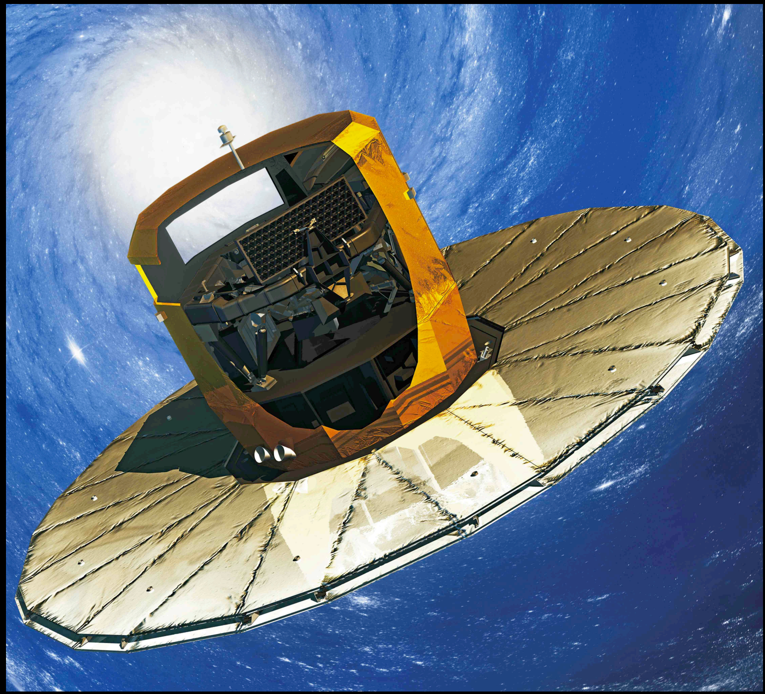
Gaia and the dynamics of the Galaxy



Benoit Famaey

(CNRS, Observatoire Astronomique de Strasbourg)

Gaia's main objective

- **Precise mass model of the Galaxy** and of each of its components (stellar populations, gas, dark matter)

- **Related questions about the Galaxy:**
  - Is Galaxy's structure in accordance with current **cosmological model**? How does the MW compare to other spirals?
  - Respective roles of **hierarchical formation** and **secular evolution** in shaping the Galaxy? How did the **different components** (halo, thick disk…) come into being?

Gaia's abilities

- Census of about 10^9 stars
- Parallax precision of 10% out to:
  - 7 kpc for RCGs in the disk
- Proper motion precision of about 0.05 mas/yr at 5 kpc for RCGs in the disk (<~1km/s)
- Will need ground-based RVs for V>16 (WEAVE, 4MOST,…)

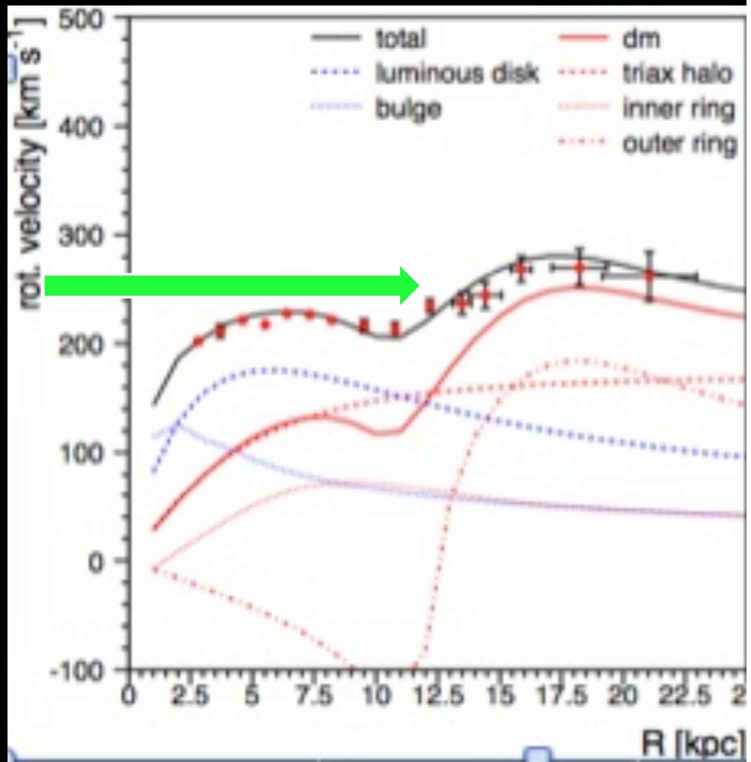
The « ideal » objective

- Choose potential, search for integrals of the motion as polynomial finite series of (x,v) for families of orbits (Bienaymé), or find closest integrable Hamiltonian (Binney), build distribution function, adjust potential by iterations…

