The *Gestalt* of Galaxy Formation

ge·stalt

/gəˈSHtält/

noun PSYCHOLOGY

an organized whole that is perceived as more than the sum of its parts.

from F. Governato

Romeel Davé

Outline

- *Id:* Ingredient of modern galaxy formation models

noun PSYCHOANALYSIS
noun: **id**; plural noun: **ids**

the part of the mind in which innate instinctive impulses and primary processes are manifest.

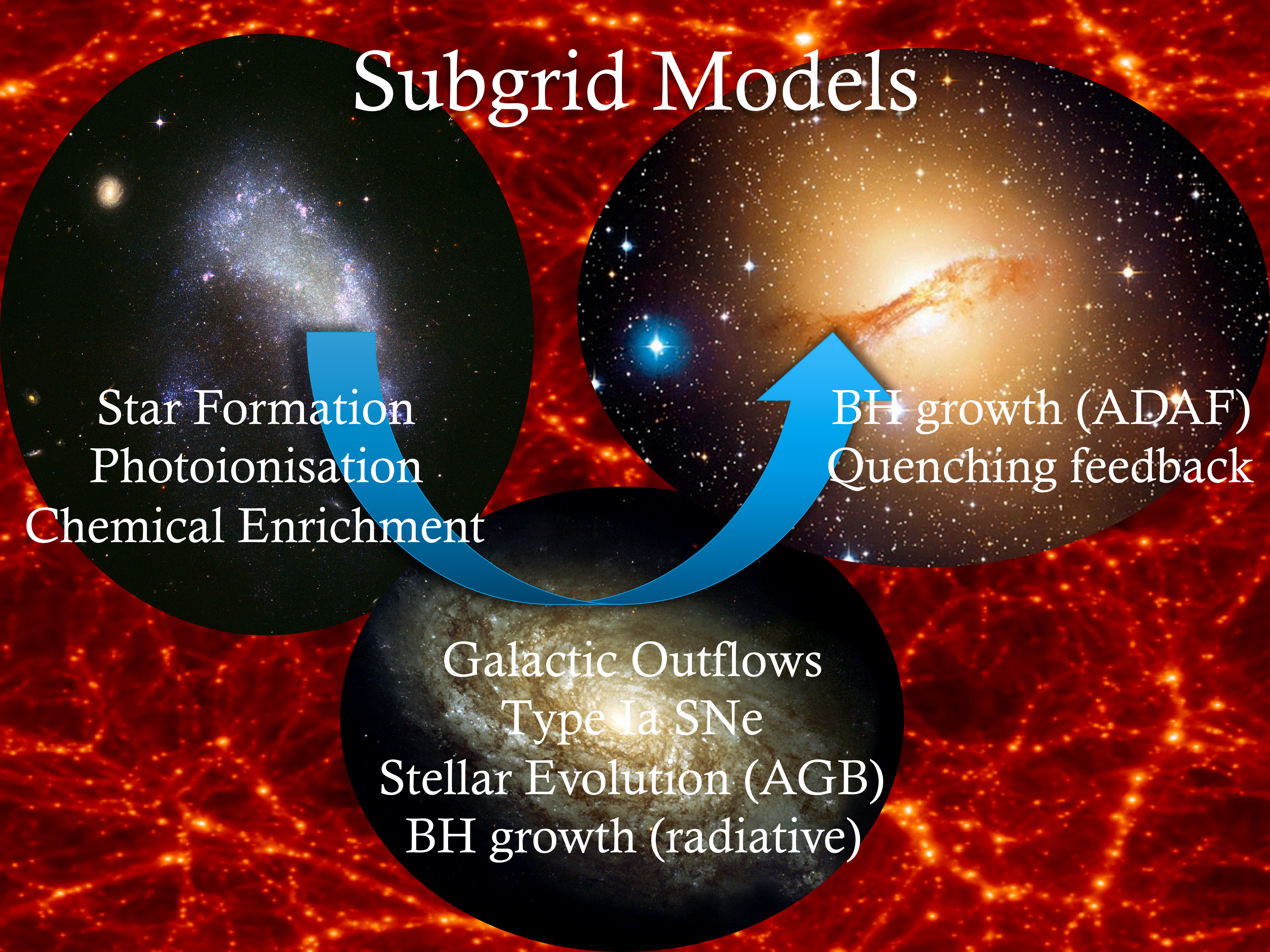
- *Ego:* Key observational comparisons

PSYCHOANALYSIS
the part of the mind that mediates between the conscious and the unconscious and is responsible for reality testing and a sense of personal identity.

- *Angst:* What are the most pressing questions & problems?

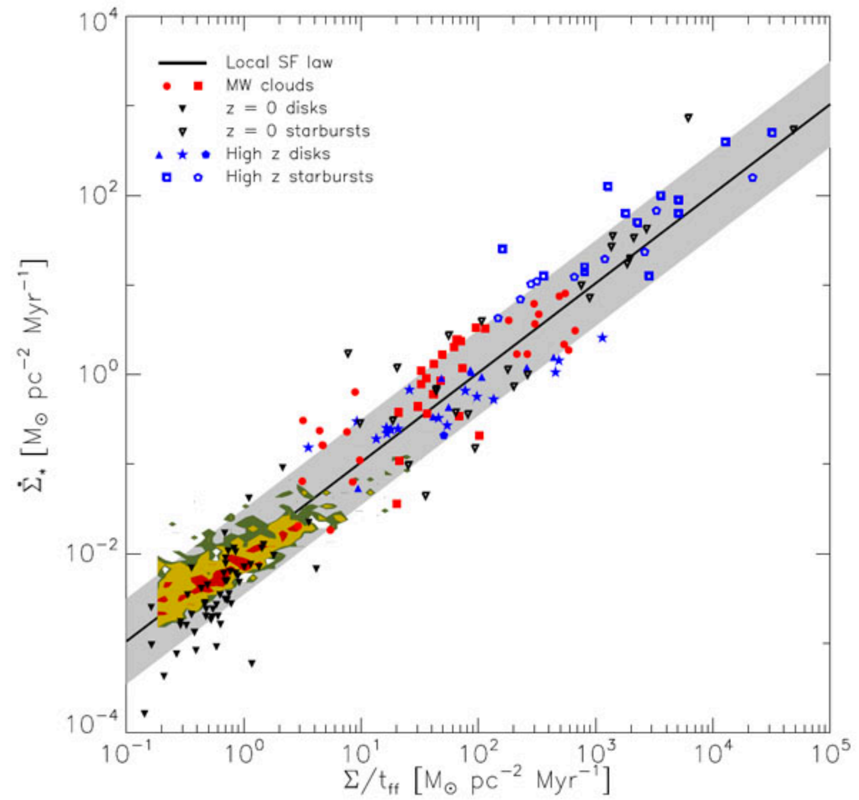
noun

a feeling of deep anxiety or dread, typically an unfocused one about the human condition or the state of the world in general.


Subgrid Models
Star Formation
Photoionisation
Chemical Enrichment
BH growth (ADAF)
Quenching feedback
Galactic Outflows
Type Ia SNe
Stellar Evolution (AGB)
BH growth (radiative)

Classic Star Formation

- Schmidt (1959) Law: $\rho_{SF}=\varepsilon_*\rho_{gas}/t_{dyn}\sim\rho_{gas}^{1.5}$
- Observed ε_* ~0.02. Luckily, this matches observations! $\Sigma_{SFR}\sim\Sigma_{gas}^{1.4}\sim\Sigma_{gas}/t_{dyn}$. (note that this t_{dyn} is for the *disk*).
- Use a threshold density – in cosmological sims, ~0.1 cm^{-3}.
- This is often called a *Kennicutt-Schmidt SF prescription*
- First implemented by Katz & Gunn (1991), standard till ~2010

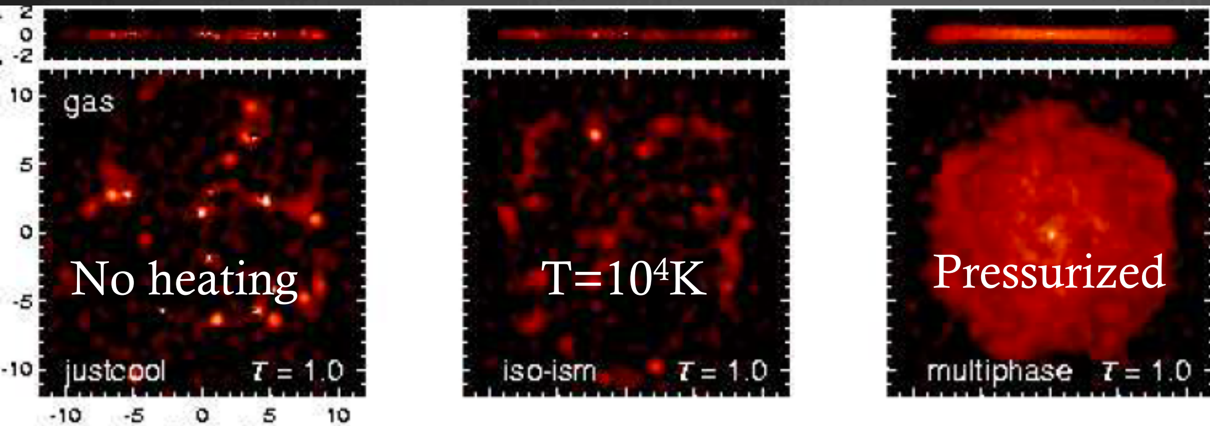


…But stars form from H_2!

