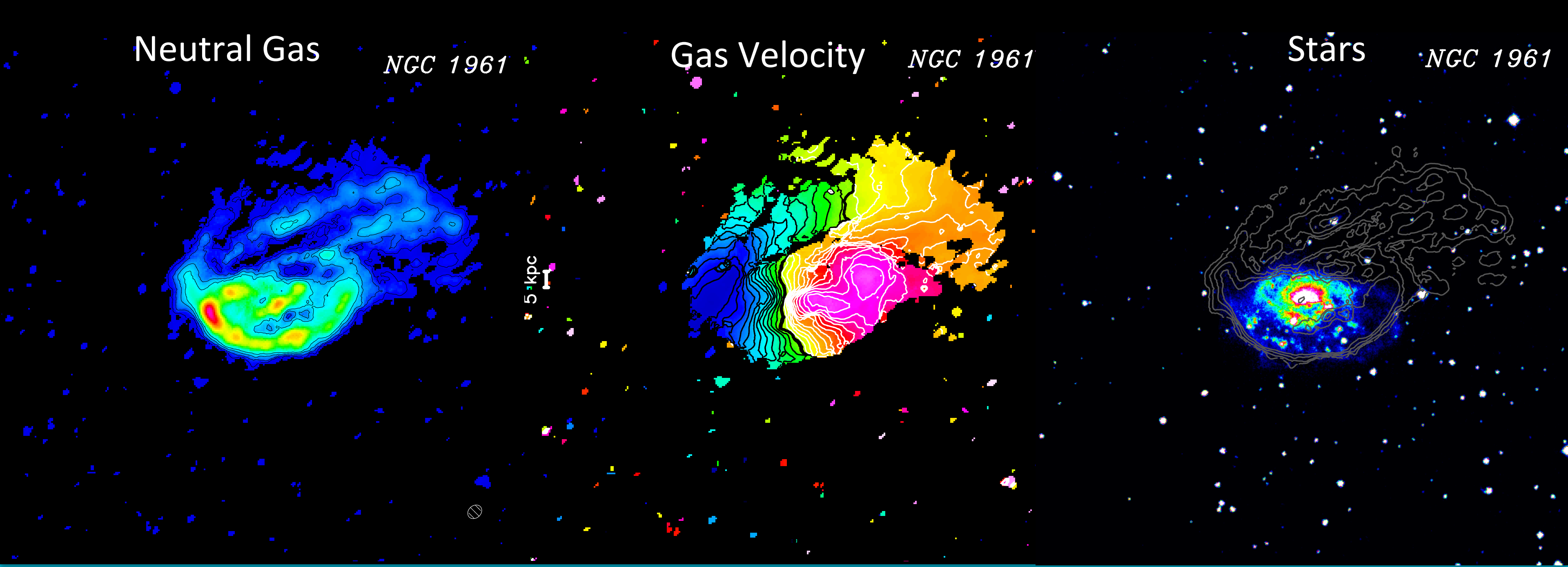

Measuring the movement of galaxies through the IGM in 3D

Sebastian Haan & Robert Braun

17 March, PHISCC2014

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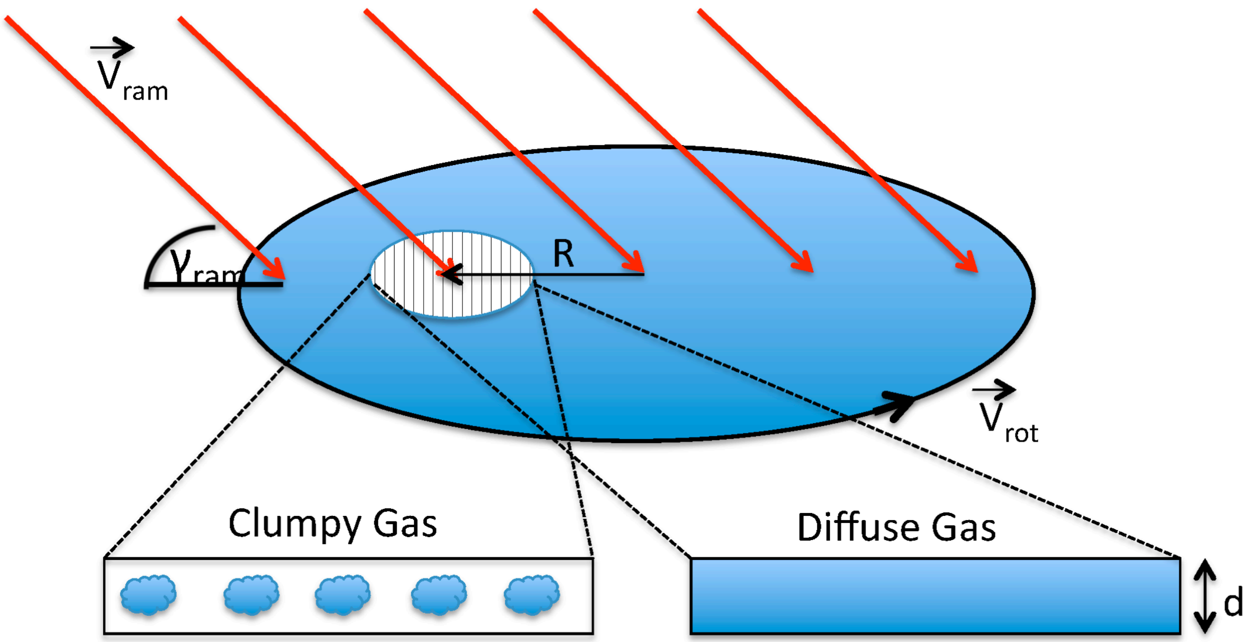
Ram Pressure Interaction



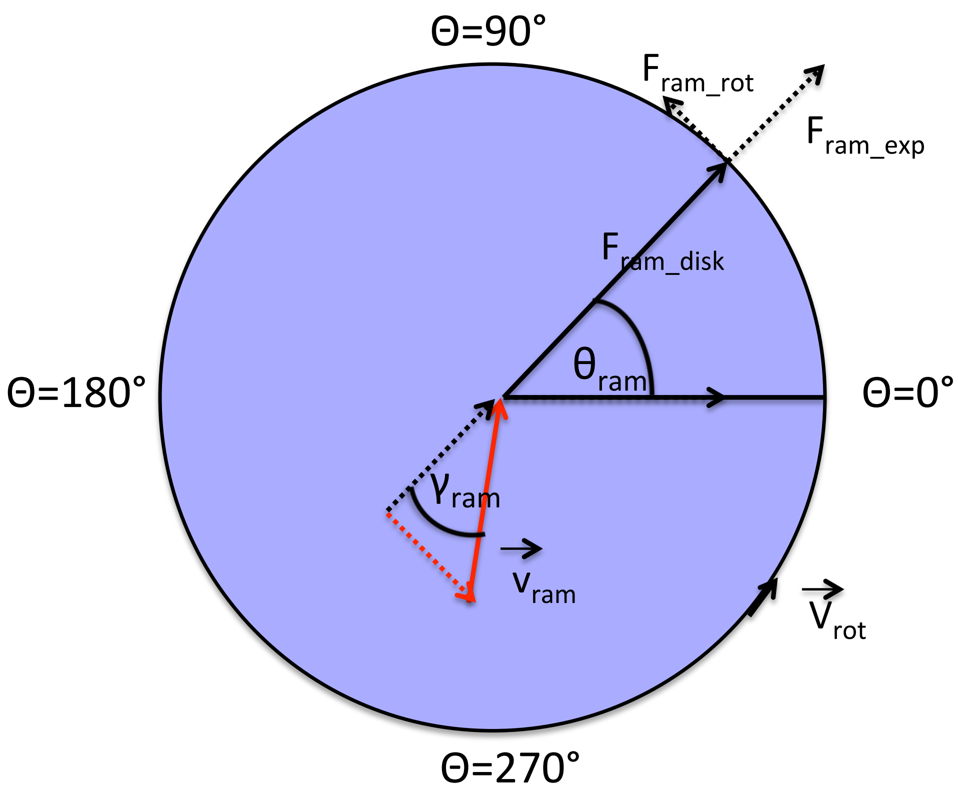
Ram Pressure:

$$P = \rho_{IGM}\ v_{Ram}^2$$

Momentum Transfer:

$$|\ \Delta v\ | \simeq |\ v_{Ram}\ |\ \frac{\rho_{IGM}}{\rho_{Diff}}$$

Kinematic Ram Pressure Terms



Velocity component perpendicular to disk:

$$v_{Ram\perp} = \mid \Delta v \mid F(\rho_{ISM}) \sin(\gamma_{Ram}),$$

Parallel to disk, rotational:

$$v_{RamRot} = \mid \Delta v \mid F(\rho_{ISM}) \sin(\theta - \theta_{Ram}) \cos(\gamma_{Ram}),$$

