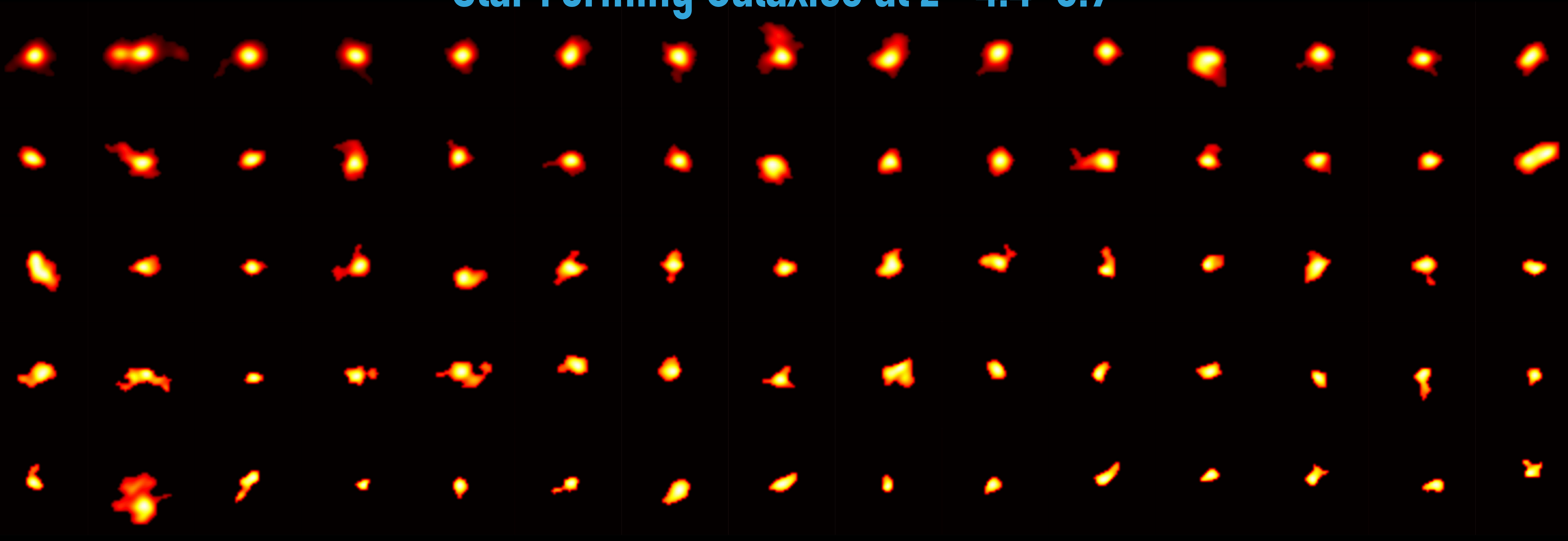


The ALPINE-ALMA [CII] Survey: Kinematic Diversity & Rotation in Massive Star Forming Galaxies at $z \sim 4.4-5.9$



Gareth Jones, ALPINE Collaboration

OUTLINE

- ▶ Background of high-redshift galaxy kinematics
- ▶ ALPINE
 - ▶ Morpho-kinematic classification
 - ▶ Use of rotating disk models
- ▶ The future of rotational characterization

GALAXY KINEMATICS

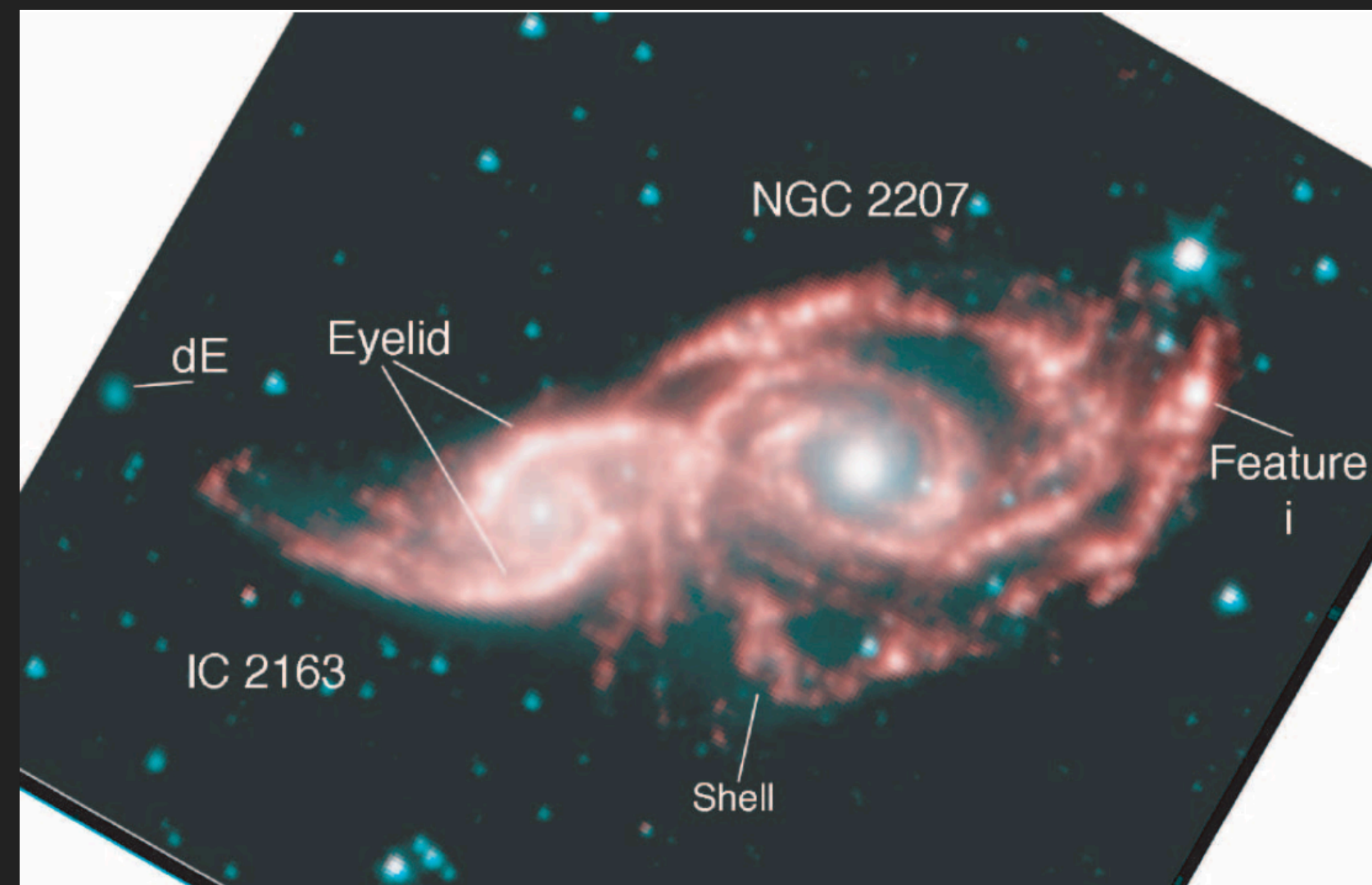
GALAXY KINEMATICS

- ▶ Very broad: How material (gas) in galaxies is moving

GALAXY KINEMATICS

- ▶ Very broad: How material (gas) in galaxies is moving

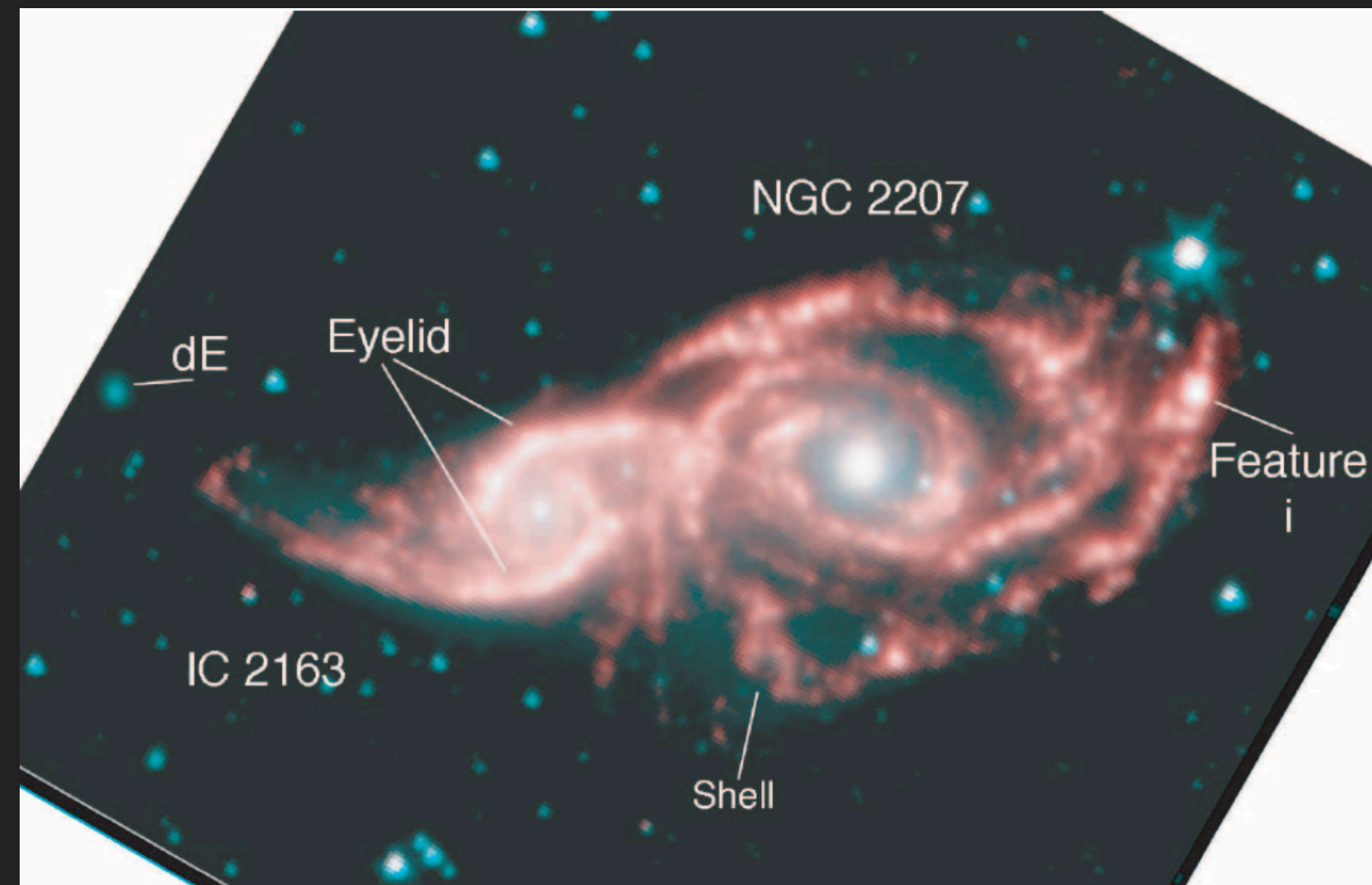
- ▶ Mergers



Elmegreen et al. (2006)

GALAXY KINEMATICS

- ▶ Very broad: How material (gas) in galaxies is moving
 - ▶ In-/Outflow
 - ▶ Mergers



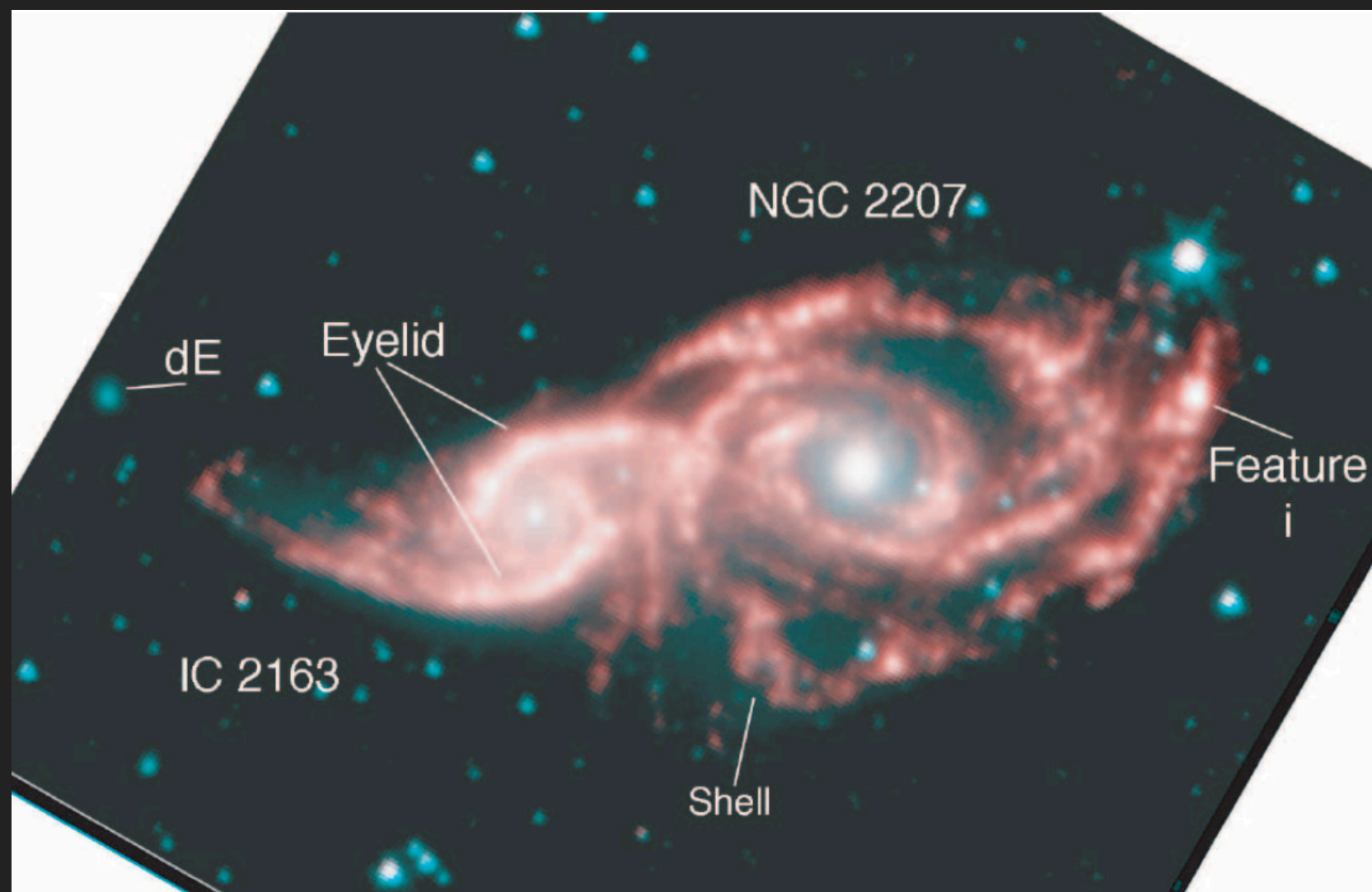
Elmegreen et al. (2006)



Engelbracht et al. (2006)

GALAXY KINEMATICS

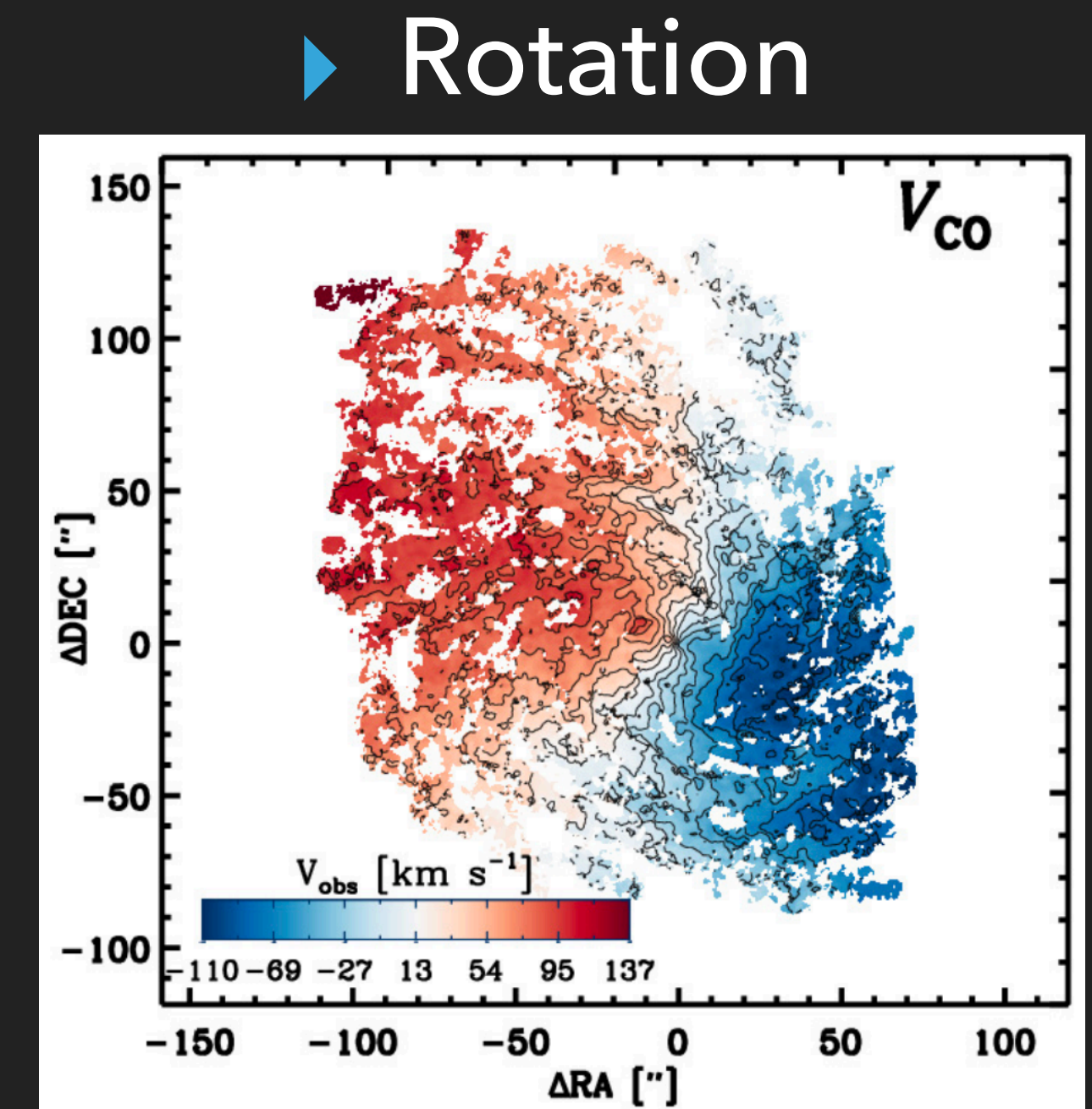
- ▶ Very broad: How material (gas) in galaxies is moving
 - ▶ In-/Outflow
 - ▶ Mergers
 - ▶ Rotation



Elmegreen et al. (2006)



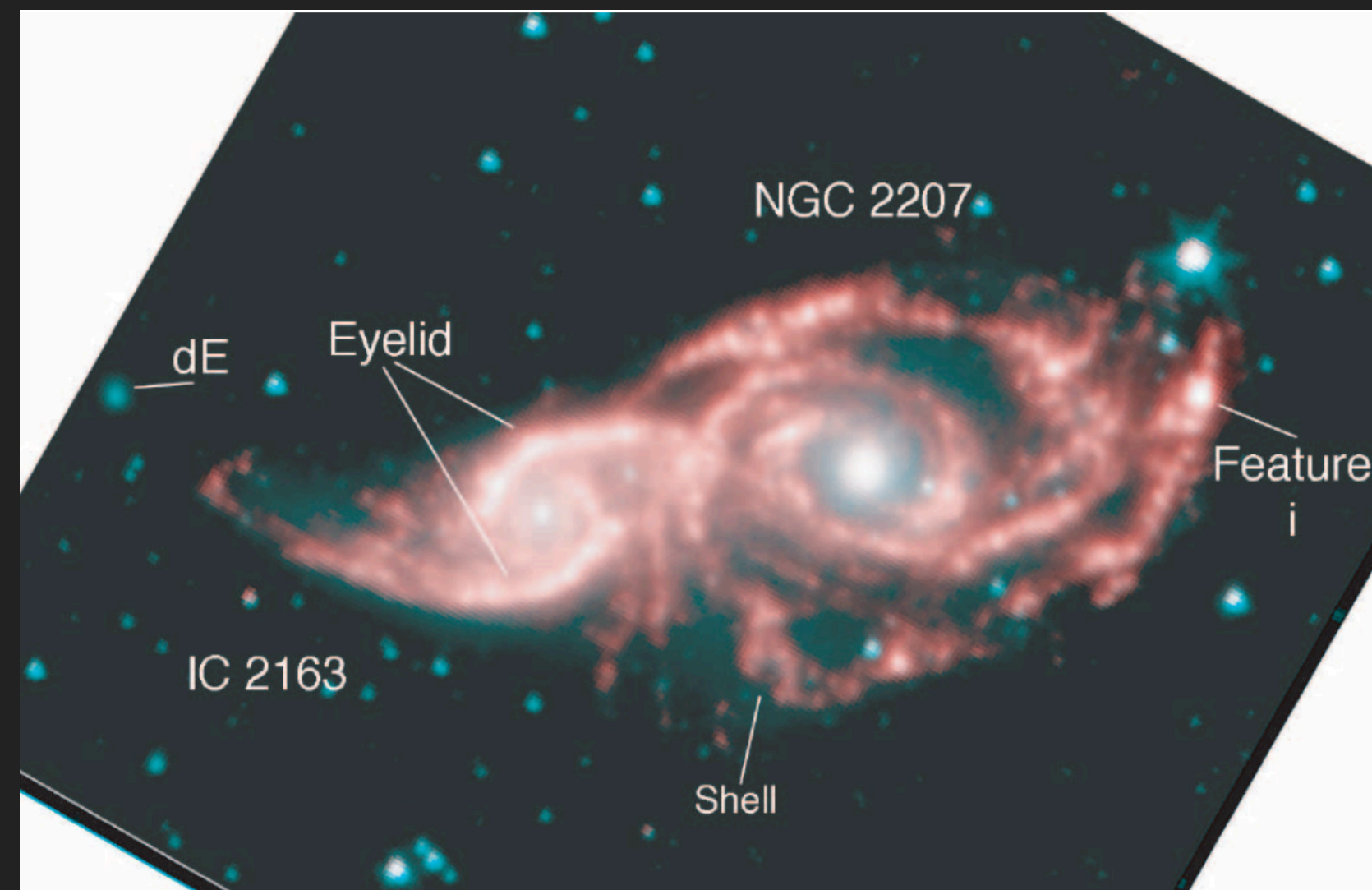
Engelbracht et al. (2006)



Lang et al. (2020)

GALAXY KINEMATICS

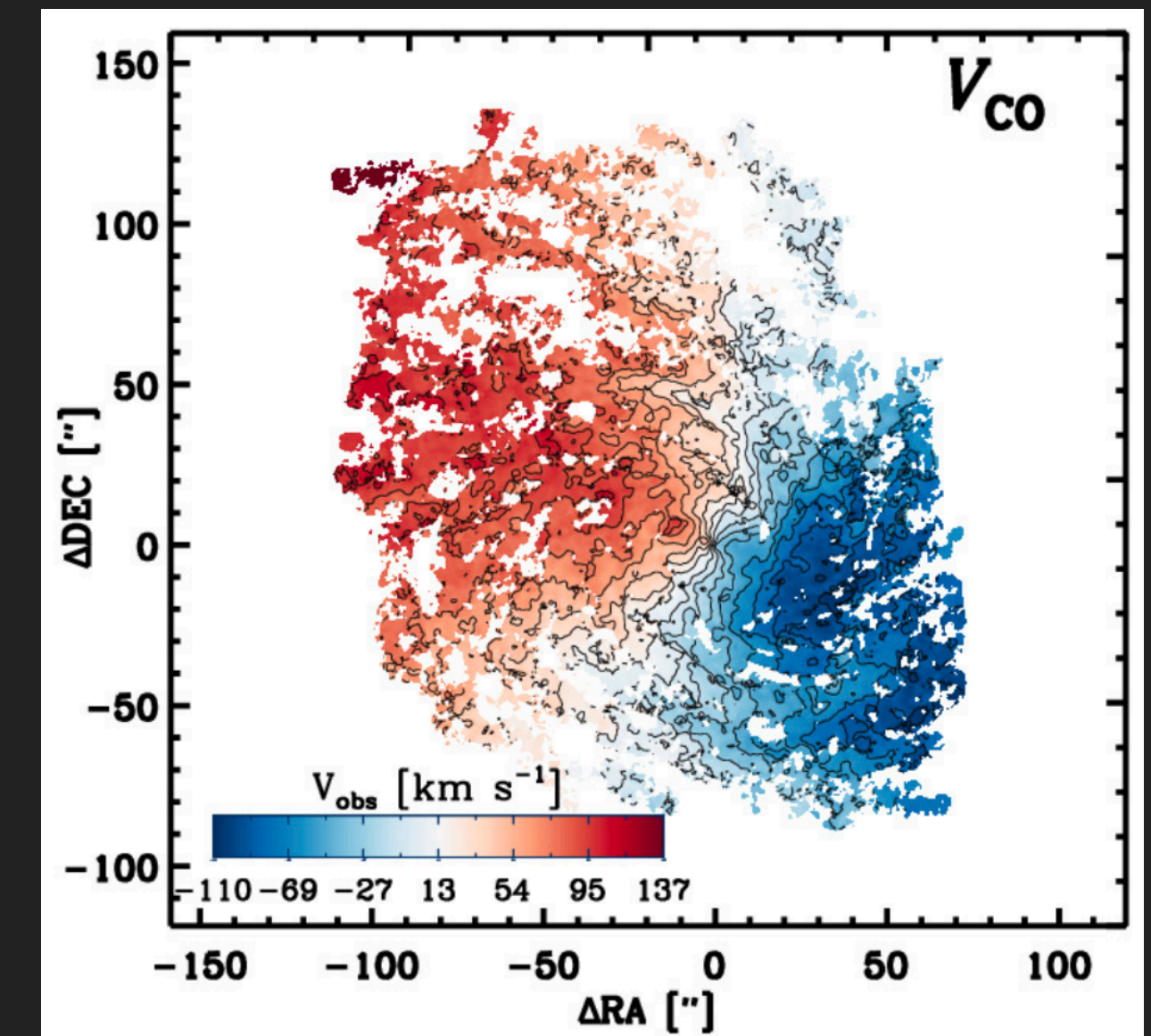
- ▶ Very broad: How material (gas) in galaxies is moving
 - ▶ In-/Outflow
 - ▶ Mergers
 - ▶ Rotation



Elmegreen et al. (2006)



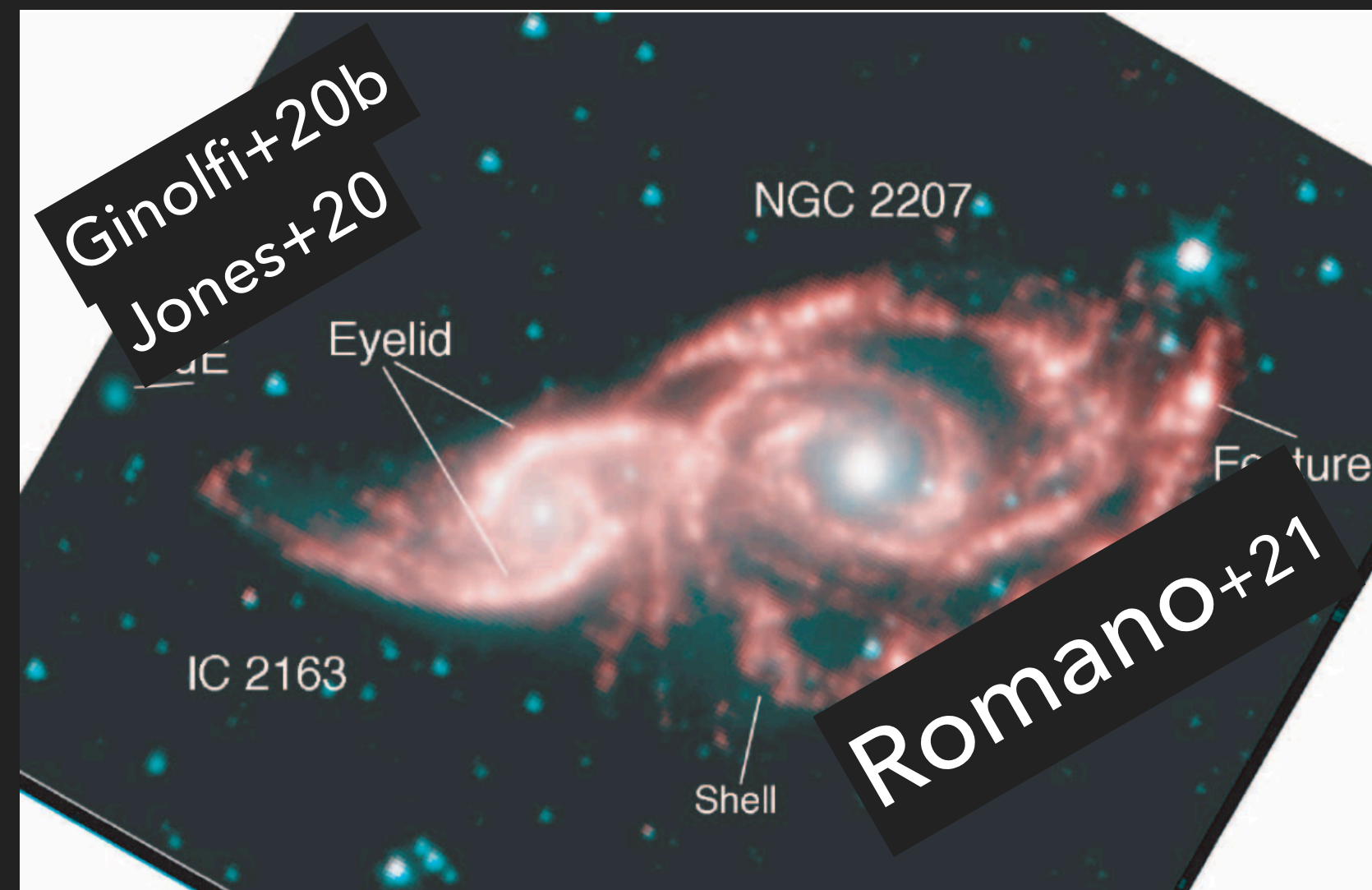
Engelbracht et al. (2006)



Lang et al. (2020)

GALAXY KINEMATICS

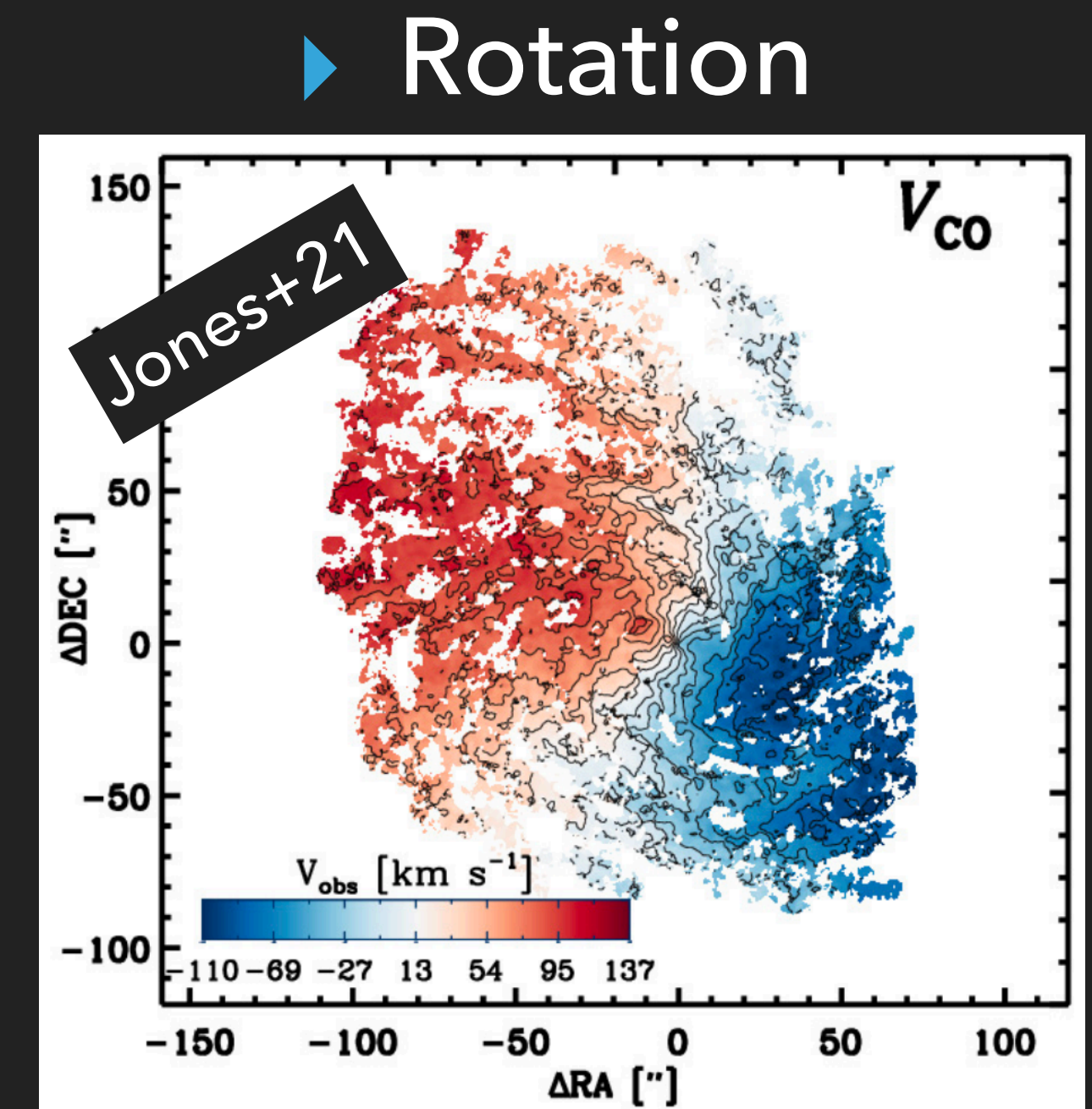
- ▶ Very broad: How material (gas) in galaxies is moving
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Elmegreen et al. (2006)

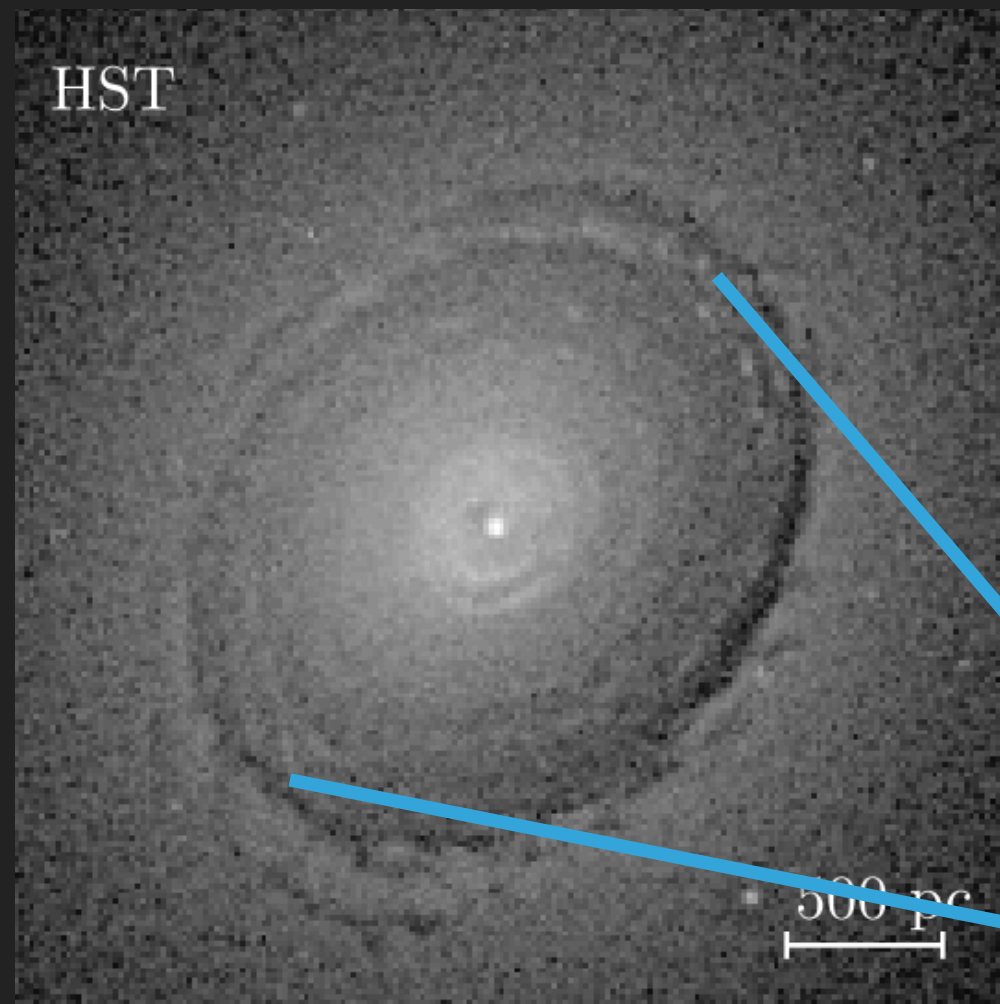


Engelbracht et al. (2006)

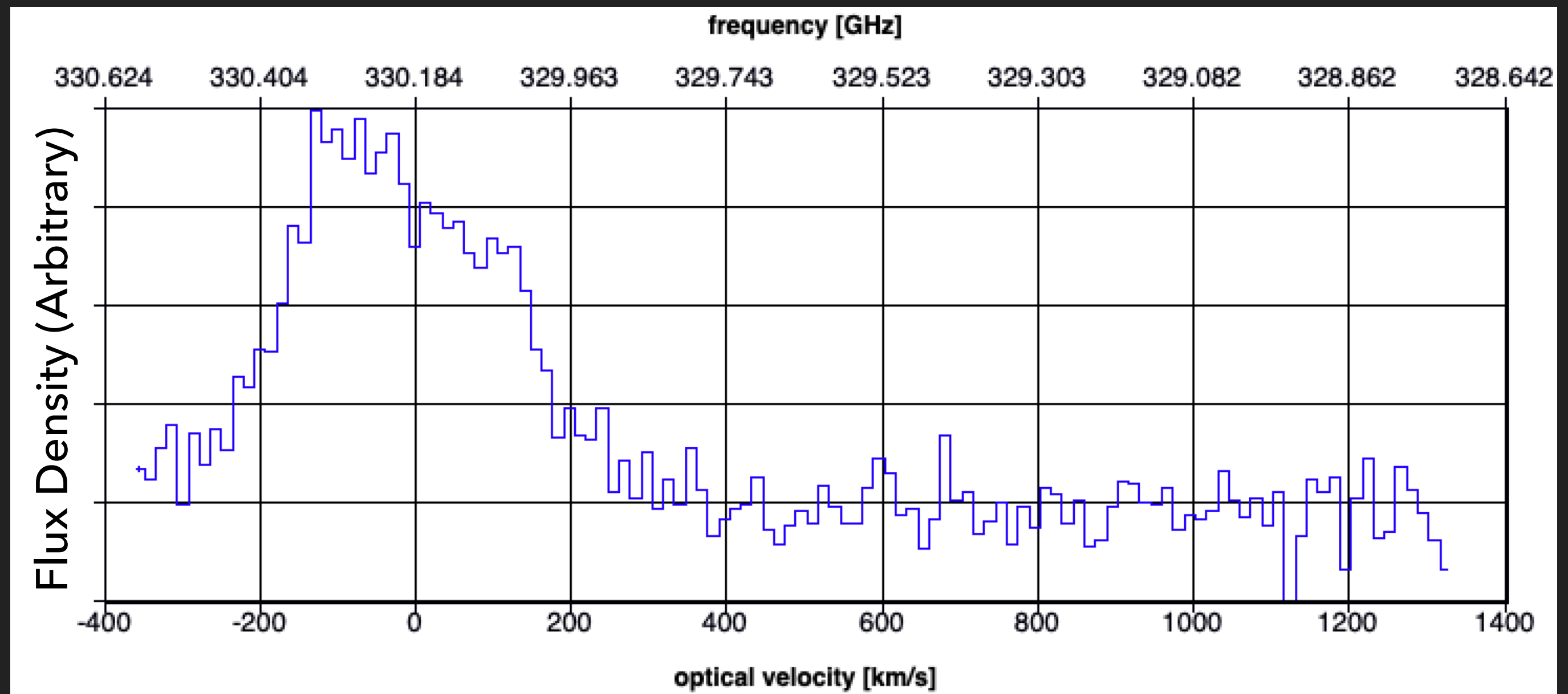


Lang et al. (2020)

