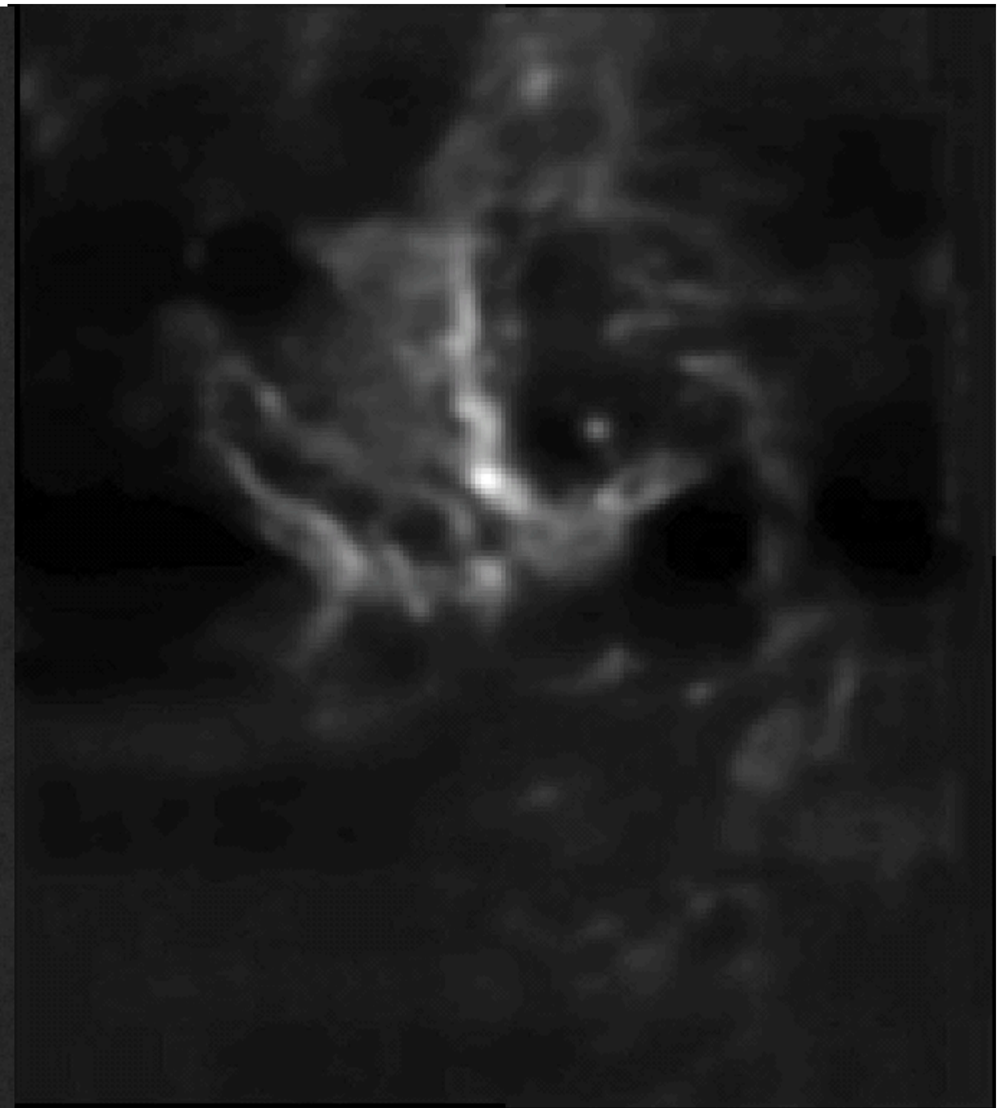
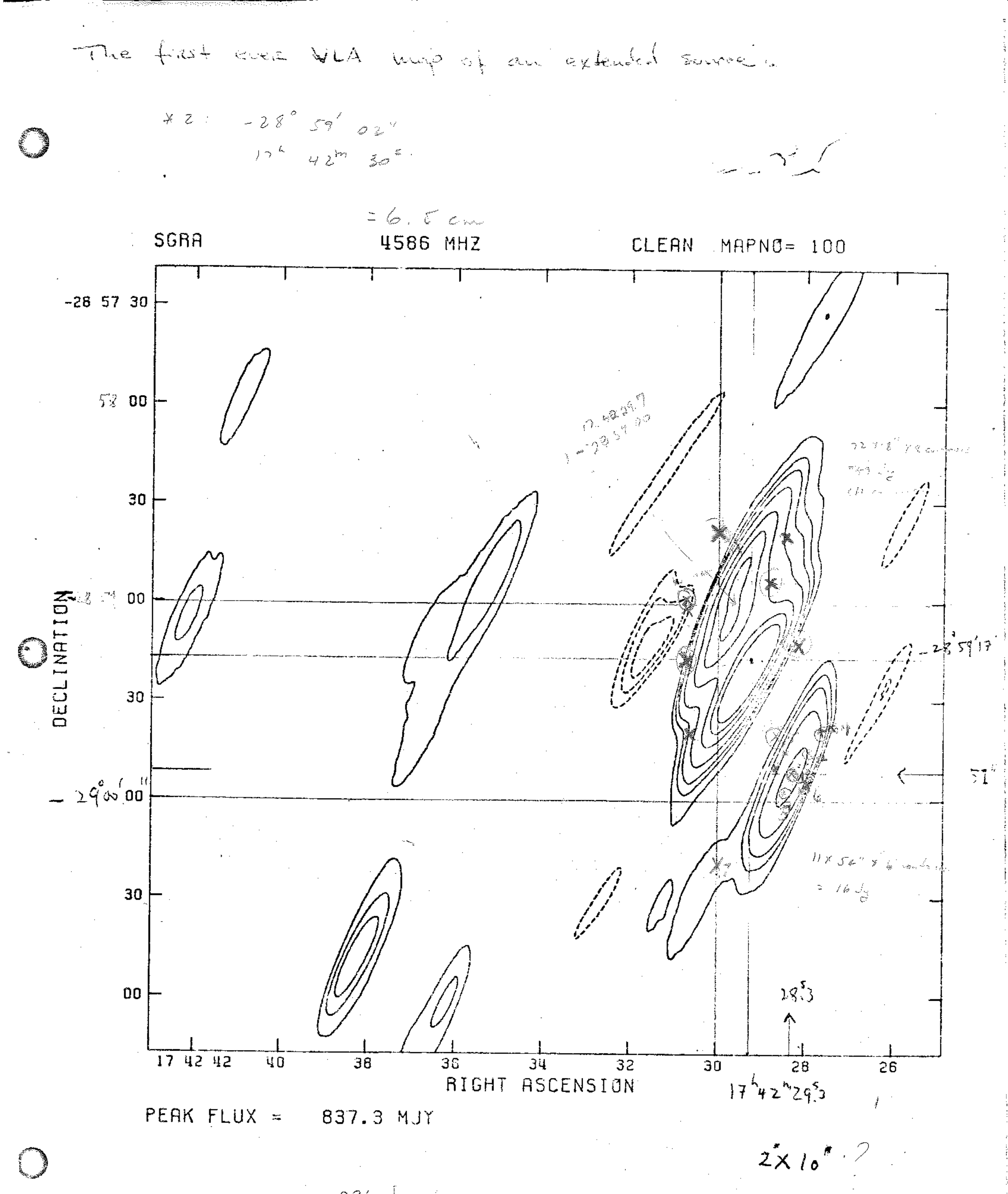
Ionized Gas Dynamics in the Inner 2 pc

John Lacy, Wes Irons, Matt Richter



VLA 6cm map ca. 1977? credit?

