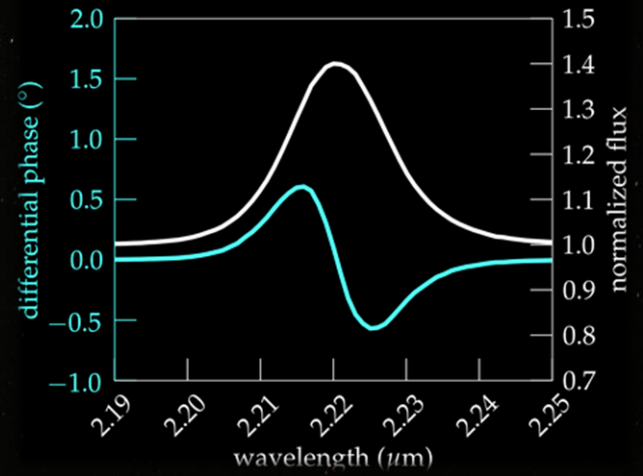
Spectro-Interferometric Signatures of the Broad Line Regions in Active Galactic Nuclei



Matthias Raphael Stock

Max Planck Institute for Extraterrestrial Physics

TORUS Conference, 10 December 2018

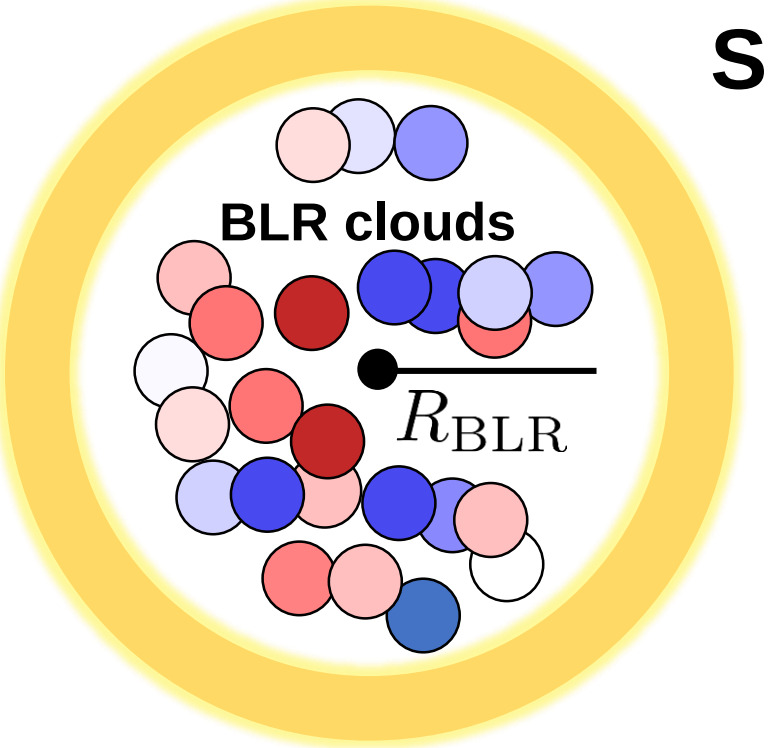
GRAVITY at the VLTI

$$R_{\rm BLR} \lesssim 0.1 \text{ mas}$$

$$\Delta\theta = \frac{\lambda}{B} = \frac{2.2\ \mu\text{m}}{130\ \text{m}} \sim 3.5 \text{ mas}$$

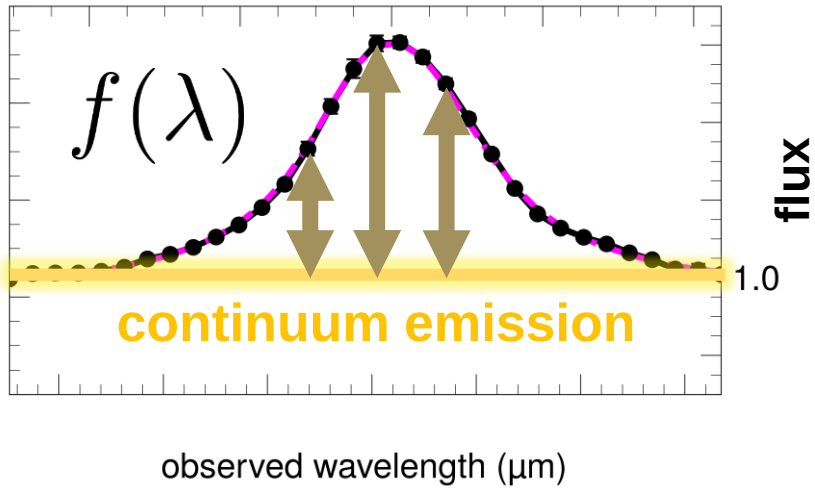
Paranal and the Pacific at Sunset.
Credit: ESO/G.Hüdepohl (atacamaphoto.com)

Spectro-Interferometry: Differential Phase



symmetric continuum

line emission



$$f_{\rm line} = \frac{f(\lambda)}{1+f(\lambda)}$$

Quasars

$$f(\lambda) \lesssim 0.5 \rightarrow |\phi| \lesssim 2.7°$$

$$\Delta\phi(\lambda) = -2\pi \, f_{\rm line} \left[\frac{\vec{B}(\lambda)}{\lambda} \cdot \Delta\vec{x}(\lambda) \right]$$

baseline — centroid

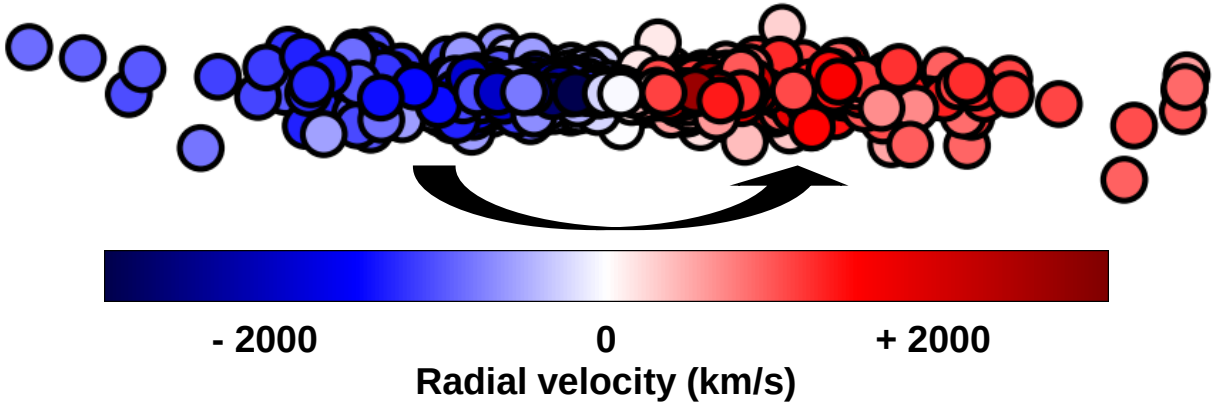
line/continuum emission

$$\frac{100 \text{ m}}{2.2 \ \mu\text{m}} \cdot 100 \ \mu\text{as}$$

sensitivity of GRAVITY $\lesssim$ 0.5° per baseline per hour

tens of micro-arcseconds astrometric precision

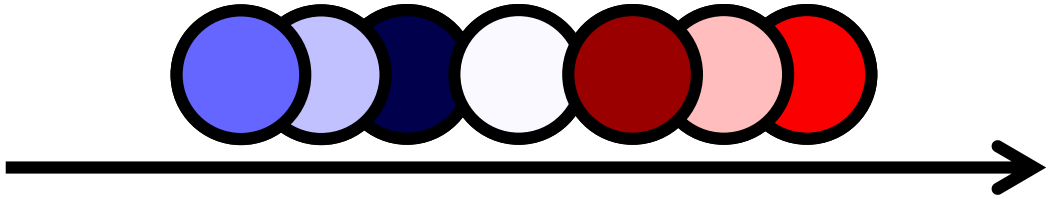
Cloud Model: flat Keplerian disk



- 2000 0 + 2000

Radial velocity (km/s)

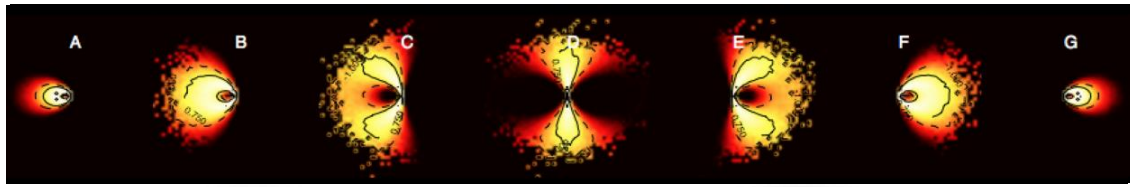
Centroids



- 0 +

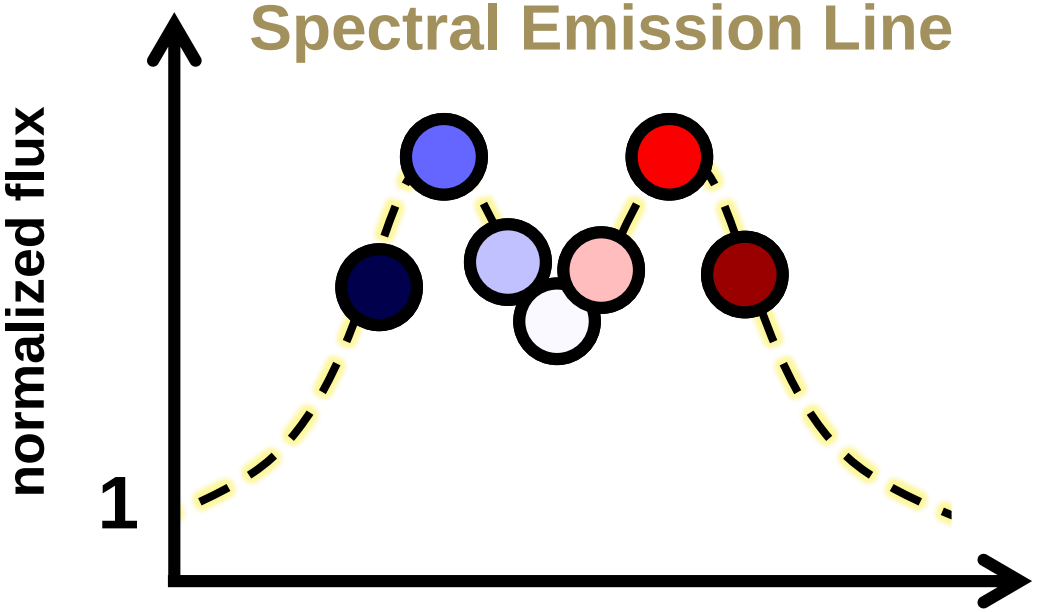
right ascension offset (μas)

