WEIGHING THE GALACTIC DISK USING PHASE-SPACE SPIRALS

DARK

AXEL WIDMARK

arXiv:2102.08955 — A&A 650, A124 (2021)

Weighing the Galactic disk using phase-space spirals: I. Tests on one-dimensional simulations

A. Widmark[1], C. Laporte[2], and P.F. de Salas[3]

arXiv:2105.14030 — A&A 653, A86 (2021)

Weighing the Galactic disk using phase-space spirals: II. Most stringent constraints to a thin dark disk using Gaia EDR3

A. Widmark[1], C. Laporte[2], P.F. de Salas[3], and G. Monari[4]

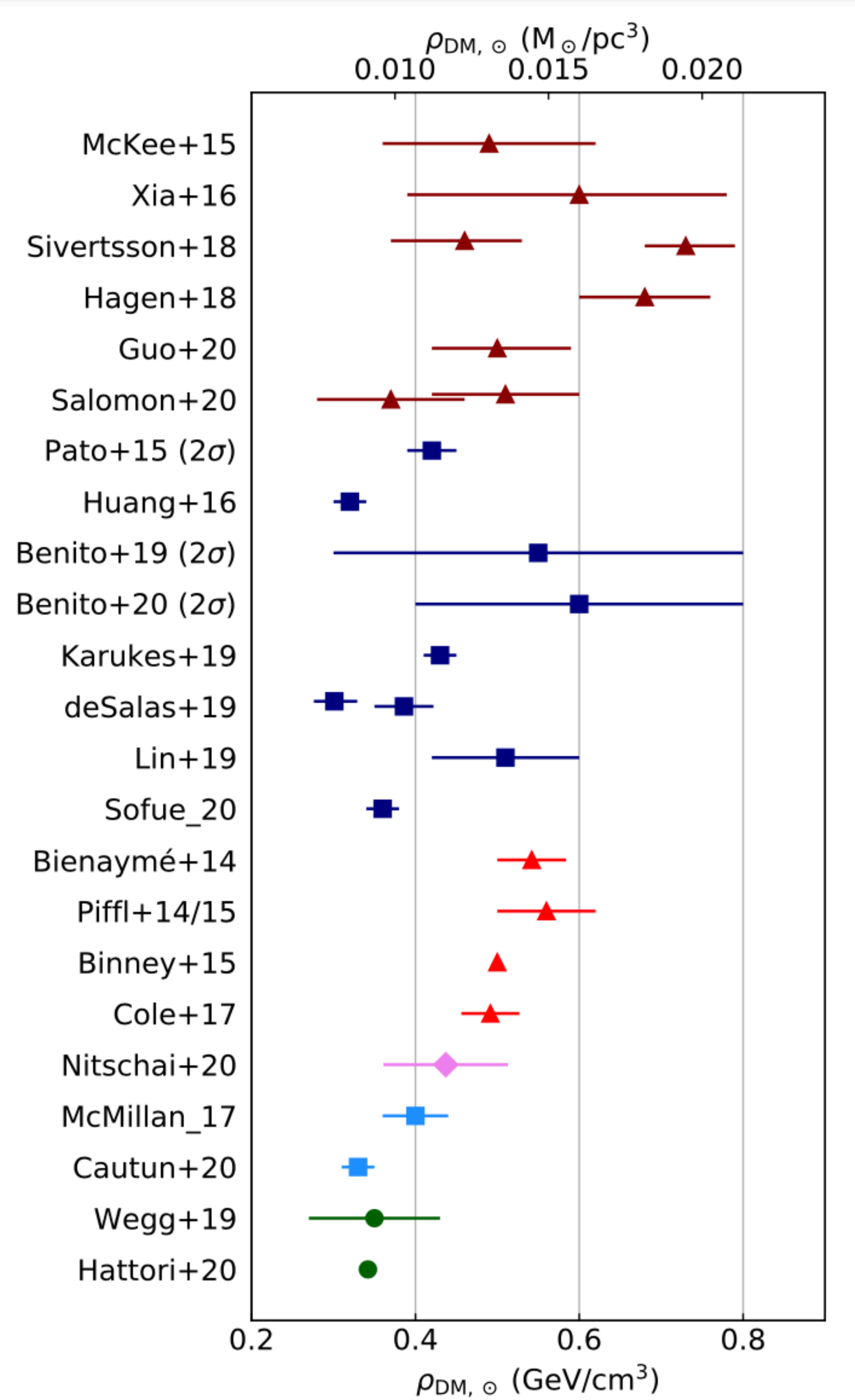
Chervin Laporte

Pablo Fernández de Salas

Giacomo Monari

BACKGROUND

- Dynamical mass measurements are important for understanding the Milky Way in general, and more specifically in terms of its dark matter
    - The local density of dark matter is a crucial quantity for indirect and direct dark matter detection experiments
    - We might be left with gravitational information for a long time, but gravitational probes could themselves shed light on the particle nature of dark matter (substructure, subhalos, cusp/core, dark matter self-interaction, thin dark disk)
- Steady state measurements have been in use for a century (other methods use stellar streams, direct stellar acceleration measurements)
- However, the Milky Way is host to non-equilibrium structures, which has become especially clear with the *Gaia* survey
- “The data has surpassed the models” – we need to think about new ways of modelling and extracting information from our increasingly complex image of the Milky Way



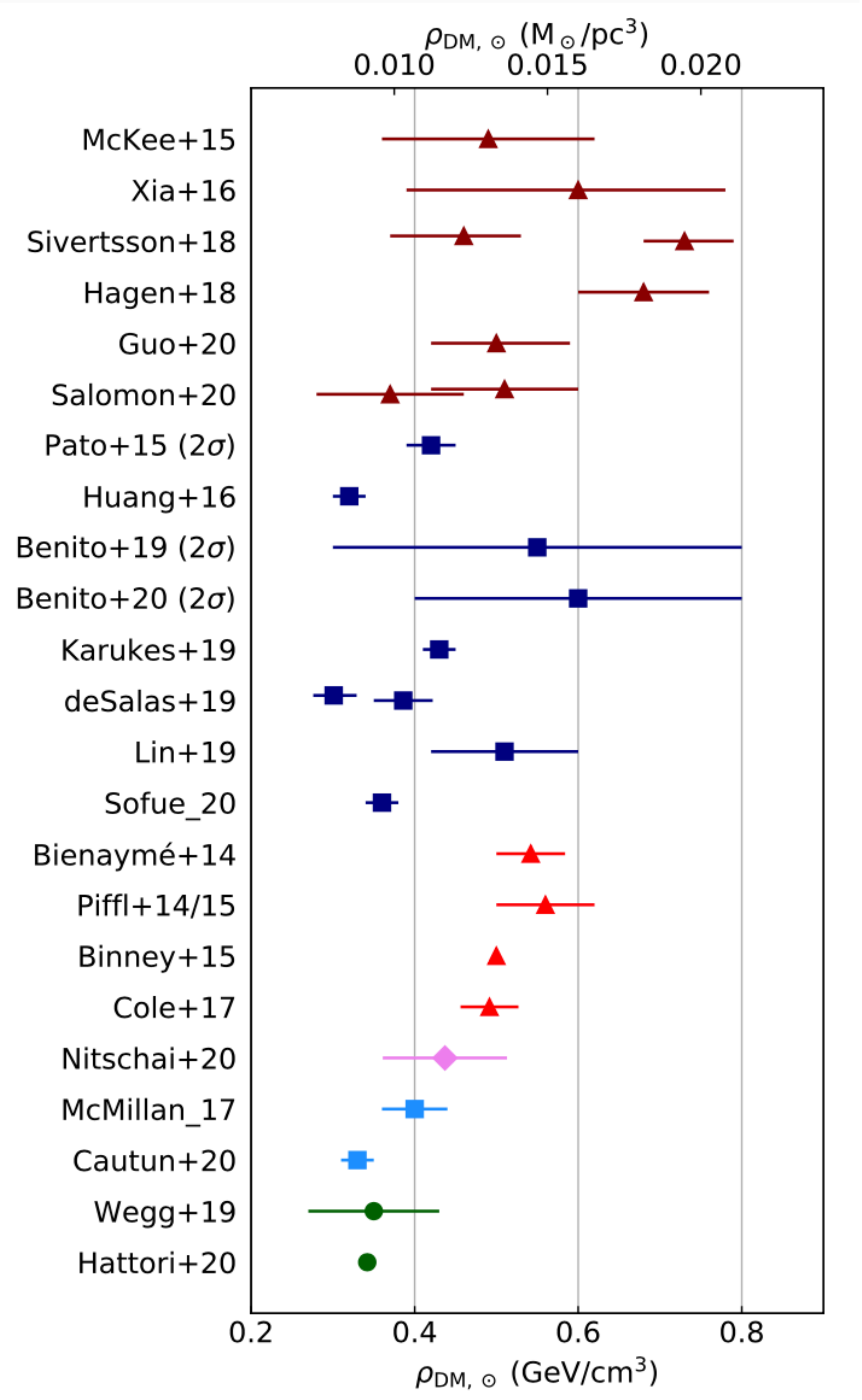
arXiv:2012.11477

Dark matter local density determination: recent observations and future prospects

Pablo Fernández de Salas, Axel Widmark
Accepted for publication in ROPP

- ▲ Local modelling of disk
- ■ Circular velocity curve
- ▲ Global models & local observations
- ◆ Global models & circ. vel. curve
- ■ Jeans anisotropic modelling of disk
- ● Halo stars

Very local analyses are missing from list, for which $\rho_{DM,\odot}$ uncertainties are large