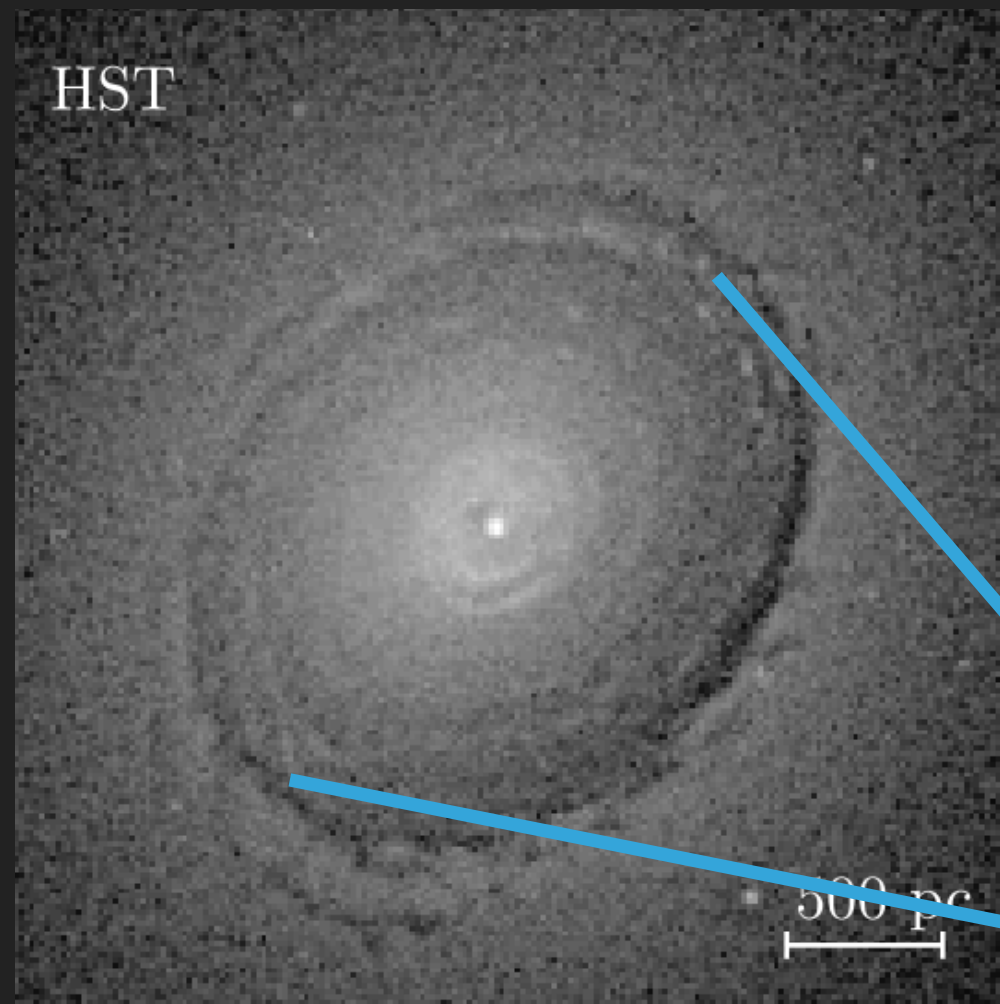
AMBIGUITY IN KINEMATICS



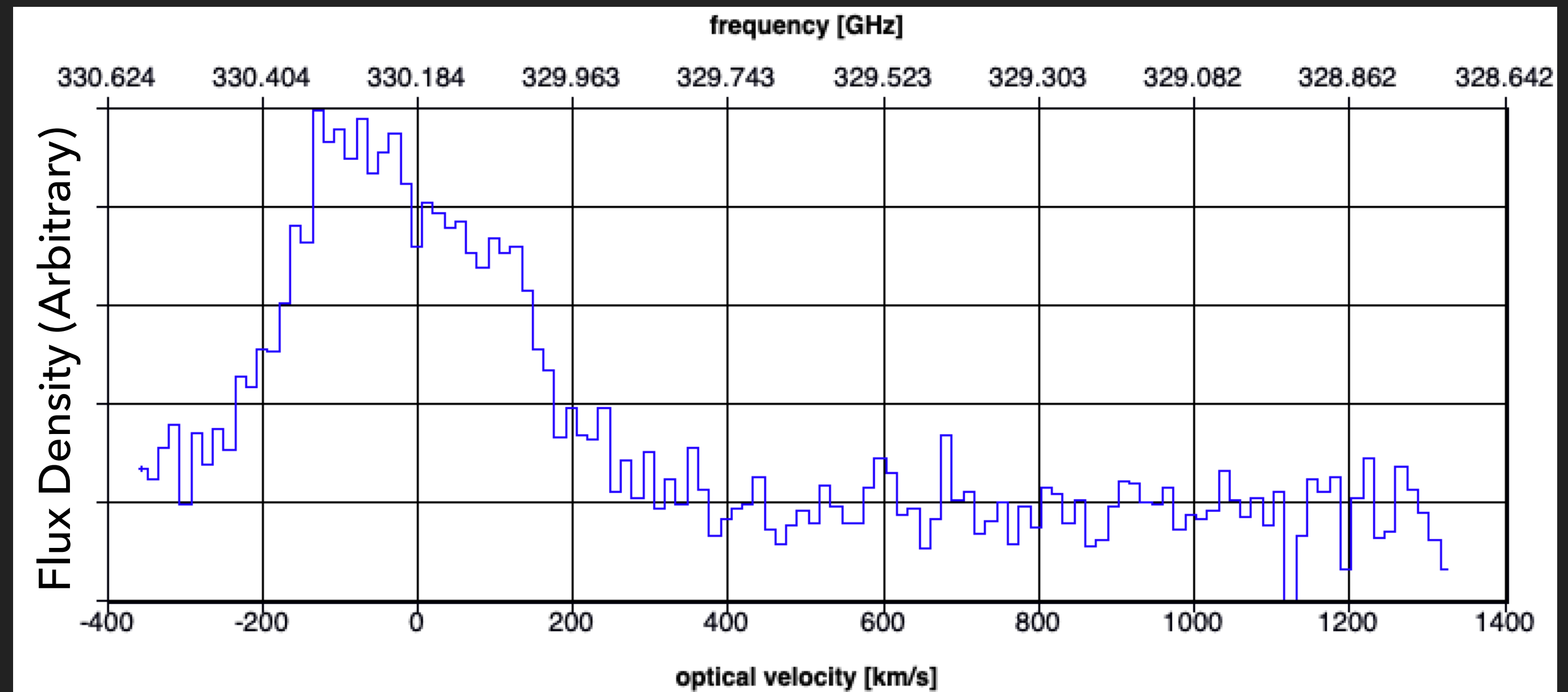
North et al. (2019)



AMBIGUITY IN KINEMATICS

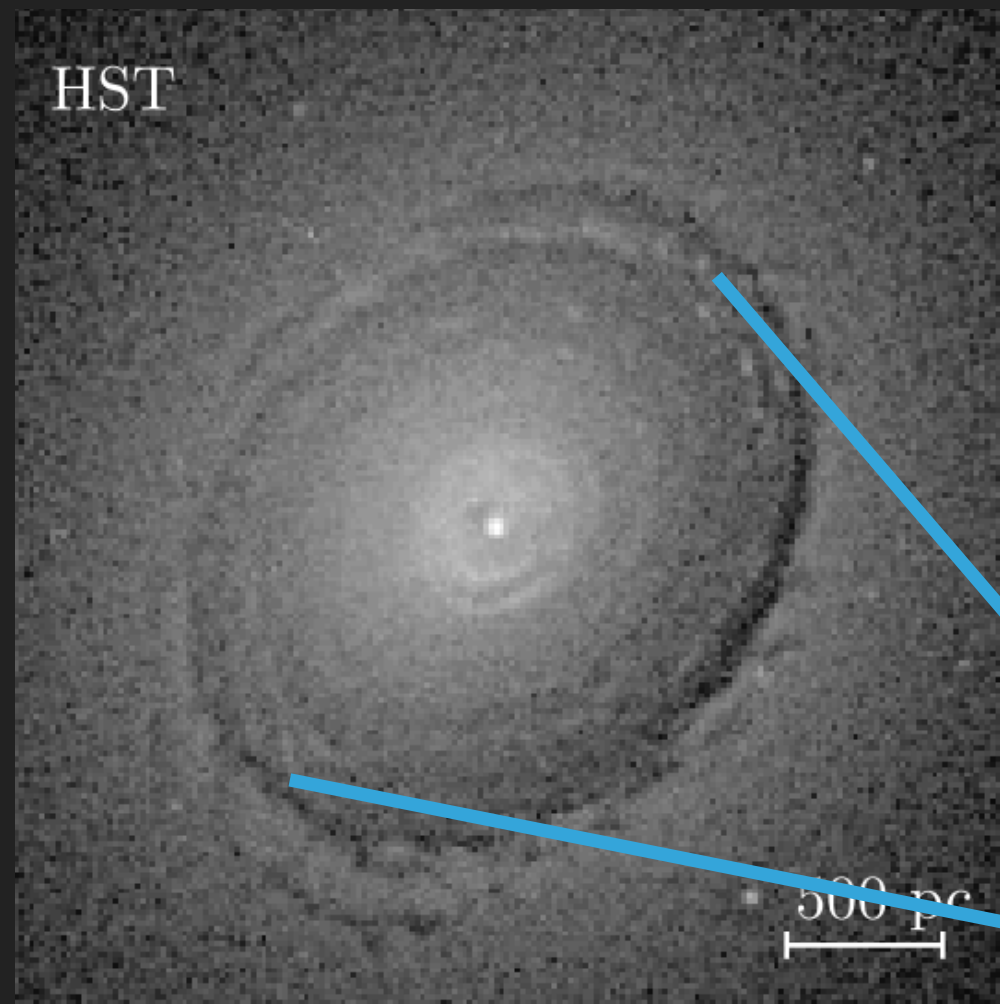


North et al. (2019)



- ▶ Doppler shift only reveals velocity along line-of-sight
 - ▶ Encodes many phenomena

AMBIGUITY IN KINEMATICS



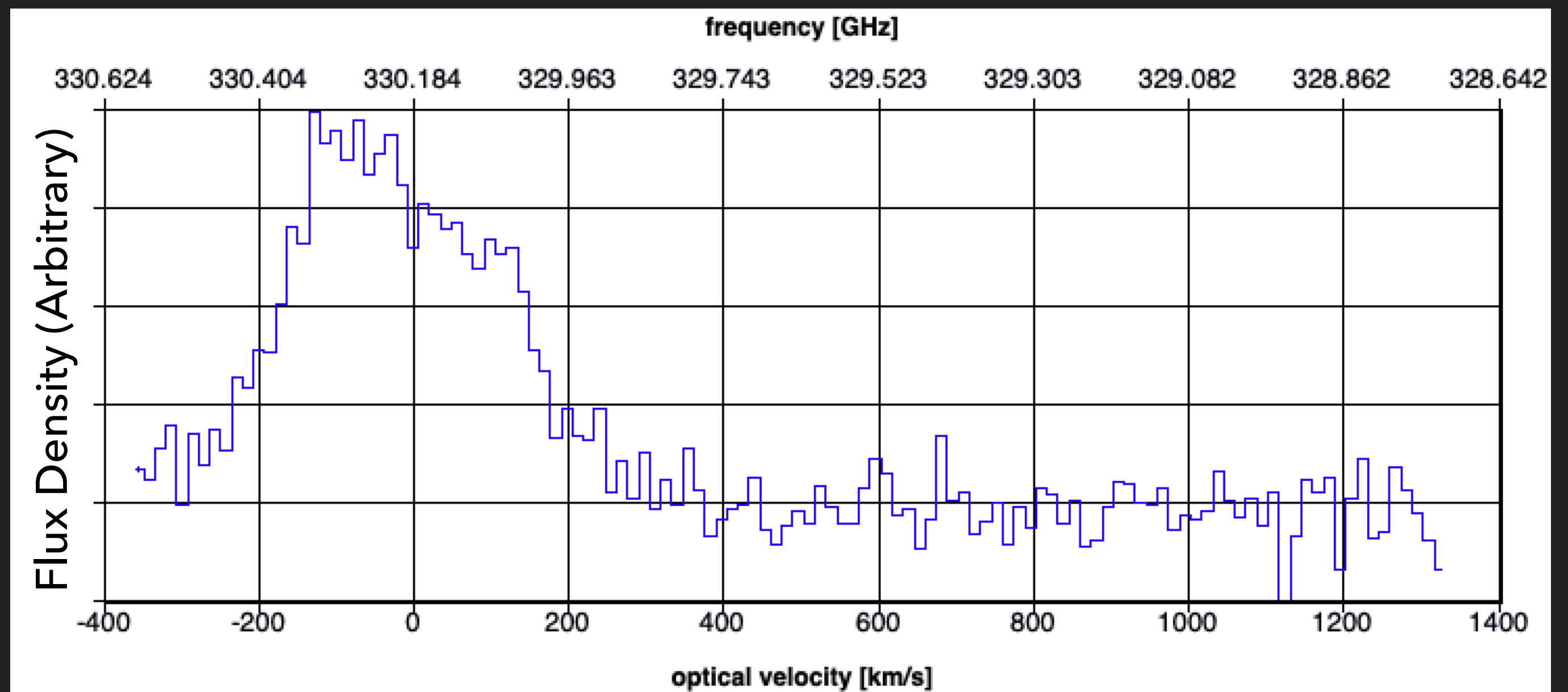
North et al. (2019)



Rotation?



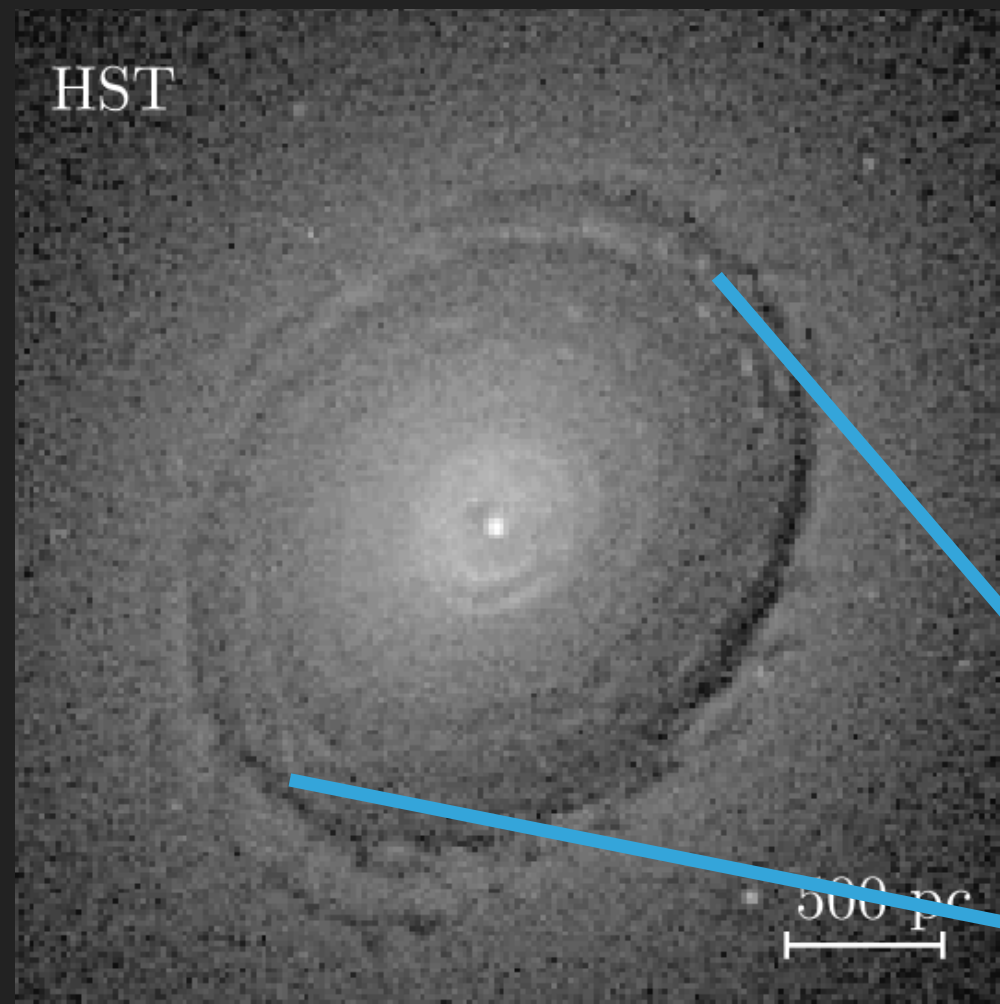
A red double-headed arrow pointing left and right, positioned below the text "Rotation?".



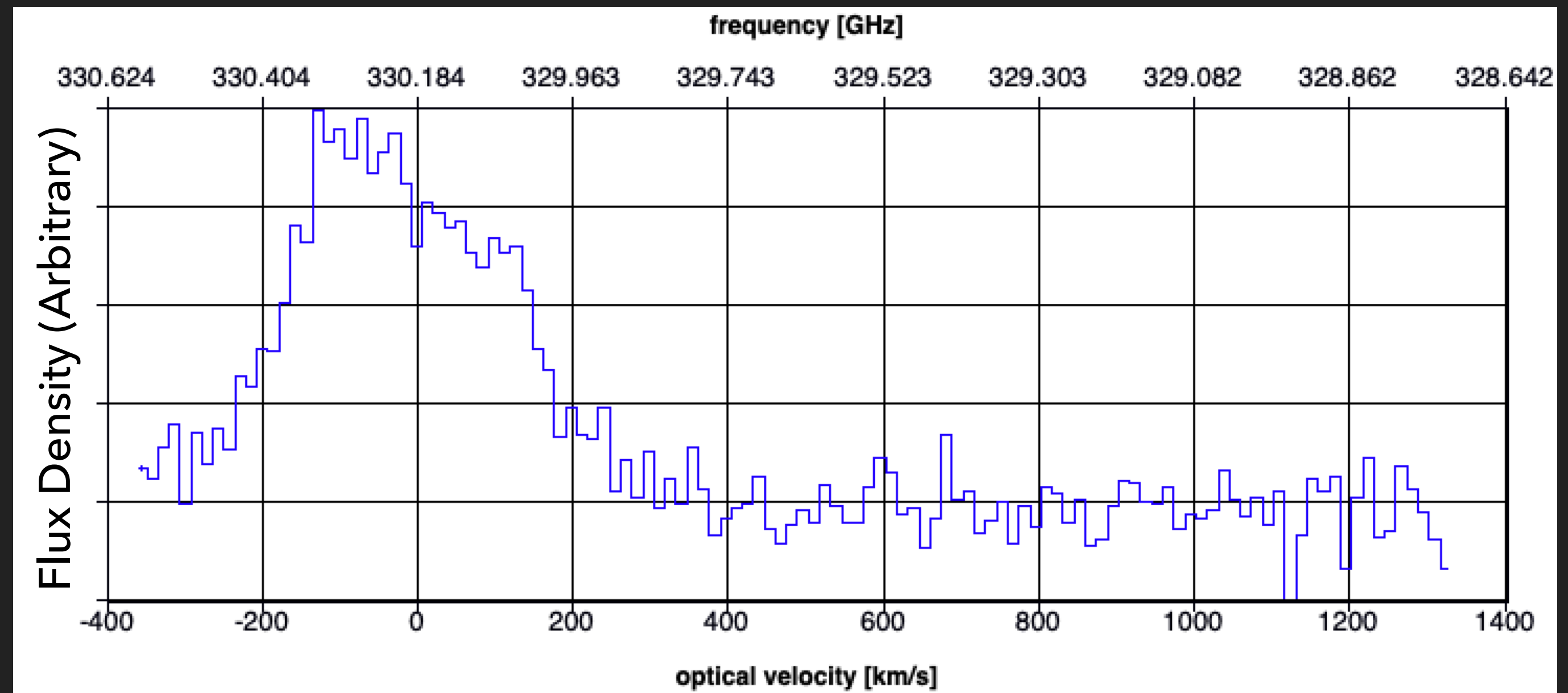
- ▶ Doppler shift only reveals velocity along line-of-sight
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AMBIGUITY IN KINEMATICS

Rotation?
Random motion?

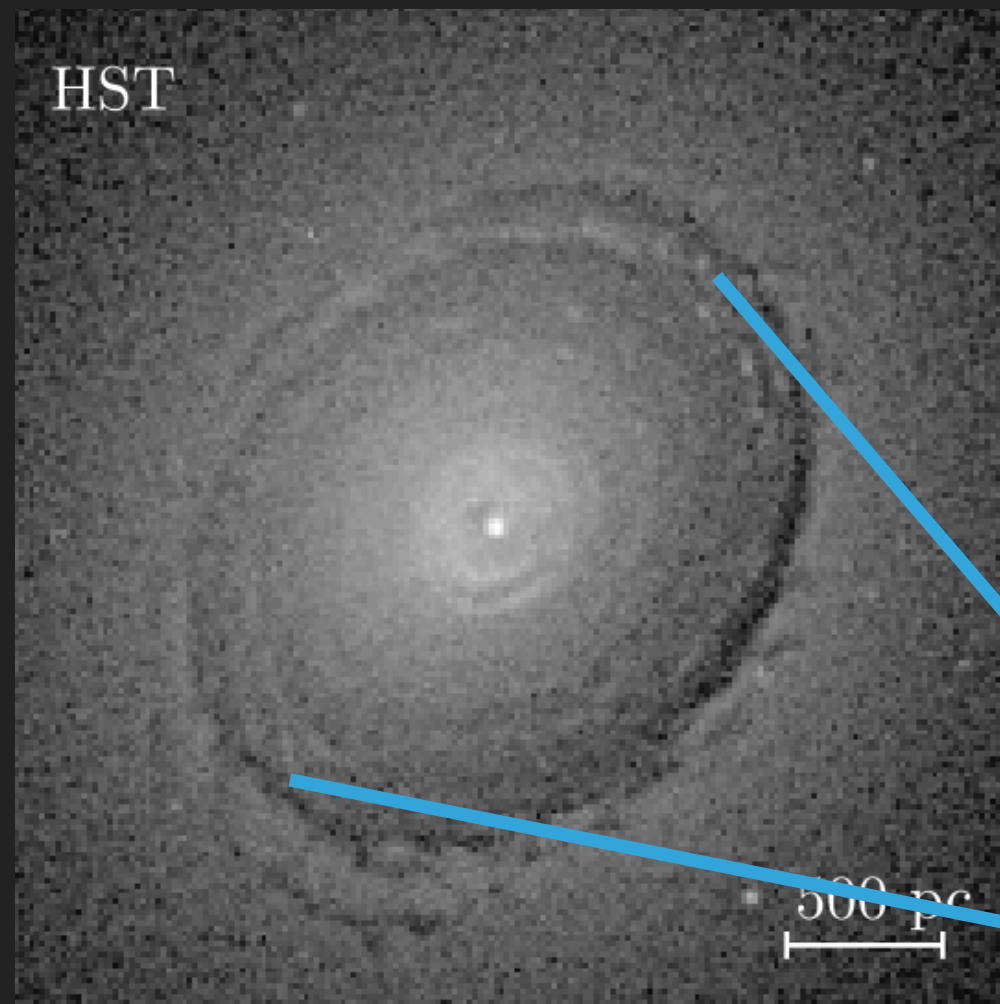
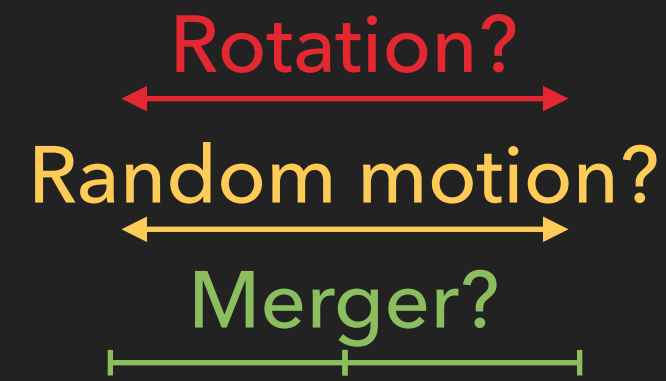


North et al. (2019)

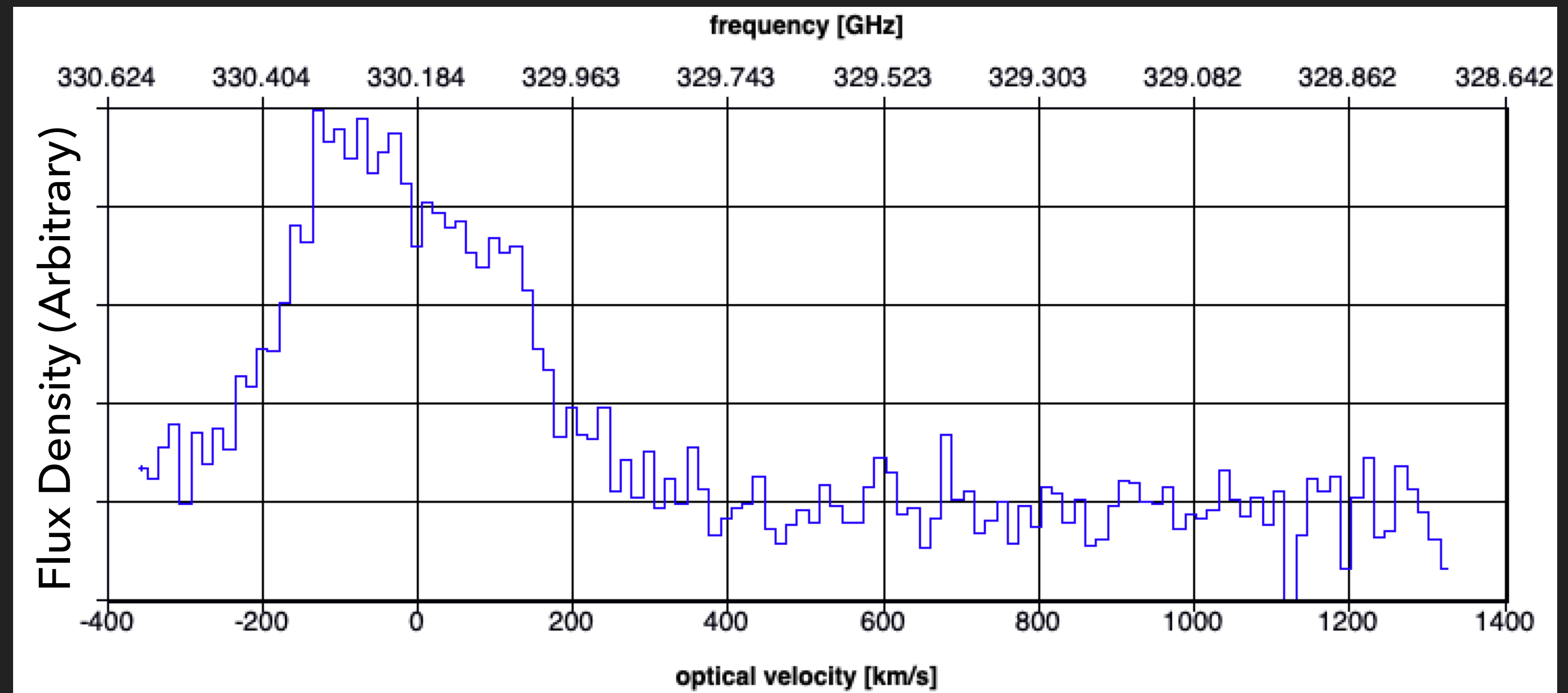


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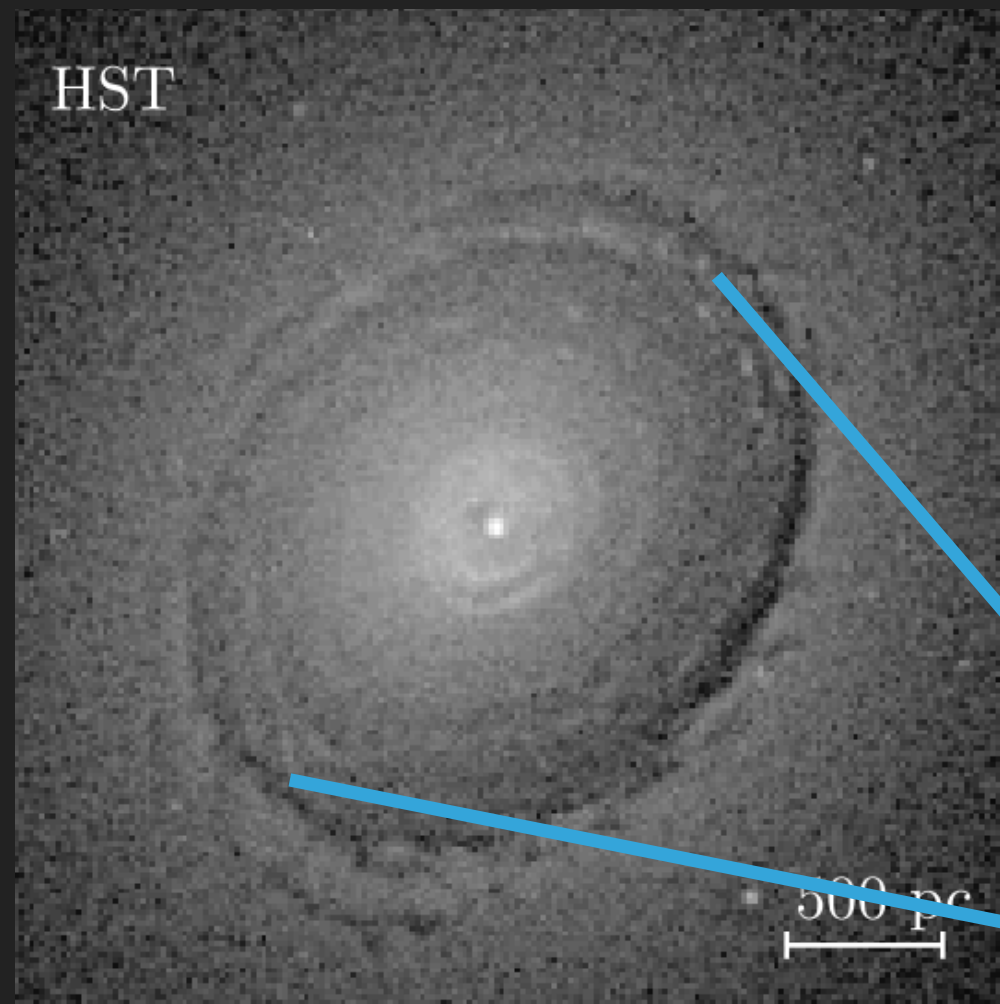
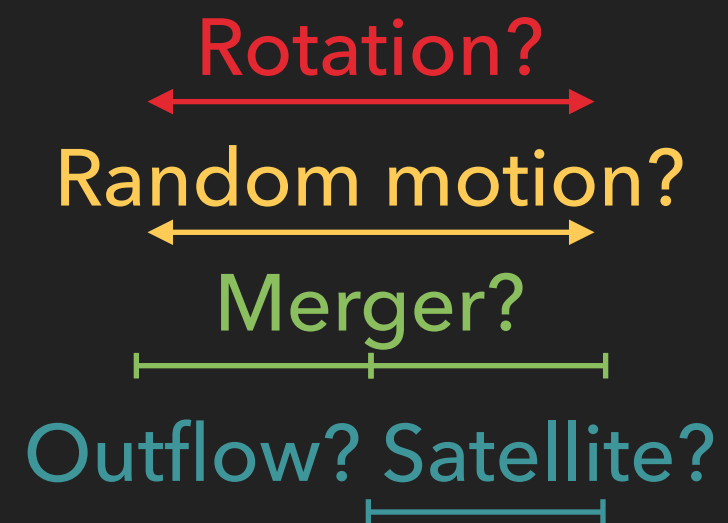


North et al. (2019)

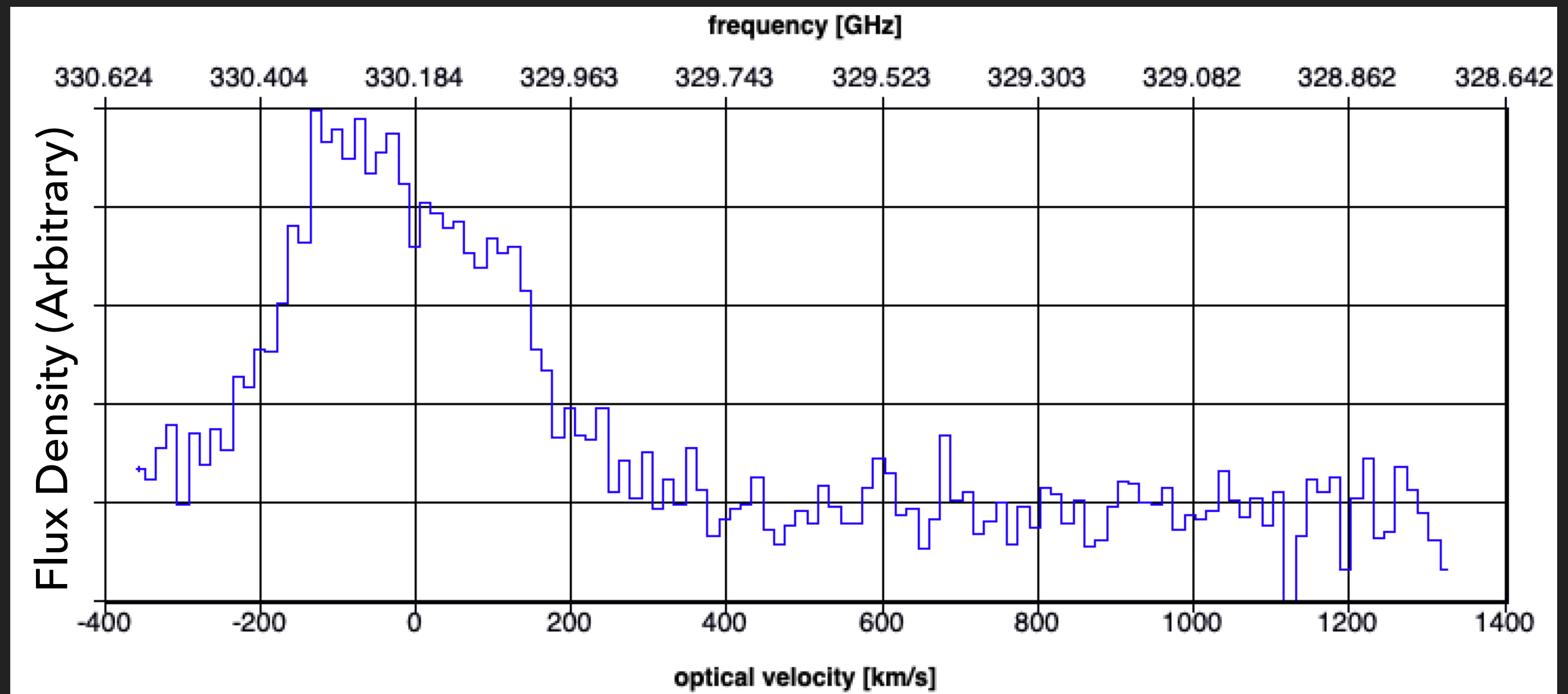


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AMBIGUITY IN KINEMATICS

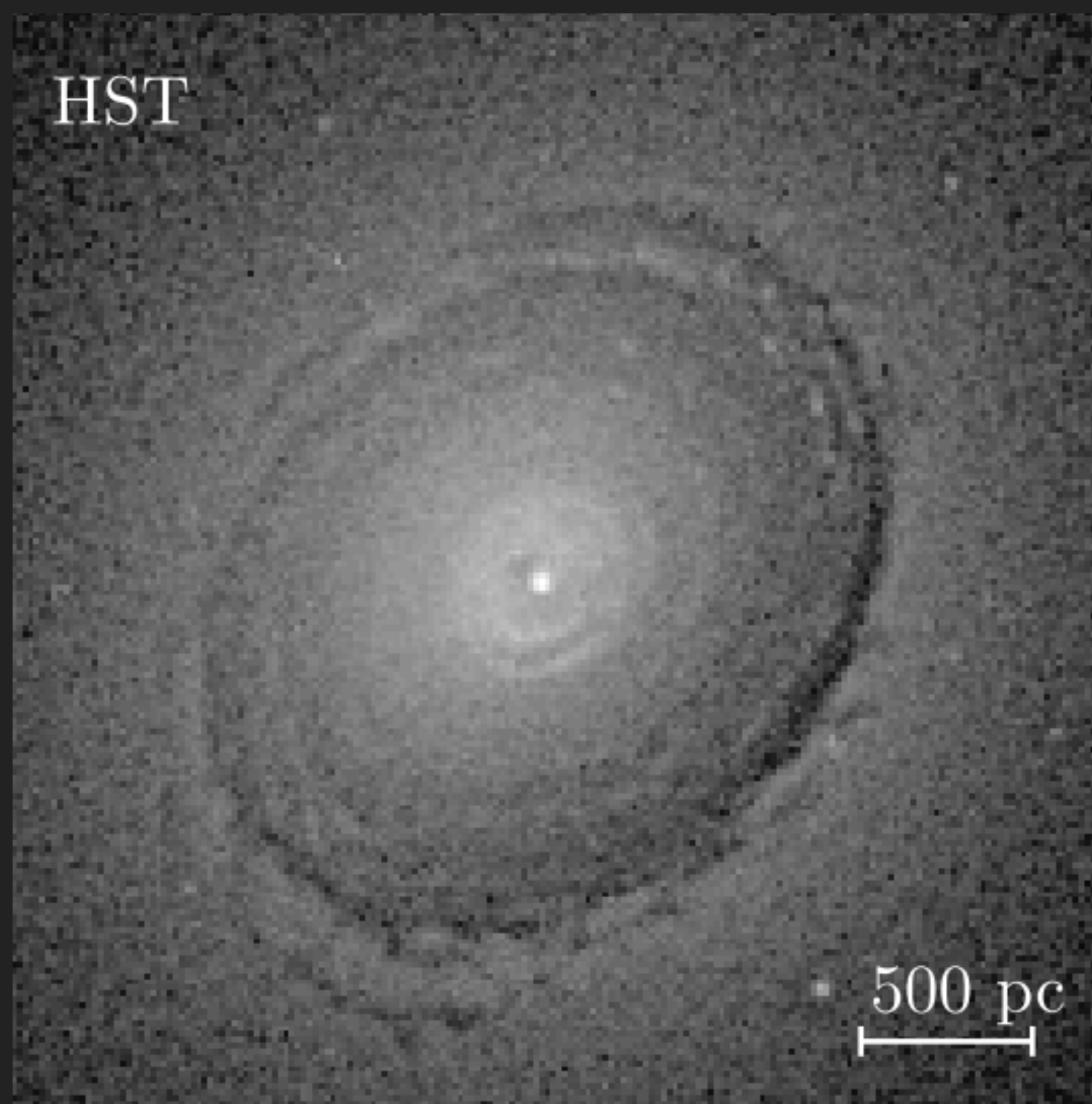


North et al. (2019)



