The MUFASA Simulations

Cosmological galaxy formation with meshless hydrodynamics

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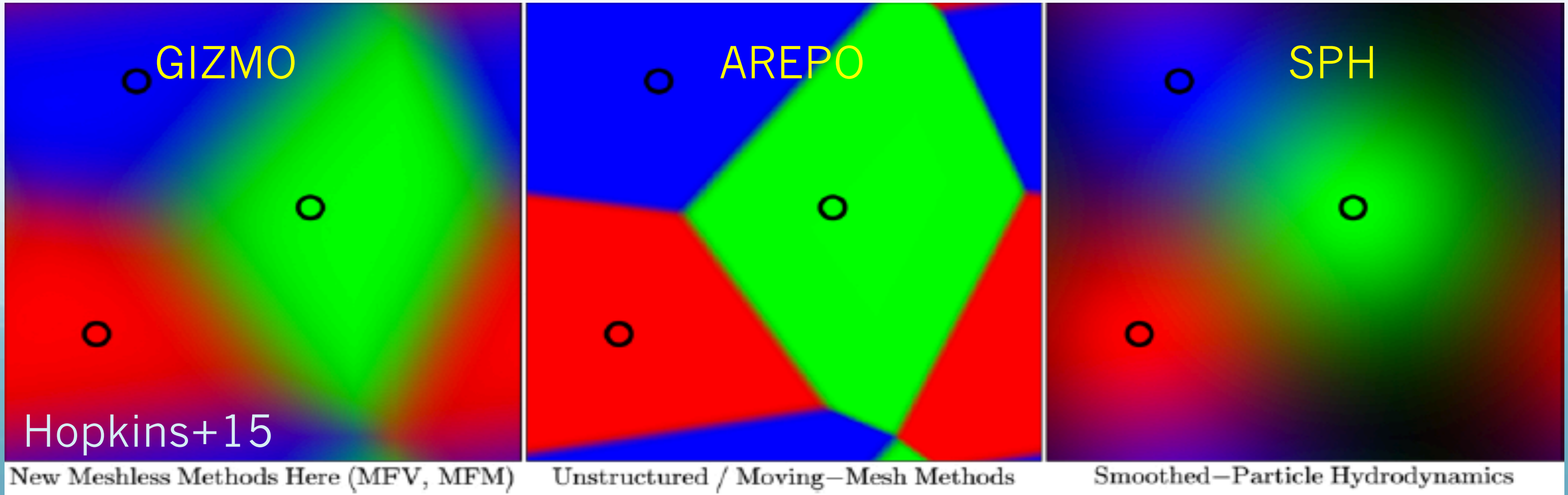
SAAO

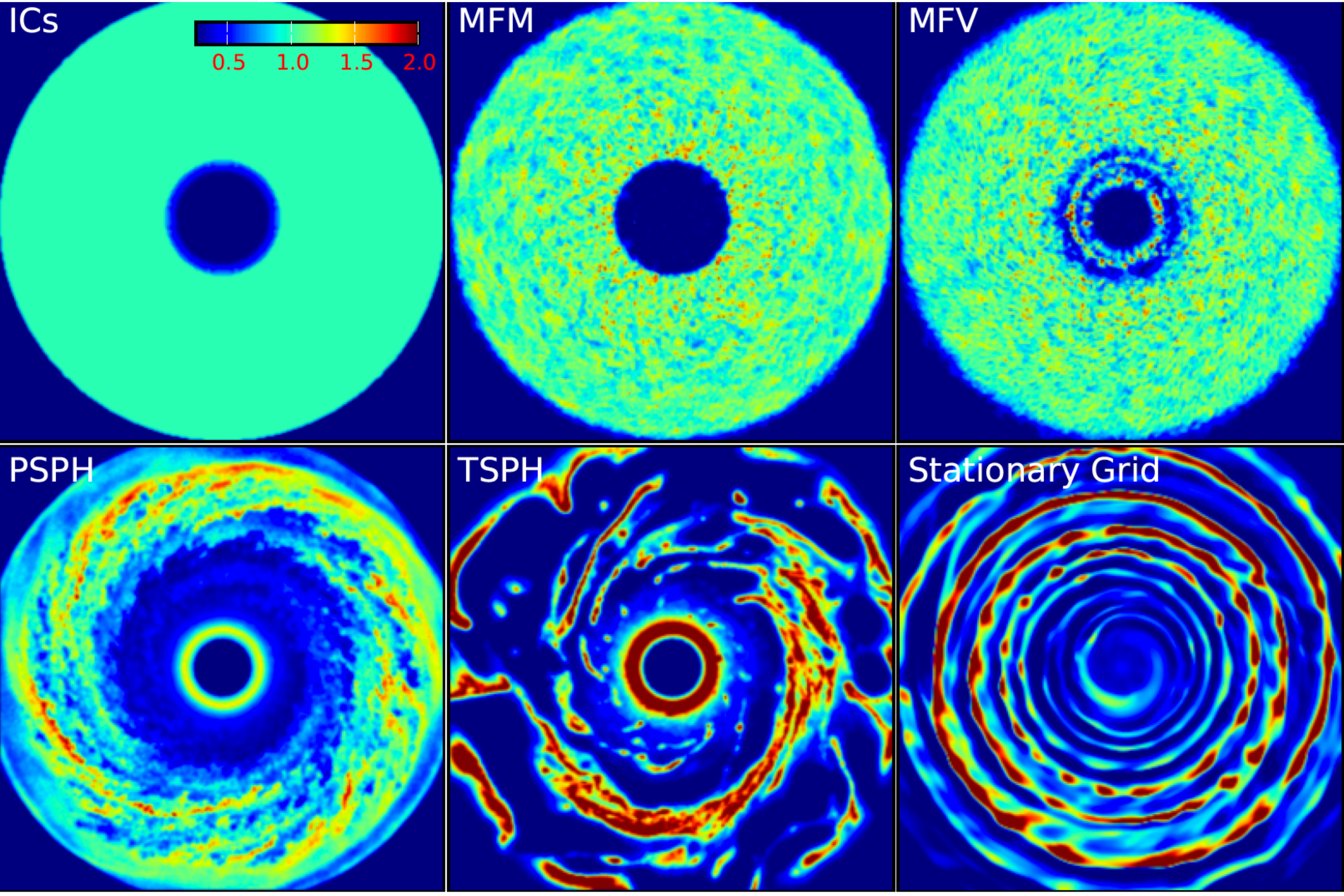
AIMS African Institute for Mathematical Sciences SOUTH AFRICA

GIZMO-MUFASA

- GIZMO: Cosmological gravity (Gadget) + hydro (MFM)
- Grackle-2.1 cooling+heating, including metal cooling
- 9-metal chemical enrichment: Type II/Ia + AGB stars&heat
- Star formation (H_2-based), minimal ISM pressure
- Kinetic, heated winds based on FIRE scalings (Muratov+15)
- Quenching via prevention of diffuse gas cooling in massive halos