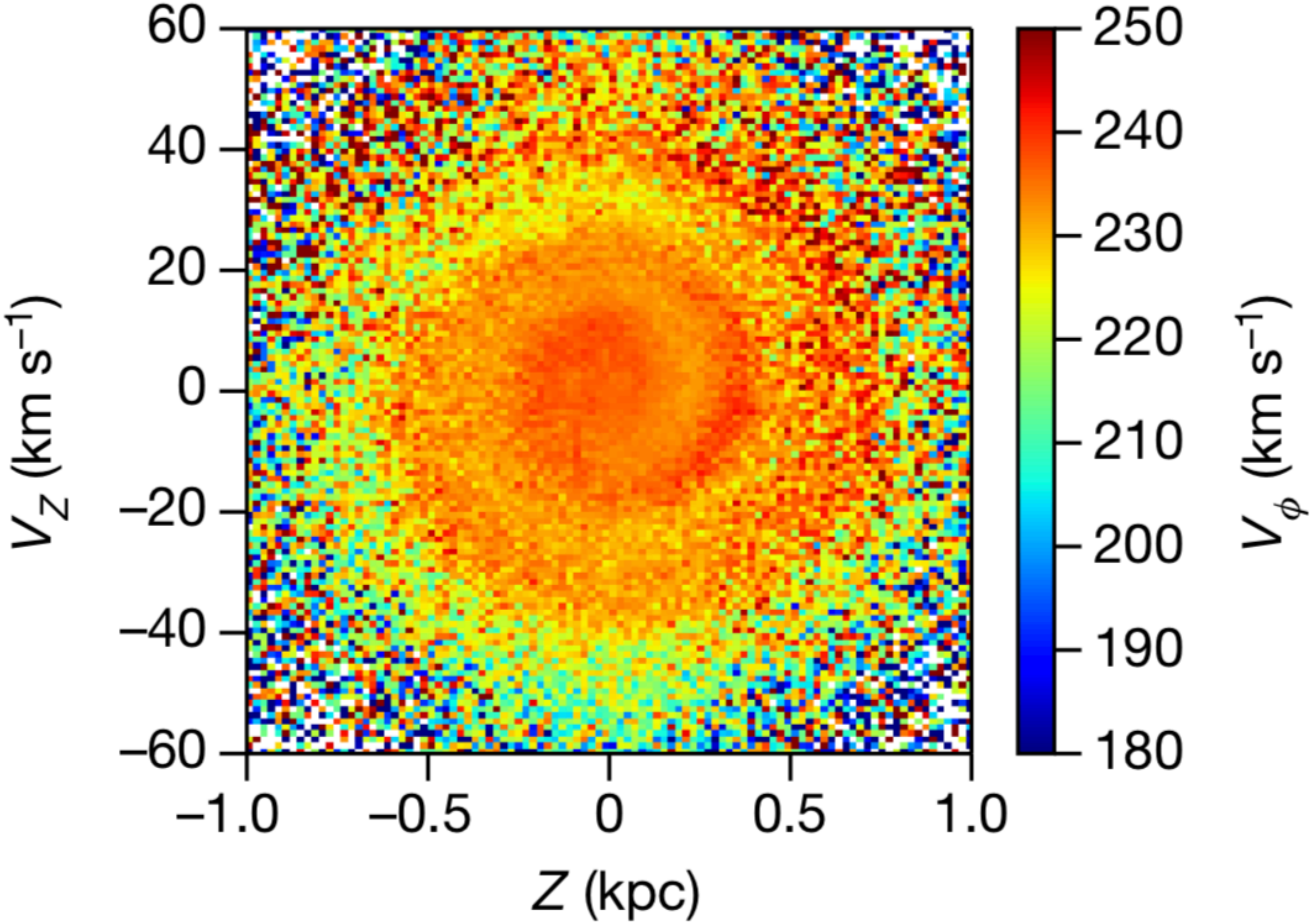
arXiv:2012.11477

Dark matter local density determination: recent observations and future prospects

Pablo Fernández de Salas, Axel Widmark
Accepted for publication in ROPP

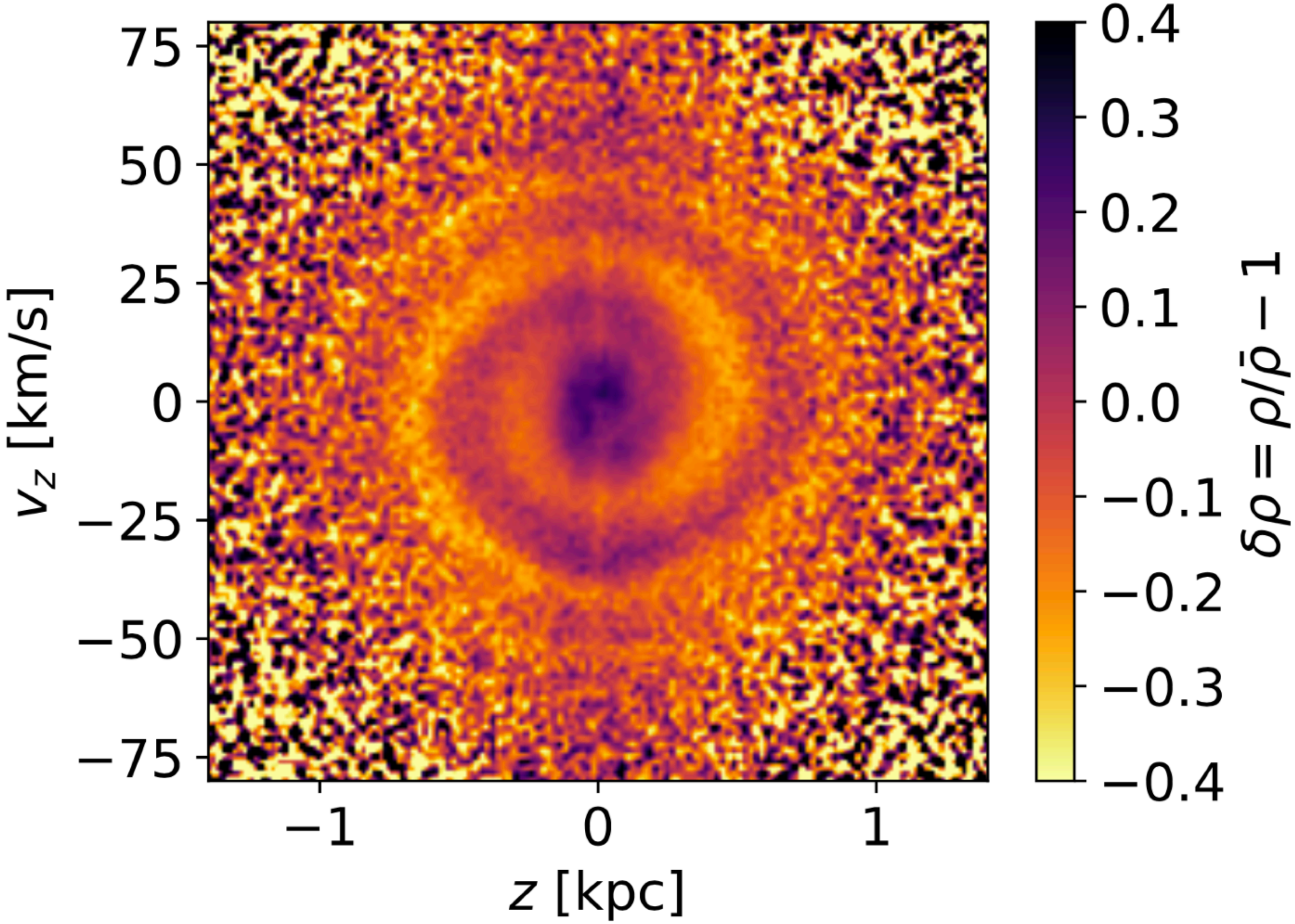
- Results are inconsistent; uncertainties must be underestimated
- This highlights the need to go beyond the common assumptions of an “Ideal Galaxy”: steady state, axisymmetry, mirror symmetry across the Galactic plane
- Uncertainties associated with the baryonic distribution are still significant (if not dominant), and often underestimated

THE LOCAL PHASE-SPACE SPIRAL



Antoja et al., Nature **561** (2018) 360–362

THE LOCAL PHASE-SPACE SPIRAL



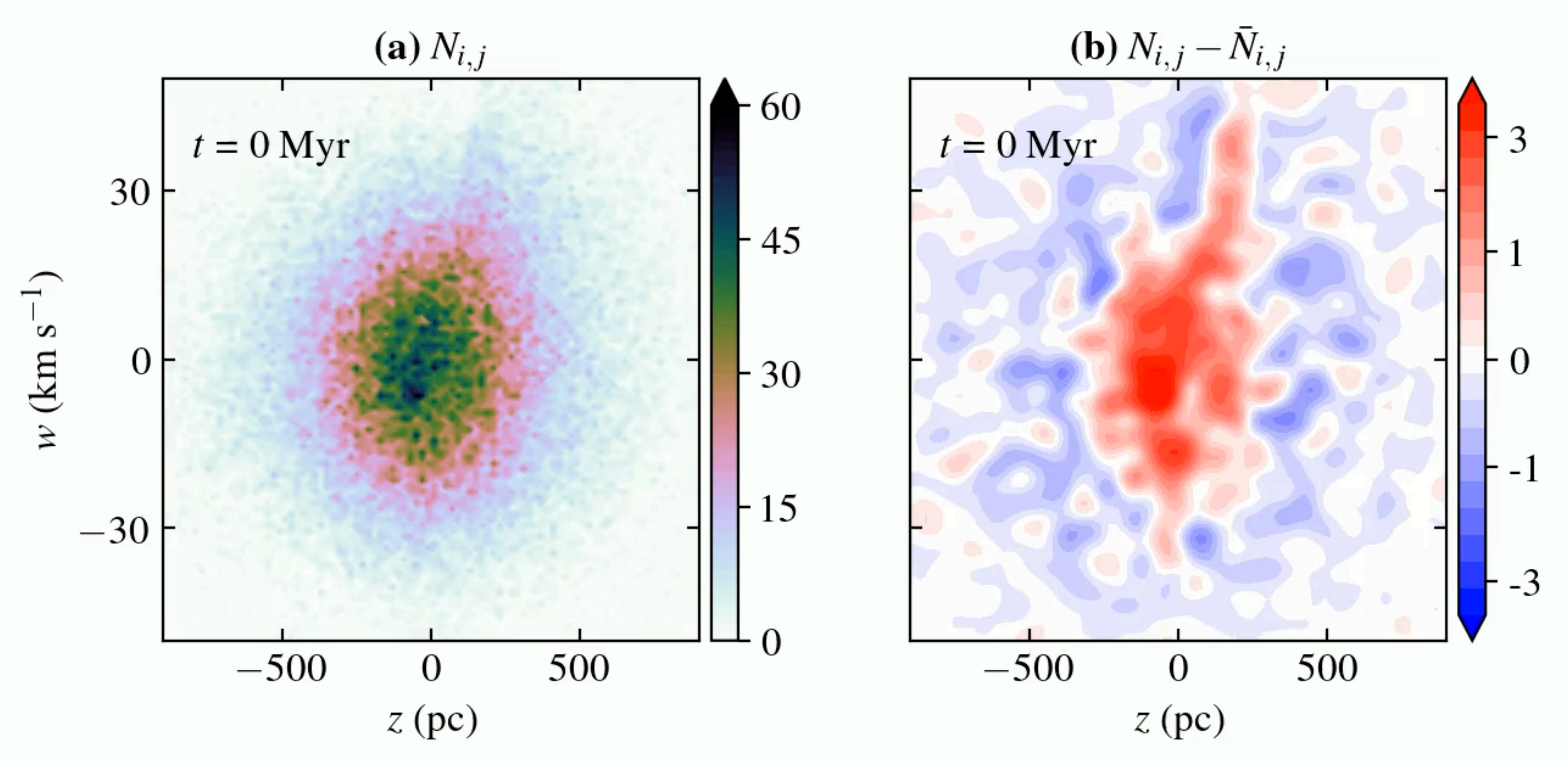
Laporte et al., MNRAS **485** (2019) 3134–3152

