Galactic dynamics in the Gaia era

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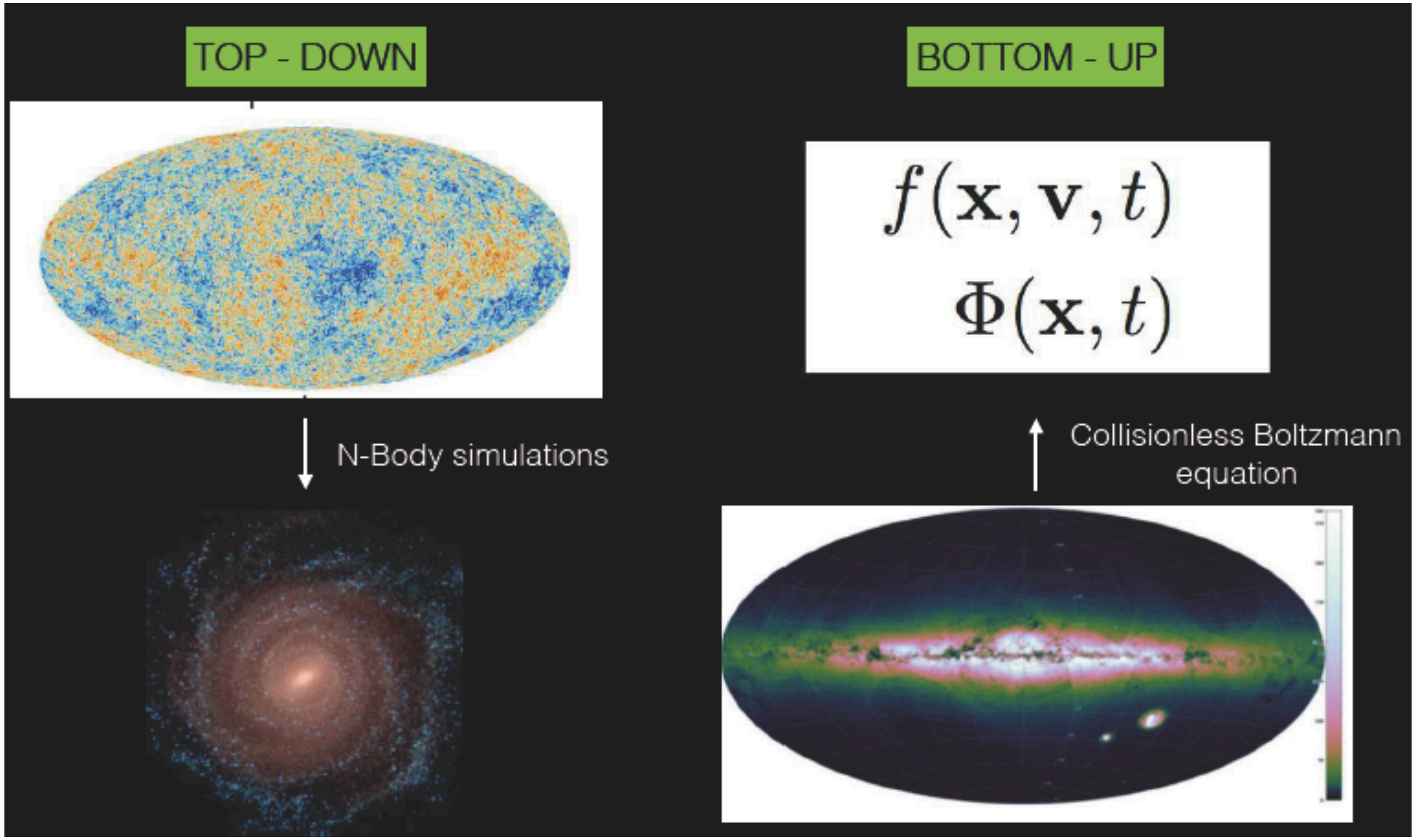
Some Gaia-era questions

- Decipher the structure of the Galaxy, and of each of its components (stellar pops, satellite population), including its **dark matter** distribution, *e.g.*:
  - **total mass,**
  - **core vs. cusp,**
  - **phase-space distribution important for direct searches…**

- How many dissolved galaxies formed the stellar halo?
- How many **stellar streams** (from GCs and dwarfs)? Use these in turn to measure the acceleration field and constrain the **DM distribution & clumping** (+ effects on secular evolution of the disk?)
- Is it consistent with ΛCDM, with specific DM alternatives (warm DM, self-interacting DM…), with modified gravity?

MW dynamical models



$$
\begin{cases}
\mathrm{d}f/\mathrm{d}t = 0 \Leftrightarrow \dfrac{\partial f}{\partial t} + [f, H] = \dfrac{\partial f}{\partial t} + \mathbf{v} \cdot \dfrac{\partial f}{\partial \mathbf{x}} - \dfrac{\partial \Phi}{\partial \mathbf{x}} \cdot \dfrac{\partial f}{\partial \mathbf{v}} = 0, \\
\nabla^2 \Phi = 4\pi G \displaystyle\int \mathrm{d}^3\mathbf{v}\, f
\end{cases}
$$

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 $H=H(\mathbf{J})$
  $\Rightarrow f_0(\mathbf{J})$ with **J** adiabatic invariants
- **A triplet of actions defines a regular orbit, angles tell us where the star is along that orbit**

