Modelling the Milky Way in the Gaia era

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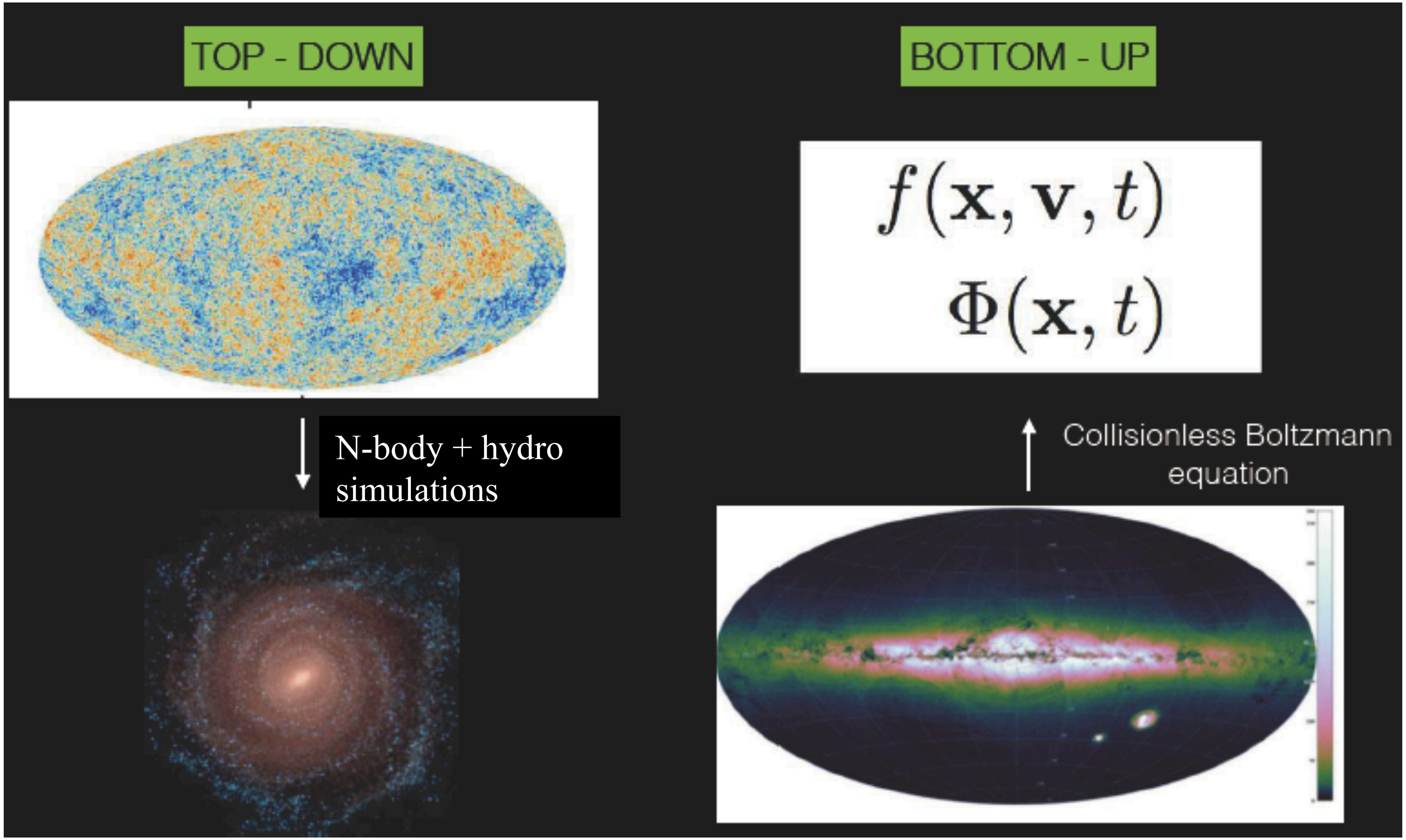
MW dynamics main questions

- Decipher the structure of the Galaxy, and of each of its components (stellar pops, gas), including its **dark matter** distribution, **in configuration space and phase-space** (total mass? core vs. cusp? , …)

- Understand the various steps in the Galaxy formation process, understand **internal** secular processes (e.g., effect of spiral arms, bar) and **external** environmental ones (e.g., interactions with satellites)

- What are the exact roles of spirals (+ today's number of arms, pitch angle, pattern speed?) and the bar (length, pattern speed?) in the secular evolution (radial migration), how did they evolve? ...

MW dynamical models



Jeans theorem

- If integrable system: $df_0/dt = 0 \Leftrightarrow f_0(I_1,I_2,I_3)$

- Natural phase-space coordinates for regular orbits in (quasi)-integrable systems: **actions J and angles θ** = phase-space canonical coordinates such that H=H(**J**)
  => f_0 (**J**) with **J** adiabatic invariants

- **A triplet of actions defines a regular orbit, angles tell us where the star is along that orbit**
- Phase-space is filled by orbital tori
  => use AGAMA (Vasiliev 2019)

ACTIONFINDER

- Deep learning algorithm (Ibata et al. 2021) designed to transform a **sample of phase-space measurements along orbits** in an (**unknown**) static potential into action and angle coordinates, using the fact that stars along a same orbit have the same actions

