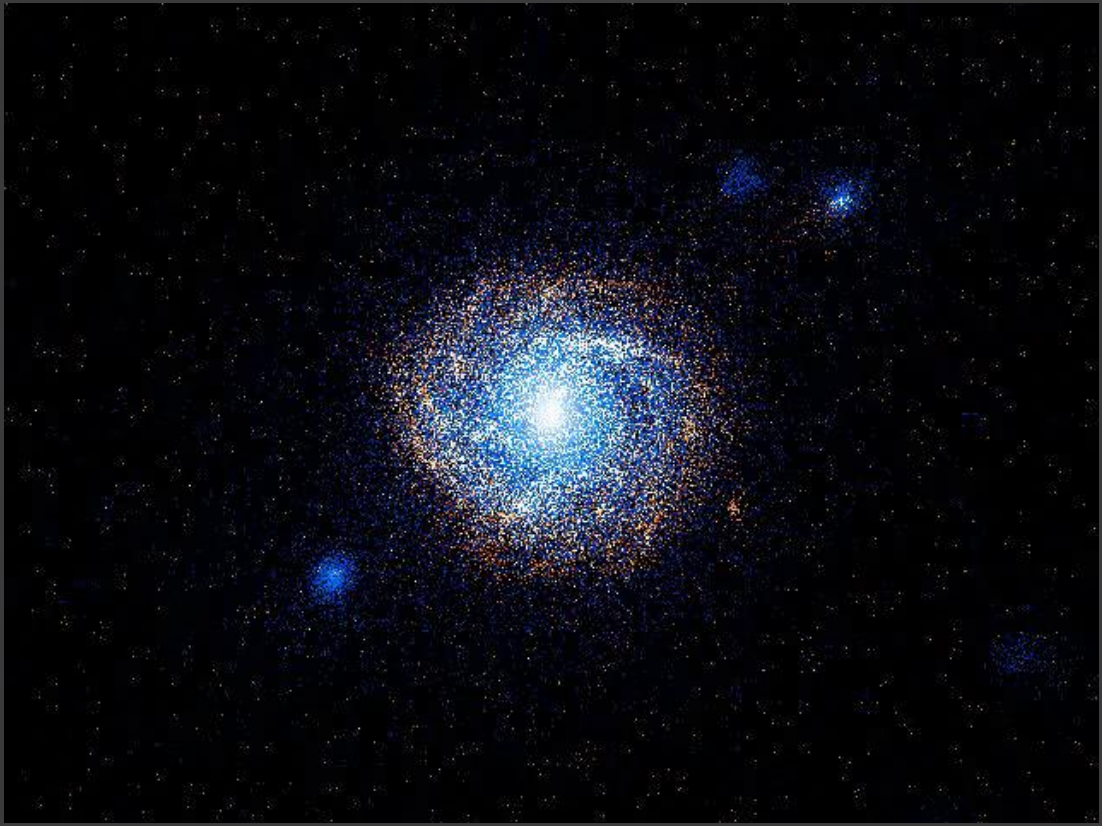
- **MEDIUM** resolution:
  force: 0.5 kpc/h
  mass (gas): 5×10^{6} Msun/h
- About 20 galaxies more massive than 10^{10} Msun/h
- Incoming: larger boxes; higher resolution for high z

