Molecular gas properties of a strongly lensed star-forming galaxy at z=3.63

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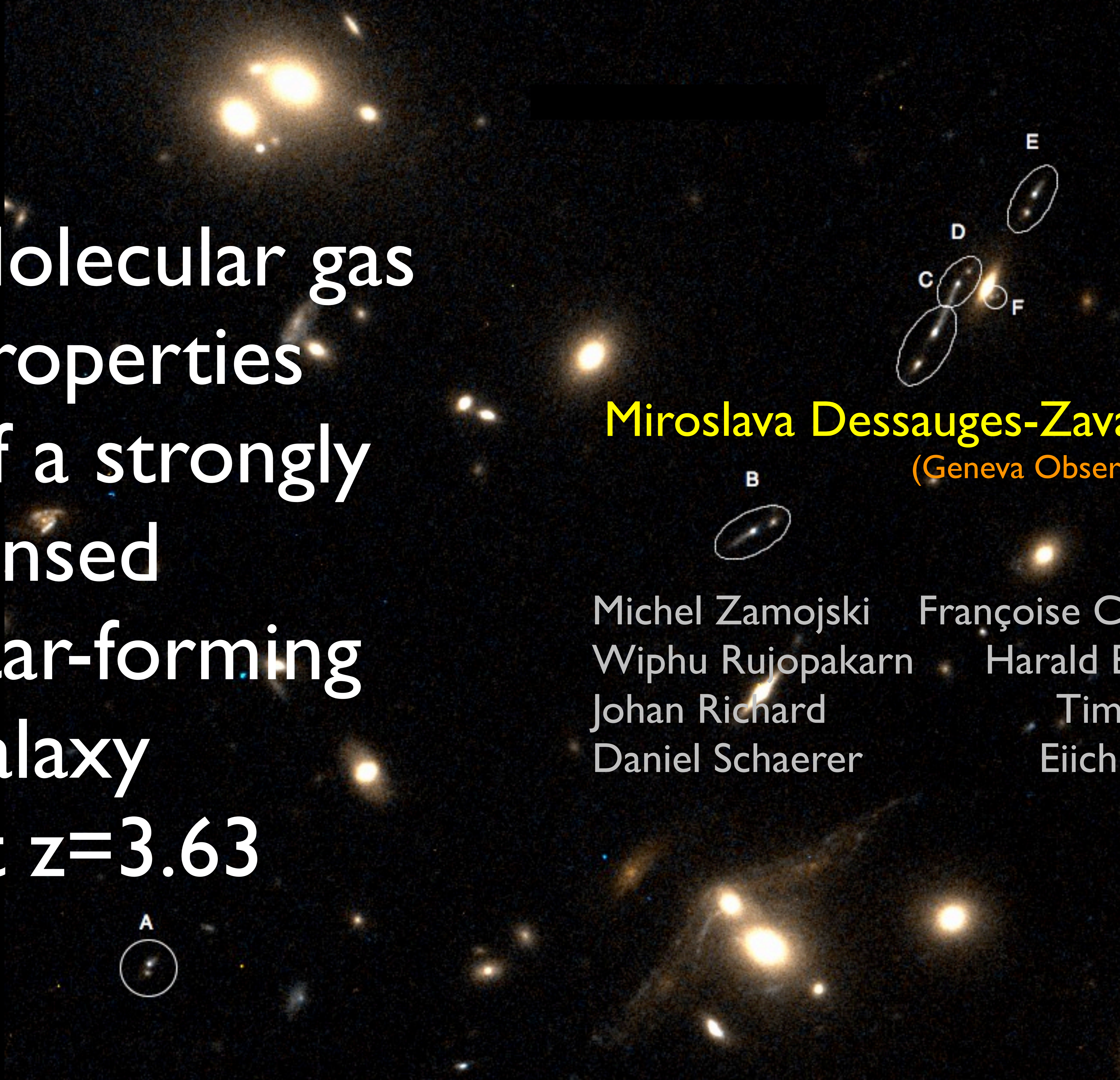


The target: MACSJ0032-arc

z=3.63 may appear as a low redshift

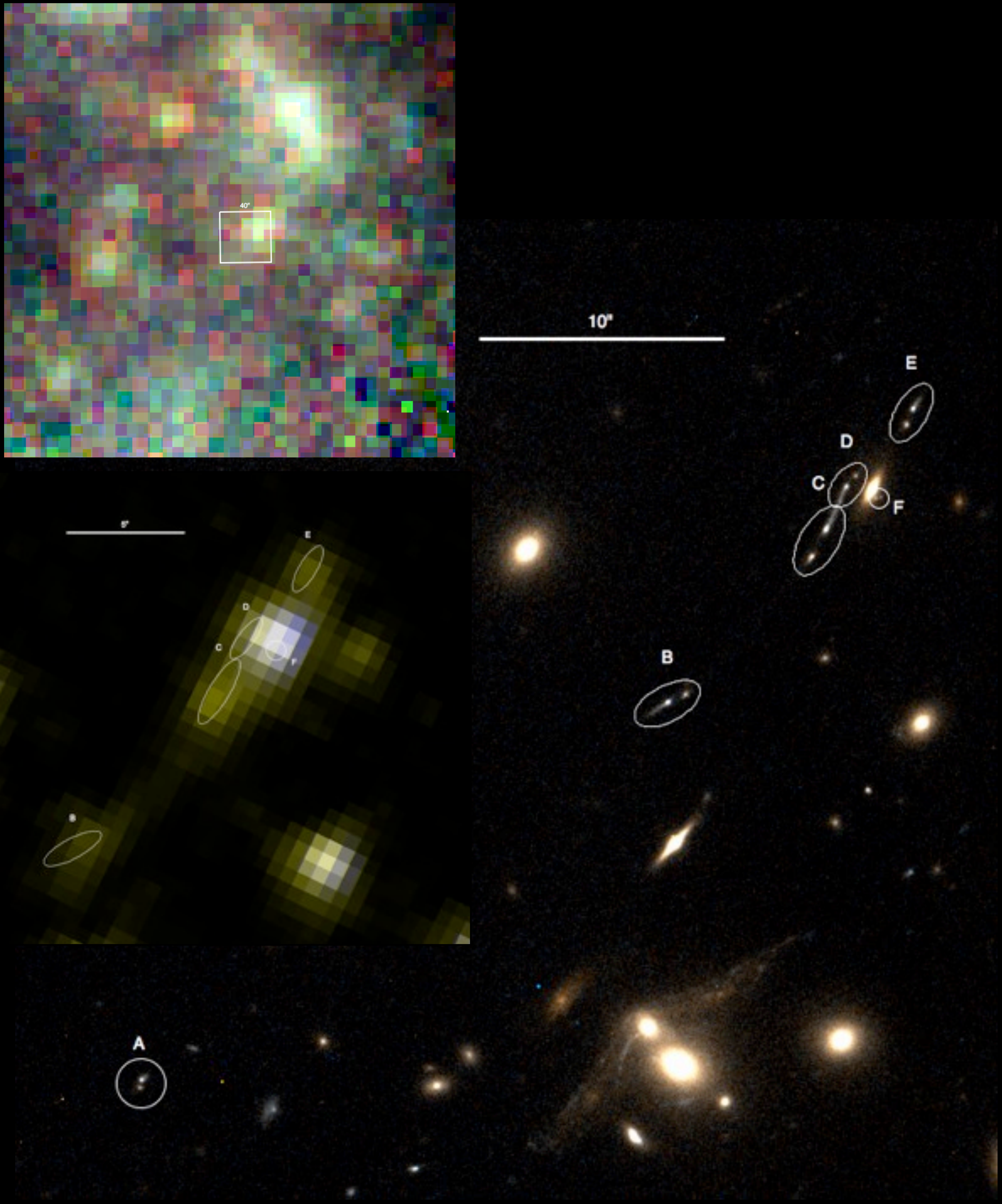
... but it is not ...

it is the highest redshift at which an estimate of the molecular gas mass has been obtained from CO in a main sequence (MS) star-forming galaxy (SFG)

how is this achievable?

thanks to strong gravitational lensing

of the 6 CO measurements performed to date for z>2.5 MS SFGs,
5 were obtained in strongly lensed SFGs (including the z=3.63 galaxy)



