FIREd up, ready to go!

Successes and Challenges of cosmological simulations of massive galaxies

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The challenge of massive galaxies

(Here massive: $M_{star} \sim 10^{10}\ M_{\odot}$ and higher)

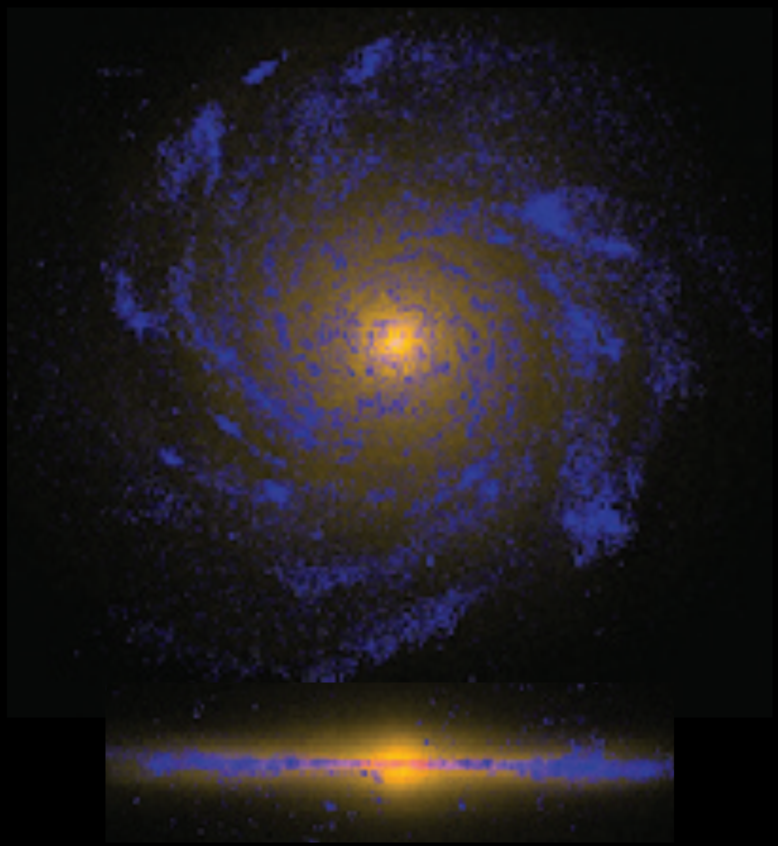
- Overcooling / too compact sizes
  - Deep potential wells: Stellar driven outflows less efficient
  - Hot halo cools over Hubble times and has low ang. mom.

- Well defined sub-classes
  - Hubble sequence, SF vs Quiescent bimodality (also at z=2!)
  - Clear differences in sizes, structure, ages

- Physics is complicated
  - Role of BH feedback, CRs, magnetic fields, th. conduction?
  - Are these processes simulated correctly (e.g., see Volker's talk)?

Remarkable Progress over the past ~5 years

MW galaxies



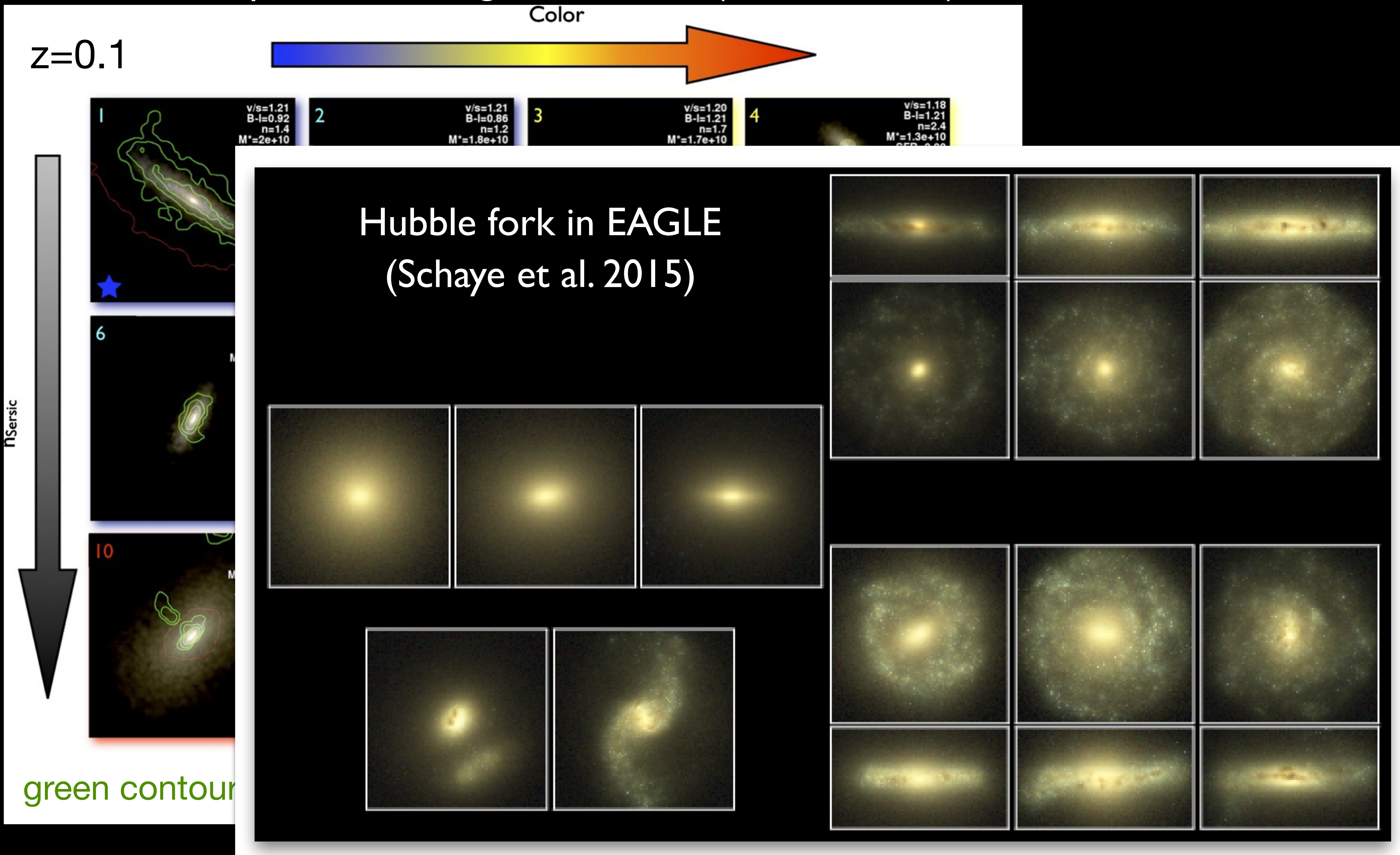
Guedes et al. 2011 ('Eris')
m_b ~ 20,000 $M_\odot$, ϵ_{gas} ~ 120 pc

'Latte' (Wetzel et al. 2016), FIRE-2
m_b ~ 7,000 $M_\odot$, ϵ_{gas} ~ 20 pc

FIRE-5 (actually M101)

