Simulating the FIR side of galaxy formation

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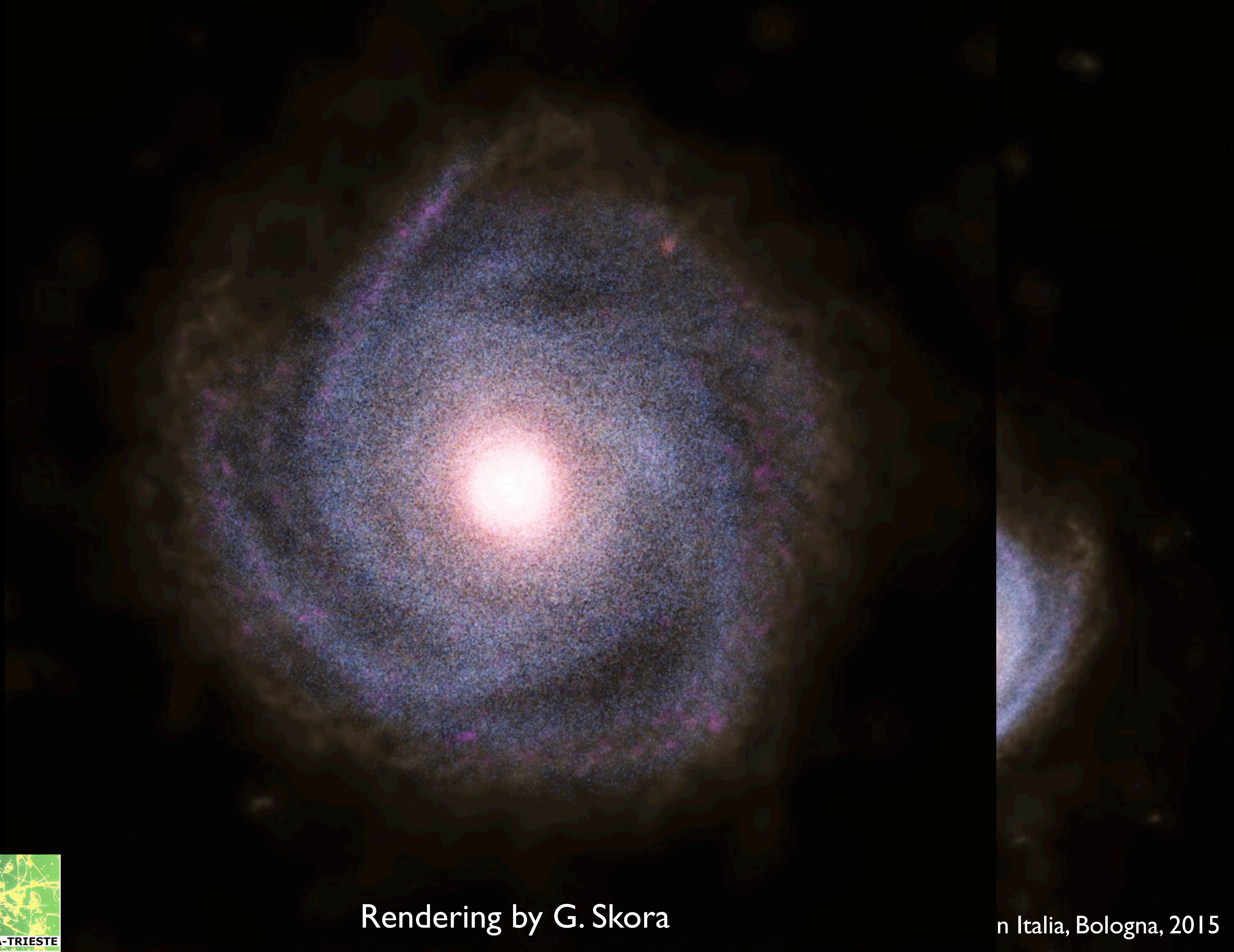
Papers:

- Murante, P.M., Giovalli, Borgani & Diaferio, 2010, MNRAS 405, 1491
- P.M., Murante, Borgani & Dolag, 2011, MNRAS 421, 2485
- Murante, Calabrese, De Lucia, P.M., Borgani & Dolag, 2012, ApJ 749, L34
- Murante, P.M., Borgani, Tornatore, Dolag & Goz, 2015, MNRAS 447, 178
- Goz, P.M., Murante & Curir, 2015, MNRAS 447, 1774
- Barai, P.M., Murante, Ragagnin, Viel, 2015, MNRAS 447, 266