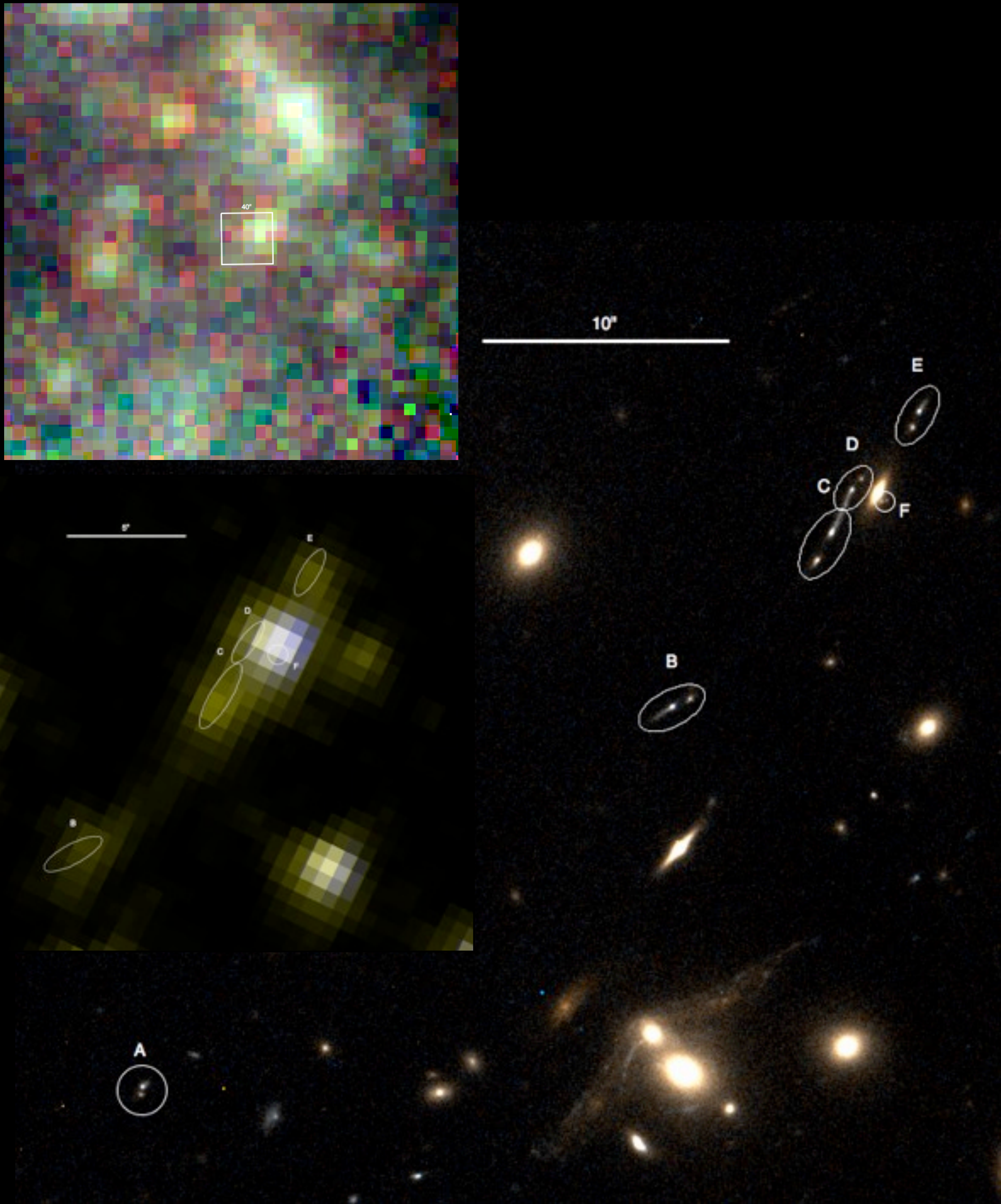
MACSJ0032-arc ID

- SFG strongly lensed by the galaxy cluster MACS J0032.1+1808
  Ebeling+11

- Discovered as a bright FIR emitter in the *Herschel*/SPIRE Lensing snapshot Survey (PI: E. Egami)

- Identified as a giant arc in the HST/ACS images extending over 42.4" and composed of 6 multiple images

- 4 multiple images detected with Spitzer/IRAC (3.6+4.5 μm)



MACSJ0032-arc ID

Physical properties derived from SED fitting of the optical, IR to FIR photometry

lensing-corrected values

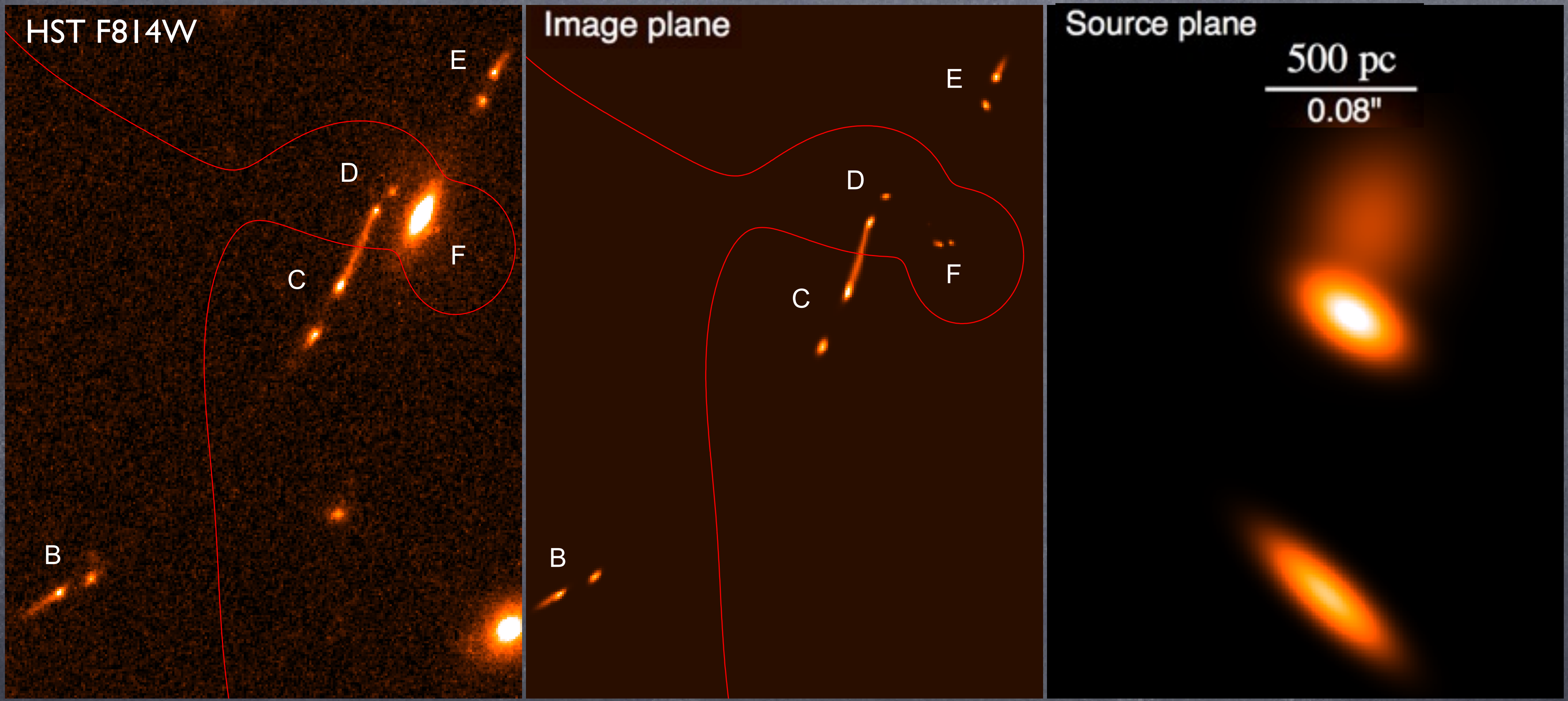
L_{UV} ($L_\odot$)	2.00E+10
L_{IR} ($L_\odot$)	4.80E+11
A_V	1.25
SFR_{IR+UV} ($M_\odot$/yr)	53
M_* ($M_\odot$)	3.20E+09
sSFR (Gyr^{-1})	16.5

Place MACSJ0032-arc on the MS with a marginal offset of +0.02 dex
(computed at the same M_* and z=3.63)
Daddi+07; Rodighiero+10; Schreiber+15

