International Centre for Radio Astronomy Research

Galaxies: Mechanisms of Galaxy Formation and Evolution

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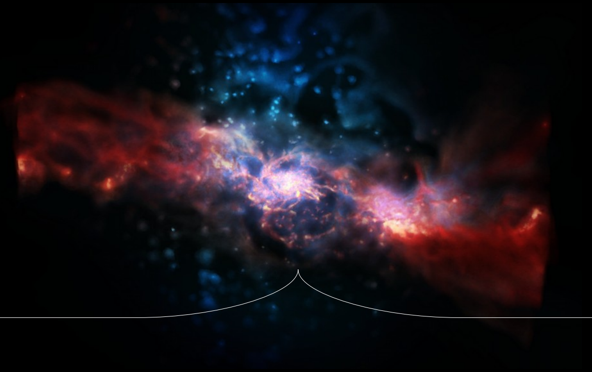
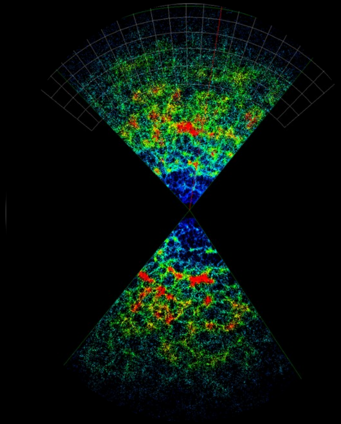
Department of the Premier and Cabinet
Office of Science

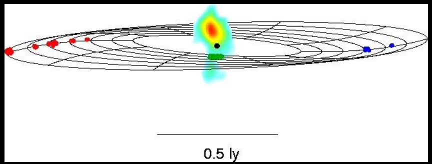
What are the necessary ingredients of a ***predictive theory*** of galaxy formation?



Large Scale Structure



ISM, star formation black hole accretion



1pc 100pc 100Mpc 1Gpc

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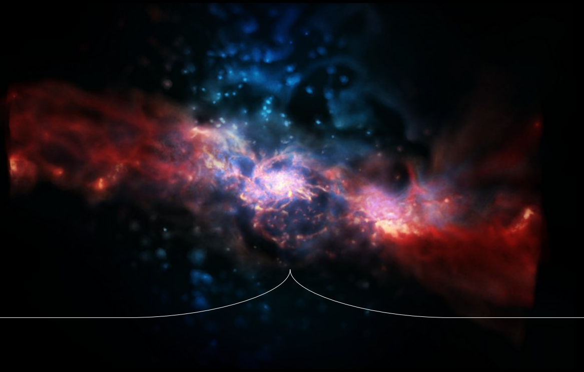

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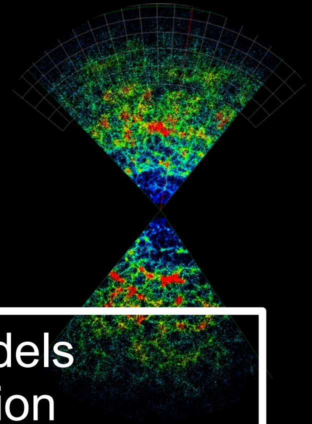

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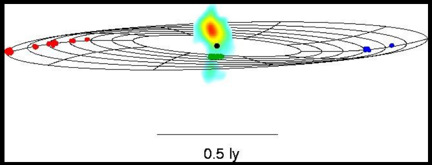

Hydro-dynamic simulations of galaxy formation

Semi-analytic models of galaxy formation

1pc

100pc

100Mpc

1Gpc

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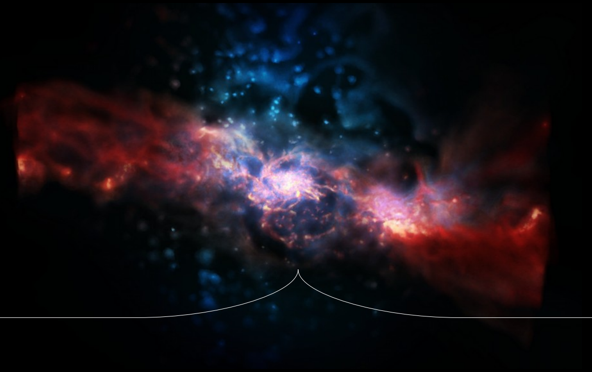

Sub-grid physics

Large Scale Structure

ISM, star formation
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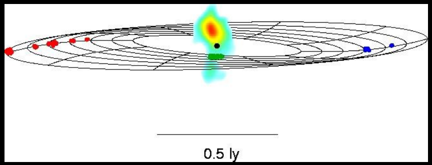

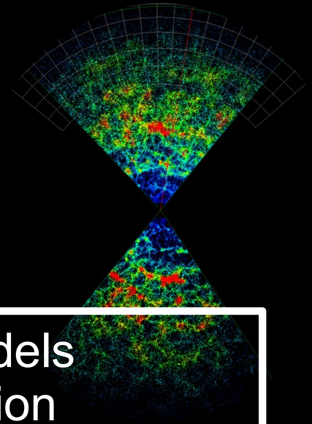

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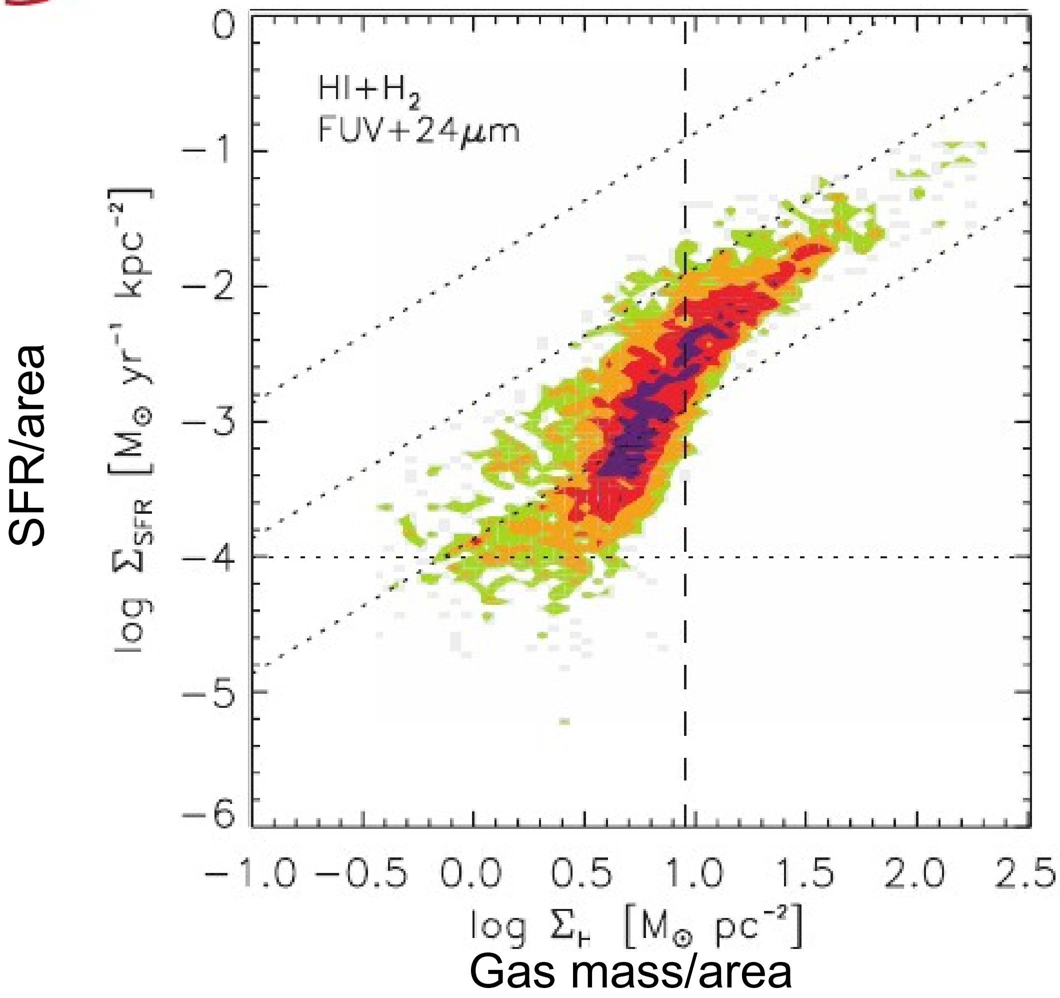
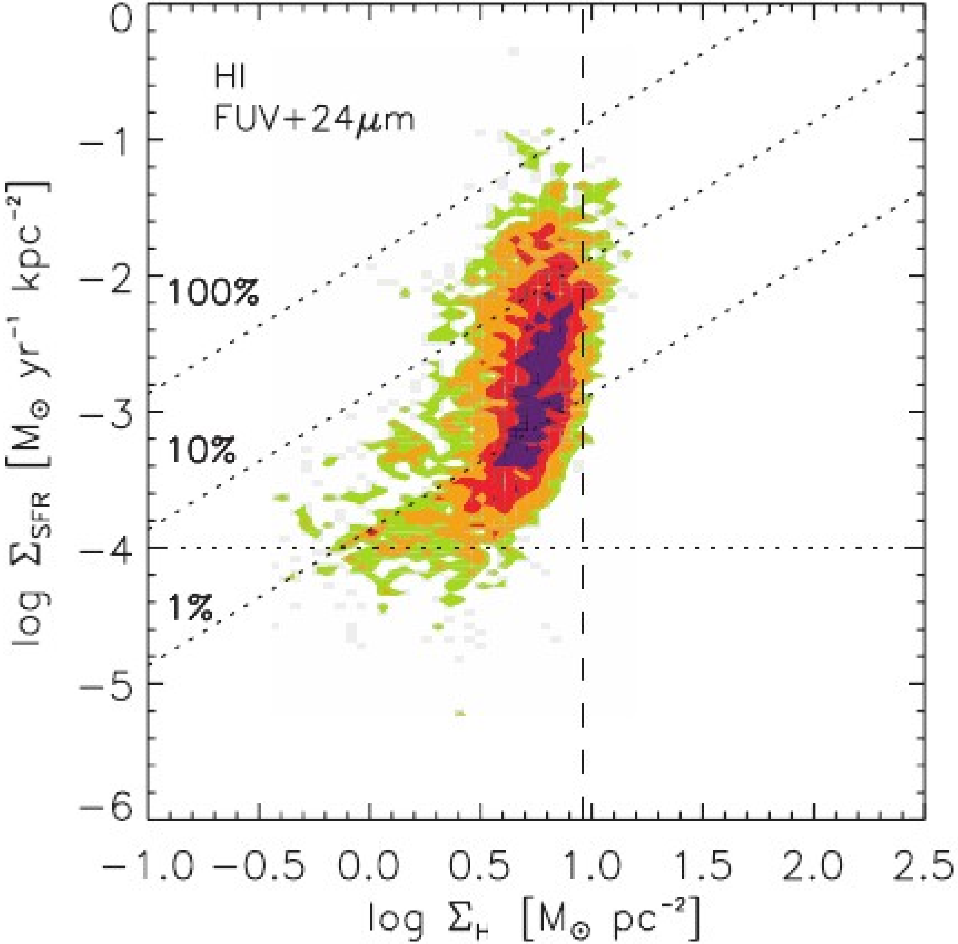
A revision required in the ISM/SF model



Bigiel et al. (2008), Leroy et al. (2008)

A revision required in the ISM/SF model

SFR/area



Gas mass/area

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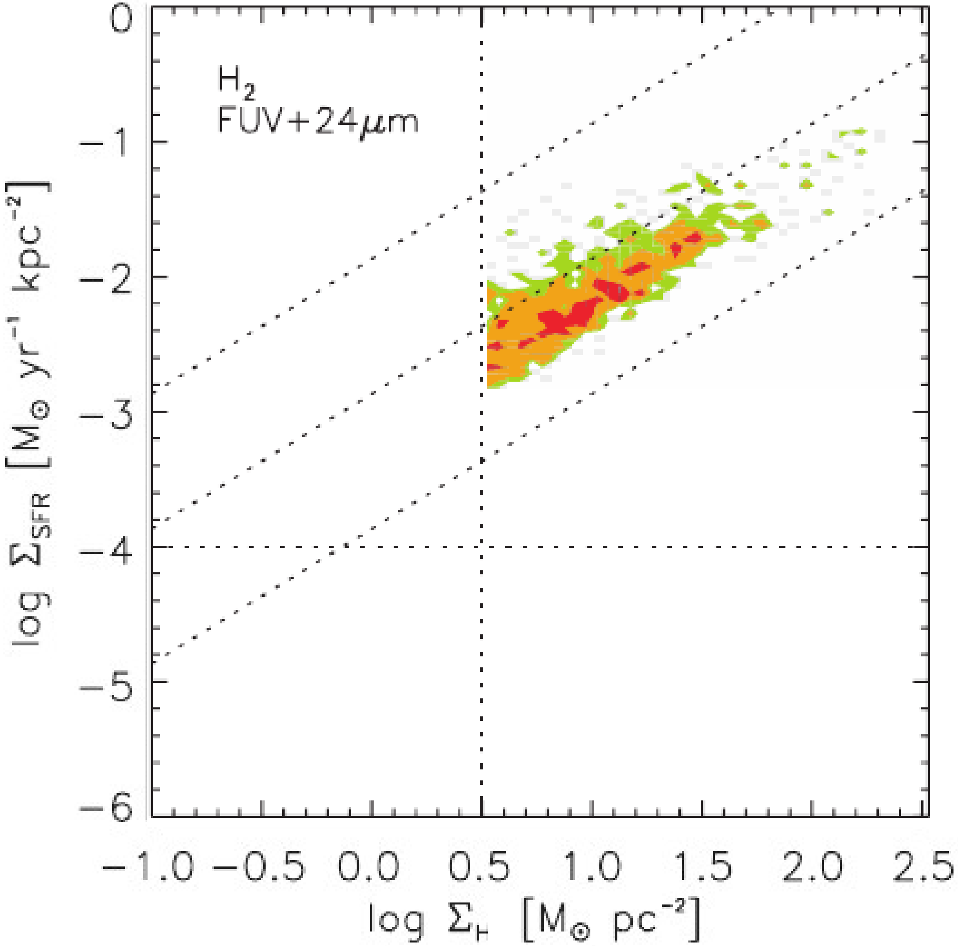

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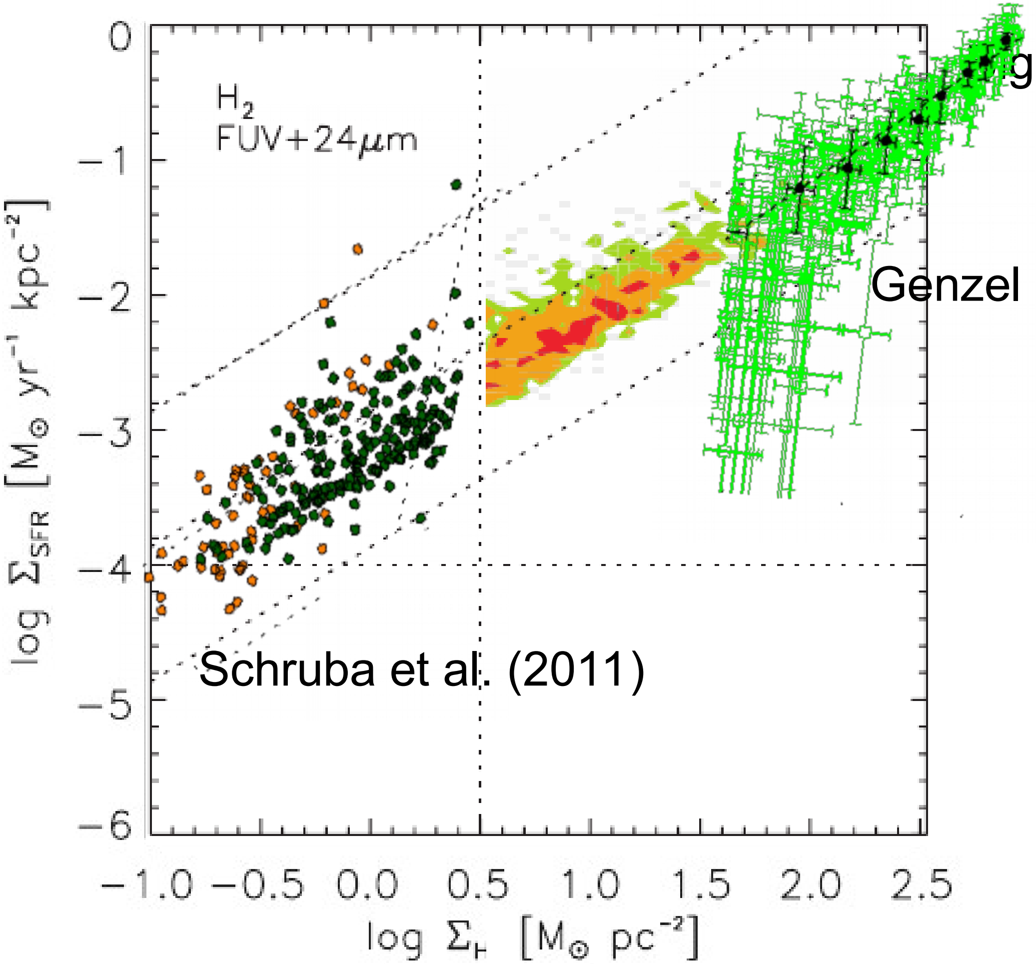

...giel et al. (2008), Leroy et al. (2008)

Genzel et al. (2013)

Schruba et al. (2011)