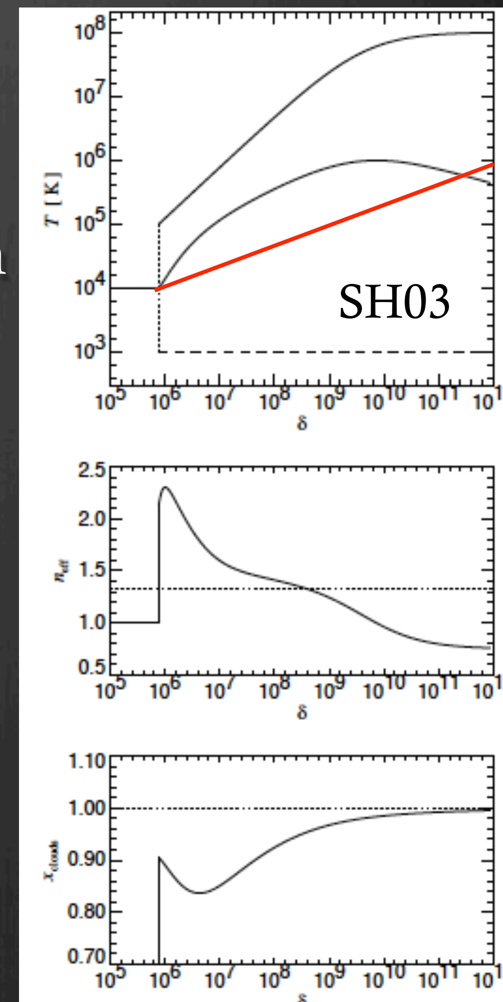
Modern Star Formation

- Dense gas: Use n_{thresh}~10-100 cm^{-3}. [RAMSES and others]
- Pressure-based SF: $\rho_{SFR} \sim \rho_{gas} P^{0.2}$ (derived from K-S), with Z-dependent n_{thresh}. [EAGLE; Crain+15]
- Subgrid H_2: [MUFASA; RD+16 and others]
  - Subgrid analytic model for $f_{H2}(\rho, \mathrm{grad}\ \rho)$ from Krumholz+.
  - Use ρ_{H2} instead of ρ_{gas} in K-S prescription.
- H_2 tracking: [GASOLINE; Christensen+14]
  - Interstellar LyW radiation field, via tree walk
  - H_2 chemical network (now available in Grackle)
- Turbulence-based criterion. Based on high-res ISM sims, but requires proper calculation of $c_s \sim T^{0.5}$ [Semenov+15]

The M_J Dilemma: ISM Pressurization



Robertson+04:
z=0 disk



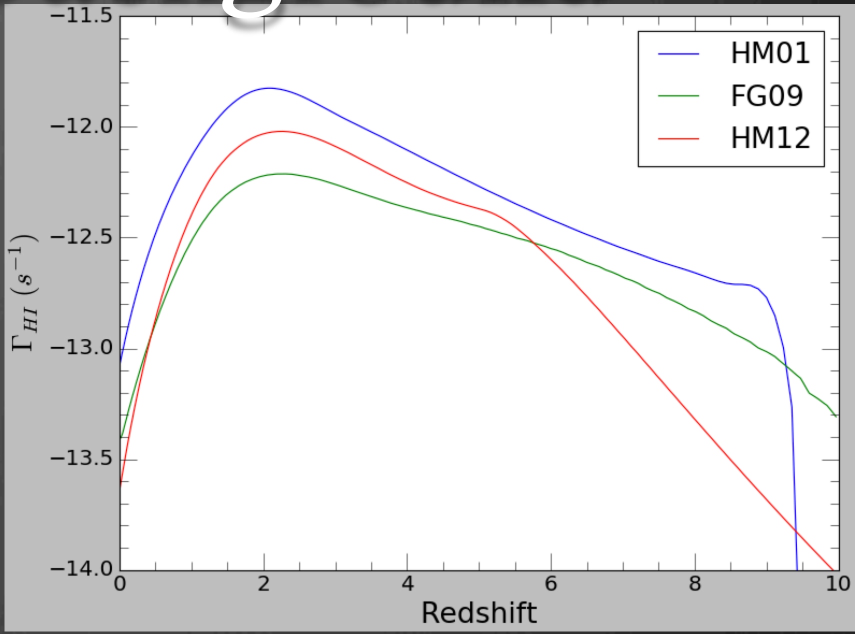
Without pressurization, get artificial fragmentation because Jeans mass is (way) unresolved.

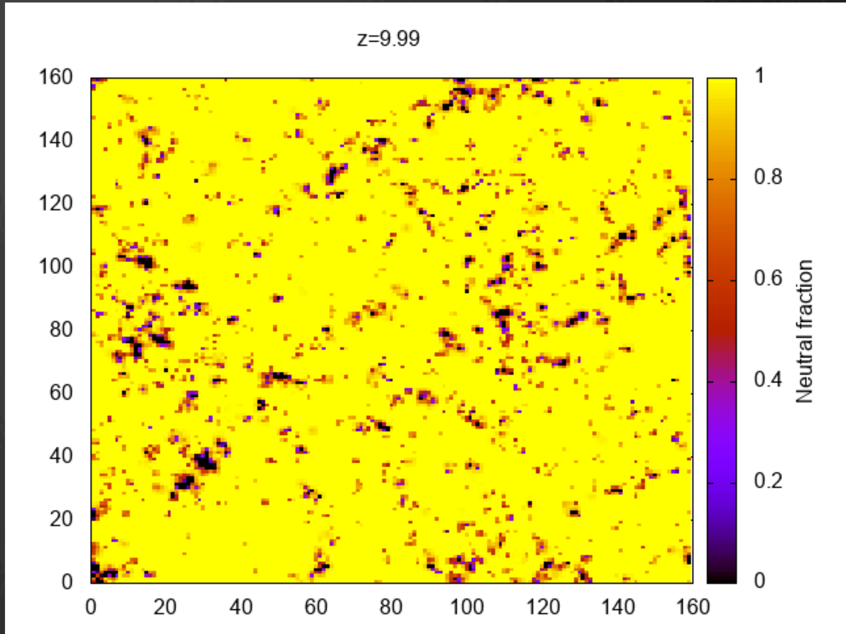
- Springel+Hernquist 03: Based on McKee +Ostriker 77, analytically split each SF-ing particle into "hot" (~10^8) and "cold" (T~10^3) component.

- Schaye+Dalla Vecchia 08: T~$\rho^{1/3}$ (keeps M_J marginally resolved). Less pressure than SH03. Applied for $n>n_{thresh}$.

Photoionising background

- Most cosmological sims assume spatially-uniform J_ν: Haardt +Madau (2001,2012), Faucher-Giguere+ (2009).
- Self-shielding in dense regions: $J_{\nu,\mathrm{eff}}(\rho)$. Doesn't impact dynamics very much, so mostly OK in post-processing.
- Radiative transfer (EoR):
  - Ray tracing/Monte Carlo
  - Moment method, closed via M1, OTVET, long char.
  - ARTIST (our new method; ask me)





Chemical Enrichment

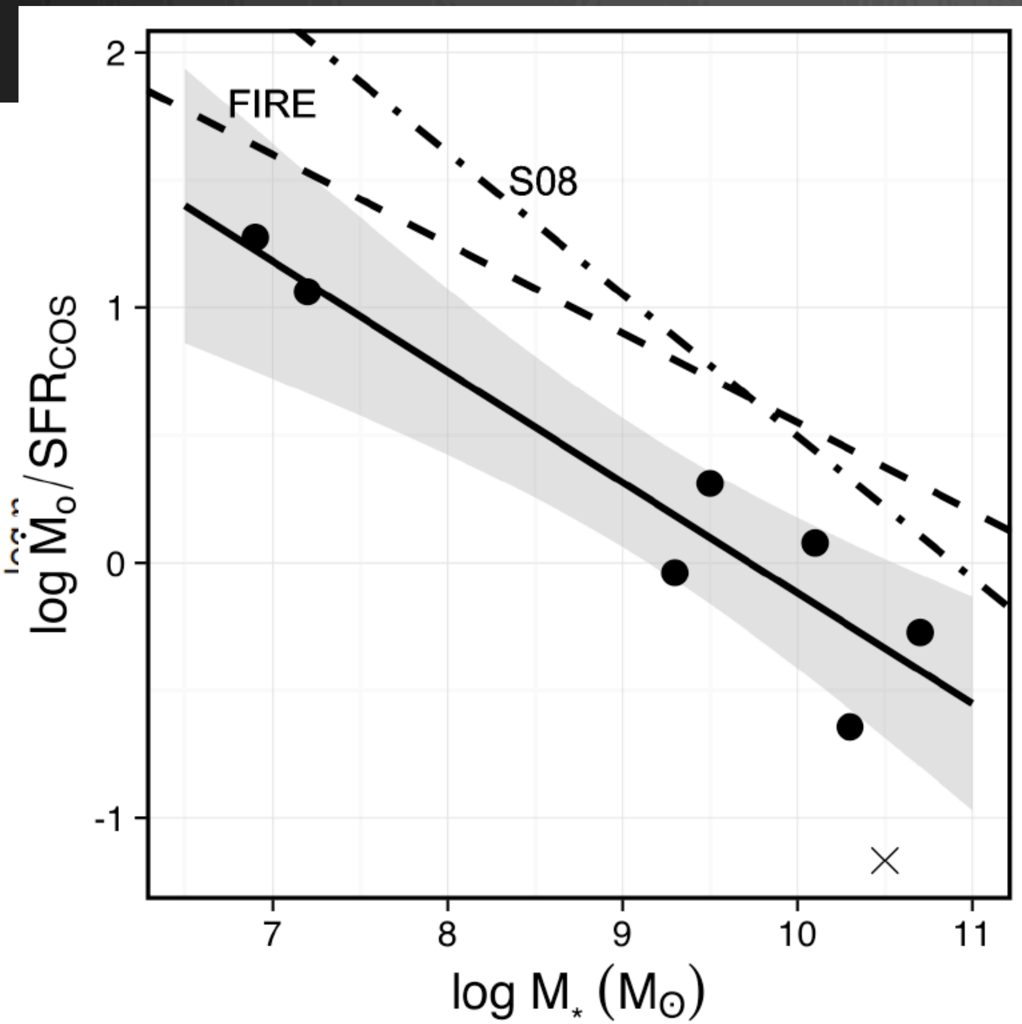
- Type II SNe: From OB stars (<~30 Myr). α-enhanced: Si, Ca, Mg, O are multiple-of-4 isotopes so particularly stable.
  - Instantaneous approx: Gas self-enriches while SF-ing.
  - SNe tracking: track stellar evolution at t~Myr; can be expensive.
- Type Ia SNe: From WD mass transfer/merger; >~10^8 yr. High in Fe, so [a/Fe] represents an *enrichment clock*.
  - Can be modeled as a "prompt" (instantaneous) vs. "delayed" component (after some delay time).
  - "Delay time distribution" – $N_{Ia}(t) \sim t^{-1}$, t>700 Myr.
- AGB stars: From long-lived stars; >~10^9 yr. High in Carbon, so much of the carbon at late epochs from this.
  - Metals added to surrounding gas based on Stellar Population Systhesis (SPS) model, e.g. Bruzual & Charlot or FSPS.