~90% of the total SFR_{IR+UV} seen through the thermal FIR dust emission
(undetected at UV because of dust obscuration)

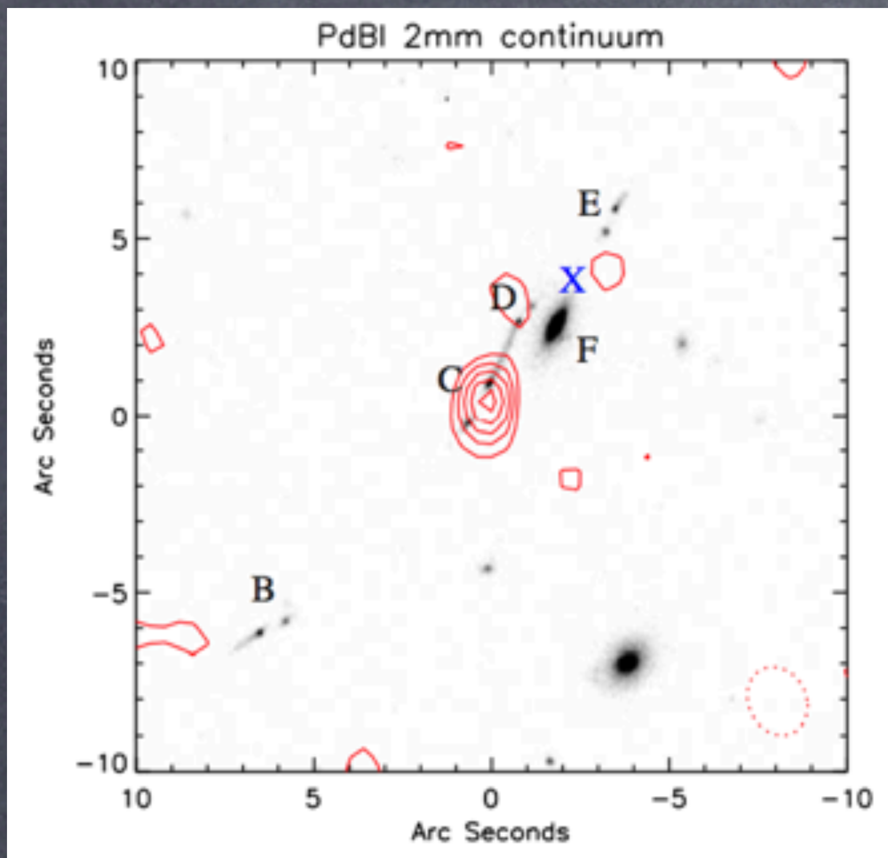
Gravitational lens model

— simulated morphology of the source with 3 elliptical Gaussian light profiles - 2 knots + tail
— match of their flux + shape to the photometry of the observed HST image (left panel)

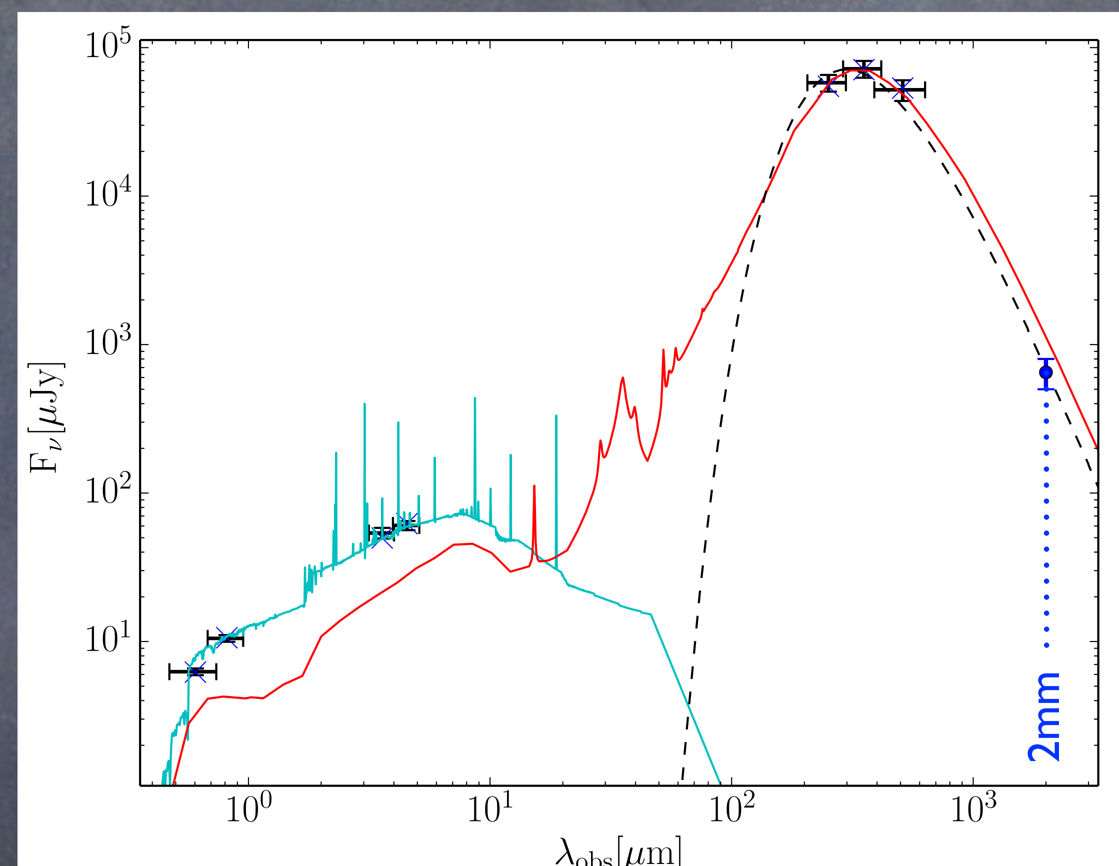


- Total magnification $\mu_{B+C+D+E}$ = 62±12 (the contribution of the image F is negligible)
- Physical separation between the 2 UV-bright knots = 1.14±0.28 kpc
- The galaxy is small with a global size < 2.5 kpc
  → typical for SFGs at 3 < z < 4 and with 9.5 < log($M_*/M_\odot$) < 10.5 (Buitrago+08;Shibuya+15)

PdBI 2mm continuum: Dust content



- detected only in the most strongly amplified image C
- useful to estimate M_{dust} with a good constraint on the ß-slope in the MBB fit



