Hydrodynamic simulation of galaxy formation

P. Monaco, University of Trieste and INAF-Trieste Observatory

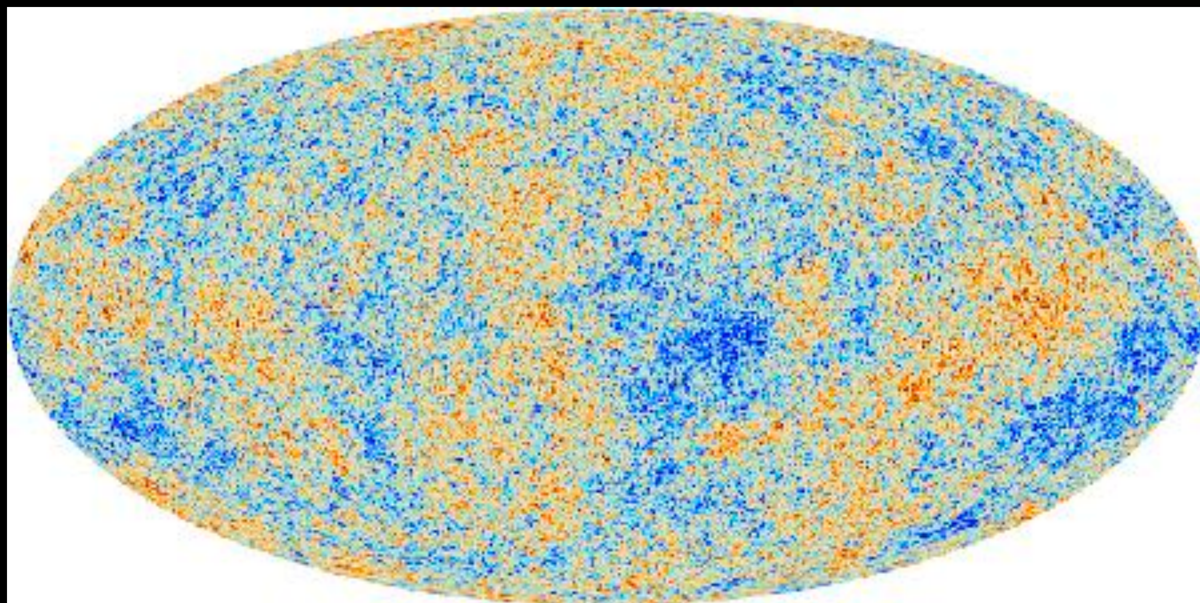
with: G. Murante, S. Borgani, G. Granato, M. Valentini, P. Barai, E. Gjerko

Papers:

- Murante, P.M., Giovalli, Borgani & Diaferio, 2010, MNRAS 405, 1491
- P.M., Murante, Borgani, Dolag, 2012, MNRAS 412, 2485
- Murante, P.M., Borgani, Tornatore, Dolag & Goz, 2015, MNRAS 447, 178
- Goz, P.M., Murante, Curir, 2015, MNRAS 447, 1744
- Barai, P.M., Murante, Ragagnin, Viel, 2015, MNRAS 447, 266
- Goz, P.M., Granato et al., 2017, MNRAS 469, 3775
- Valentini, Murante, Borgani, P.M., Bressan, Beck, 2017, MNRAS 470, 3167
- Gjerko, Granato, Ragone-Figueroa, Murante, in preparation

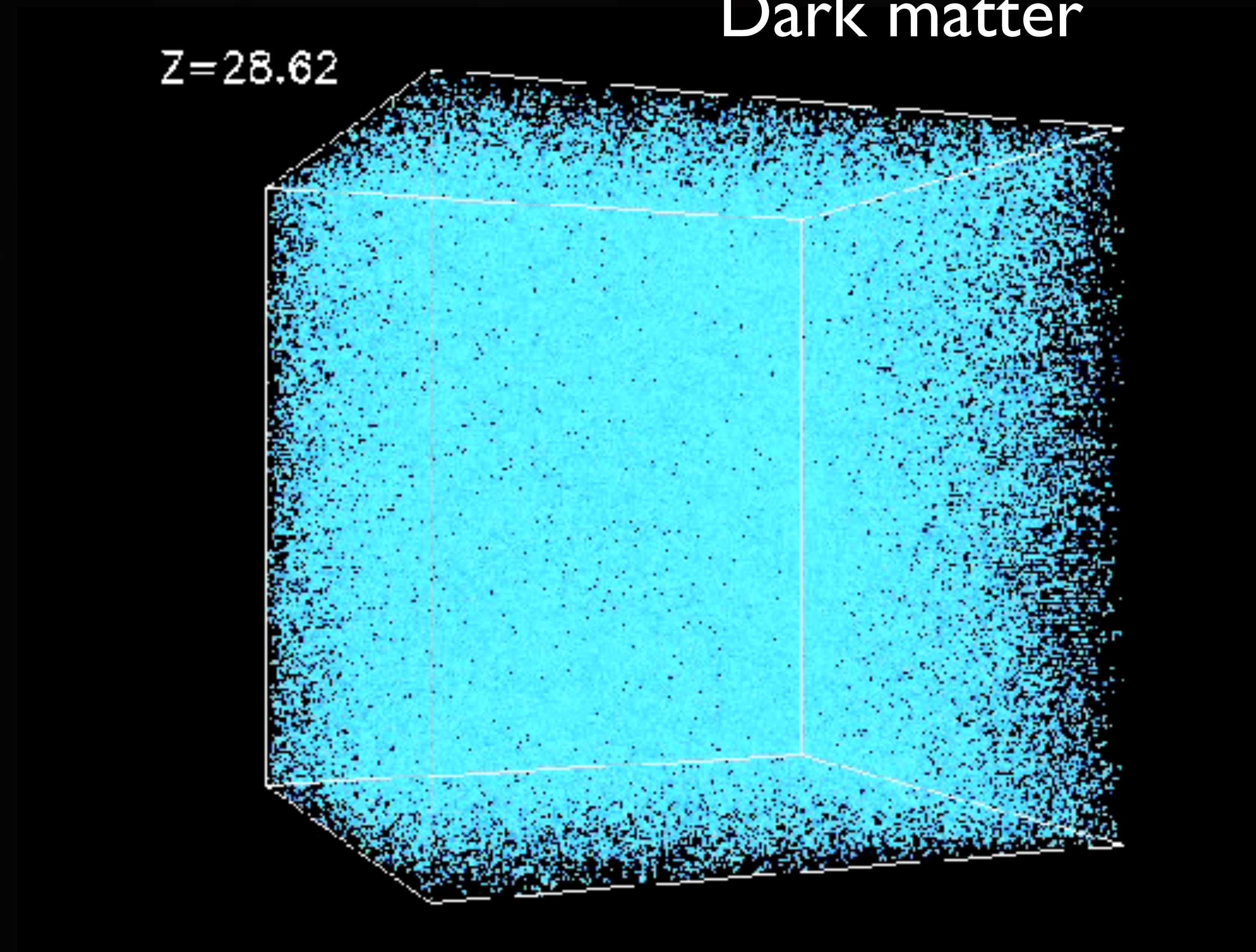
1. The context

Cosmology (ΛCDM)

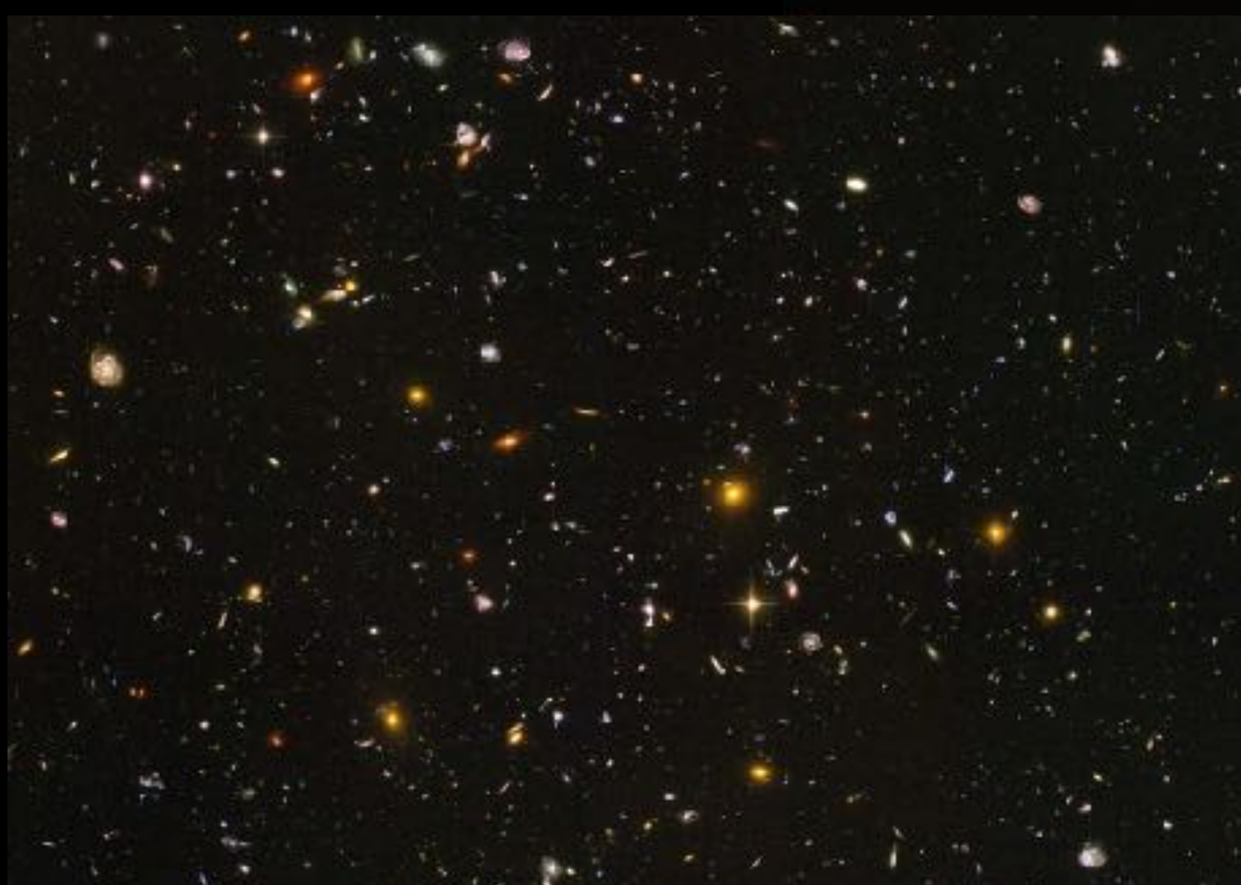


gravitational evolution

Dark matter

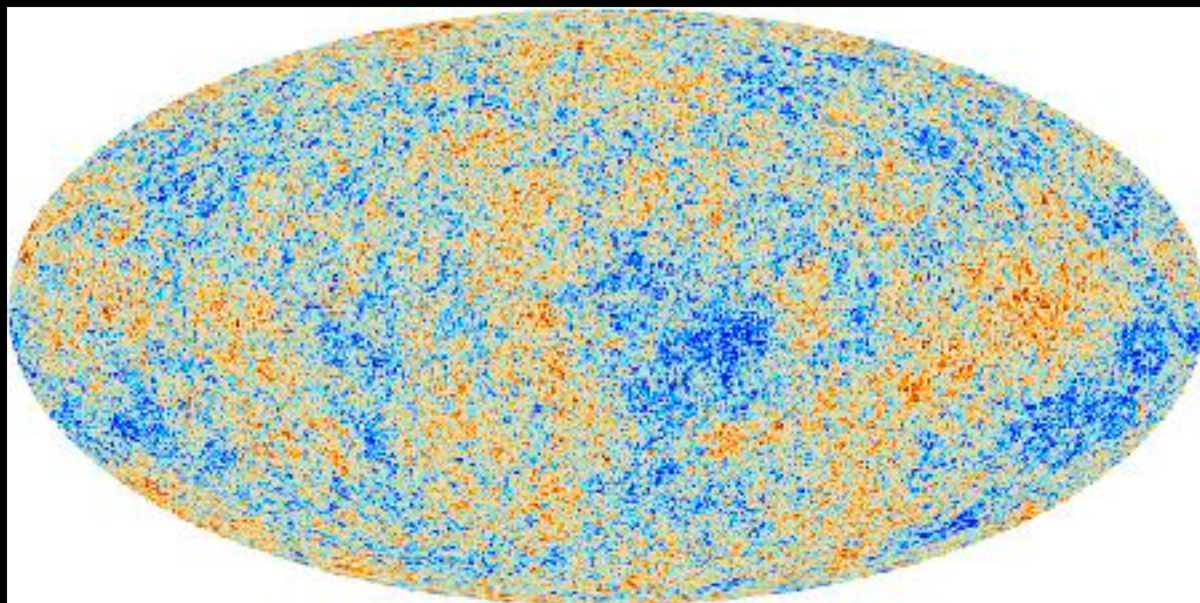


Galaxies



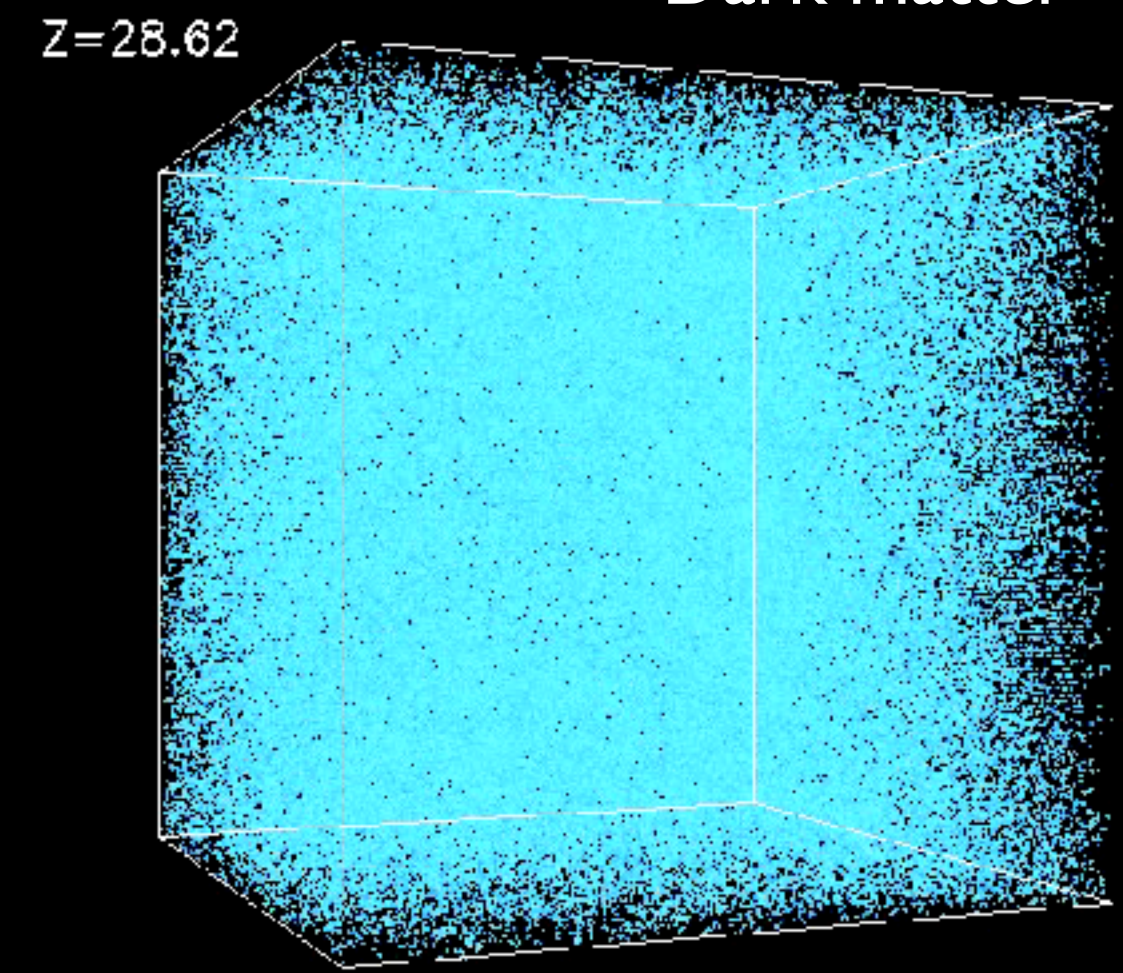
baryon physics

Cosmology (ΛCDM)