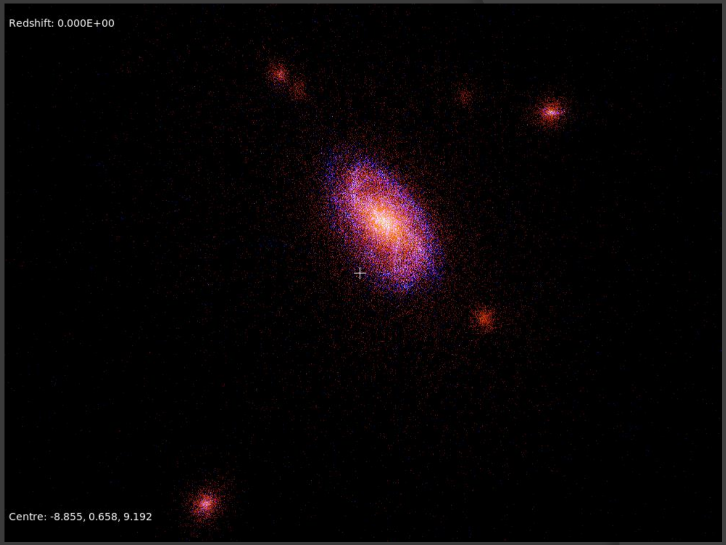
18 Mpc/h**, 2×256^{3}** particles

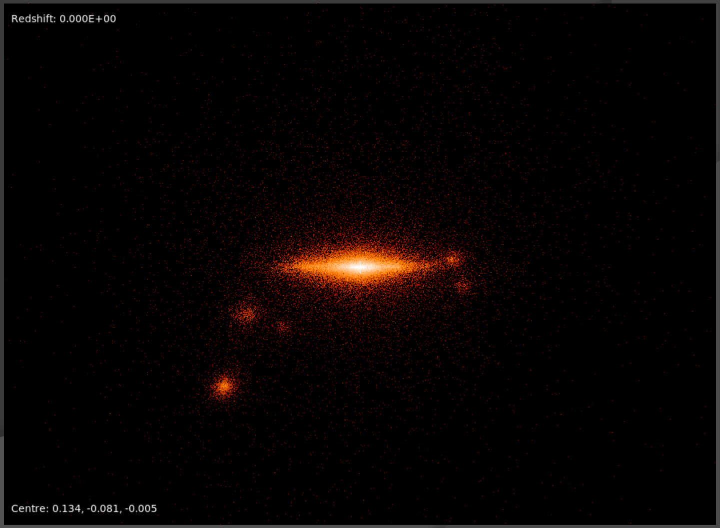
Bulge/Total mass ratios



Best disk galaxy in the box







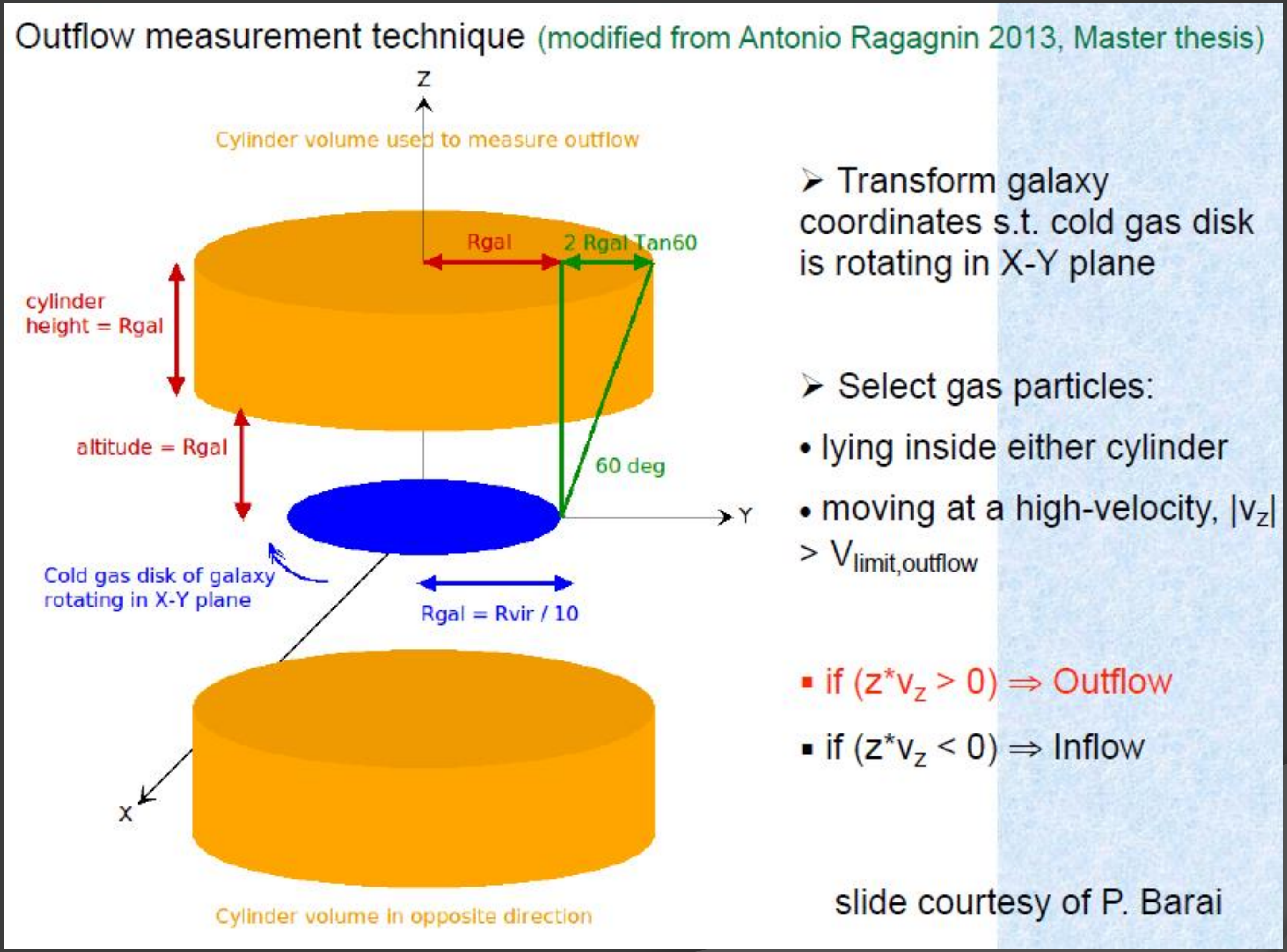
Mass: stars, 7.2x10^{10} Msun; gas, 3.4x10^{10}

f_{bar}: 0.075 (galaxy) 0.12 (halo)

B/T: 0.21; mass of stellar disk: 5.65x10^{10}

approx. 10^5 baryon particles in the galaxy

Outflows in MUPPI Boxes

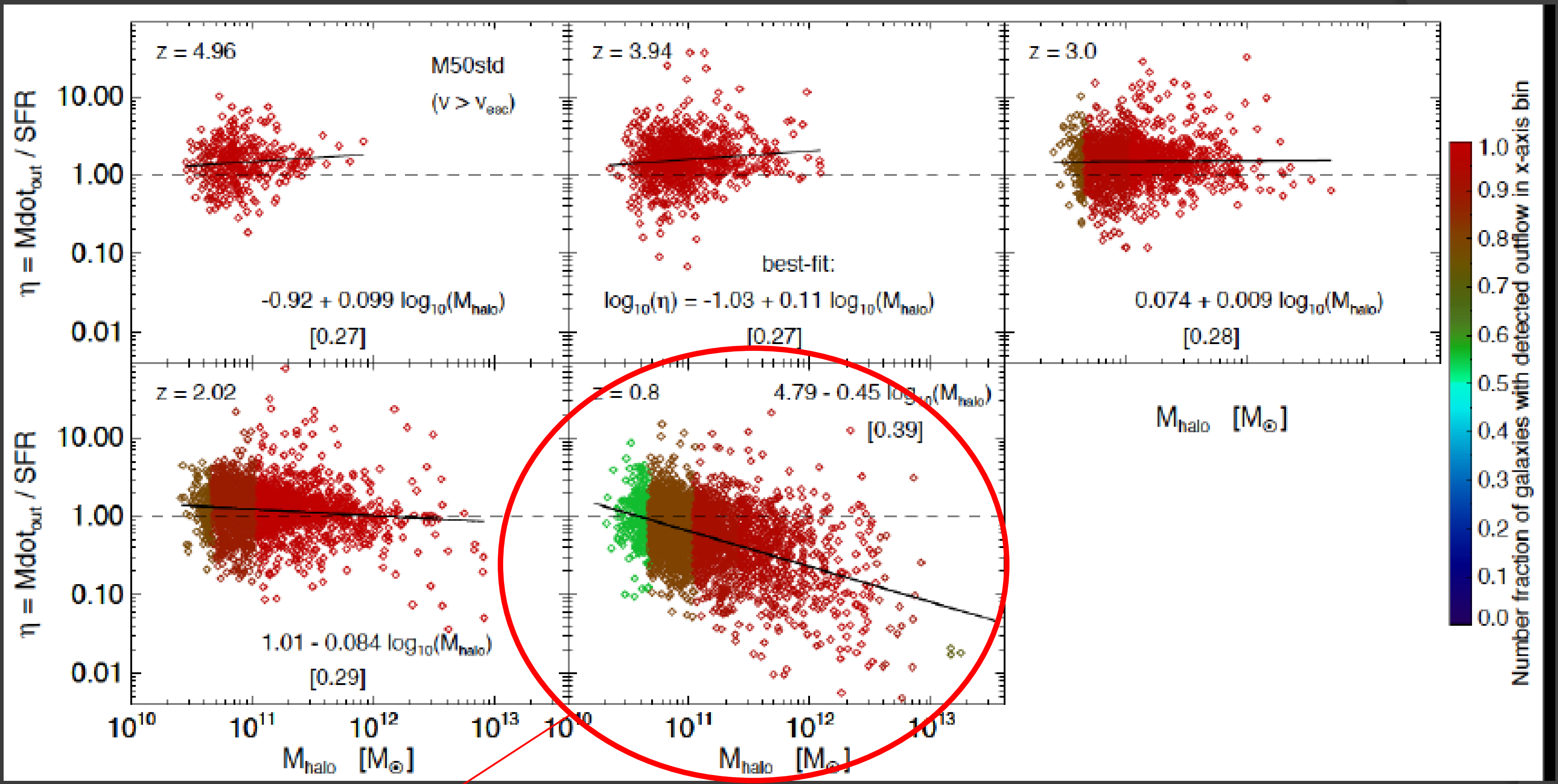


Outflow measurement technique (modified from Antonio Ragagnin 2013, Master thesis)

- ➢ Transform galaxy coordinates s.t. cold gas disk is rotating in X-Y plane
- ➢ Select gas particles:
- • lying inside either cylinder
- • moving at a high-velocity, $|v_z| > V_{limit,outflow}$
- ▪ if $(z^*v_z > 0) \Rightarrow$ Outflow
- ▪ if $(z^*v_z < 0) \Rightarrow$ Inflow

slide courtesy of P. Barai

Redshift Evolution of Mass-Loading factor vs Halo Mass



Illustris puts this by hand (momentum driven winds)
Not lots of info on Eagle outflows.

