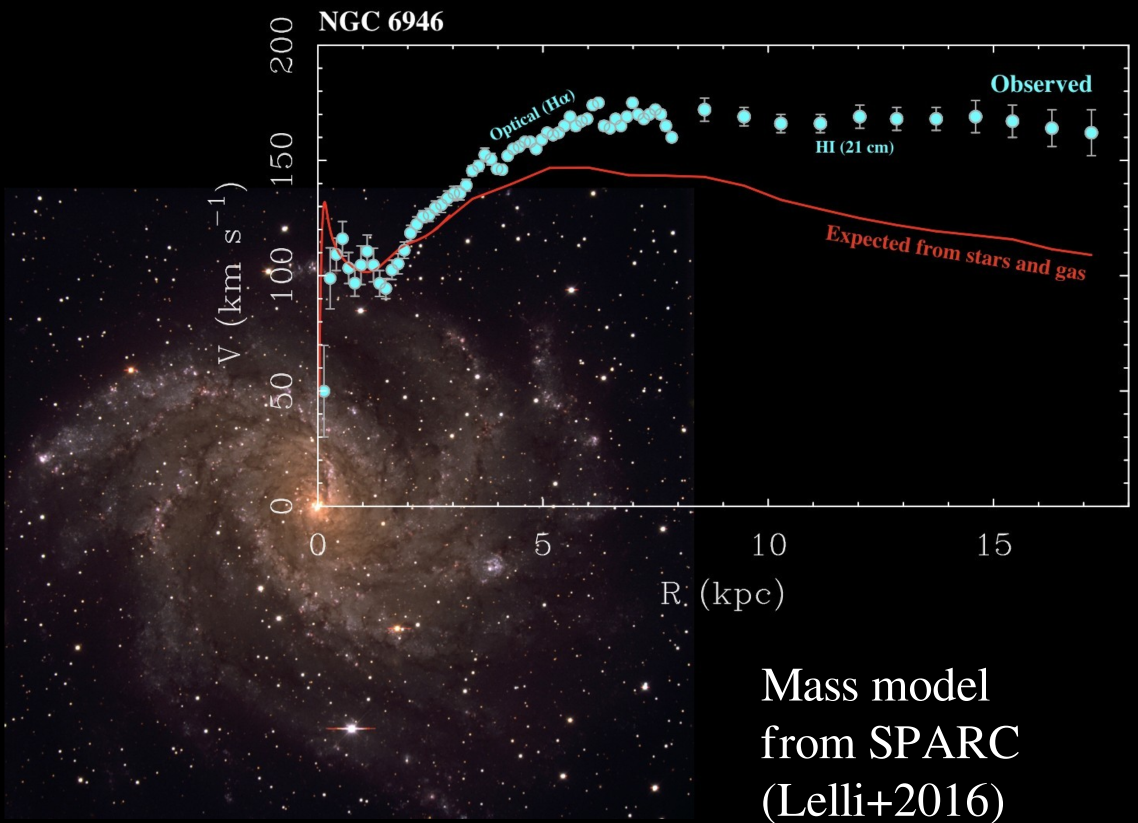
Cold Gas Dynamics in High-z Galaxies

Federico Lelli
Arcetri Observatory

Main Collaborators: T. Bisbas, C. De Breuck, E. Di Teodoro, P. Li, L. Lin, A. Man, A. Marasco, S. McGaugh, P. Papadopoulos, J. Schombert, Z.-Y. Zhang.

Gas Dynamics: Key Role in Galaxy Evolution



- Rotation Curves

→ Mass models (baryons & DM)

Mass model
from SPARC
(Lelli+2016)

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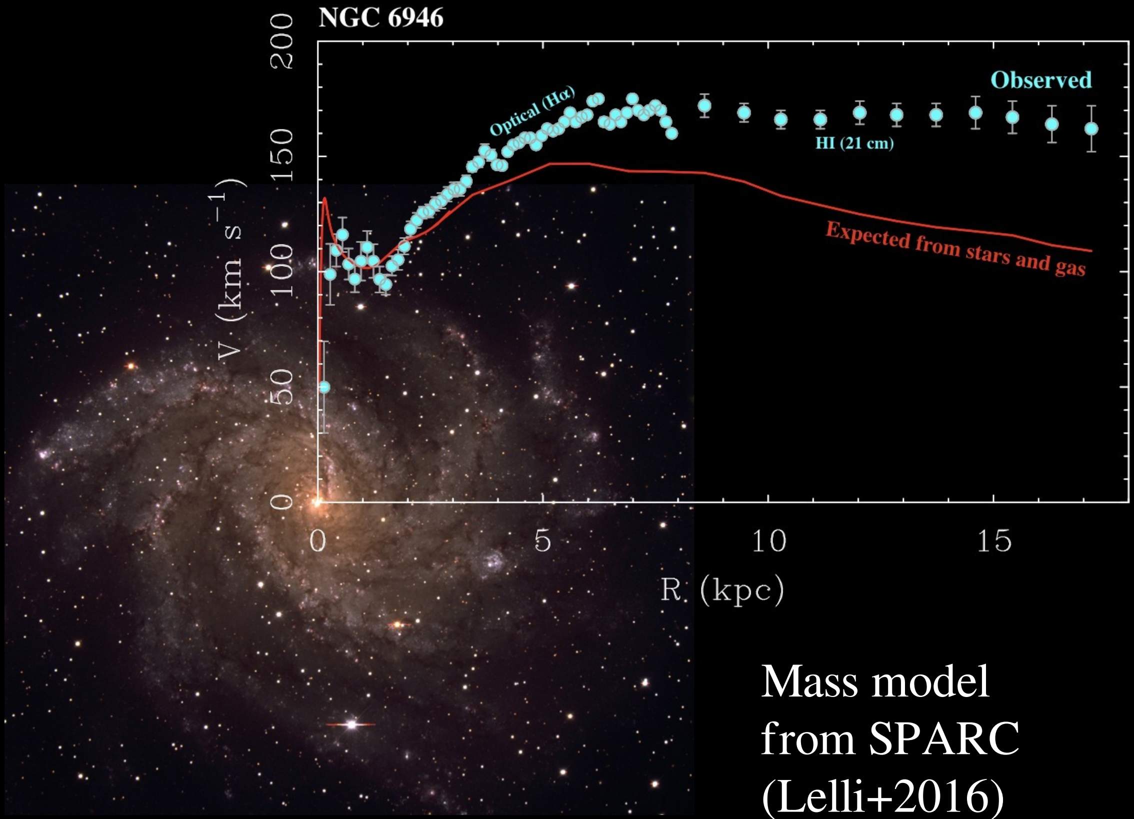

Mass model
from SPARC
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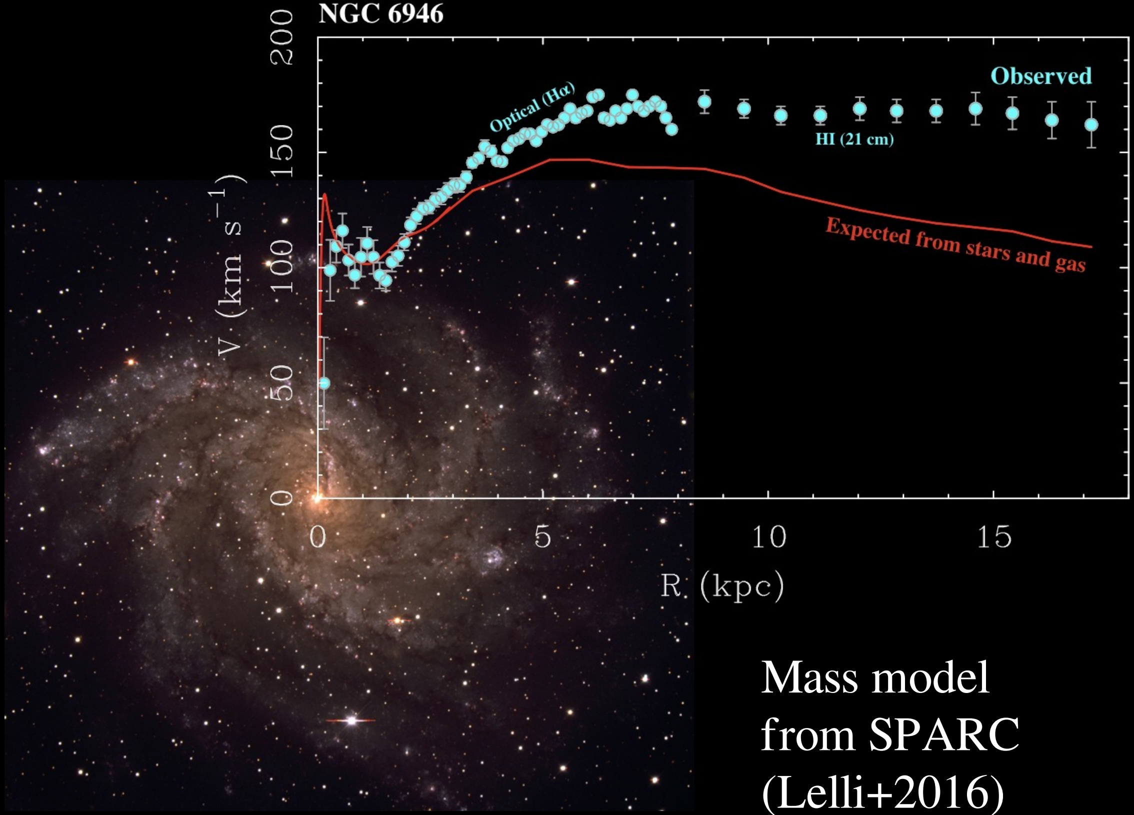
 → Mass models (baryons & DM)

- Non-circular motions

 → Inflows, outflows, bars & spiral arms

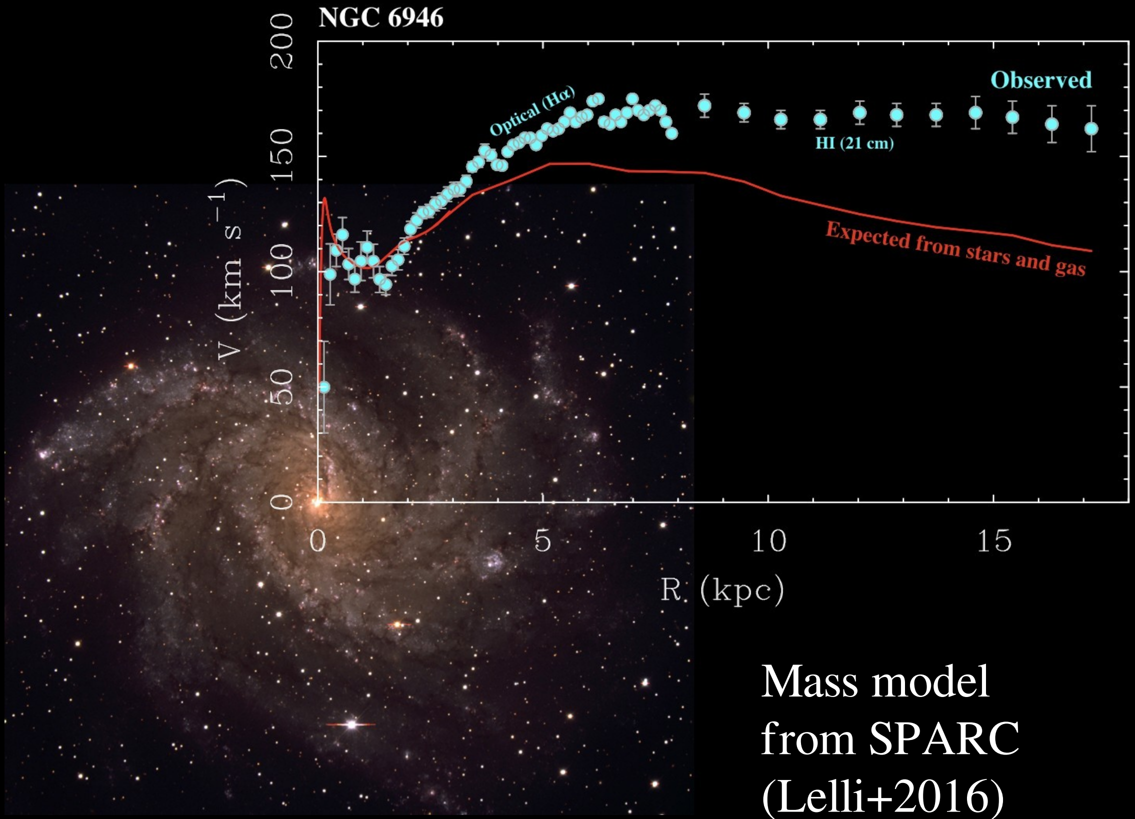
Gas Dynamics: Key Role in Galaxy Evolution



Mass model from SPARC (Lelli+2016)

- Rotation Curves
  → Mass models (baryons & DM)
- Non-circular motions
  → Inflows, outflows, bars & spiral arms
- Gas turbulence
  → Star formation & feedback

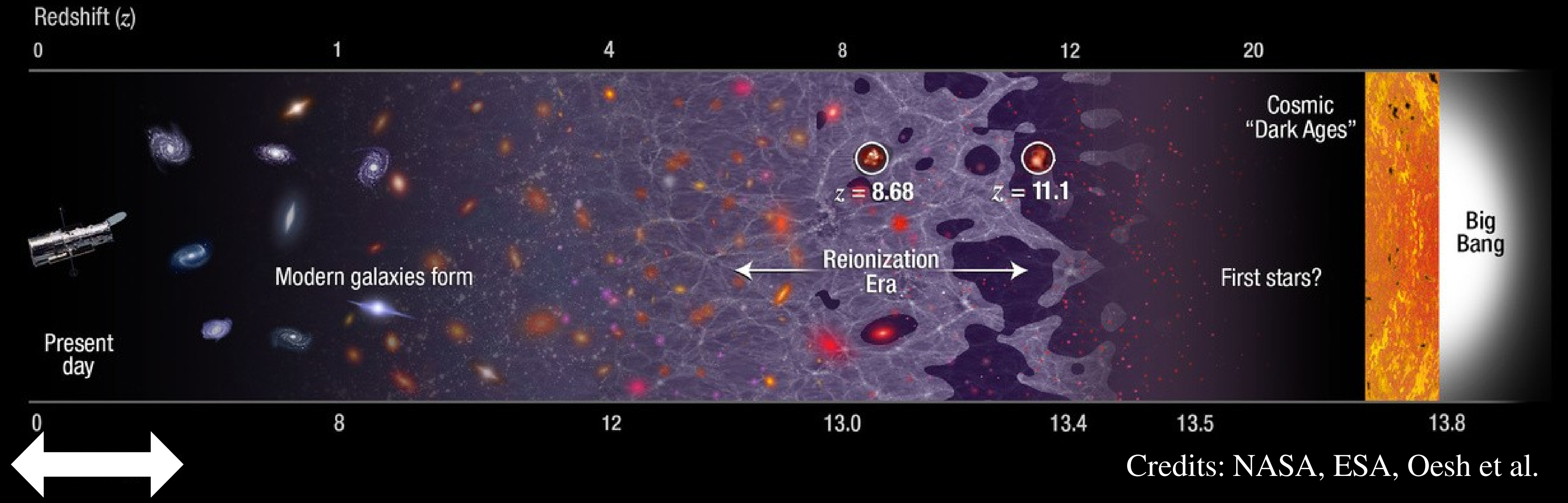
Gas Dynamics: Key Role in Galaxy Evolution



Mass model
from SPARC
(Lelli+2016)

- Rotation Curves
  → Mass models (baryons & DM)
- Non-circular motions
  → Inflows, outflows, bars & spiral arms
- Gas turbulence
  → Star formation & feedback
- Gas stripping phenomena
  → Interactions, mergers, environment

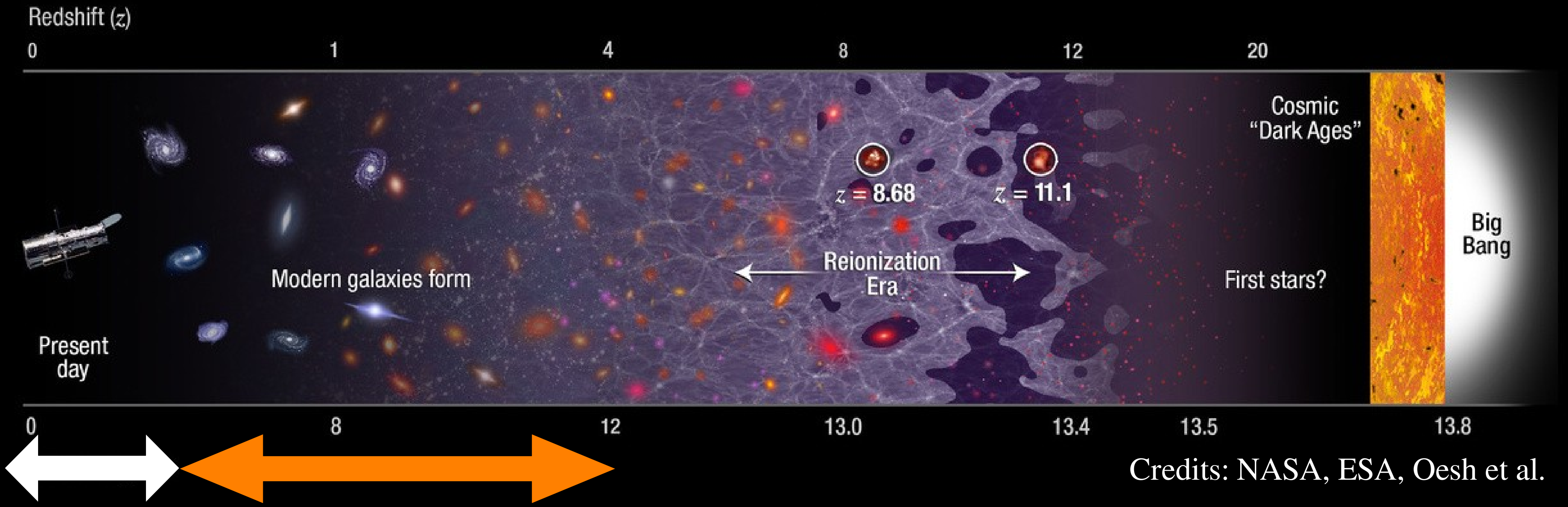
Gas Dynamics across Cosmic Time



Credits: NASA, ESA, Oesh et al.

Ionized gas (Hα)
Molecules (CO)
Atomic gas (HI)

Gas Dynamics across Cosmic Time



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Ionized gas (Hα)
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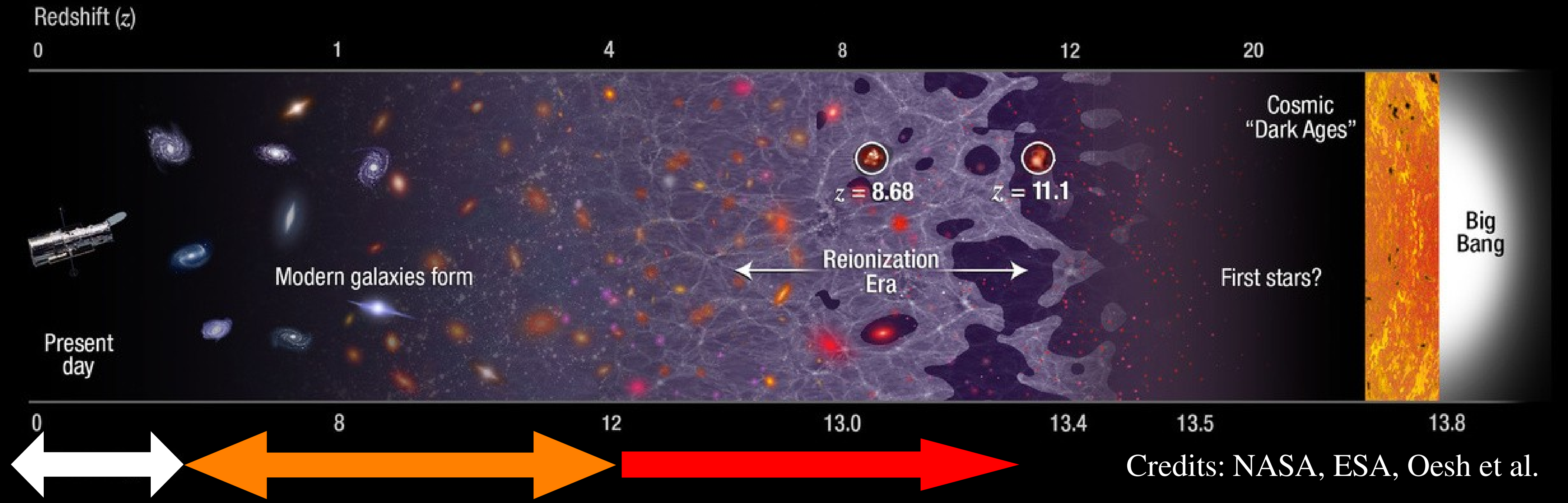
Hα, [OIII]λ5007
More recently:
High-J CO lines
[CI] lines

Gas Dynamics across Cosmic Time



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Ionized gas (Hα)
Molecules (CO)
Atomic gas (HI)

Hα, [OIII]λ5007
More recently:
High-J CO lines
[CI] lines

Ionized Carbon: [CII]
Next future:
JWST: Hα, [OIII]λ5007

Talk Outline:

1. Introduction: Galaxy dynamics at z~0

2. Galaxy dynamics at high z from ionized gas

3. Galaxy dynamics at high z from cold gas

1. Introduction: Galaxy dynamics at z~0

Galaxy Dynamics: Basic Theory

For a stationary axisymmetric system embedded in $\Phi(R, z)$:

$$V_c^2 \equiv R \frac{\partial \Phi}{\partial R}$$

Galaxy Dynamics: Basic Theory

For a stationary axisymmetric system embedded in $\Phi(R, z)$:

$$V_c^2 \equiv R\frac{\partial \Phi}{\partial R} = \overline{v_\theta}^2 + \sigma_R^2\left[\frac{\sigma_\theta^2}{\sigma_R^2} - 1 - \frac{\partial \ln \rho}{\partial \ln R} - \frac{\partial \ln \sigma_R^2}{\partial \ln R} - \frac{R}{\sigma_R^2}\frac{\partial \overline{v_R v_z}}{\partial z}\right]$$

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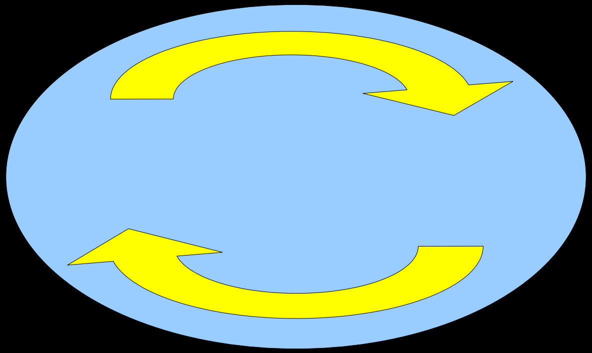
$\overline{v}_\theta = V_{rot}$ (ordered motions)



Galaxy Dynamics: Basic Theory

For a stationary axisymmetric system embedded in $\Phi(R, z)$:

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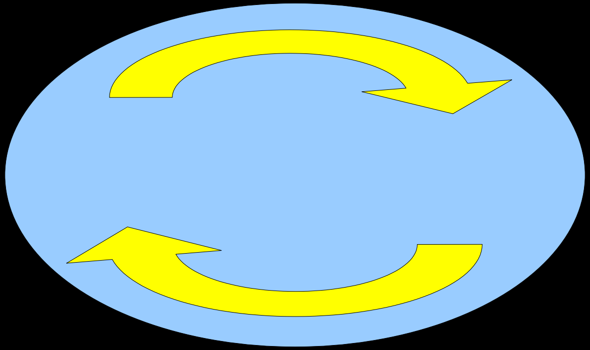
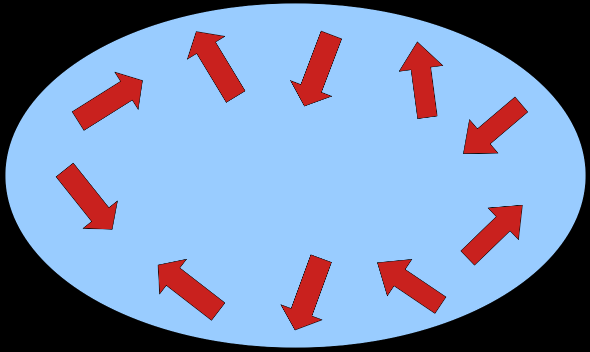
$\overline{v}_\theta = V_{rot}$ (ordered motions) Velocity dispersion (random motions) $\simeq \sigma_{los}$





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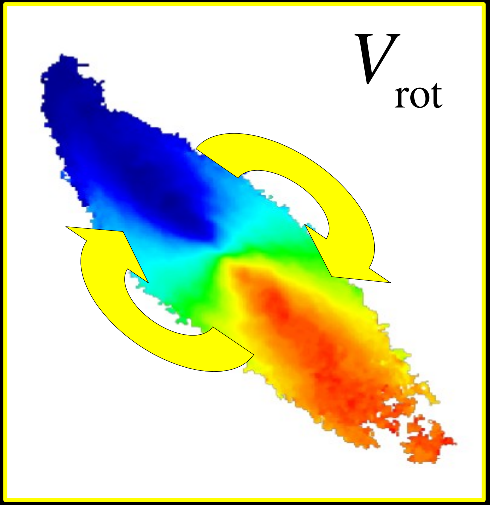
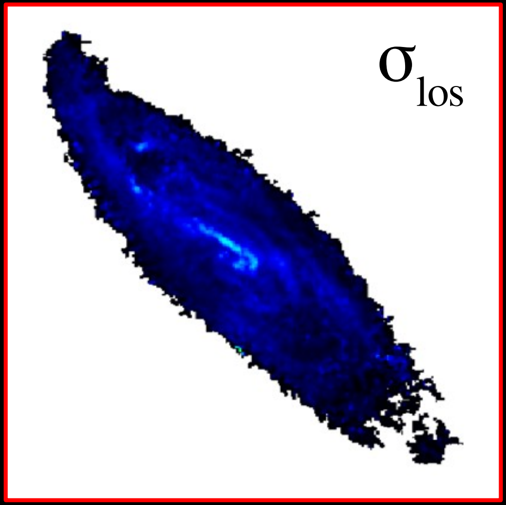
For cold gas disks at z=0:

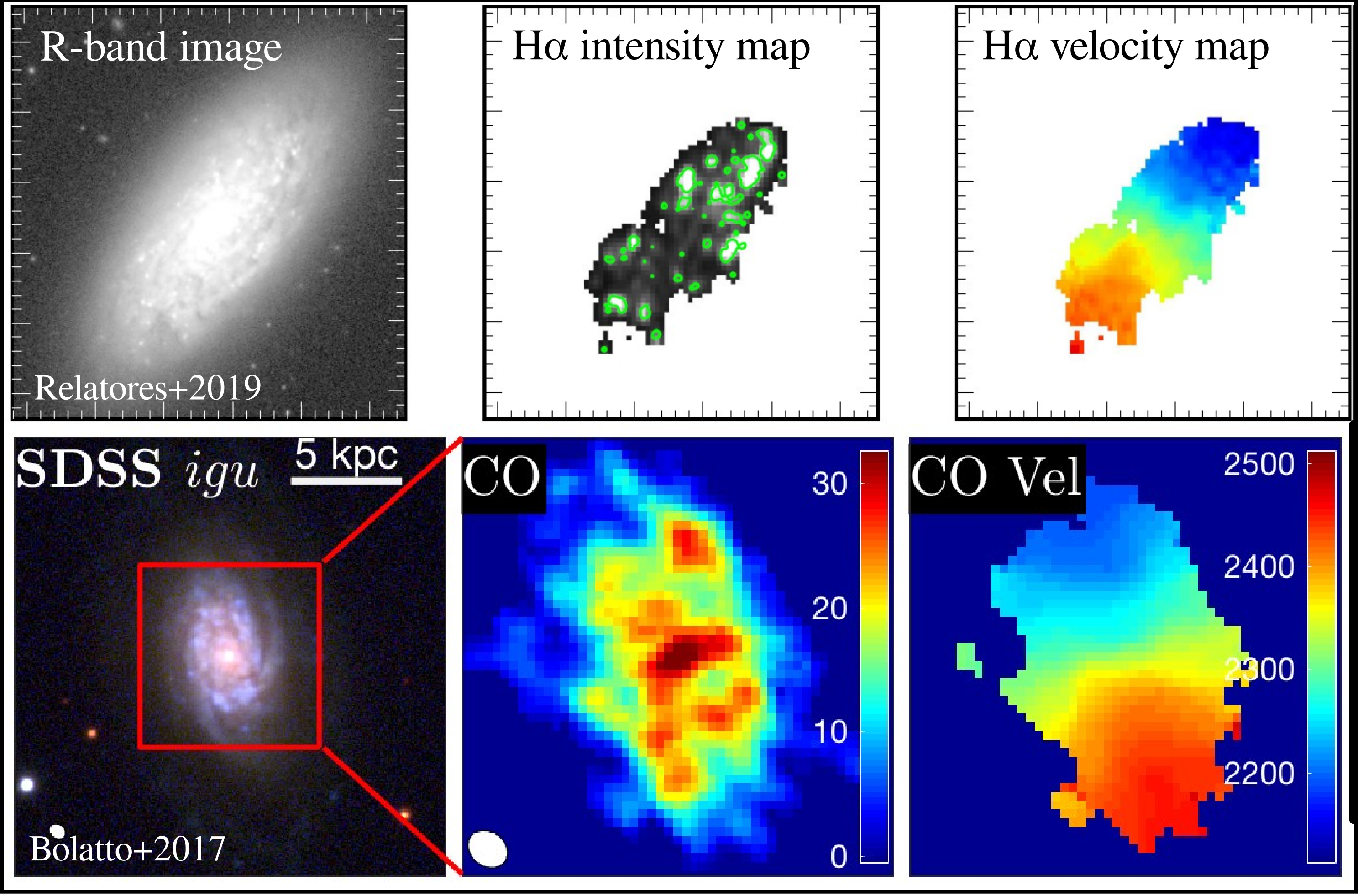
$V_{rot}/\sigma_{los} \gg 1 \rightarrow V_c \simeq V_{rot}$

(unlike stellar disks)





Inner Galaxy Regions: Ionized and Molecular Gas



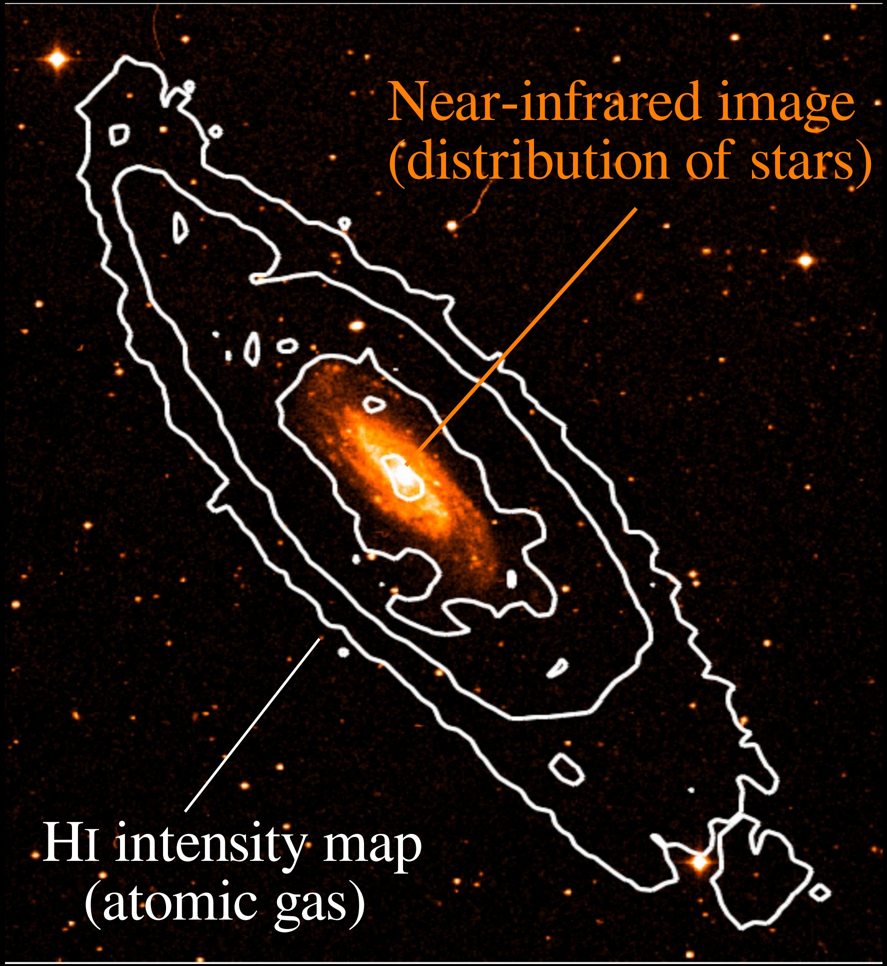
Hα from spectroscopy or Fabry-Perot interfer.

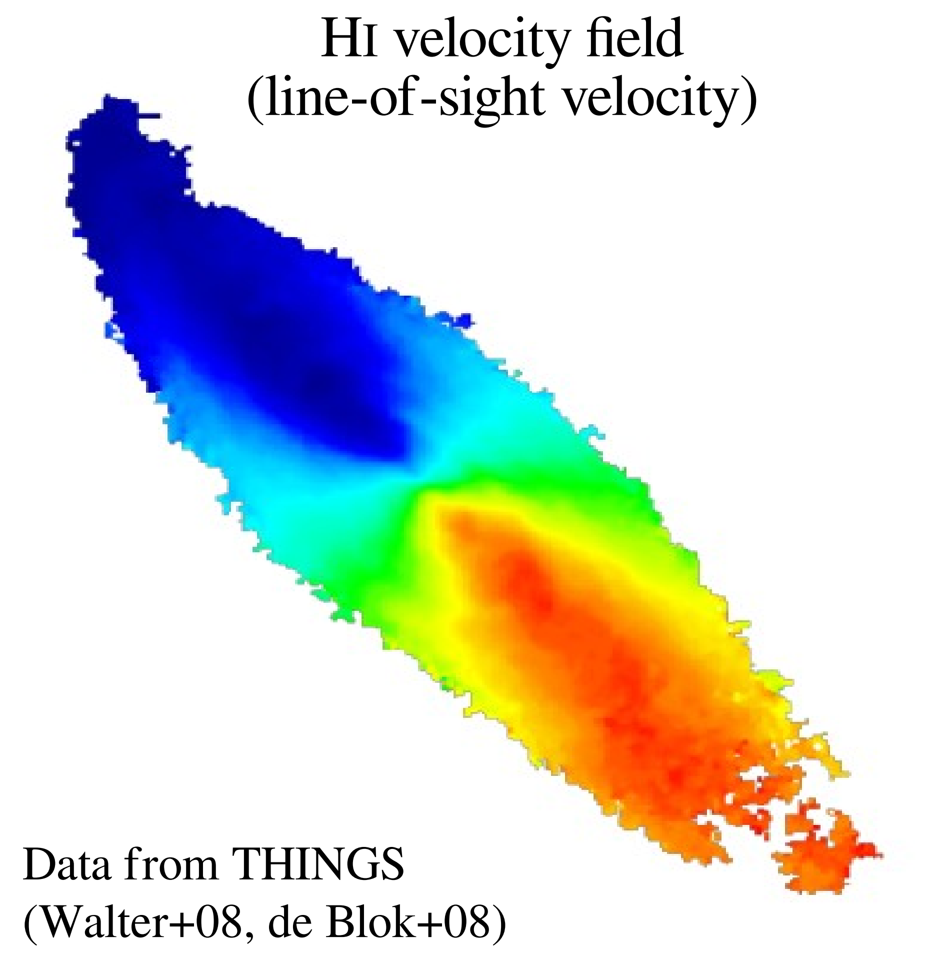
Some Hα refs: McGaugh+2001; Blais-Ouellette+04; Garrido+04; Daigle+06; Dicaire+08; Kuzio de Naray+06; 08; Relatores+19; Gómez-López+19; den Brok+20; DiTeodoro+2021.

CO transitions from submm interferometry

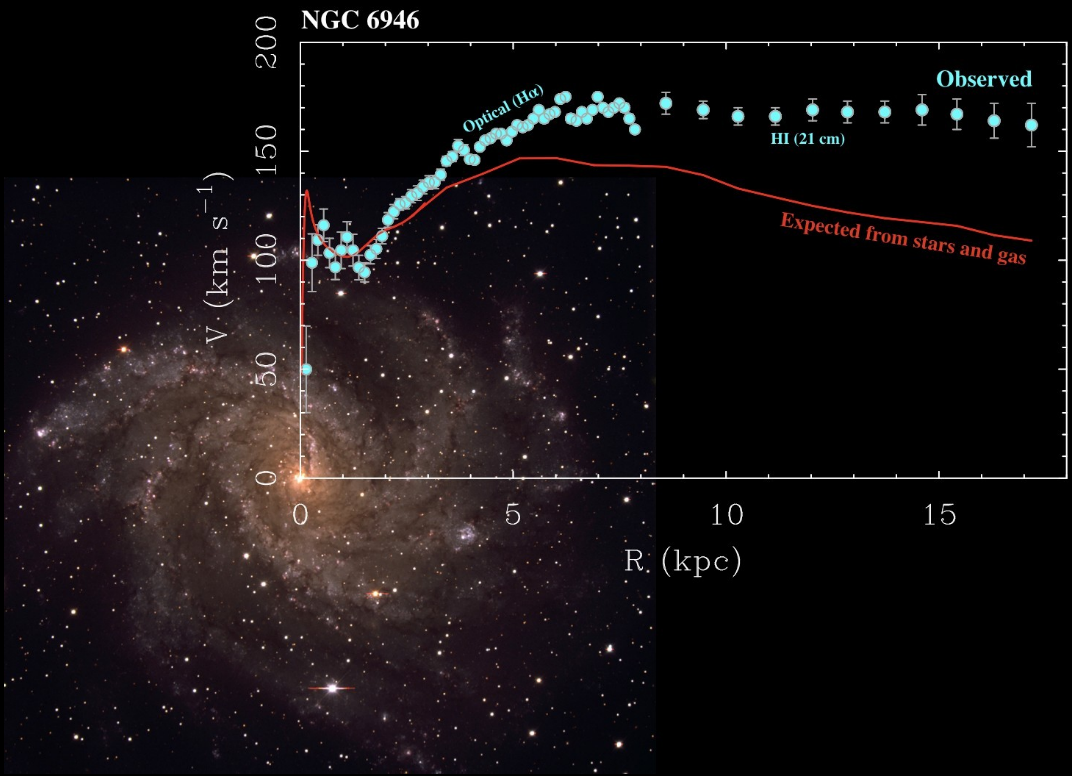
Some CO refs: Sorai+00; Sofue+03; Simon+03, 05; Leroy+09; Davis+11, +13, +17, +18, +19, +20; Leung+18; Levy+18; Lin+19; Salak+19; Shelest & Lelli 20; Smit+20; Lelli+22.

Outer Galaxy Regions: Atomic Gas (HI)





Dynamics for 175 Late-Type Galaxies (S & dIrr)



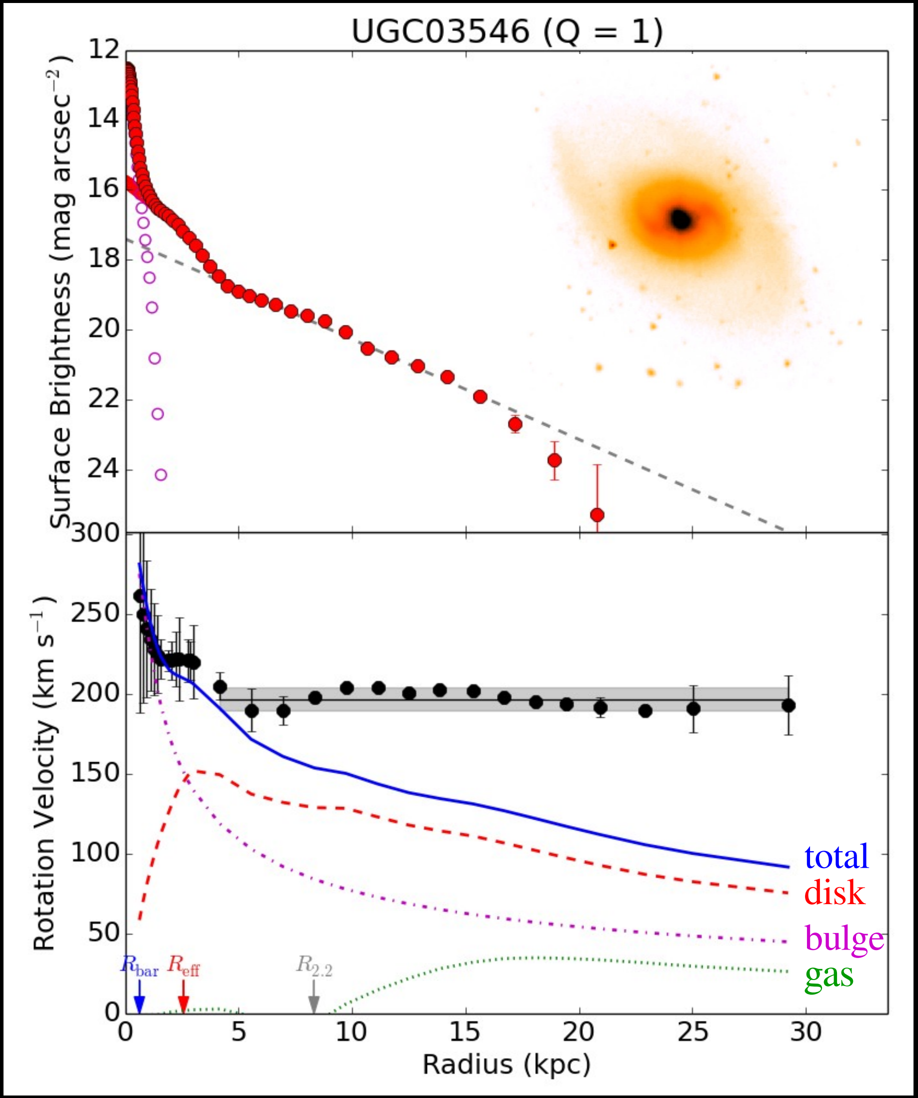
SPARC

Spitzer Photometry & Accurate Rotation Curves

- HI rotation curves from the literature (> 40 papers or thesis over 40 years)
- Hα rotation curves for 30% of sample (long-slit, IFU, and Fabry-Perot data)
- Homogeneous Spitzer [3.6] photometry Best tracer of stellar mass distribution

Public data: astroweb.cwru.edu/SPARC

Lelli, McGaugh, Schombert (2016)



Mass Model: Sa Galaxy

- Solve (numerically) Poisson's equation:

$$\nabla^2 \Phi_i(R,z) = 4\pi G \rho_i(R,z)$$

- Find circular velocity in the disk plane:

$$V_i^2(R,z=0) = -R\frac{\partial \Phi_i(R,z=0)}{\partial R}$$

- Sum over gravitational fields ($g_i = V_i^2/R$):

$$V_b^2(R) = \Upsilon_{bul} V_{bul}^2 + \Upsilon_{disk} V_{disk}^2 + \Upsilon_{gas} V_{gas}^2$$

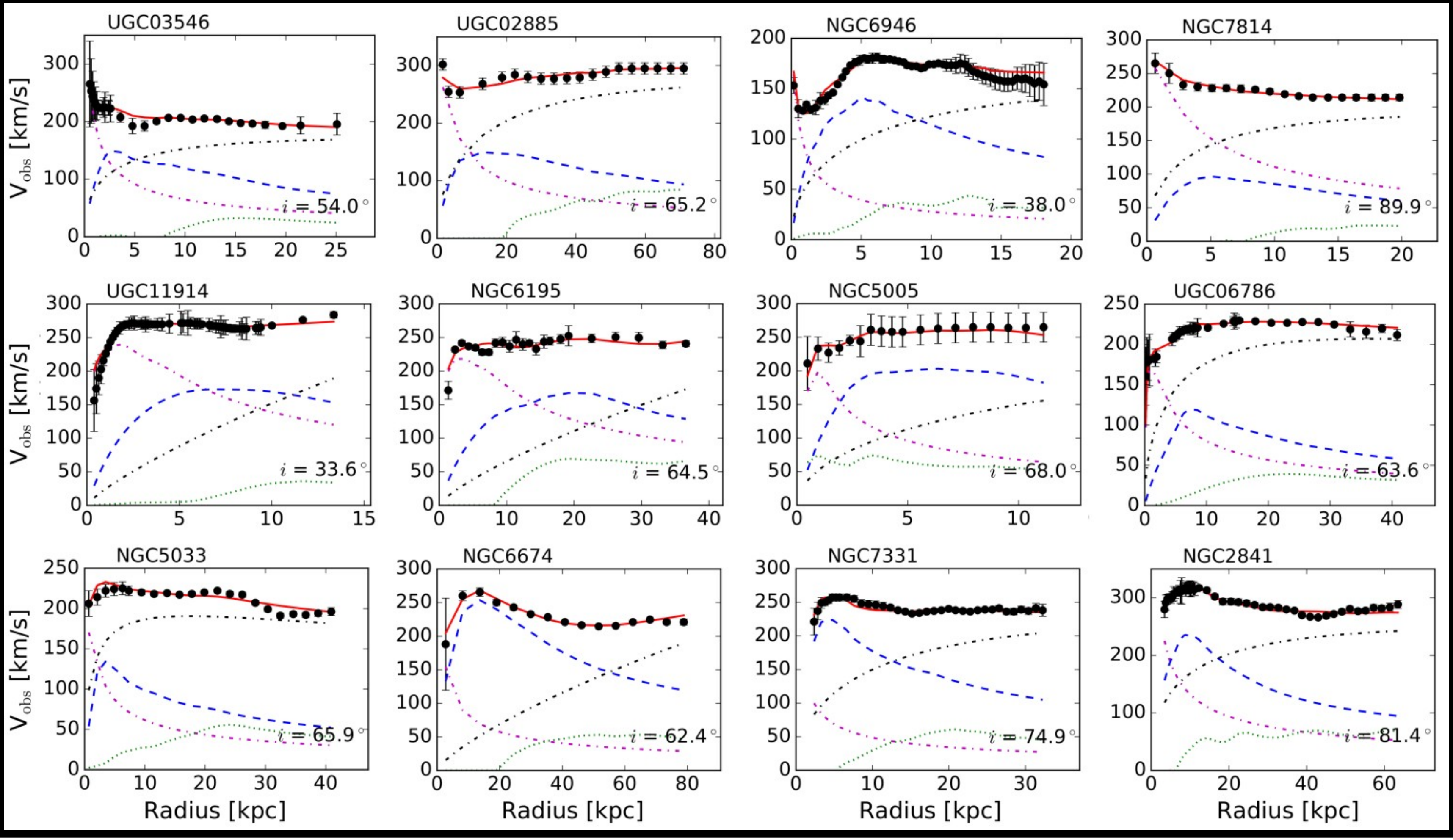
Lelli+(2016)

SPARC

Spitzer Photometry & Accurate Rotation Curves

1. Basic Data & Structural Relations: Lelli+2016a, AJ
2. Baryonic Tully-Fisher Relation (I): Lelli+2016b, ApJL
3. Central Surface Density Relation: Lelli+2016c, ApJL
4. Radial Acceleration Relation (I): McGaugh+2016, PRL
5. Radial Acceleration Relation (II): Lelli+2017a, ApJ
6. The Cusp-*vs*-Core Problem: Katz+2017, MNRAS
7. Testing Emergent Gravity: Lelli+2017b, MNRAS
8. Radial Acceleration Relation (III): Li+2018, A&A
9. Maximum-Disk Fits: Starkman+2018, MNRAS
10. Missing Baryons: Katz+2018, MNRAS
11. Scaling Relations for DM Halos: Li+2019, MNRAS
12. Halo Mass – Velocity Relations: Katz+2019, MNRAS
13. Stellar M/L ratios (I): Schombert+2019, MNRAS
14. Residuals in BTFR: Desmond+2019, MNRAS
15. Tully-Fisher Relation (II): Lelli+2019, MNRAS
16. The Halo Mass Function: Li+2019, ApJL
17. Catalog of DM Halo Fits: Li+2020, ApJS
18. H0 from TF relation: Schombert+2020, AJ
19. Testing the SEP in MOND (I): Chae+2020, ApJ
20. Testing the SEP in MOND (II): Chae+2021, ApJ
21. Cautionary Tale in Bayesian Fits: Li+2021, A&A
22. Local-Group TF relation: McGaugh+2021, AJ
23. Adiabatic Halo Compression (I): Li+2022, ApJ
24. Stellar M/L ratios (II): Schombert+2022, AJ
25. Testing the SEP in MOND (III): Chae+2022, PRD
26. Adiabatic Halo Compression (II): Li+2022, A&A

Mass Models for Massive Spirals (Sa/Sb)



Declining RC → inner bulge

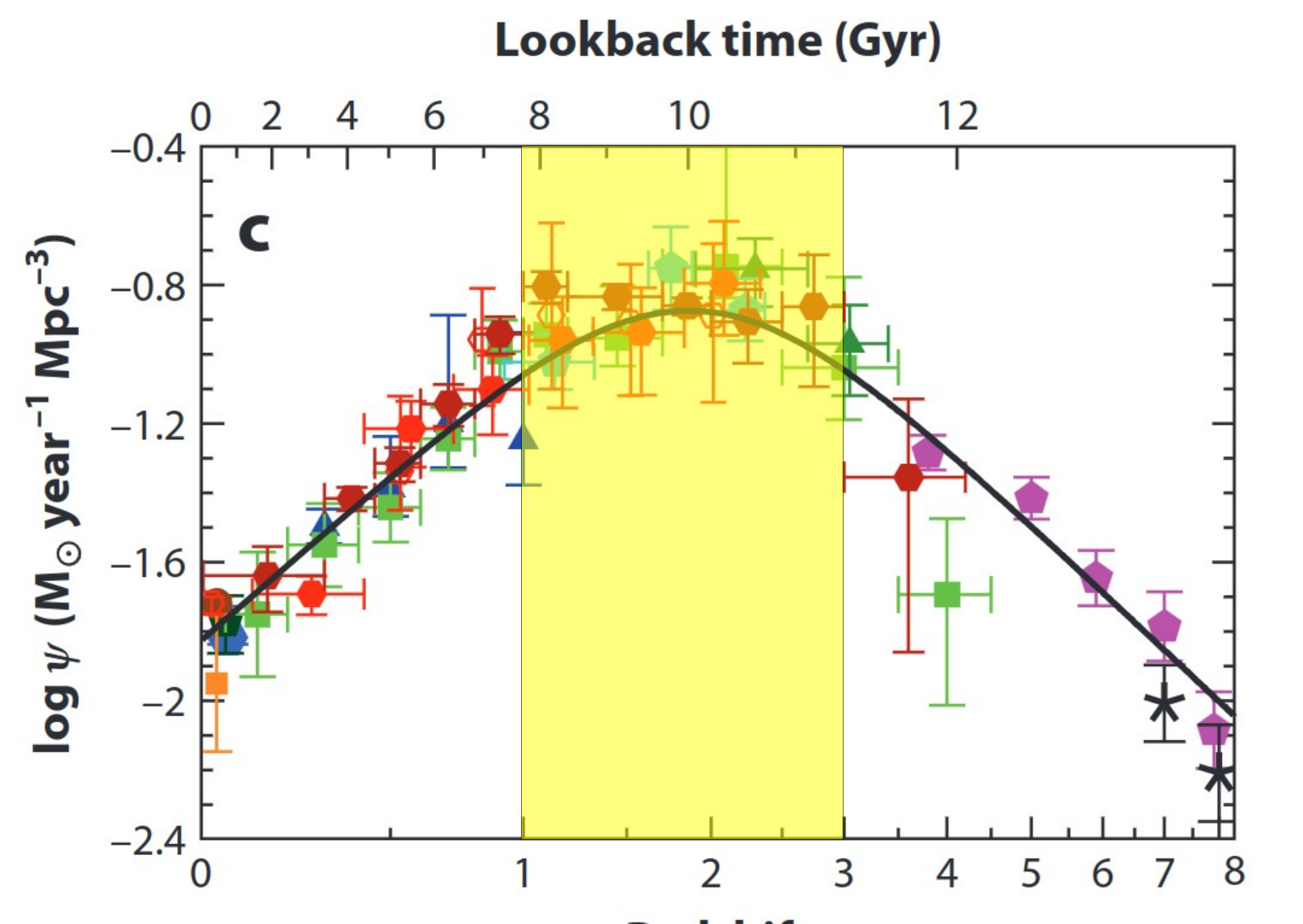
Flat RC → bulge + disk

Flat RC → disk > bulge

All 175 galaxies: Li, Lelli+ (2020)