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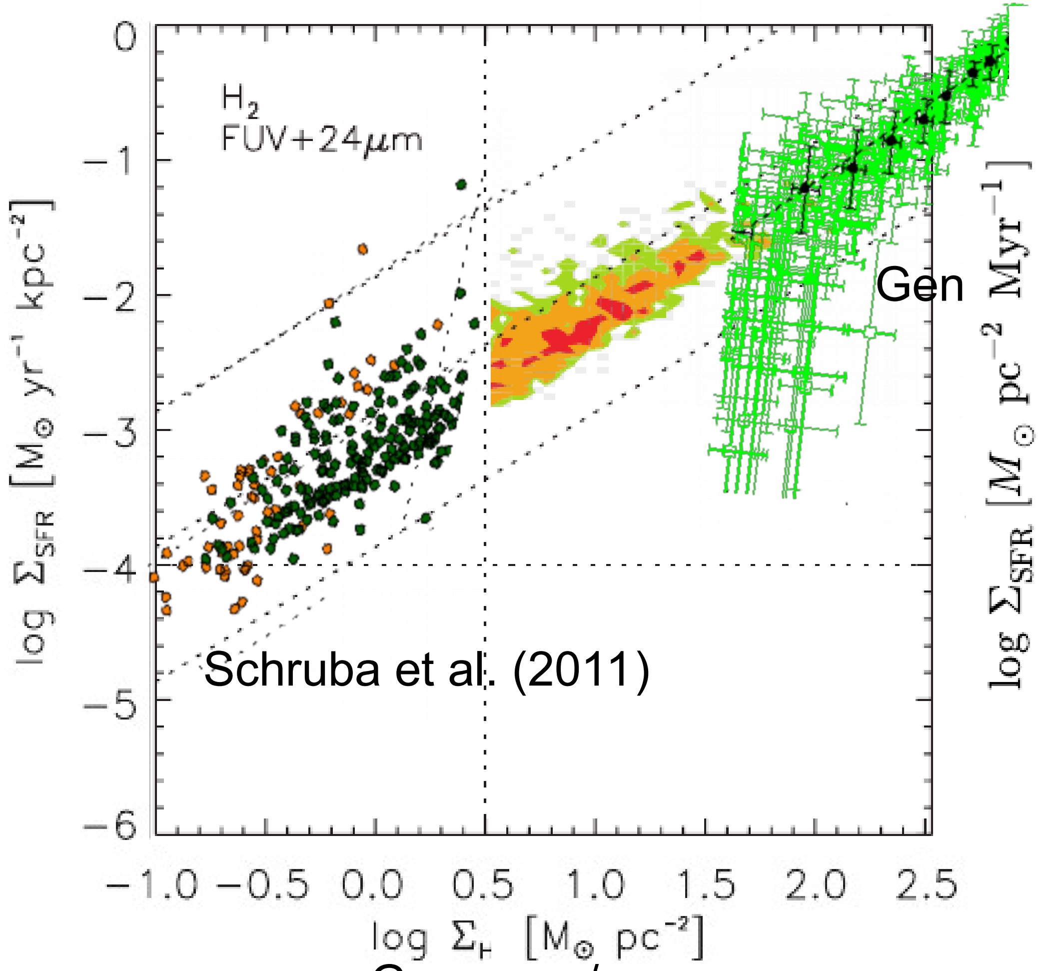

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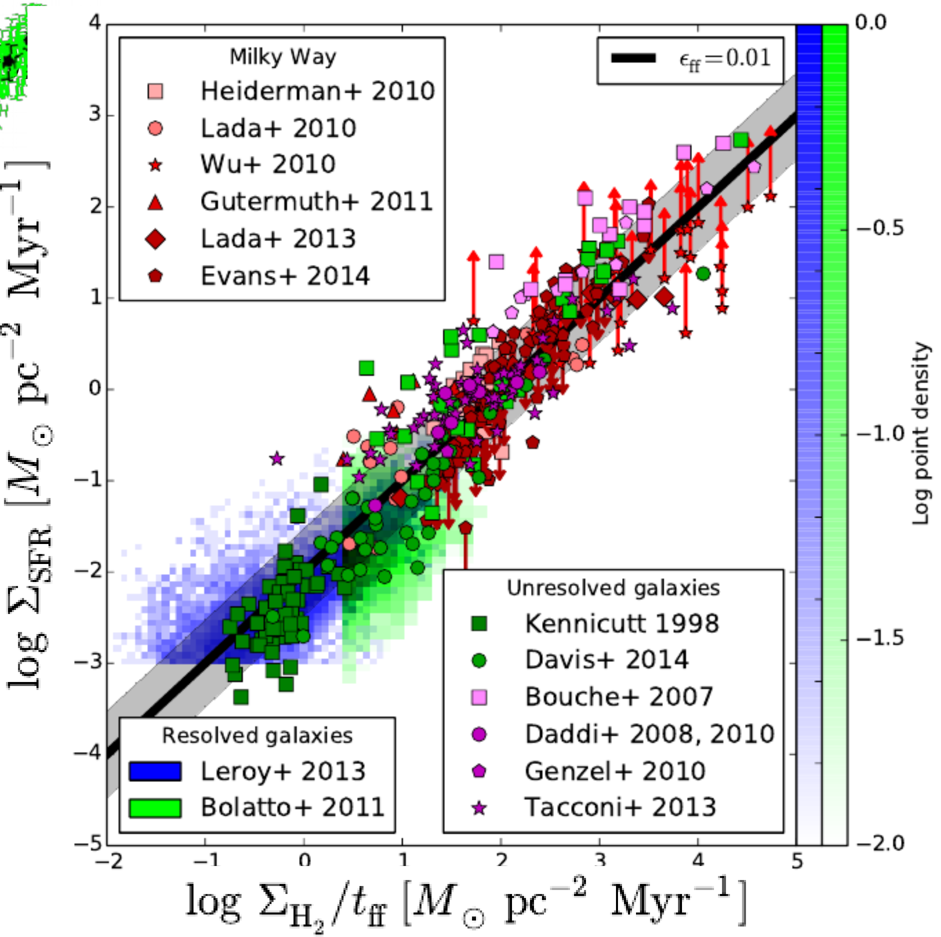

Krumholz (2014; review)

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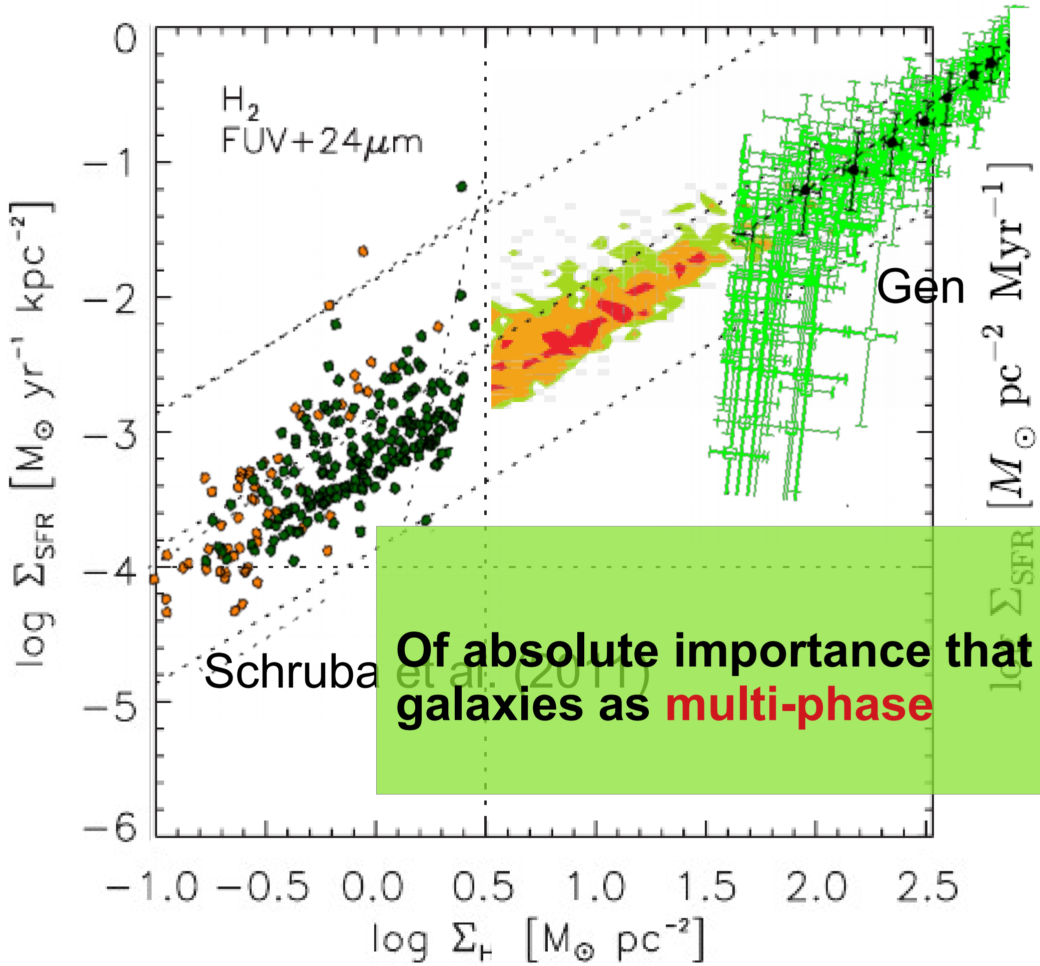
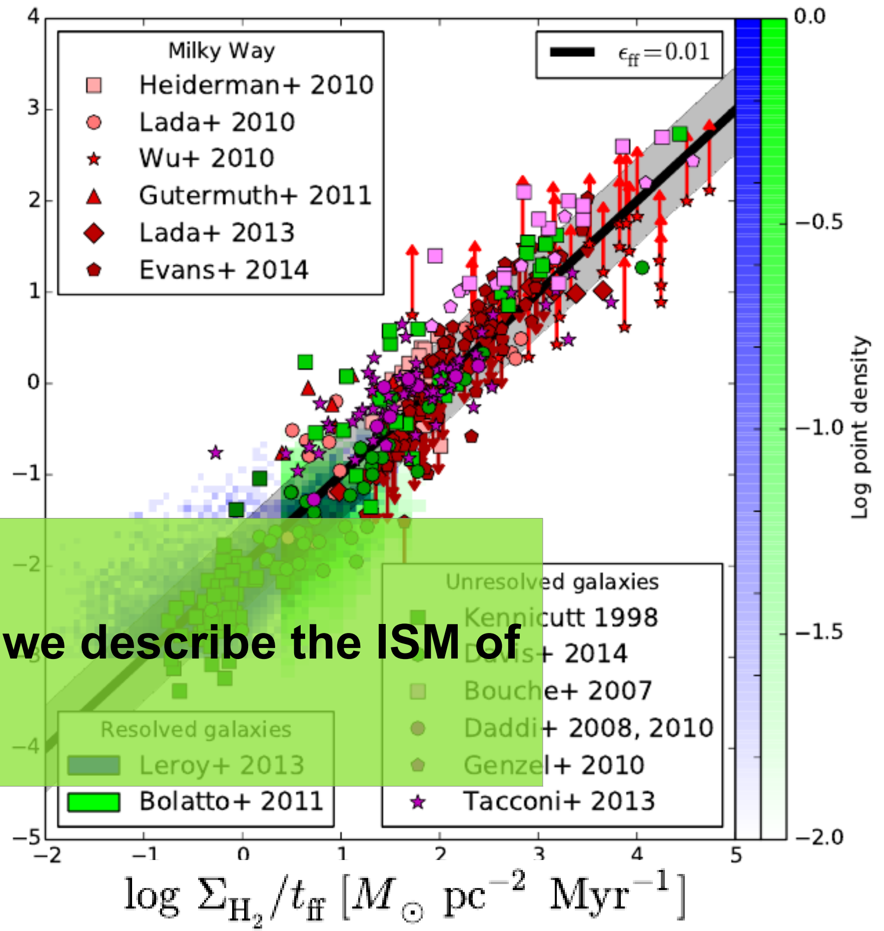


Schruba et al. (2011)

Gen

Gas mass/area



Of absolute importance that we describe the ISM of galaxies as multi-phase

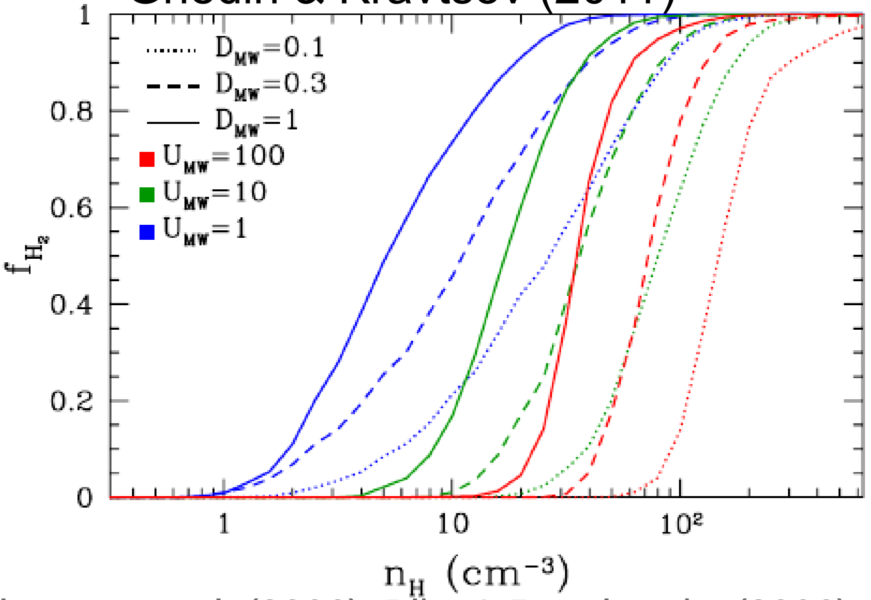
Krumholz (2014; review)

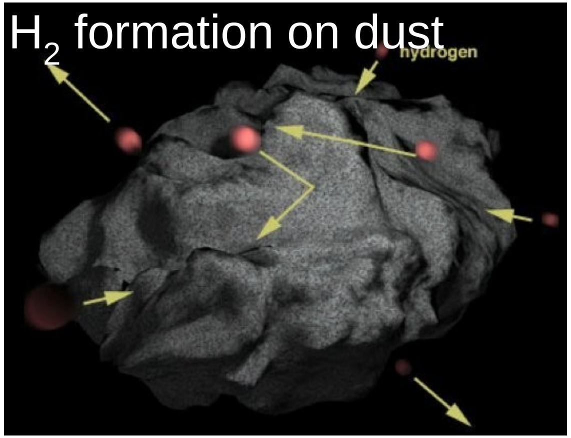
Modelling of star formation/molecular gas

Fraction of star-forming gas

$$\Sigma_{\rm SFR} = \boxed{f_{\rm SF}}\,\epsilon_{\rm ff}\,\frac{\Sigma}{t_{\rm ff}}$$

Gnedin & Kravtsov (2011)





Pelupessy et al. (2006); Blitz & Rosolowsky (2006); Robertson & Kravtsov (2008); Ostriker et al. (2010); Krumholz (2011; 2013); Glover & Clark (2012); Gnedin and Draine (2014); Sternberg et al. (2014); Bialy et al. (2017); Semenov et al. (2016, 2018), ...

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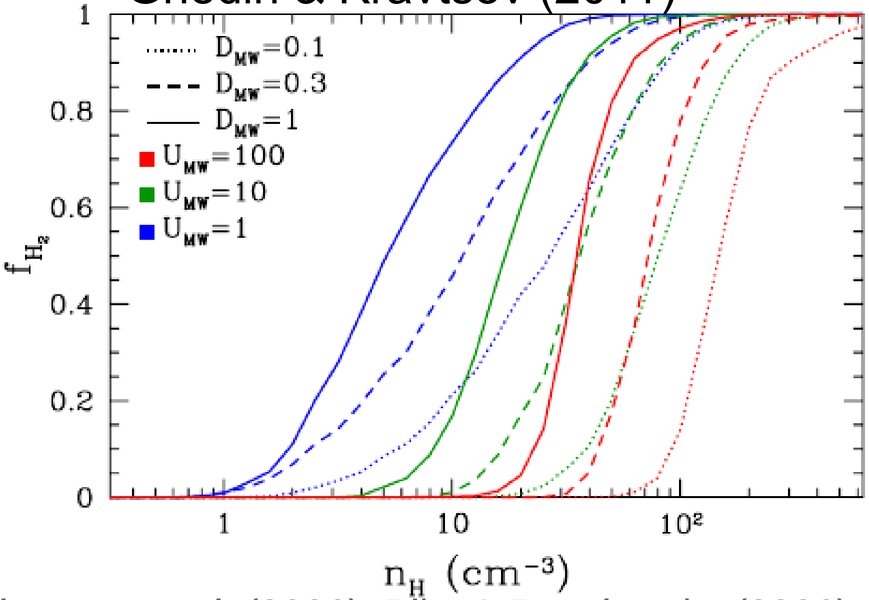

