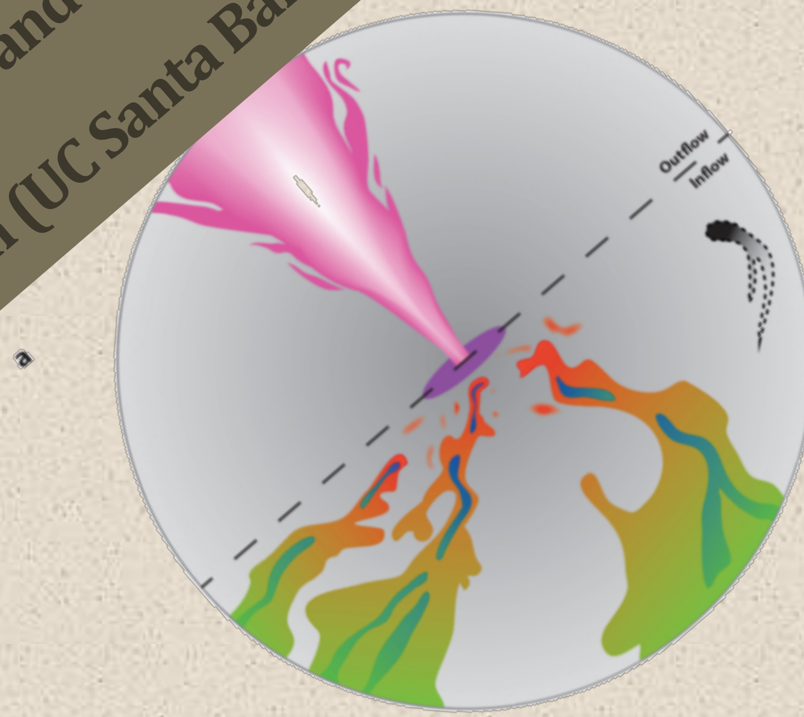
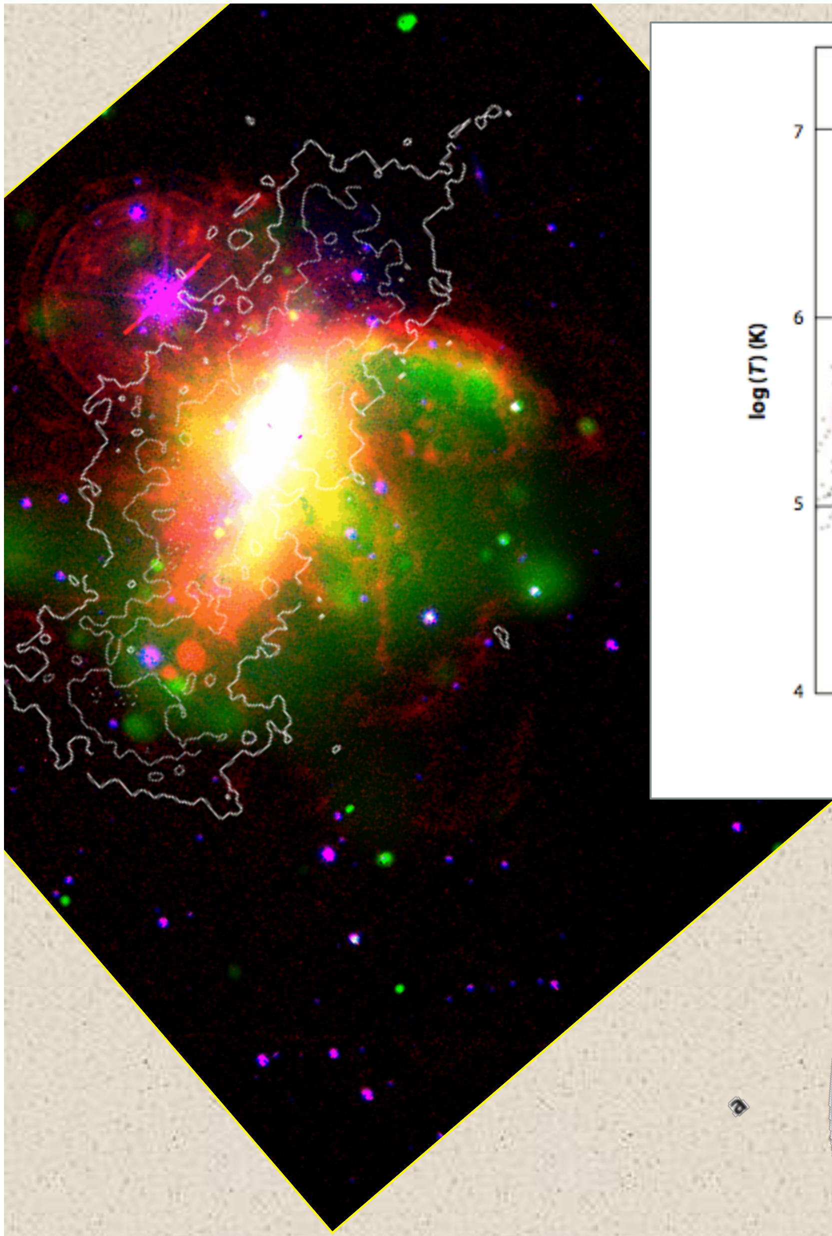
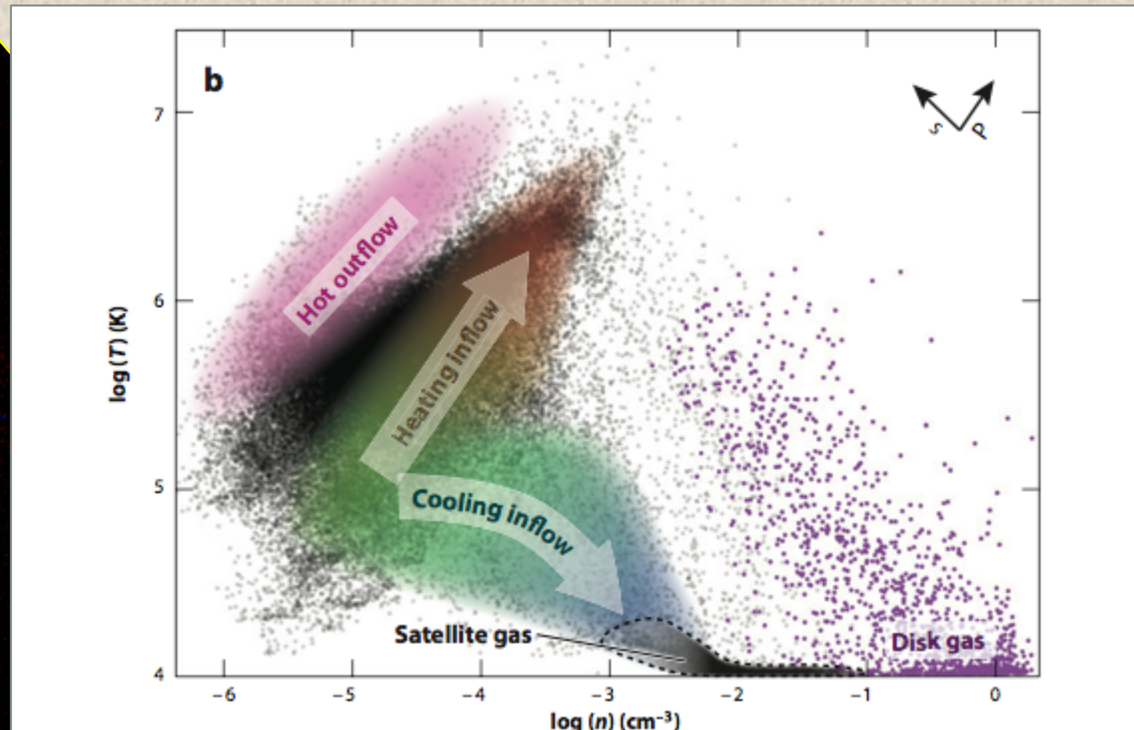
Feedback Challenges

"Connecting Theory and Observation"

Crystal Martin (UC Santa Barbara)







Putman, Peek, Joung 2012

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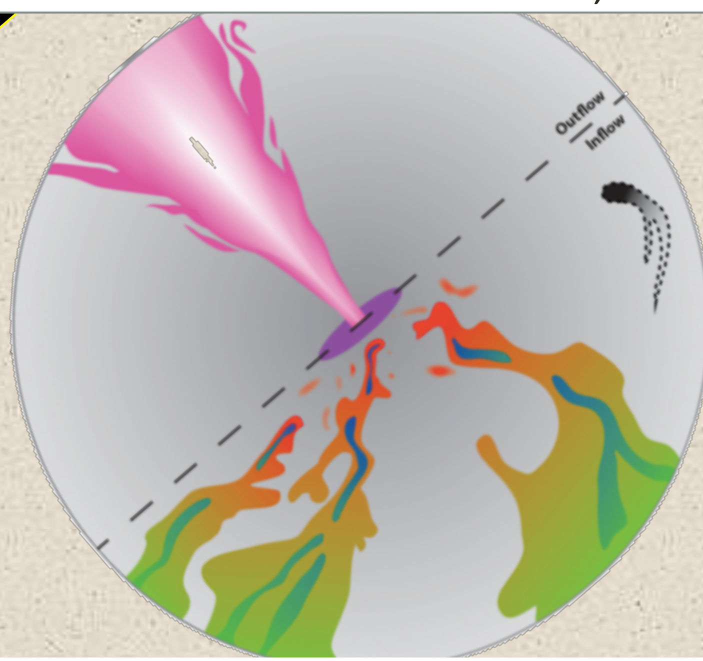


Current Shortcomings: I. Cosmological Models

- Cosmological simulations tune the feedback to match properties of the galaxy population.
  - Need a mass loading factor $\eta \sim V_c^{-1}$ or V_c^{-2} to match the galaxy mass function and M-Z relation.

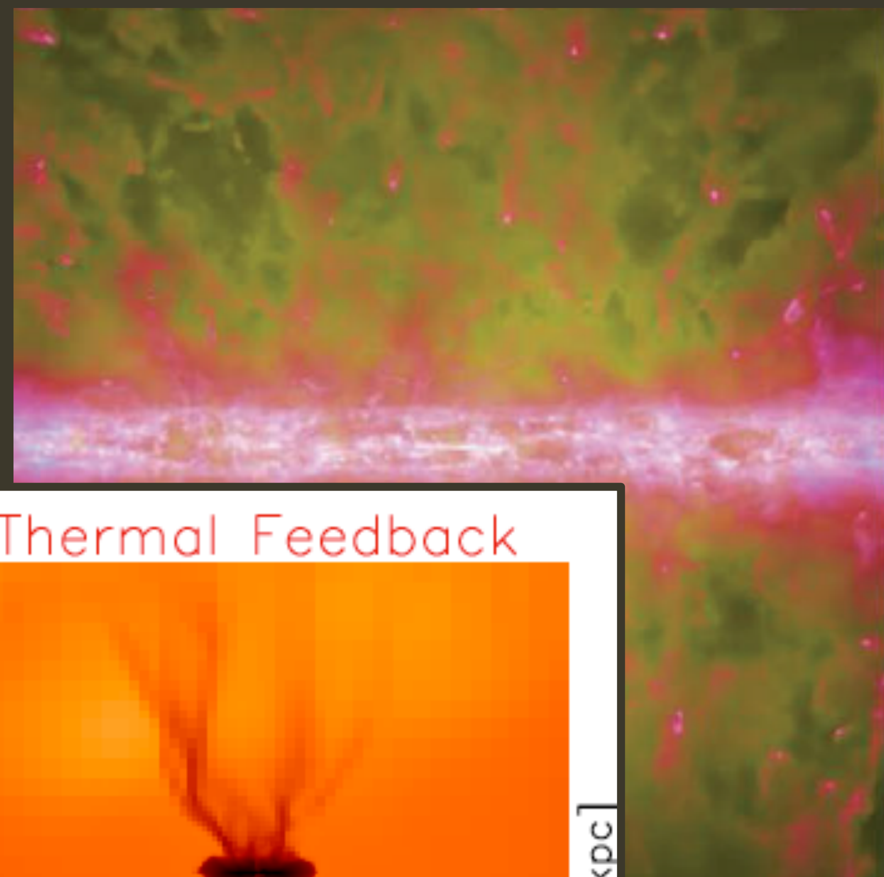
    Example: *Dave, Oppenheimer, Finlator 2011*
  - Need a separate mode of feedback to heat the gas in large halos.

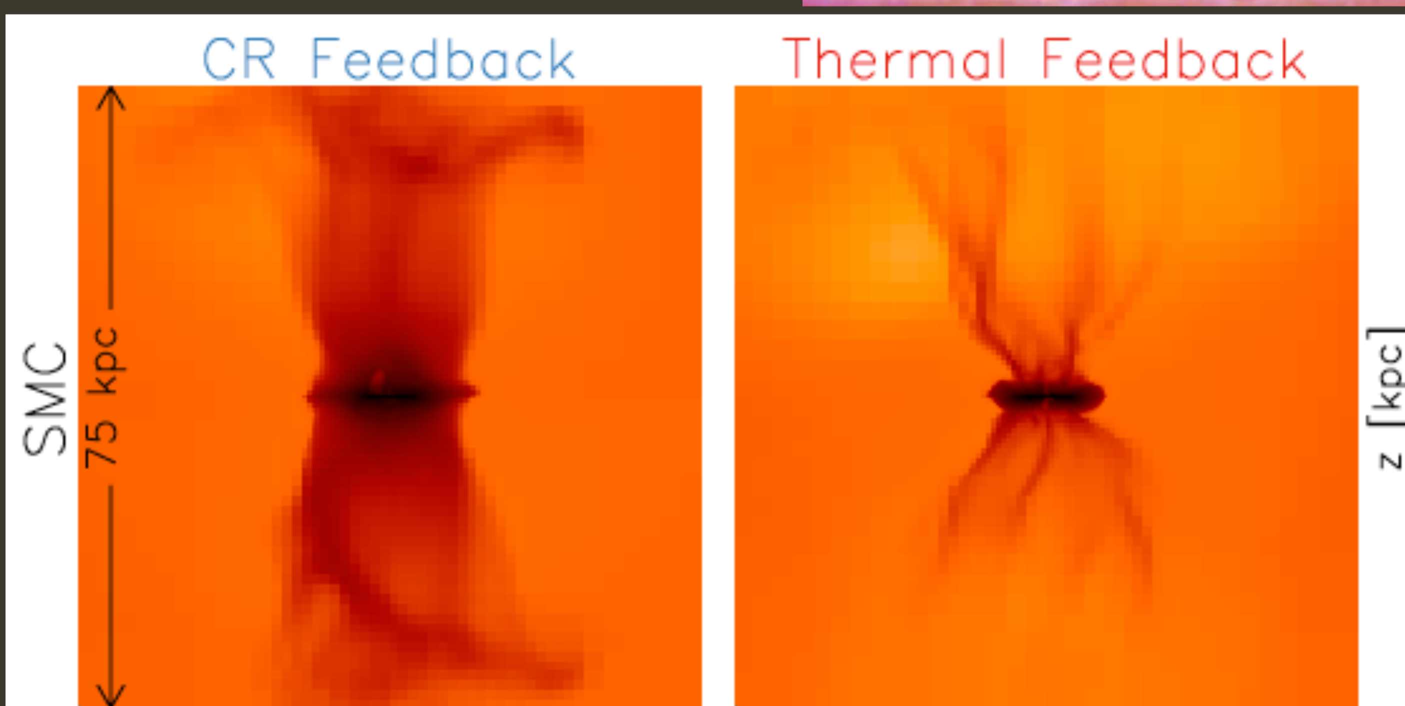
    Example: *Croton et al. 2006*
  - Need to recycle a substantial fraction of the outflowing wind mass.

    Example: Ford et al. 2014, 2016
- Is this solution consistent with the real universe?
  - Zoom Simulations
  - Direct Observations

Current Shortcomings: II. Zoom Simulations

- Resolution
- Physics
- Boundary Conditions





Hopkins + 2012, Booth + 2013,
See also Roskar + 2015

Current Shortcomings: III. Observations

- Measured quantities are a step (perhaps several) removed from physical properties (**v**, T, ρ).
  - Hot wind only directly observed for nearby starbursts.
    - Enrichment demonstrated.
    - Temperature measured for M82.
    - Kinematics not yet directly measured.
  - Emission measure drops below detectable limits just a few kpc above galactic disks.
  - Absorption measurements offer sensitivity advantage but provide 1D picture.
  - Velocity of outflows (cool gas) typically described by a single number.
    - Line profile contains information about speed of clouds over a range of optical depths.
    - Projection effects need to be considered.
  - Mass flux in outflow uncertain at factor of few level.
    - Ionization correction
    - Launch radius

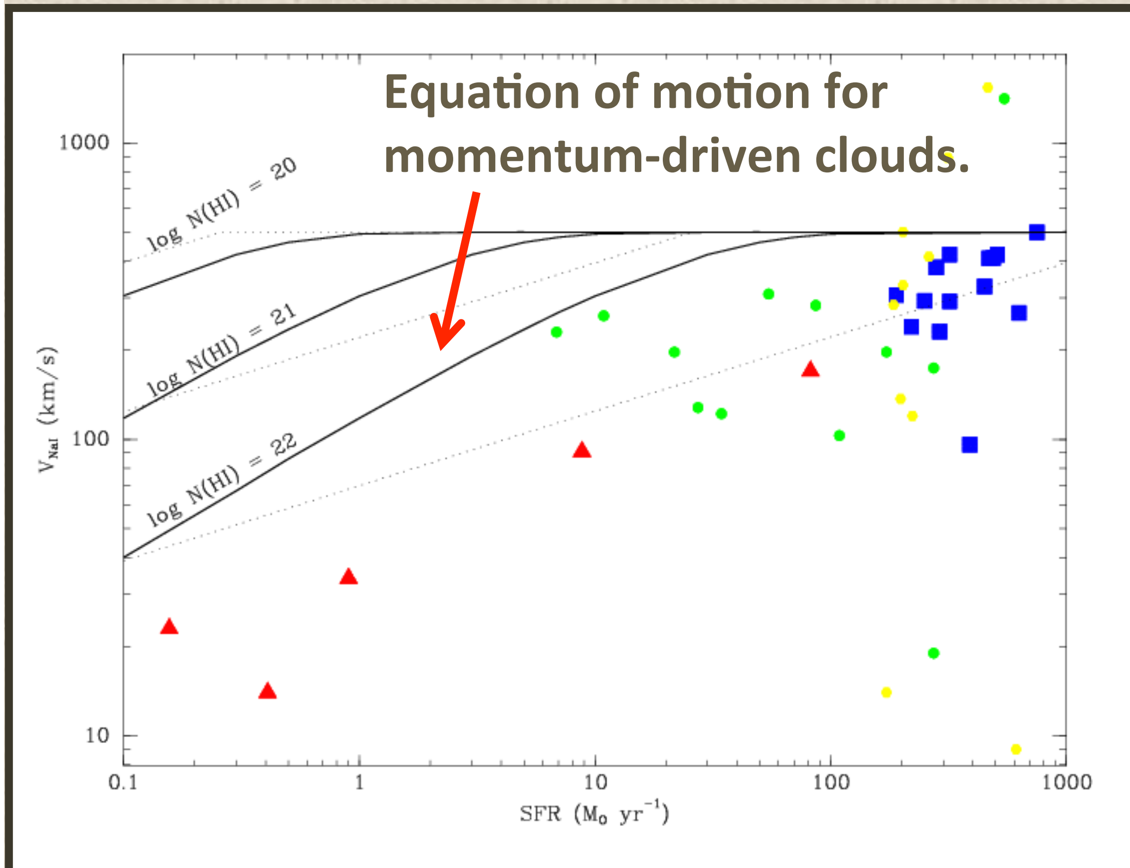
Scaling Relations: The Interface between Cosmological Simulations, Observations, and Zoom Simulations

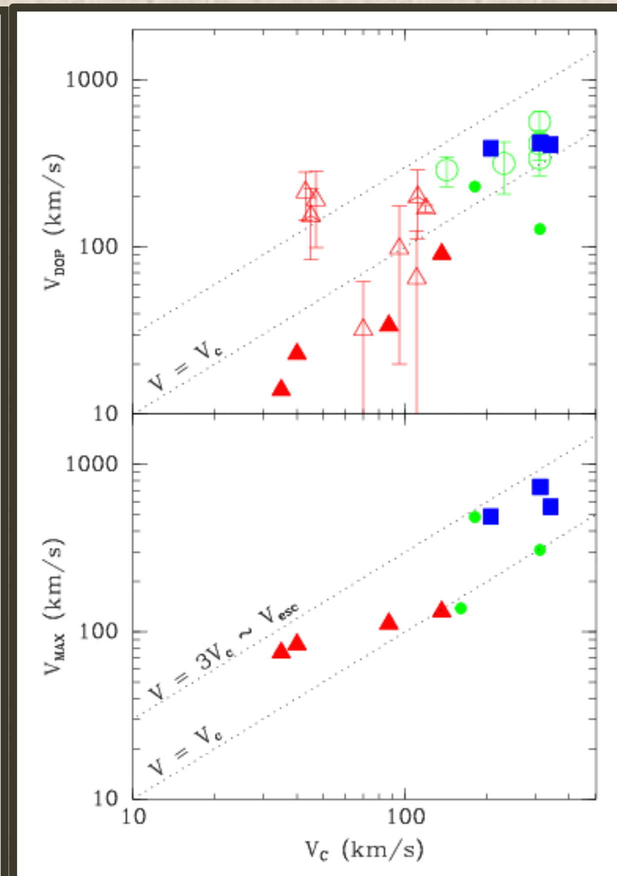
1. **Outflow speeds**
2. **Thresholds for winds**
3. *Mass loss rates*

Empirical Outflow Velocities. Galactic Scale

Velocities from Doppler Shifts of resonance absorption lines.