The challenge of galaxy formation

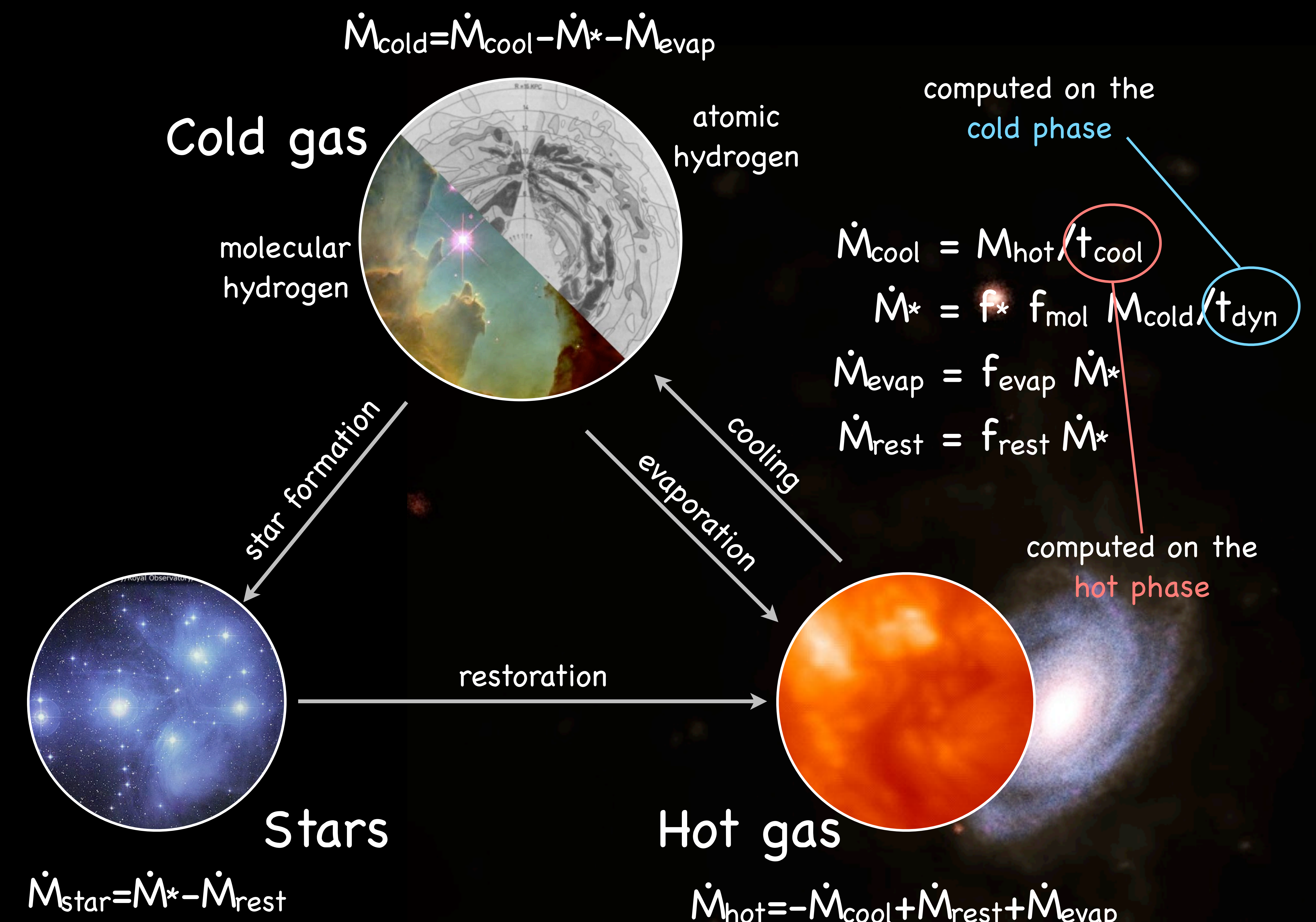


Rendering by G. Skora

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

Murante, PM et al (2012); 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



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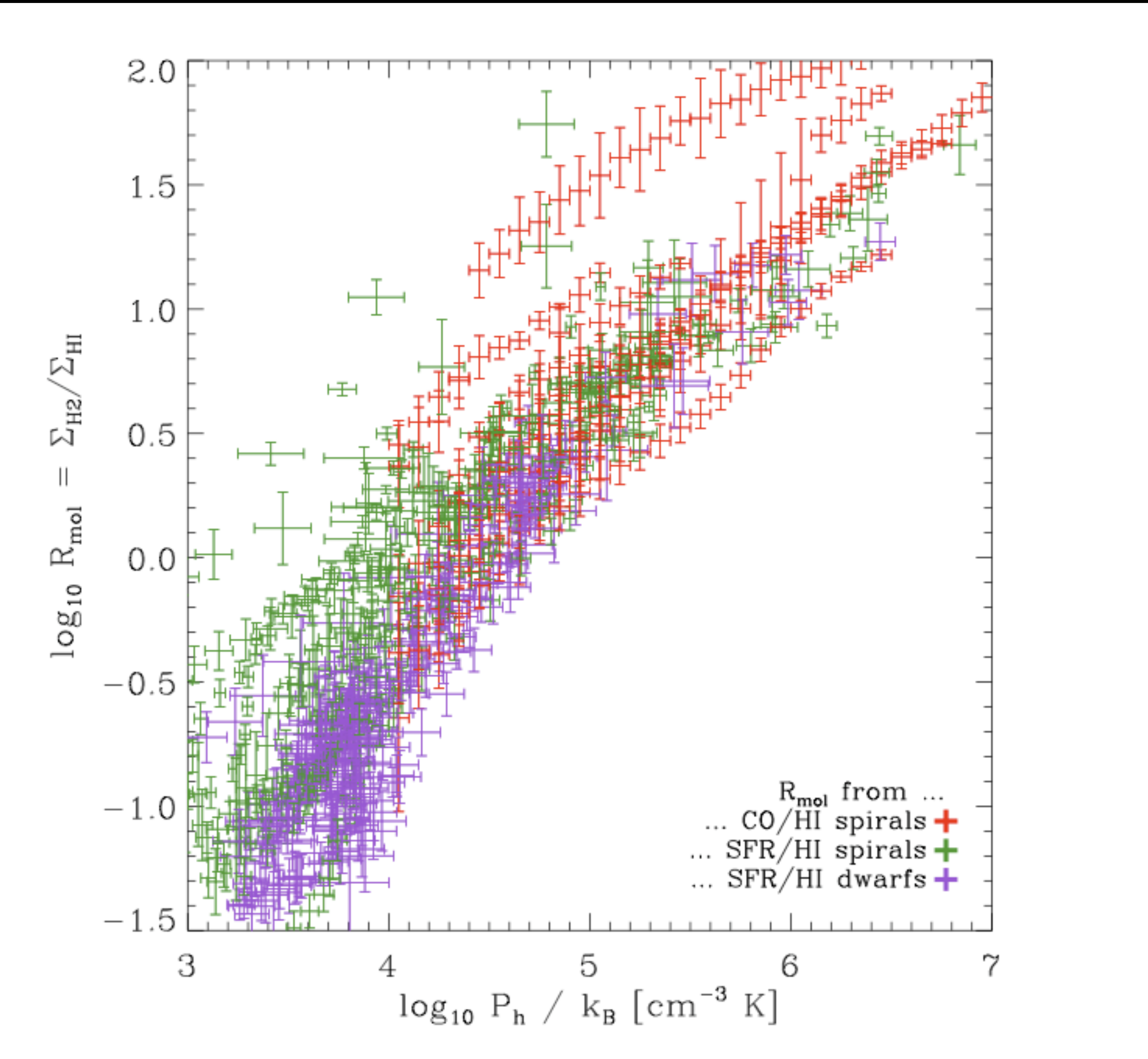
Molecular fraction f_{mol}



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

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

Leroy et al. (2009)

- Kinetic feedback
- Chemical evolution (Tornatore et al. 2007)
- Metal cooling (Wiersma et al. 2009)
- *in progress: molecular cooling*
- *in progress: AGN feedback*
- *in progress: improved SPH hydro*

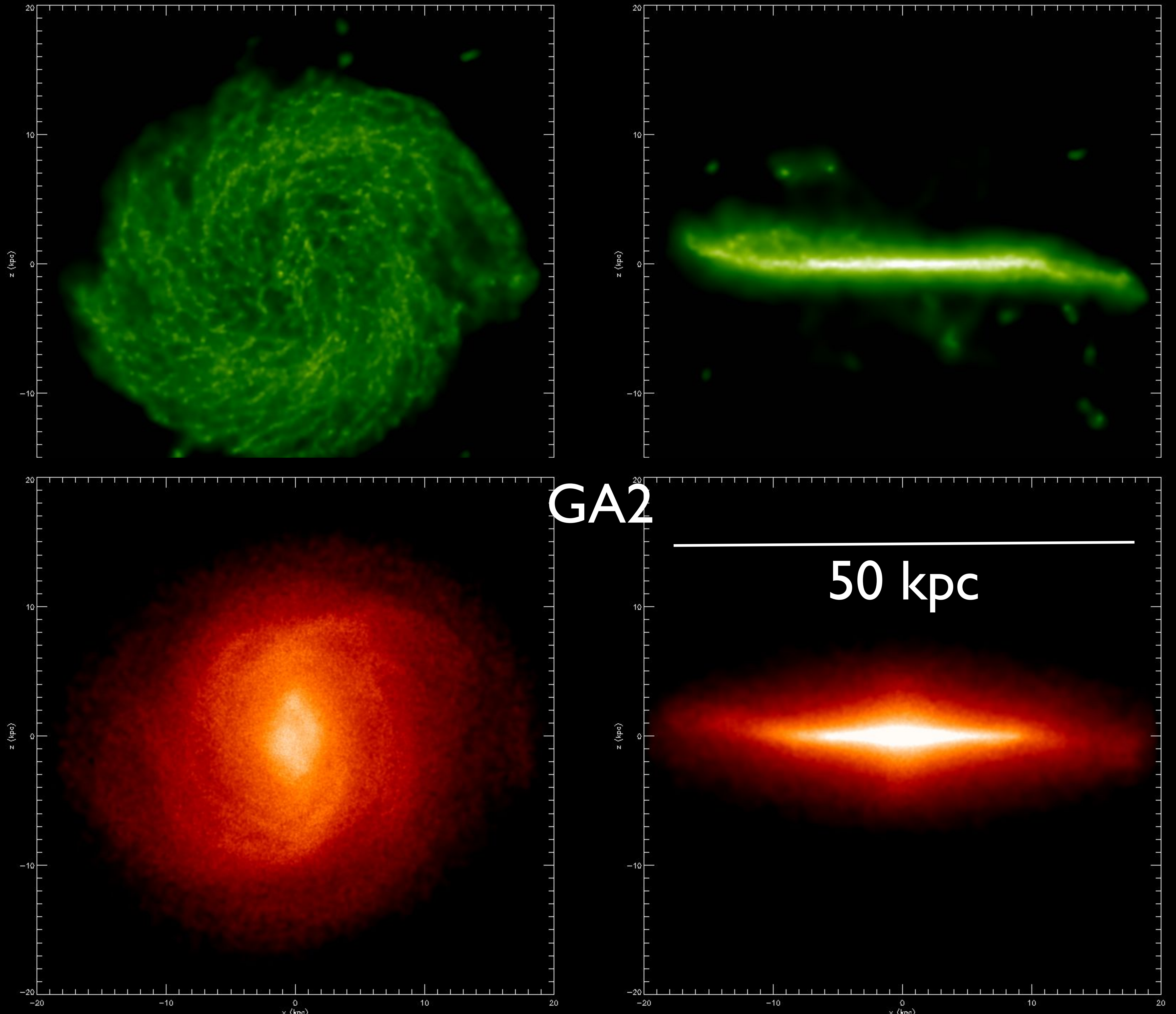
MW-like halos (Murante et al. 2015)