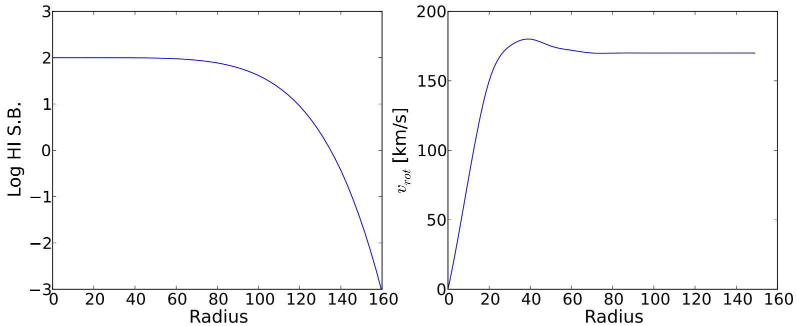
Parallel to disk, radial:

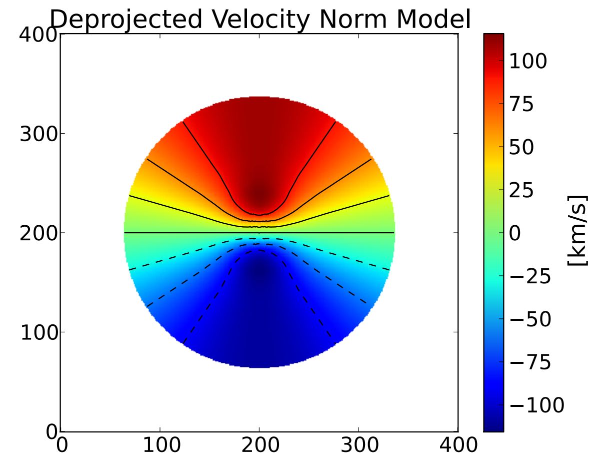
$$v_{RamExp} = \mid \Delta v \mid F(\rho_{ISM}) \cos(\theta - \theta_{Ram}) \cos(\gamma_{Ram})$$

$$v_{LoS} = v_{Sys} + [v_{Rot}(r) + v_{RamRot}] \cos(\theta) \sin(i) + [v_{Exp}(r) + v_{RamExp}] \sin(\theta) \sin(i) + v_{Ram\perp} \cos(i)$$

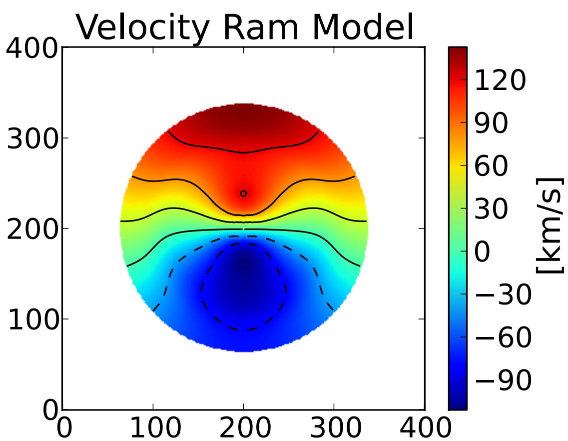
Kinematic Galaxy-Ram Model

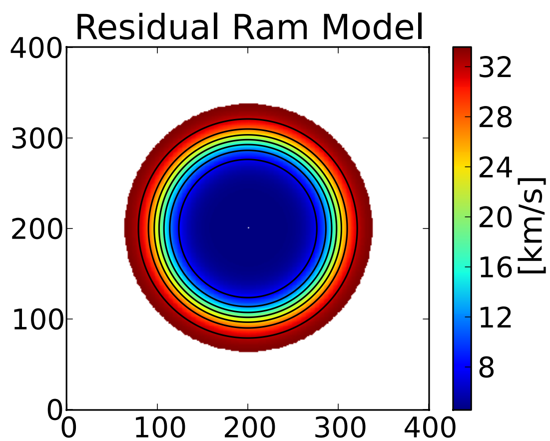
- Regular rotating disk (no ram pressure):





- Ram wind perpendicular to disk:



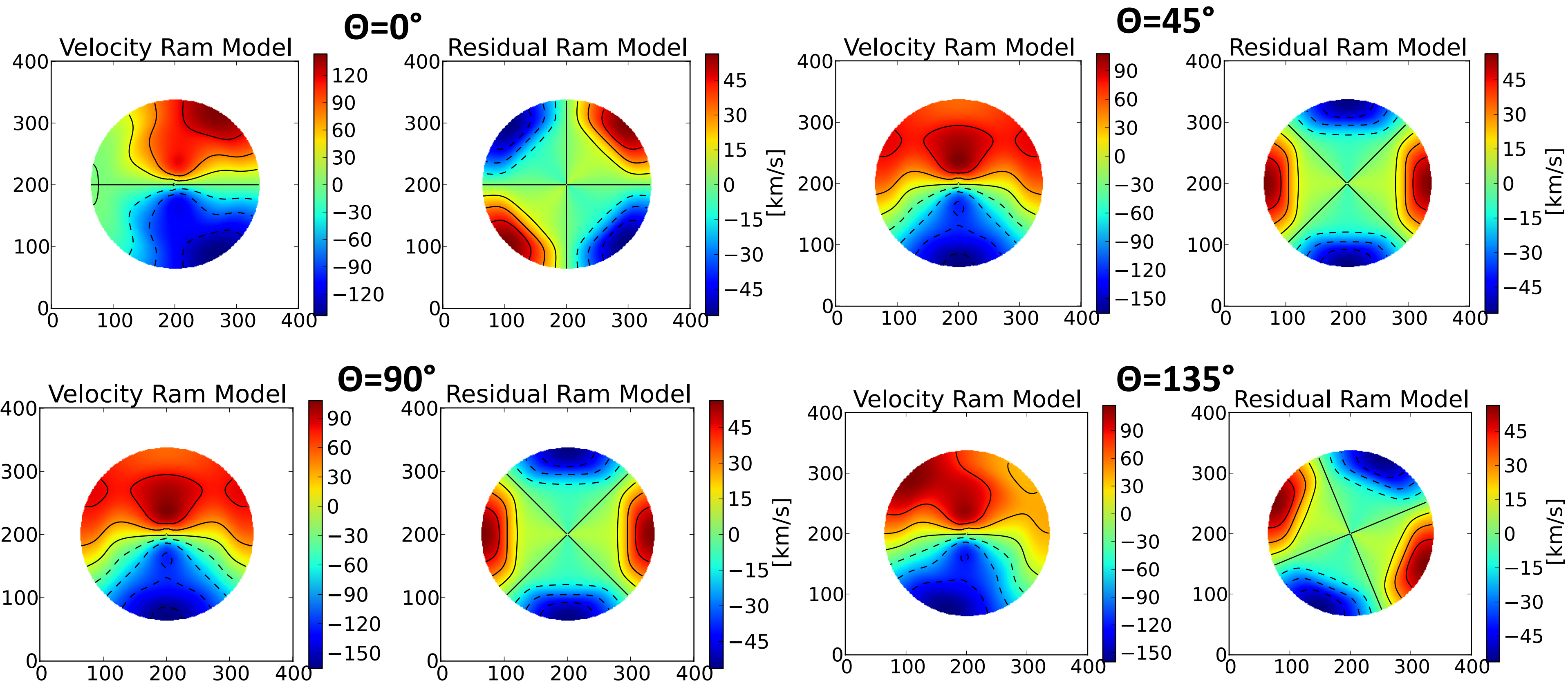


Induced velocity component:

m=0 mode

Kinematic Galaxy-Ram Model

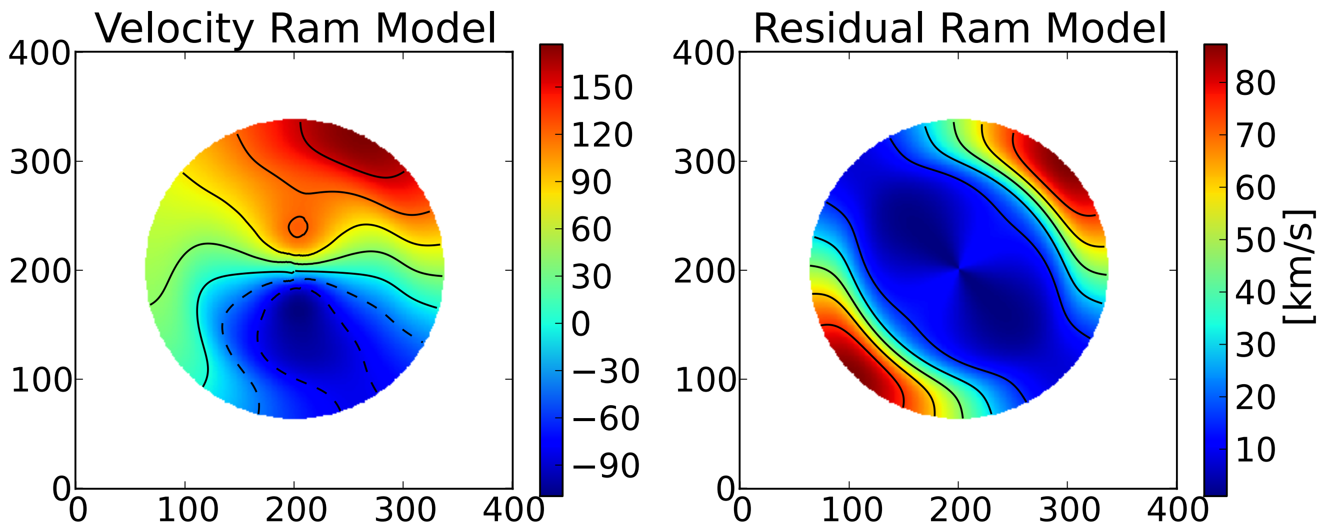
- Ram wind parallel to disk:



Induced velocity component: **m=2 mode**

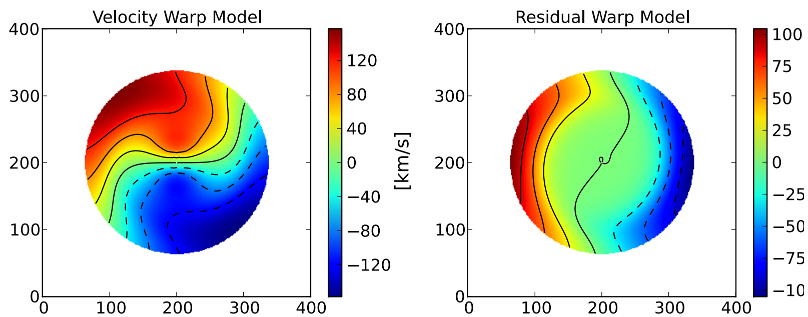
Kinematic Galaxy-Ram Model

- Ram wind 45° inclined to disk:

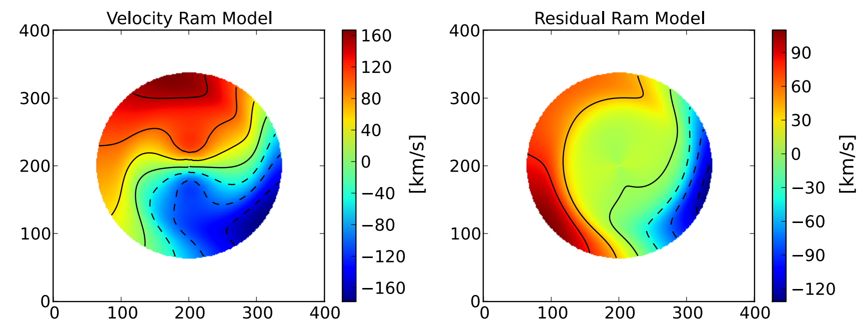


Model of Warped Disk

Warp (no ram wind):



Warp + ram wind:



-> Induced velocity component: m=1 mode

$$v_{Res} = c_0(r) + c_1(r)\cos[\theta_{warp*}(r)] + c_2(r)\sin[2\theta_W(r) - \theta_{Ram}(r)]$$

Mathematical Decomposition:

$$\begin{aligned} c_0(r) &= \mid \Delta v \mid F(\rho_{ISM}) \cos[i(r)] \sin[\gamma_{Ram}(r)] \\ c_1(r) &= v_{Rot}(r) \sin[i(r)]\ 2\sin[\phi_W(r)/2] \\ c_2(r) &= \mid \Delta v \mid F(\rho_{ISM}) \cos[\gamma_{Ram}(r)] \sin[i(r)] \end{aligned}$$

Combination of m = 0, 1, 2 mode

→ Decomposition into kinematic ram pressure terms and terms due to geometric disk variations

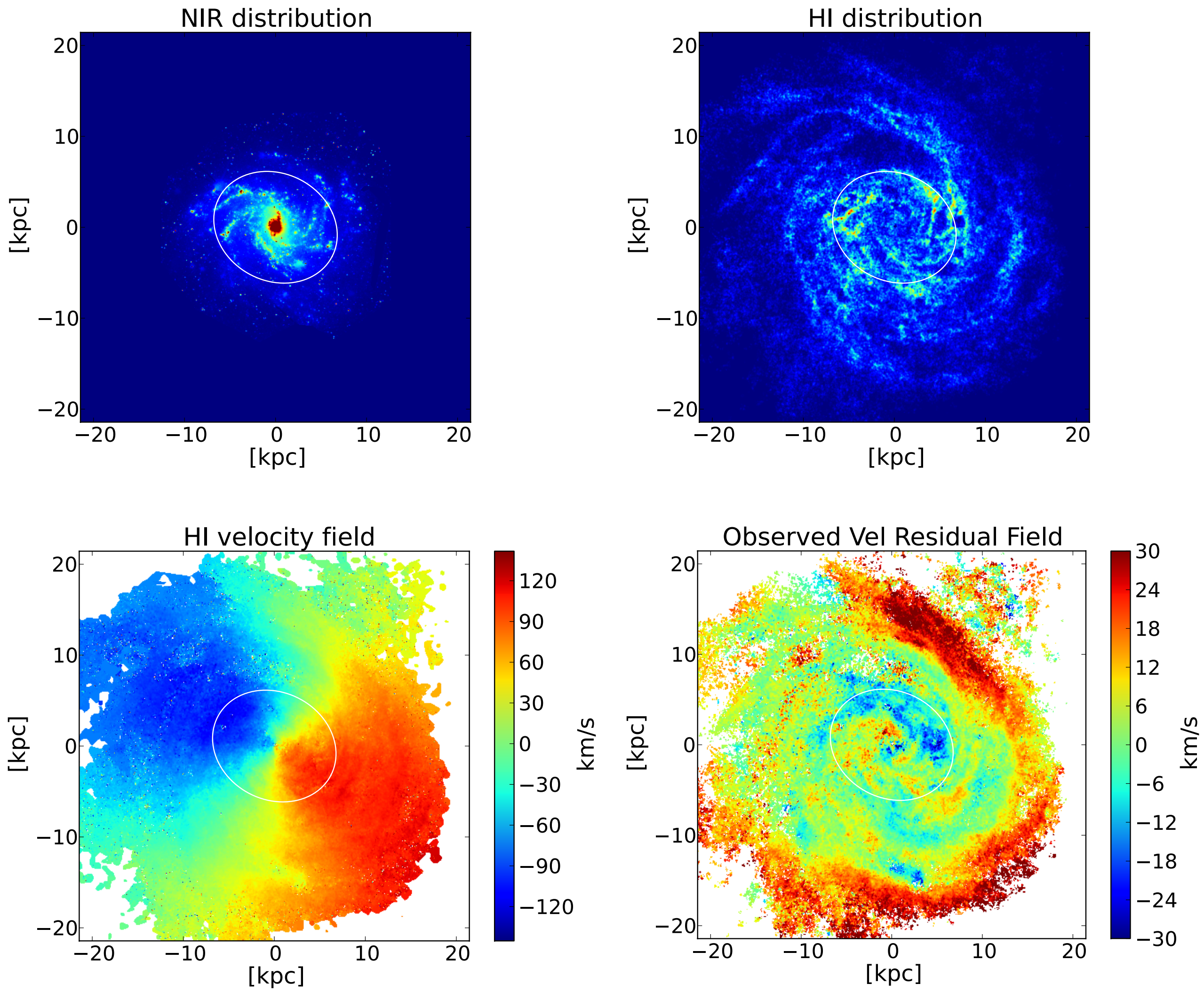
Haan & Braun, MNRAS (in review)

