ALMA, VLA, & GBT Observations of the First SCUBA Galaxy: SMMJ02399-0136 (z=2.808)

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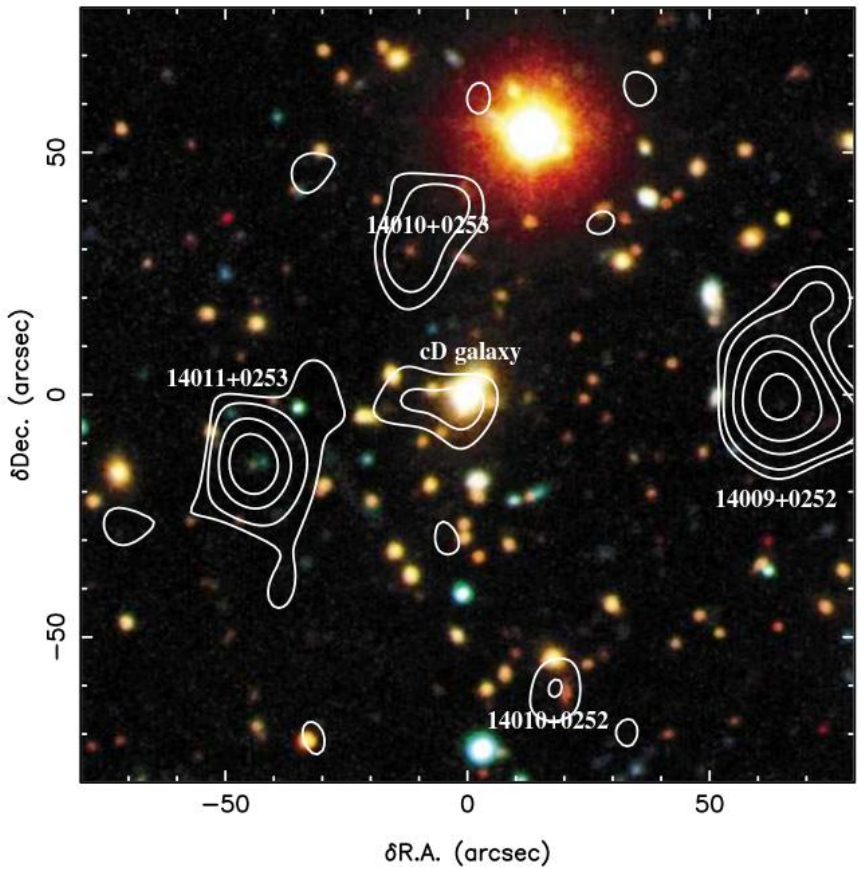
{Co-I's on ALMA and Cycle-2,3 and NRAO/GBO 16A, 17B proposals}

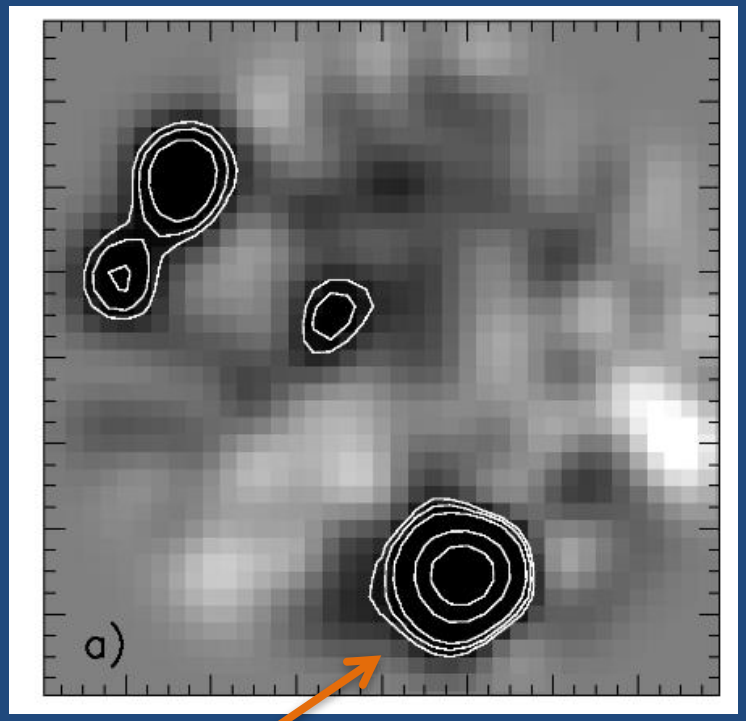
JCMT-SCUBA: The Discovery of SMGs

SMGs=
Sub**M**illimeter-
selected **G**alaxies

SCUBA Cluster Lensing Survey

(Smail, Ivison, Blain 1997)



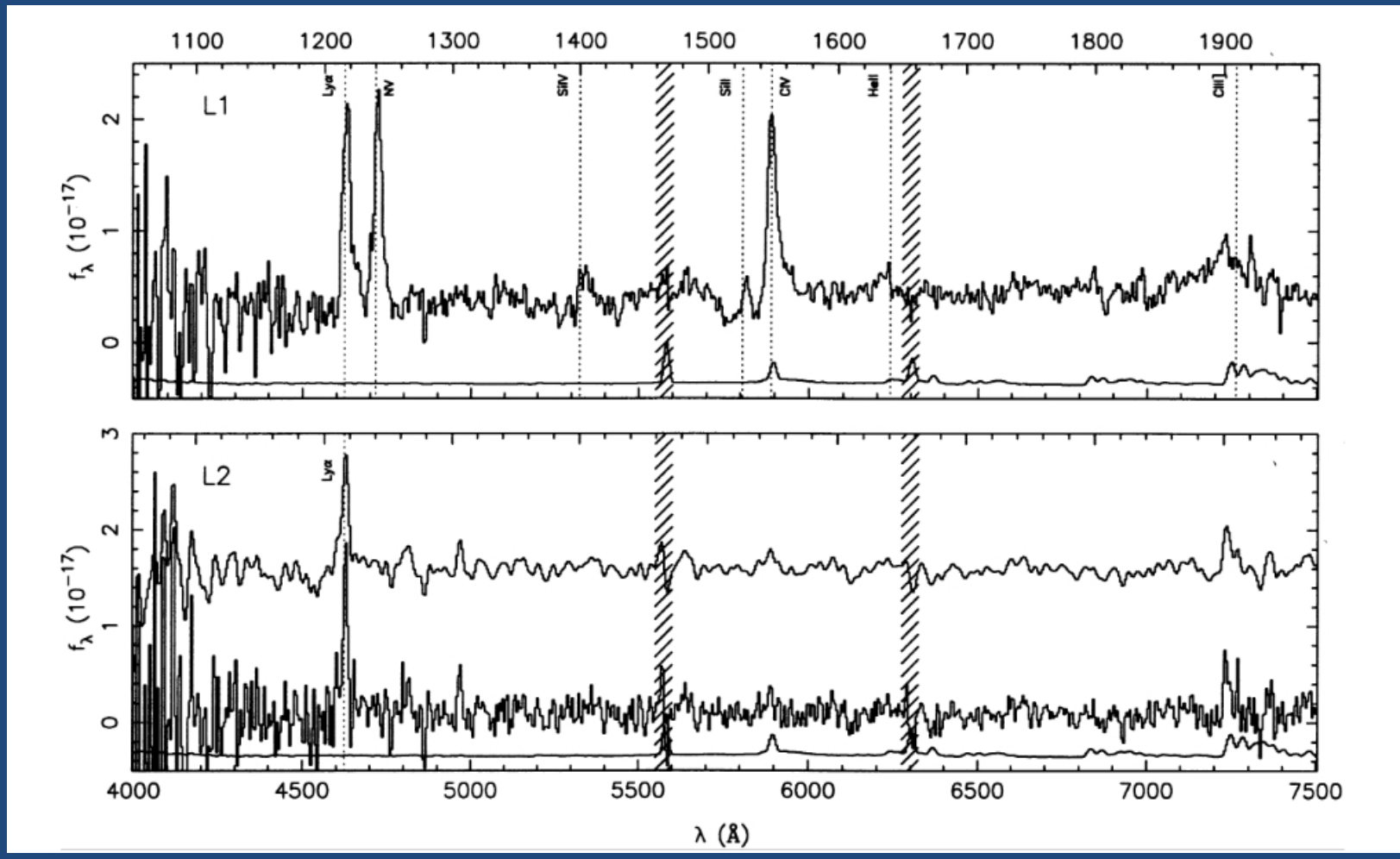


SMM J02399-0136 was the first SMG discovered by SCUBA. Above is the 850um SCUBA image (SMG behind cluster Abell 370, Smail+97) --
Differential lensing not significant for cluster lensing

Example of multiple SMGs behind cluster Abell 1835 (Ivison+00)

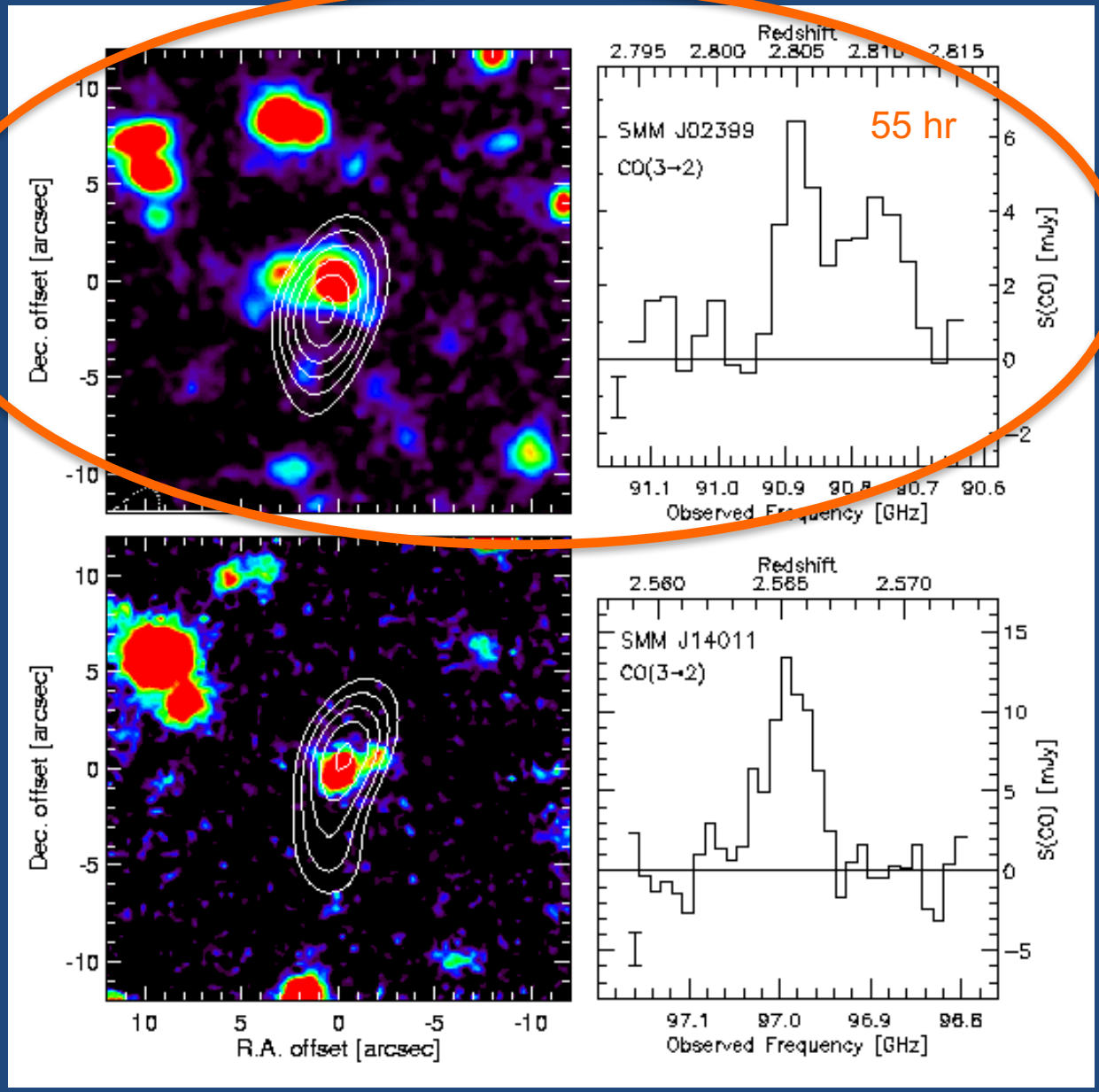
Redshift and Source-ID

Ivison+1998 (initial redshift from the CFHT) – imaging with UKIRT and Keck within a couple of nights of discovery and redshift from the CFHT within a week
L1: shows broad Lyα, NV, CIV (AGN)
L2: narrower Lyα



The First CO detections of SMGs were done by the OVRO MM-Array

- $M(H_2) \sim 10^{11}$ M(sun), Mgas from CO which is consistent with gas/dust mass estimated using the Scoville+16 method.
- Enough gas to fuel the star formation implied by the submm data [$L(IR) \sim 10^{13}$ L(sun)]
- Scaled-up ULIRGs?
- Mergers; SMMJ02399 ~Mrk231 and SMMJ14011 ~ Arp220 in global properties