2. Galaxy Dynamics at high-z from Ionized Gas

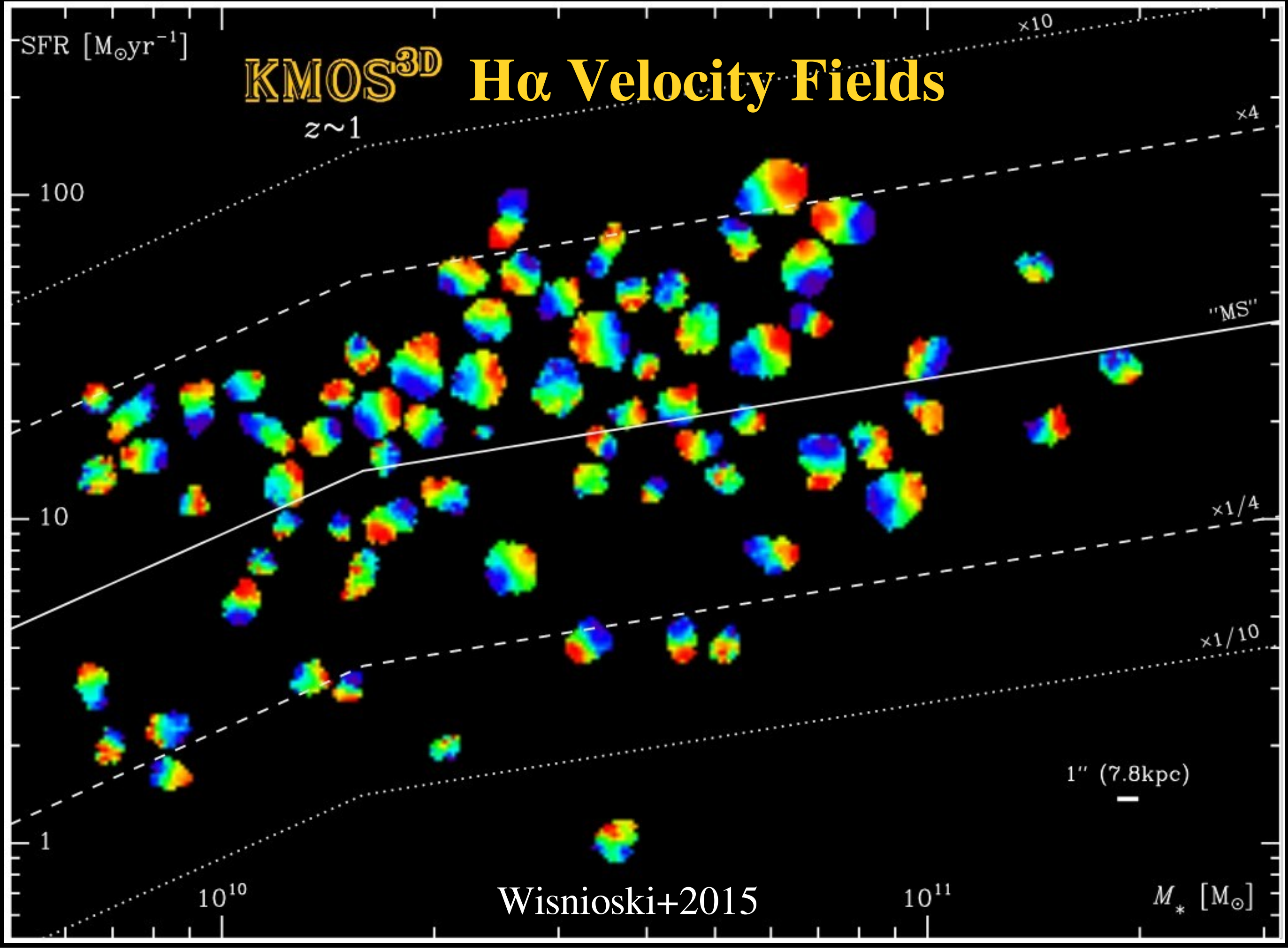
Warm Ionized Gas at Cosmic Noon



Madau & Dickinson 2014

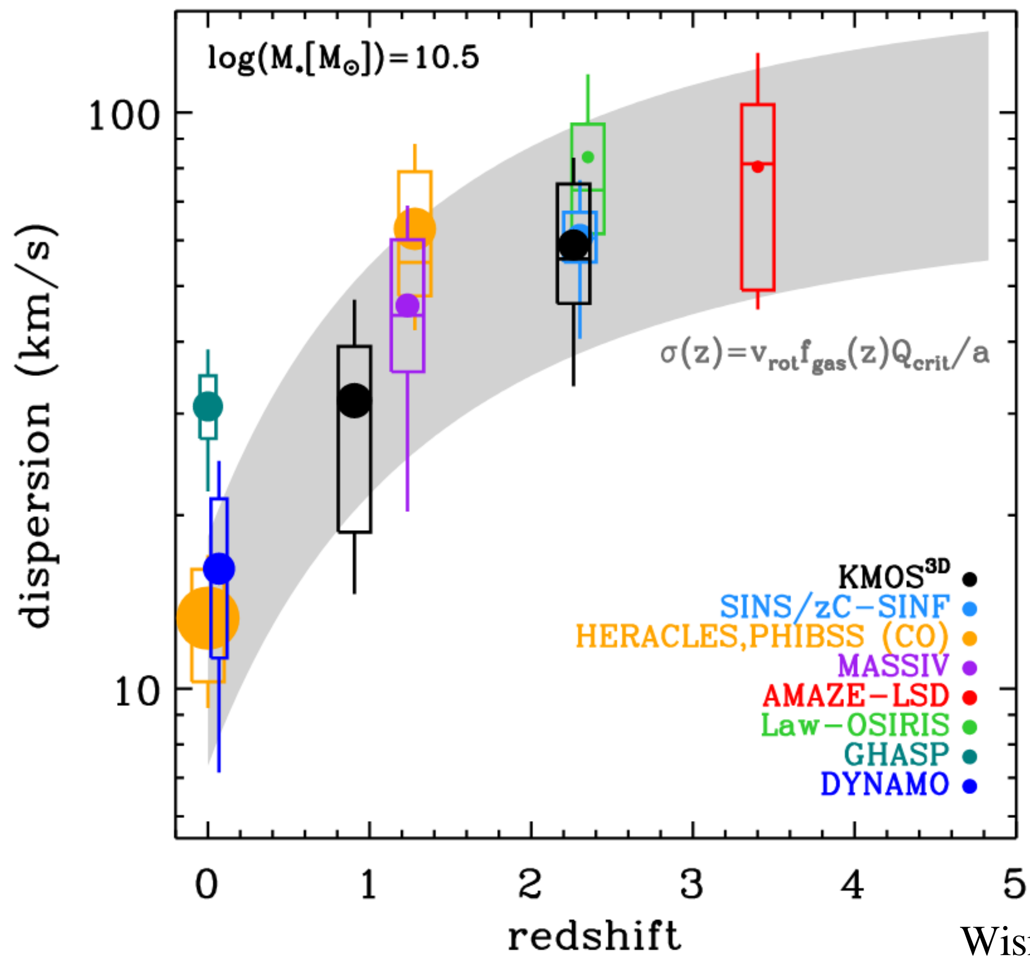
NIR IFU spectroscopy:
Hα and [OIII]λ5007 at
z ≃ 1-3 (cosmic noon).

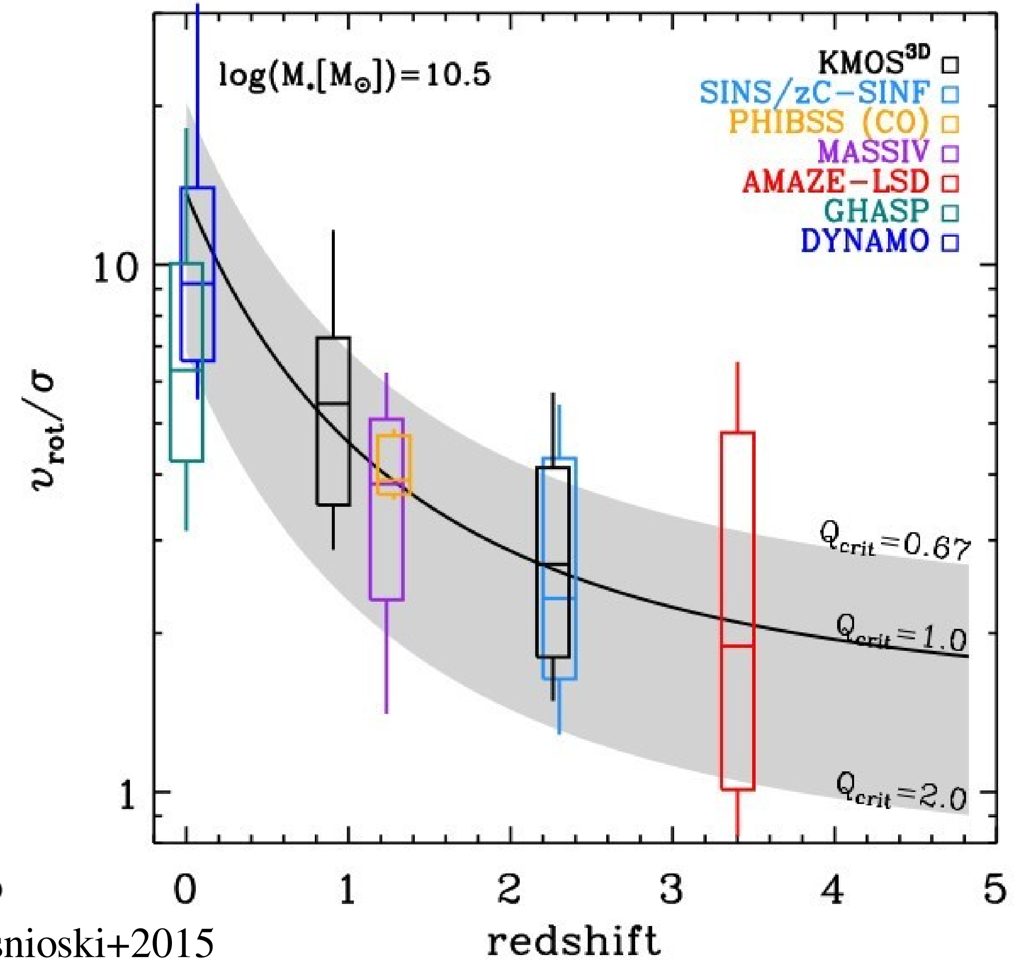
Ionized Gas in Main-Sequence Galaxies at z≃1-3



- More than 80% of main-sequence galaxies host a rotating disk.
- Most star formation occurs in regular disks, not in galaxy mergers.

Results from Ionized Gas: Turbulent Disks?

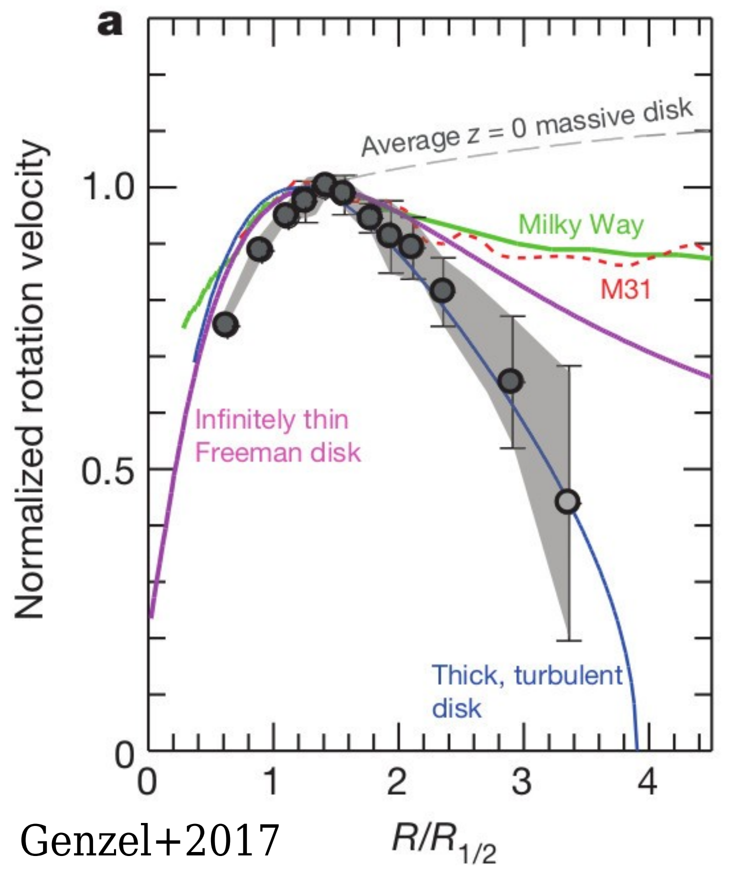




Wisnioski+2015

Shapes of Rotation Curves at Cosmic Noon

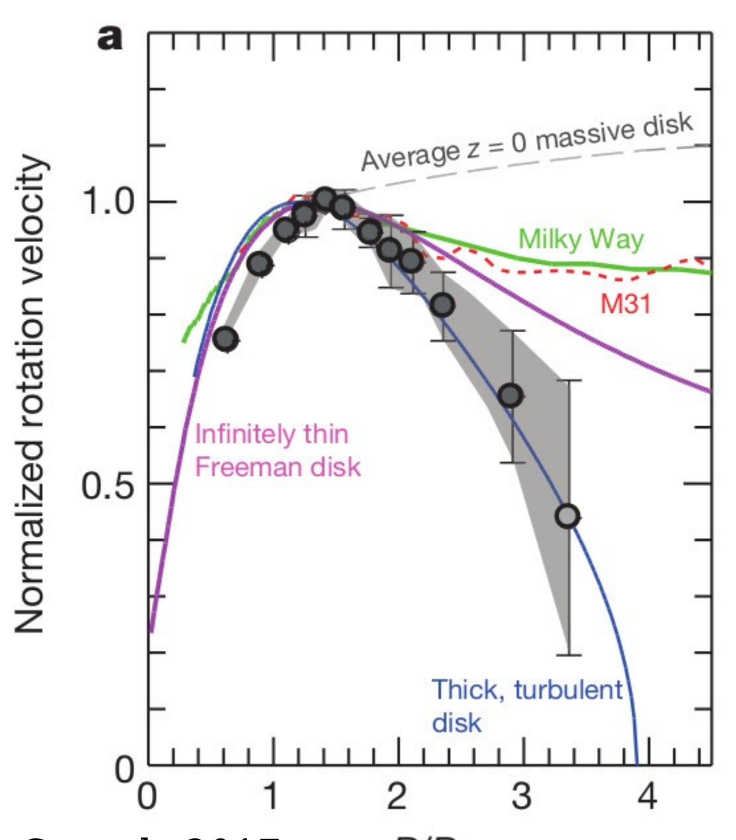
Declining rotation curves



Genzel+2017

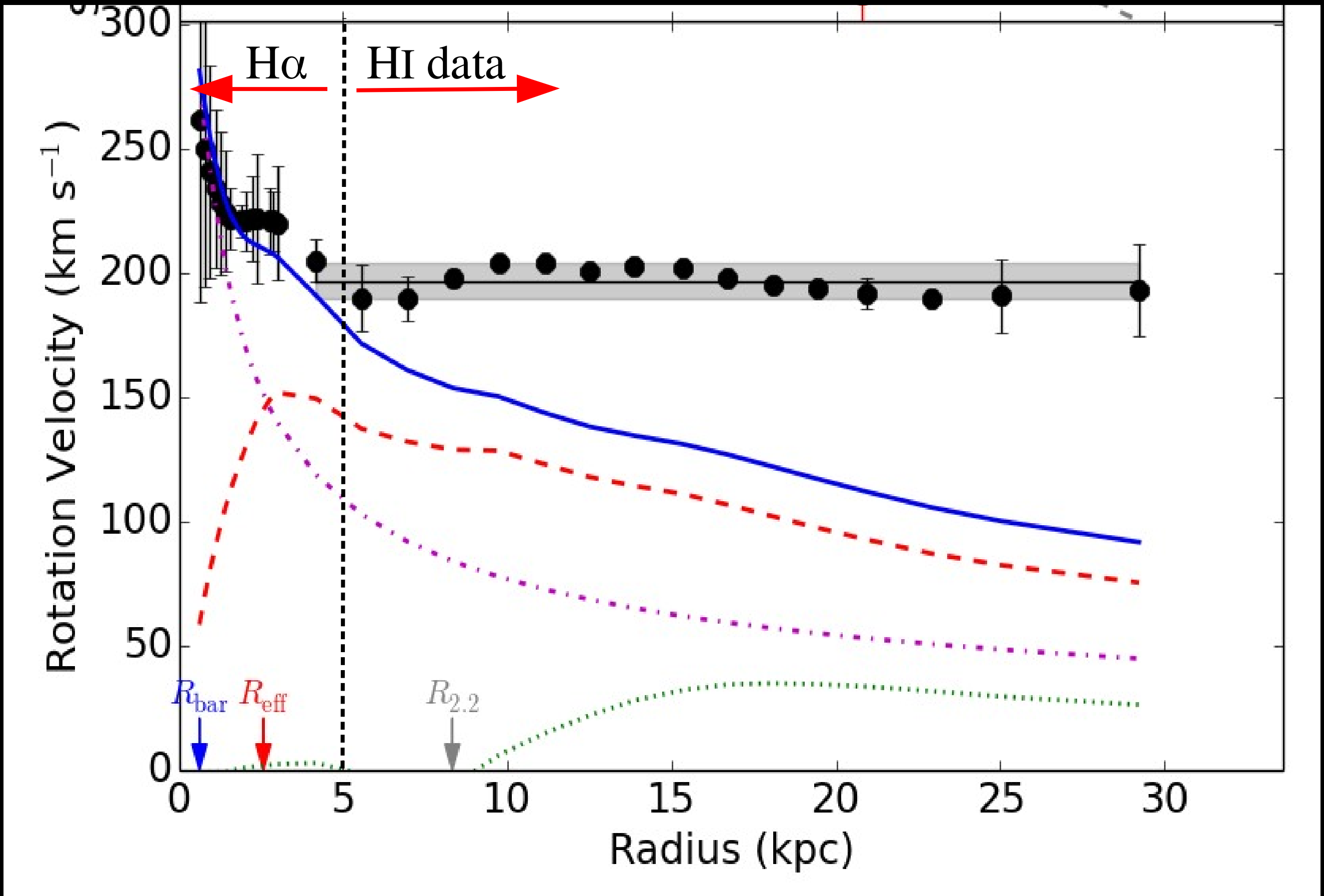
Shapes of Rotation Curves at Cosmic Noon

Declining rotation curves



Genzel+2017

...observed at z=0 too! (Noordermeer+2007, Lelli+2016)



Shapes of Rotation Curves at Cosmic Noon

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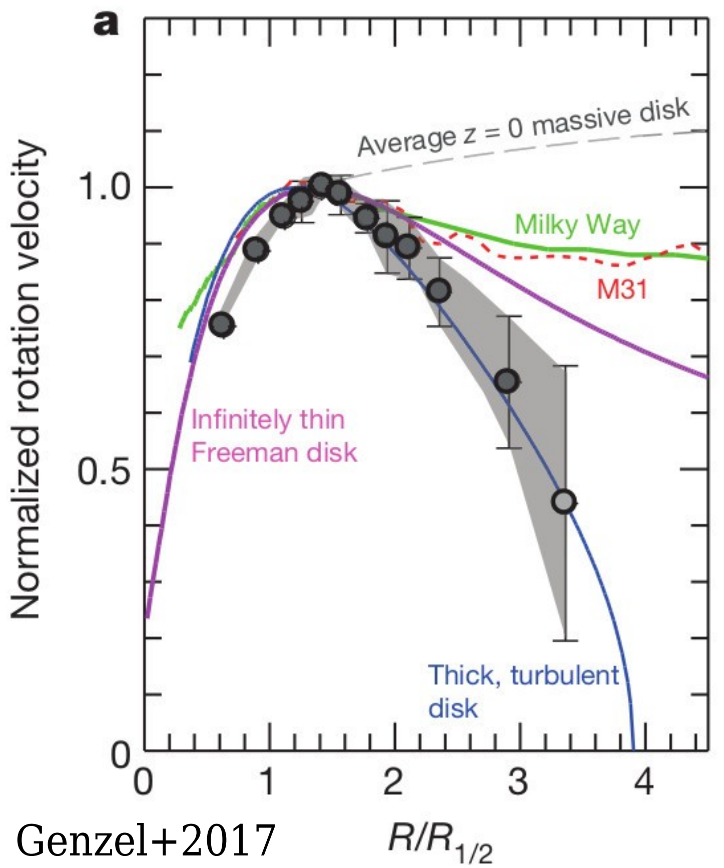


Genzel+2017

Outer decline is steeper than Keplerian!

Strong Pressure Support?

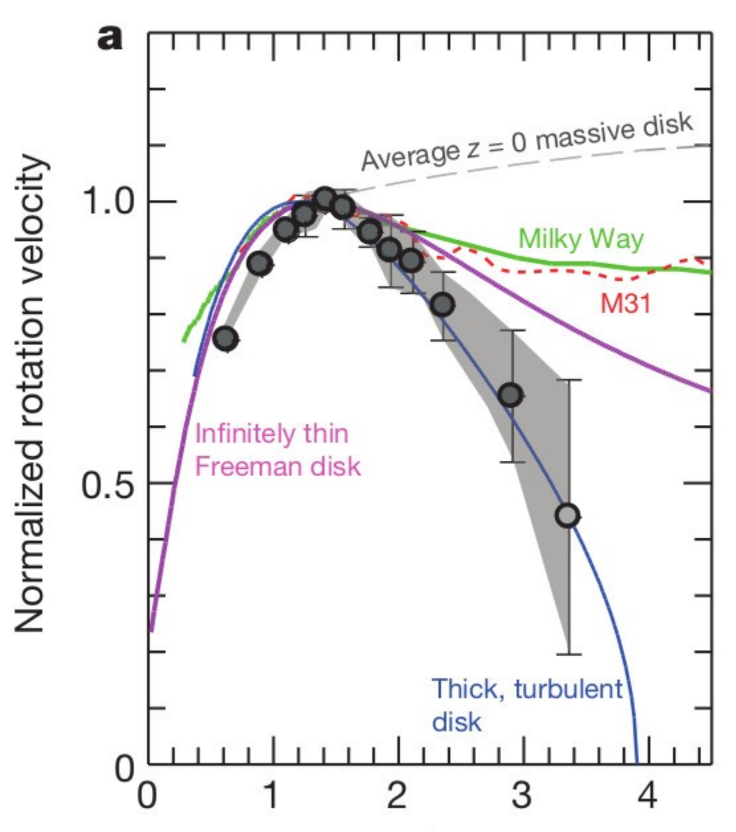
$$V_c^2 = V_{rot}^2 + \sigma_V^2 \left(-2 \frac{\partial \ln \sigma_V}{\partial \ln R} - \frac{\partial \ln \rho}{\partial \ln R} \right)$$

(for isotropic rotators)

If $V_{rot} \simeq \sigma_V$, the outer decline can be steeper than Keplerian...

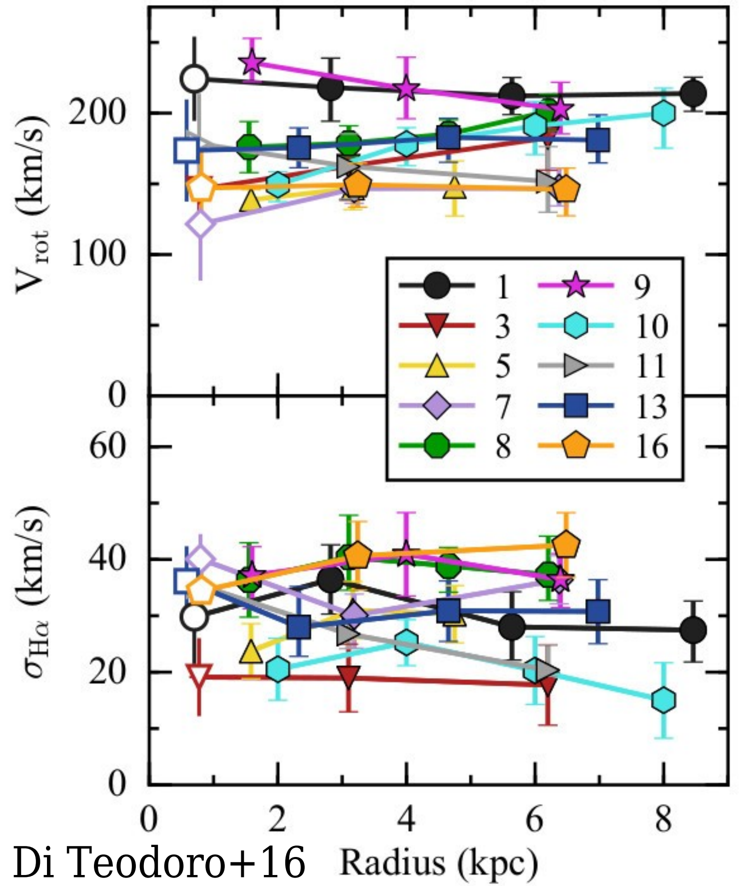
Shapes of Rotation Curves at Cosmic Noon

Declining rotation curves



Genzel+2017

Flat rotation curves & low turbulence



Di Teodoro+16

$V_{rot}/\sigma_V \sim 4\text{-}10$

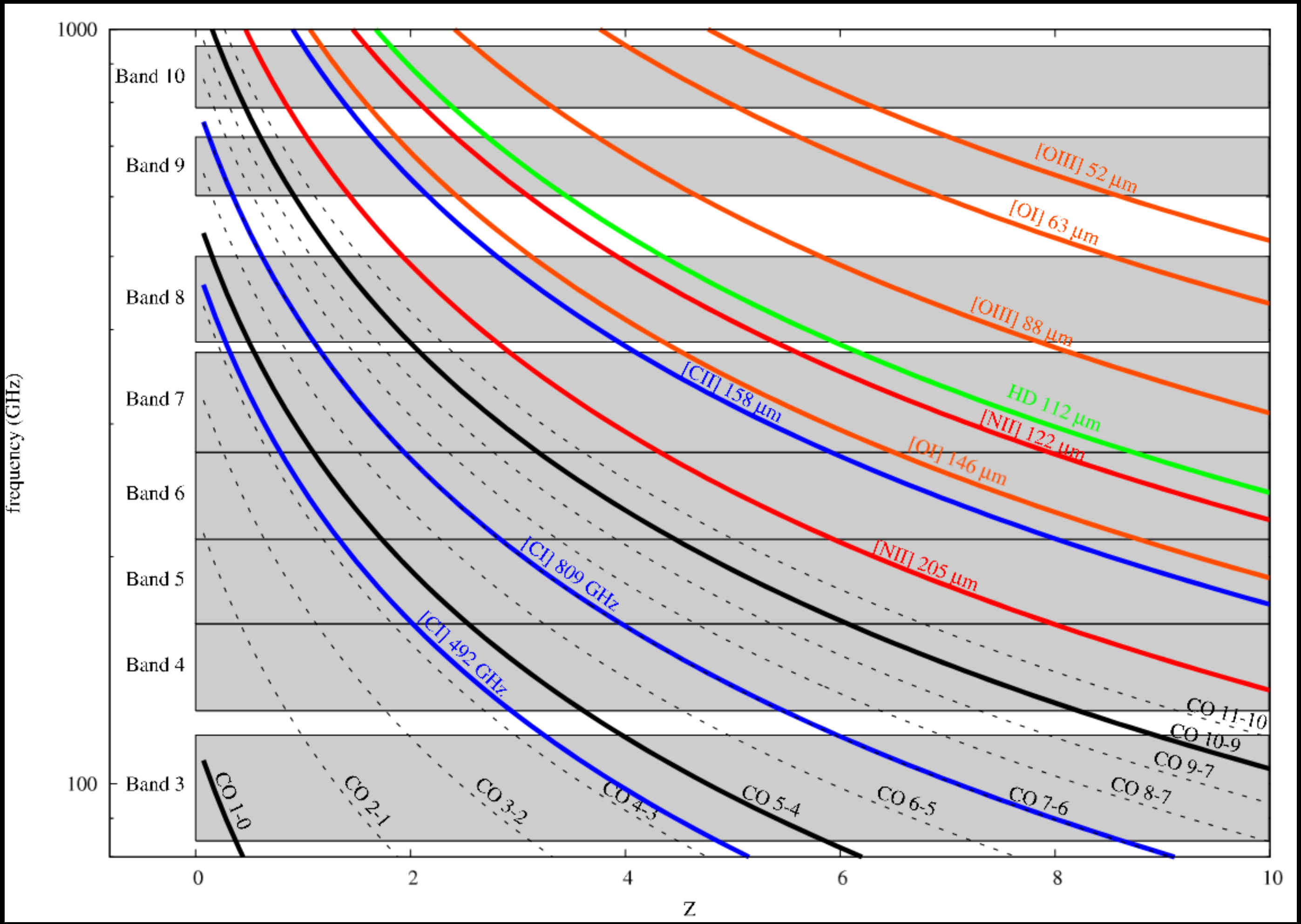
Two Observational Challenges

1. Spatial resolution is relatively low at z=1-3:
   Beam smearing can severely affect σ_V and V_{rot}/σ_V!

2. Mass of the ISM is dominated by cold/neutral gas:
   Is warm/ionized gas (a few % of M_{ISM}) representative of the overall dynamical state of the gas disk?

