Unravelling the 3D effects of the bar and spirals in the Milky Way

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Work done with A. Siebert, G. Monari & C. Faure

0th order models: axisymmetry & equilibrium

Pair (f_0, Φ_0) collisionless Boltzmann + Poisson

$$[f_0, H_0] = 0 \quad ; \quad \nabla^2 \Phi_0 = 4\pi G \int \mathrm{d}^3\mathbf{v}\, f_0;$$

↓

1st order with ONE main perturber

bar — spiral pattern

spiral pattern → quasi-static — transient

↓

Combine multiple perturbers

Learn about the nature of the non-axisymmetries

How much can be explained by them alone?

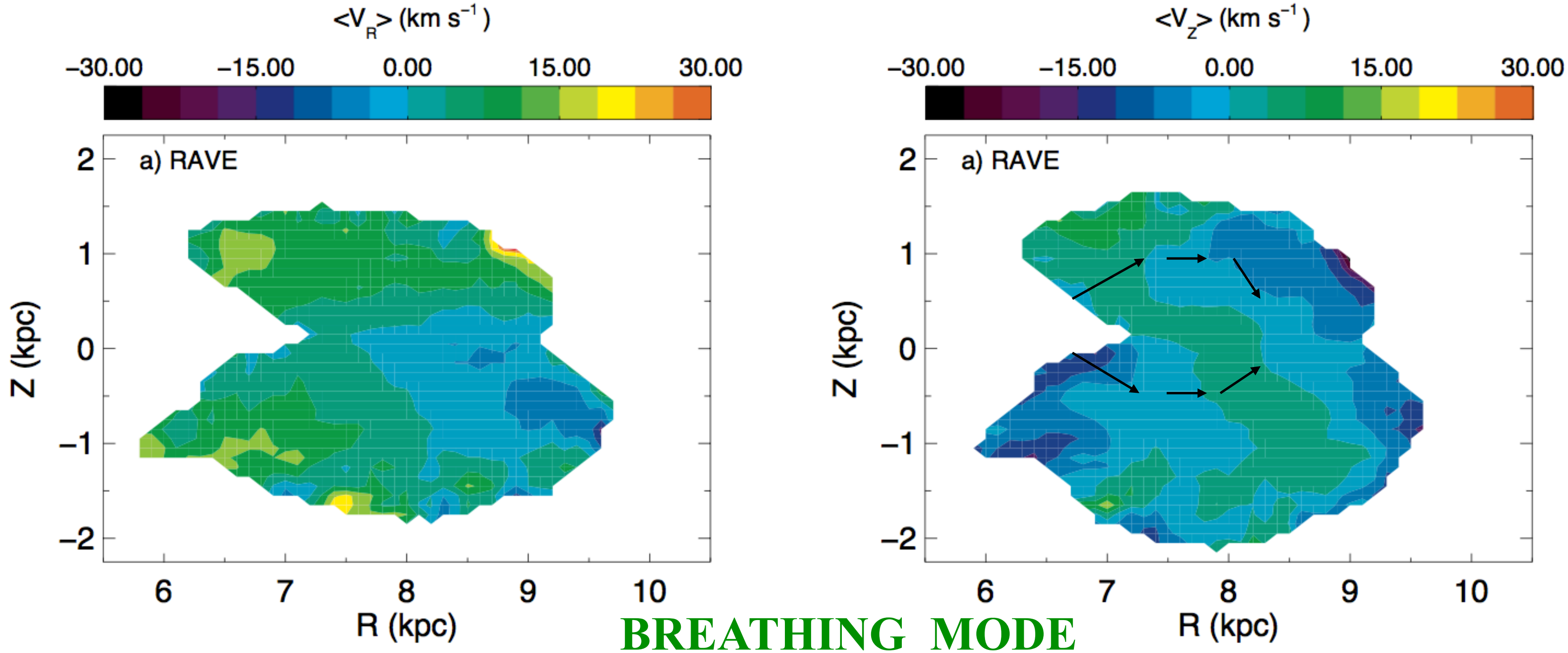
Influence on secular evolution?

Existing non-axisymmetries can bias the axisym. fit !

(test robustness of approximation at each step)

Signatures of non-axisymmetry in recent spectroscopic surveys

- **RAVE** (Siebert, Famaey, et al., 2011, 2012): gradient in the mean radial velocity of 4 km/s/kpc in extended solar neighbourhood (~200 000 stars)
- **Affects stars substantially above (and below) the plane**
- And mean **vertical** motions are non-zero too (Williams et al. 2013: **RAVE**, see also Widrow et al. 2012: **SEGUE** and Carlin et al. 2013: **LAMOST**)



BREATHING MODE

Linearized Jeans equations for cold stellar fluid in 3D

Assume only one main non-axisymmetric perturber, long-lived enough (~1 Gyr) so that the stationary response is meaningful (Faure, Siebert & Famaey 2014)