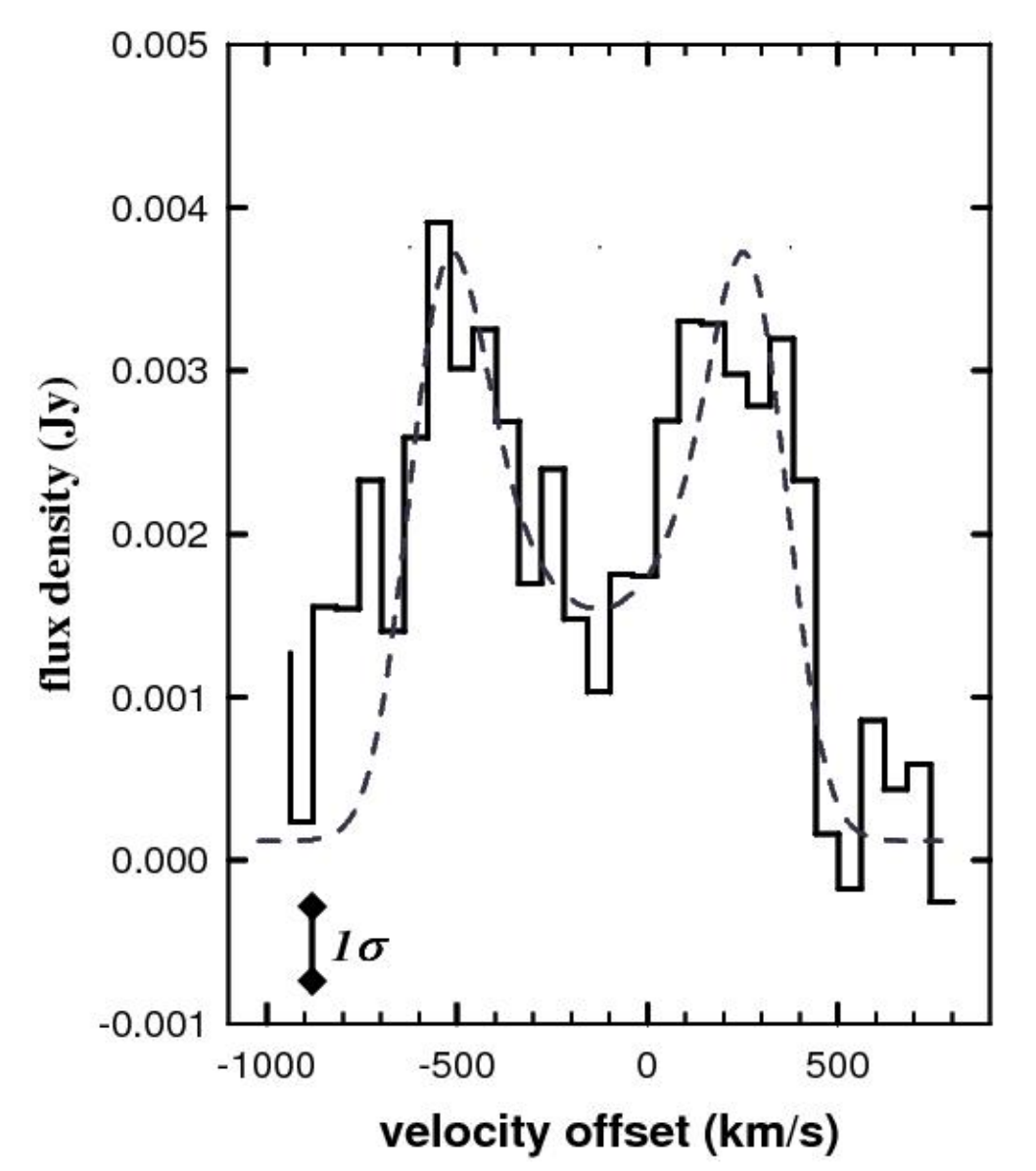
Frayer et al. 1998, 1999

CO(3-2) PdBI follow-up observations

Genzel et al. 2003 argued for rotating disk around QSO based on double-horn CO(3-2) profile (but future data shows that this is not correct)

Ivison et al. 2010 shows CO(1-0) peaks on L2SW instead.

Need better resolution CO imaging ➔ ALMA



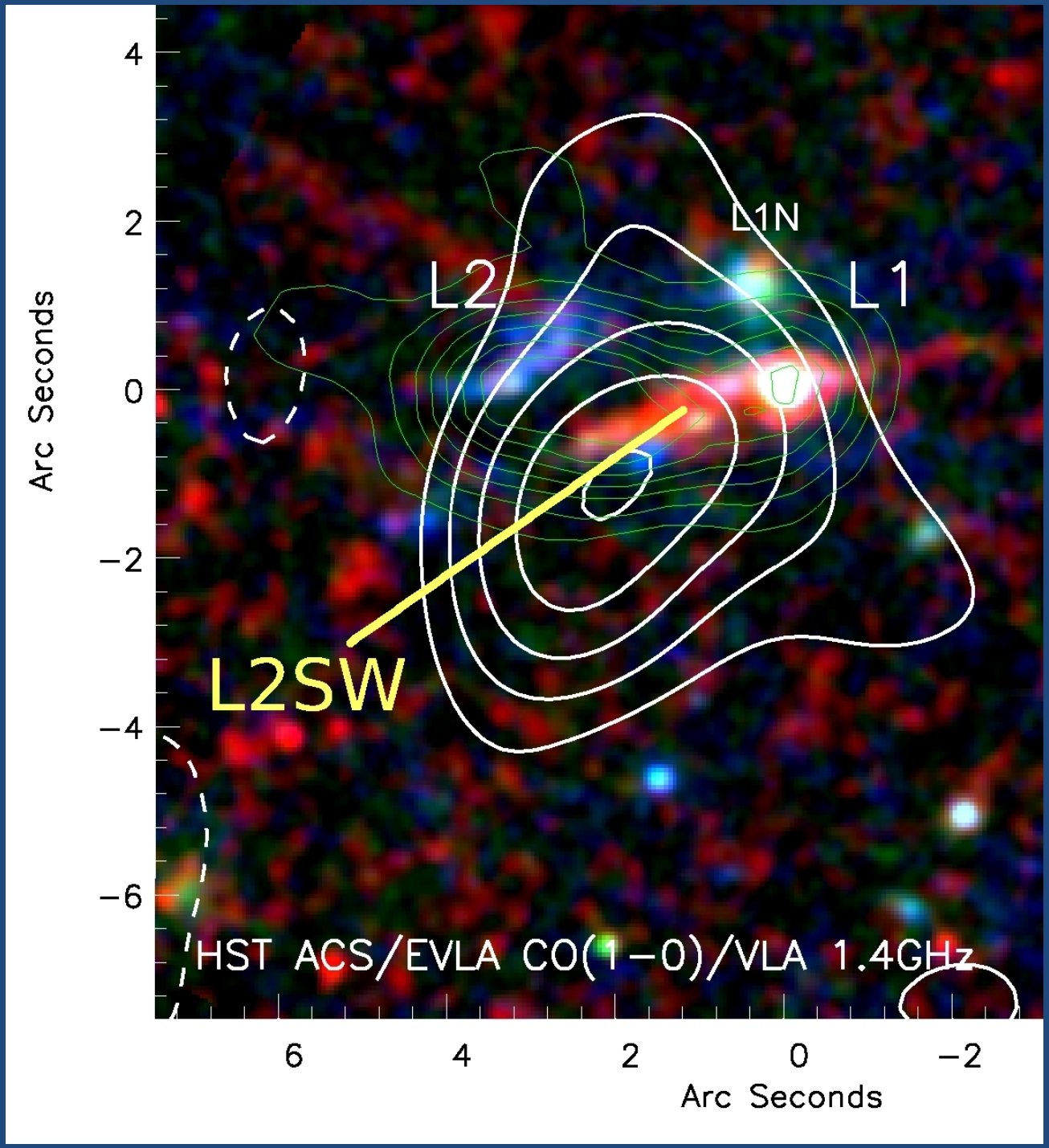
4-Components of SMMJ02399 (Ivison+2010):

- L1: QSO
- L2SW: ERO starburst (L1SB in Aguirre+13)
- L2: Ly-alpha
- L1N

HST image + Green Contours = VLA 1.4 GHz

White Contours = VLA CO(1-0) tapered C-array data

➔Still need better resolution



SMMJ02399-0136

The source contains many of the diverse properties seen in samples of SMGS:

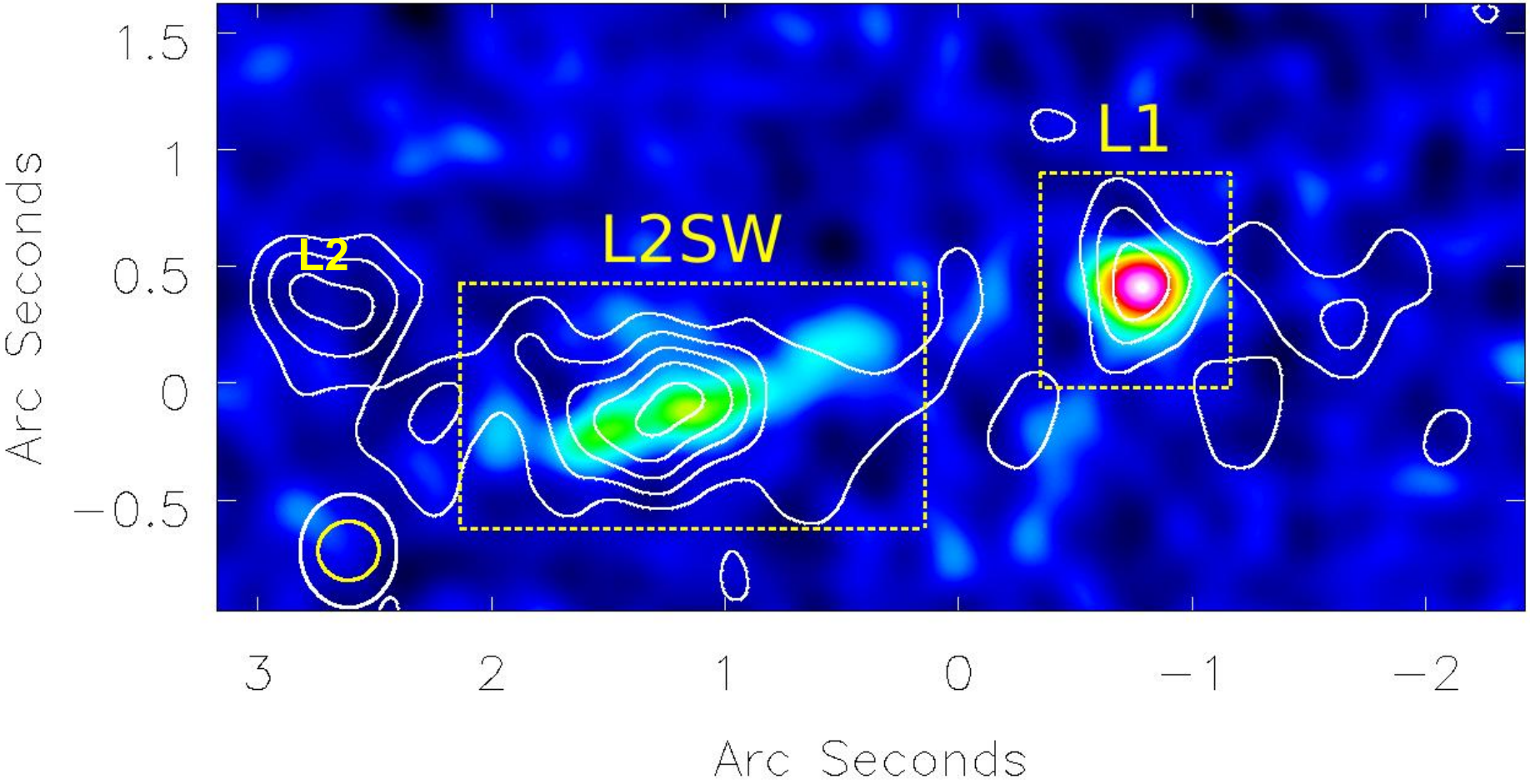
- Multi-component starburst +AGN
- Merger-morphology
- Large Ly-alpha cloud
- Extremely red starburst region
- Radio loud AGN
- Broad-line QSO

Major Questions:

- Which component(s) is(are) responsible for L(IR)?
- What is the spatial distribution and kinematics of the molecular gas?

AGN Feedback – inducing the L2SW starburst?

VLA C-band contours (3uJy rms) on Band-9 ALMA image: low IR/radio q(L2SW) ➔ radio-loud lobe; q(L1)~starburst value

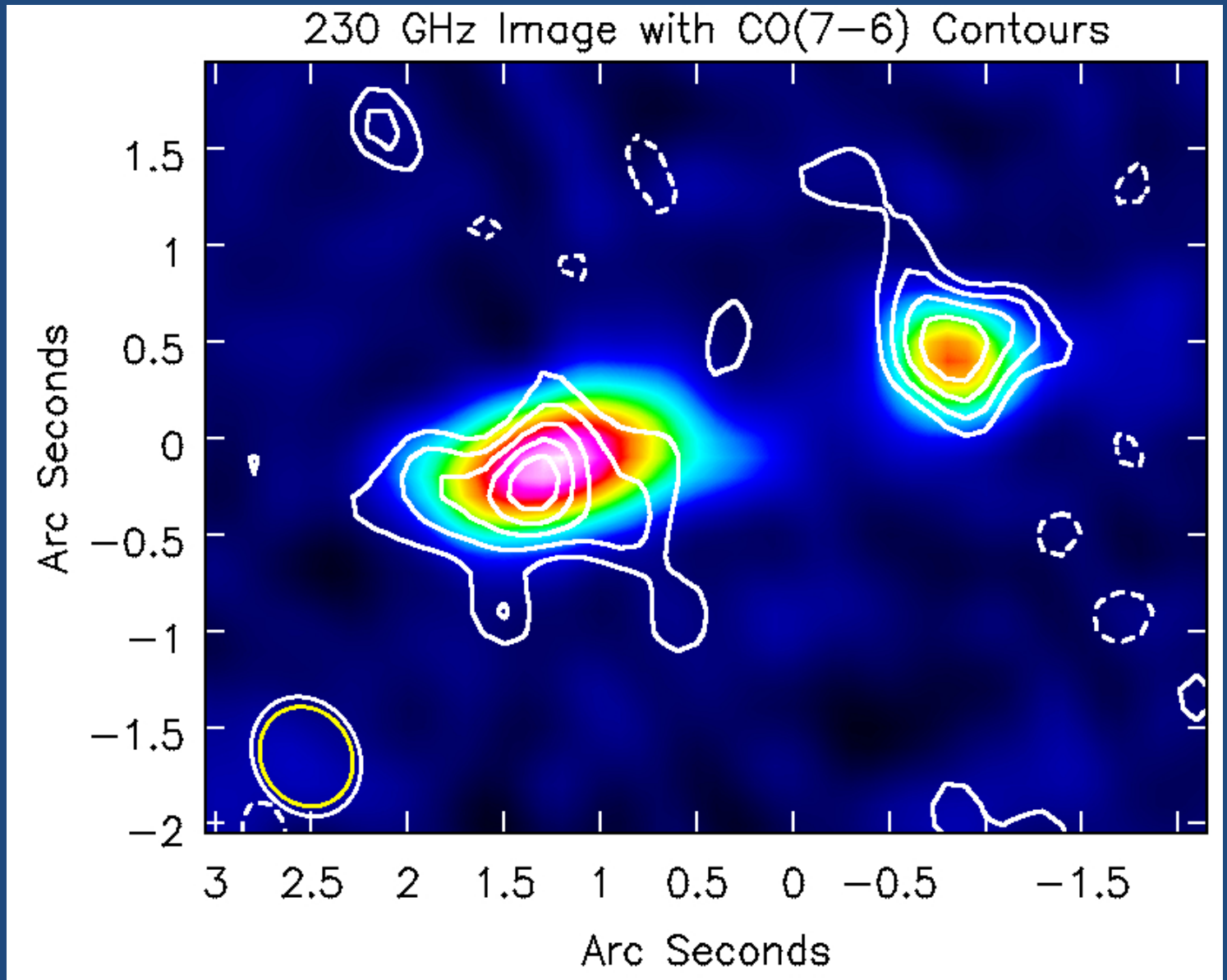


ALMA CO(7-6) contours on Band-6 continuum (14min on-source cycle-2)

