The MUFASA Simulations

Cosmological galaxy formation with meshless hydrodynamics

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SAAO

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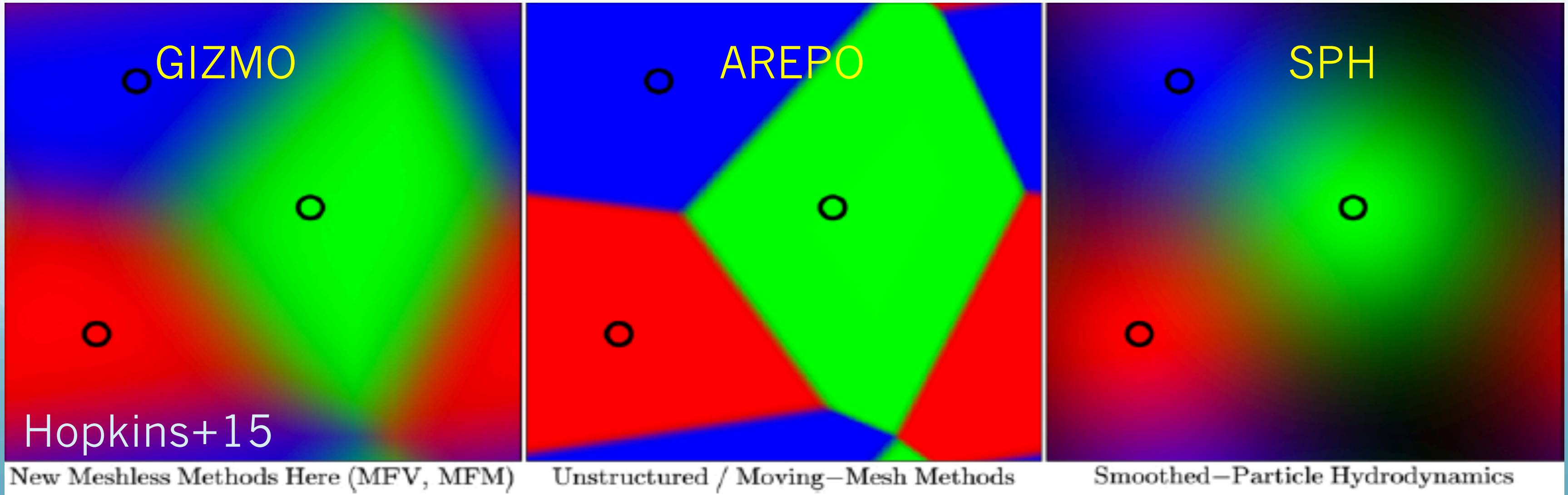
Numerical Galaxy Formation

- Multi-physics (with gas dynamics):
  - Direct: Gravity, pressure, shocks, cooling & heating
  - "Sub-resolution": Star formation, black hole growth, chemical enrichment, *feedback* (AGN, SNe, ...)
  - Optional: Radiative transfer, magnetic fields, conduction, cosmic rays ...
- Multi-scale:
  - "Hubble volume" – Approaching the whole Universe
  - "Cosmological" – Representative volume for statistics
  - "Zoom" – Individual object(s) within a cosmo volume
  - "Isolated" – Single object for controlled experiments

GIZMO-MUFASA

- GIZMO: New cosmological gravity+"meshless" hydro code by Hopkins (2015) – mesh cells conserve mass!
- Grackle-2.1 cooling+heating, including metals
- Star formation (H_2-based), minimal ISM pressure
- 9-metal chemical enrichment: Type II/Ia + AGB stars+heat
- Kinetic winds (+ SN heating), quenching via "radio mode"



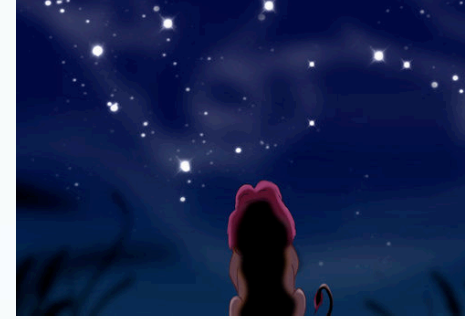
MUFASA runs

- Cosmological "random" volumes:
  - 2×512^3 particles, 12.5, 25, 50 Mpc/h volumes
  - ε_{min} = 0.125, 0.25, 0.5 kpc/h resolution (adaptive)
  - $M_{*,min} = 10^7\ M_\odot$, 8x higher at each larger box.

Name	L^a	ϵ^b	$m_{\rm gas}$	$m_{\rm dark}$	$m^c_{\rm gal}$
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

- Zooms underway…

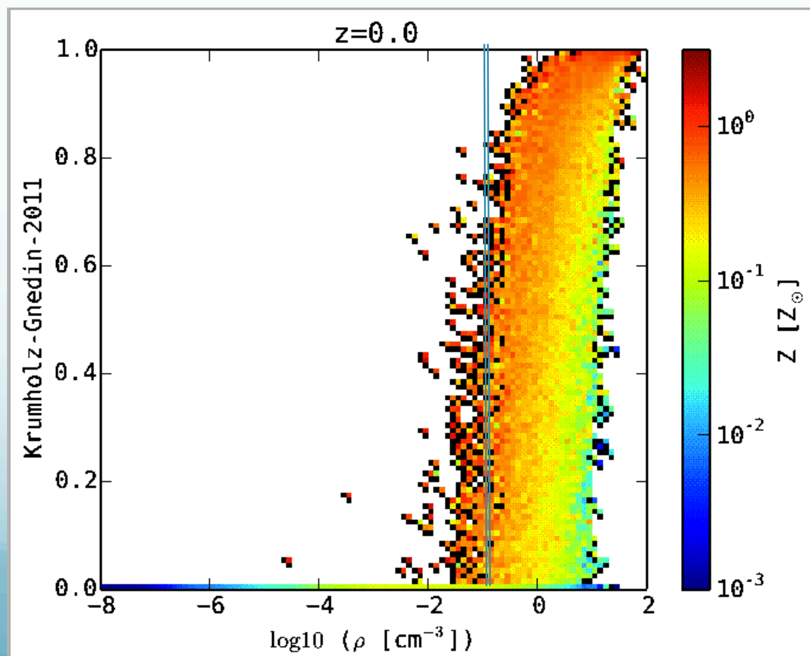
Star formation

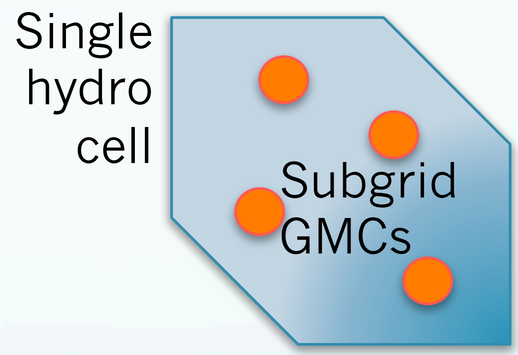


- Krumholz & Gnedin 11. C=30 in fiducial case, but scale w/ε:
  - $C = 30\,(\varepsilon/0.5\text{ kpc})$.
  - $\Sigma = \rho^2/|\nabla\rho| \sim \rho h \sim C^{2/3}$.
- M_{Jeans}-based pressurized ISM

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

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



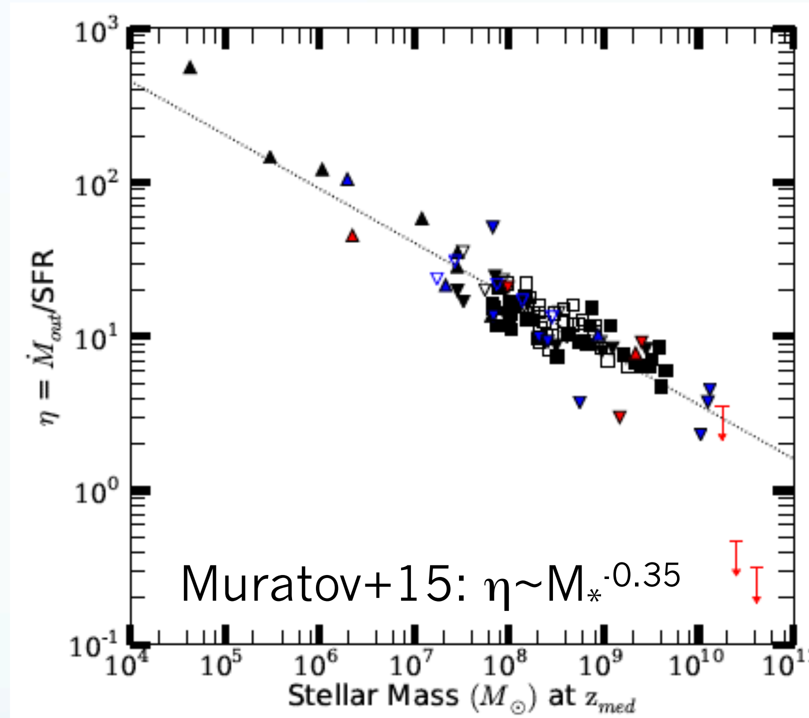


Decoupled kinetic winds

- 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

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

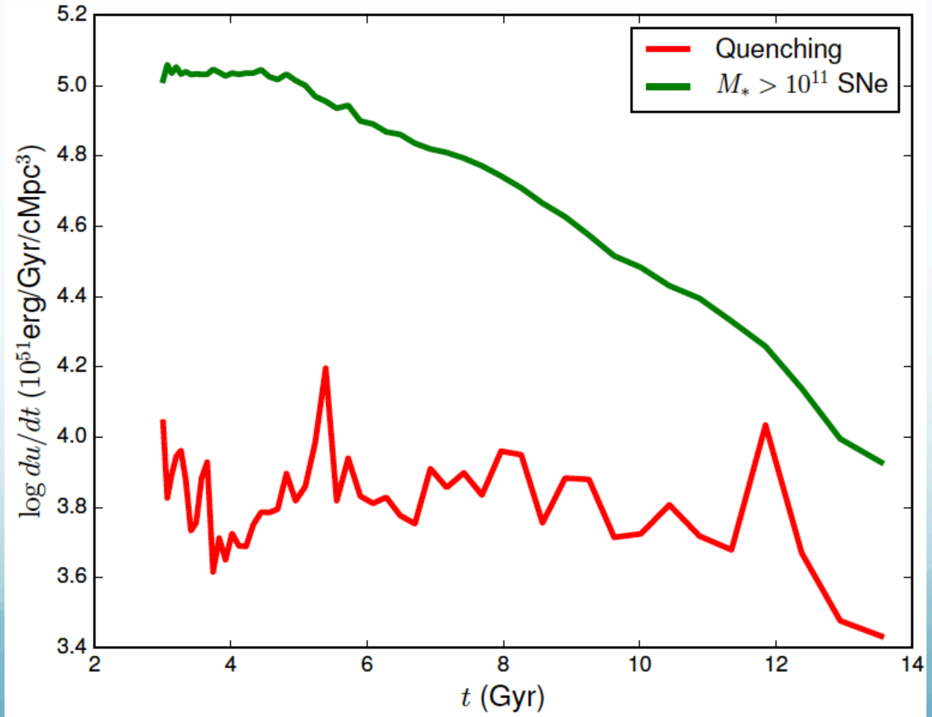
- Two-phase winds: 30% ejected "hot" from E_{SN}

