6th Workshop on Compact Steep Spectrum and GHz-Peaked Spectrum Radio Sources **13 May 2021, Torun Poland**

CO kinematics unveil outflows likely driven by a young jet in the Gigahertz Peaked Radio Core of NGC6328

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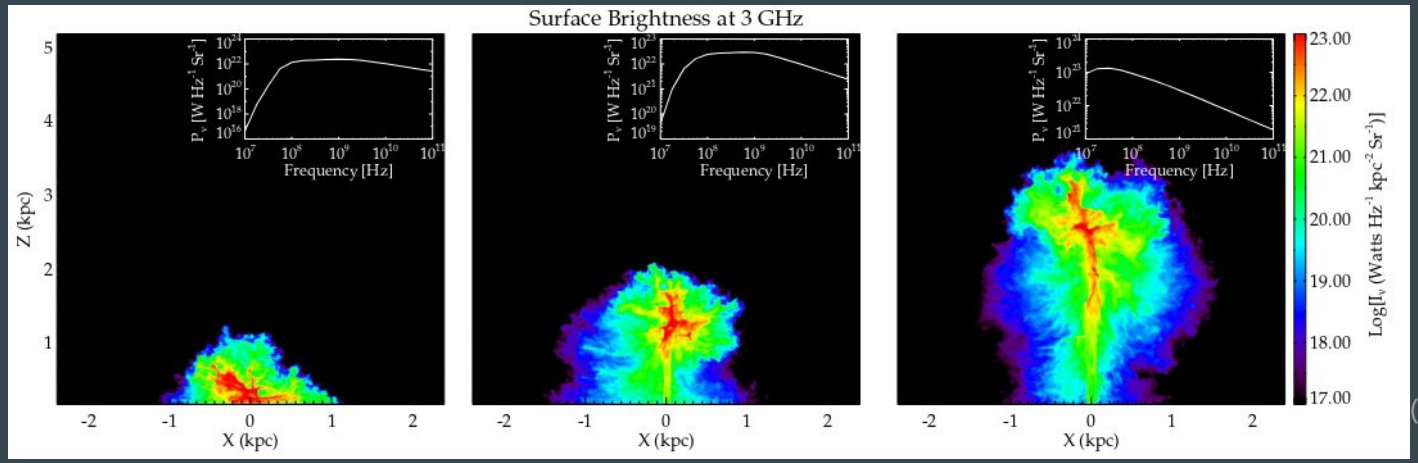
Outflows and Jets

Molecular gas outflows are important for regulating star formation,

and jets are efficient in launching outflows

- ➢ Initiate shock heating & drive adiabatic bubbles, that apply pdV work and ram pressure accelerating clouds
- ➢ provide extra Cosmic Rays that deposit momentum on clouds

PS sources are among the best examples to study the interaction of young jets with clouds.



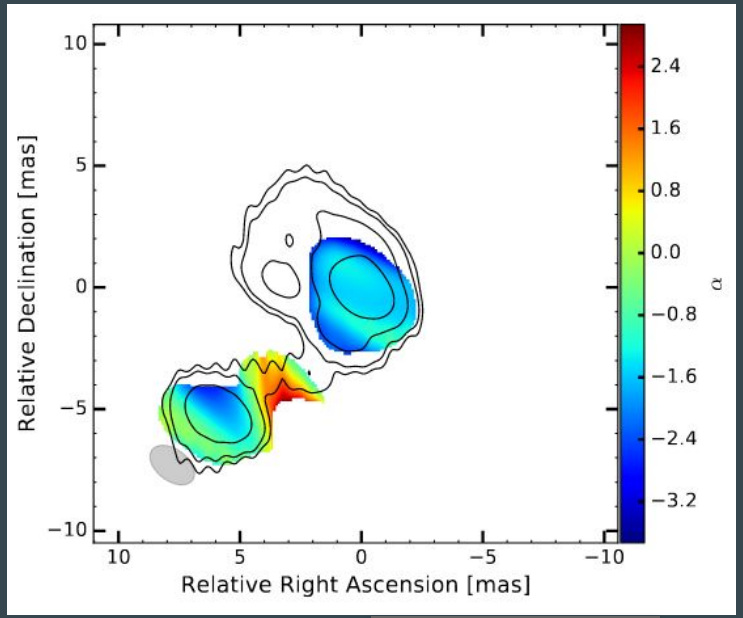
(Bicknell+ 2018)

PKS 1718-649 / NGC6328:

One of the sources in a **survey of CO in radio galaxies in the ALMA archive**, including calibrators CO-ARC: PI Dasyra; Audibert et al. 2021 in prep

Radio Source

- VLBI Higher angular resolution (2.3, 4.8, 8.4 GHz)
  - Resolved: 2 anti-diametric hot spots separated by 2 pc
  - Position Angle of -40°



VLBI 8.4GHz [Angioni et al 2019]

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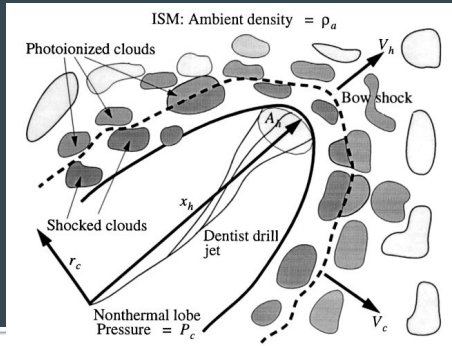
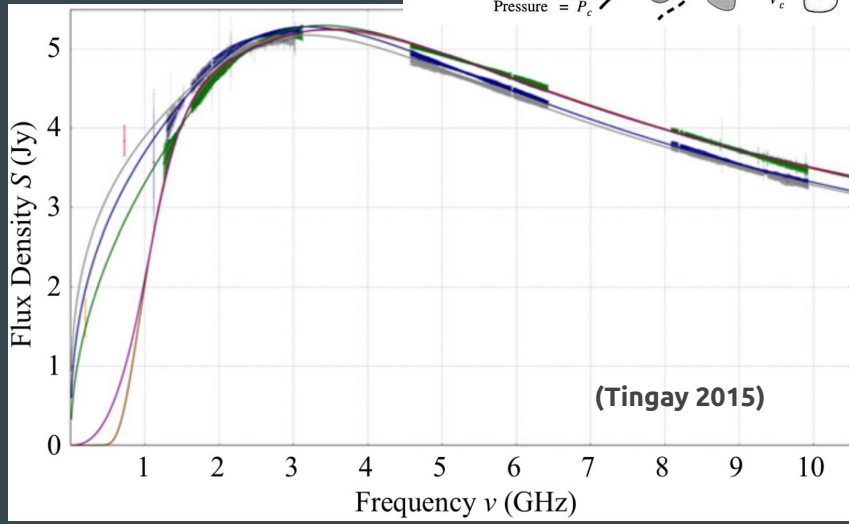
Radio Source

- VLBI Higher angular resolution (2.3, 4.8, 8.4 GHz)
  - Resolved: 2 anti-diametric hot spots separated by 2 pc
  - Position Angle of -40°
- Typical GPS radio spectrum (v_0 ~ 3.8 GHz)
  - Best modelled through Free-Free absorption (Bicknell+1997) [Tingay+ 2007]
  - Significant Variability (Tingay+ 2015)
    - Dense Environment



(Bicknell+. 1997)

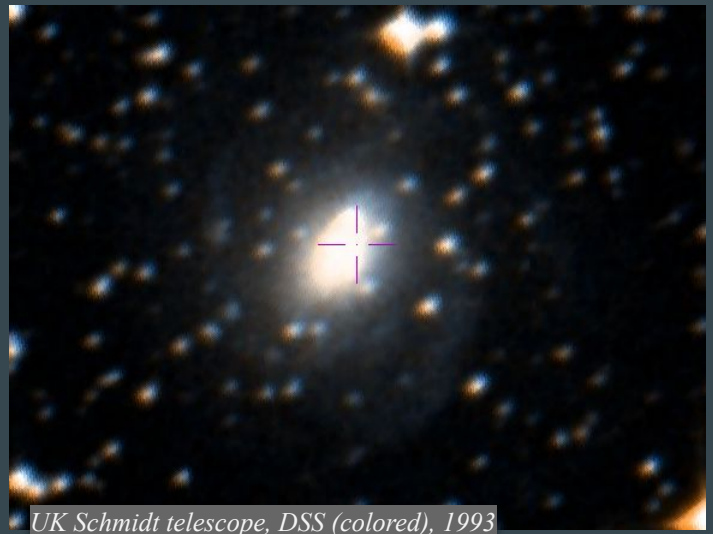


(Tingay 2015)

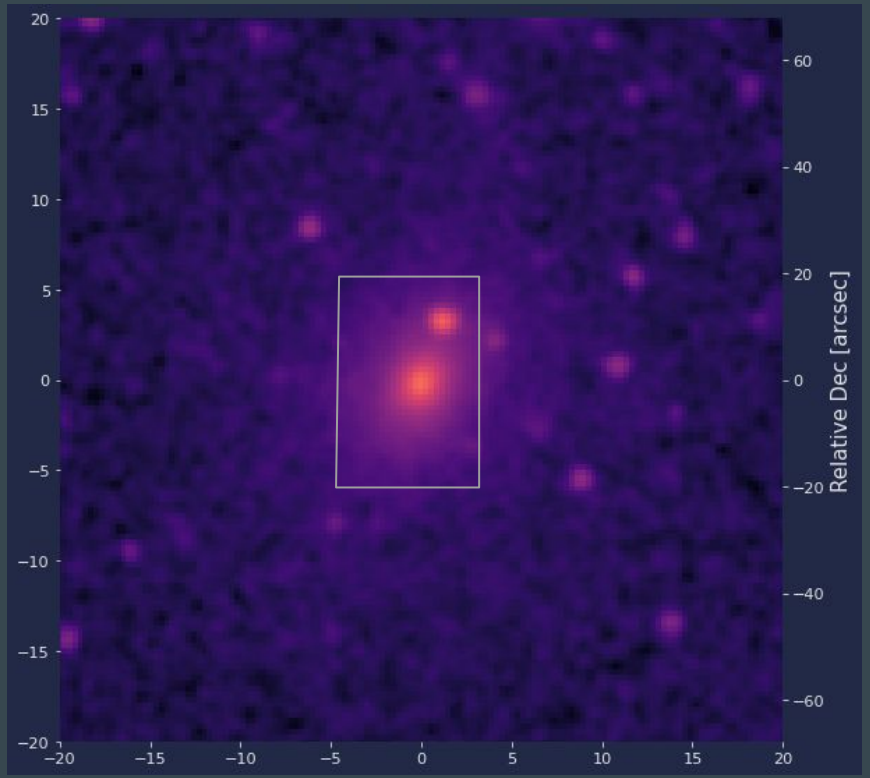
NGC 6328 - Host Galaxy

(z=0.014313; D=62 Mpc)