GIZMO tests



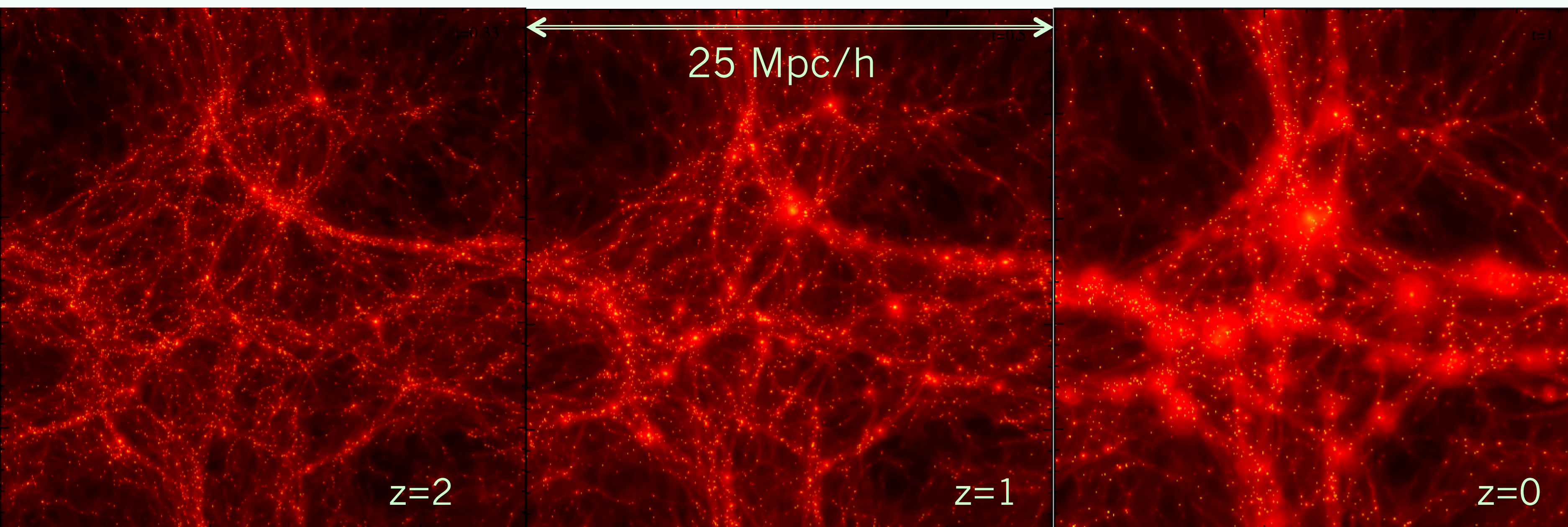
MUFASA runs

- Cosmological boxes:

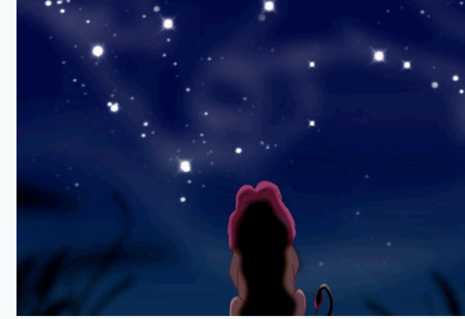
Name	L^a	ϵ^b	m_{gas}	m_{dark}	m_{gal}^c
m12.5n512	12.5	0.125	2.85×10^5	1.5×10^6	9.1×10^6
m25n512	25	0.25	2.28×10^6	1.2×10^7	7.3×10^7
m50n512	50	0.5	1.82×10^7	0.96×10^8	5.8×10^8

Resolves all H-cooling halos

Yields z=0 halos to >~10^{14} $M_\odot$.



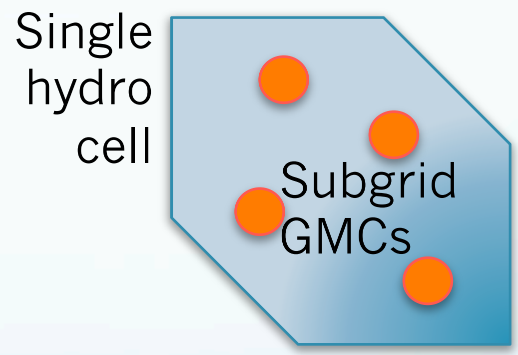
H_2–based star formation

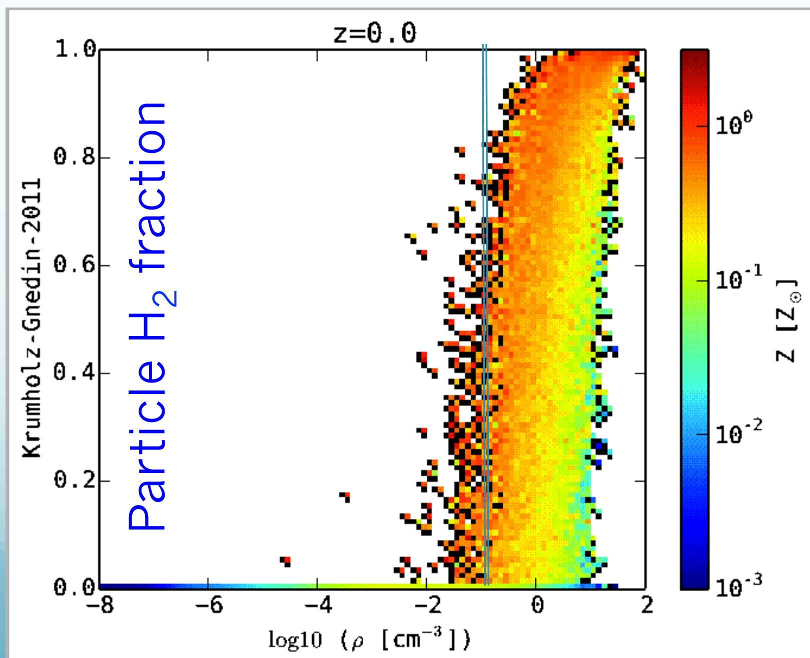


- Krumholz & Gnedin 11. C=30 in fiducial case, but scale w/ε:
  - C = 30 (ε/0.5 kpc).
  - $\Sigma = \rho^2/|\nabla\rho| \sim \rho h \sim C^{2/3}$.
- M_{Jeans}-based pressurized ISM

$$f_{H2} = 1 - 0.75\frac{s}{1+0.25s}$$

$$s = \frac{\ln(1+0.6\chi+0.01\chi^2)}{0.0396(Z/Z_\odot)(\Sigma/M_\odot \mathrm{pc}^{-2})},$$