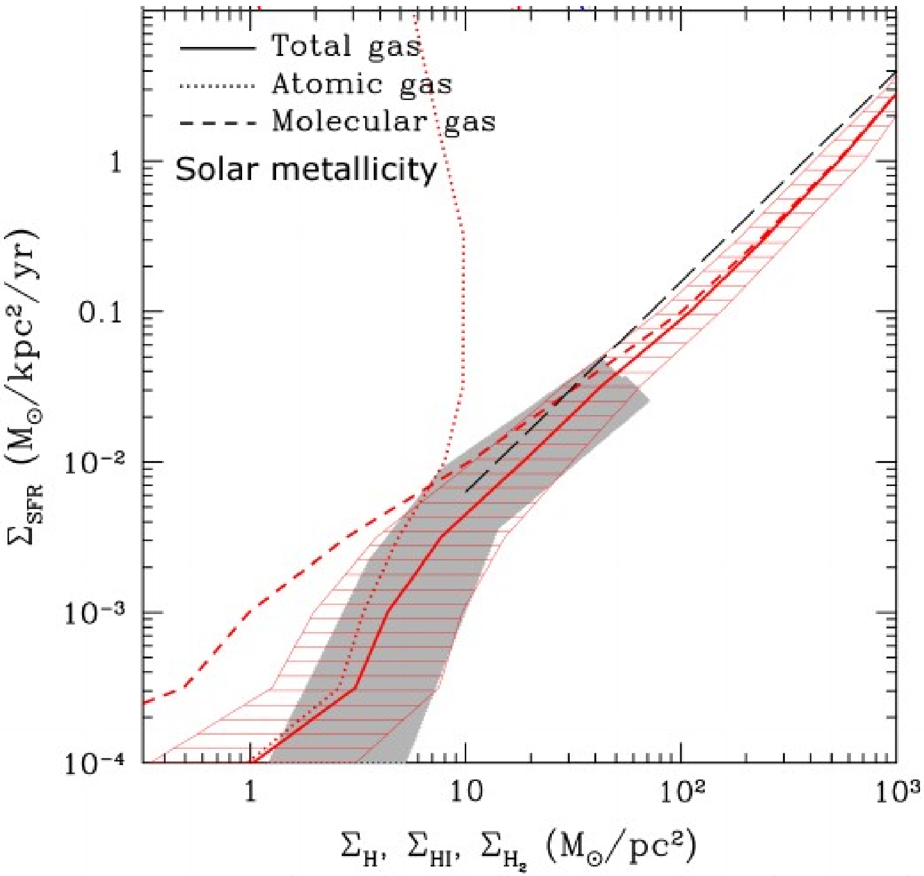

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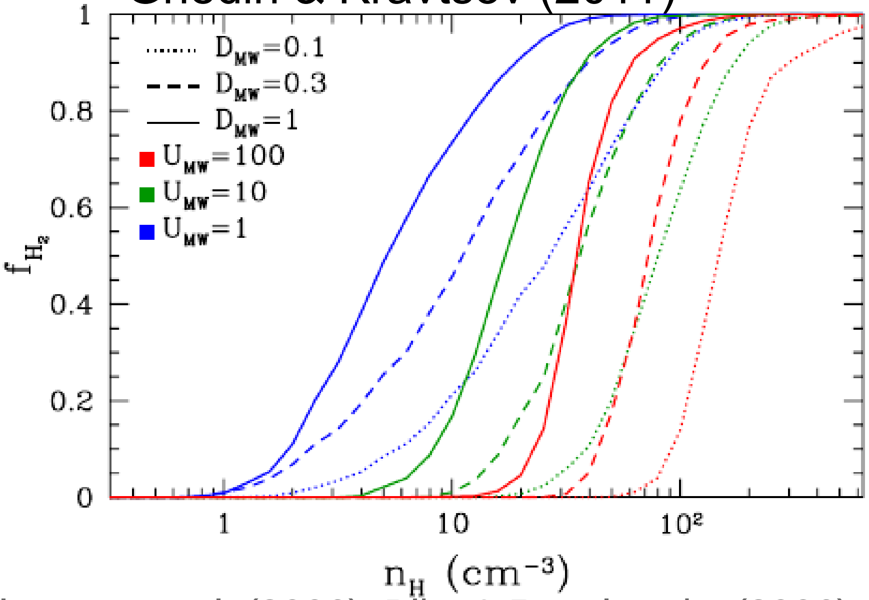

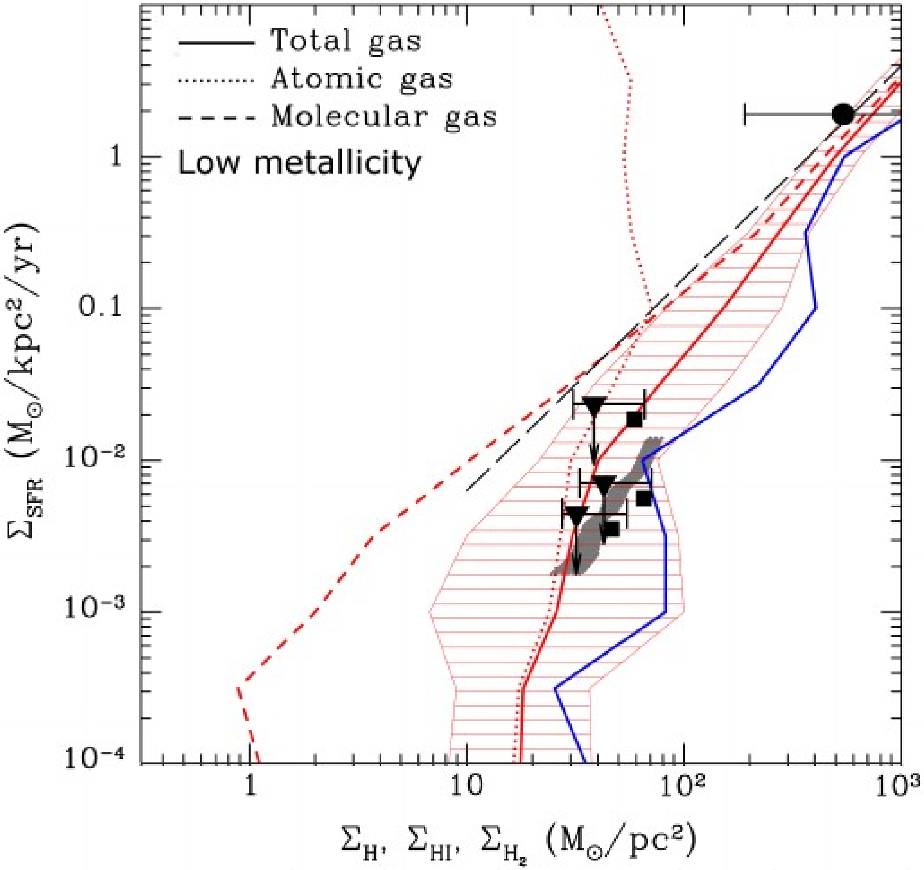

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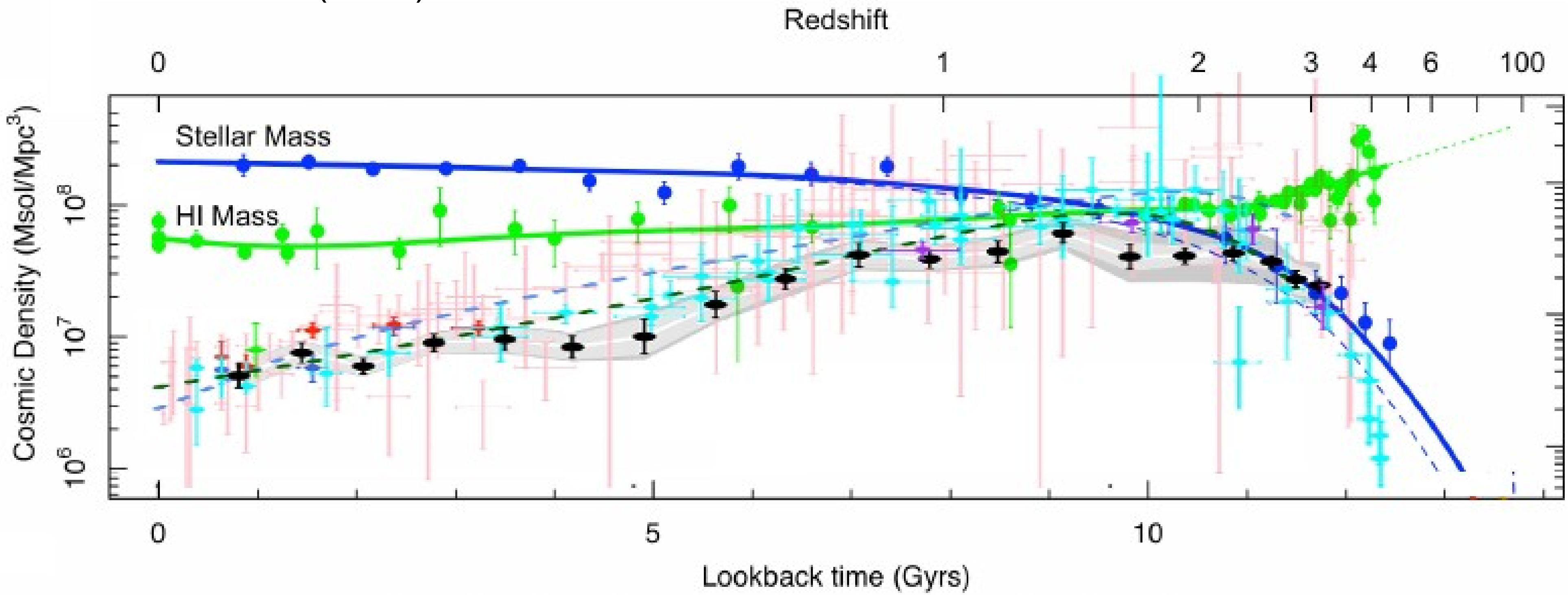
Applications in cosmological simulations

ISM phases – HI/H2 distinction
Star formation that is H2-based with H2 being calculated from gas properties (dust, ISRF, density)

Popping et al. (2009), Obreschkow et al. (2009); Power et al. (2010); Cook et al. (2010); Fu et al. (2010); Lagos et al. (2011a,b); Altay et al. (2011); Kuhlen et al. (2011; 2013); Hopkins et al. (2012); Christensen et al. (2012); Duffy et al. (2012); Popping et al. (2014); Somerville et al. (2015); Lagos et al .(2015); Bahe et al. (2016); Stevens et al. (2016); Dave et al. (2016); Crain et al. (2017); Xie et al. (2017); Diemer et al. (2018); Stevens et al. (2018); Lagos et al. (2018),…

A fundamental question: cosmic gas vs. SFR

Driver et al. (2018)

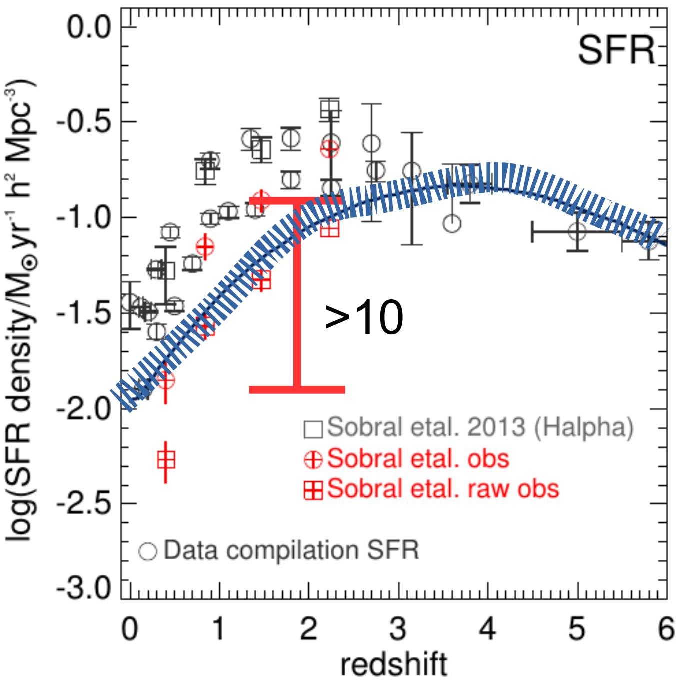


Striking differences in the evolution of the cosmic SFR and HI! Imply strong evolution and diversity of the HI gas conversion efficiency into stars...

Answering fundamental questions: cosmic gas

Lagos et al. (2014a) (see also Lagos+11,15,18, Rahmati+15, Popping+14, Xie+17, Dave+16, ...)

SFR density



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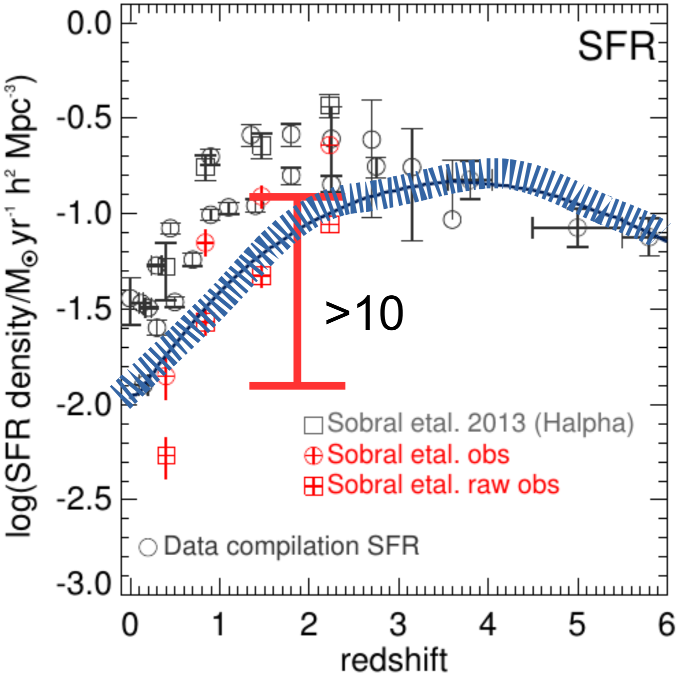
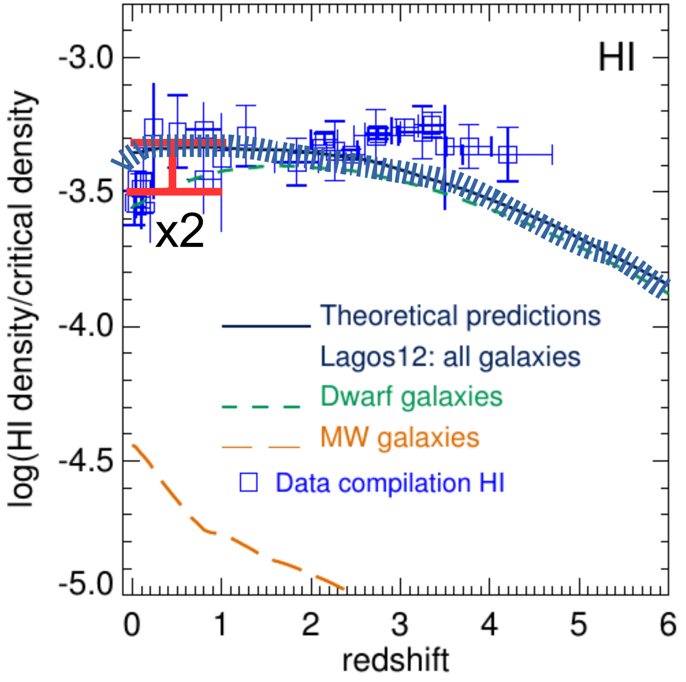


Omega HI



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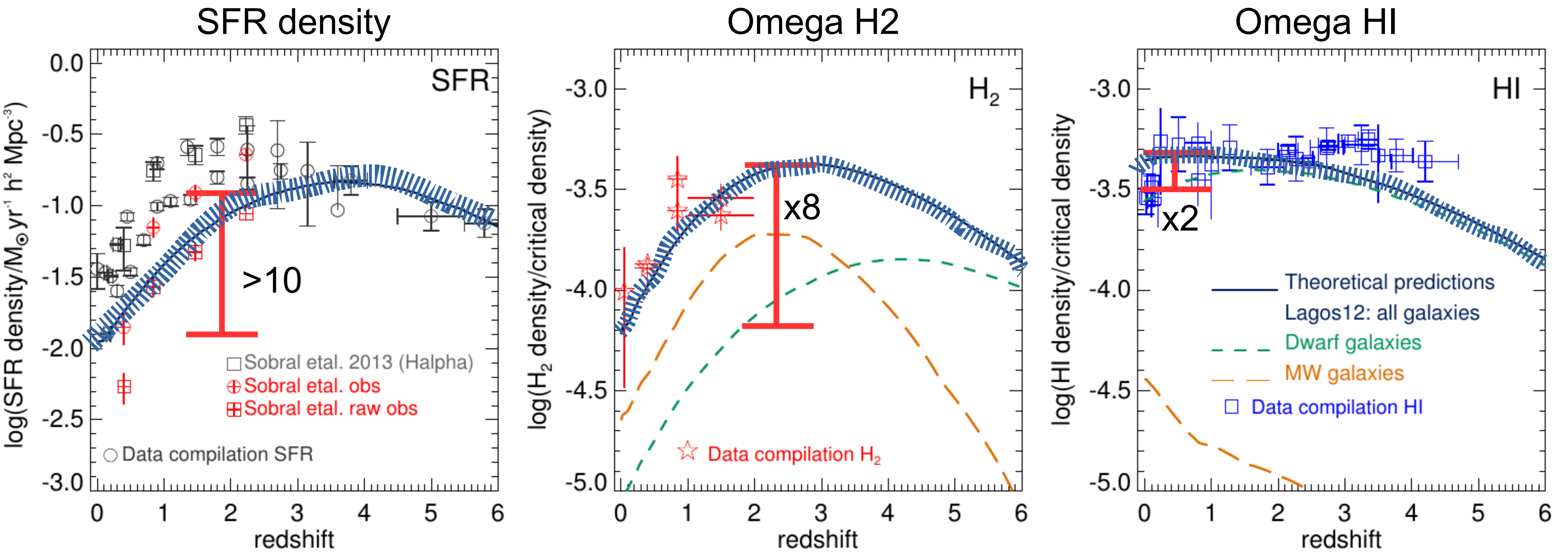