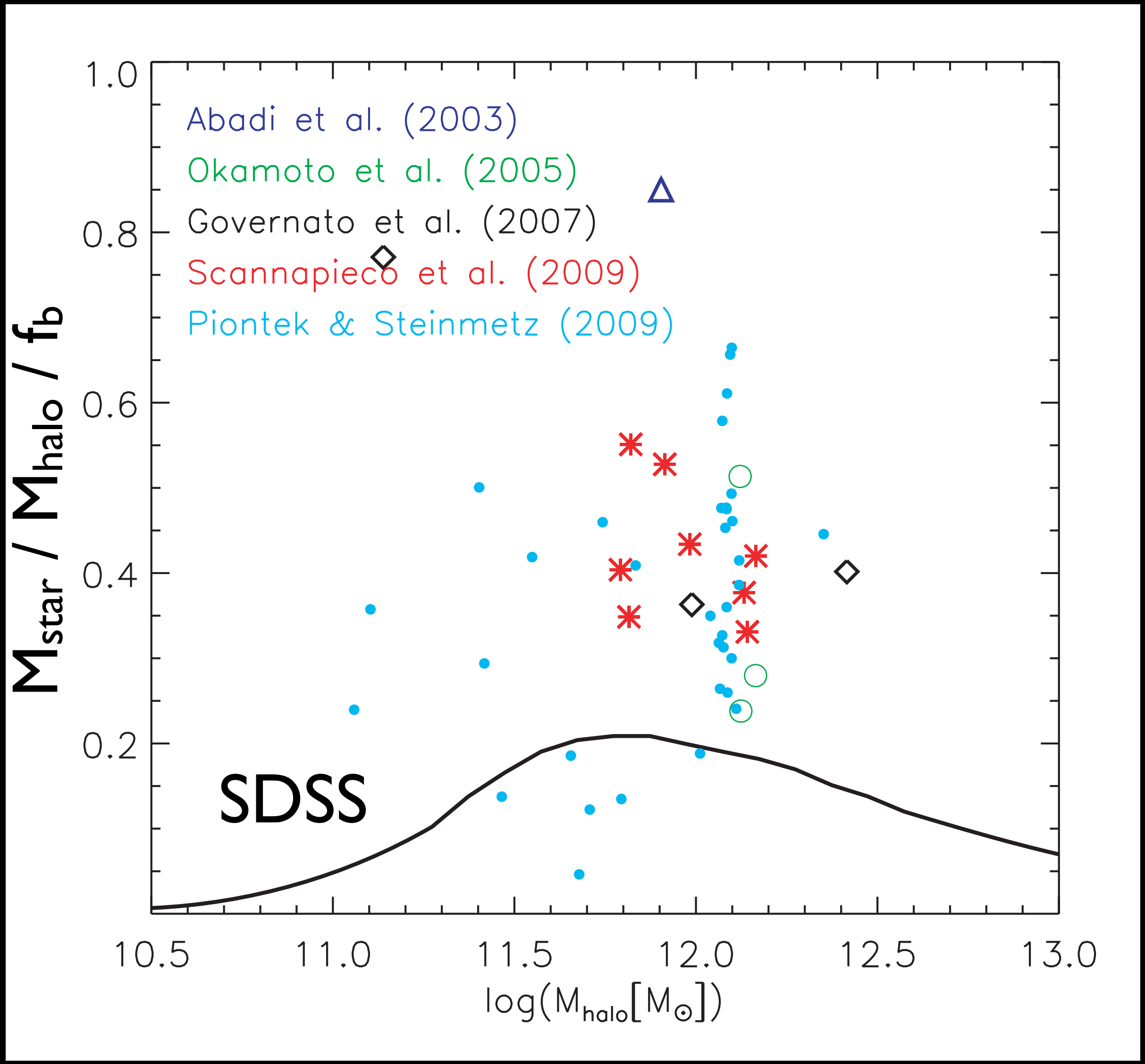
Remarkable Progress over the past ~5 years

Hubble sequence in a single simulation (RF et al. 2011)

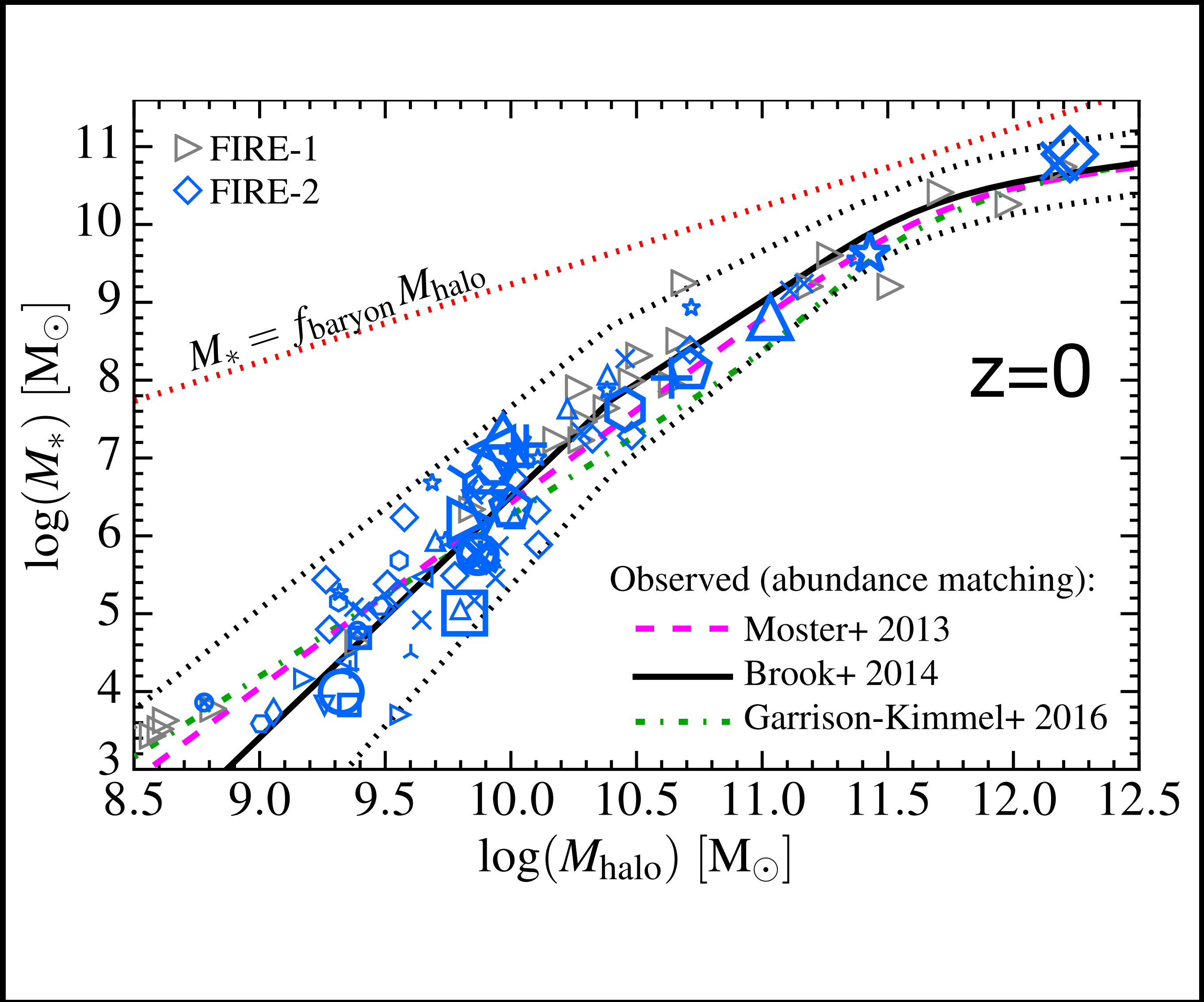


Remarkable Progress over the past ~5 years

Guo et al. 2010



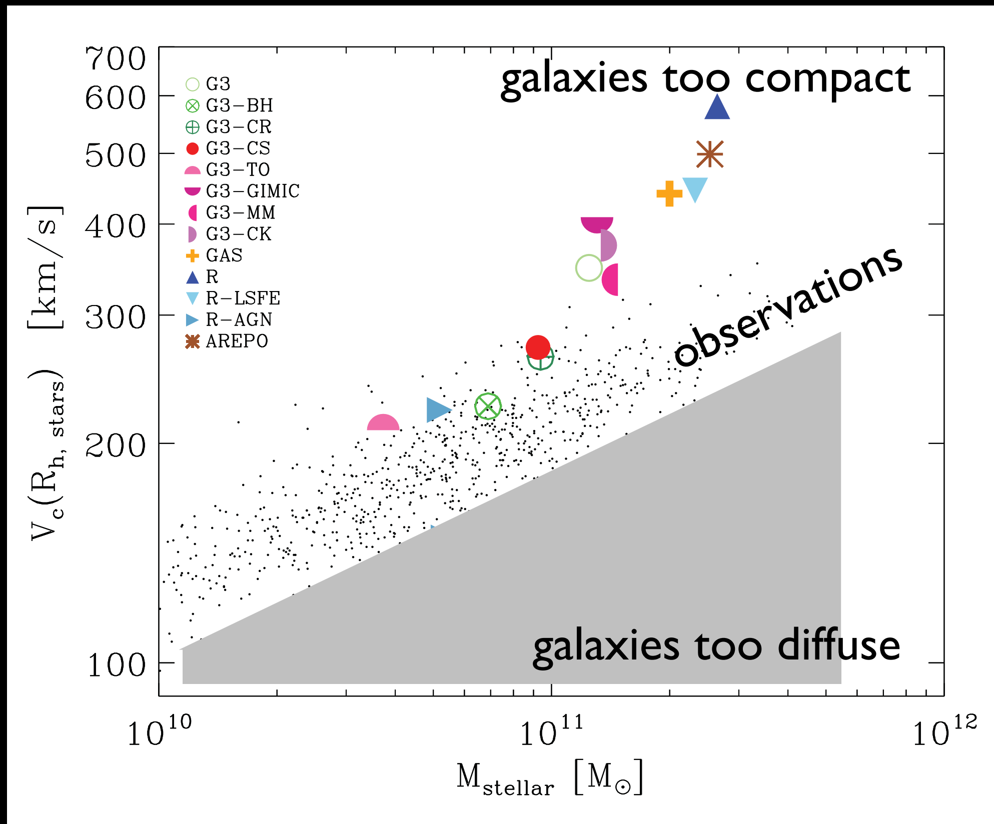
FIRE-2 (Hopkins et al. to be submitted)



Today effectively all simulations reproduce (to a degree) M_{star} – M_{halo} for Milky Way masses and below.

