Gas flows around Galaxies

their impact on galaxy formation

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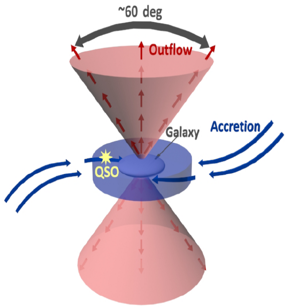
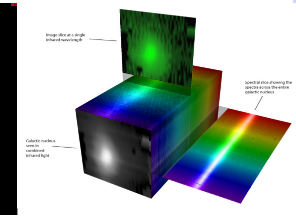
Outline

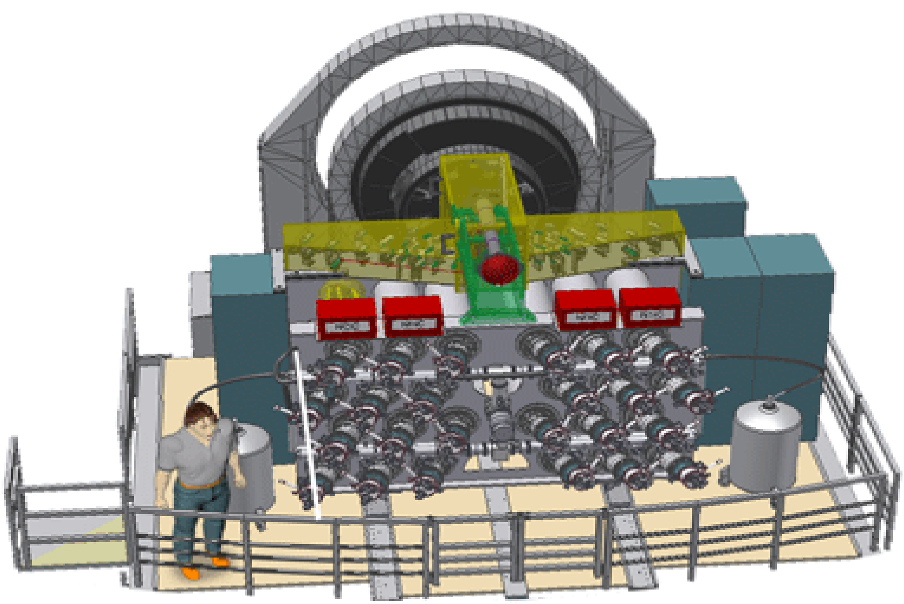
- Current challenges
- Role of inflows/outflows
- Observational constraints
- Perspectives w/ MUSE

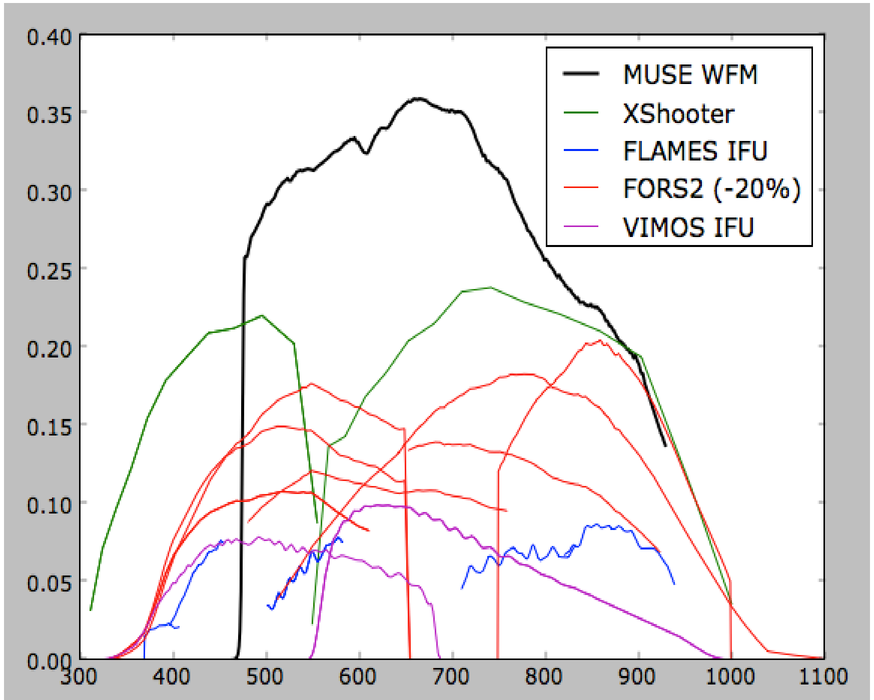


- Giant IFU 1’x1’ (500 – 950nm)
  - AO
  - F > 3e-18 erg/s/cm2



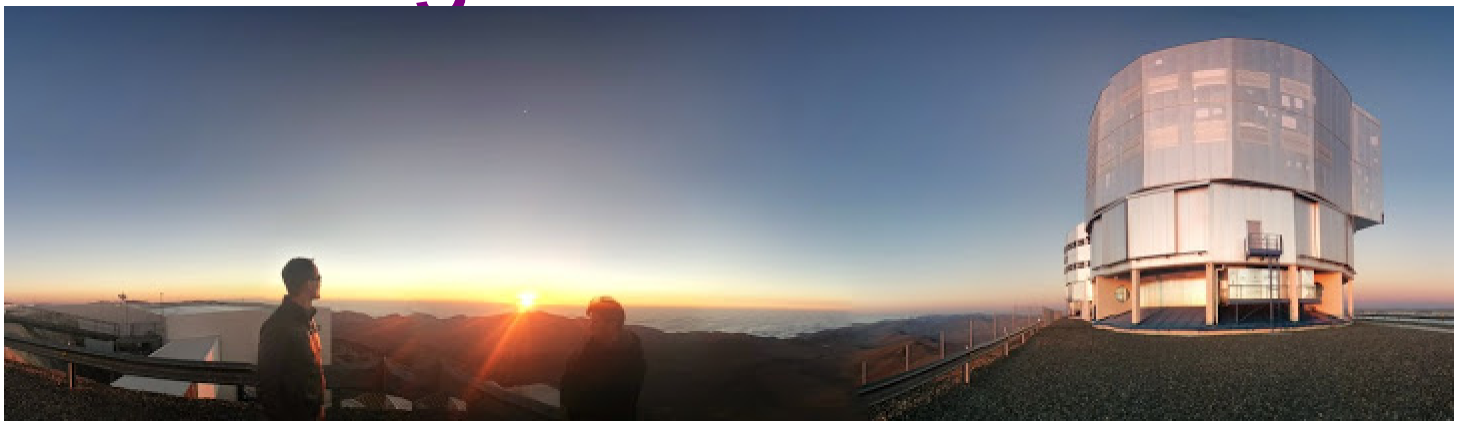
- Giant IFU 1’x1’ (500 – 950nm)
  - AO
  - F > 3e-19 erg/s/cm2

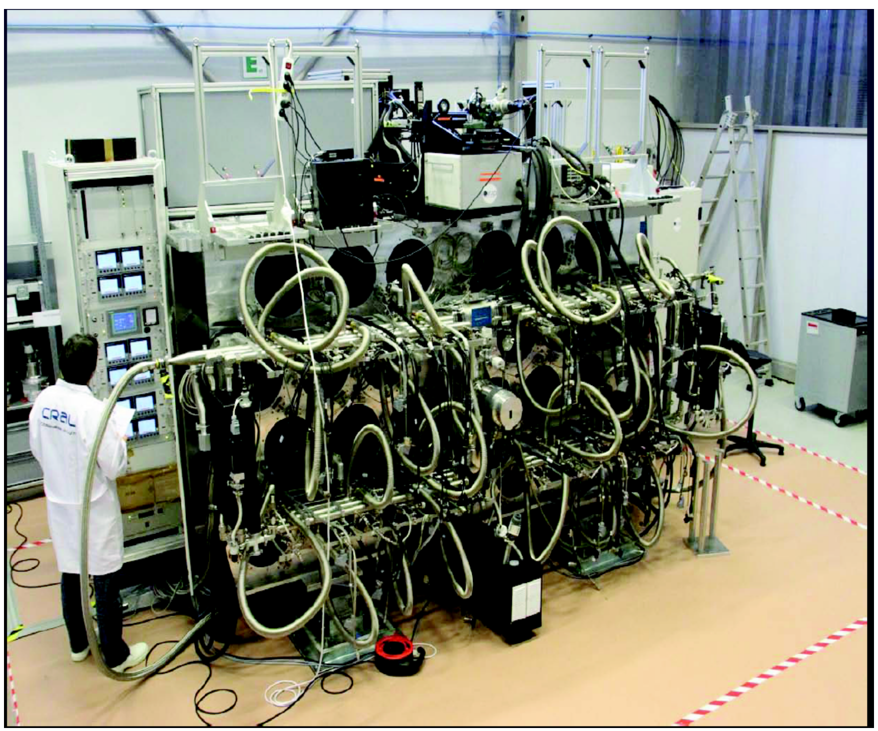


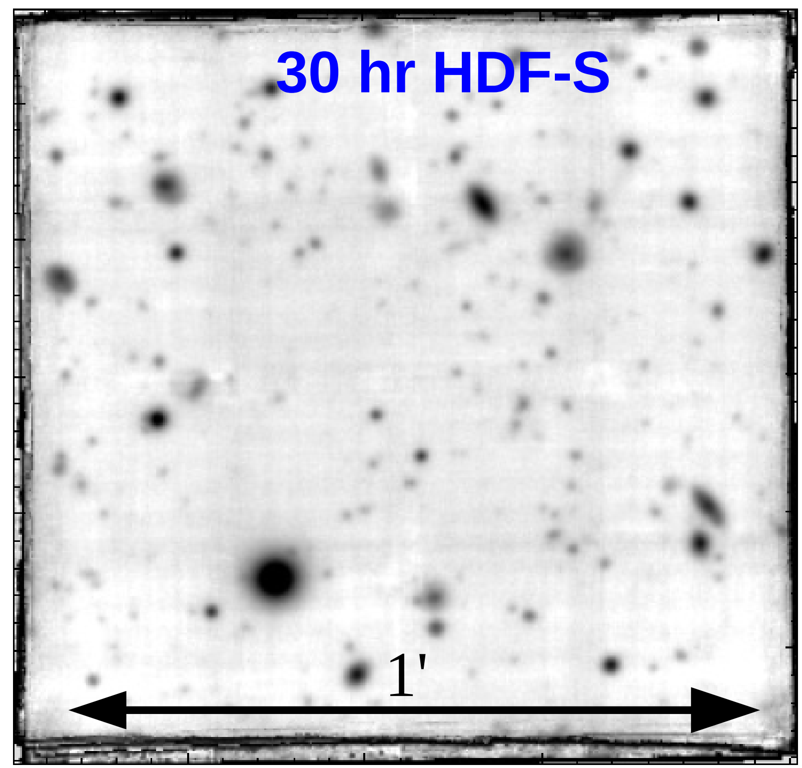


Bacon et. 2014 (1411.7667)

Probing winds with MUSE



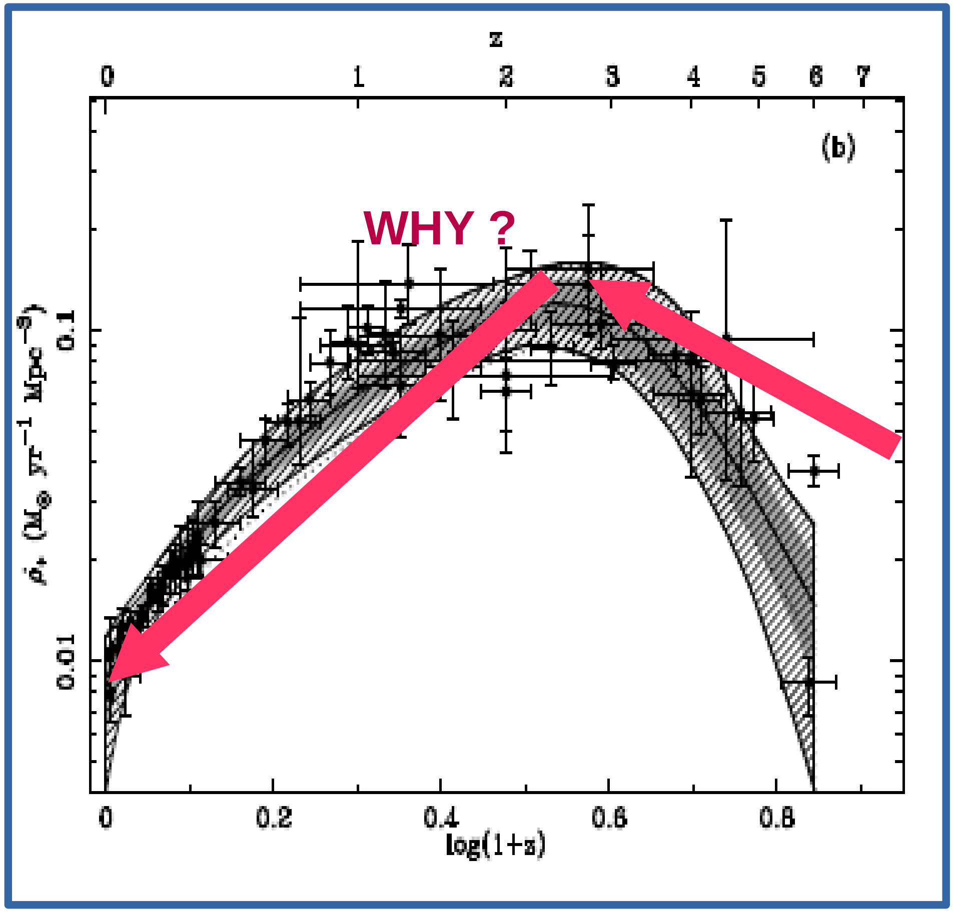




Bacon et. 2014 (1411.7667)

What regulates Star-formation?

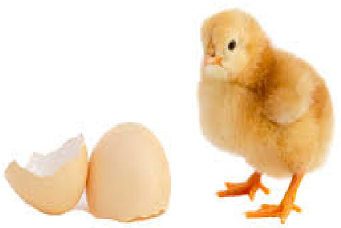
Lilly 1997, Madau 1997, Fardal & Katz 2007,
Hopkins Beacom 2008, Burgarella et al. 2013



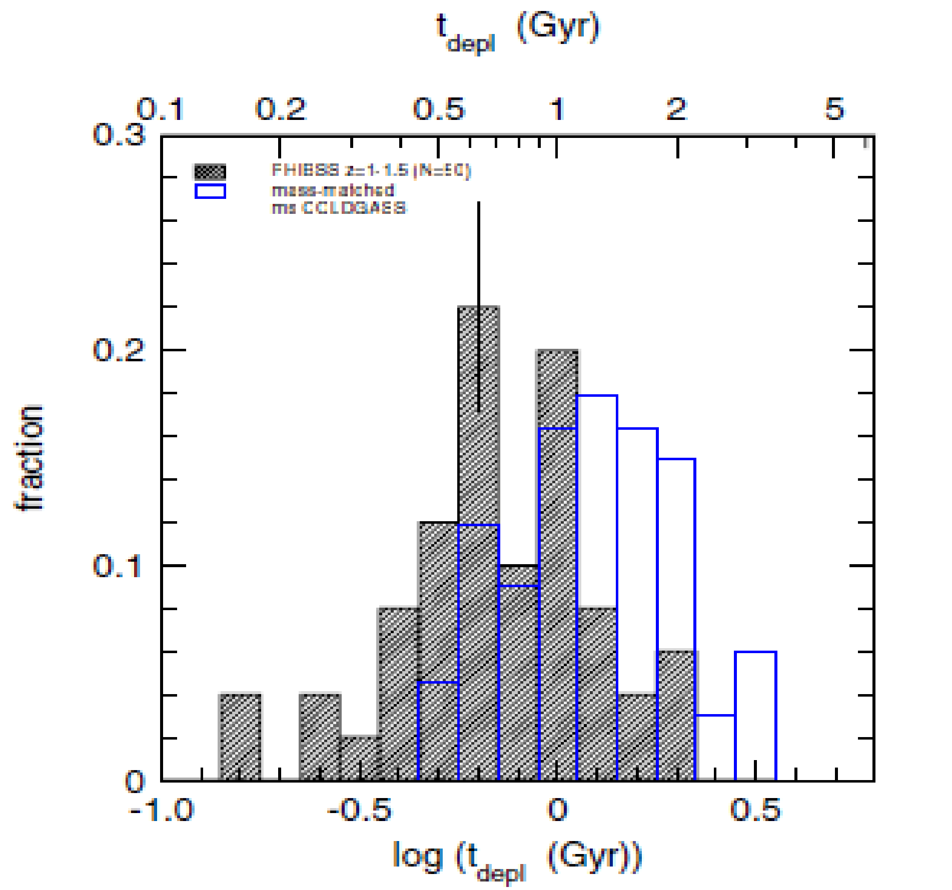
- Outflows ?
- Accretion ?
- Mergers ?
- Gas fraction?

Not very tight constraint...

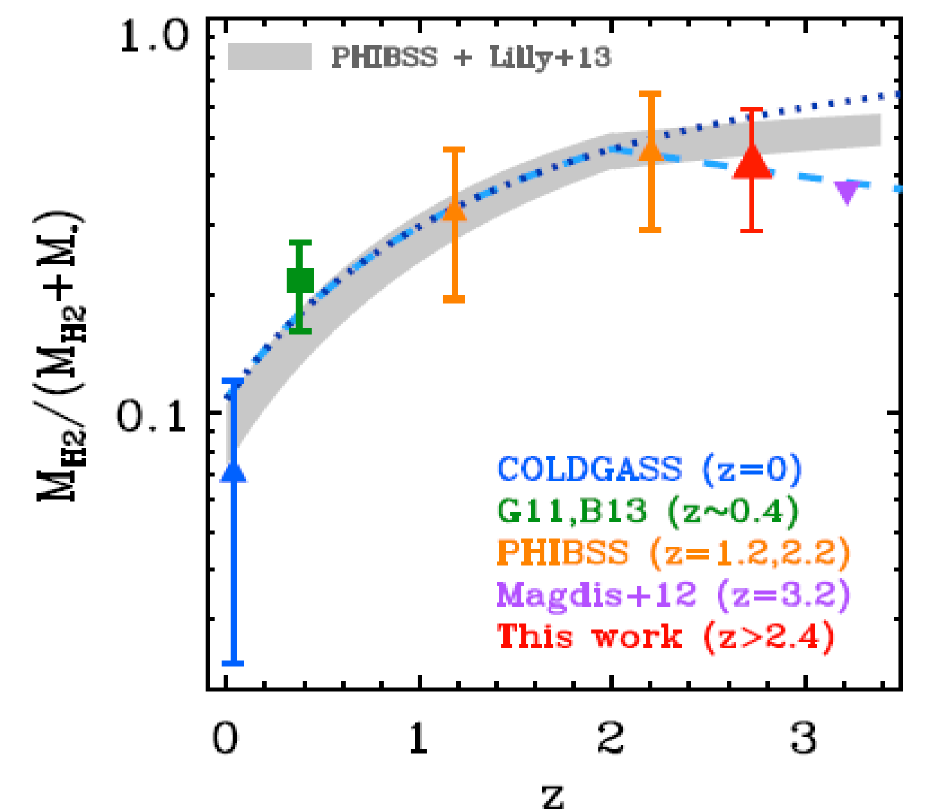
Fgas regulates SFR ?



Tacconi 2013

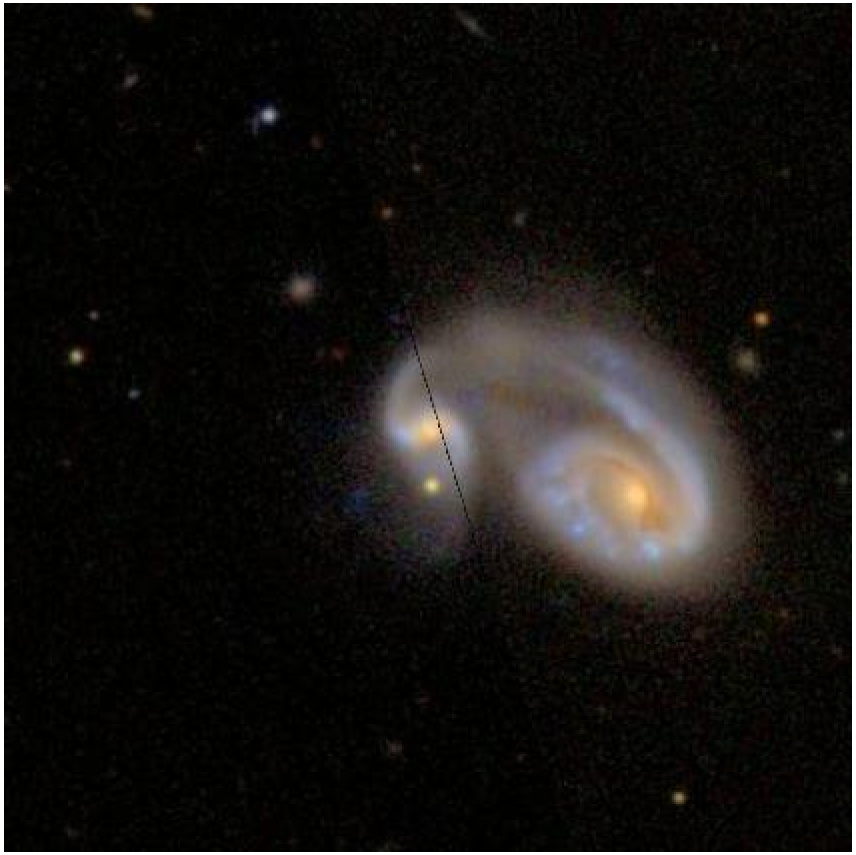


Saintonge 2014



See also Daddi et al. 2011, Genzel et al. 2010, **Tacconi et al. 2010, 2013**, Freundlich et al. 2013, Geach et al. 2011

(Minor) Mergers regulate SF?



Can satellites be the accretion?

– Σ Mgas(i) ? = ? SFR

Kauffman, Li, Heckman 2010

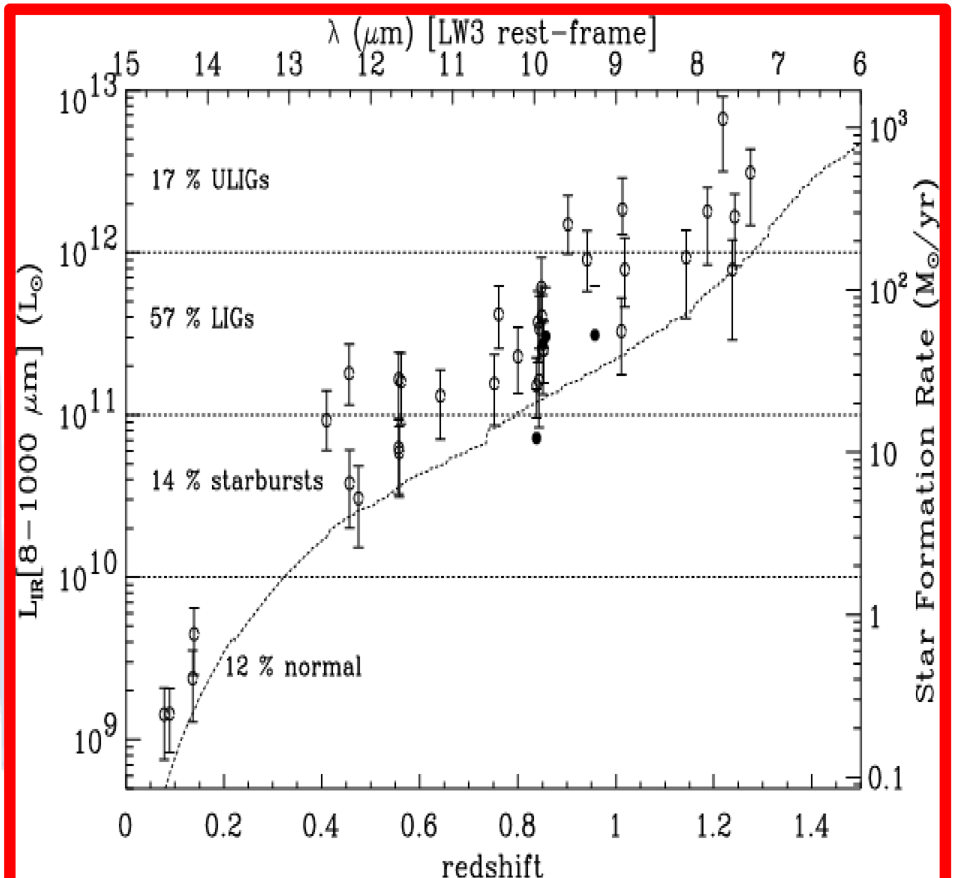
→ SDSS: 100x too short!

→ WHISP: 5x too short!