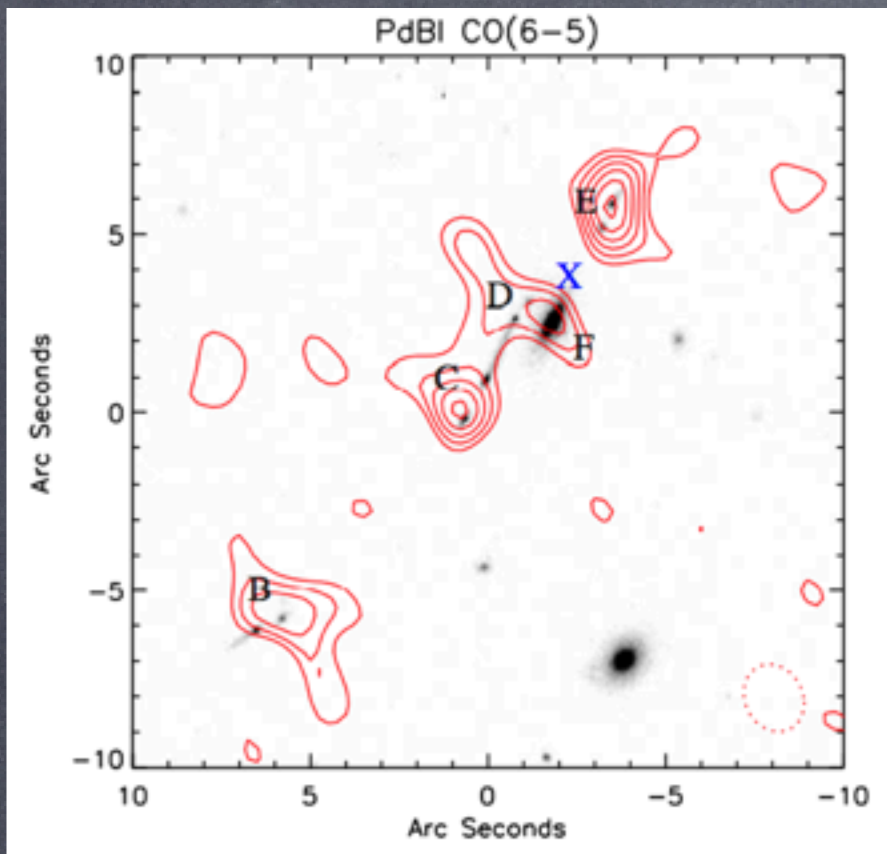
lensing-corrected values

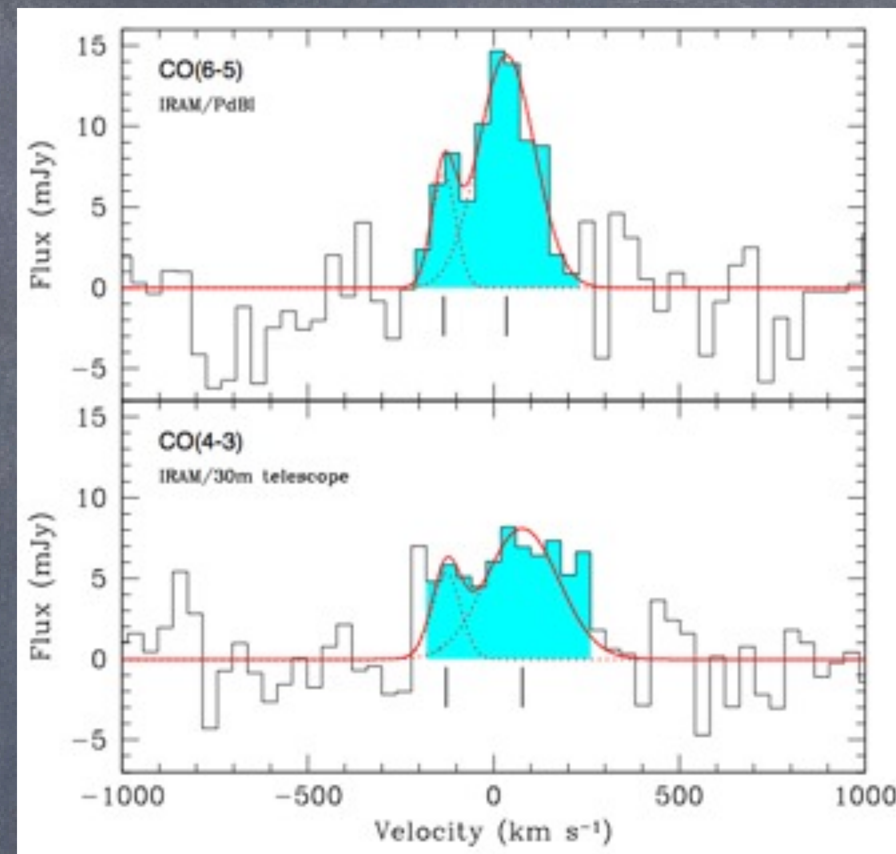
M_{dust} ($M_\odot$)	1.90E+07
T_{dust} (K)	43

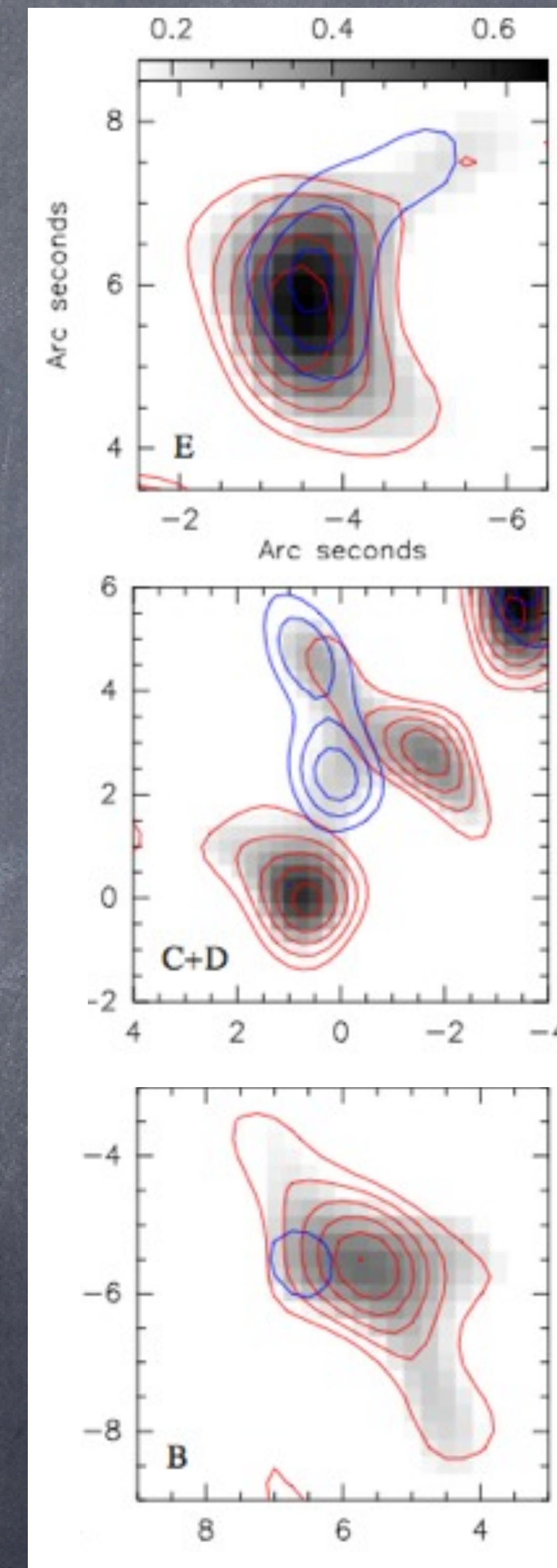
$\log(M_{dust}/M_*) \approx -2.6$ as expected

