SUPERWINDS FROM MASSIVE STAR-FORMING CLUMPS AT Z~2

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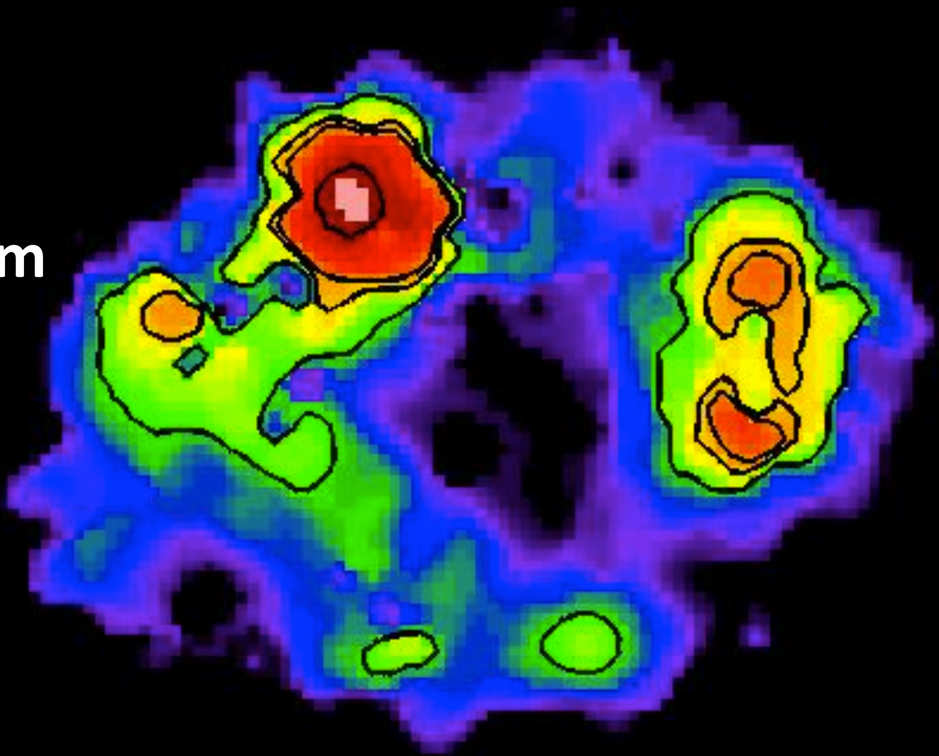
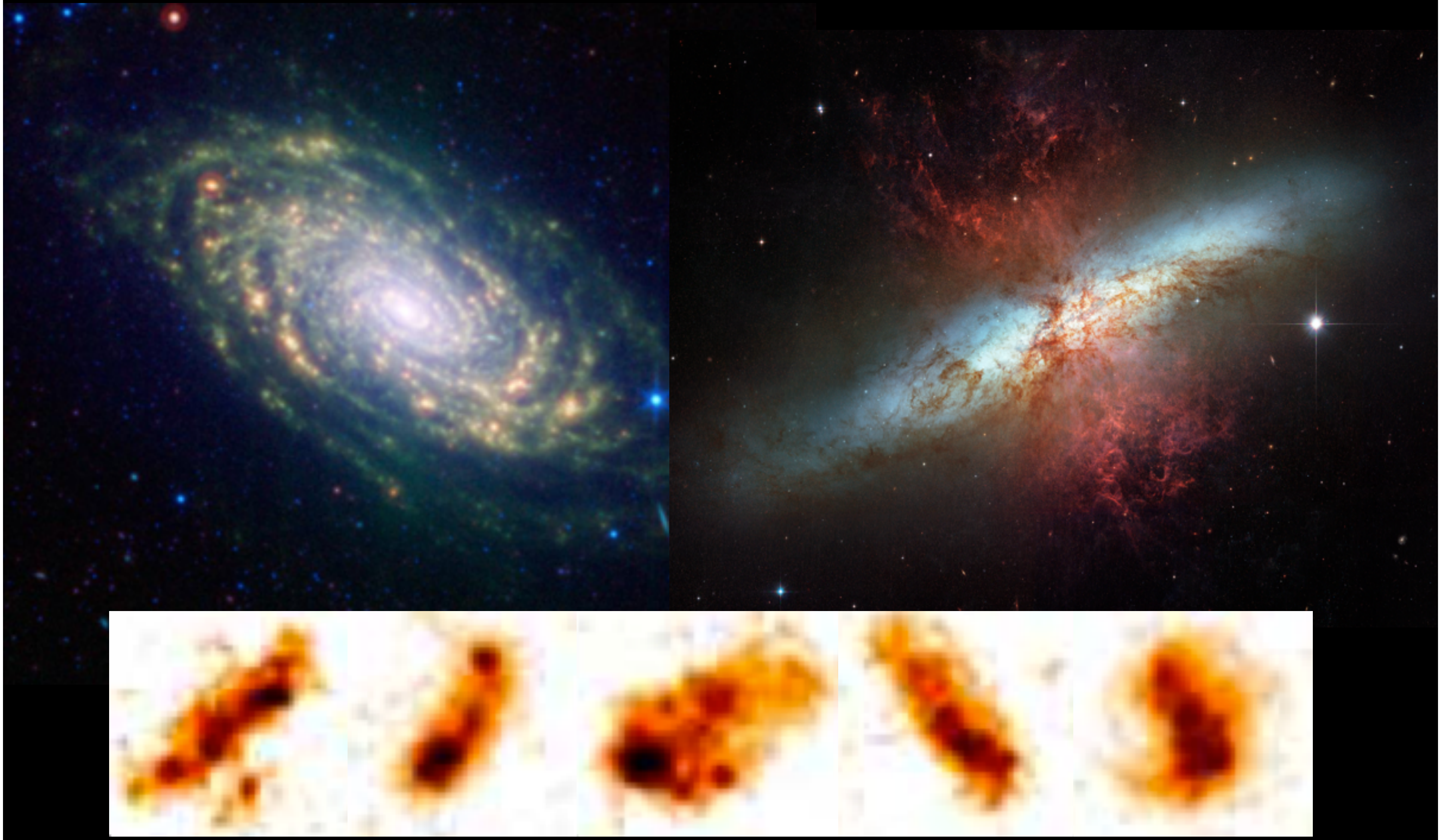
see Genzel et al. 2011:
arXiv: 1011.5360
Newman et al. in prep.