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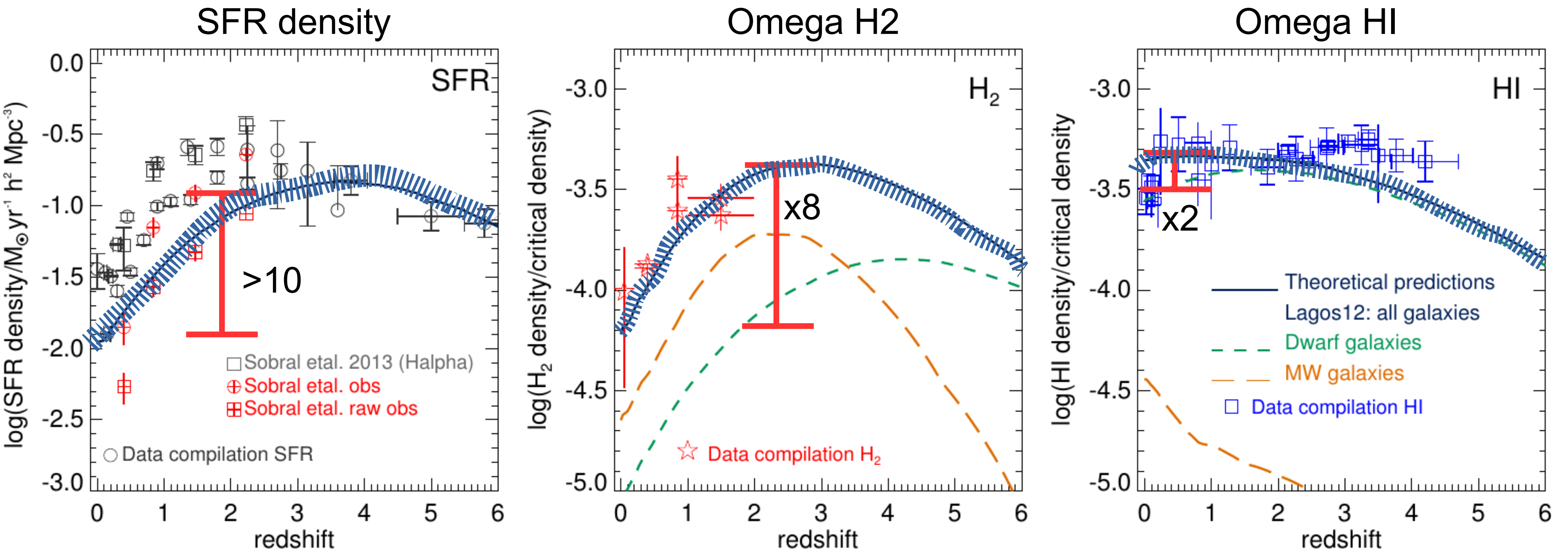

Efficiency of atomic→molecular gas conversion is evolving strongly!
Aided by the size evolution of galaxies

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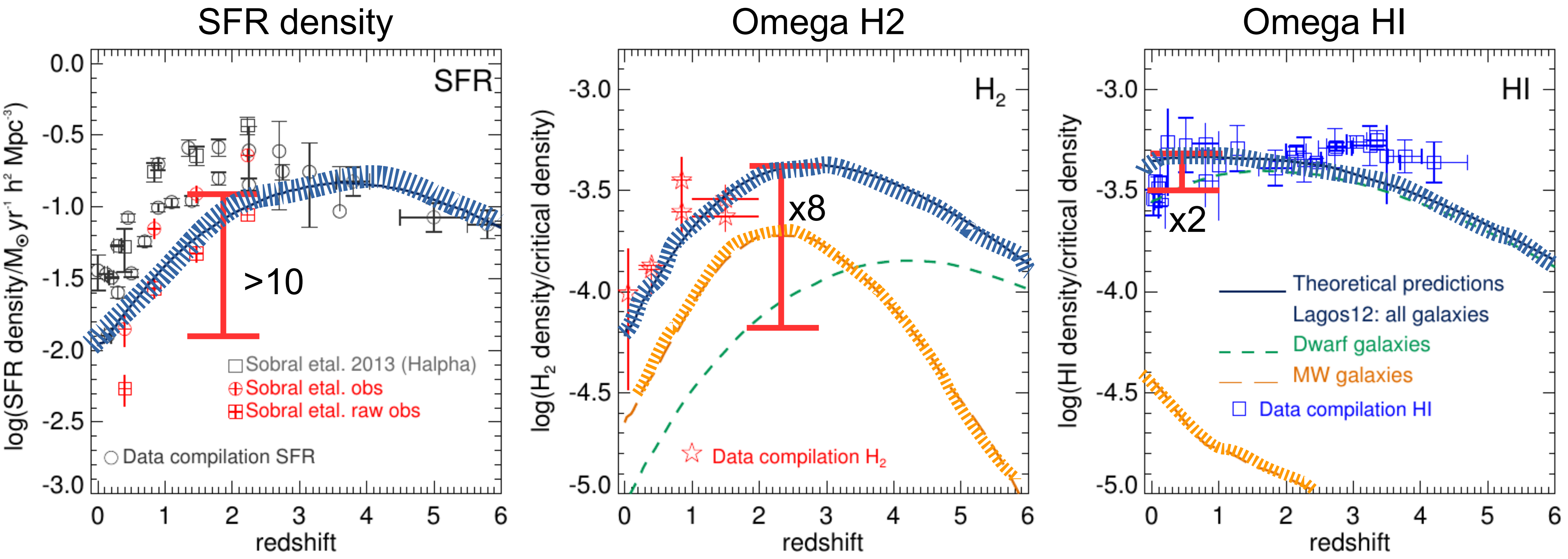

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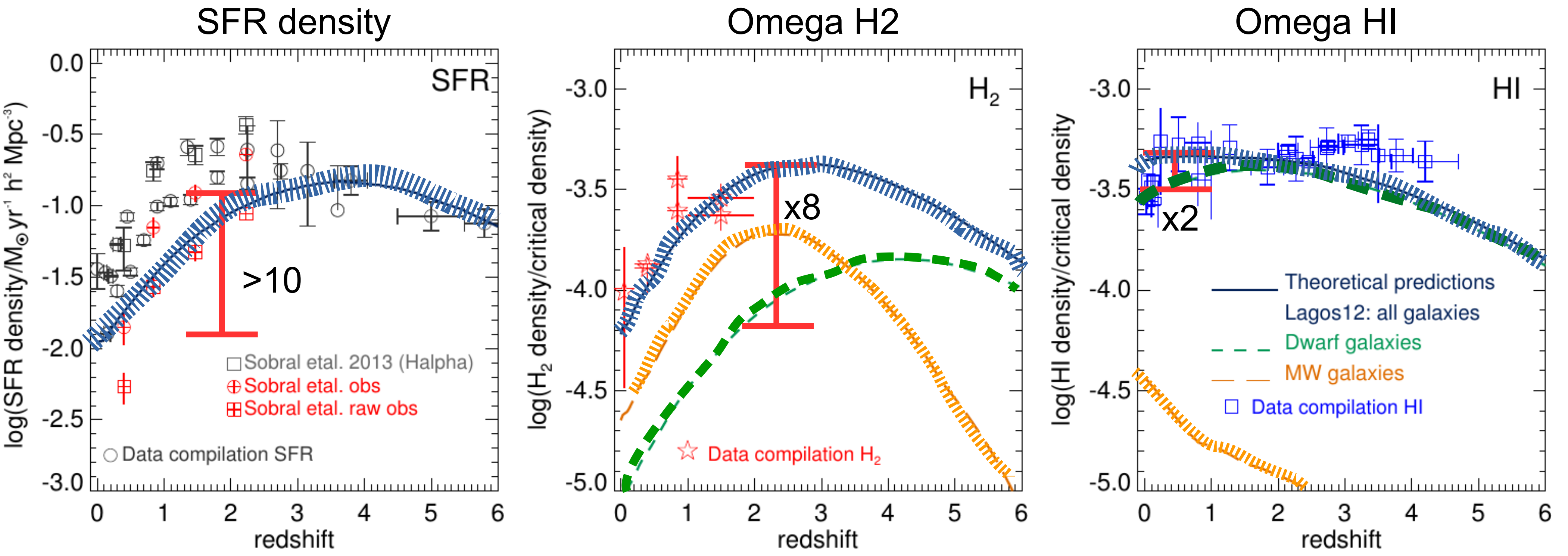

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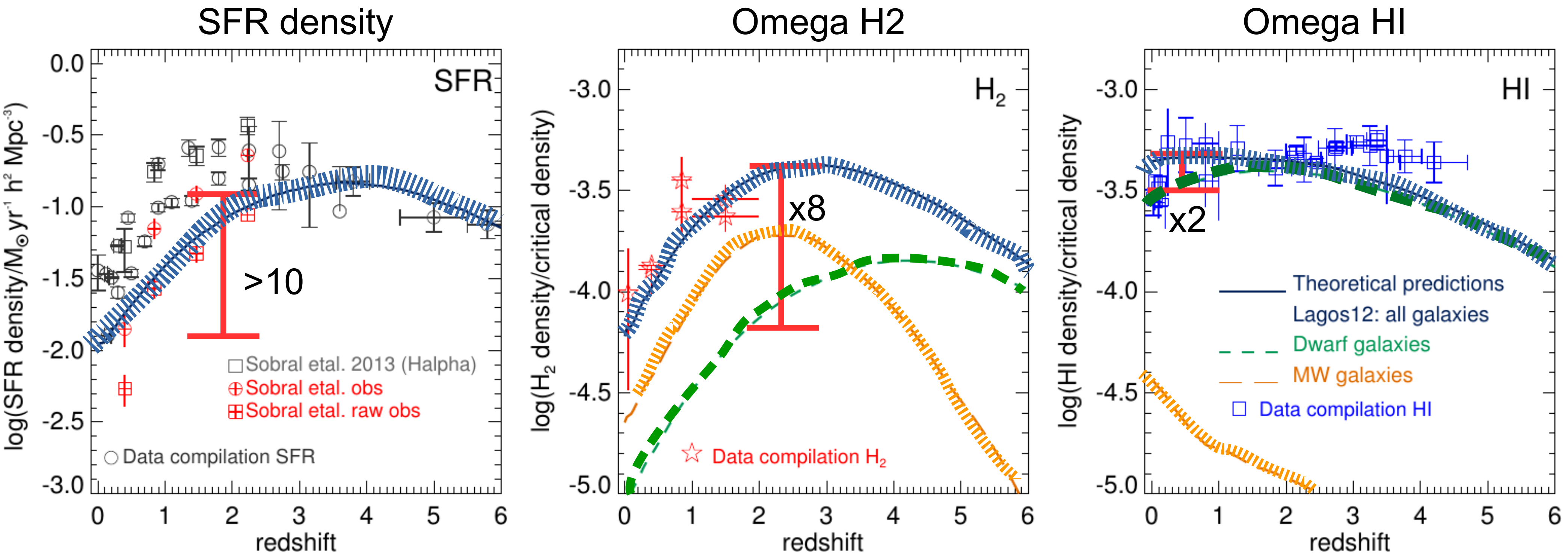
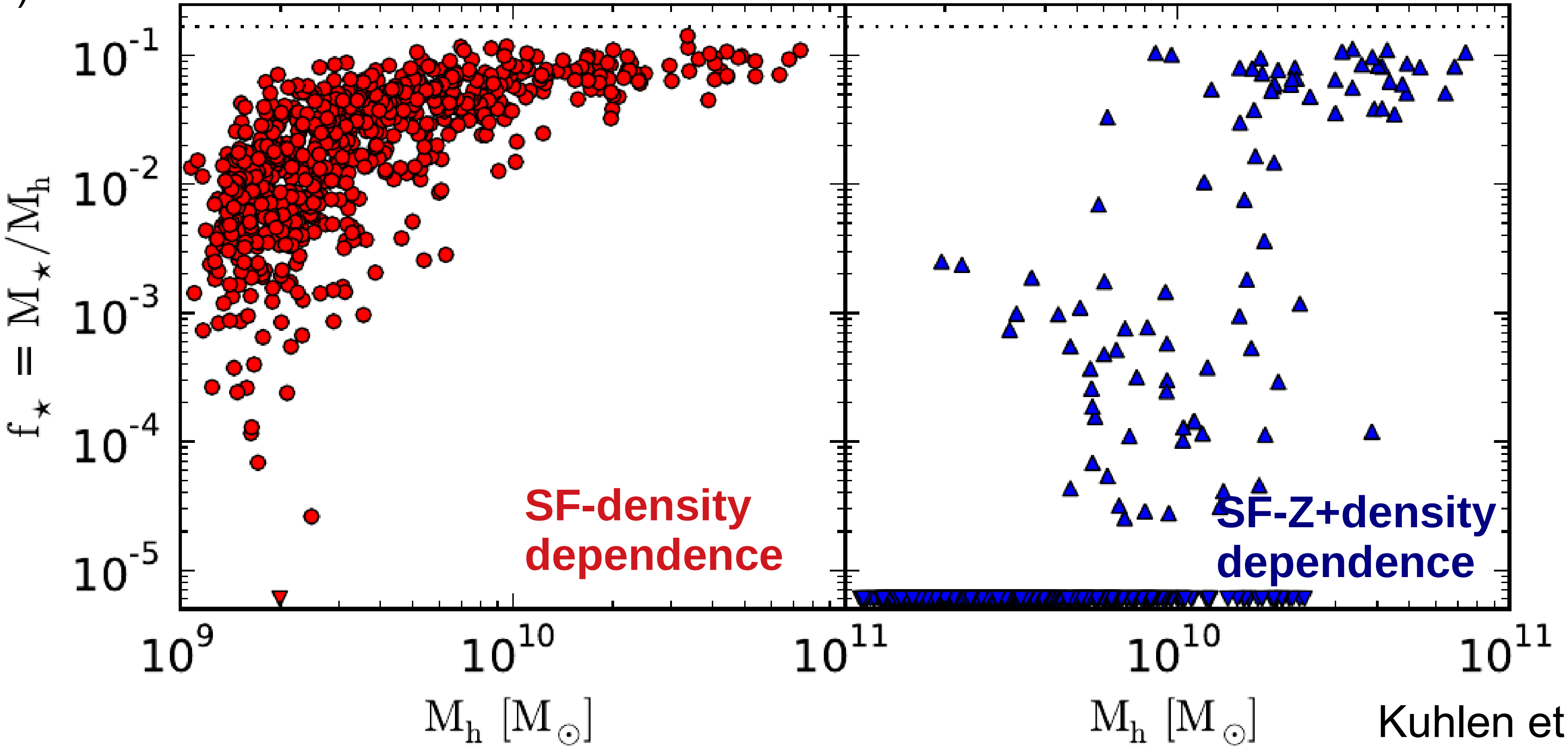


Important implications for what we expect for future HI and CO surveys
(discussed in Lagos et al. 2014a and Power, Lagos+15)

Star formation in dwarf galaxies

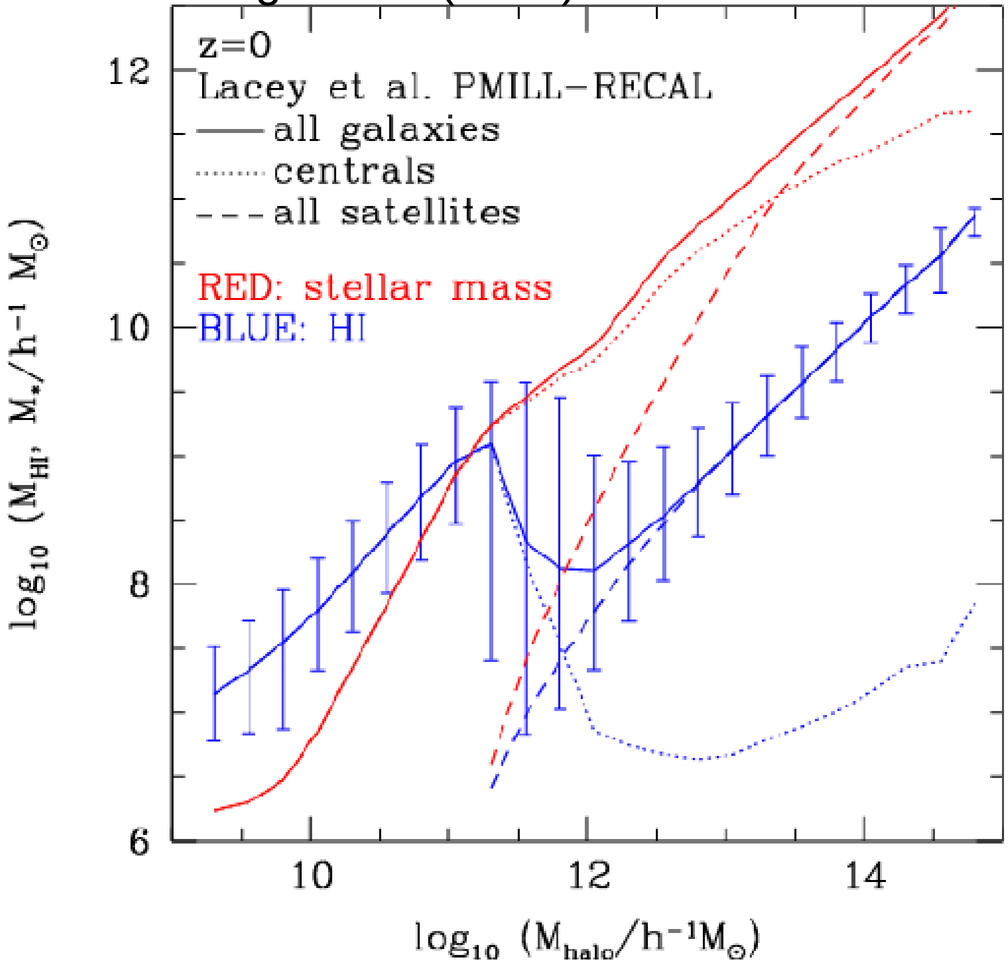
Inhibit star formation in low-metallicity galaxies (dwarfs) → replace feedback mechanisms? (e.g. Krumholz et al. 2009; Gnedin et al. 2009, 2011; Kuhlen et al. 2012,2013; Christensen et al. 2012)



Kuhlen et al. (2012)

HI in galaxies/halos: a key constrain needed

Baugh et al. (2019)