- Start from "toy" potential (isochrone) with known actions and search for canonical transform:

$$G = G(\boldsymbol{\theta}, \boldsymbol{J}') \quad \Rightarrow \quad \begin{aligned} \boldsymbol{J} &= \boldsymbol{J}' + \frac{\partial G}{\partial \boldsymbol{\theta}} \\ \boldsymbol{\theta}' &= \boldsymbol{\theta} + \frac{\partial G}{\partial \boldsymbol{J}'} \, . \end{aligned}$$

The neural network then **searches for G**, minimizing a loss function (basically the spread in actions along each orbit)

ACTIONFINDER

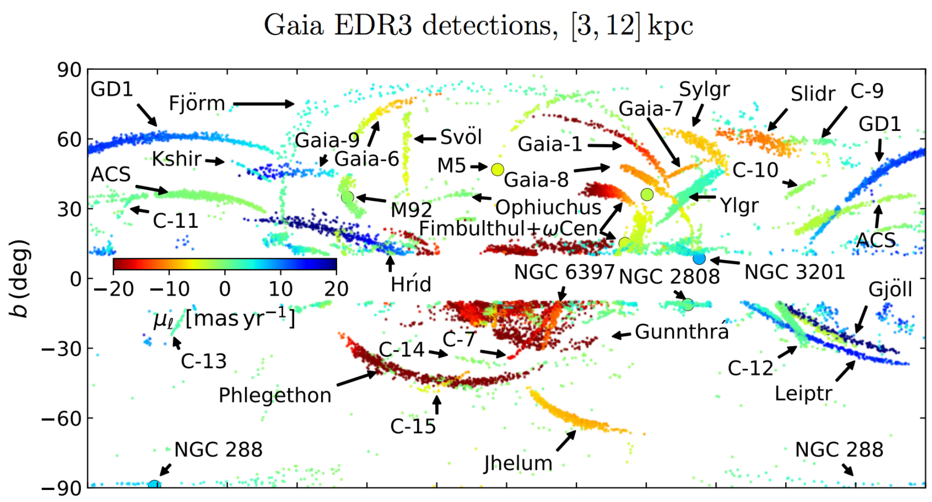
- With 8 points per orbit and 128 orbits (hence 1024 phase-space points), recovers the actions and angles from the Torus machinery of Binney & McMillan with 0.6% precision

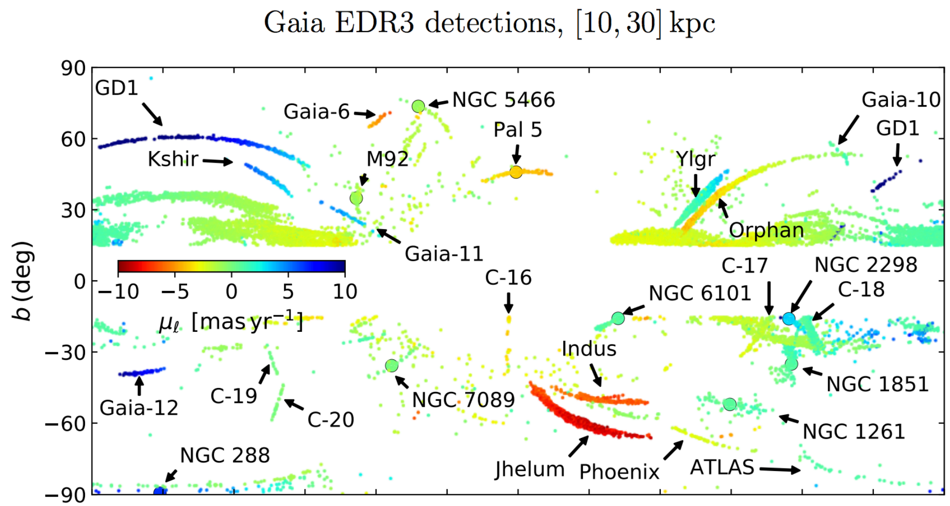
- But most importantly**: recovers the (unknown) Hamiltonian and therefore Galactic potential**

Stellar streams *nearly* trace orbits

Streams (Ibata et al., Gaia EDR3):
32 streams in Gaia DR2, 7 new ones without an obvious progenitor in EDR3

Find single stellar pops. and integrate streams orbits in a tube by exploring all distances and radial vel. until sream candidate found (STREAMFINDER)





15 with a globular cluster progenitor

(good distance, SSP template, and GC on the actual orbit)

Modelling the MW disc

Adjust comination of parametric DFs:

$$f_0(J_R, J_\phi, J_z) = \frac{\Omega(R_g(J_\phi))}{(2\pi)^{3/2} 2\kappa(R_g(J_\phi))} \frac{\tilde{\Sigma}(R_g(J_\phi))}{\tilde{\sigma}_r^2(R_g(J_\phi))\tilde{\sigma}_z^2(R_g(J_\phi)) z_0} \times e^{-\frac{J_R \kappa}{\tilde{\sigma}_r^2} - \frac{J_z \nu}{\tilde{\sigma}_z^2}}$$