- **Problem:** all this works better for disk orbits (low energies) than halo orbits. Also typically needs axisymmetry and equilibrium. Multiple time-dependent disk non-axisymmetric perturbations could be a killer (NO integrals of the motion: all orbits chaotic to some degree)

« Simpler » approach to mass modelling: 1. Rotation Curve

At $R<R_0$: $V_c(R_0 \sin l) = V_{rmax} + V_c(R_0) \sin l$
BUT at $R>R_0$: one measures $\Omega(R)$-$\Omega(R_0)$
and one needs the distance of tracers
(cepheids P-L relation up to now) → Bump?

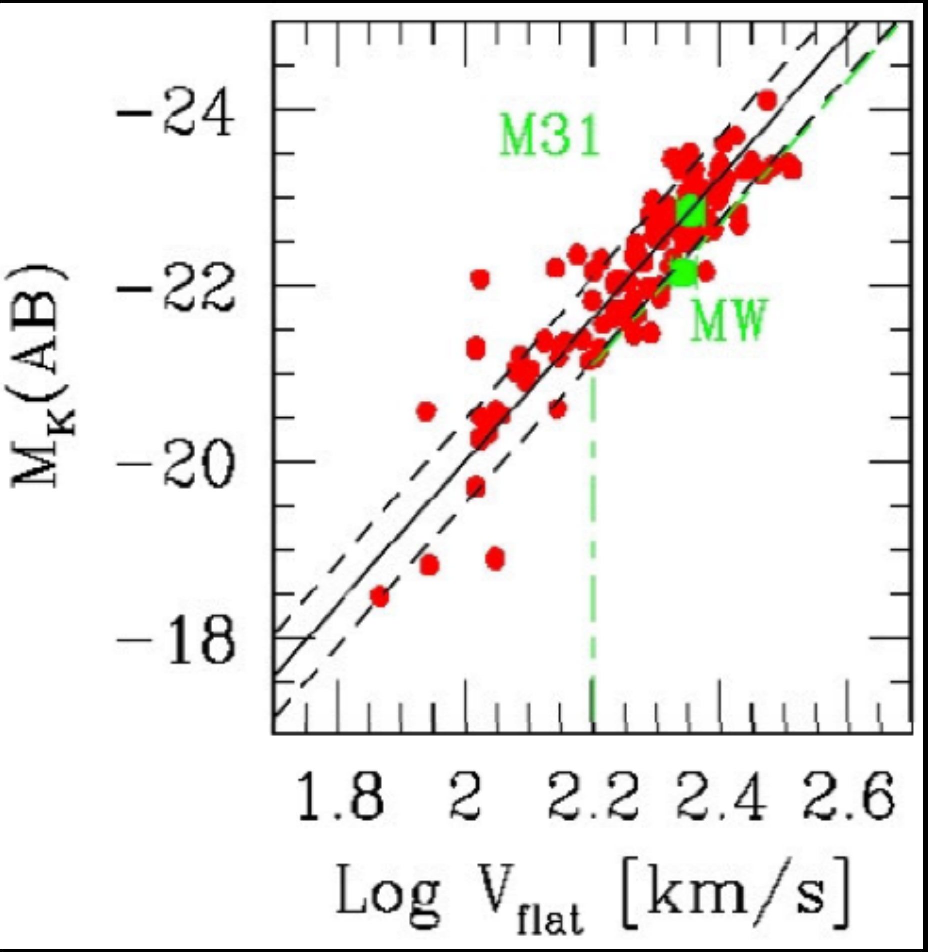


Binney & Dehnen (1997): data compatible with a *gently declining RC* if overdensity of TRACERS

Gaia distances will settle the debate:
But beware of the asymmetric drift: $V_c = \langle V_\phi \rangle + V_a$

$$v_a \simeq \frac{\overline{v_R^2}}{2v_c}\left[\frac{\sigma_\phi^2}{\overline{v_R^2}} - 1 - \frac{\partial \ln(\nu \overline{v_R^2})}{\partial \ln R} - \frac{R}{\overline{v_R^2}}\frac{\partial(\overline{v_R v_z})}{\partial z}\right]$$

DM halo fit(s)



Offset from the Tully-Fisher relation?

