Flows

How Do Gas~~eous Halos~~ Affect Galaxy Evolution? YES!

 

Crystal Martin

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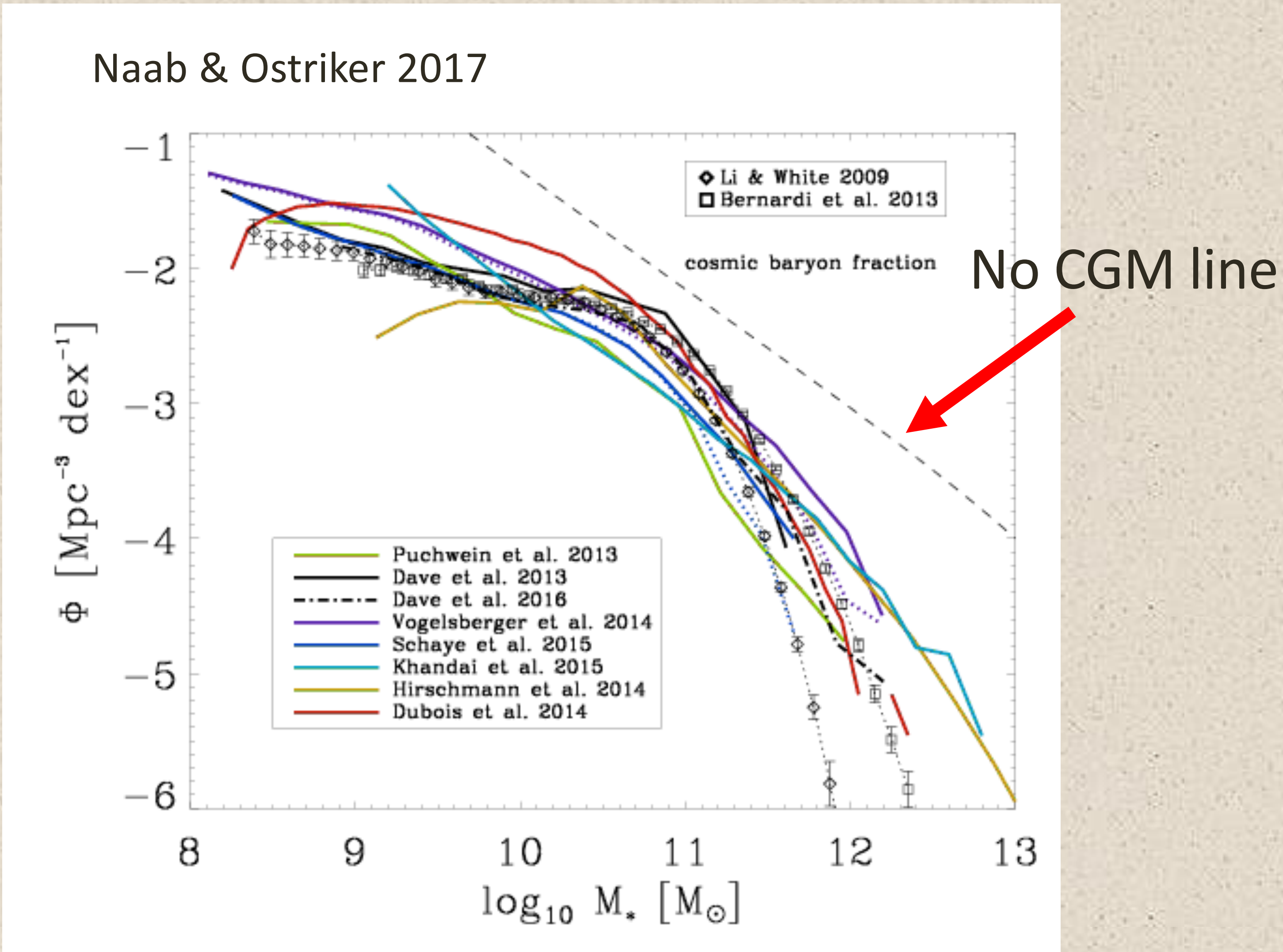
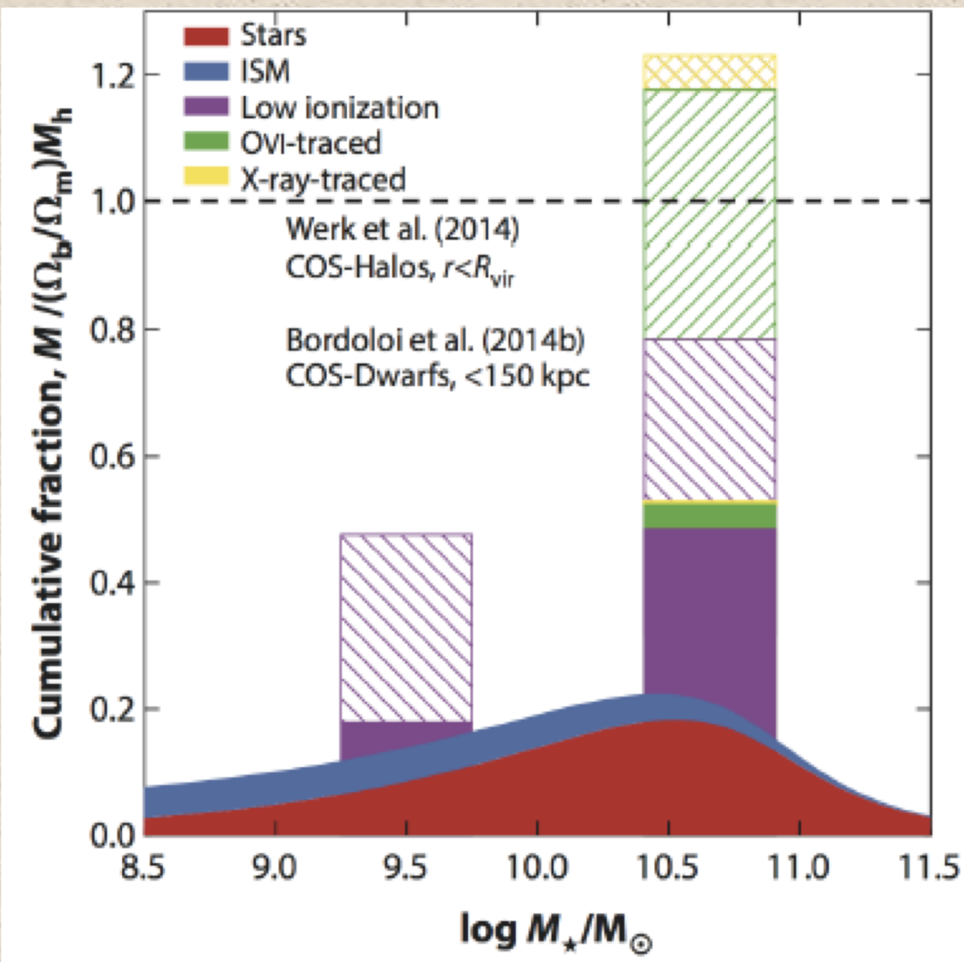
Stellar Mass.

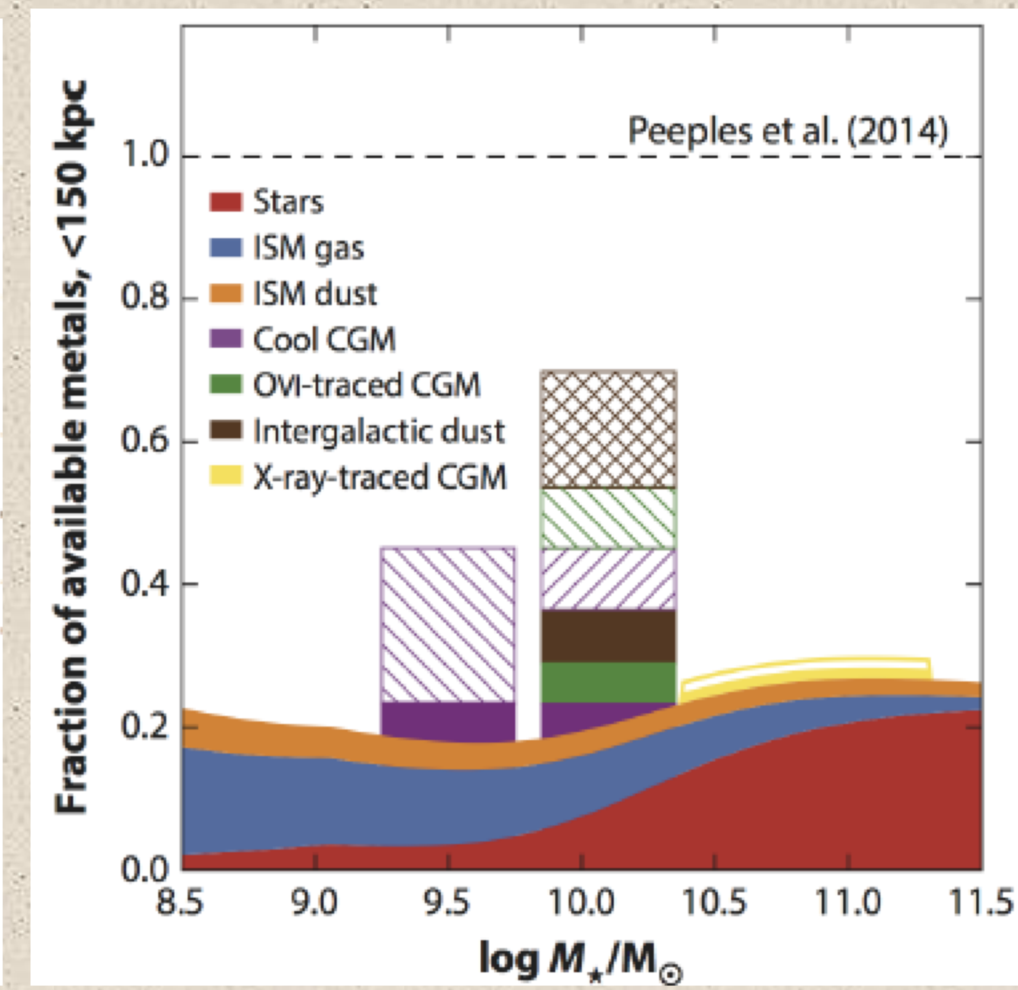
Feedback greatly reduces the stellar mass in the Universe today.



Chemical Evolution.

Significant Fraction of Metals in CGM.

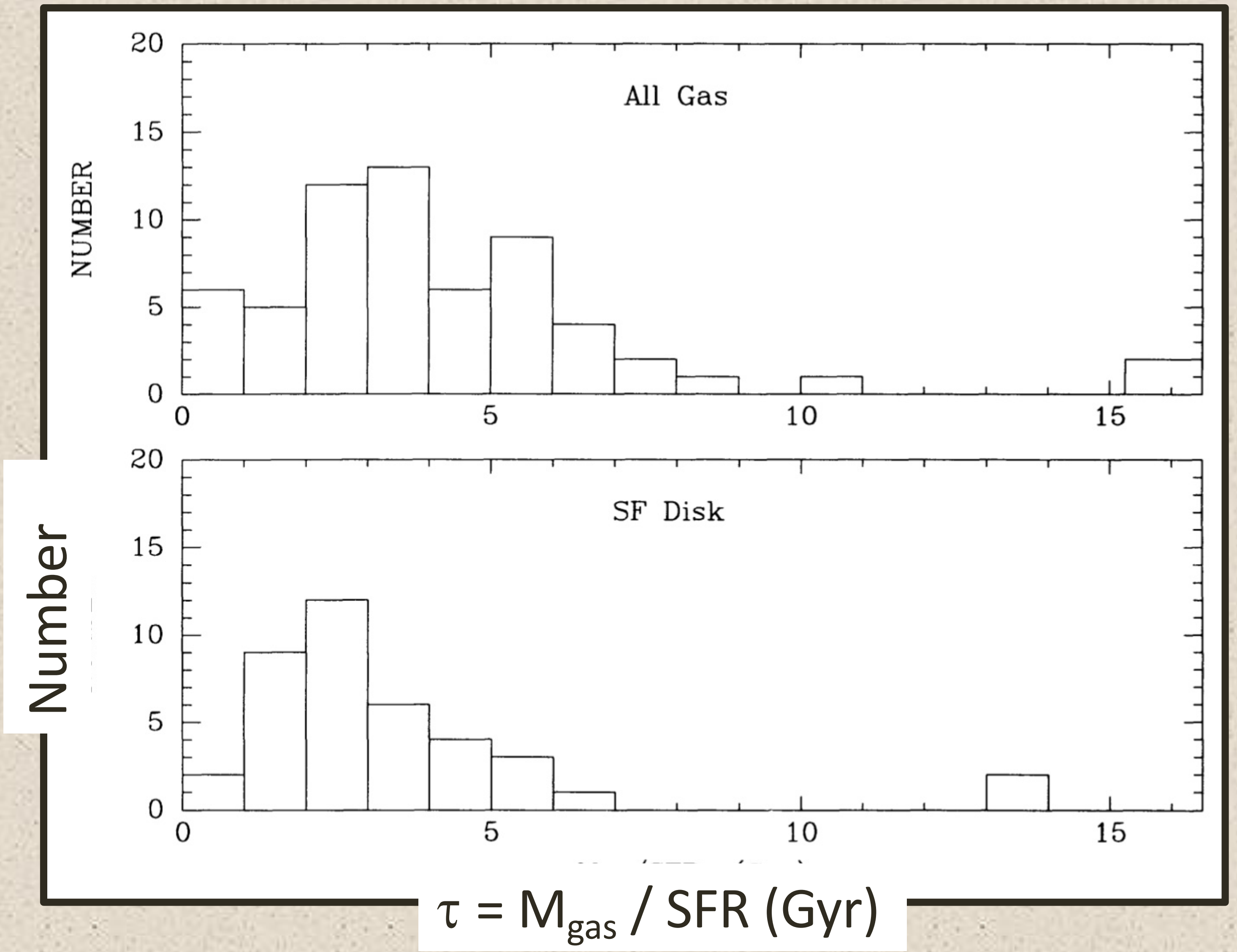




Tumlinson, Peeples, & Werk 2017

Gas Consumption Timescale Is Short

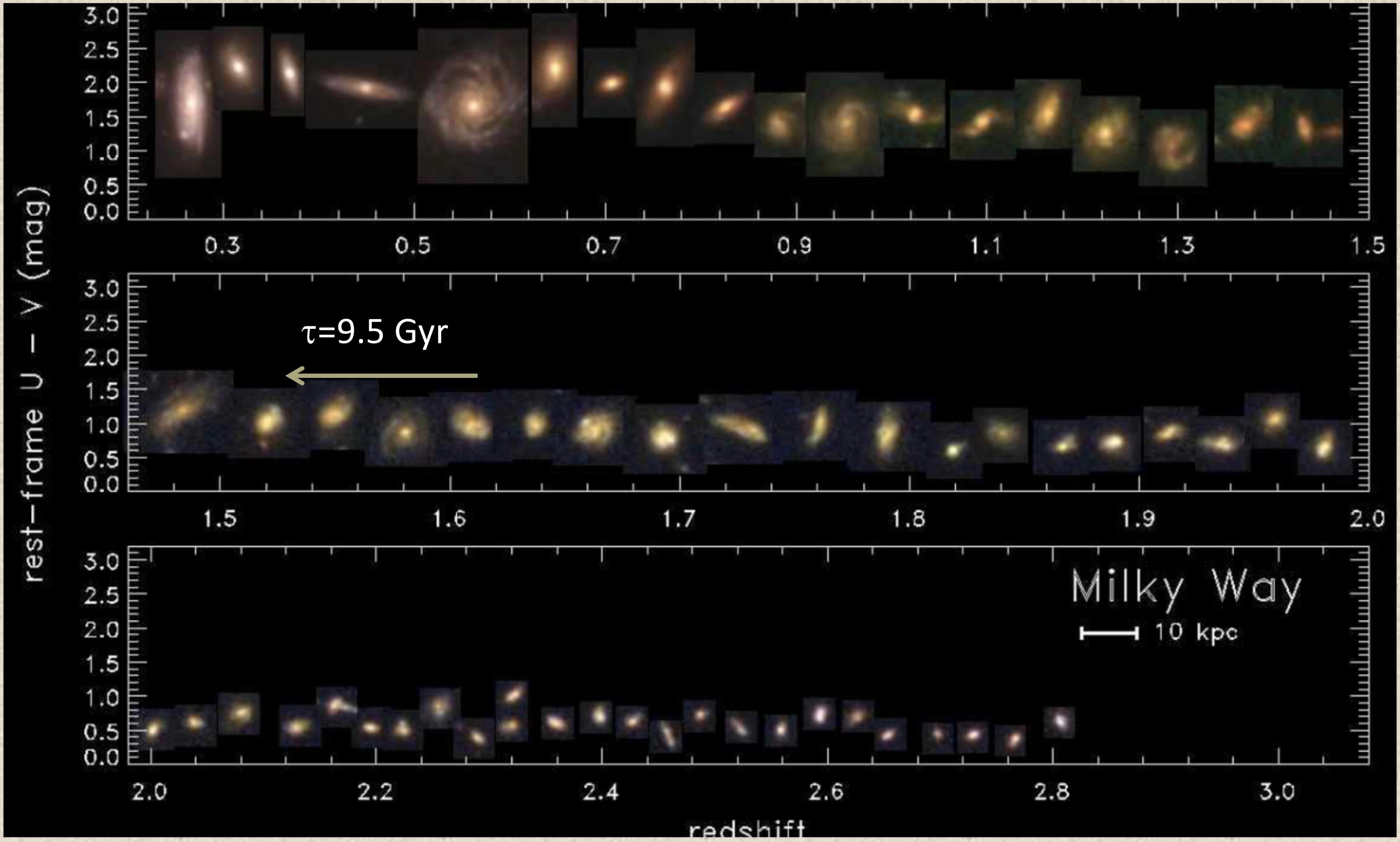
Compared to Disk Assembly Timescale



Kennicutt, Tamblyn & Congdon (1994)

Disk Assembly Timescale is Long

Requires nearly continuous inflow from CGM.

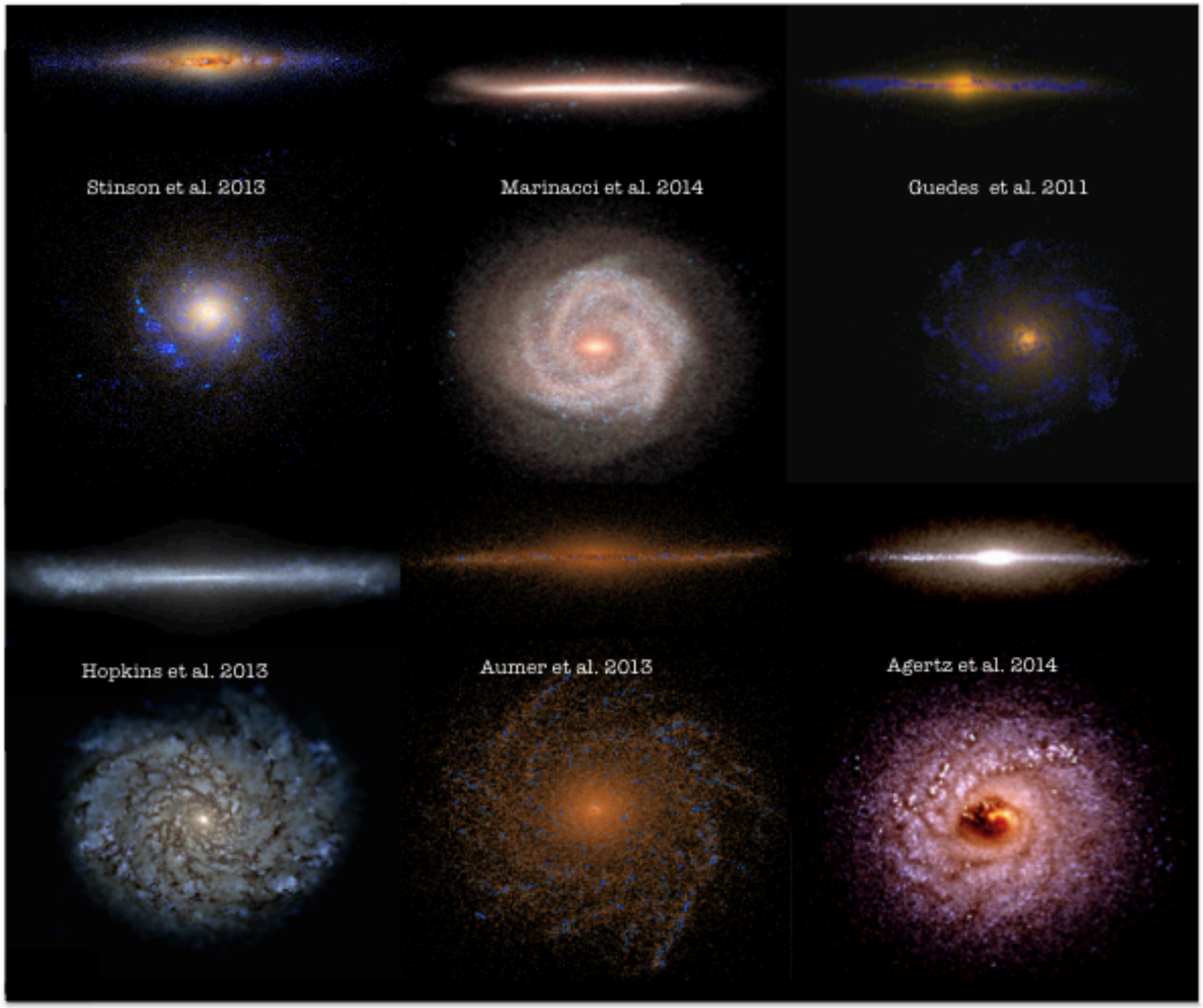


Papovich+2015

Morphologies.