Tightly-wound spiral:

$$\Phi_s = \mathbf{Re}\{\Phi_a(R,z)\exp[i\,m(\Omega_P t - \theta)]\}$$

with

$$\Phi_a = -A\,\mathrm{sech}^2\left(\frac{z}{z_0}\right)\exp\left(i\frac{m\ln(R)}{\tan p}\right).$$

Parameter	Spiral potential
m	2
A (km^2 s^{-2})	1000
p (deg)	-9.9
z_0(kpc)	0.1
Ω_P(kms^{-1} kpc^{-1})	18.6
R_{ILR}(kpc)	1.94
R_{IUHR}(kpc)	7.92
R_{CR}(kpc)	11.97

Linearized Jeans equations (zero dispersion):

$$\frac{\partial v_{R1}}{\partial t} + \frac{v_{\theta 0}}{R}\frac{\partial v_{R1}}{\partial \theta} - \frac{2 v_{\theta 0} v_{\theta 1}}{R} = -\frac{\partial \Phi_1}{\partial R}$$

$$\frac{\partial v_{\theta 1}}{\partial t} + v_{R1}\frac{\partial v_{\theta 0}}{\partial R} + \frac{v_{\theta 0}}{R}\frac{\partial v_{\theta 1}}{\partial \theta} + v_{z1}\frac{\partial v_{\theta 0}}{\partial z} + \frac{v_{R1} v_{\theta 0}}{R} = -\frac{1}{R}\frac{\partial \Phi_1}{\partial \theta}$$

$$\frac{\partial v_{z1}}{\partial t} + \frac{v_{\theta 0}}{R}\frac{\partial v_{z1}}{\partial \theta} = -\frac{\partial \Phi_1}{\partial z}$$

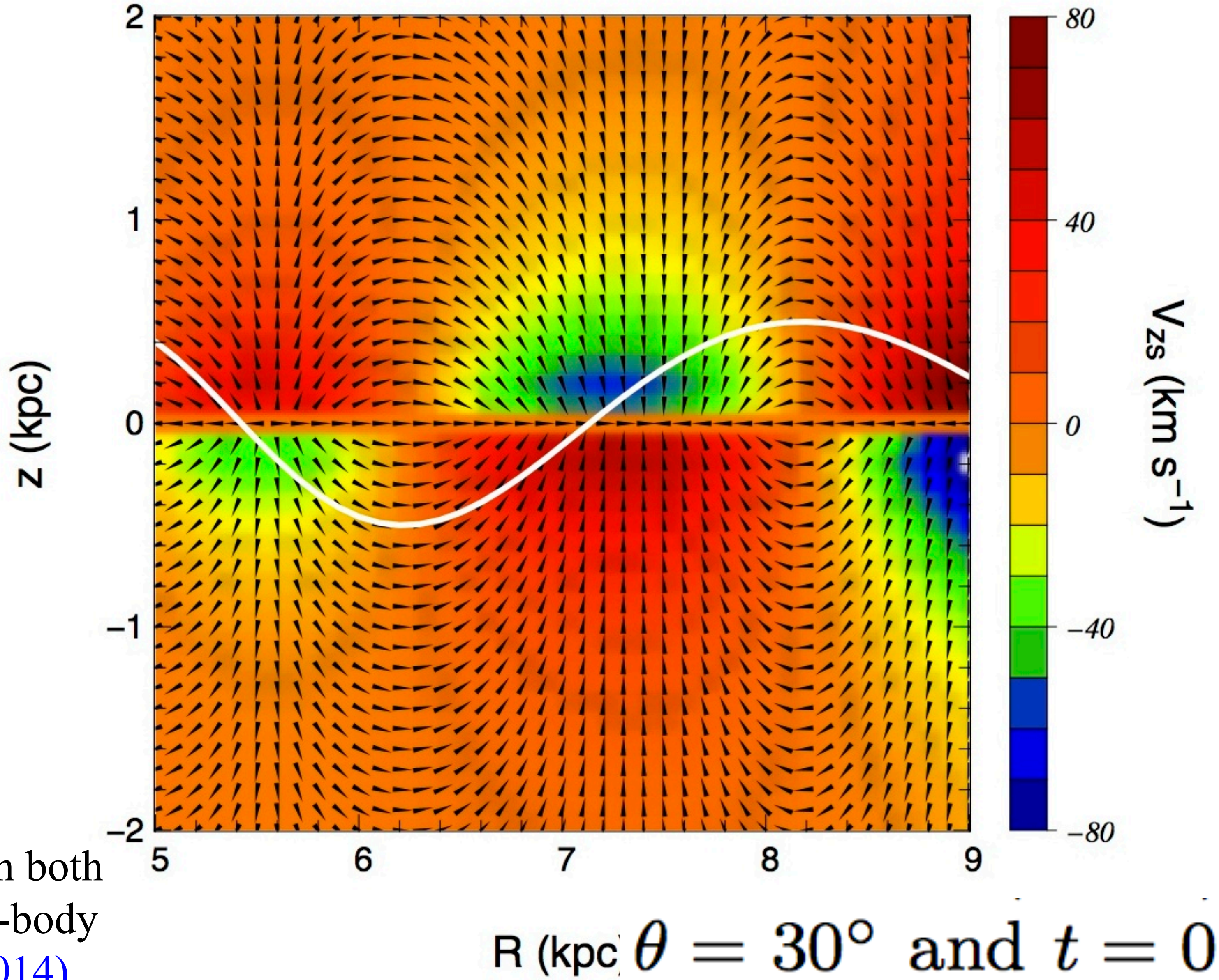
Solution is sum of terms of the form:

$$v_{R\,1} = \mathbf{Re}\{v_{Ra}(R,z)\exp[i\,m(\Omega_P t - \theta)]\}$$

$$v_{Ra} = -\frac{m(\Omega - \Omega_P)}{\Delta}k\Phi_a$$

$$v_{za} = -\frac{2i}{m(\Omega - \Omega_P)z_0}\tanh\left(\frac{z}{z_0}\right)\Phi_a$$

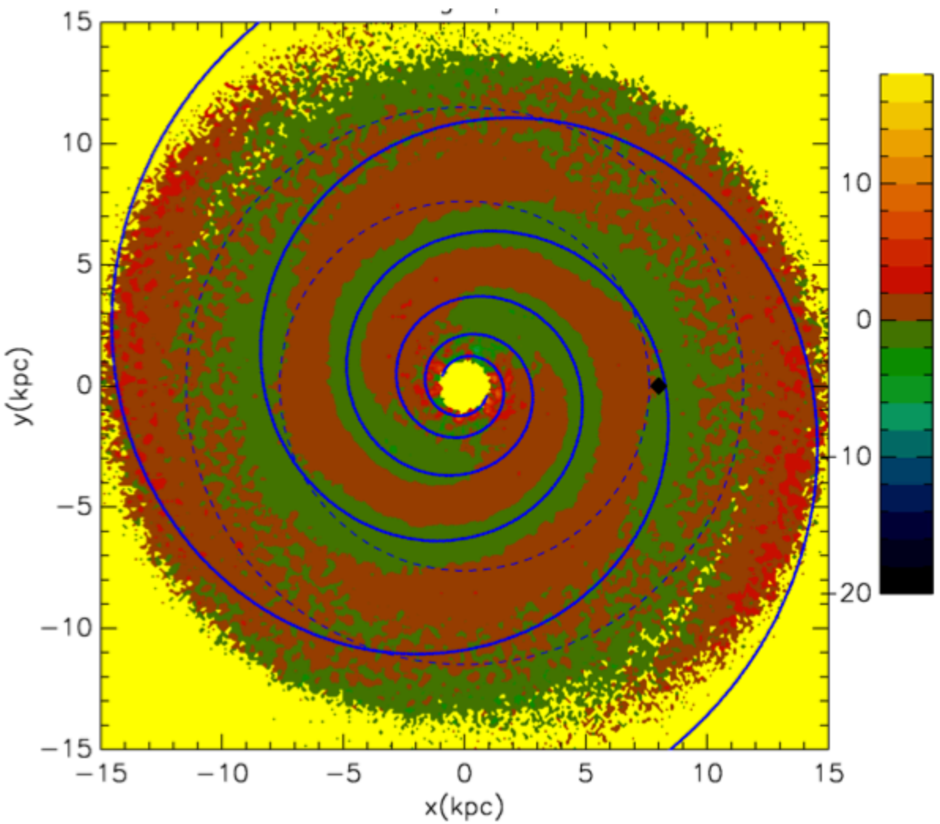
Faure, Siebert & Famaey (2014 MNRAS 440 2564)



$\theta = 30^\circ$ and $t = 0$

Effect confirmed in both test-particle and N-body sims (Debattista 2014)