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

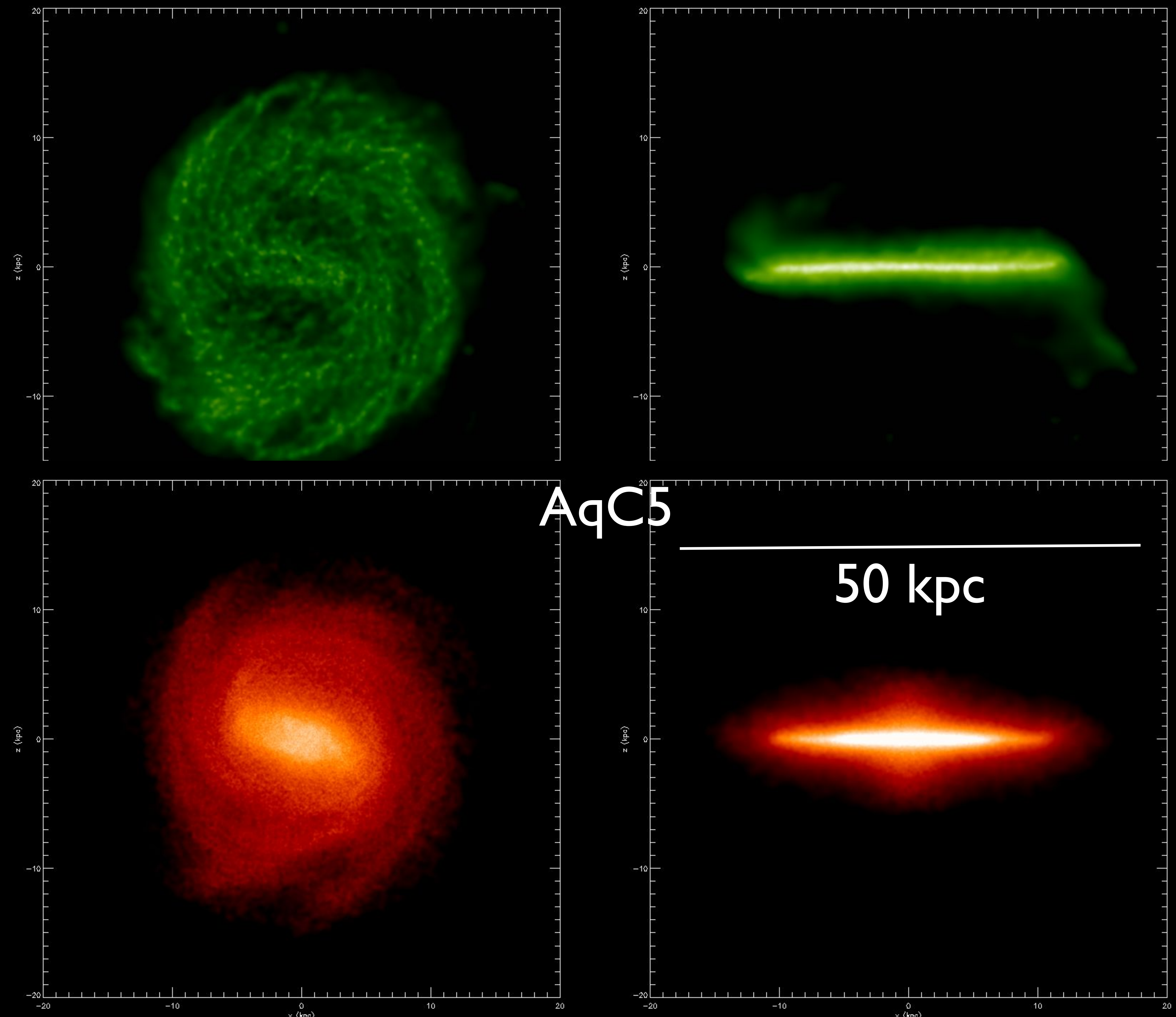
- GA series (Stoher et al. 2002)
- Aquila series (Scannapieco et al. 2012)

	GA0	GA1	GA2	GA3	Aq6	Aq5	Aq4
M_{gas} (Msun/h)	2.6e 7	2.8e 6	3.0e 5	3.2e 4	2.4e 6	3.0e 5	3.4e 4
M_{dm} (Msun/h)	1.4e 8	1.5e 7	1.6e 6	1.7e 5	1.3e 7	1.6e 6	1.9e 5
soft. (kpc/h)	1.4	0.65	0.325	0.155	1.0	0.5	0.25

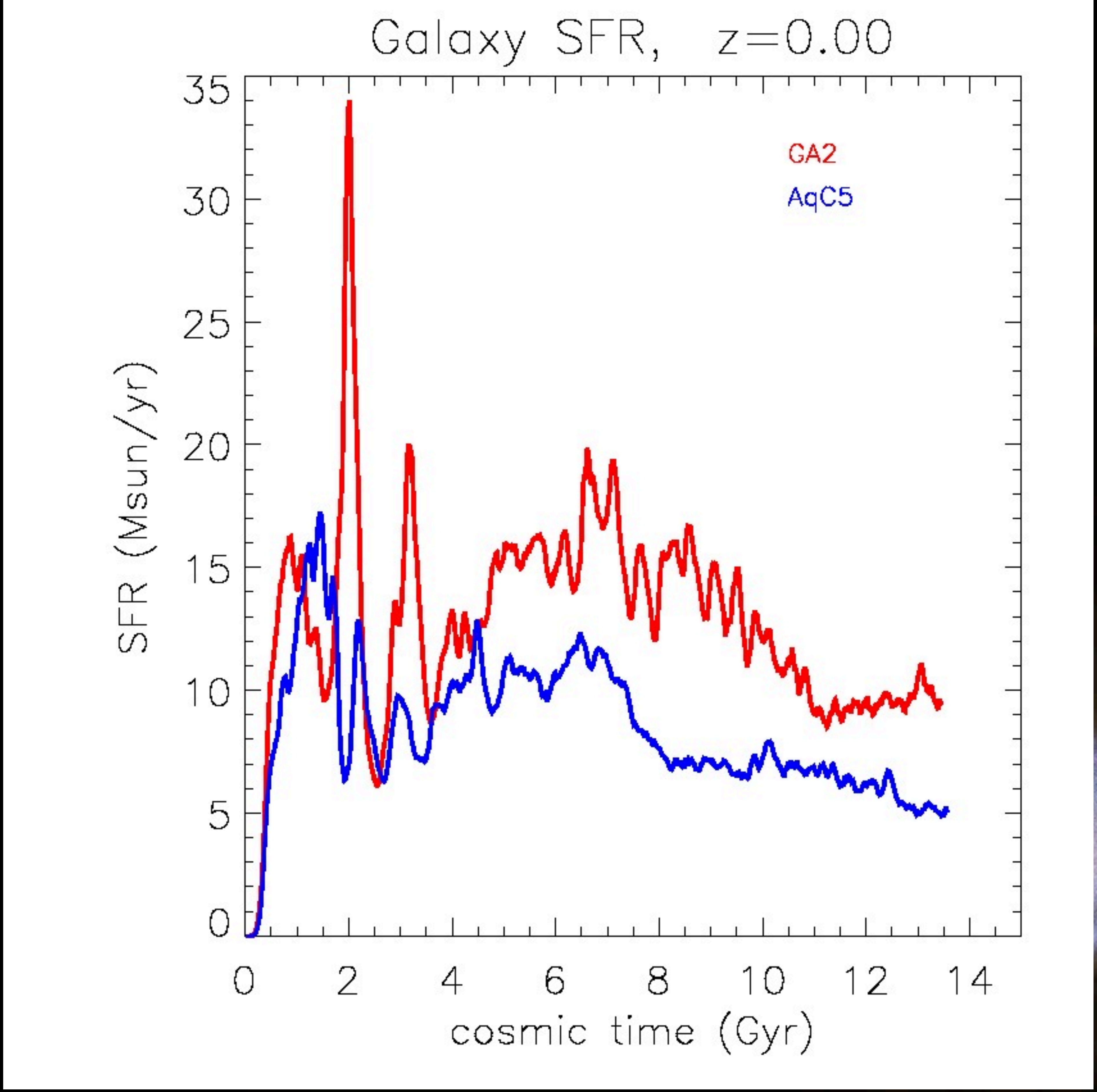
Murante et al. (2014)