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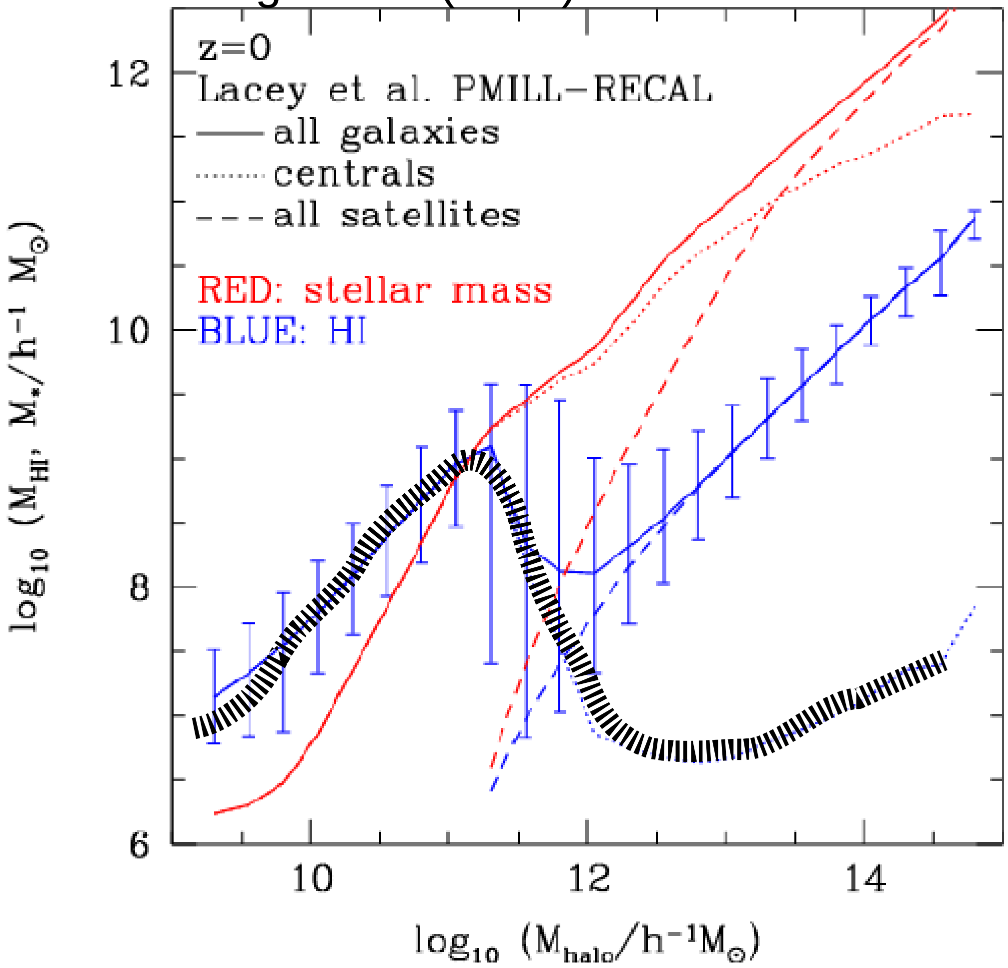

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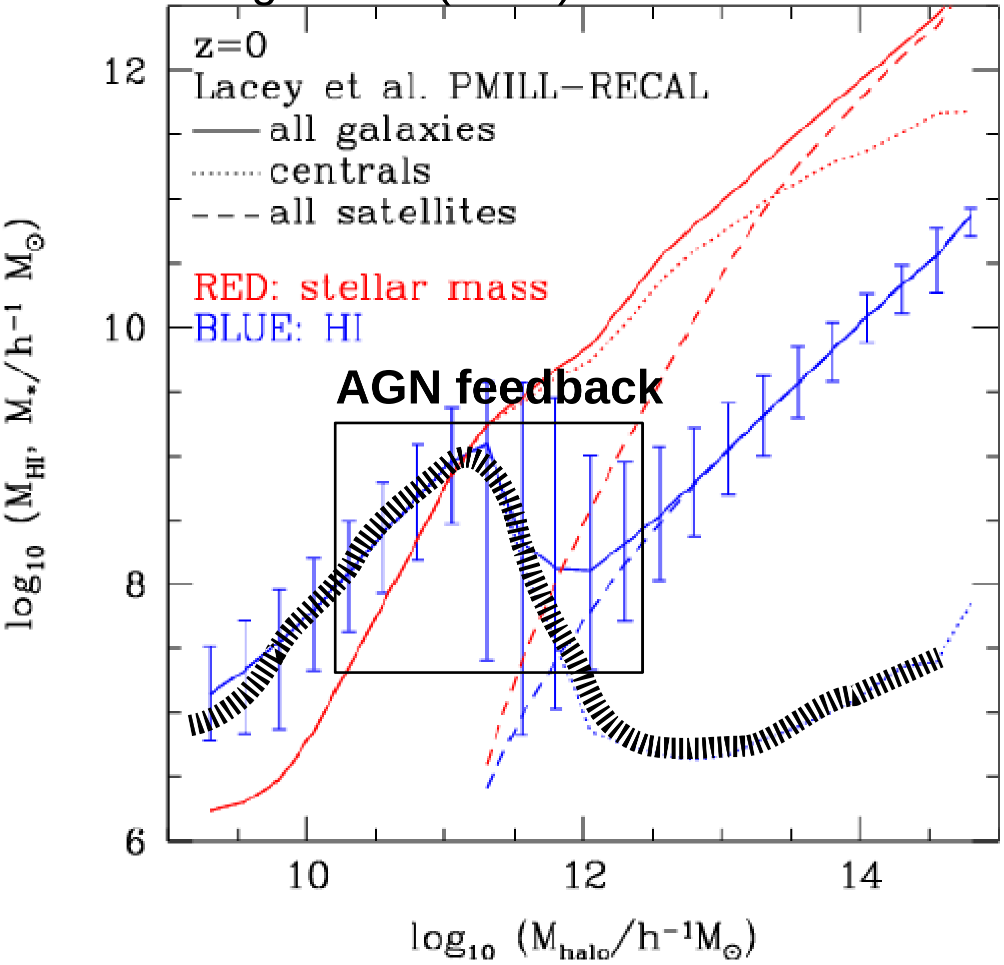

HI in galaxies/halos: a key constrain needed

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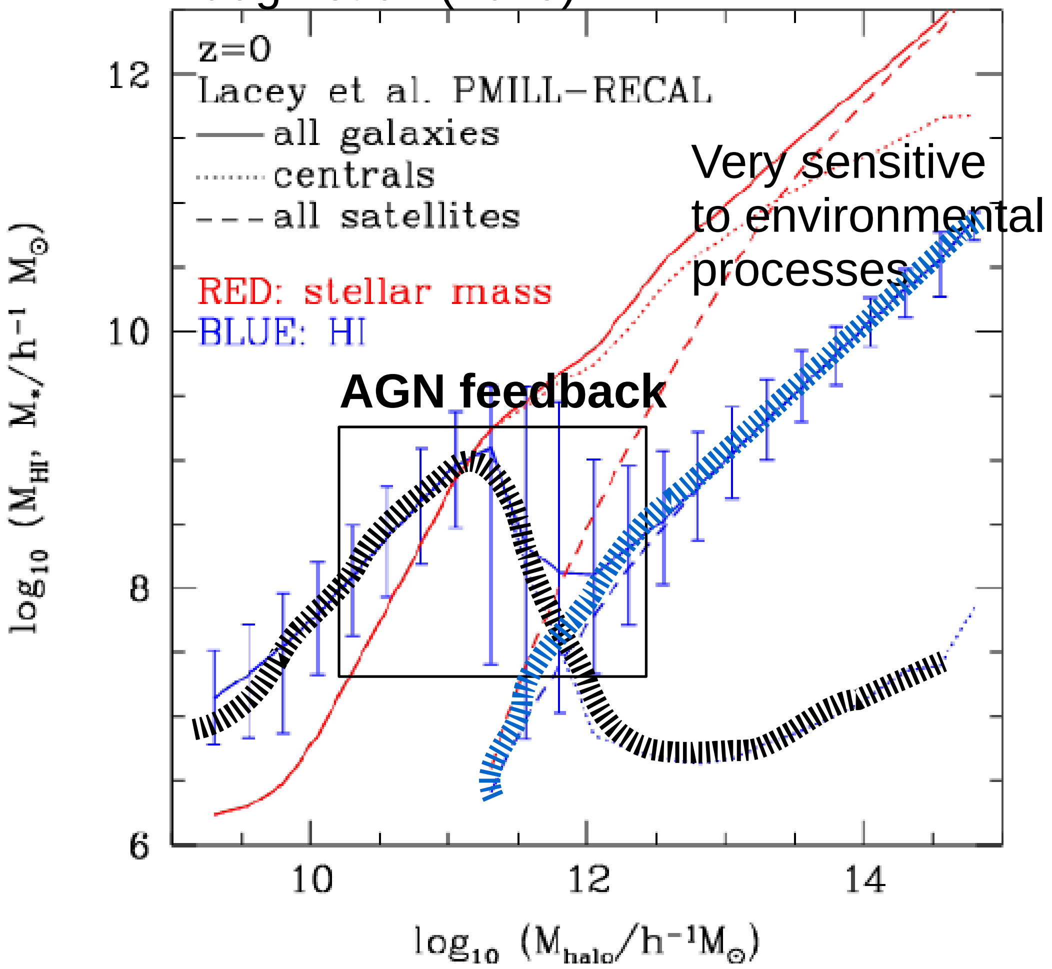

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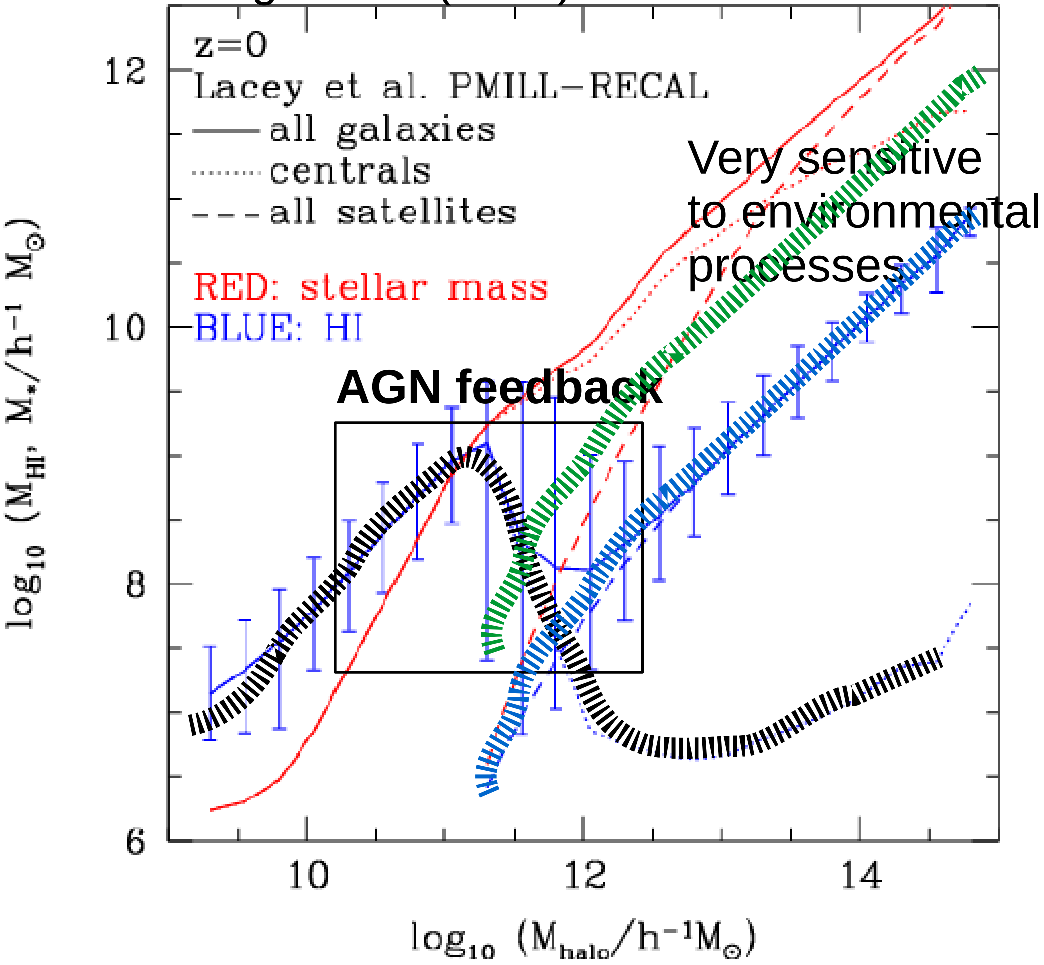

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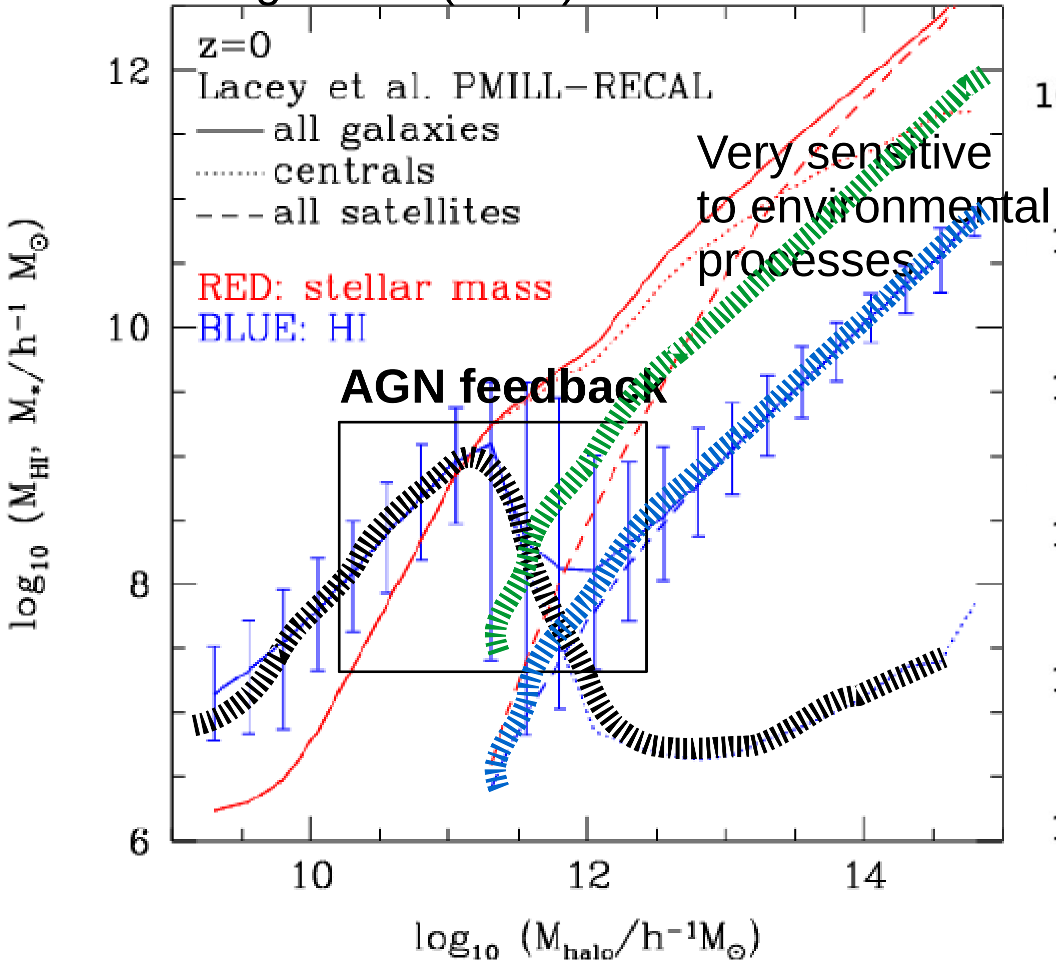
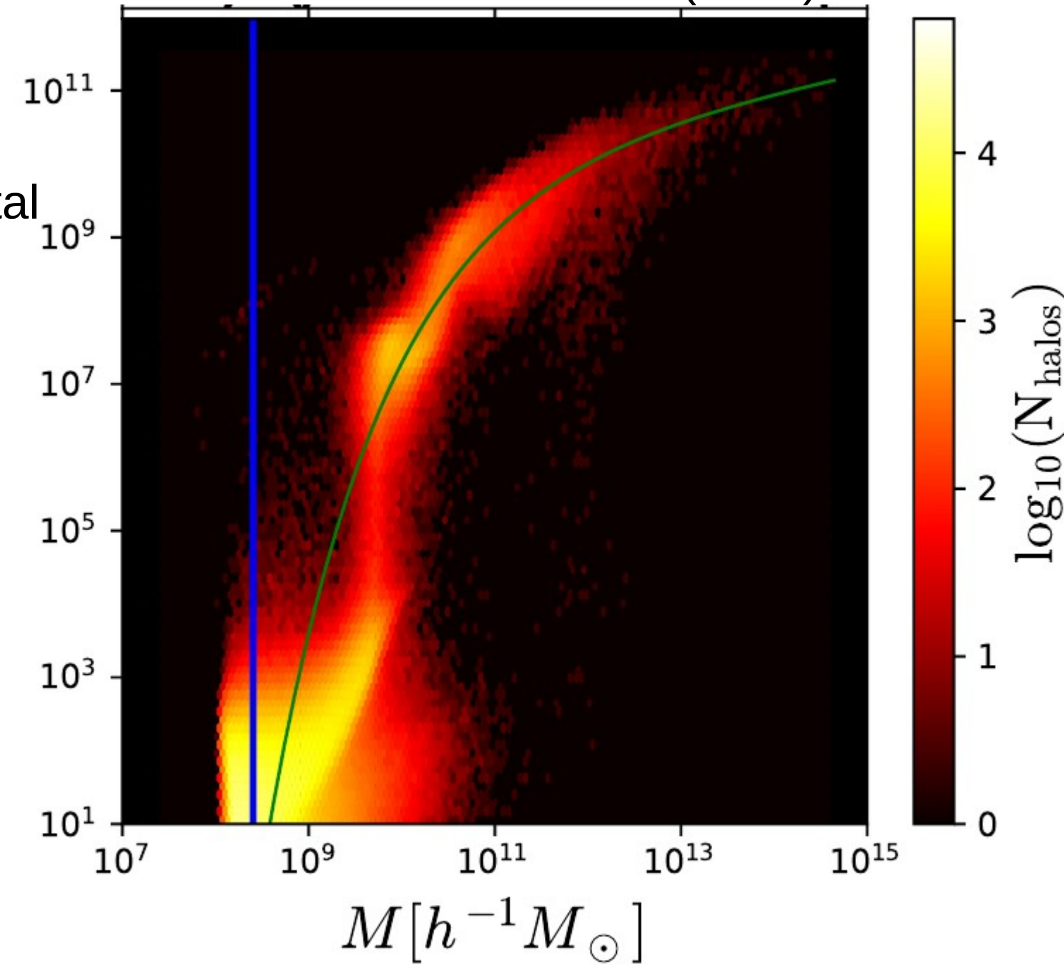


