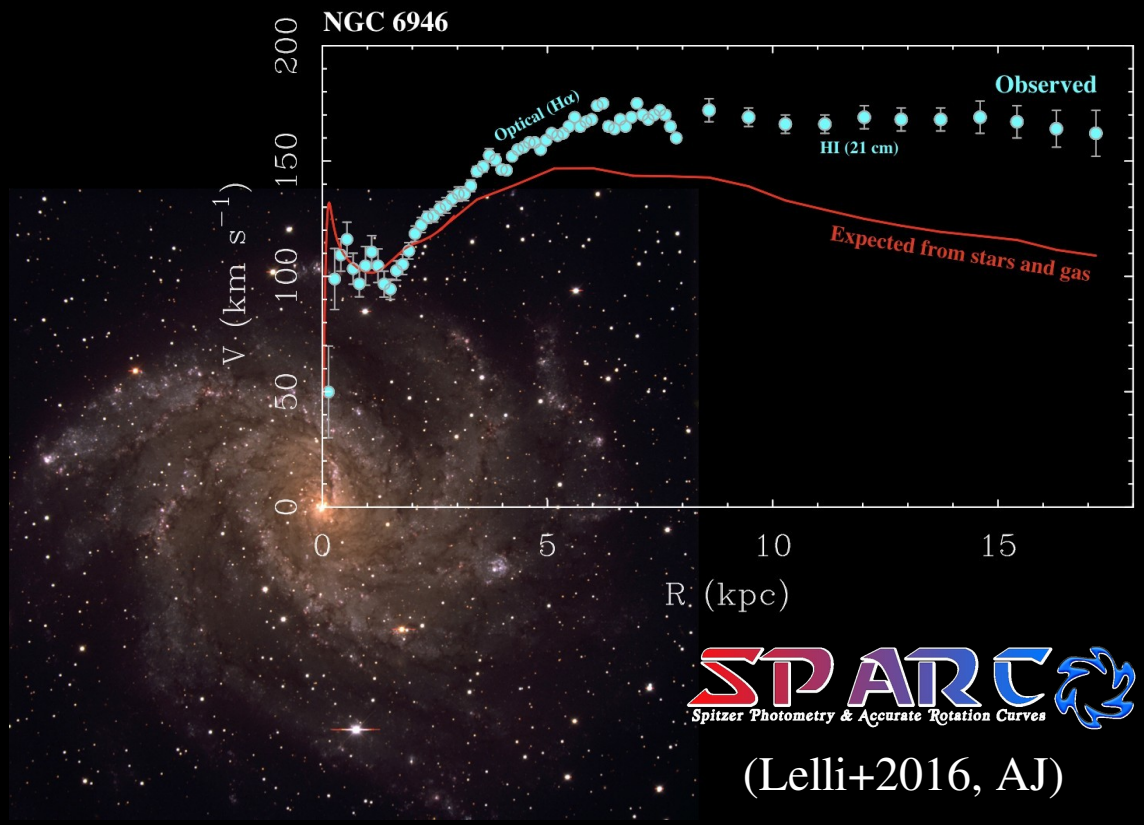
Cold Gas Dynamics in High-z Galaxies

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



SPARC
Spitzer Photometry & Accurate Rotation Curves

(Lelli+2016, AJ)

- Rotation Curves

→ Mass models (baryons & DM)

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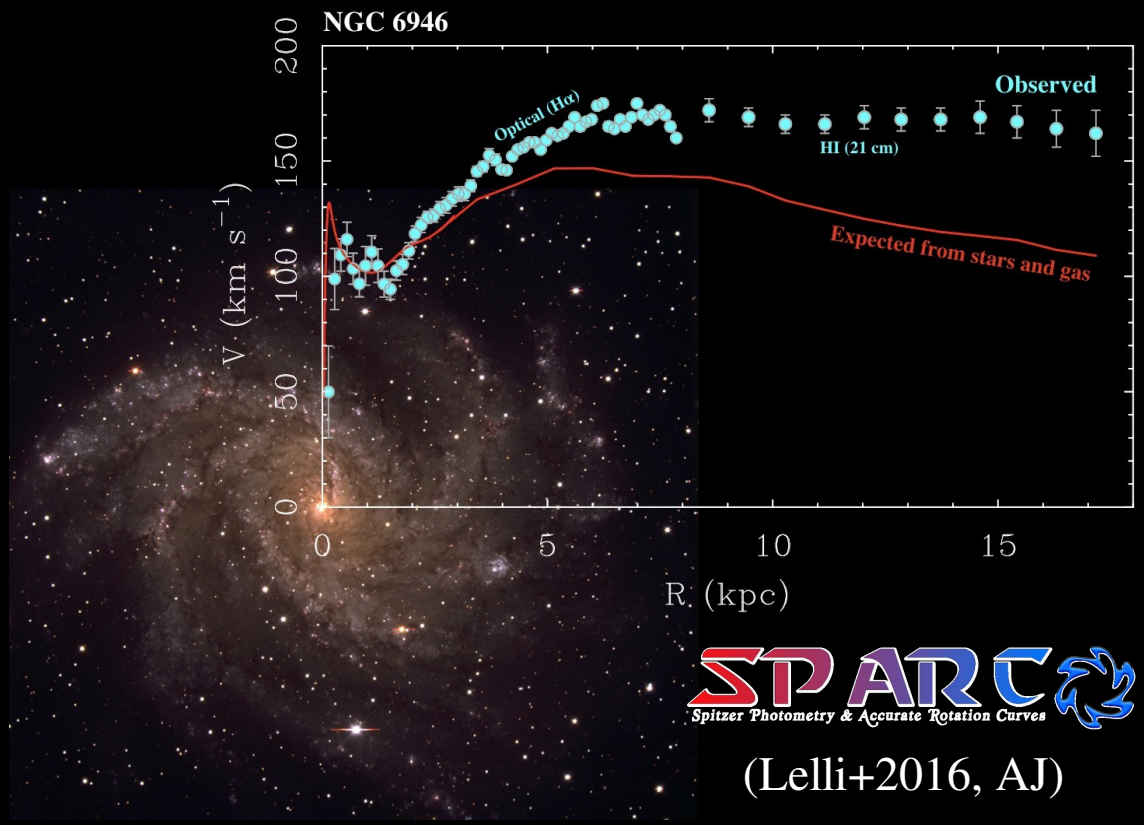

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  → Inflows, outflows, bars, spirals

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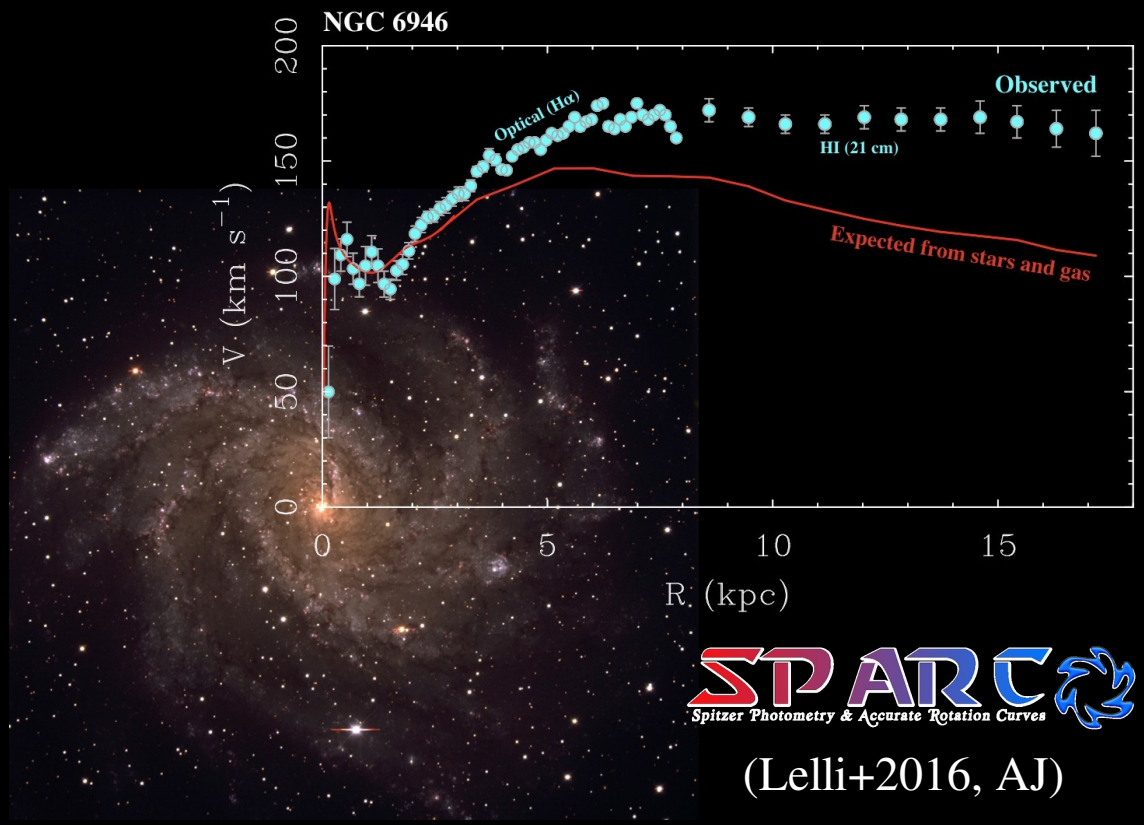

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  → Star formation & feedback

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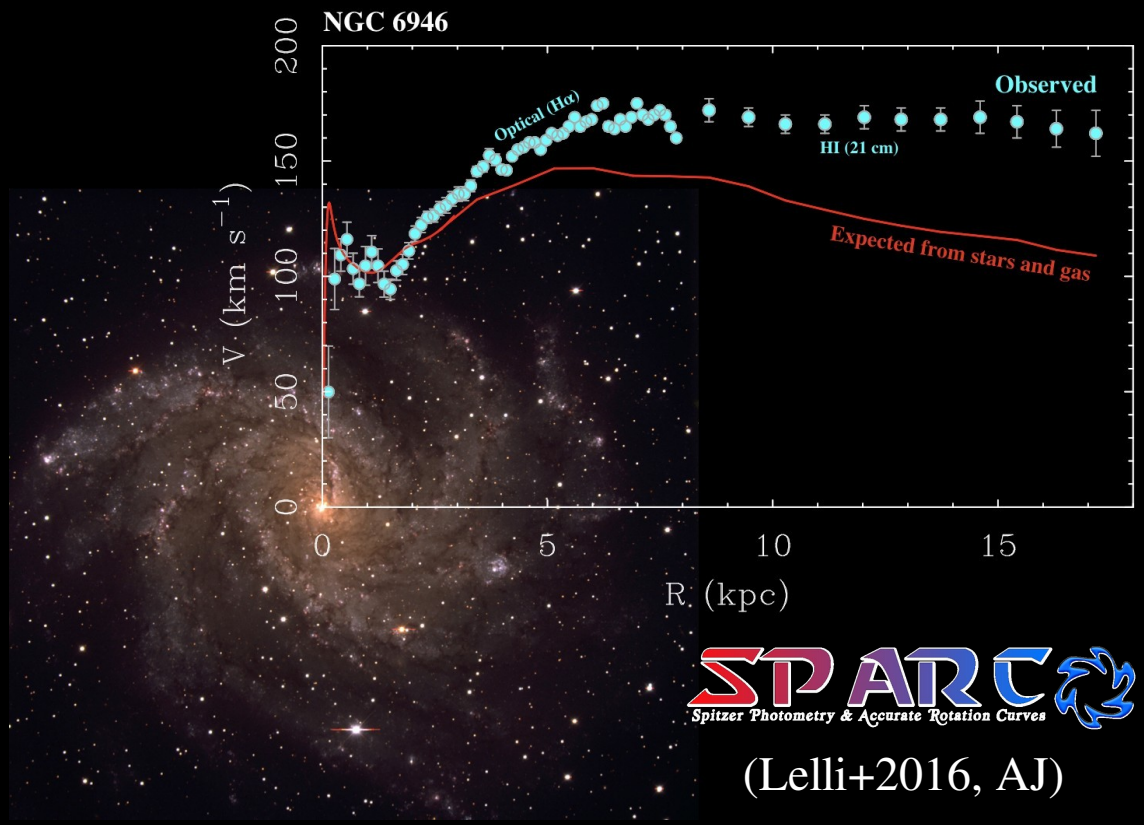

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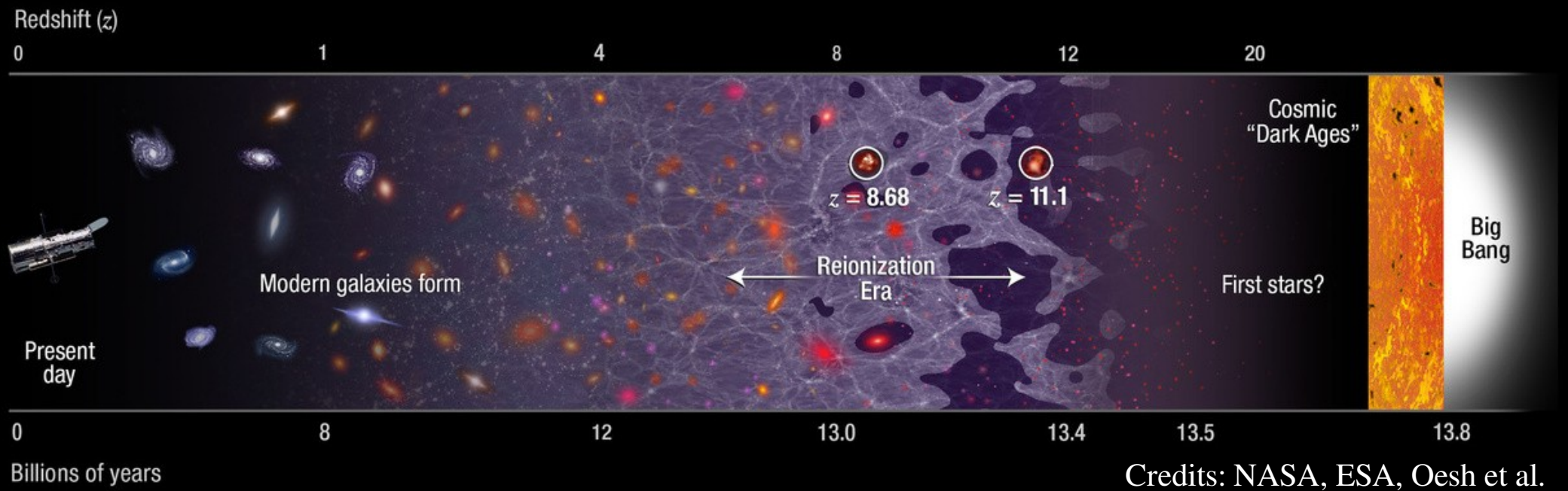
- Gas turbulence
  → Star formation & feedback
- Environmental phenomena
  → Interactions, mergers, gas stripping

Gas Dynamics across Cosmic Time



Credits: NASA, ESA, Oesh et al.

Ionized gas: Hα
Atomic gas: HI
Molecules: CO

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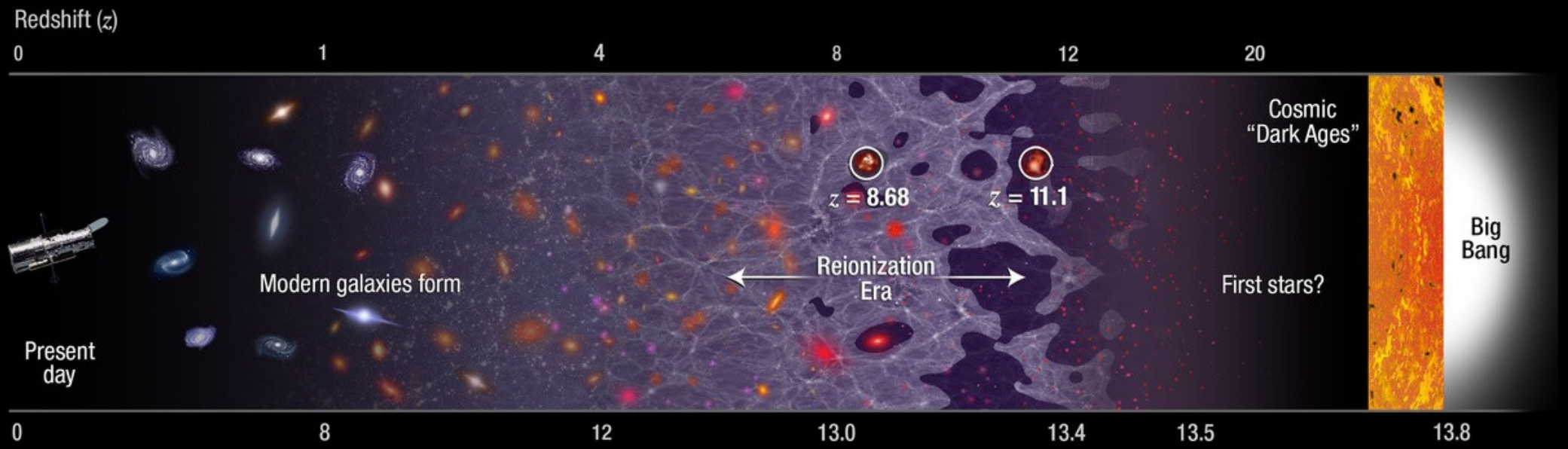

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Hα, [OIII]λ5007
With ALMA:
High-J CO lines