Santini+10; Smith+12; Sklias+14

PdBI CO(6-5) emission: Kinematics



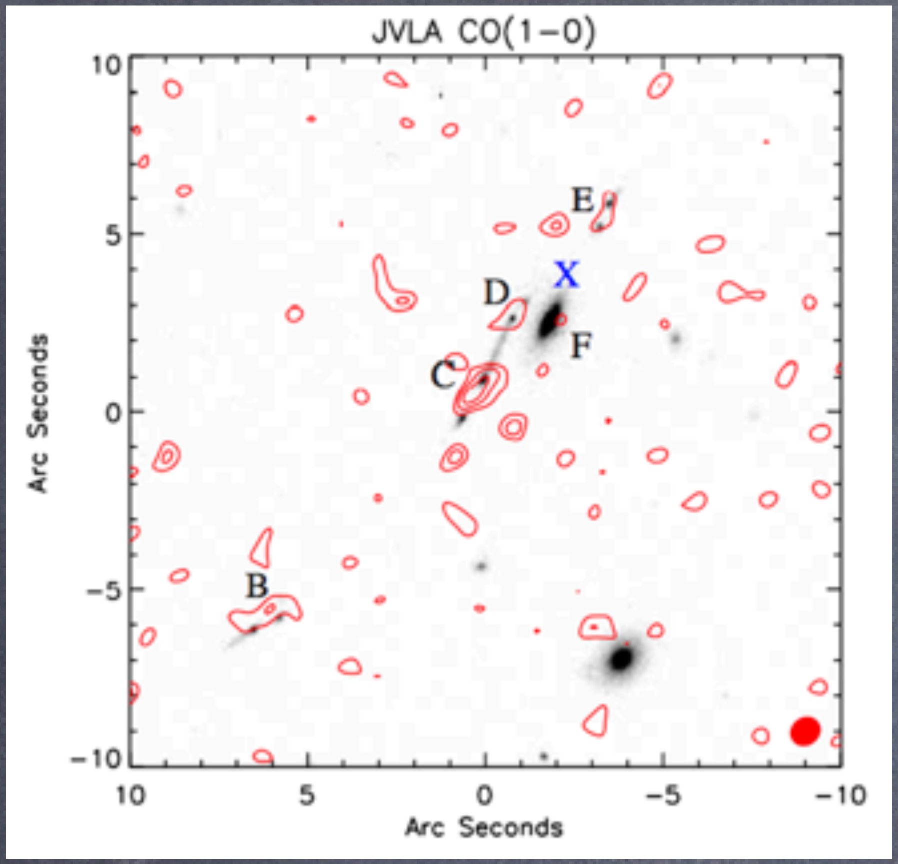


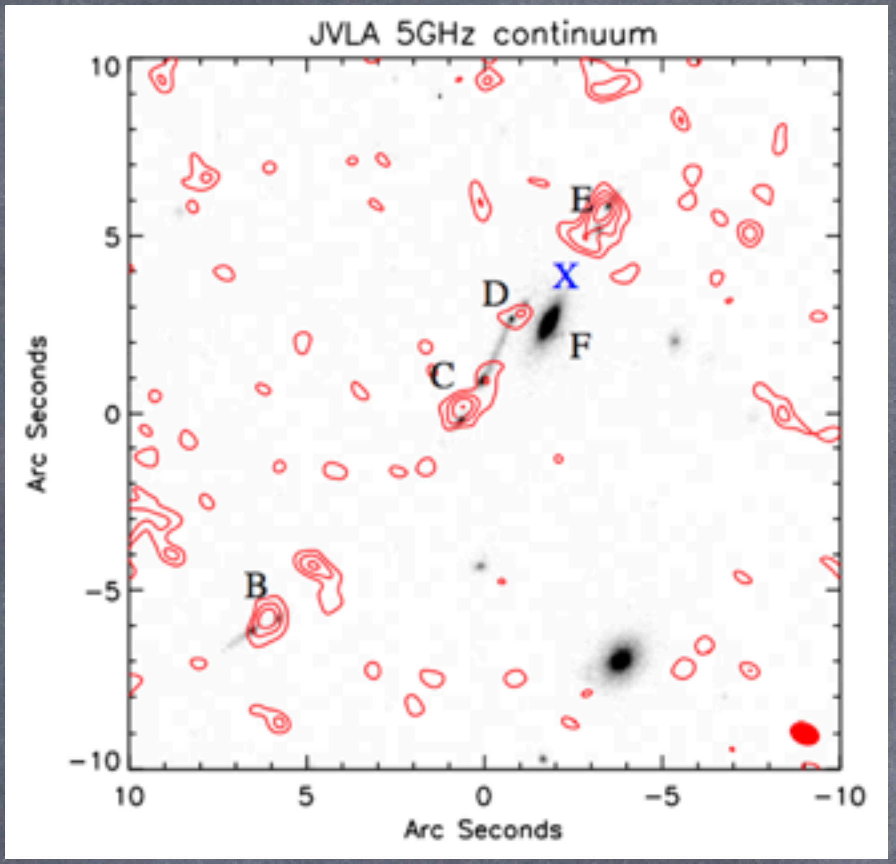


- detected in all strongly amplified images B, C, D, E
- UV-bright knots separated by 0.8" unresolved in CO(6-5)
  (PdBI beam = 1.96"x 1.62")
- double-peaked CO(6-5) and CO(4-3) emission line profiles
  (velocity separation = 185 km/s)
- blue and red contours spatially offset
  (following the HST inversions from one counter-image to the other)

> suggestive of rotation in this z=3.63 MS SFG

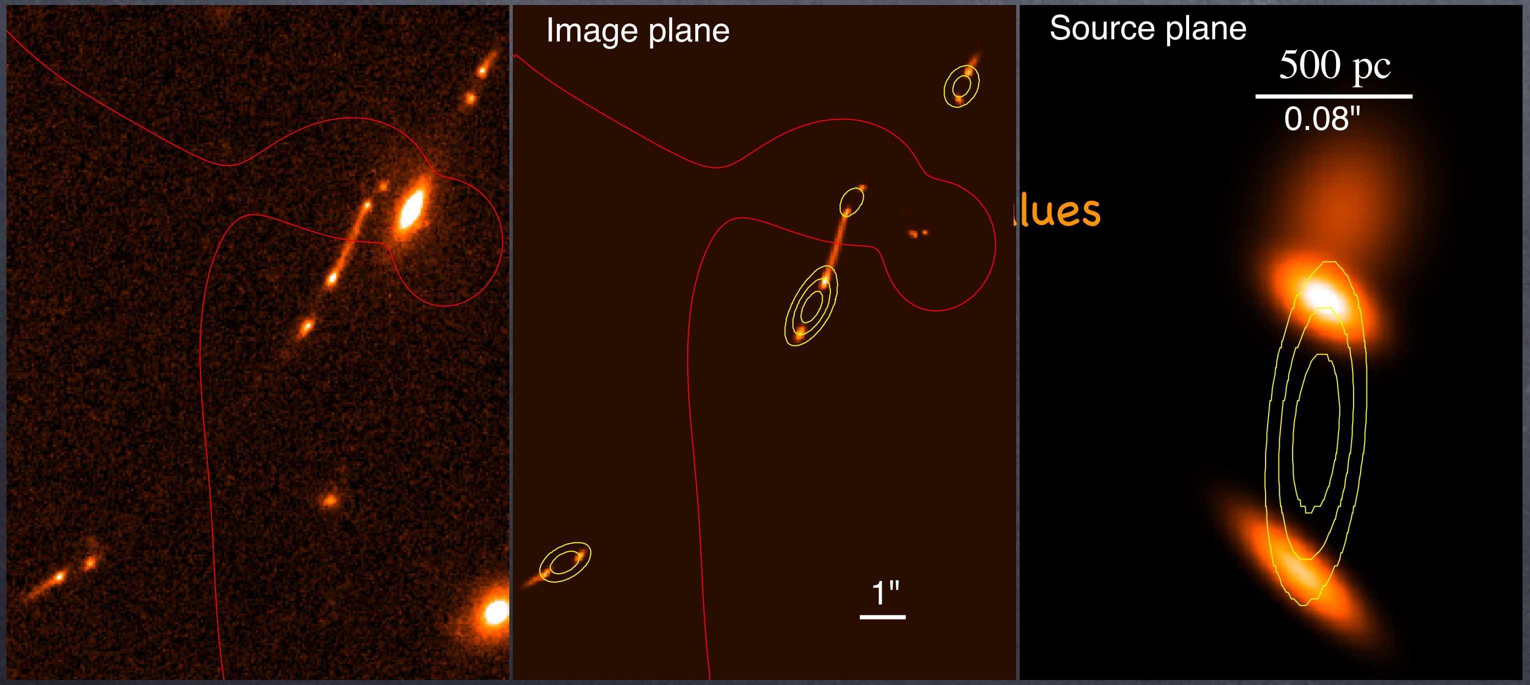
JVLA CO(1-0) + radio continuum:
Molecular gas + star formation spatial distributions





- CO(1-0) securely detected in image C
- CO(1-0) peaks between the 2 UV-bright knots
  (JVLA CO beam = 0.90"x 0.79")
- radio continuum also peaks between the UV knots
  (5GHz beam = 0.87"x 0.62")

Test of the spatial origin of CO and radio continuum in the source plane:



Source plane:
CO/radio emission simulated by an extended elliptical Gaussian between the UV knots

Image plane:
corresponding beam-convolved CO(1-0) emission resembles the JVLA CO(1-0) observations

Total magnification B, C, D, E:
$\mu \simeq 65$ in CO/radio (against $\mu = 62 \pm 12$ in UV)
→ negligible differential magnification