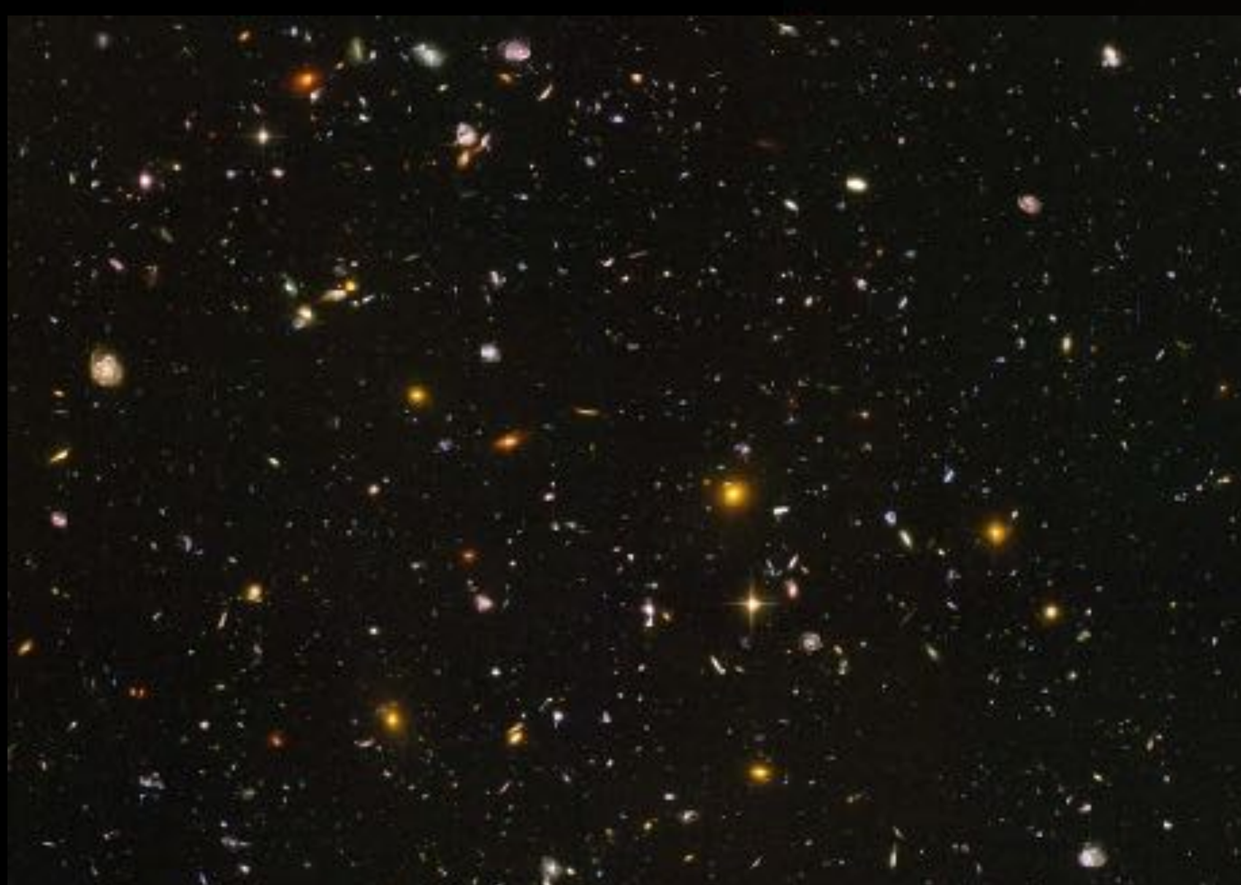
gravitational evolution

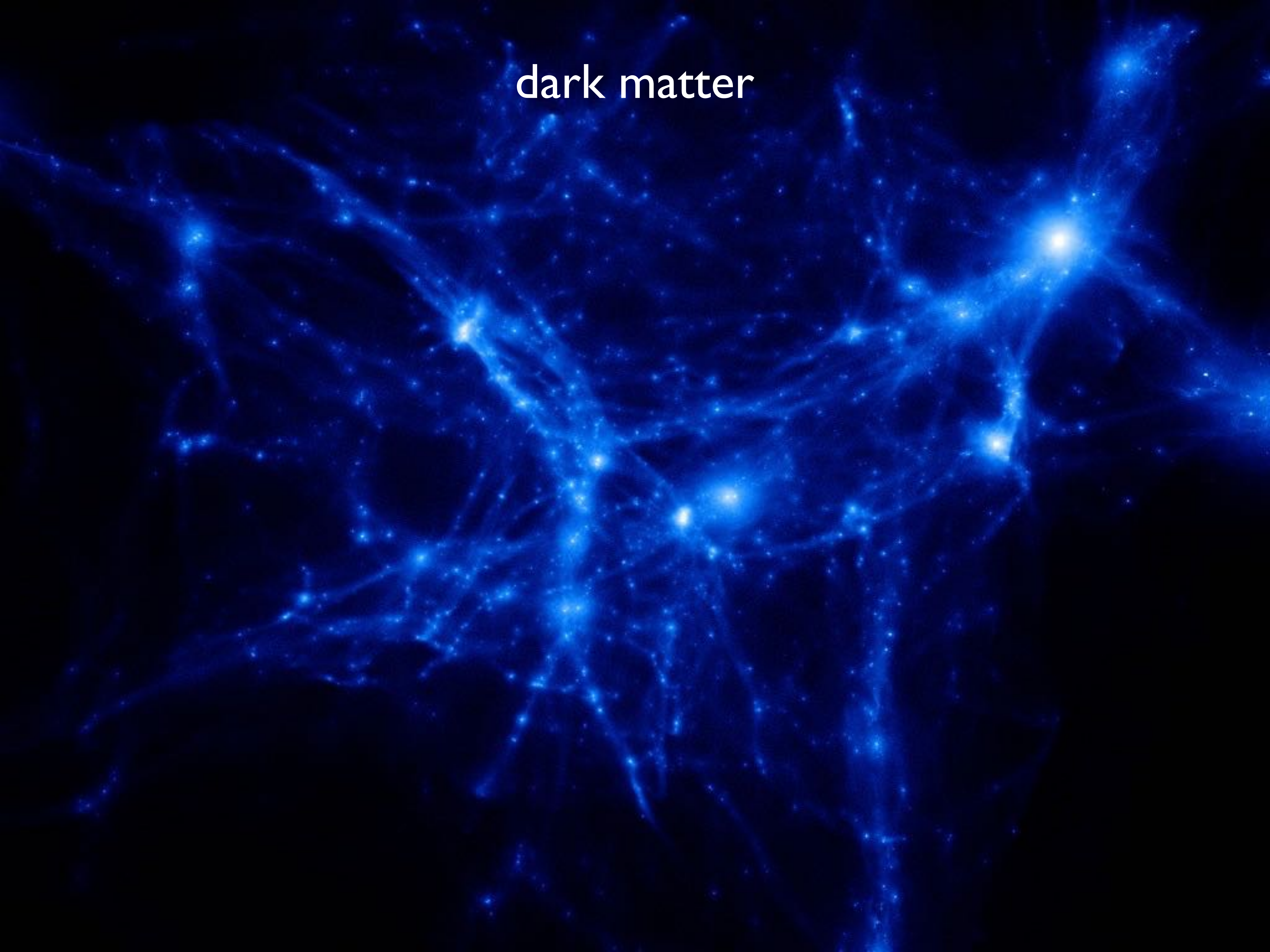
Dark matter



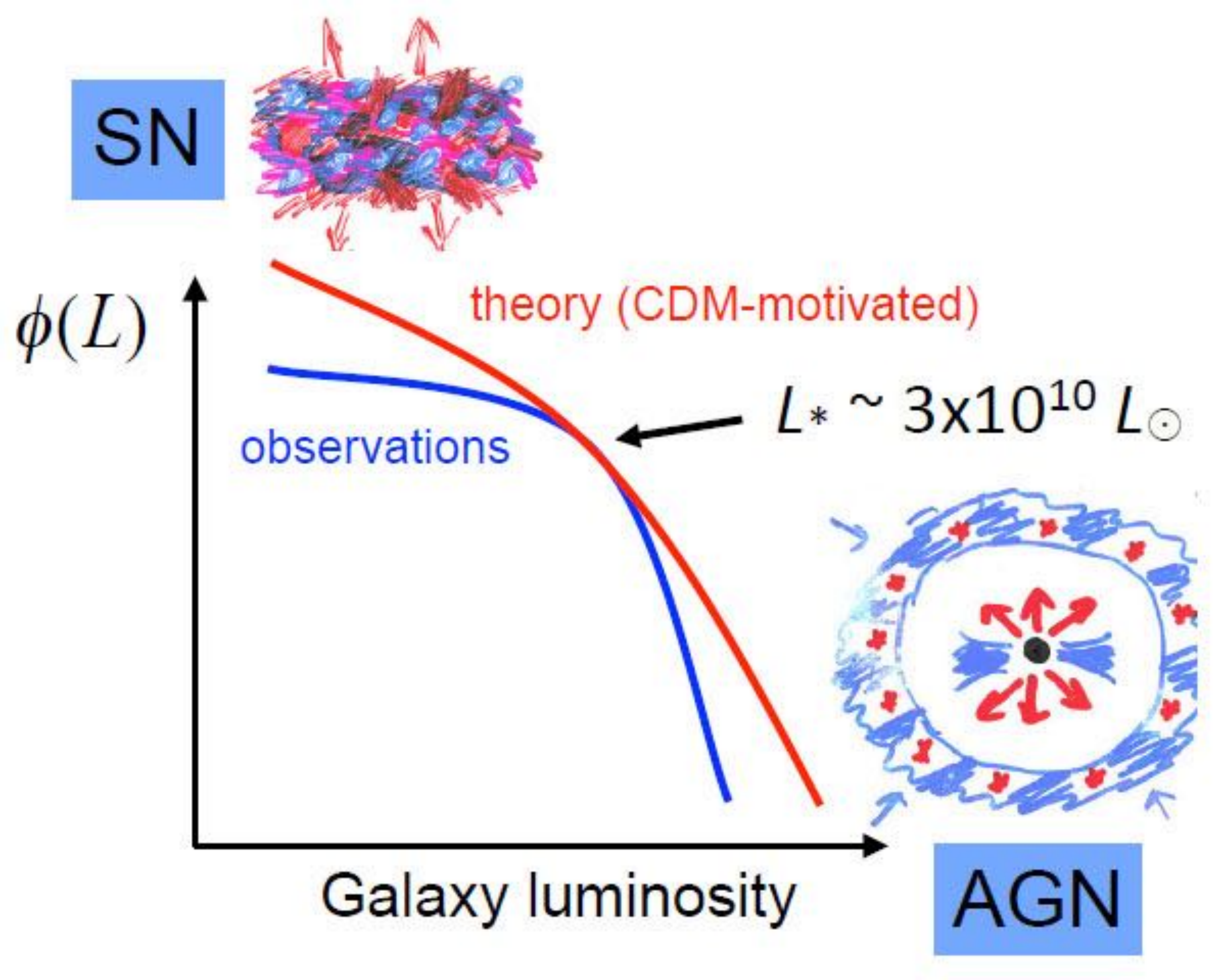
baryon physics

Galaxies




dark matter

Galaxy formation efficiency must be a strong function of halo mass



Silk & Mamon (2012)

A problem of resolution

galaxy formation	feedback	star formation
> 1 kpc	1 pc - 1 kpc	< 1 pc

Formation of star-forming (molecular) clouds

physics that can be resolved in cosmological simulations

physics that can be addressed with stellar evolution and an assumption on the IMF

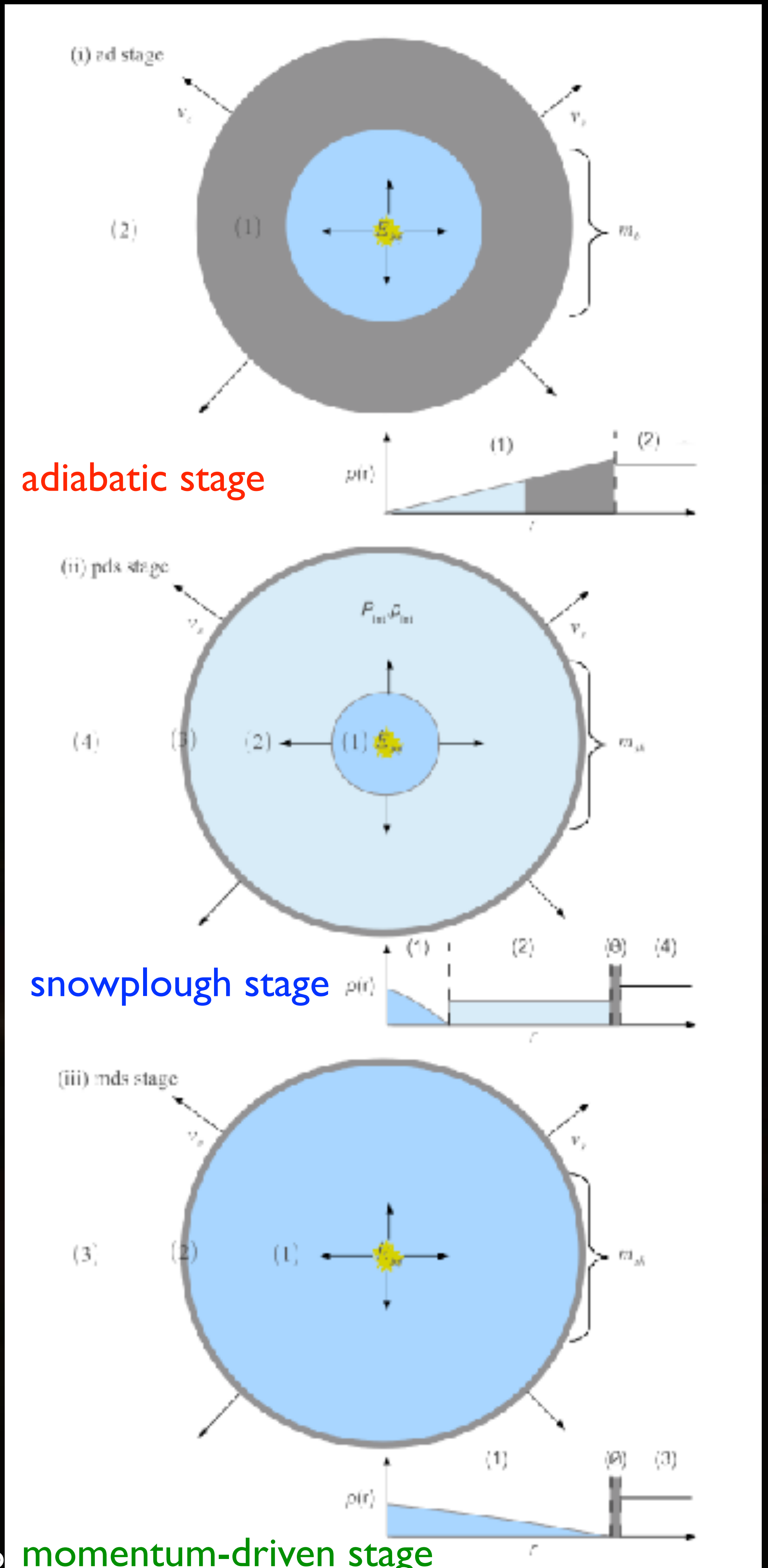
Emergence of energy through shock waves
(and radiation pressure, cosmic rays, magnetic fields...)

Massive and dying stars

Physical process:	Energy budget:
SN explosions	10^{51} erg each >8 M_{sun} star + type Ia SNe
Ionising radiation	up to 10^{50} erg each >10 M_{sun} star
Stellar winds	up to 10^{50} erg each >10 M_{sun} star
Radiation pressure	~10^{52} erg for a ~10 M_{sun} star