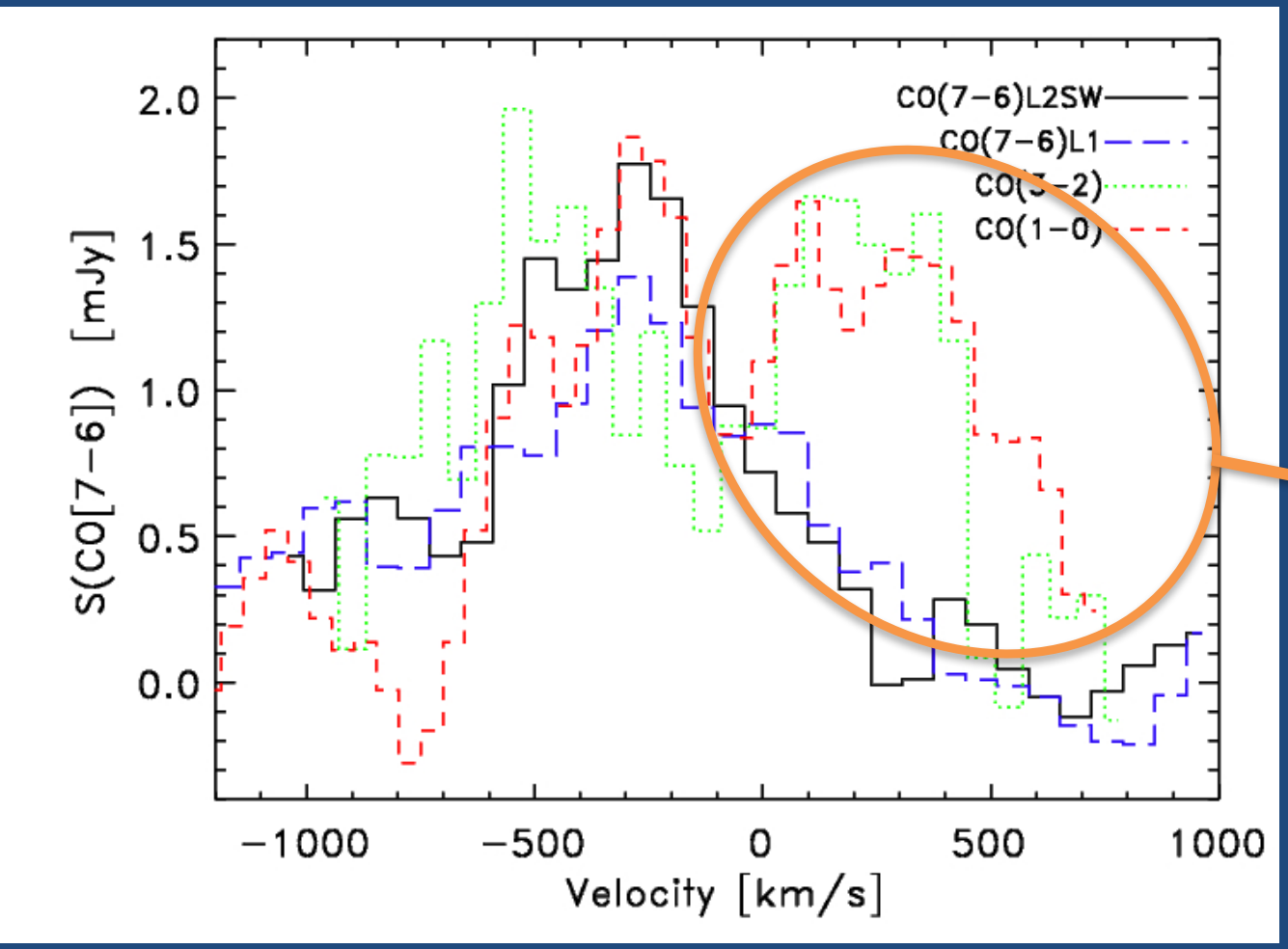
60% of IR luminosity from L2SW and 40% from L1 (ALMA Band-9); 70% dust mass from L2SW and 30% from L1 (ALMA Band-6)
-- ALMA sub-arcsec imaging recovers all the IR flux implied by Herschel and the JCMT

CO(7-6) peaks on L1 and L2SW.

No evidence for significant emission from L2 or L1N.



CO(7-6) misses large "cool" component of gas at high velocities

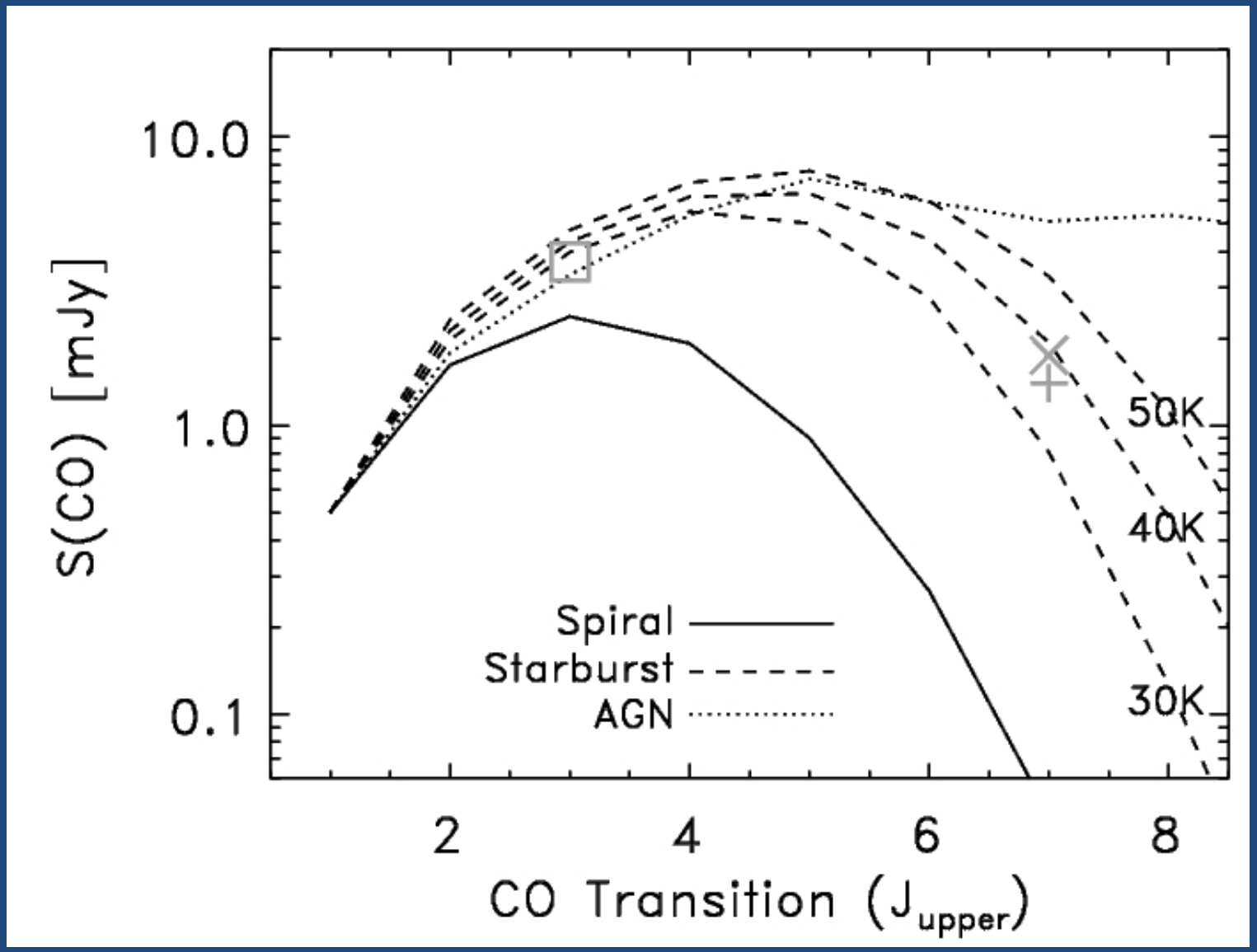


L2SW and L1 CO(7-6) profiles similar – misses high-velocity peak seen in the CO(3-2) profile [green, Genzel+2003] and CO(1-0) profile [red,Thomson+2012]

Missing cool molecular gas ~ >½ the mass

Need ALMA CO(3-2) imaging

CO Spectral-Line Energy Distribution (SLED)



The cores of L1 and L2SW are consistent with ~40K starbursts.

L2sw =X

L1 = +

This is where things stood in 2015,

and we still need better resolution and sensivitity and low-J CO….

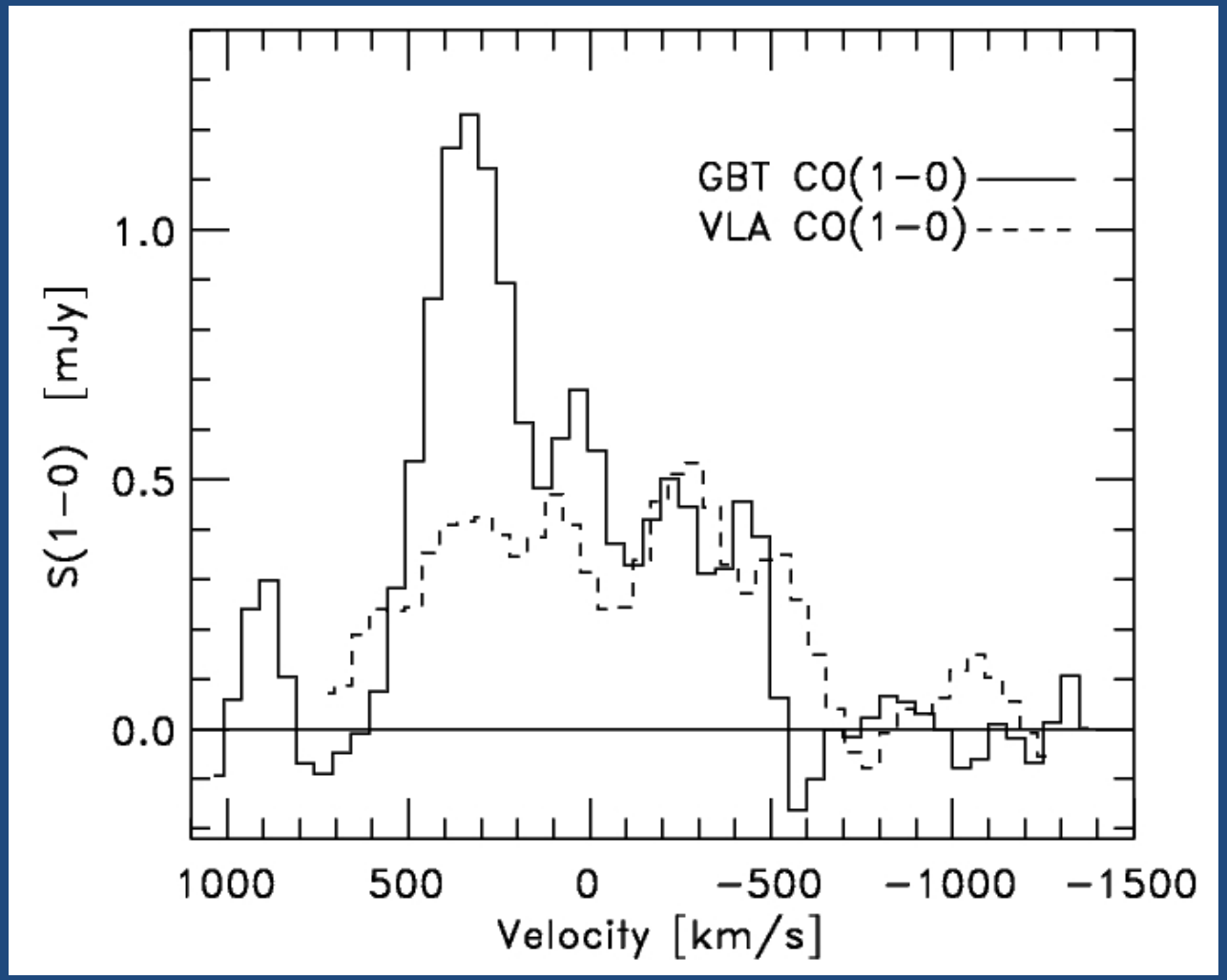
New Data/Observations in 2016:

- Public release of deep Frontiers HST imaging of Abell 370
- New ALMA CO(3-2) Cycle-3 high-resolution data
- GBT CO(1-0) observations (more data coming Oct. 2017)
- VLA CO(1-0) observations at higher resolution (B-array)

GBT CO(1-0) detects new feature in source. The GBT spectrum shows significant excess at positive velocities (VLA CO(1-0) from Thomson+12)

Is there a component of extended gas missed by the interferometers ?

Need to confirm with night-time data (Oct 2017). The excess appears real, but its strength is uncertain.