- Host galaxy stellar properties
  - Bright sersic ¼ Bulge
  - Very Faint Spiral Structure



UK Schmidt telescope, DSS (colored), 1993



2 Mass (K-band)

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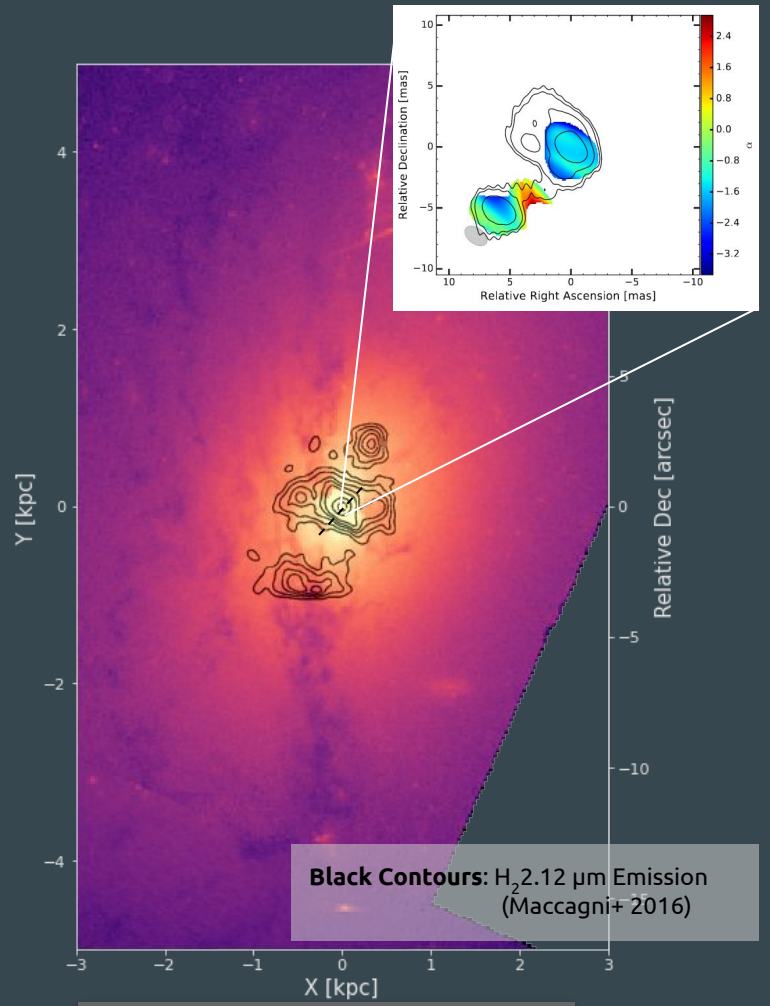
- Complex Dust structure inner 8 kpc [HST]
- Warm H2 (2.12 μm, 1.95 μm) [Maccagni+ 2016]
  - Likely tracing shocks
  - Inner Disk (PA ~ 70°, R<650 pc)



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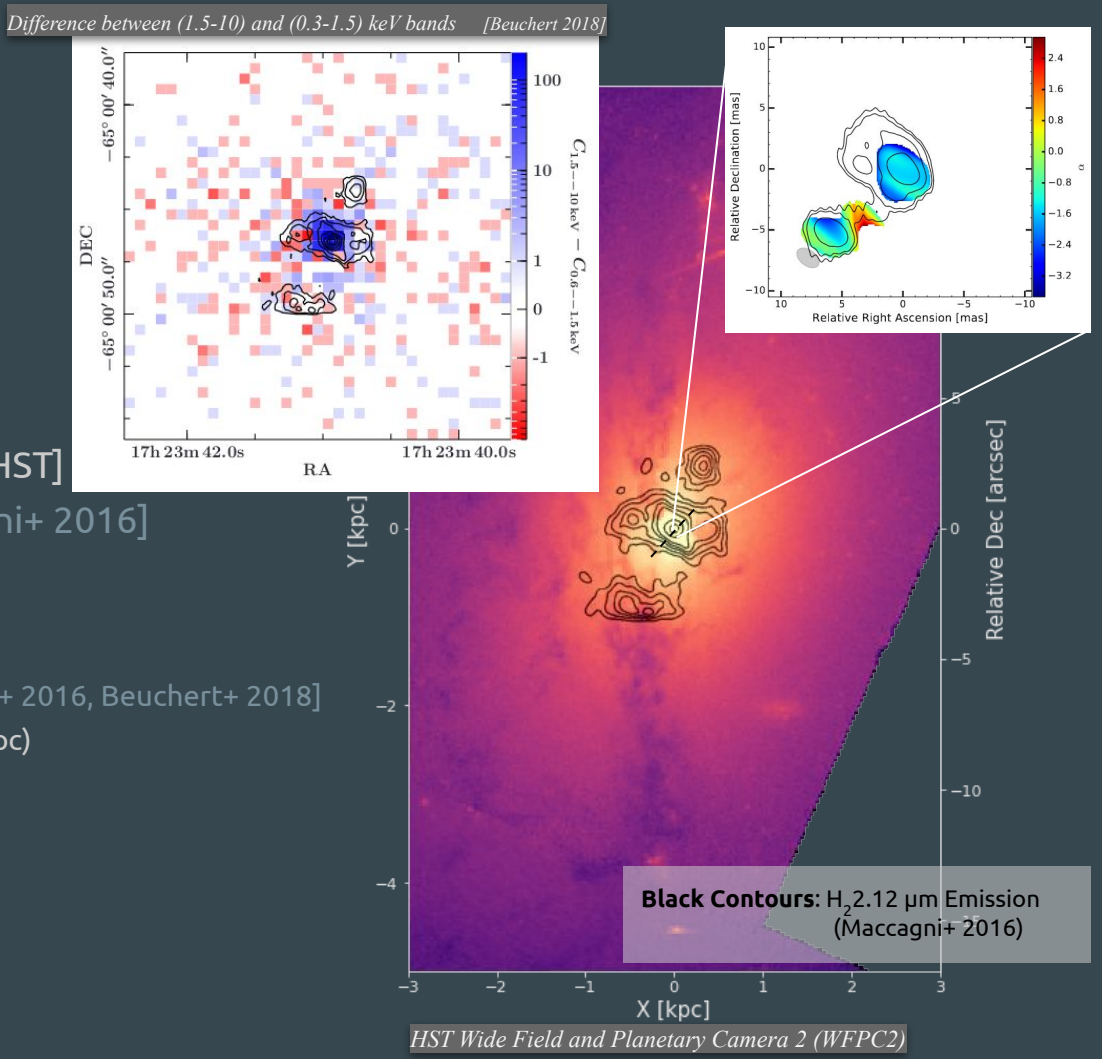

