Morphology and Kinematics of Molecular Gas in the Double-barred Galaxy NGC 3504

Yu-Ting Wu[1], Alfonso Trejo[2], Daniel Espada[3] and Yusuke Miyamoto[1]

[1]National Astronomical Observatory of Japan, Mitaka, Tokyo, Japan

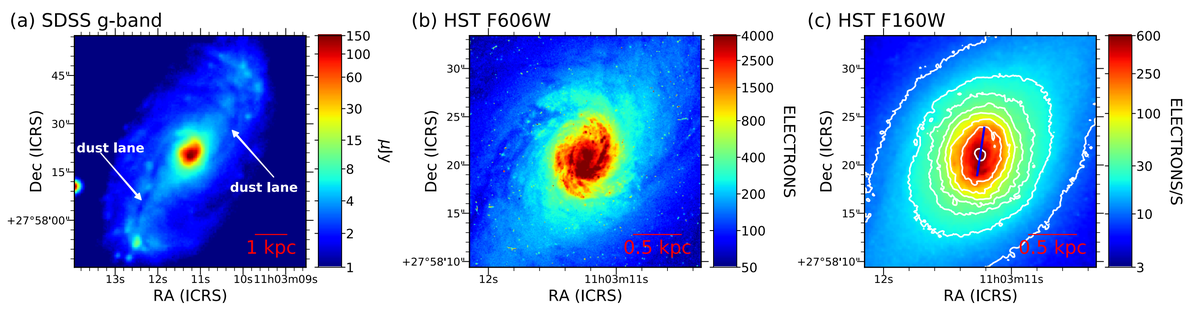
[2]Institute of Astronomy and Astrophysics, Academia Sinica, Taipei, Taiwan

[3]SKA Organisation, Macclesfield, Cheshire, UK

Abstract

About one-third of barred galaxies have an inner secondary bar embedded within an outer primary bar (Laine et al. 2002; Erwin & Sparke 2002). They are so called double-barred galaxies. The investigation of inner bars is especially important as they can drive gas inflow to the nucleus of galaxies (Kormendy 1982; Shlosman, Frank & Begelman 1989). Here we present the results of ALMA CO (2-1) observation of the double-barred galaxy NGC 3504. With three times higher angular resolution (~0.8") than previous works, our observations reveal an inner molecular gas bar, a nuclear ring, and four inner spiral arm-like structures in the central 1 kpc region. The total molecular gas mass in the observed region (50"x57") is estimated to be 3.1×10^9 $M_\odot$. We used the Kinemetry package (Krajnović et al. 2006) to fit our velocity field and quantify the contribution of circular rotation as well as non-circular perturbations. Our results give a new example of an inner gas bar within a gas-rich double-barred galaxy and suggest that the formation of double-barred galaxies could be associated with the existence of such gas structures. Based on this study, we are looking for an opportunity to observe double-barred galaxies at high redshifts using new-generation radio telescopes, such as SKA.