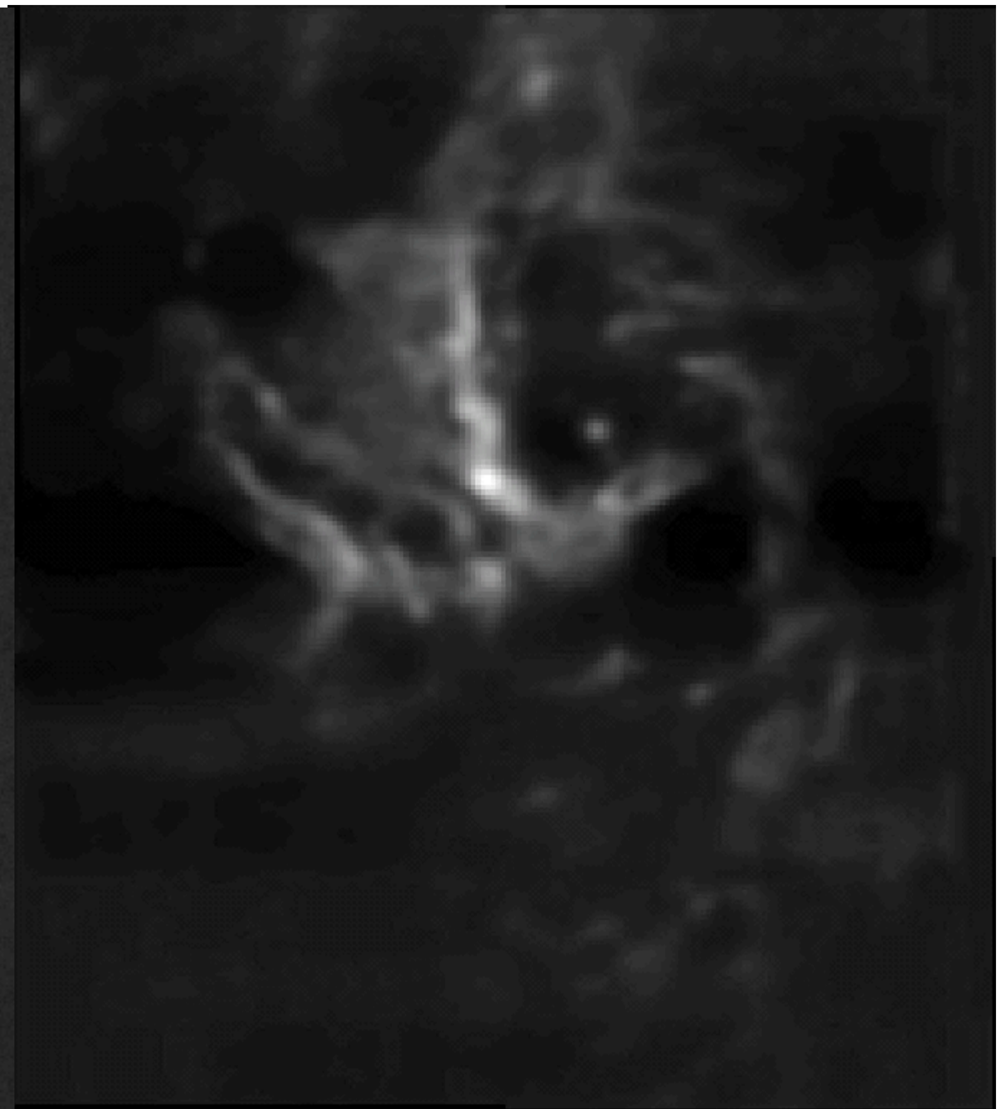


[Ne II] and HI ionized gas kinematics

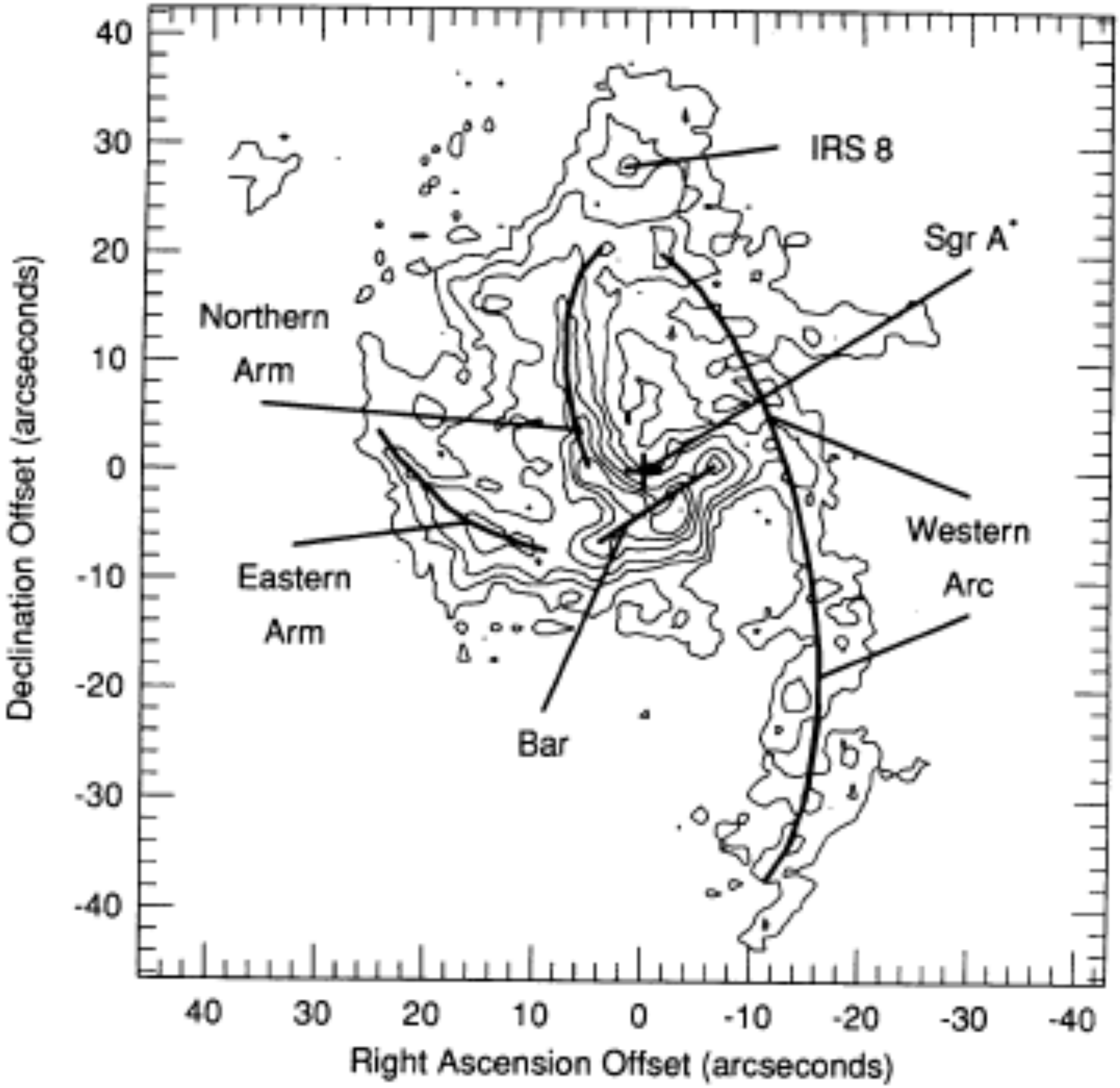
Wollman + 1977	spectra showing high velocities	
Lacy + 1980	grid of spectra	independent clouds
Serabyn + 1985	spectra along N, W arms	infalling streamers
Lacy + 1991	data cube	spiral pattern
Irons + 2012	higher resolution cube	spiral wave
Roberts + 1993	H92α data cube	
Paumard + 2004	Br γ integral field grid	sheets or bundles of orbits
Zhao + 2009	H92α and proper motions	elliptical orbits
Zhao + 2010	H30α	Keplerian orbits

3.6 cm ff
Roberts + 1993

[Ne II]
Irons + 2012

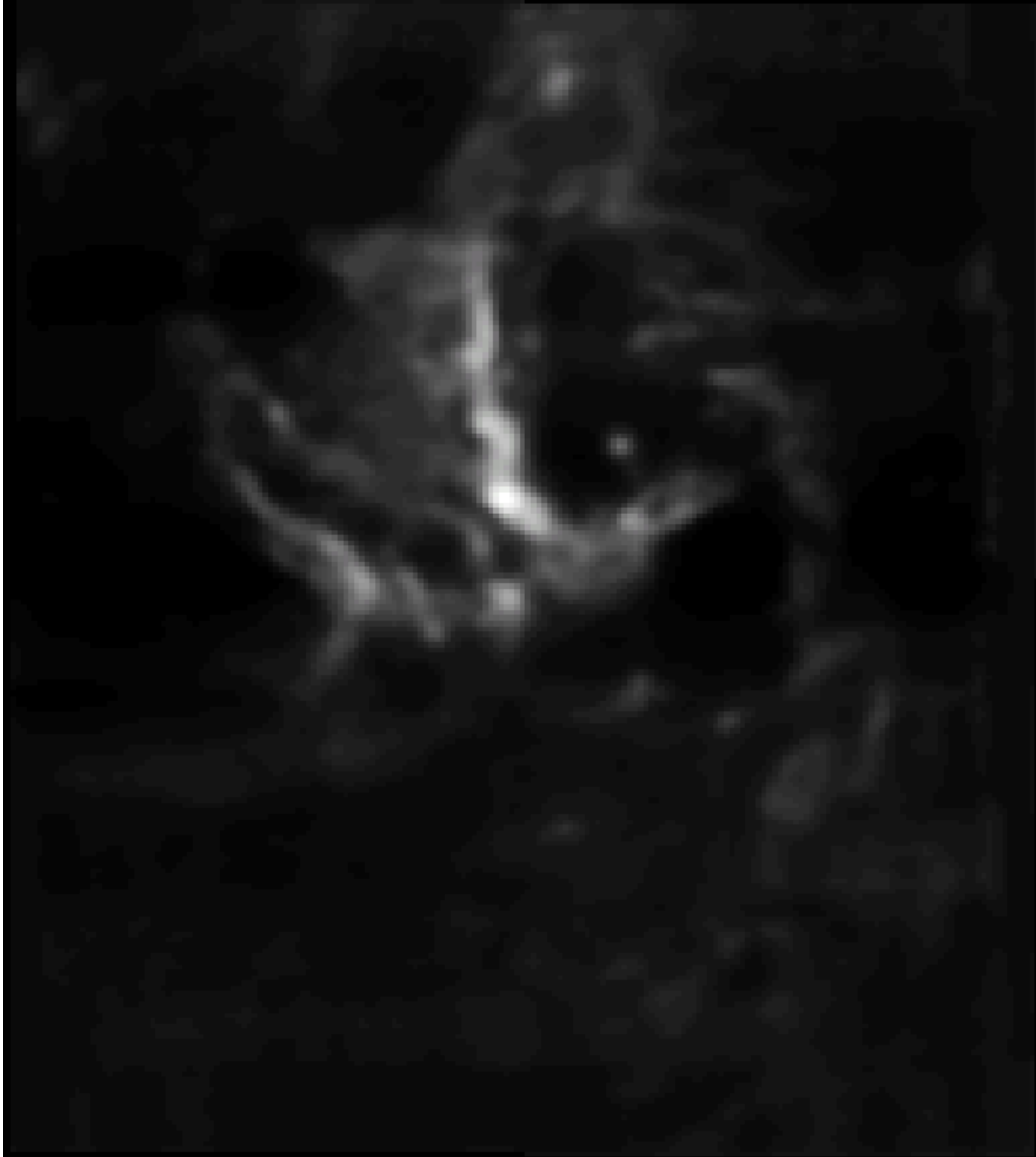


Nomenclature on [Ne II] map



TEXES observations
Irons et al. 2012

Map [Ne II] emission
- central 3 pc of Sgr A
- 4 km/s, 1" resolution
- covering +/- 400 km/s