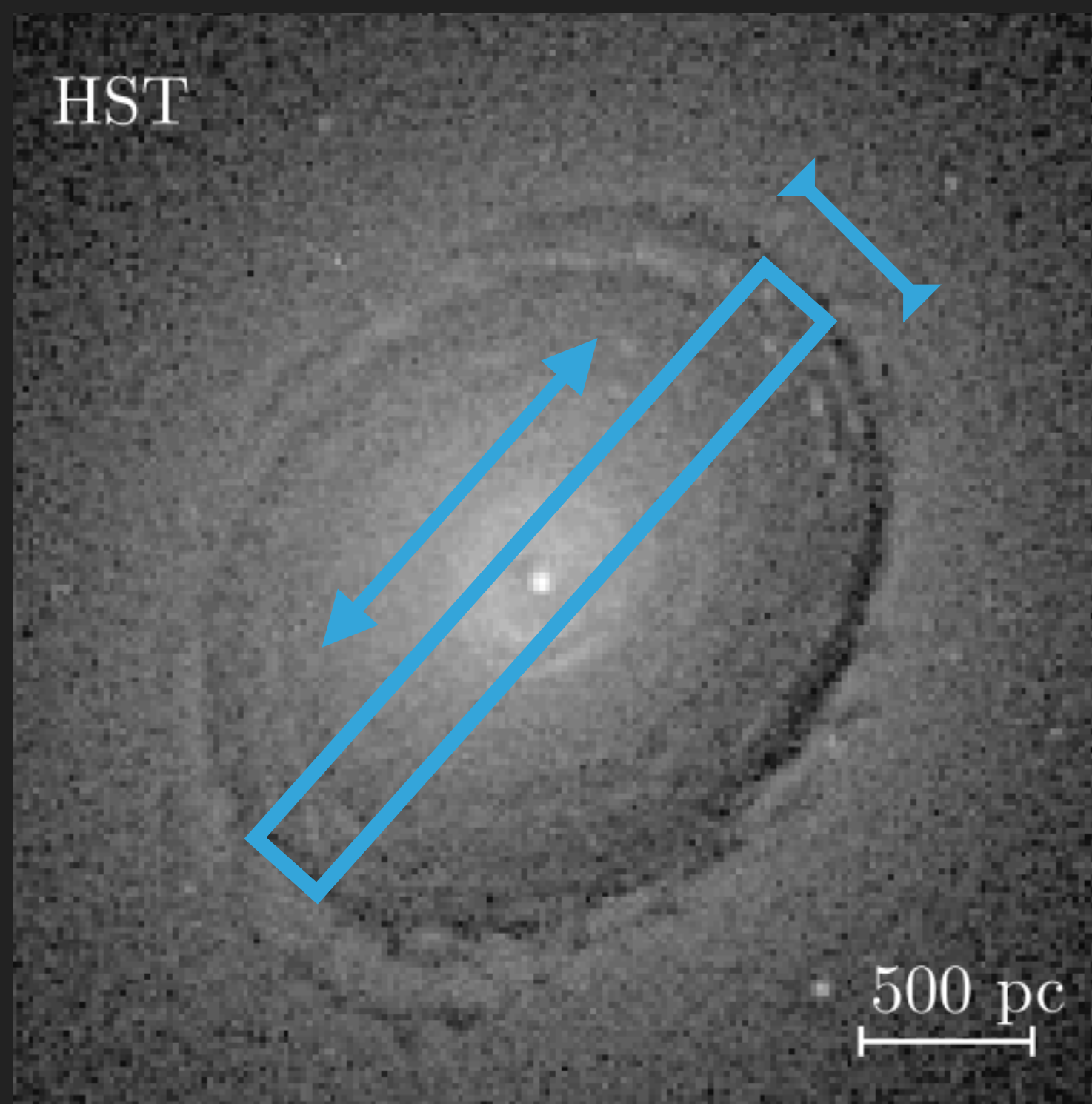
- ▶ Doppler shift only reveals velocity along line-of-sight
 - ▶ Encodes many phenomena

NEED FOR MORE DATA



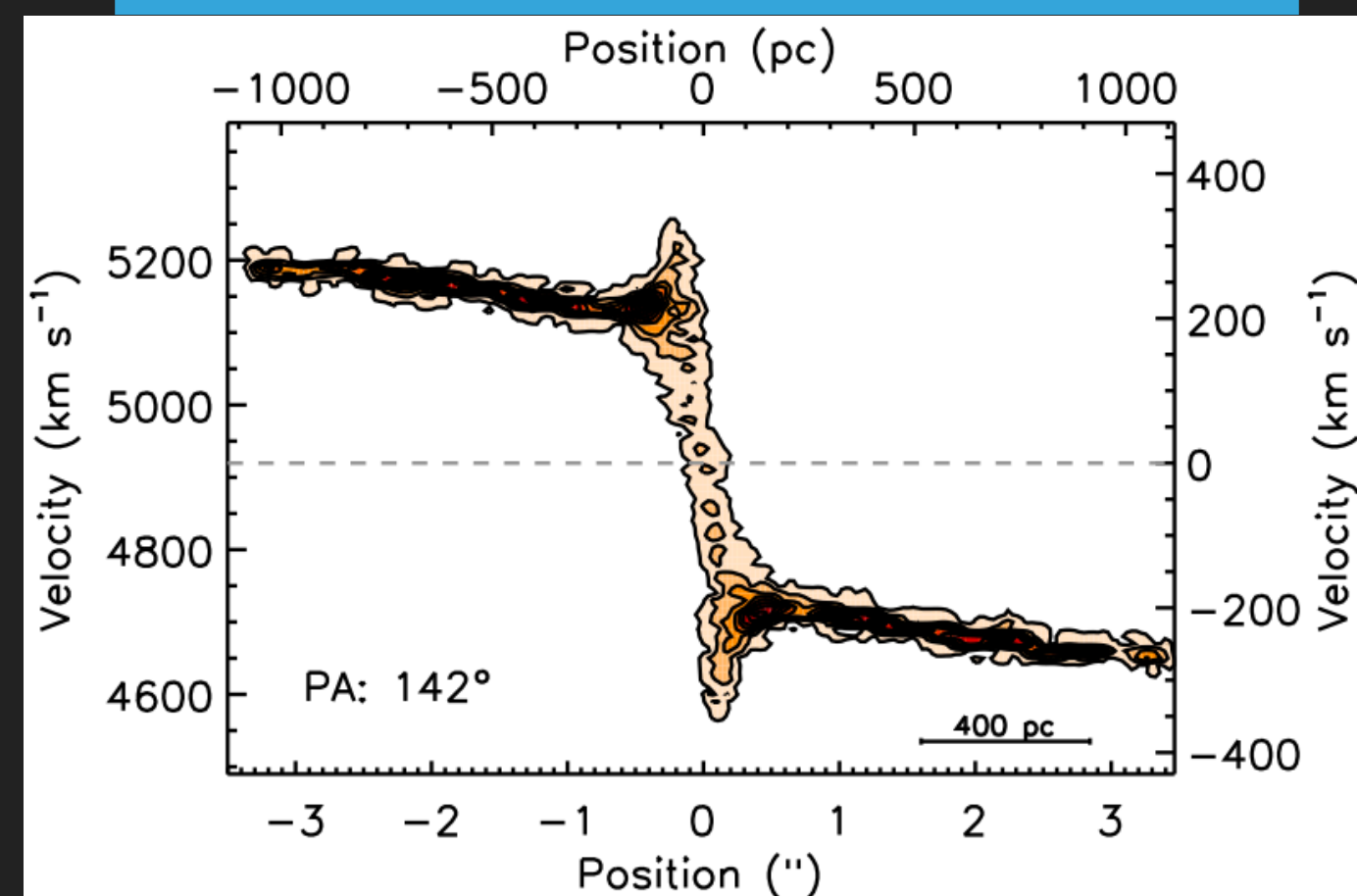
North et al. (2019)

NEED FOR MORE DATA



North et al. (2019)

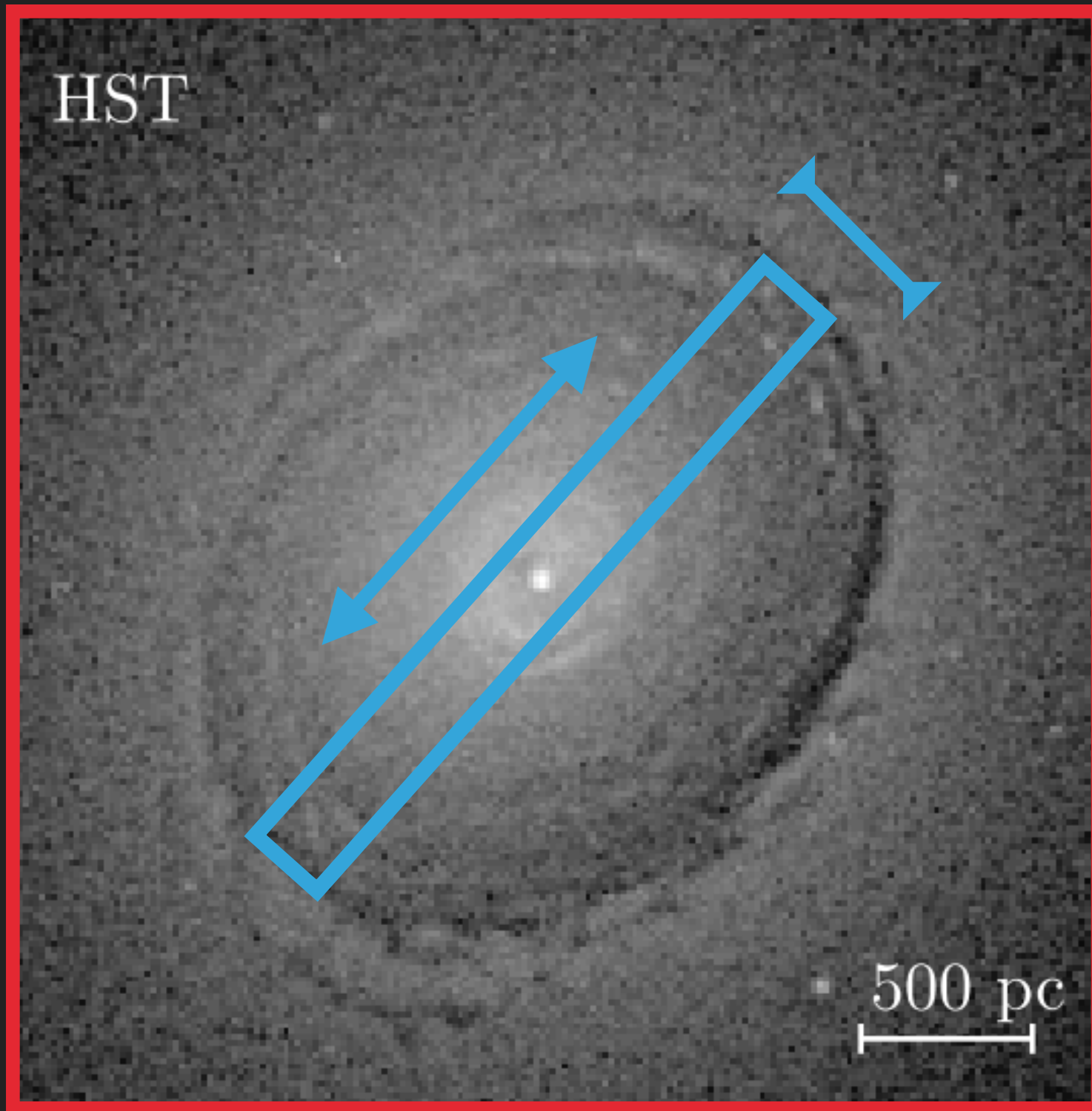
▶ Slit Spectroscopy



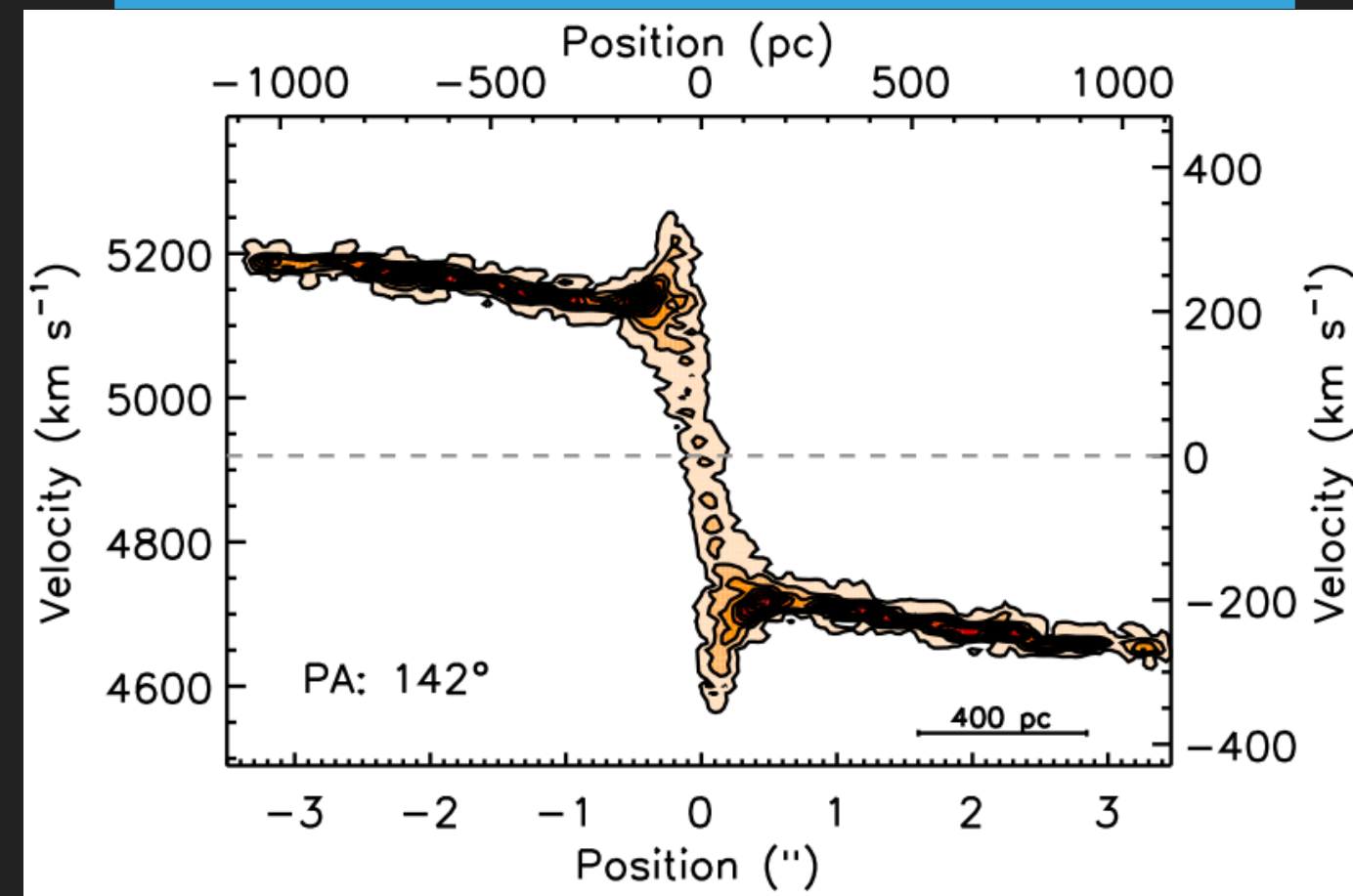
Position-Velocity Diagram

NEED FOR MORE DATA

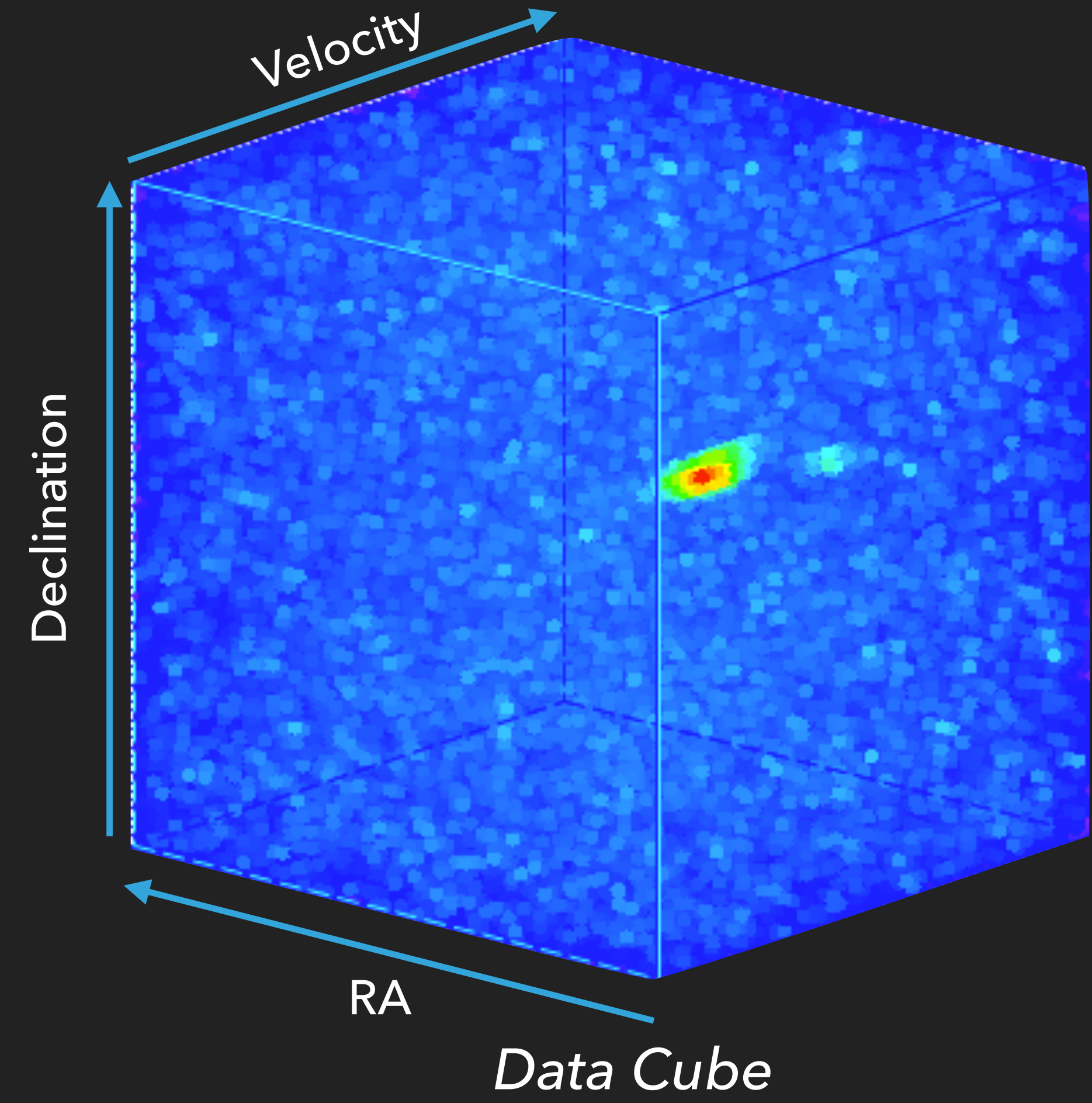
▶ IFU/Interferometers



▶ Slit Spectroscopy

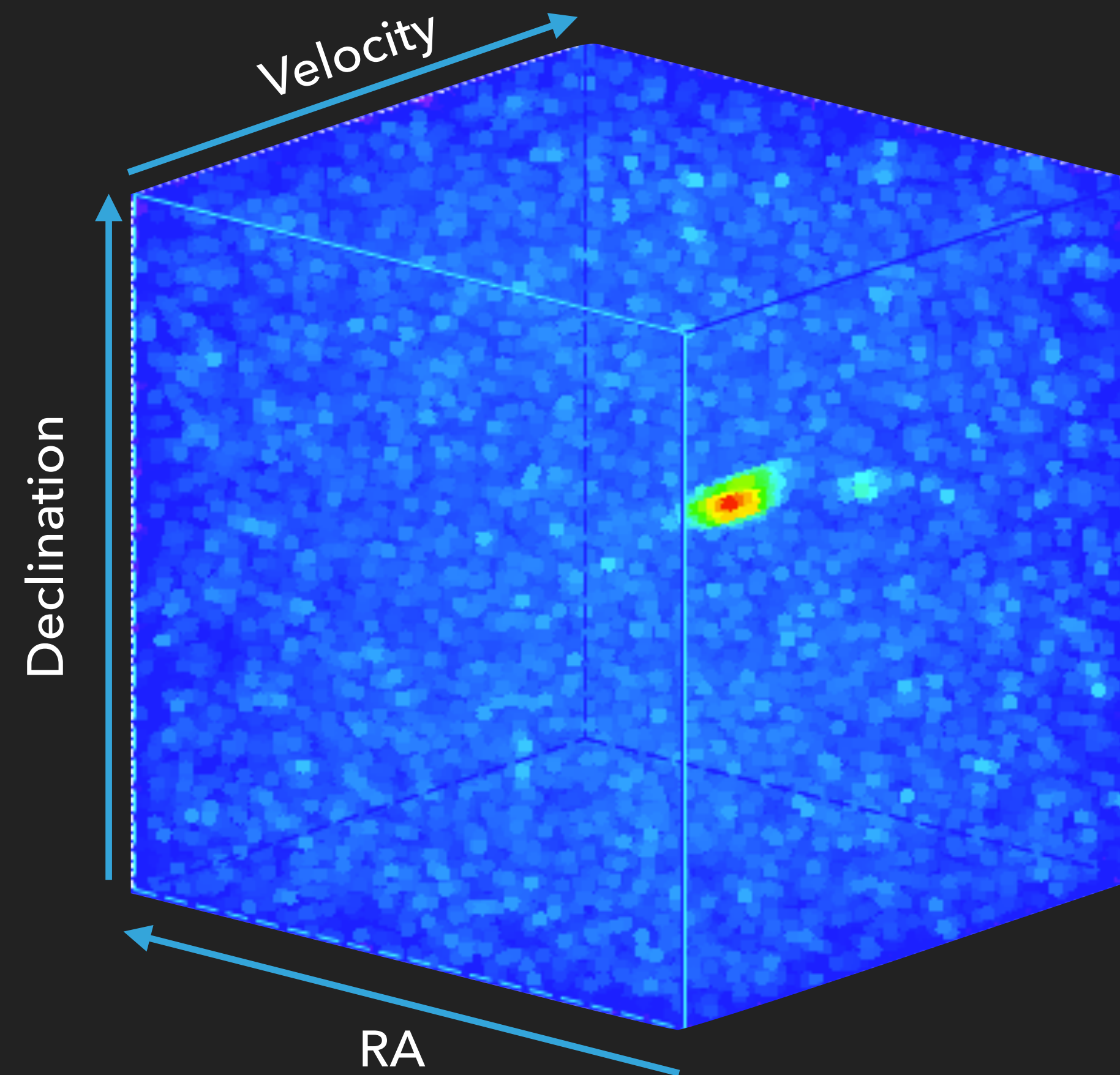


Position-Velocity Diagram



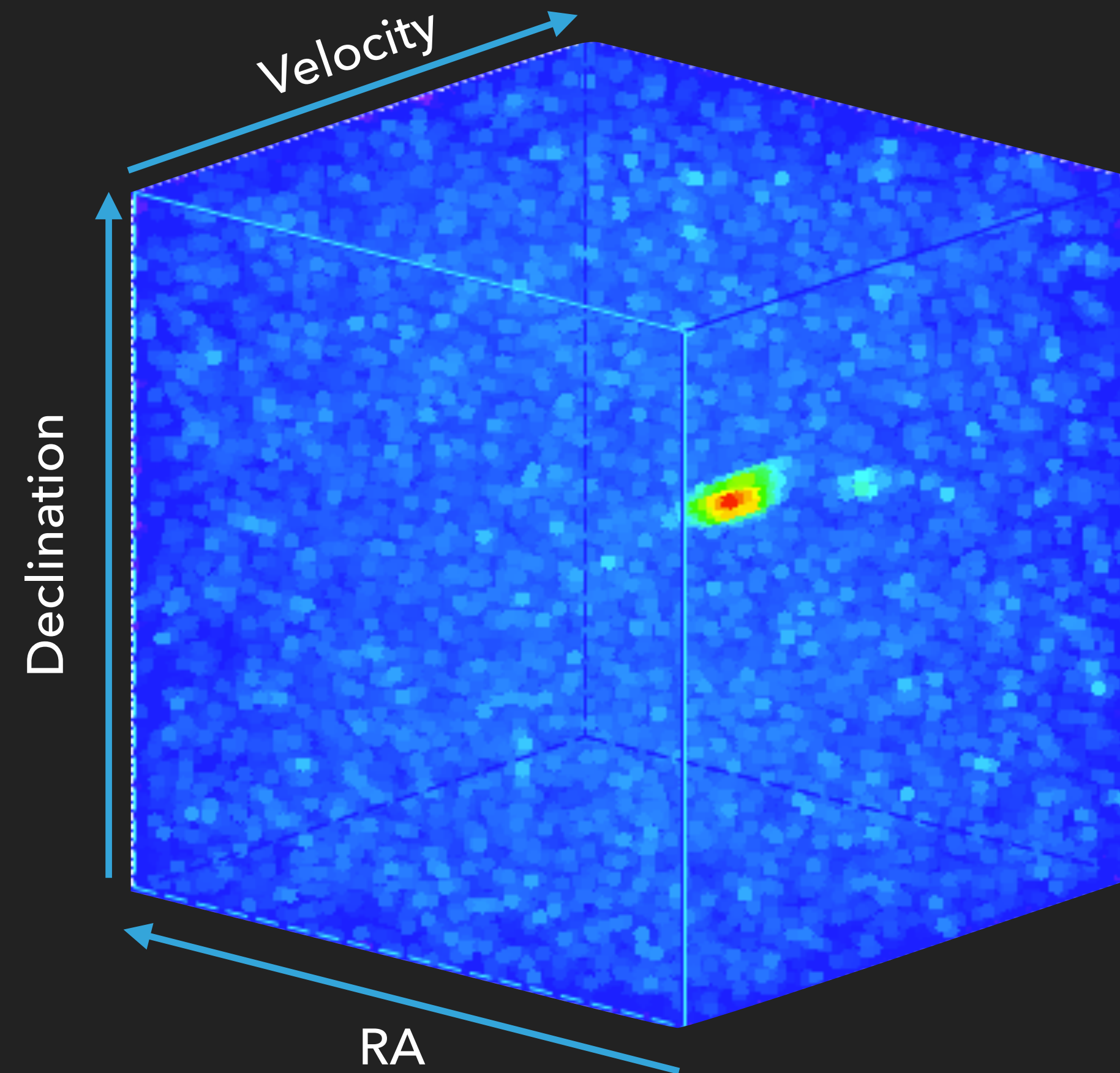
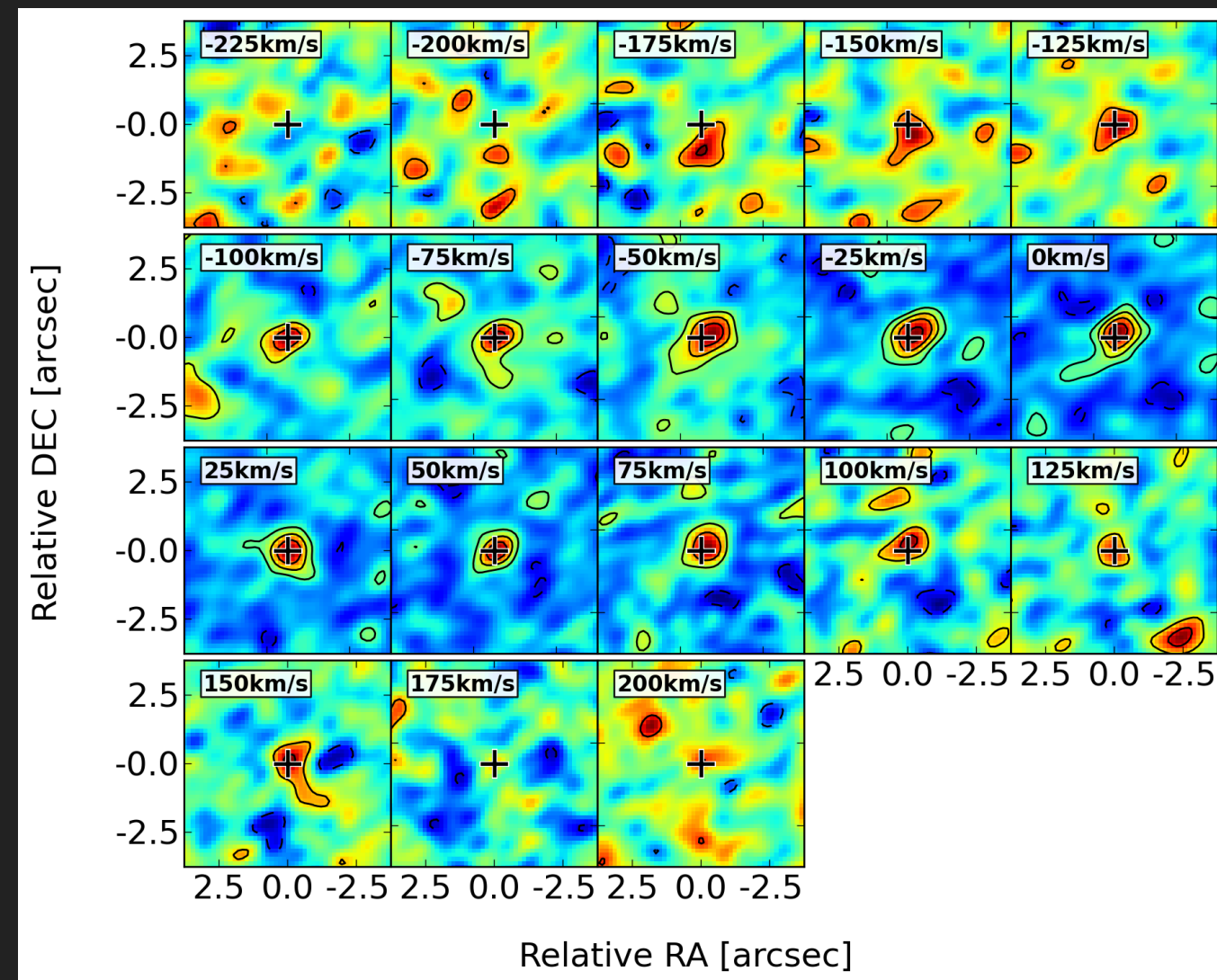
North et al. (2019)

THE VERSATILITY OF DATA CUBES



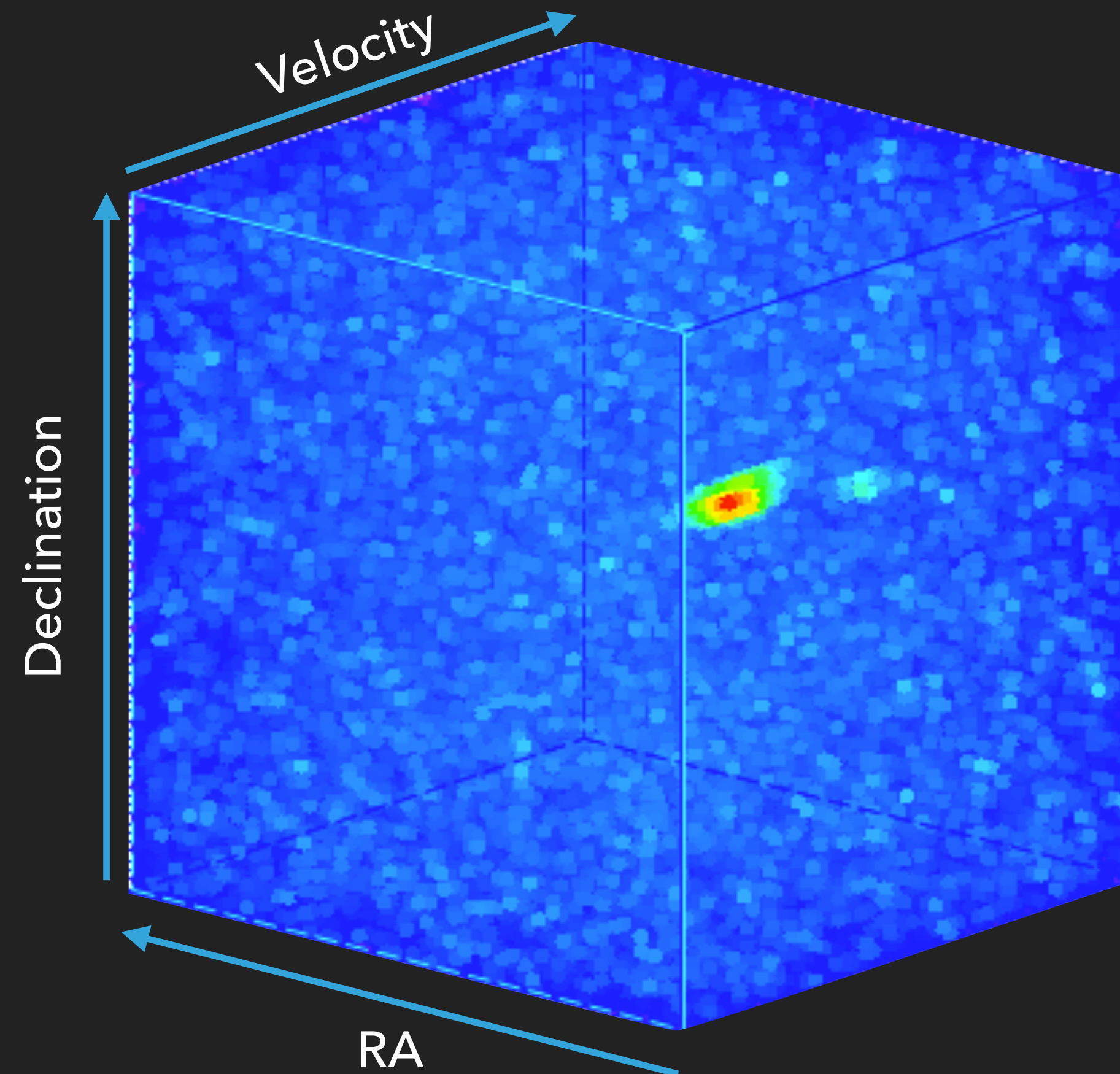
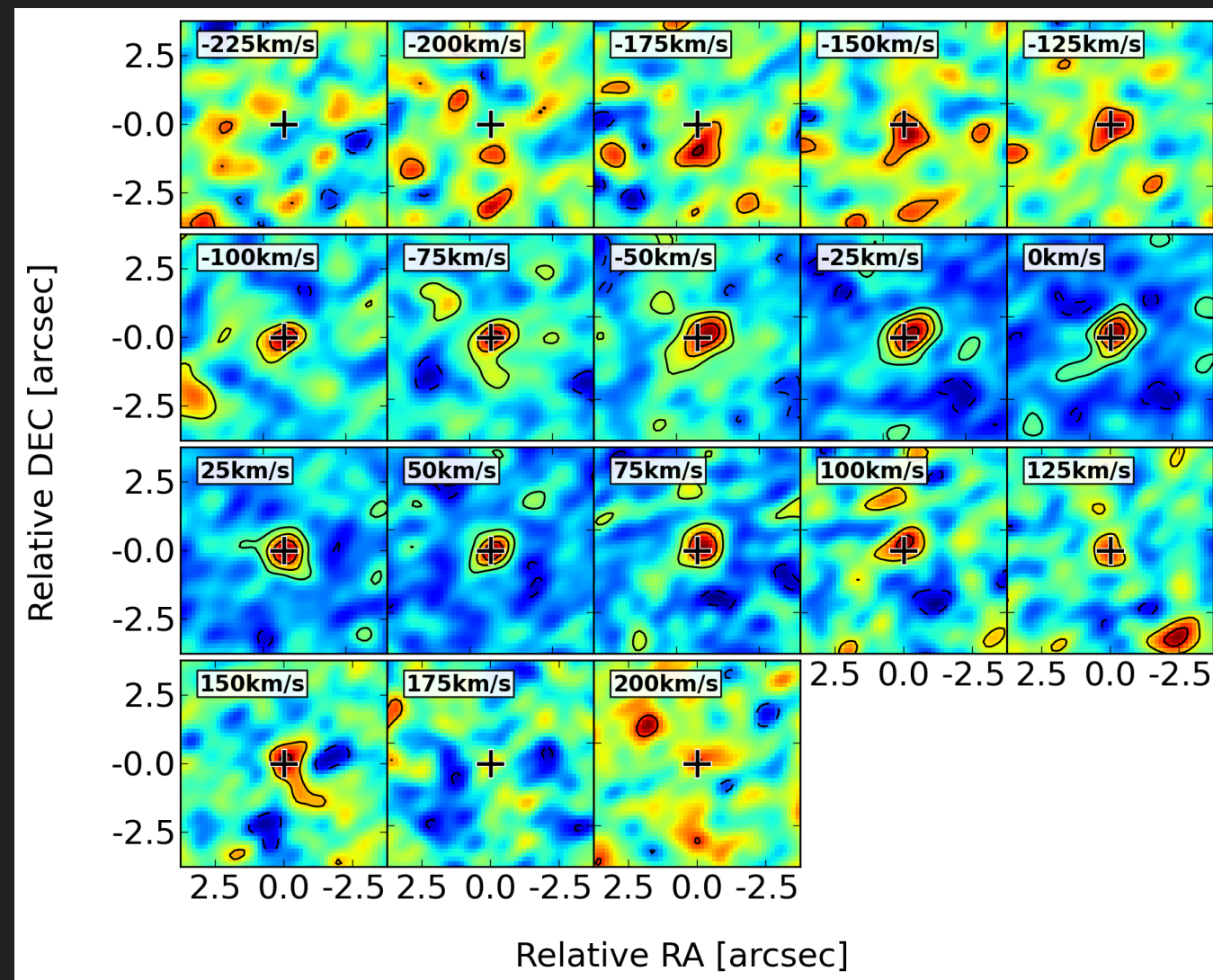
THE VERSATILITY OF DATA CUBES