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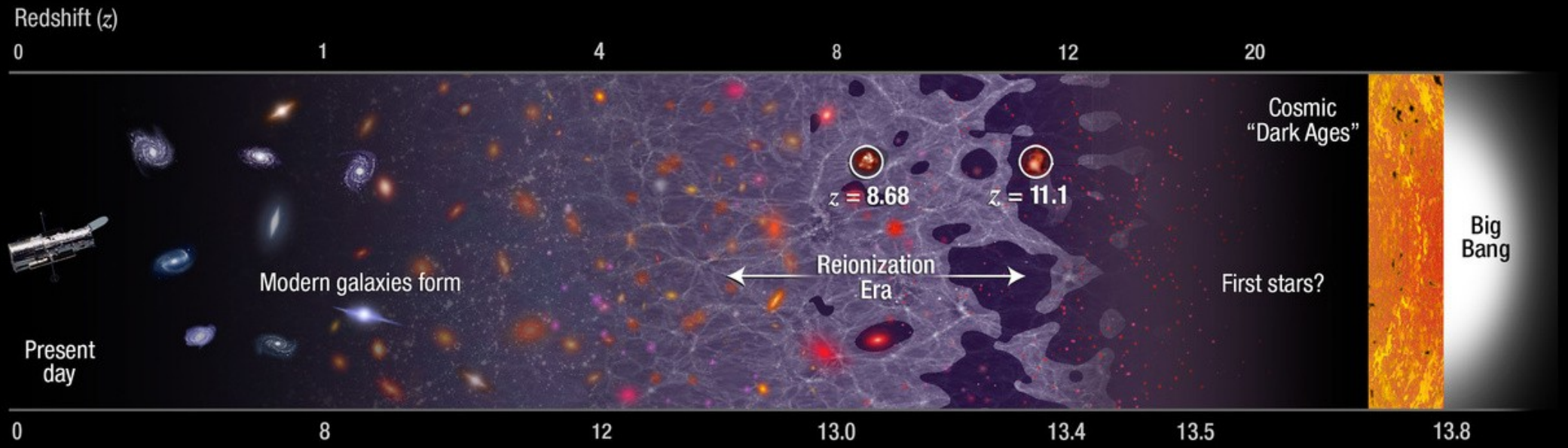

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Hα, [OIII]λ5007
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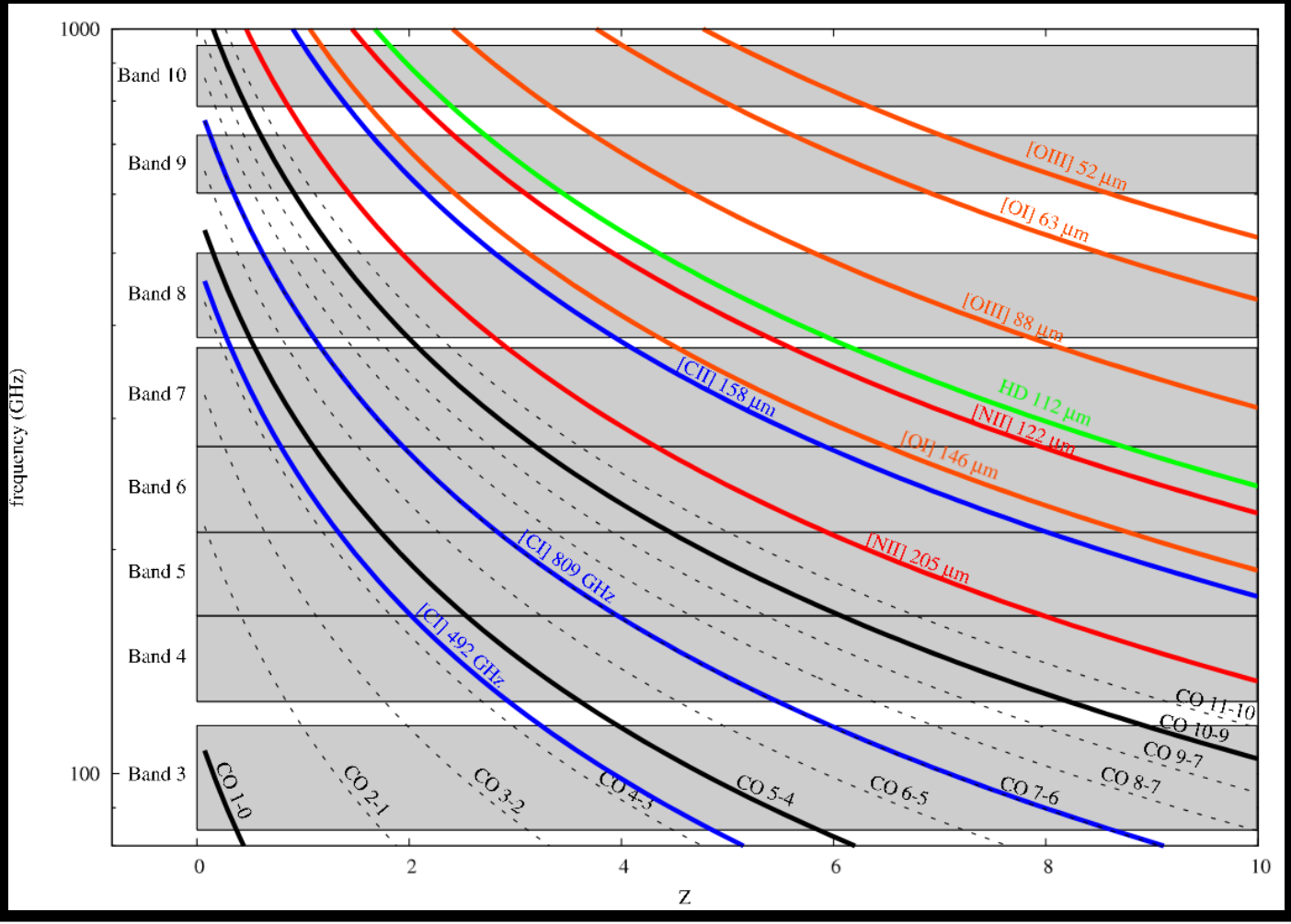
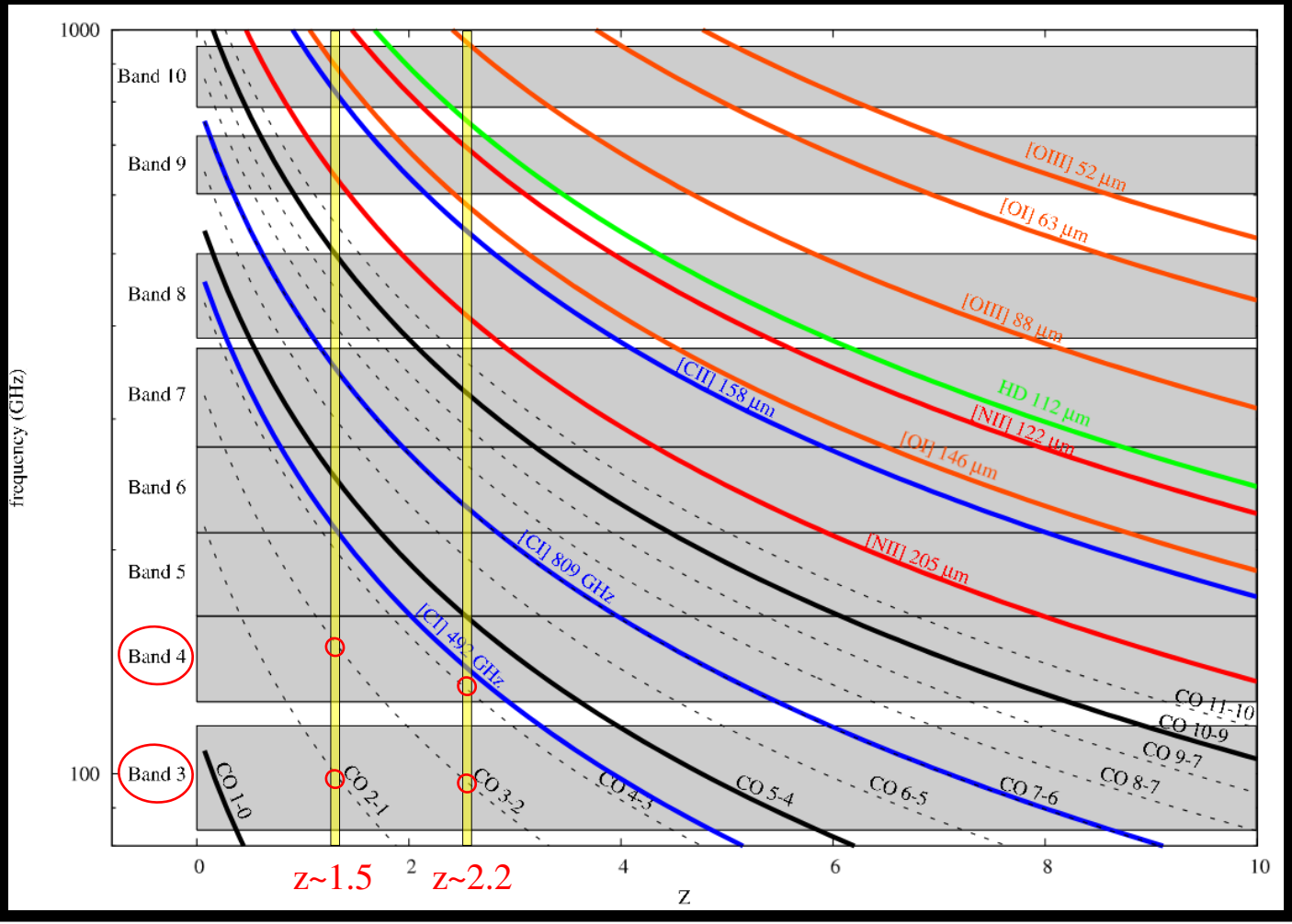
JWST: Hα, [OIII]λ5007
With ALMA:
Ionized Carbon: [CII]

Cold Gas Tracers at high-*z* with ALMA



De Ugarte Postigo+(2012, A&A)

Cold Gas Tracers at high-*z* with ALMA

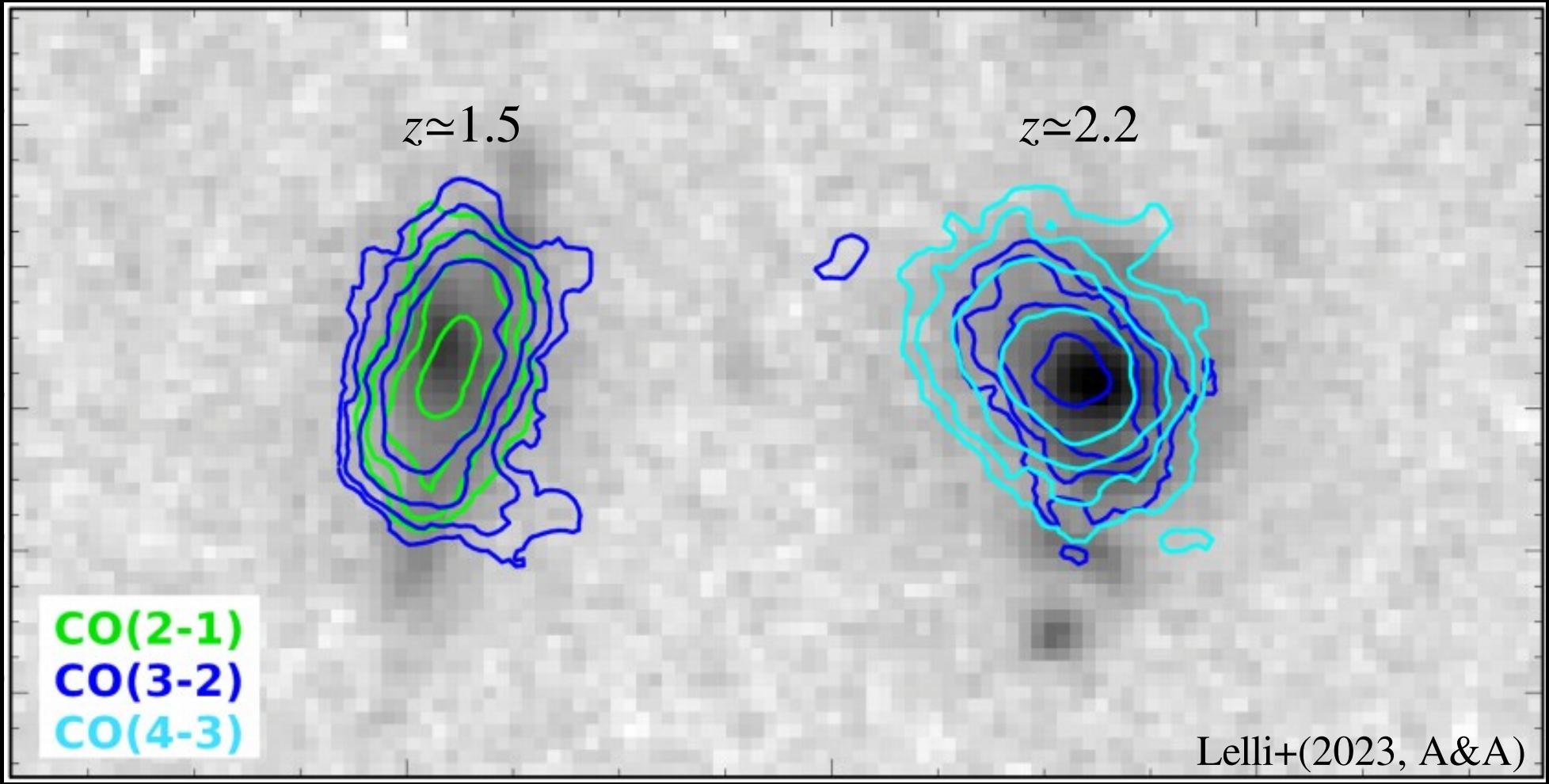


High-resolution study of two disk galaxies:

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

Lelli+(2023, A&A)

Two main-sequence galaxies at cosmic noon



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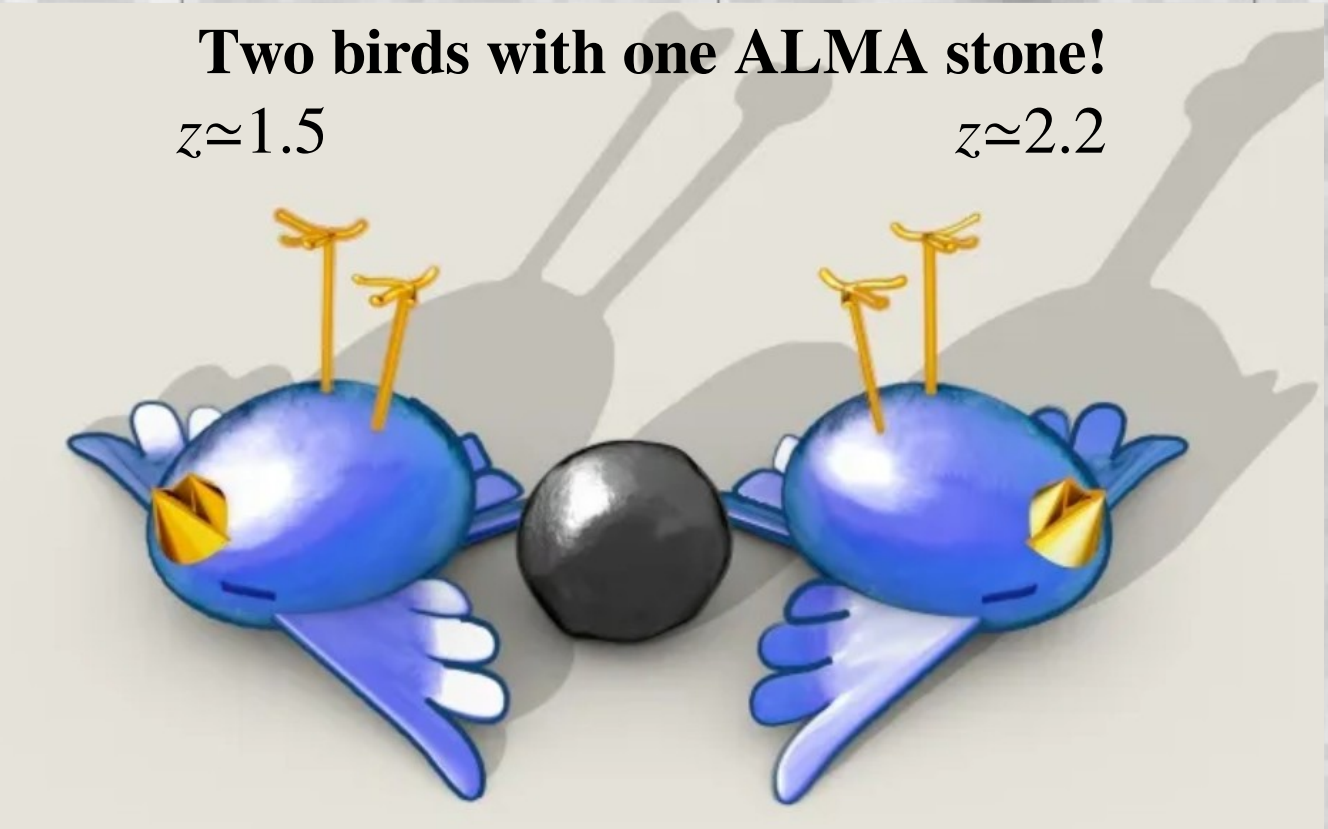
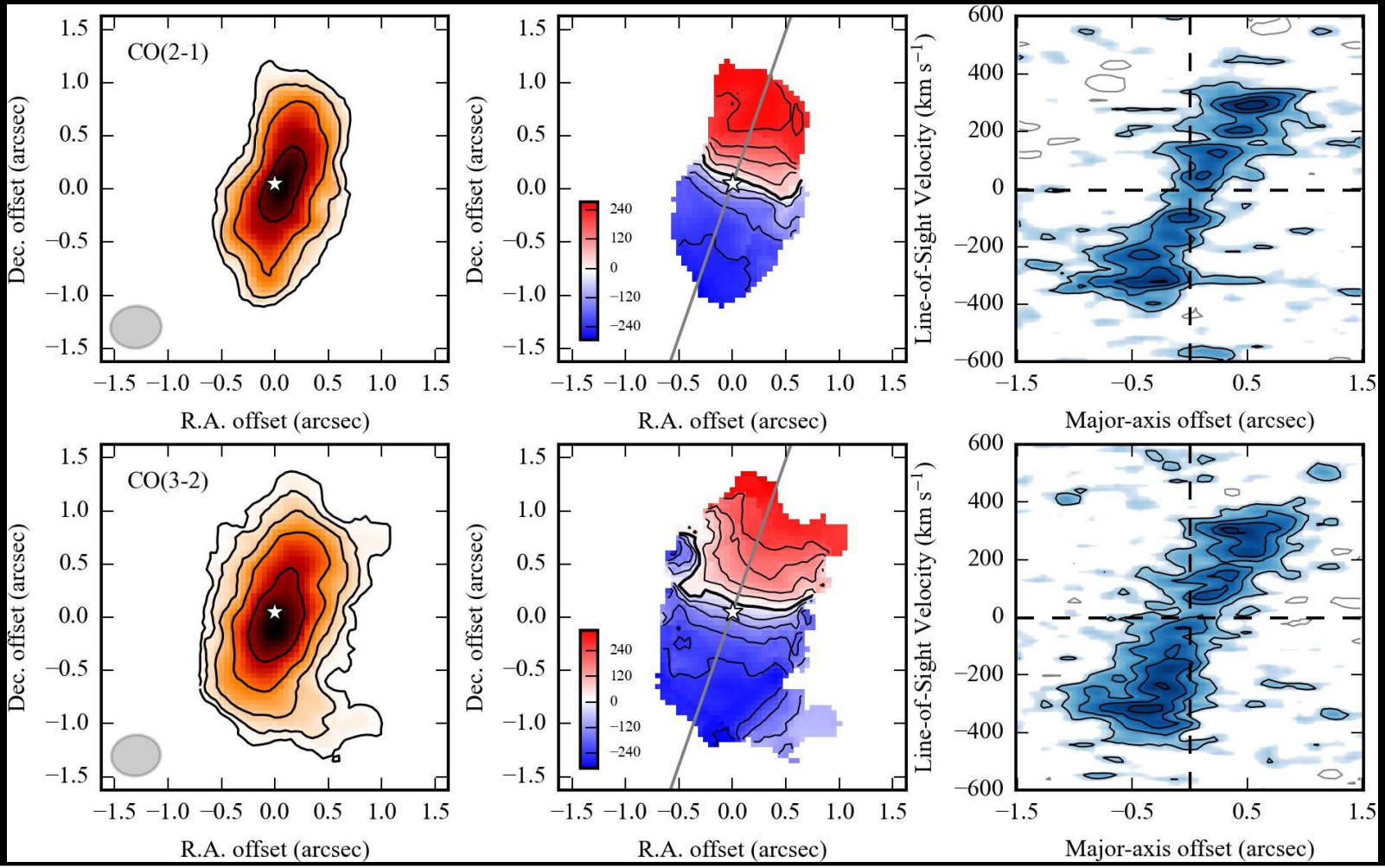