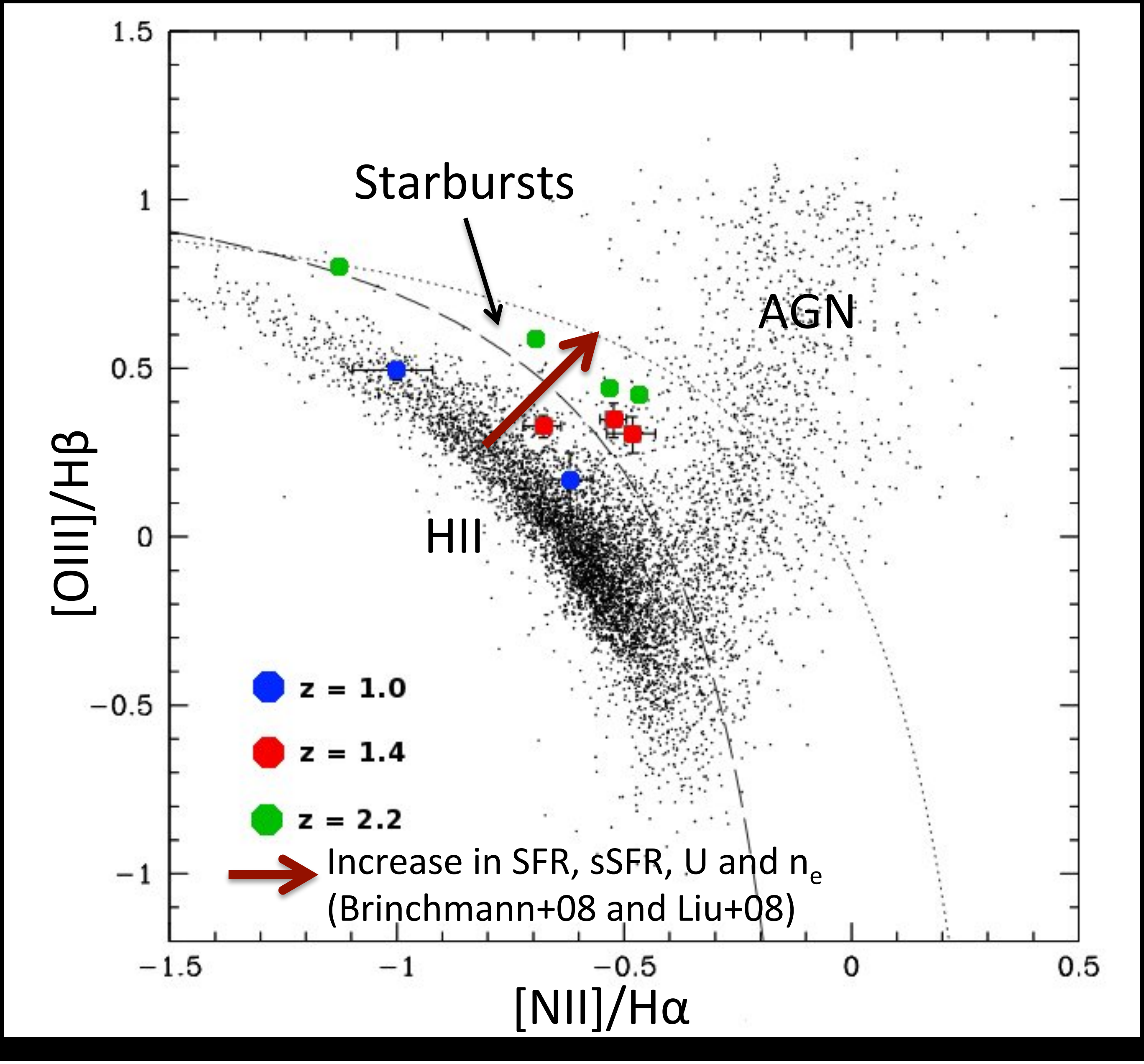
Understanding high-z SF



Forster Schreiber+11

BPT diagram with high-z galaxies

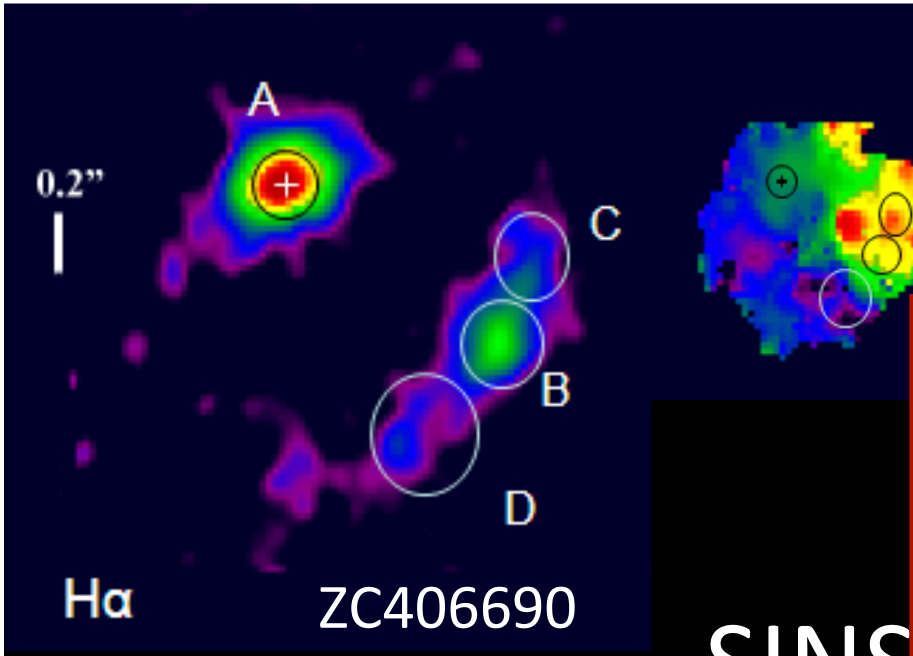
Kauffmann et al. 2003,
Shapley et al. 2005, Erb et al. 2006

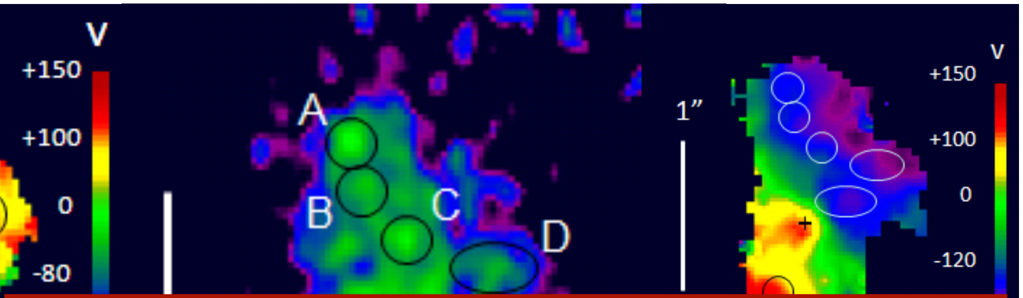


Increase in SFR, sSFR, U and n_e
(Brinchmann+08 and Liu+08)

Observations

- SINFONI/VLT IFU K-band spectroscopy with AO
  - 0.2” FWHM ~ 1.7 kpc
  - T_{int} = 2-18h
  - 0.05”/px
- J- and H-band with natural seeing
  - 0.6” FWHM ~ 5 kpc
  - T_{int} = 2h
  - 0.05”/px
- Selection:
  - ZC, D3a: rest-frame optically selected, with BzK color
  - BX: rest-frame UV selected, BX color
- Hα-bright, ~ 1 kpc clumps
- SFR and Σ_{gas} from $L_{H\alpha}$