3. Galaxy Dynamics at high z from Cold Gas

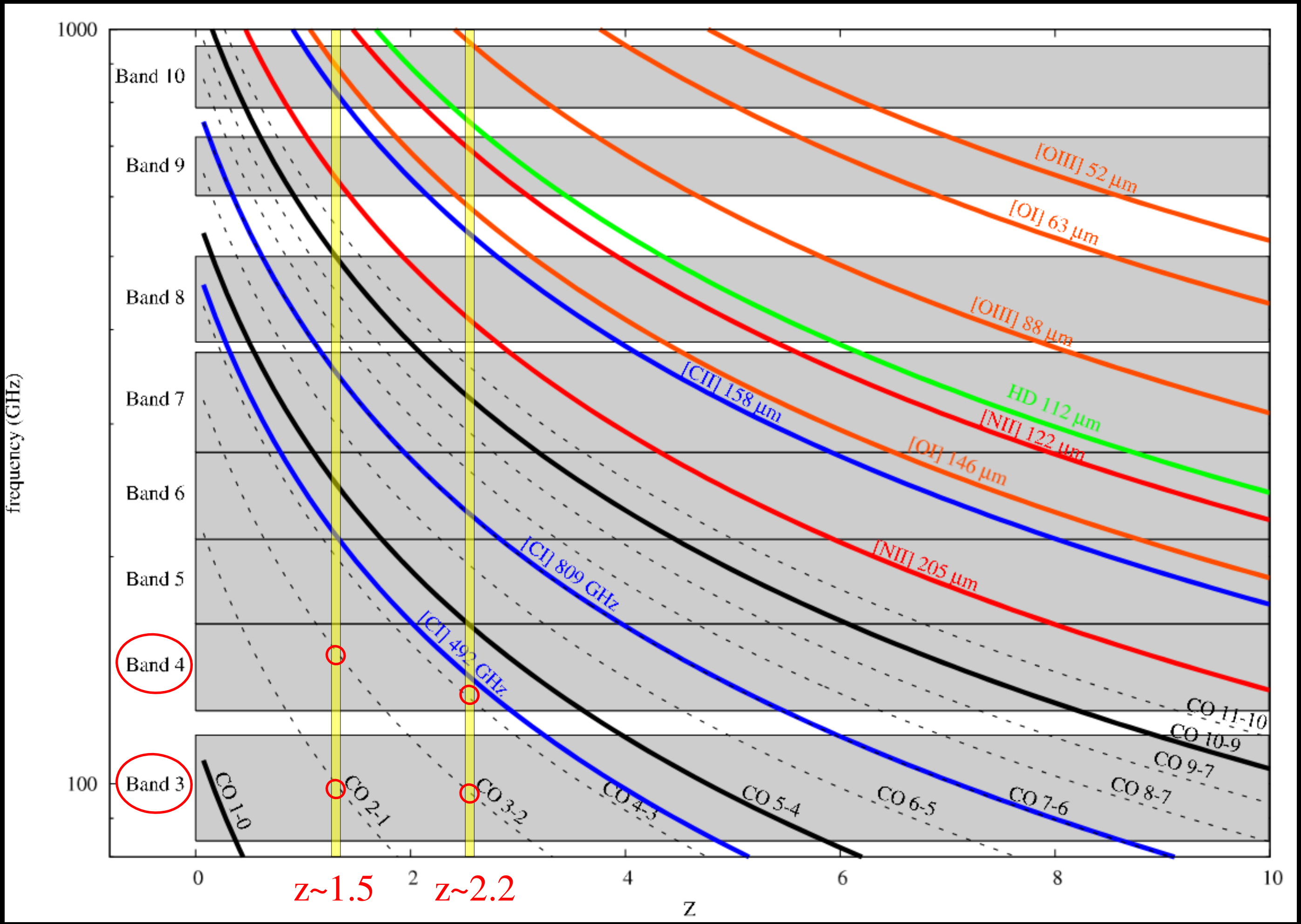
Cold gas tracers at high z with ALMA



High-resolution studies of individual galaxies

De Ugarte Postigo+(2012, A&A)

Cold gas tracers at high z with ALMA



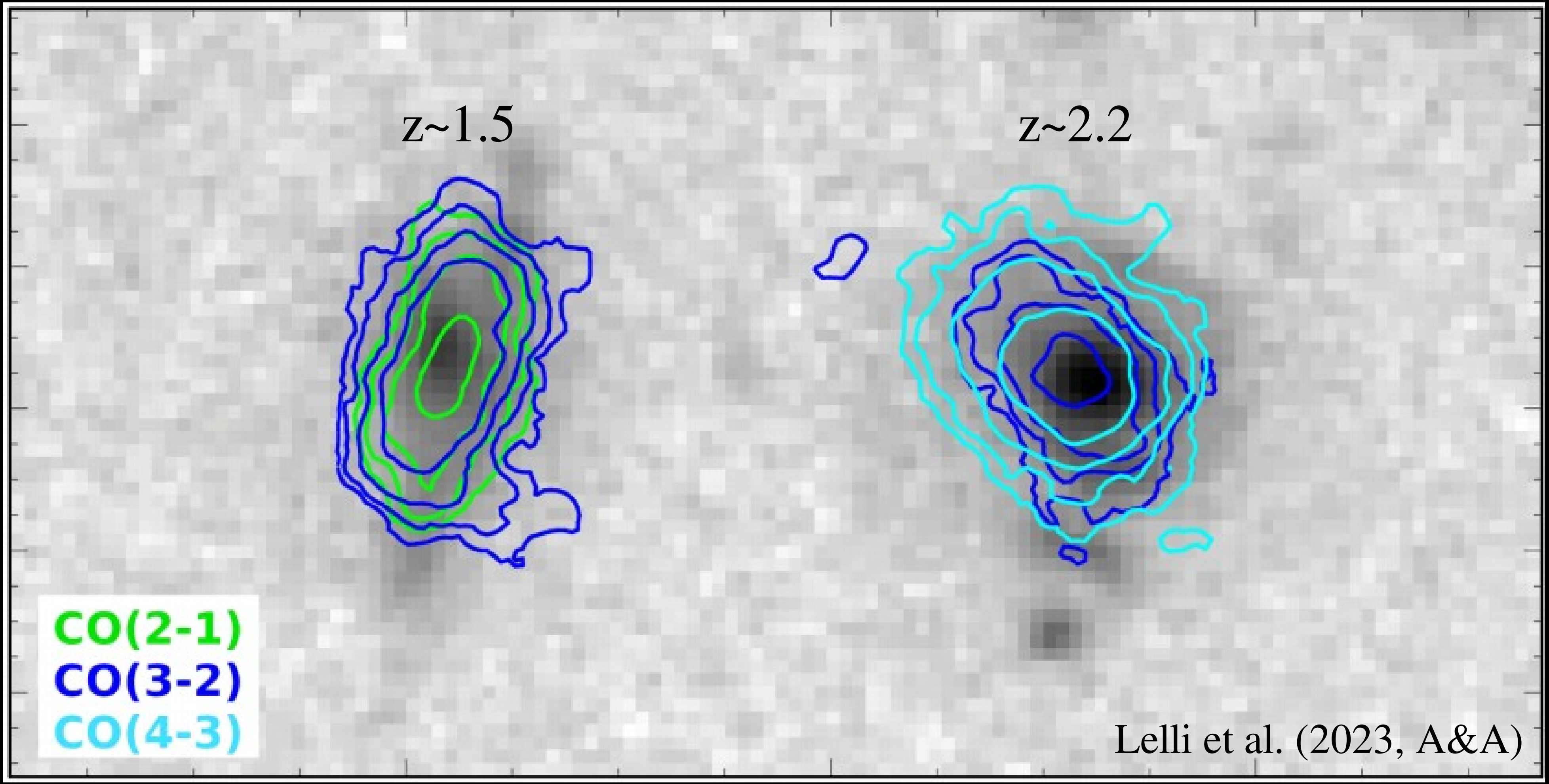
High-resolution studies of individual galaxies

Two main-sequence galaxies

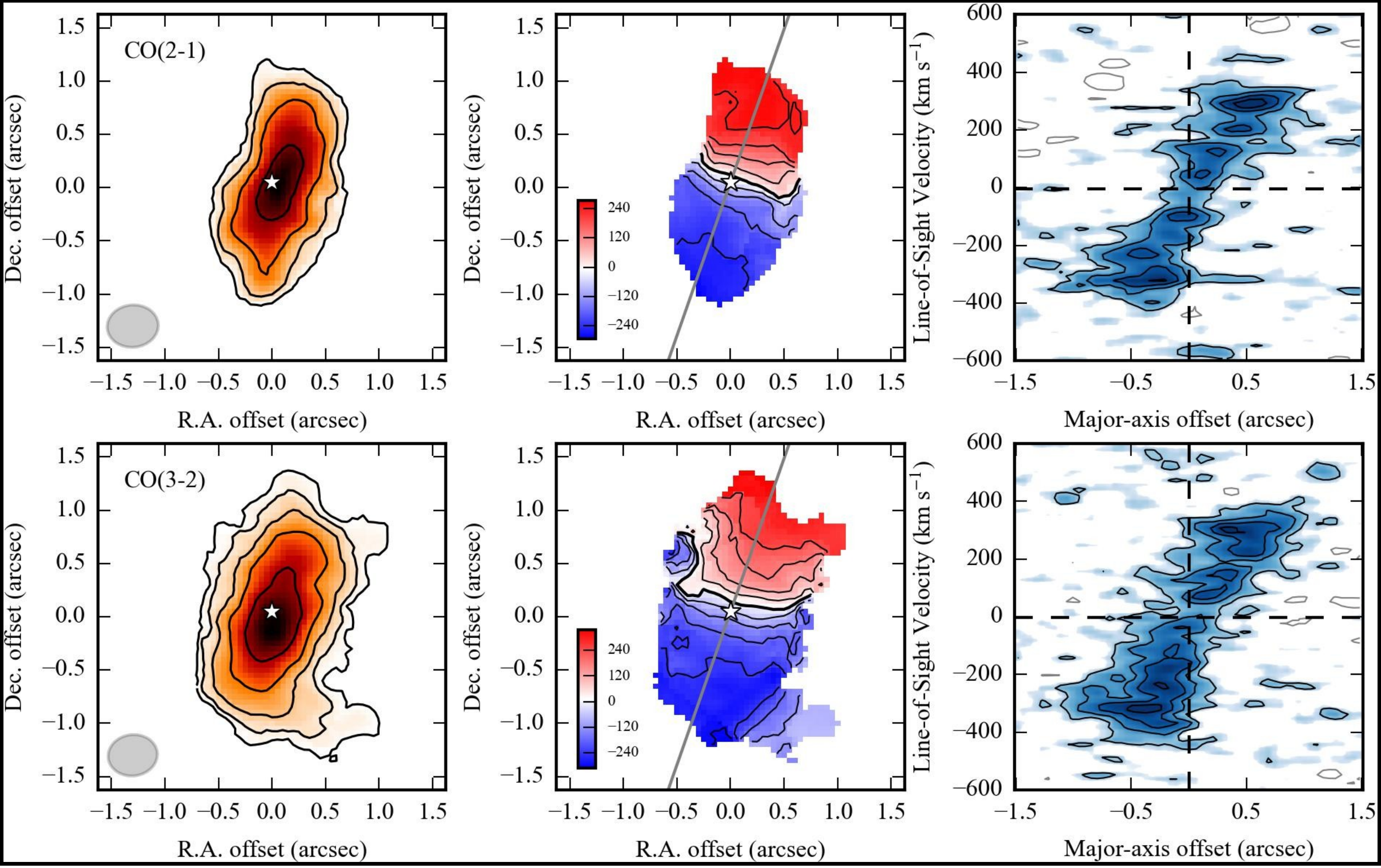
- z~1.5: CO(2-1), CO(3-2)
- z~2.2: CO(3-2), CO(4-3)

(Lelli+ 2023, A&A)

Two main-sequence galaxies at cosmic noon

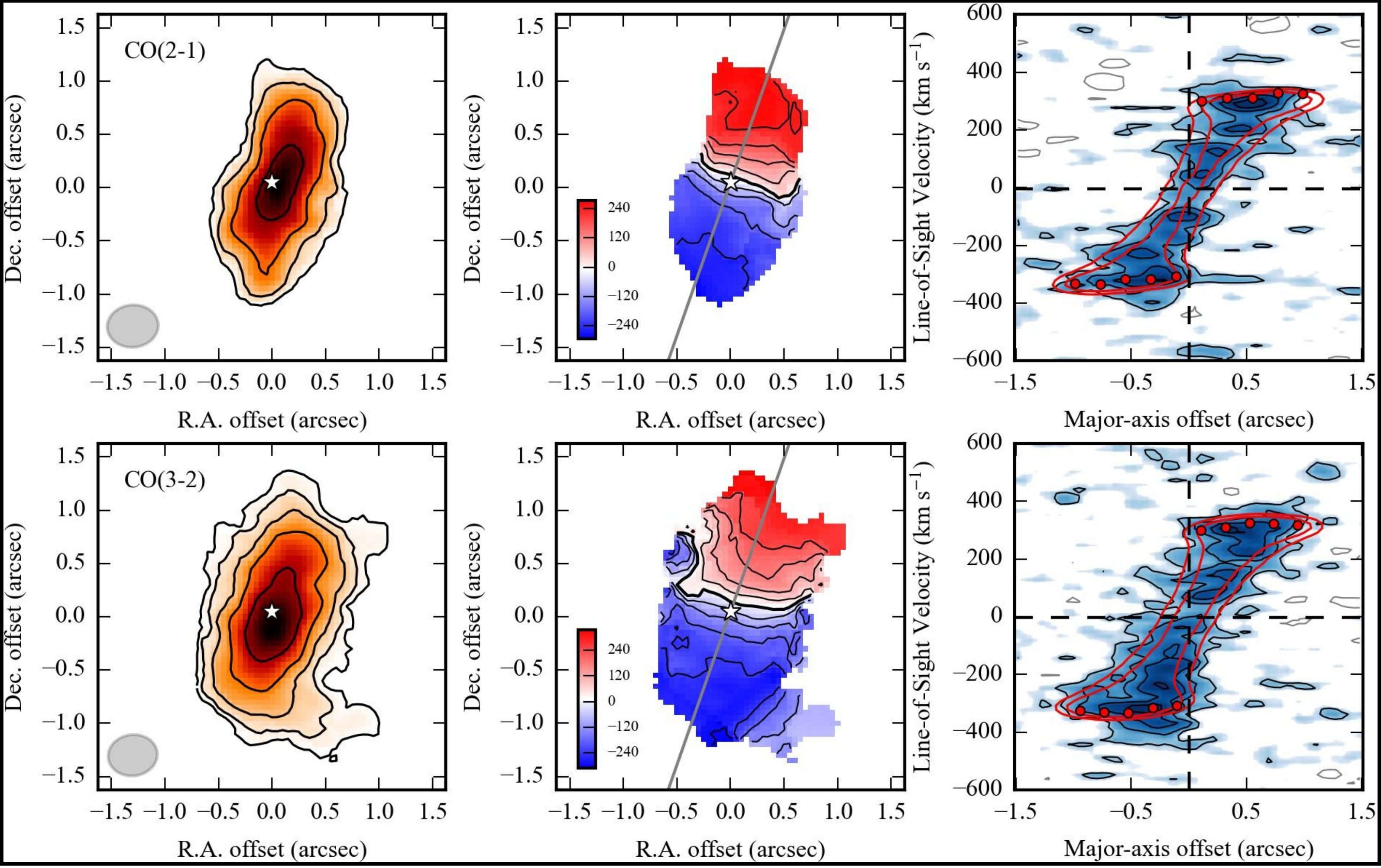


Star-Forming Main-Sequence Galaxy at z~1.5



Lelli+(2023, A&A)

Star-Forming Main-Sequence Galaxy at z~1.5



Fit the datacube with ^{3D}Barolo (Di Teodoro+15):

V_{rot} ~ 340 km/s

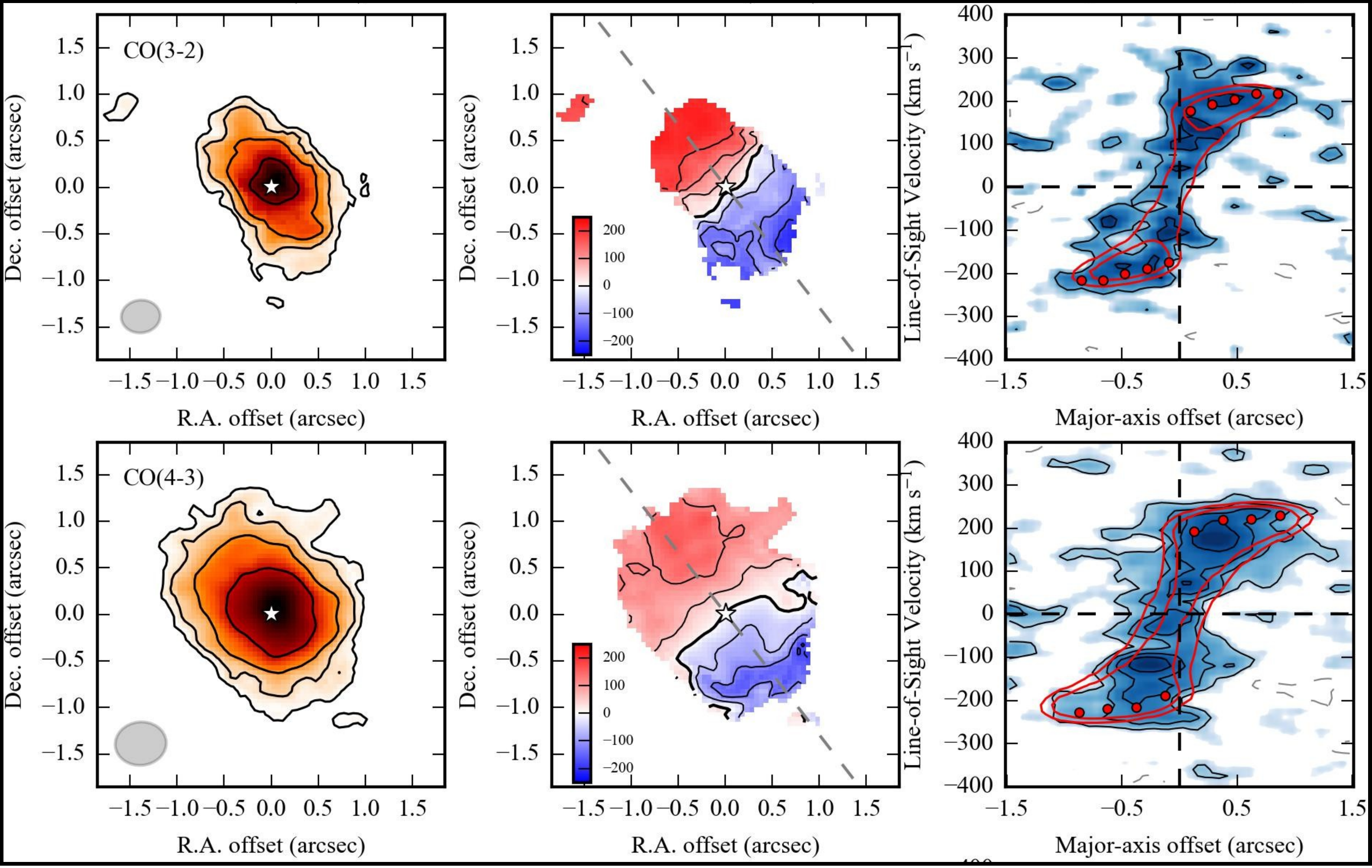
σ_{CO} < 15 km/s

V_{rot}/σ_{CO} > 22

(as local disks)

Lelli+(2023, A&A)

Star-Forming Main-Sequence Galaxy at z~2.2



Fit the datacube with [3D]Barolo (Di Teodoro+15):

V_{rot} ~ 254 km/s

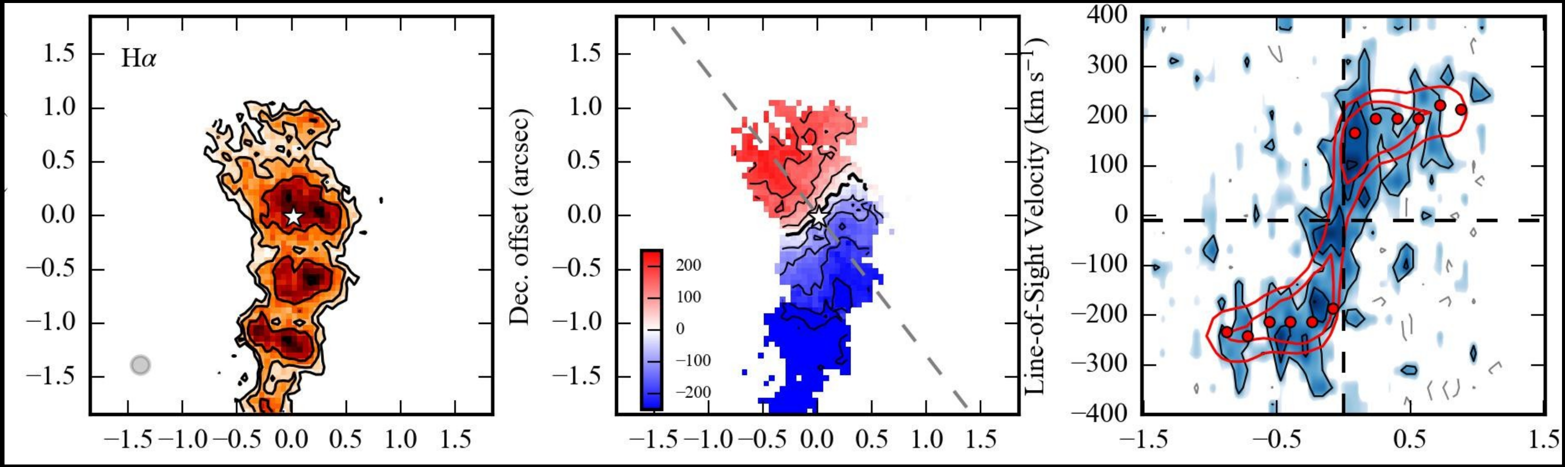
σ_{CO} < 15 km/s

V_{rot}/σ_{CO} > 17

(as local disks)

Lelli+(2023, A&A)

Star-Forming Main-Sequence Galaxy at z~2.2



Fit the datacube with [3D]Barolo (Di Teodoro+15):

V_{rot} ~ 254 km/s

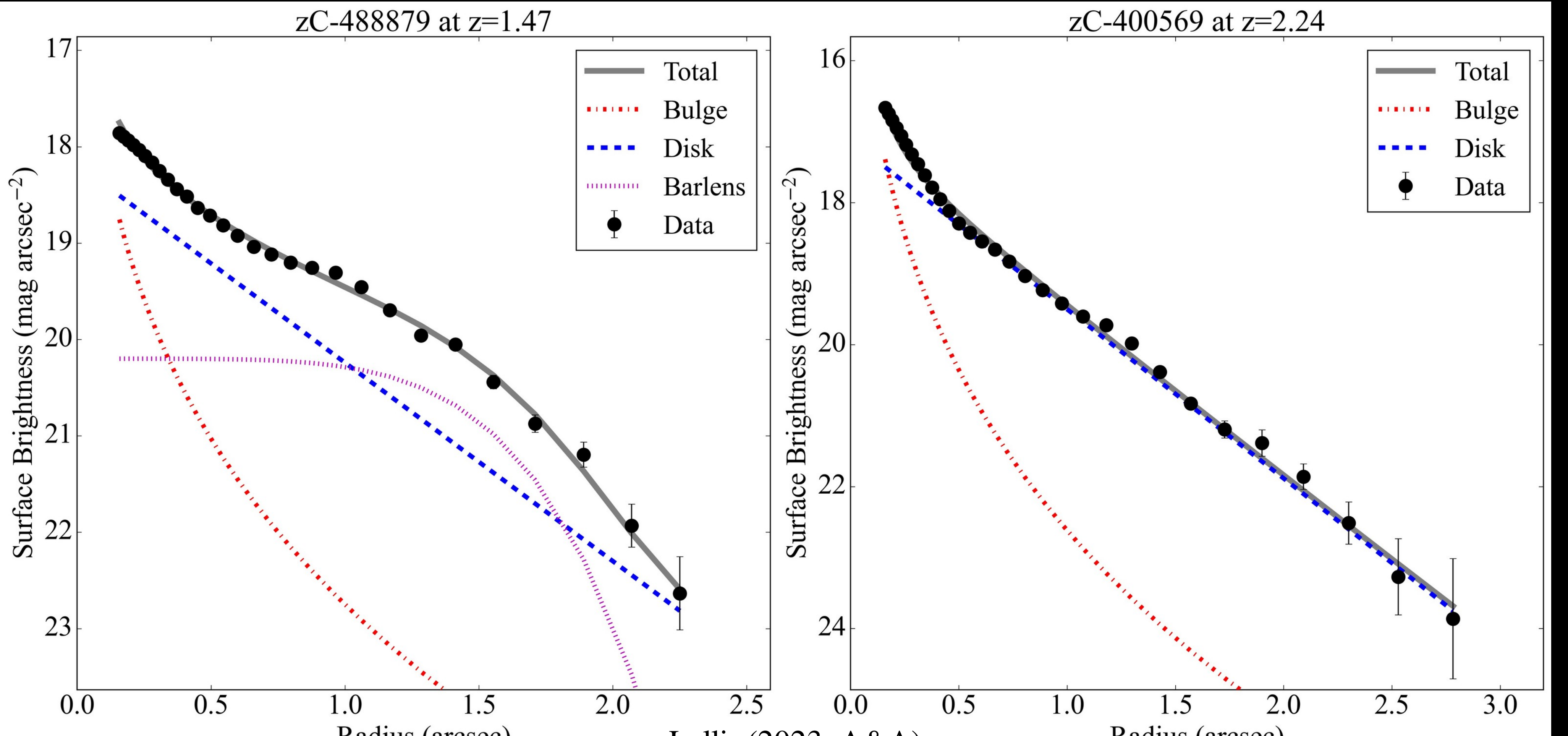
$\sigma_{H\alpha}$ < 37 km/s

$V_{rot}/\sigma_{H\alpha}$ > 7

(as local disks)

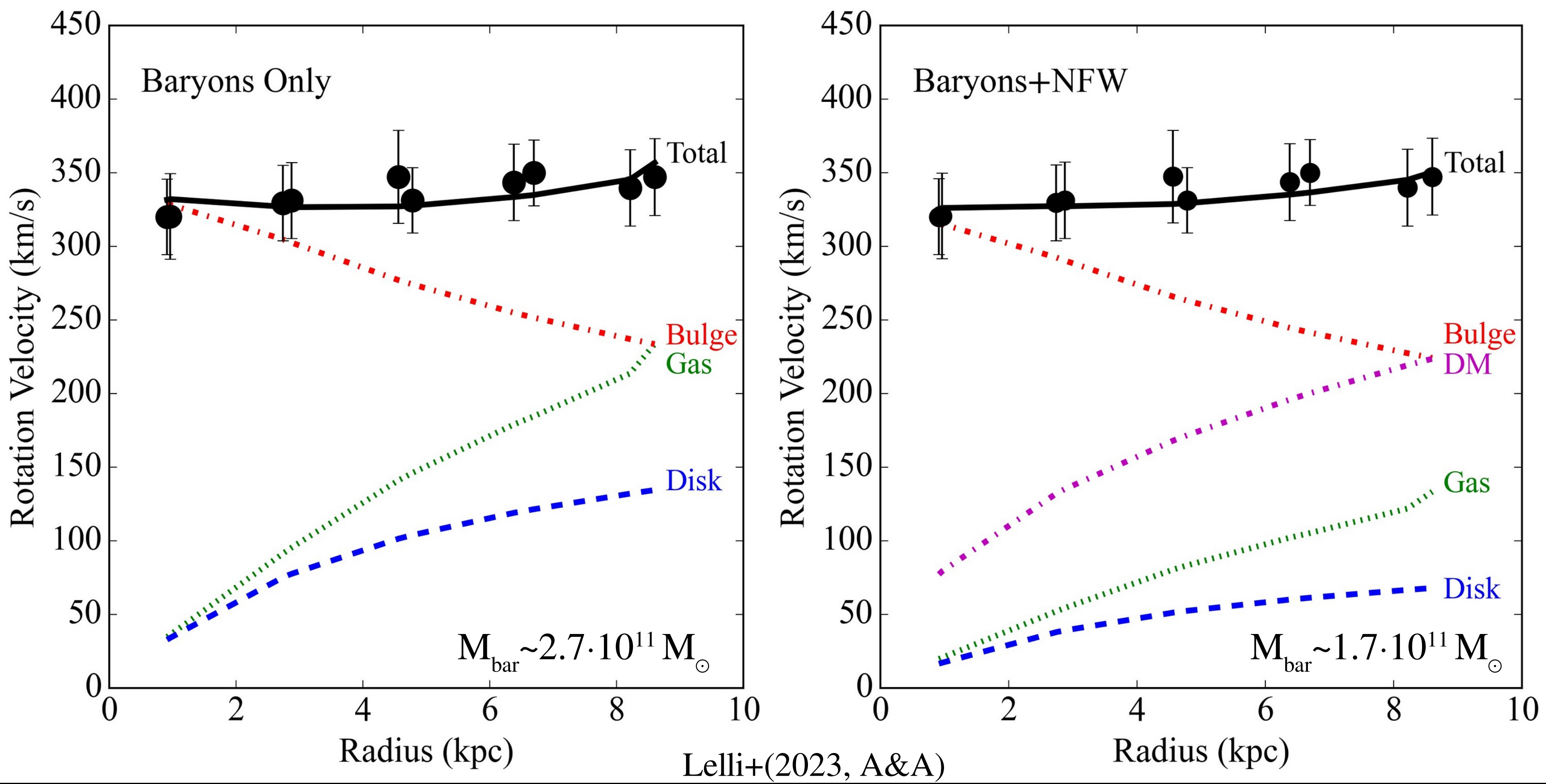
Lelli+(2023, A&A)

