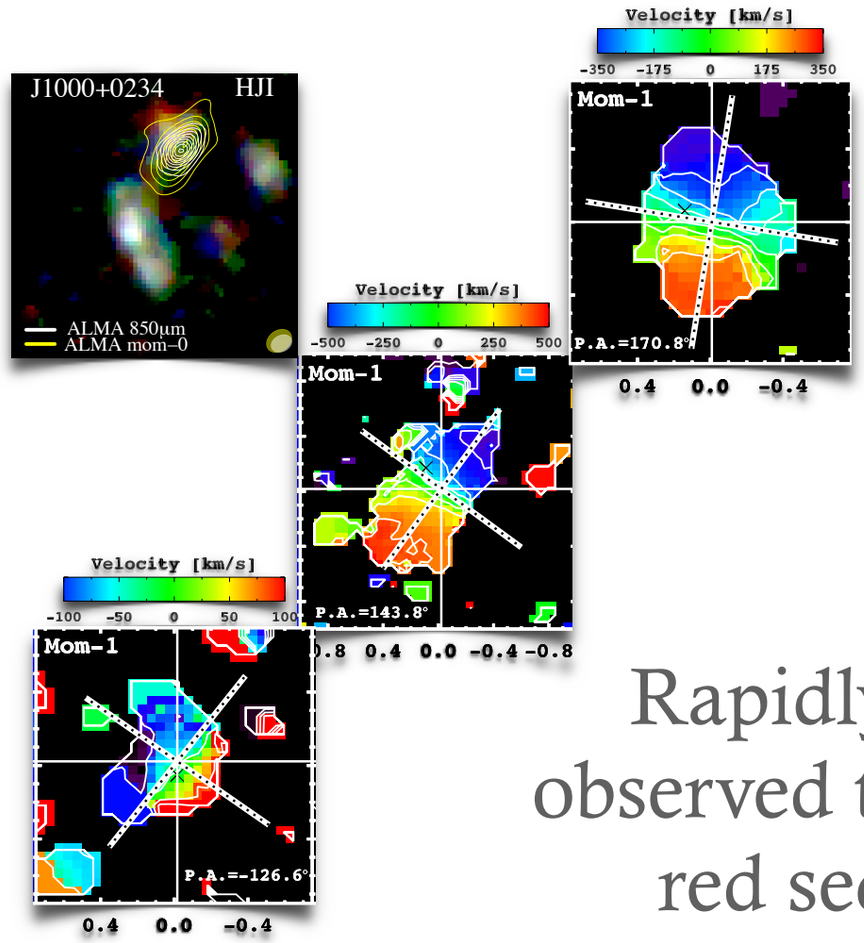


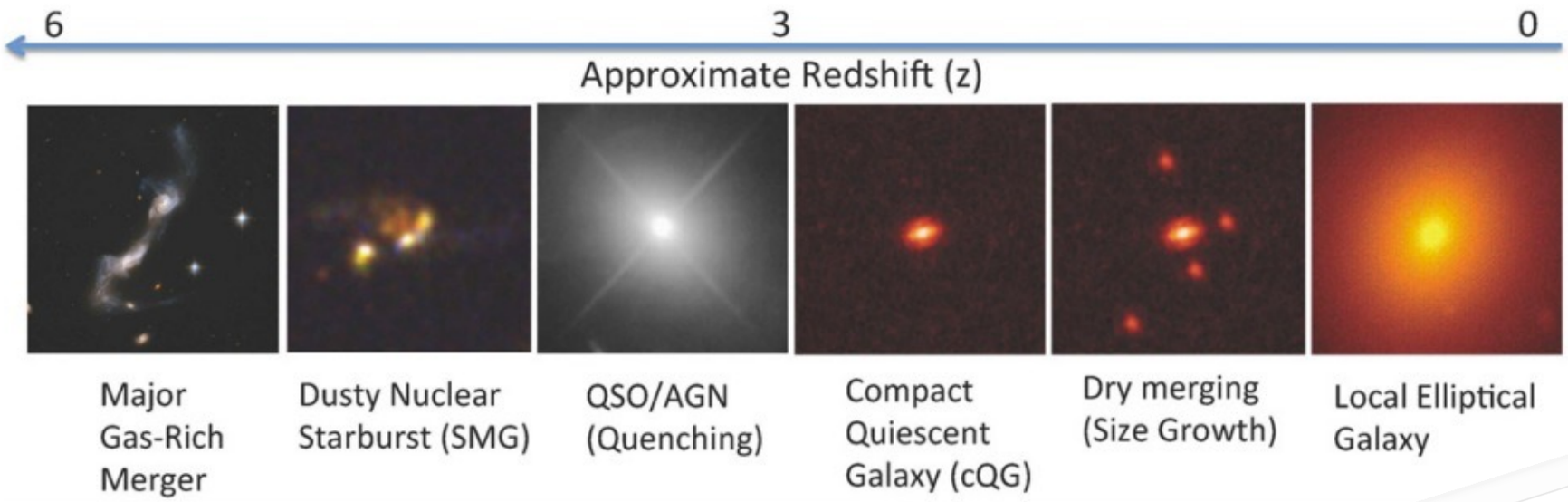
Rapidly spinning gas disks observed towards massive z~4.5 red sequence progenitors

Alexander Karim (AIfA Bonn/EU ARC Network)

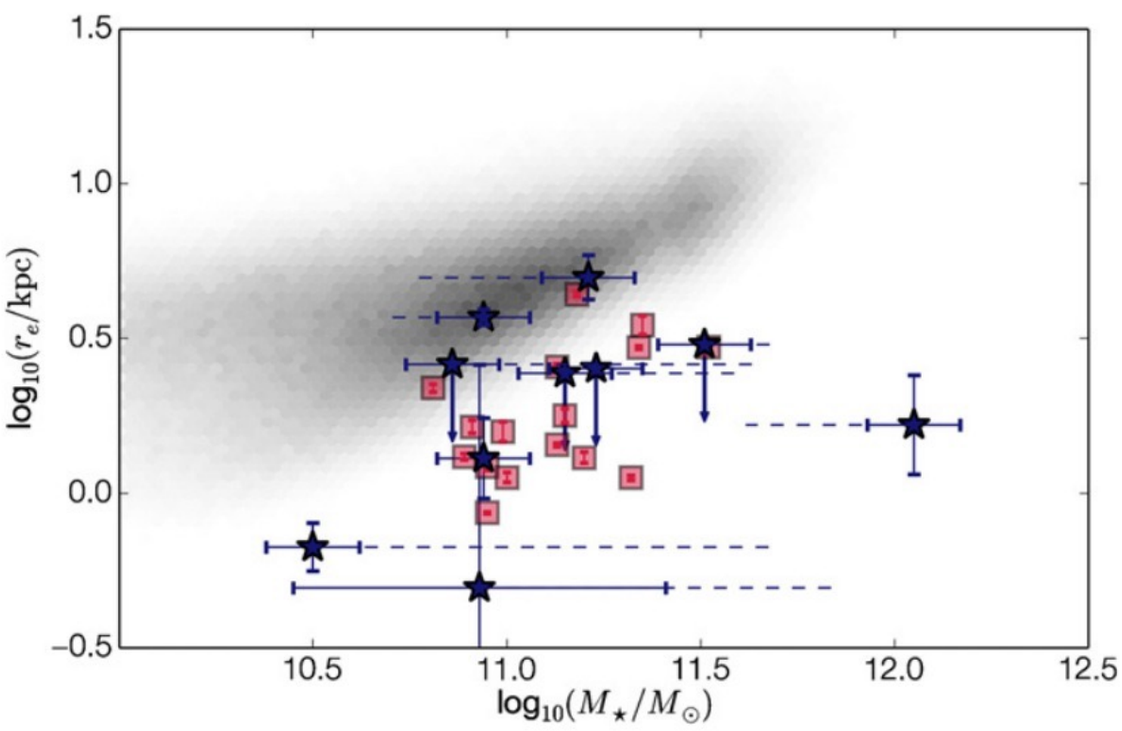
Team Bonn: **E. F. Jimenez-Andrade**, B. Magnelli, F. Bertoldi, E. Romano-Diaz
Team Copenhagen: S. Toft, **C. Gomez-Guijarro**, G. Magdis
Team Socorro: C. Carilli, **G. Jones**
Others: Fraternali, Smolcic, Schinnerer, Capak, Riechers, Aravena, Sheth, Sargent, Swinbank, Smail, Koekemoer, van Kampen, Staguhn

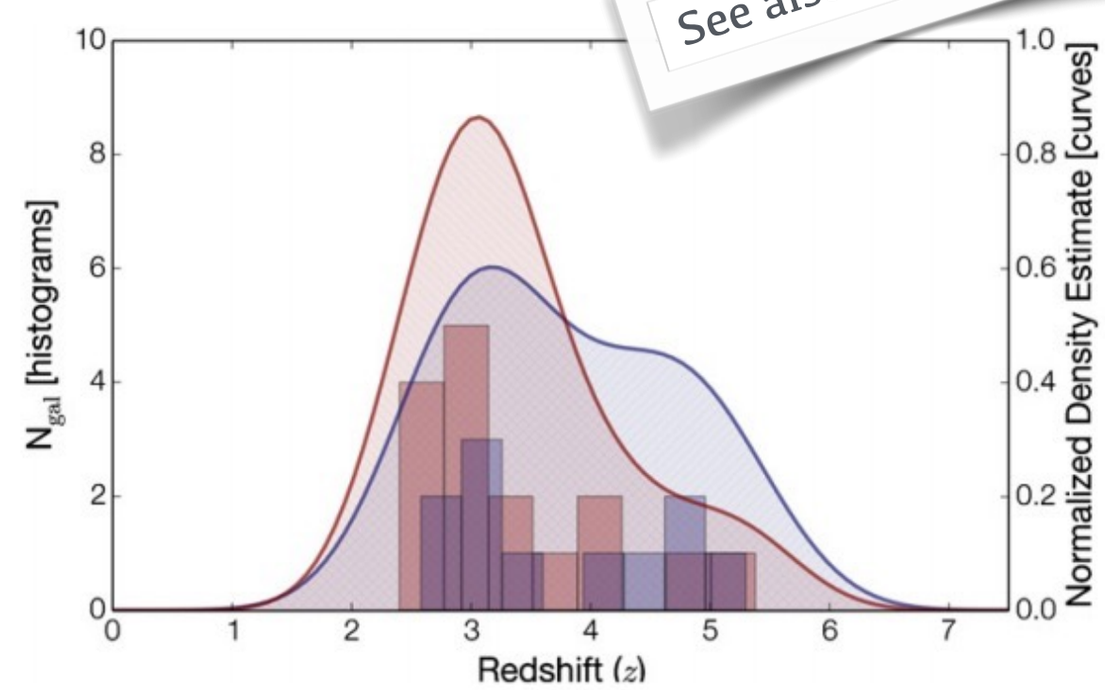
How to form the first massive galaxies?

Toft et al. (2014): z>3 SMGs as progenitors of $>10^{11}$ M_{Sun} compact z~2 quiescent galaxies



See also Simpson talk

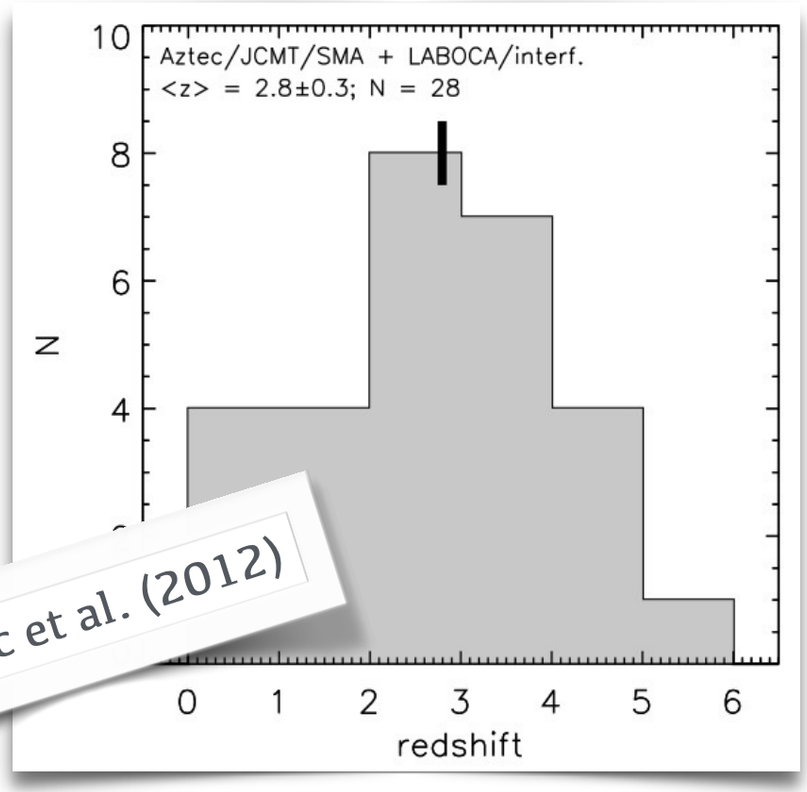




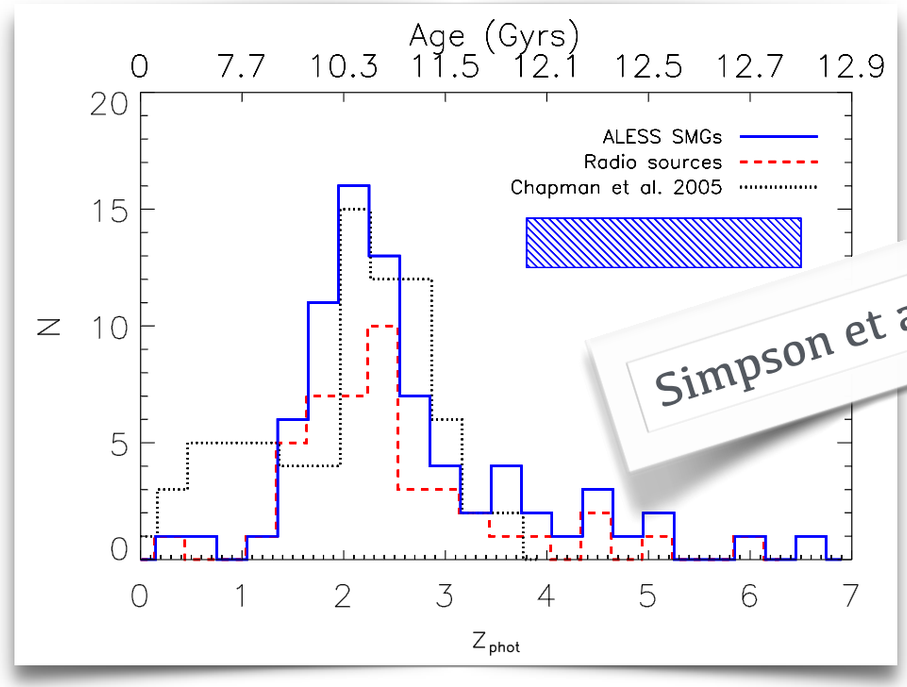
- Space densities of populations consistent if mean duty cycle of bursts < 100 Myr
- Roughly half the Toft et al. (2014) SMG-sample at z>4 ([CII]158um redshifted into ALMA's band-7)

Evidence for a z>4 SMG population

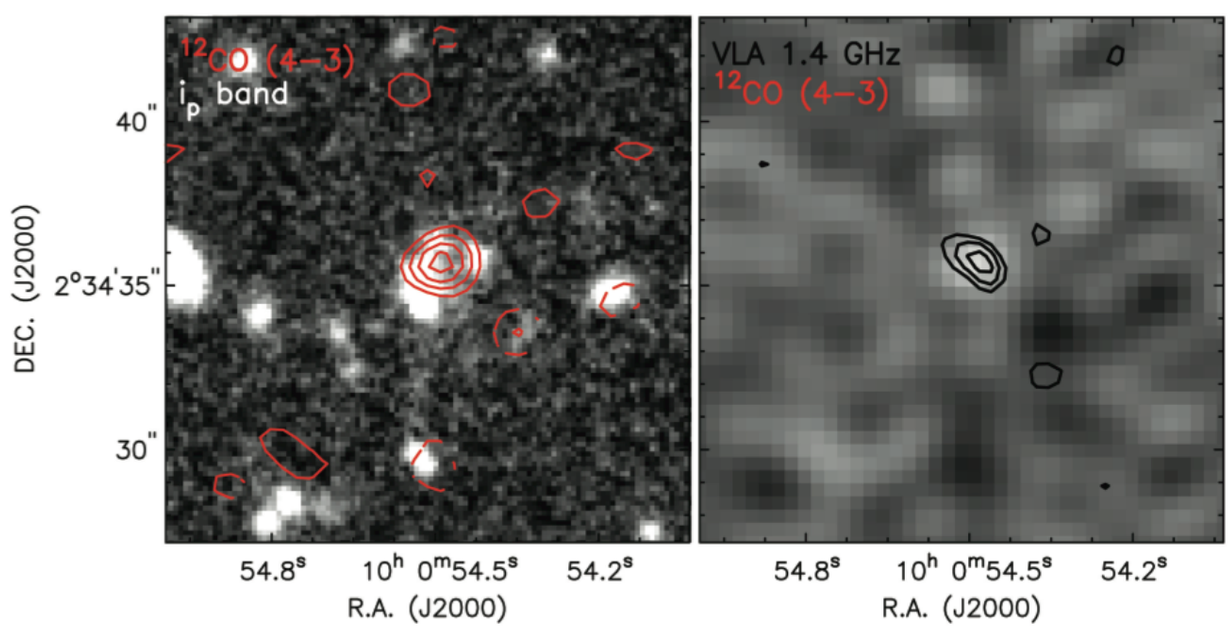
See also Weiß et al. (2013); Note: Some found among optical dropouts with radio counterpart

