Testing MOND in High-z Galaxies

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Why testing MOND at high z?

1. Dynamical laws of galaxies (RAR, etc):

In MOND, fundamental Laws of Nature → exist at any z

In ΛCDM, emerge from galaxy formation → break at some z

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   $a_0 \simeq c \cdot H_0 \rightarrow a_0(z) \simeq c \cdot H(z)$ or some $f(z)$?

   $a_0 \simeq c^2 \sqrt{\Lambda} \rightarrow a_0$ does *not* vary with z ?

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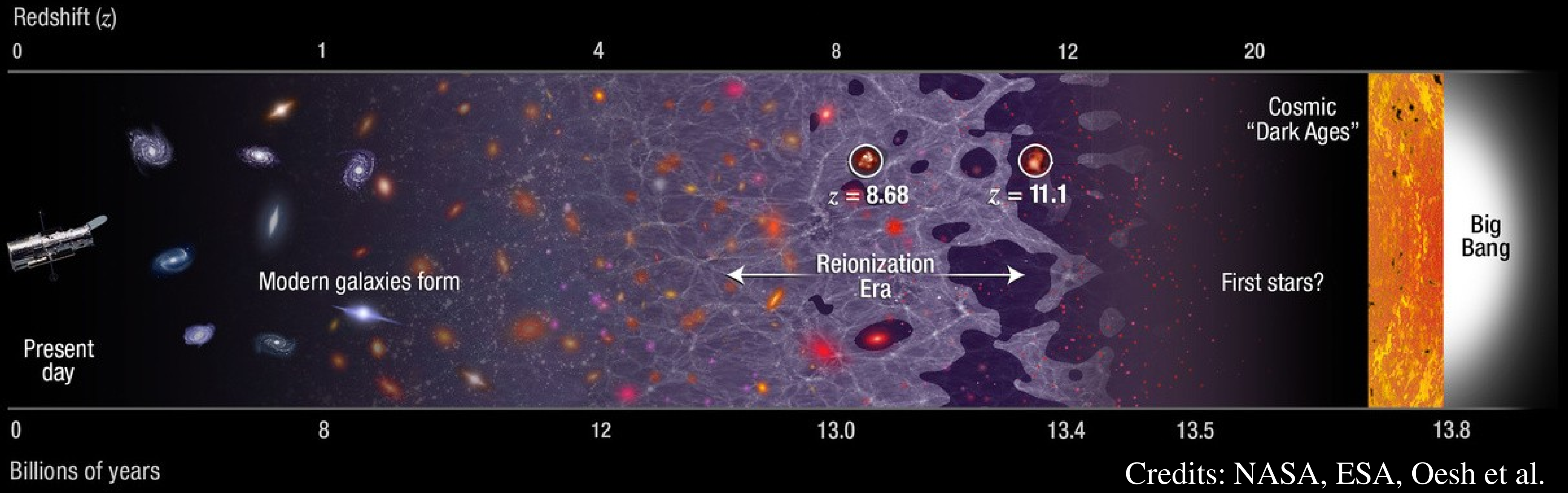
3. Distance – redshift relation:

   In ΛCDM → High-z galaxies are extremely compact (R_h<1 kpc)

   In MOND → Same $D_A(z)$? Or a different one?

Rotation Curves across Cosmic Time



Credits: NASA, ESA, Oesh et al.

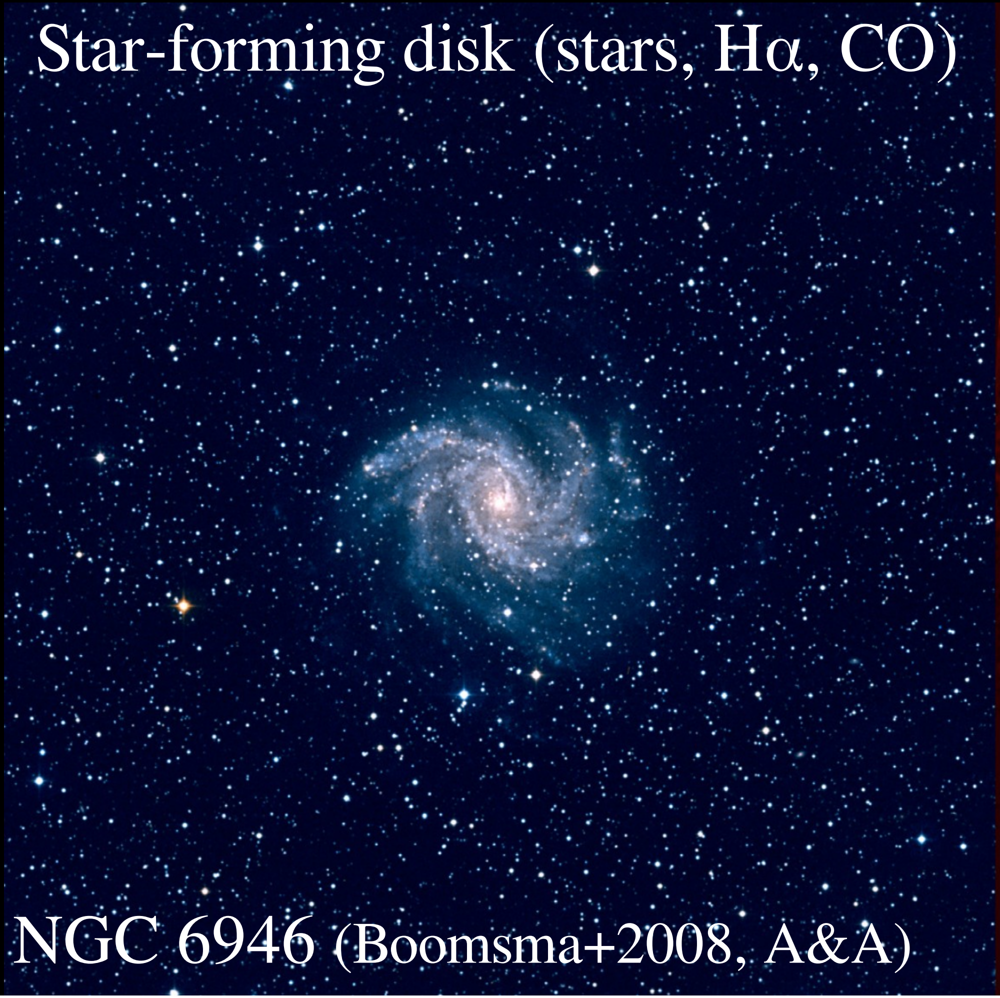
Multiple phases

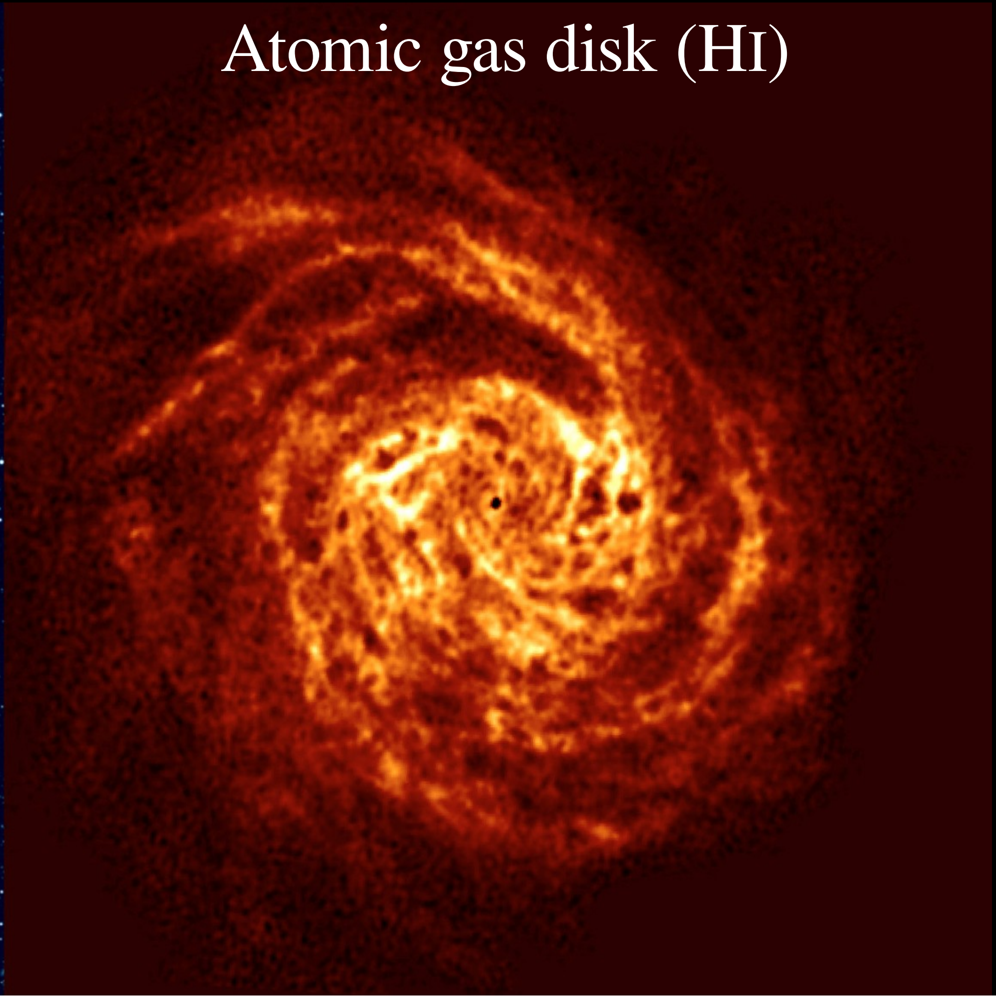
Ionized gas: Hα

Molecules: CO

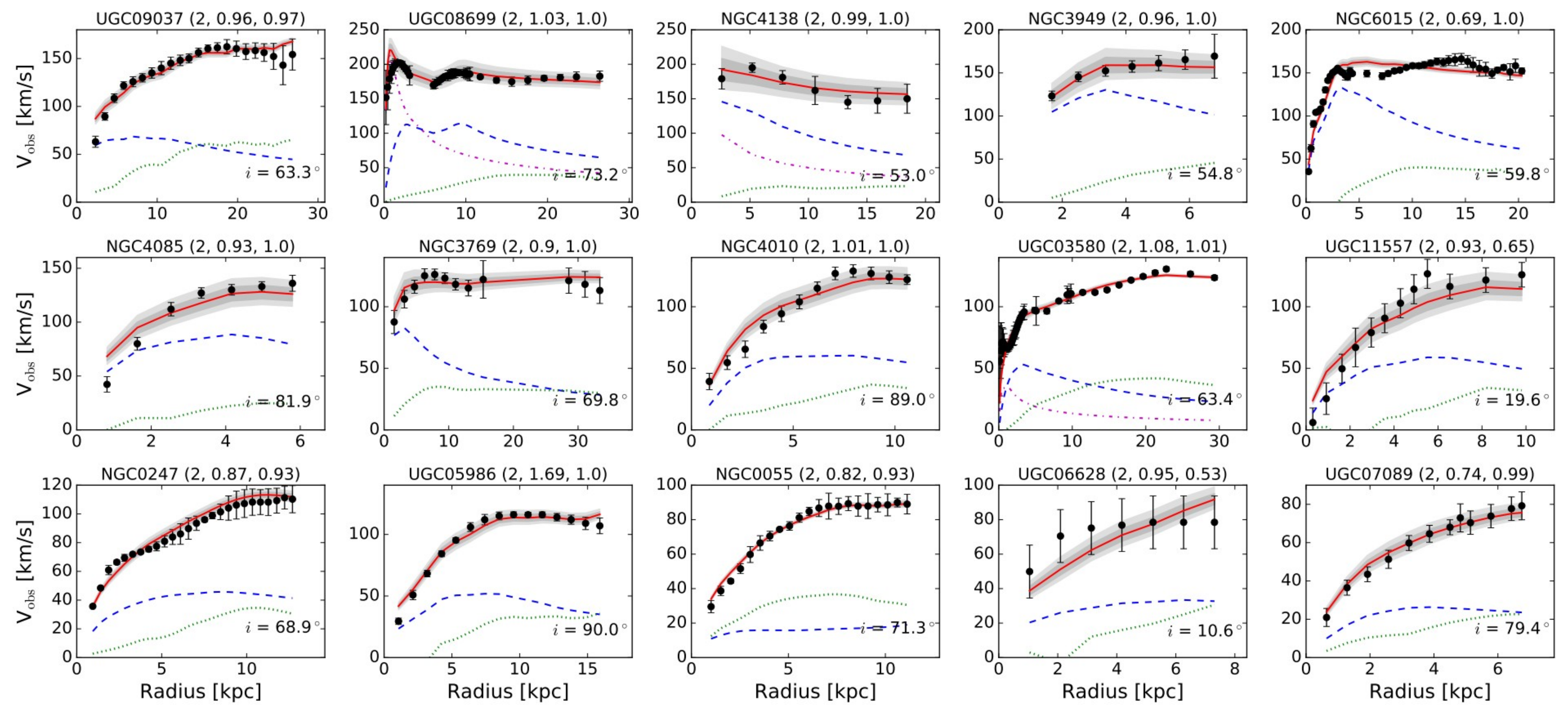
Atomic gas: HI

Key lesson from z=0: Extended HI disks





MOND fits to 175 HI Rotation Curves at z=0



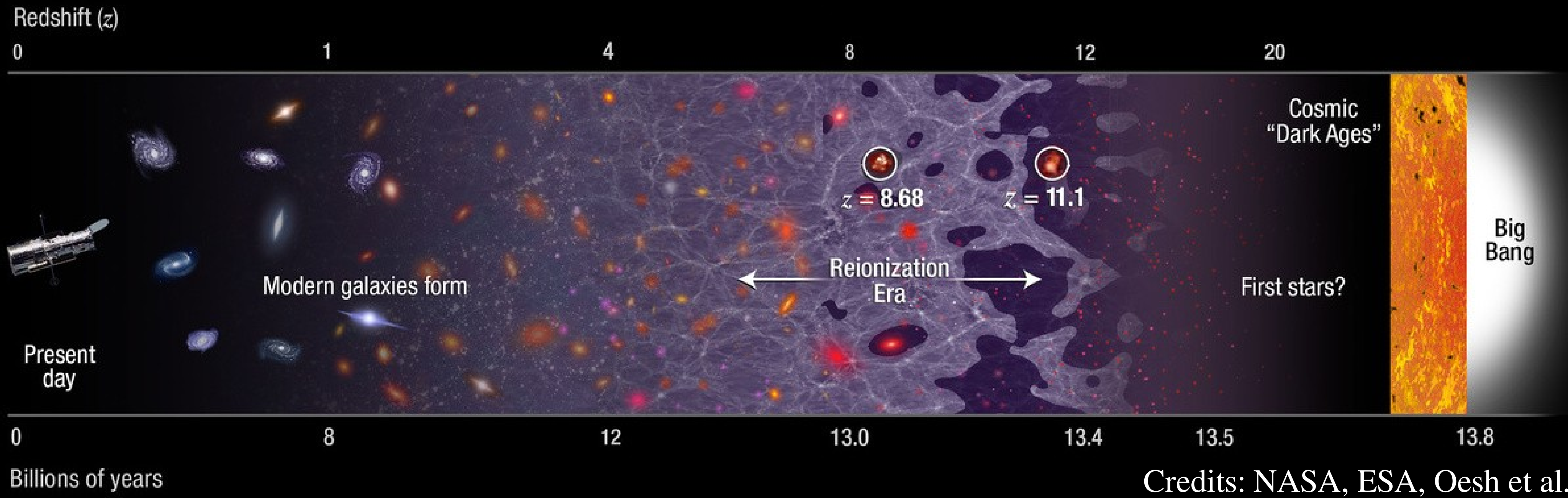
Li, Lelli, McGaugh et al. (2018) - after - Begeman, Broeils, Sanders (1991), Sanders (1996), Sanders & Verheijen (1998)

Near Future: Square Kilometre Array (SKA)

MeerKAT (existing) → SKA-mid (~2030)

Goal: detect $M_{HI} \simeq 10^{10}\, M_{\odot}$ at $z \simeq 1$ (possibly spatially resolved)

