Disk non-axisymmetries and Galactoseismology

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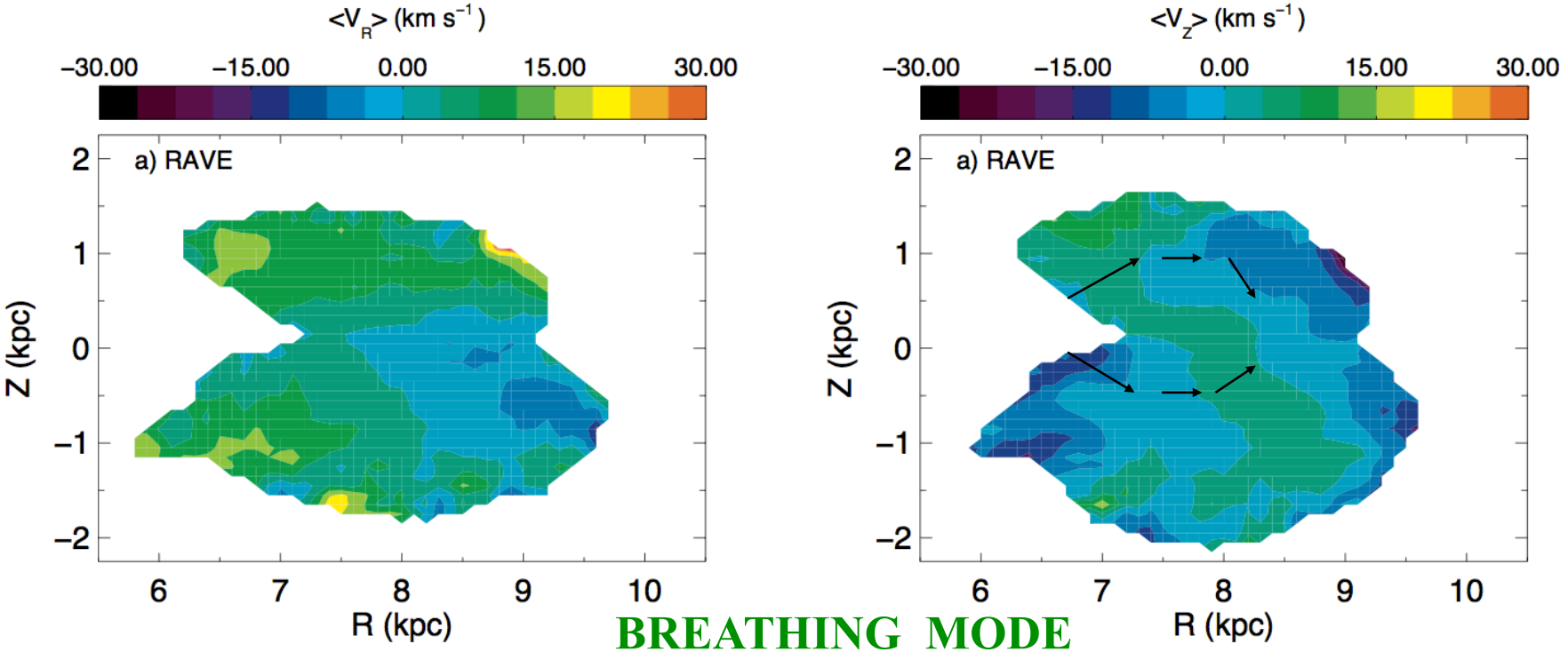
Work in collaboration with **G. Monari & A. Siebert**

