The self-regulation of star-forming galaxies

Nicolas Bouché

Observations:
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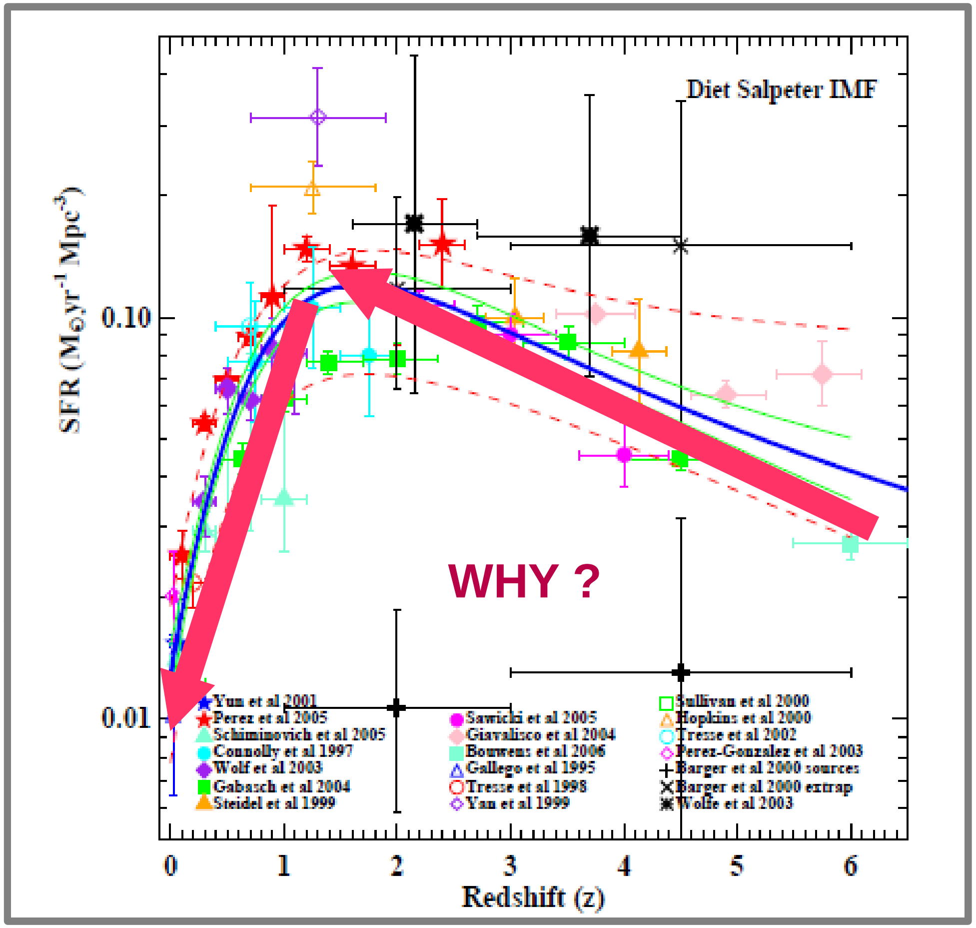
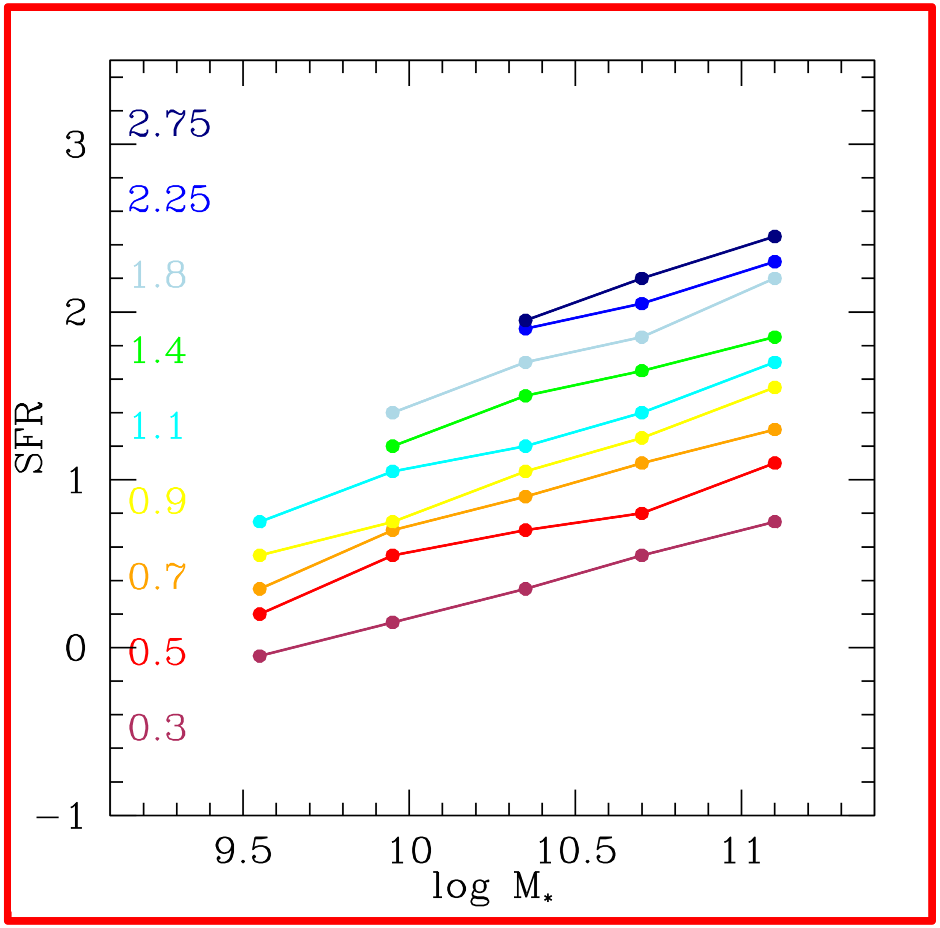
T. Contini (IRAP)
+ I. Schroetter (Ph.D.)
Theory:
A. Blanchard (IRAP)

What regulates Star-formation?

Lilly 1997, Madau 1997, Fardal & Katz 2007, Hopkins Beacom 2008, Bouwens et al. 2009

Main sequence SFR_M*
Karim et al. 2010, 10^5 galaxies Cosmos





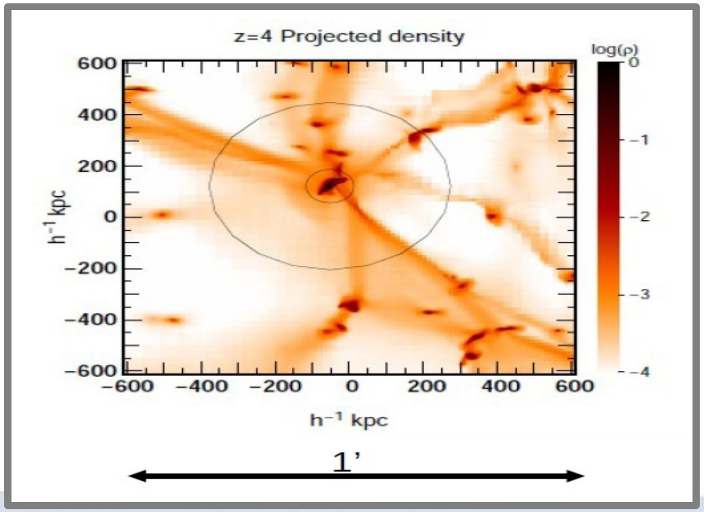
Outflows ? Accretion ? Mergers ?

Open Questions?

Inflows

- How does gas get in?
- Streams?
- How much dM_{in}/dt ?

Ocvrick 2008



Outflows

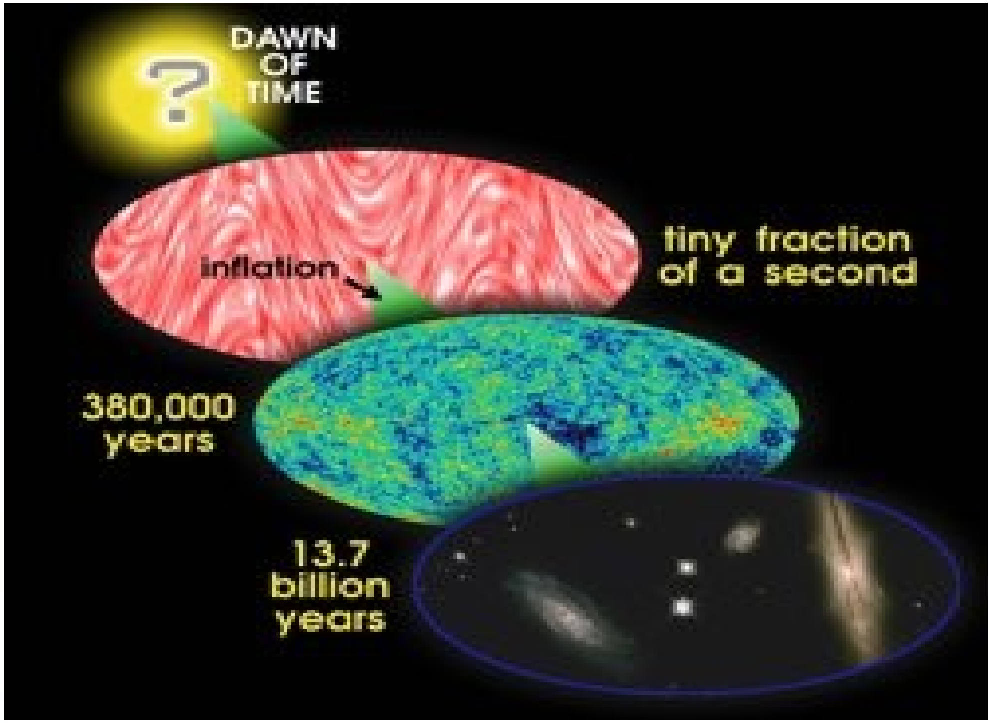
- Do winds escape ?
- How far do they go?
- How much mass loading?