1. Channel Maps

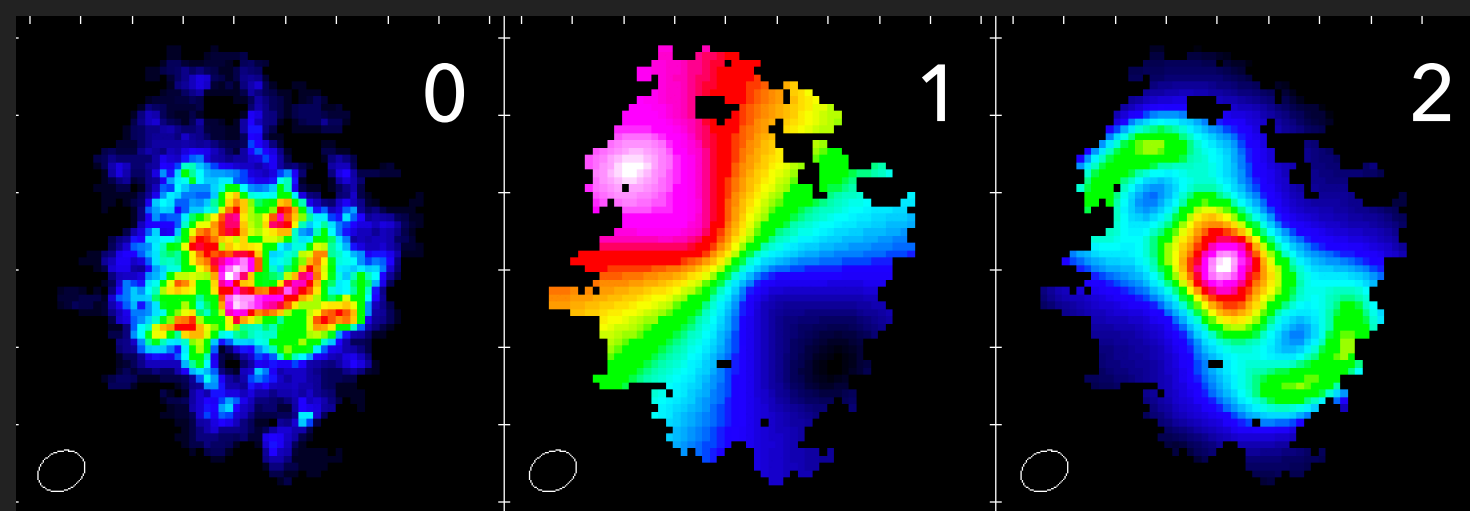


THE VERSATILITY OF DATA CUBES

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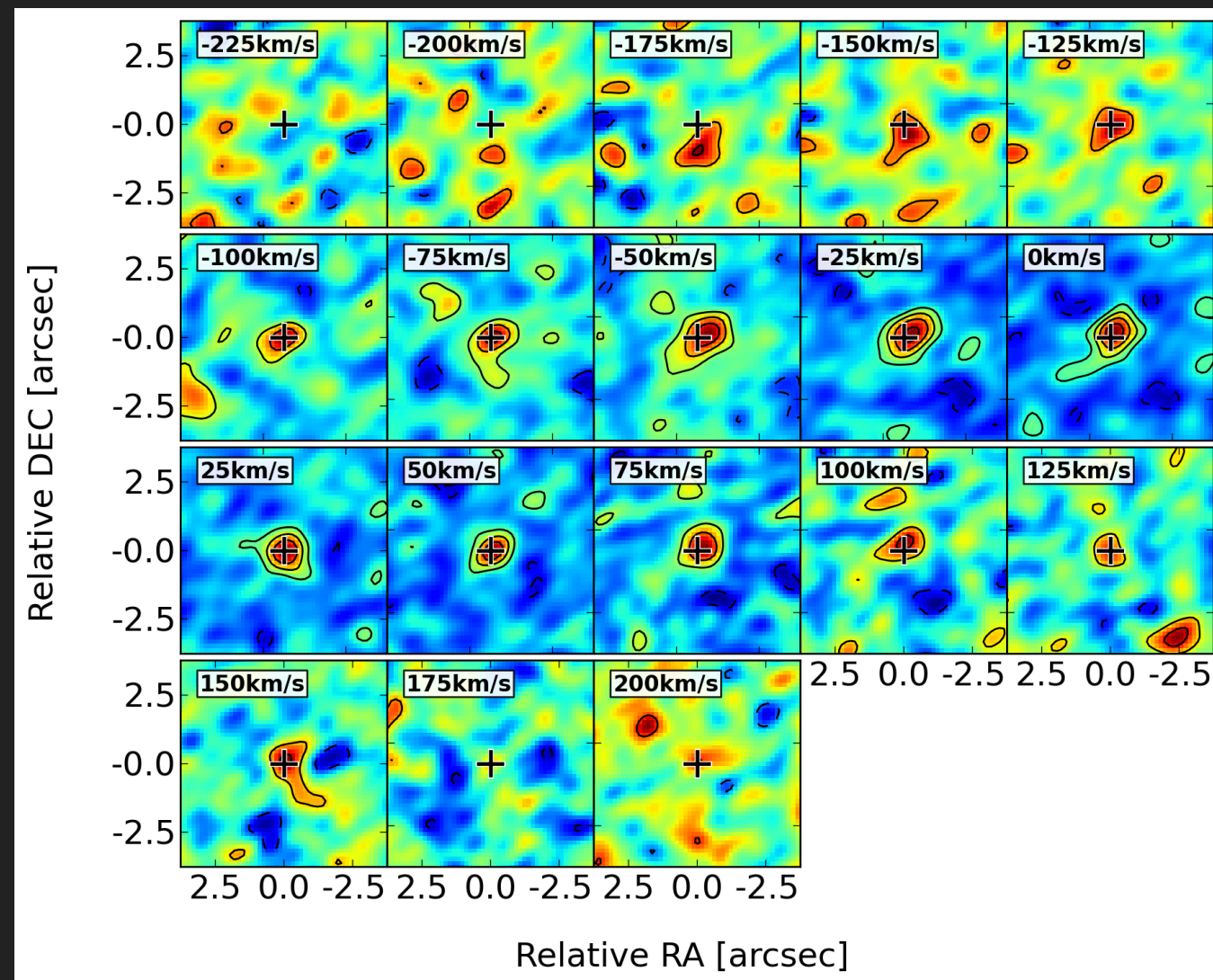


2. Moment Maps

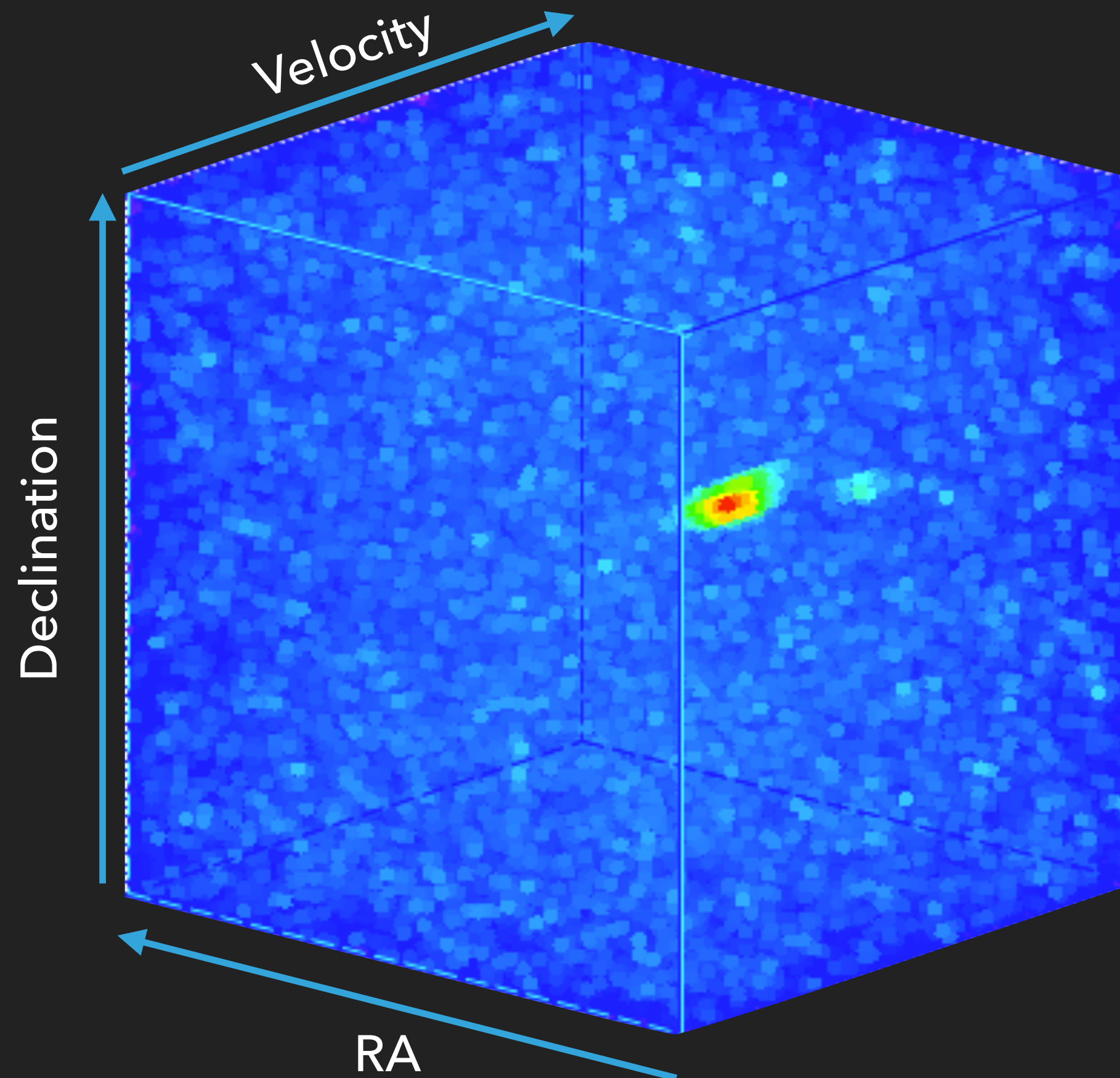
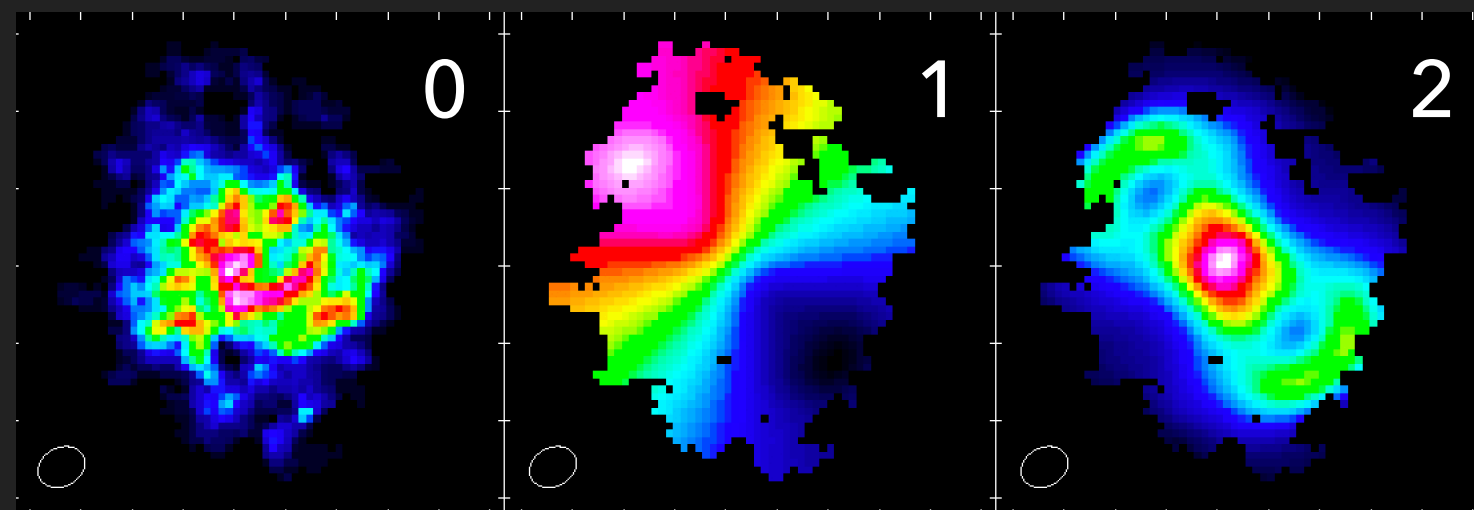


THE VERSATILITY OF DATA CUBES

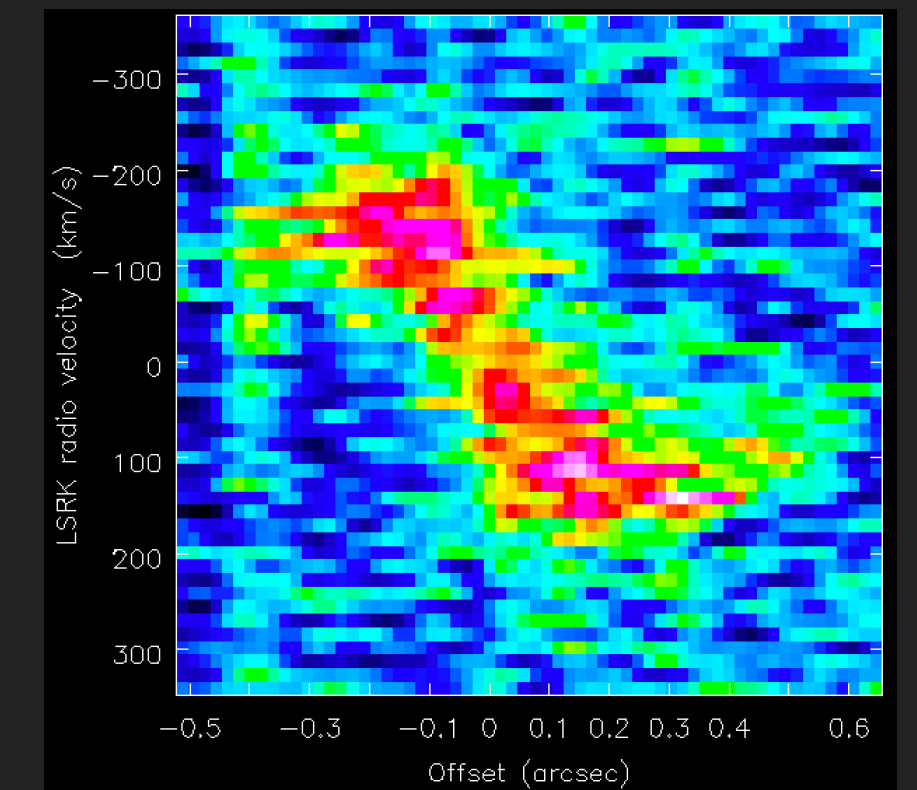
1. Channel Maps



2. Moment Maps

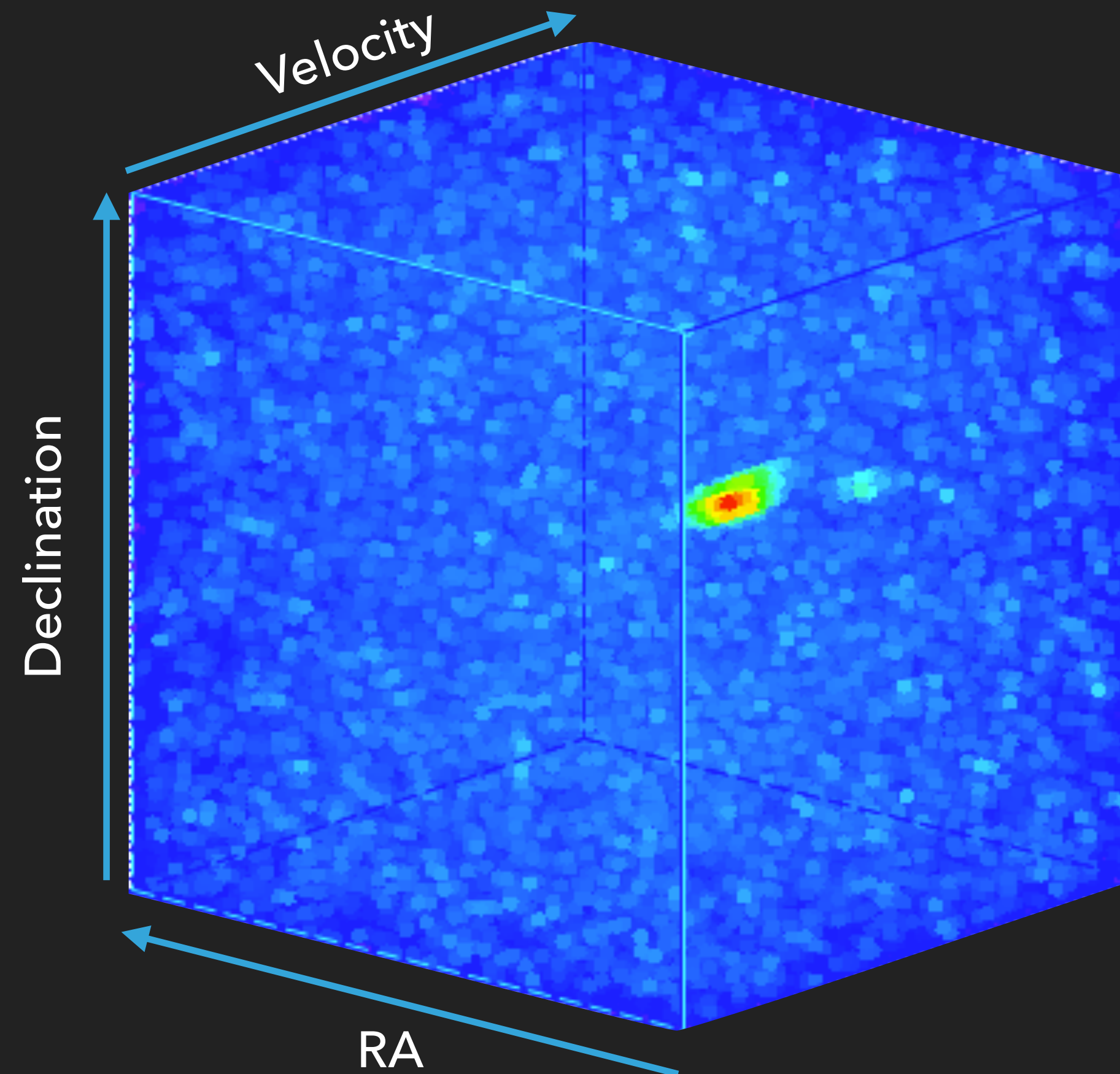
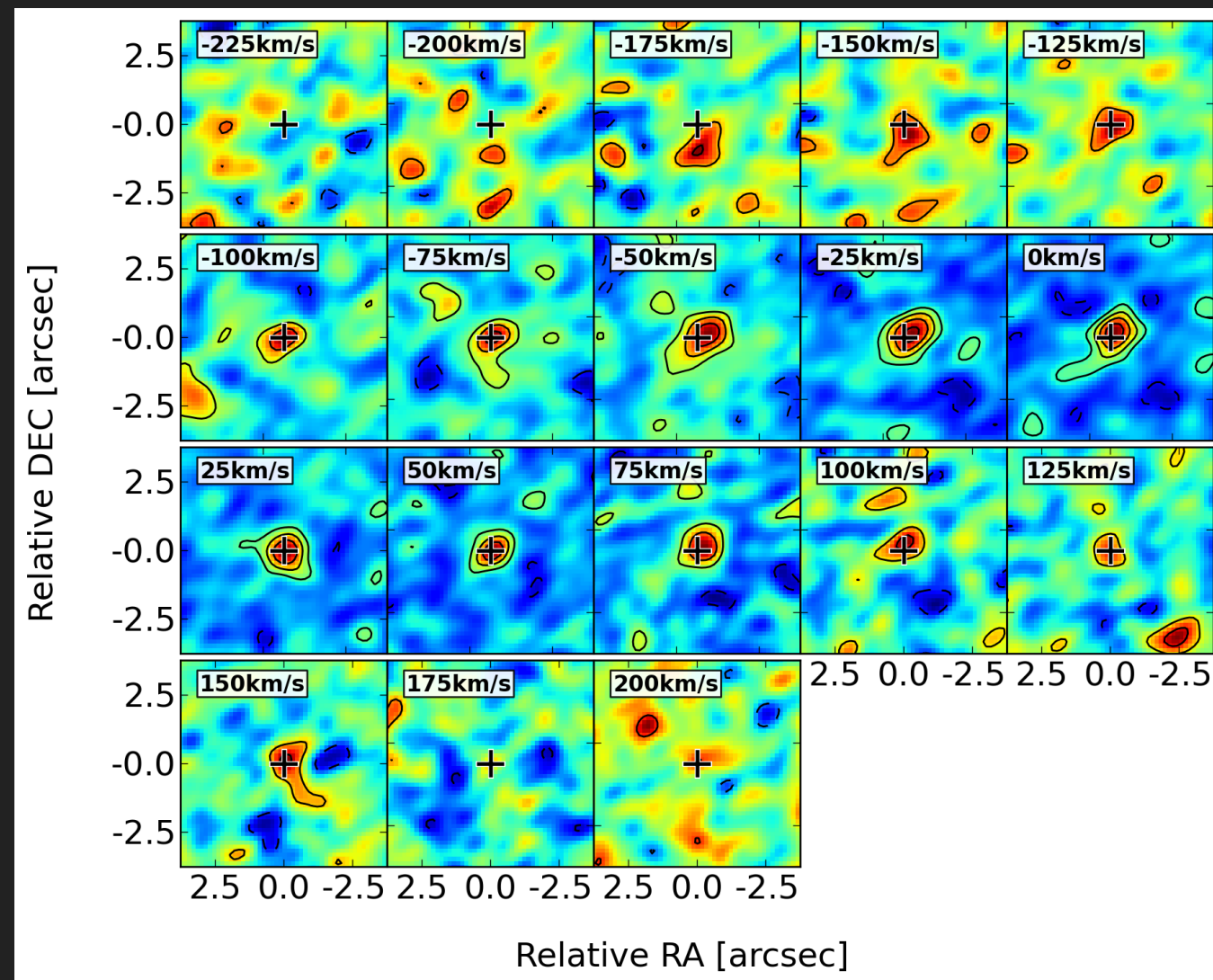


3. PVDs

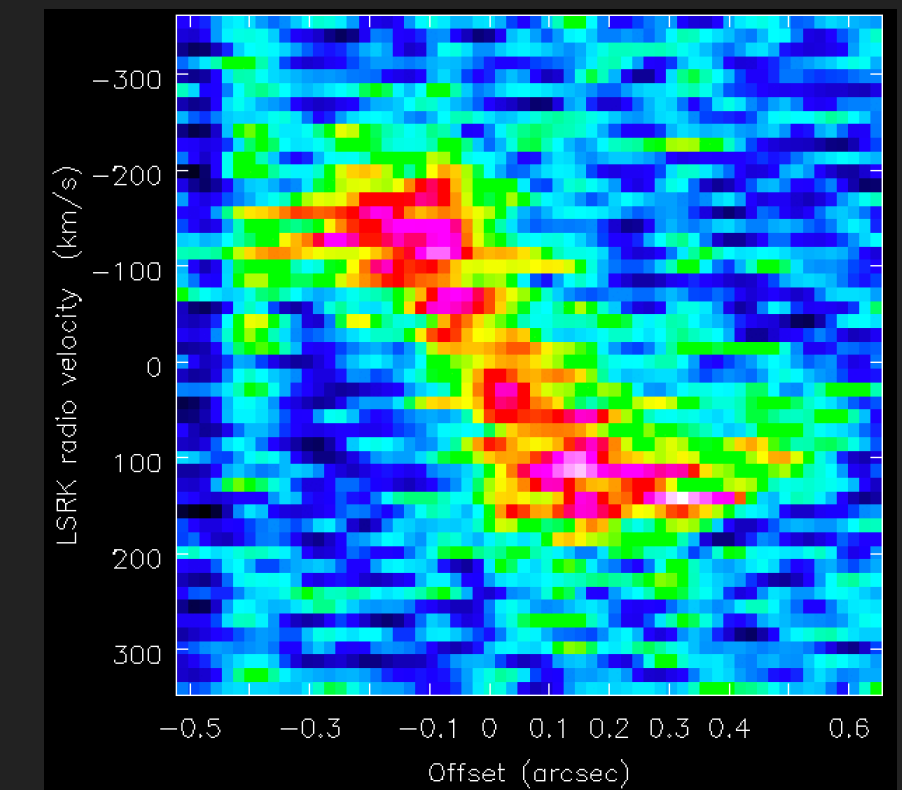


THE VERSATILITY OF DATA CUBES

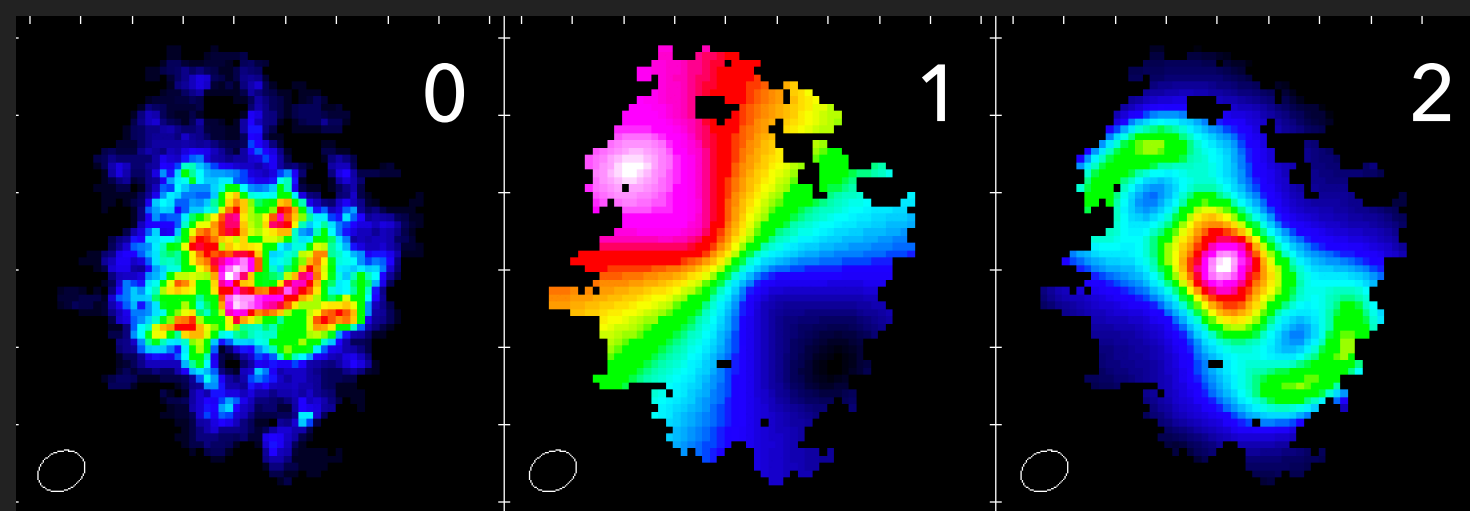
1. Channel Maps



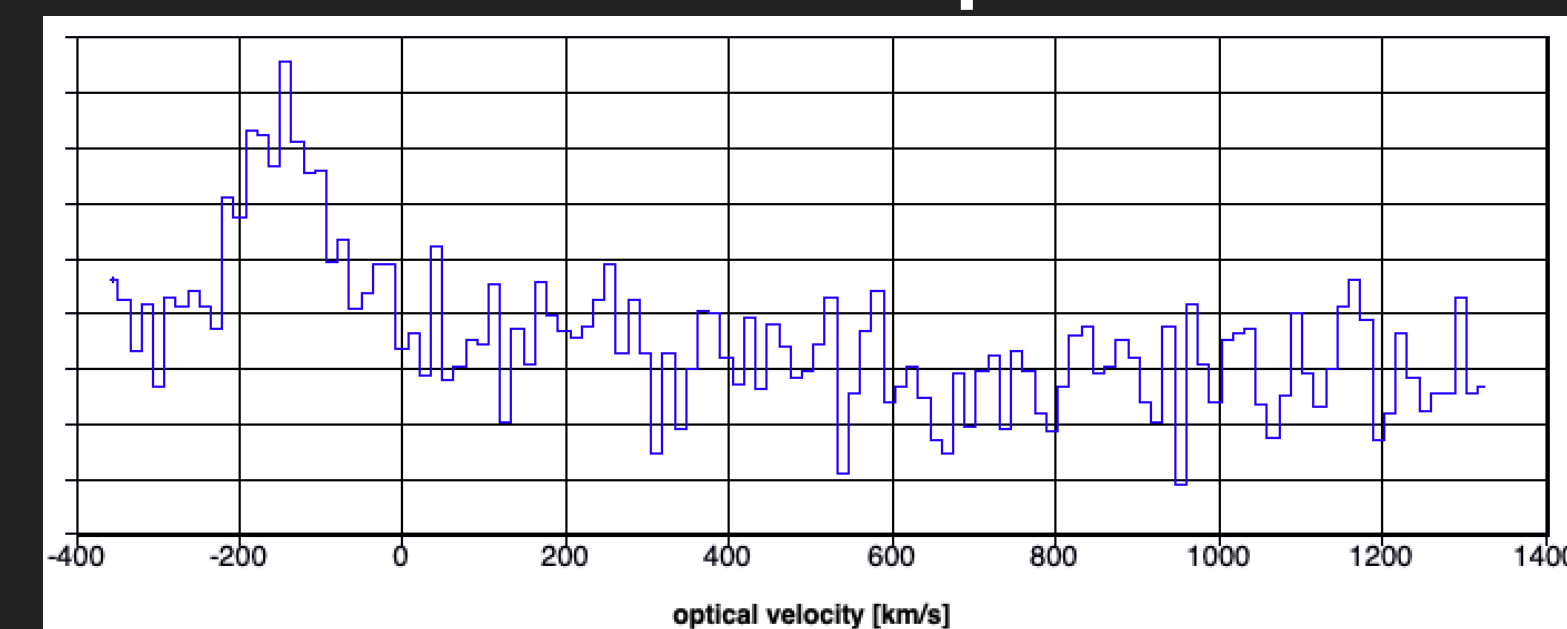
3. PVDs



2. Moment Maps



4. Various Spectra

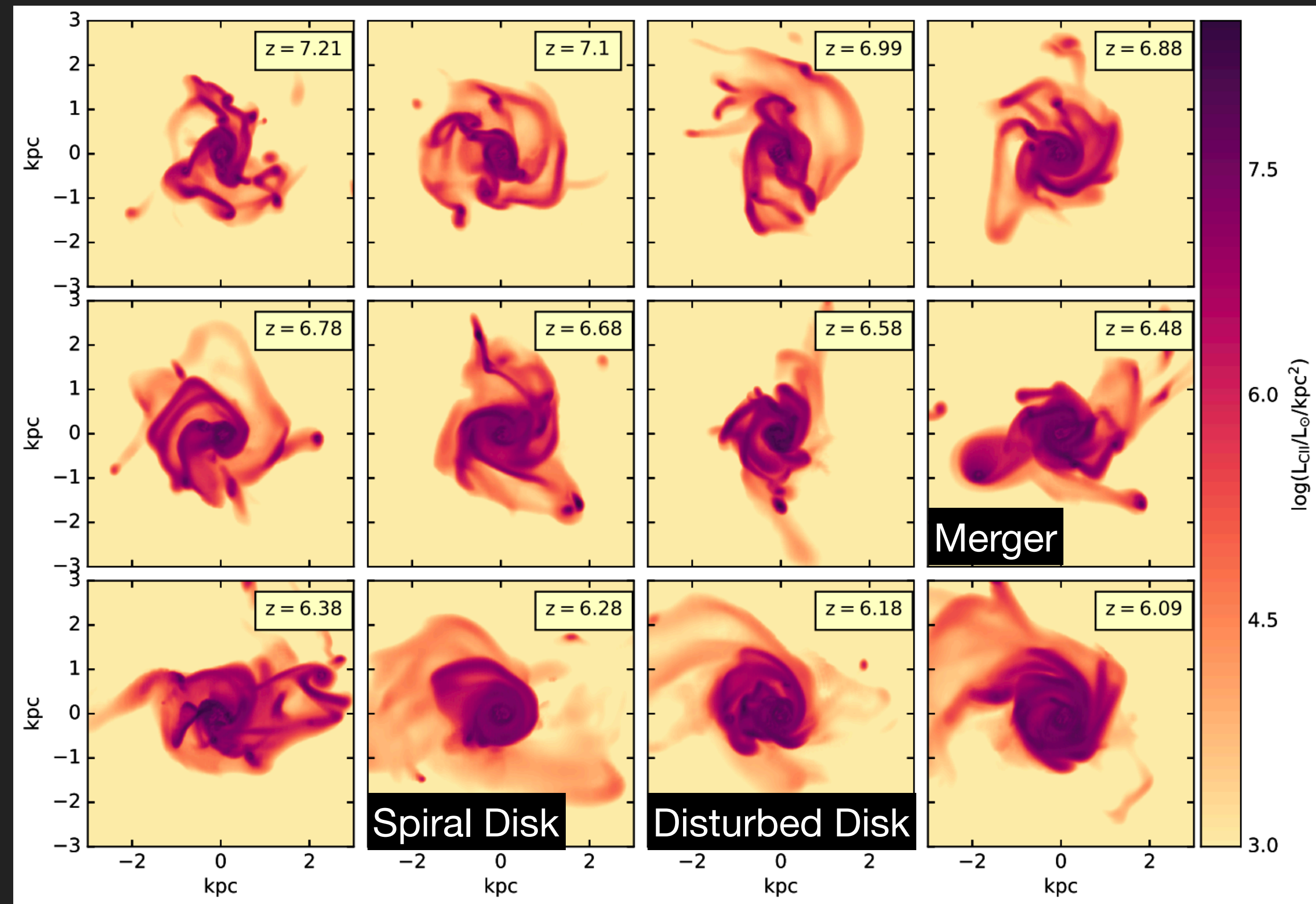
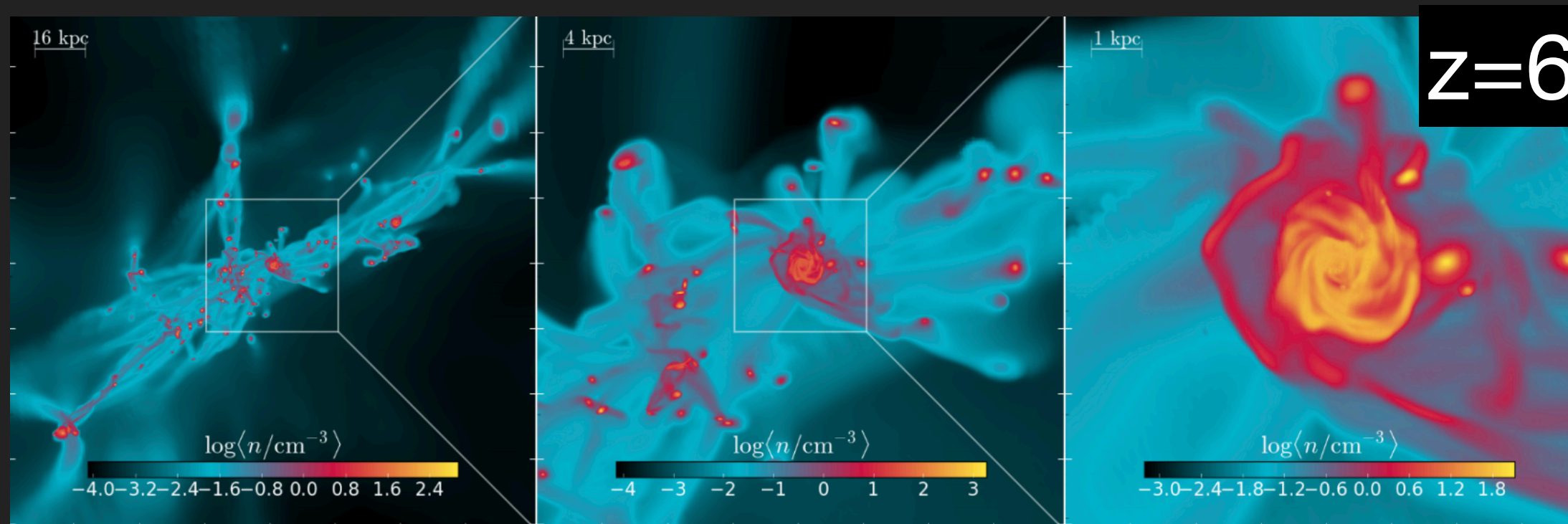


HIGH-REDSHIFT COMPLEXITY

- ▶ Simulations show strong merger influence
- ▶ Complex kinematics

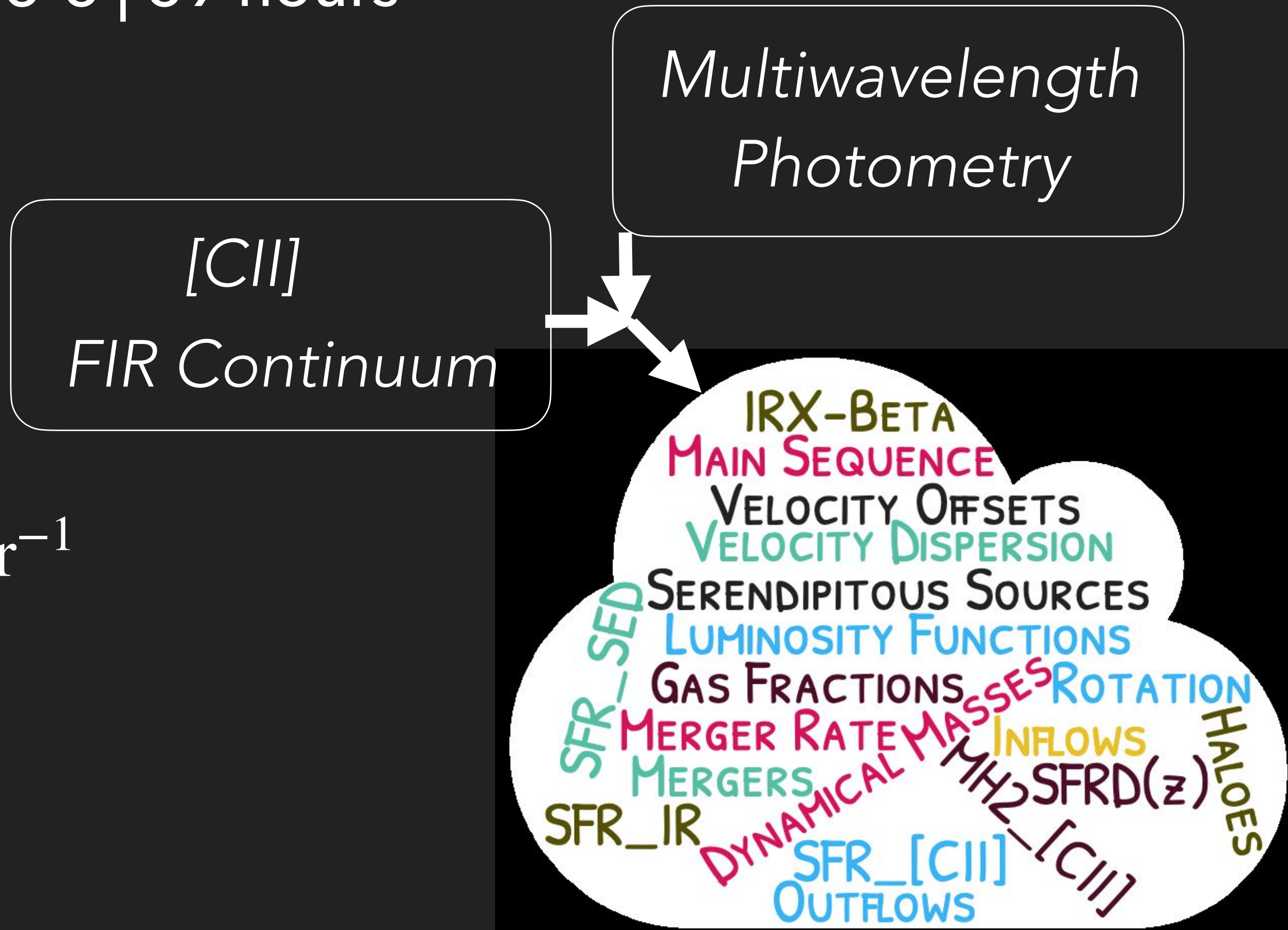
Kohandel et al. (2019)