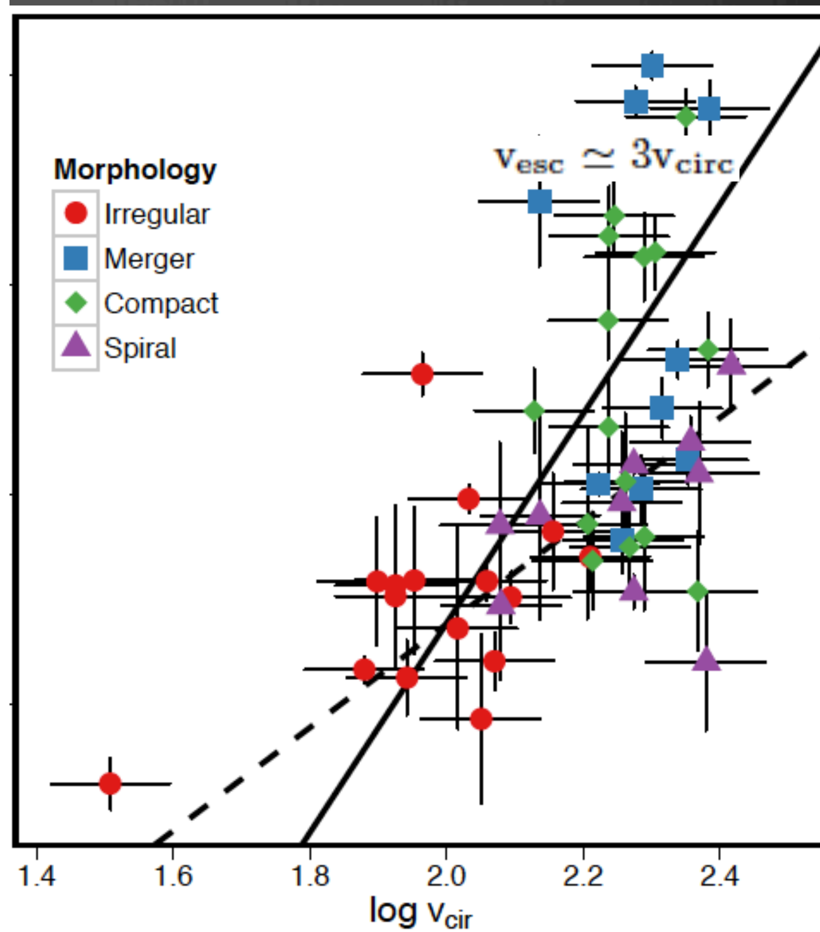
All yields are uncertain by typically ~x2!!

Galactic outflows

- *Thermal:* Add heat to surrounding (dense) gas. Immediately cools so ~no effect! [Katz+Gunn 91, up thru ~2000]
- *Cooling shutoff:* Turn off for Sedov-Taylor blast wave timescale, assuming this can't be resolved [Gasoline]. Alternatively, store E until T becomes high enough so cooling timescale is long [EAGLE].
- *Kinetic:* Kick gas with some velocity v_w, with a mass loading factor η
  - SH03: Constant η=2 v_w~500 km/s gets cosmic SFRD(z) roughly right.
  - Oppenheimer+RD 06,08: momentum-driven wind scalings ($v_w \sim v_{circ}$, $\eta \sim v_{circ}^{-1}$) as expected from radiative feedback (Murray+05) and observed (Martin+05) works better for galaxies + IGM.
  - Zoom/high-res sims can predict these quantities (Muratov+15, Christensen+16), so can use these scalings directly [e.g. MUFASA].
  - NOTE: Wind fluid is generally *not subject to hydro forces* ("decoupled") until they escape from ISM.

Observations of outflow scalings





$\eta \propto M_*^{-0.58}$

$v_{90} = [38 \pm 22.4 \text{ km s}^{-1}]\ v_{circ}^{0.46\pm0.12}$

$\dot{M}_o \propto SFR^{3/4} M_*^{-1/3}$

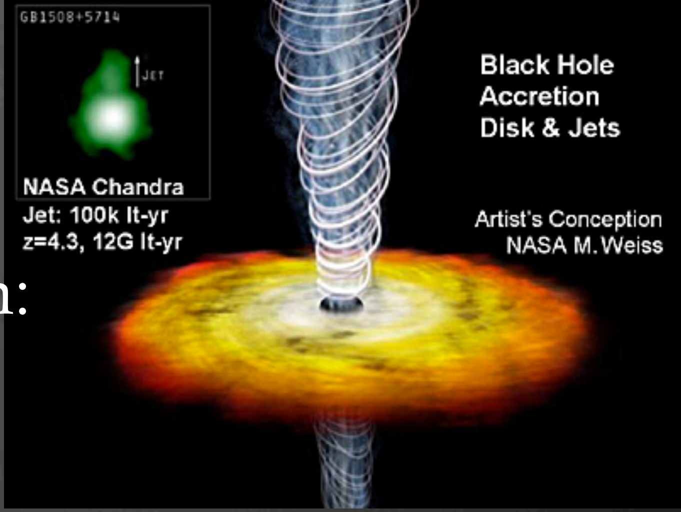
BH seeding, merging, positioning

- Seeding: How do first BHs form?
  1. Start at ~10^5 $M_\odot$ (i.e. about the resolution of 1 particle), since that represents simulation resolution – most use this.
  2. Start from massive low-Z stars (~100 $M_\odot$), allow merging -- need super hi-res, end up with lots of BH. (Bellovary+ in Gasoline).

- Merging: What happens when BHs come near each other?
  1. Merge instantaneously when within each other's softening length.
  2. Include subgrid model to follow inspiral (LISA predictions).

- Positioning: How can we keep BHs in galaxy centers?
  1. Reposition BH on potential minimum every timestep.
  2. Include strong drag term (e.g. overmassive BH) or high dynmaical mass to simulate the deep potential well.
  3. Do nothing – and end up with lots of wandering BHs!

BH Accretion: Bondi



Gravitational capture from a hot medium:

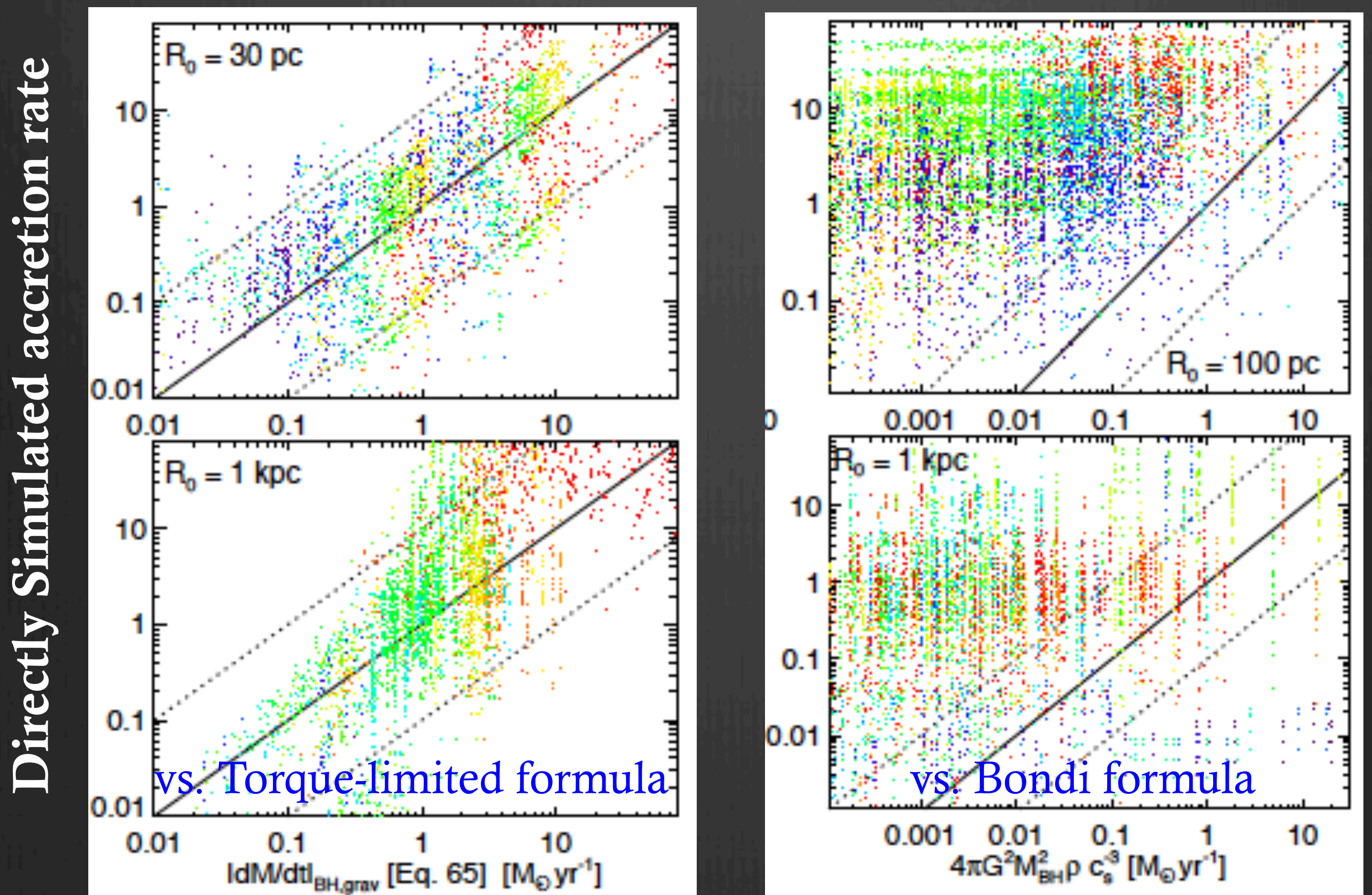
$$\dot{M}_{\rm Bondi} = \alpha \frac{4\pi G^2 M_{\rm BH}^2 \rho}{(c_s^2 + v^2)^{3/2}}$$