Rotation Curves across Cosmic Time



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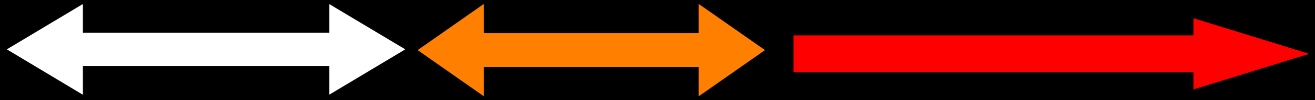
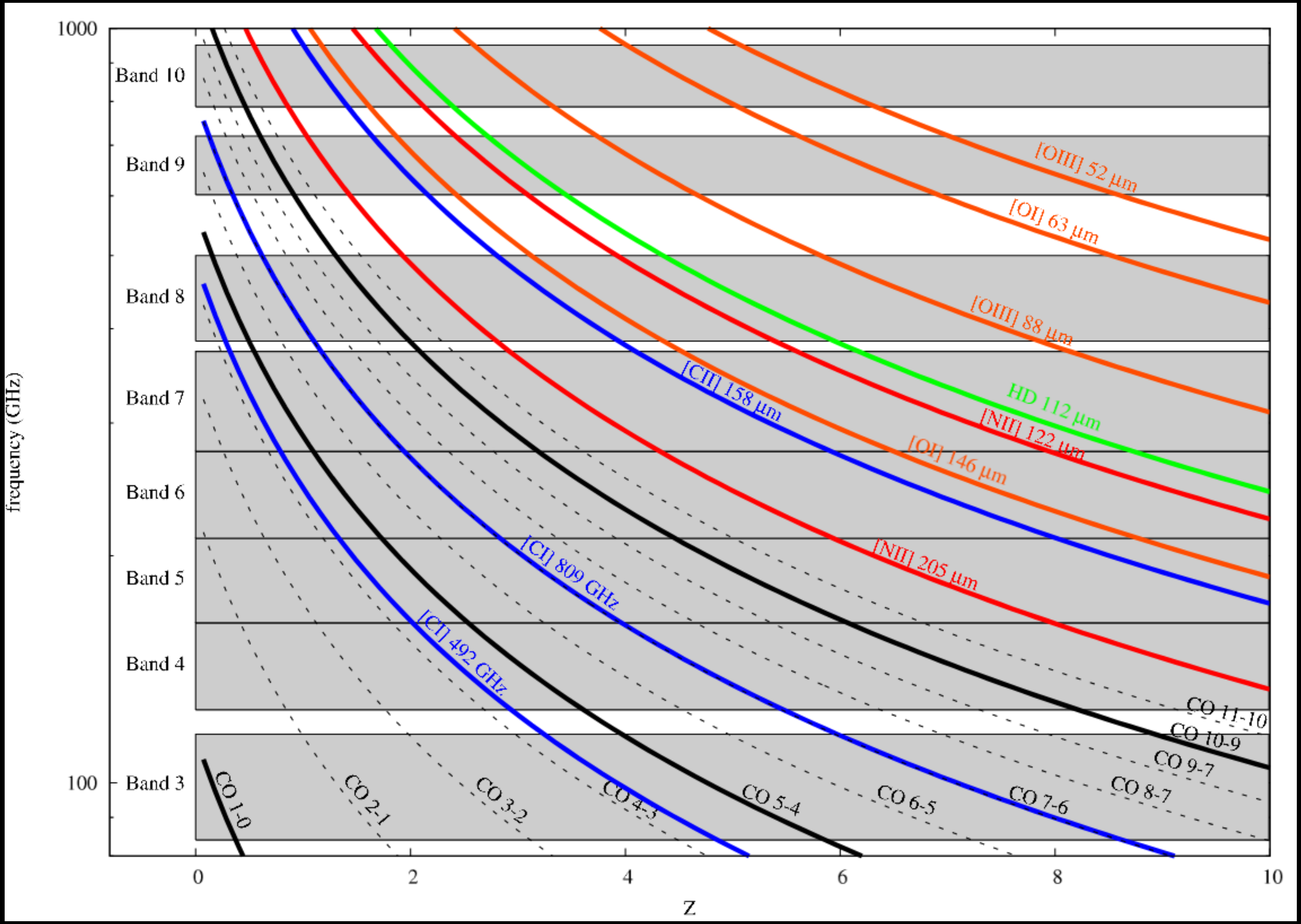


Ionized gas: Hα	Hα, [OIII]λ5007	JWST: Hα, [OIII]λ5007
Molecules: CO	*More recently:*	*Most Promising:*
Atomic gas: HI	High-J CO lines	Ionized Carbon: [CII]

Cold Gas Tracers at high-z with ALMA



De Ugarte Postigo+(2012, A&A)

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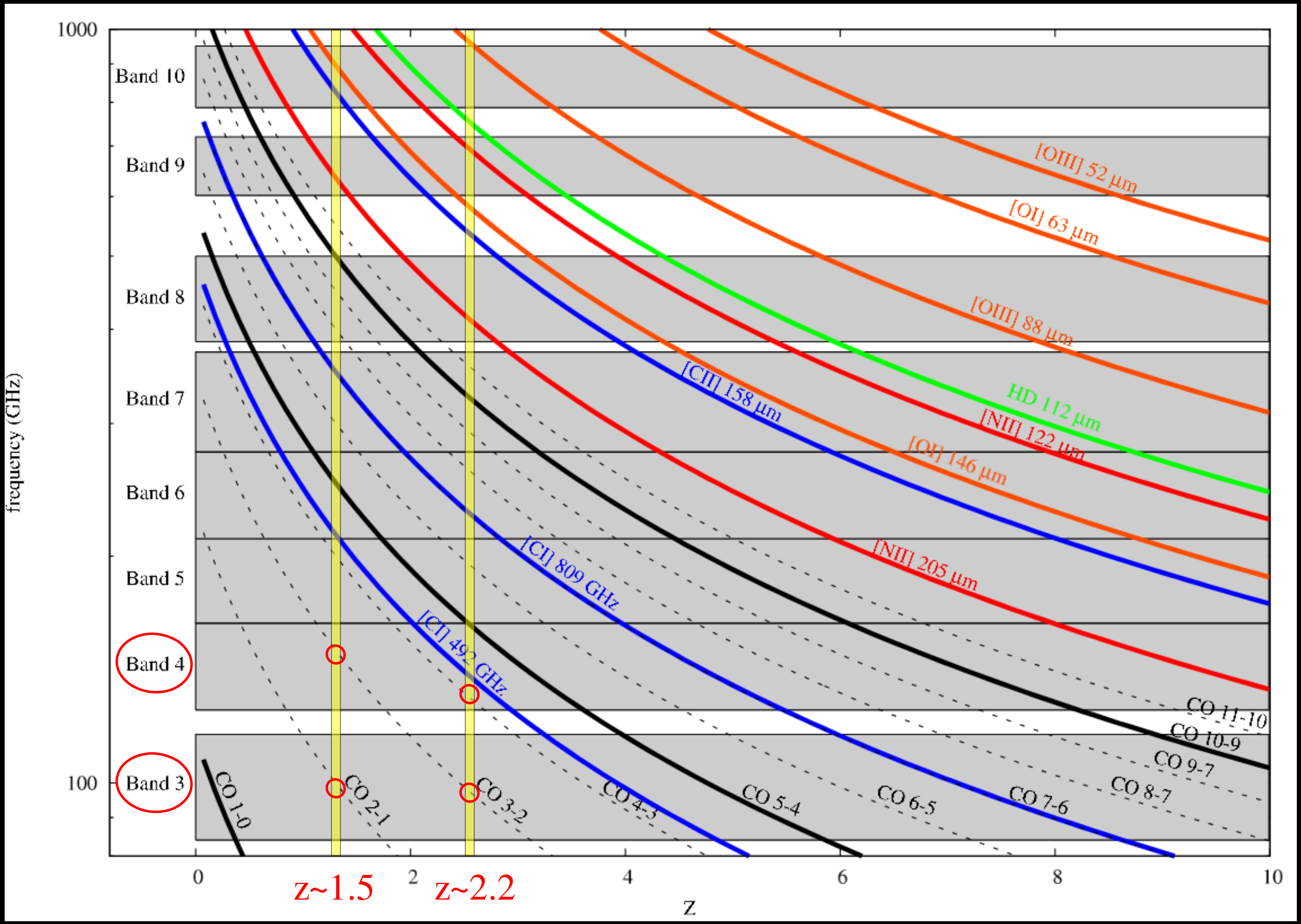
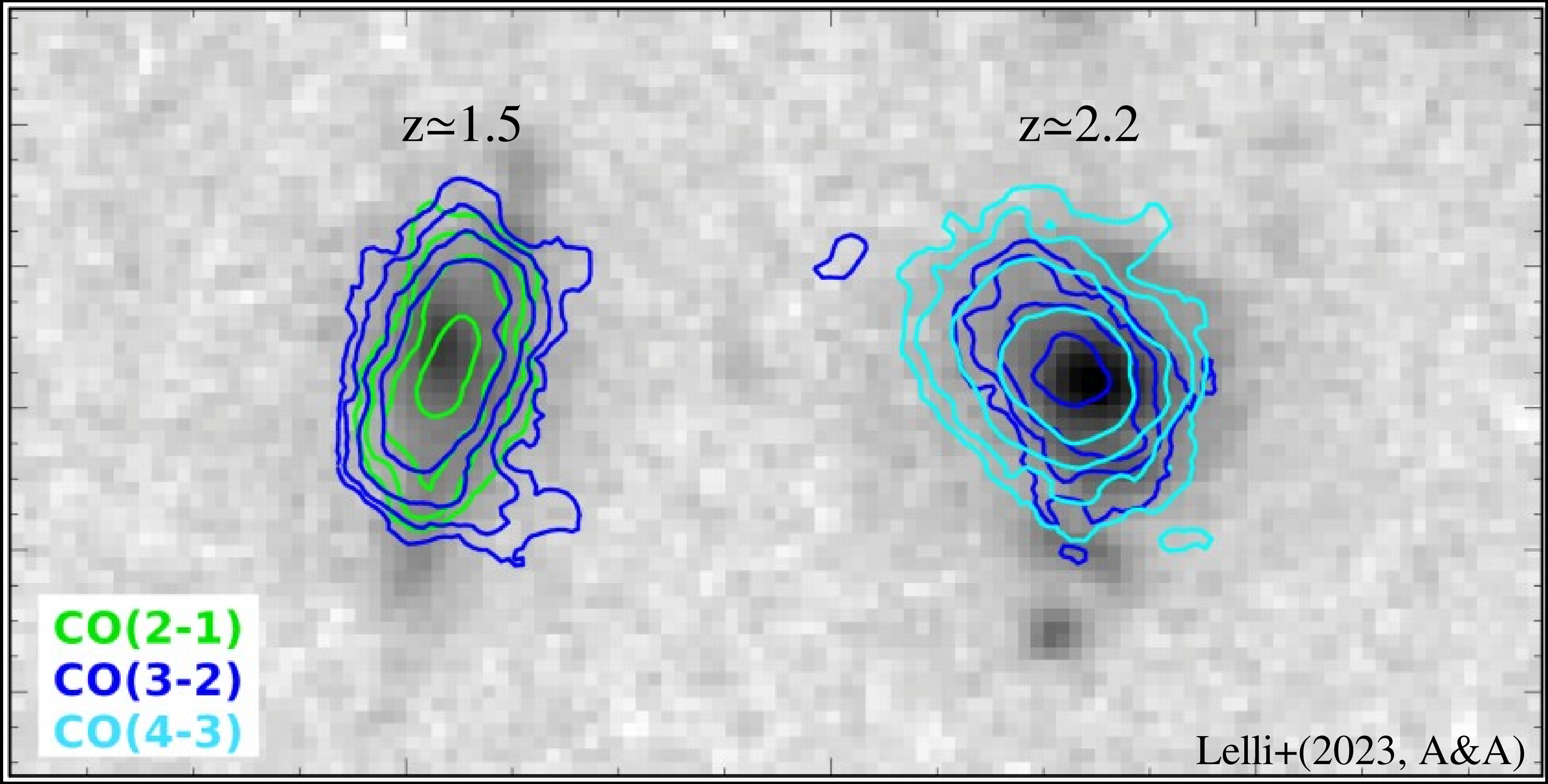


High-resolution study of two disk galaxies:

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

Lelli+(2013, A&A)

Two main-sequence galaxies at cosmic noon



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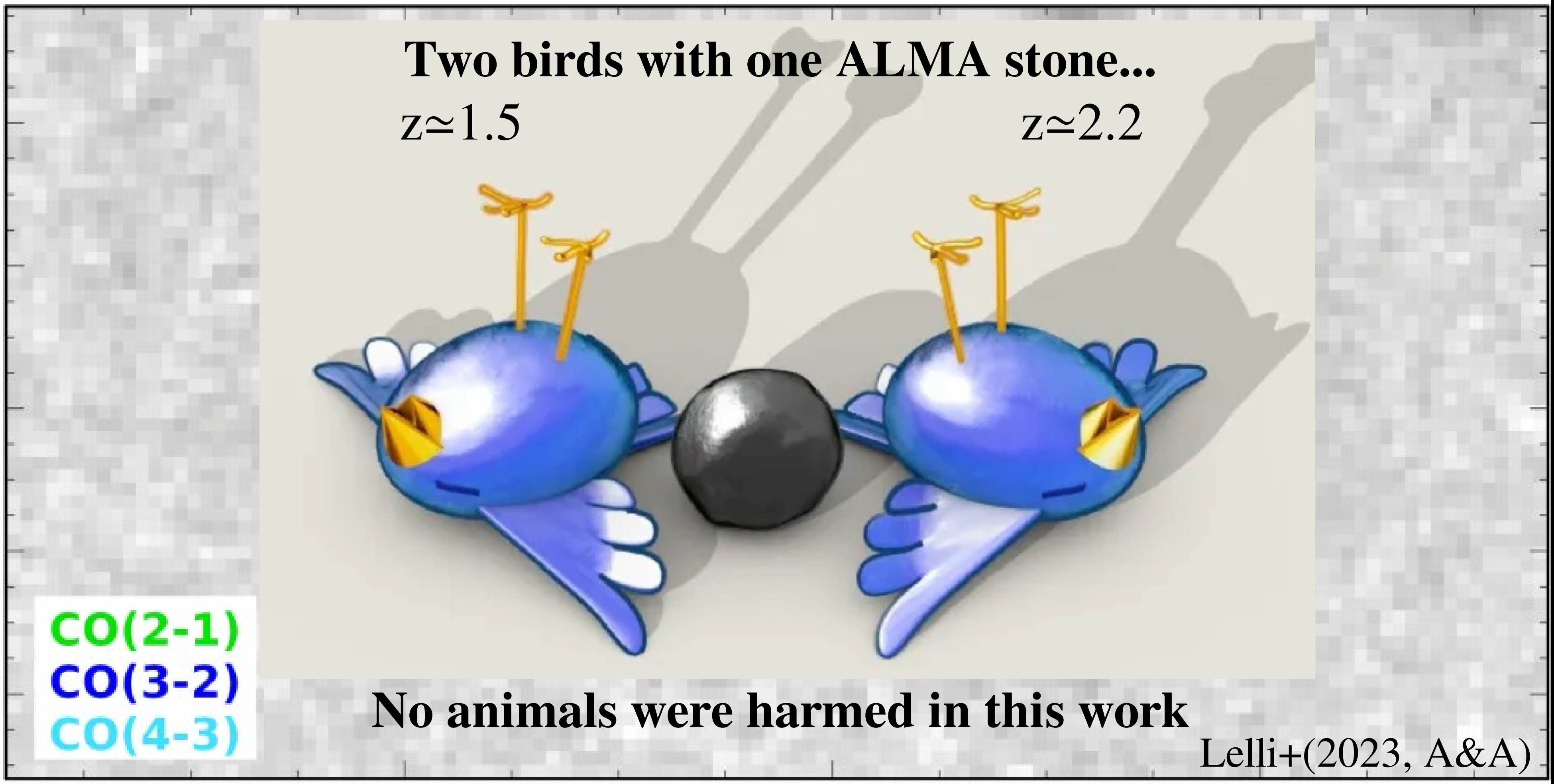
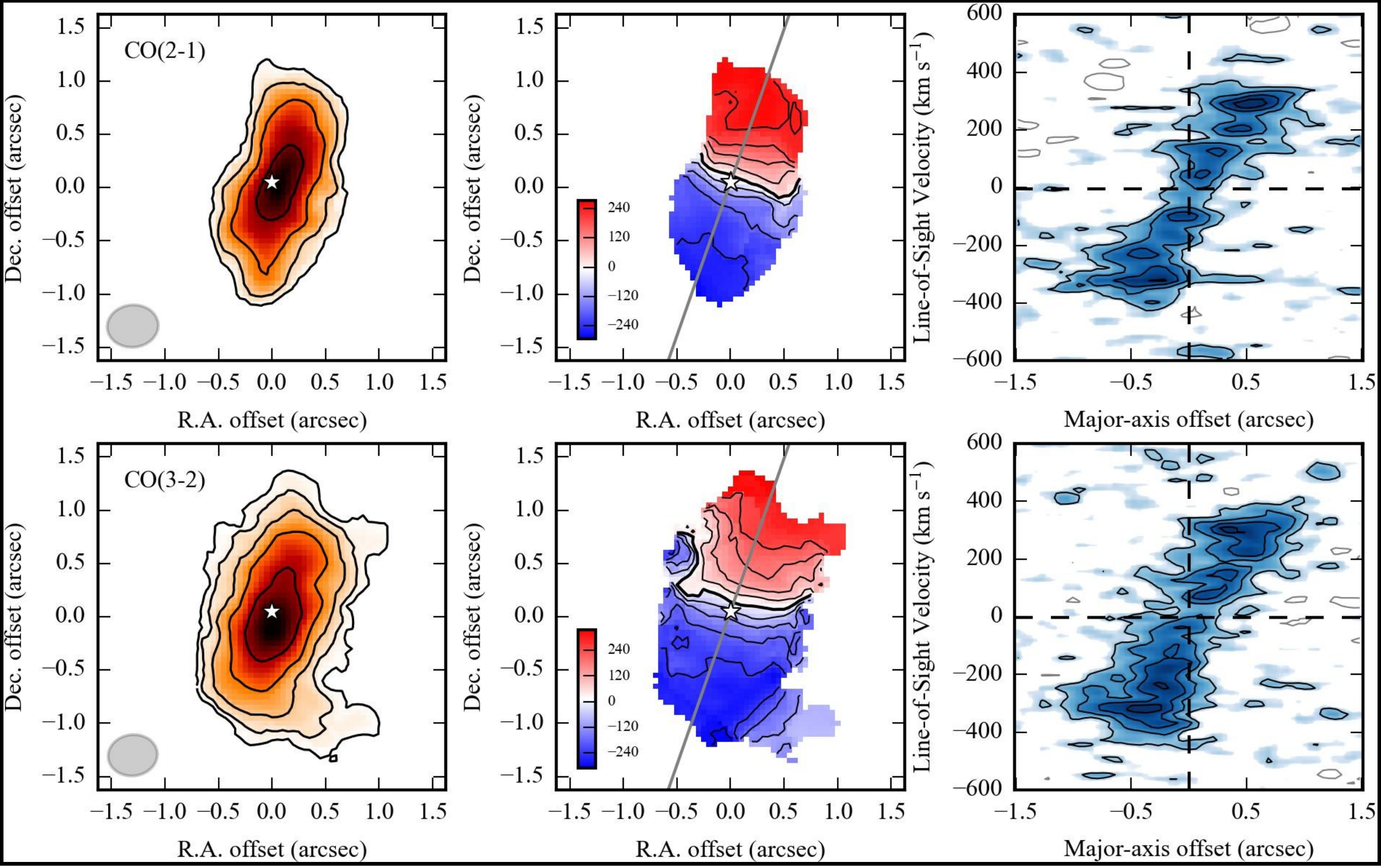