SINS

~2 ga

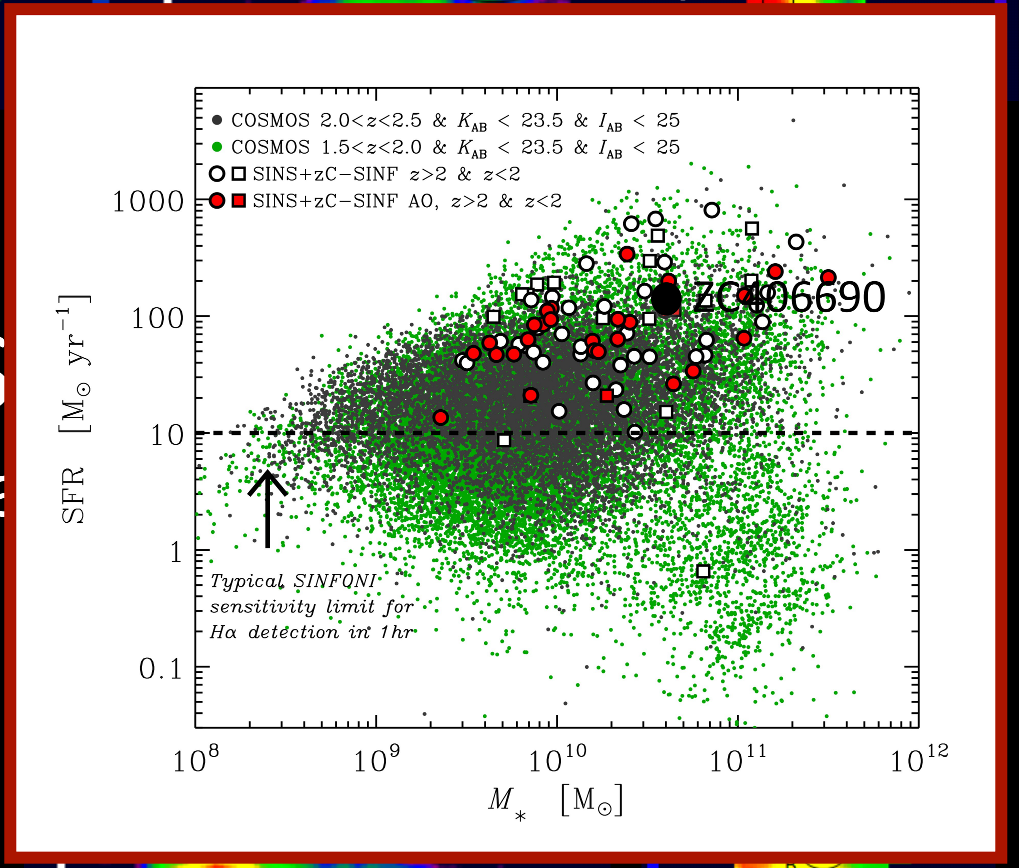
$SFR_{H\alpha}$ = 290 $M_\odot$/yr

M_* = 4.2x10^{10} $M_\odot$

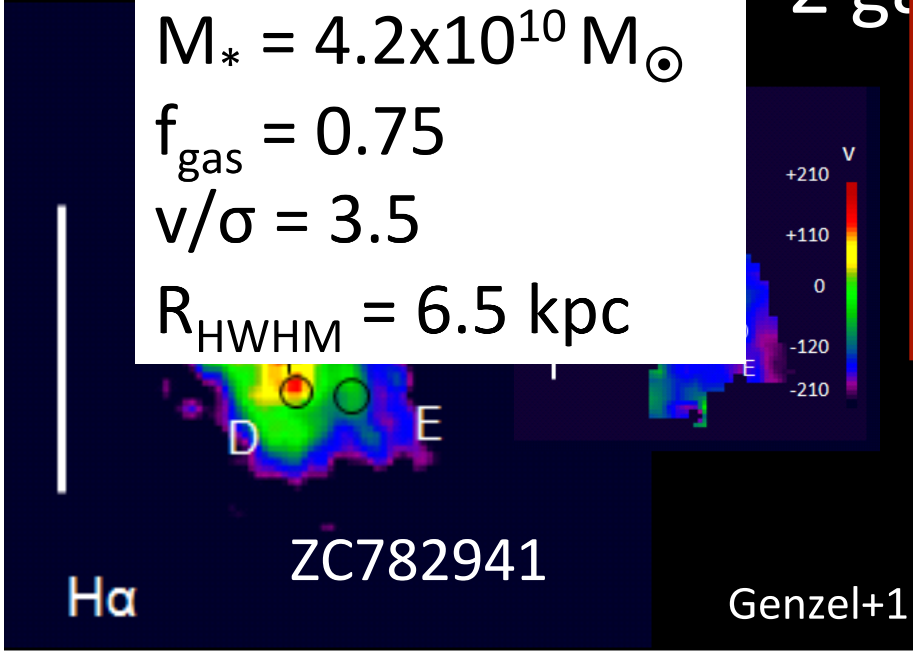
f_{gas} = 0.75

v/σ = 3.5

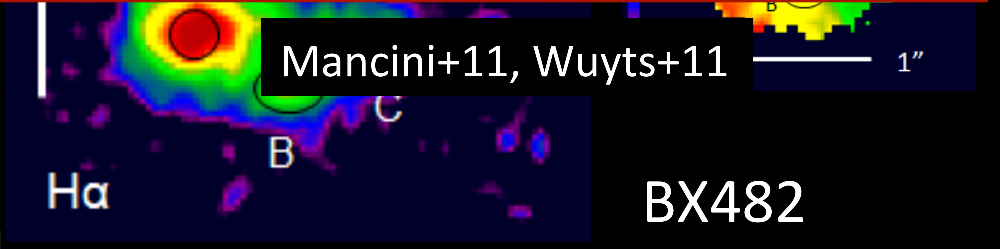
R_{HWHM} = 6.5 kpc



