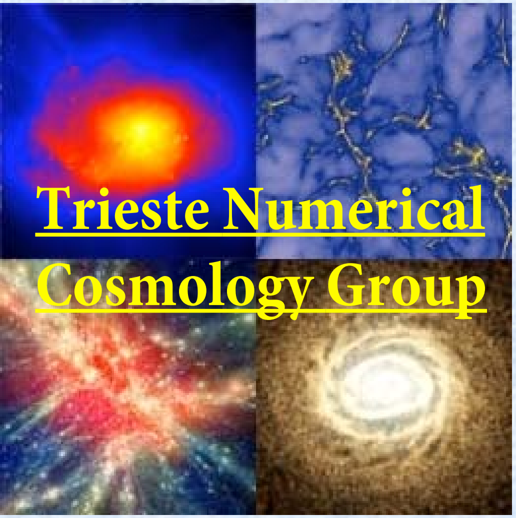
Gas Outflow/Inflow versus Star-formation Correlations of Cosmologically Simulated Galaxies



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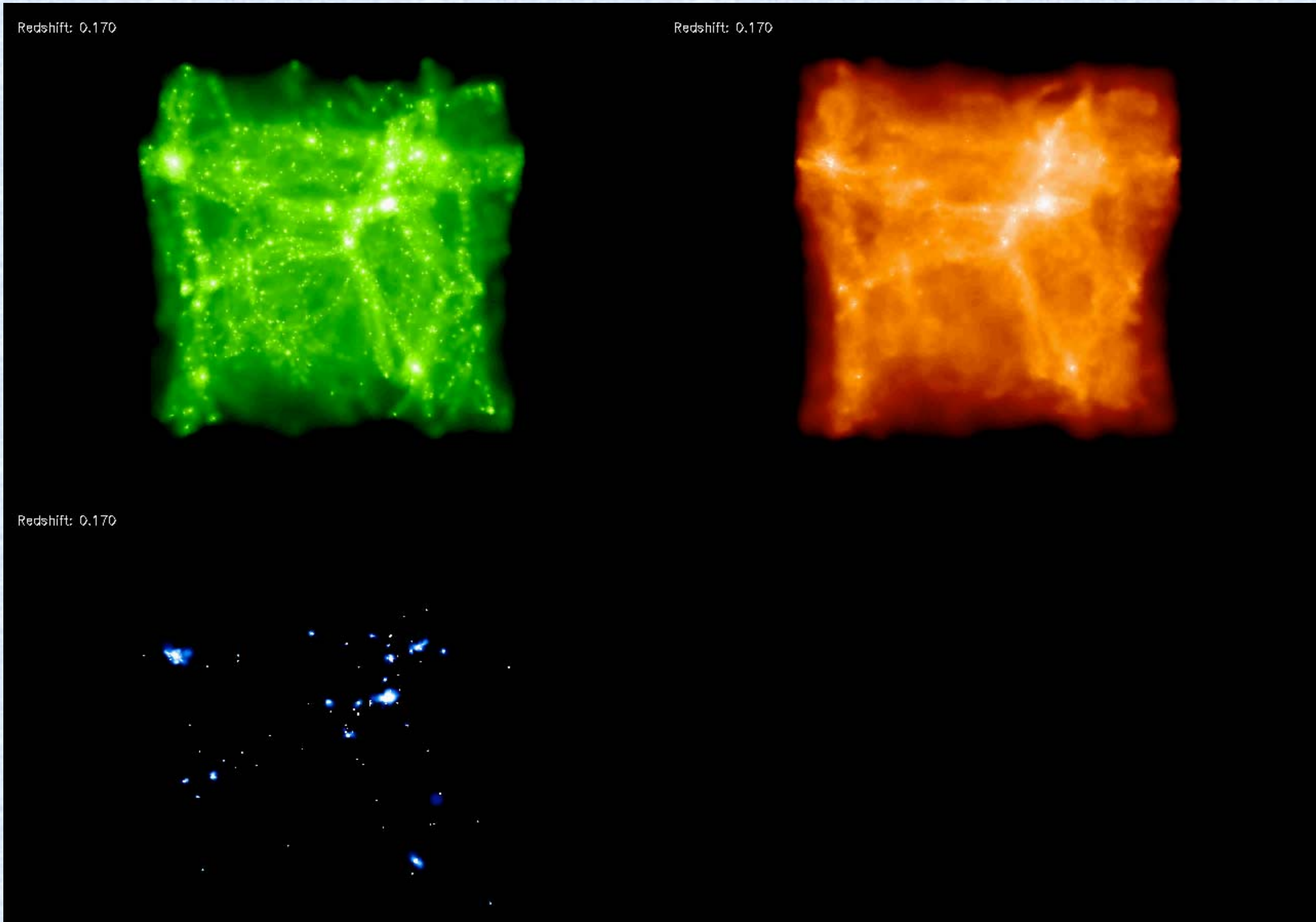
- Our work: few 10s Mpc side cosmological volume.
- Enable us to study:
  - ✓ effect of Mpc-scale power fluctuations during structure formation
  - ✓ effect of cosmological large-scale events like galaxy mergers
  - ✓ statistical populations of galaxy populations over a mass range
- Complementary to high-resolution, isolated galaxy sims.



Large-scale filaments.

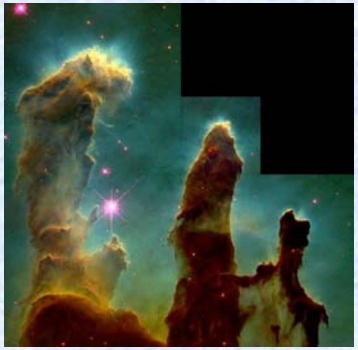
(7 Mpc)[3] box at low-z.

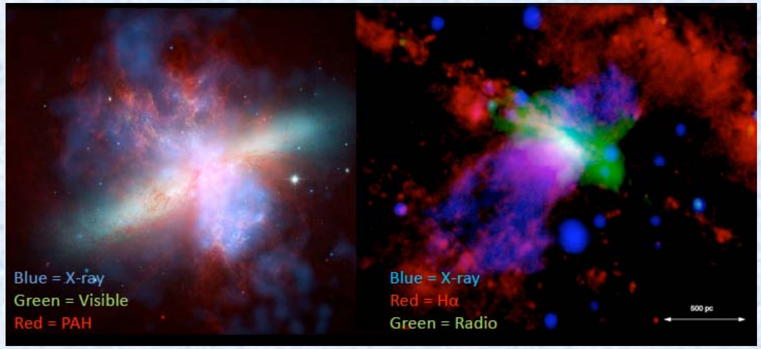
Dark matter - green,

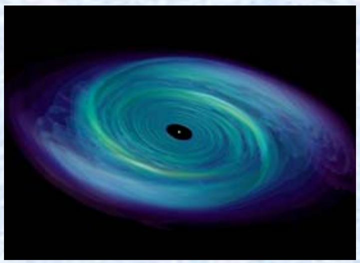
Gas - red,

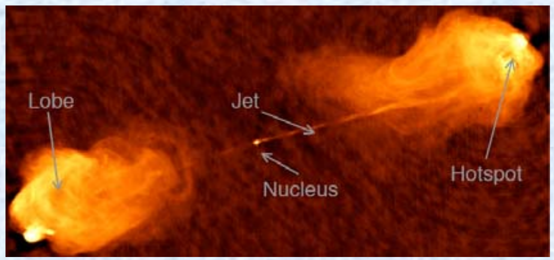
Stars - blue

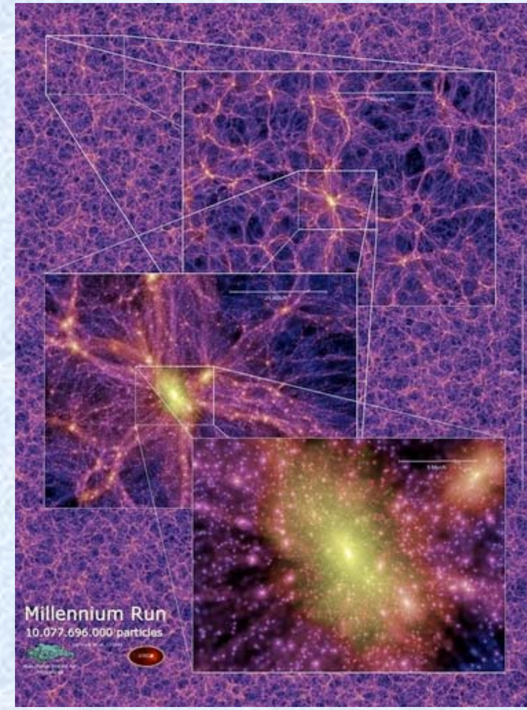
Why Sub-Resolution Models ?