Outflow speeds appear to be momentum limited.



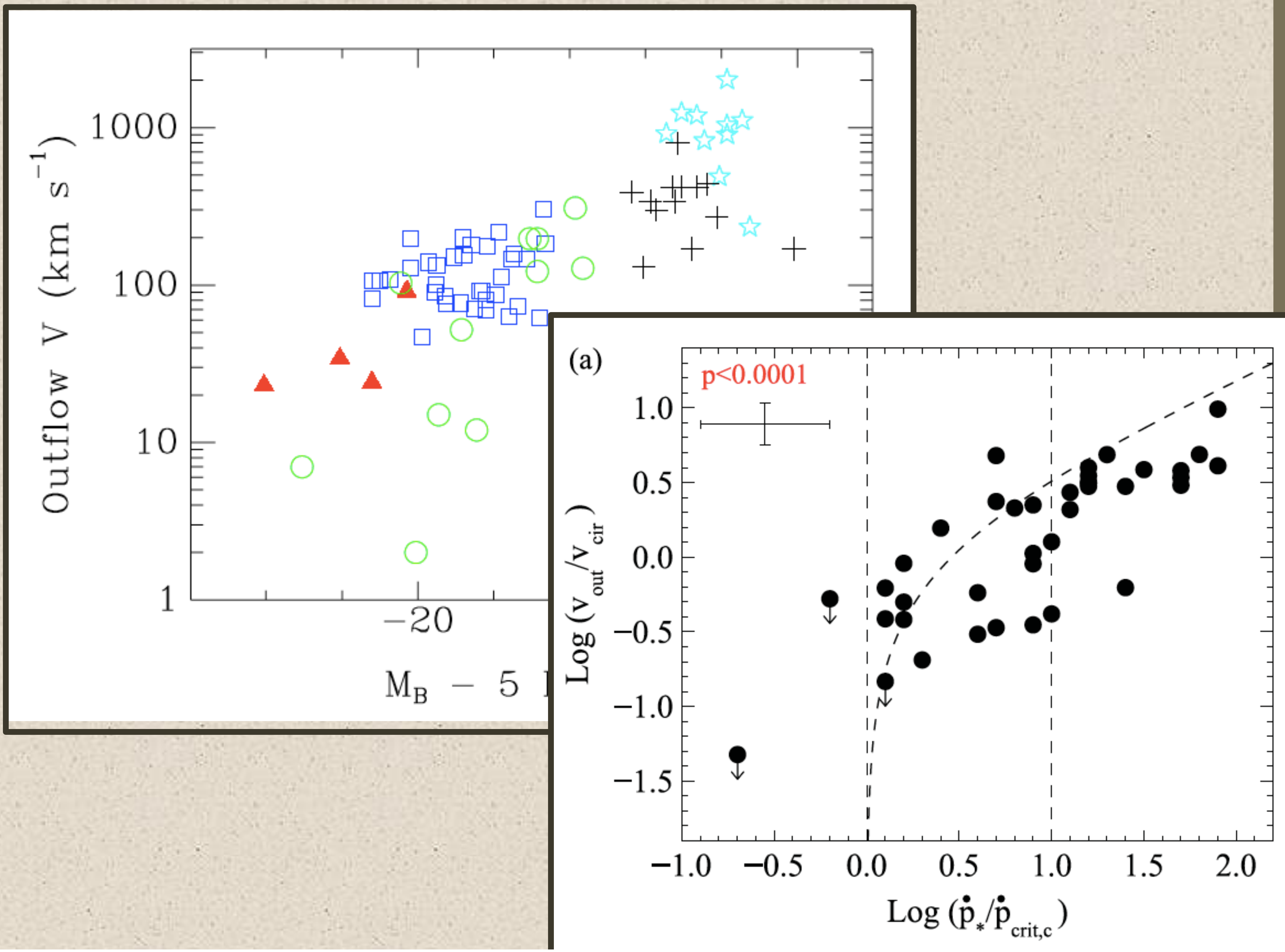


SFR ➔ Momentum Injection Rate

Rotation Speed

CLM 2005

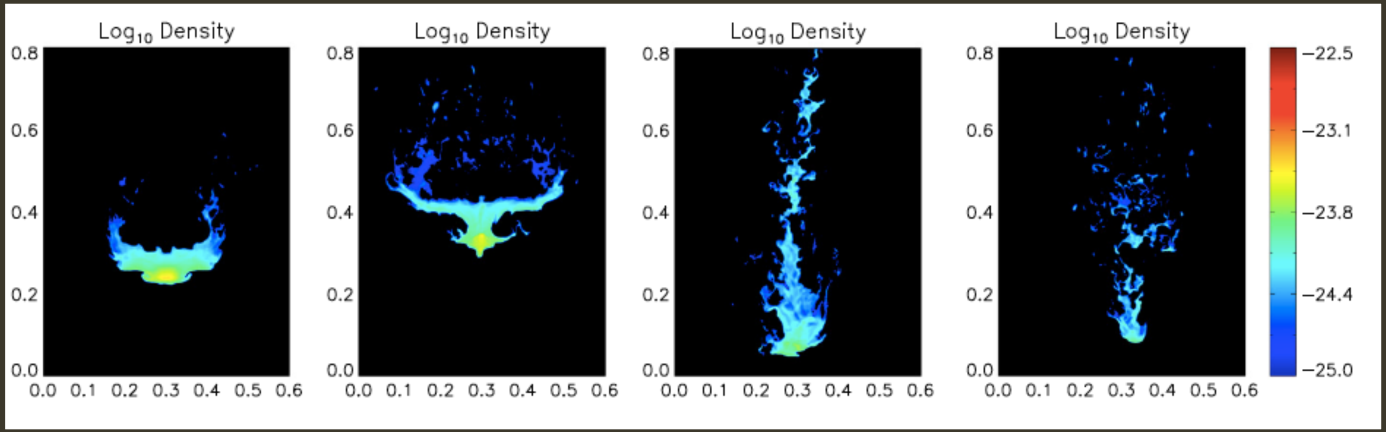
Empirical Outflow Velocities. Galactic Scale



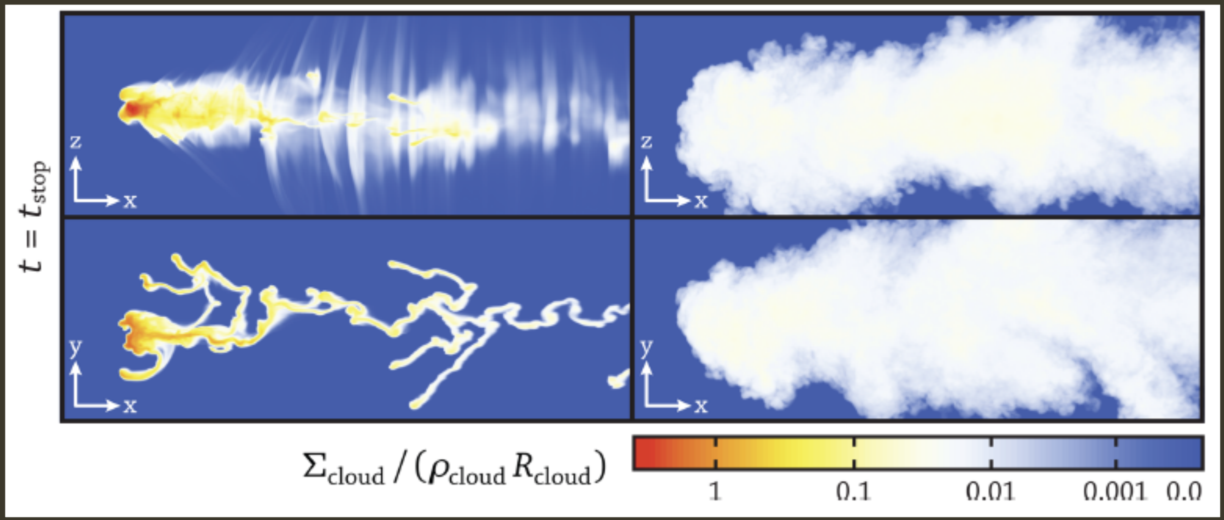
CLM+2012, Heckman+2015

Acceleration of Gas Clouds is a Problem

Cloud crushing timescale << Outflow timescale

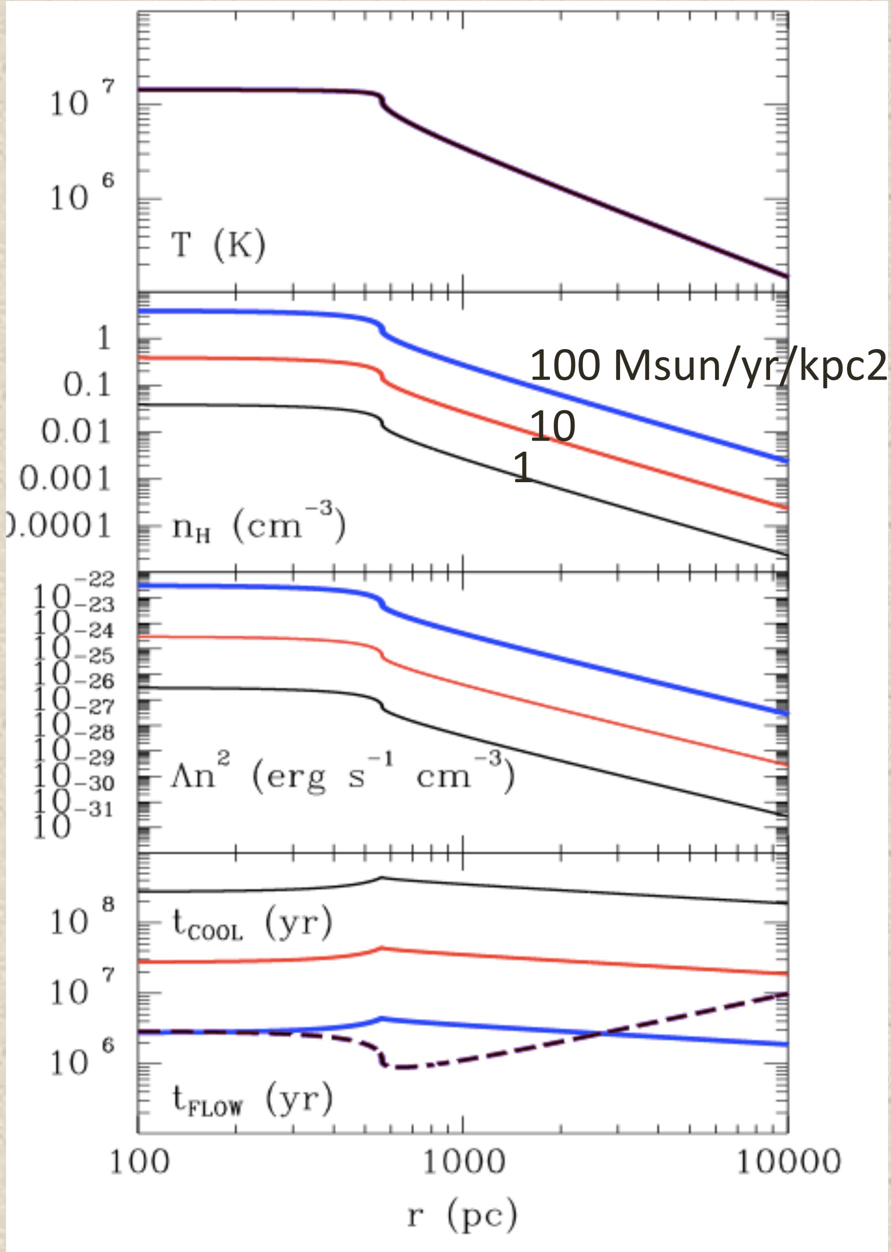


Tangled B-Field Helps



Questions: cross sections, terminal velocities, line profiles

Scannapieco+2015, McCrout + 2015, Bruggen + 2016, Robertson+2016



CC85 Models

- Define extreme starbursts by concentration of massive stars.

$$\dot{\Sigma}_* \equiv \mathrm{SFR}/\pi R_0^2$$

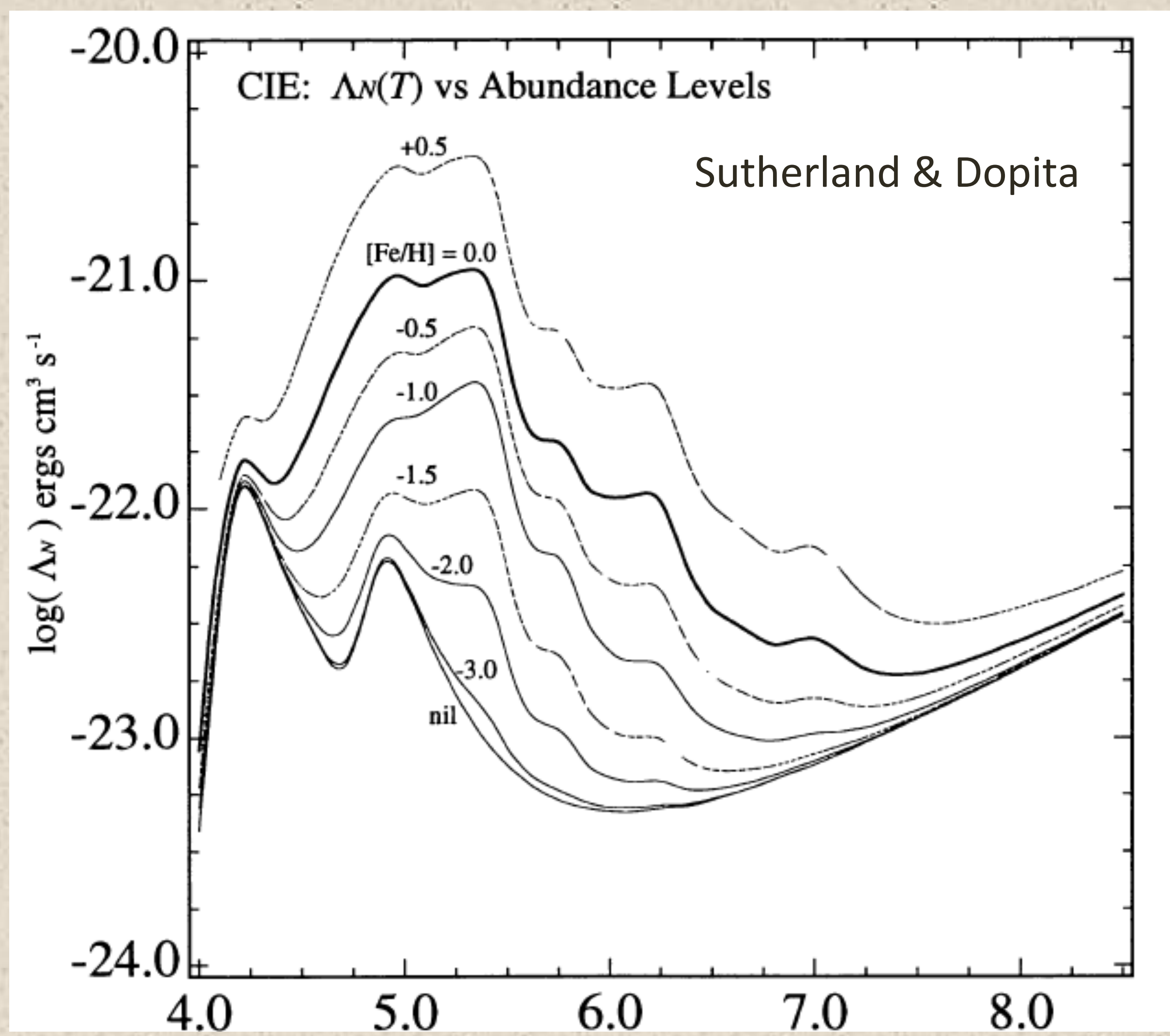
- The density of the hot wind increases with the SFR surface density.
- The cooling rate declines.

$$t_{\rm cool}(R) = \frac{P(n,T)}{(\gamma-1)\Lambda(T)n_e n_{\rm H}}$$

- Cooling radius move in to kpc scales for ULIRGs.
- See also Thompson et al. arXiv.1507.04362