Pallottini et al. (2017)



ALMA LARGE PROGRAM TO INVESTIGATE CII AT EARLY TIMES (ALPINE)

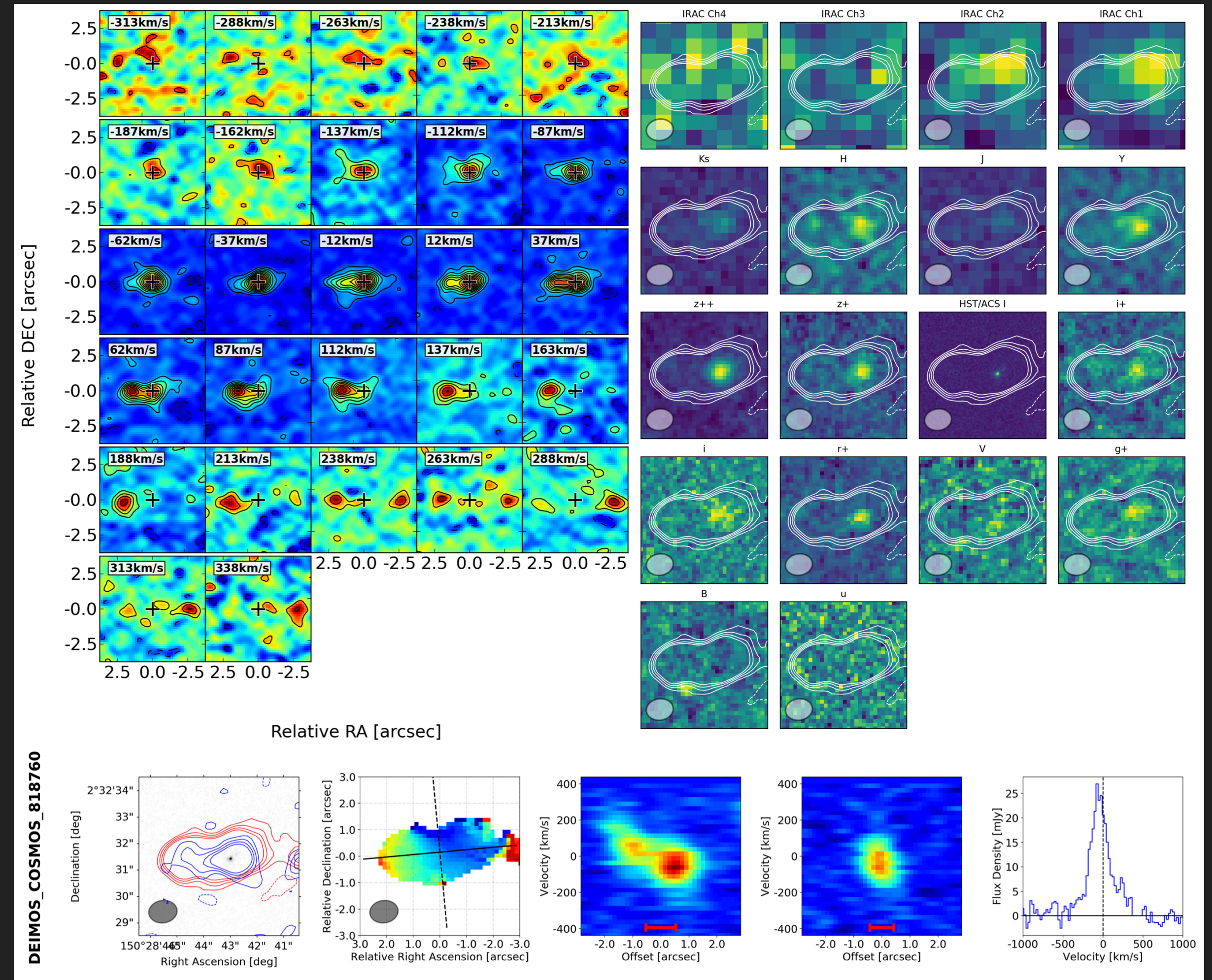
- ▶ ALMA: $\sim 1.0'' \sim 5.8 - 6.7$ kpc | Cycle 5-6 | 69 hours
- ▶ 118 Galaxies
 - ▶ $z \sim 4.4 - 4.7, 5.1 - 5.9$
 - ▶ COSMOS or GOODS-S/ECDFS
 - ▶ $M_{1500\text{\AA}} < -20.2$, or $\text{SFR} > 10 M_{\odot} \text{yr}^{-1}$
 - ▶ No AGN



Le Fèvre et al. (2020)

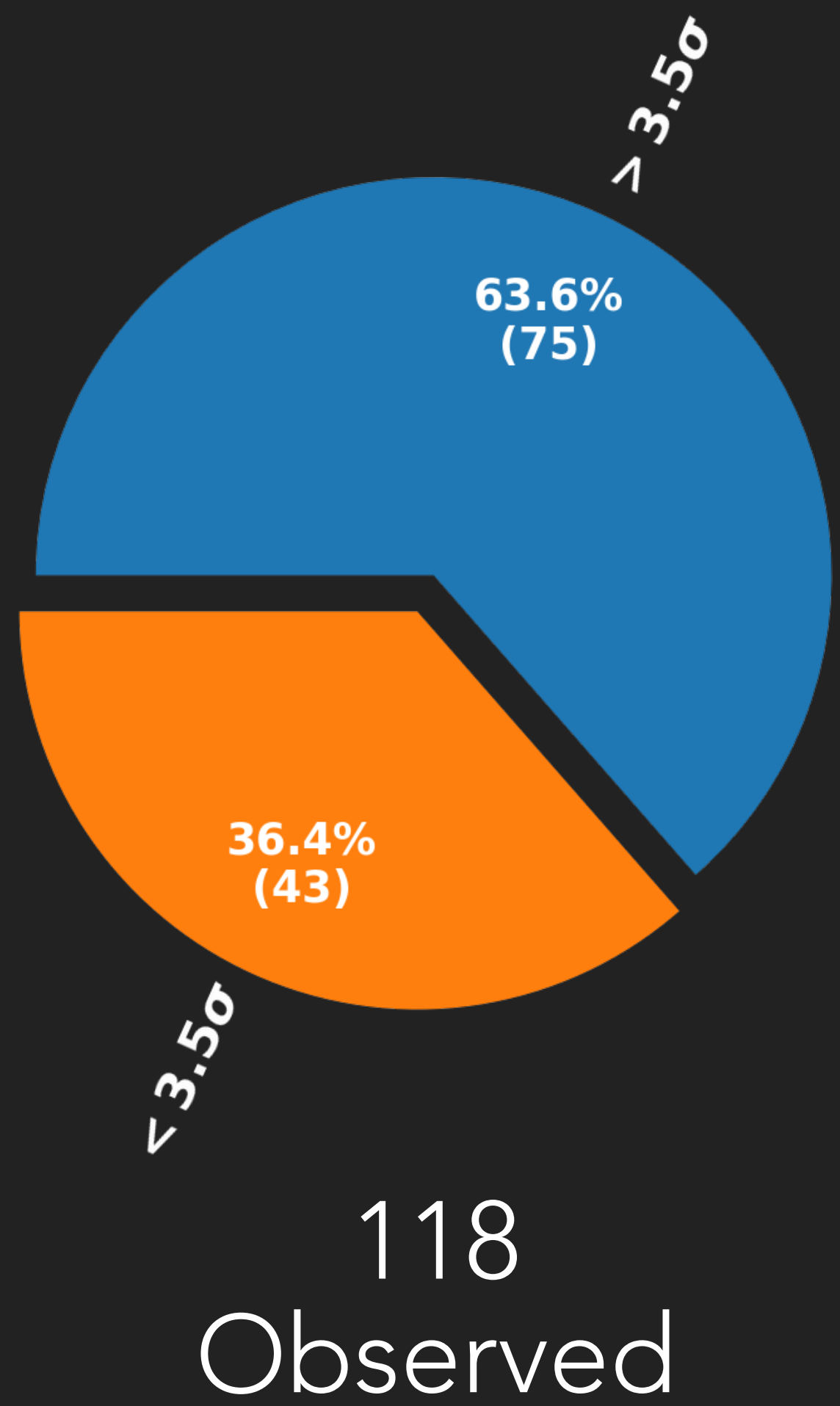
MORPHO-KINEMATIC CLASSIFICATION

- ▶ Visual inspection by 8 members
- ▶ 5 Classes:
 - ▶ Rotator
 - ▶ Merger
 - ▶ Extended Dispersion-Dominated DD_E
 - ▶ Compact Dispersion-Dominated DD_C
 - ▶ Too Weak To Tell



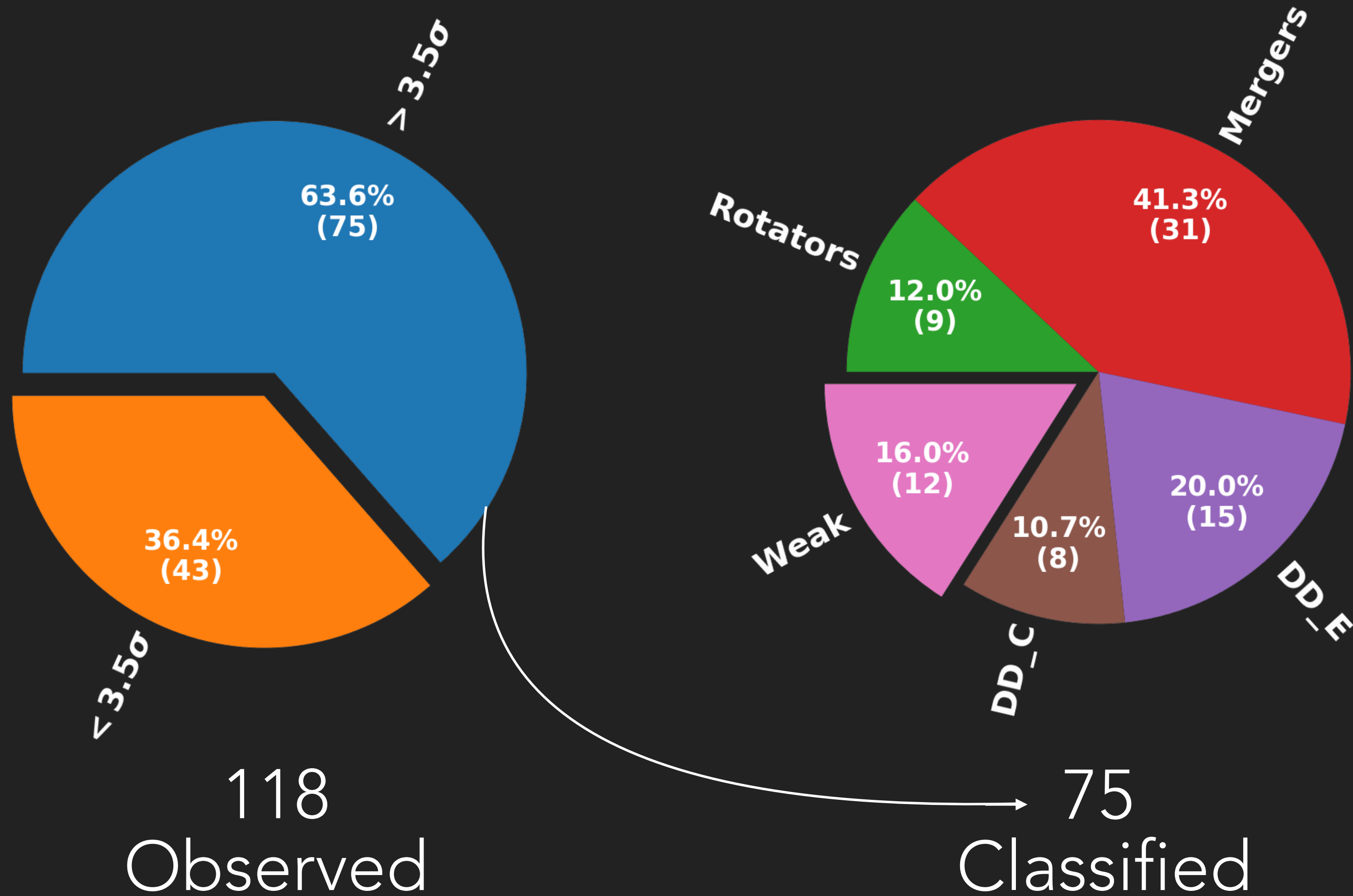
Le Fèvre et al. (2020)

KINEMATIC CLASSIFICATION (RESULTS)



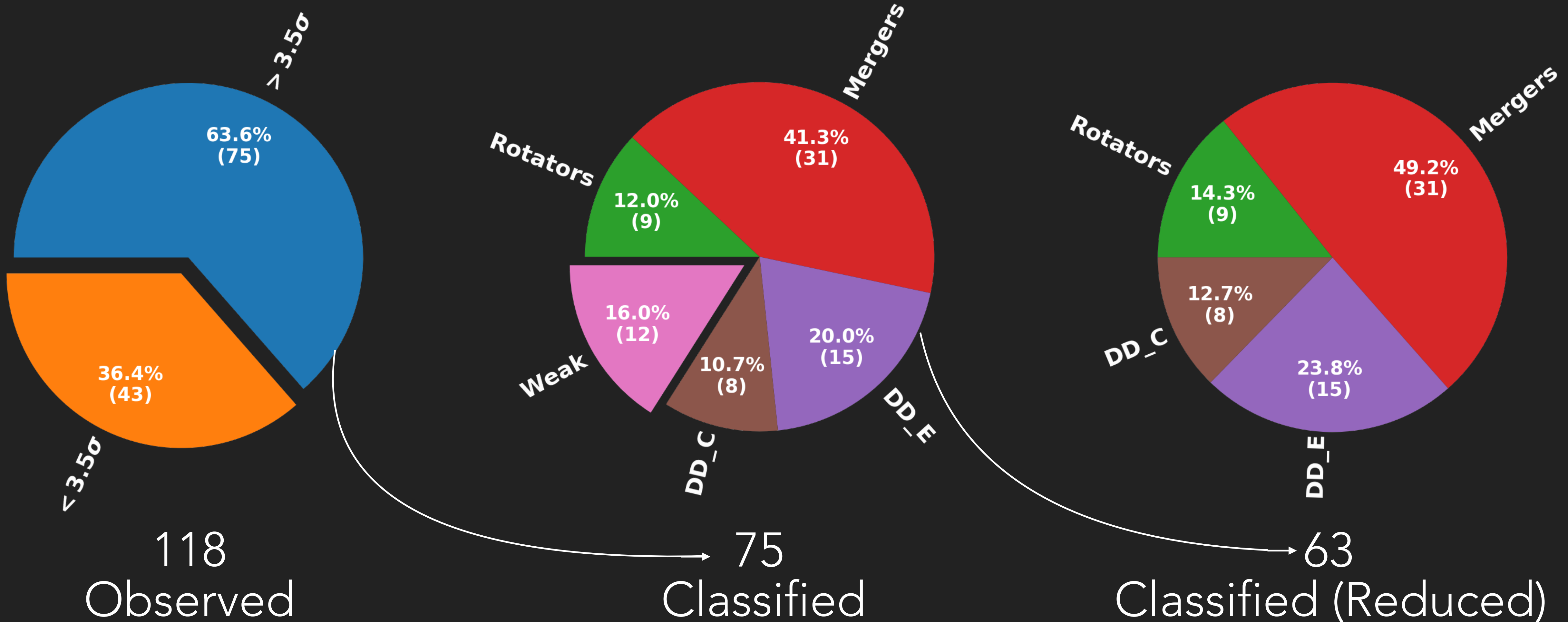
Le Fèvre et al. (2020)

KINEMATIC CLASSIFICATION (RESULTS)



Le Fèvre et al. (2020)

KINEMATIC CLASSIFICATION (RESULTS)



TILTED RING MODEL FITTING

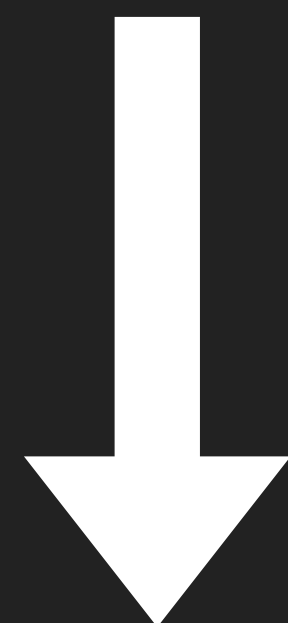
TILTED RING MODEL FITTING

$R, \delta R, Z_0, \text{incl}, \text{PA}$

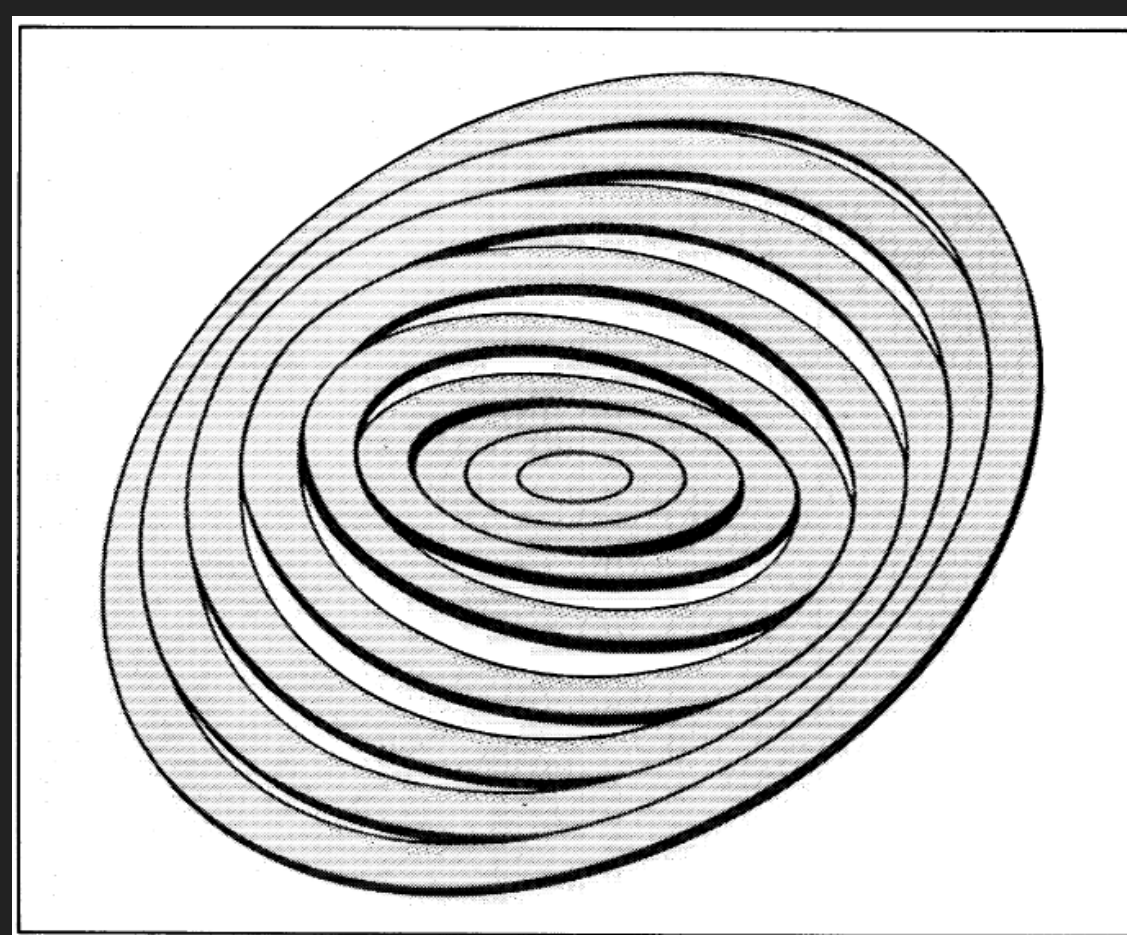
$V_{\text{rot}}(r), V_{\text{disp}}(r), V_{\text{sys}}$

TILTED RING MODEL FITTING

$R, \delta R, Z_0, \text{incl}, \text{PA}$
 $V_{\text{rot}}(r), V_{\text{disp}}(r), V_{\text{sys}}$



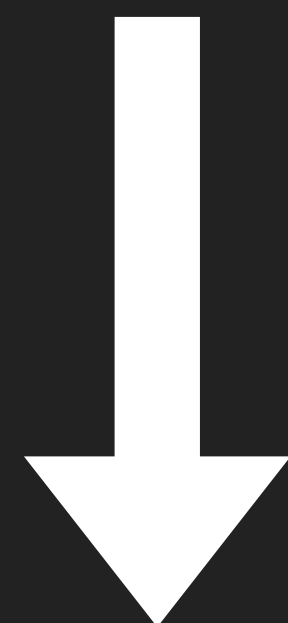
Physical Model Cube



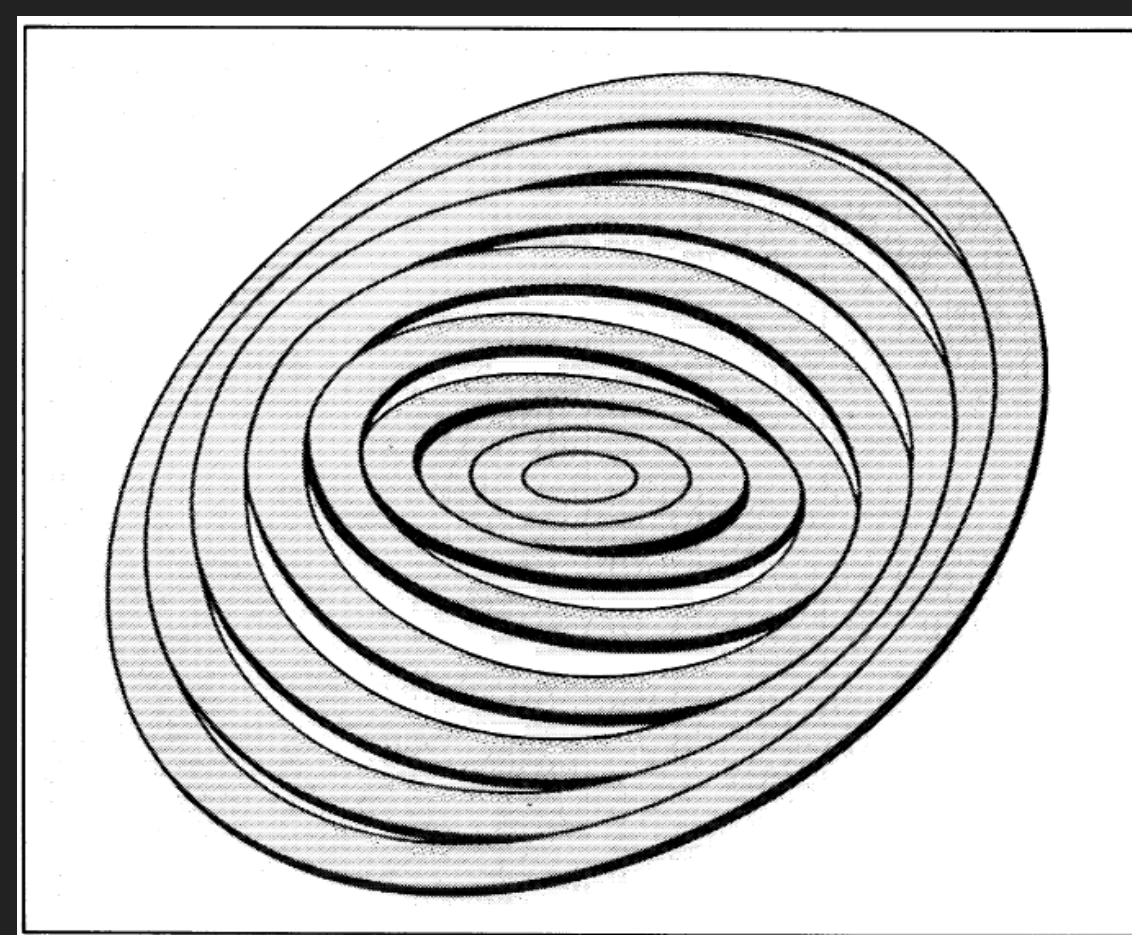
Rogstad et al. (1974)

TILTED RING MODEL FITTING

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 $V_{\text{rot}}(r), V_{\text{disp}}(r), V_{\text{sys}}$

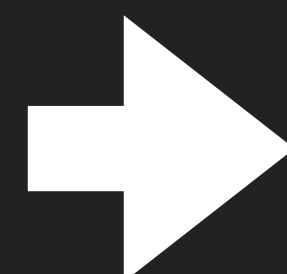
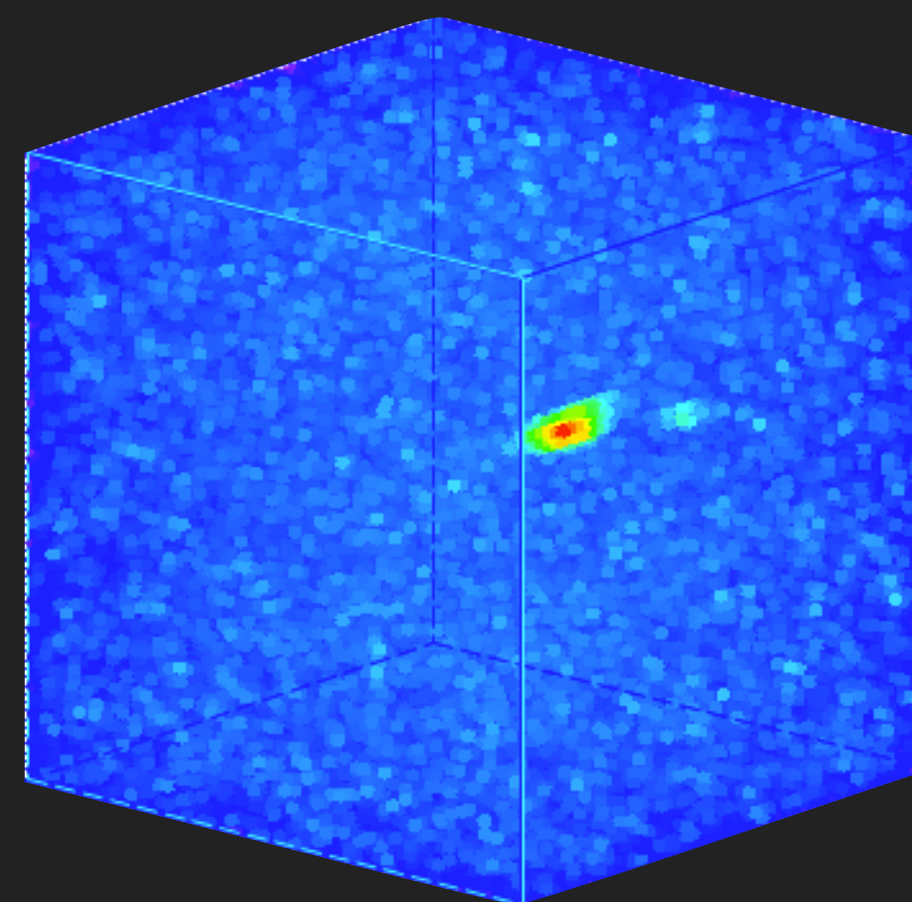


Physical Model Cube



Rogstad et al. (1974)

Observational Model Cube

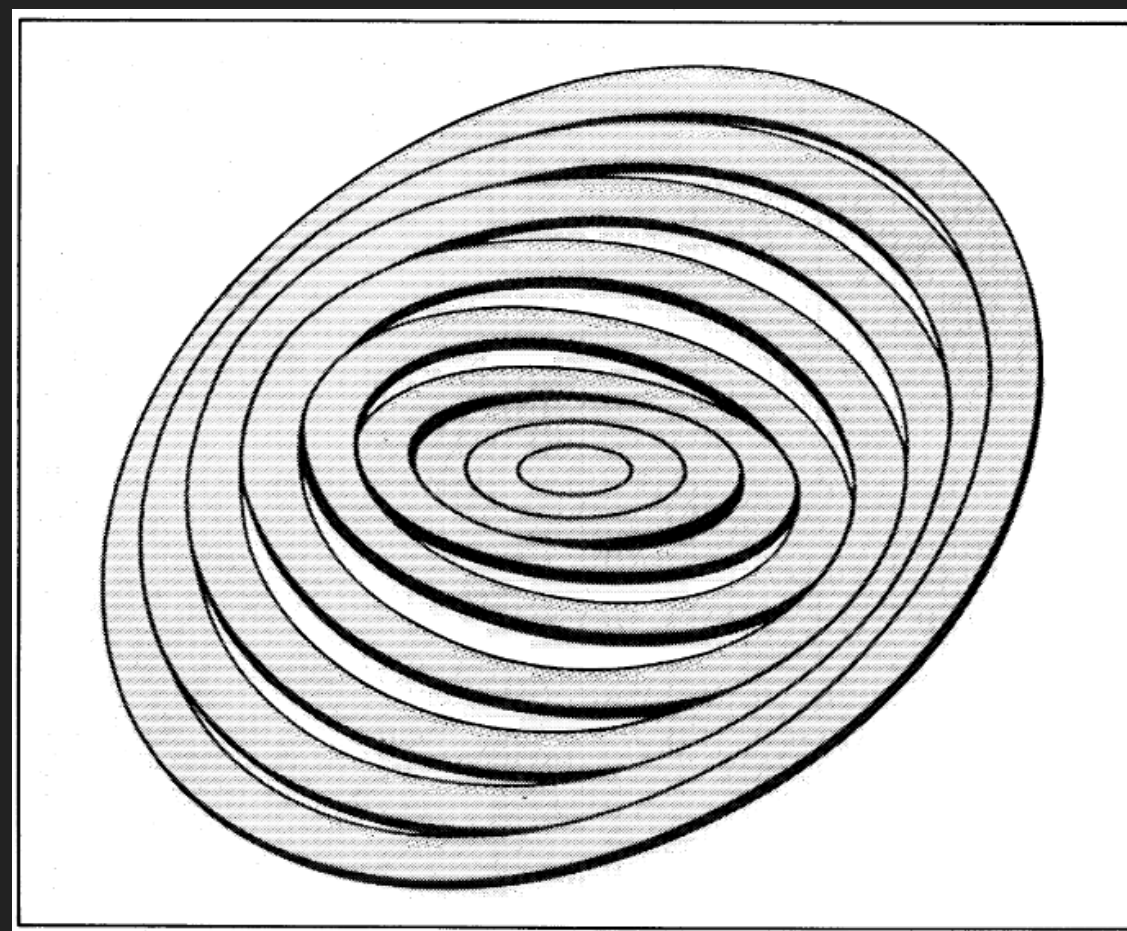


TILTED RING MODEL FITTING

$R, \delta R, Z_0, \text{incl}, \text{PA}$
 $V_{\text{rot}}(r), V_{\text{disp}}(r), V_{\text{sys}}$

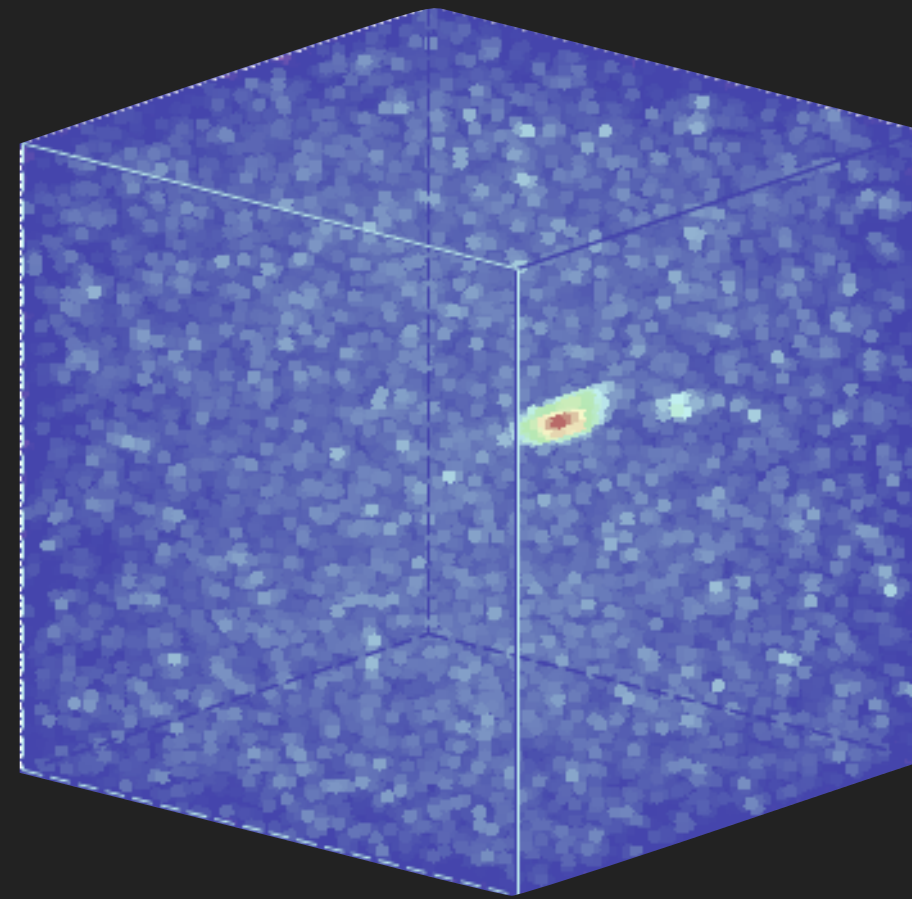


Physical Model Cube

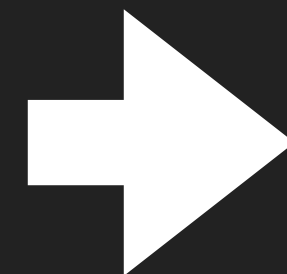
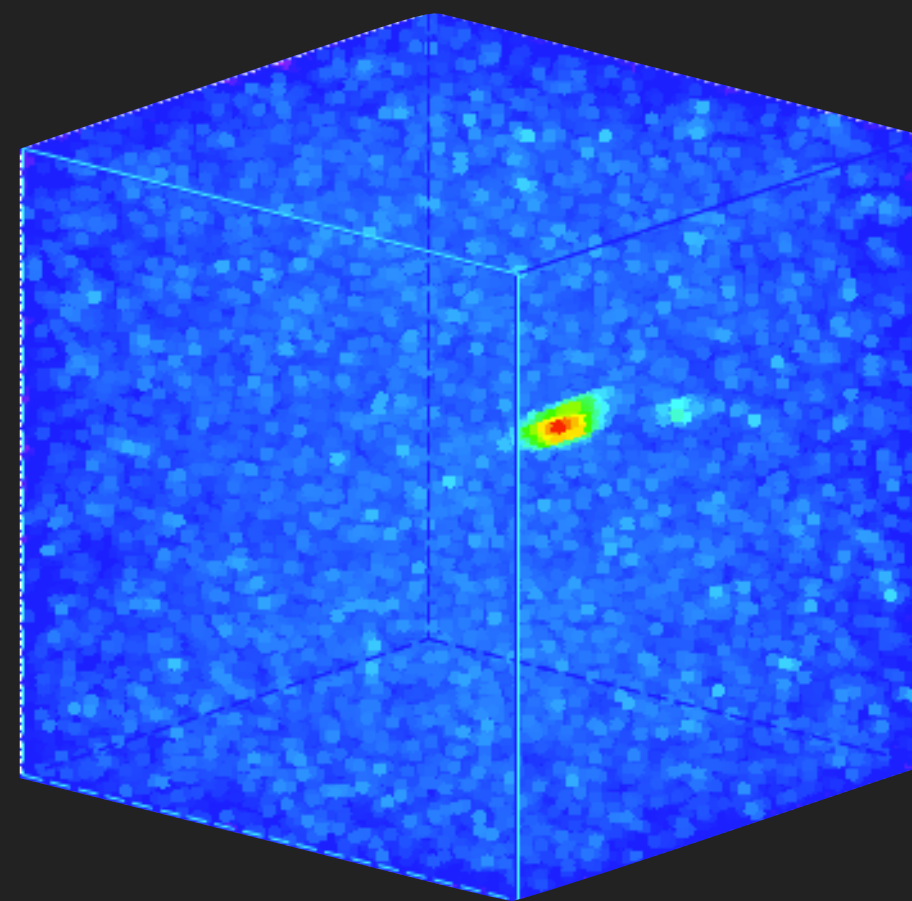


Rogstad et al. (1974)

Observational Data Cube

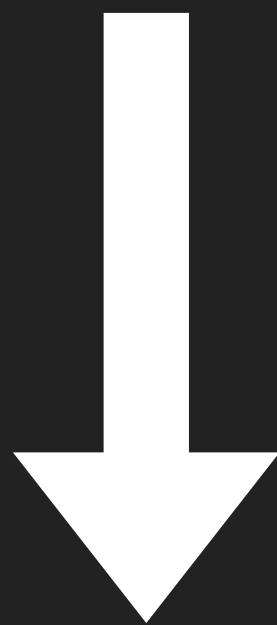


Observational Model Cube

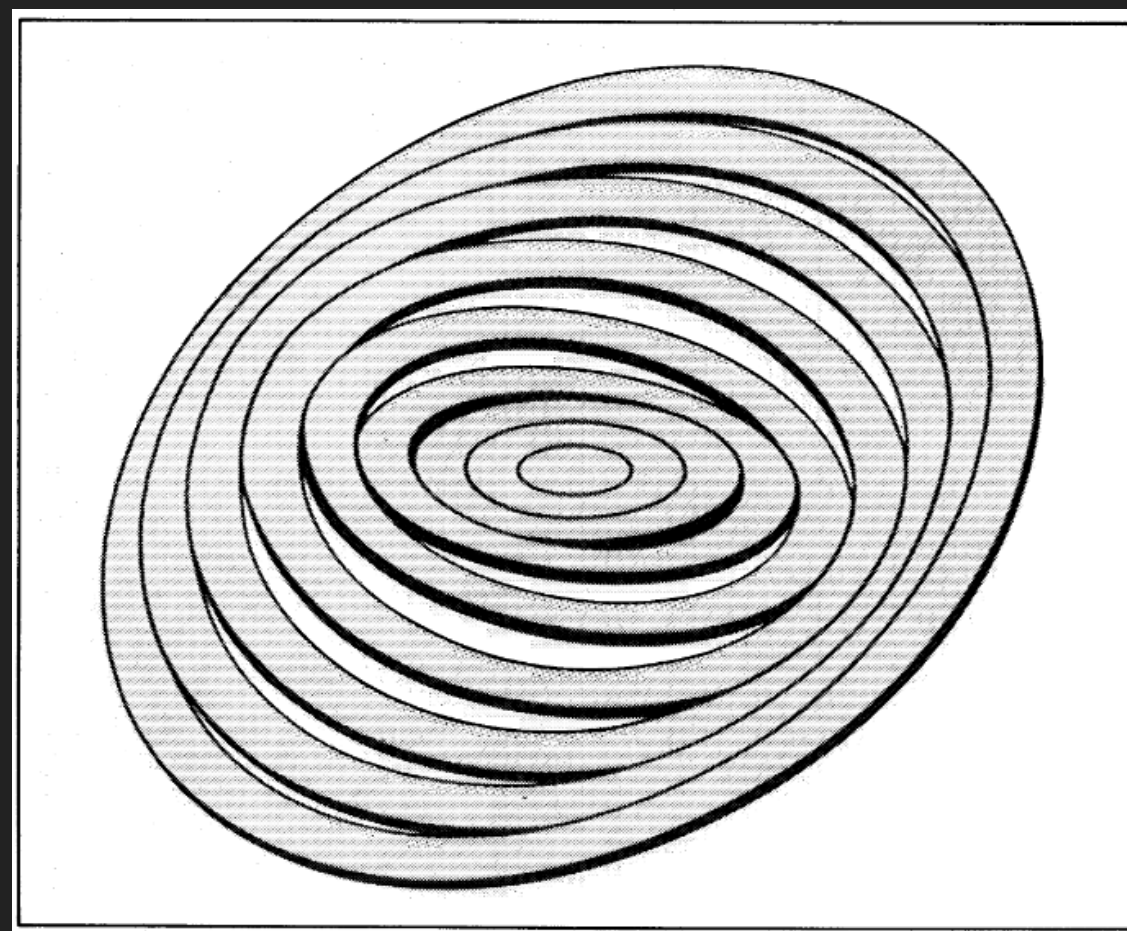


TILTED RING MODEL FITTING

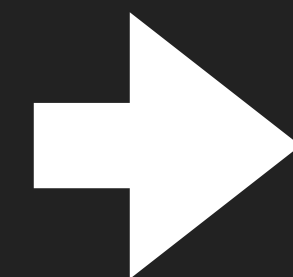
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 $V_{\text{rot}}(r), V_{\text{disp}}(r), V_{\text{sys}}$