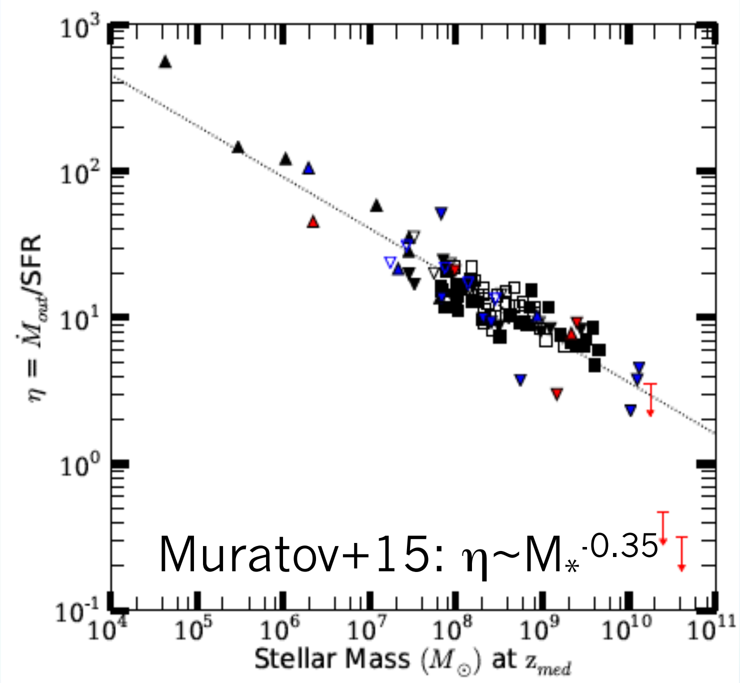


Two-phase kinetic winds

- FIRE (Muratov+15) scalings, with increased v_w amplitude:

$$\eta = 3.55\left(\frac{M_*}{10^{10}M_\odot}\right)^{-0.351}$$

$$v_w = 2\left(\frac{v_c}{200}\right)^{0.12} v_c + \Delta v_{0.25}.$$



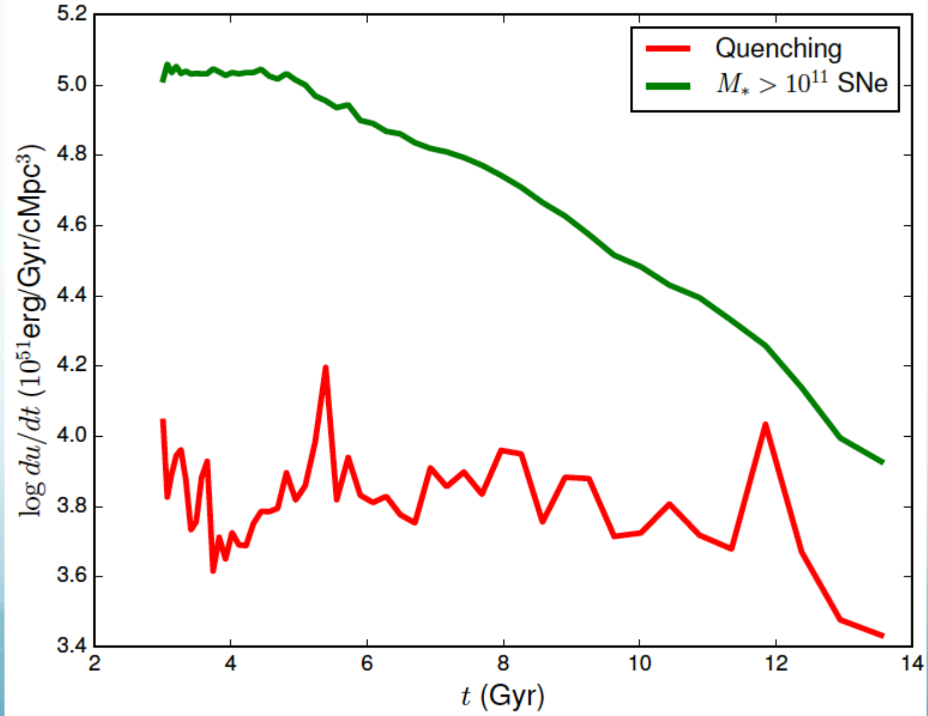
- On-the-fly FOF galaxy finder

$$v_c = (M_b/102.329)^{0.26178}(H(z)/H_0)^{1/3}$$

- Two-phase winds: 30% ejected "hot" with E_{SN} in **v**×**a**
- Recouple @ $0.01t_H$ or $\mathcal{M}<0.5$

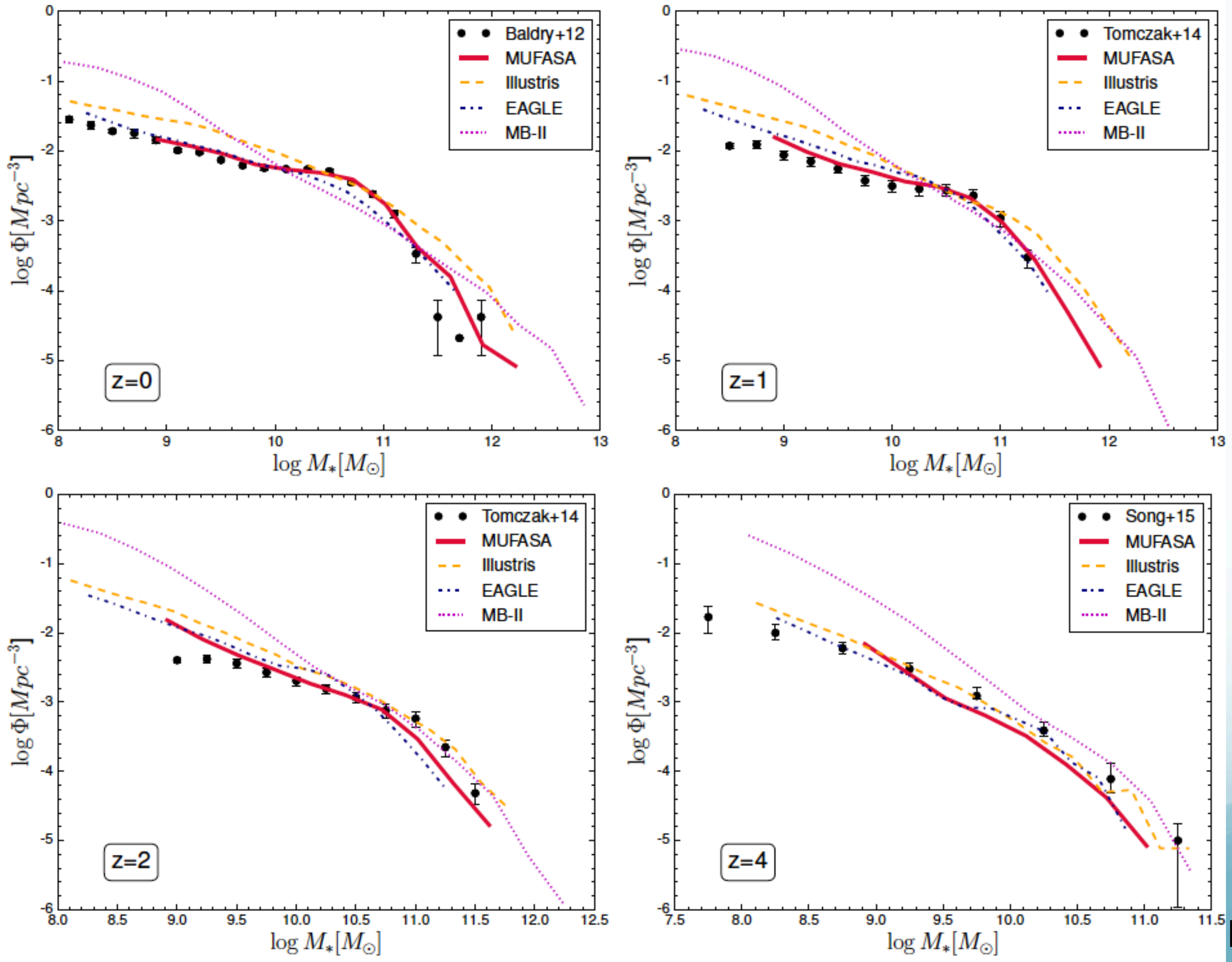
Quenching ("AGN") Feedback

- *Quenching feedback:* Keep the hot gas hot (Gabor+RD12,15), for $M_h > M_q = 10^{12+0.48z}$ (from equilibrium model of Mitra+15).
- All *non-shielded, hot* gas out to R_{vir} heated to $T \sim T_{vir}$.
- Total energetics requires 0.01-0.1% of BH rest energy, comparable to (cumulative) SNe energy in quenched galaxies