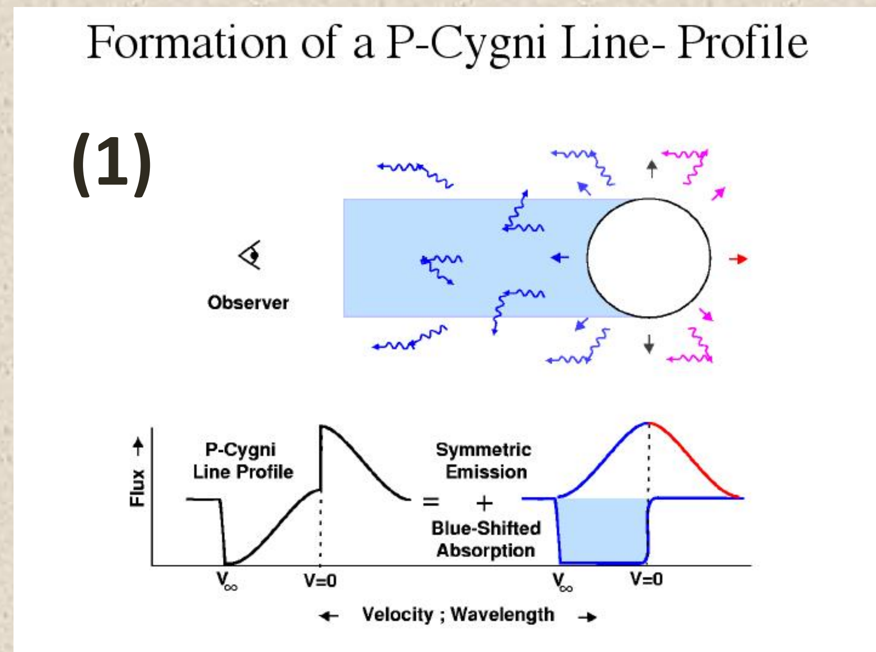
CLM, Dijkstra + 2015; see also Thompson + 2016

Cooling Will Lead to Instability. Expect Dense Clumps in Fast Wind

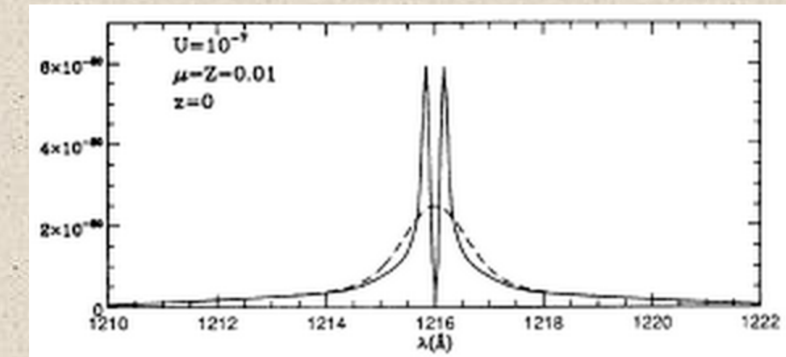


Expected Lya Profiles of ULIRGs

(1)

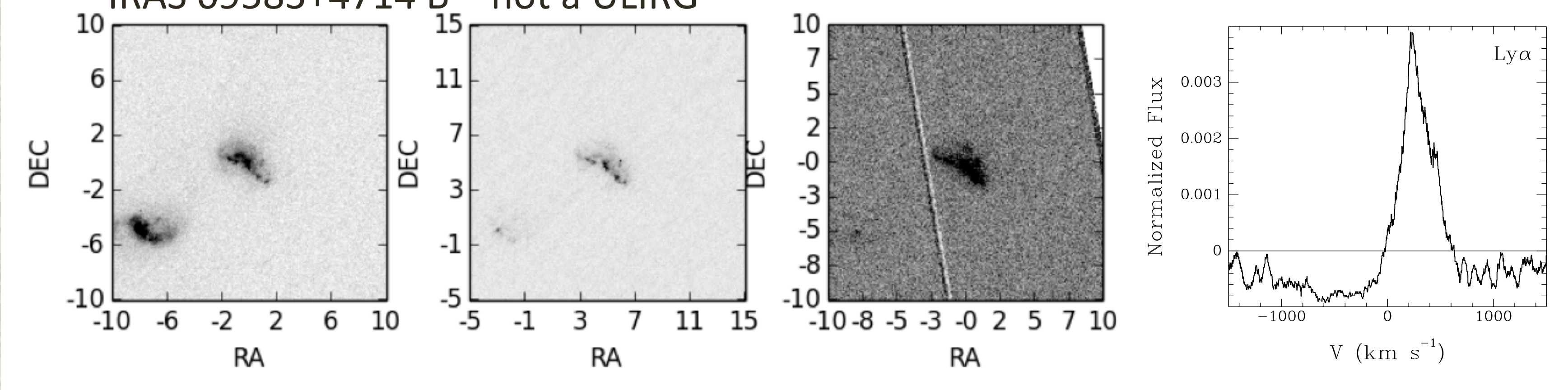


(2) Static Slab



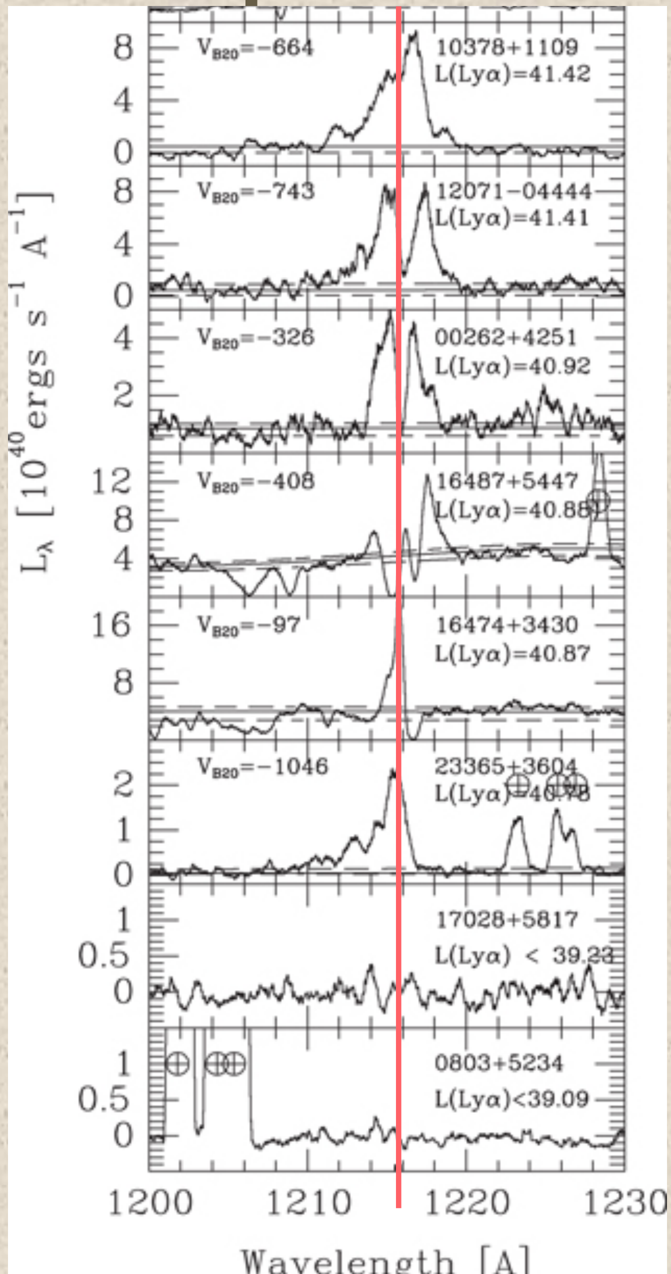
Find one P Cygni profile out of 11 spectra!

IRAS 09583+4714 B – not a ULIRG



CLM, Dijkstra + 2015 ApJ 803, 6

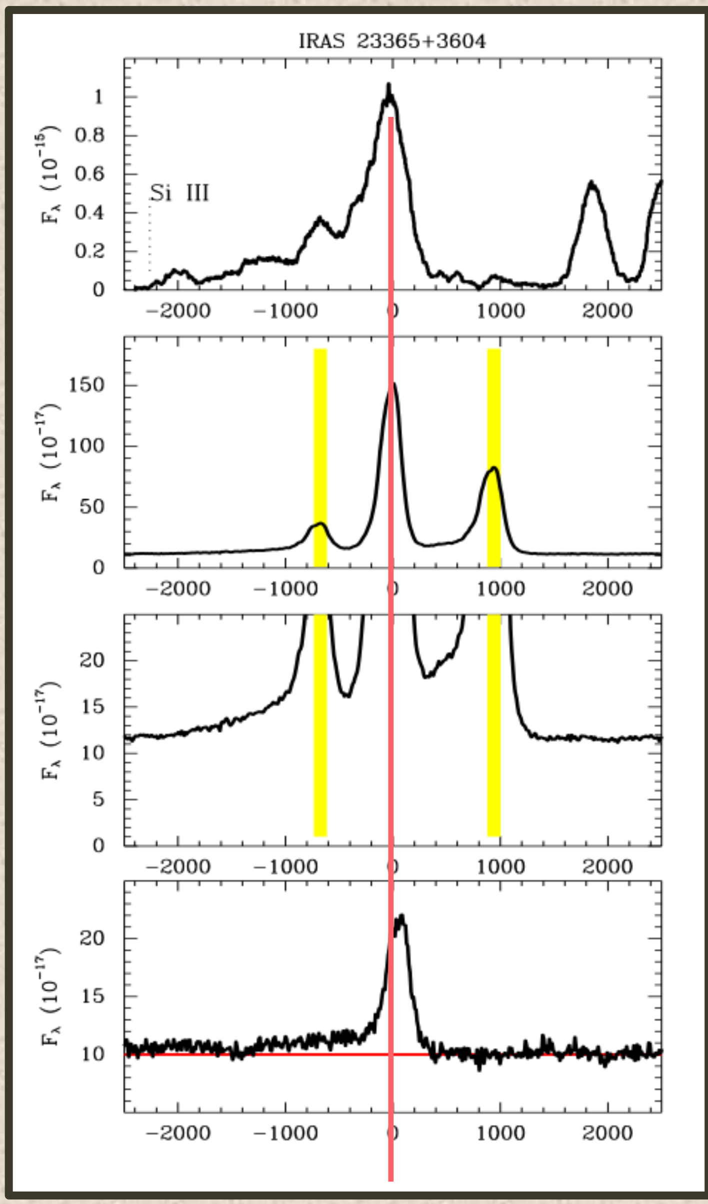
Unexpected Blueshifted Line Wings on Lya

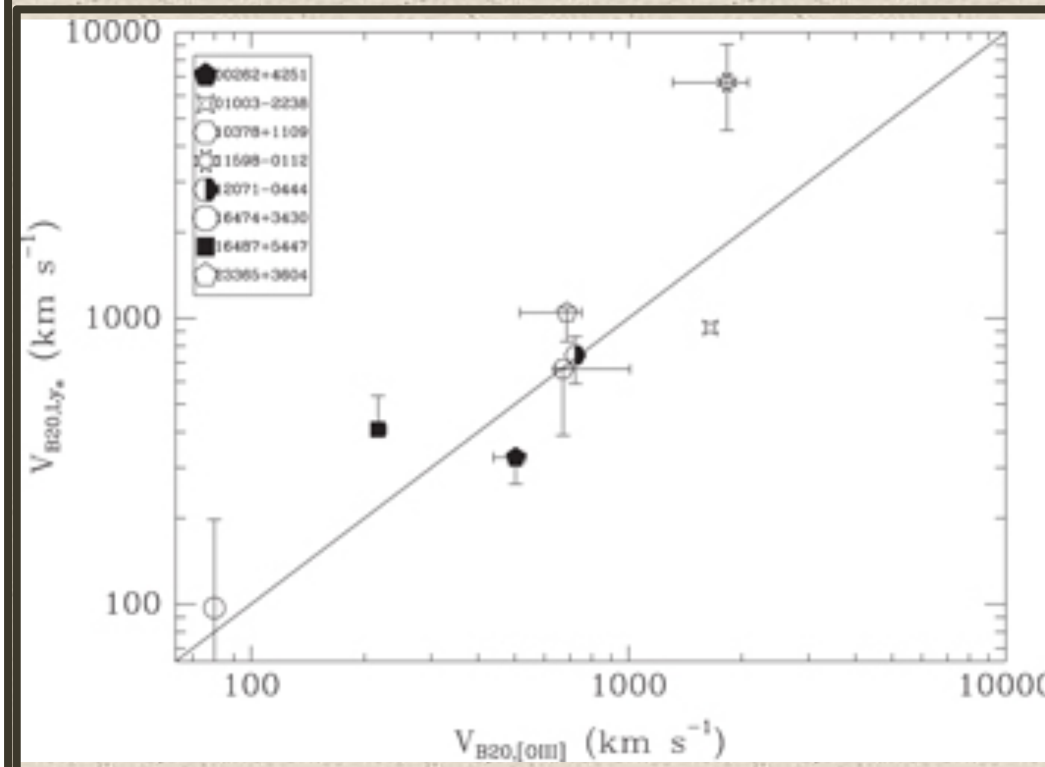


- Starburst dominated galaxies
- Blueshift = 1000 – 2000 km/s
- **Scattering in frequency space? Or bulk motion?**
- The optical spectrum answers this question.

CLM, Dijkstra + 2015 ApJ 803, 6

Blueshift is from Bulk Motion at ≈ 1500 km/s





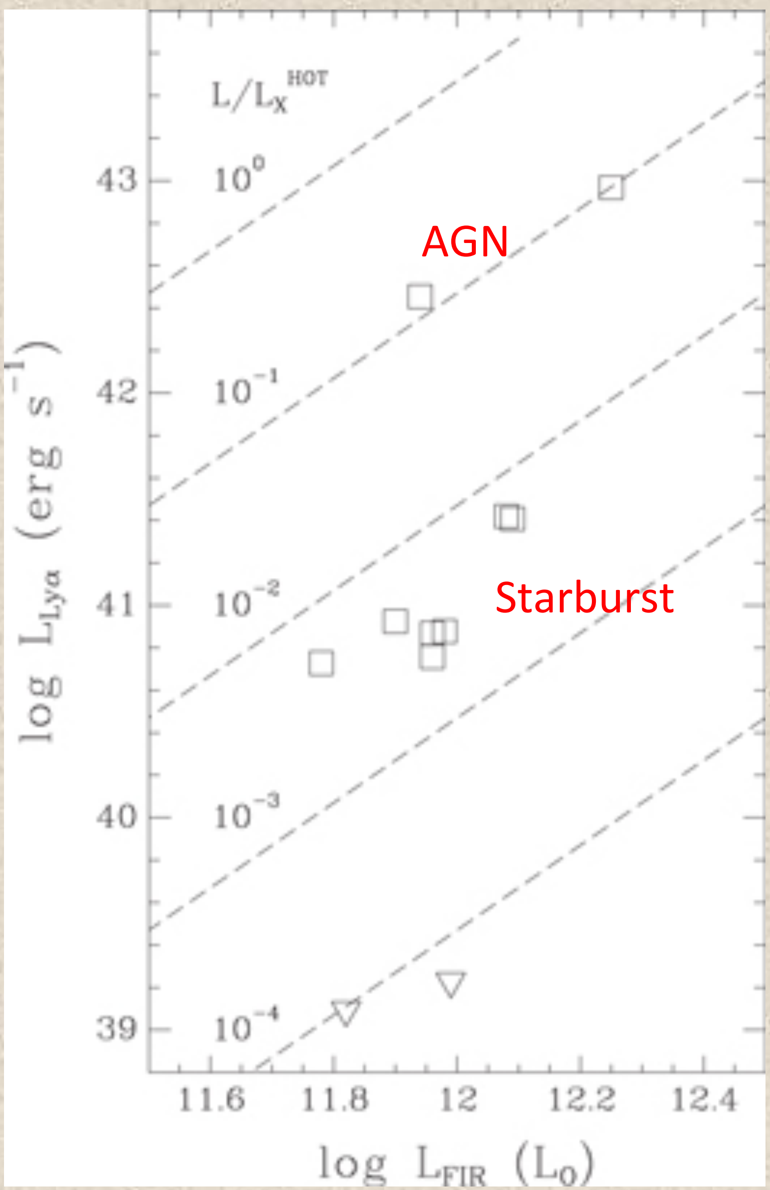
CLM, Dijkstra + 2015 ApJ 803, 6

Lyα Luminosity

- Expect only ~$10^4/10^7$ of the cooling in Lyα
- L_x from CC85 solution also scales as SFR^2 (Zhang+2014)
- Find $L_{Ly\alpha}$ increases as $(L_{FIR})^2$, or SFR^2

$$L_X^{\rm hot}[0.5 - 8.0\,{\rm keV}] = 10^{43}\,{\rm ergs\,s^{-1}} \left(\frac{\rm SFR}{100\,M_\odot {\rm yr}^{-1}}\right)^2 \times \left(\frac{200\,{\rm pc}}{R_0}\right),$$

- $L_{ly\alpha}$ is 0.3% of the total cooling expected.
- Energetically feasible that this emission comes from cooling hot wind.