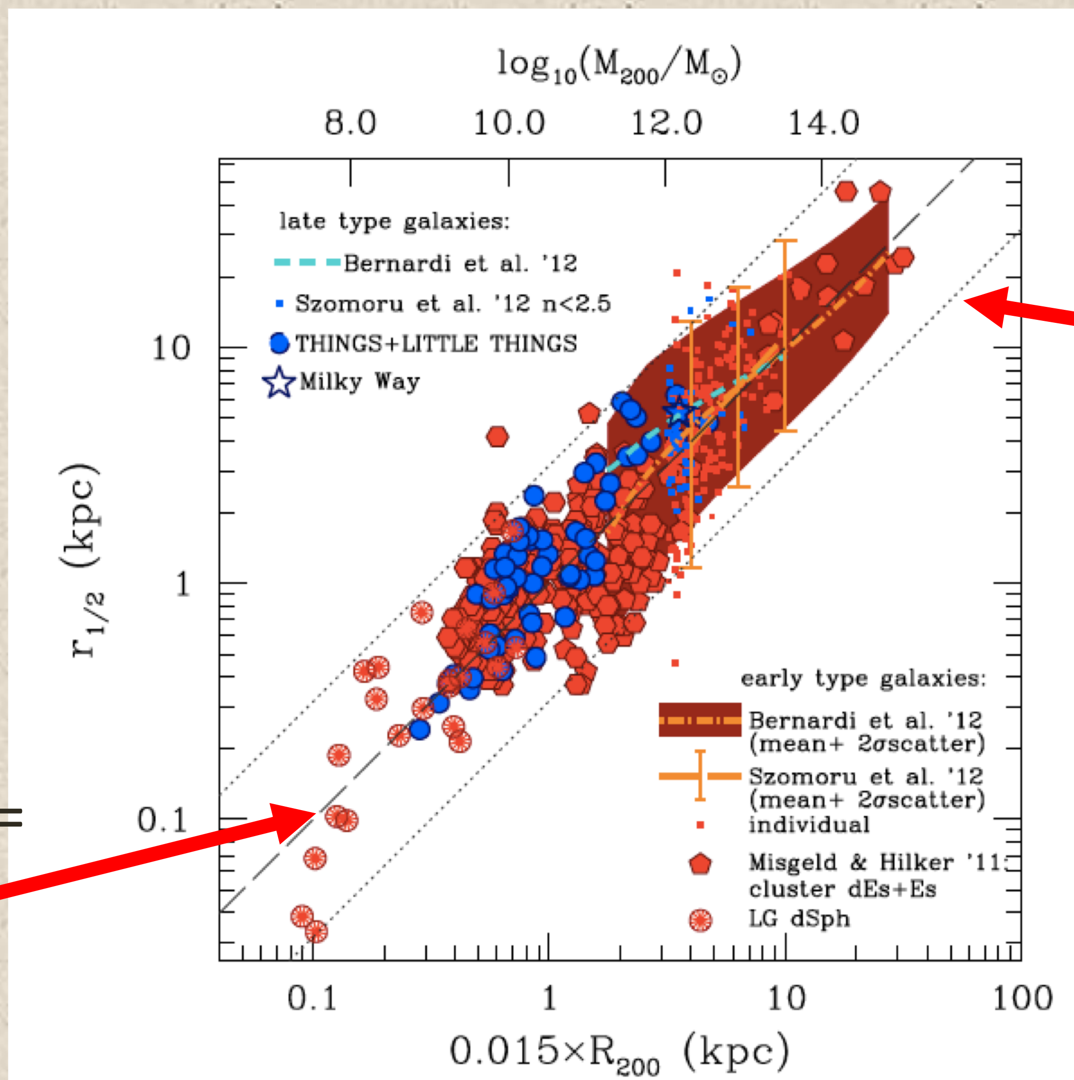
Producing Big Disks Requires Strong Feedback.

Naab & Ostriker 2017



Morphologies.

Galaxies are Big.

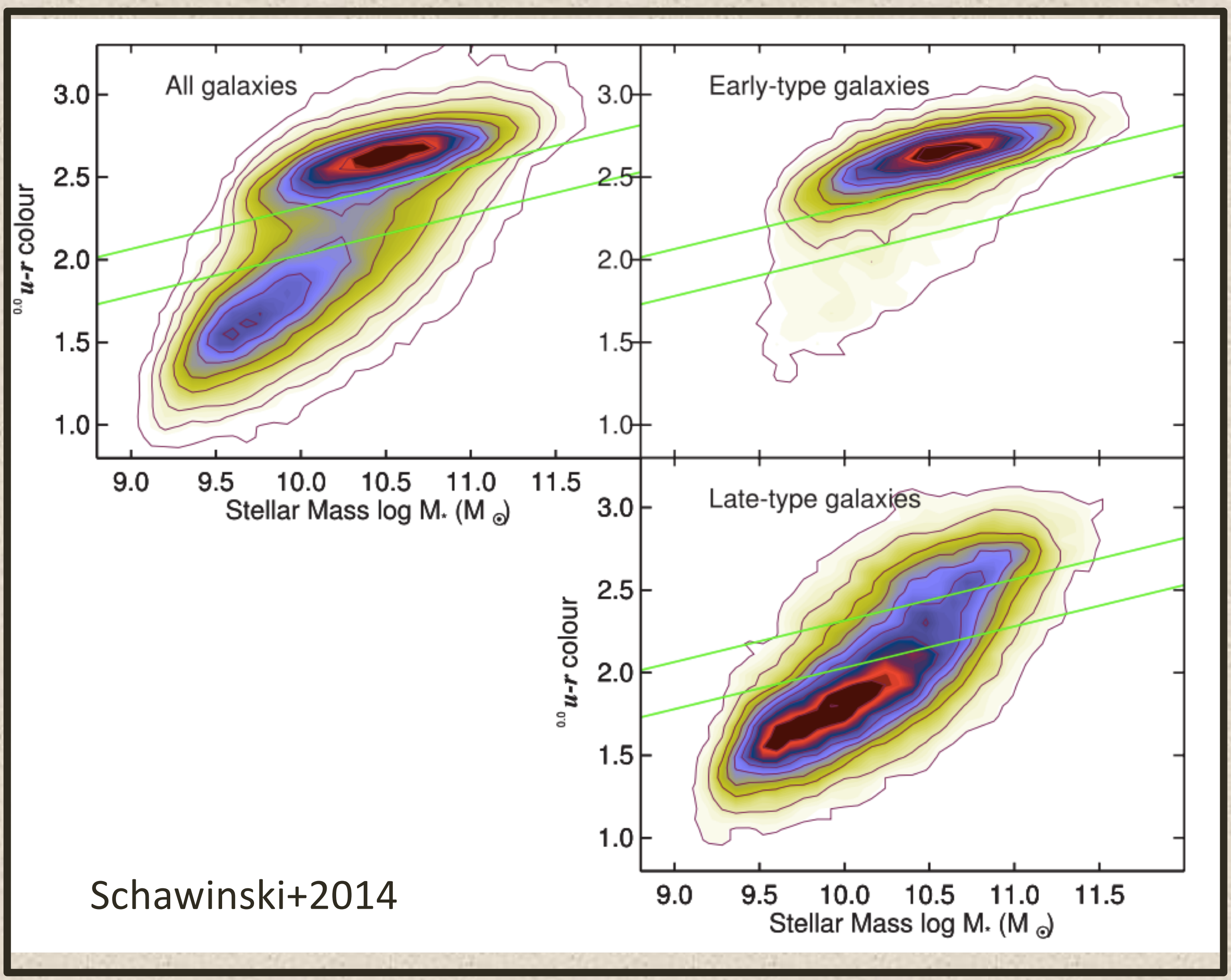


Scatter (0.5 dex) is consistent with the distribution of halo spins.

R(half mass) = 0.015 R_{200}

Kravtsov 2017

Star Formation Is Eventually Quenched



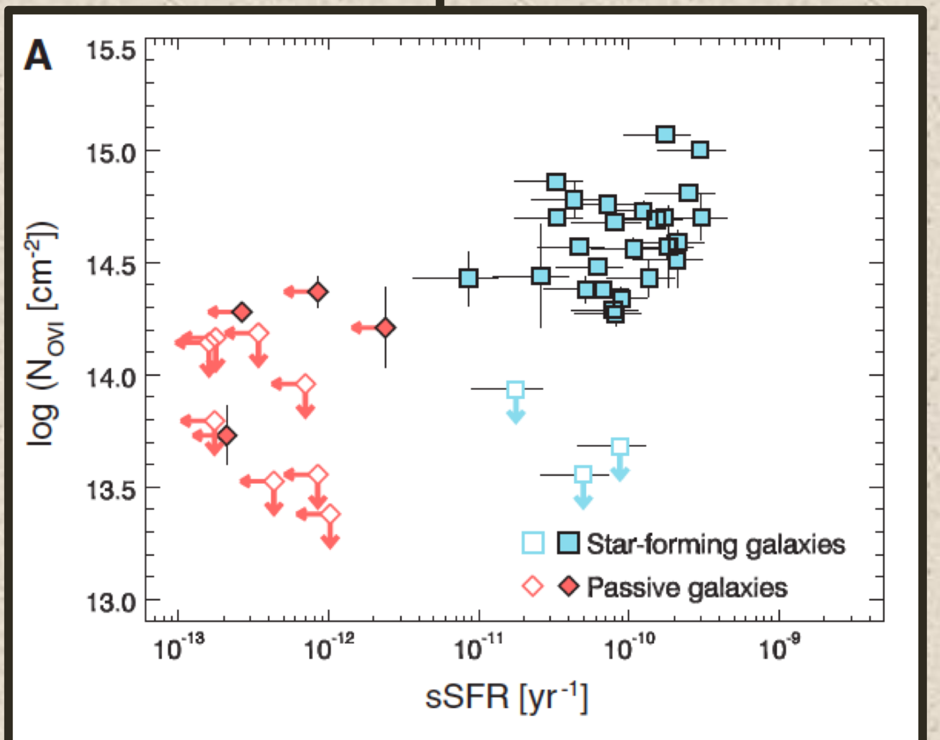
Schawinski+2014

… as mass of galaxy and supermassive black hole increases.

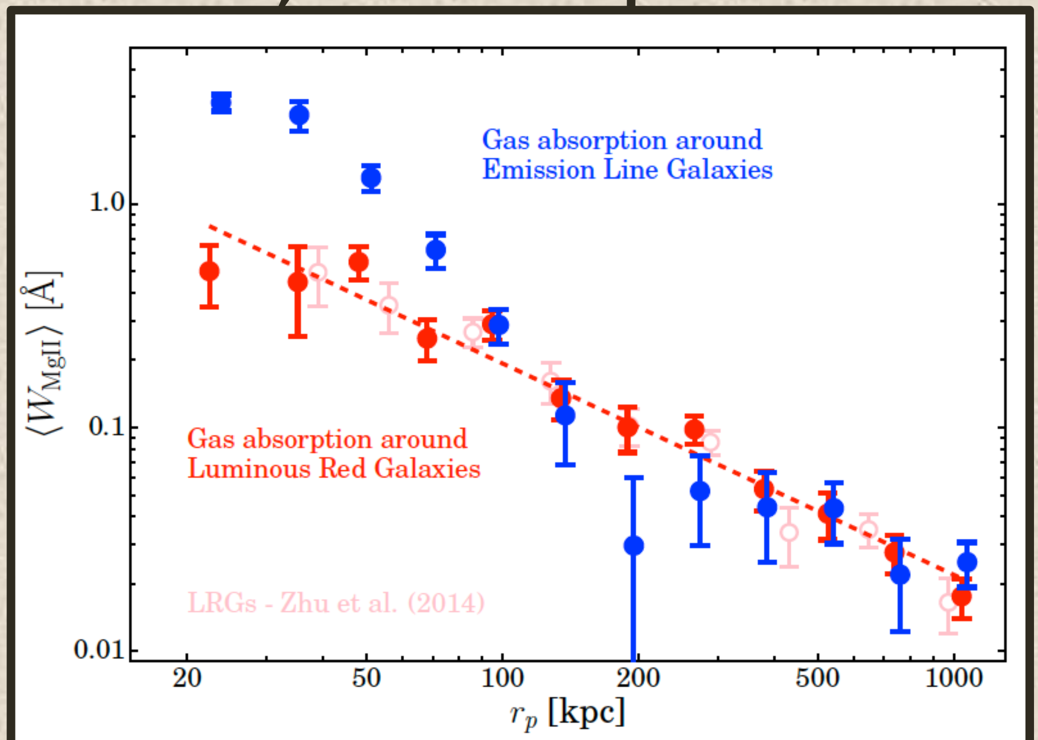
Different Physical Conditions in CGM of Red/Blue Galaxies

High-ionization O VI 1031, 1036 A absorption

Low-ionization Mg II 2796, 2803 absorption



Tumlinson + 2011



Lan&Mo 2018

Perspectives: How Gas Reaches the Disk

In Simulations:

- Keres+2005; Stewart+2011; Stewart +2013; Danovich+2015; Stewart+2017; Keres' week 6 Trapp+ upcoming results!
  - High specific AM in CGM relative to DM halo
  - Gas settles close to outer disk edge
  - Transported radially (~20 km/s 30-40 kpc from the center)
- Hot gas partially supported by AM– Oppeheimer+2018
- Stern+2020 – outside-in CGM virialization tied to thin disk formation

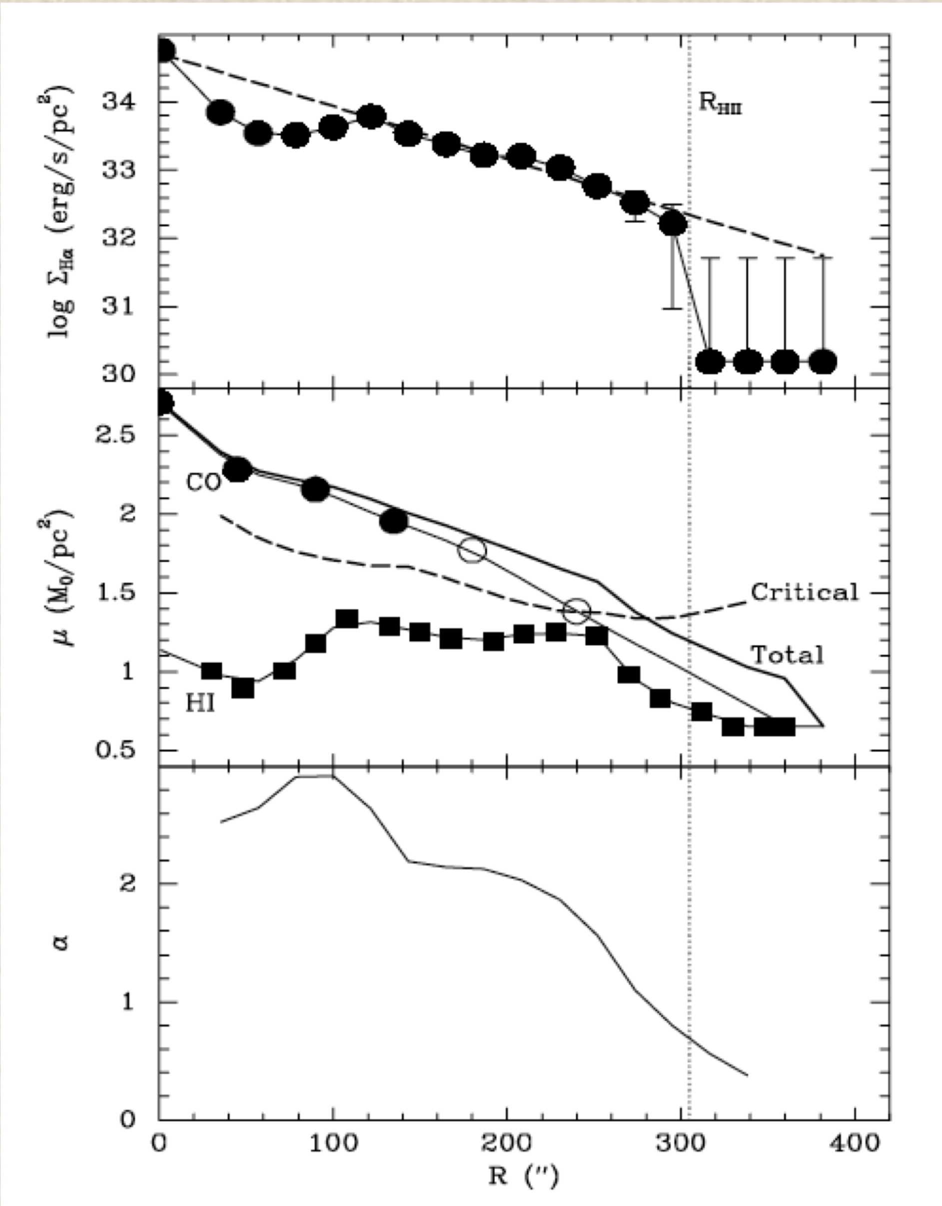
In Chemical Evolution Models:

- See Fraternali's talk from week 4
  - Argues for vertical infall
  - Otherwise, radial inflow speeds > 10 km/s would be observed.

What do observations tell us?

Gas Depletion Timescales in Disks

CLM & Kennicutt 2001; Leroy+2008



Inner disk

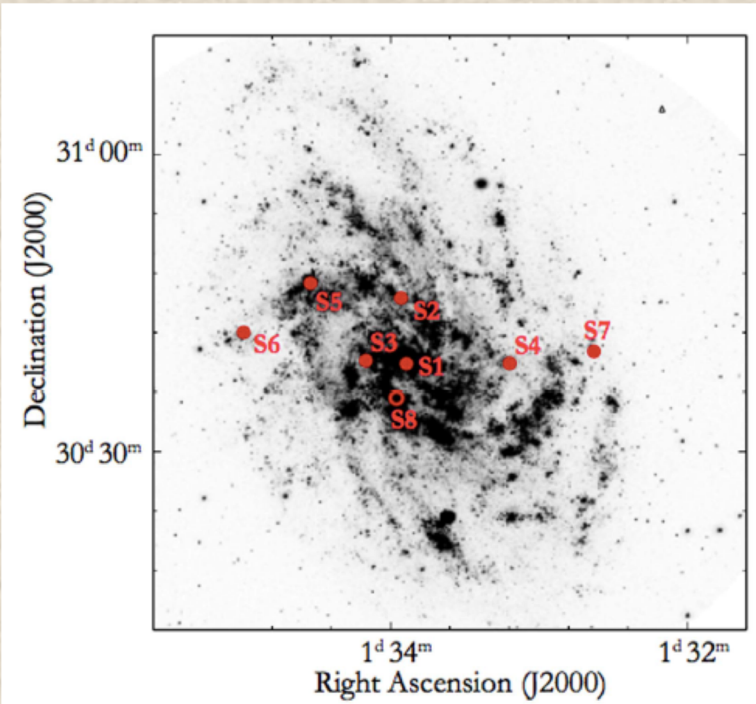
- SFR and molecular gas surface density decline exponentially with radius
- Constant SFE (depletion time)
- Requires highest accretion rates in inner disk

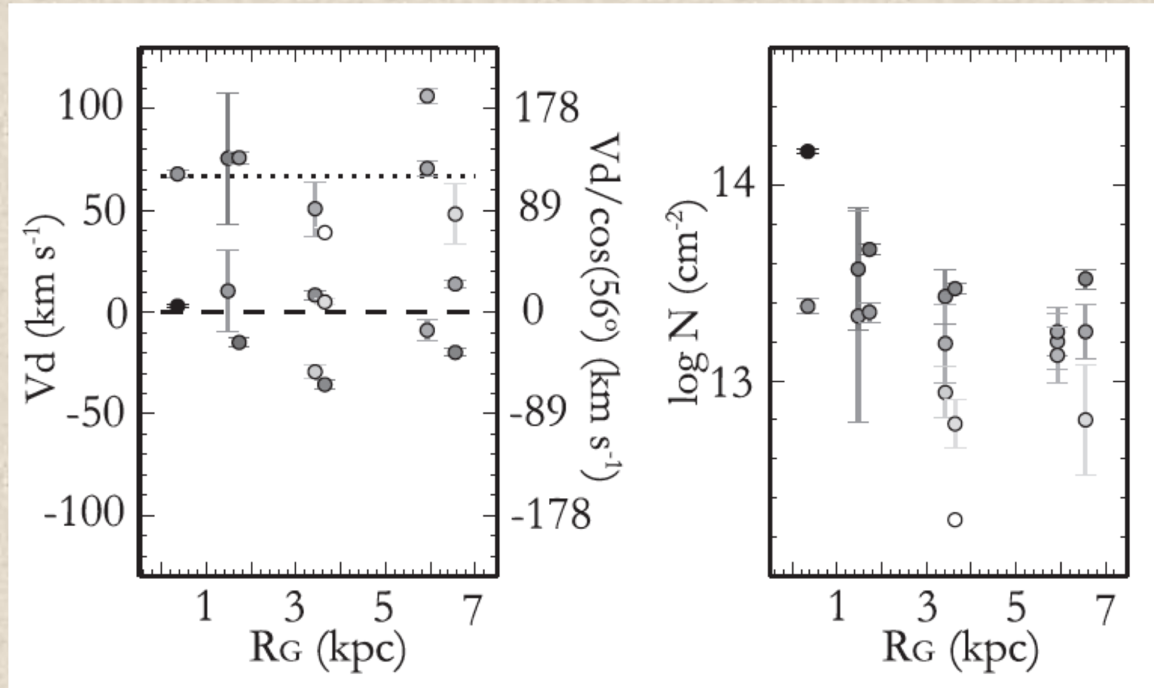
Outer disk & Dwarfs (H I > H_2):

- SFR ~ $\mu^{1.5}$
- $\tau \sim \mu^{-0.5}$ is longer at large R, and SFE is lower
- Even more important to get gas to inner region

M33: Accreting Layer or Halo Cloud?

