Constraints on gas flows from background quasars

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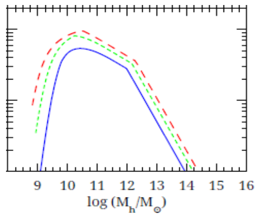
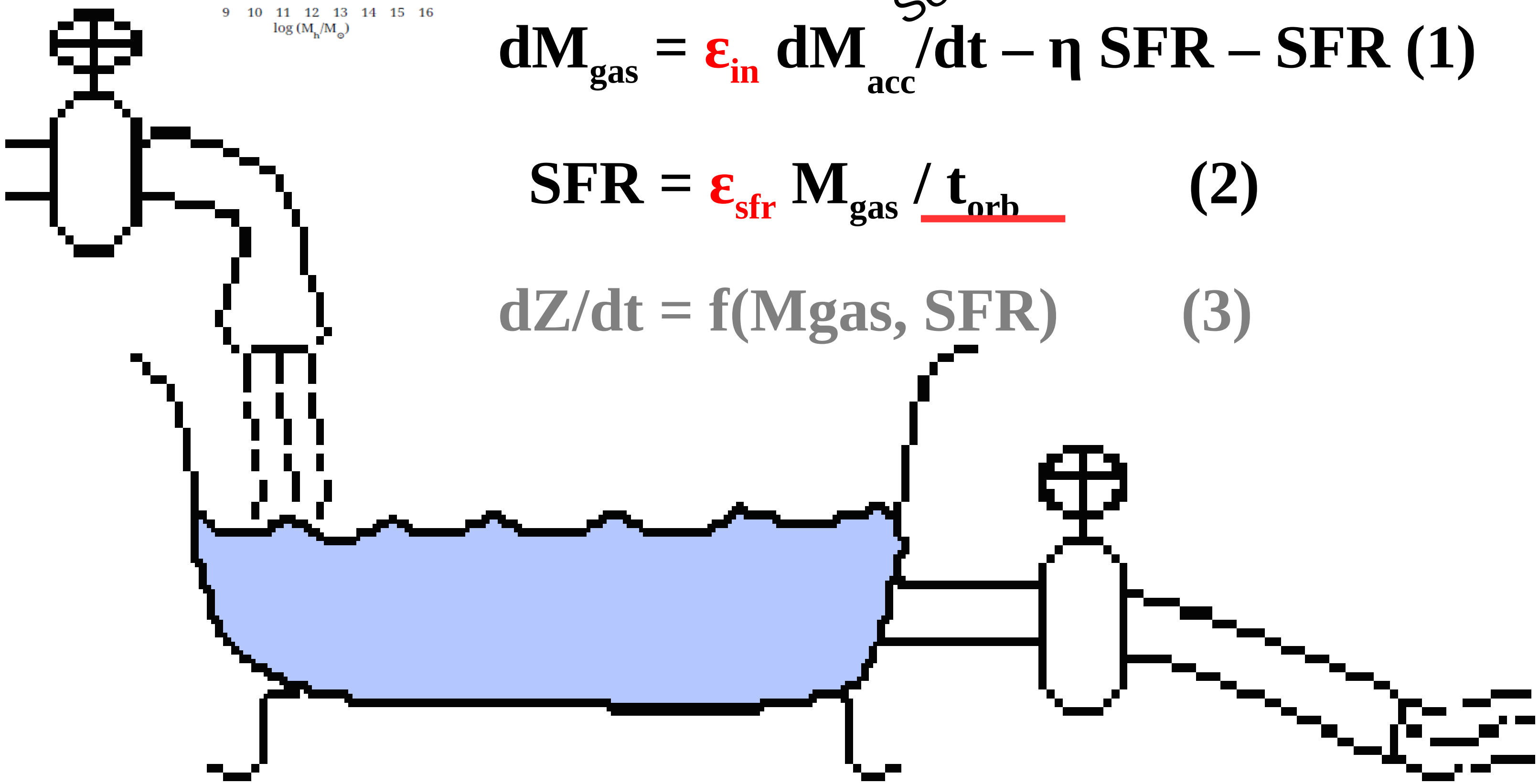
+ I. Schroetter (IRAP)

1) Bouché et al. 2012, 2013
2) Kacprzak et al. 2014
3) Schroetter et al. 2015
4) Bouché et al., 2015

SFR@50: The bathtub model



Bouché et al. 2010



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

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

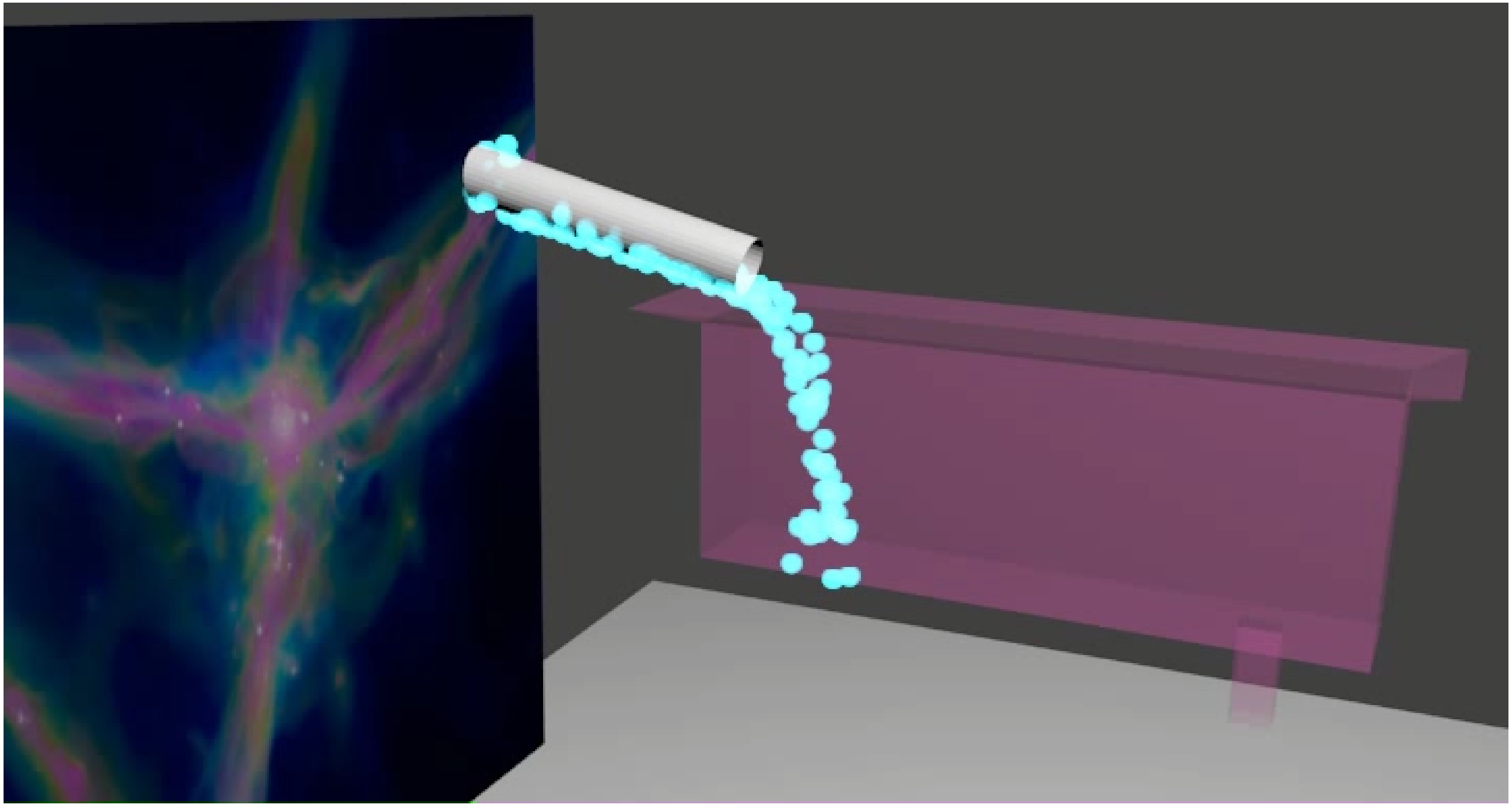
$$dZ/dt = f(Mgas, SFR) \quad (3)$$

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, Mitra 14

SFR@50: The bathtub model

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

➔ SFR (& Mgas) follows accr. Rate



Open Questions?

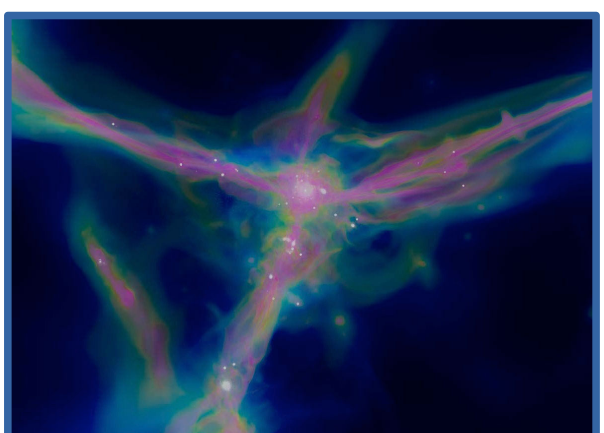
In

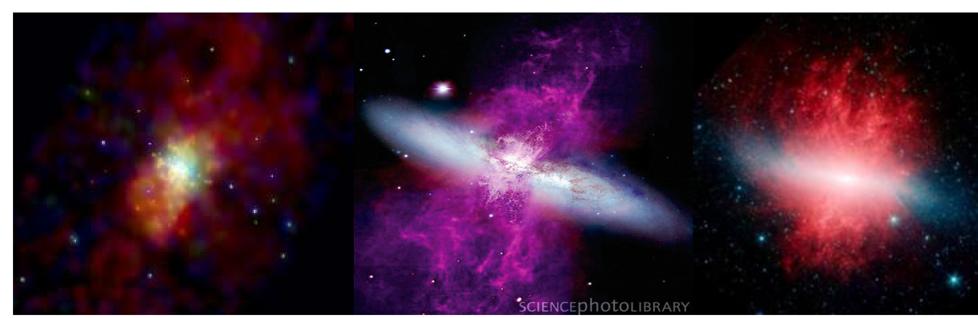
Does accretion occur?

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

Out

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





What we know about Gas Flows:

In

1) Stellar pop. Arguments:

Tinsley 1980, Mannucci et al., Maraston et al.

G-dwarf problem

2) Gas mass arguments:

Leroy 2013; Freundlich et al. 2013; Daddi et al. 2010; Saintongue 2013 Tacconi et al. 2013; Nordon et al. 2013

Tdepl(z=0)=2 Gyr; Tdepl(z=2)=0.5 Gyr

3) Global HI vs. SFRD:

Out

- Ubiquitous & **collimated**:

Chen, Tremonti et al. 2010,

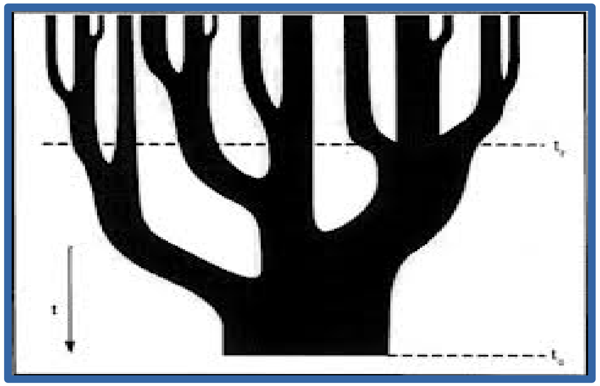
Bouché et al. 2012;