Barai+, 2015,
MNRAS, 447, 266

Galaxy SED with GRASIL3D

Dominguez-Tenreiro+ 2014; Goz+, MNRAS submitted

Comparison with observed emission in various bands

- Radiative Transfer post-processing code
- Particular attention to dust reprocessing
- Arbitrary geometry
- Modified to be used with MUPPI (e.g., H_2 given by the simulation)

GRASIL3D parameters calibrated againts PEP and LVL samples

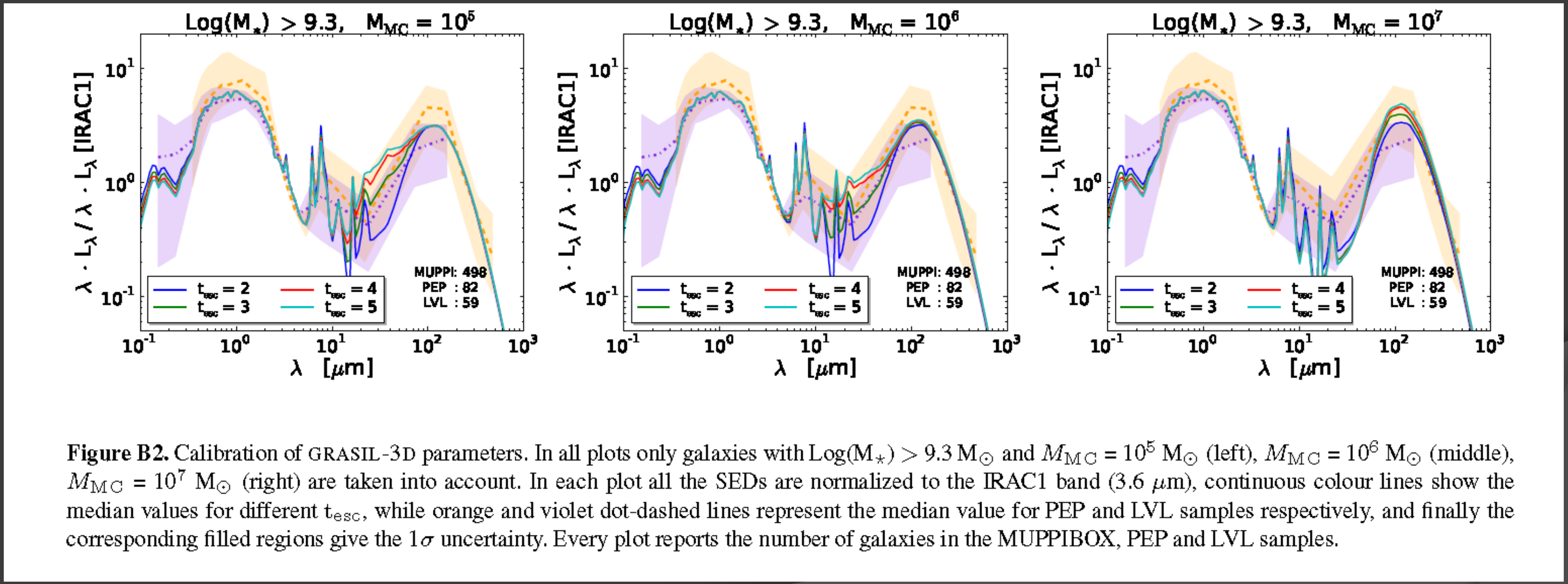


Figure B2. Calibration of GRASIL-3D parameters. In all plots only galaxies with $\mathrm{Log}(M_*) > 9.3\,M_\odot$ and $M_{MC} = 10^5\,M_\odot$ (left), $M_{MC} = 10^6\,M_\odot$ (middle), $M_{MC} = 10^7\,M_\odot$ (right) are taken into account. In each plot all the SEDs are normalized to the IRAC1 band (3.6 μm), continuous colour lines show the median values for different t_{esc}, while orange and violet dot-dashed lines represent the median value for PEP and LVL samples respectively, and finally the corresponding filled regions give the 1σ uncertainty. Every plot reports the number of galaxies in the MUPPIBOX, PEP and LVL samples.

Example: calibration of M_{MC} and t_{esc}

Galaxy SED with GRASIL3D: results

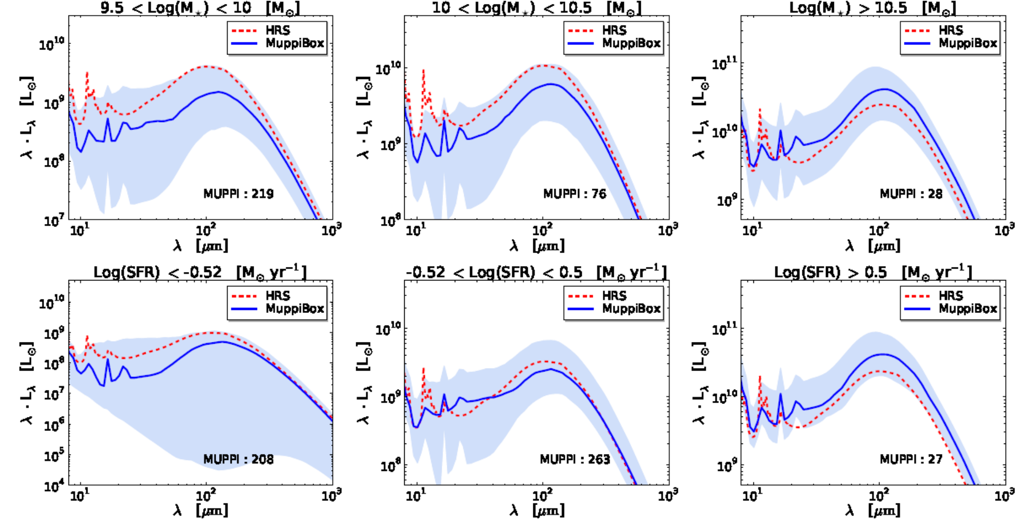


Figure 5. Comparison between median SEDs of simulated galaxy sample (blue continuous lines) and HRS (red dashed lines) for galaxies in various bins of stellar mass (first row) or SFR (second row). The blue filled region marks the 1σ uncertainty of the simulated sample, defined by the 16th and 84th percentiles. Above each panel we report the selection criterion used to define the subsample, while the number of simulated galaxies (MUPPI [number]) is reported in each figure.

