Nuclear rings in in barred galaxies

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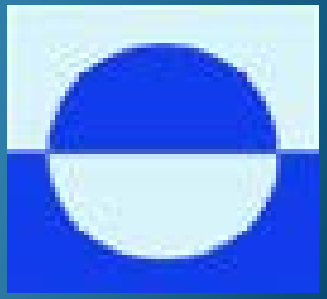


Outline

- Introduction & Motivations
- Galaxy model
  - Potential and assumptions
- Gas inflow patterns in barred galaxy
  - Varying pattern speed & central mass concentrations
- Future work

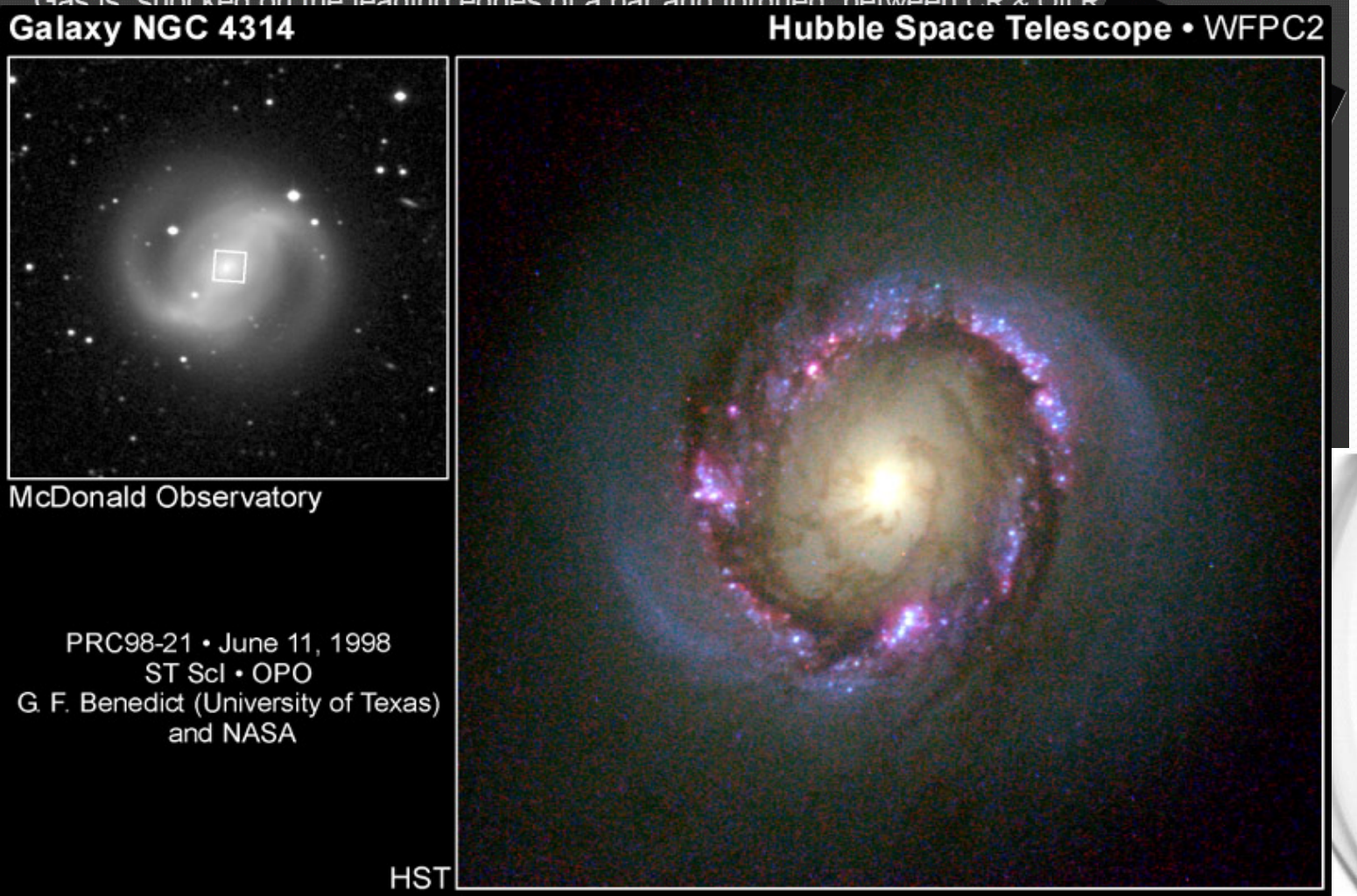
Impact of bars on galaxy evolution

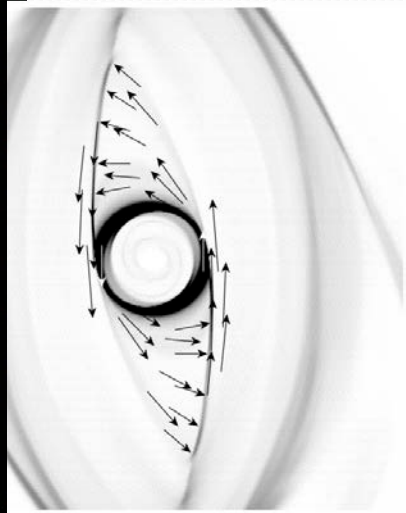
- Strongest internal disturber: influence disk, bulge, and dark matter halo
- Drive gas flow inward (along dust lanes)
- Ignite circum-nuclear starbursts (nuclear rings)
- Build up pseudo-bulges
  - Different from classical bulges
  - Secular evolution (Kormendy + Kennicutt 2004)
- Bars exchange angular momentum with dark matter halos via dynamical friction
- **<u>Understanding bars is an integral part of understanding galaxy formation and evolution.</u>**

Motivations

Bar-driven gas inflows

Gas is shocked on the leading edges of a bar and torqued between CR & OLR





Simulation details (Athanassoula , 1992)

- Equations

$$\left(\frac{\partial}{\partial t}+\mathbf{u}\cdot\nabla\right)\Sigma=-\Sigma\nabla\cdot\mathbf{u}$$

$$\left(\frac{\partial}{\partial t}+\mathbf{u}\cdot\nabla\right)\mathbf{u}=-C_s^2\frac{\nabla\Sigma}{\Sigma}-\nabla\Phi_{ext}+\Omega_b^2\mathbf{R}-2\Omega_b\times\mathbf{u}$$

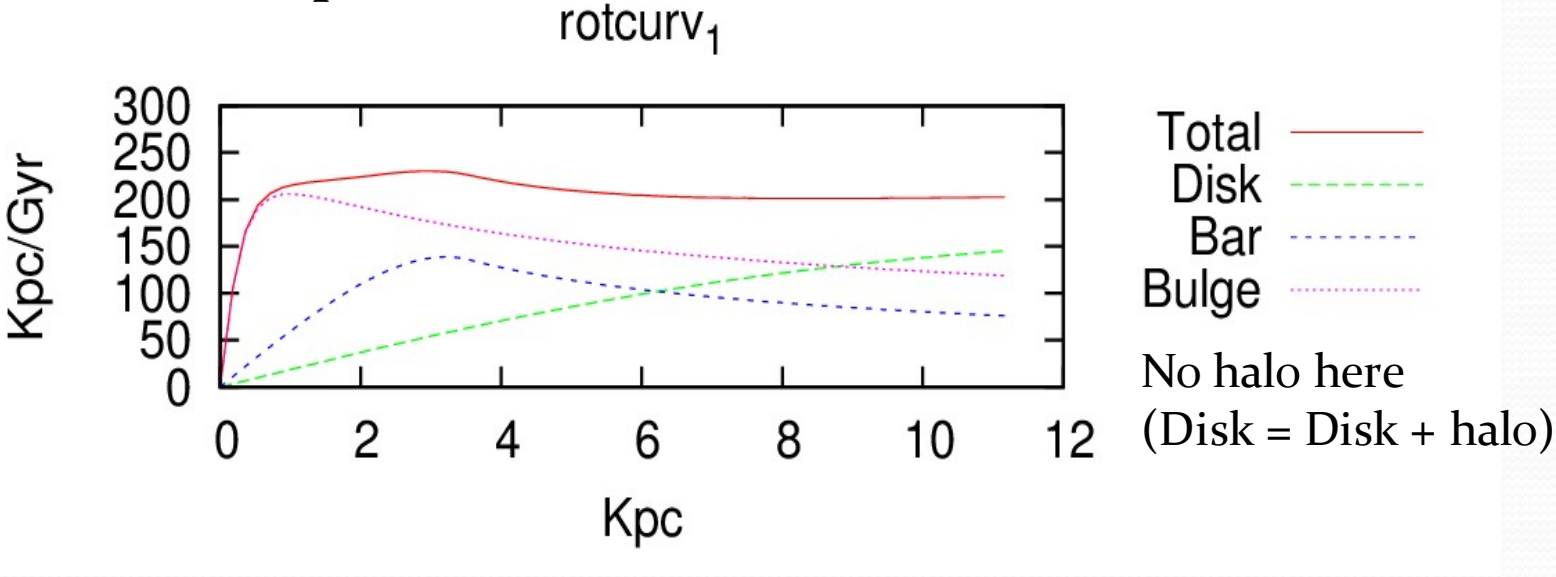
- Free parameters:
  - C_s
  - Ω_b
  - Φ_{ext}