Bordoloi et al. 2011, Kacprzak et al. 2012

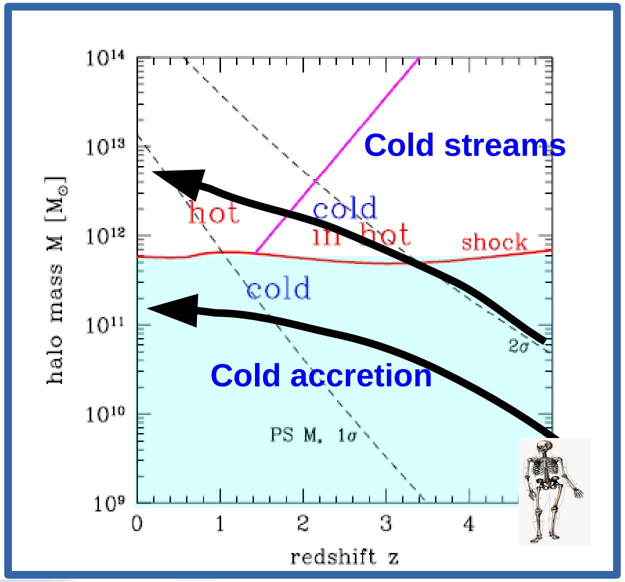
Martin 2012, Rubin 2013, Bordoloi 2013

The main challenge of galaxy formation

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



Dekel et al. 2007
++



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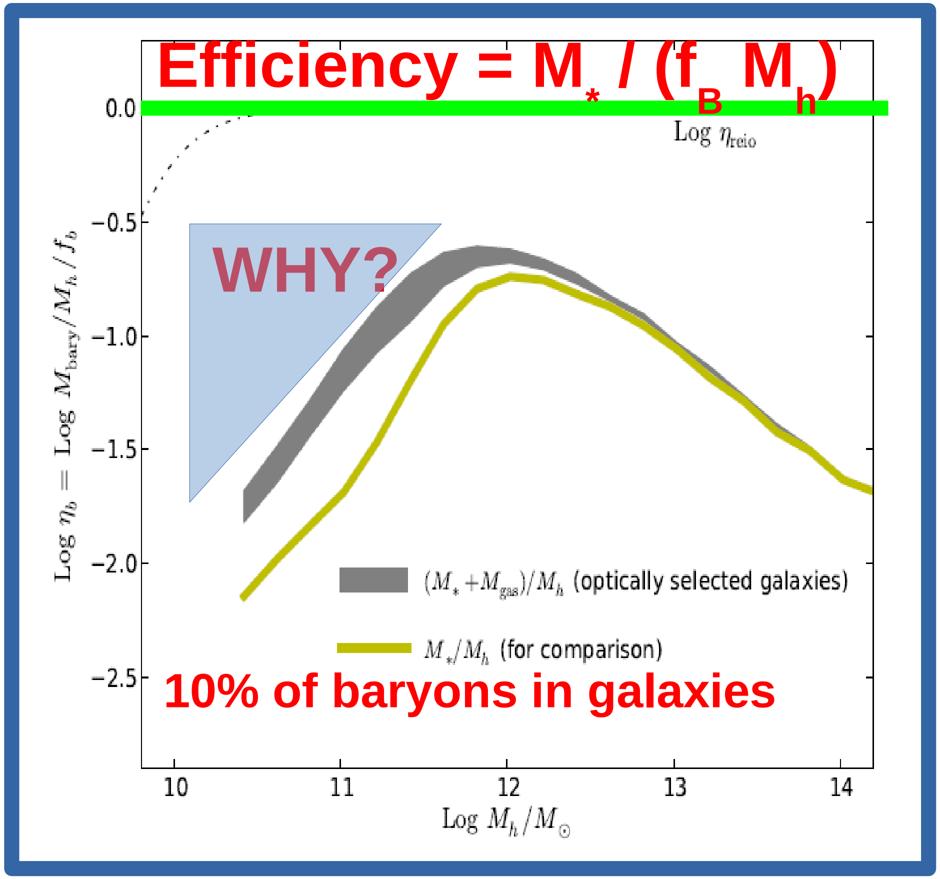
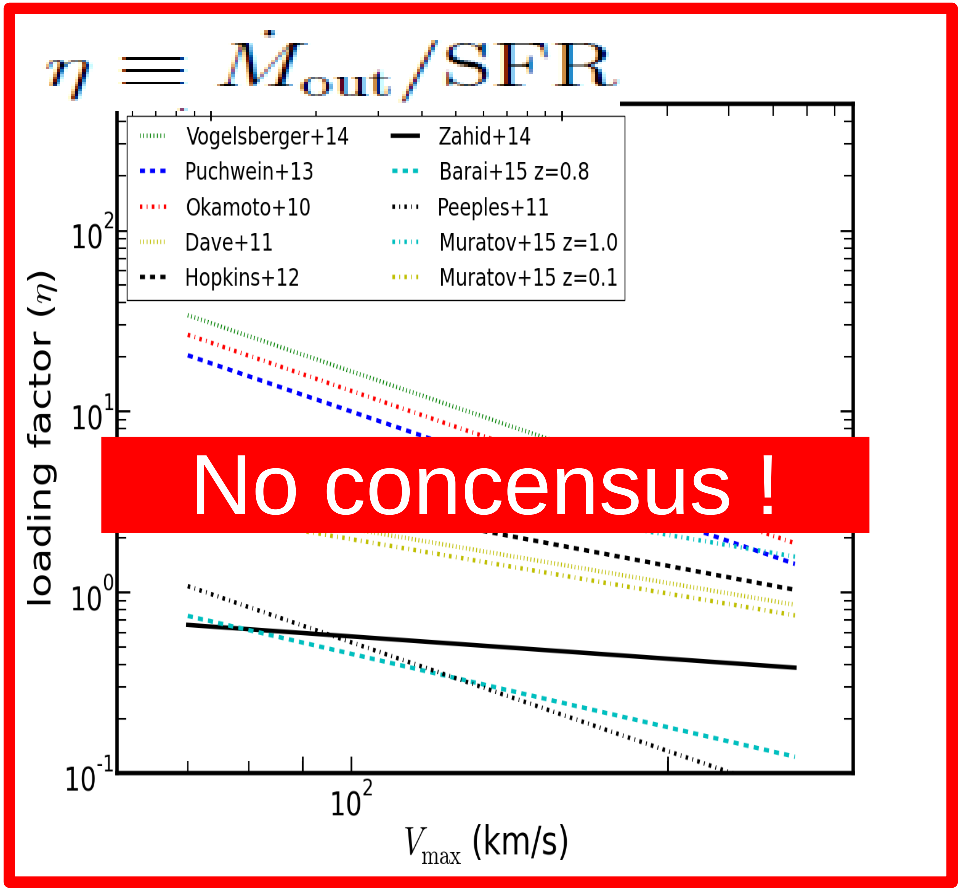


Papastergis, Cattaneo et al 2012

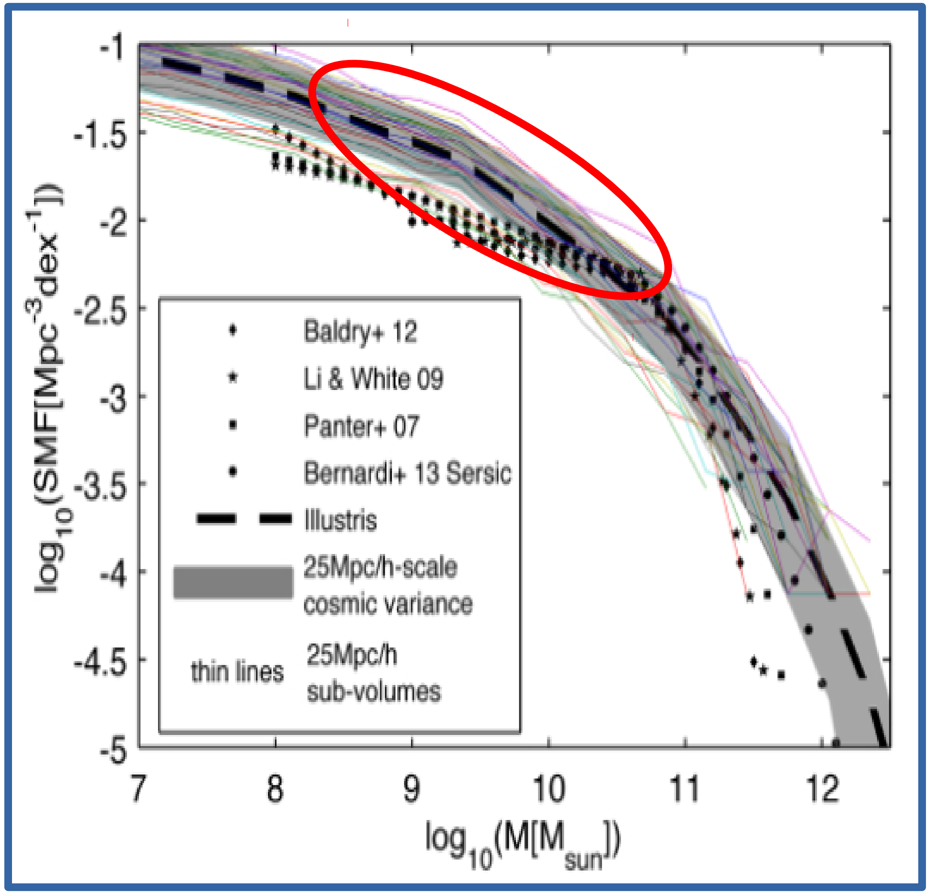
Yesterday and today' s challenge:
The low baryon fraction

Solution: invoke winds



Schroetter 2015
See also Zahid 2014

The challenge remains



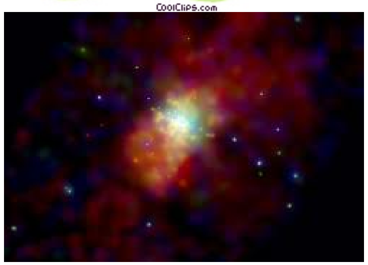
Illustris, Genel 2014

Outflows are multi-phased!

$$\eta \equiv \dot{M}_{out}/SFR$$

Heckman T.; Martin 2002;

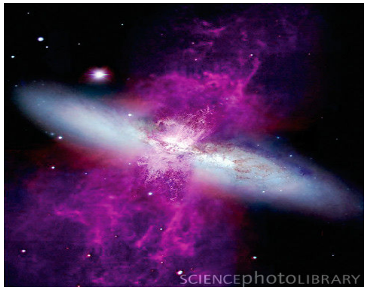
- Xray **emission**
  - Hot $(10^6$ K)



Eta <<1

Zhang & Thompson 2014

- Ha **emission**
  - Ionized $(10^4$ K)



Eta ~ 2

Genzel/ Newman 2012

- Neutral gas
  - Optical spectra (NaD, Mg II)

Lehnert/Heckman, Martin C., Weiner, Rupke

Eta ~ 1

- Dense molecular
  - F-IR spectroscopy (OH)

Sturm et al. 2011

Eta ~ 1-10

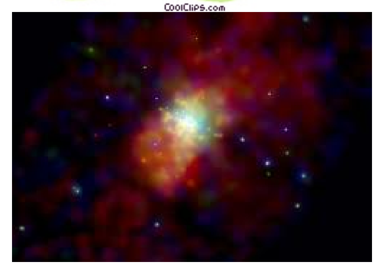
  - CO **emission**

Bolato et al. 2013, Nature

Outflows are multi-phased!

In bkgr qso

Heckman T.; Martin 2002;



- Xray **emission**
  - Hot $(10^6$ K)

OVI

- Ha **emission**
  - Ionized $(10^4$ K)

- Neutral gas
  - Optical spectra (NaD, Mg II)

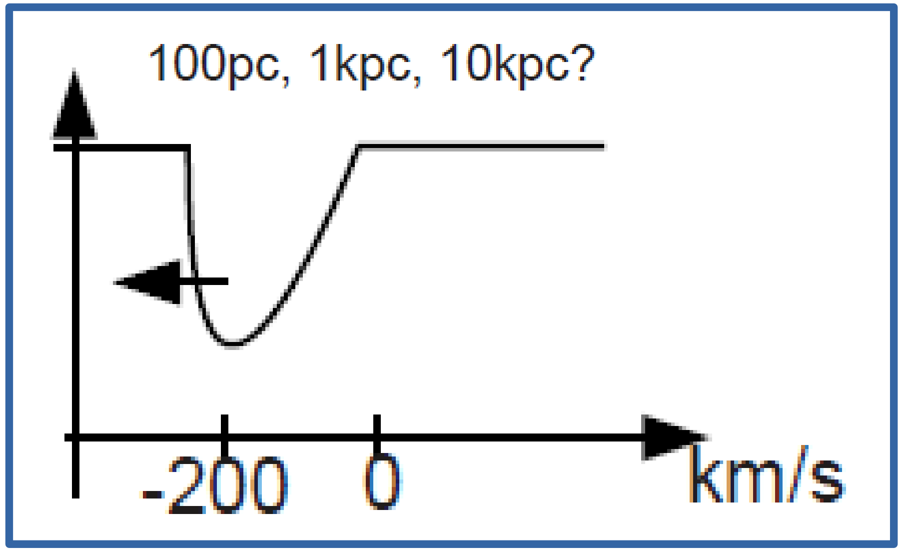
MgII

(HI)

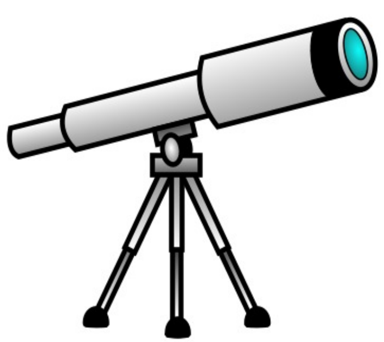
- Dense molecular
  - F-IR spectroscopy (OH)
  - CO **emission**

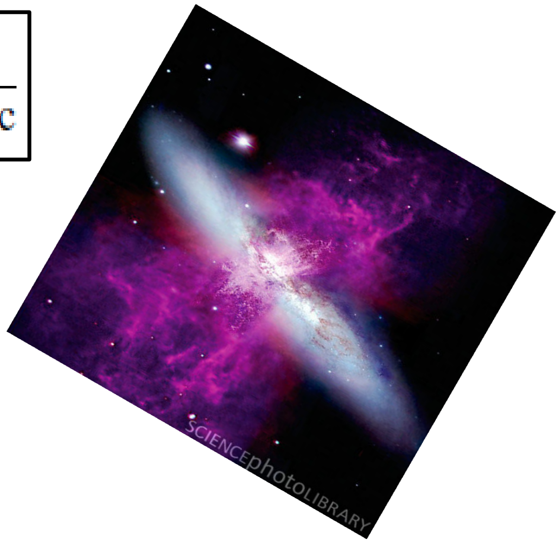
Not there!