BEYOND EQUILIBRIUM

- It’s possible to model the dynamics and measure the mass of a time-varying system
- In the absence of a steady state, we must make some other strong assumption:
  - Quasi steady state, 1st order perturbation
  - Something is conserved (e.g. the orbits of stellar streams)
  - Strong prior on initial conditions (e.g. BORG, large-scale structure formation, Gaussian prior)
  - External forces acting on the system are known over time-scales longer than the equilibration time

GENERAL PRINCIPLES

MAKING A SPIRAL



MODELLING ASSUMPTIONS

1. Separability of the vertical dimension (1d approximation)
2. The spiral inhabits a static gravitational potential (neglecting self-gravity)
3. The perturbation that gives rise to the spiral has no initial winding

ANALYTIC MODEL

Gravitational potential

$$\Phi(z) = \sum_{h=1}^{4} \frac{4\pi G \rho_h}{(2^{h-1} \times 100\ \mathrm{pc})^2} \log\left[\cosh\left(\frac{z}{2^{h-1} \times 100\ \mathrm{pc}}\right)\right]$$

Total matter density

$$\rho(z) = \sum_{h=1}^{4} \rho_h \cosh^{-2}\left(\frac{z}{2^{h-1} \times 100\ \mathrm{pc}}\right) + \Delta\rho$$

Period as function of vertical energy

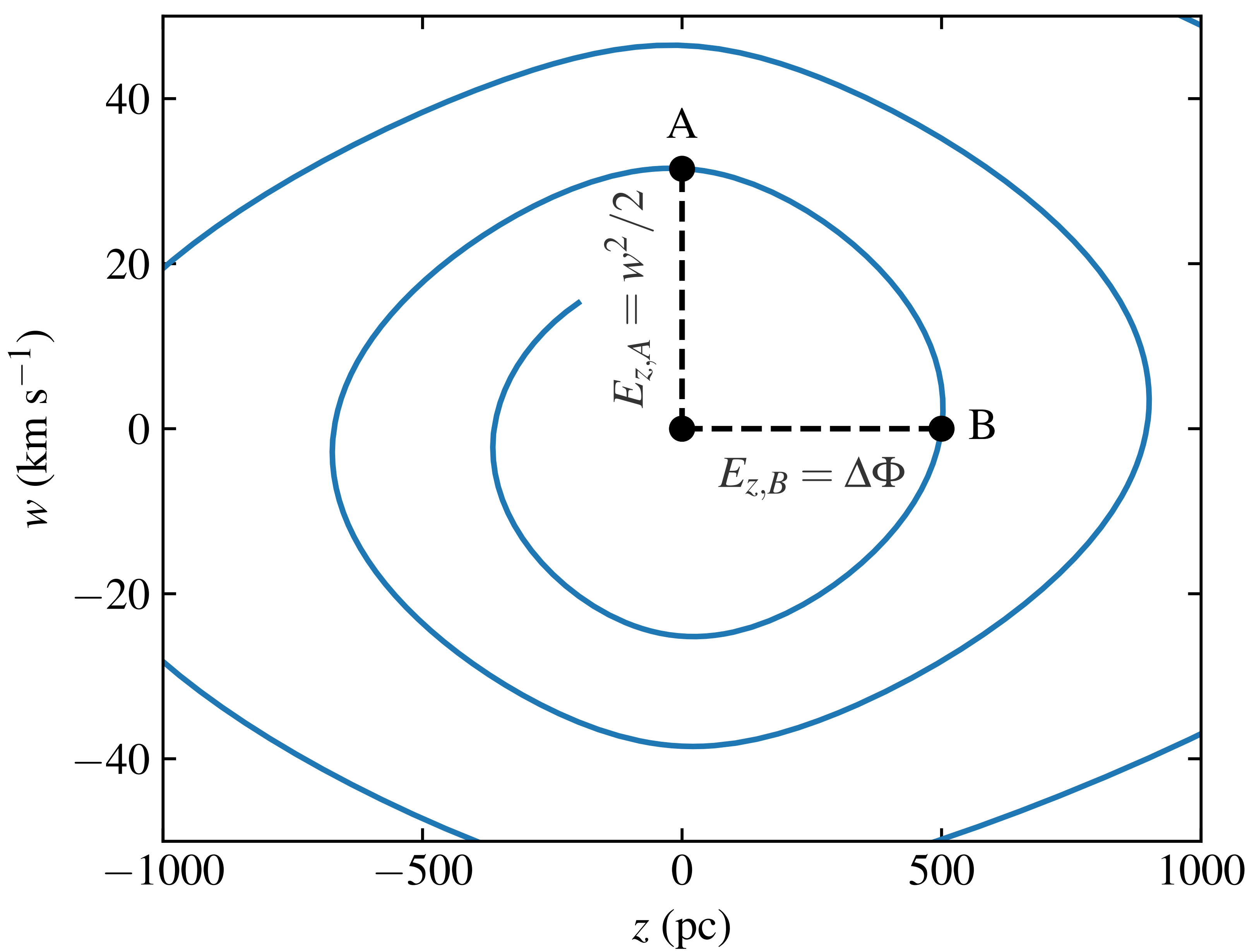
$$P(E_z \,|\, \Phi) = \oint \frac{dz}{w} = 4 \int_0^{z_{\max}} \frac{z}{\sqrt{E_z - \Phi(z)}}$$

Spiral angle

$$\tilde{\varphi}(t, E_z \,|\, \Phi, \tilde{\varphi}_0) = \tilde{\varphi}_0 + 2\pi \frac{t}{P(E_z \,|\, \Phi)}$$

A SIMPLE EXAMPLE

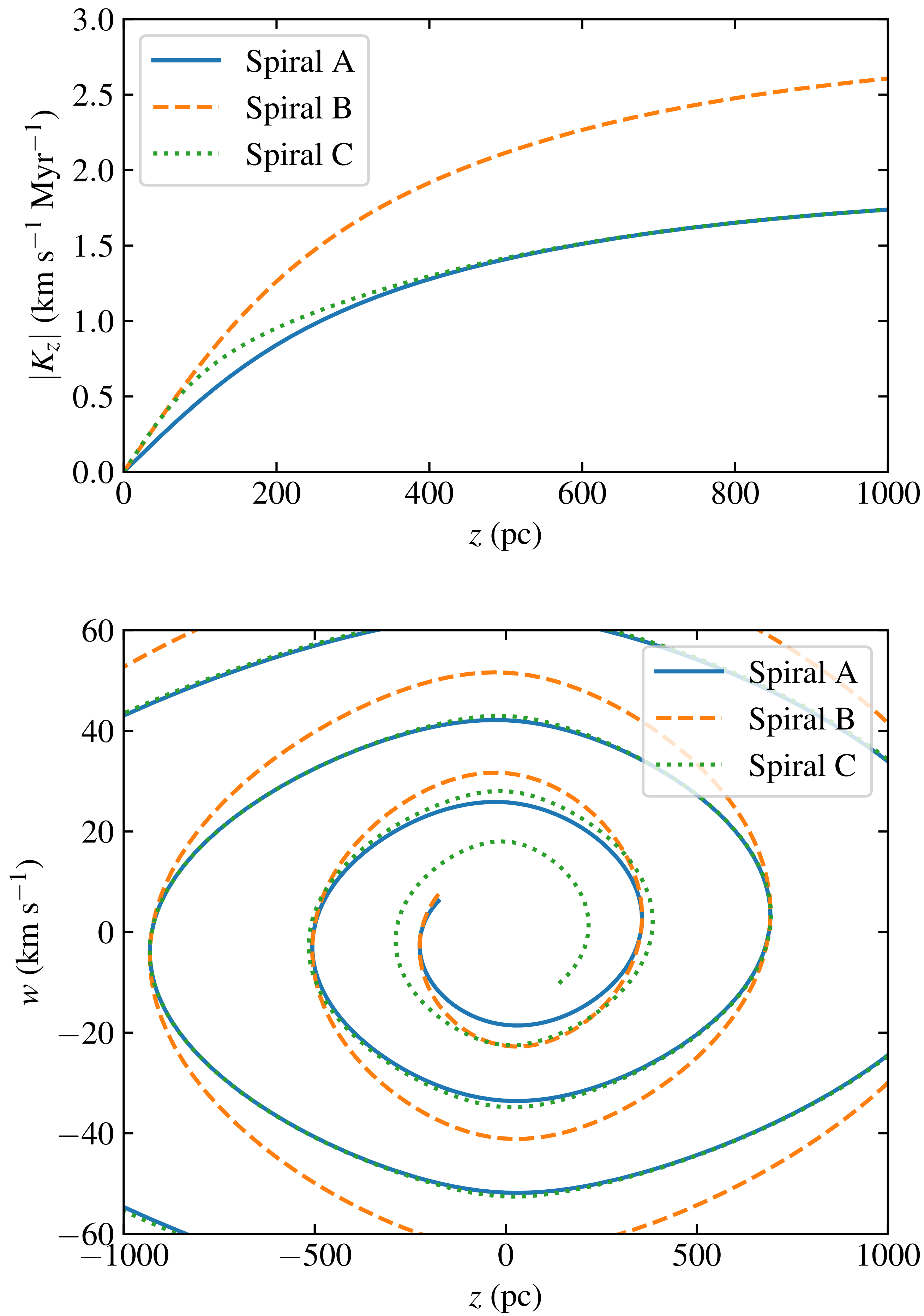
$$\tilde{\varphi}(t, E_z \,|\, \Phi, \tilde{\varphi}_0) = \tilde{\varphi}_0 + 2\pi \frac{t}{P(E_z \,|\, \Phi)}$$