CO(2-1)
CO(3-2)
CO(4-3)

No animals were harmed in this work

Lelli+(2023, A&A)

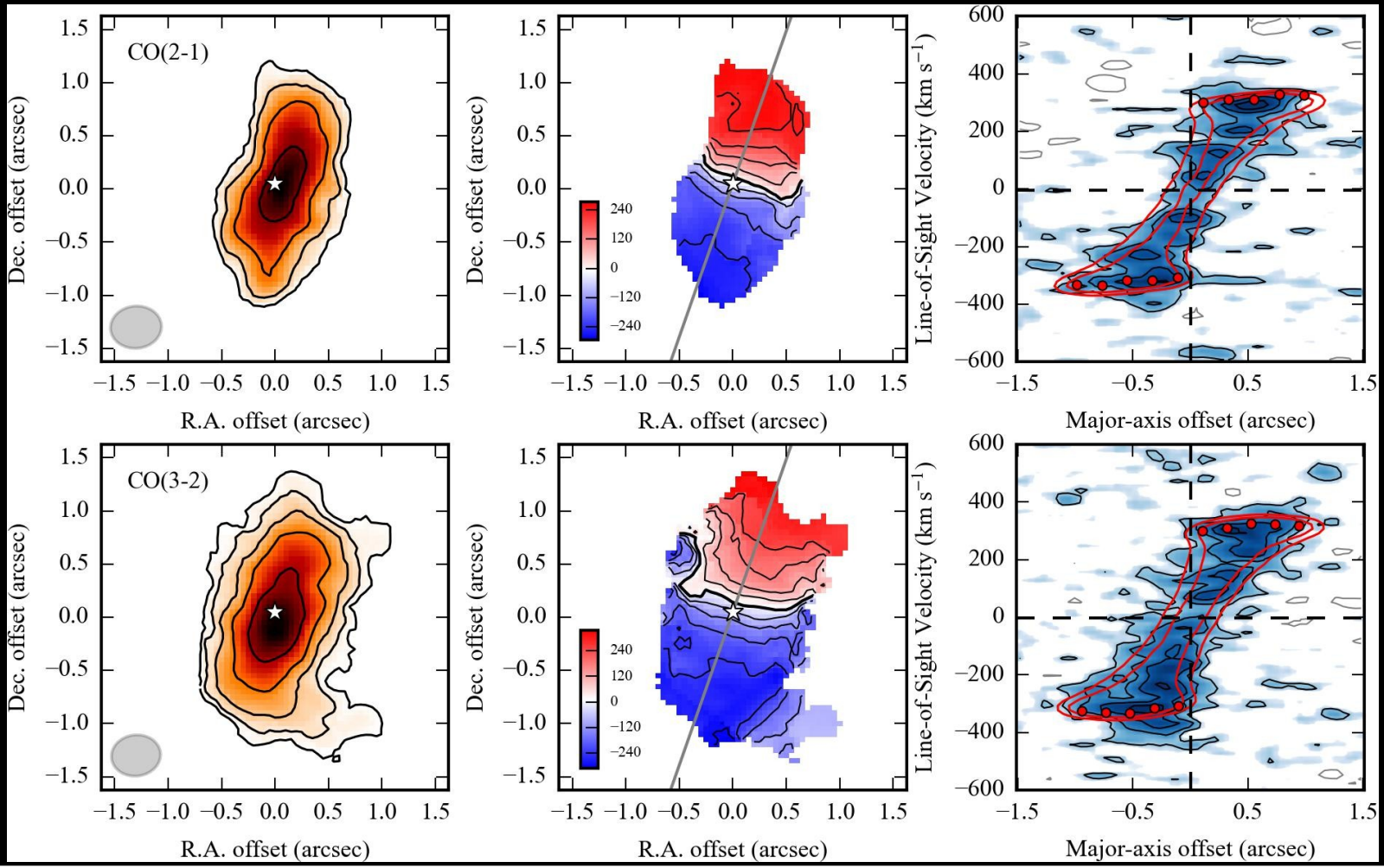
Star-forming main-sequence galaxy at $z \simeq 1.5$



Top-quality ALMA data!

Lelli+(2023, A&A)

Star-forming main-sequence galaxy at $z \simeq 1.5$



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

$V_{rot} \simeq 340$ km/s

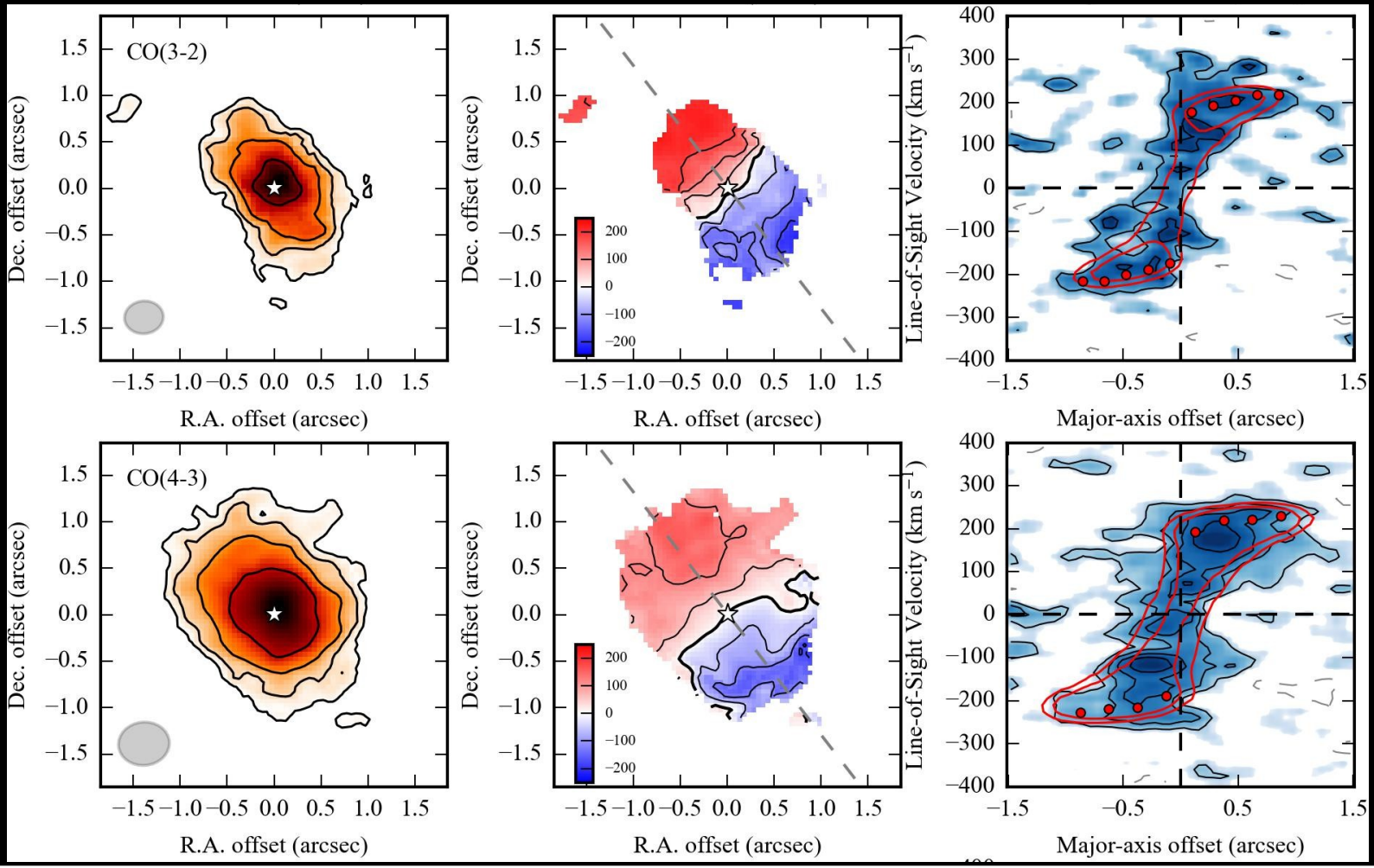
$\sigma_{CO} < 15$ km/s

$V_{rot}/\sigma_{CO} > 22$

(as local disks)

Lelli+(2023, A&A)

Star-forming main-sequence galaxy at $z \simeq 2.2$



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

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

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

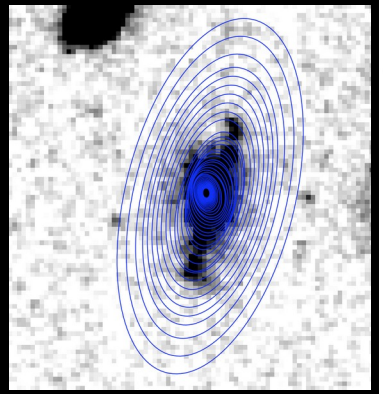
$V_{rot}/\sigma_{CO} > 17$

(as local disks)

Lelli+(2023, A&A)

Mass Models from HST+ALMA Synergy

HST → V_{bul}, V_{disk}



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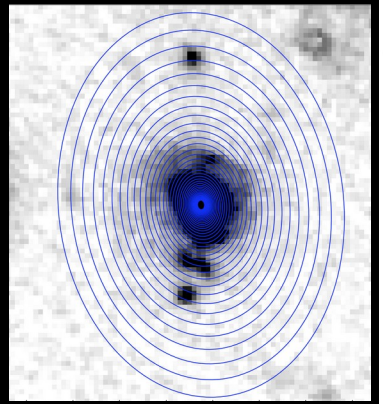

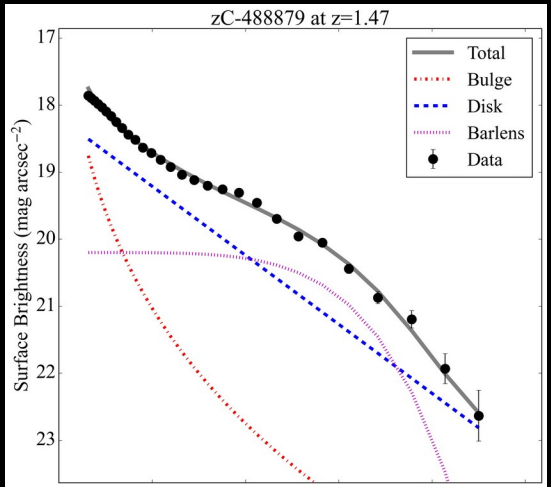

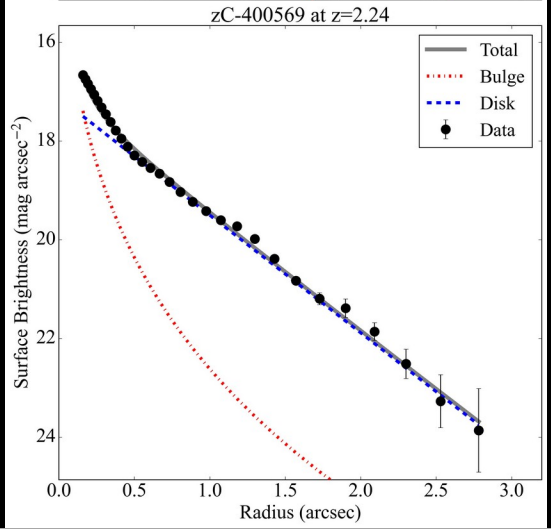

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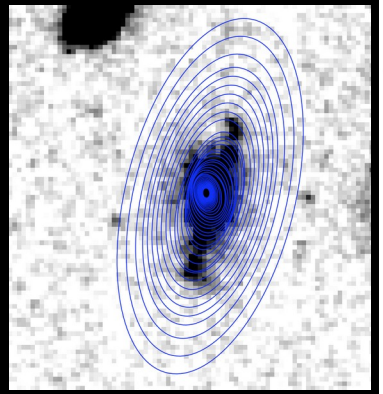

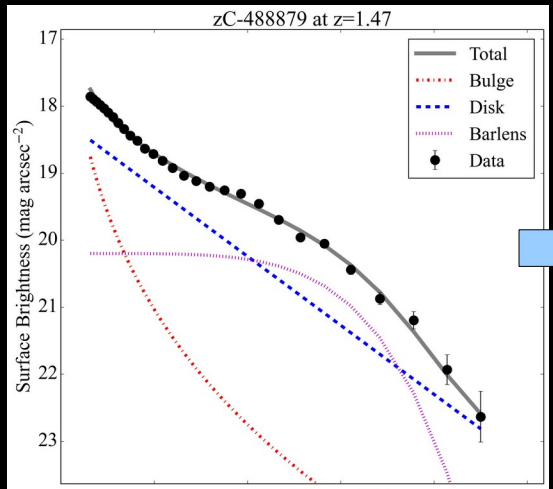

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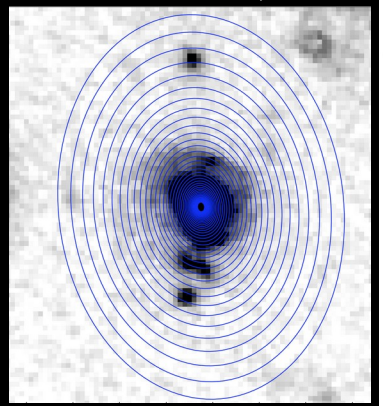
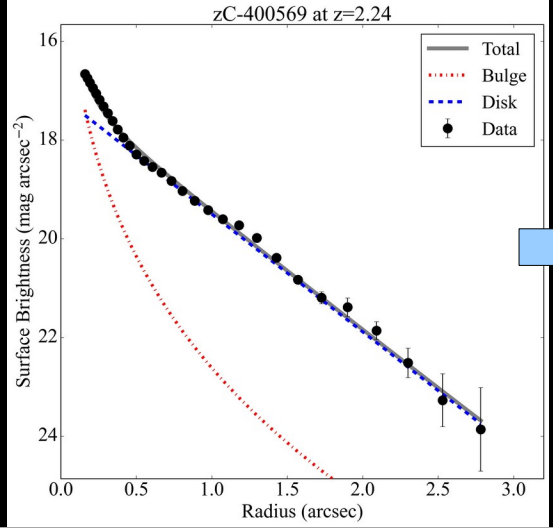
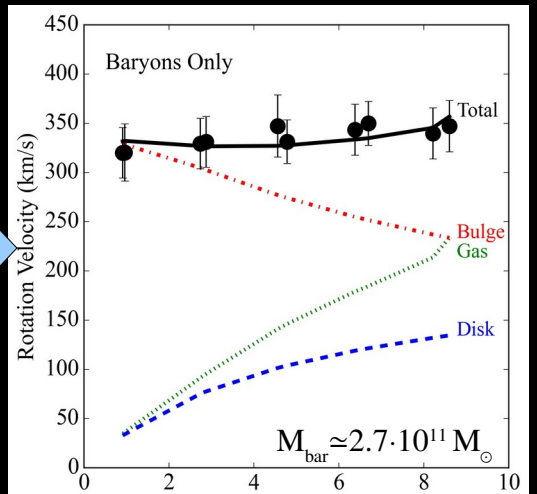
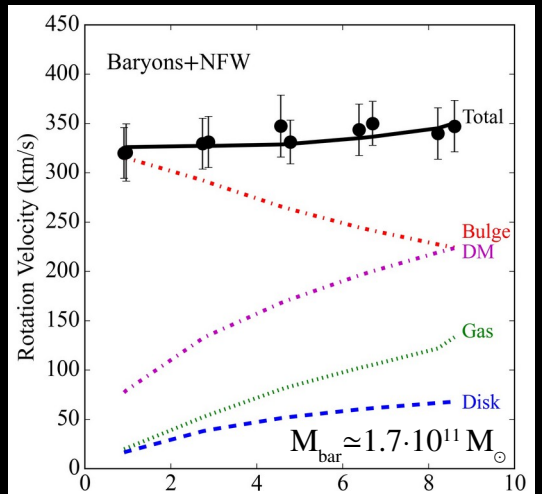
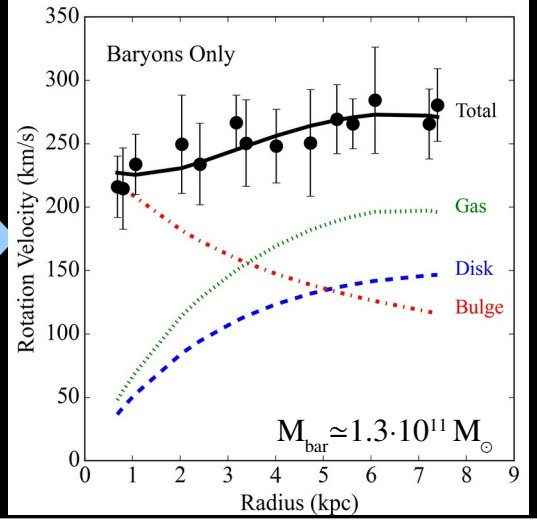
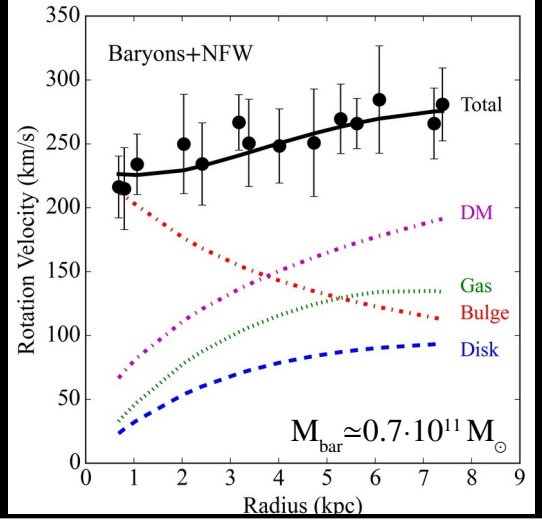