Di Teodoro & Fraternali 2014

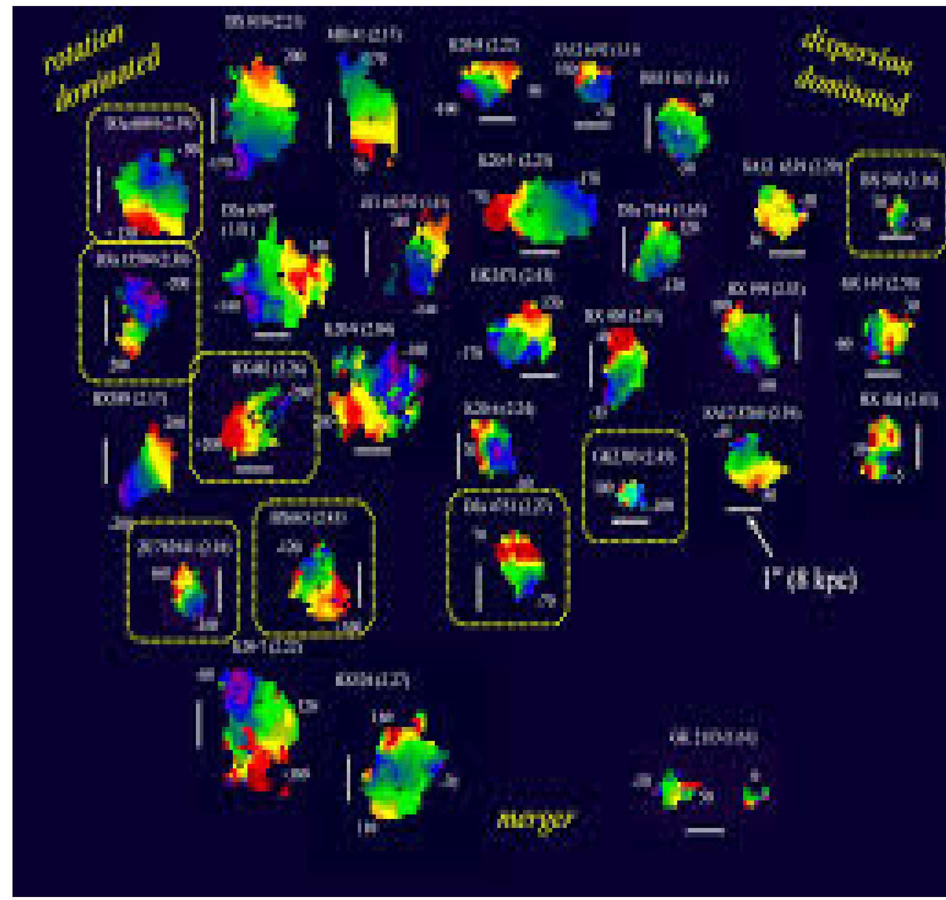
(Major) Mergers regulate SF?

Before 2004:



Elbaz et al. 2002

After 2004



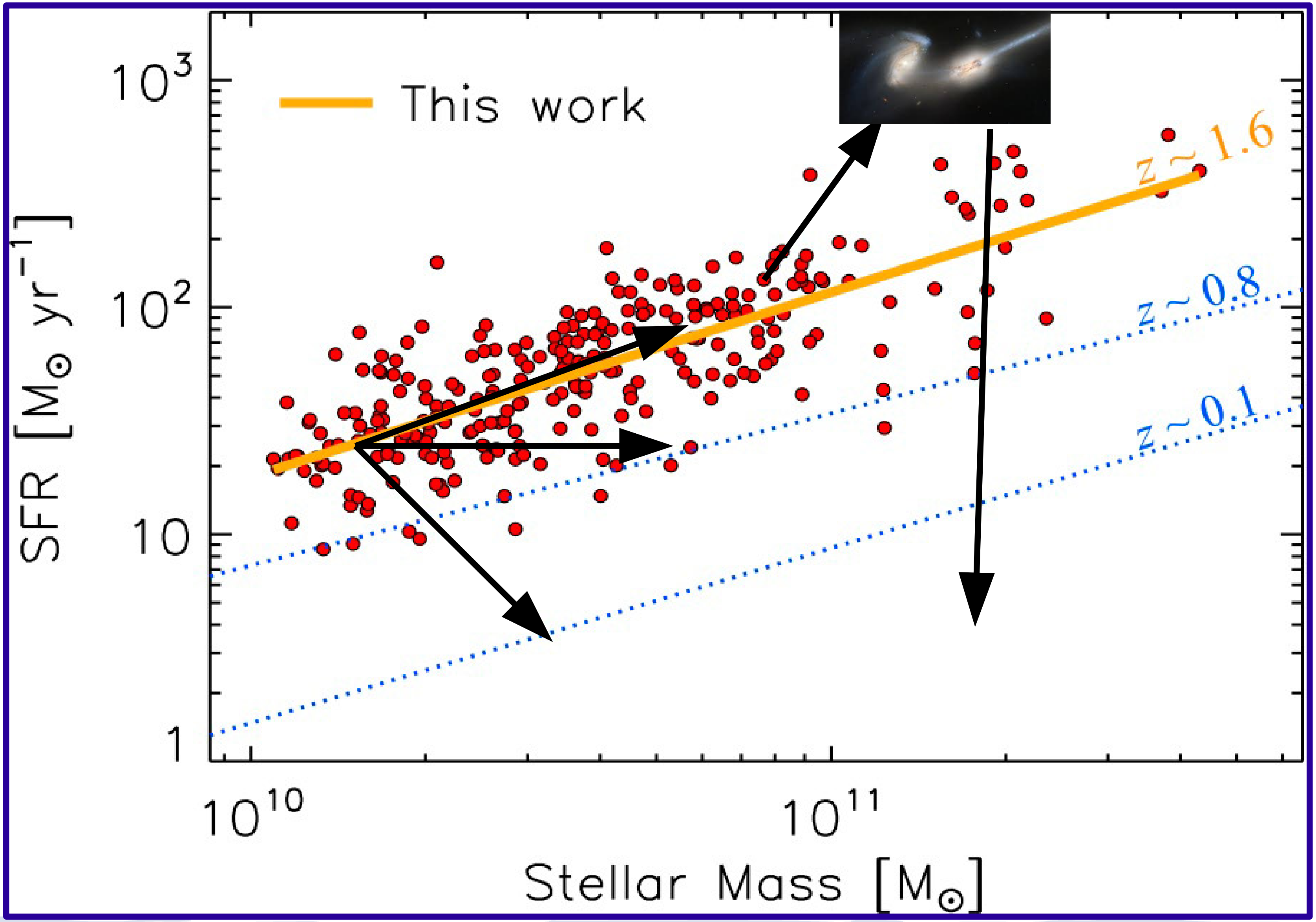
SINS / ForsterSchreiber – Genzel - Bouche

See also Bundy 2009 on marjor merger rates

The main SFR sequence:

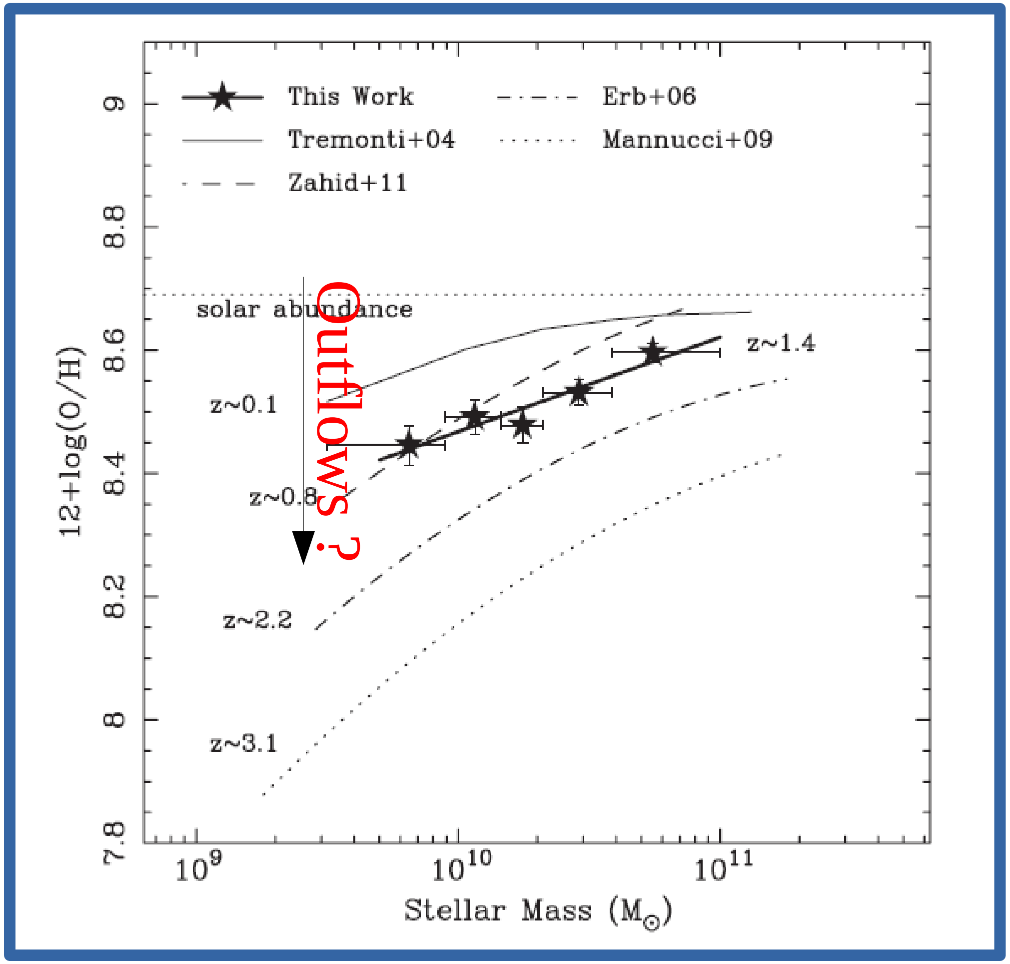
The most fundamental sequence

Kashino 2013.



Another key relation: MZR
What is the driver?

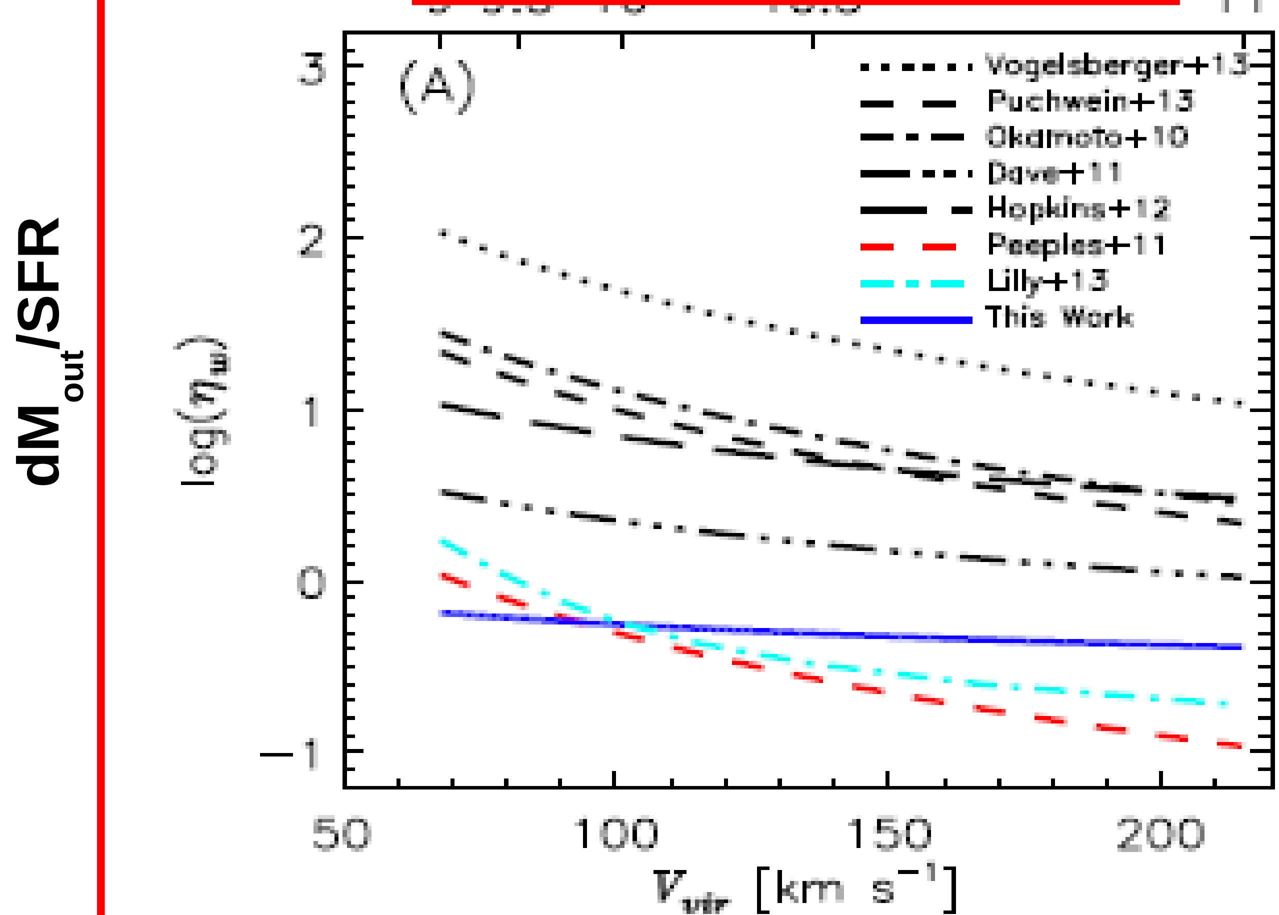
Yabe et al. 2014, Zahid et al. 2014



- – Outflows ?
- – Accretion ?
- – Mergers ?
- – Gas fraction?

Outflows regulate SF?
Hydro perspective

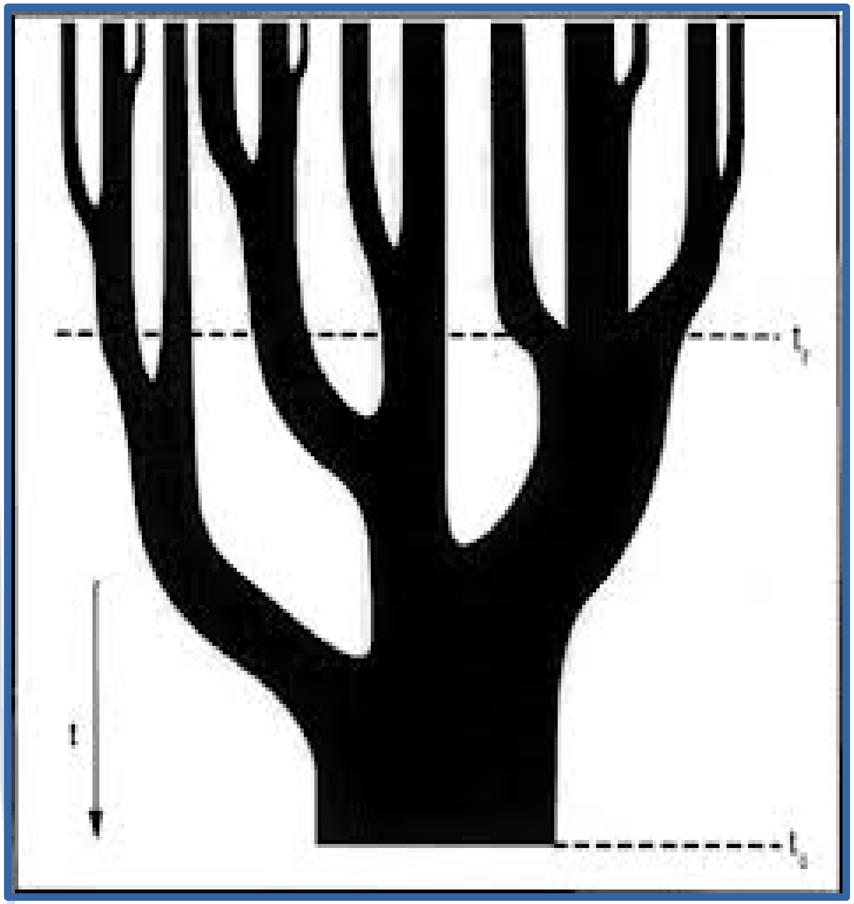
No concensus !