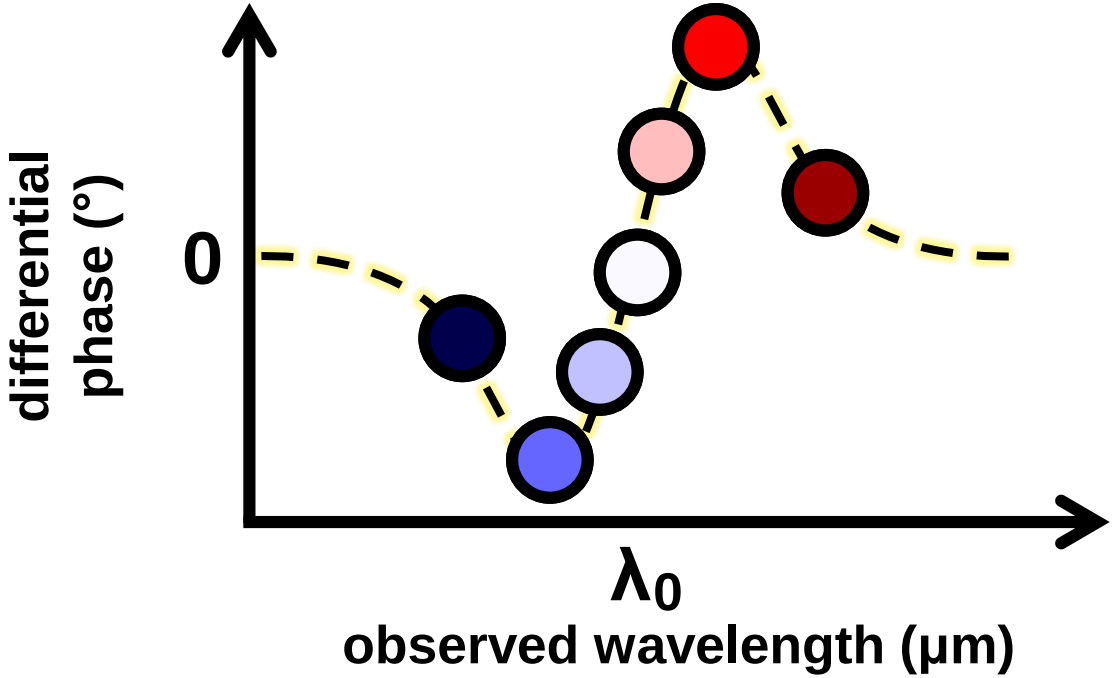
Line Intensity Map



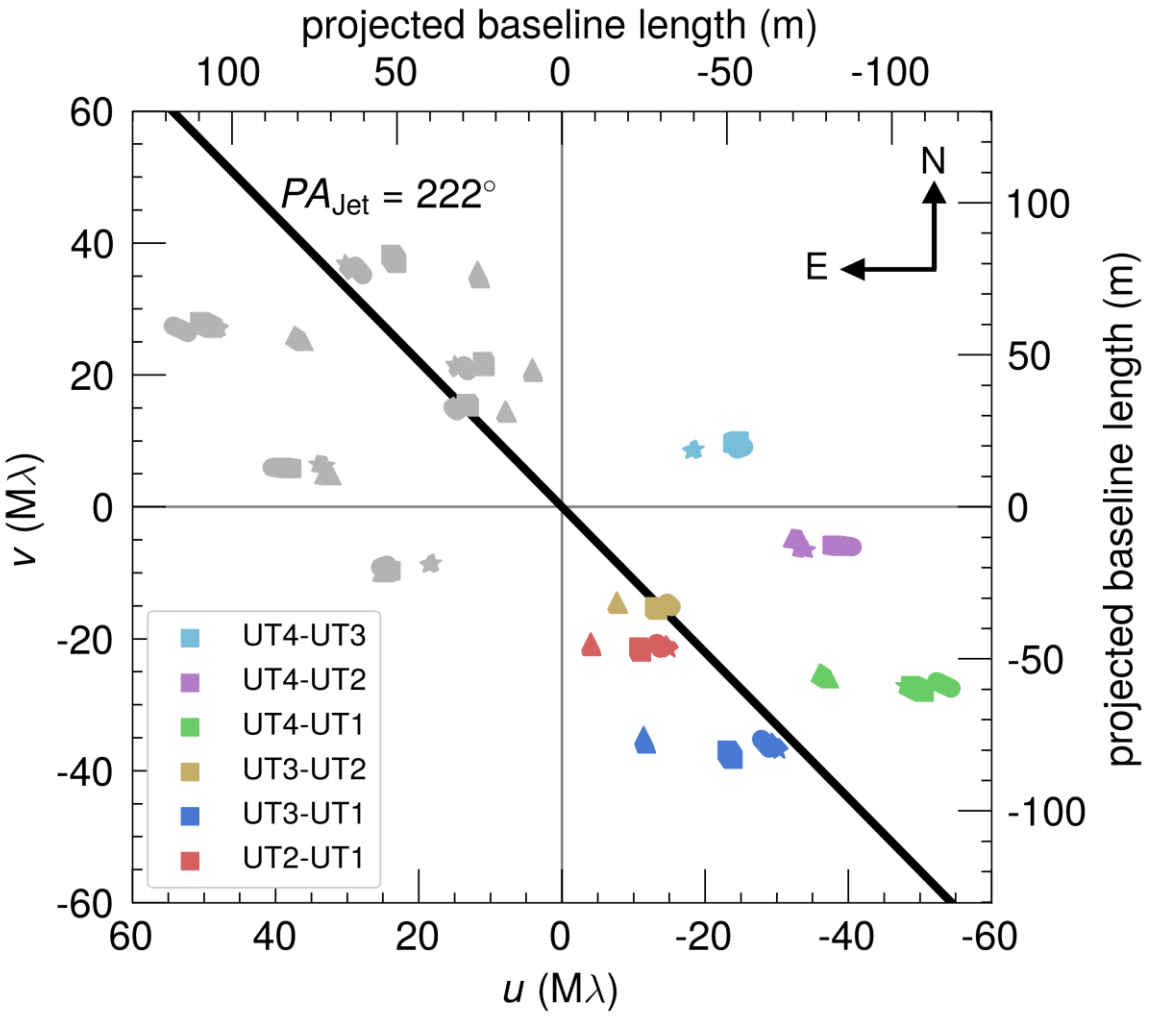
S. Rakshit et al. 2015

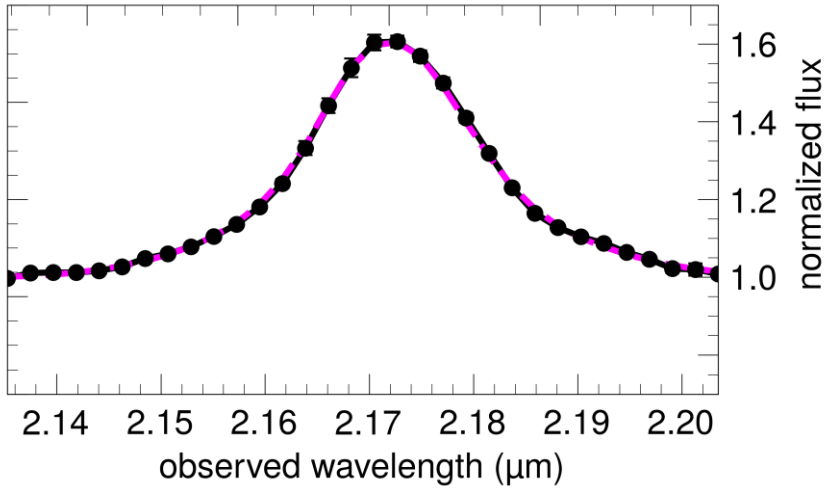
Spectral Emission Line





Detection of the BLR of the Quasar 3C 273 with VLTI/GRAVITY





line/continuum

baseline

$$\phi_{\rm MC}(\lambda,\vec{x}) = -2\pi \left(\frac{r(\lambda)}{1+r(\lambda)}\right) (\vec{u}\cdot\vec{x})$$

centroid

sum over all baselines

$$\chi^2(\lambda,\vec{x}) = \sum_{i=1}^{\rm Bl} \left(\frac{\phi_{\rm GR}(\lambda)-\phi_{\rm MC}(\lambda,\vec{x})}{\Delta\phi_{\rm GR}(\lambda)}\right)^2$$

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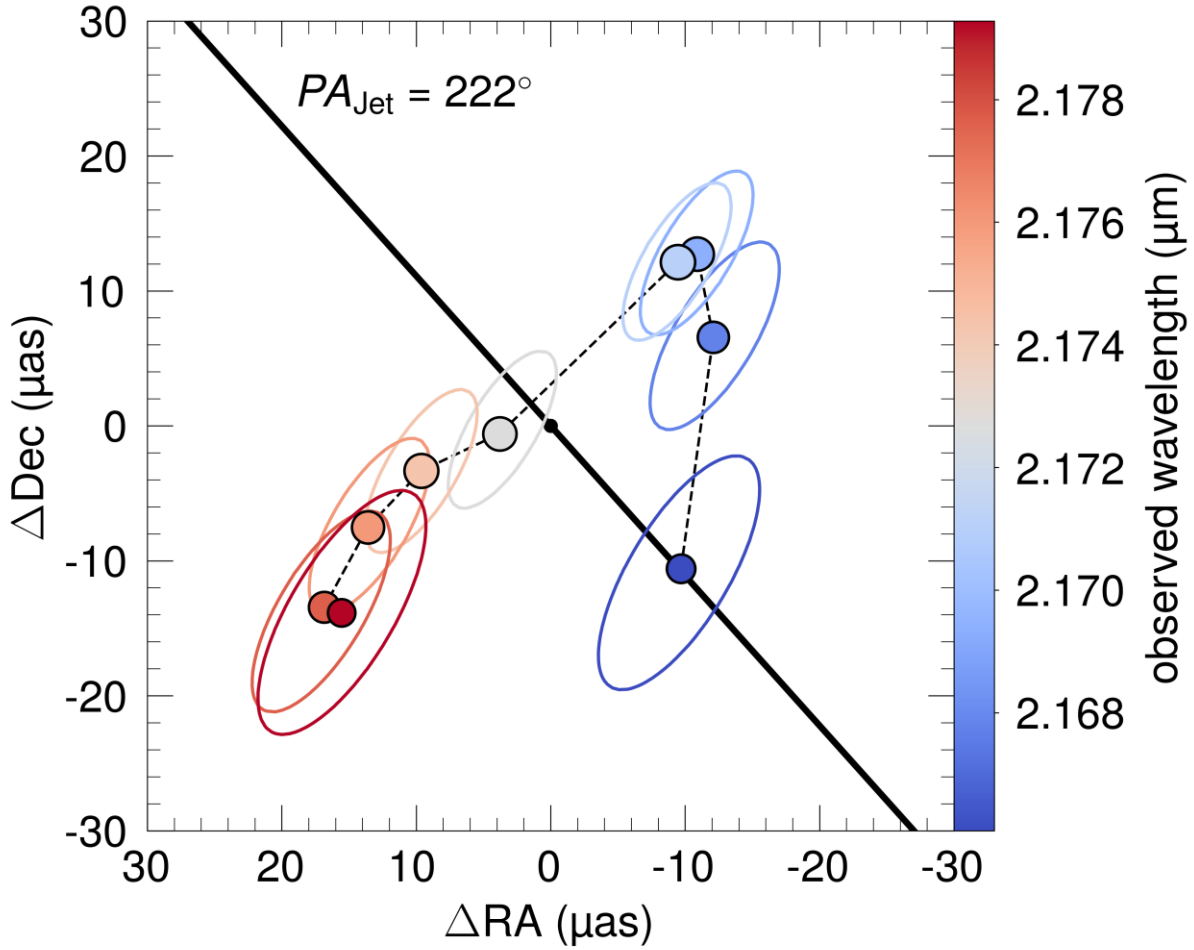
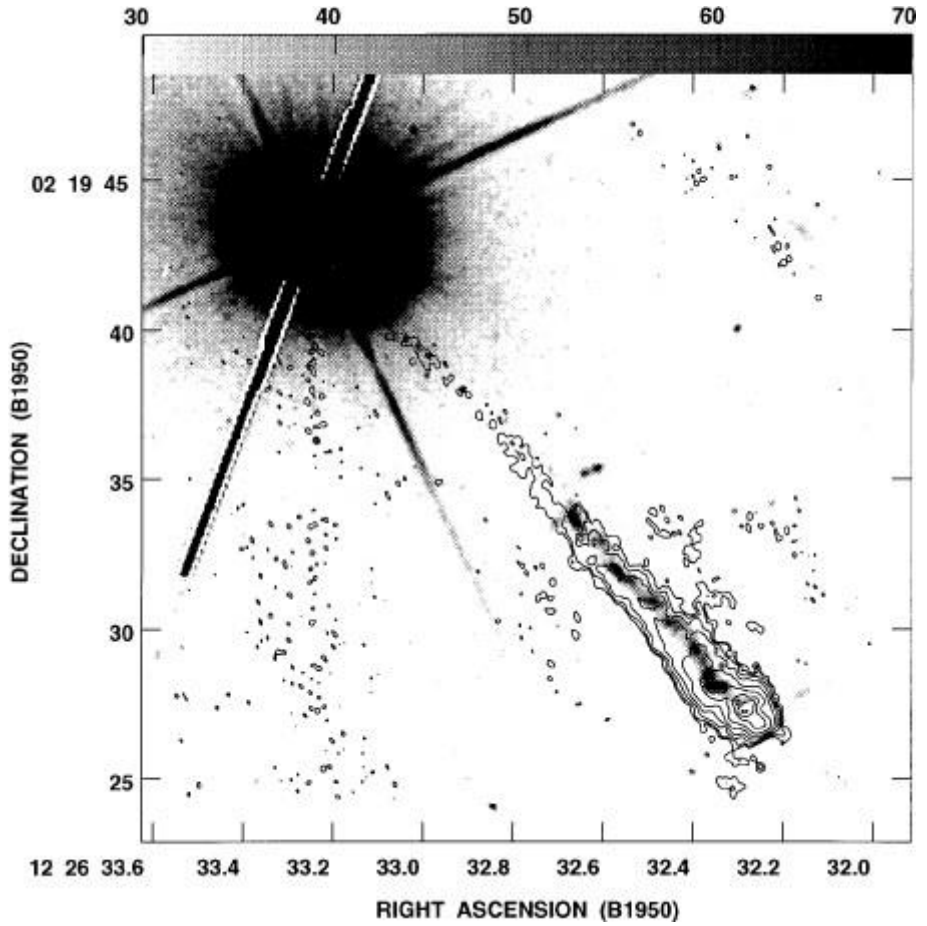
Ordered Rotation in the BLR of the Quasar 3C 273