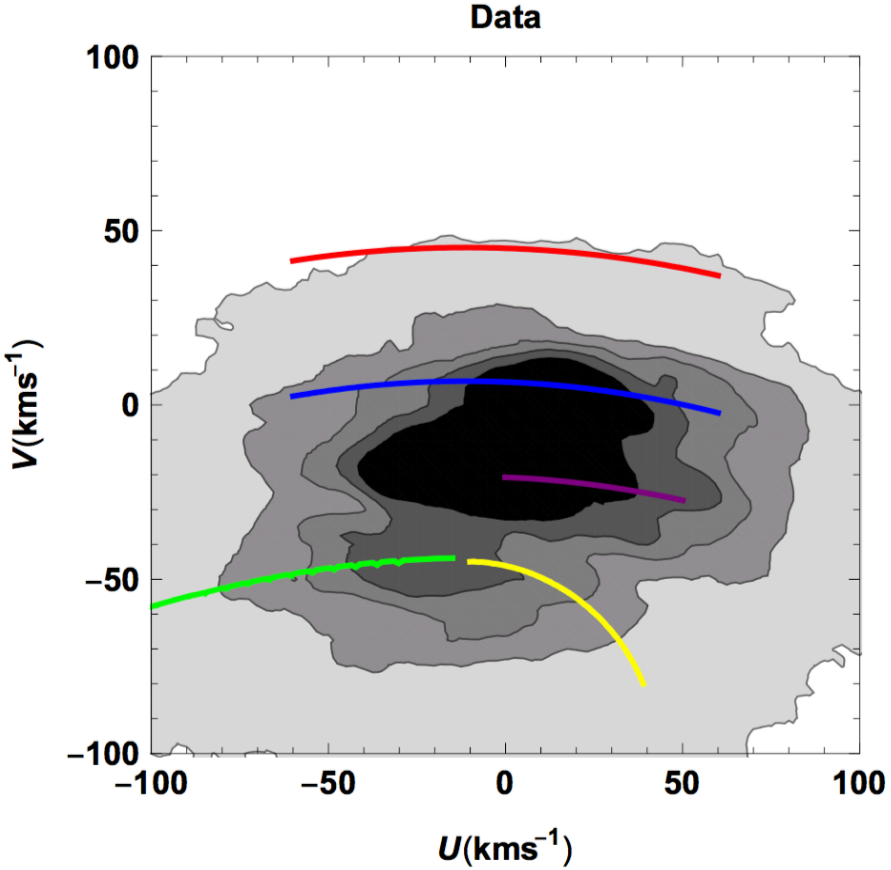
radial distribution in $R_g(J_\phi)$

velocity ellipsoid together with the velocity disp.dependence in previous factor

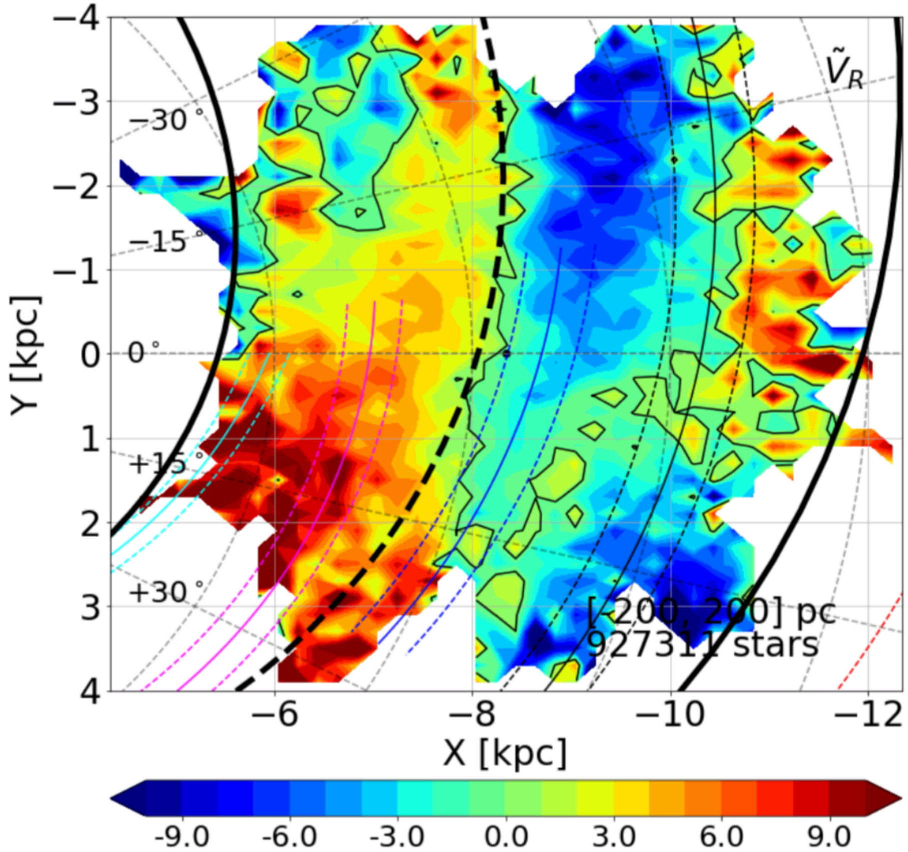
Even better: **non-parametric DF:** adjust with neural nets

But not so « simple »: the disc is perturbed by both internal non-axisymmetries and external perturbations!