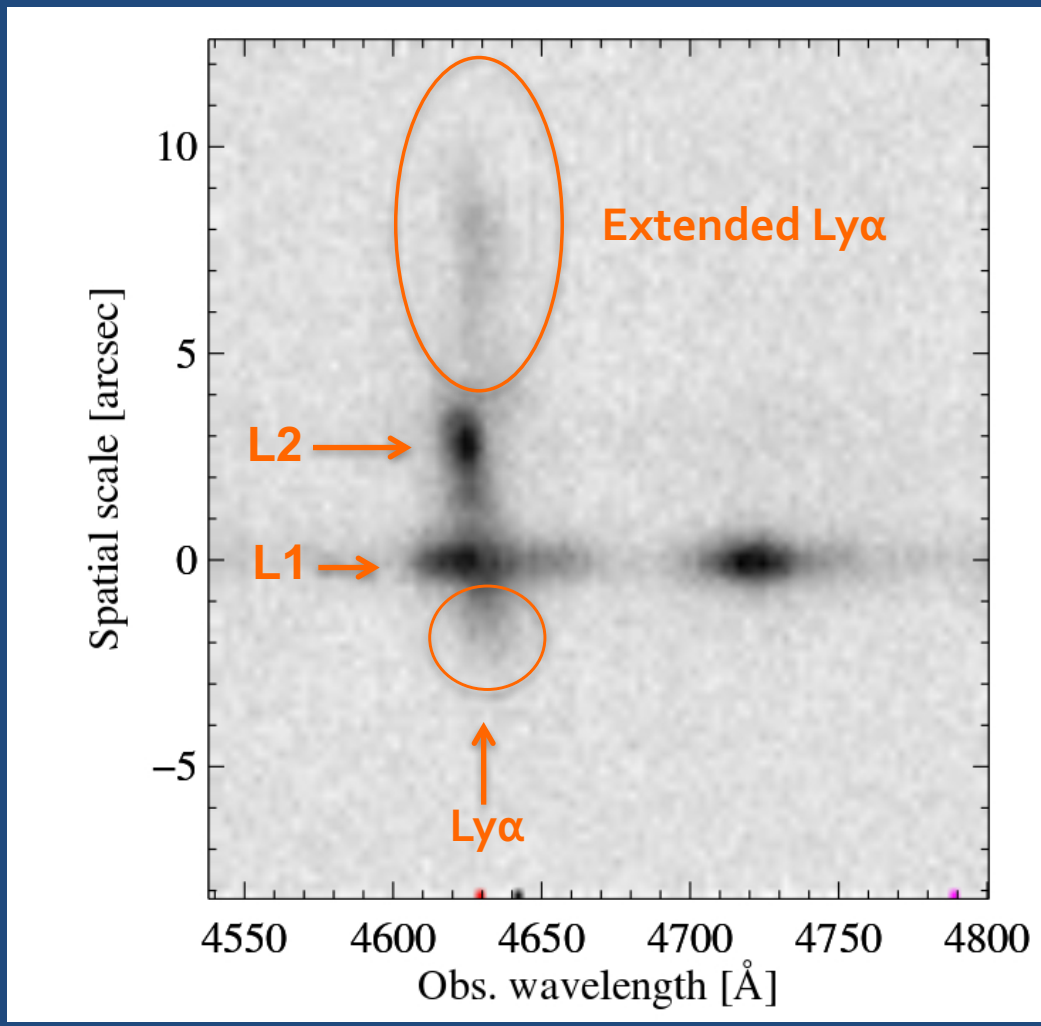


Extended Ly-alpha emission

(Vernet & Cimatti 2001) VLT optical spectroscopy

Extended Ly-alpha emission (12″).

Also, Ivison+10 reported marginal evidence for CO(1-0) on ~10″ scale from C-array data.

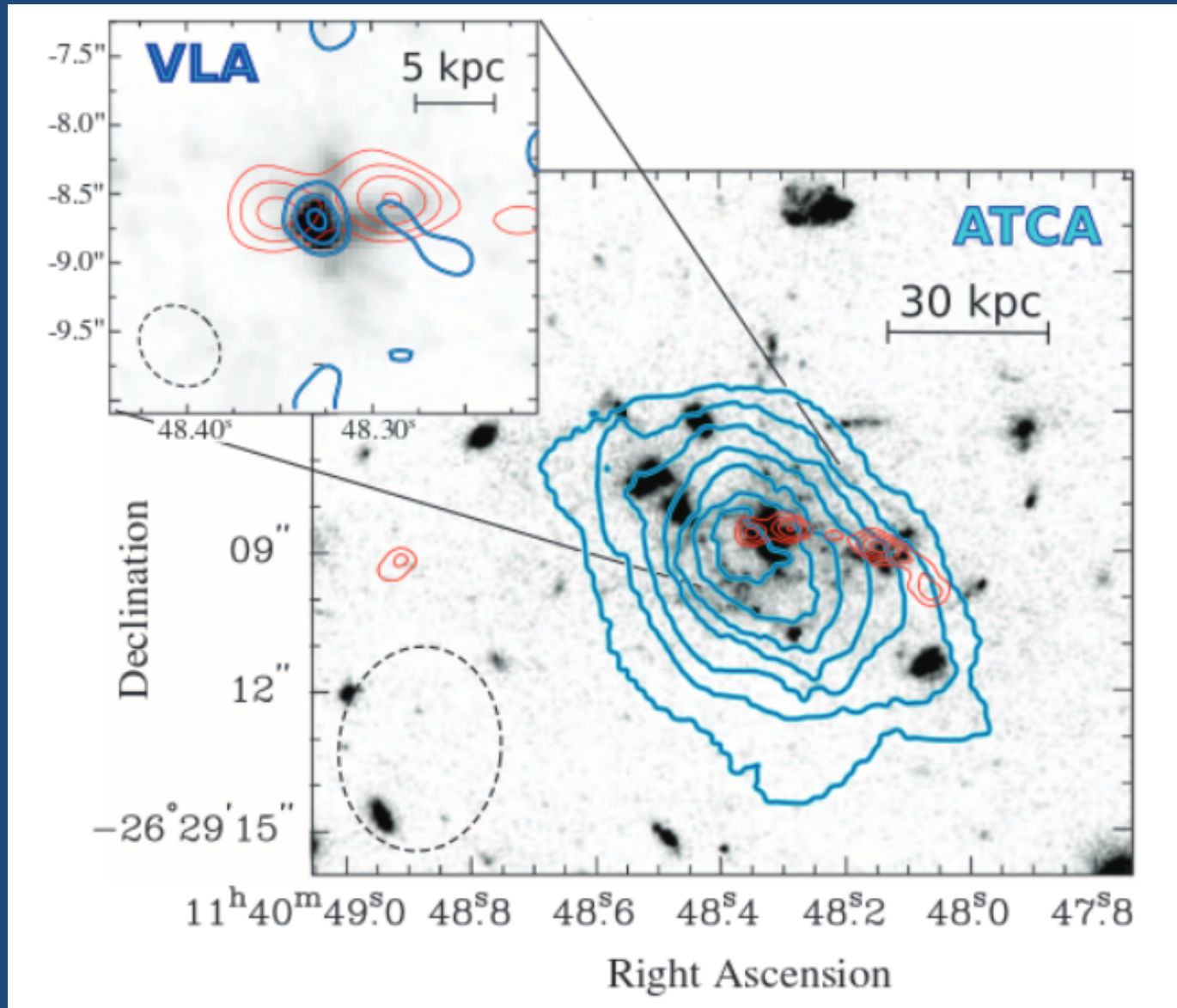


Molecular gas has been detected on large spatial scales, e.g., Spiderweb group of galaxies at z=2.2 (Emonts+16)

e.g., Helmut Dannerbauer's poster

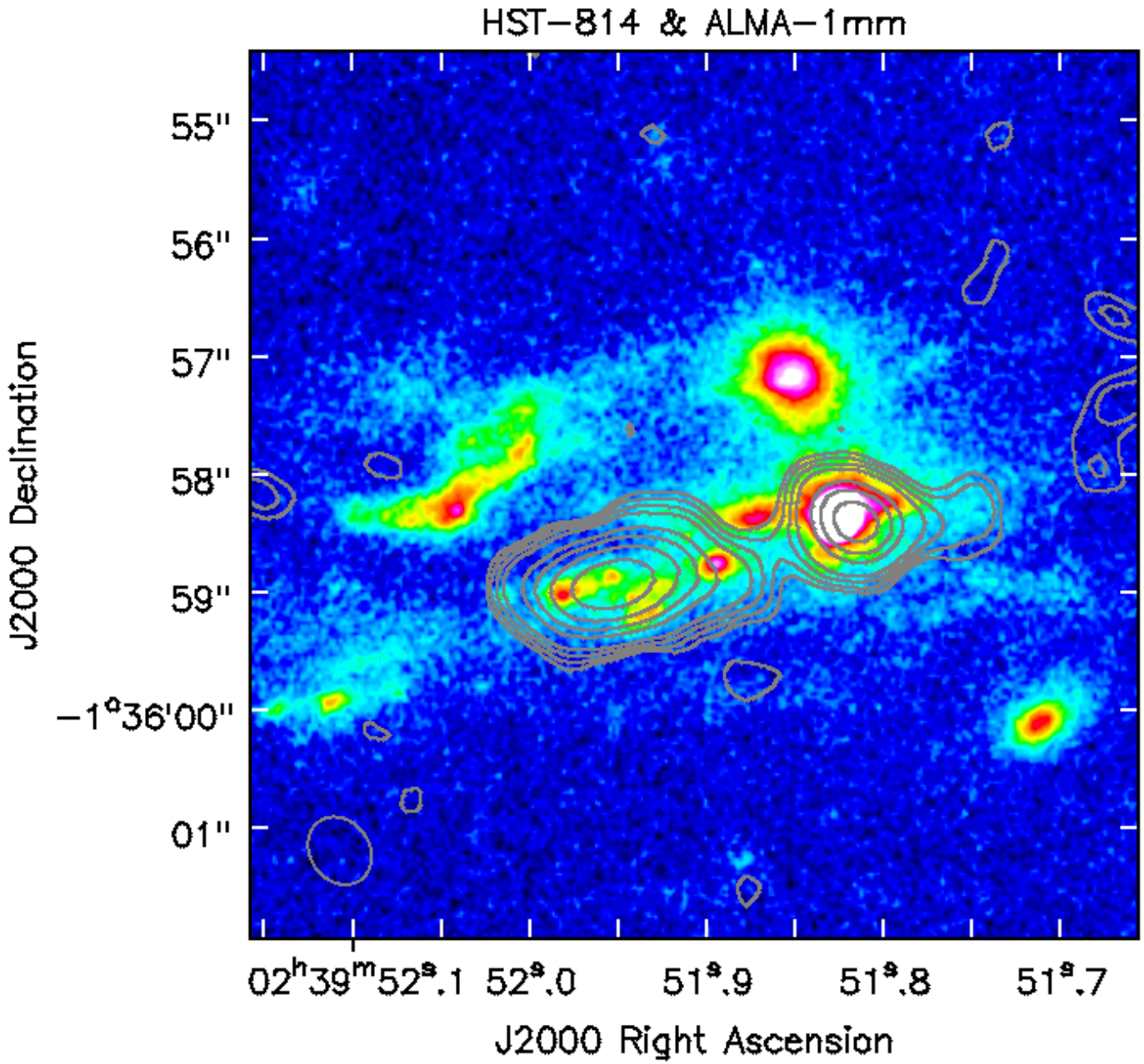
Red=VLA continuum, blue=CO(1-0) where VLA only detects the core, while ATCA detects gas on a large spatial scale.

What are we missing in high-resolution imaging?



ALMA 1.3mm continuum on HST

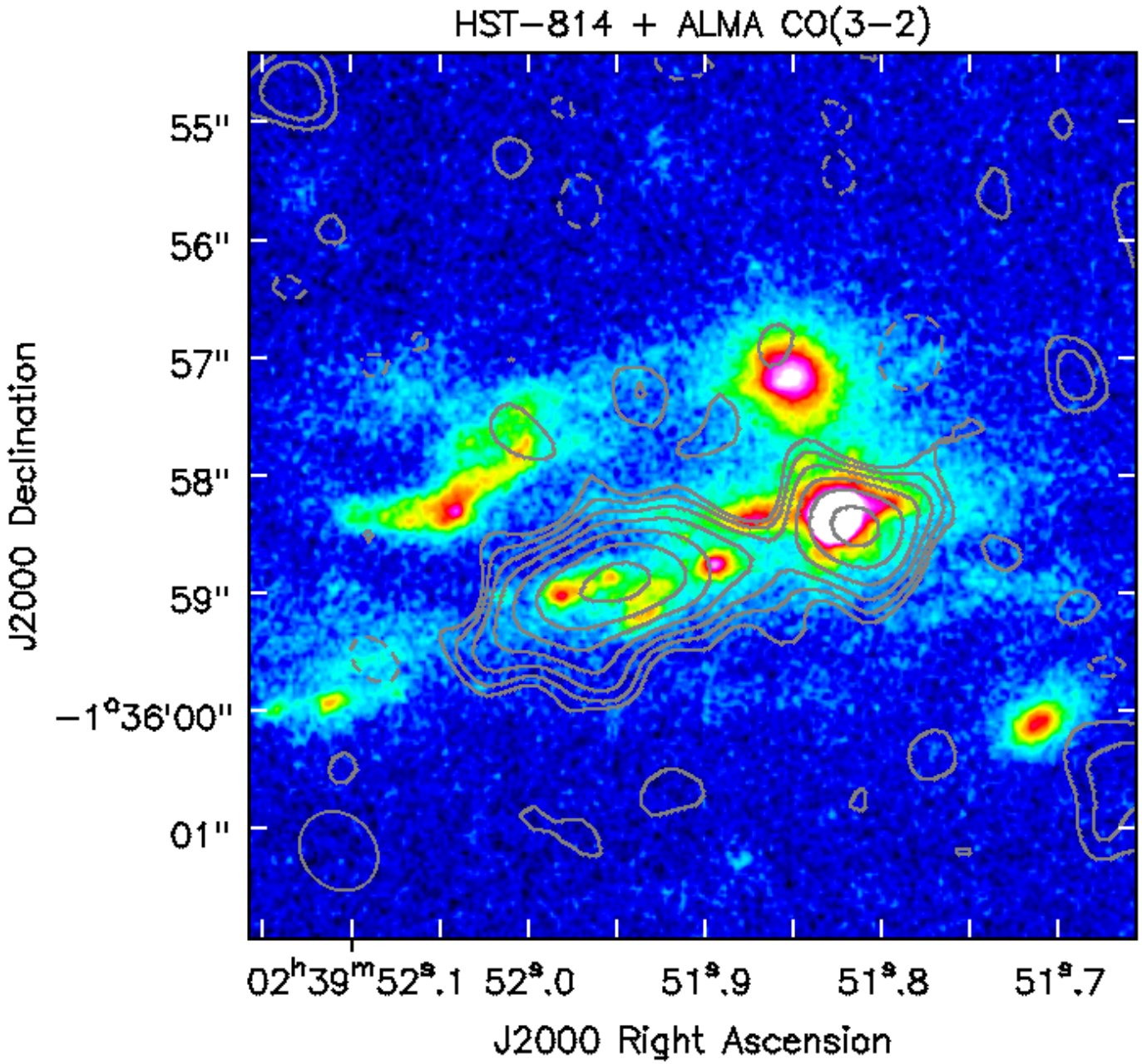
(contours start at 2 sigma and increase by root-2 (2,2.83,4,5.66,8,11.3,16,22.6,32)