RD+16

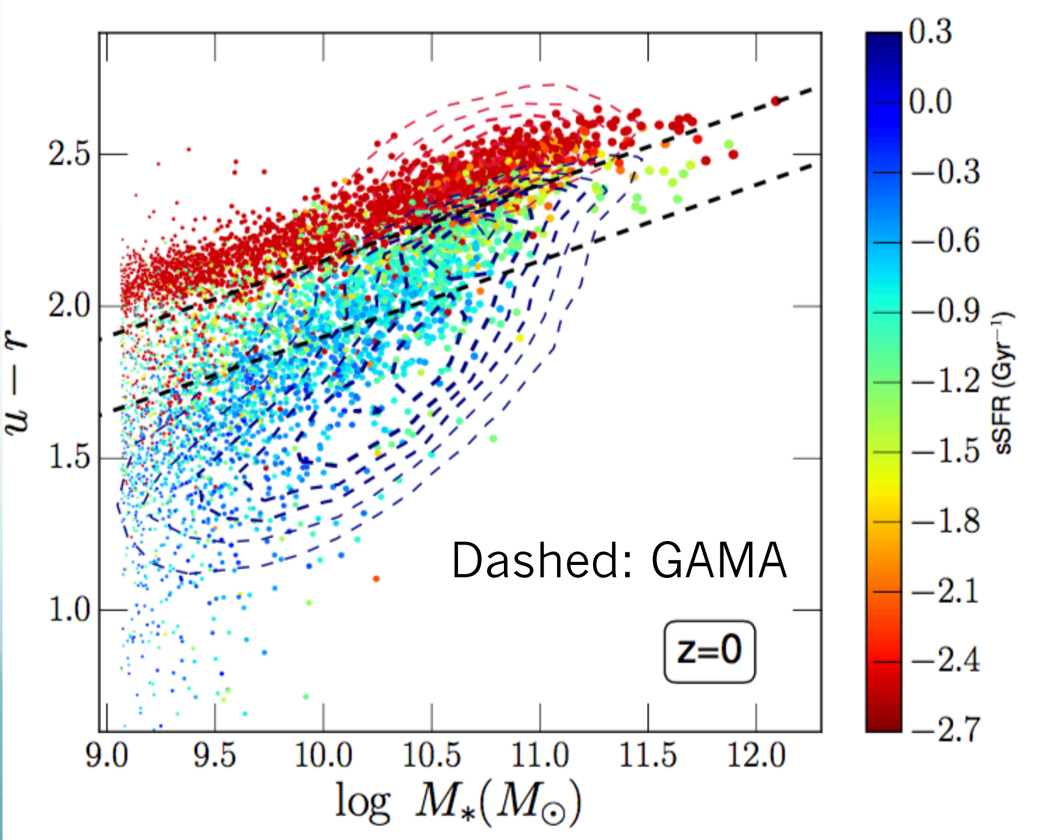
Stellar mass functions

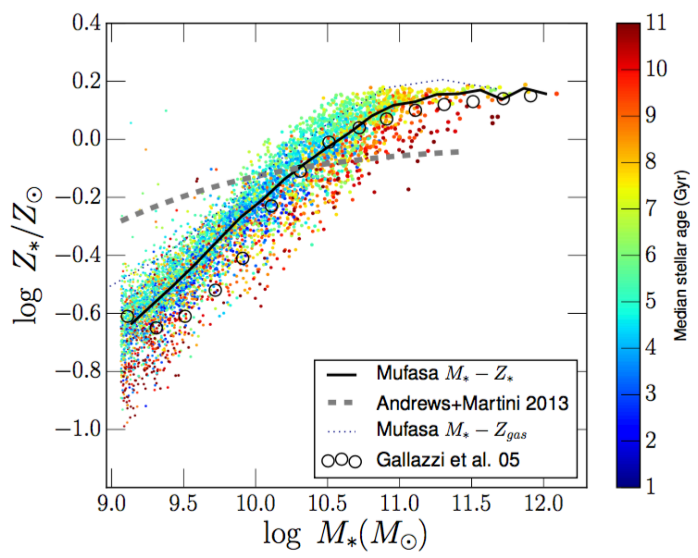


RD+16

Red sequence, blue cloud

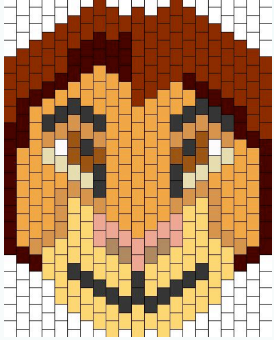
- Colors from LOSER (bitbucket.org/romeeld/closer): FSPS+A_V from Z column along LOS
- Slope & amplitude correct “out of the box” – slope driven by $Z_*(M_*)$ relation.