Lelli+(2023, A&A)

Star-forming main-sequence galaxy at z≃1.5



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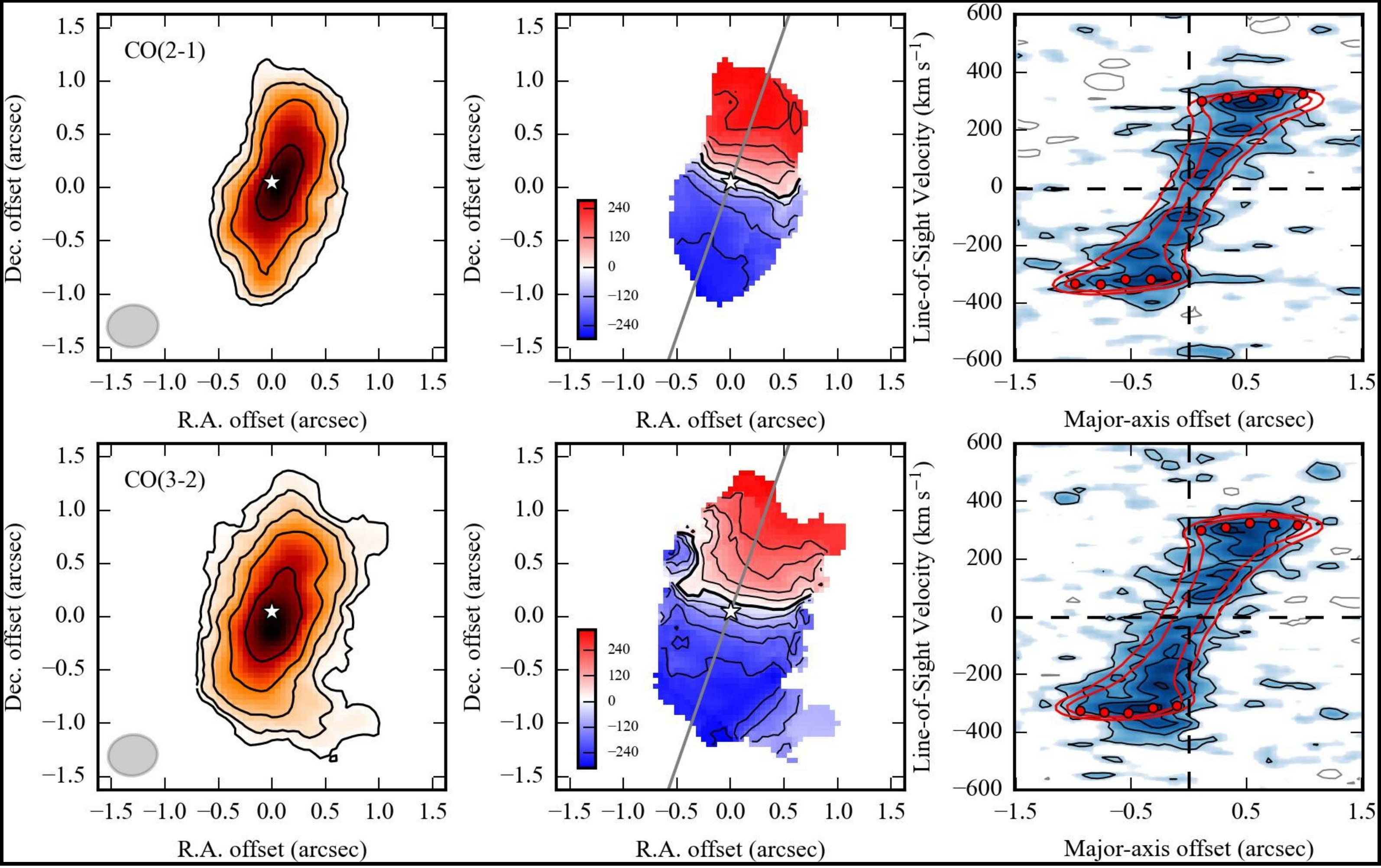


Fit the datacube with [3D]Barolo (Di Teodoro+15):

V_{rot} ~ 340 km/s

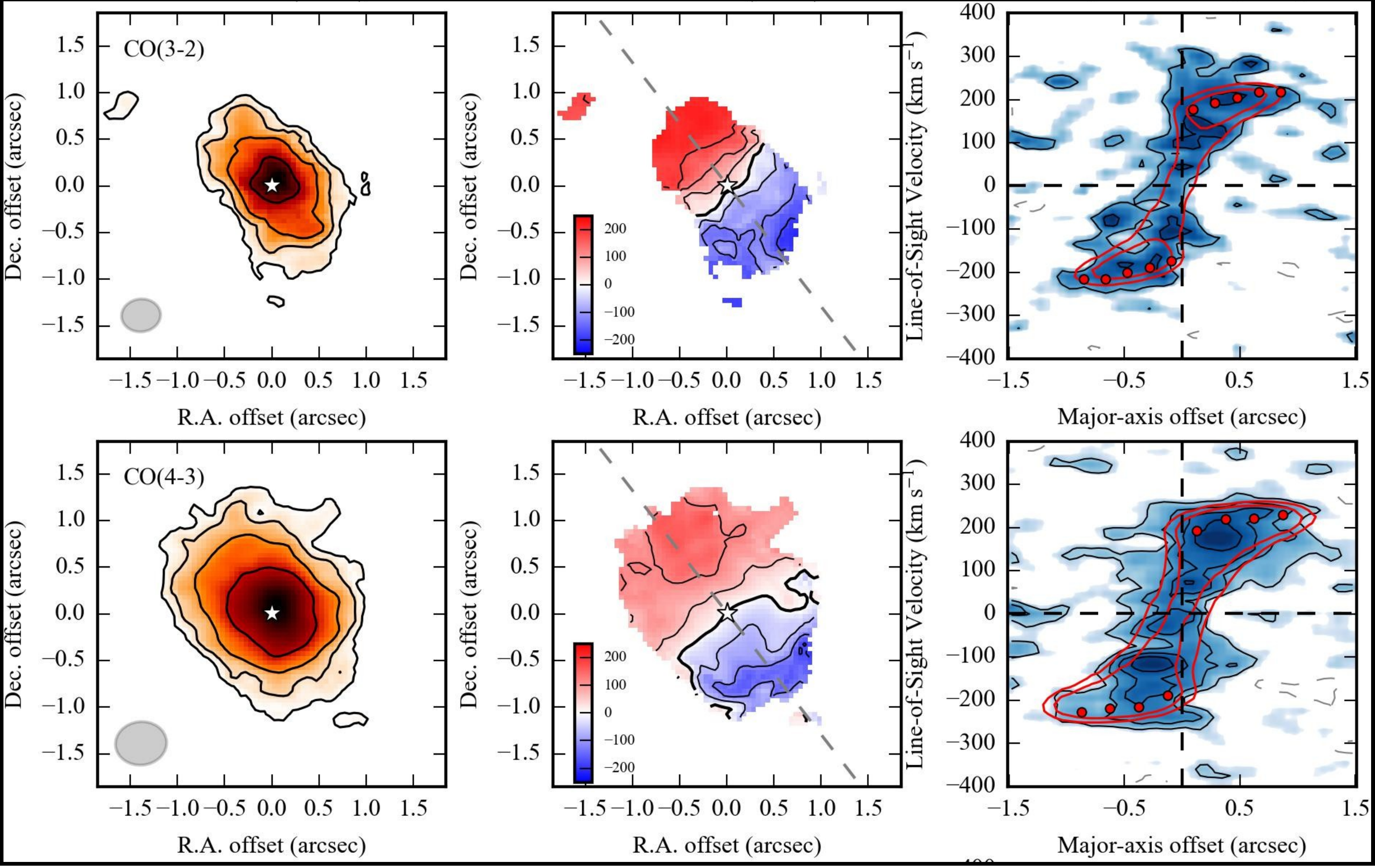
σ_{CO} < 15 km/s

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):

$V_{rot} \sim 254$ km/s

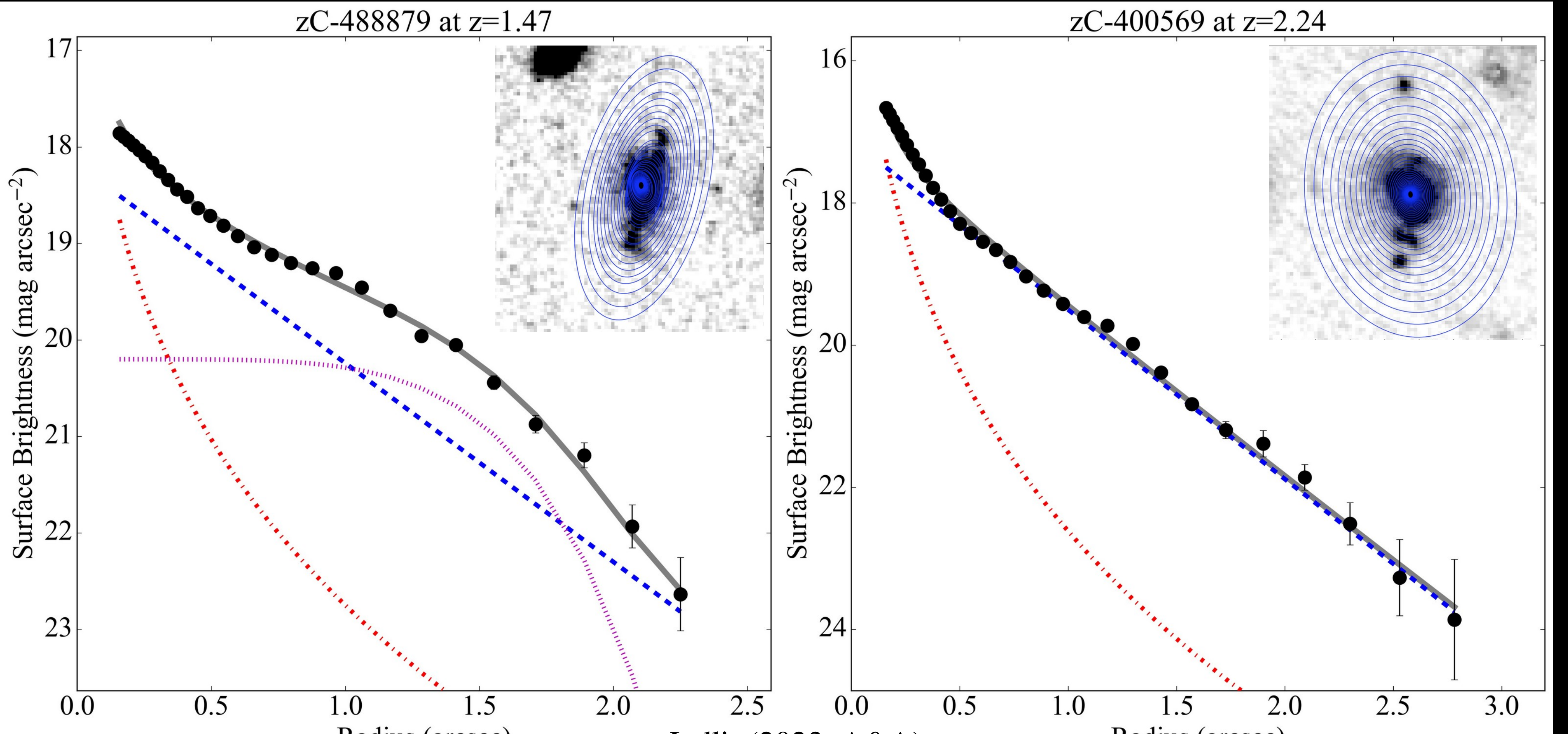
$\sigma_{CO} < 15$ km/s

$V_{rot}/\sigma_{CO} > 17$

(as local disks)

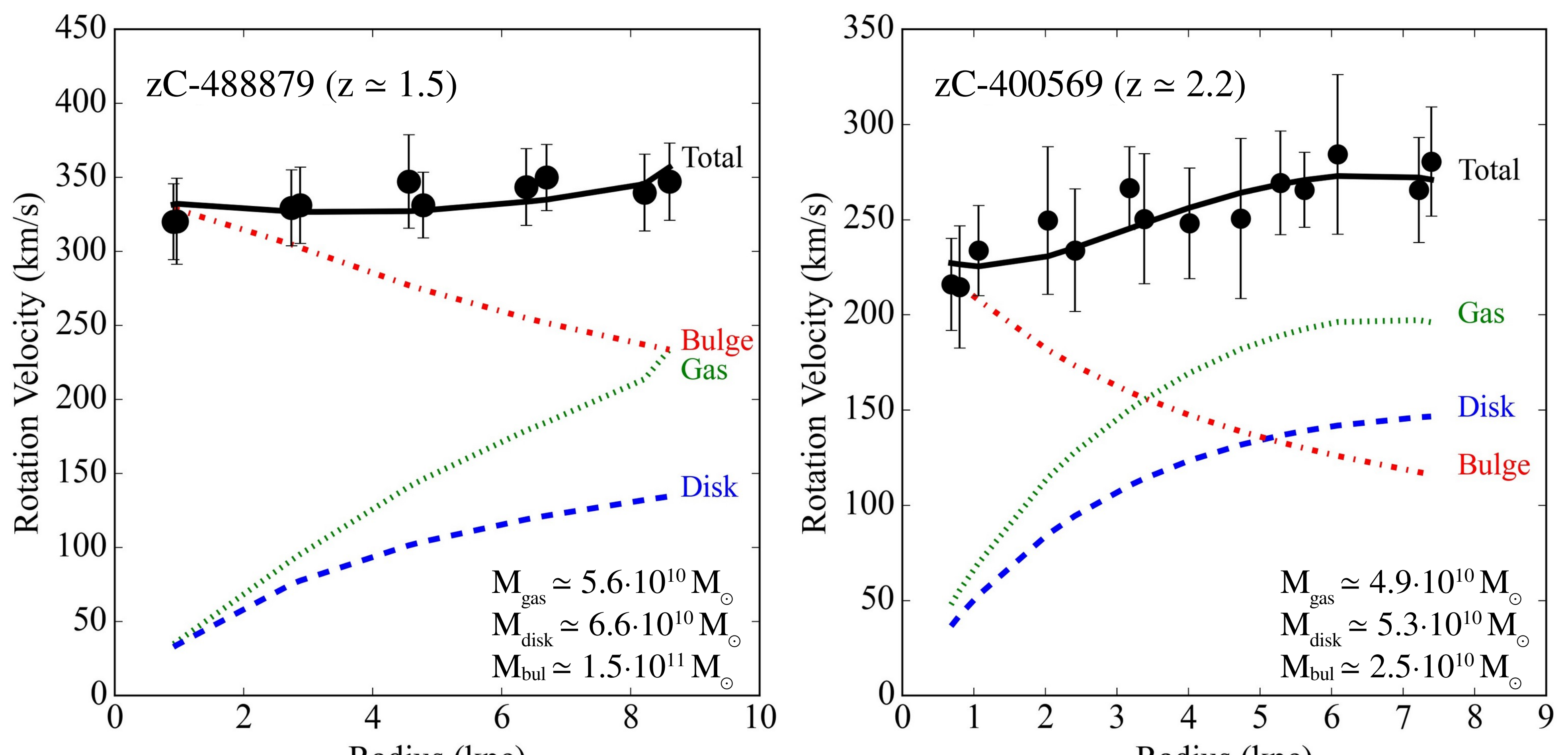
Lelli+(2023, A&A)