Bulk vertical motions in recent spectroscopic surveys

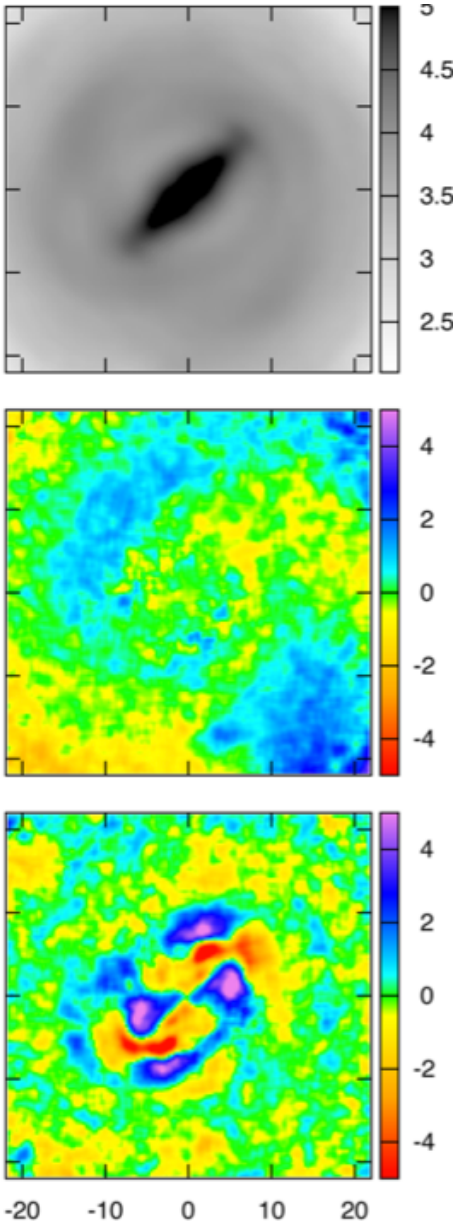
- **RAVE** (Siebert, Famaey, et al., 2011): gradient in the mean radial velocity of 4 km/s/kpc in extended solar neighbourhood with **RAVE** (~200 000 stars)

- And mean **vertical** motions are non-zero too (Williams et al. 2013 for **RAVE**, Widrow et al. 2012 for **SEGUE**, or Carlin et al. 2013 for **LAMOST**)



BREATHING MODE

Galactoseismology



Satellite-induced bar in Widrow et al. (2014):

- **Breathing mode** associated to the bar in inner disk, with **compression ahead of the bar** and **expansion behind the bar**

- **Bending mode** in outer disk

$$\Delta v_{z,\mathrm{bend}} \equiv \frac{1}{2}\left(\Delta v_z\,(x,\,h) + \Delta v_z\,(x,\,-h)\right)$$

and

$$\Delta v_{z,\mathrm{breathe}} \equiv \Delta v_z\,(x,\,h) - \Delta v_z\,(x,\,-h)\,.$$

Breathing modes from non-axisymmetries alone (bar/spiral)

Consider small-amplitude azimuthal Fourier modes for perturbing potential (bar or spiral), density wake, and horizontal bulk motions:

$Q=Q_0 + \varepsilon Q_1$ and $Q_1 = \mathrm{Re}\{Q^a \exp[i\, m(\Phi-\Omega_b t)]\}$

If h_R of $\Phi_1 > \max[u_{R1}, \sigma_R]/\kappa$ (valid for bar or cold stellar pop for spirals), linearized Jeans equations for $u_i = \langle v_i \rangle$ (Kuijken & Tremaine 1991)

$$\Rightarrow \quad u_R^a(R,z) = \frac{i}{\tilde{\Delta}}\left[m\left(\Omega_b - \tilde{\Omega}\right)\frac{\partial \Phi^a}{\partial R} - \frac{2m\tilde{\Omega}}{R}\Phi^a\right],$$

$$u_\phi^a(R,z) = -\frac{1}{\tilde{\Delta}}\left[2\tilde{B}\frac{\partial \Phi^a}{\partial R} + \frac{m\left(m\Omega_b - m\tilde{\Omega}\right)}{R}\Phi^a\right]$$

Breathing modes from non-axisymmetries alone (bar/spiral)

Monari, Famaey & Siebert (2015, arxiv:1505.07456):

Use the linearized continuity equation

$$\frac{\partial \rho_1}{\partial t} + \frac{1}{R}\frac{\partial \left(R\rho_0 u_{R,1}\right)}{\partial R} + \frac{\rho_0}{R}\frac{\partial u_{\phi,1}}{\partial \phi} + \frac{u_{\phi,0}}{R}\frac{\partial \rho_1}{\partial \phi} = -\frac{\partial \left(\rho_0 u_{z,1}\right)}{\partial z}$$

Take the same vertical variation of the background and perturbed density wake $\tilde{\rho} \equiv \rho_1 / \rho_0$ not depending on z:

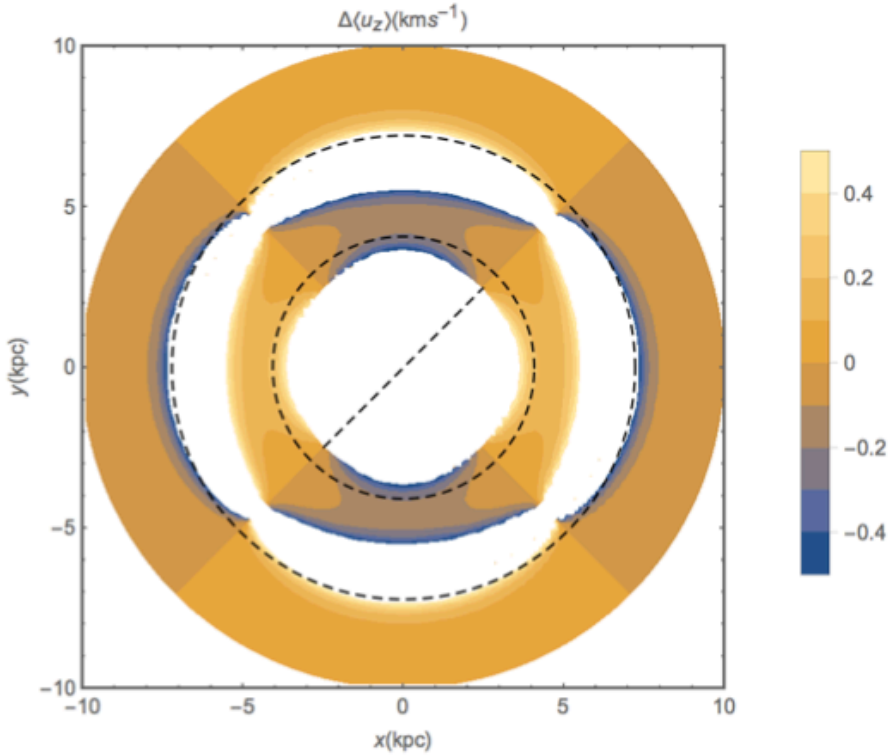
$$\Rightarrow \quad \boxed{u_z(z) = \epsilon\ \mathrm{sgn}(z) h_z \left[\mathcal{G}(0)\left(1 - \mathrm{e}^{|z|/h_z}\right) + \frac{\partial^2 \mathcal{G}}{\partial z^2}(0)\left(\frac{z^2}{2} + h|z| + h^2 - \mathrm{e}^{|z|/h_z} h^2\right)\right]} \quad \text{for exponential disk}$$

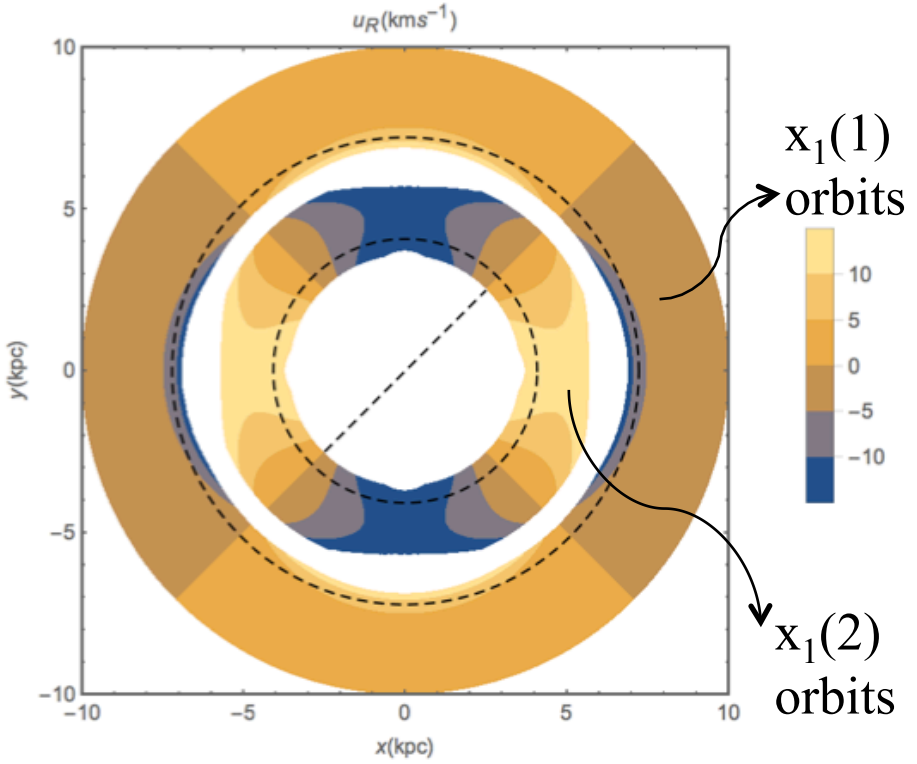
$$\text{with} \quad \mathcal{G}\left(R, \phi, z, t\right) \equiv \frac{\partial \tilde{\rho}}{\partial t} + \frac{u_{\phi,0}}{R}\frac{\partial \tilde{\rho}}{\partial \phi} - \frac{u_{R,1}}{h_R} + \frac{\partial u_{R,1}}{\partial R} + \frac{1}{R}\frac{\partial u_{\phi,1}}{\partial \phi}$$