- Very successful model (Springel+05, di Matteo+07), grows BHs in accord with M-σ, gives decent AGN luminosity fcn.
- Issues:
  - ρ and c_s poorly resolved for radiative (cold) mode; arbitrary α.
  - Steep scaling w/BH mass: $dM_{BH}/dt \sim M_{BH}^2$ requires *self-regulation,* which drives models to ~spherical feedback. All Bondi models use spherical feedback, but observed feedback is not spherical.
  - BH accretion models find that *angular momentum loss* limits BH accretion, not local dispersion.

Torque-Limited BH Accretion

- Angular mom dissipated via disk instabilities (Hopkins&Quataert 2011):

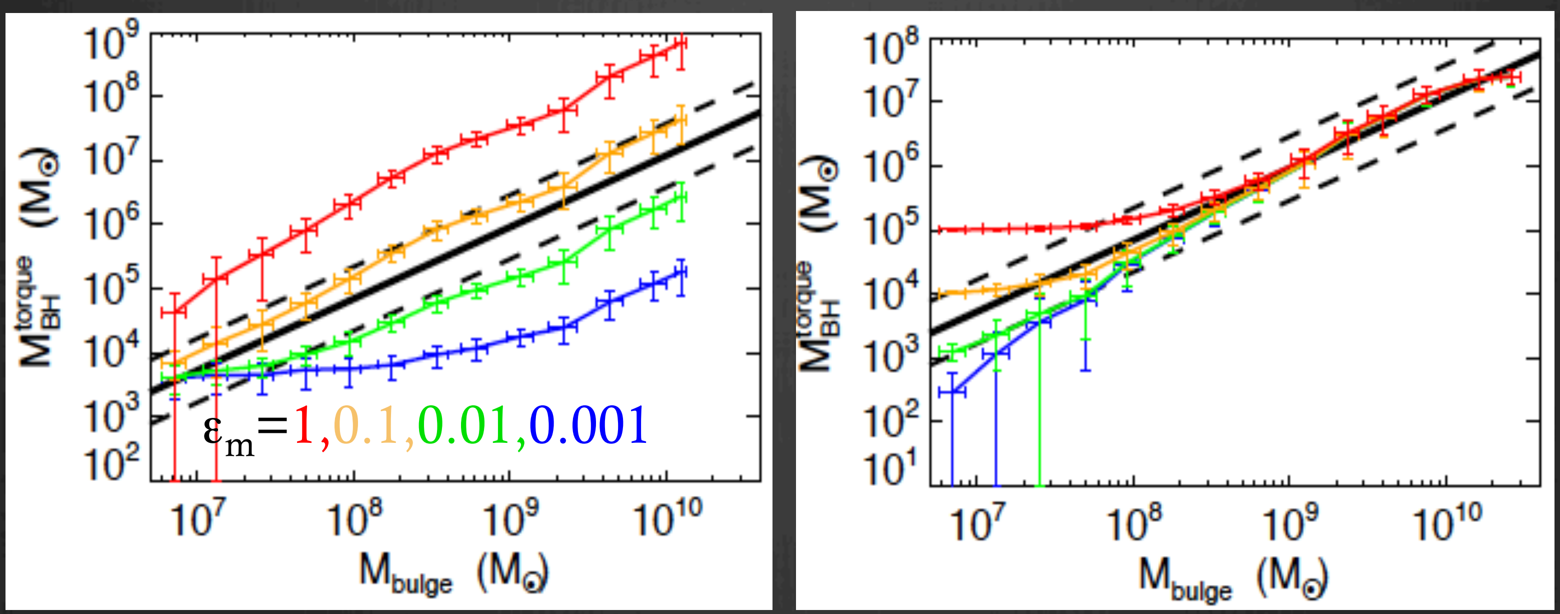
$$\dot{M}_{\rm Torque} \approx \alpha_{\rm T}\, f_{\rm disk}^{5/2} \times \left(\frac{M_{\rm BH}}{10^8\,{\rm M}_\odot}\right)^{1/6} \left(\frac{M_{\rm disk}(R_0)}{10^9\,{\rm M}_\odot}\right)^{1} \times \left(\frac{R_0}{100\,{\rm pc}}\right)^{-3/2} \left(1+\frac{f_0}{f_{\rm gas}}\right)^{-1} {\rm M}_\odot\,{\rm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



Hopkins & Quataert 11

Torque-Limited BH Accretion

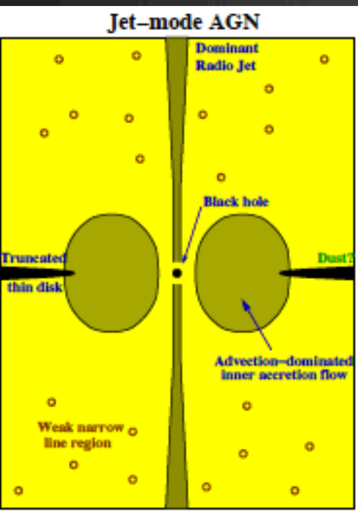
- Galaxies evolve along M-σ – without self-regulating feedback!
- Free parameter ϵ_m: Fraction of mass falling into accretion disk that accretes onto BH (~5-10%). $dM_{BH}/dt = \epsilon_m \dot{M}_{Torque}(t)$
- M-σ relation is an attractor solution, independent of M_{seed}.

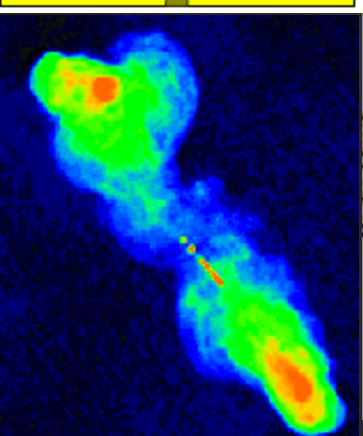


Anglés-Alcázar+14

BH feedback: Radiative vs Jet/ADAF

- Data&theory suggest dichotomy in accretion modes @λ~0.01
- Strong jets when λ<~0.01; molecular outflows when λ>~0.01

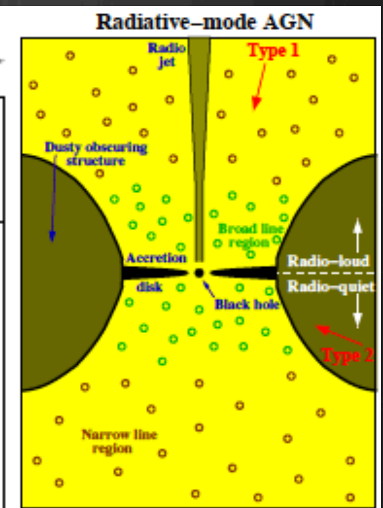




$L/L_{Edd} \lesssim 0.01$ ⟷ | $L/L_{Edd} \gtrsim 0.01$ ⟷

	Jet mode LERG	Radiative mode Type 2	HERG Type 1
Radio Loud	**Low–excitation radio source** * Very massive early–type galaxy * Very massive black hole * Old stellar population; little SF * Moderate radio luminosity * FR1 or FR2 radio morphology * Weak (or absent) narrow, low ionisation emission lines	**High–excitation radio source** * Massive early–type galaxy * Massive black hole * Old stellar population with some on–going star formation * High radio luminosity * Mostly FR2 morphology * Strong high–ionisation narrow lines	**Radio–loud QSO** Host galaxy properties like high–excitation radio source, but with addition of: * Direct AGN light * Broad permitted emission lines * Sometimes, beamed radio emission
Radio Quiet	**AGN LINER** * Massive early–type galaxy * Massive black hole * Old stellar population; little SF * Weak, small–scale radio jets * Moderate strength, low–ionisation narrow emission lines	**Type 2 QSO / Seyfert 2** * Moderately massive early–type disk galaxy with pseudo–bulge * Moderate mass black hole * Significant central star–formation * Weak or no radio jets * Strong high–ionisation narrow lines * QSOs more luminous than Seyferts	**Radio Quiet QSO / Seyfert 1** Host galaxy properties like Type–2 QSO and Seyfert 2, respectively, but with addition of: * Direct AGN light * Broad permitted emission lines * Bias towards face–on orientation