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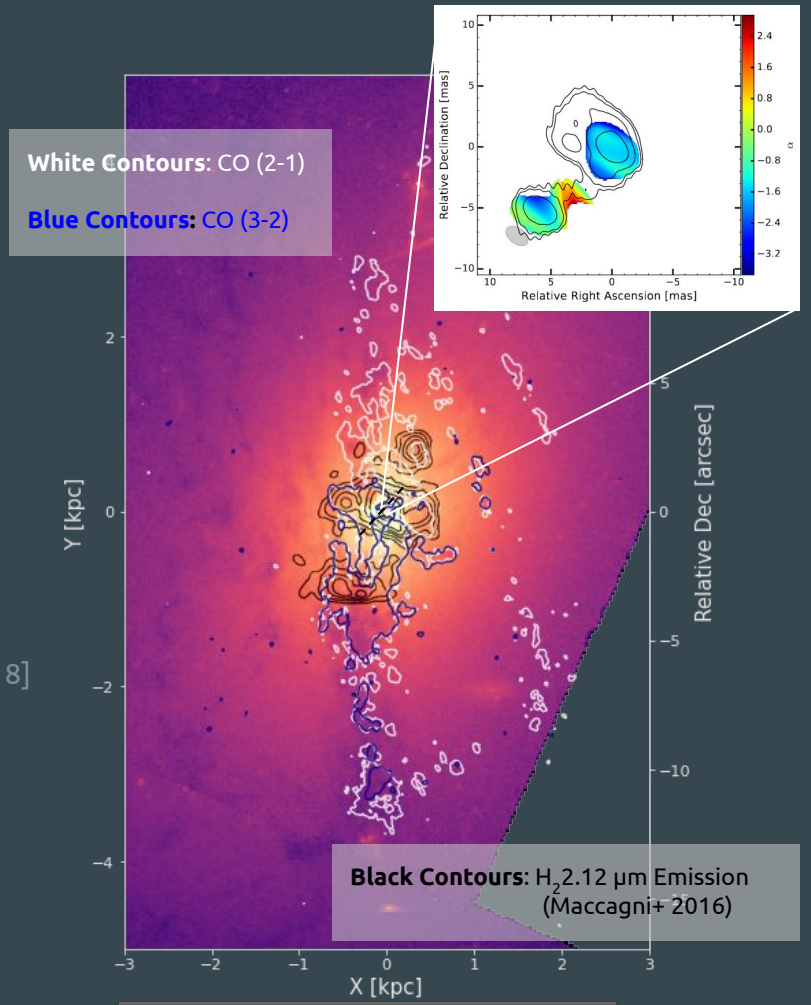
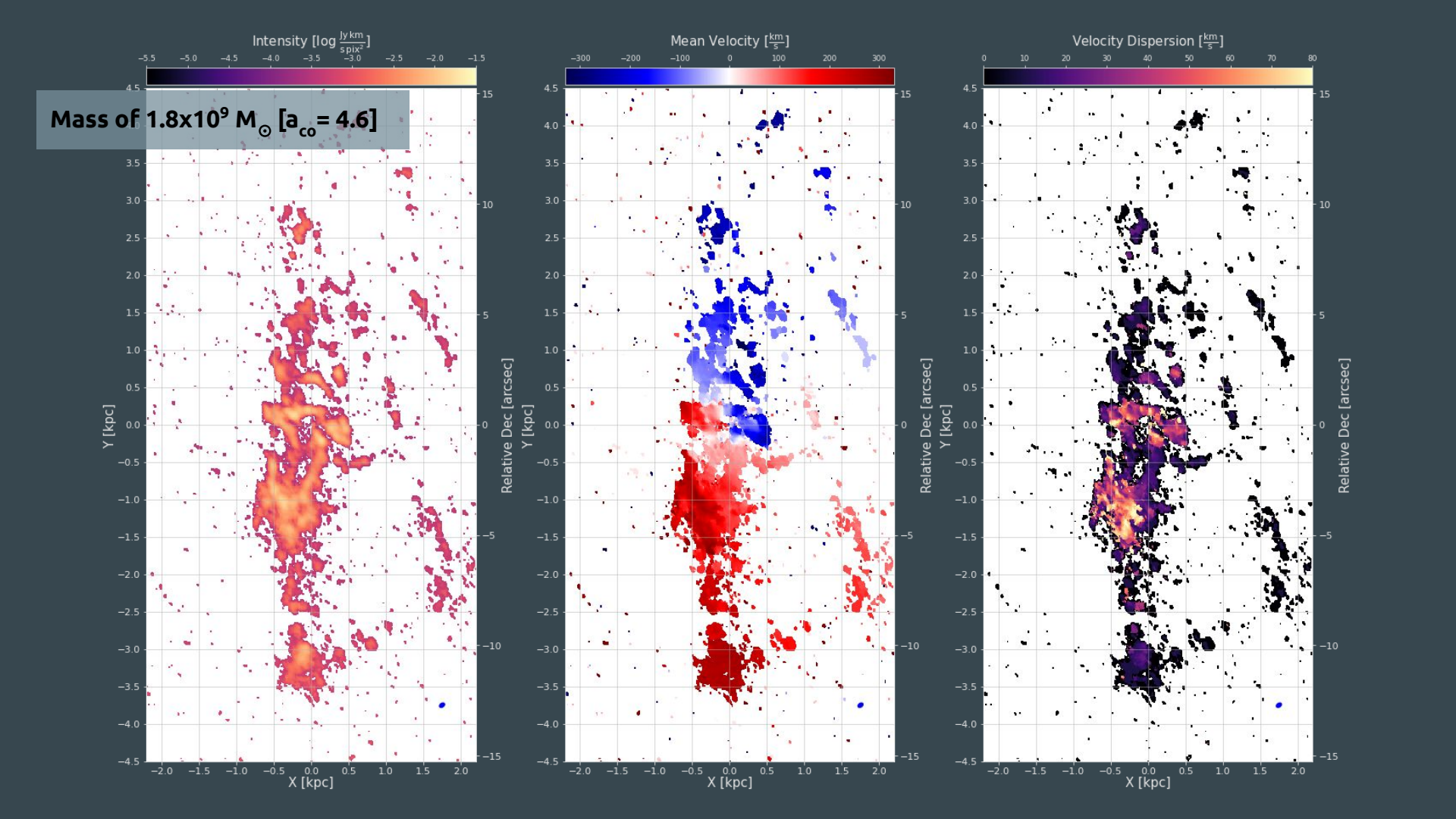
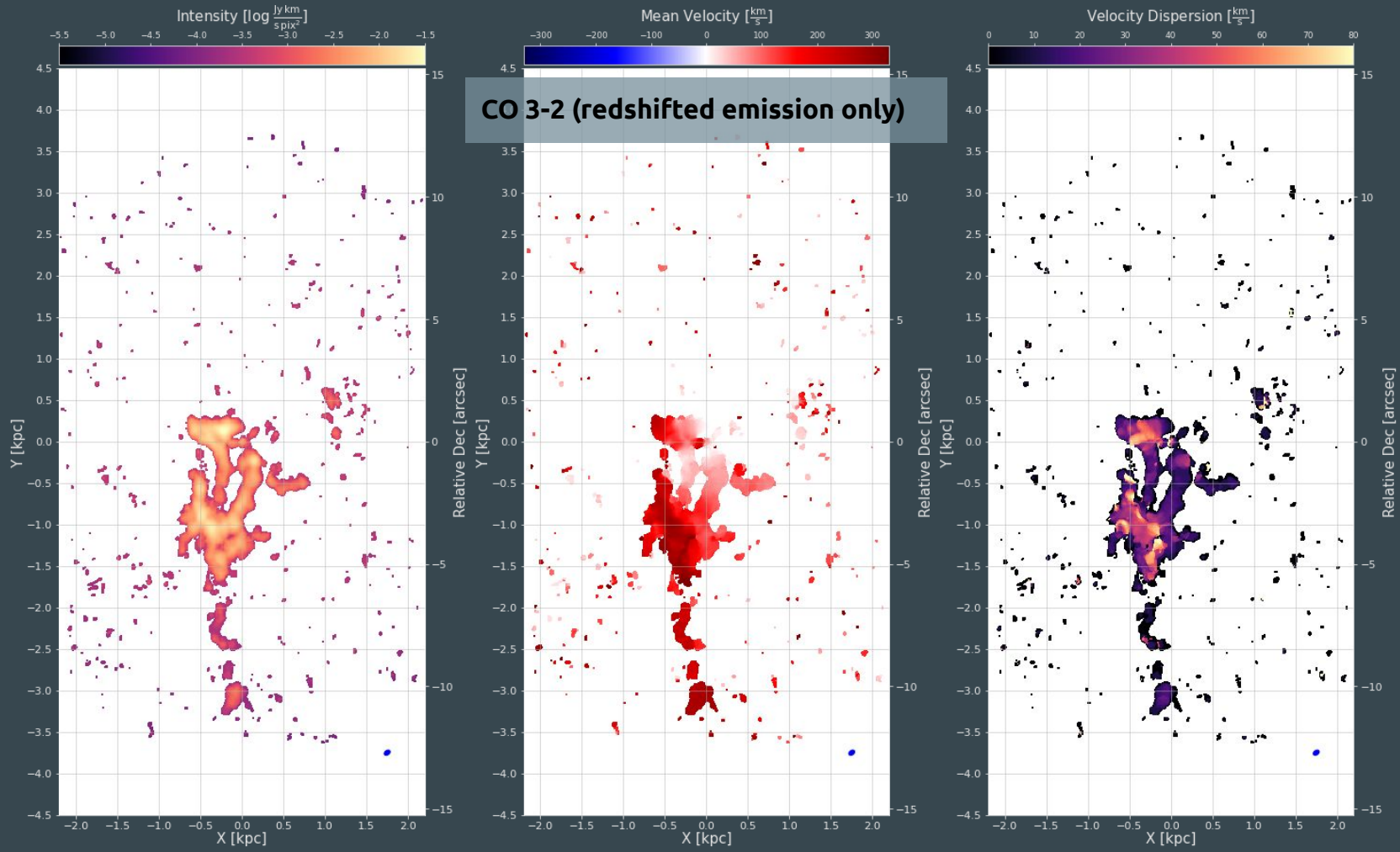
  - collisionally ionized and hot gas (R>600 pc)
- ALMA data
  - CO (2-1) (PI: F. Maccagni)
  - CO (3-2) (PI: S. Kameno): only **redshifted** emission




Mass of 1.8x10^9 M⊙ [a_co = 4.6]
Intensity [log Jy km/s pix²]
Mean Velocity [km/s]
Velocity Dispersion [km/s]
Y [kpc]
X [kpc]
Relative Dec [arcsec]


Intensity [log $\frac{Jy\,km}{s\,pix^2}$]
Mean Velocity [$\frac{km}{s}$]
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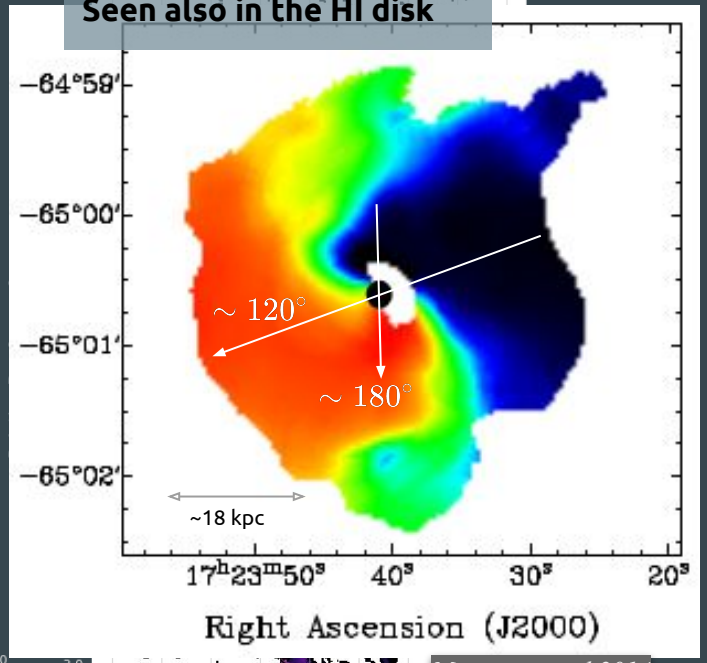
CO 3-2 (redshifted emission only)
Y [kpc]
X [kpc]
Relative Dec [arcsec]