Bahcall et al. 1995



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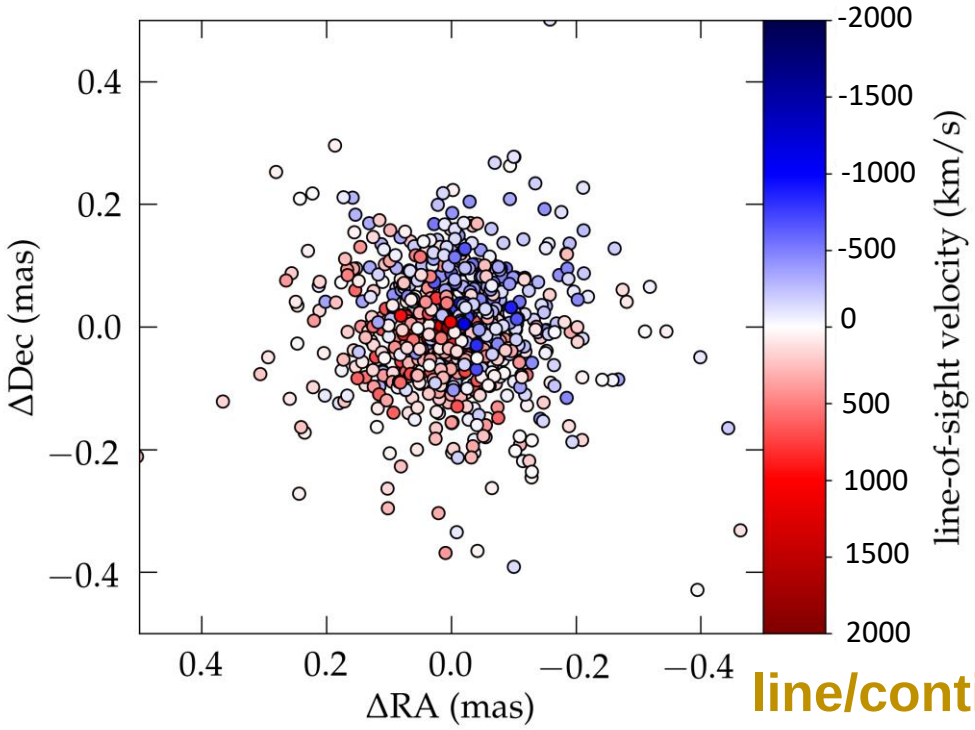
Phenomenological Model of the BLR

following:

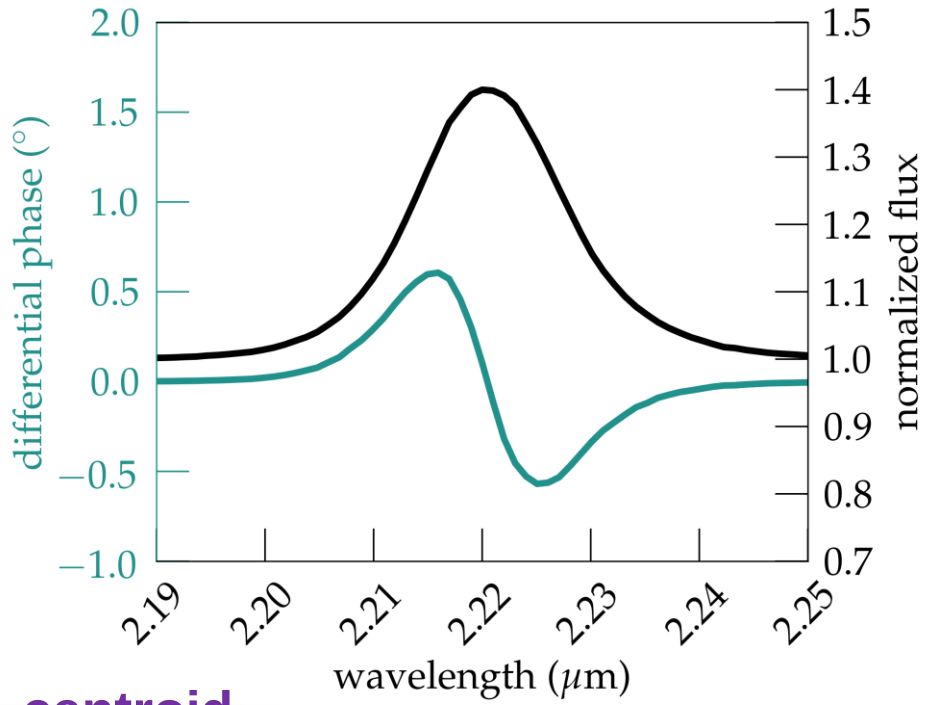
- **A. Pancoast et al. 2014:** reverberation mapping
- **S. Rakshit et al. 2015:** interferometric observables