Idealized isothermal gas 8 km/s

Solid body rotation 33 km/s/kpc

Contains three parts:
Bulge: symmetric , inner region (Modified Hubble Bulge)
Bar: asymmetric , near bar region (Ferrers Ellipsoid Bar)
Disk+DM halo: symmetric , outer region (Kuzmin-Toomre Disk)

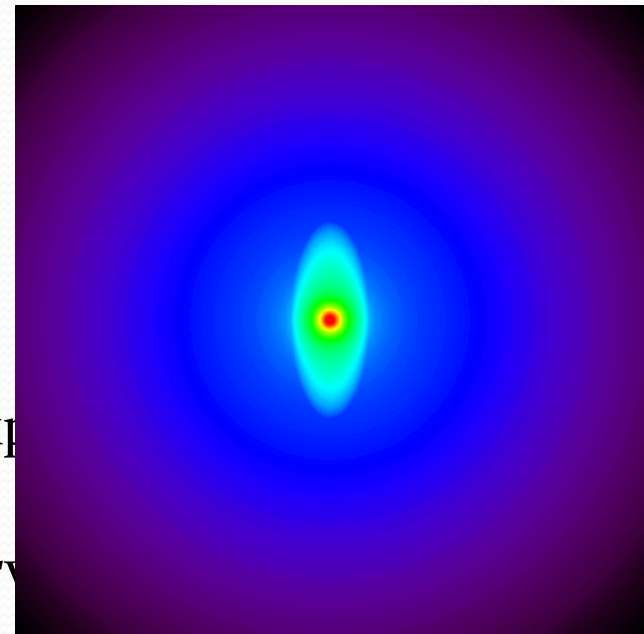
- External potential



No halo here
(Disk = Disk + halo)

- Assumption for the gas
  - infinitesimally thin
  - isothermal (C_s =8 km/s)
  - non-self-gravitating
- Initial conditions
  - Density: gas uniformly spread on the 8 kp plane with a value of **10** $M_\odot kpc^{-2}$
  - Velocity: as described in the rotation curv

32 kpc



Typical gas flow pattern

Off-axis shocks
(Dust lanes)

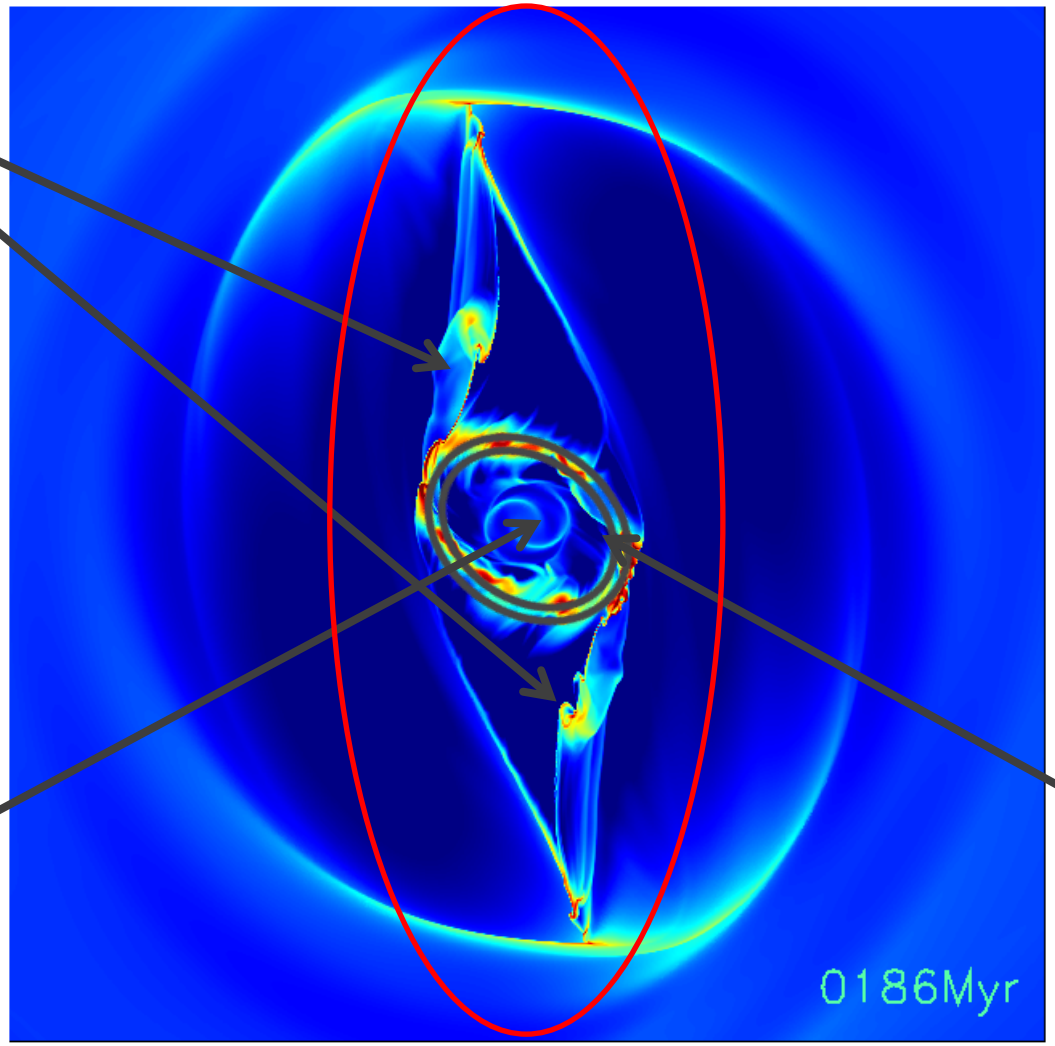
Code: Athena 4.1
Exact Riemann Solver
Resolution: $4\times4\,pc^2$
Parameters:

Bar: a=5kpc b=2kpc
vertical

Gas Disk: r=8kpc circular

Pattern speed: 33km/s/kpc

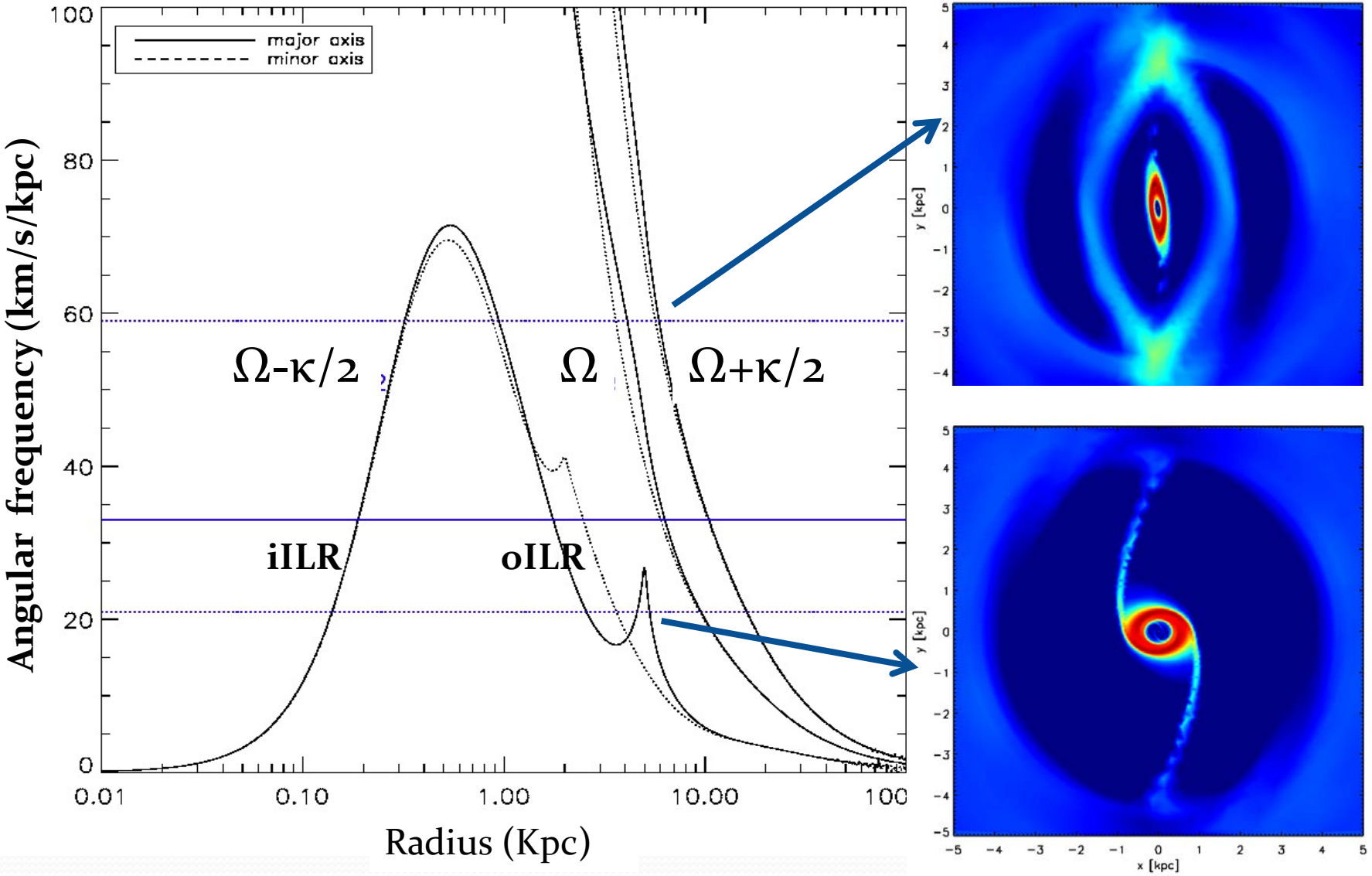
Nuclear spirals



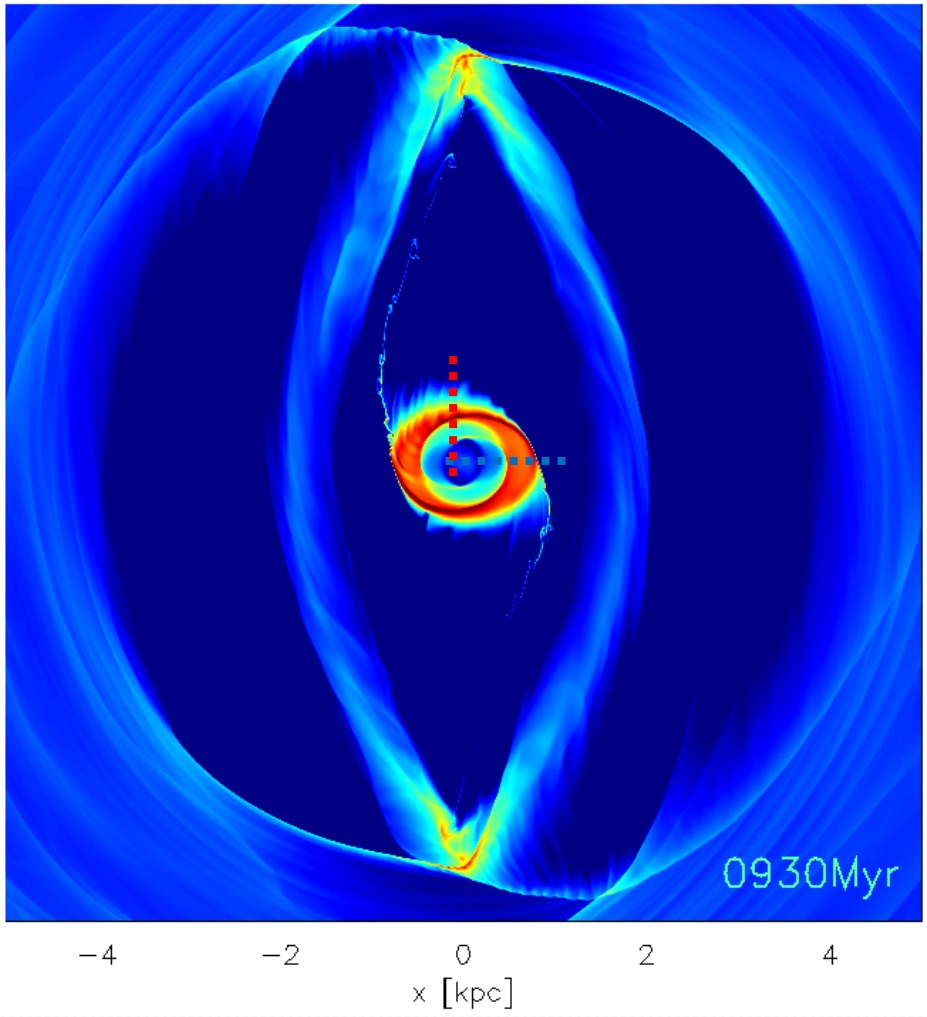
10 kpc

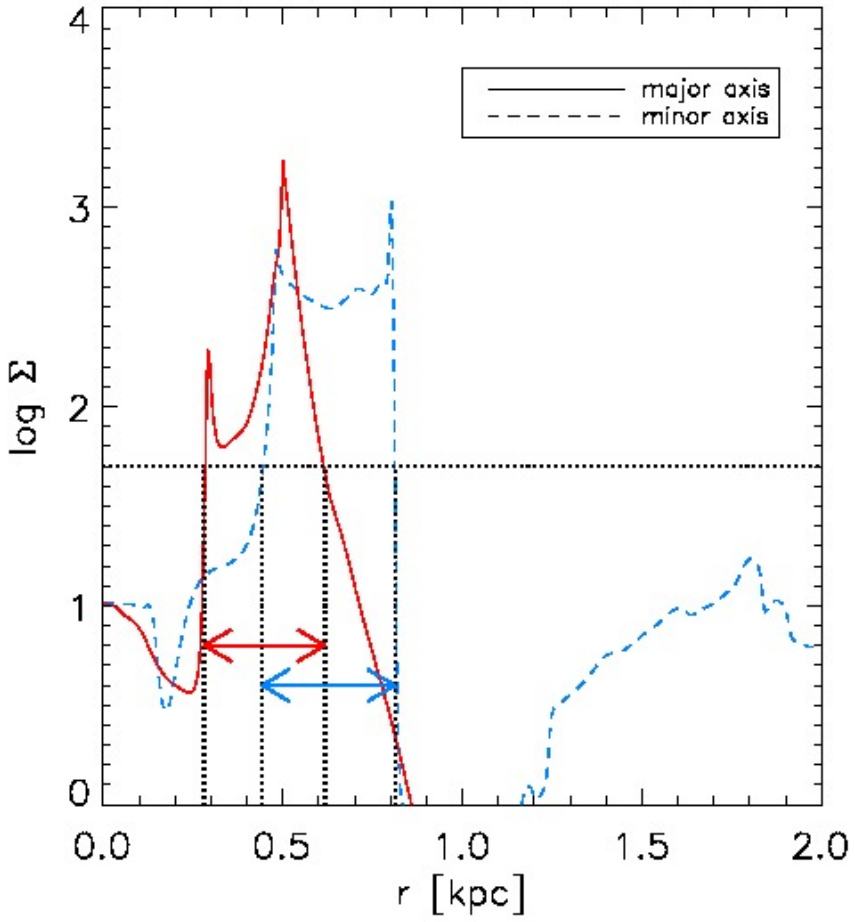
Nuclear ring

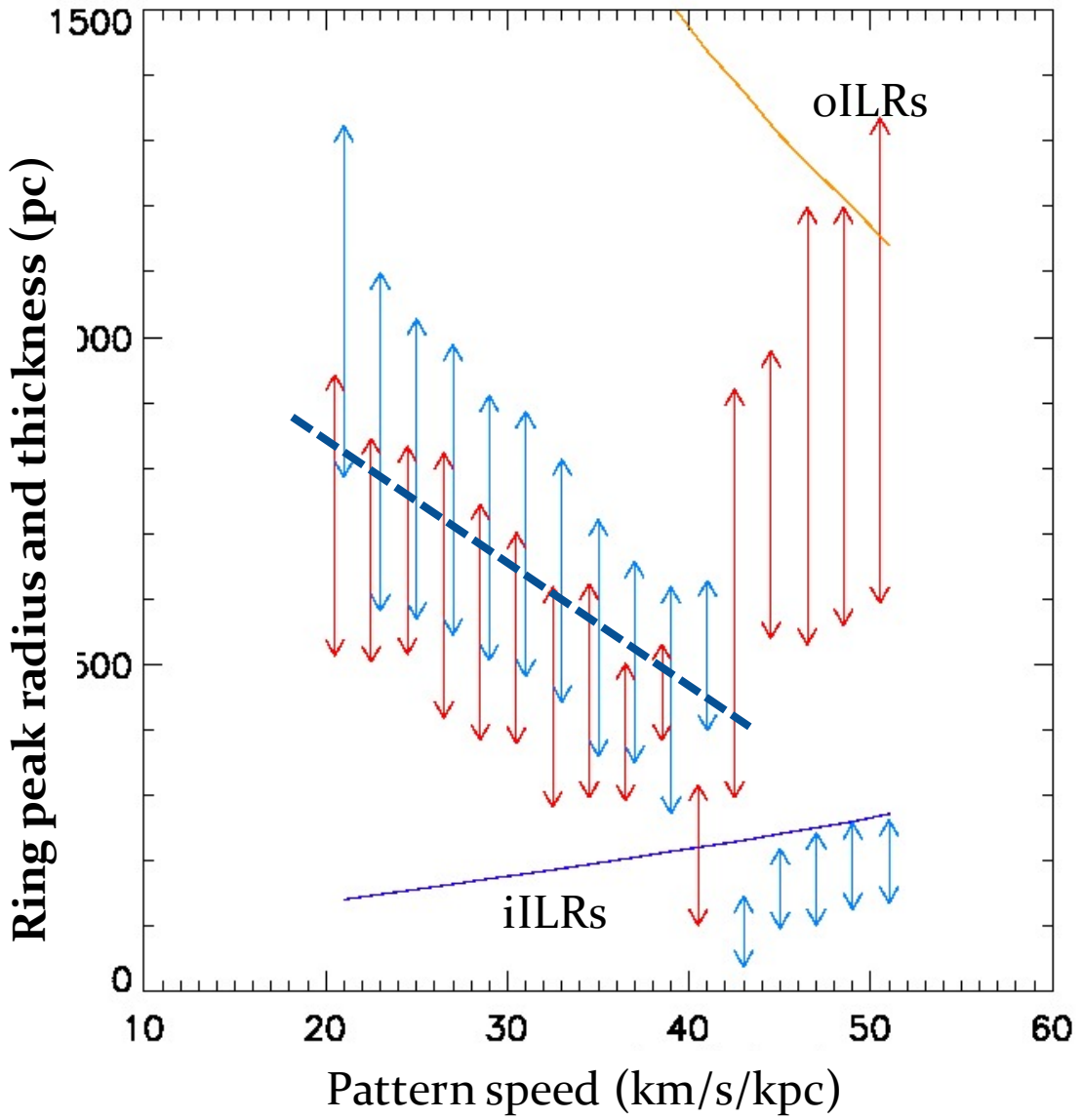
Different patterns with pattern speed



Nuclear ring analysis







Nuclear ring vs. Ω_b

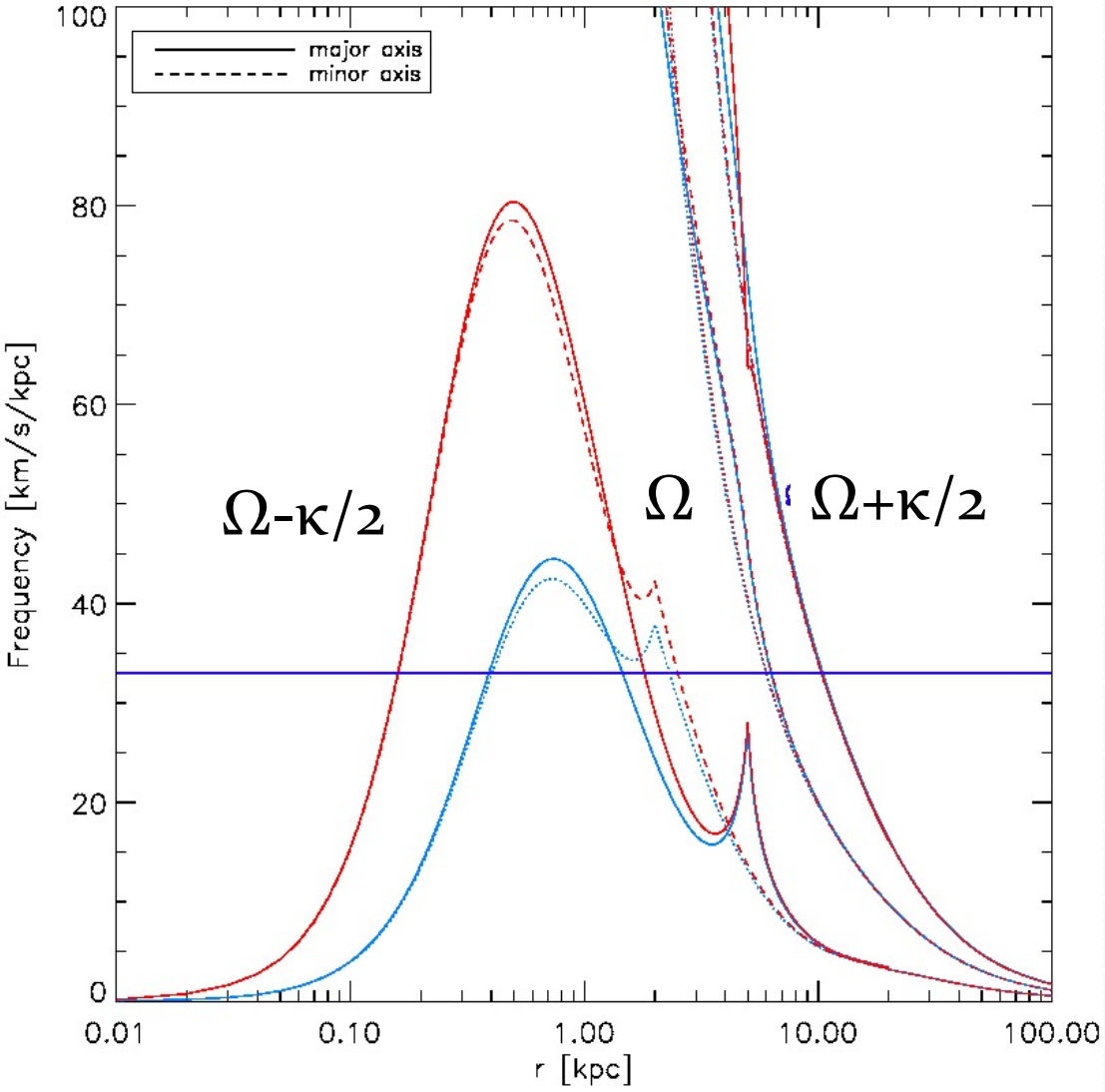
Red arrows:
Ring along bar major axis

Blue arrows:
Ring along bar minor axis

Blue line: iILRs

Orange line: oILRs

Different patterns with compactness

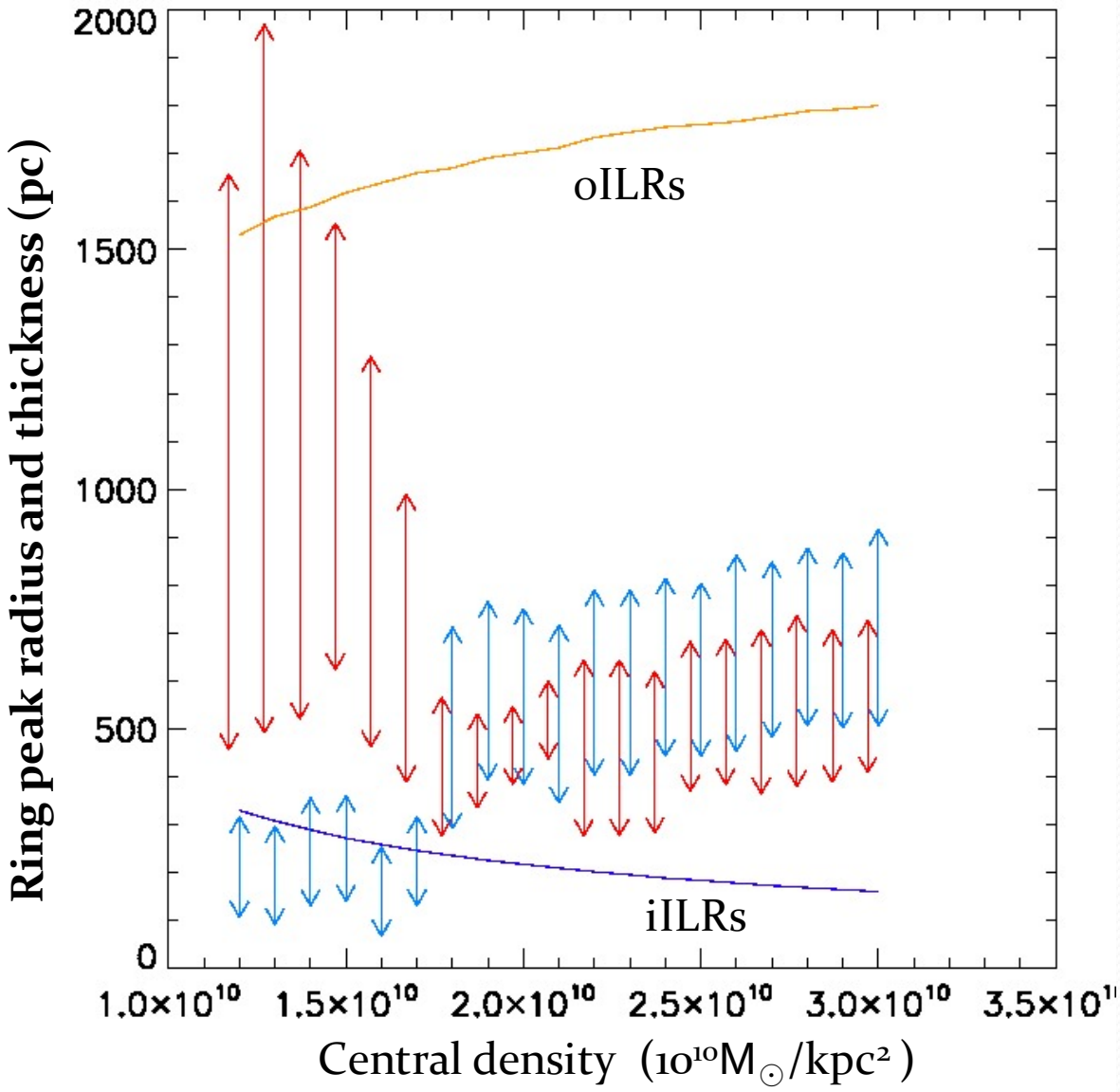


Changing central density from $1.0*10^{10}$ to $3.0*10^{10}$ Solarmass/kpc^2

$$Q_b \equiv \left. \frac{F_T(r,\phi)}{F_R(r)} \right|_{\max}$$

Changes from 0.25 to 0.24 at ~ 3kpc from center

Nearly constant



Nuclear ring vs. Central density

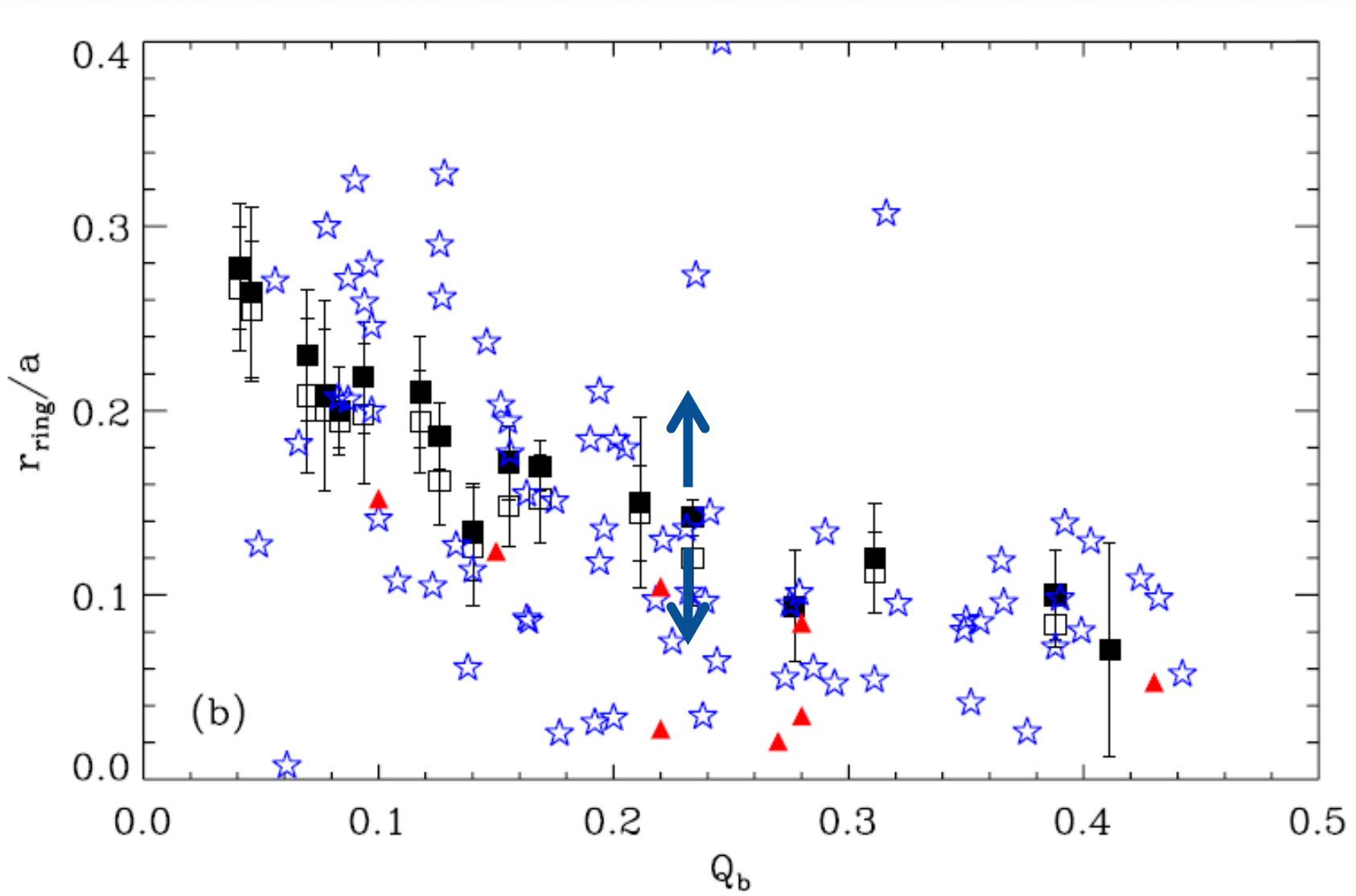
Red arrows:
Ring along bar major axis