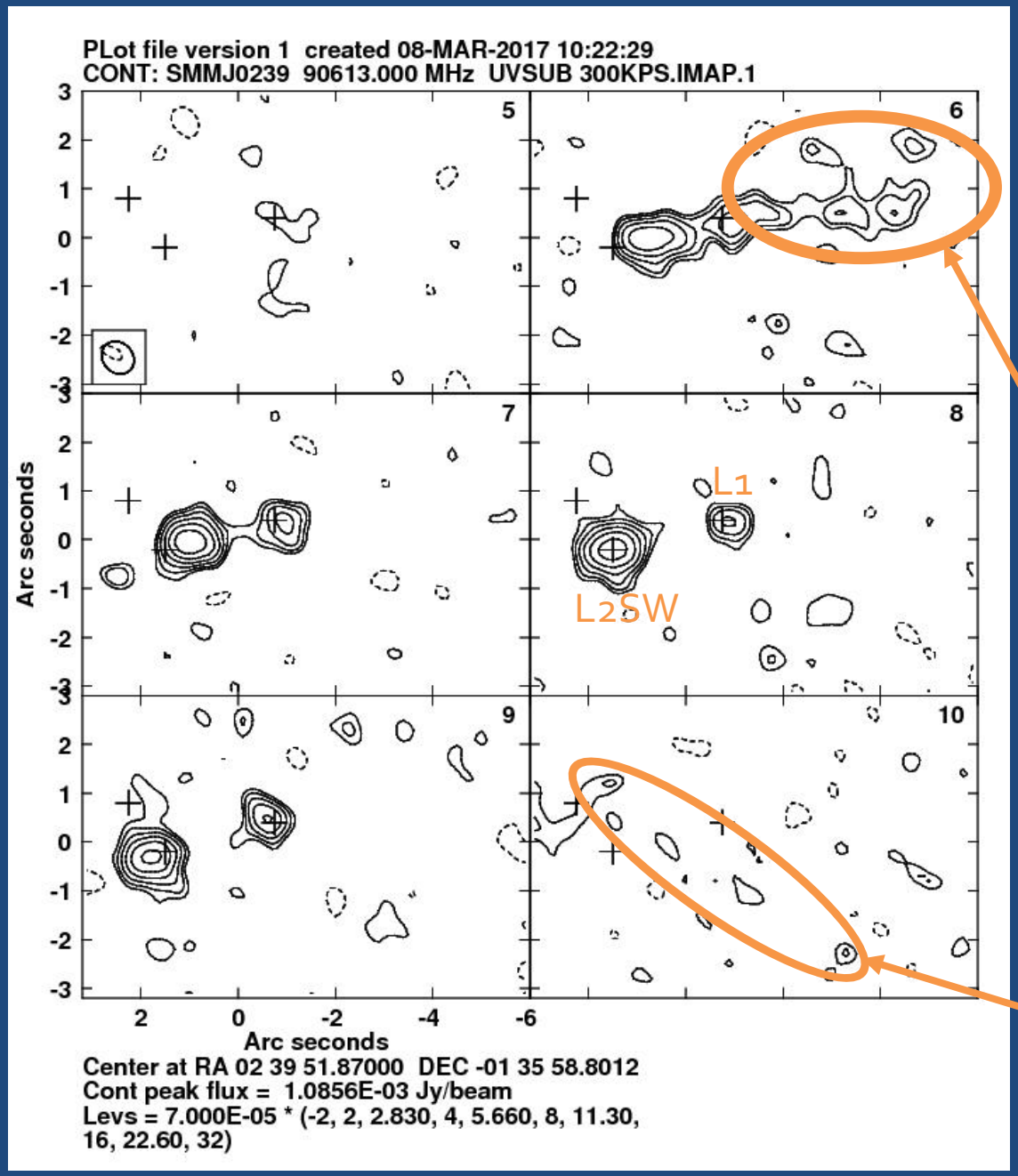


ALMA CO(3-2) on HST

Note ALMA 3mm data taken 3 times (cycle-2, "test" before cycle-3, and cycle-3)!?!

Increased sensitivity permitted studying fainter emission outside the cores.



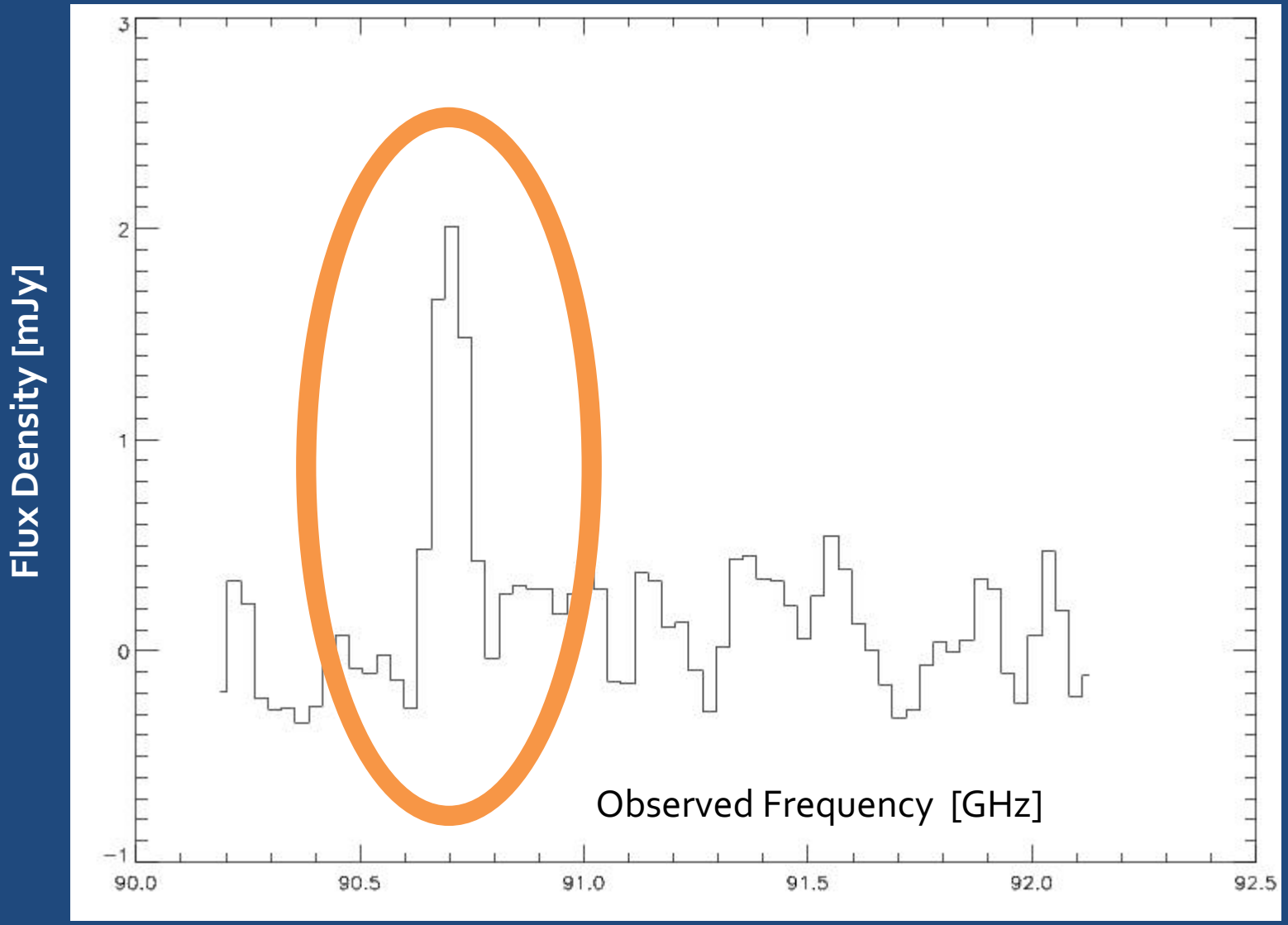


ALMA CO(3-2) channel maps separated by 300 km/s.

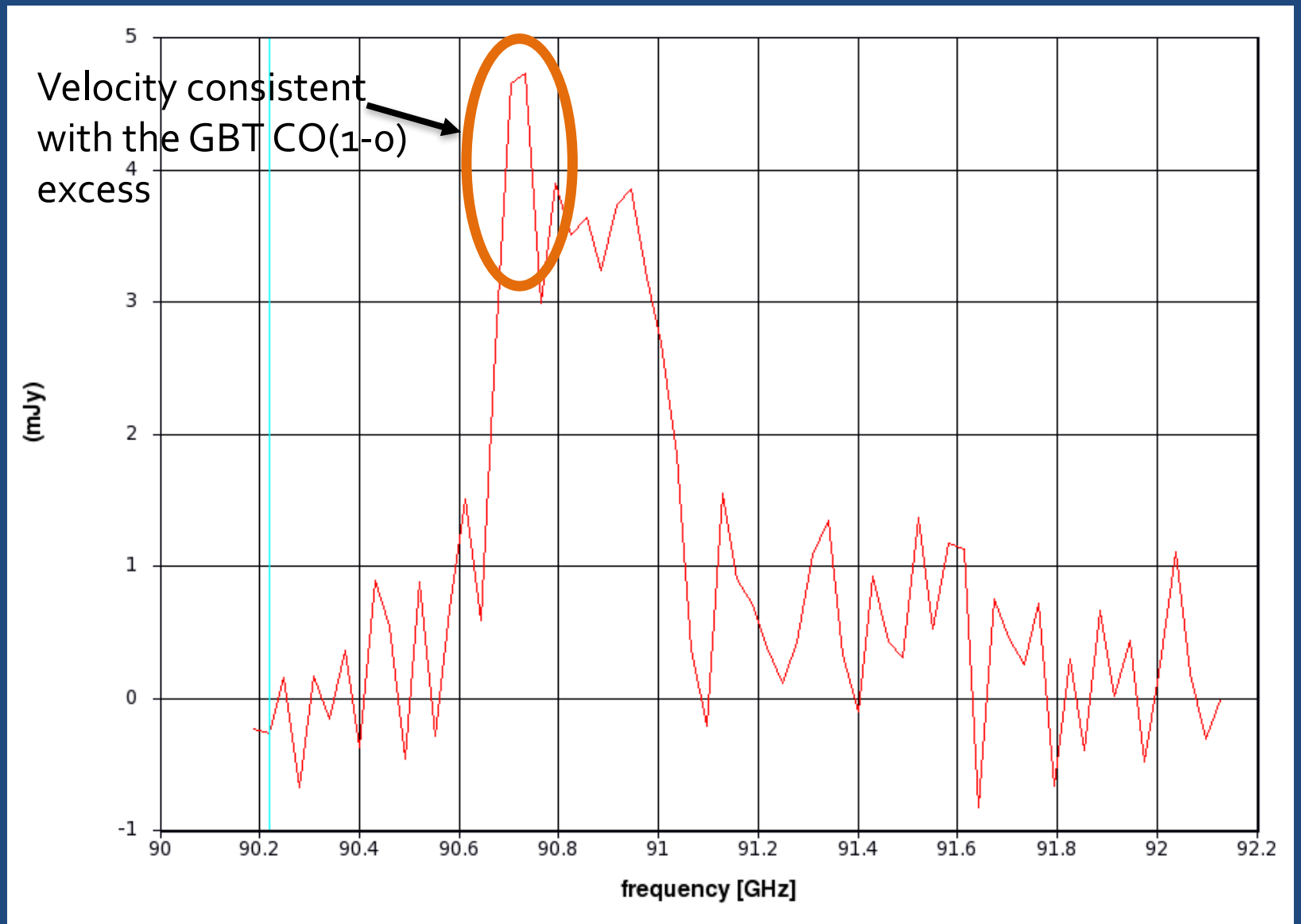
- Most of gas centered around L2SW
- L2SW shows rotational velocity gradient along L1-L2SW direction; L1 shows velocity gradient perpendicular to radio jet.
- New linear feature detected west of L1 at +350km/s
- Is this a tidal feature from the merger of L1 and L2Sw or possible infalling gas along a filament?

Marginal evidence for another linear feature at -800km/s

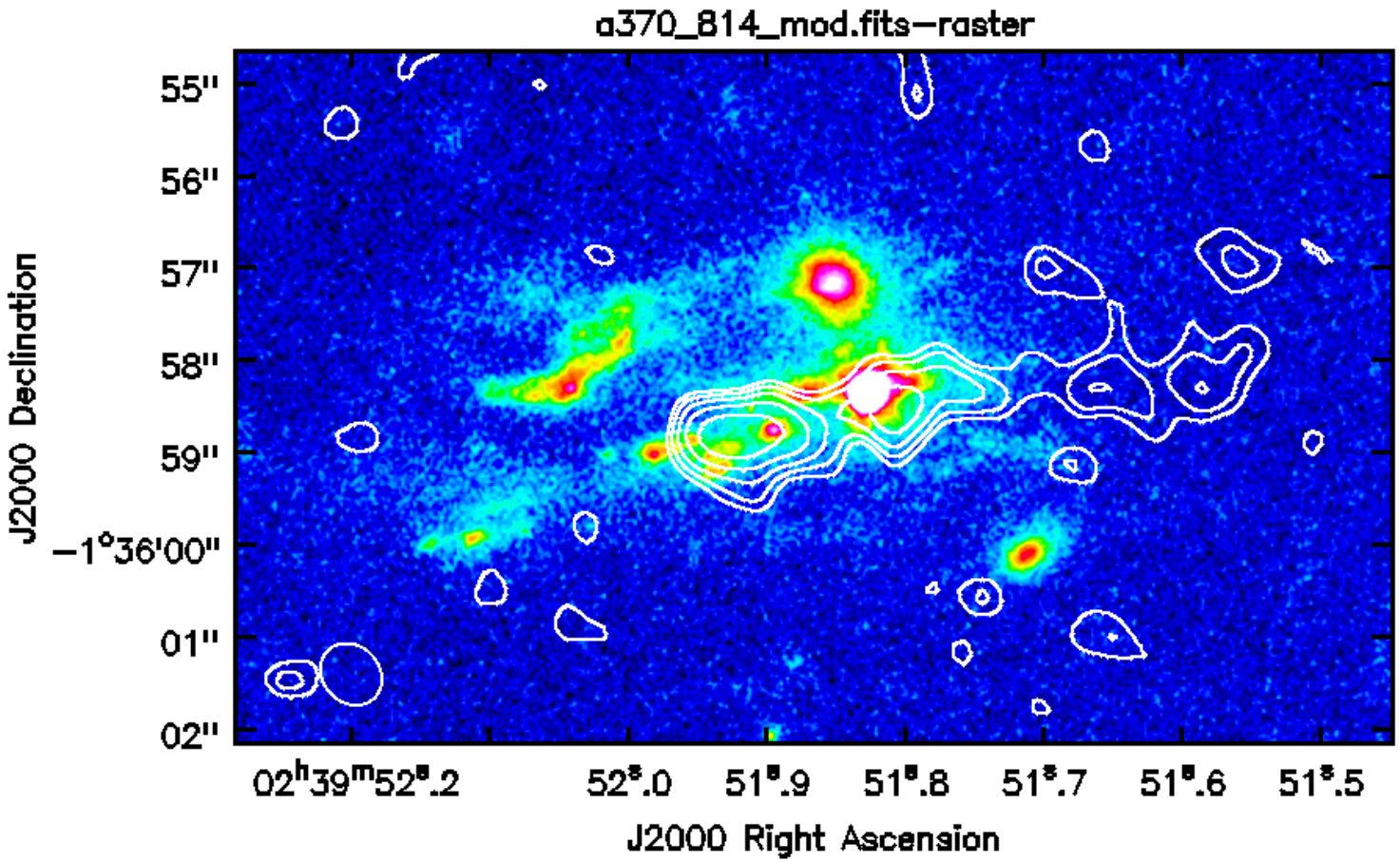
CO(3-2) spectrum of western feature
Velocity is consistent with GBT CO(1-0) excess).