Problem with traditional spectroscopy

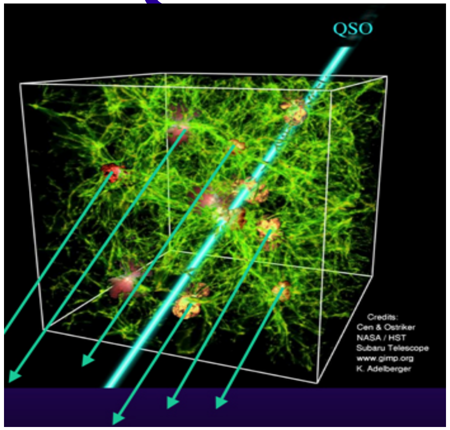


$$\dot{M}_{\rm out}(b) = 0.41 {\rm M}_\odot\, {\rm yr}^{-1} \frac{\mu}{1.5} \frac{\Omega_w}{2} \frac{N_H(b)}{10^{19}{\rm cm}^2} \frac{V_{\rm out}}{200{\rm km\, s}^{-1}} \frac{b}{25\ {\rm kpc}}$$





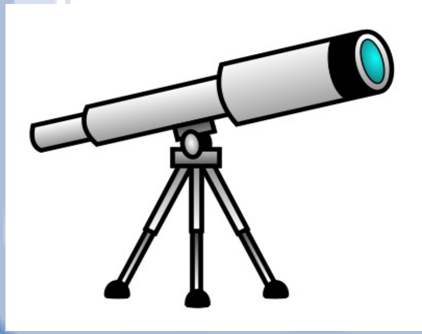
Outflows using background QSO

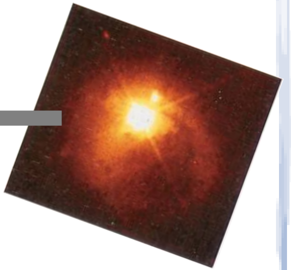


- Pros
  - Radial information
  - Can probe wind around ***any*** galaxy

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

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





Gas Flows using background QSOs

- A) Galaxy selected sample: 1/3 success
  - SDSS L* galaxies @z~0.1--0.3
  - *b ~ 20-100 kpc*
  - *Need LRIS follow-up for MgII*

Barton & Cooke 2009
Kacprzak et al. 2014
Bouché et al. In prep.
Martin in prep.

- B) Absorber selected SIMPLE: 2/3 success!
  - MgII from SDSS @ z~0.8-1.0
  - *b ~ <20 kpc* ← by selection
  - SINFONI + UVES data

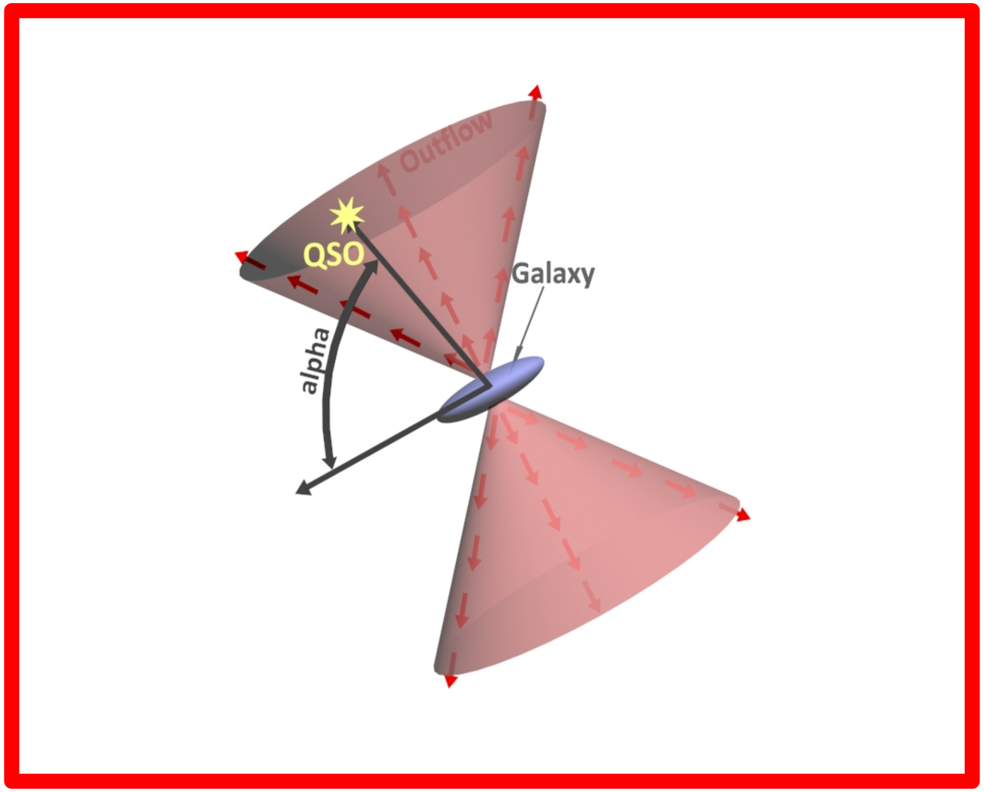
Bouché et al. 2007
Schroetter et al. 2015

3/4 success!

- Next: MUSE Gas FloW (MEGAFLOW).

→ which pairs favorable for winds ?

Background quasars: geometry matters



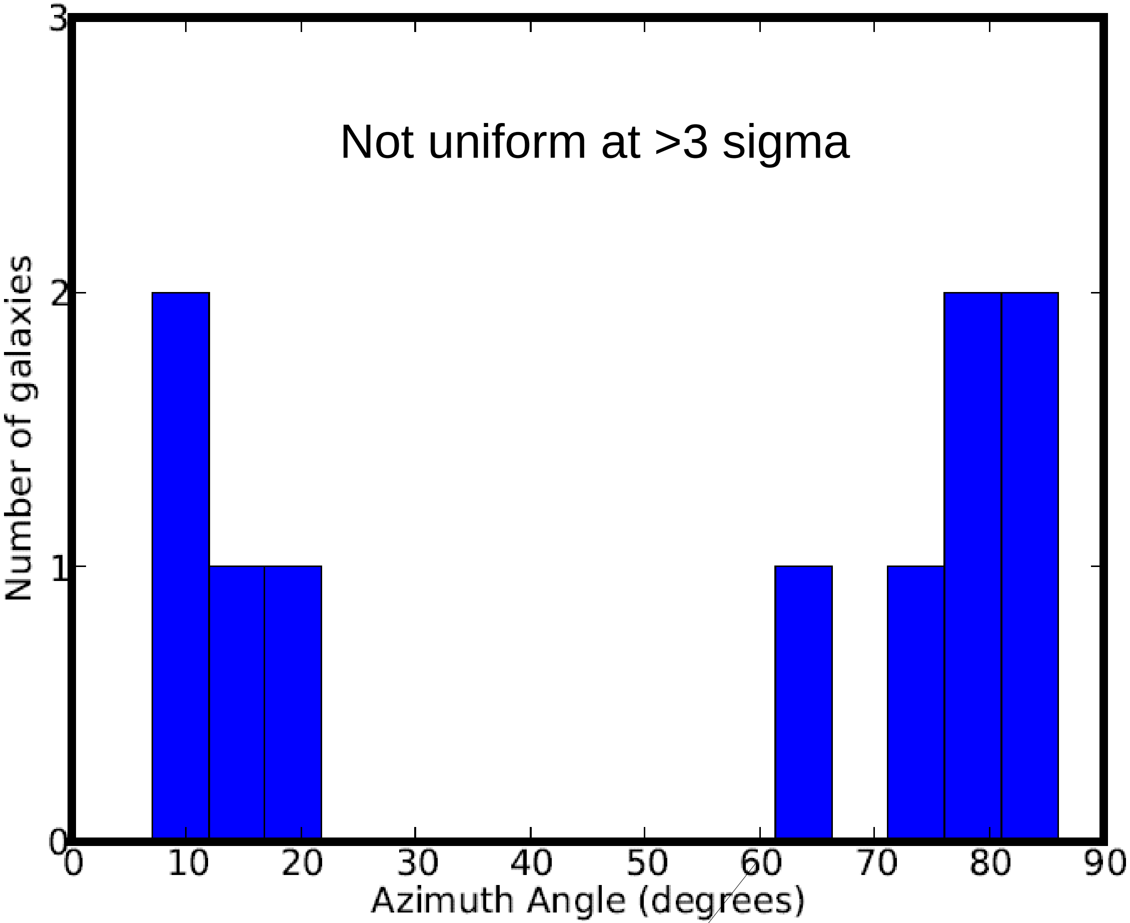
Credit: I. Schroetter

Strategy A) galaxy selection

MgII around L* @ z~0.1

Accretion?

Wind?



<SFR> = 0.5 M/yr

<SFR> = 2 M/yr

Chen Tremonti 2010,
Bordoloi et al. 2011
Bouché et al. 2012,
Rubin et al. 2013
Lan & Ménard 2014,
Nielsen et al. 2015

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

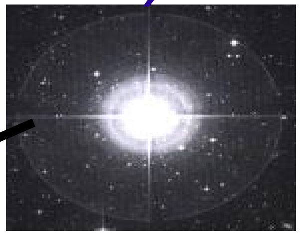
Strategy B) MgII Selection

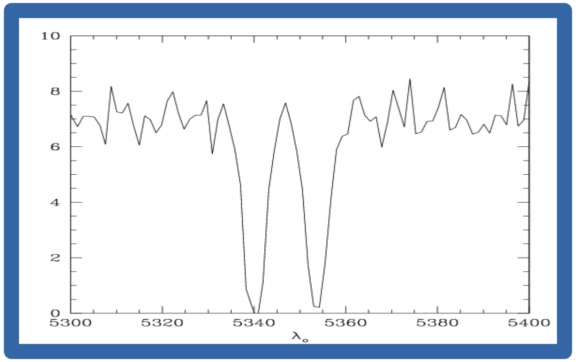
SINFONI MgII Program for Line Emitters (SIMPLE)

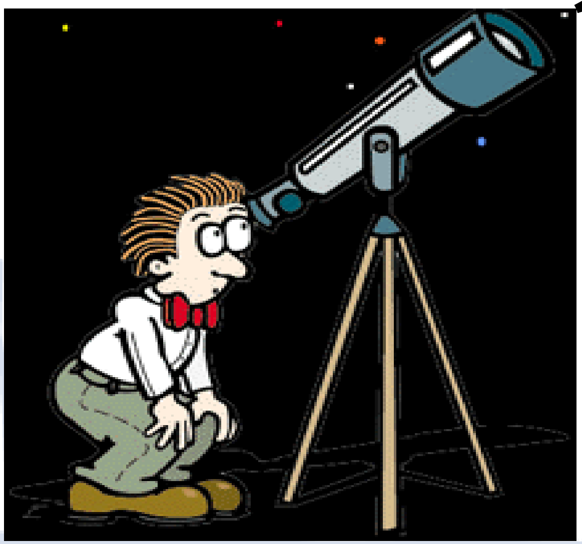
14 QSO fields **Bouché et al. 2007, Schroetter et al. 2015**

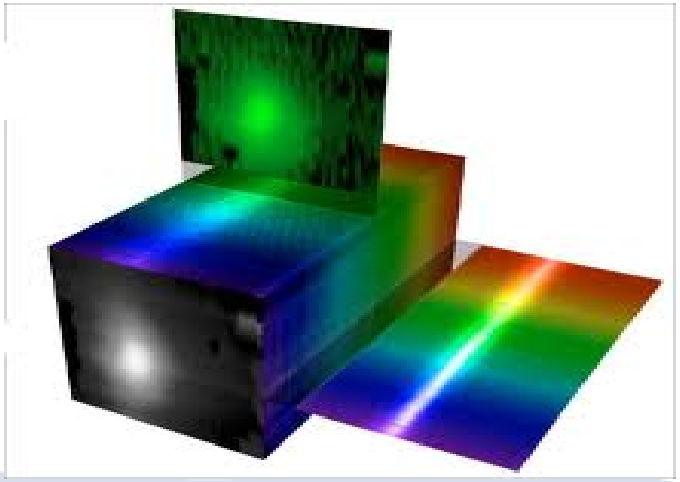
MUSE Gas Flow and Wind Survey (MEGAFLOW)