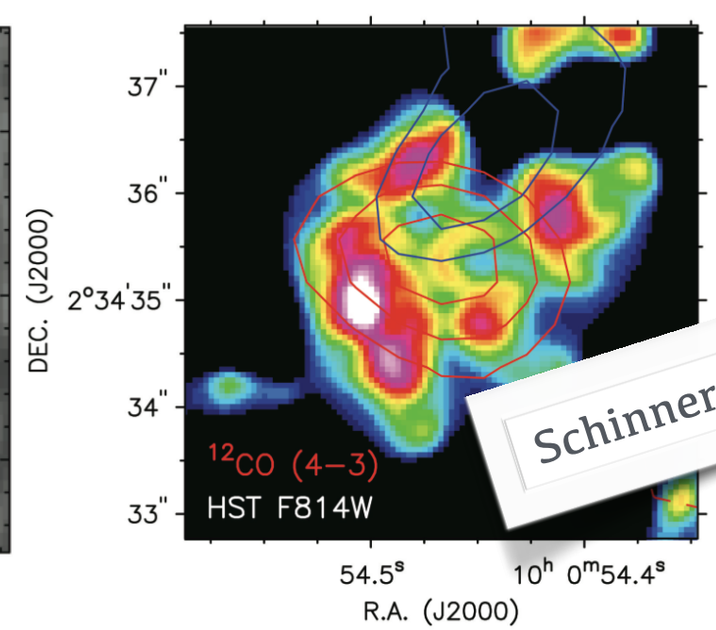


Smolcic et al. (2012)

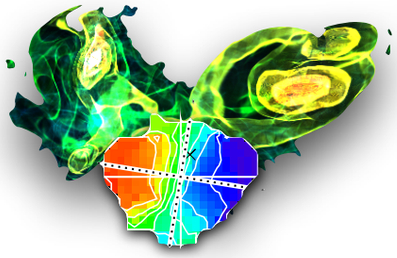


Simpson et al. (2014)



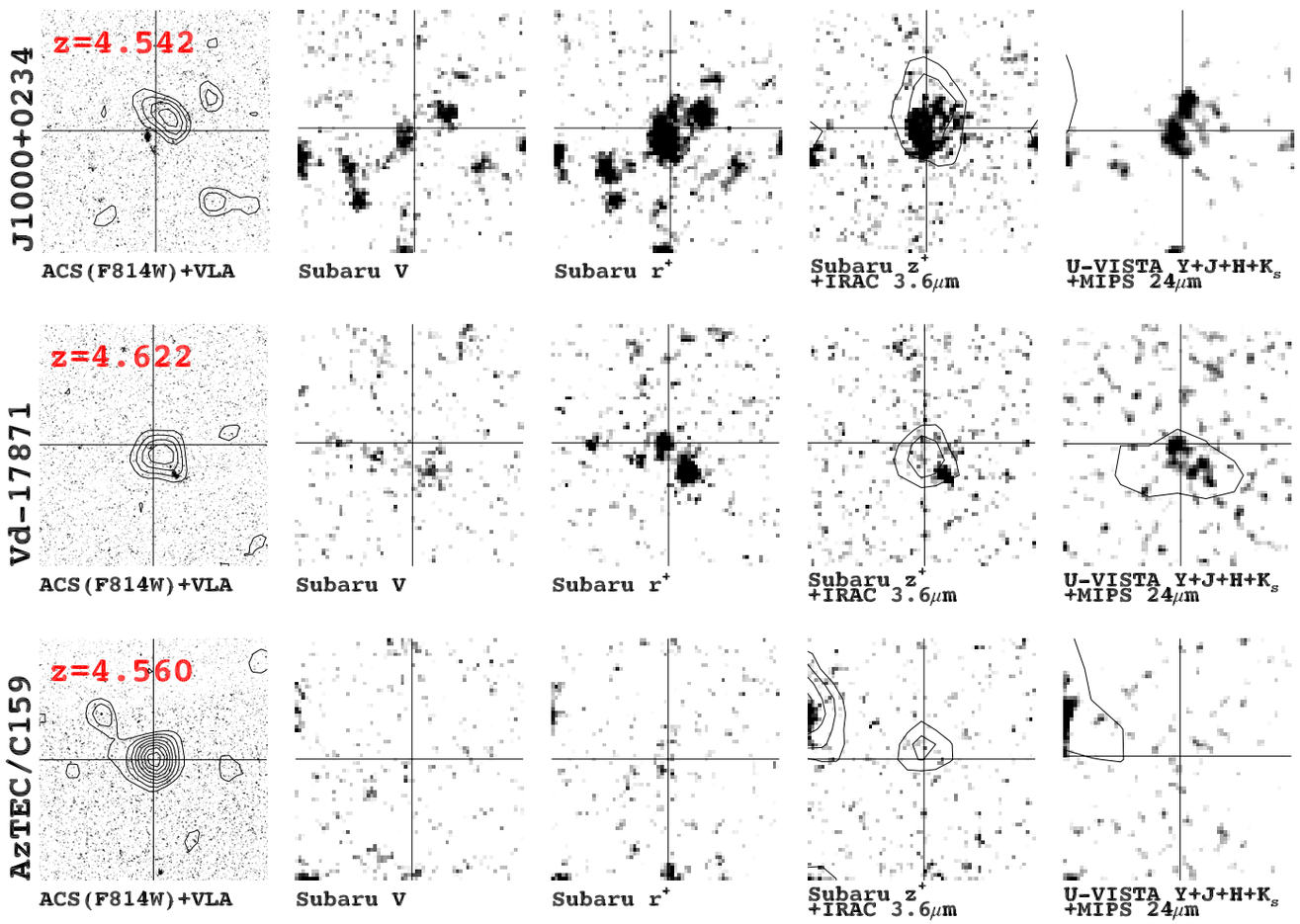


Schinnerer et al. (2008)



z>4 field sample in central COSMOS

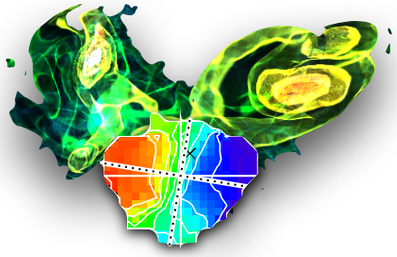
Mix of morphologies, mostly IRAC & radio-detected, flat/red in SPIRE (Smolcic, AK+ 2015)



Name	t_{form} [Myr]	τ_V [mag]	M_* [$M_\odot$]	L_{dust} [$L_\odot$]	M_{dust} [$M_\odot$]
AzTEC1	199	2.897	7.4×10^{10}	2.2×10^{13}	3.9×10^{9}
AzTEC3	140	3.952	1.4×10^{11}	1.1×10^{13}	5.2×10^{9}
AzTEC/C159	114	3.568	1.1×10^{11}	1.1×10^{13}	1.6×10^{9}
J1000+0234	149	31.644	8.7×10^{10}	7.0×10^{12}	9.1×10^{8}
Vd-17871	199	2.897	4.6×10^{10}	1.4×10^{13}	1.5×10^{9}
AK03-N*	474	4.721	1.0×10^{11}	1.4×10^{12}	3.6×10^{8}
AK03-S*	713	6.243	3.9×10^{11}	3.4×10^{13}	5.6×10^{10}

$S_{100\mu m}$ [mJy]	$S_{160\mu m}$ [mJy]	$S_{250\mu m}$ [mJy]	$S_{350\mu m}$ [mJy]	$S_{500\mu m}$ [mJy]
< 6.8	< 13.6	19.5 ± 6.0	29.8 ± 7.6	28.8 ± 9.0
< 6.8	< 13.6	22.3 ± 7.1	21.1 ± 7	< 32.0
< 6.8	< 13.6	6.2 ± 1.9	< 10.8	< 20.4
< 6.8	< 13.6	< 15	< 20.0	< 30.0
< 6.8	< 12.0	9.5 ± 2.0	12.3 ± 2.4	13.0 ± 3.7
< 6.8	< 13.6	< 8.0	< 12.0	< 20.0

- Massive (~5×10^{10}-2×10^{11} M_{Sun}) Ultra/High-LIRGs > generally starbursts
- Covering top OR bottom end of sub-mm deep field selection function



A more detailed view

Concerted follow-up: total mass & distribution and conditions of gas/dust/stars (PI: AK)

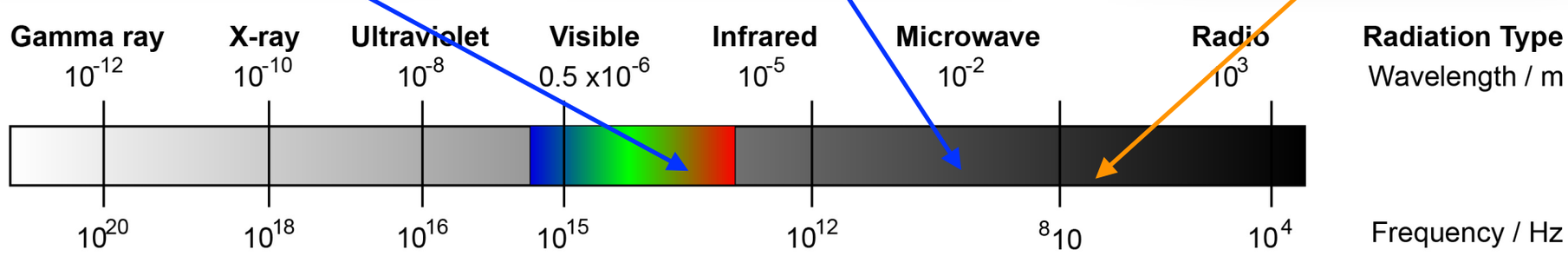
Results in the following for 3 of our z>4 objects
with [CII]158um line detections (papers being drafted)

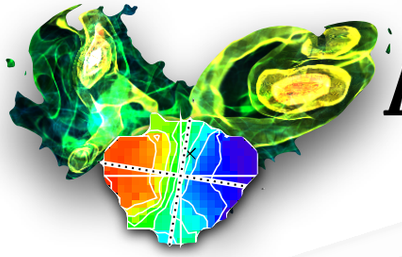
See Poster #22!

Distribution of young stellar populations.
C. Gómez-Guijarro+

Gas/dust distribution and kinematics.
A. Karim+

Molecular gas properties
E.F. Jiménez-Andrade+

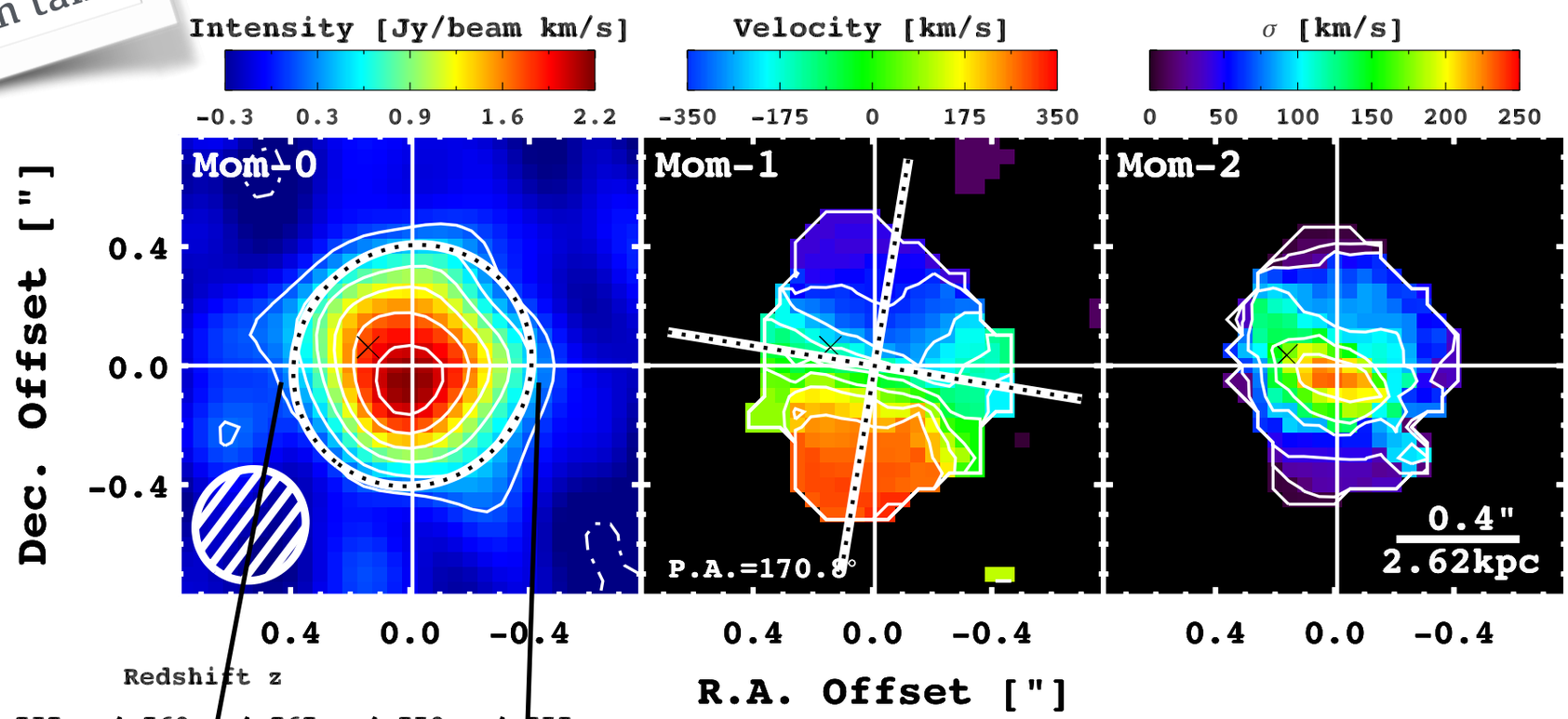


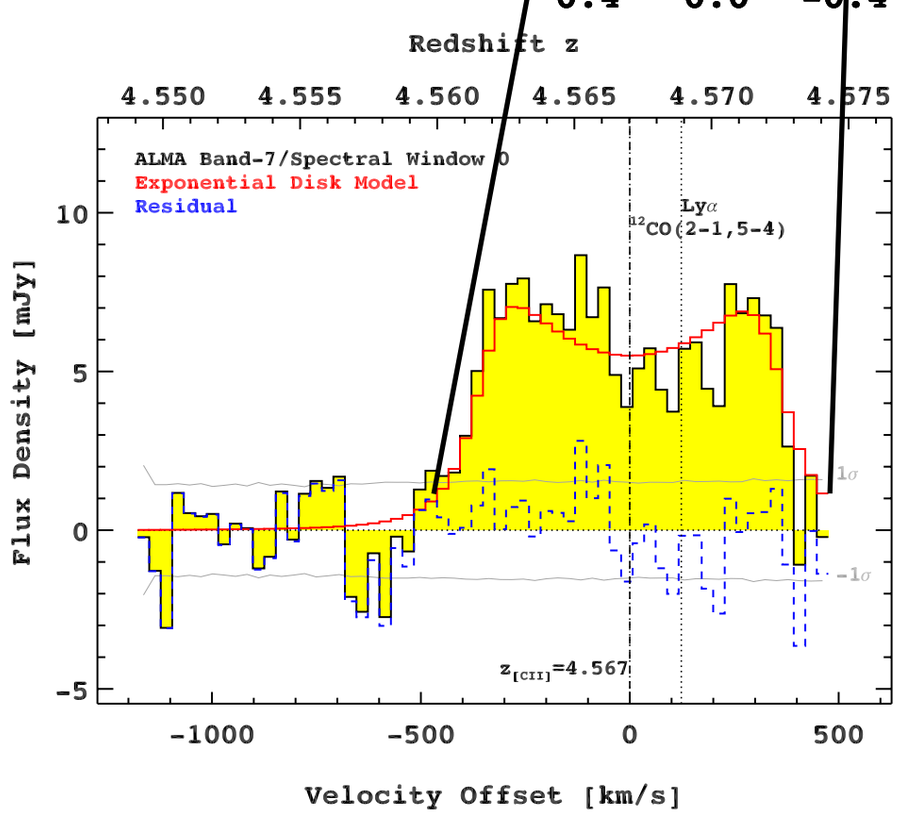


All objects show steep [CII] velocity gradient

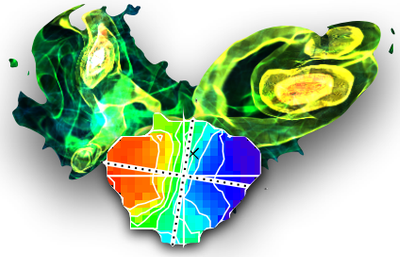
A star forming gas disk 1.3Gyr after the Big Bang seen in [CII] emission by ALMA?

See also Chapman talk!



