Towards non-equilibrium Galactic disk modelling

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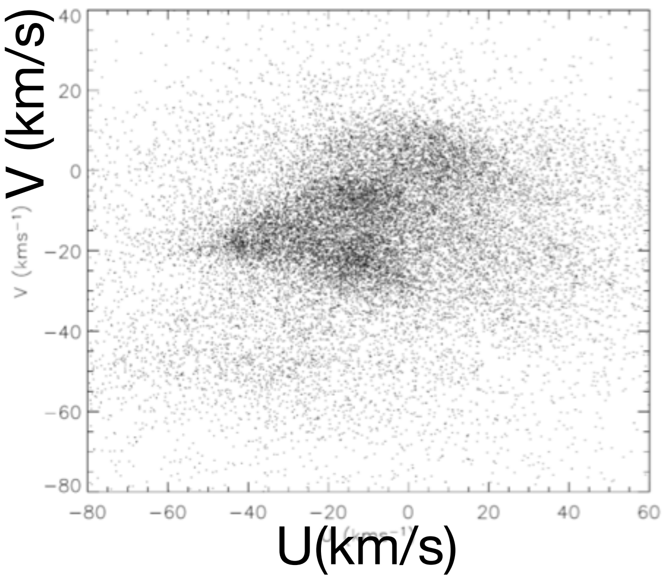
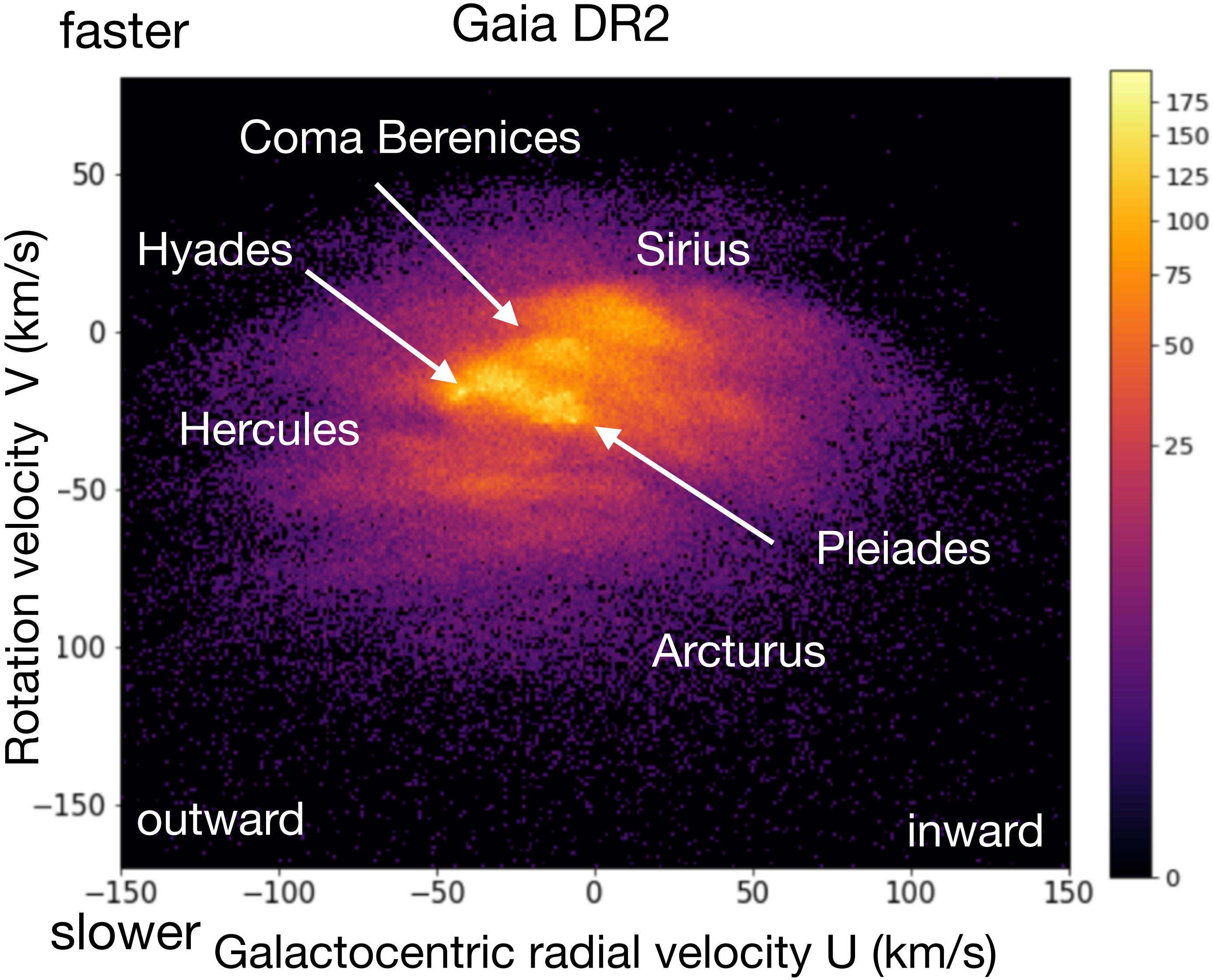
Stellar velocity distribution in the solar neighbourhood
Many velocity structures!

Hipparcos



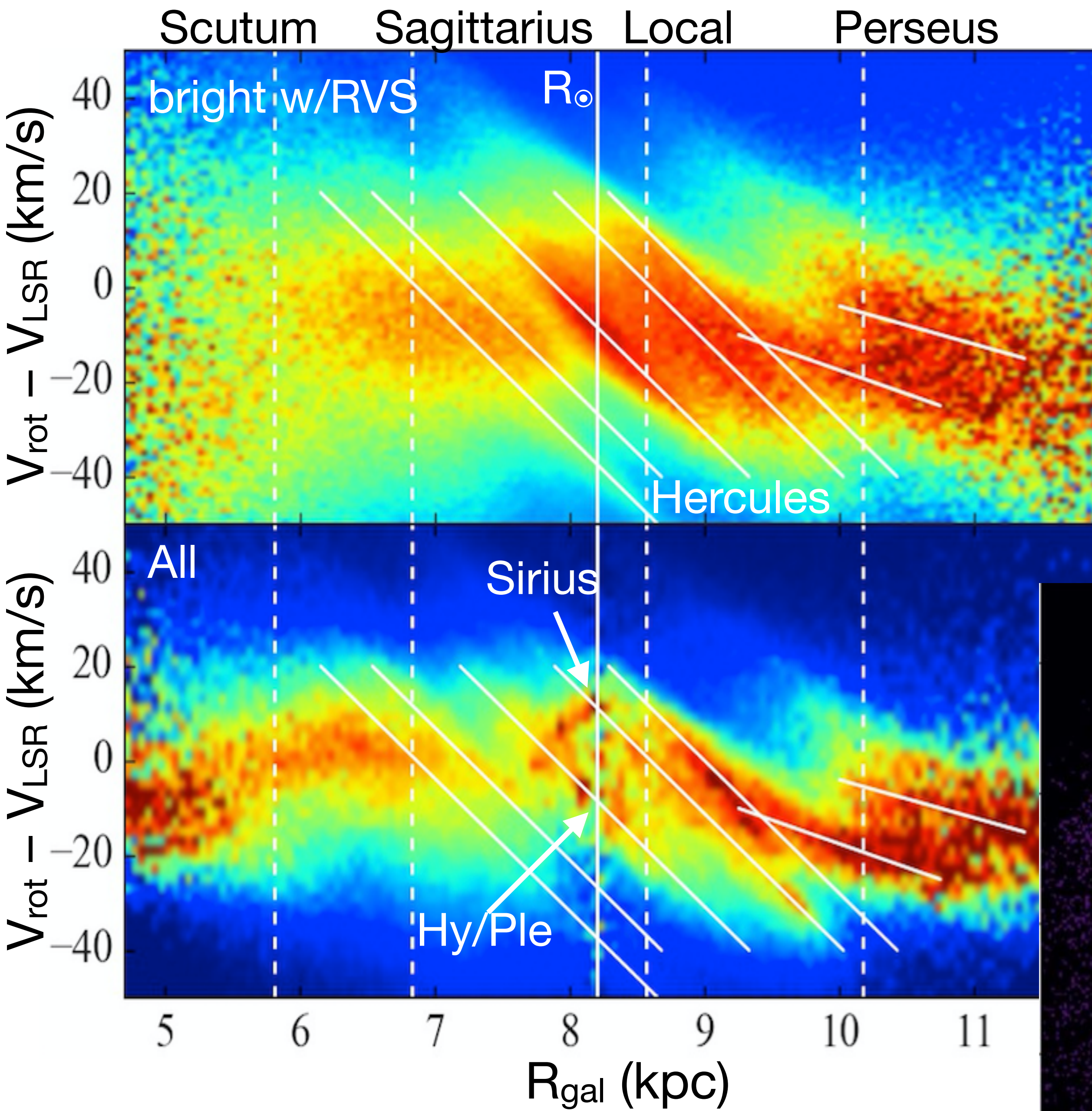
Antoja et al. (2008)

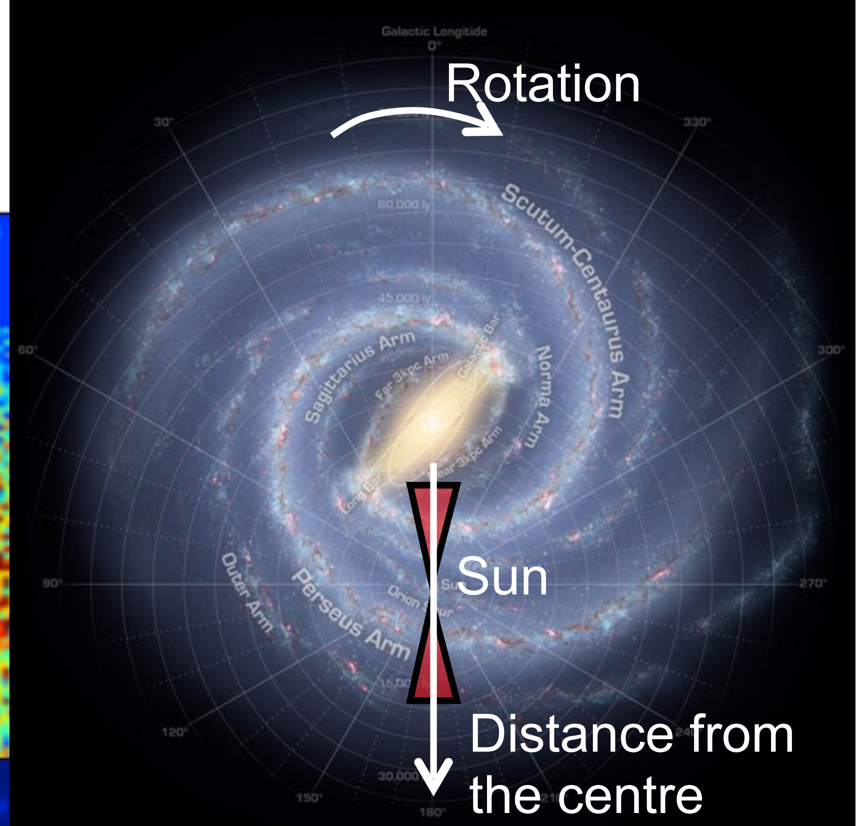
Gaia DR2

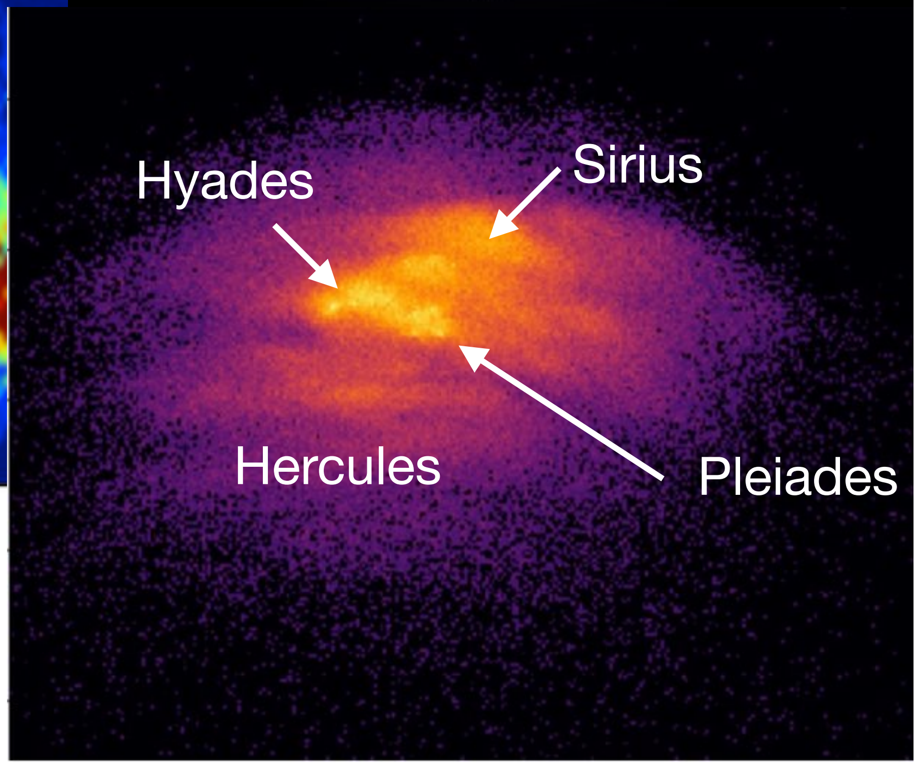


Gaia Collaboration, Katz et al. (2018)