Hammer et al. 2007
Laurent Chemin

2. Vertical equilibrium

$$-4\pi G\Sigma(Z) = \int_{-Z}^{Z} \frac{1}{R}\frac{\partial}{\partial R}(RF_R)dz + 2\cdot[F_z(Z) - F_z(0)],$$

Poisson eq.

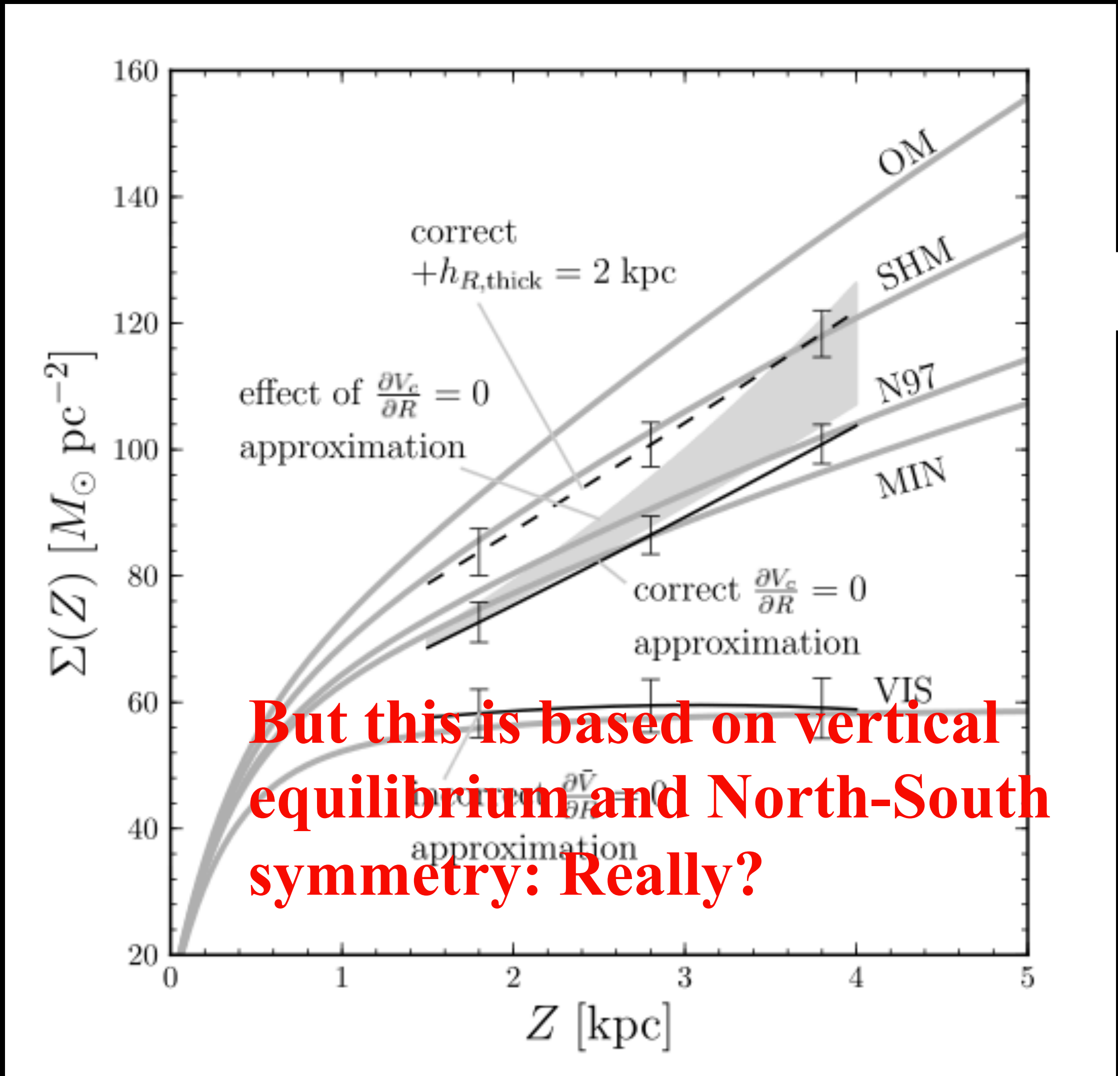
$$F_R = -\frac{\partial\phi}{\partial R} = \frac{1}{\rho}\frac{\partial(\rho\overline{U^2})}{\partial R} + \frac{1}{\rho}\frac{\partial(\rho\overline{UW})}{\partial Z} + \frac{\overline{U^2}-\overline{V^2}}{R} + \frac{1}{\rho}\frac{\partial(\rho\overline{U})}{\partial t},$$

