Testing universal dark-matter caustic rings with galactic rotation curves

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Highlights

- We have tested the hypothesis of the universal dark-matter caustic rings with a large independent set of rotation curves by means of an improved statistical method.
- No evidence for universal caustic rings was found in the new analysis.

Data analysis

Individual rotation curves

- We are looking for caustic rings, where the concentration of dark matter is enhanced.
- Even without caustics, the rotation curves are not flat, and individual gas clouds observed in a galaxy may have peculiar velocities independent of any caustic structure.
- To quantify the presence or lack of features, the authors of Ref. [3] proposed to use the procedure for separation the background rotation of the galaxy and for quantifying the "noise".

The hypothesis of Ref. [3] predicts caustic rings at:

$$\tilde{r} = a_n \frac{j_{\max}}{0.25} \frac{0.7}{h}$$

where the rescaled radius is defined as:

$$\tilde{r} \equiv r \left(\frac{220 \text{ km/s}}{v_{\text{rot}}} \right) \qquad (1)$$

n = 1, 2, 3 . . . enumerates the caustic rings formed by the particles experiencing the *n*th infall:

$$a_n = \{39, 19.5, 13, 10, 8, \dots\} \text{ kpc}$$

are the universal rescaled positions of these caustics, j_{max} is the peak of the distribution of dimensionless angular momenta of dark-matter particles and *h* is the dimensionless local Hubble constant.

Iterative procedure

1. The rescaled rotation curve is determined iteratively. Initial data are fitted by the parabola, $\overline{v}_0$(r), and the mean v_{rot} is calculated for this parabola over $r_i \geq 10$ kpc.

2. Then Eq. (1) is used to obtain rescaled radii $\tilde{r}$, and all points with $\tilde{r}_i < 10$ kpc are removed.

3. At the next iteration, the new fitting function $\overline{v}_1(\tilde{r})$ is constructed, new v_{rot} and $\tilde{r}_i$ are calculated and the condition $\tilde{r}_i \geq 10$ kpc is checked again.

Ensemble of rotation curves

- For each galaxy we define

$$\sigma_i \equiv \frac{v_i - \overline{v}(\tilde{r}_i)}{\Delta v_i}$$

- For each σ_i we assign a p_i value ($0 \leq p_i \leq 1$) with the meaning of the probability of a random deviation to $\geq \sigma_i$ for the Gaussian distribution with the mean 0 and variance 1:

$$p_i = 1 - \text{CDF}(\sigma_i) = \frac{1}{2}\left(1 - \text{erf}\left(\frac{\sigma_i}{\sqrt{2}}\right)\right)$$

- For each galaxy *j*, we then obtain a function $p_j(\tilde{r})$ by the linear interpolation of the corresponding points ($\tilde{r}_i$, p_i) for this galaxy.

- Then we construct the averaged likelihood function $L(\tilde{r})$ as

$$L(\tilde{r}) = -\sum_{j=1}^{N(\tilde{r})} \frac{\log[p_j(\tilde{r})]}{N(\tilde{r})}$$

where $N(\tilde{r})$ is the number of galaxies, for which p_j is determined at the point $\tilde{r}$.

- *The interpretation* of this likelihood function is straightforward. Random statistical fluctuations and individual rotation-curve features caused by particular velocity flows are expected to occur at different $\tilde{r}$ and therefore to cancel in the sum *L*. Contrary, coinciding bumps related to universal caustics would add coherently resulting in a peak in $L(\tilde{r})$.

References:

1. D. Davydov and S. Troitsky, Testing universal dark-matter caustic rings with galactic rotation curves, 2022. 10.48550/ARXIV.2206.10260.
2. F. Lelli, S. S. McGaugh and J. M. Schombert, Sparc: Mass models for 175 disk galaxies with spitzer photometry and accurate rotation curves, The Astronomical Journal 152 (2016) 157.
3. W. H. Kinney and P. Sikivie, Evidence for universal structure in galactic halos, Phys. Rev. D 61 (2000) 087305 [astro-ph/9906049].

Data on rotation curves

- We use the Spitzer Photometry and Accurate Rotation Curves (SPARC) database of rotation curves for 175 galaxies with various morphologies and luminosities [2]. The rotation velocities were obtained from interferometric observations of atomic hydrogen which is one of the best tracers of kinematics of nearby galaxies for a wide range of radial distances, which is important for our purposes.

- The previous study [3] made use of a sample of 32 rotation curves. Of these 32 galaxies, 29 are present in the SPARC database. In order to perform an independent test of the hypothesis of Ref. [3], we remove these 29 rotation curves from the sample. In addition, 25 curves have been removed to satisfy the quality condition described below in Sec. 3.1. The main, independent from Ref. [3], sample we use thus contains 121 rotation curves.