Physics of baryons

- Radiative cooling and (photo + collisional) ionization heating of gas
- Fragmentation, clumping, multiphase ISM
- Star formation
- Metal production & chemical enrichment
- SN feedback, galactic wind
- AGN accretion + feedback
- …

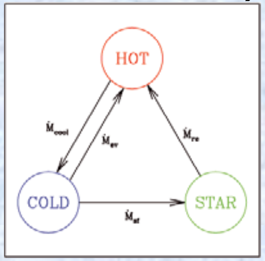
In cosmological hydrodynamical simulations

(few - 10's Mpc) box : Resolution $\sim 10^6 M_{Sun}$, 1 kpc

- Baryonic physics occur on much smaller scales
- Implemented as sub-resolution models

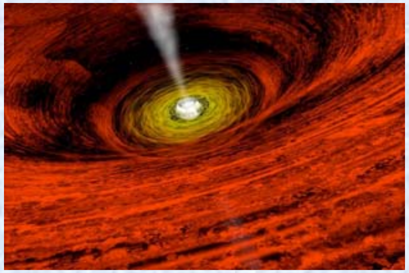
Modified-GADGET3 code: Sub-Resolution Physics

- GADGET3 : TreePM (gravity) - SPH (hydro)
  - Springel 2005, MNRAS, 364, 1105
- Metal-line cooling & radiative heating (Wiersma et al. 2009, MNRAS, 399, 574) in the presence of UV photoionizing background (Haardt & Madau 2001)



- Star Formation
- Stellar & Chemical Evolution (Tornatore et al. 2007, MNRAS, 382, 1050)
  - Metal (C, Ca, O, N, Ne, Mg, S, Si, Fe) release from SN type-II, type-Ia, & AGB stars; stellar age, mass & yield; different IMF; mass & metal loss from starburst

- SN Feedback
  - Thermal feedback (↑ T) : inefficient, energy radiated away quickly
  - ∴ Kinetic feedback (↑ v)
- AGN accretion + feedback



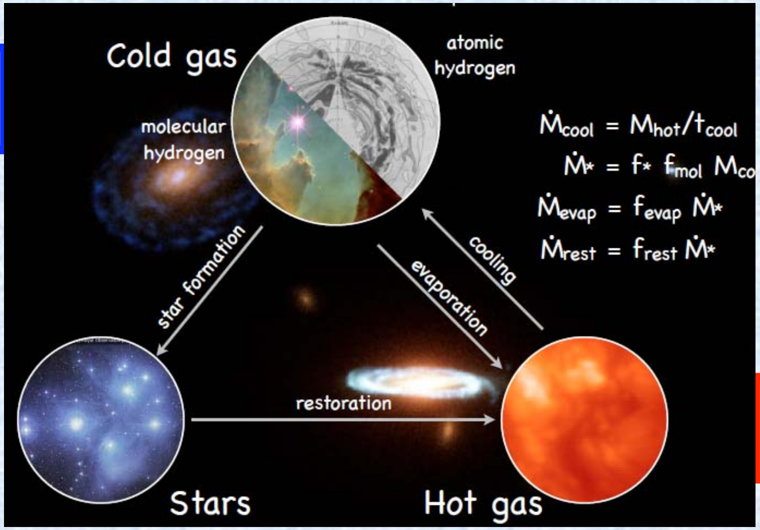
Star-Formation in Multiphase ISM: MUPPI model

- High-density SPH particle represents a part of ISM
  - Composed of 2 gas phases & stars

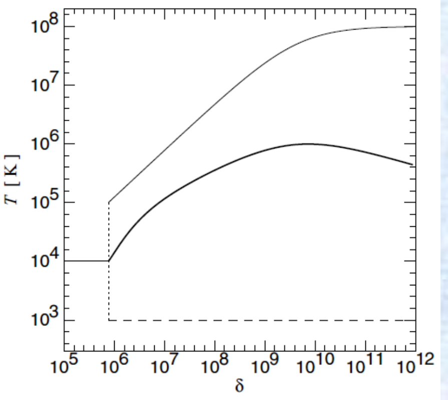
$$\rho > \rho_{SF,th}$$

COLD gas

STARS



HOT gas



- Effective model *(Springel & Hernquist 2003)*
  - Equilibrium solution
  - Self-regulated SF: constant effective pressure
- MUPPI = MUlti-Phase Particle Integrator *(Murante et al. 2010)*
  - Molecular fraction of gas ∝ Pressure
  - Mass & energy flows between components explicitly followed by numerically integrating system of ODEs within SPH timestep

Existing Models of SN Feedback

- Kinetic feedback : give velocity kick to gas
  - Energy-driven wind
    - Springel & Hernquist (2003)

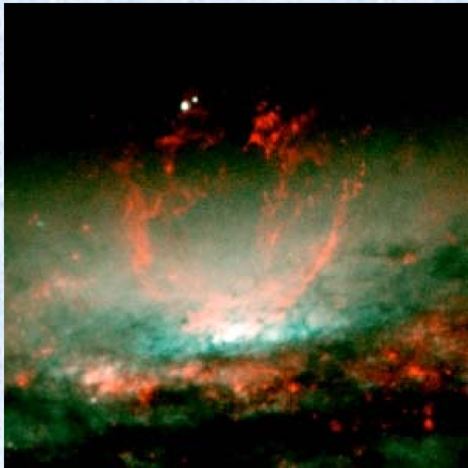
$$v_w, \eta = \text{constant}$$

$$v_w = 3\sigma\sqrt{\frac{L}{L_{crit}} - 1}$$

Most of the models assume that wind velocity and mass-loading scales with some global galaxy property (mass, velocity dispersion, SFR)

  - Radially-varying wind velocity
    - Barai et al. (2013)
  - Combinations & variations of energy and momentum-driven
    - Schaye et al. (2010)
    - Dave et al. (2013)
    - Volgelsberger et al. (2014)

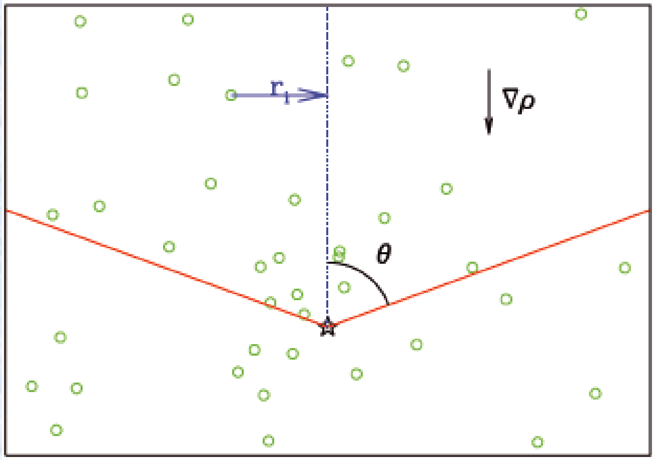
- Thermal feedback : increase gas temperature
  - Dalla Vecchia & Schaye (2012), Schaye et al. (2014)
- Turn off radiative cooling
  - Stinson et al. (2006)
- …



P. Barai, INAF-OATs

SN Energy Feedback in MUPPI *(Murante et al. 2015)*

- Energy imparted to gas particles
  - Inside SPH smoothing length and cone with semi-aperture angle = 60^o
  - Along path of least resistance
    - Negative density gradient



- Direct distribution of
  - Thermal energy
    - Efficiency fraction
    - Injected to local hot phase
  - Kinetic energy
    - Efficiency fraction, Probability