Mass of 3.1x10^8 to 1.8x10^9 M$_\odot$
[a$_{co}$= 0.8 and 4.6]

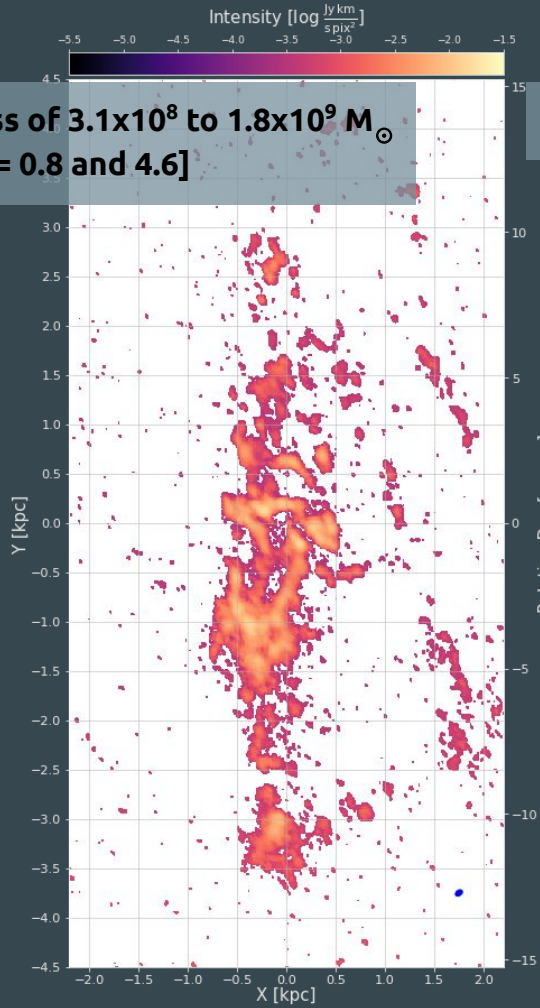
Warped Disk Structure

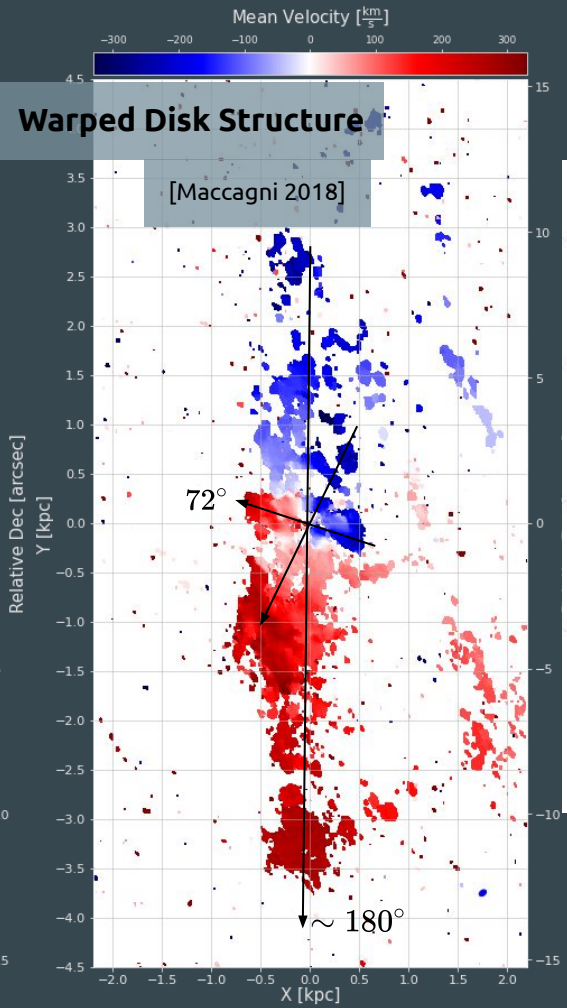
[Maccagni 2018]

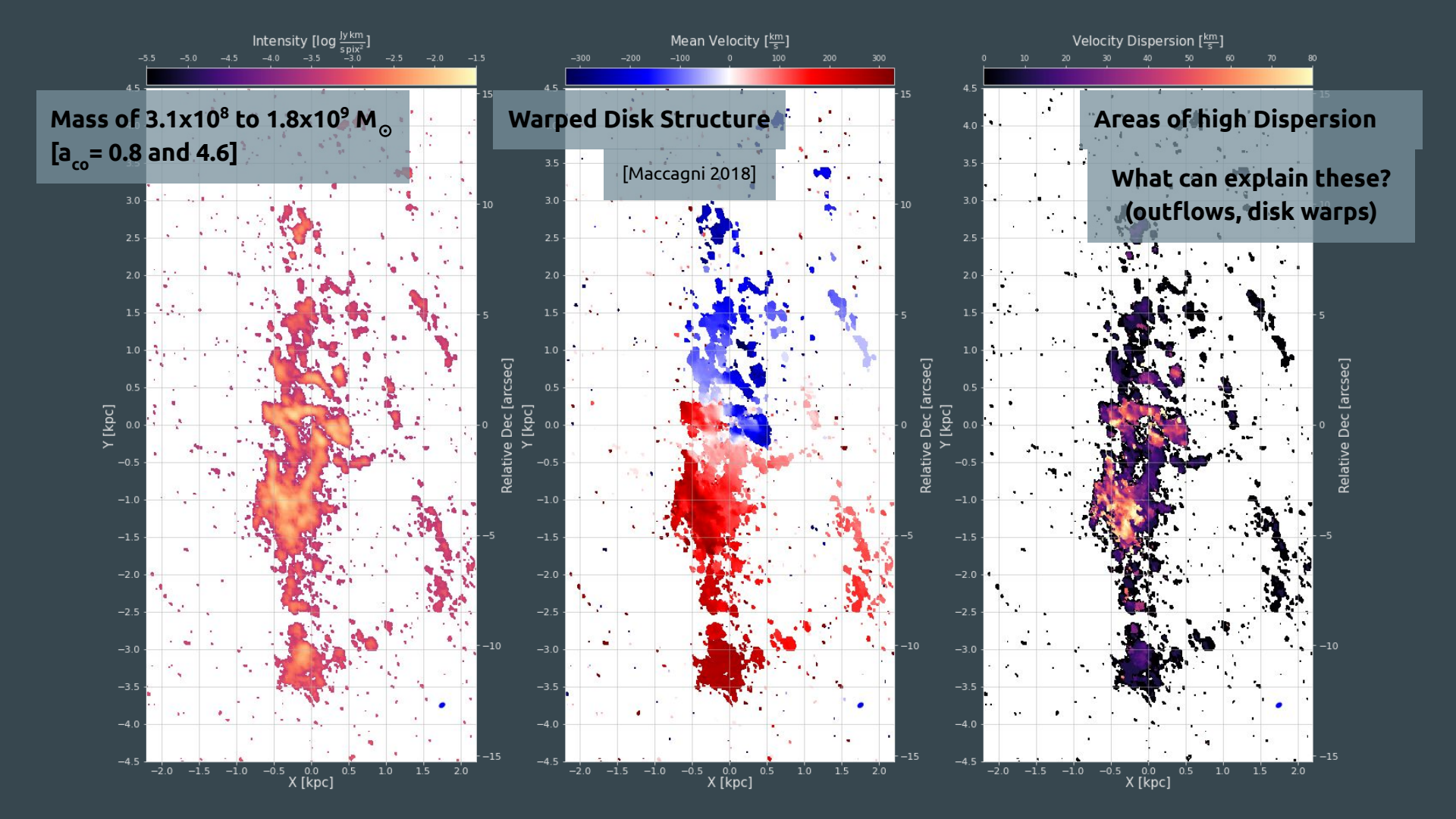
Seen also in the HI disk



Maccagni et al 2014



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Mass of 3.1x10^8 to 1.8x10^9 M$_\odot$
[a$_{co}$= 0.8 and 4.6]
Warped Disk Structure
[Maccagni 2018]
Areas of high Dispersion
What can explain these?
(outflows, disk warps)

CO emission modelling - Newly developed 3D code [Papachristou+ 21, in prep]

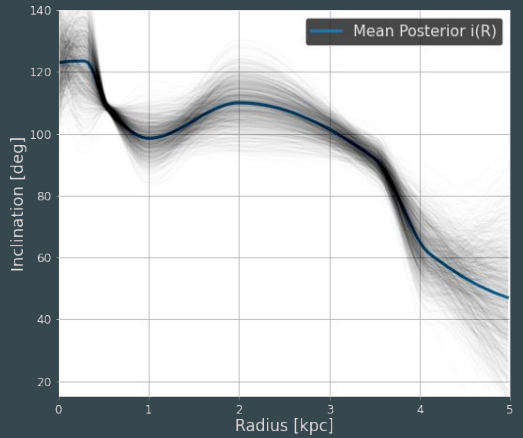
- **Warped disk emission**
  - Tilted rings approximation
  - Fitting (analytic) potential based circular velocities for each ring, unlike Barolo3d and similar codes
  - Φ(R): SMBH +Stellar Bulge (Triaxial Hernquist modified)+Dark Matter (NFW)

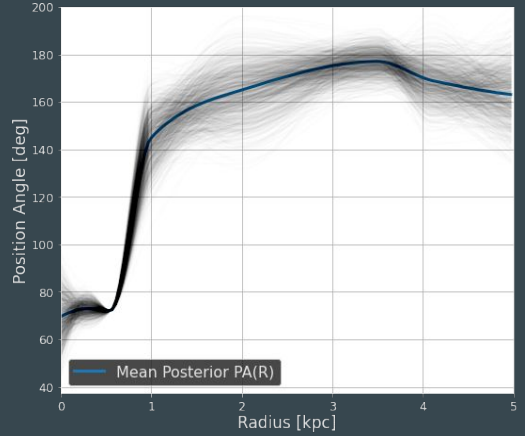
- PA(R) and i(R) are modelled as **monotonic** cubic splines between standard fixed rings.