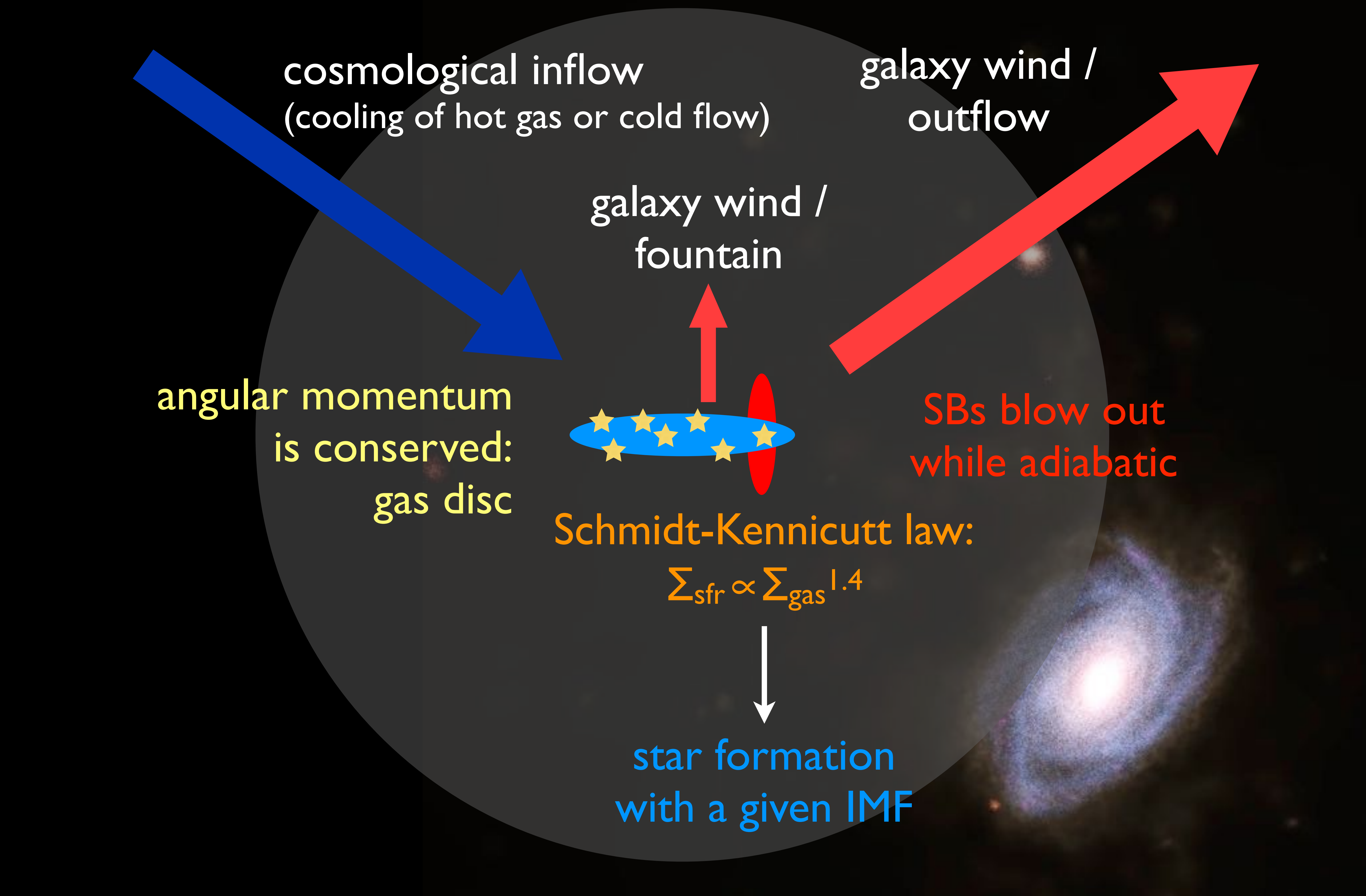
Efficiency of feedback

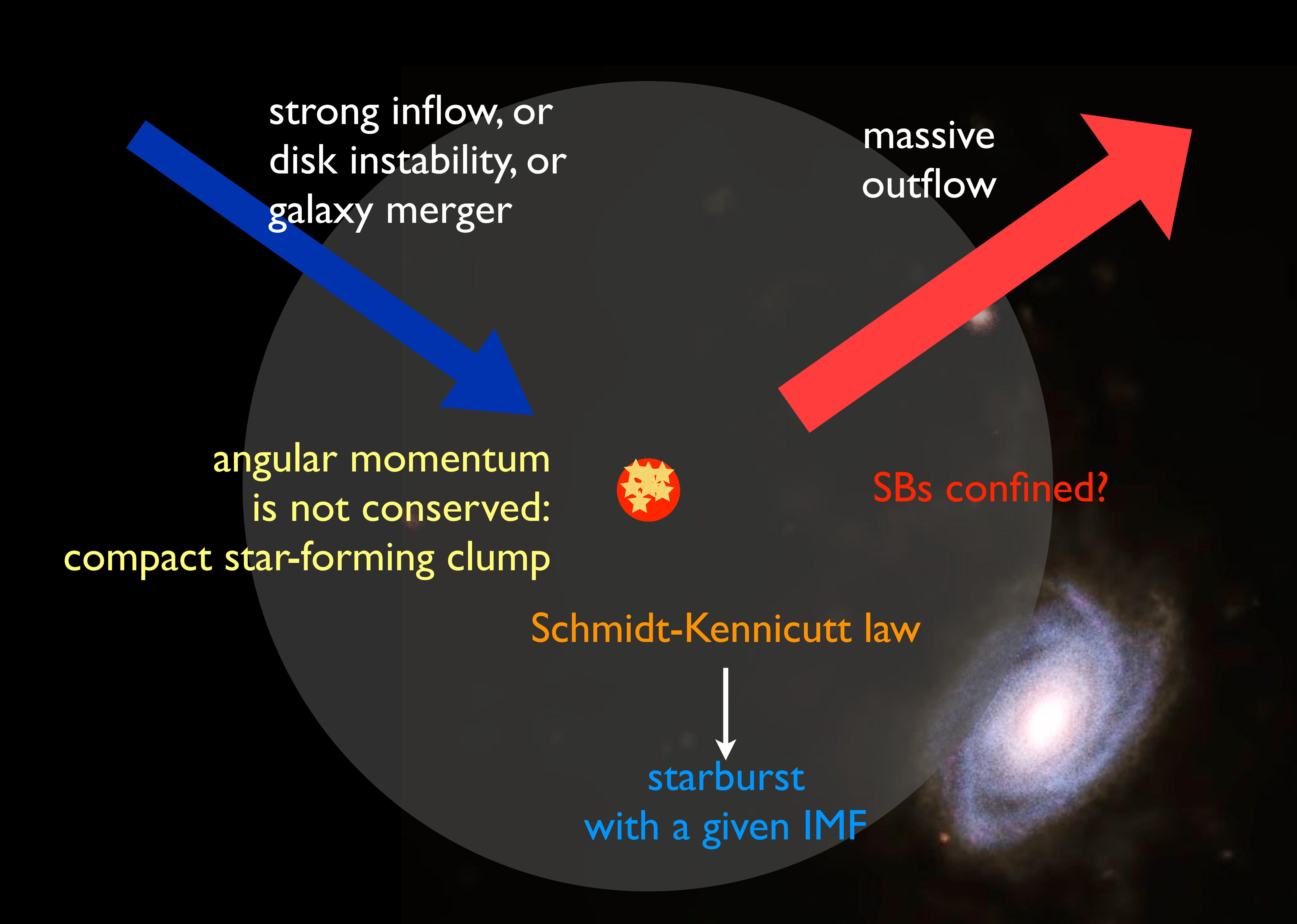
- Stars are born in clouds / clusters
- SNII explode when the cloud has almost being destroyed by massive stars
- Correlated type II SNe create an expanding super-bubble (SB)
- SBs expand in the hottest phases
- SBs heat the ISM in the adiabatic stage
- SBs cool the ISM in the snowplough stage
- SBs end by pressure confinement or by blowing out of the disc
- Feedback efficiency is set by the stage in which the SB ends



P. Monaco

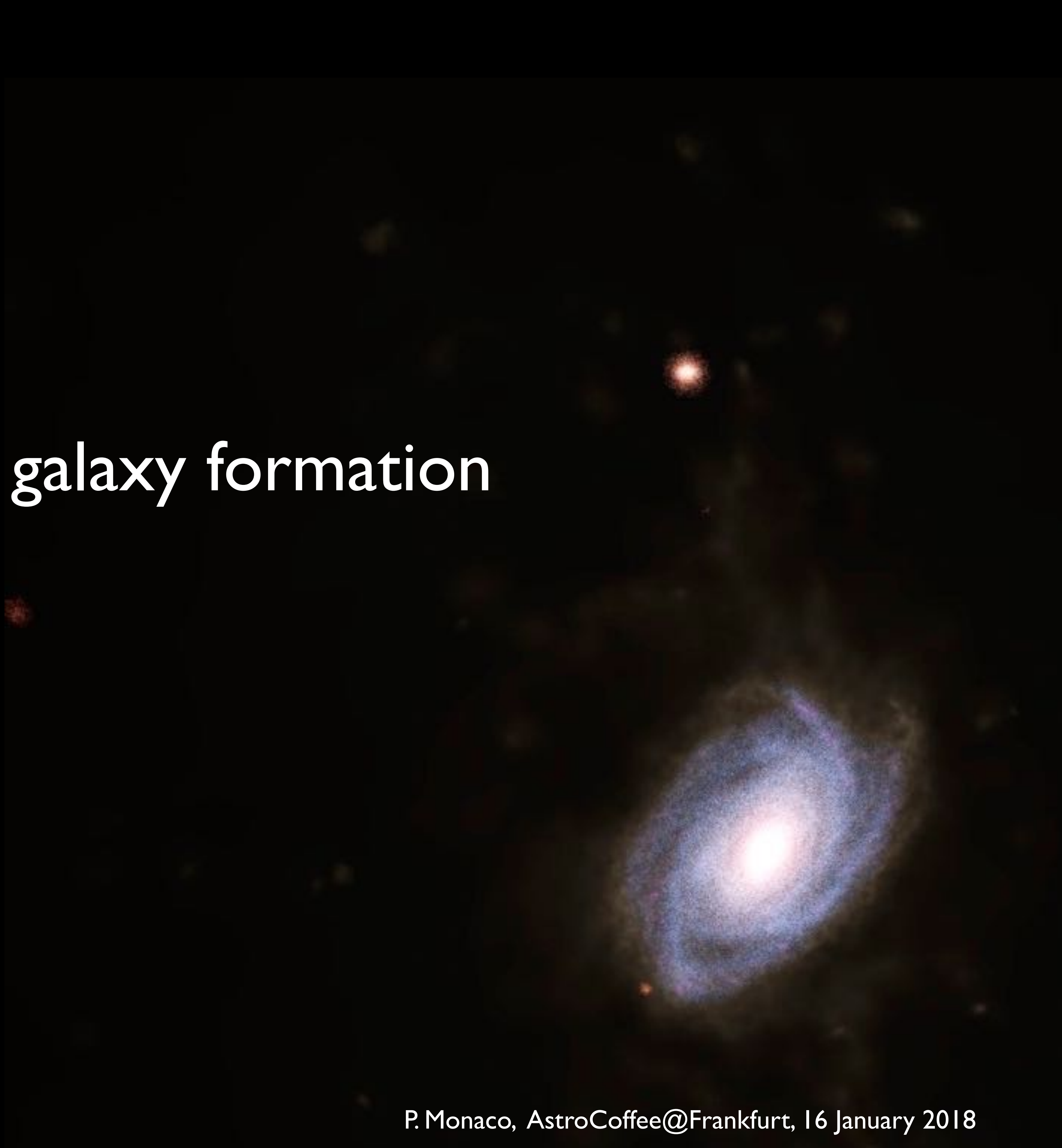
Monaco (2004), Lagos et al. (2013)

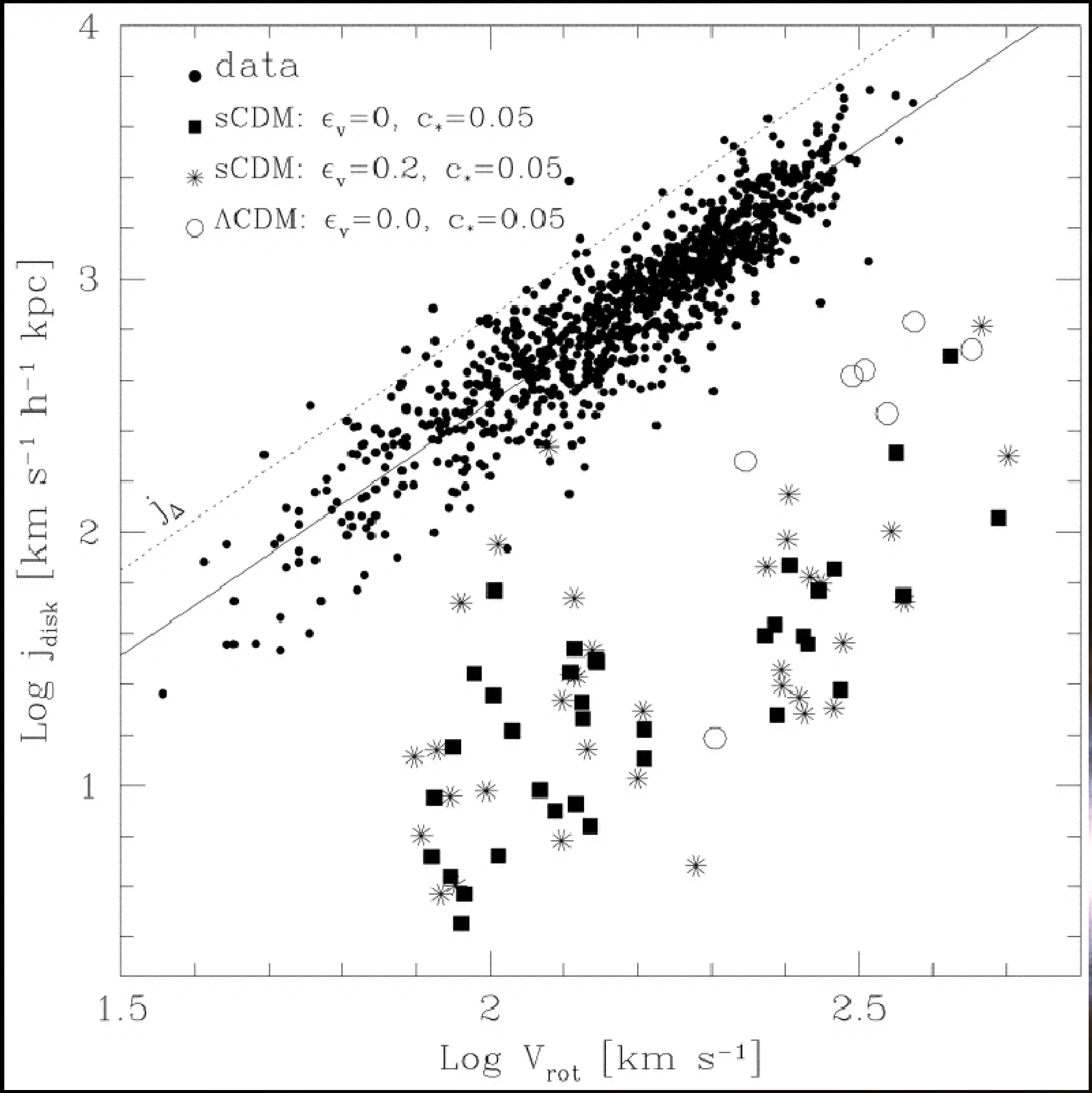

cosmological inflow
(cooling of hot gas or cold flow)
galaxy wind / outflow
galaxy wind / fountain
angular momentum is conserved: gas disc
SBs blow out while adiabatic
Schmidt-Kennicutt law:
$\Sigma_{sfr} \propto \Sigma_{gas}^{1.4}$
star formation with a given IMF


strong inflow, or
disk instability, or
galaxy merger
massive
outflow
angular momentum
is not conserved:
compact star-forming clump
SBs confined?
Schmidt-Kennicutt law
starburst
with a given IMF


M82

2. Simulating galaxy formation





Burkert & D'Onghia 2004

arXiv:1112.0315v1 [astro-ph.GA] 1 Dec 2011

The Aquila comparison Project: The Effects of Feedback and Numerical Methods on Simulations of Galaxy Formation

C. Scannapieco,[1] M. Wadepuhl,[2] O.H. Parry,[3,4] J.F. Navarro,[5] A. Jenkins,[3] V. Springel,[6,7] R. Teyssier,[8,9] E. Carlson,[10] H.M.P. Couchman,[11] R.A. Crain,[12,13] C. Dalla Vecchia,[14] C.S. Frenk,[3] C. Kobayashi,[15,16] P. Monaco,[17,18] G. Murante,[17,19] T. Okamoto,[20] T. Quinn,[10] J. Schaye,[13] G. S. Stinson,[21] T. Theuns,[3,22] J. Wadsley,[11] S.D.M. White,[2] R. Woods[11]

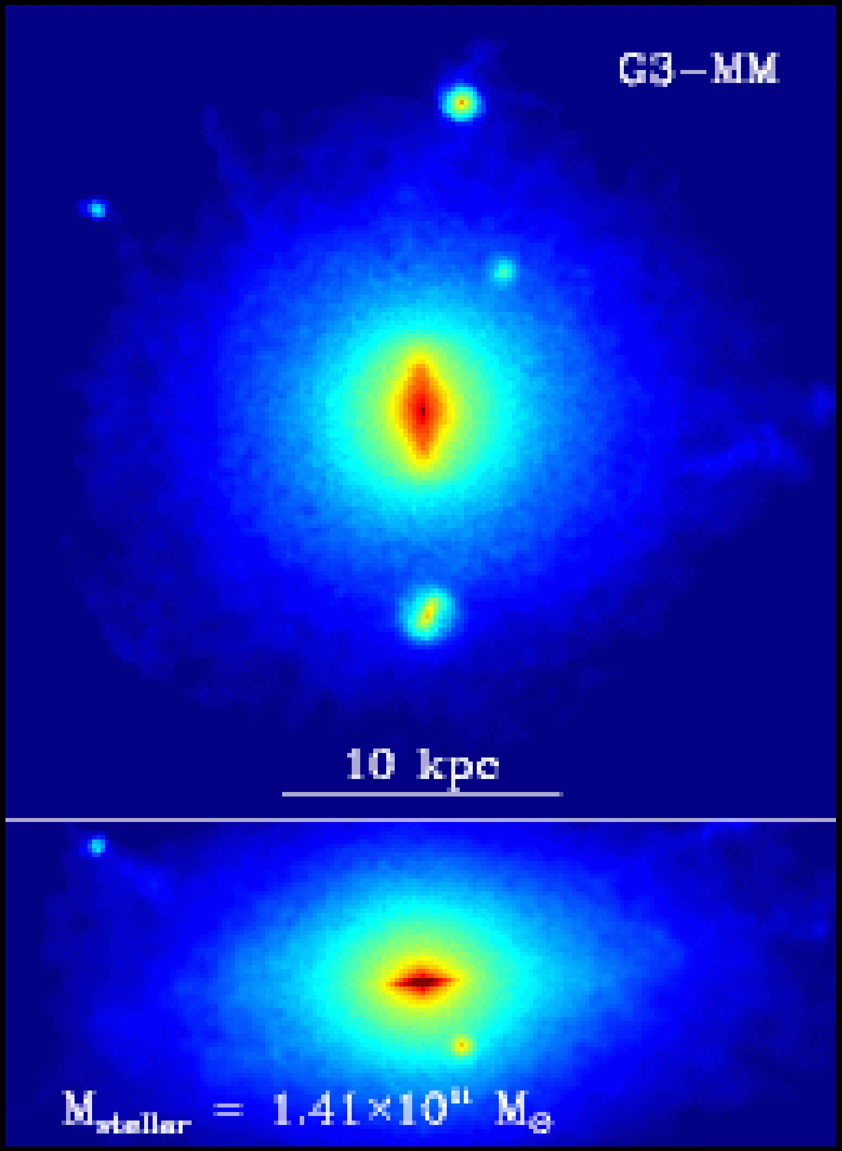
[1] *Leibniz-Institute for Astrophysics Potsdam (AIP), An der Sternwarte 16, 14482 Potsdam, Germany*
[2] *Max-Planck Institute for Astrophysics, Karl-Schwarzschild-Str. 1, 85741 Garching, German*
[3] *Institute for Computational Cosmology, Department of Physics, Durham University, Durham DH1 3LE, United Kingdom*
[4] *Department of Astronomy, University of Maryland, College Park, MD 20745, USA*
[5] *Department of Physics and Astronomy, University of Victoria, Victoria, BC, V8P 5C2, Canada*
[6] *Heidelberg Institute for Theoretical Studies, Schloss-Wolfsbrunnenweg 35, 69118 Heidelberg, Germany*
[7] *Zentrum für Astronomie der Universität Heidelberg, ARI, Mönchhofstr. 12-14, 69120 Heidelberg, Germany*
[8] *CEA, IRFU, SAp, 91191 Gif-sur-Yvette, France*
[9] *Institute for Theoretical Physics, University of Zürich, CH-8057 Zürich, Switzerland*
[10] *Department of Astronomy, University of Washington, Box 351580, Seattle, WA 98195-1580, USA*
[11] *Department of Physics & Astronomy, McMaster University, Hamilton, ON L8S, 4M1, Canada*
[12] *Centre for Astrophysics & Supercomputing, Swinburne University of Technology, Hawthorn, Victoria 3122, Australia*
[13] *Leiden Observatory, Leiden University, PO Box 9513, 2300 RA Leiden, The Netherlands*
[14] *Max Planck Institute for Extraterrestrial Physics, Gissenbachstraße 1, 85748 Garching, Germany*
[15] *School of Physics, Astronomy and Mathematics, University of Hertfordshire, Hatfield AL10 9AB, UK*
[16] *Research School of Astronomy & Astrophysics, The Australian National University, Cotter Road, Weston, ACT 2611, Australia*
[17] *Dipartimento di Fisica - Sezione di Astronomia, Università di Trieste, via Tiepolo 11, I- 34131 Trieste, Italy*
[18] *INAF, Osservatorio Astronomico di Trieste, Via Tiepolo 11, I-34131 Trieste, Italy*
[19] *INAF, Osservatorio Astronomico di Torino, Strada Osservatorio 20, I-10025 Pino Torinese, Italy*
[20] *Center for Computational Sciences, University of Tsukuba, 1-1-1 Tennodai, Tsukuba 305-8577 Ibaraki, Japan*
[21] *Max-Planck-Institut für Astronomie, Königstuhl 17, 69117, Heidelberg, Germany*
[22] *Universiteit Antwerpen, Campus Groenenborger, Groenenborgerlaan 171, B-2020 Antwerpen, Belgium*