Measuring Ram Interaction

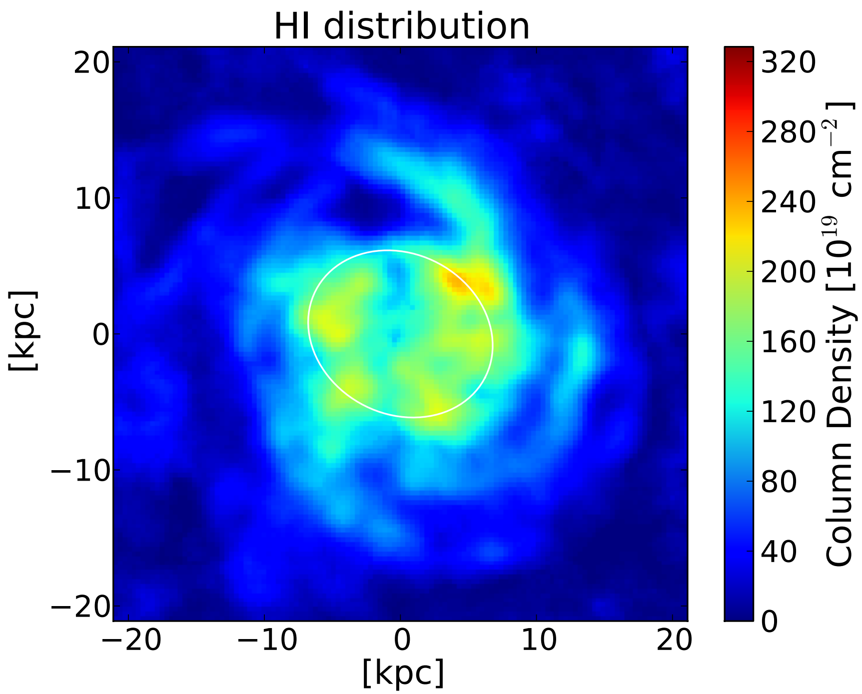
Model recipe

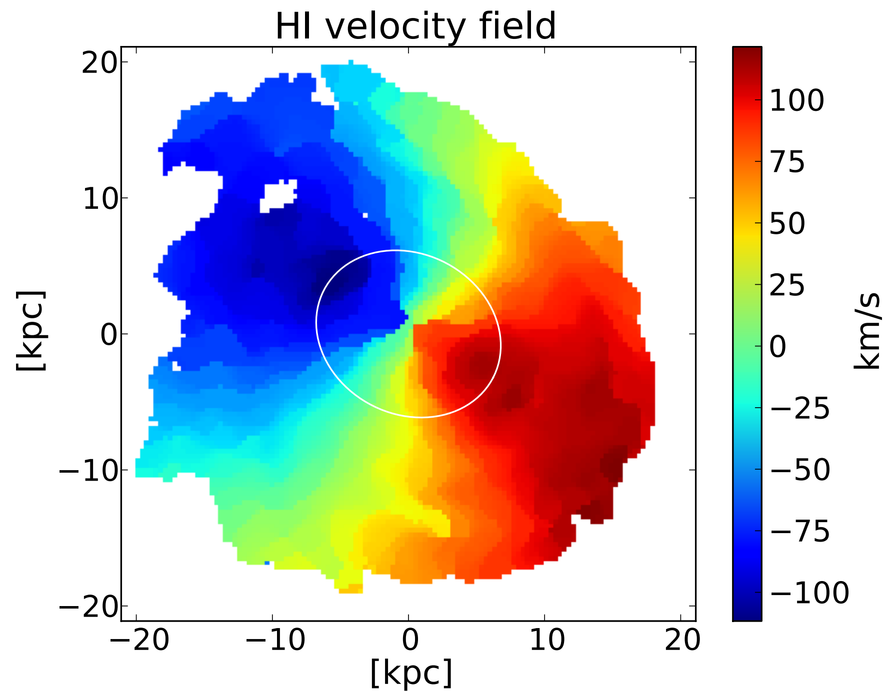
- **Input**: 2-dim velocity field + HI column density distribution, and initial estimates of geometry of disk
- 9 free parameters (warped geometry, ram pressure terms: wind direction, amplitude, scaling function for ISM density)
- Least square minimization of Markov Chain Monte Carlo (MCMC) samplers (e.g. *emcee* Python implementation)
- **Output**: decomposition of non-circular velocity field into m=0, 1, 2, 3 modes as function of azimuthal angle, HI column density (2-dim) and radial scale.
- Ram wind direction and velocity amplitude of perturbation, + possible warp geometry.