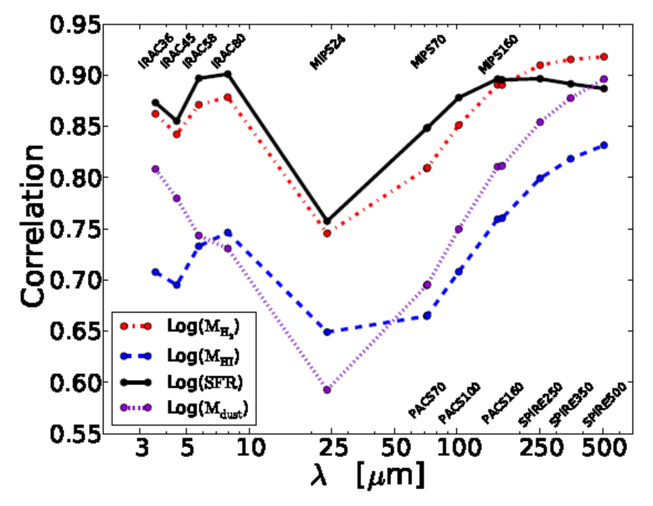


Figure 6. Spearman Correlation coefficients of IR luminosity in *Spitzer* (IRAC and MIPS) and *Herschel* (PACS and SPIRE) bands with $M_{\rm H_2}$ (dot-dashed red line), $M_{\rm HI}$ (dashed blue line), SFR (continuous black line) and $M_{\rm dust}$ (dashed violet line).

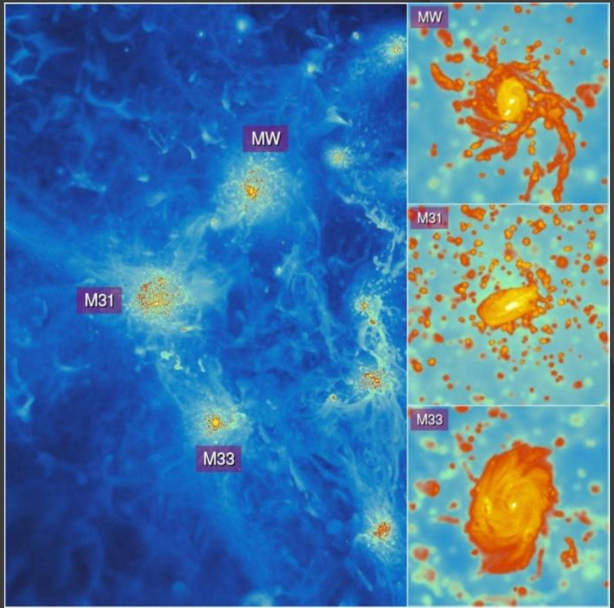
Simulated SEDs in classes of galay masses and SFR, compared with HRS

Correlation between IR luminosities and various physical quantities

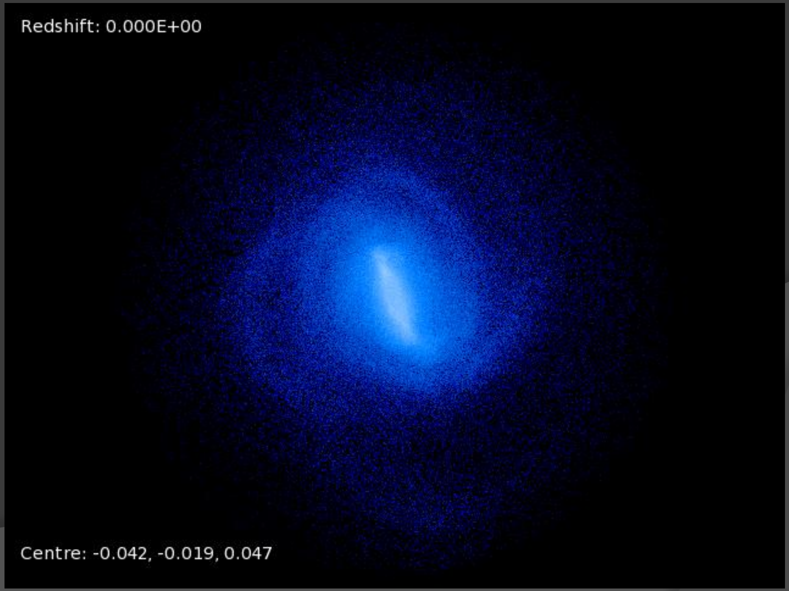
CLUES

Very preliminar, with Gustavo Yepes

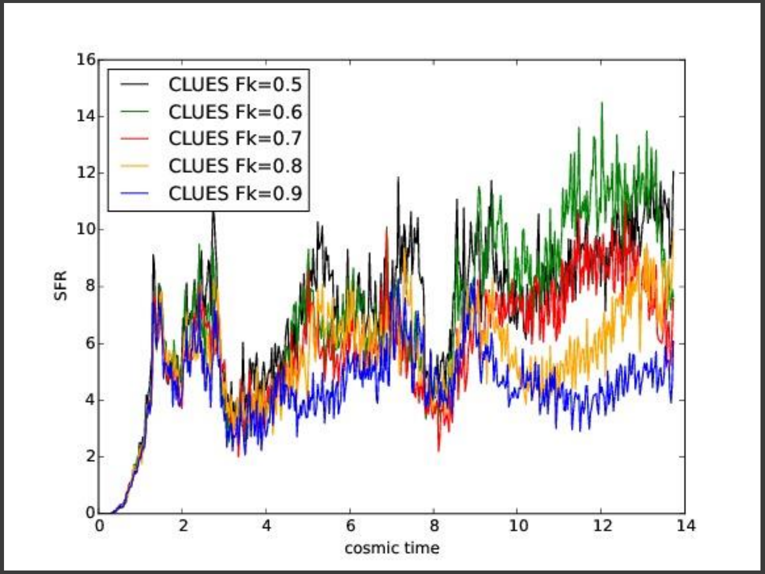
Constrained simulation of the Local group – tests at “medium”resolution (force 350pc, gas mass 10^5 M_{sol})