- Any point on the spiral is associated with a vertical energy
- Point A is purely kinematic energy; point B is purely potential energy
- In the limit of high winding, $E_{z,A}$ approaches $E_{z,B}$ from above
- Even if winding is not very high, $\tilde{\varphi}(E_z)$ is a smooth function; this strongly constrains $\Phi(z)$ if we consider a longer segment of the spiral

A FEW MORE EXAMPLES

- Three spirals, sitting in three different gravitational potentials
- Even though the three spirals have the same amount of winding (in terms of laps around the origin), they are clearly differentiable from each other



MODEL OF INFERENCE

MODEL OF INFERENCE

Free parameters

$\boldsymbol{\Psi}_{\rm bulk}$	Bulk phase-space density parameters
a_k	Weights of the Gaussian mixture model
$\sigma_{z,k}, \sigma_{w,k}$	Dispersions of the Gaussian mixture model
$\boldsymbol{\Psi}_{\rm spiral}$	Spiral phase-space density parameters
$\rho_{h=\{1,2,3,4\}}$	Mid-plane matter densities
t	Time since the perturbation was produced
$\tilde{\varphi}_0$	Initial angle of the perturbation
α	Relative density amplitude of the spiral

Full phase-space density

$$f(z, w \,|\, \boldsymbol{\Psi}) = B(z, w \,|\, \boldsymbol{\Psi}_{\rm bulk}) \times \left[1 + m(z, w \,|\, \rho_h)\, S(z, w \,|\, \boldsymbol{\Psi}_{\rm spiral})\right]$$

Spiral relative density

$$S(z, w \,|\, \boldsymbol{\Psi}_{\rm spiral}) = \alpha \cos\left[\varphi(z, w \,|\, \rho_h) - \tilde{\varphi}(t, E_z \,|\, \rho_h, \tilde{\varphi}_0)\right]$$

Bulk density

$$B(z, w \,|\, \boldsymbol{\Psi}_{\rm bulk}) = \sum_{k=1}^{K} a_k \frac{\exp\left(-\frac{z^2}{2\sigma_{z,k}^2}\right)}{\sqrt{2\pi\sigma_{z,k}^2}} \frac{\exp\left(-\frac{w^2}{2\sigma_{w,k}^2}\right)}{\sqrt{2\pi\sigma_{w,k}^2}}$$

Gaussian mixture model, constrained to be symmetric with respect to *z* and *w*

Spiral angle

$$\tilde{\varphi}(t, E_z \,|\, \rho_h, \tilde{\varphi}_0) = \tilde{\varphi}_0 + 2\pi \frac{t}{P(E_z \,|\, \rho_h)}$$

FITTING PROCEDURE

We fit the likelihood of the phase-space density in two separate steps:

1. Fit the bulk density (without spiral)
2. Fit the spiral (with fixed bulk)

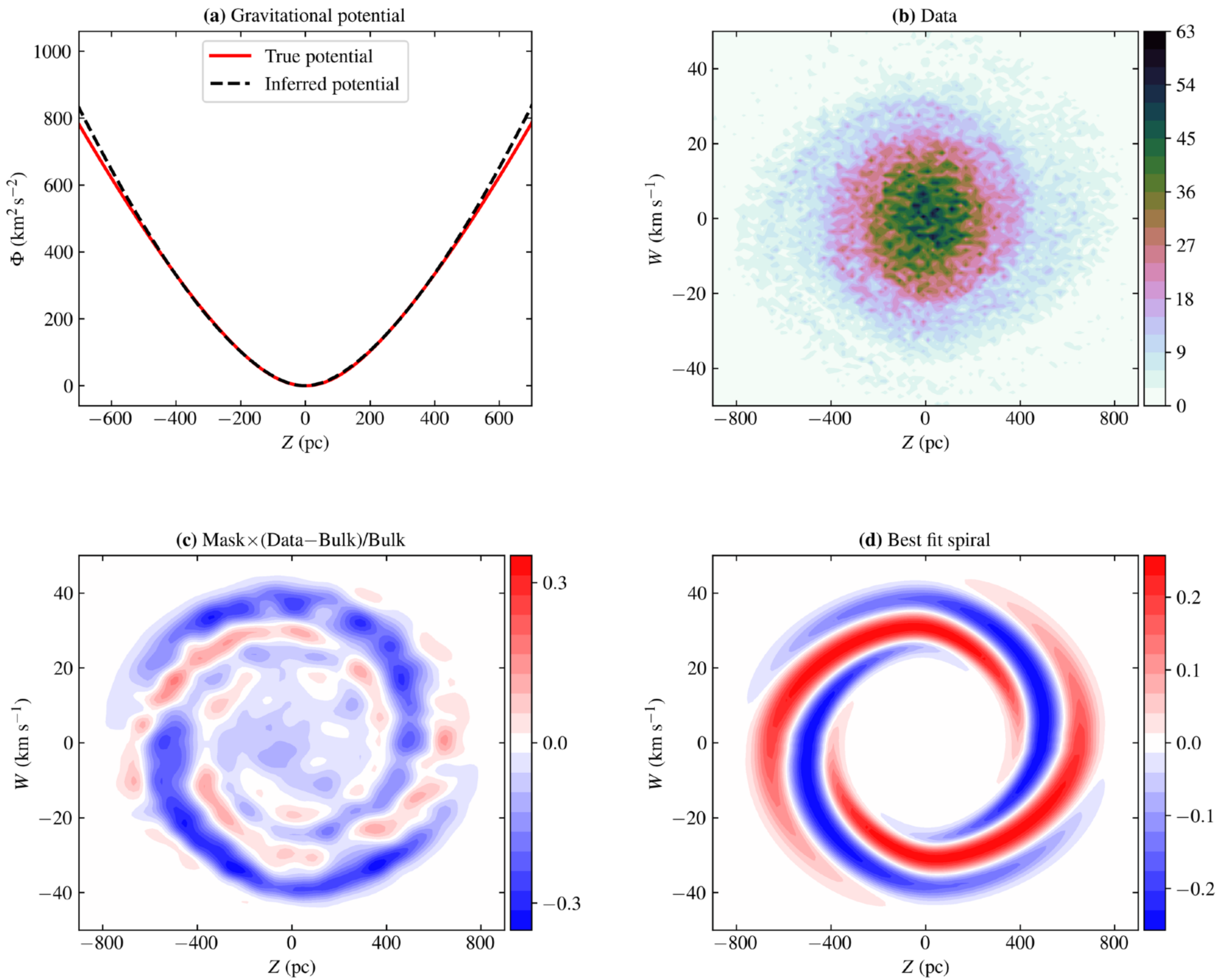
The second step is very computationally intensive. Our method is implemented in TensorFlow (allows for auto-differentiation and efficient minimisation). The code is available online: `github.com/AxelWidmark/SpiralWeighing`

TESTS ON SIMULATIONS

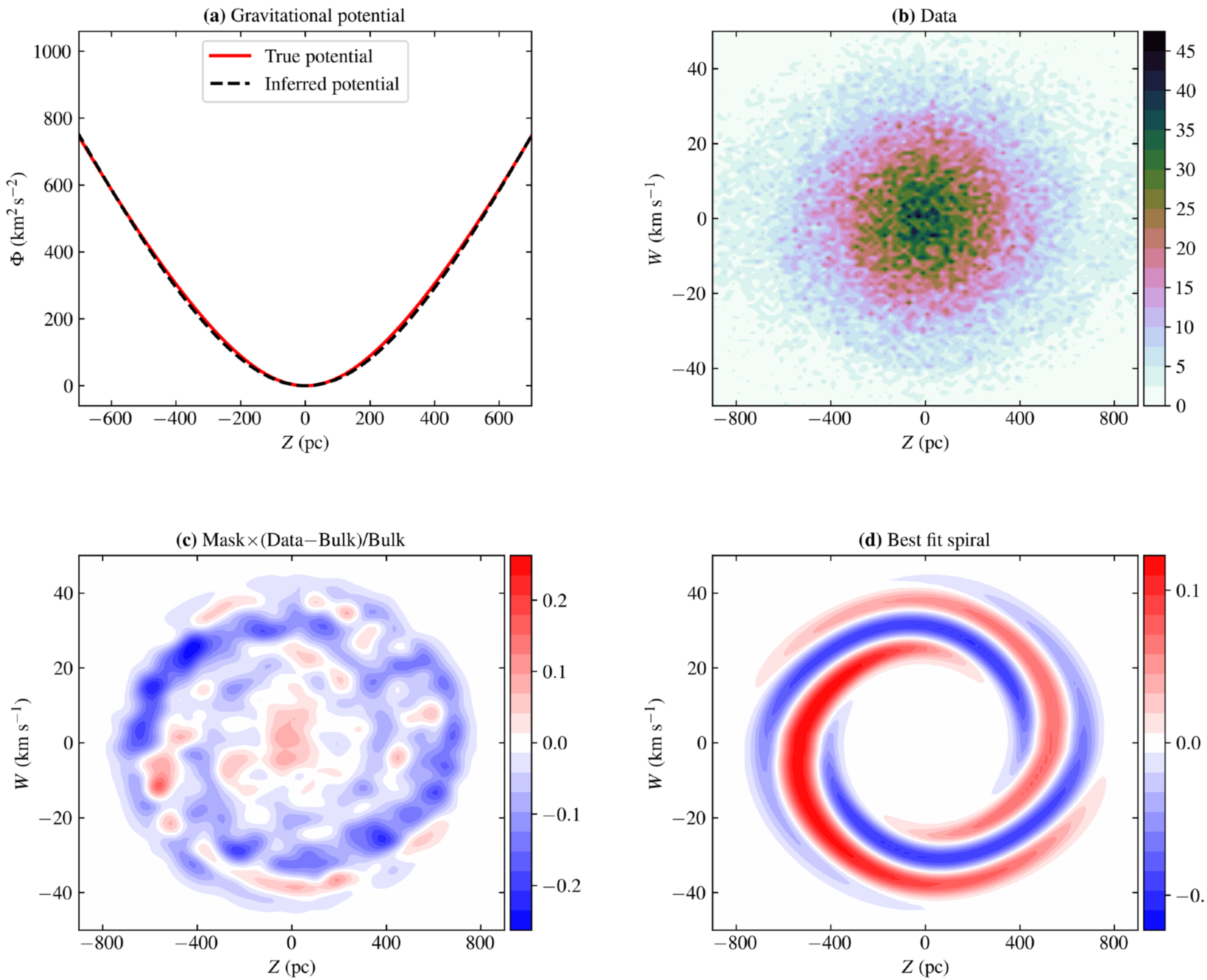
1D SIMULATIONS

- 10^5 particles representing stars and gas, also a constant density contribution from halo dark matter
- The data histogram in the (z, w)-plane is constructed from stars only
- Initialised in a steady state, then perturbed by a passing satellite
- Evolves for a few hundred Myr after the perturbation