Analytical predictions for bar

$$\Phi^{\rm a}(R,z) = \frac{V_0^2}{3}\left(\frac{R_0}{R_{\rm b}}\right)^3 \frac{R^2}{r^2}\mathcal{U}(r), \quad \text{with } \mathcal{U}(r) = \begin{cases} -(r/R_{\rm b})^{-3} & \text{for } r \geqslant R_{\rm b} \\ (r/R_{\rm b})^3 - 2 & \text{for } r < R_{\rm b} \end{cases}$$

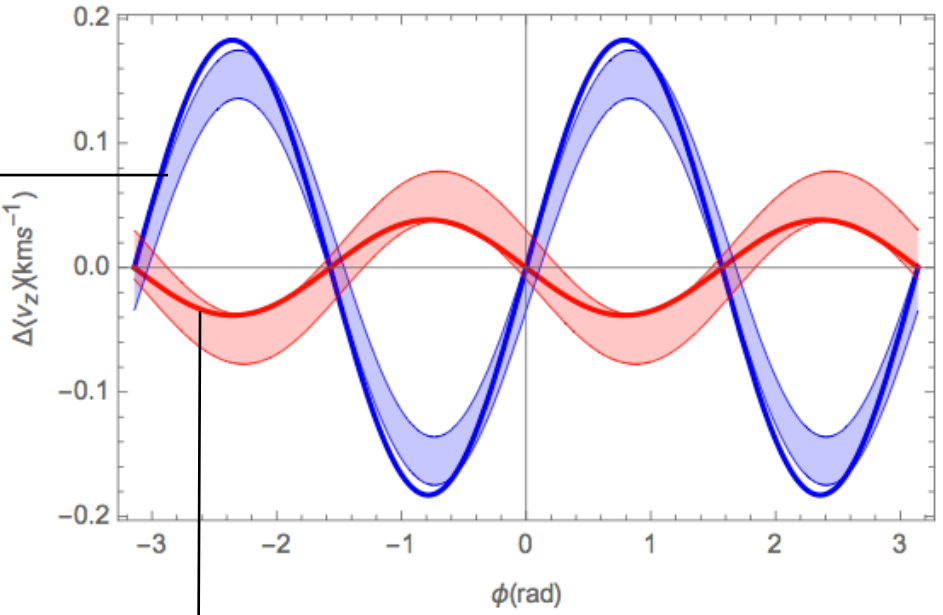
ε=1% & m=2 in $\Phi_1(R,\phi,z,t) = \mathrm{Re}\{\Phi^{\rm a}(R,z)\exp[im(\phi-\Omega_{\rm b}t)]\}$