7+ QSO fields with Nabs=4,5 **Coming soon !**

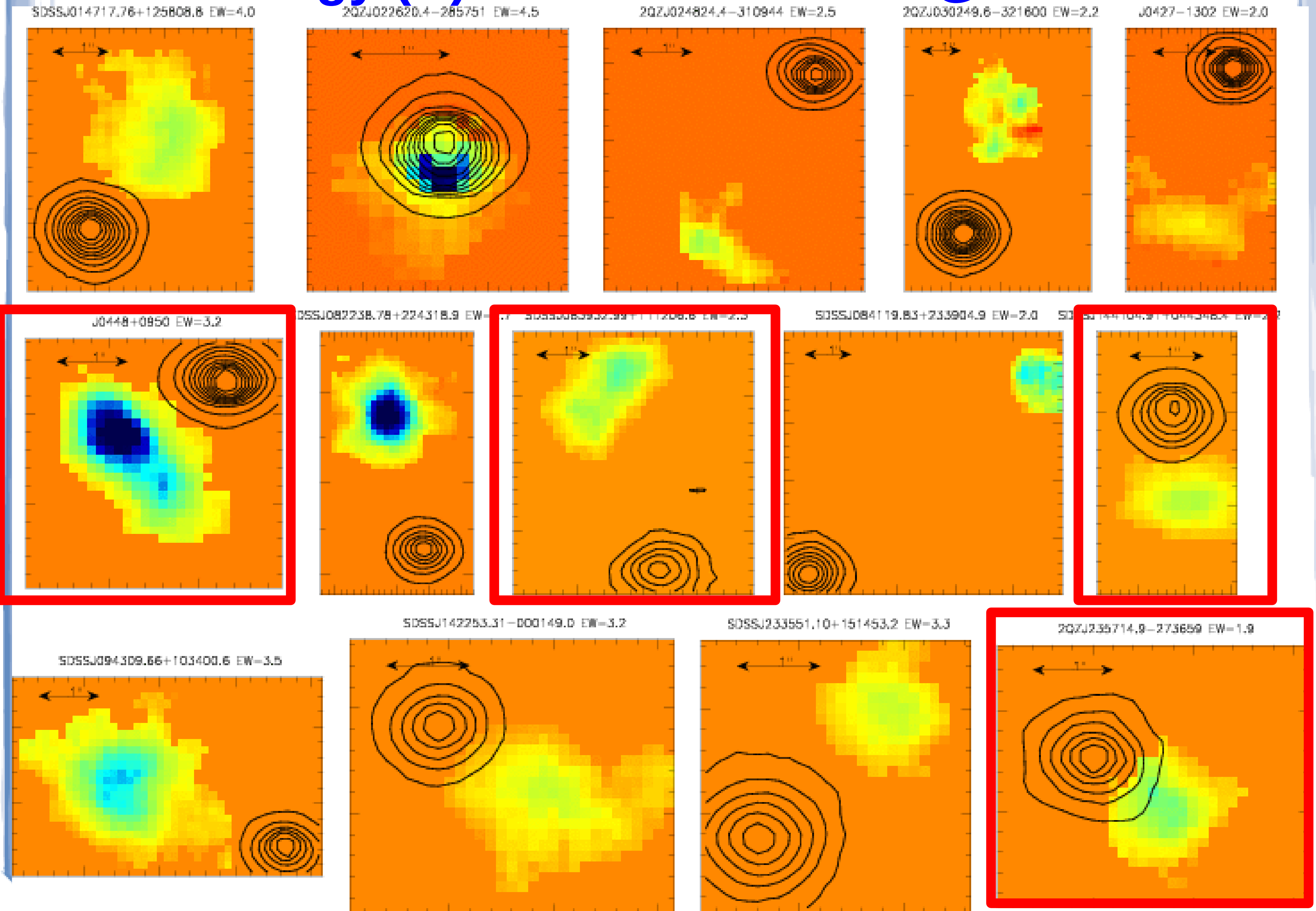








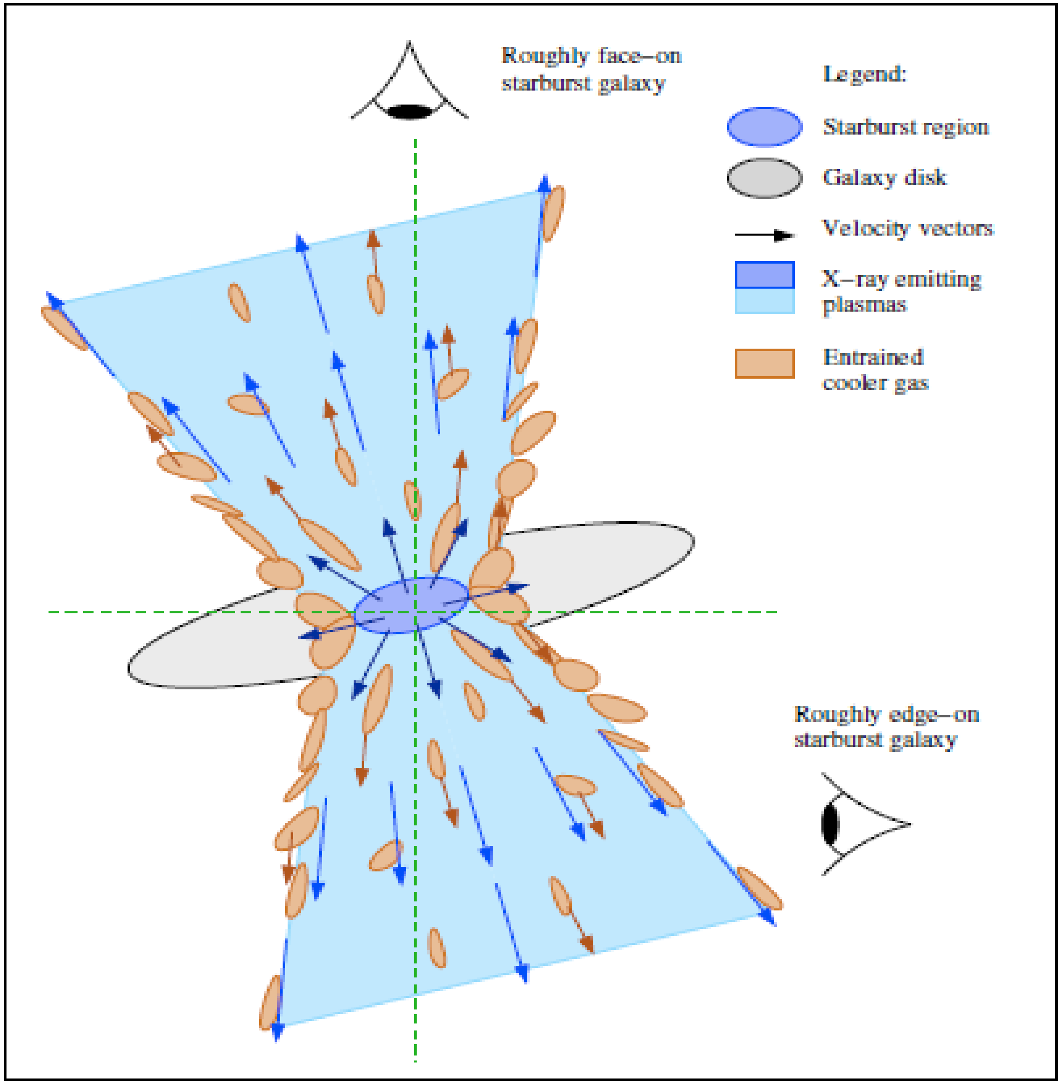
Strategy (B) SINFONI & UVES @z=1.0



Wind modeling with 1 parameter

- Steady flow
- Mass conserved

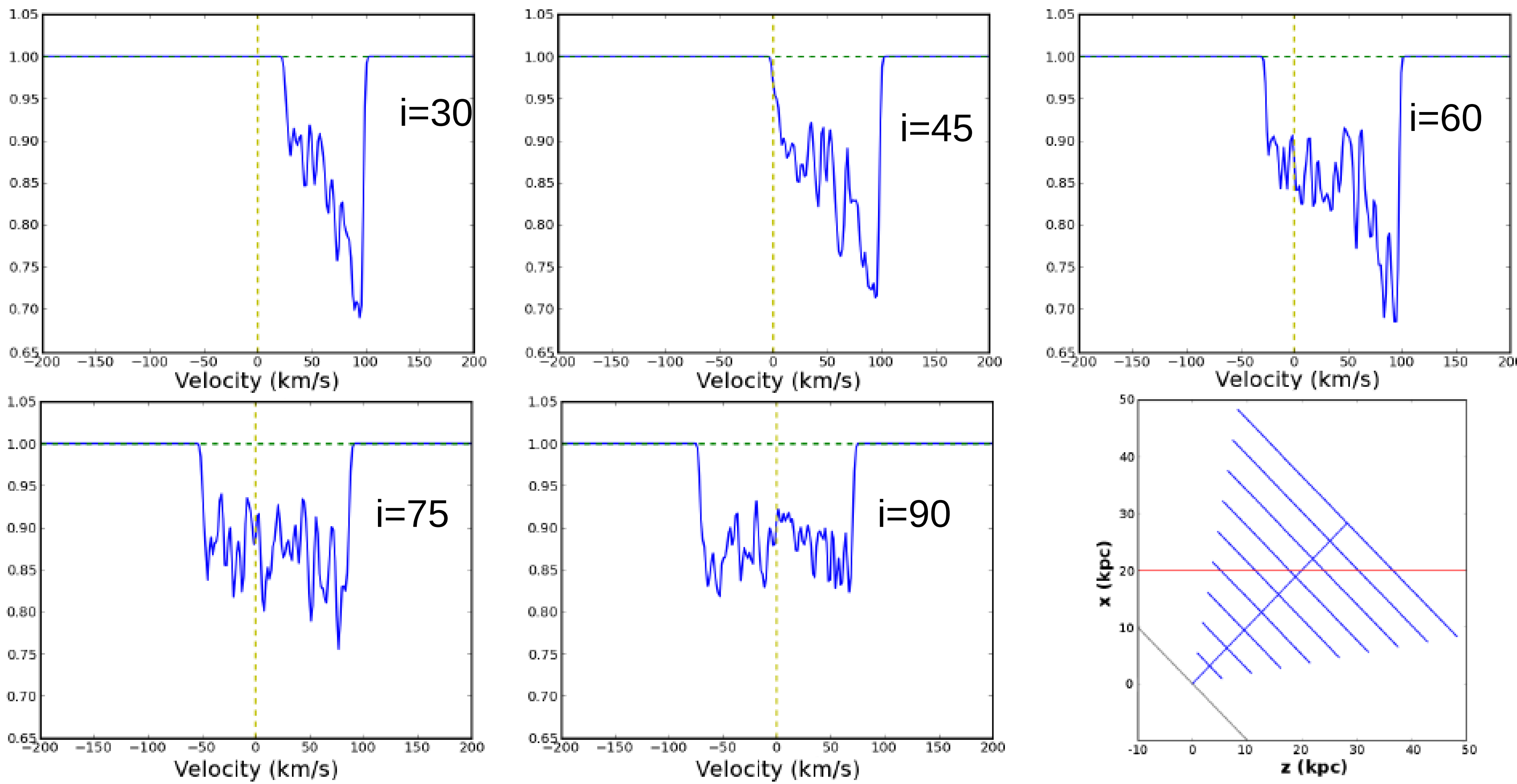
  → $\rho \sim 1/r^2$
- Vout ~ Cst



Strickland D.