Example: NGC 6946

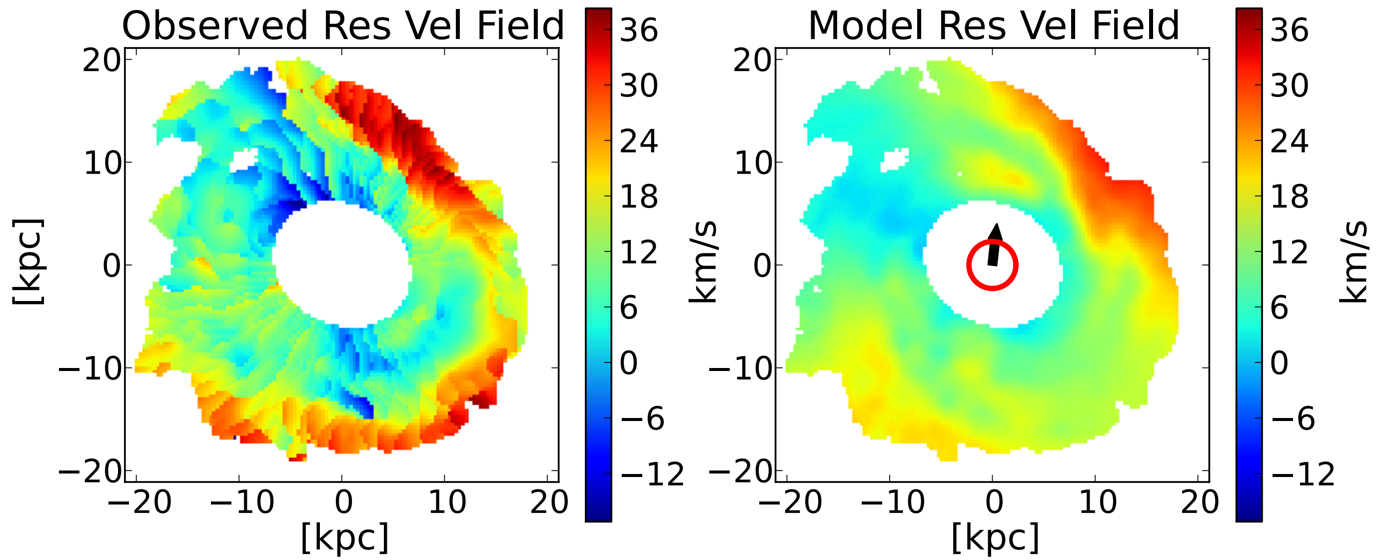


Example: NGC 6946

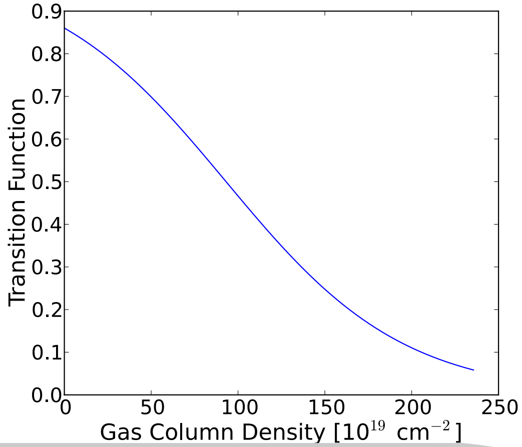




Example: NGC 6946

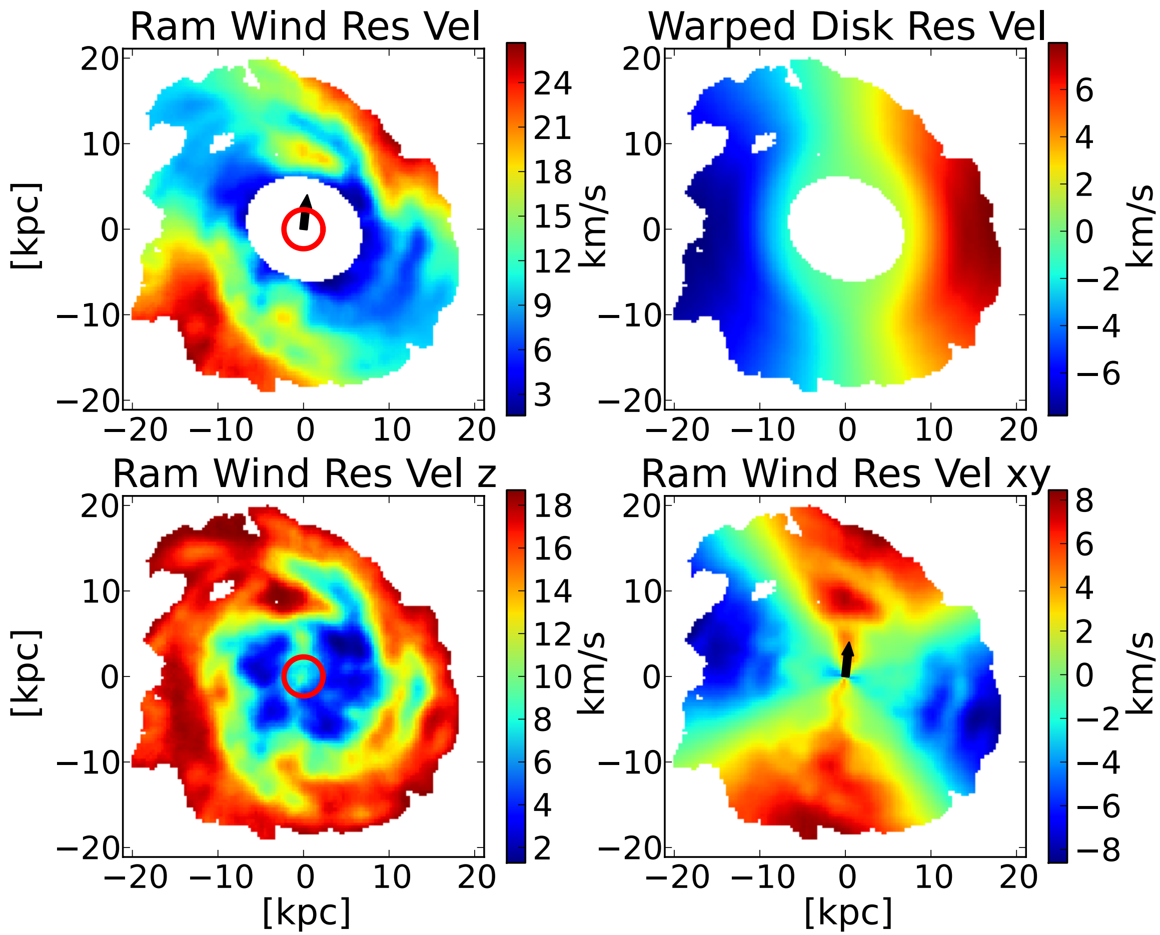


ram pressure induced H_I velocity ≅30 km/s at H_I column densities < (4-10) x 10^{20} cm^{-2}



Example: NGC 6946

Decomposition of non-circular velocity field:

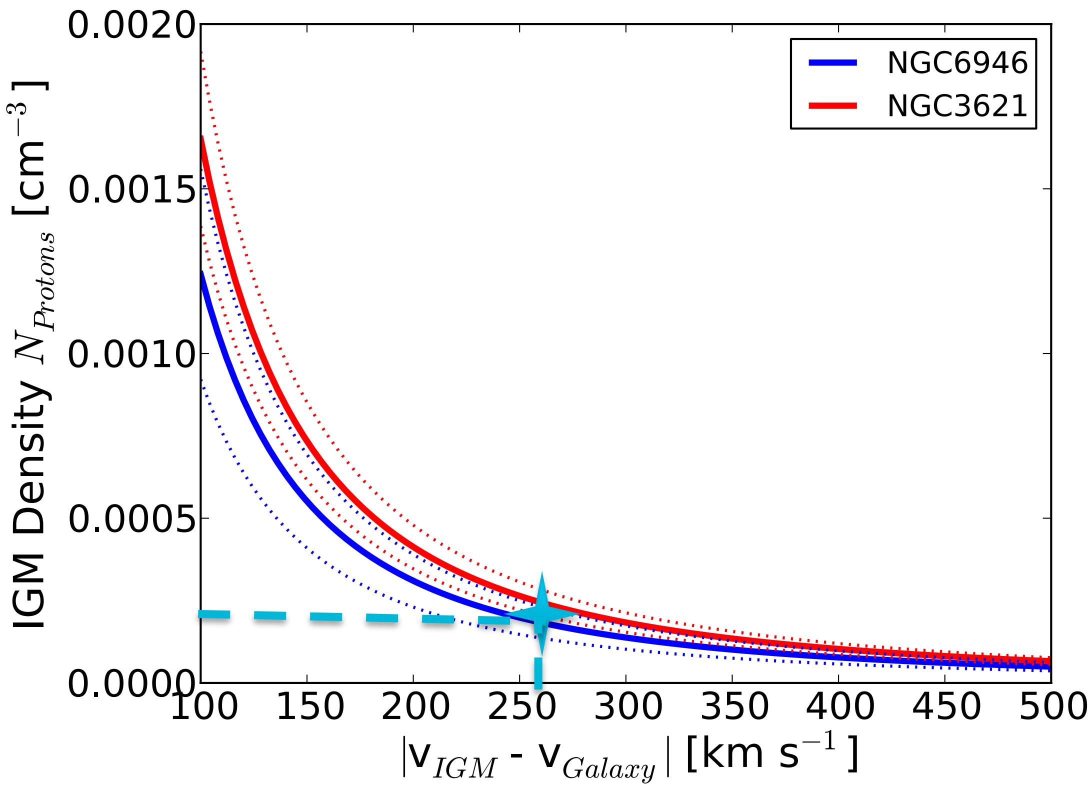


Applications

- Measurement of 3D vector of the galaxies' movement through IGM
- Constrain phase space: relative velocity × IGM density

Galaxy Groups:

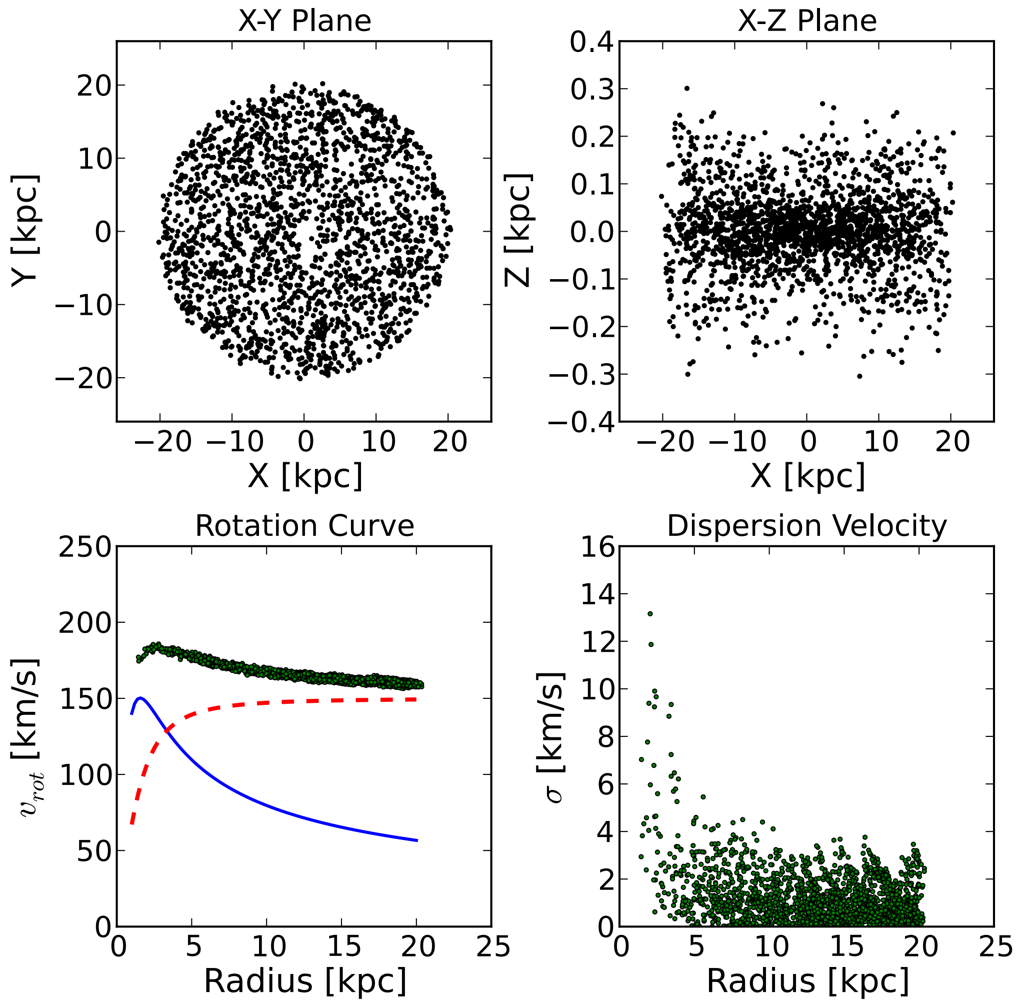
- Determine galaxy orbits and IGM density profile