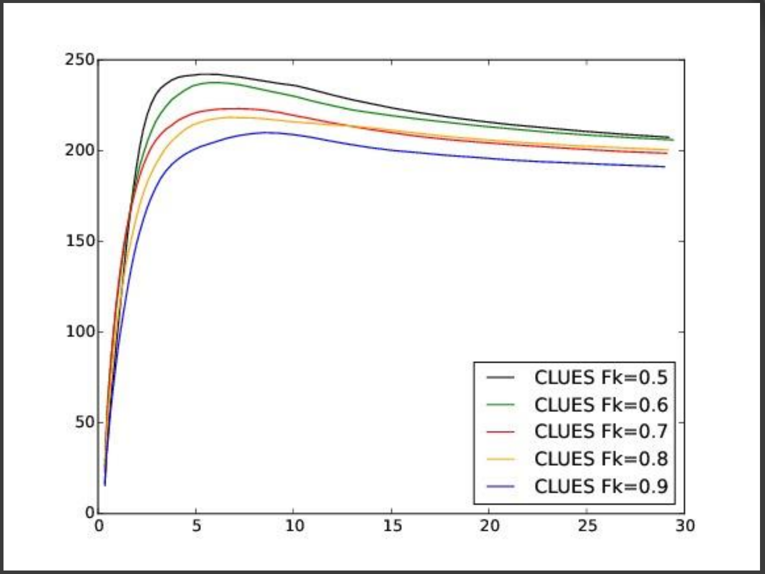


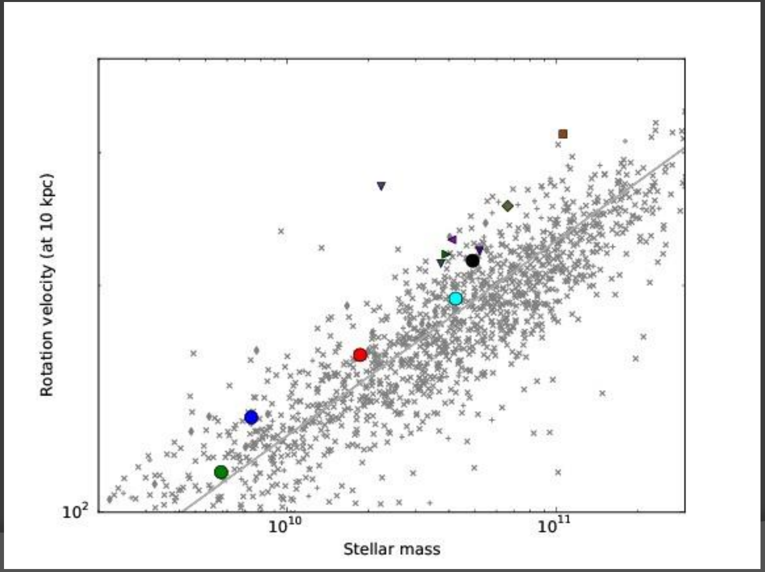
(Credits: K. Riebe, PMVIEWER, and the CLUES collaboration)

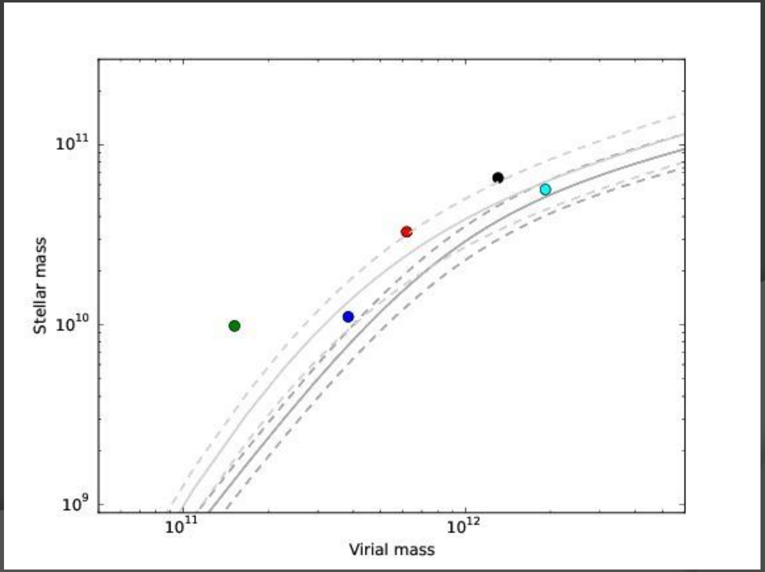


CLUES – first analysis









Developments

- Include improved SPH (done; needs parameter tuning; note, introduce additional resolution dep.)

- Improve FB schemes (ongoing: with M. Valentini, PhD st.)

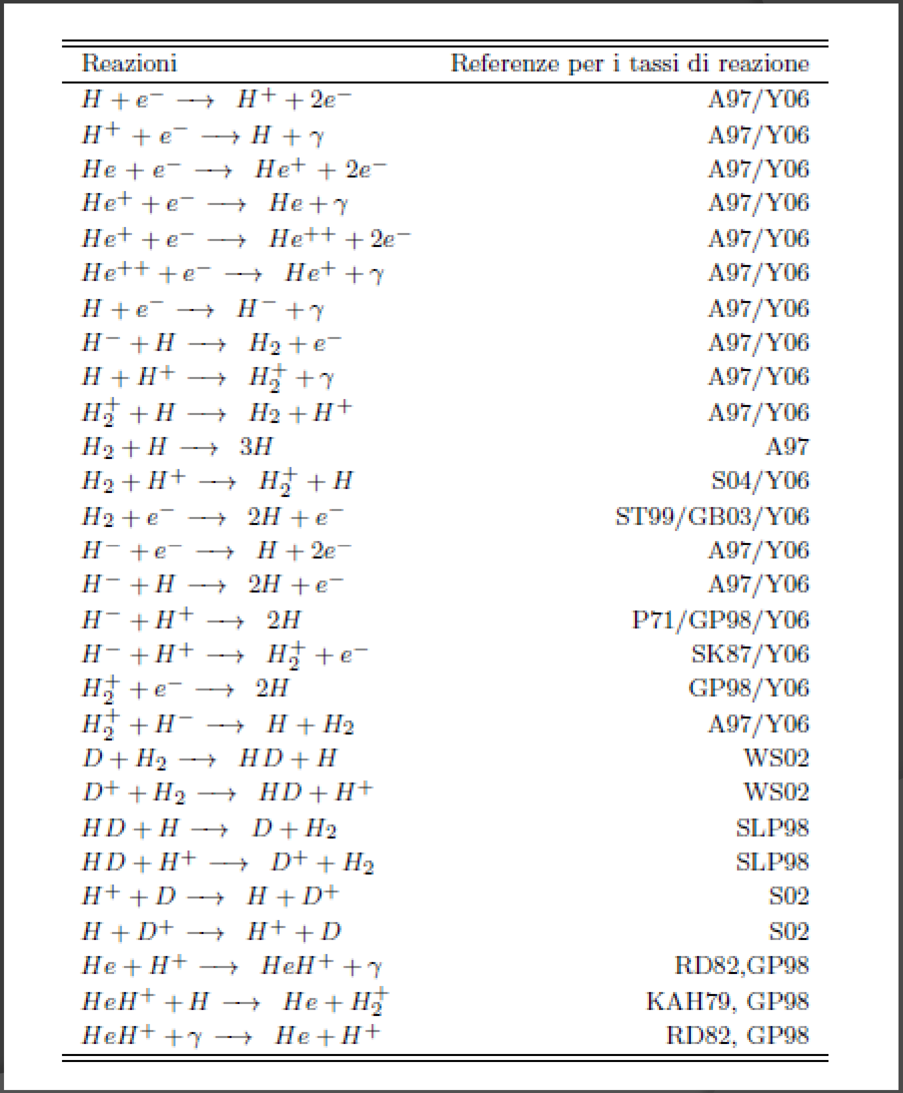
- Include AGN feedback in MUPPI (ongoing; using Steinborn+new model)

- Include non-equilibrium chemistry (by U. Maio) with self-consistent formation of H_2 (1 PhD, D. Goz; 1 graduate, P. Di Cerbo; + U. Maio)

- Kinetic AGN feedback (with P. Barai)