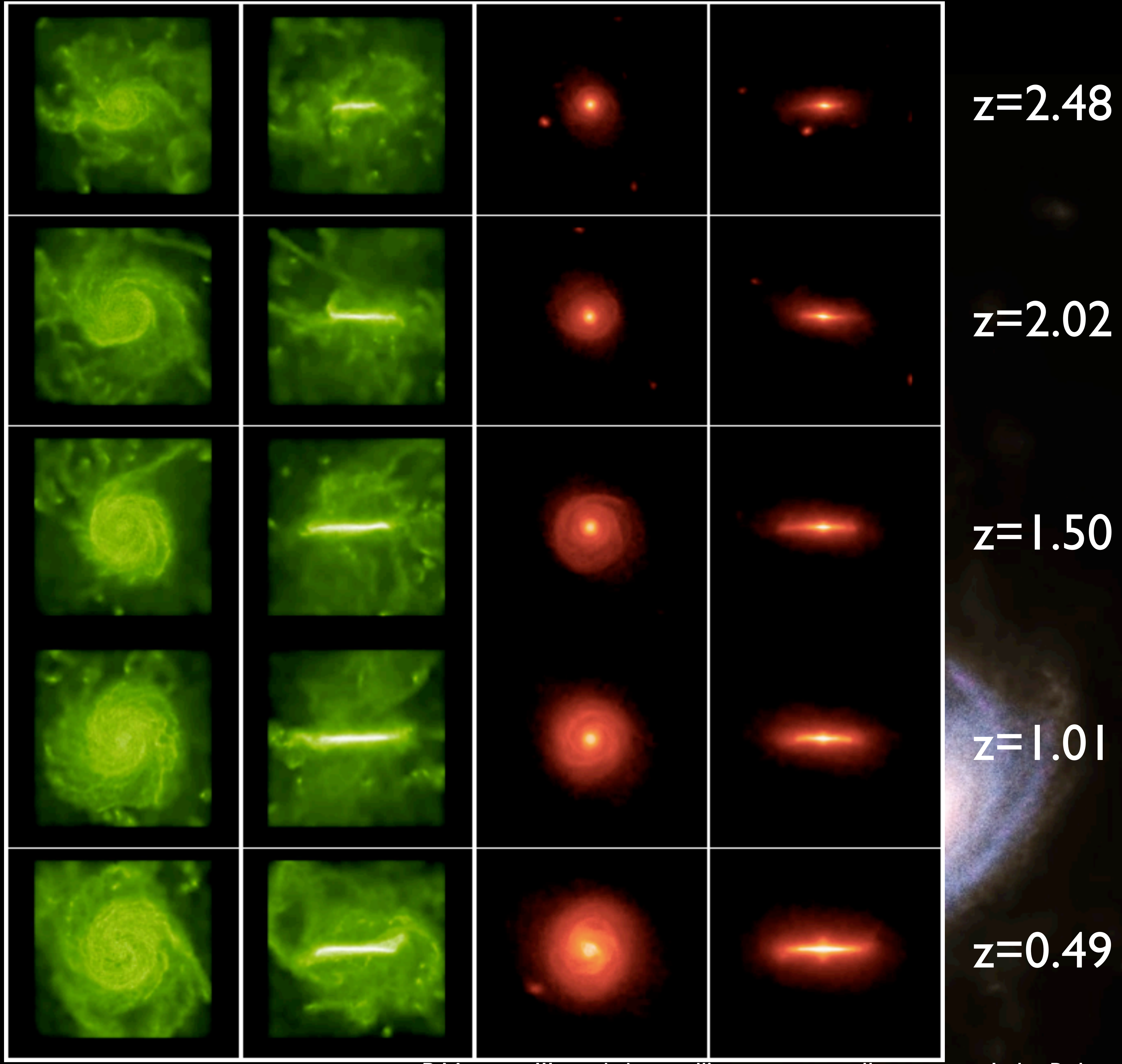
a, 2015



a, 2015


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

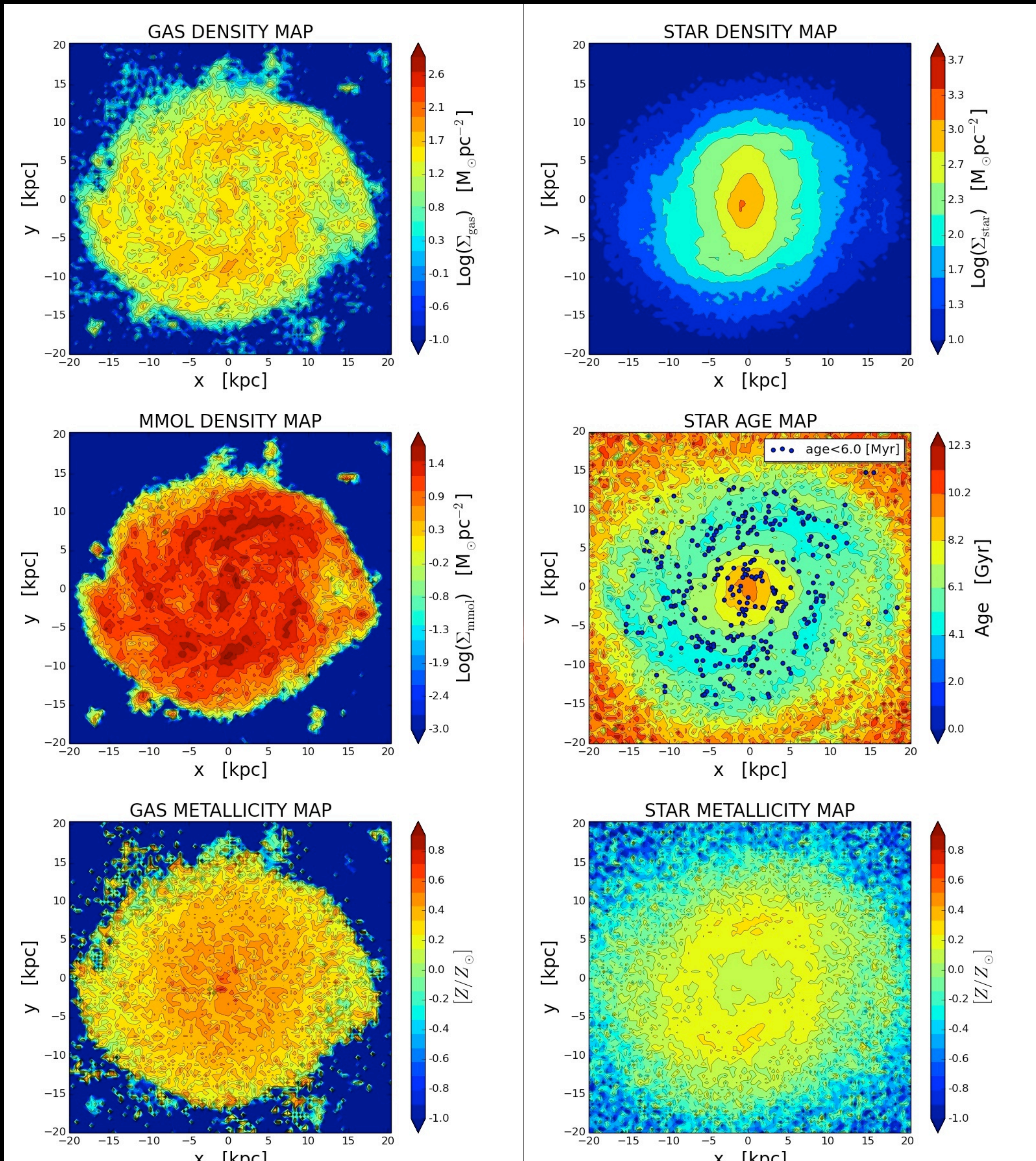
Aq-C5



Radiative transfer in a dusty ISM

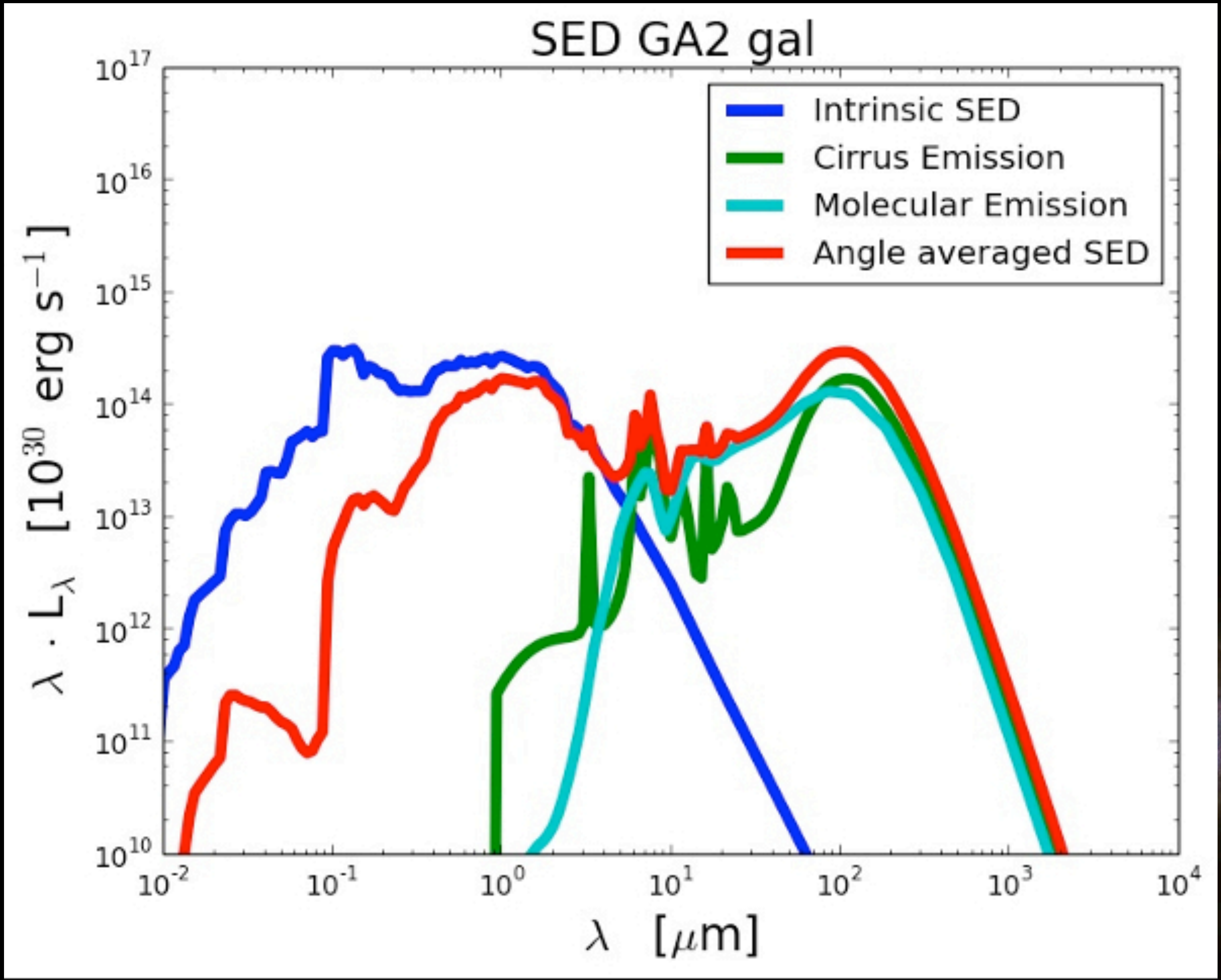
GRASIL3D (Silva et al. 1998; Dominguez-Tenreiro et al. 2014)