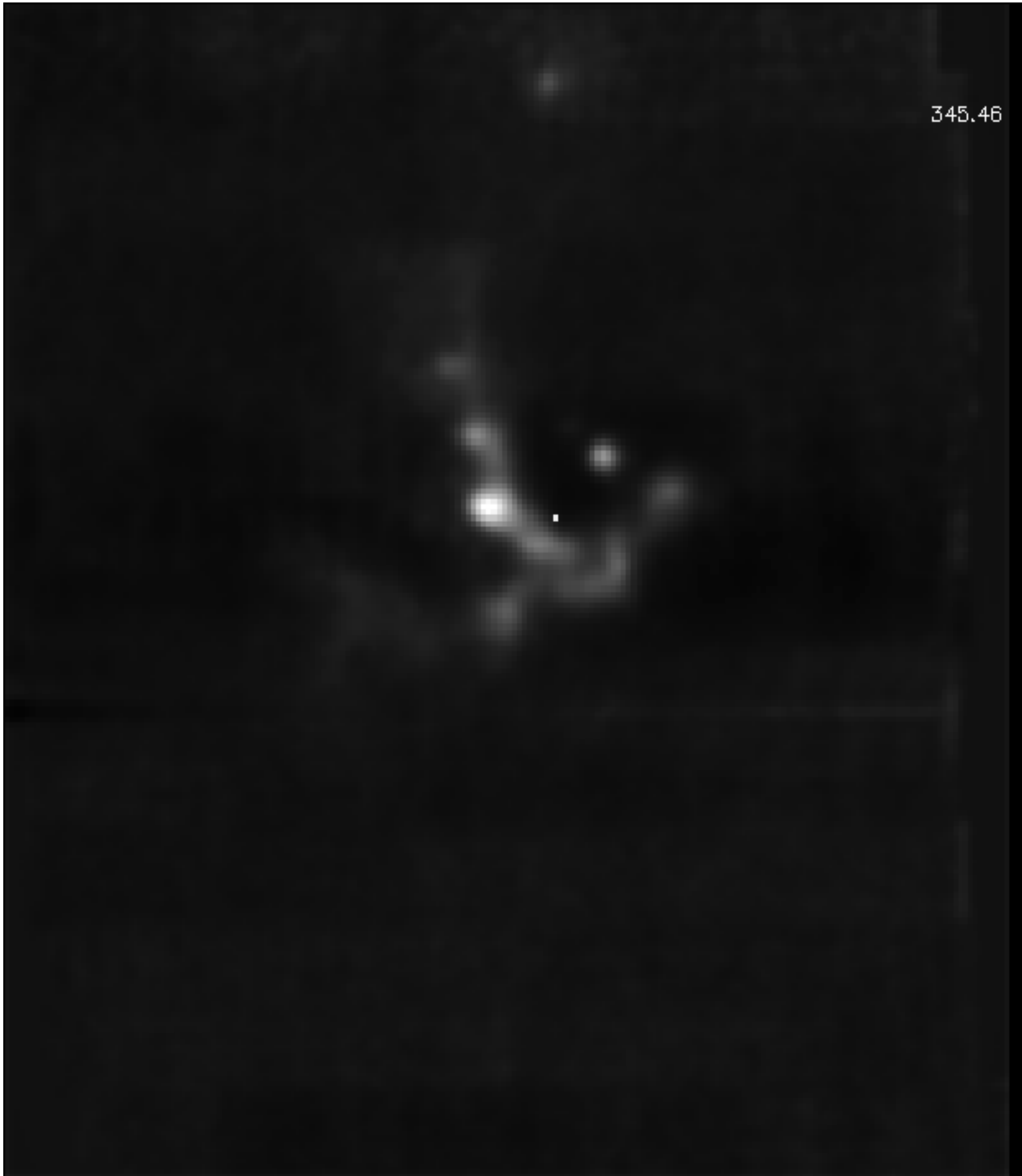
TEXES observations
Irons et al. 2012

Map [Ne II] emission

- central 3 pc of Sgr A
- 4 km/s, 1” resolution
- covering +/- 400 km/s

Download from ApJ

(Irons et al. erratum)



Kinematic Models

Concentrate on two models for Northern Arm and Western Arc:

Elliptical orbit or tidally stretched cloud model

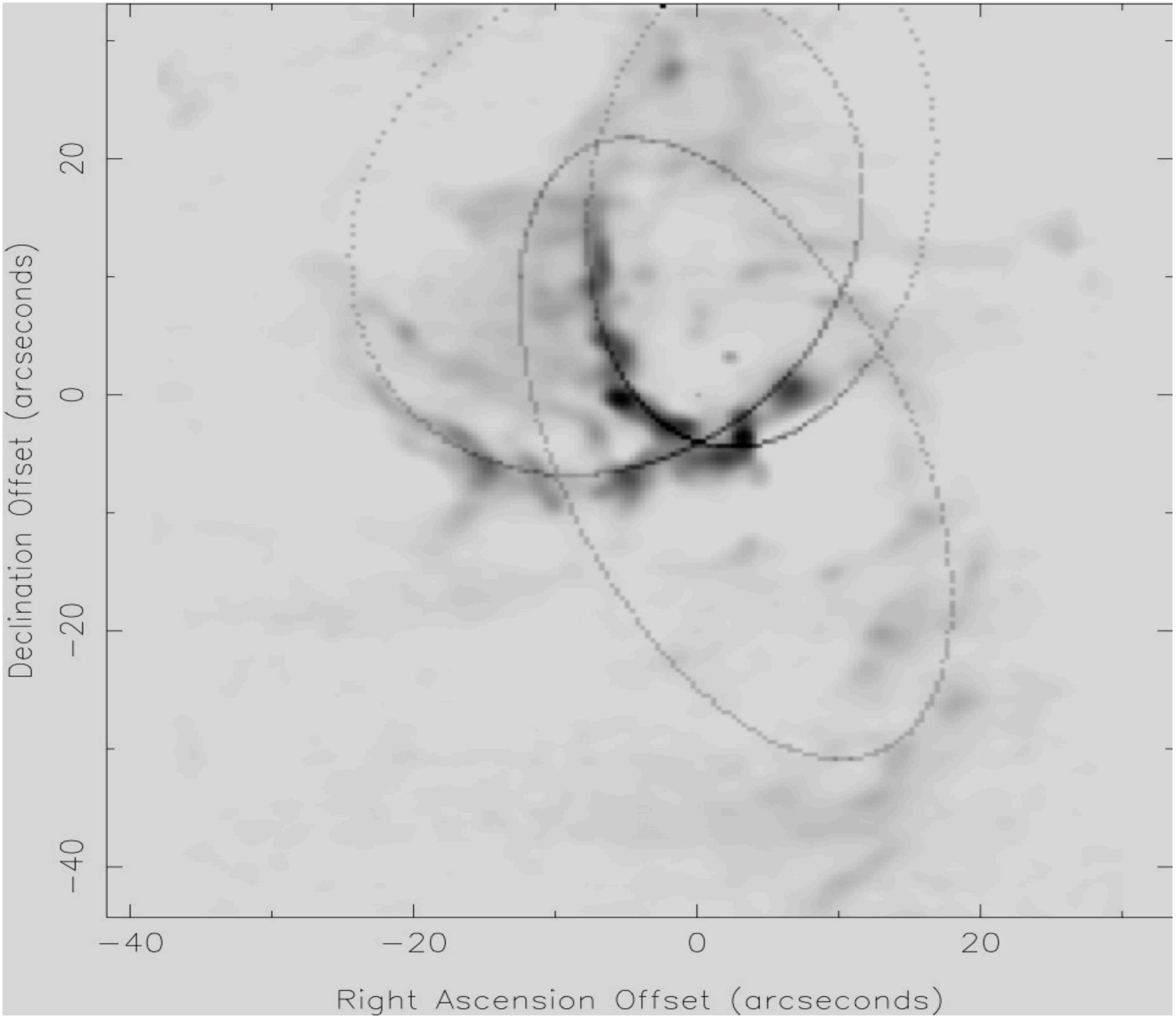
- Serabyn et al.
- Zhao et al.