Many ridge-like features

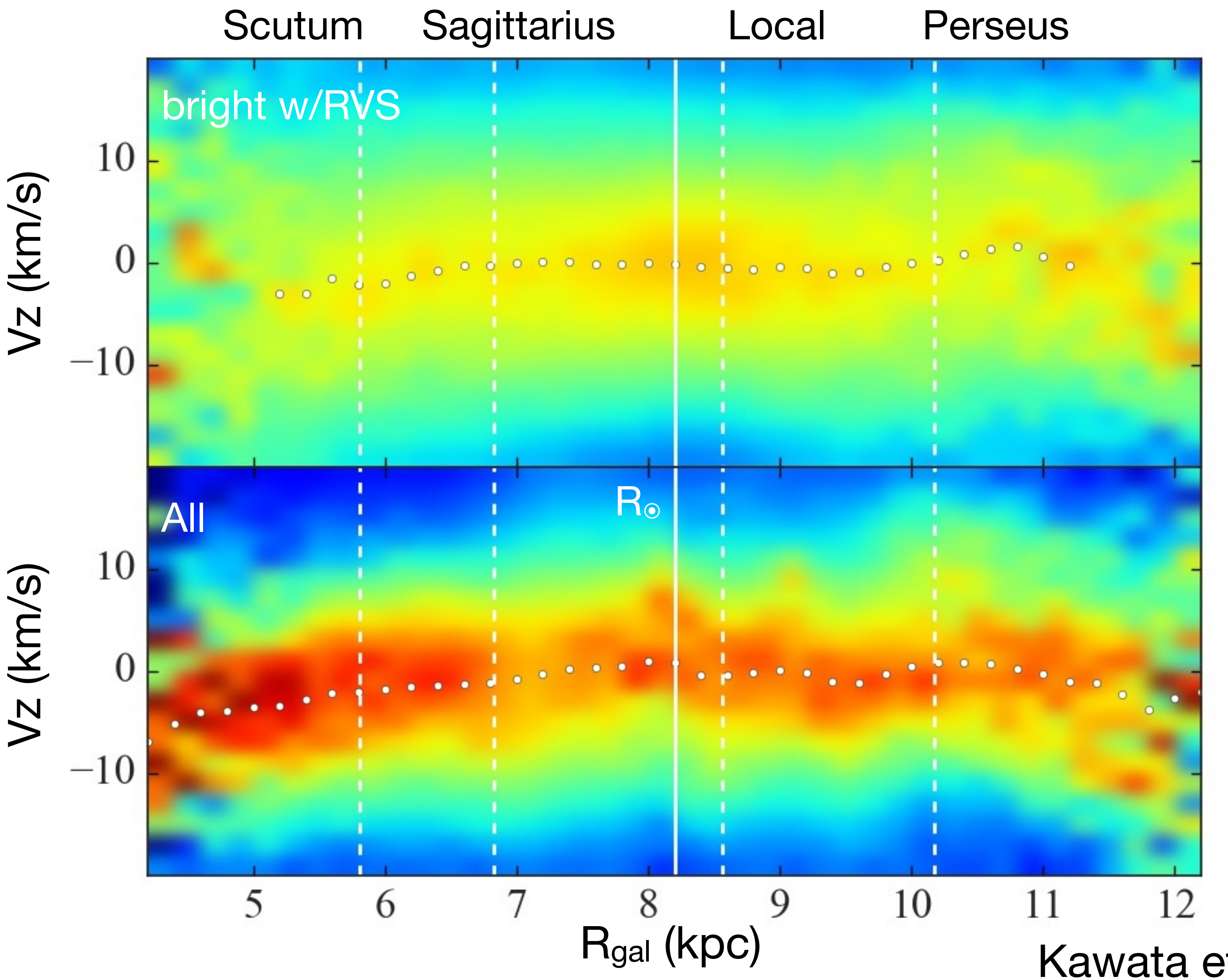






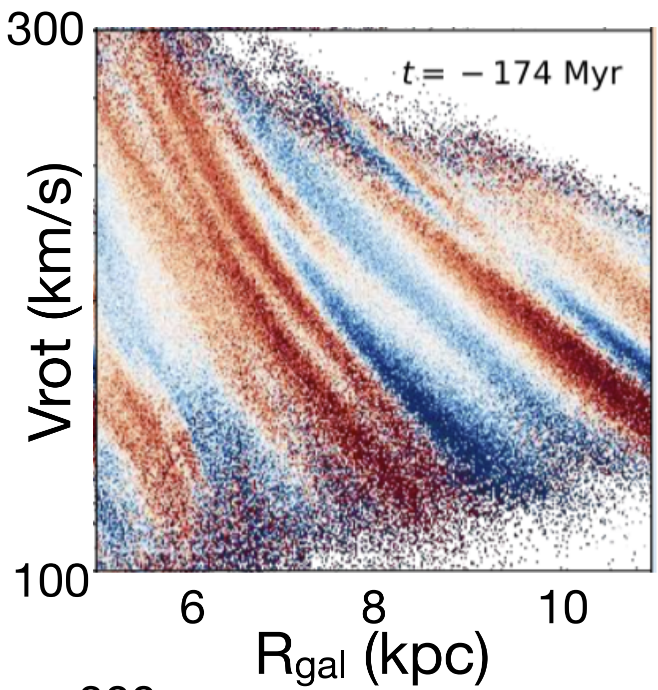
Kawata et al. (2018, MNRAS, 479L, 108)
See also Antoja et al. (2018)

Vertical Oscillation
Galactic disk is heavily perturbed!



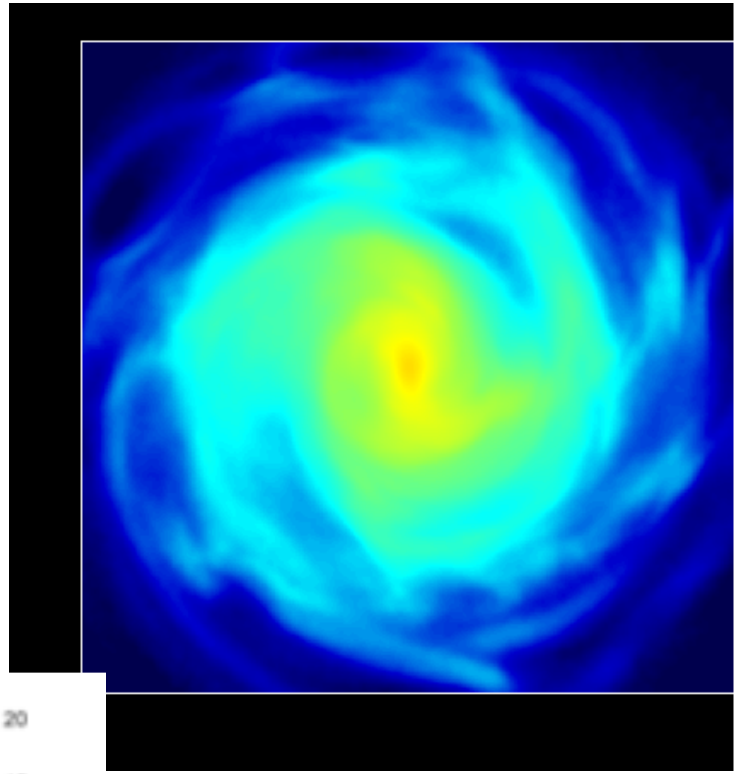
Kawata et al. (2018)

In-plane perturbation from transient winding spiral arms?
(Hunt, Hong, Bovy, Kawata, Grand 2018, Hunt et al. in prep.)

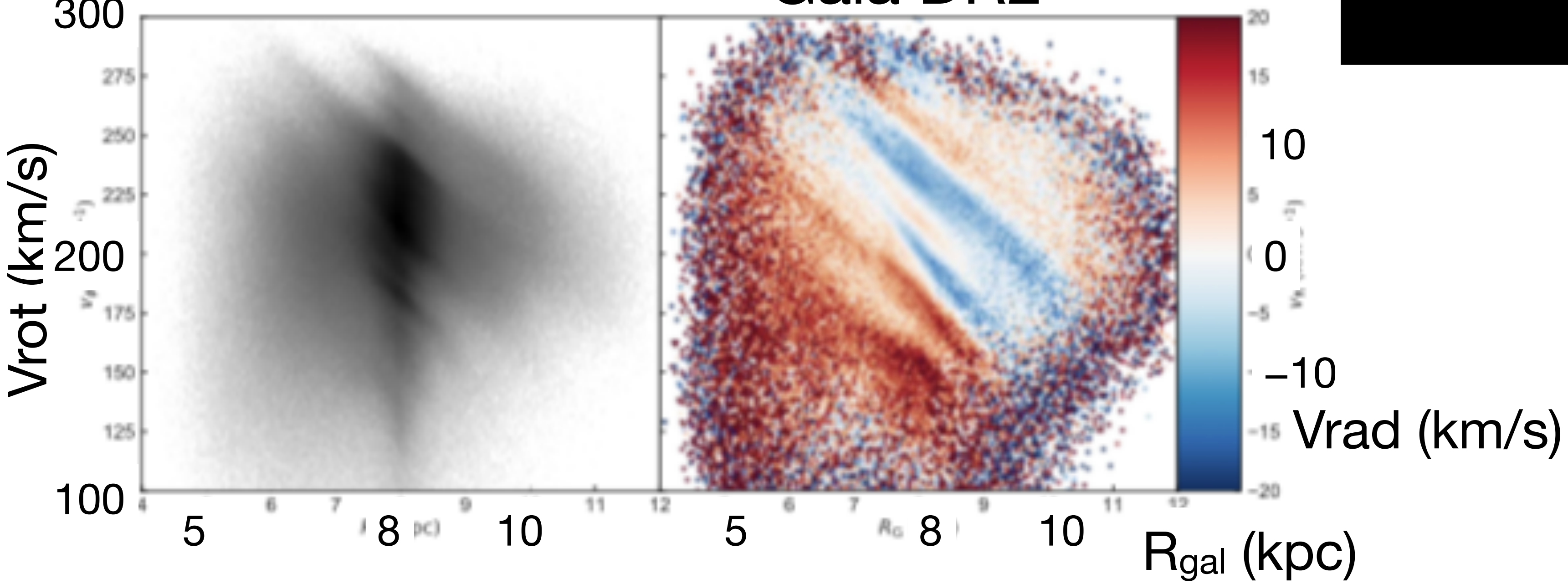


N-body sims =transient arms e.g. Selwood (2011), Grand, Kawata Cropper (2012a,b, 2013, 2014), Wada et al. (2011), Baba et al. (2013)