$$\Delta u = u_{SN} - \frac{1}{2}\eta v_w^2.$$

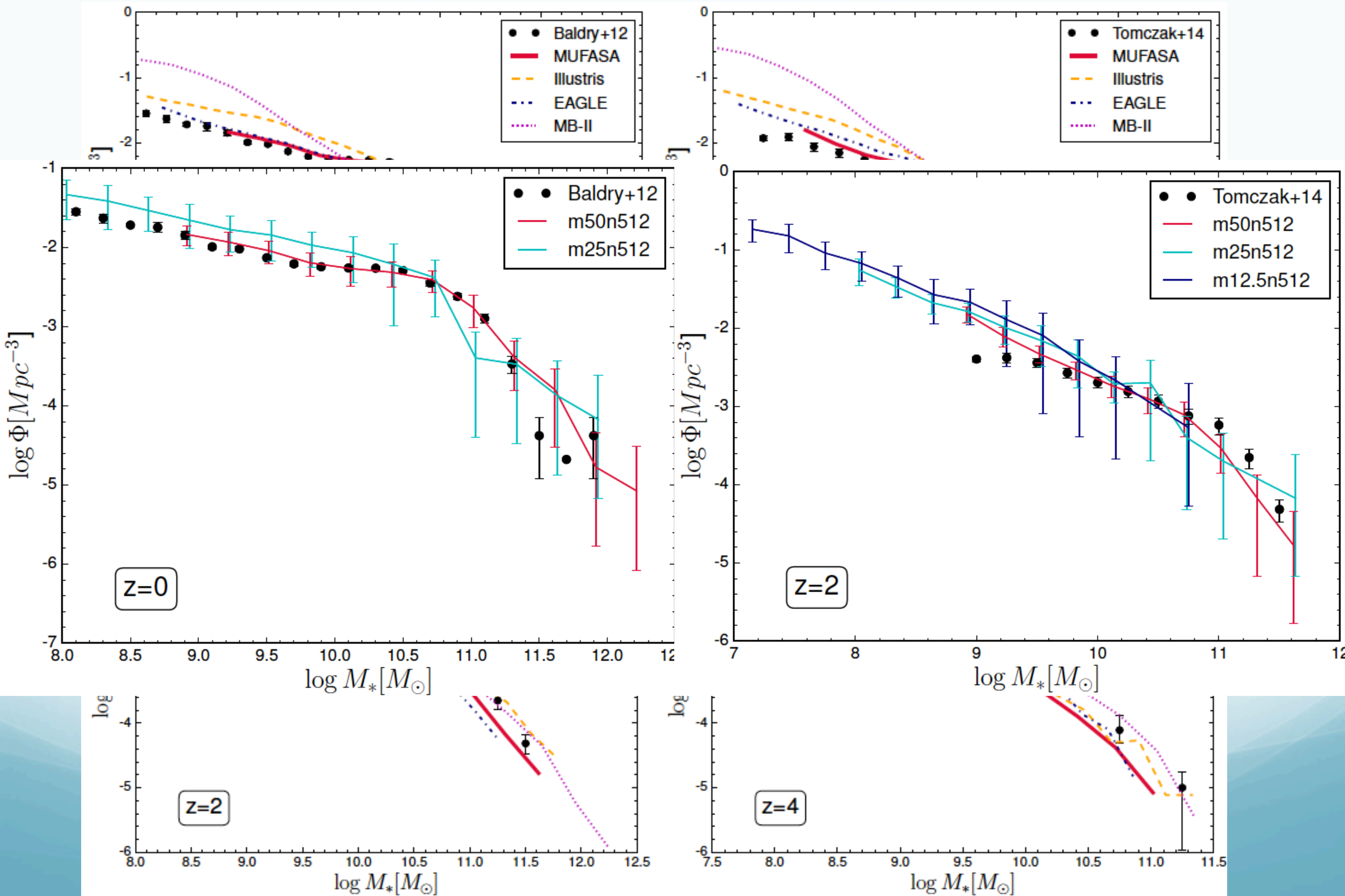
- Recouple @ $0.01t_H$ or $\mathcal{M}<0.5$

Quenching ("AGN") Feedback

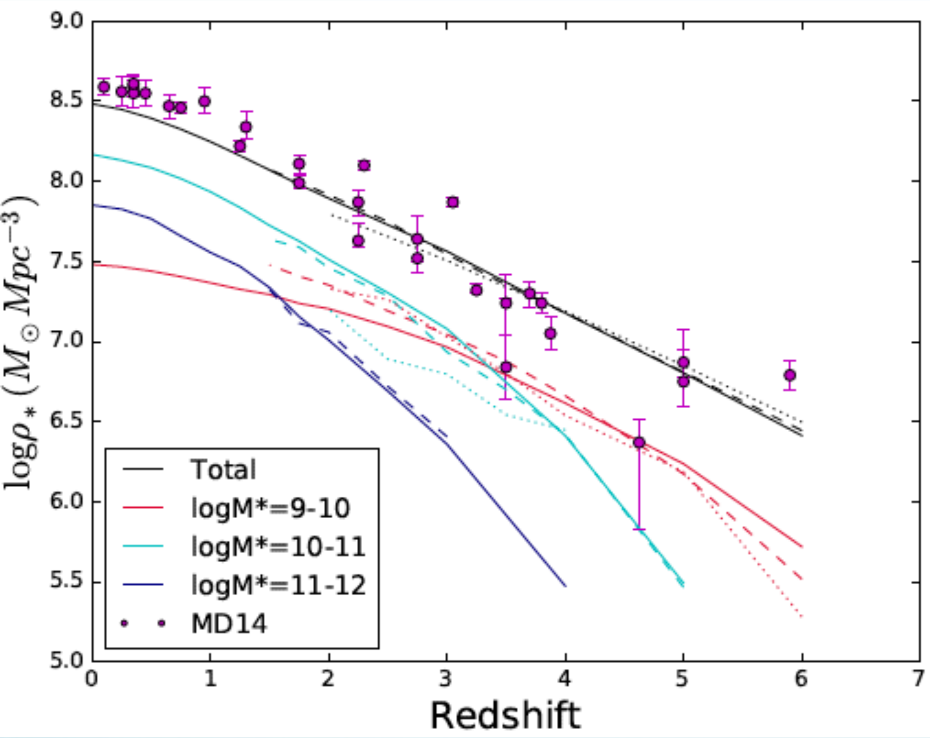
- *Quenching feedback:* Keep the hot gas hot (Gabor+RD12), for $M_h > M_q = 10^{12+0.48z}$ (from equilibrium model of Mitra+15).
- All *non-shielded* gas out to R_{vir} is heated up to $T \sim T_{vir}$.
- Total energetics requires 0.01-0.1% of BH rest energy, comparable to (cumulative) SNe energy in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