Modelling the MW disc

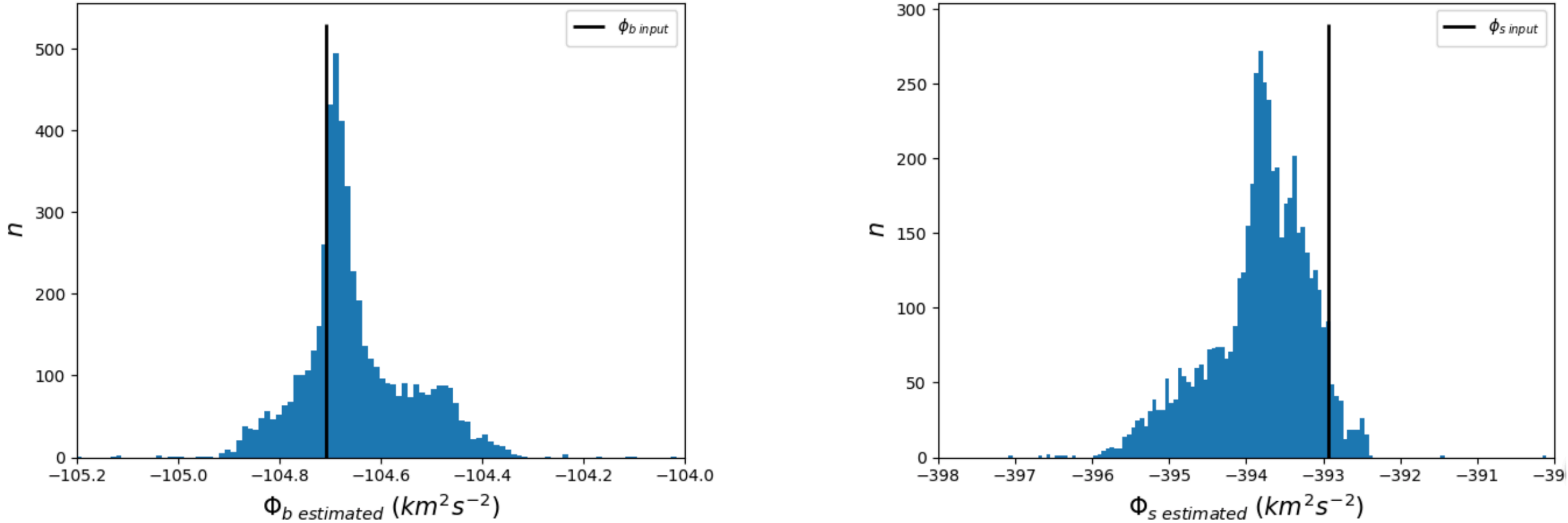


Local velocity space



Galactocentric radial velocity map

Expressing the bar potential in actions and angles



$$\Phi_1(R,\varphi,z) = \mathrm{Re}\left\{\sum_{j,l} \phi_{jml}(J_R, J_z, J_\varphi)\mathrm{e}^{\mathrm{i}(j\theta_R + m\theta_\varphi + l\theta_z)}\right\}$$

Al Kazwini et al. (2021)

Linearized CBE

$$\frac{\mathrm{d}f_1}{\mathrm{d}t} = \frac{\partial f_0}{\partial \mathbf{J}} \cdot \frac{\partial \Phi_1}{\partial \boldsymbol{\theta}}$$

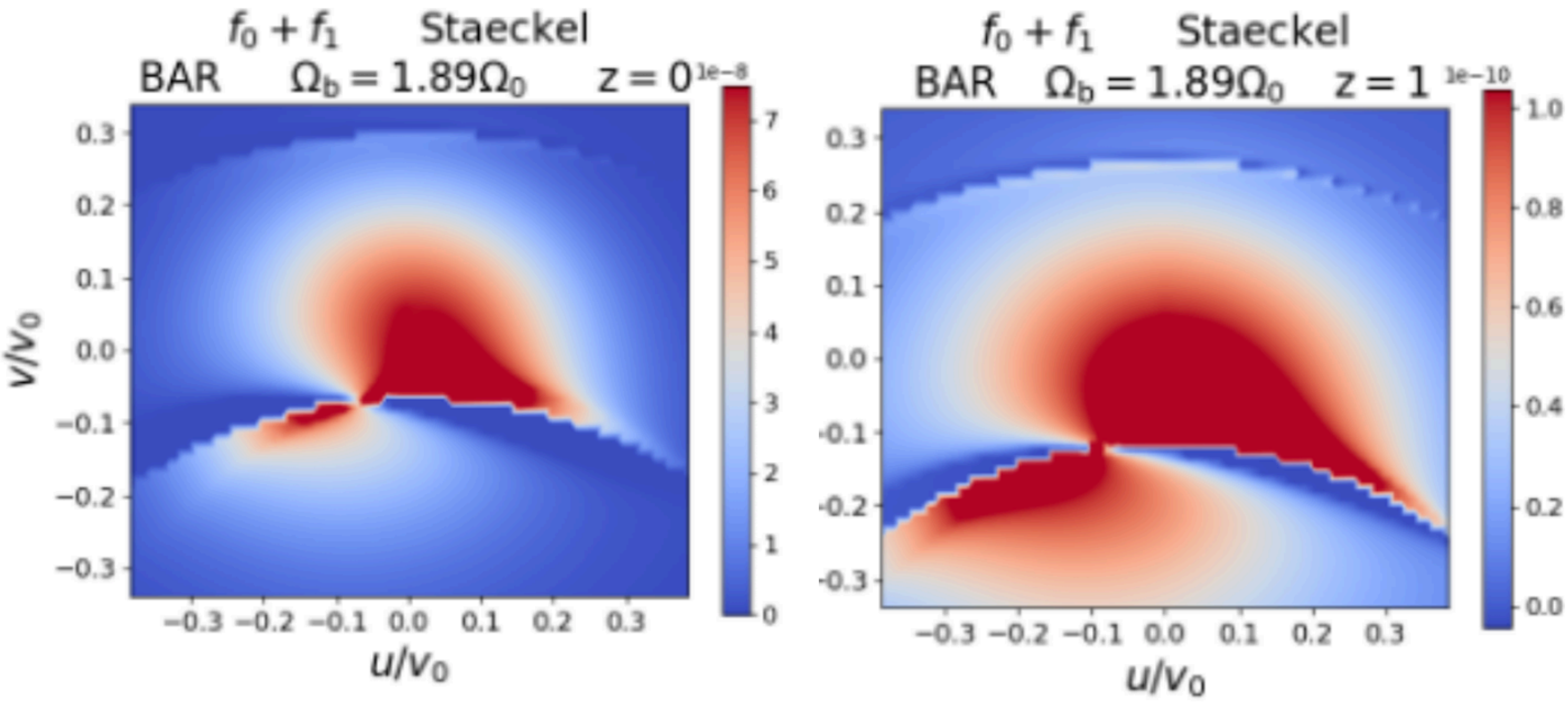
Integrate from zero amplitude bar to plateau of constant amplitude:

$$f_1(\boldsymbol{J}, \boldsymbol{\theta}, t) = \mathrm{Re}\left\{ \sum_{j,l=-n}^{n} f_{jml}\, \mathrm{e}^{\mathrm{i}[\, j\theta_R + m(\theta_\varphi - \Omega_\mathrm{p} t) + l\theta_z]} \right\},$$

$$f_{jml} = \phi_{jml} \times \frac{j\frac{\partial f_0}{\partial J_R} + m\frac{\partial f_0}{\partial J_\varphi} + l\frac{\partial f_0}{\partial J_z}}{j\omega_R + m(\omega_\varphi - \Omega_\mathrm{p}) + l\omega_z}$$

Monari et al. (2016)

E.g., imposing $f_1 < f_0$ for resonance (1,2,0) of a fast bar:



Displacement of the resonance with z (corotation moves faster)
+ depends on the potential => new constraints with Gaia DR3

Treating resonances

Consider in-plane resonances (l,m): use **Arnold averaging principle**

=> change to slow angles that almost don't evolve at resonance and **average over fast angles :**

$$\theta_s = l\theta_R + m(\theta_\phi - \Omega_b t), \qquad J_\phi = mJ_s,$$

$$\theta_f = \theta_R, \qquad J_R = lJ_s + J_f.$$

$$\overline{H} = H_0(J_f, J_s) - m\Omega_b J_s + \mathrm{Re}\left\{\Phi_{lm}(J_f, J_s)e^{i\theta_s}\right\}$$

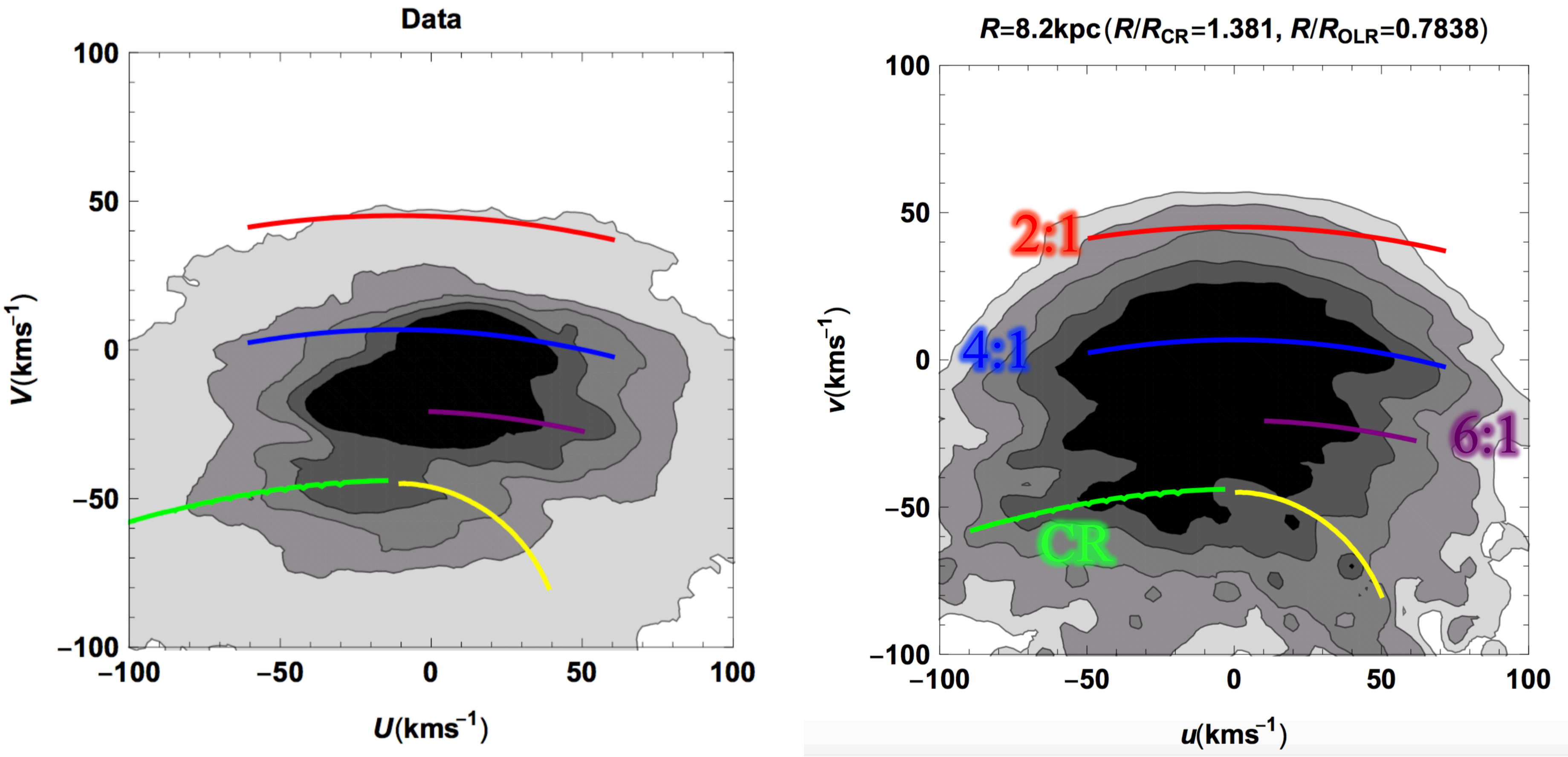
For each J_f, define J_{sres} such that $\omega_s=0$ and expand around J_{sres}