Circular orbit or spiral wave model

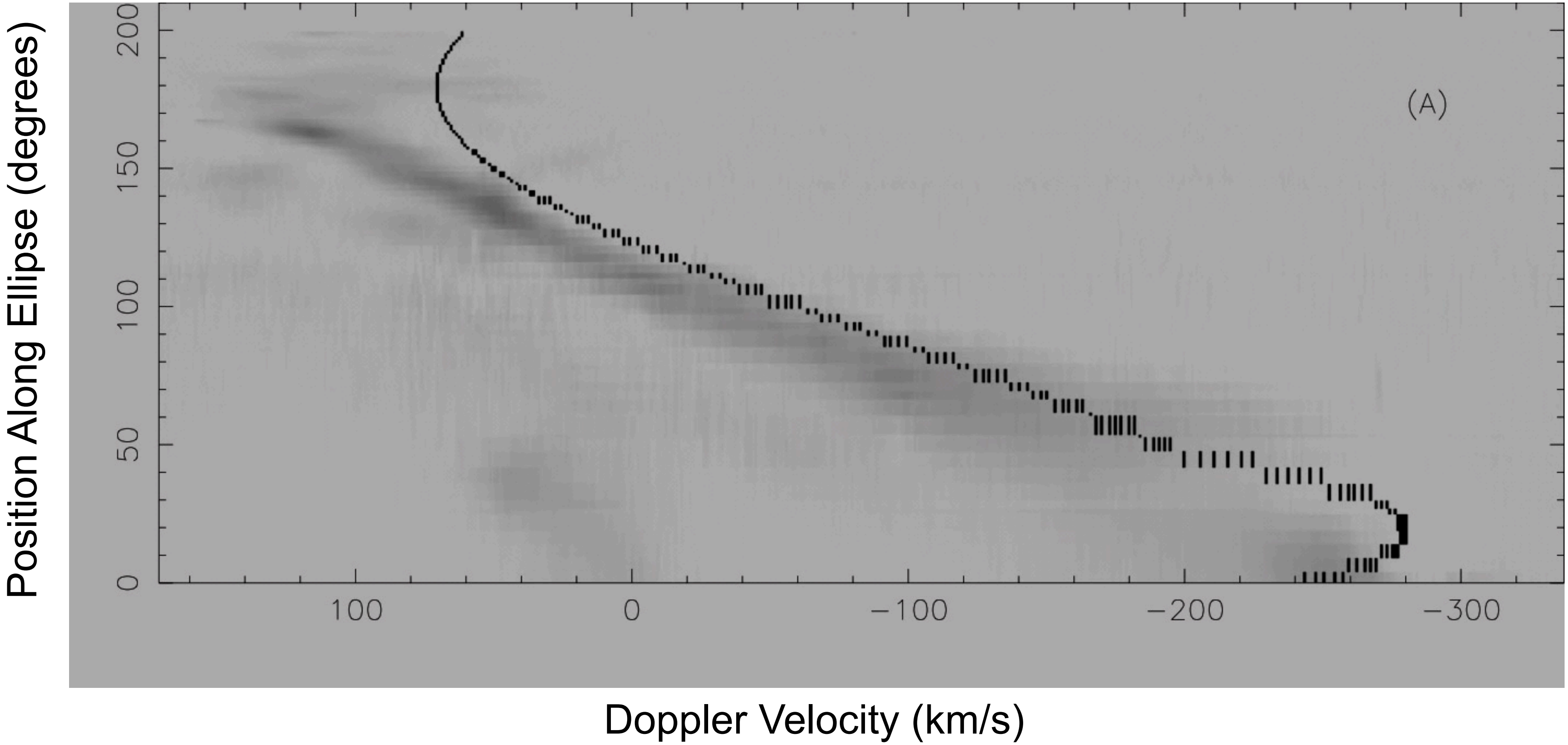
- Lacy et al.
- Irons et al.

Both conclude that this gas is in the same plane as the molecular CND.

Zhao et al. ellipse model on [Ne II] image



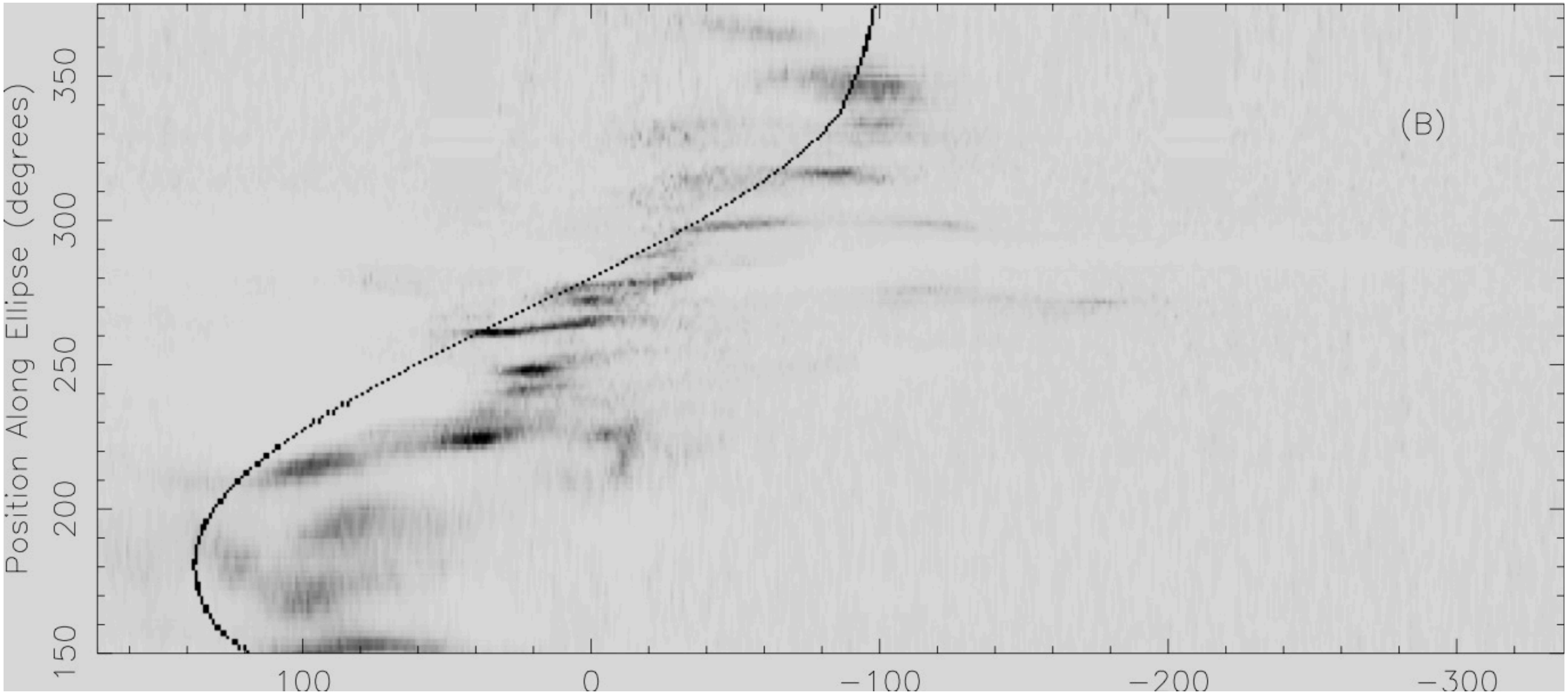
Northern Arm Ellipse Position-Velocity Diagram



Model is systematically offset from the data

-Suggests velocity vectors tipped relative to ellipse

Western Arc Ellipse Position-Velocity Diagram

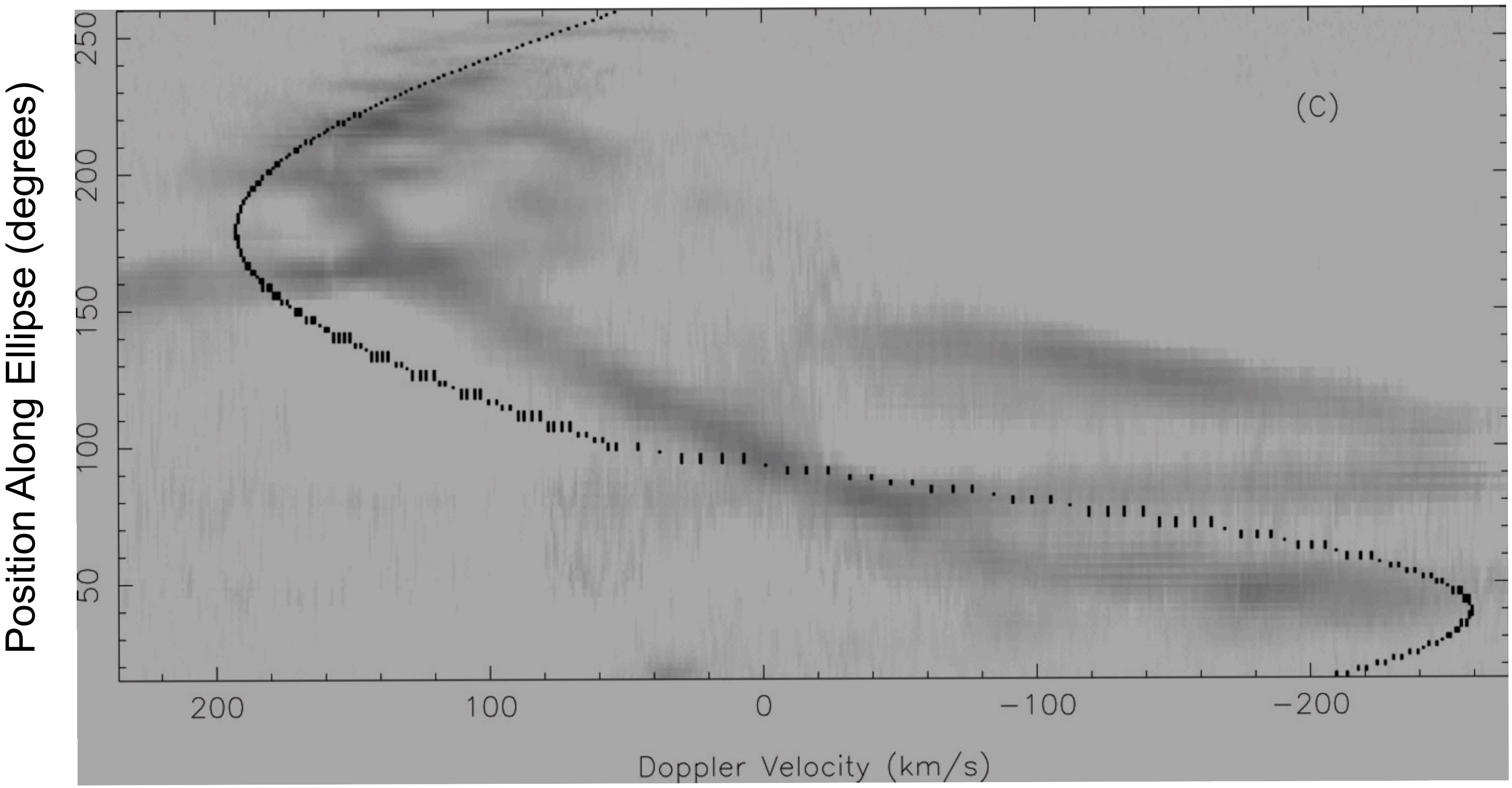


Doppler Velocity (km/s)