⟷ Light dominated by host galaxy | ⟷ Direct AGN light



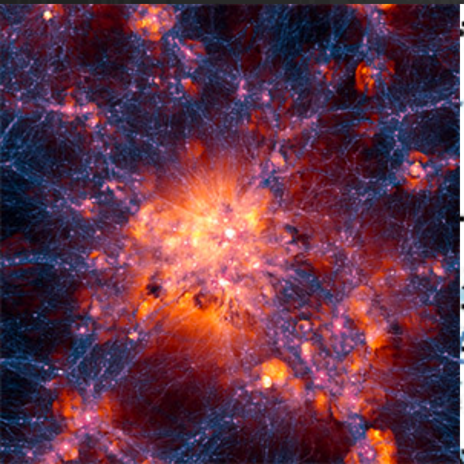
Heckman+Best 14

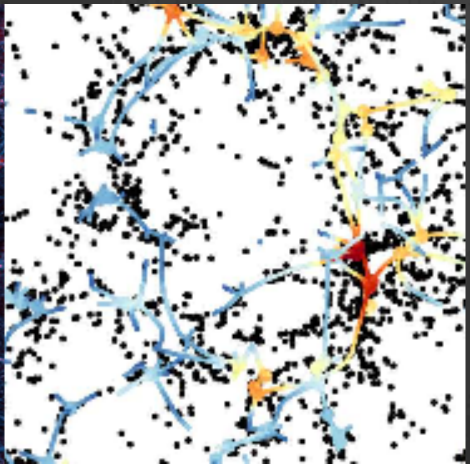
BH feedback

- *Thermal:* Energy added spherically to surrounding gas, with some (tunable) radiative efficiency (~5%).
- *Super-heating:* Energy is stored up to reach T~$10^{7.5+}$K, drives fast outflows.
- *Kinetic:* Similar to SF feedback, gas is kicked with a chosen velocity ~1000 km/s, typically bipolar (±L direction). Can scale velocity with galaxy and/or BH properties [SIMBA].
- *Eddington cap:* Bondi models use this, otherwise get huge accretion rates when BH is large. Torque-limited models cap well above Eddington (if at all), and it is rarely reached.
- Some recent models use a distinct kinetic jet mode at low λ.

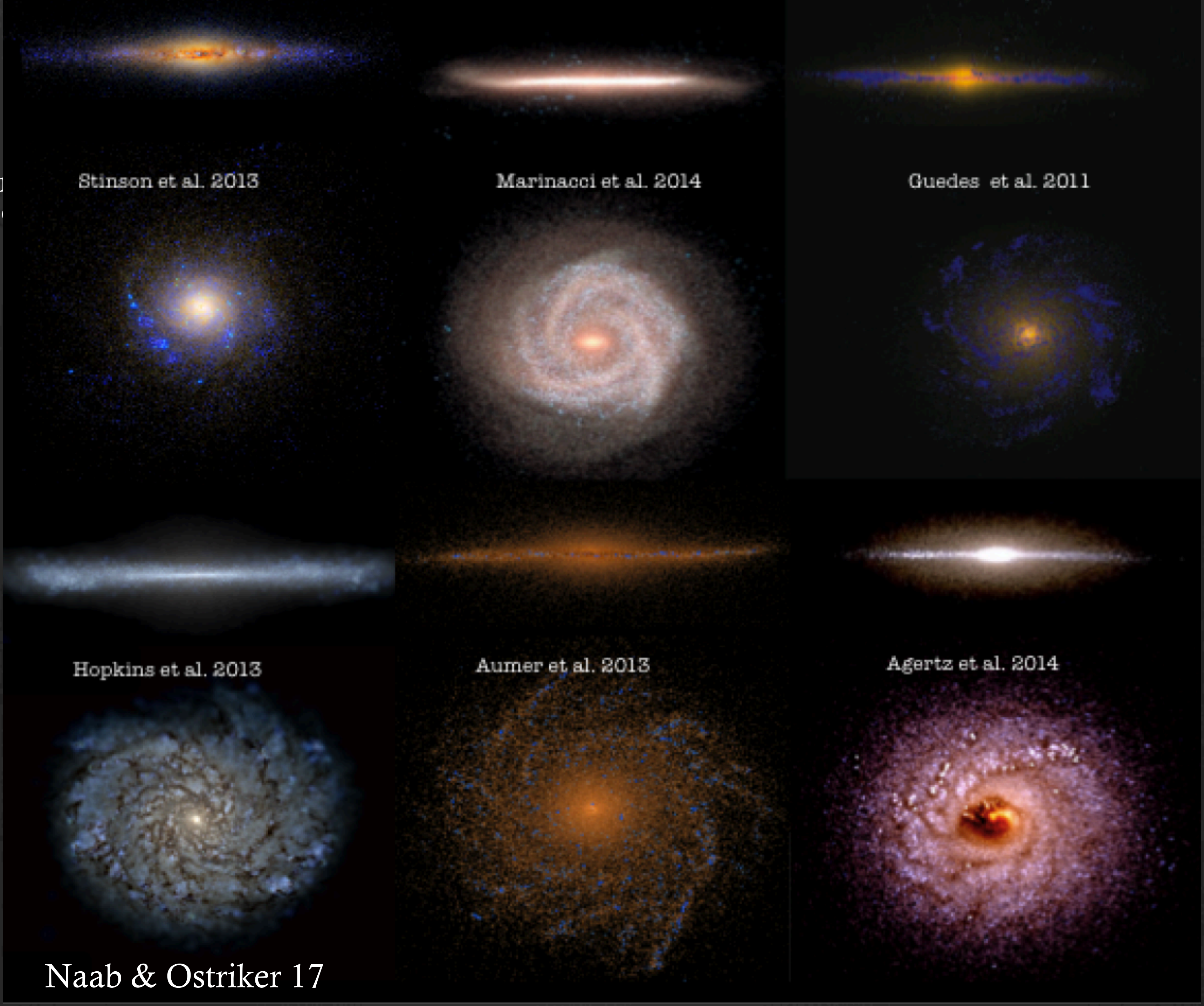
Some cosmological simulations

- Horizon (Dubois+14) – RAMSES, 100 Mpc/h, 1024^3 cells.
- Illustris (Vogelsberger+14,Genel+14) – AREPO, 75 Mpc/h, 1820^3.
- EAGLE (Schaye+15,Crain+15) – PE-SPH, 100 Mpc/h, 1800^3
- BlueTides (Feng+16) – EC-SPH, 400 Mpc/h, 7000^3(!), to z~7.
- Mufasa/Simba (RD+16,17) – MFM, 50 Mpc/h, 512^3/1024^3.
- Illustris-TNG (Pillepich+17) – AREPO, 37.5/75/205 Mpc/h, 2500^3





La
res

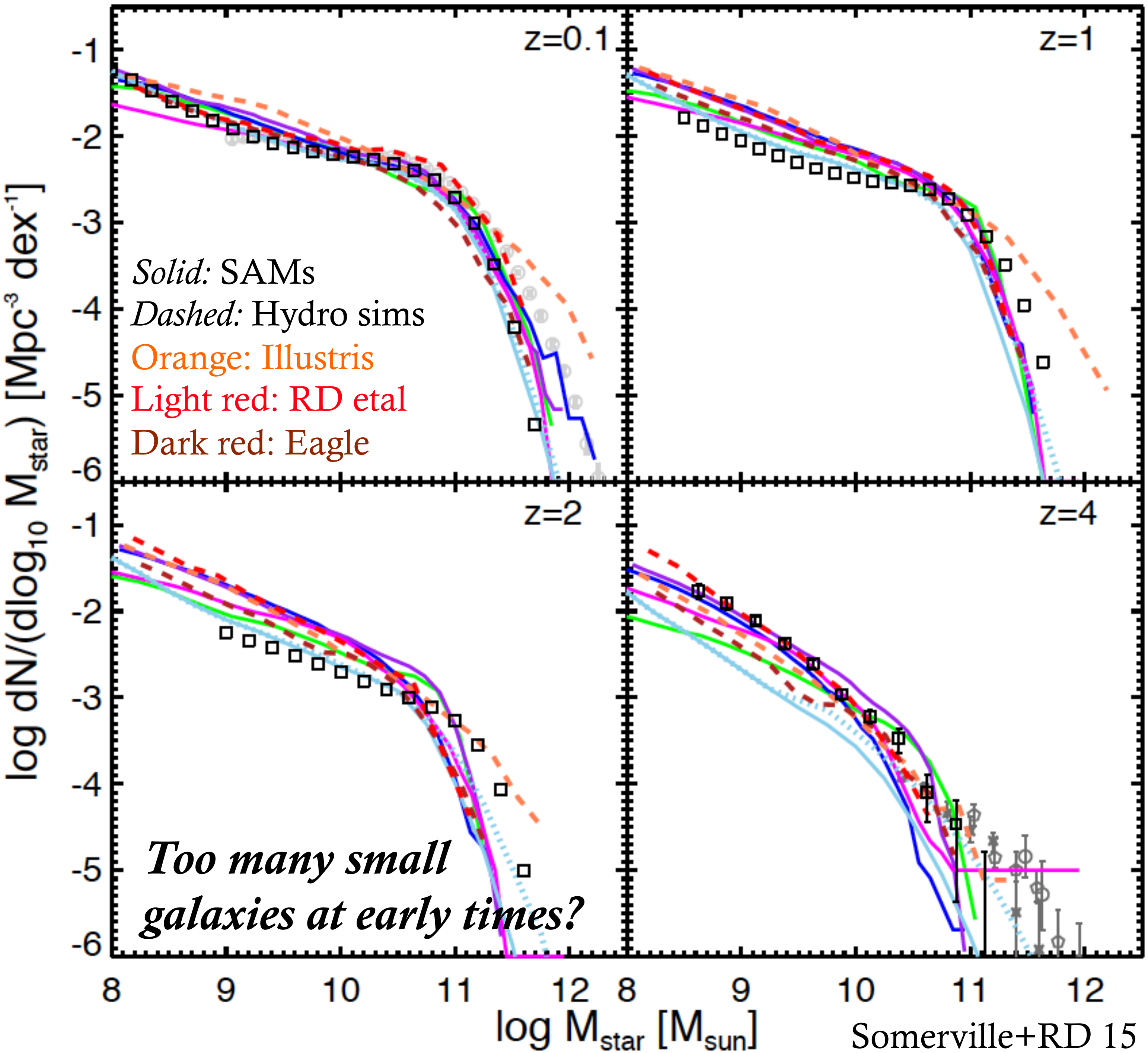

Stinson et al. 2013
Marinacci et al. 2014
Guedes et al. 2011
Hopkins et al. 2013
Aumer et al. 2013
Agertz et al. 2014
Naab & Ostriker 17