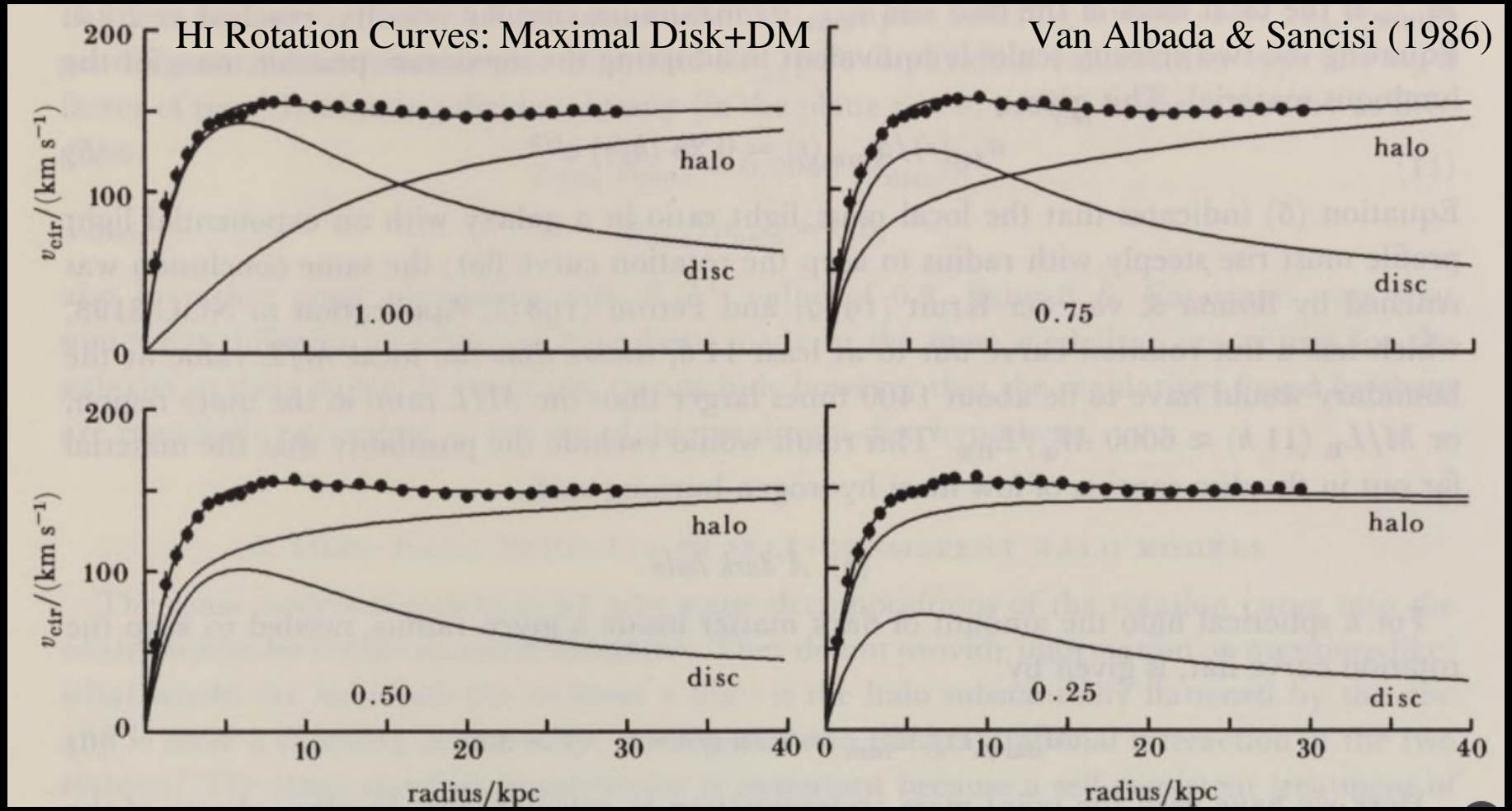




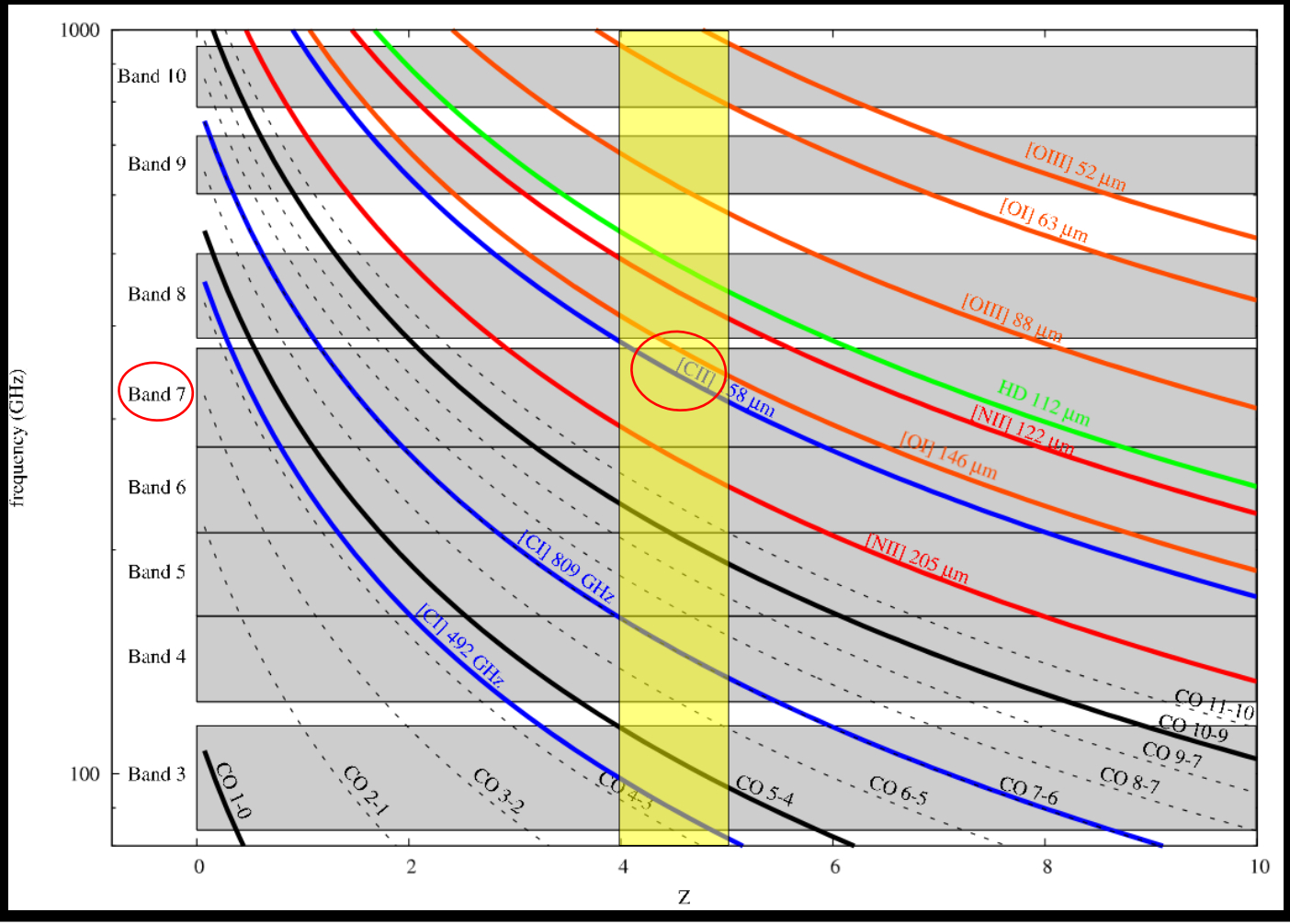




Disk-halo degeneracy: Long-known issue at z=0



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

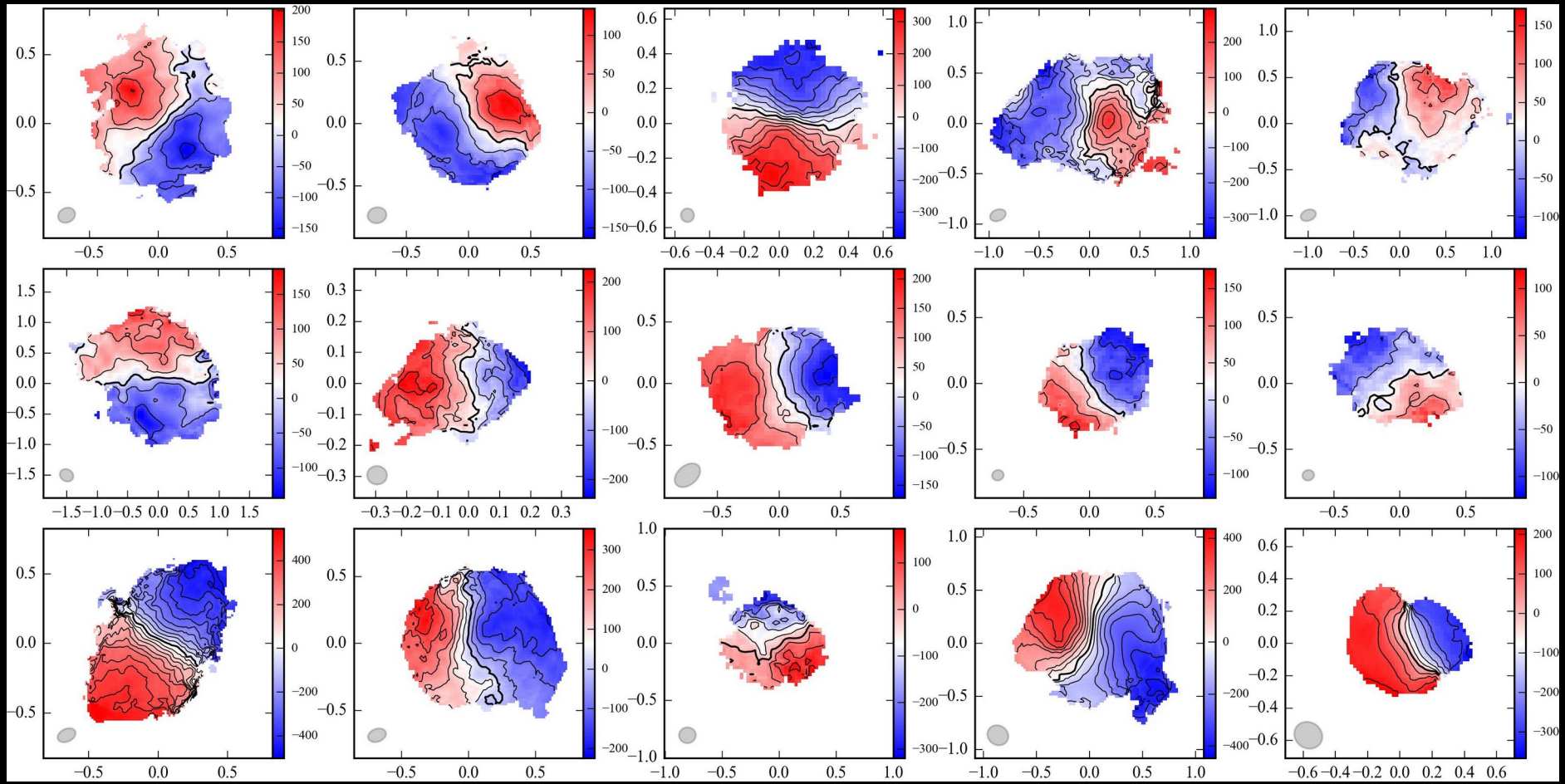
TRICEPS

Tracing Rotation with Ionized Carbon in Early Primeval Systems

- 15 galaxies at $z \simeq 4$-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, 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

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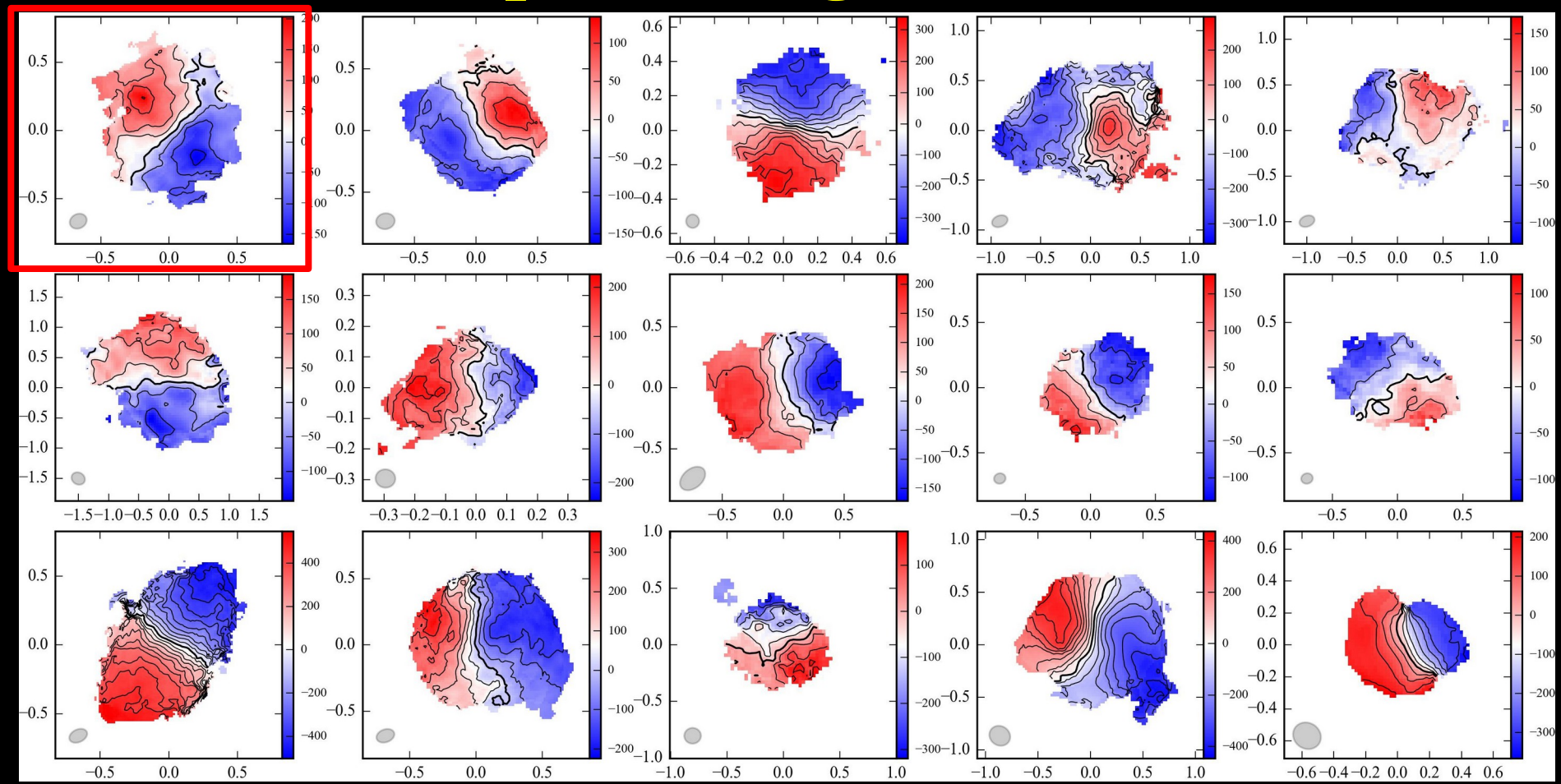

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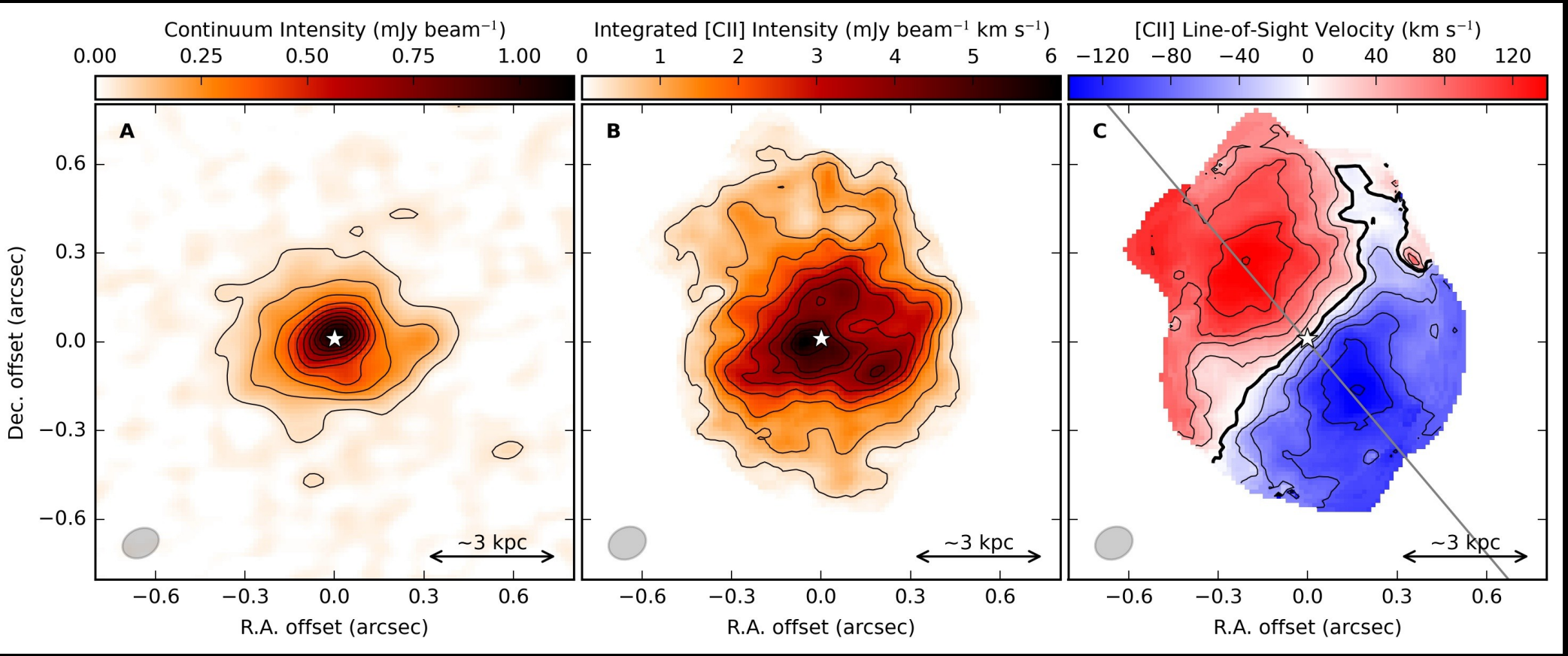
ALESS 73.1 at z≃4.75 (Lelli+2021, Science)