JVLA CO(1-0) + radio continuum:
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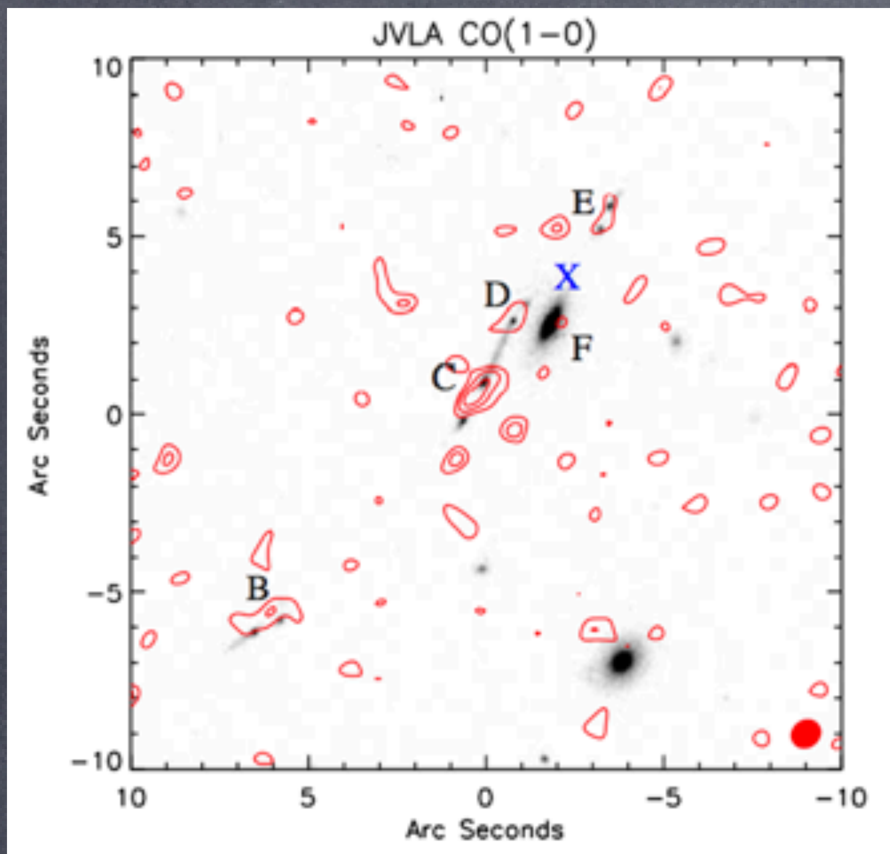

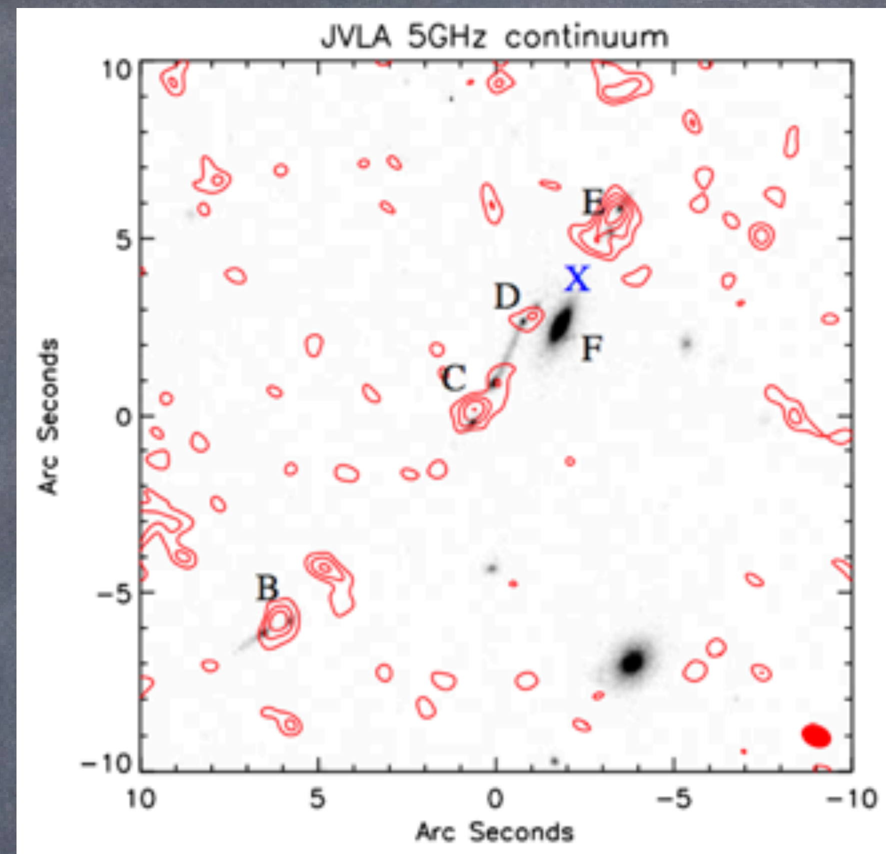

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  (JVLA CO beam = 0.90"x 0.79")
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✓ Bulk of the molecular gas reservoir located between the UV-bright knots

✓ Same for the dust-obscured star formation ≈ 90% of the total star formation in MACJ0032-arc (traced here through synchrotron radiation)

lensing-corrected values

SFR_{radio} ($M_\odot$/yr)	58

in very good agreement with SFR_{IR+UV}

CO SLED: Gas excitation state

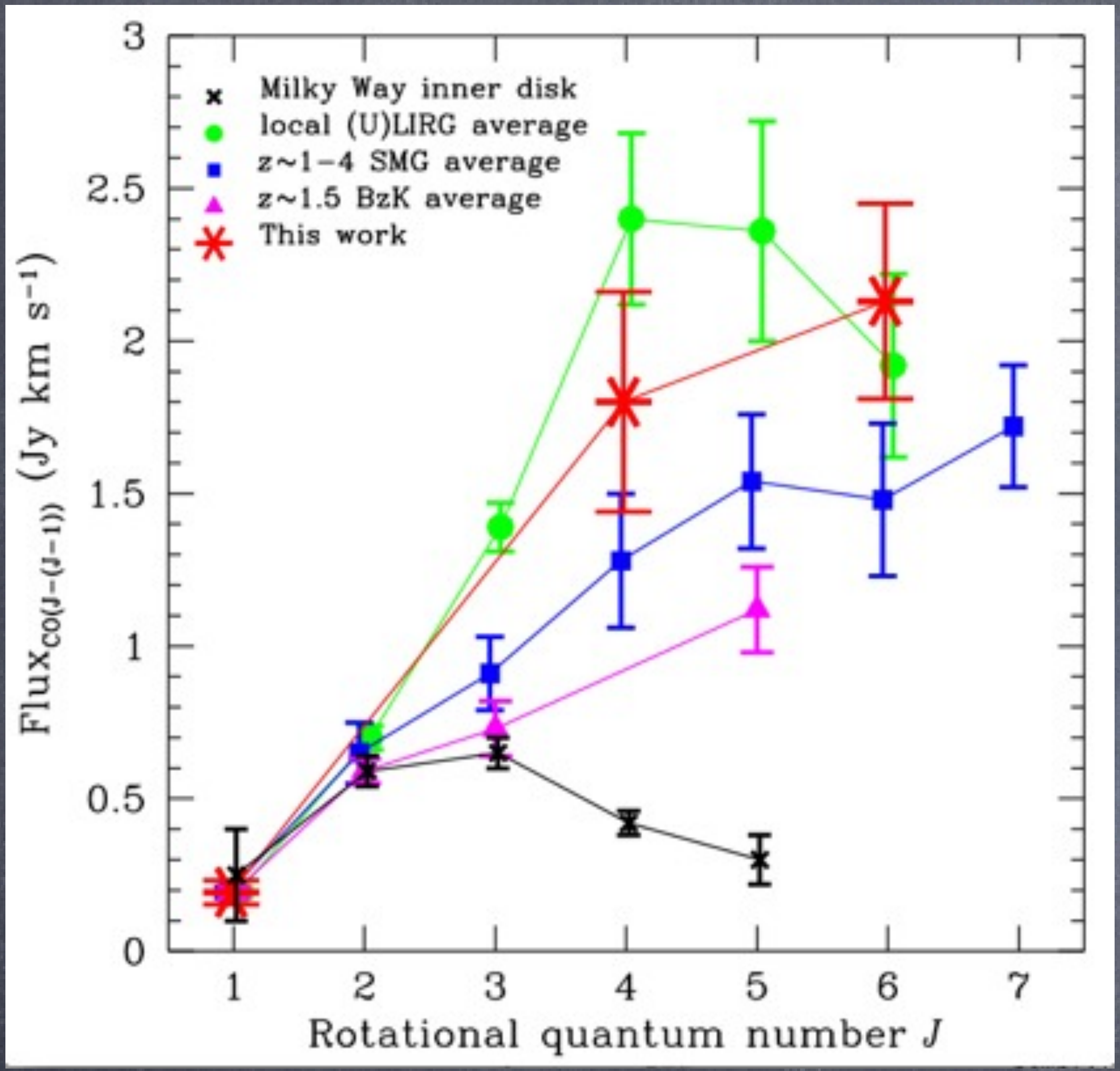
Rare opportunity to characterize the CO SLED for high-*J* CO transitions in a MS SFG at a high z=3.63 with direct CO(1-0) measurement