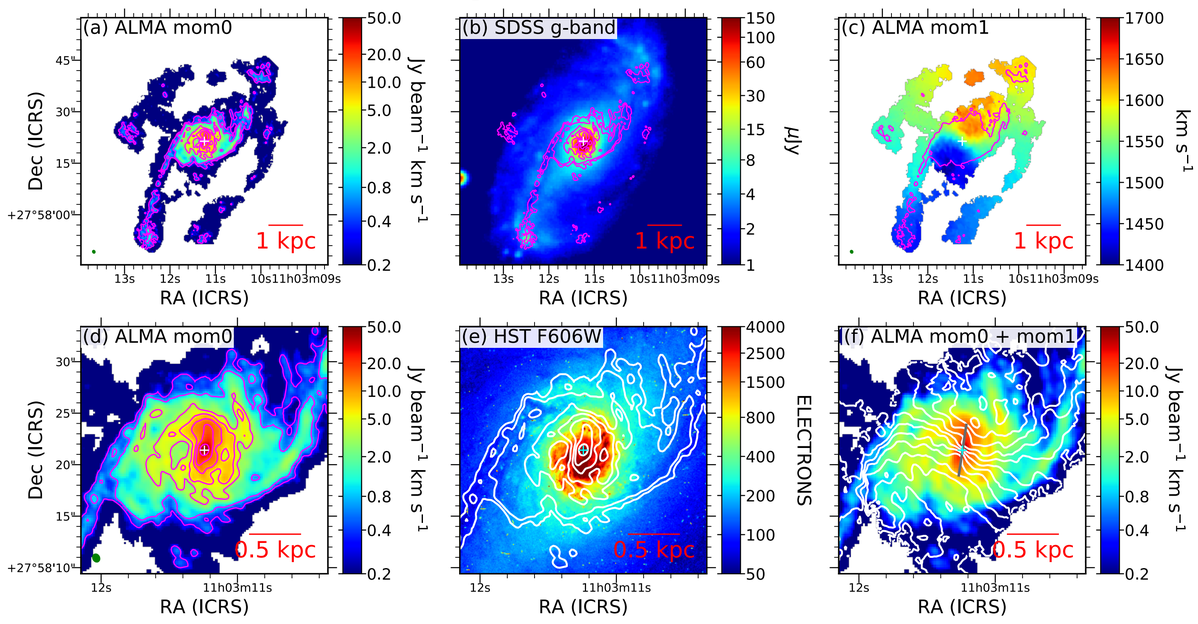
NGC 3504



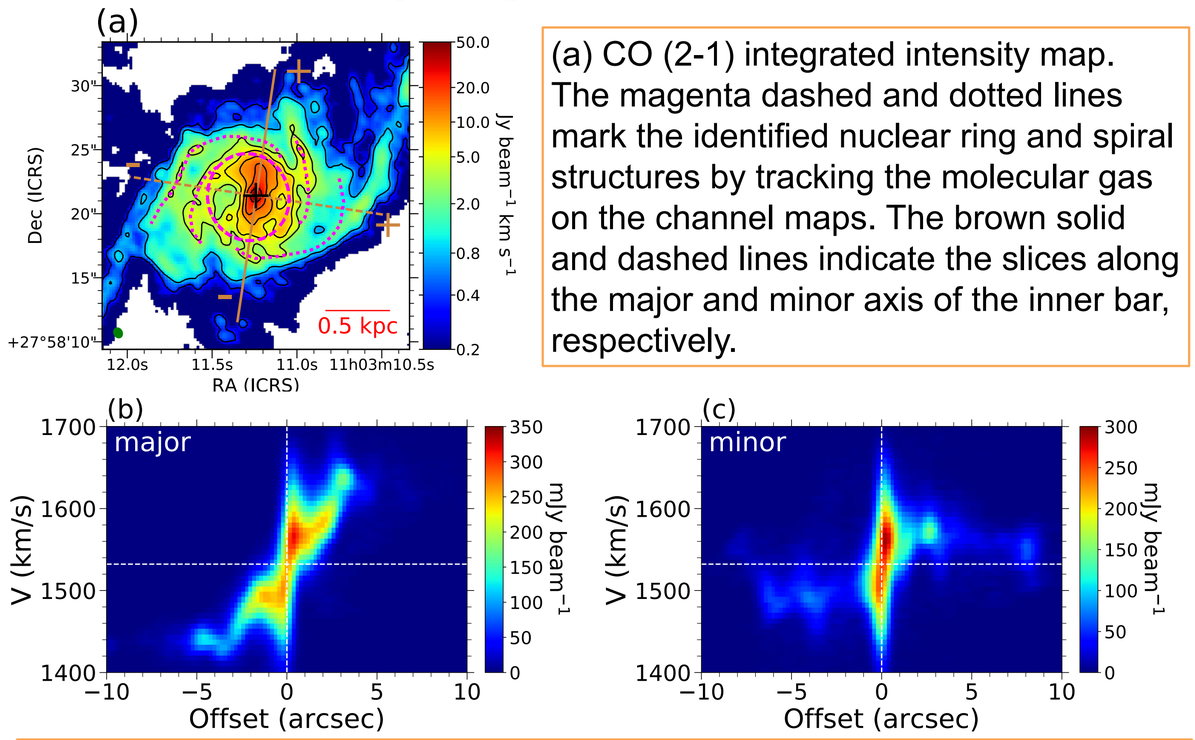
(a) The SDSS g-band image. The white arrows indicate the dust lanes.
(b) The HST/WFPC2 F606W image, showing the central 2.4 kpc region.
(c) The HST/WFC3 F160W image. The contour levels are 10, 20, 30, 40, 60, 100, 200, and 600 electrons/s. The blue line represents the major axis of the inner bar with a length of 5".2 and position angle of 172°.