transient spiral
+ slow bar

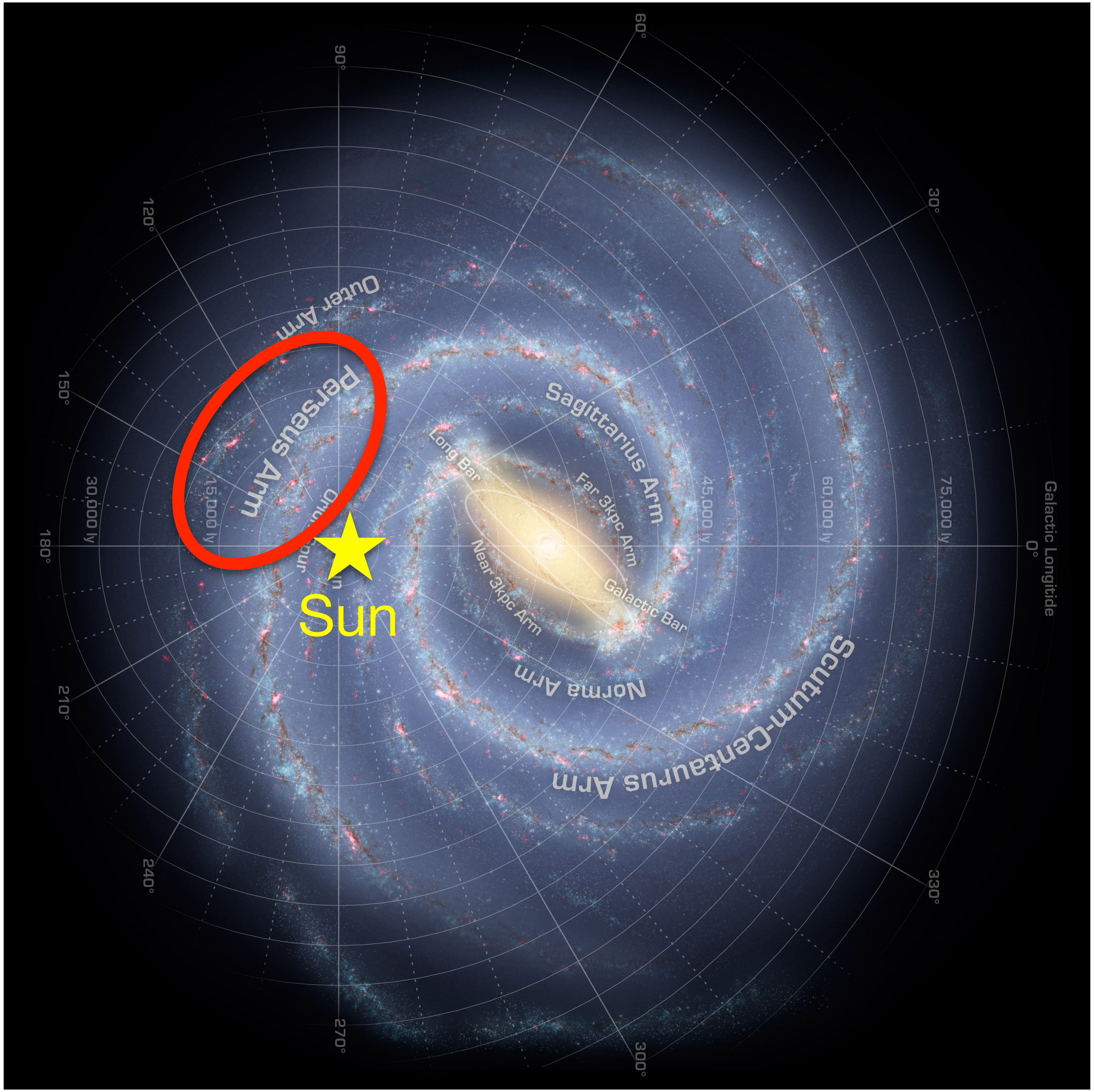


Gaia DR2



Disrupting Perseus Arm!

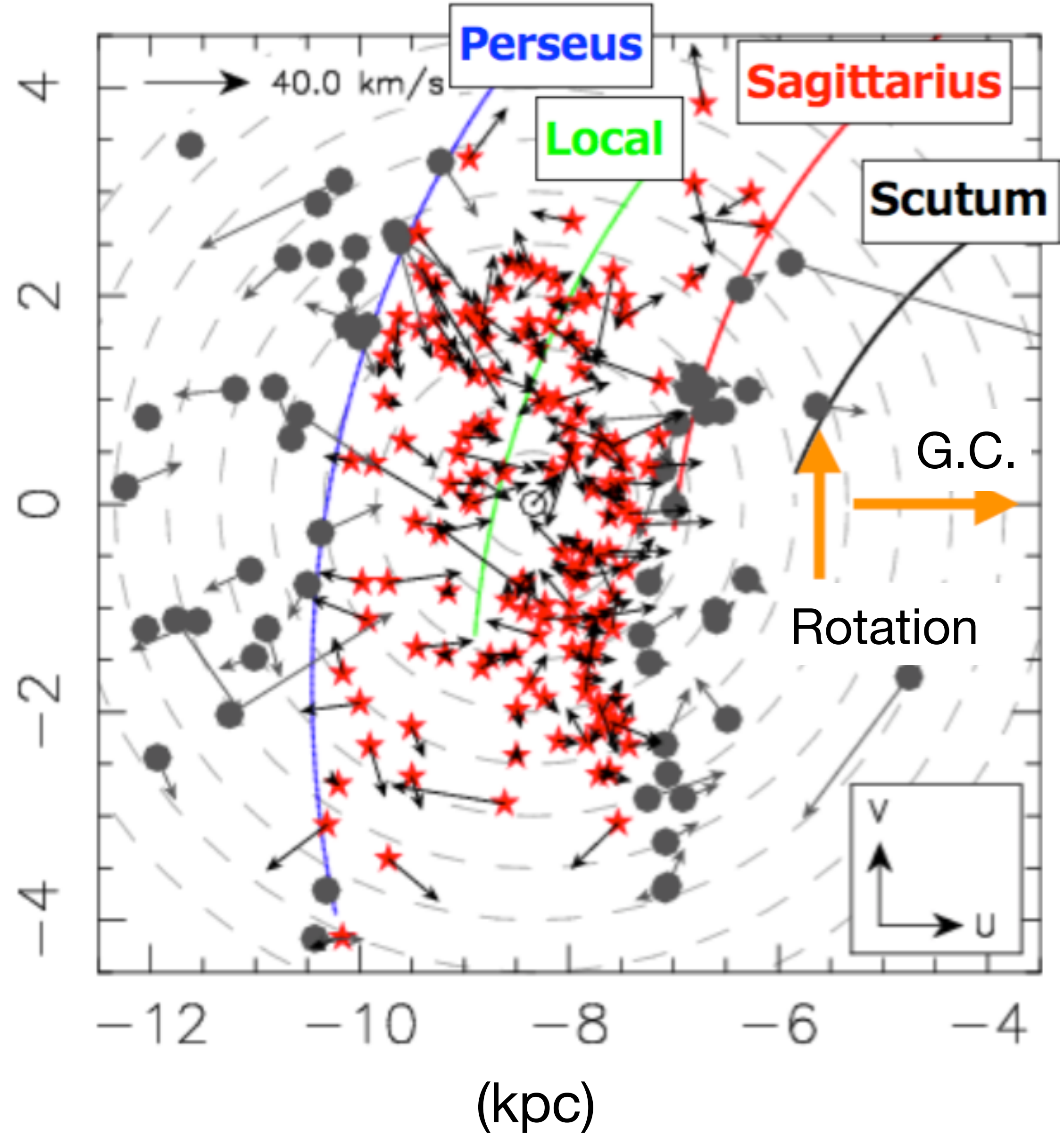
Baba, Kawata, Matsunaga, Grand, Hunt (2018)

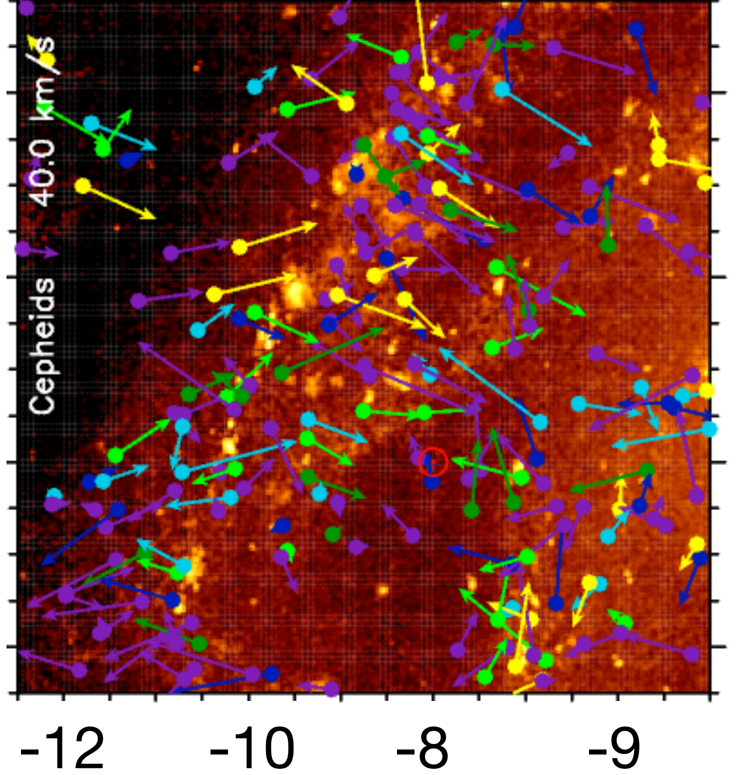


Disrupting Perseus Arm!

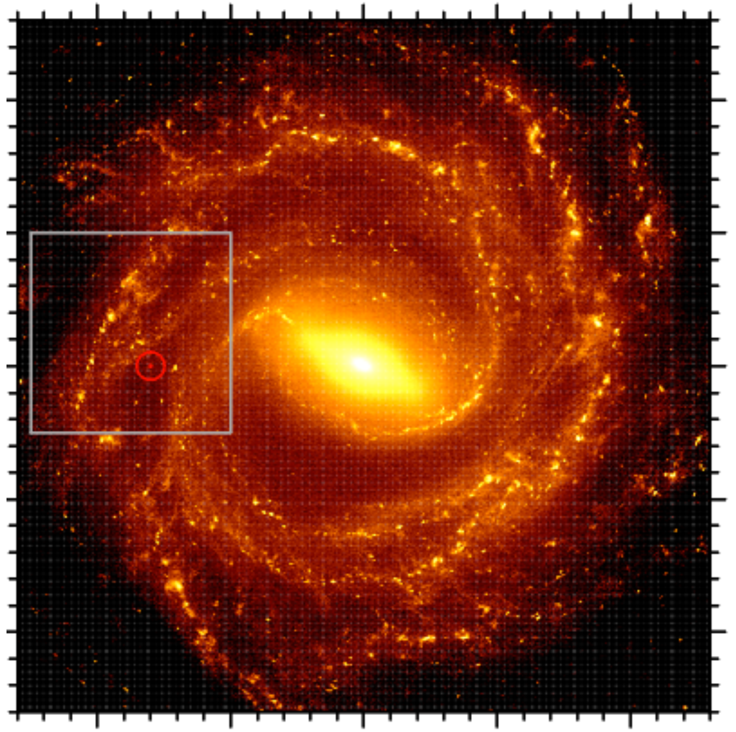
Baba, Kawata, Matsunaga, Grand, Hunt (2018)

Cepheids distance + DR1 proper motion confirmed with DR2!