Villaescusa-Navarro et al. (2018)



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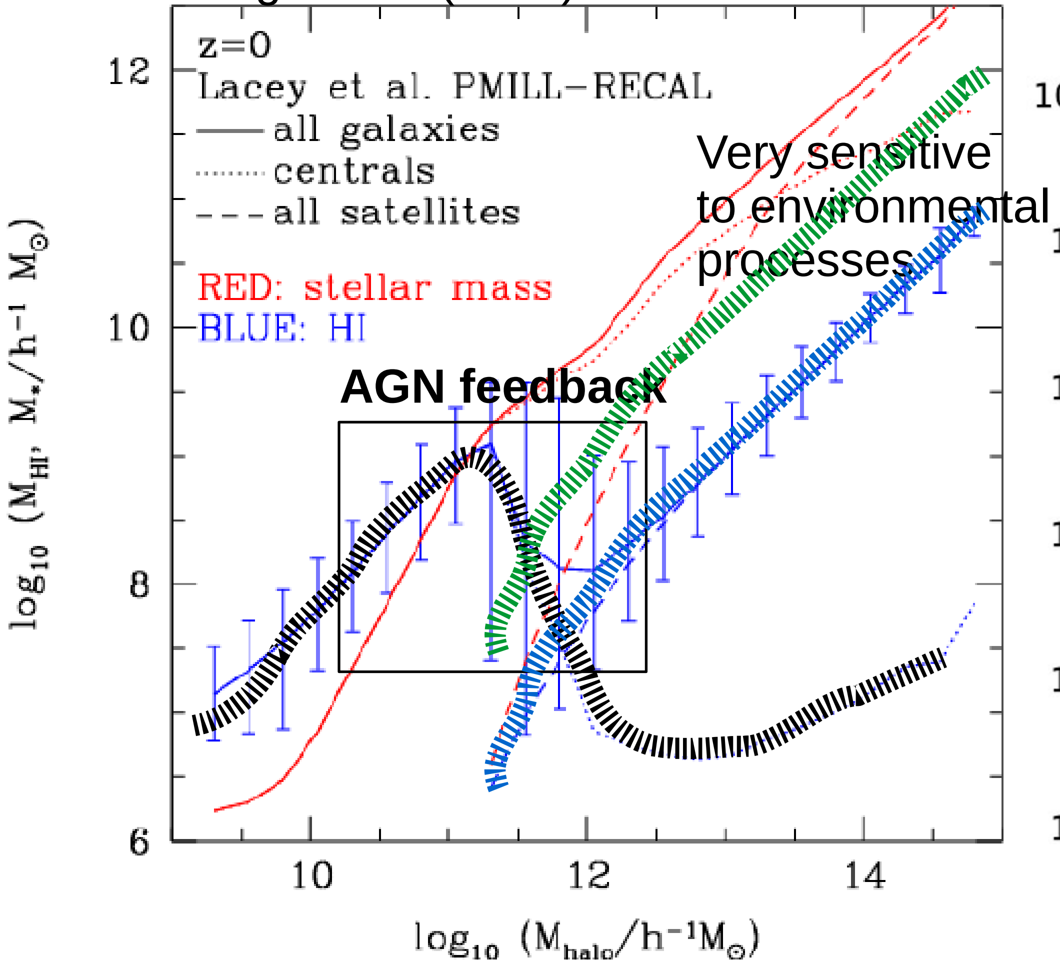

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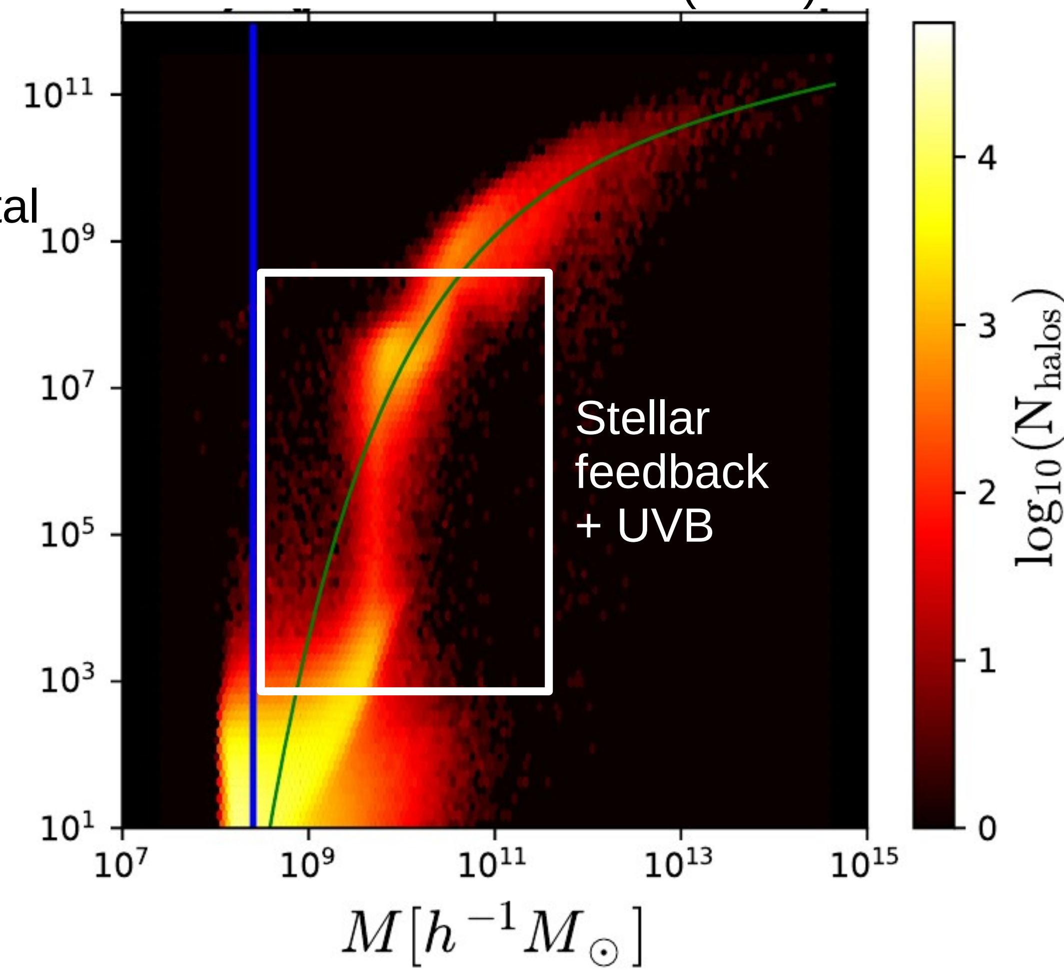
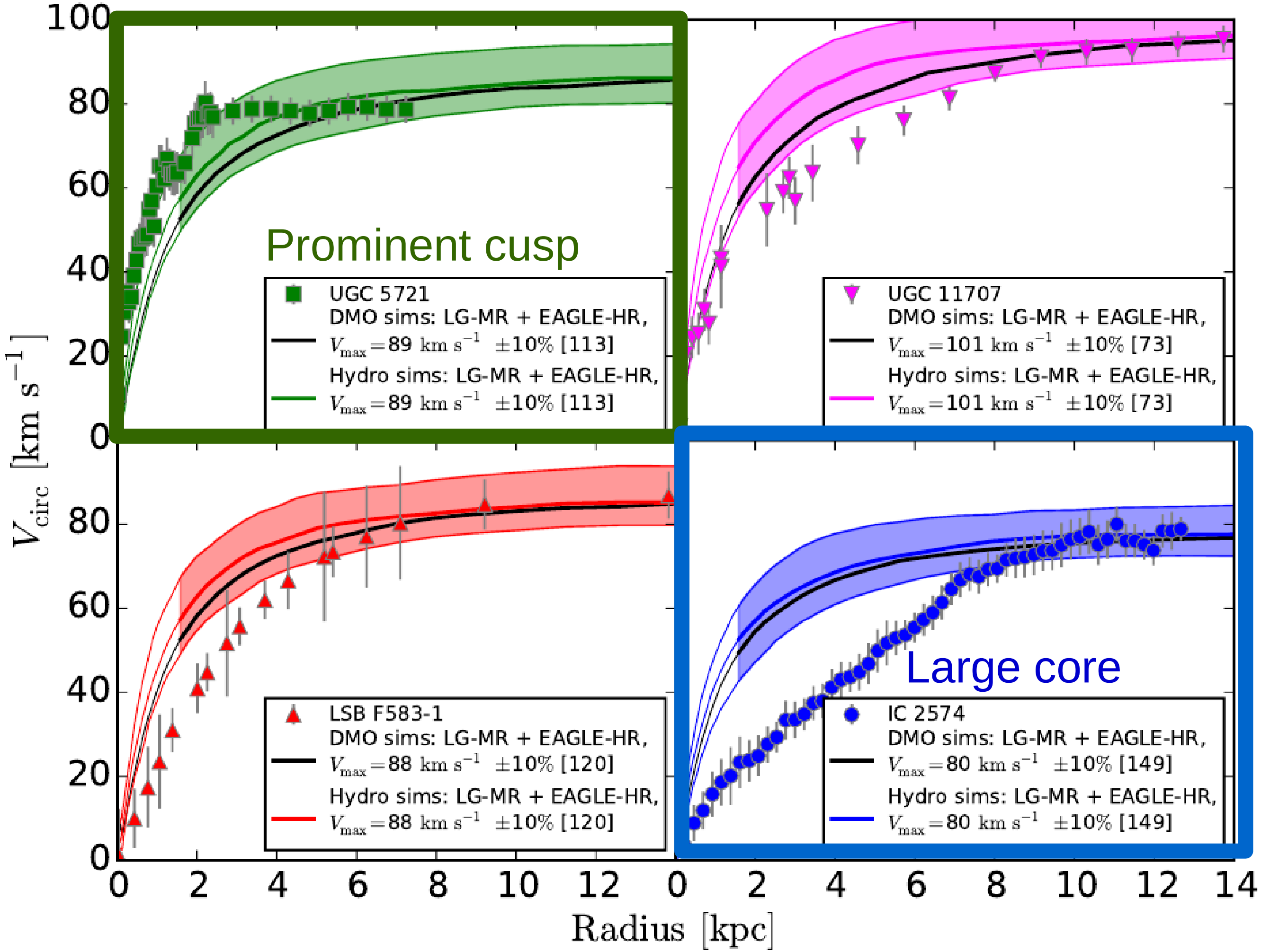


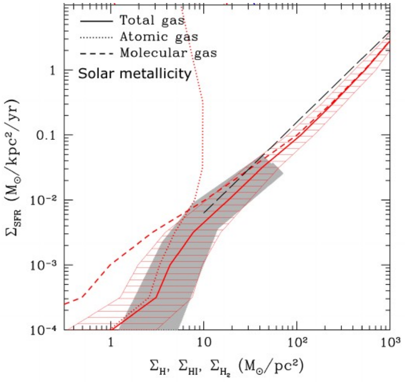
HI rotation curves: cusps vs. cores?

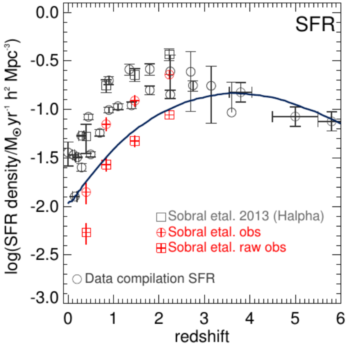
Oman et al. (2015): *dwarf galaxies have cores and cusps*; require a wide diversity of rotation curves!

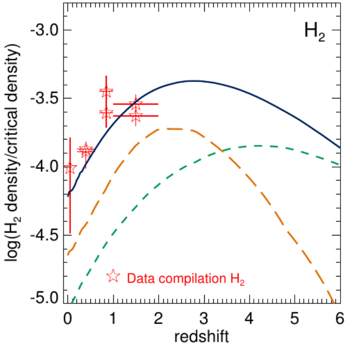


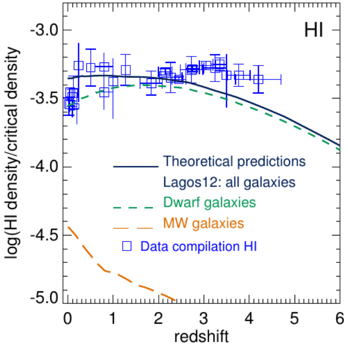
Conclusions and prospects

Observations have *allowed much better understanding of SF in galaxies*: (i) global gas/SFR evolution, (ii) self-regulation in galaxies, (iii) SF suppression in dwarf galaxies

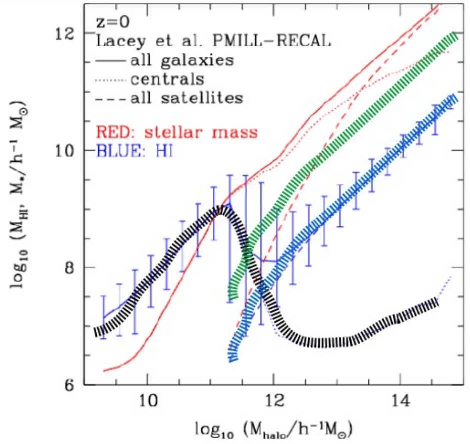


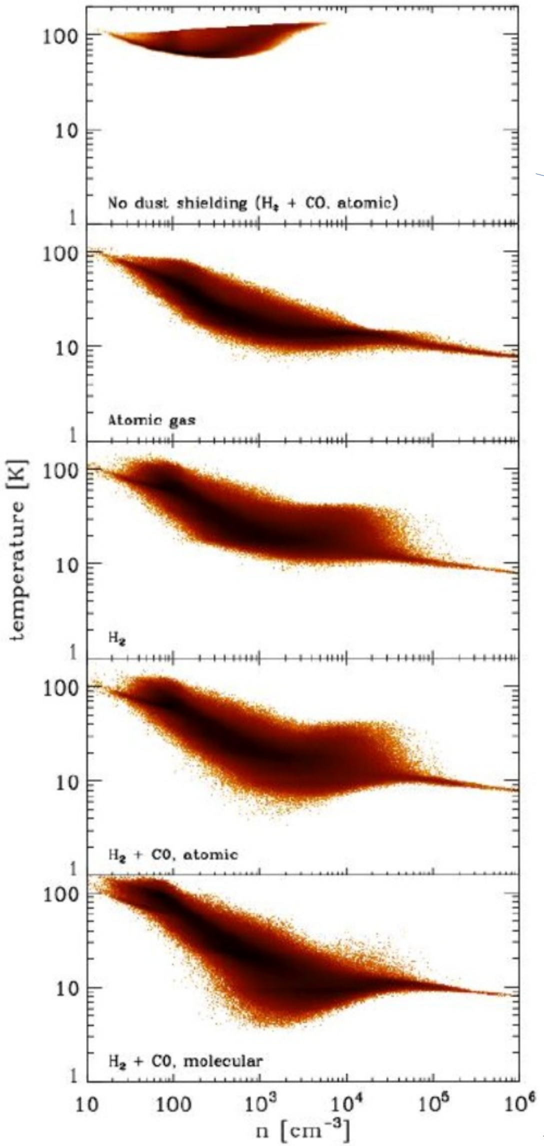






Future gas observations (ISM, CGM, IGM) are all *key to constrain the most unknown physics* in galaxy formation (feedback) and to disentangle gastrophysics from cosmological effects





Glover & Clark (2012a)

H_2 is a very good tracer of dense gas (dust shielded)

Dense gas forms after dust shielding screens ionising radiation

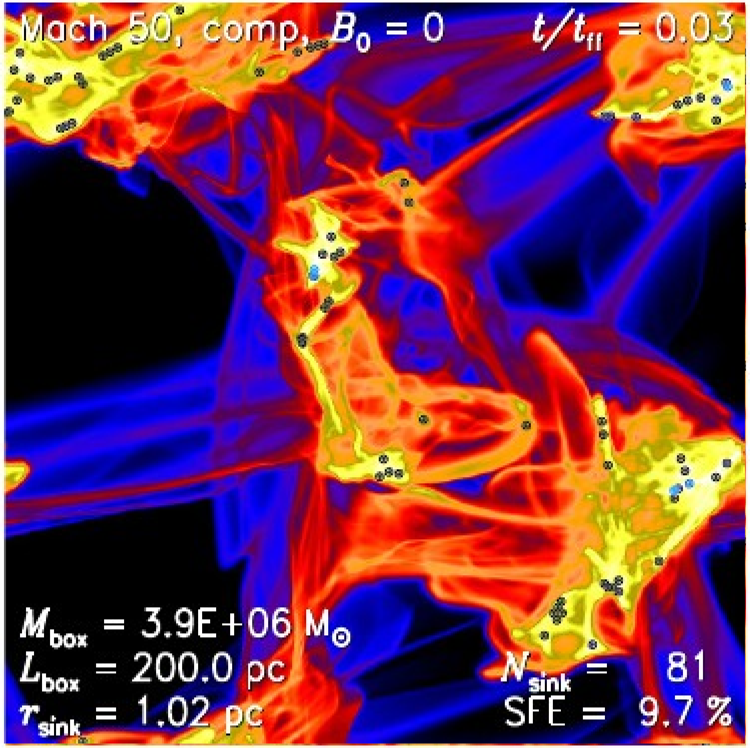
Suggestion: H2 can be used by simulations to trace where stars should form

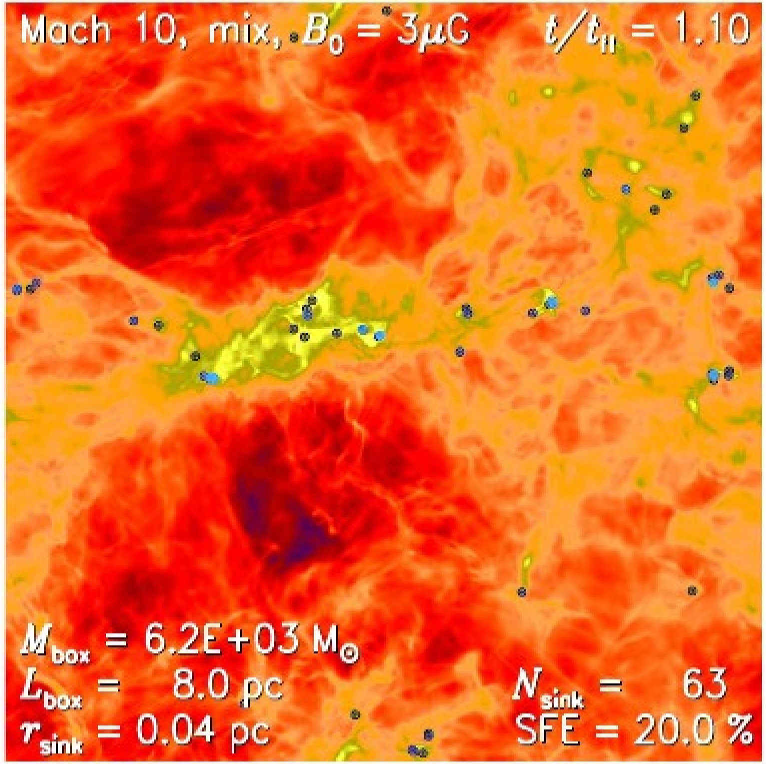
Neither H_2 nor CO are needed to cool the gas down to the temperatures necessary for SF.