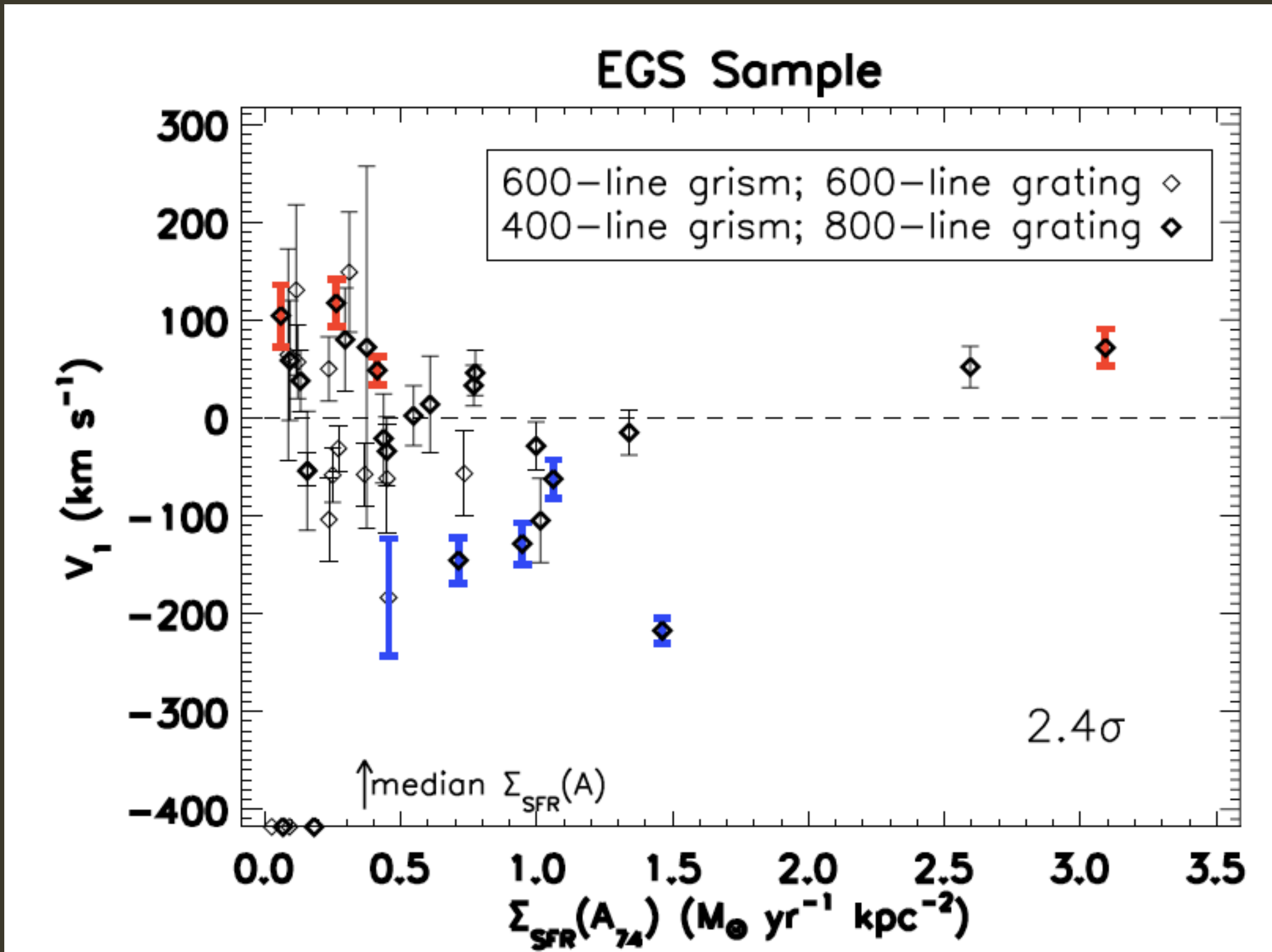


CLM, Dijkstra + 2015 ApJ 803, 6

SFR Surface Density Thresholds for Winds

- Is SFRSD = 0.1 M_0/yr/kpc^2 a threshold for outflows?
  - Heckman 2002 – starburst sample
  - Murray + 2011 – radiation pressure theory
- Or does turbulence set the threshold?
  - Scannapieco + 2013 - Found SFRSD > 0.1 M_0/yr/kpc^2
  - Hayward & Hopkins 2015 – Critical gas fraction > 30%
- Growing evidence for outflows at lower levels of activity
  - Milky Way – Everett + 2008
  - Kornei + 2012 - 50 galaxies at z = 0.9
  - I-Ting Ho + 2015 – 40 galaxies at z = 0.05
  - Yoon + 2016 - Case study of NGC 891

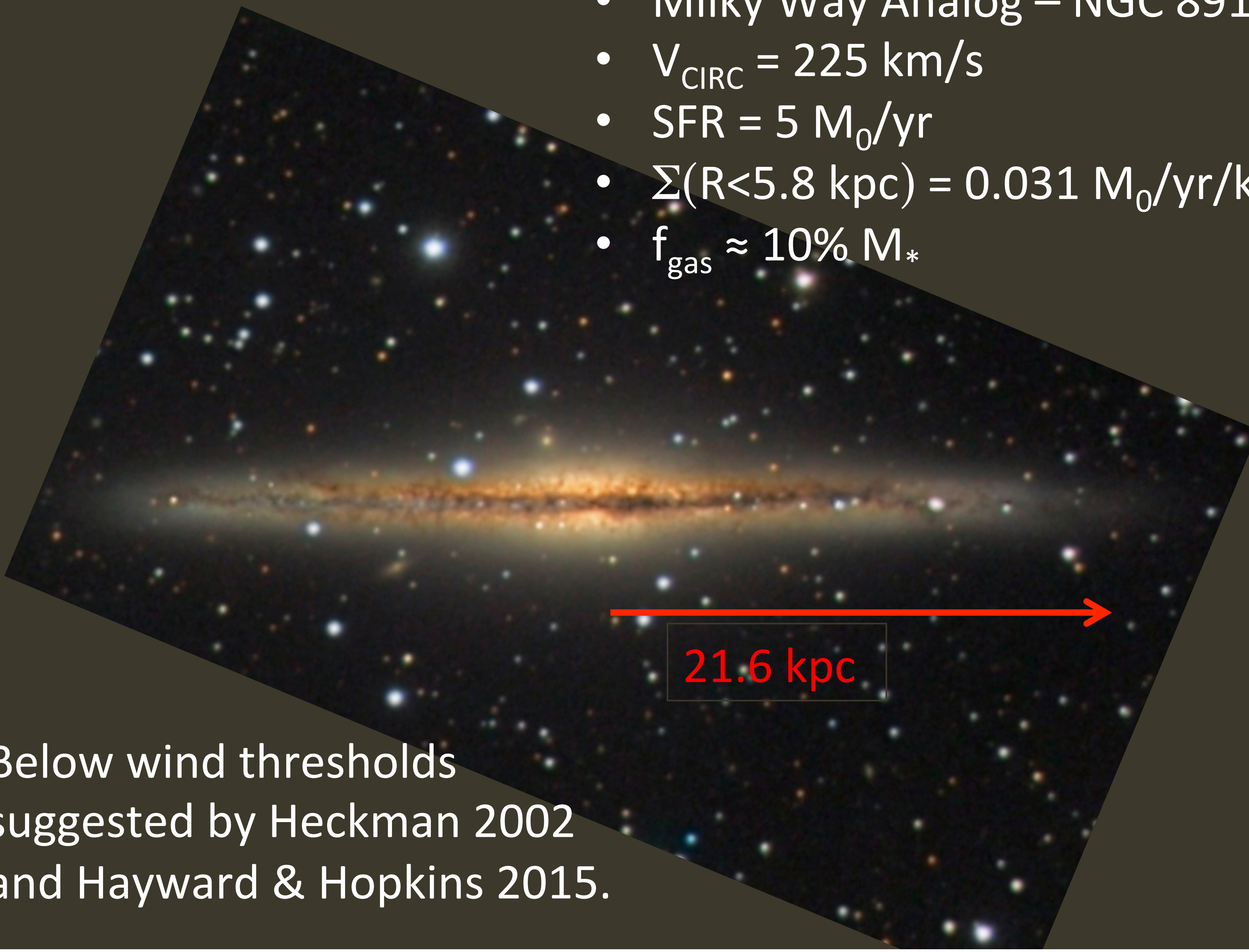
SFR Surface Density Thresholds for Winds



Kornei + 2012

Disk-Halo Interface: Do Normal Galaxies Have Winds?

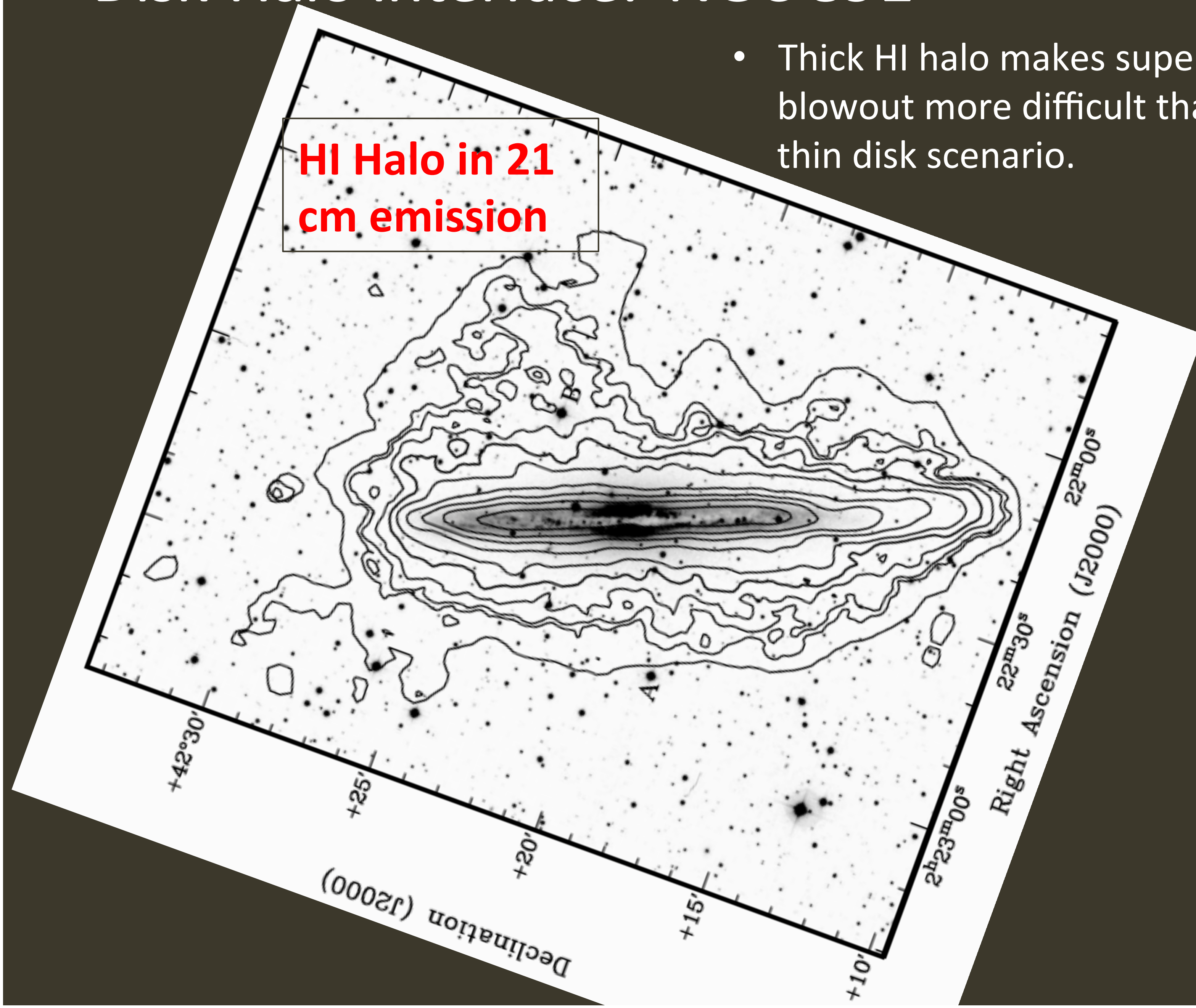
- Milky Way Analog – NGC 891
- V_{CIRC} = 225 km/s
- SFR = 5 M_0/yr
- Σ(R<5.8 kpc) = 0.031 $M_0/yr/kpc^2$
- $f_{gas} \approx$ 10% M_*



- Below wind thresholds suggested by Heckman 2002 and Hayward & Hopkins 2015.

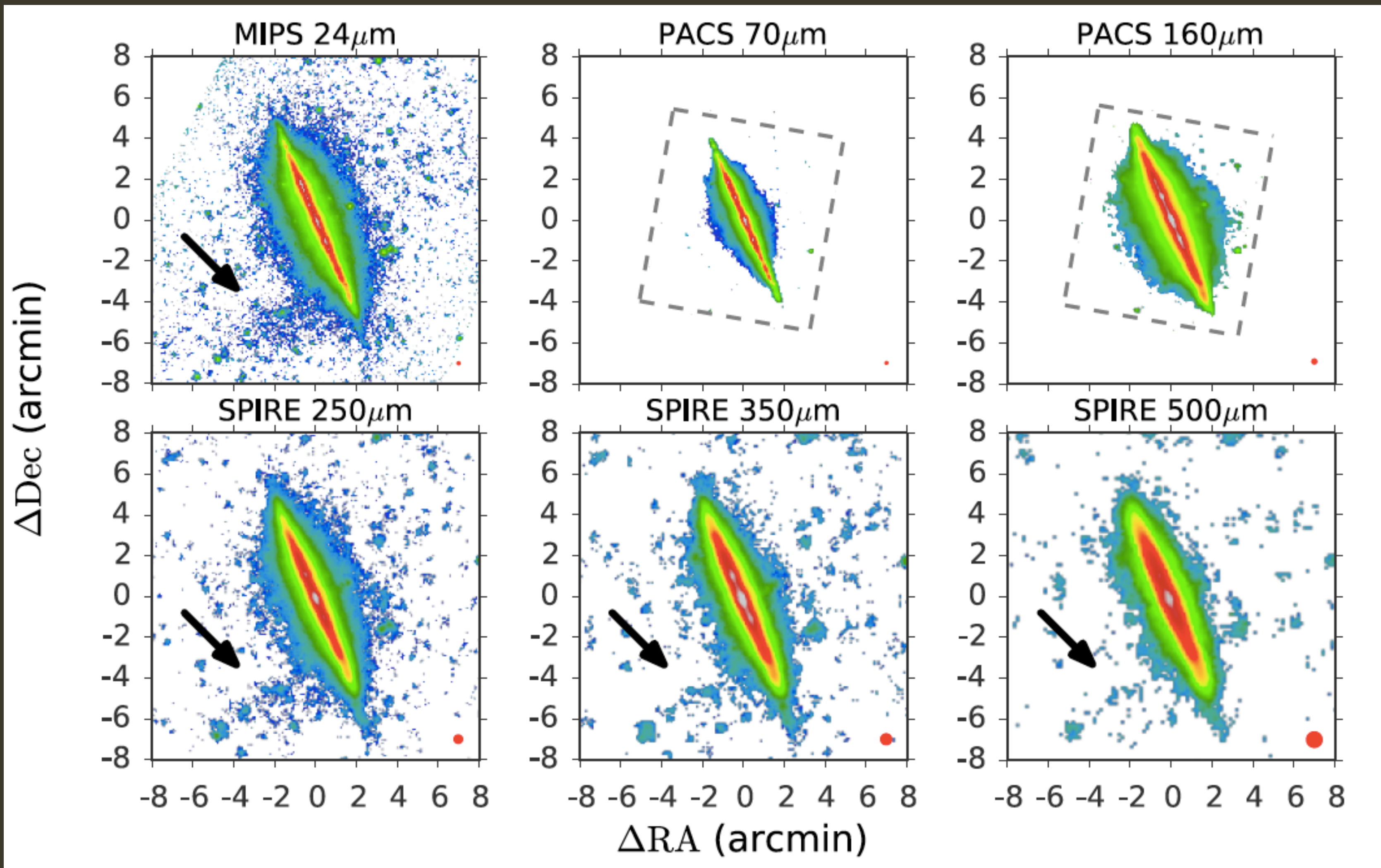
Disk-Halo Interface: NGC 891

- Thick HI halo makes superbubble blowout more difficult than in the thin disk scenario.



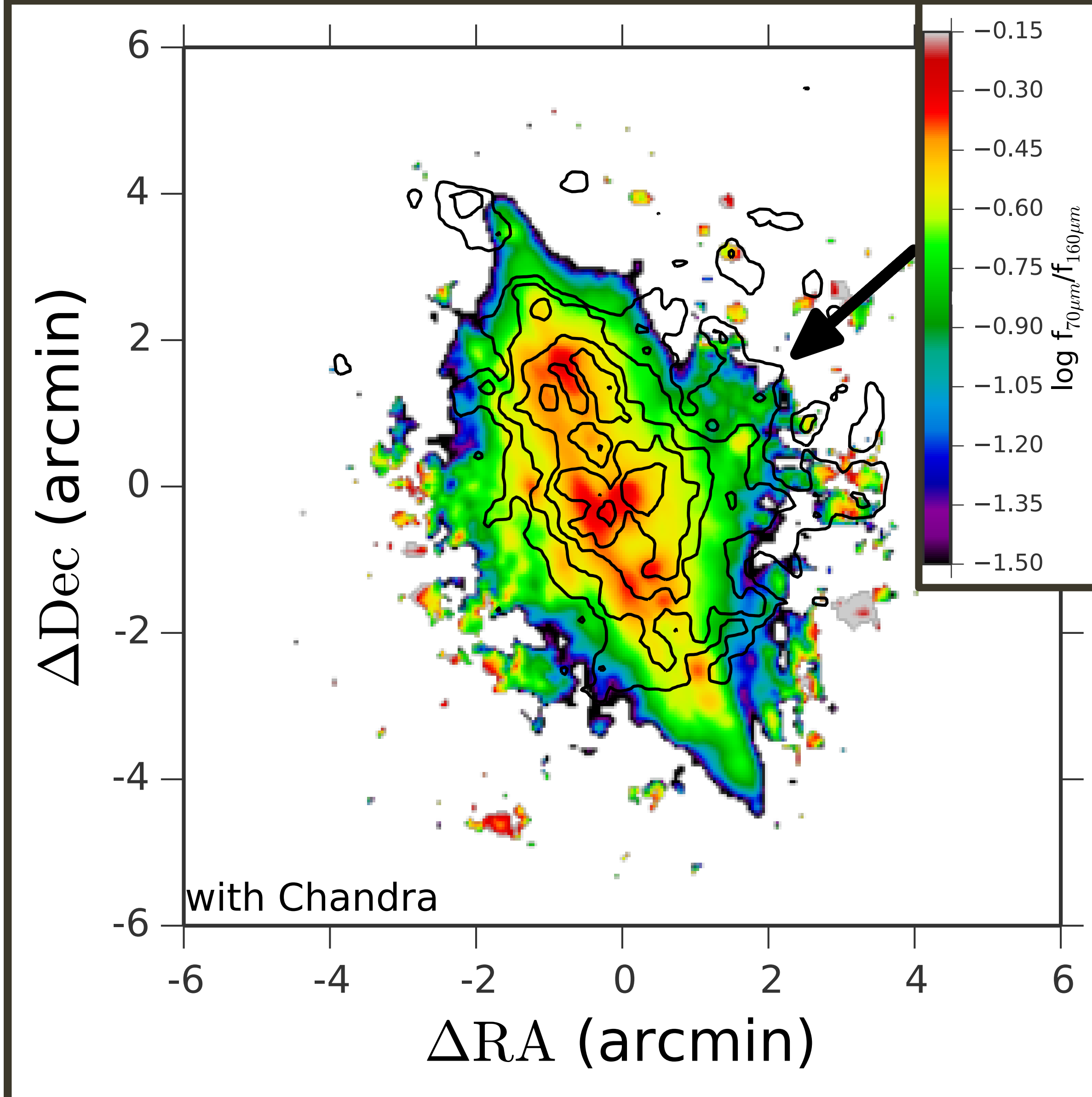
Oosterloo + 2007

Disk-Halo Interface: Spitzer and Herschel Observations of NGC 891



Yoon, Martin, Melendez, Veilleux+ 2016, submitted

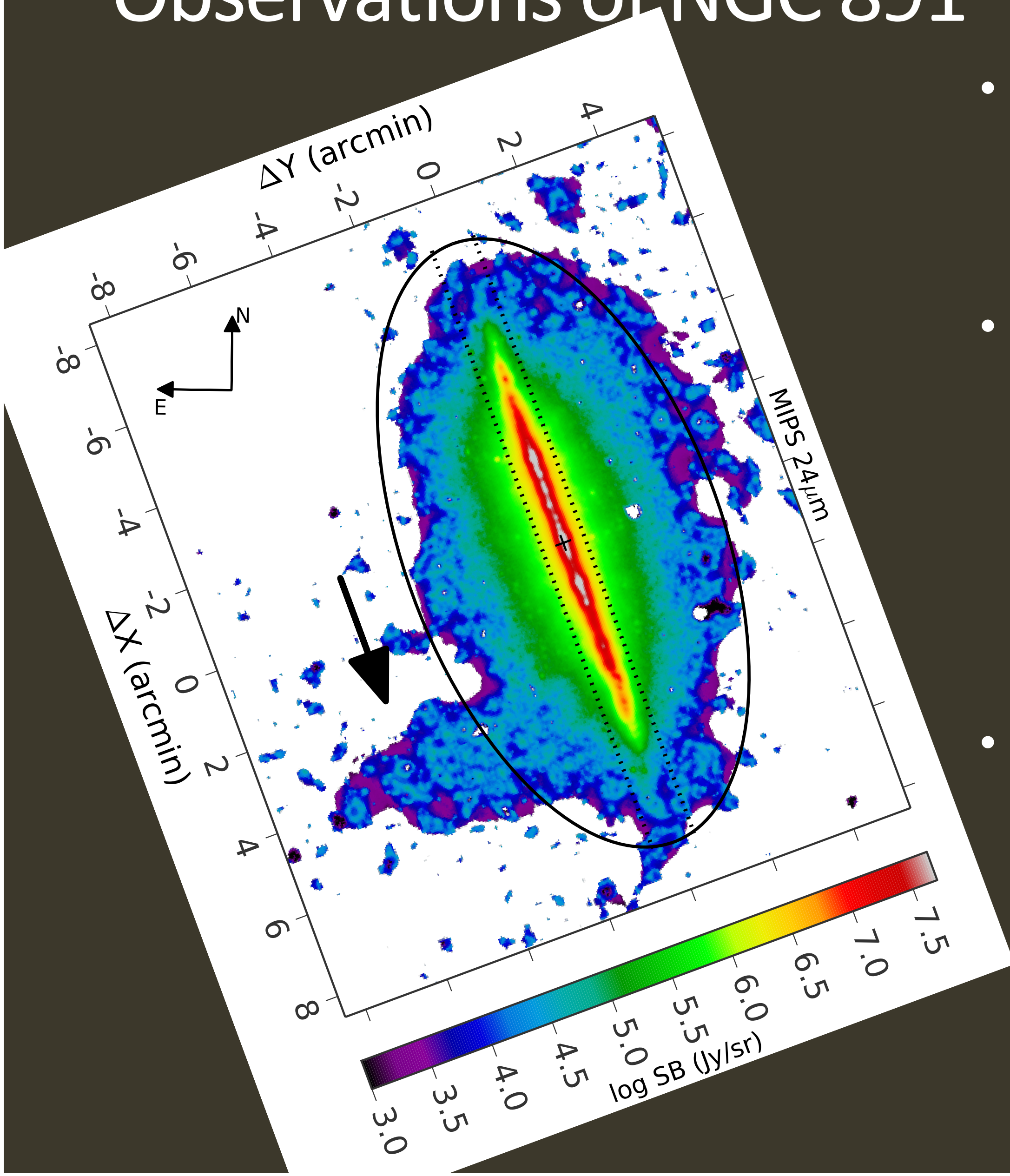
Disk-Halo Interface: Herschel Observations of NGC 891