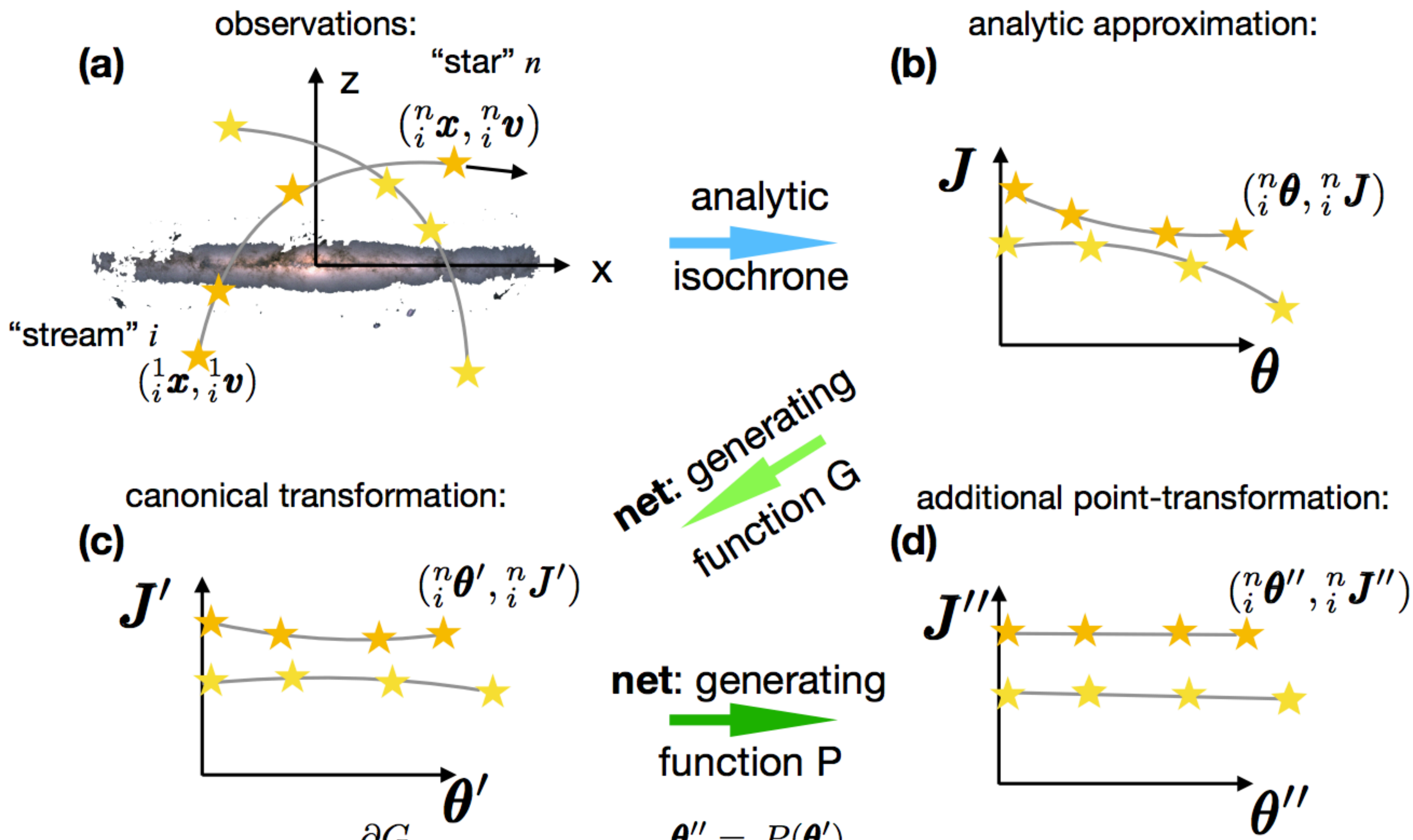
ACTIONFINDER

- 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

- Find the actual potential !

ACTIONFINDER



iterative solution to:

$$\boldsymbol{J} = \boldsymbol{J}' + \frac{\partial G}{\partial \boldsymbol{\theta}}$$