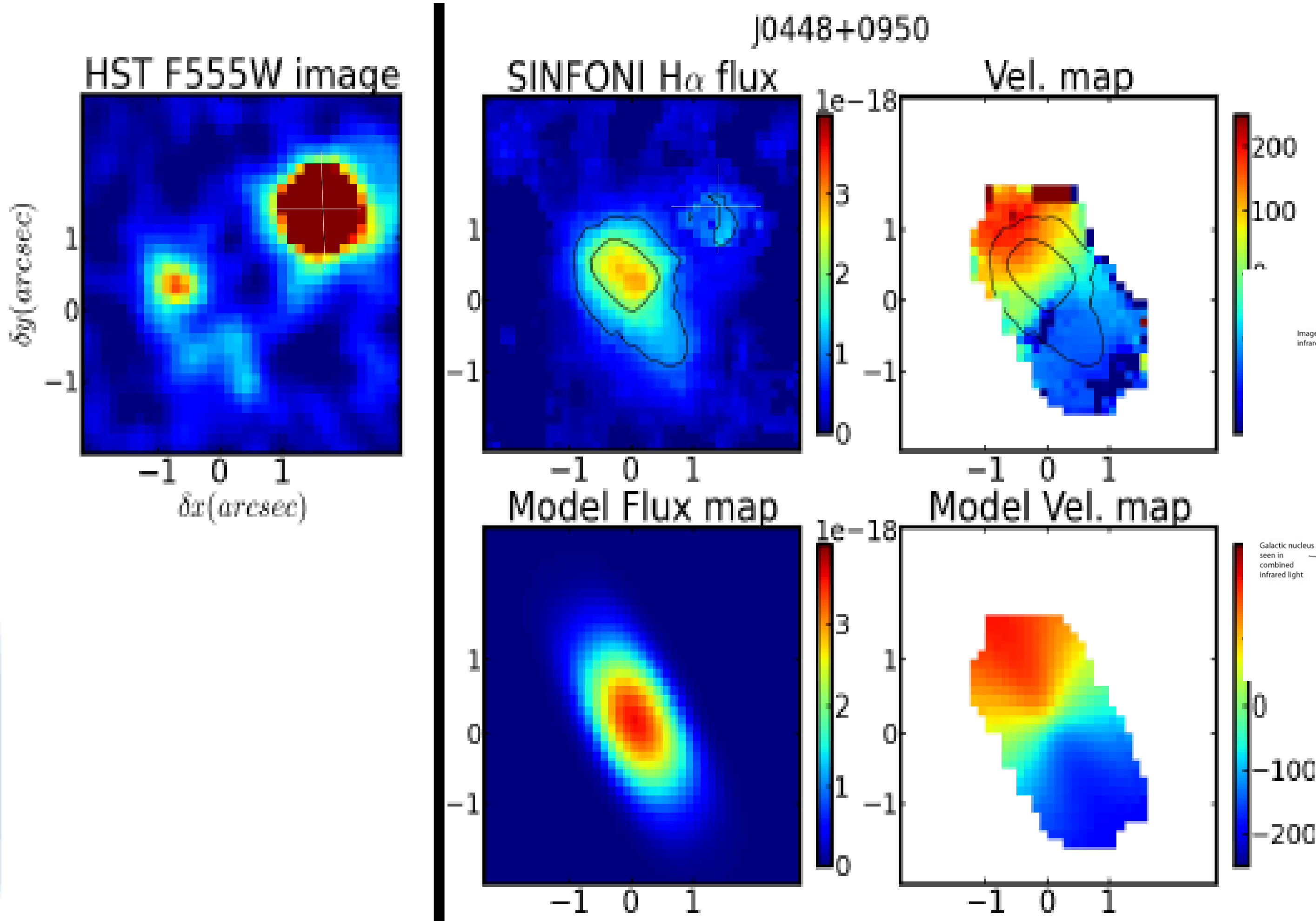
Wind model & inclination

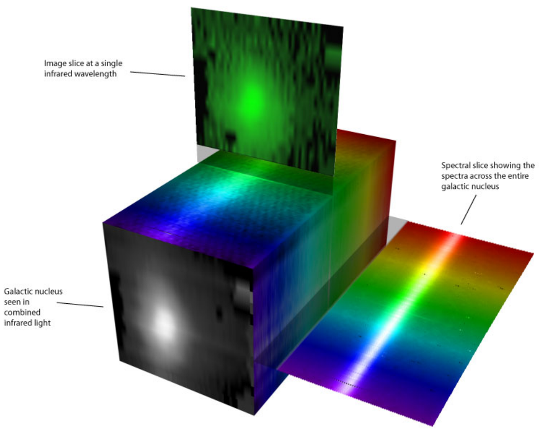
$$\dot{M}_{out}(b) = 0.41 M_{\odot}\, yr^{-1} \frac{\mu}{1.5} \frac{\Omega_w}{2} \frac{N_H(b)}{10^{19} cm^2} \frac{V_{out}}{200 km\, s^{-1}} \frac{b}{25\ kpc}$$



3D fitting with GalPak^{3D}

Bouché et al. 2015, 1501.06586

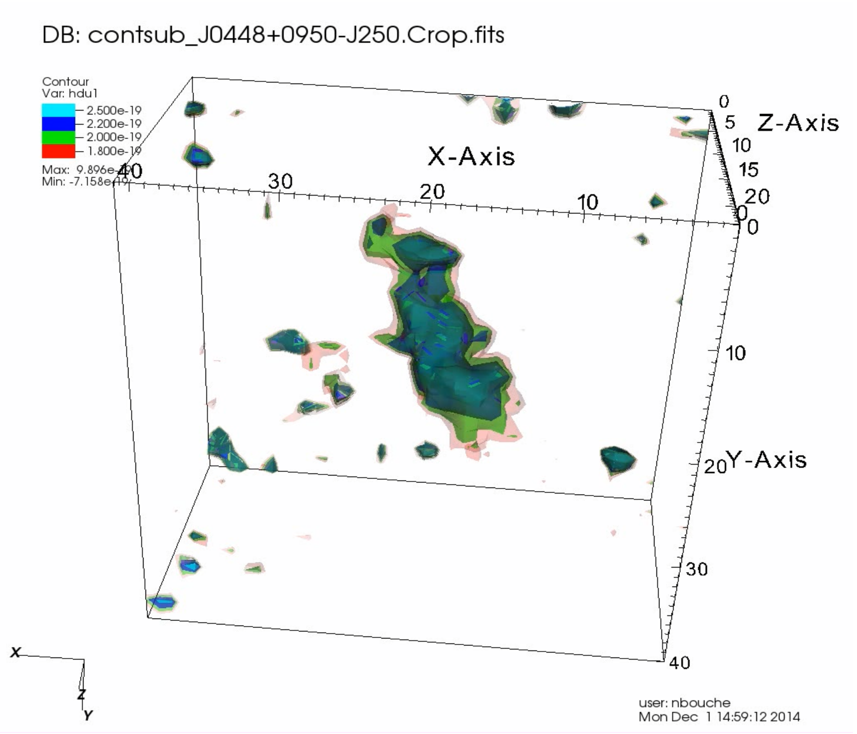


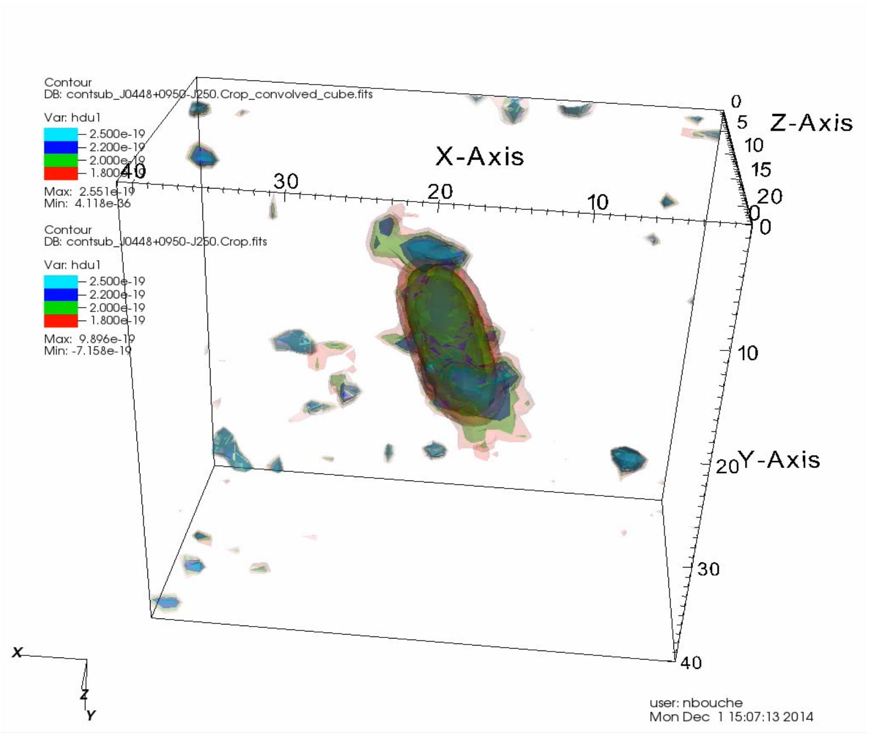


$$\dot{M}_{\rm out}(b) = 0.41 \mathrm{M}_\odot\, \mathrm{yr}^{-1} \frac{\mu}{1.5} \frac{\Omega_w}{2} \frac{N_H(b)}{10^{19}\mathrm{cm}^2} \frac{V_{\rm out}}{200 \mathrm{km\, s}^{-1}} \frac{b}{25\ \mathrm{kpc}}$$

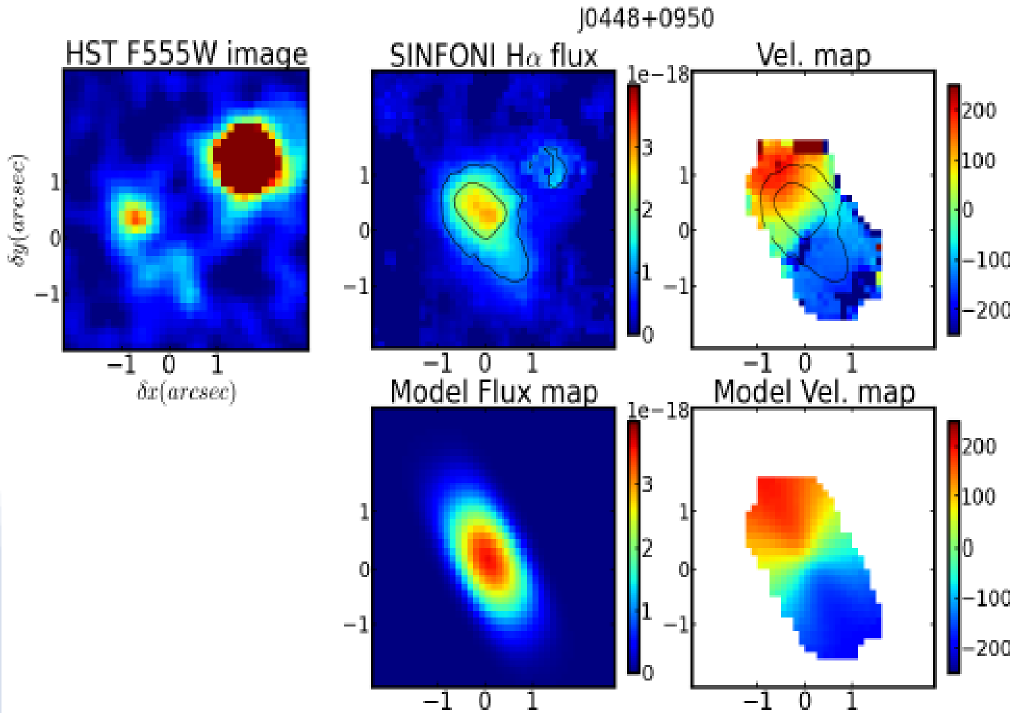
3D fitting with GalPak^{3D}

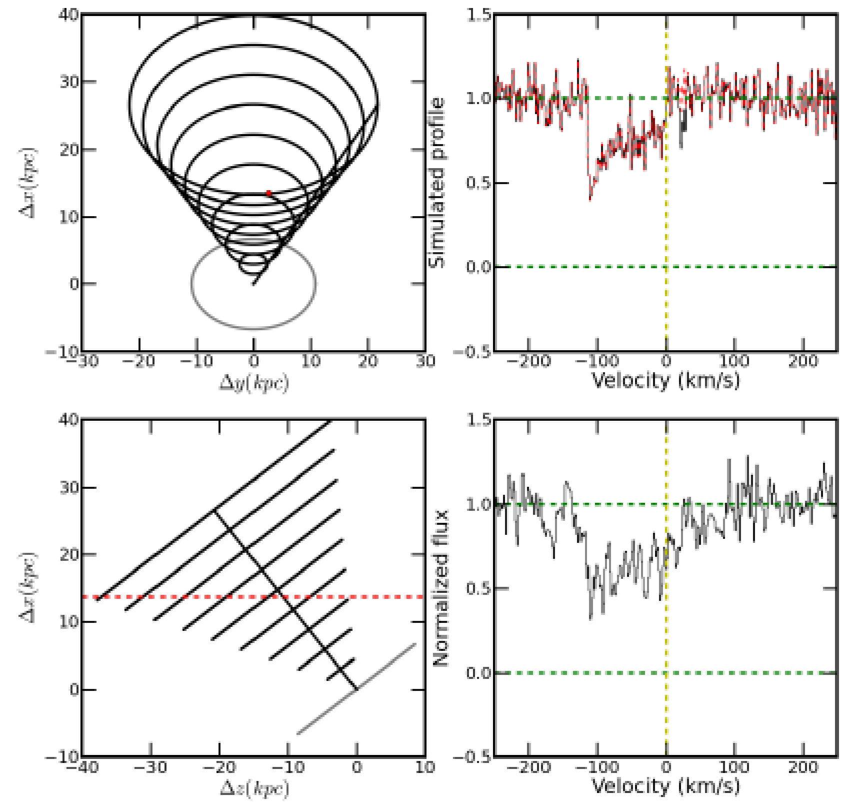
http://galpak.irap.omp.eu



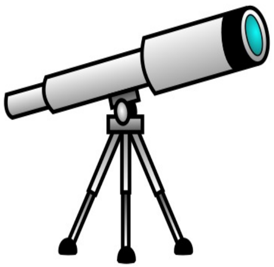


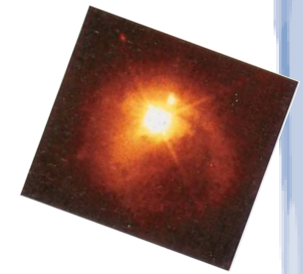
J0448

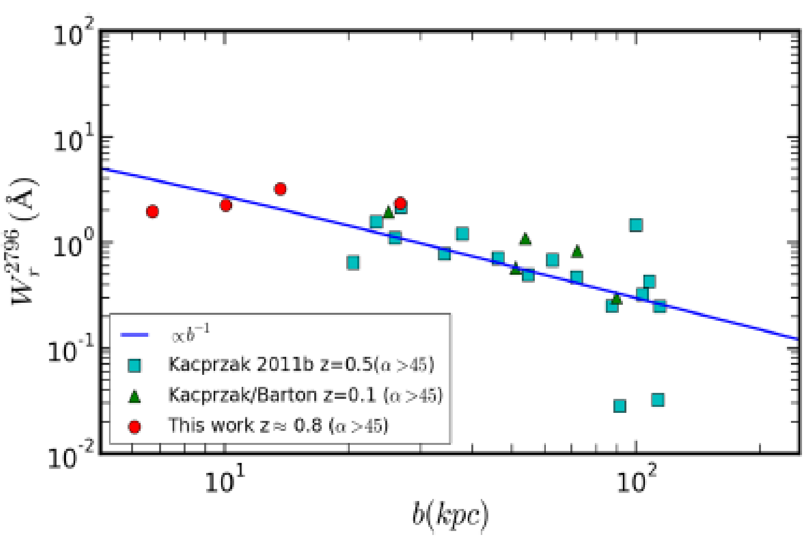

J0448+0950
HST F555W image
SINFONI Hα flux
Vel. map
Model Flux map
Model Vel. map
δy(arcsec)
δx(arcsec)
1e−18