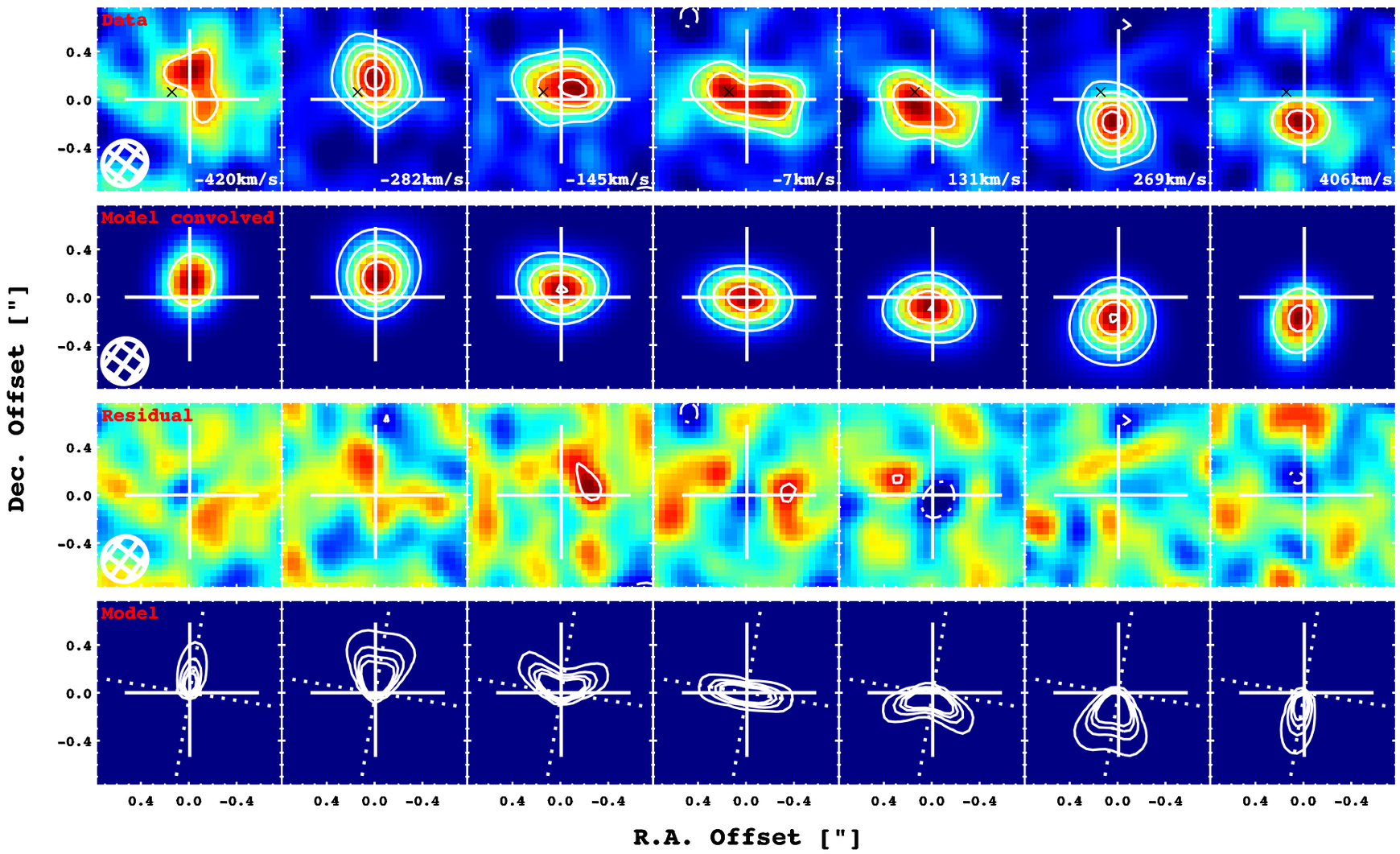


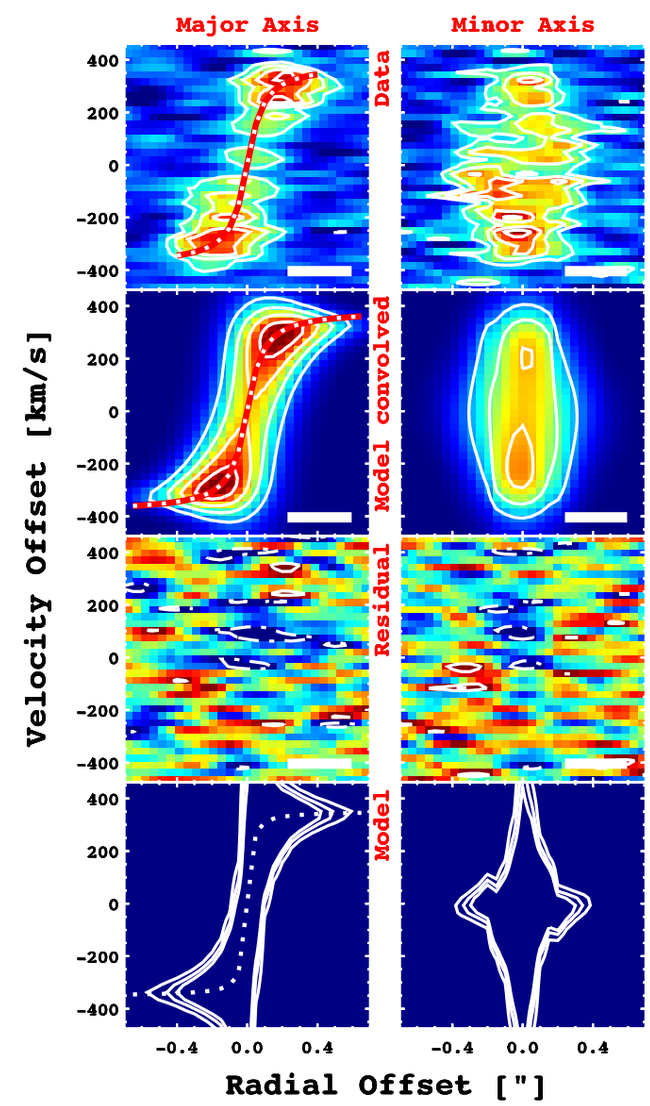
- No robust information on stellar distribution
- Asymptotic velocity ~500km/s
- 2.4kpc intr. eff. radius; 130pc intr. turnover radius
- Likely highly rotation-supported



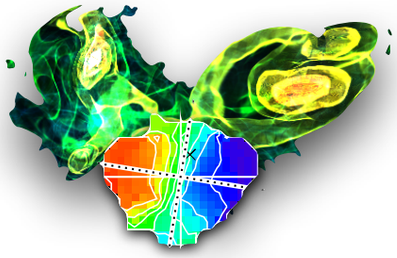
Simple tilted ring modelling - (expon.) disk

3D modelling using GalPaK and 3D-Barolo (Bouche et al. 2015; Teodoro & Fraternali 2015)





- Relatively low inclination (~45deg)
- Difficult to determine intrinsic velocity dispersion given strong velocity gradient
- Additional 2D modelling using GIPSY/rotcur consistent with these results (Jones et al. in prep.)



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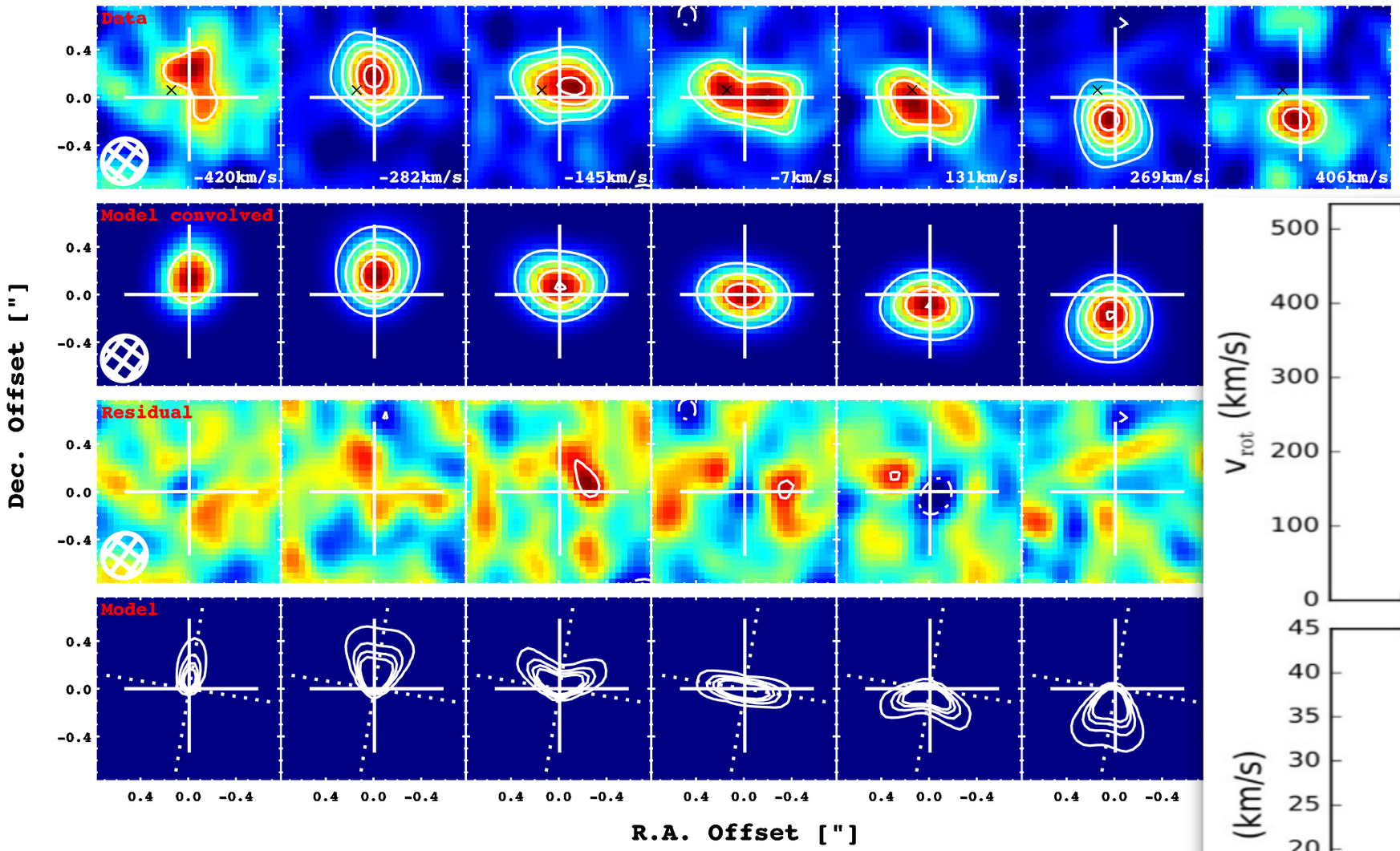

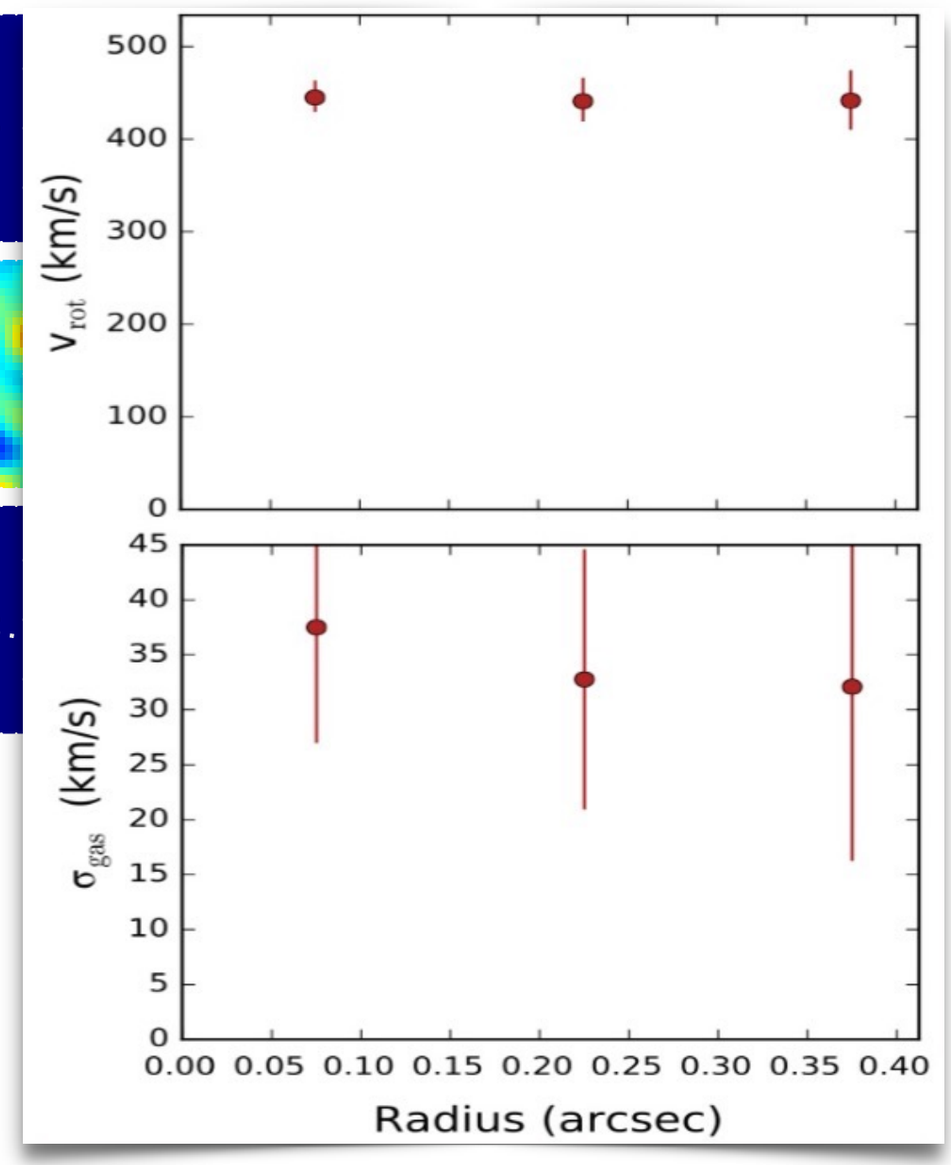

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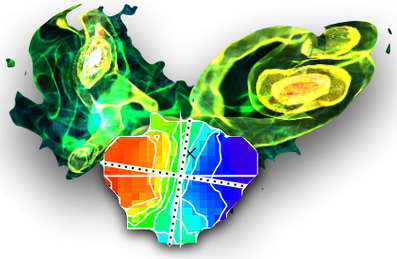
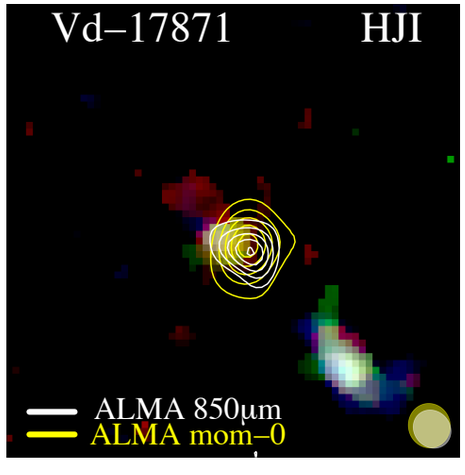
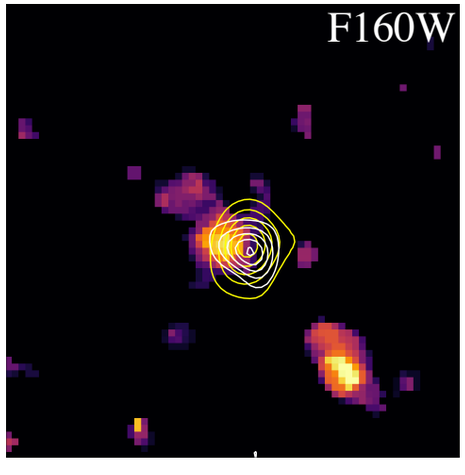
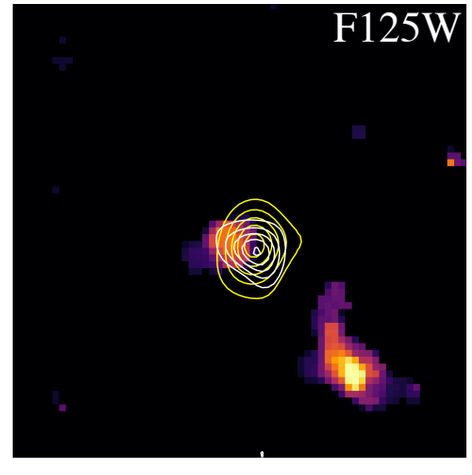


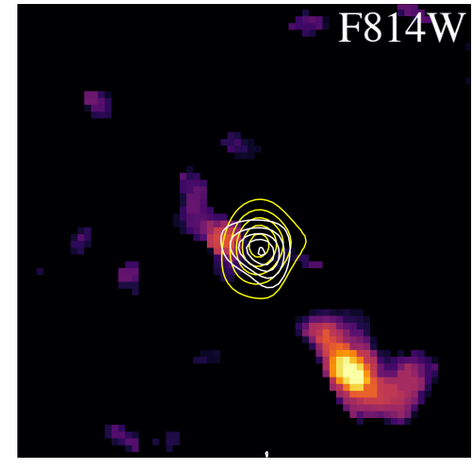
However, disk signatures also in "mergers"

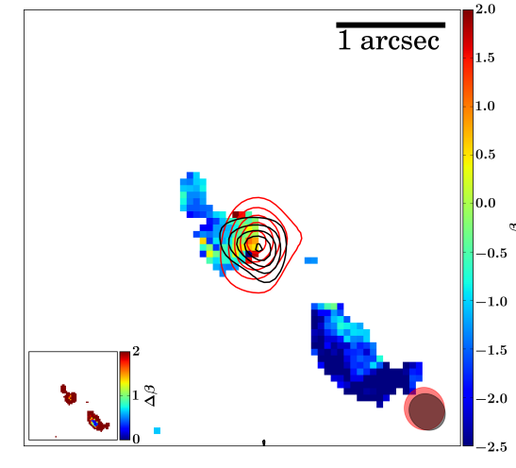
Data delay: carry-over and QA2-fail; HST analysis from Gomez-Guijarro, AK+ (in prep.)