ALMA Observations

- **CO (2-1) observations were carried out with the 12-m (C43-1 and C43-4) and 7-m arrays (Project code: 2016.1.00650.S, PI: Yu-Ting Wu).**
- **With a robust weighting of 0.5, the achieved beam size is about 0".79 x 0".64 and the rms noise is ~ 1 mJy/beam for the velocity resolution of 6.5 km/s.**
- **Moment 0 and 1 maps**



- **Position-velocity diagram**

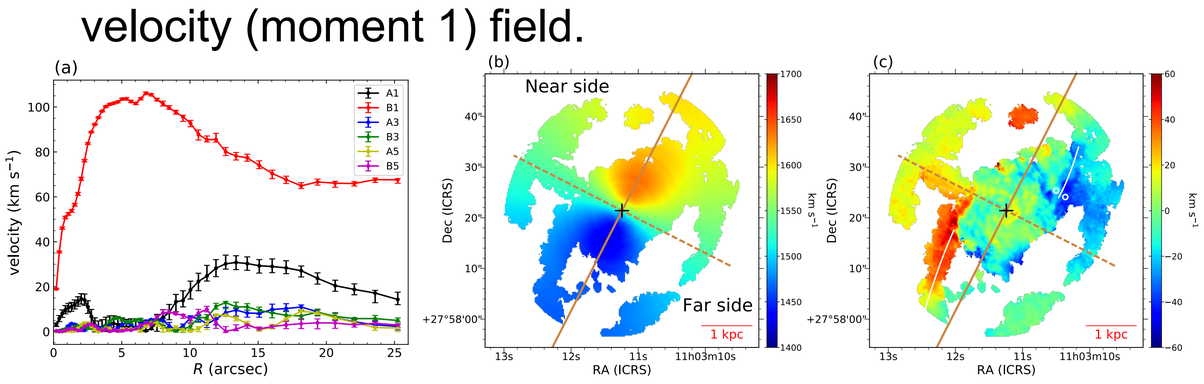


(a) CO (2-1) integrated intensity map. The magenta dashed and dotted lines mark the identified nuclear ring and spiral structures by tracking the molecular gas on the channel maps. The brown solid and dashed lines indicate the slices along the major and minor axis of the inner bar, respectively.

(b) and (c): The position-velocity diagrams along the major and minor axes of the inner bar with a width of the slice of 0".8. The horizontal dashed line is drawn at the system velocity of 1532.2 kms^{-1}.

- **Kinematic Modelling**

  - We used *Kinemetry* (Krajnović et al. 2006) to fit the velocity (moment 1) field.



(a) Coefficients of the Fourier components obtained from the *Kinemetry* analysis as a function of the semi-major axis length of the ellipses.
(b) Modelled velocity field generated by the term $A_0+B_1\cos(\psi)$ derived from *Kinemetry* and then corrected for the inclination and the position angle.
(c) Residual velocity map after subtracting the modelled velocity field from the CO (2-1) velocity field. The white lines indicates the two dust lanes identified on the SDSS g-band image and the two white circles mark the locations where the difference of the residual velocities is ~30 kms^{-1} across the northern dust lane. The brown solid and dashed lines represent the galactic major and minor axes, respectively.

  - Fitting results: a systemic velocity of the galaxy of 1532.2±0.2 kms^{-1}, an inclination angle of 25°±1°, and a position angle of 153°±2°.