SIMULATION A, 400 MYR



SIMULATION B, 500 MYR



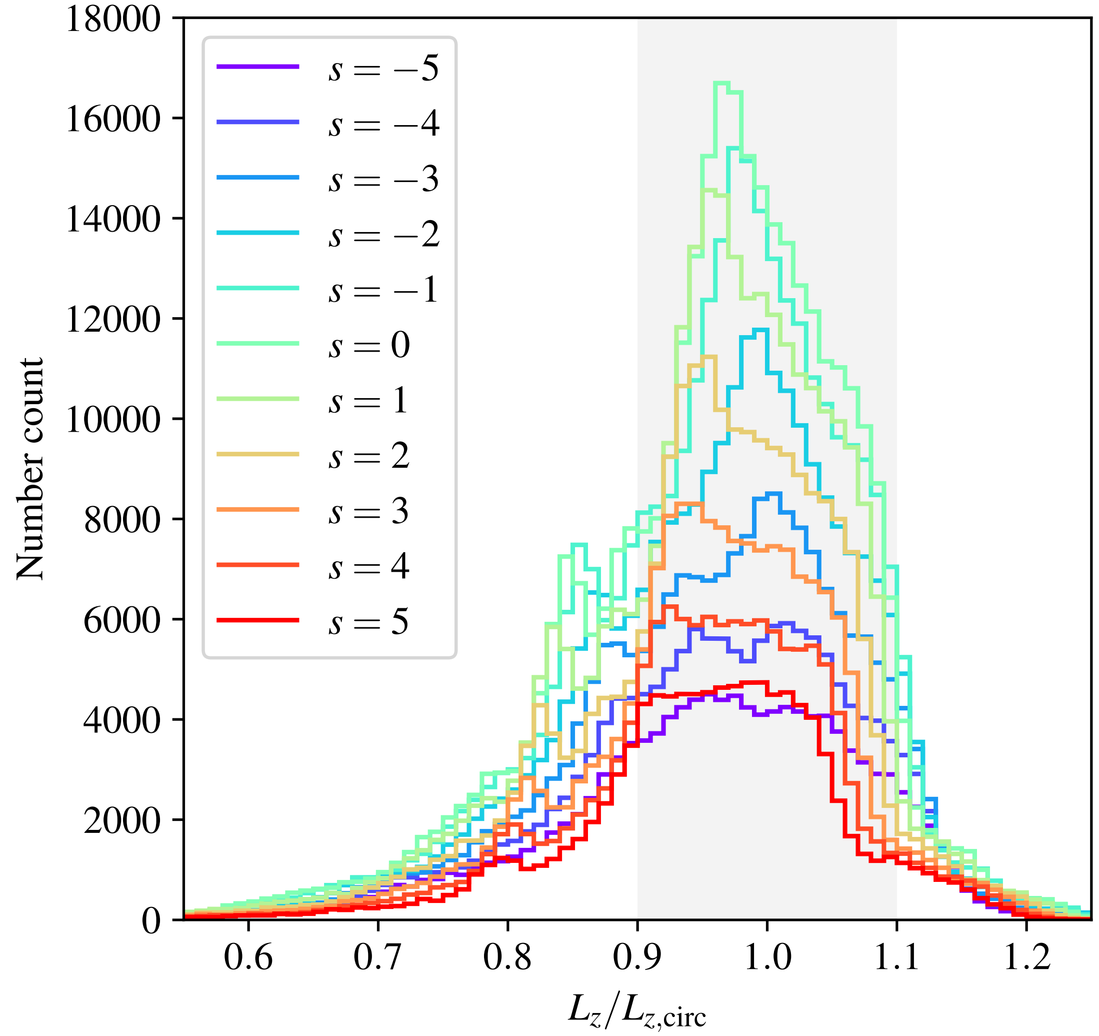
TESTS ON SIMULATIONS

- Our method works well
- Results are especially accurate for $\Phi(400-500\,\mathrm{pc})$, with a relative error of only a few percent
- The precise shape of the matter density distribution is less robust (as for any dynamical mass measurement)