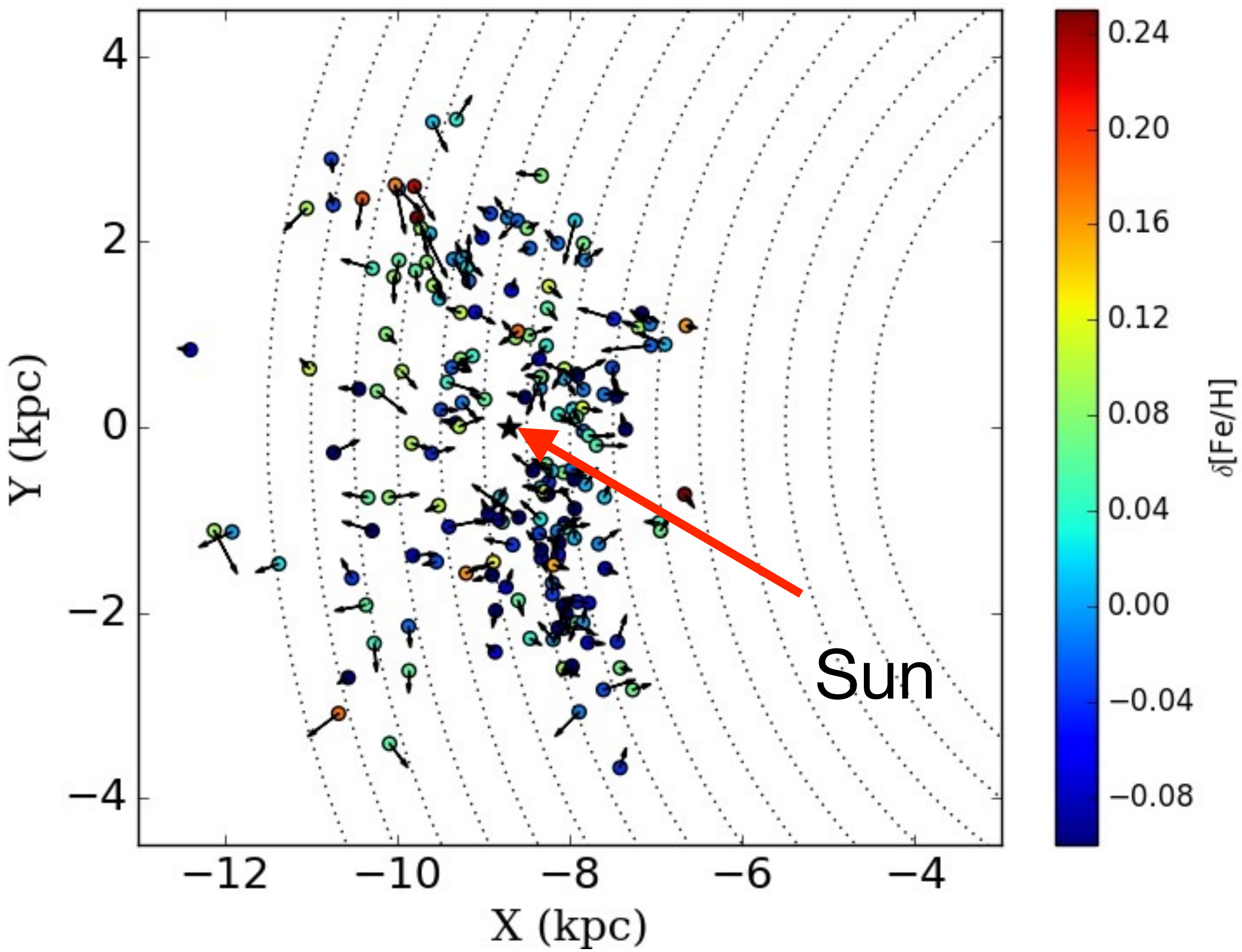
N-body simulation



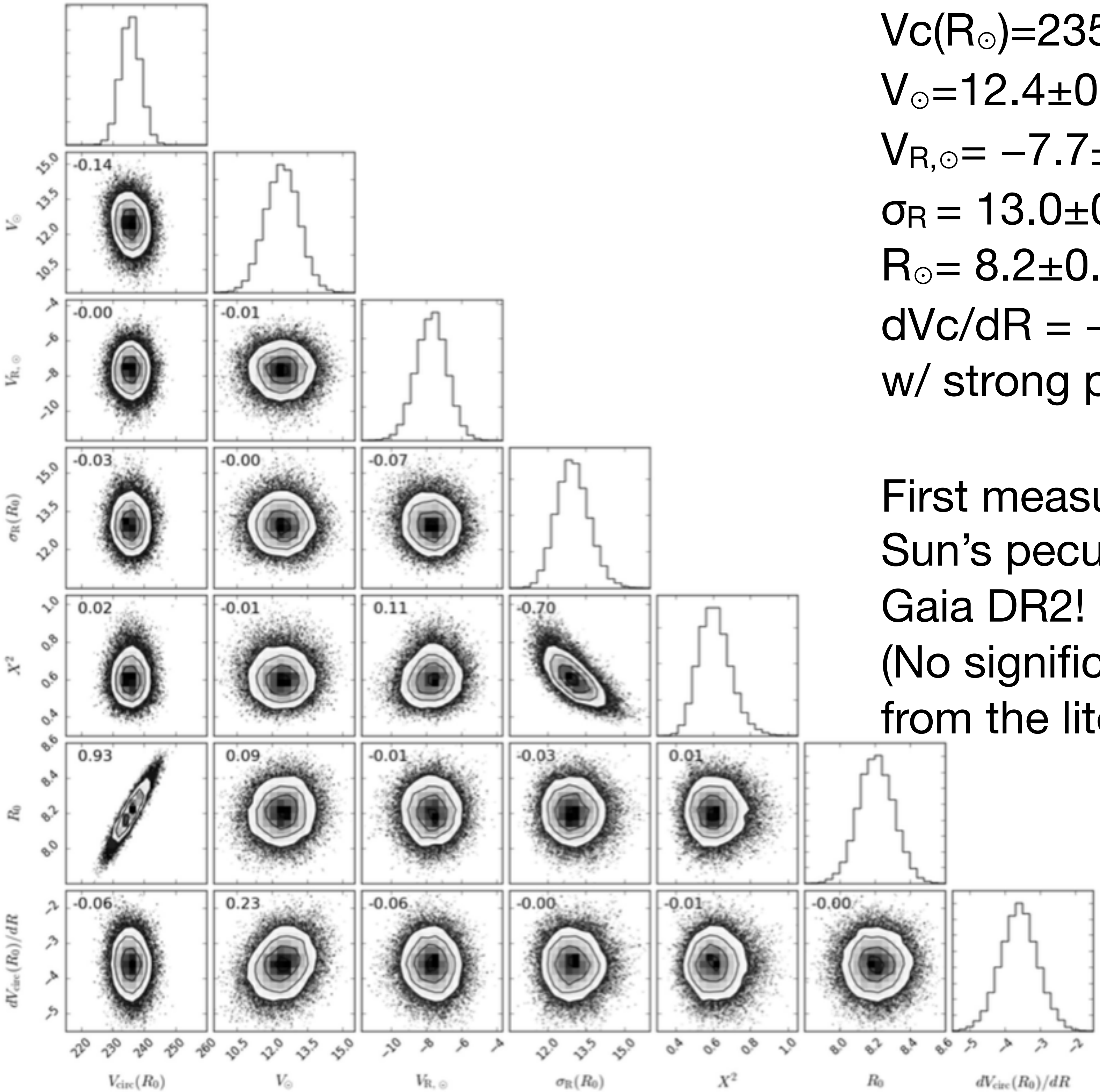
Non-axisymmetric features heavily affecting
the stellar kinematics!

How wrong a naive axisymmetric model can be?

Measuring local rotation curve with Cepheids data (accurate distance) + the DR2 proper motions. Kawata, Bovy, Matsunaga, Baba (2019)



Run MCMC with Likelihood of having an axisymmetric rotation with $V_c(x_\odot, y_\odot)$, $V_{R,\odot}$, $V_{\phi\odot}$, σ_R, σ_ϕ, $R_\odot$ and dV_c/dR.