PRELIMINARY: H_2 chemistry

Umbero Maio's chemical network in MUPPI



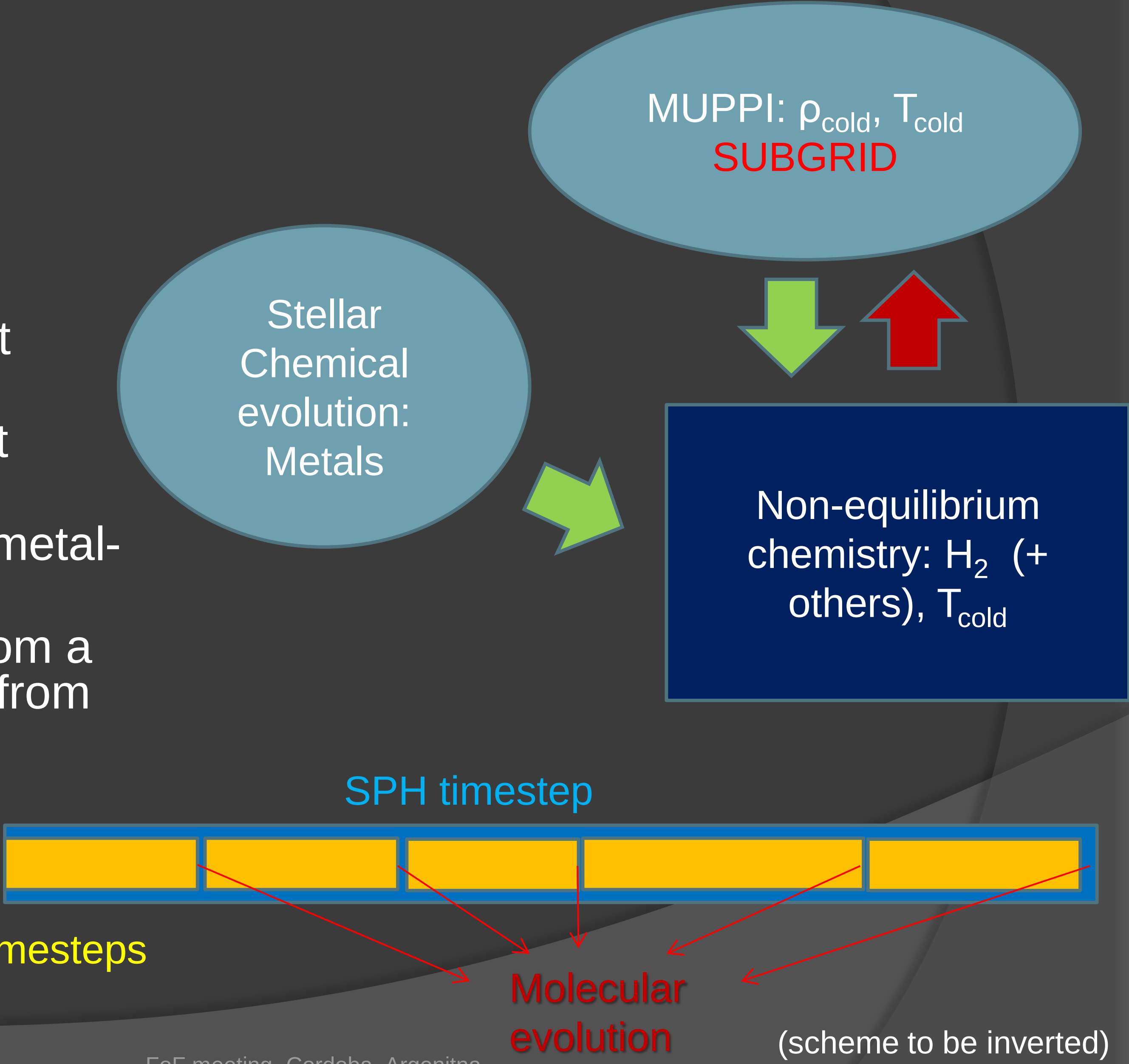
Reazioni	Referenze per i tassi di reazione
$H + e^- \longrightarrow H^+ + 2e^-$	A97/Y06
$H^+ + e^- \longrightarrow H + \gamma$	A97/Y06
$He + e^- \longrightarrow He^+ + 2e^-$	A97/Y06
$He^+ + e^- \longrightarrow He + \gamma$	A97/Y06
$He^+ + e^- \longrightarrow He^{++} + 2e^-$	A97/Y06
$He^{++} + e^- \longrightarrow He^+ + \gamma$	A97/Y06
$H + e^- \longrightarrow H^- + \gamma$	A97/Y06
$H^- + H \longrightarrow H_2 + e^-$	A97/Y06
$H + H^+ \longrightarrow H_2^+ + \gamma$	A97/Y06
$H_2^+ + H \longrightarrow H_2 + H^+$	A97/Y06
$H_2 + H \longrightarrow 3H$	A97
$H_2 + H^+ \longrightarrow H_2^+ + H$	S04/Y06
$H_2 + e^- \longrightarrow 2H + e^-$	ST99/GB03/Y06
$H^- + e^- \longrightarrow H + 2e^-$	A97/Y06
$H^- + H \longrightarrow 2H + e^-$	A97/Y06
$H^- + H^+ \longrightarrow 2H$	P71/GP98/Y06
$H^- + H^+ \longrightarrow H_2^+ + e^-$	SK87/Y06
$H_2^+ + e^- \longrightarrow 2H$	GP98/Y06
$H_2^+ + H^- \longrightarrow H + H_2$	A97/Y06
$D + H_2 \longrightarrow HD + H$	WS02
$D^+ + H_2 \longrightarrow HD + H^+$	WS02
$HD + H \longrightarrow D + H_2$	SLP98
$HD + H^+ \longrightarrow D^+ + H_2$	SLP98
$H^+ + D \longrightarrow H + D^+$	S02
$H + D^+ \longrightarrow H^+ + D$	S02
$He + H^+ \longrightarrow HeH^+ + \gamma$	RD82,GP98
$HeH^+ + H \longrightarrow He + H_2^+$	KAH79, GP98
$HeH^+ + \gamma \longrightarrow He + H^+$	RD82, GP98

What the network does

Given ρ_{cold}, T_{cold}:
Given Metals:
Given T_{cmb}, UV background:

- Calculates new abundances in Δt
- Gives new temperature in Δt

- H_2 formation on metal-dependent dust
- H_2 destruction from a FIXED UV field (from stars…)



