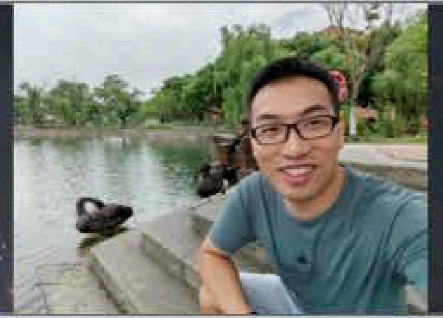
Measuring the Milky Way Vertical Potential with the Phase Snail in a Model Independent Way

Rui Guo (郭锐), Zhao-Yu Li, Juntai Shen, Shude Mao, Chao Liu

Department of Astronomy, School of Physics and Astronomy, Shanghai Jiao Tong University, China



Contact

Dr. Rui Guo (郭锐)

Email: guorui20@sjtu.edu.cn

1. Abstract

◆ The vertical phase-space spiral (snail) found by Antoja et al. (2018) is a direct sign of dis-equilibrium of Milky Way's disc. Nevertheless, the wrapping of the phase snail contains information of the vertical potential.

◆ We propose a novel method to measure the vertical potential utilizing the intersections between the snail and z/V_z axes, for which we know the maximum vertical heights (Z_{max}) or the maximum vertical velocities ($V_{z,max}$). **Using a refined linear interpolation method, we directly obtain (Z_{max}, $\frac{1}{2}V_{z,max}^2$) for these snail intersections to constrain the vertical potential profile empirically. Our method is model independent since no assumptions about the snail shape or the vertical potential have been made.**

◆ We apply our method to Gaia DR3. The interpolated potential points are then directly compared with popular MW potential models, and are utilized in the further mass modelling. In the Solar neighborhood, our method results in a local dark matter density of $\rho_{dm} = 0.0150 \pm 0.0031\ M_\odot\ pc^{-3}$. These results are consistent with previous relative studies.

2. Background

- The vertical phase spiral (snail) is the result of incomplete phase-mixing. Stars will gradually wind up to a spiral feature in z-V_z space after a perturbation due to the differential rotation. The wrapping of the phase snail thus contains the information of the vertical potential.
- Though the phase snail is a sign of dis-equilibrium, many works (e.g. Widmark et al. 2021; Li & Widrow 2021) have been tried to measure the MW vertical mass profile with the consideration of the phase snail.
- Other studies about the snail, such as the perturbation time (e.g. Frankel et al. 2022; 152 Darragh-Ford et al. 2023) and its orientation (e.g. Darragh-Ford et al. 2023; Alinder et al. 2023), strongly depend on the snail shape measurement and the vertical potential. The quantitative study on the relation between these two aspects is necessary and important.

3. Method

- Assume that the vertical energy is conserved:

$$E_z = \frac{1}{2}V_z^2 + \Psi(z) = \Psi(Z_{max}) = \frac{1}{2}V_{z,max}^2$$

- Intersections between snail and z/V_z axes:
  - on z axis (odd points) ⇒ known Z_{max}
  - on V_z axis (even points) ⇒ known $V_{z,max}$
- Linear interpolation such as:

$$V_{z,max,3} = (V_{z,max,2} + V_{z,max,4})/2\ .$$

- **We can obtain (Z_{max}, $\Psi(Z_{max}) = \frac{1}{2}V_{z,max}^2$) for each intersection.**