$\Rightarrow$ Hamiltonian of a pendulum of angle θ_s

$\Rightarrow$ New canonical transform to pendulum actions and angles (J_p , θ_p)

$\Rightarrow$ Phase-mix the original DF over θ_p

Treating resonances



Monari et al. (2019)

$V_\odot$ = 0 km/s, declining RC allows to get a more realistic $V_\odot$ = 8 km/s

Ridges as a function of azimuth

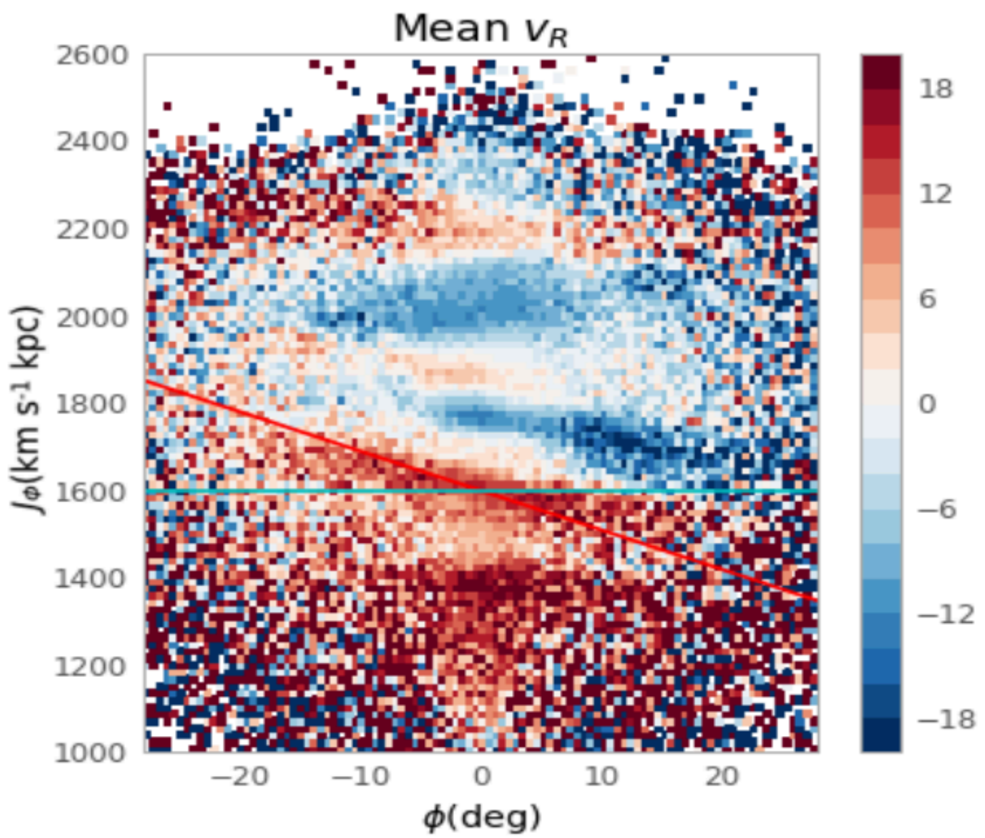
$$\theta_{\mathrm{s}} = l\theta_R + m\left(\theta_\phi - \Omega_{\mathrm{b}}t\right), \qquad J_\phi = mJ_{\mathrm{s}},$$
$$\theta_{\mathrm{f}} = \theta_R, \qquad J_R = lJ_{\mathrm{s}} + J_{\mathrm{f}}.$$

At the (l,m) = (1,2) OLR, the azimuthal angles of trapped orbits can vary fast while the angular momentum varies slowly.