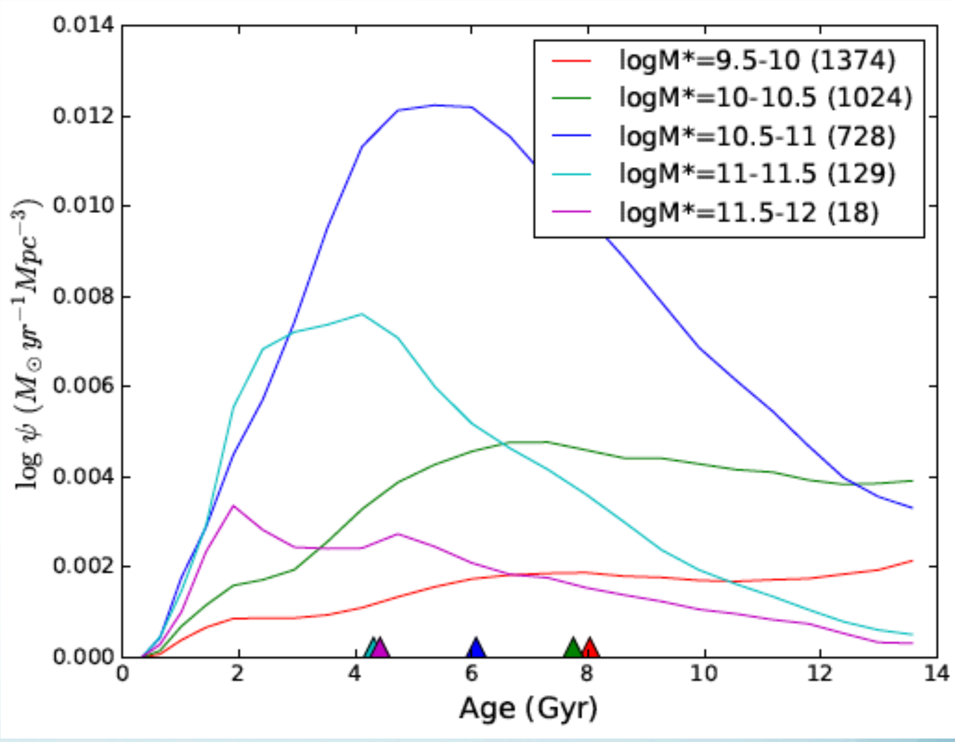


Stellar mass functions



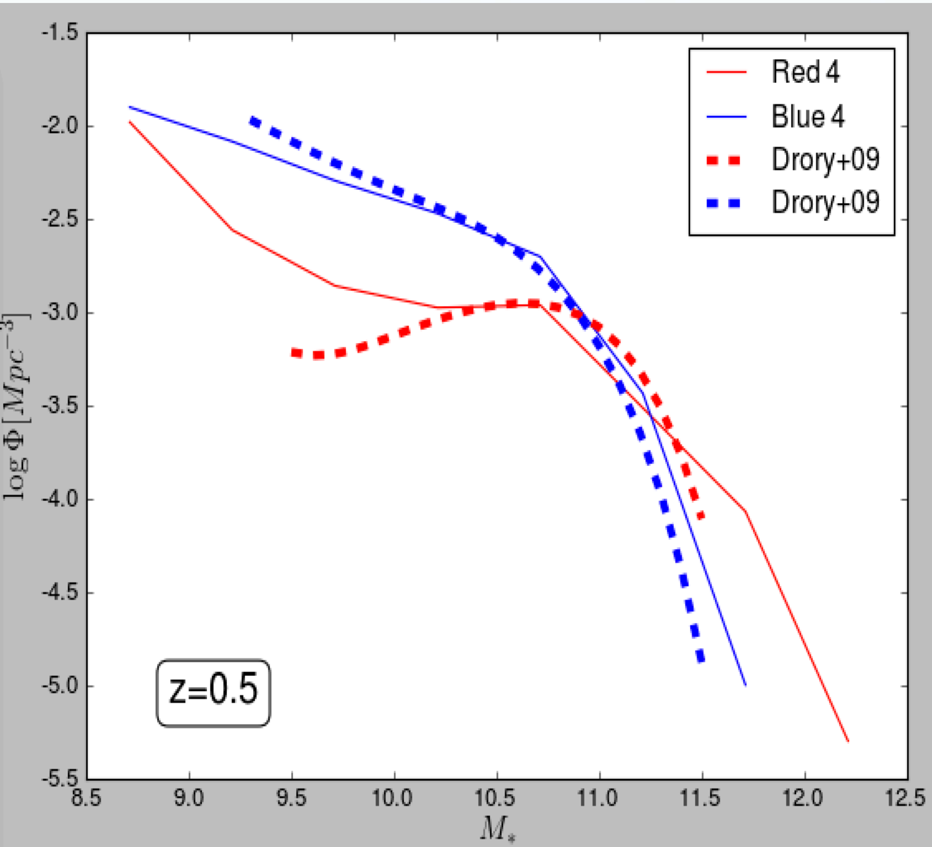
Stellar growth & downsizing

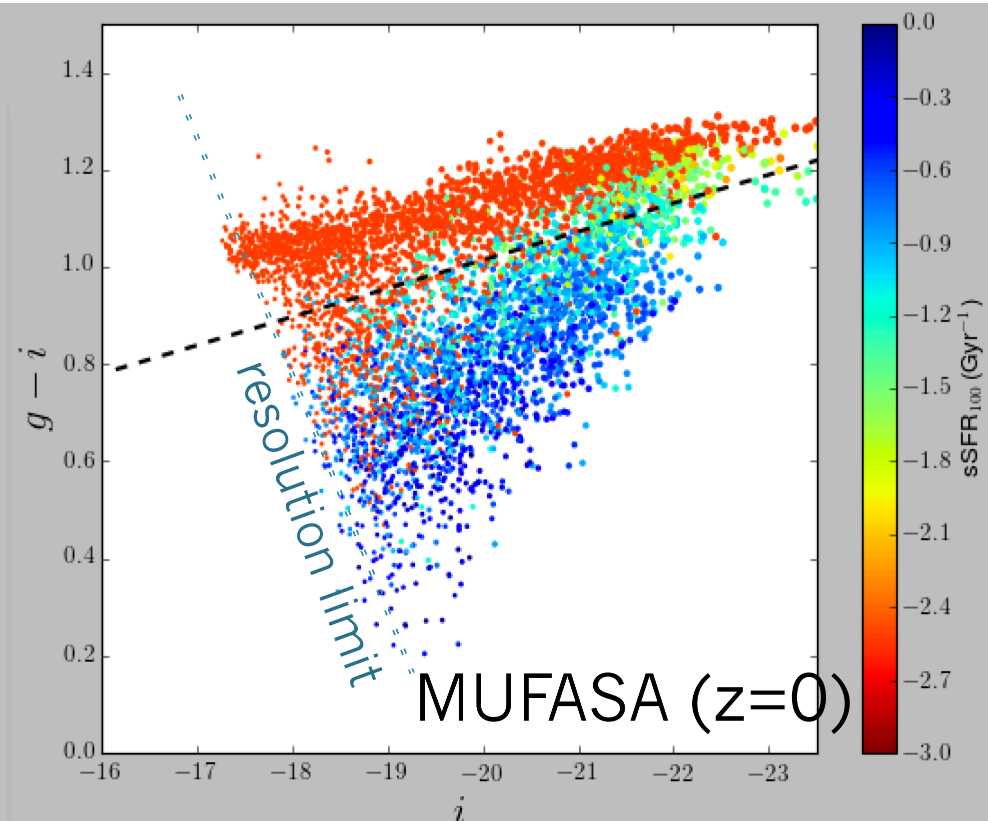




Color Bimodality

- Colors from LOSER: FSPS+A_V from Z column along LOS
- Nice, but it seems that there are too many red dwarfs?