$$E_{th} = E_{SN} f_{fb,th} \frac{\Delta M_*}{M_{*,SN}}$$

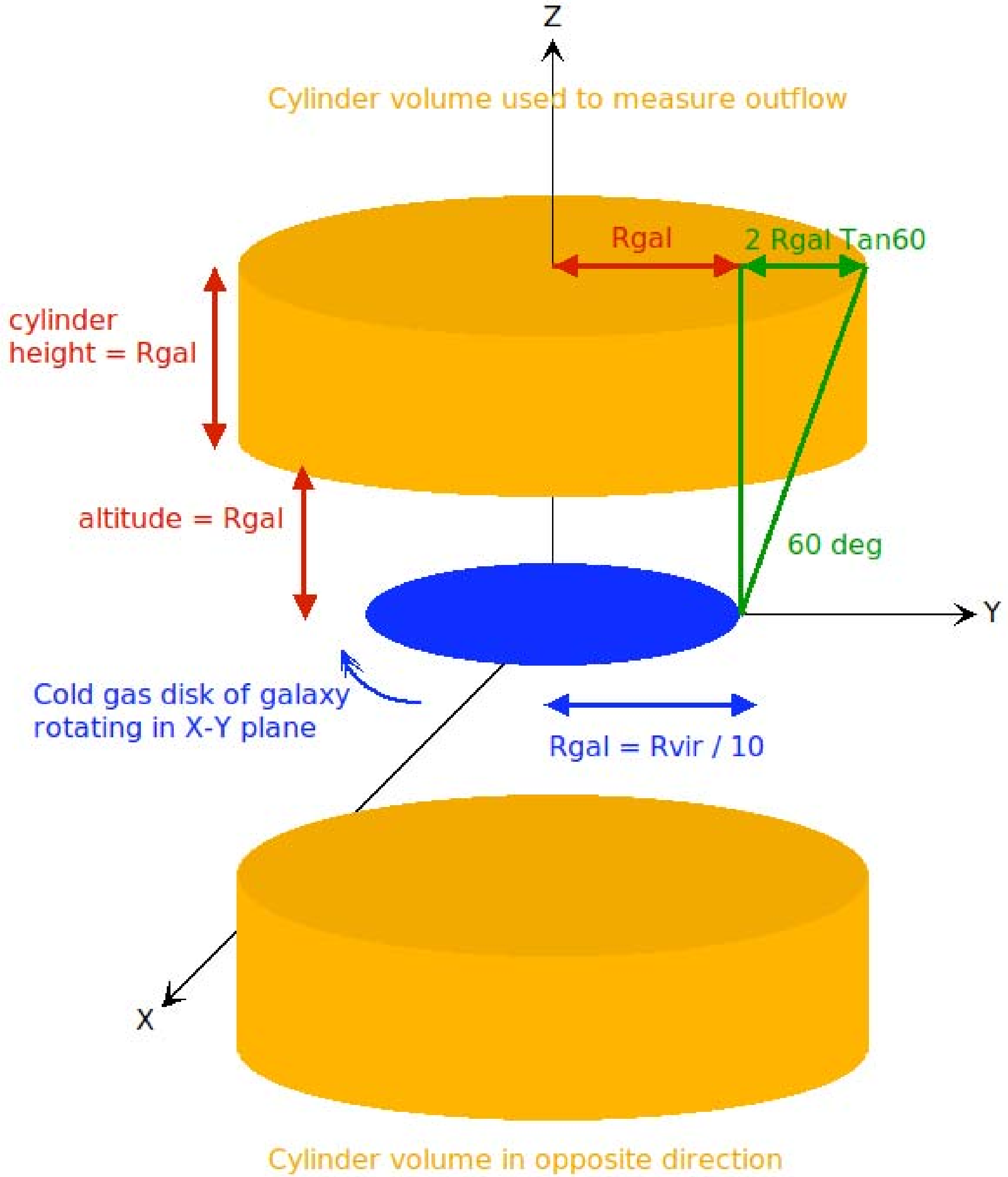
$$E_{kin} = E_{SN} f_{fb,kin}$$

- No direct input expression of wind velocity & outflow mass loading

Simulation Runs (Barai et al. 2015)

Run Name	$L_{\rm box}$ [Mpc]	$N_{\rm part}$	$m_{\rm gas}$ [$M_{\odot}$]	$m_{\star}$ [$M_{\odot}$]	$L_{\rm soft}$ [kpc]	SF & SN feedback sub-resolution physics: Model	v_w	$f_{\rm fb,out}$	$f_{\rm fb,kin}$	$P_{\rm kin}$
E35nw	35.56	2×320^3	8.72×10^6	2.18×10^6	2.77 (comoving)	Effective	0			
E35rvw	35.56	2×320^3	8.72×10^6	2.18×10^6	2.77 (comoving)	Effective	$v_w(r)$			
E25cw	25	2×256^3	5.36×10^6	1.34×10^6	0.69 (physical)	Effective	350			
M25std	25	2×256^3	5.36×10^6	1.34×10^6	0.69 (physical)	MUPPI		0.2	0.6	0.03
M25a	25	2×256^3	5.36×10^6	1.34×10^6	0.69 (physical)	MUPPI		0.4	0.4	0.03
M25b	25	2×256^3	5.36×10^6	1.34×10^6	0.69 (physical)	MUPPI		0.2	0.8	0.03
M25c	25	2×256^3	5.36×10^6	1.34×10^6	0.69 (physical)	MUPPI		0.2	0.6	0.01
M25d	25	2×256^3	5.36×10^6	1.34×10^6	0.69 (physical)	MUPPI		0.2	0.6	0.06
M50std	50	2×512^3	5.36×10^6	1.34×10^6	0.69 (physical)	MUPPI		0.2	0.5	0.03

Outflow measurement technique



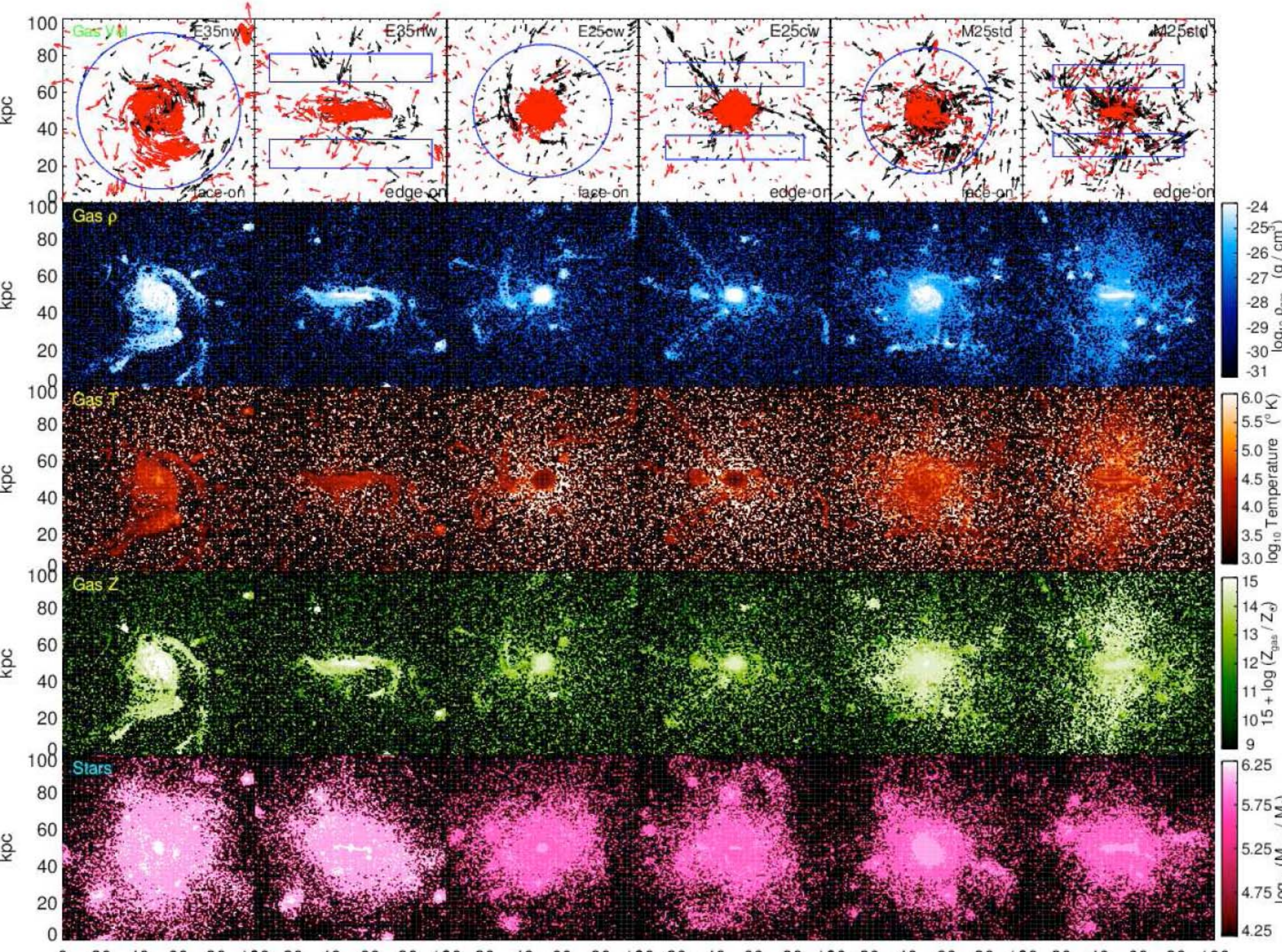
➢ Transform galaxy coordinates s.t. cold gas disk is rotating in X-Y plane

➢ Select gas particles:

- lying inside either cylinder
- moving at a high-velocity, $|v_z| > V_{limit,outflow}$