$$F_Z = -\frac{\partial\phi}{\partial Z} = \frac{1}{\rho}\left[\frac{\partial(\rho\overline{W^2})}{\partial Z} + \frac{\rho\overline{UW}}{R} + \frac{\partial(\rho\overline{UW})}{\partial R} + \frac{\partial(\rho\overline{W})}{\partial t}\right],$$

Jeans eqs.

$$\langle V^2\rangle = \sigma^2_V + \langle V\rangle^2$$

Beware of the asymmetric drift: as $\langle V^2_R\rangle(R)$ not constant, V_c =cst does not mean $\langle V_\phi\rangle$ = cst !
(Bovy & Tremaine 2012)



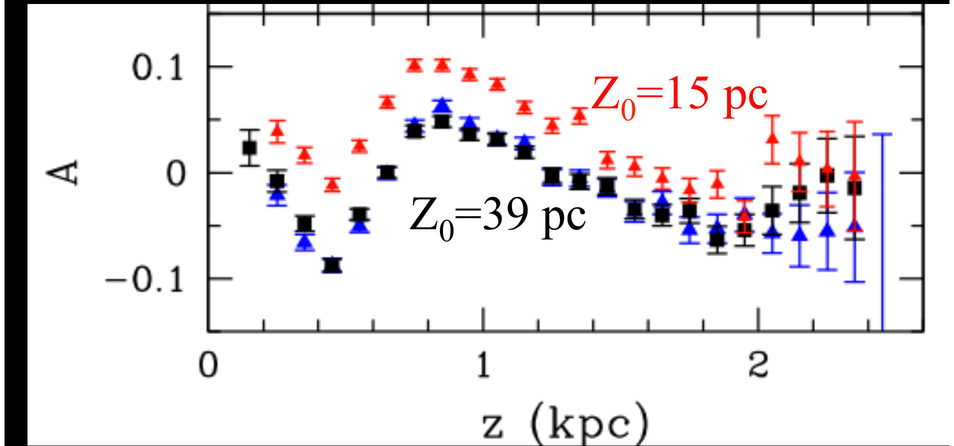
Bovy & Tremaine 2012

DM halo fits
(vertical structure)

Same as a function of *R* with Gaia data
=> dynamical scale length, existence of a dark disk? …

SDSS: Widraw et al. (2012)