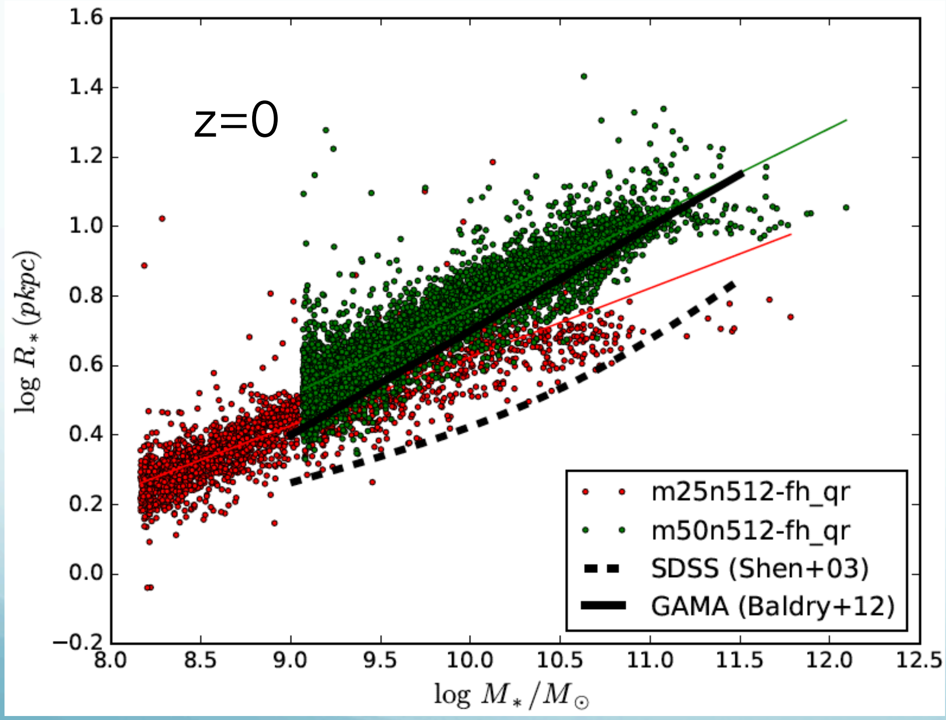


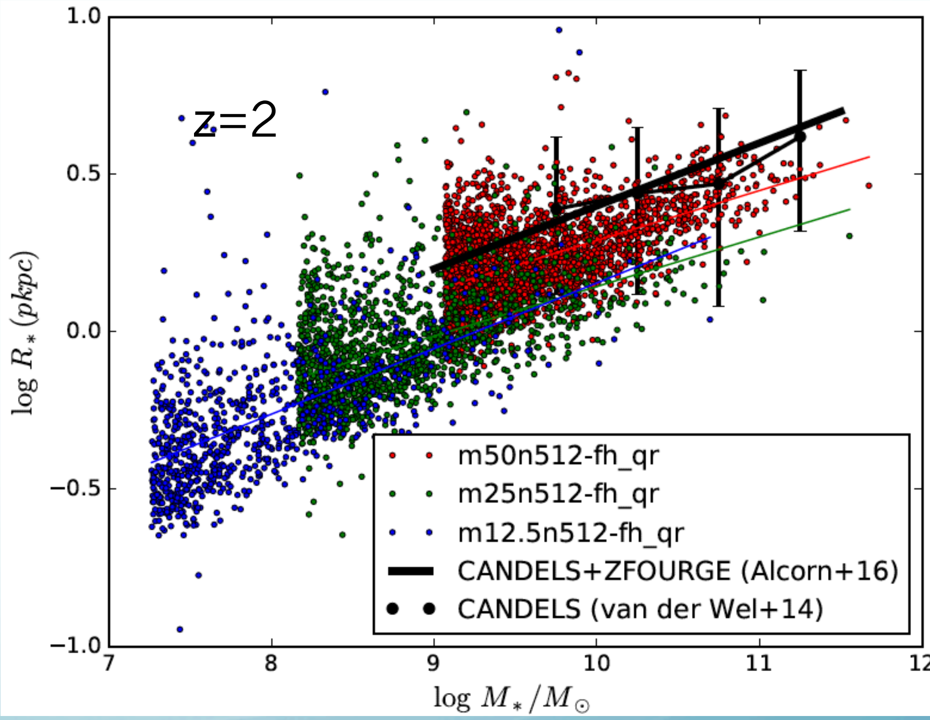


LOSER: https://bitbucket.org/romeeld/closer

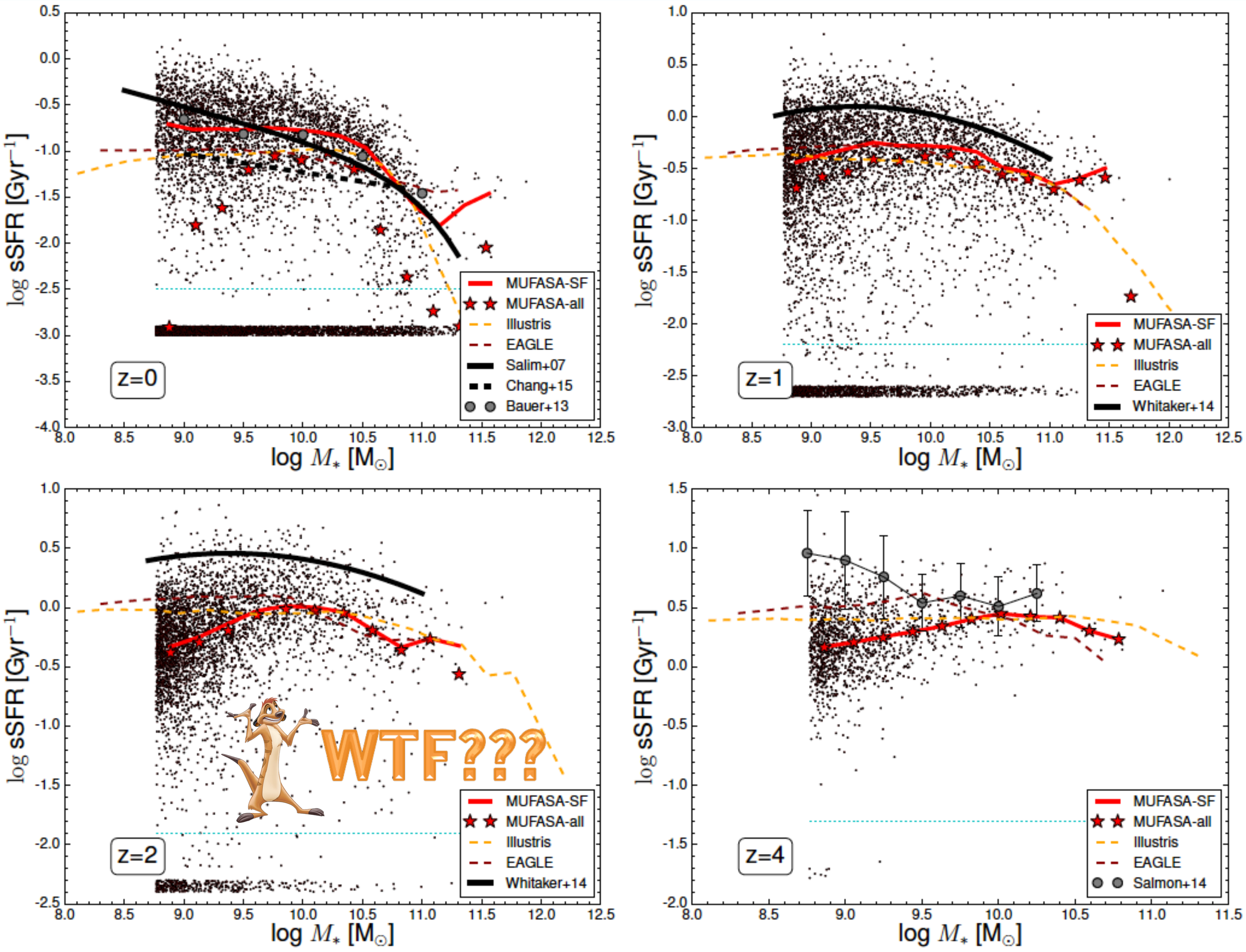
Galaxy Sizes

- $R_{1/2,*}$ a bit too small at high-z, OK at low-z
- Not great resolution convergence, but perhaps Illustris/EAGLE resolution is ok.



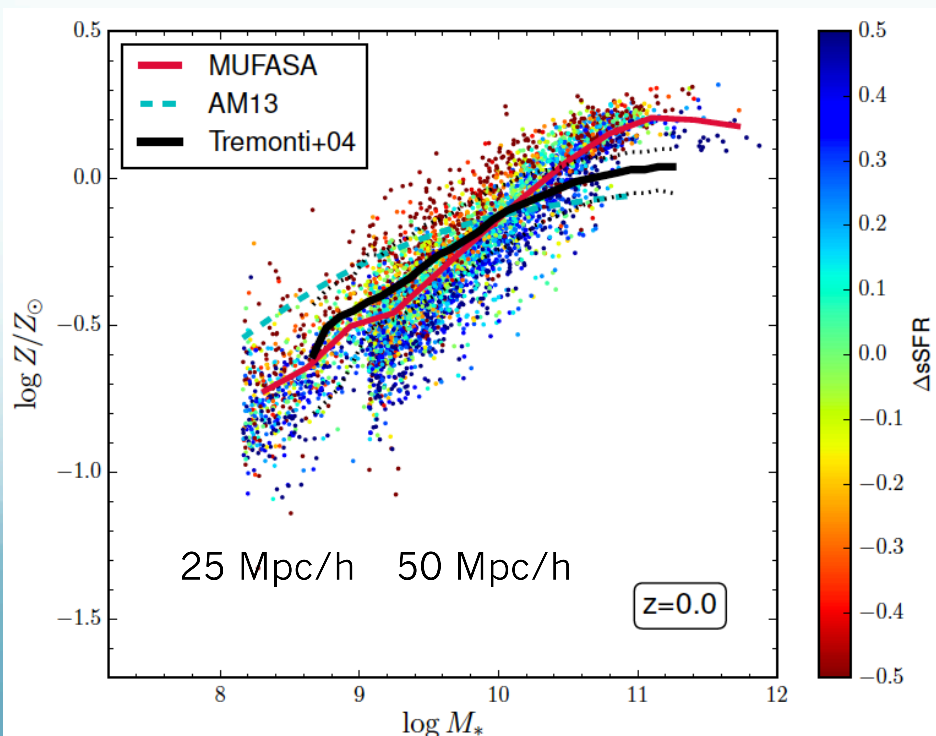


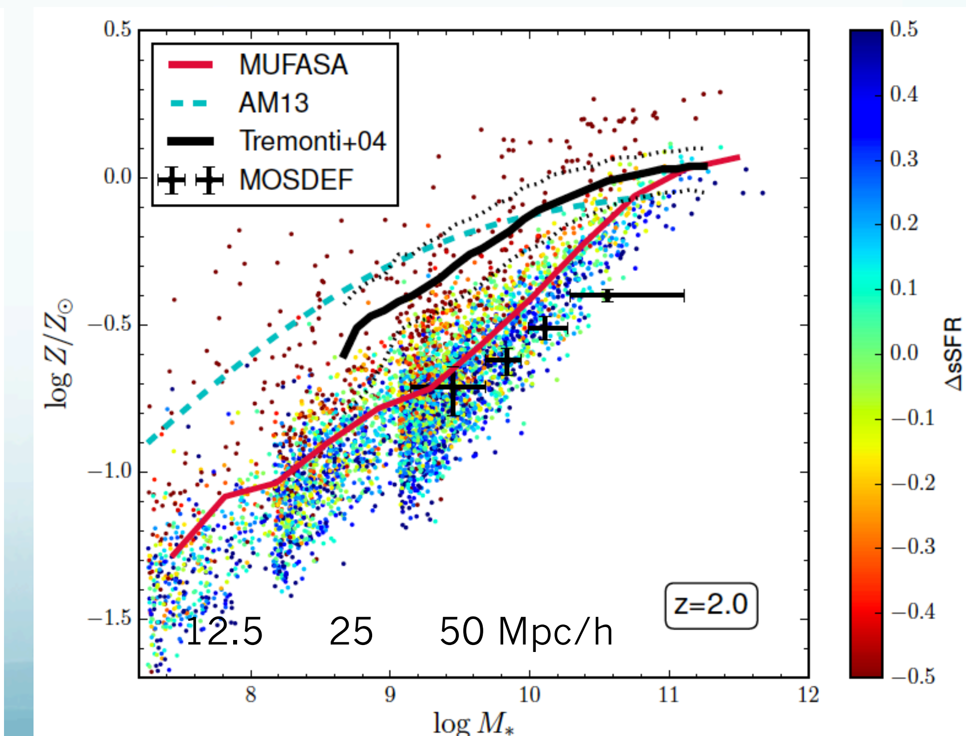
Main sequence evolution



Mass-Metallicity

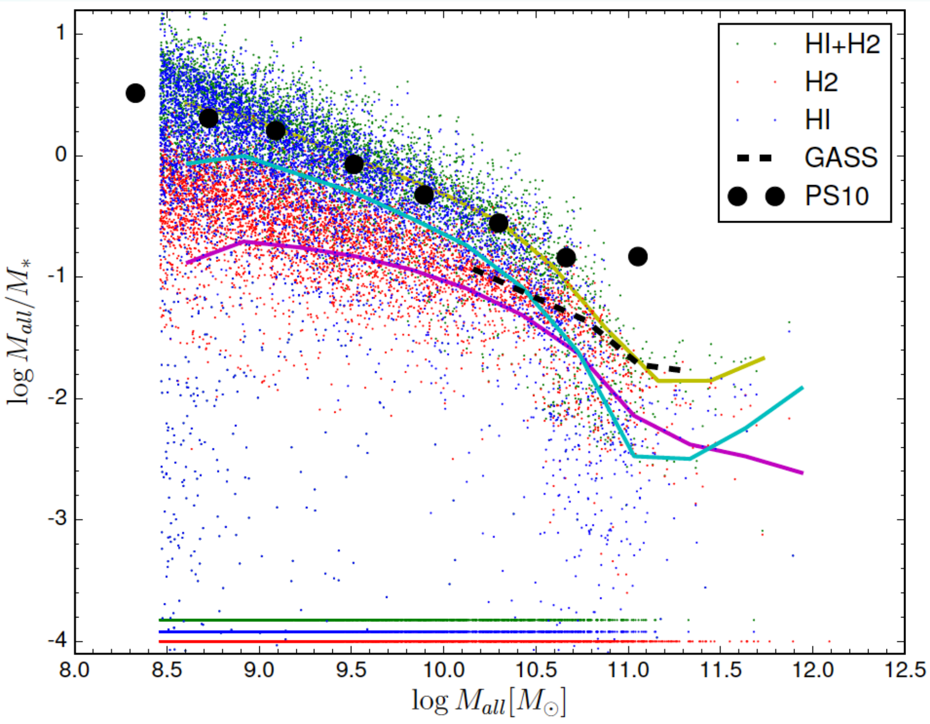
- SNII yields (Limongi&Chieffi) x0.5.
- Stellar mass from star particles vs. SFR-weighted gas oxygen abundance.
- Too steep at $M_{*}>10^{10}$
- Shows "fundamental metallicity relation"