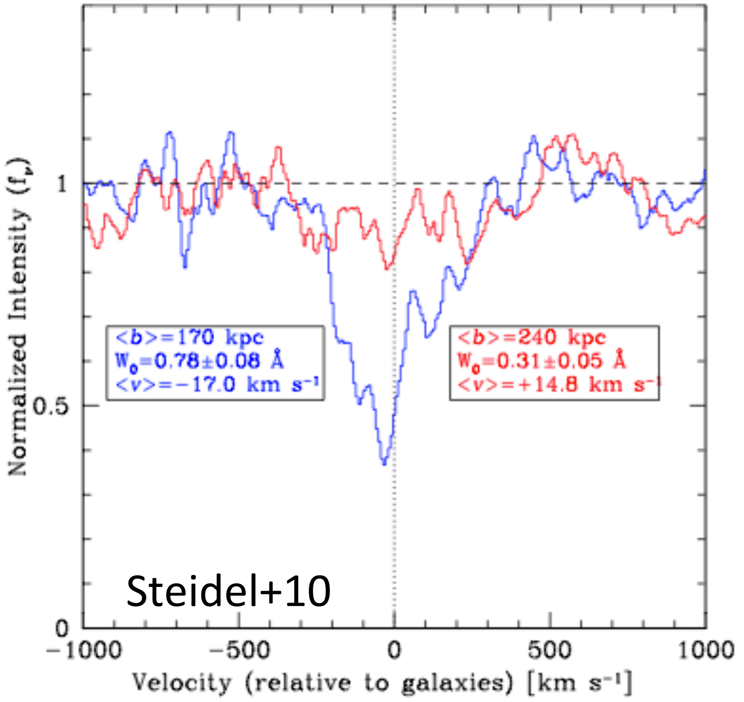
Mancini+11, Wuyts+11



Genzel+11

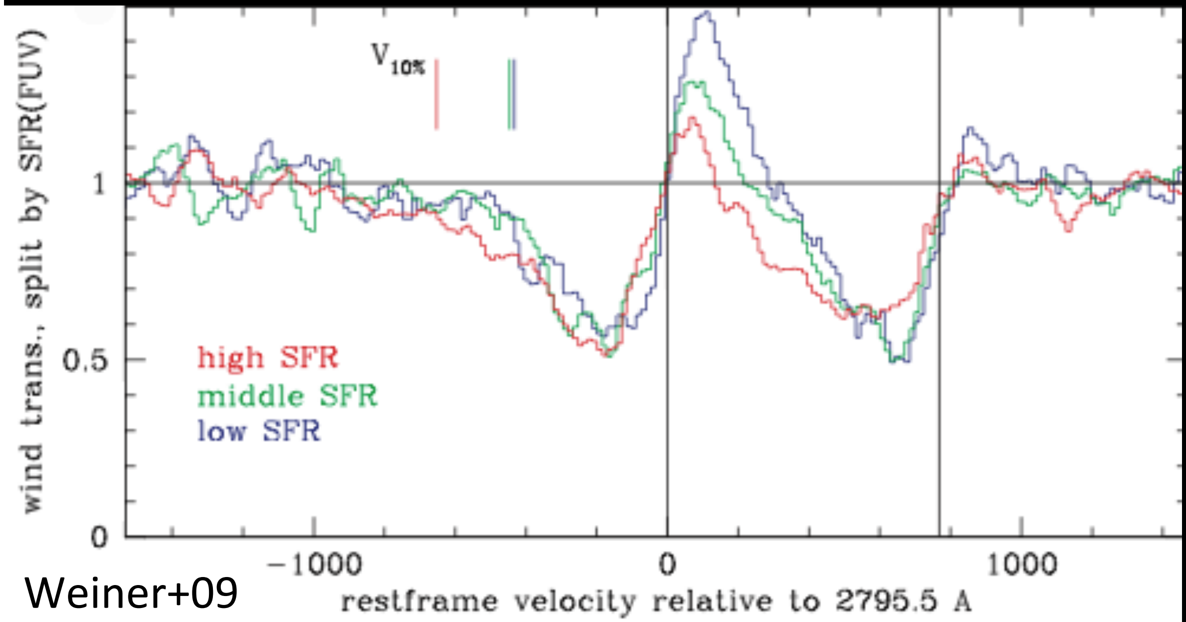


Superwinds



Steidel+10

NGC 3079. HST + CXO. Veilleux+05

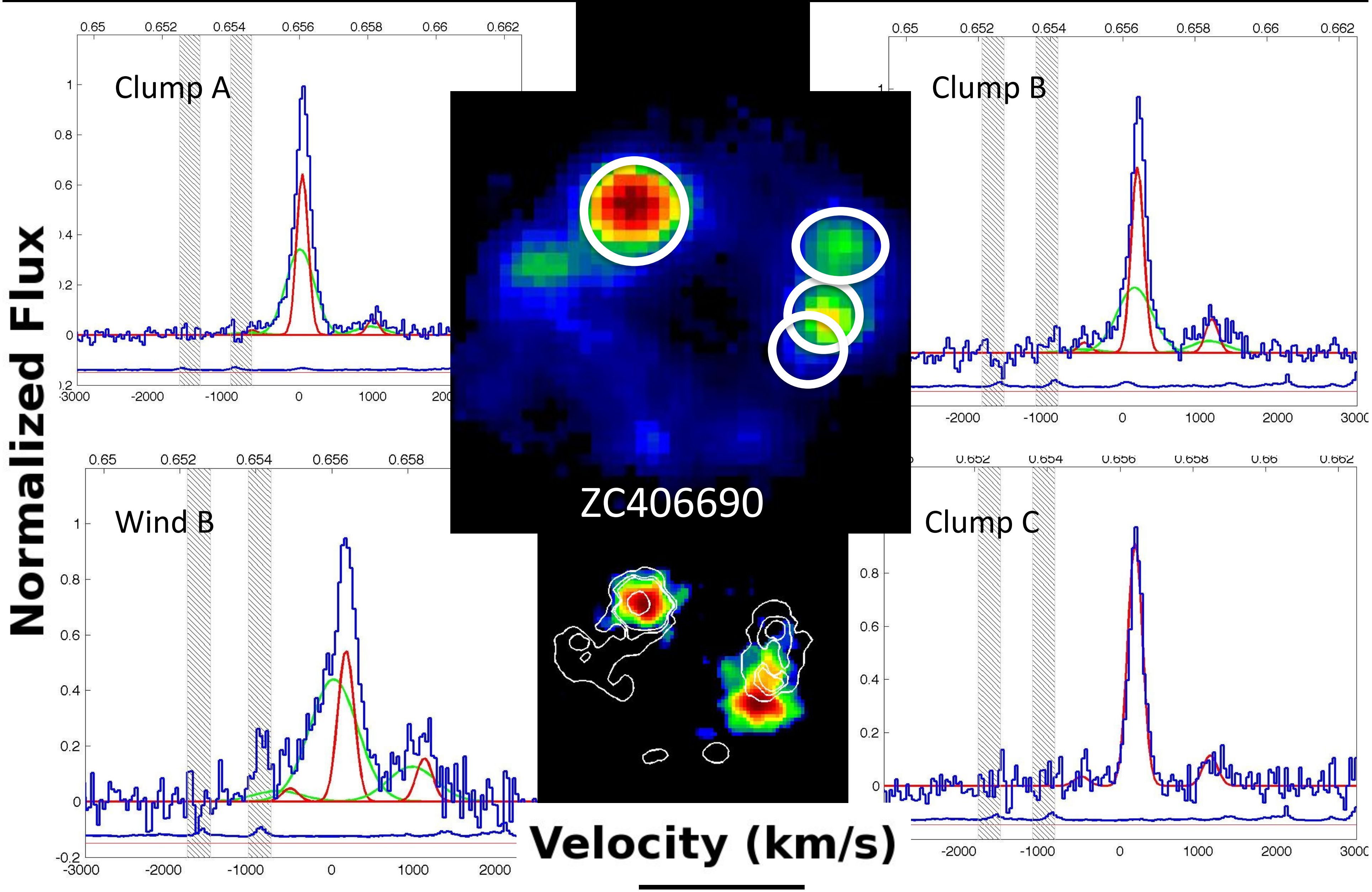


Weiner+09

At High-z:

- Winds are ubiquitous
- Not spatially resolved

Broad Hα emission from winds



Outflow rates for clumps

- Outflow of gas into solid angle Ω
  - case B photoionization with $T = 10^4$ K

$L_{H\alpha,br} \approx \gamma_{H\alpha} n_e n_p dV$

$M_{H+} \approx \mu n_p dV \approx \mu L_{H\alpha}/\gamma_{H\alpha} n_e$

$\dot{M}_{H+} \approx M_{H+} v_{wind}/R_{out}$

$n_{e,wind} \leq 100\ \mathrm{cm}^{-3}$

$V_{wind} \sim 500$ km/s

$R_{out} \sim 1$ kpc

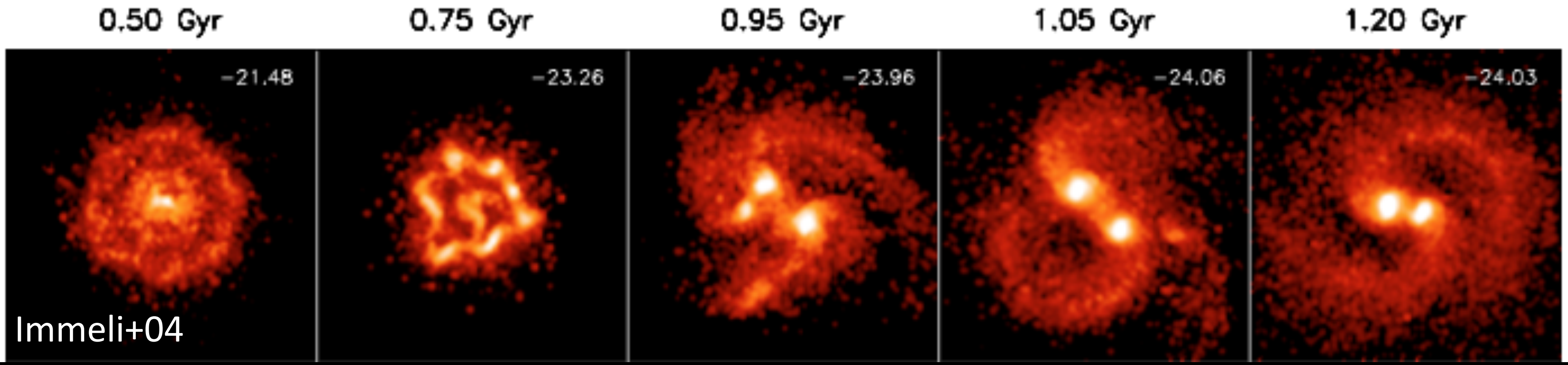
- Warm ionized component only, neglecting hot ionized gas (x-rays), molecular and atomic gas
- Outflow rates for individual clumps:

$10 - 200\ M_{\odot}/\mathrm{yr} \sim 1\text{-}8 \times \mathrm{SFR}$

vs. $\dot{M}_{out} \geq \mathrm{SFR}$ (Steidel+10, Pettini+00, Weiner+09)

Can clumps inspiral to form bulge?

- $t_{expulsion} \sim f_{corr} * M_{clump,mol} / \dot{M}_{out} \sim$ **150-1500 Myr**
- $t_{migration} \sim (v_c/\sigma)^2 * t_{dyn} <$ **0.5 Gyr** (Noguchi 99, Immeli+04)



Immeli+04

Simulations: (Elmegreen+09, Ceverino+08) find long lived clumps, (Oppenheimer and Dave 06 and S. Genel+10) find clumps disrupted in 50-100 Myr

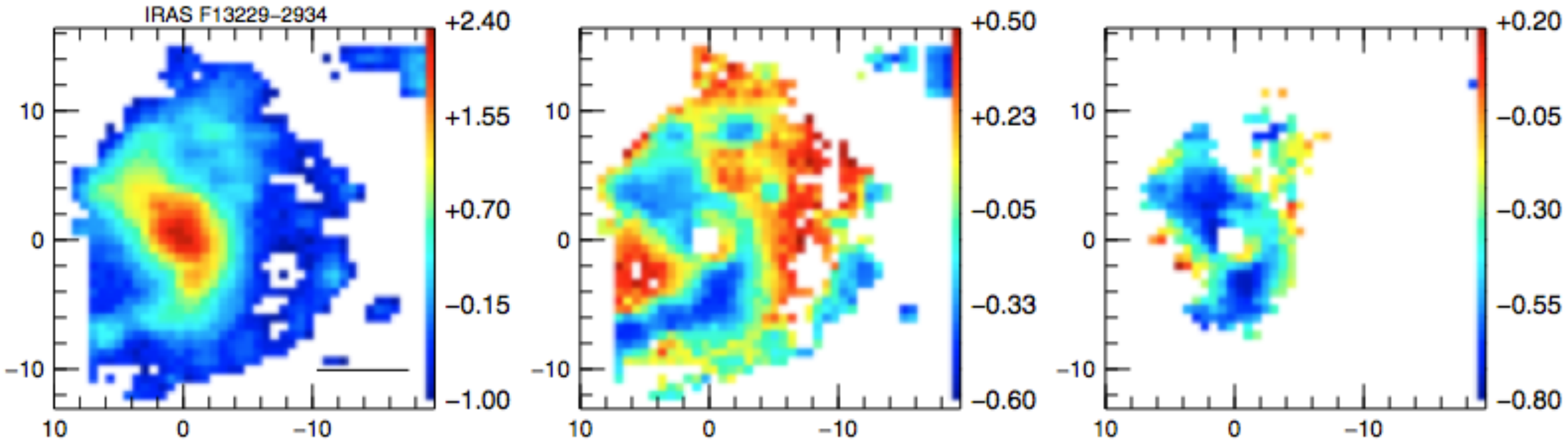
Observations: Forster Schreiber+11, Wuyts+09, Elmegreen+09