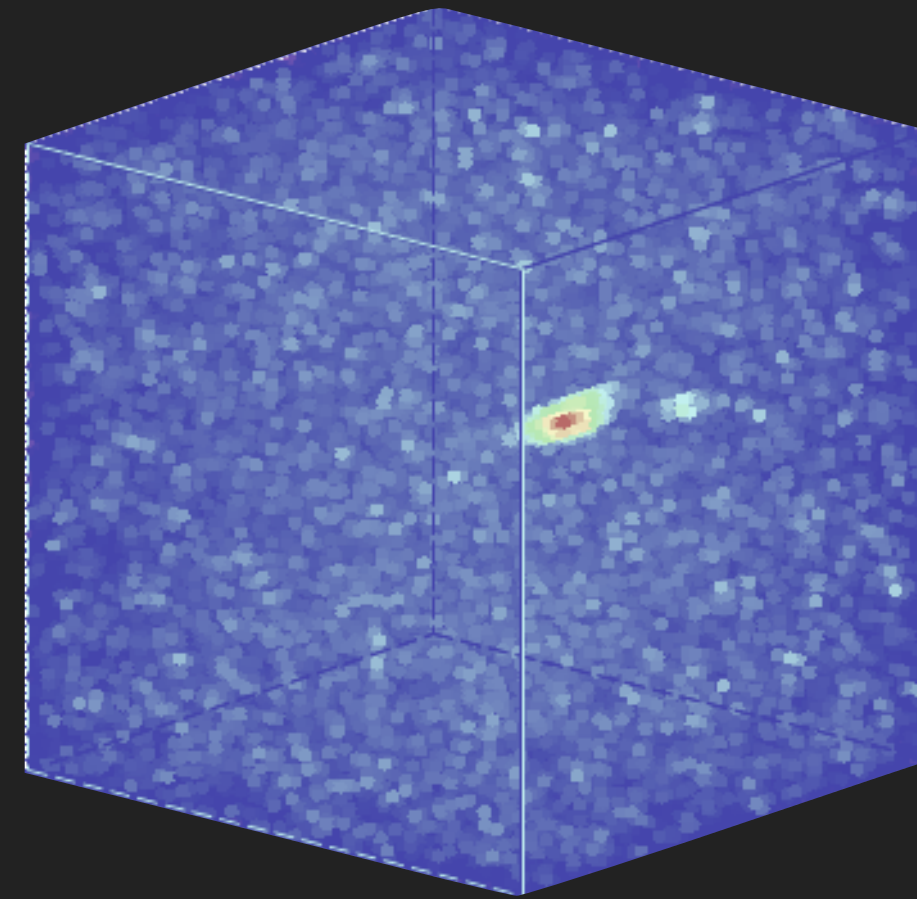
Physical Model Cube



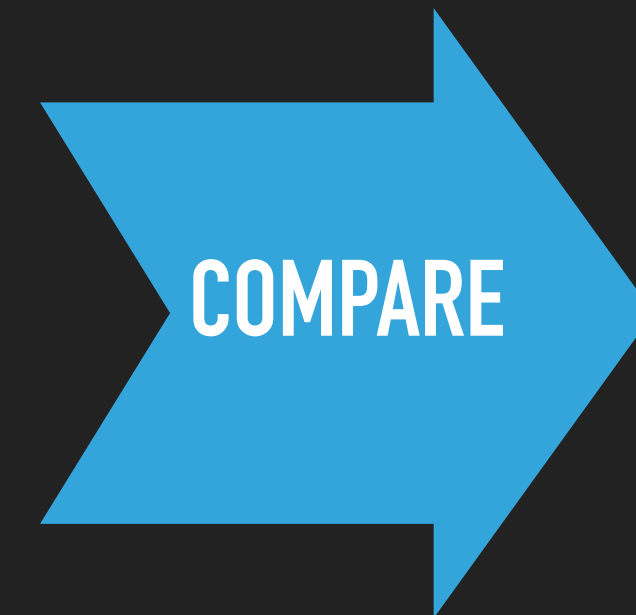
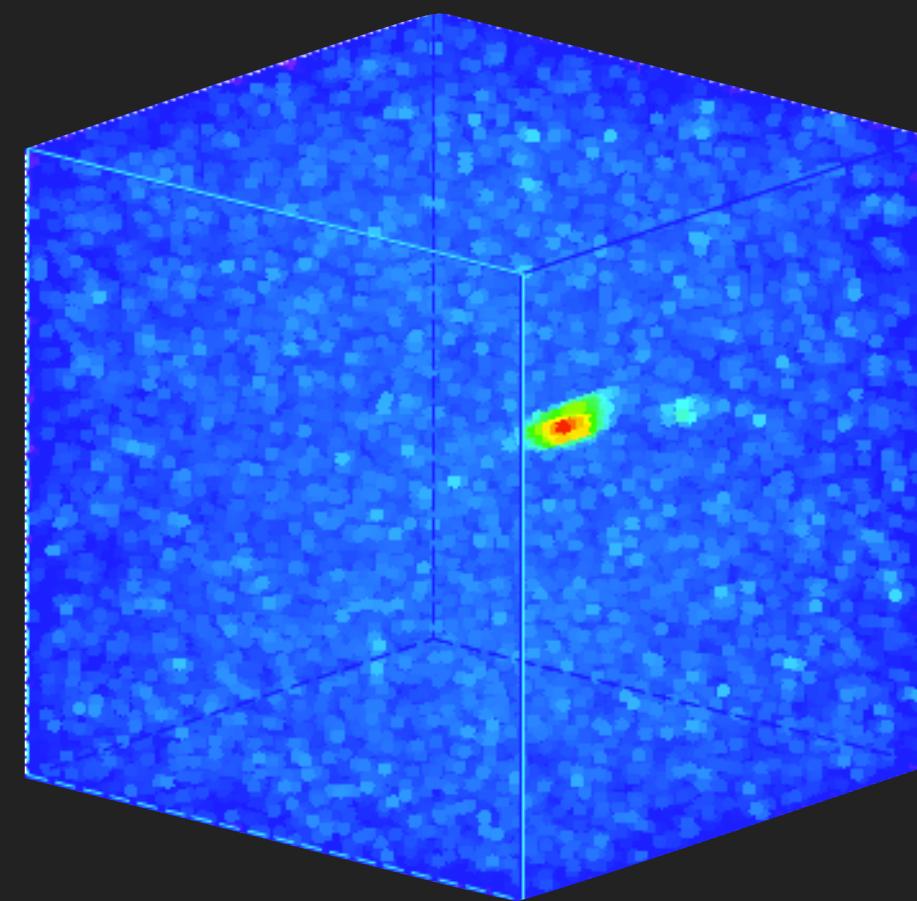
Rogstad et al. (1974)



Observational Data Cube



Observational Model Cube

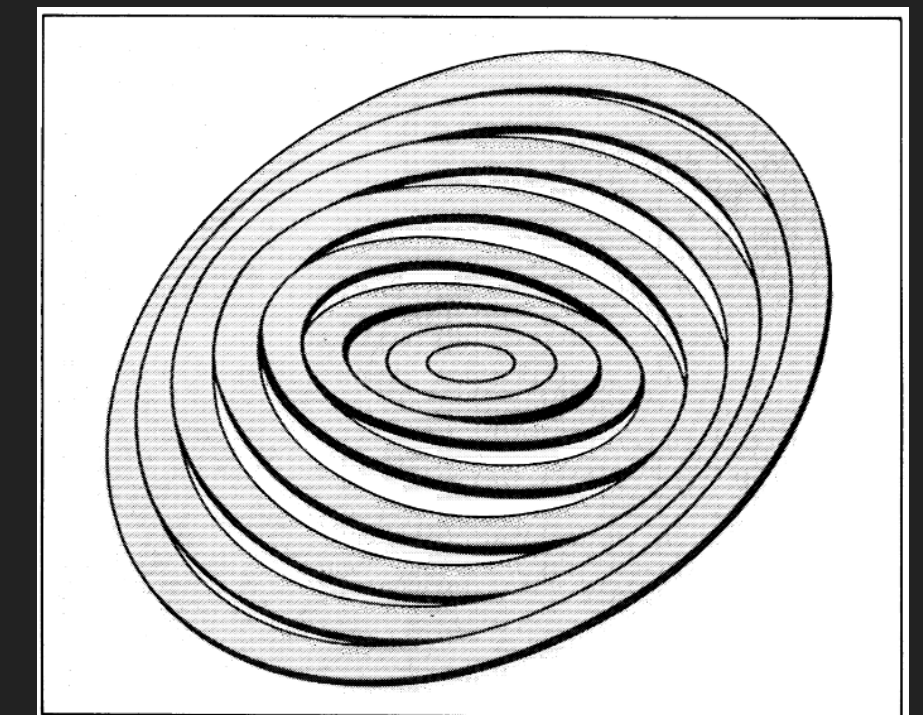
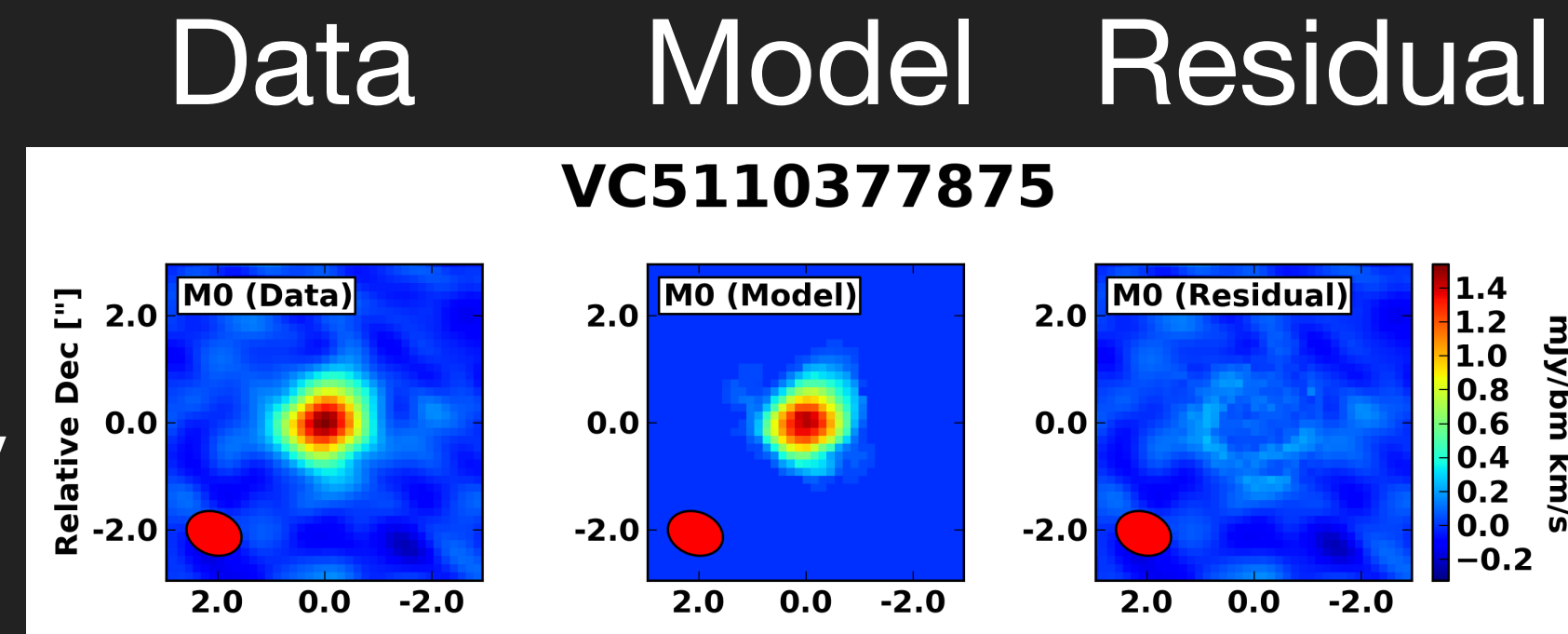


- ▶ Best-fit parameters
- ▶ Model cube

ROTATIONAL MODELLING (3DBAROLO)

Fujimoto et al. (2020)
Jones et al. (2021)

Integrated Intensity



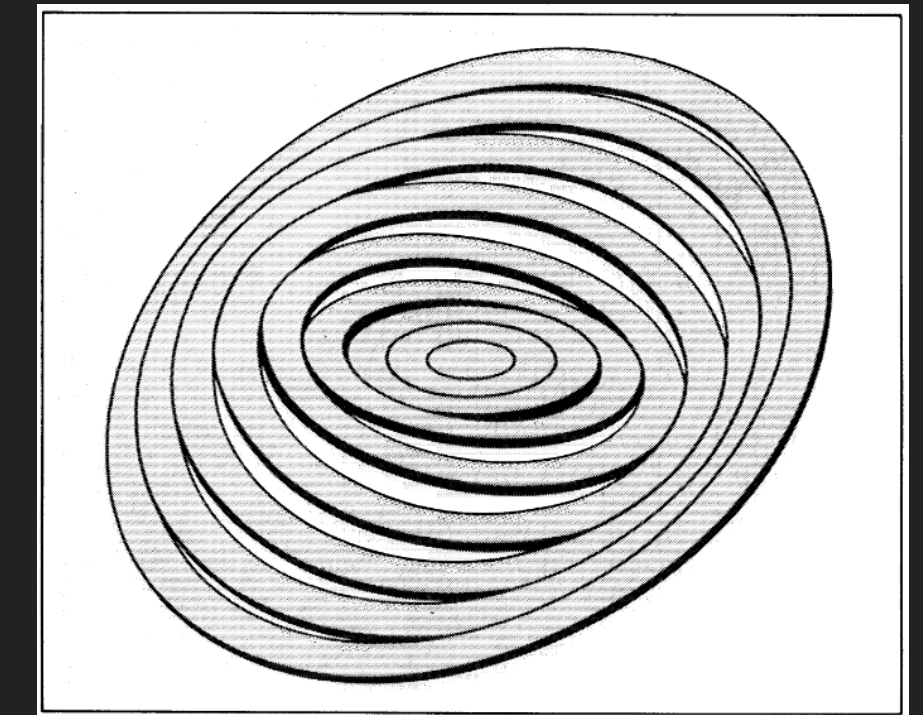
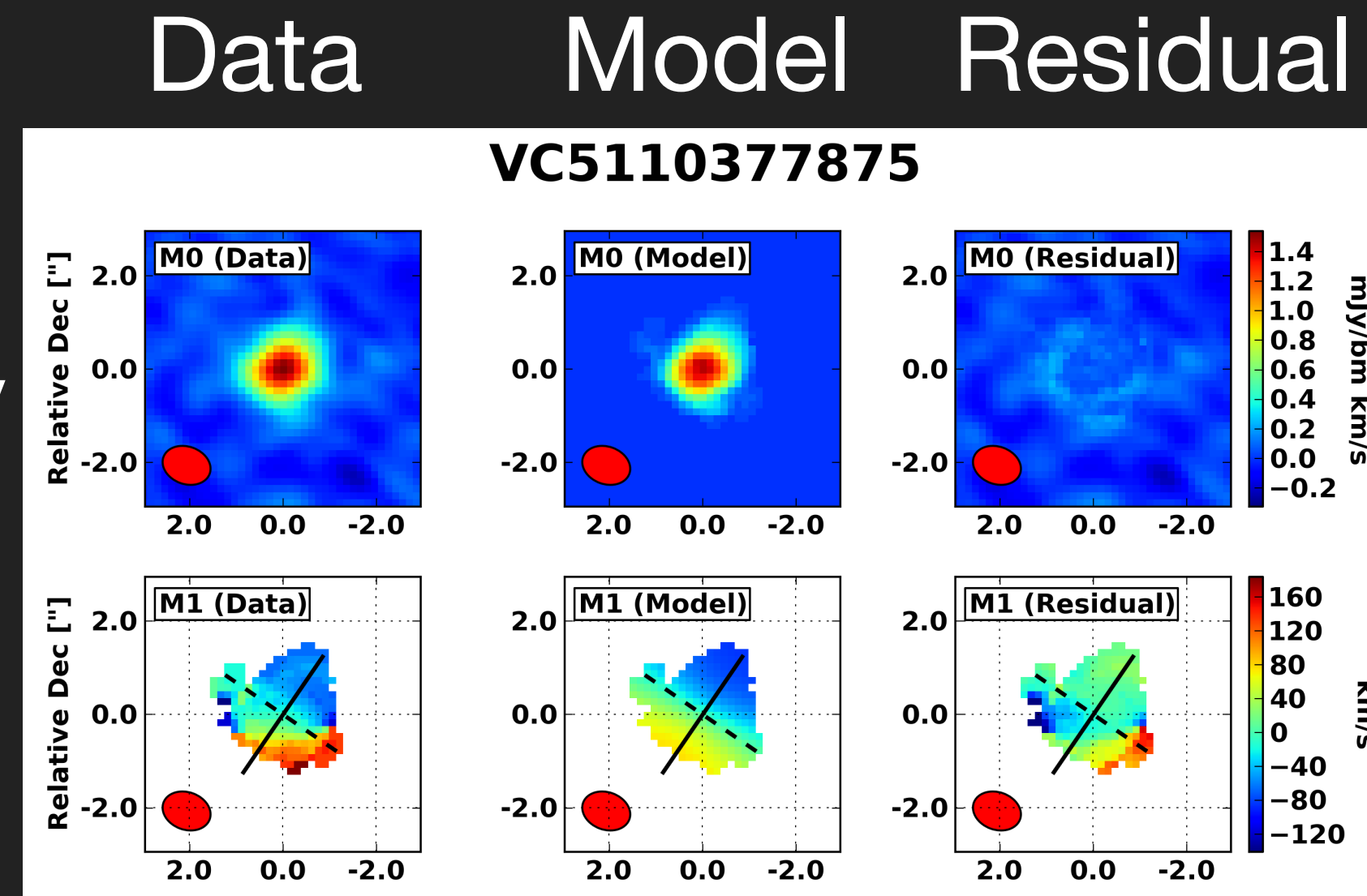
Rogstad et al. (1974)

ROTATIONAL MODELLING (3DBAROLO)

Fujimoto et al. (2020)
Jones et al. (2021)

Integrated Intensity

Velocity Field



Rogstad et al. (1974)

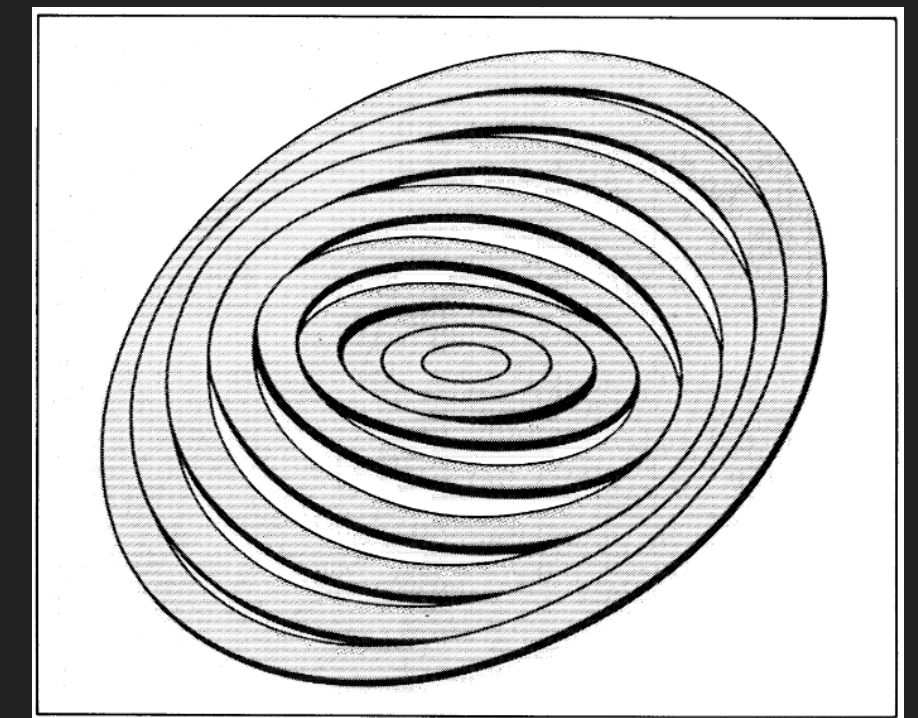
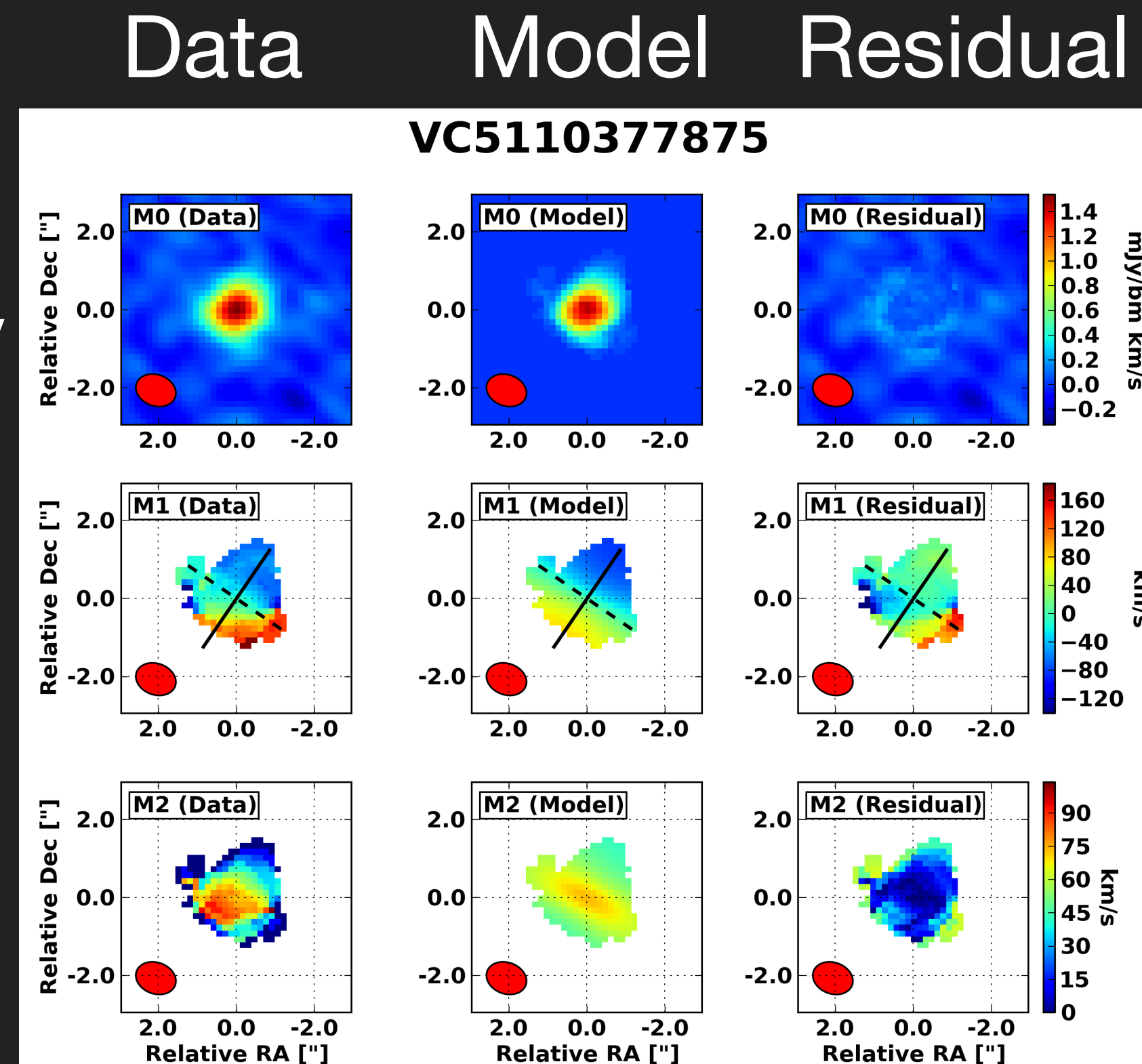
ROTATIONAL MODELLING (3DBAROLO)

Fujimoto et al. (2020)
Jones et al. (2021)

Integrated Intensity

Velocity Field

Velocity Dispersion



Rogstad et al. (1974)

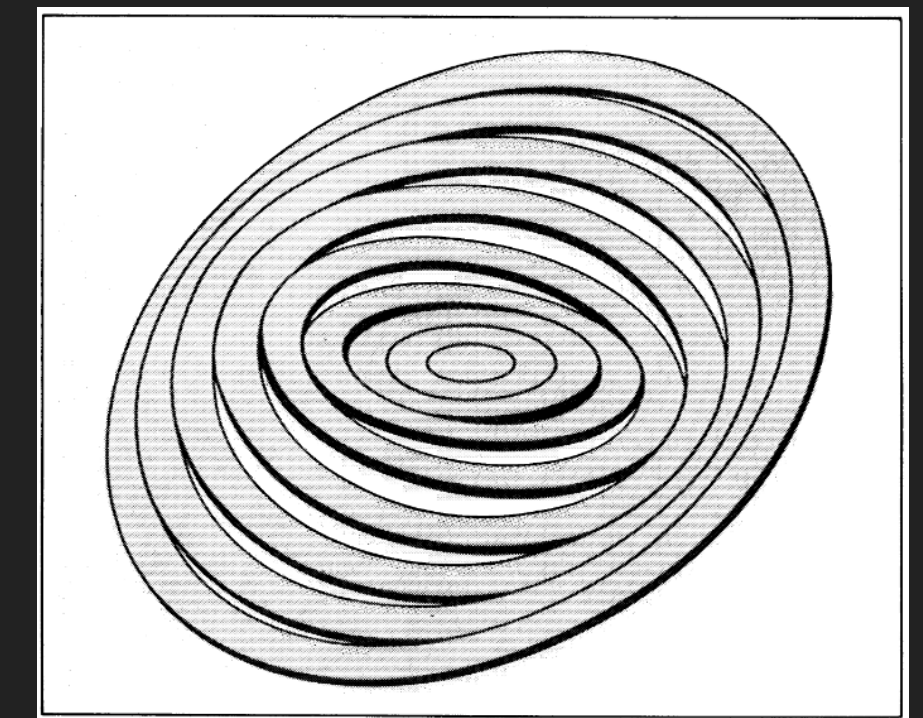
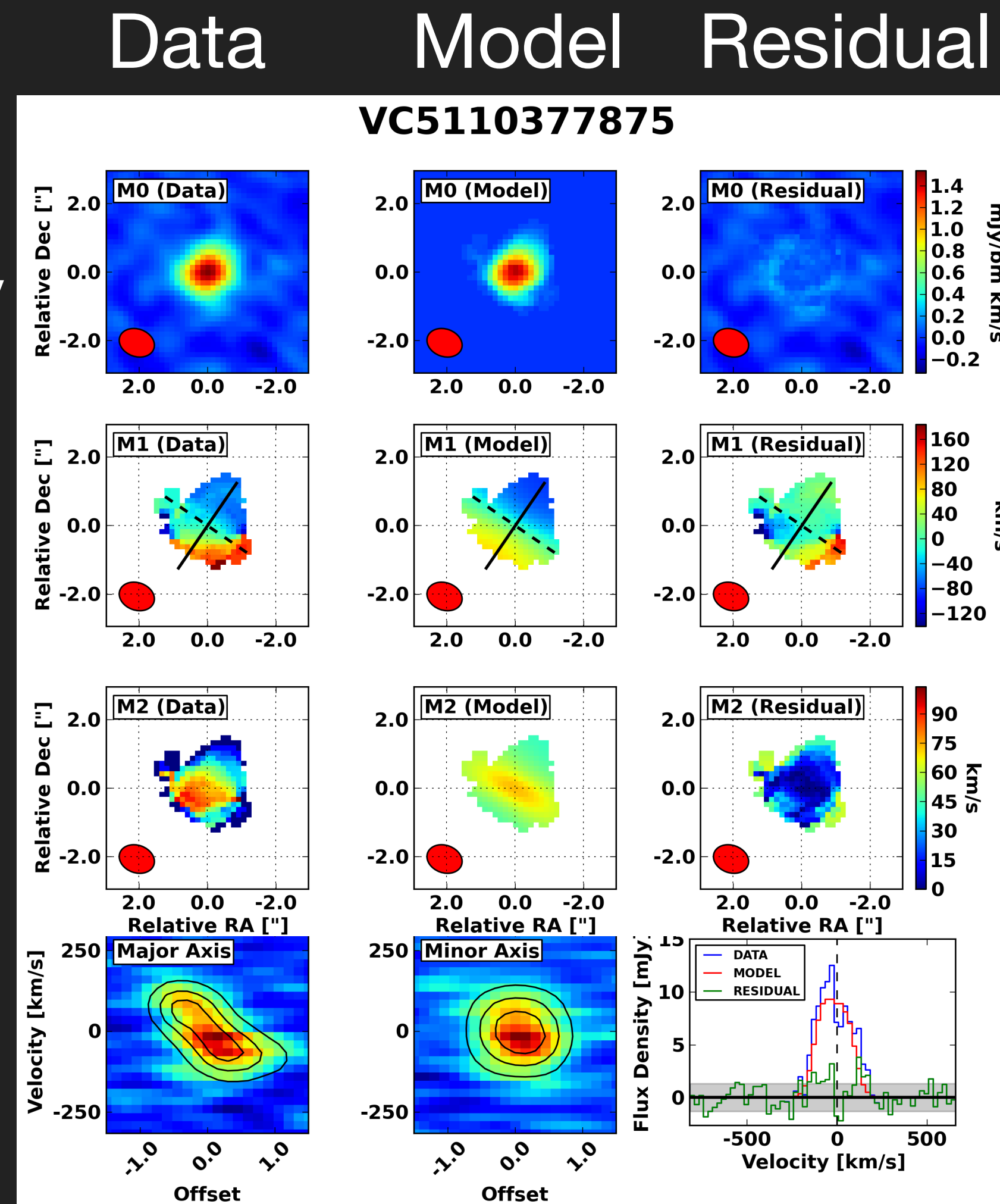
ROTATIONAL MODELLING (3DBAROLO)

Fujimoto et al. (2020)
Jones et al. (2021)

Integrated Intensity

Velocity Field

Velocity Dispersion



Rogstad et al. (1974)

PVDs

Spectra

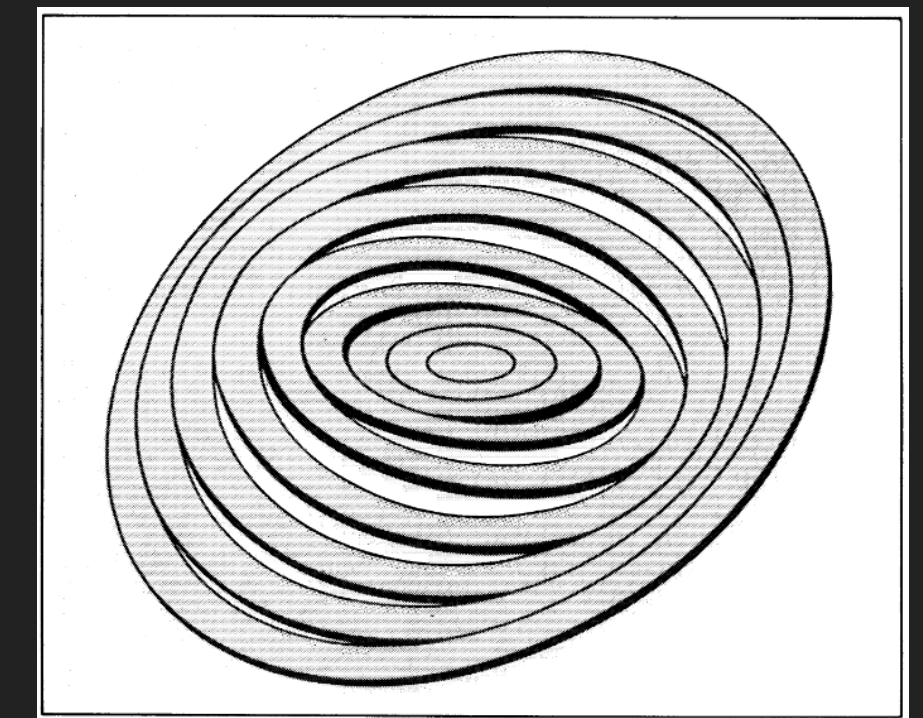
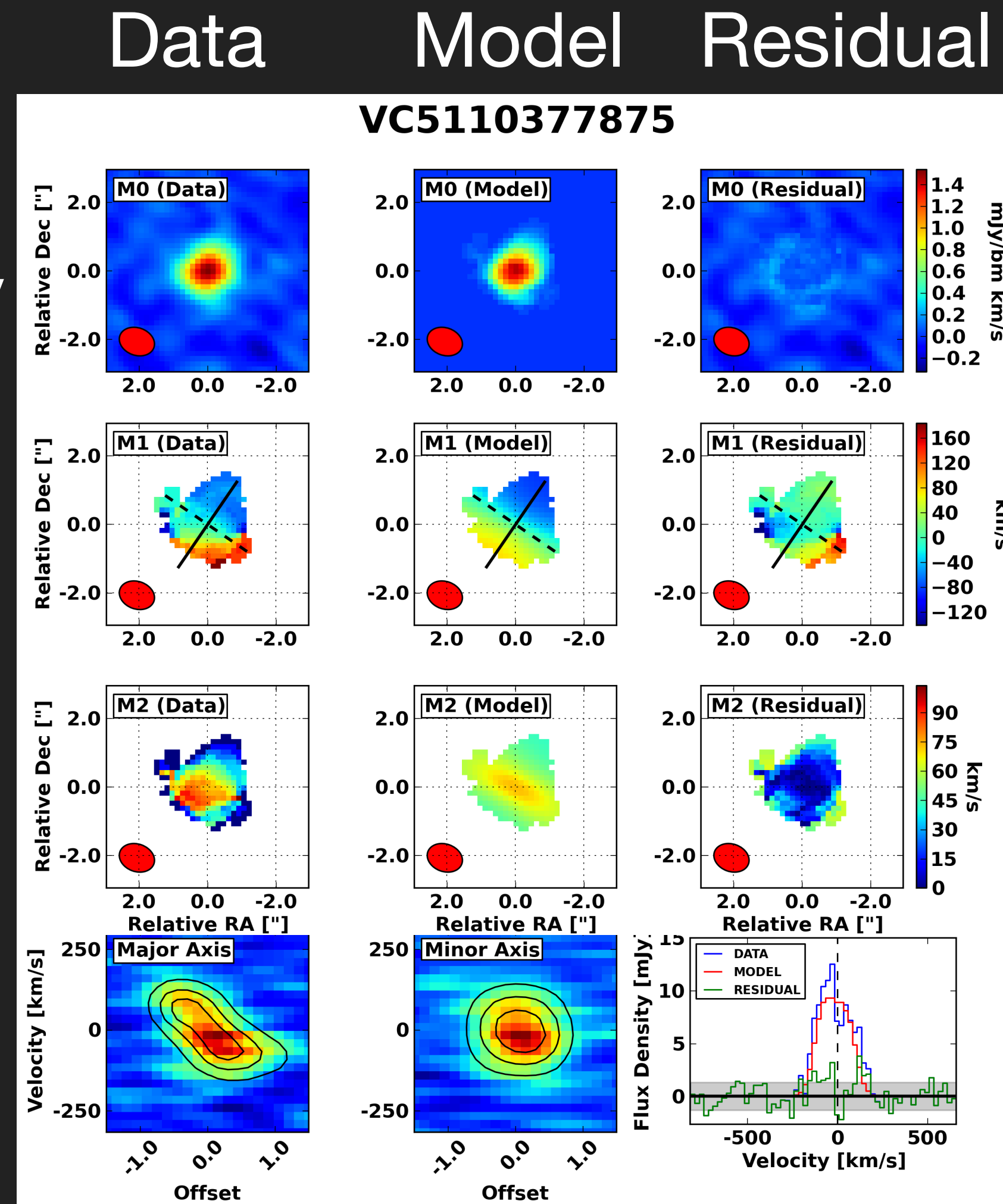
ROTATIONAL MODELLING (3DBAROLO)

Fujimoto et al. (2020)
Jones et al. (2021)