Results

- **Both axisymmetric and non-axisymmetric structures, including the inner molecular gas bar, the nuclear ring, and the nuclear spirals, are found in the central 1 kpc region. These inner structures were not recognized in previous publications due to the lack of sufficient angular resolution.**
- **The estimated total molecular mass is about 3.1×10^9 $M_\odot$, corresponding to 17 per cent of the stellar mass.**
- **Circular motion strongly dominates at R = 3"- 8" (0.3 - 0.8 kpc, but radial motion becomes important in the regions where the bars are present, corresponding to R < 3" (0.3 kpc) and R = 10" - 25" (1.0 - 2.5 kpc).**
- **The existence of the inner gas bar and the large amount of gas in NGC 3504 support the scenario for the formation of double-barred galaxies associated with the existence of molecular gas.**

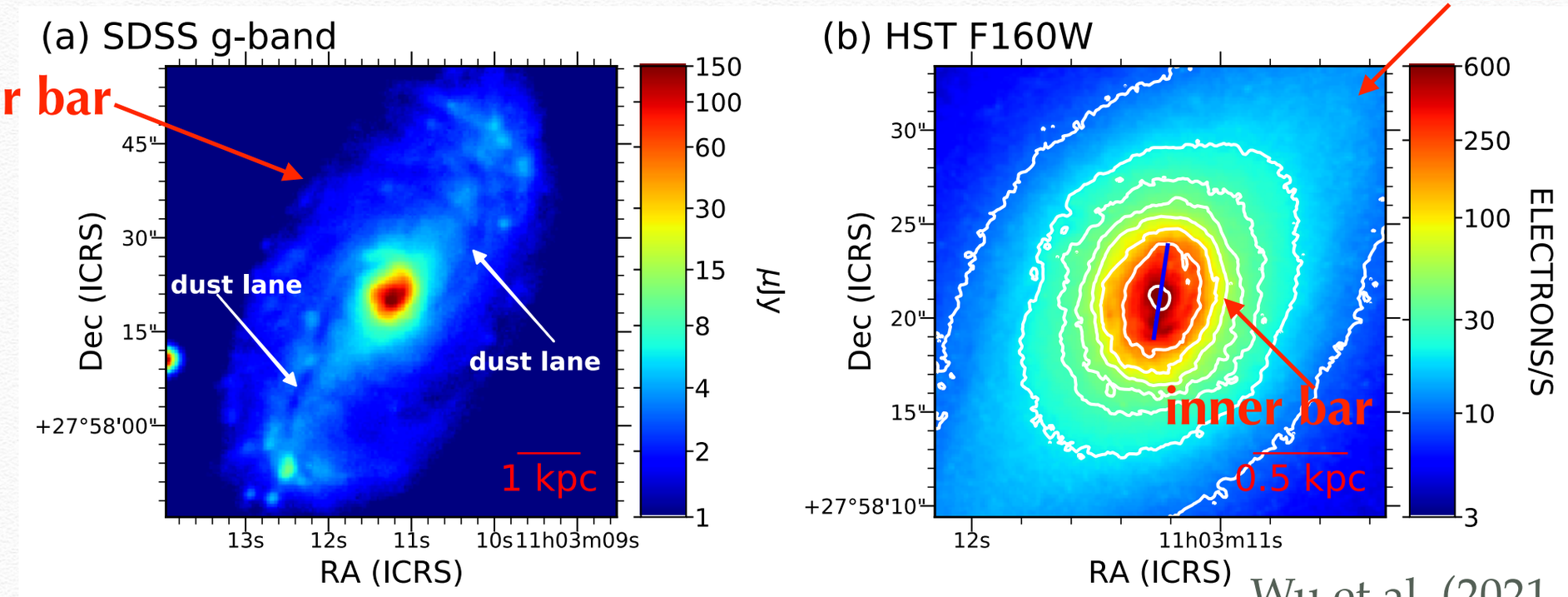
Morphology and Kinematics of Molecular Gas in the Double-barred Galaxy NGC 3504

Yu-Ting Wu (NAOJ)

Alfonso Trejo (ASIAA), Daniel Espada (SKA Organisation) and Yusuke Miyamoto (NAOJ)

What are double-barred galaxies?