Zheng+2017

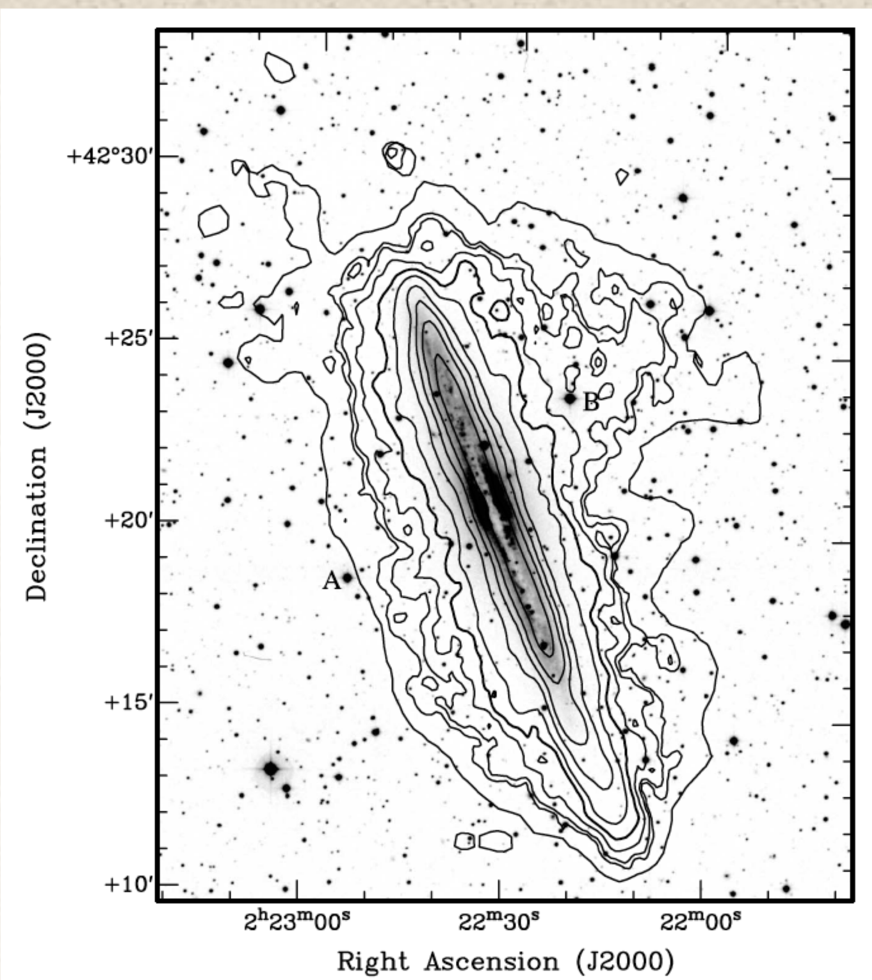


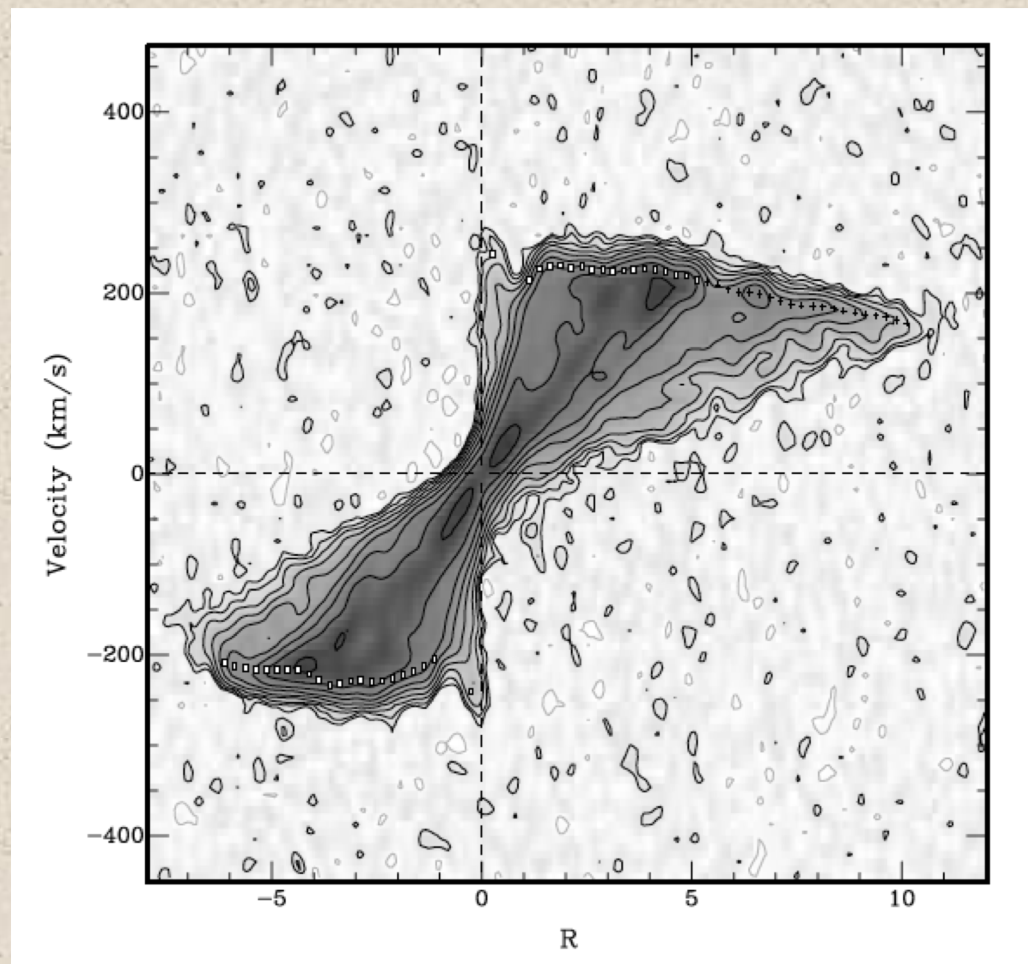


- Redshifted, non-disk component consistently detected in **Si IV**
- The non-disk components indicate the influence of **M33's rotation**, something a distant cloud with uniform velocity fails to reproduce.
- Accreting layer near disk (**h = 0.5-2.5 kpc**) depositing ~3 M_O/yr
- **Fallback** from galactic fountain or gas pulled out by M31

Accretion from Thick H I (and H II) Disks

Oosterloo+2007; Fraternail+2004; Marasco+2019

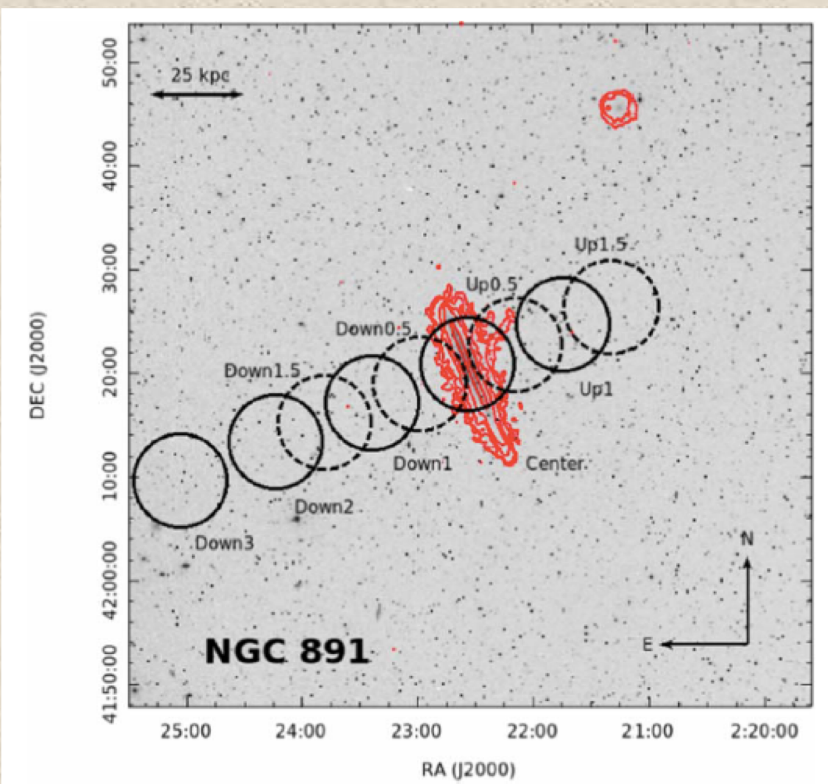


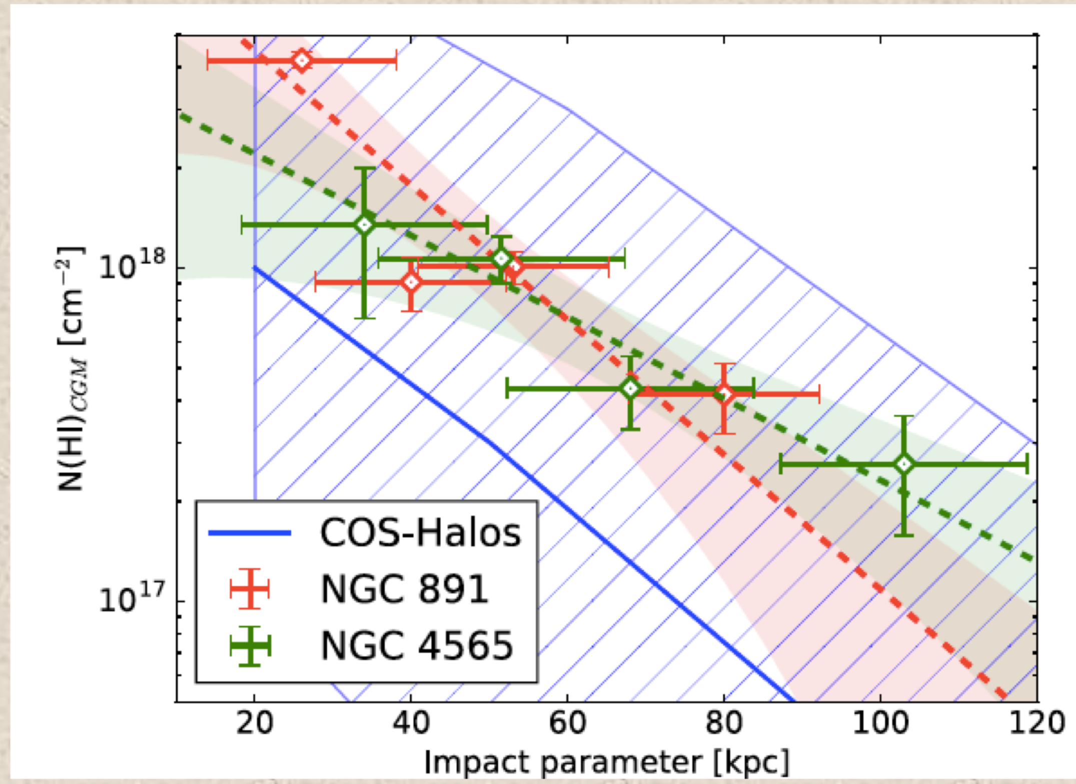


- Rotation of thick H I disk lags the thin disk
- Braking through interaction with fountain would speed up hot halo
- Inflow of 20-30 km/s in vertical and radial directions is common

Emission from H I in the CGM

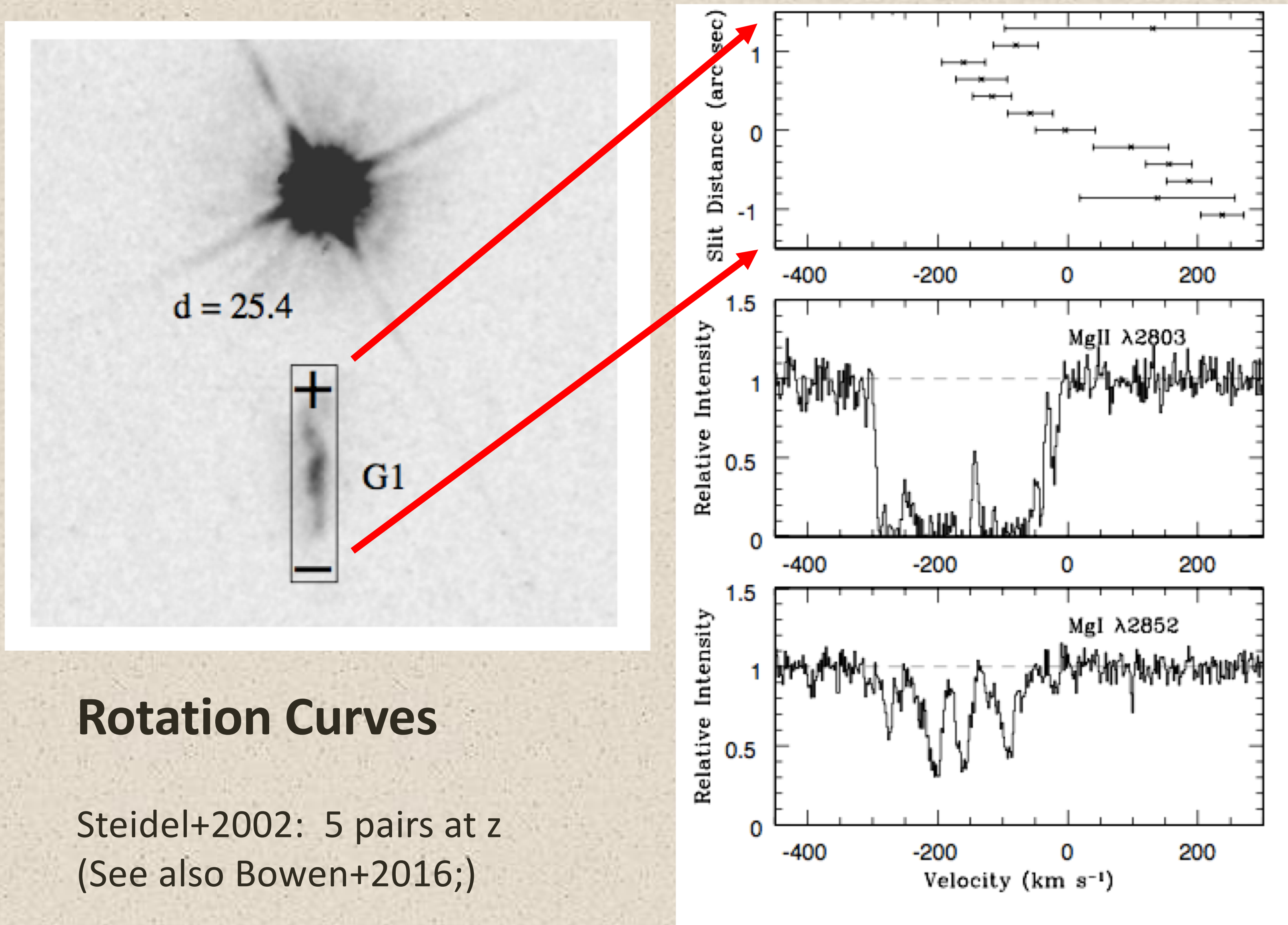
Das+2020





- Single-disk pointings reach N (H I) ~ 10^{17} cm^{-2}; broad lines ~500 km/s
- COS-Halos has substantial uncertainties on N (H I) from Lyman series
- NGC 891: diffuse H I contributes roughly 5% the total M (H I)

Is Corotation with the Galactic Disk Common?

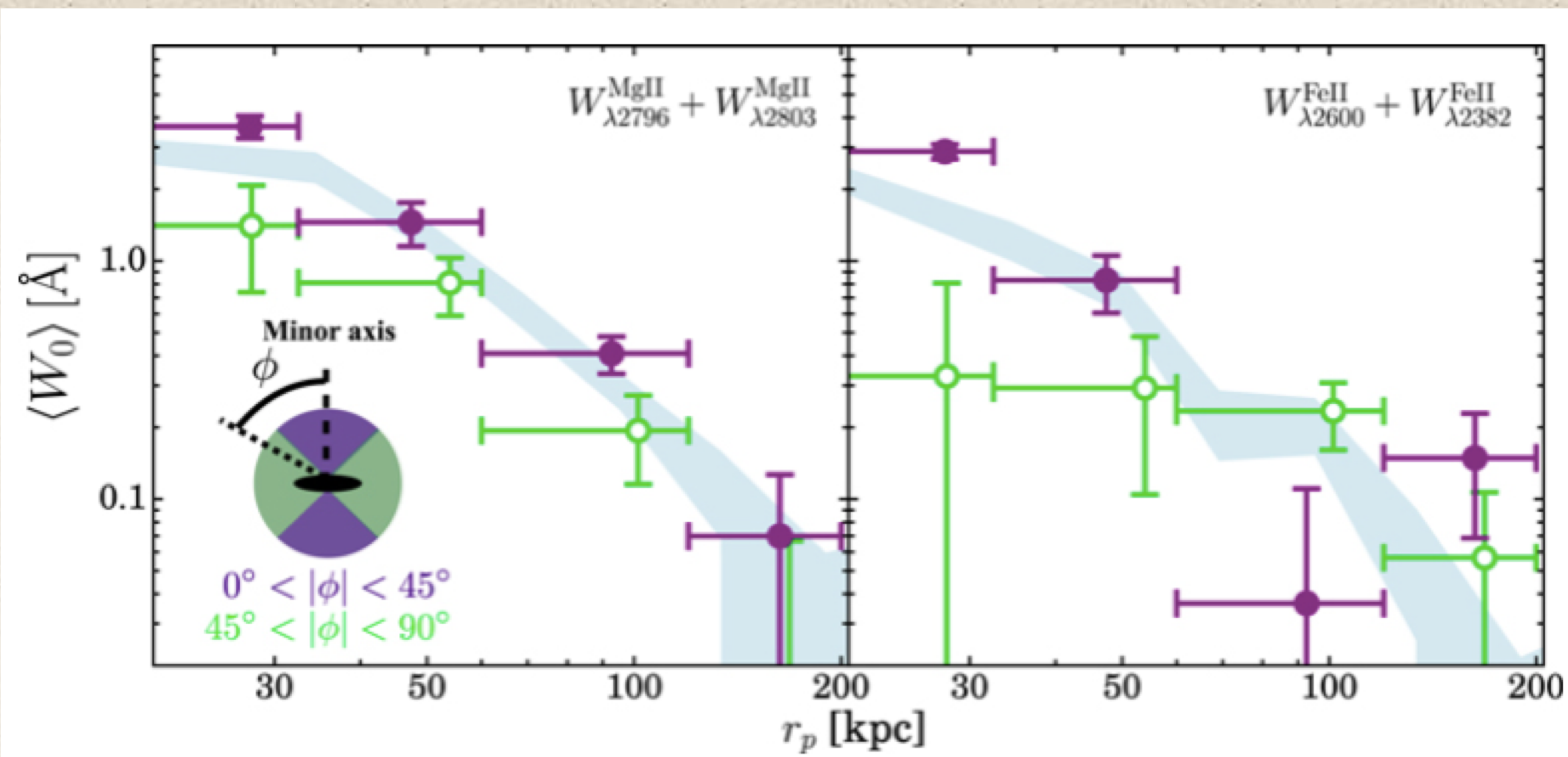


Rotation Curves

Steidel+2002: 5 pairs at z
(See also Bowen+2016;)

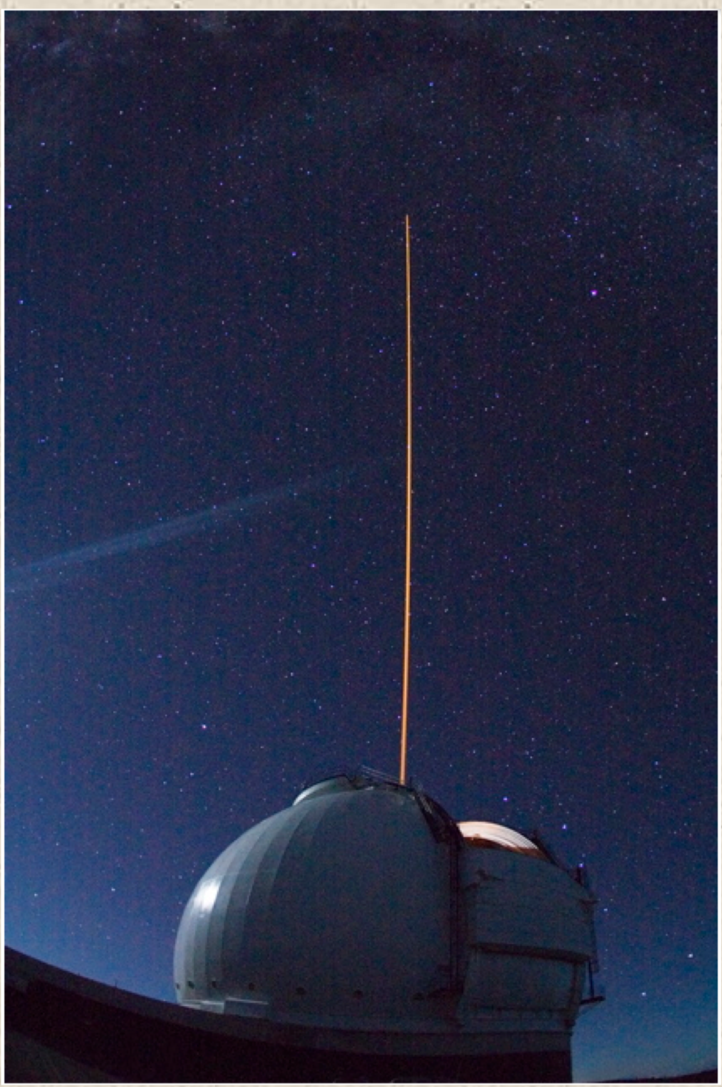
Spherical (Point Symmetric) Models Are Ruled Out for Late-type Galaxies.