- Massive stars reside in highly opaque molecular clouds
- They exit the clouds after some time t_{exit}
- Radiative transfer is computed on the “cirrus” (diffuse) component
- Stellar emission follows Padova tracks
- Dust temperature is computed self-consistently
- Results depend on the line of sight



Input to GRASIL3D:

- star & gas surface densities
- star & gas metallicities
- star ages
- H_2 fraction



SED GA2 gal
Intrinsic SED
Cirrus Emission
Molecular Emission
Angle averaged SED
$\lambda \cdot L_\lambda$ [10^{30} erg s^{-1}]
λ [μm]
10^{17}
10^{16}
10^{15}
10^{14}
10^{13}
10^{12}
10^{11}
10^{10}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}

GA2 map
in RGB colors

Cosmological volumes (Barai et al. 2015)

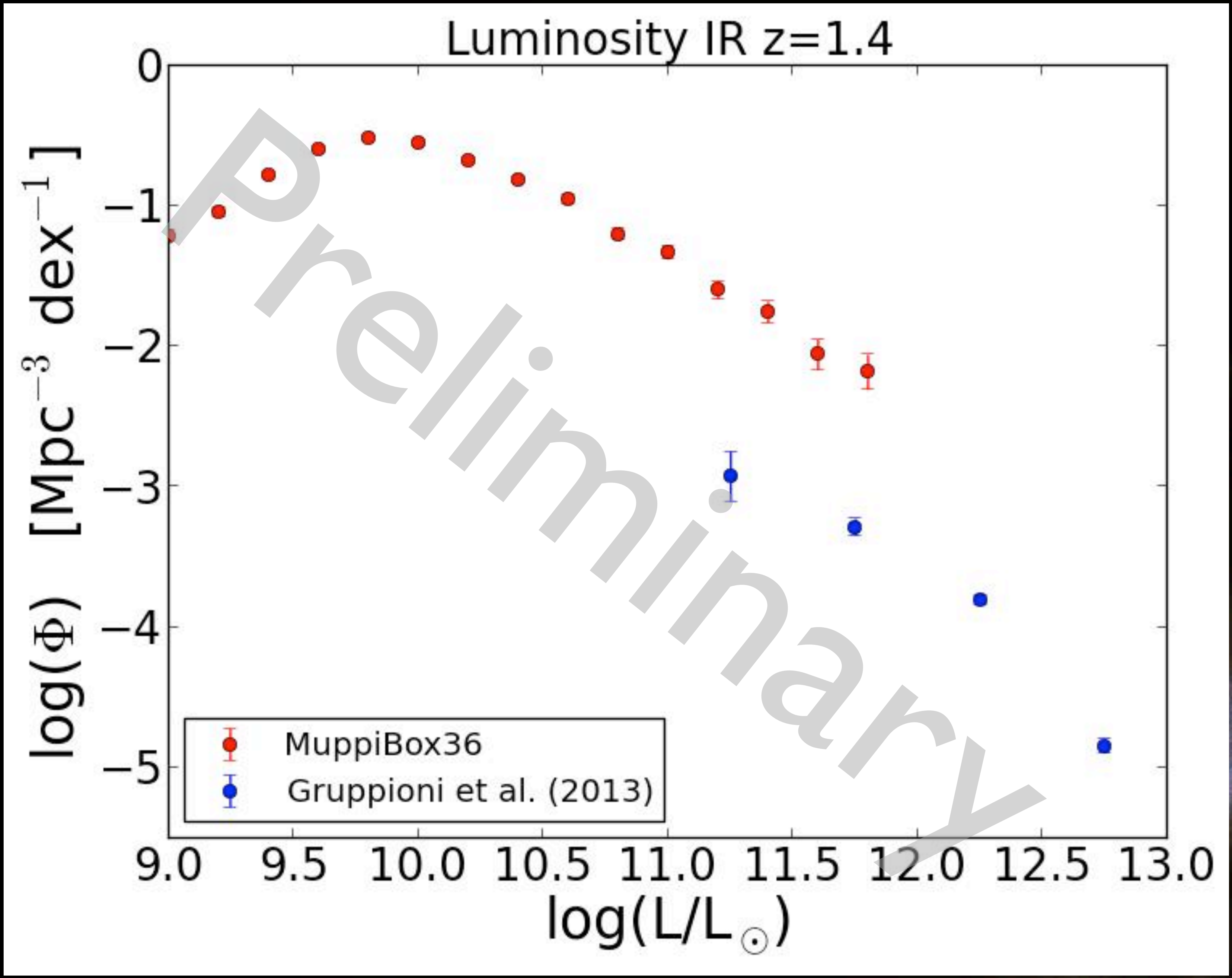
Box size: 25 and 50 Mpc (H_0=72 km/s/Mpc)