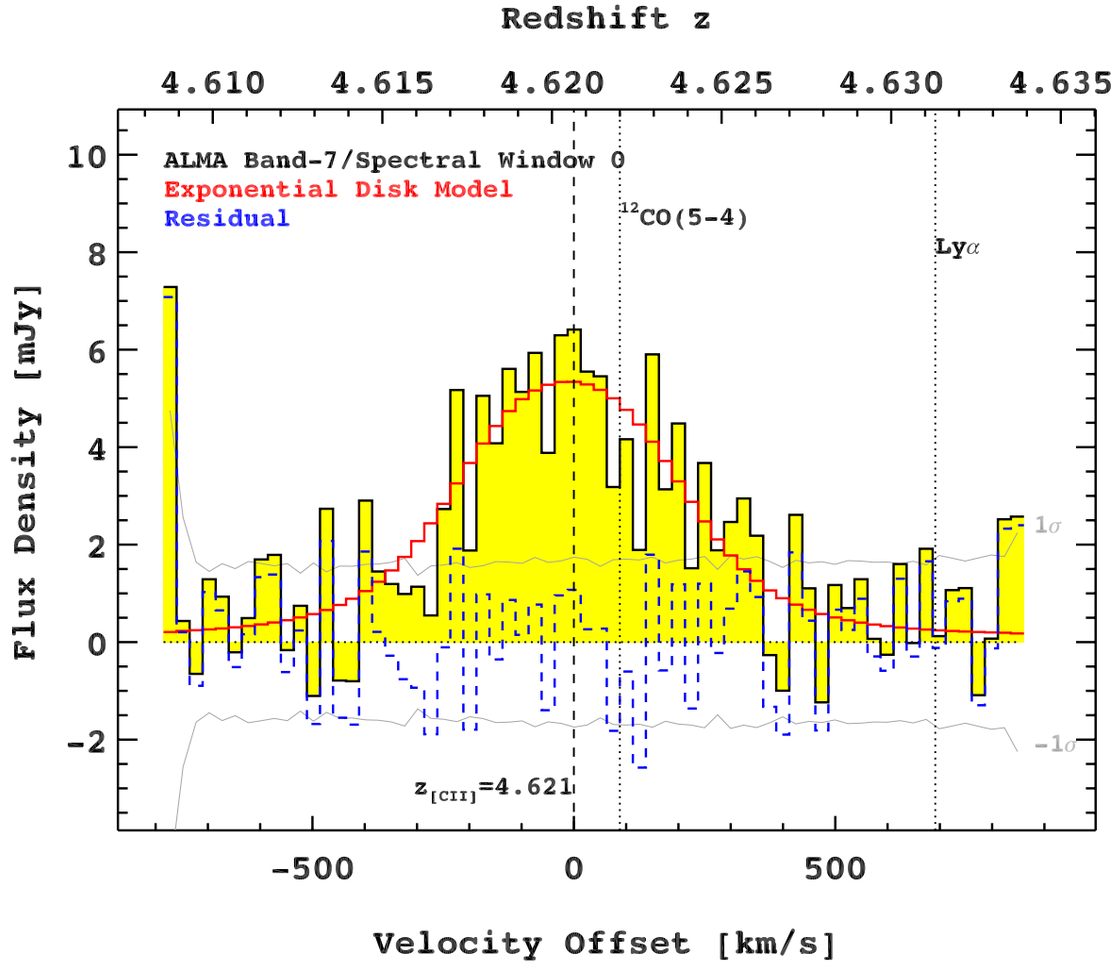


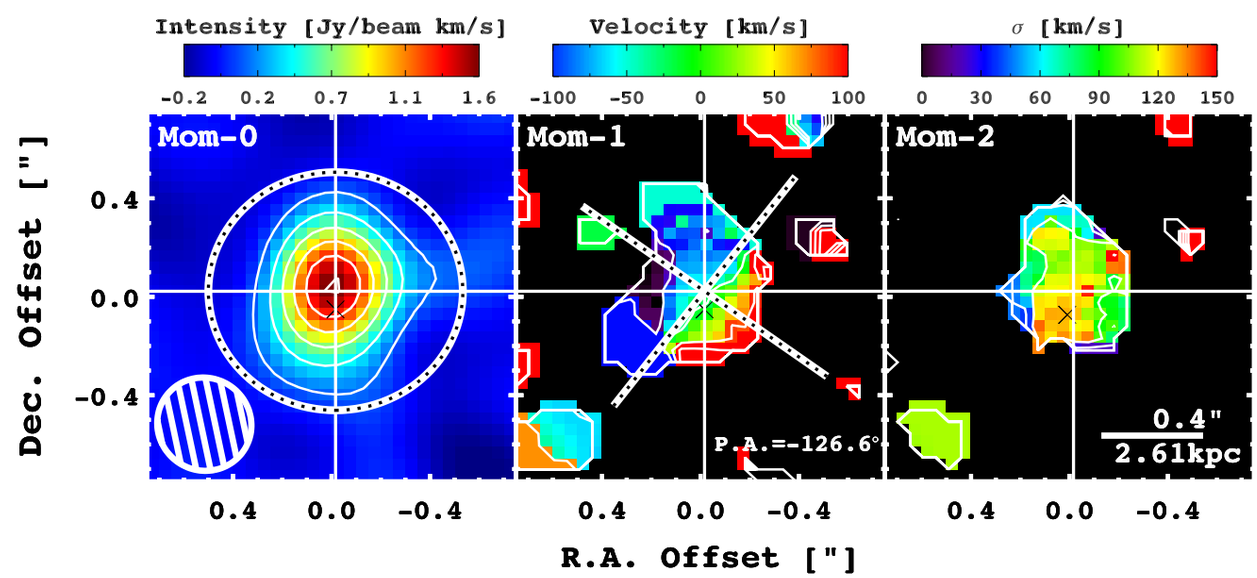






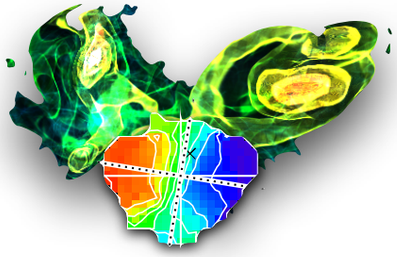






- Asymptotic velocity ~800km/s
- 760pc intr. eff. radius

- **Ongoing minor merger perhaps not the trigger for the starburst. If previous major merger started the process, dynamical time is short enough to regularise the gas**



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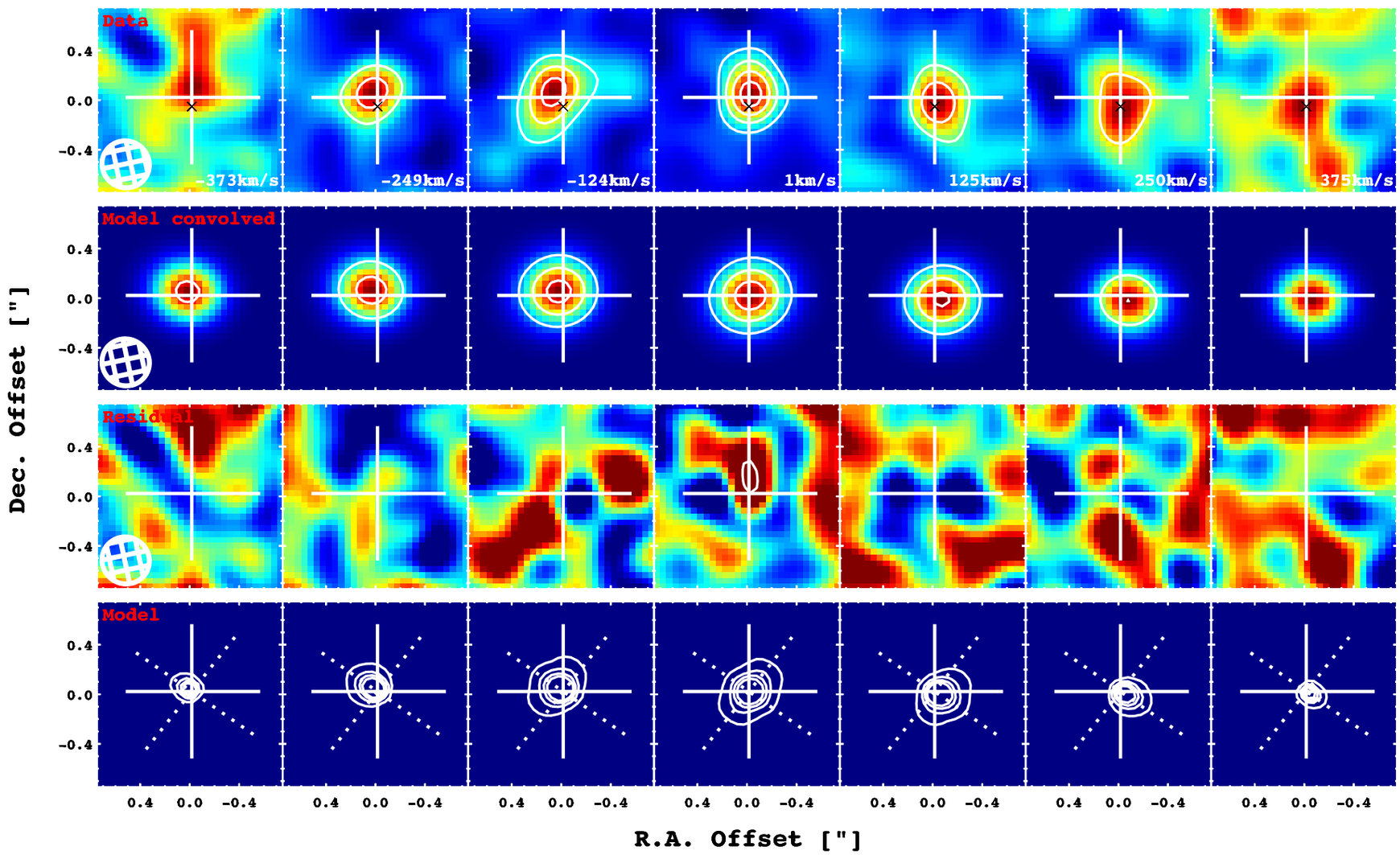
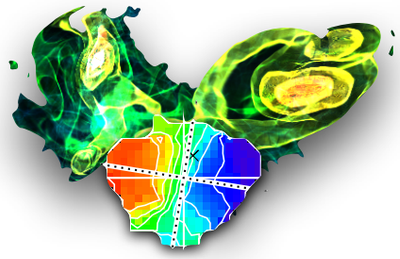
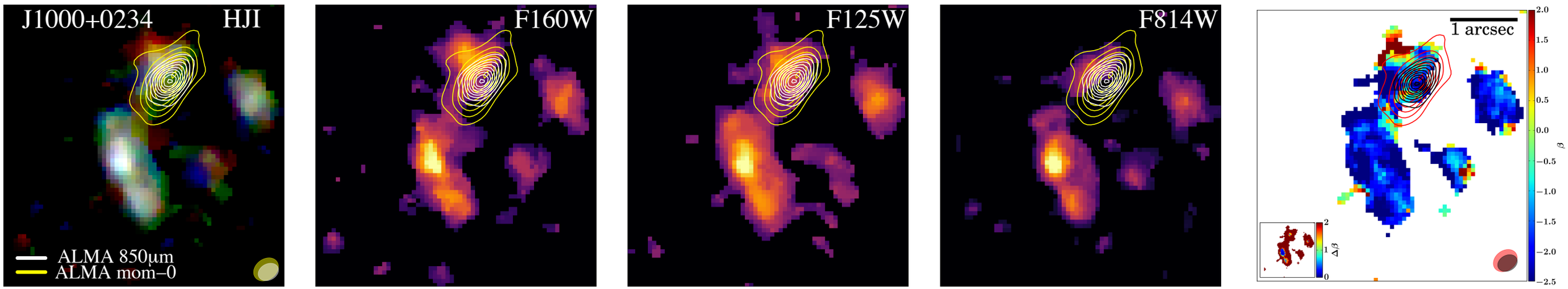
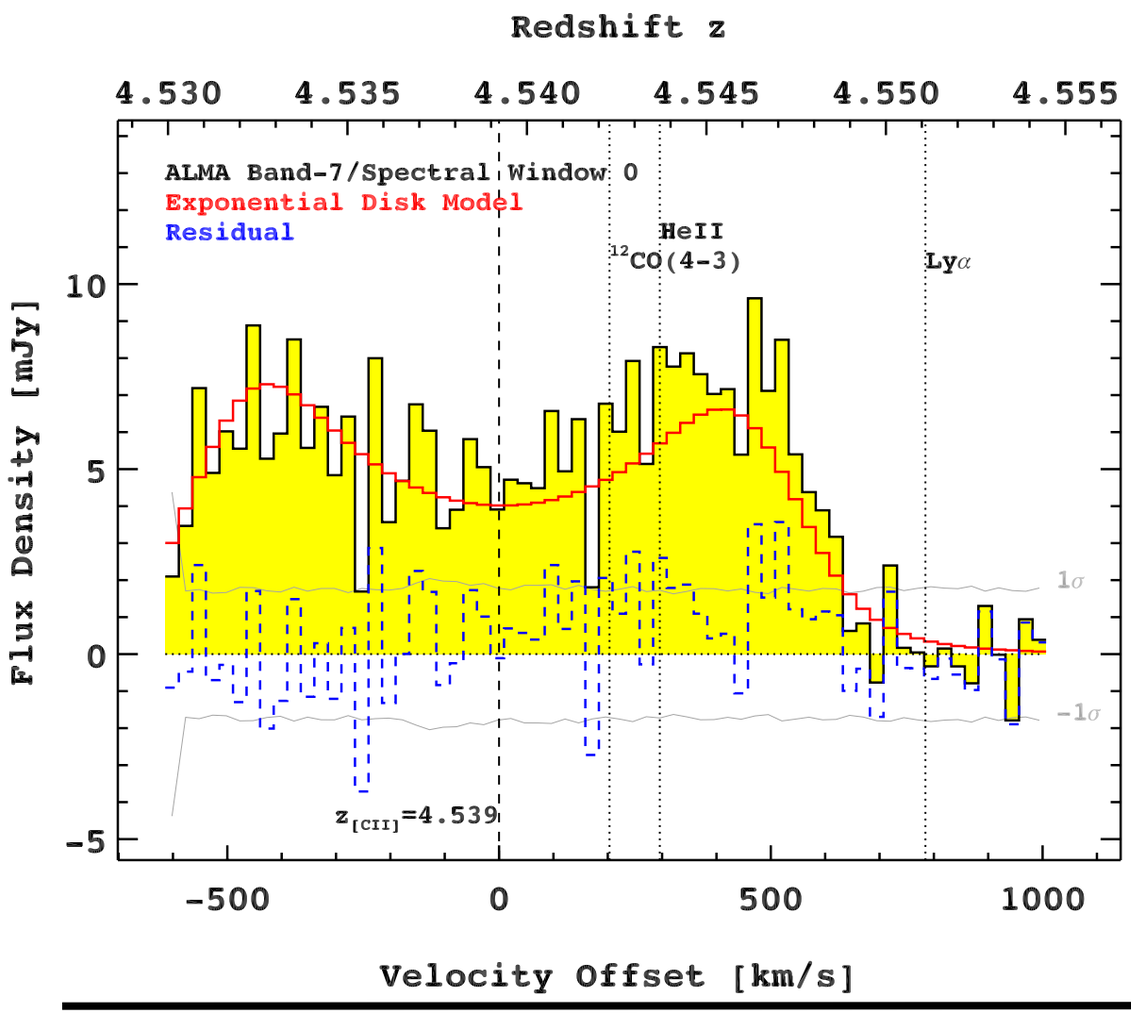


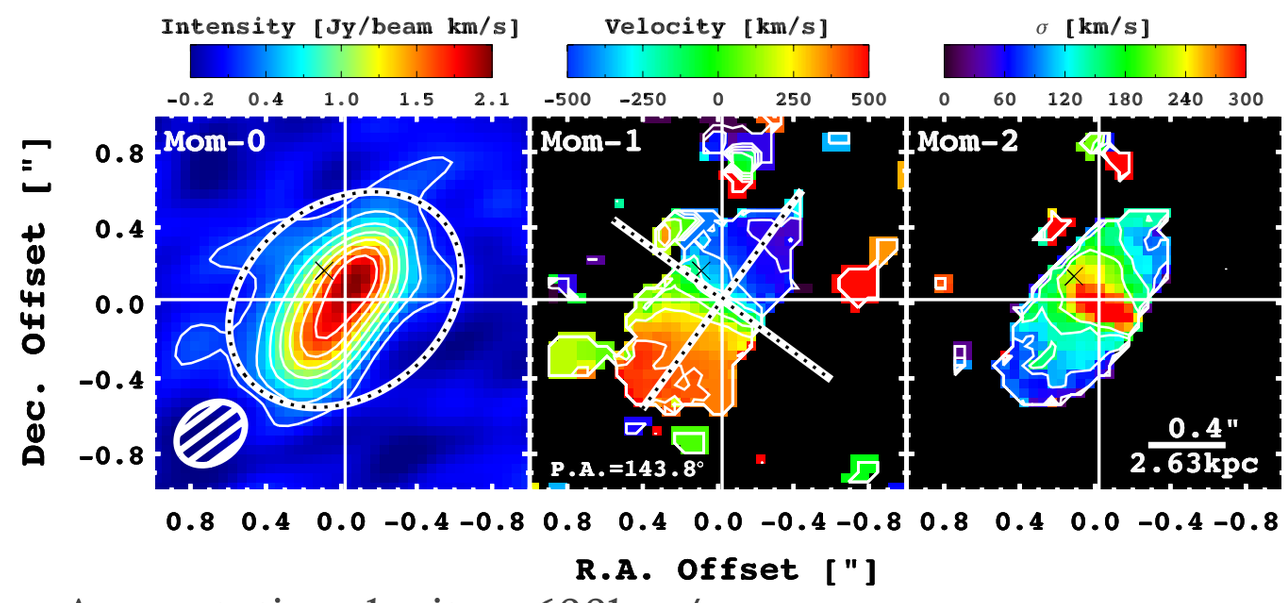


...and more spectacular

Almost doesn't fit into spectral window; geometric challenges for energy balance SED fitting