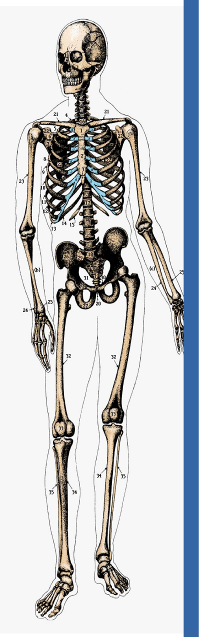


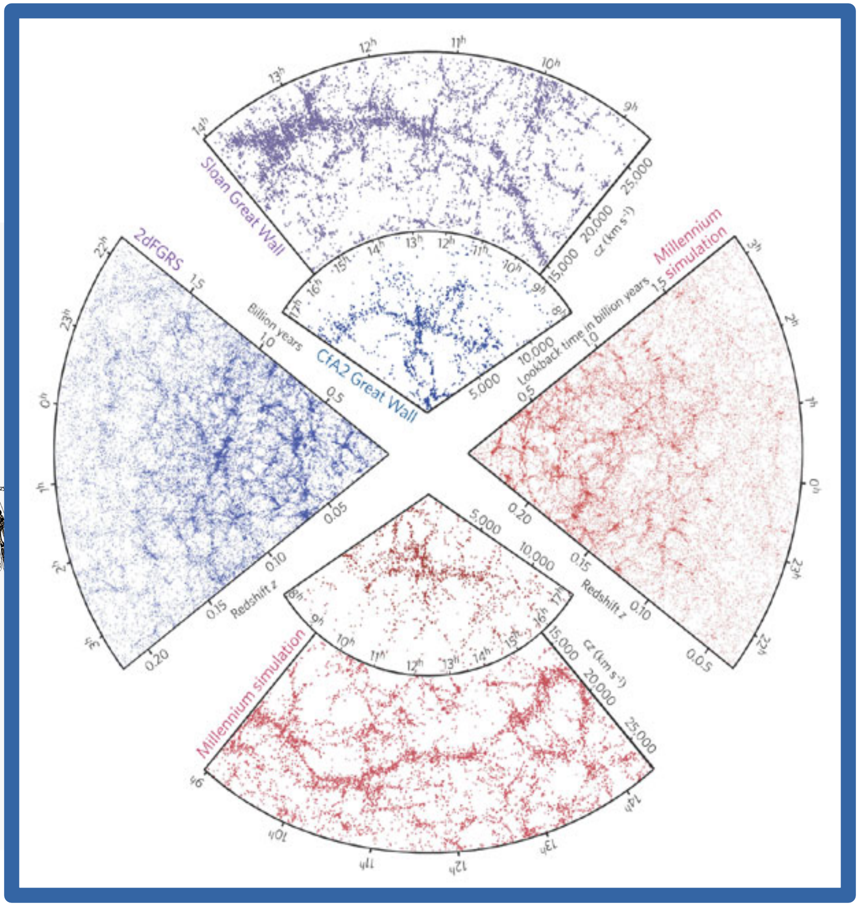
Zahid 2014

A step back

Let's begin with a consensus: halo growth





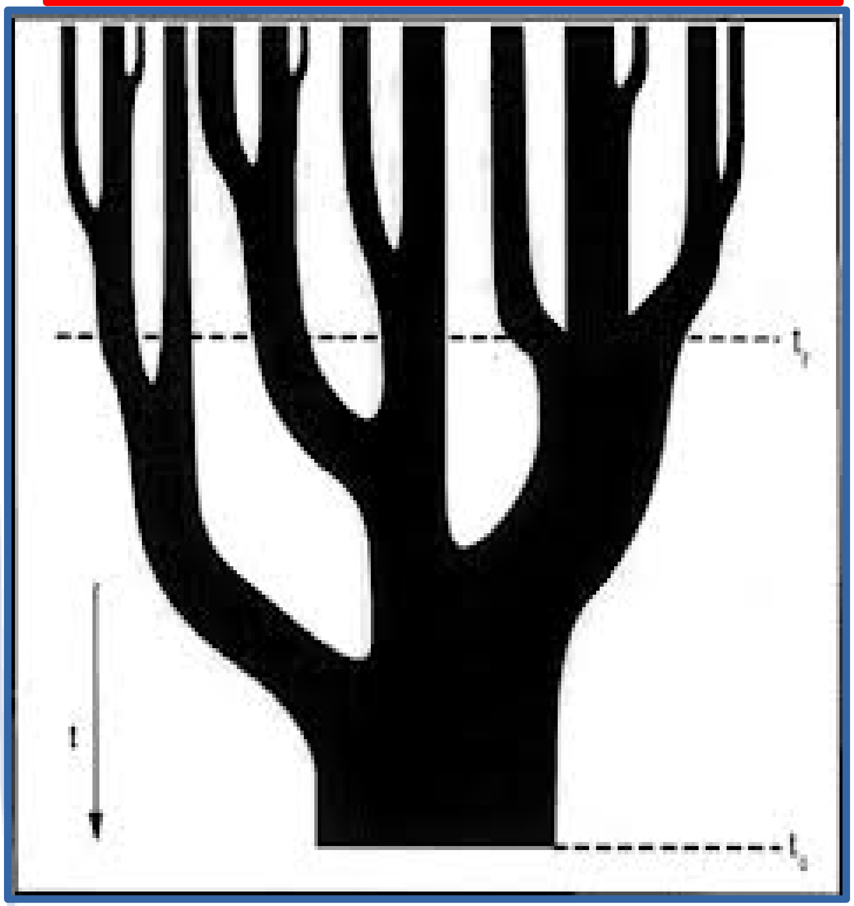


Springel et al. 2006

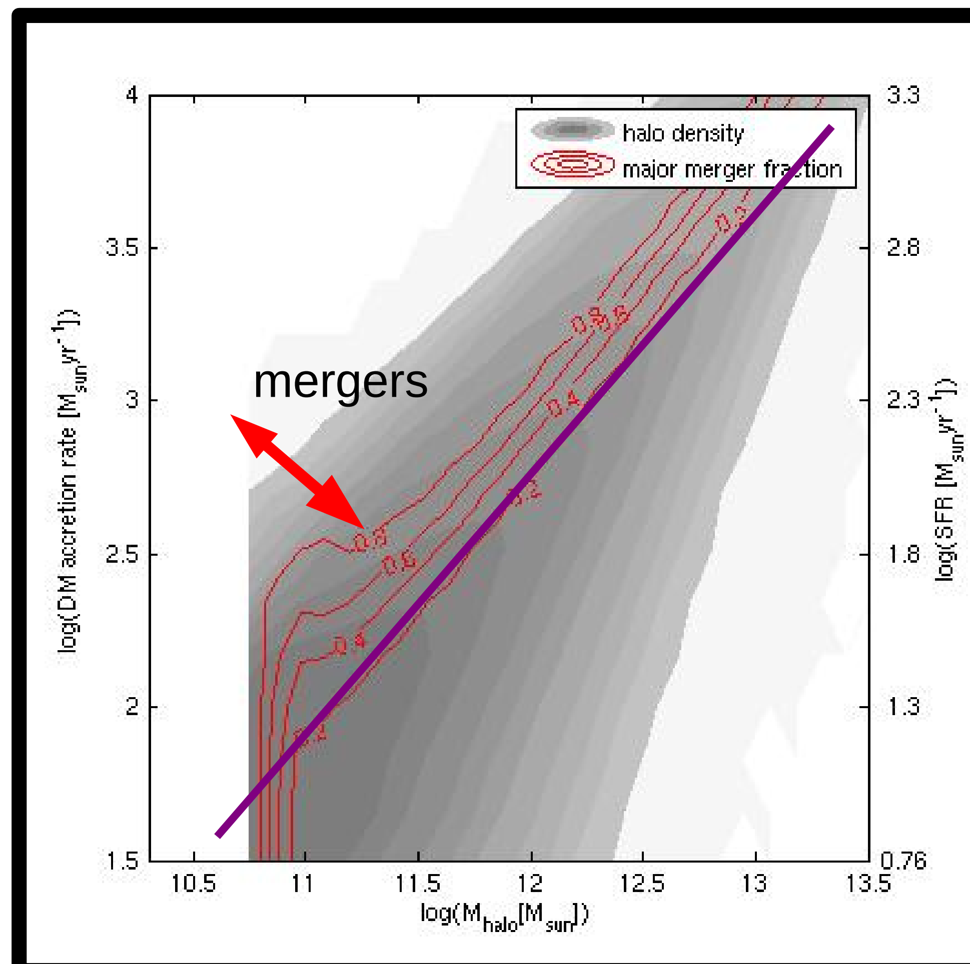
Caveat: Need DM + DE

Let's begin with a consensus: halo growth

$dM/dt \sim M_h^{1.1}\ (1+z)^{2.2}$



Genel et al. 2008, 2010

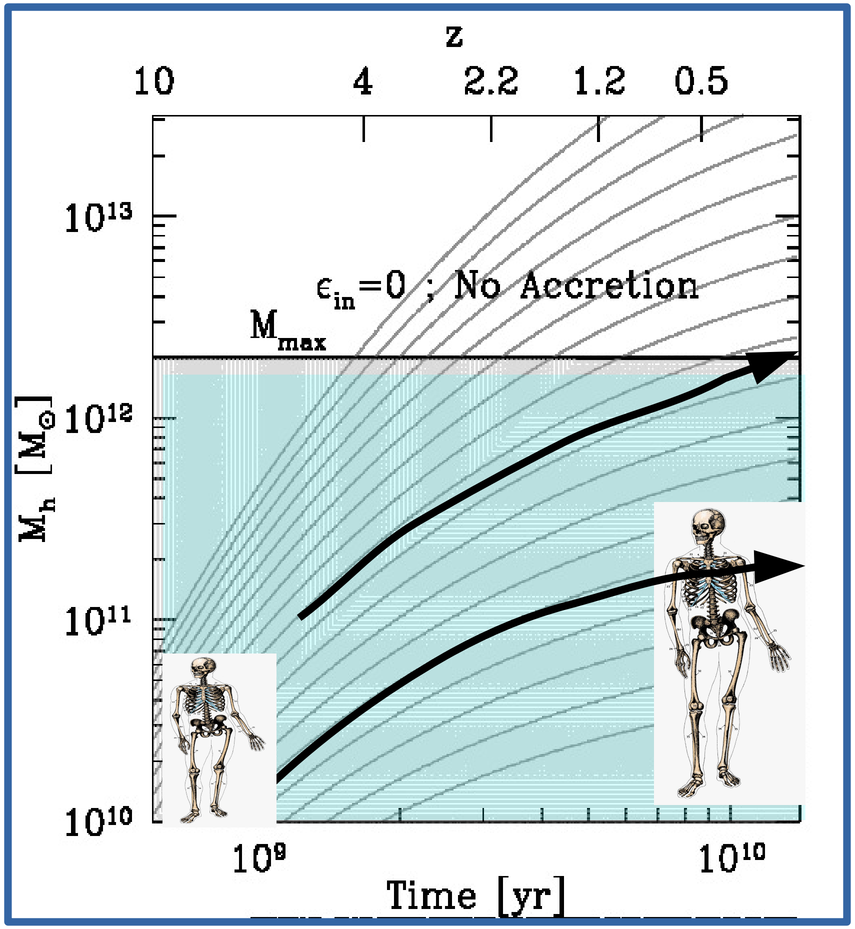


- **f_mergers** Kaviraj, Cohen et al. 2012
- **Scatter increases at low Mh !**

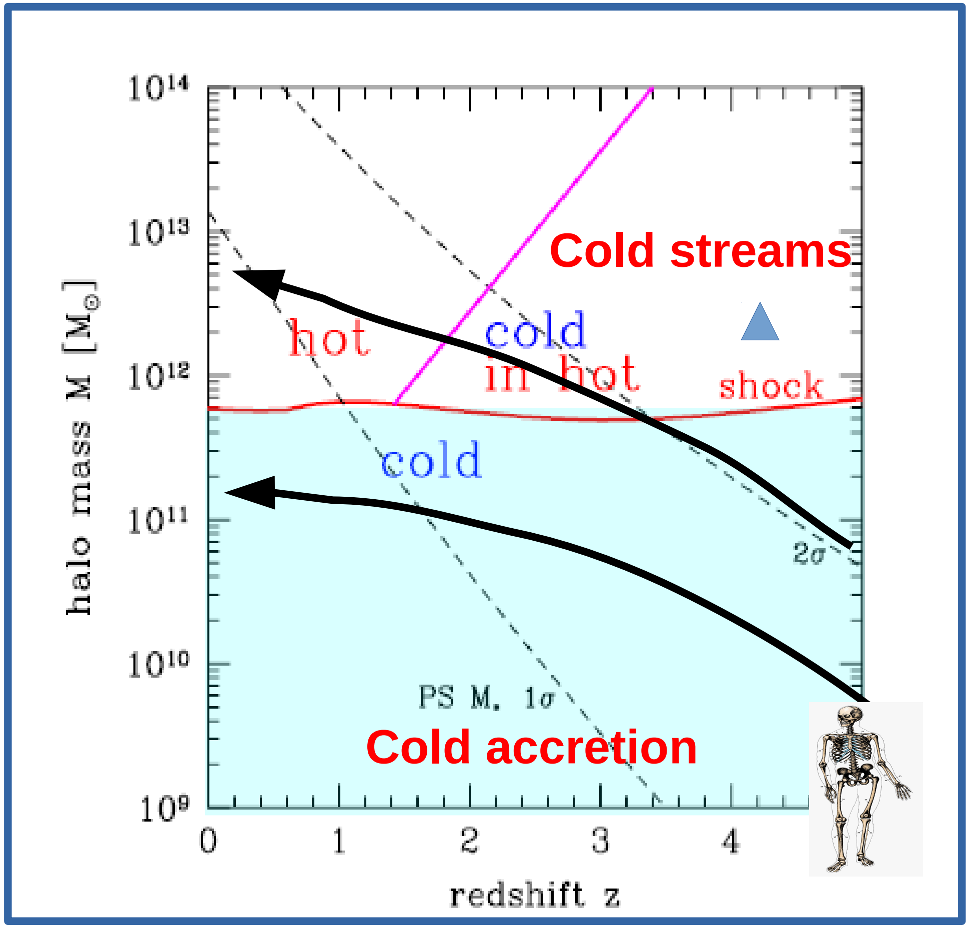
… add the current paradigm

See also White 1991

Bouché et al. 2010

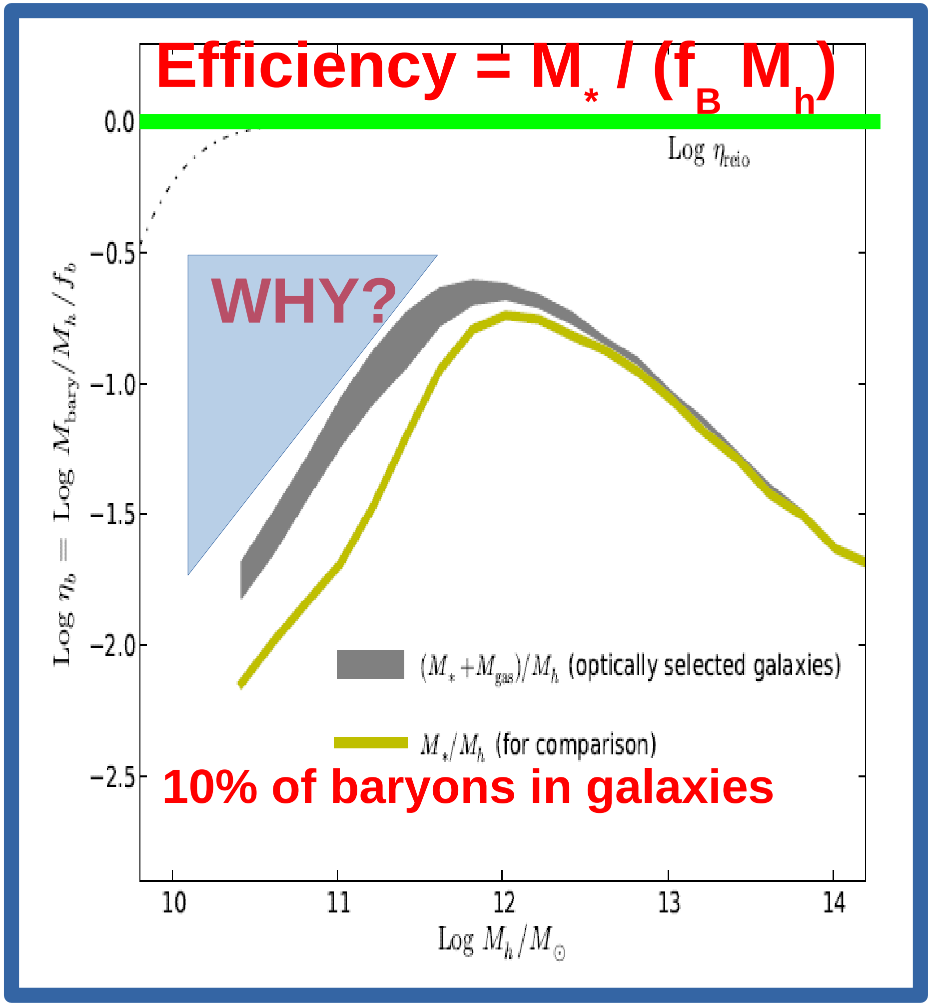


Dekel et al. 2007



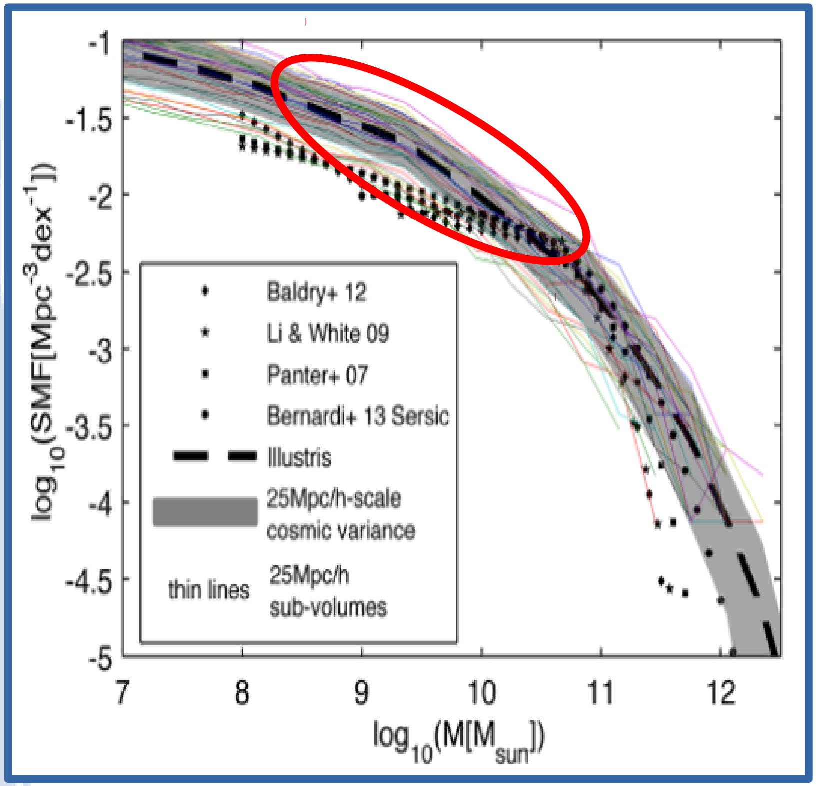
… to find a challenge:

Too many stars in models



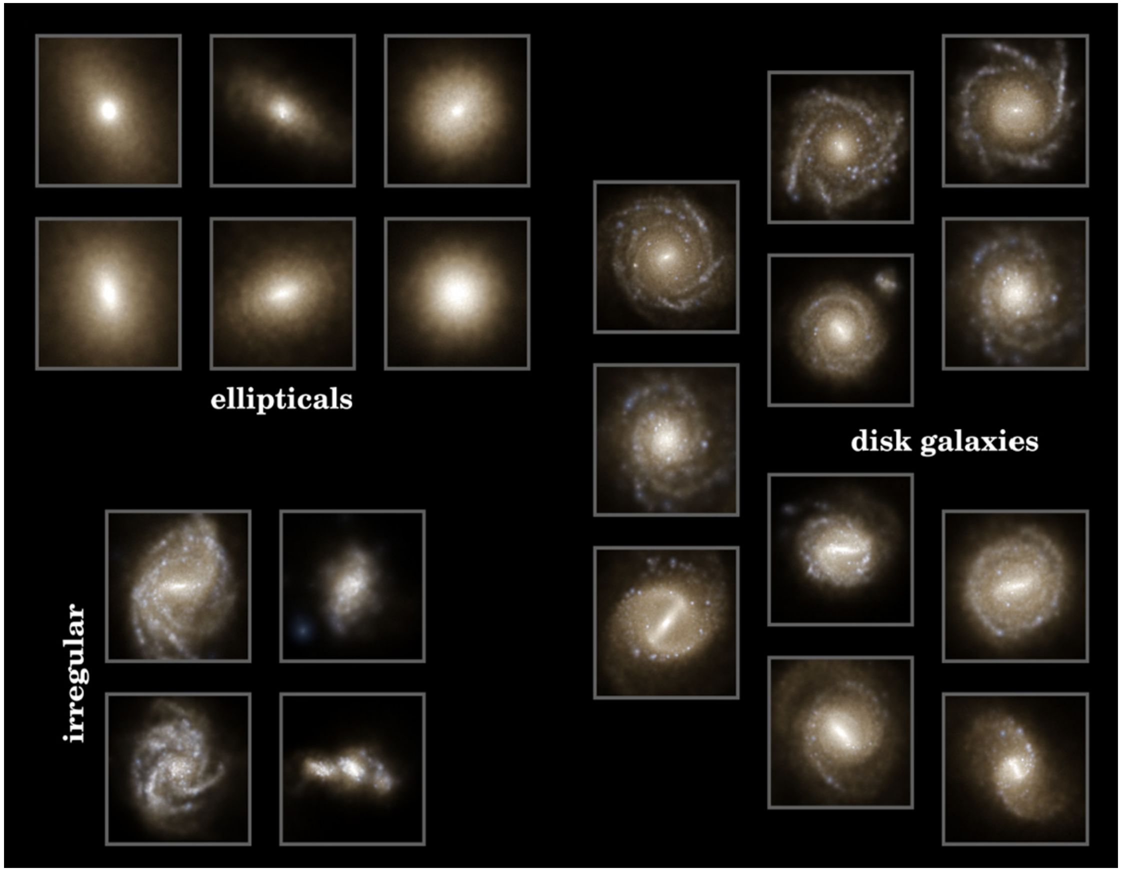
Papastergis, Cattaneo et al 2012

Challenge remains with the state-of-the art



Illustris, Genel 2014

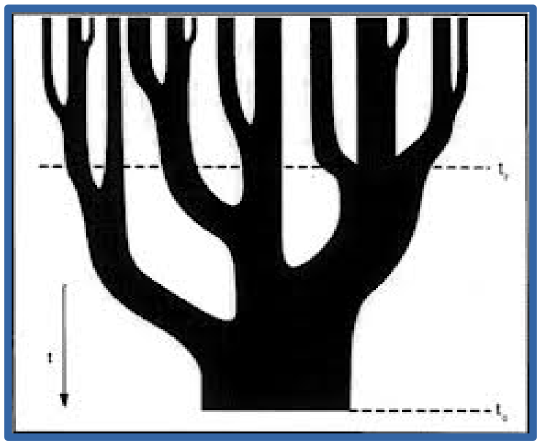
Illustris



Volgelsberger et al. Nature 2014
Genel et al. 2014

To recap

- Dark matter growth understood
- Inflows are necessary (Obs. & Theor.)



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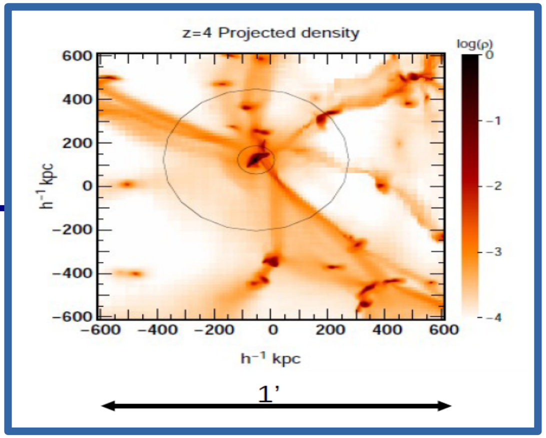

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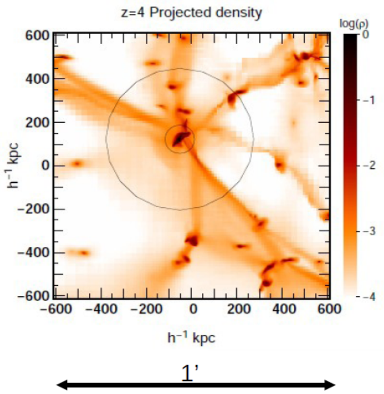
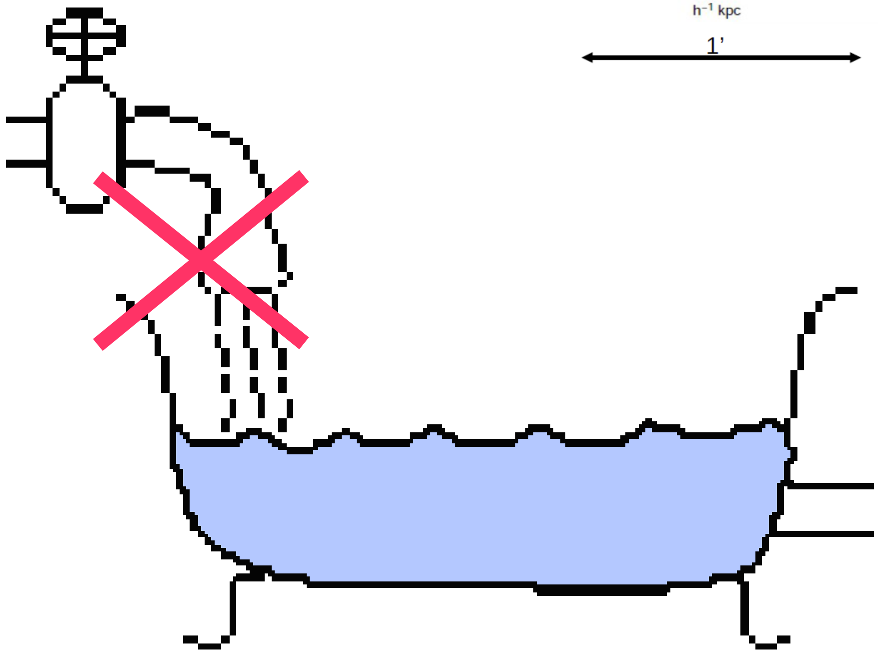
Two possibilities

Bouché et al . 2010





Blanchard A. 1992
Ricotti et al. / Schaerer; Cantalupo et al. 2010
Cattaneo 2010, Mo 2005, Lu Mo 2013

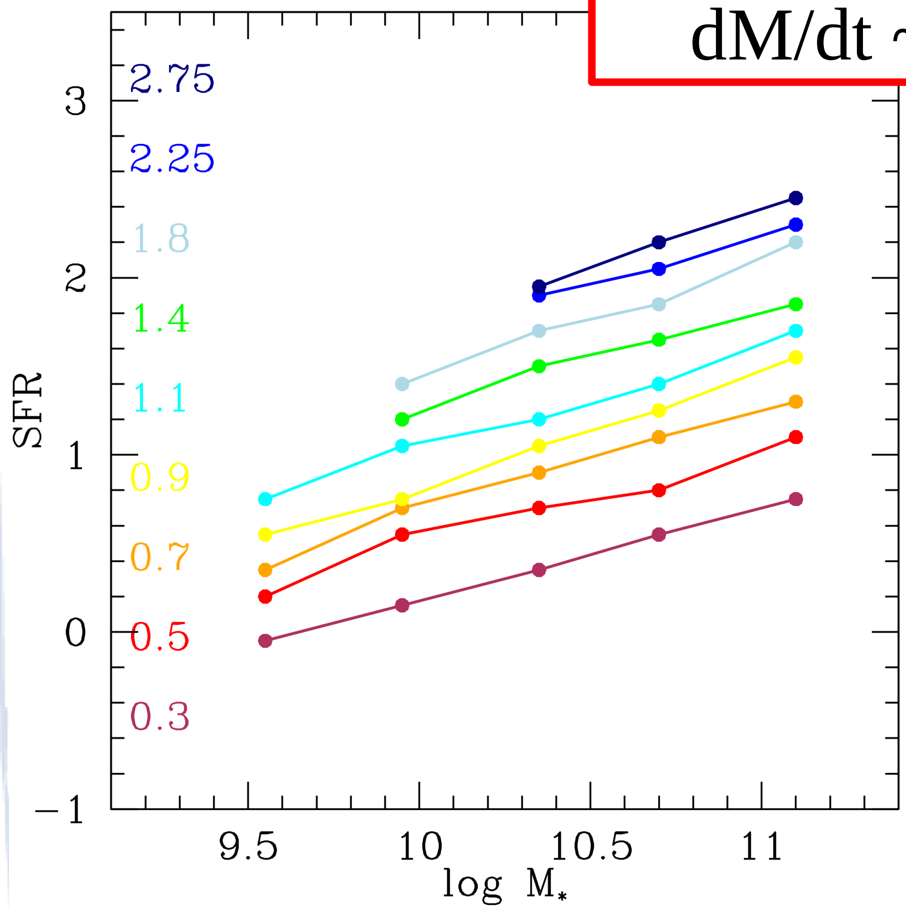
Bouché et al . 2012
Schroetter et al. 2014

Baryons vs. DM halos

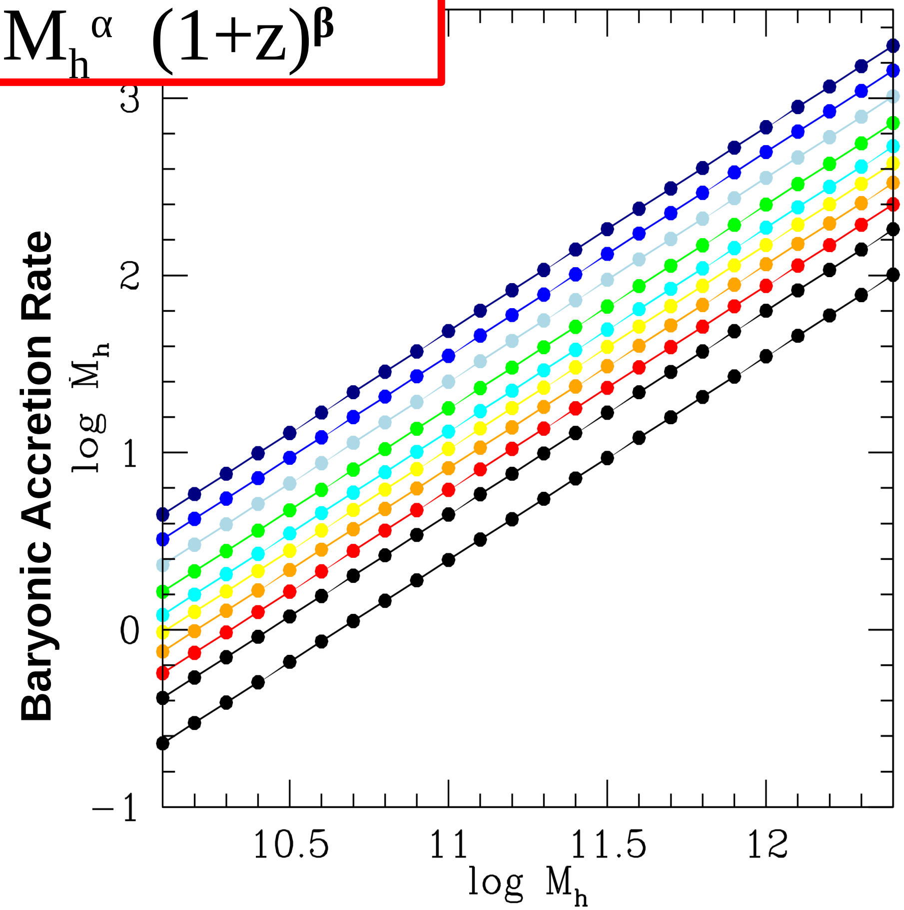
Karim et al. 2010
(COSMOS 10^5 galaxies)

Neistein & Dekel 2007
Genel 2008; McBride/Fakhouri

$$dM/dt \sim M_h^{\alpha} (1+z)^{\beta}$$



Log Mstellar



Log Mhalo

Scaling relations

DM halos — **Baryons**

- Halo Growth
  - $dM/dt \sim M^{1.1}$
- Virial relation
  - $M \sim V^3$

?