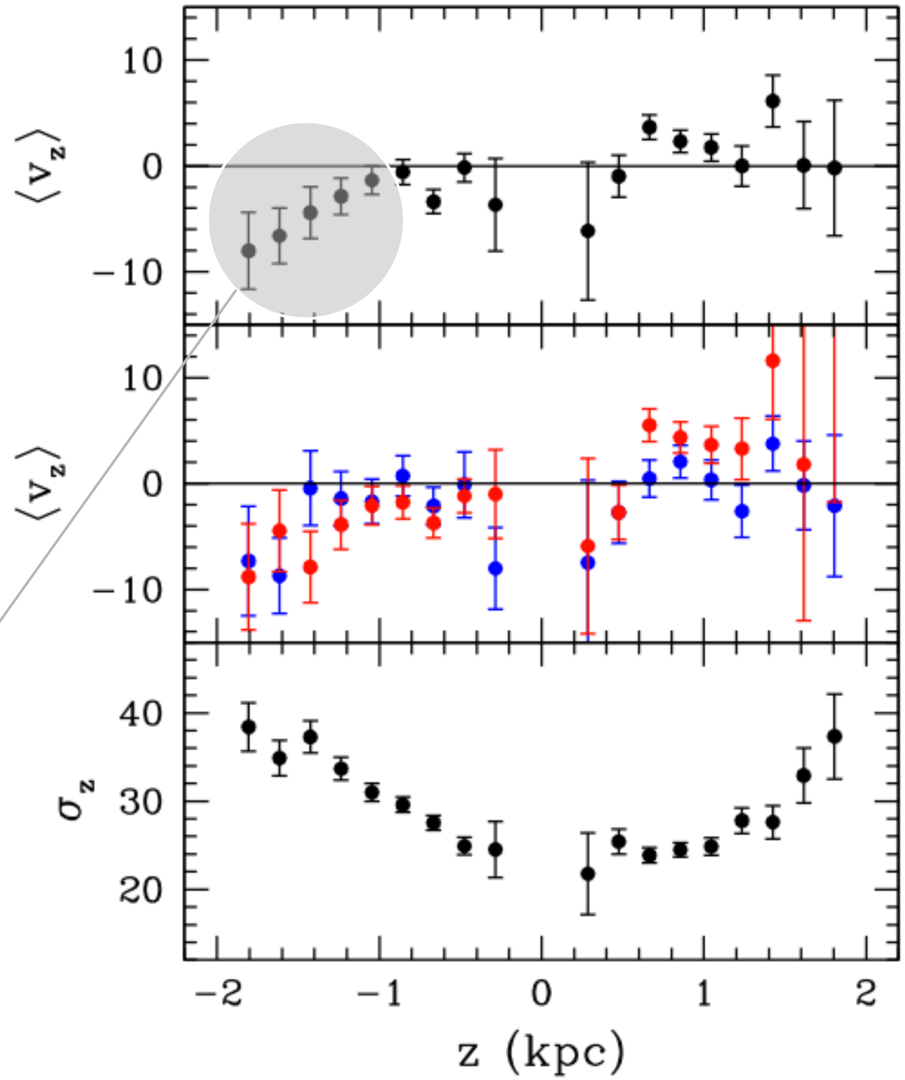
300 000 stars



1 kpc-wide « cylinder »

A(z) = [n(z)-n(-z)]/n(|z|)

Bulk vertical motion of 10 km/s out from the plane !



SEGUE : 11 000 stars

Vertical perturbation excited by the passage of a satellite galaxy

=> vertical waves (linearized Boltzmann and Poisson eqs.)

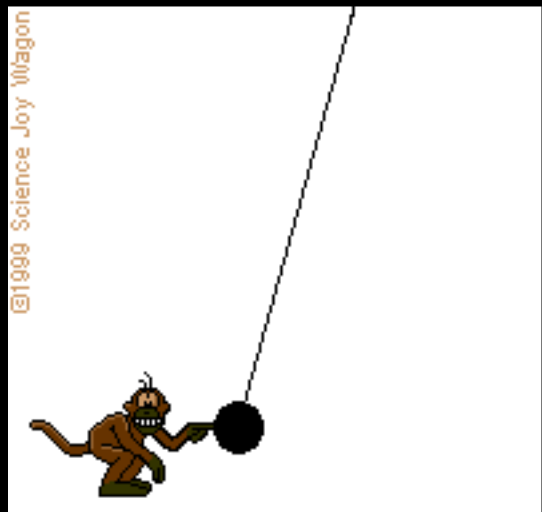
OR self-excited vertical instabilities due to spiral arms

=> More direct modelling might be needed concerning the density above and below the plane:

Compute high-resolution simulations with bars and spirals (+satellite bombardment?),compare directly to vertical velocity field structure