Effect of spirals on mean motions



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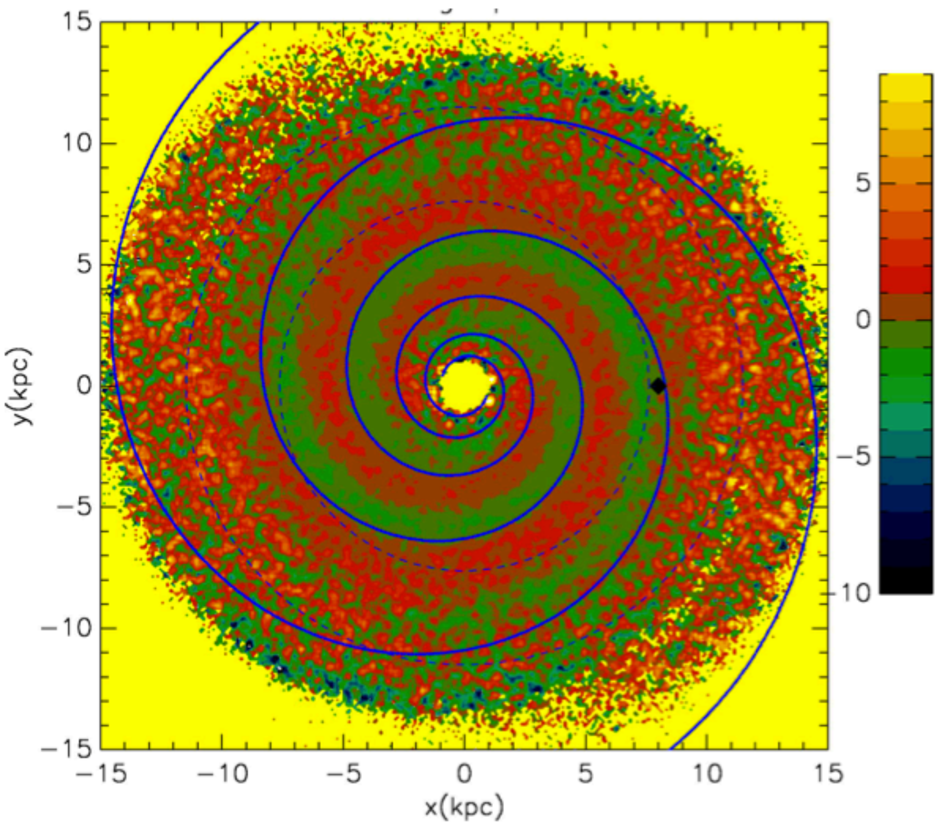
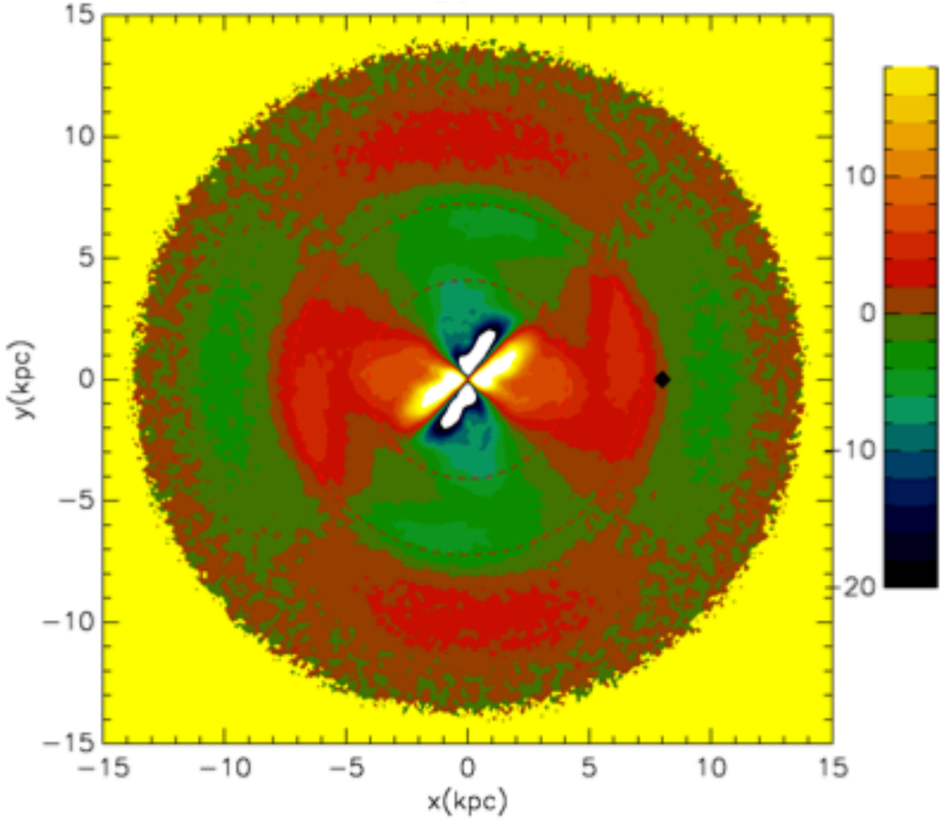