optically thin emission
from orbiting BLR clouds



$\vec{v} \rightarrow \lambda$

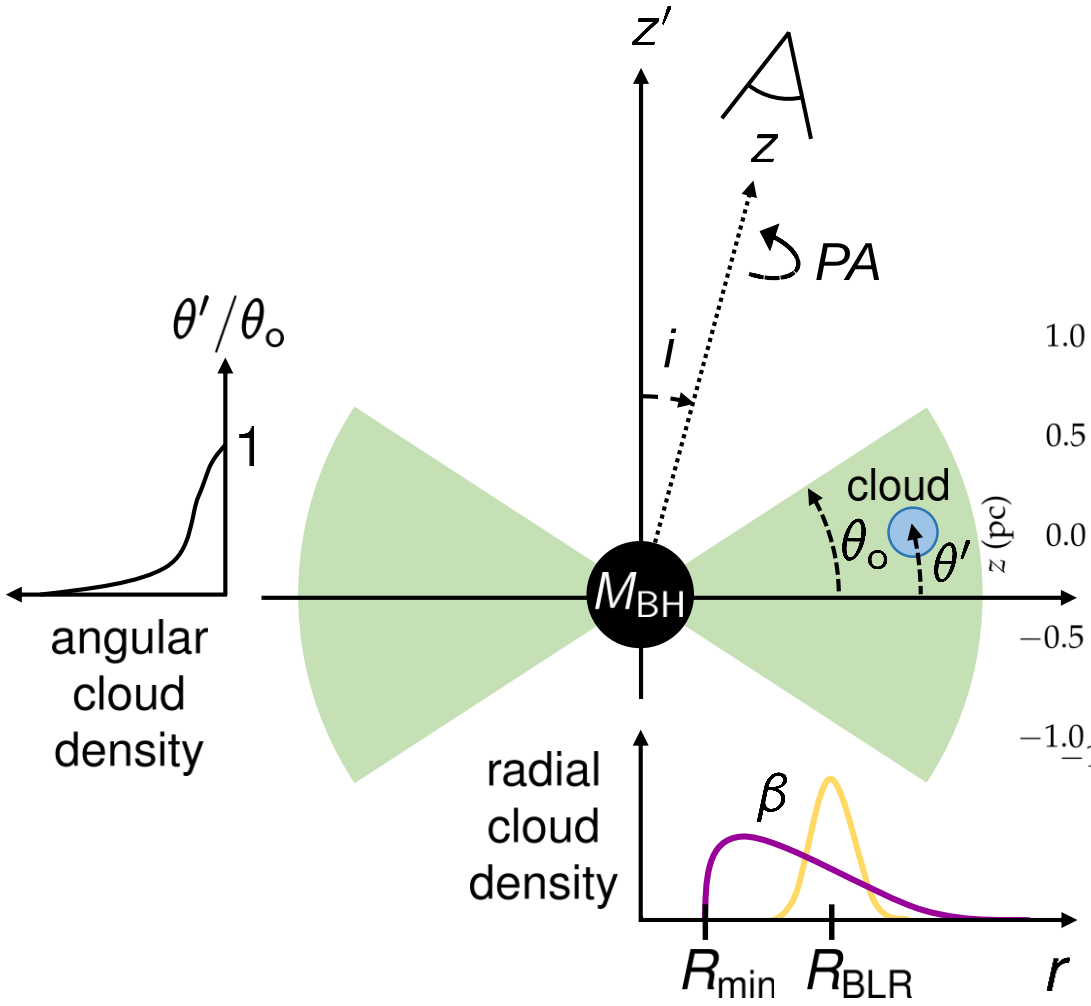
wavelength bins

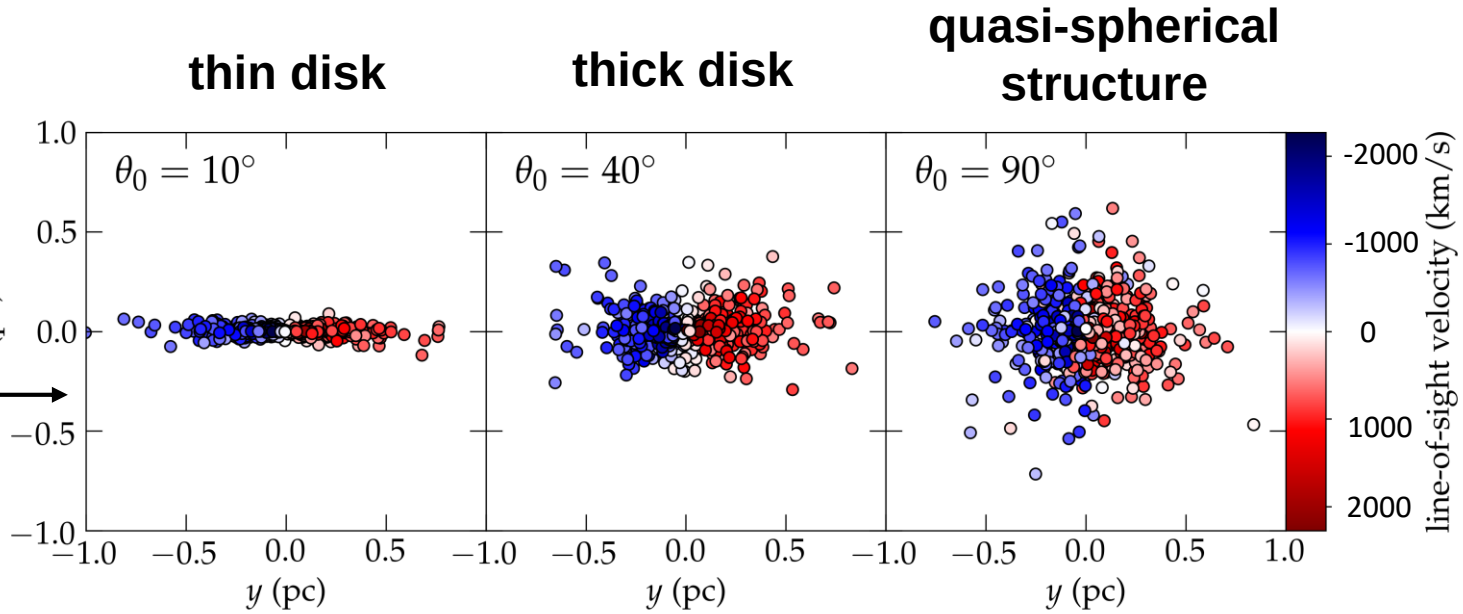


line/continuum emission — baseline — centroid

$$\Delta\phi(\lambda) = -2\pi \frac{f(\lambda)}{1+f(\lambda)} \left[\vec{u} \cdot \frac{\sum W_j \vec{x}_j}{\sum W_j} \right]$$

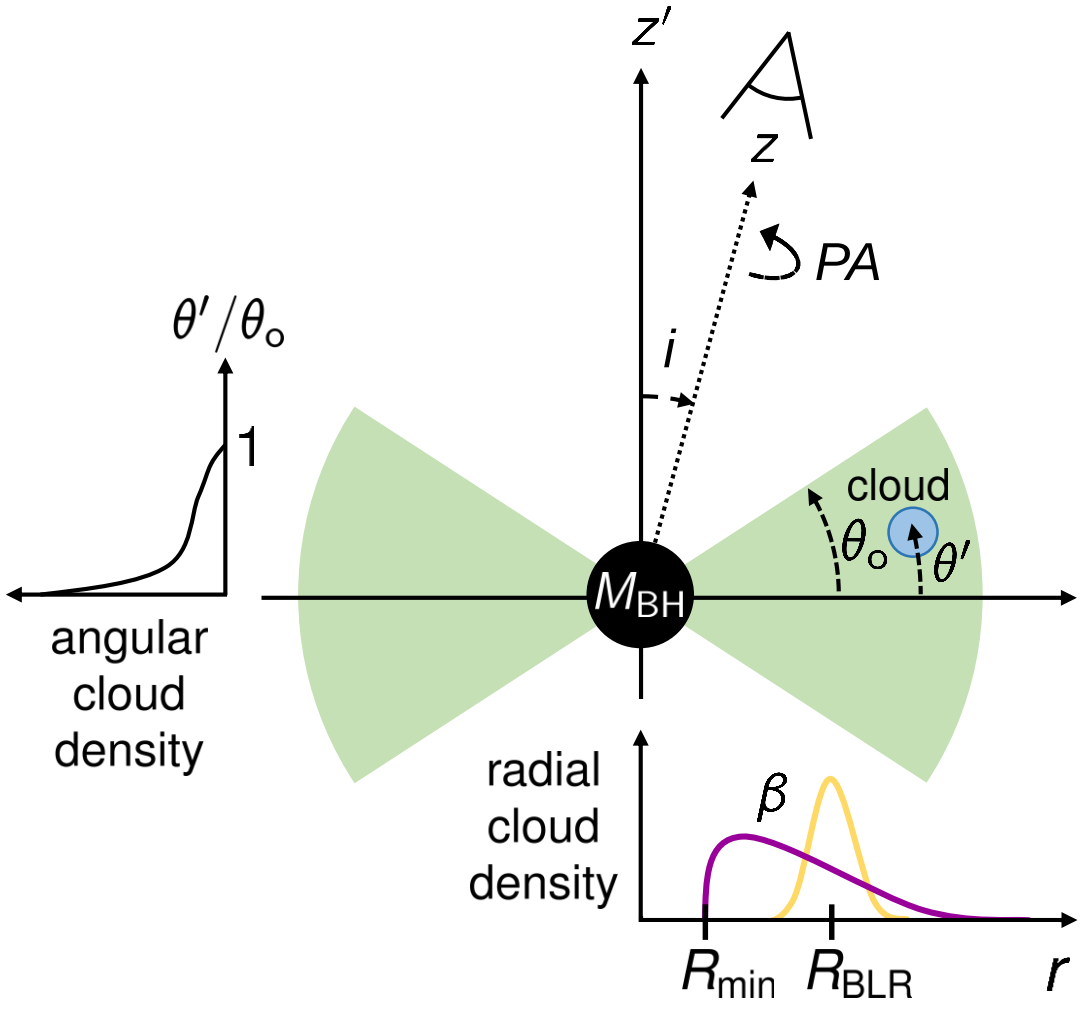
Opening Angle

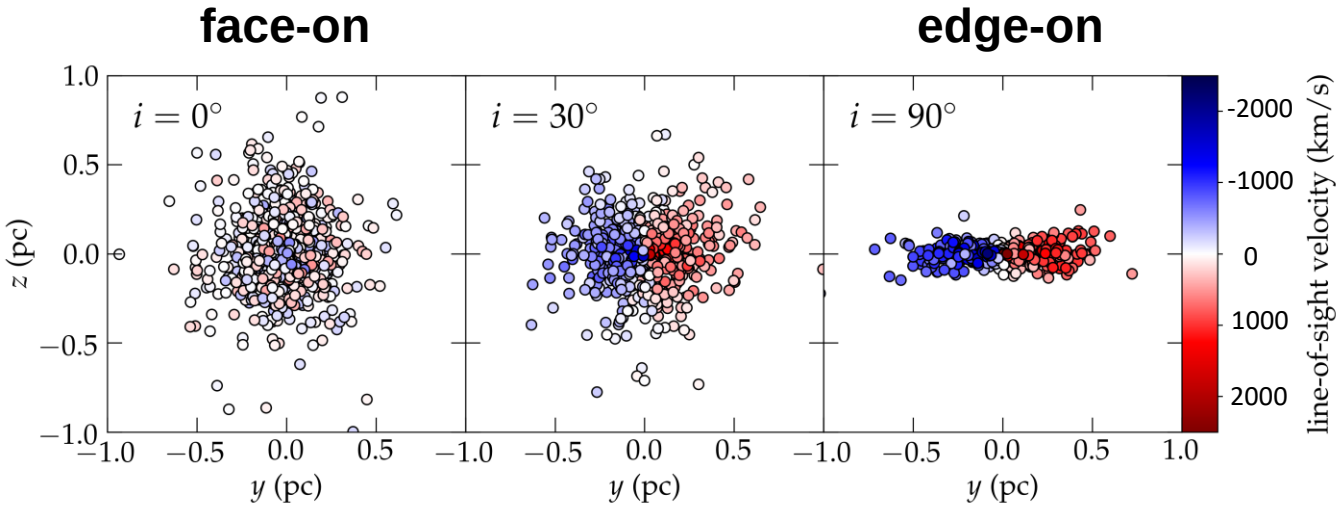




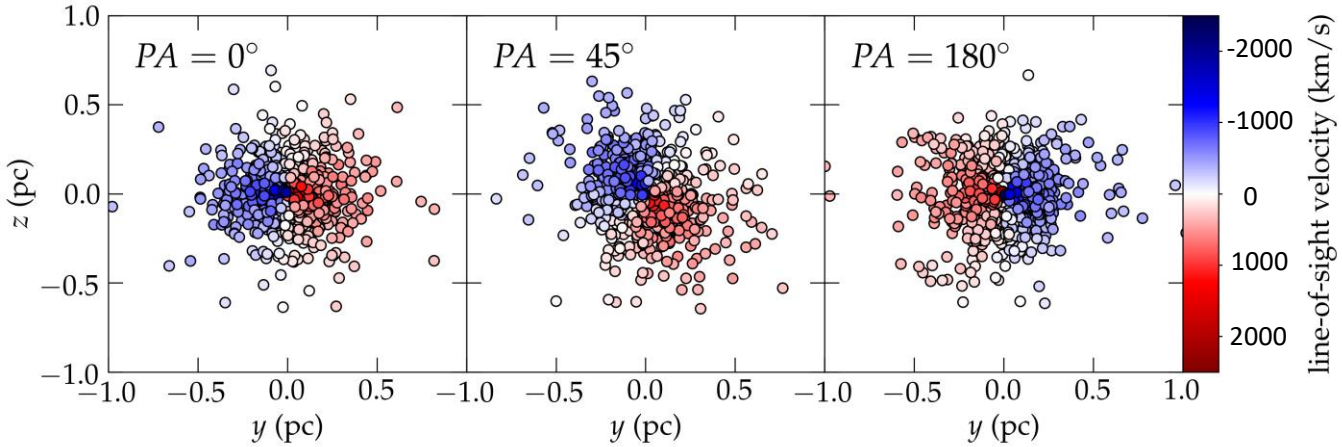
(view from edge-on perspective)