MUPPI: ρ_{cold}, T_{cold}
SUBGRID

Stellar Chemical evolution: Metals

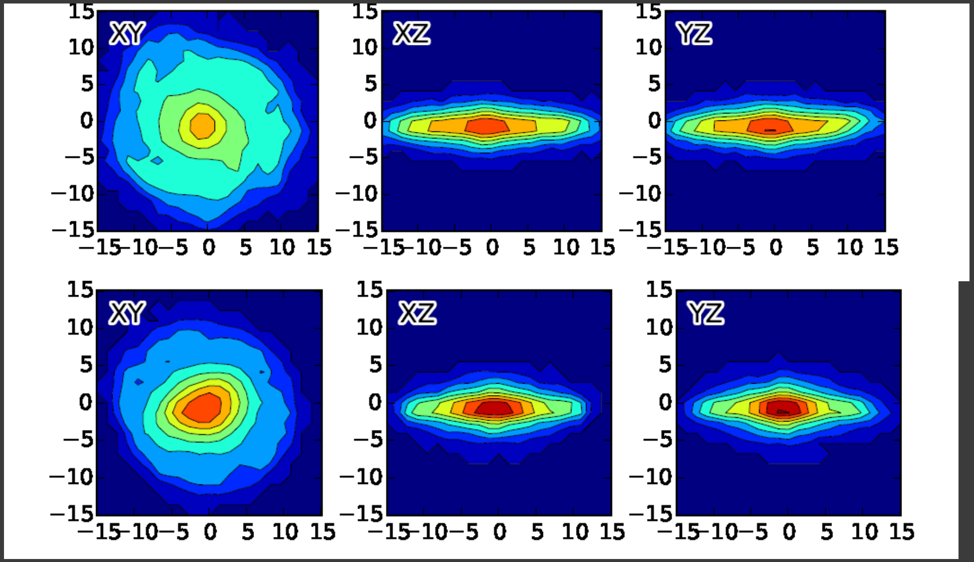
Non-equilibrium chemistry: H_2 (+ others), T_{cold}

SPH timestep

RK MUPPI timesteps

Molecular evolution

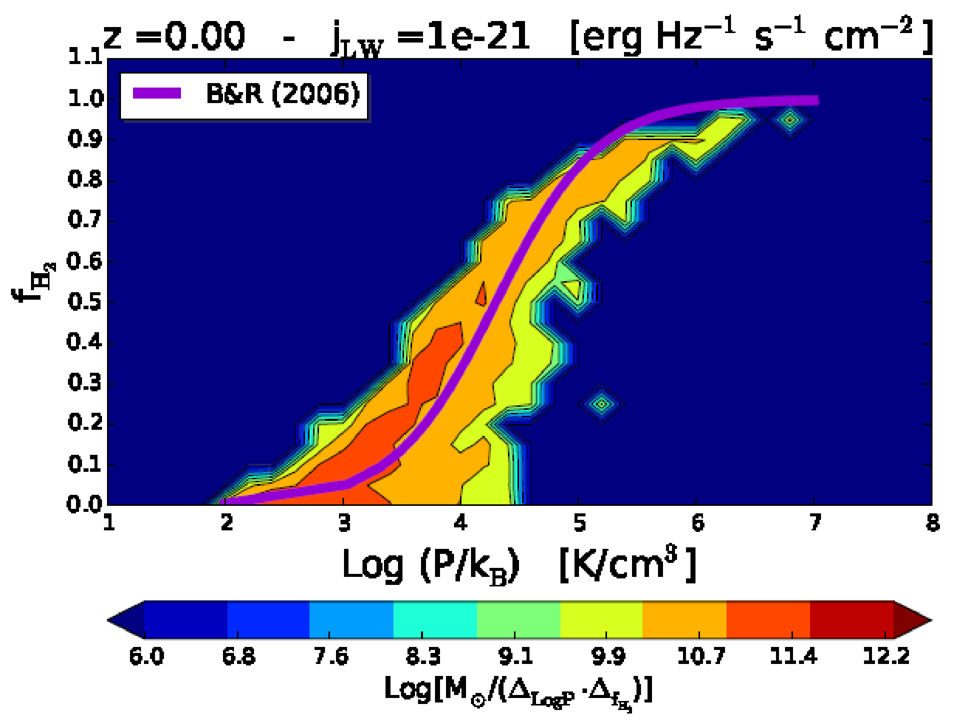
(scheme to be inverted)



AqC6, std

AqC6, H_2, fixed UV

Predicted Blitz-Rosolowsky



ExaNeSt

WHAT we do:

ExaNeSt develops and prototypes solutions for **Interconnection Networks**, **Storage**, and **Cooling**, as these have to evolve in order for the production of *exascale-level supercomputers* to become feasible. **We tune real HPC Applications**, and we use them to evaluate our solutions.

WHY we do it:

HPC is a precious tool for all of modern technology, science, and society. For the next generation of HPC systems, we need millions of low-power-consumption computing cores, tightly interconnected and packaged together and appropriately cooled, and with a new storage architecture.

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INAF

monetdb solutions

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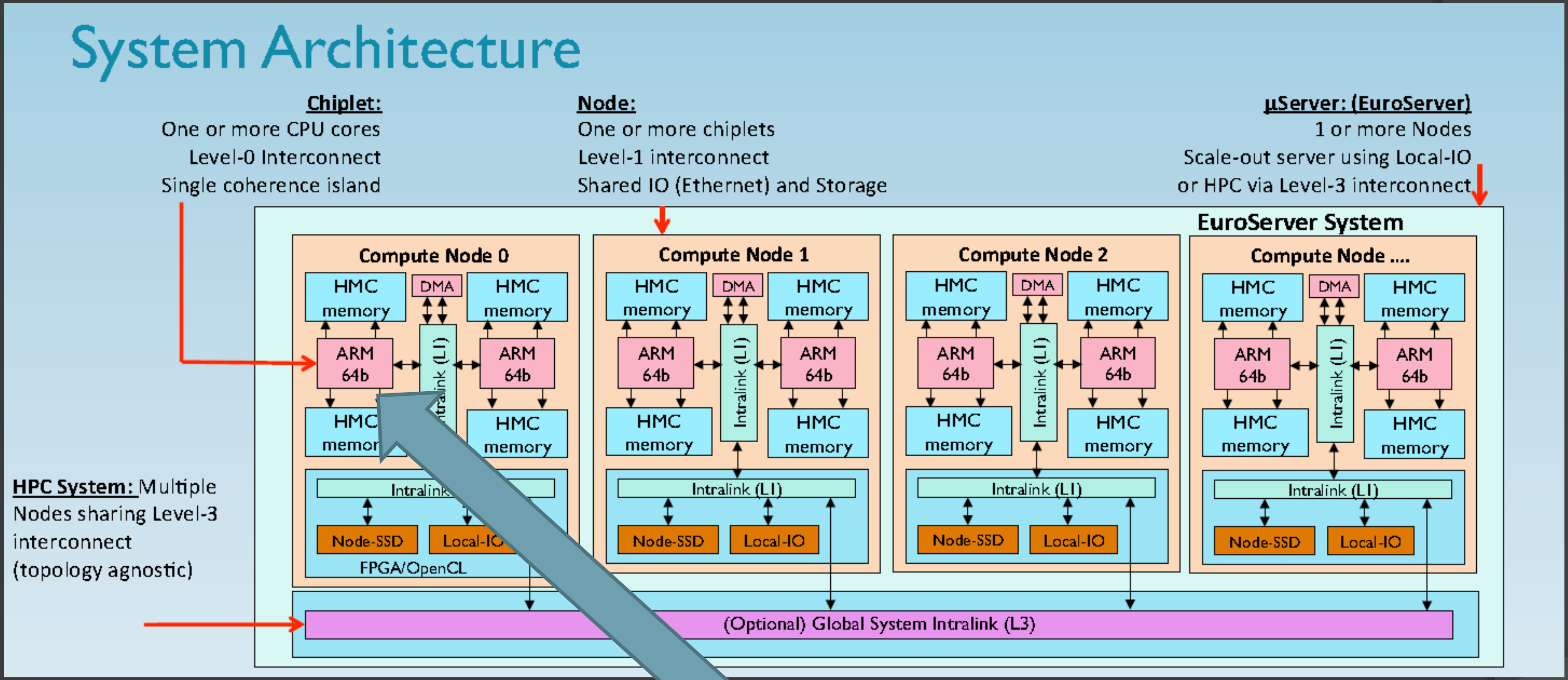
New technologies..