$<Vz>_{z>0} - <Vz>_{z<0}$

Effect of bar on mean motions



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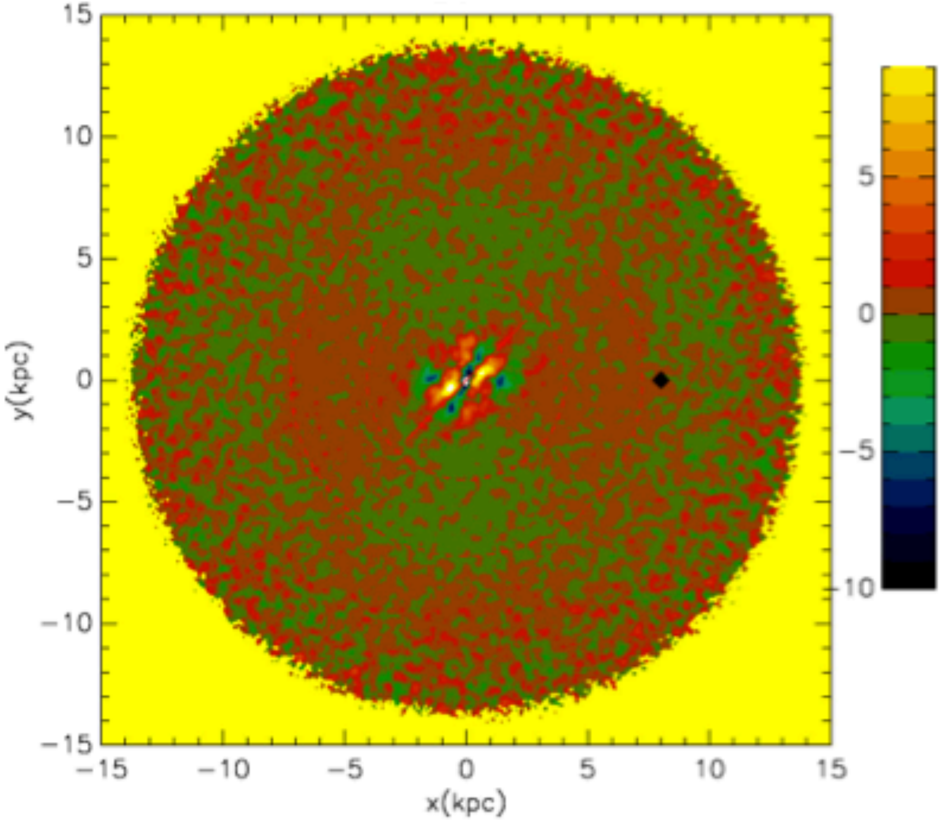
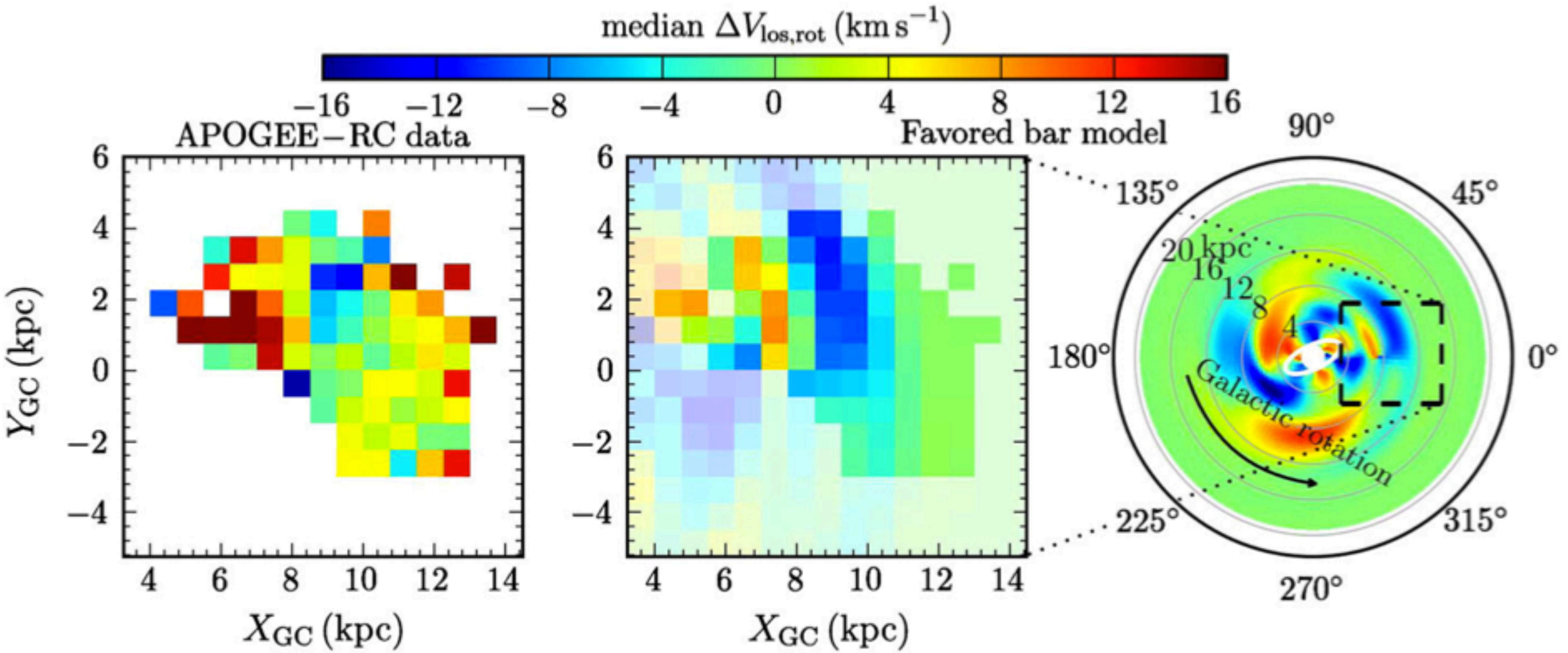