Inclination Angle

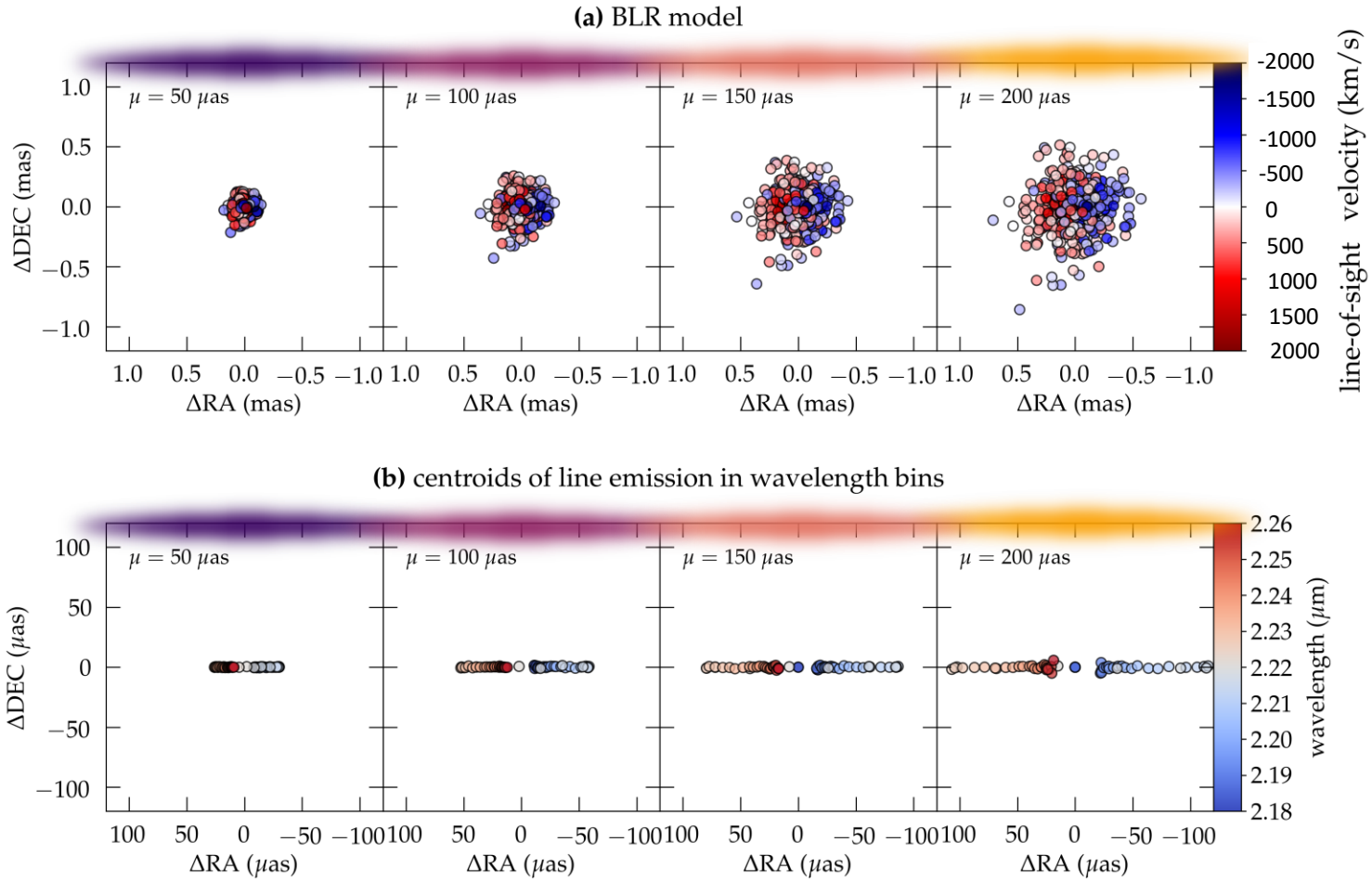


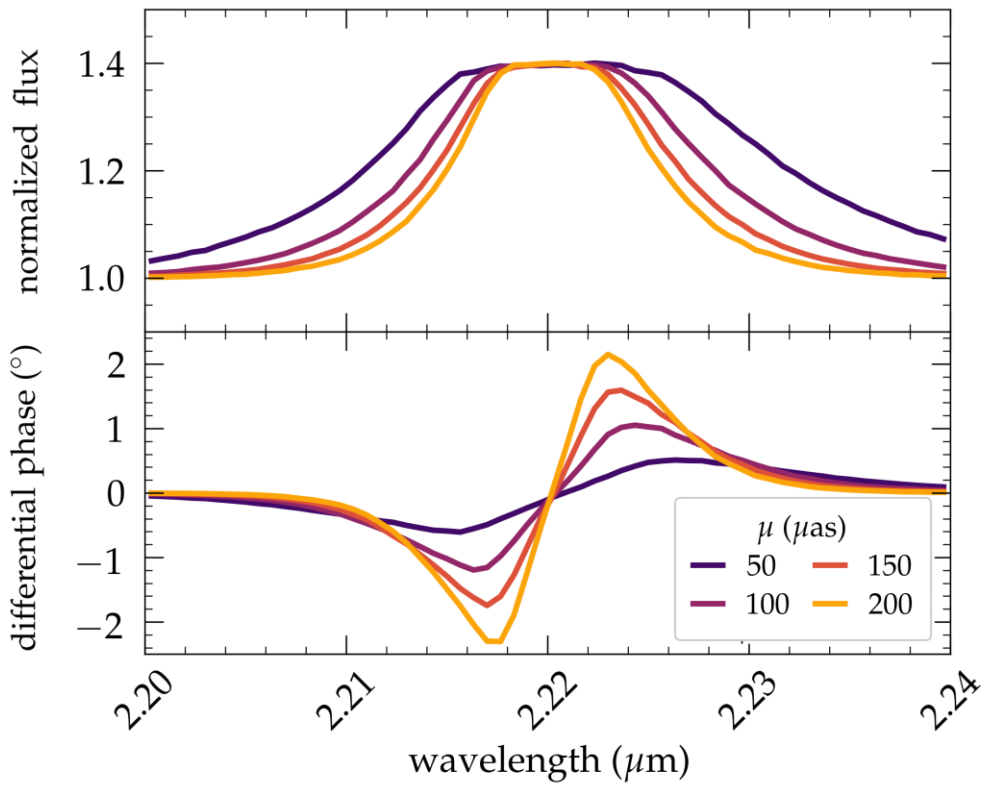


Position Angle

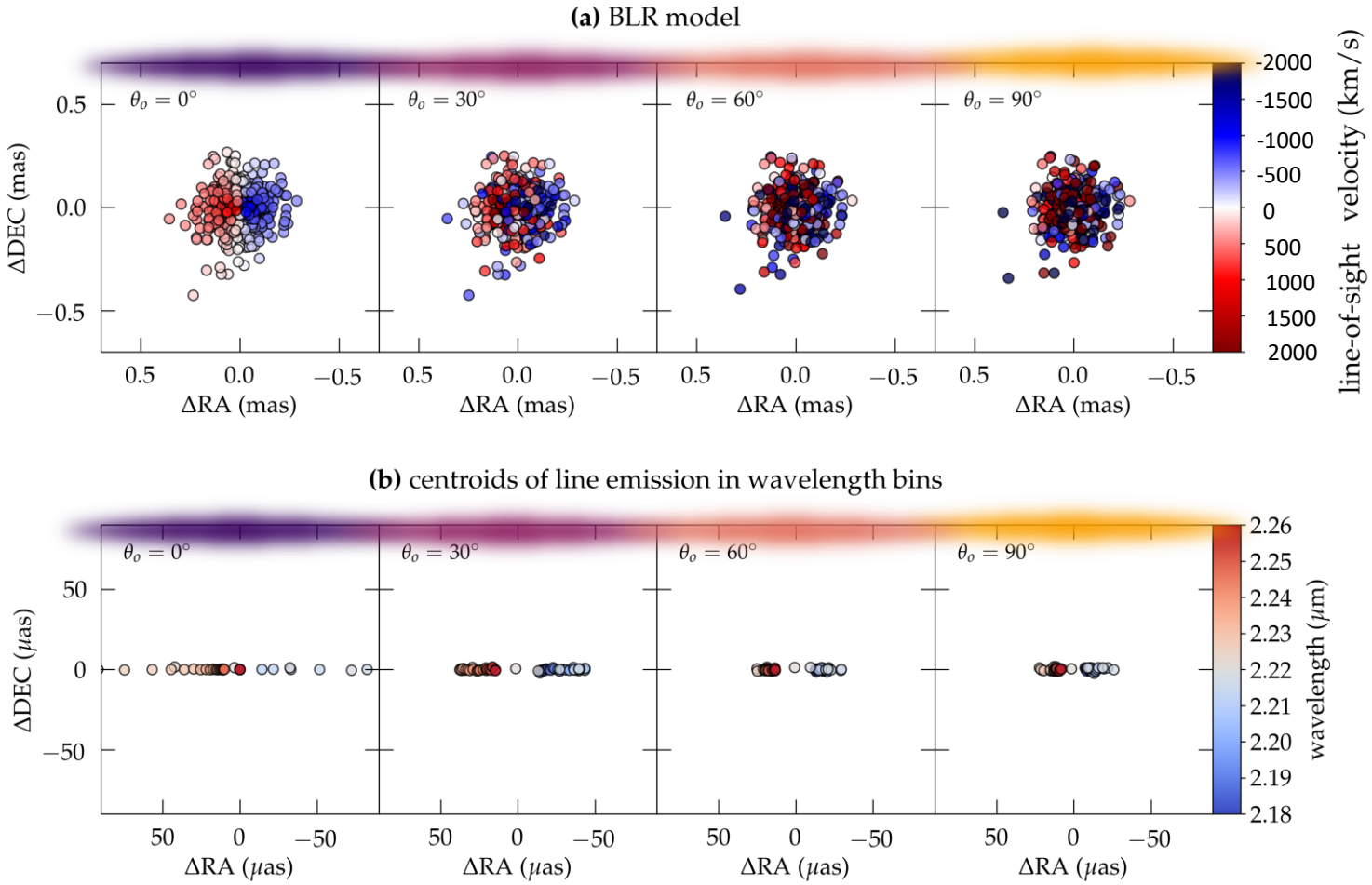


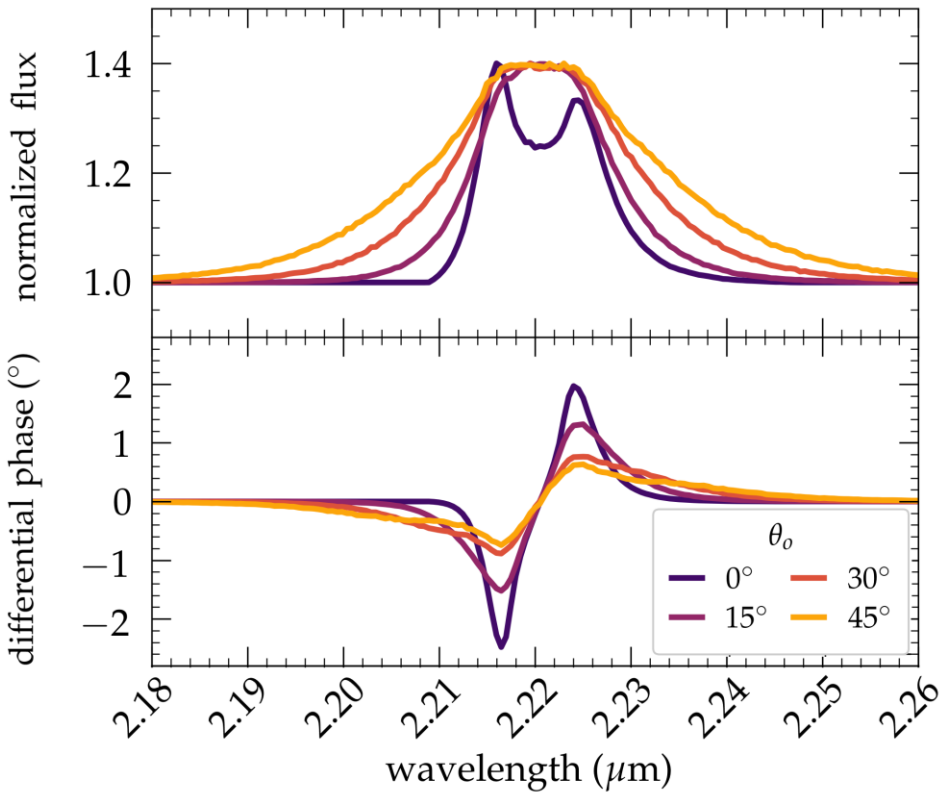
Mean Radius of the BLR



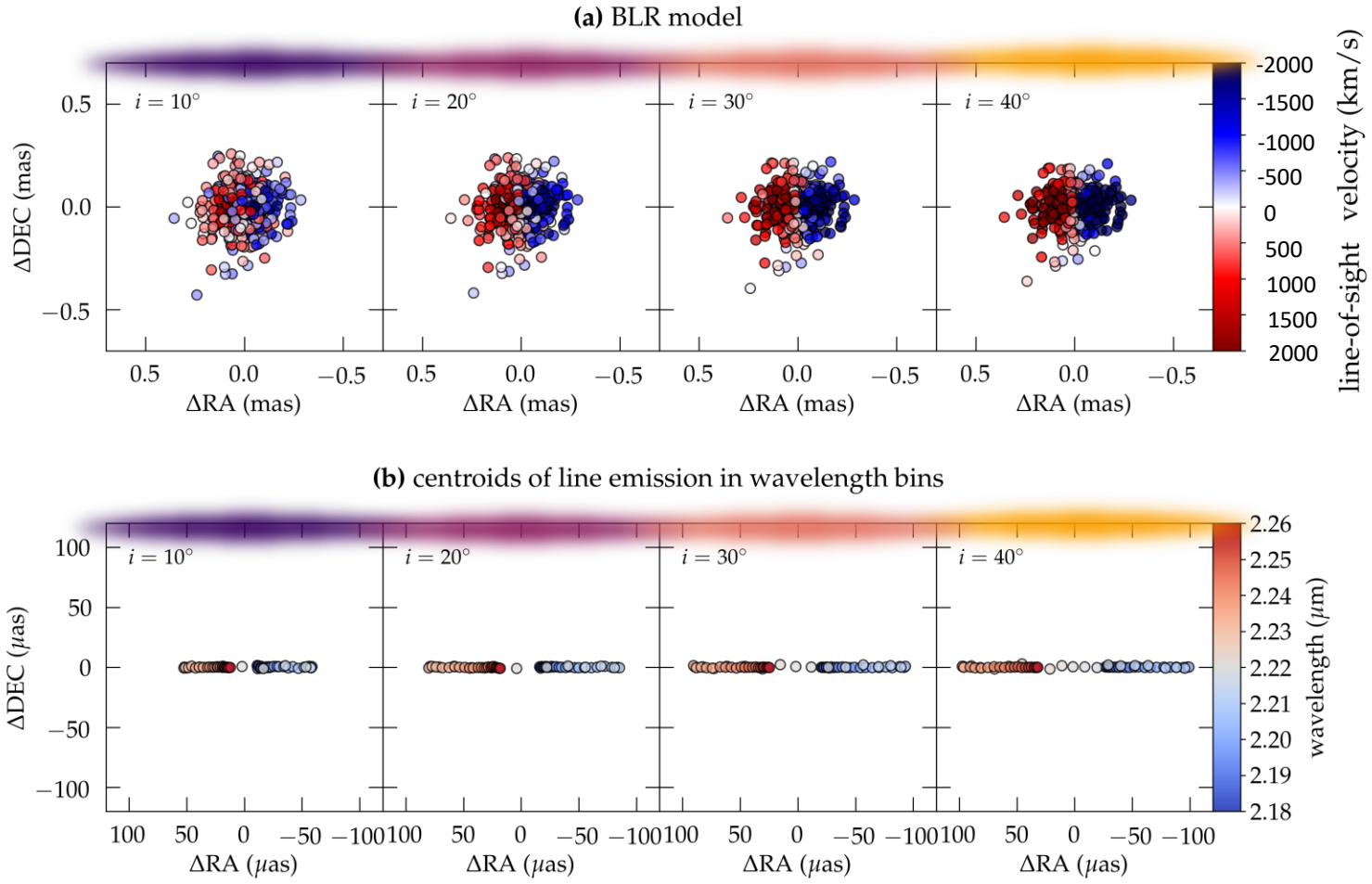


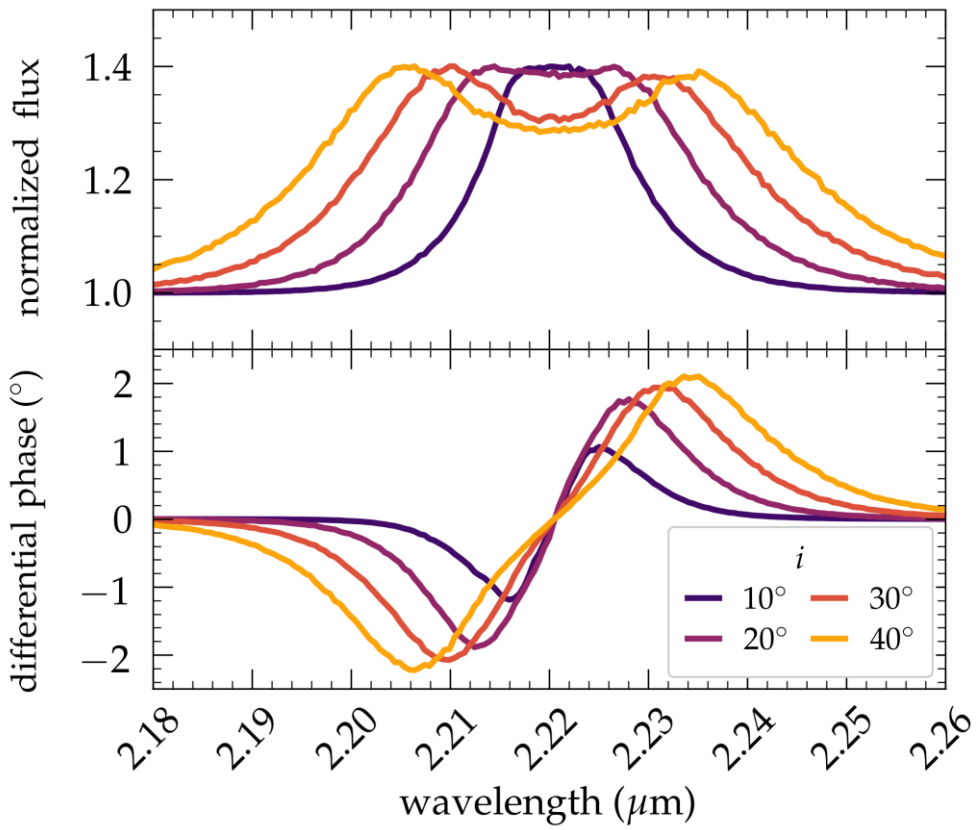
Opening Angle



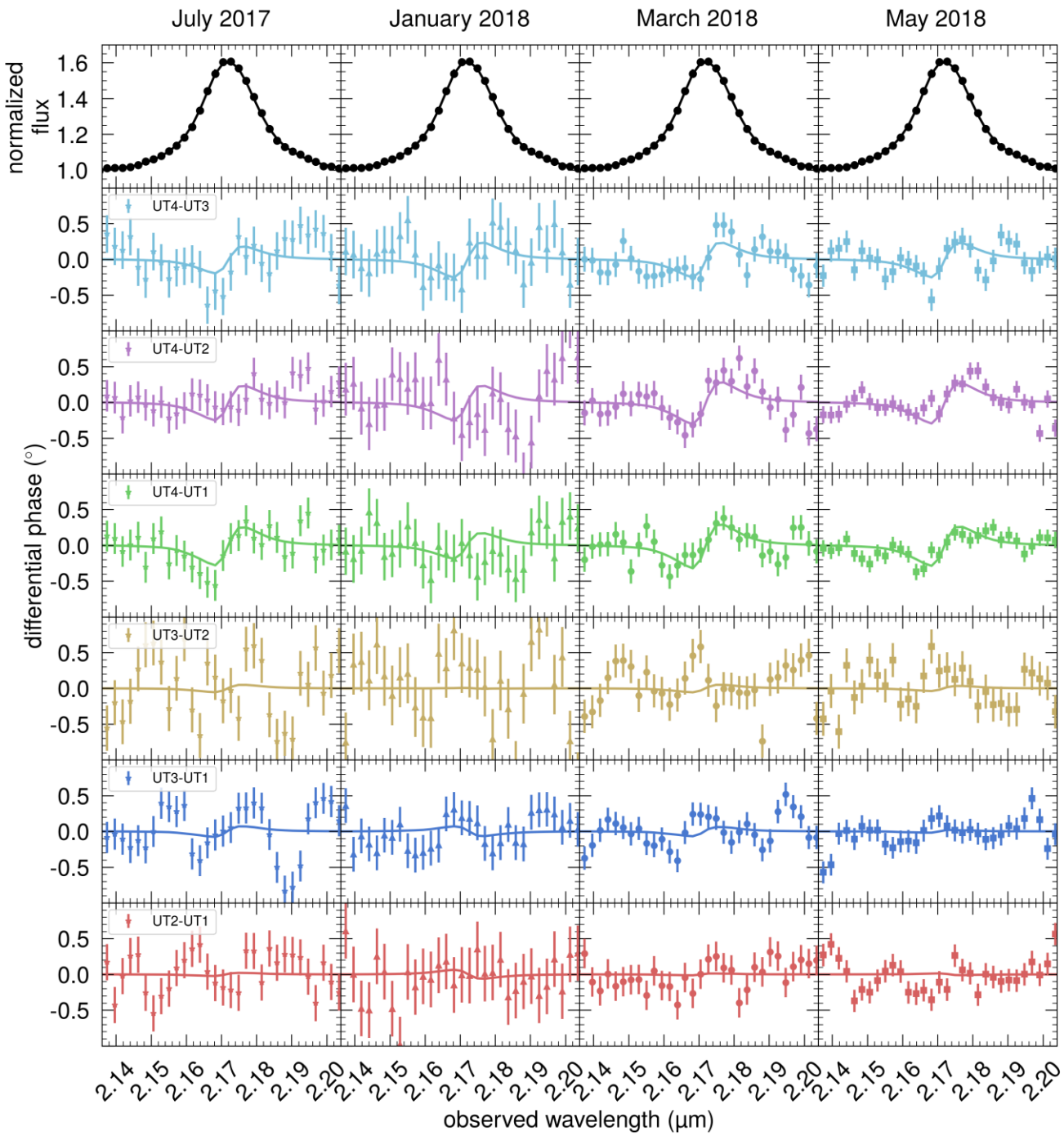


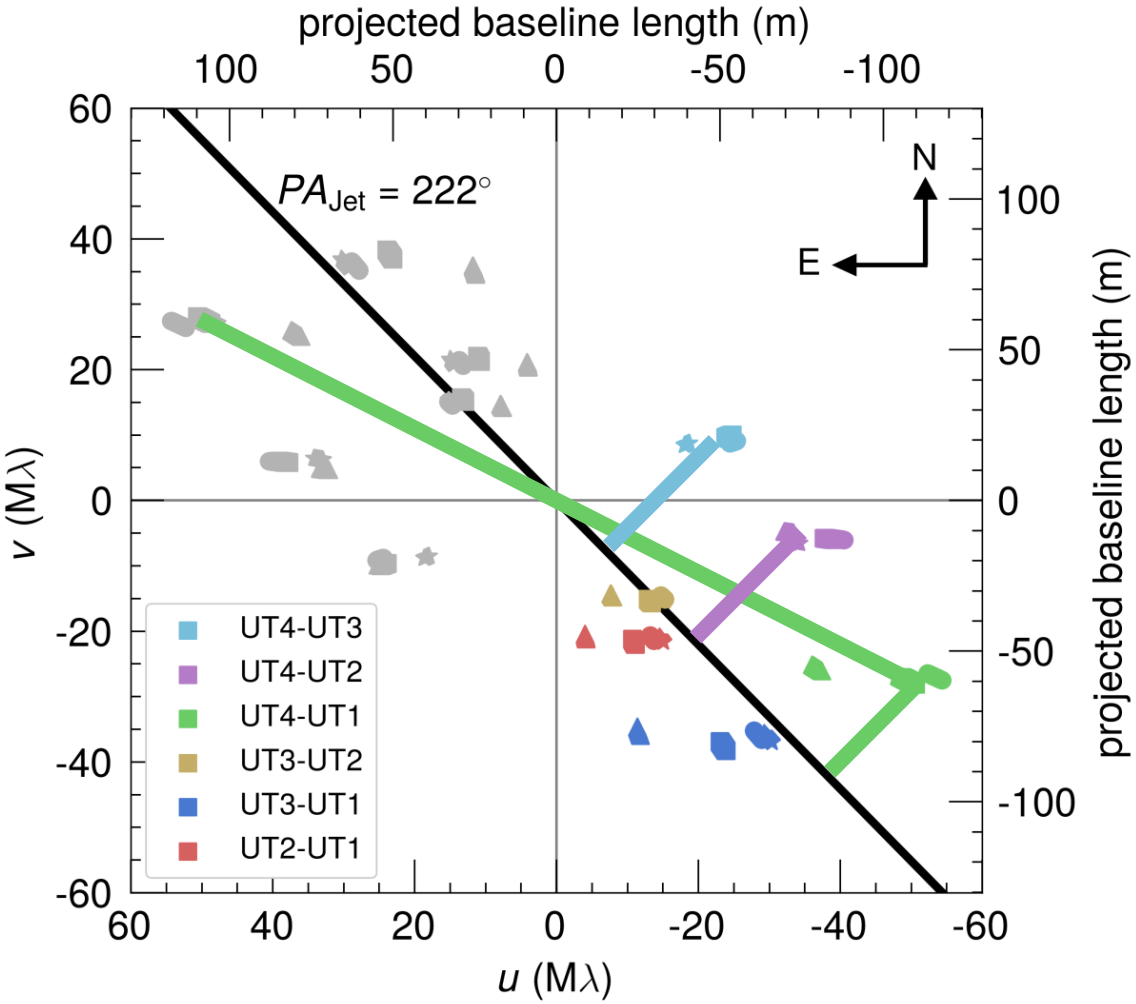