But NOT at the (l,m)=(0,2) CR, where any large change in azimuthal angle is accompanied by a large change of angular momentum

=> **The J_Φ location of the CR varies faster in azimuth than the OLR**

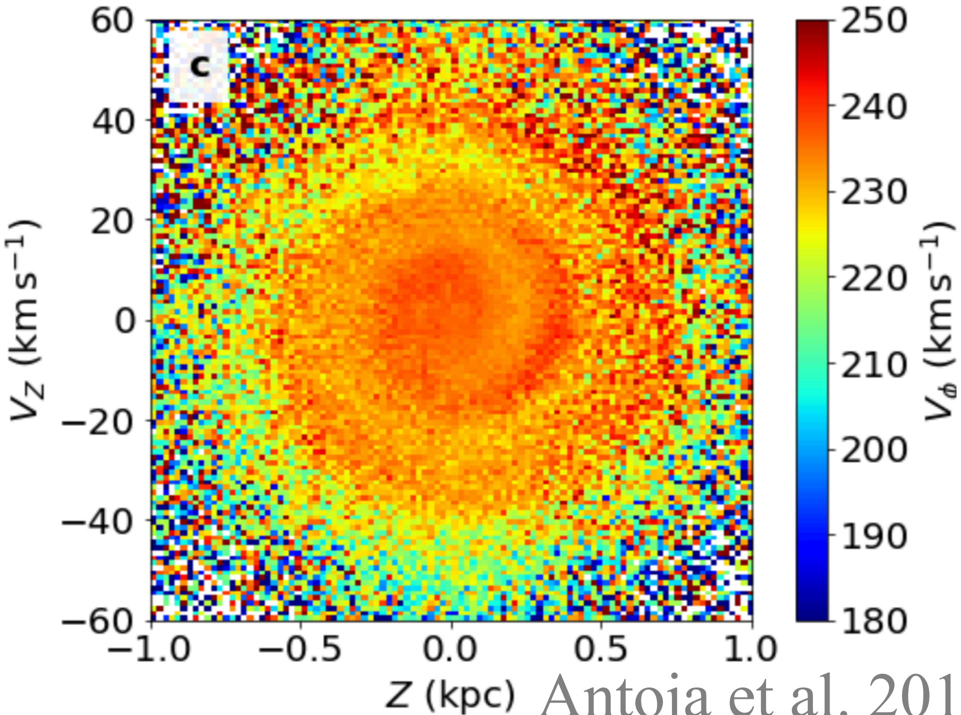
Ridges as a function of azimuth



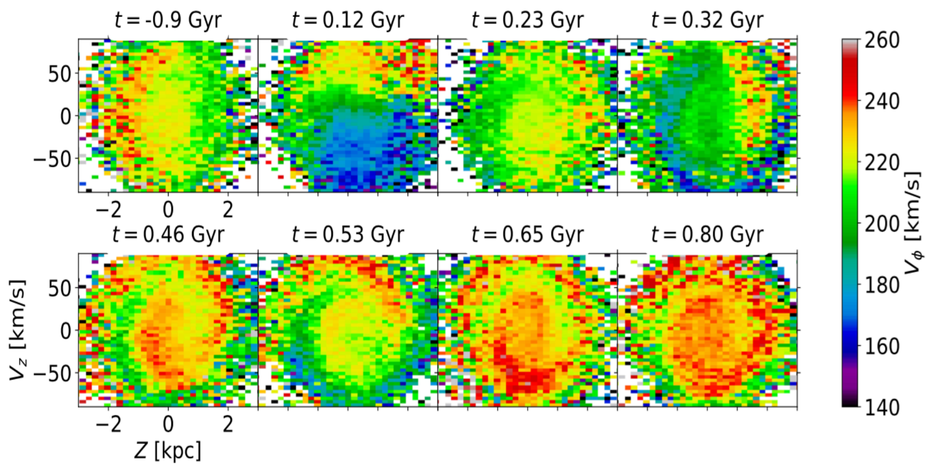
400 pc annulus around the Sun
(StarHorse bayesian distance estimates)

Monari et al. 2019

The disk is vertically perturbed too



Antoja et al. 2018



Laporte et al. 2018
(last pericentric passage of Sgr dwarf at t=0)

⇒Can traditional Jeans modelling be applied? **NO** (Haines et al. 2019)
⇒Can we neglect self-gravity of the disc? **NO** (Khoperskov et al. 2019)

Similar (but less intense) phase spirals survive > 1 Gyr after bar buckling

The disk is vertically perturbed too

Taking self-gravity into account needs simultaneously solving **CBE** and **Poisson**

=> Use bi-orthogonal basis functions that solve Poisson (basis functions appropriate for thickened disks)

$$\psi^{\mathrm{s}}(\mathbf{x},t) = \sum_p a_p(t)\psi^{(p)}(\mathbf{x})\,;\;\; \psi^{\mathrm{e}}(\mathbf{x},t) = \sum_p b_p(t)\psi^{(p)}(\mathbf{x})$$

The Sgr dwarf potential

$$a_p(t) = -\int \mathrm{d}\mathbf{x} \int \mathrm{d}\mathbf{v}\; f_1(\mathbf{x},\mathbf{v},t)\,\psi^{(p)*}(\mathbf{x})$$