$V_c(R_\odot)$=235±3 km/s

$V_\odot$=12.4±0.7 km/s

$V_{R,\odot}$= −7.7±0.9 km/s

σ_R = 13.0±0.6 km/s

$R_\odot$= 8.2±0.1 kpc

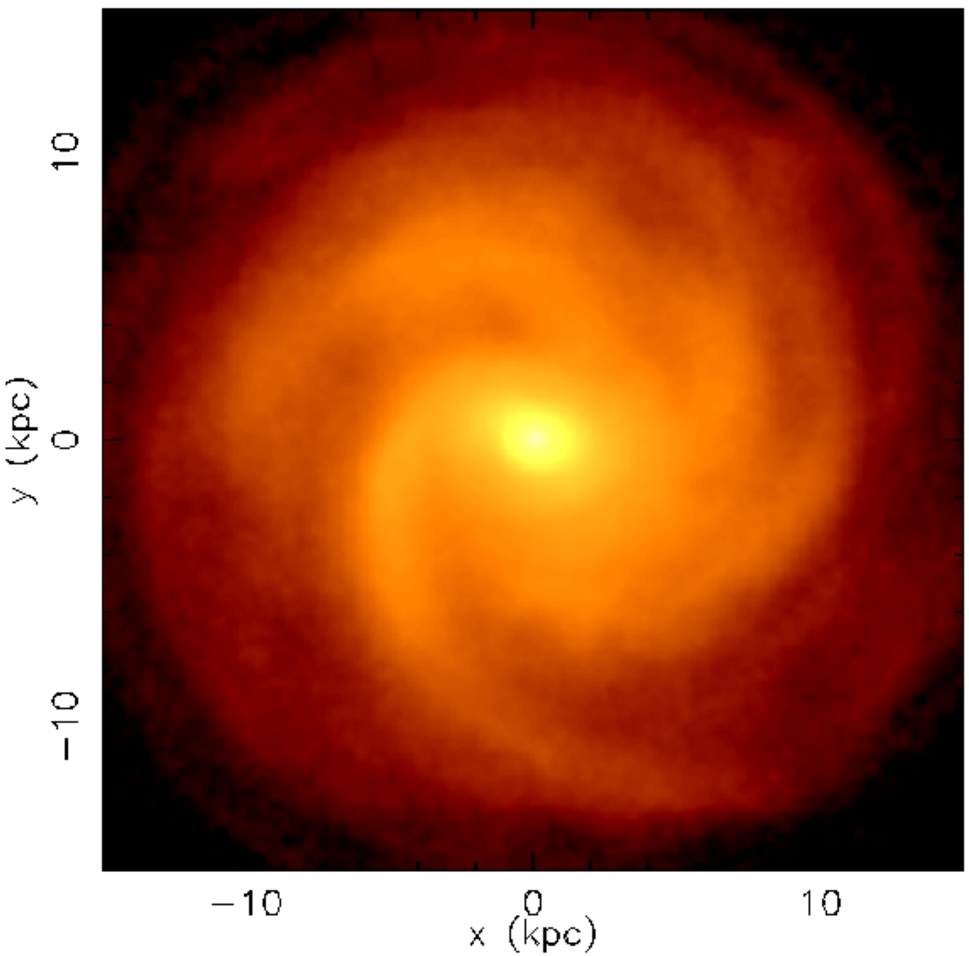
dVc/dR = −3.6±0.5 km/s/kpc

w/ strong prior of $R_\odot$ and $\omega_\odot$

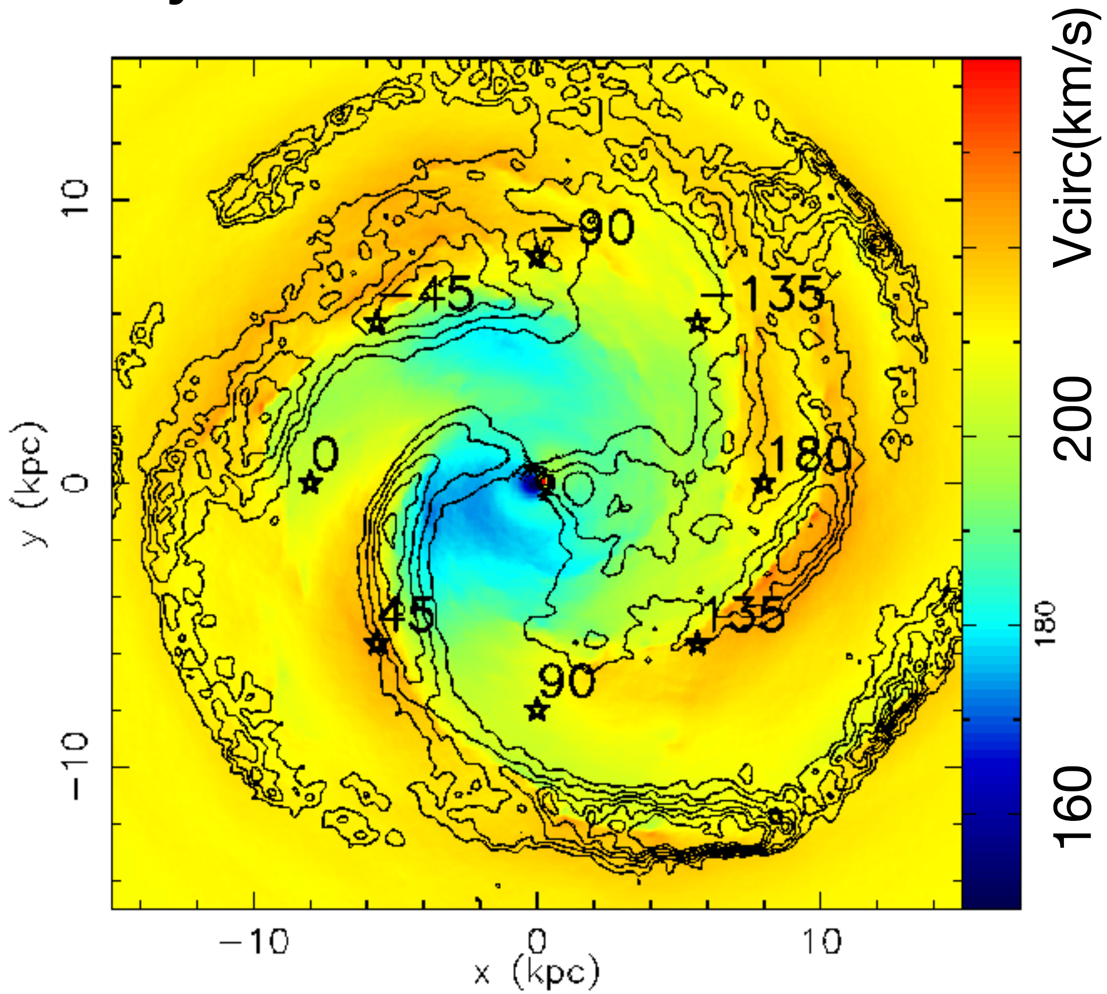
First measurement of Sun's peculiar velocity with Gaia DR2!

(No significant difference from the literature values)

Rotation velocity ("local centrifugal speed") is sensitive to the location! e.g. N-body disk

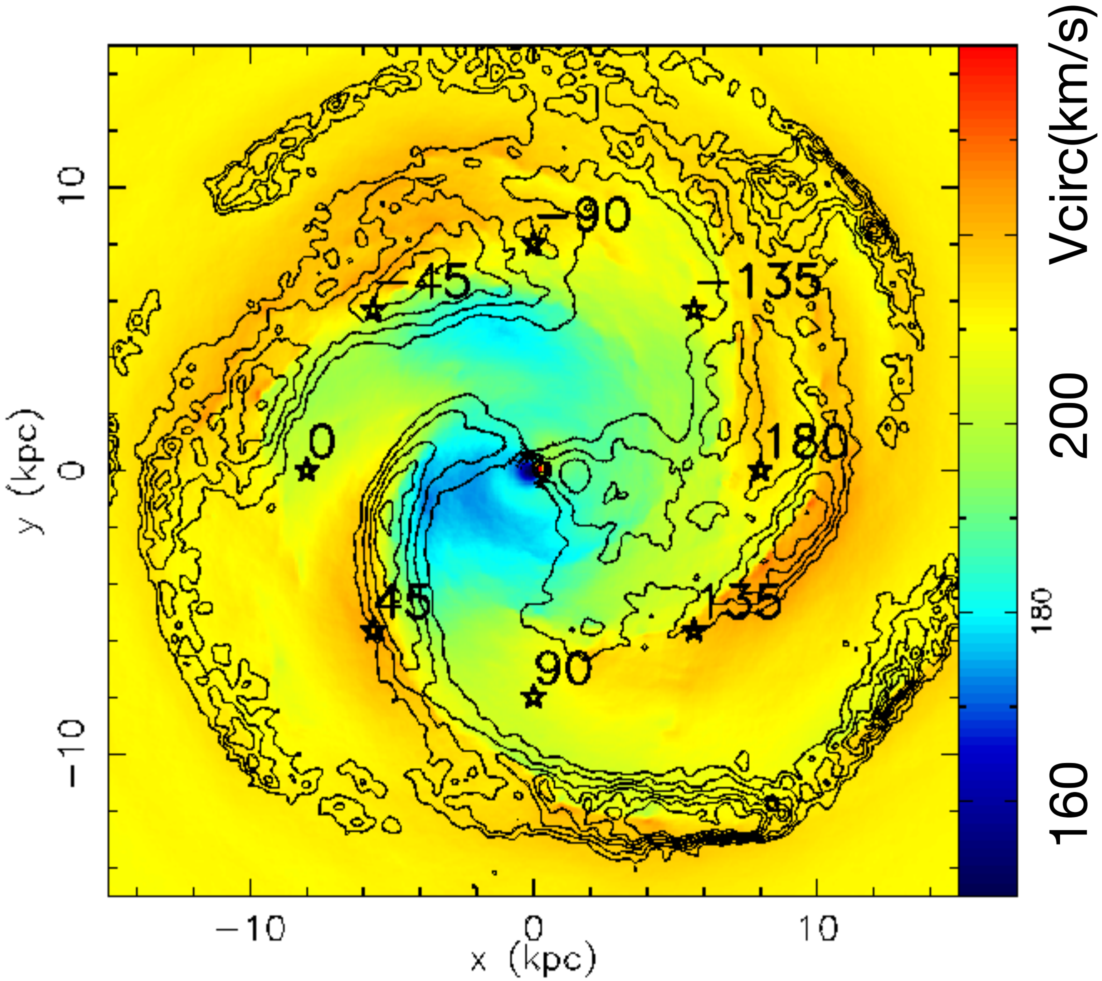


density map



Vcirc=sqrt(Frad x r)

Measurement of local rotation curve, Vc(x,y)



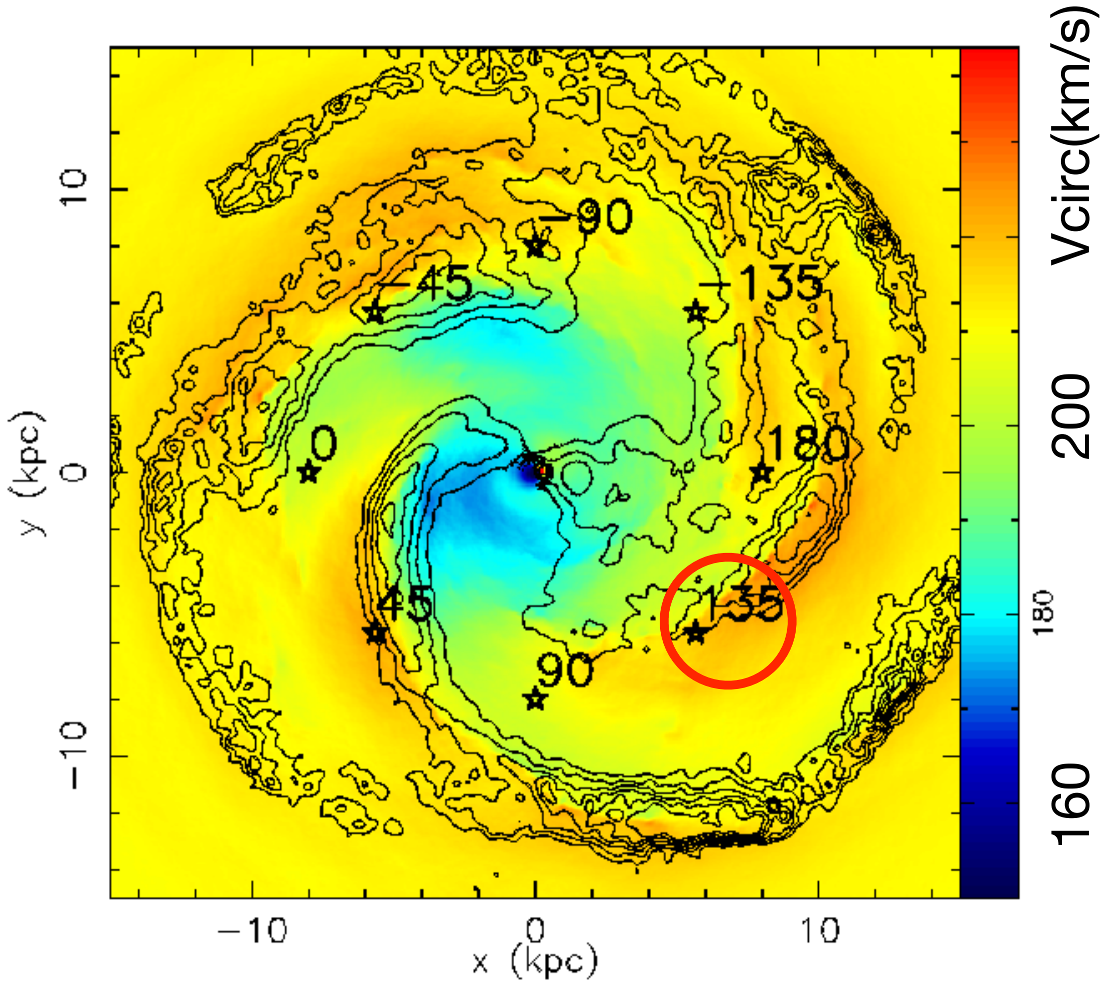
Vcirc=sqrt(Frad x r)

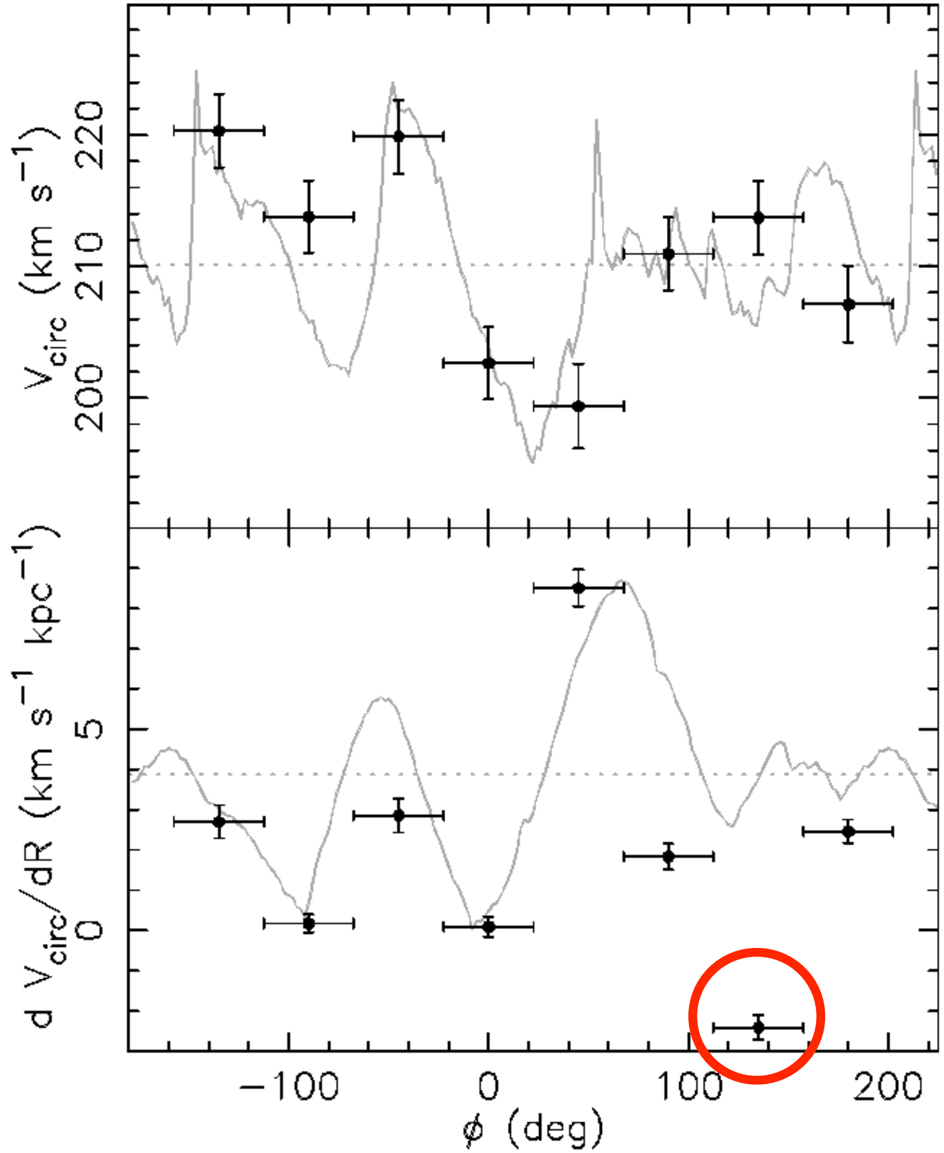
- Sampling stars within D < small distance (3 kpc chosen) from the selected location, x,y, and close to the plane.
- Run MCMC with Likelihood of having an axisymmetric rotation with Vc(x,y), $V_{R,\odot}$, $V_{\phi\odot}$, σ_R, σ_ϕ, $R_\odot$ and dVc/dR.