- Find bubble of warm dust above and below the molecular ring.
- Height = 7.7 (6.8) kpc, 4x the scale height of the halo gas
- M(dust) ≈ 3 X 10^6 M_O.
- L_w/L_{crit} ≈ 380
- Blowout!

Yoon, Martin, Melendez, Veilleux+ 2016, submitted

Disk-Halo Interface: Herschel Observations of NGC 891

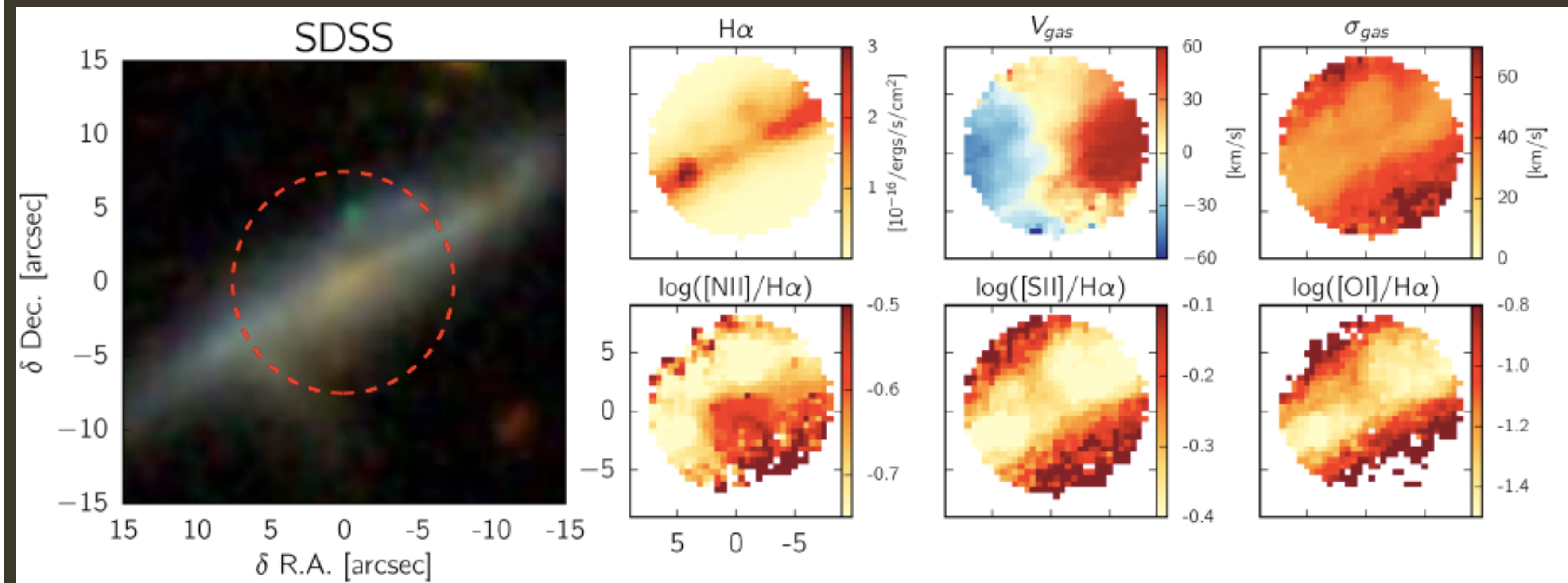


- Superbubble breakout and satellite – disk interaction both pull dust into halo.
- 4 x 10^7 M_O of dust in the halo, roughly 43% of the dust mass in the thick disk.
  - Similar to dust in MgII systems (Menard & Fukugita 2012)
- For M(dust) / M(gas) ≤ 110, we estimate ≥ 4 x 10^9 M_0 of gas in the halo.

Yoon, Martin, Melendez, Veilleux+ 2016, submitted

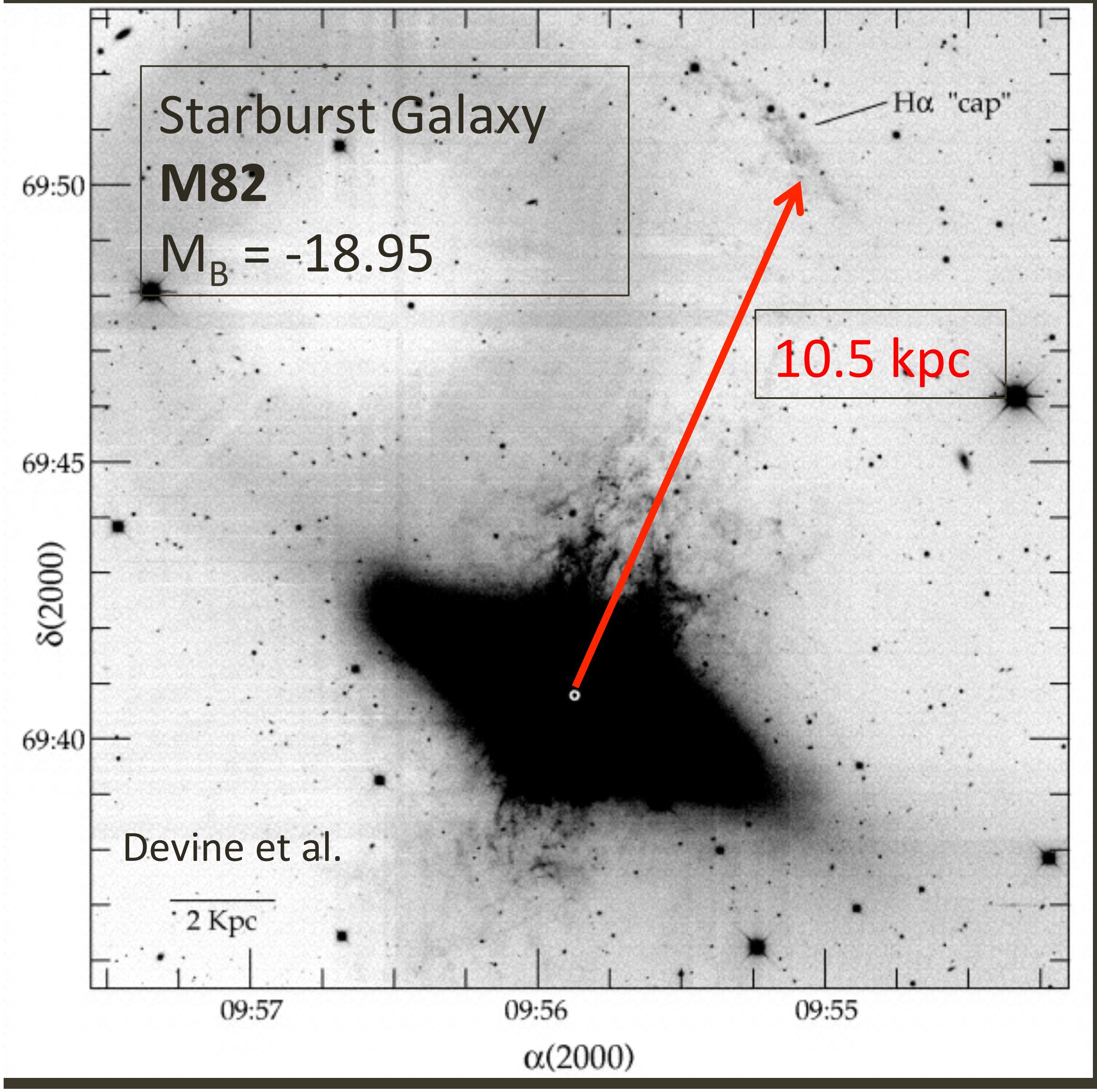
Immediate Future: Integral Field Spectroscopy of the Disk-CGM Interface

- I-Ting Ho + 2016 – Identify outflows in bursty, normal galaxies with l SFR surface density of just 0.001 to 0.03 M_0/yr/kpc^2



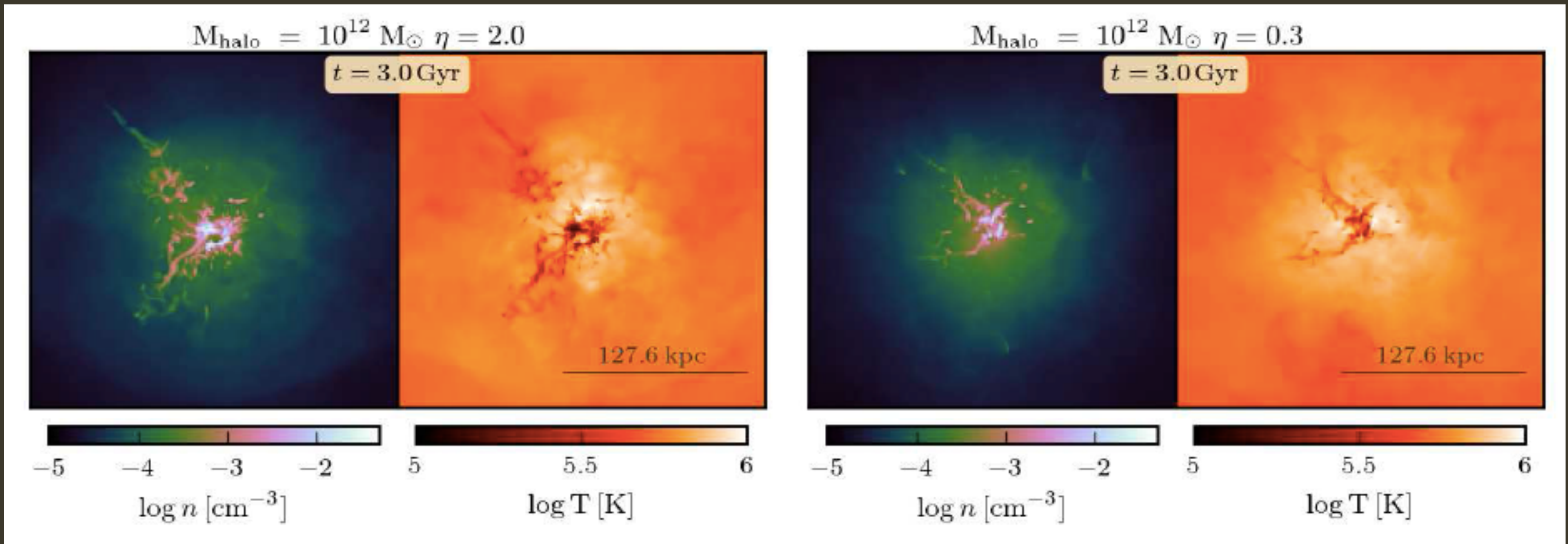
- See also MANGA (SDSS) and MUSE (VLT) papers.
- Keck KCWI soon to be commissioned.

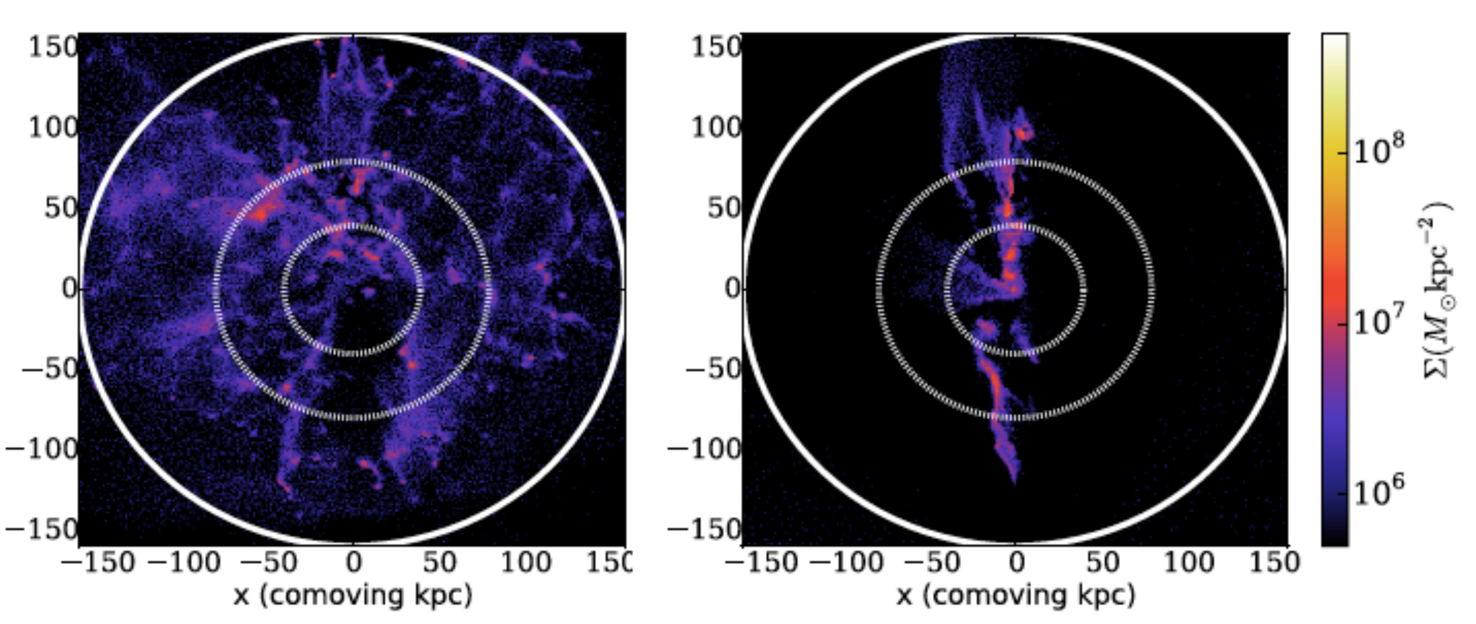
Disk-Halo Interface: A Boundary Condition for the CGM?



- Winds propagate well beyond the optically visible filaments.
- Density is too low to detect them directly in emission.