- Creates 3D model from the Velocity and position of clouds within rings.

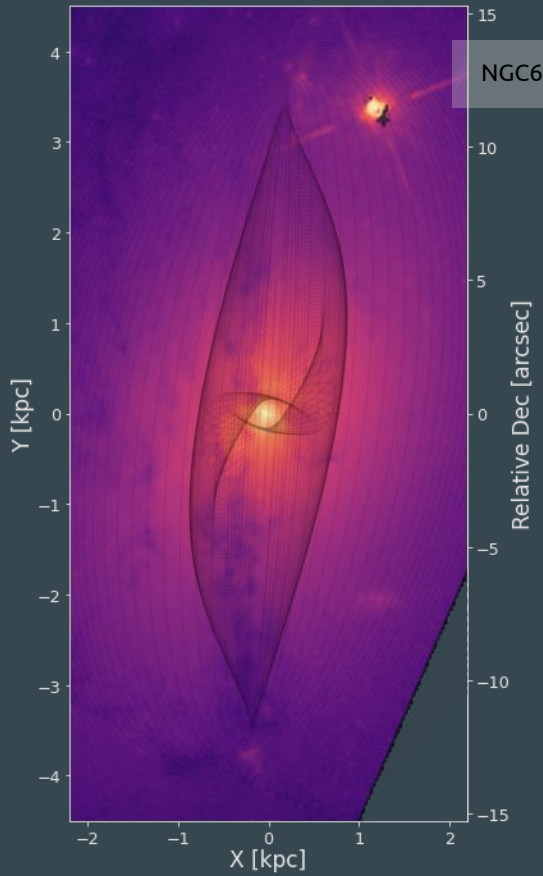
- Parameter estimation by comparing **CO** and **3D model cubes**, taking into account **HI velocities** for the rotation curve

- **Bayesian inference**, with a MCMC posterior sampling of a multidimensional Gaussian Likelihood and prior information on parameters (eg Stellar Mass, i, pa)



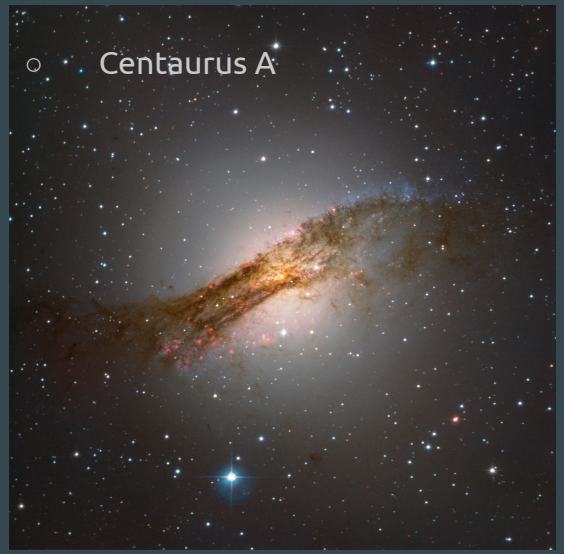


Results - Sky Projection

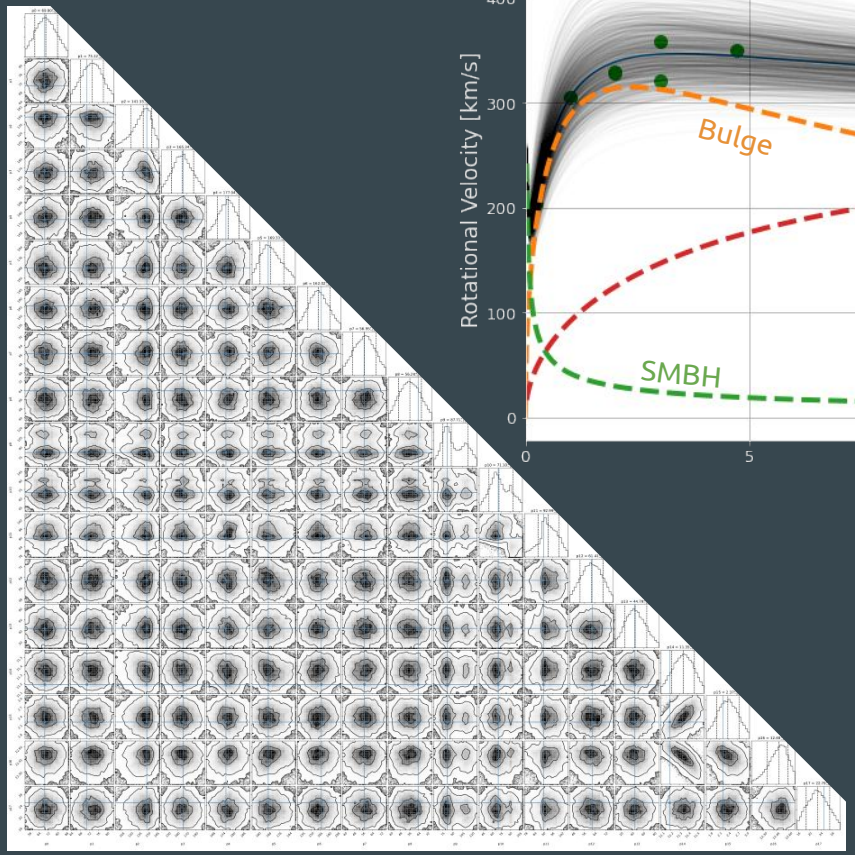


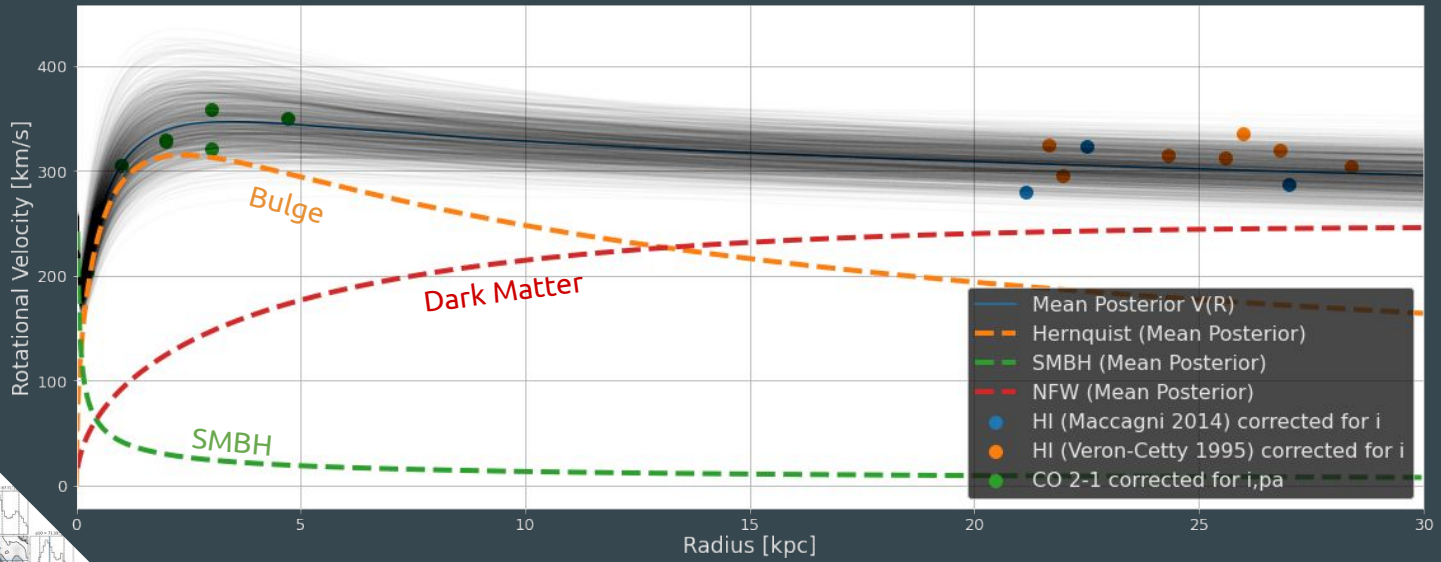
NGC6328, with projected rings

- Model consistent with dust structure
  - Twisting of dust seen also in other warped disks (e.g. Centaurus A)