- SFR-Mass
  - $SFR \sim M_*^{0.8}$
- Tully Fisher
  - $M_* \sim V^4$

Let's build a toy model

Let's build a toy model

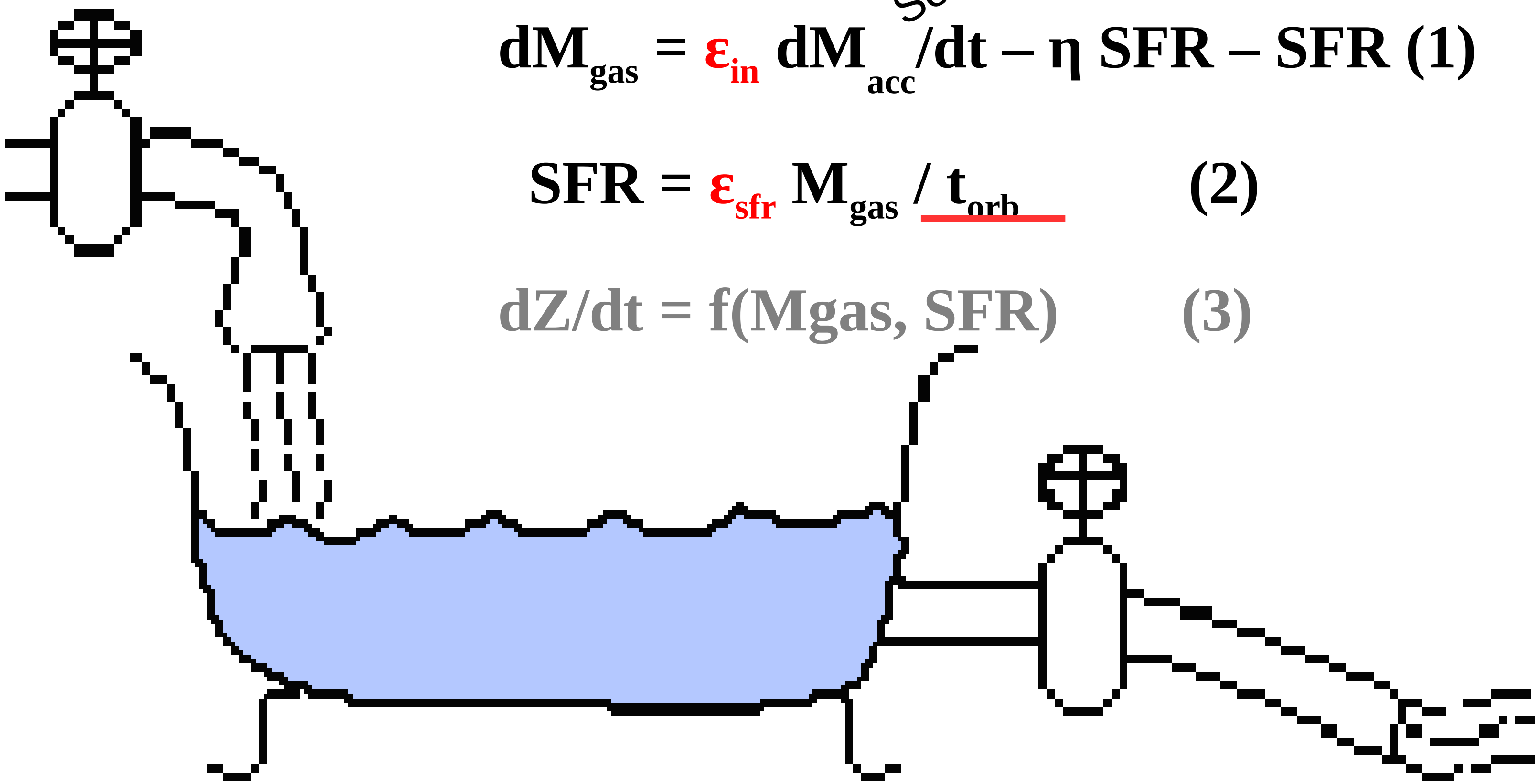
Bouché et al. 2010

Set by cosmology   Outflows

$$dM_{gas} = \varepsilon_{in}\ dM_{acc}/dt - \eta\ SFR - SFR \quad (1)$$

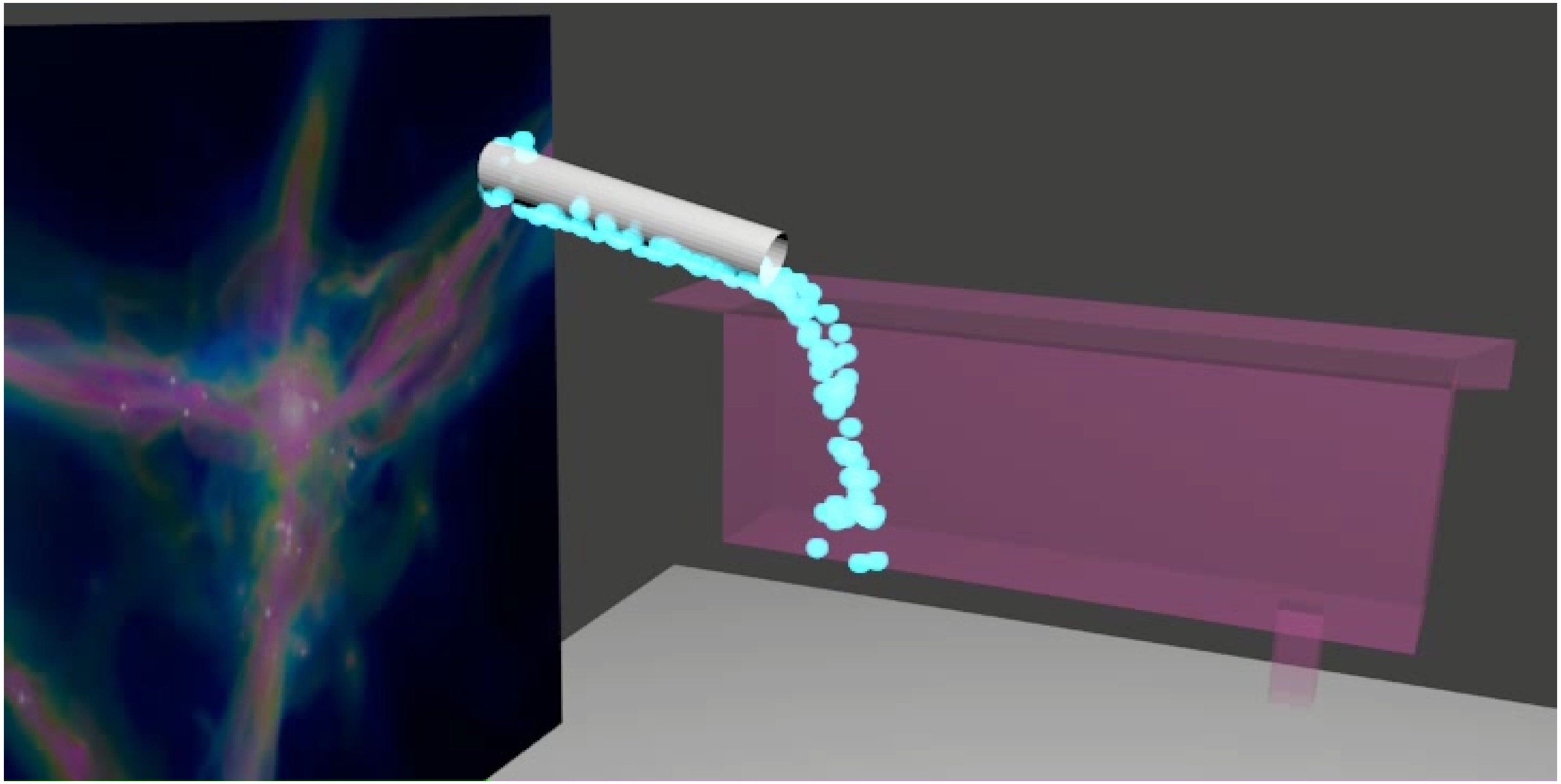
$$SFR = \varepsilon_{sfr}\ M_{gas}\ /\ \underline{t_{orb}} \quad (2)$$

$$dZ/dt = f(Mgas, SFR) \quad (3)$$



See also Cattaneo et al. 2010, Neistein, Weinmann 2010, Lu Mo et al. 2013
Krumholz & Dekel 2011, Khochfar & Silk, Reddy et al. 2012,...
Lilly et al. 2013; Peng & Maiolino 2014; Dekel et al. 2014

Toy model: Steady State

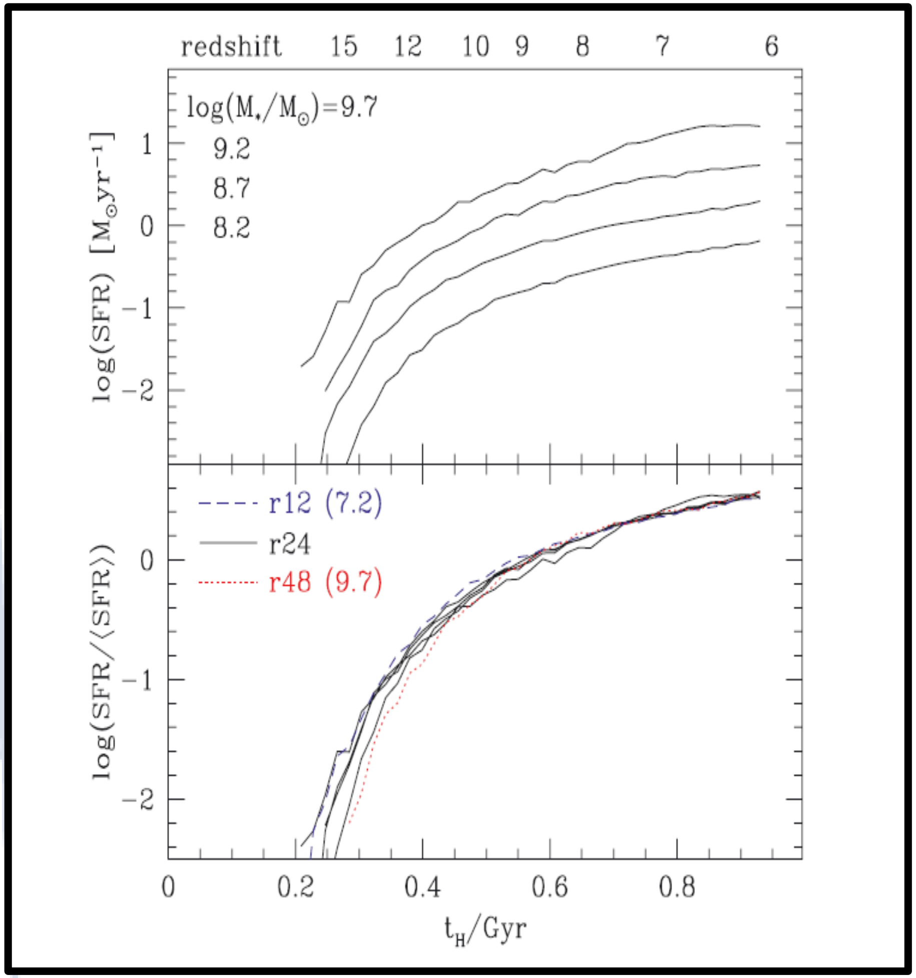


➔ Reach a quasi-steady state under condition: $t_{sfr} < t_{acc}$:

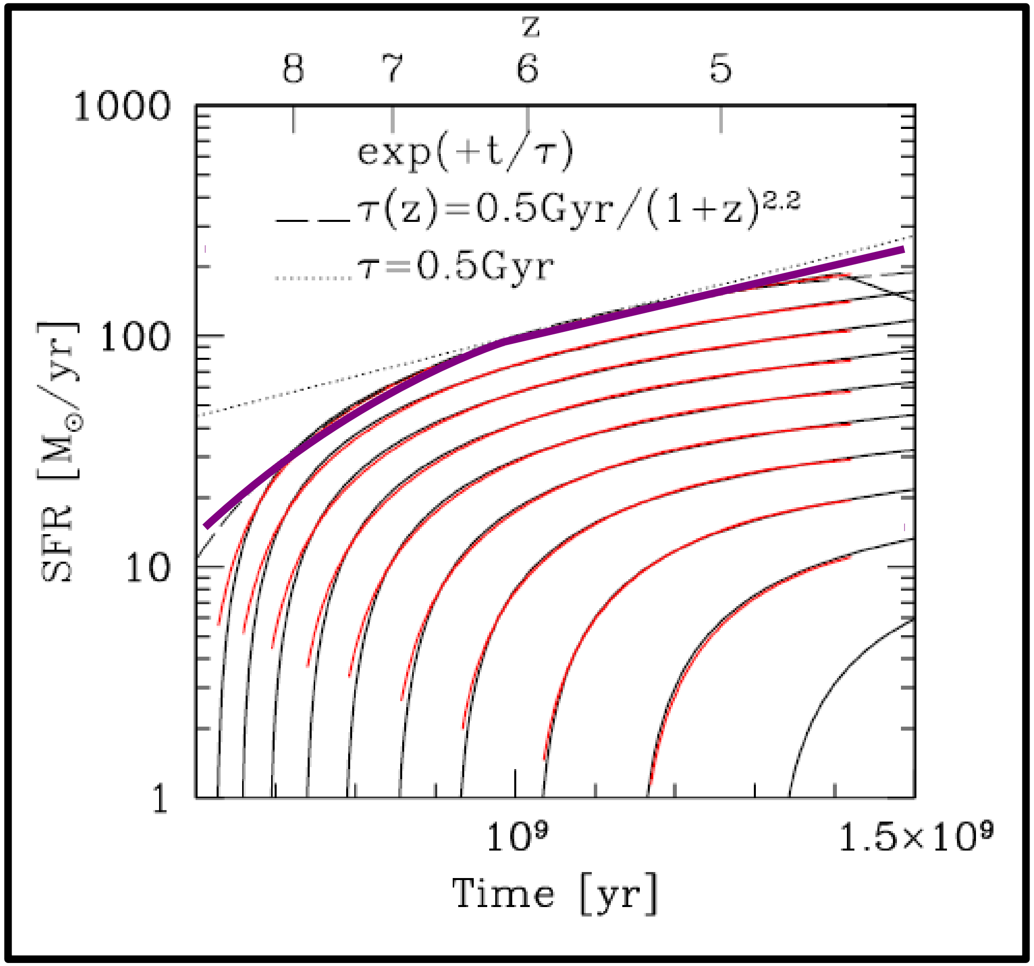
➔ SFR (& Mgas) follows accr. Rate

SPH vs Toy Model

See Papovich et al. 2011

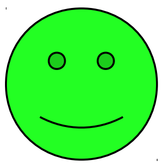


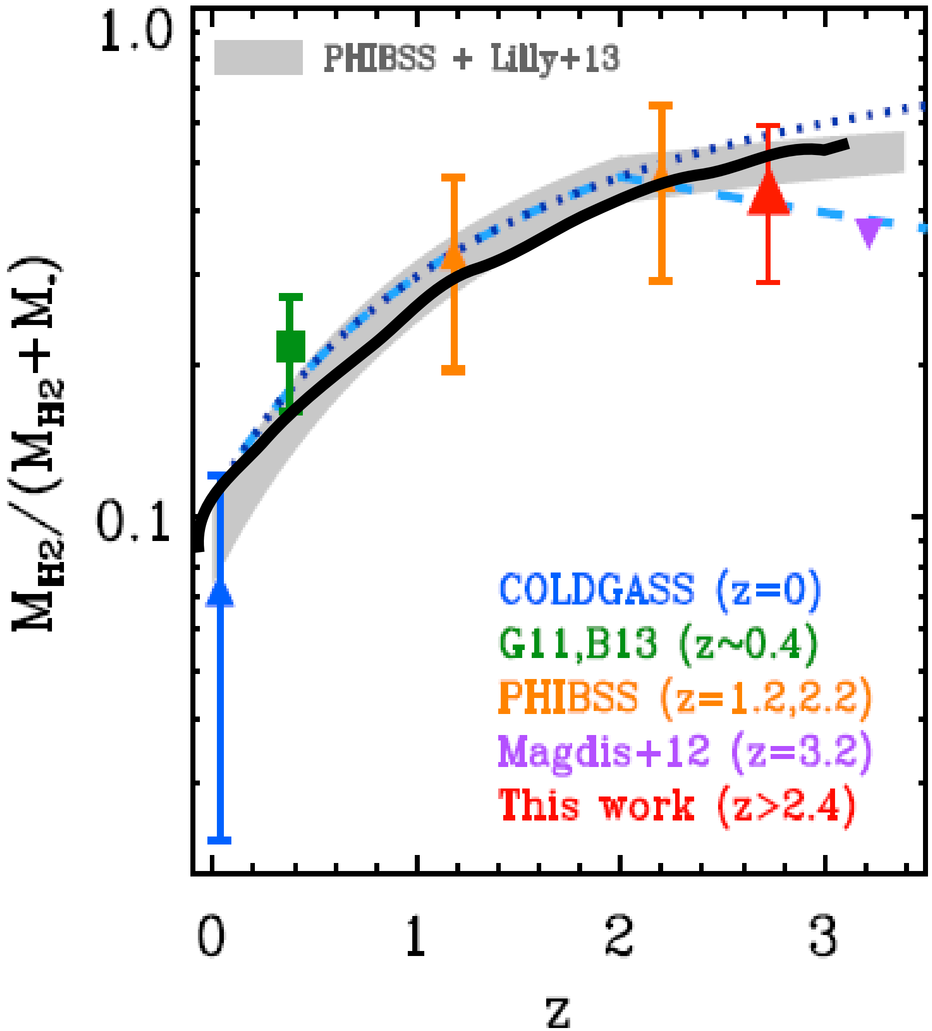
Finlator et al. 2011; SPH



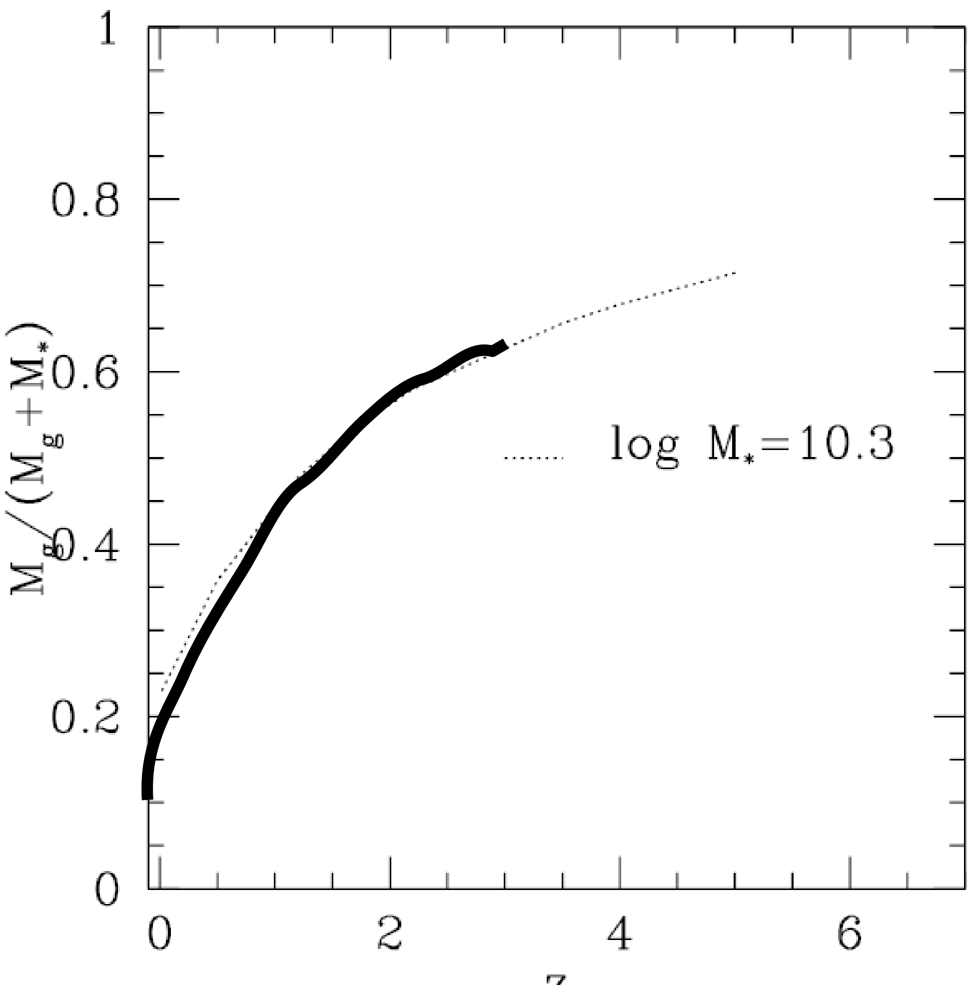
Bouché, Dekel et al. 2010

Gas fractions:
No problem with evolution



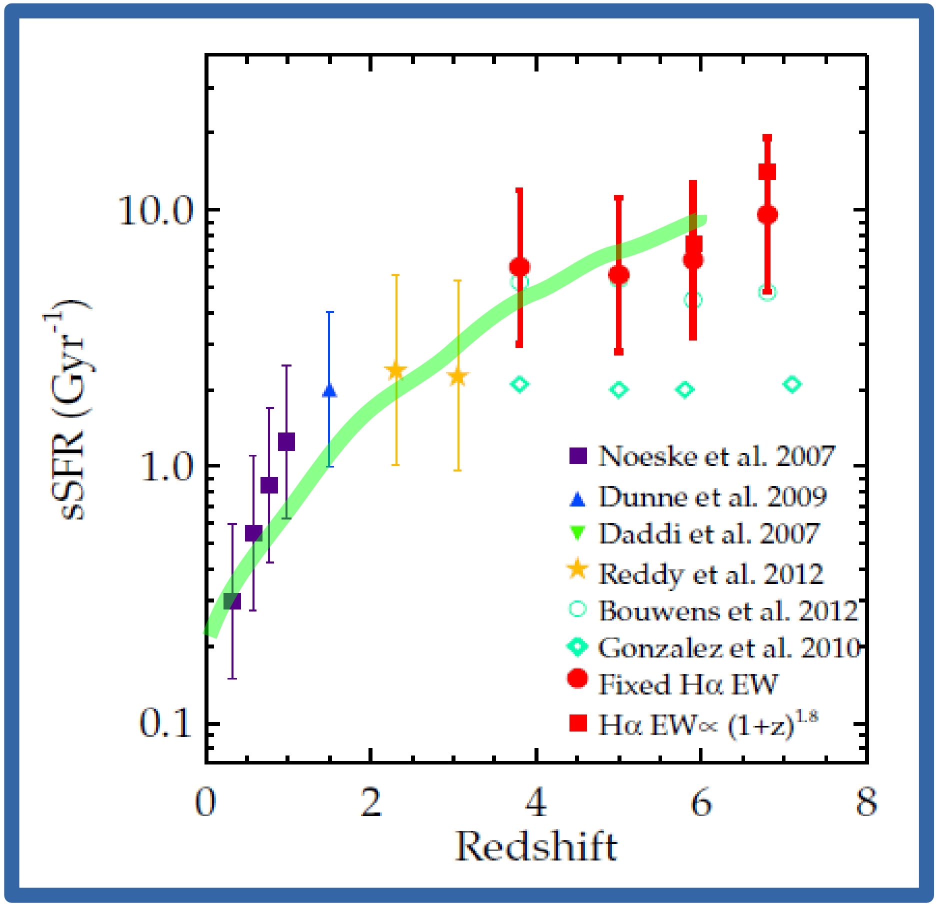


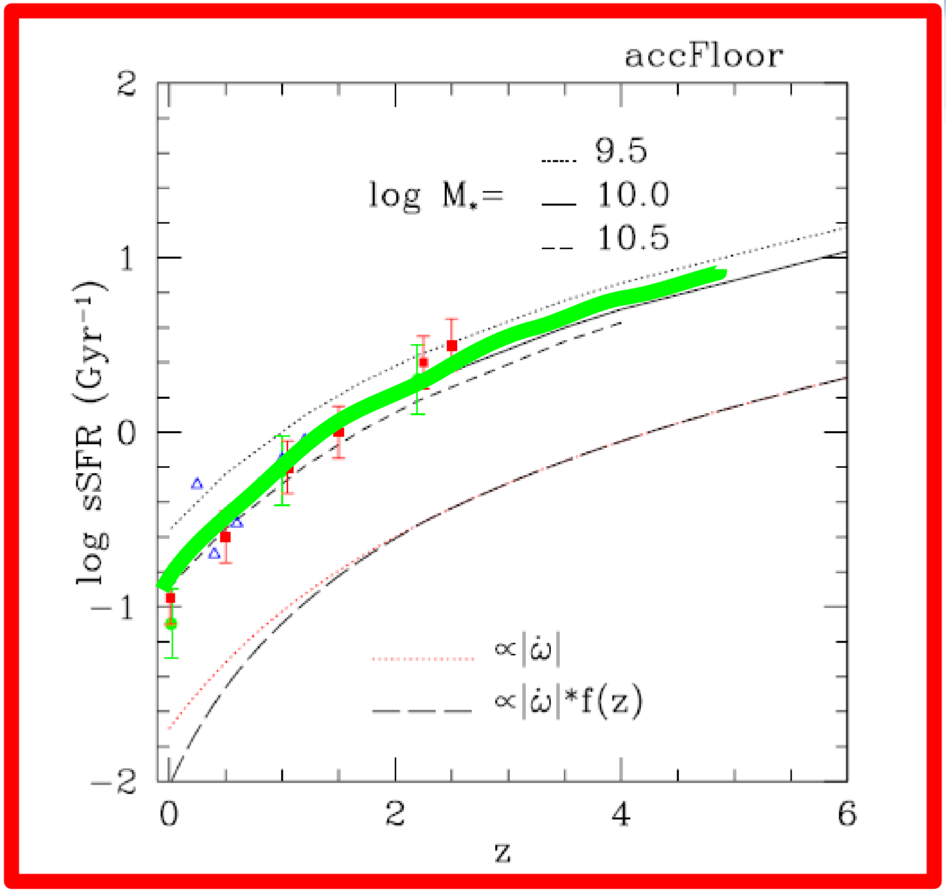
Saintonge A. 2013



Bouché et al. 2010

Main Sequence:
No problem with Evolution





Stark et al. 2013

Bouché et al. 2010

Toy model: generic features

Peng & Maiolino 2014
Dekel et al. 2014

Bouché et al. 2010

Global properties:

- Galaxies are in *quasi-steady* state
- SFR follows accretion rate → MS
- Gas mass given by balance In&Out → fgas(z)

Galaxies roughly self-regulate

The Balance Between *Accretion* and *SFR(KS)*

Note:the KS relation is a product of local self-regulation (Hopkins's 2014)

Up to now: Nothing Controversial

- Feedback included (!) (V^{-1} or V^{-2})
- BUT **<u>wrong</u>** LF & scaling relation