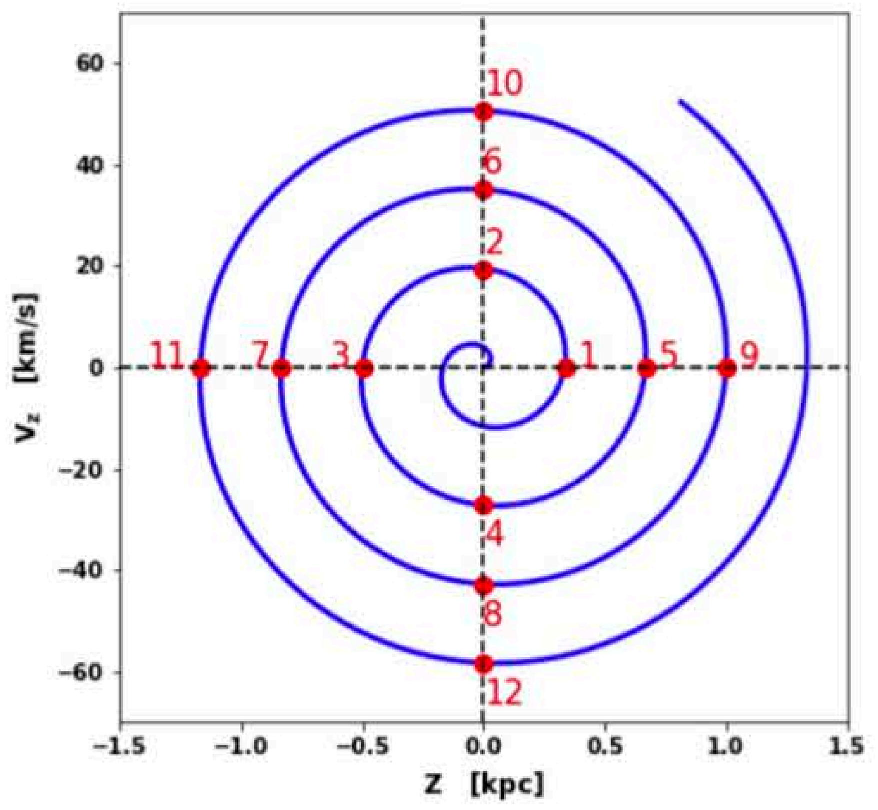


Fig. 1 - Sketch plot of the intersections between the phase snail and z/V_z axes.

- **Adjacent intersections have $\Delta\theta_z=\pi/2$, and thus constant $\Delta\Omega_z$.**
- $V_{z,max}$ ($\sqrt{Z_{max}}$) has better linear relation with Ω_z than E_z (Z_{max}). They are better for the linear interpolation.
- Thus, the **refined linear interpolation** is:

$$\begin{cases} \sqrt{Z_{max,i+1}} = \frac{1}{2}(\sqrt{Z_{max,i}} + \sqrt{Z_{max,i+2}}) \\ V_{z,max,i+1} = \frac{1}{2}(V_{z,max,i} + V_{z,max,i+2}) \end{cases}$$

- R_g-binned snails show better clarity than R-binned snails (Li 2021). However, we find **R_g-binned snail traces a shallower vertical potential than R-binned snail**, which would result in systematical underestimation if ignored. We apply an empirical method to correct this effect.
- **Our method makes no assumptions about the snail shape or the vertical potential model. It is model independent!** It works well when applied to the test-particle simulation.

(Z_{max}, $\Psi(Z_{max}) = \frac{1}{2}V_{z,max}^2$)