HST surface brightness profiles → $g_\star = V_\star^2/R$



Lelli+(2023, A&A)

Mass Models: Newton without DM



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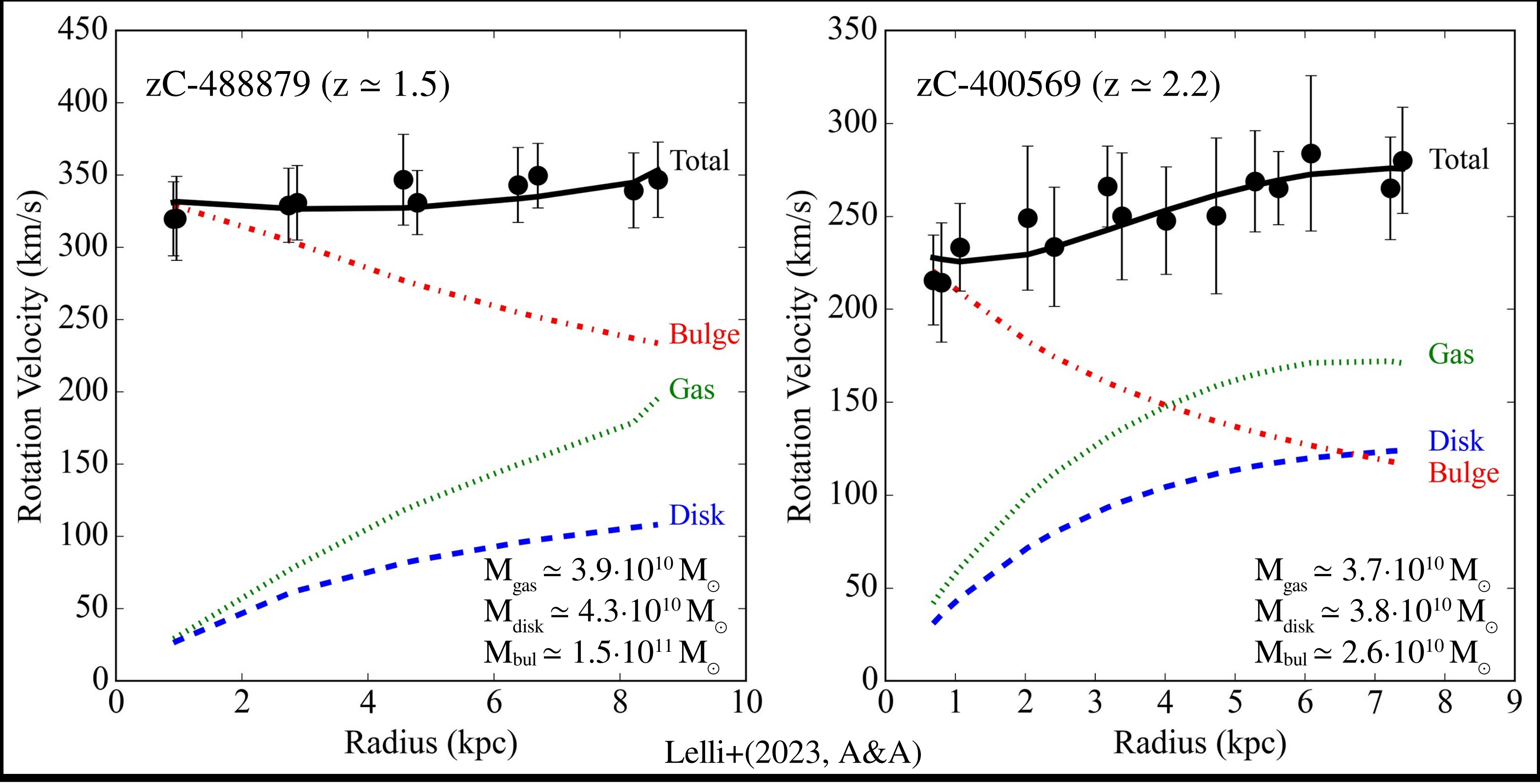
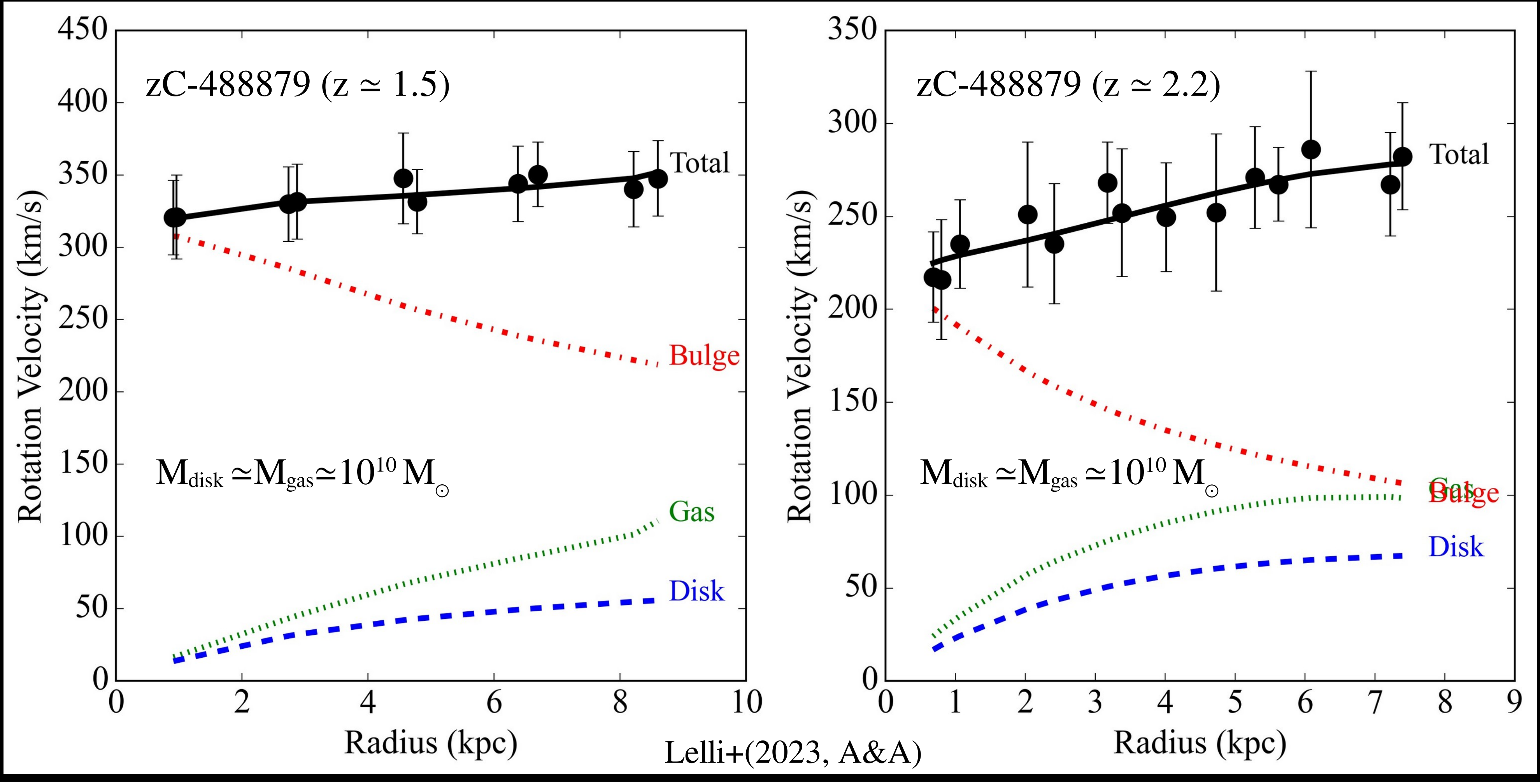
Mass Models: MOND with $a_0 = 1.2 \cdot 10^{-10}$ m/s^2



Mass Models: MOND with $a_0(z) \propto (1+z)^{3/2}$



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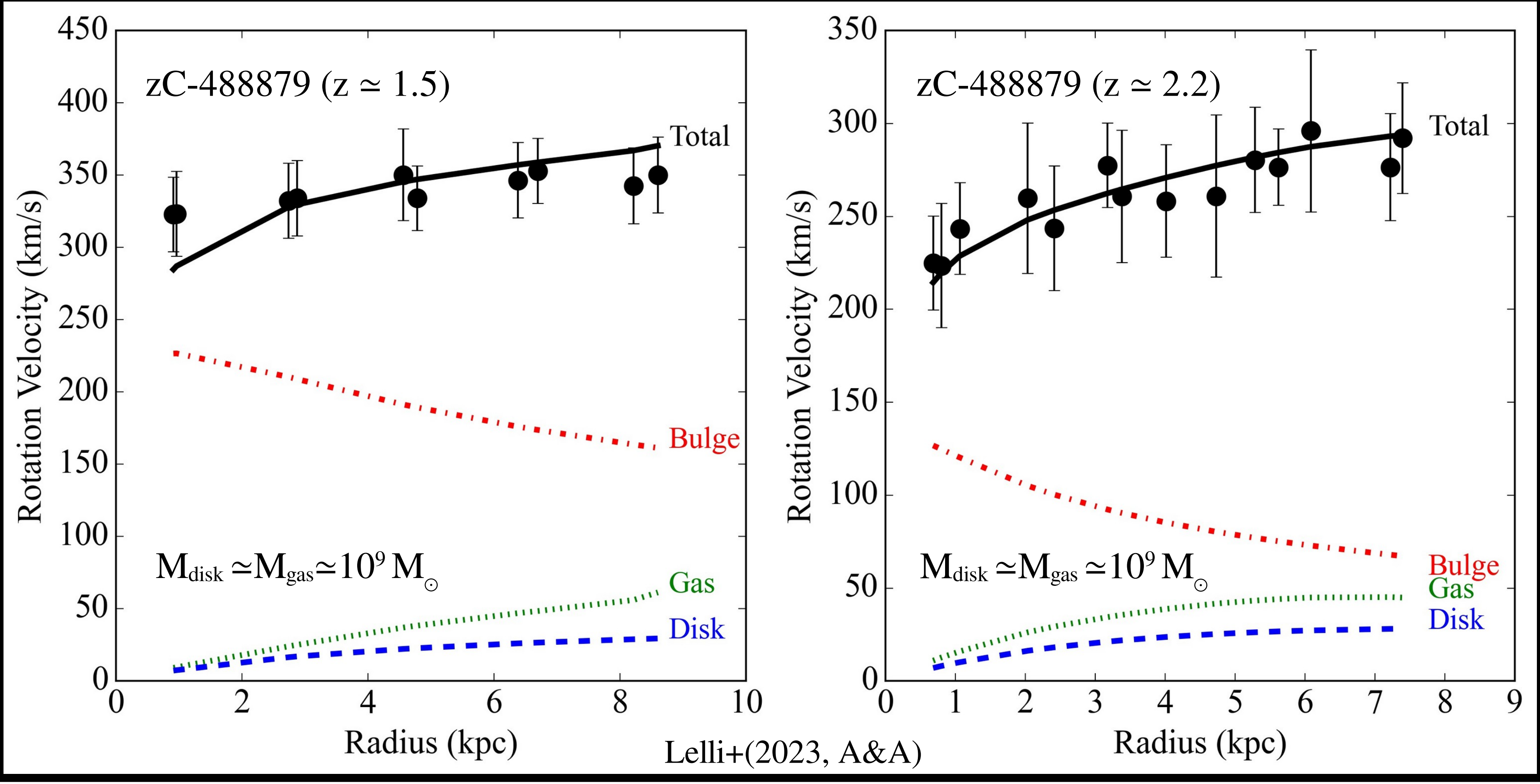
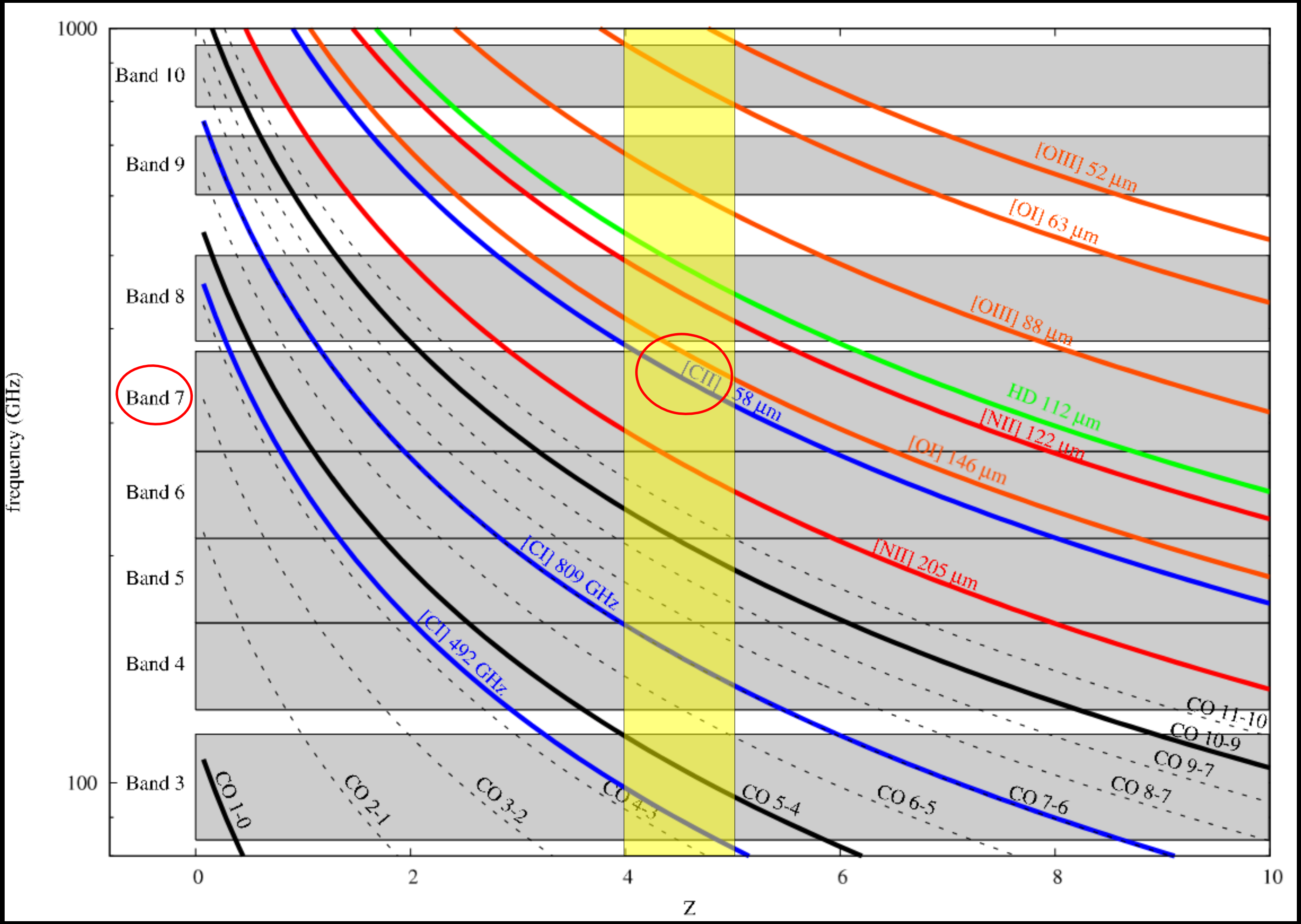