Shocks in (U)LIRG winds

- Caused by AGN, tidal torques, SF
- Shocked regions characterized by

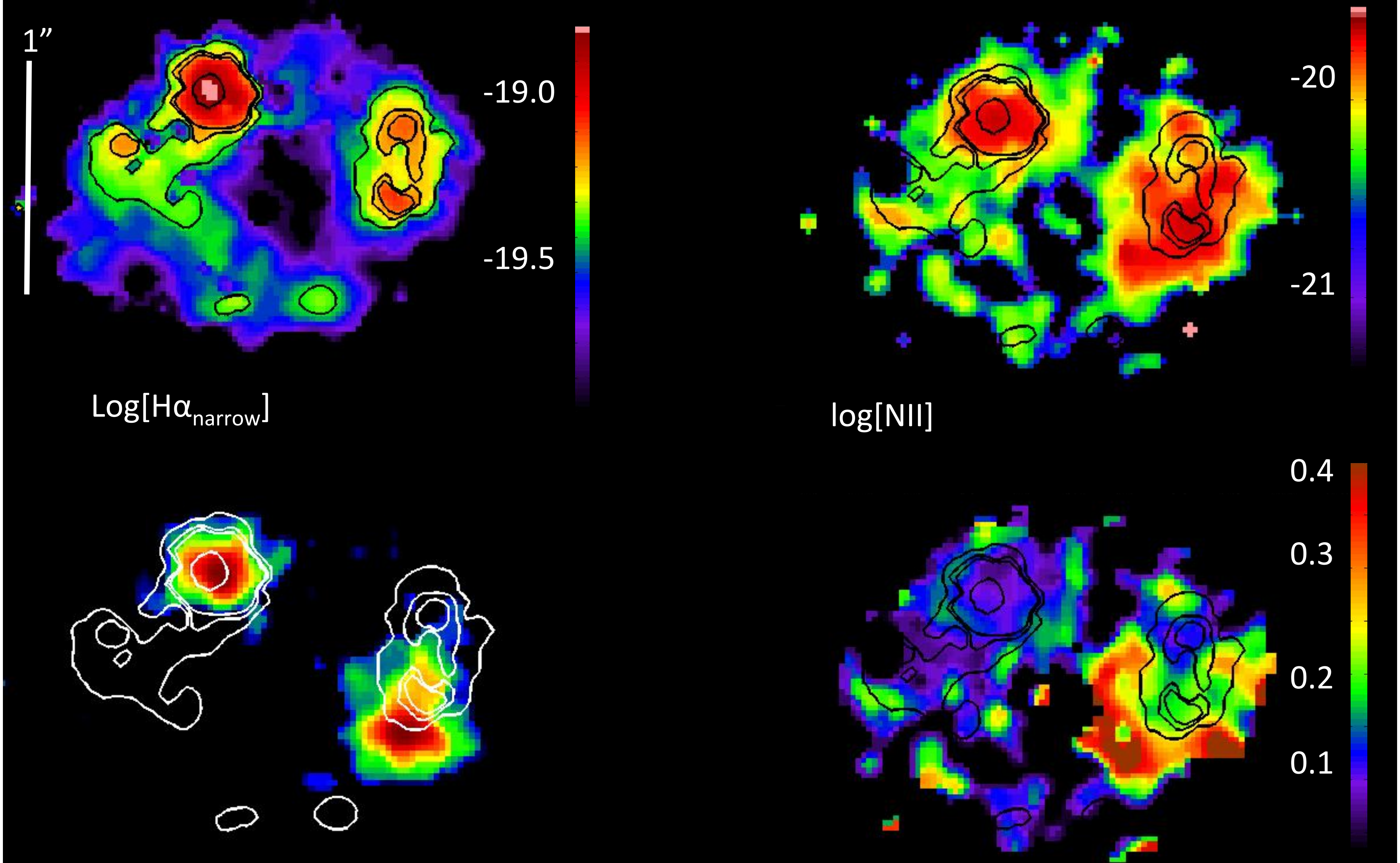
  [NII]/Hα > 0.5 & [SII]/Hα > 0.3

Monreal-Ibero+10



Hα NII/Hα SII/Hα

ZC406690 line maps



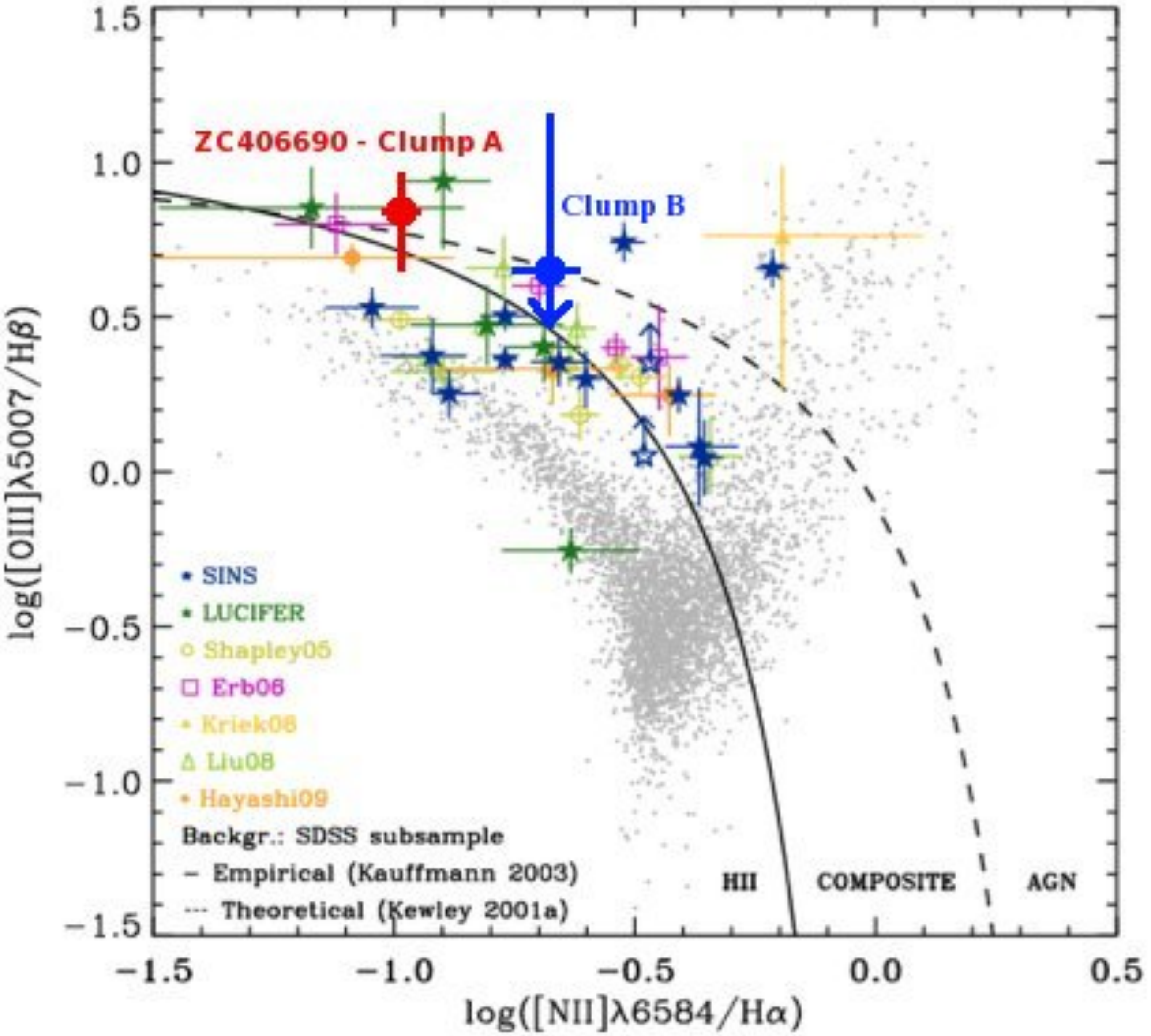
Log[$H\alpha_{narrow}$]

log[NII]

Log[$H\alpha_{broad}$]

[NII/Hα]