Integrated ALMA CO(3-2) Spectrum



CO(3-2) +350km/s


a370_814_mod.fits—raster
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56''
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59''
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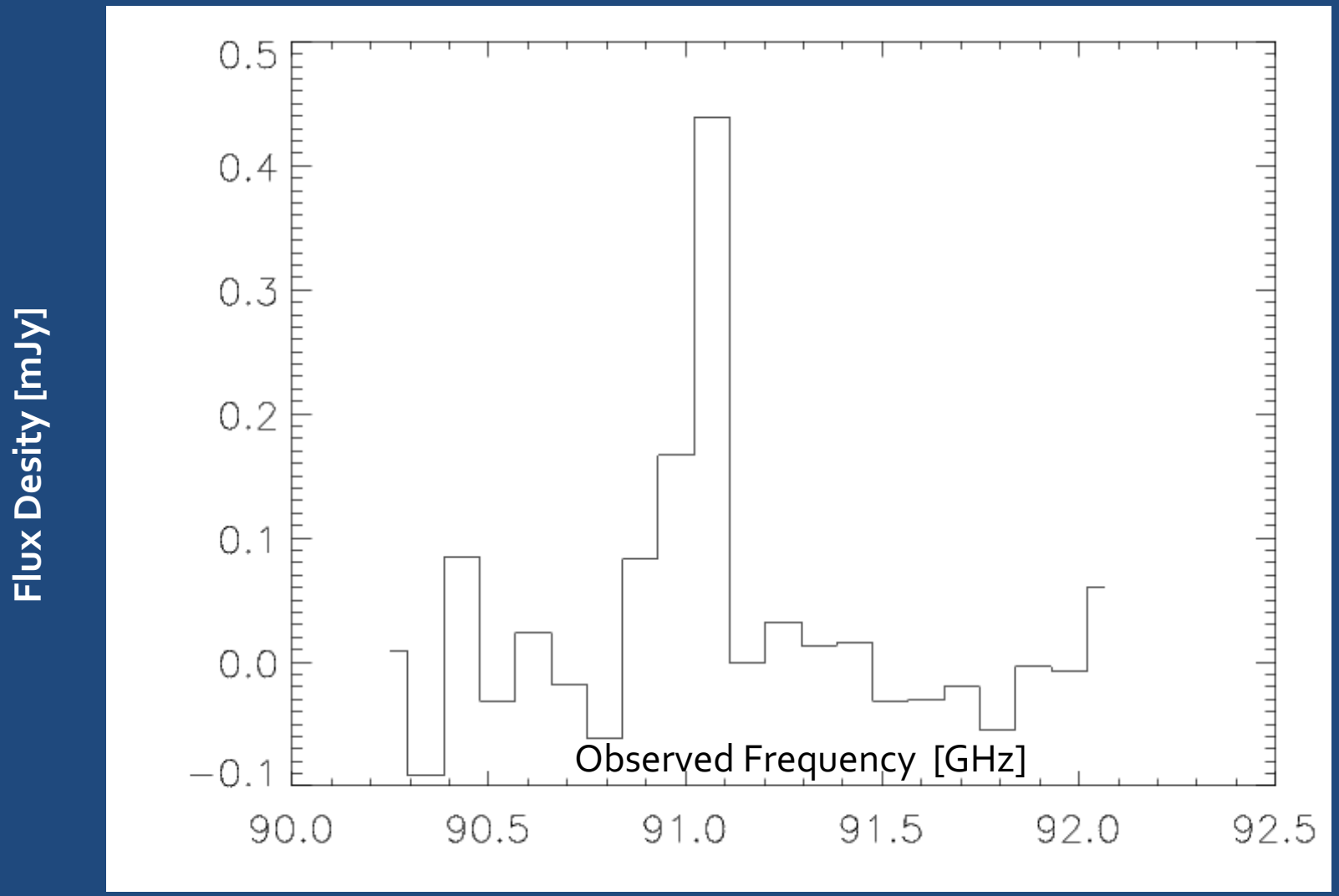
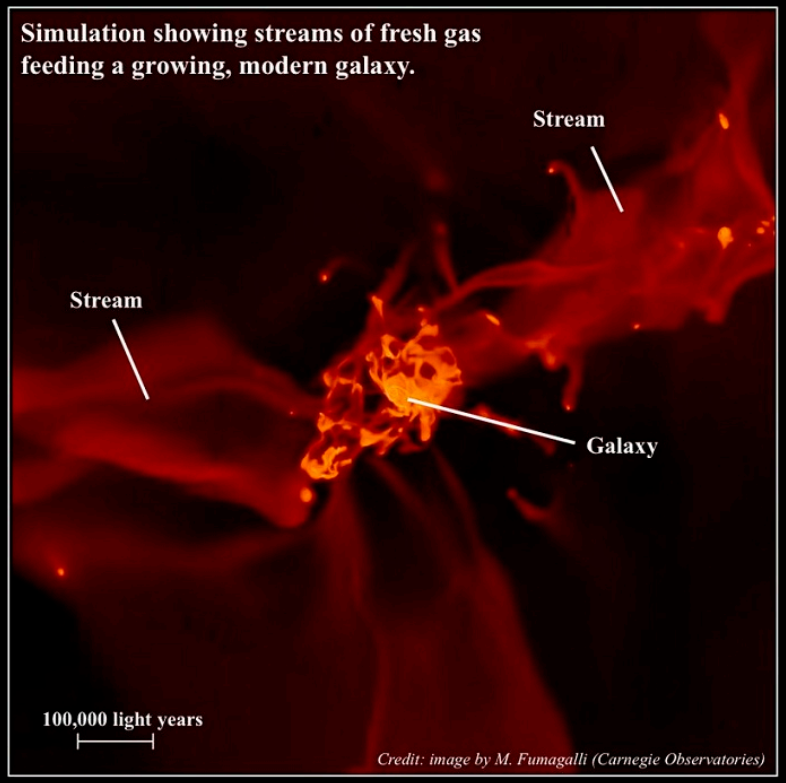
01''
02''
J2000 Declination
02h39m52s.2
52s.0
51s.9
51s.8
51s.7
51s.6
51s.5
J2000 Right Ascension

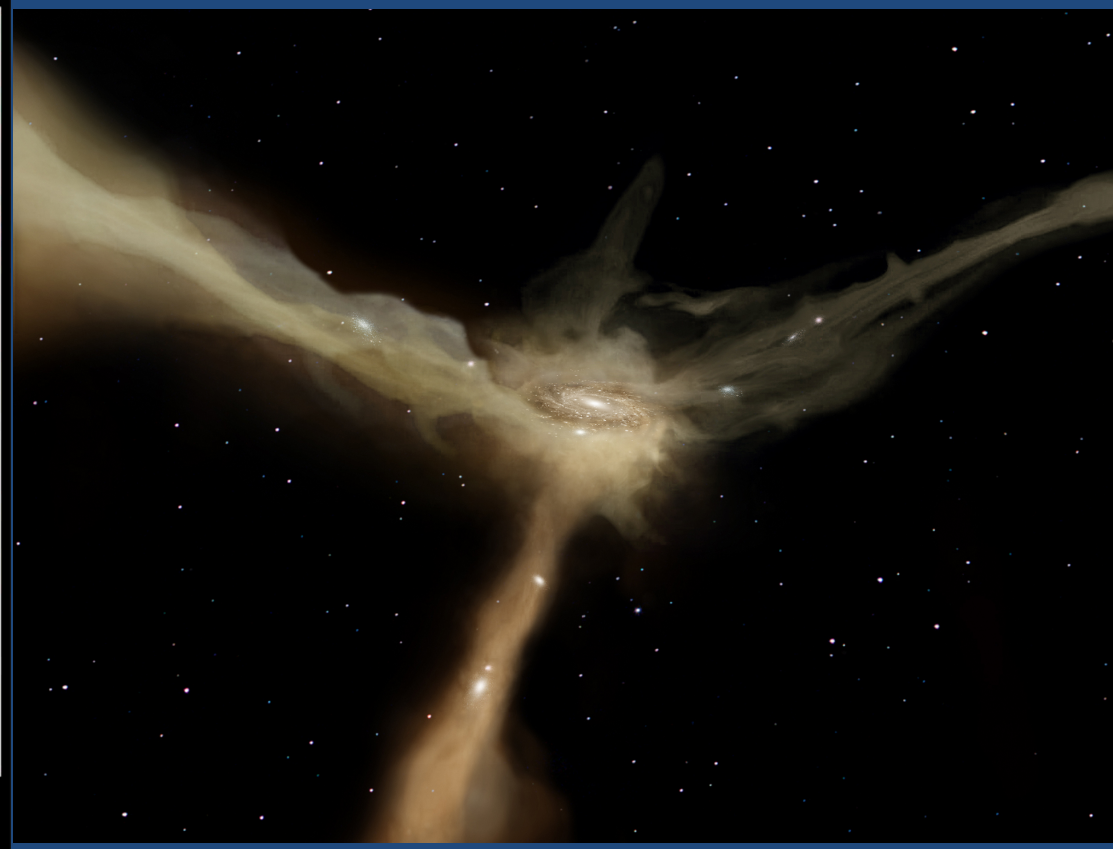
CO(3-2) spectrum of weaker possible feature at -800km/s



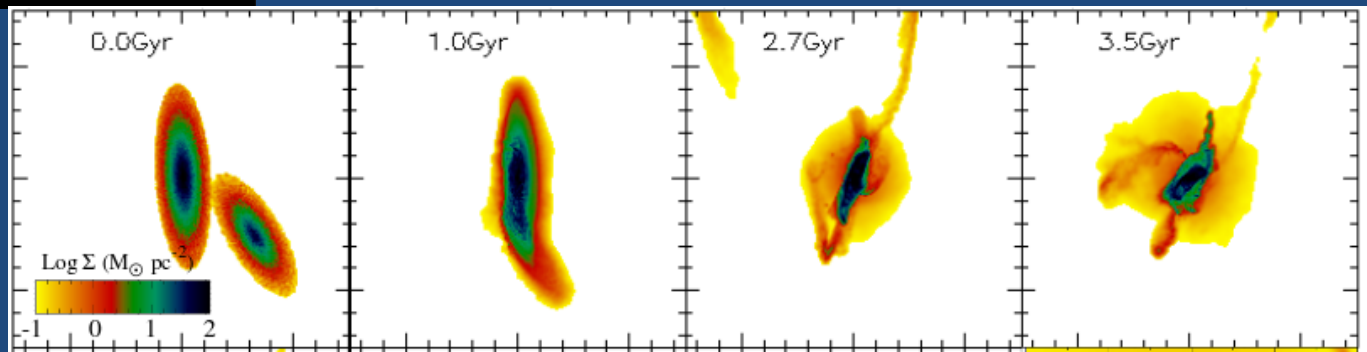
Infall along filaments or merger tidal features?



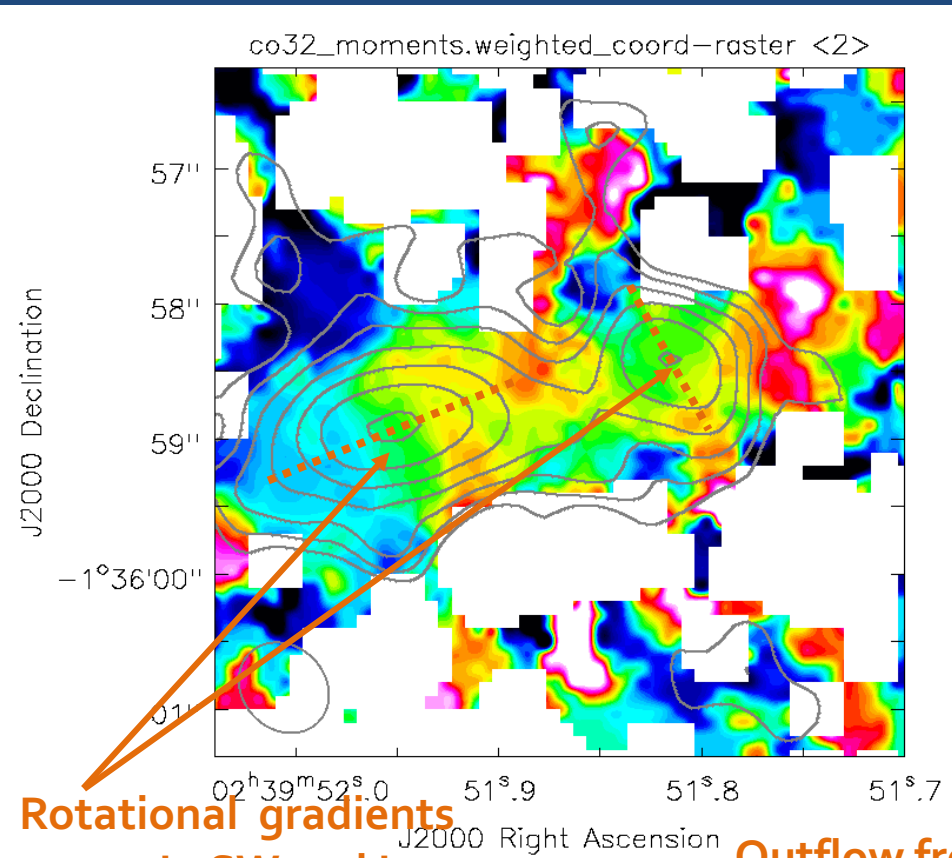
This image from a simulation of galaxy formation shows a galaxy feeding on streams of cool gas. Nicolas Lehner and his team have now provided empirical evidence for these gas flows. Using new observations from the Hubble Space Telescope, they show large quantities of cool gas with very low quantities of heavy elements are in the gaseous surrounding of modern galaxies as predicted in simulations.