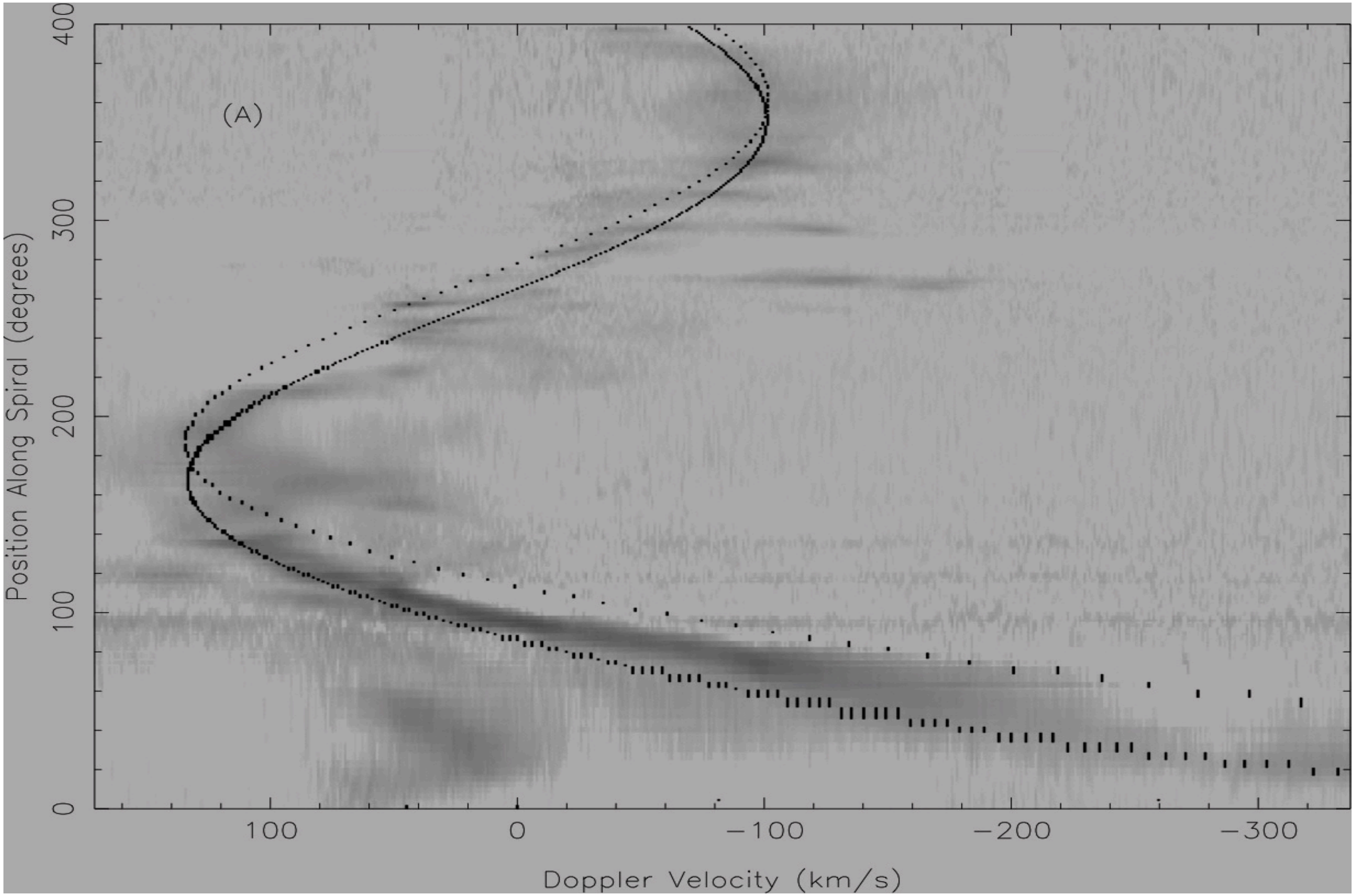
Model is systematically offset from the data