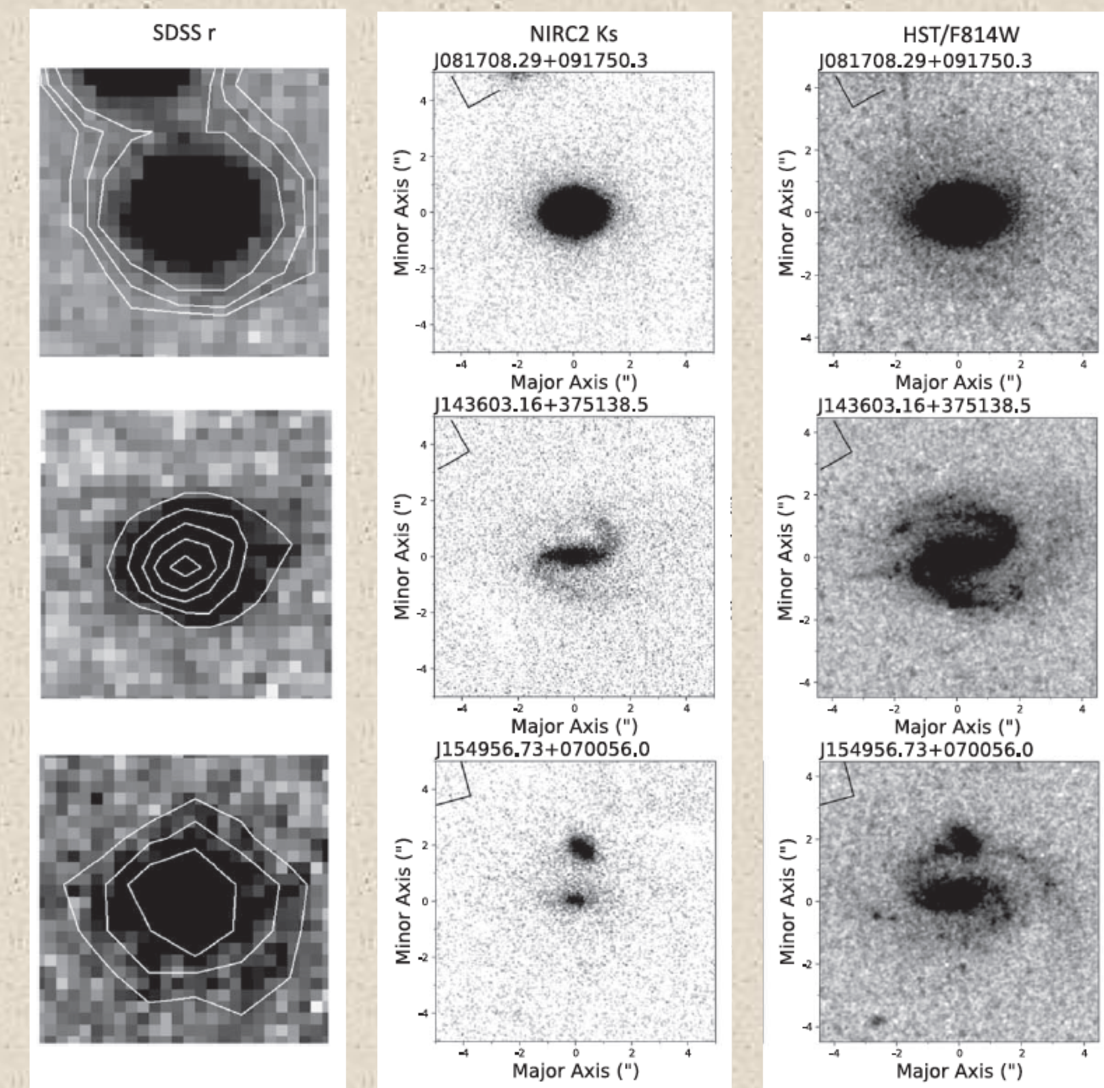
Azimuthal Dependence of Low-Ionization Absorption



Bordoloi+2011,2014; Bouche+2012; Kacprzak+2012;
Keeney+2013; Lan+2014; Nielson+2015; **Lan & Mo 2018**

Quality Control:
High-resolution Images of z~0.2 Galaxies

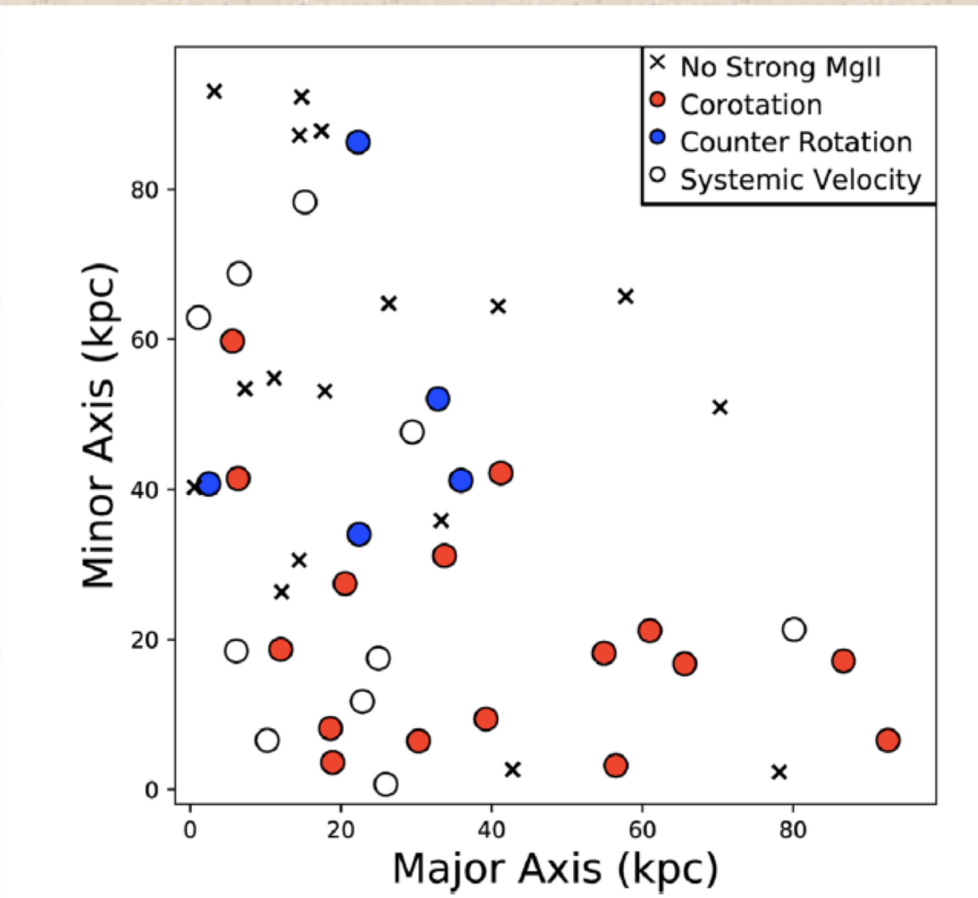


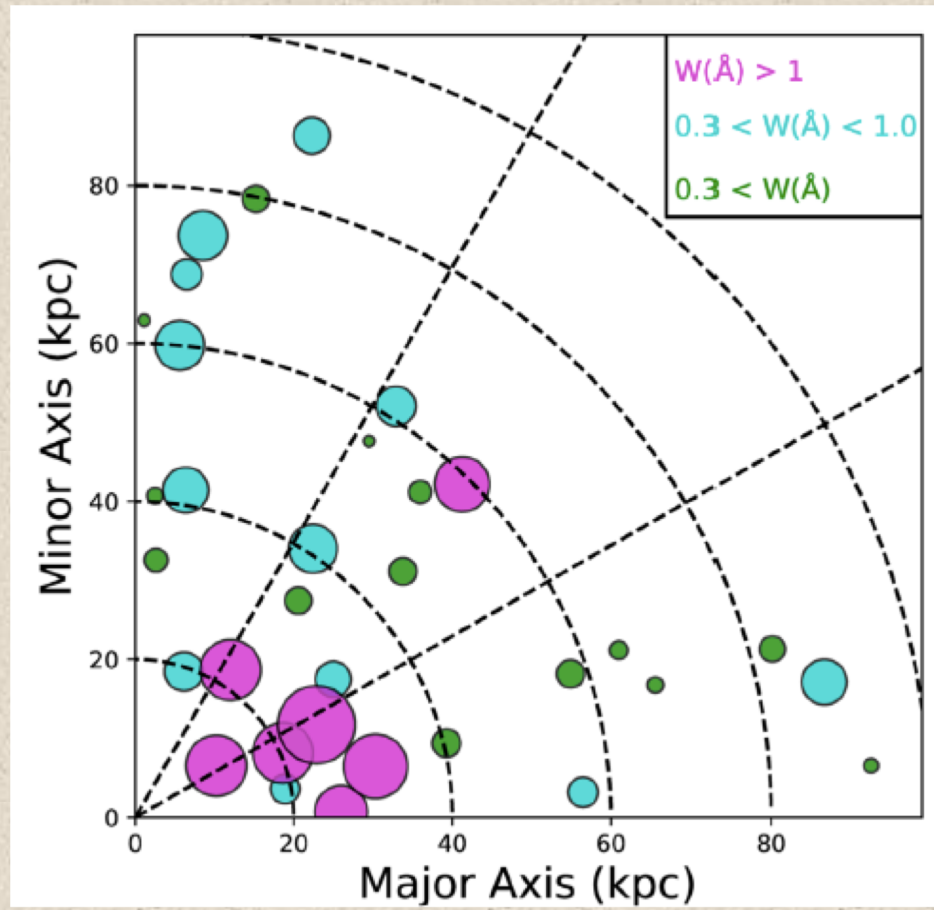


Martin, Ho +2019; Ho+2020a

Corotation of Low-Ionization (Mg II) Gas

Bouche+2012; Ho+2017; **Martin+2019**

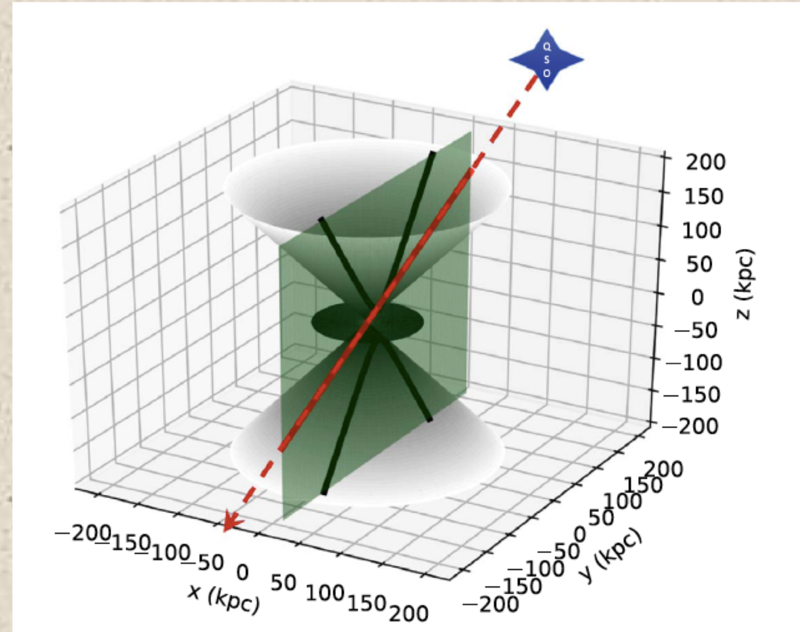




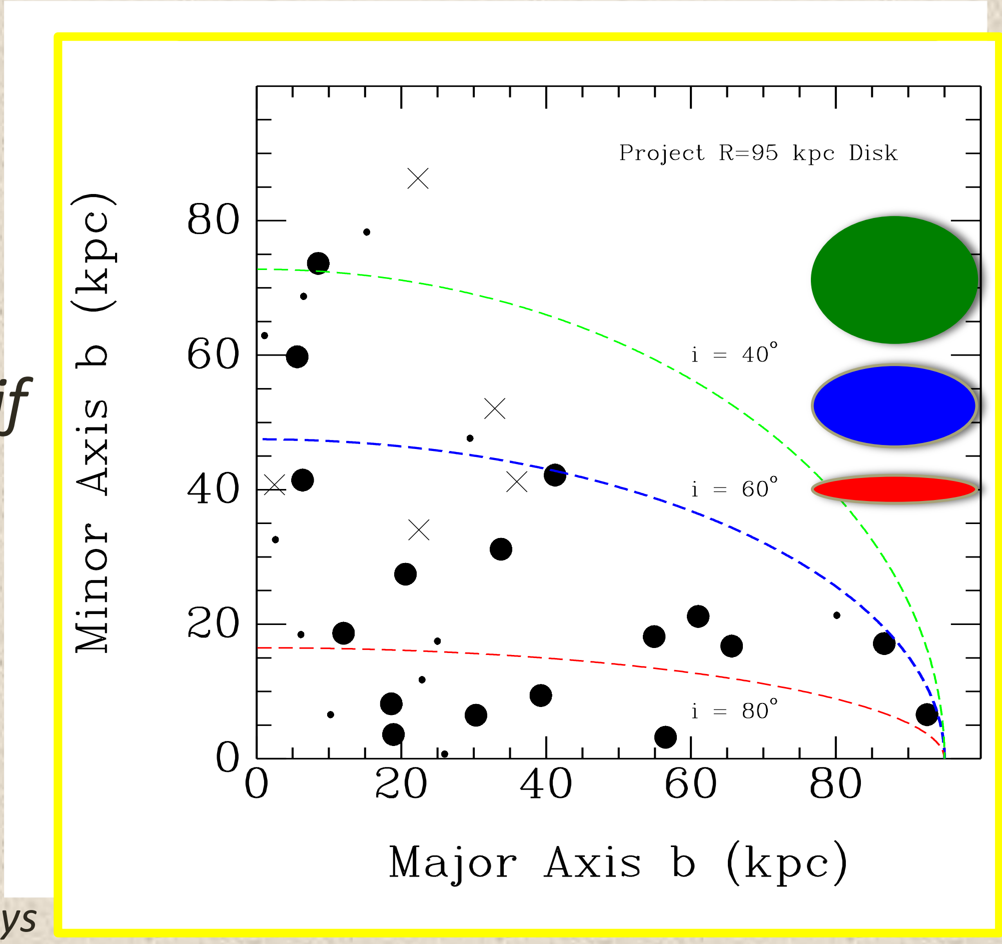
- These are blue galaxies observed at **disk inclinations > 45°.**
- Average velocity is **corotating** with disk or near v_{sys} near major axis
- Persists to z~1 (Bordoloi+2013; Zabl+2019)
- **Line strength** also shows azimuthal dependence

Sightline Geometry Determined Relative to Disk .

Where are the Mg II Components Along the Sightline?



Gain insight from making simple assumptions and examining the consequences.



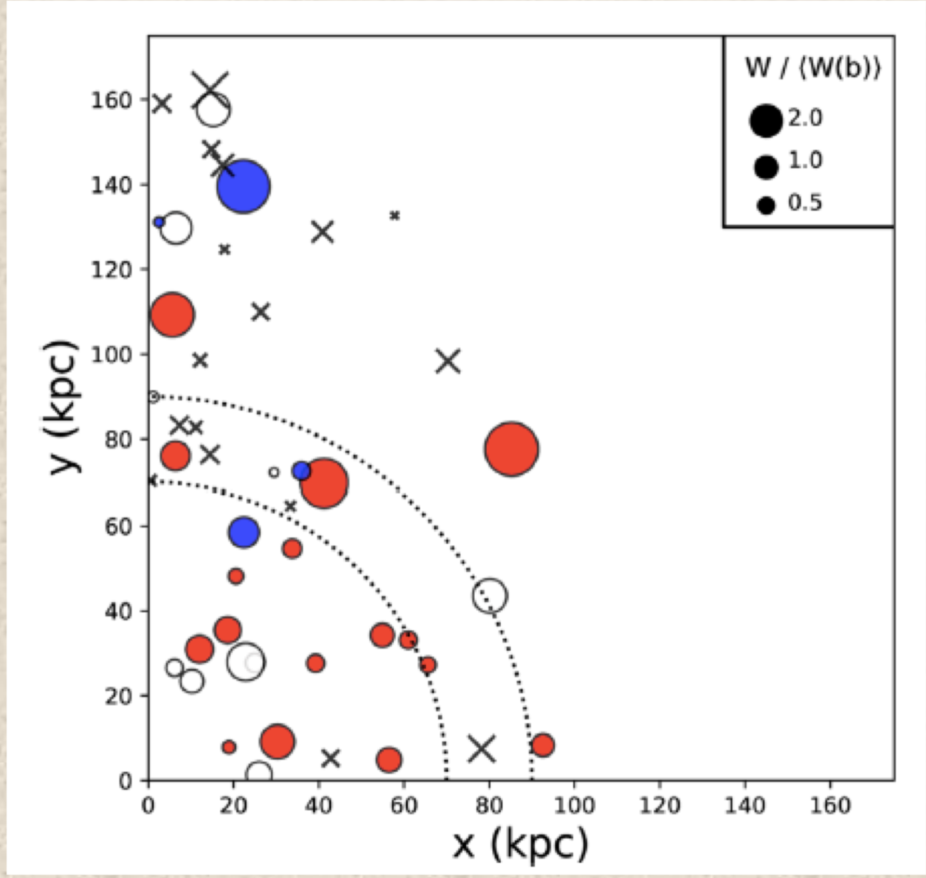
Example: What velocity is expected if the gas is on circular orbits in a thin disk?