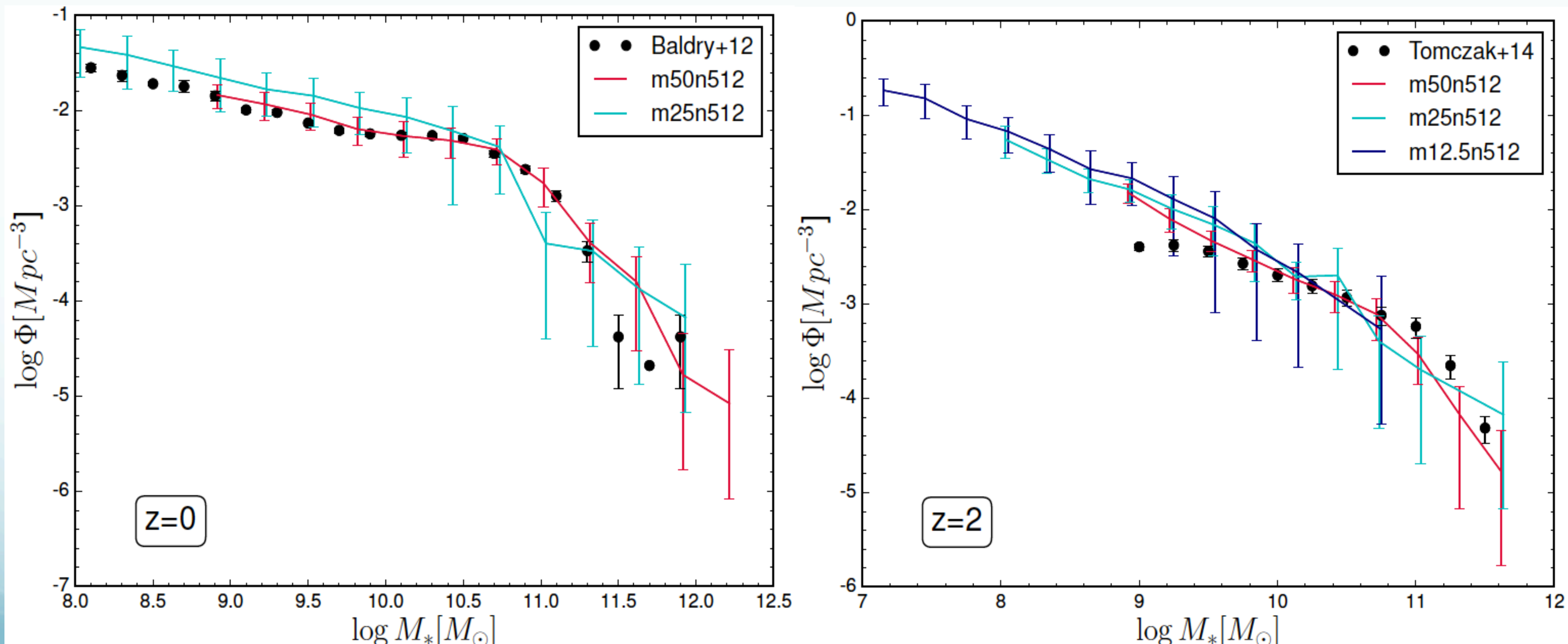


RD+ in prep

Resolution convergence



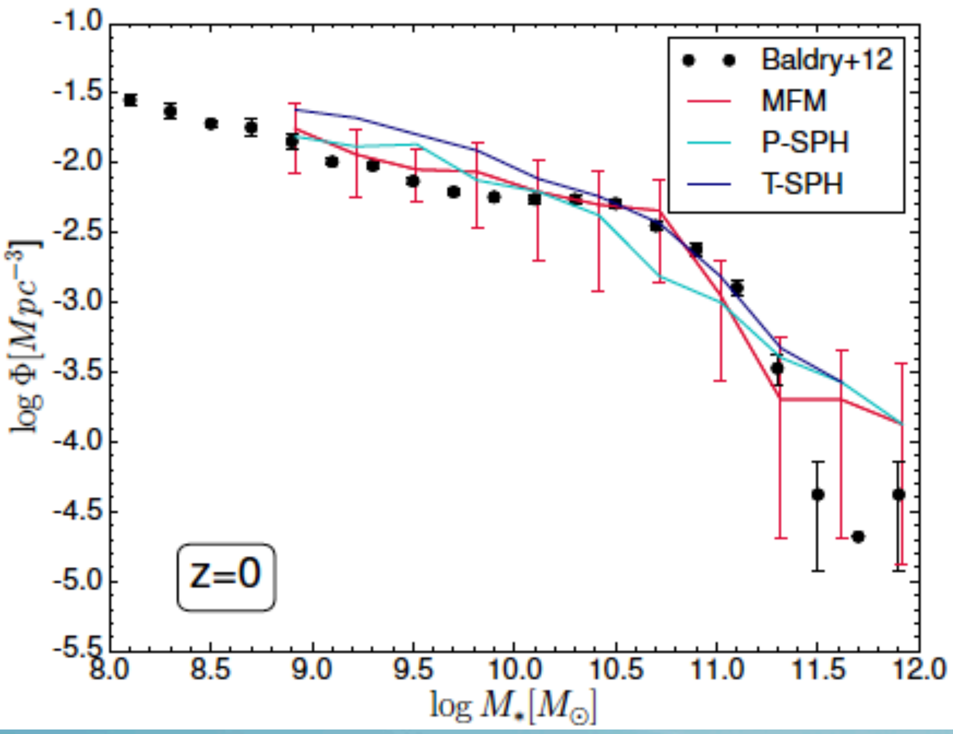
- Generally good, but at low redshifts less good owing to wind recycling (recoupling)

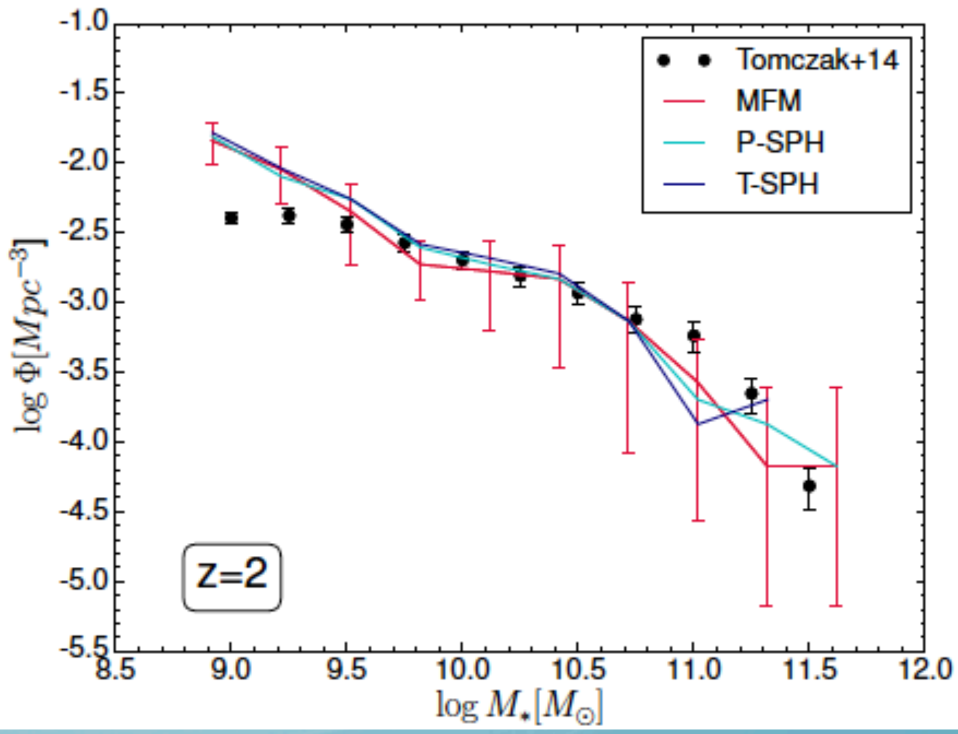


RD+16

Does Hydro Matter?