Vc(x,y) and dVc(x,y) /dR recovered well at inter-arm, but difficult at closer to spiral arms.

Need better model with bar and spiral arm

+ vertical perturbation!





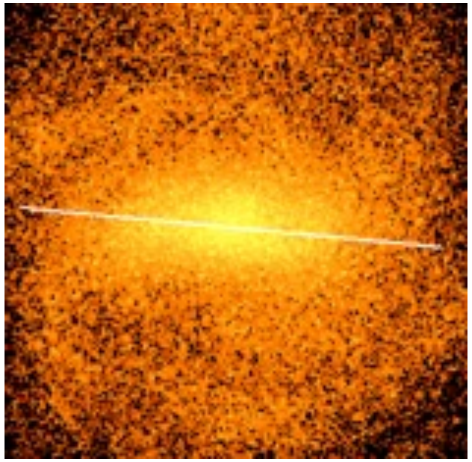
Self-gravity Made-to-Measure (M2M) model!

Made-to-Measure (M2M)

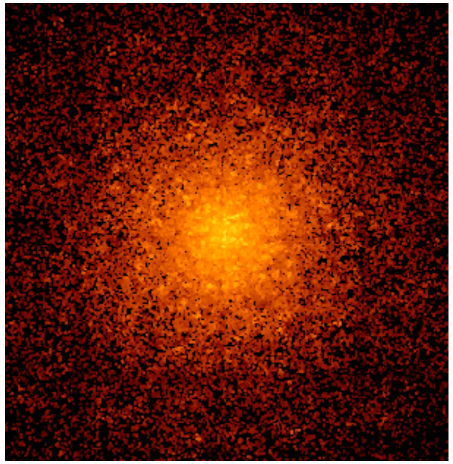
(Syer & Tremaine 1996, de Lorenzi et al. 2007, Long & Mao 2010, Portail et al. 2015,17,18)

N-Body Model or test particle

Observation

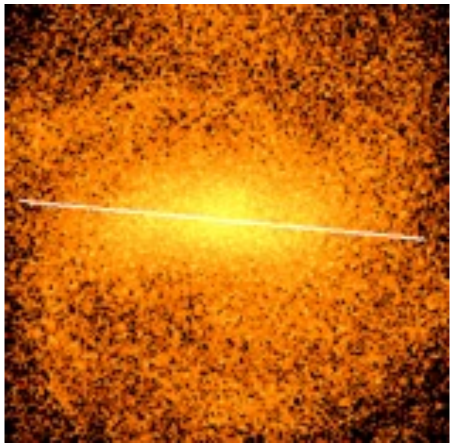


Compare



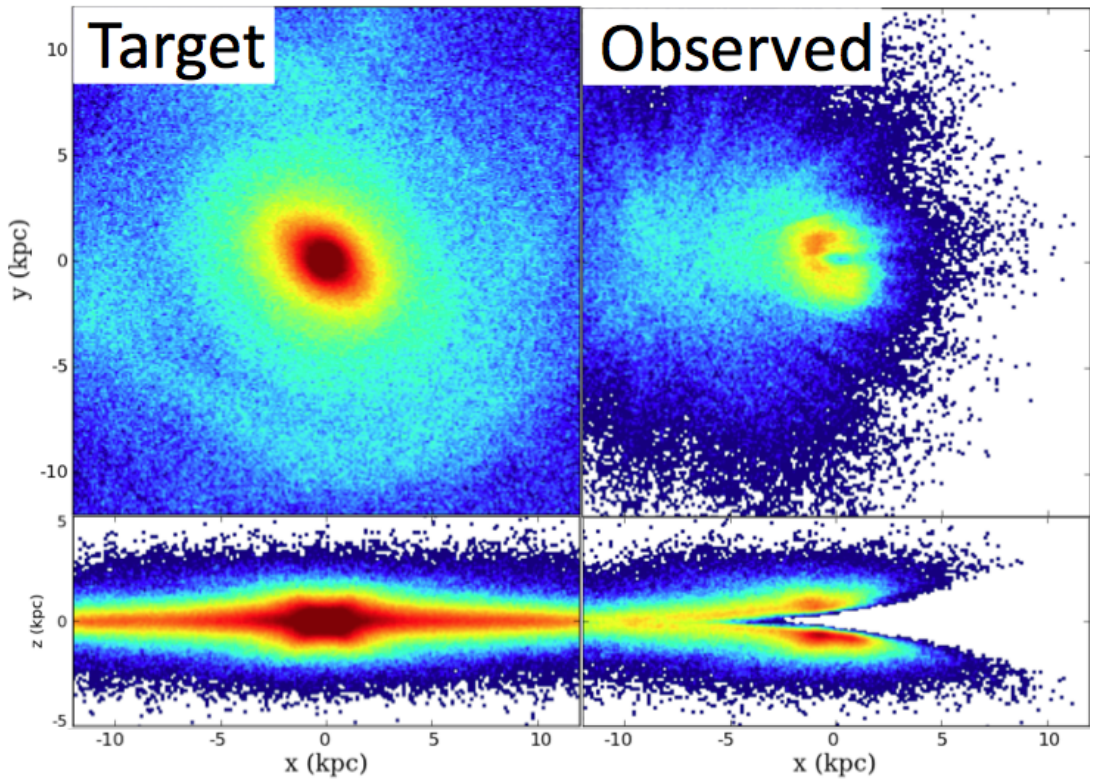
Before

Alter



After

PRIMAL: Testing with mock target disk created with N-body simulations a star particle = M0 giant star +3D extinction and Gaia errors



Target data (V<16 mag) created from N-body simulations

Hunt & Kawata (2014)

M2M in a nutshell

Particle weight, w_i, changes with "force of change"

prior — density X^2 — velocity X^2

$$\frac{\mathrm{d}w_i}{\mathrm{d}t} = \epsilon w_i \left[\frac{\partial S}{\partial w_i} - \frac{1}{2} \sum_j \frac{\partial \chi^2_{j,\nu}}{\partial w_i} - \frac{1}{2} \sum_j \frac{\partial \chi^2_{j,v}}{\partial w_i} \right]$$

e.g. density X^2

model density at j → $\nu(\tilde{z}_j)$; observed density at j → ν_j^{obs}

$$\chi^2_{j,\nu} = [\Delta_j^\nu / \sigma_{\nu,j}]^2 = \left(\nu(\tilde{z}_j) - \nu_j^{\mathrm{obs}}\right)^2 / \sigma^2_{\nu,j}$$

uncertainty in v^{obs}_j

If $\Delta_j > 0$, decrease w_i. If $\Delta_j < 0$, increase w_i.

An advanced M2M: fitting Nuisance parameters
(Bovy, Kawata, Hunt 2018)

e.g. solar vertical distance from the disk plane, $z_\odot$.

$$\frac{\mathrm{d}z_\odot}{\mathrm{d}t} = \epsilon_\odot \left[-\frac{1}{2} \sum_j \frac{\partial \chi^2_{j,\nu}}{\partial z_\odot} - \frac{1}{2} \sum_j \frac{\partial \chi^2_{j,v}}{\partial z_\odot} \right]$$

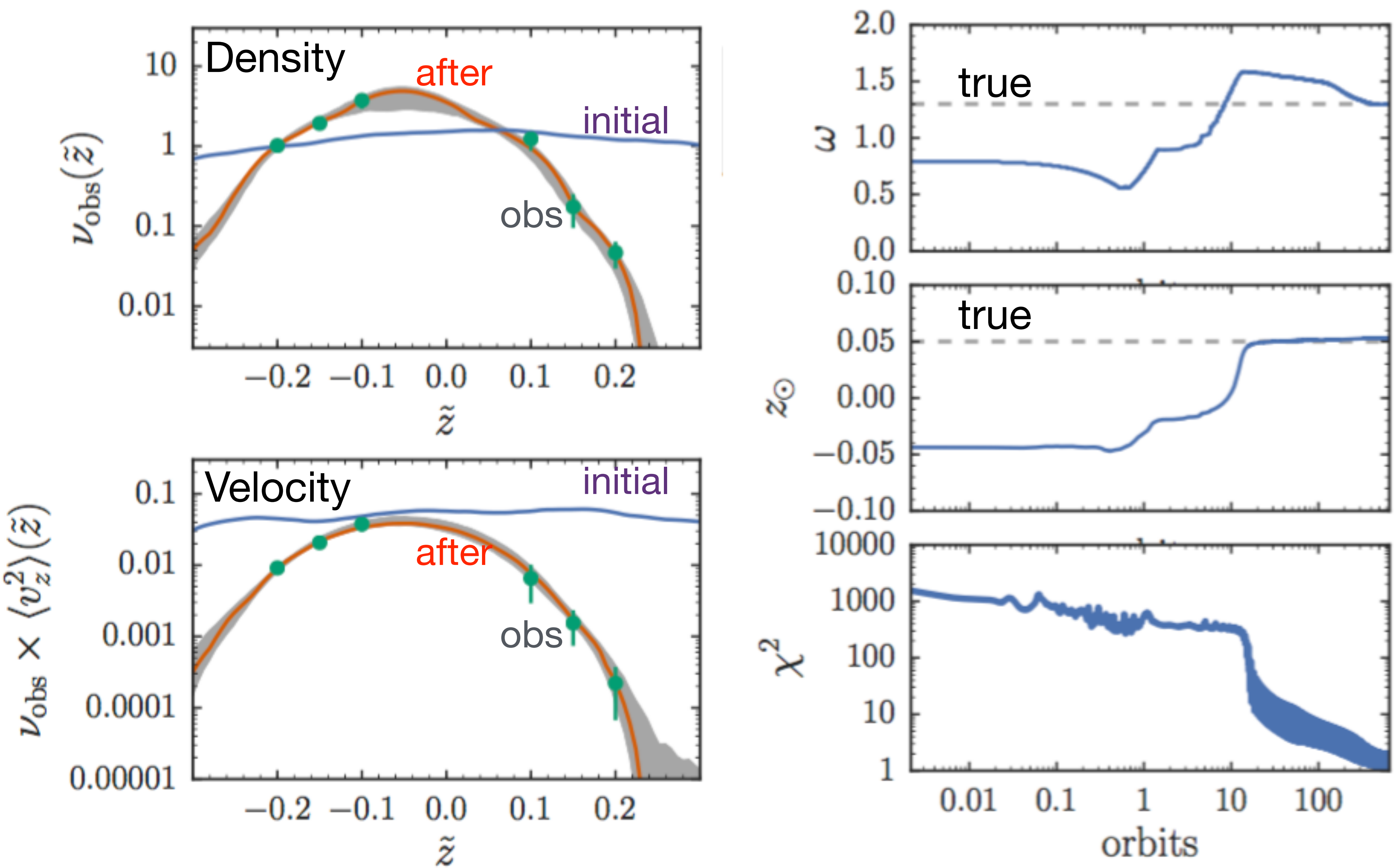
If $\partial X^2/\partial p$ can be calculated (even numerically), parameter p is adjustable with M2M algorithm.