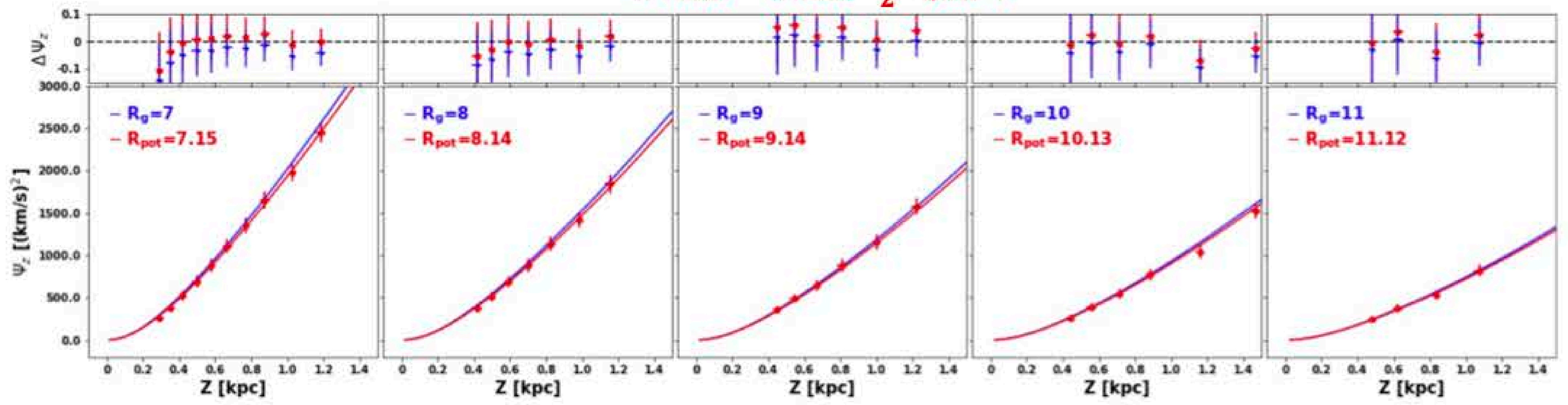
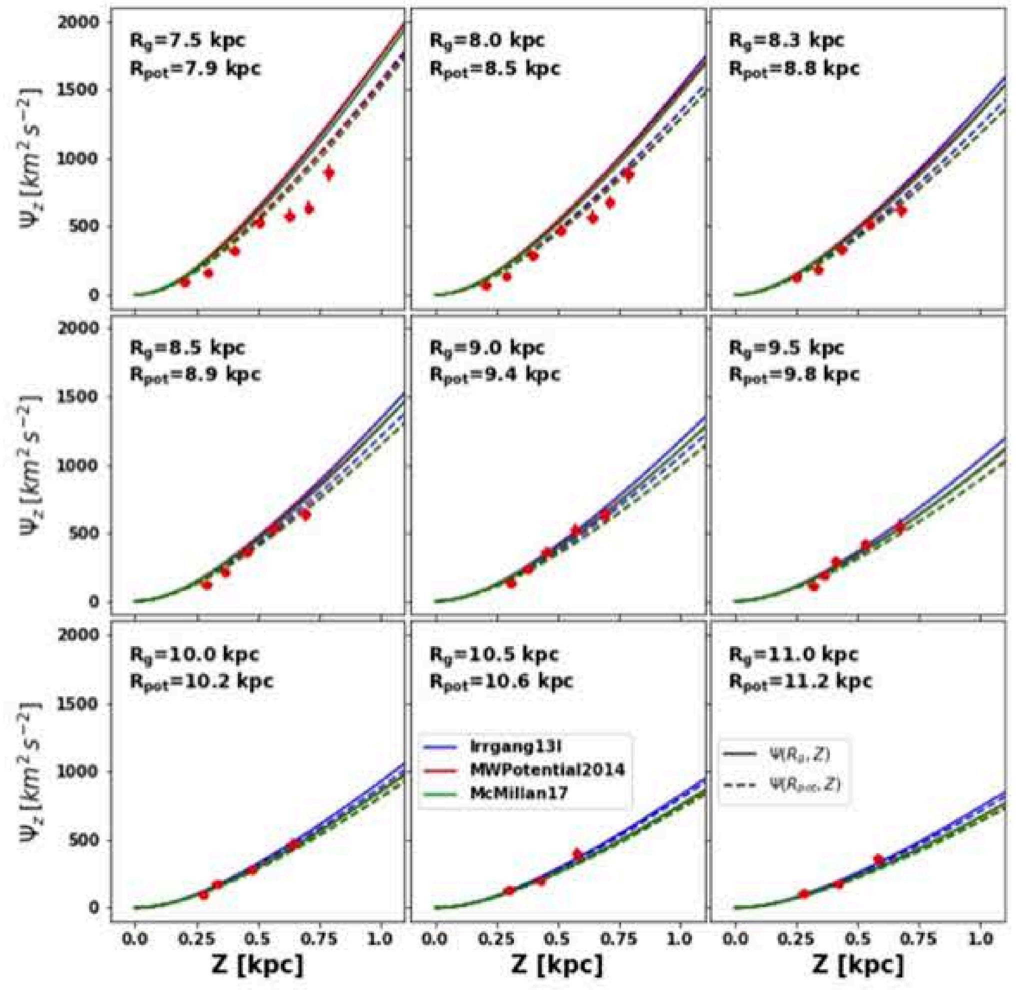


Fig. 2 – Vertical potential measurements from the refined interpolation method (red points) compared to the vertical potential profiles at radii with (red lines) and without (blue lines) the empirical correction. The top row shows the residuals.

4. Results

- We apply our method to 9 R_g bins from 7.5 to 11 kpc from Gaia DR3 and to the Solar neighborhood. The interpolated potential points can be directly compared to popular MW potential models, or be applied in the further mass modeling.



(Z_{max}, $\Psi(Z_{max}) = \frac{1}{2}V_{z,max}^2$)

The derived potential points (red points) are **consistent with potential profiles at radii with the empirical correction (dashed lines),** and are significantly lower than those without the correction (solid lines), especially at inner radii.

Fig. 3 – Compare the potential points (red points) interpolated from snail intersections with three popular MW potential models (colored lines).

- According to the empirical correction, it is **the snail at R_g= 7.91 kpc that represents the SN vertical potential $\Psi(R_\odot$=8.34 kpc).**
- Our results are consistent with previous literature. The mass modeling results in a local dark matter density of **$\rho_{dm} = 0.0150 \pm 0.0031\ M_\odot/pc^3$**.