Corollary: SF could proceed in cool gas before it becomes molecular (very low Z)

The efficiency of SF in individual clouds

Federrath & Klassen (2012, 2013)
(see also Krumholz & McKee 2005, Padoan & Nurlund 2011; Hennebelle & Chabrier 2011, 2013)





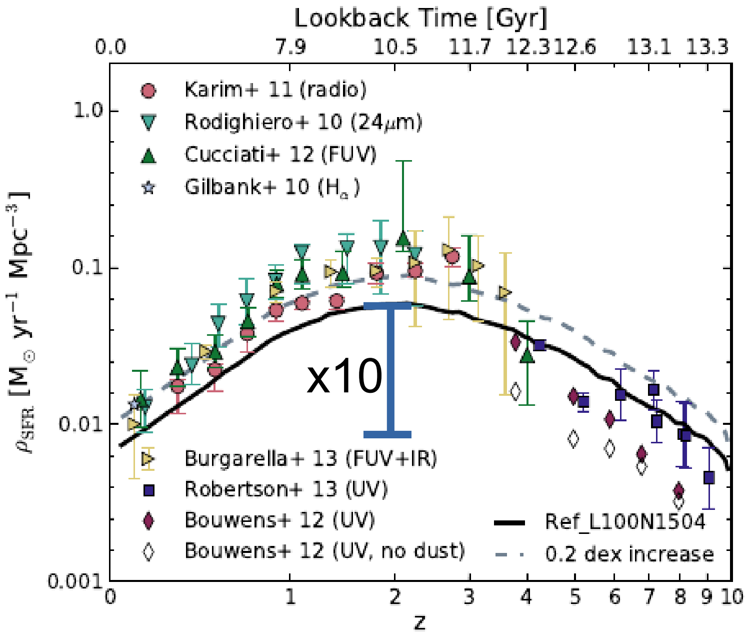
Efficiency of ~0.01 can be achieved with a combination of (selenoidal) magnetic fields + slightly super virial turbulence

$$\alpha_{\rm vir} = 2E_{\rm kin}/|E_{\rm grav}|$$

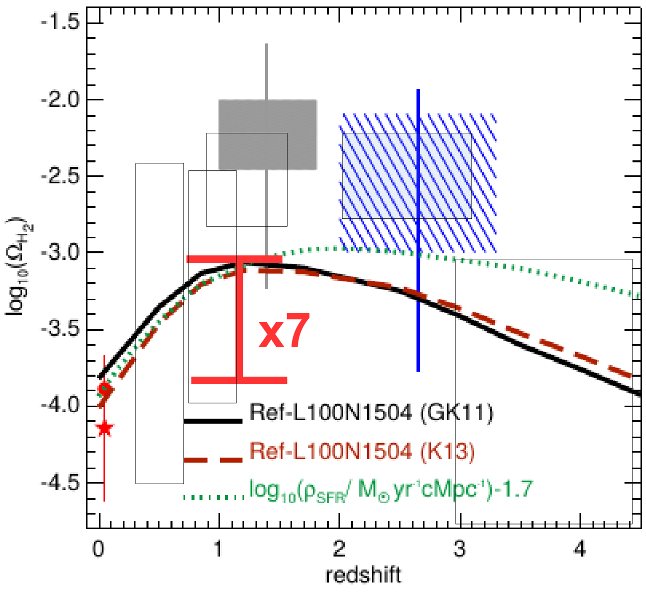
Confirmation by the EAGLE sims

Connecting the SFR evolution with different gas phases...

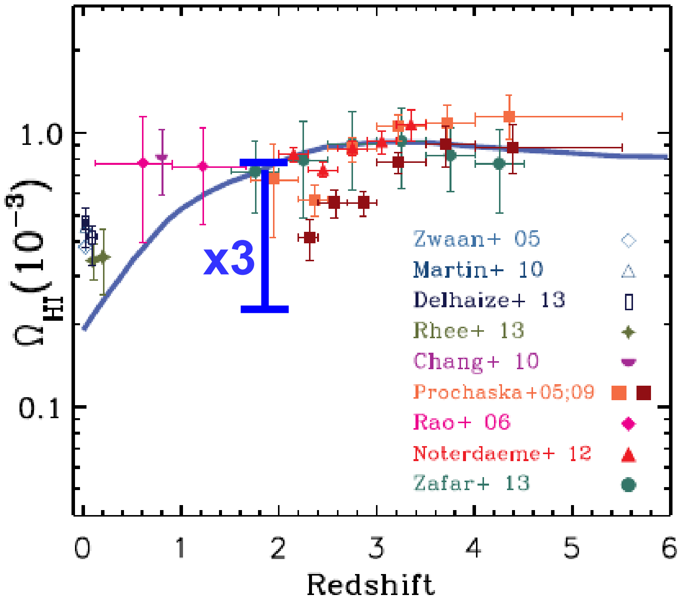
Furlong et al. (2015):
SFR density



Lagos et al. (2015b):
Omega H2

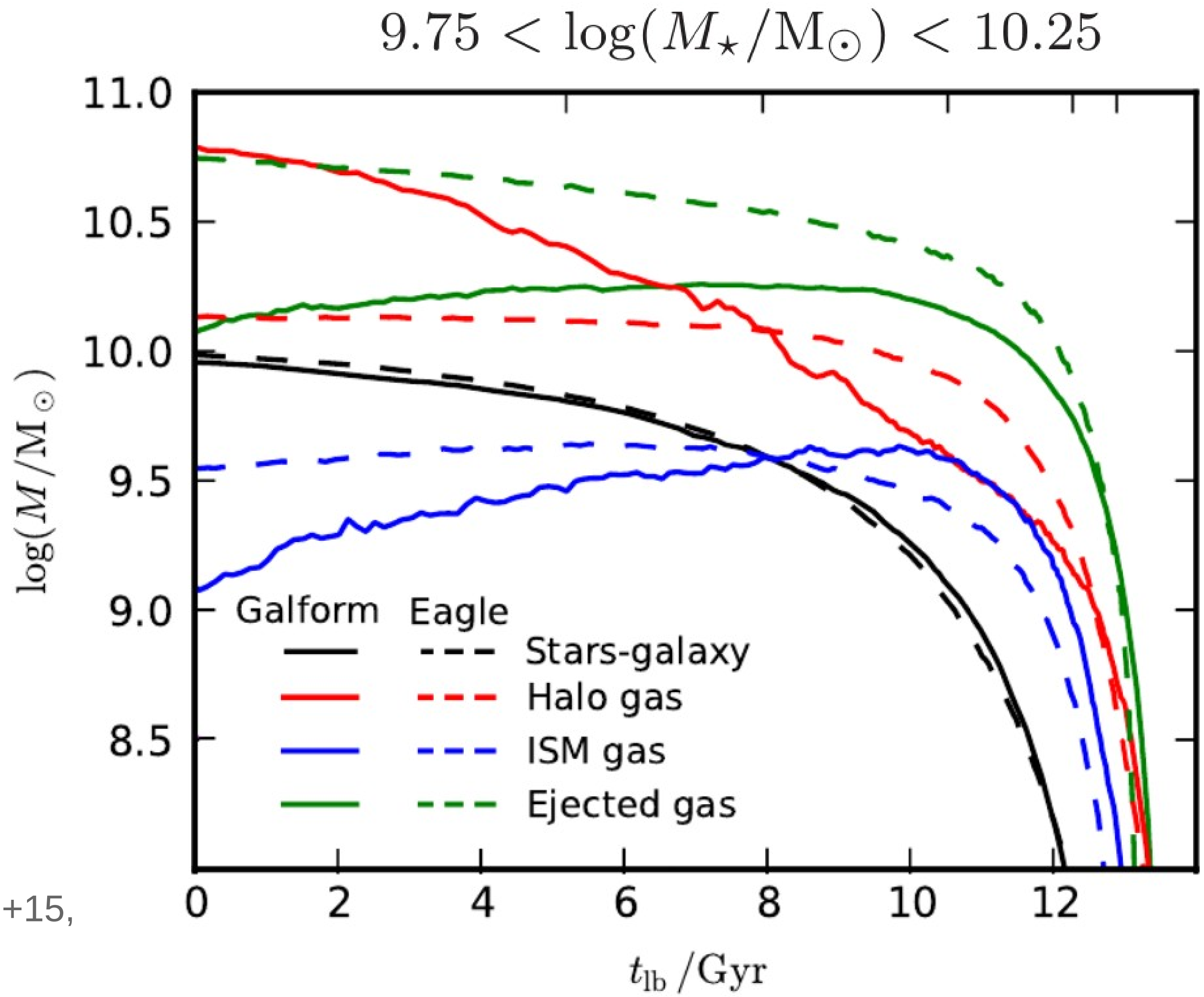


Rahmati et al. (2015):
Omega HI



Self-regulation of galaxy formation

Mitchell, Lacey, Lagos et al. (2018): a one-to-one comparison between EAGLE and GALFORM



See also Schaye+10, Hopkins+12, Dave+12, Lilly+13, Lagos+14, Crain+15, Lagos+16, ...

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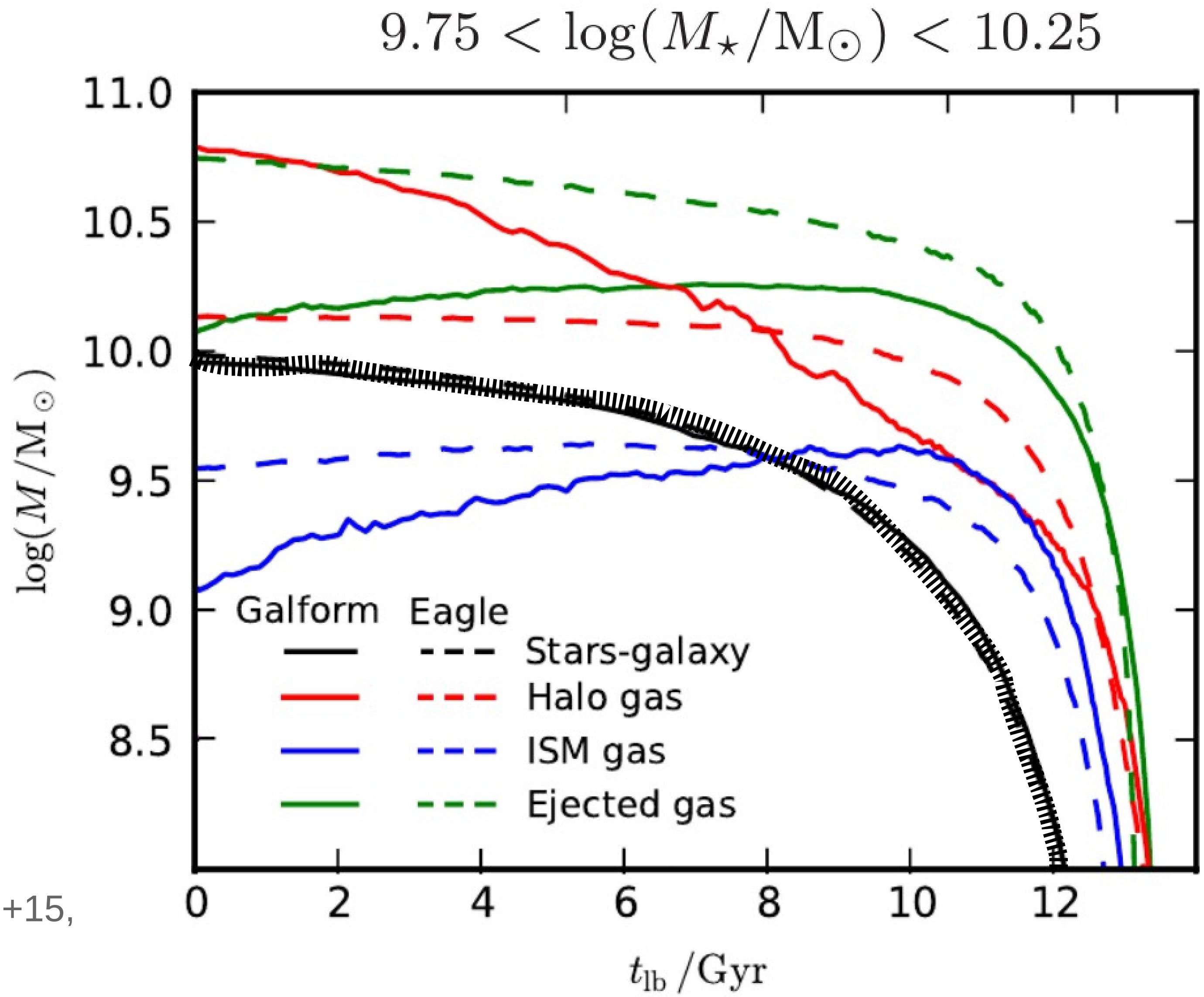

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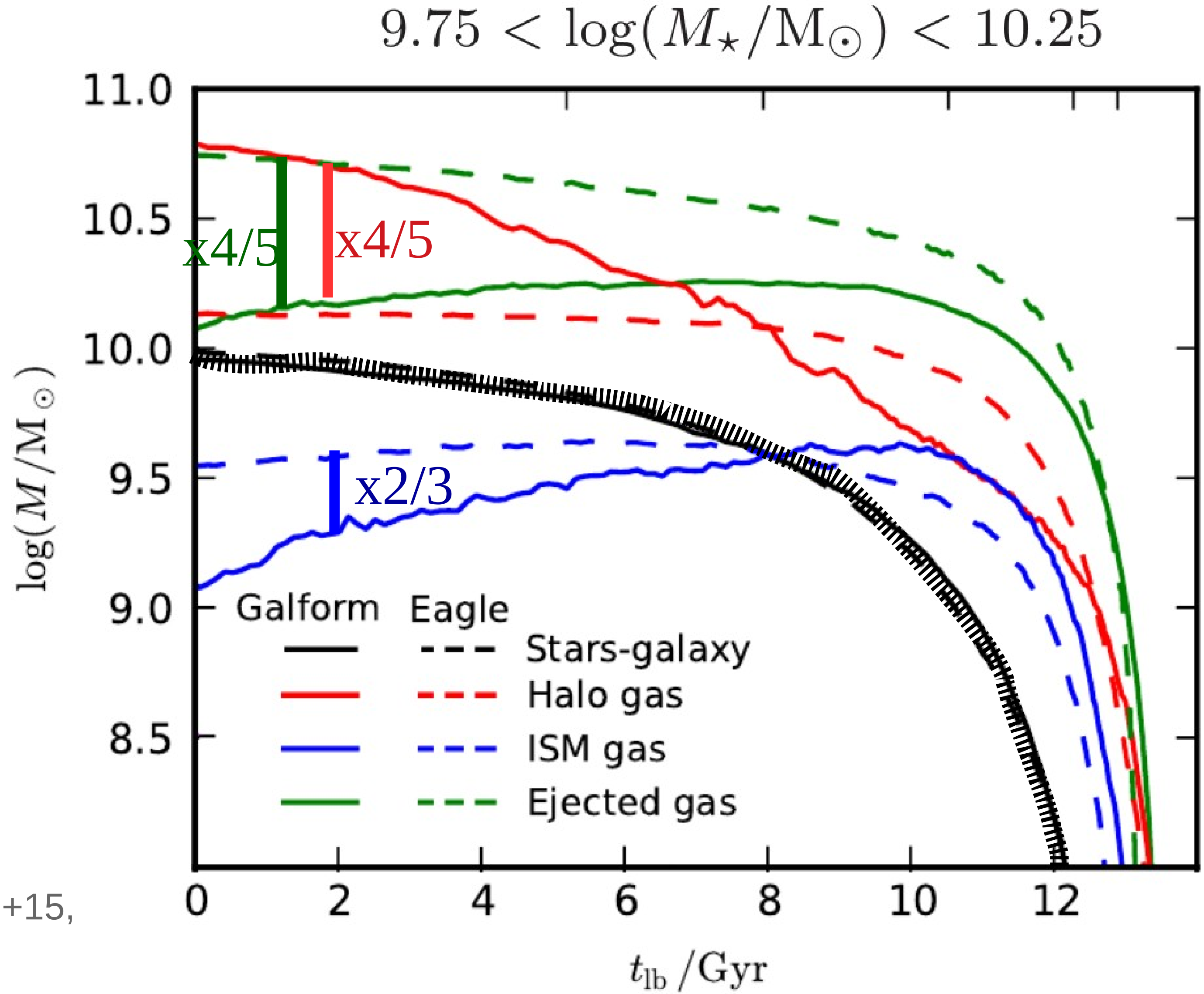