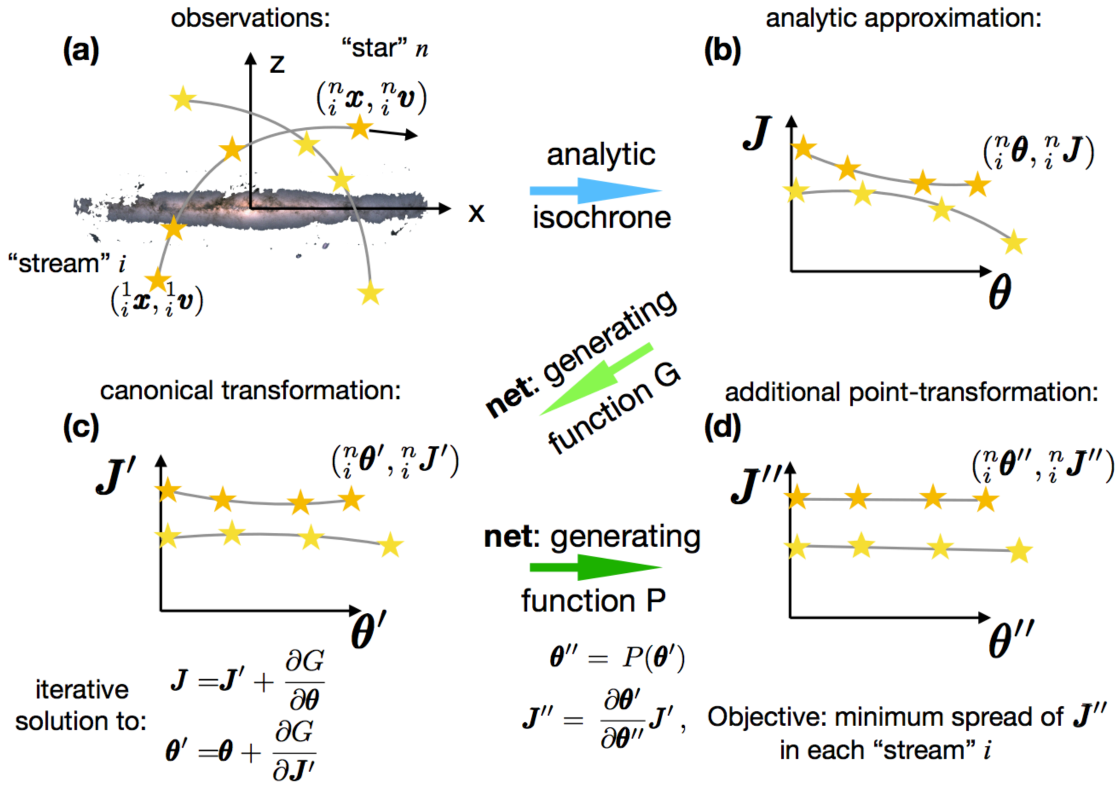
$$\boldsymbol{\theta}' = \boldsymbol{\theta} + \frac{\partial G}{\partial \boldsymbol{J}'}$$

$$\boldsymbol{\theta}'' = P(\boldsymbol{\theta}')$$

$$\boldsymbol{J}'' = \frac{\partial \boldsymbol{\theta}'}{\partial \boldsymbol{\theta}''} \boldsymbol{J}',$$

Objective: minimum spread of $\boldsymbol{J}''$ in each "stream" i

ACTIONFINDER



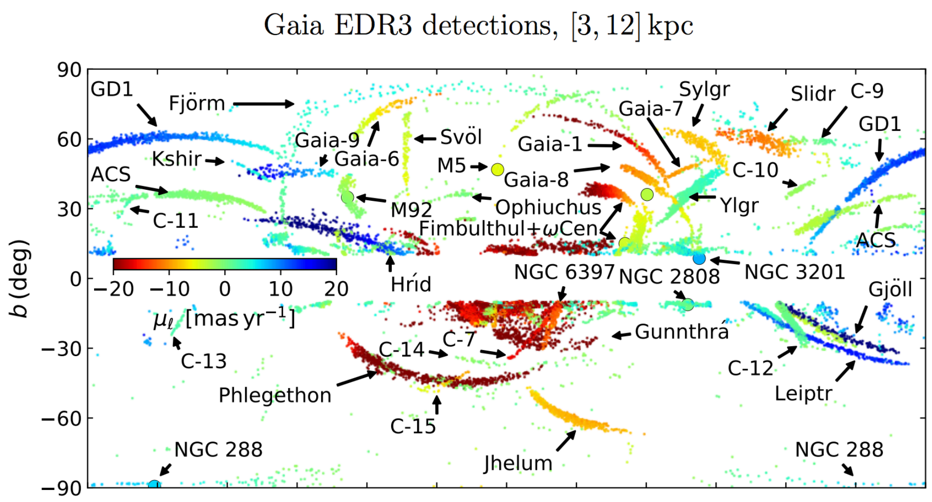
- With 8 points per orbit and 128 orbits (hence 1024 phase-space points), recovers the actions and angles from the Torus machinery of Binney & McMillan with 0.6% precision

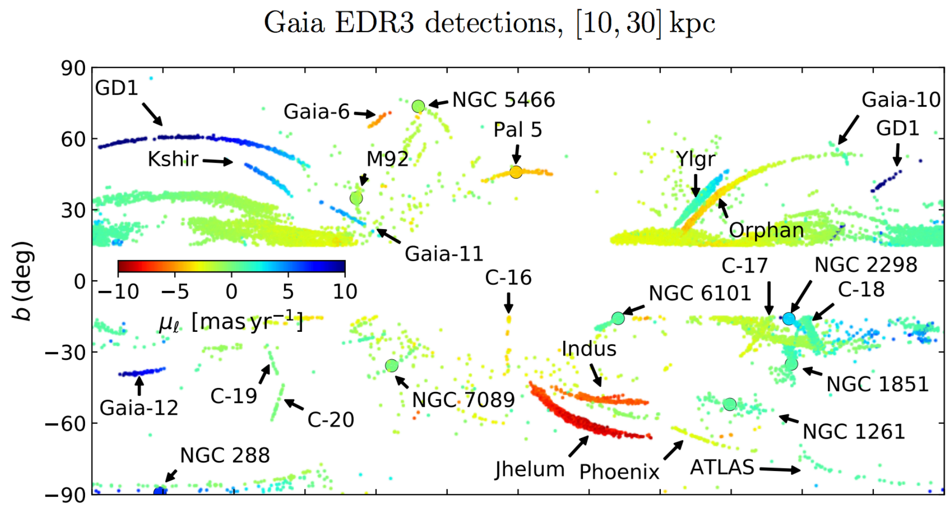
- But most importantly**: recovers the (unknown) Hamiltonian and therefore Galactic potential !**