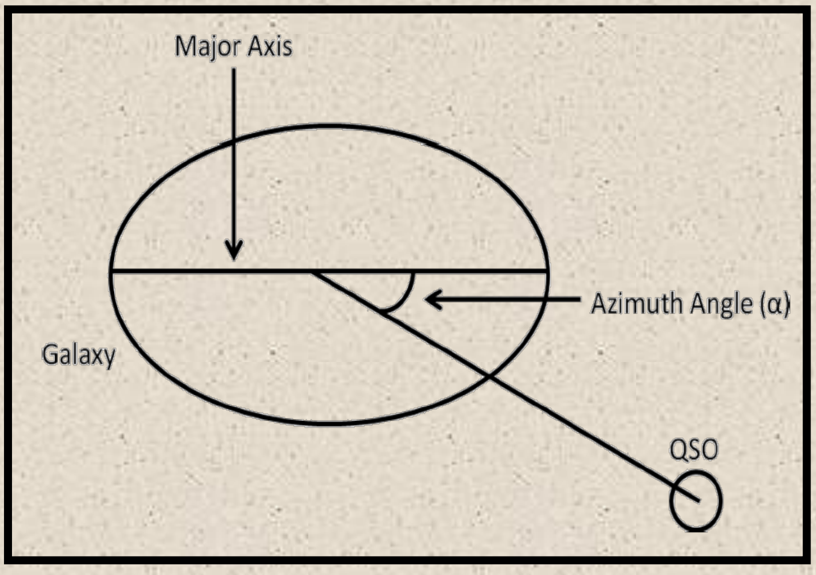
Properties of the CGM May Constrain Feedback: Theory

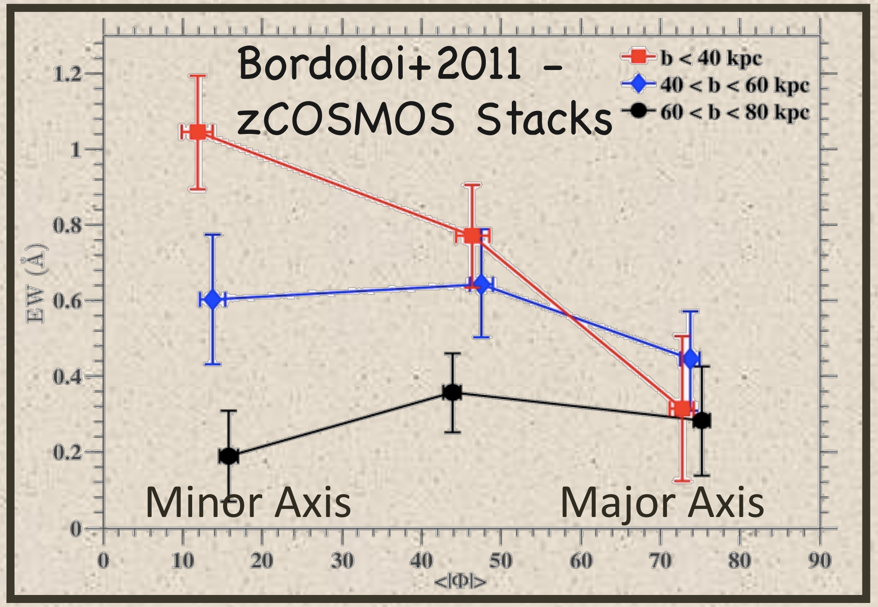


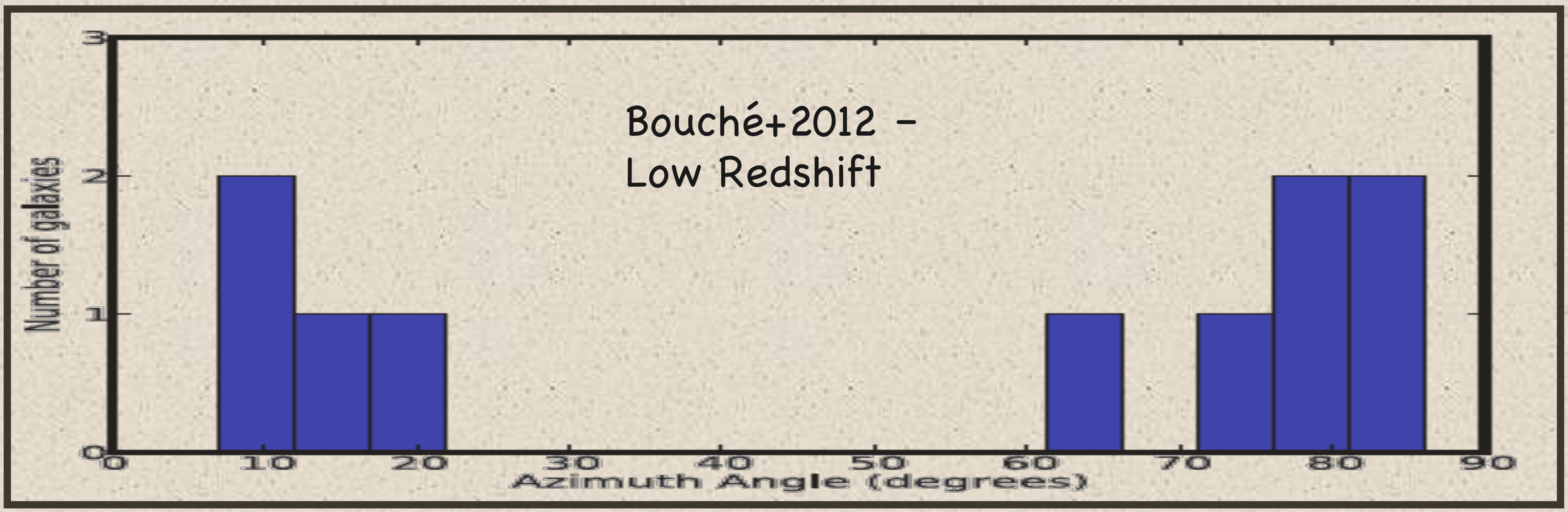


Muratov + 2015, Fielding+2016

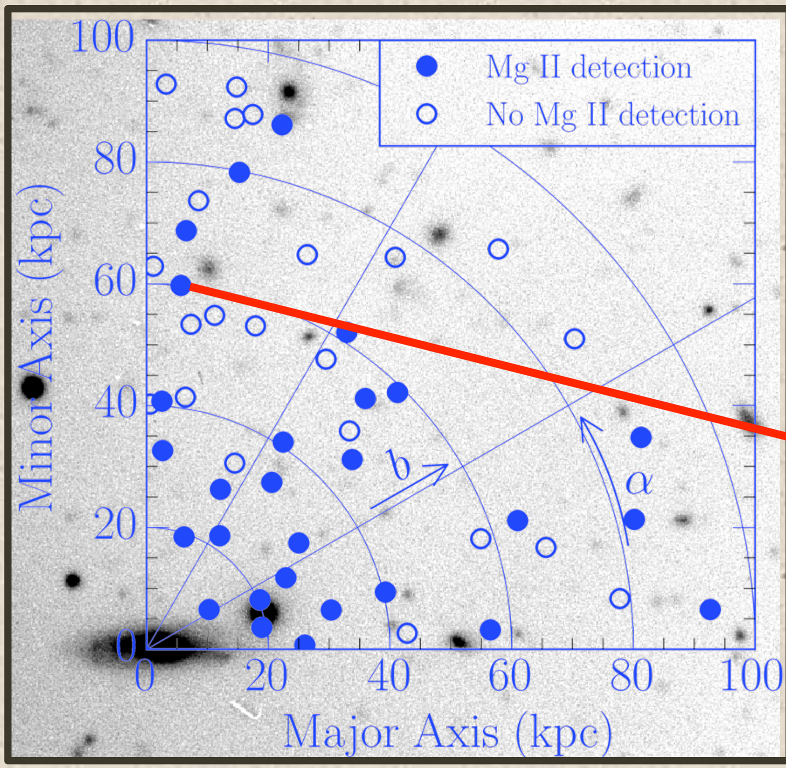
Orientation of Sightline Relative to the Disk May Determine Origin of Strong Absorption

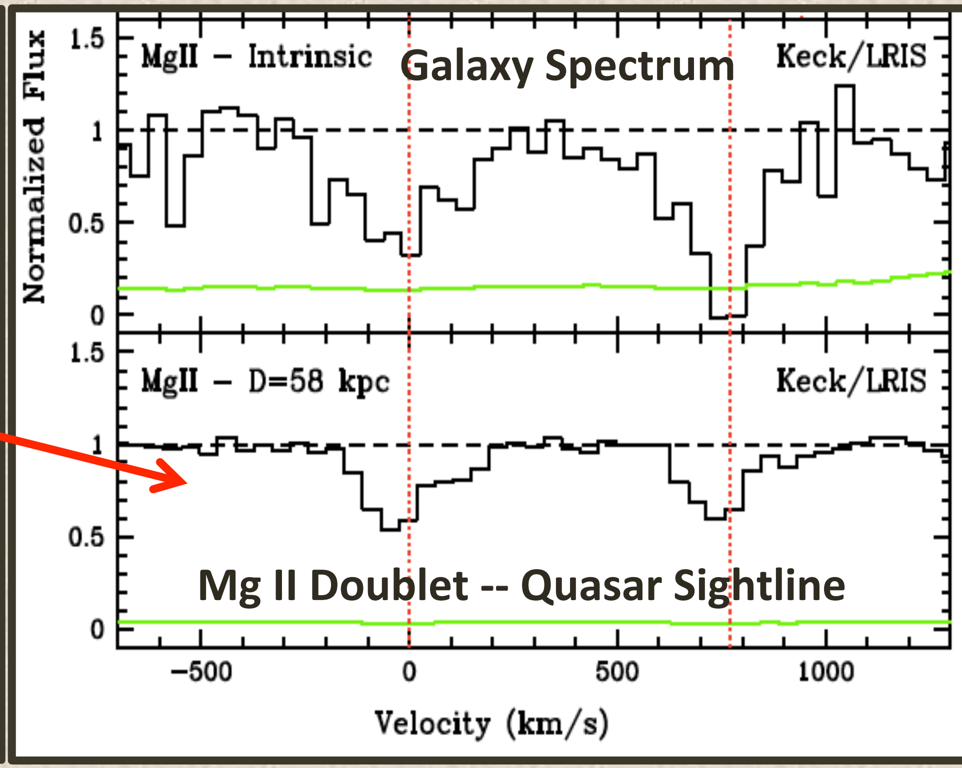


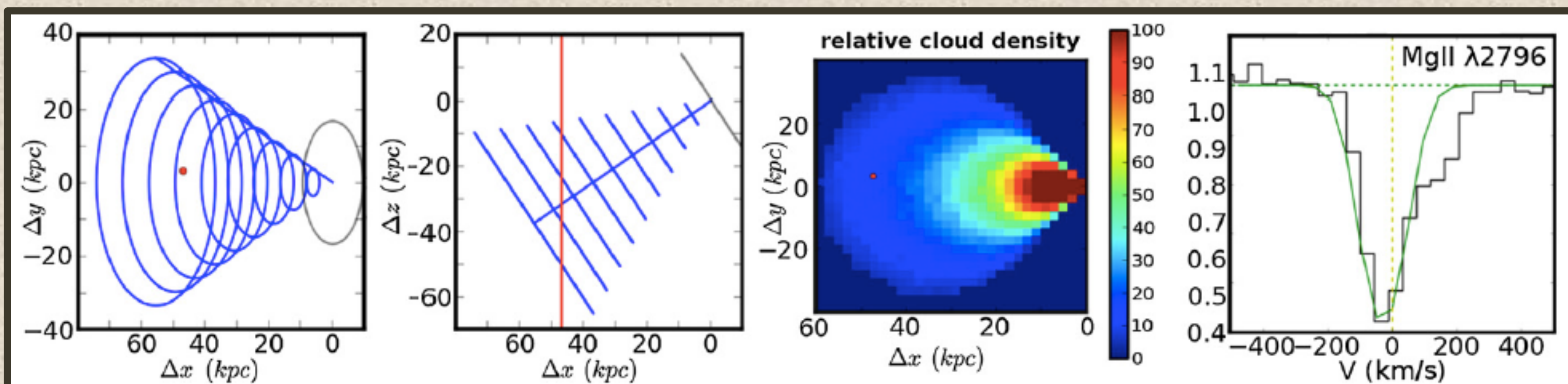




Keck QpG Survey: Outflow Example



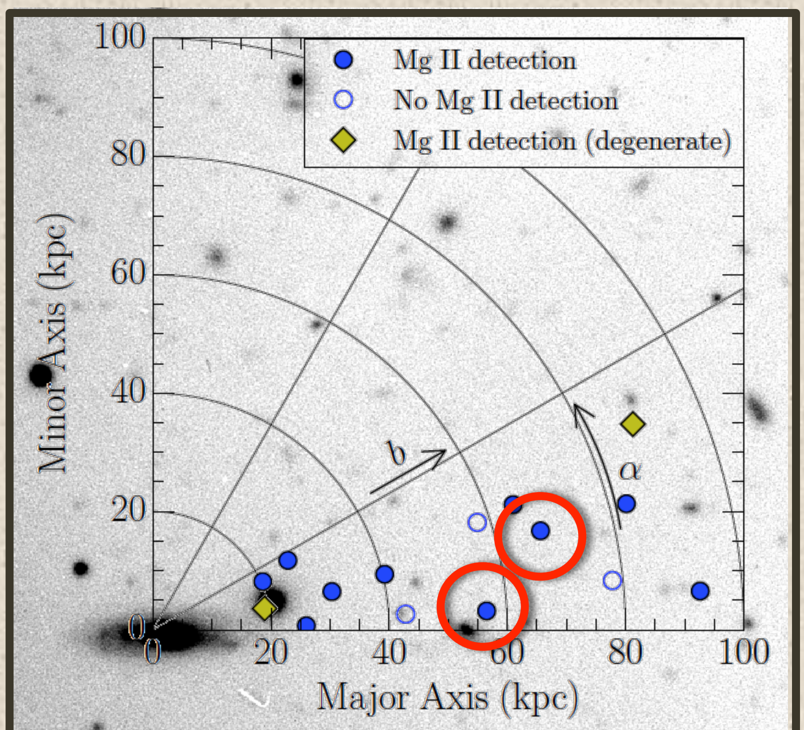


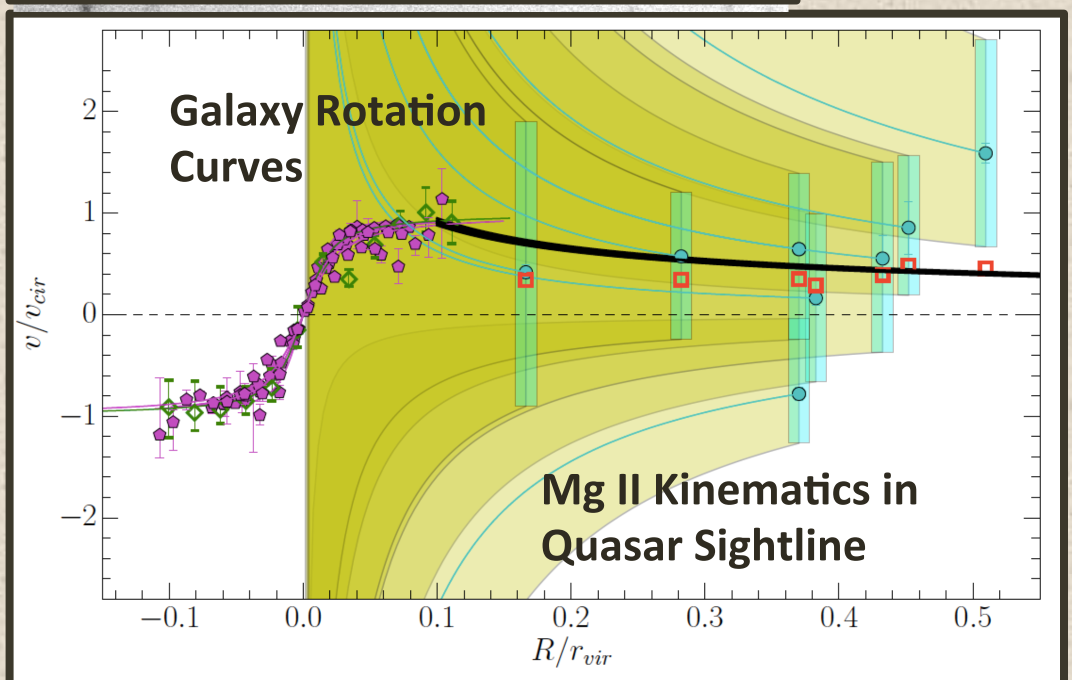


Fitted Model: V = 40-80 km/s; SFR = 5-15 Msun/yr; η= 0.1-0.9

QpG Survey (Martin + 2016)
Kacprzak, CLM, Bouche + 2014

Keck QpG Survey: Gas Accretion Sightlines

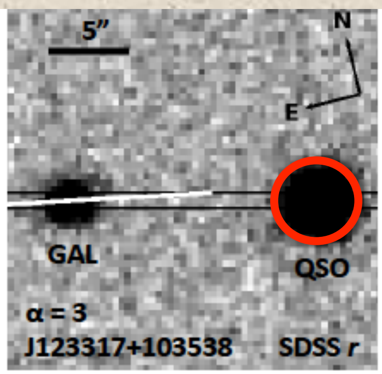


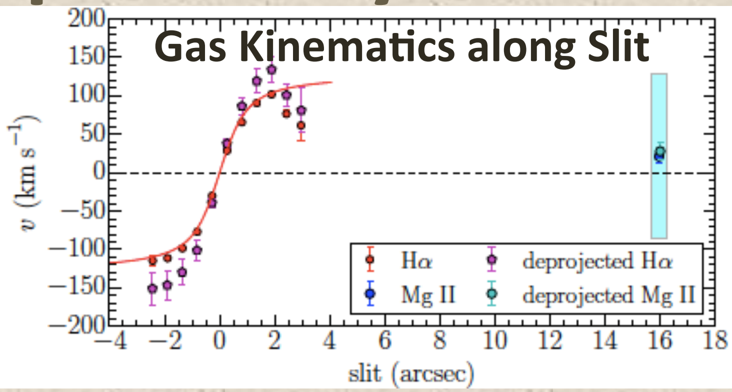


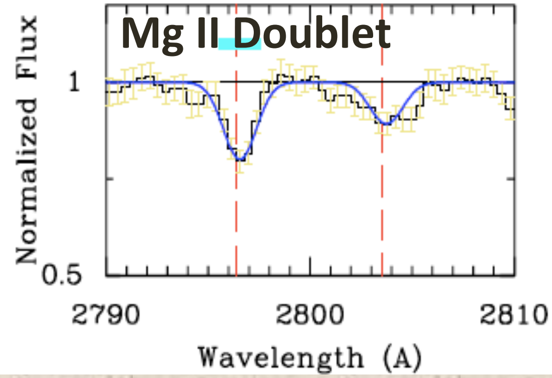
- Doppler shift of CGM along major axis correlated with sign of disk rotation.
- If the gas is near the disk plane, much of it is not moving fast enough to be on a circular orbit.
- An inflowing component can be added to simple models for the line-of-sight velocity range.