Notice that minor axis sightlines

- *intersect the disk at larger radii*
- *Projected rotation velocity near v_{sys}*

Projection onto the Disk Plane

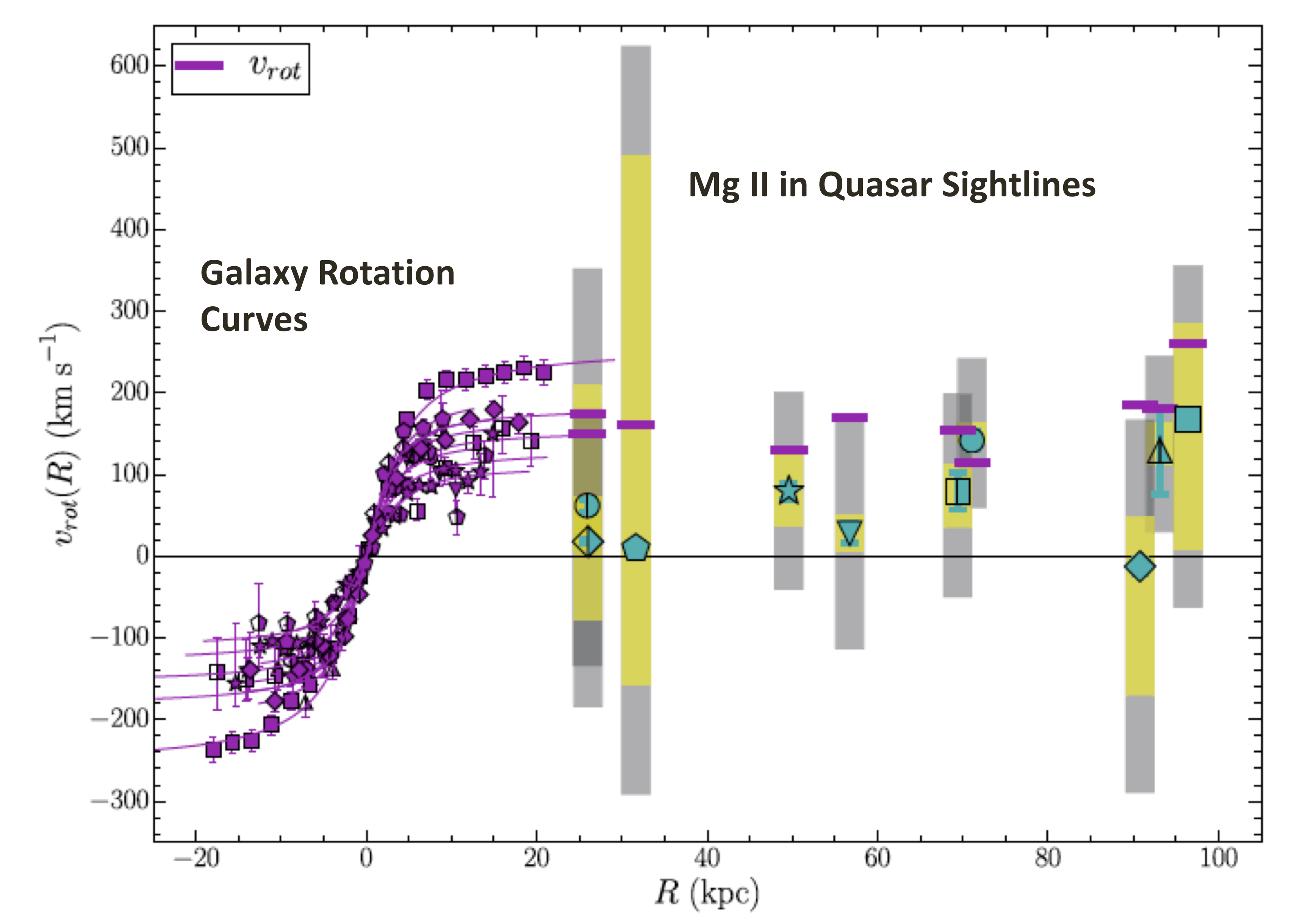
Martin+2019



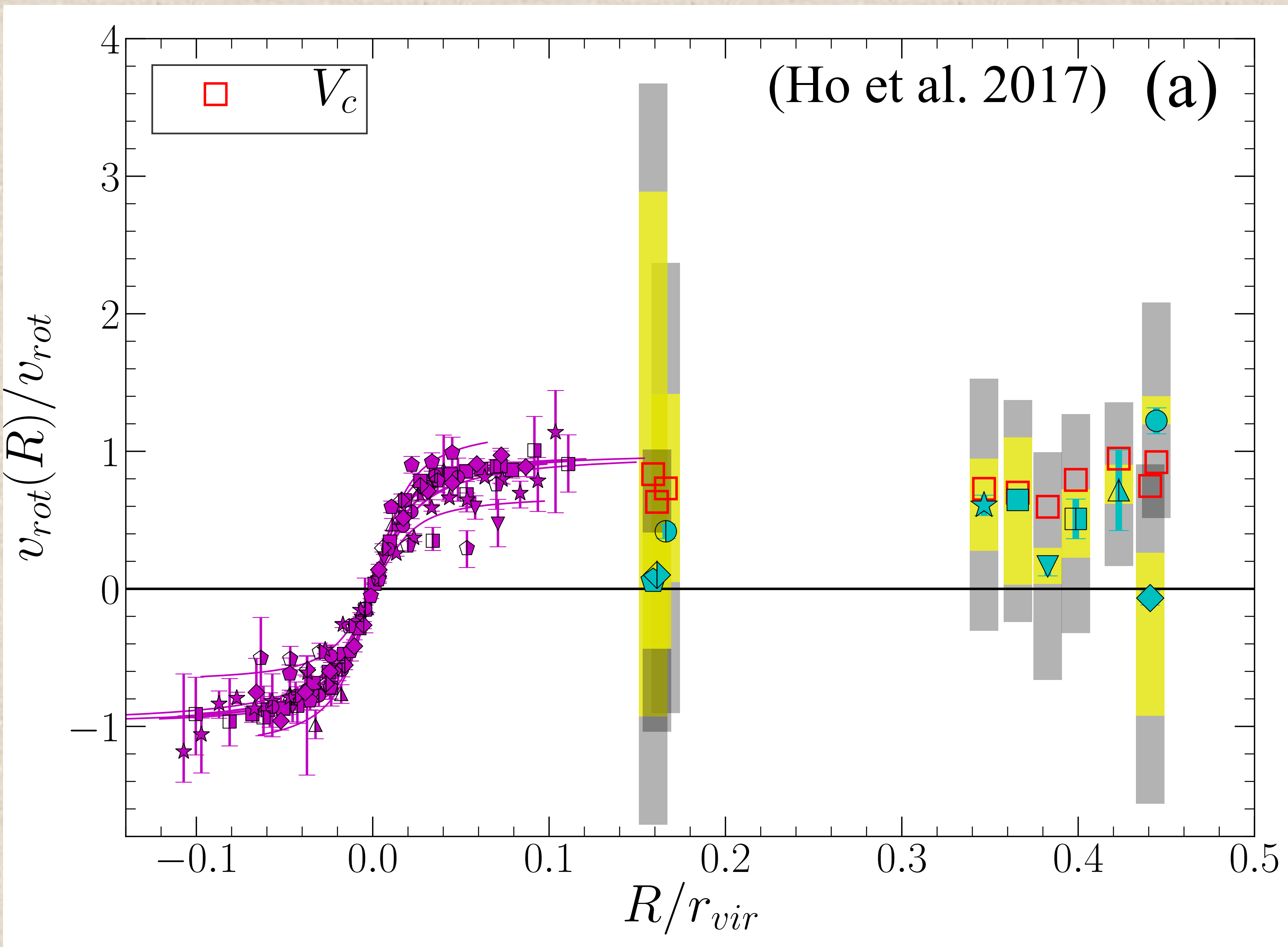
- Corotating gas extends to at least **R = 70-90 kpc**
- **Compare to galaxy rotation curves …**

Comparison to Galaxy Rotation Curves

Ho+2017

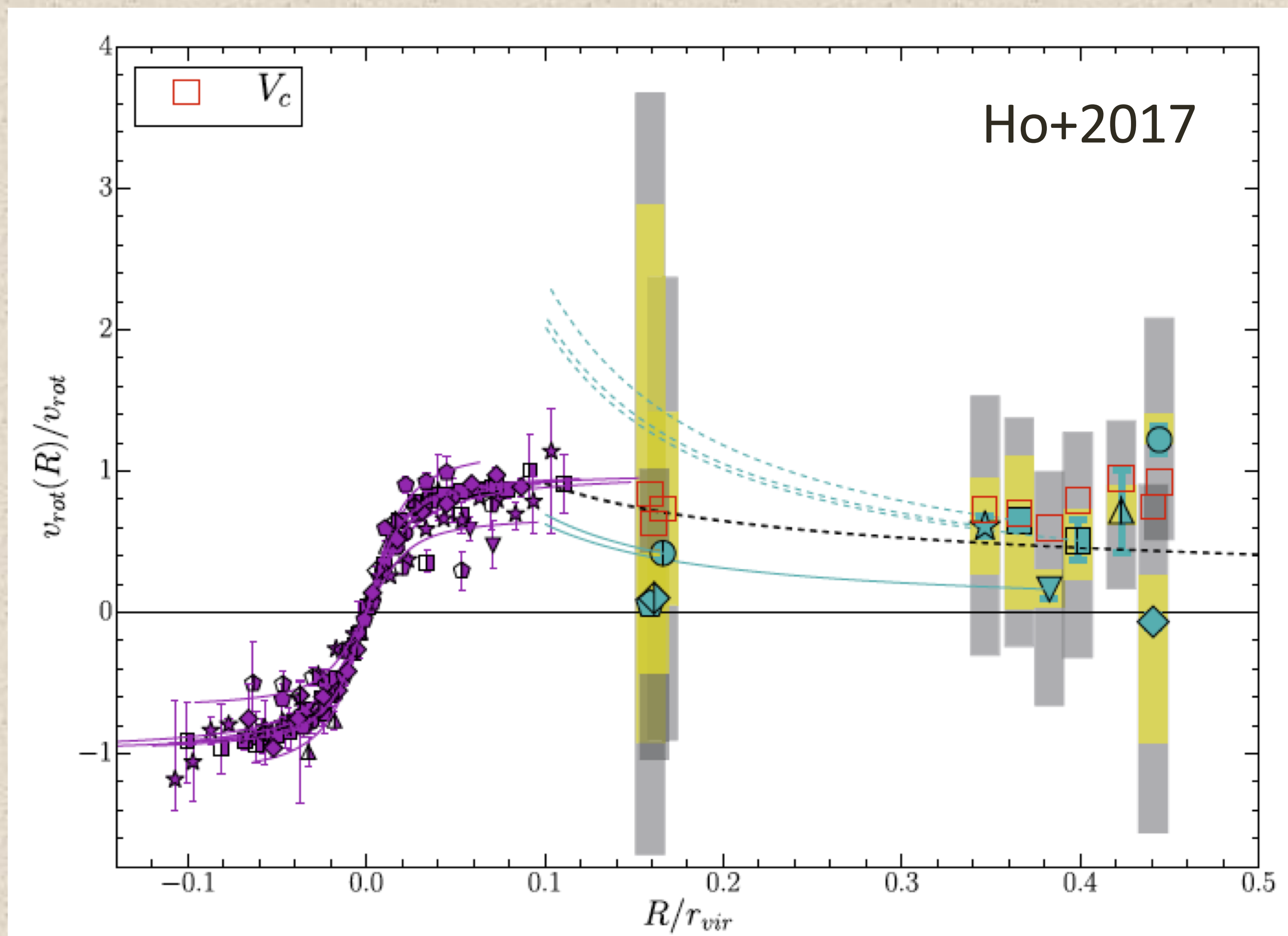


Comparison to Galaxy Rotation Curves



Continuing in the context of a disk…

Where would this gas end up in the absence of angular momentum transfer?



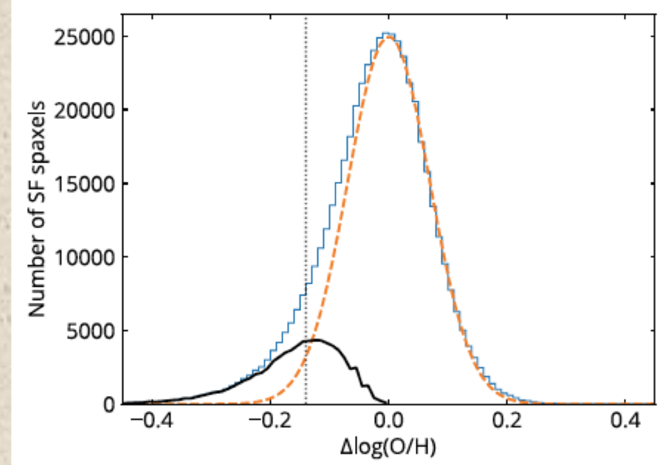
- Much of it, but not all of it, would reach the outer disk.
- Some would reach the inner disk.

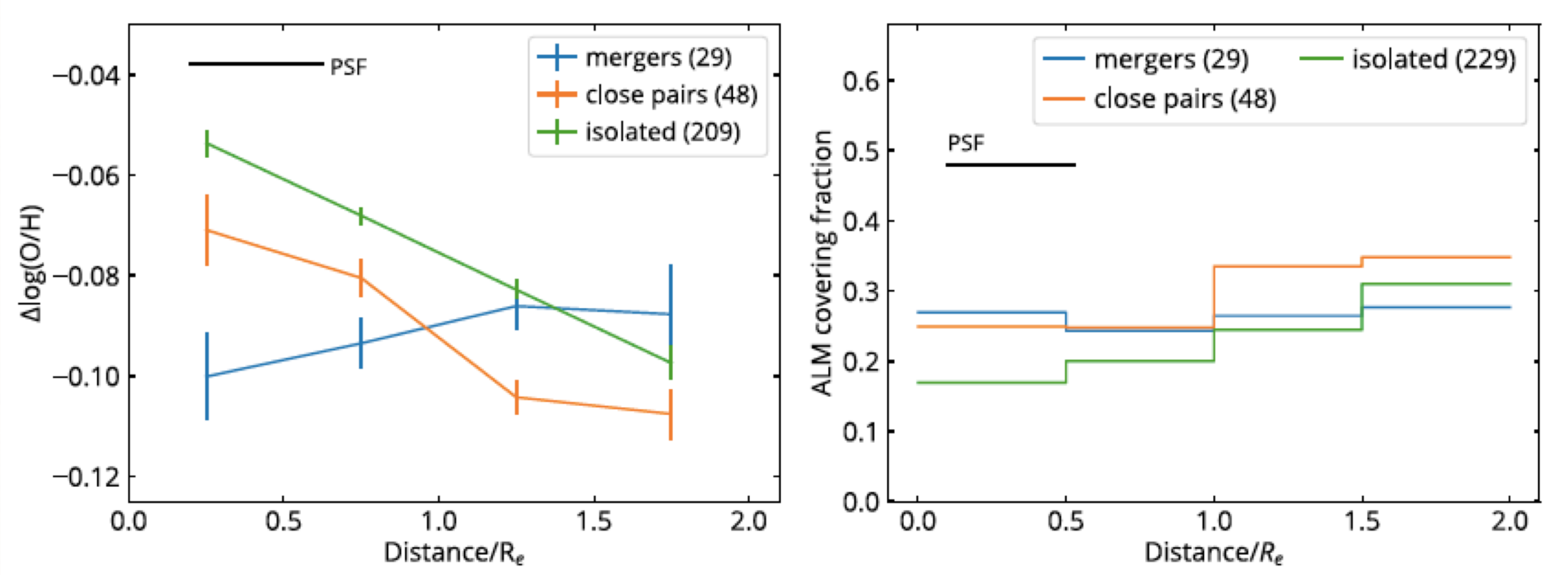
Chemical Abundance Anomalies

Deposition of Metal Poor Gas Favors the Outer Disk

Hwang+2019

(see also Luo 2021)

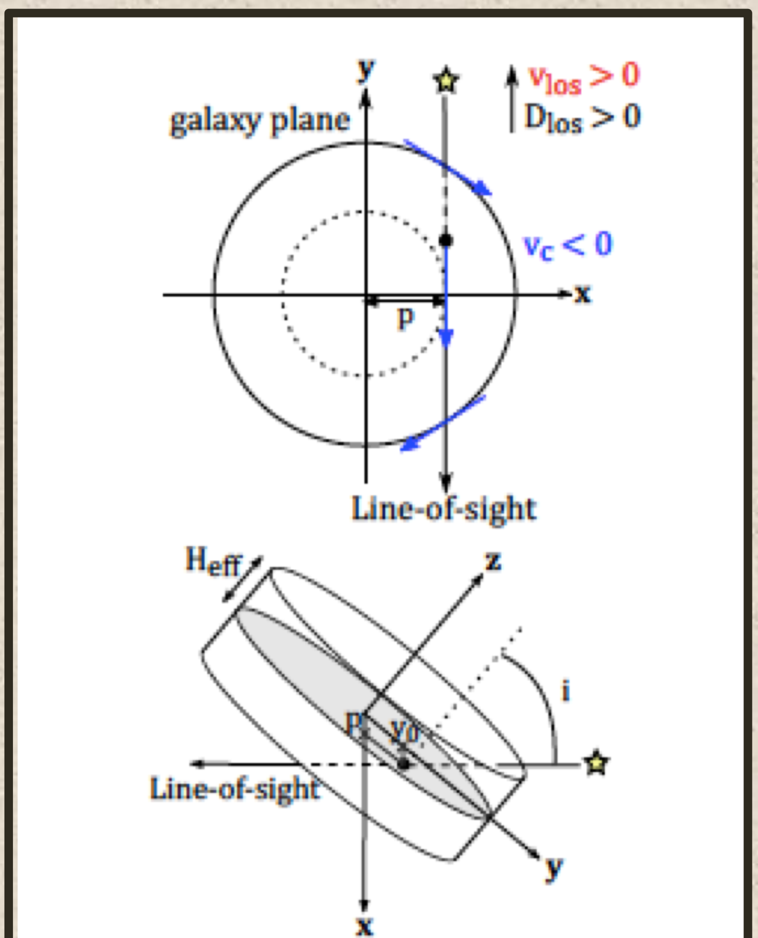


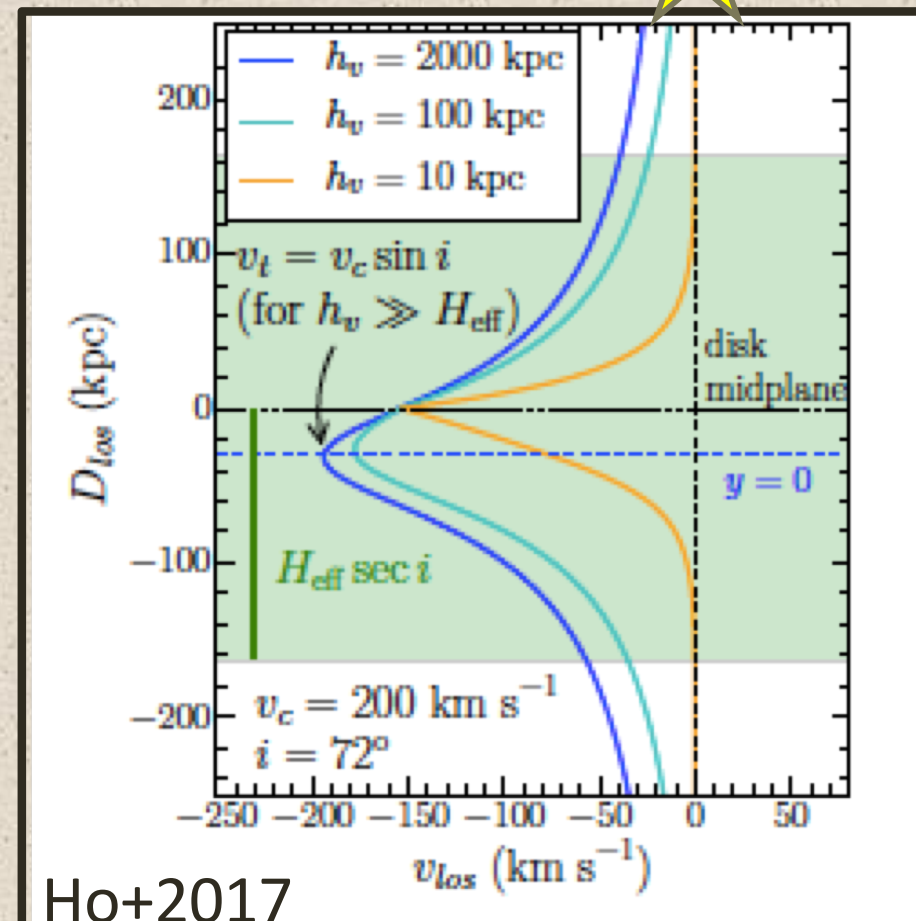


Thin Disk != CGM Kinematics

Thin disks produce line profiles that are **too narrow**.

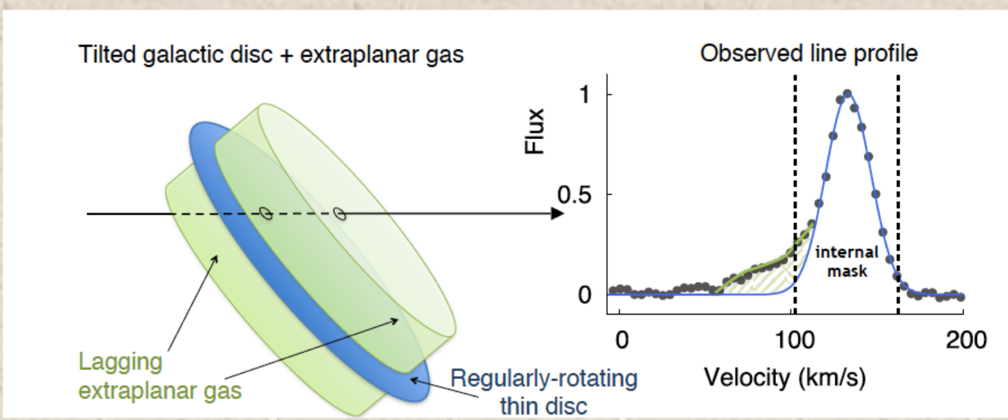
- **Thick disks** with H_{eff} approaching r_{vir} produce broad lines.
- But never produce absorption on both sides of V_{sys}.