Observational comparisons

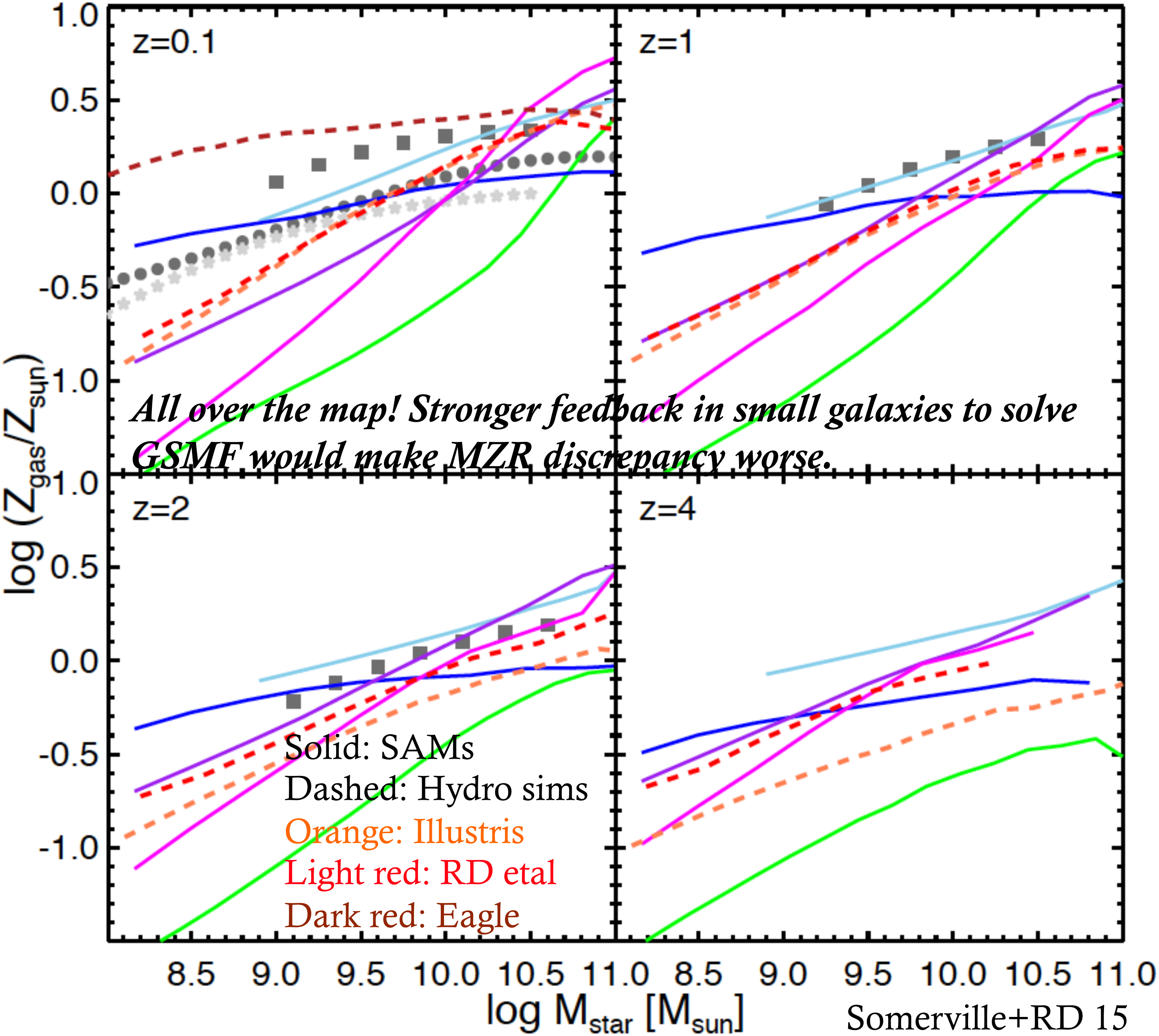
How well do modern cosmological simulations (and SAMs) reproduce observed galaxy evolution?

- Key barometers:
  - Galaxy stellar mass function: *Does it reproduce the fraction of baryons in stars as a function of halo mass?*
  - Galaxy mass—metallicity relation: *Does the outflow prescription properly distribute metals between galaxies and CGM?*
  - Galaxy SFR-M_* relation: *Is the growth rate of galaxies across cosmic time consistent with observations?*
  - Galaxy sizes: *Is angular momentum loss/redistribution from outflow handled correctly on ~kpc scales?*
  - CGM: *Does the energy and metals from outflows impact the circum-galactic gas in accord with data?*

Galaxy Stellar Mass Function



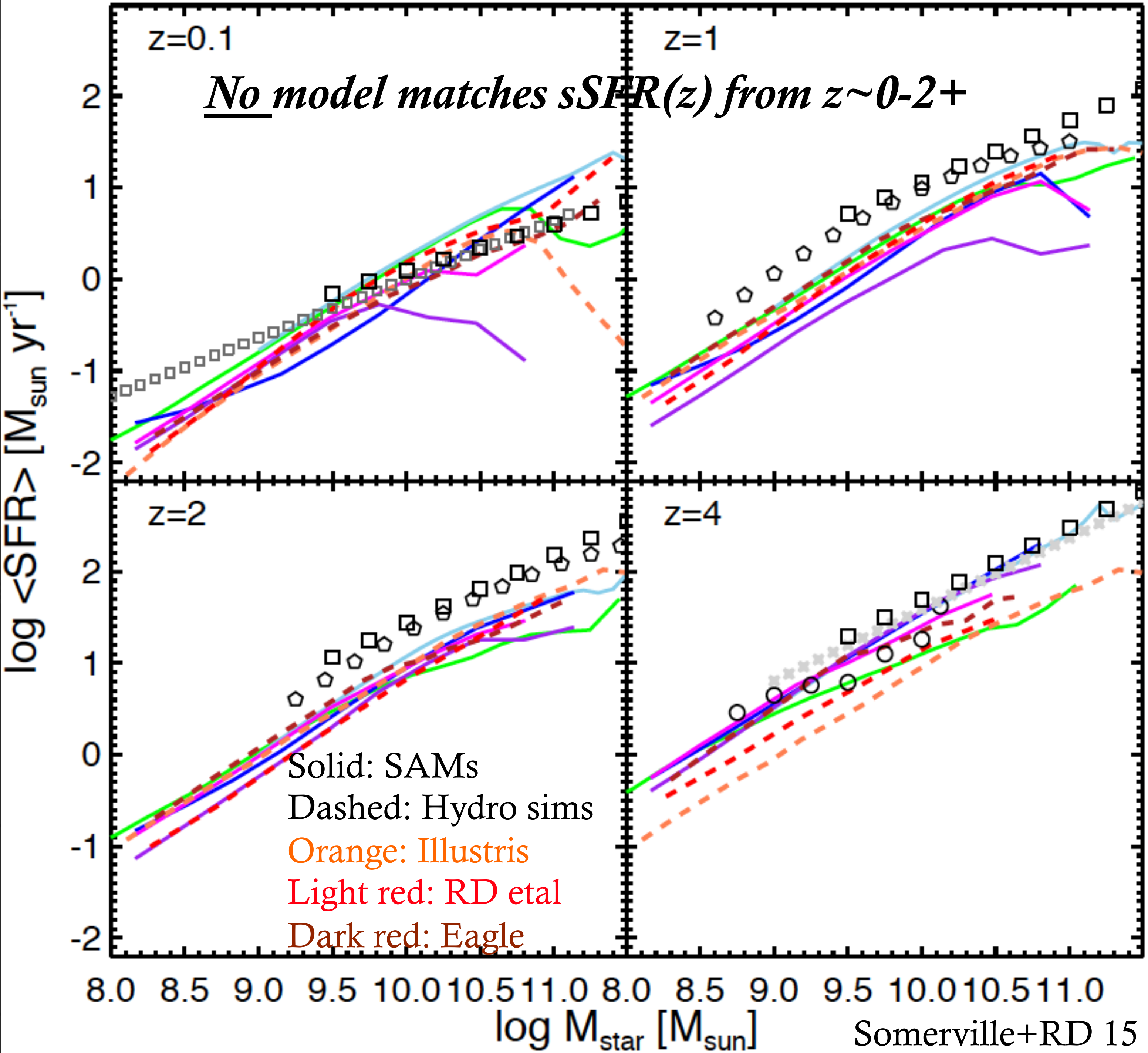
Mass-Metallicity Relation



All over the map! Stronger feedback in small galaxies to solve GSMF would make MZR discrepancy worse.