Surface brightness profiles from HST photometry



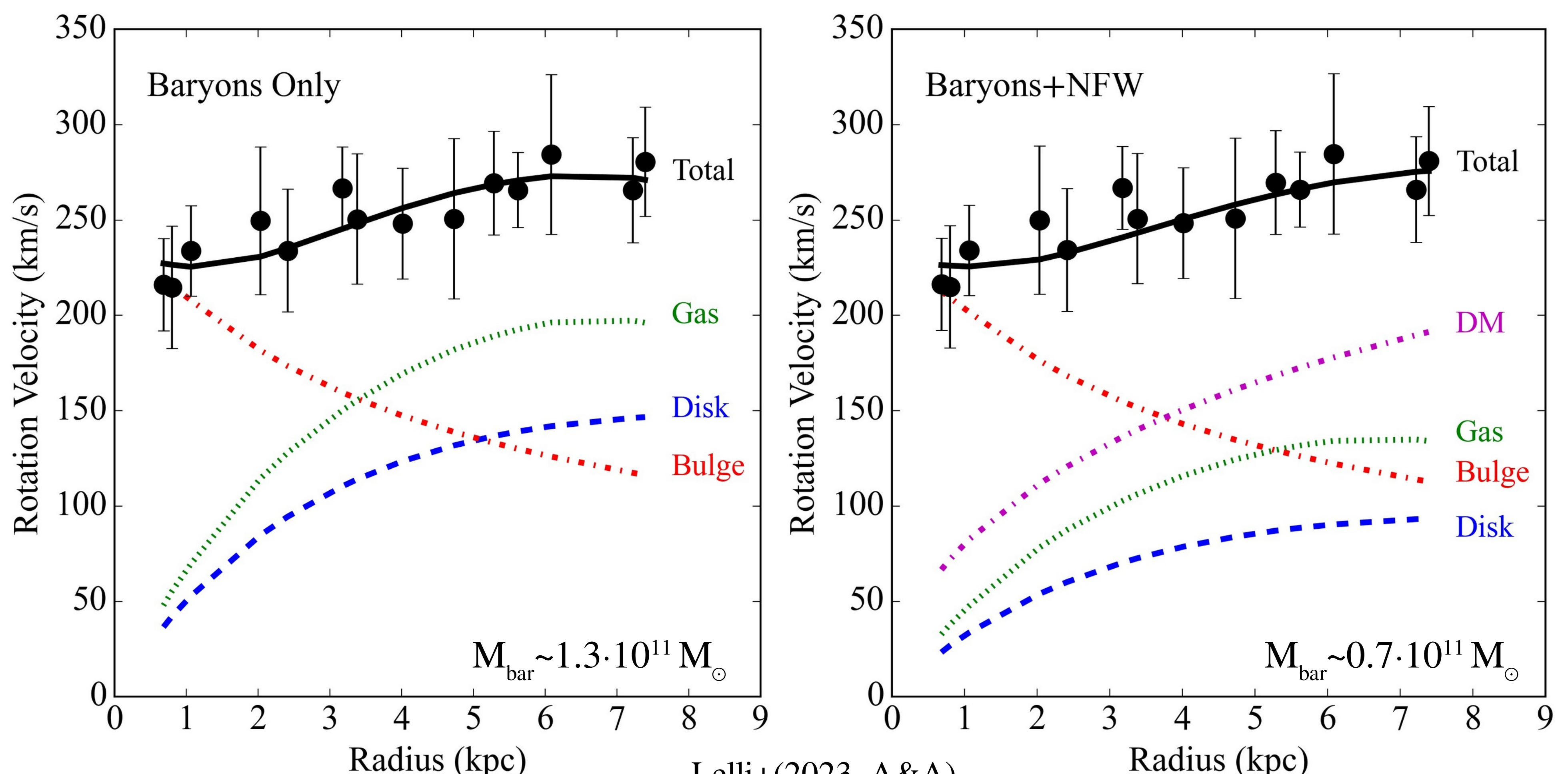
Lelli+(2023, A&A)

Mass Models: Disk-Halo Degeneracy at z~1.5



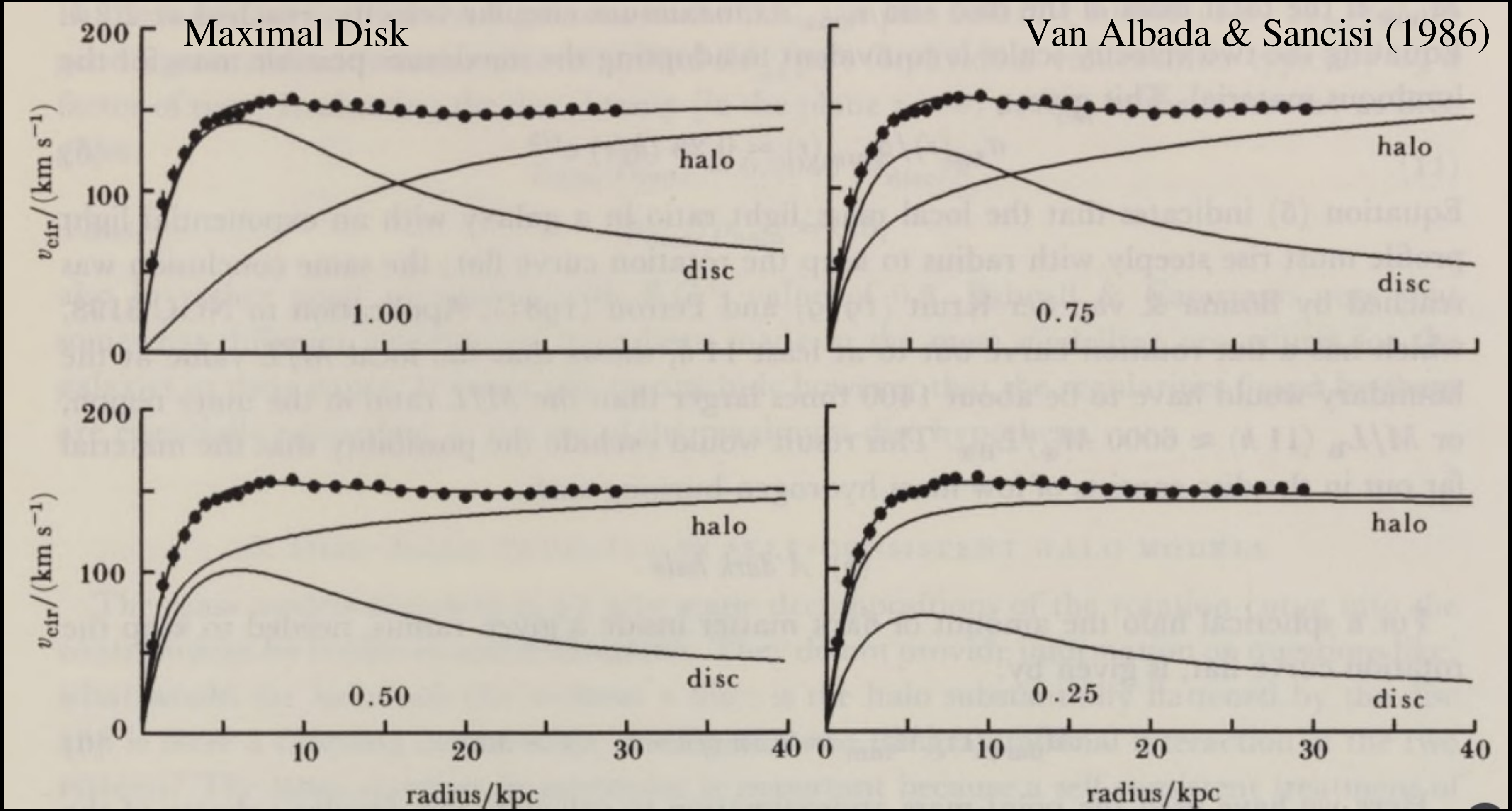
Lelli+(2023, A&A)

Mass Models: Disk-Halo Degeneracy at z~2.2



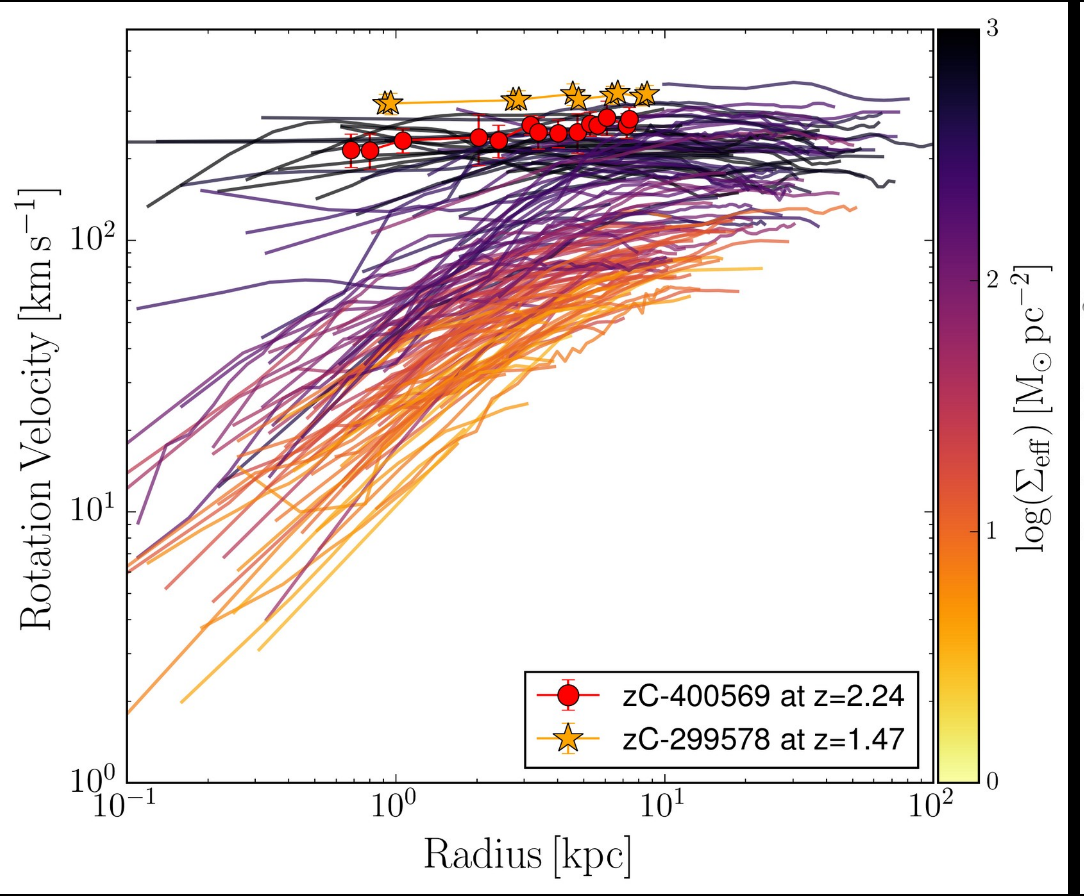
Lelli+(2023, A&A)

Disk-halo degeneracy: Long-standing issue at z=0

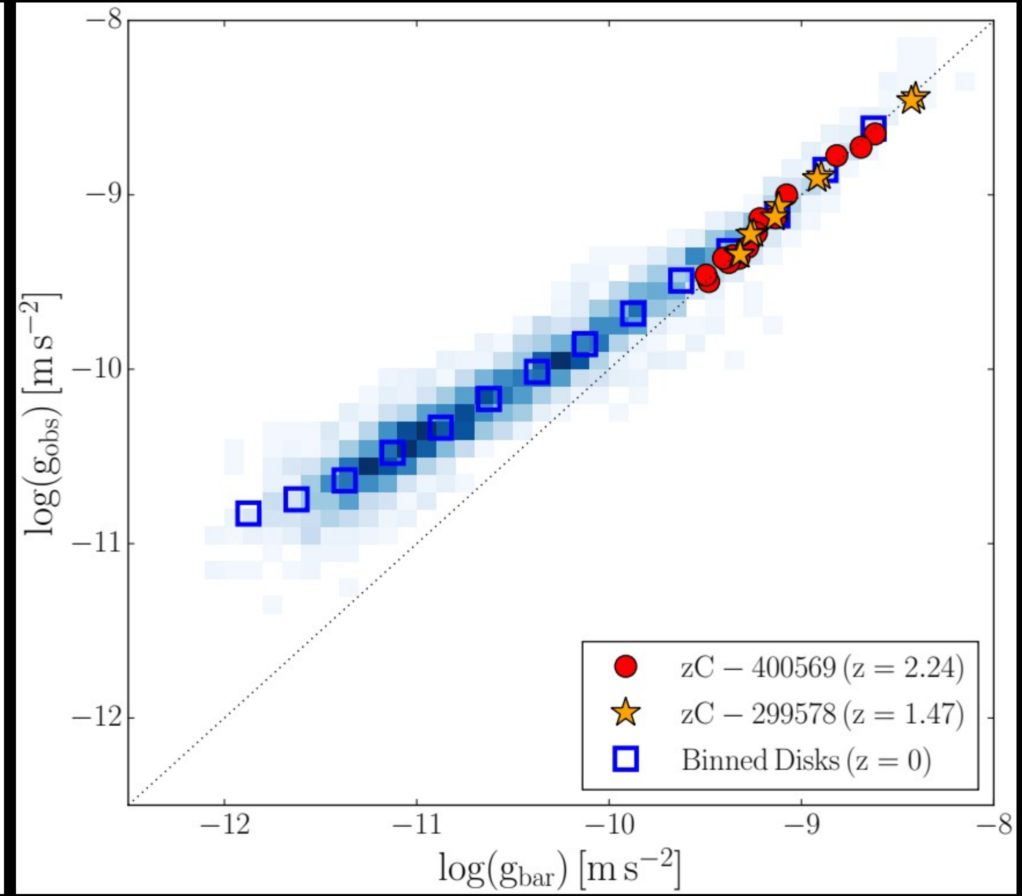


Progenitors of Massive Spirals at z=0?

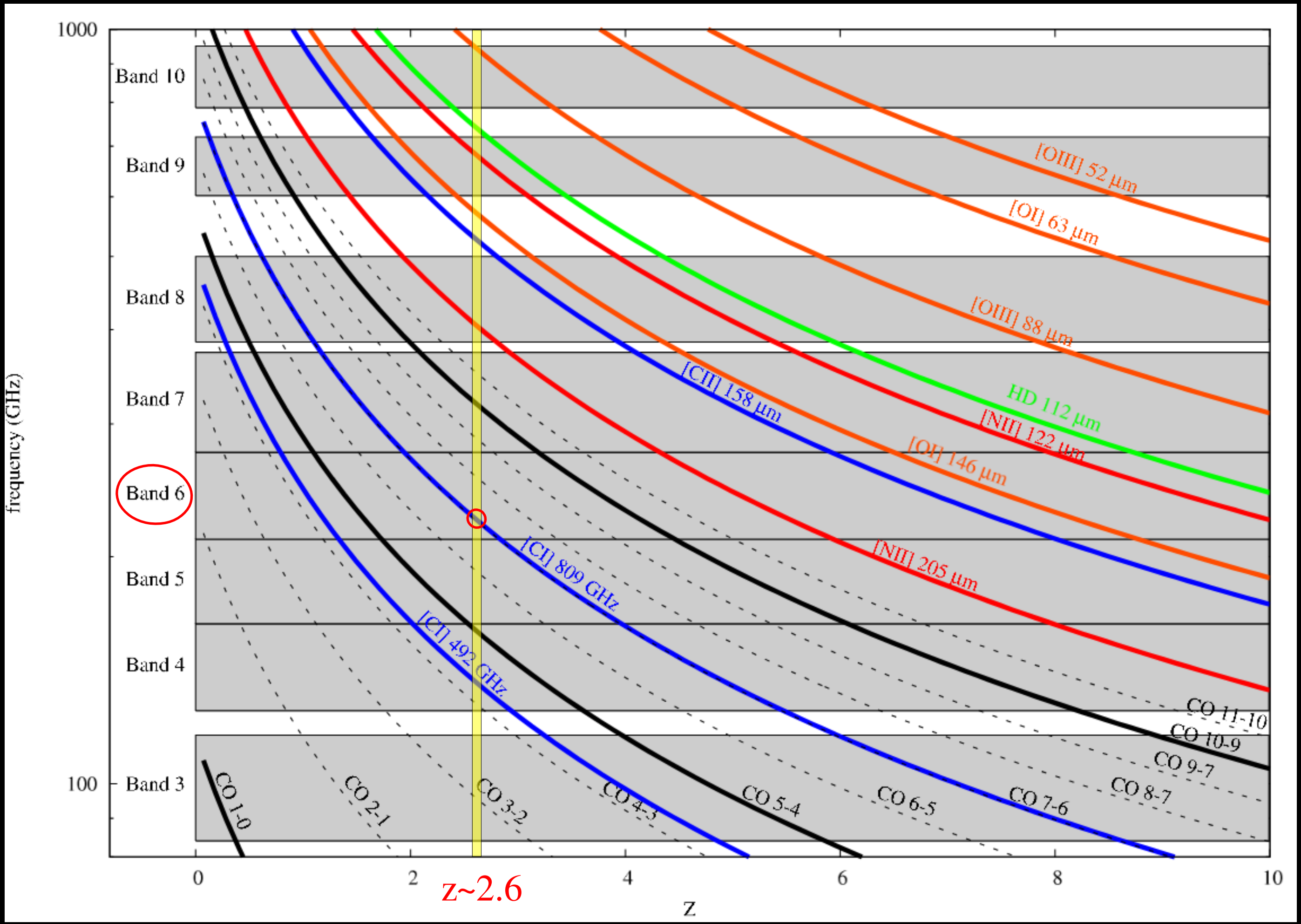
Rotation Curve Shapes



Radial Acceleration Relation



Cold gas tracers at high z with ALMA



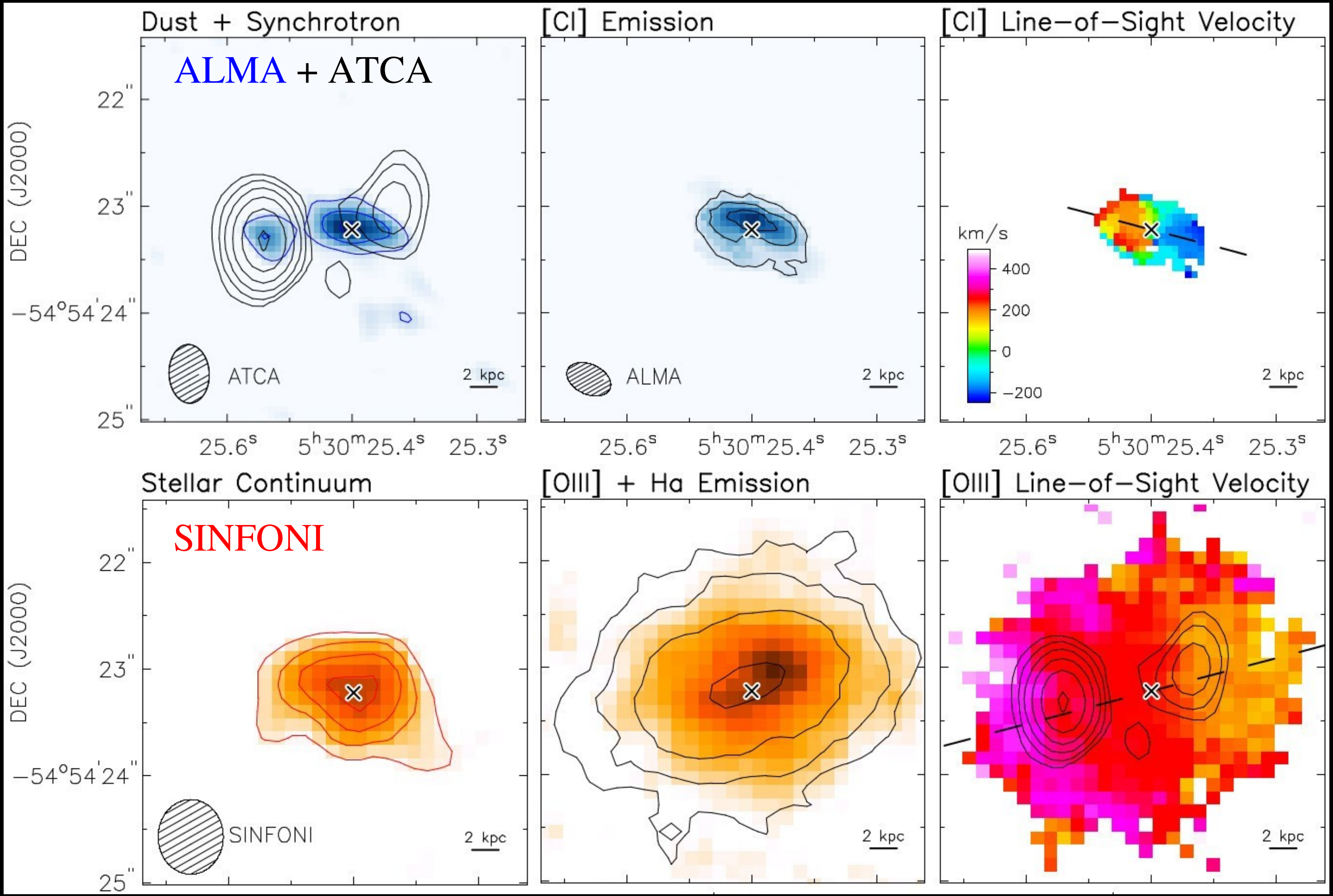
High-resolution studies of individual galaxies

Starburst galaxy at z~2.6

- AGN with radio lobes
- Bright in [CI](2-1) line

(Lelli+ 2018, MNRAS)

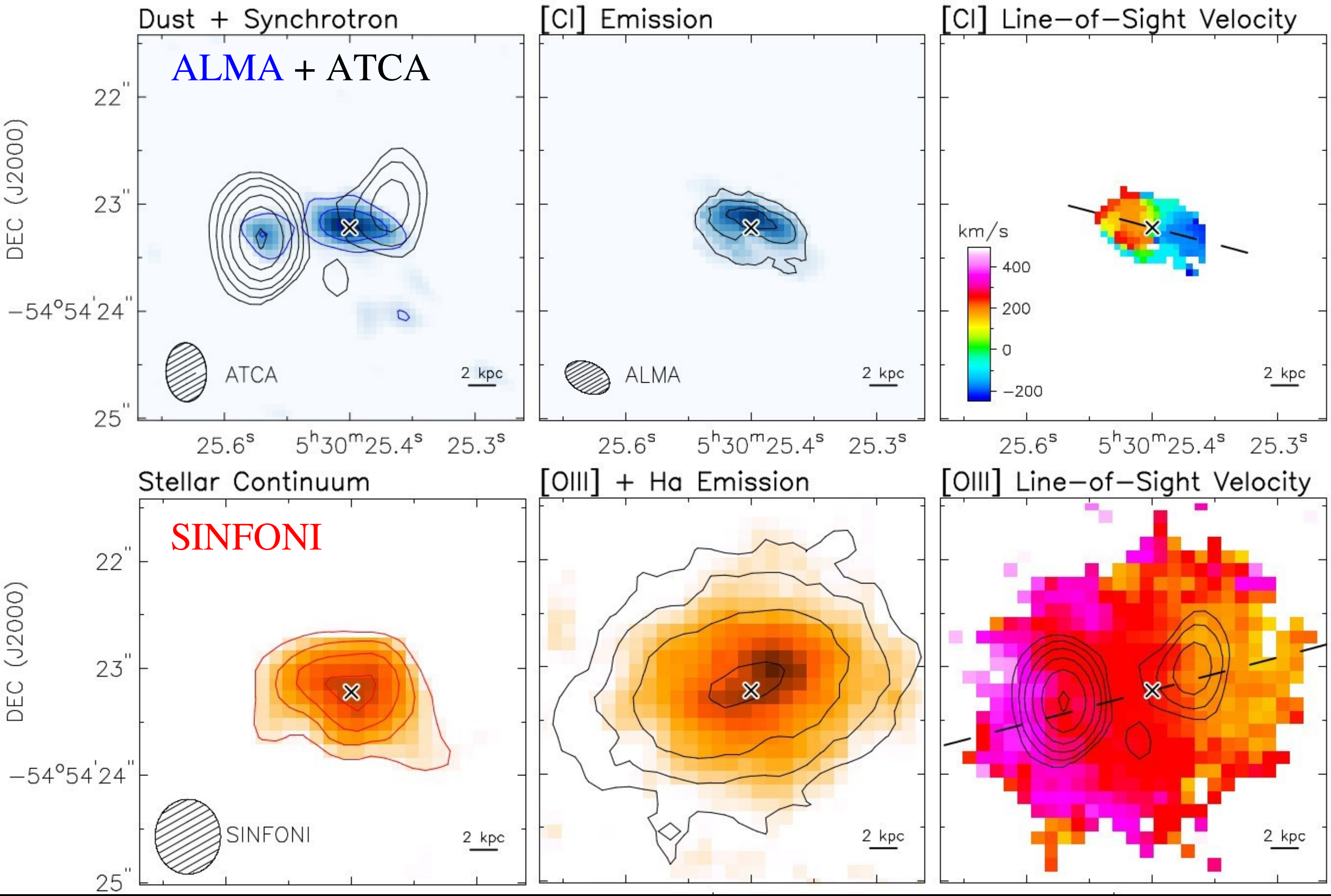
AGN-host Starburst Galaxy at z~2.6



[CI](2-1) line
→ rotating disk

Lelli+2018, MNRAS

AGN-host Starburst Galaxy at z~2.6

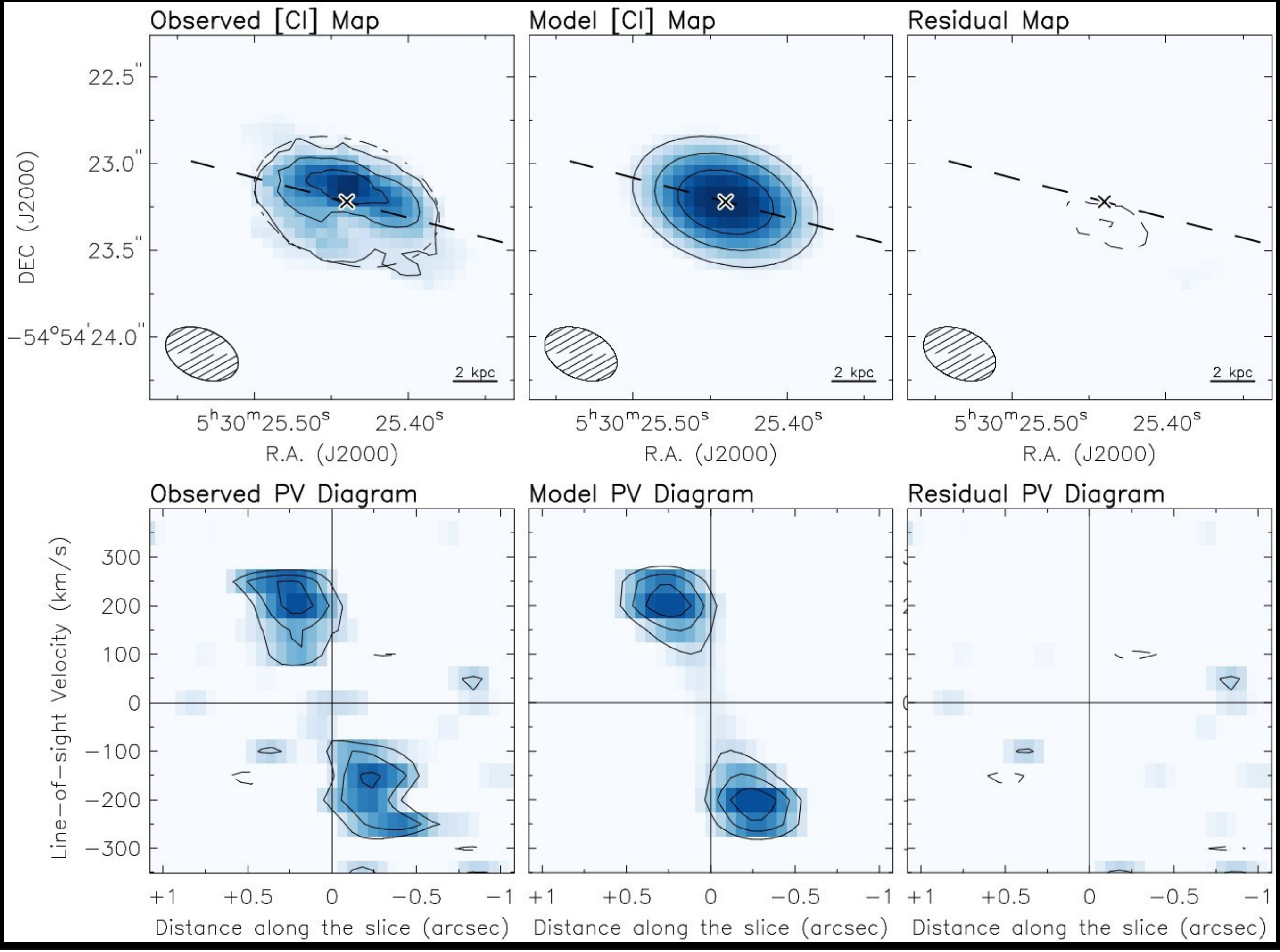


[CI](2-1) line
→ rotating disk

Hα & [OIII]λ5007
→ extended outflow
(aligned with radio jets)