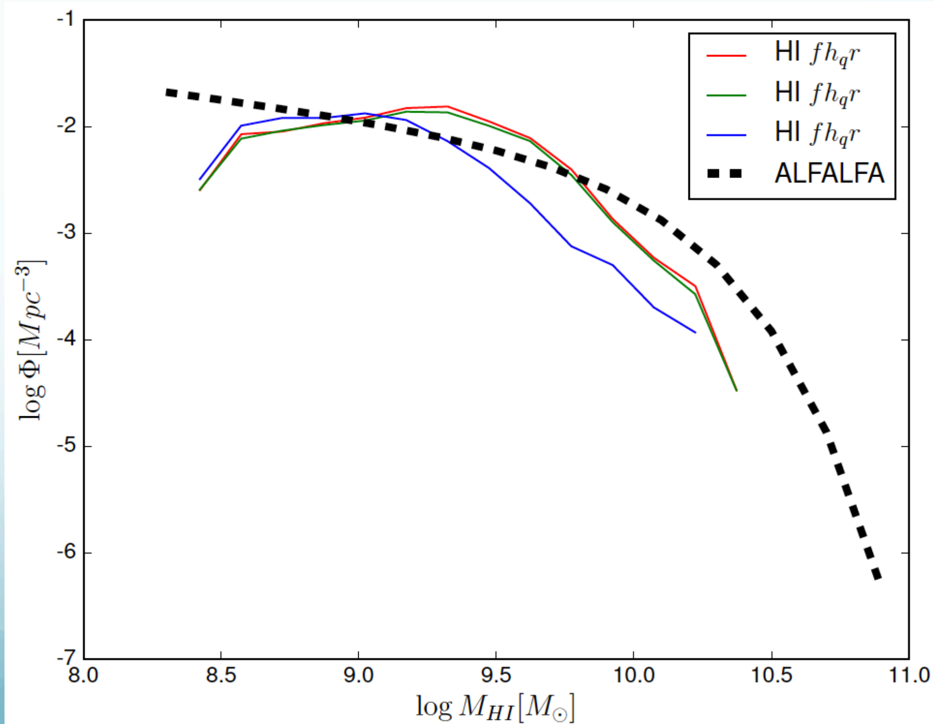




HI & H2 content

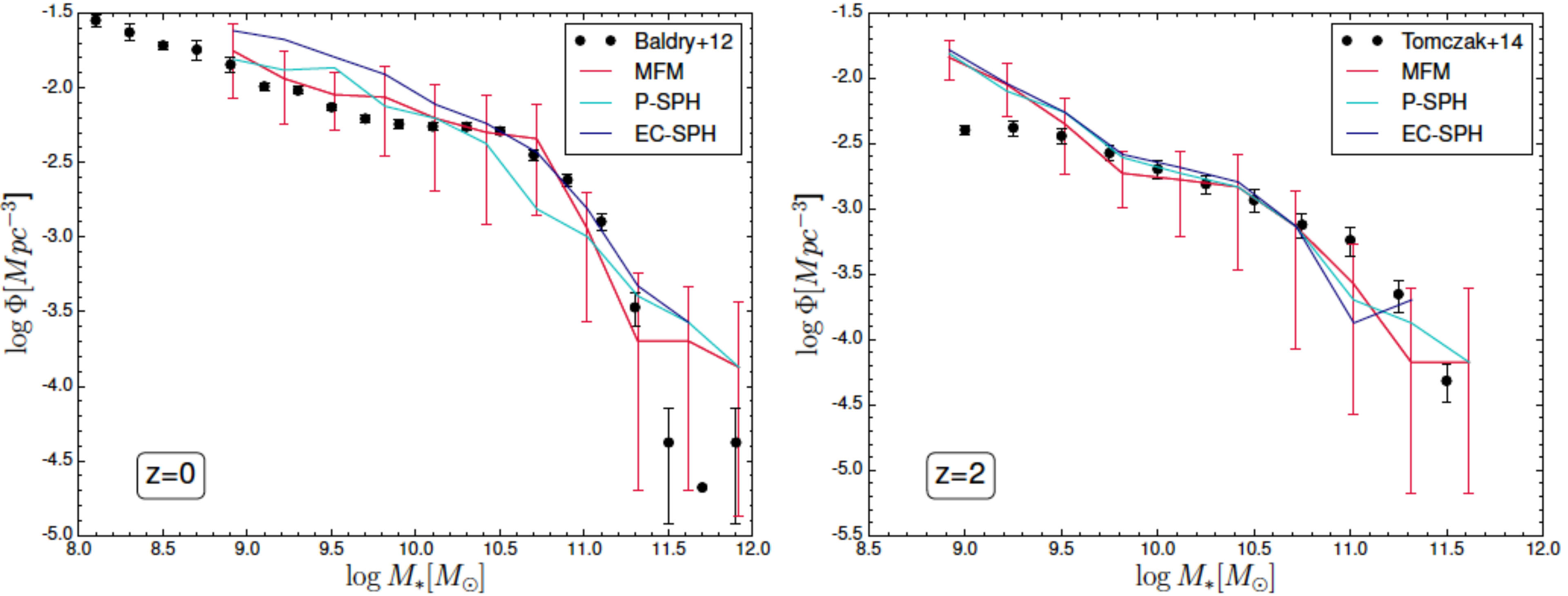
- Need to post-process self-shielding; differences.
- Total gas & HI are in reasonable agreement, but HIMF looks cut off at high & low masses.
- H_2 looks low; possible tweaks needed to H_2 model





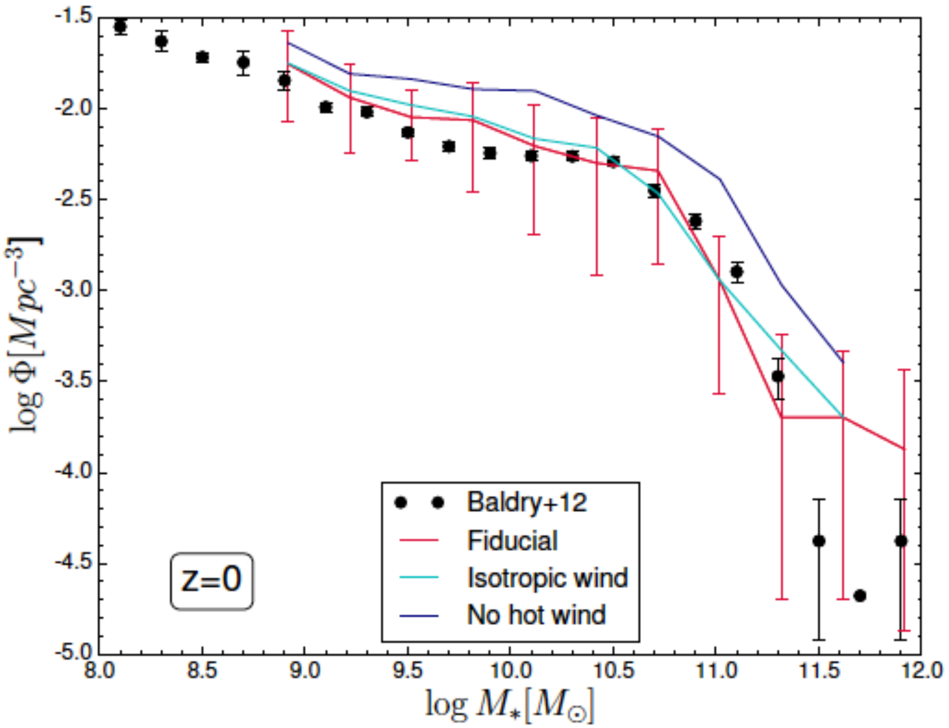
Does Hydro Matter?

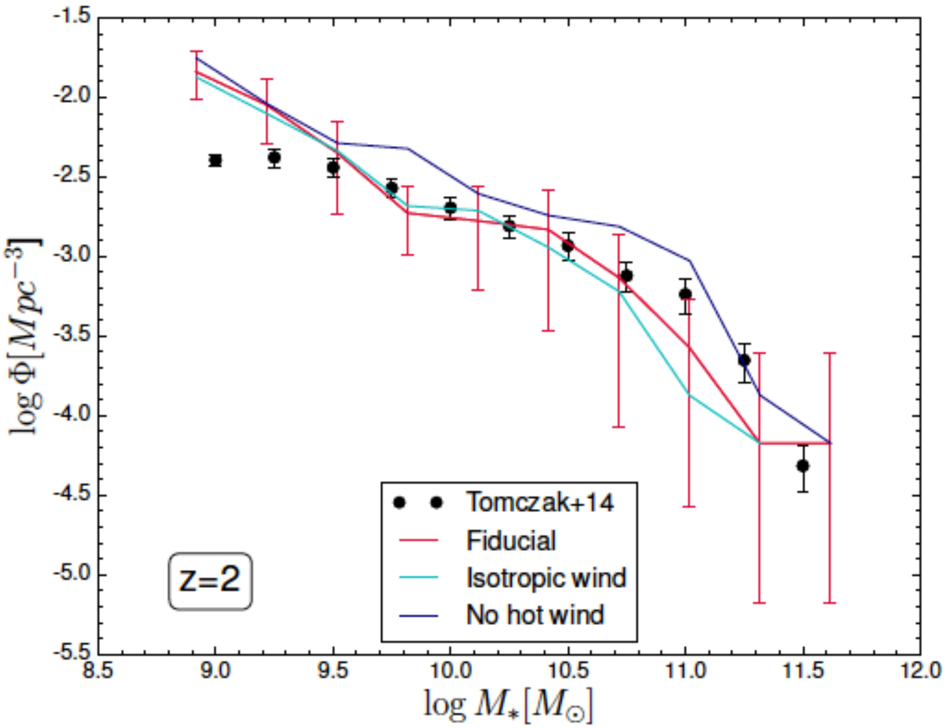
- Mostly at low-z, when recycling happens
- Not a generic trend: Likely dependent on outflows