Blue arrows:
Ring along bar minor axis

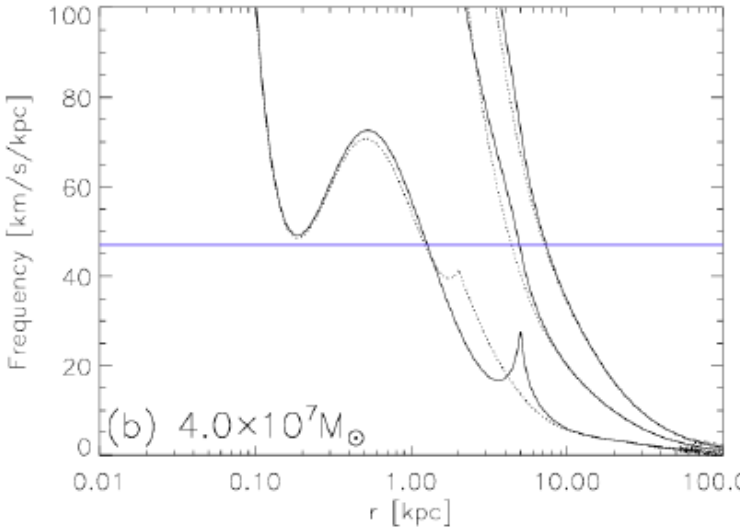
Blue line: iILRs

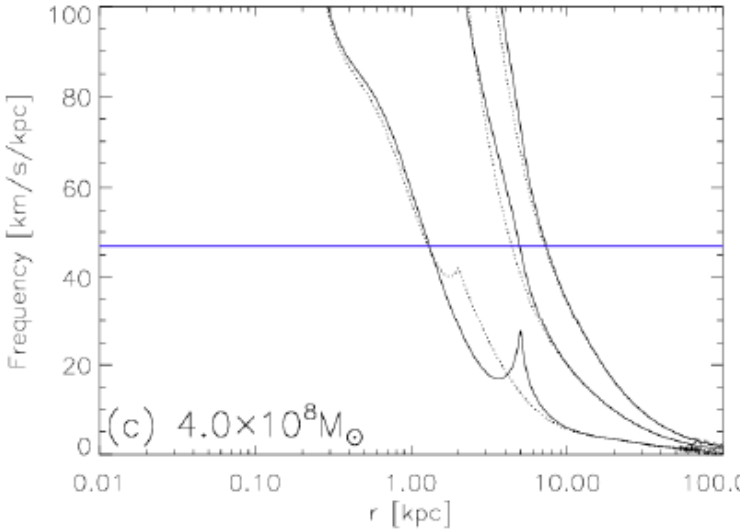
Orange line: oILRs

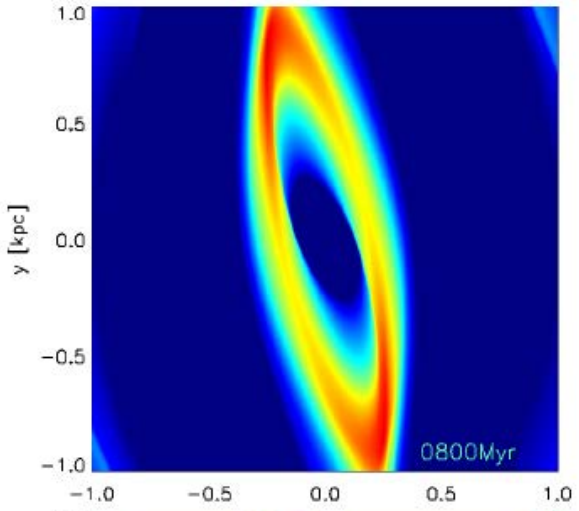
Compare to Q_b variations

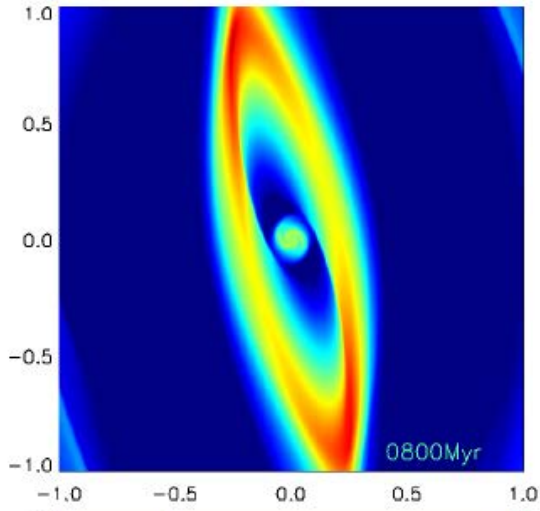


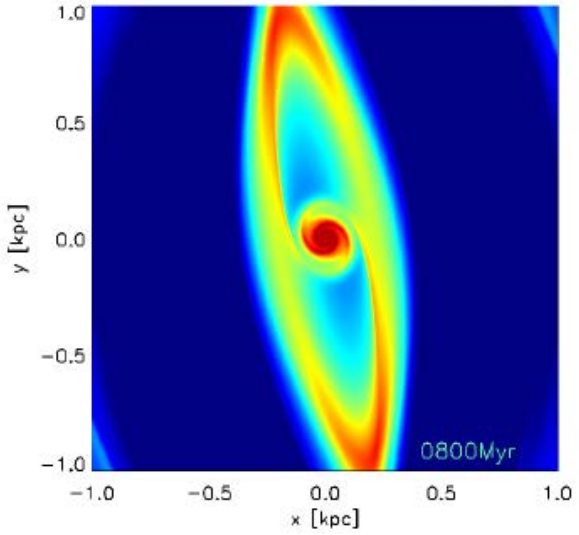
Adding a black hole

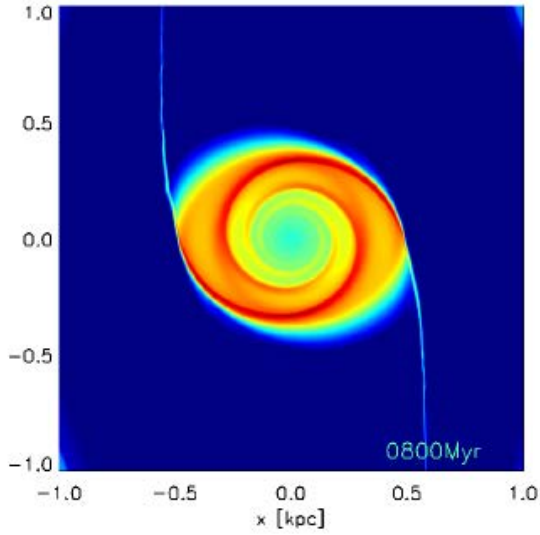




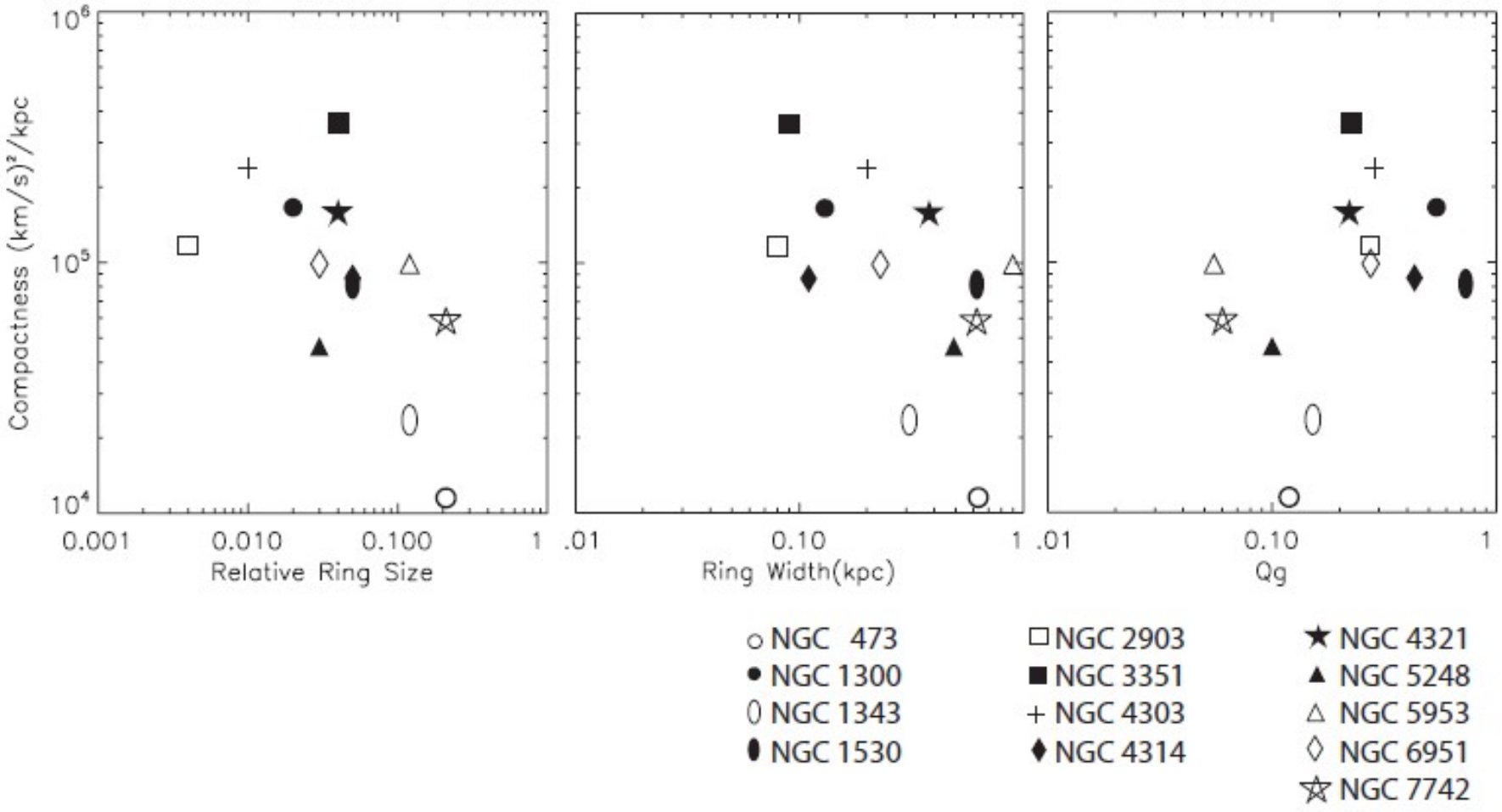






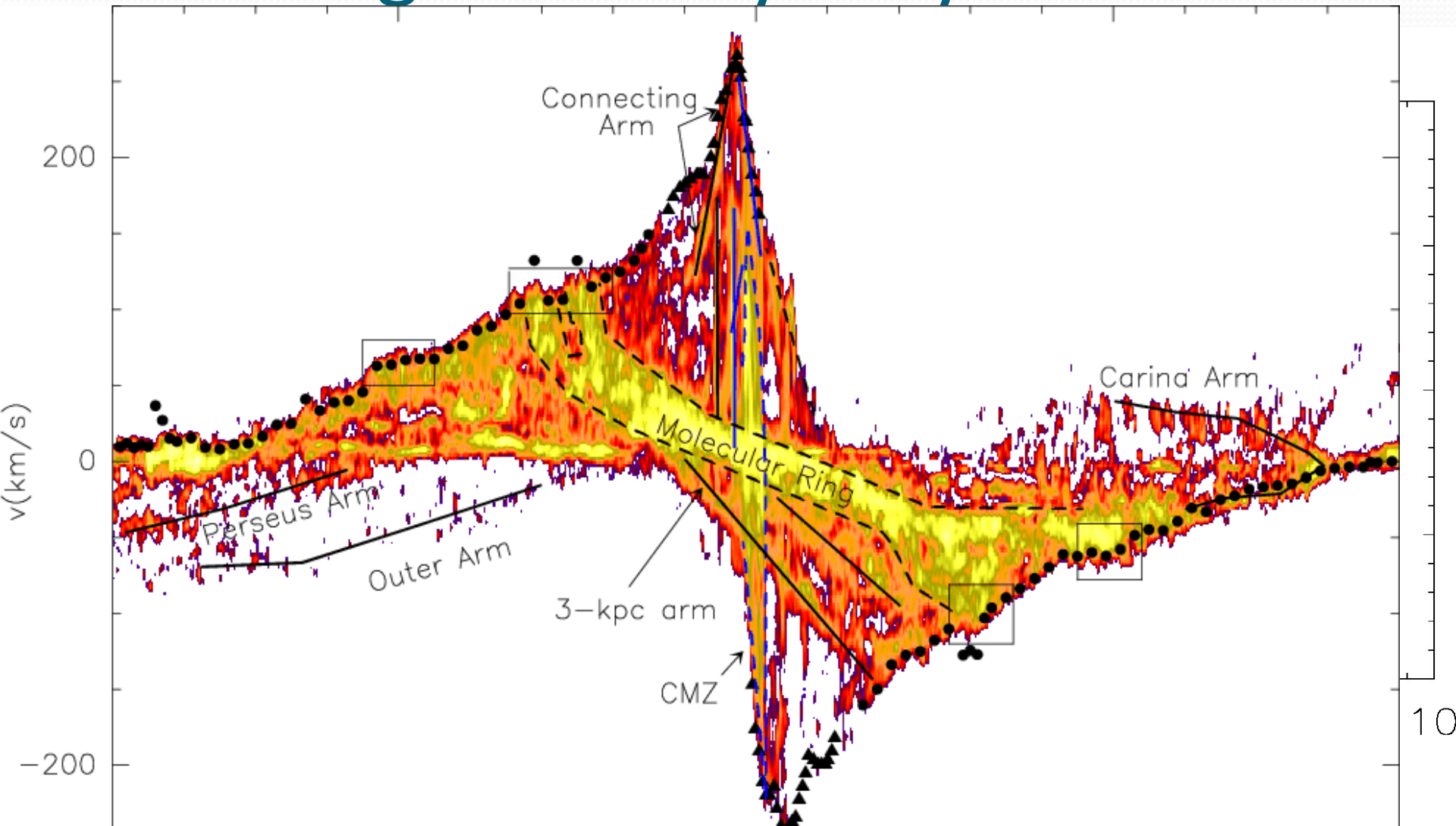