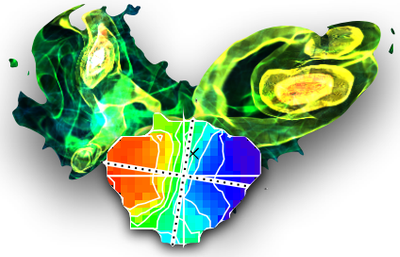






- Asymptotic velocity ~600km/s
- 2kpc intr. eff. radius; 170pc intr. turnover radius
- [CII] properties overall very similar to first object

- **Young stellar emission offset from gas/dust; hints for partial foreground UV-emission (IRX/beta analysis: see poster #22)**



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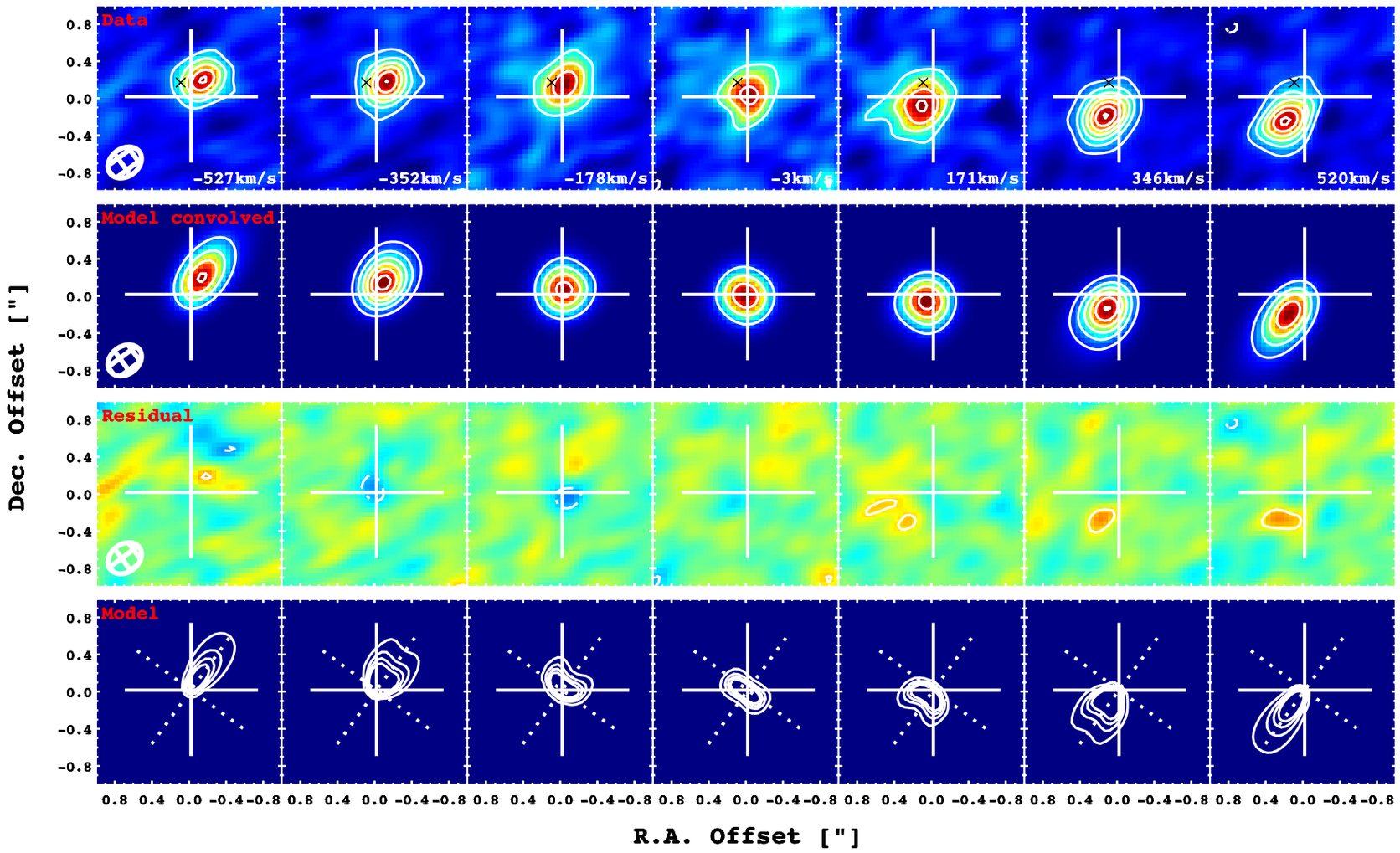
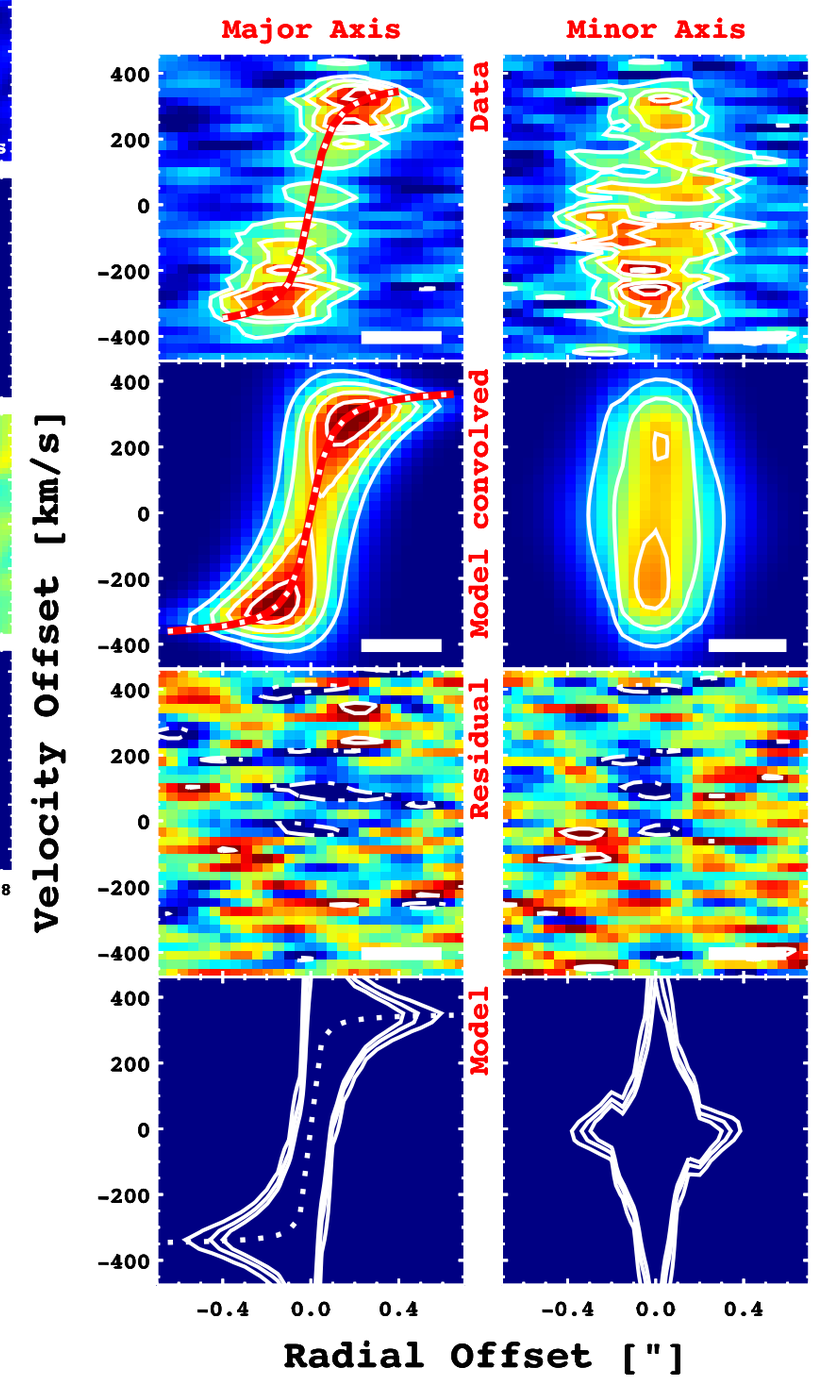
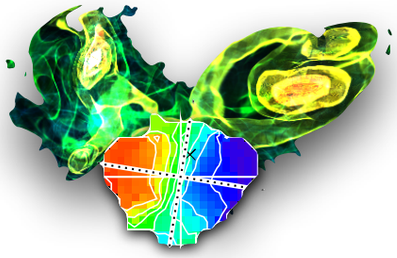




- Relatively high inclination (closer to edge-on view)
- Somewhat better spatial deblending of steep velocity gradient, still challenging to determine intrinsic dispersion



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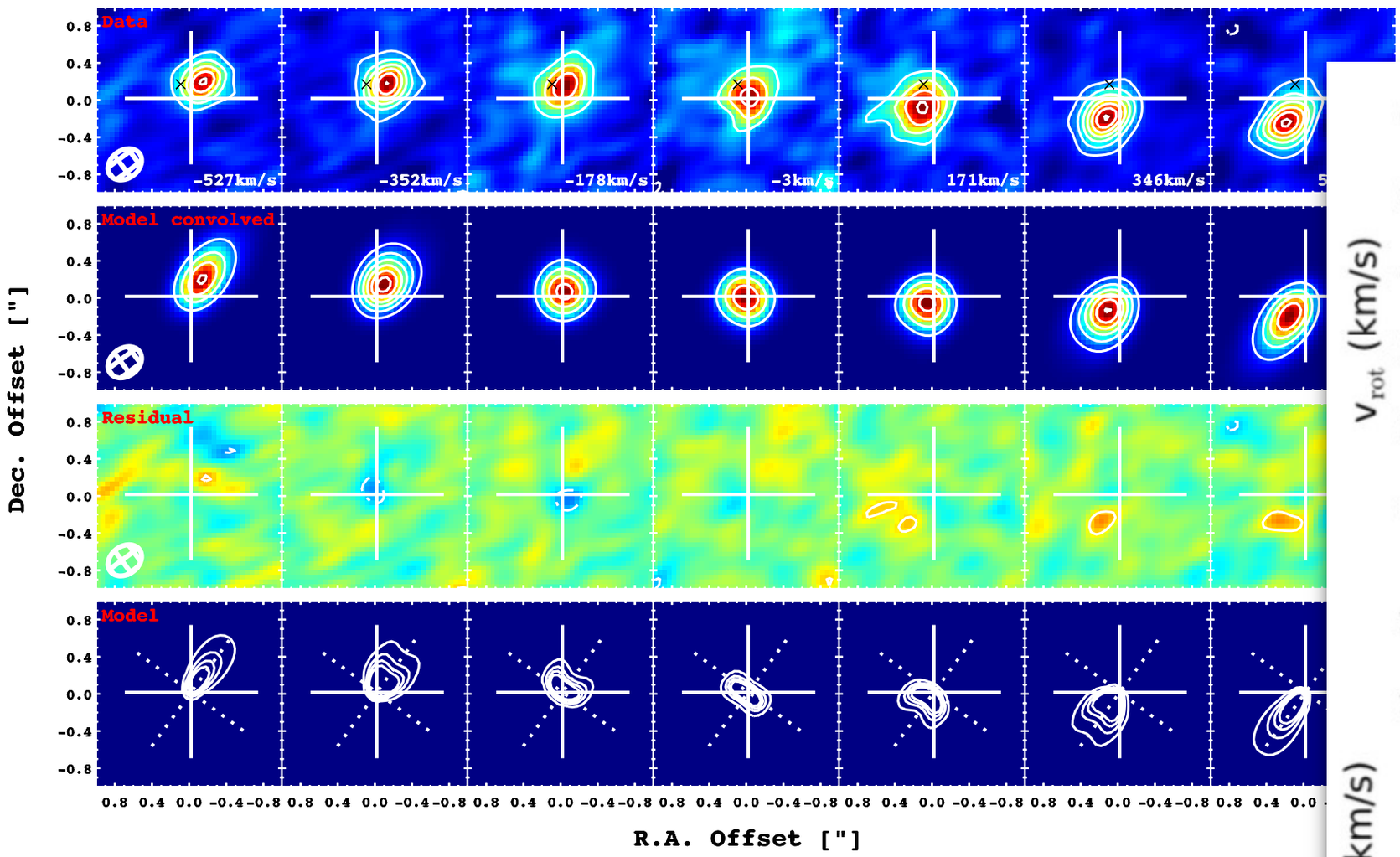