= dM/dt / SFR

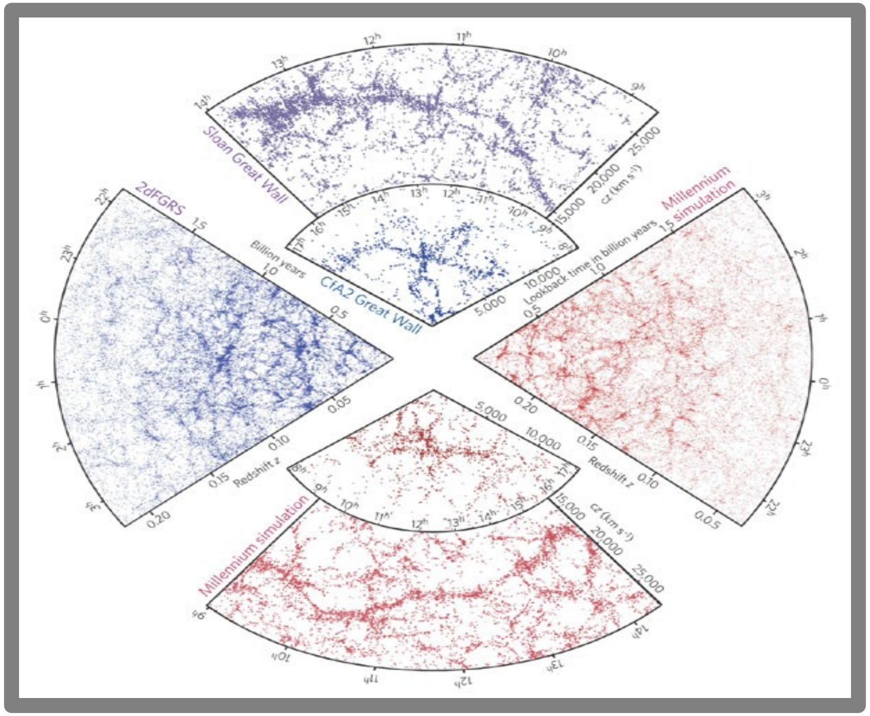
Ha + HST

PAH Spitzer

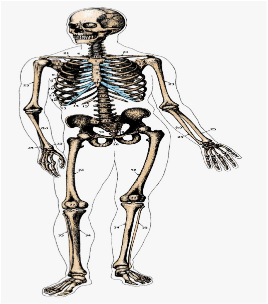
Cosmological success



T=13,000,000 yr



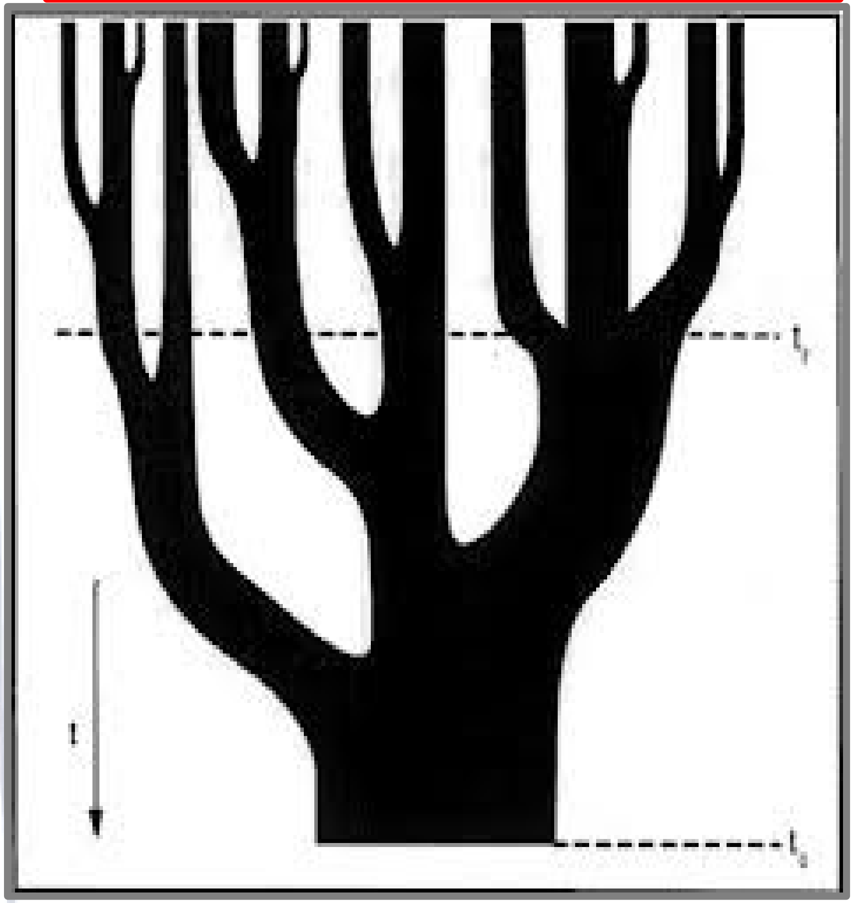
Springel et al. 2006
cf. Efstathiou et al. 1985