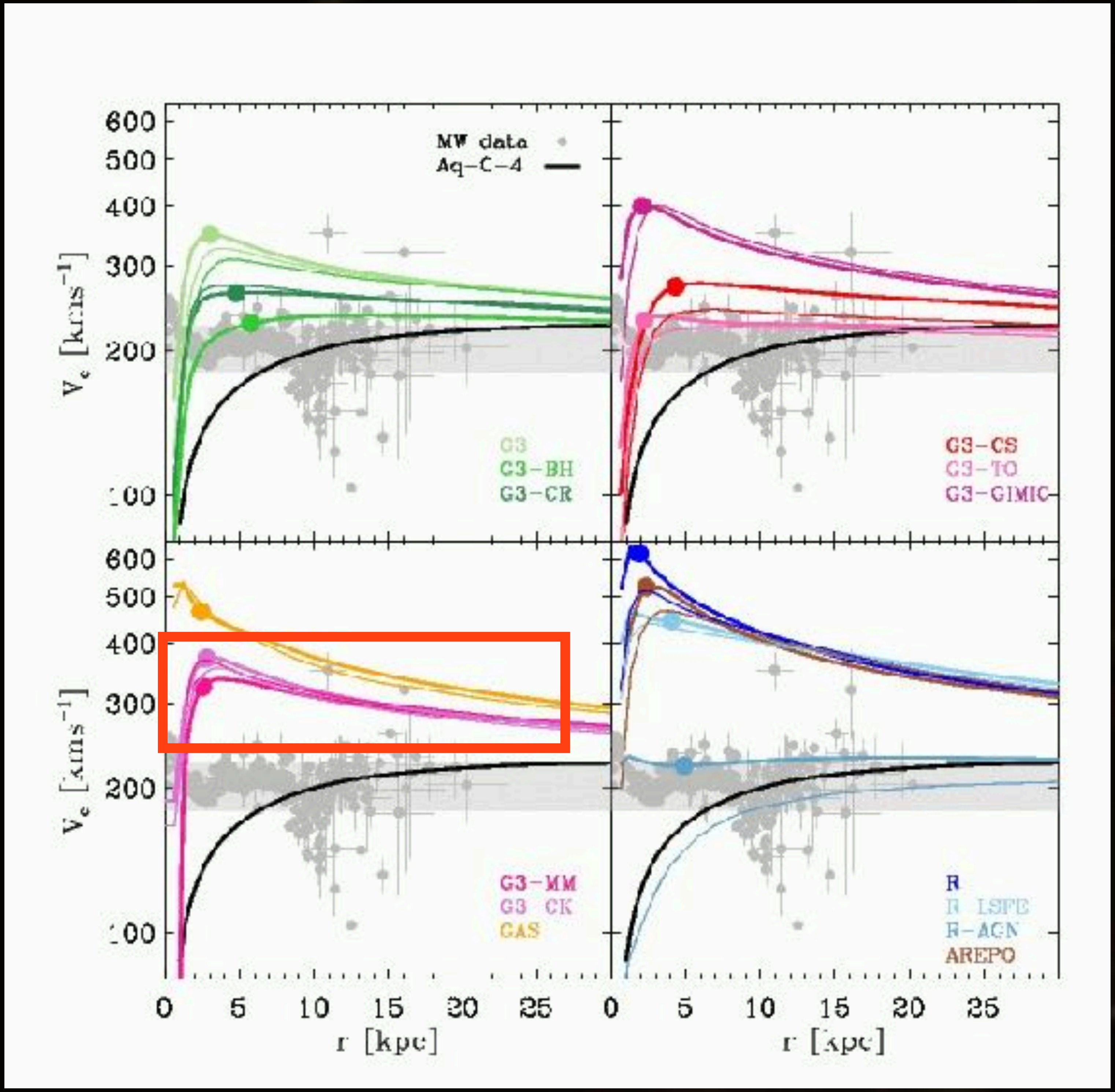
5 December 2011

ABSTRACT

We compare the results of various cosmological gas-dynamical codes used to simulate the formation of a galaxy in the ΛCDM structure formation paradigm. The various runs (thirteen in total) differ in their numerical hydrodynamical treatment (SPH,

Rotation curves

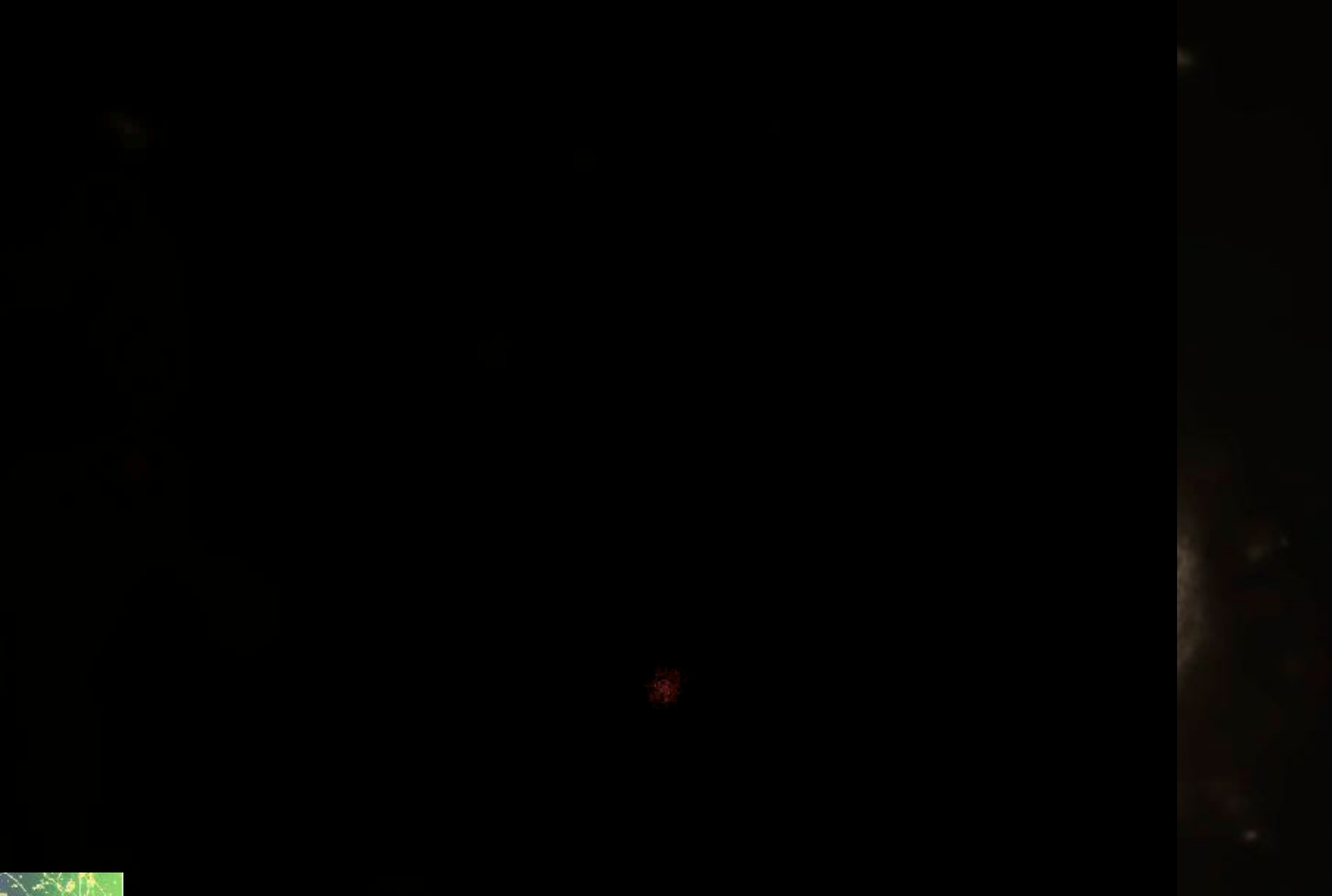




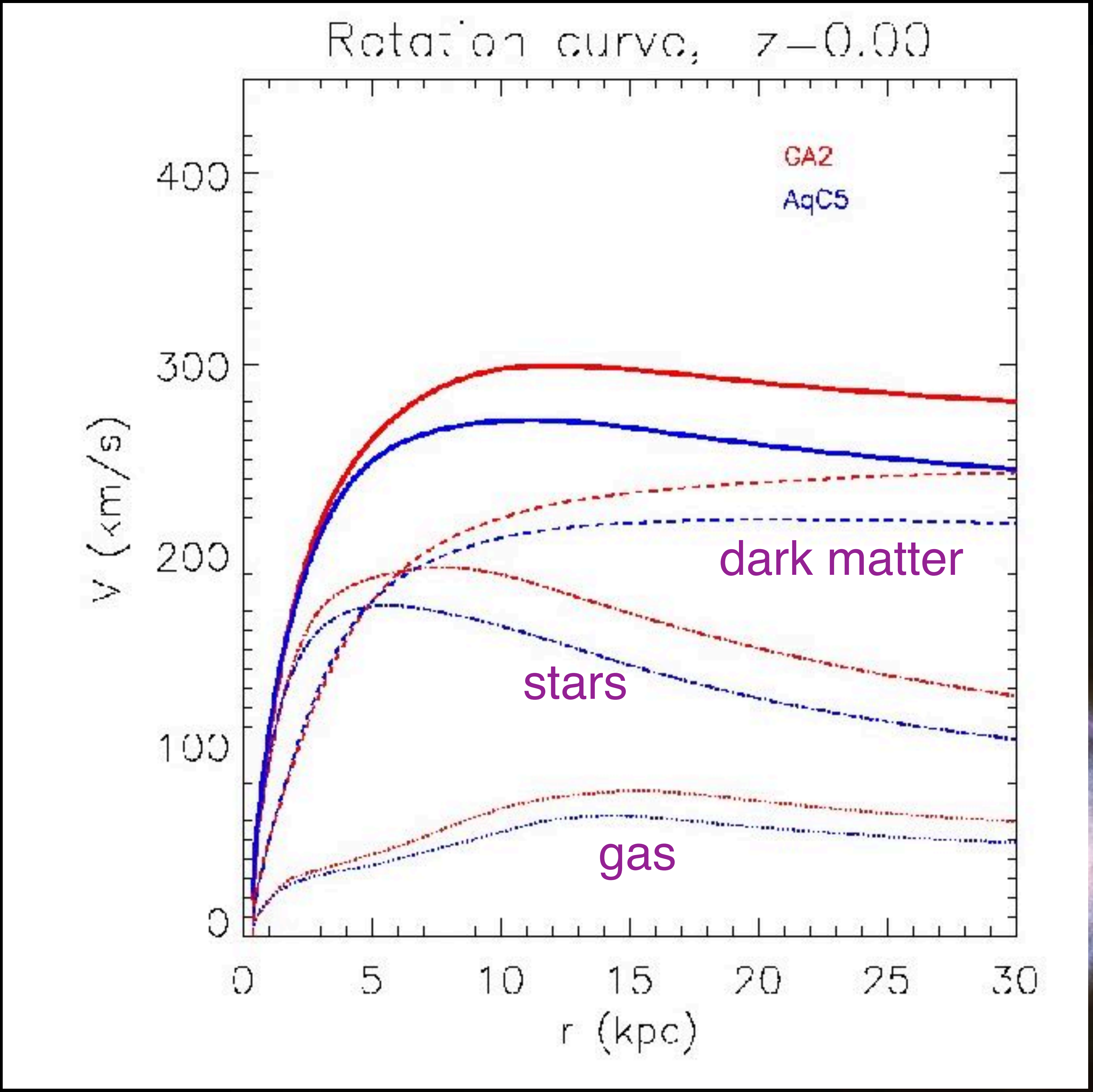
Aq-C5 with our code, two years later

Rendering by G. Skora

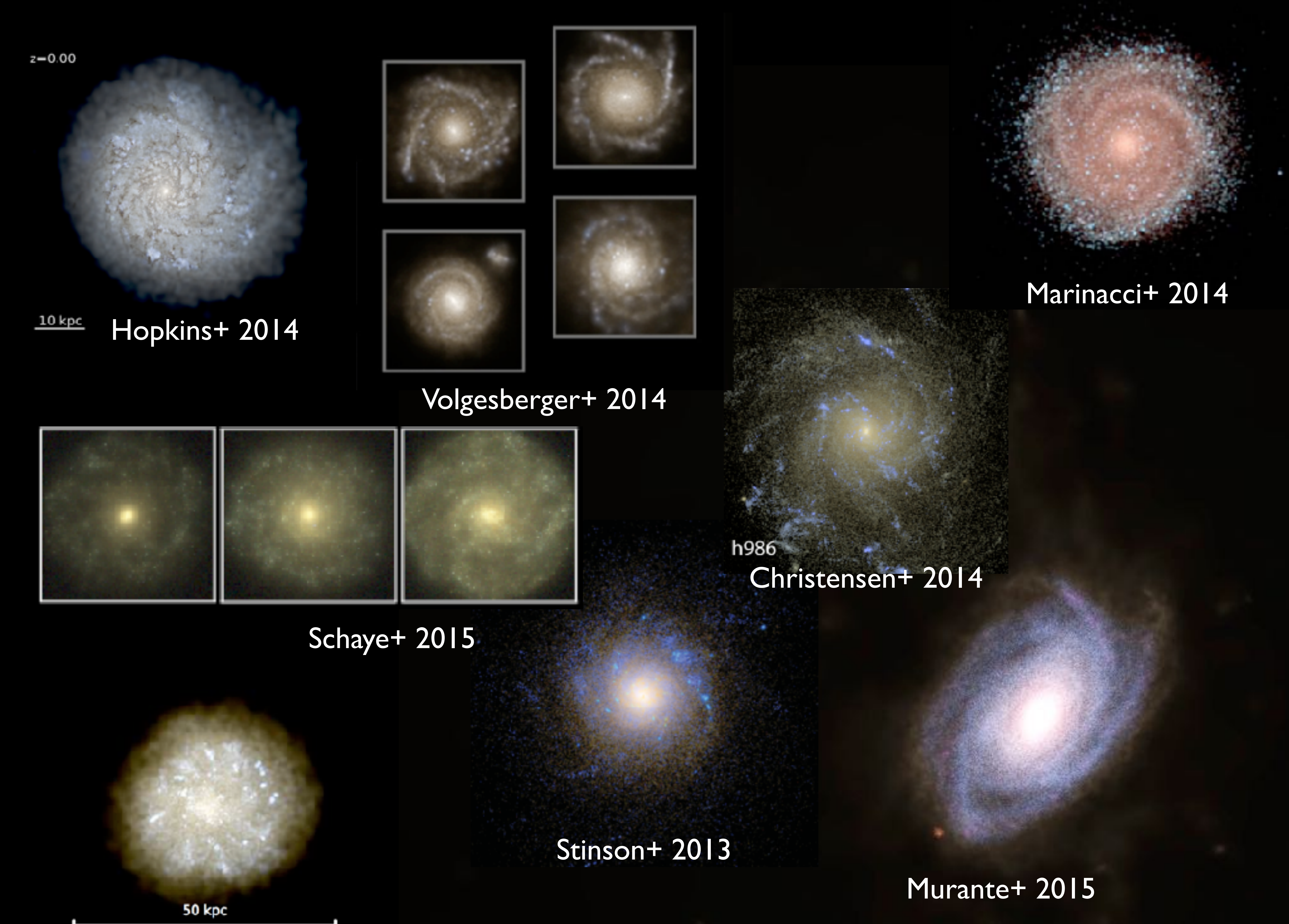
Aq-C5 with our code, two years later



Rendering by G. Skora



Rotation curve, z=0.00
GA2
AqC5
V (km/s)
r (kpc)
dark matter
stars
gas
0
100
200
300
400
0
5
10
15
20
25
30


z=0.00
10 kpc
Hopkins+ 2014
Volgesberger+ 2014
Marinacci+ 2014
Schaye+ 2015
h986
Christensen+ 2014
Stinson+ 2013
Murante+ 2015
50 kpc
Keller+ 2015

Sub-resolution SF&FB in simulations

- Kinetic winds to improve efficiency (Navarro & Steinmetz 00)
- Effective model (Springel & Hernquist 03)
- Blastwave feedback (Stinson+ 06)
- Momentum-driven winds (Oppenheimer & Dave` 06)
- Sticky particles (Booth+ 07)
- Hypernovae (Kobayashi+ 07)
- Effective equation of state (Schaye & Dalla Vecchia 08)
- Scaling with halo circular velocity (Tescari+ 09, Okamoto+ 10, Oser+ 10)
- Density estimation of hot gas (Scannapieco+ 10)
- Multi-Phase Particle integrator (Murante+ 10)
- Early feedback (Stinson+ 13)
- Heating to a critical temperature (Schaye & Della Vecchia 13)
- Accelerating wind (Barai+ 2013)
- Resolving feedback (Ceverino & Klypin 09, Gnedin & Kravtsov 12)
- Radiation pressure (Hopkins+ 14)
- Superbubble feedback (Keller+ 2015)

3. MUlti-Phase Particle Integrator

MUlti-Phase Particle Integrator (MUPPI): a sub-resolution model for star formation and feedback in SPH simulations with Gadget-3