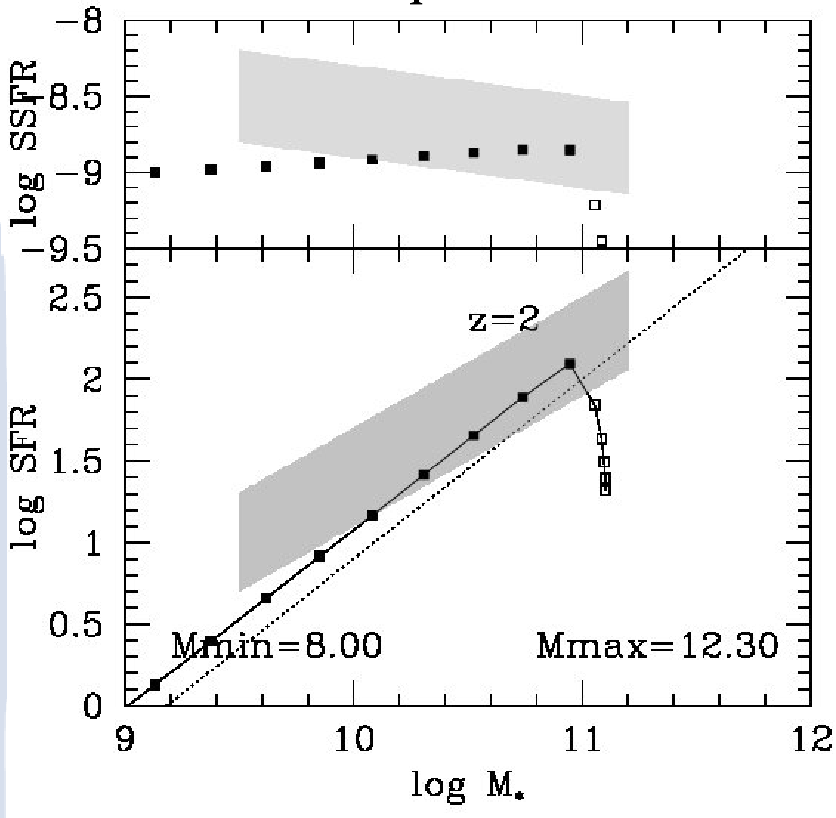
$$dM_{gas} = \varepsilon_{in}\, dM_{acc}/dt - \eta\, SFR - SFR \quad (1)$$

$$SFR = \varepsilon_{sfr}\, M_{gas} / t_{orb} \quad (2)$$

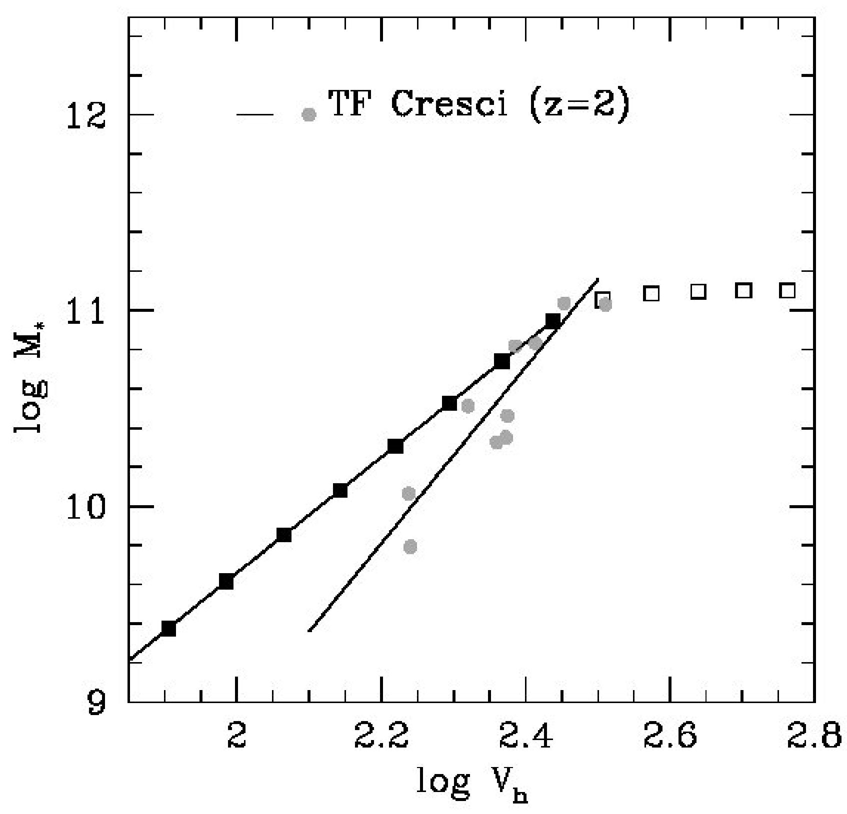
$$dZ/dt = f(Mgas, SFR) \quad (3)$$

Option 1: Change SF efficiency

SFR sequence



TF relation



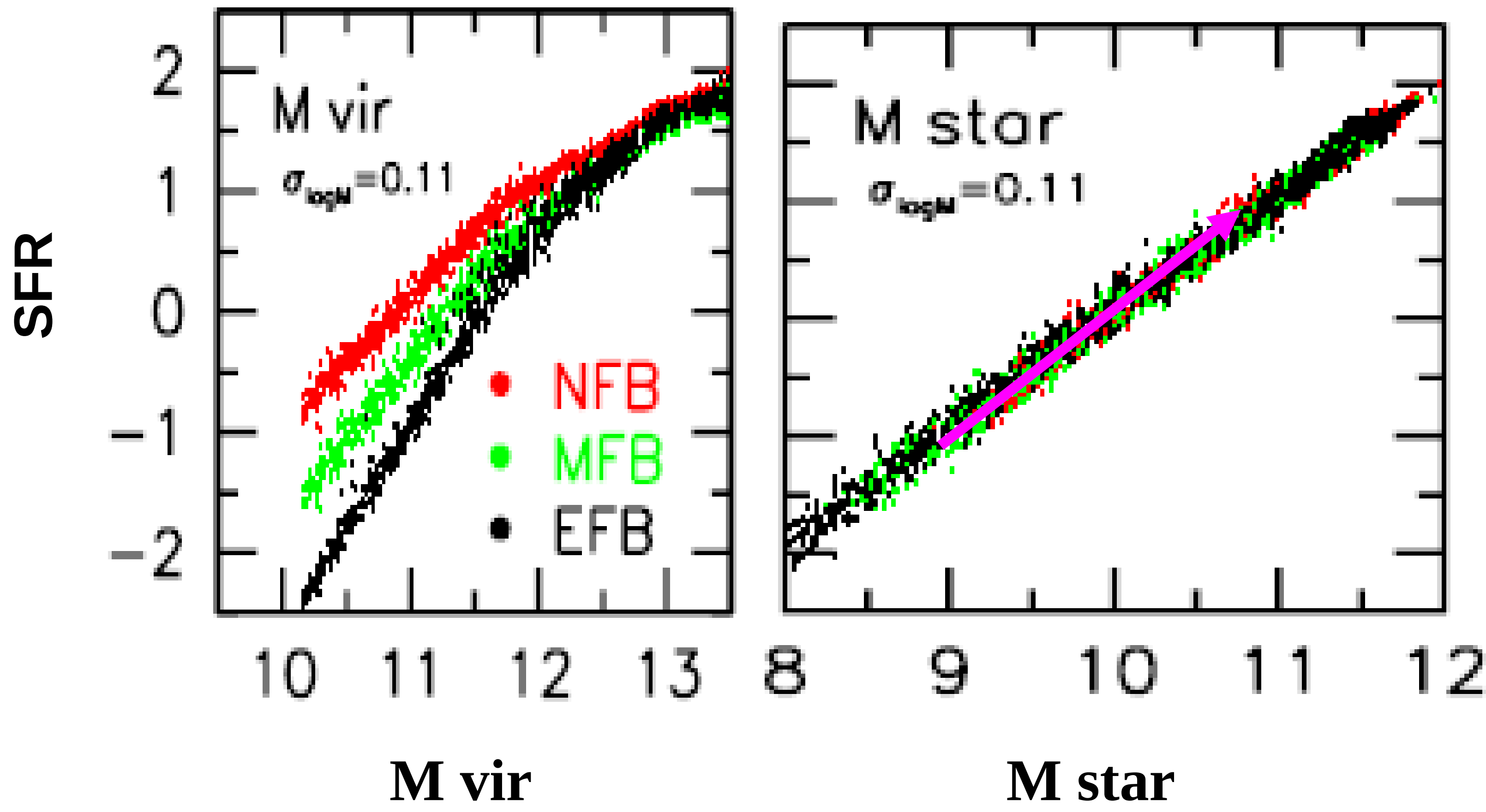
Same for SF threshold !

But see Krumholz & Dekel 2011

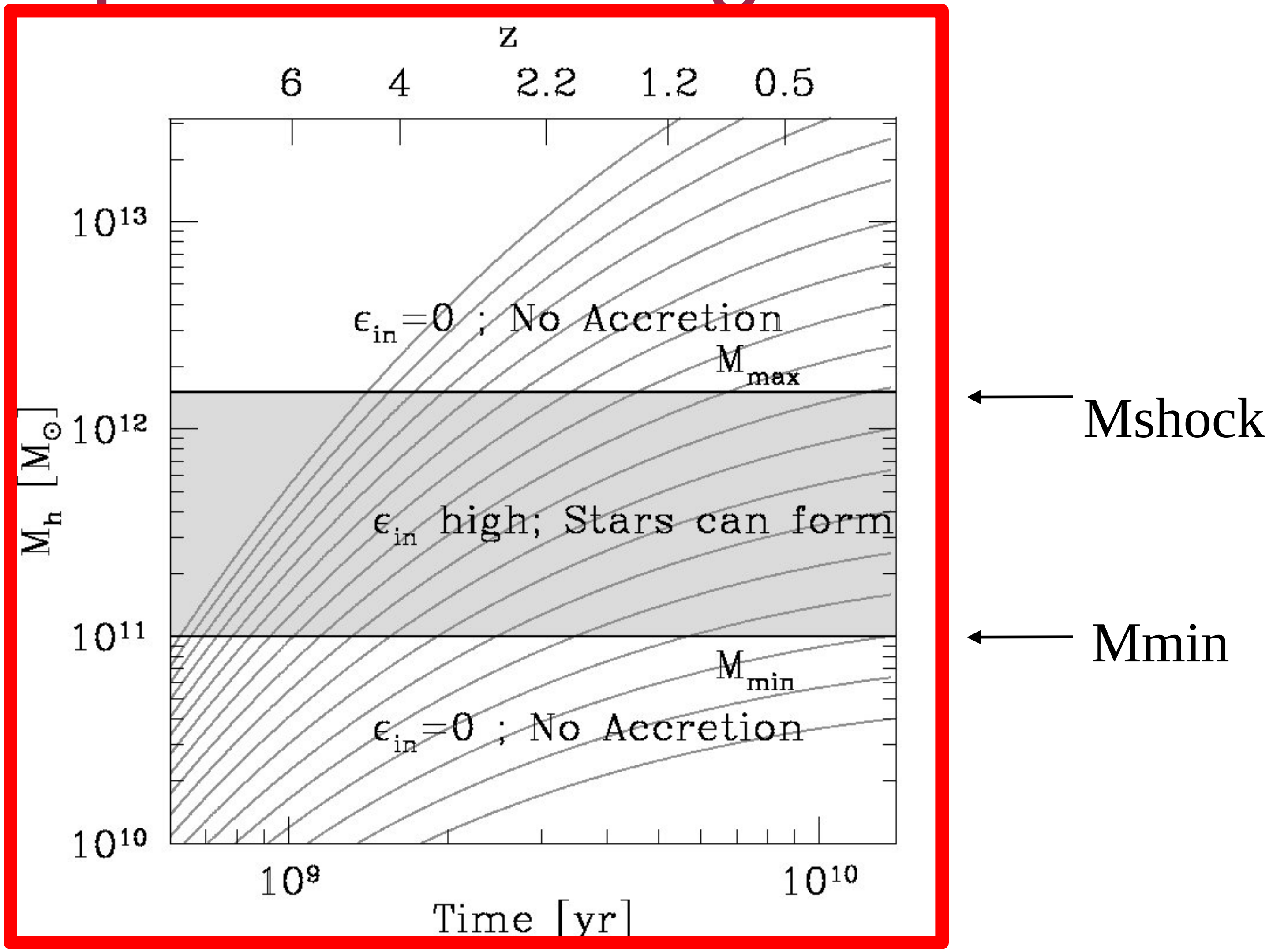
Option 2: Change feedback

==> Good for M-Z relation

Dutton et al. 2009,2010



Option 3: Change accretion

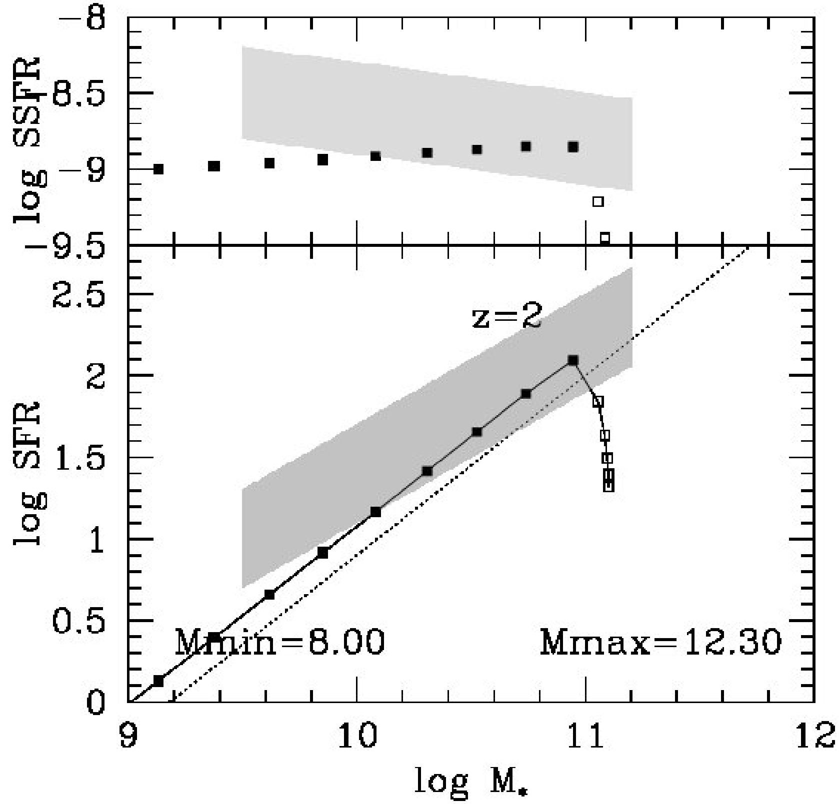


See also Cattaneo et al. 2011
Neistein, Weinmann 2010

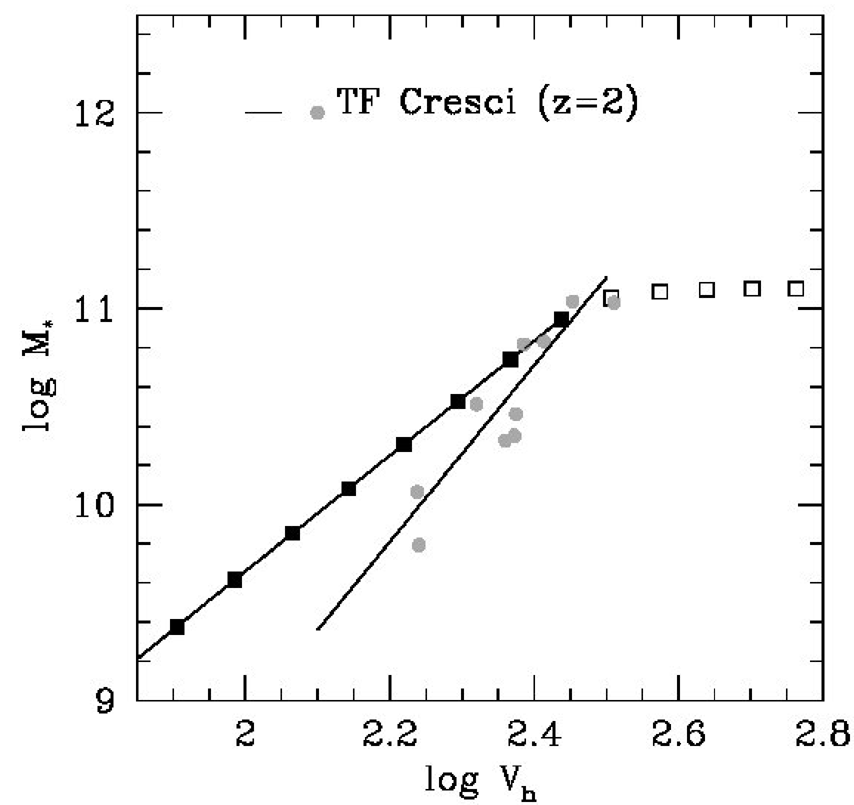
Blanchard A. 1992
Ricotti et al. / Schaerer; Cantalupo et al. 2010
Cattaneo 2010, Mo 2005, Lu Mo 2013

Without Mmin

SFR sequence

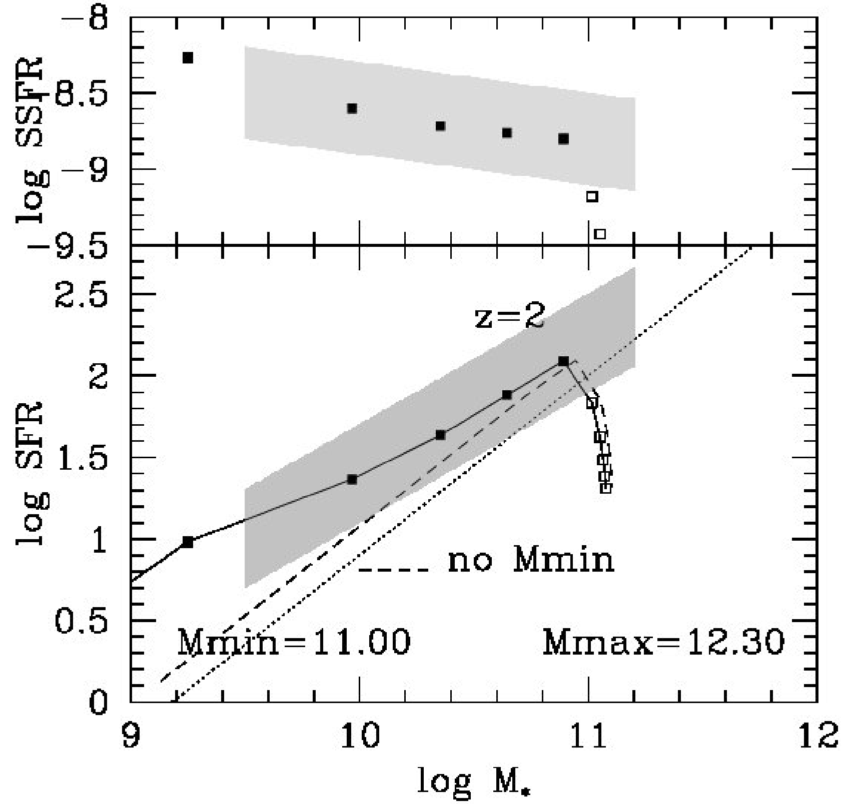


TF relation

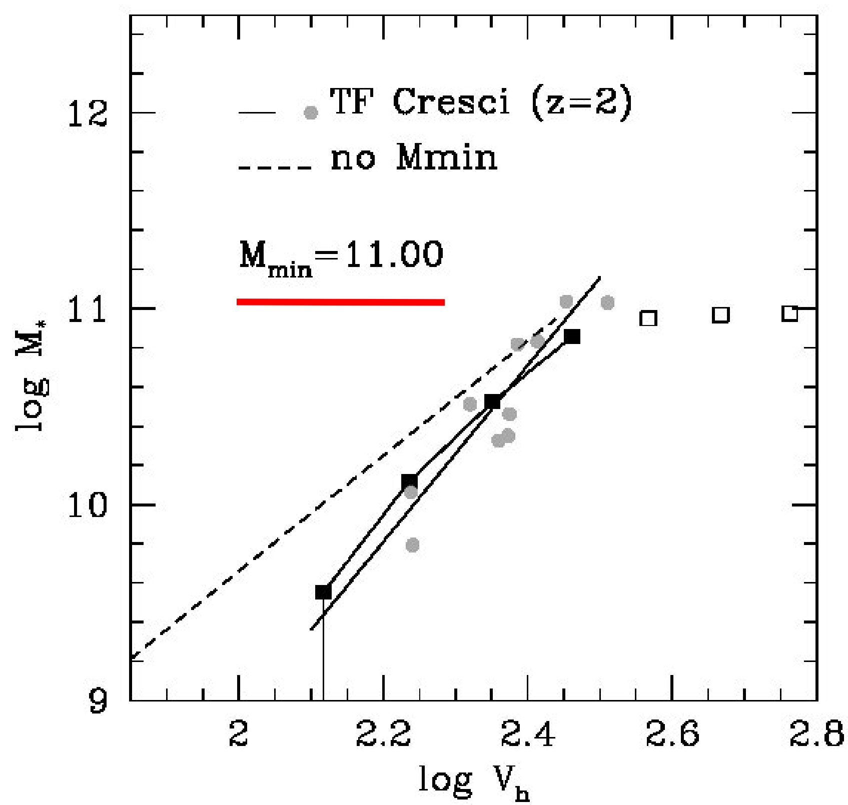


With Mmin

SFR sequence



TF relation



Scaling relations

DM halos

- Halo Growth
  - $dM/dt \sim M_h^{1.1}$
- Virial relation
  - $M_h \sim V^3$

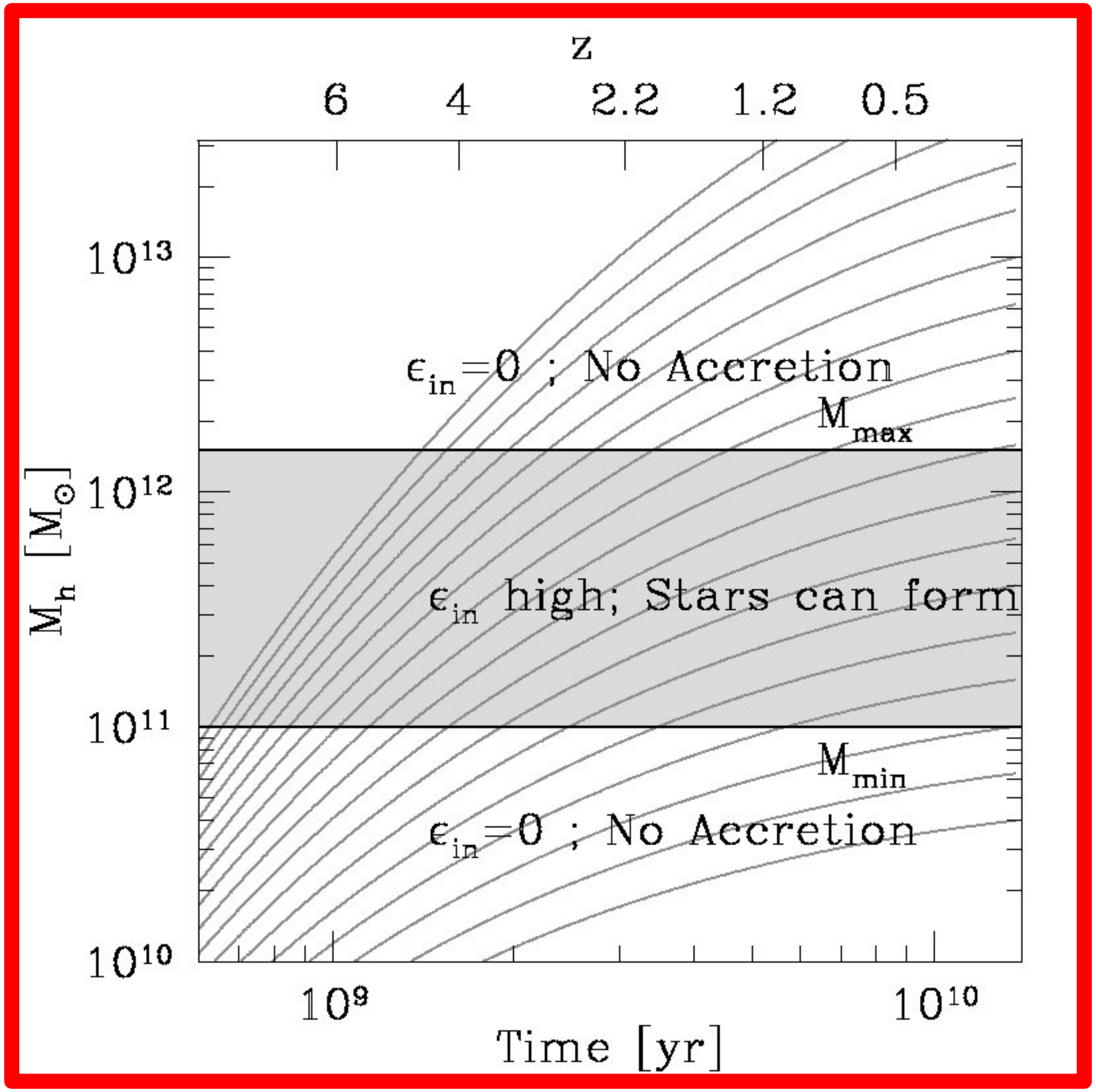
→

Baryons

- SFR-Mass
  - $SFR \sim M_*^{0.8}$
- ~~Tully Fisher~~
  - ~~$M_* \sim V^4$~~

Accretion floor: Other predictions

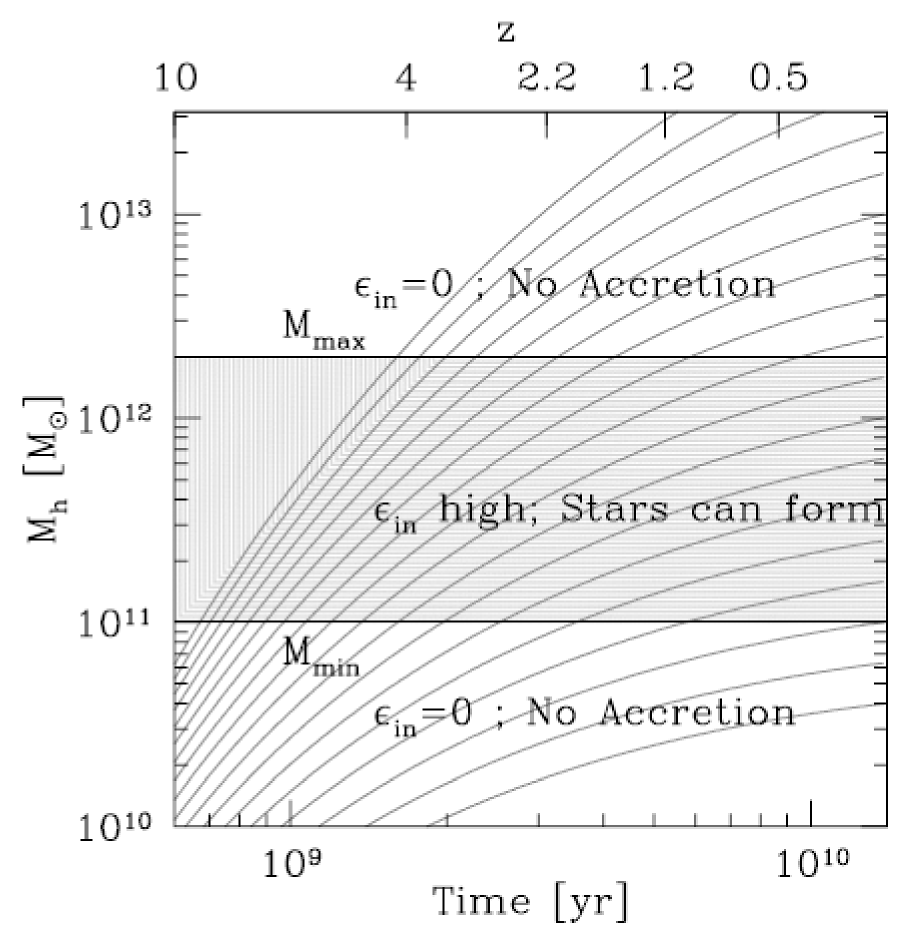
- SFR-Mass; TF
- sSFR (z)
- Stellar fractions
- F_gas (M*)
- F_gaz (z)
- SFRD (z)
- Downsizing
  Neistein et al. 2006
- FMZ Relation
  Mannucci et al. 2011



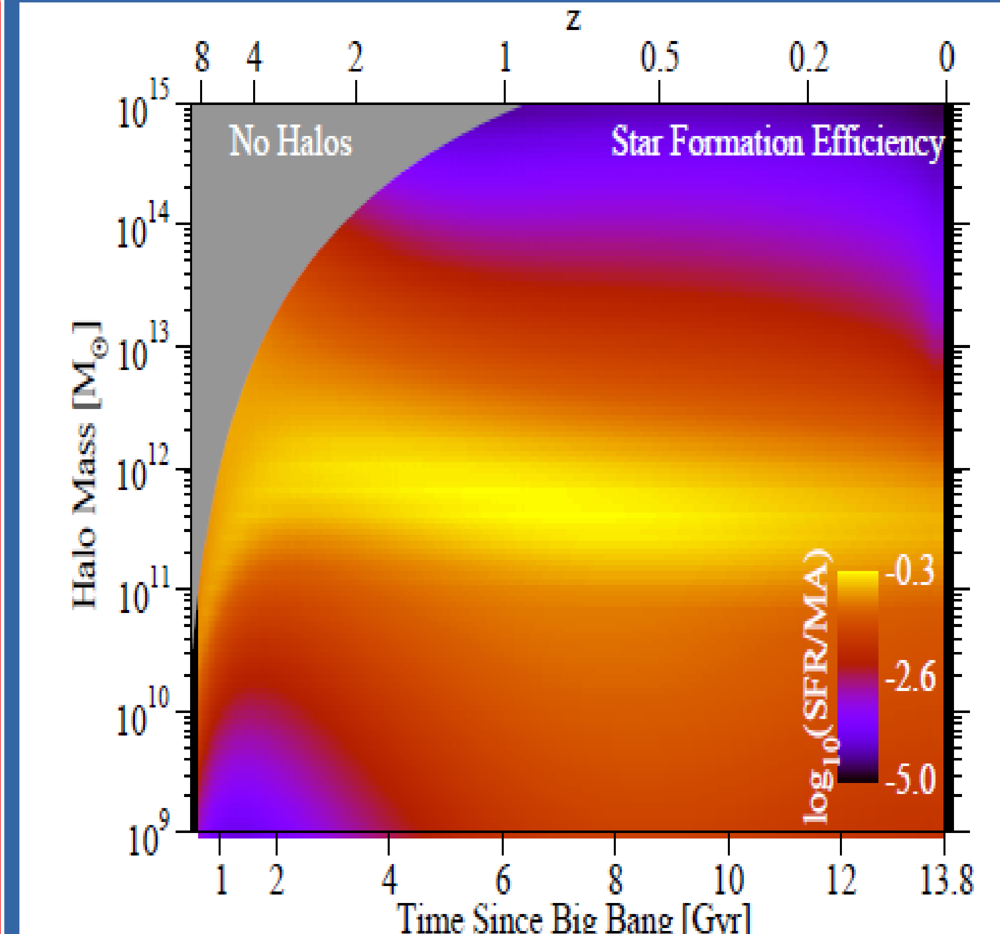
Bouché Dekel et al. 2010

An indirect evidence for accretion?