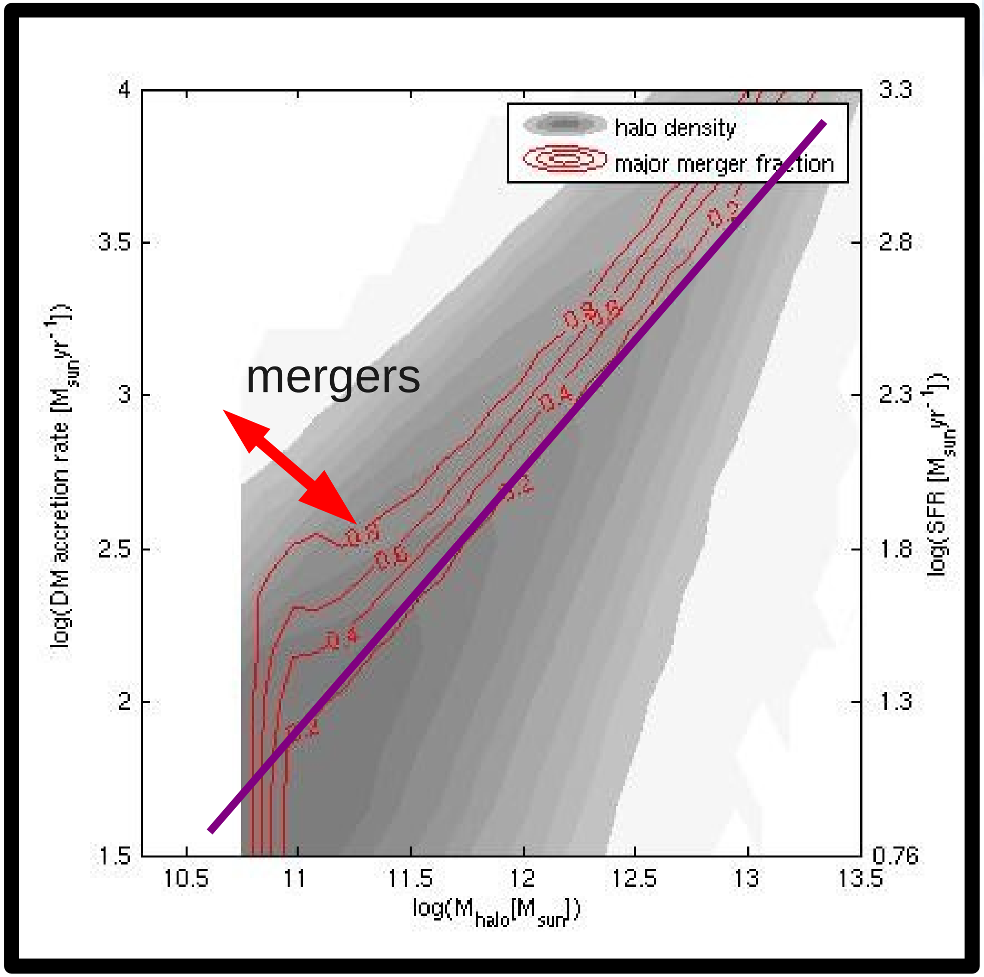


Halo growth

Genel et al. 2008, 2010

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

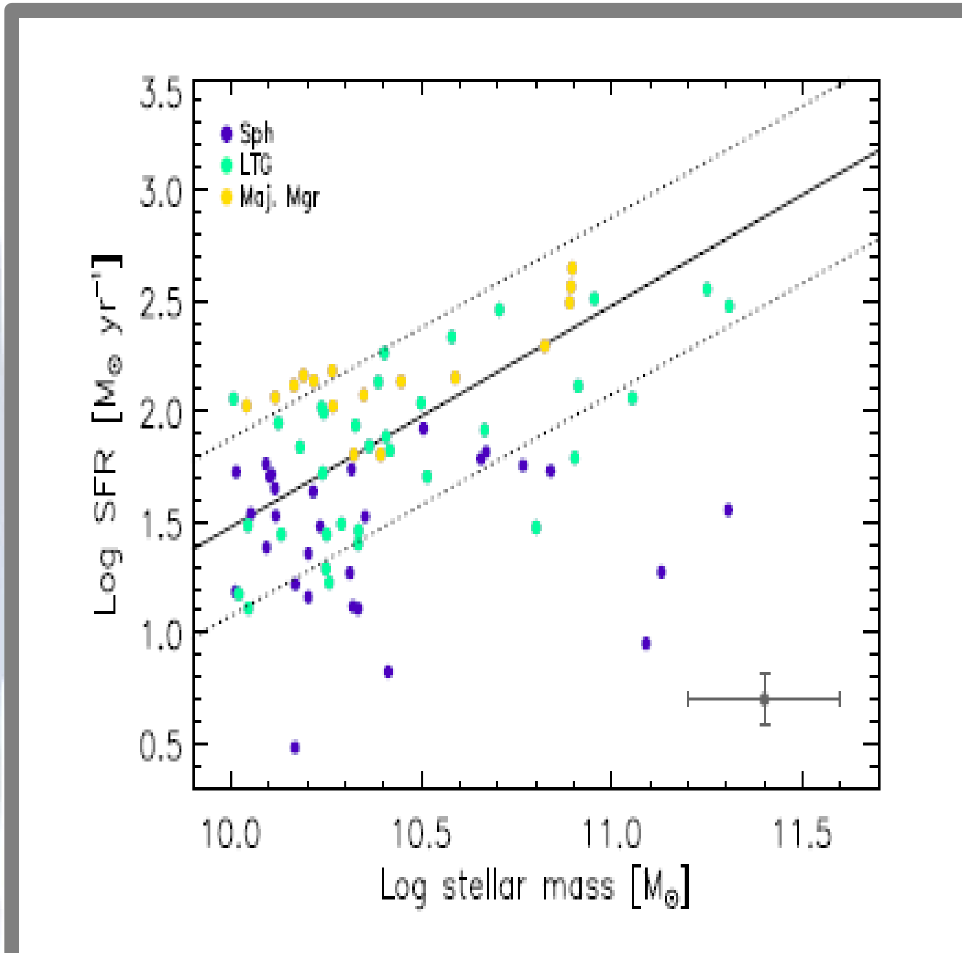




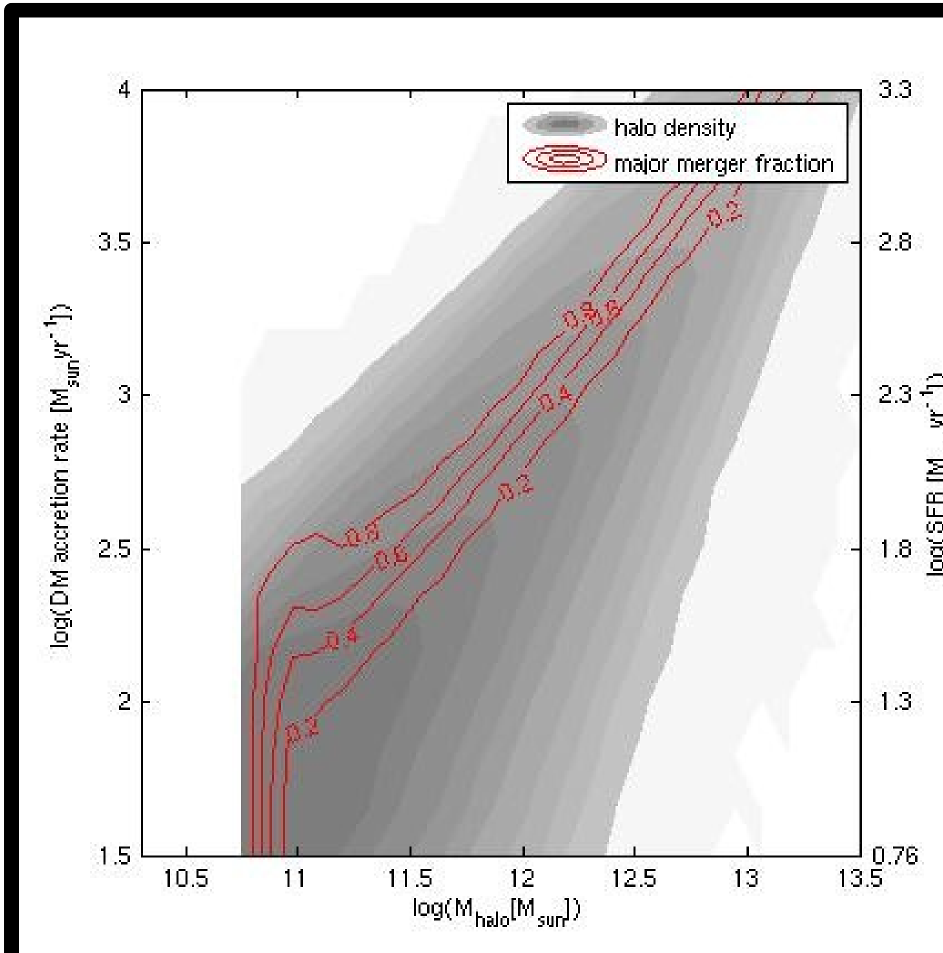
\\ 40% smooth DM accretion //

The main Sequence at z=2

Kaviraj, Cohen et al. 2012



Genel et al. 2008



→ DM growth drives galaxy growth

Bouché et al. 2010

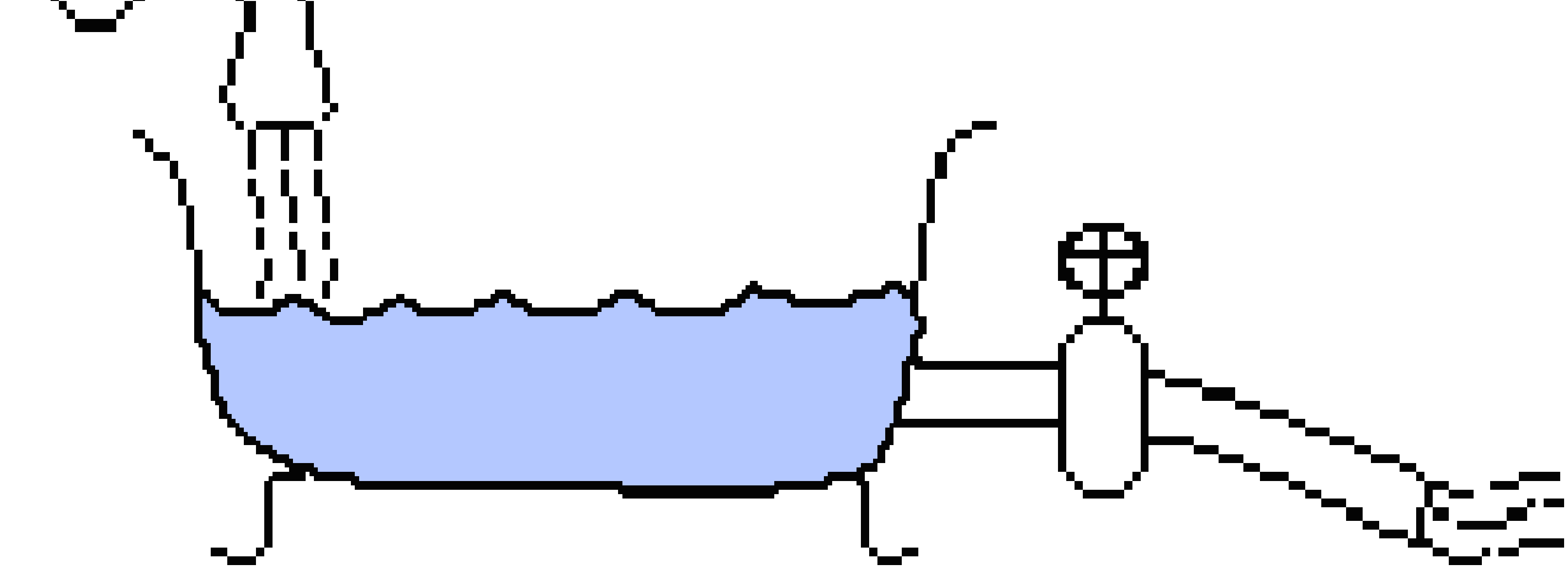
Let's build a toy model

Set by cosmology

Outflows

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

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



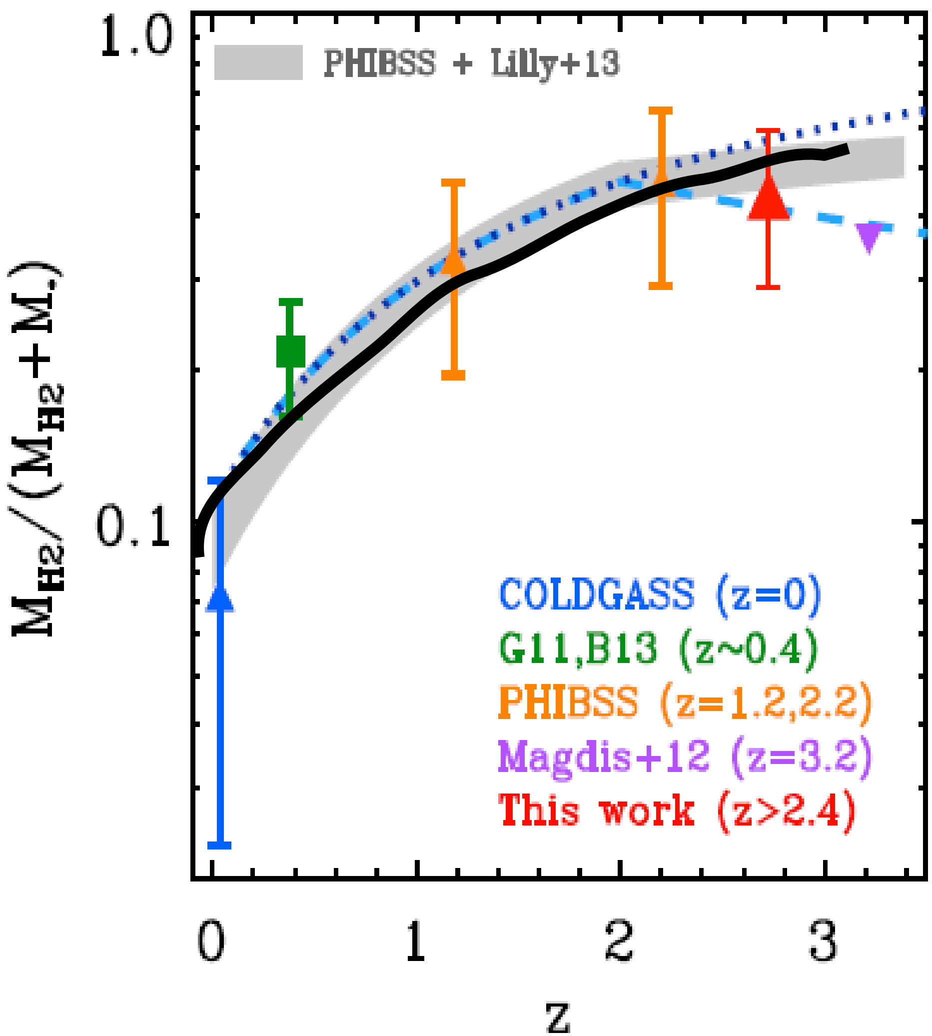
See also Cattaneo et al. 2010, Neistein, Weinmann 2010, Lu Mo et al. 2013
Krumholz & Dekel 2011, Khochfar & Silk, Reddy et al. 2012,...
Lilly et al. 2013; Peng & Maiolino 2014; Dekel et al. 2014