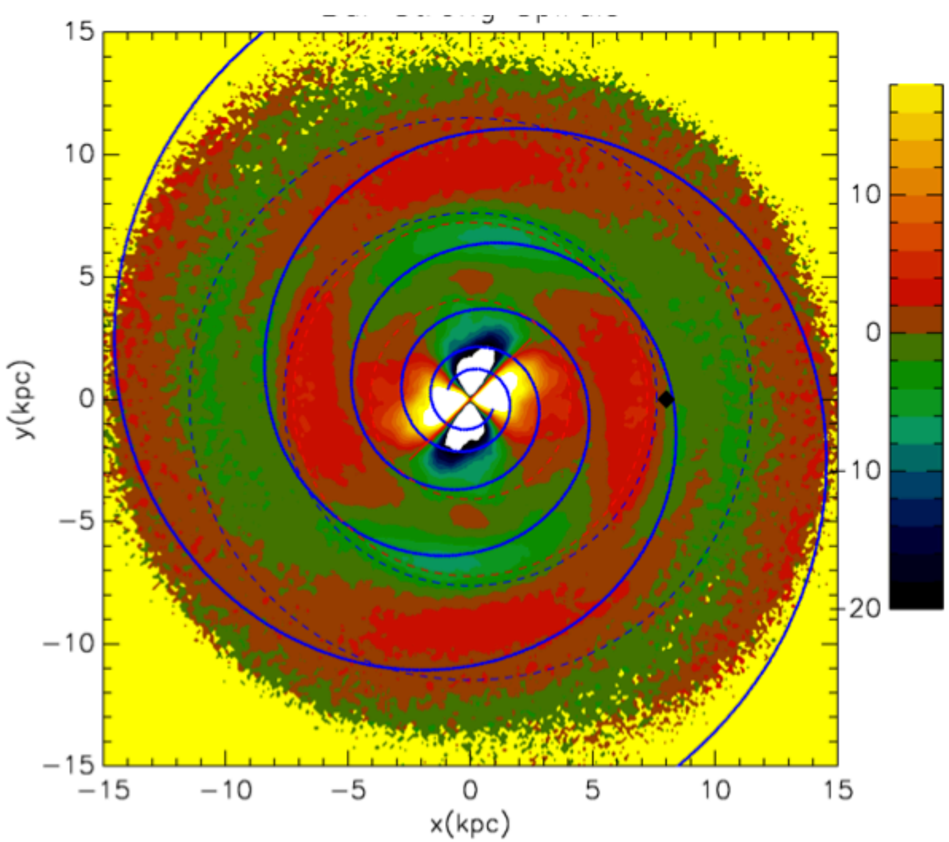
$\langle Vz\rangle_{z>0} - \langle Vz\rangle_{z<0}$

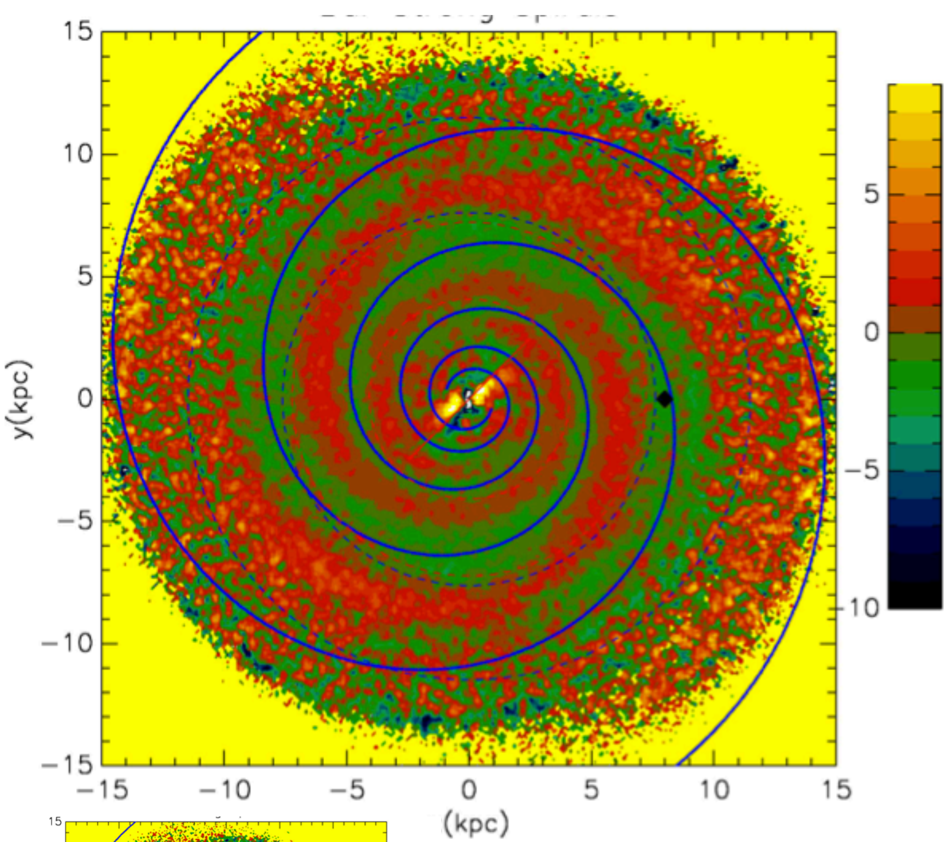
Signatures of non-axisymmetry in recent spectroscopic surveys