Inclination Angle





Best-fit Model for the BLR of Quasar 3C 273





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Best-fit Model for the BLR of Quasar 3C 273

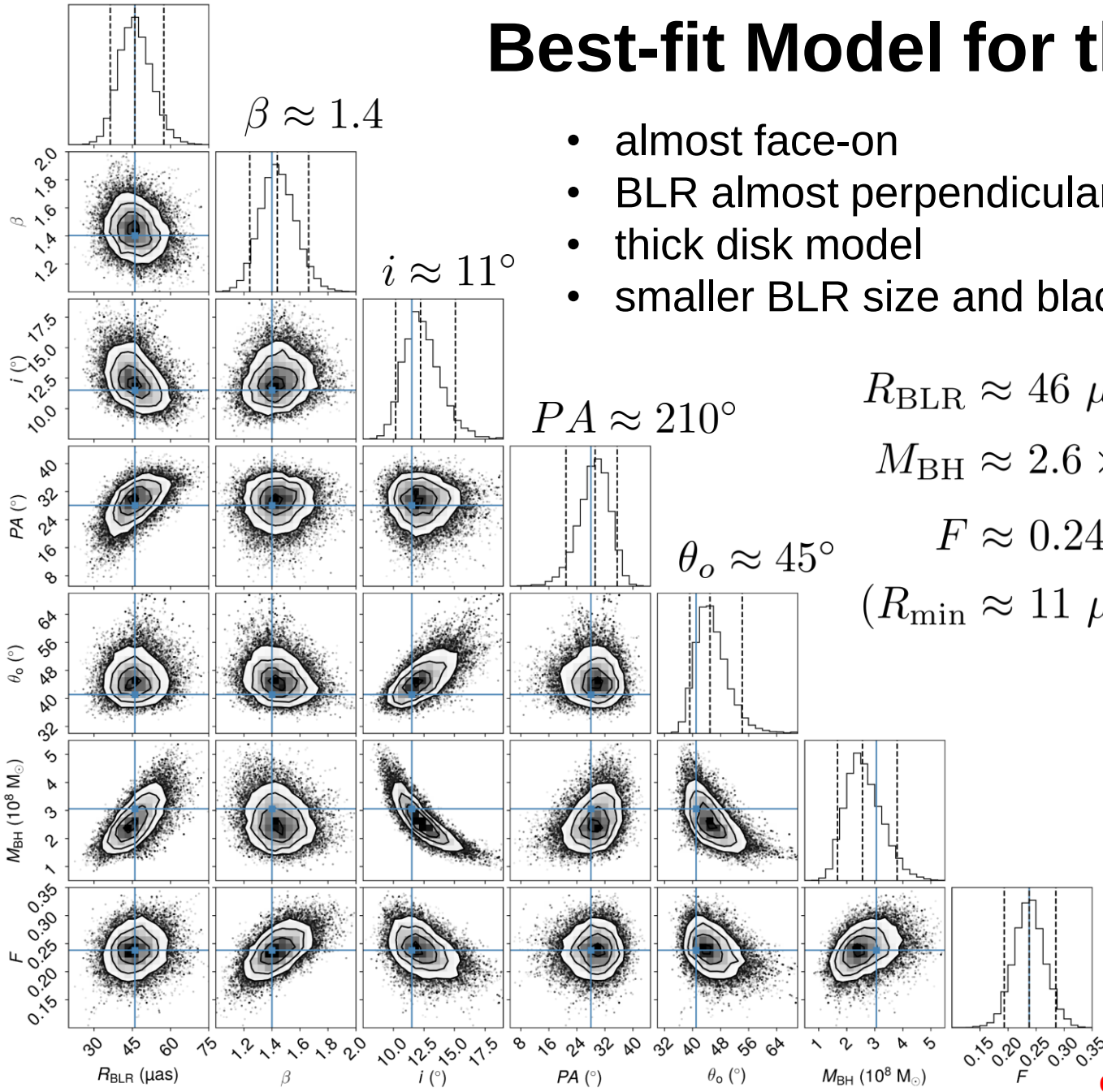
- almost face-on
- BLR almost perpendicular aligned to radio jet
- thick disk model
- smaller BLR size and black hole mass than from reverberation mapping