Galaxy sizes

Aquila (Scannapieco et al. 2012)



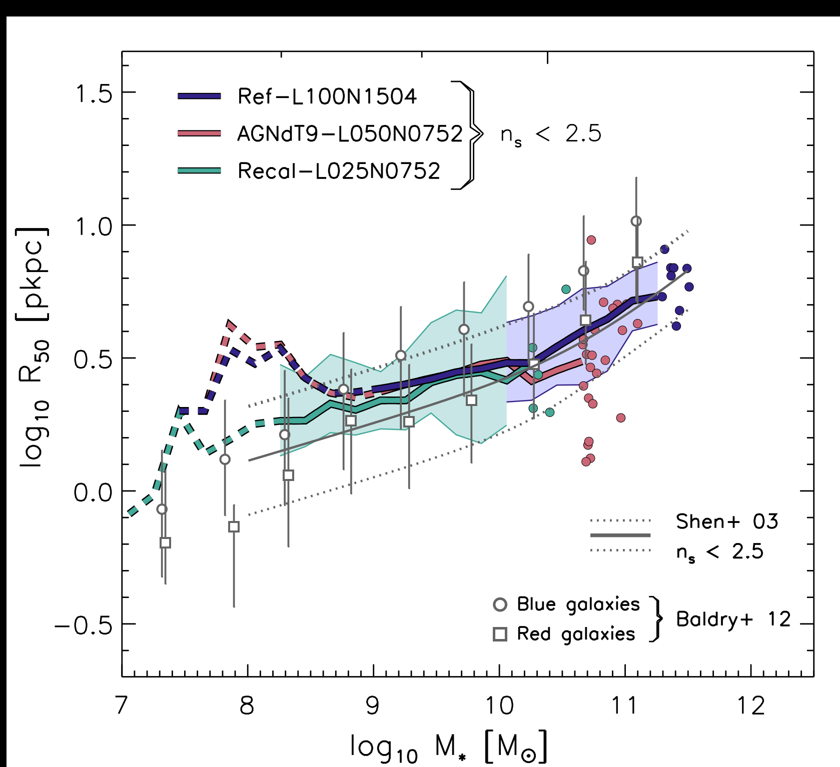
Classic problem:

- galaxies too massive and too small, i.e. too compact

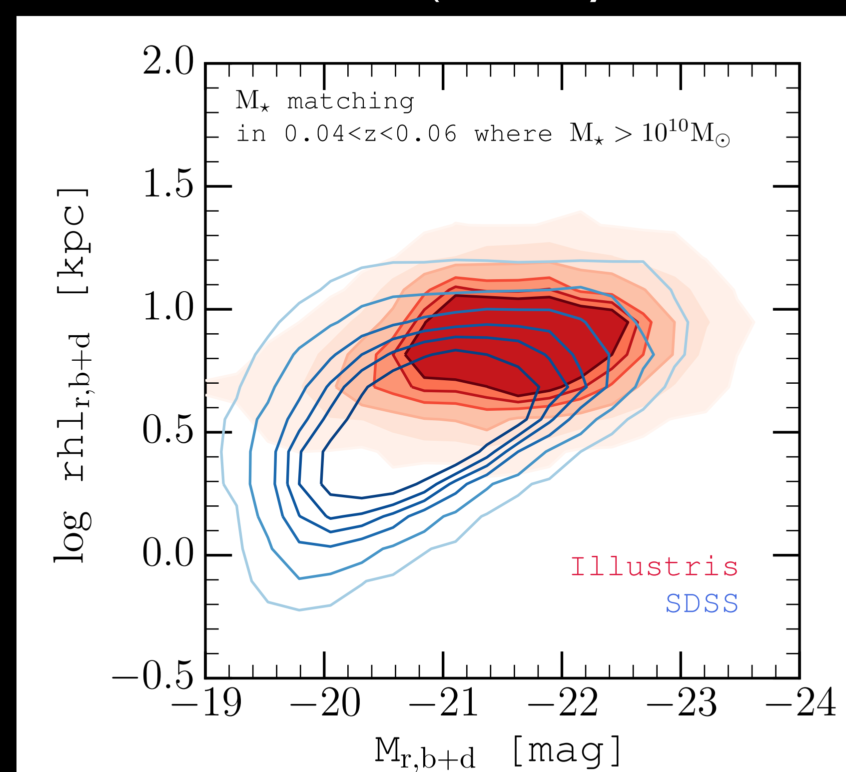
Recent simulations:

- some agree well with obs. (e.g. EAGLE),
- others seem to somewhat **over-**predict the sizes for given mass & luminosity
- see also Annalisa's talk

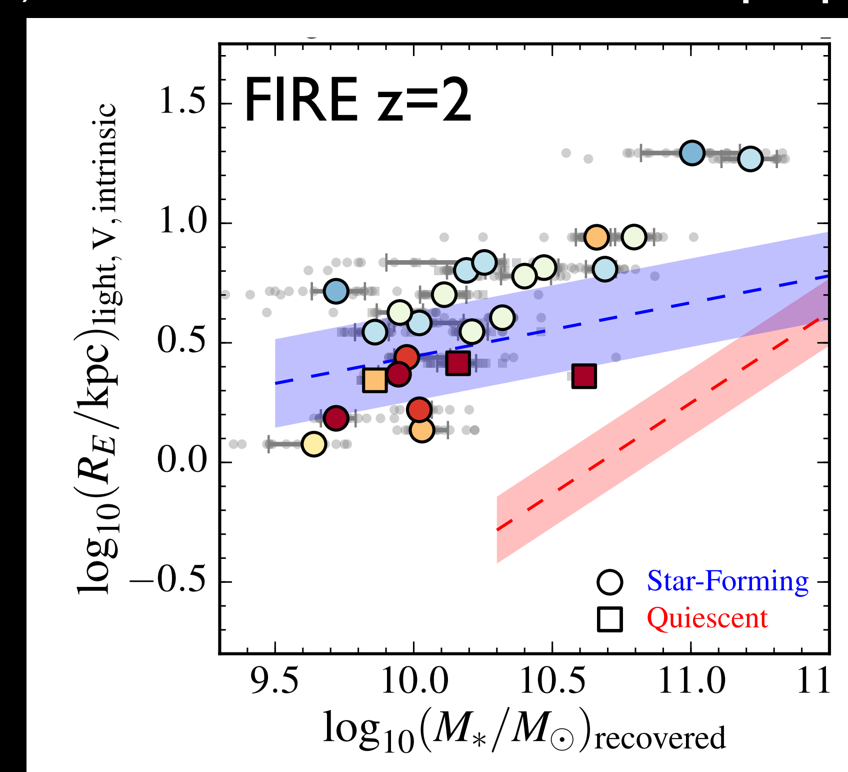
EAGLE (Schaye et al. 2015)



Bottrell et al. 2017 (also Snyder et al. 2015)