Δx(kpc)
Δy(kpc)
Δz(kpc)
Simulated profile
Normalized flux
Velocity (km/s)

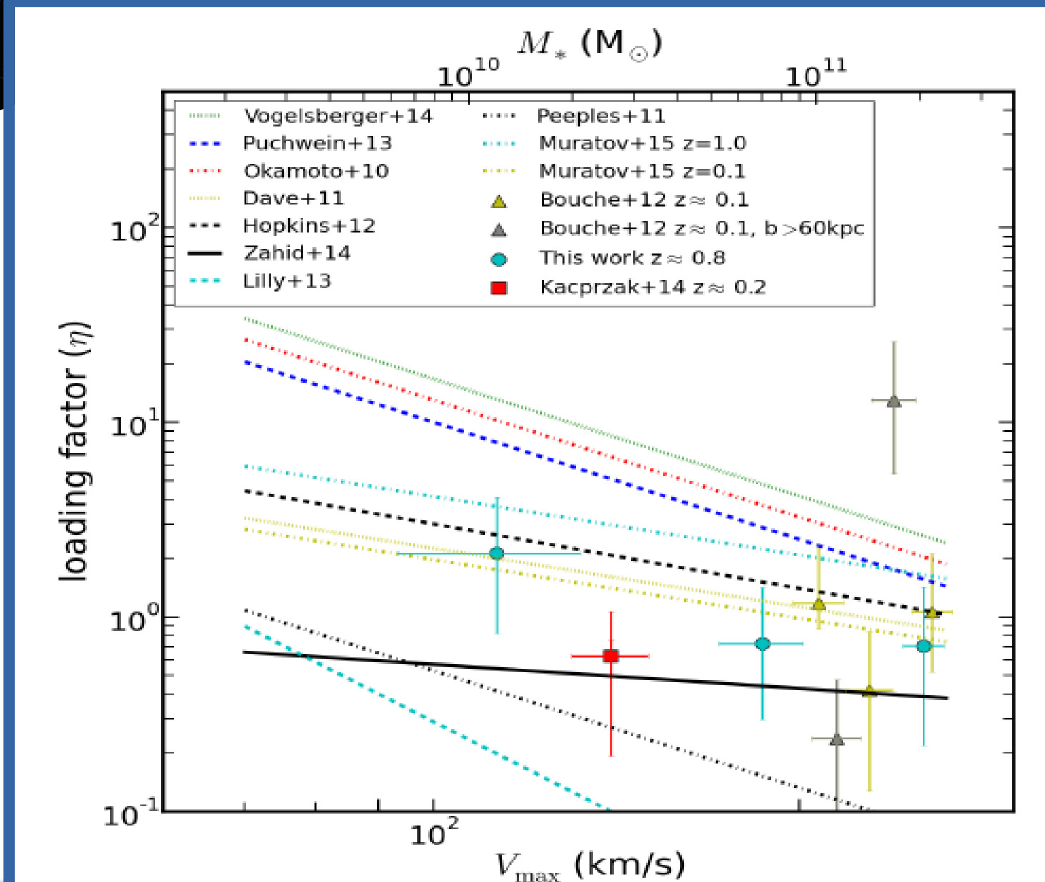
Winds properties from background QSOs



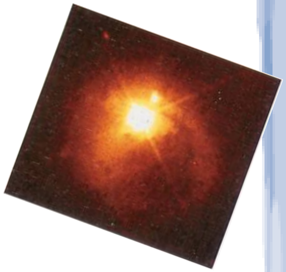




Schroetter et al. 2015



Outflow properties from background QSOs



- Does wind escape ?
  - ~~$V_{wind} > V_{esc}$~~ NO
- How far do they travel ? b^{-1} up to 100 kpc
- Does wind carry enough mass?

$$\eta \equiv \dot{M}_{\rm out}/{\rm SFR}$$

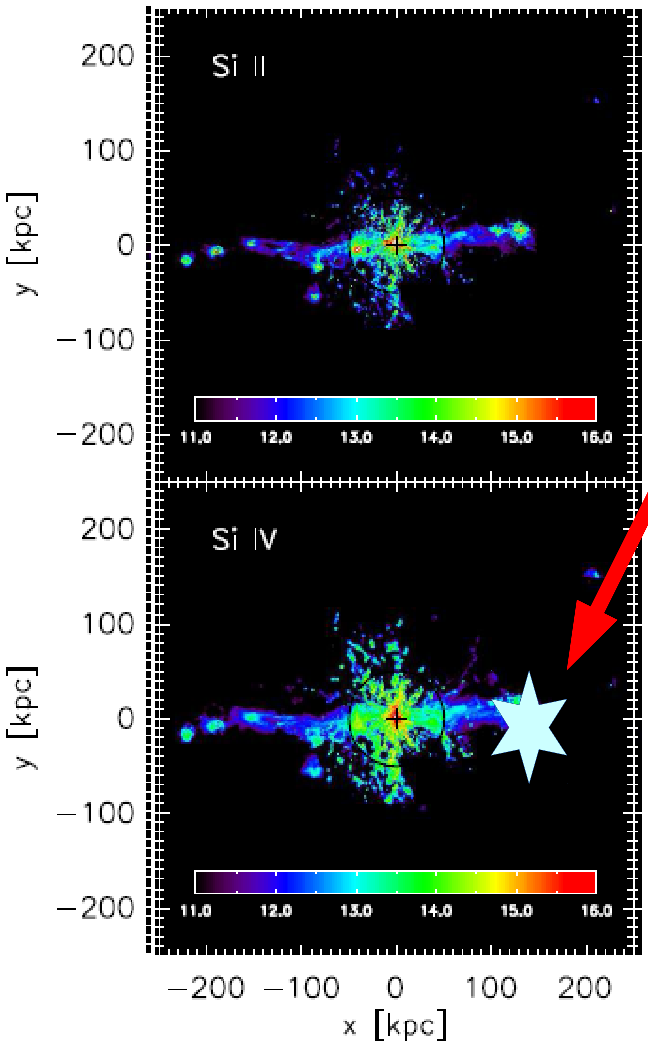
Stay tuned:

$\sim V^{-1 \text{ or } -2 \text{ or } -4}$

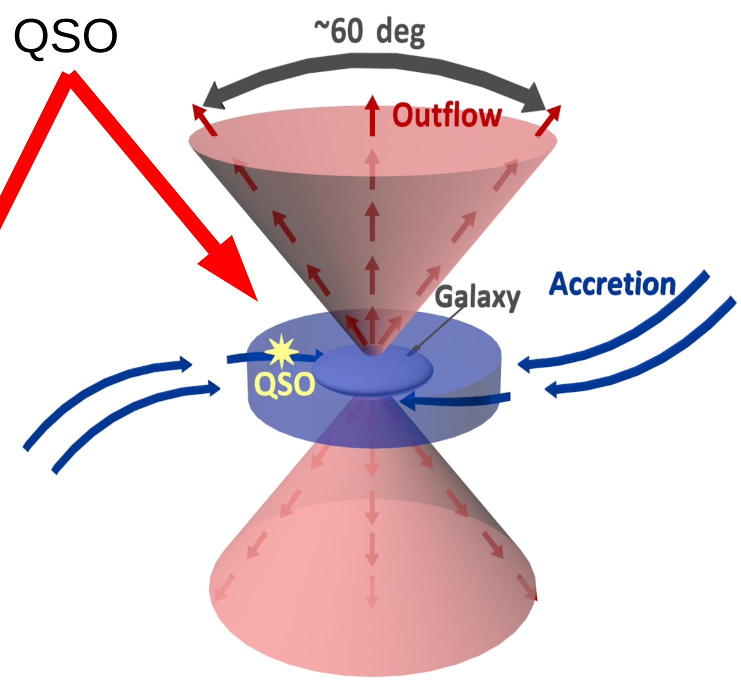
see Schroetter Thesis

Inflows/Outflows are not co-spatial

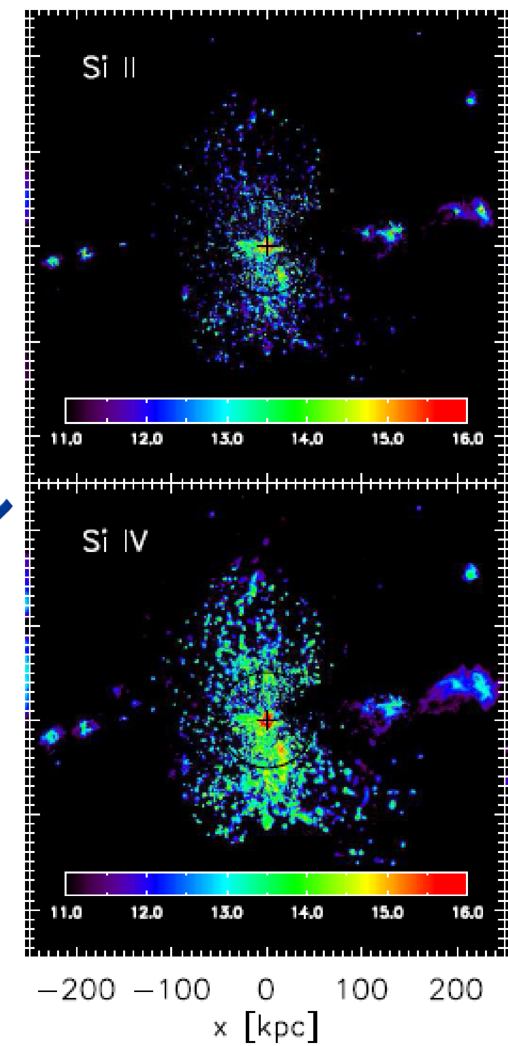
Shen, Madau et al. 2013
Also Stewart et al. 2011,
Goerdt/ Brook /Wetzel's talk ...