Toy model: Steady State

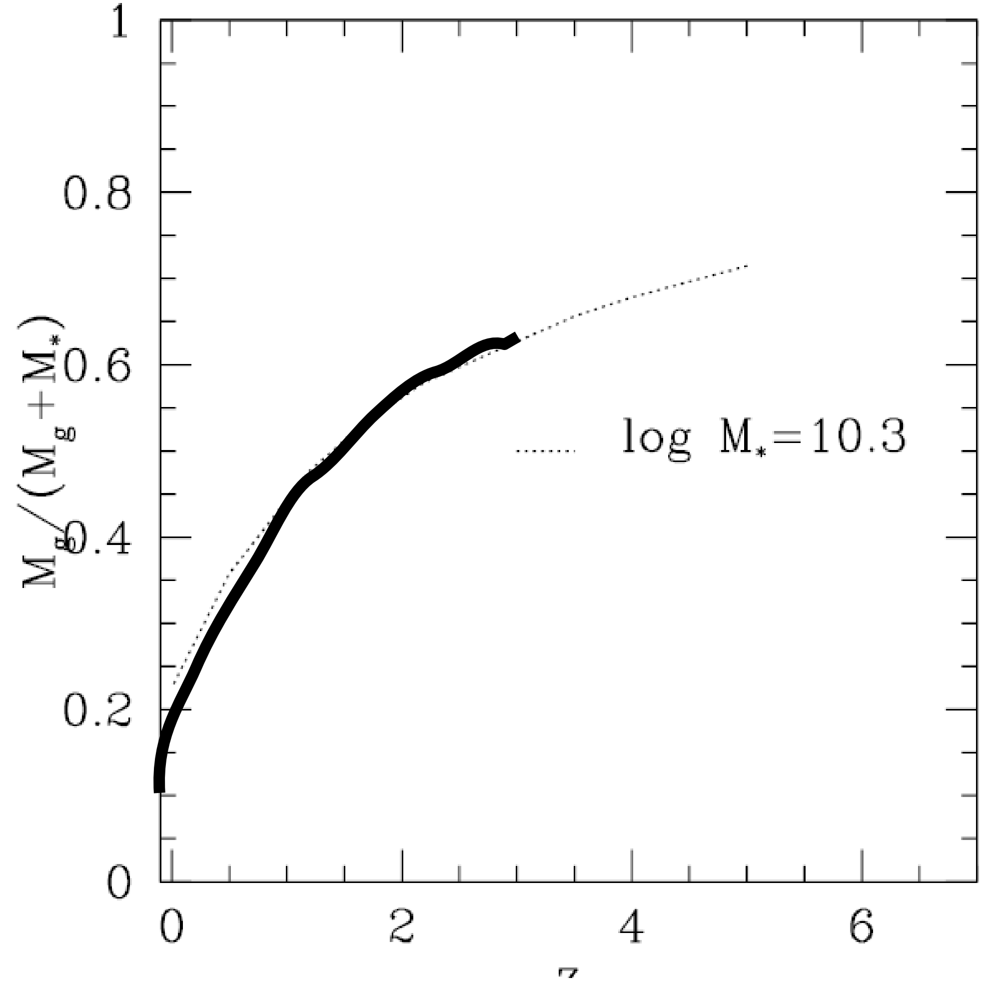
➔ **Reach a quasi-steady state:**

➔ **SFR (& Mgas) follows accr. Rate**

Gas fractions

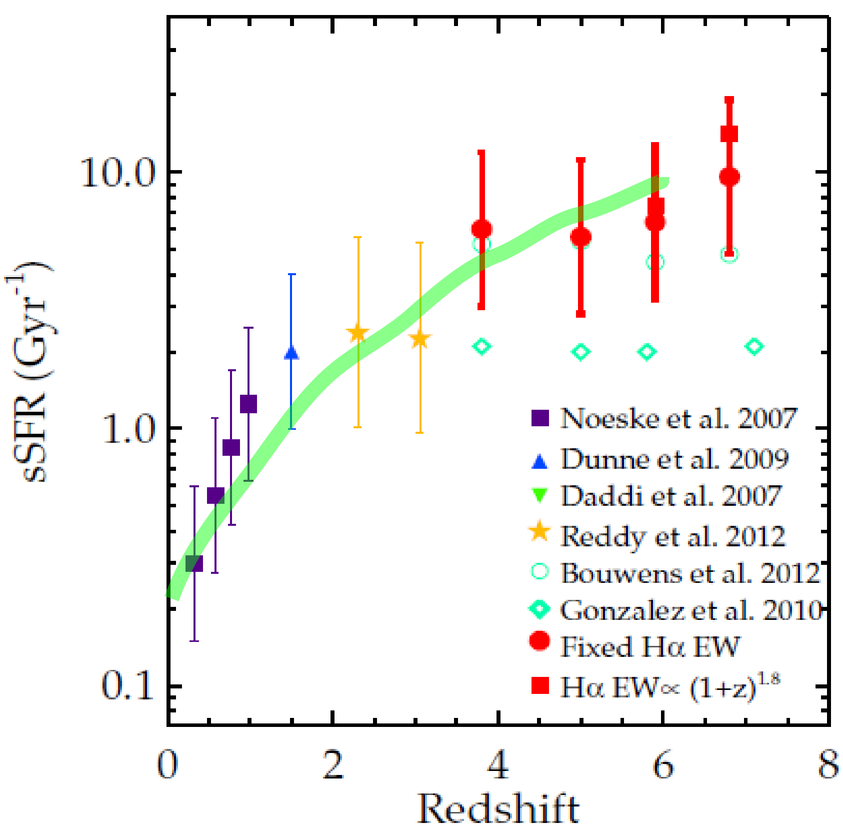


Saintonge A. 2013

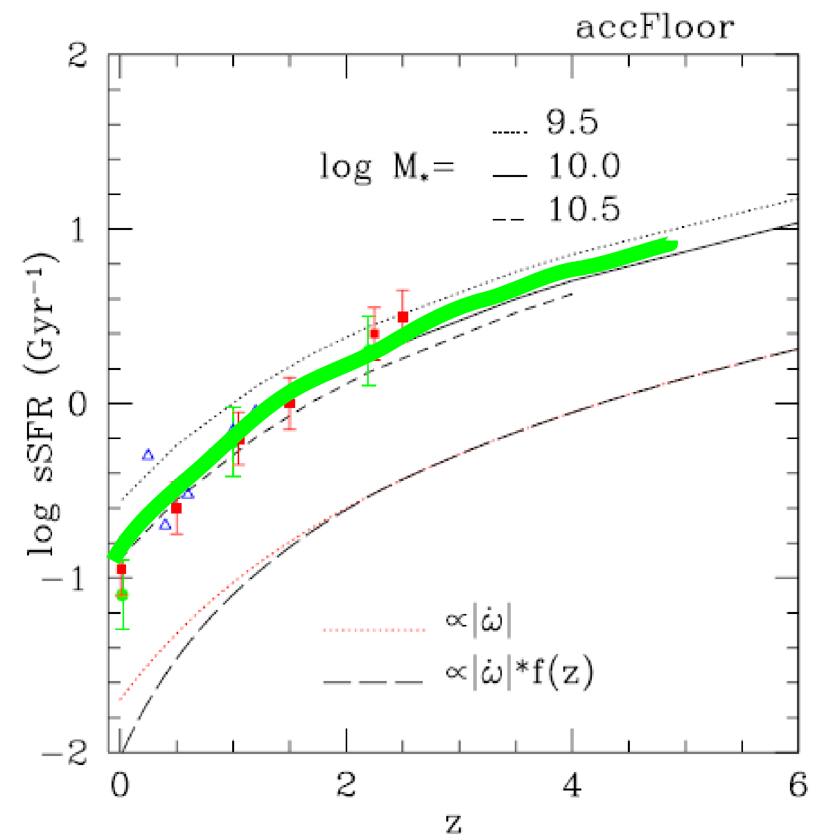


Bouché et al. 2010

No Problem with evolution IF



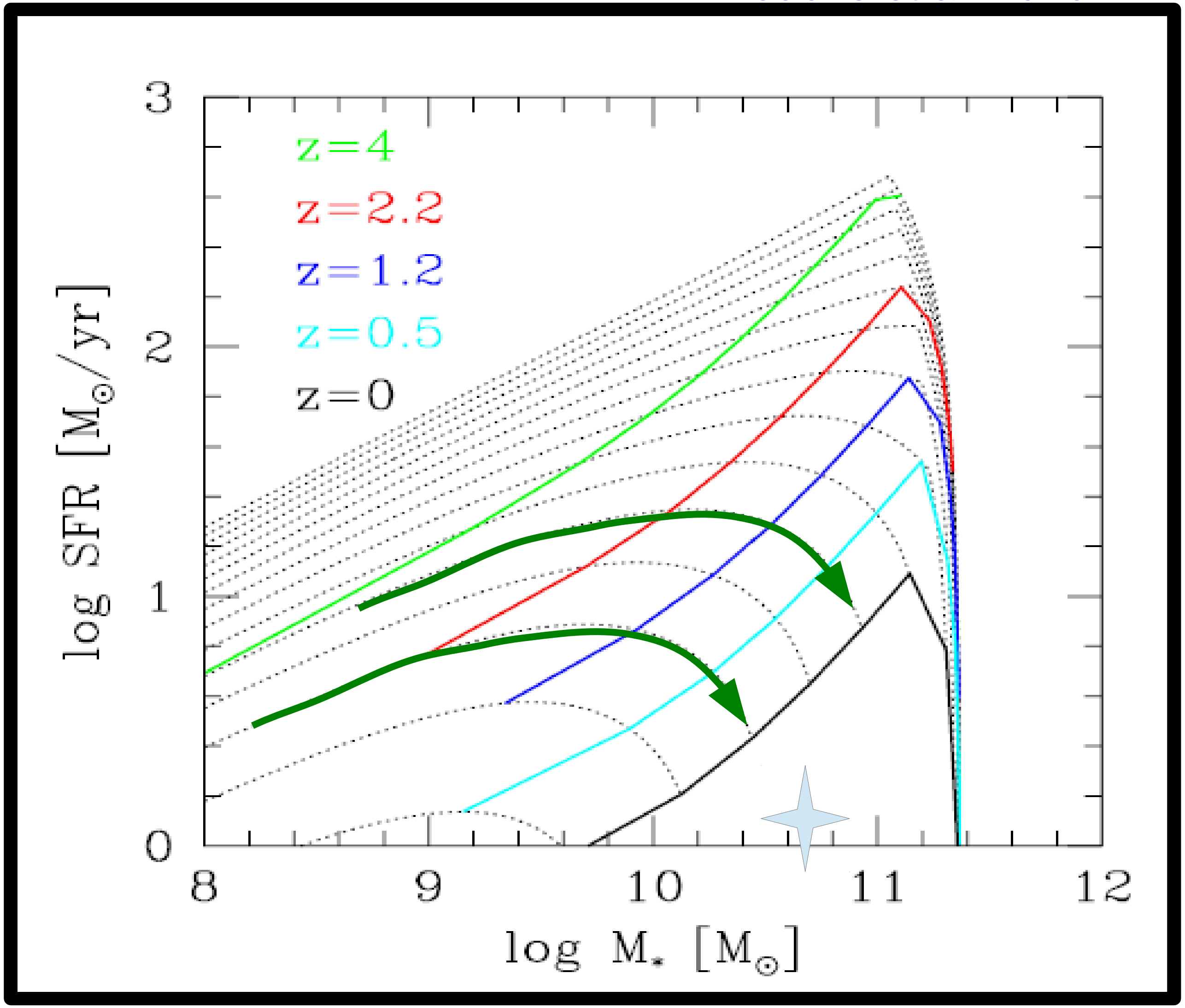
Stark et al. 2013



Bouché et al. 2010

The M*-SFR defines isochrones

Bouché et al. 2010



Explains fundamental M-Z relation (Bothwell et al. 2013)

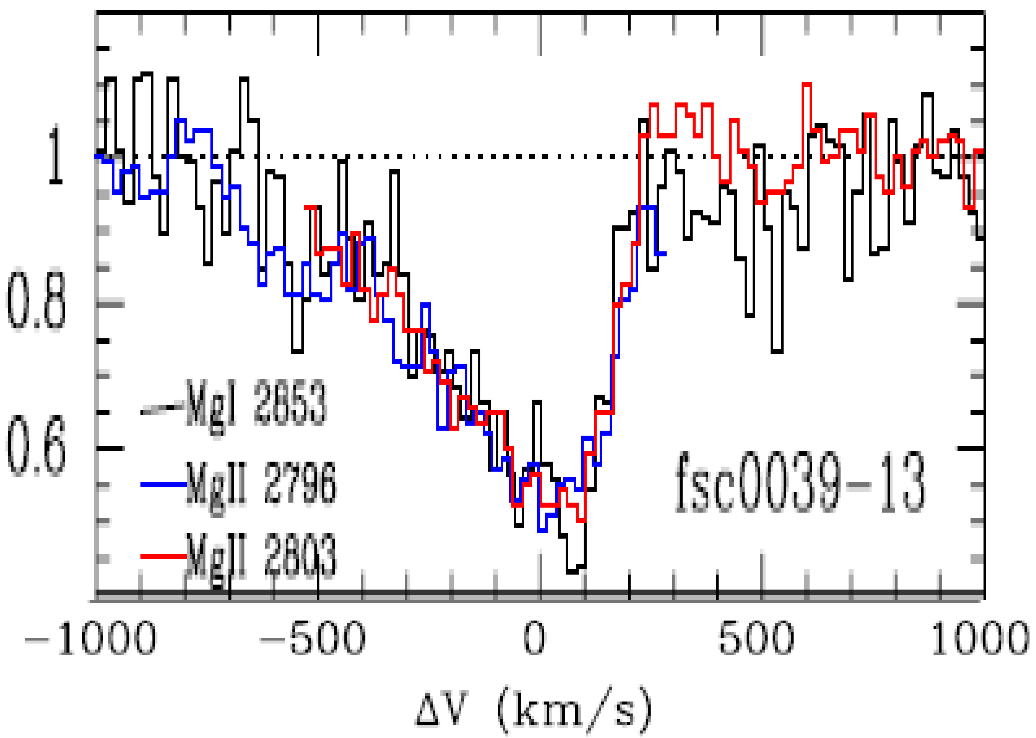
Conclusion:
Galaxies are in *quasi*-equilibrium