Hot outflows

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





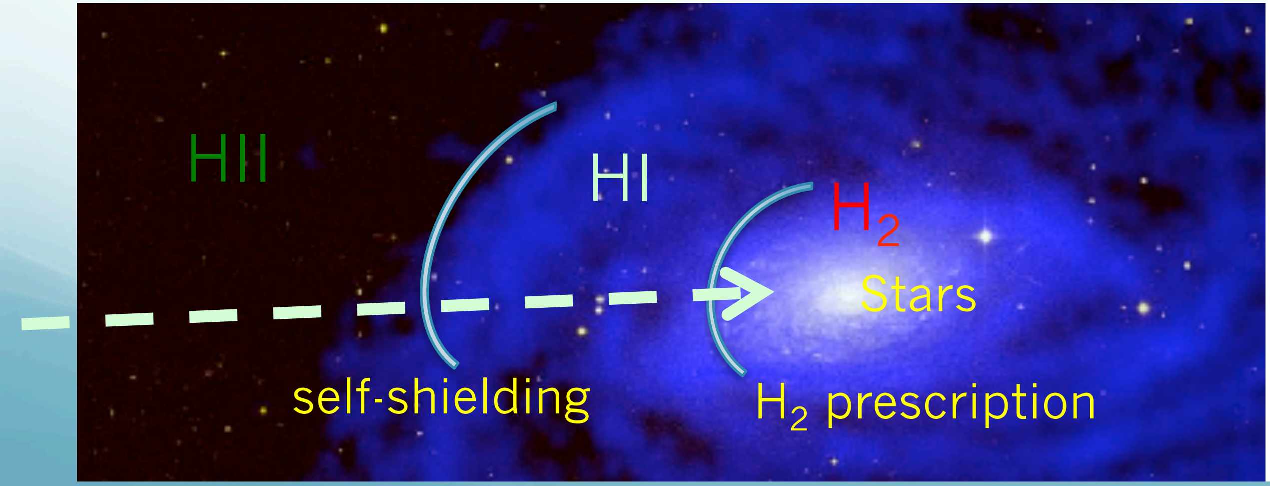
The Sequel

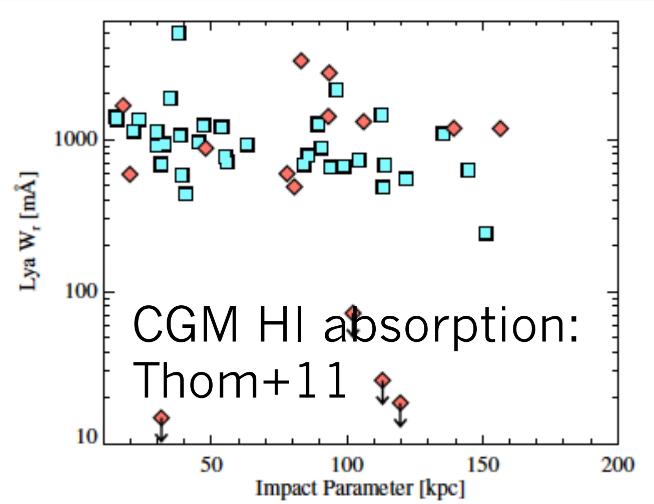
- A more physical BH model using Daniel's torque-limited accretion, with kinetic feedback.
- Quenching via a low-f_{Edd} reservoir with periodic bursts (Fabrice) – *keep the knee!*
- Improve sub-grid thermal outflow model.
- MW zooms, group zooms, cluster zooms… dwarf zooms vs. FIRE?
- Do science.
- Profit.


HAKUNA MATATA

The Trouble with Hydrogen

- HI is not a direct prediction of models! Must subdivide H gas into ionized, neutral, molecular.
- So far, fairly simple self-shielding & H_2 prescriptions have been used.
- Crucial issue: CGM neutral gas. There's a lot! Cold cloud masses may be $\sim 10^{3\text{-}4} M_\odot$ (Crighton+15) << anything sims can resolve.





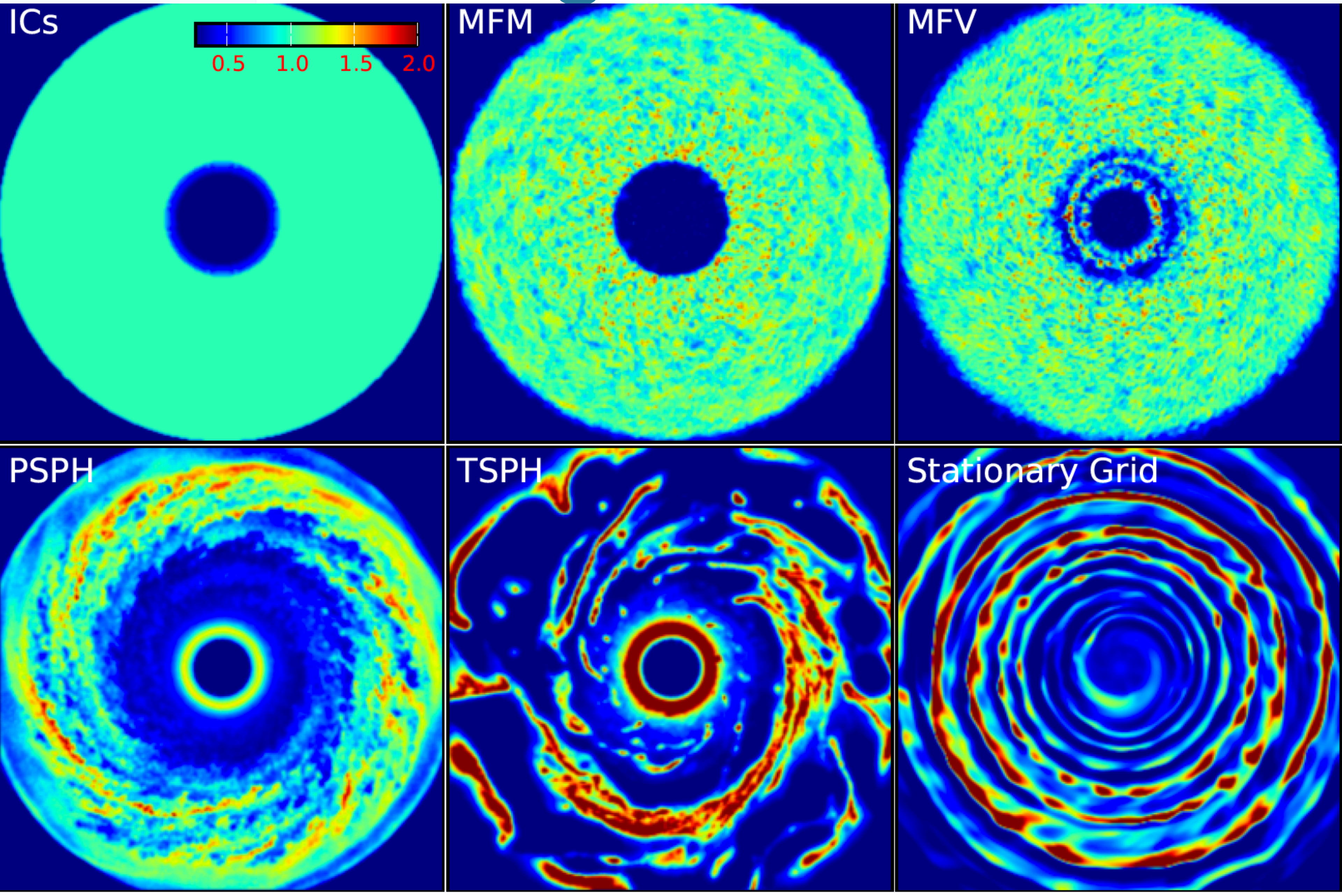
SPHGR(-yt)

(Robert Thompson)

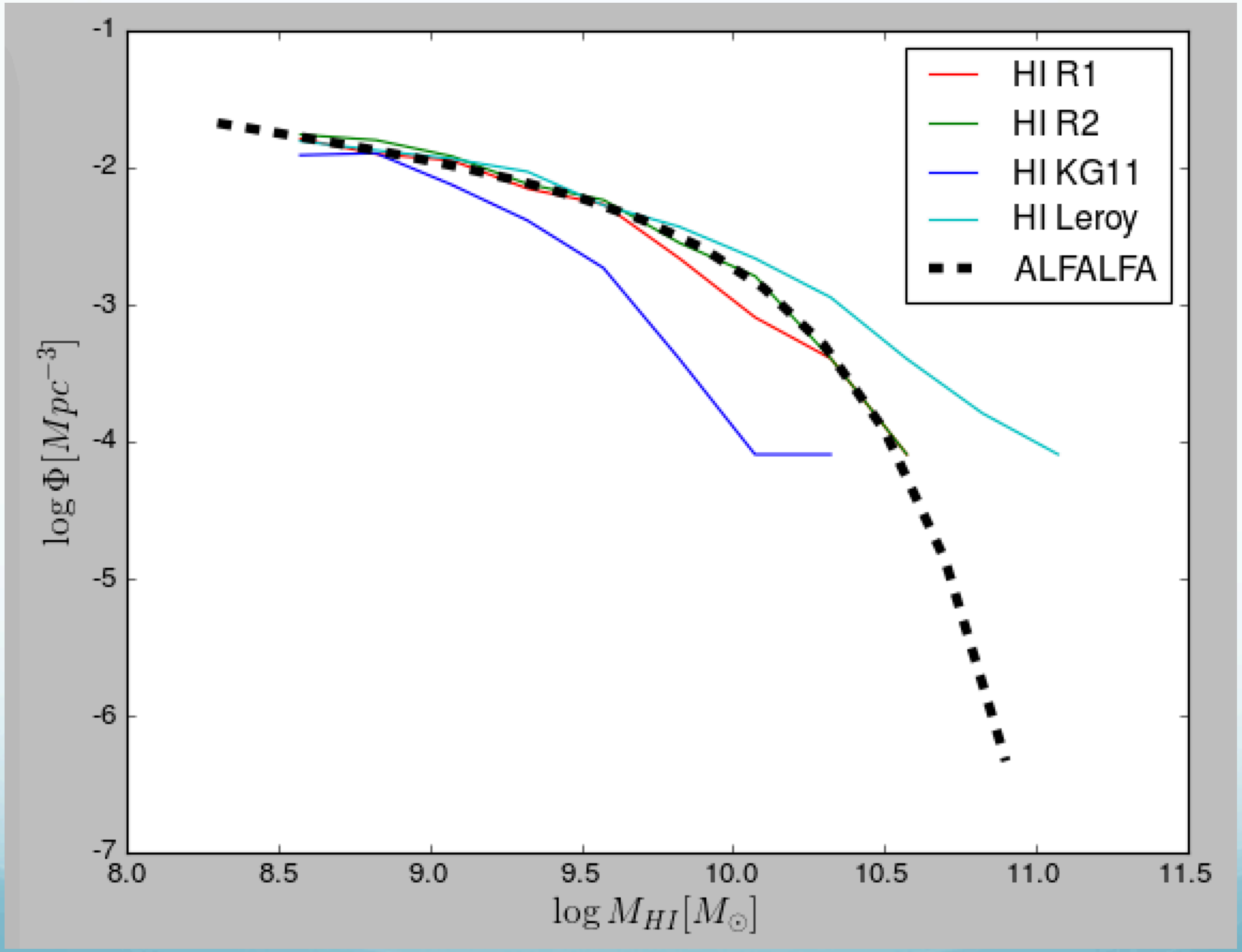
- SPHGR: "One-touch" galaxy catalog generation from a simulation snapshot (written in Python).
- Now incorporating into the *yt* package (SPHGR-yt), which adds much more functionality.
- Runs galaxy finder, halo finder, cross-correlates.
- Creates hdf5 file containing galaxy catalogs at every snapshot (redshift), including all galaxy properties e.g. M_*, SFR, M_{HI}, Z, **J**, $r_{1/2}$, ..., also with halo info.
- Magnitudes/spectra using LOSER. Merger trees, movies... *Light cones?*