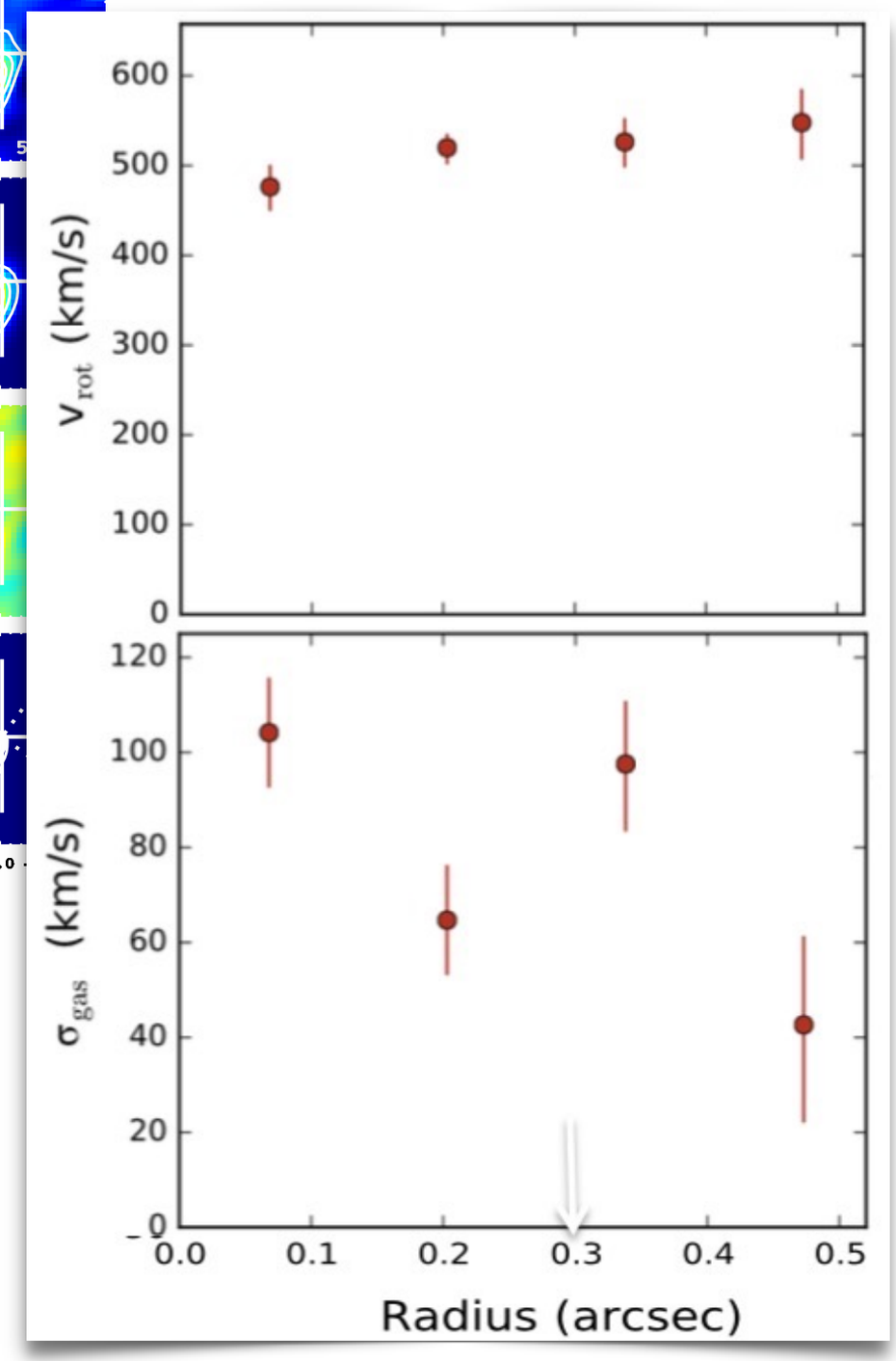

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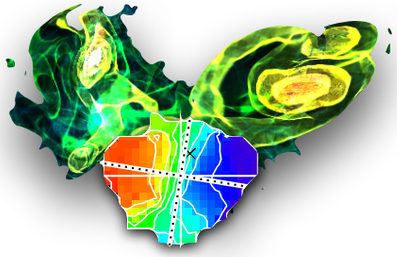
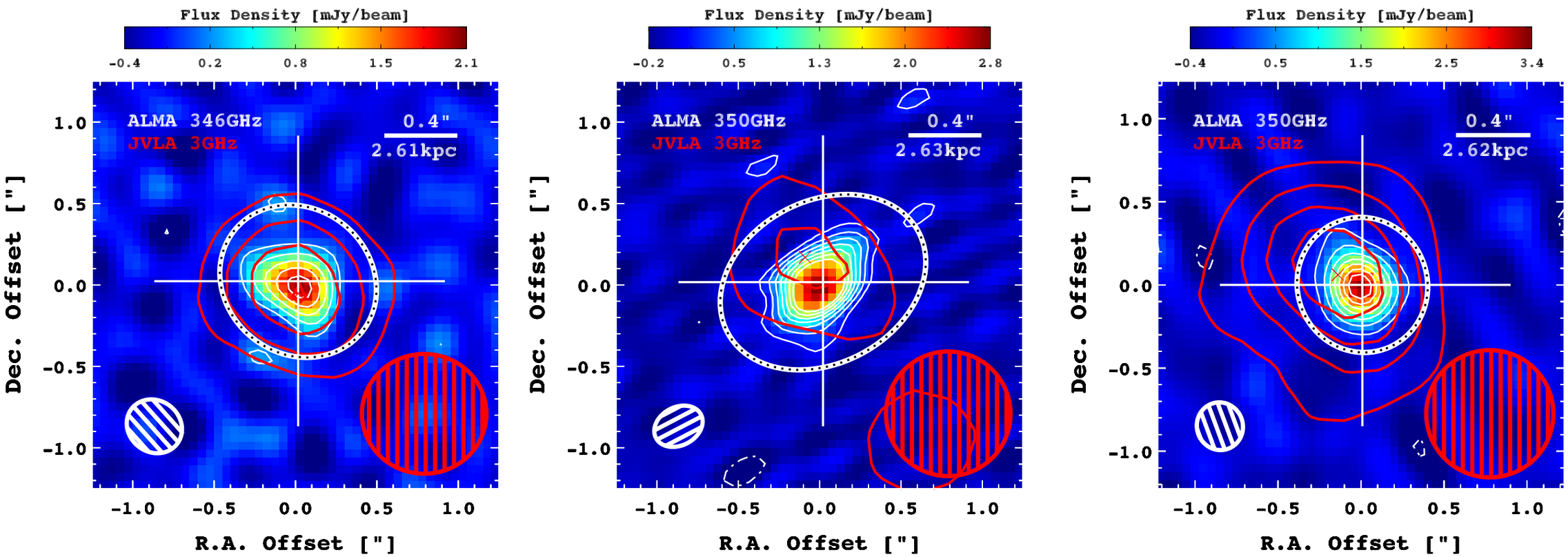
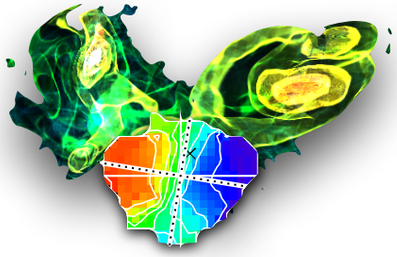


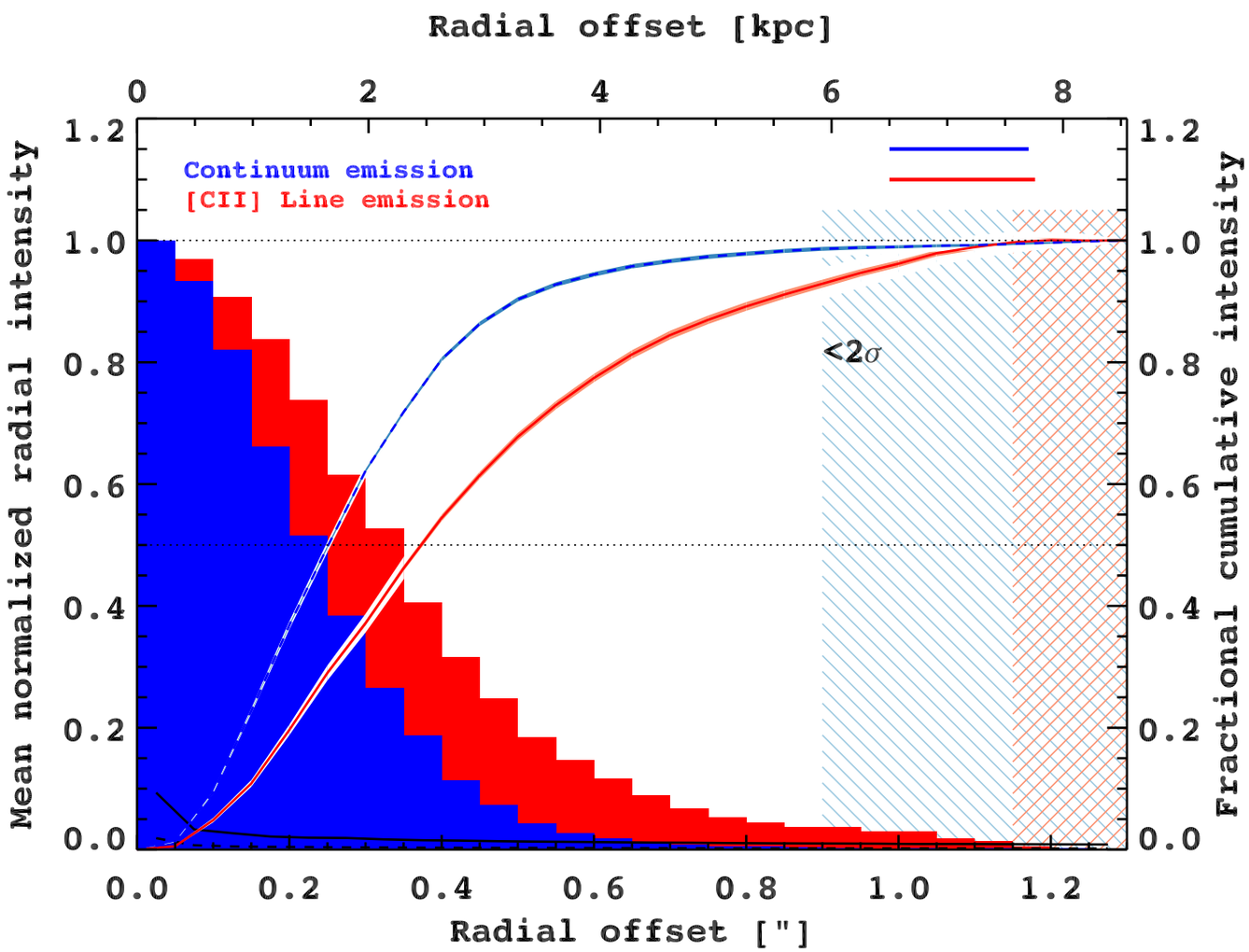
Rest-frame 160um/16.5GHz continuum

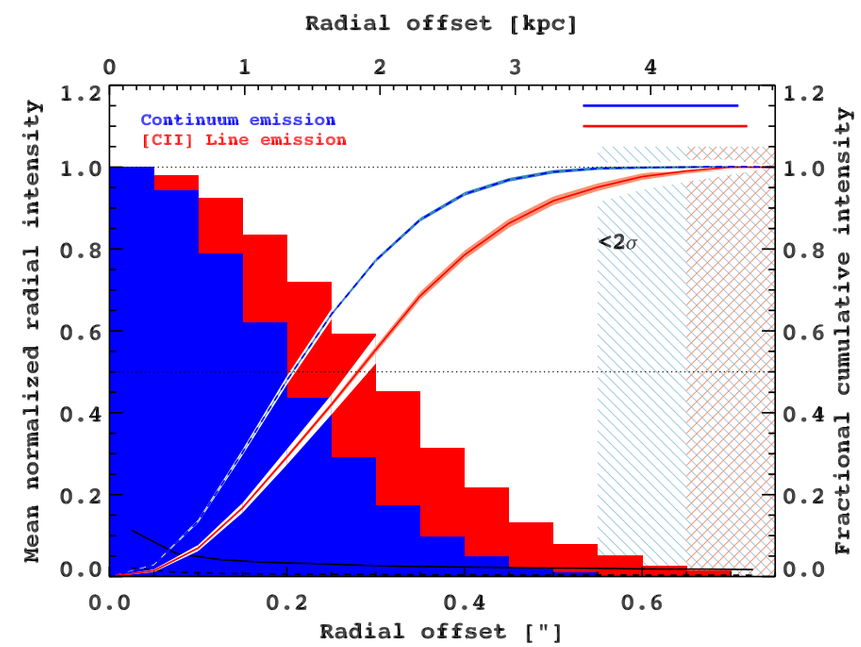
20min on-target, 0.3”-0.4” beam (<0.3” in uniform weighting for high-SNR continuum)

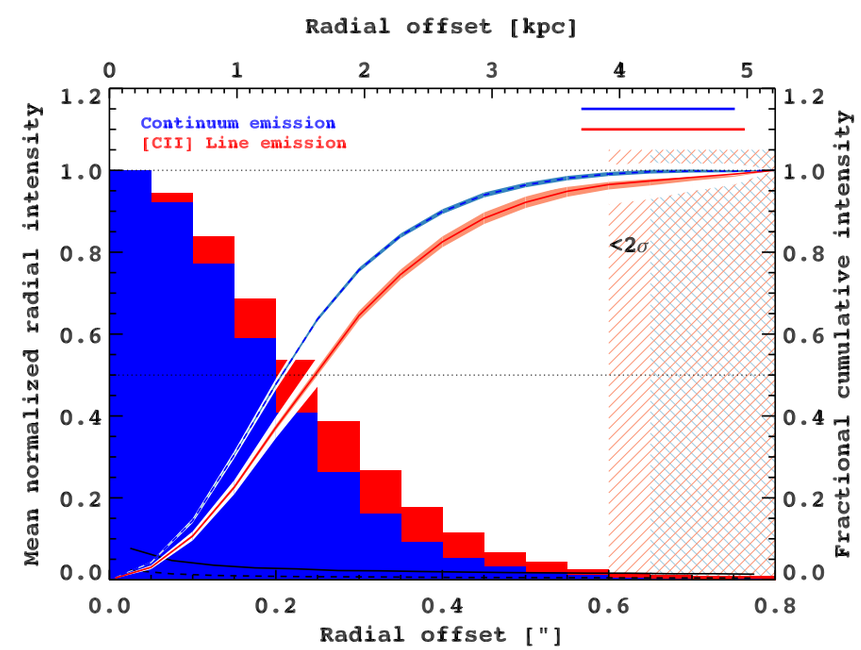


- Far-IR Continuum generally more compact compared to [CII] extent (factor ~2)
- Radio continuum centroid shows small but significant offset in most cases
- where it shows an offset, radio emission either largely extended or tentatively multi-component
- Perhaps hinting to radio-AGN driving the mild offset from the observed far-IR/radio trend









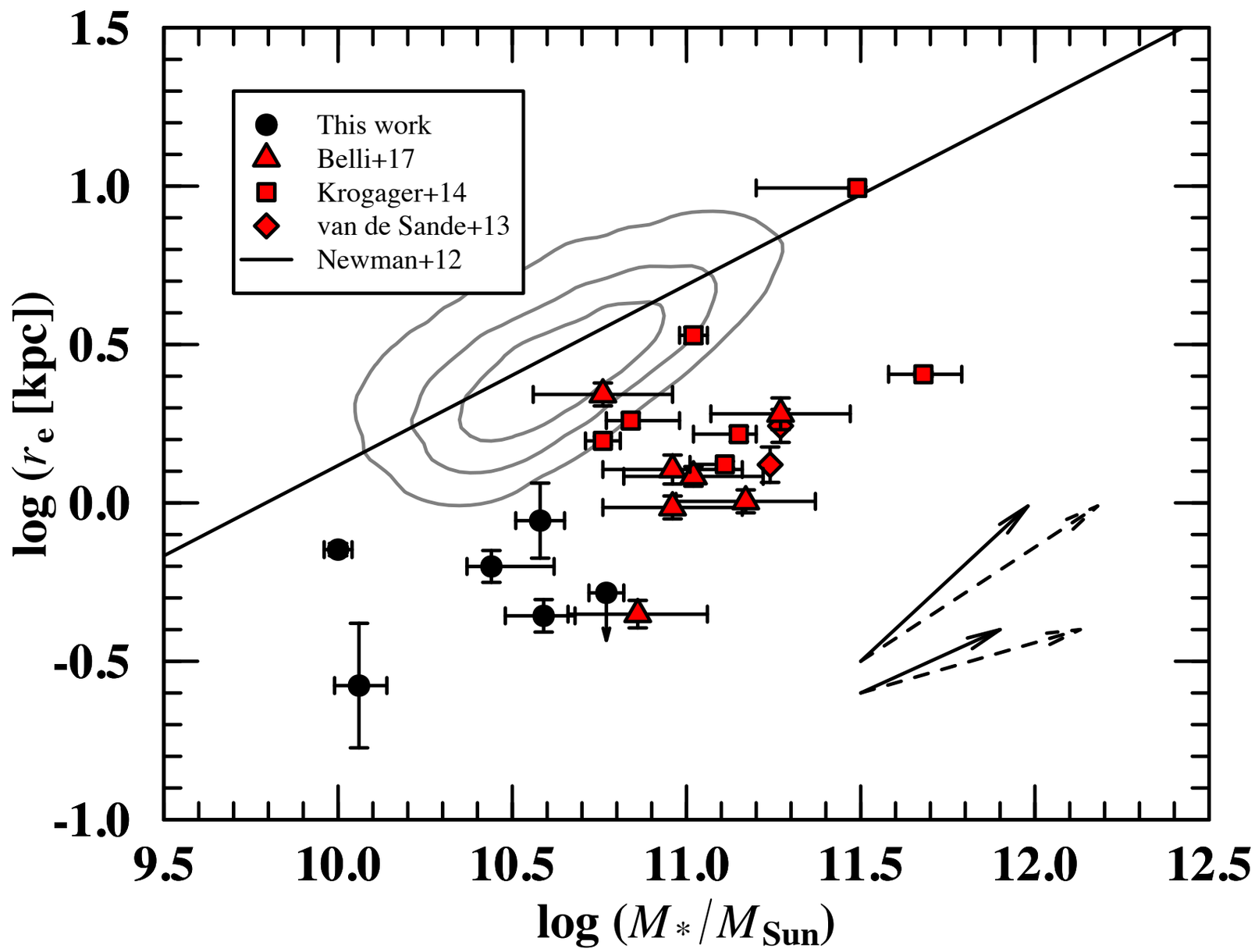
Implications for high-z [CII]-deficit

see also, e.g., de Breuck et al. (2014), Oteo et al. (2016), Diaz-Santos et al. (2016)

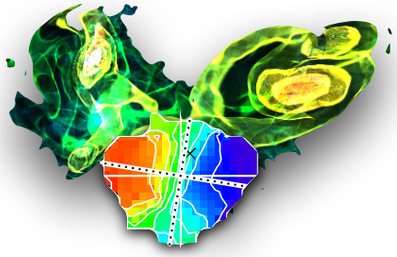
- Integrated [CII]/LIR comparable to Swinbank, AK+ (2012)
- At outer part of disk more in line with "normal" galaxies

Possible evolutionary tracks to z~2

Plausible connection (from full sample of 6 from COSMOS); Gomez-Guijarro, Toft, AK+ (in prep.)