-Suggests velocity vectors tipped relative to ellipse

Eastern Arm Ellipse Position-Velocity Diagram



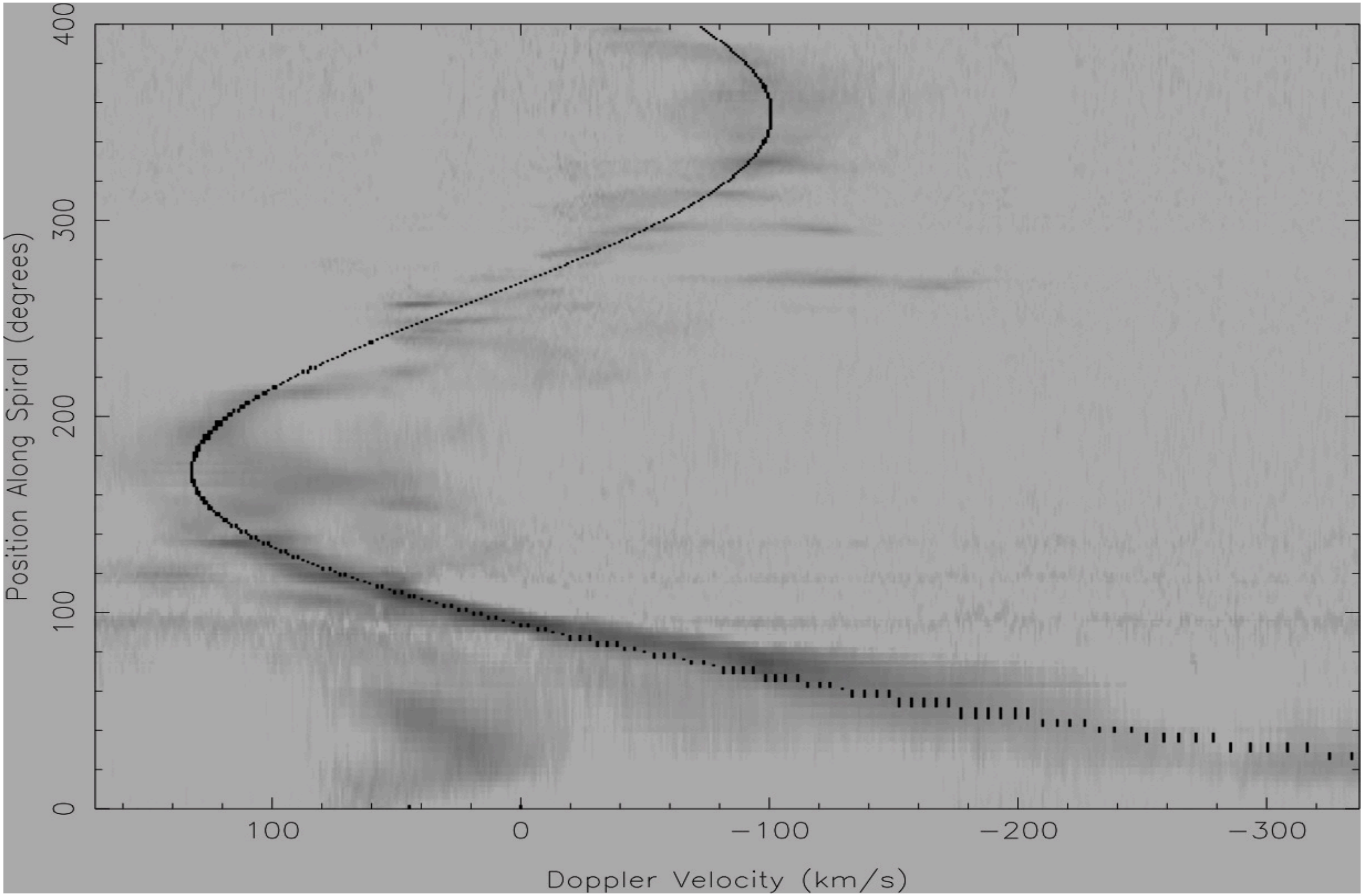
Spiral Position-Velocity Diagram



Top model: motion along spiral

Bottom model: purely circular motion

Spiral Position-Velocity Diagram



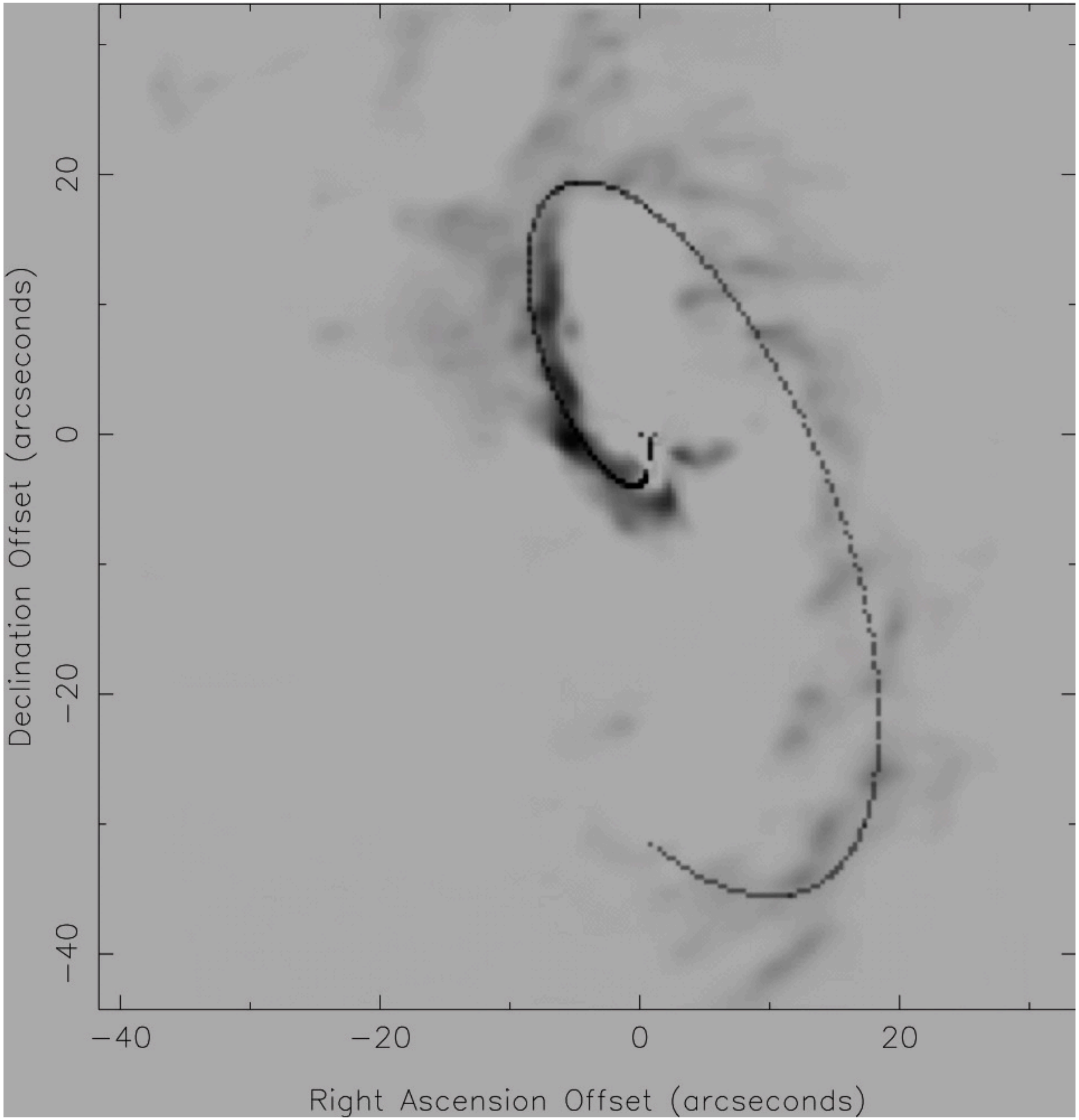
With small inward radial component, a = -0.06

[Ne II] emission that fits within 30km/s

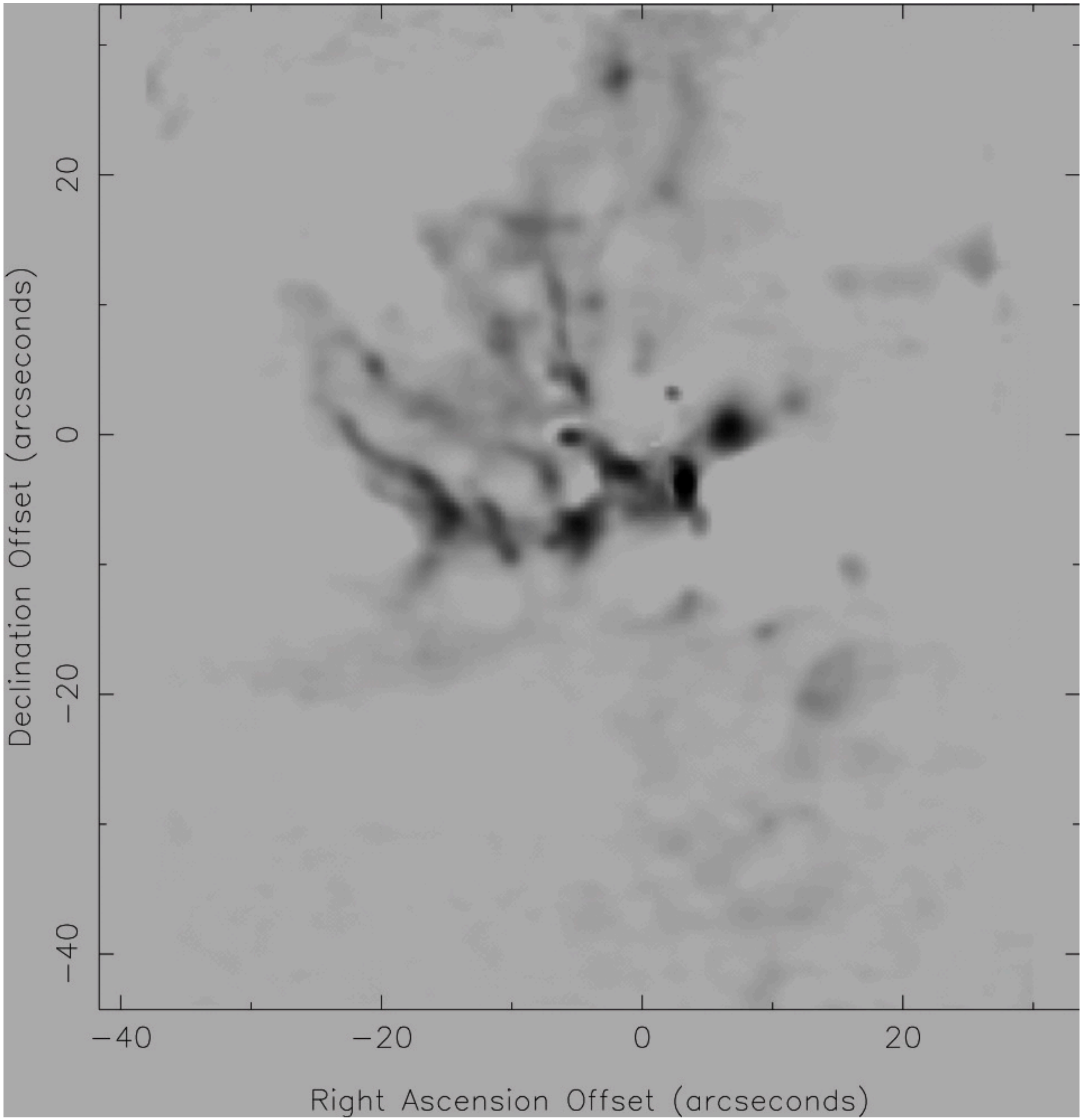
For best fit:
i = 66 degrees
Ω = 23 degrees
M_{bh} = 3.5E+06 M_{sun}
$\rho_\circ$ = 0.25E+06 M_{sun} pc^{-3}
R_c = 0.5 pc
a = -0.06 pc

*45% of emission fits within 10% of the velocity range

Nearly linear spiral:
$r(\theta) = 0.27\text{pc}\ \theta^{0.93}$



Emission that does not fit within 30 km/s



Conclusions from observations

About half of ionic line emission is from gas in plane of CND (~30^{o} from Galactic plane).

Gas in plane moves on nearly circular orbits. It does not move along the northern arm and western arc streamers.

Orbital speeds are close to those expected in potential of black hole + star cluster, but maybe somewhat low.

Ellipse model fits spatial pattern acceptably, but spiral fits better.

Eastern arm region is not well fitted by elliptical or circular motions.

Is there a physical explanation for the spiral?

Density Wave?

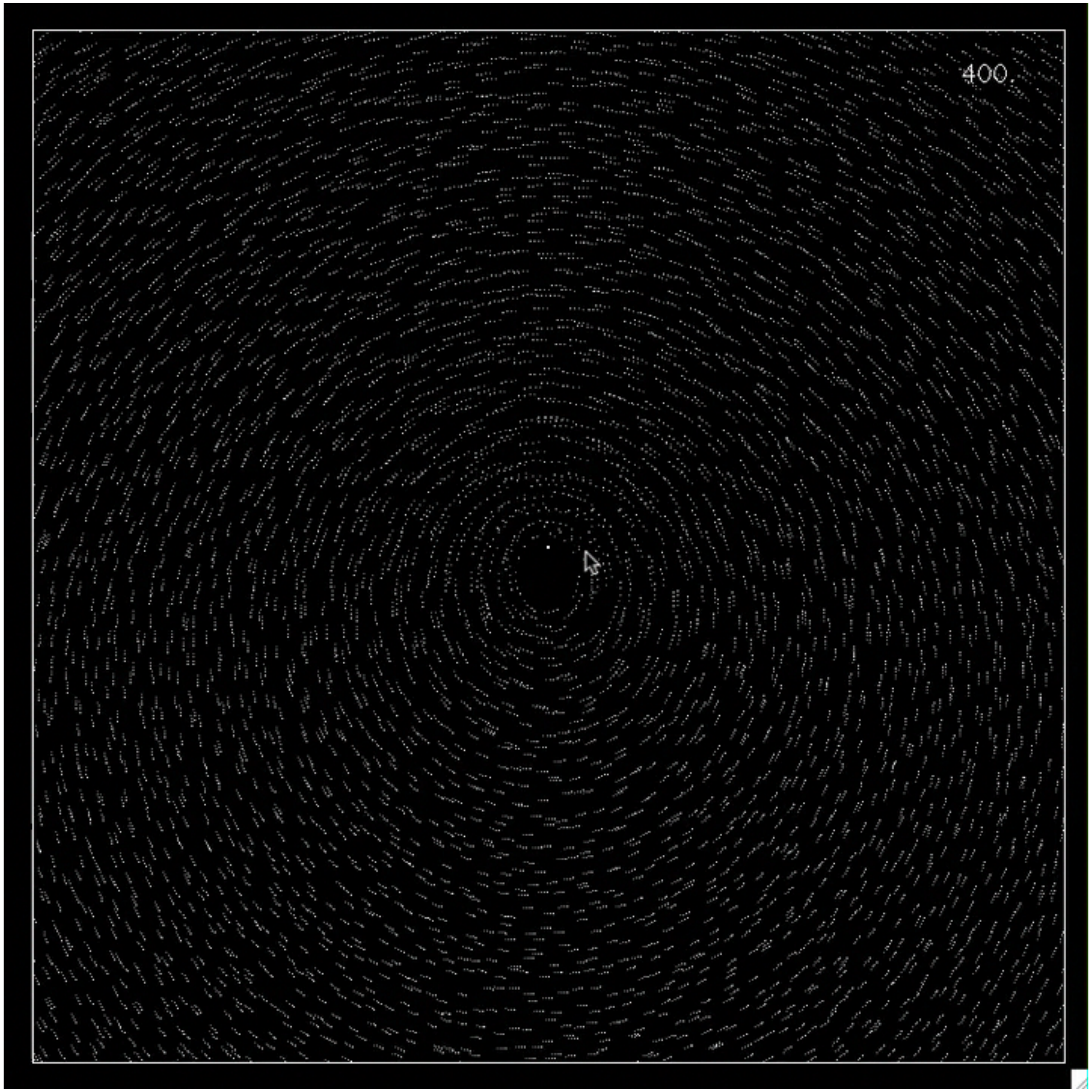
One-armed spiral expected in Keplerian disk