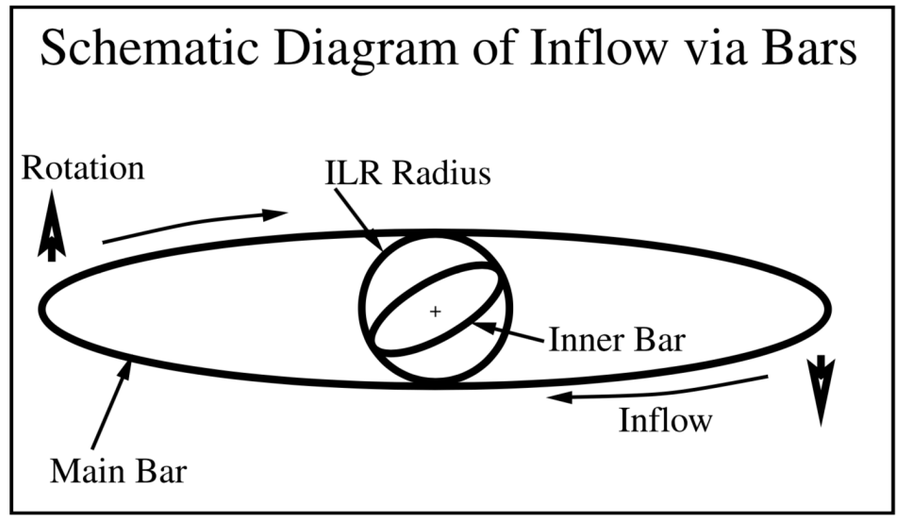
An example of a double-barred galaxy: NGC 3504



Wu et al. (2021, in revision)

Why we care about double-barred galaxies?

- ~ 30% of local barred galaxies are double-barred galaxies (Erwin & Sparke 2002; Laine et al. 2002).
- One of mechanisms to drive gas inflow to the nucleus of galaxies (Kormendy 1982; Shlosman, Frank & Begelman 1989).