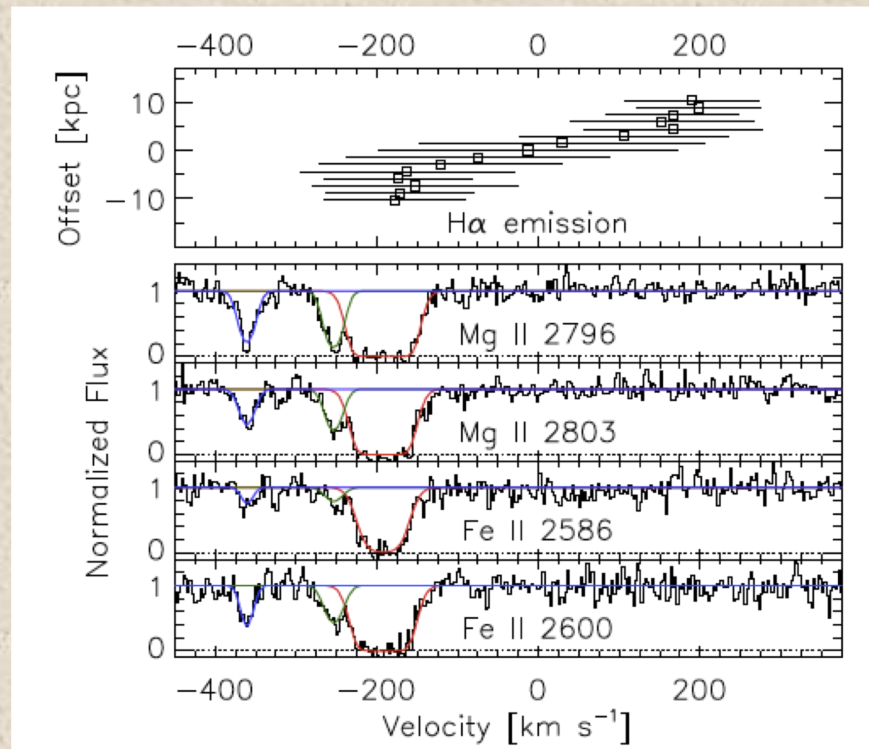


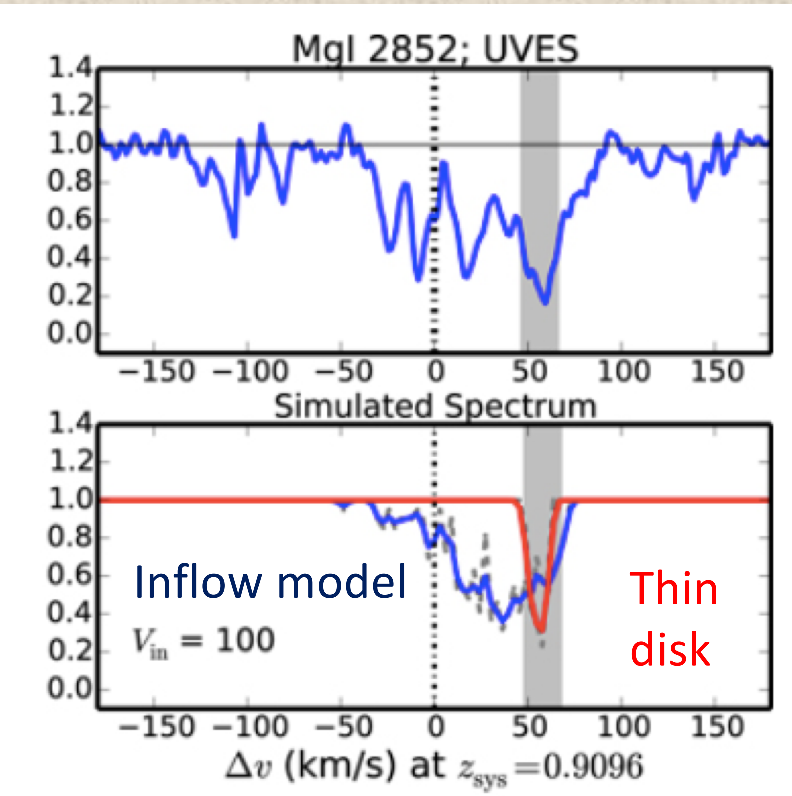


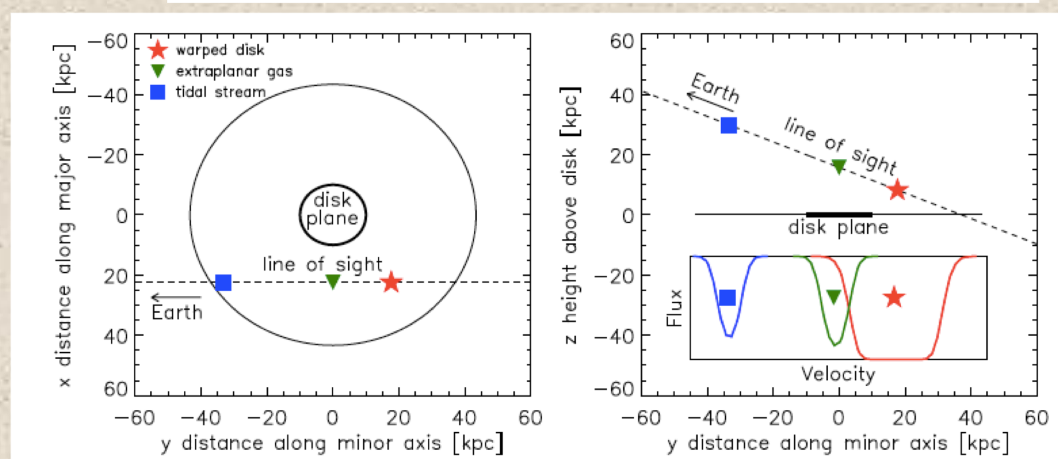
Low Velocity Tails: Lagging Disks and Inflow

Bouche+2016; Diamond-Stanic+2016; Marasco+2019



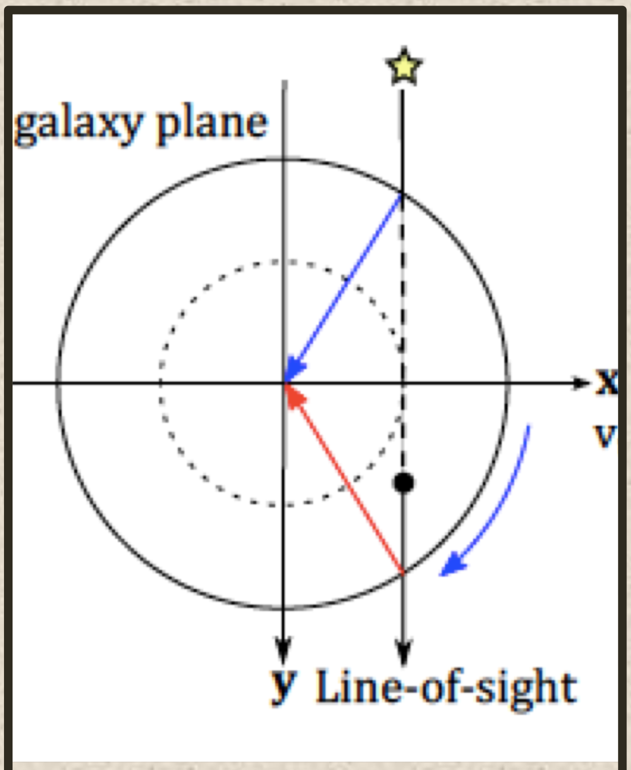


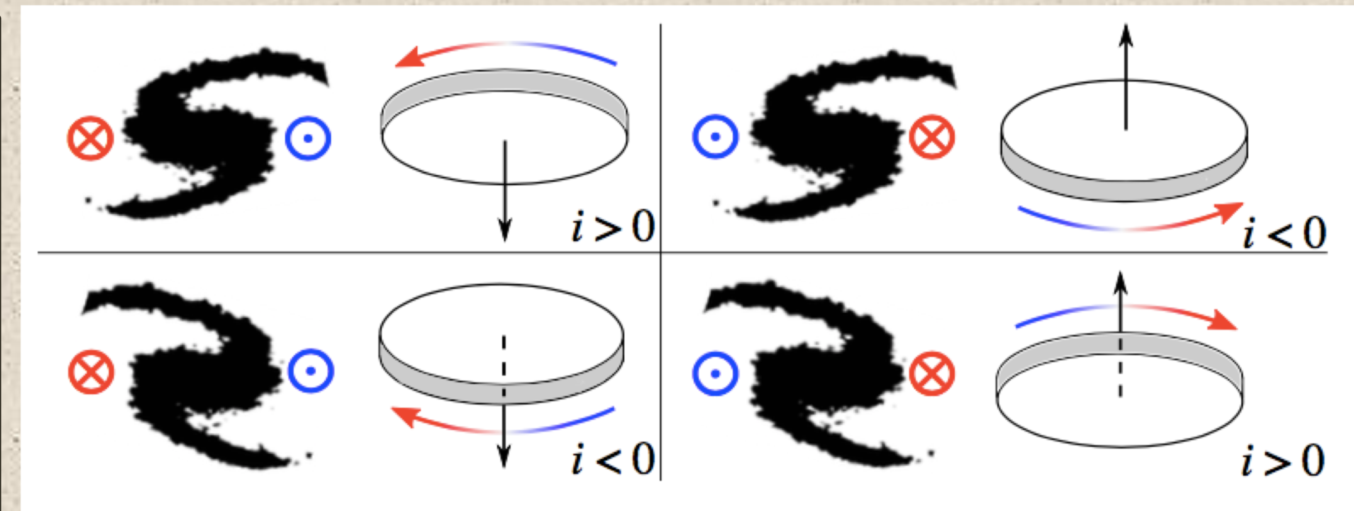




What If … Radial Inflow in Disk Plane?

Ho+2020a





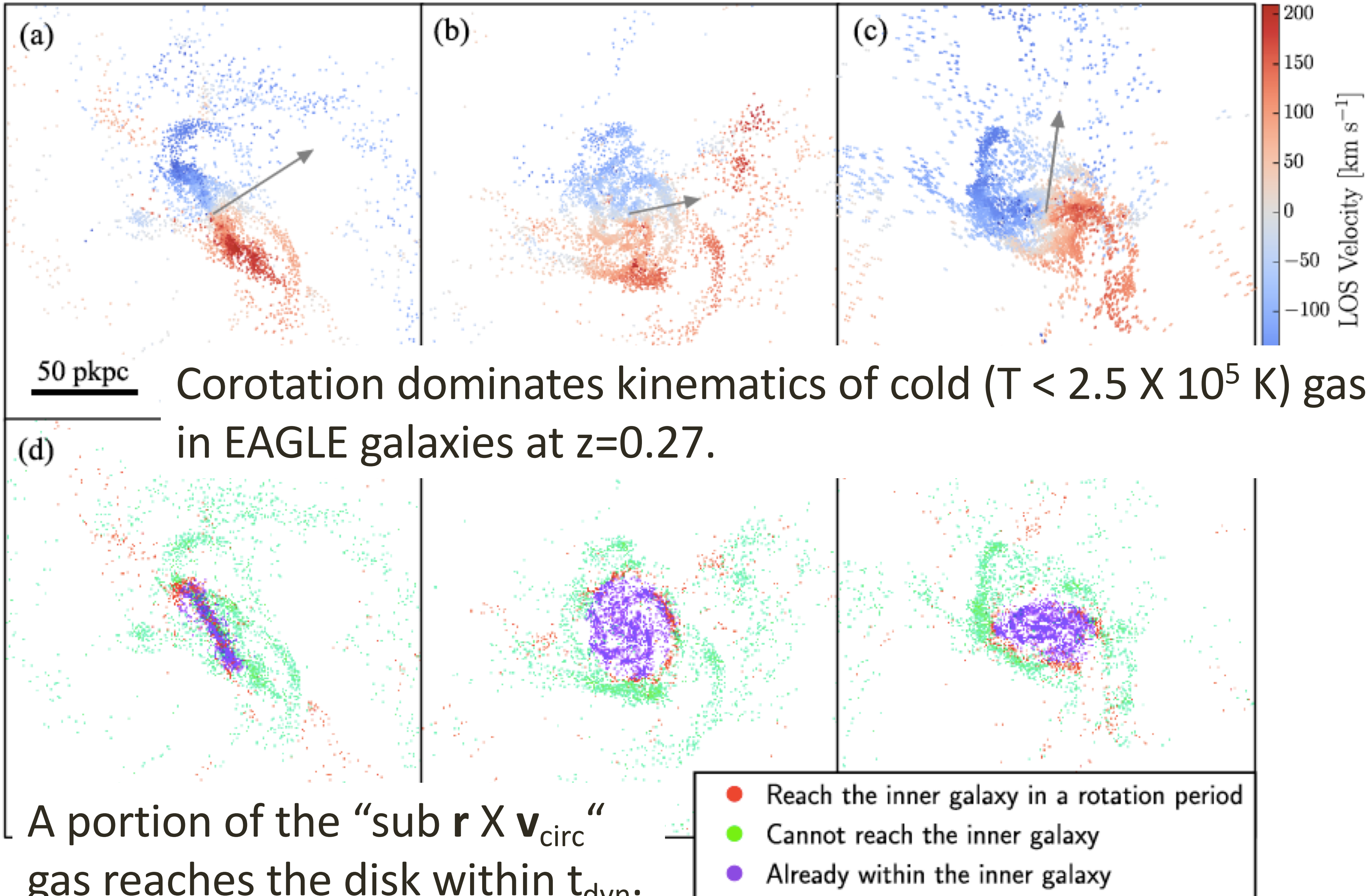
Cool observational effect:
Disk inclination and quasar azimuthal angle are insufficient; AL profile changes with disk tilt.

Measure disk tilt: resolve spiral arms and assuming the arms trail

1. J0919+2913: Consistent with v_r = **30 km/s**; rule out v_r = 140 km/s
2. J1029+4217: Consistent with v_r = **40 km/s**; rule out v_r = 80 km/s
3. J1429+3821: Radial inflow makes fit worse.

"Observing" Simulations

Ho+2019; see also Peroux+2020; DeFelippis+2021

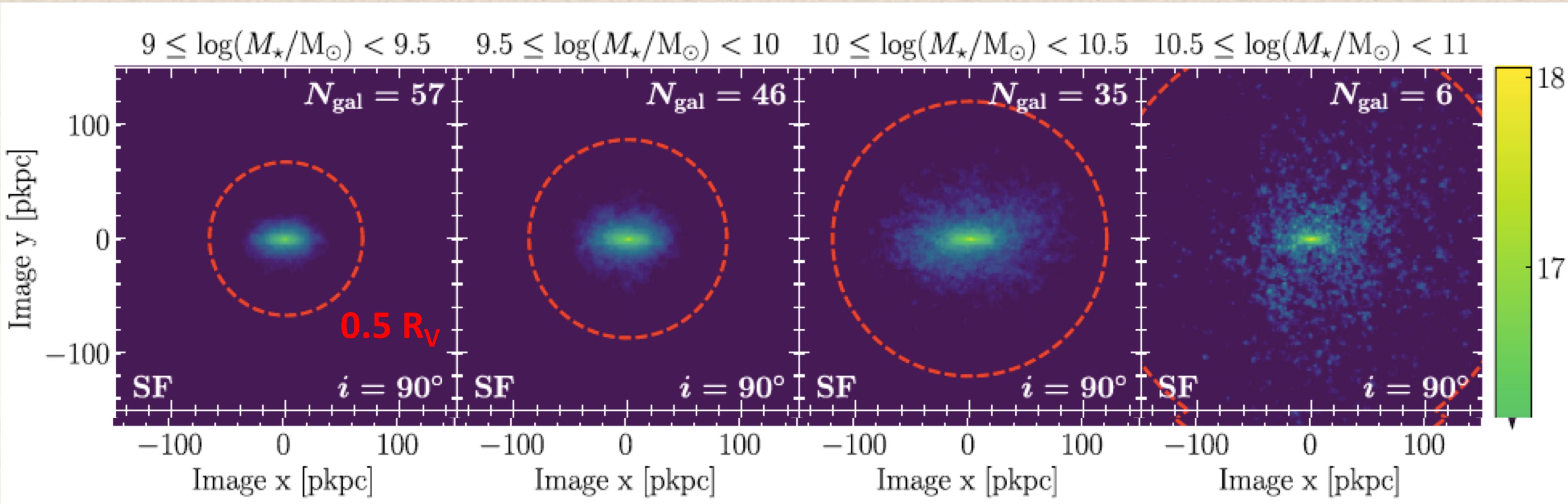


Corotation dominates kinematics of cold ($T < 2.5 \times 10^5$ K) gas in EAGLE galaxies at z=0.27.

A portion of the "sub $\mathbf{r} \times \mathbf{v}_{circ}$" gas reaches the disk within t_{dyn}.

Corotating Mg II Depends on Galaxy Properties

Ho+2020b – Stacks of EAGLE galaxies



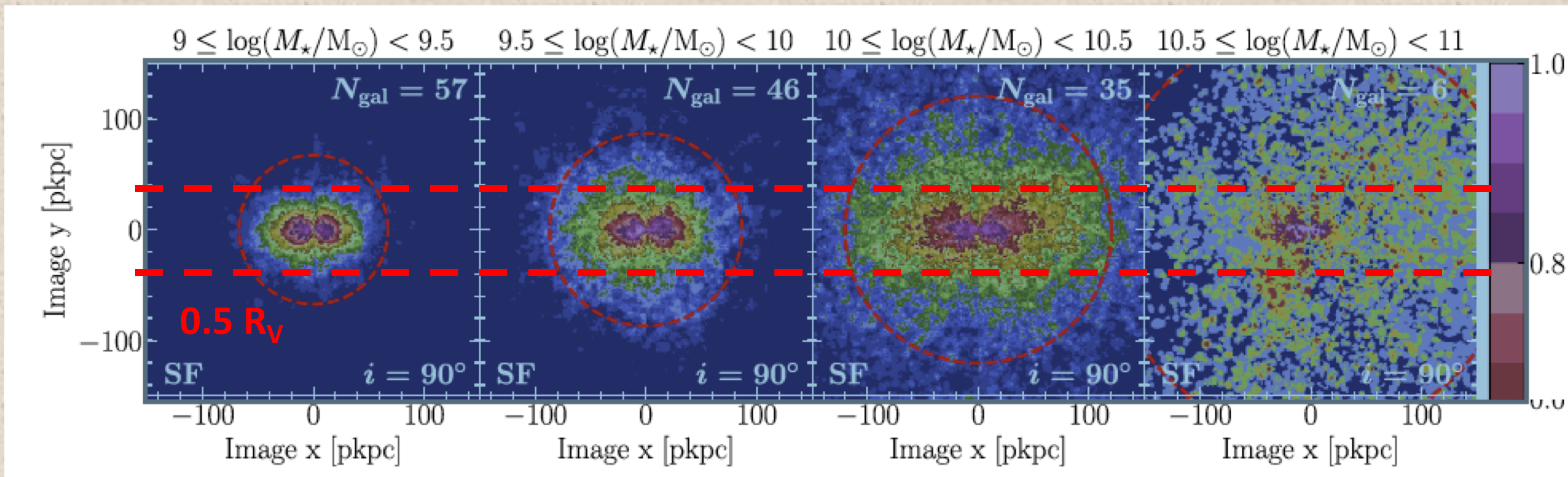
The Mg^+ gas is **axisymmetric** rather than spherical.

- More extended around more massive galaxies.
- The minor axis is the net rotation axis of the Mg II gas.

'What fraction of sightlines at a particular azimuthal angle (and disk inclination) will detect corotating Mg II gas?'

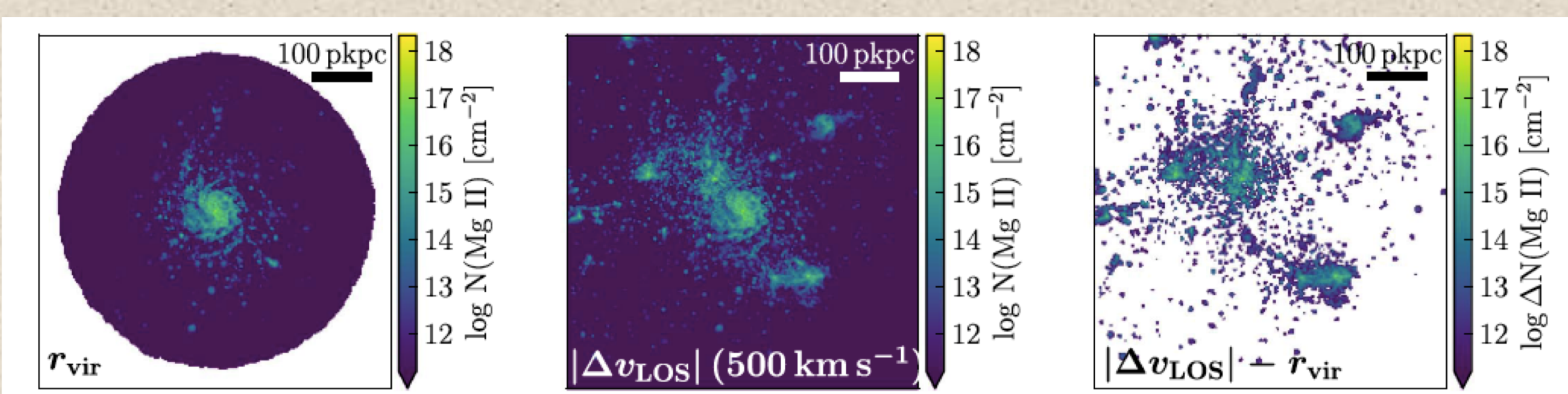
Corotating Mg II Depends on Galaxy Properties

Ho+2020b – Stacks of EAGLE galaxies



… most sightlines at H < 20 kpc and b < 0.5 R_V, independent of mass

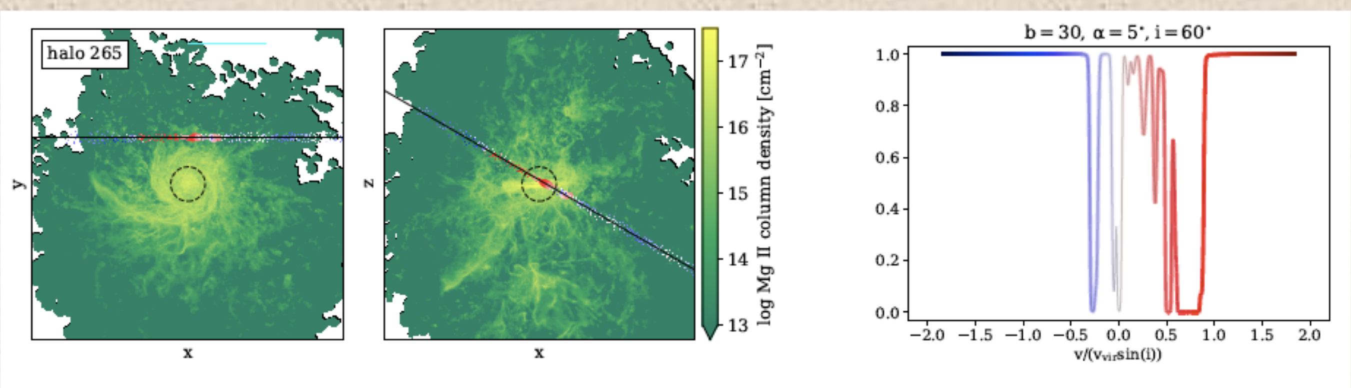
- Observations, however, will be contaminated by infalling gas at R > R_V.