Murante, PM et al (2010, 2015); loosely following PM (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

$$\dot{M}_{cold} = \dot{M}_{cool} - \dot{M}_{*} - \dot{M}_{evap}$$

$$\dot{M}_{cool} = M_{hot}/t_{cool}$$

$$\dot{M}_{*} = f_{*}\, f_{mol}\, M_{cold}/t_{dyn}$$

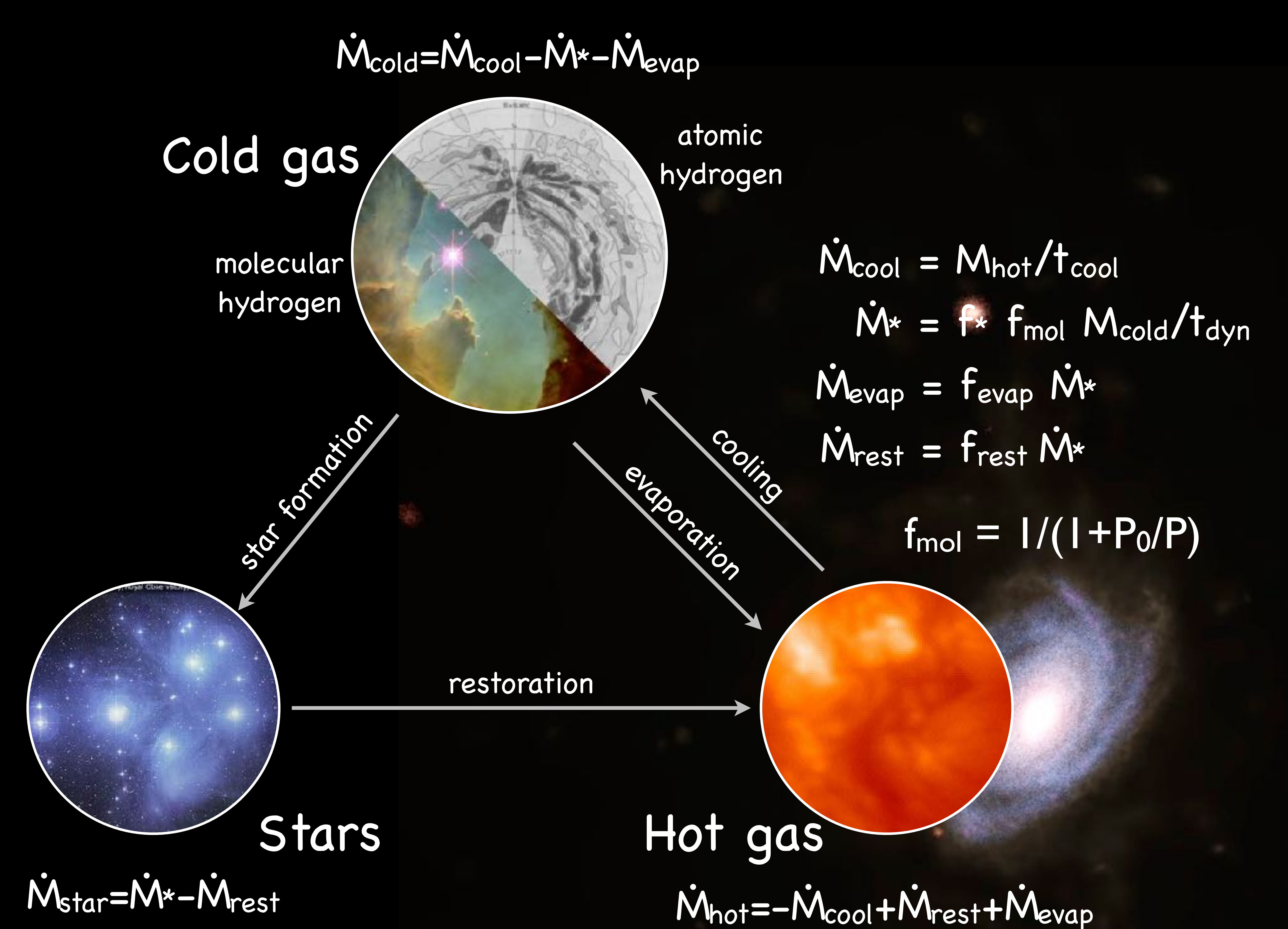
$$\dot{M}_{evap} = f_{evap}\, \dot{M}_{*}$$

$$\dot{M}_{rest} = f_{rest}\, \dot{M}_{*}$$

$$f_{mol} = 1/(1+P_0/P)$$

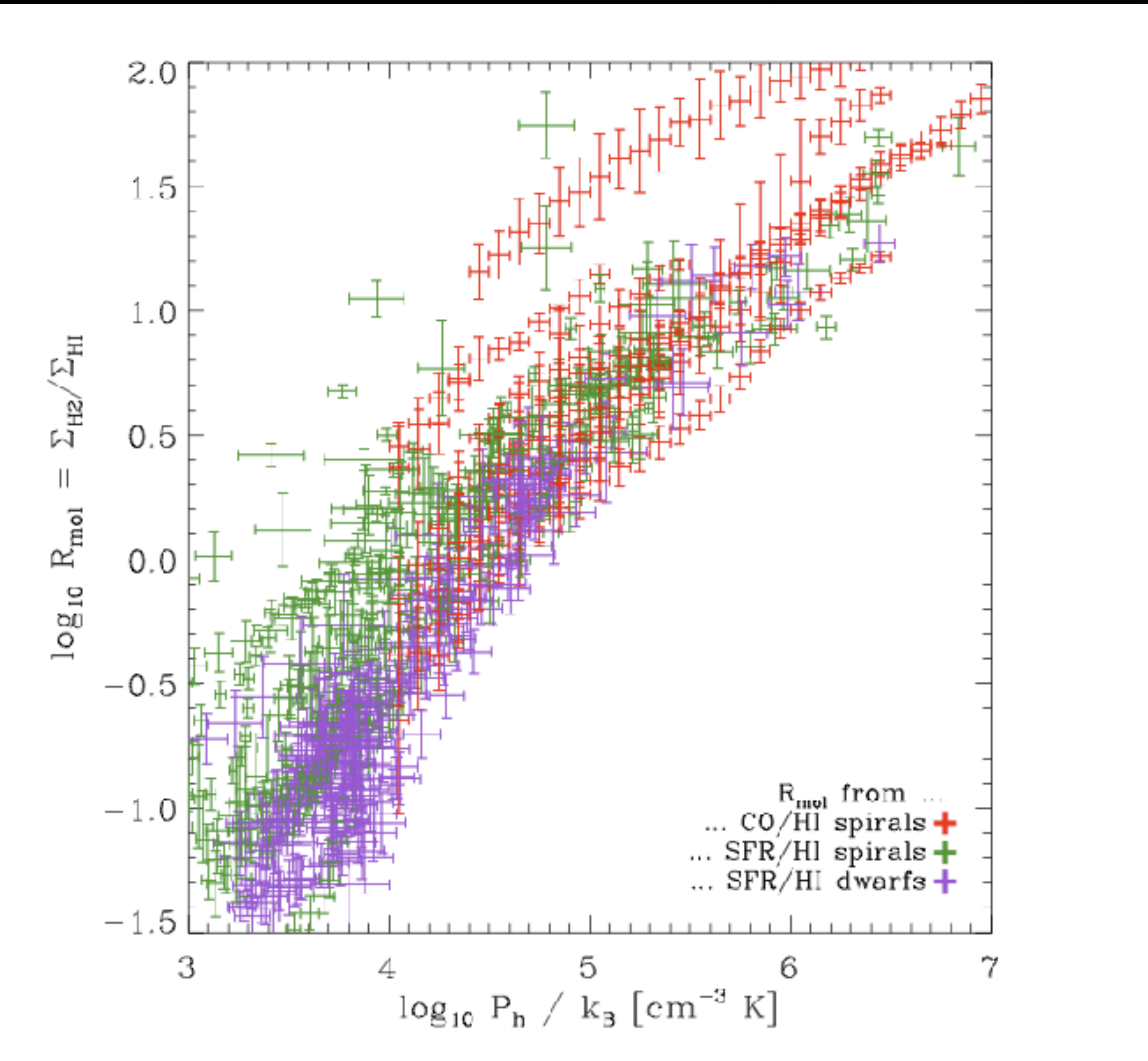
$$\dot{M}_{star} = \dot{M}_{*} - \dot{M}_{rest}$$

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



$\dot{M}_{cold}=\dot{M}_{cool}-\dot{M}_{*}-\dot{M}_{evap}$
Cold gas
atomic hydrogen
molecular hydrogen
$\dot{M}_{cool} = M_{hot}/t_{cool}$
$\dot{M}_{*} = f_{*}\ f_{mol}\ M_{cold}/t_{dyn}$
$\dot{M}_{evap} = f_{evap}\ \dot{M}_{*}$
$\dot{M}_{rest} = f_{rest}\ \dot{M}_{*}$
$f_{mol} = 1/(1+P_0/P)$
star formation
evaporation
cooling
restoration
Stars
Hot gas
$\dot{M}_{star}=\dot{M}_{*}-\dot{M}_{rest}$
$\dot{M}_{hot}=-\dot{M}_{cool}+\dot{M}_{rest}+\dot{M}_{evap}$

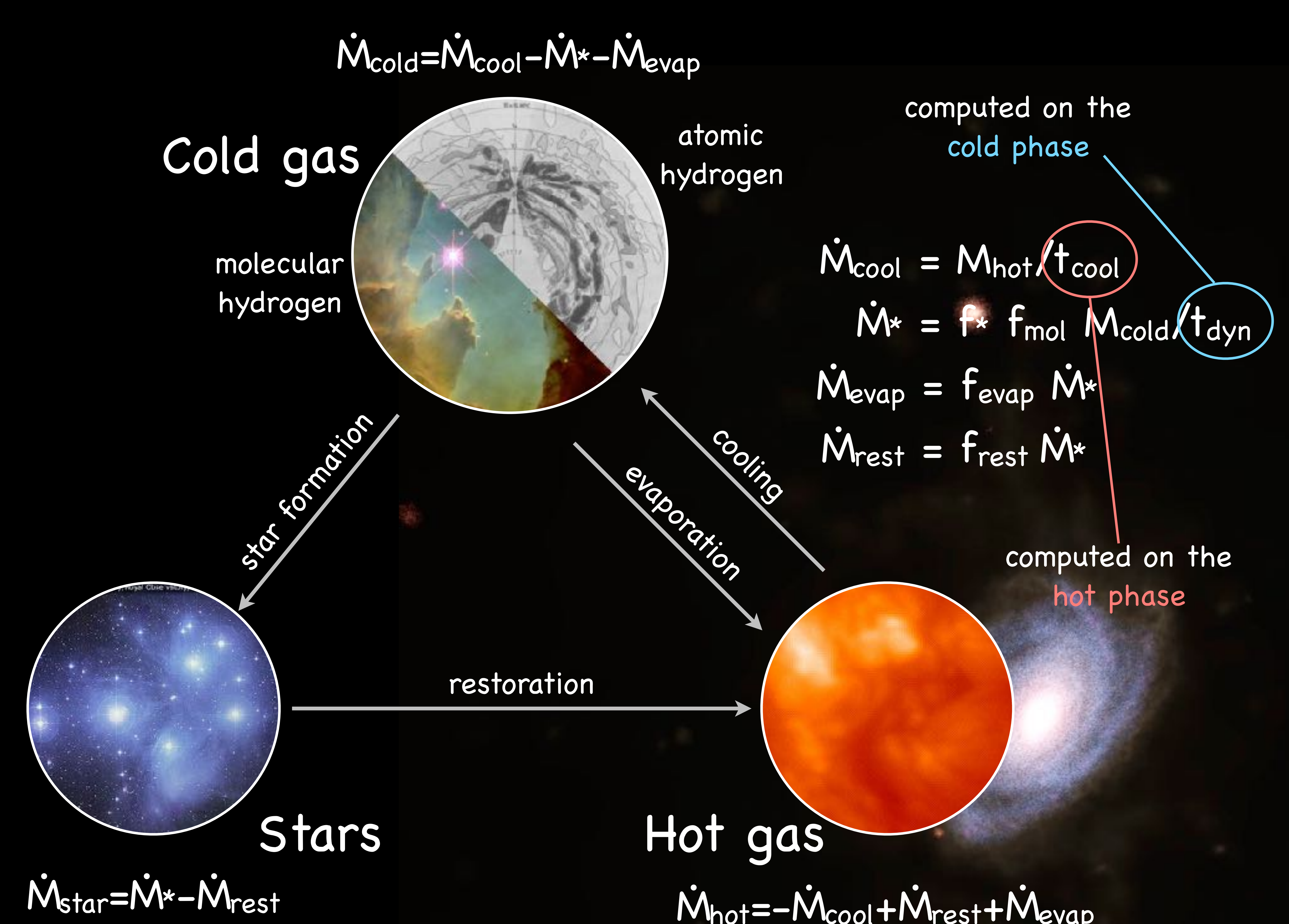
Molecular fraction f_{mol}



Leroy et al. (2009)

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

$$f_{mol} = 1/(1+P_0/P)$$


$\dot{M}_{cold}=\dot{M}_{cool}-\dot{M}_{*}-\dot{M}_{evap}$
Cold gas
atomic hydrogen
molecular hydrogen
computed on the cold phase
$\dot{M}_{cool} = M_{hot}/t_{cool}$
$\dot{M}_{*} = f_{*}\ f_{mol}\ M_{cold}/t_{dyn}$
$\dot{M}_{evap} = f_{evap}\ \dot{M}_{*}$
$\dot{M}_{rest} = f_{rest}\ \dot{M}_{*}$
star formation
evaporation
cooling
computed on the hot phase
restoration
Stars
Hot gas
$\dot{M}_{star}=\dot{M}_{*}-\dot{M}_{rest}$
$\dot{M}_{hot}=-\dot{M}_{cool}+\dot{M}_{rest}+\dot{M}_{evap}$

Star formation starts

↓

Energy from SNe increases pressure

↓

Pressure increases f_{mol}

↓

f_{mol} increases star formation

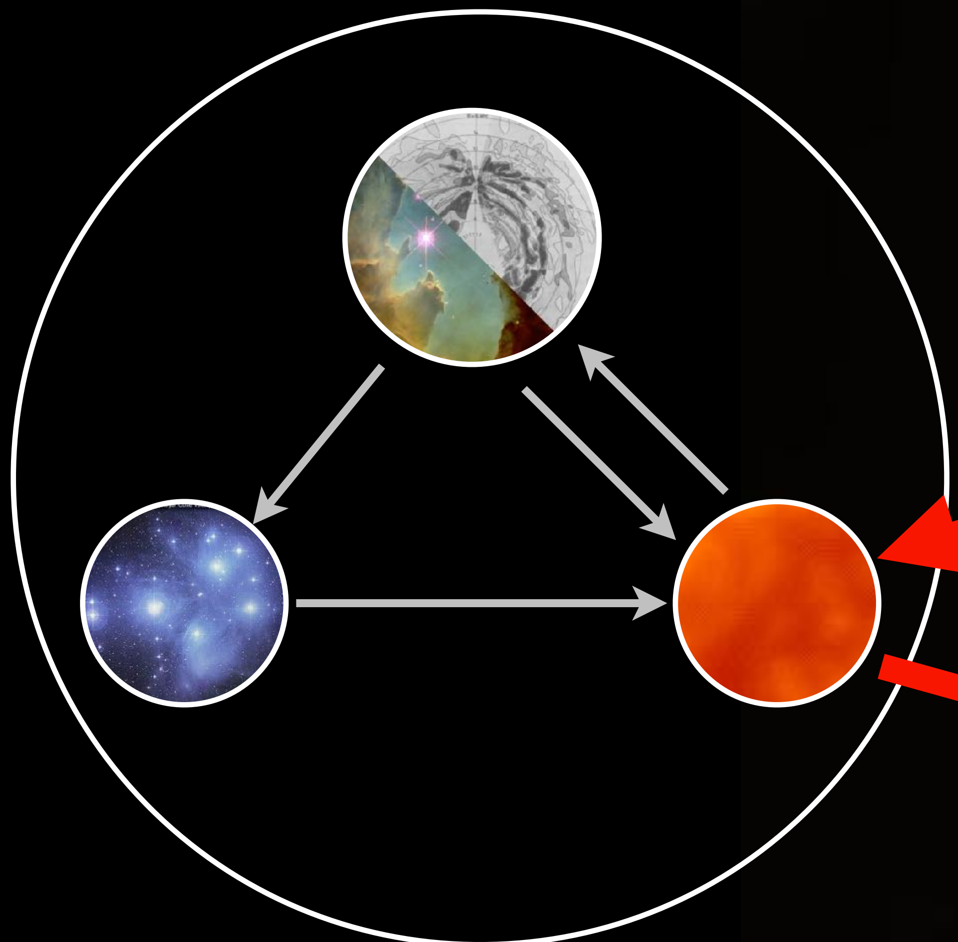
↓

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

NO EQUILIBRIUM SOLUTIONS

SPH

Multi-Phase particle



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

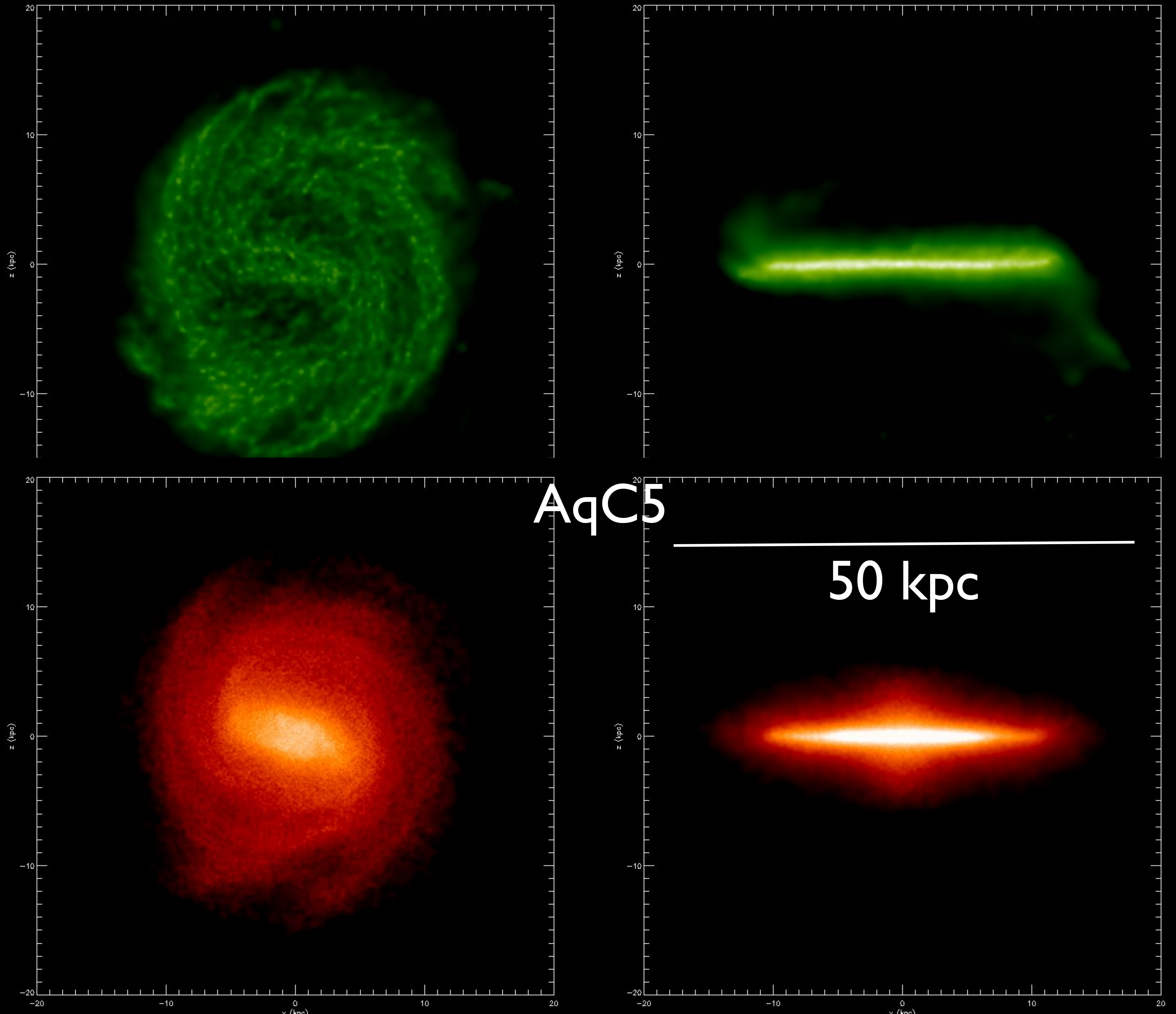
$\dot{E}_{hydro} = \Delta[S/(\gamma-1)\rho^{(\gamma-1)}]/\Delta t$