BPT with SINS/Lucifer

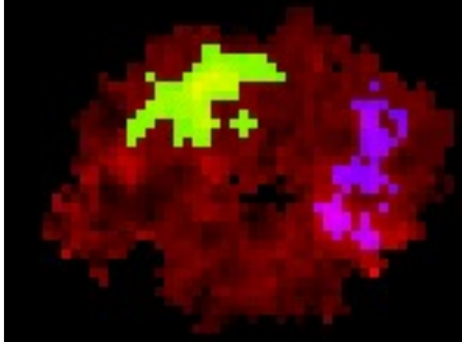


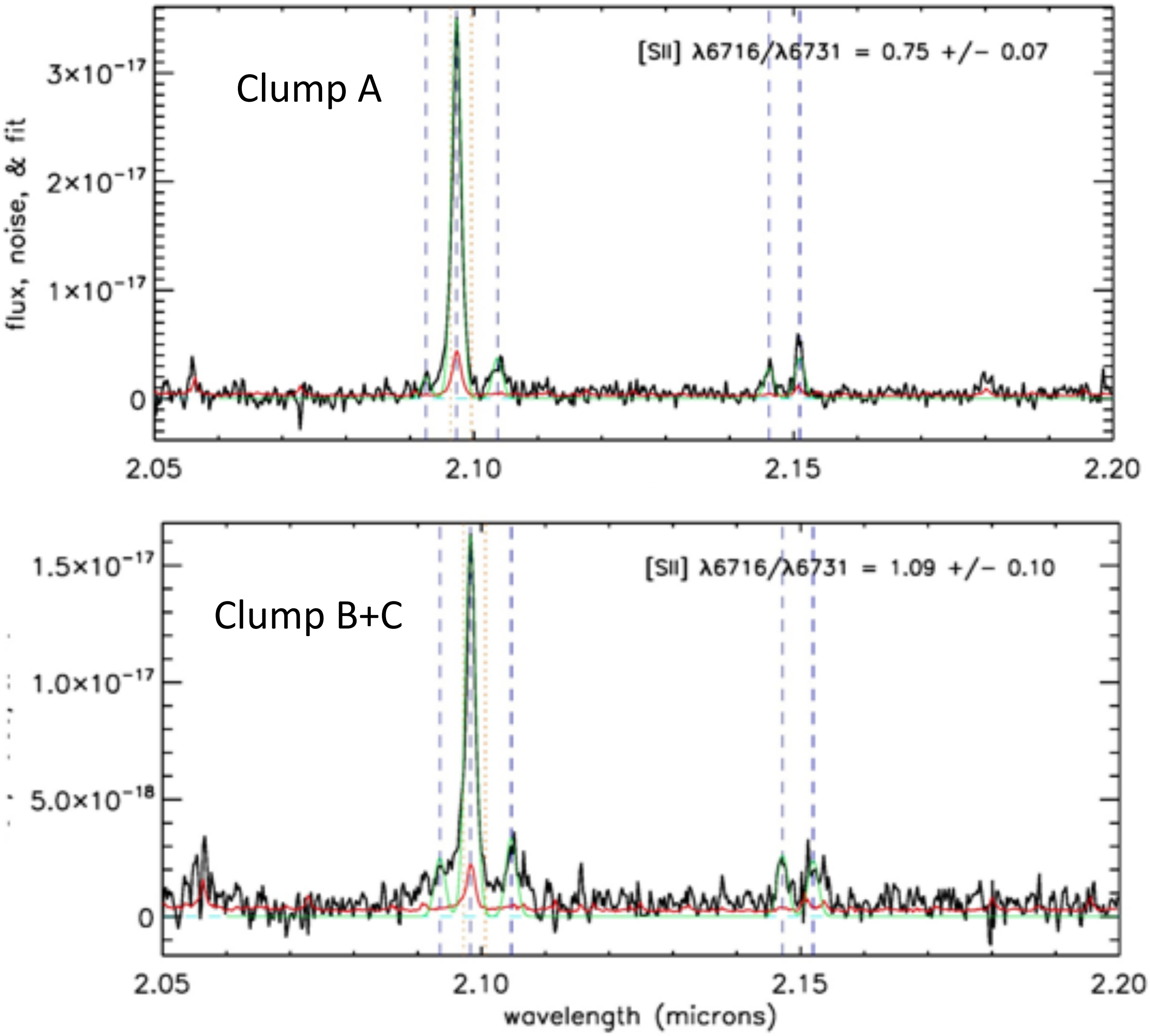
Buschkamp, Kurk et al. in prep

Summary

- SF in z~2 SFGs occurs in ~ 1 kpc clumps outside the center, which are more similar to starbursting regions than normal HII regions.
- Winds with Δv ~ 100s km/s and $\dot{M}_{out}$ ~ 1-8 x SFR originate from clumps
- Some clumps disrupted by winds ~ 100 Myr
- Broad region corresponds to increased [NII]/Hα and [SII]/Hα
- Winds may contain shocks, partially contributing to high velocity dispersions

SII – maximizing S/N





Clump Timescale

- SED modeling

t_{cl} ~ 100-300 Myr (Elmegreen+09, Maraston+10)

- Metallicity

t_{metal} ~ 300-1000 Myr (Erb 08, closed and leaky box)

- EW

t_{cl} ~ 30-800 Myr (Forster Schreiber+11)