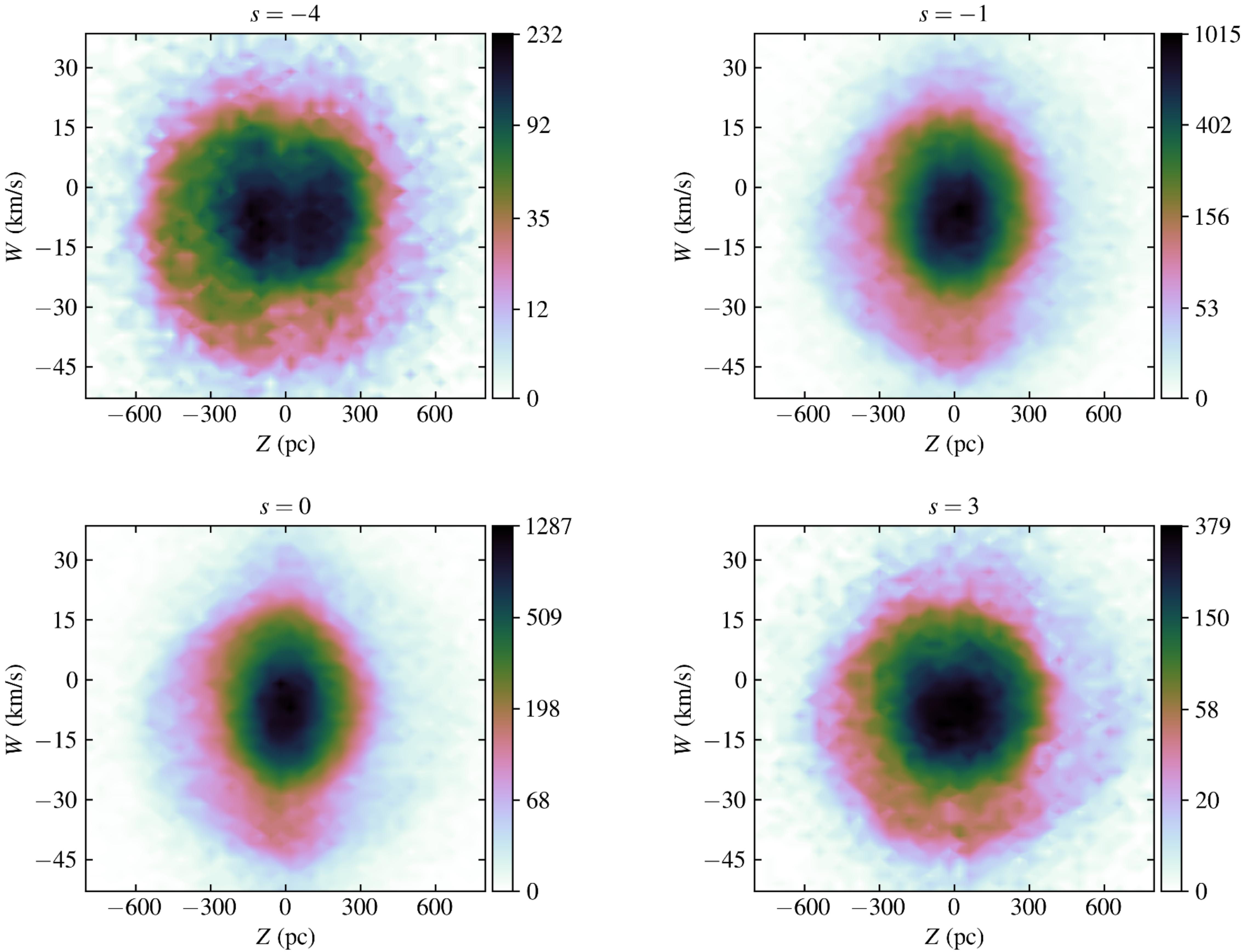
APPLICATION TO GAIA DATA

DATA SAMPLE CONSTRUCTION

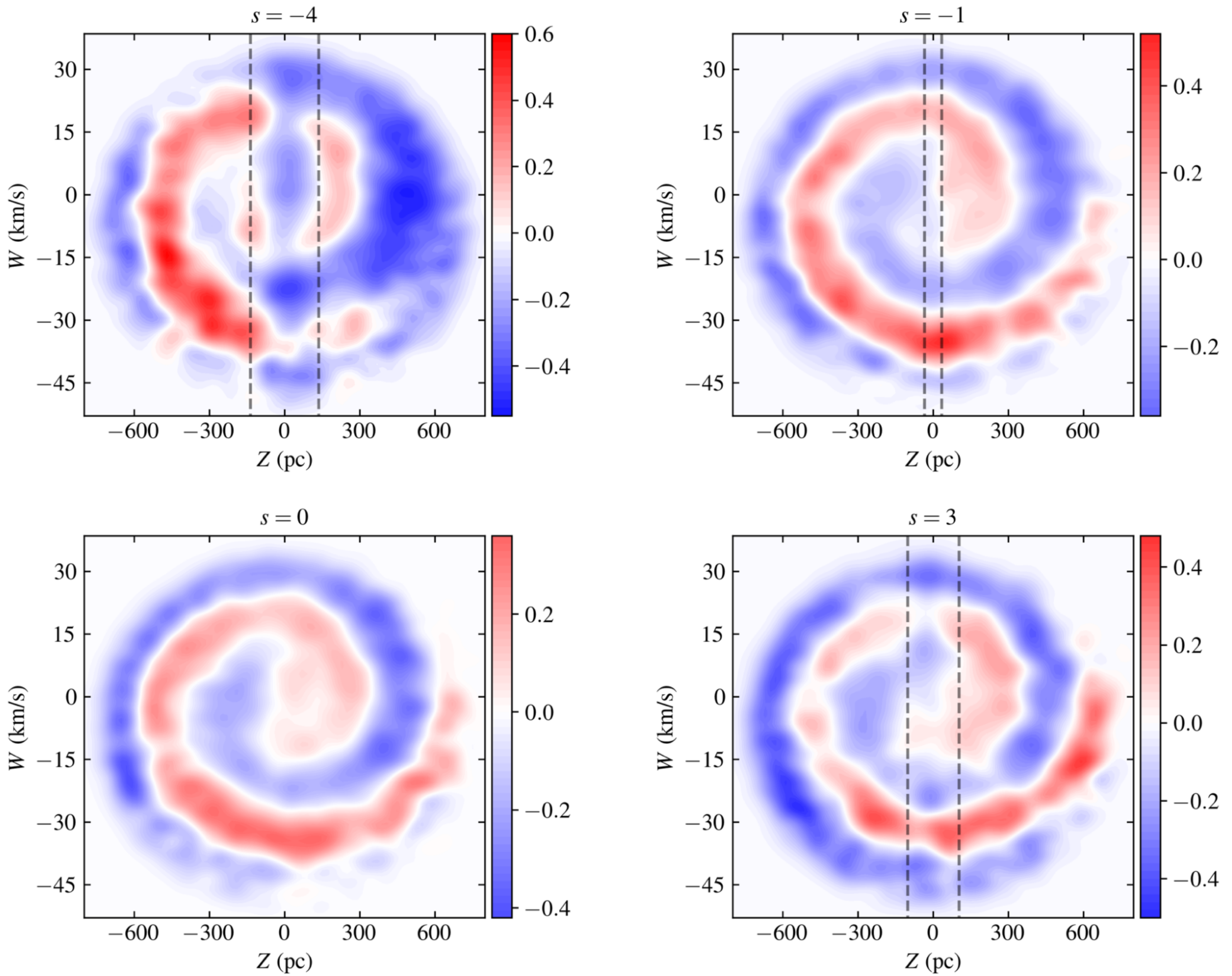
- Data from Gaia EDR3, with supplementary radial velocity information from legacy spectroscopic surveys (LAMOST, GALAH, RAVE, APOGEE, SEGUE, GES)
- Data quality cuts: $G < 15$; $\sigma_{RV} < 3$ km/s; RUWE < 1.4; $\sigma_{\varpi} < 0.05$ mas.
- Construct eleven main data samples, labelled by an index *s* in range [-5,5]:
  1. $\frac{R - R_\odot}{\text{pc}} \in [100s - 50, 100s + 50]$,
  2. $\frac{Y}{\text{pc}} \in [-400, 400]$,
  3. $\frac{L_z}{v_c \times [R_\odot + (100s \text{ pc})]} \in [0.9, 1.1]$.
- We fix $Z_\odot = \{0, 10, 20\}$ pc



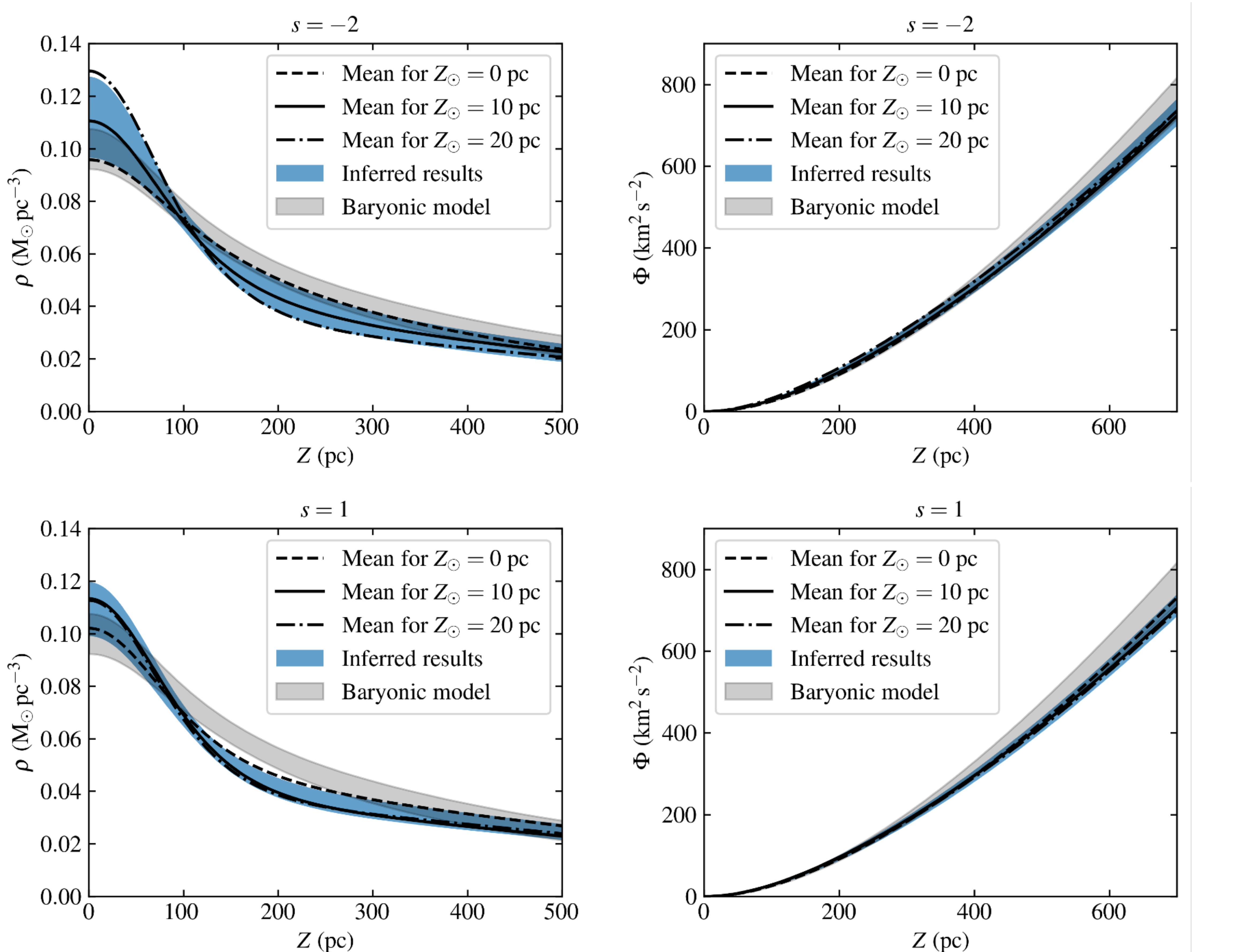
A FEW DATA HISTOGRAMS



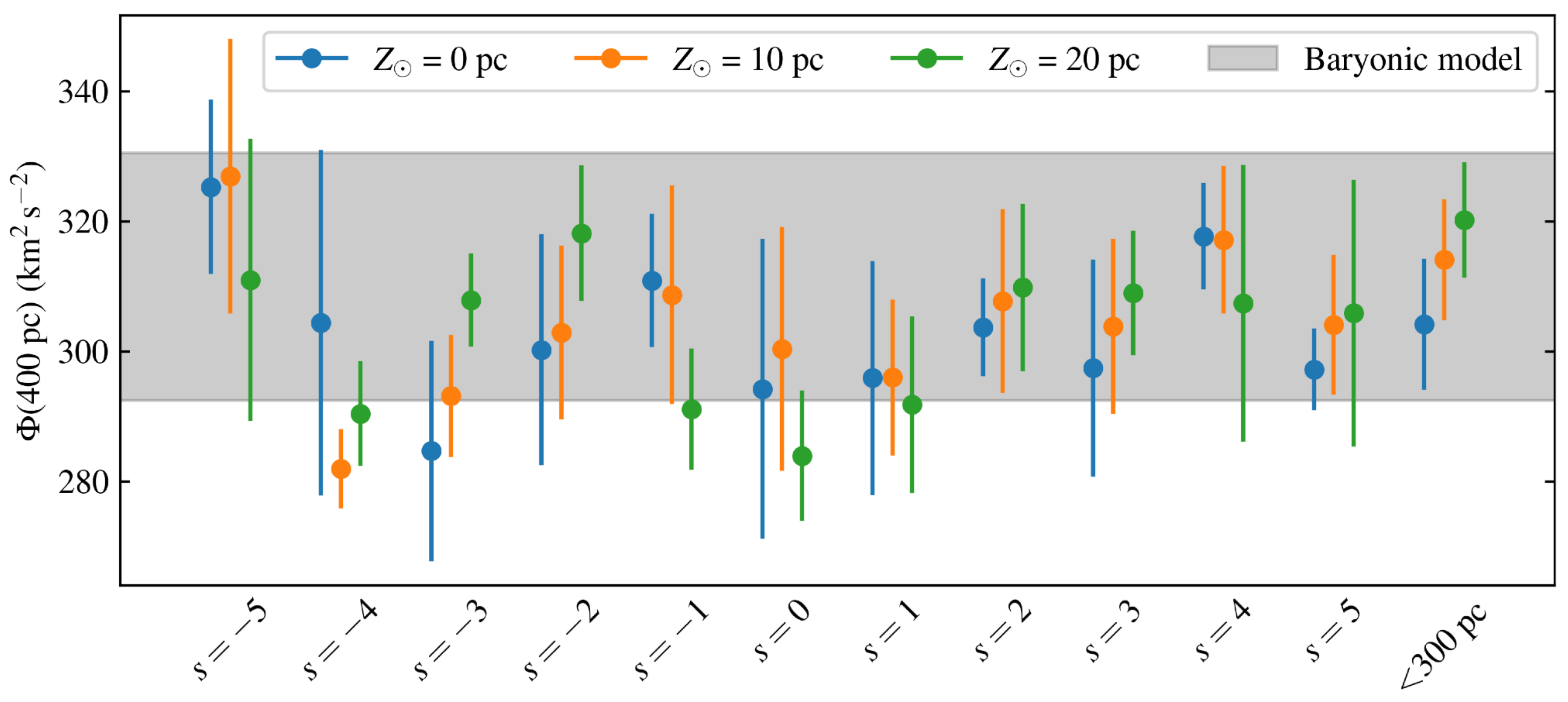
A FEW SPIRALS (AFTER FITTING THE BULK)



INFERRED MATTER DENSITIES / GRAV. POTS.