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

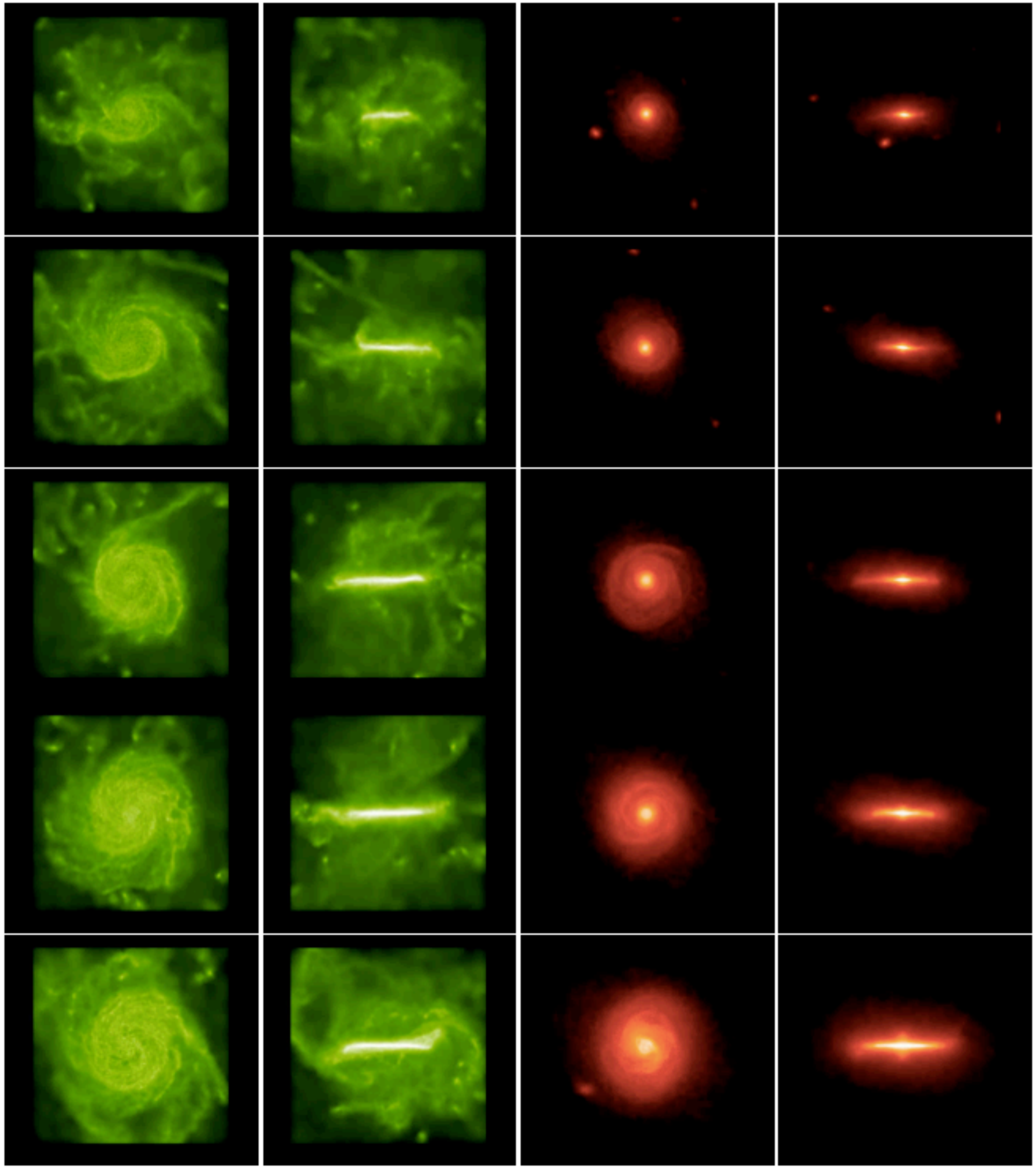
new ΔS

etc...

SPH interaction with surrounding particles halts the runaway


AqC5
50 kpc

Aq-C5



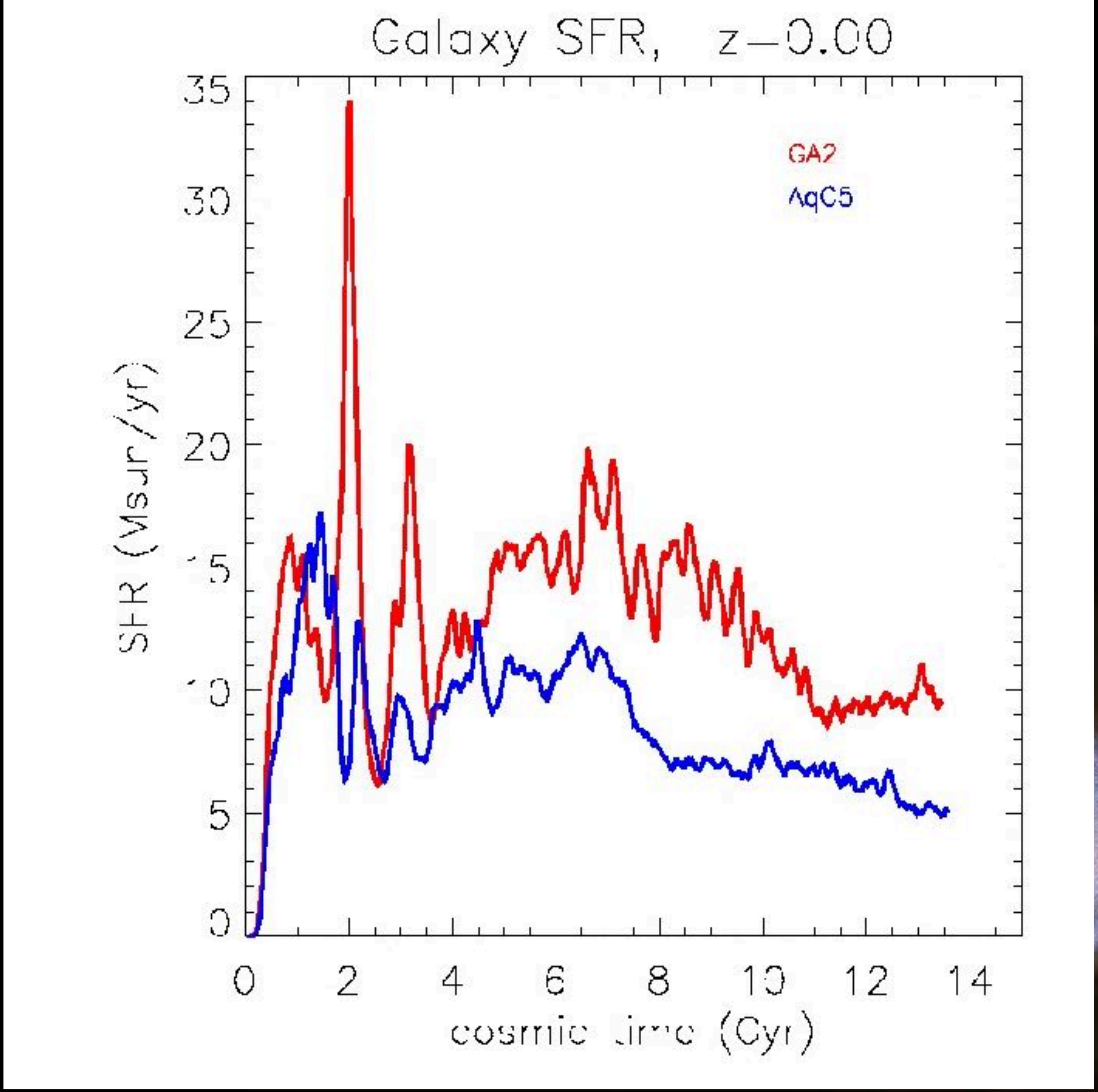
z=2.48

z=2.02

z=1.50

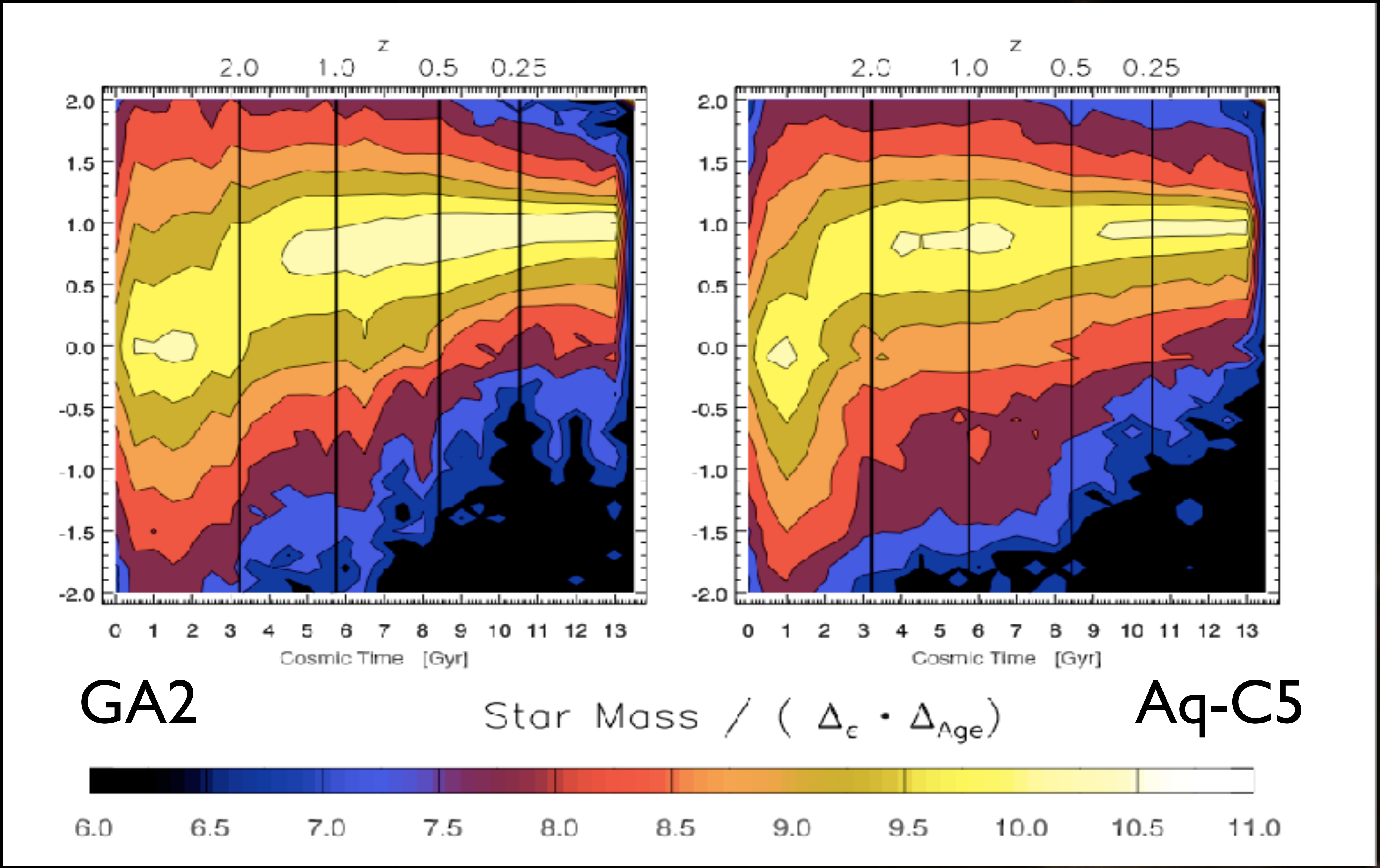
z=1.01

z=0.49

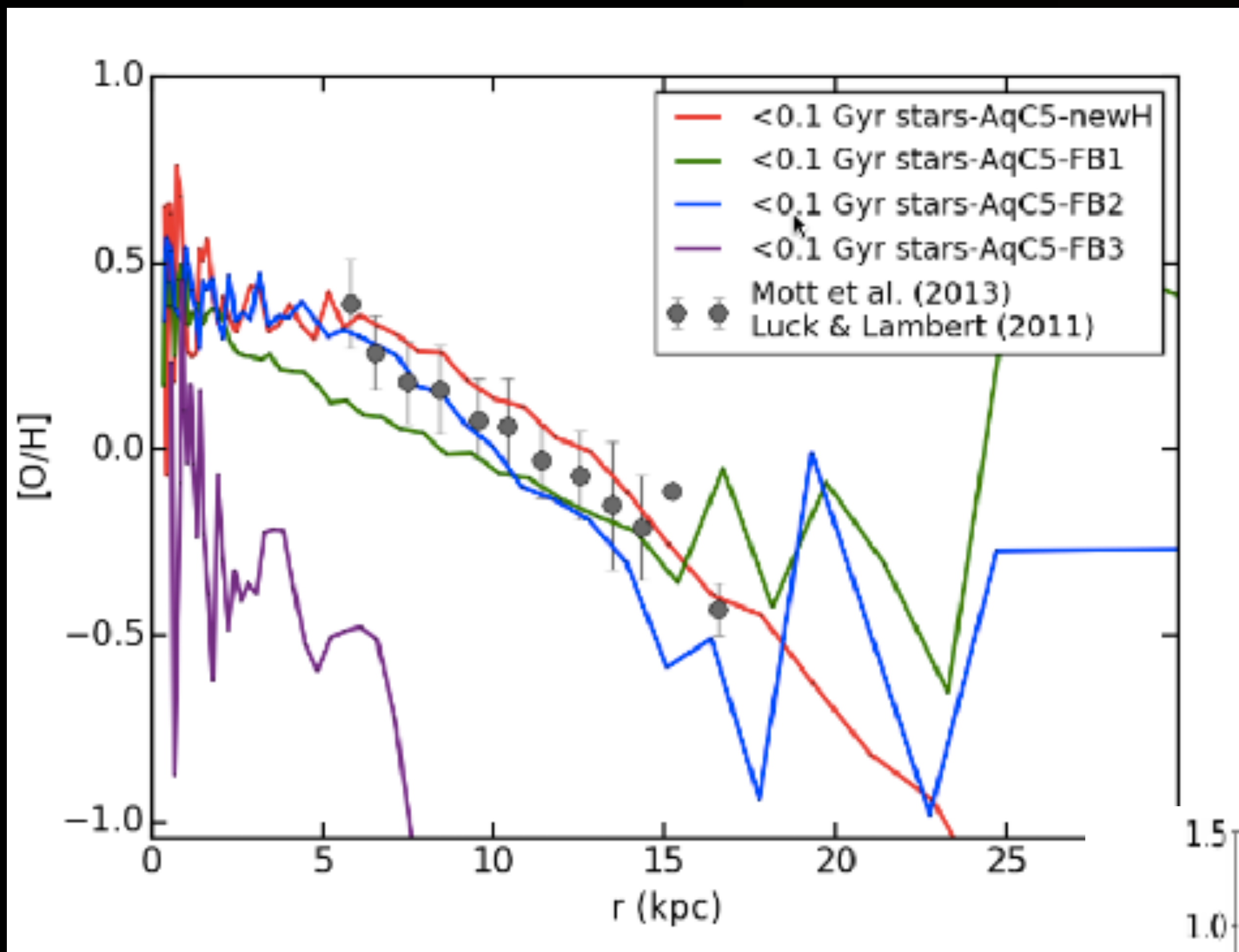


Galaxy SFR, z=0.00
GA2
AqC5
SFR (Msun/yr)
cosmic time (Gyr)
0
5
10
15
20
25
30
35
0
2
4
6
8
10
12
14