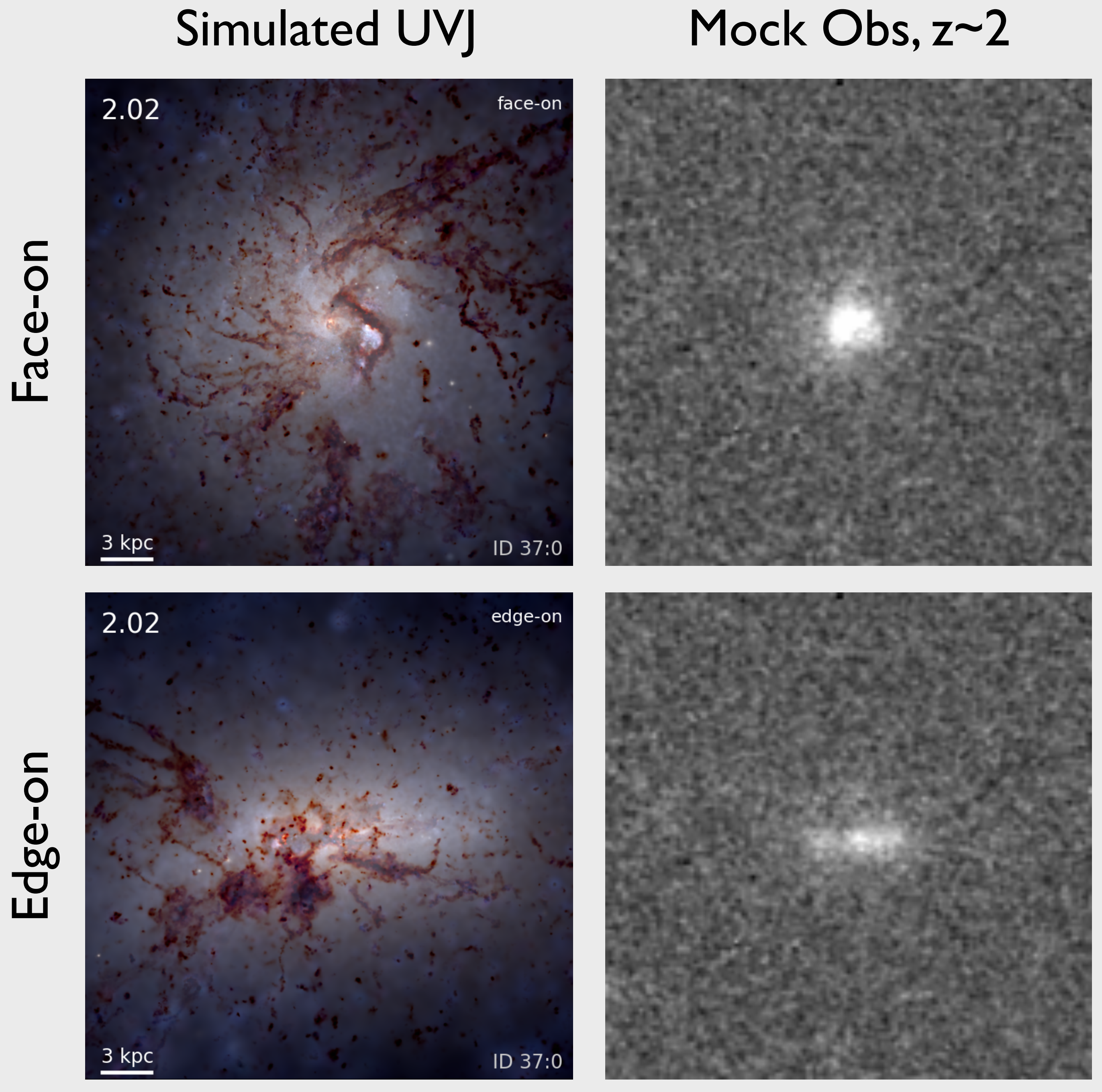


RF et al. in prep



How comparable are sizes in simulations and observations?

- Observations: **2D** Sersic fit (Galfit), **extrapolated** to infinity, based on **light** (optical bands)
- Simulations: often **3D** radii in **apertures**, based on **mass**



Two dozen galaxies from MassiveFIRE (z=2)

simple RT accounting for dust absorption

Mock WFC3 images:

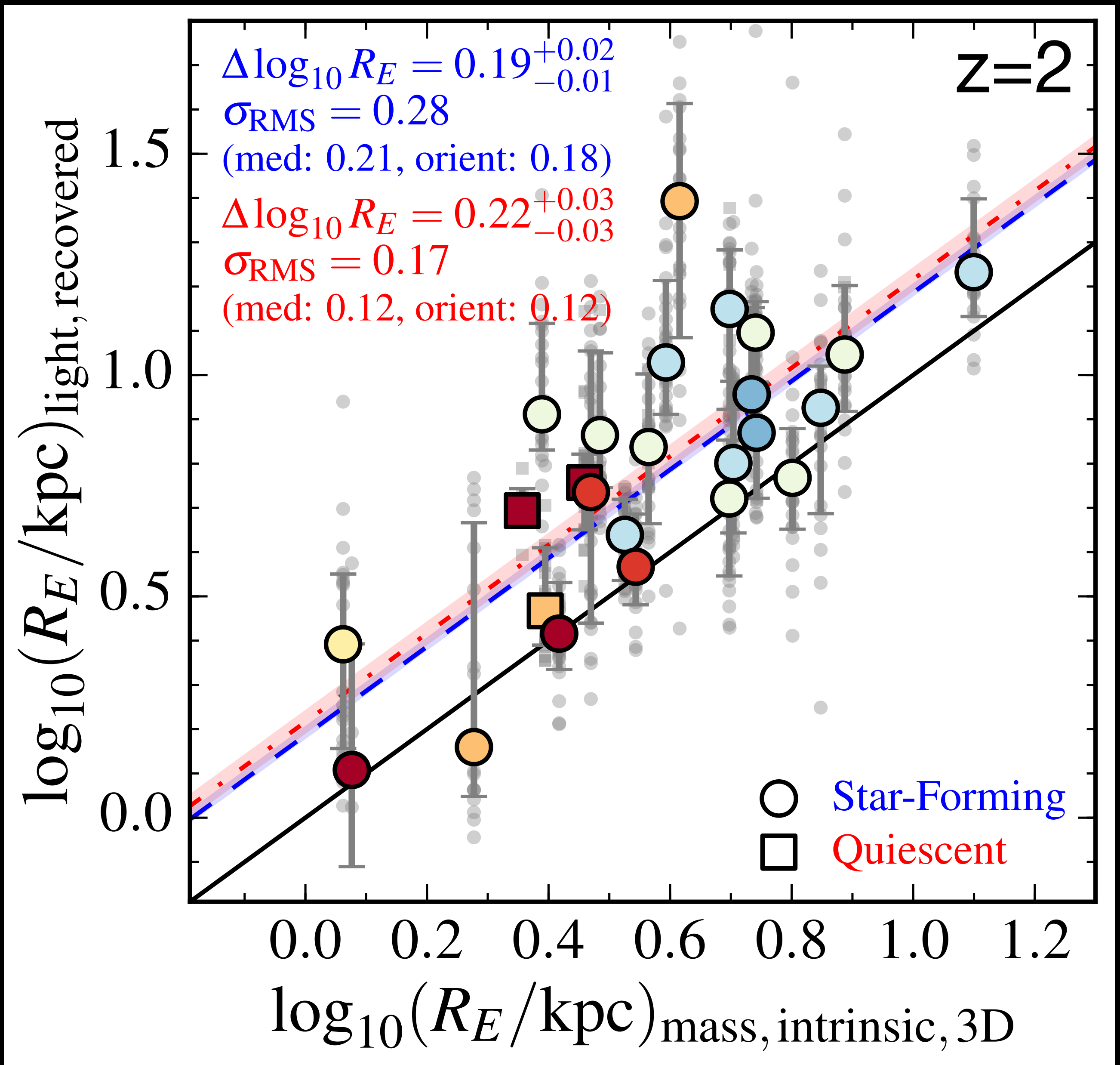
- Artificially redshift
- Convolve with CANDELS F160W PSF
- Add average-depth CANDELS noise