Lelli+2018, MNRAS

Dynamically Cold Rotating Disk



3D disk model:

V_{rot} ~ 310 km/s

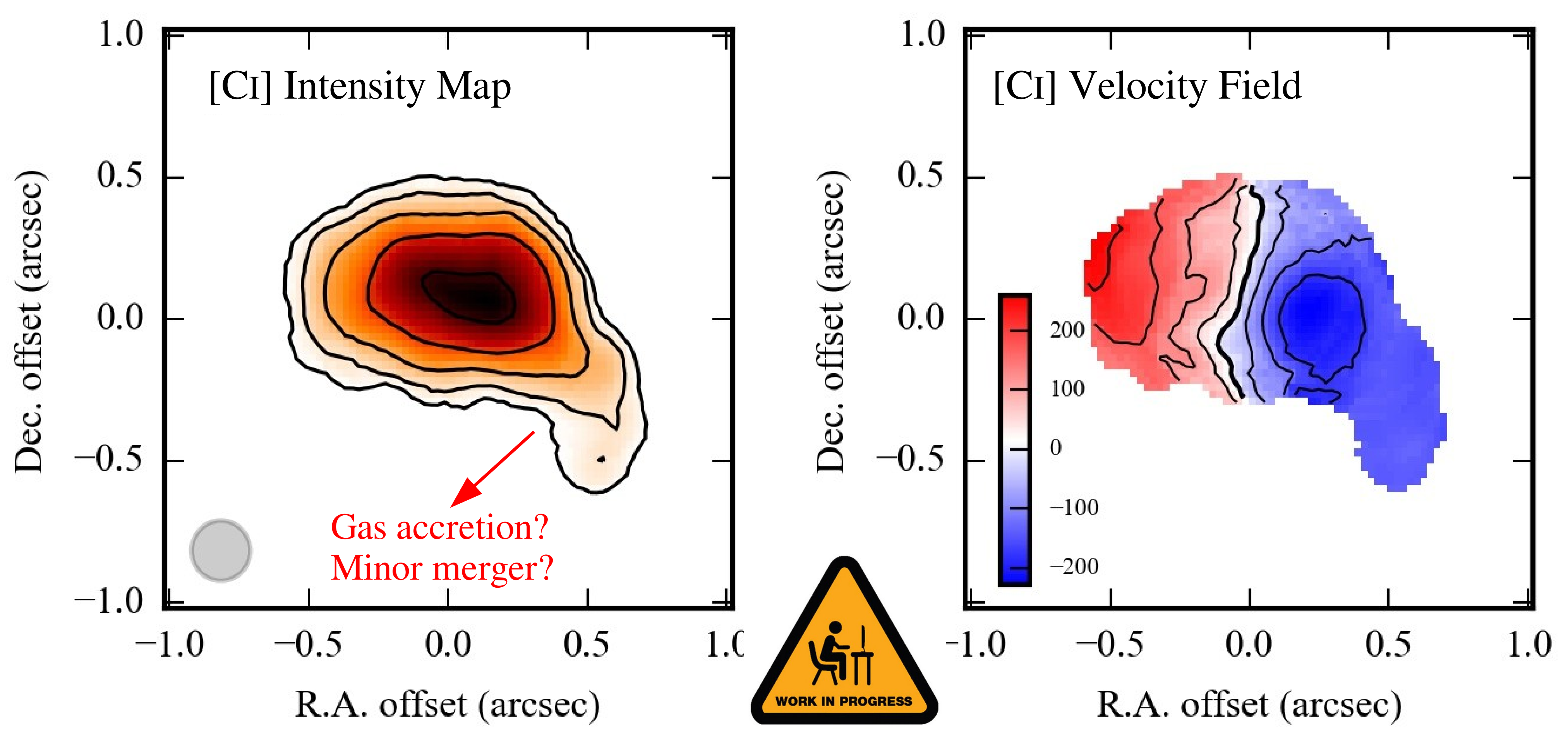
σ_{CO} < 30 km/s

$V_{rot}/\sigma_{[CI]}$ > 10

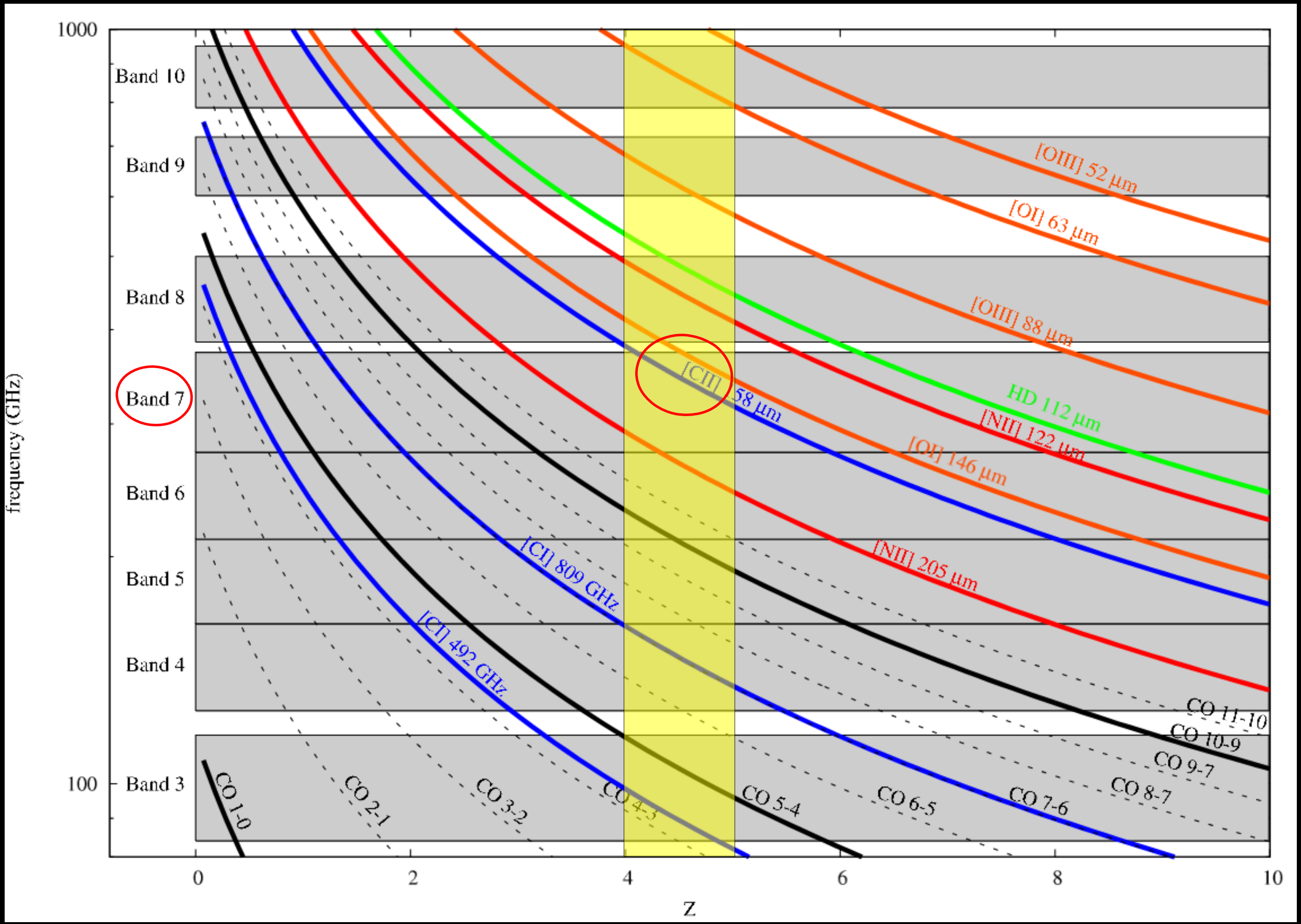
(as local disks)

Lelli+2018, MNRAS

New [CI](2-1) observations at 0.2'' resolution



Cold gas tracers at high z with ALMA



High-resolution studies of galaxies at z≃4-5

[CII] line at 158 μm:

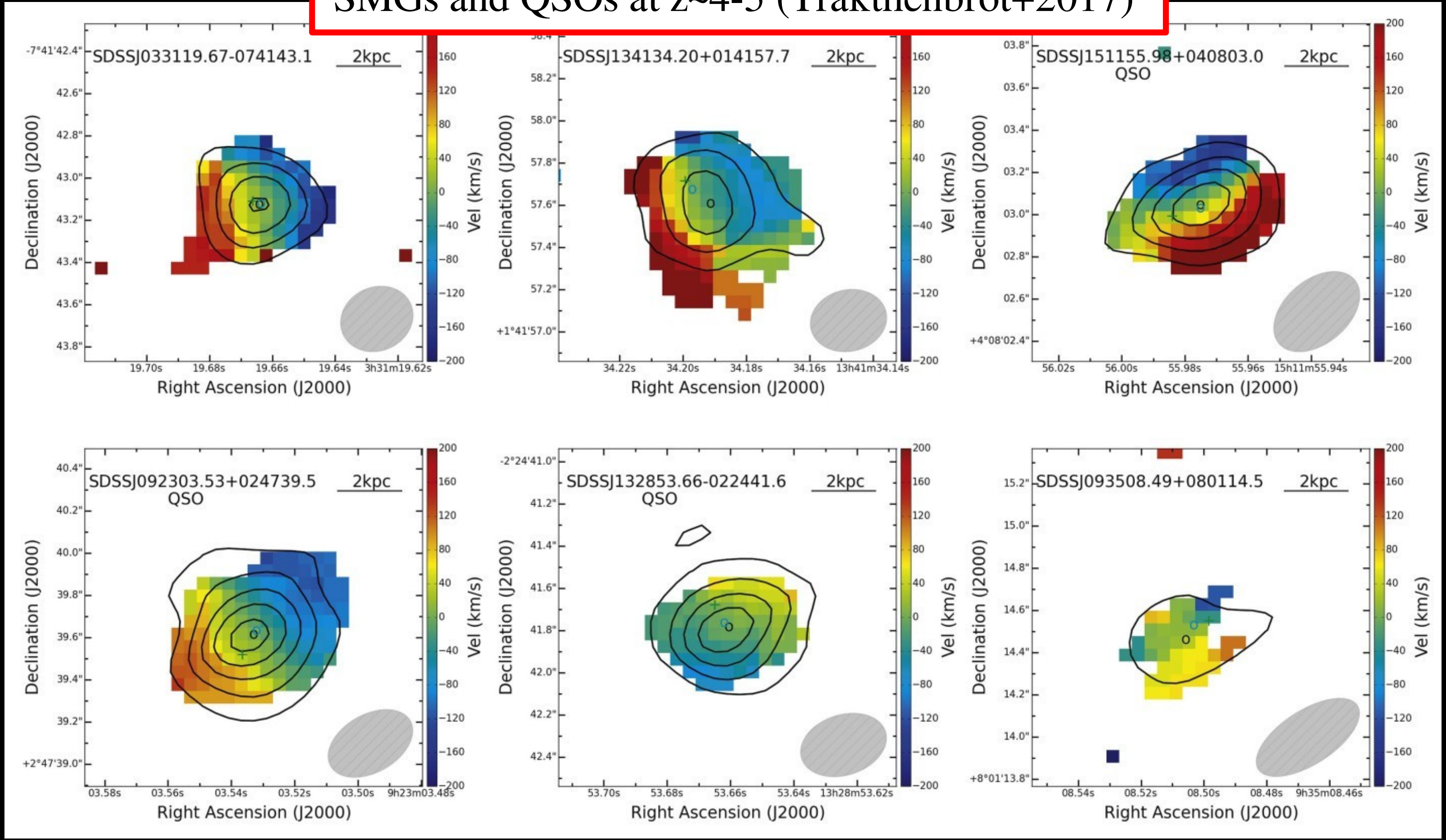
→ main coolant of the ISM

→ ion. potential ~11.26 eV

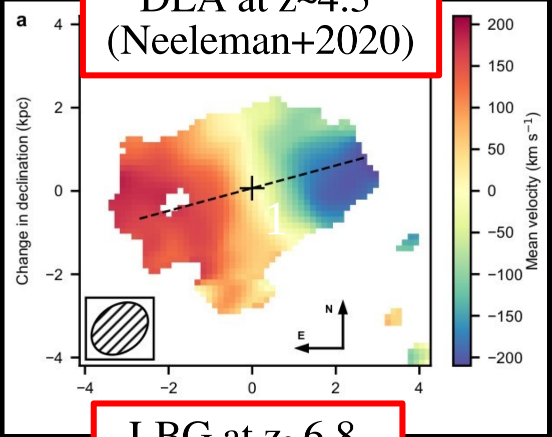
→ multiphase gas: atomic, molecular and ionized

Rotating [CII] disks at z>4?

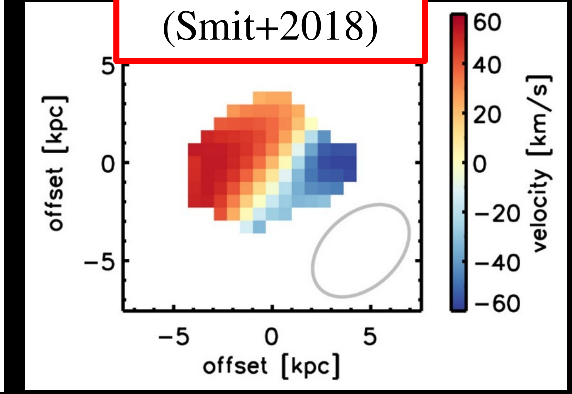
SMGs and QSOs at z~4-5 (Trakthenbrot+2017)



DLA at z~4.3 (Neeleman+2020)



LBG at z~6.8 (Smit+2018)



[CII] ref: De Breuck+2014; Venemans+2016, 2019; Jones+2017, 2021; Willot+2015, 2017; Pavesi+2018; DeCarli+2018; Tadaki+2019, 2020; Leung+2019; Banados+2019; LeFevre+2019; Pensabene+2020; Rizzo+2020, 2021; Fraternali+2021.

TRICEPS

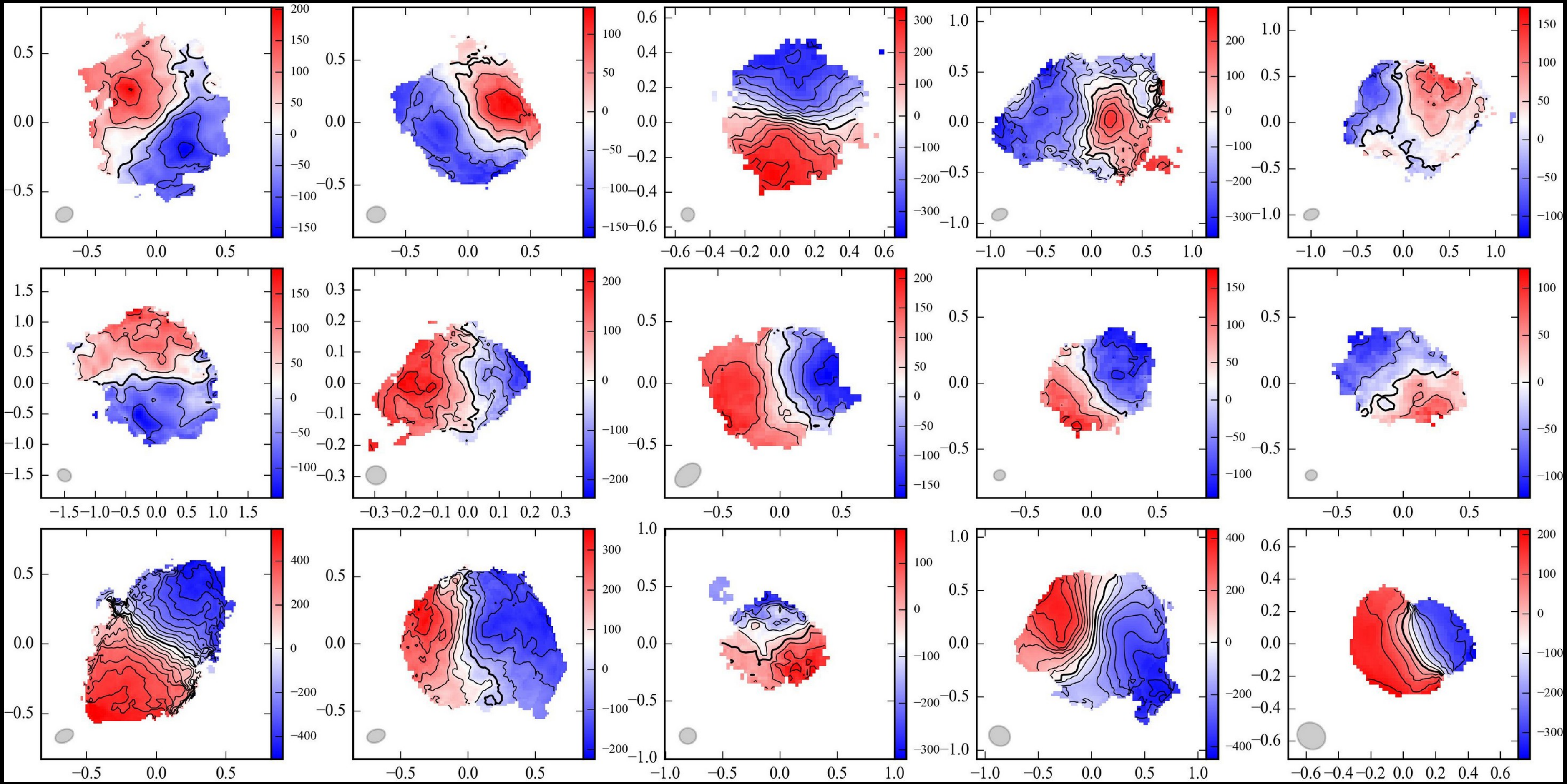
Tracing Rotation with Ionized Carbon in Early Primeval Systems

- 16 galaxies at z=4-5 with [CII] flux > 2 Jy km/s
- Follow-up observations at 0.05” – 0.20” → 0.5-1.0 kpc
- Originally identified as SMGs, QSOs, LBGs, even a DLA

→ high mass ($M_\star \simeq 10^{10}$-10^{11} $M_\odot$) & high SFR (~10^2-10^3 $M_\odot$/yr)

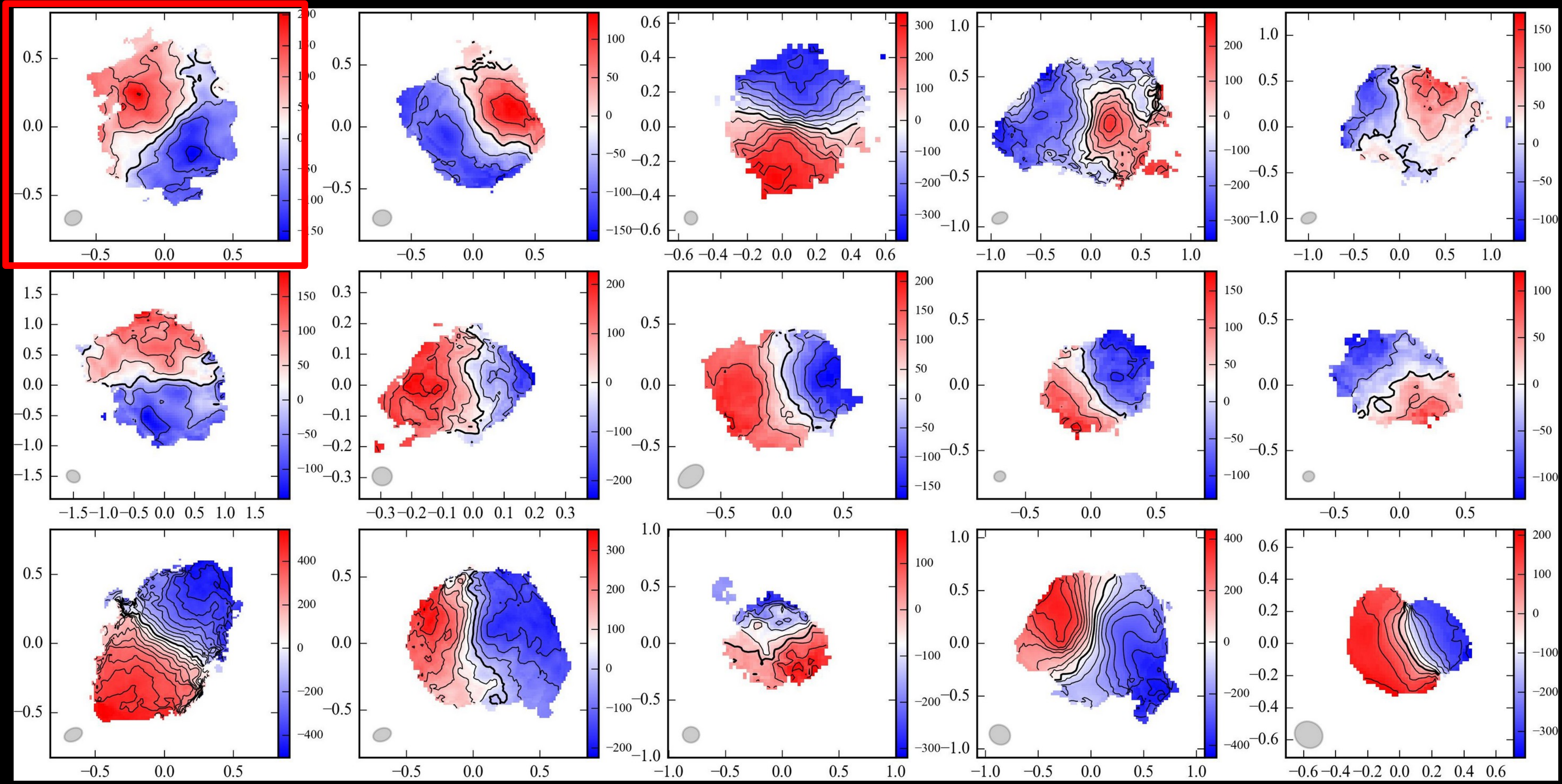
- Data analysis in progress (Lelli+ in prep.)