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 stream candidate found (STREAMFINDER)





15 with a globular cluster progenitor
(good distance, SSP template, and GC on the actual orbit)

Modelling the MW disc

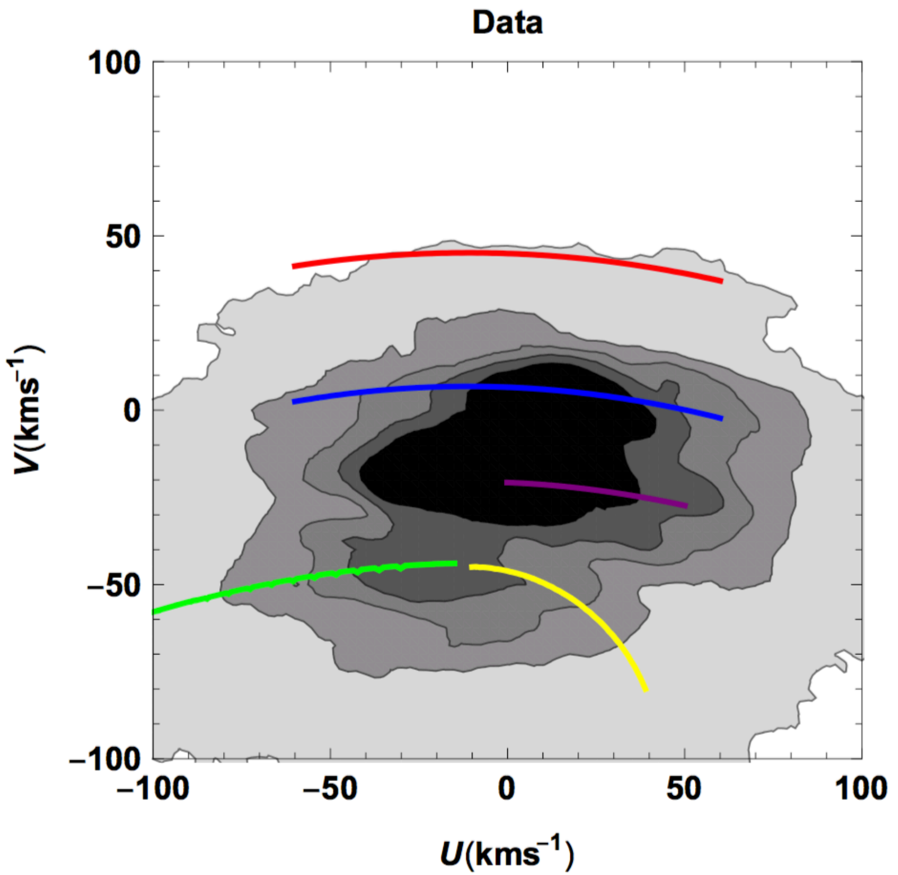
Adjust comination of parametric DFs:

$$f_0(J_R, J_\phi, J_z) = \frac{\Omega(R_g(J_\phi))}{(2\pi)^{3/2} 2\kappa(R_g(J_\phi))} \underbrace{\frac{\tilde{\Sigma}(R_g(J_\phi))}{\tilde{\sigma}_r^2(R_g(J_\phi))\tilde{\sigma}_z^2(R_g(J_\phi))z_0}}_{\text{radial distribution in } R_g(J_\phi)} \times \underbrace{e^{-\frac{J_R\kappa}{\tilde{\sigma}_r^2} - \frac{J_z\nu}{\tilde{\sigma}_z^2}}}_{\text{velocity ellipsoid together with the velocity disp.dependence in previous factor}}$$

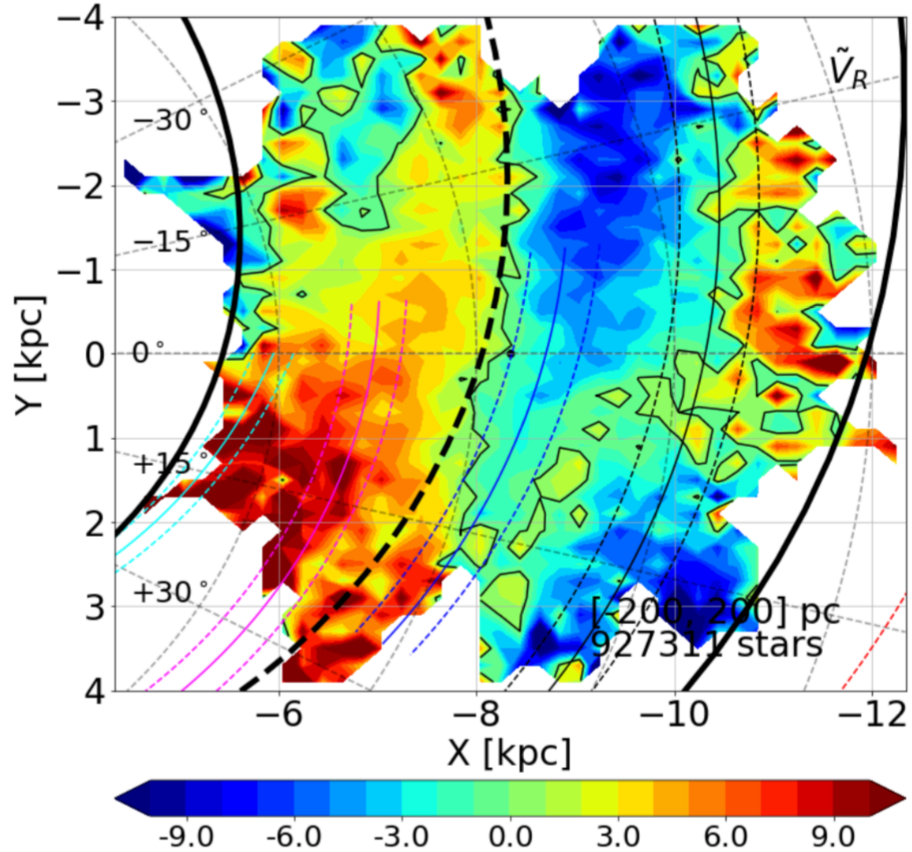
Even better: **non-parametric DF:** adjust with neural nets