Circularity of stellar orbits versus stellar birth date

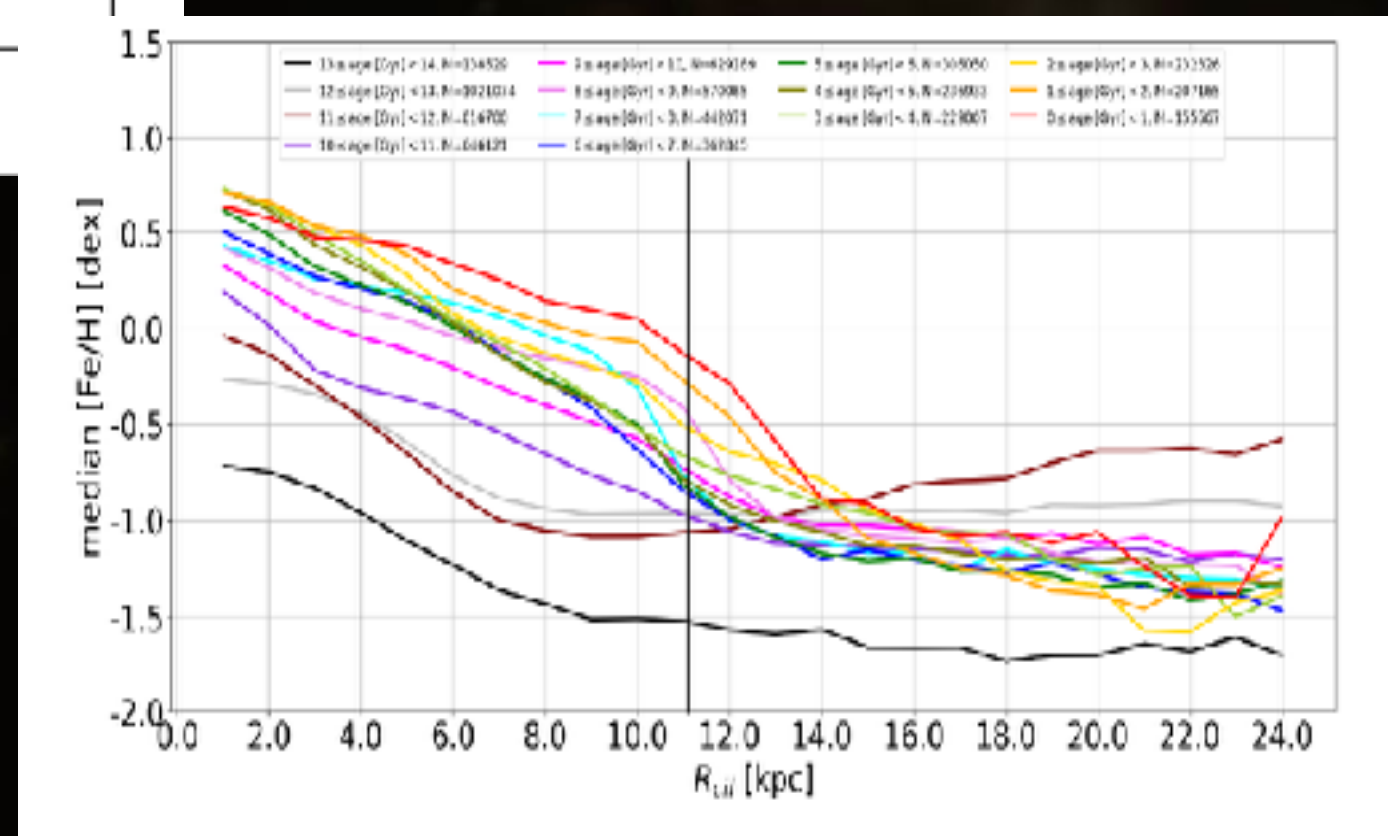


Detailed chemical evolution broadly matches the MW



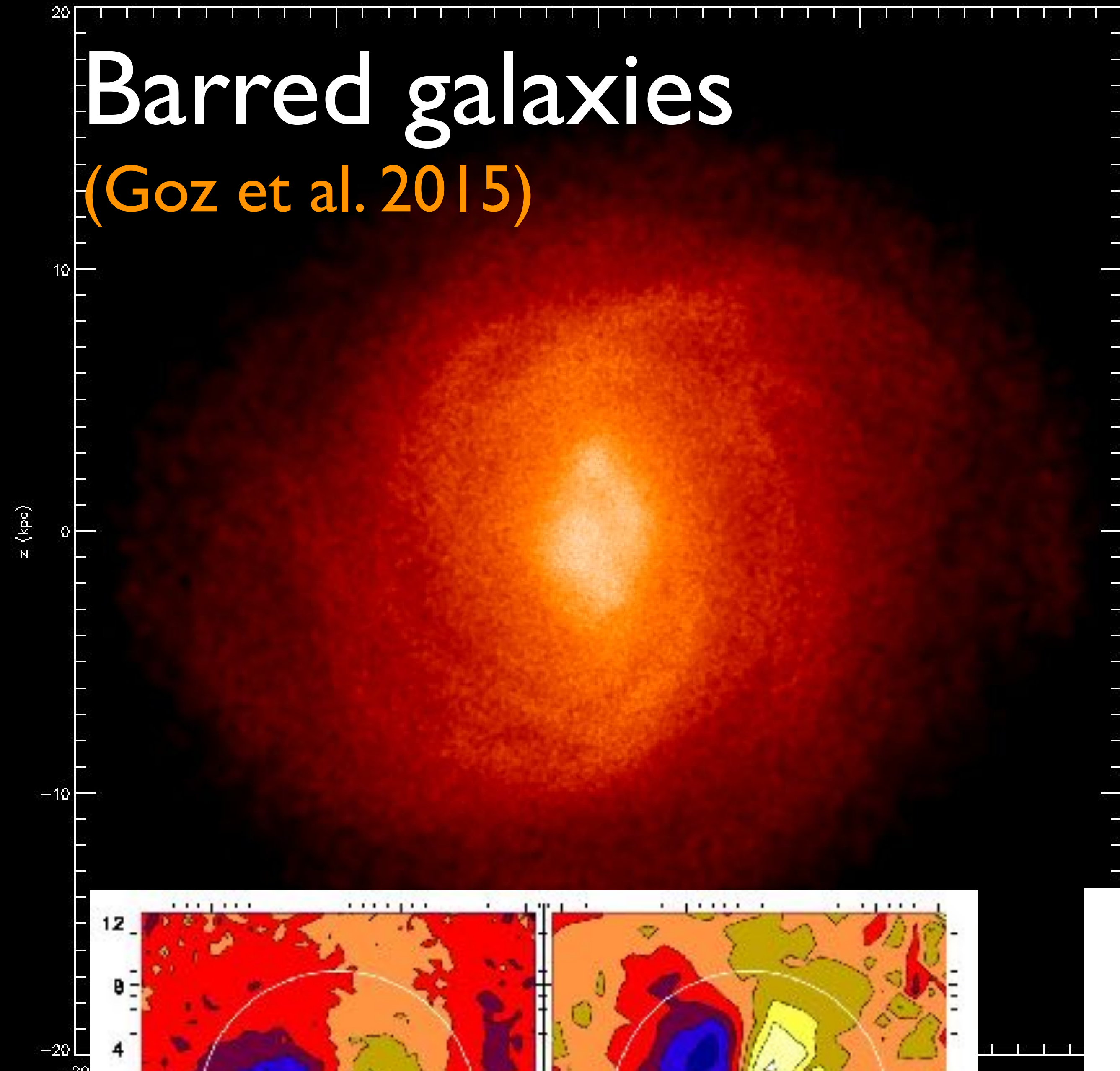
Test of metallicity gradients using various feedback schemes from Valentini et al. (2017)

Ongoing analysis of AqC4 simulation with the GAIA group in Torino (Spagna, Lattanzi, Giammaria, Crosta, Curir)

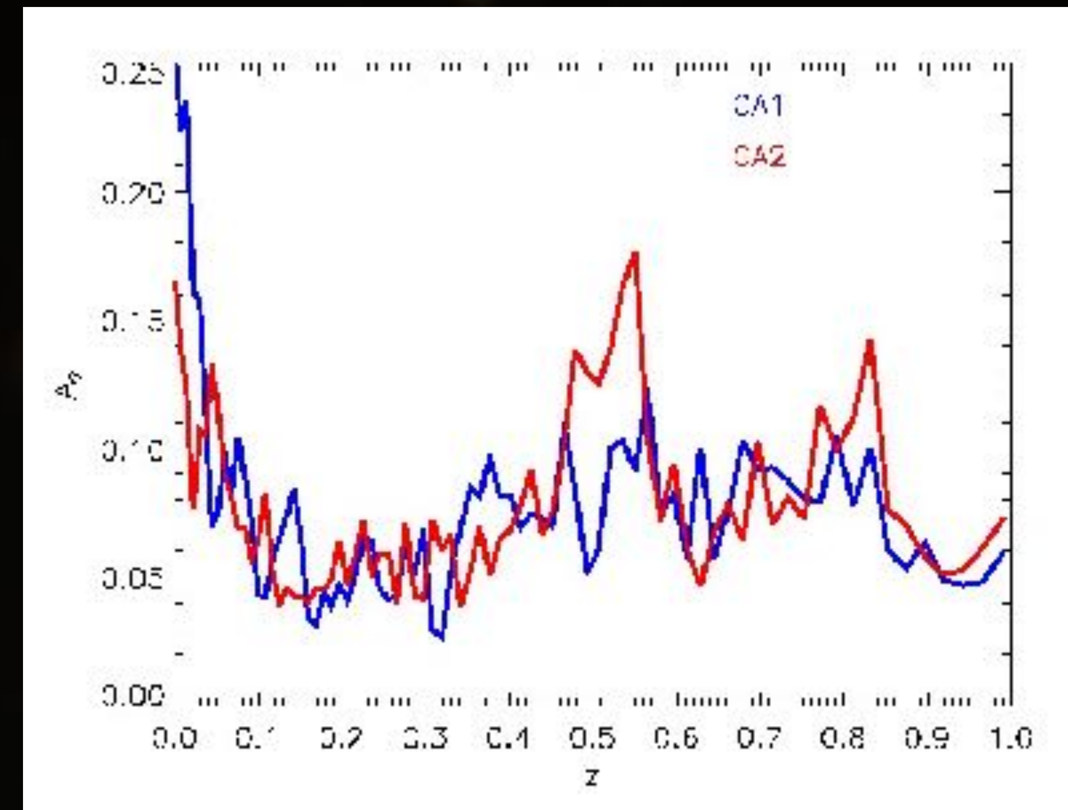


Barred galaxies

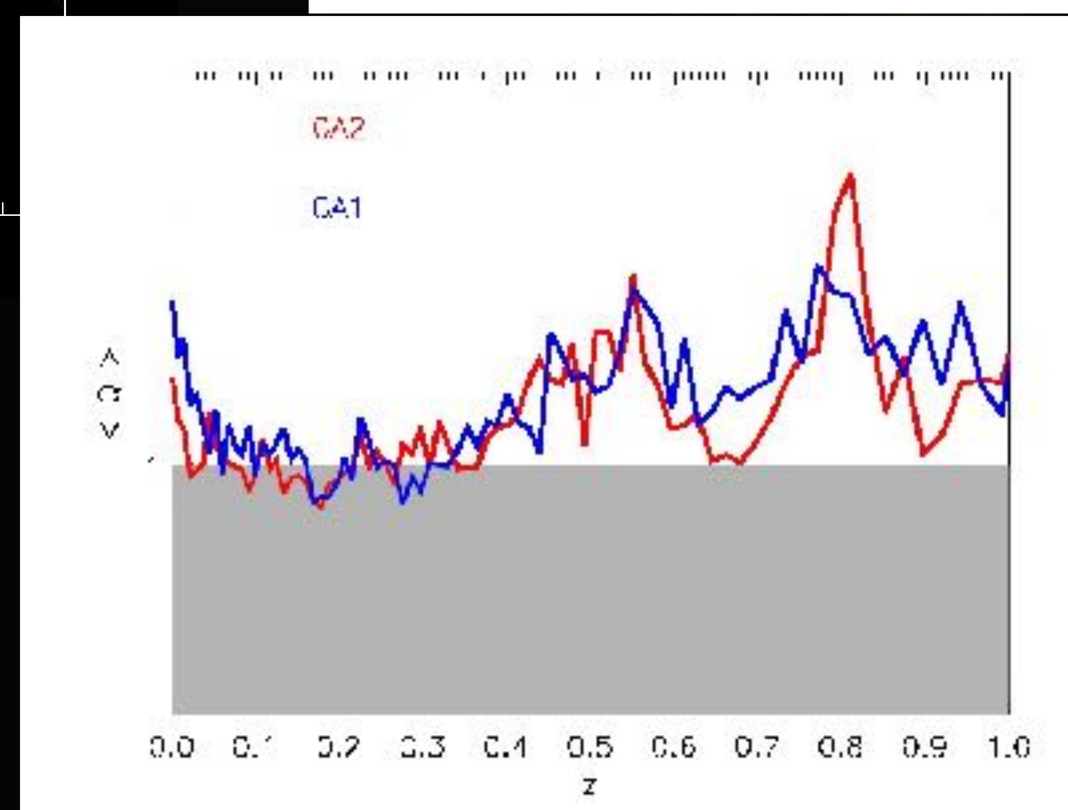
(Goz et al. 2015)