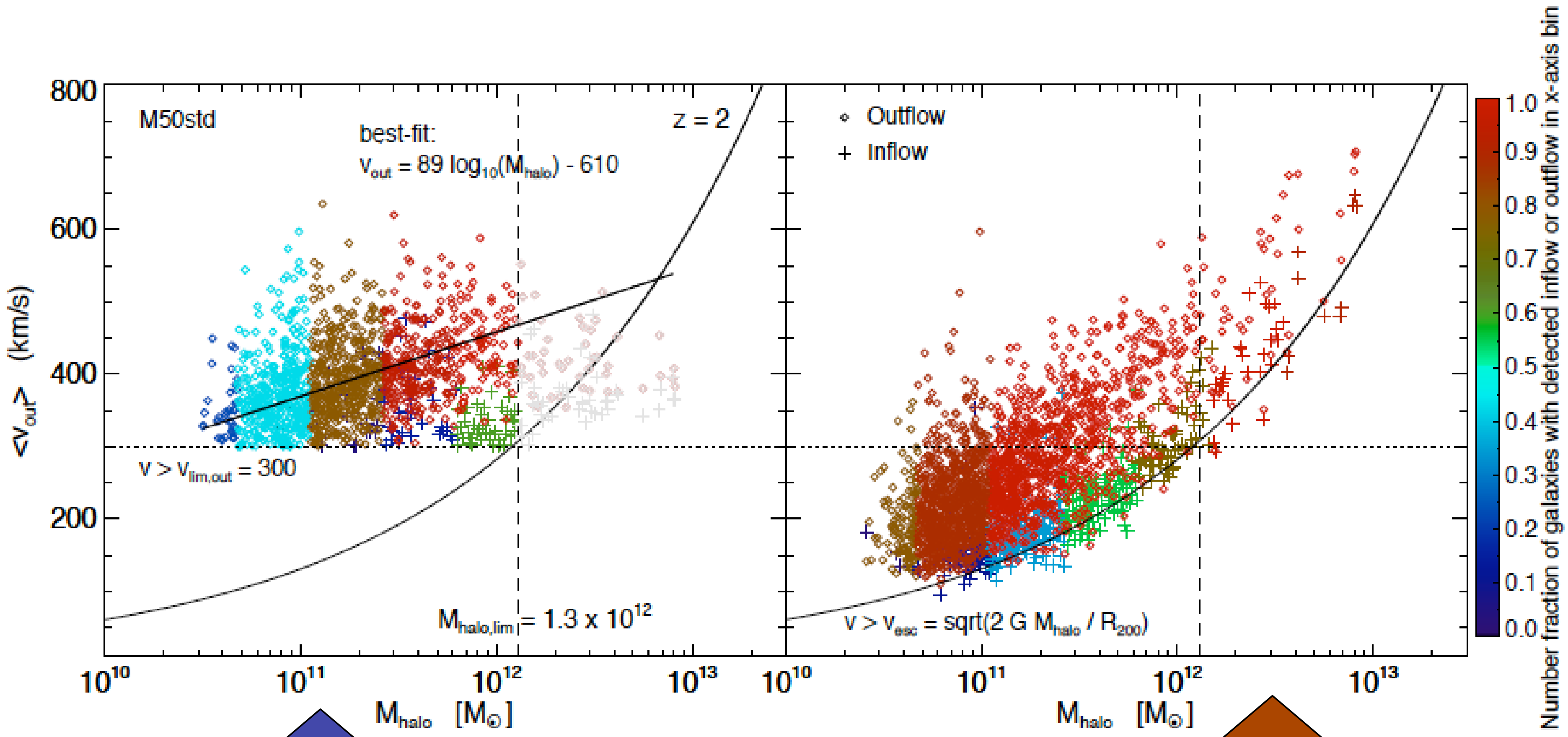
▪ if $(z*v_z > 0) \Rightarrow$ Outflow

▪ if $(z*v_z < 0) \Rightarrow$ Inflow



Gas Vel
E35nw
E35nw
E25cw
E25cw
M25std
M25std
face-on
edge-on
face-on
edge-on
face-on
edge-on
Gas ρ
Gas T
Gas Z
Stars
kpc
log₁₀ Temperature (°K)
15 + log (Z_gas / Z☉)

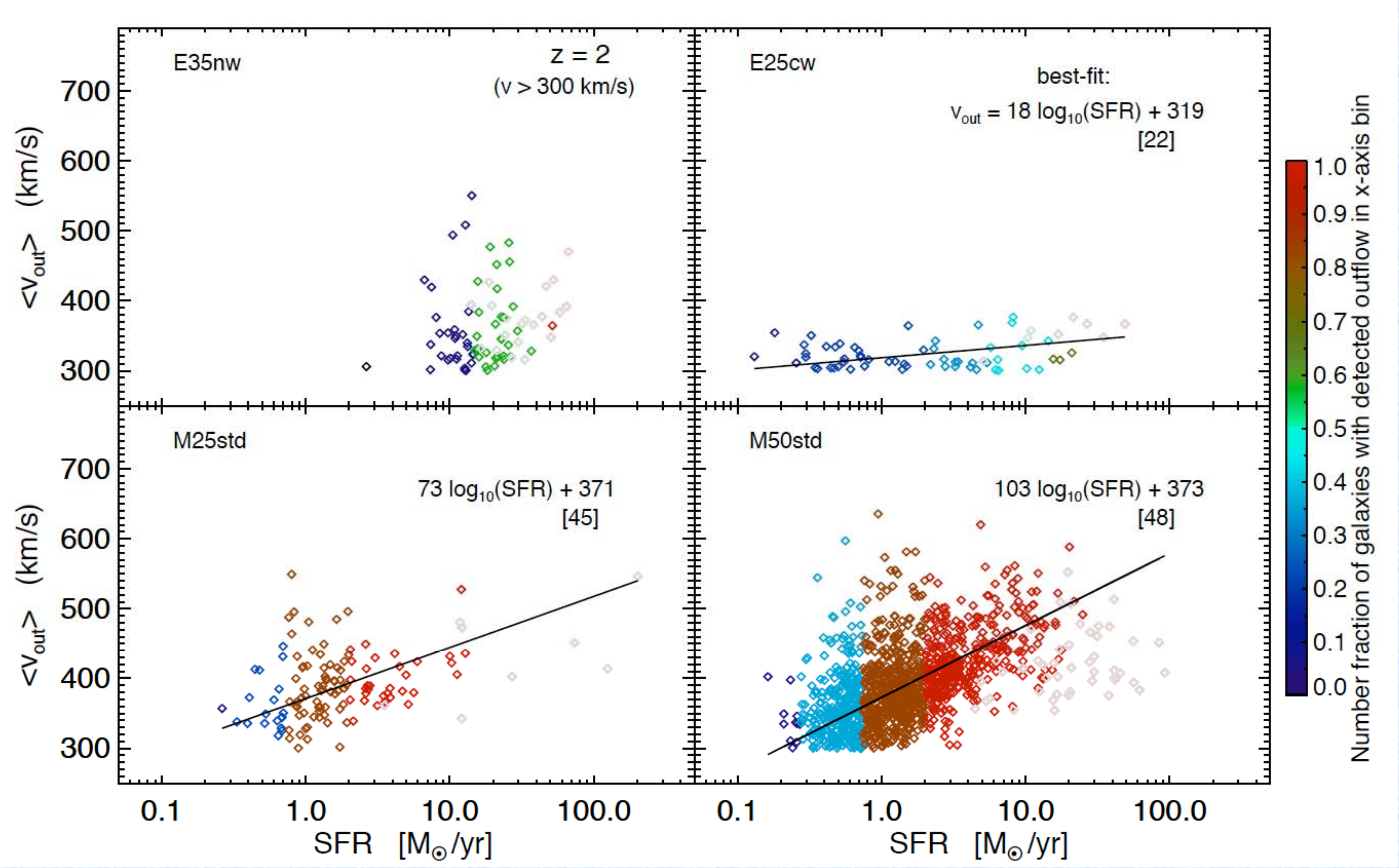
Setting the lower velocity threshold for outflow measurement