Multiple projections for each simulated galaxy, multiple filters/projection

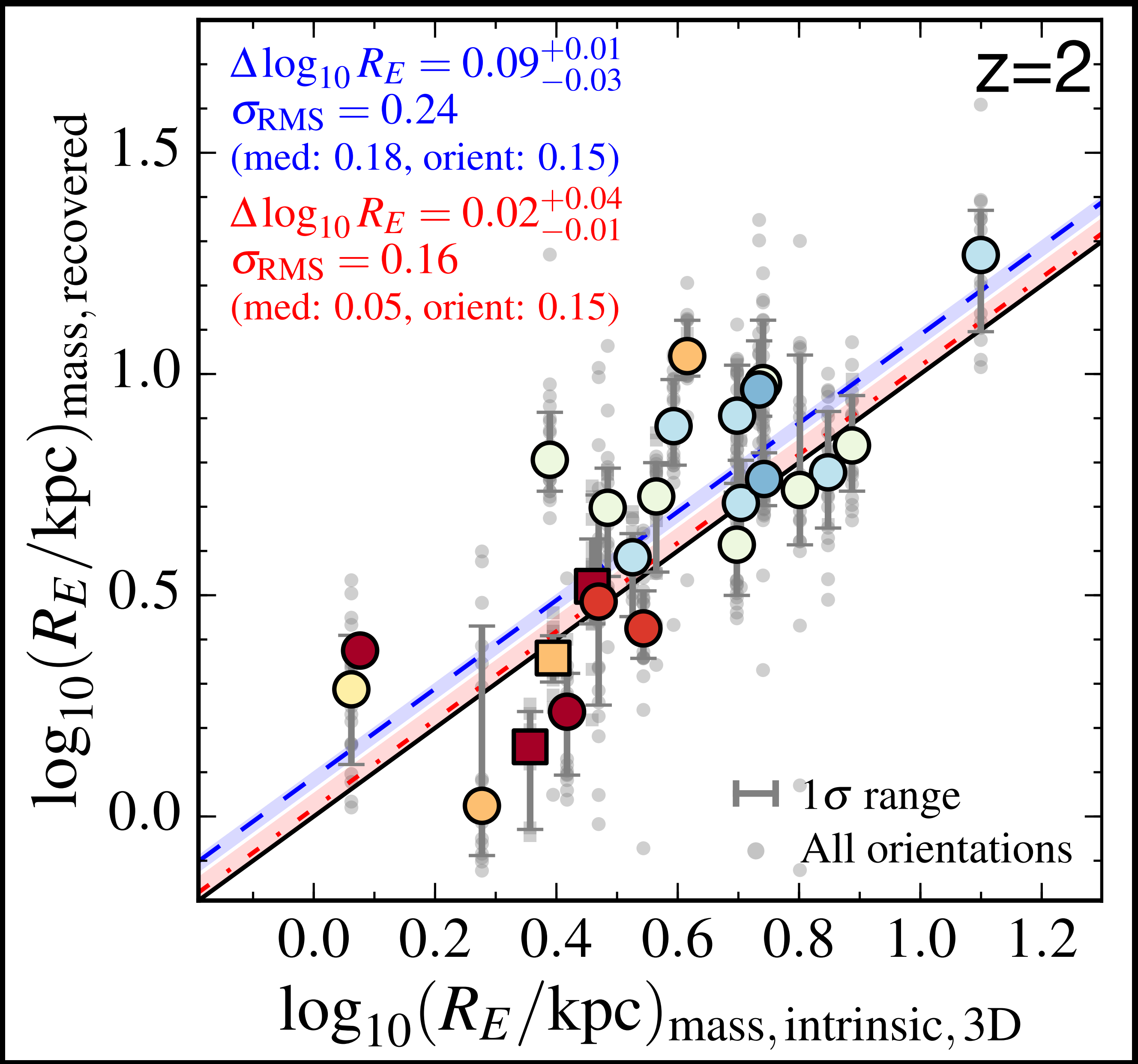
Price, Kriek, RF et al in prep

How comparable are sizes in simulations and observations?

Comp. with half-light radii



Correction based on color gradient



Price, Kriek, RF et al in prep

- Half-light radii are larger than half-mass radii
- After color correction: no strong tilt, modest scatter, only small offset

Massive FIRE

Feedback In Realistic Environments

RF et al. 2016

- Cosmological, hydrodynamical zoom-in sims of ~40 central galaxies in halos ~3×10^{12} – 3×10^{13} $M_\odot$ (@z=2)
- SPH in pressure-entropy formulation, Cullen-Dehnen AV
- **no BH feedback**
- High numerical resolution: **tens of pc**, m_b ~ few $\mathbf{10^4\ M_\odot}$

Gas

- adaptive softening: grav. softening ϵ_{gas} = SPH smoothing length h_{gas}
- *minimum* h_{spline} ~ 12 pc (but not a meaningful quantity)
- typical: star forming gas: $\langle h_{spline}\rangle$ ~ 28 pc, $\langle n\rangle$ ~ 1000 cm^{-3}

SF

- in **self-gravitating** gas [& dense (n_{crit} = 5 cm^{-3}), molecular]

Note:

- ϵ_{gas} => max. density n_{max} at which self-gravity computed correctly
- if n_{crit} ~ n_{max}, SF sensitive to choice of n_{crit}
- if n_{crit} > n_{max} can form stars only if $h_{gas} << \epsilon_{gas}$; turbulence
- cold gas properties incorrect, lower SFR, more bursty SF

	MassiveFIRE	Eris	Illustris	EAGLE
n_{max} / cm^{-3}	~700	0.14	0.04	0.06
n_{crit} / cm^{-3}	5	5	0.13	0.04 (Z=0.01)

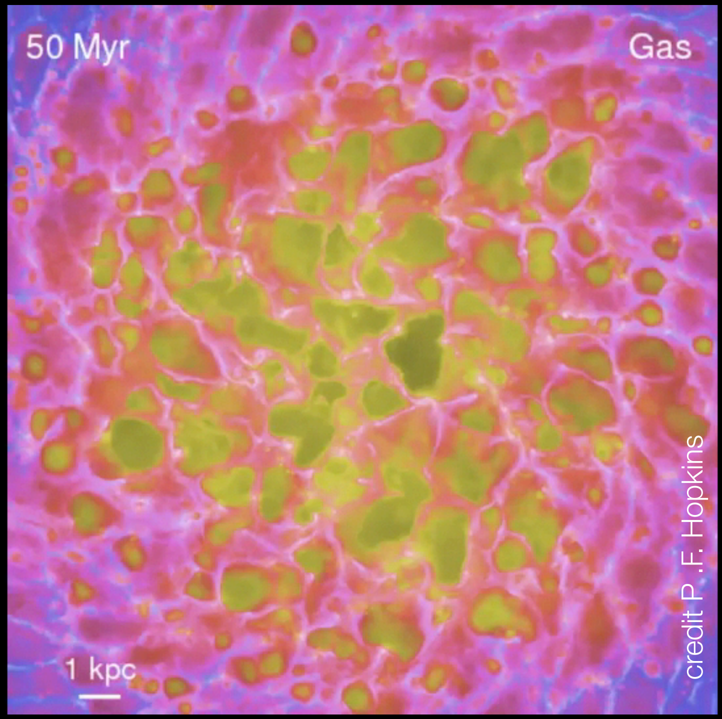
300,000 l.y.

R. Fe

Feedback in Realistic Environments (FIRE)

Hopkins et al. 2014

Star formation:



- in locally bound, dense, Jeans unstable, molecular gas
- $\rho_{SFR} = \rho_{H2} / t_{ff}$
- only small fraction of molecular gas is locally bound
- FB self-regulates SF to ~few % eff. per ff even in dense gas

Feedback:

SN
- mass, energy, momentum
- individual SN are time-resolved (i.e., ≤1 per time step)
- inject mom. at end of adiab. phase of Sedov-Taylor (if cooling radius unresolved)

stellar winds (OB/AGB) treated same way as SN but continuous injection

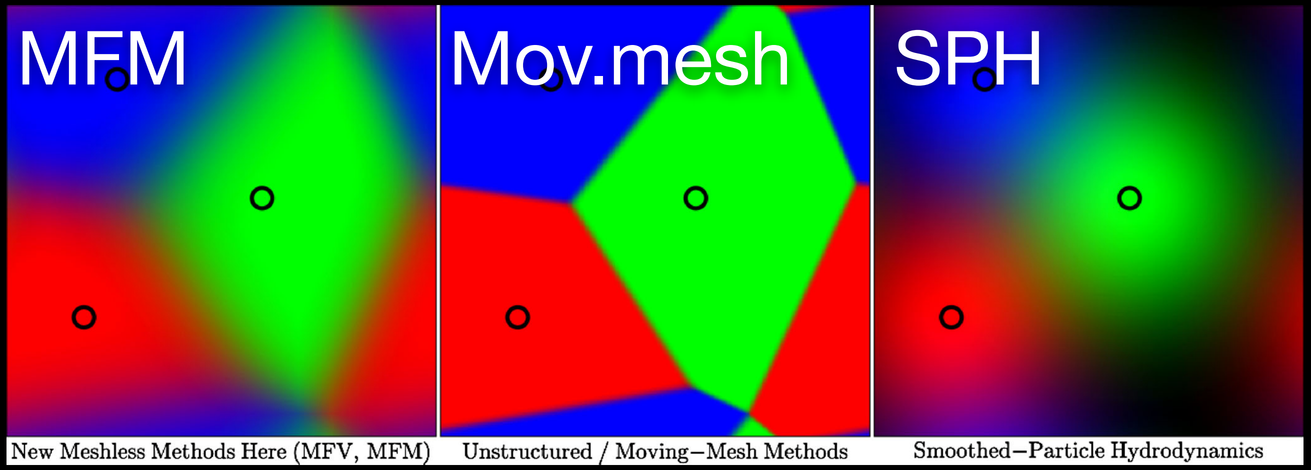
photo-ionization/photo-eletric heating:
- simple RT (local absorption & opt. thin long range transport)
- 5 bands (ionizing, far-UV, near-UV, optical/near-IR, mid/far-IR)
- luminosity absorbed (locally) by dust re-emitted in the mid/far-IR band

Radiation pressure:
- momentum only from absorption followed explicitly via RT (radial away from source)
- can in principle result in multiple scattering (IR) but typically <10% of rad.pressure

Hopkins et al. to be submitted

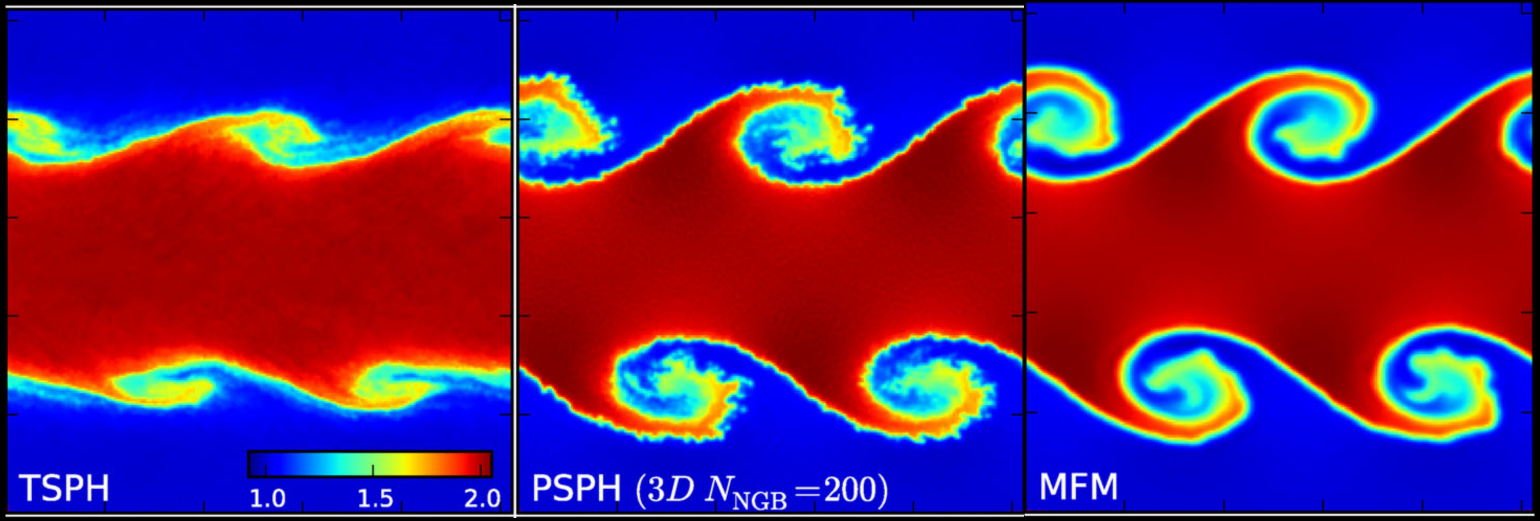
Comparison FIRE – FIRE-2

- MFM instead of P-SPH: perhaps largest, most important difference



Hopkins et al. 2015

- complete partition of space into overlapping volumes
- discretize integral form of Euler equations,
- results in a scheme similar to Godunov with effective faces between particles
- higher effective resolution for similar #particles than P-SPH

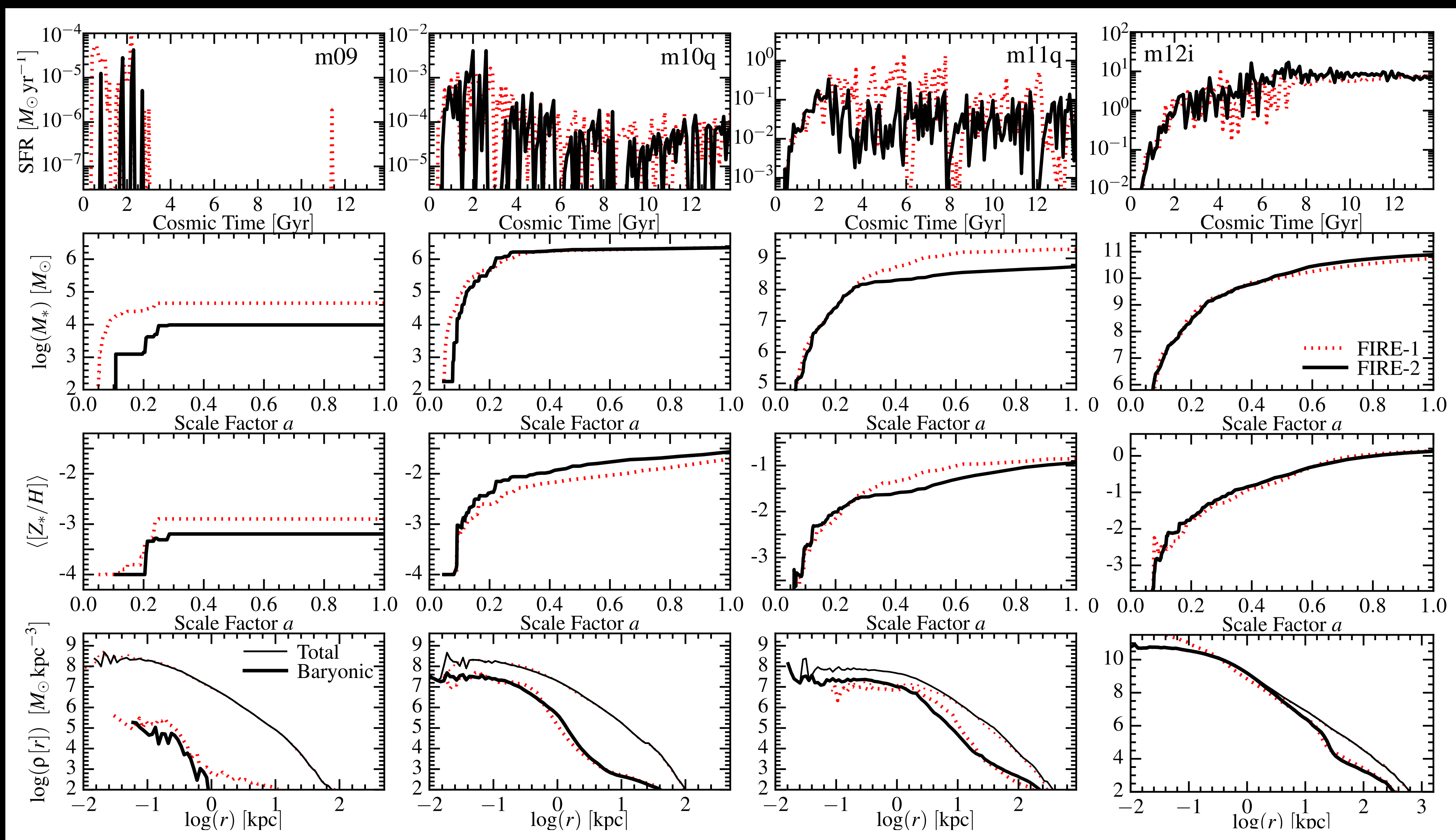


Hopkins et al. to be submitted

Comparison FIRE – FIRE-2

- new SN injection scheme that ensures isotropic injection
- no artificial pressure floor in FIRE-2: “does more harm than good”
- increased mass resolution: e.g., for MW m_b ~ 7000 $M_\odot$