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

- **Open questions in sub-L***
  - Direct evidence for accretion ?
  - Wind loading ?

Next-gen IFU

Feedback from galaxy spectra
dM/dt unconstrained



?

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

Gas flows using background QSO

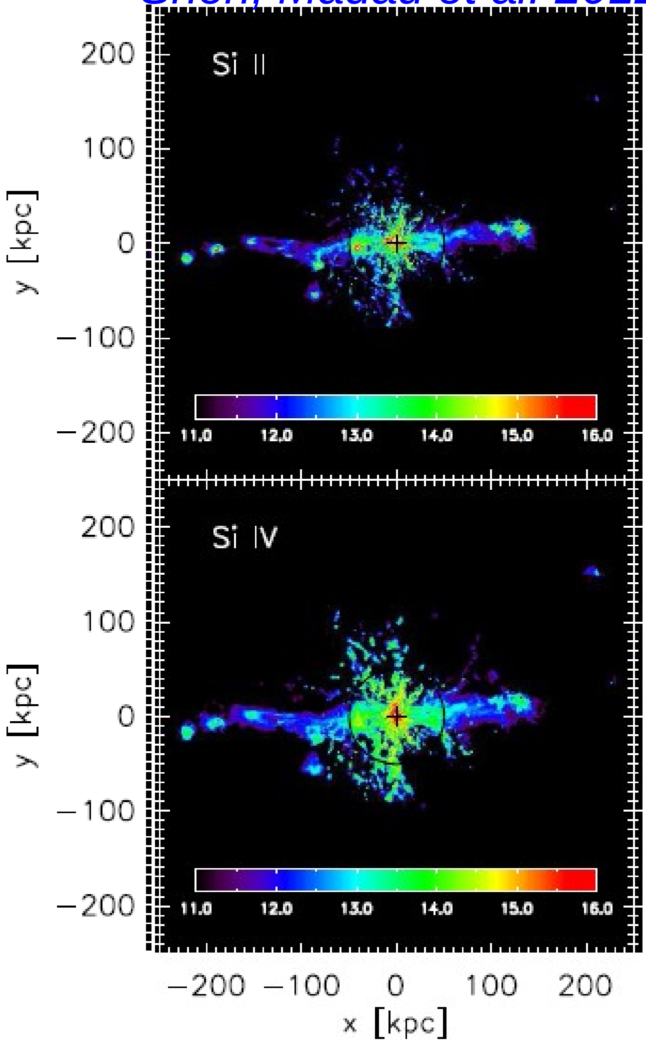
- Pros
  - Radial information (key!)
  - Can probe wind around *<u>any</u>* galaxy

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

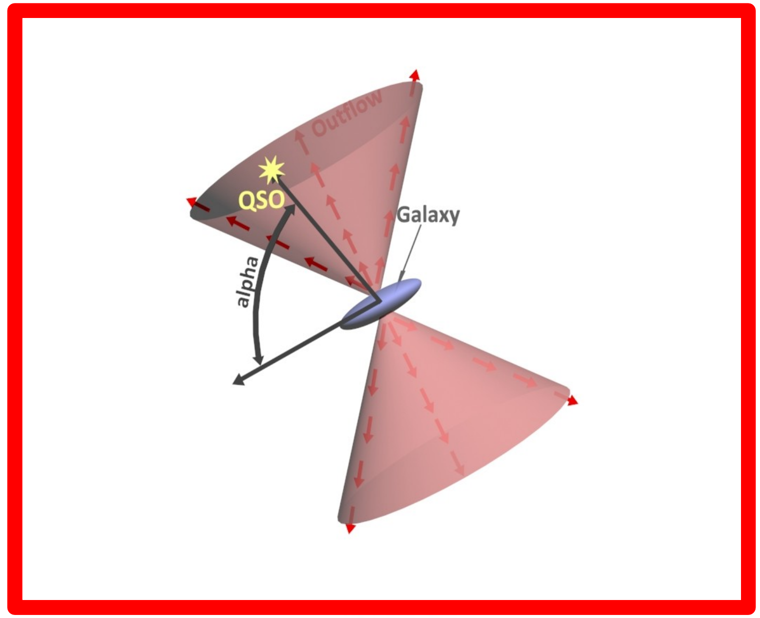
- Cons:
  - Rare!
  - Can probe anything else (disk, accretion)