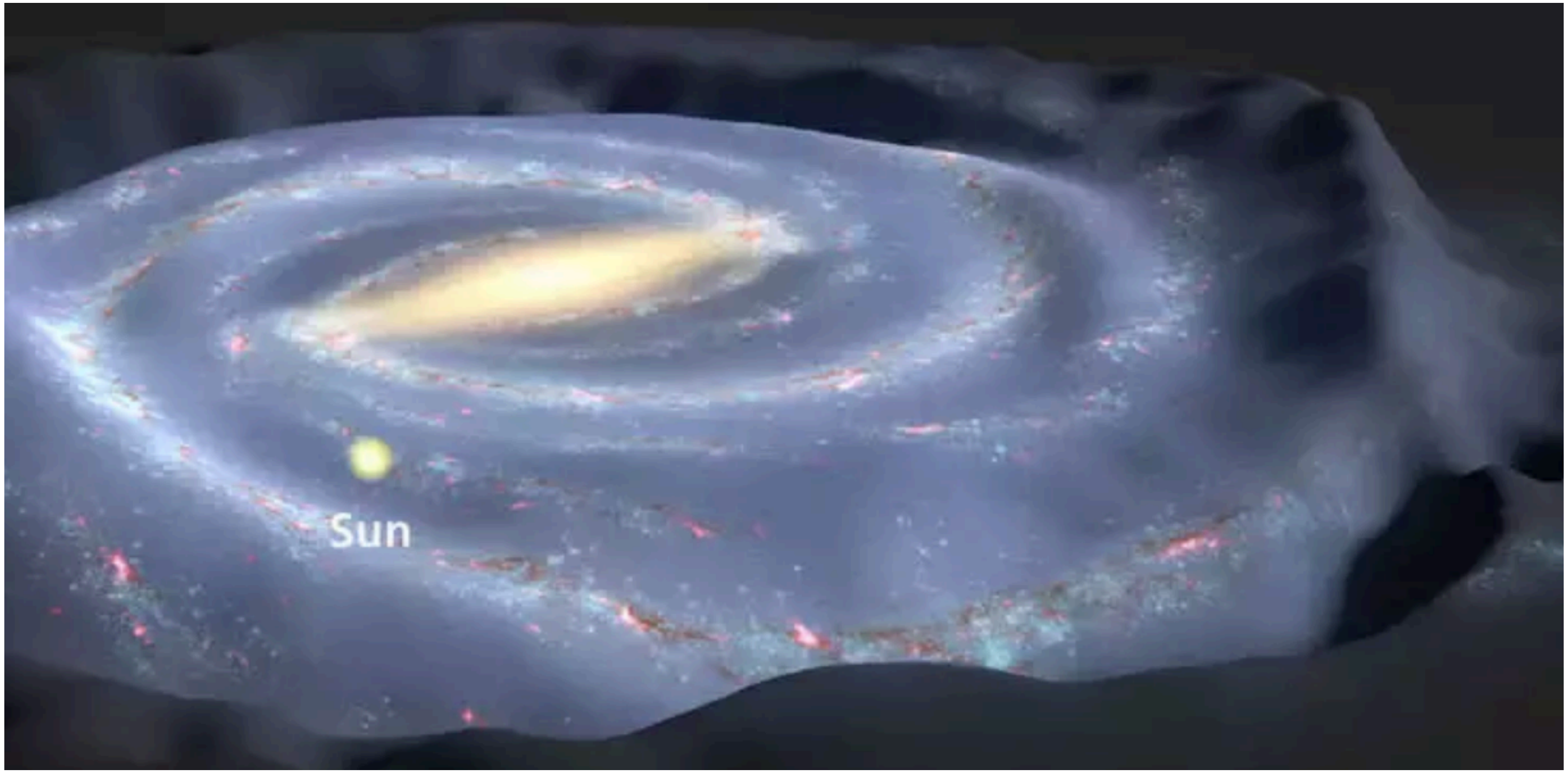
[equivalent to integrating over J and θ]

insert solution of linearized CBE and develop the perturbing potential (Ψs+Ψe) on the basis functions (as a sum over q)

$$\mathbf{a}(t) = \int_0^t \mathrm{d}\tau\, \mathbf{M}(t-\tau)\left[\mathbf{a}(\tau) + \mathbf{b}(\tau)\right]$$

Work led by S. Rozier

$$\mathbf{M}_{pq}(t) = -\mathrm{i}\,(2\pi)^3 \sum_{\mathbf{n}} \int \mathrm{d}\mathbf{J}\,\mathbf{n}\cdot \frac{\partial F_0}{\partial \mathbf{J}}\,\psi_{\mathbf{n}}^{(p)*}(\mathbf{J})\,\psi_{\mathbf{n}}^{(q)}(\mathbf{J})\,\mathrm{e}^{-\mathrm{i}\,\mathbf{n}\cdot\mathbf{\Omega}\,t}$$



Conclusion and next steps

- Detected dozens of streams => probes of the Galactic potential making use of ACTIONFINDER (+ self-consistent phase-space modelling of DM and testing alternatives)

- Disc: 2D analytic formalism for resonances of bar and spirals

⇒ **MW bar with CR at 6 kpc** qualitatively reproduces a surprisingly large amount of features in local action-space and velocity-space

- Next step: combine the treatment at resonances with the linear response to combine the bar an spiral arms (when no resonance overlap), **fit** to data on larger scales (velocity field, ridges,…)

- Vertically perturbed disk => Jeans modelling inappropriate

⇒ We need to work on the appropriate analytic formalism (Matrix method, SEGAL ANR)

Data: what's next?

- Next year: Gaia DR3 will improve even more the observational situation (e.g., RVS data for $3.5x10^7$ stars down to G~15)

- Next year: **WEAVE** as spectroscopic counterpart to Gaia. High-res survey (R~20000) will allow chemical labelling to G~16 for ~$1.2x10^6$ stars

  + Low-res surveys (disk and HighLat) for ~$2.75x10^6$ stars (R~5000) deep in the disk and halo down to G~20