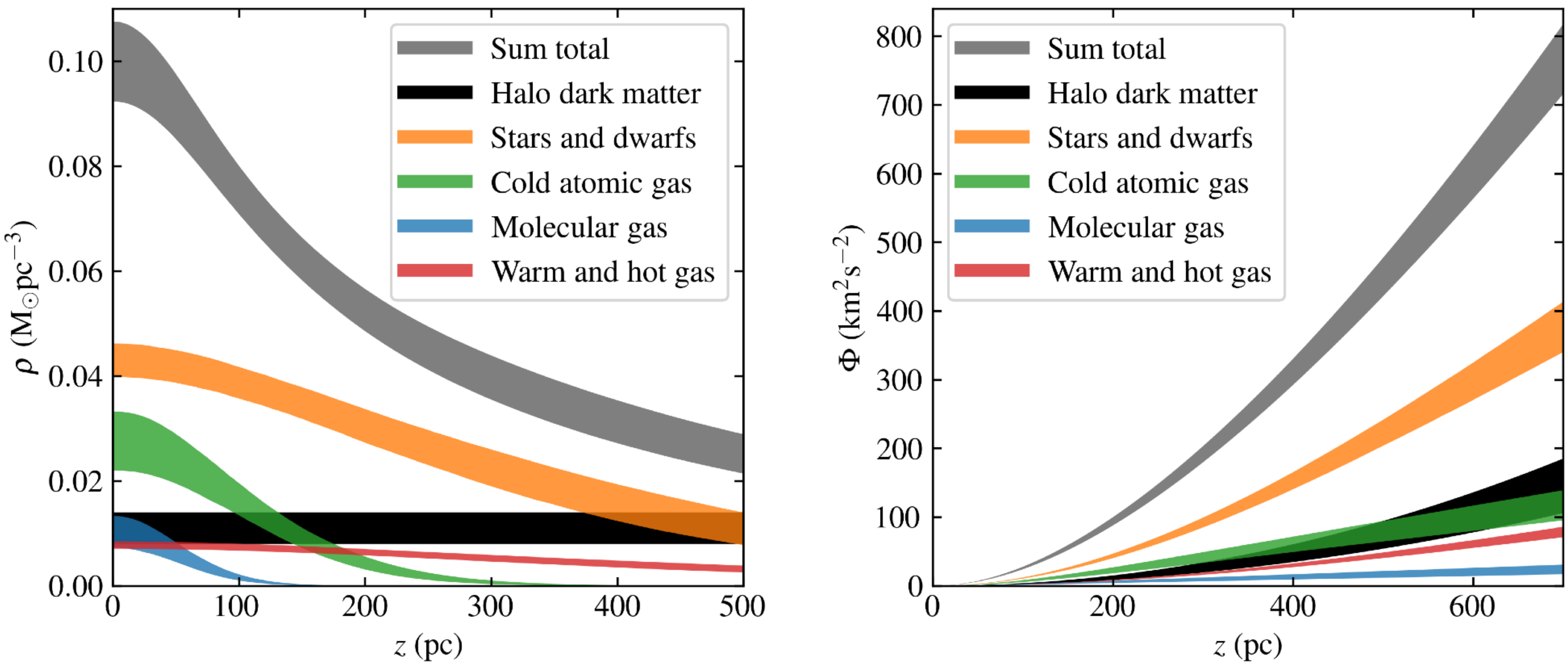


SUMMARY OF INFERRED GRAVITATIONAL POTENTIALS



Robust despite highly varied selection effects!

BARYONIC MODEL



BARYONIC MODEL

Component	ρ_t ($M_\odot$pc^{-3})	σ_t (kms^{-1})
Molecular gas	0.0104 ± 0.00312	3.7 ± 0.2
Cold atomic gas	0.0277 ± 0.00554	7.1 ± 0.5
Warm atomic gas	0.0073 ± 0.0007	22.1 ± 2.4
Hot ionised gas	0.0005 ± 0.00003	39.0 ± 4.0
Giant stars	0.0006 ± 0.00006	15.5 ± 1.6
Stars, $M_V < 3$	0.0018 ± 0.00018	7.5 ± 2.0
Stars, $3 < M_V < 4$	0.0018 ± 0.00018	12.0 ± 2.4
Stars, $4 < M_V < 5$	0.0029 ± 0.00029	18.0 ± 1.8
Stars, $5 < M_V < 8$	0.0072 ± 0.00072	18.5 ± 1.9
Stars, $M_V > 8$	0.0216 ± 0.0028	18.5 ± 4.0
White dwarfs	0.0056 ± 0.0010	20.0 ± 5.0
Brown dwarfs	0.0015 ± 0.0005	20.0 ± 5.0

- This model was taken from Schutz et al. (arXiv:1711.03103)
- Suffers from some potentially severe systematic uncertainties
- Model assumes the different components are iso-thermal (with strictly Gaussian vertical velocity distributions)
- Gas content is highly uncertain, difficult to measure, non-uniform etc.

INFERRED DARK MATTER DENSITY

- The local halo dark matter density is inferred from $\Phi(400\ \text{pc})$, by comparing its measured value with the contribution from the baryonic model
- The combined statistics of data samples $s \in [-3,3]$, including the variance coming from different $Z_\odot$ values, gives $\Phi(400\ \text{pc}) = 301.8 \pm 6.0\ (\text{km/s})^2$
- The baryonic model contributes $265.0 \pm 16.0\ (\text{km/s})^2$, so its uncertainty dominates
- The inferred local halo dark matter density is $0.0085 \pm 0.0039\ \text{M}_\odot\text{pc}^{-3} = 0.32 \pm 0.15\ \text{GeV cm}^{-3}$