Potentially adjustable parameters:

- solar position and proper motions, $z_\odot$, $R_\odot$, $U_\odot$. $V_\odot$. $W_\odot$
- DM density profile, e.g. total mass, core size, slope
- Bar pattern speed and viewing angle

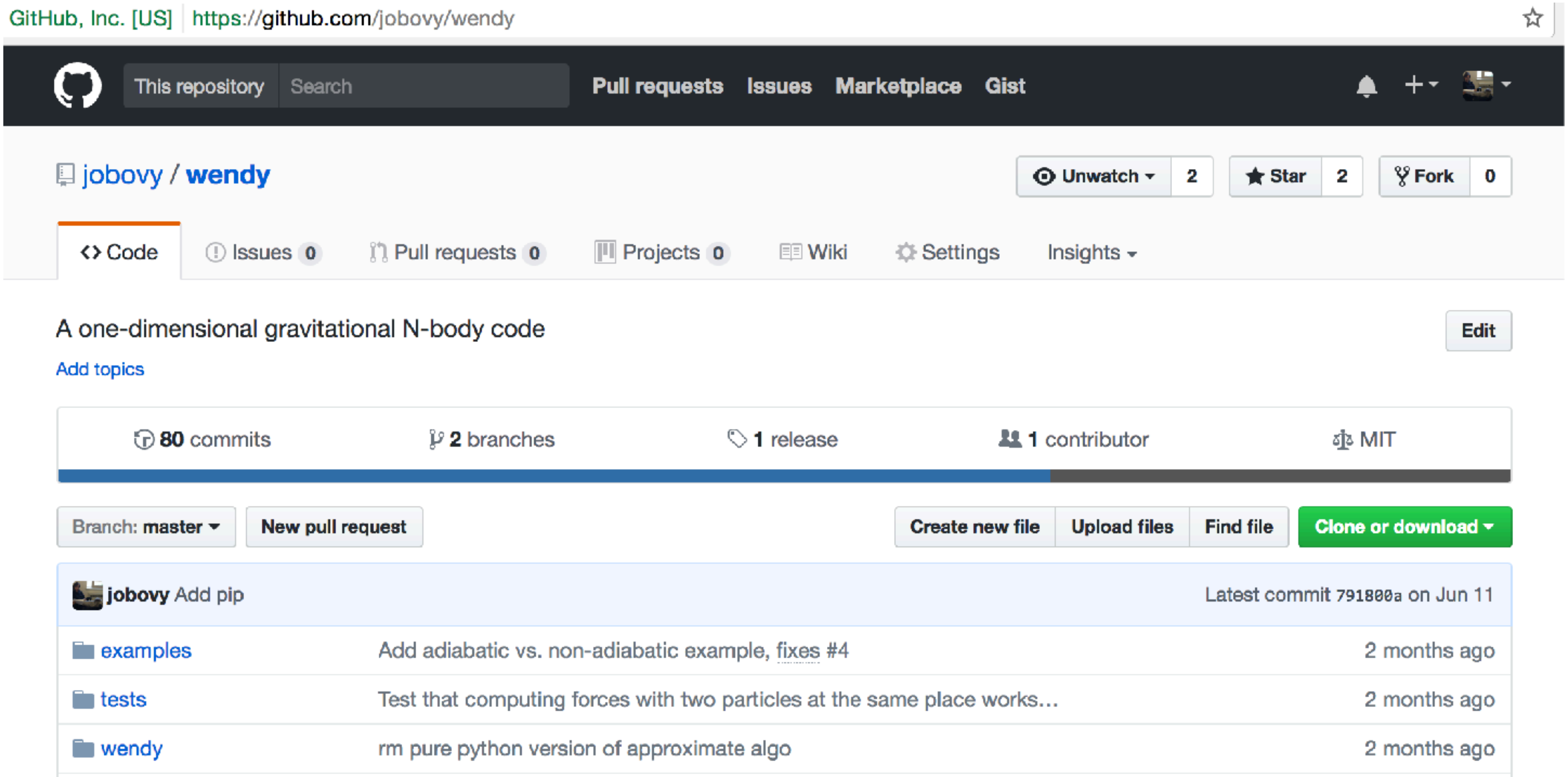
Proof-of-concept: 1D Harmonic Oscillator model

observer's position $z_\odot$ and frequency (potential constant) ω



Bovy, Kawata, Hunt (2018)

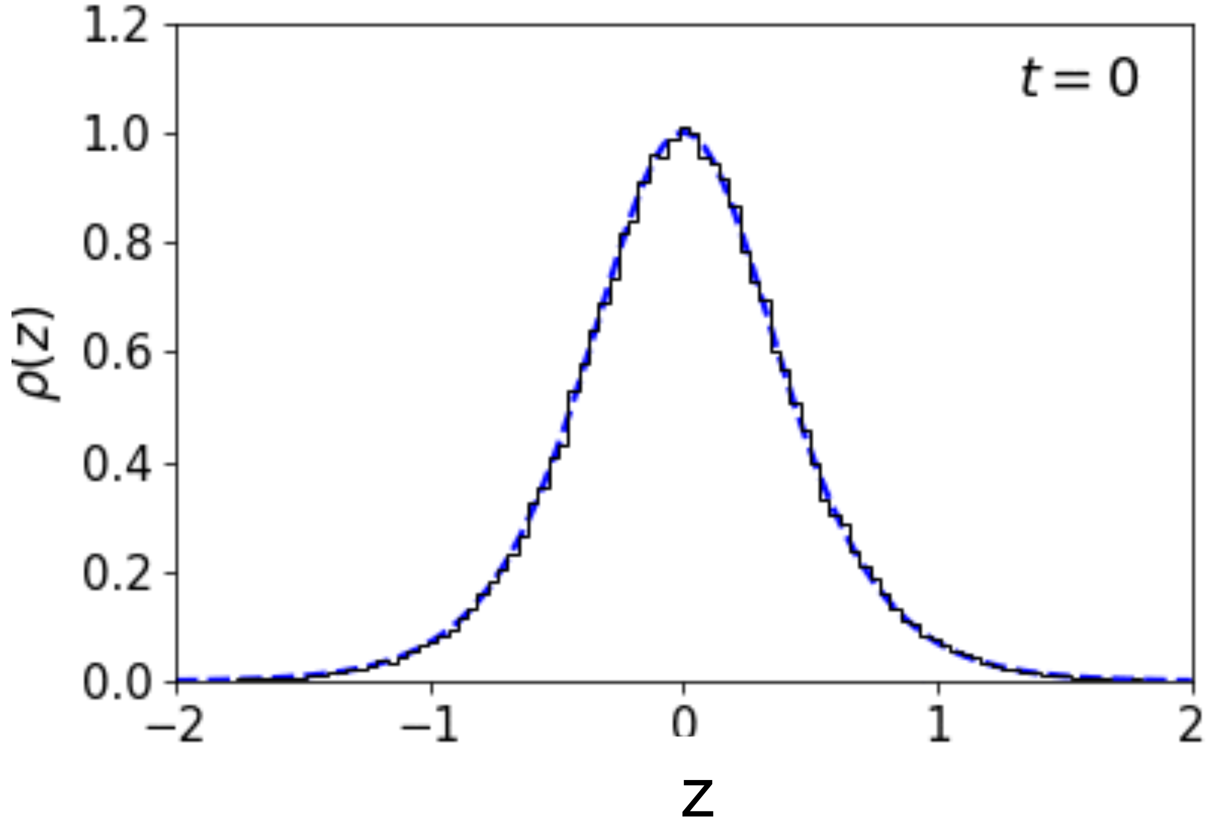
1D self-gravity M2M with Wendy 1D N-body model, Wendy (Bovy github)

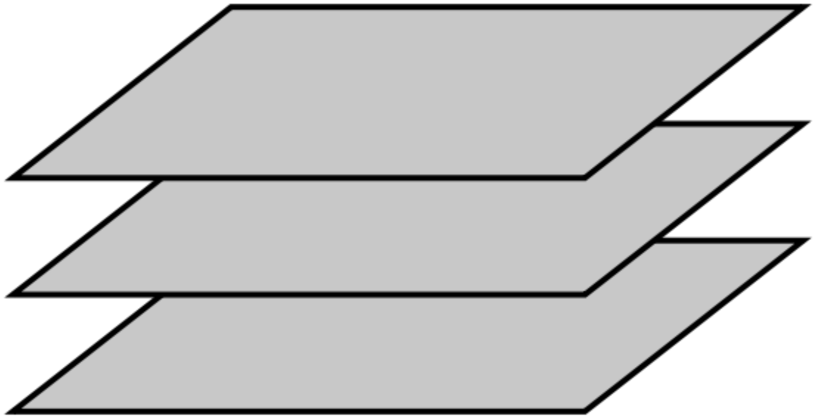


Target: 1D “vertical disk structure” with 1D N-body

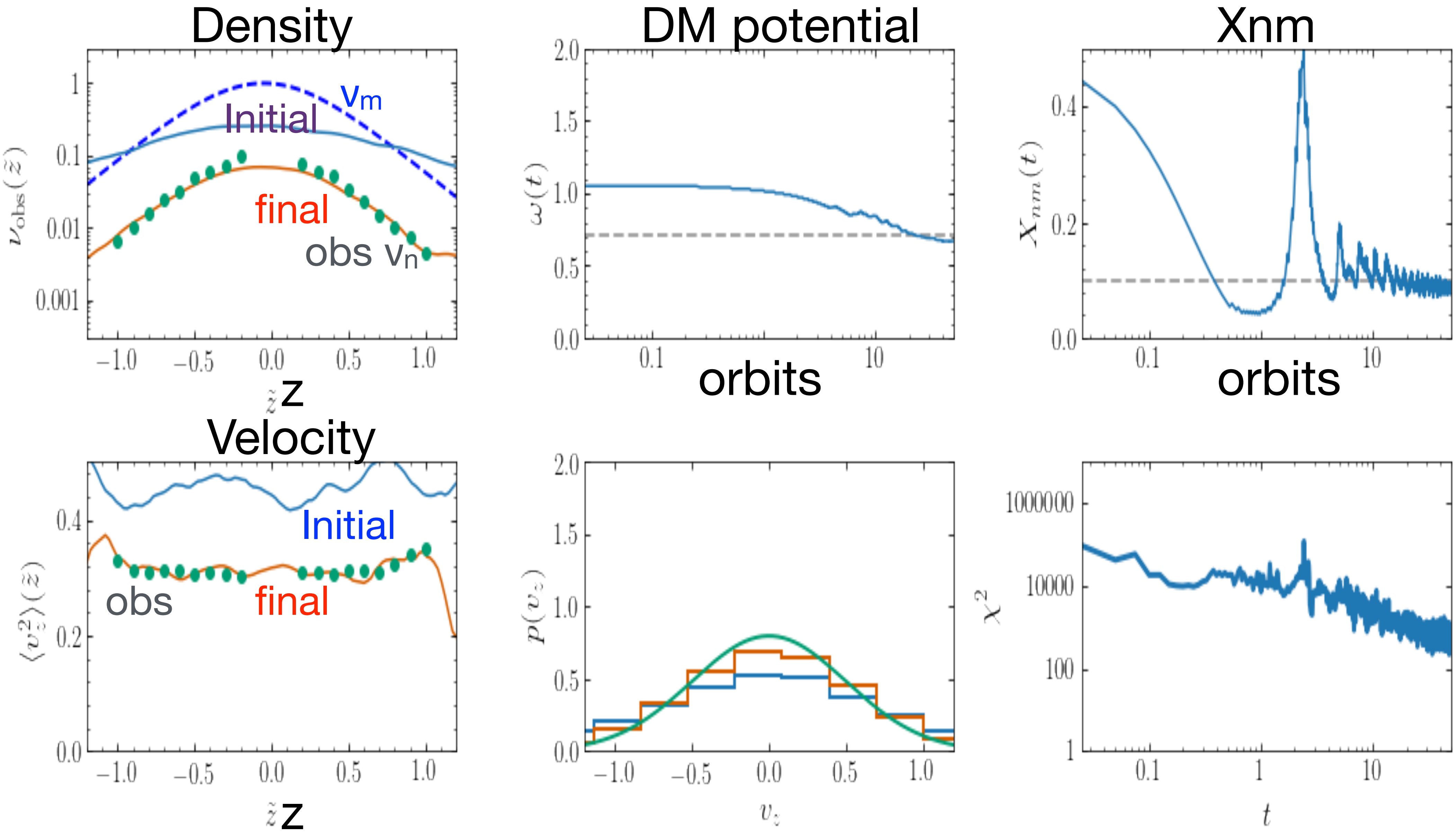
$\rho(z) = \rho_0 \,\mathrm{sech}^2\left(\frac{z}{2H}\right)$ disk, adding DM potential of