Fixed value:
Reveals correlations.
Adopt this for
outflow velocity

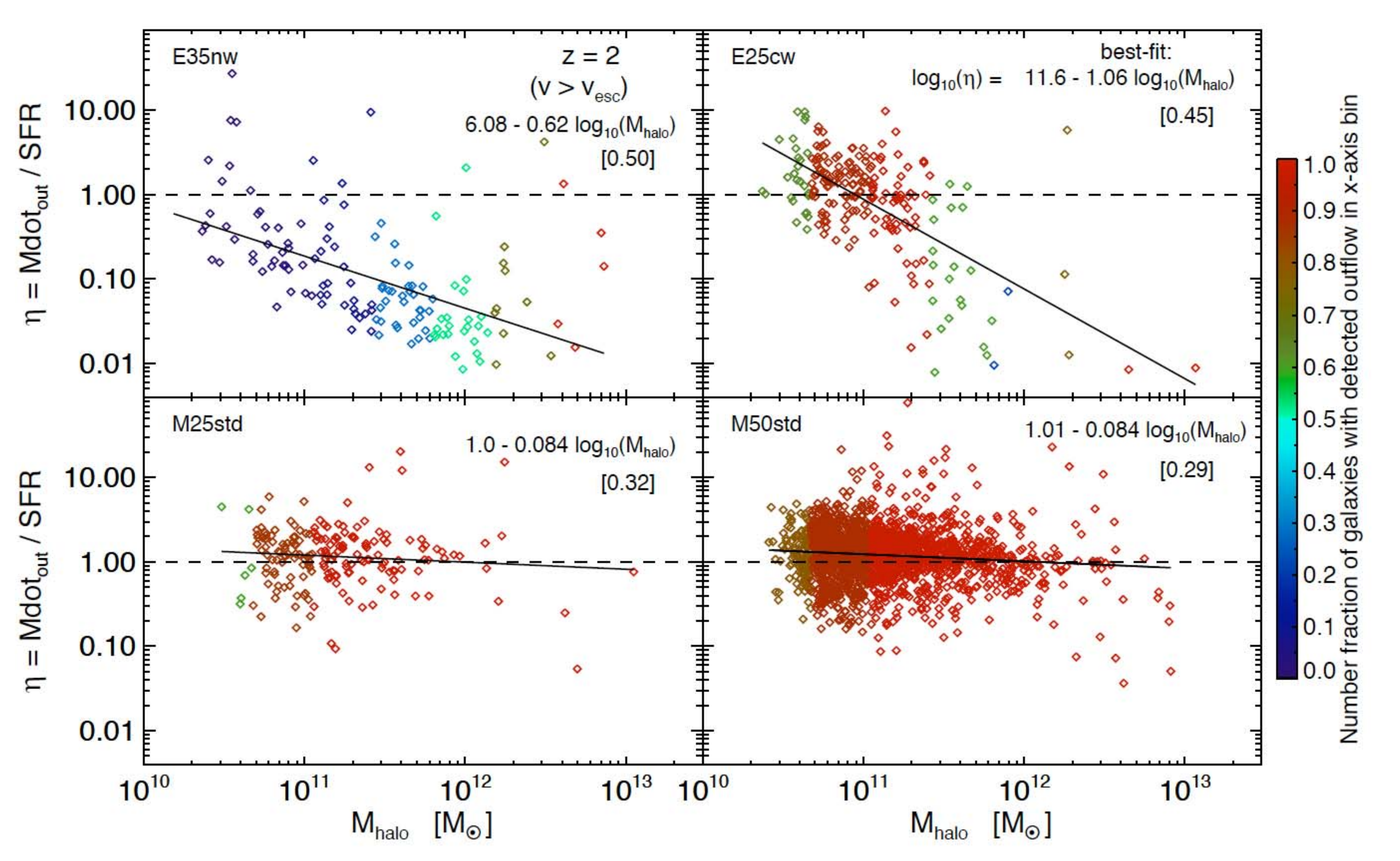
Escape velocity:
Measures escape outside halo
Adopt this for
mass outflow rate

Outflow velocity vs. galaxy SFR

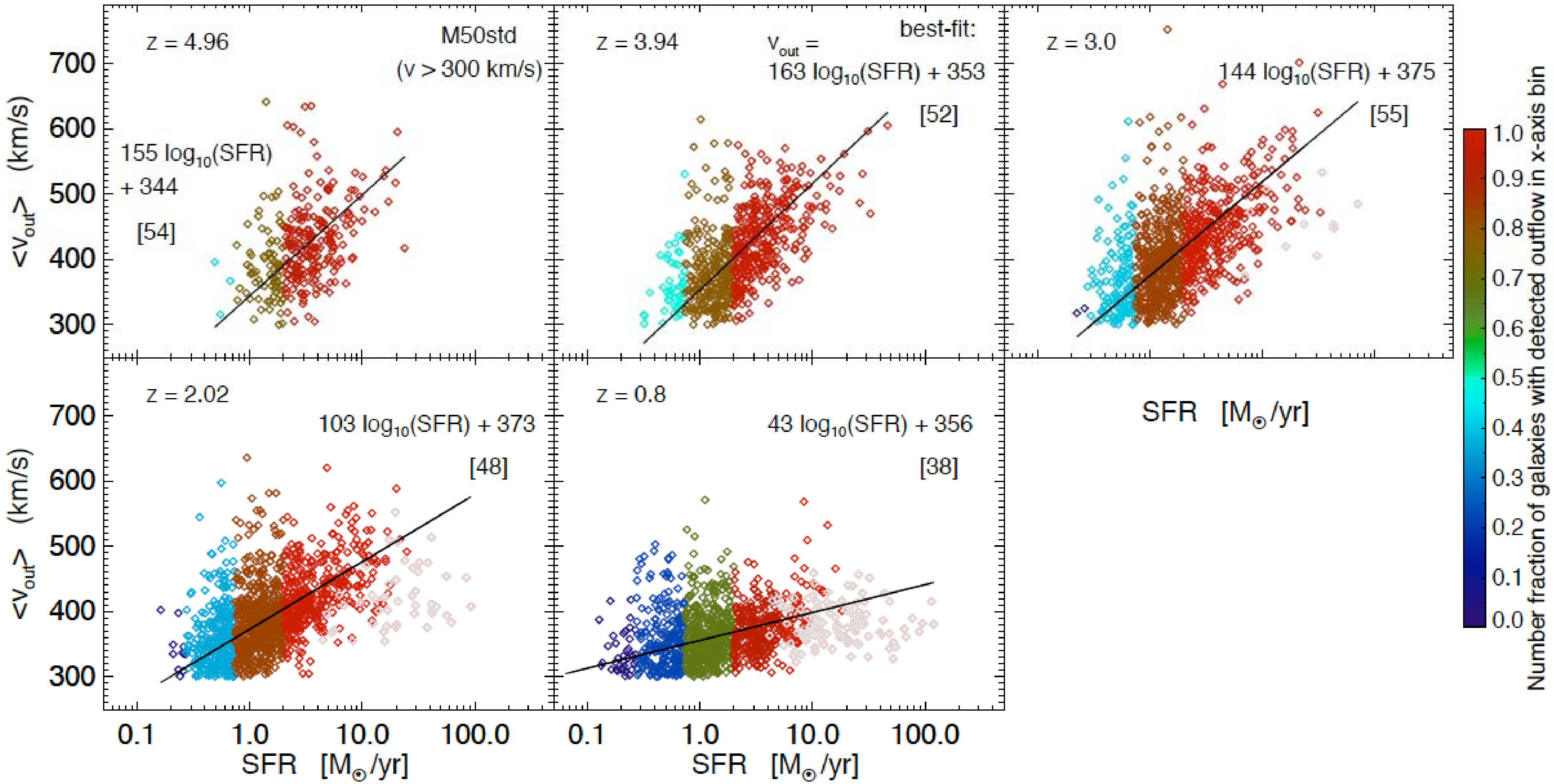


Observation : Martin (2005), Grimes et al. (2009), Banerji et al. (2011), Bordoloi et al. (2013)
- positive correlation of outflow speed with galaxy mass and SFR.