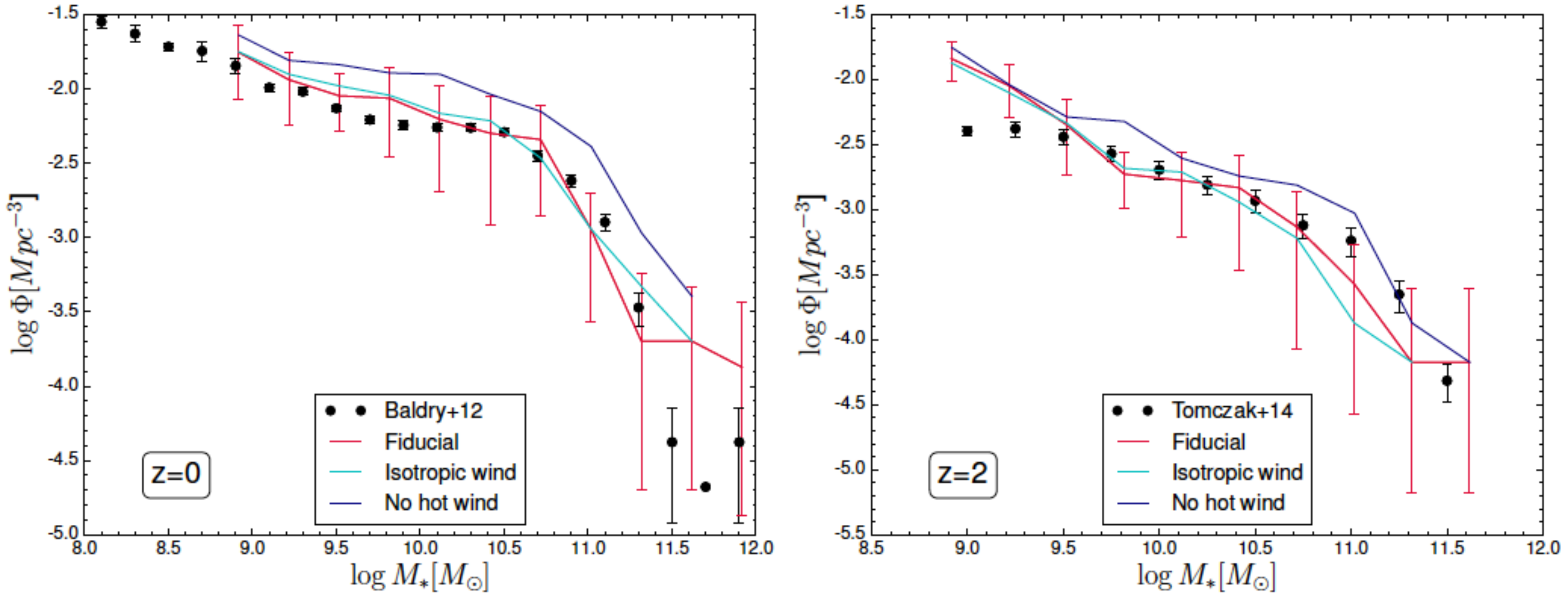
- Mostly at low-z, when recycling happens
- Not a generic trend: Likely dependent on outflows





Hot outflows

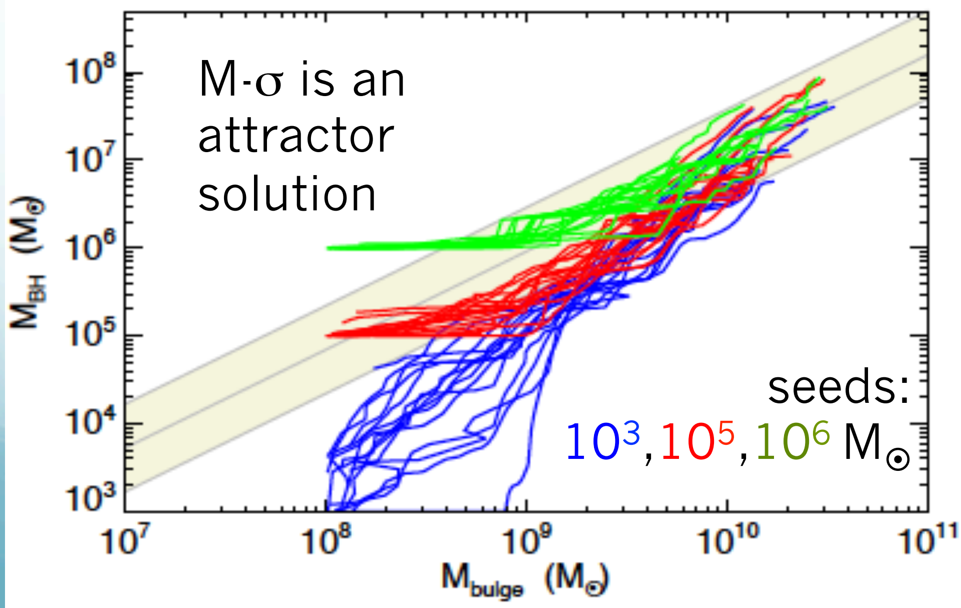
- Hot winds crucial; wind direction ~irrelevant
- SN heating affects high-M* more (winds take less E)



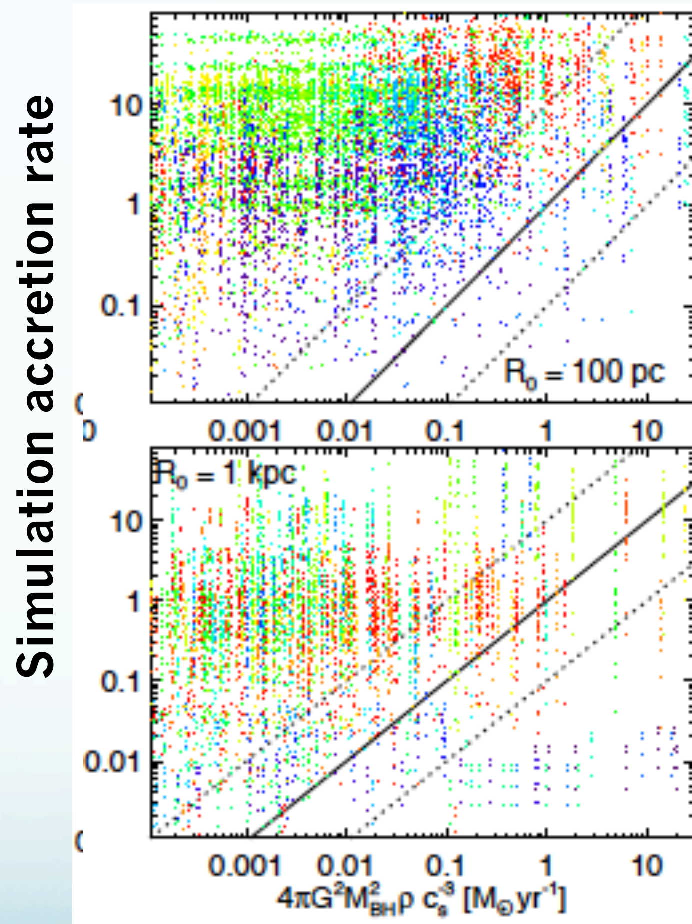
Modeling Black Hole Growth: Torque-Limited Accretion