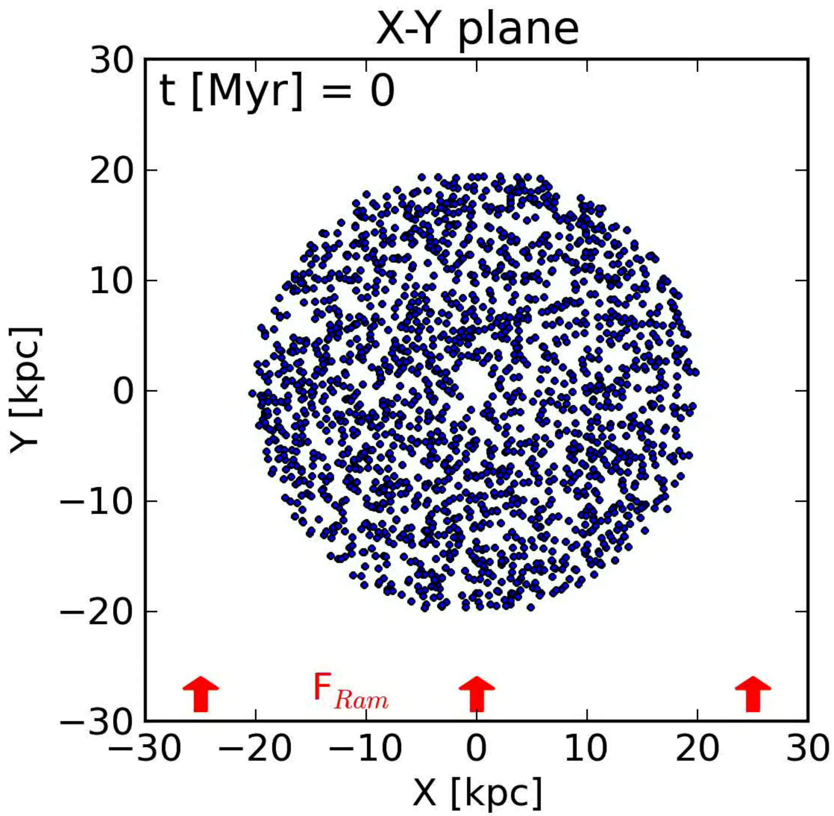
Haan & Braun, MNRAS (in review)

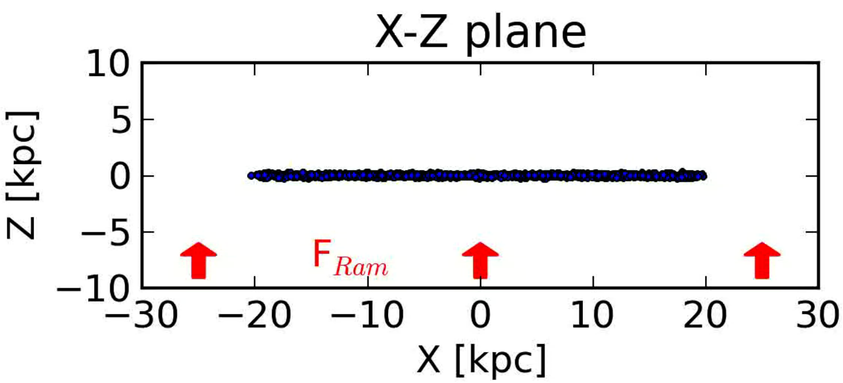
Long-Term Consequences of Ram Pressure

How about testing the response of gas cloud orbits in a realistic galaxy potential?



Long-Term Consequences of Ram Pressure





Continuous exposure to a ram wind induces a "classical" S-shaped warp of outer disk

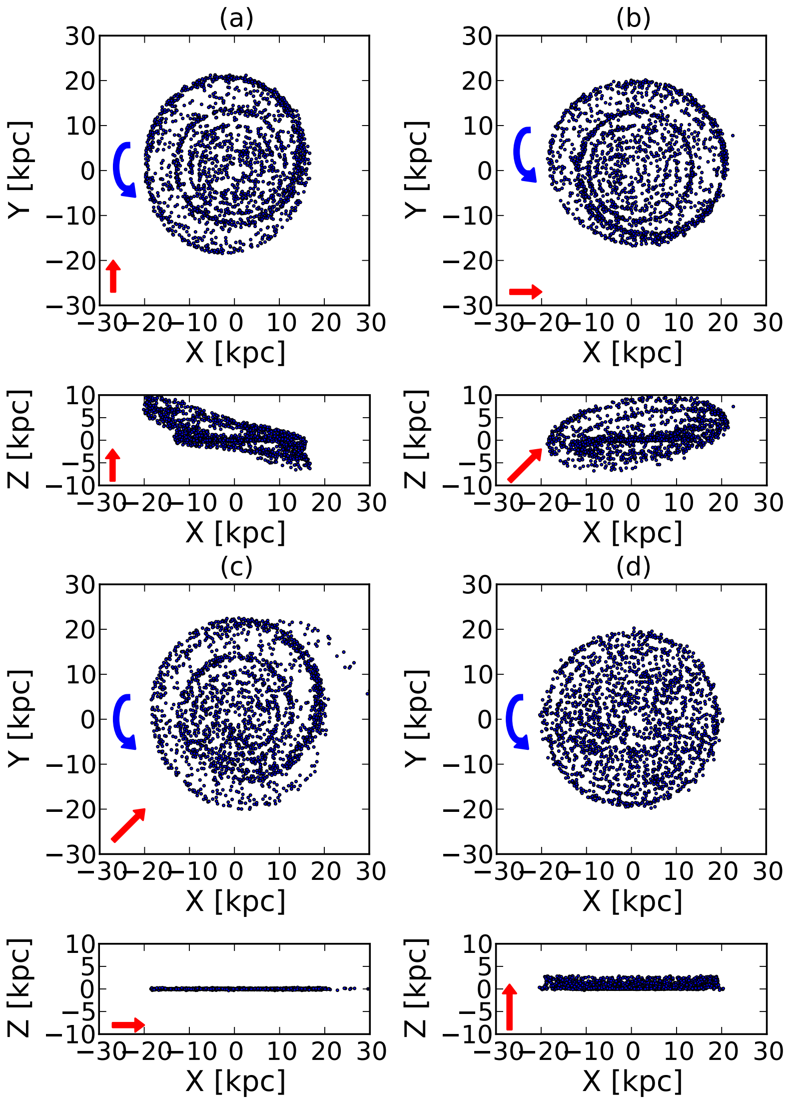
- warp sets in within $2P_{Rot}$
- warp is stable for $>10P_{Rot}$