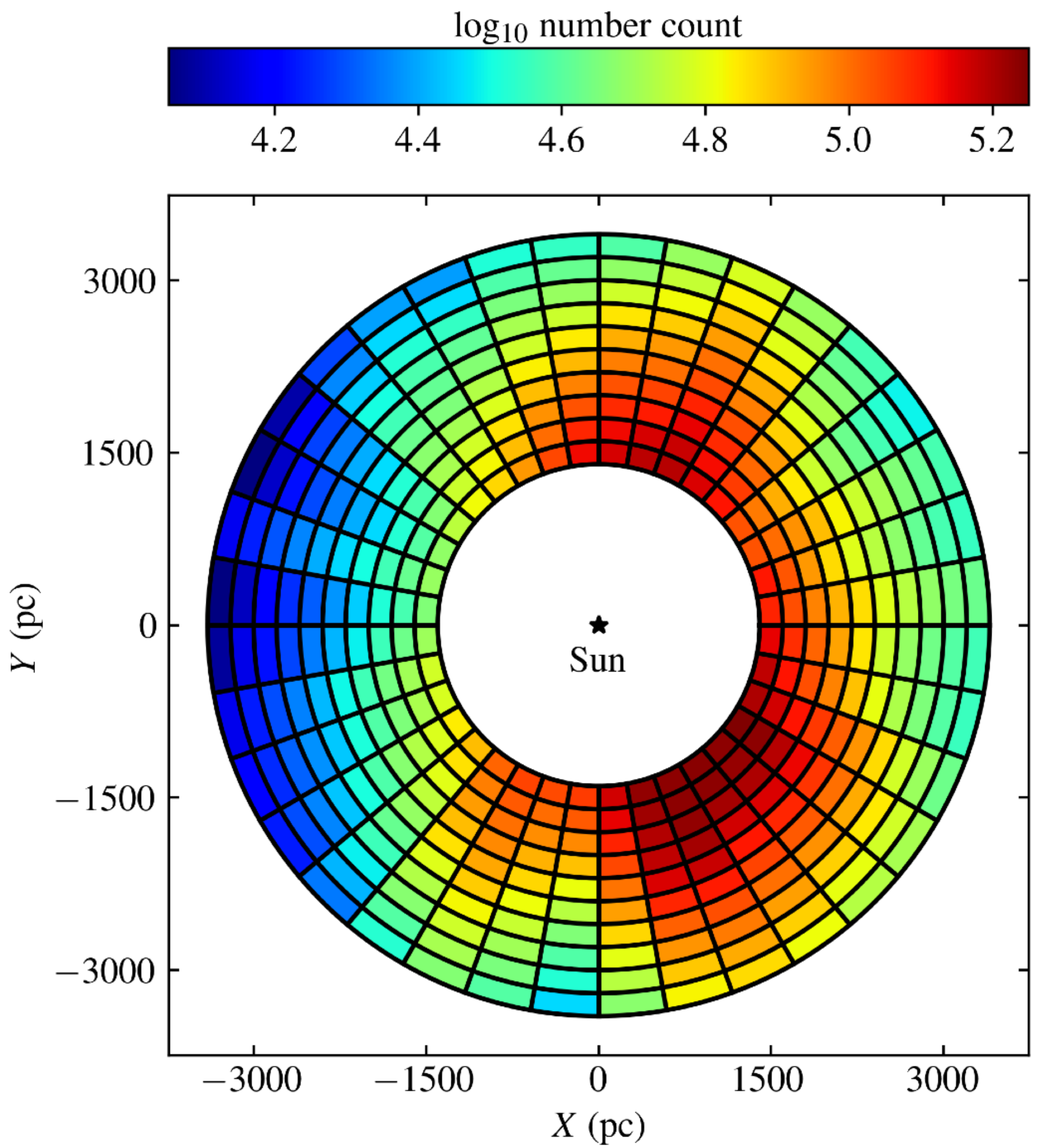
CONSTRAINTS TO A THIN DARK DISK

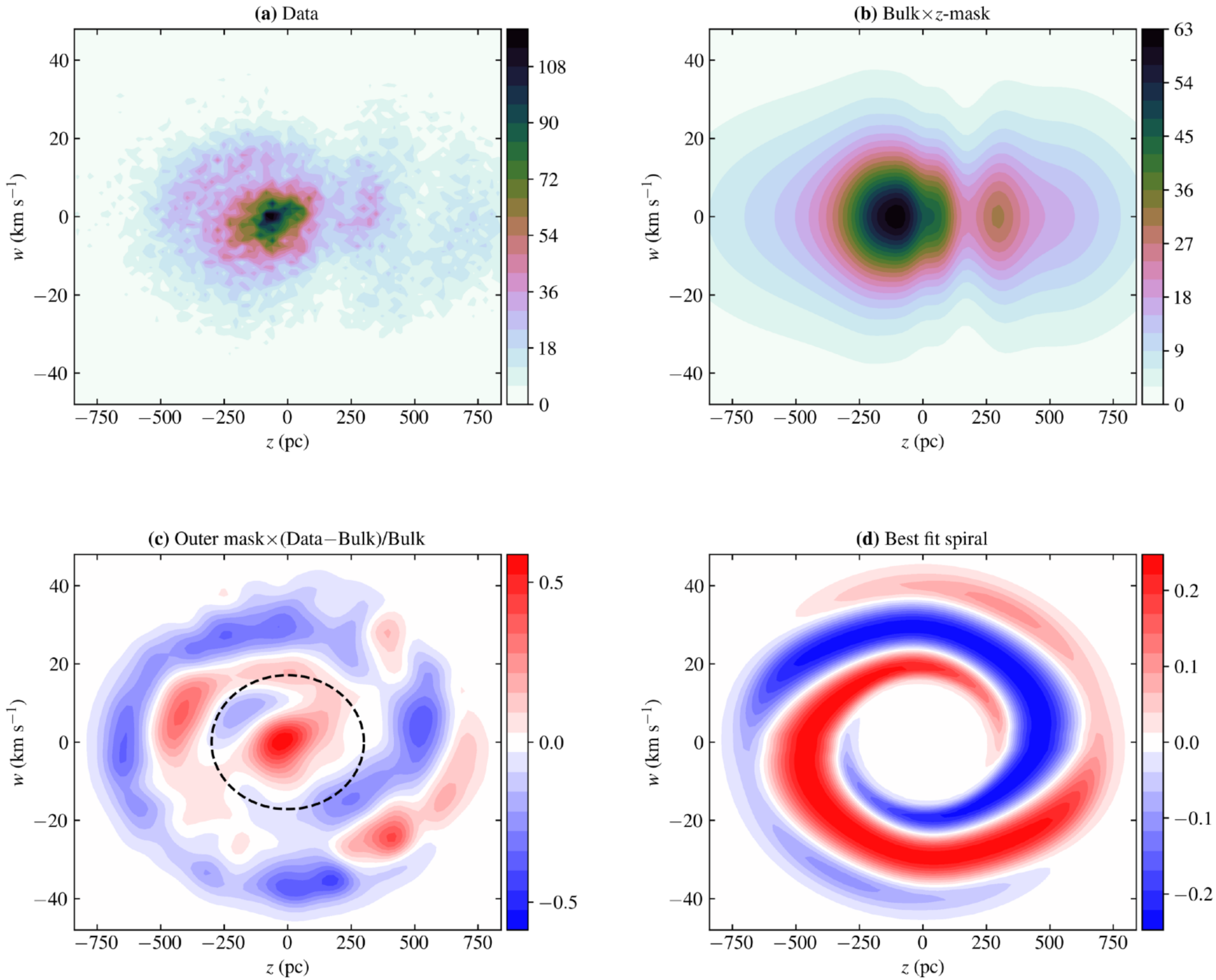
- A thin dark disk, embedded within the stellar disk, can form from a dark matter sub-component with strong dissipative self-interactions (searched for/constrained with local measurements of the Galactic disk)
- Again, we use $\Phi(400\ \mathrm{pc})$
- For these constraints, we assume a halo dark matter density of $0.009 \pm 0.003\ \mathrm{M_{\odot}pc^{-3}}$, coming from independent circular velocity curve measurements
- Assuming a dark disk scale height ≤ 50 pc, we place an upper 95 % limit of $4.6\ \mathrm{M_{\odot}pc^{-2}}$, roughly twice as strong as any other limit
- Even if we assume no halo dark matter, we still set the most stringent limit ($7.9\ \mathrm{M_{\odot}pc^{-2}}$)
- Our method is highly competitive compared to traditional methods

ONGOING WORK

USING THE PROPER MOTION SAMPLE

- We can see the spiral in far away regions of the disk, using the *Gaia* EDR3 proper motion sample
- Because Galactic latitude is small for distant disk stars, their proper motion in the latitudinal direction has a close projection with vertical velocity
- We divide the disk into area cells out to a distance of 3.4 kpc

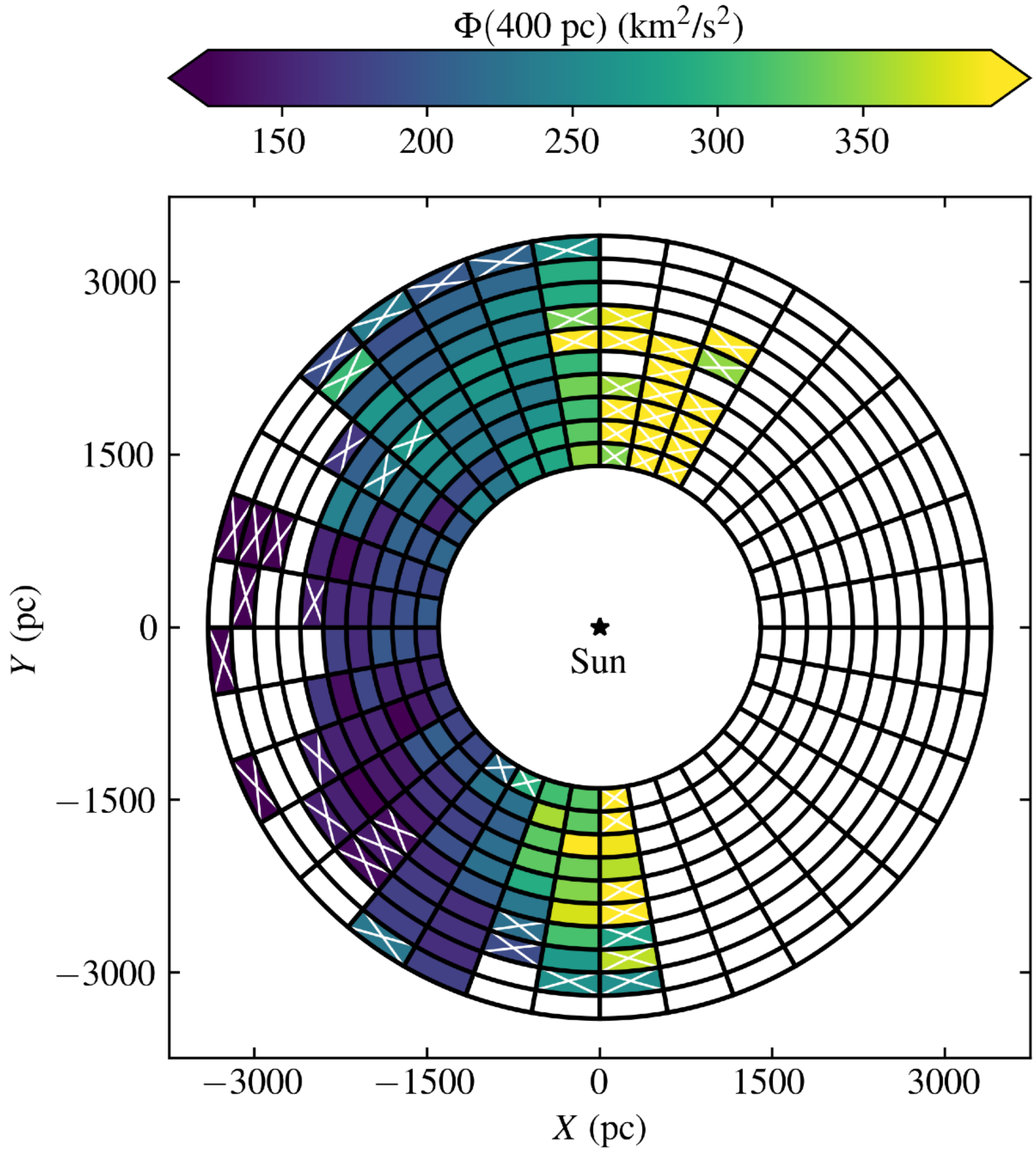




$l \in [120, 130]$ degrees

$\sqrt{X^2 + Y^2} \in [2000, 2200]$ pc

- Selection effects are severe, but have a spatial dependence only and can be modelled (at least decently)
- Our method is robust as long as the shape of the phase-space spiral can be extracted from the data



- Many data samples had to be disqualified (cells left blank) due to severe selection effects; others were marked as dubious (crossed over)
- Results are reasonable and appear robust; we infer a thin disk scale length of 2.5 ± 0.4 kpc
- Indications of broken axisymmetry, on the order of 30-40 %
- Systematic errors are estimated to about 10 %

OUTLOOK

FUTURE WORK

- Make more sophisticated tests on full 3d galaxy simulations (using billion particle simulations of Hunt et al., arXiv:2107.06294); this is also ongoing and will be published within a few months
- Update the baryonic model
- In a general sense, explore other applications of non-equilibrium dynamical modelling

CONCLUSION

- Our method is competitive with traditional methods that assume a steady state (e.g. we set the strongest limits to a thin dark disk)
- Our method is complimentary – not subject to the same biases, robust with respect to severe selection effects
- Useful for measuring the potential of the disk at large distances
- Shows that time-varying dynamical structures are not only obstacles, but can also be regarded as assets for dynamical mass measurements

BACKUP SLIDES

Disk non-equilibrium — arXiv:2011.02490

Weighing the Galactic disk in sub-regions of the solar neighbourhood using *Gaia* DR2

A. Widmark[1], P.F. de Salas[2], and G. Monari[3]

- Divide the local volume into sub-regions
- Potential steep close to the Galactic plane
- Does not imply a matter density surplus per se, but rather a very pinched matter density
- Matter density profile decays too fast – result must be biased by non-equilibrium