- Angular mom dissipated via disk instabilities (Hopkins&Quataert 2011): $dM_\bullet/dt \sim M_\bullet^{1/6}$

$$\dot{M}_{\rm Torque} \approx \alpha_{\rm T}\, f_{\rm disk}^{5/2} \times \left(\frac{M_{\rm BH}}{10^8\,{\rm M}_\odot}\right)^{1/6} \left(\frac{M_{\rm disk}(R_0)}{10^9\,{\rm M}_\odot}\right)^{1} \times \left(\frac{R_0}{100\,{\rm pc}}\right)^{-3/2} \left(1+\frac{f_0}{f_{\rm gas}}\right)^{-1} {\rm M}_\odot\,{\rm yr}^{-1},$$



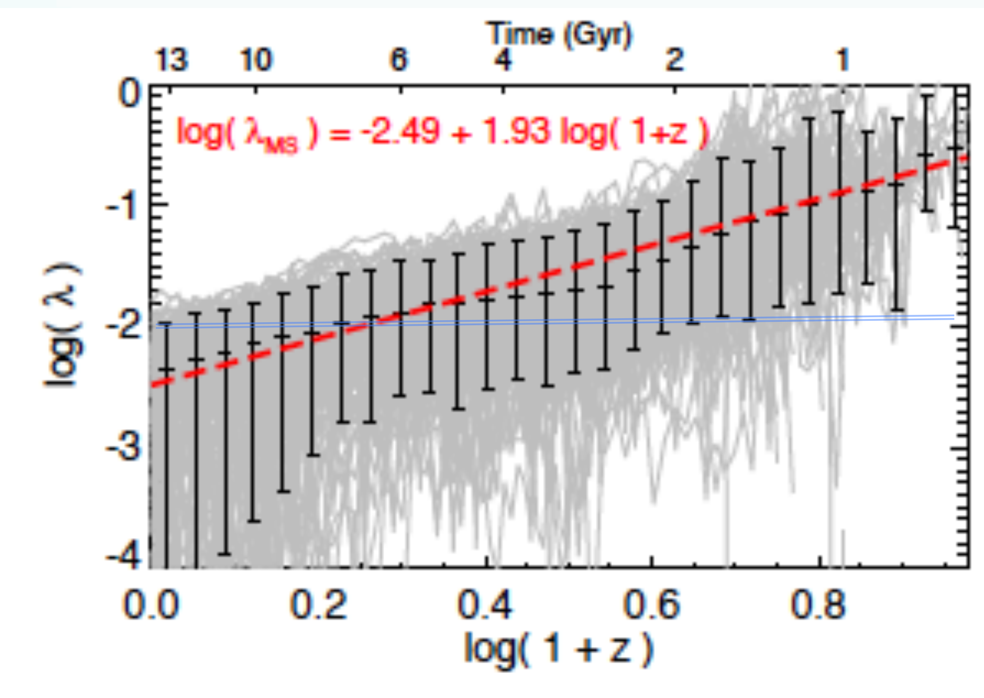
DAA+14

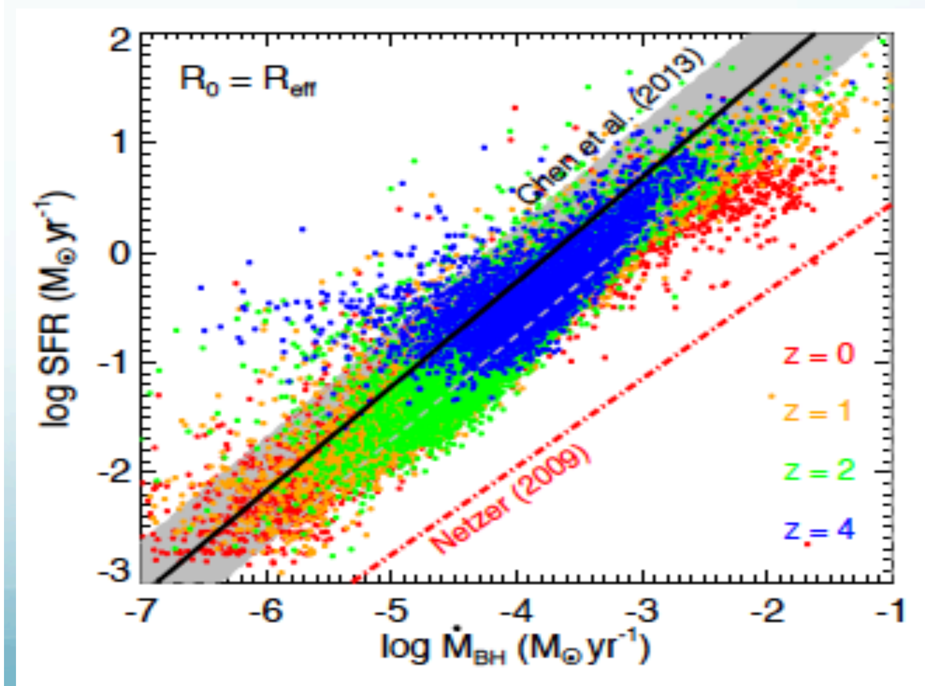


Hopkins & Quataert 11

Torque-limited BH growth

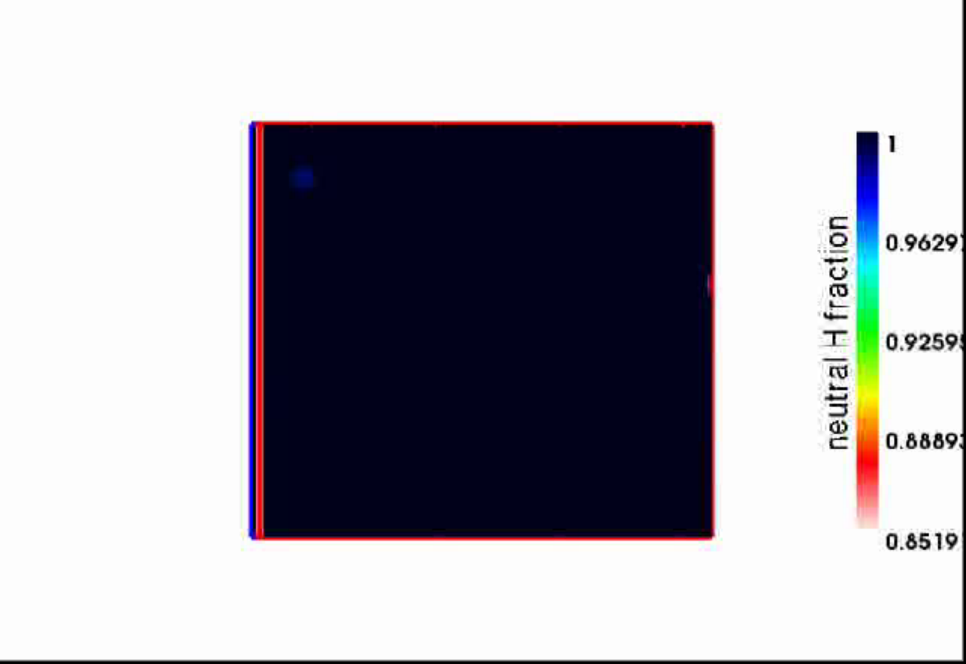
- *Smoother BH growth* tracks SFR (not mergers).
- $M_{\bullet}$-M_{bulge} relation is an attractor; depends only on ε~0.1.
- Typical Eddington fraction drops to low-z; large scatter.
- Now merged into Gizmo-Mufasa w/ BAL wind feedback.
- **v**×**a** winds at ~1000 km/s; ~no effect on BH growth