In- and Out-flows in Simulations

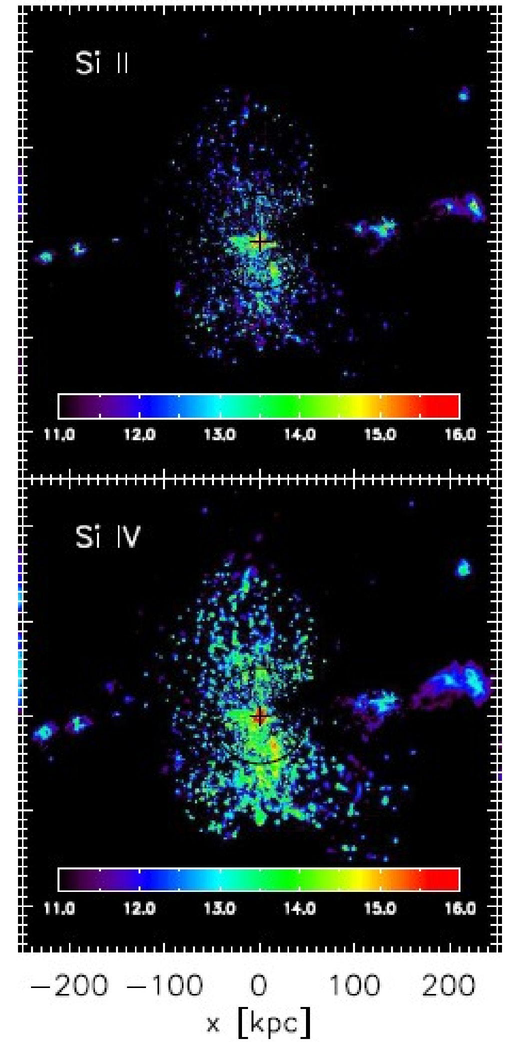
Shen, Madau et al. 2012



Inflowing particles



Credit: I. Schroetter



Outflowing particles

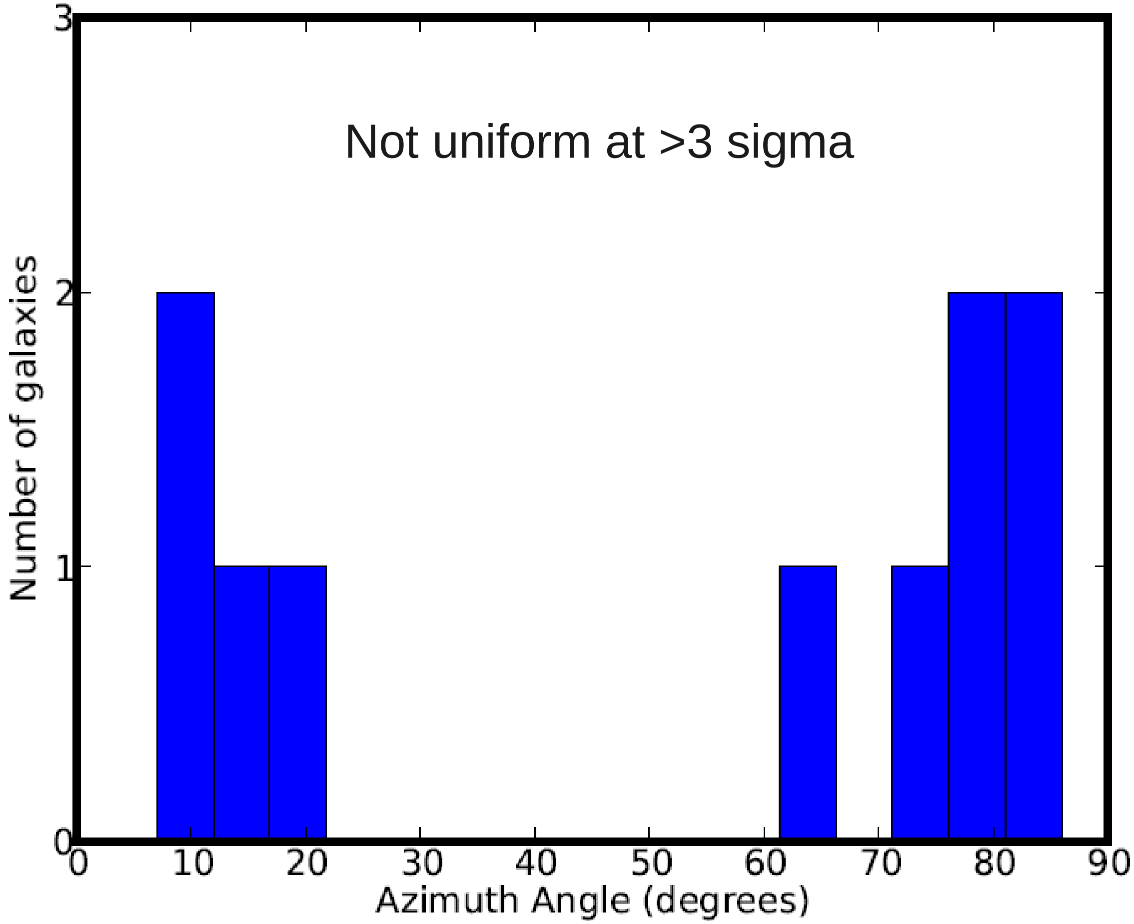
Both can be studied with background QSOs!

Gas flows around z~0.1 L* (SDSS)

<SFR> = 0.5 M/yr

Accretion?

Wind?



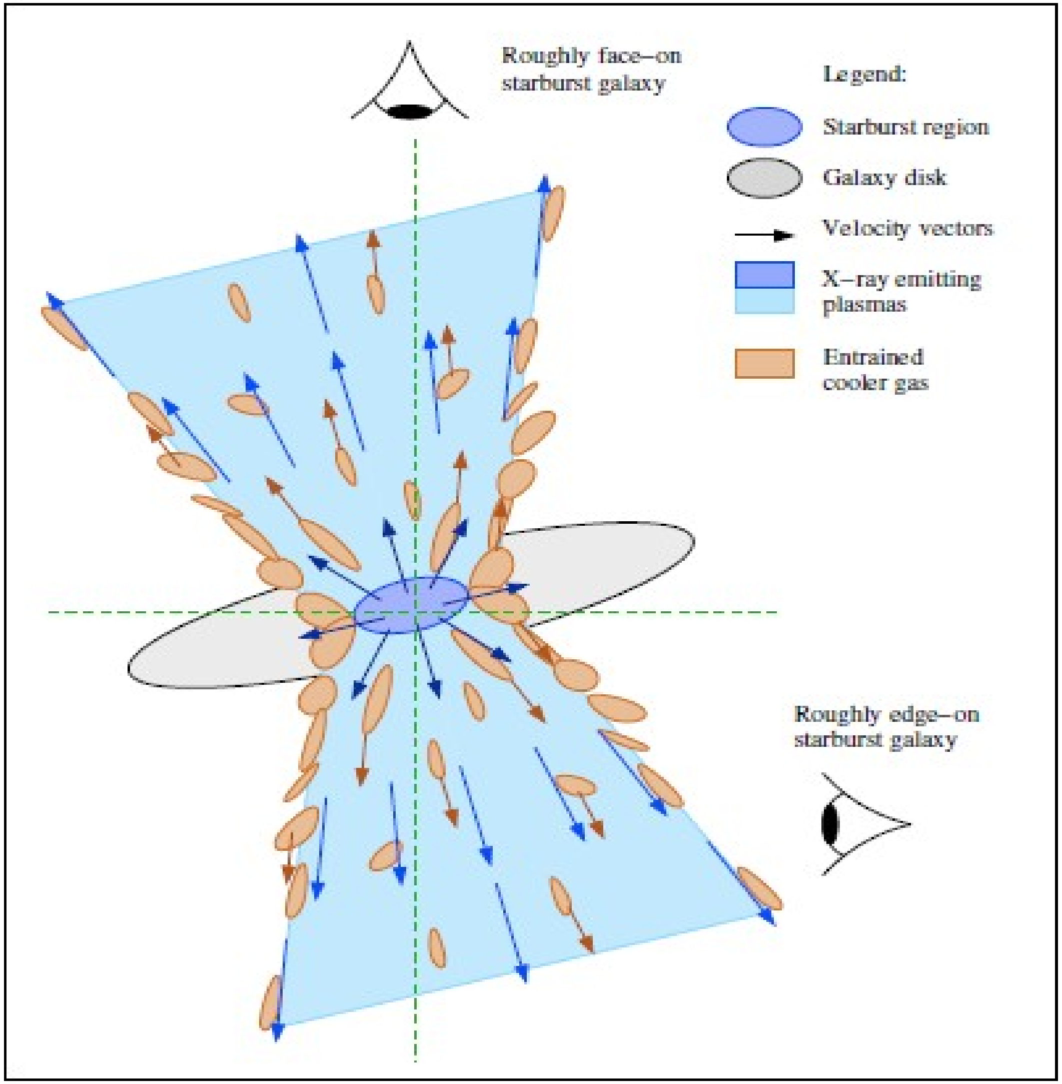
<SFR> = 2 M/yr

Bouché et al. 2012, confirmed in Kacprzak et al. 2012
Also Bordoloi et al. 2011, 2013, Chen Tremonti 2010, Rubin et al. 2013