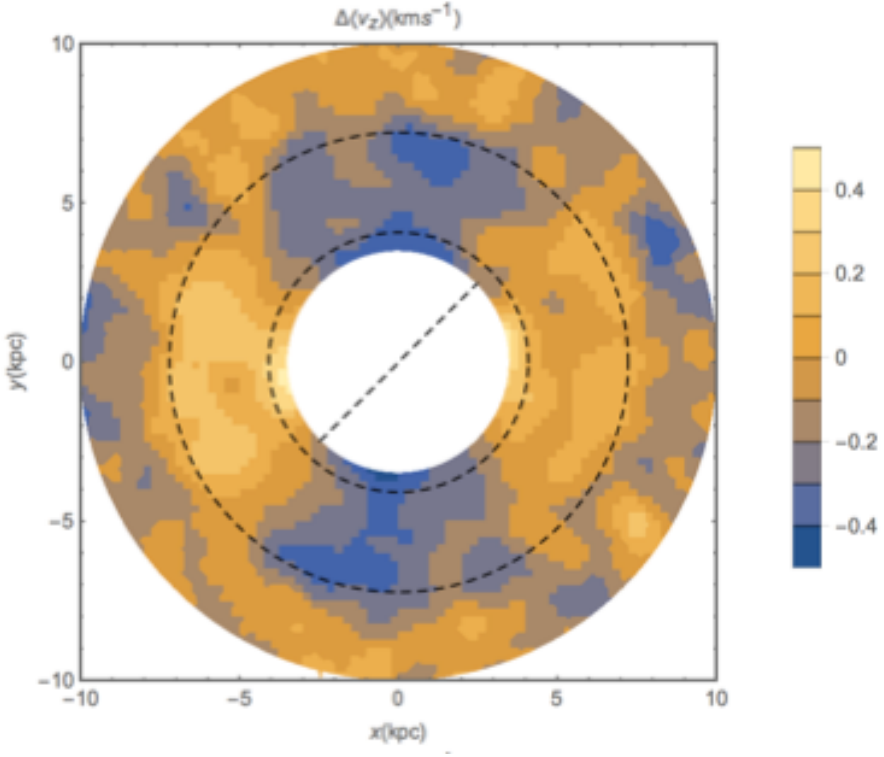


Comparing with test particles

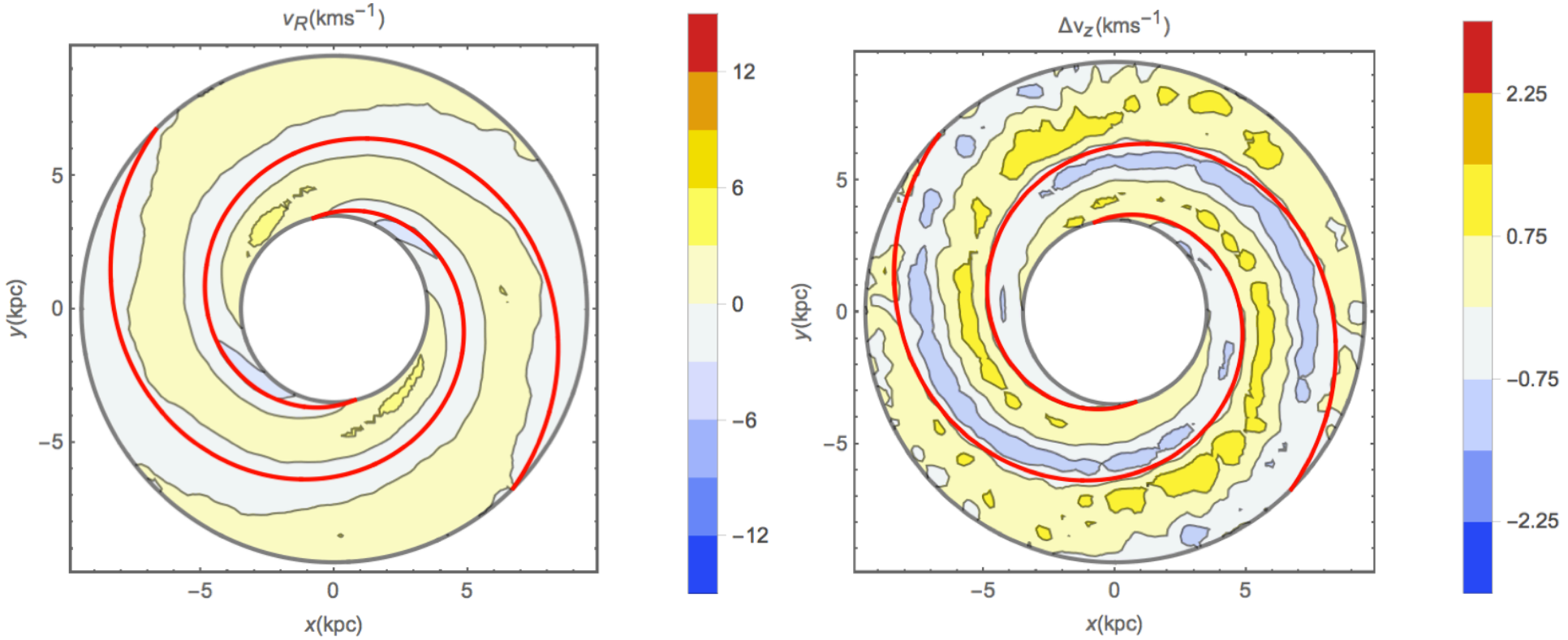
R=5 kpc



R=8.5 kpc



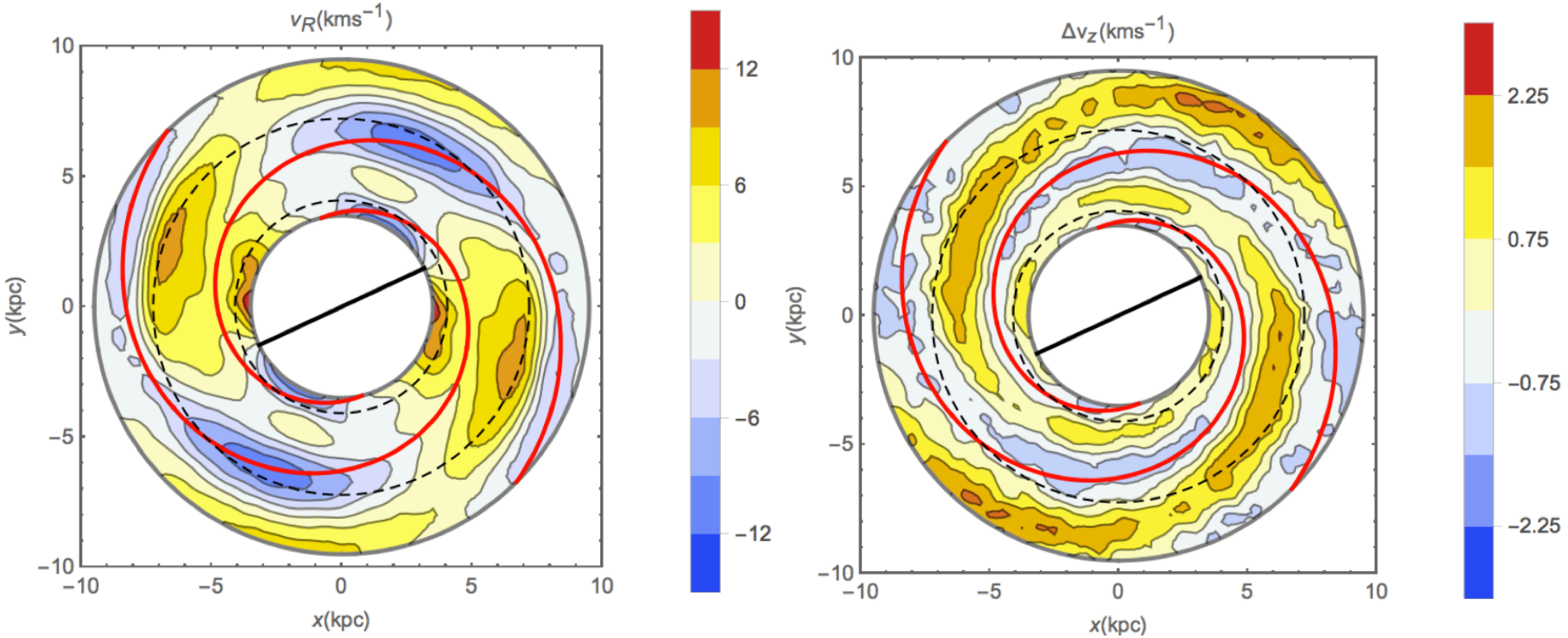
Effect of spirals on bulk motions



<VR>

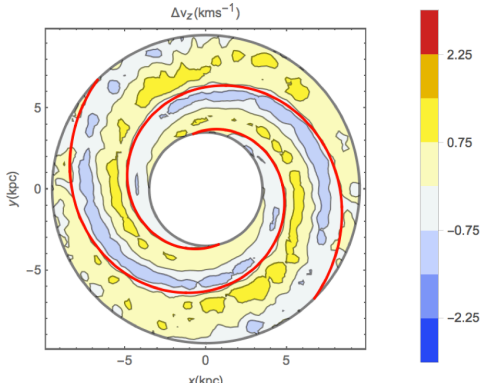
$\Delta Vz = \langle Vz \rangle_{z>0} - \langle Vz \rangle_{z<0}$

Work in progress: bar+spiral



Monari, Famaey, Siebert, Grand,
Kawata et al., in prep

Spiral-only =>



Conclusions & perspectives

- Bar and spirals have effects on **both horizontal and vertical motions (breathing mode)**: phase-shift depending on the form of the perturbing potential (+ non-linear effects in combination)

- Main effect on large-scale radial motions: bar (see Rob Grand's talk)
- Main effect on vertical motions in the inner disk (breathing mode): bar+spiral. Bar well-constrained from large-scale radial motions

⇒ learn about spirals

- Spirals can be partly satellite-induced

⇒ Breathing mode in inner disk, but bending mode in outer disk

=> With upcoming surveys, disentangle effects from the bar (inner Galaxy radial motions), spirals (inner Galaxy breathing modes) and satellites or DM subhalos crossing disk (outer Galaxy bending modes)