Results- Rotation Curve



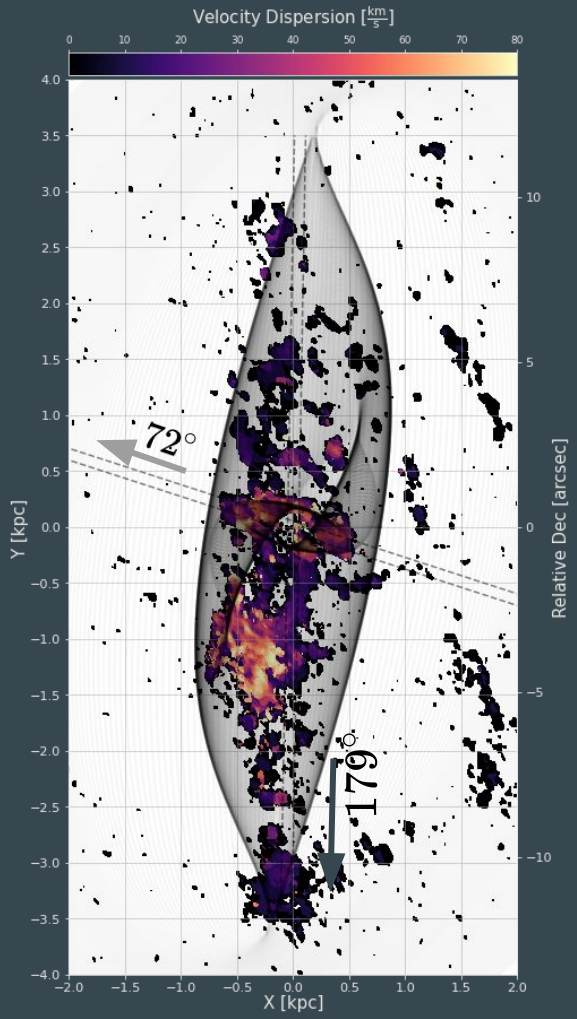


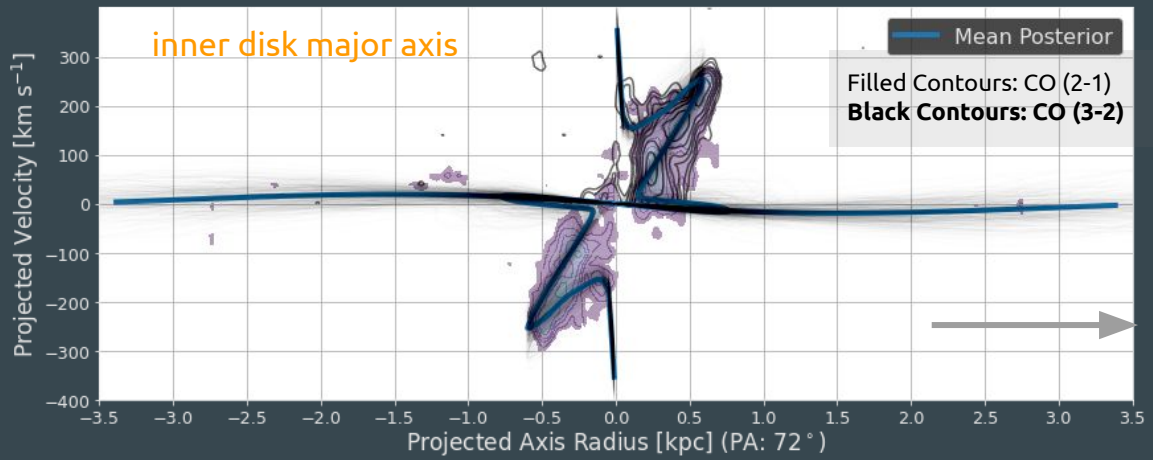
Unimodal Posterior probabilities (unimportant degeneracies, valid and reliable solution)

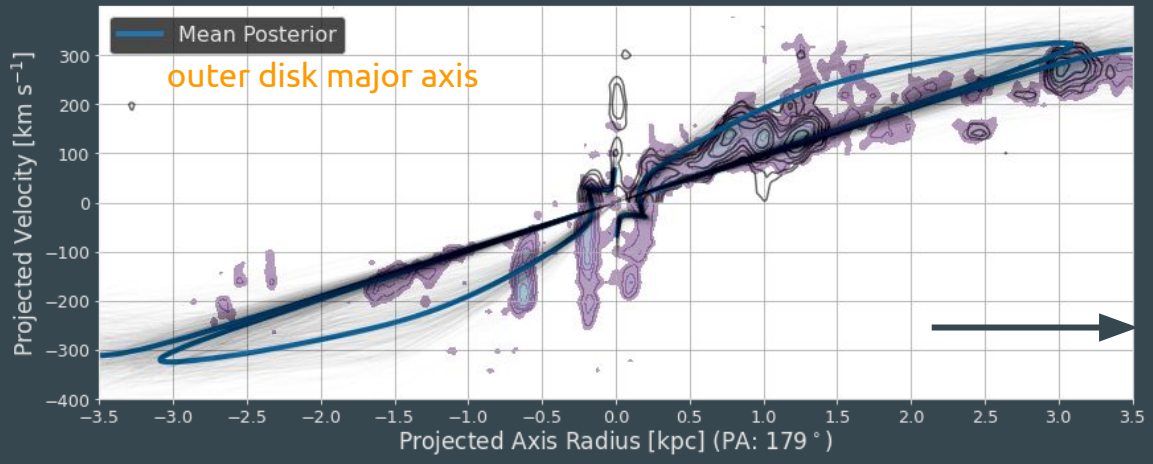
$$\mathrm{M}_* = 2.2^{+0.8}_{-0.6} \times 10^{11}\mathrm{M}_\odot$$ (Consistent with SED fitting)

$$\mathrm{M}_{\mathrm{vir}} = 3.1^{+0.9}_{-0.8} \times 10^{12}\mathrm{M}_\odot$$

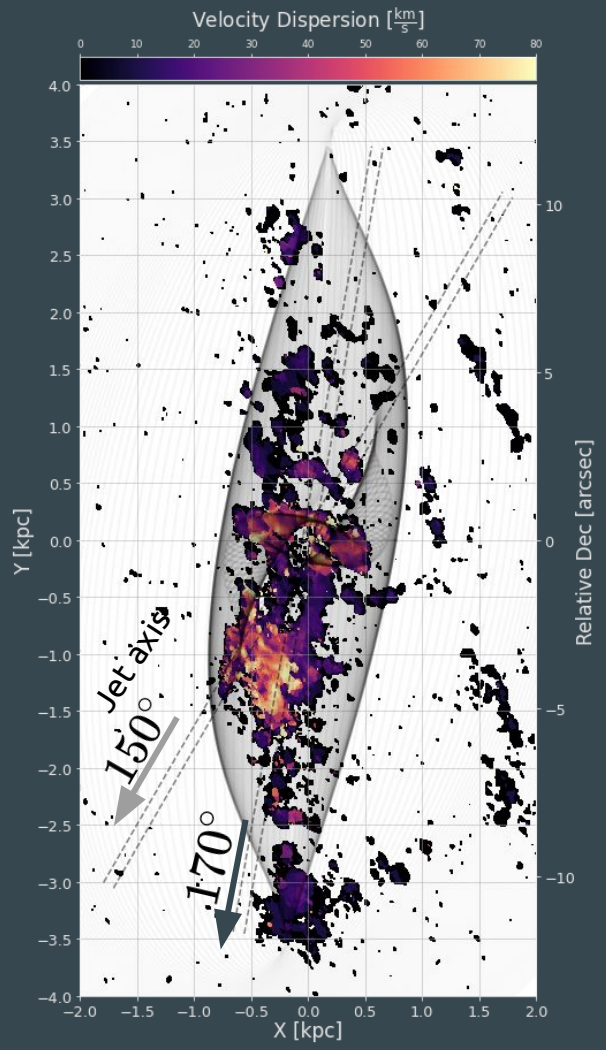
Results - PVDs (good fit of systematic motions at all PAs)