Wind modeling with 1 parameter

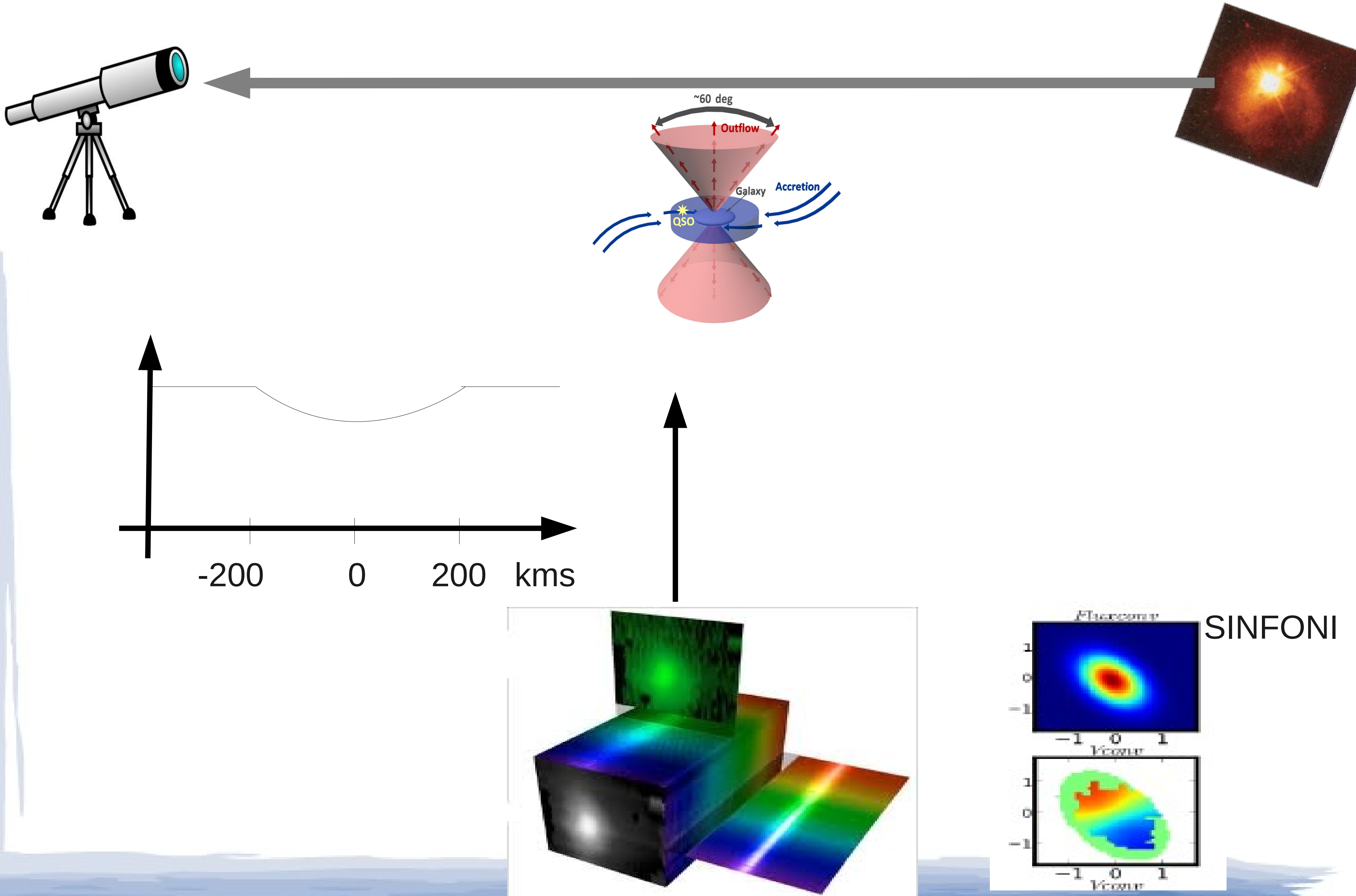
- Steady flow
- Mass conserved

  → $\rho \sim 1/r^2$
- Vwind ~ Cst

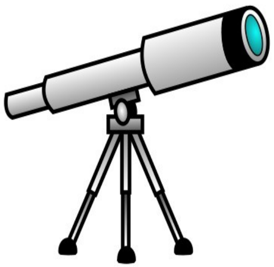


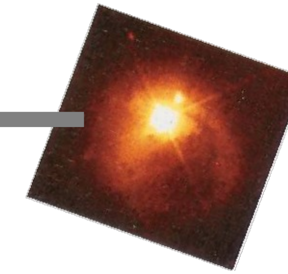
Strickland D.

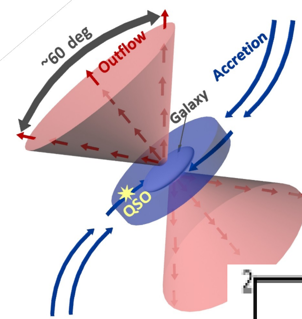
Geometrical effects



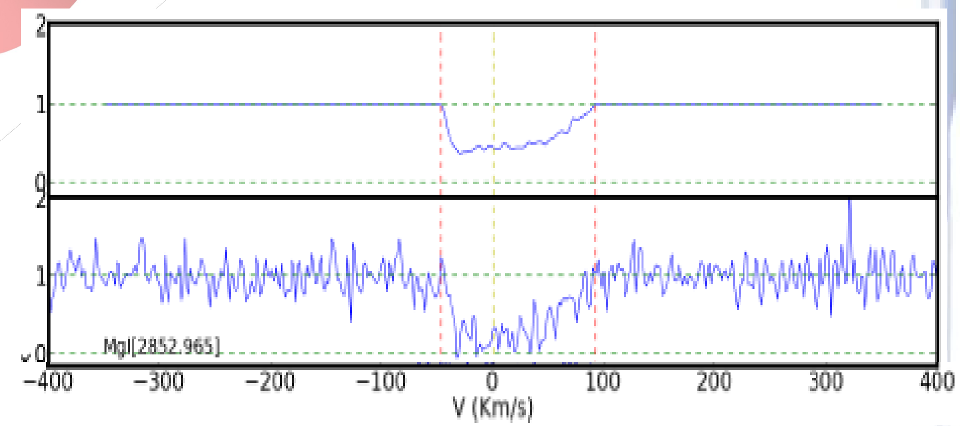
Geometrical effects!

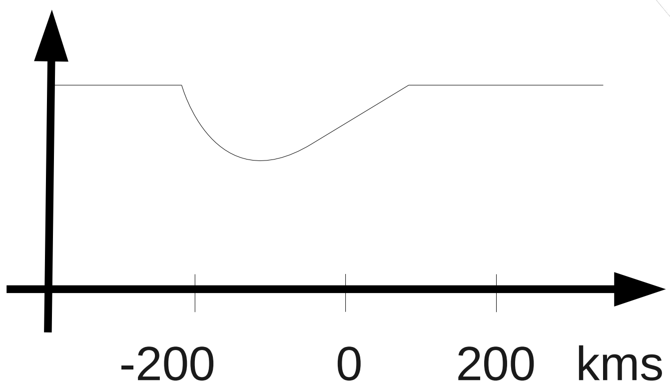


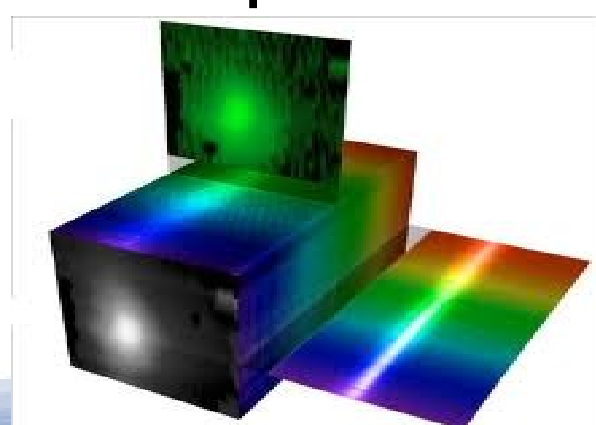


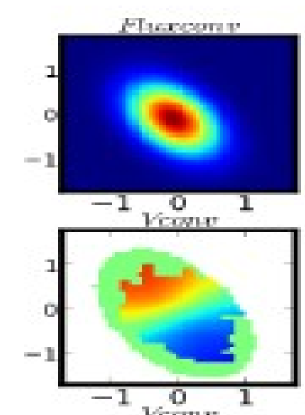


UVES VLT; MgI 2852; Schroetter et al.



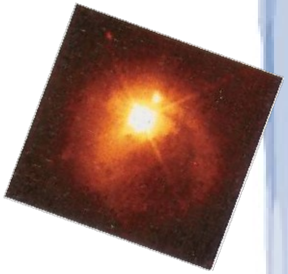






SINFONI

Winds properties from background QSOs



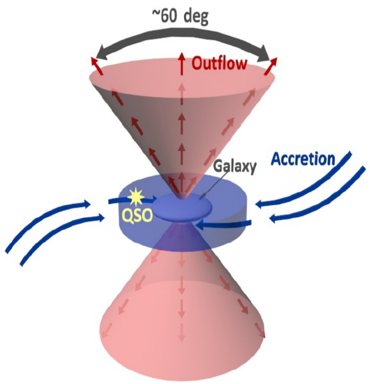
- Results:

Bouché et al. 2012

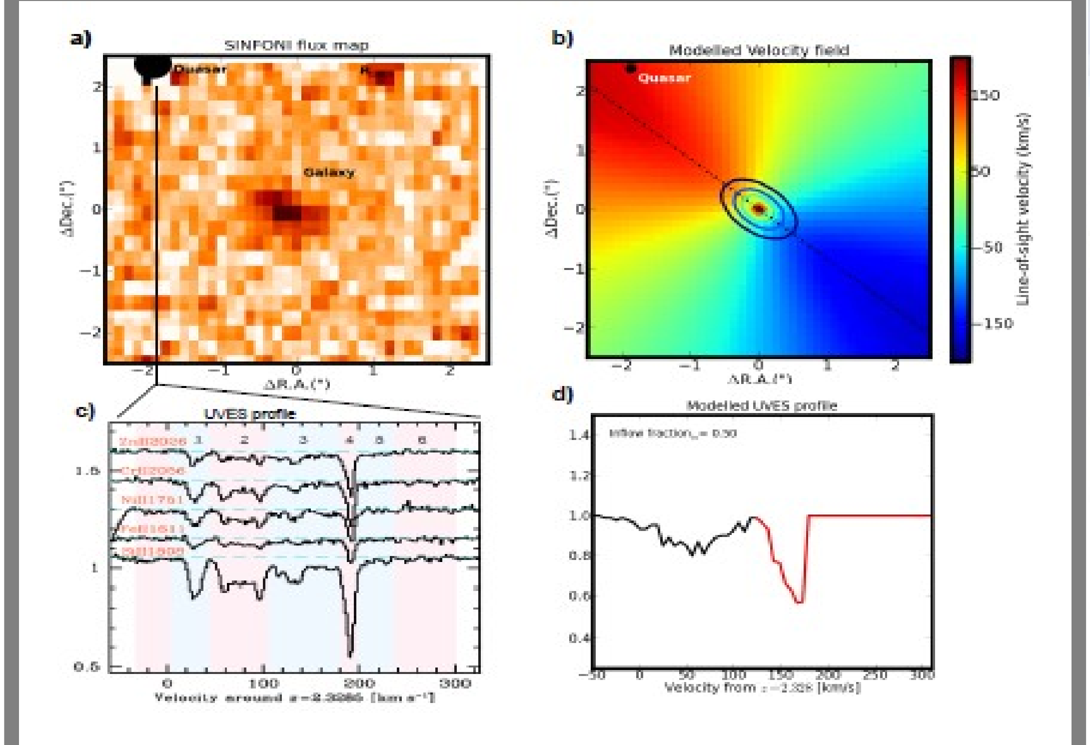
Cone ~ +/- 30 deg
NH(b) ~ 1 / b
Vout ~ ½ Vesc

dM_{out}/dt (L*) ~ 2 or 3 SFR

- Distinct kinematic signatures of infall
- Direct constraint on dM_{in}/dt ~ SFR
- “Low-Z”, but not pristine.