Cold gas tracers at high z with ALMA



[CII] line at 158 μm:

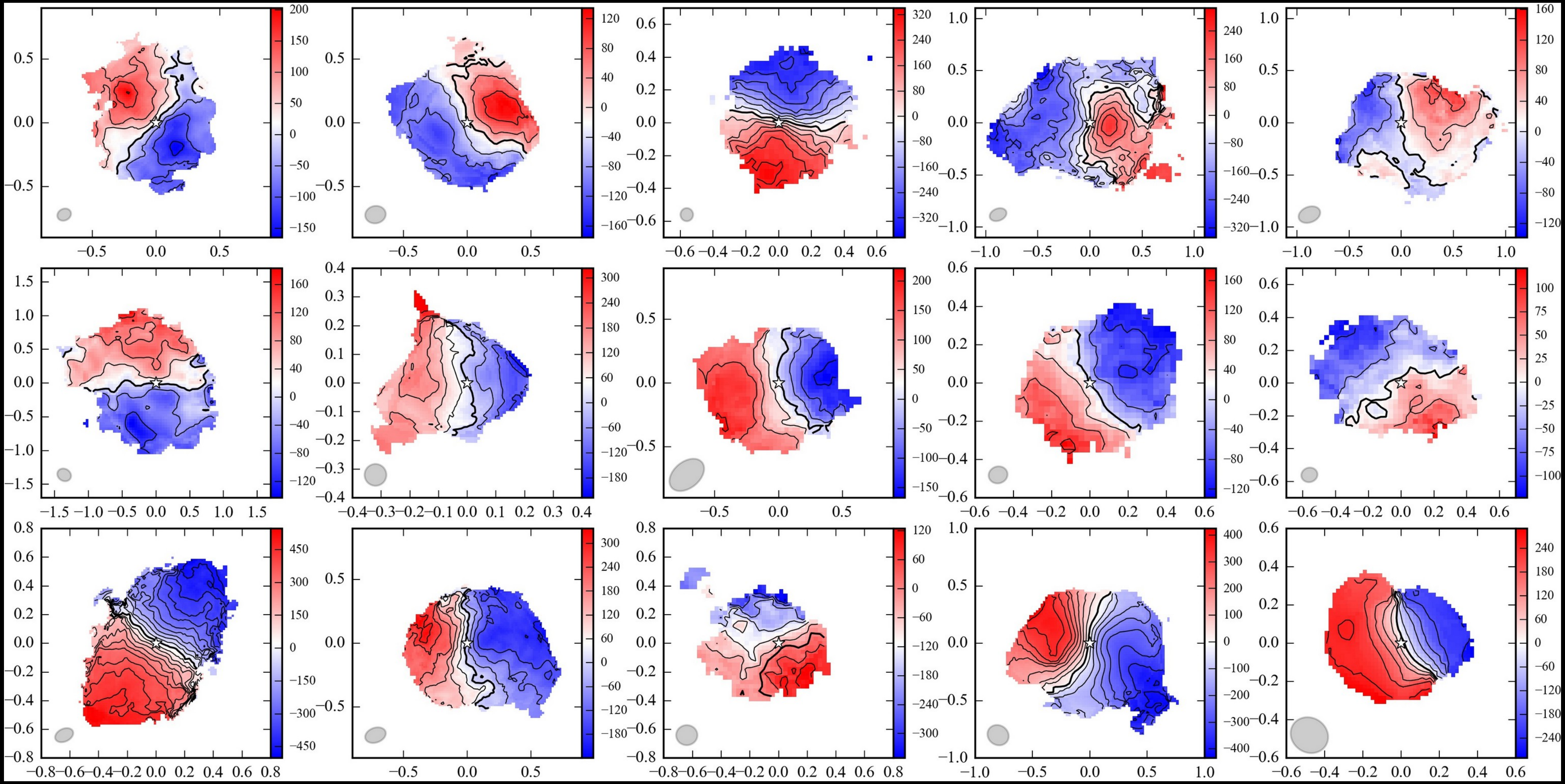
- Main coolant of the ISM: strong & trace cold gas
- Ion. potential of 11.3 eV, similar to HI (13.6 eV)
- Multiphase tracer: atomic, molecular and ionized gas

TRICEPS

Tracing Rotation with Ionized Carbon in Early Primeval Systems

- 15 galaxies at z=4-5 with known [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, DLAs
  → 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



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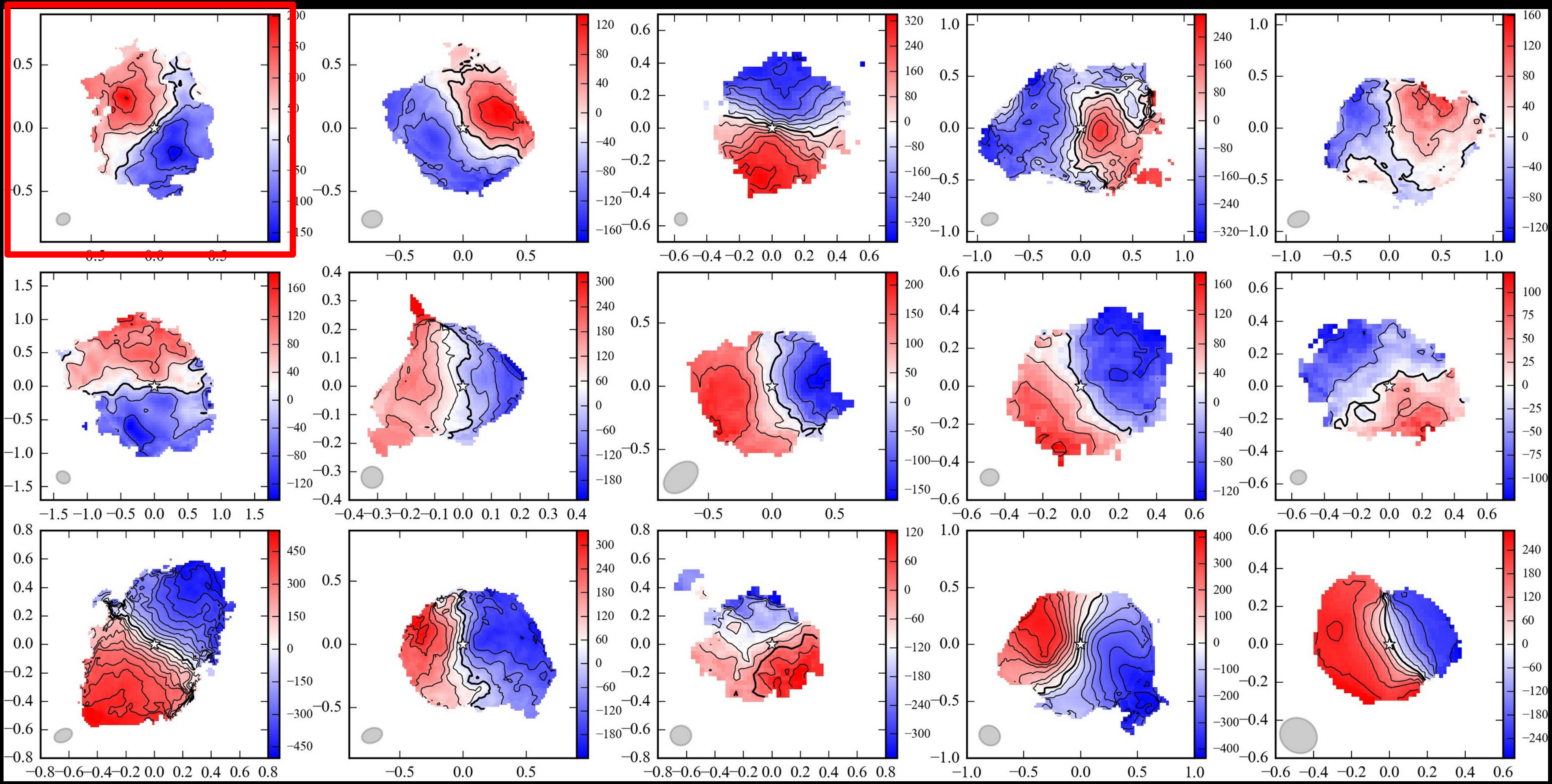
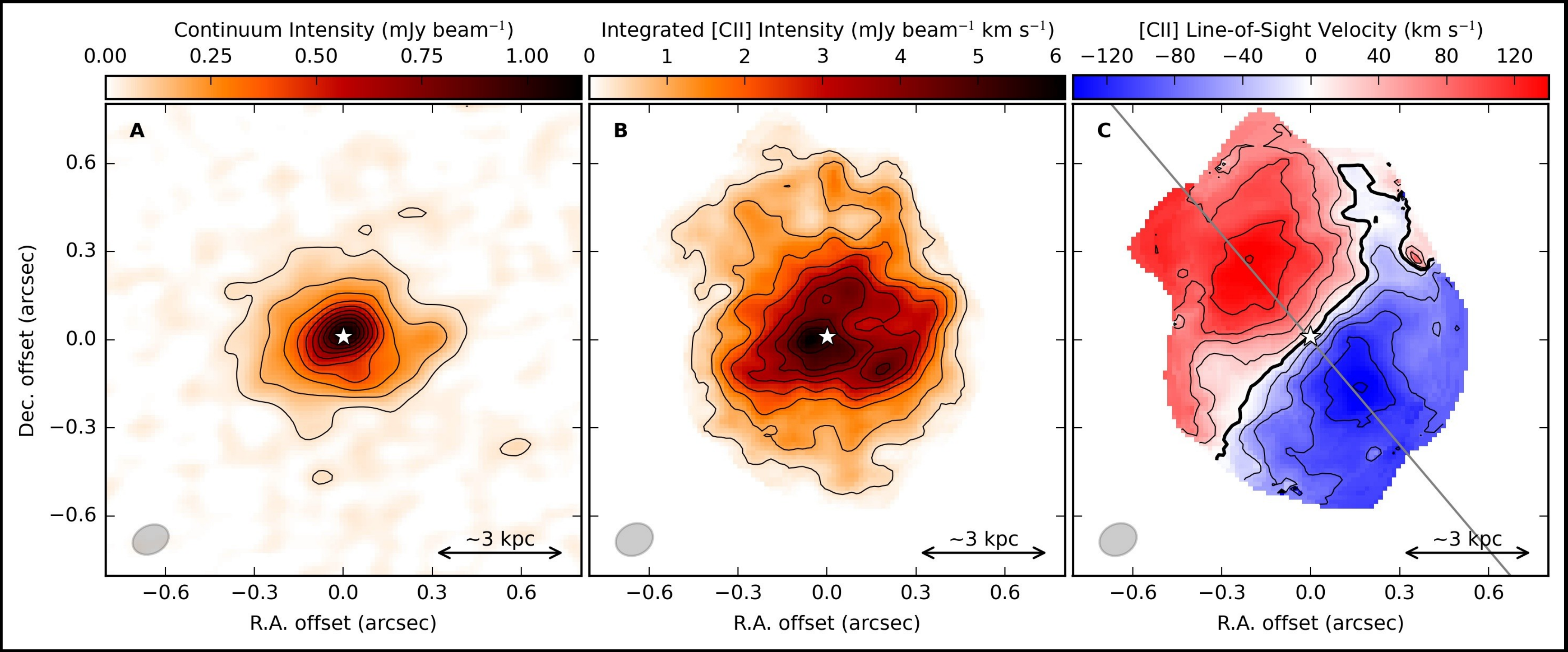


ALESS 73.1 at z≃4.75 (Lelli+2021, Science)



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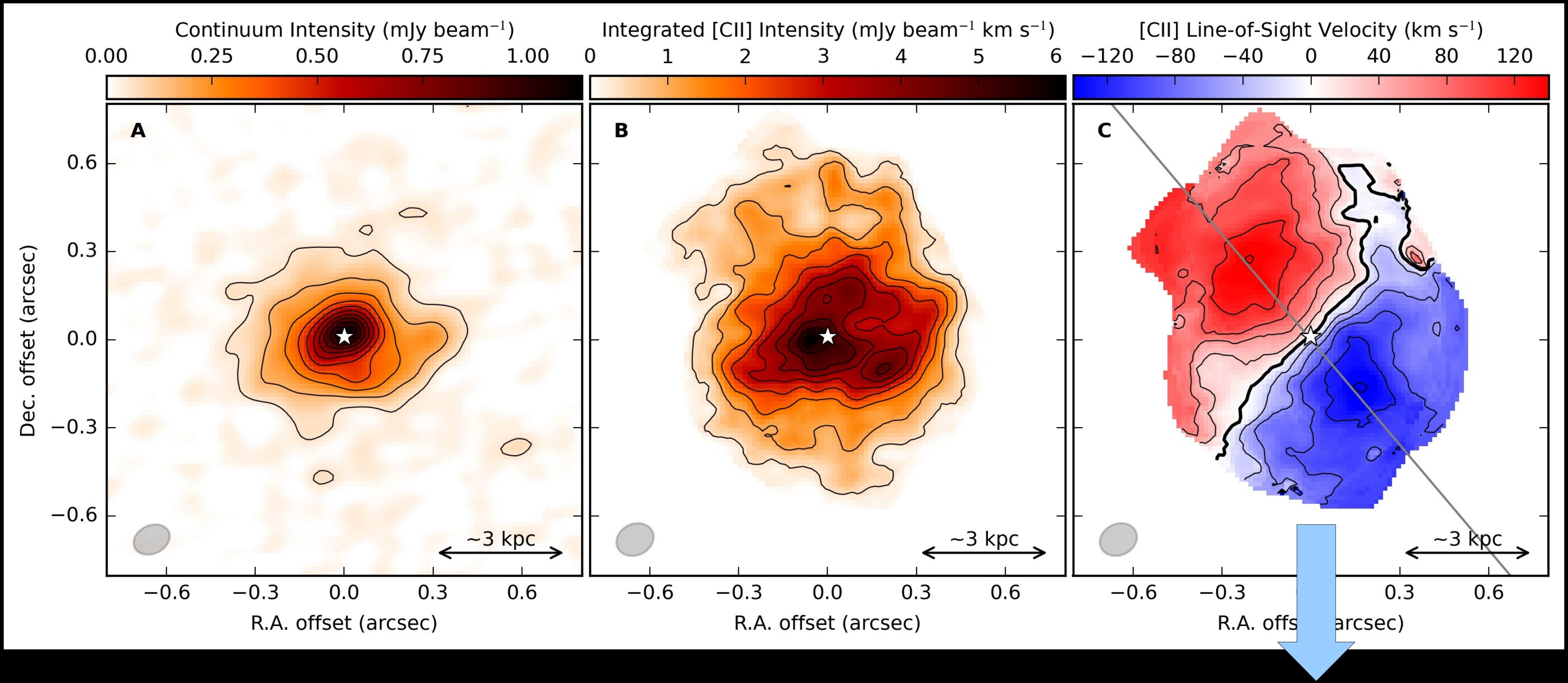