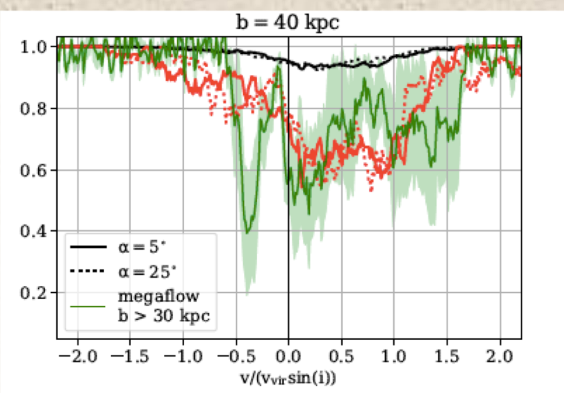


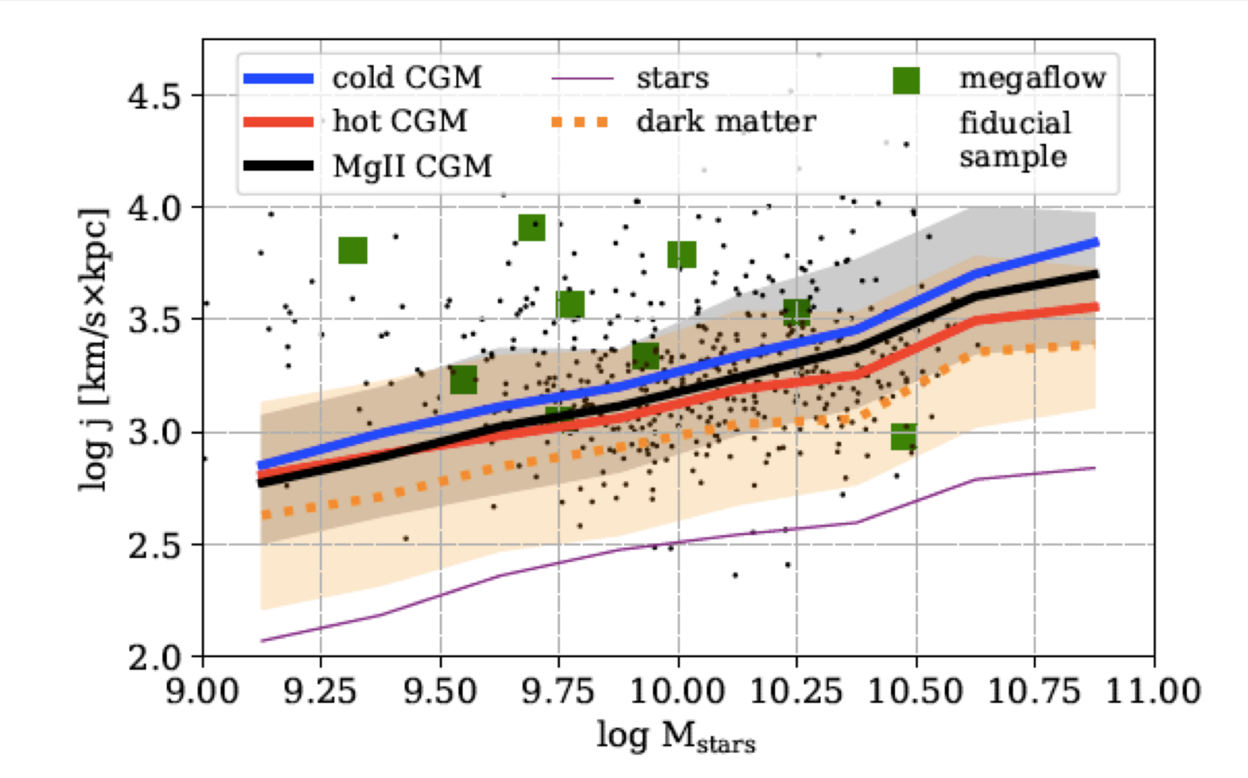
MEGALFOW (z~1) vs. TNG50

Schroetter+2016,2019,2021; **Zabl+2019**,2020,2021; Wendt+2021

DeFelippis+2021







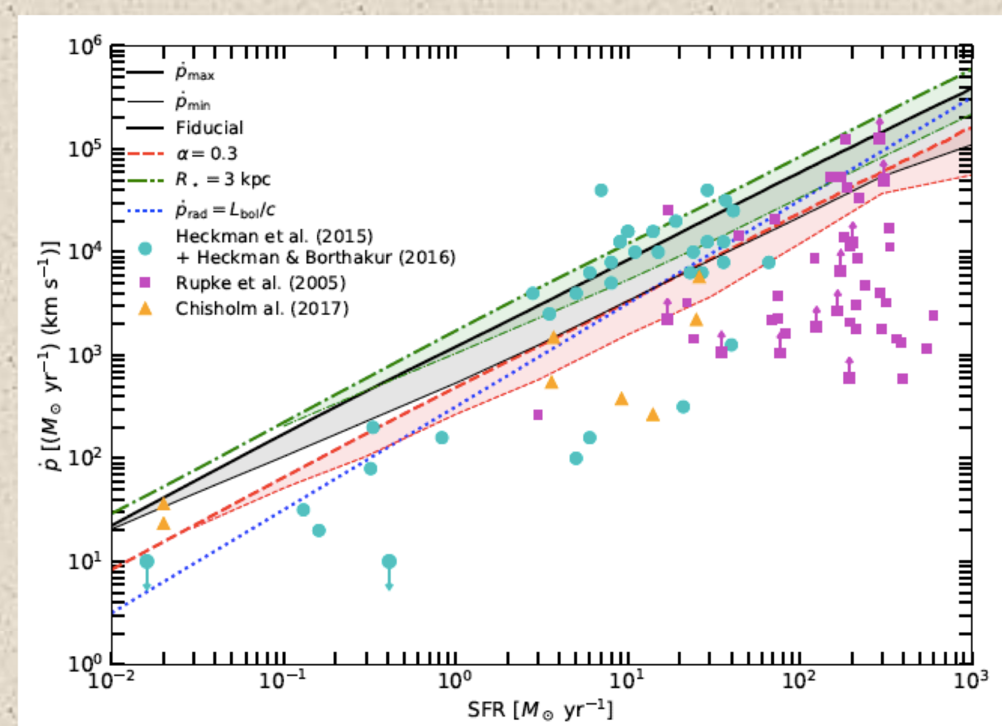
Simulated line profiles produce observed width of strong absorbers.

Estimates for the specific angular momentum of the MEGAFLOW Mg II absorbers are consistent with the halo mass-selected fiducial sample.

2. Outflows.

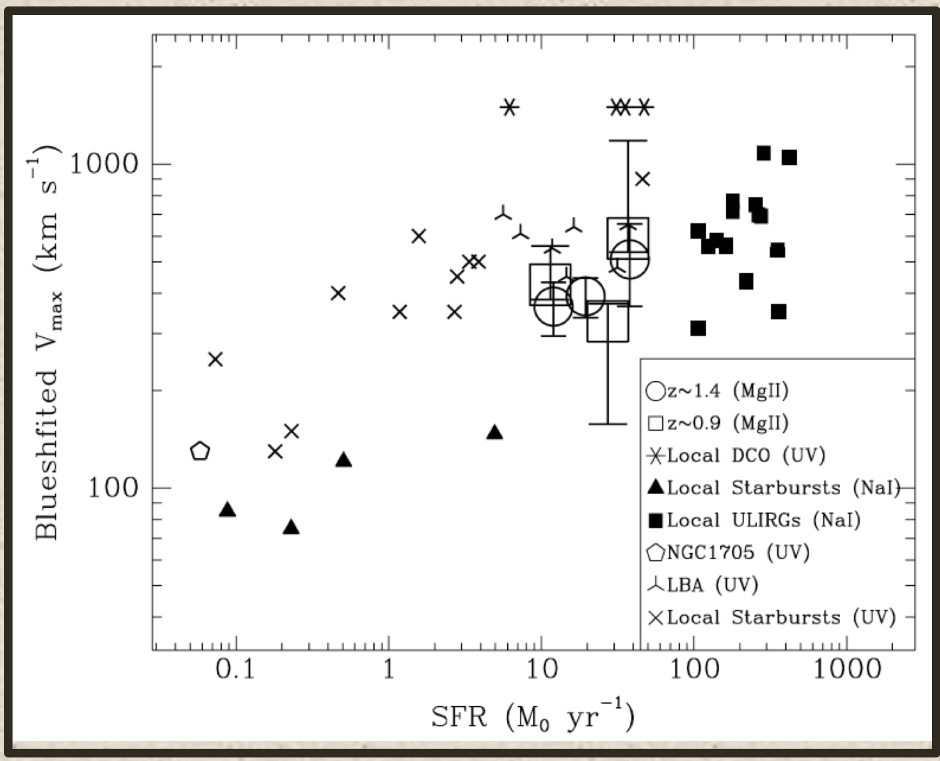
Challenging to connect the observational diagnostics

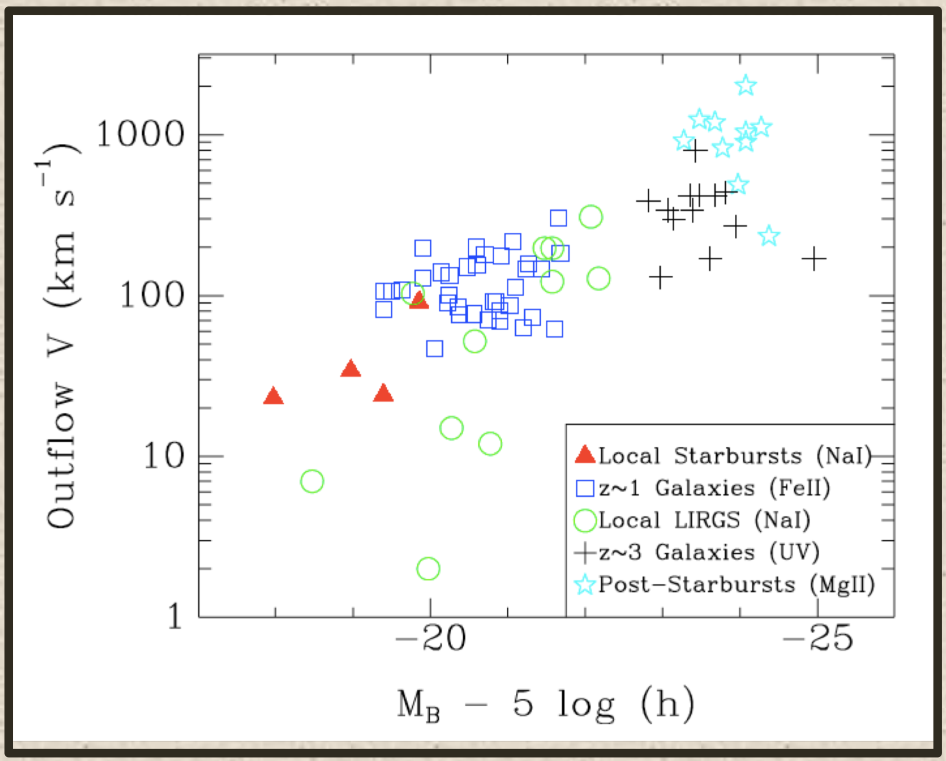
- Down-the-barrel sightlines, transverse sightlines, maps of broad emission line, and combinations therein.
- Will a new theoretical picture (Schneider+2020; Lochhaas+2020) help?



Scaling Relations for Outflows

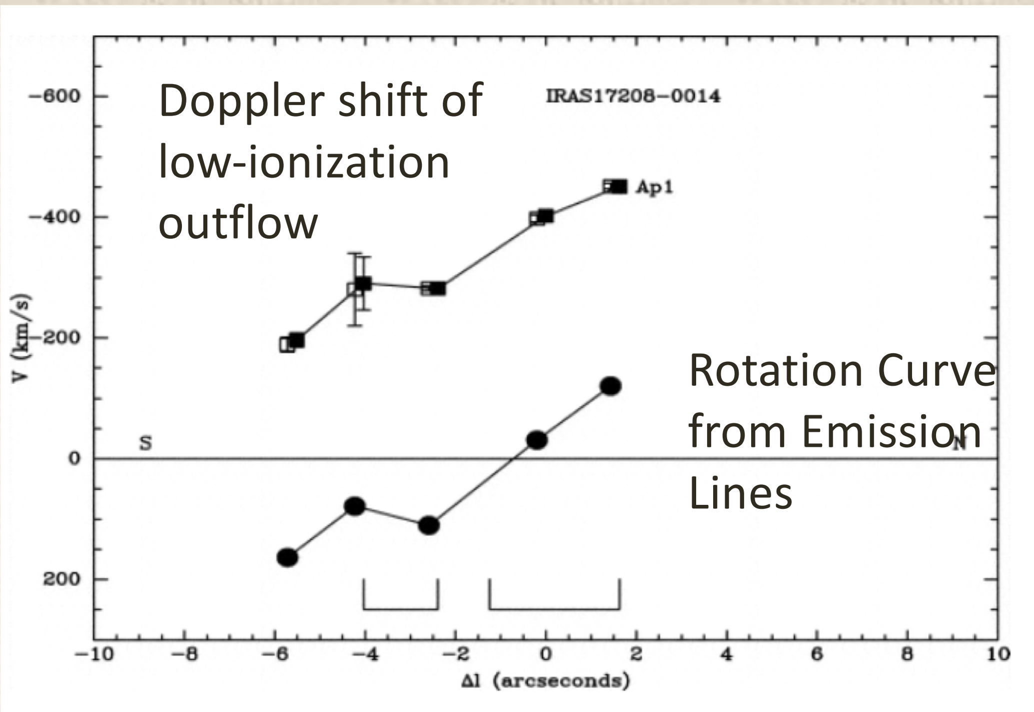
Martin+2012

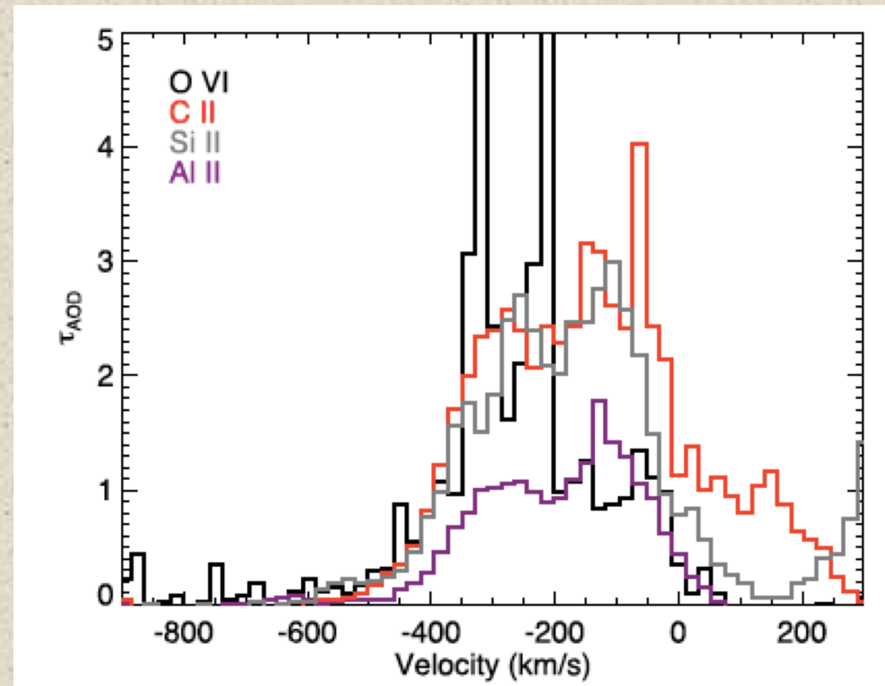




- Velocities increase with SFR
- But no redshift dependence at fixed SFR
- Typical SFR increases with redshift

Down-the-Barrel Observations





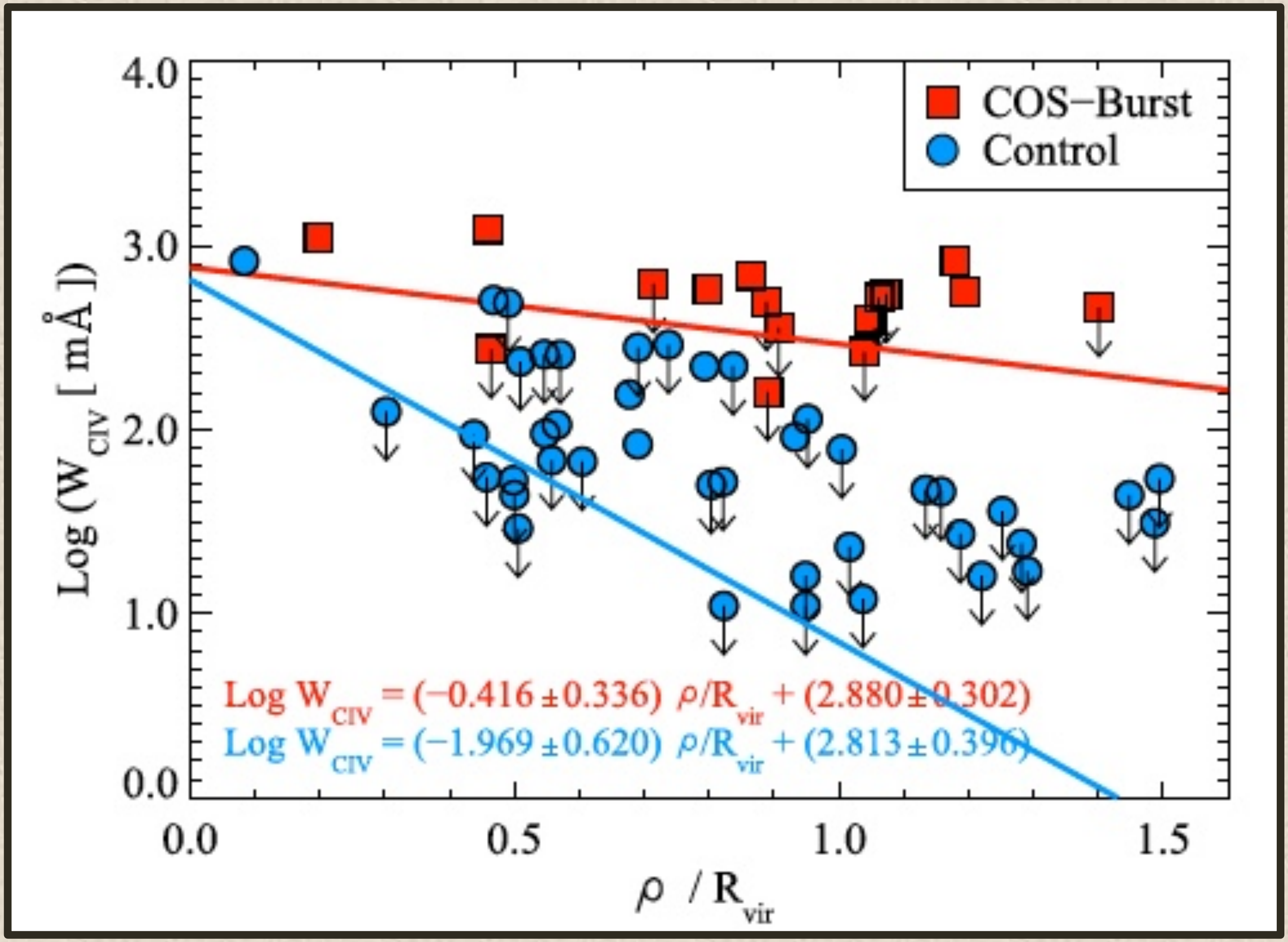
Martin 2006

Chisholm+2018

- Typically Weighted Toward Gas Near Disk
- Evidence for transition to higher ionization state at high velocity
- Very fast AL outflows (1500 km/s, Rupke+2019)
- Very broad emission-line wings (500-800 km/s, Martin+2015)