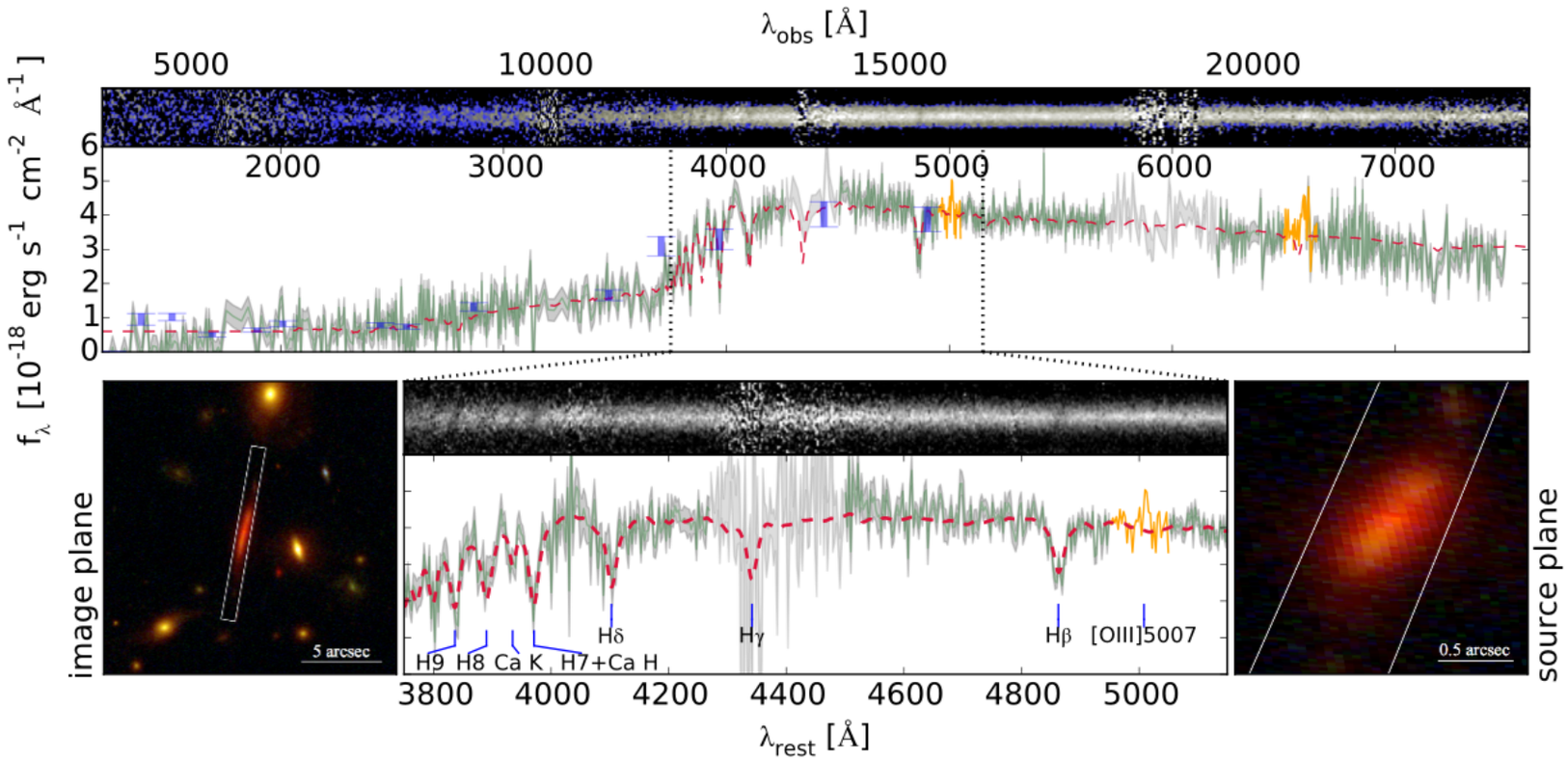


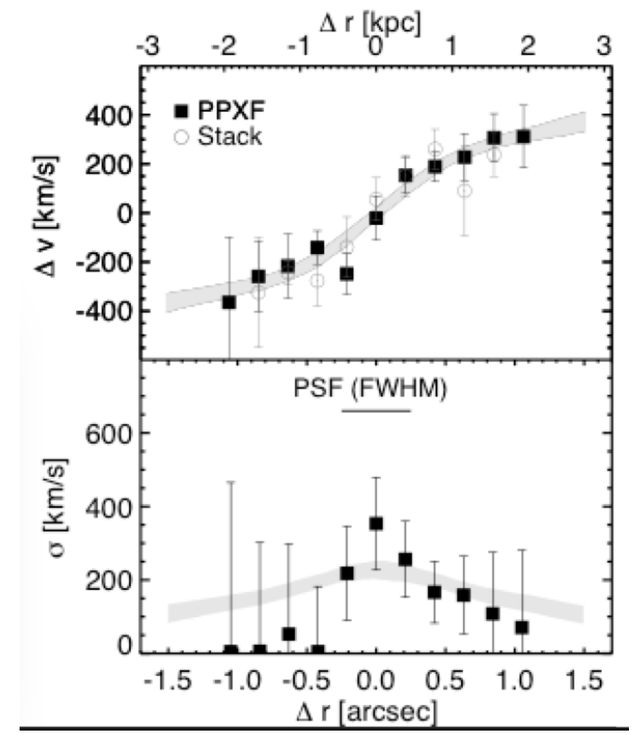
- Found 1.3 satellites (mass ratio ~1:5) on average; some hints for additional 1:10 mergers (up to 5; upper trends)
- Assumes size growth through minor mergers according to Bezanson et al. (2009) - simple scaling given the observed mass ratios
- Solid/dashed arrows assume 50/100Myr gas depletion timescales (see also upcoming slides)

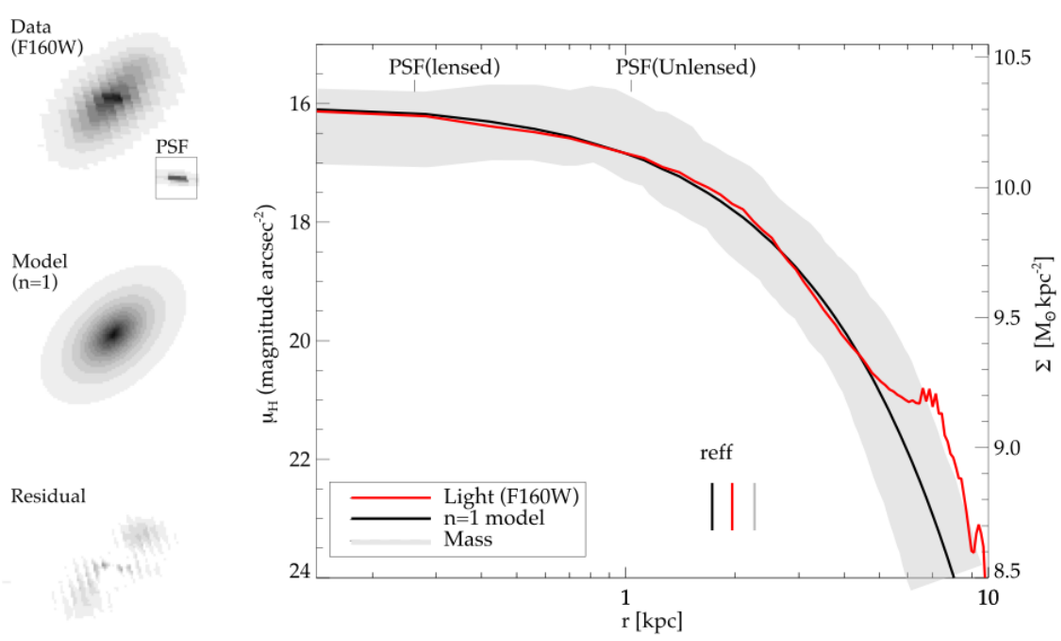


Kinematically compatible with descendants!

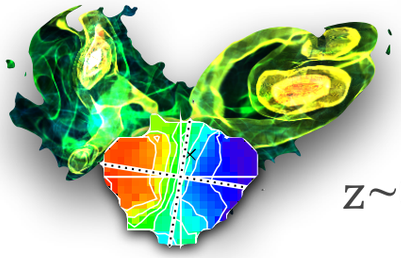
Toft+ suggesting a massive dead lensed disk (from 2.7hr XSHOOTER and 14-band HST)





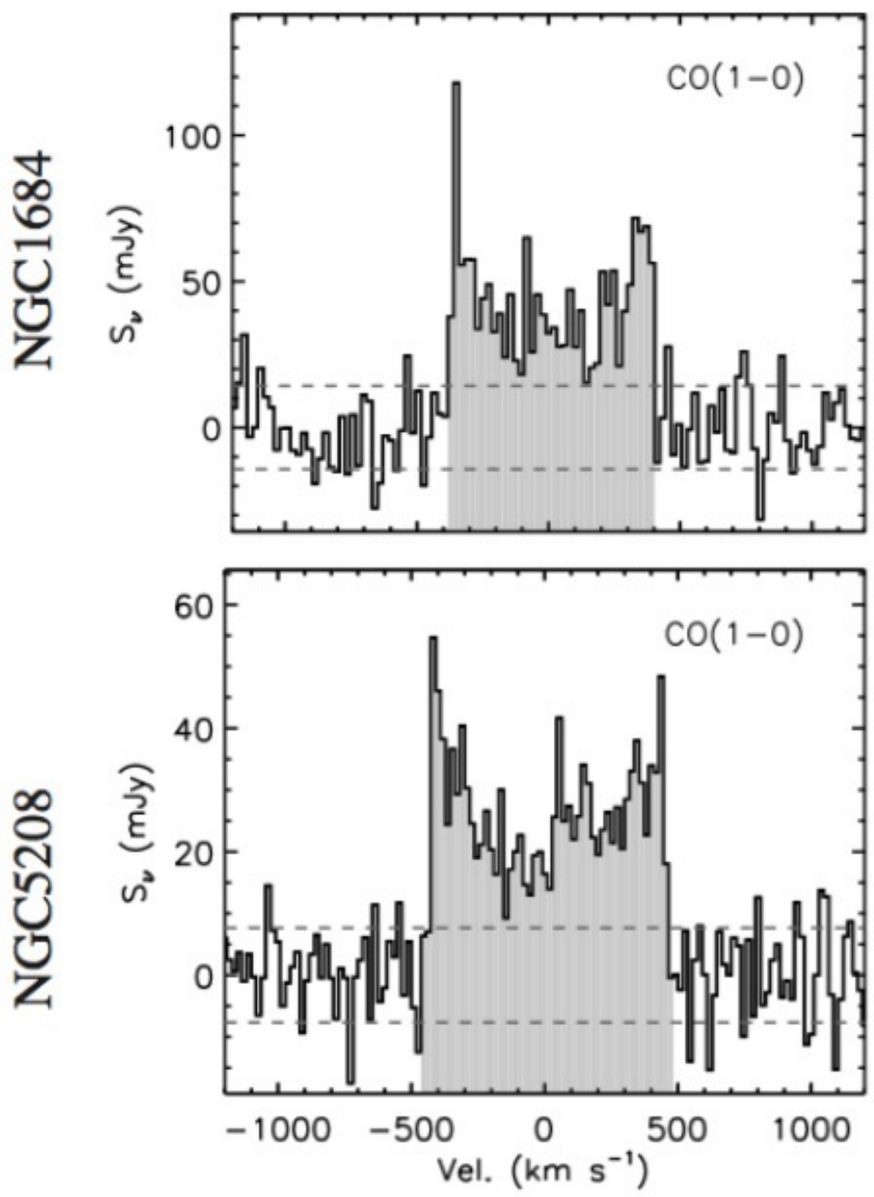


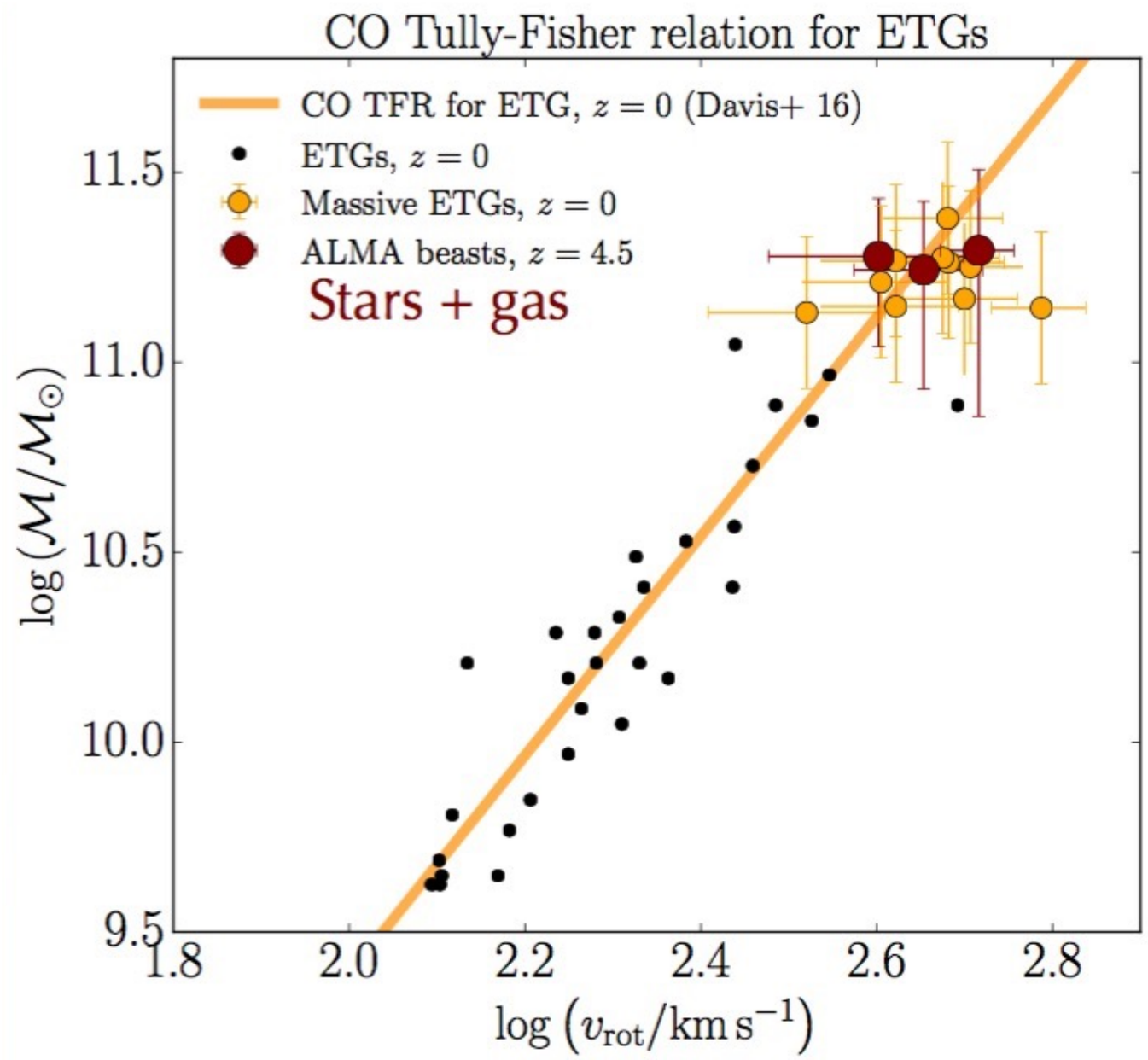
- Typical z~2 compact post starburst galaxy (1.5×10^{11} M_{Sun}, age ~1Gyr, r_{eff}~1.7kpc)
- Compact exponential disk light and surface mass density profile (n=1)
- Vmax~500km/s, 500pc turnover radius, $v/\sigma>3$



Potential well similar to local giant ETGs

z~0 ellipticals with residual star formation (10x below main sequence; ATLAS^{3D}/Davis et al. 2016)