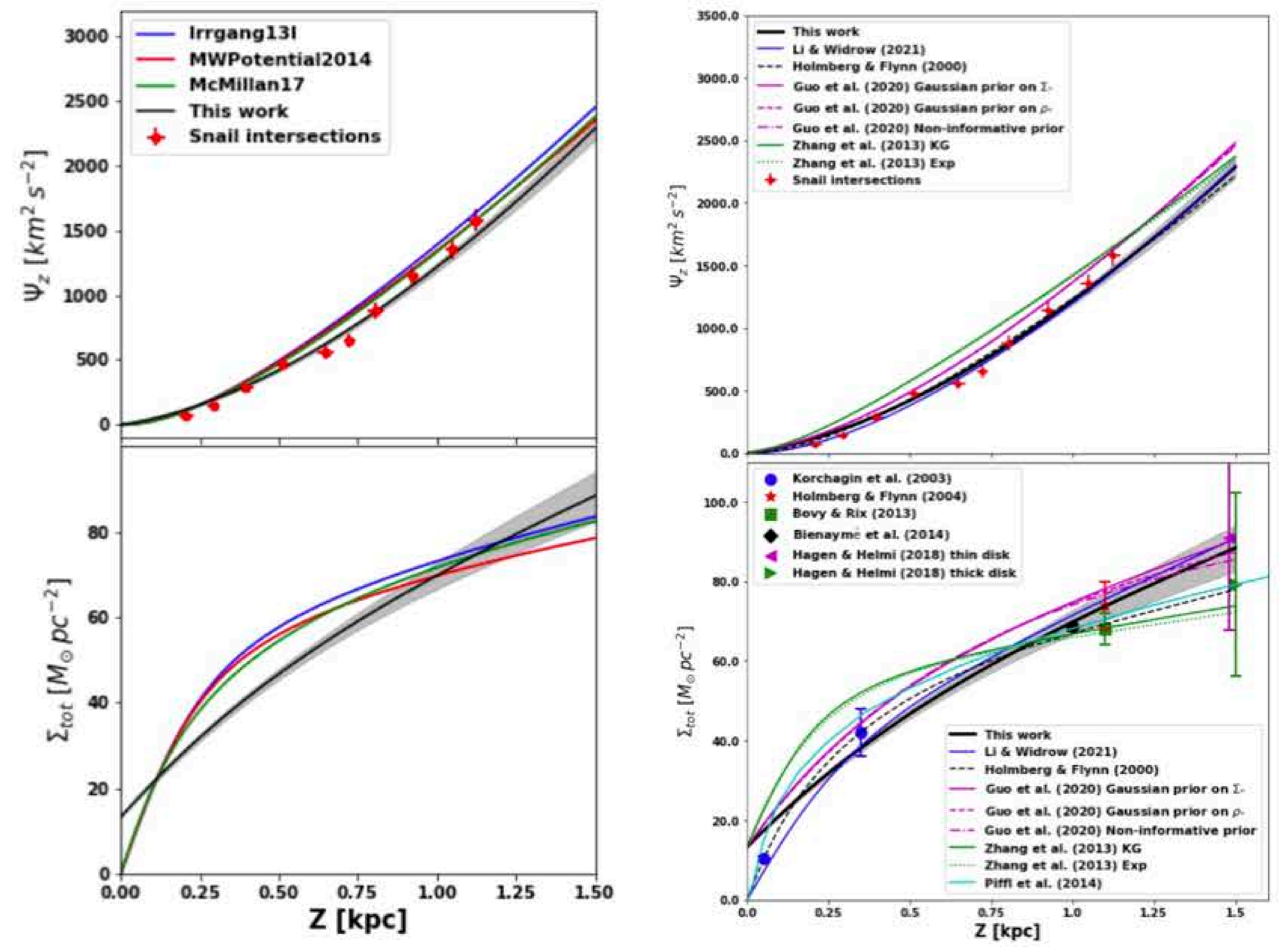


Fig. 4 – Compare the interpolated potential points (red points) at SN and its modelling result (black solid line) with popular MW potential models (left) and other local kinematic studies (right).

5. Summary

We propose a model-independent measurement of the vertical potential using intersections between phase snail and z/V_z axes.

- Our method works well in the test-particle simulation.
- We find **R_g-binned snail traces a shallower vertical potential than R-binned snail.**
- Appy to snails in Gaia DR3: results are consistent with popular MW potentials.
- Apply to SN: $\rho_{dm} = 0.0150 \pm 0.0031\ M_\odot/pc^3$; consistent with previous measurements.

References

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