Integrated Intensity

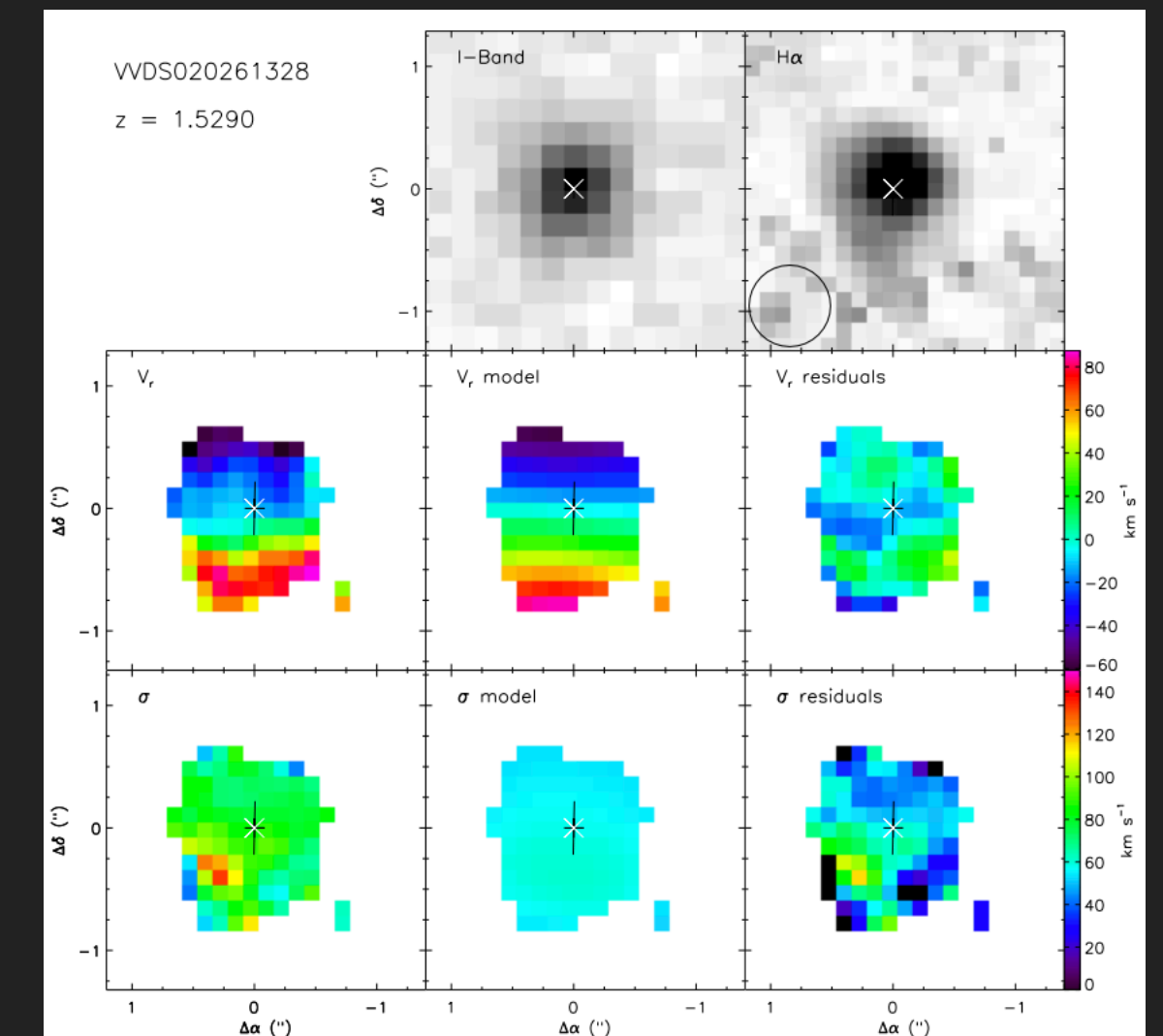
Velocity Field

Velocity Dispersion



Rogstad et al. (1974)

Epinat et al. (2012)



PVDs

Spectra

TILTED RING MODELS - CLASSIFICATION

Rotator

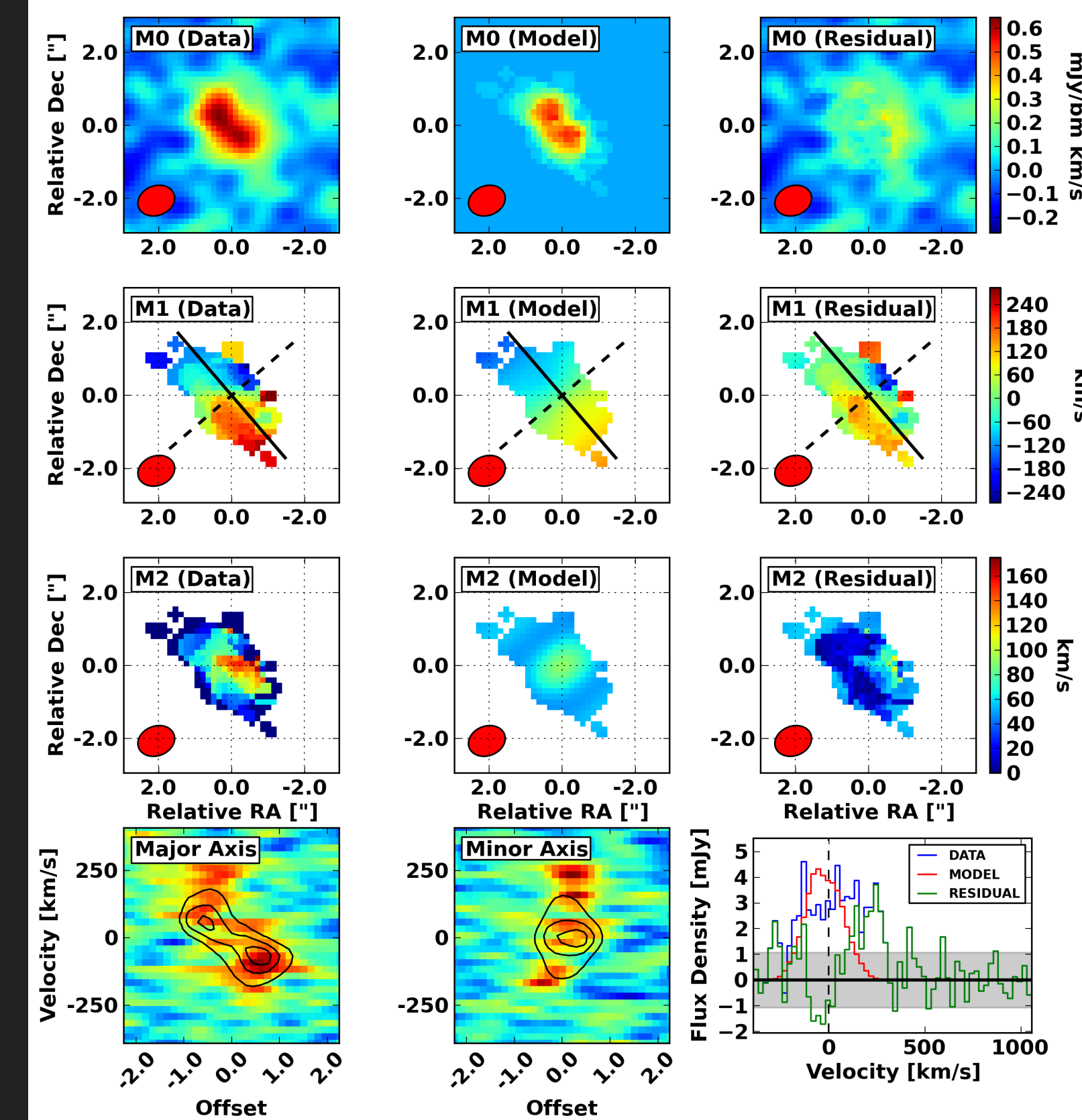
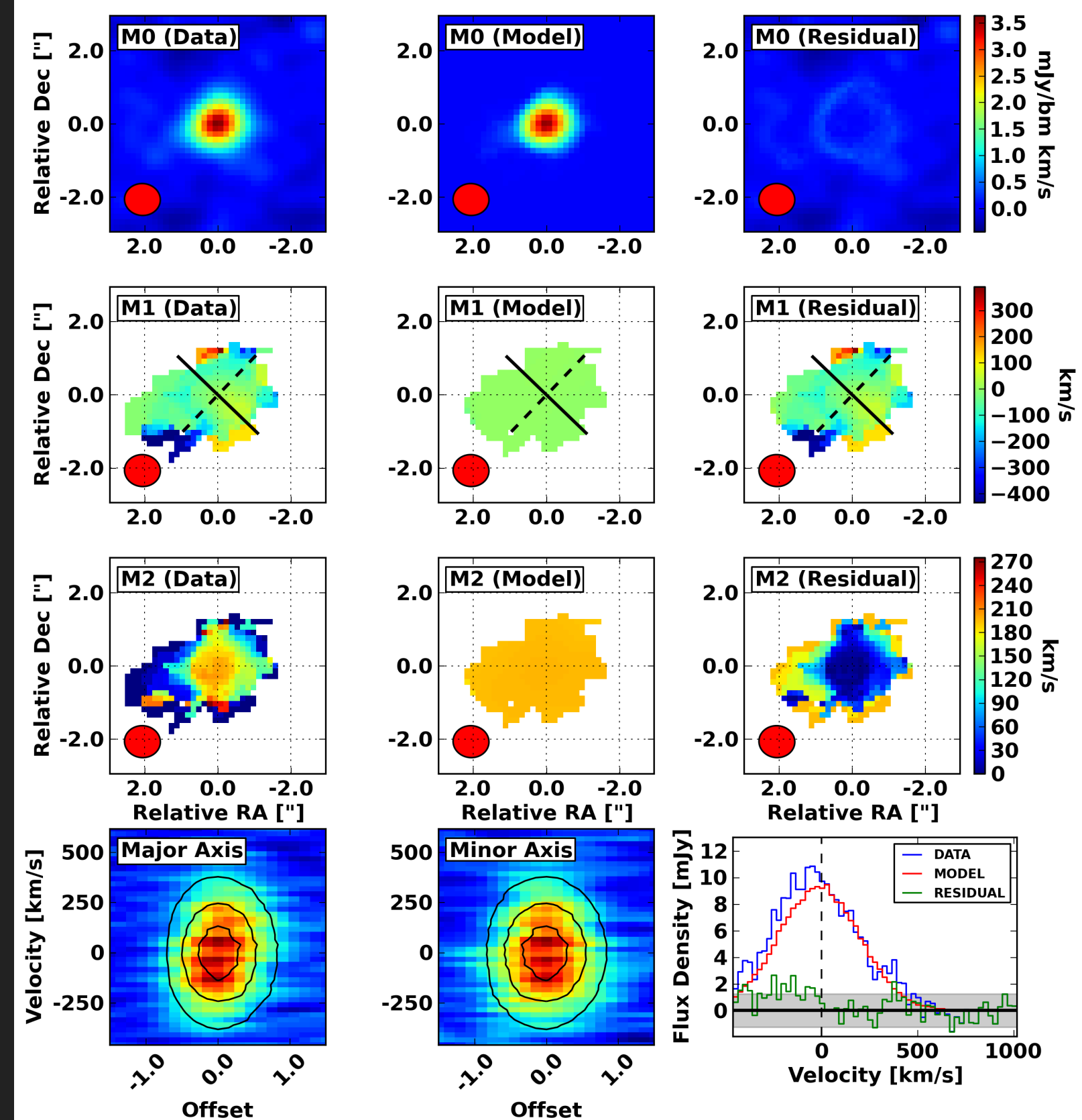
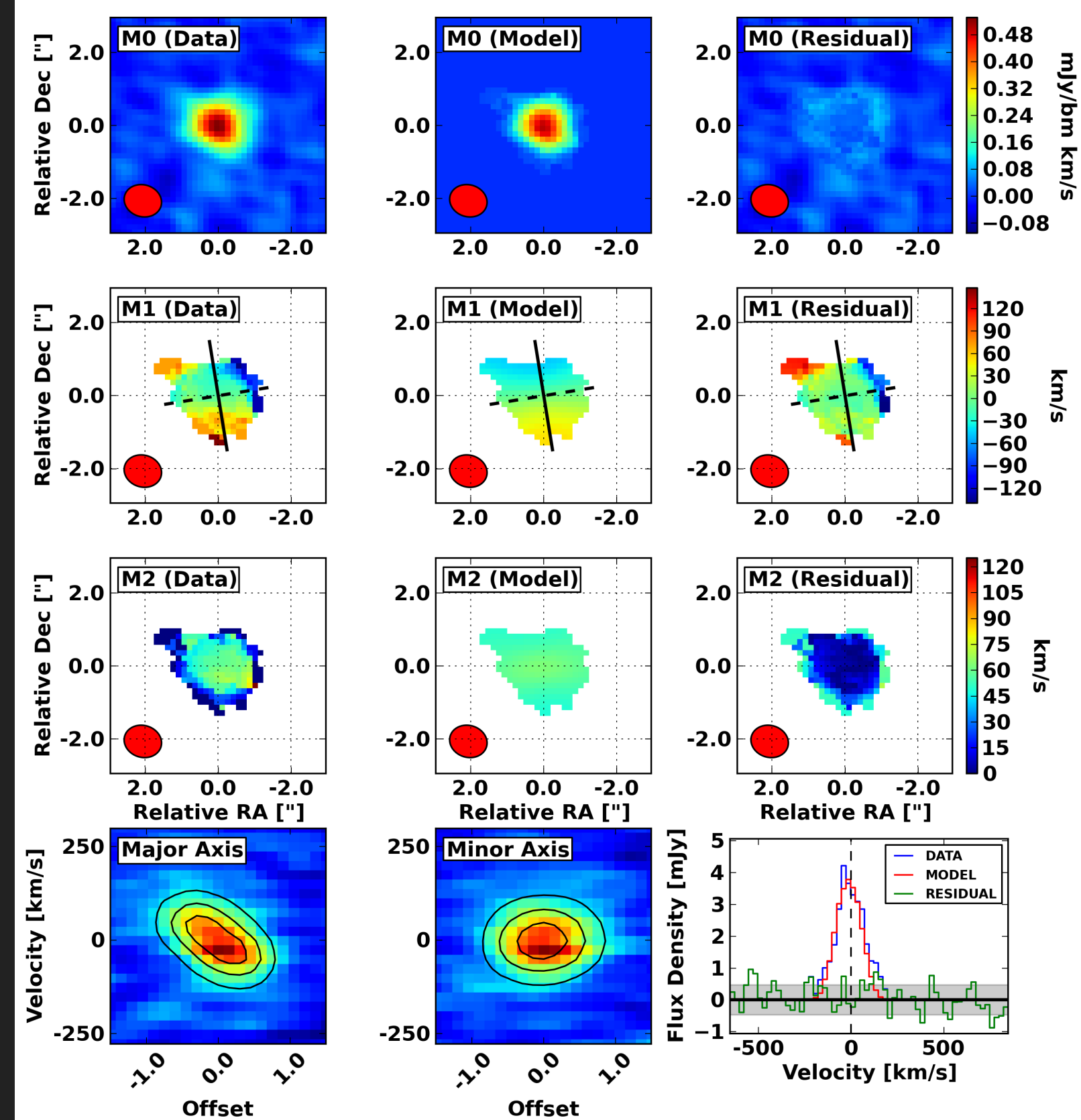
Dispersion Dominated

Merger

DC494057

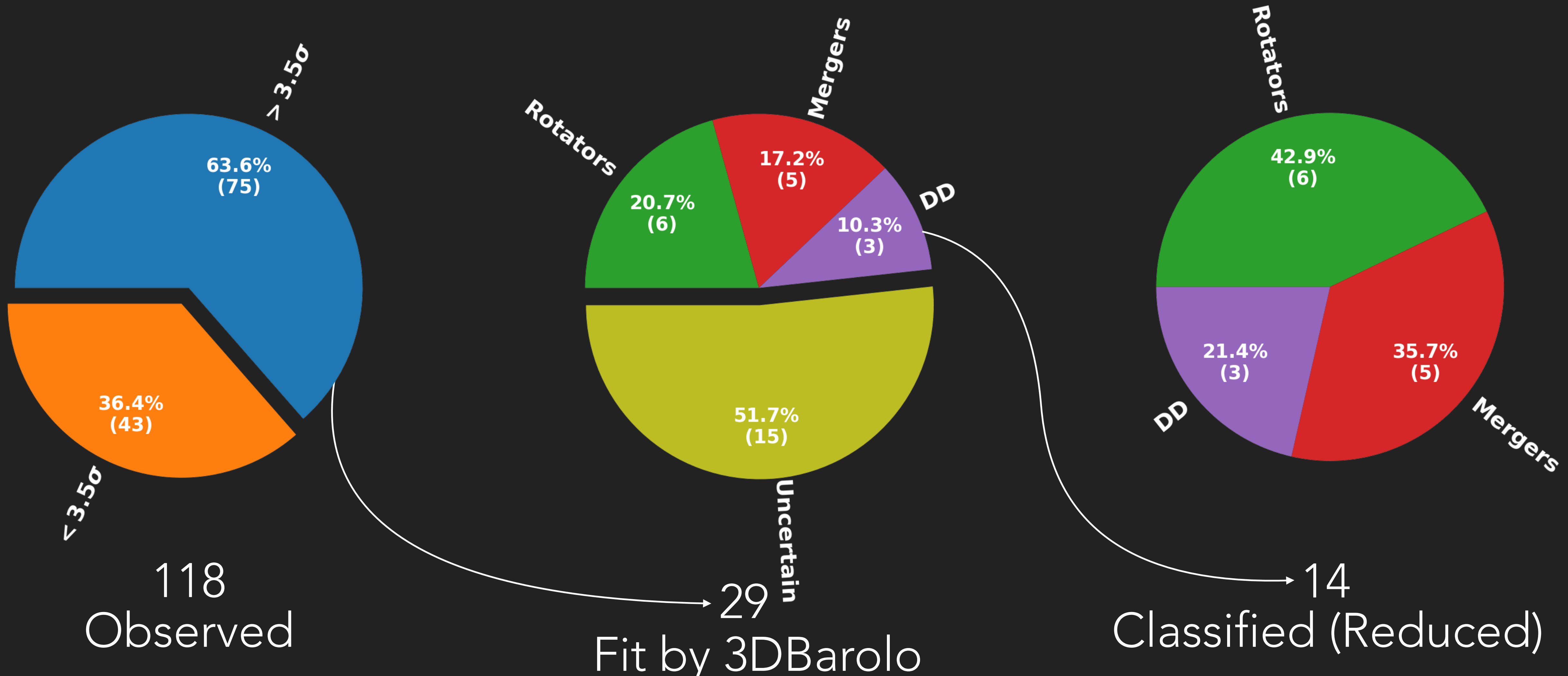
DC873756

DC434239

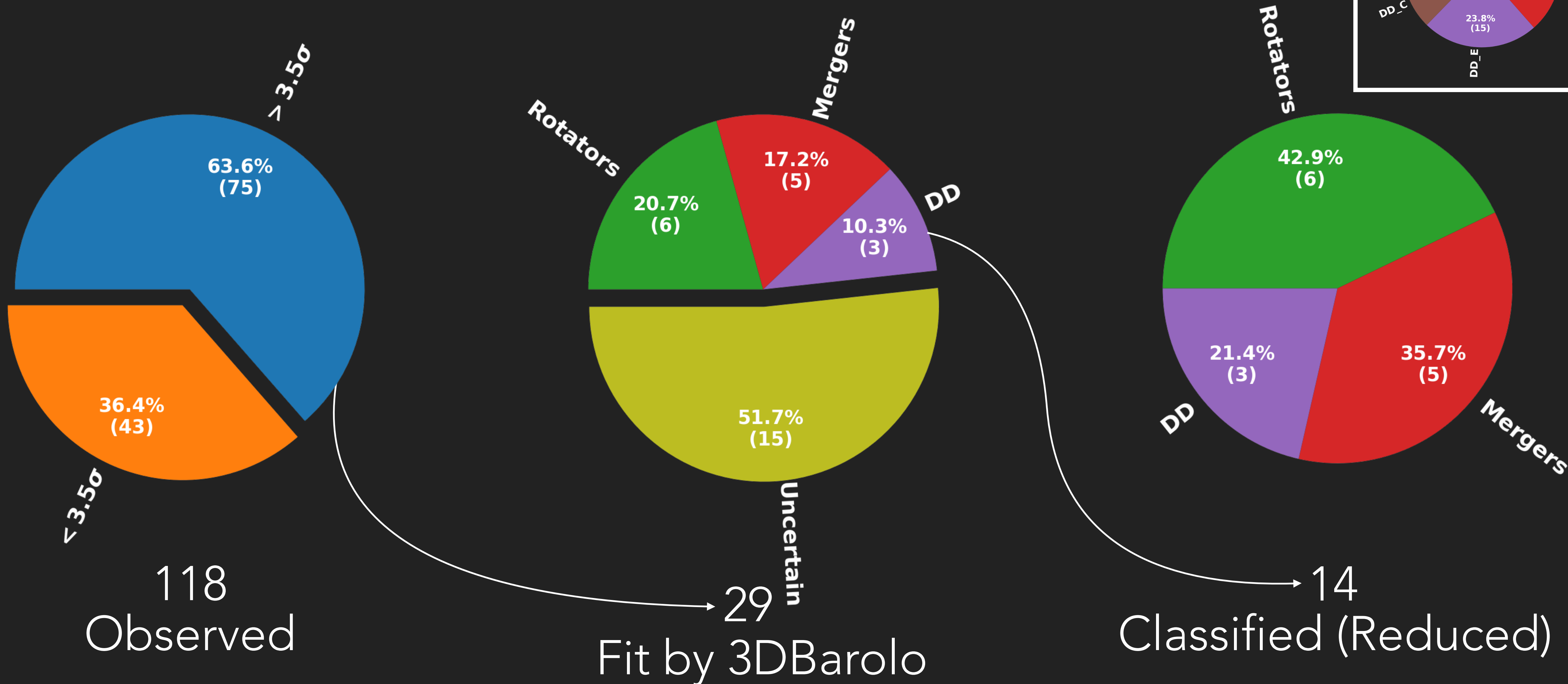


Jones et al. (2021)

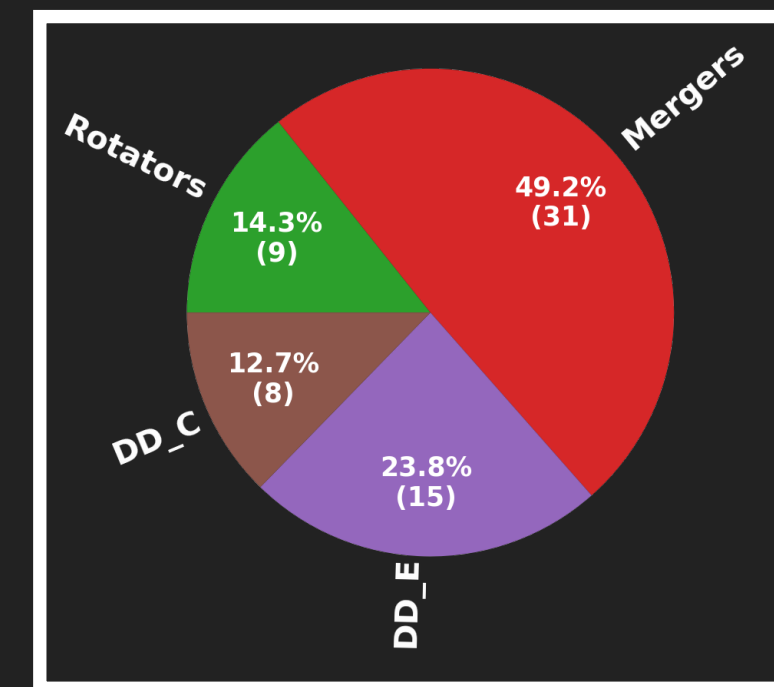
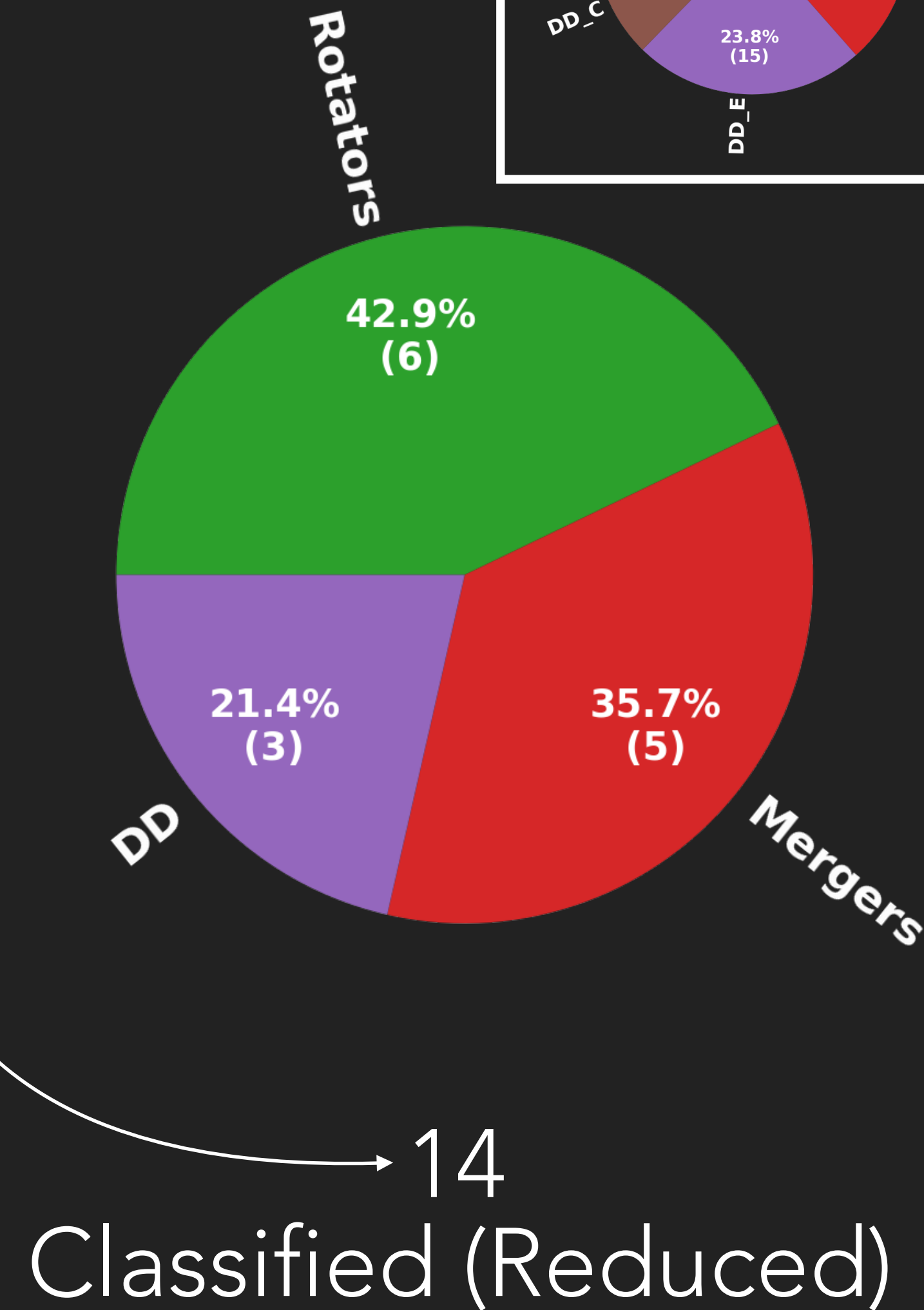
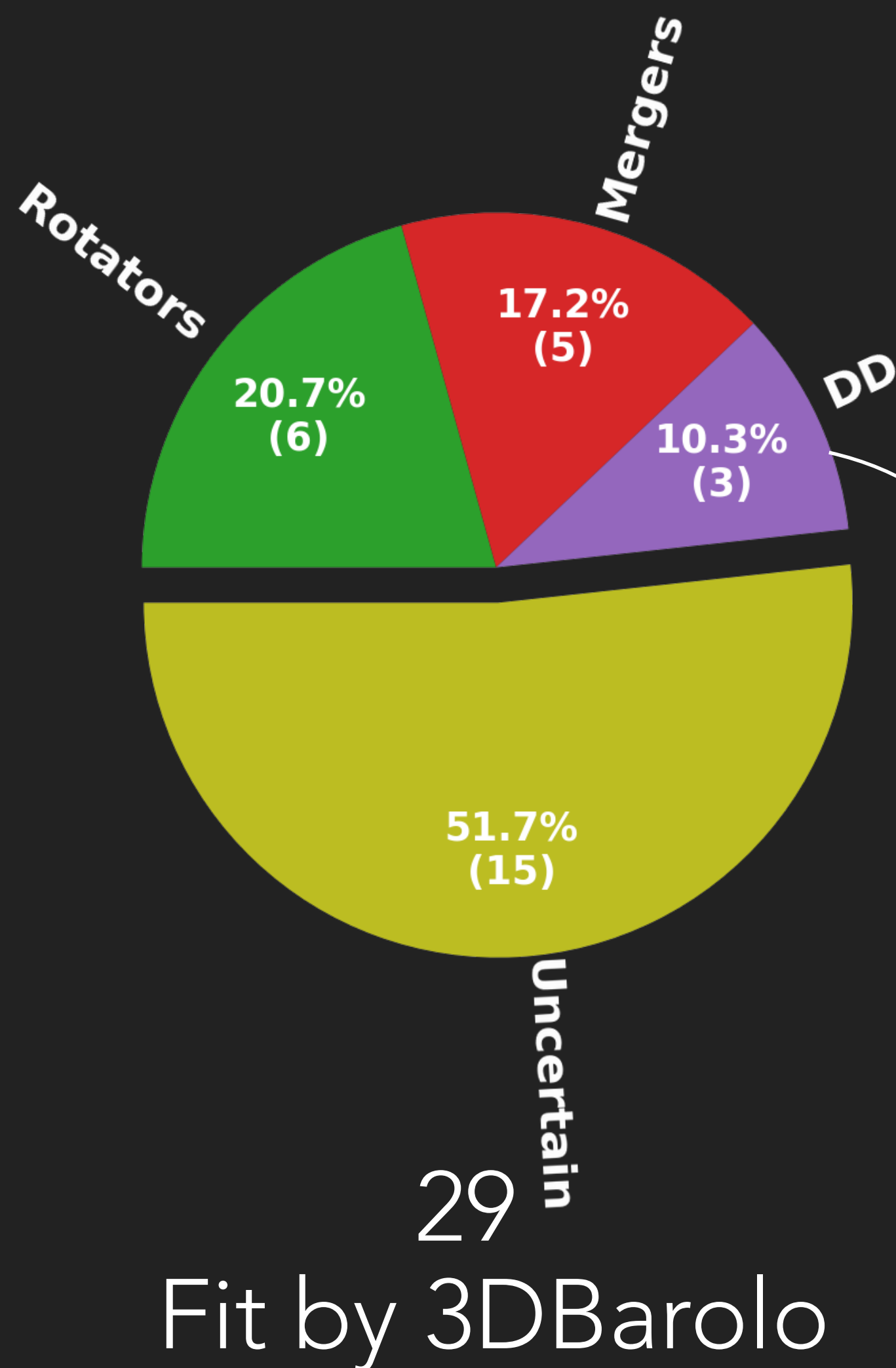
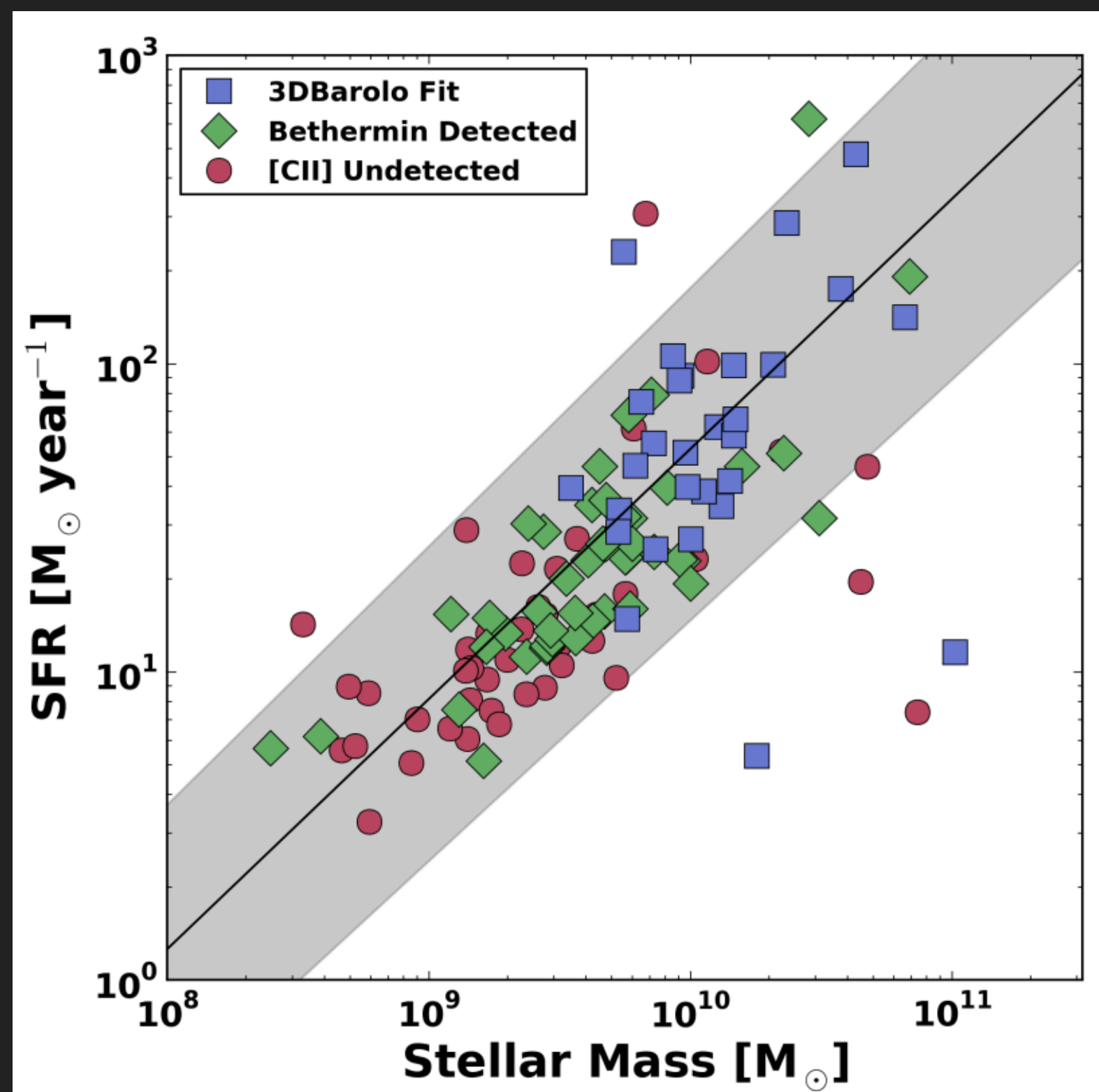
KINEMATIC CLASSES