Rotation Curve: $V_{obs}^2 = -R\nabla\Phi_{tot}$

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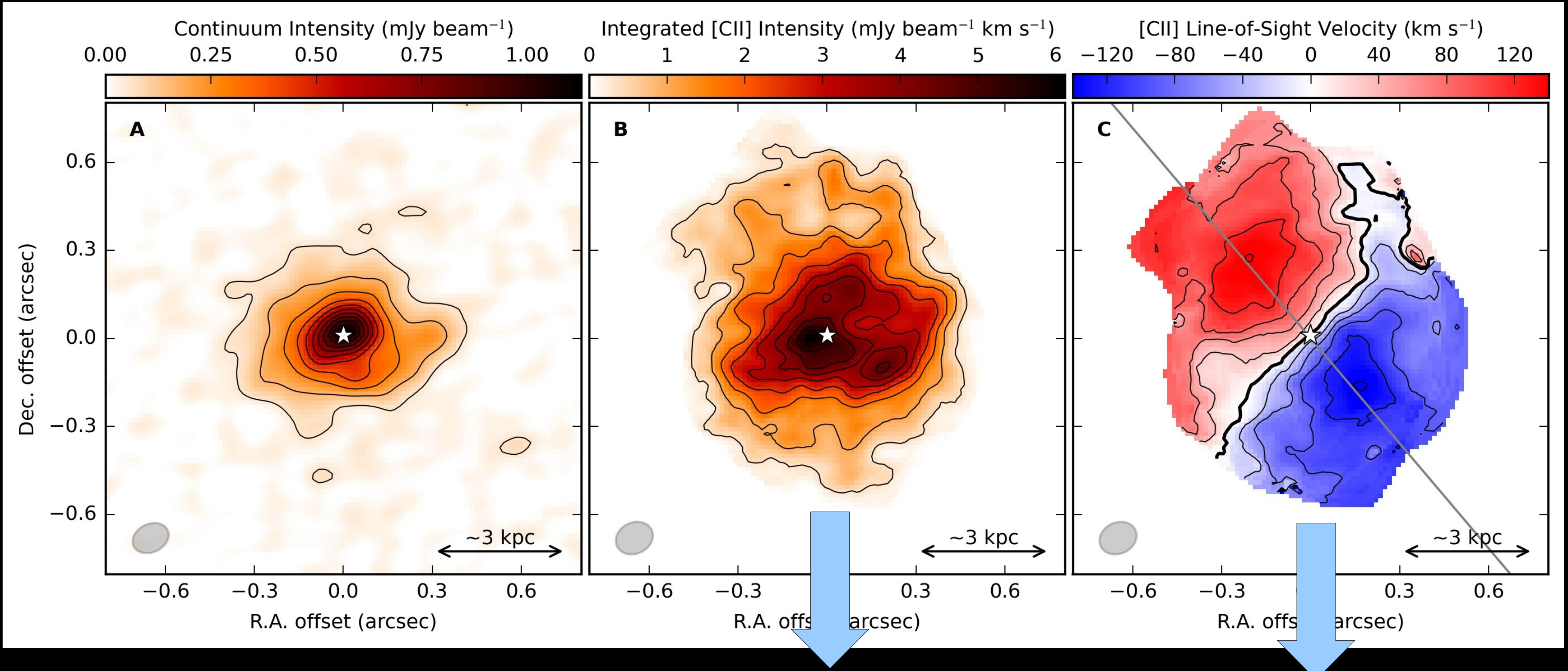

Gas Distribution: $V_{gas}^2 = -R\nabla\Phi_{gas}$ Rotation Curve: $V_{obs}^2 = -R\nabla\Phi_{tot}$

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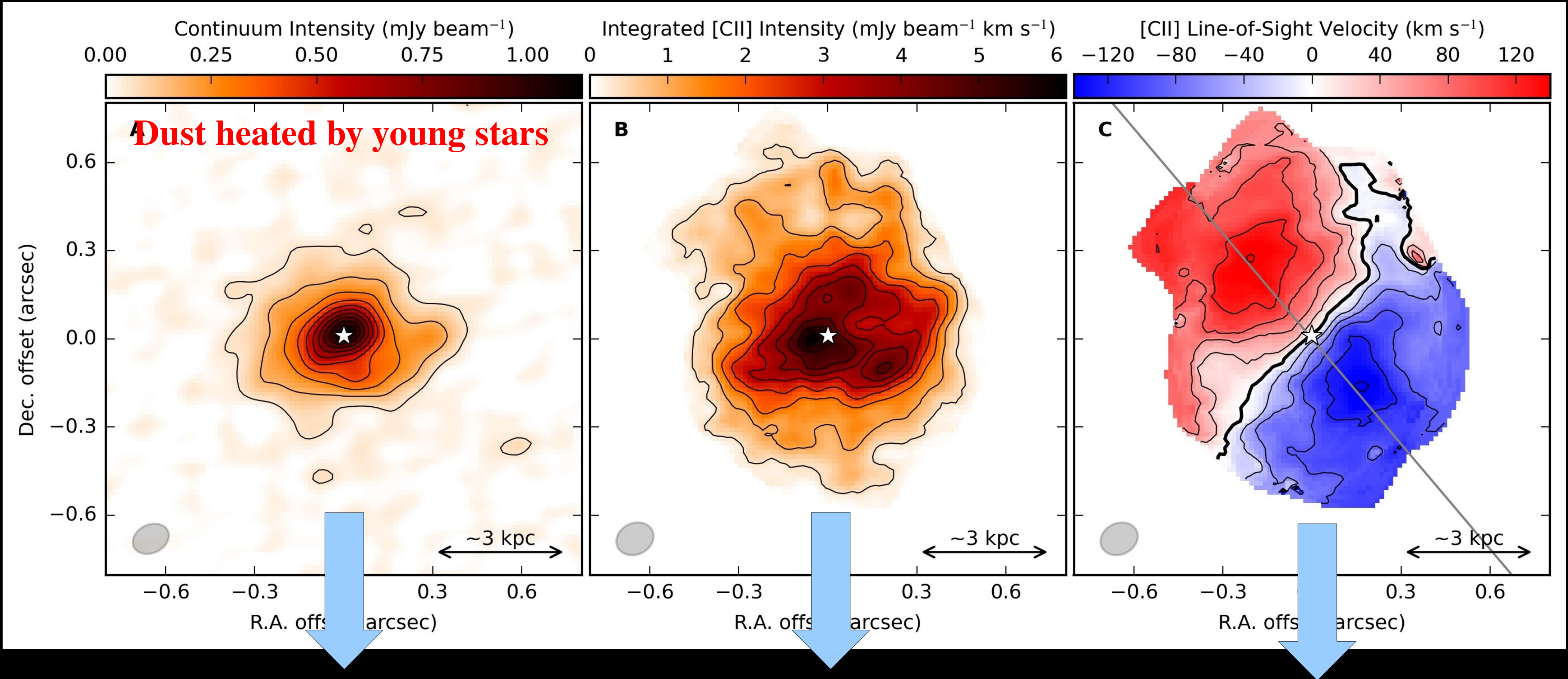
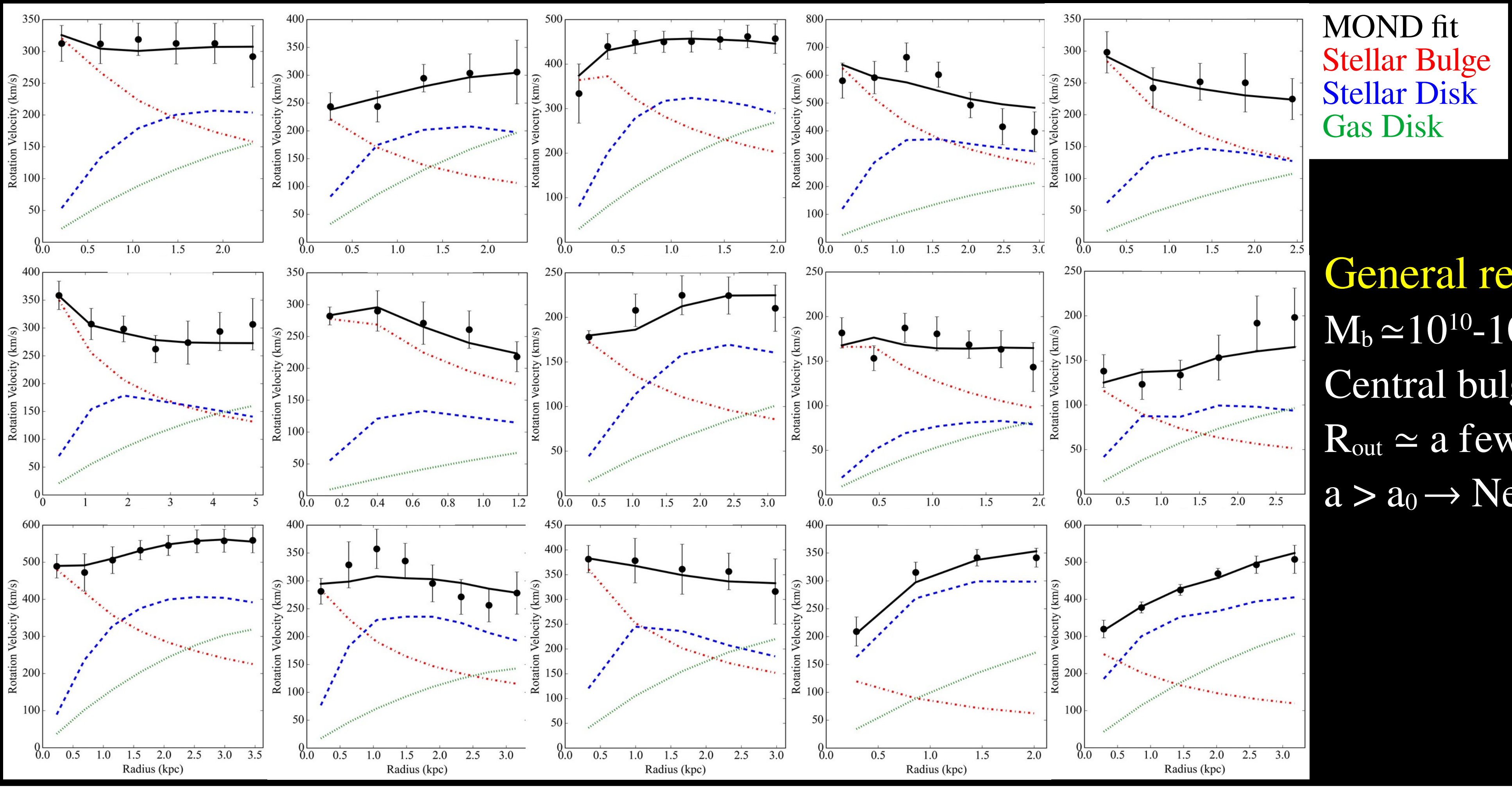


Disk Distribution: $V_{disk}^2 = -R\nabla\Phi_{disk}$ Gas Distribution: $V_{gas}^2 = -R\nabla\Phi_{gas}$ Rotation Curve: $V_{obs}^2 = -R\nabla\Phi_{tot}$

MOND fits at $z \simeq 4\text{-}5$ with $a_0 = 1.2 \cdot 10^{-10}$ m/s^2



General results:

$M_b \simeq 10^{10}\text{-}10^{11}\, M_\odot$

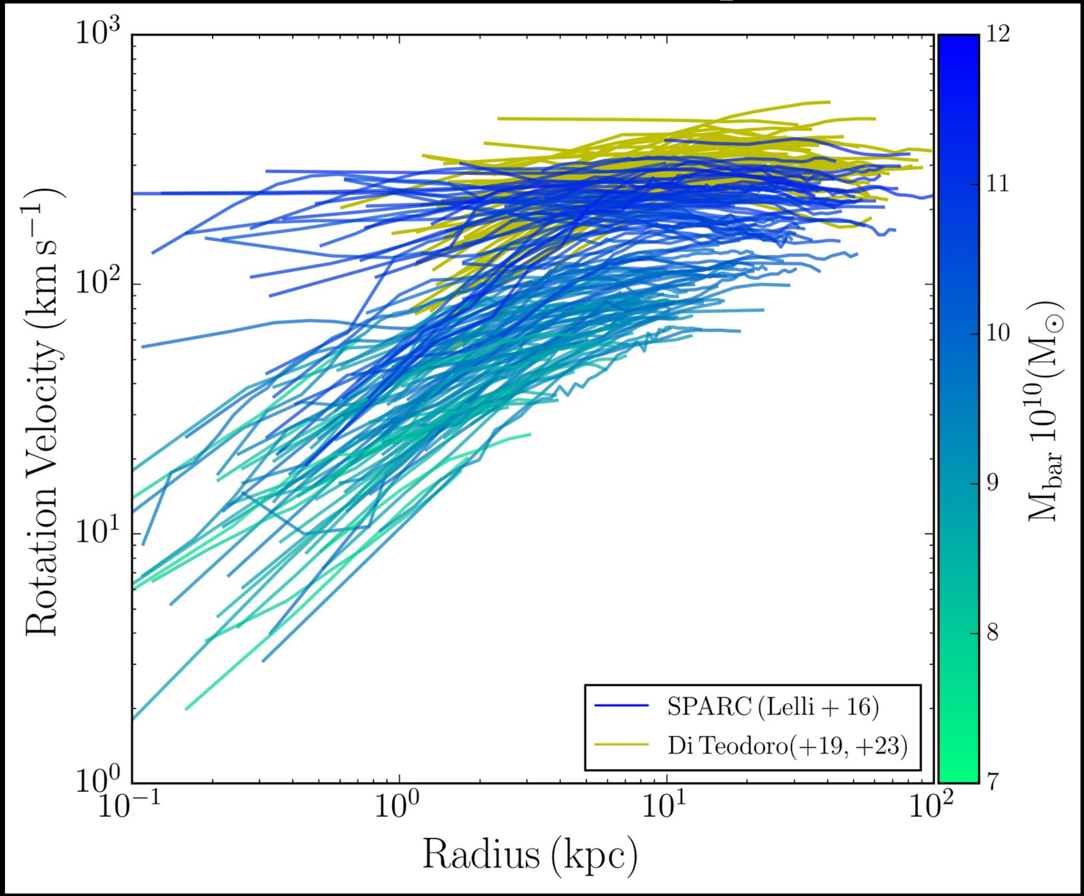
Central bulges

$R_{out} \simeq$ a few kpc

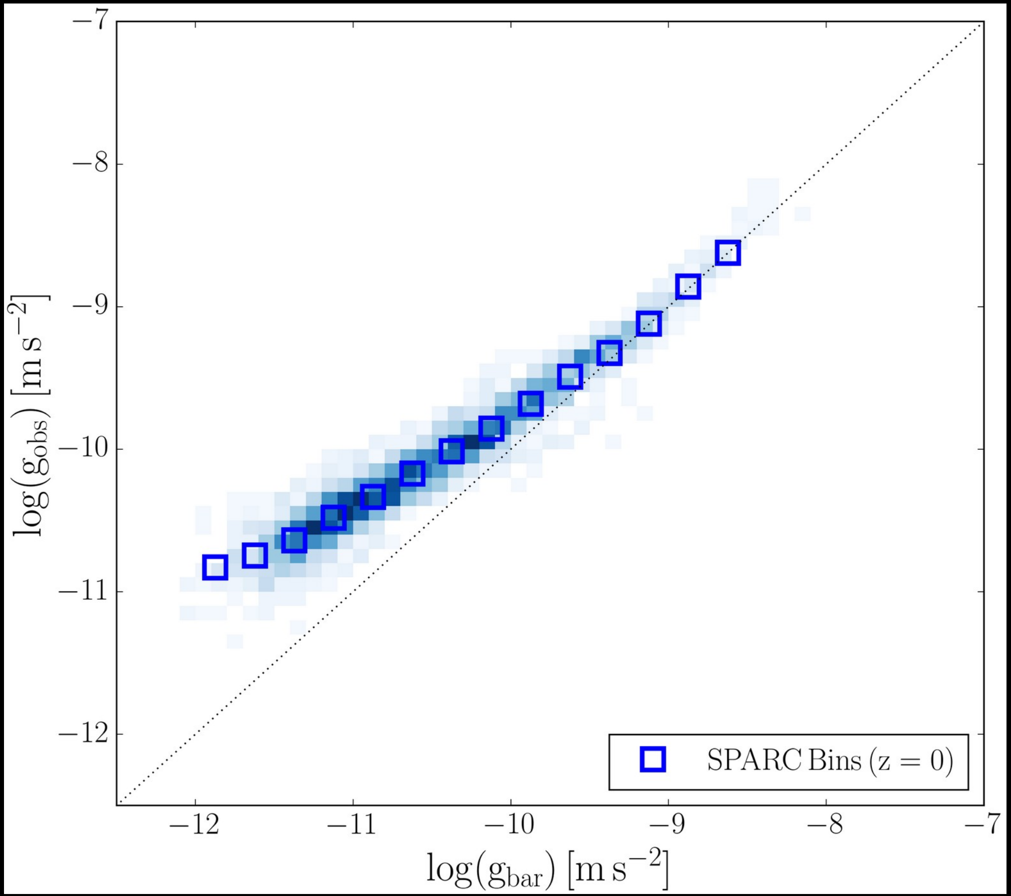
$a > a_0 \rightarrow$ Newton

Comparison with Massive Spirals at z=0

Rotation Curve Shapes



Radial Acceleration Relation



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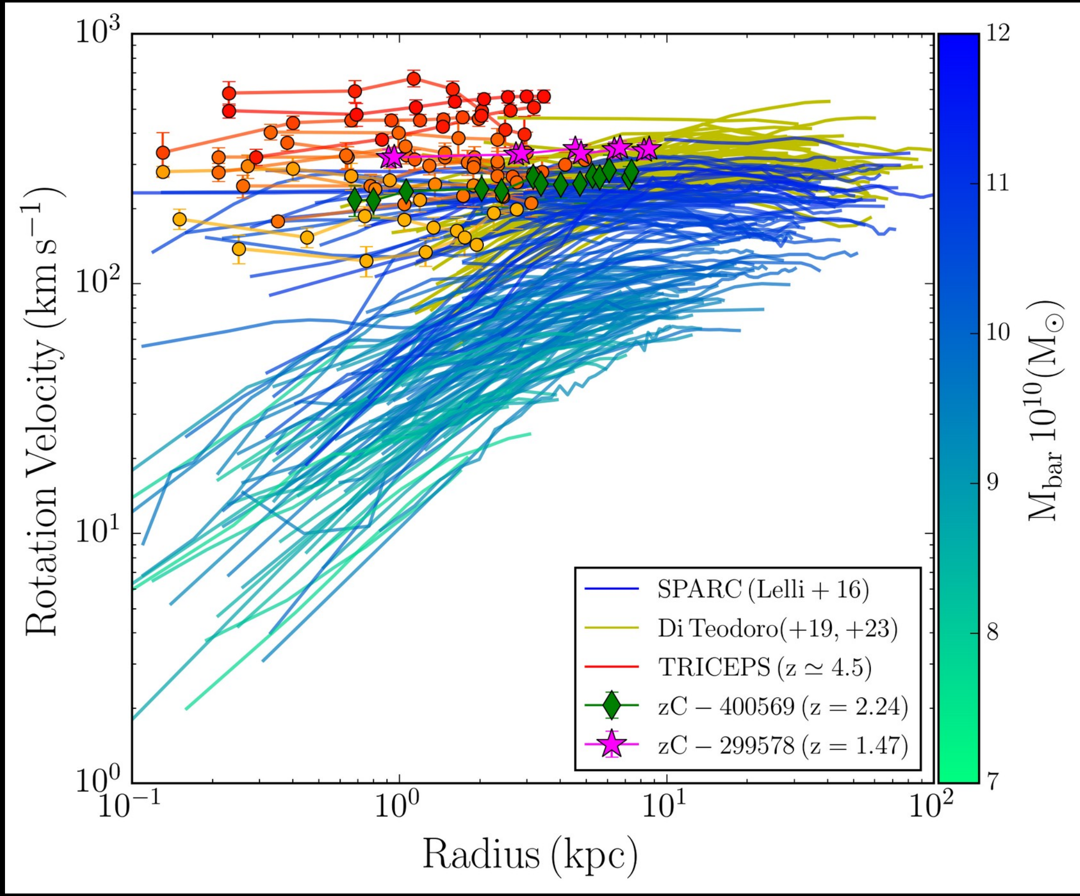