APOGEE (Bovy et al. 2015) finds (for ~8000 RC stars within 250 pc from plane) large-scale line-of-sight velocity fluctuations in the disk (associated with the **bar**)



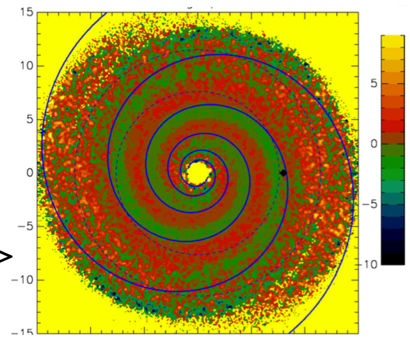
Work in progress: bar+spiral



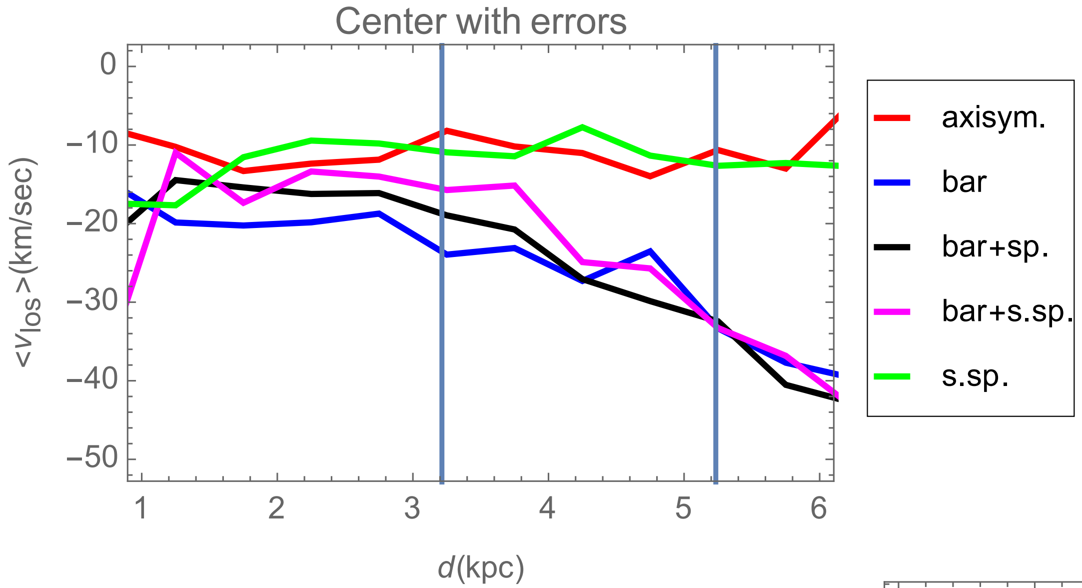


Monari, Famaey, Siebert in prep

Spiral-only =>



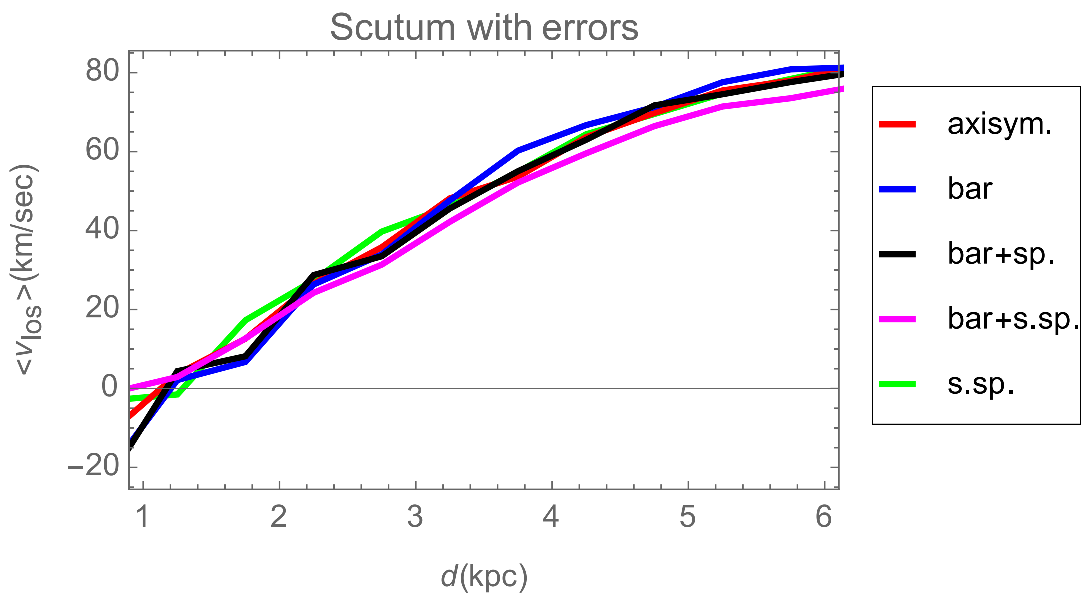
Examples of kinematic signatures



l=0°

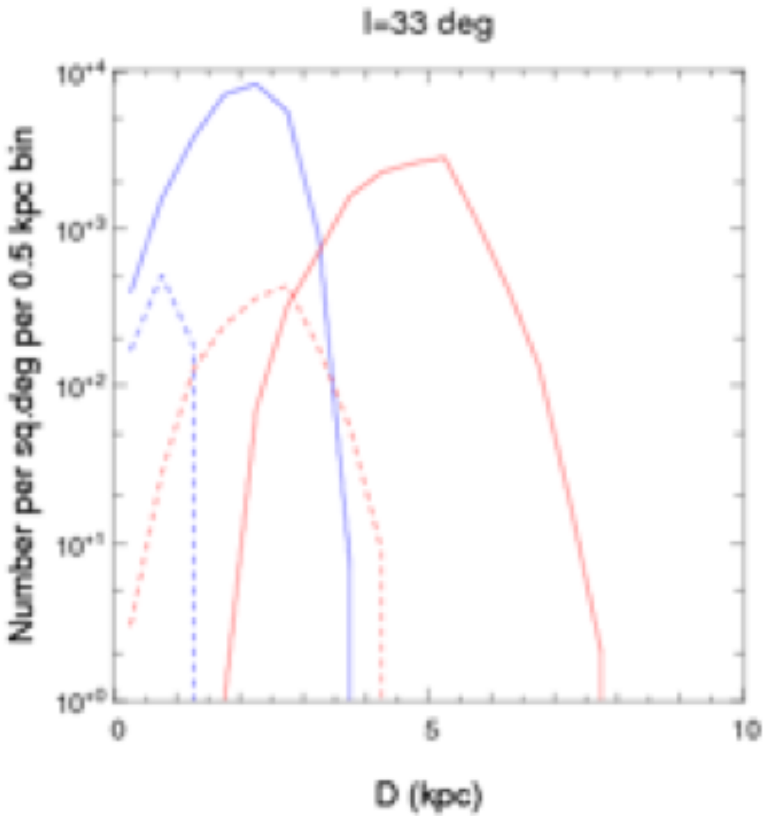
20% error on distances

l=30°



WEAVE LR strategy

A lot (100) l.o.s for total of several 10^6 stars



17<V<20
Blue: GKM dwarfs
Red: Giants

Gaia DR2 + gal plane phot surveys (e.g. IPHAS)

Conclusions

- Clear signatures of non-axisymmetries in recent spectroscopic surveys
- RAVE radial velocity gradient can be explained by either bar or spiral… but spiral needs to be quite strong
- Strong variations of vertical motions **cannot be induced by bar**, but breathing mode **qualitatively ok for spiral**
- APOGEE confirms main effect of **bar** on large scales
- Work in progress:**bar+spiral can enhance effect on vertical motions**
- Soon (work in progress): also compare **different spiral arms** simulations (with D. Kawata)
- **Velocities along ≠ lines of sight at large distances (WEAVE) can bring a lot of information even without very precise distances**
- Clear that one can **BIAS** axisymmetric fit if one neglects effects of non-axisymmetries… => NO A PRIORI & GET QUANTITATIVE!

Conclusions & perspectives II

- Try to **include the effects into MW modelling**… Include effects of spirals and bar in DF (by e.g. perturbation theory)

- Test axisym. assumption on non-axisym. simus to test robustness
- Effect on estimating MW parameters such as **local circular velocity** or **local DM density**…

- Ideally, ultimately fit all effects **simultaneously** without too many priors on axisymmetric background

- BUT ALSO disentangle from additional effects due to **non-equlibrium dynamics** from satellites (bending modes) => history of accretion, possibility of dark matter subhalos interacting with disk etc.