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

Modelling the MW disc: it's a mess

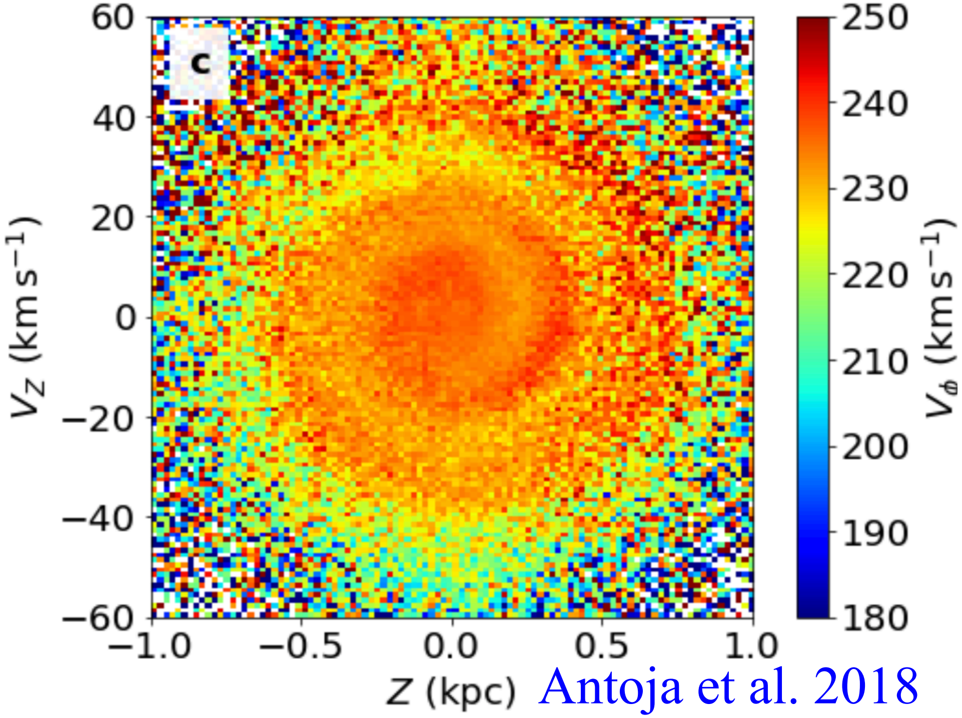


Local velocity space
(Monari et al. 2019)

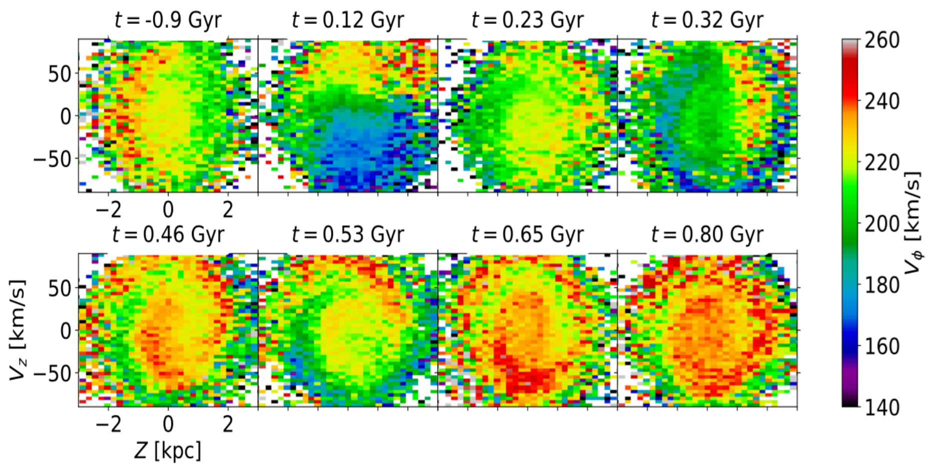


Galactocentric radial velocity map
(Katz et al. 2018)

Modelling the MW disc: it's a mess



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)

Relevant to testing gravity too!!