TRICEPS: Ubiquitous regular rotation at z=4-5



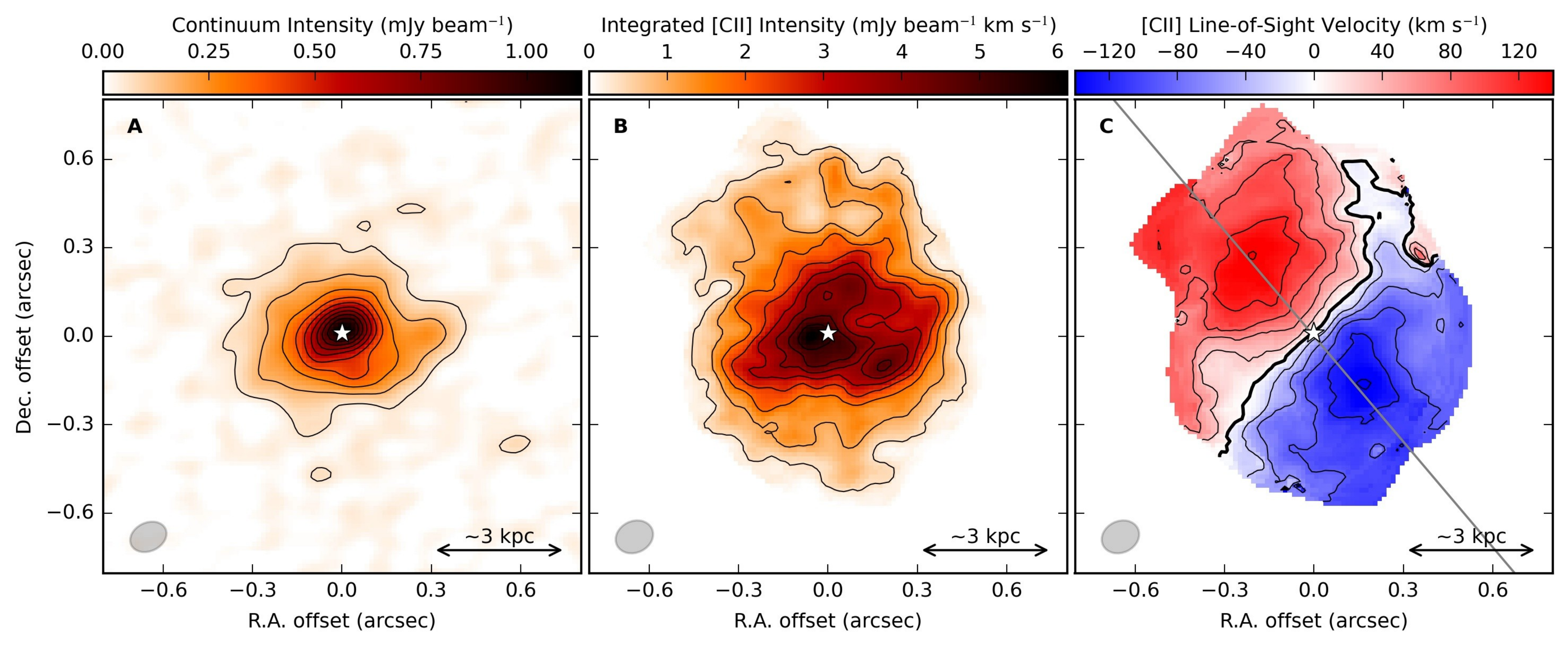
See also: De Breuck+14; Jones+17, 21; Tadaki+19, 20; LeFevre+2019; Neeleman+20; Rizzo+20, 21; Lelli+21; Fraternali+21

TRICEPS: Ubiquitous regular rotation at z=4-5



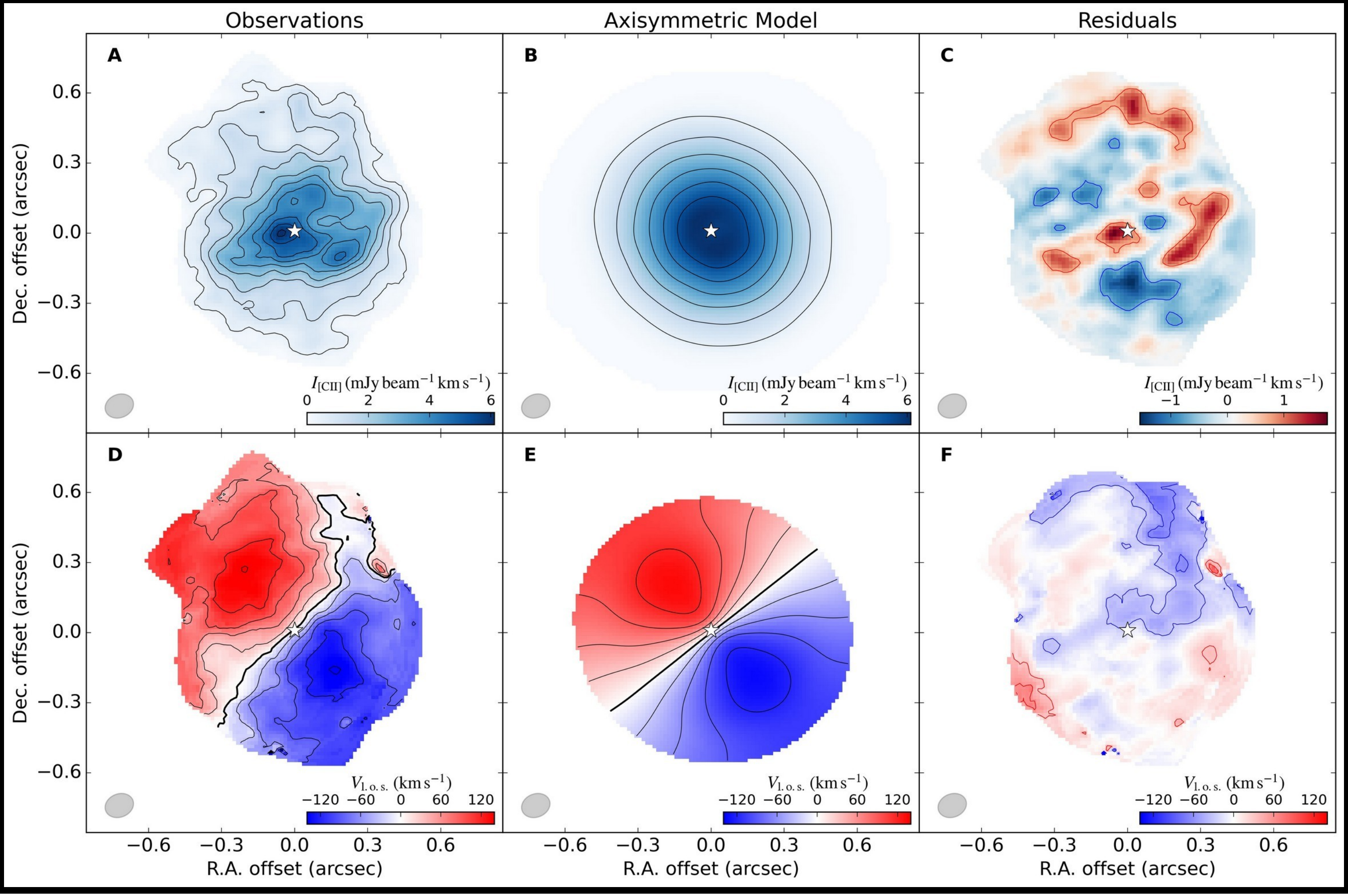
See also: De Breuck+14; Jones+17, 21; Tadaki+19, 20; LeFevre+2019; Neeleman+20; Rizzo+20, 21; Lelli+21; Fraternali+21

Galaxy ISM at z≃4.8 at 700 pc resolution!



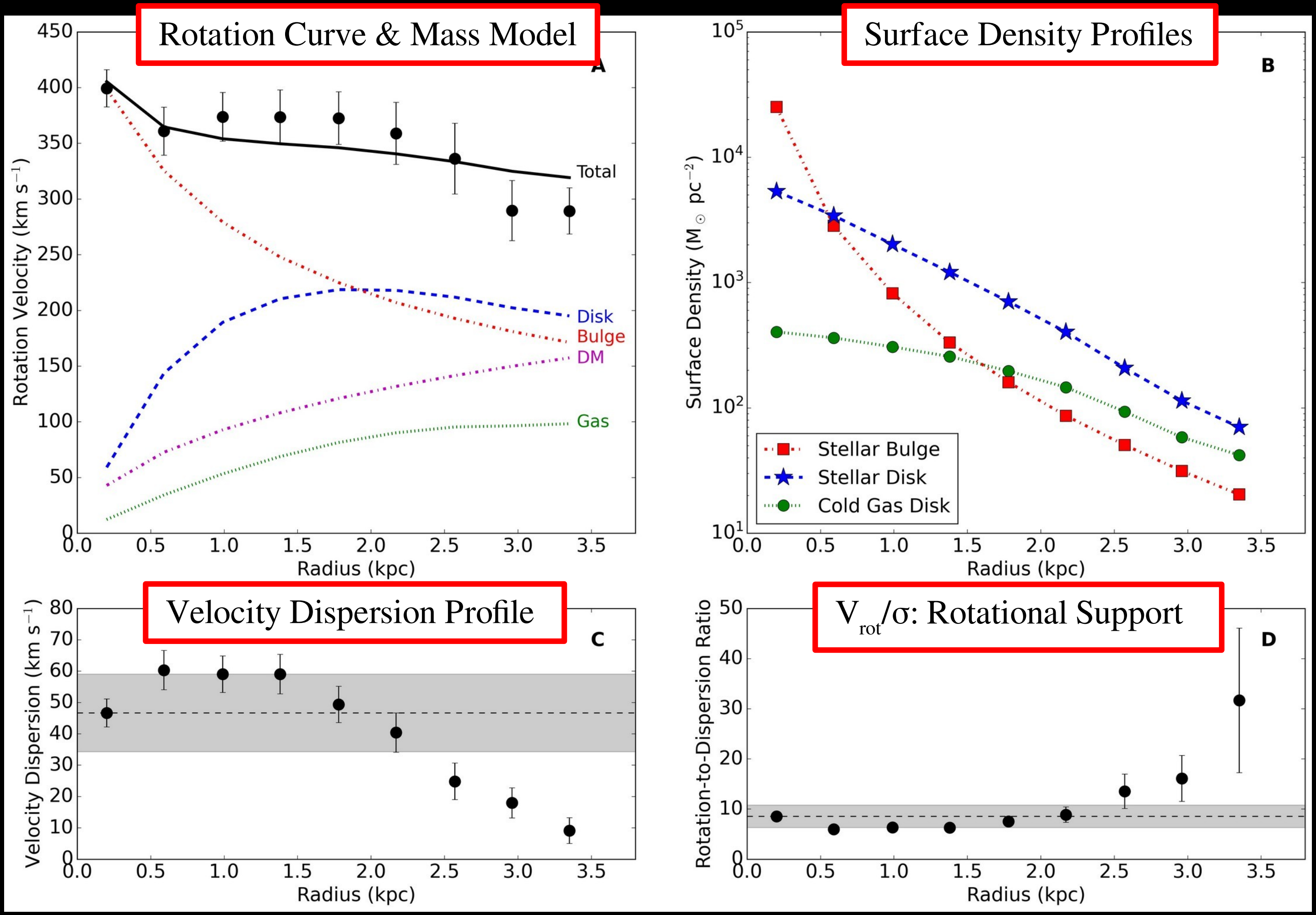
Galaxies do NOT explode even if they have SFR≃1000 $M_\odot$/yr (Lelli+2021, Science)

Weak Non-Circular Motions at z~4.8



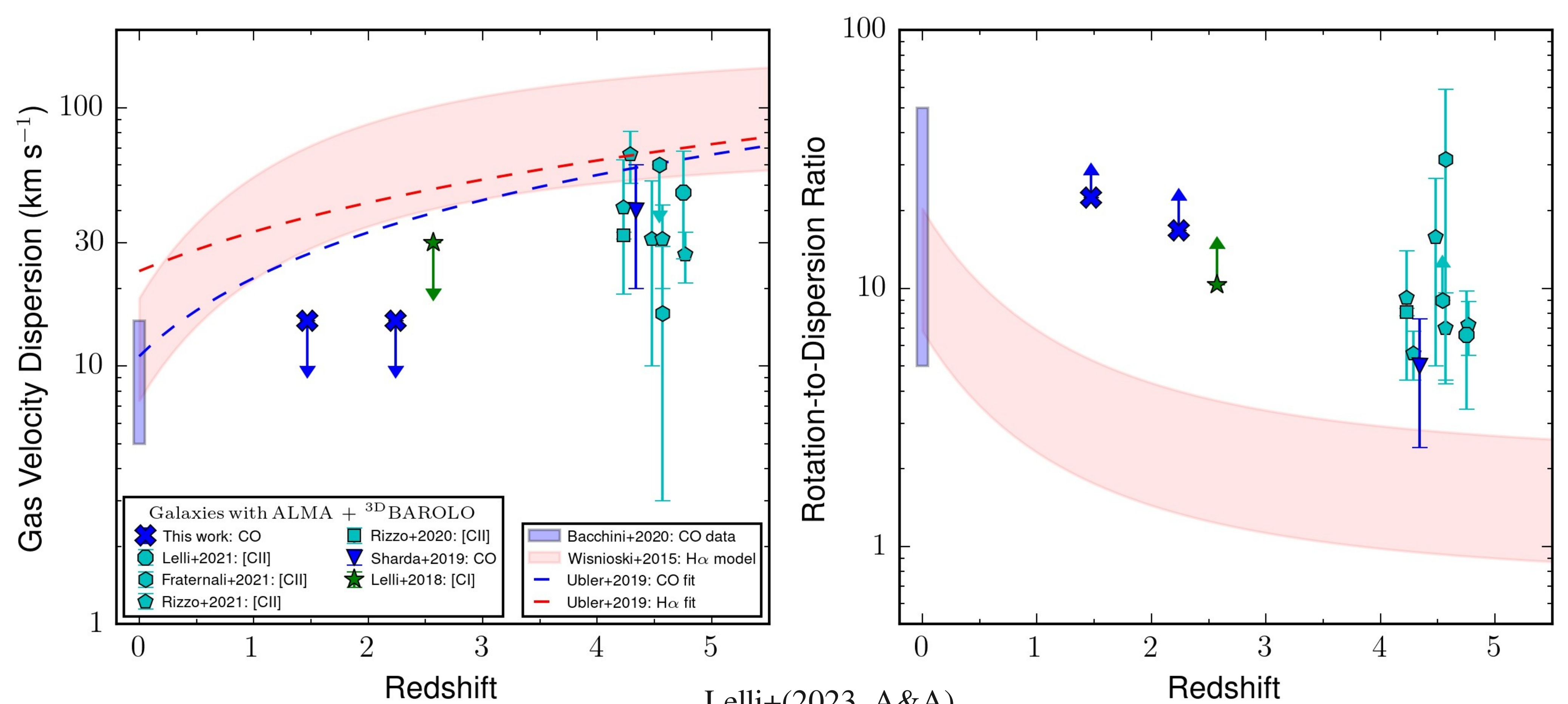
Lelli+2021, Science

Massive Bulge at z~4.8 with B/D~0.4



Lelli+2021, Science

Dynamically-cold gas disks may be common!



Lelli+(2023, A&A)

Conclusions:

1. Dynamically cold gas disk at high z ($V_{rot}/\sigma_V > 10$)

→ contrary to common view of turbulent high-z disks

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→ weak/no dynamical evolution over ~10-12 Gyr

Conclusions:

1. Dynamically cold gas disk at high z ($V_{rot}/\sigma_V > 10$)

→ contrary to common view of turbulent high-z disks

2. Rotation curves similar to massive spirals at z=0

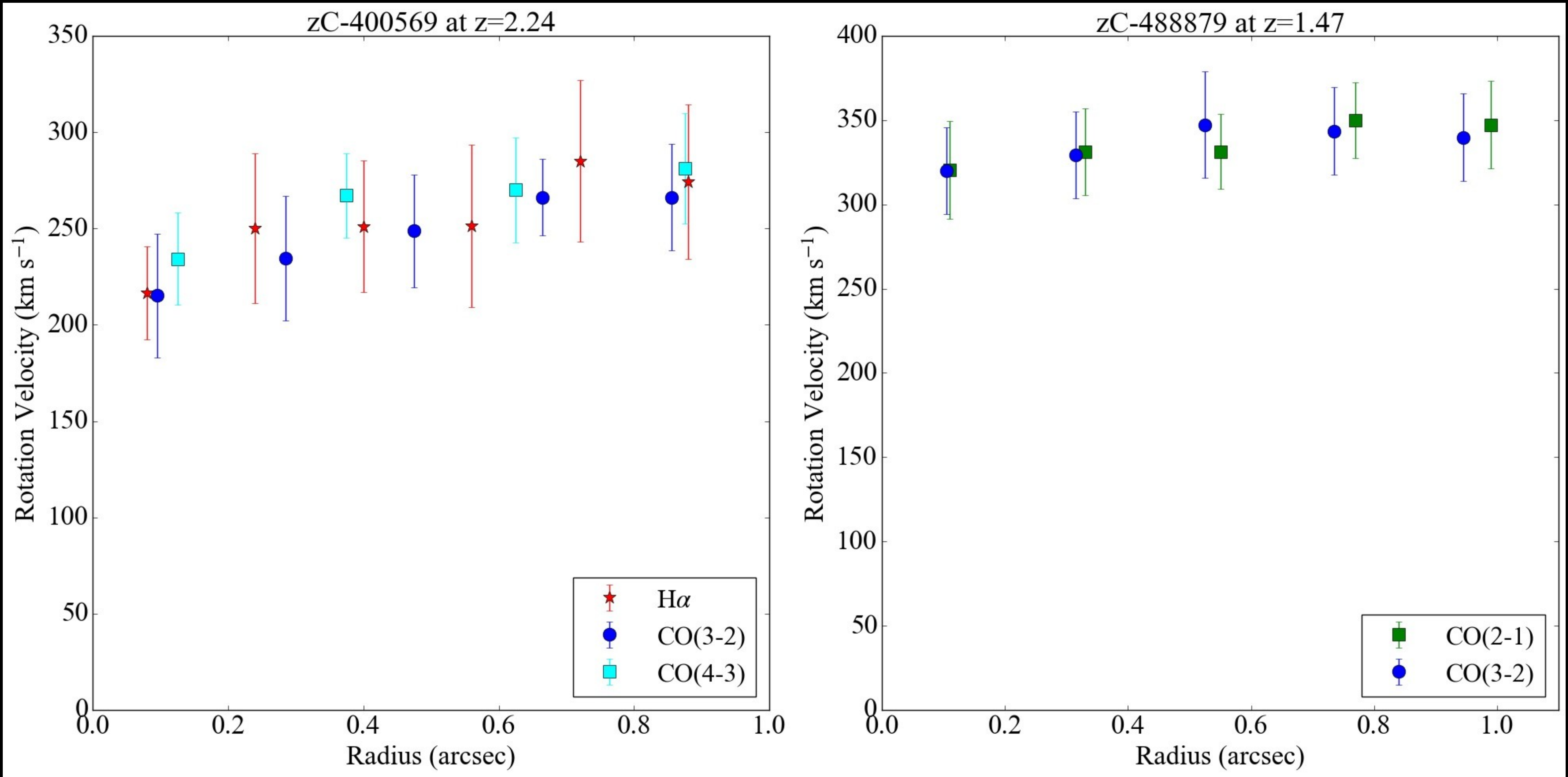
→ weak/no dynamical evolution over ~10-12 Gyr

3. Mass models often require the presence of bulges

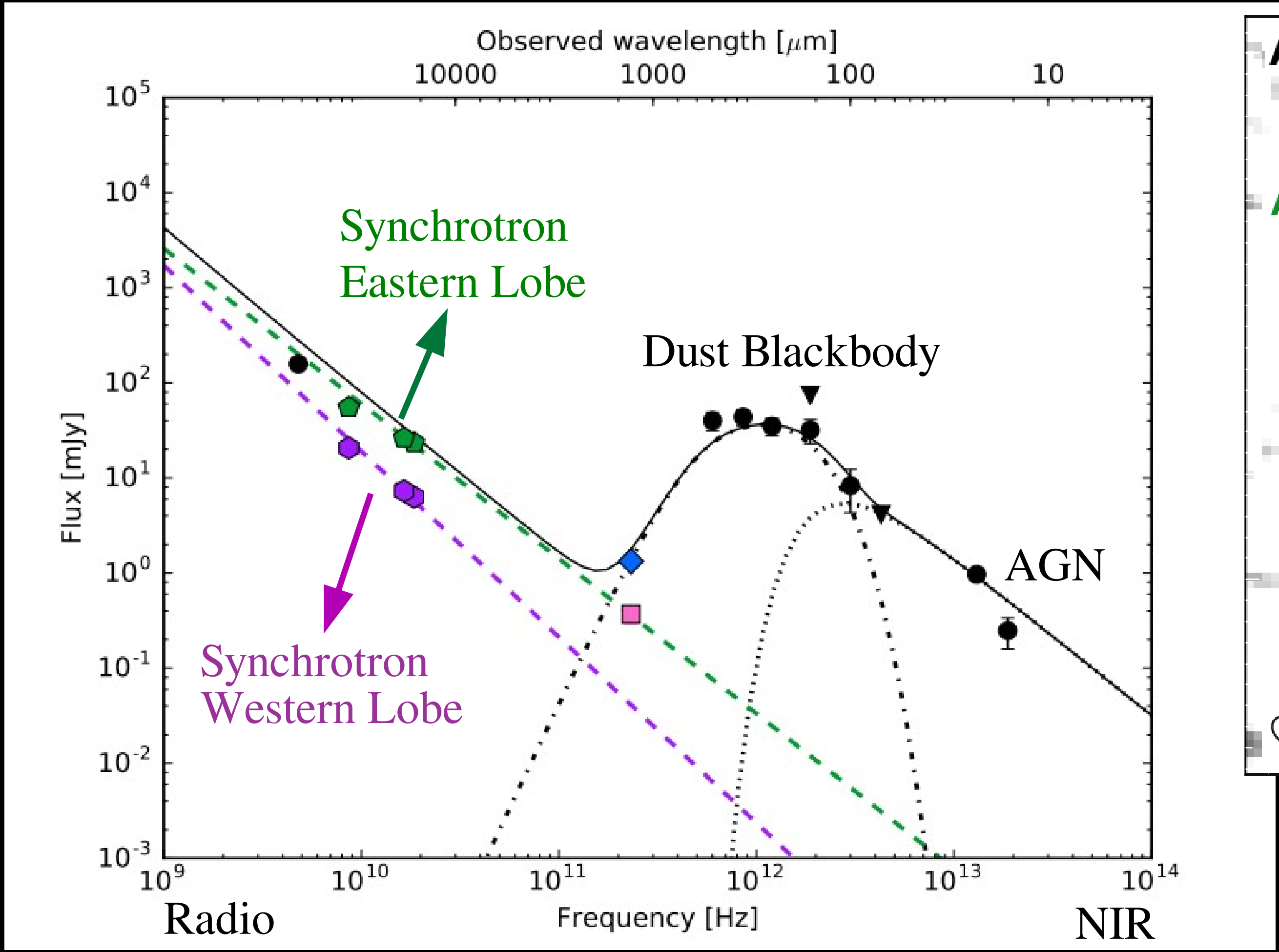
→ fast bulge formation (monolithic collapse? early merger?)

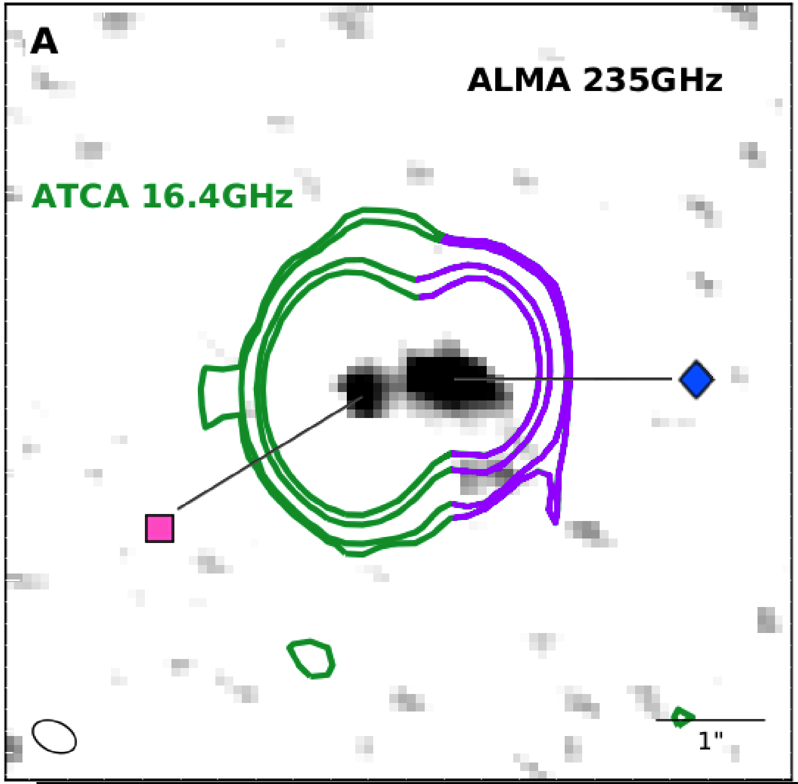
Thank you!

Rotation curves from different emission lines



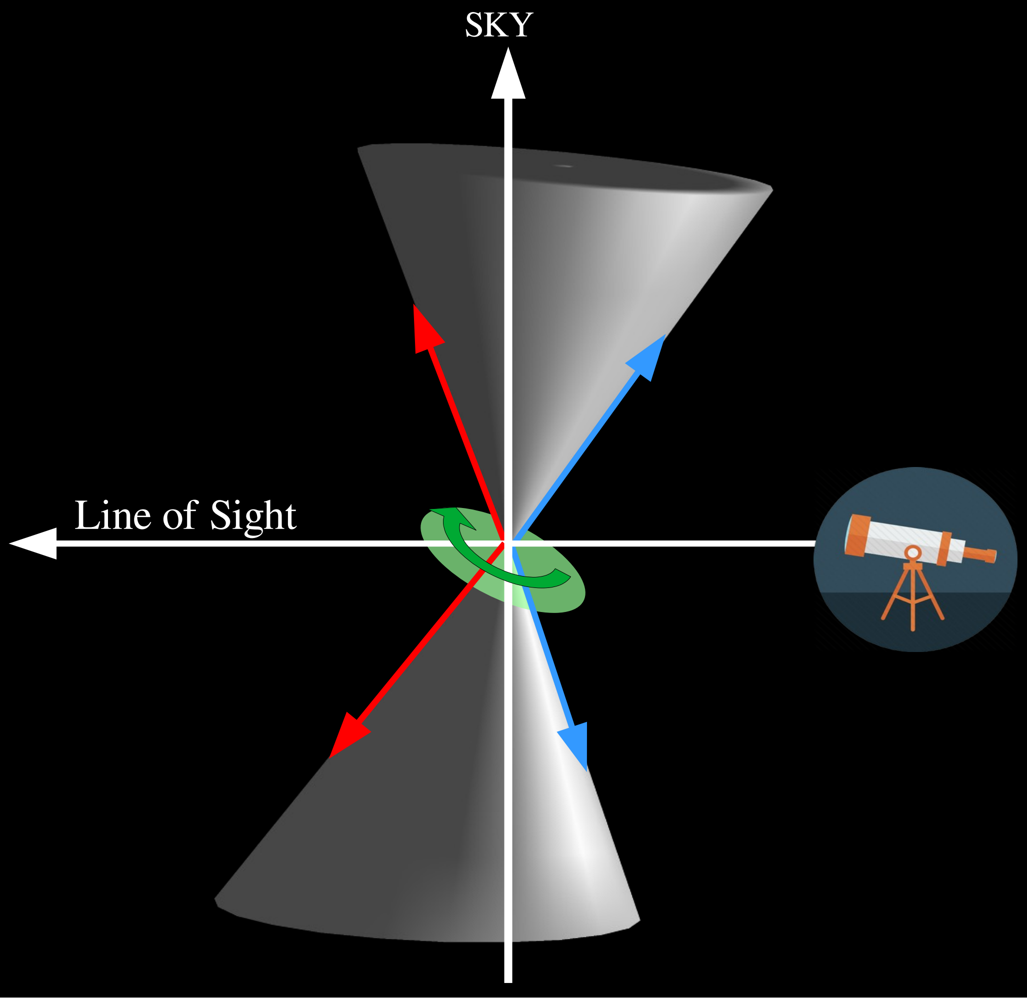
SED fitting of Starburst/AGN Galaxy at z = 2.6



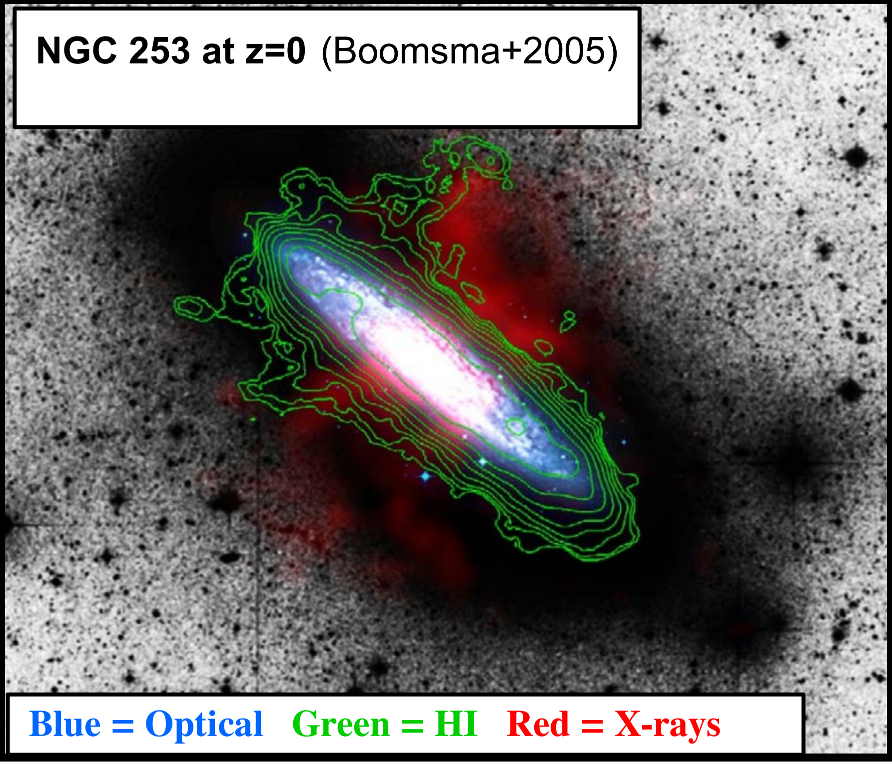


Falkendal+(2020)