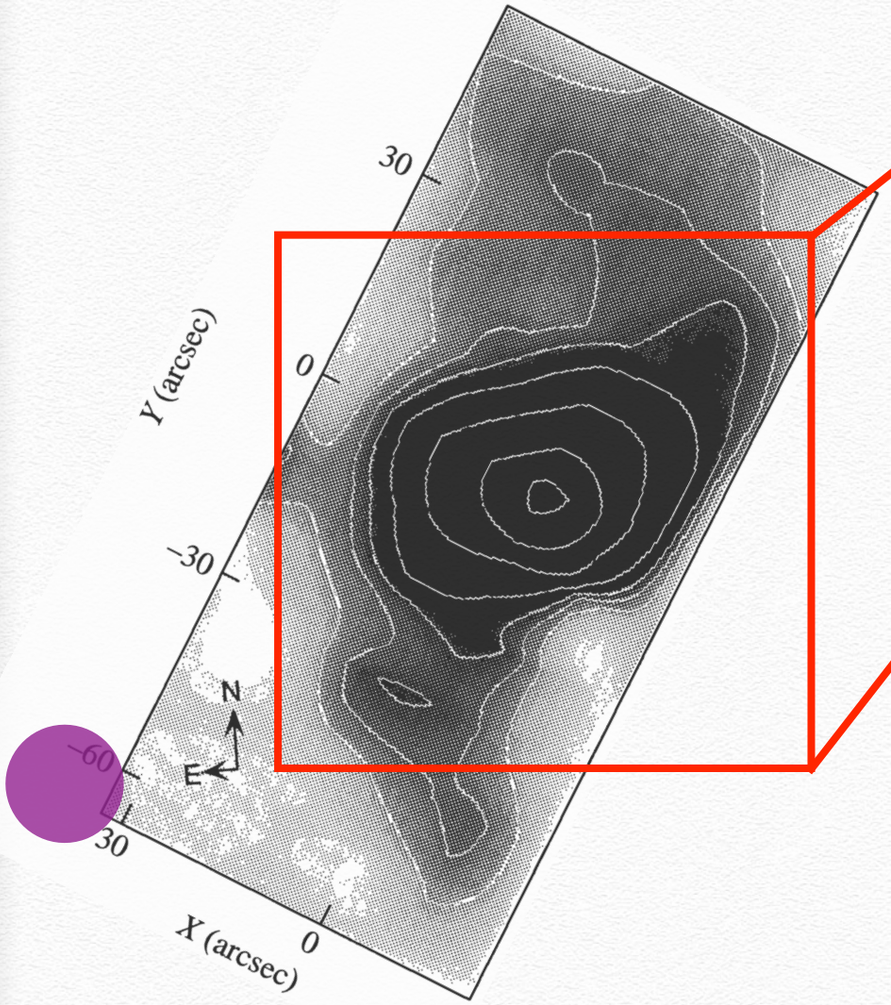


Petitpas and Wilson (2002)