$$\Phi_{\rm DM} = \omega^2 z^2/2$$

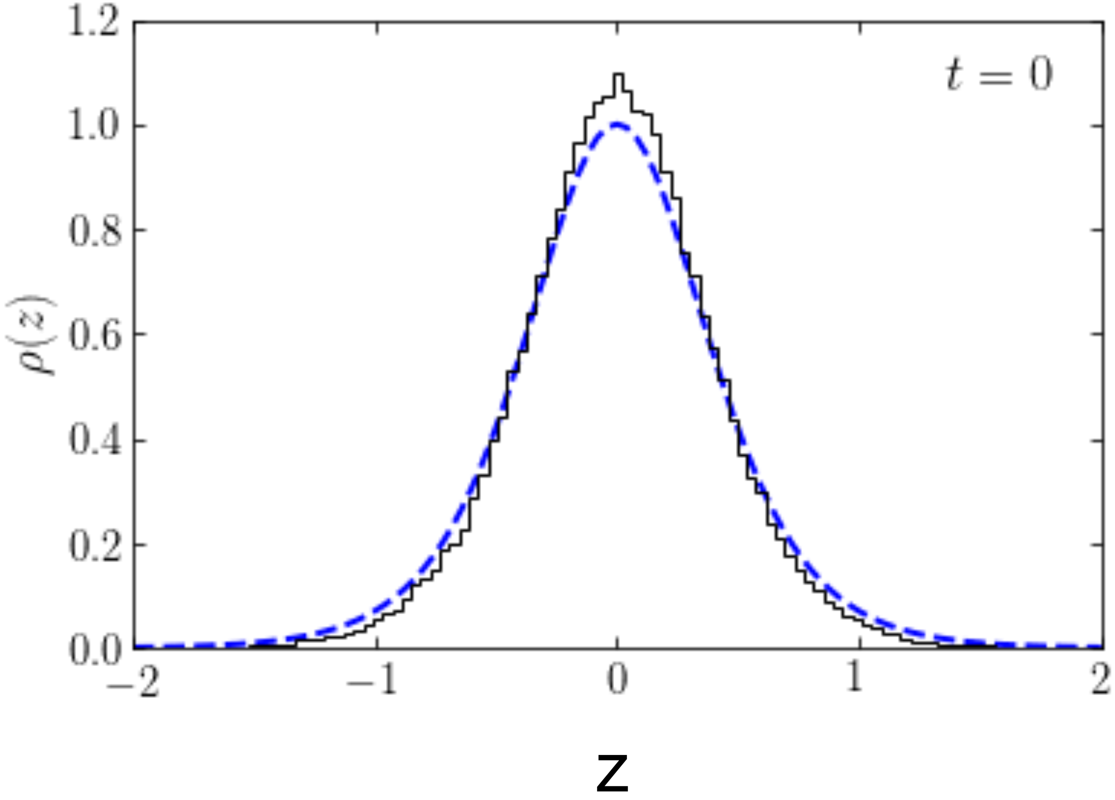


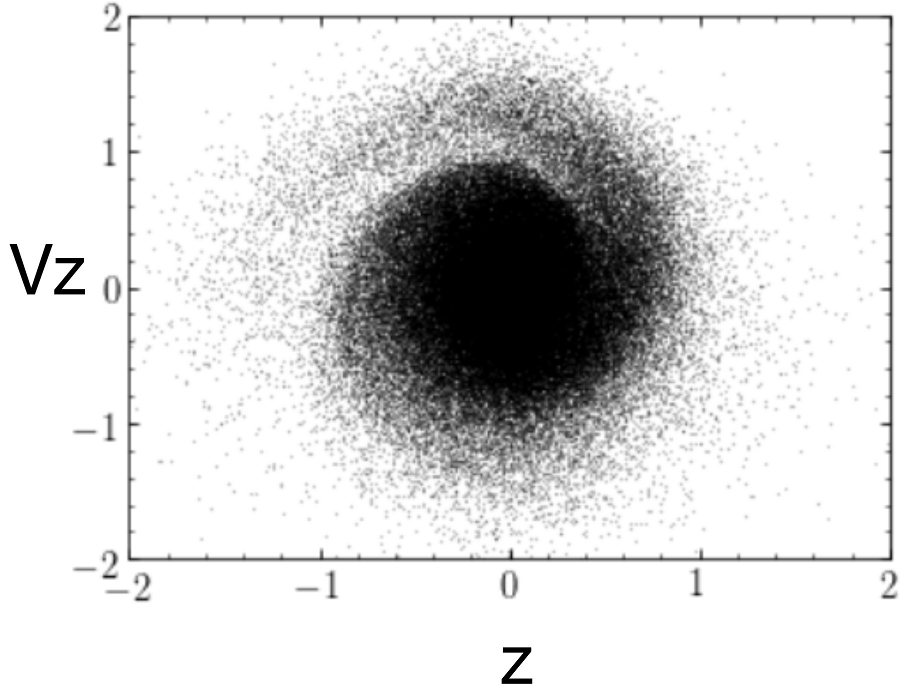


WendyM2M can fit both DM potential and Xnm=Ms/Nobs

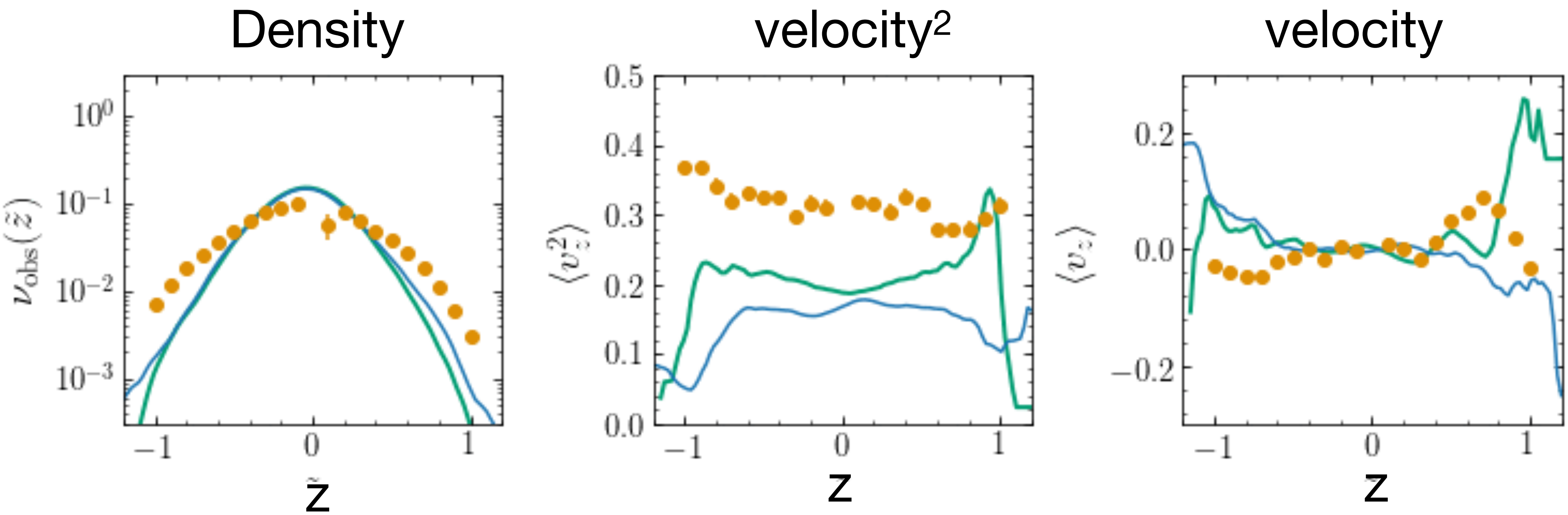


Target: 1D "vertical disk structure" with 1D N-body + perturbation (a heavy sheet passing through)

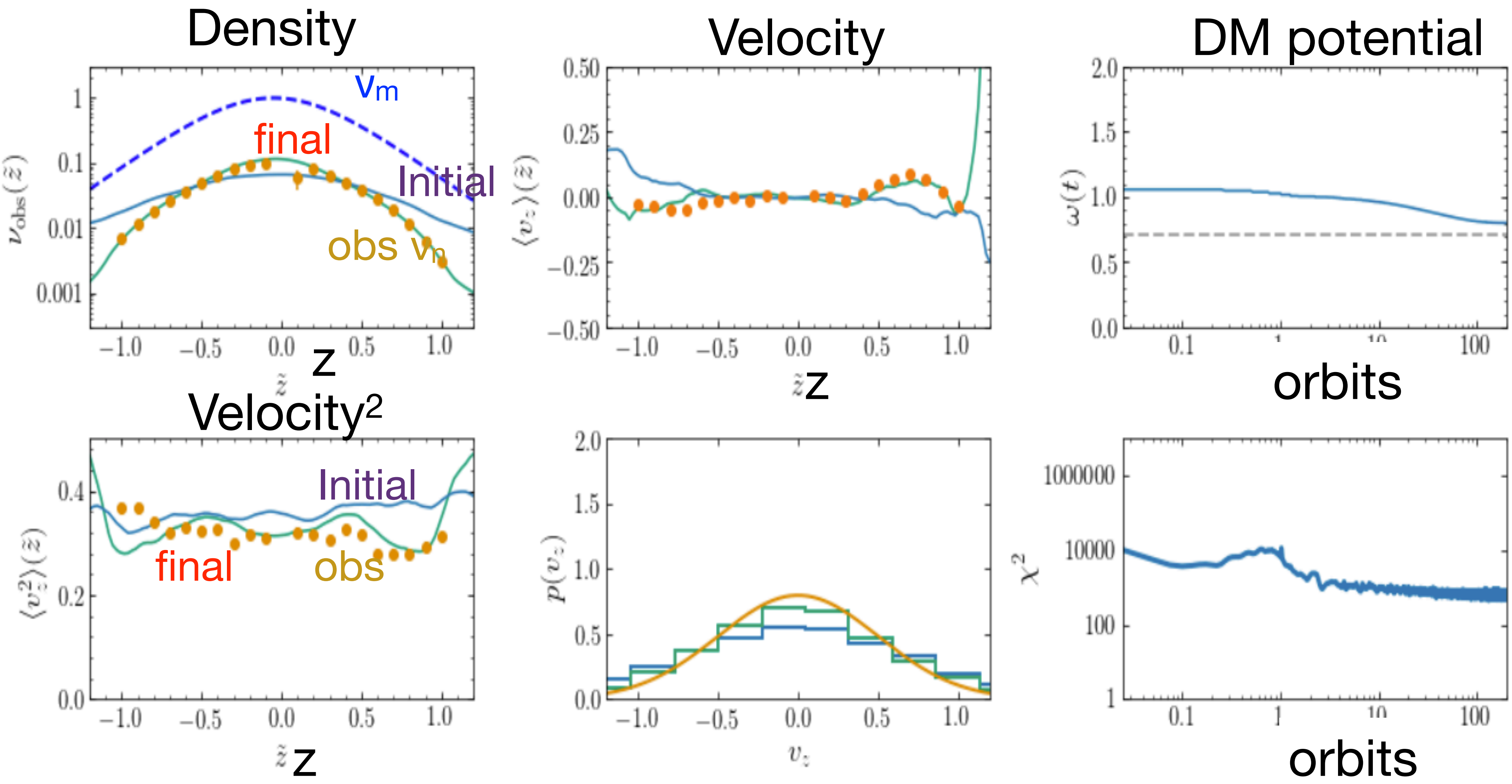




M2M fit with “known” DM potential and Xnm=Ms/Nobs
Good recovery of density and velocity,
though they are not in equilibrium.



Fitting both DM potential with known Xnm=Ms/Nobs ongoing…



Future: multiple populations, 3D modelling