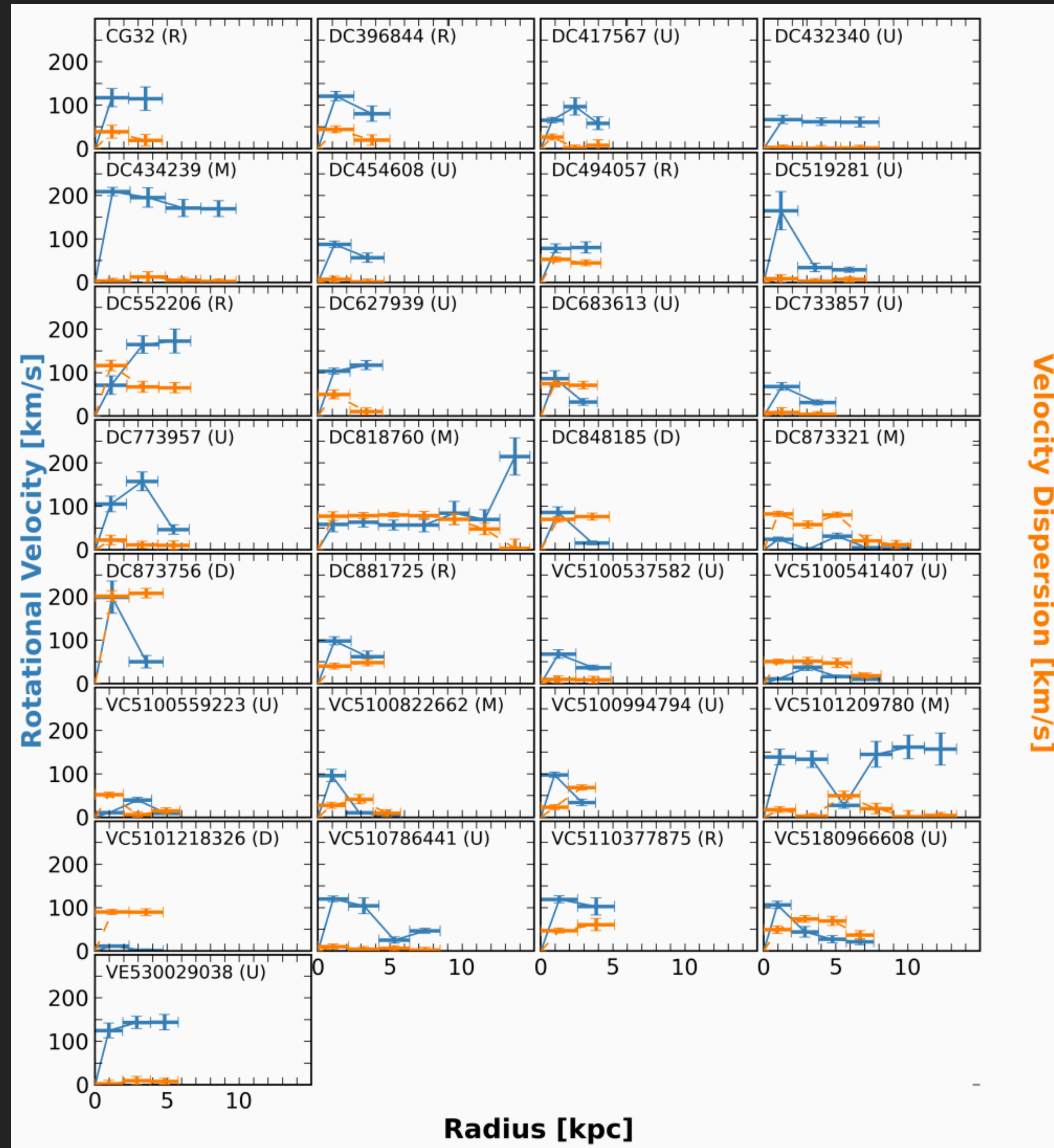
KINEMATIC CLASSES



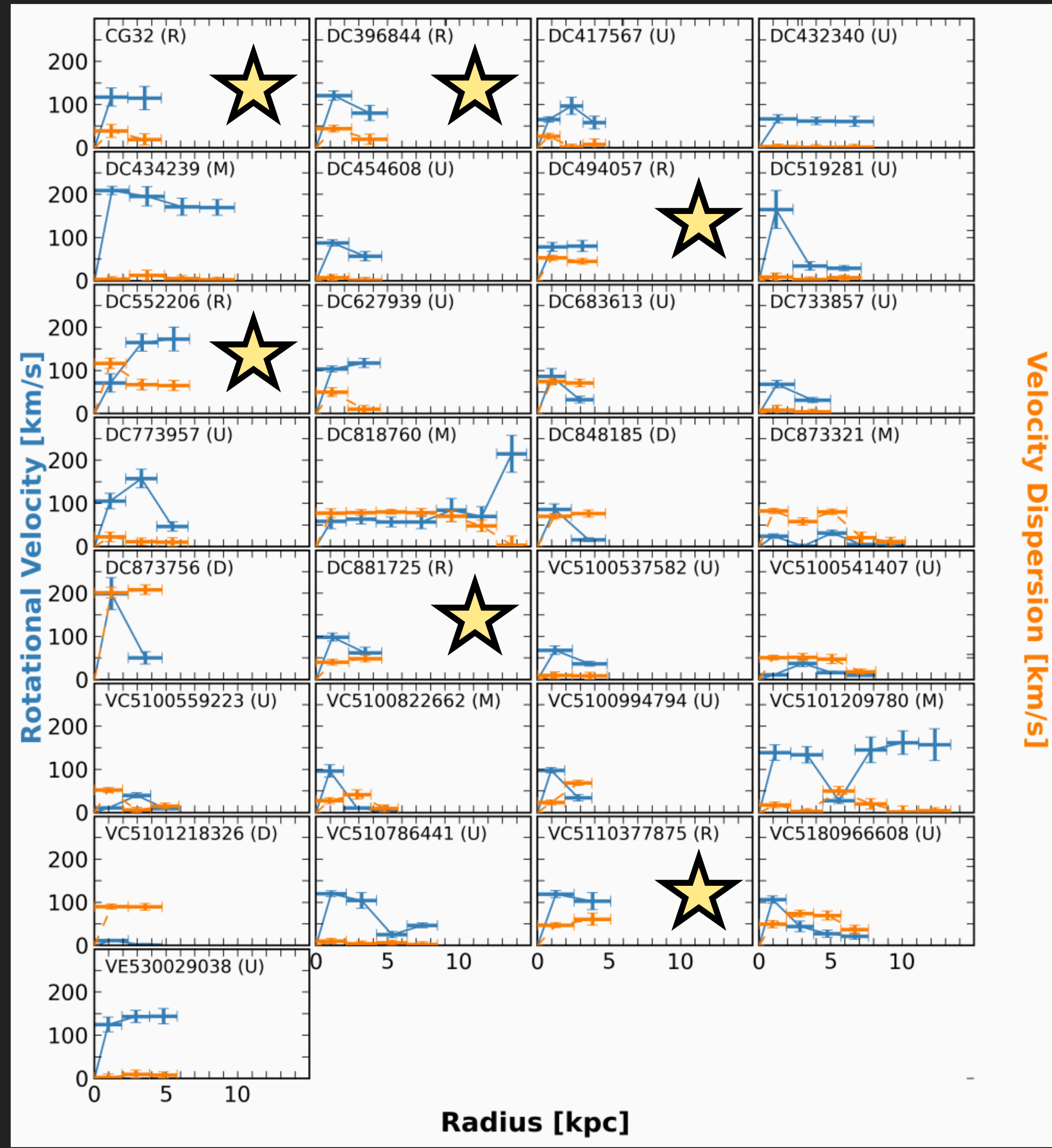
KINEMATIC CLASSES



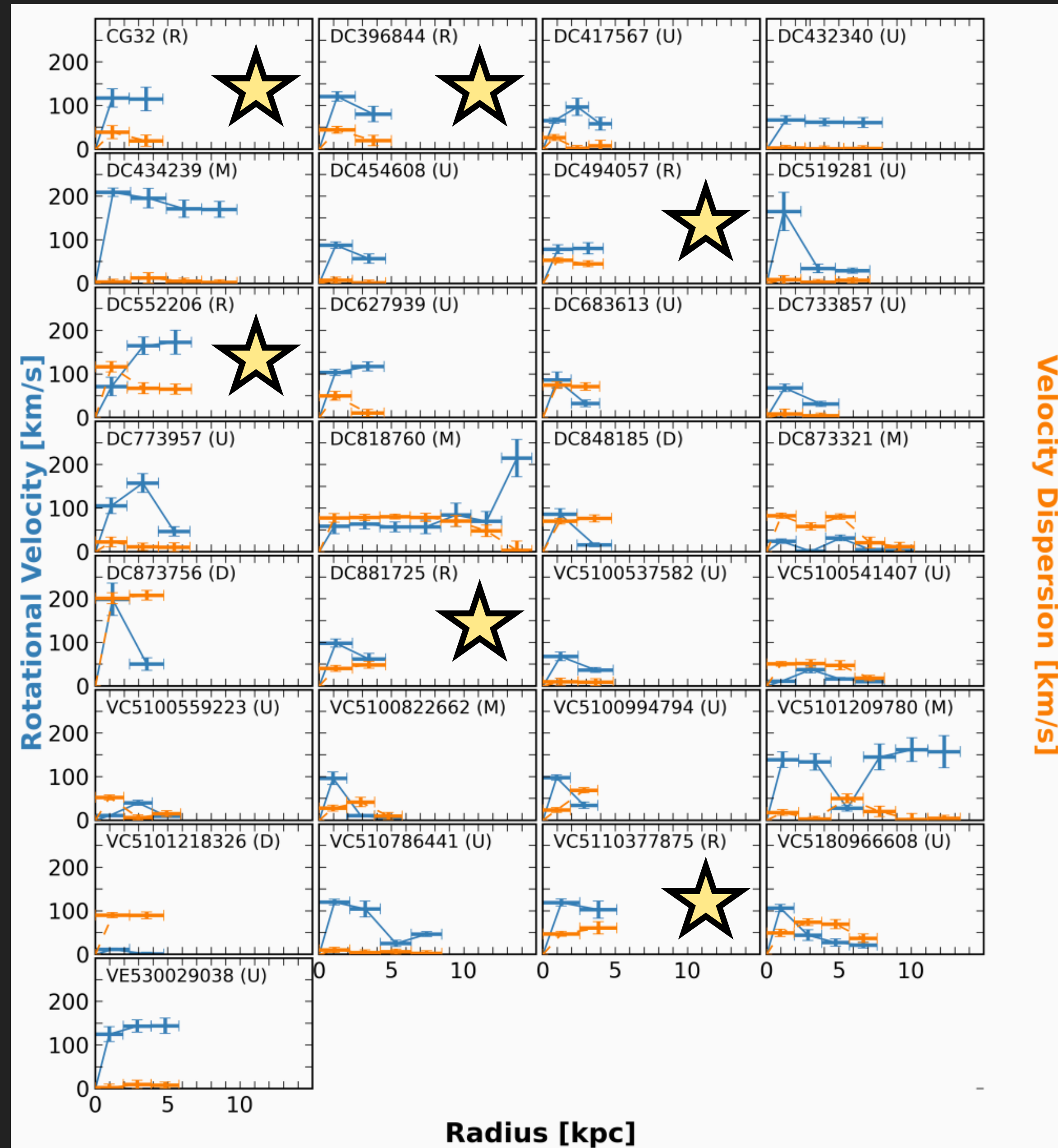
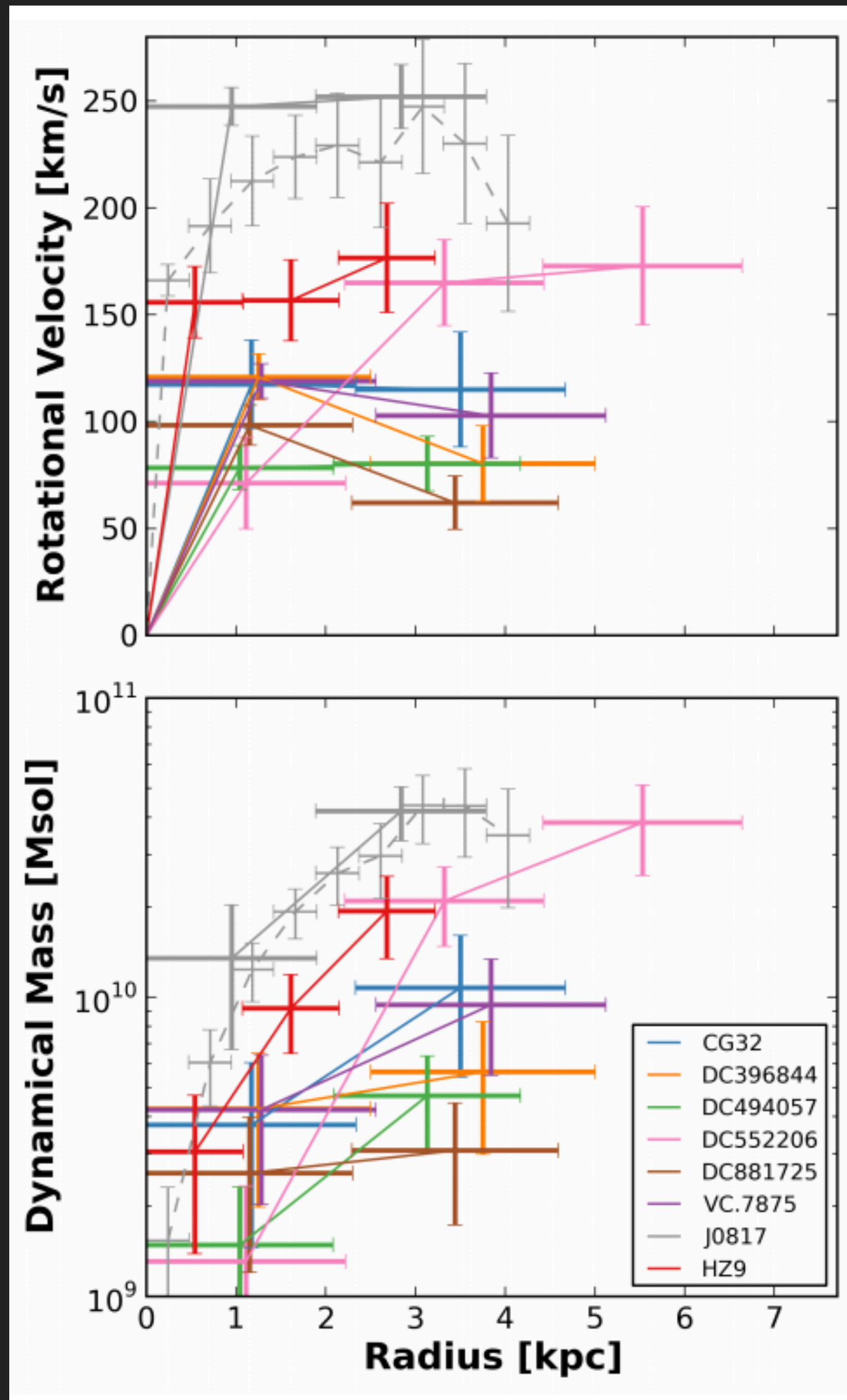
ROTATION CURVES



ROTATION CURVES



ROTATION CURVES



Velocity Dispersion [km/s]

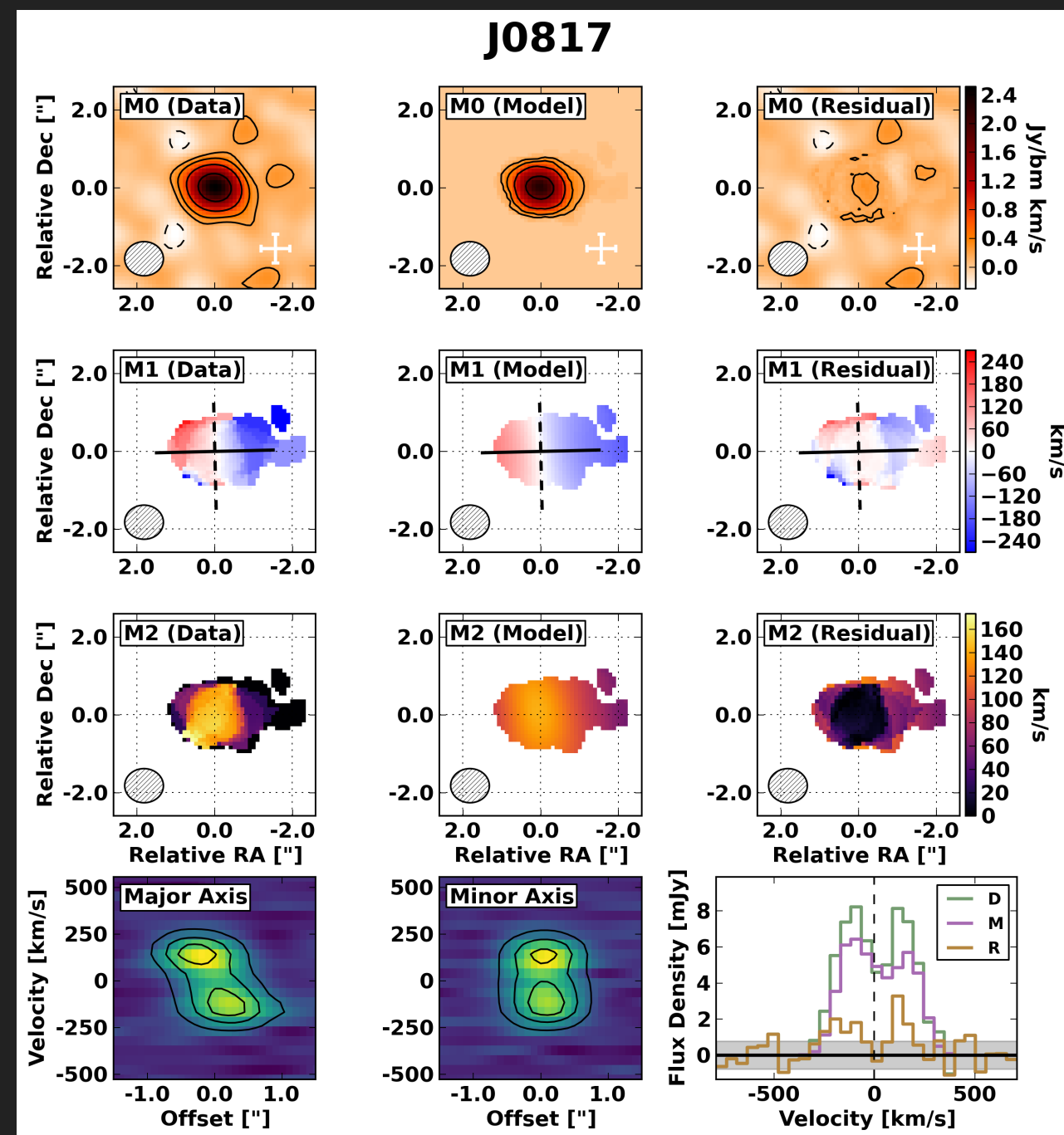
THE NEXT GENERATION OF UNLENSED $Z > 4$ [CII] OBSERVATIONS

SOURCE	Type	REDSHIFT	REFERENCE	Resolution
J0817+1351	SFG	4.260	Neeleman et al. (2020)	$\sim 0.1''$, ~ 0.7 kpc
BRI 1335-0417	SMG	4.407	Tsukui et al. (2021)	$\sim 0.2''$, ~ 1.2 kpc
J1000+0234	SMG	4.542	Lelli et al. (TBO)	$\sim 0.1''$, ~ 0.7 kpc
AzTEC/C159	SMG	4.567	Lelli et al. (TBO)	$\sim 0.1''$, ~ 0.7 kpc
J0923+0247	QSO	4.650	Lelli et al. (TBO)	$\sim 0.1''$, ~ 0.7 kpc
J1511+0408	QSO	4.679	Lelli et al. (TBO)	$\sim 0.1''$, ~ 0.7 kpc
BR 1202-0725	SMG/QSO	4.69	Lelli et al. (TBO)	$\sim 0.1''$, ~ 0.7 kpc
J1341+0141	QSO	4.700	Lelli et al. (TBO)	$\sim 0.1''$, ~ 0.7 kpc
J0331-0741	QSO	4.737	Lelli et al. (TBO)	$\sim 0.1''$, ~ 0.7 kpc
ALESS 73.1	SMG	4.756	Lelli et al. (2021)	$\sim 0.1''$, ~ 0.6 kpc
HZ7	SFG	5.250	Aravena et al. (In Prep)	$\sim 0.2''$, ~ 1.2 kpc
HZ4	SFG	5.543	Herrera-Camus et al. (2022)	$\sim 0.4''$, ~ 2.2 kpc
HZ9	SFG	5.548	Aravena et al. (In Prep)	$\sim 0.2''$, ~ 1.2 kpc
CLM1	SFG	6.166	Aravena et al. (In Prep)	$\sim 0.2''$, ~ 1.1 kpc
COS2987	SFG	6.808	Posses et al. (2022)	$\sim 0.2''$, ~ 1.1 kpc
COS3018	SFG	6.850	Witstok et al. (In Prep)	$\sim 0.3''$, ~ 1.1 kpc
ALPINE (118)	SFG	4.4-5.9	Le Fèvre et al. (2020), et al.	$\sim 1.0''$, $\sim 6-7$ kpc
CRISTAL (19)	SFG	$\sim 4-5$	Herrera-Camus et al.	$\sim 0.1-1.0''$, $\sim 0.6-7$ kpc
REBELS (40)	SFG	6.5-8.6	Bouwens et al. (2021), et al.	$\sim 1.2-1.6''$, $\sim 6-9$ kpc

THE NEXT GENERATION OF UNLENSED $z > 4$ [CII] OBSERVATIONS

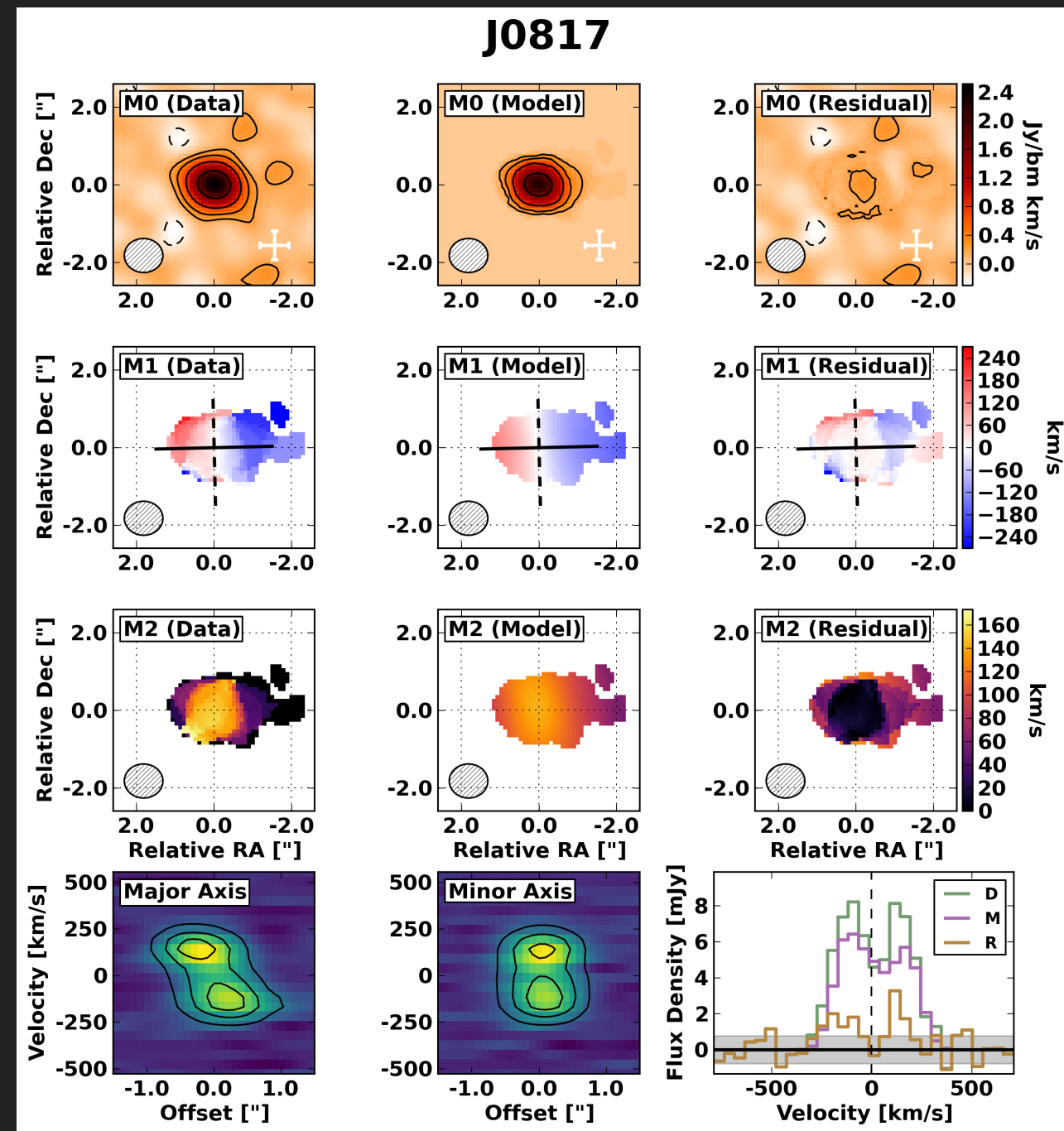
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INCREASED RESOLUTION: J0817

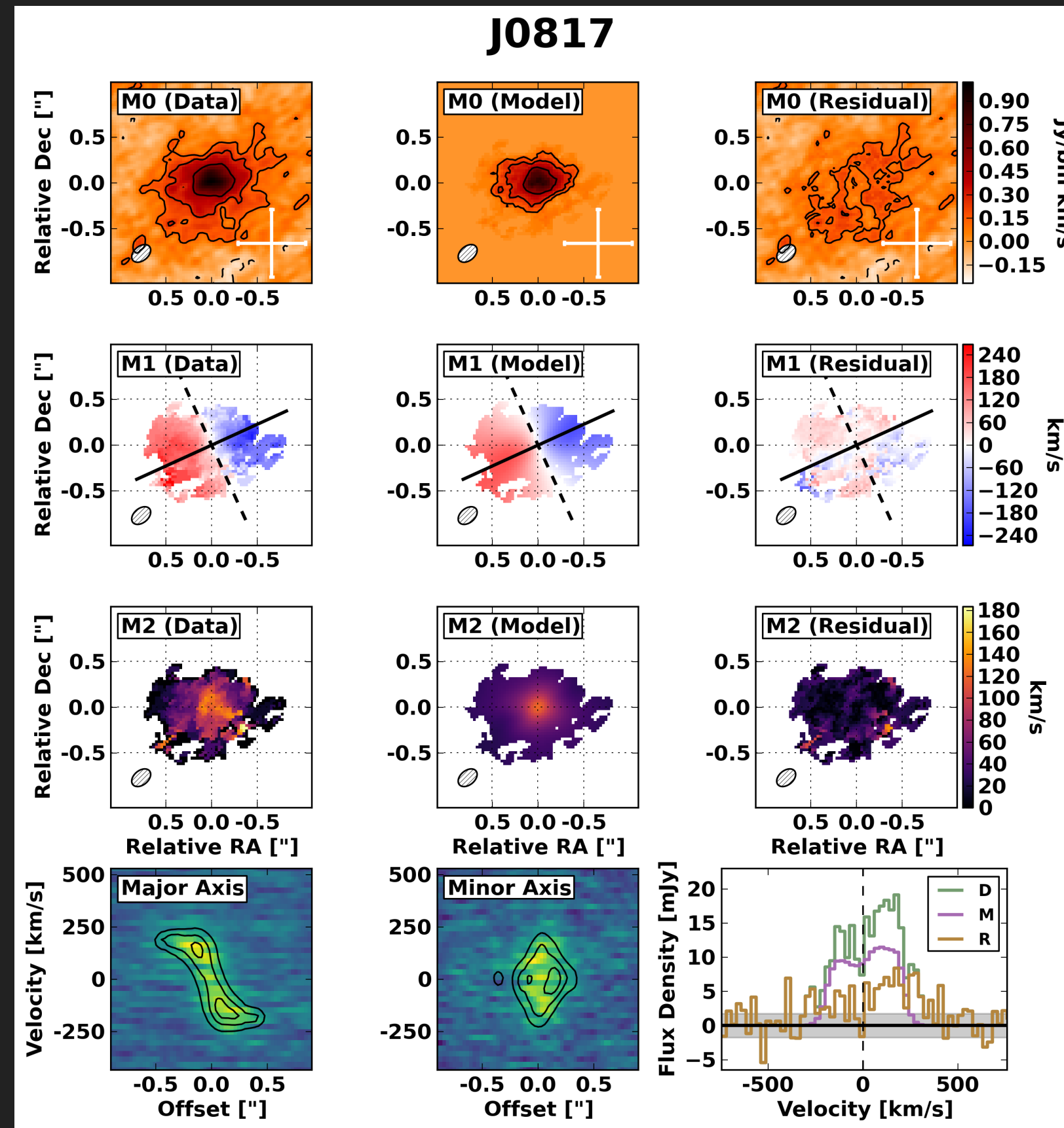


- > Cycle 3
- > $\sim 0.75''$ Resolution
- > ~ 44 min total

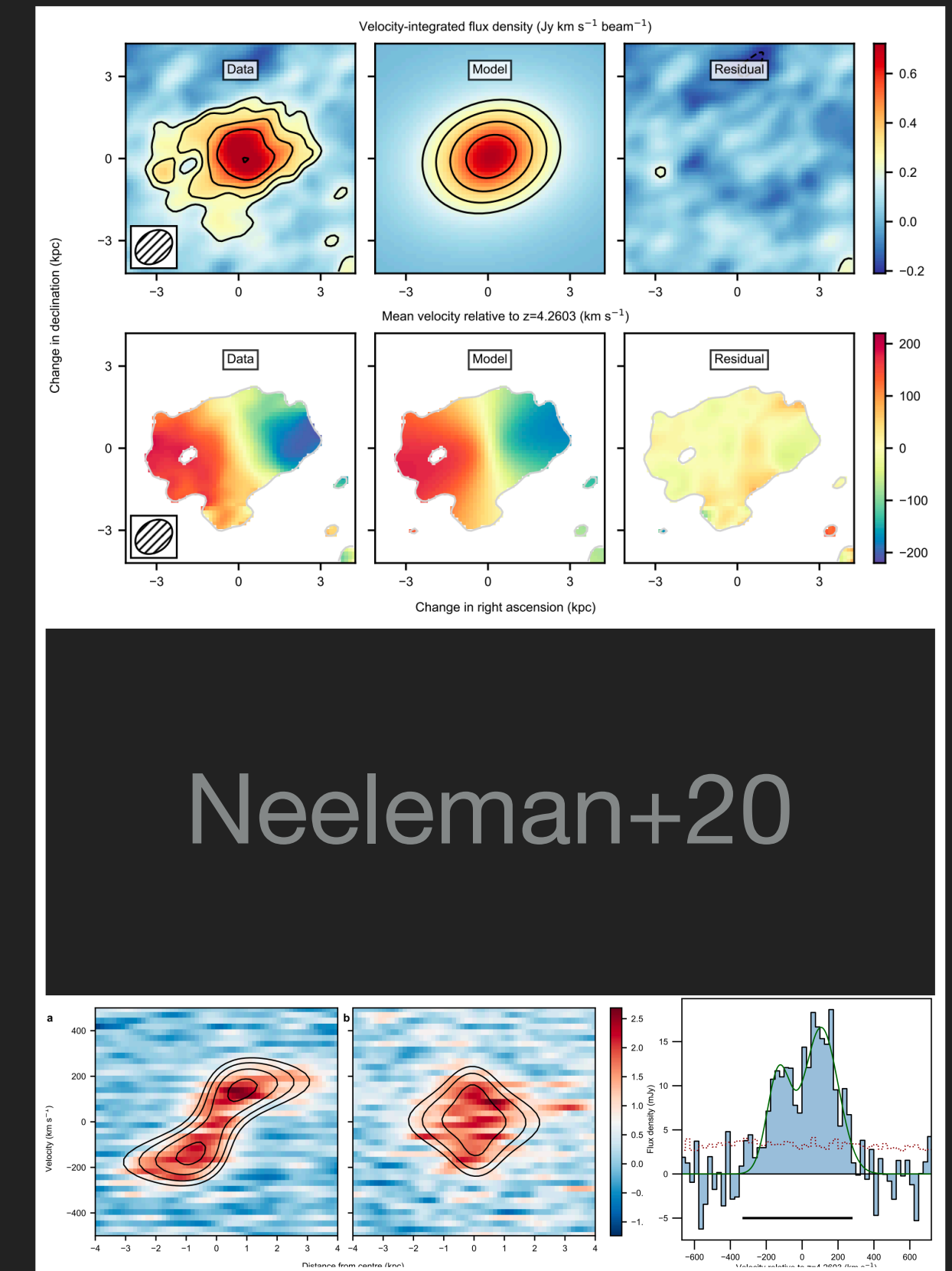
INCREASED RESOLUTION: J0817



- > Cycle 3
- > $\sim 0.75''$ Resolution
- > ~ 44 min total

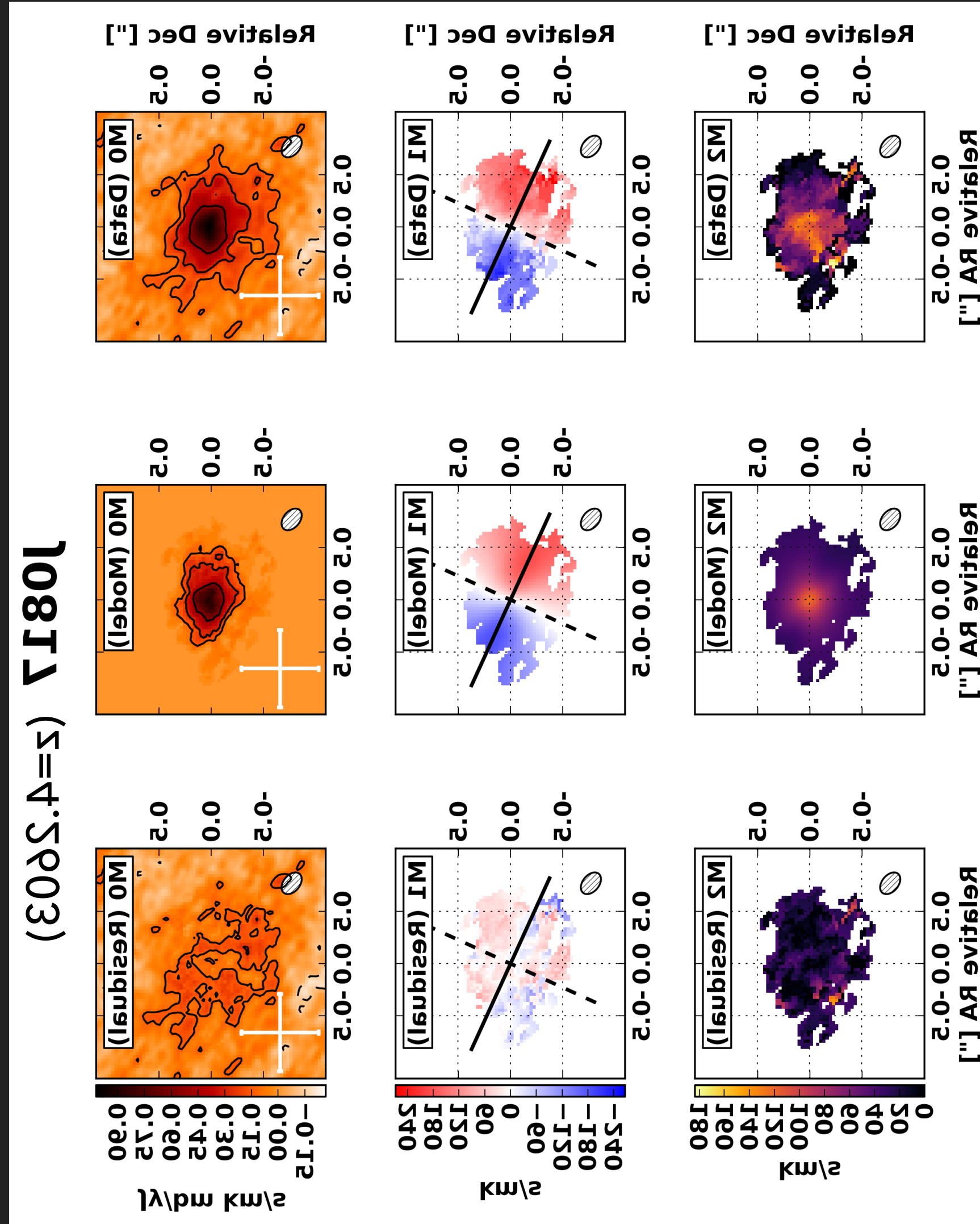


- > Cycle 5
- > $\sim 0.11''$ Resolution
- > ~ 1.7 hour total

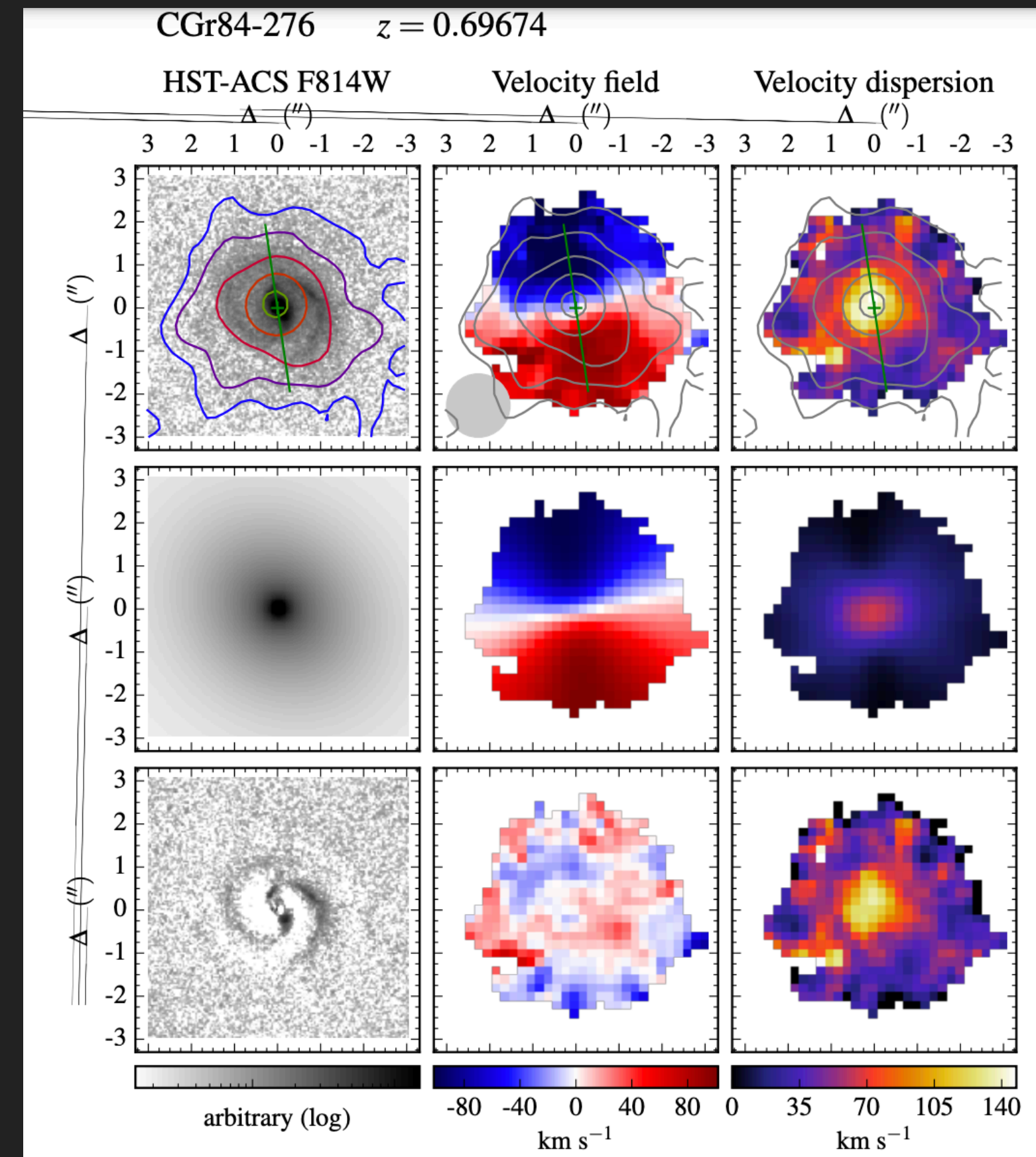
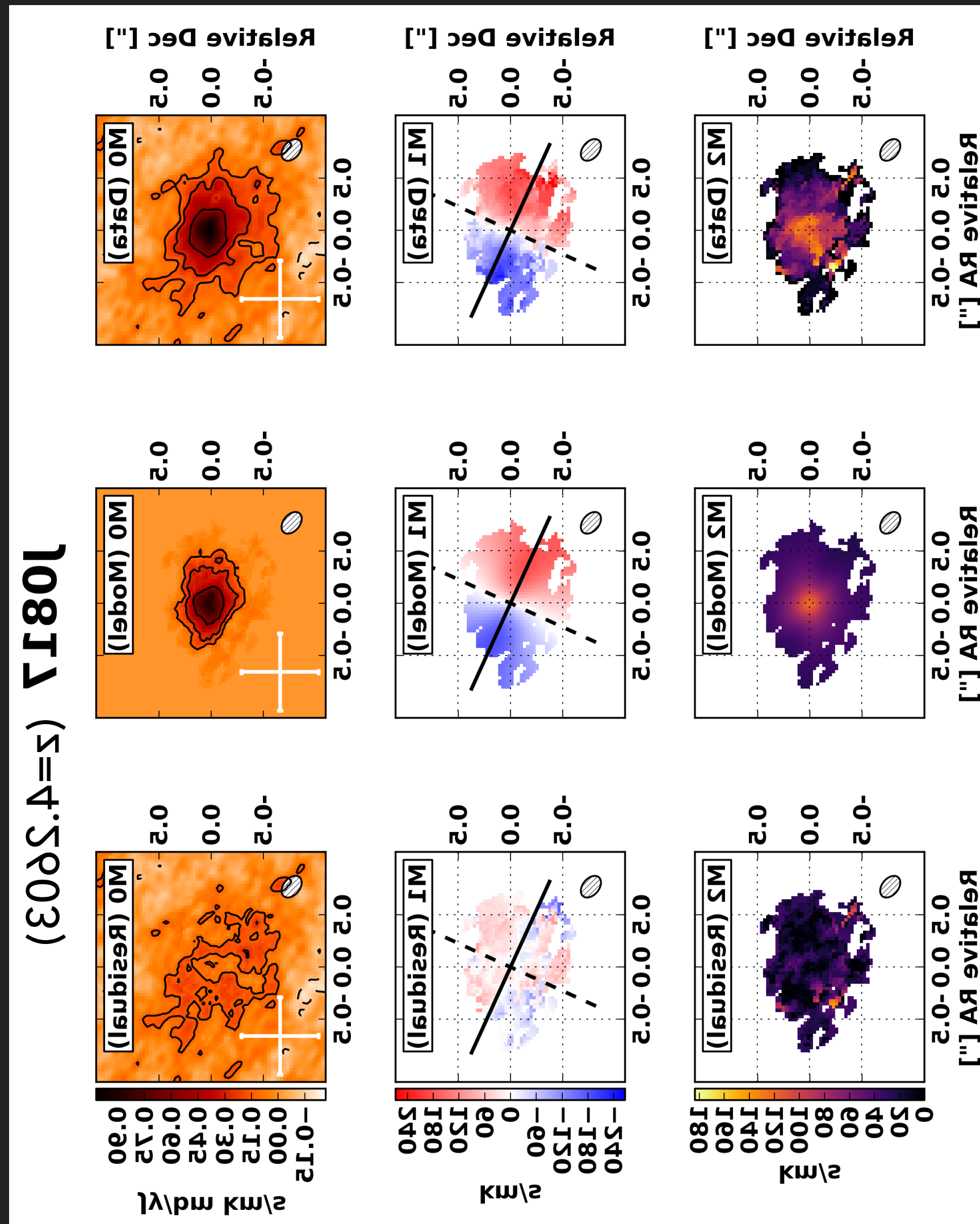


Neeleman+20

INCREASED RESOLUTION: J0817



INCREASED RESOLUTION: J0817



Abril-Melgarejo+21

CONCLUSIONS

- ▶ ALPINE allowed for the first test of morpho-kinematic diversity in SFGs at $z \sim 4-6$
 - ▶ ~30-50% mergers, ~14% rotators
- ▶ Even with low resolution ($1'' \sim 6\text{kpc}$), we find new evidence for 6 rotating galaxies
 - ▶ Previously only 2 unlensed rotating SFGs in $z \sim 4-6$
- ▶ These observations are already acting as a crucial stepping stone for other studies (e.g., REBELS, CRISTAL, TRICEPS, JWST/NIRSPEC IFS)