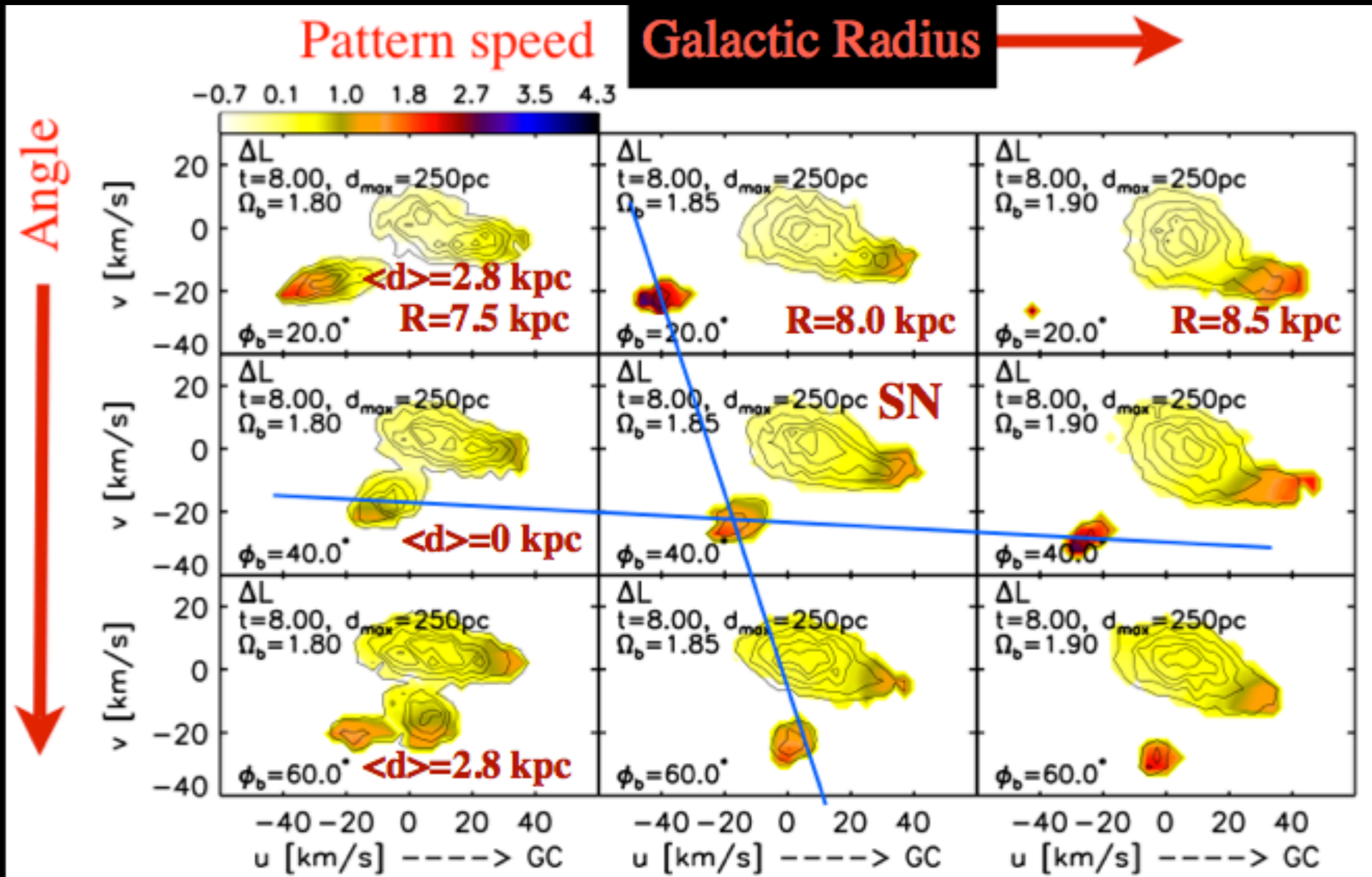
3. Non-axisymmetric features

- Obvious non-axisymmetric components of the Galactic potential: the bar and the spiral arms
- For each perturber, resonances occur between the rotation frequency $\Omega - \Omega_p$ in the frame of the perturber and the epicyclic frequency κ, meaning that stars are « hit » regularly with the same position w.r.t. the perturber