Motivation: $L'_{CO(1-0)} \rightarrow M_{molgas}$

⚠ only high CO rotational transitions accessible at high z with NOEMA/ALMA

J=6 up to z=7.2 J=4 up to z=4.5 Carilli & Walter 13

CO SLED: Gas excitation state



MACSJ0032-arc

- highest J probed so far in a MS SFG
- J≤6 CO transitions remain excited !!!
- high $r_{4,1}$=0.58 and $r_{6,1}$=0.30 luminosity corrections

> CO molecular gas highly excited

Comparison with other galaxies

- clear SLED enhancement of high-z SFGs over the MW SLED Daddi+15; Fixsen+99
- similar arc's SLED to that of high-z SMGs Bothwell+13; Spilker+14

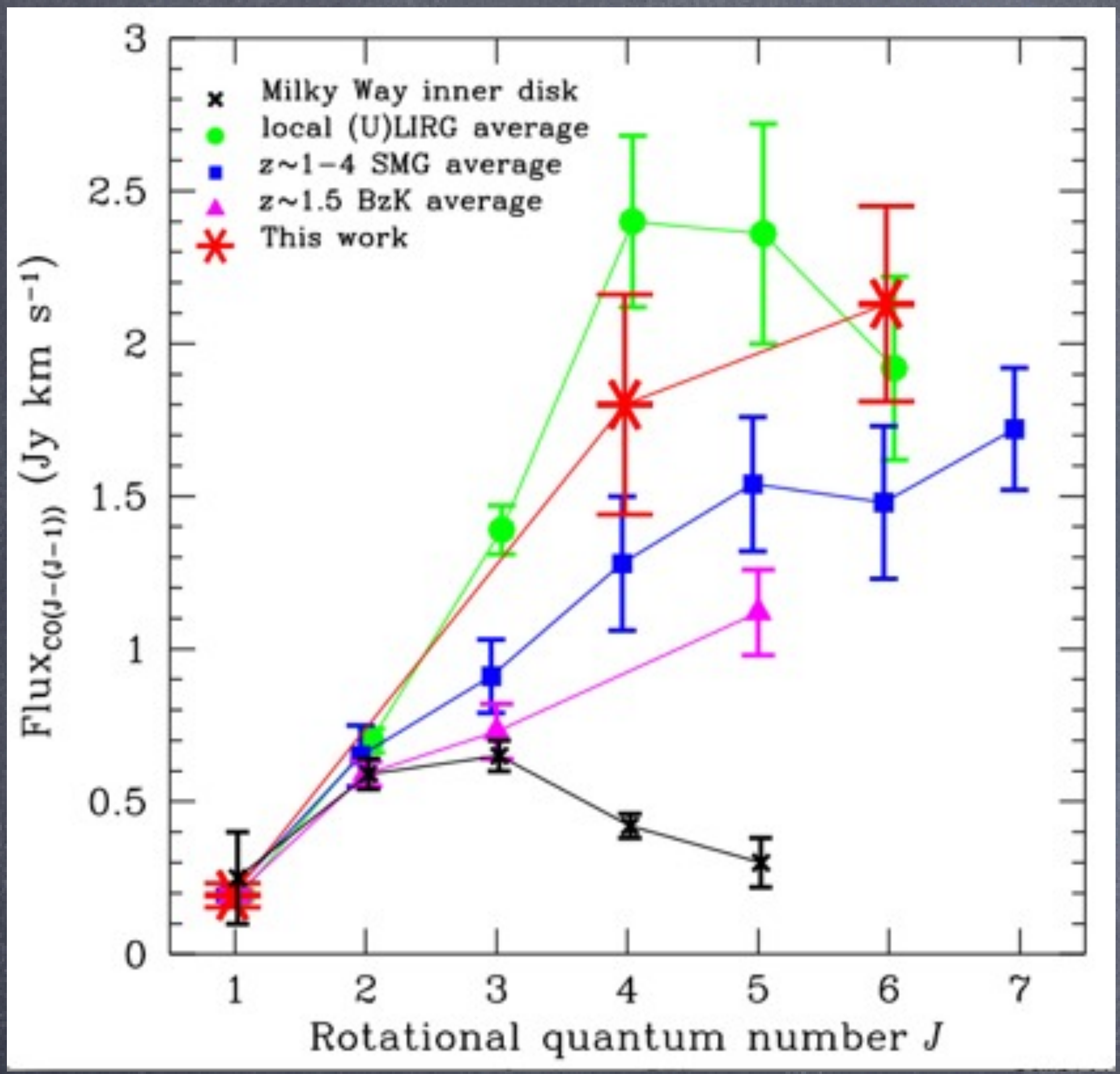
Simulation predictions

✓ Papadopoulos+12: no turnover at J<6
✓ Narayanan & Krumholz 14:
turnover at J=5-6 for the arc's Σ_{SFR}
✓ Bournaud+15: turnover at J=5

What causes this high CO excitation? the compactness

the compactness induces a higher molecular gas density
leading to more CO excitation by collisions with H_2 Solomon+97; Weiss+05,07
not mandatorily due to a merger (not supported by the MS nature and the kinematics in MACSJ0032-arc)

CO SLED: Gas excitation state



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What causes this high CO excitation? the compactness

Possibly galaxies at higher z (z≳3.5) are more compact, and hence have more excited CO molecular gas, because of their smaller sizes