- Exhaustion timescale

$t_{expulsion} \sim f_{corr} * M_{clump,mol}/M_{out}$ ~ **150-1500 Myr**

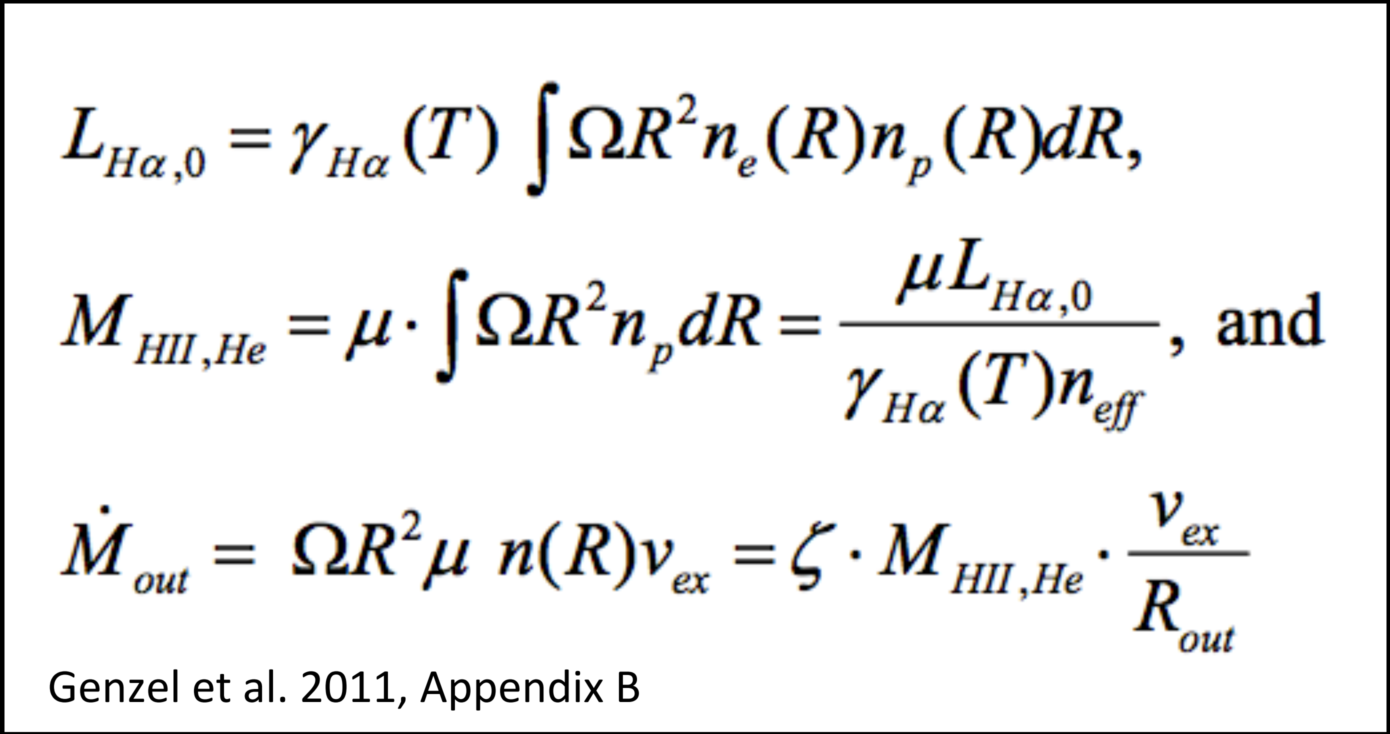
- TS explosion

$$R_s = 12.8\left(\frac{t_{exp}}{10^4}\right)^{2/5}\left(\frac{E_{51}}{n_0}\right)^{1/5} pc$$

$$E = \dot{M} v_{out}^2 t_{exp} \varepsilon_{ff}$$

t_{TS} ~ 100-400 Myr

Outflow model continued…



$$L_{H\alpha,0} = \gamma_{H\alpha}(T)\int \Omega R^2 n_e(R) n_p(R)\, dR,$$

$$M_{HII,He} = \mu \cdot \int \Omega R^2 n_p\, dR = \frac{\mu L_{H\alpha,0}}{\gamma_{H\alpha}(T) n_{eff}}, \text{ and}$$

$$\dot{M}_{out} = \Omega R^2 \mu\, n(R) v_{ex} = \zeta \cdot M_{HII,He} \cdot \frac{v_{ex}}{R_{out}}$$

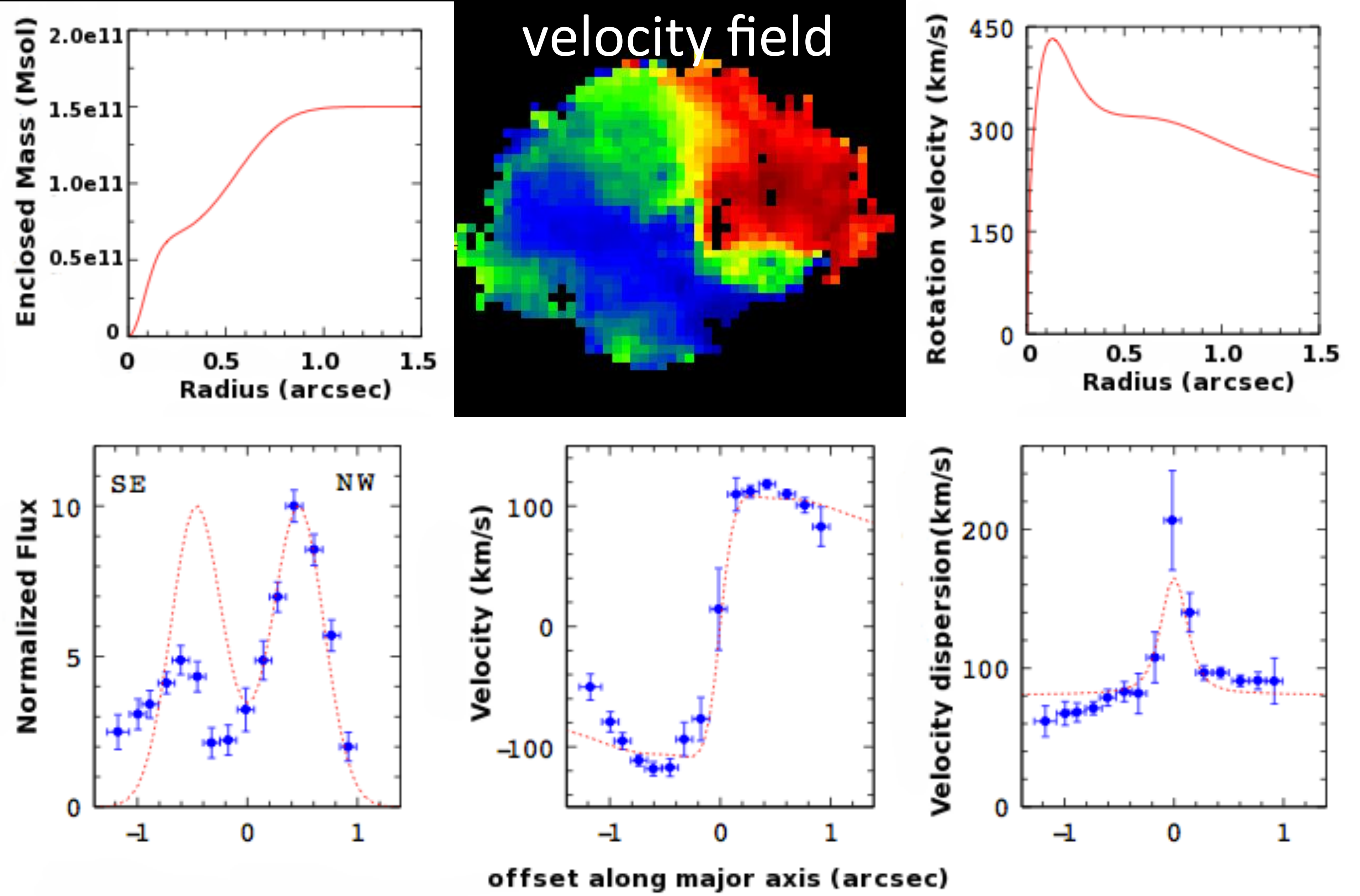
Genzel et al. 2011, Appendix B

- Model 1 (upper limit): $n_{avg} \sim R^{-2}$, $n_{eff} \sim 100\ cm^{-3}$, $R_{out} \sim R_{HWHM}$
- Model 2 (lower limit): n_{avg} and $n_{local} \sim R^{-2}$, $n_{eff} \sim n_{in}(R_{in}) \times R_{in}/R_{out}$,
  $R_{out} \sim R_{disk} \sim 10 \times R_{in}$, $n_{in} \sim n(SII)$, n_{cl_vir}, n_{KS}, $n_{gas\text{-}GMC}$
- ζ (geometrical factor) ~ 1, constant expansion velocity
- Models vary by x4-5

Ostriker and Shetty (2011) Model

- $P_{kin} = \rho_0 \sigma_z^2$
- $P_{weight} = \pi G \Sigma^2/2$
- $P_{turb} = f_p/4 \; p_*/m_* \; \Sigma_{SFR}$
- $P_{rad} = \varepsilon^* c \kappa_{IR} \Sigma \Sigma_{SFR}/4$
- $v_z = 2.3 \varepsilon_{eff} G \Sigma^2/\Sigma_{SFR}$

ZC406690 Central Mass


velocity field