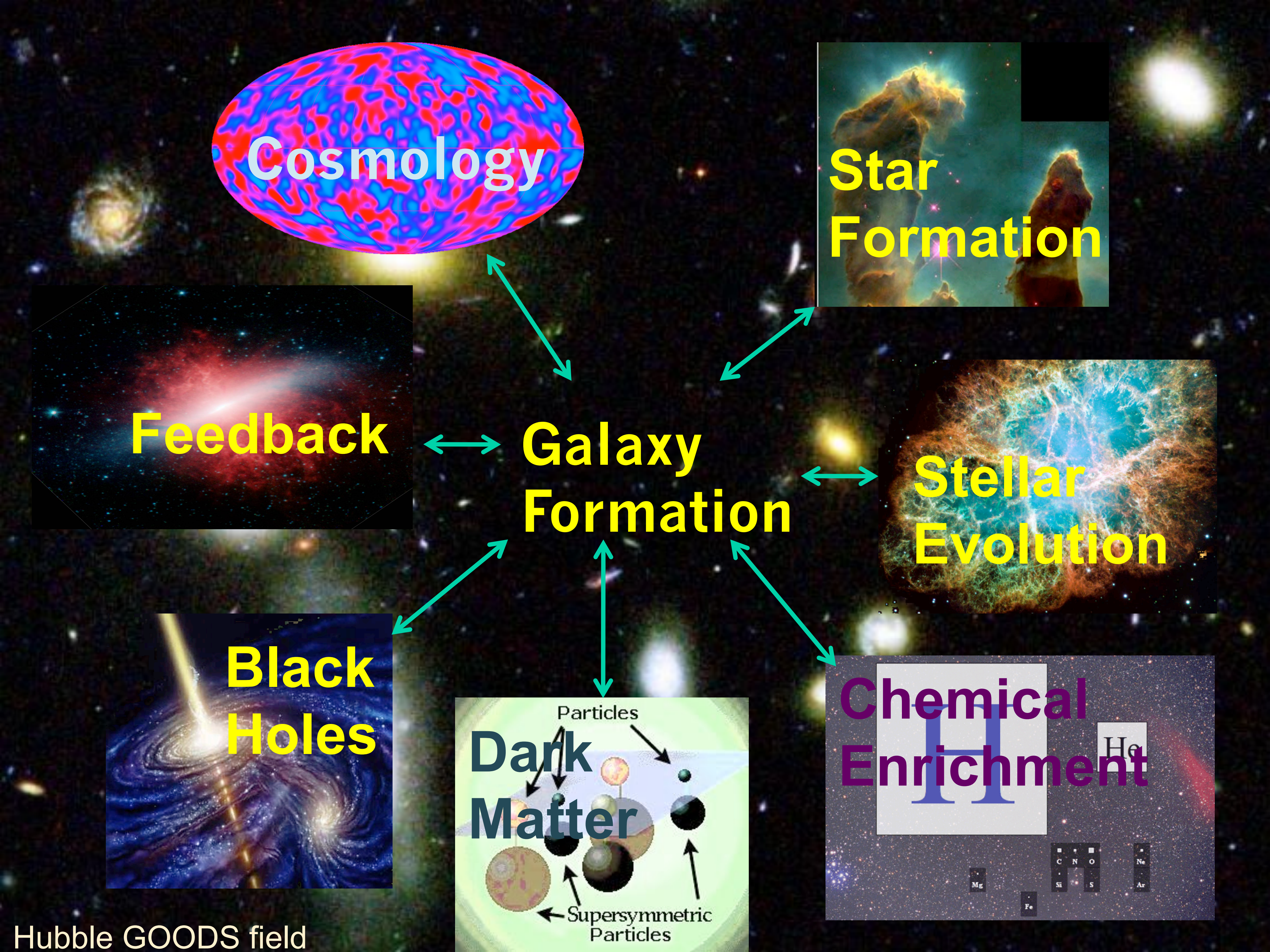
https://bitbucket.org/rthompson/sphgr

Advantages of GIZMO

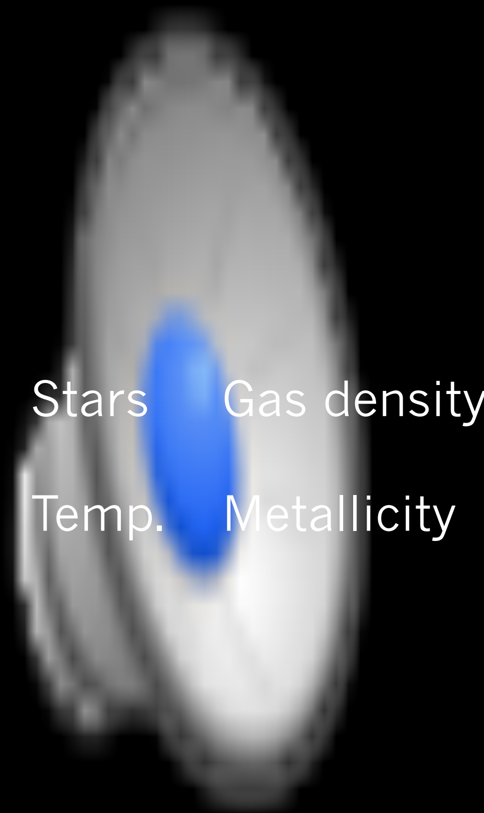


Wanna see something *really* scary?



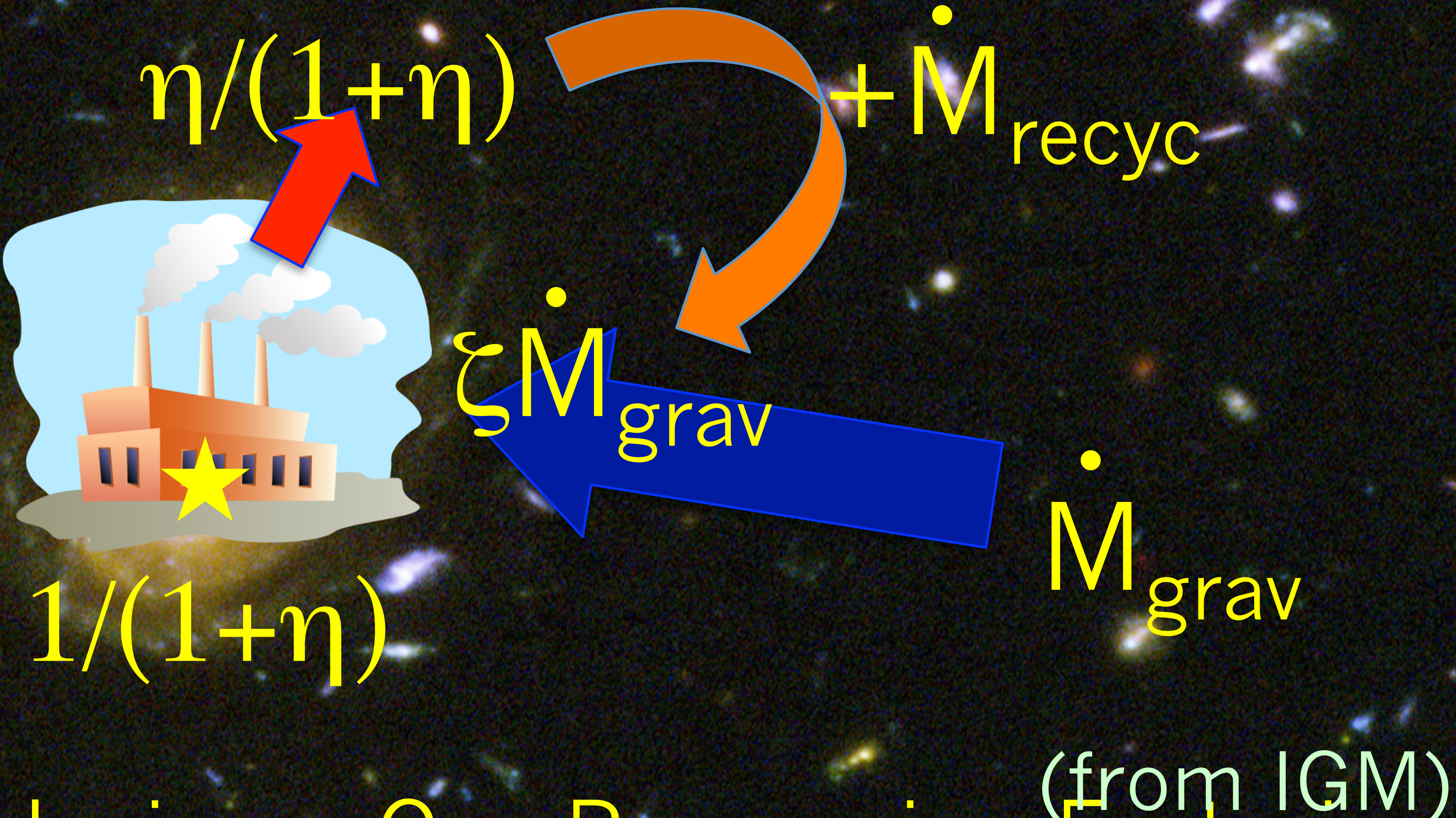

Cosmology
Star Formation
Feedback
Galaxy Formation
Stellar Evolution
Black Holes
Particles
Dark Matter
Supersymmetric Particles
Chemical Enrichment
H
He
Hubble GOODS field