CO-to-H_2 conversion: Molecular gas mass

Known to vary with metallicity

$$\alpha_{\rm CO}^{Z} = \alpha_{\rm CO,MW} \times \chi(Z)$$

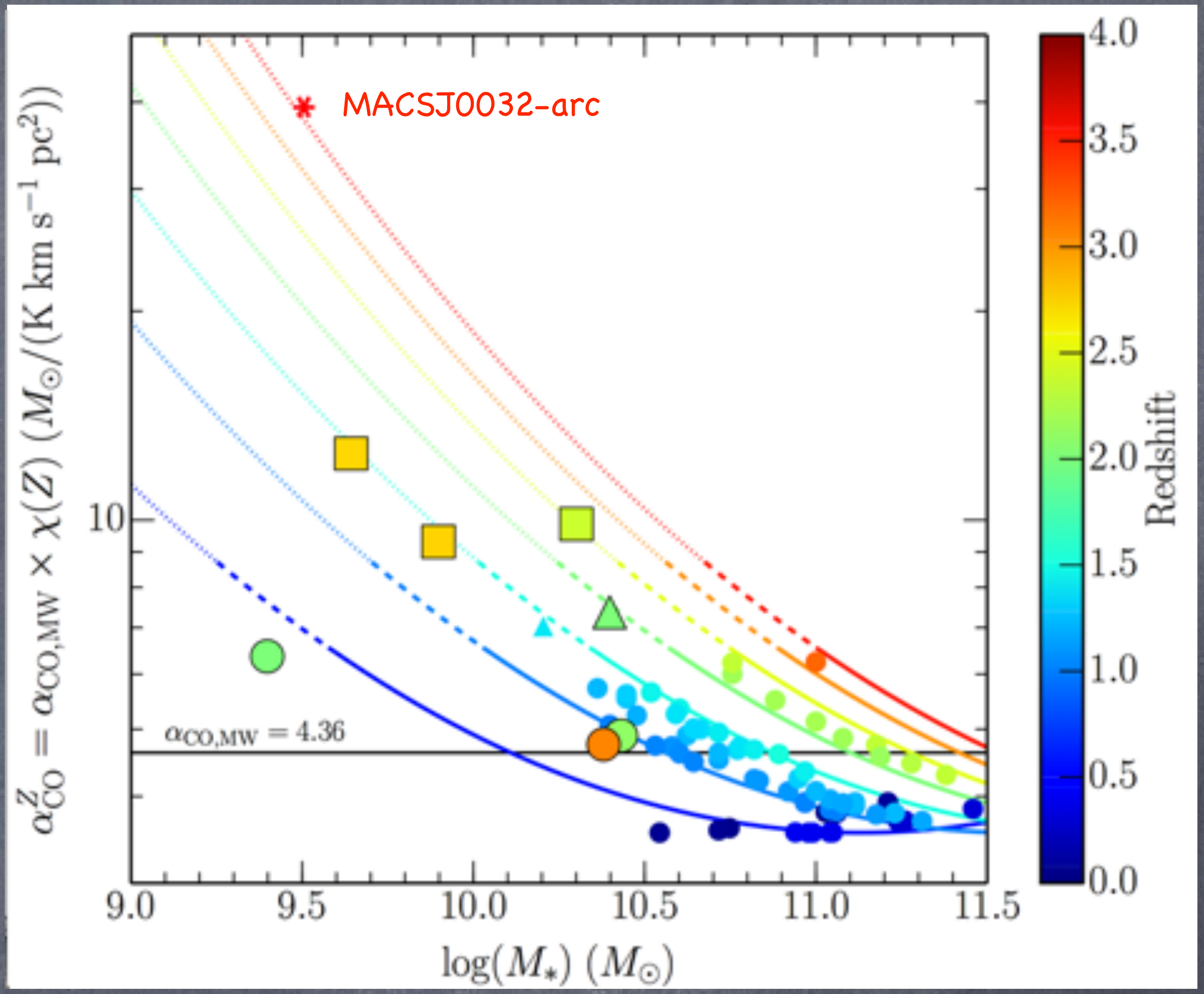
with

$$\chi(Z) = 10^{-1.27(12+\log({\rm O/H})_{\rm PP04}-8.67)}$$

(calibrated on local galaxies by Leroy+11; Bolatto+13)

With metallicities derived from the mass-metallicity z-dependent relation:

$\alpha_{\rm CO}^{Z}(M_*, z)$	increases with z for any given M_* and at any given z, increases with decreasing M_*



MACSJ0032-arc

12+log(O/H)	7.9
$\alpha^{Z}_{\rm CO}$ $(M_\odot/({\rm K\ km/s\ pc^2}))$	39

CO-detected SFGs from the literature

$\alpha^{Z}_{\rm CO}$ less extreme: lower z/higher M_*

$M_{\rm molgas}$ = 9.60E+10 $M_\odot$ → $\Sigma_{\rm molgas}$ > 2.40E+4 $M_\odot/{\rm pc}^2$

while $\Sigma_{\rm molgas}$ ~ 200 $M_\odot/{\rm pc}^2$ in MW GMCs

and $\Sigma_{\rm molgas}$ ~ 1.00E+4 $M_\odot/{\rm pc}^2$ in local ULIRG

CO-to-H_2 conversion: Molecular gas mass

Known to vary with metallicity

$$\alpha^{Z}_{CO} = \cancel{\alpha_{CO,MW}} \times \chi(Z)$$

$\alpha_{CO,ULIRG} \simeq 0.8$

with

$$\chi(Z) = 10^{-1.27(12+\log(O/H)_{PP04}-8.67)}$$

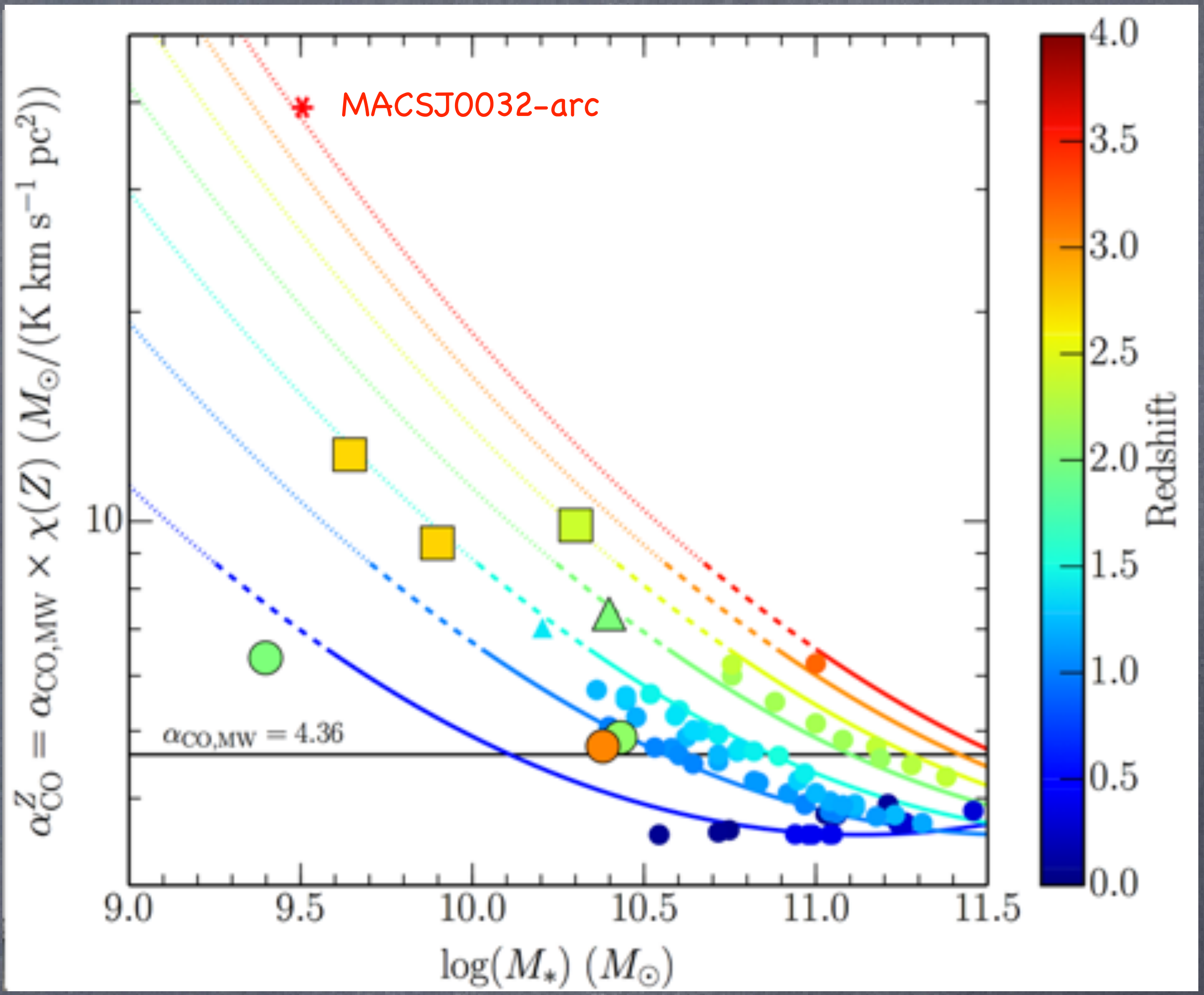
(calibrated on local galaxies by Leroy+11; Bolatto+13)

Can be derived from dust mass

$$\alpha^{dust}_{CO} = \frac{1}{\delta_{DGR}} \times \frac{M_{dust}}{L'_{CO(1-0)}}$$

Magdis+11

with a metallicity-dependent dust-to-gas mass ratio (calibrated on local galaxies by Leroy+11)



MACSJ0032-arc

12+log(O/H)	7.9
α^{Z}_{CO} $(M_\odot/(K\ km/s\ pc^2))$	~~39~~ 7
α^{dust}_{CO} $(M_\odot/(K\ km/s\ pc^2))$	3.4
α_{CO} $(M_\odot/(K\ km/s\ pc^2))$	0.7

How to reconcile α^{Z}_{CO} with α^{dust}_{CO}?

— errors on $L'_{CO(1-0)}$ and M_{dust} insufficient

☑ when high CO excitation is accounted for

> equality solved for $Z \approx Z_\odot$ and $\alpha_{CO} = 0.7$

(acceptable for an error on M_* by a factor of 2-3)

Conclusions

Highest redshifted main sequence SFG (z=3.63)
with measured stellar, dust, and molecular gas properties

- M_{molgas} and star formation spatially decoupled from UV
- ~90% of the total SFR seen through thermal FIR dust emission and radio synchrotron radiation, undetected in UV because of obscuration by dust
- High-J CO transitions excited to J≤6: SLED resembling that of high-z SMGs
- High CO gas excitation due to the galaxy's compactness (not mandatorily to a merger)
  → possible trend for galaxies at higher z to be more compact
- CO excitation to be considered in the estimate of the CO-to-H_2 conversion factor
- $t_{depl}(z)$, but at a lesser degree than predicted
- Confirmed continued $f_{molgas}(z)$ increase, despite a plateau between z~1.5-2.5