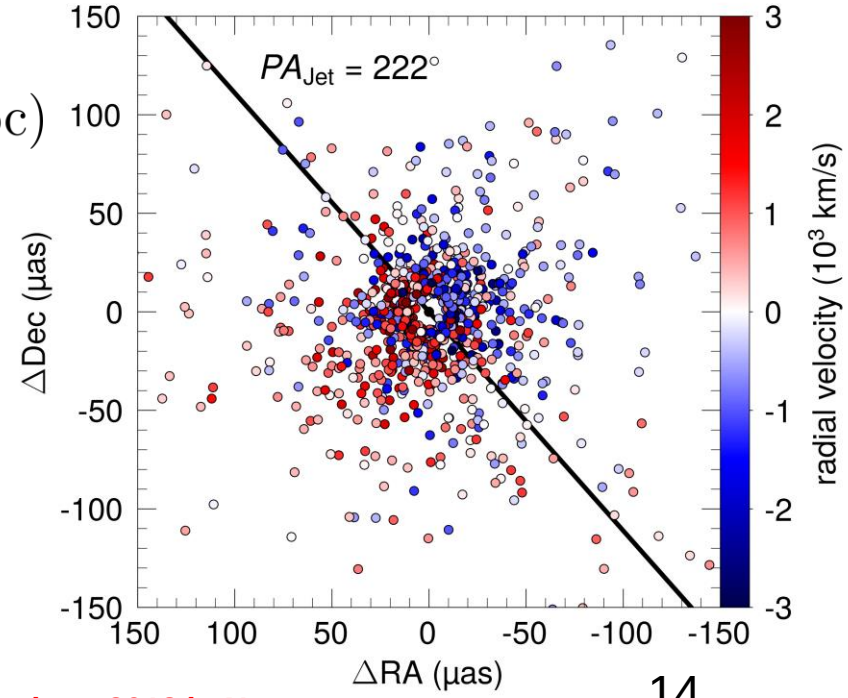
$$R_{\rm BLR} \approx 46\ \mu{\rm as}\ (= 0.13\ {\rm pc} = 150\ {\rm light\text{-}days})$$

$$M_{\rm BH} \approx 2.6 \times 10^8\ {\rm M}_\odot$$

$$F \approx 0.24$$

$$(R_{\rm min} \approx 11\ \mu{\rm as} = 0.03\ {\rm pc})$$





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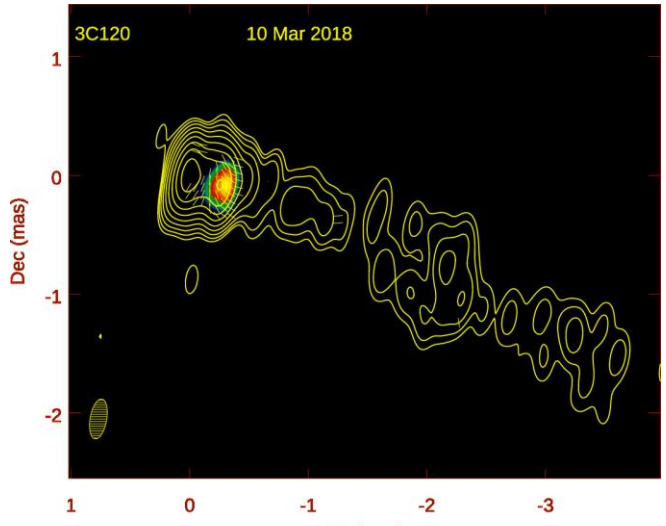
https://www.bu.edu/blazars/VLBA_GLAST/3c120.html