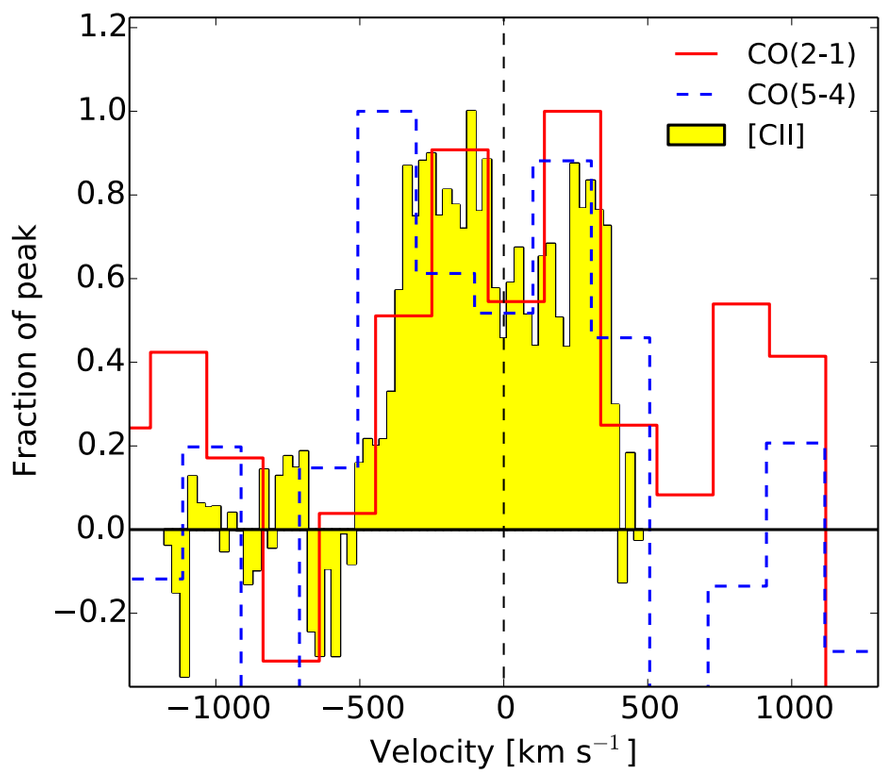


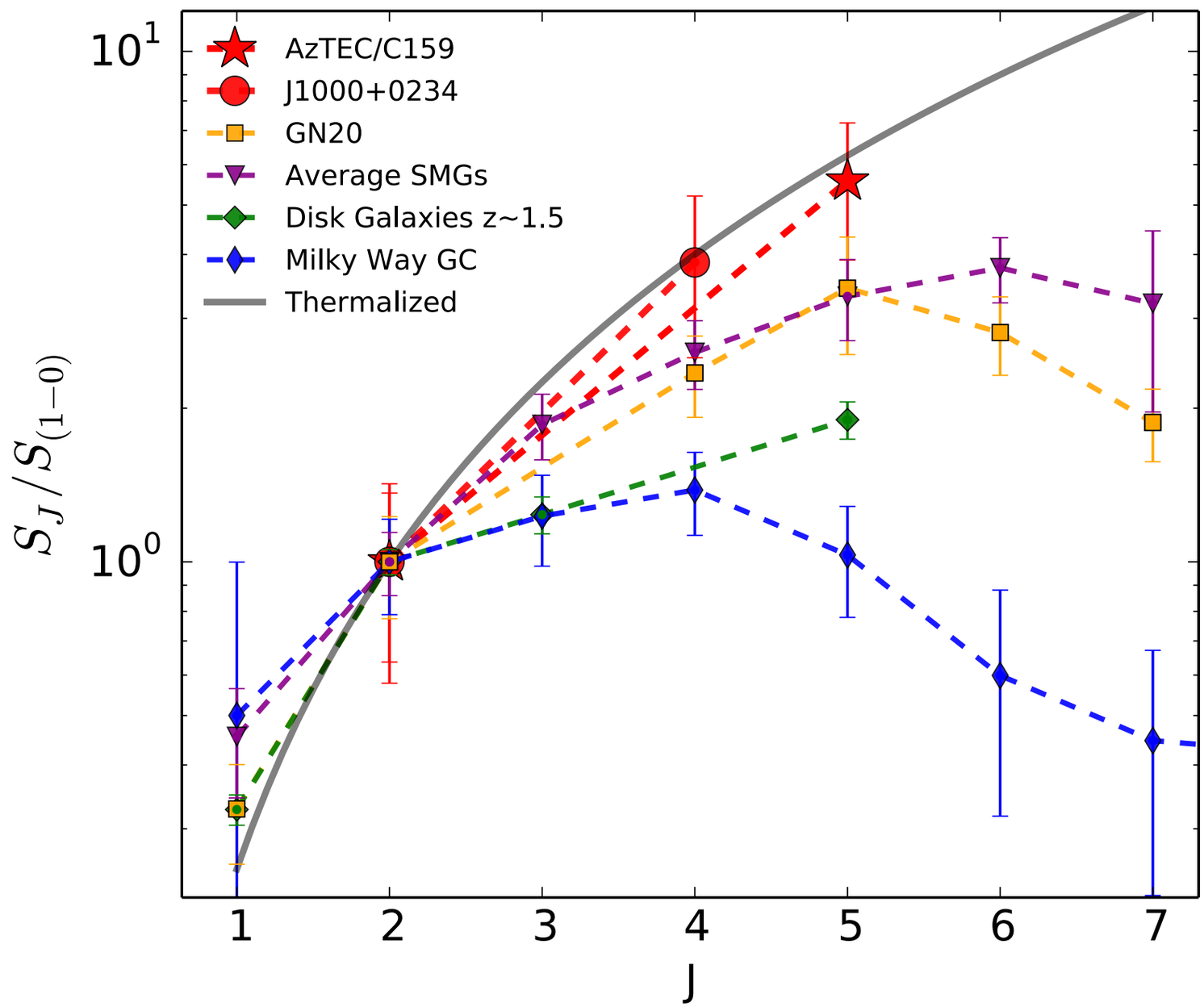


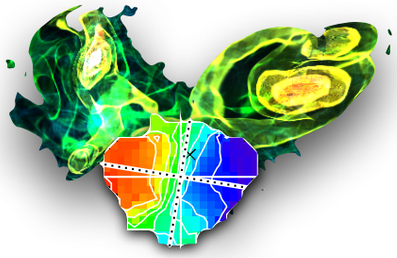
- Includes Oteo et al. (2015) z~4.4 source; plot being updated currently for clearer picture
- Trend below that for spirals; but be aware that spirals do not reach such high velocities (<400km/s)
- **M_{H2}~few 10^9 M_{Sun} within inner 1-2kpc in massive ETGs - similar potential well to our z~4.5 sources**

Mol. gas thermalized to J=5, unusually high

Jimenez-Andrade et al. (in prep.) with data from Schinnerer et al. (2008)

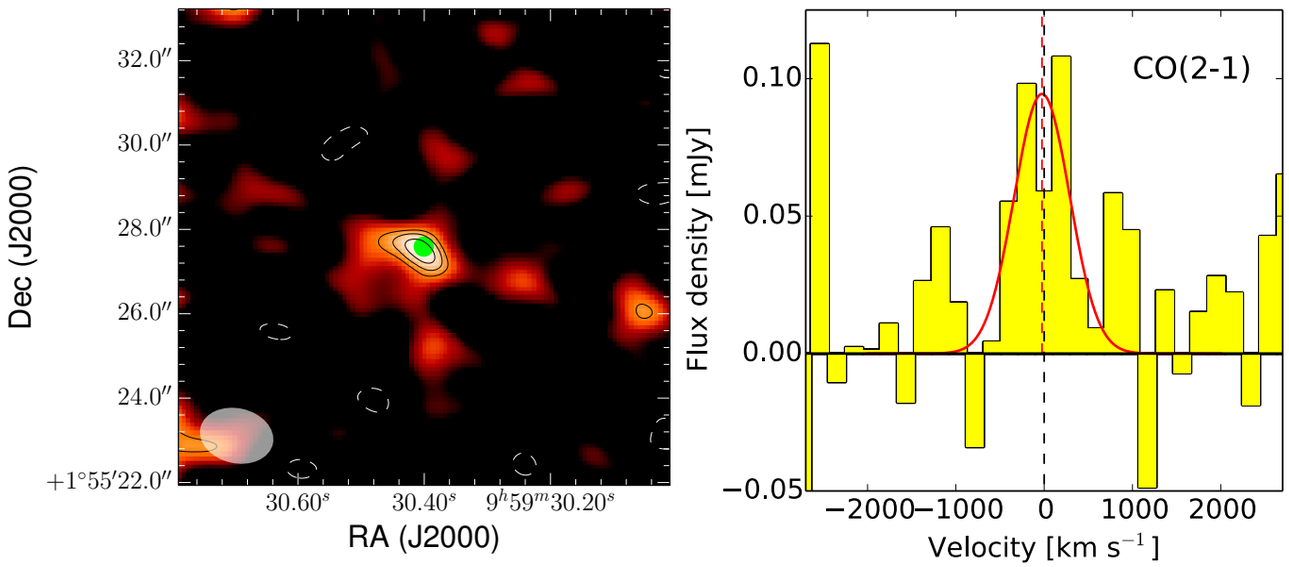






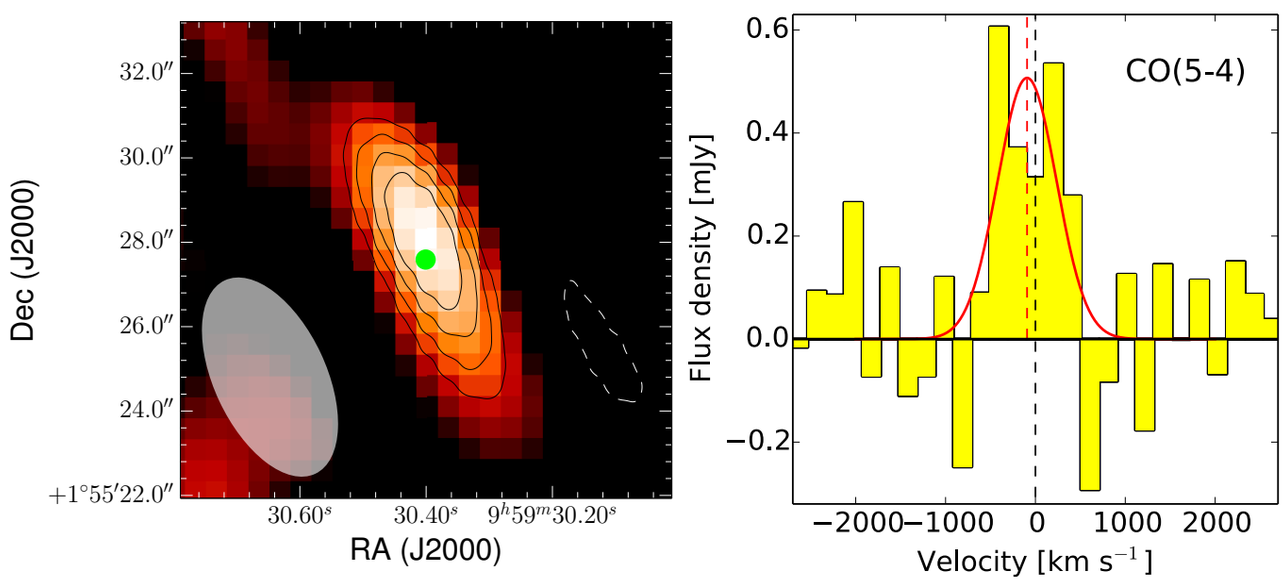
Molecular gas content from CO

Jimenez-Andrade et al. (in prep.); 19/17hr total for NOEMA/JVLA (PI AK)



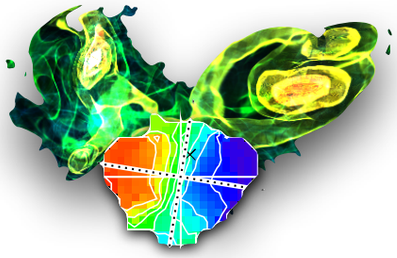
$$M_{gas} \propto L_{\rm CO}$$

$$\tau_{gas} = M_{gas}/{\rm SFR} = 16\,{\rm Myr}$$



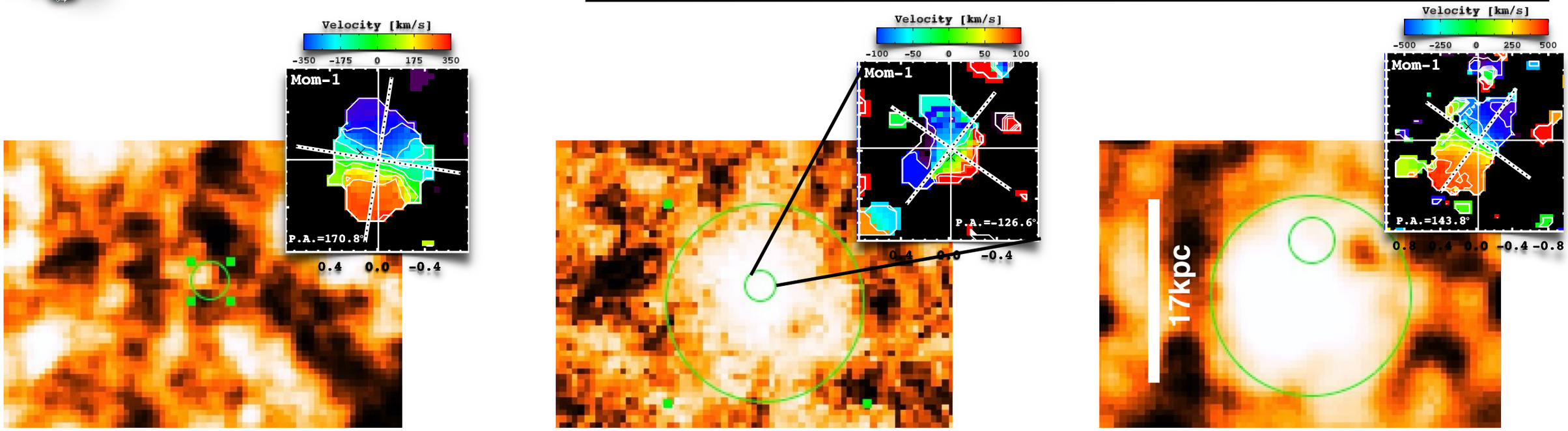
Jiménez-Andrade et al. (in prep.)

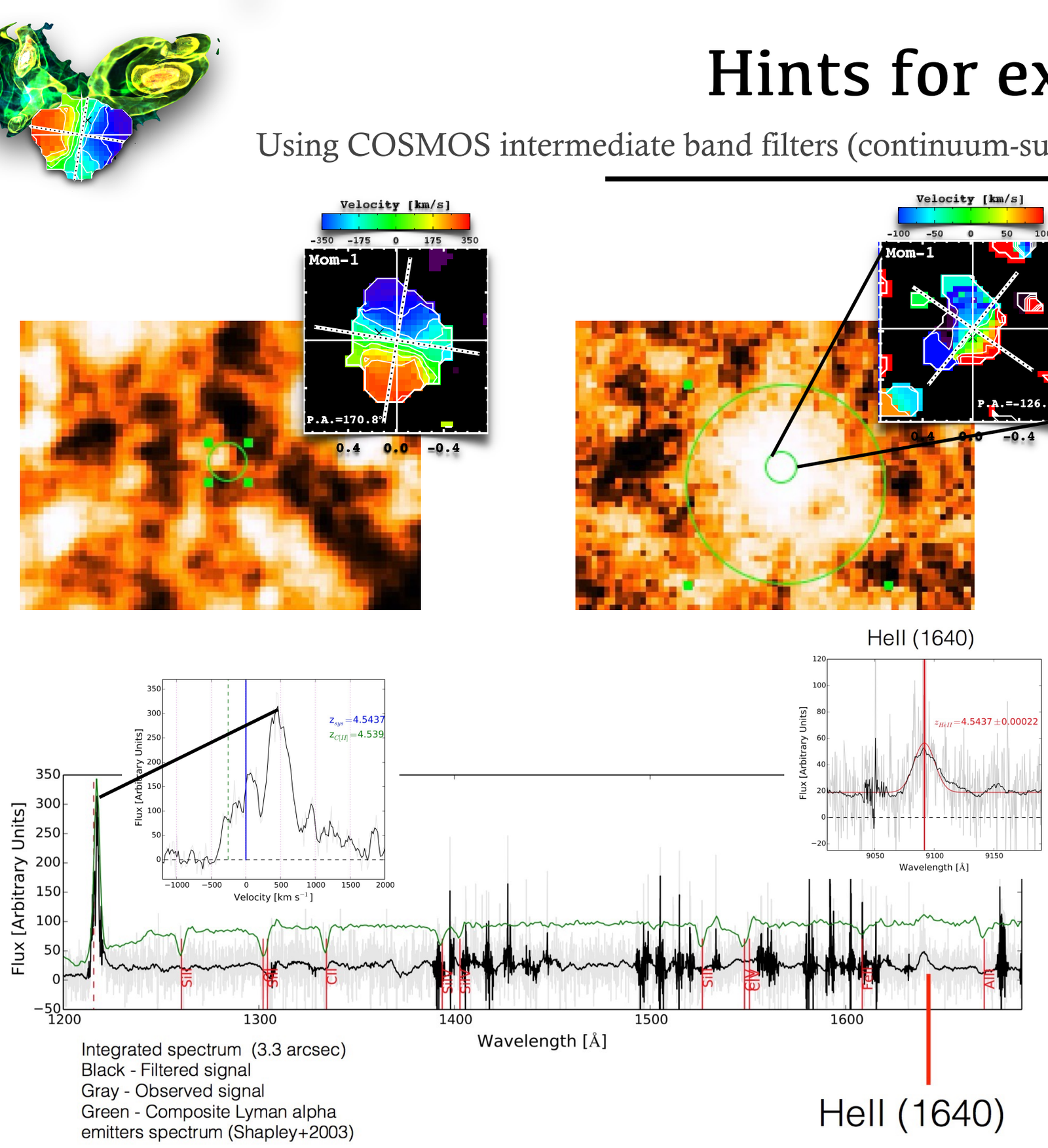
- Very low, but assumes alpha=0.8
- from dynamical mass, M_* limit OR gas from dust could accommodate for 4x more gas
- Then M_{gas}/M_{bar} ~40% (M_{gas}~6x10^{10} M_{Sun})
- Realistic depletion time hence ~86 Myr (see evolutionary considerations above)

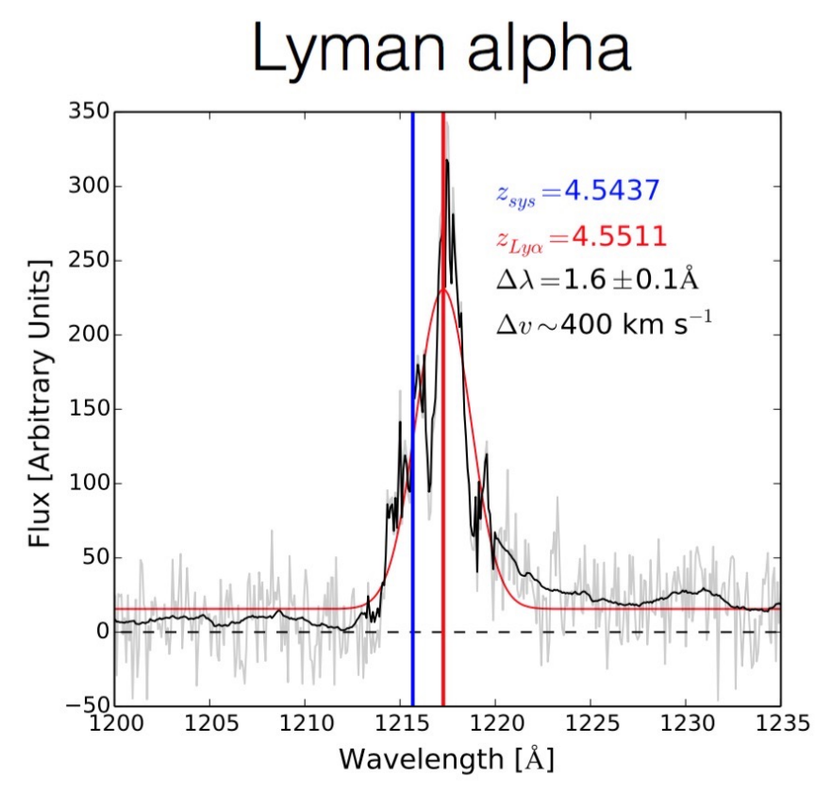


Hints for expanding halo gas

Using COSMOS intermediate band filters (continuum-subtracted); see also Capak et al. (2008)







Conclusions/outlook

Open question: How did these early starbursts come into being (major mergers?) and what is their fate?

ALMA, HST, NOEMA and JVLA reveal

- Complex rest-frame UV-morphologies (mostly minor mergers)
- Large velocity gradients in surrounding [CII], likely in Keplerian rotation
- Hints for young stellar emission projected in front of dust/gas
- High molecular gas excitation, efficient star formation

Progenitors of z~2 massive compact quiescent galaxies?

- Residual total mass and depletion timescale compatible
- Size-growth plausible given ongoing minor mergers
- Similar potential well as observed towards local massive early type galaxies
- Very tentative hints for radio-mode feedback

Some possible next steps for this sample

- Disk substructure? Gas turbulence? > higher resolution ALMA needed
- MUSE would be very valuable to study halo gas