Monte-Carlo estimate of significance

To simulate artificial rotation curves without universal features, we assume that:

- the fitted functions $\overline{v}(\tilde{r})$ represent the true smooth rotation curves;
- the measurements were done at the same sets of r_i as in the real data;
- the measurement errors are Gaussian with the same widths as quoted for the real data.

We repeat *M* times the same procedure with simulated rotation-curve measurements and obtain a set of simulated $L^{(k)}_{max}$, $k = 1, \dots, M$.

The significance of the strongest universal feature in the set of rescaled rotation curves is determined by the p-value counting how often the observed or larger value of L_{max} happens by chance in the simulated sets, that is the number of cases for which $L^{(k)}_{max} > L_{max}$ divided by *M*.

Results

No significant peaks of $L(\tilde{r})$ are observed at the expected positions of caustic rings found in Ref. [3], nor elsewhere.

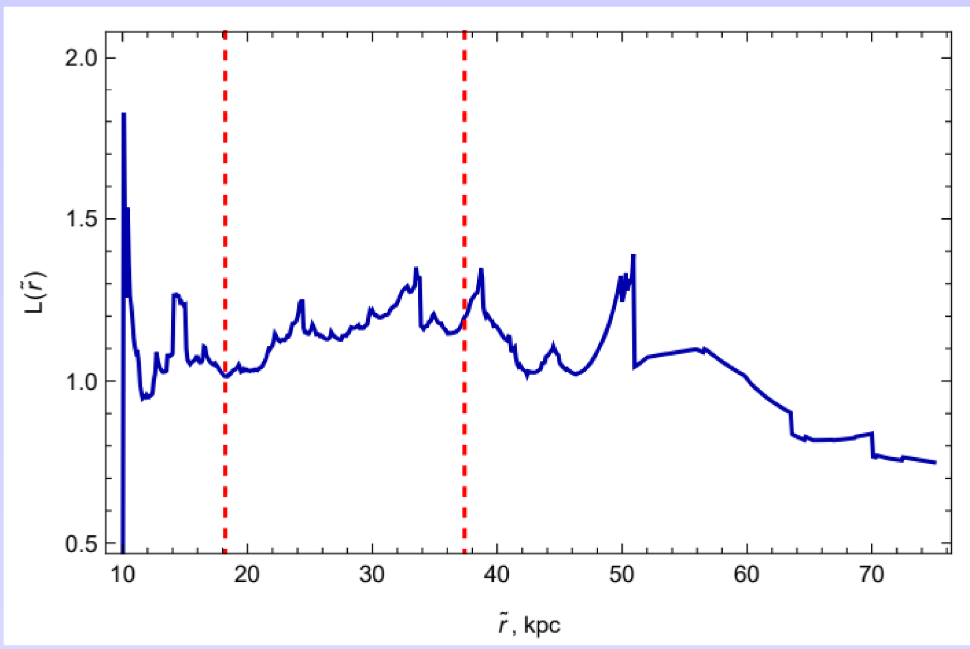
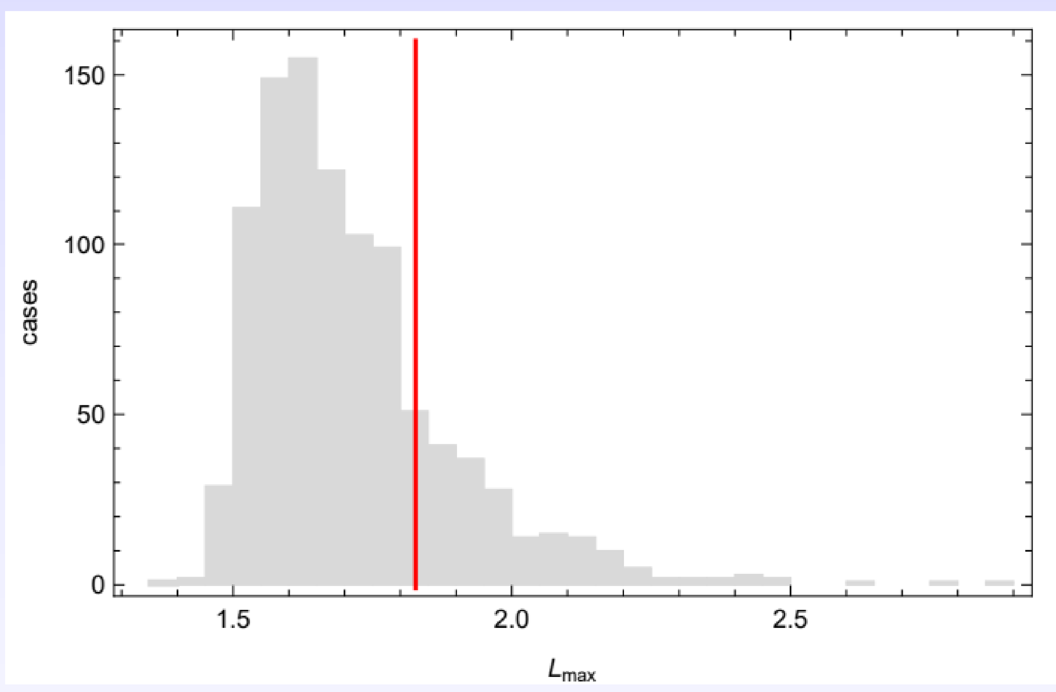
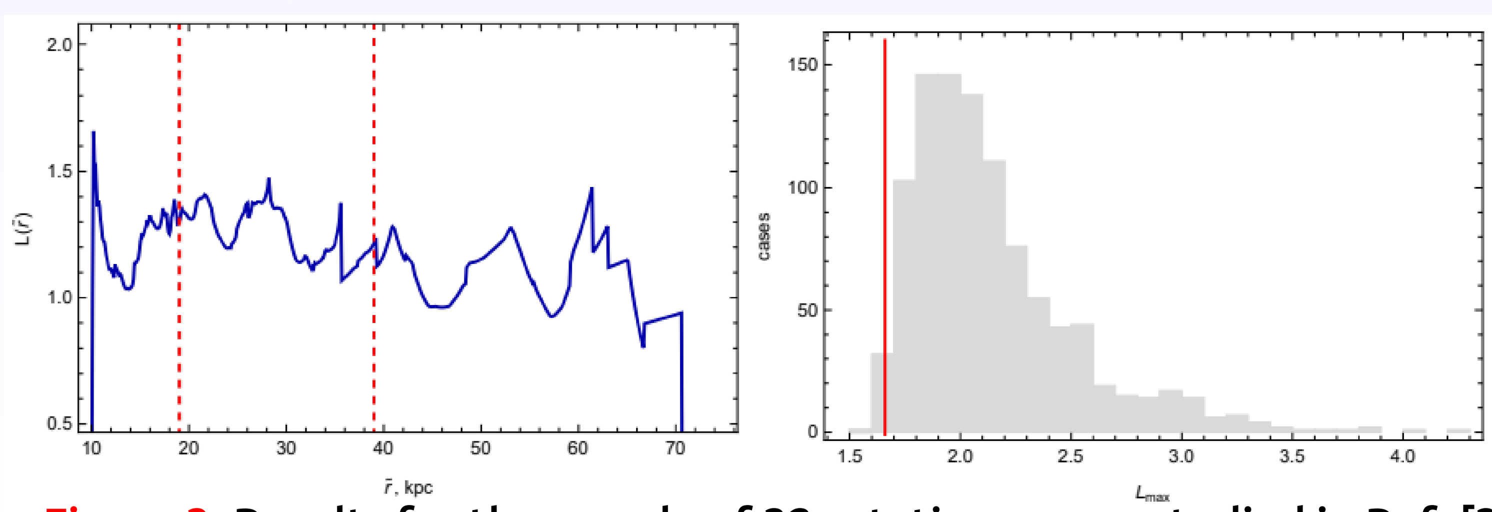