Inflowing particles



Credit: I. Schroetter



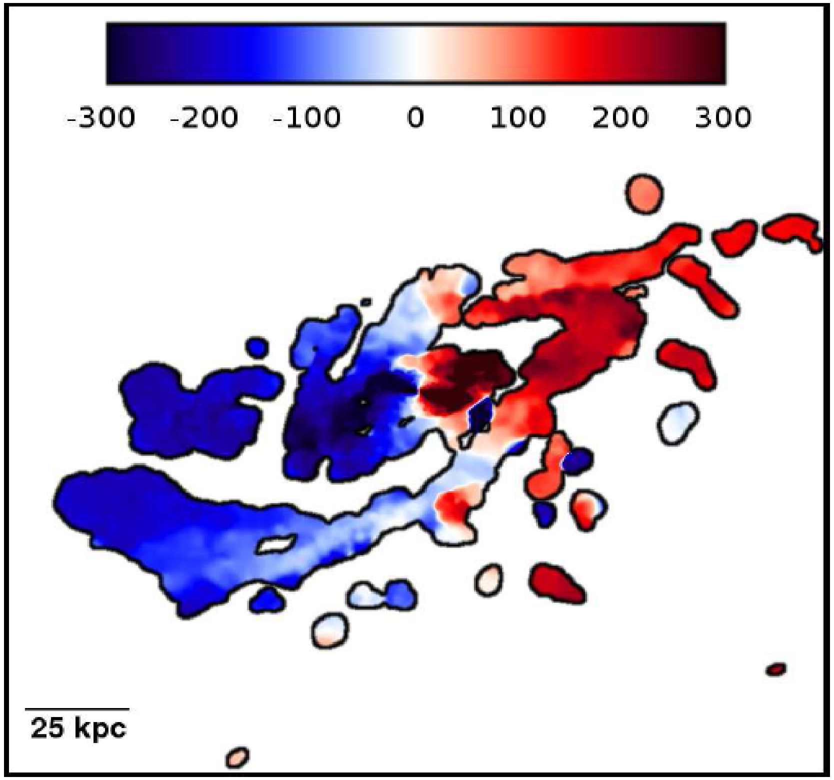
Outflowing particles

Accretion with absorption line

- Cold gas co-rotating,
- ~co-planar

GASOLINE SPH

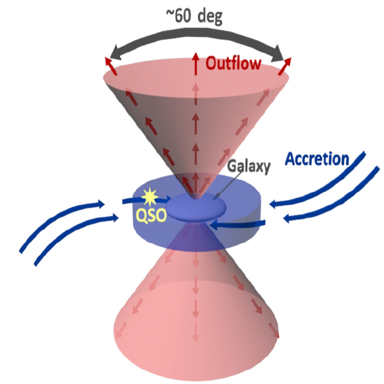
K. Stewart et al. 2011



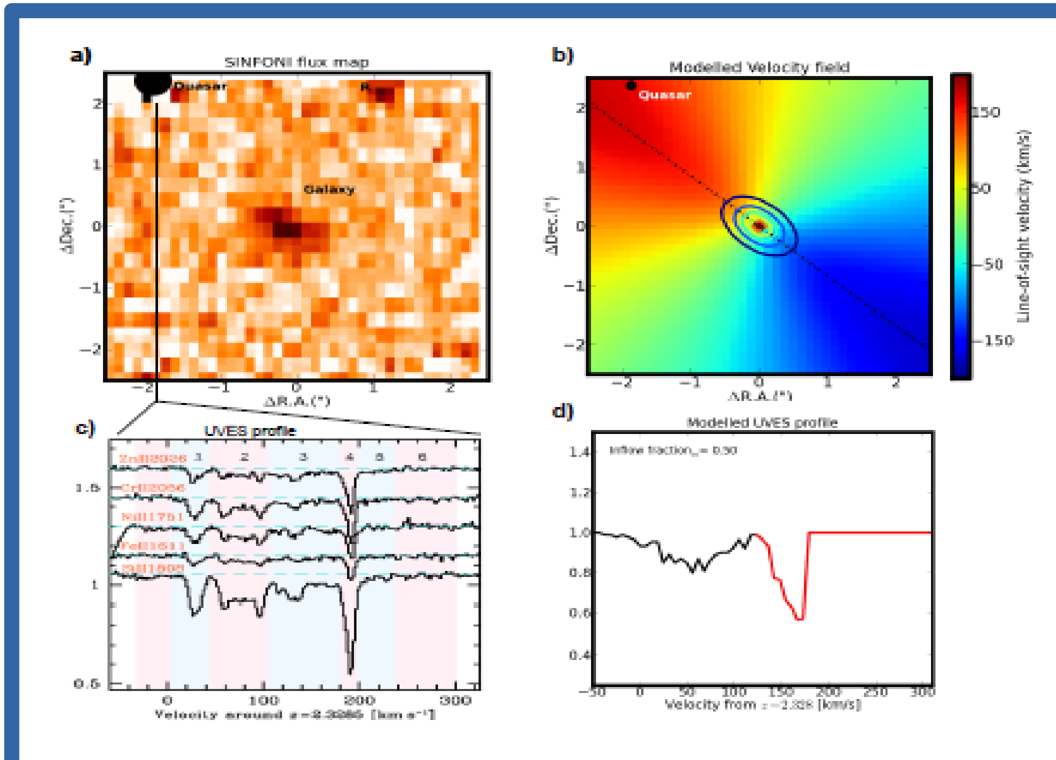
“ disk. This signature of cosmological accretion should be observable using background-object absorption line studies as features that are offset from the galaxys systemic velocity by $\sim 100\ \mathrm{km\,s^{-1}}$. In most cases, the accreted gas co-rotates with the central disk in the form of a warped, extended cold flow disk, such that the observed velocity offset will be in the same direction as galaxy rotation. This prediction provides a means to observationally distinguish accreted gas ”

Also Fumagali et al 2011; Goerdt et al. 2012; Van de Voort & Schaye J 2012;

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

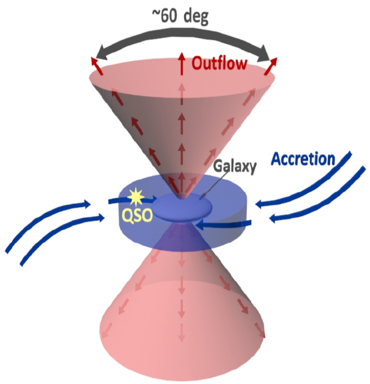


Bouché et al. 2013, Science

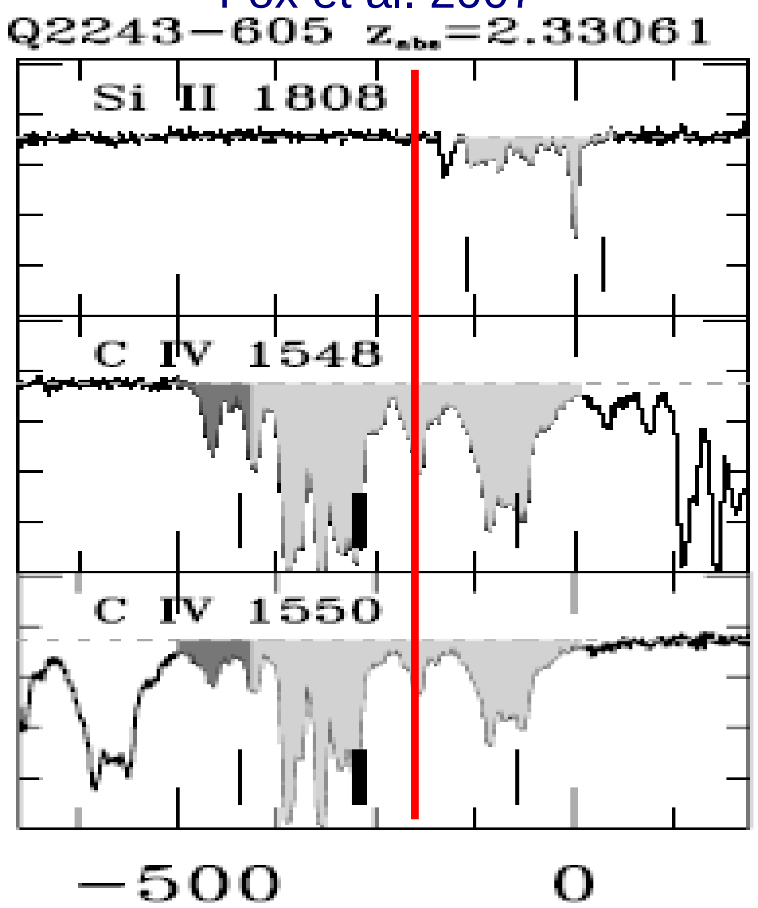


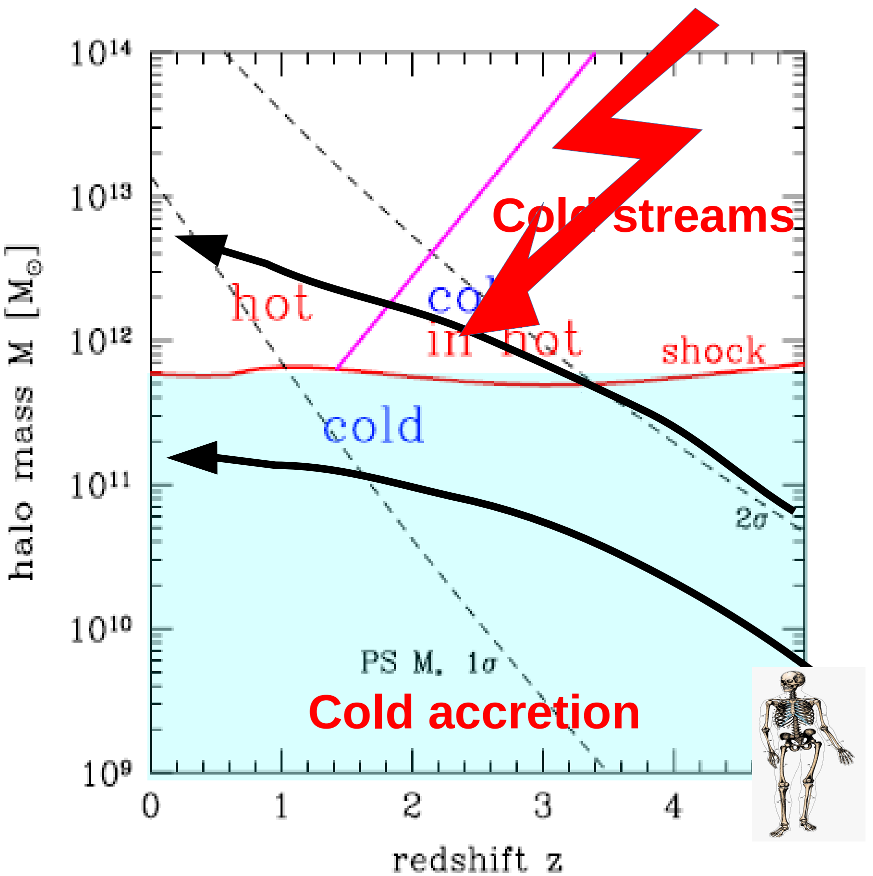
→ Vin, b, NH → **dM/dt ~ SFR !**

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

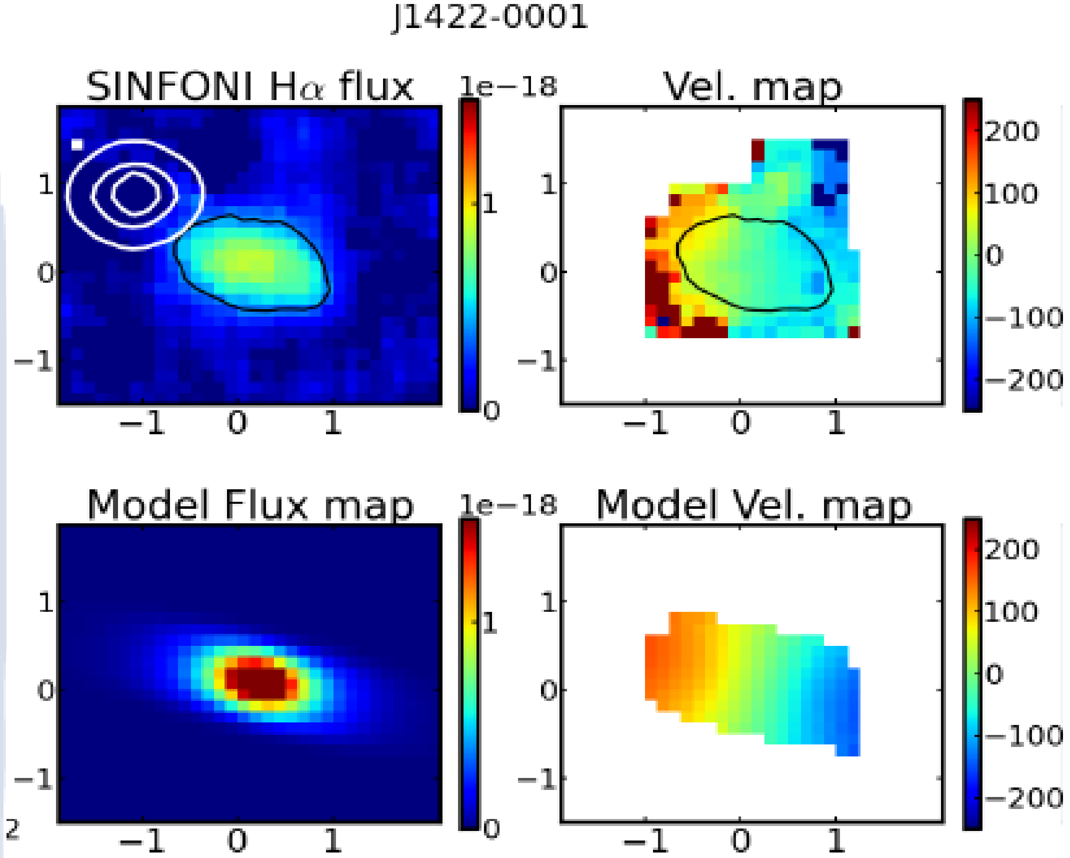


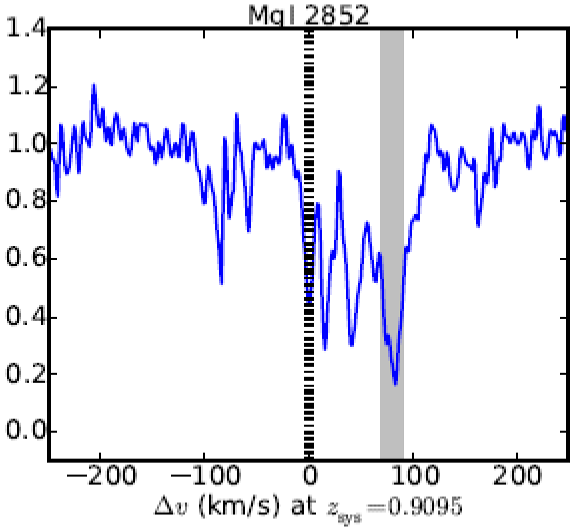
Fox et al. 2007



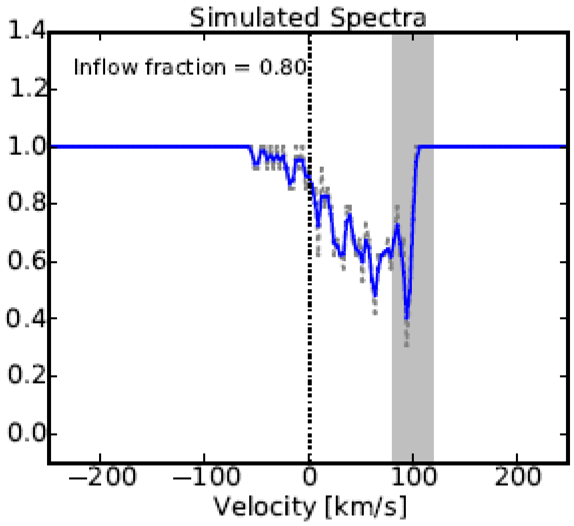


Another accretion? J1422-001





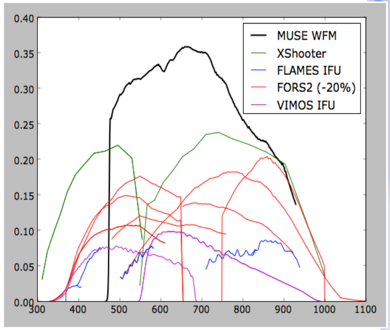
(b)