Somerville+RD 15

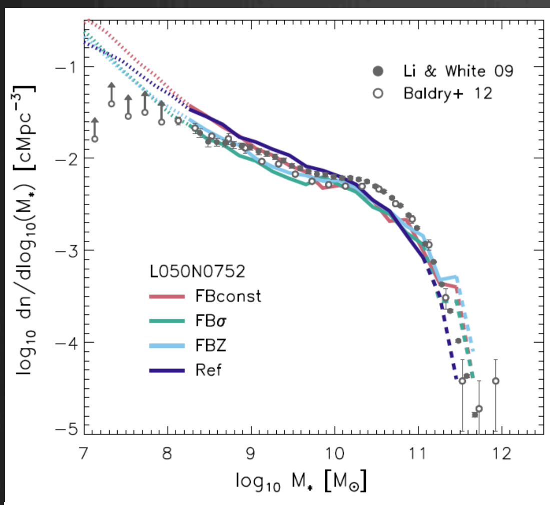
Galaxy “Main Sequence”

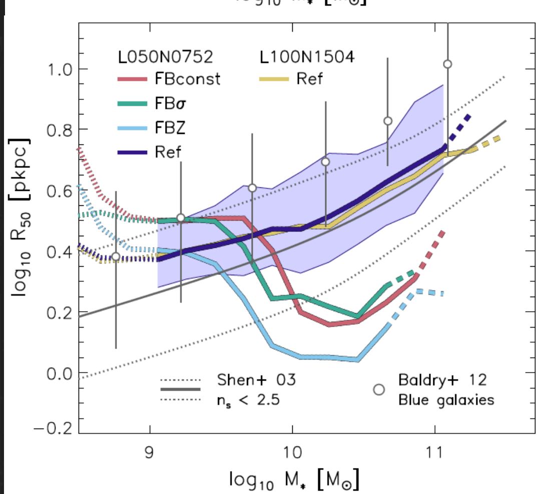


Somerville+RD 15

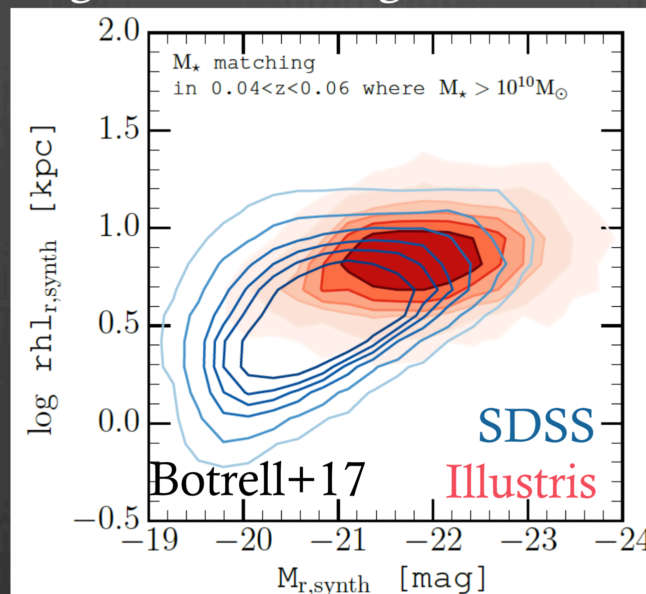
Galaxy sizes

EAGLE: Sizes strongly constrain subgrid model

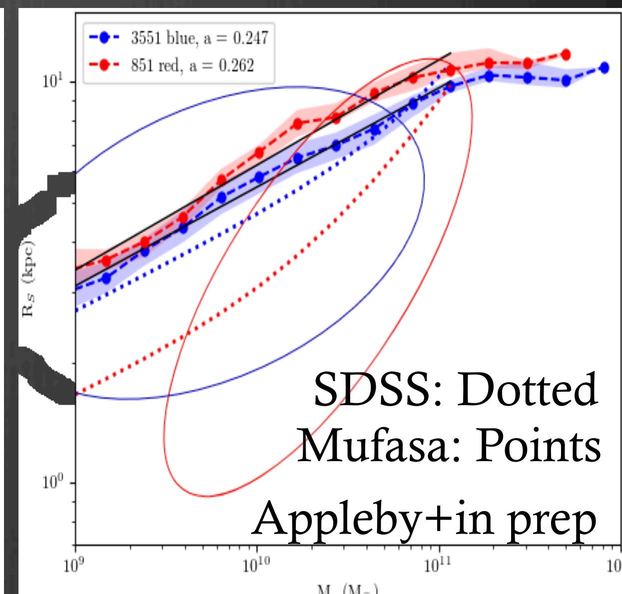




Illustris: Sizes too large, galaxies too bright



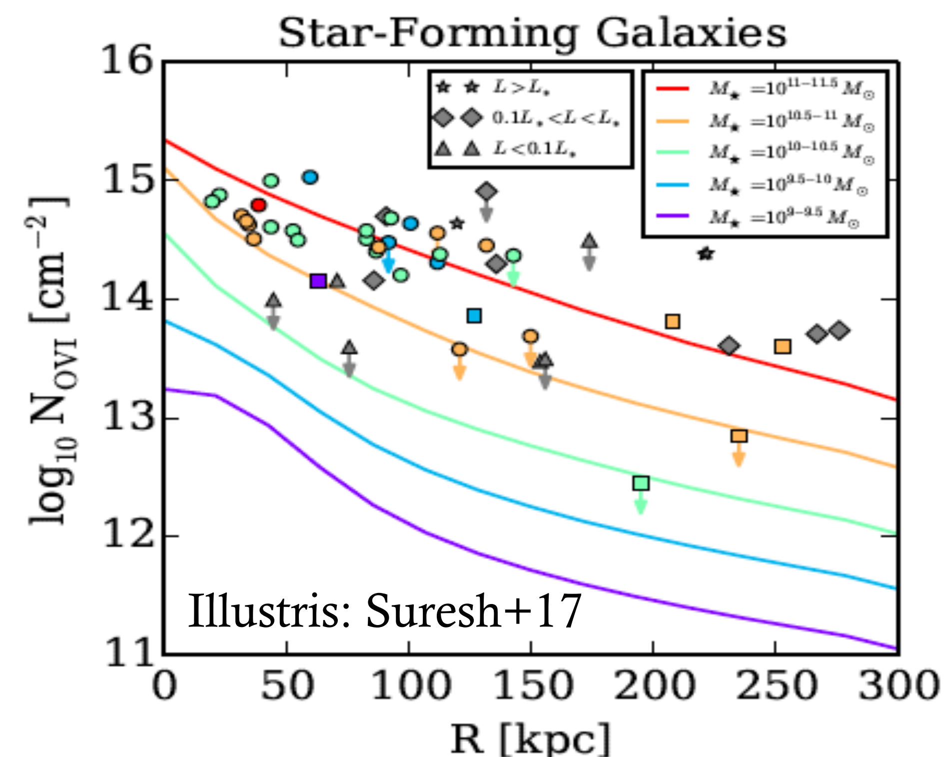
Mufasa: Blue galaxies ok but red dwarfs too large