Haan & Braun, MNRAS Letters 2014

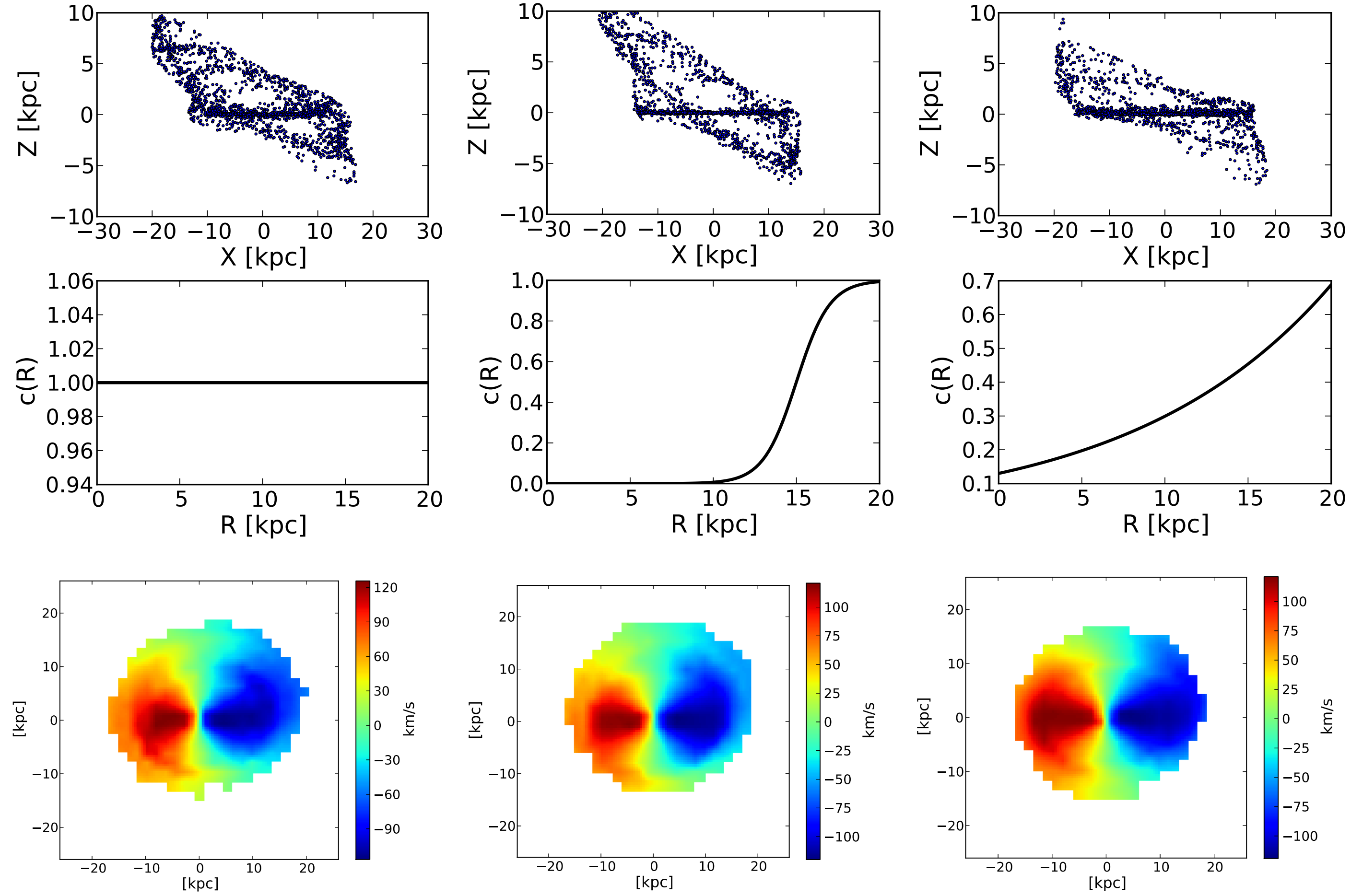
Long-Term Consequences of Ram Pressure

How does outcome depend on relative orientation?

- Pure edge-on only yields one arm spiral
- Pure face-on only yields flaring/ U-shaped warp
- Arbitrary angle yields S-shaped warp

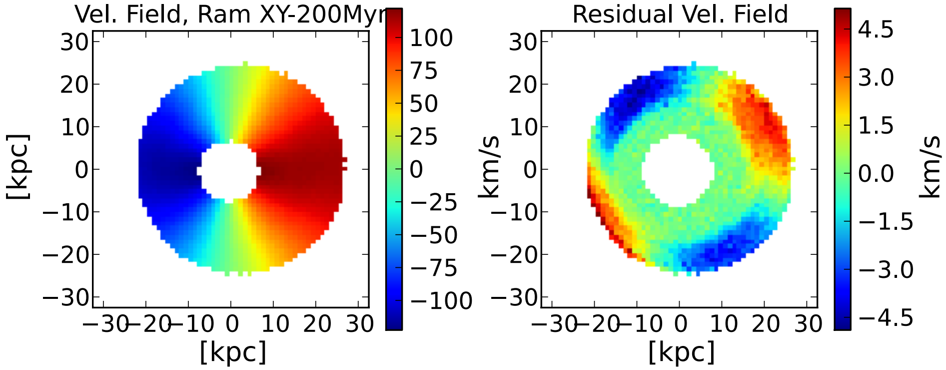


Long-Term Consequences of Ram Pressure

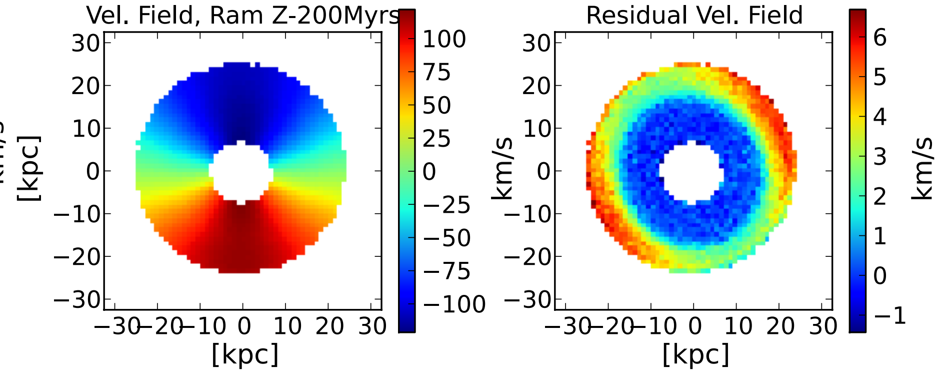


Simulation: Derived Velocity Fields

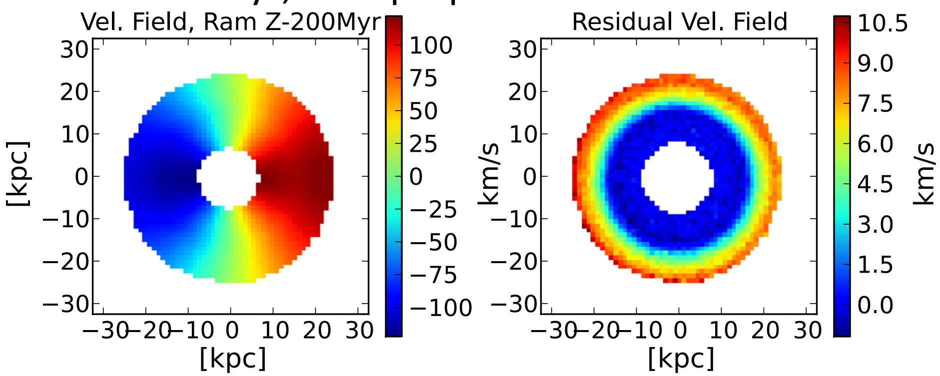
200 Myr, Ram parallel to Disk



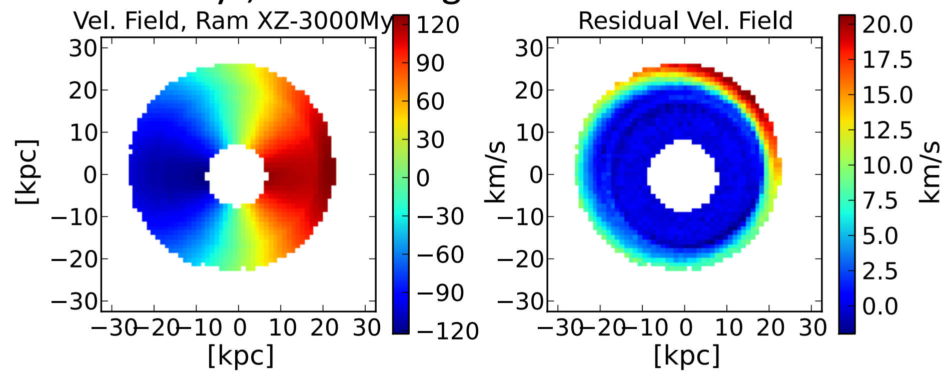
200 Myr, Ram 45deg inclined to Disk



200 Myr, Ram perpendicular to Disk



3 Gyr, Ram 45deg inclined to Disk



How do the simulations compare with the analytic approximations?

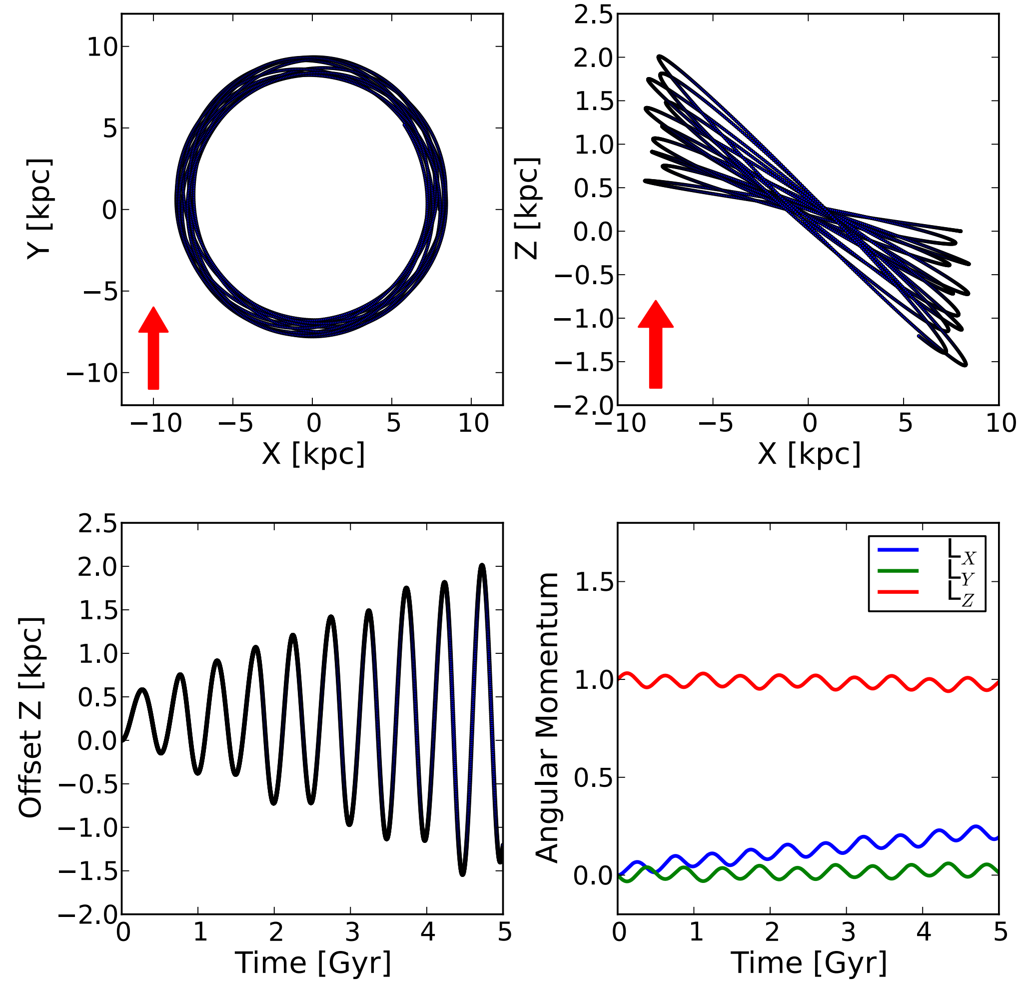
- Same Fourier mode distortions: m=2 in-plane, m=0 out-of-plane
- Warp builds up as superposed m=1 mode