Figure 1. The function $L(\tilde{r})$ for the main sample of 121 galaxies which does not include those studied in Ref. [3]. The vertical dashed lines indicate the expected positions of the n = 1, 2 caustic rings claimed in Ref. [3], corrected for the slightly different value of *h*.



The observed $L_{max} \approx 1.83$ or larger was found 202 times out of 1000, resulting in the *p*-value of 0.2 for the null hypothesis of the absence of universal caustic rings.

Figure 2. The distribution of the maxima of 1000 Monte-Carlo simulated $L(\tilde{r})$ functions for the main sample of rotation curves. The vertical line indicates the value of L_{max} obtained for the data.



We find the *p*-value of 0.98 for the null hypothesis.

Figure 3. Results for the sample of 32 rotation curves studied in Ref. [3]. Left: the function $L(\tilde{r})$. The vertical dashed lines indicate the expected positions of the *n* = 1, 2 caustic rings claimed in Ref. [3]. Right: the distribution of the maxima of 1000 Monte-Carlo simulated $L(\tilde{r})$. The vertical line indicates the value of L_{max} obtained for the data.

Discussion: comparison with the previous result

- We use the unbinned likelihood while the analysis of Ref. [3] was based on binning.
- We use Monte-Carlo based on the null hypothesis to estimate the significance, while Ref. [3] assigned statistical errors to the binned data by hand.

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