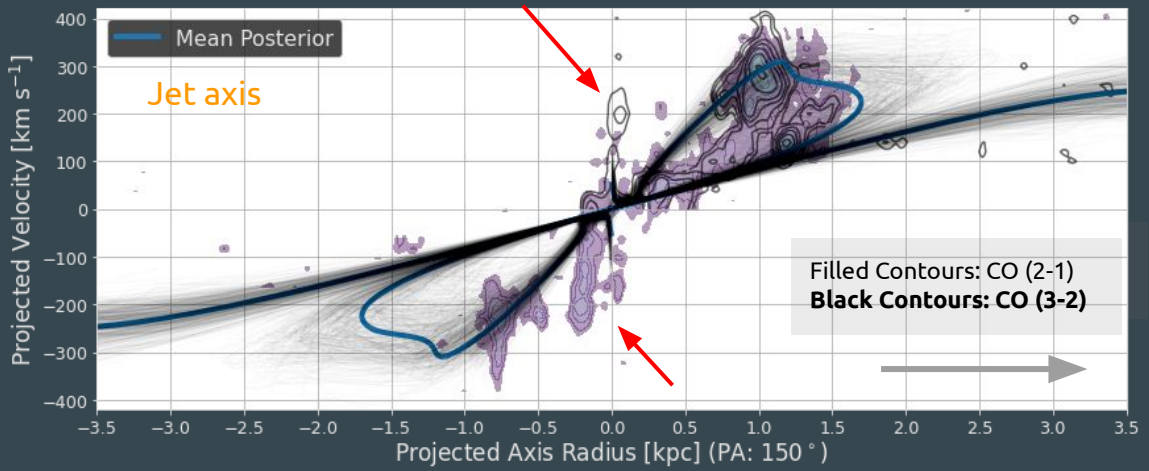


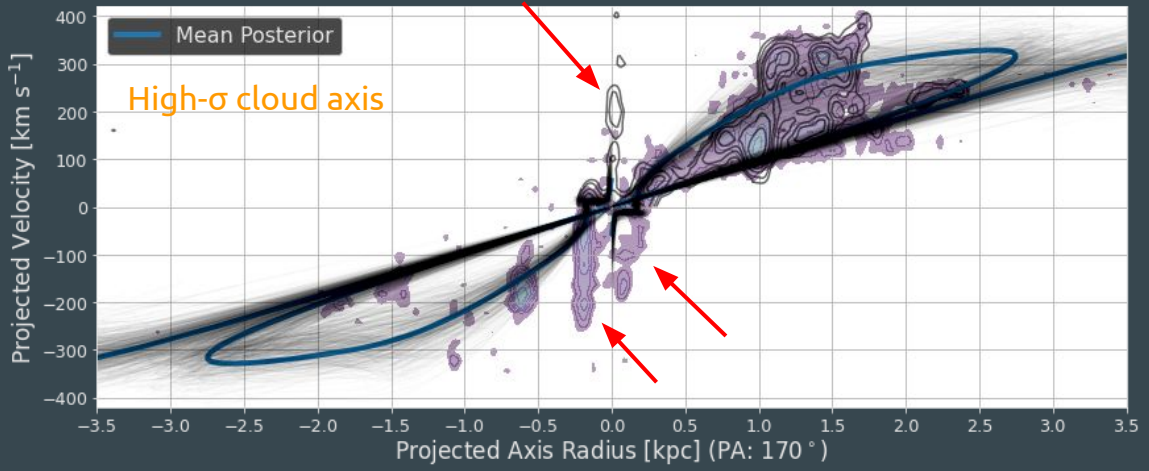




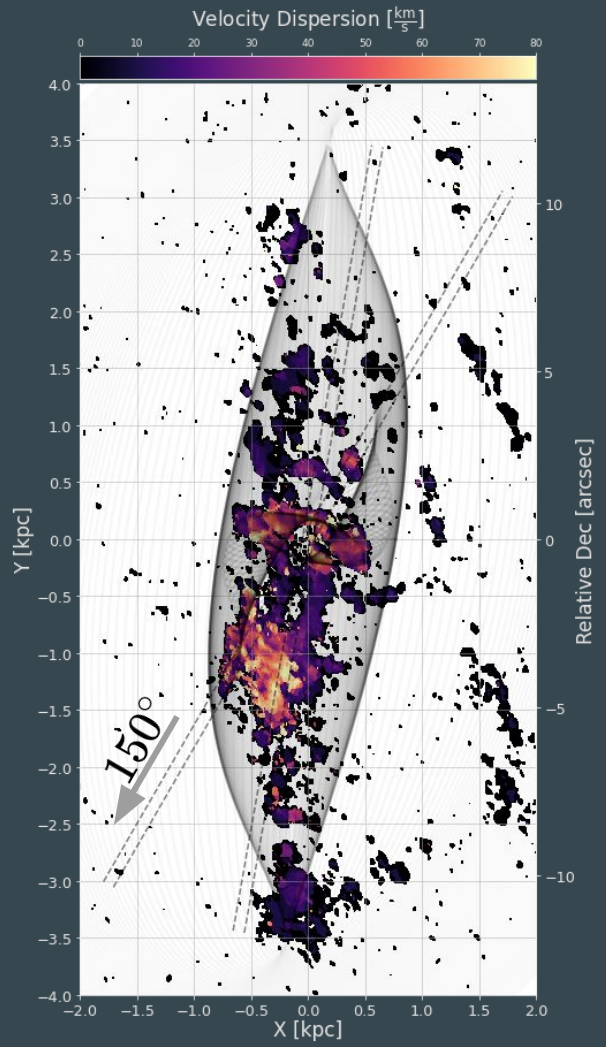
Results - PVDs (good fit of systematic motions + unsettled gas)

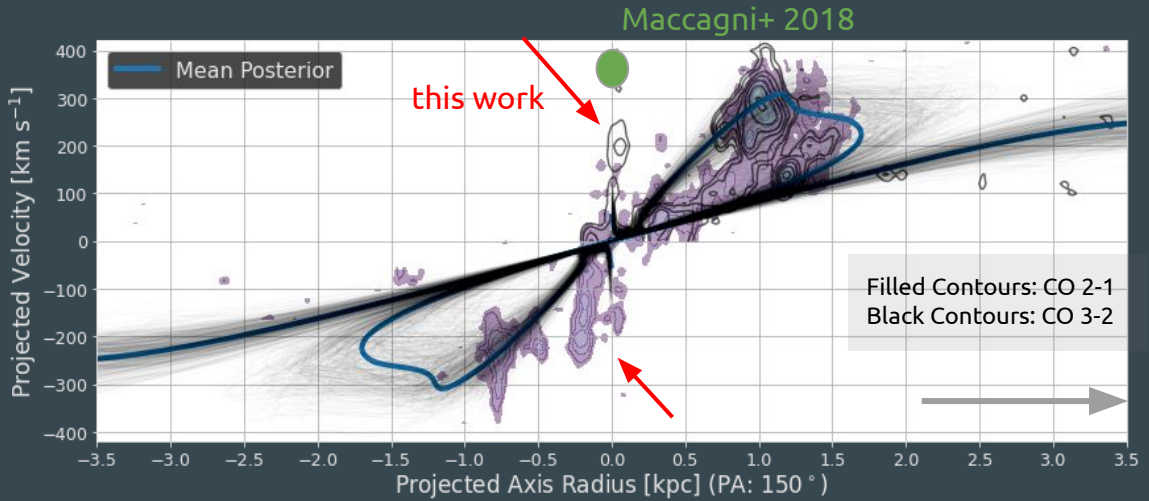






Unsettled Molecular Gas: evidence for outflows





Fast, gas components, with motions that cannot be attributed to projection:

- outside of BH sphere of influence: Gas Inflowing or Outflowing
- Maccagni+ 2018: CO (2-1) clump in absorption at **360 km/s** and **σ ~ 60 km/s**
  Proposed as an inflow

- **More clouds: 0-250 km/s**, near nucleus (<100pc) in CO(3-2)
- High-σ (>150km/s) clouds ±>200 pc from nucleus (~antidiametric positions)

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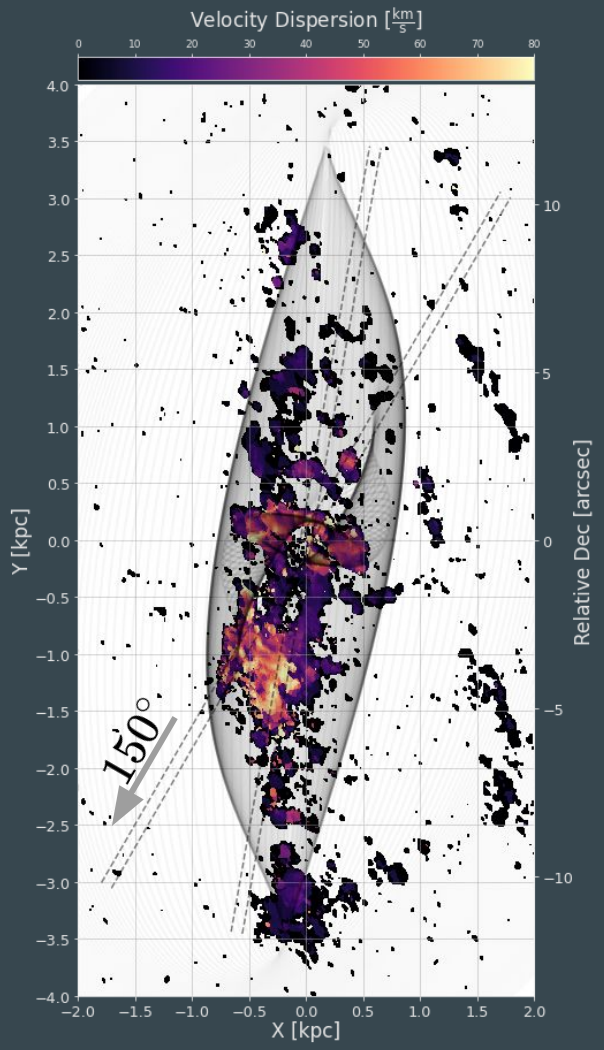

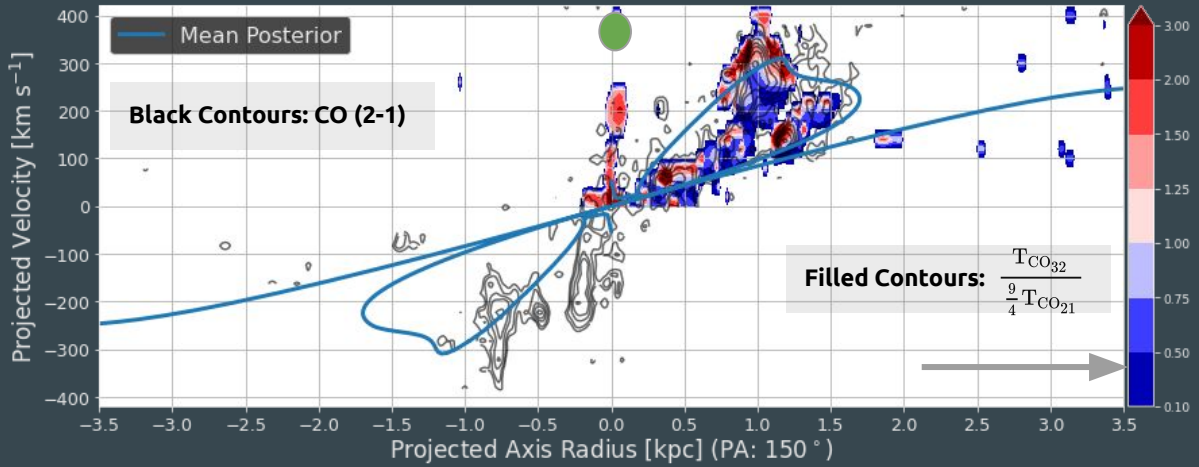

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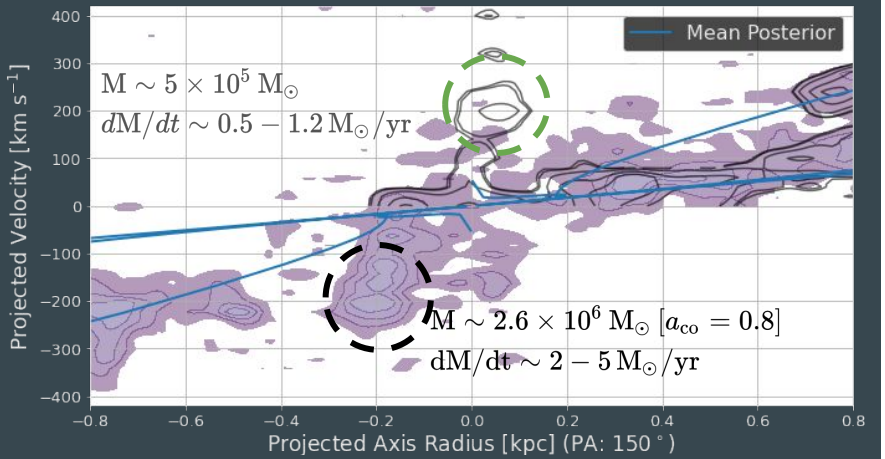
- Unsettled gas: highest excitation (as IC5063; Dasyra+2016, Oosterloo+2017)