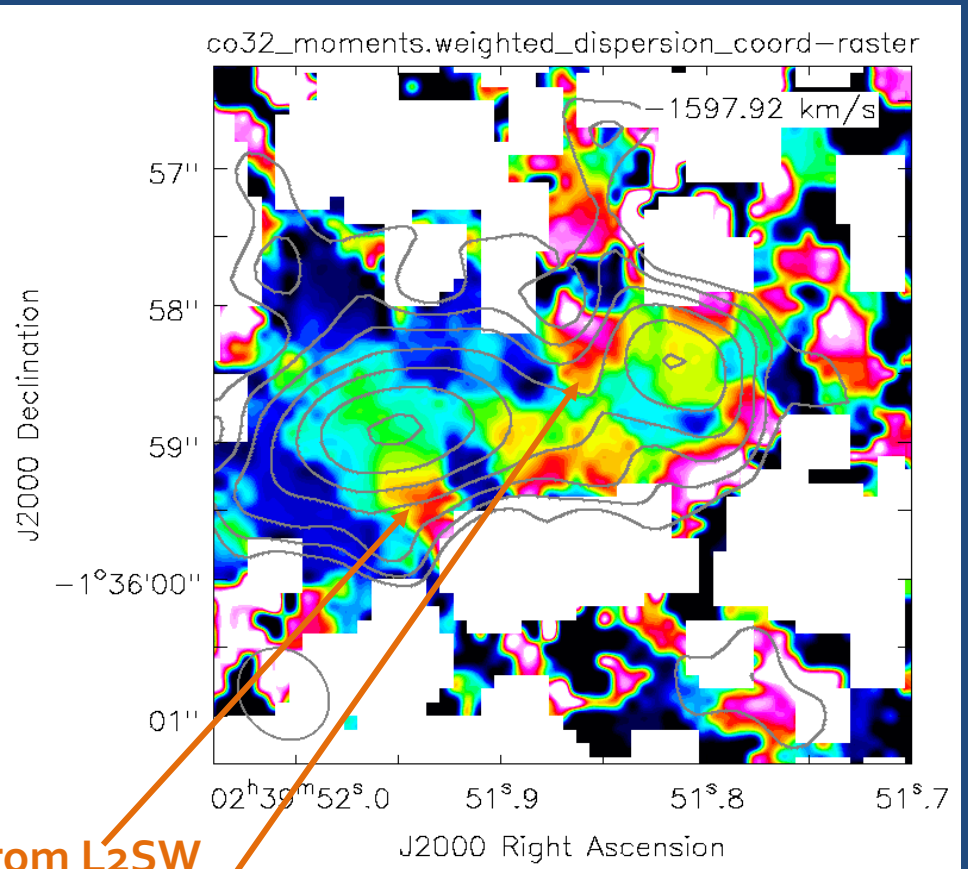


Wang+12 merger simulation



ALMA CO(3-2) Moment Maps





Rotational gradients across L2SW and L1

Outflow from L2SW starburst? and high-velocity dispersion between L1 and L2SW

Mom-0 integrated map shown in contours on Mom-1 velocity map.

Mom-0 integrated map shown in contours on Mom-2 velocity dispersion map.

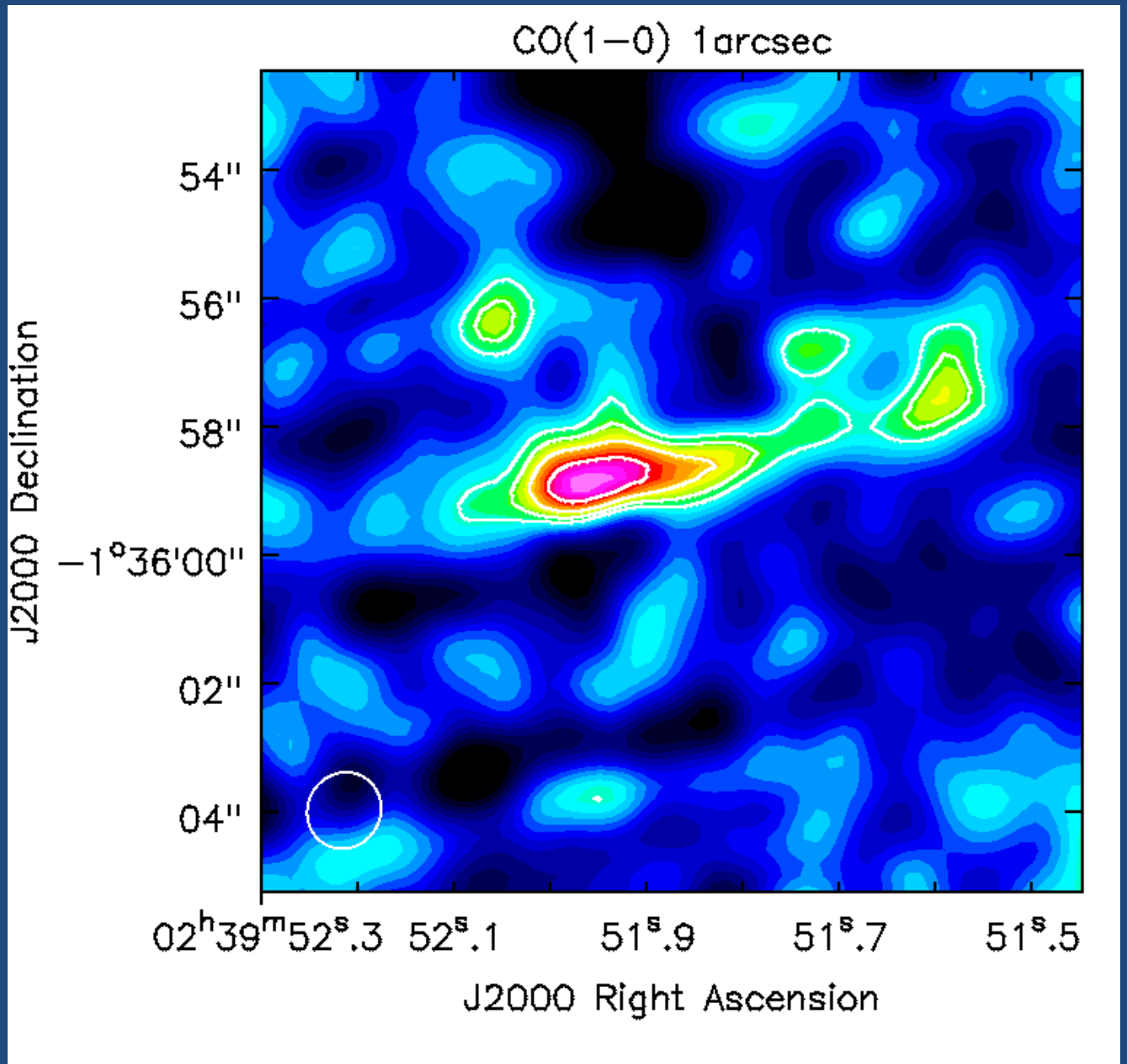
VLA B-array CO(1-0) data

0.4" resolution data, but taper to 1" to improve S/N.

Total CO(1-0) emission consistent with GBT spectrum and with previous estimate from Ivison+10

➔ CO emission is not resolved out, but comprised of unresolved clumps spread over a large area.

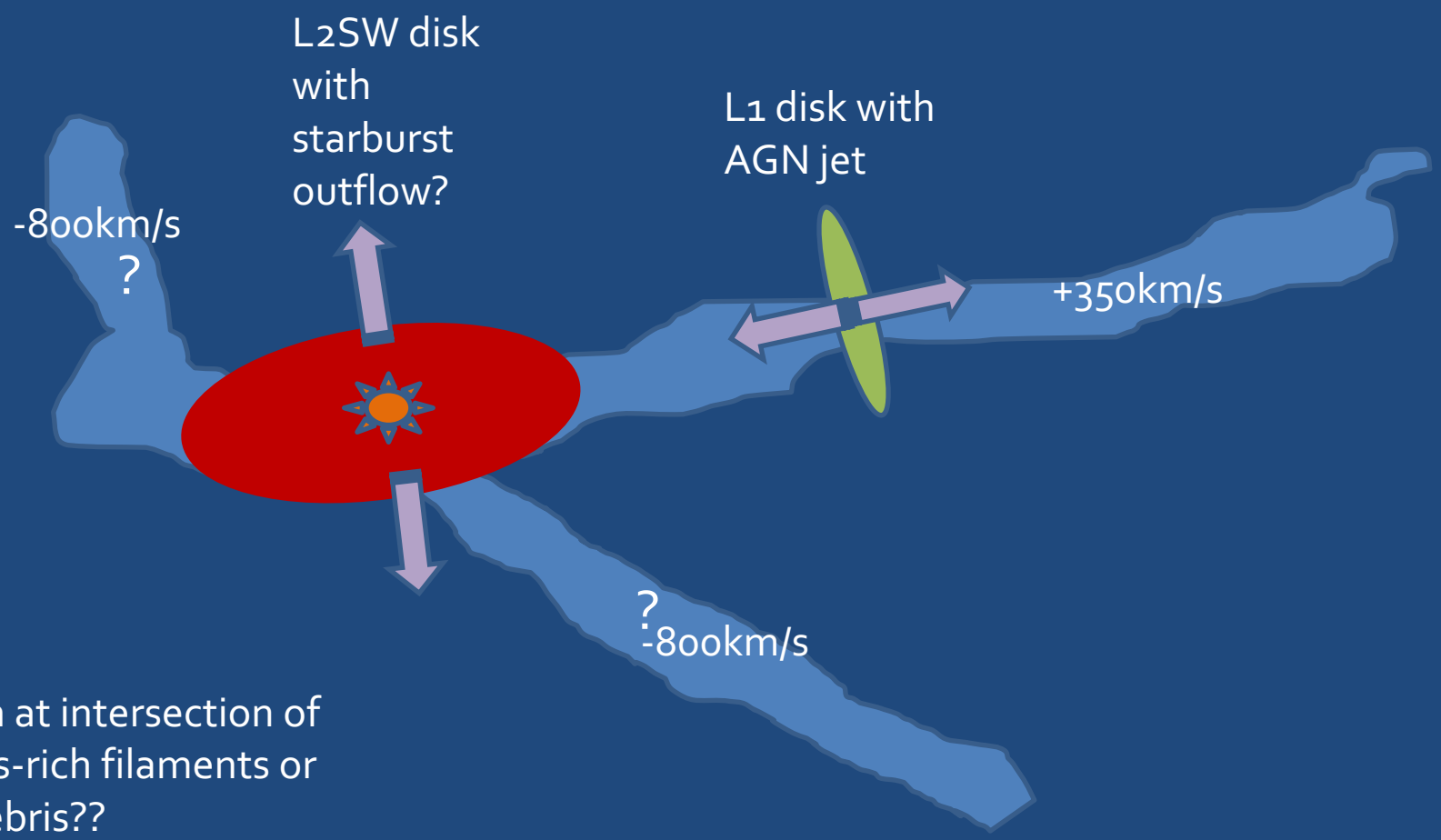
Need to combine with archived D-array data.



Molecular gas in SMMJ02399-0136?

- 15% of CO(3-2) emission is from western filament
- 60% of CO(3-2) is associated with L2SW starburst
- 25% of CO(3-2) is associated with L1
- L2SW and L1 have CO SLED consistent with starburst which could imply a low H2/CO conversion factor (alpha~1), while the filament may have a high-alpha so **~50% of the gas mass may be in the filament/tidal feature** (the GBT results will help constrain the total amount of molecular gas).

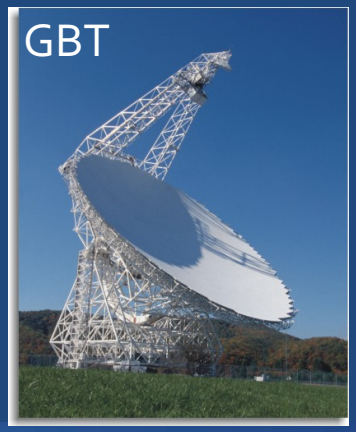
Toy Model



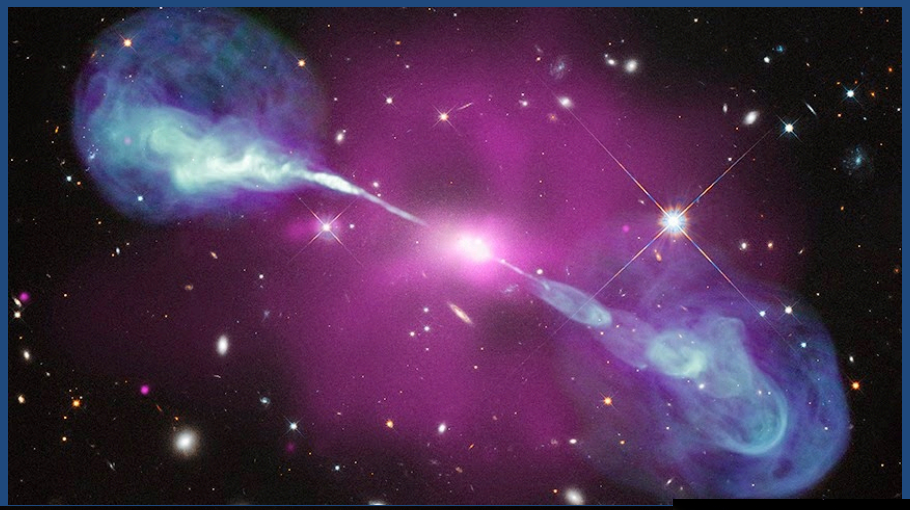
System at intersection of two gas-rich filaments or tidal debris??