- Toomre Q >> 1 for ionized and atomic gas
- Maybe Q ~ 1 for molecular gas in CND
- Q ~ 1 for stars, but not in a disk
- Non-gravitational perturbations?
  - Magnetic fields ~ mG

Contrast too high?

- Northern arm ~ 100 times brighter than just to west
- Requires density contrast ~10
- Possible with shock compression
  - but gas would have to slow by ~10
- How much can orbit crowding contribute?

Density wave model and [Ne II] emission



Conclusions

Much of the ionized gas in the Galactic center moves on nearly circular orbits and is organized into a one-armed spiral pattern.

(I don't have an explanation for the eastern arm or bar.)

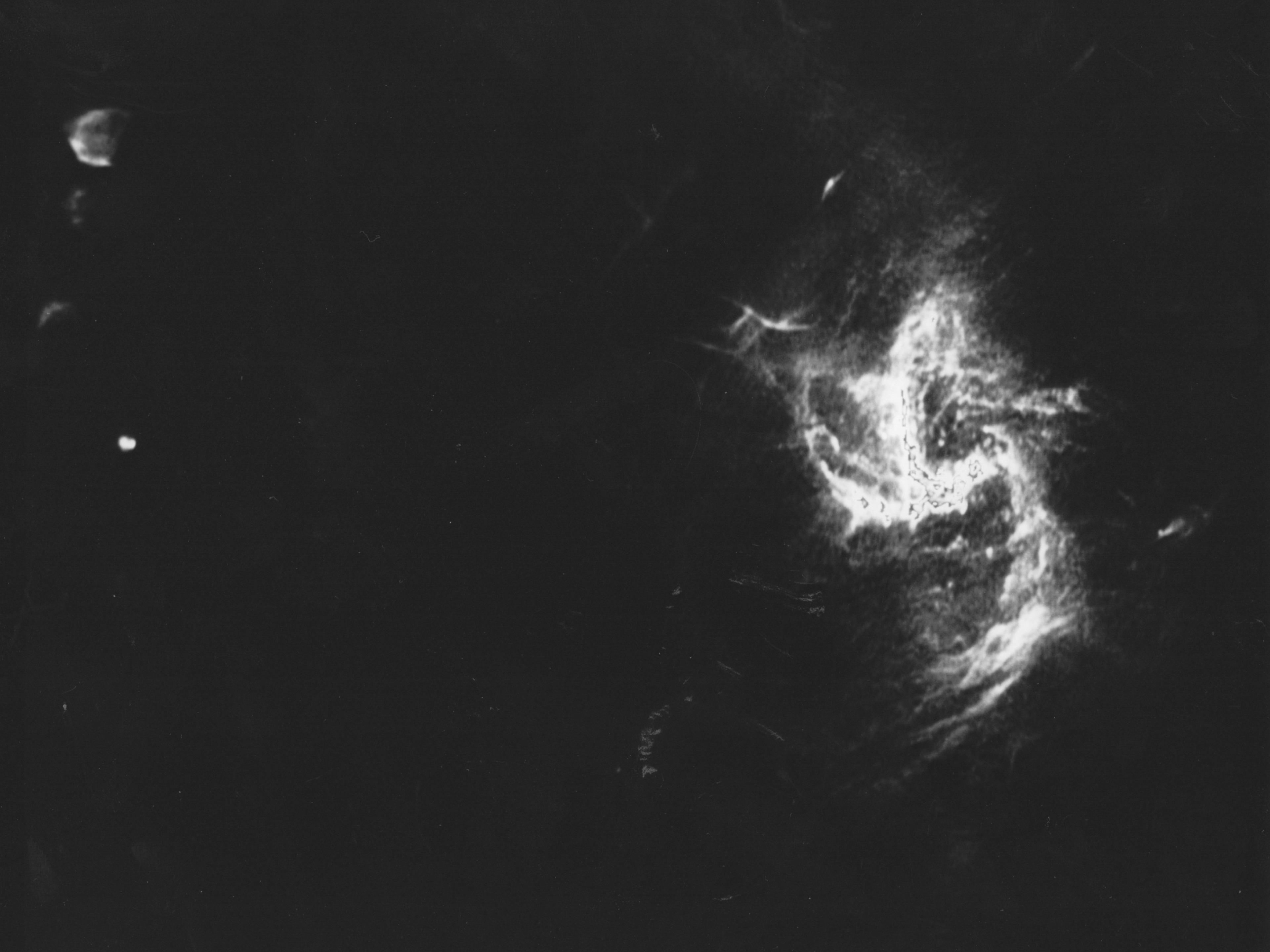
A one-armed spiral is the expected density wave in a potential dominated by a point mass, and the motions expected in such a density wave are consistent with the observed motions.

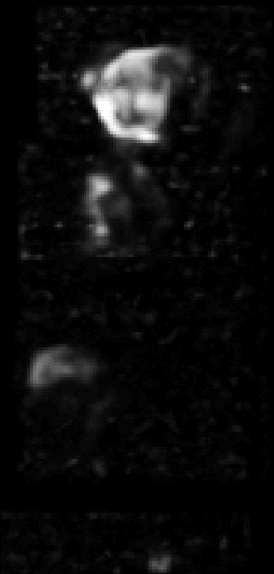
Because gas flows through the wave just past apocenter, velocities less than circular Keplerian, with a small inward component, are expected.

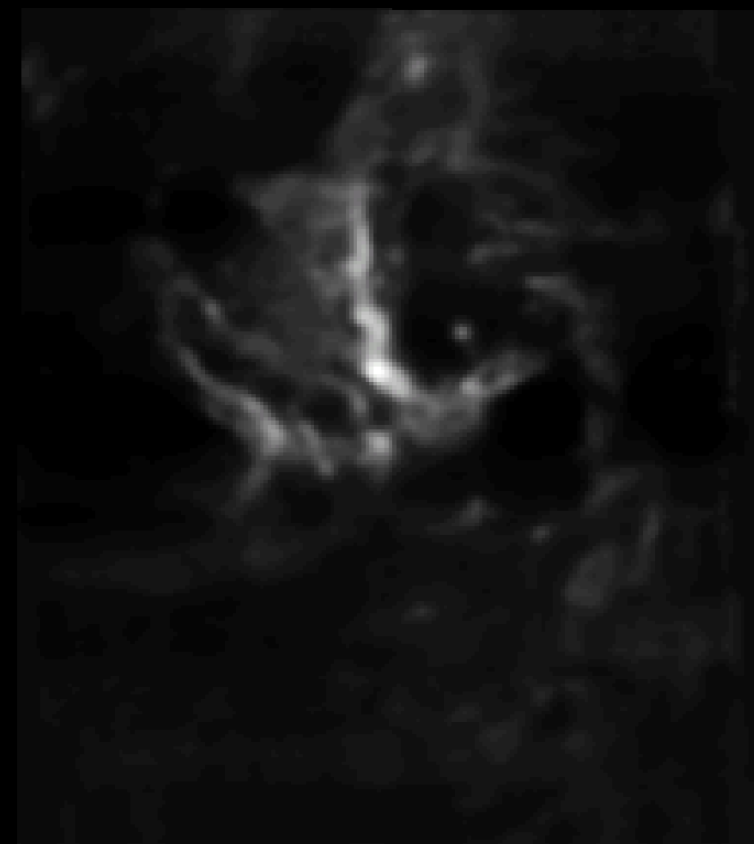
Such a density wave should persist over the precession timescale (few x 10^5 yr), rather than the orbital timescale (few x 10^3 yr).

Inflow rate < 10^{-3} M_o yr^{-1}.

This may be greater than the current accretion rate. Probably much of the inflowing gas is expelled. Is the eastern arm outflowing?