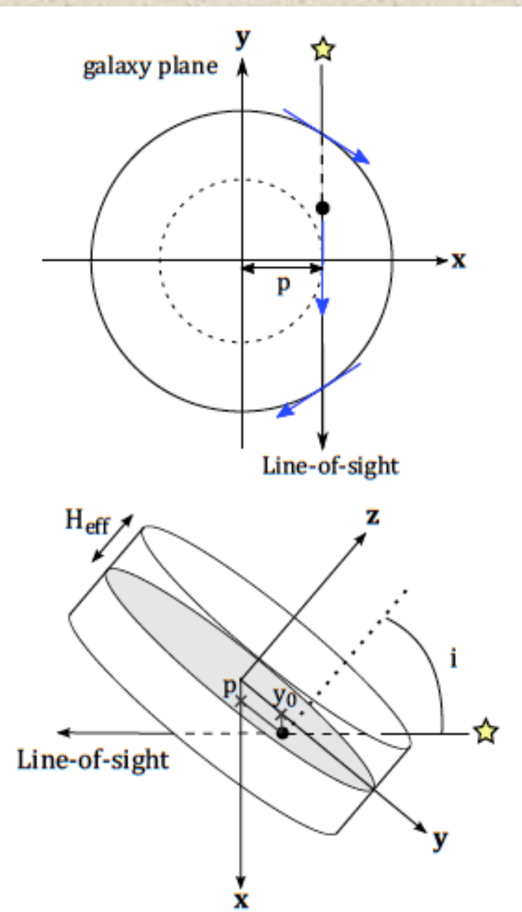
Stephanie Ho, CLM, Kacprzak, Churchill, Bouche

Keck QpG Survey: Inflow Example #1

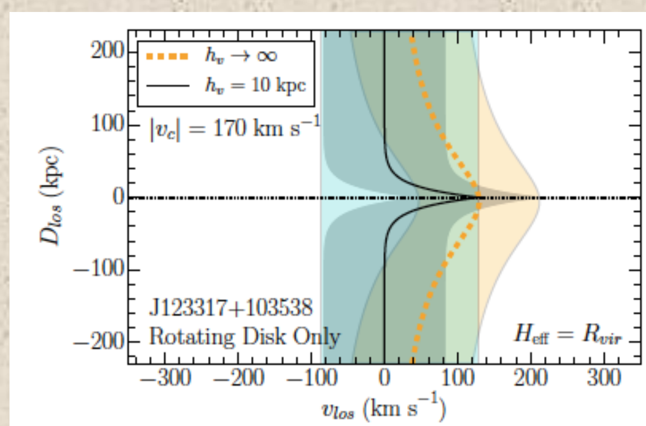


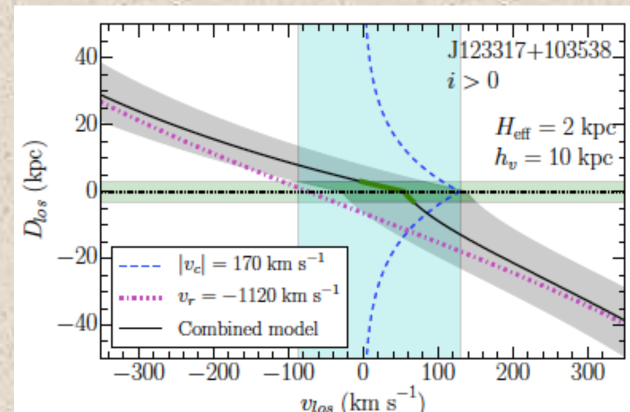






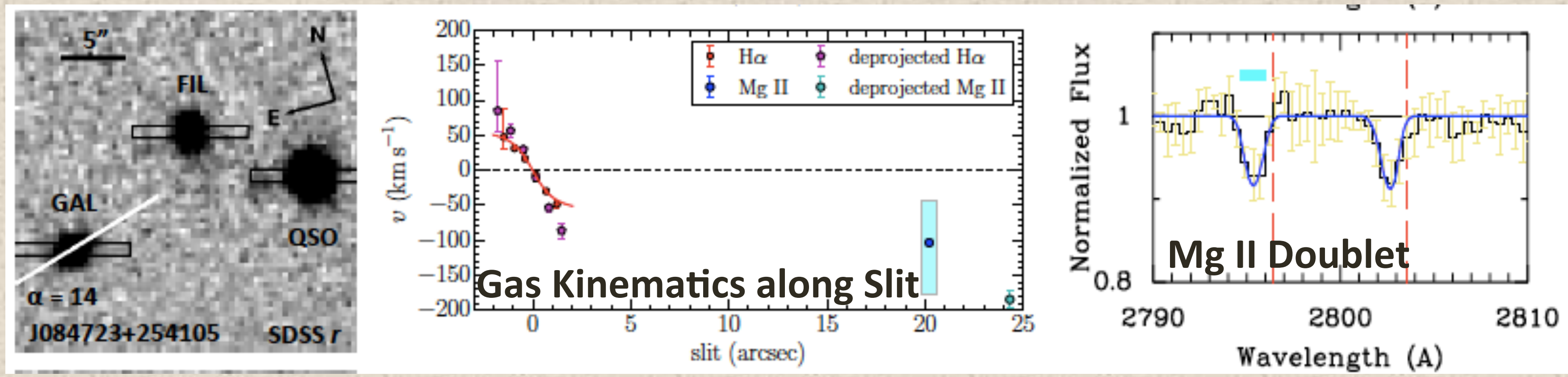
- Disk model does not produce two-sided absorption.
- Forced "best fit" requires very thick rotating cylinder, no longer a disk.
- Inflow solution exists with gas in a disk
  - v_R = -1120 km/s
  - H_{eff} = 2 kpc
  - dv/dz = 20 km/s/kpc

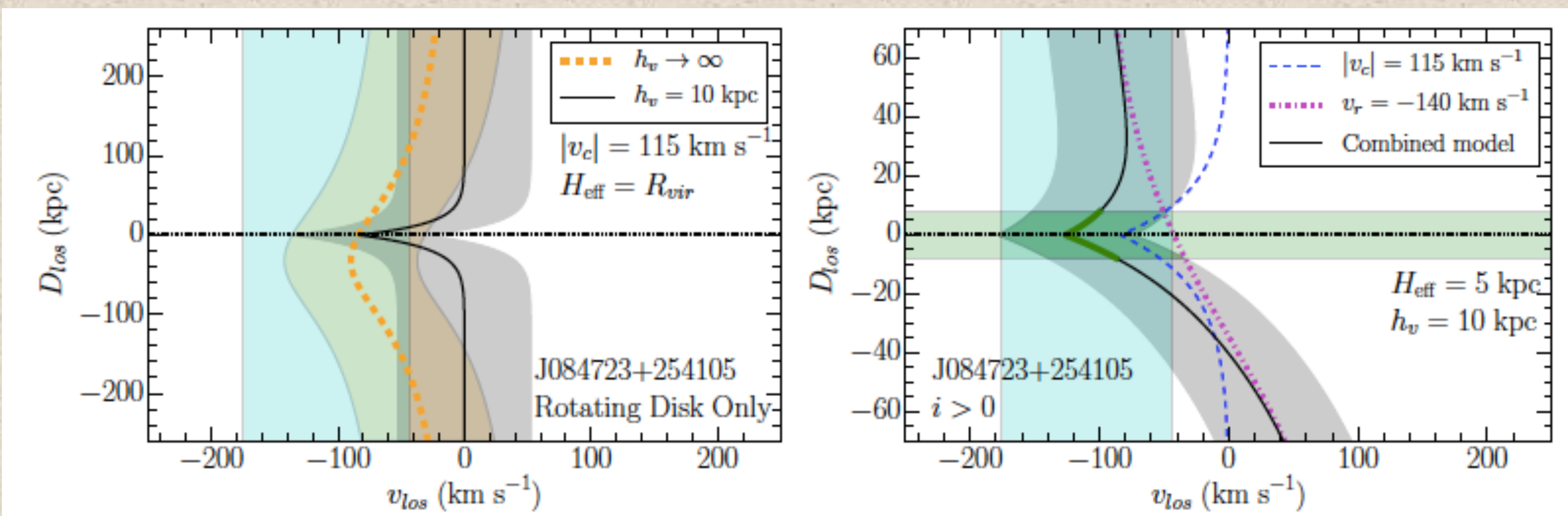




Stephanie Ho, CLM, Kacprzak, Churchill, Bouche

Keck QpG Survey: Inflow Example #2





- **Simple disk can not produce absorption at $v_{los} > v_c \sin I$**
- **Forced fit is not really a disk either, $H_{eff} \sim r_{vir}$.**
- **Plausible fit found with radial inflow:** $v_R = -100$ km/s, $H_{eff} = 5$ kpc, dv/dz = 20 km/s/kpc

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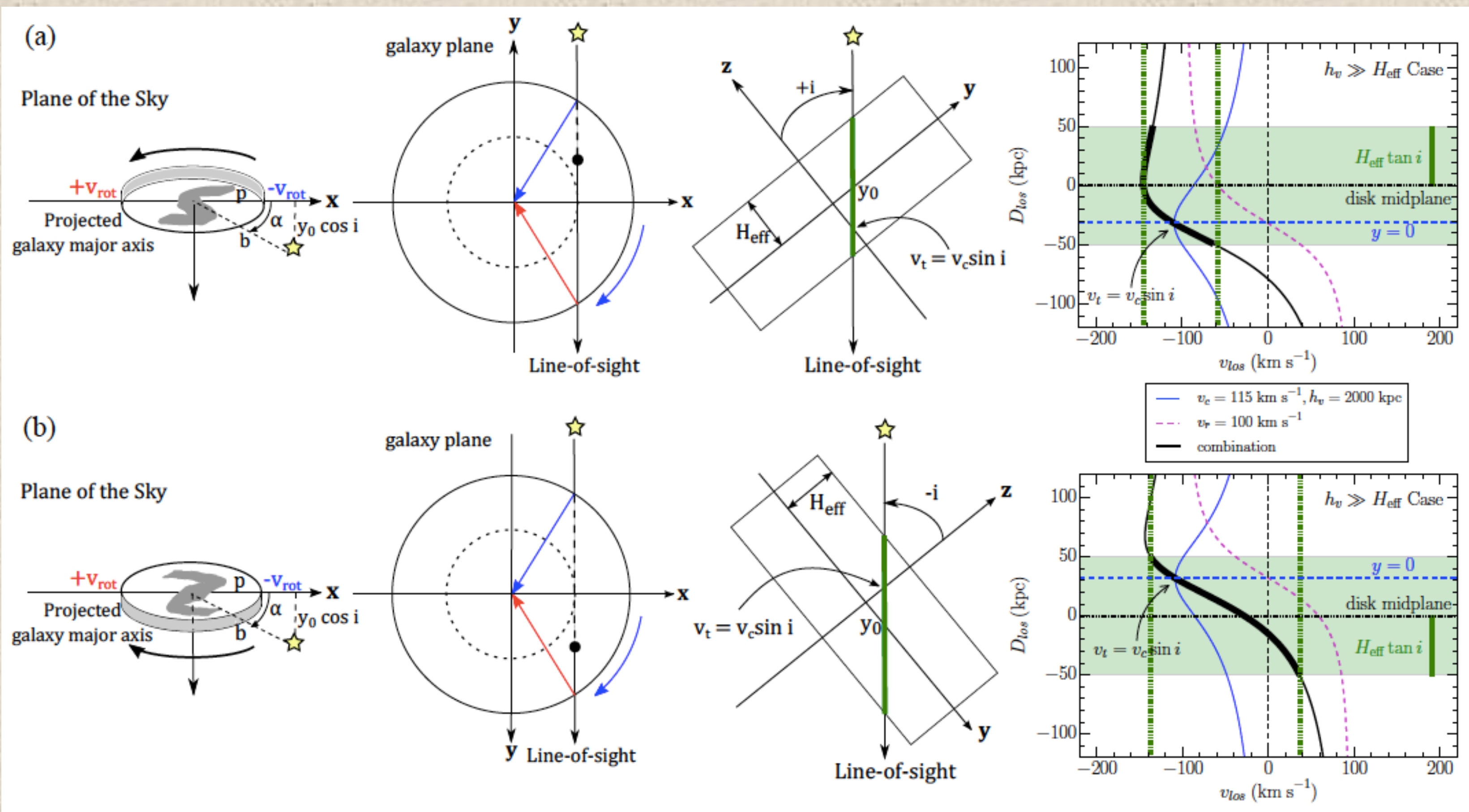
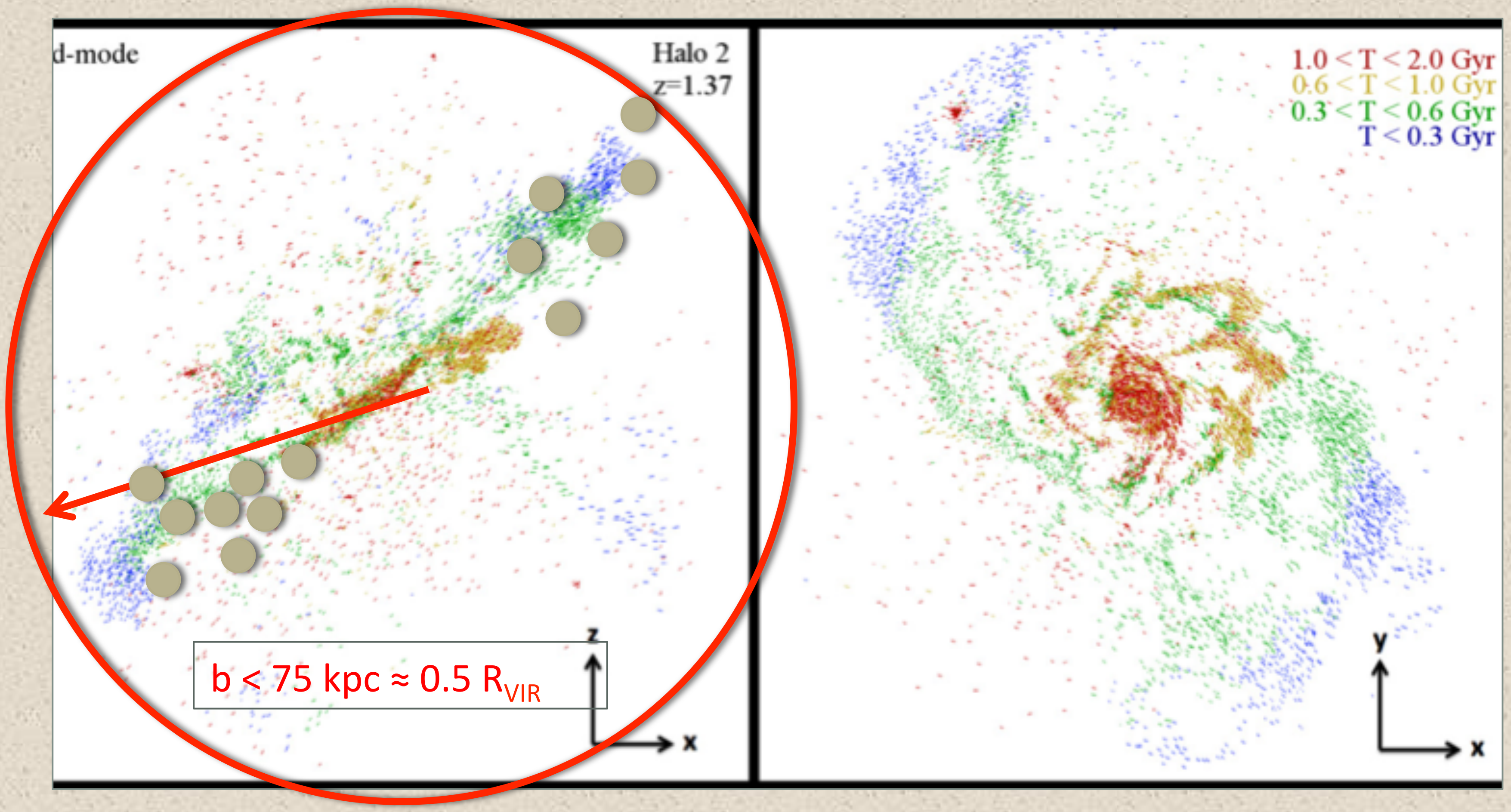
Keck QpG Survey:
Proposed Test of Inflow Scenario



- The tilt of the disk required to fit the line profile is often unique.
- Should be possible to measure the tilt by resolving the spiral arms, which tend to be trailing.

Stephanie Ho, CLM, Kacprzak, Churchill, Bouche

Context for Observations: Recent Accretion

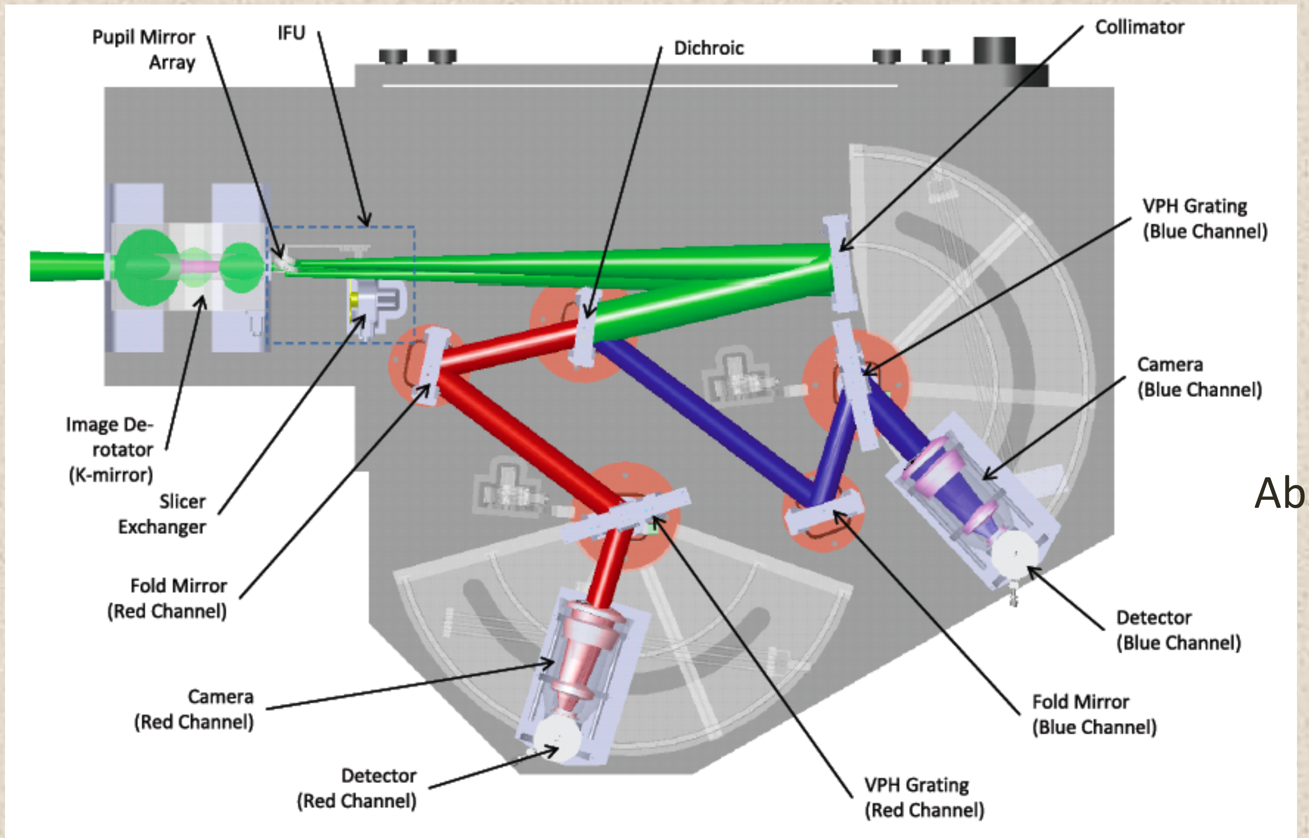


Stewart + 2013

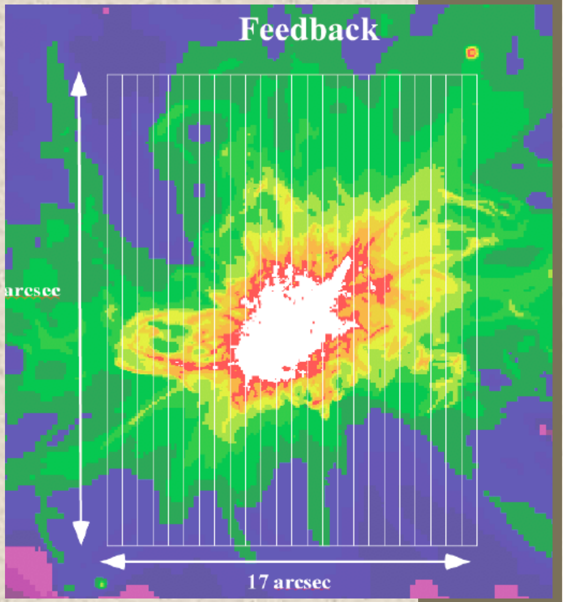
The Future Looks Promising

Very Soon: Keck Cosmic Web Imager (KCWI)

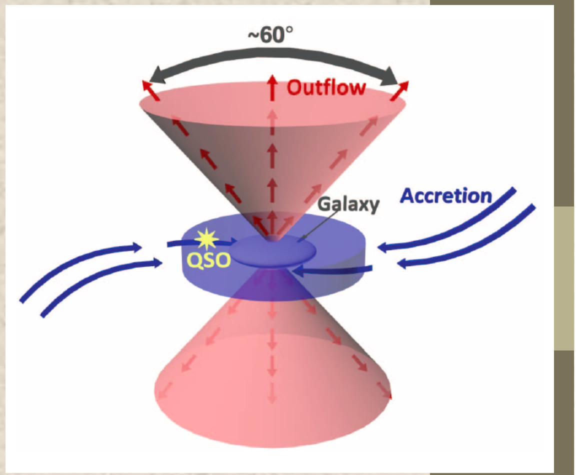
PI: Chris Martin (Caltech)