$\Omega(R) - \Omega_p = +- \kappa(R)/m$

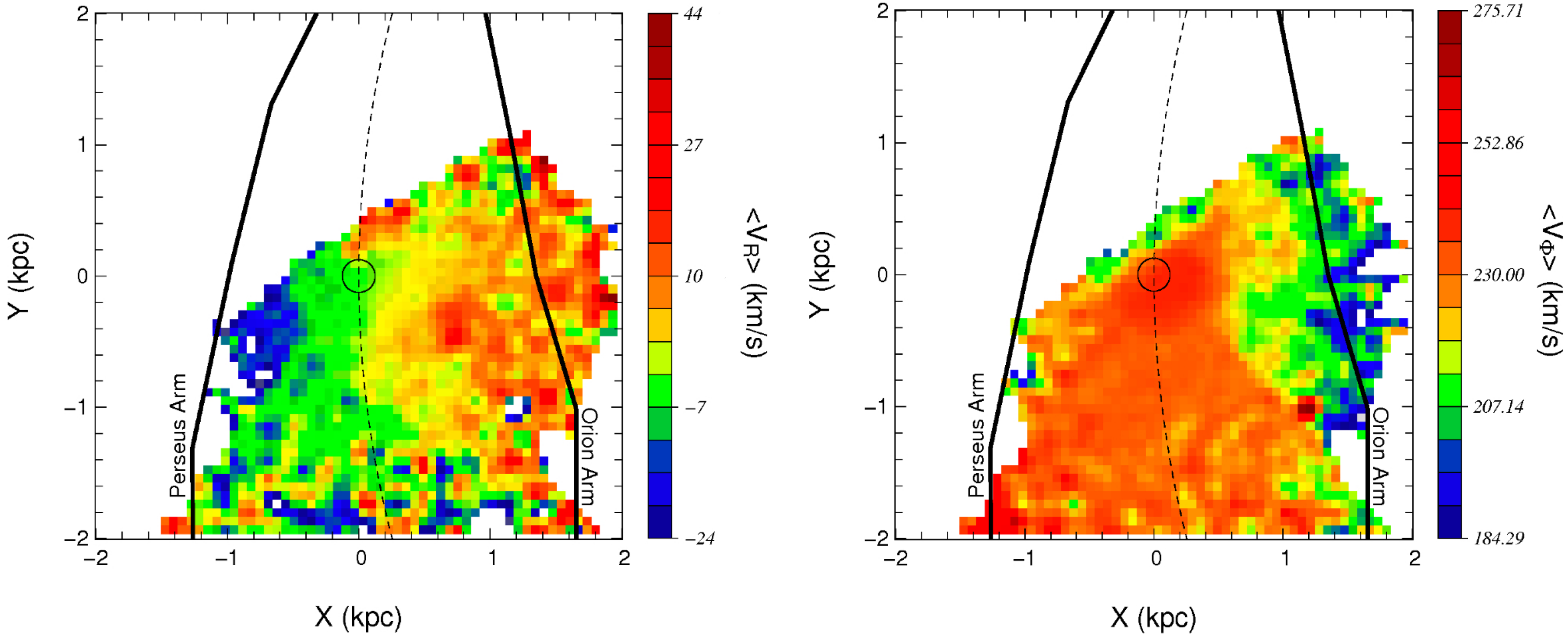
<=> m:1 resonance



Effect of the bar (Minchev et al. 2010)

RAVE survey: Hercules stream moves to smaller |V| (less lag) for smaller R (Antoja et al. 2012) => consistent with OLR of the bar

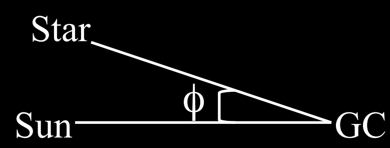
200 000 stars from RAVE:
mean radial velocity gradient (Siebert et al. 2011, 2012)



Assume R_0= 7.8 kpc, v_{c0}= V_{LSR}= 247 km/s, U_{LSR}= 0 km/s

$(U,V,W)_0$ = (11,12,7) km/s (Schoenrich et al.)

$$\begin{cases} V_R = (V + V_0 + V_{LSR}) \sin\phi - (U + U_0 + U_{LSR}) \cos\phi \\ V_\phi = (V + V_0 + V_{LSR}) \cos\phi + (U + U_0 + U_{LSR}) \sin\phi \end{cases}$$



In reality, multiple spiral arms + bar: resonance overlap

Resonance overlap => chaos

(e.g. Chirikov 1960; Walker & Ford 1969; Quillen 2003)

Chaos => migration

Signature with Gaia?