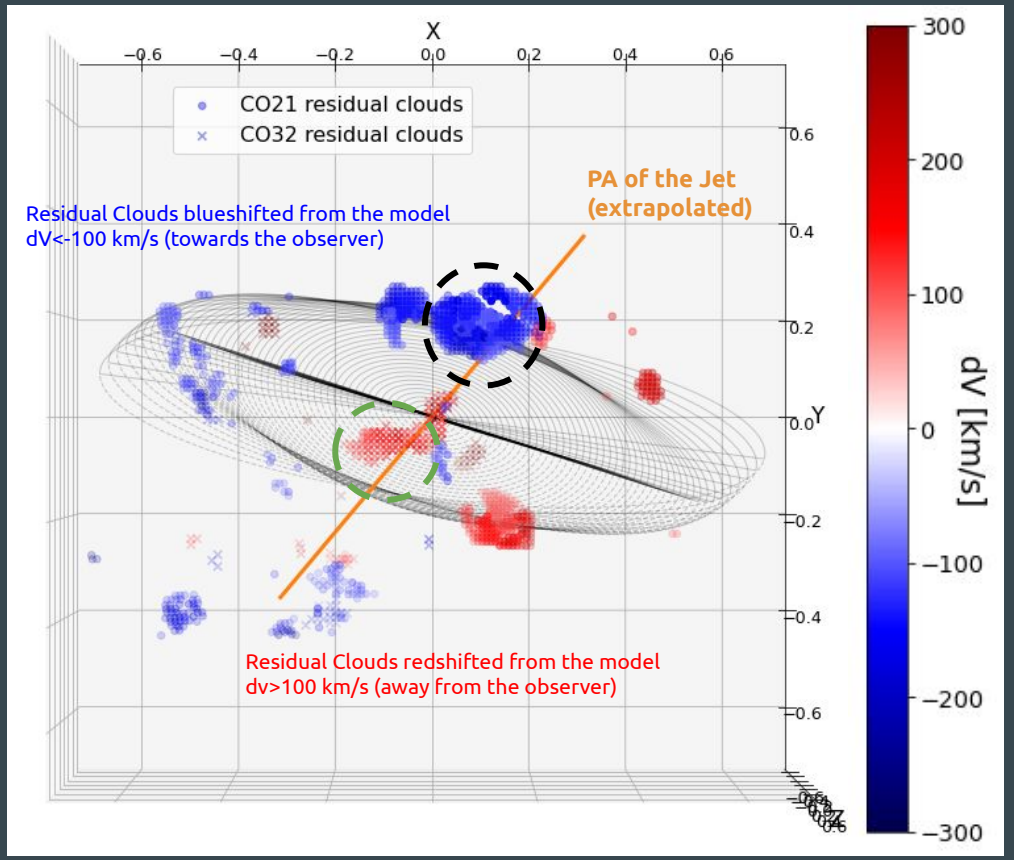
Numerous pieces of evidence for outflows

Unsettled Molecular Gas: geometric connection to jet?

Cube of the Residual (model-data) gas at inner disk:

- Study of two position angles indicates that clouds closer to the jet axis move faster (~2X) than clouds further away
- Jet (+cocoon?) driven outflows





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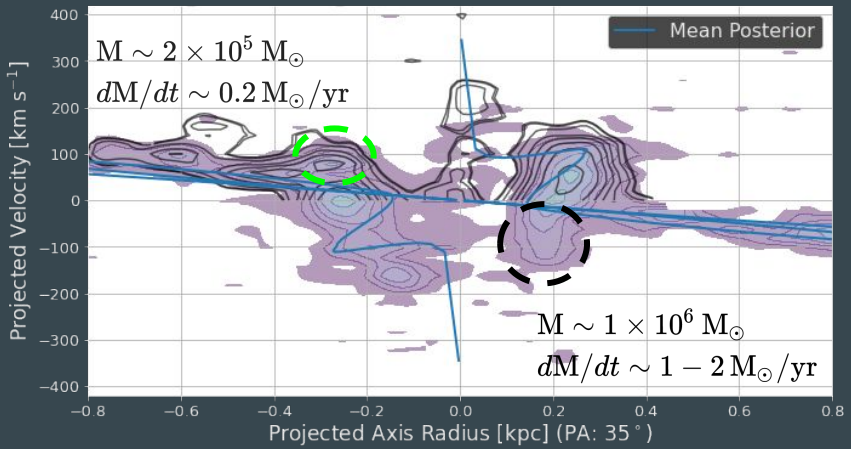
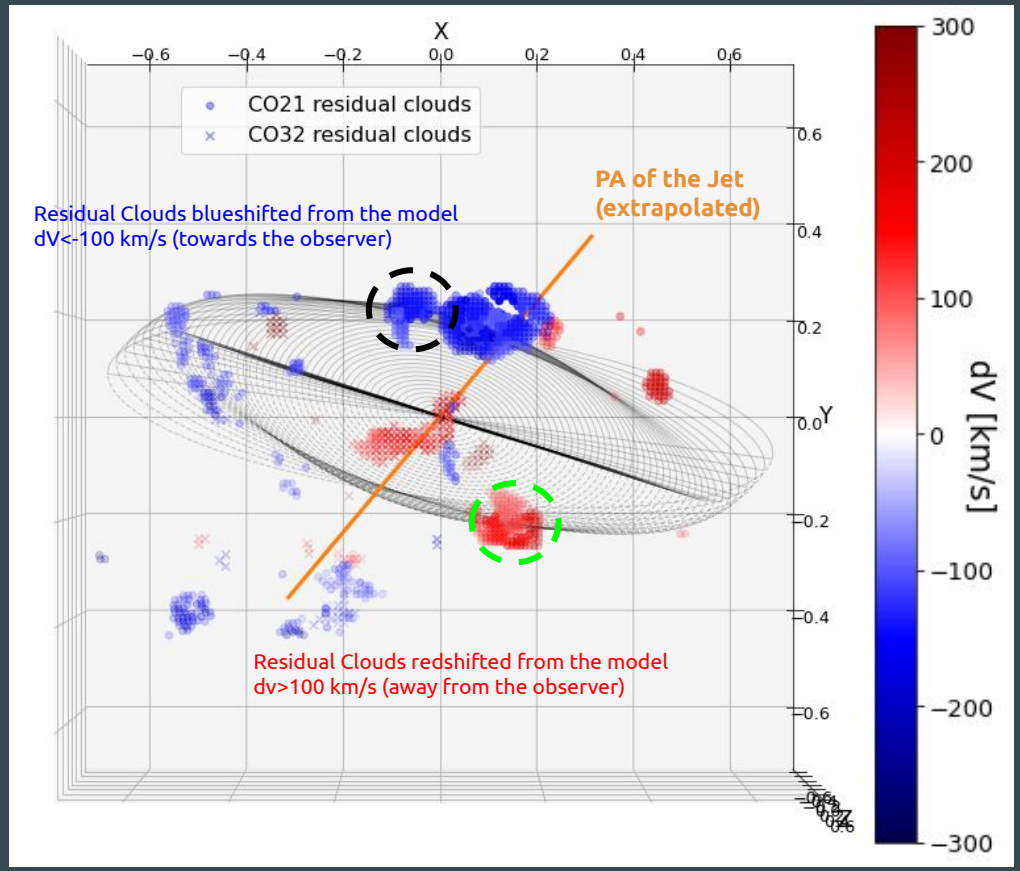
- Total Mass of the outflow = 3-4 x $10^6 M_\odot$ [a_{co}=0.8]
  Rate of 3-8 $M_\odot$/yrs





Molecular Outflow Energetics: can be driven by BH feedback

- SF: Galaxy Integrated SFR ~ 0.8-1.8 $M_{\odot}$/yr [Willet+ 2010]
  - Supernovae kinetic power <10^{40} erg/s
  - Stellar Radiation Pressure <5×10^{31} dyn
    (using that nucleus has ~1.2% of stellar mass - R<300pc)
- AGN
  - AGN radiation Pressure 4.3×10^{31} dyn
    (Luminosity ~ 1.3×10^{42}erg/s; X-rays)
- Jet Power
  - >3×10^{42} with most likely value 2×10^{43}erg/s [Wójtowicz+ 2020]
  - $P_{jet}/L_{edd} \sim 5 \times 10^{-4} > 10^{-4}$ [critical value from Wagner+ 2012]

- Outflow kinetic power: ~$2\text{-}7 \times 10^{40}$ erg/s
- Outflow momentum rate ~ $1\text{-}7 \times 10^{33}$ dyn

- Most likely a jet drives the outflow
  - Either associated with low-L or past emission (relic) **(?)**

Conclusions

- We used CO (2-1) and (3-2) to study the kinematics of molecular gas of the GPS galaxy NGC 6328
- The data were fit with a new 3D tilted rings model. They showed a strongly warped disk
- A molecular gas outflow of 3-8 $M_{\odot}$/yrs is detected in the central 300 pc of the galaxy
- The outflow is plausibly Jet-driven

Thank you