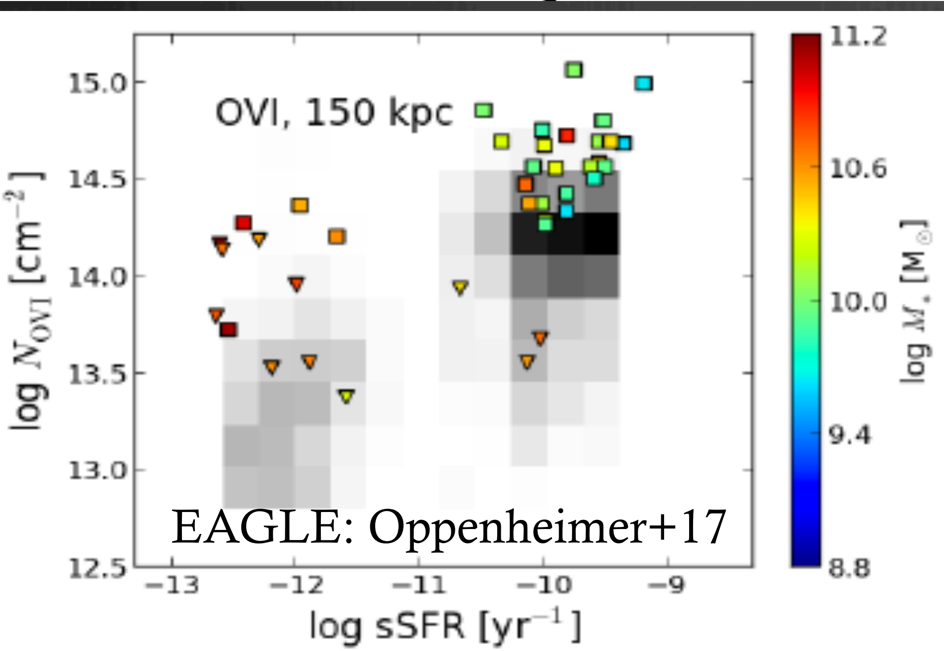


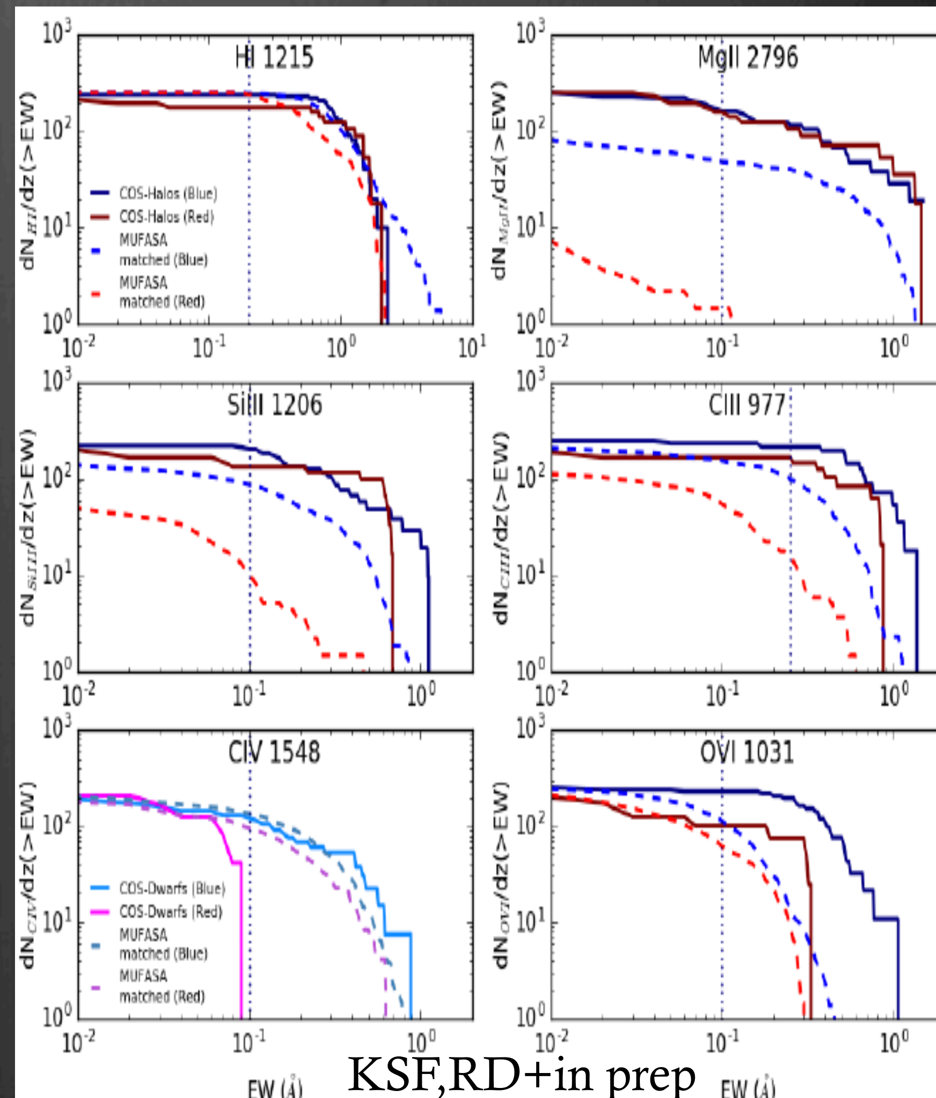
Key constraint that is not naturally satisfied in cosmological models

CGM: OVI

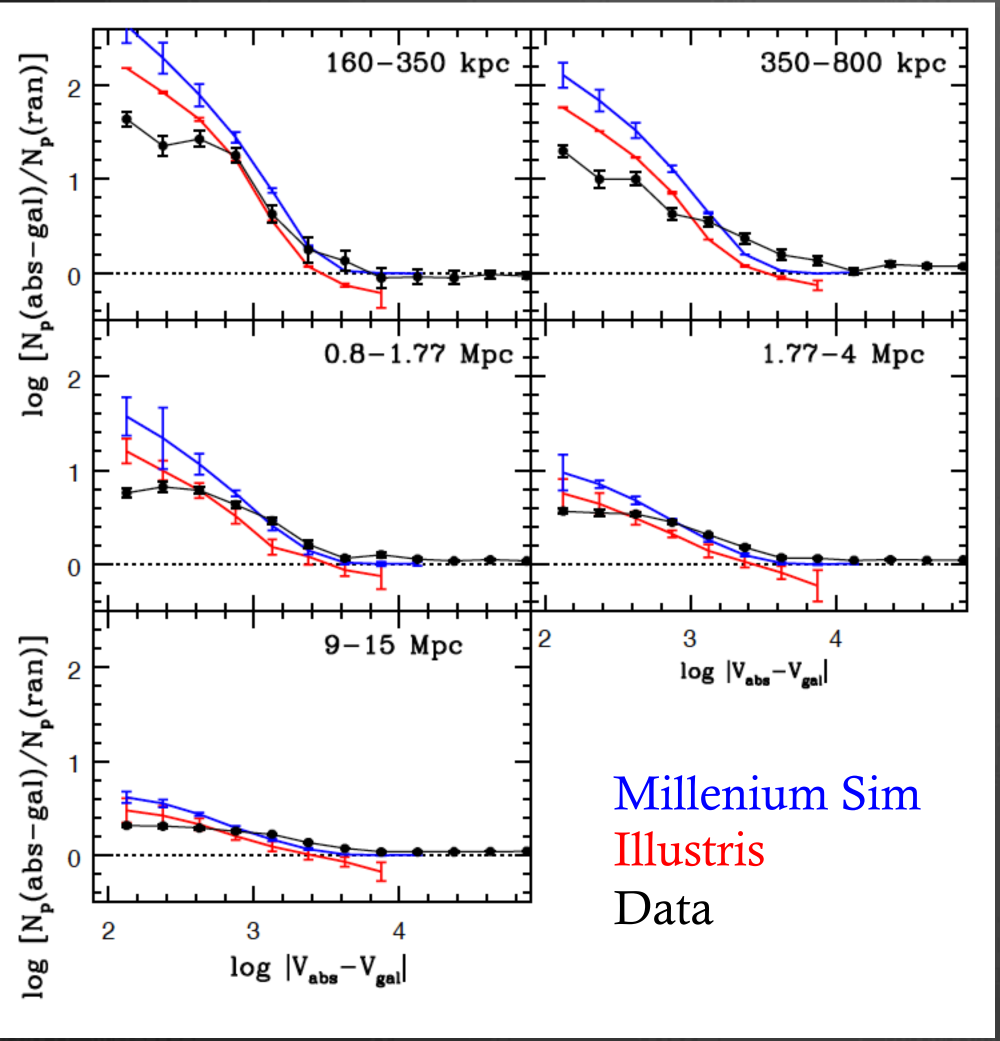
1032,1037Å



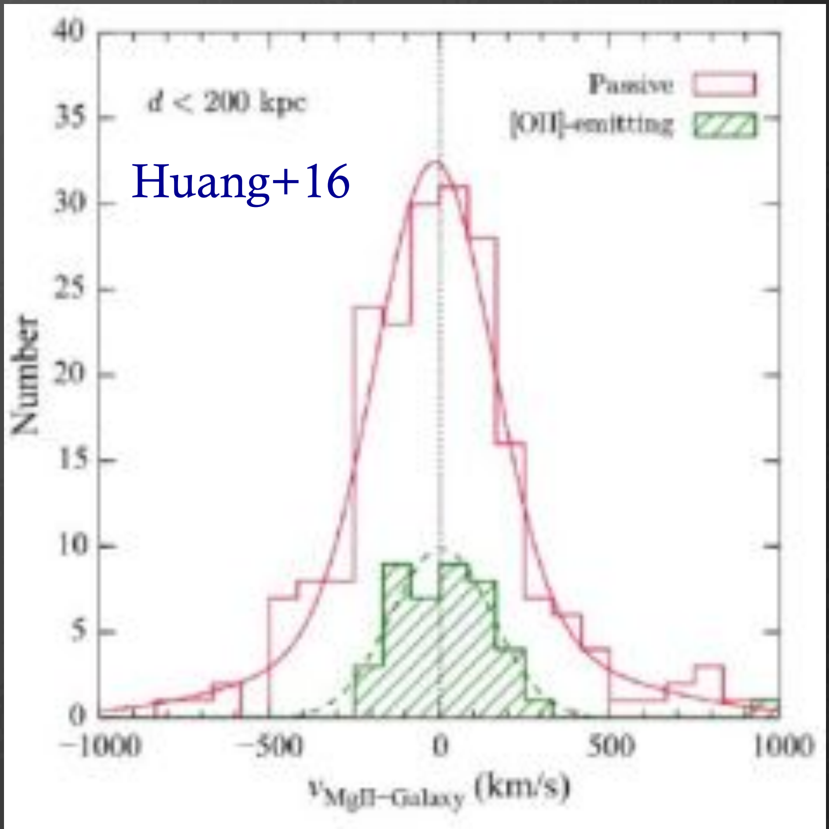




CGM MgII
2793,2803Å



MgII traces DM on large scales (Millenium) does not reproduce data; adding baryonic effects (Illustris) reduces clustering but not shape.



MgII around LRG have σ~160 km/s, while LRG halo σ~270 km/s – MgII should not be dynamically supported!

Some puzzles
(A short list of personal angsts)

- Sharpness of GSMF turn-down: Extreme onset of quenching?
- MZR gas-phase vs stellar phase: Yields? IMF? Dust?
- SFR-M* at 1<z<3: IMF? Observed SFRs wrong?
- Cold enriched clouds in hot halos: Condensing out? Raining in from filaments? In thermal equilibrium?
- Cold gas in fast outflows: Magnetic sheathing? Cosmic ray pressure? Formed in-situ in outflow?
- OVI deficiency: Insufficient metal expulsion? Interface layers?

Summary

- Galaxy formation models can now match data equally well (or poorly) with very different subgrid prescriptions – *more guidance needed from high-resolution simulations and data.*

- Key subgrid modeling improvements needed:
  - Better handling of ISM physics
  - Better understanding of outflow launching
  - Better modeling of outflow interaction with ambient gas
  - … solutions could plausibly involve new physics such as cosmic rays/magnetic fields, better stellar evol models, DM properties, etc.

- It's exciting that various models are now in a position to be discriminated by data! Need careful & robust comparisons.