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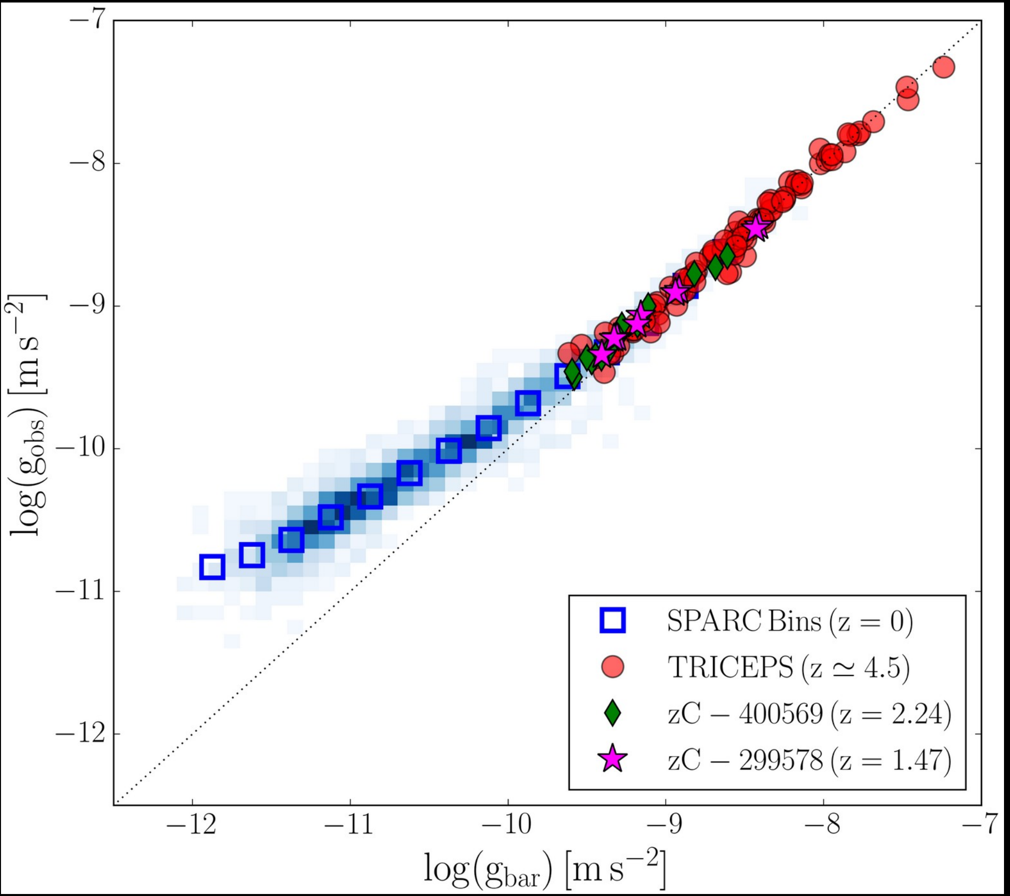
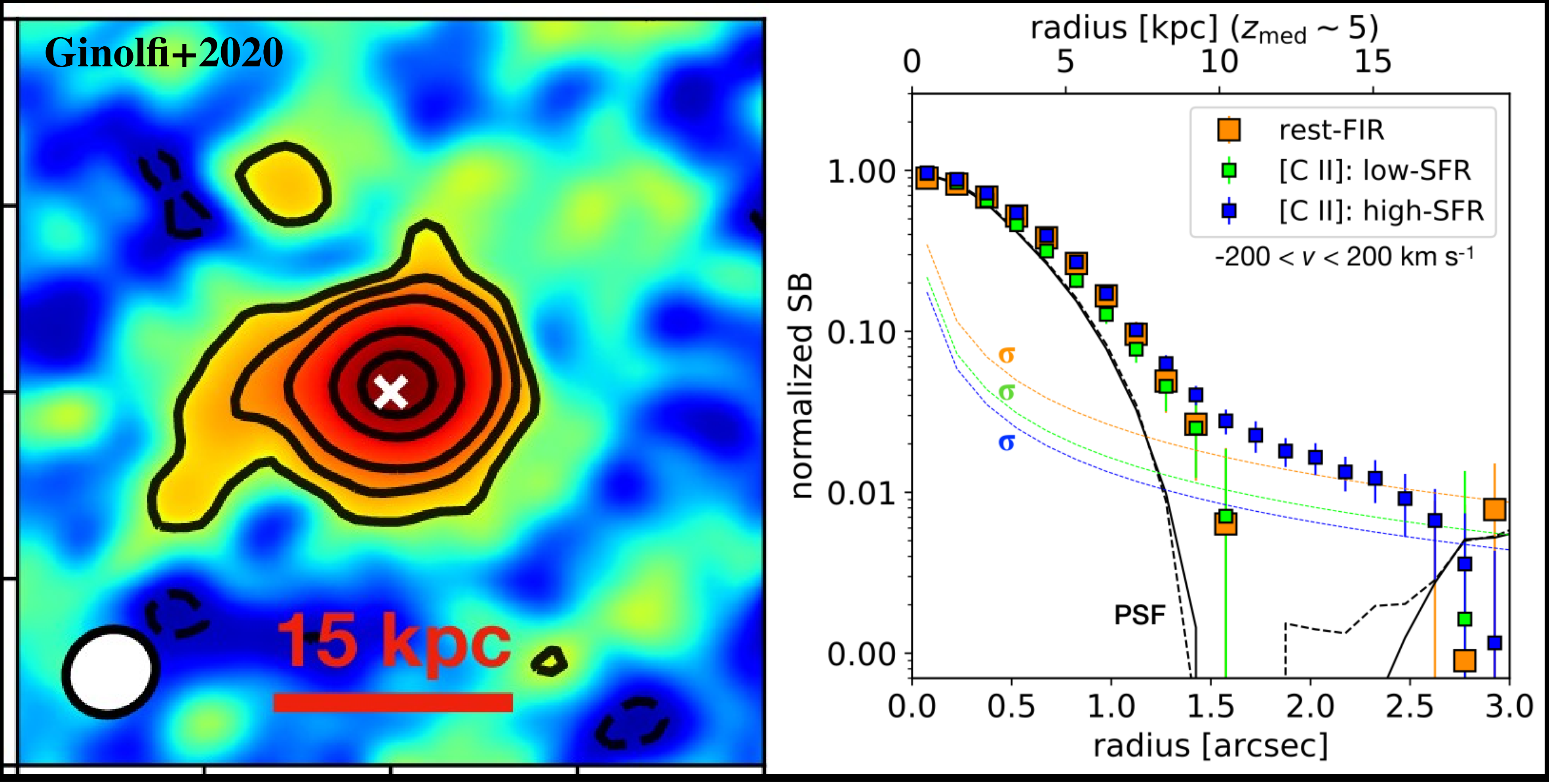


[CII] Stacking: Extended Gas Emission



Future Prospects:

Ultra-deep [CII] observations:

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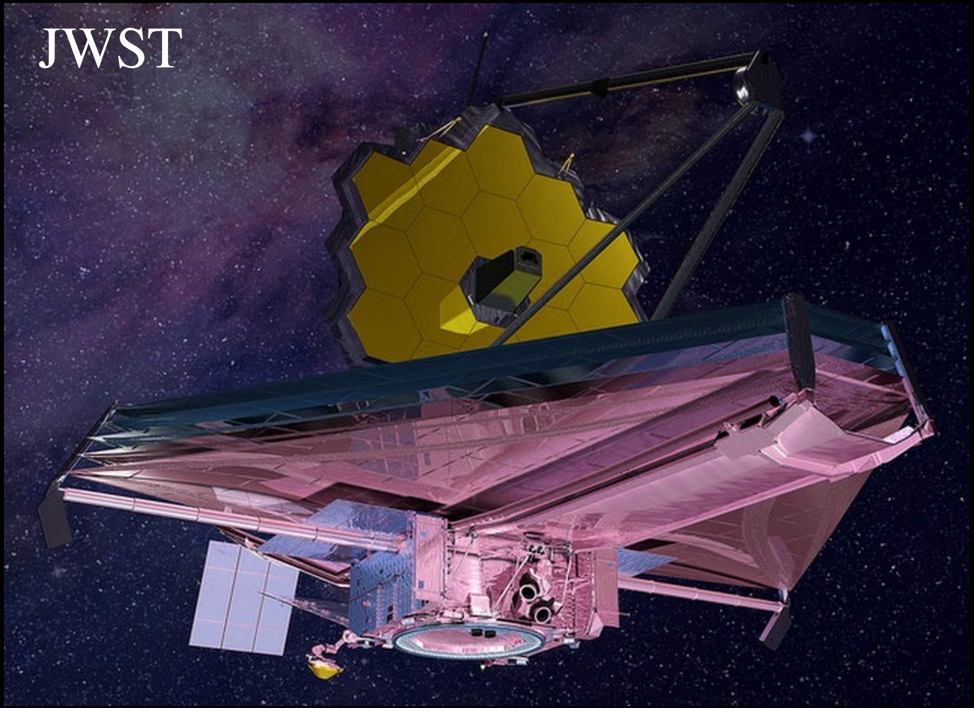

Ultra-deep [CII] observations:
→ More extended rotation curves
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Rest-frame UV-to-NIR imaging:
→ Actual stellar mass distribution
→ Proposal approved!!!

Conclusions:

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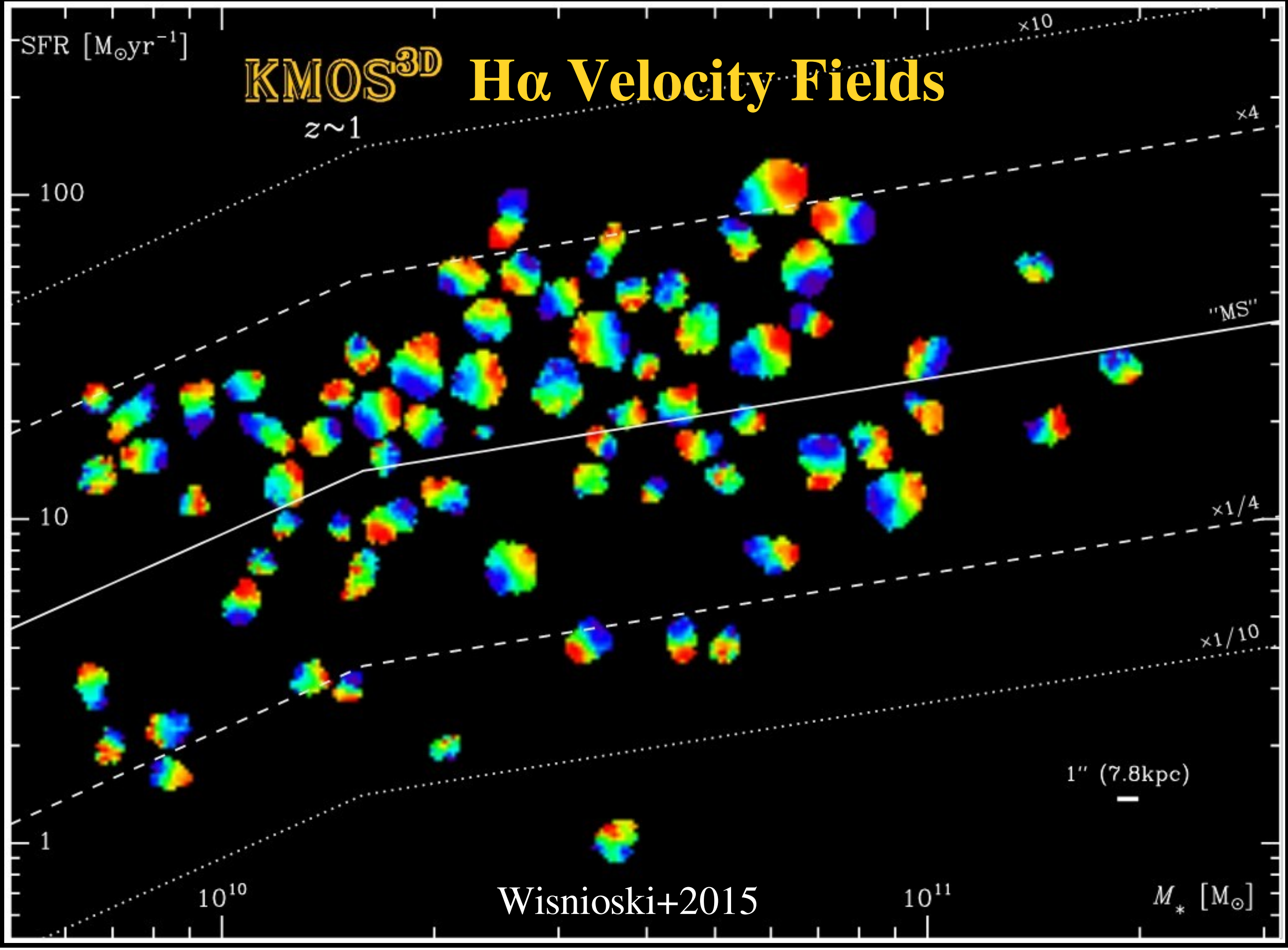
3. Evolution of a_0 with z

   $a_0 \propto (1+z)^b$ with $b>3 \rightarrow$ ruled out (too low M_{bar})

   $a_0 \propto (1+z)^{3/2} \rightarrow$ seems unlikely (need accurate M_{bar})

More Slides

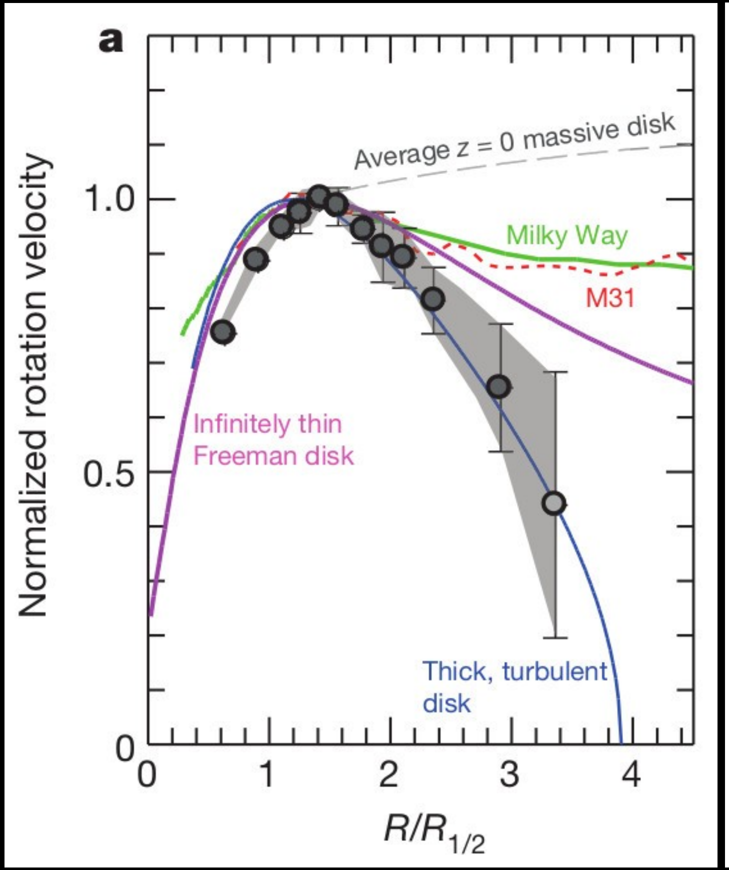
Warm ionized gas in galaxies at z~1-3



- IFU observations of Hα and [OIII]λ5007 redshifted in the NIR.
- More than 80% of main-sequence galaxies host a rotating disk.
- Most star formation occurs in regular disks, not in galaxy mergers.