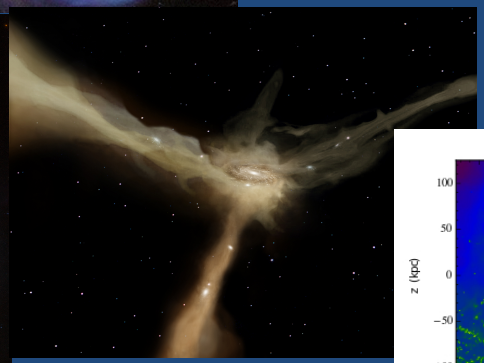
Concluding Remarks

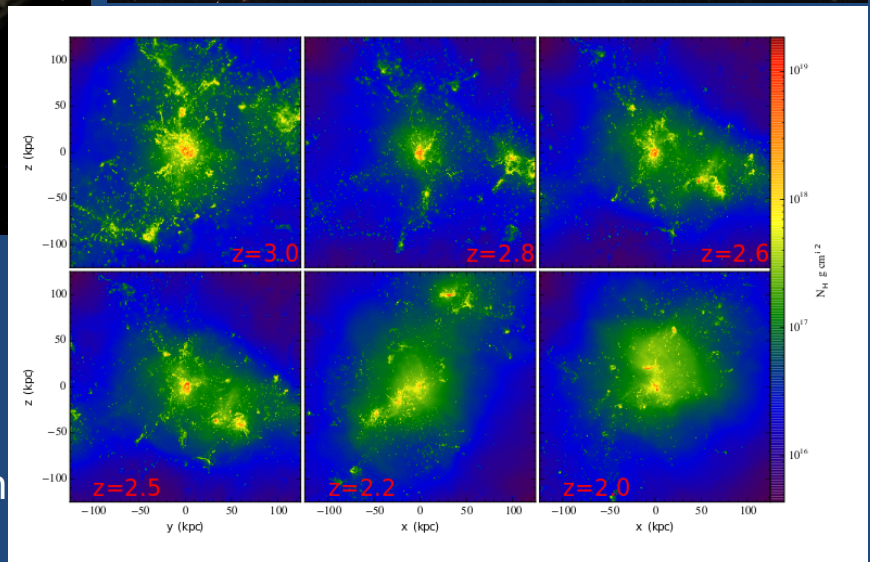
- SMM J02399-0136 is an extremely fascinating source that began the SMG revolution 20 years ago.
- The next decade will greatly advance our knowledge of galaxy evolution using ALMA (gas & dust studies)
- Low-J CO important (total molecular gas mass) ➔ highlights the importance of the GBT and VLA (and ngVLA) for high-z studies
- Note that the GBT operates up to 115GHz with a beam of 6" and has the point-source sensitivity sensitivity of the VLA and ALMA. With multi-element arrays, we can increase the mapping speed of the GBT by factors of 10x—1000x – very cost effective.



What spatial scale does the star-formation occur during the early stages of galaxy formation?







Narayanan+15
SMG simulation

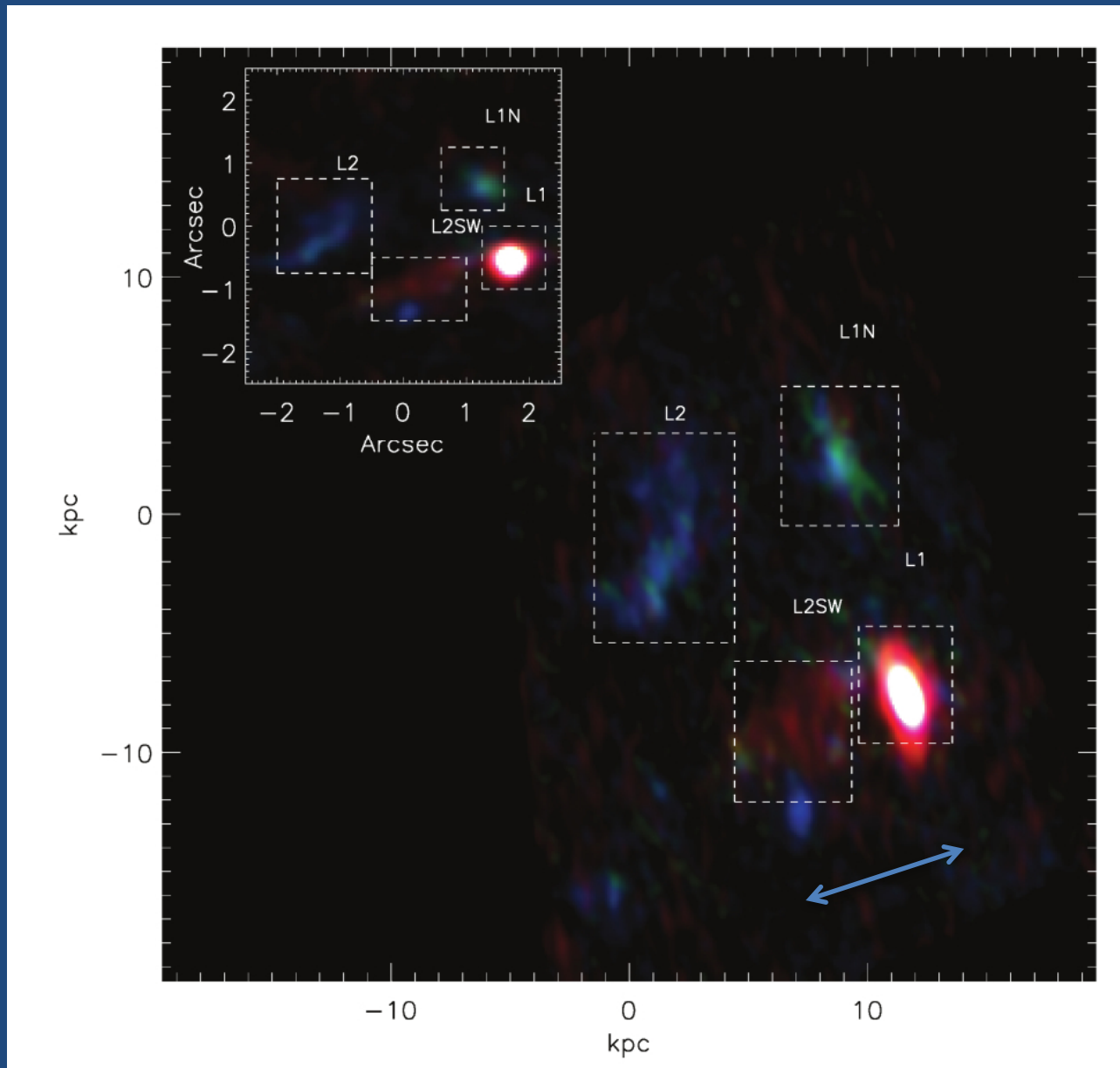
Extra Slides – Bonus Material

Field De-lensed

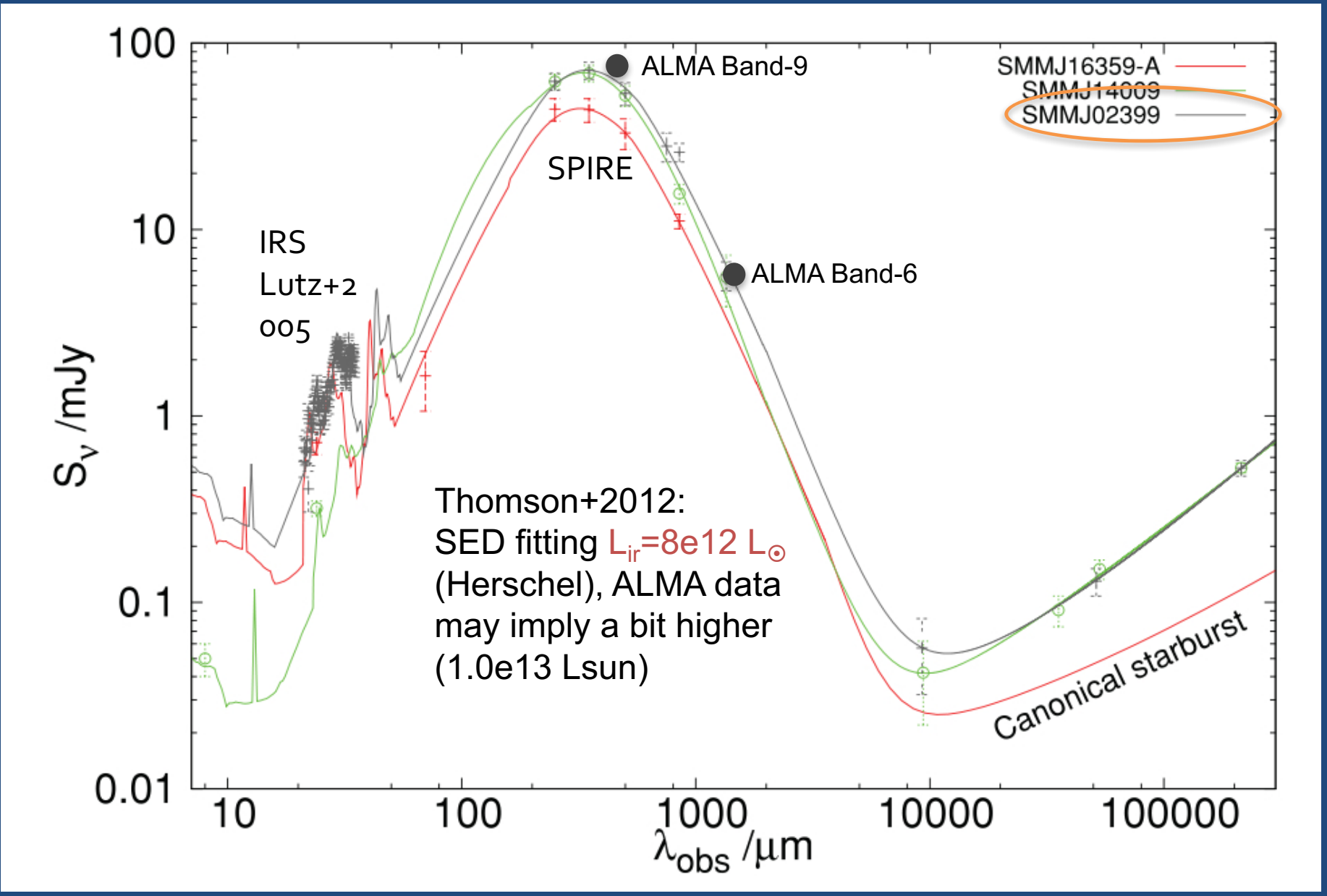
De-lensed image (mag=2.38)

Ivison+2010

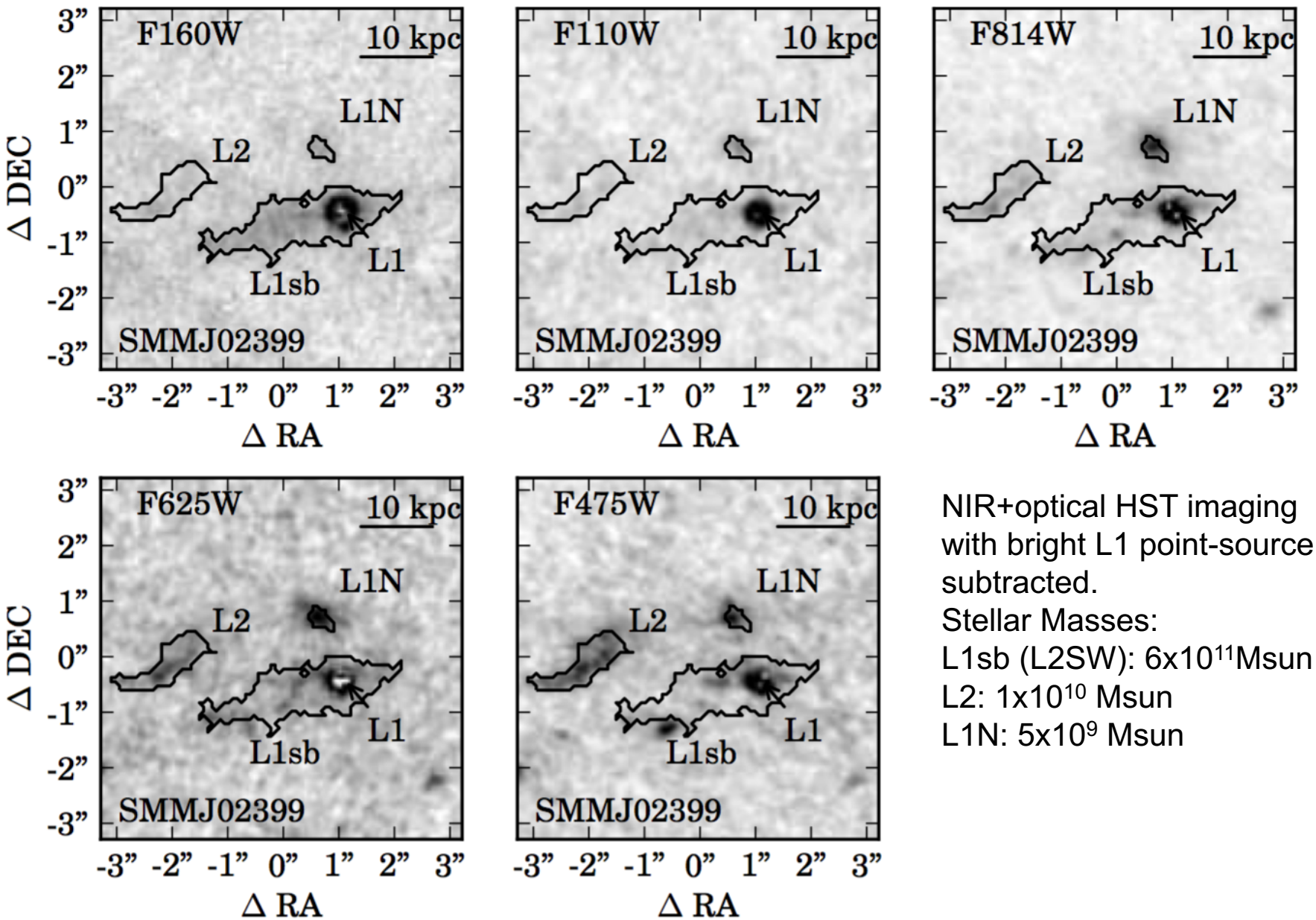
Radio Jet and L1 <-> L2sw alignment nearly along lensing vector allowing us to better resolve the interaction.



Global SED Optical, IR, Sub-mm, Radio



HST Imaging (Aguirre et al. 2013)



NIR+optical HST imaging with bright L1 point-source subtracted.

Stellar Masses:

L1sb (L2SW): 6×10^{11} Msun

L2: 1×10^{10} Msun

L1N: 5×10^{9} Msun