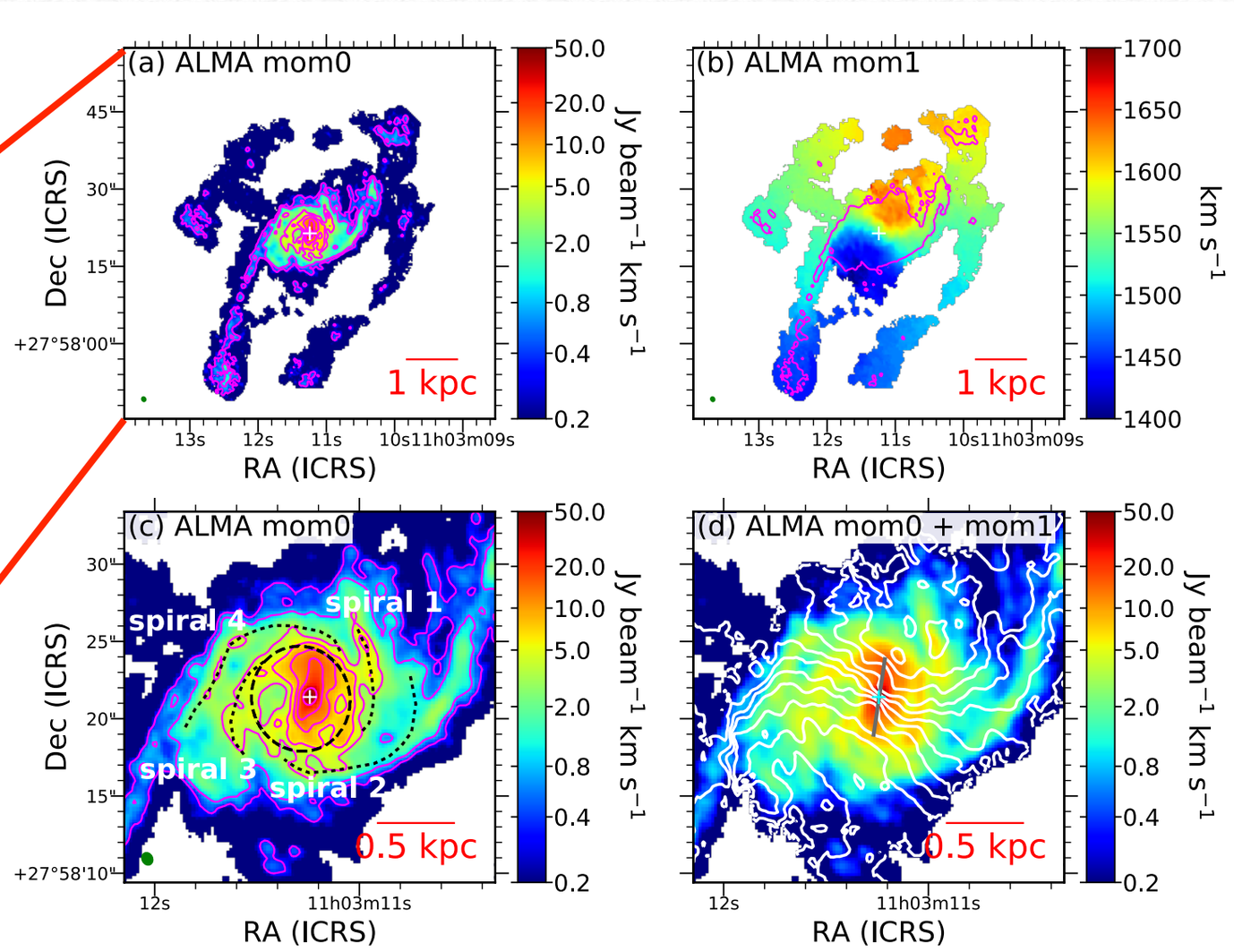
NGC 3504

- 45m telescope at Nobeyama Radio Observatory
- CO (1-0)
- HPBW=16''

- ALMA 12m + 7m
- CO (2-1)
- synthesized beam: 0″.79 x 0″.64 (PA=26 deg)



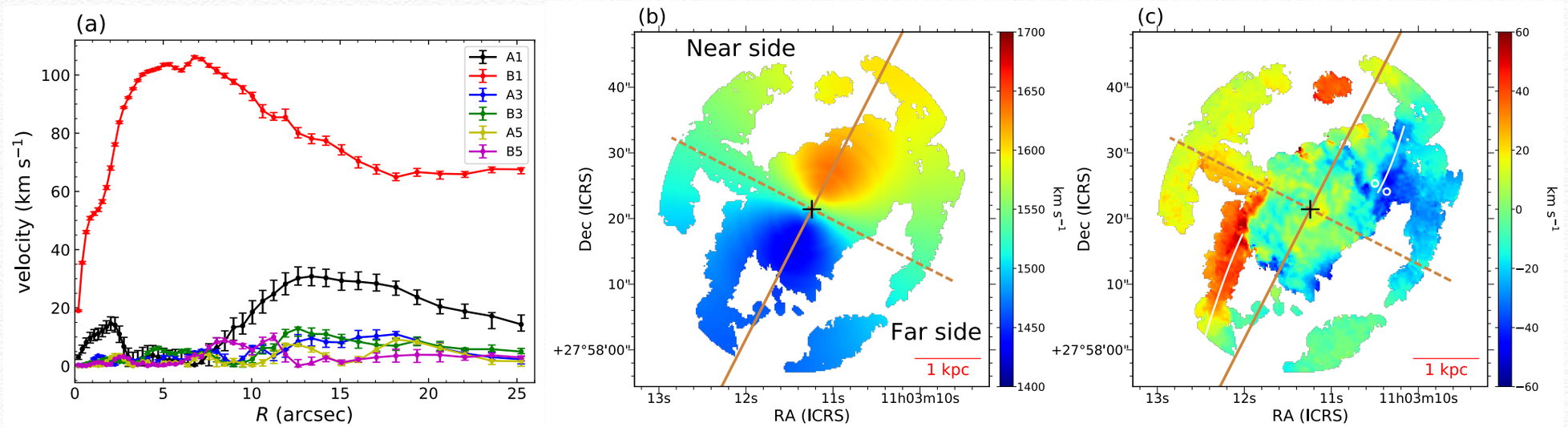
Kuno et al. (2000)



Wu et al. (2021, in revision)

Kinematic modelling

- We used *Kinemetry* (Krajnović et al. 2006) to fit the ALMA CO (2-1) velocity (moment 1) field.



Results

- Both axisymmetric and non-axisymmetric structures, including the inner molecular gas bar, the nuclear ring, and the nuclear spirals, are found in the central 1 kpc region.
- The estimated total molecular mass is about 3.1×10^9 M_{sun}, corresponding to 17 per cent of the stellar mass.
- The existence of the inner gas bar and the large amount of gas in NGC 3504 support the scenario for the formation of double-barred galaxies associated with the existence of molecular gas.