Perturbation theory

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

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

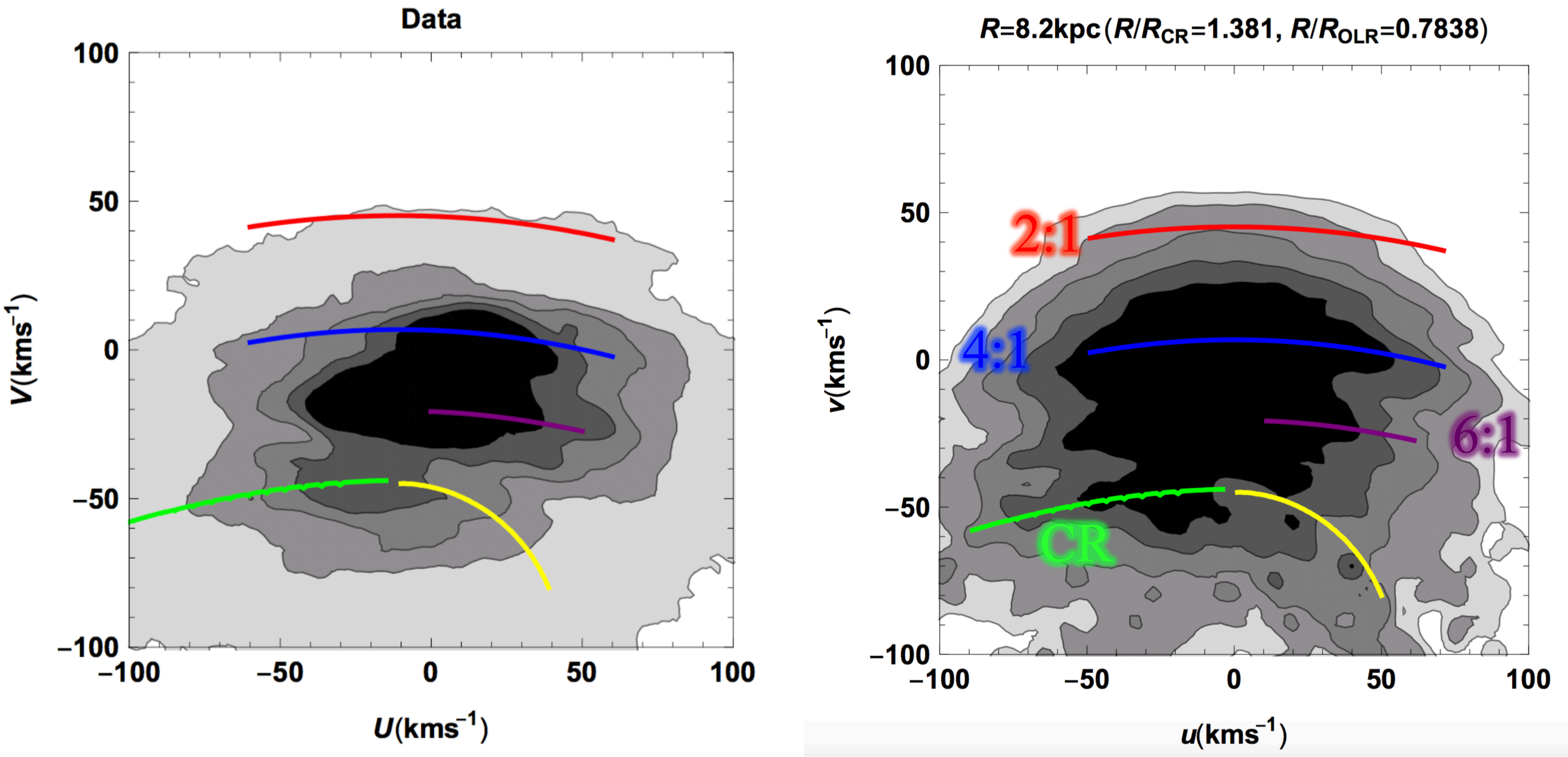
Integrate from zero amplitude bar to plateau of constant amplitude:

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

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

Monari et al. (2016); Al Kazwini et al. (2021)

Treating resonances



Monari et al. (2017; 2019) with bar model of Portail et al. (2017)

Vertical perturbations

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)

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

Work led by
S. Rozier with A. Siebert
& G. Monari

Response of the DM halo?

- LMC (could have 10%-15% of MW mass!), Sagittarius dwarf and their own DM halo can perturb the DM and stellar halos

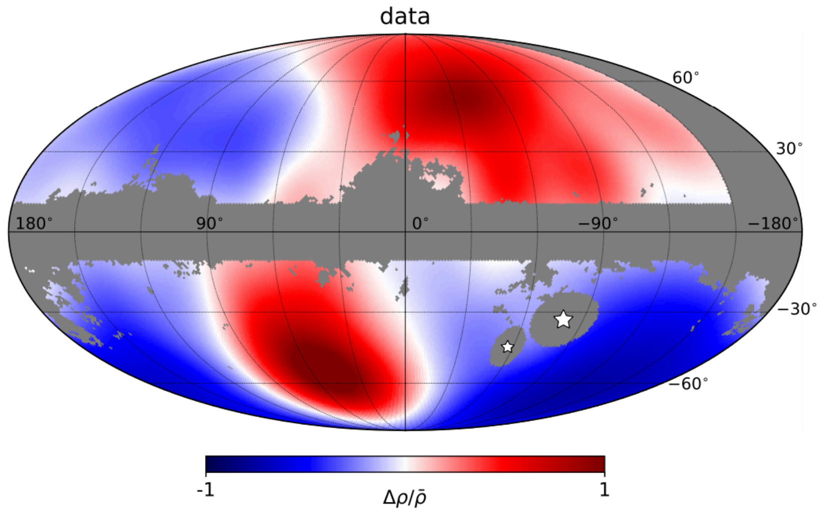
$\Rightarrow$ Analytical perturbation theory relevant too!