Fitting Routine

- Use the discrepencies in the ellipse model as motivation to reevaluate circular orbit model of Lacy et al. (1991)

- Search through parameter space to fit the most emission on circular velocities
  - Free parameters: Angles defining a plane, mass distribution, inward radial component

$$\rho(r) \approx \rho_\circ\left(\frac{R_c^2}{r^2 + R_c^2}\right)$$

$$M_*(r) \approx 4\pi \rho_\circ R_c^2 \left(r - R_c \arctan\left(\frac{r}{R_c}\right)\right)$$

    - Inward radial component: the fraction (a/r) of the angular component (gravitational)
    - Allows gas to flow along spiral $r(\theta) = a\theta$(rad)

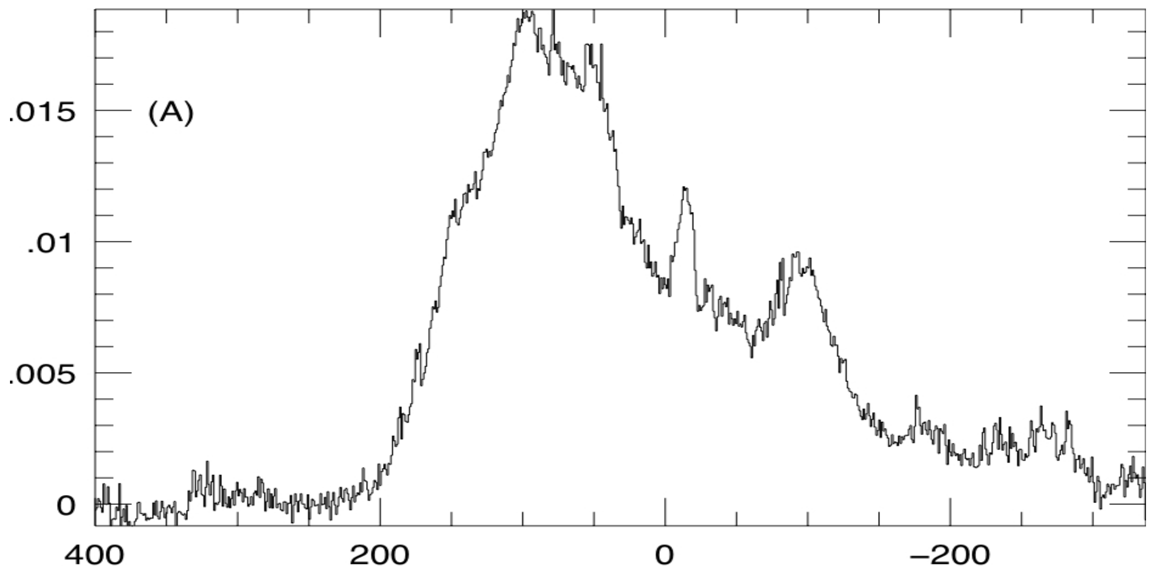
- Shift datacube spectrally to align emission that fits circular velocities in each plane at zero-velocity pixel

- Compare to a Gaussian

- Is the “best fit” a “good fit?”

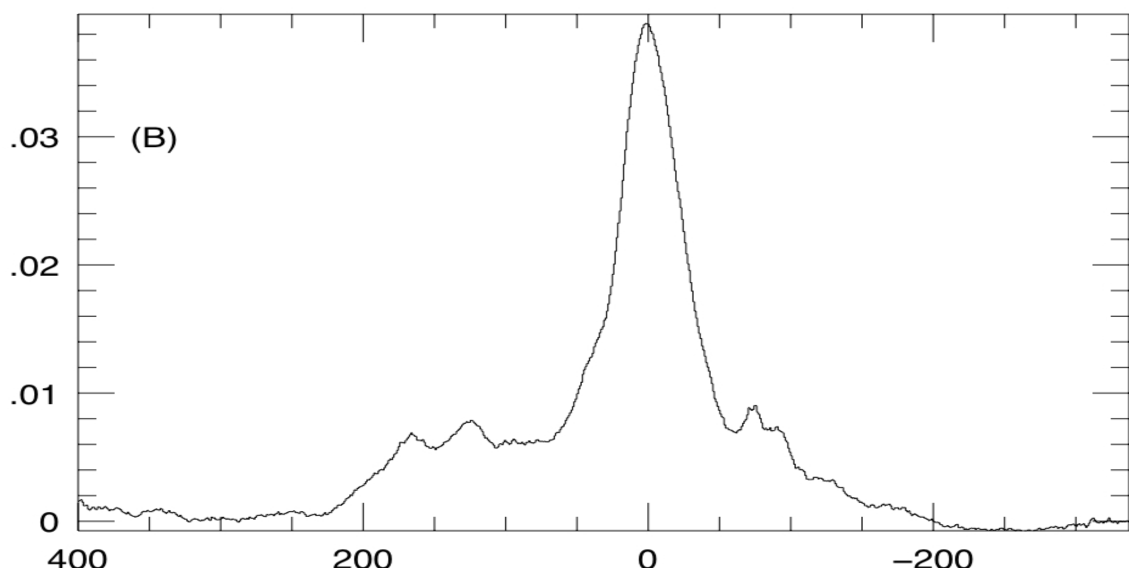
Fitting Routine

No shifting



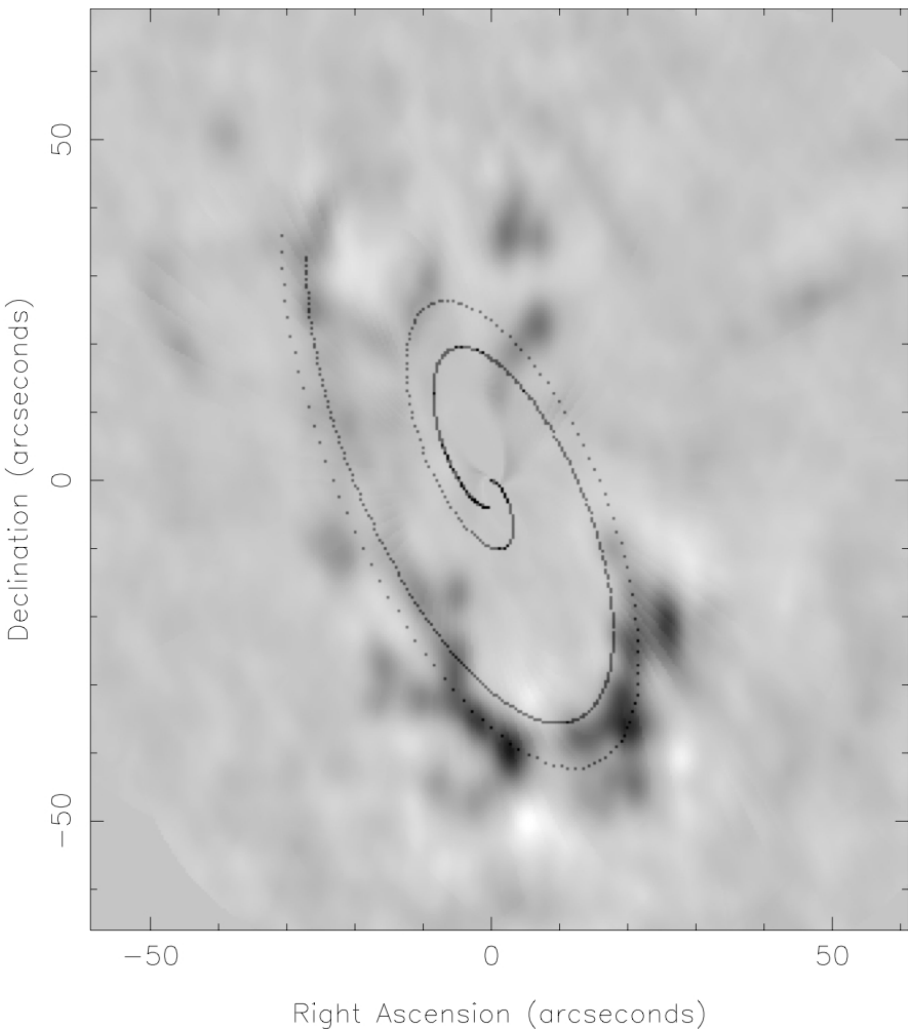
15% emission within 30 km/s of zero velocity point

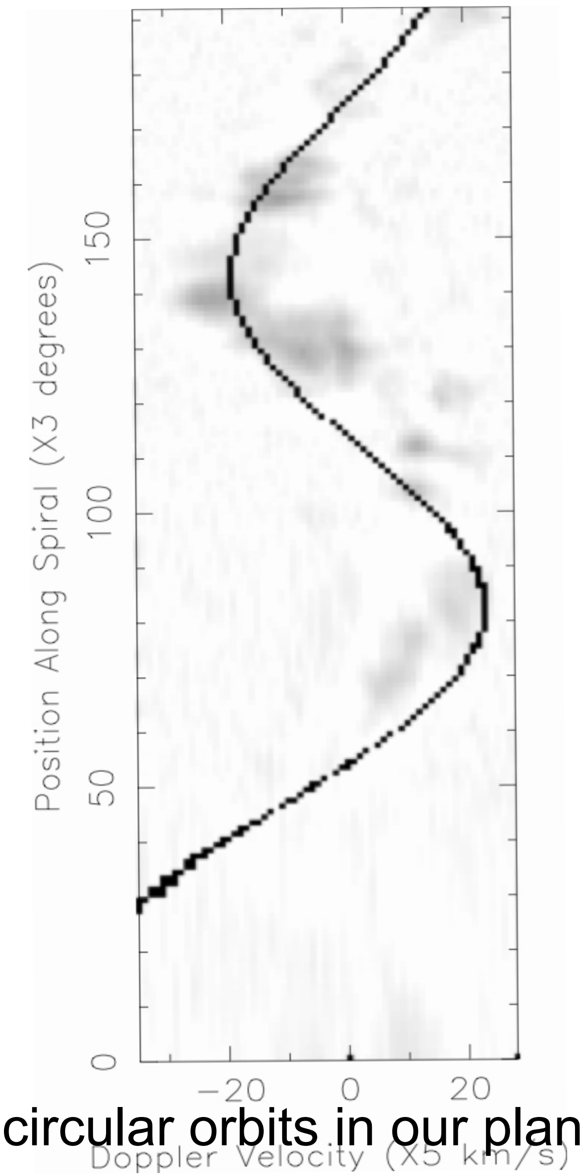
Best fit



45% emission within 30 km/s of zero velocity point

HCN(4-3) Data (Montero-Castaño et al.)





HCN(4-3) emission that fits within 30km/s of circular orbits in our plane