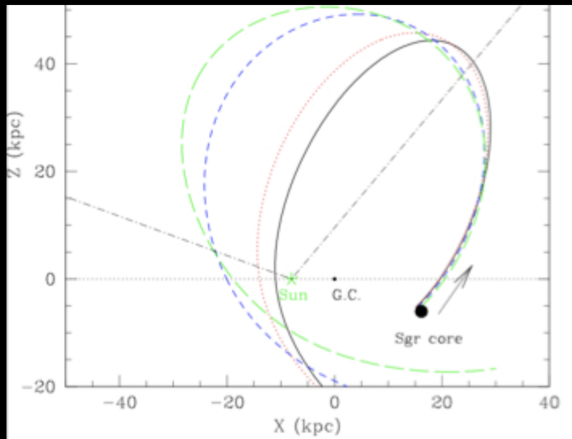
- Extended disk profile and high or low σ_R

- Flattening of $<J_z> \sim <E_z/\nu>$ profile with age

(Minchev et al. 2012ab)

4. Stellar halo dynamics

- Jeans equations (or integrations thereof) for bright stars in the outer halo: beware of tracer density and cutoff + anisotropy
- Streams orbits: quantify how much deviation between stream and orbit, and find likelihood for millions of possible orbits (MCMC, Ibata et al.) Repeat this for multiple streams

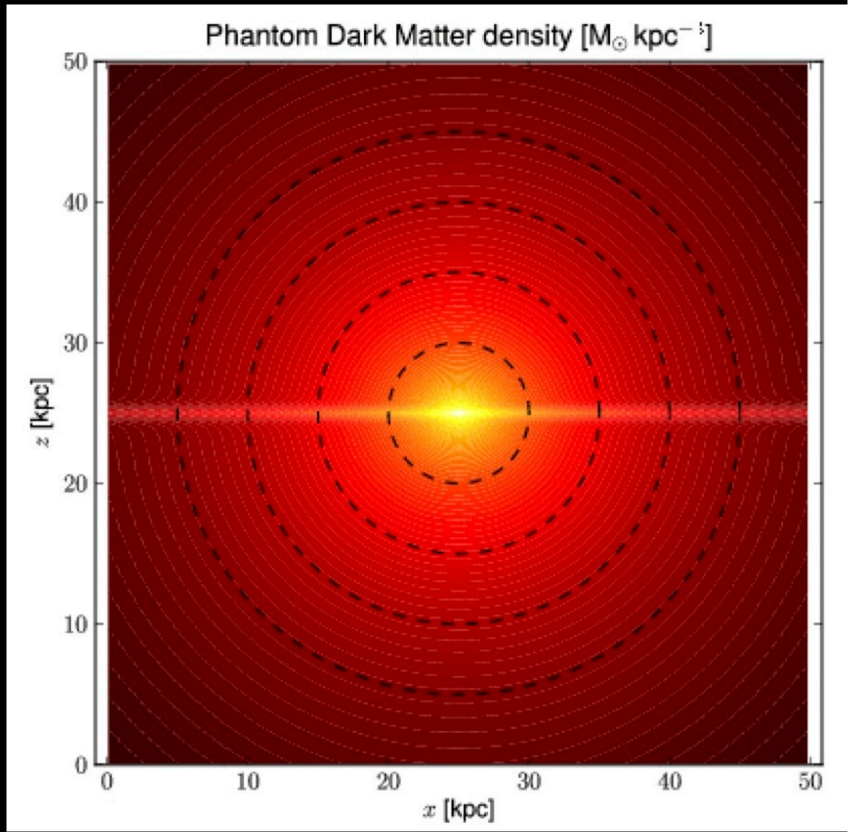


-> constraints on mass model and shape of halo

-> compare predicted rotation curve with independently measured one!

5. Testing gravity

- Modified gravity working well at galaxy scales: MOND
- Only the relation between potential and matter source altered, so one can constrain the potential in the usual way
- Crucially depends on our knowledge of the baryonic distribution
- Depends on the exact choice for the transition between Newton and MOND
- Then, the theory makes a unique and falsifiable prediction for the galactic potential



Conclusion

- Ultimate goal is to have a precise mass model for the Galaxy
- Various techniques:
  - Global ones based on equilibrium distribution functions, but beware of chaos in the disk
  - More mundane ones including:

  1) rotation curve, 2) Jeans analysis of vertical equilibrium,

  3) constraining non-axisymmetric features (bar and spirals), effects on radial migration,

  4) stellar halo dynamics (Jeans and streams)
- Ultimately confront the mass model with models of Galaxy formation in a cosmological context