$\Rightarrow$ Use the Matrix method to compute the response of the dark and stellar halos to the LMC infall (Rozier et al. in prep.)

$\Rightarrow$ Allows to isolate the relevant resonances

Response of the DM halo ?

- We found that self-gravity is unimportant => the response of the DM halo does not affect the response of the stellar halo (tentatively detected by Petersen & Penarrubia 2020; Erkal et al. 2020; Conroy et al. 2021)



The strength of the response can teach us about the dynamical state of the stellar halo (but not of the DM halo)

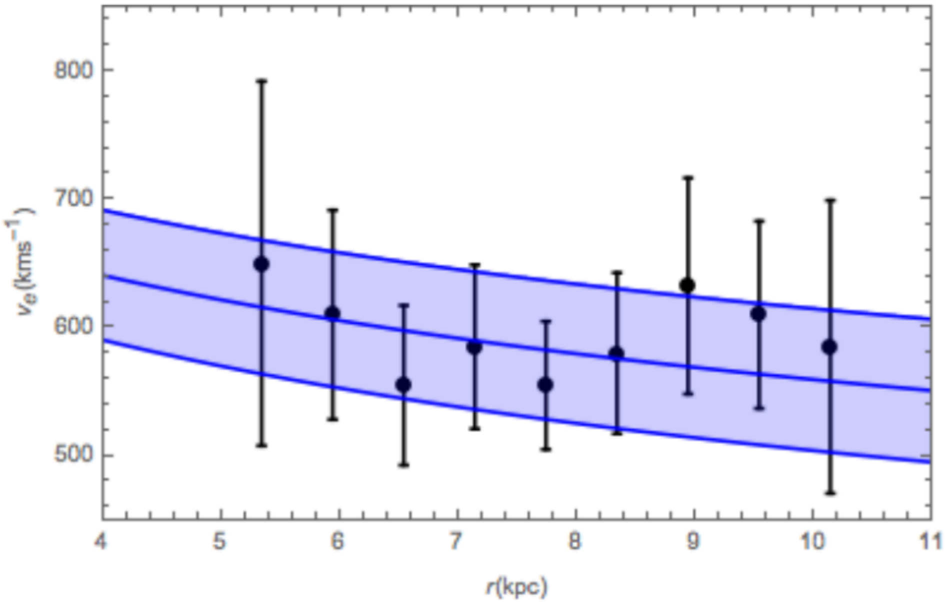
- The situation regarding self-gravity is probably different regarding the feedback on the halo response on the disk concerning the Sgr dwarf perturbation (Laporte et al. 2018)

Some Gaia-era answers...

- It's **complicated**… but here are some (preliminary) answers on:
  - **total mass,**
  - **local DM density**
  - **DM core vs. DM cusp**

Milky Way mass ?

Escape speed :



Assuming that v_e allows to reach $3xR_{340}$, as well as the mass-concentration relation of ΛCDM, one gets: $\mathbf{M_{200} = 1.55(-0.51, +0.64) \times 10^{12}\ M_\odot}$

Use 2850 counter-rotating stars at $d<5$kpc and $\varepsilon_d/d<10\%$ (StarHorse bayesian distance estimates)

Fit the tail of the velocity distribution to ~100 Monte Carlo realizations at Galactocentric radii 5 kpc< R<10.5 kpc

$$f(v|v_e, k) = \begin{cases} (k+1)(v_e - v)^k/(v_e - v_{cut}), & v \leq v_e \\ 0, & v > v_e \end{cases}$$

=> $\mathbf{v_e (R_\odot) = 580 \pm 63}$ km/s

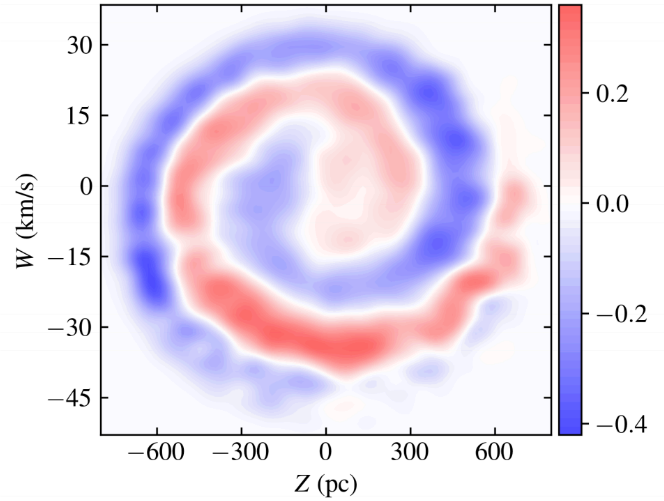
Monari et al. (2018)

Local DM density ?

Non-equilibrium => needs development of appropriate framework including self gravity in 3D

But… **first attempts**, in 1D and neglecting self-gravity
(Binney & Schonrich 2018; Widmark et al. 2021)

Perturb $f(J_z)$ into $f(J_z, \theta_z)$ and let each star oscillate with its **own vertical frequency** which depends on the **Hamiltonian**
$\Rightarrow$ Shape of phase-spiral depends on the potential and time since pert.