Includes:
Gravity
Gas (moving mesh)
Star formation
Photoionizing bkgd
Black hole growth
10-species chemistry
Type II SNe feedback
Type Ia SNe feedback
AGB stellar evol
AGN feedback



~6 billion cells
1 kpc resolution
100 Mpc volume

The Illustris Project: AREPO



Galaxies = Gas Processing Factories

$$SFR = (\zeta\dot{M}_{grav} + \dot{M}_{recyc})/(1+\eta)$$

$$Z = y\ SFR/\zeta\dot{M}_{grav}$$

Finlator+08
Bouché+10
Davé+11,12
Lilly+13
Dekel+14

Parameterize, Bayesian MCMC

- Turns out we need 8 parameters (Bayesian evidence analysis shows that removing any more is not preferred):

Mitra+14

$$\eta = \left(\frac{M_h}{10^{\eta_1+\eta_2\sqrt{z}}}\right)^{\eta_3}$$

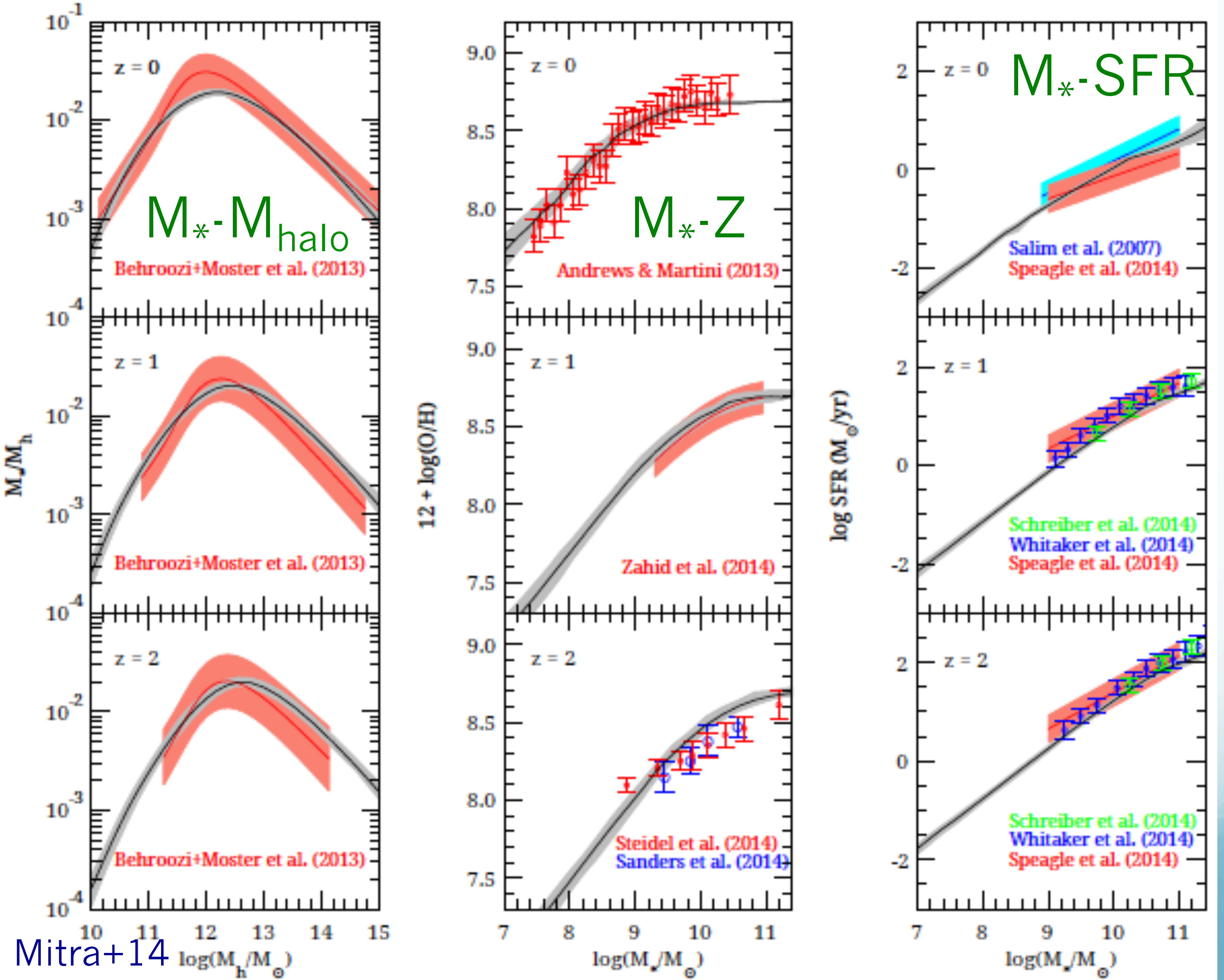
$$\zeta_{\rm quench} = {\rm MIN}\left[1, \left(\frac{M_h}{M_q}\right)^{\zeta_1}\right], \frac{M_q}{10^{12}M_\odot} = (0.96+\zeta_2 z).$$

$$t_{\rm rec} = \tau_1 \times 10^9 {\rm yr} \times (1+z)^{\tau_2}\left(\frac{M_h}{10^{12}}\right)^{\tau_3}$$

Observational Constraints

- M_*-M_{halo} (equivalent to GSMF, z=0-2): Inferred from GSMF(z~0-6) data, consistent w/SFR evol. [Behroozi+13, Moster+13].
- Mass-Metallicity relation: Now seen out to z~2 thanks to Keck/Mosfire. [Steidel +14,Sanders+14]
- SFR-M_* (z=0-2): Recent compilation with consistent calibrations from Speagle+14. [also Whitaker+14,Schreiber+14].

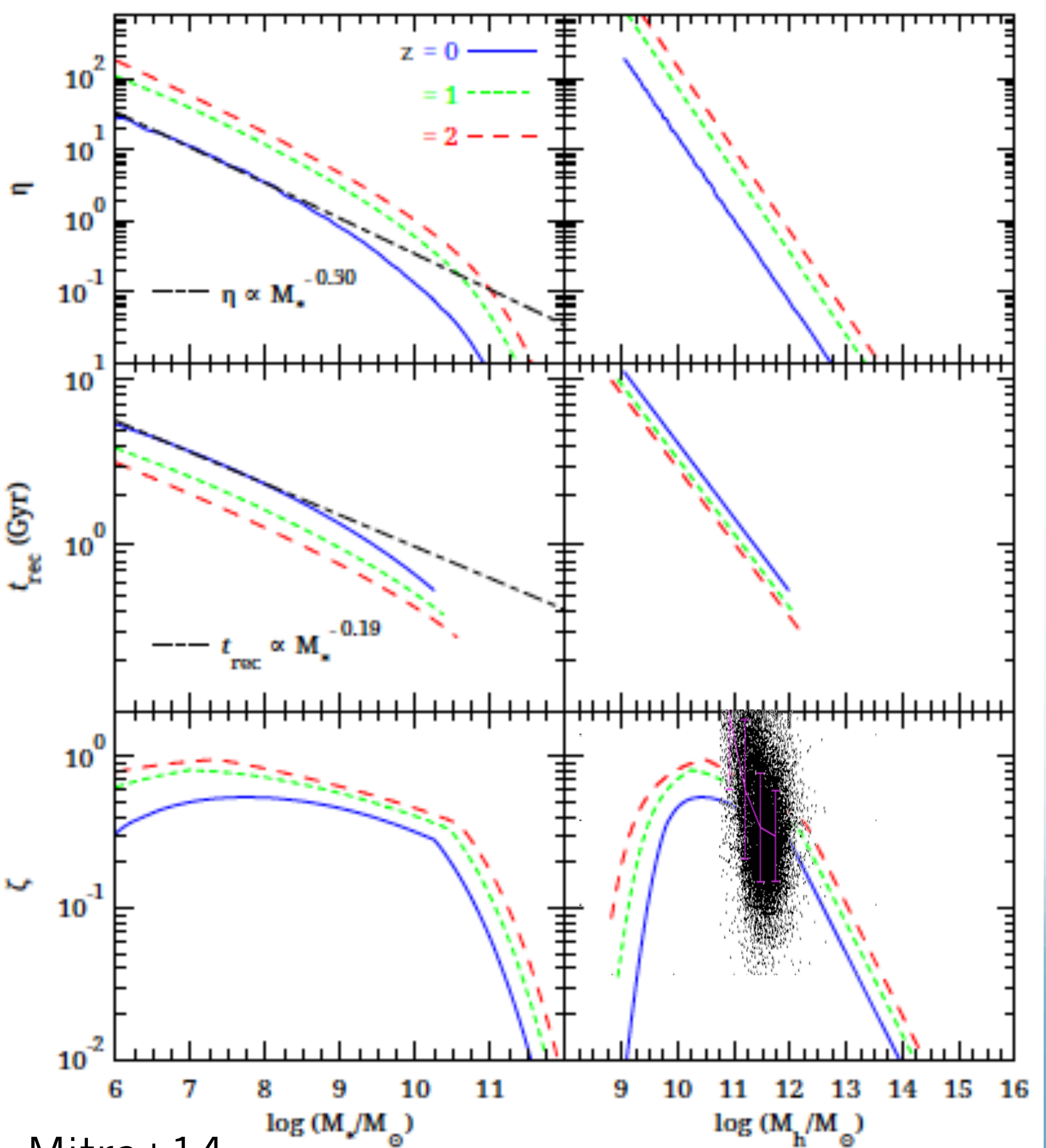
(χ^2~1.6)



Mitra+14

Outflows stronger in low-mass galaxies

- $\eta \sim M_h^{-1.2} \sim M_*^{-0.3}$
- Stronger at hi-z
- FIRE (Muratov +15): $\eta \sim M_*^{-0.35}$, amplitude like at z~2 but invariant w/z.
- $t_{rec} \sim M_h^{-0.45} \sim M_*^{-0.2}$
- Opp,RD+08, 10 best-fit hydro sims: $t_{rec} \sim M_h^{-0.5}$



Mitra+14