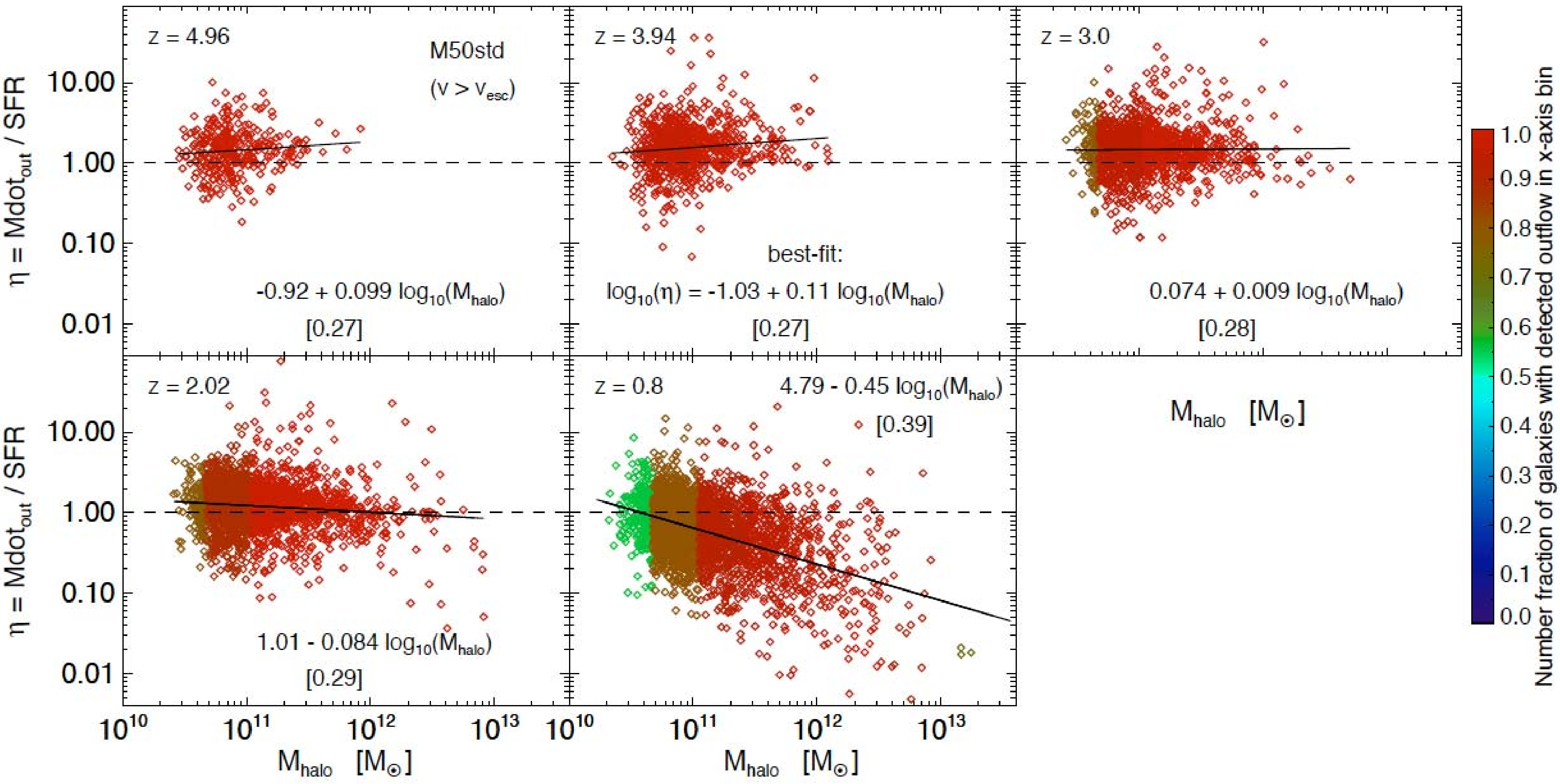
Mass loading factor (η = Mass outflow rate / SFR) vs. halo mass



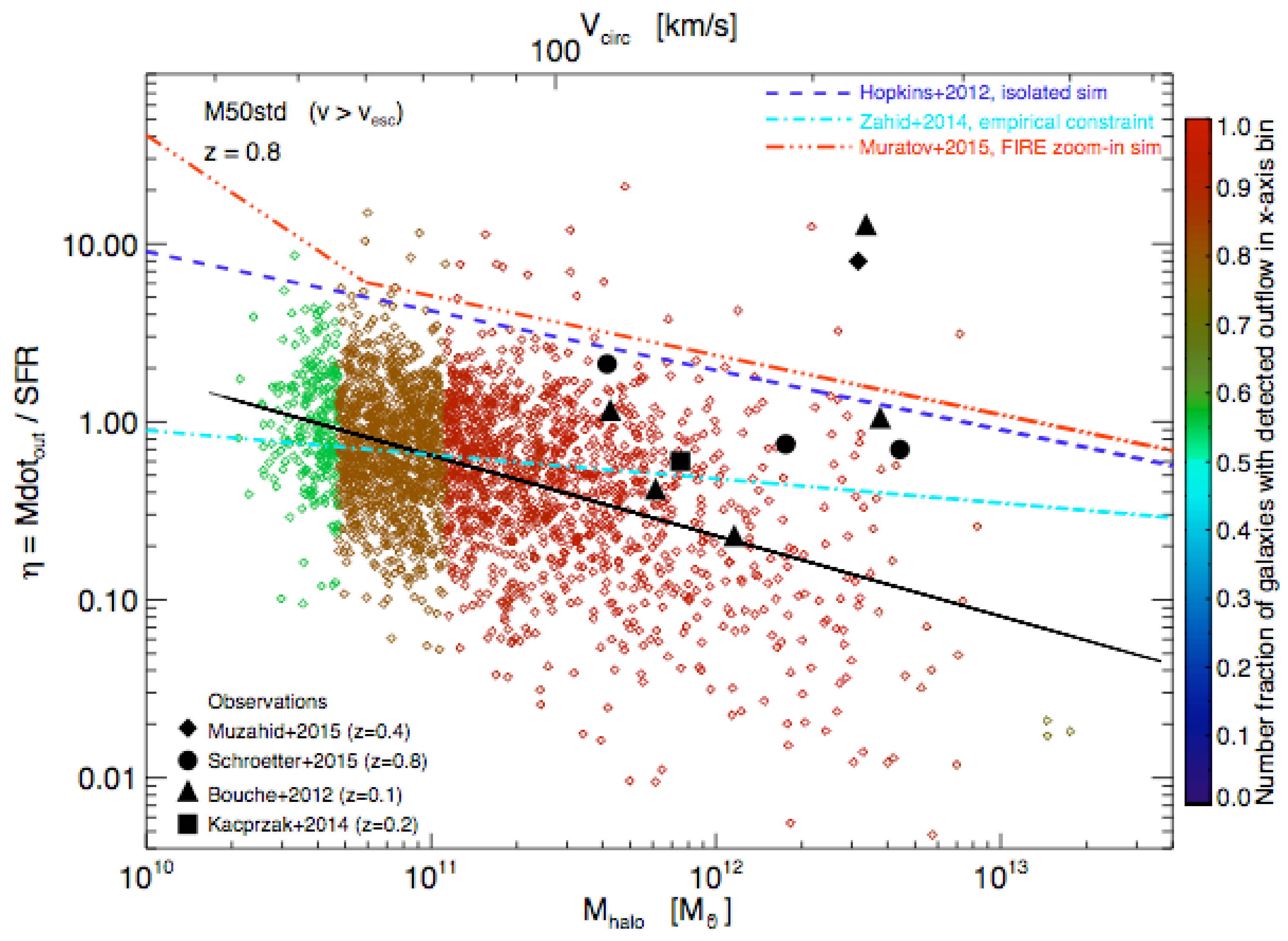
Redshift Evolution of Outflow Velocity vs SFR