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Self-regulation of galaxy formation

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Challenge: Same SFH but for very different reasons! **Essential to study ISM and halo gas**

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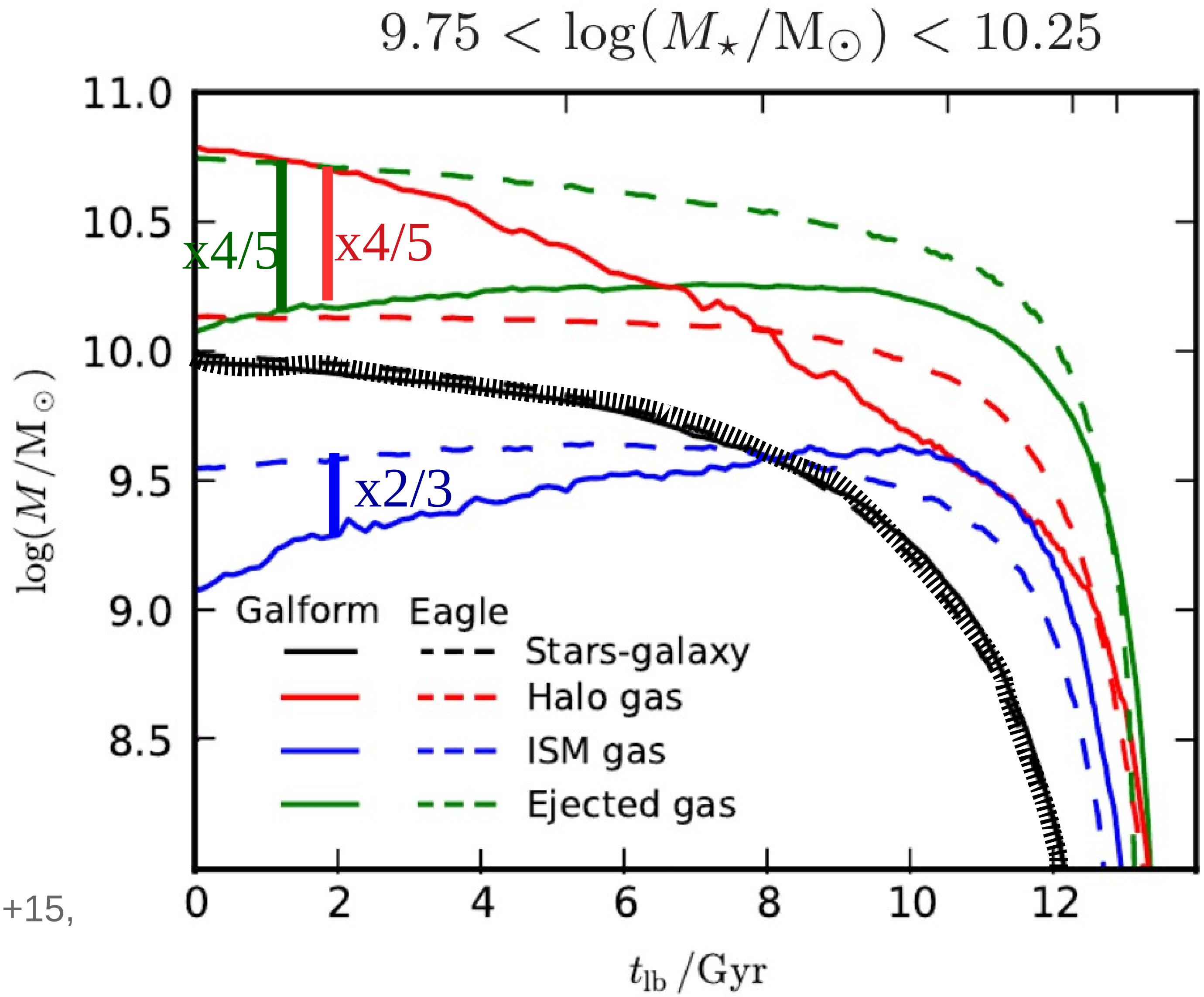
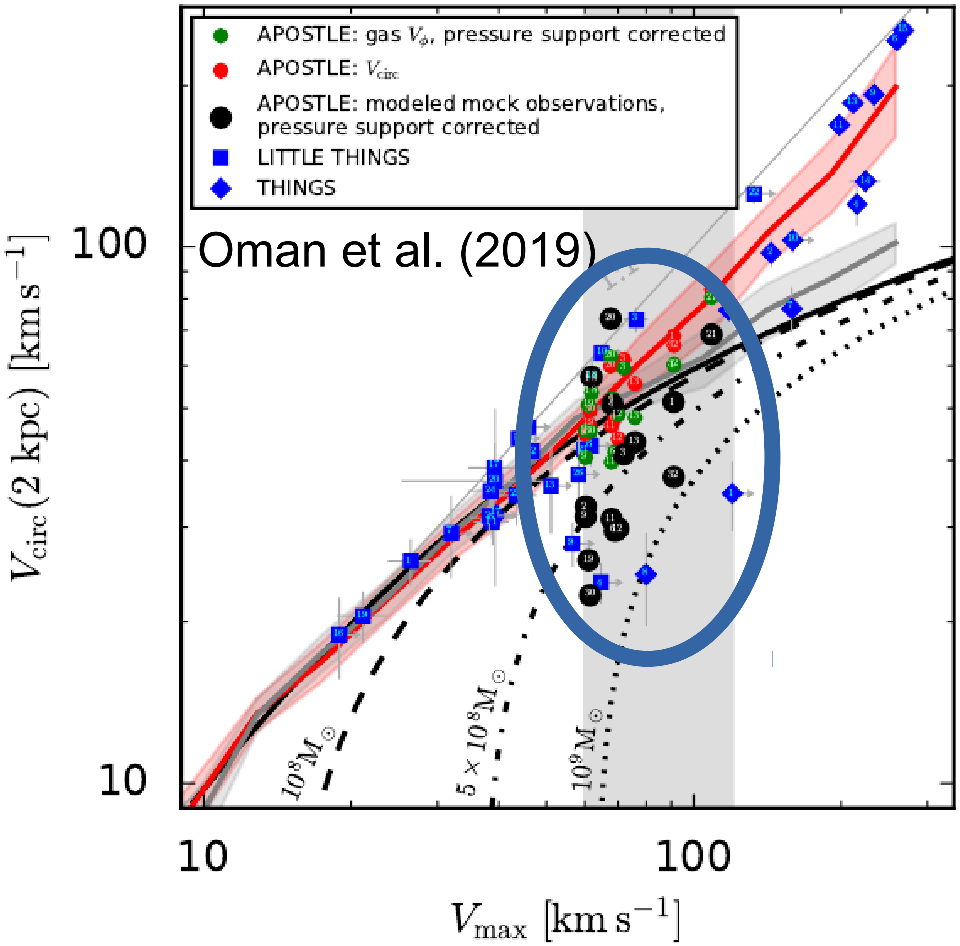
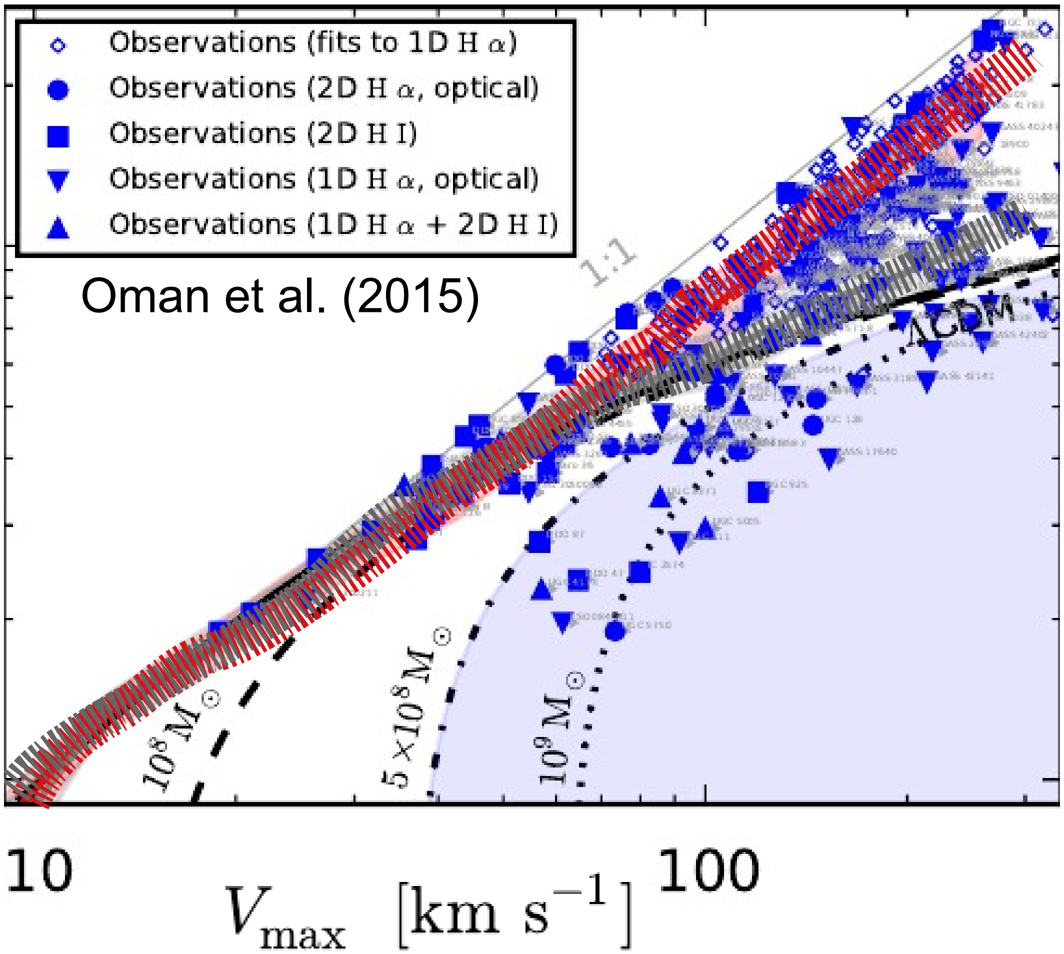


Simulations lack the diversity of HI rot curves





Conclusions

Empirical and theoretical SF laws parameter-free (to some degree)

The Blitz & Rosolowski law (BR)
Leroy et al. (2008), Bigiel et al. (2008)
Pressure defined as
in Elmegreem (89,91)

$$\frac{\Sigma(\mathrm{H_2})}{\Sigma(\mathrm{HI})} = \left(\frac{P_{\rm ext}}{P_0}\right)^{\alpha}$$

$$\Sigma_{\rm SFR} = \nu_{\rm SF}\,\Sigma_{\rm mol}$$

Popping et al. (2009), Obreschkow et al. (2009); Power et al. (2010); Cook et al. (2010); Fu et al. (2010); Lagos et al. (2011a,b); Altay et al. (2011); Duffy et al. (2012); Popping et al. (2014); Somerville et al. (2015), Bahe et al. (2016), Xie et al. (2017), Lagos et al. (2018),...

The Krumholz, McKee & Tumlinson theoretical law (KMT; 2009)

$$\Sigma_{\rm SFR} = \nu_{\rm SF}(\Sigma_{\rm gas})\, f_{\rm mol}\, \Sigma_{\rm gas}$$

Fu et al. (2010); Lagos et al. (2011a,b); Kuhlen et al. (2011); Altay et al. (2011); Hopkins et al. (2012); Kuhlen et al. (2012); Popping et al. (2014), Lagos et al. (2018),...

Most of these SF law explicitly partition HI and H2 and ***form stars from H2 only*** (dense gas tracer)

Gnedin and Kravtsov (2011); theoretical law

$$f_{H_2}(r) = \left[1 + \frac{\tilde{\Sigma}}{\Sigma_{HI+H_2}(r)}\right]^{-2}$$

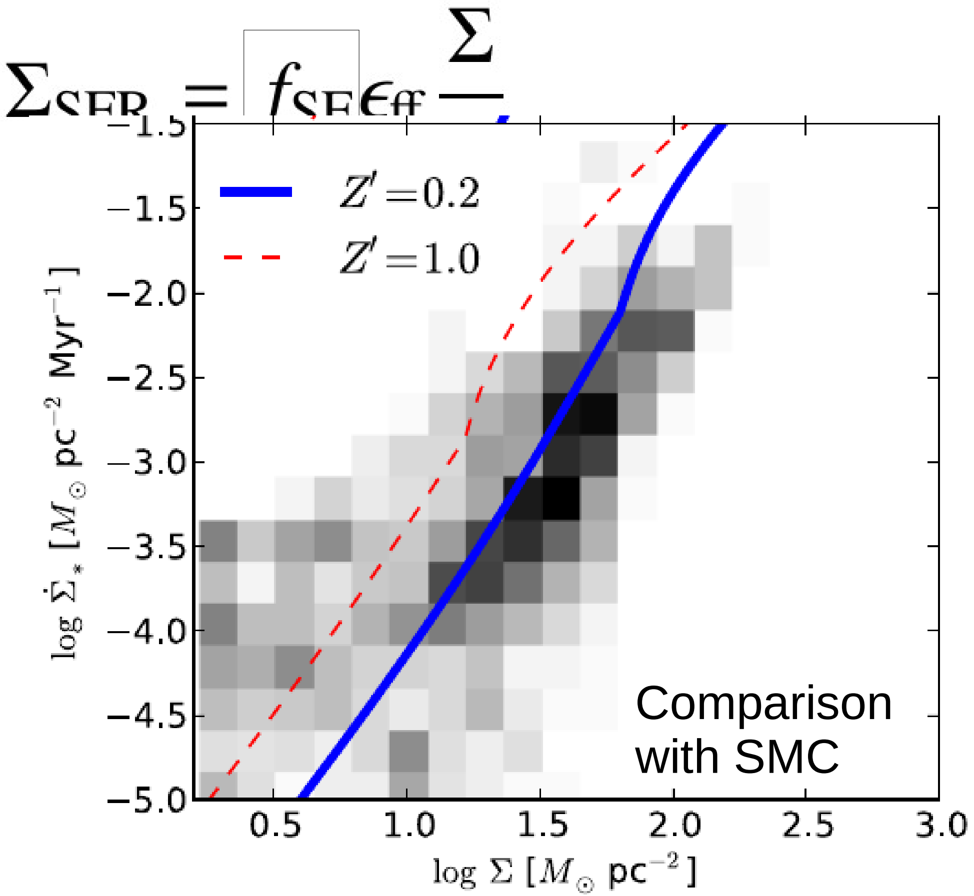
where

$$\tilde{\Sigma} = 20\,\mathrm{M_\odot pc^{-2}} \frac{\Lambda^{4/7}}{D_{\rm MW}} \frac{1}{\sqrt{1 + U_{\rm MW} D_{\rm MW}^2}}$$

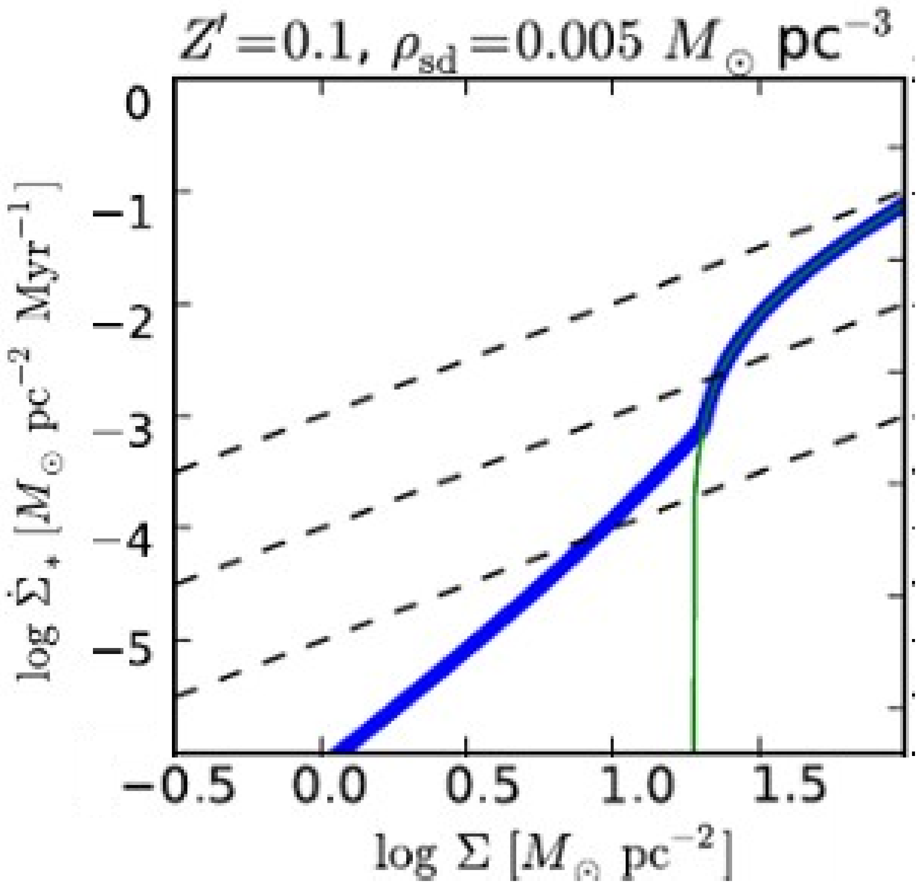
Popping et al. (2014), Lagos et al. (2015b); Somerville et al. (2015), Lagos et al. (2018), ...

Schaye et al. (2015): Use metallicity and gas density proxy of cool gas (Schaye 2004)

Modelling of star formation/molecular gas



Krumholz (2013)



SF/Gas in galaxies

Significant improvements in galaxy formation theory from ISM observations

- Understand cosmic evolution of SF and gas
- Star formation in dwarf galaxies and feedback
- Cosmological implications of HI rotation curves