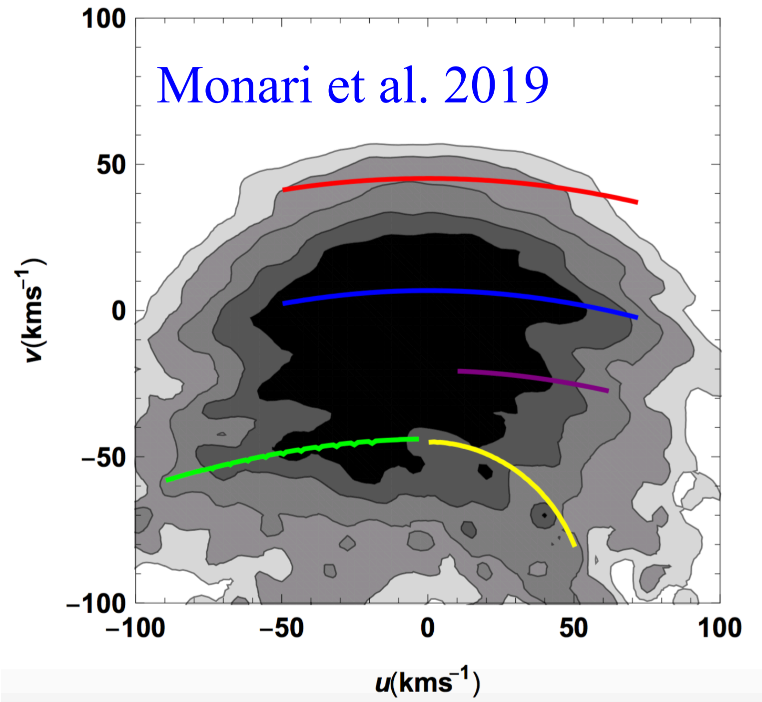
Widmark et al. (2021) fit to quasi-circular orbits, compare potential to baryonic one and infer

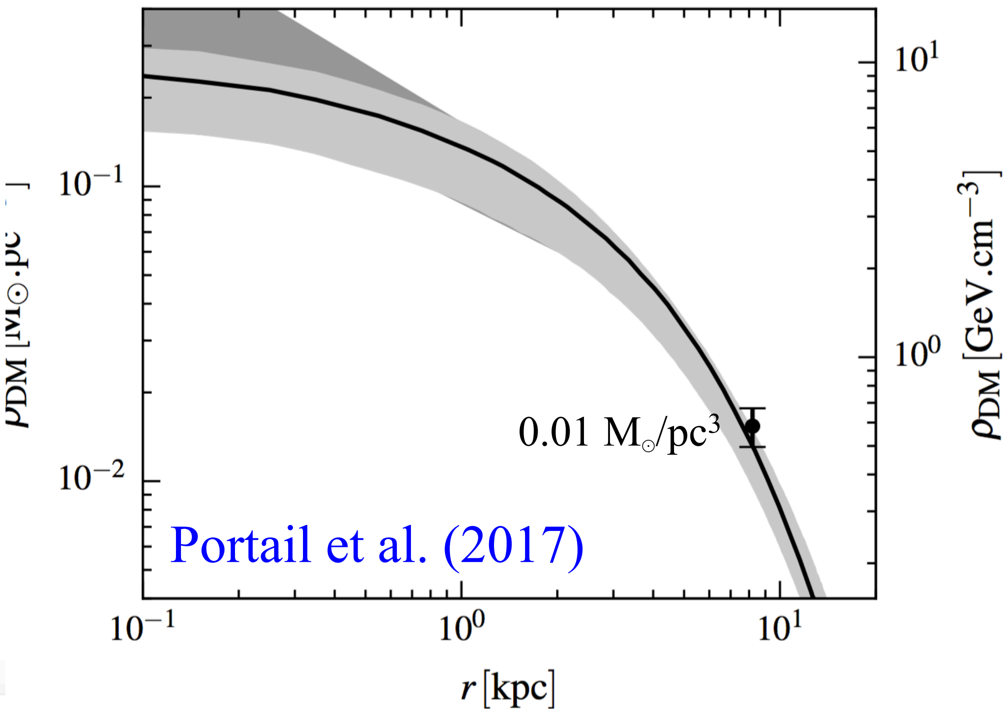
$\rho_{DM} = 0.0085 \pm 0.004\ M_\odot/pc^3$

$= 0.32 \pm 0.15\ GeV/cm^3$

A DM core in the MW?

- Bulge mass (2.2 kpc, 1.4 kpc, 1.2 kpc): 1.85×10^{10} $M_\odot$
  - Dark matter mass: 3.2×10^{9} $M_\odot$





Bar model + keep the RC constant between 6 kpc and 8 kpc
=> **cored DM profile at the center**

What's next?

- Next data releases will improve even more the observational situation (e.g., RVS data for 3.5×10^7 stars down to G~15)

- FROM « US » **(DYNAMICISTS):** improvements needed: on the **MODELLING** side (vertical perturbations with collective effects, bar and spiral arms formation, chemo-dynamical modelling…)

- Are the LMC and Sgr influences sufficient to explain 'everything' in terms of perturbations of the stellar halo and disk? Is the Sgr stream fully understood for instance?

- At the horizon 2022: **WEAVE** as spectroscopic counterpart to Gaia. High-res survey (R~20000) will allow chemical labelling to G~16 for $\sim 1.2 \times 10^6$ stars

  \+ Low-res surveys (disk and HighLat) for $\sim 2.75 \times 10^6$ stars (R~5000) deep in the disk and halo down to G~20