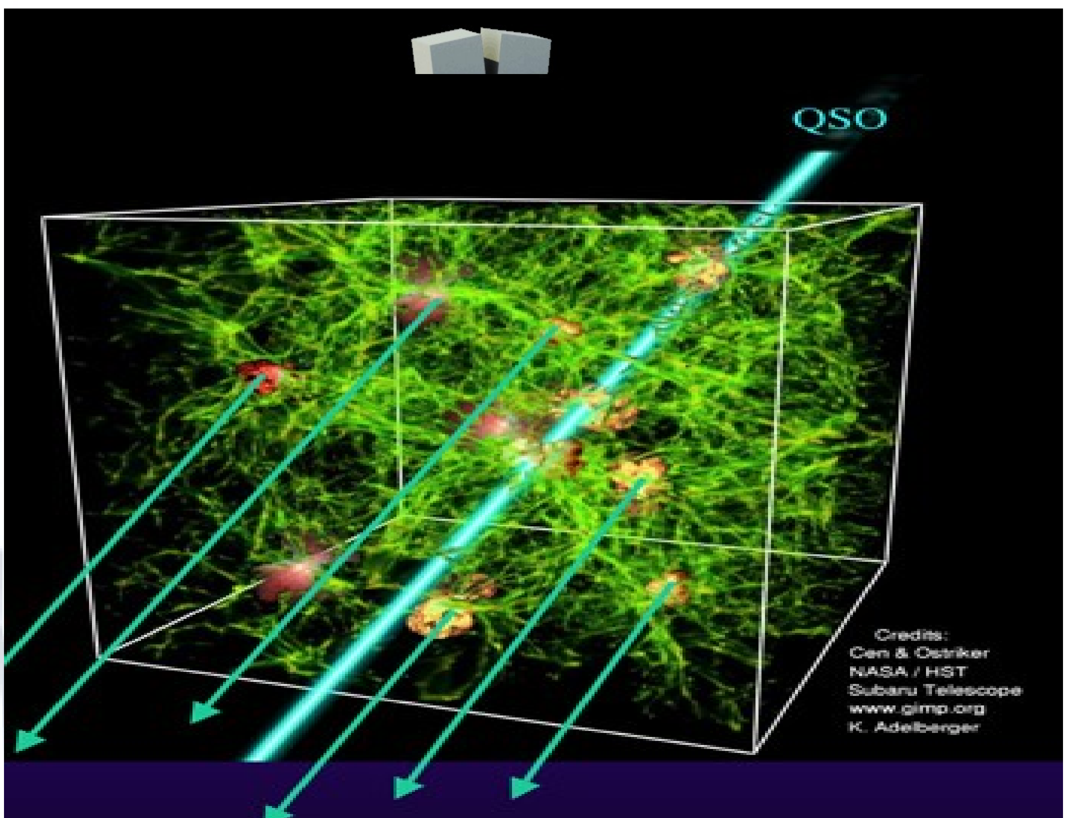
Bouché et al. 2013, Science

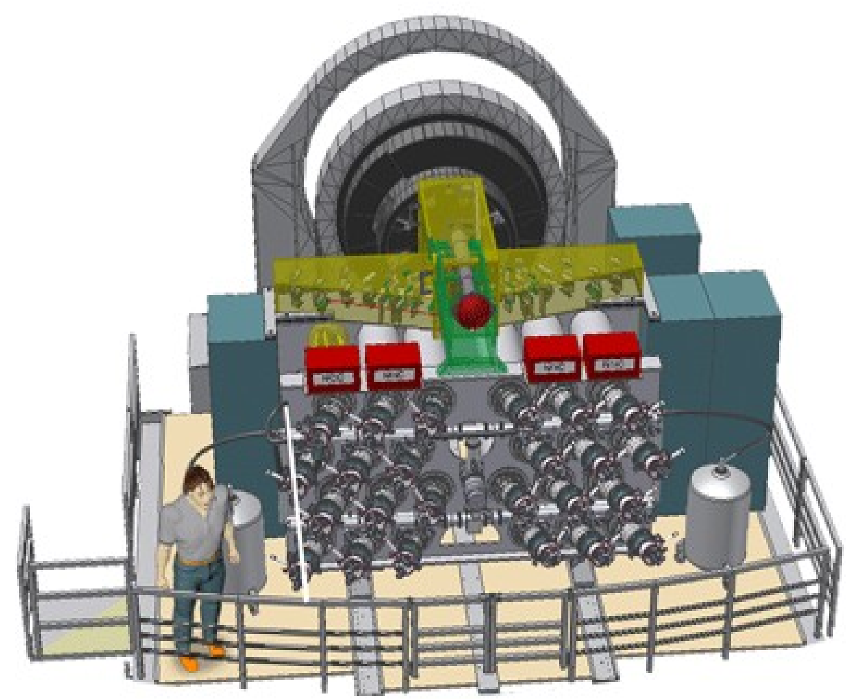


→ Vin, b, NH → **dM/dt ~ SFR !**

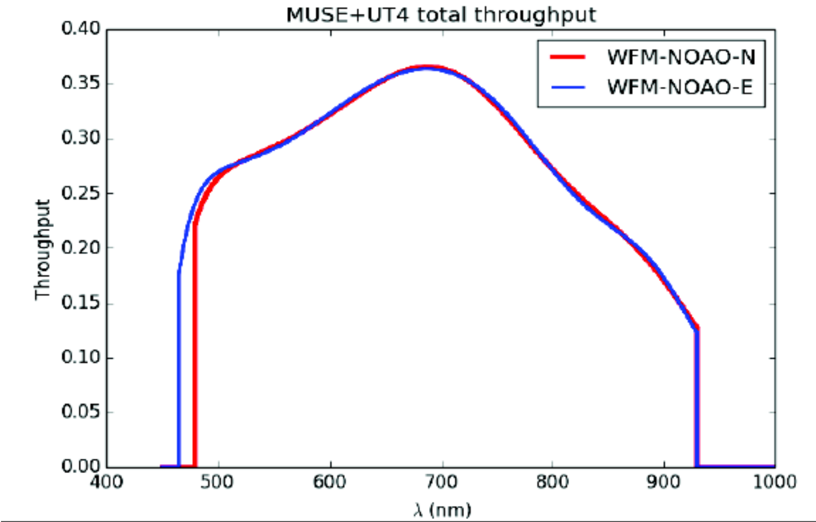
Prospects with MUSE

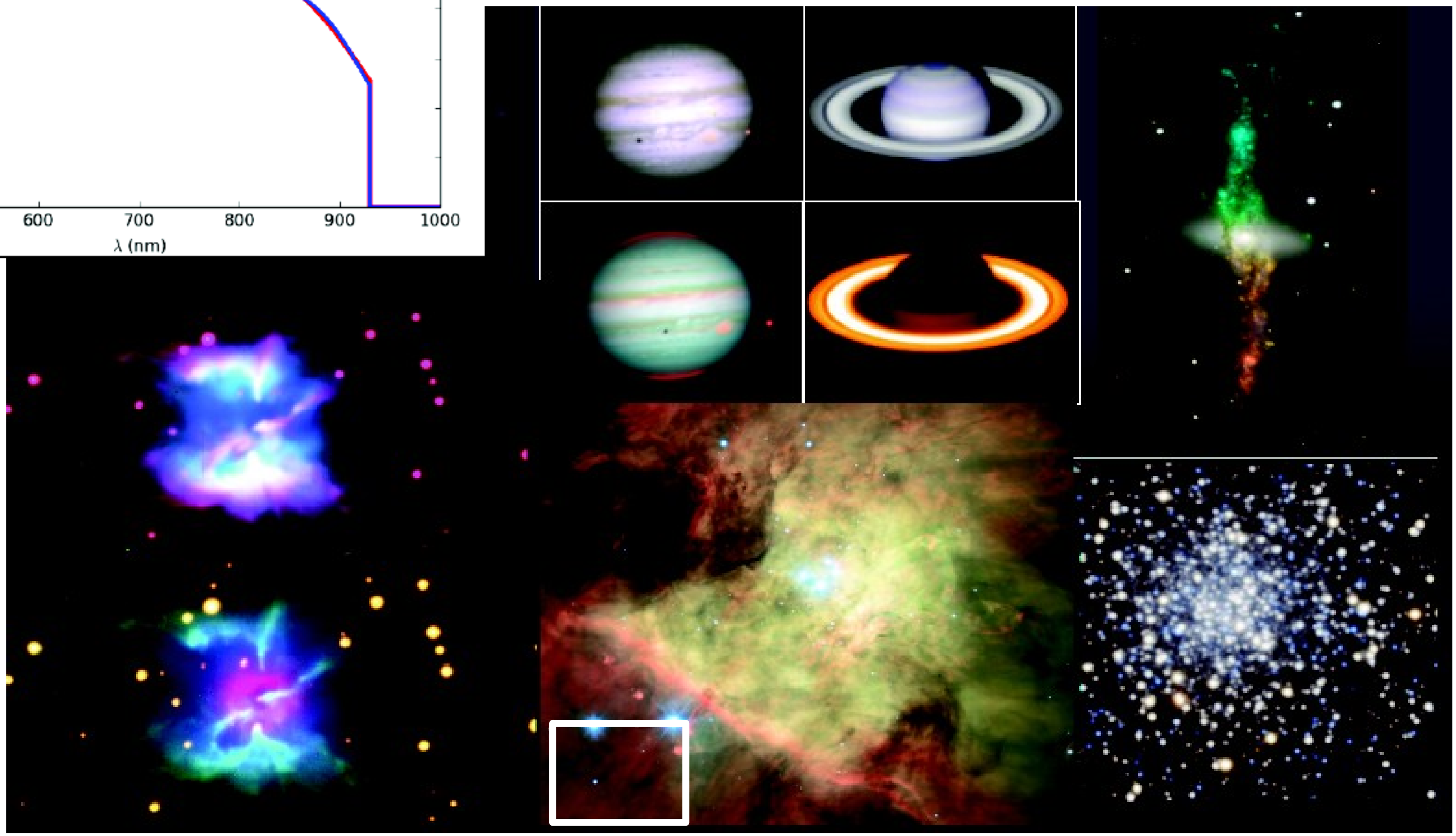
- Giant IFU 1’x1’ 0.2”/pix (0.5 – 0.95μm)
  - AO
  - Flux(80hr) > 3e-19 erg/s/cm2





MUSE ShowCases





Conclusions

- Gas accretion regulate star-forming galaxies
- Both inflows & outflows can be studied with background quasars NOW
  - Winds do not escape
  - Small loading factor

Bouché et al. 2013, Science
Bouché et al. 2012

What REgulates the growth of GALaxies [REGAL] (OCEVU)

- I. Schroetter (PhD)
- H. Ramani (Post-doc14 OCEVU @LAM)
- + Post-doc16 OCEVU @IRAP

+ 2 PhDs (disks build up)