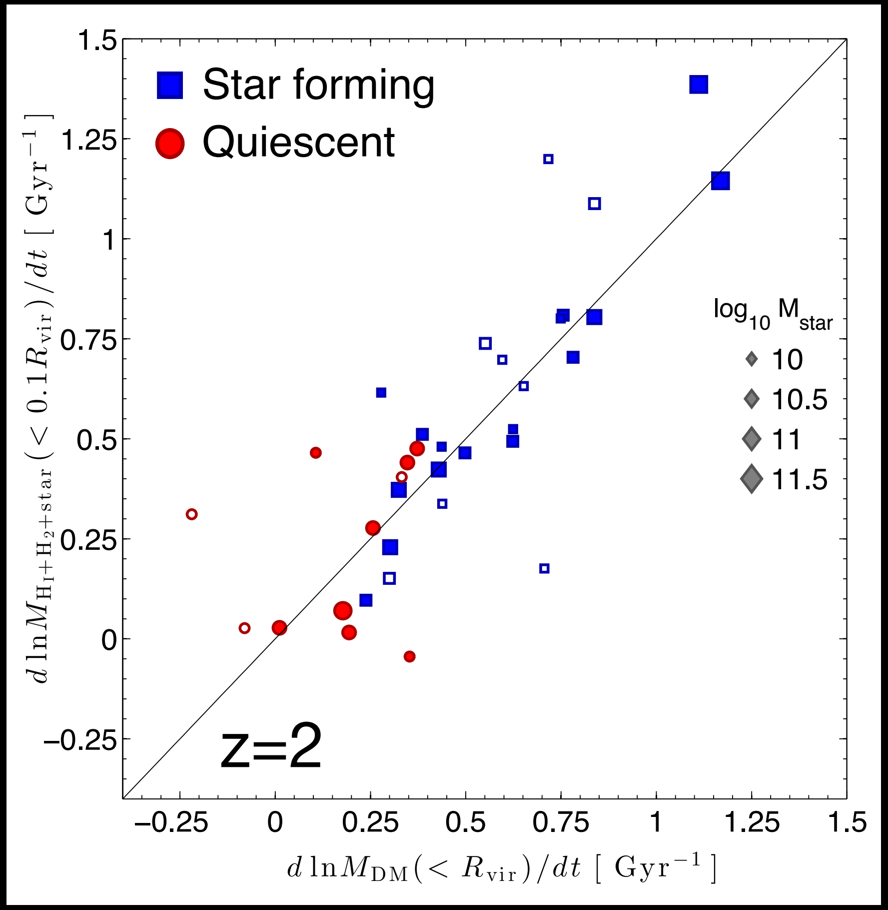
- overall good agreement between FIRE and FIRE-2



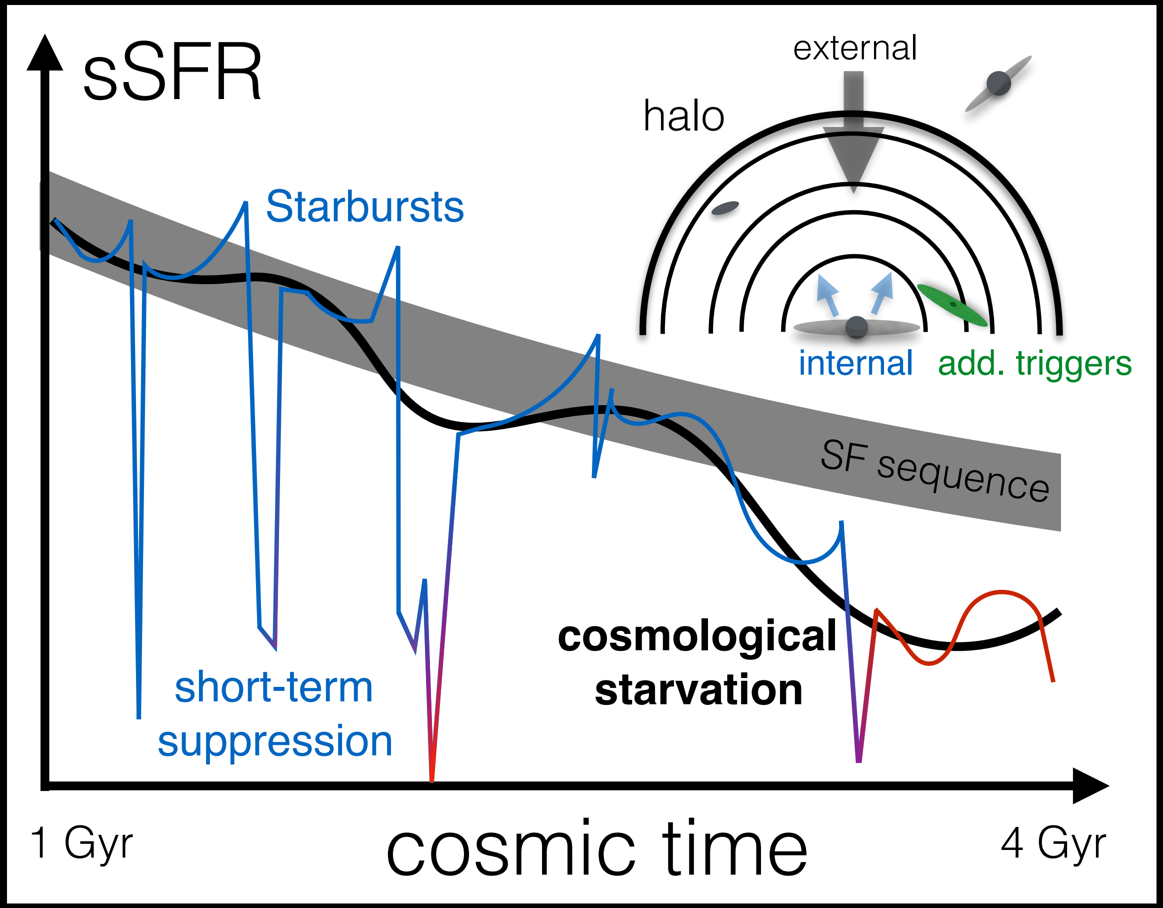
What have we learned?

A lot! For example,

- Feedback => self-regulate SF on galactic scales, Kennicutt-Schmidt relation
- On cosmological scales: SFR set by the gas inflow into galaxies, counter-intuitive: SFR sets gas mass of galaxies (not the other way round)
- halos mass drives many galaxy properties, but halo accretion rate 2nd parameter (especially for SFR: 'cosmological starvation')



at z≳2: comb. of starbursts & cosm. starv.



RF et al. 2015, 2016, 2017, RF et al in prep

What are the current challenges?

- What is the origin of quiescent galaxies at low and high z?
- What is stopping the mass growth of massive galaxies?
- What is the role of AGN feedback? (see also e.g. Joop’s, Yohan’s talks)
- How do galaxies grow in size (mergers, progenitor bias, ‘compaction’)?