Redshift Evolution of Mass-Loading factor vs Halo Mass

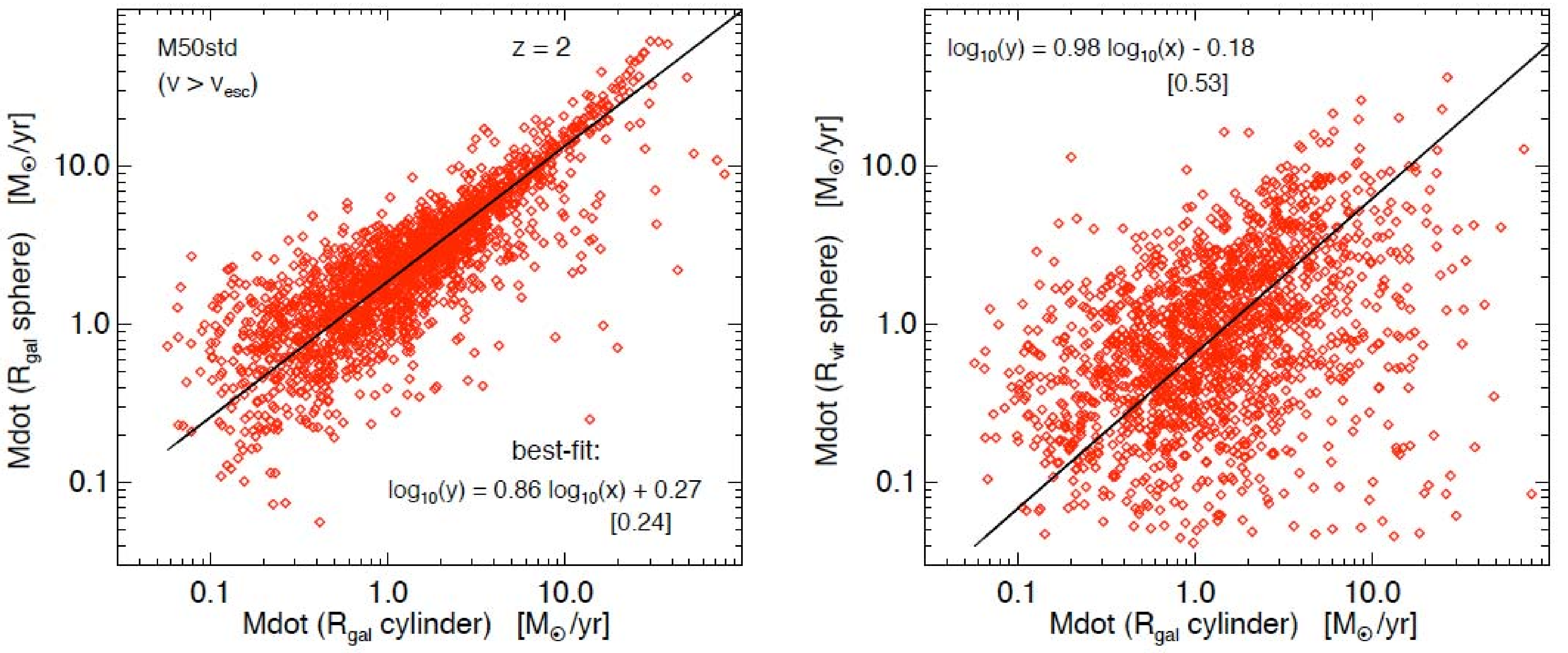


Mass-Loading factor comparison with other studies



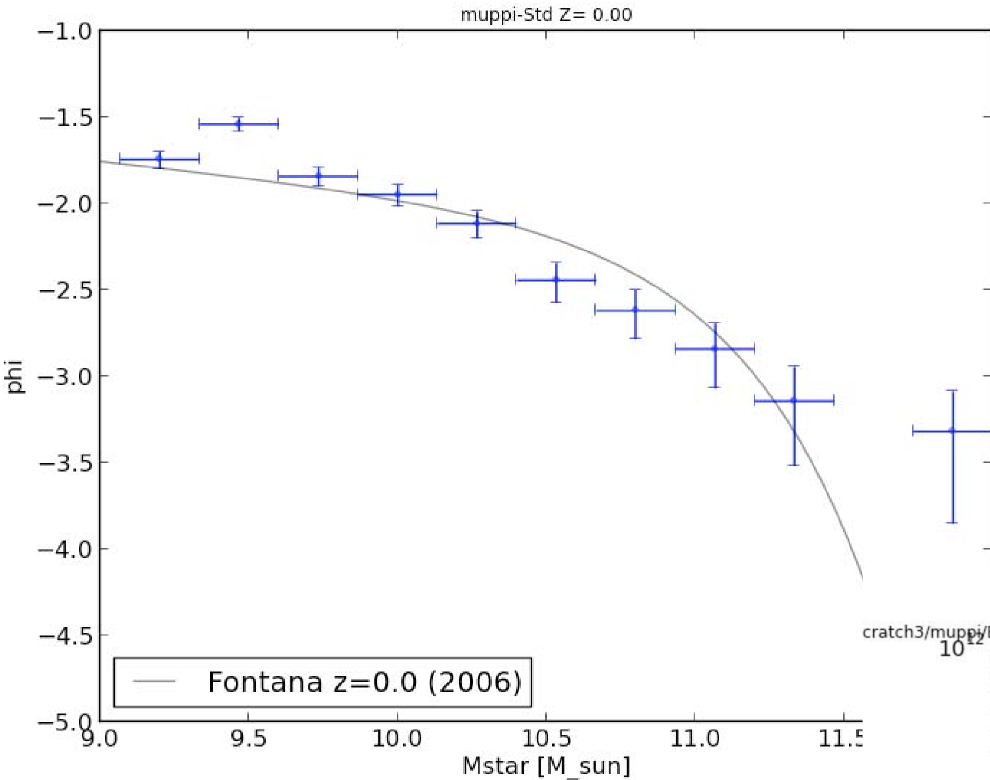
How many outflows escape the galaxy halo? (at R_{gal} versus at R_{vir})

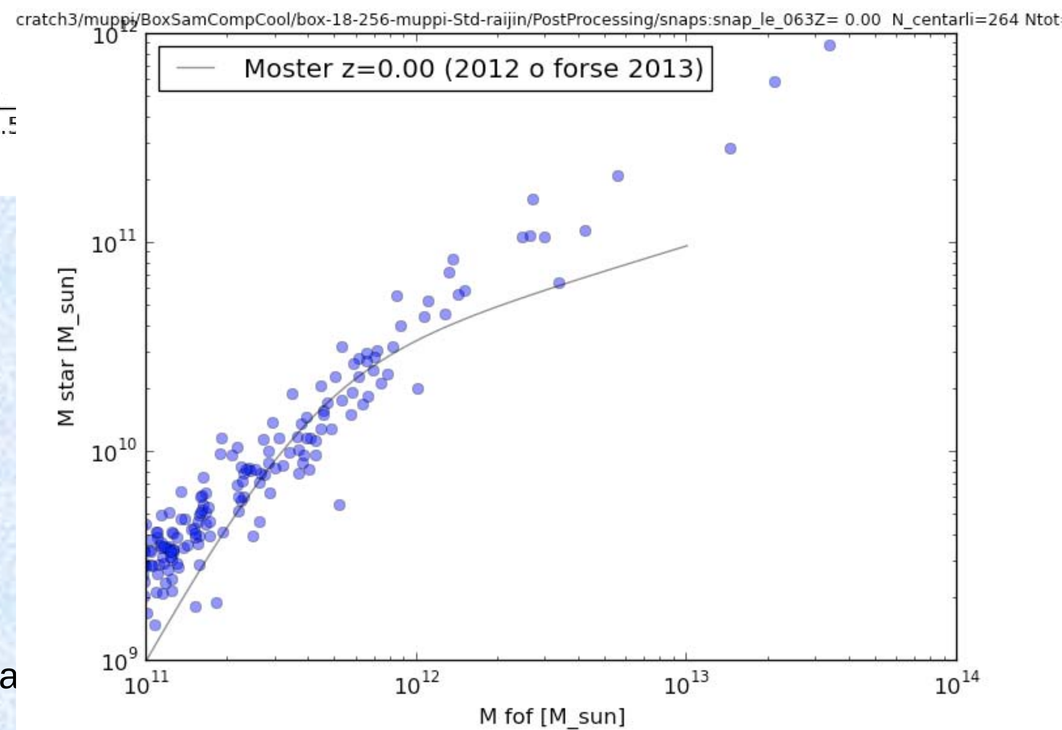
Method	N_{outflow}	f_{outflow}
At R_{gal} using $\lvert v_r \rvert > v_{\mathrm{esc}}(R_{\mathrm{gal}})$, in a cylinder	1842	0.93
At R_{gal} using $\lvert v_r \rvert > v_{\mathrm{esc}}(R_{\mathrm{gal}})$, in a sphere	1936	0.97
At R_{vir} using $\lvert v_r \rvert > v_{\mathrm{esc}}(R_{\mathrm{vir}})$, in a sphere	1734	0.87



Galaxy stellar properties at z=0

(Ragagnin et al. 2015, in prep.)





Simulating realistic disk galaxies with MUPPI, in zoom-in cosmological simulations using moderate resolution *(Murante et al. 2015, MNRAS)*