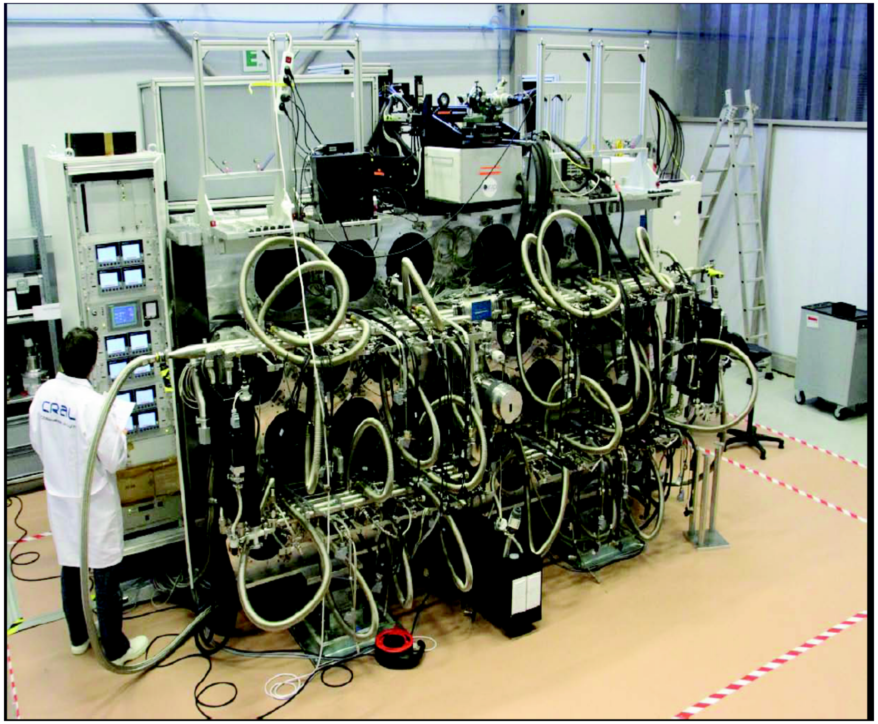


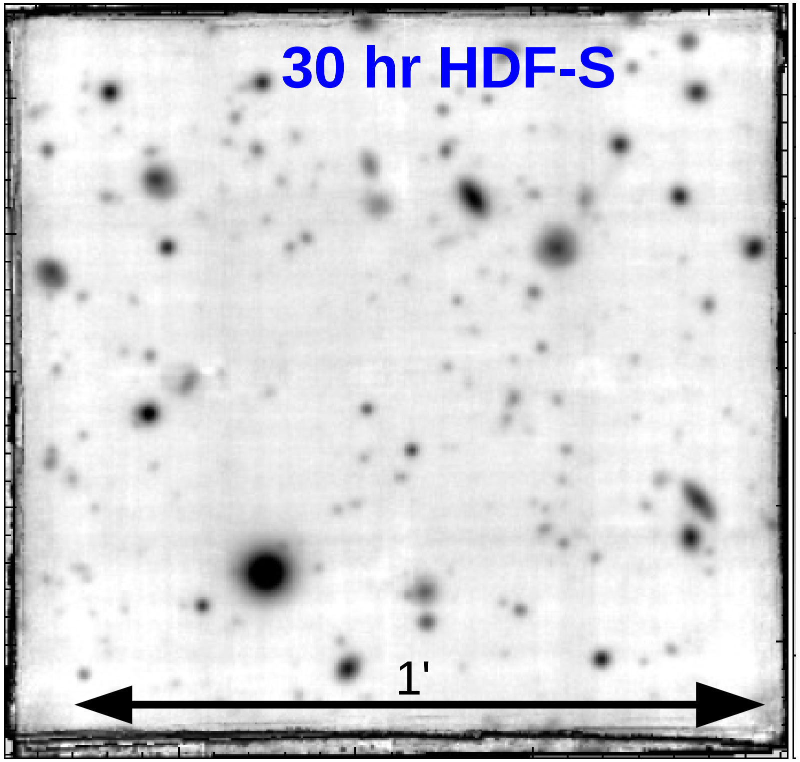
Probing IGM with muse

multi unit spectroscopic explorer

- Giant IFU 1'x1' 0.2"/pix (0.5 – 0.95μm)
  - AO
  - Flux(30hr) > 1e-19 erg/s/cm2/arcsec2



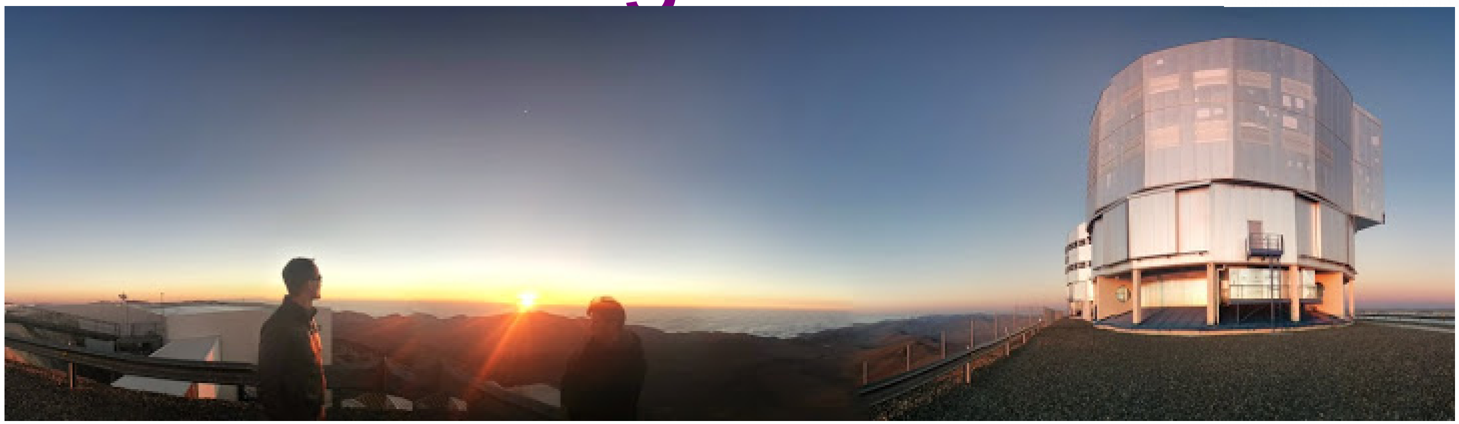


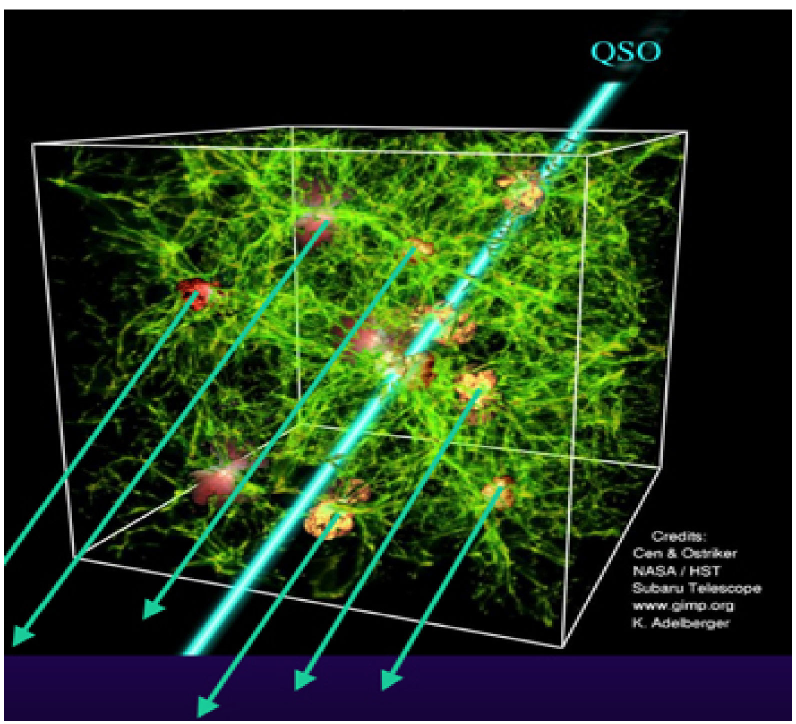


Bacon et. 2014 (1411.7667)

Probing IGM with MUSE

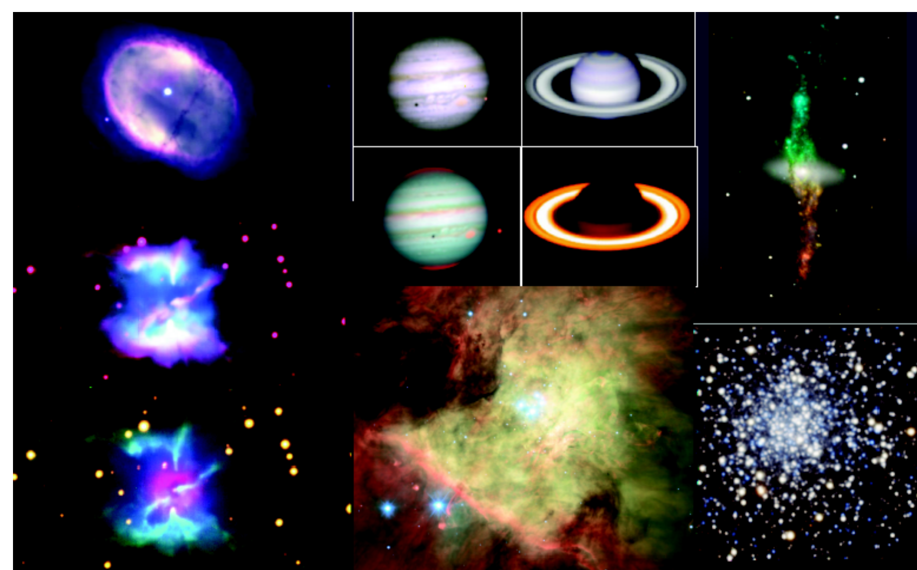
multi unit spectroscopic explorer





L. Straka's talk

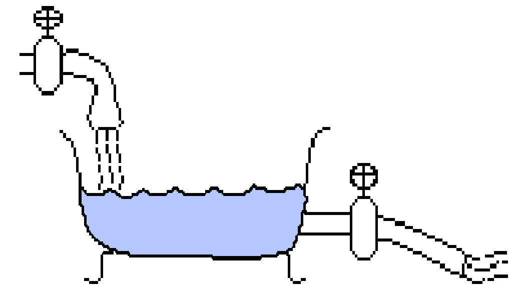
Fov: 1’x1’



Conclusions

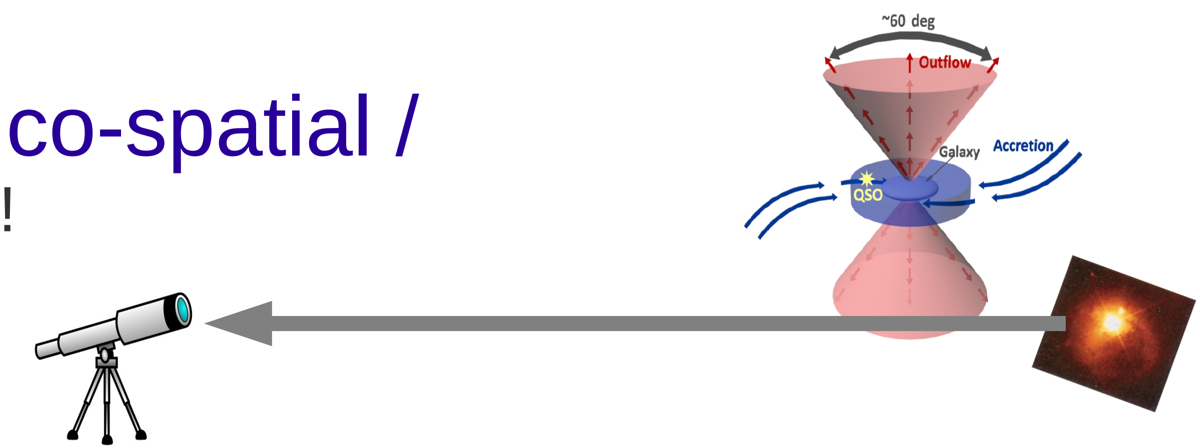
Galaxies are in *quasi*-equilibrium

- SFR follows accretion rate → Main-sequence
- Accretion drives galaxy growth, SFR(z), Mgas(z)
- MZR (in prep.)



In/Outflows are not co-spatial /

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



Stay tuned for more with MUSE

- MEGAFLOW: observations on winds/accretion
- Fluorescence emission (Cantalupo S.; Martin C.)
- Ly-gal IGM (Straka L.)
- IGM tomography