Summary

- Ram pressure interactions between Galaxy – IGM ram produces a significant kinematic (and ultimately morphological) signature in the diffuse HI disk.
- Kinematic ram pressure terms are characterized by m=0 and m=2 modes in the residual velocity field and have a strong dependence on ISM density (e.g. outer disk NGC 6946).
- Long term consequences: Formation of warped gas disks, primarily S-shaped warp, m=1 mode (typical warped shape in most galaxies)
- Application: reveal the 3D vector of the galaxies' movement through the IGM, might be used to reconstruct both the IGM density profile and individual member orbits within galaxy groups
- Large-scale interferometric HI surveys as planned with the SKA/Apertif will be sensitive enough to test the gas dynamics in the outer disk of thousands of nearby galaxies

Long-Term Consequences of Ram Pressure

How does the orbit of a cloud in a spherical potential evolve in response to continuous ram pressure interaction over multiple rotation periods?

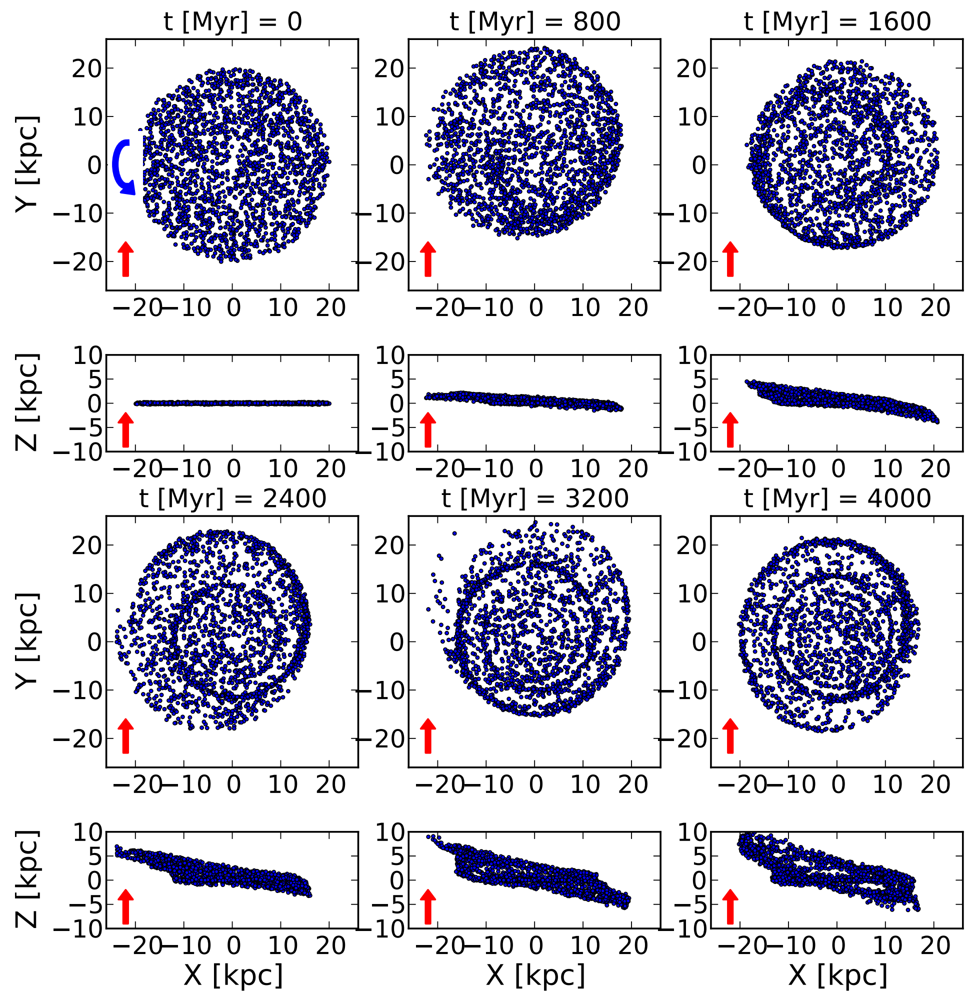


Long-Term Consequences of Ram Pressure

Continuous exposure to a ram wind induces a “classical” S-shaped warp of outer disk

- warp sets in within $2P_{Rot}$
- warp is stable for $>10P_{Rot}$

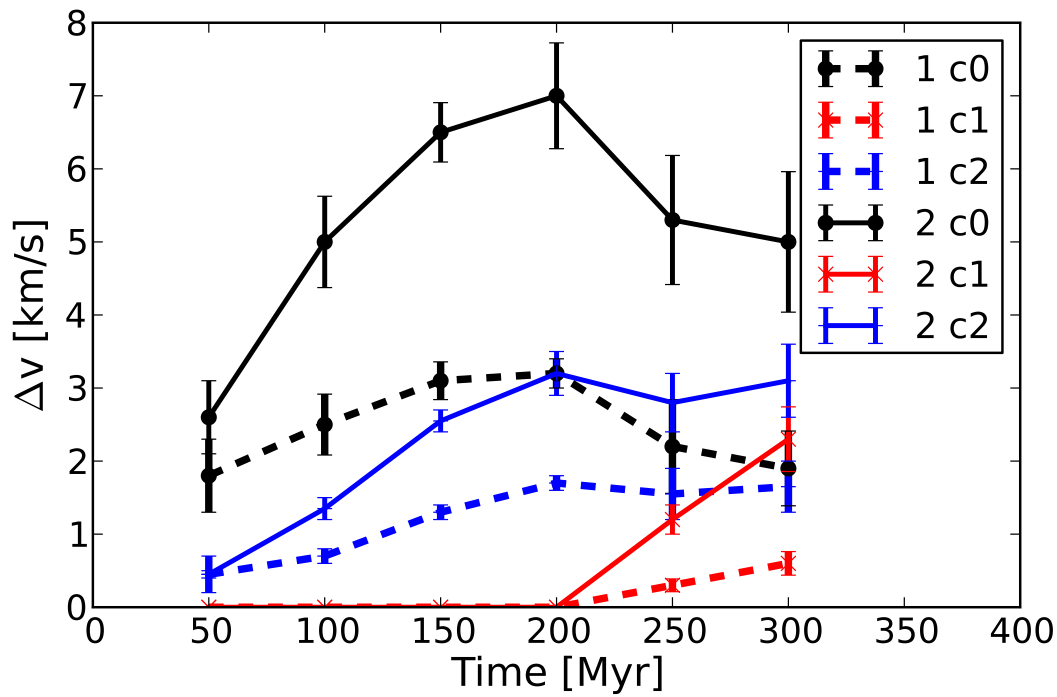
Also induces one arm retrograde spiral density wave pattern in disk



Connecting Short-Term and Long-Term Consequences

How do the simulations compare with the analytic approximations?

- "Short-term", m=0 & 2 modes build up rapidly, $T < P_{Rot}/4$ and then stabilize at values comparable to "theory"
- "Long-term", m=1 warp mode builds up over $T > 2\ P_{Rot}$



Long-Term Consequences of Ram Pressure