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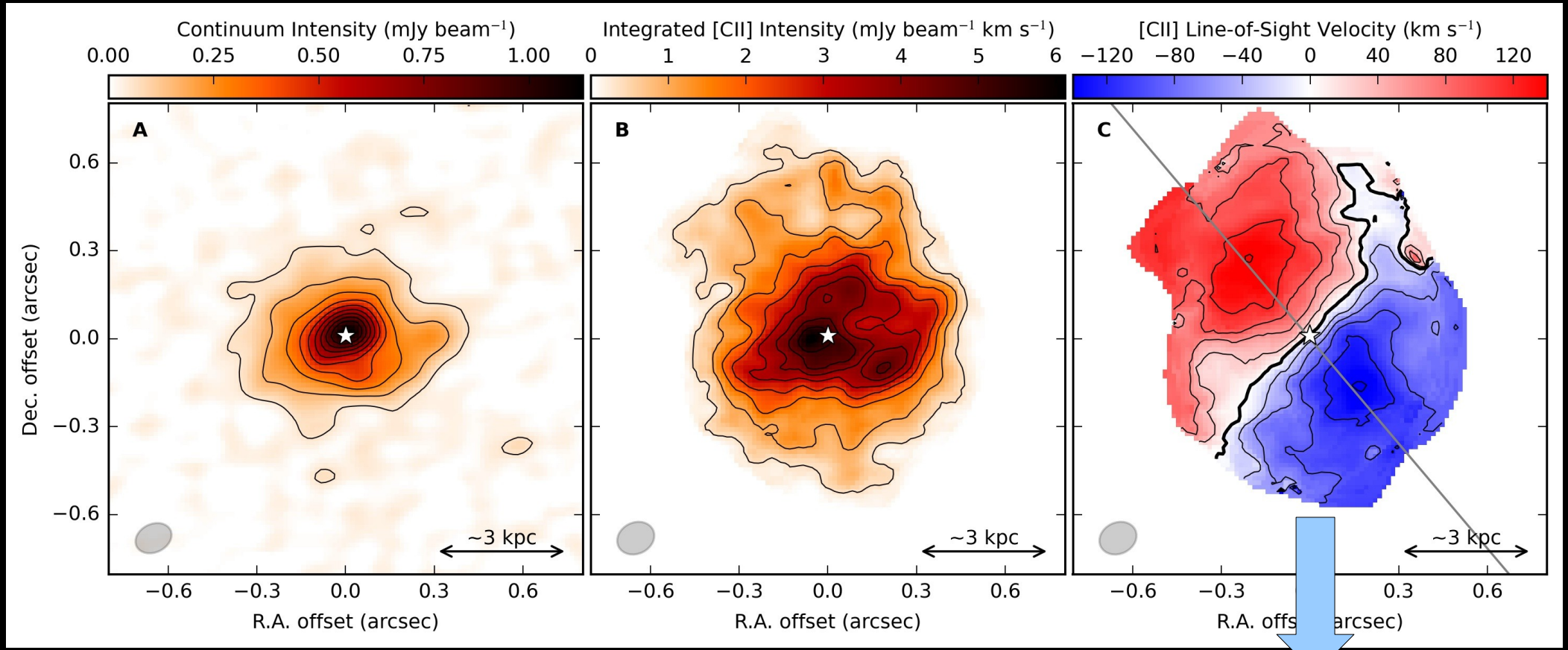

Rotation Curve: $V_{obs}^2 = -R\nabla\Phi_{tot}$

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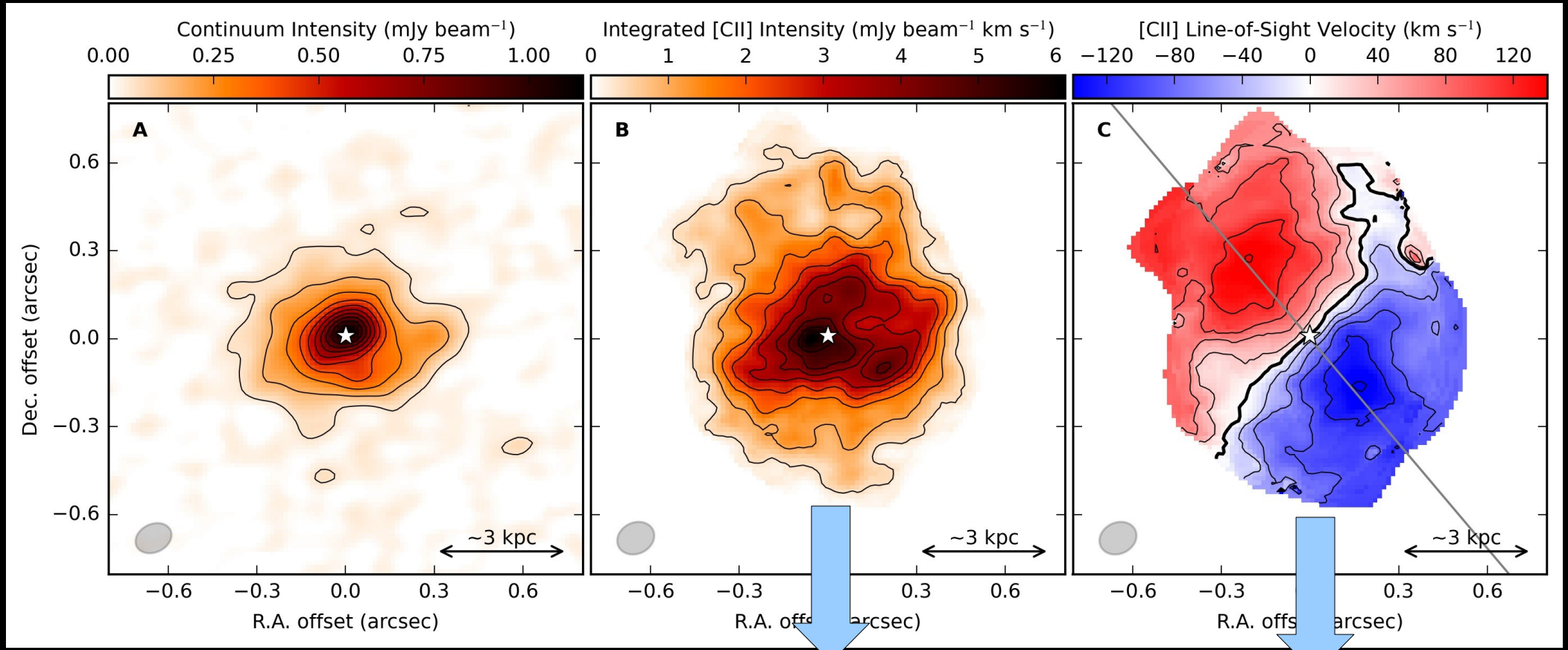

Gas Distribution: $V_{gas}^2 = -R\nabla\Phi_{gas}$ Rotation Curve: $V_{obs}^2 = -R\nabla\Phi_{tot}$

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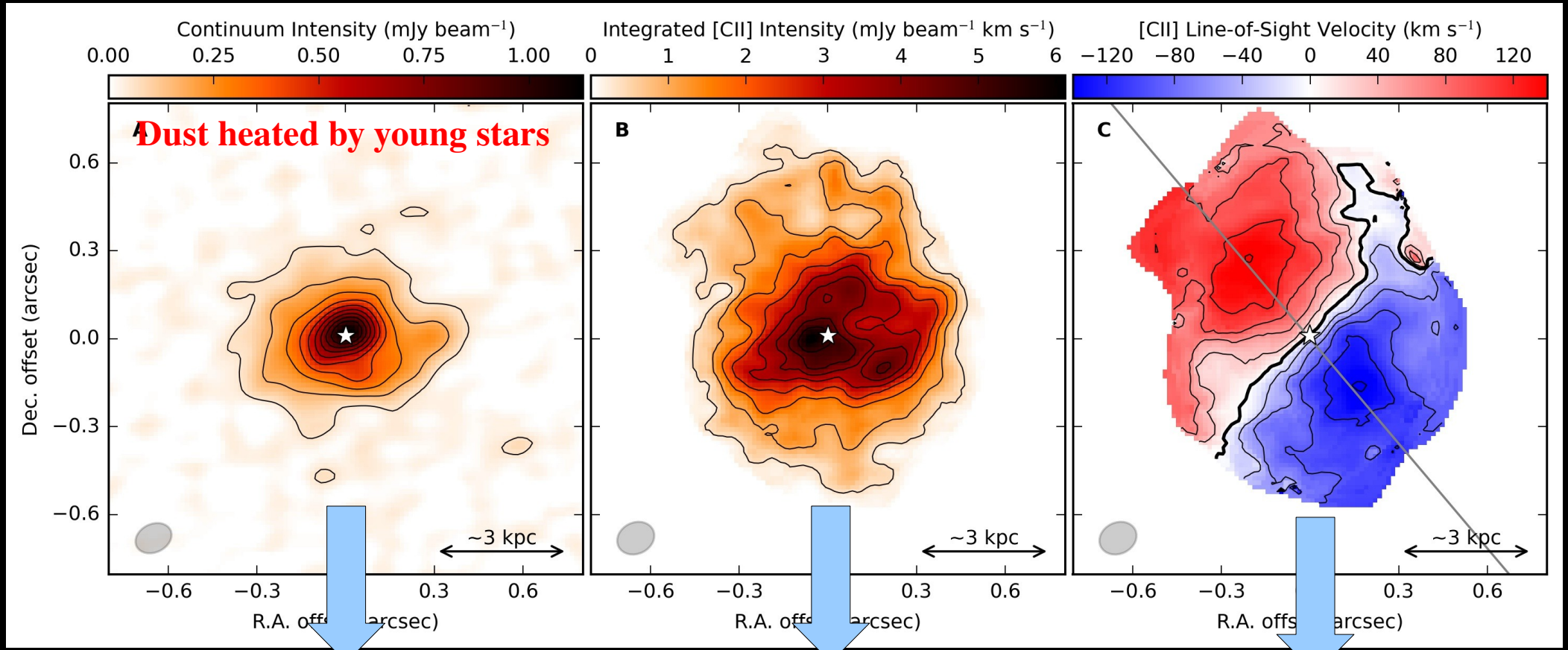
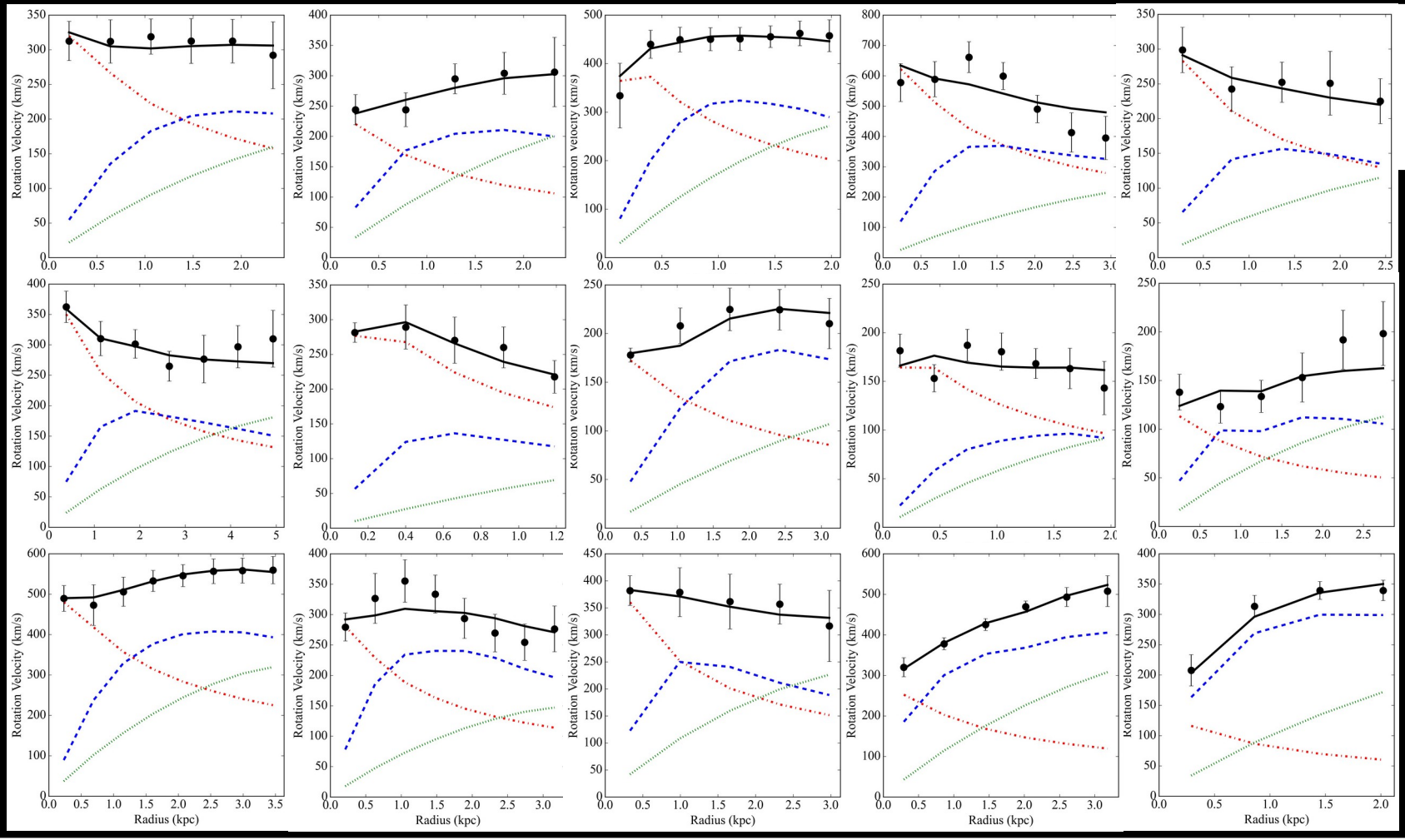


Disk Distribution: $V_{disk}^2 = -R\nabla\Phi_{disk}$
+ De Vauc. Bulge (put in by hand)

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

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

Mass Models with Baryons Only



Legend:
Stellar Bulge
Stellar Disk
Gas Disk

General results:

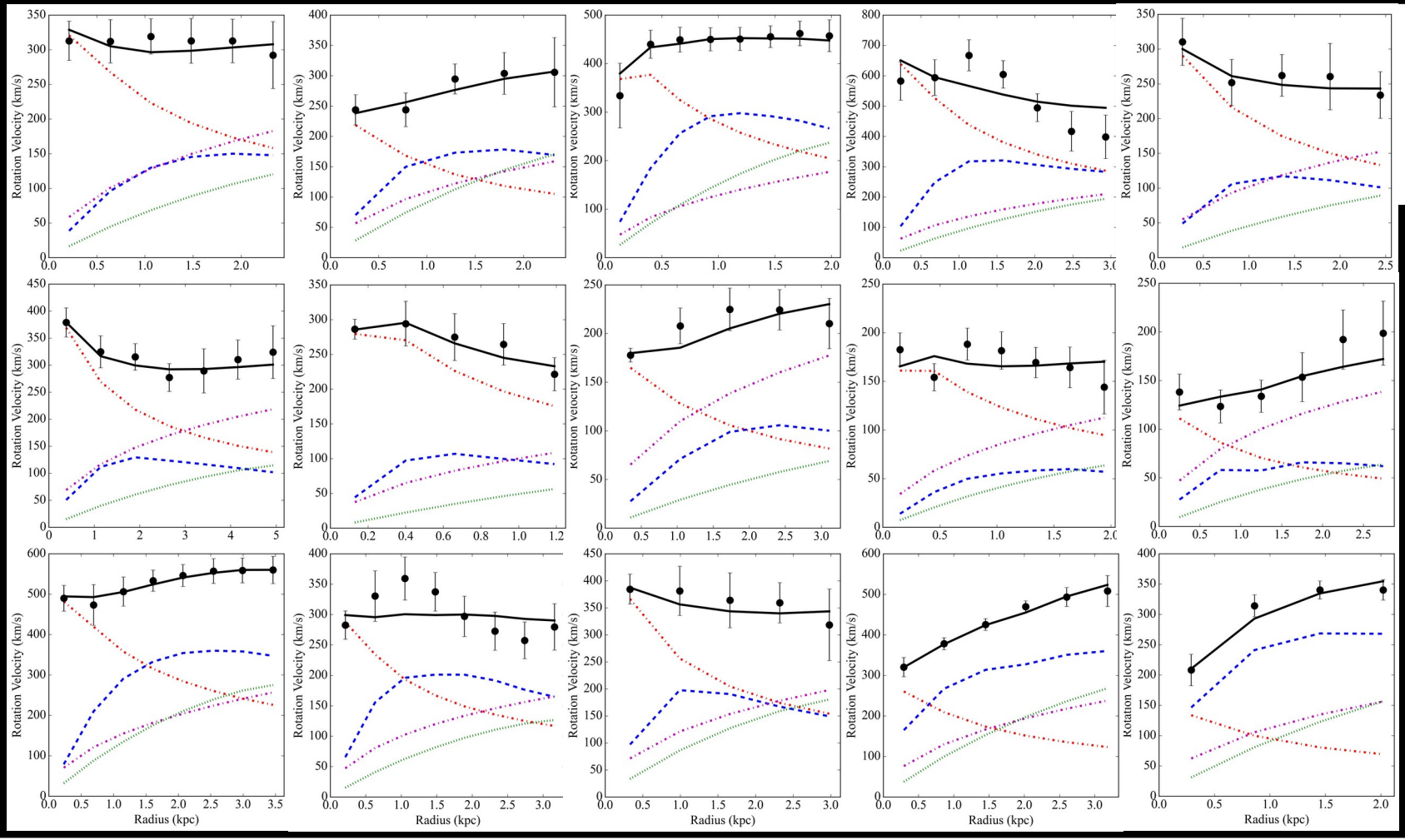
Halo properties unconstrained

$R_{out} \simeq$ a few kpc

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

Central bulges

Mass Models with NFW Halo



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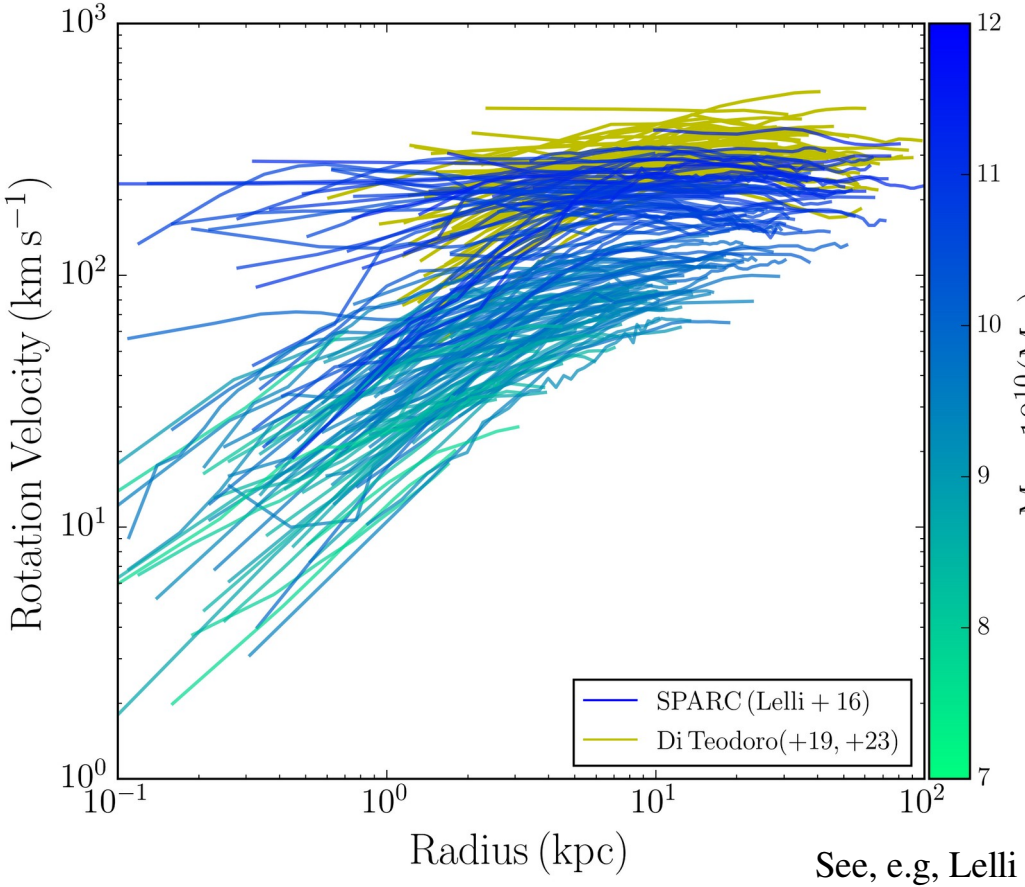
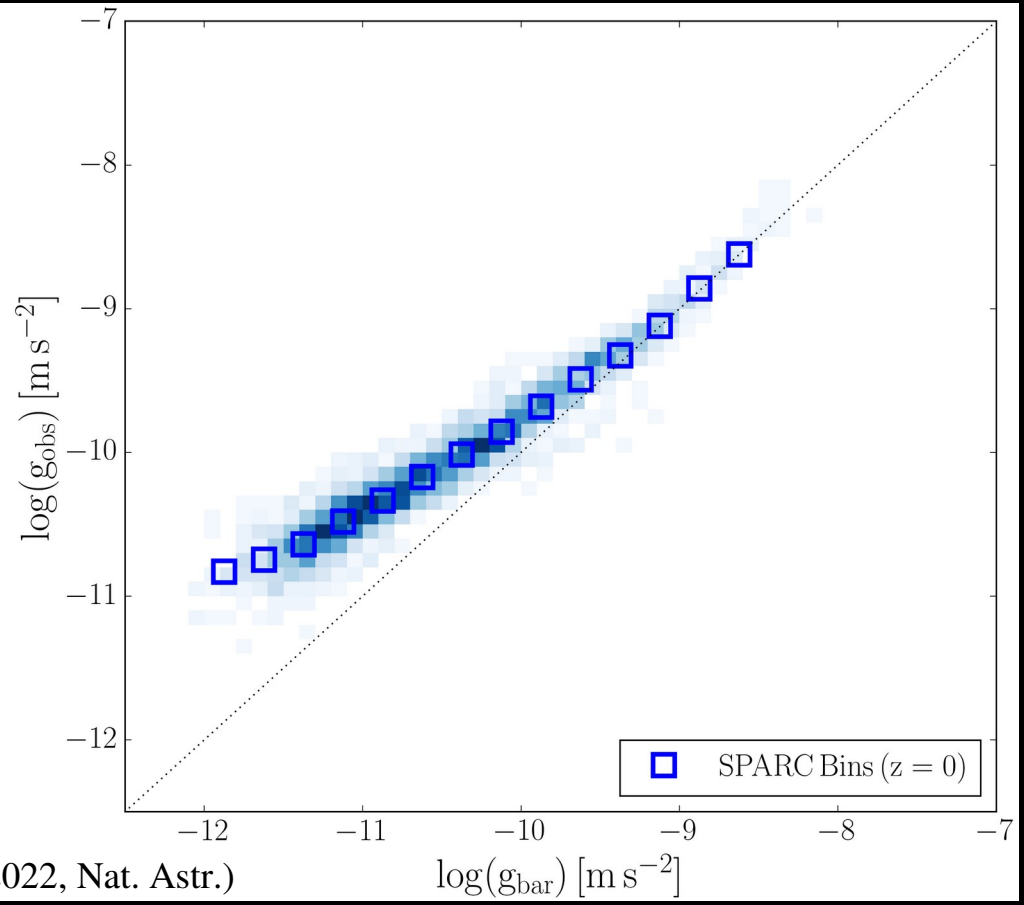
Comparison with Massive Spirals at z=0

Rotation Curve Shapes



Radial Acceleration Relation



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Comparison with Massive Spirals at z=0

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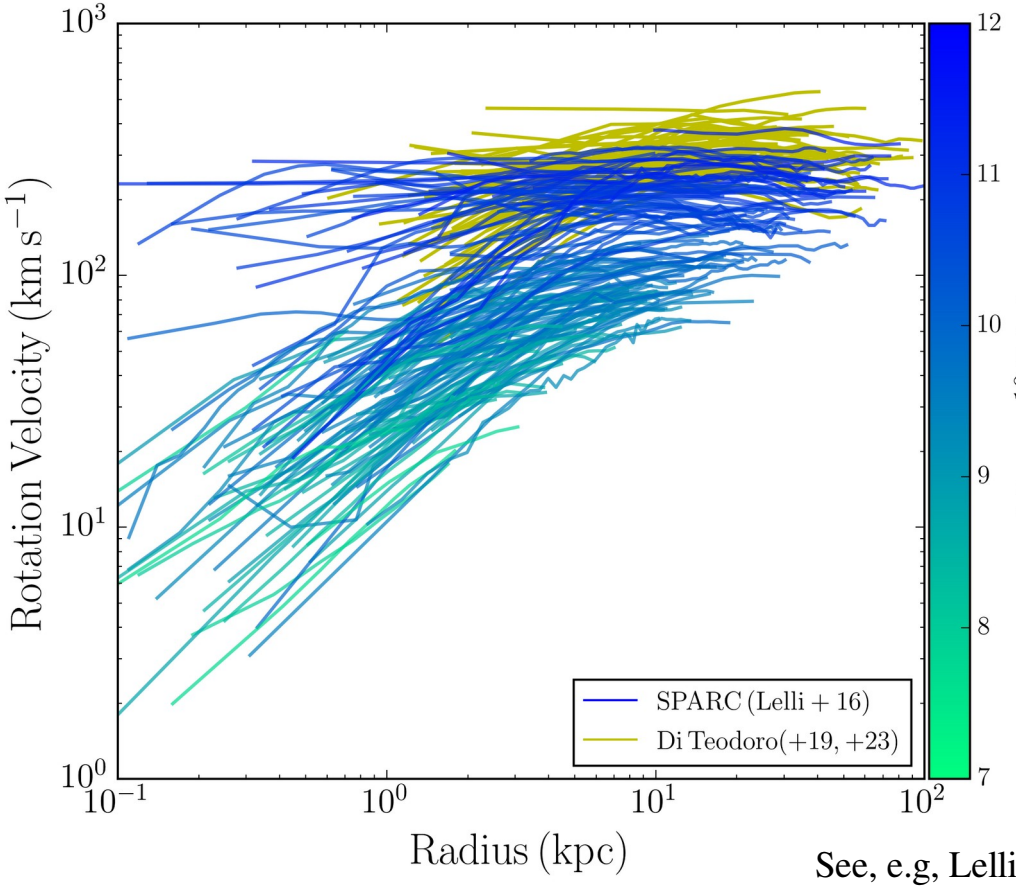

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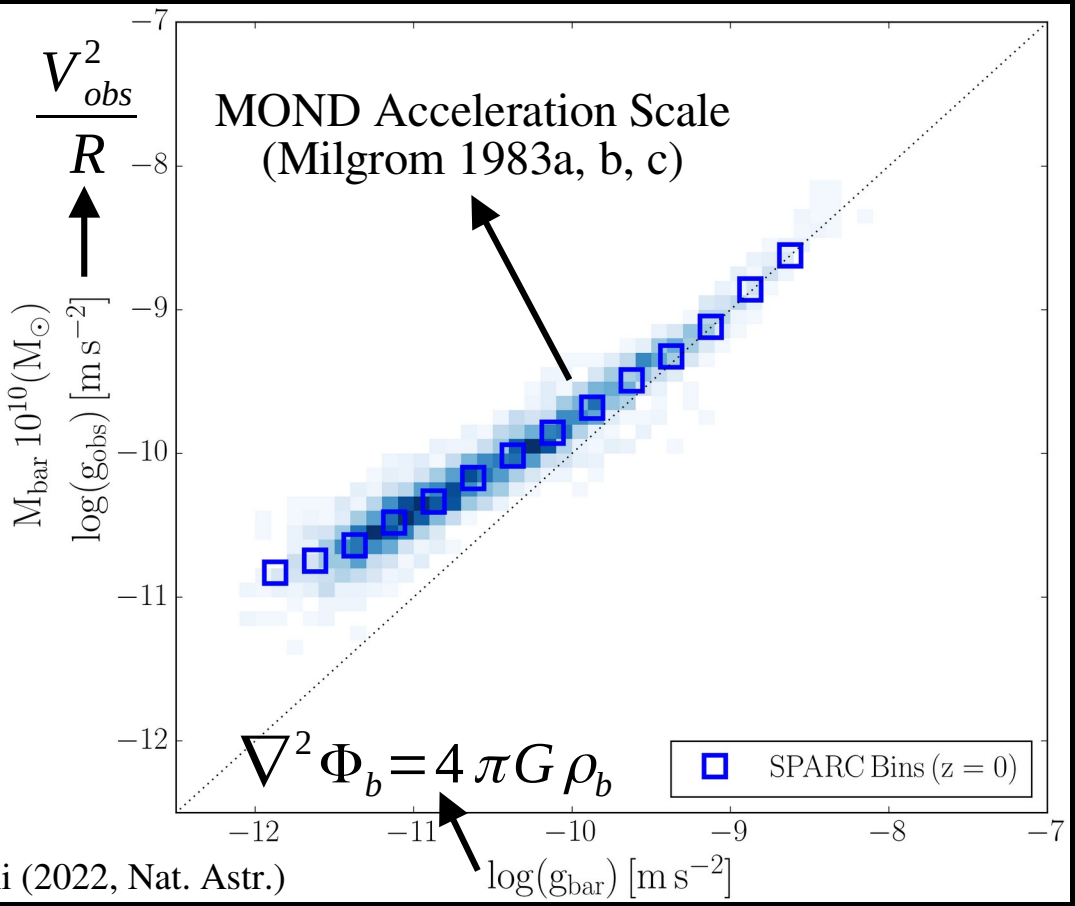

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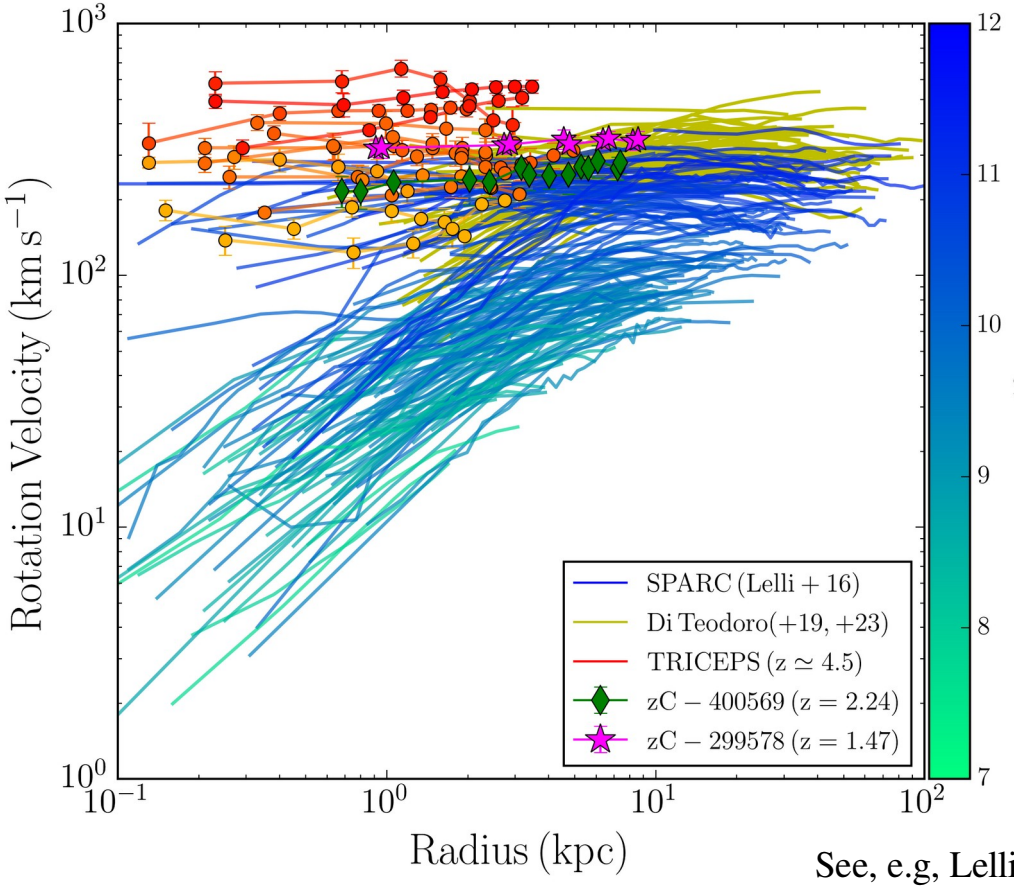

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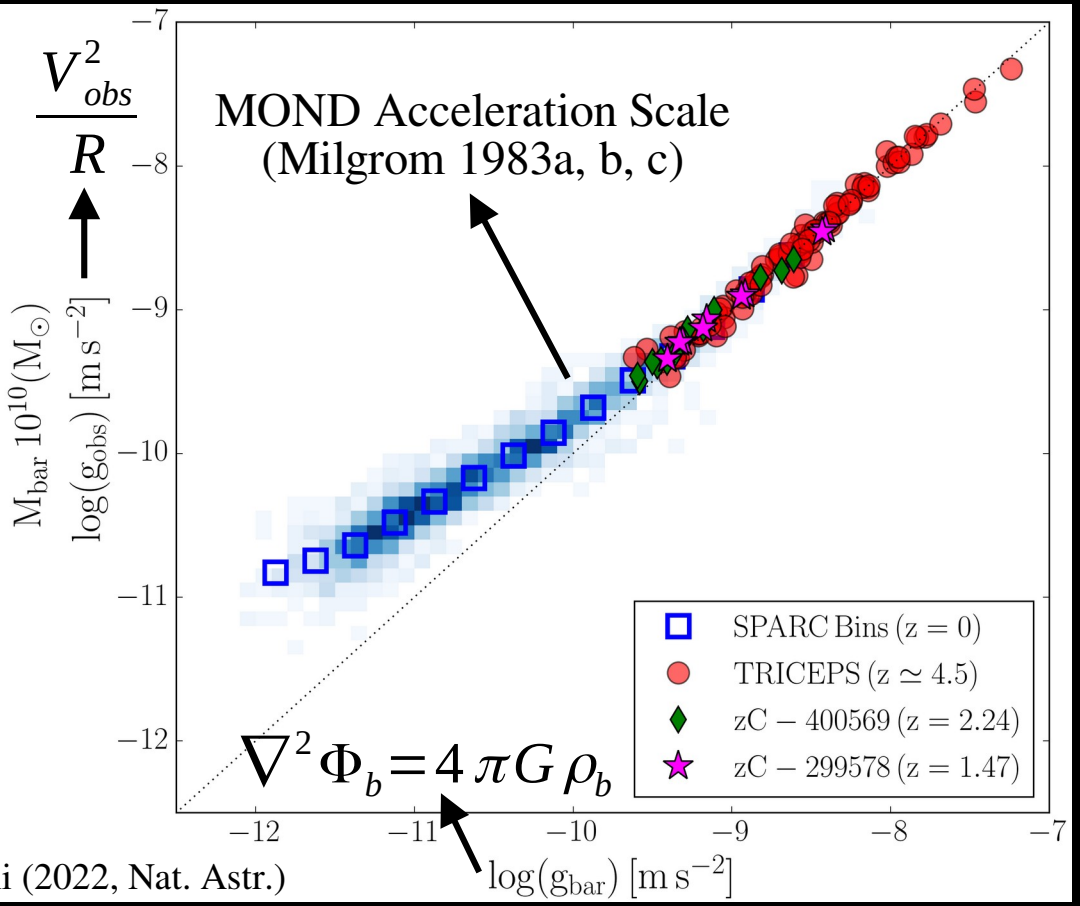