Map scattered emission



Absorption-line Tomography

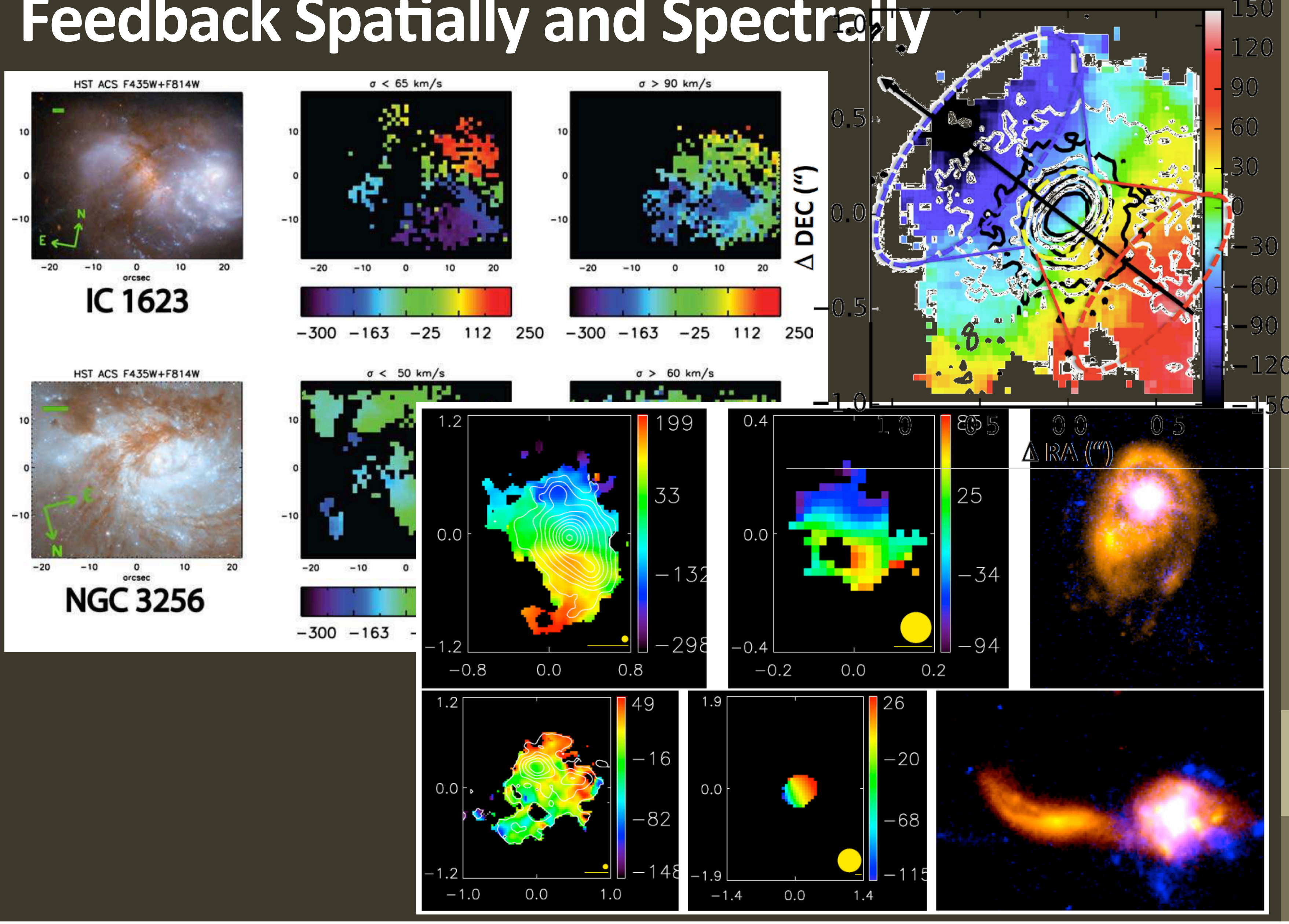


Very Soon: JWST

- JWST will provide high sensitivity to (rest-frame optical) line emission over a very broad redshift range.
- Provides a new tool to study flows of metals, mass, and energy through the circumgalactic medium.
  - Evolution of the mass - metallicity relation will determine which galaxies ejected metals and when.
  - Mapping emission-line flux ratios and kinematics can identify AGN, galactic outflows, and possibly cold flows. Shock speeds and mass fluxes can be measured.
  - Galactic outflows can be identified in integrated spectra sometimes.
- The evolution of these physical properties of outflow, in parallel to the evolution in the galactic mass-metallicity relation, promise to sharpen our view of how galaxies came to be surrounded by a web of metal-enriched filaments.
- Strong synergies with ALMA

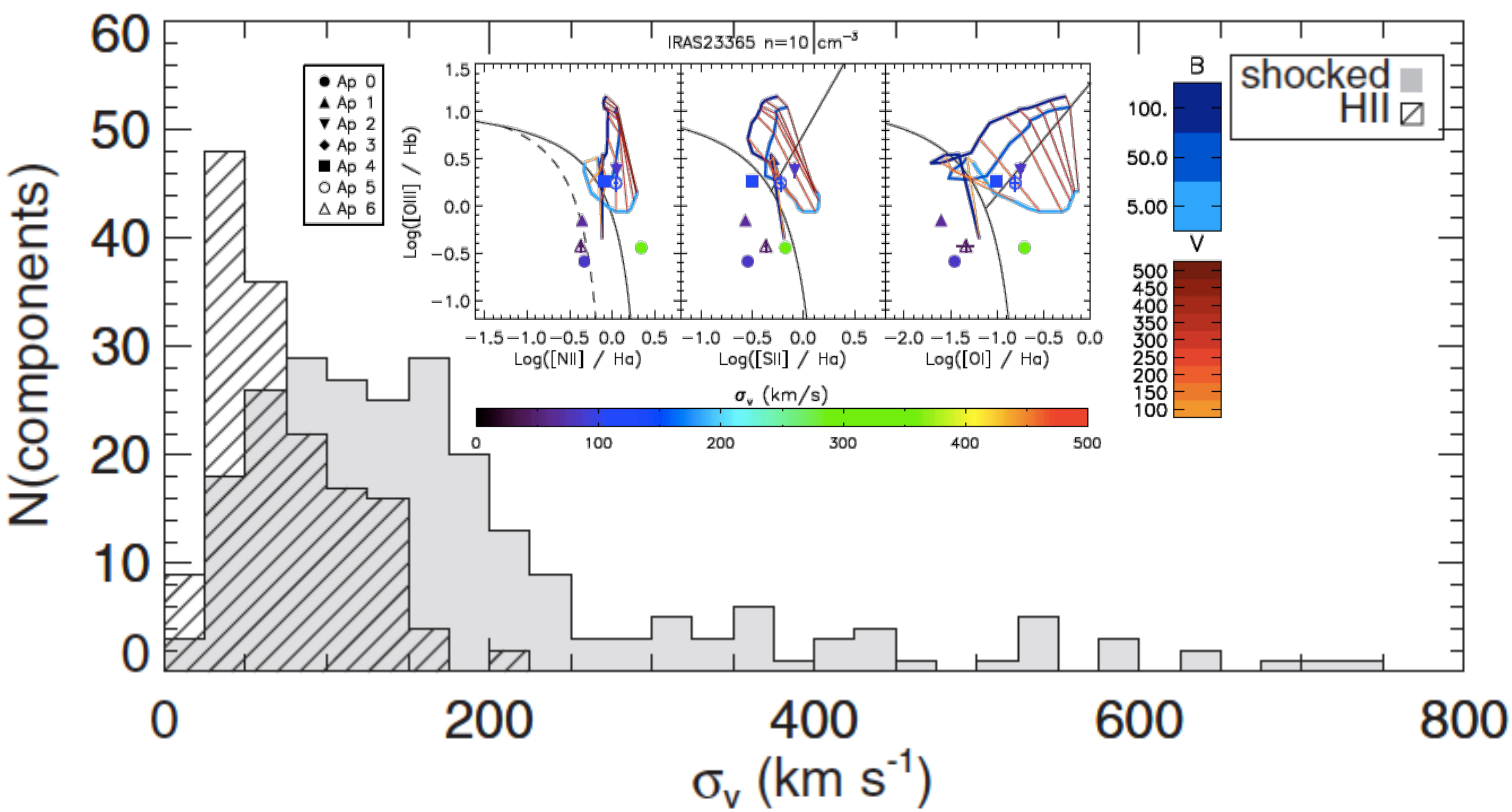
See Martin 2011 – JWST Symposium

JWST Integral Field Spectroscopy: Decompose Feedback Spatially and Spectrally



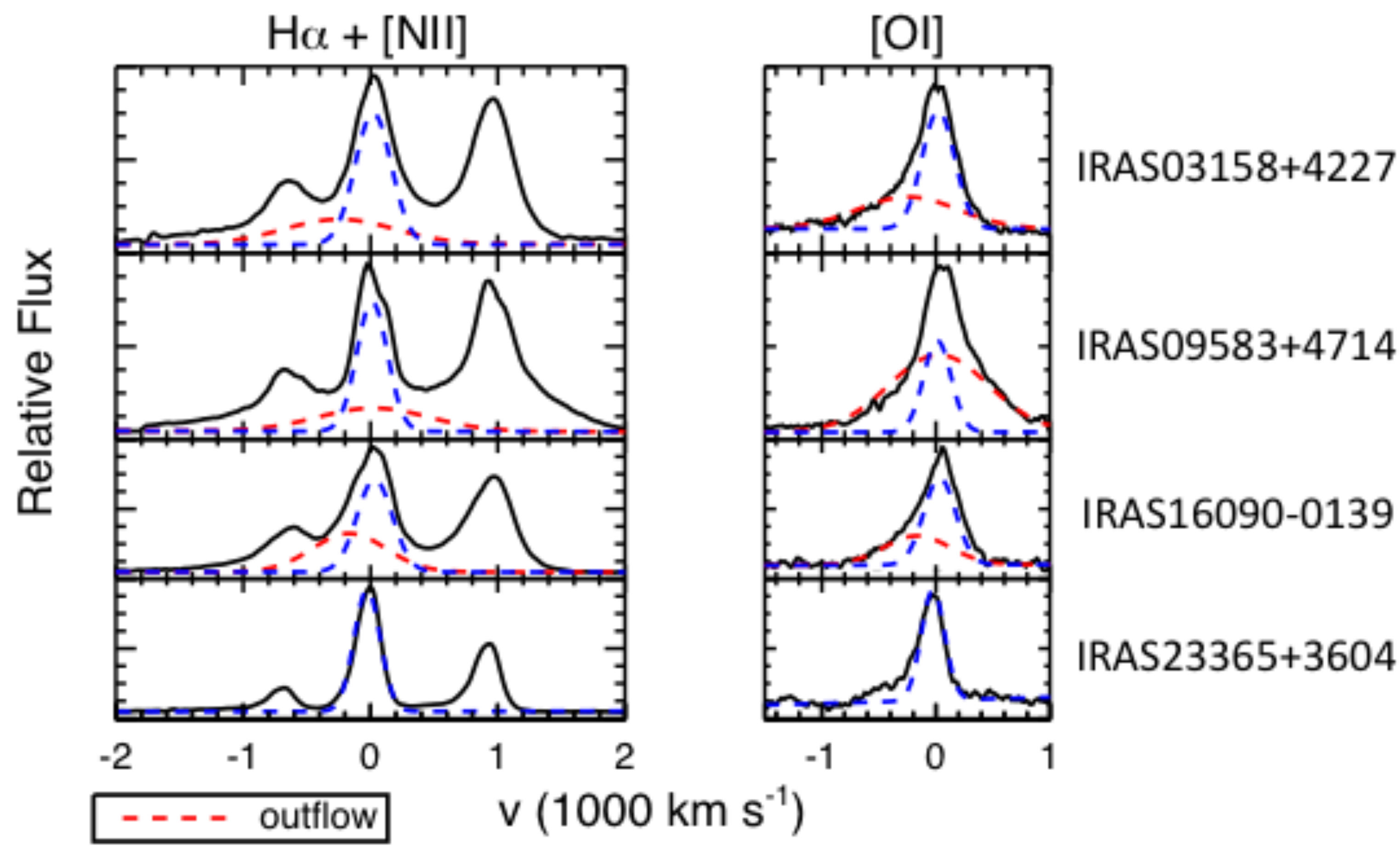
Goncalves + 22010, Rich + 2011, Martin+2016

JWST Integral Field Spectroscopy: Gas Excitation Connected to Gas Kinematics



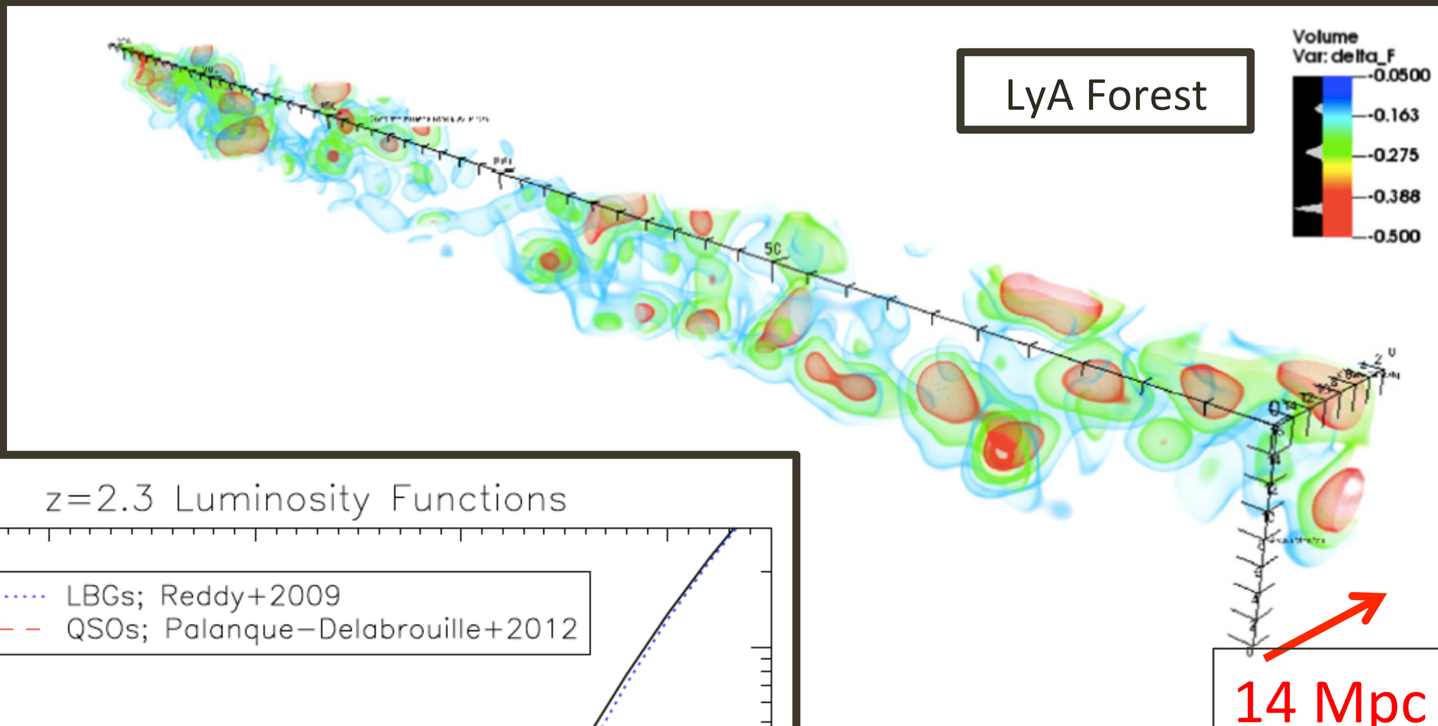
Soto + 2012a

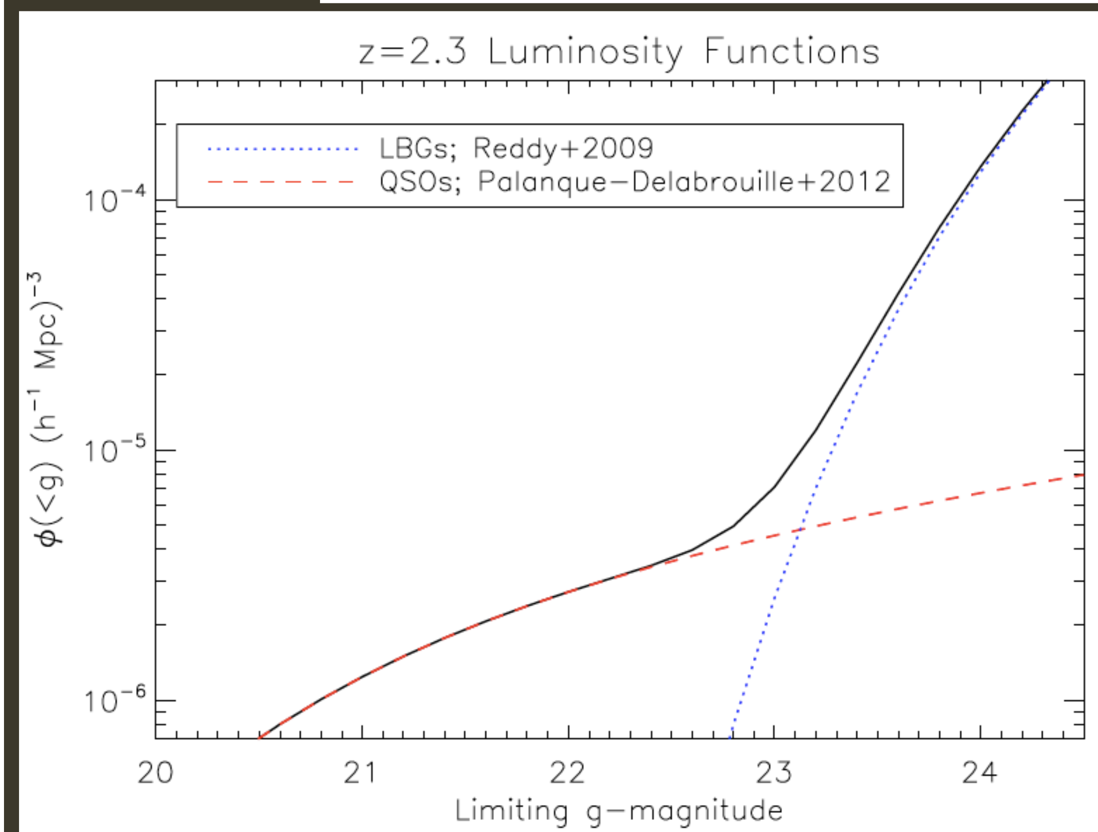
JWST R≈3000: Can Identify Dense, High Velocity Clumps in Emission Line Wings



See Martin 2011 – JWST Symposium

Future: ELT Tomography





- Pioneering work on the Lya forest now.
- TMT enables circumgalactic medium to be studied.
- Large gain in number of background sources.

Lee + 2014, 2016