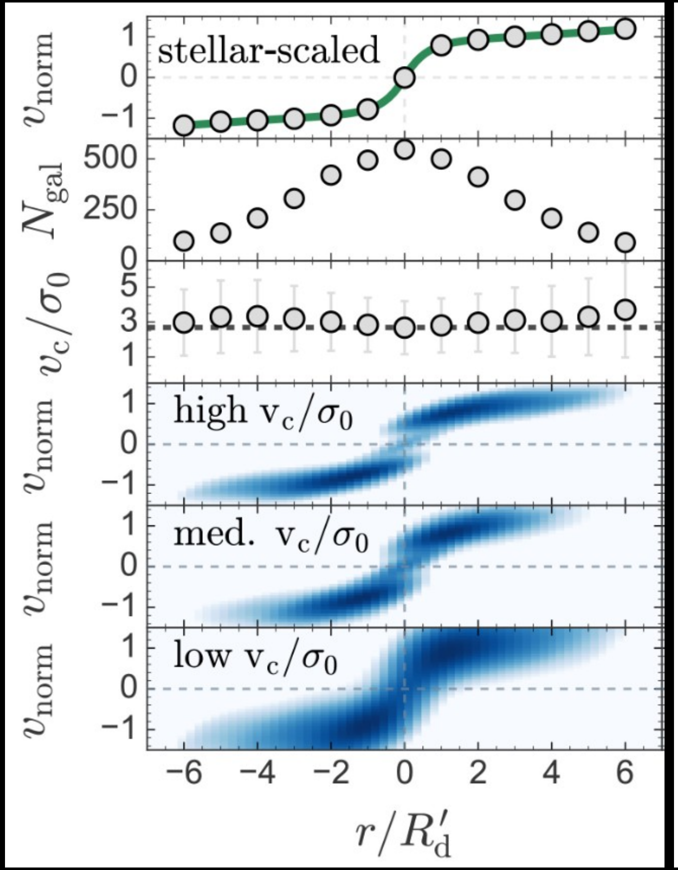
Ionized Gas Dynamics: Confusing Situation!

Declining RCs & low V_{rot}/σ_V



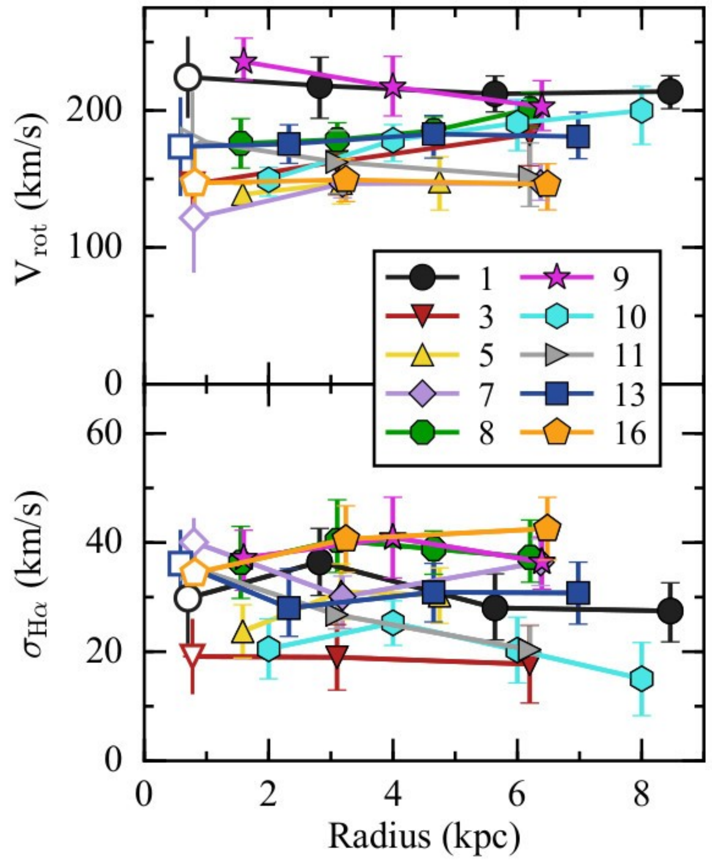
Lange+2017; Genzel+2017, 2020

Flat RCs & low V_{rot}/σ_V



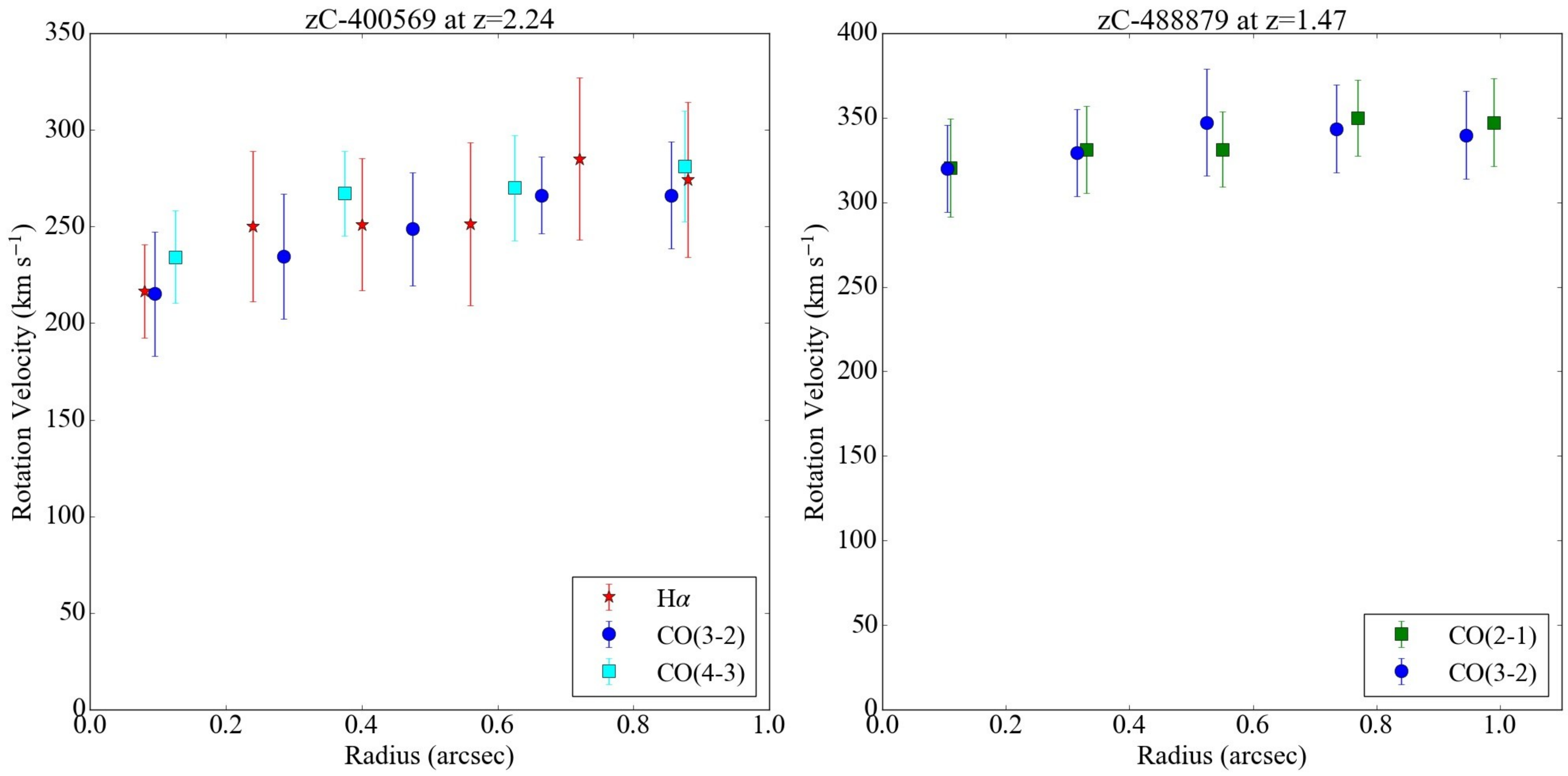
Tiley+2019; Puglisi+2023

Flat RCs & high V_{rot}/σ_V

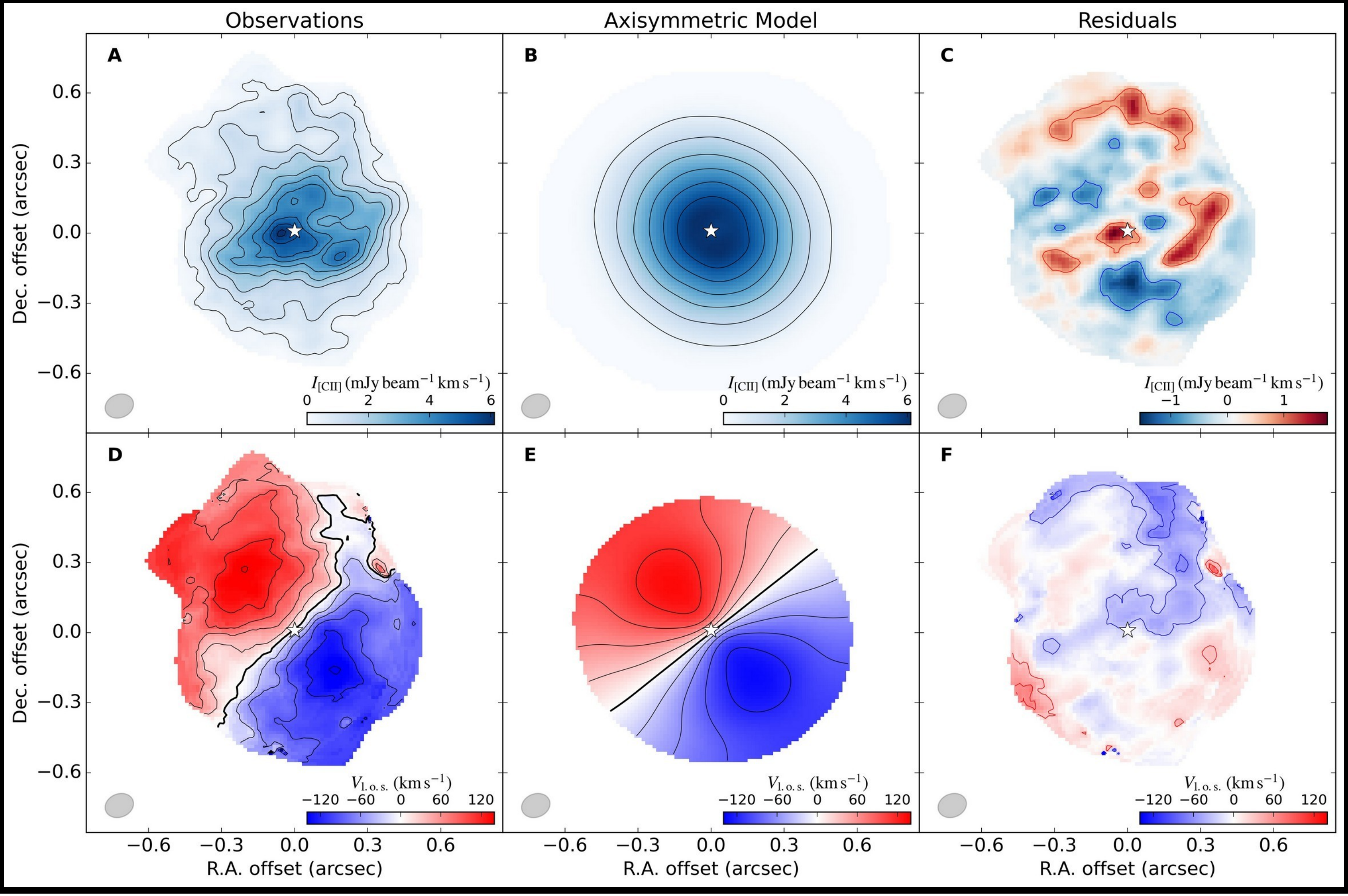


Di Teodoro+2016; 2018

Rotation curves from different emission lines

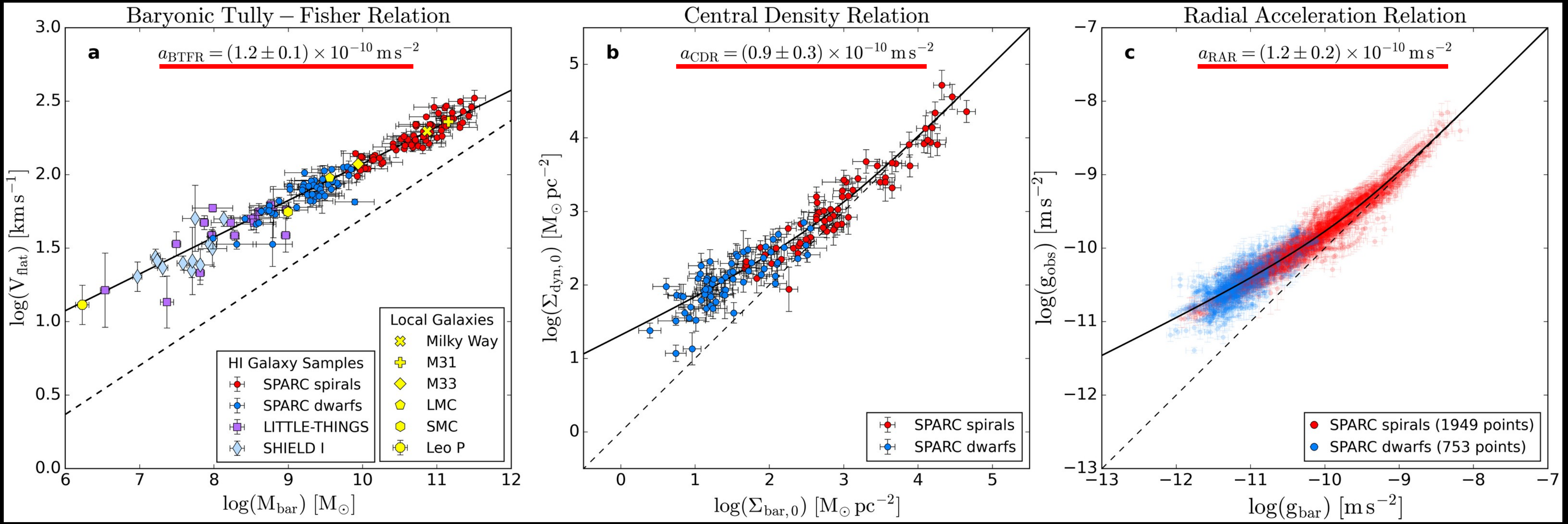


Weak Non-Circular Motions at z~4.8



Lelli+2021, Science

Three Scaling Laws → Three Acceleration Scales



$a_{\rm BTFR}$ → Normalization BTFR
→ Global baryon-to-DM ratio across galaxies

$a_{\rm CDR}$ → Critical Surface Density
→ Transition baryon to DM dominated galaxies at R=0

$a_{\rm RAR}$ → Acceleration Scale
→ Transition baryon to DM domination inside galaxies

Galaxy Dynamics: Basic Theory

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

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

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

Velocity dispersion (random motions) $\simeq \sigma_{los}$