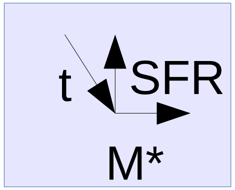
Bouché Dekel et al . 2010



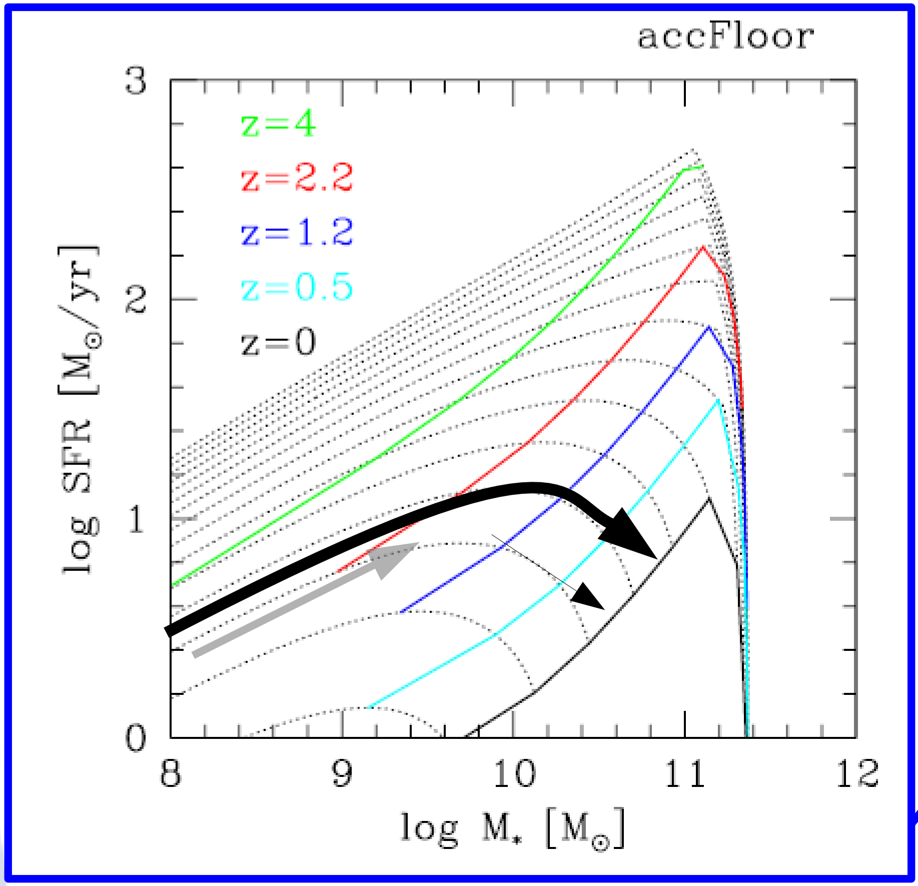
Behroozi, Wechsler, Conroy. 2013



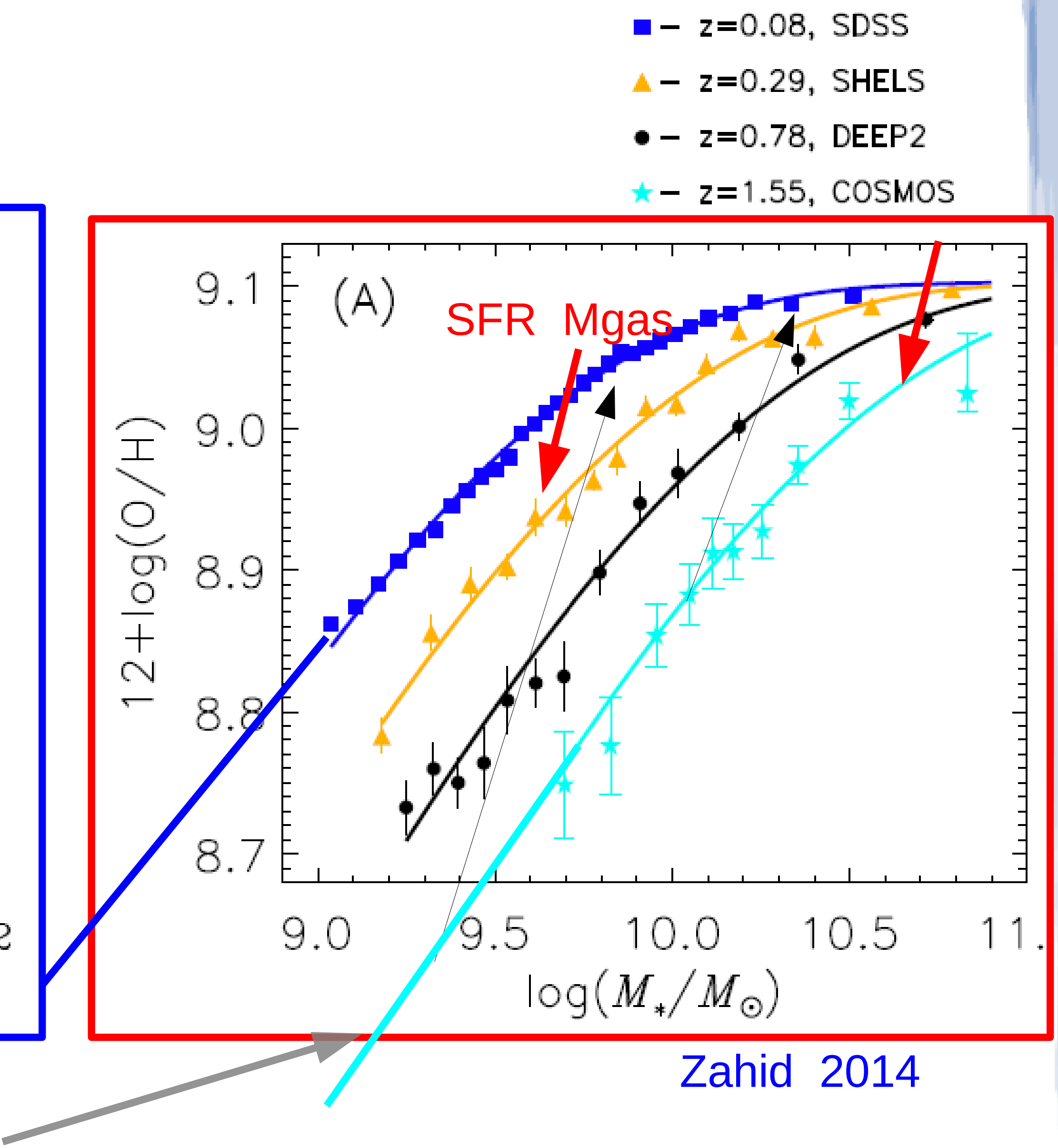
Scaling relations are isochrones



→ *M-Z-SFR plane ??*



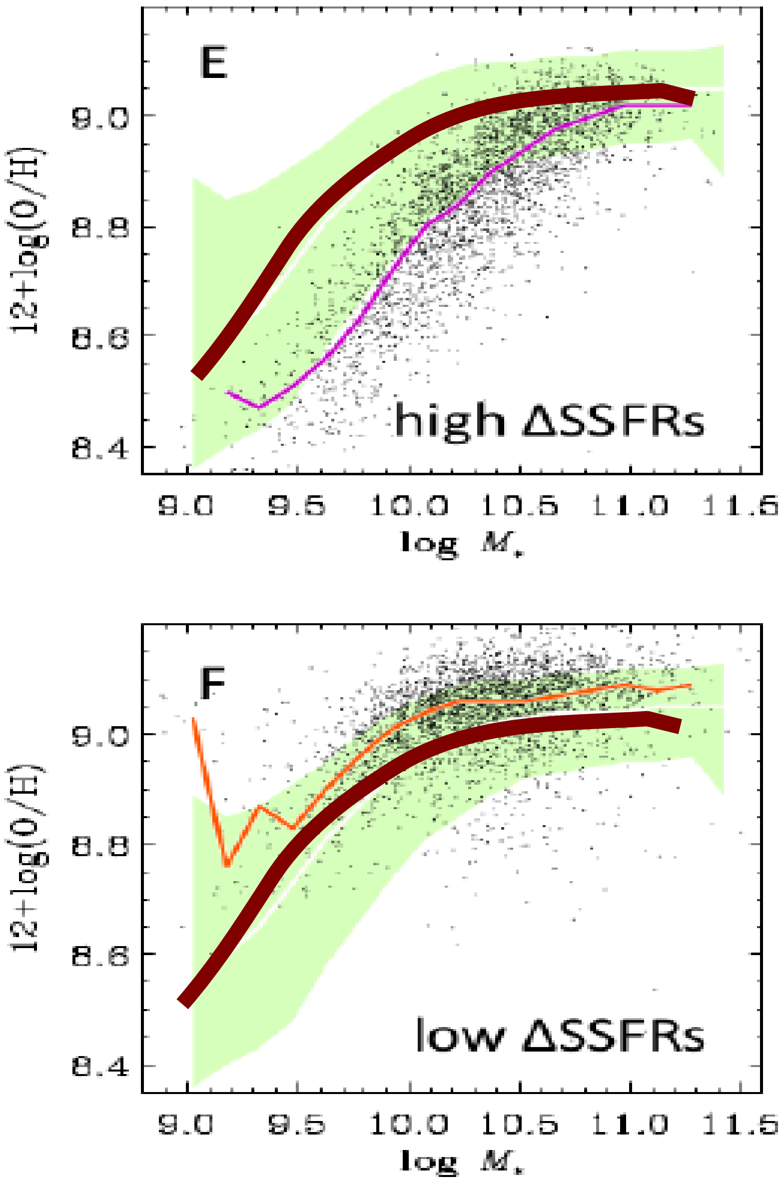
B2010

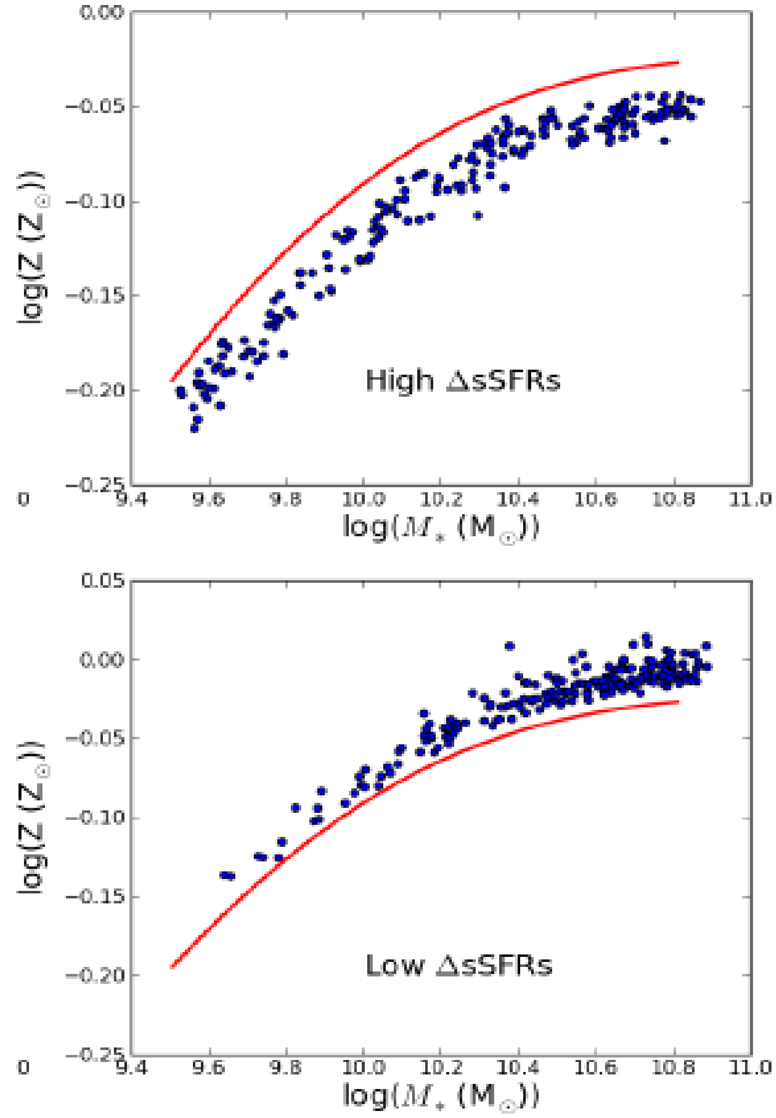


Zahid 2014

FMR relation

Salim et al. 2014 (SDSS)





Galaxies are in *quasi*-equilibrium

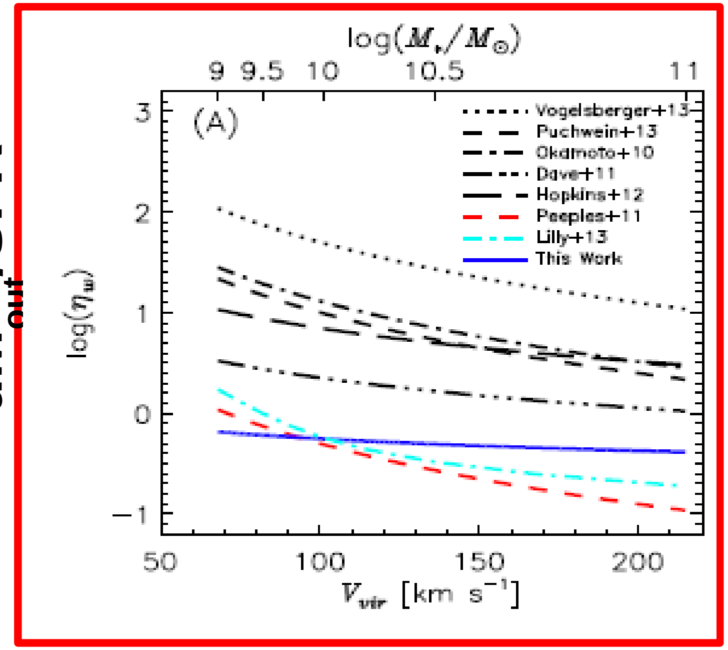
- SFR follows accretion rate → Main-sequence
- What drives galaxy growth M(z) ? **Accretion**
- What drives SFR(z) ? **Accretion**
- What drives Mgas (z) ? **Accretion**

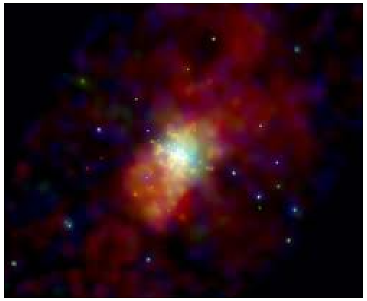
- What drives Metallicity(M*,z) ?
- Are there direct evidence for accretion ?

What about outflows ?

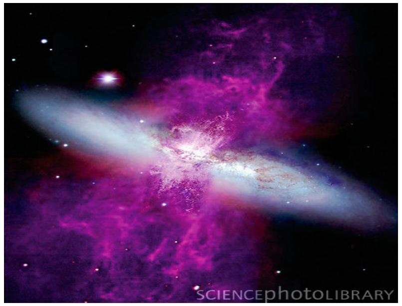
- <u>Ubiquitous & collimated</u>
  Chen, Tremonti et al. 2010; Bouché et al. 2012; Bordoloi et al. 2011, Kacprzak et al. 2012; Martin 2012, Rubin 2013, Bordoloi 2013
- Does wind escape ?
  - $V_{wind} > V_{esc}$
- How far do they travel ?
- Does wind carry enough mass?

dM_{out}/SFR





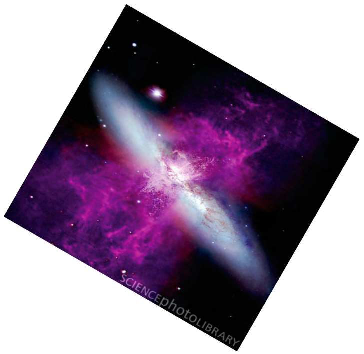
X ray

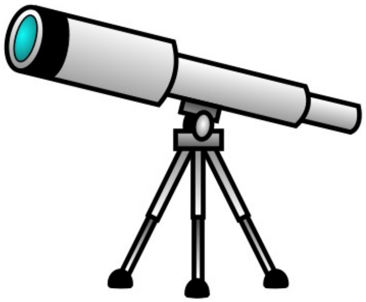


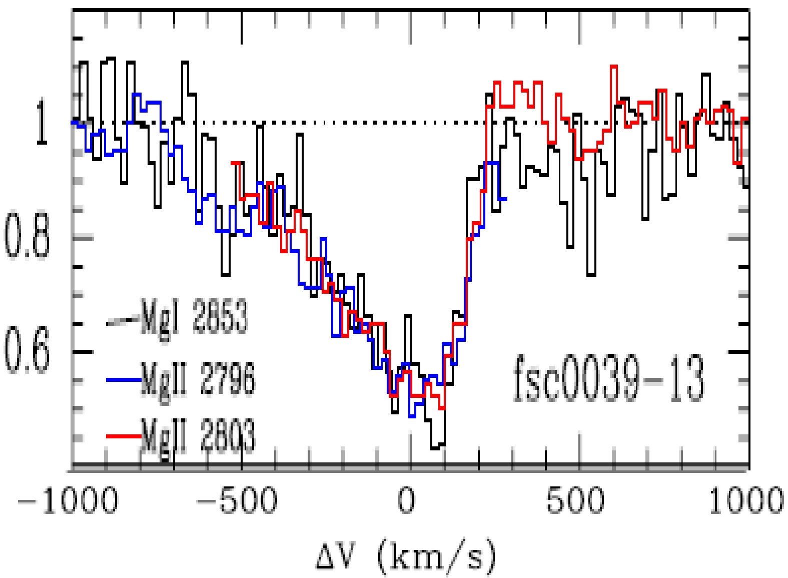
Ha + HST

PAH Spitzer

Problem with traditional spectroscopy







100 pc, 1kpc, 5kpc

??

$$\dot{M}_{\rm out}(b) = 0.41 {\rm M}_{\odot}\,{\rm yr}^{-1}\,\frac{\mu}{1.5}\,\frac{\Omega_w}{2}\,\frac{N_H(b)}{10^{19}{\rm cm}^2}\,\frac{V_{\rm out}}{200{\rm km\,s}^{-1}}\,\frac{b}{25\,{\rm kpc}}$$

Gas flows using background QSO

- Pros
  - Radial information (key!)
  - Can probe wind around *<u>any</u>* galaxy

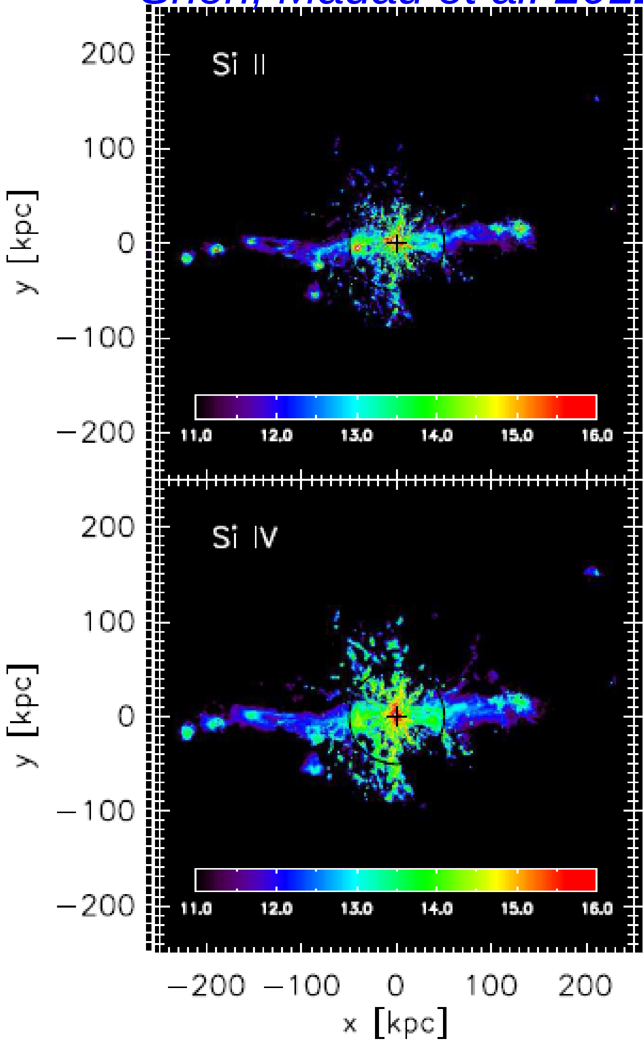
$$\dot{M}_{\rm out}(b) = 0.41 {\rm M}_\odot\,{\rm yr}^{-1}\,\frac{\mu}{1.5}\,\frac{\Omega_w}{2}\,\frac{N_H(b)}{10^{19}{\rm cm}^2}\,\frac{V_{\rm out}}{200{\rm km\,s}^{-1}}\,\frac{b}{25\ {\rm kpc}}$$

- Cons:
  - Rare!
  - Can probe anything else (disk, accretion)

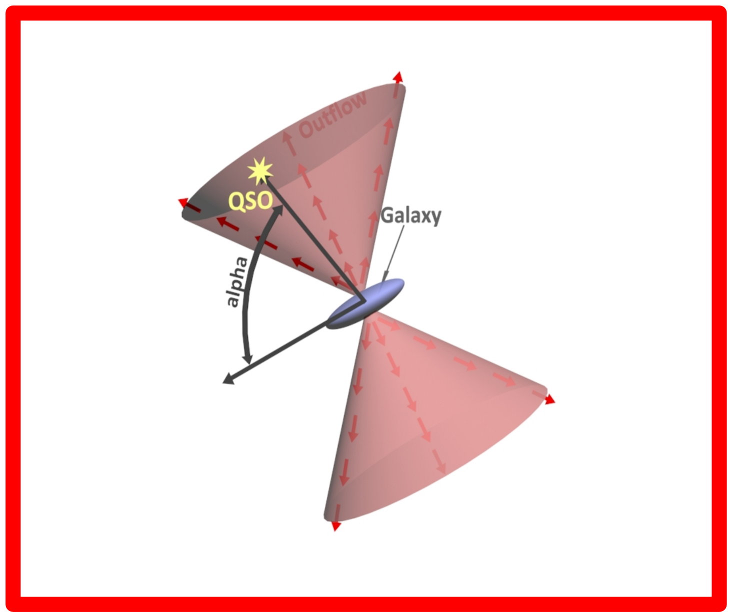
Both In- and Out-flows exist

Both can be studied with QSOs!