N. particles: 2 x 256^3 and 2 x 512^3

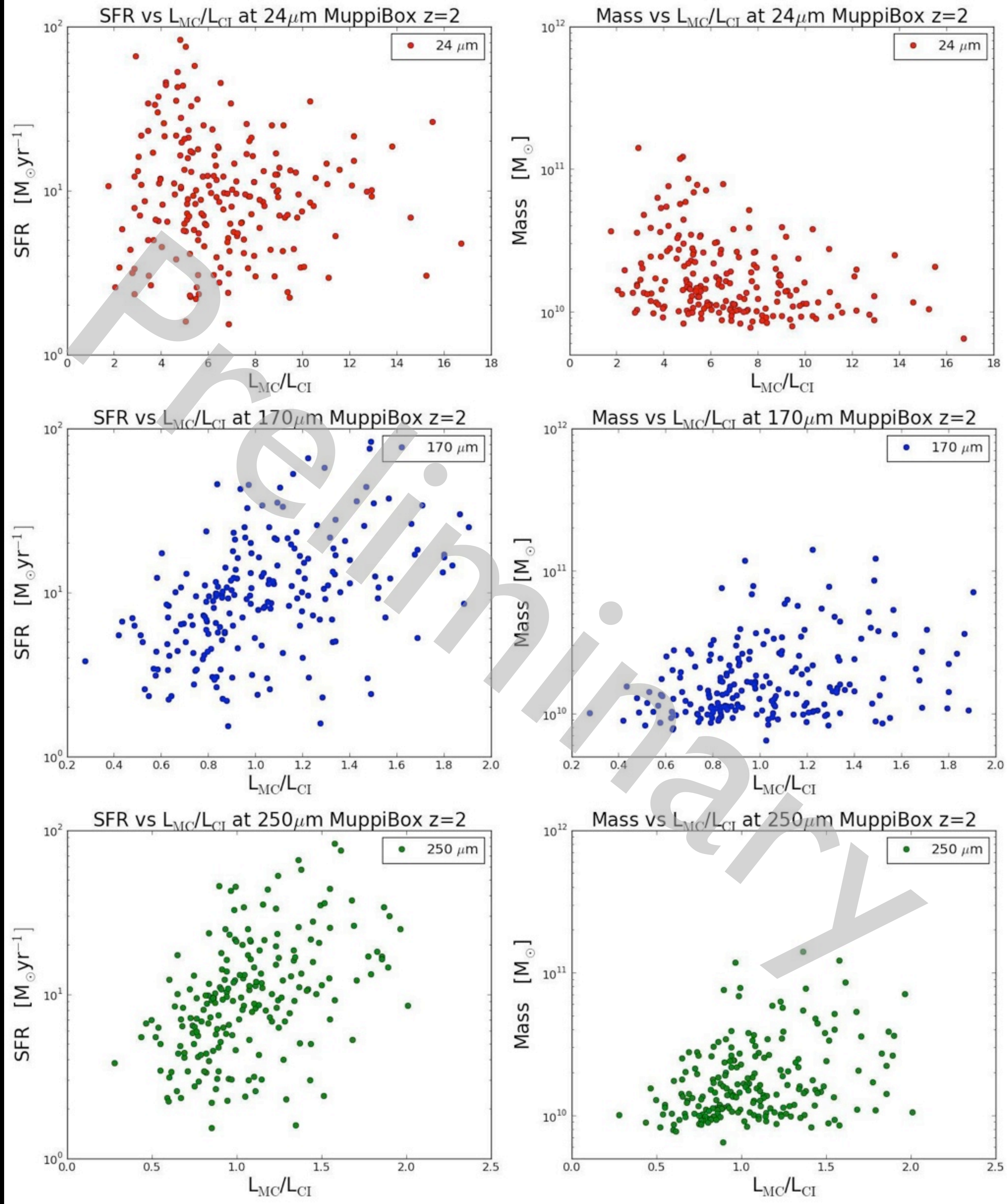
Mgas: 5.4×10^6 M_{sun}

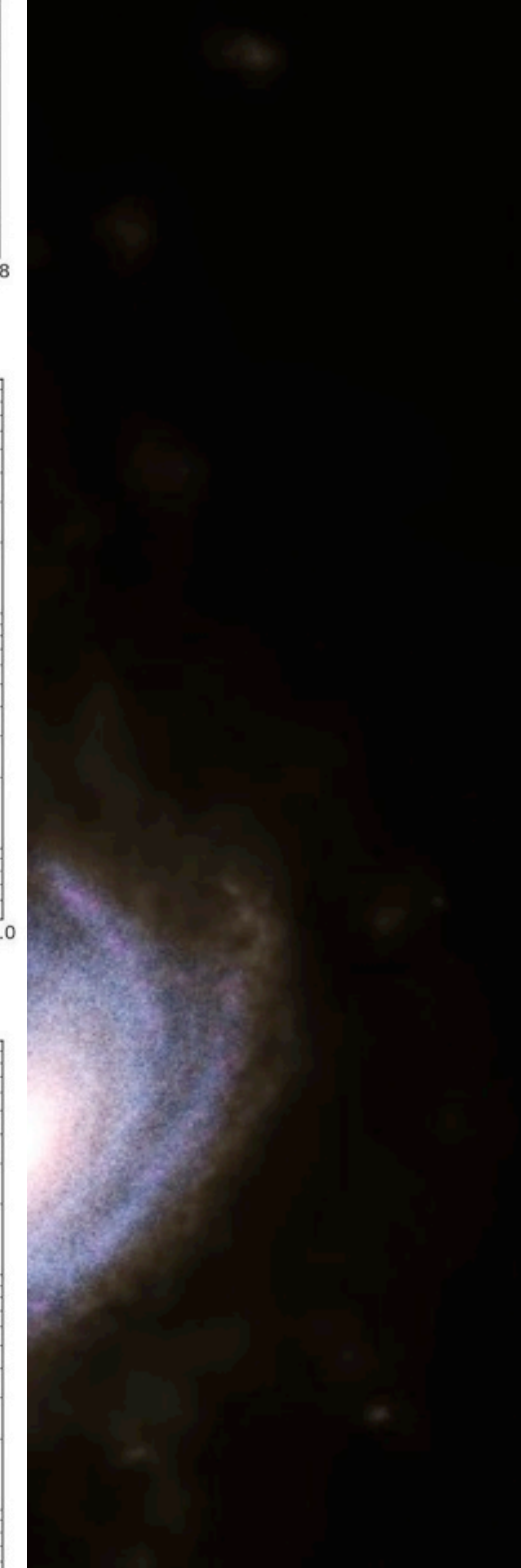
Mstar: 1.3×10^6 M_{sun}

softening: 0.5 physical kpc (comoving for z>5)

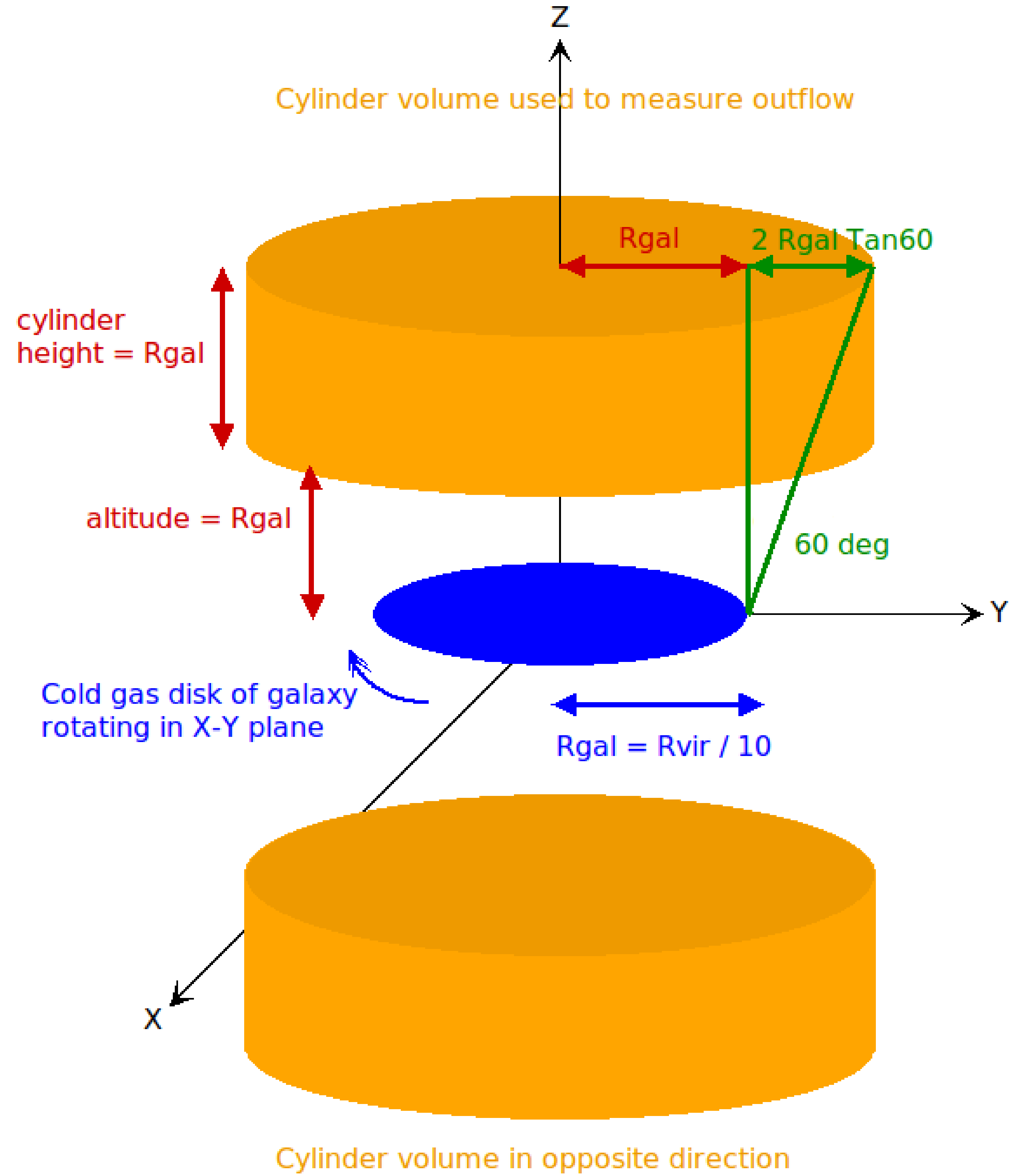


Luminosity IR z=1.4
Preliminary
log(Φ) [Mpc⁻³ dex⁻¹]
0
−1
−2
−3
−4
−5
9.0
9.5
10.0
10.5
11.0
11.5
12.0
12.5
13.0
log(L/L⊙)
MuppiBox36
Gruppioni et al. (2013)


SFR vs L_MC/L_CI at 24μm MuppiBox z=2
Mass vs L_MC/L_CI at 24μm MuppiBox z=2
SFR vs L_MC/L_CI at 170μm MuppiBox z=2
Mass vs L_MC/L_CI at 170μm MuppiBox z=2
SFR vs L_MC/L_CI at 250μm MuppiBox z=2
Mass vs L_MC/L_CI at 250μm MuppiBox z=2
24 μm
170 μm
250 μm
SFR [M☉yr⁻¹]
Mass [M☉]
L_MC/L_CI
Preliminary



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



- ➢ Transform galaxy coordinates s.t. cold gas disk is rotating in X-Y plane

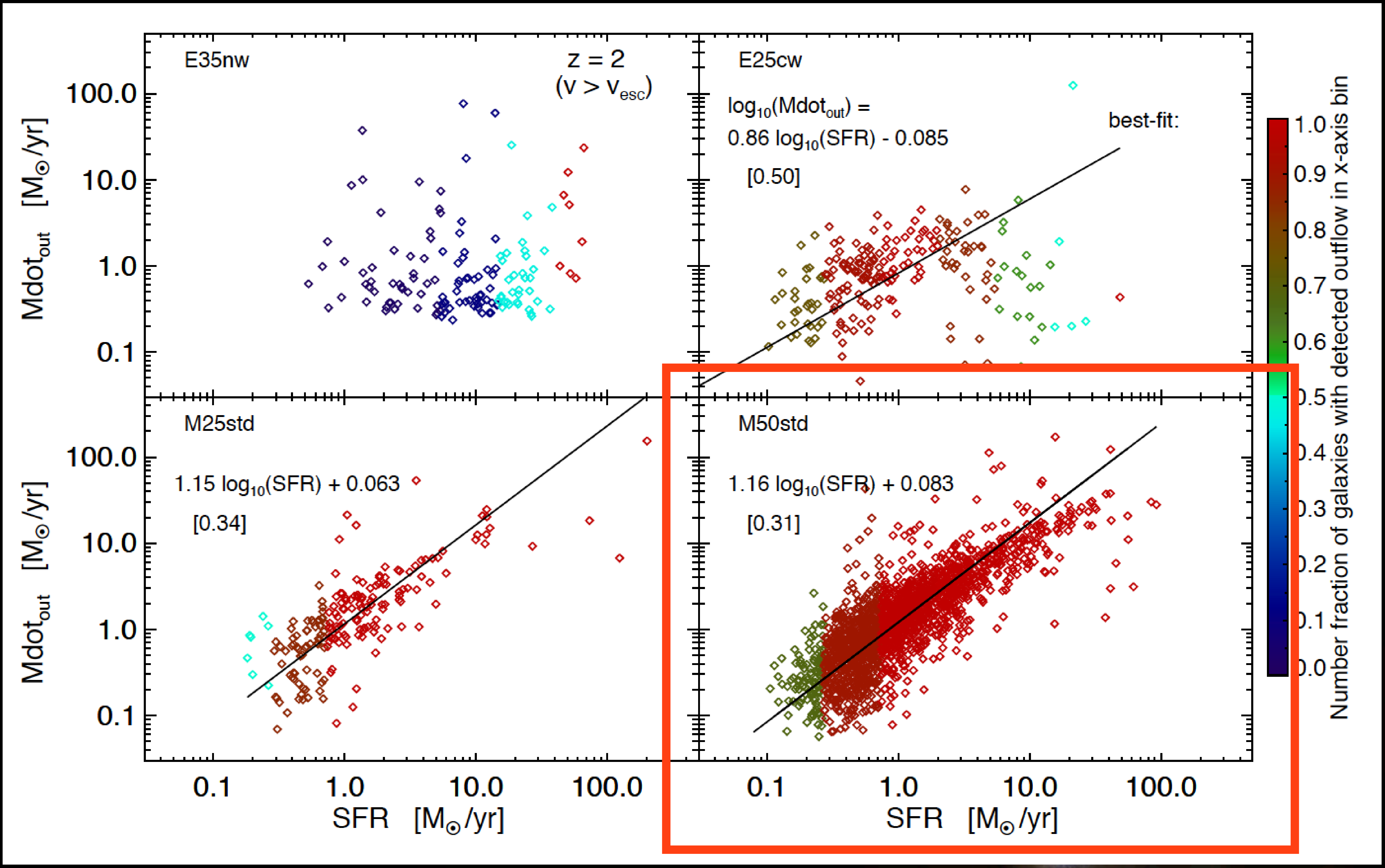
- ➢ Select gas particles:

- • 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

Mass outflow rate vs. galaxy SFR



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How can we “measure” these outflows through gas lines?

Approximate procedure

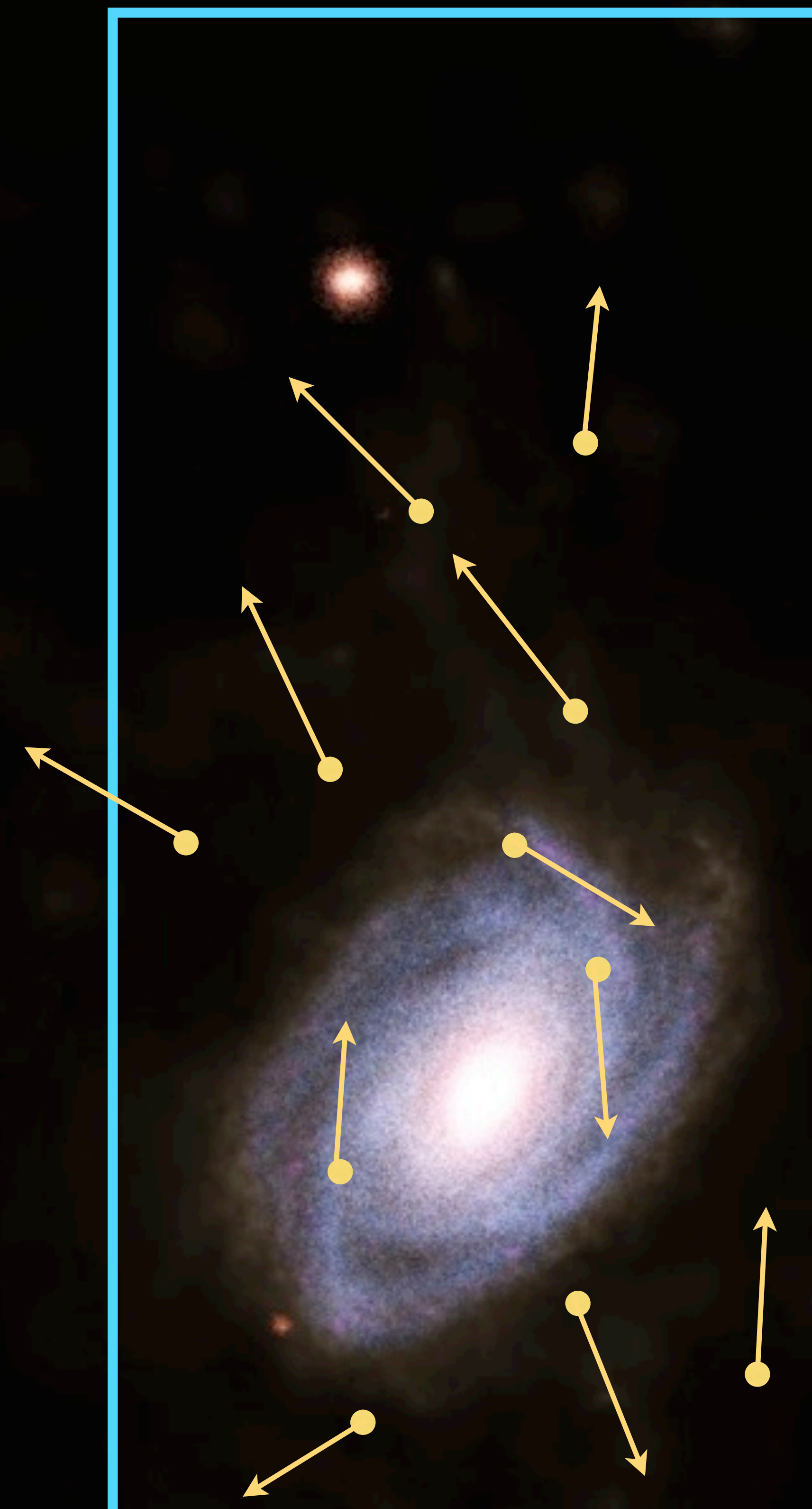
Choose the three box axes as three (random) lines of sight

Select gas particles that would contribute to some line

- molecular phase of MP particles → molecular emission lines
- warm (<10^5 K) single-phase particles → atomic absorption lines

Draw histogram of velocities

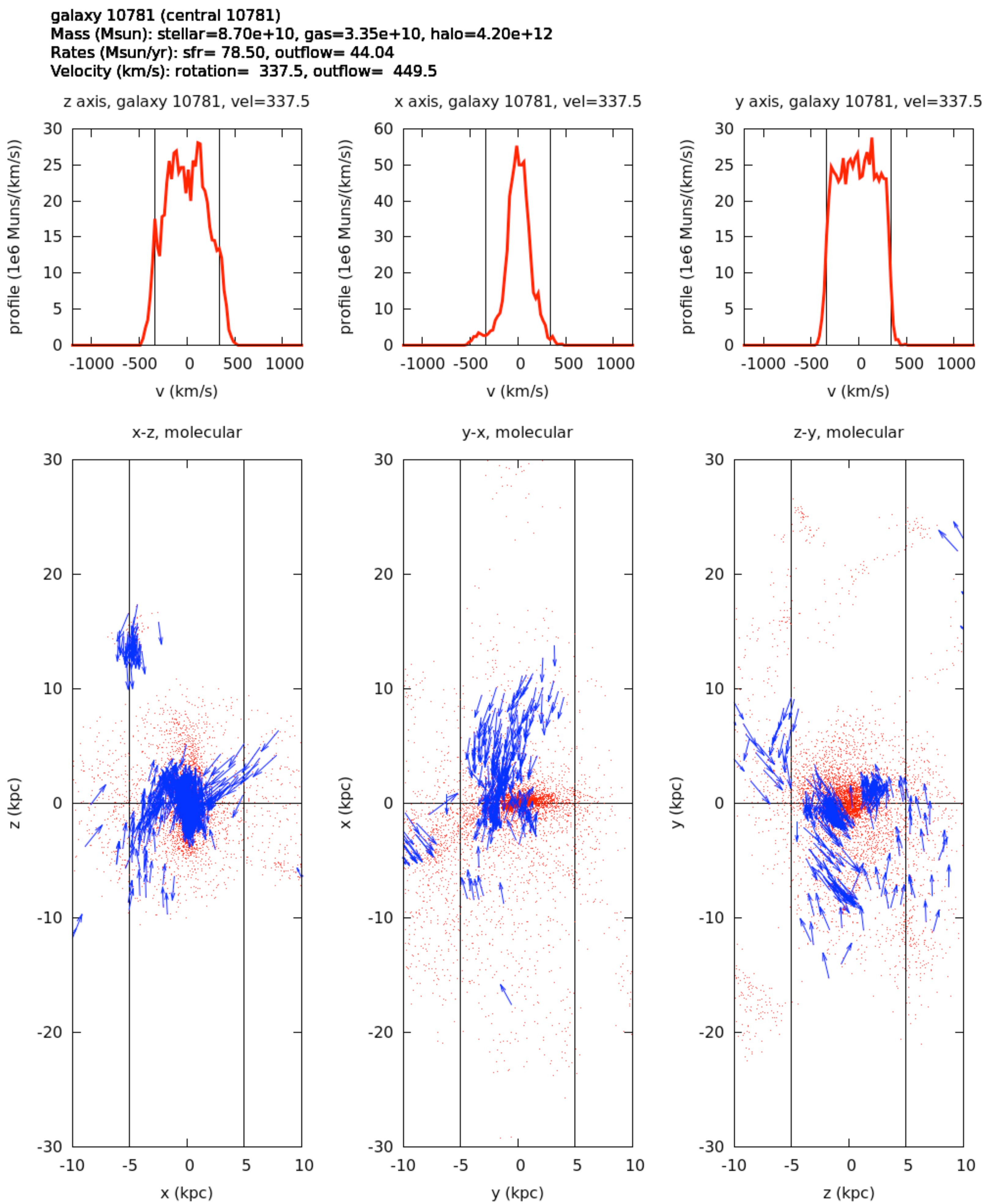
- across the galaxy for molecular emission lines
- on one side of the galaxy for atomic absorption lines