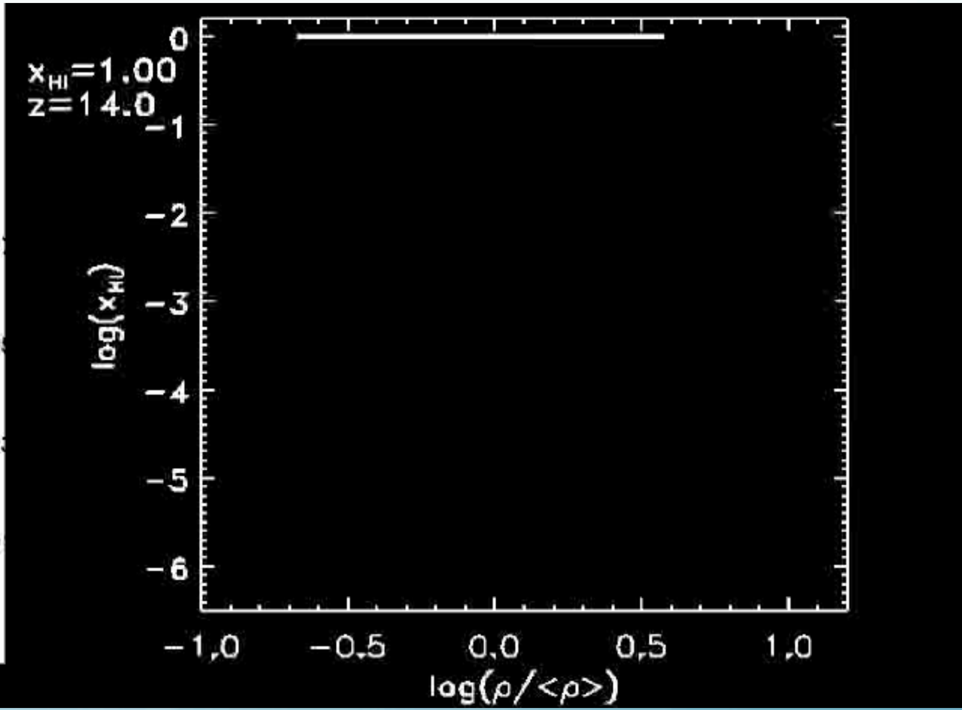




Cosmological rad-hydro: MARCH + Gadget-3
(Finlator+ …)

- VET moment method, closure (**f_{Edd}**) via long characteristics.
- Multi-frequency, chemical network, fixed mesh; *c*=*c*.
- Photons from star formation, f_{esc} ~ *20-50%.*
- Particularly useful for IGM studies (Finlator+15,16).



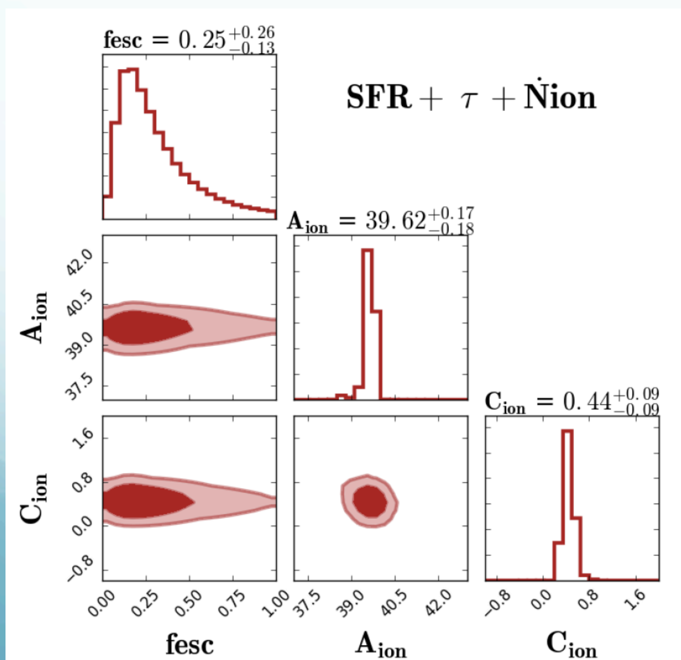


21cm EoR via Semi-numerical sims: SimFast21

(Hassan+ …)

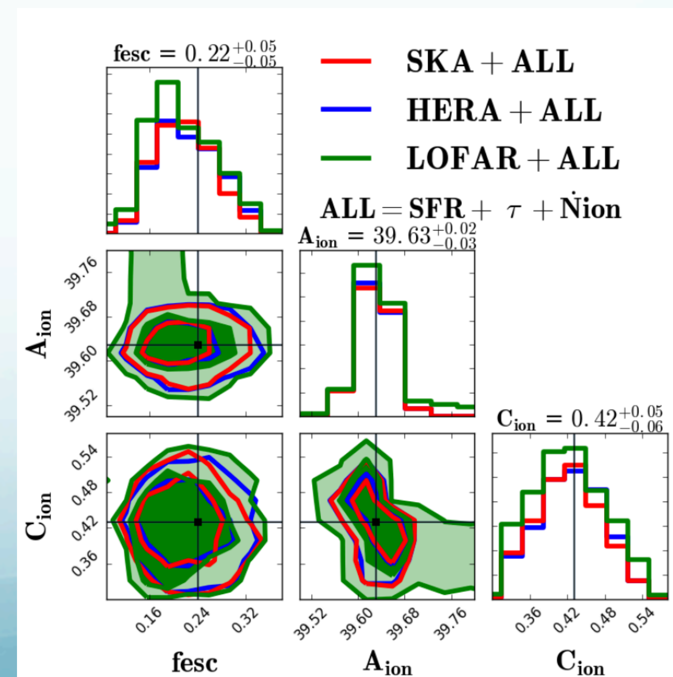
- SimFast21 (Santos+11): Quasi-linear density field evol, EPS-based spherical ionisation regions.
- Hassan+16: Include recombinations (instantaneously) & ionisations as a function of M_{halo} taken from MARCH sims.
- Hassan+17: Track recombinations through time, put in MCMC and constrain to data: τ_e, UVLF(z=6-8), Γ(z~5).

$$R_{ion} = A_{ion}\,(M_h/10^8)C_{ion}\,(1+z)^{2.3}\exp[-(10^8/M_h)^3]$$



←Without 21cm *(current)*

With 21cm *(future)* →



The Sequel

MUFASA provides a nice platform. Extensions include

- A more physical BH model using torque-limited accretion, with f_{Edd}-dependent feedback.
- Radiative transfer with MARCH, add adaptivity
- Implement updated feedback parameters from more recent zooms, and from our equilibrium model.
- PHEW: Phenomenologically evolved winds – compute wind propagation analytically instead of decoupling
- Couple these results into large-scale sims for 21cm EoR, DE studies.