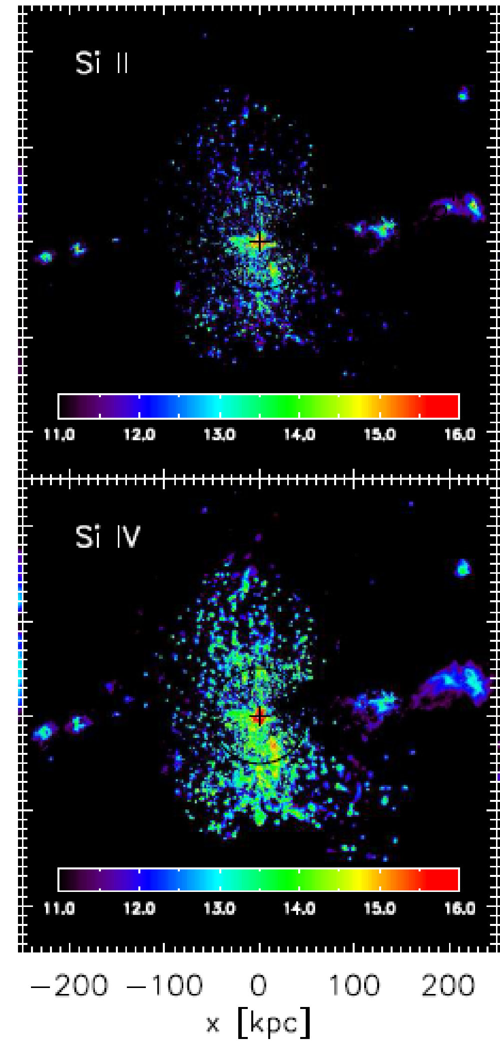
Shen, Madau et al. 2012



Inflowing particles



Credit: I. Schroetter



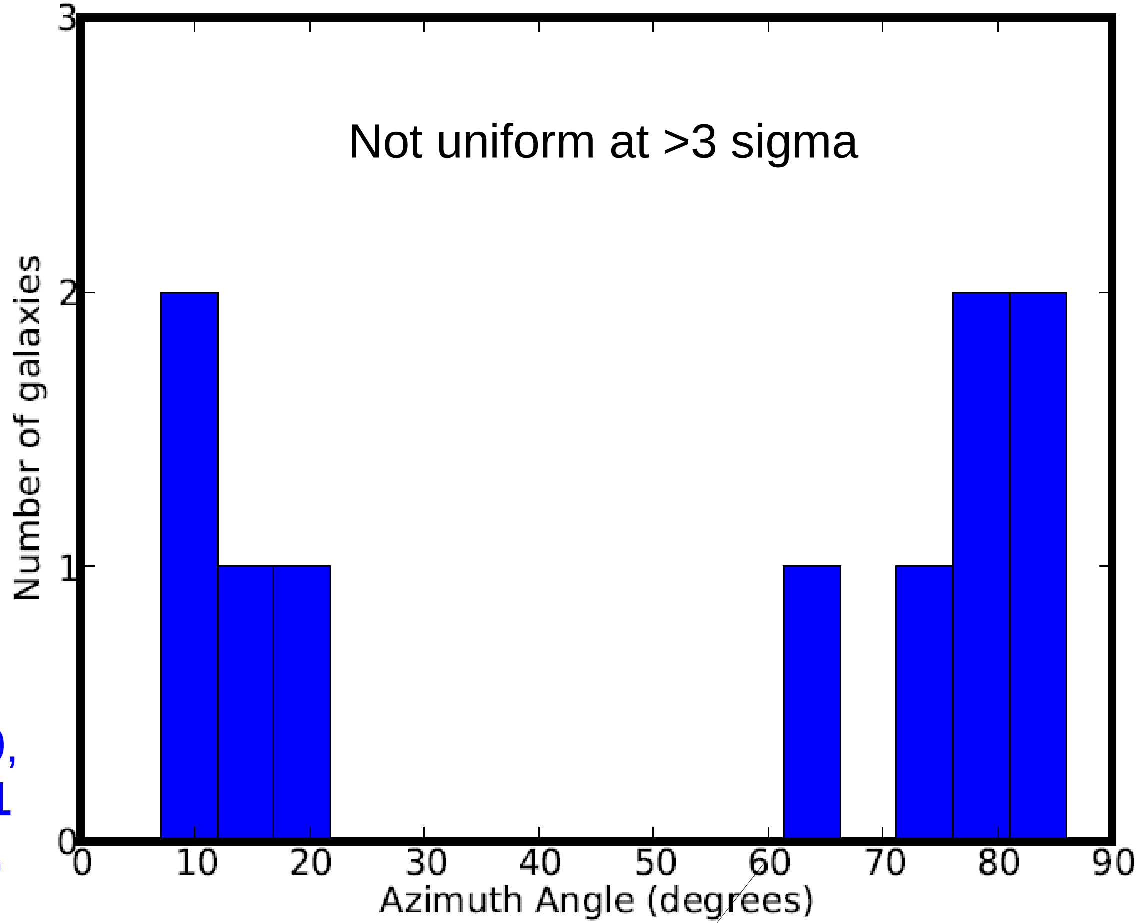
Outflowing particles

A) MgII around z~0.1 L* (SDSS)

<SFR> = 0.5 M/yr

Accretion?

Wind?



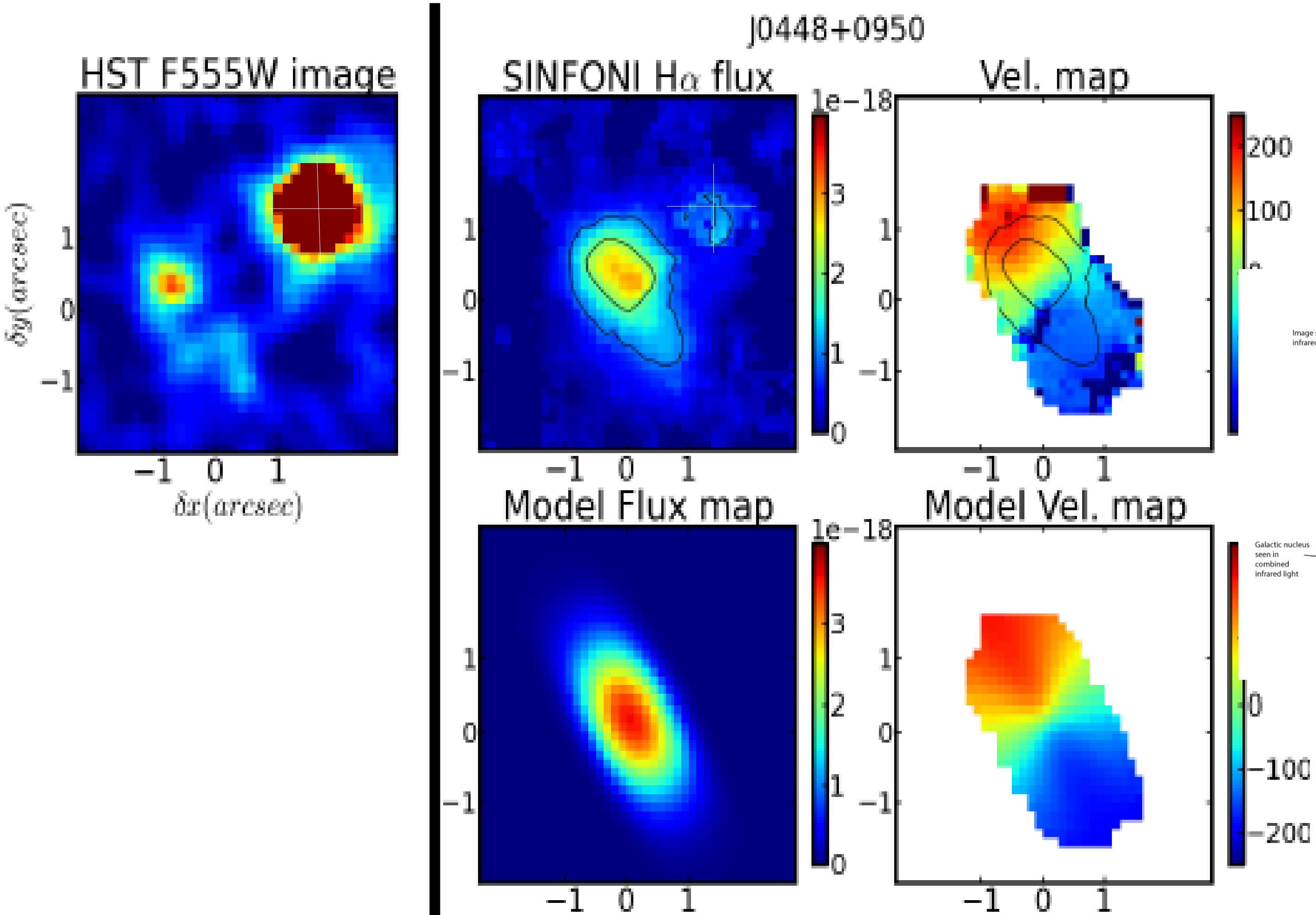
<SFR> = 2 M/yr

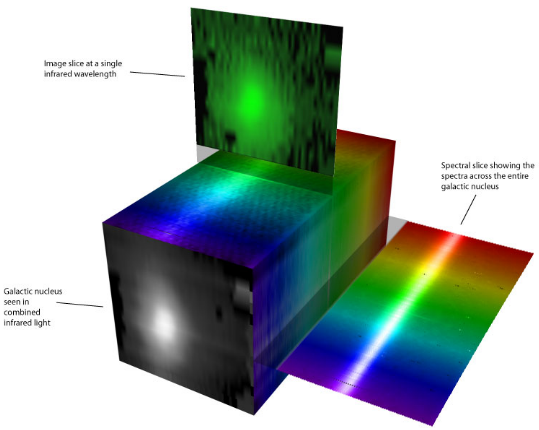
Chen Tremonti 2010,
Bordoloi et al. 2011
Bouché et al. 2012,
Rubin et al. 2013
Lan & Ménard 2014

$$\dot{M}_{\rm out}(b) = 0.41 {\rm M}_\odot\,{\rm yr}^{-1}\,\frac{\mu}{1.5}\,\frac{\Omega_w}{2}\,\frac{N_H(b)}{10^{19}{\rm cm}^2}\,\frac{V_{\rm out}}{200{\rm km\,s}^{-1}}\,\frac{b}{25\ {\rm kpc}}$$

3D fitting with GalPak^{3D}

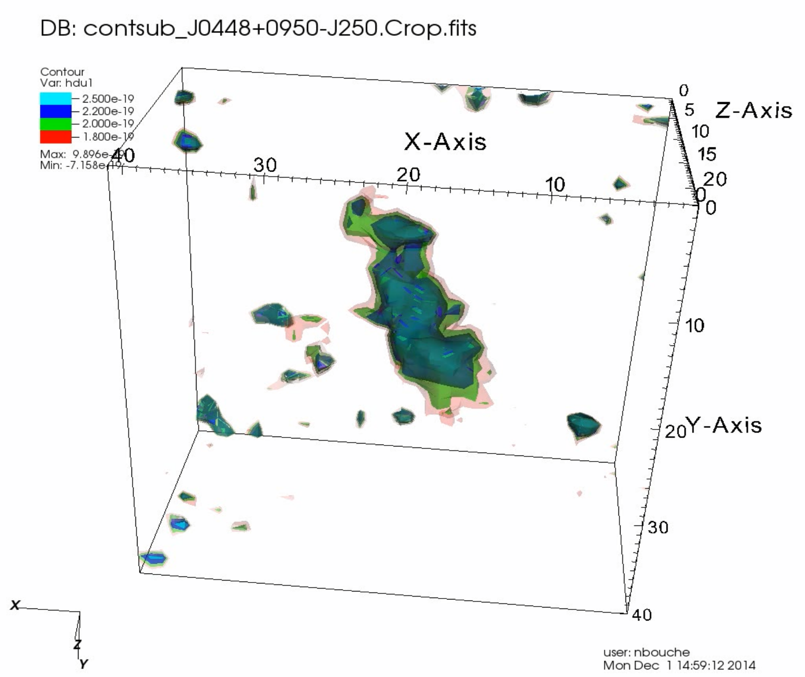
Bouché et al. 2015, 1501.06586

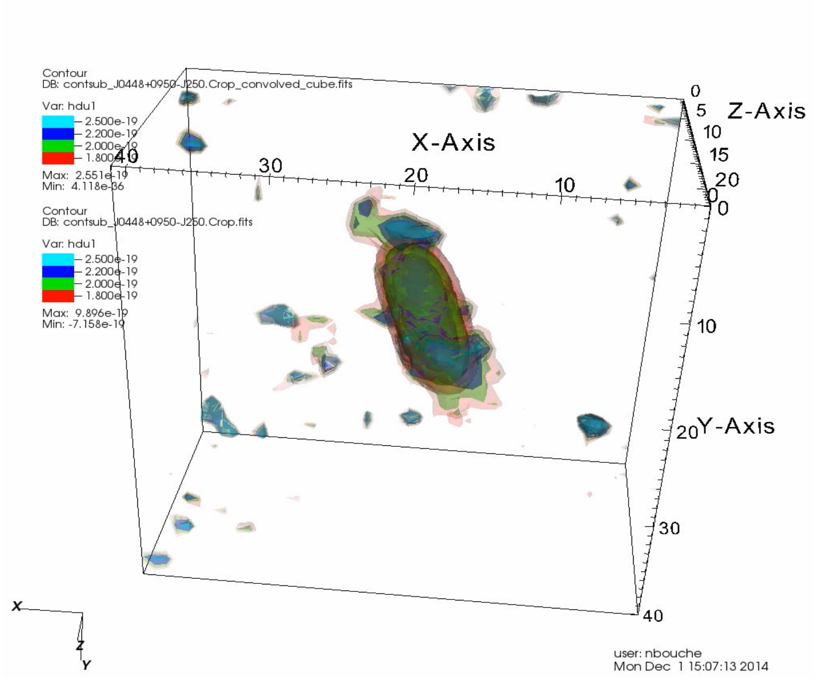




$$\dot{M}_{\rm out}(b) = 0.41 {\rm M_\odot\, yr^{-1}} \frac{\mu}{1.5} \frac{\Omega_w}{2} \frac{N_H(b)}{10^{19} {\rm cm^2}} \frac{V_{\rm out}}{200 {\rm km\, s^{-1}}} \frac{b}{25\ {\rm kpc}}$$

3D fitting with GalPak^{3D}

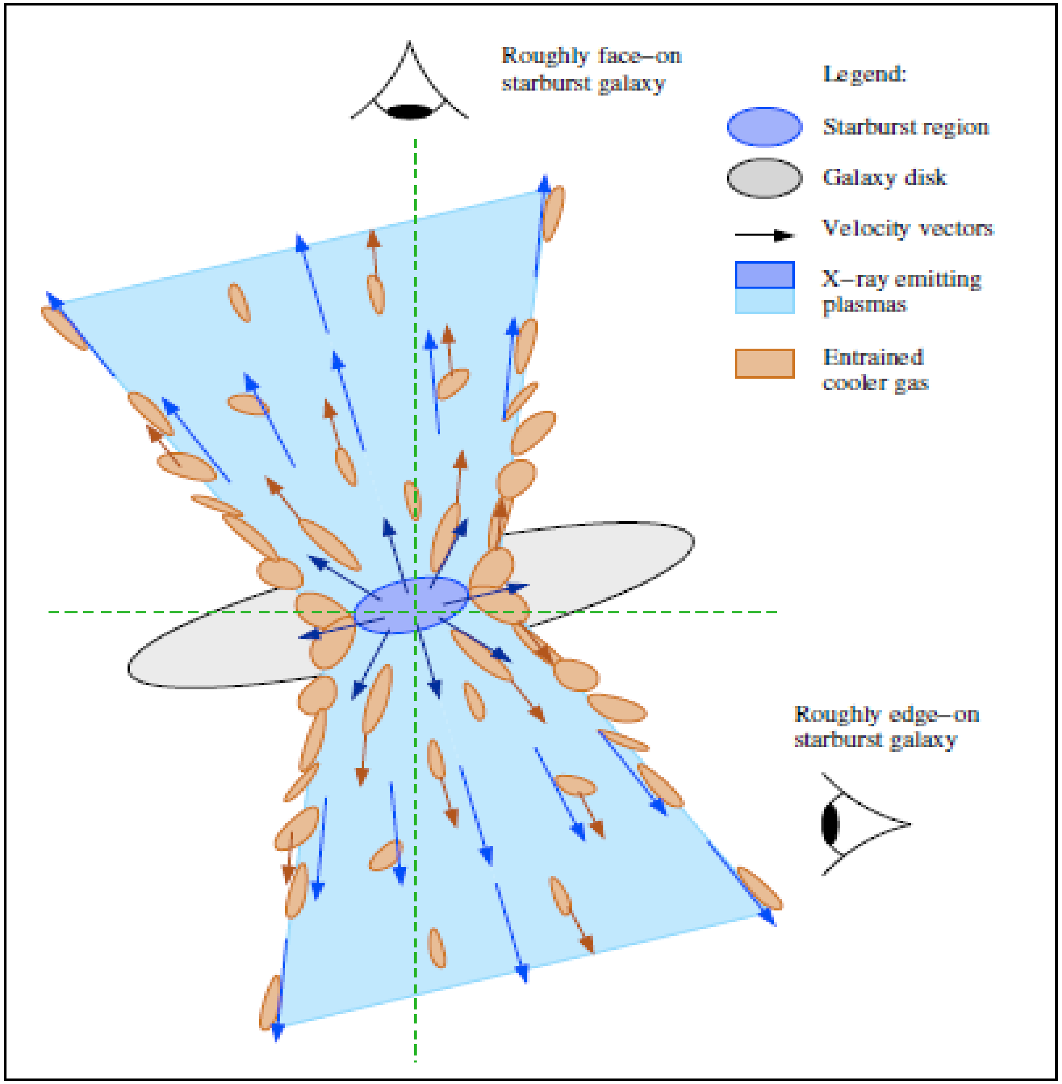




Wind modeling with 1 parameter

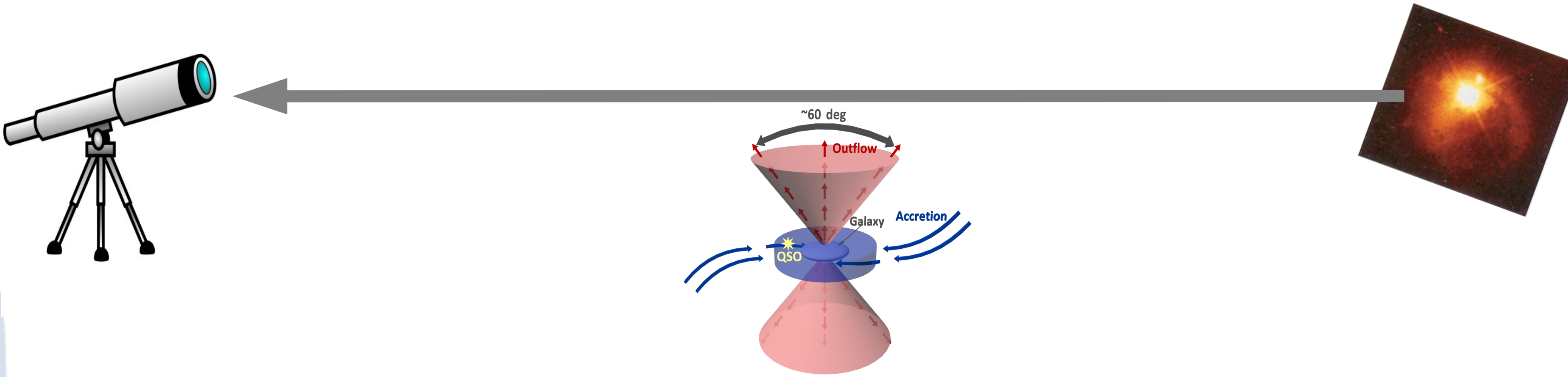
- Steady flow
- Mass conserved

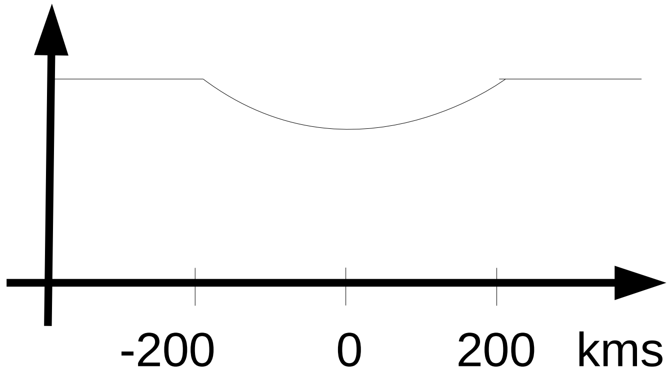
  → $\rho \sim 1/r^2$
- Vwind ~ Cst

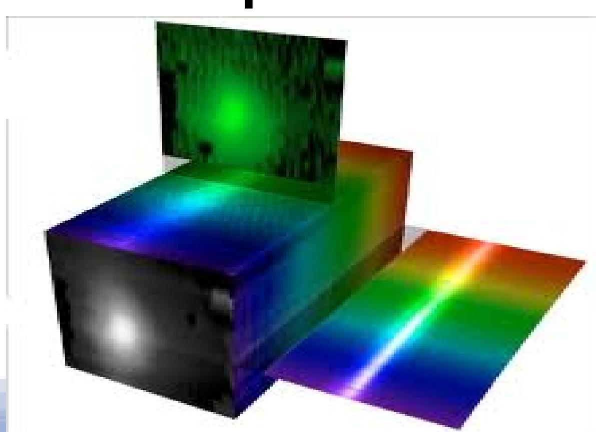


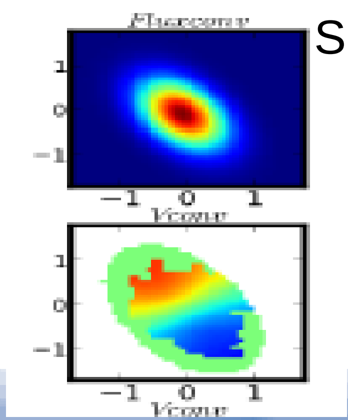
Strickland D.

Geometrical effects



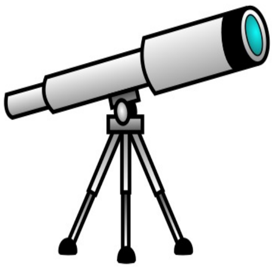


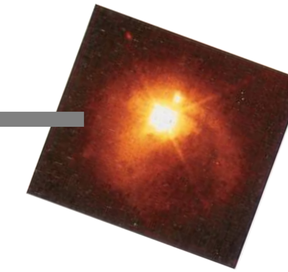


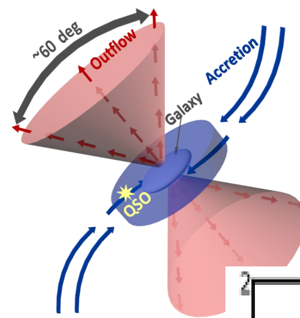


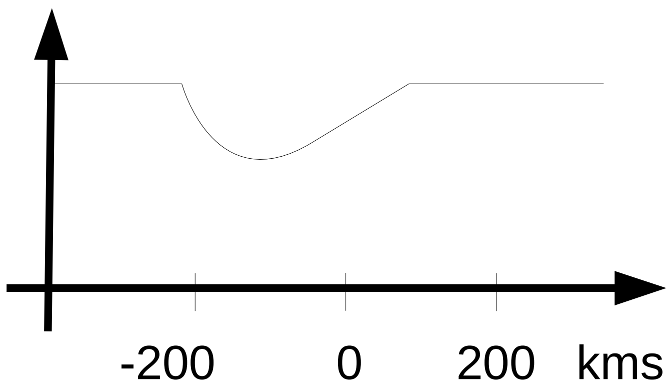
SINFONI

Geometrical effects!

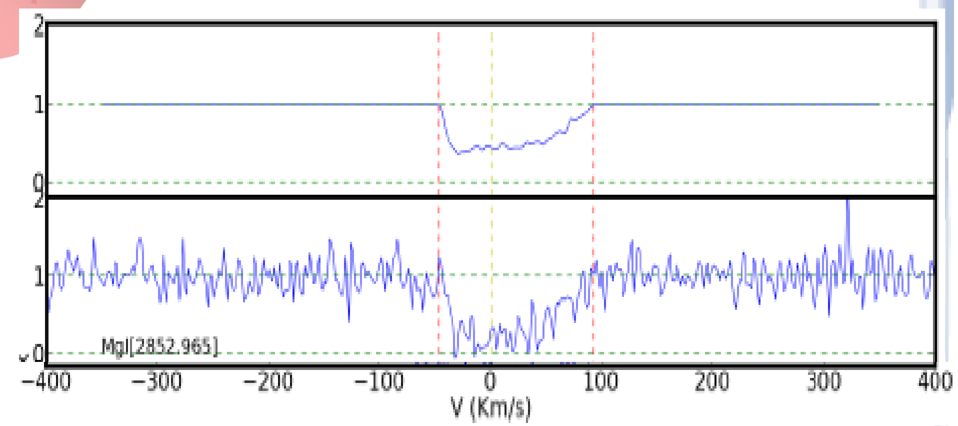


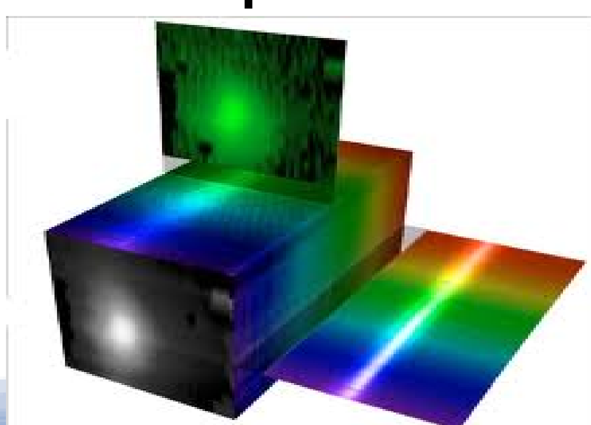






UVES VLT; MgI 2852; Schroetter et al.