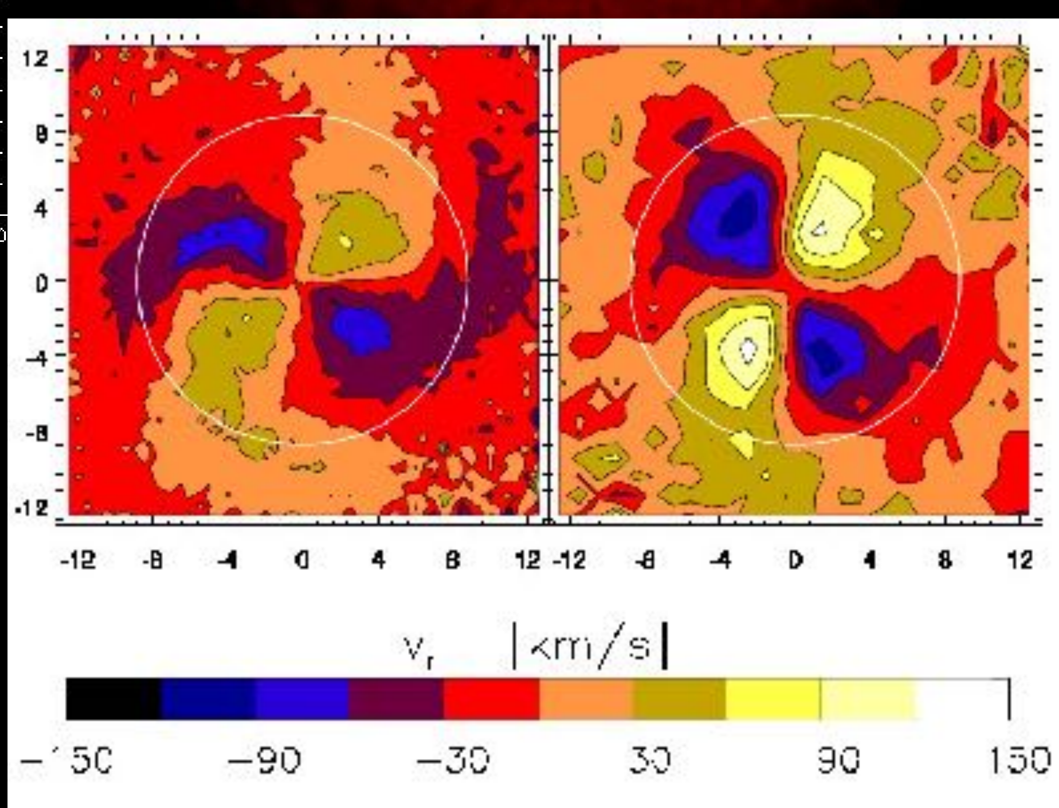


bar strength



bar origin

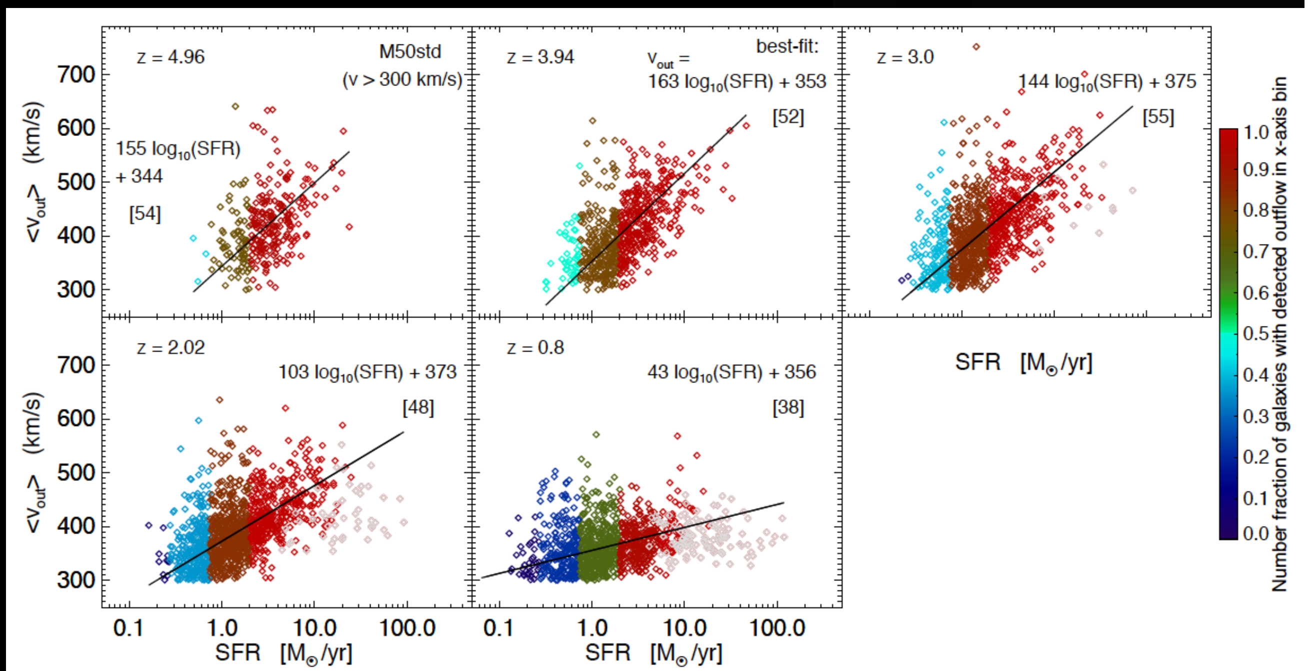




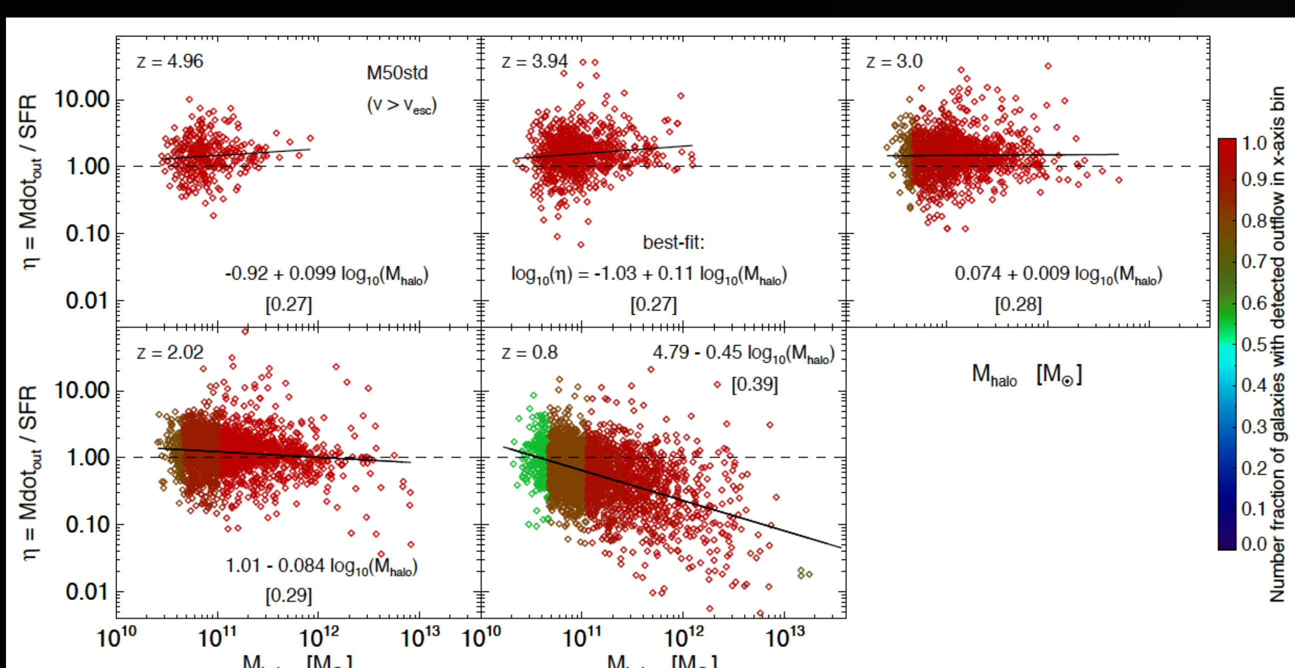
bar kinematics

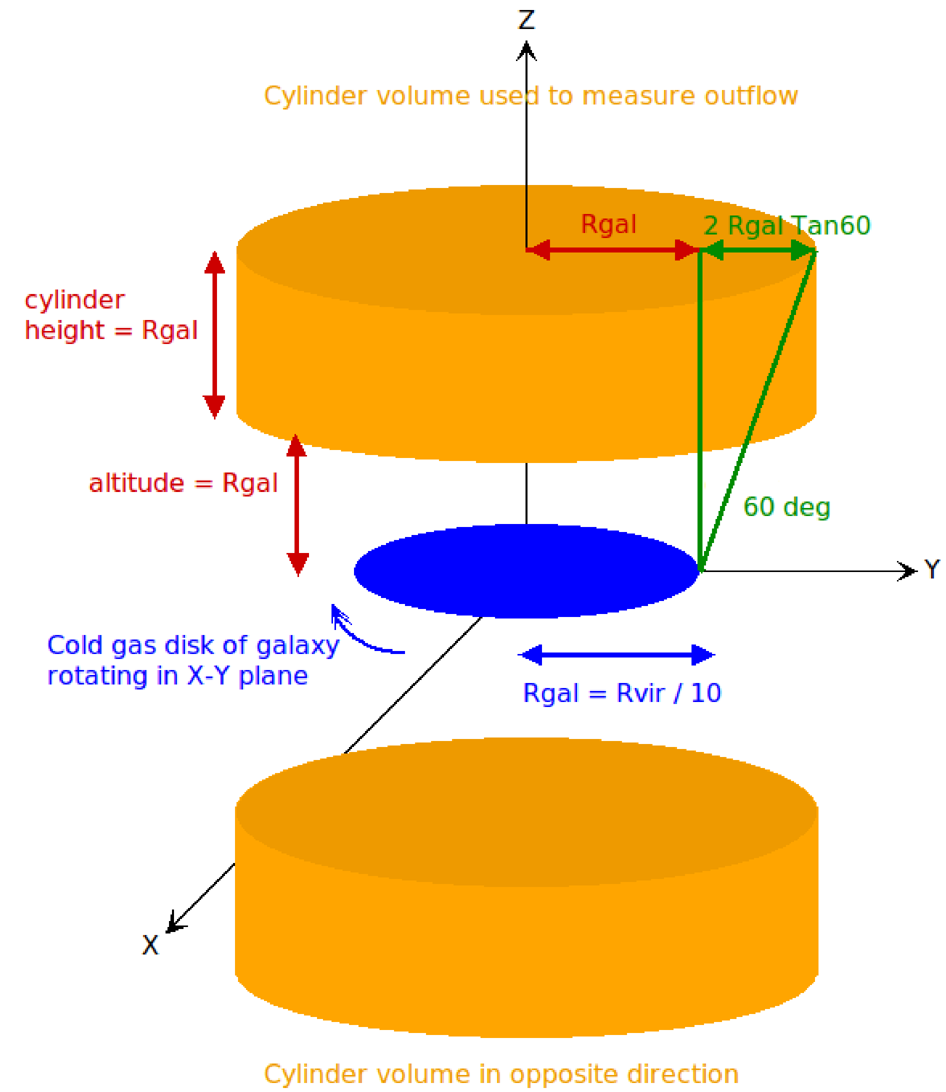
Outflows
(Barai et al. 2015)

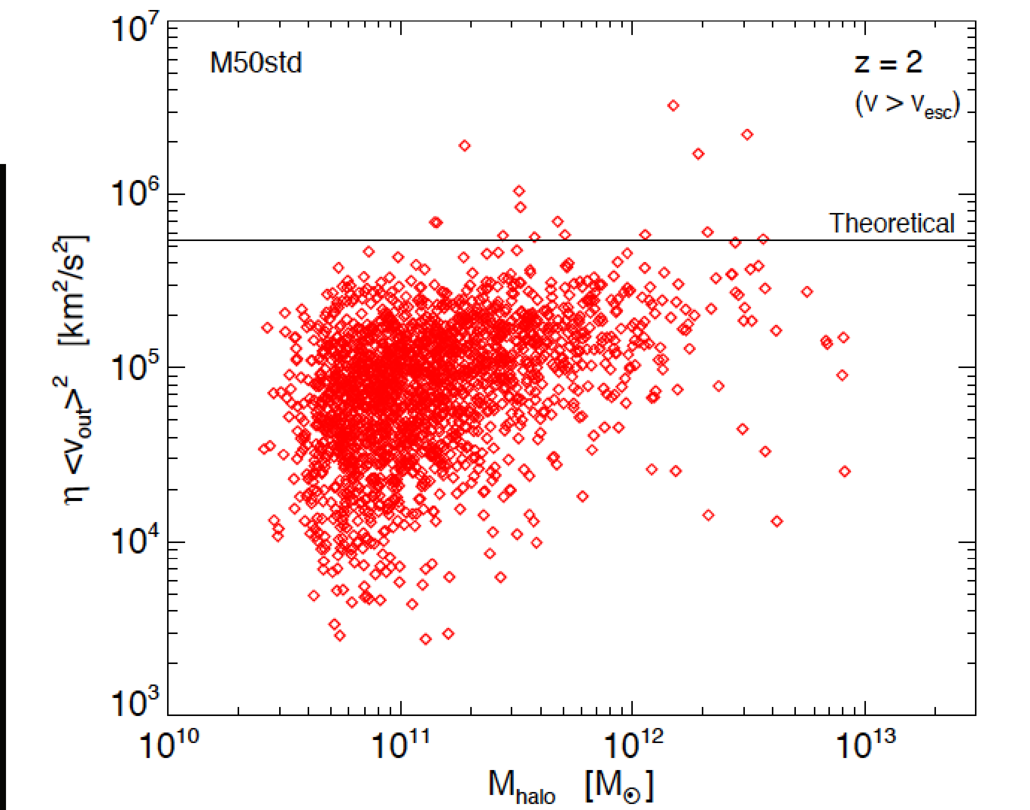
Dependence of v_{out} with redshift



Dependence of mass load with redshift







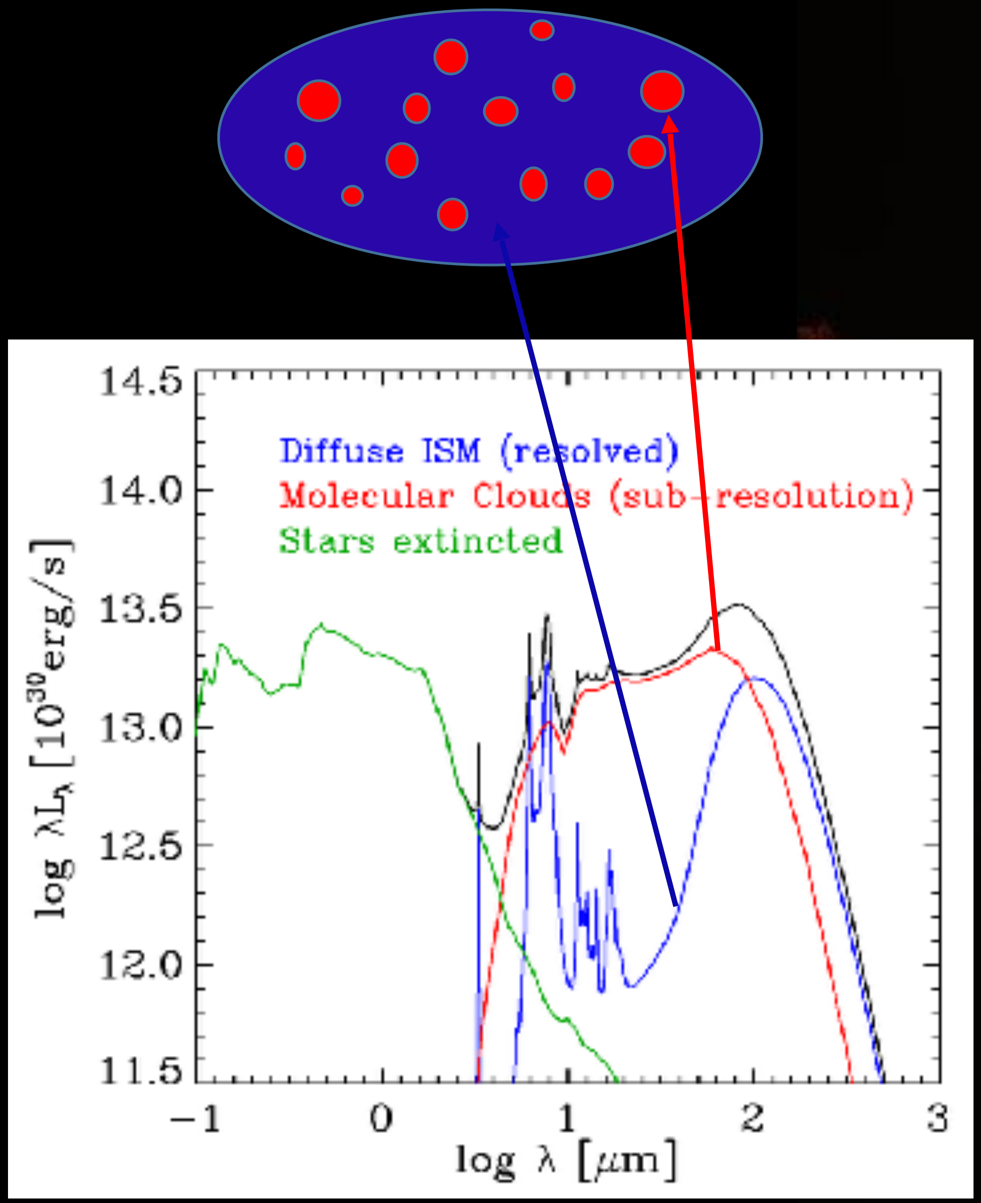
P. Monaco, AstroCoffee@Frankfurt, 16 January 2018

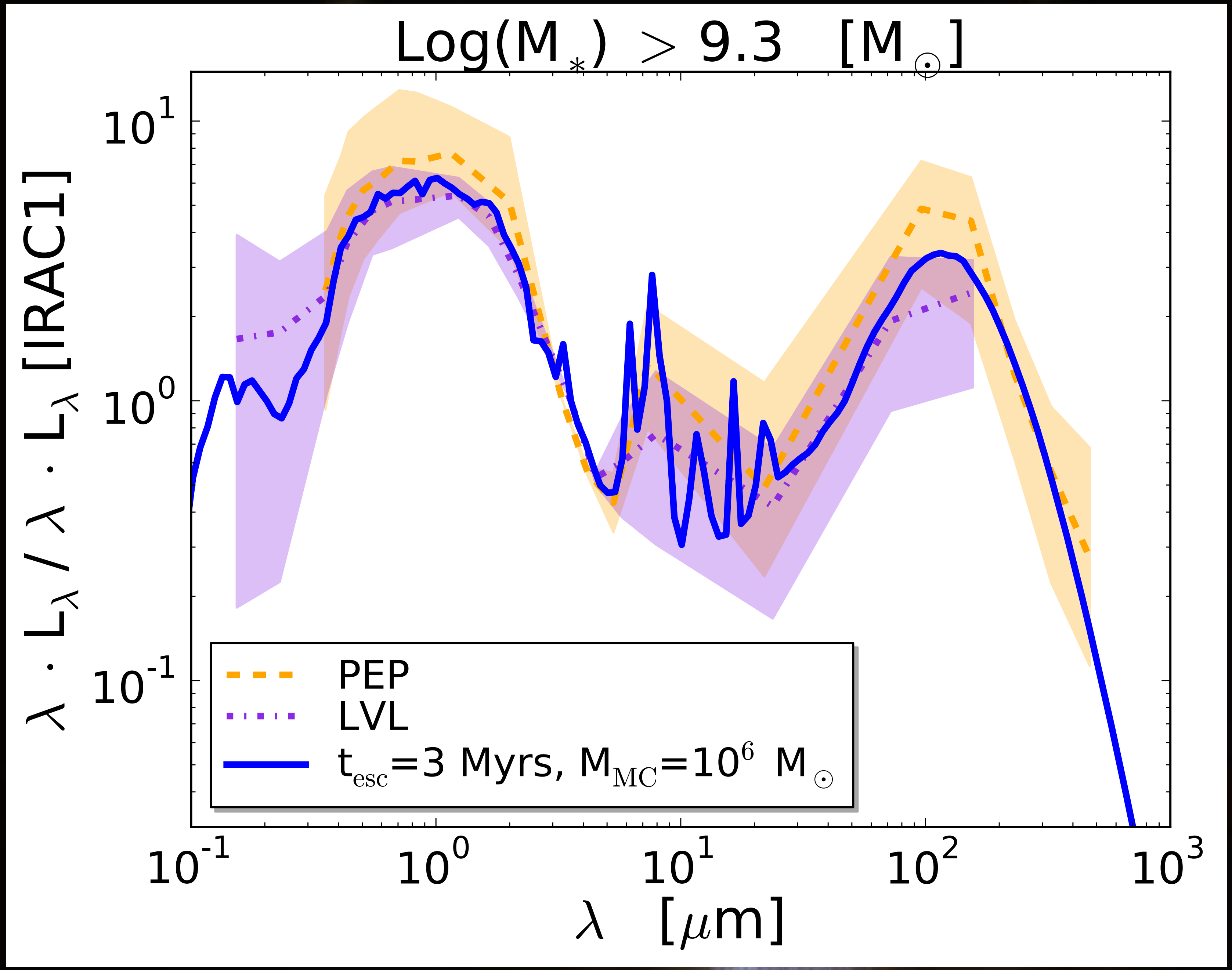
Panchromatic SEDs

(Goz et al. 2017)

Grasil3D for radiative tranfer

- a cooler component due to diffuse cirrus,
- a warmer component due to unresolved MCs





Treatment of dust

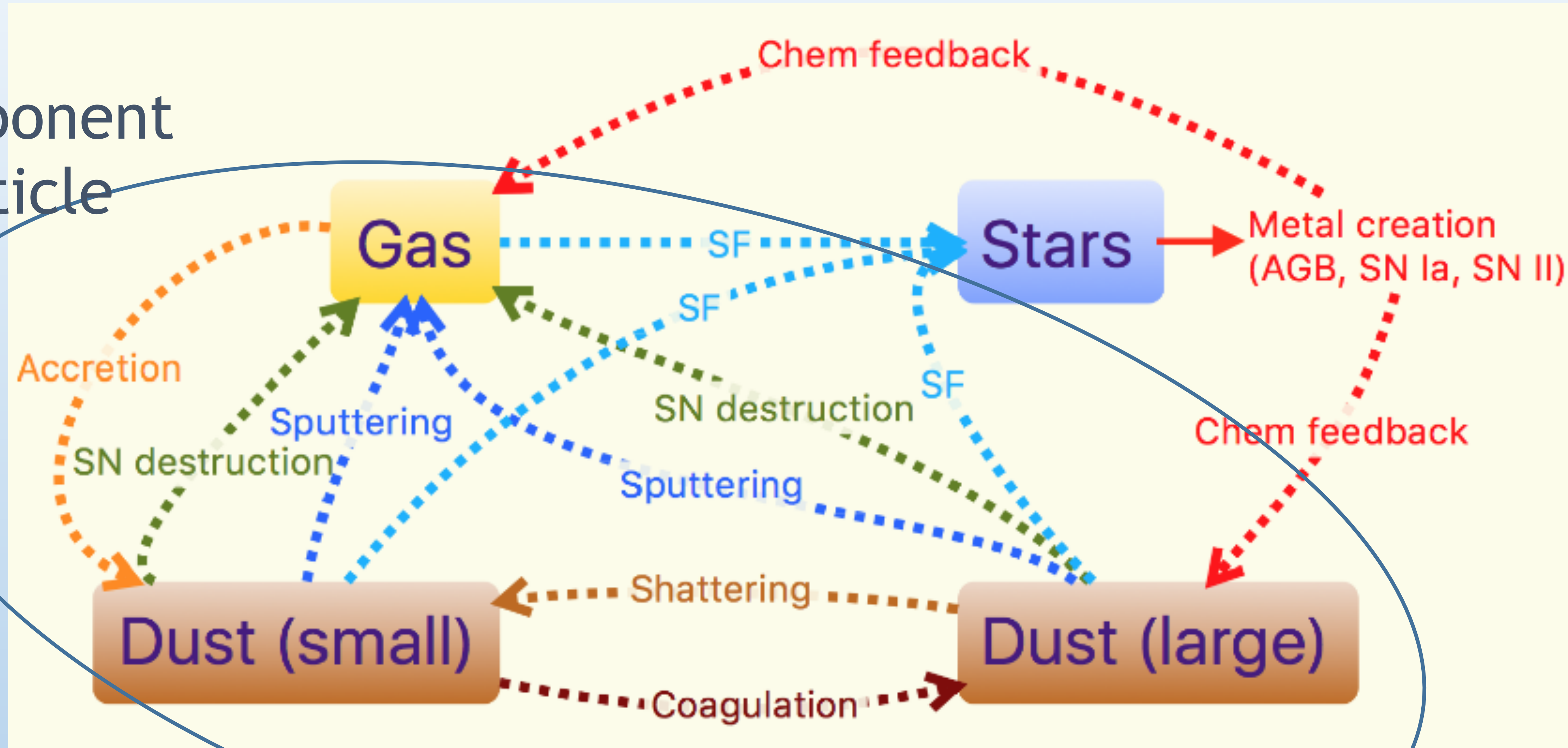
- Dust is made up of carbonaceous and silicate spherical grains, + PAH
- Optica properties as in Laor & Draine (1993)
- Dust mixture as in Weingartner & Draine (2001)
- PAH ionization fraction as in Li & Draine (2001)
- Size distribution as in Silva et al. (1998)
- Parameters calibrated on a set of observations
- Dust temperature is computed self-consistently

Treatment of dust

Modeling Dust Evolution in P-GADGET3

Eda Gjergo[1,2], Gian Luigi Granato[1], Cinthia Ragone-Figueroa[1,3], Giuseppe Murante[1].

Multicomponent "gas" particle



- Evolution of "gas" particles over code time-steps with SAM methods;
- We predict abundances of small and large, carbon and silicate dust grains (2x2=4 dust abundances)

Process	Small grains	Large grains	Total
Stellar ejecta	Δ	$\nearrow$	$\nearrow$
Accretion	$\nearrow$	Δ	$\nearrow$
Shattering	$\nearrow$	$\searrow$	$\longrightarrow$
Coagulation	$\searrow$	$\nearrow$	$\longrightarrow$
SN destruction	$\searrow$	$\searrow$	$\searrow$
SF	$\searrow$	$\searrow$	$\searrow$
Sputtering	$\searrow$	$\searrow$	$\searrow$

Conclusions

Brute force is impossible in forming galaxies: simulating disc galaxies requires suitable modeling of sub-grid physics

Our key ingredients for a successful simulation:

- strong feedback able to generate massive outflows
- a model of sub-resolution physics that makes gas particles very reactive to energy injection
- a good radiative transfer code to extend predictions to all wavelengths

Toward a theory of galaxy formation, are our models predictive?