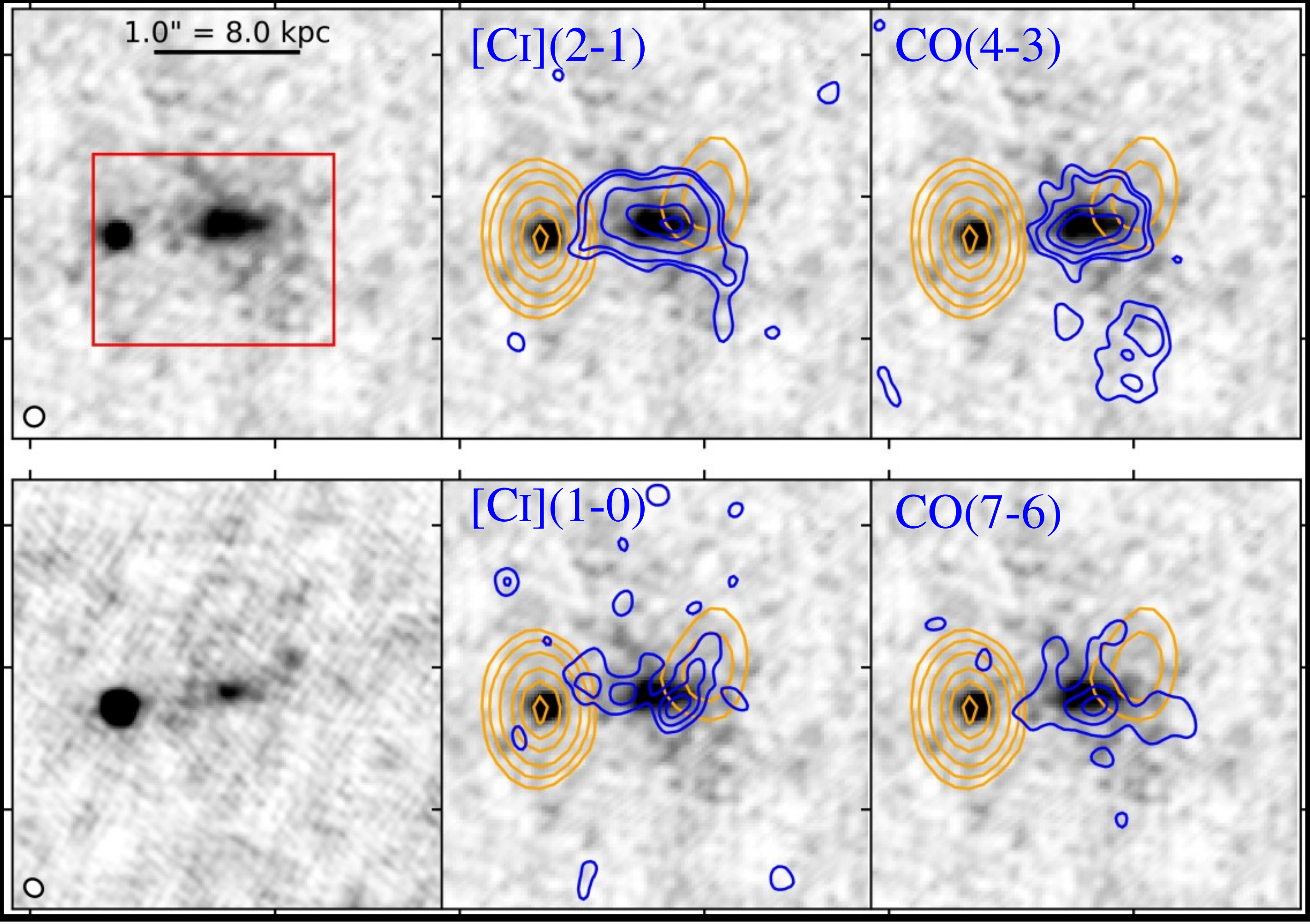
Ionized Gas Outflow in Starburst/AGN Galaxy



[CI] – [OIII] velocity offset:
Are we seeing only the back redshifted side of the outflow?

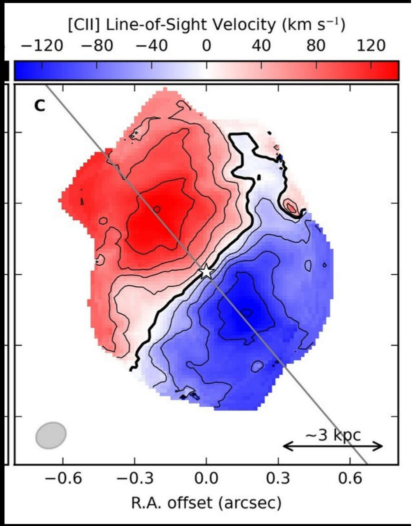


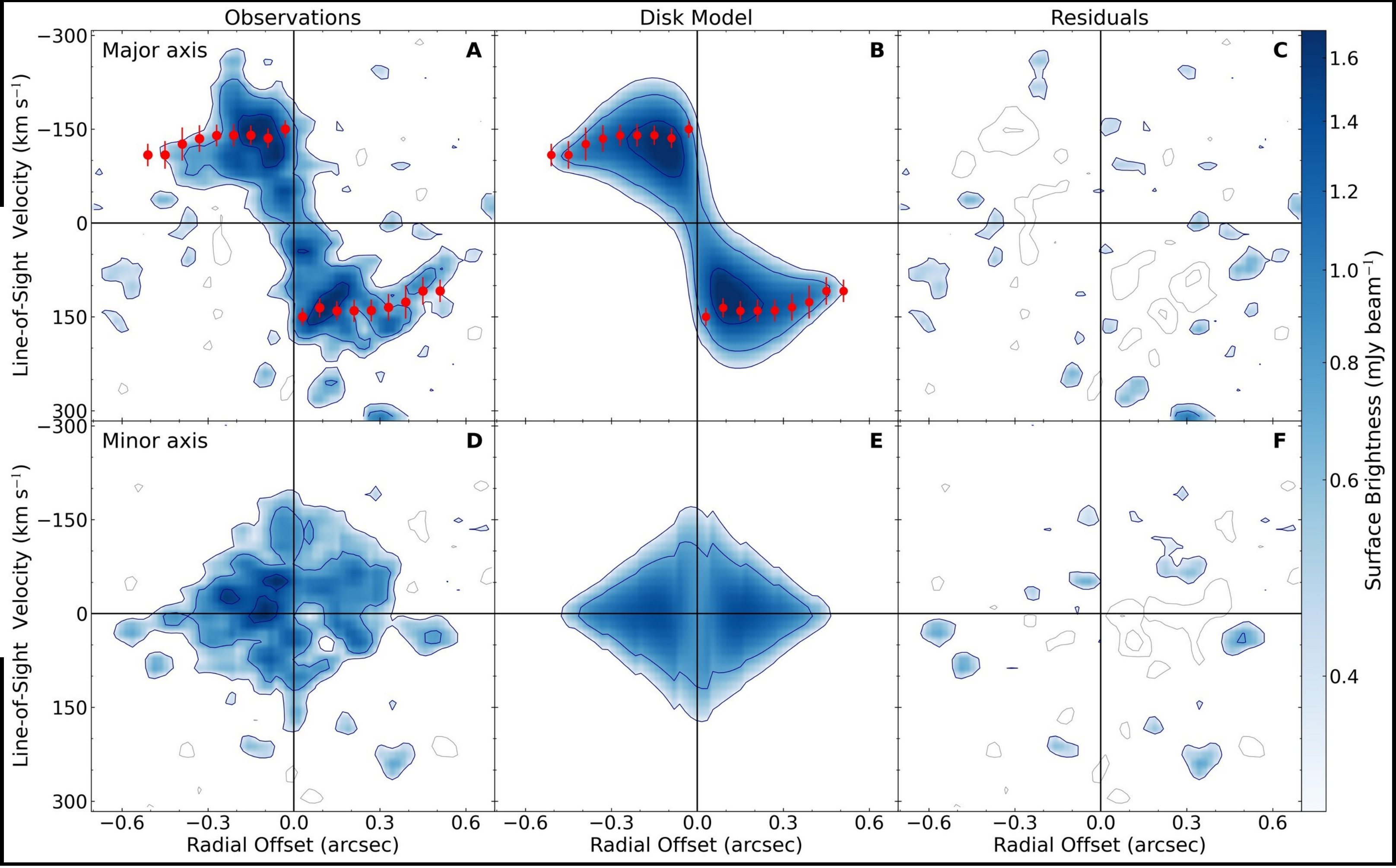
Additional lines: [CI](1-0), CO(4-3), CO(7-6)



Huang+ in prep.

[CII] Kinematics: Very Regular Rotating Disk



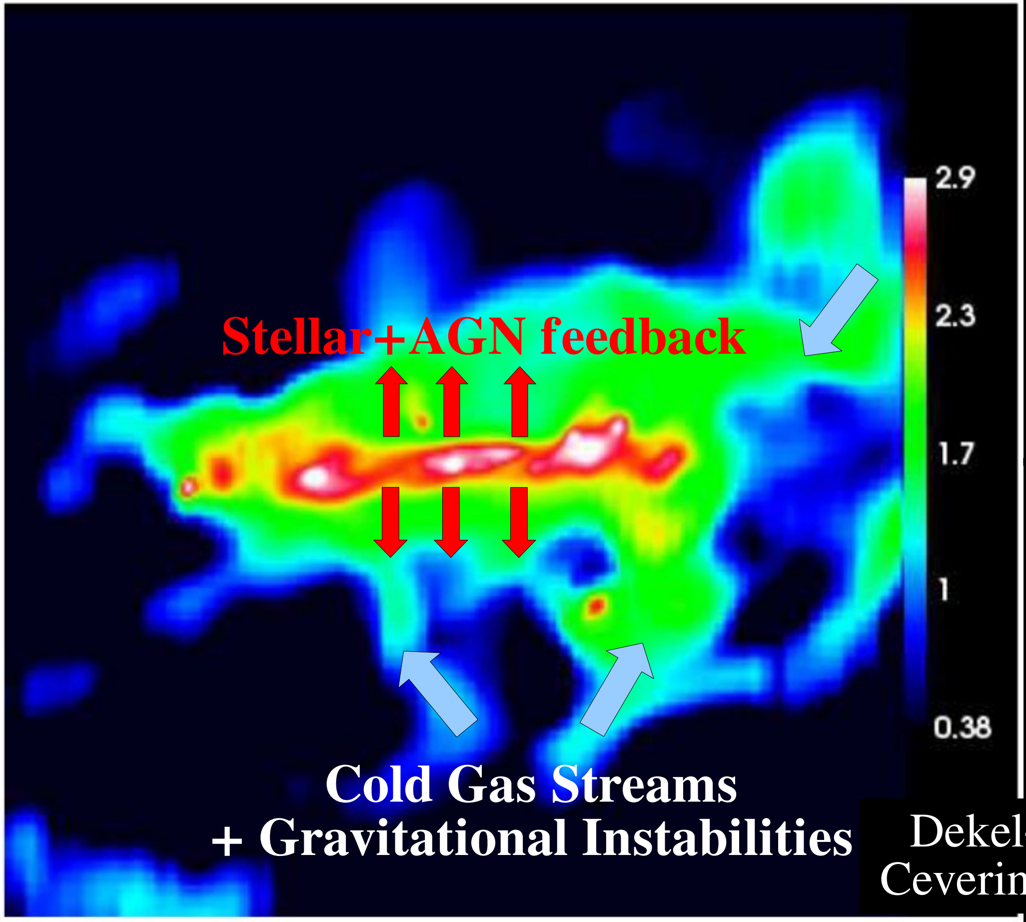


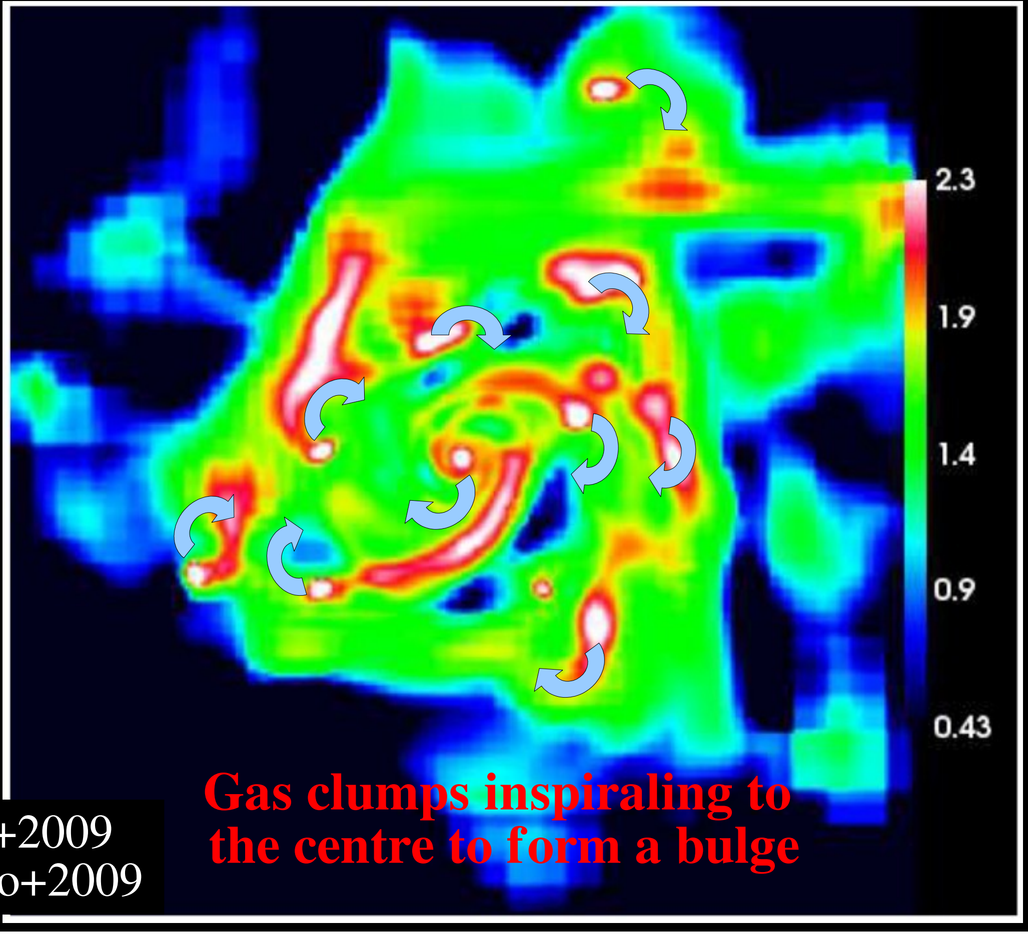
Lelli+2021, Science

Expectations from ΛCDM simulations

Edge-on view: thick, turbulent disk

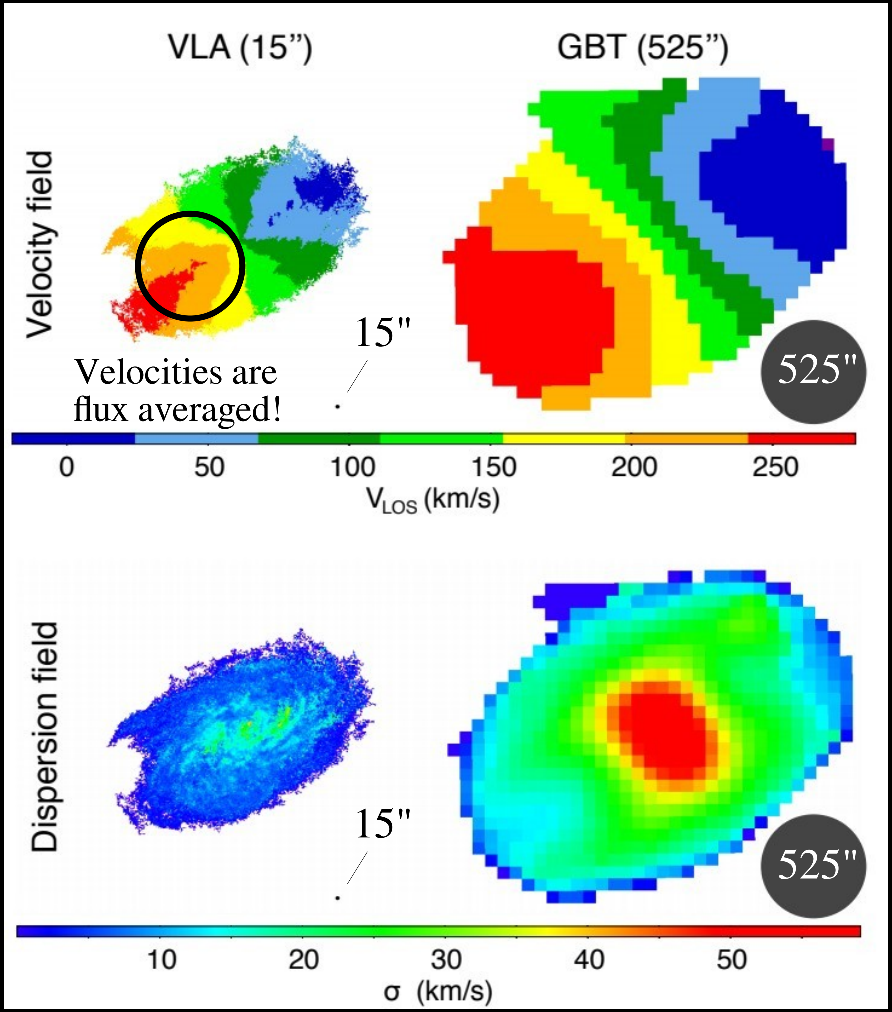
Face-on view: massive gas clumps





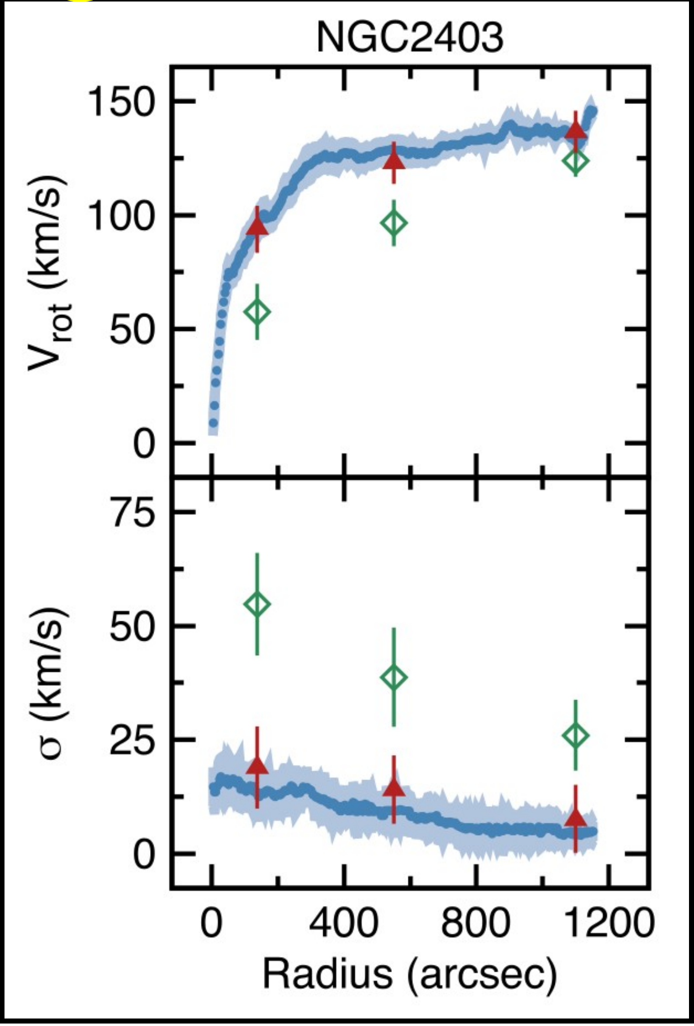
Dekel+2009
Ceverino+2009

Beam smearing: lessons from galaxies at z=0



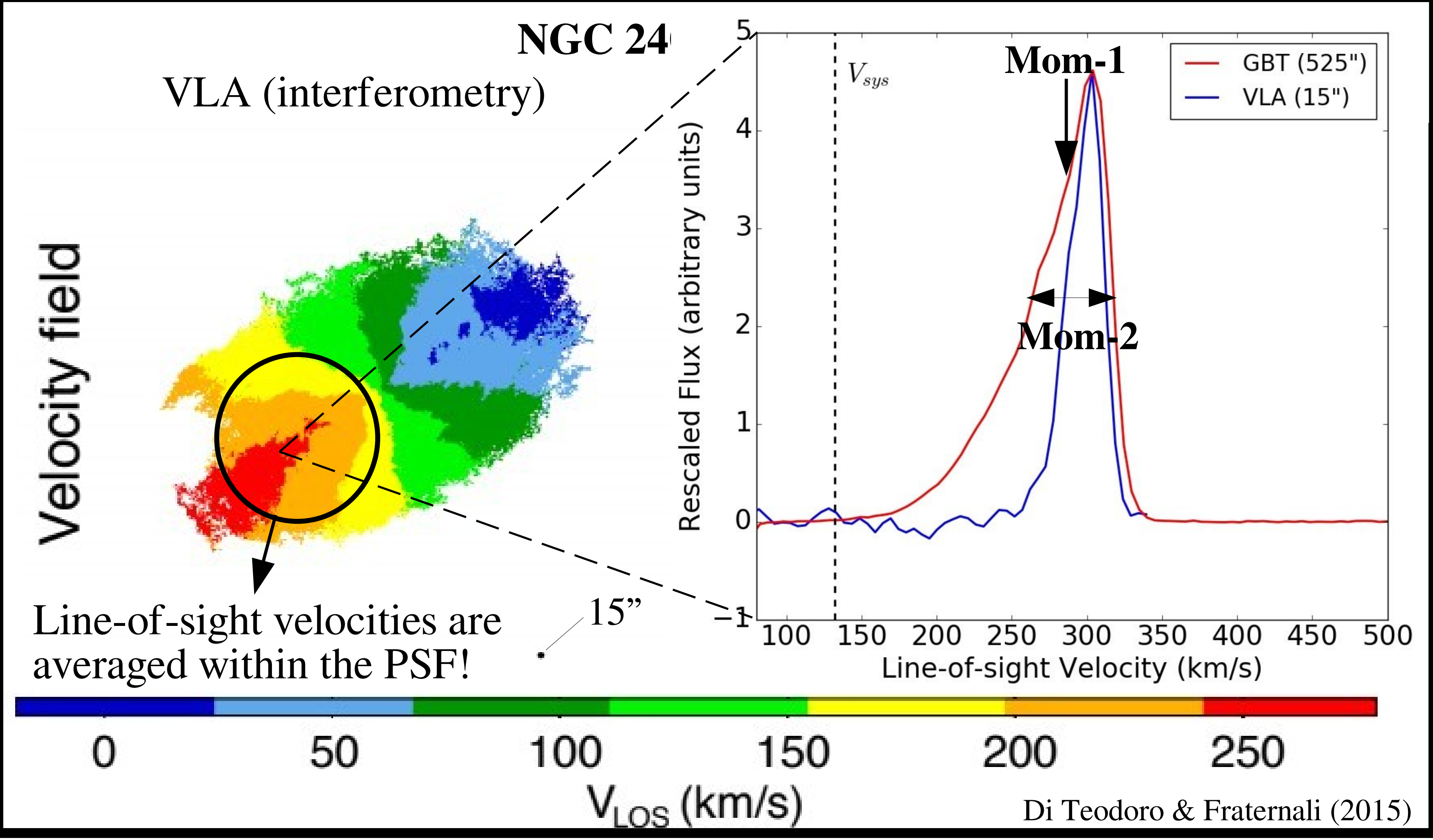
3D FIT

3D FIT

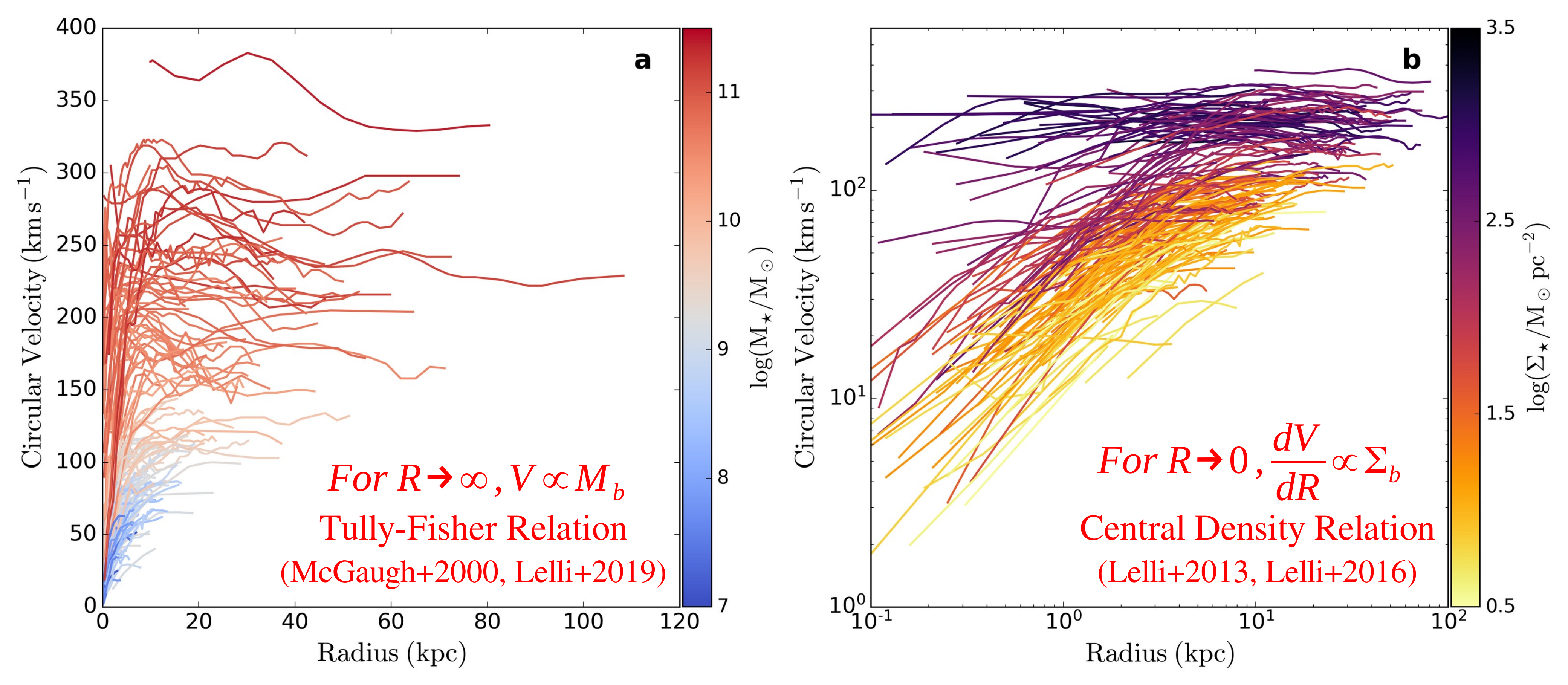


Di Teodoro & Fraternali (2015)

Beam Smearing: Lessons from HI radio data



Rotation Curve Shapes ↔ Baryon Distribution



Lelli (2022, Nature Astronomy, Review)