Adding BH to MassiveFIRE

Accretion:

Galactic scales (>>10 pc)	Intermediate scales (BH sphere of influence)	Local scales (<<0.1 pc)
torques from bars, spiral arms etc	eccentric nuclear disk (disk fraction, disk mass)	viscous stress
explicitly resolved	Hopkins & Quataert 2010	

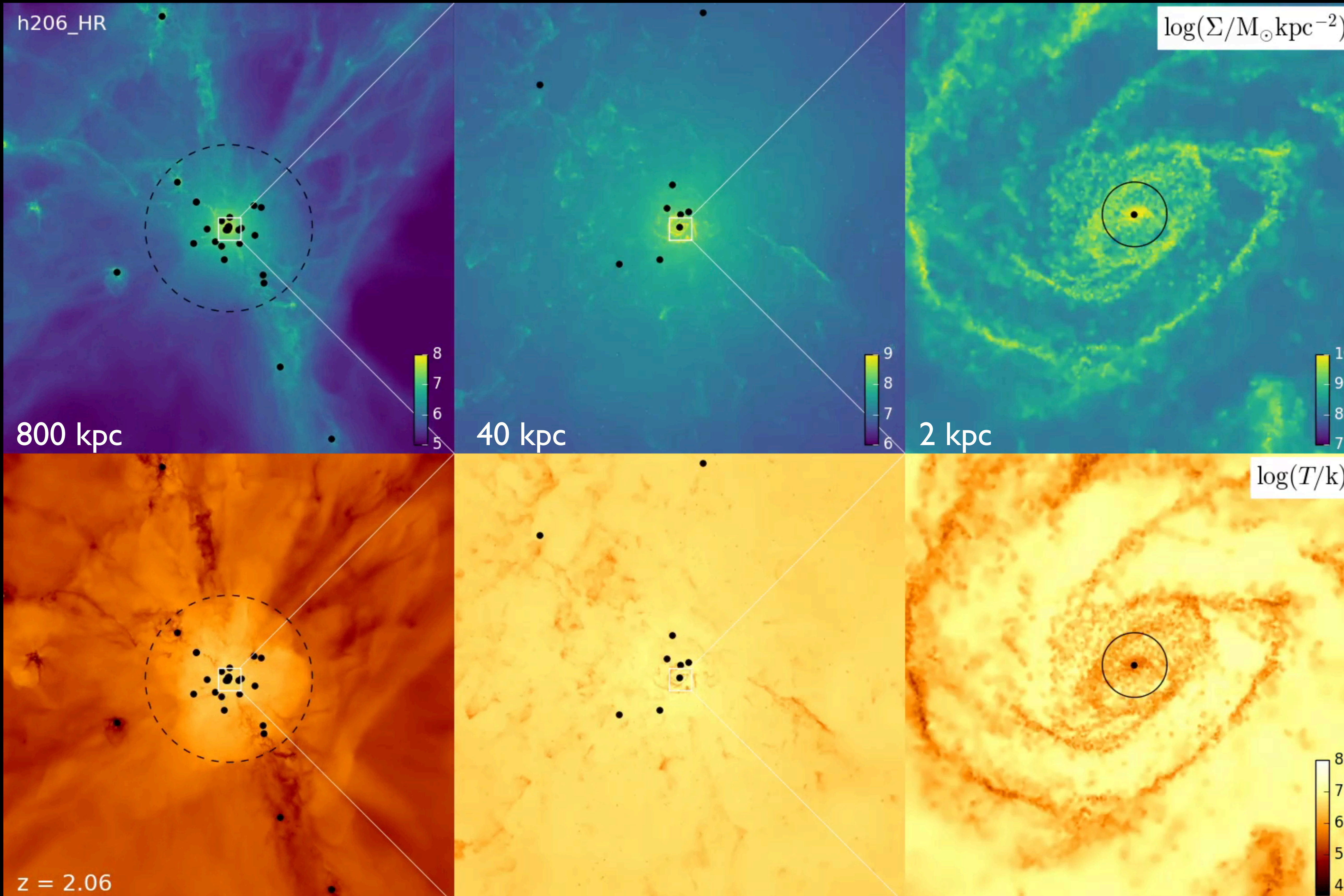
- cap at 10 x Eddington (rad. efficiency 10%)
- fraction of mass from gas particles in accretion radius (R0~100 pc) added to BH

BH dynamics:

- $M_{seed} \sim 10^4\, M_\odot$ in $10^7\, M_\odot$ halos
- dynamical friction on resolved scales: boost dynamical mass by x300
- merge if within accretion radius and relative velocity < escape speed

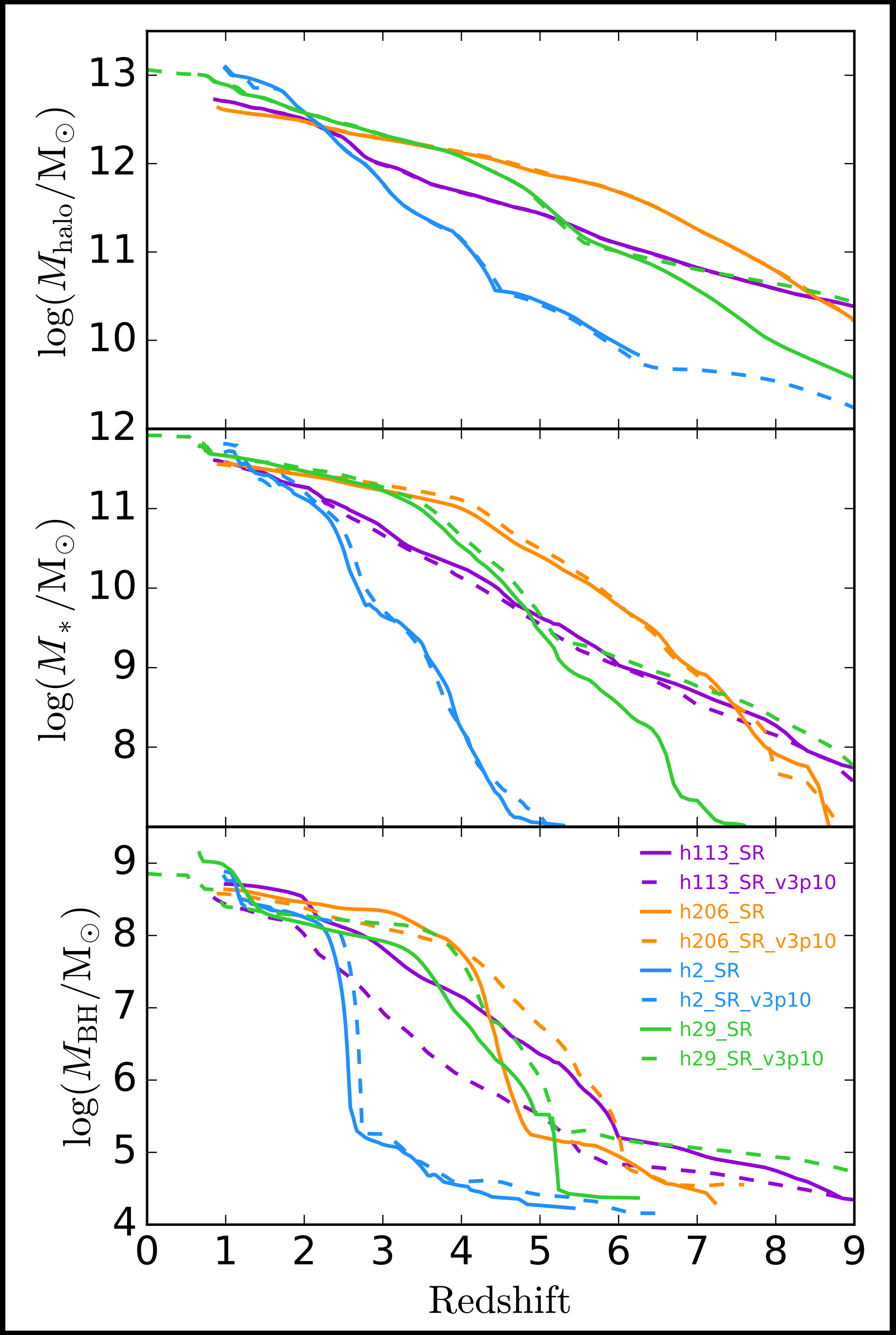
Feedback:
- model: BAL winds
- particles around BH kicked radially: v~1000 km/s, dP/dt ~ 10 L/c
- no decoupling from hydro, cooling not turned-off

Adding BH to MassiveFIRE



Angléz-Alcázar et al. in prep

Some (preliminary) results



- large variations in accretion rate (esp. at high z, where often near Eddington)
- BH feedback appears to not affect galaxy masses
- BH feedback affects BH growth at z<2 but no consistent effect at high z

Summary

- Massive galaxies are complex systems that pose a number of challenges
- significant progress over the past ~5 years but some major questions still open e.g.,
    - origin of quiescent galaxies
    - reproducing galaxy morphologies
    - galaxy sizes
    - other drivers besides halo mass
- BH feedback promising candidate to solve some of these problems but proper modeling remains challenging