Future work I: compare with IFU data



DensePak IFU Mazzuca et al. 2011

Future work II: *l*-*v* diagram for modeling the Milky Way



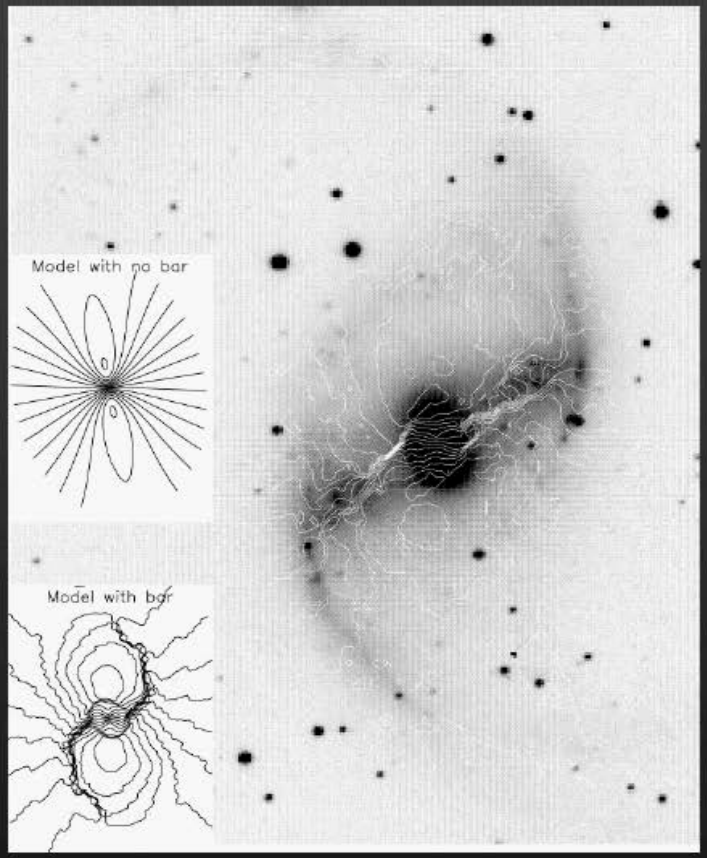
Conclusion

- Gas flow patterns
  - Dust lanes, nuclear rings, nuclear spirals, etc
- Nuclear ring diagram
  - Bigger nuclear ring with smaller pattern speed
  - Bigger nuclear ring with larger central density

- Future work
  - Compare the simulation results with observation data