Red: multi-phase particles

Blue: velocity of "fast" particles

line of sight

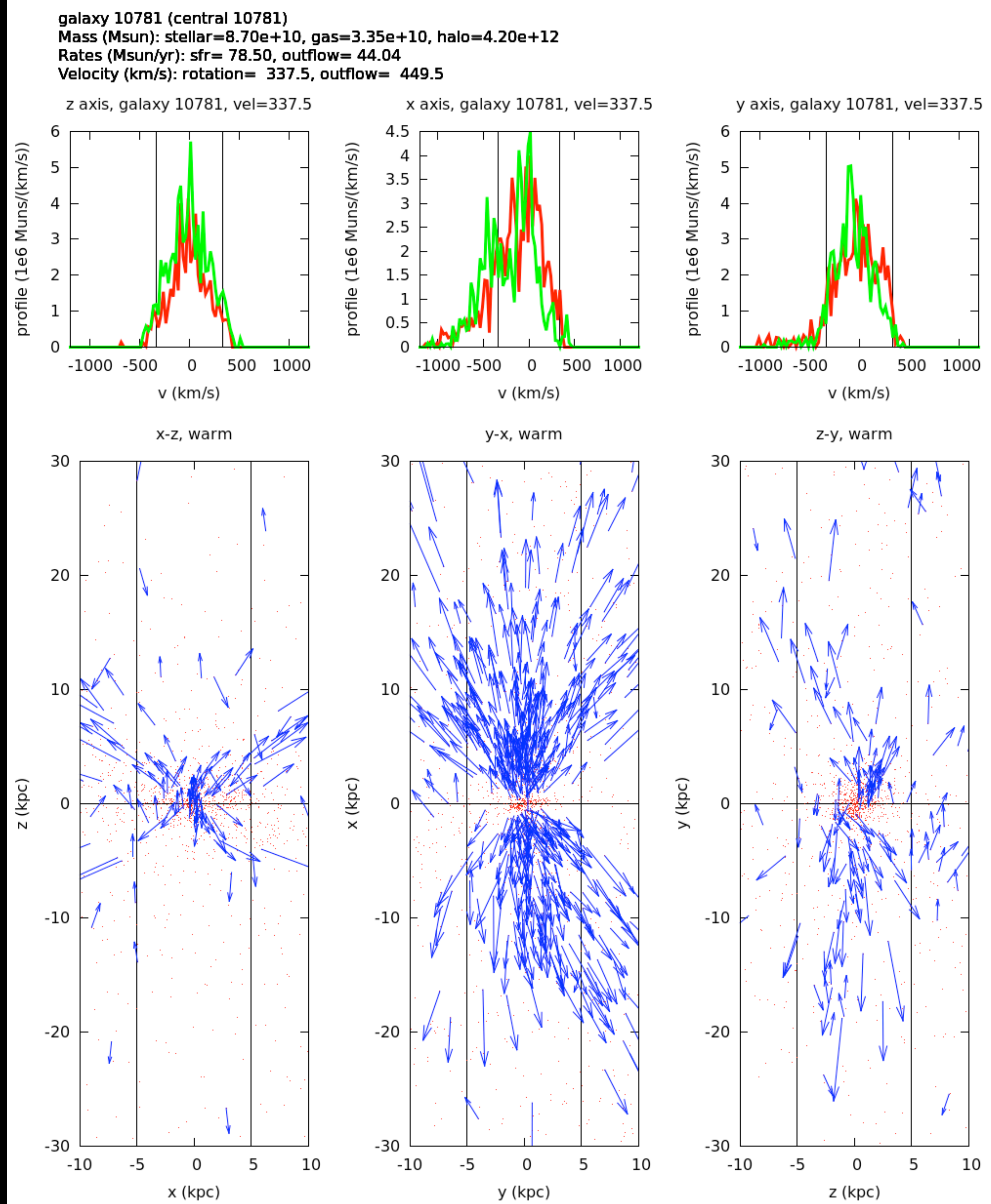


molecular emission lines

Bologna, 2015

Red: single-phase particles
Blue: velocity of "fast" particles

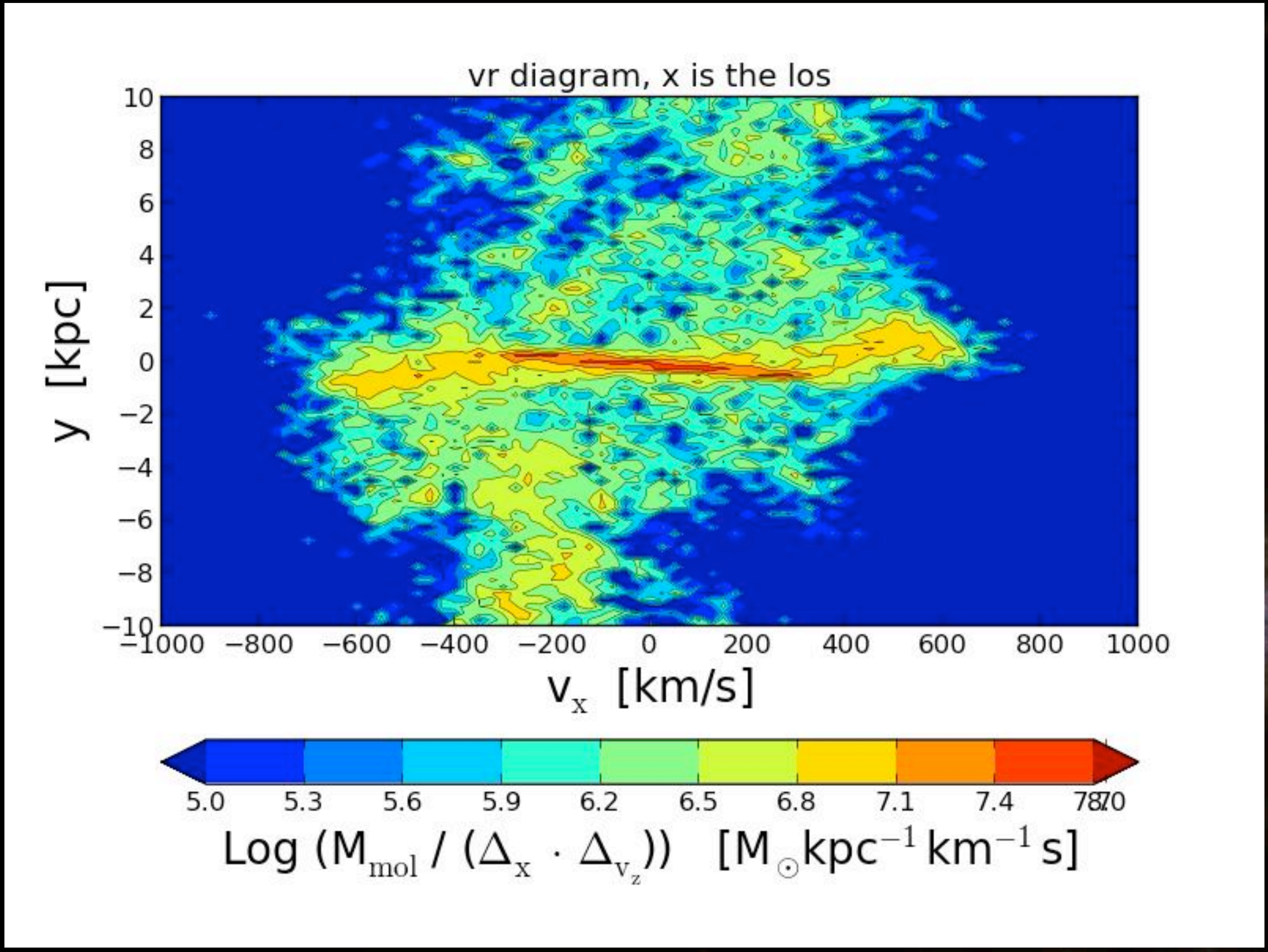
line of sight



atomic absorption lines

Bologna, 2015

A molecular outflow? a false positive!



Summing up

Simulation program to follow the formation of galaxies:

- extension to IR/radio thanks to GRASIL3D
- in progress: detailed treatment of molecular cooling → prediction of molecular lines
- in progress: AGN feedback, improved SPH

Outflows:

- molecular outflows are hardly produced without AGN feedback
- gas absorption lines on stellar continuum are a better probe
- molecular lines can produce false positives