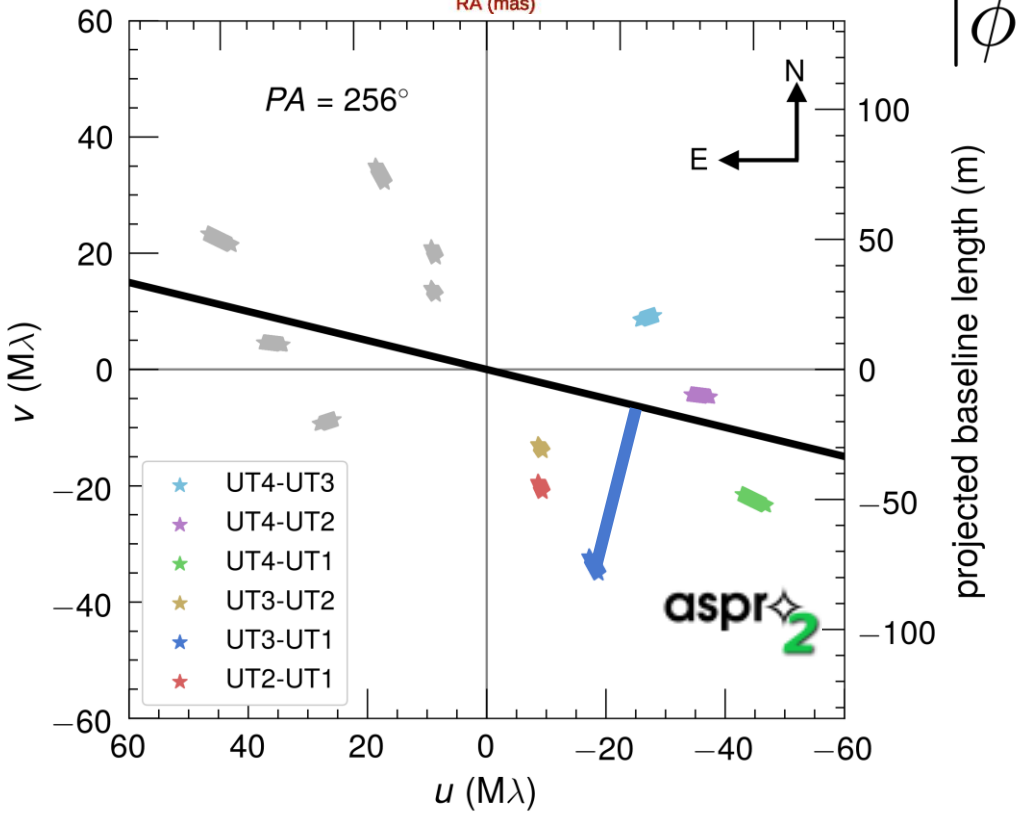
Predicting Phase Signal for 3C 120

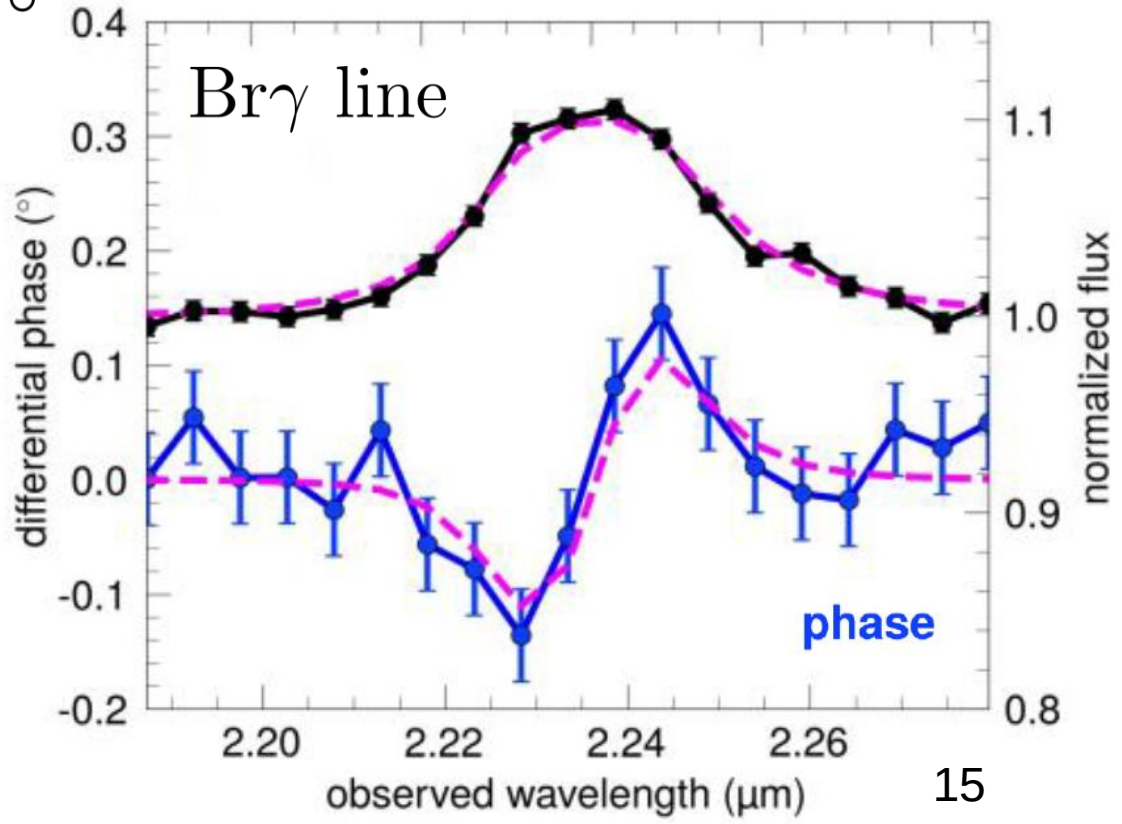
- Interesting target to compare results from reverberation mapping

$$PA_{\mathrm{BLR}} = PA_{\mathrm{Jet}}$$

- Using similar model from Pancoast+ 2014 and reverberation size

$$|\phi| \lesssim 0.1^{\circ}$$

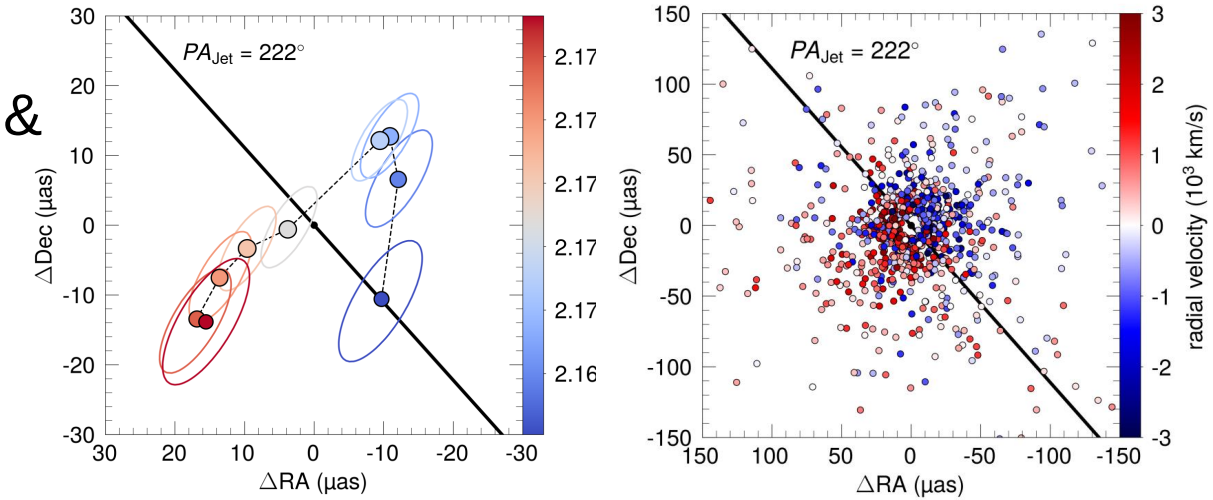




Summary

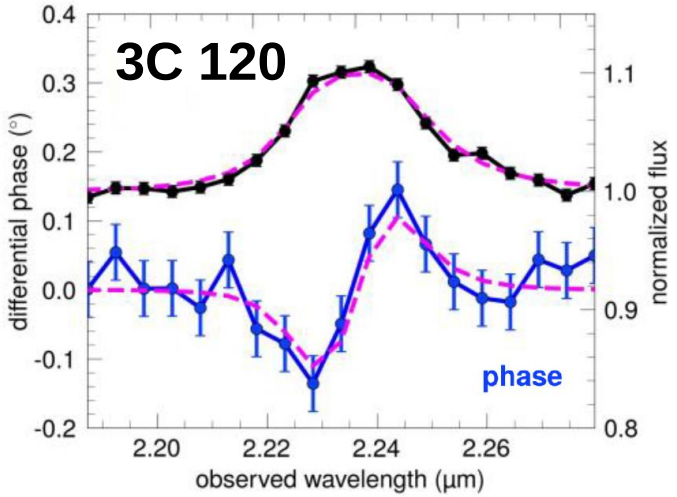
- GRAVITY detected the BLR of a quasar
- Flexible BLR model to predict emission lines & differential phases for observations

3C 273

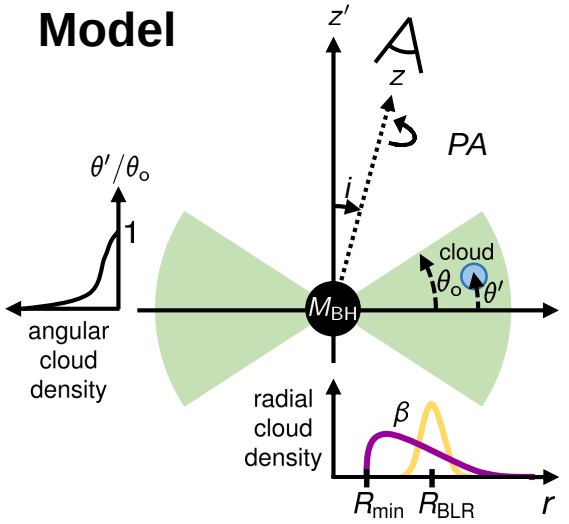


Direct Modeling of the BLR of 3C 273:

- Small differential phases due to: almost face-on inclined, thick disk structure perpendicular aligned to the jet/ unfortunate uv-coverage
- BLR size and black hole mass are smaller than from reverberation estimates



Model



Outlook:

- Test for anisotropic emission etc…
- Developing disk-wind models


Thanks for your attention!