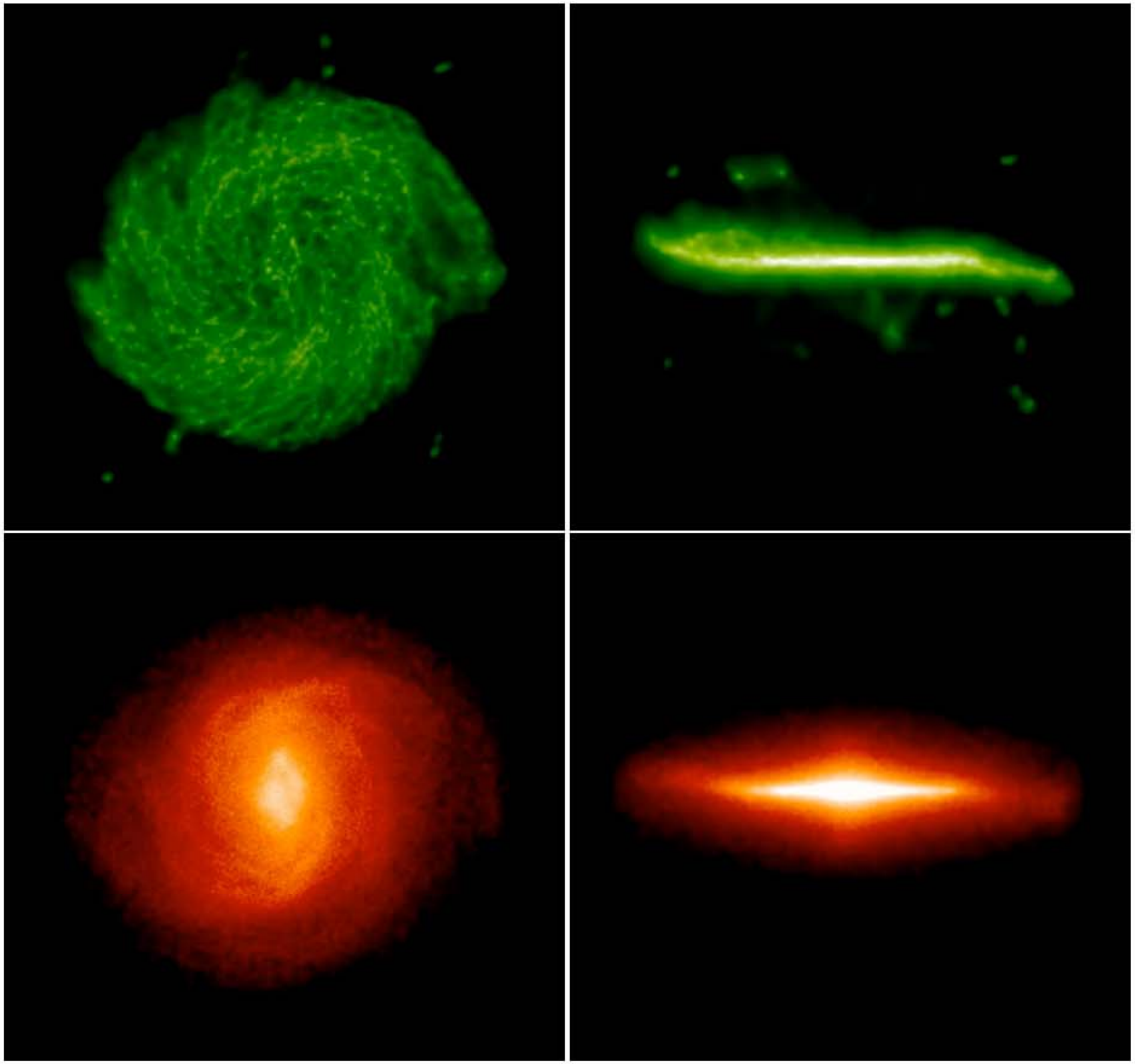
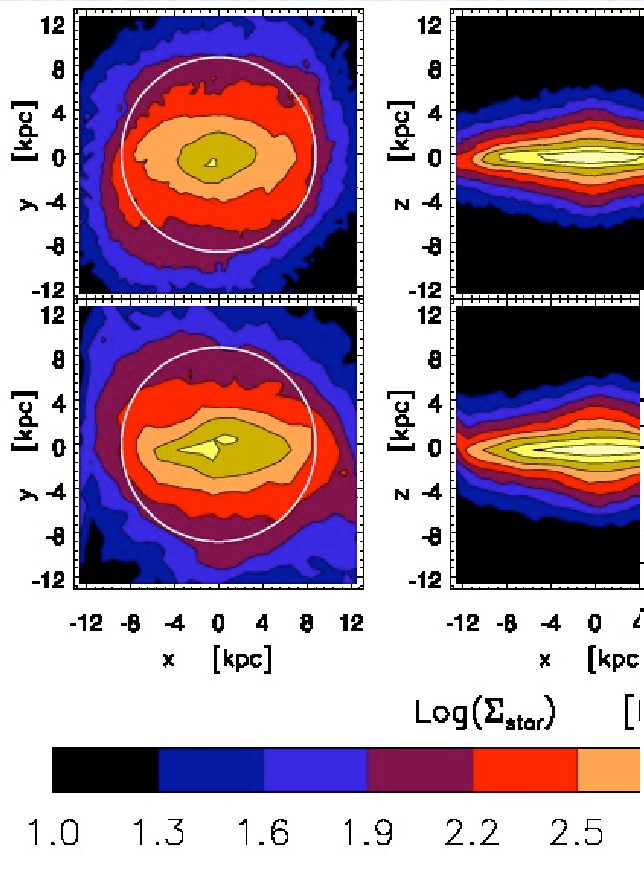
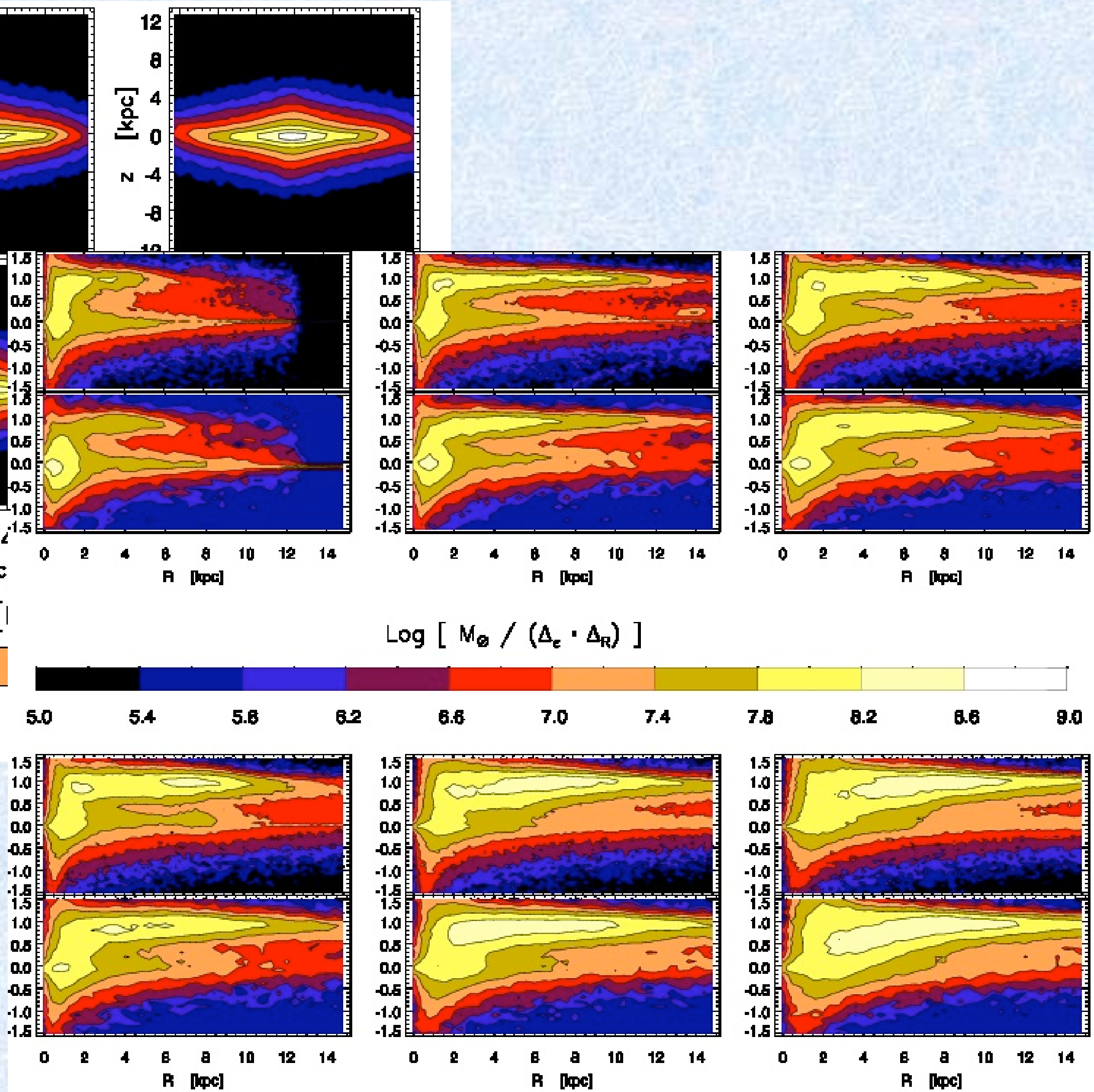


Figure 1. Projected gas (upper panels) and stellar (lower panels) density for the GA2 simulation. The z-axis of the coordinate system is aligned with the angular momentum vector of the gas enclosed within the inner 8 kpc. Left panels show face-on densities, right column shows edge-on densities. Box size is 57 kpc.

Study of barred spiral disk galaxies, in zoom-in cosmological simulations
(Goz et al. 2015, MNRAS)





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Summary

- Can study impact of galactic winds on galaxy & IGM properties in cosmological hydrodynamic simulations
  - Still far away from self-consistently driving these winds in such sims

- Crucial to measure in post-processing the outflow properties w.r.t. that input in the sub-grid model

- MUPPI is more physically-motivated sub-resolution model that uses only local properties of gas and generates realistic:
  - Galactic outflows
    - Outflow velocity positive correlation with global galaxy SFR
    - Contant mass-loading value at z=2
    - Redshift evolution predicted over z = 1 - 5
    - Need more observational data
  - Disk galaxies

- Need connection and synergy between large-scale sims and isolated system high-resolution sims, to physically model processes, and still have a predictive power