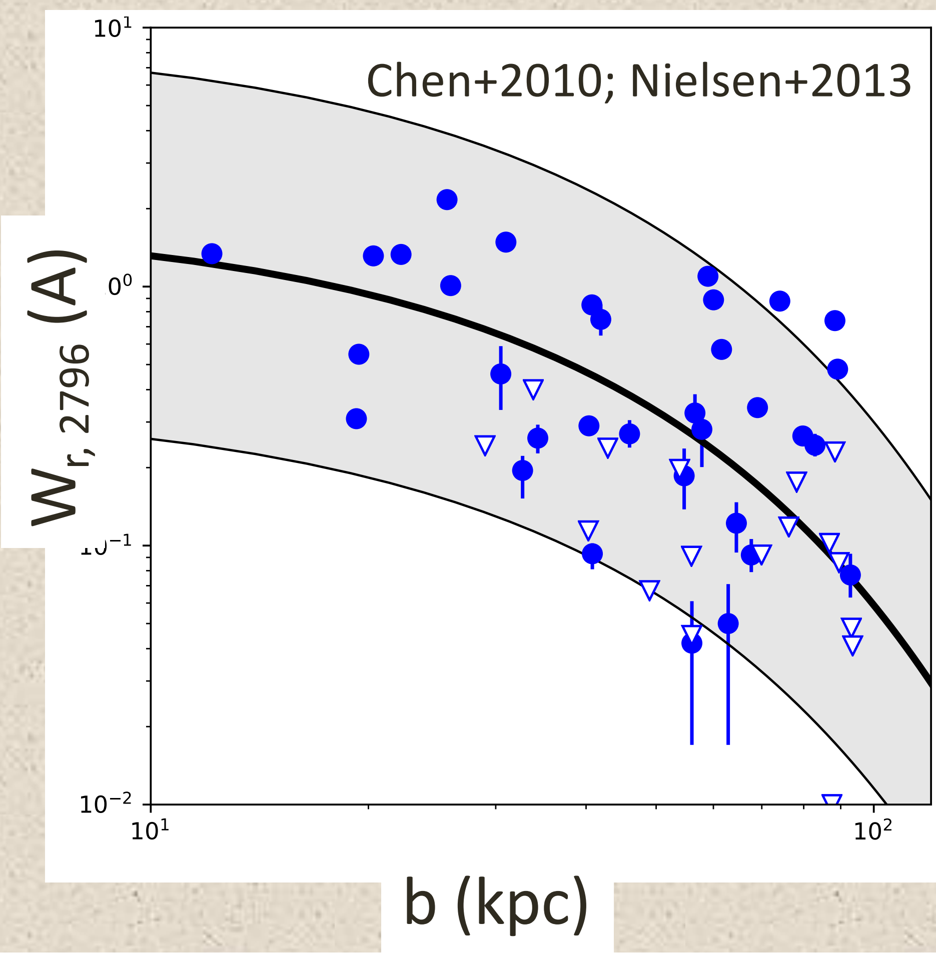
Connection to Transverse Sightlines

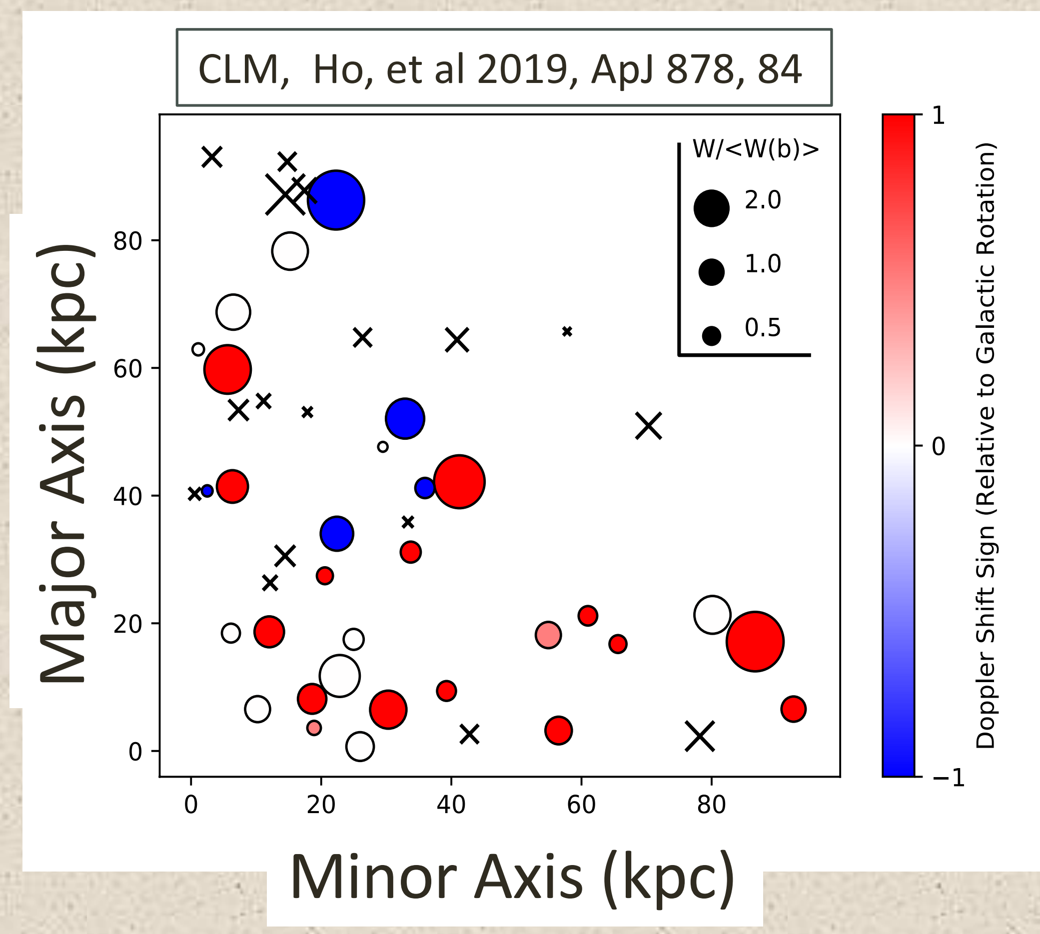
Heckman+2017



Minor Axis Excess Absorption

- Average equivalent width declines with impact parameter.
- Most ‘excess absorption’ is detected in minor axis sightlines
- This is a kinematic disturbance.

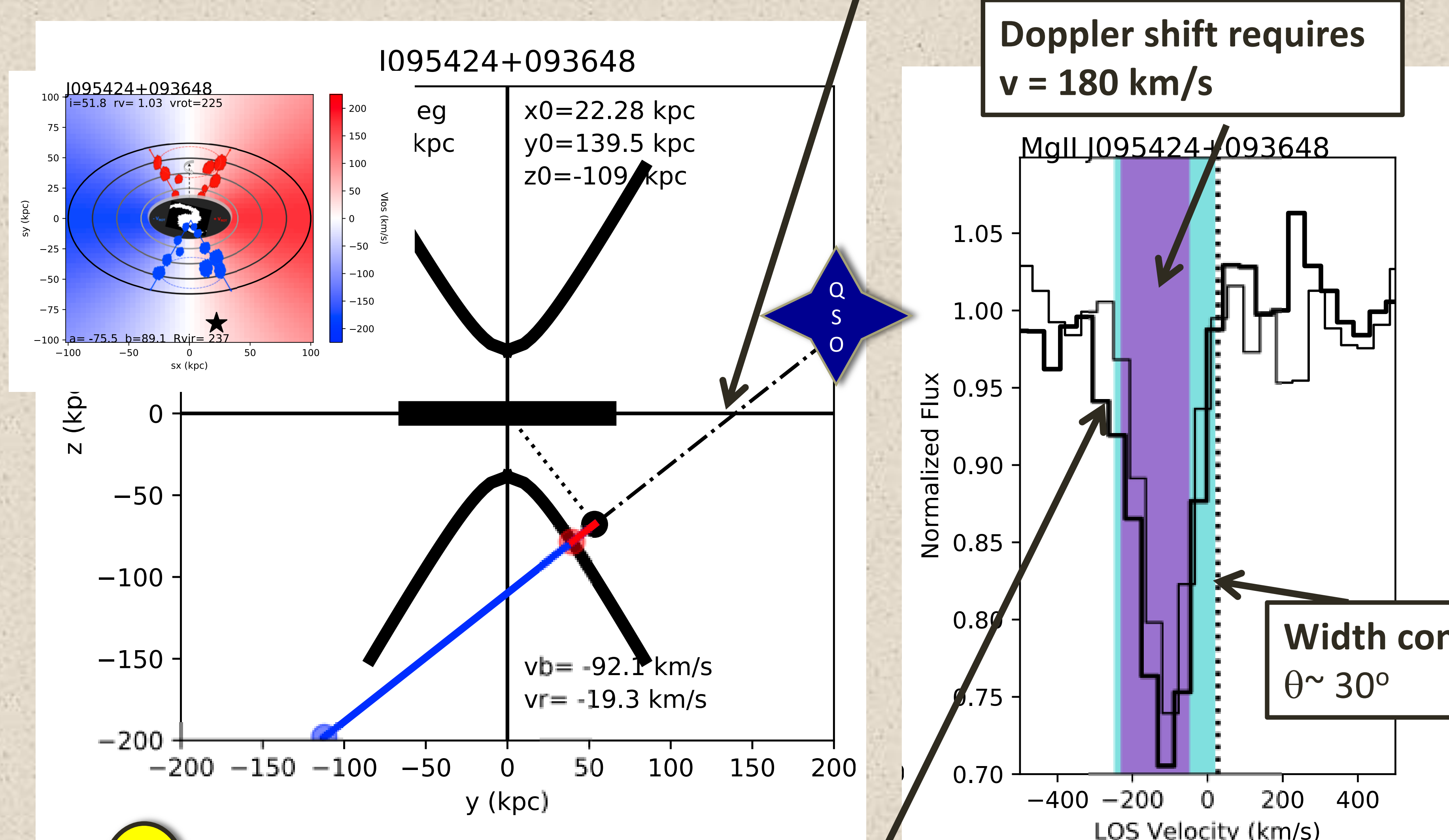




Minor-Axis Sightlines with Strong Mg II: Example with No Disk Component

R = 141 kpc, so sightline misses disk.

Doppler shift requires v = 180 km/s



Width constrains θ~ 30°

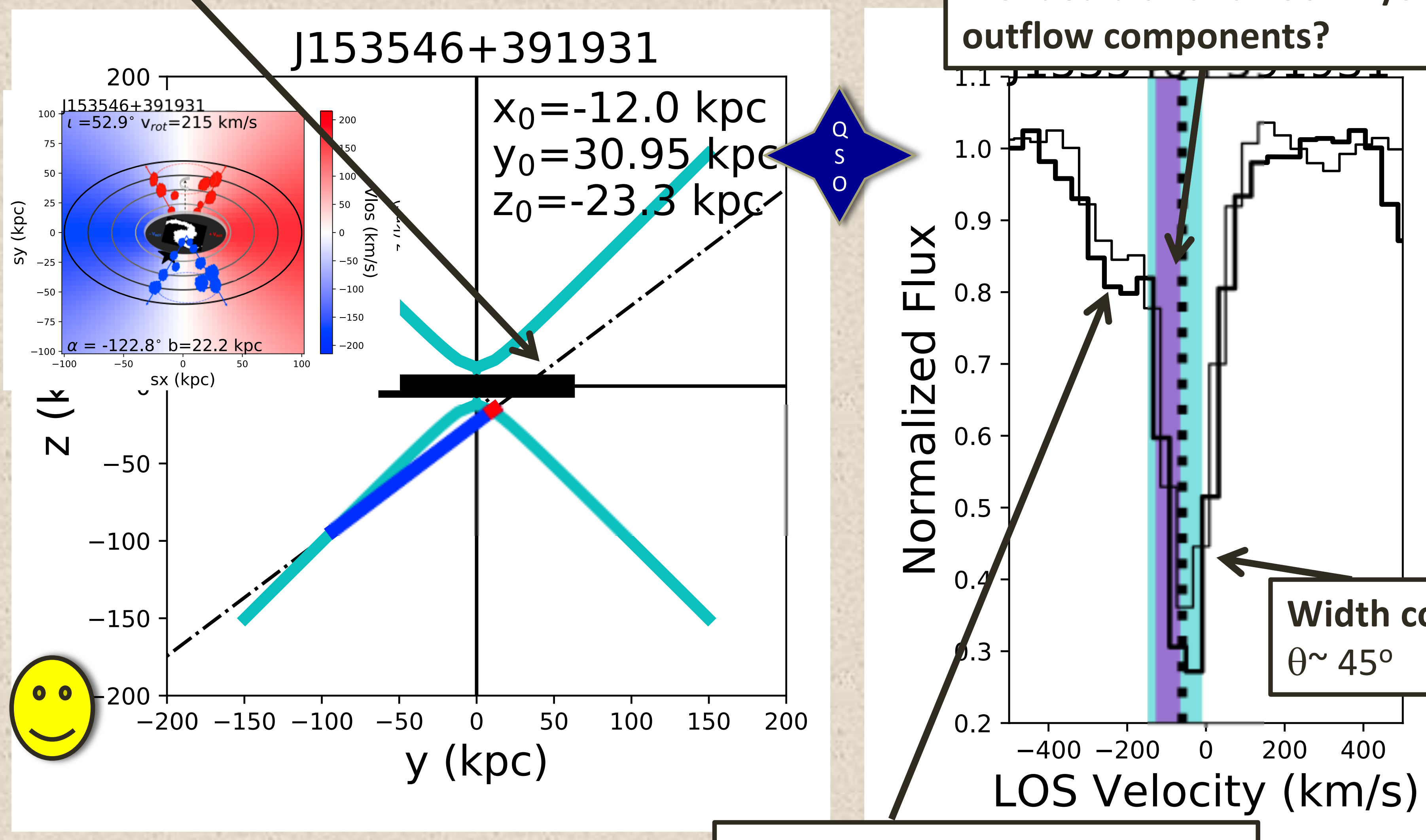
Is line wing part of outflow?

Martin+2019

Minor-Axis Sightlines with Strong Mg II: Example with Possible Disk Component

R = 33 kpc, so not surprising that sightline intersects disk.

Blended disk and 150 km/s outflow components?



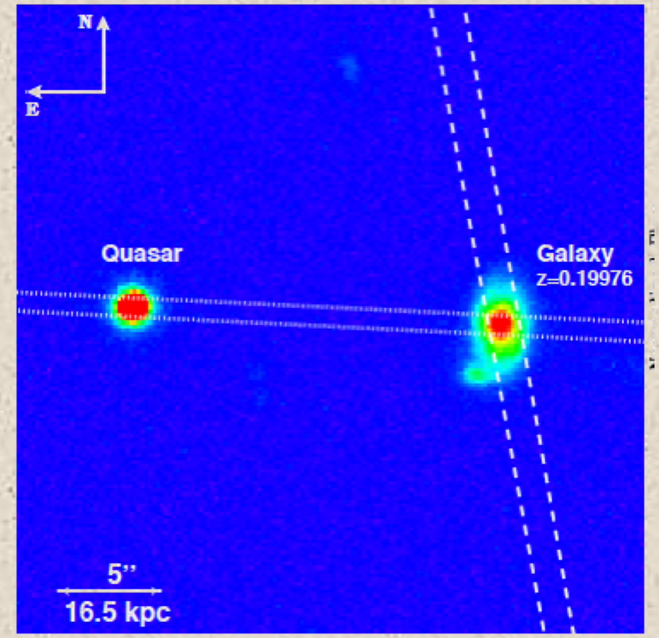
Width constrains
θ~ 45°

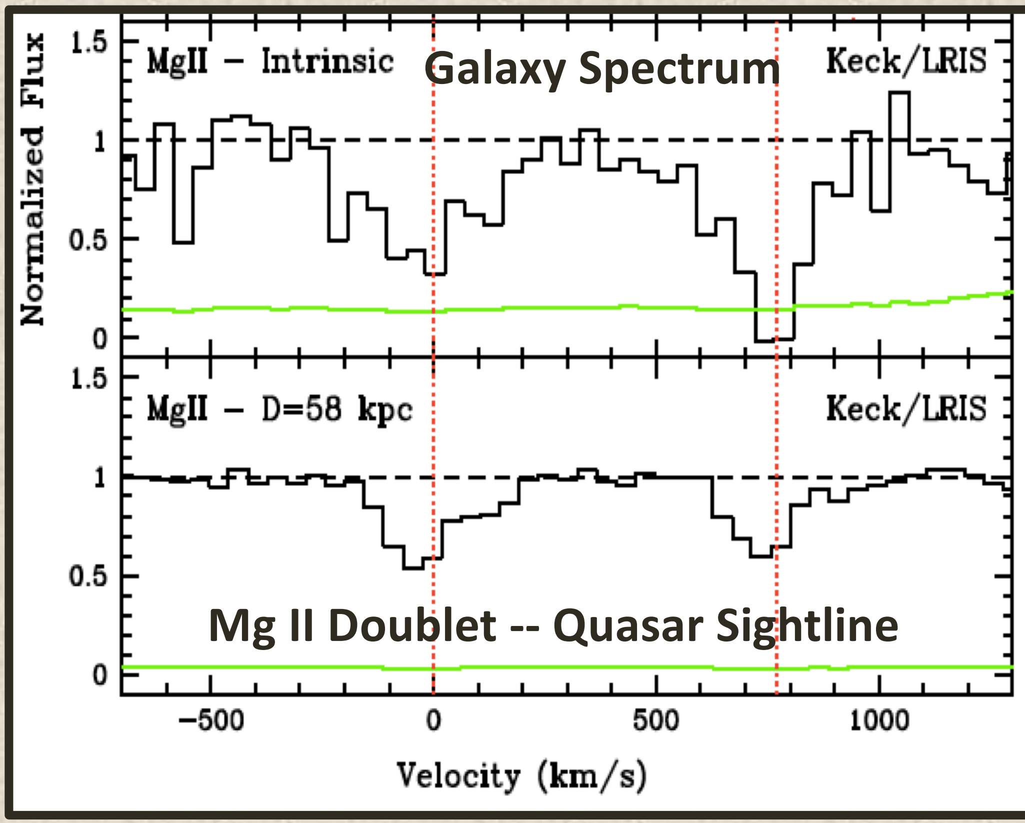
Is line wing part of outflow?

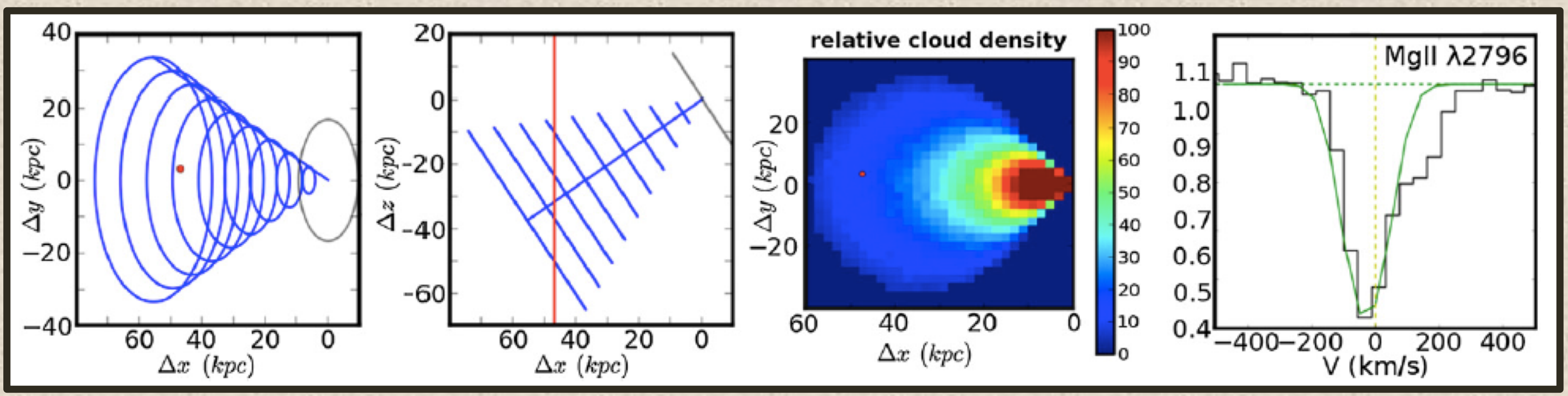
Martin+2019

Transverse and Down-the-Barrel Sightlines

Kacprzak+2014







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

Summary: Angular Momentum is an important factor in determining 'how gaseous halos affect galaxy evolution.'

- Observations of disk galaxies from redshift 0.2 to at least 1 show that the cool CGM has some net rotation in the same direction as the galactic disk.
  - Thin disks are not good descriptions of the broad line profiles; very thick "disks" extend to radii of at least 80 kpc.
  - The specific AM is high enough to grow the star-forming disk, but feeding over a range of disk radii is not ruled out.
  - Gaseous halos appear to have higher specific AM than the DM.
- Chemical abundance anomalies suggest deposition of low-metallicity gas favors large radii.
- Winds imprint signatures on the CGM on large (100 kpc) scales, so low AM gas is indeed transported large distances.

Looking Forward

Observational Challenges:

- AM of intermediate T and hot CGM
- Emission-line imaging of outflows and CGM

Challenges at the Theory – Observation Interface:

- Do the Mg II inflows connect to the H I beards? Or does this gas follow a different path to reach the thin disk?

- How should new theoretical insight about wind launching and mass loading change the way observers estimate outflow properties from line profiles?