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Future Prospects:

Ultra-deep [CII] observations:

→ More extended rotation curves

→ Proposal currently under review

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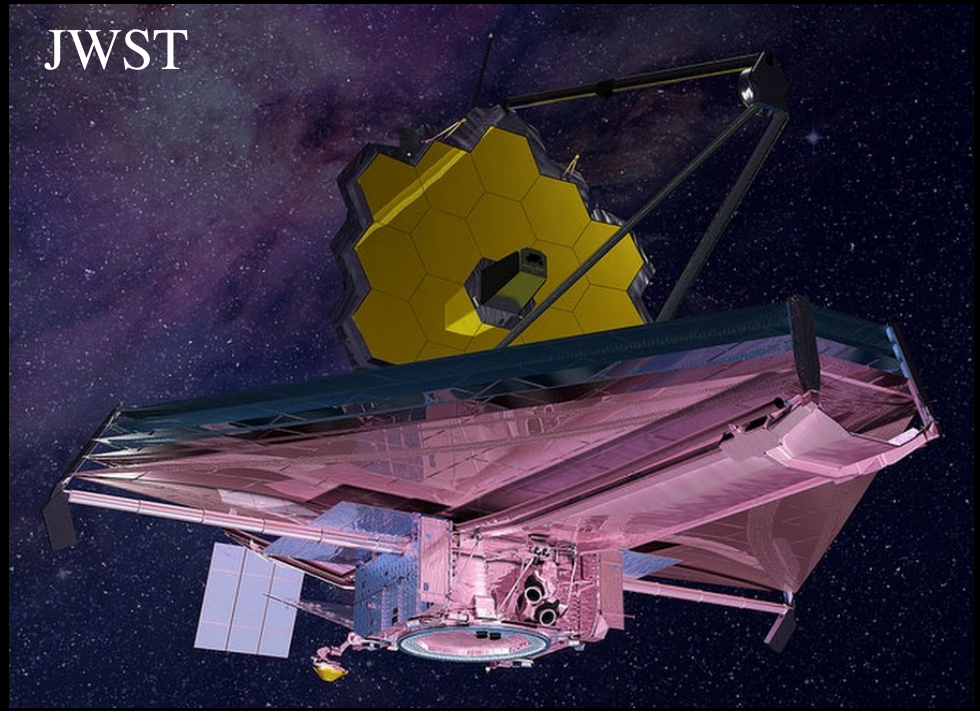

Ultra-deep [CII] observations:
→ More extended rotation curves
→ Proposal currently under review

Rest-frame UV-to-NIR imaging:
→ Actual stellar mass distribution
→ Proposal approved!!!

Conclusions:

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→ in contrast to common view of turbulent high-z disks

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Conclusions:

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

→ in contrast to common view of turbulent high-z disks

2. Strong disk-halo degeneracy at high z

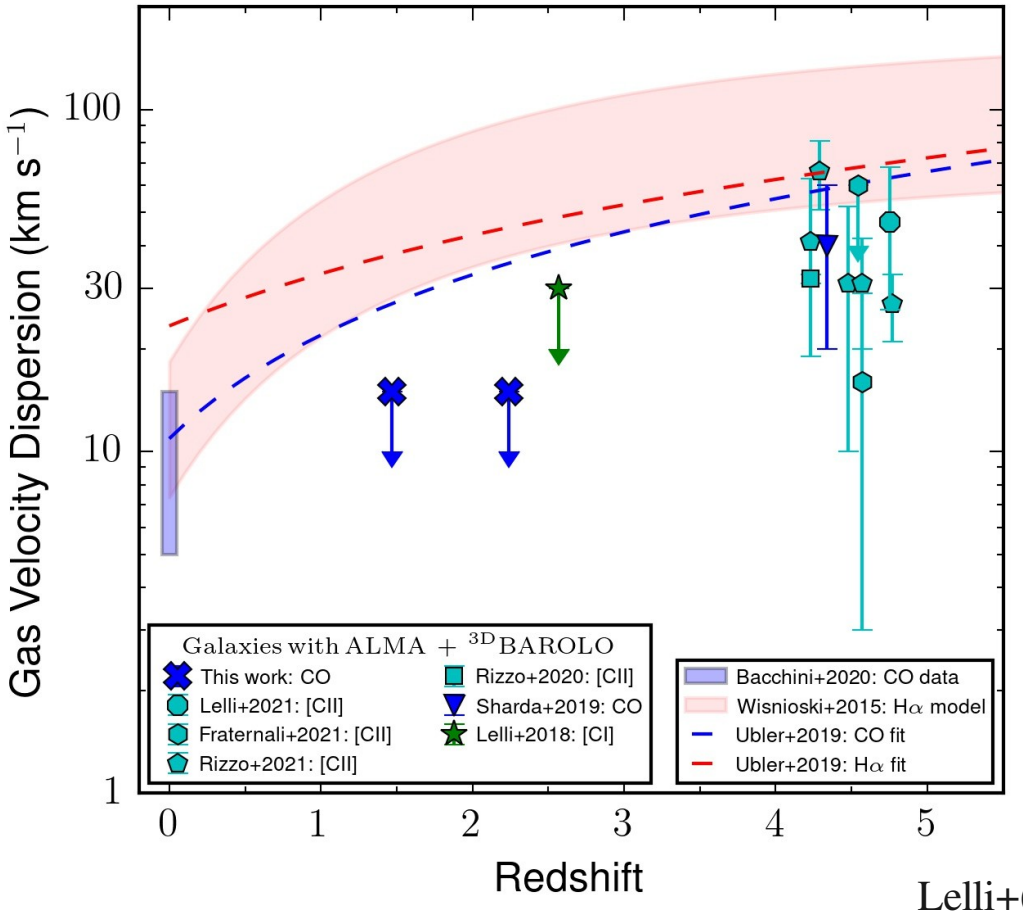
→ DM fractions and halo properties are totally unconstrained

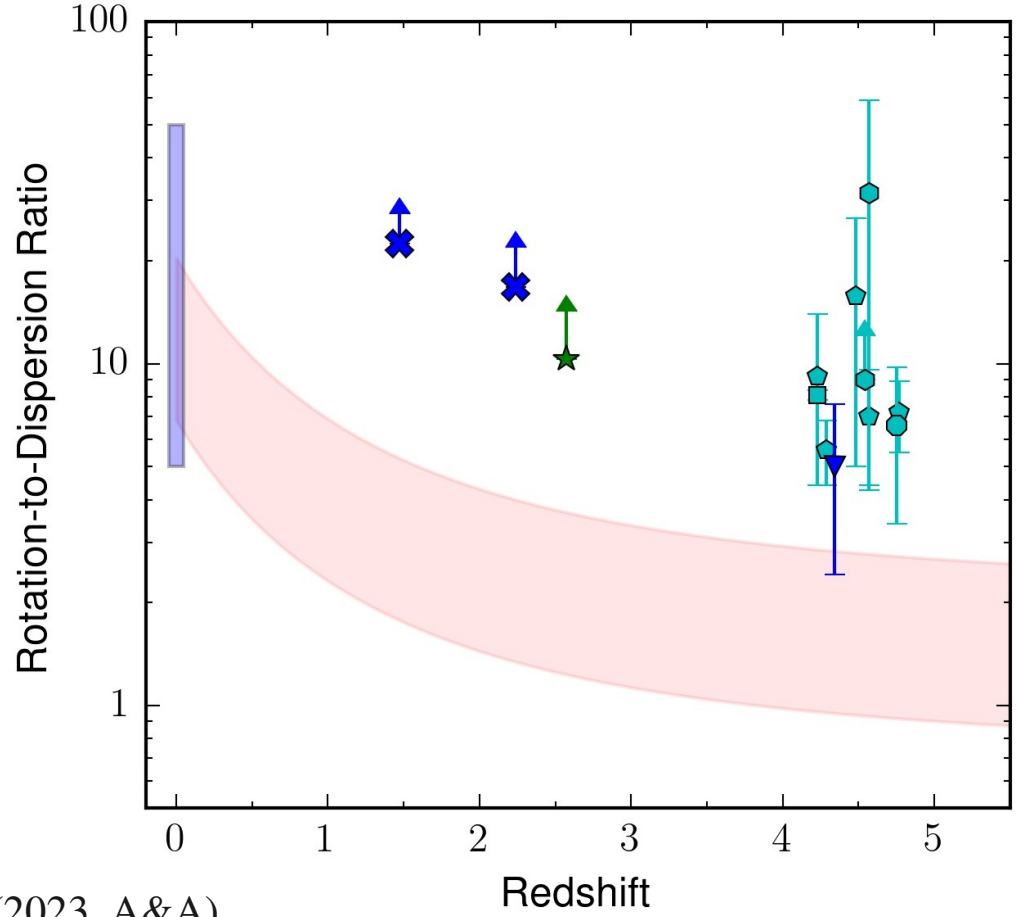
3. Mass models often require the presence of bulges

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

Thank you!

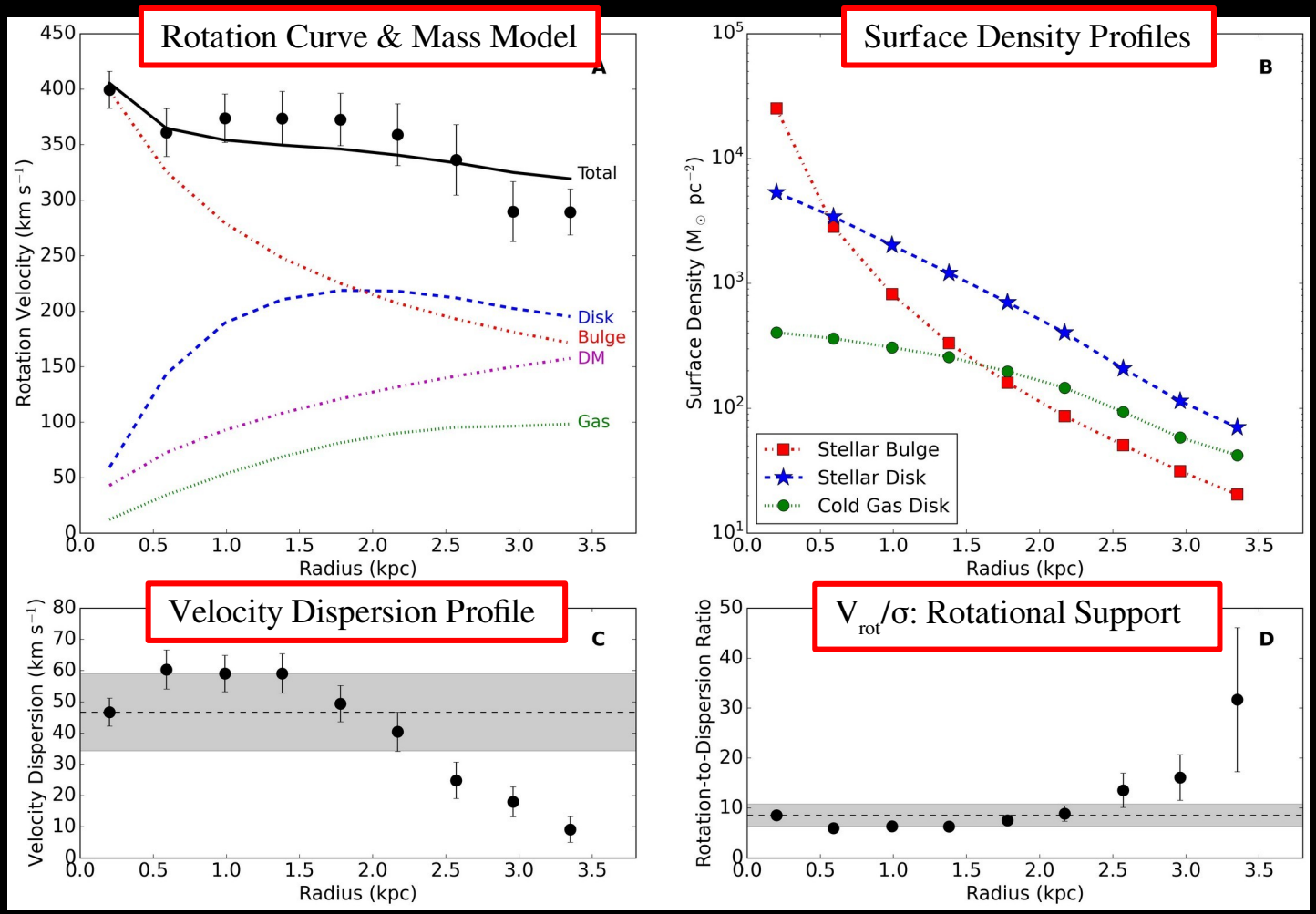
Dynamically-cold gas disks may be common!





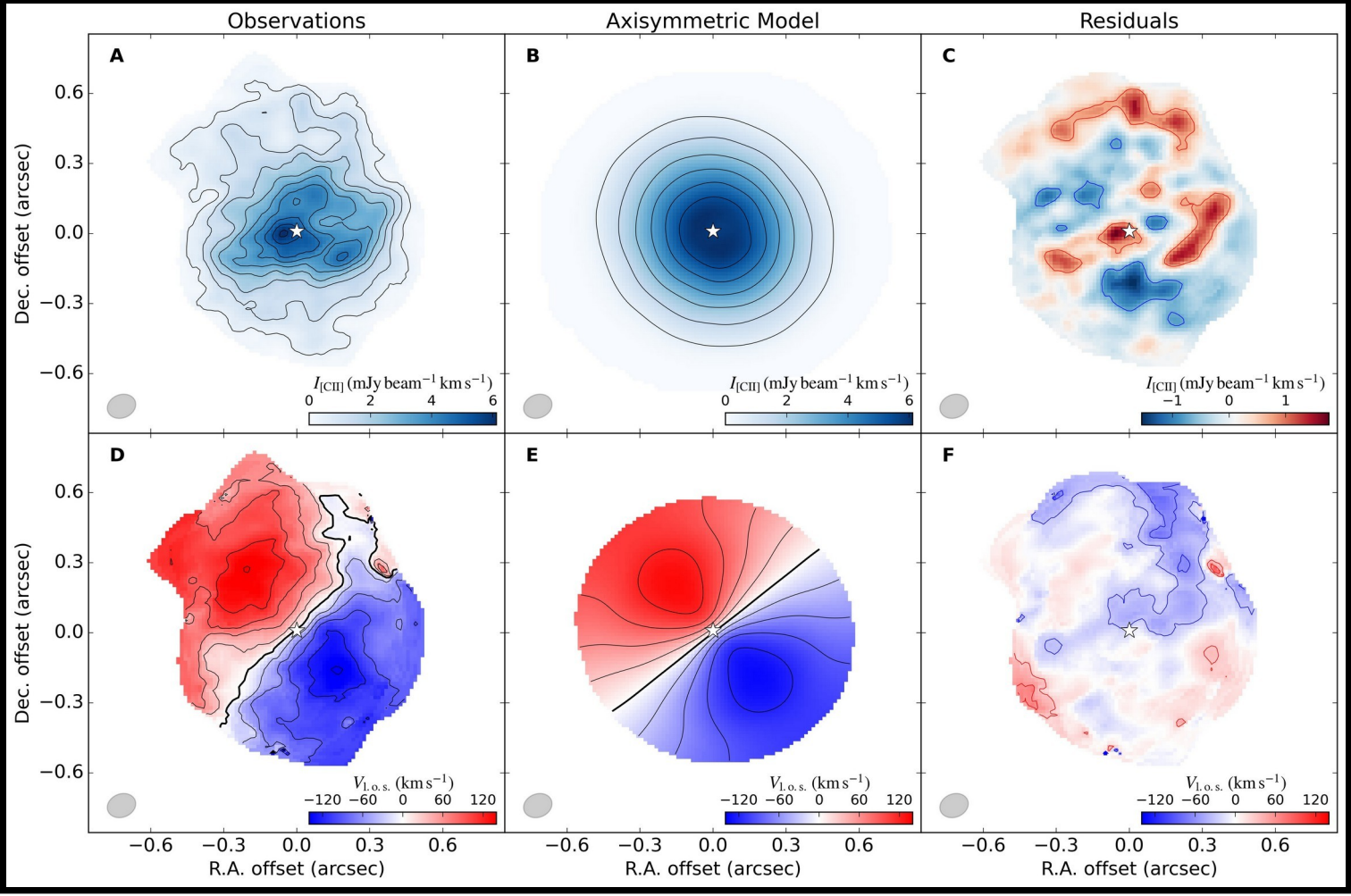
Lelli+(2023, A&A)