  - Using recent Milky way potential to model the gas *l*-*v* diagram and constrain the Milky way properties

Appendix

Bar-driven gas inflows



Velocity field of ionised gas along bar of NGC 1530 velocity pinching and non-circular motions (Regan, Teuben, & Vogel 1997)

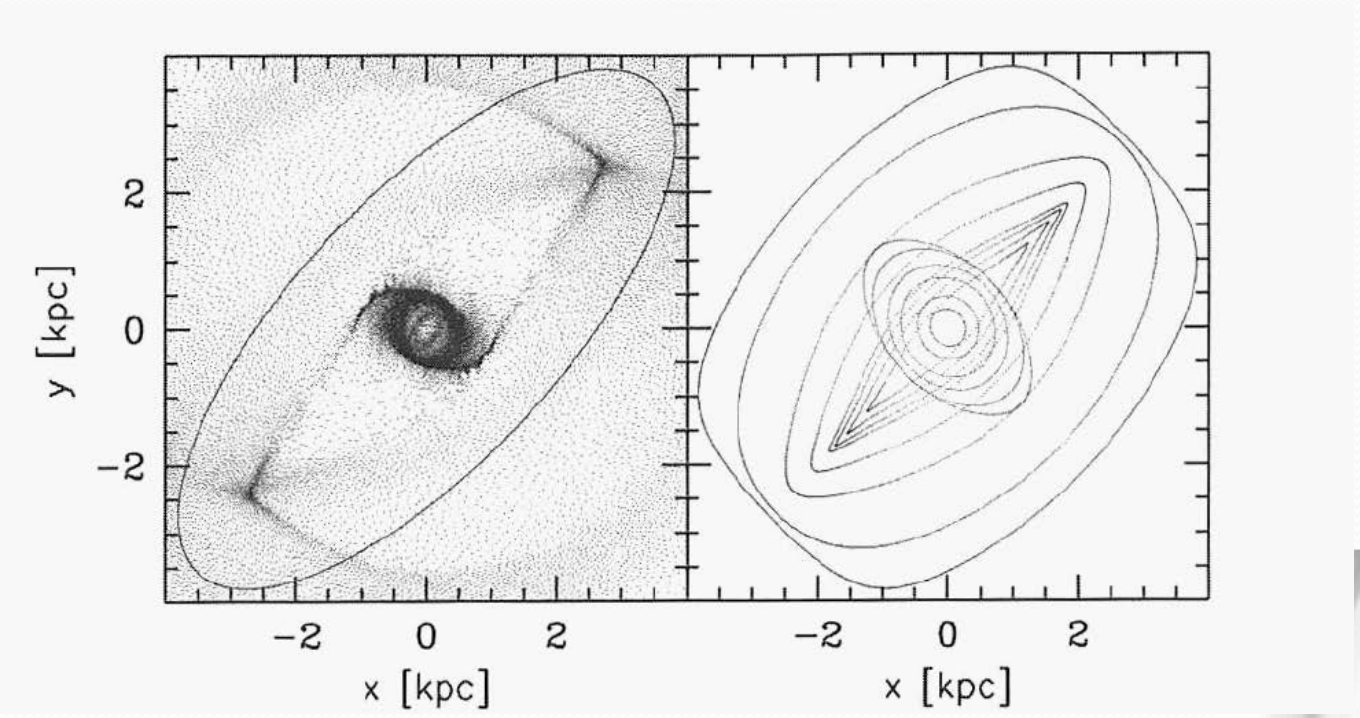
Estimated inflow rates : a few $M_o\ yr^{-1}$

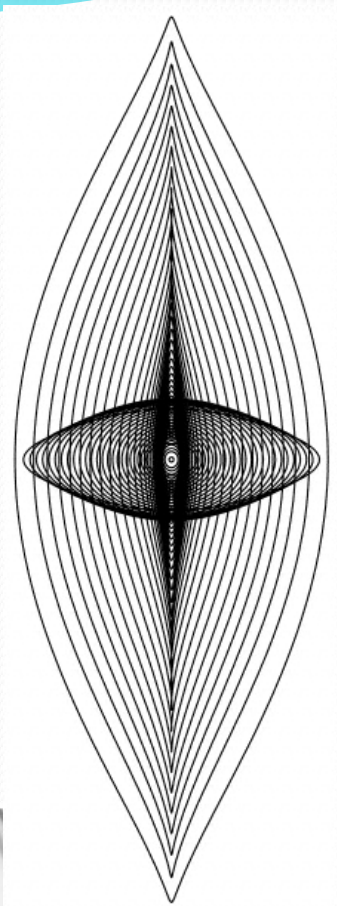
4 +- 2: along bar of NGC 7479 (Quillen et al. 1995)

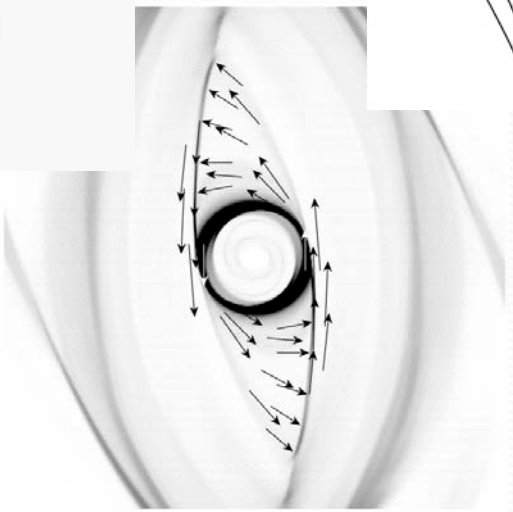
4 to 6 : at 1 kpc radius in NGC 7479 (Laine et al. 1998)

~1 : into 1 kpc ring in NGC 1530 (Regan et al 1997)

Appendix







Appendix

- Central density
  - modified Hubble bulge profile

$$\rho(r) = \rho_{\text{bulge}} (1 + r^2 / r_b^{\,2})^{-1.5}$$

  - Ferrers ellipsoid bar profile

$$\rho = \begin{cases} \rho_{\text{bar}} (1 - g^2)^n & g^2 = y^2/a^2 + (x^2 + z^2)/b^2 \\ & n = 0,1 \\ 0 & a > b \end{cases}$$

  - Central density

$$\rho_{\text{bulge}} + \rho_{\text{bar}}$$