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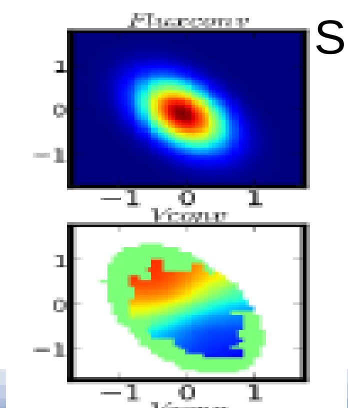
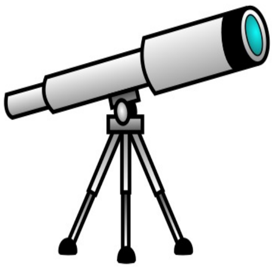
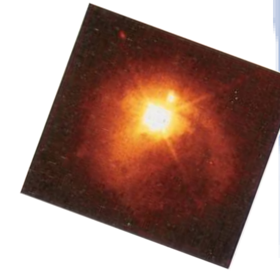
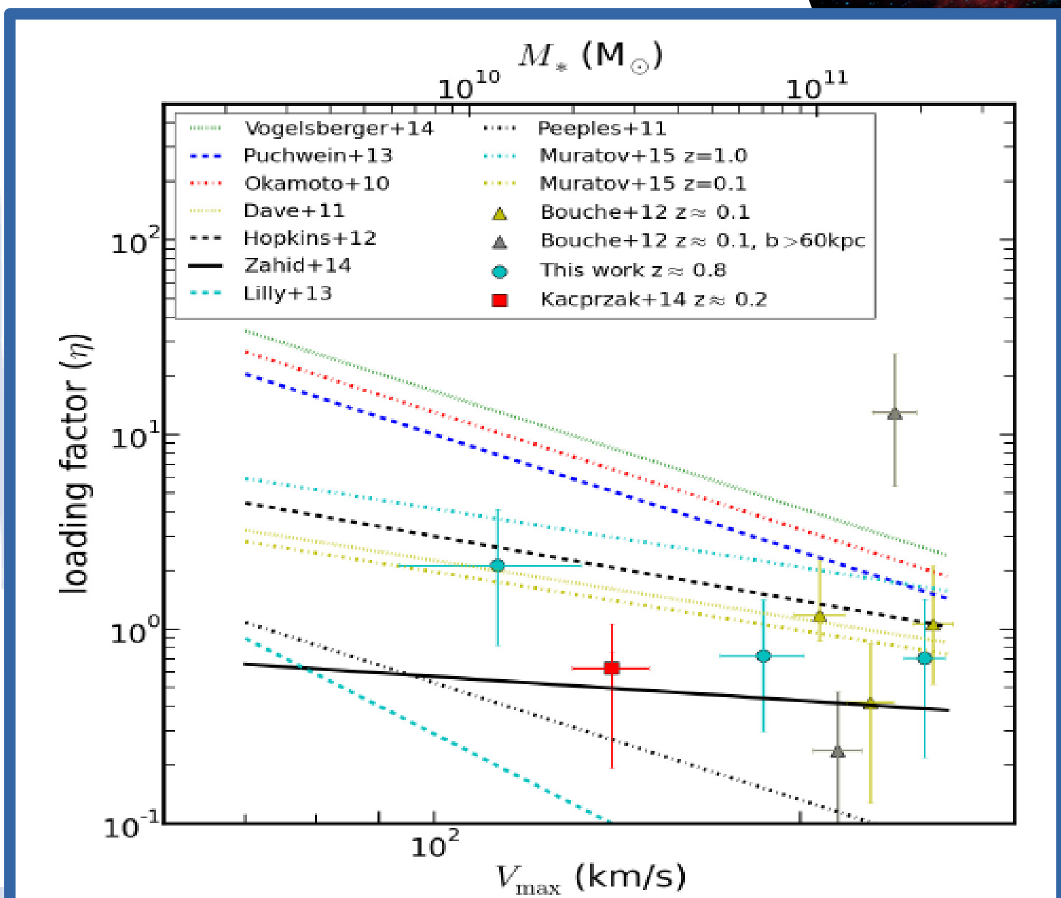


Winds properties from background QSOs

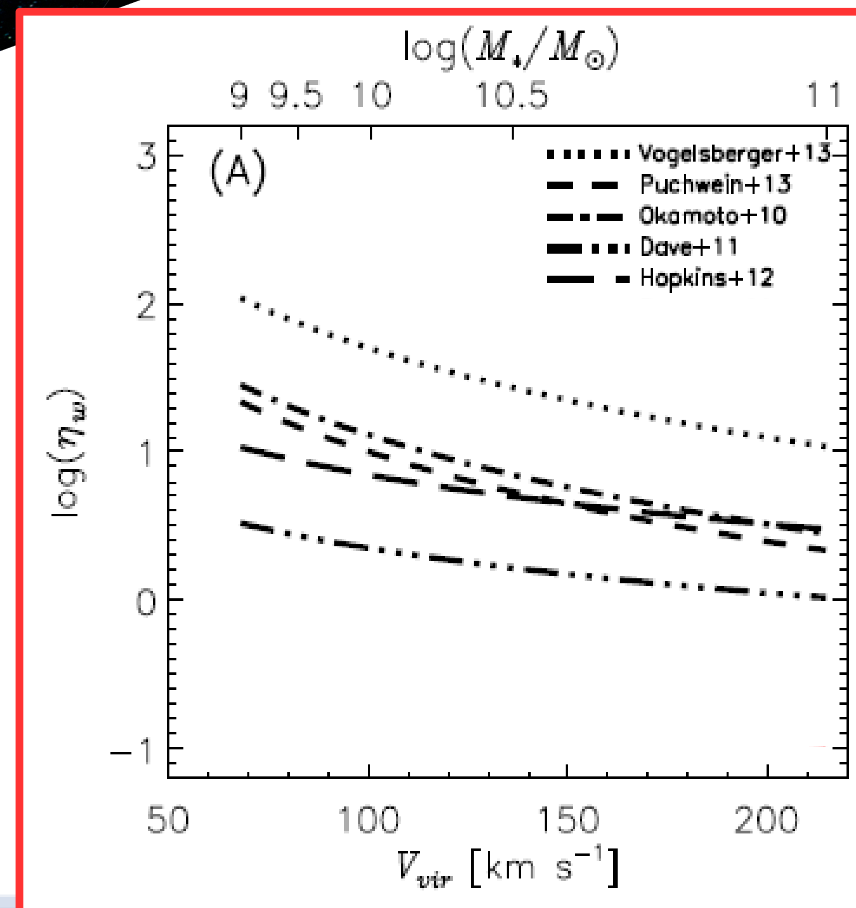




Schroetter et al.

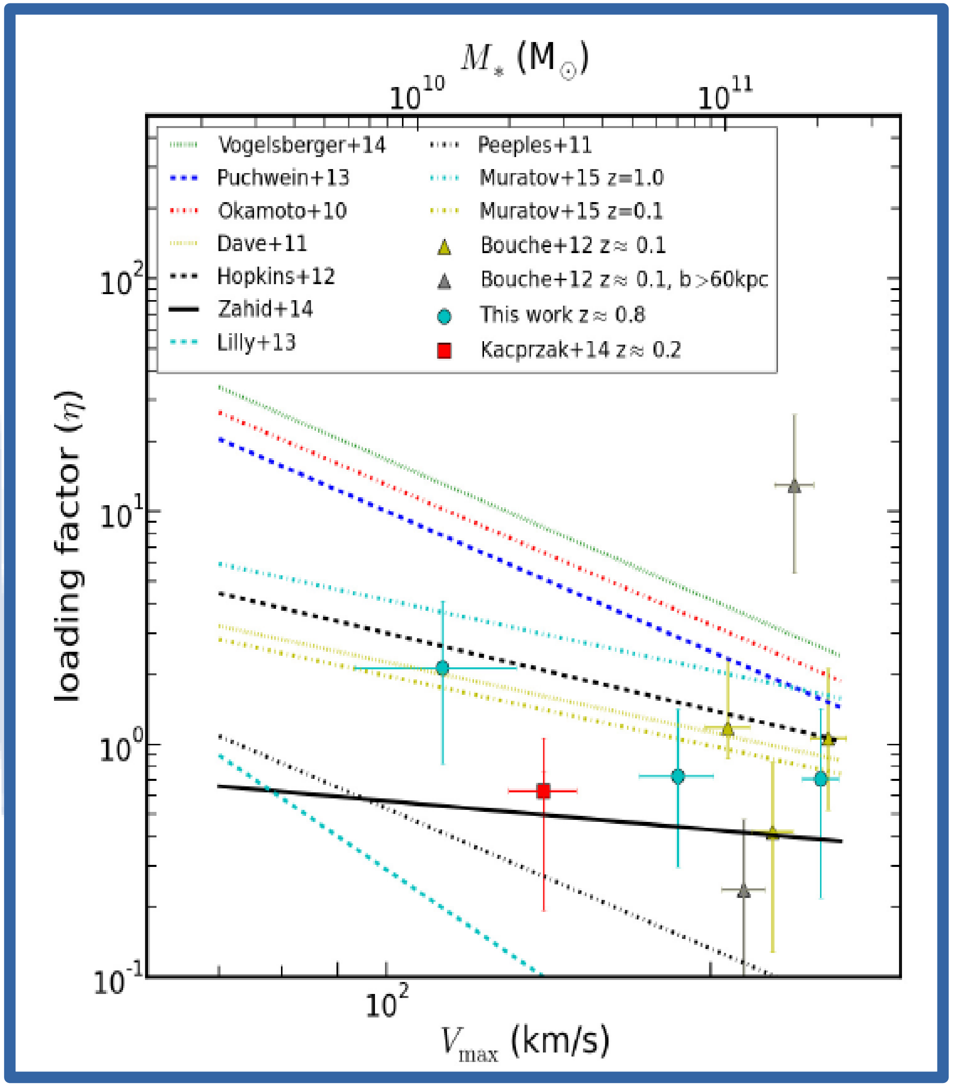


Zahid et al. 2013

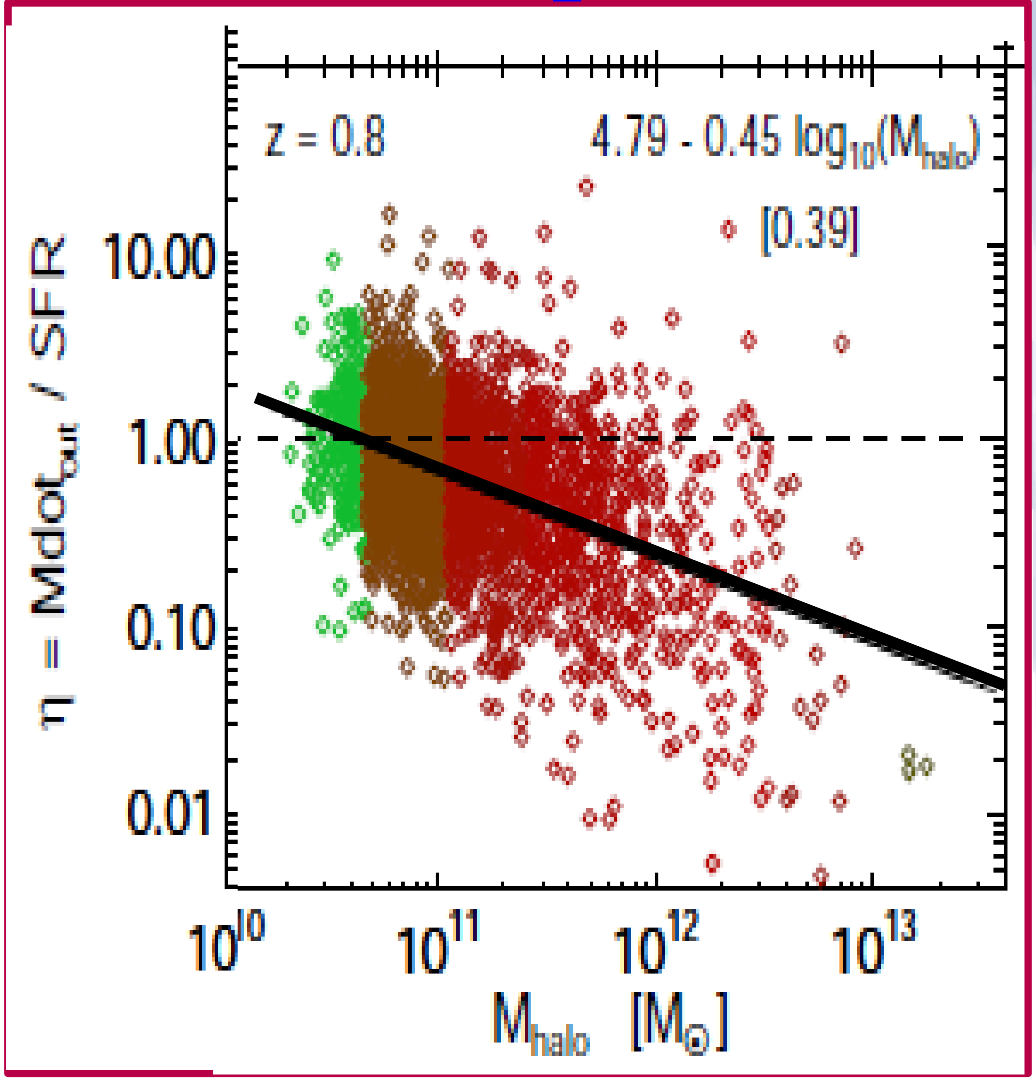


Observation vs. Simulations

Schroetter et al. 2015, z=0.8



Barai, P 2015 z=0.8, v>v_esc



Accretion using background QSO

“Detection of cool gas accretion near a z=2 star-forming galaxy”

Bouché et al. 2013

→ SFR ~ dM_{in}/dt ←

→ Accretion efficiency 30-50 %

→ see talk tomorrow

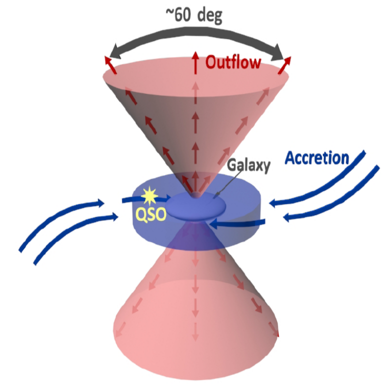
• <u>Kinematic arguments:</u>

Rubin et al. 2012 (inflow in gal. Spectra); Martin et al. 2012 (5% inflows in gal. Spectra); Giavalisco et al. 2011 (bkgrd galaxies)

• <u>Metallicity arguments:</u>

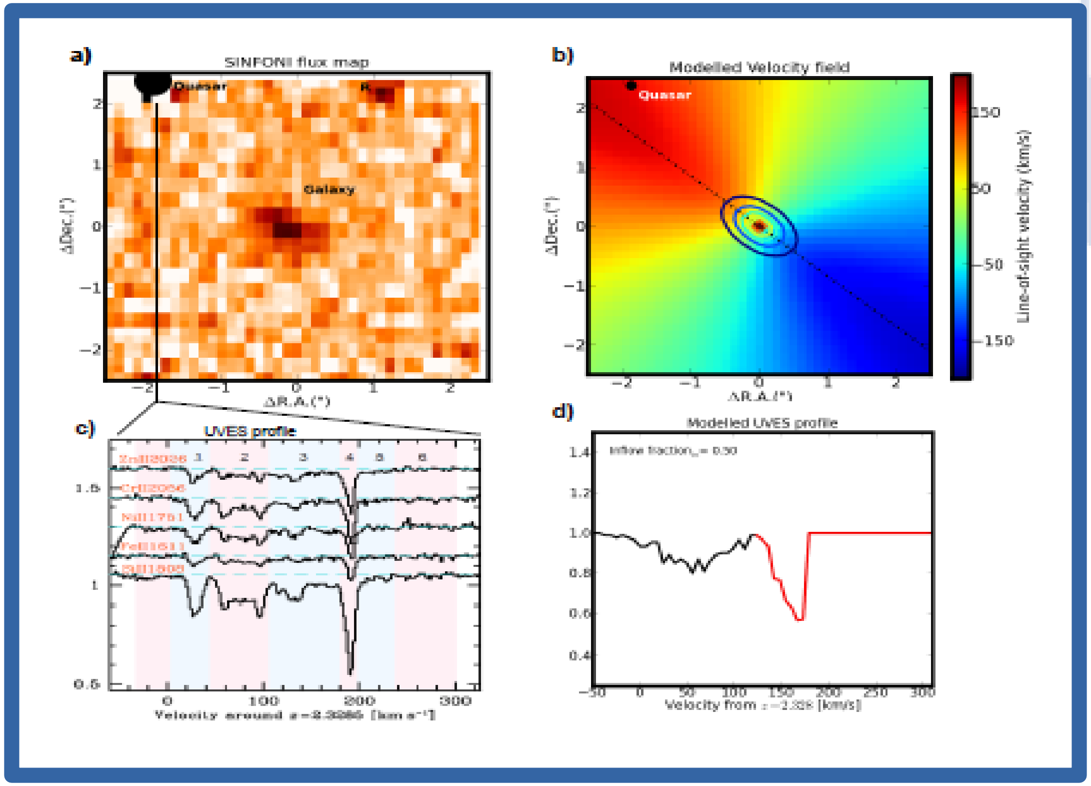
Ribaudo et al. 2011; Kacprzak G. 2012; Dave 2011, Yabe (2014)

Any Evidence for Accretion?



in Absorption

Bouché et al. 2013, Science

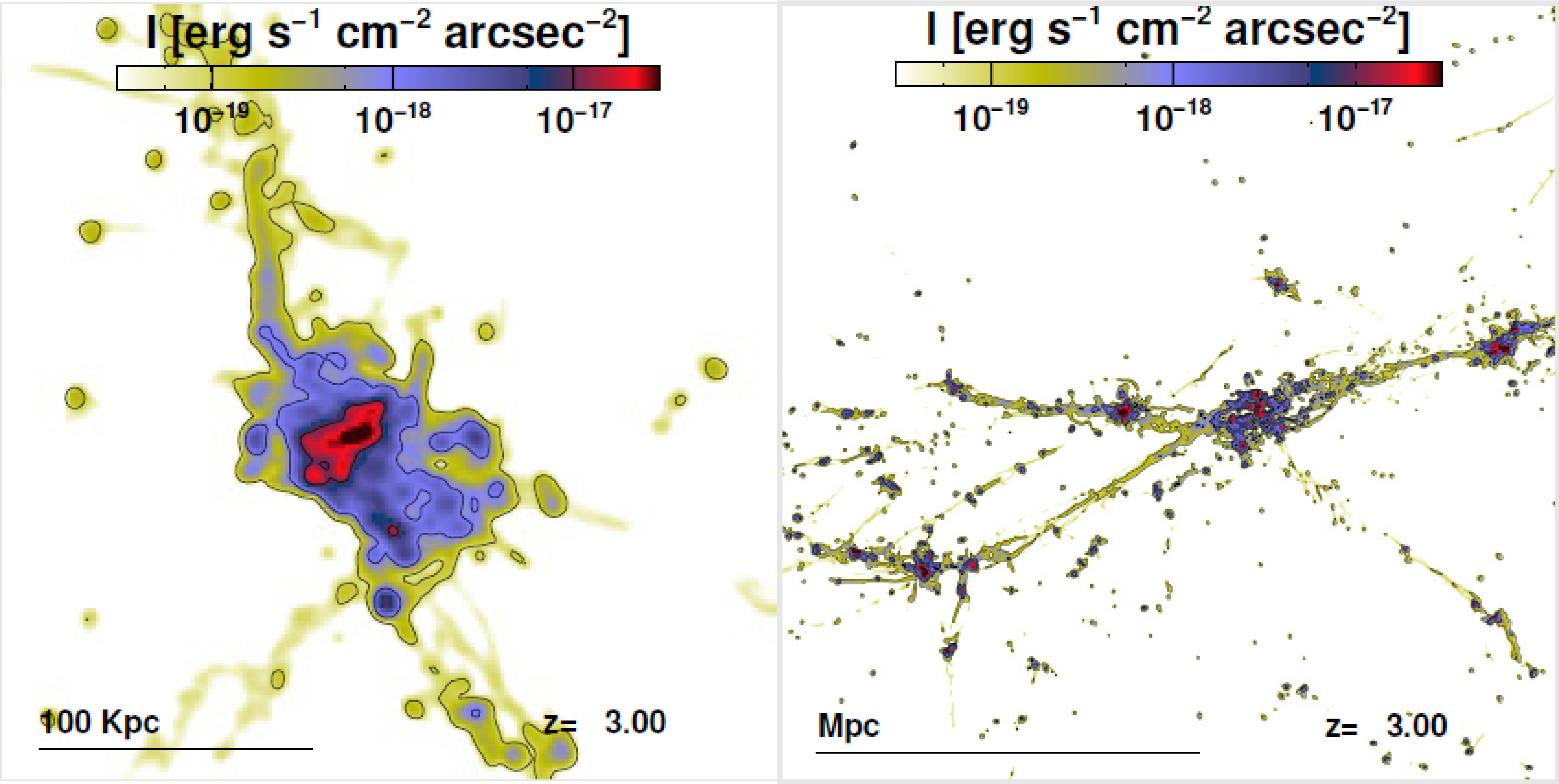


→ Vin, b, NH → **dM/dt ~ SFR !**

Any Evidence for Accretion?

in Emission?

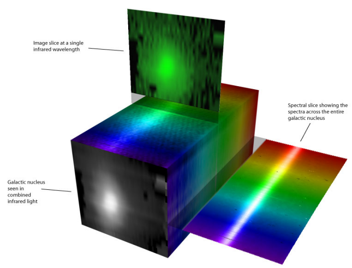
Mock MUSE observation (Ly-alpha)   Rosdhal & Blaizot 2012



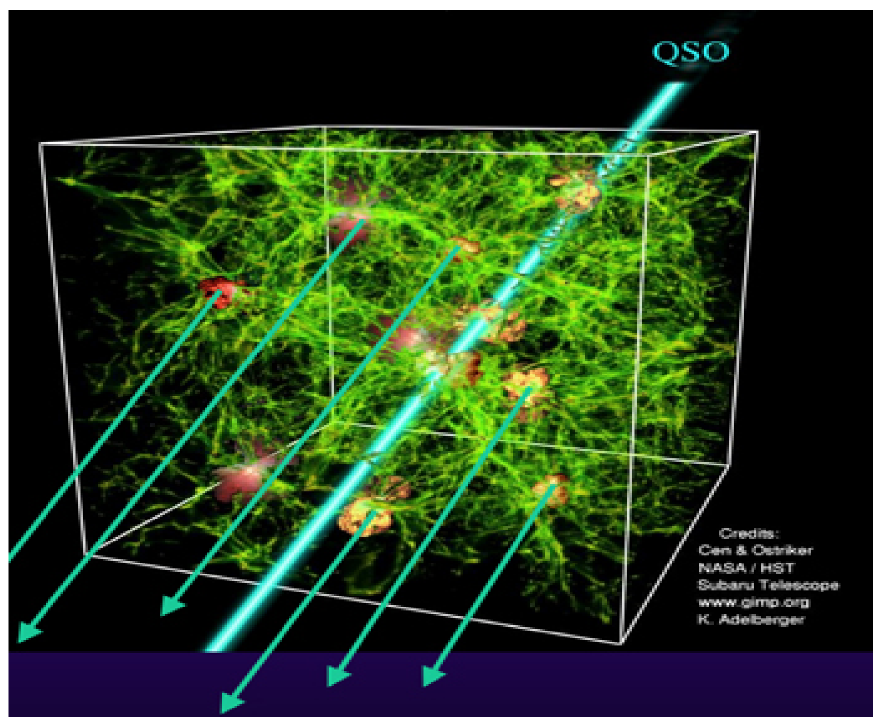
See also Faucher-Giguere 2011, Dijkstra et al. 2011, van de Voort et al. 2011

IFU revolution

8” FOV



60” FOV

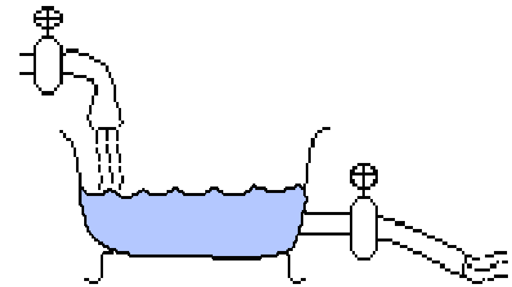


2014

MUSE

Conclusions

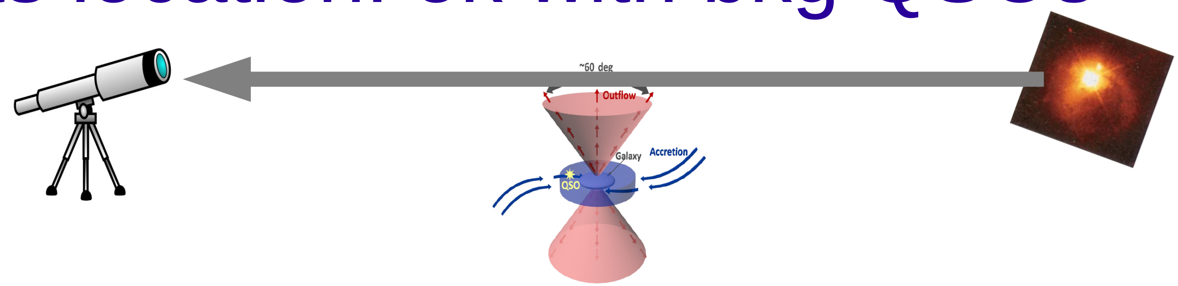
Galaxies are in *quasi*-equilibrium



- SFR follows accretion rate → Main-sequence
- Accretion drives galaxy growth, SFR(z), Mgas(z)
- Scaling relations ok with accretion floor

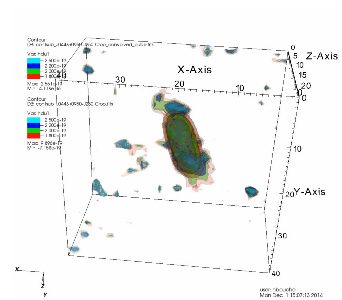
In/Outflows need gas location: ok with bkg QSOs

- Strong geometric effects!
- Inflow rate ~ SFR
- Outflow rate ~ SFR



Next tools available

- MUSE
- MANGA
- GalPak^{3D}



GalPaK
galaxy parameters and kinematics

A physical mechanism ?

- For SFR floor
  - H_2 formation *(Robertson; Krumholz & Dekel 2011)*
  - Existing stars 'Extended' KS law (Shi, Helou 2011)
  - SN outflows (Dekel & Silk 1986)
- For Accretion floor
  - UV heating / Re-heating *(Mo 2005; Cantaneo 2011)*
  - Cooling threshold (Cantalupo 2010)
  - Globular Clusters (Shaerer 2011, Ricotti 2002)

Cooling Curve !

Cantalupo 2010