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



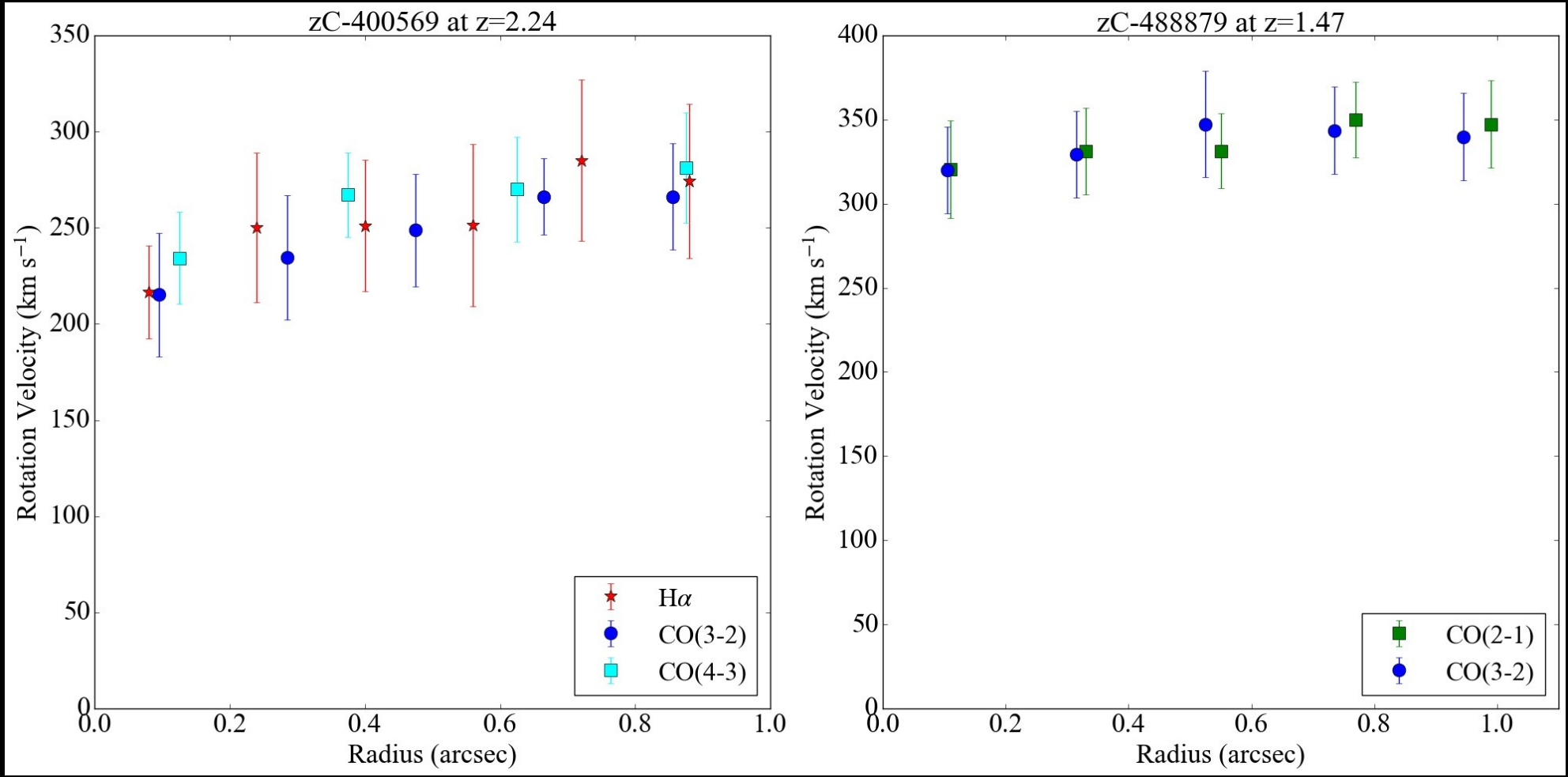
Lelli+2021, Science

ALESS 73.1 at $z \simeq 4.75$: weak noncircular motions

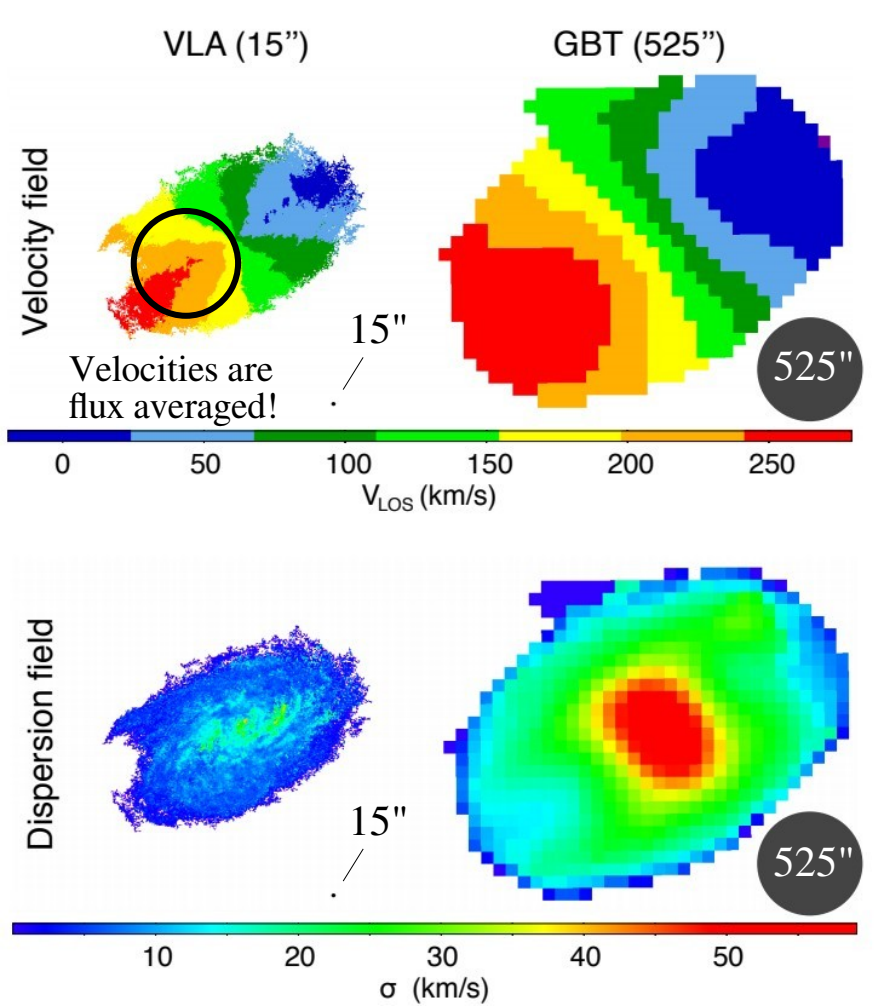


Lelli+2021, Science

Rotation curves from different emission lines

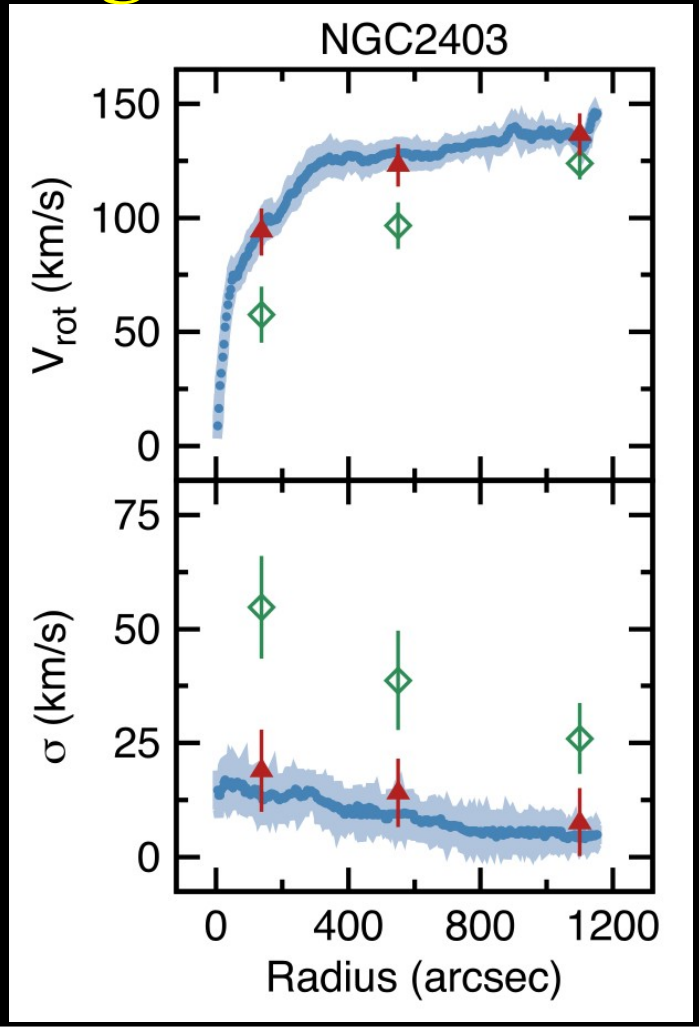


Beam smearing: Lessons from galaxies at z=0



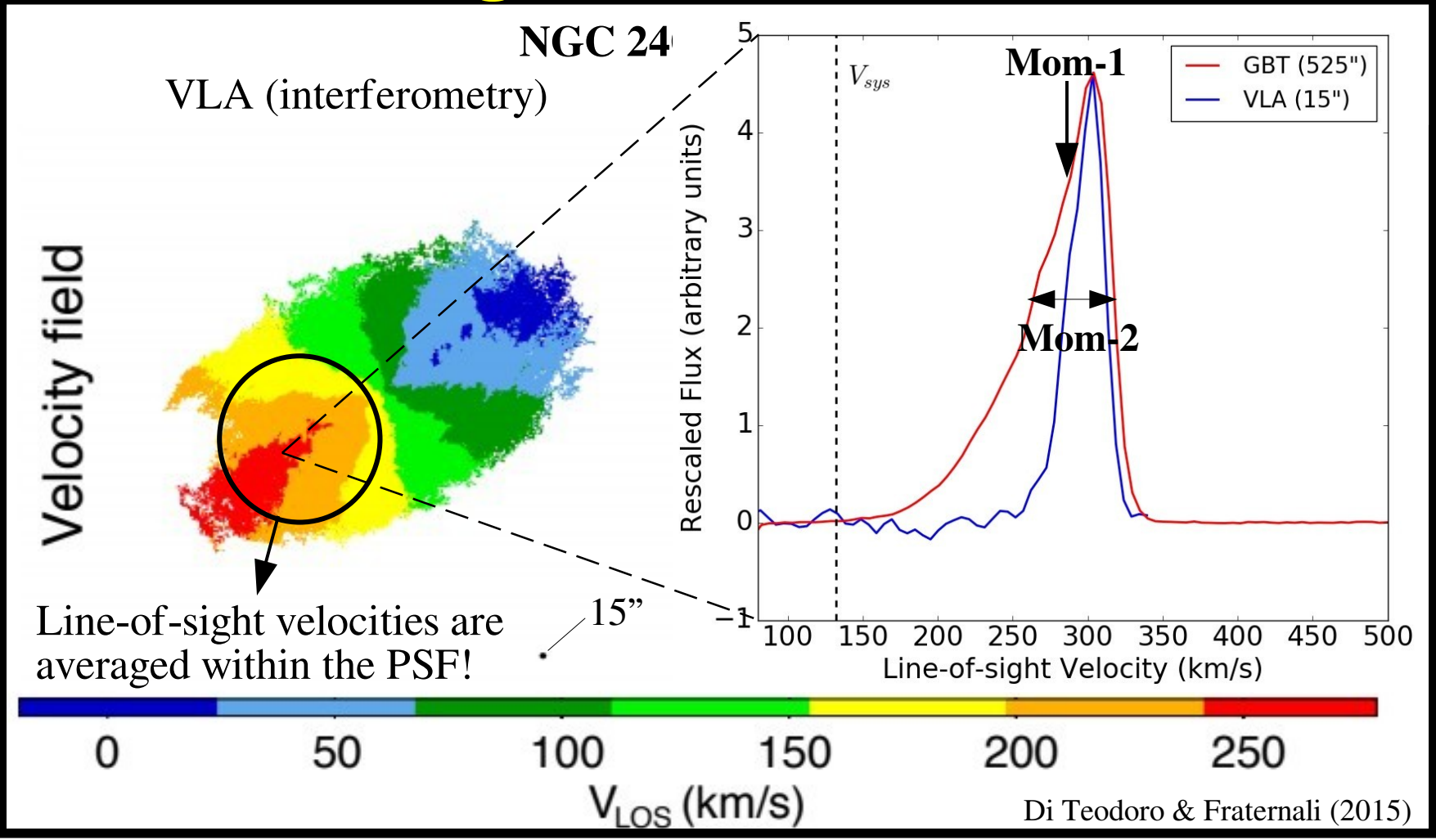
3D FIT

3D FIT



Di Teodoro & Fraternali (2015)

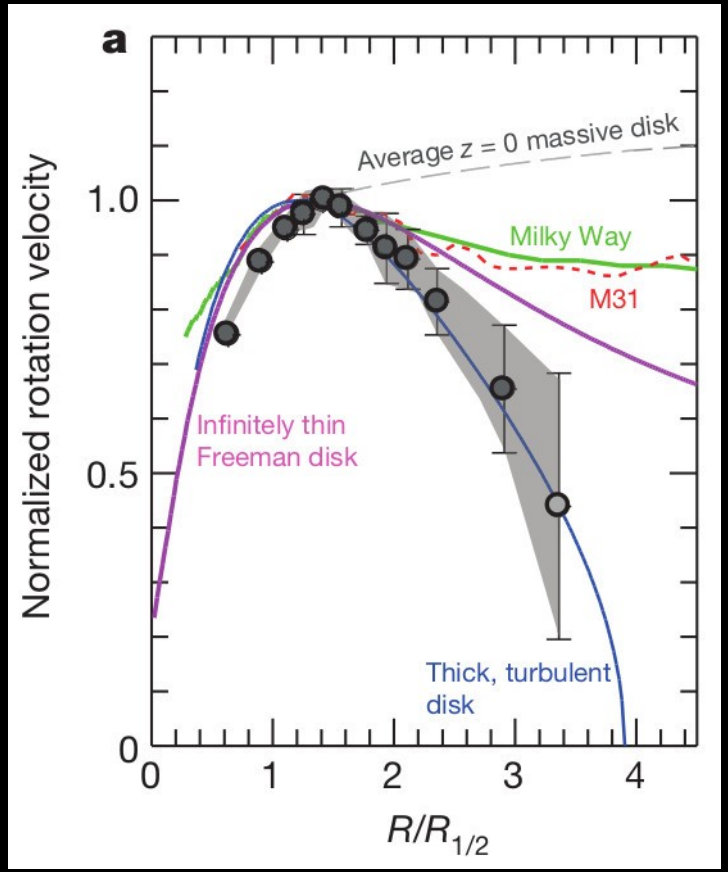
Beam Smearing: Lessons from HI radio data



Di Teodoro & Fraternali (2015)

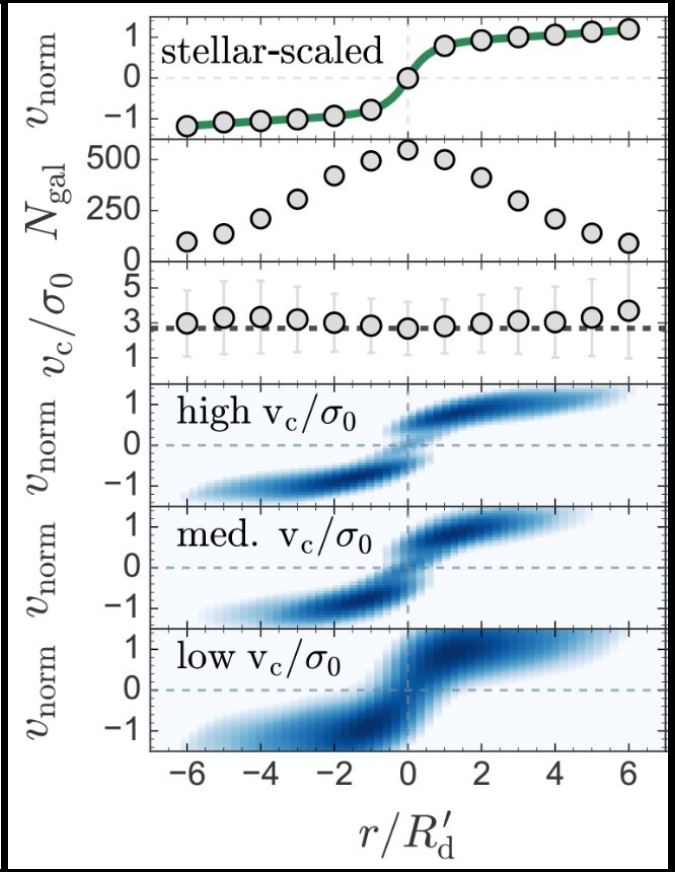
Ionized Gas Dynamics: Confusing Situation!

Declining RCs & low V_{rot}/σ_V



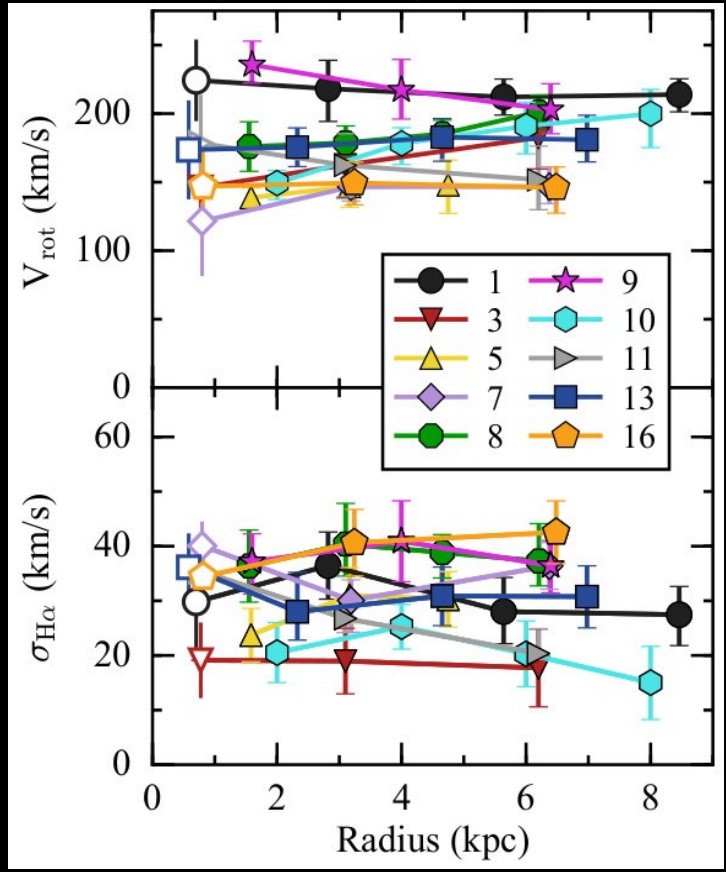
Lange+2017; Genzel+2017, 2020

Flat RCs & low V_{rot}/σ_V



Tiley+2019; Puglisi+2023

Flat RCs & high V_{rot}/σ_V



Di Teodoro+2016; 2018

Science "perspective" article by Julie Wardlow commenting on Lelli+(2021, Science).

→ Speedy galaxy evolution now confirmed by many JWST results