System Architecture

Chiplet:
One or more CPU cores
Level-0 Interconnect
Single coherence island

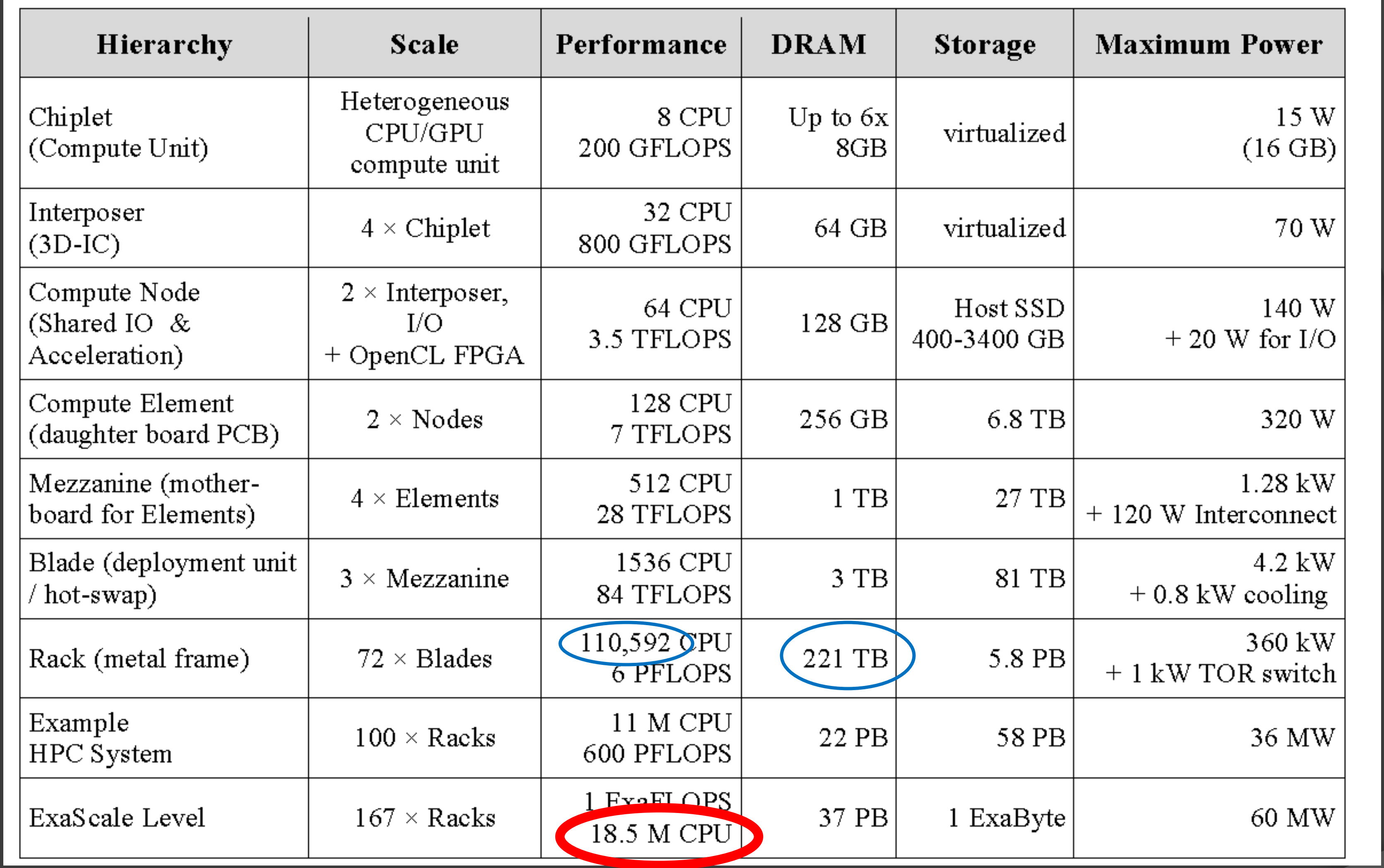
Node:
One or more chiplets
Level-1 interconnect
Shared IO (Ethernet) and Storage

µServer: (EuroServer)
1 or more Nodes
Scale-out server using Local-IO
or HPC via Level-3 interconnect

HPC System: Multiple Nodes sharing Level-3 interconnect (topology agnostic)

!

This project is supposed to be "application driven"



Hierarchy	Scale	Performance	DRAM	Storage	Maximum Power
Chiplet (Compute Unit)	Heterogeneous CPU/GPU compute unit	8 CPU 200 GFLOPS	Up to 6x 8GB	virtualized	15 W (16 GB)
Interposer (3D-IC)	4 × Chiplet	32 CPU 800 GFLOPS	64 GB	virtualized	70 W
Compute Node (Shared IO & Acceleration)	2 × Interposer, I/O + OpenCL FPGA	64 CPU 3.5 TFLOPS	128 GB	Host SSD 400-3400 GB	140 W + 20 W for I/O
Compute Element (daughter board PCB)	2 × Nodes	128 CPU 7 TFLOPS	256 GB	6.8 TB	320 W
Mezzanine (mother-board for Elements)	4 × Elements	512 CPU 28 TFLOPS	1 TB	27 TB	1.28 kW + 120 W Interconnect
Blade (deployment unit / hot-swap)	3 × Mezzanine	1536 CPU 84 TFLOPS	3 TB	81 TB	4.2 kW + 0.8 kW cooling
Rack (metal frame)	72 × Blades	110,592 CPU 6 PFLOPS	221 TB	5.8 PB	360 kW + 1 kW TOR switch
Example HPC System	100 × Racks	11 M CPU 600 PFLOPS	22 PB	58 PB	36 MW
ExaScale Level	167 × Racks	1 ExaFLOPS 18.5 M CPU	37 PB	1 ExaByte	60 MW

Required level of parallelism…

THIS MEANS THAT WE NEED TO RE-DESIGN OUR CODES!!

Conclusions

- Our sub-resolution star formation and feedback models produces realistic disk galaxies
- Key ingredient: effective (kinetic) feedback producing high-z galactic winds, gas reacts strongly to energy injection
- Many groups obtain realistic disk galaxies.
  And they have different treatments for SF&FB

- Properties of our galaxy populations in cosmological volumes still not in perfect agreement with data
- …but promising halo mass dependance of winds mass-load and SEDs with GRASIL3D
- Improvements incoming!

- **New technologies will require a significant technical effort**

- *We cannot avoid sub resolution models. But* ***be aware not to over-state****……..*

THANK YOU