Potential of Milky Way given analytically

XI Bulgarian-Serbian Astronomical Conference
14-18.05.2018. - Belogradchik,

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A NEW

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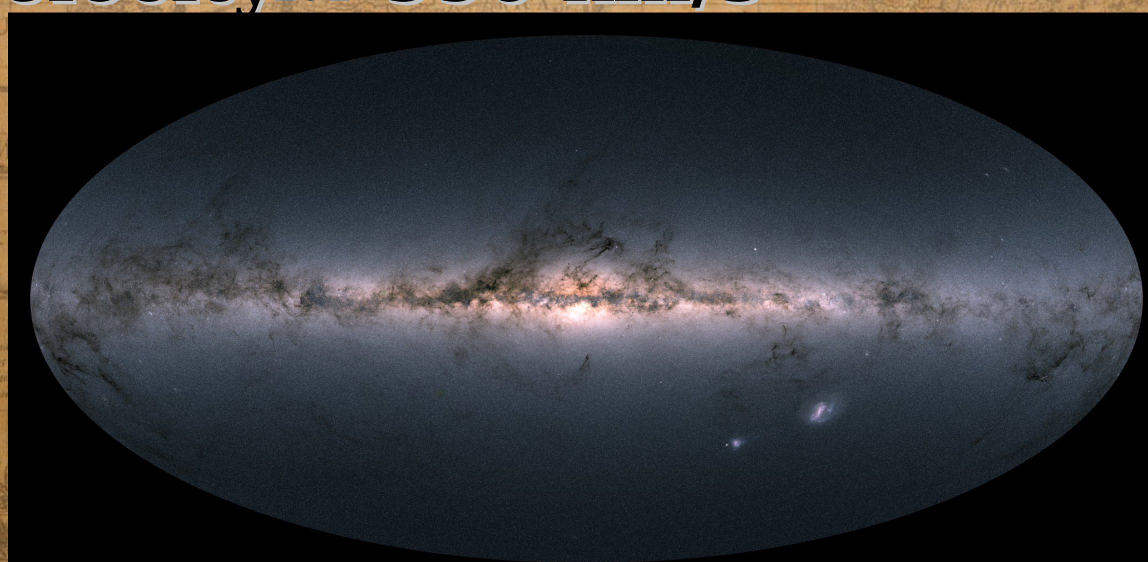
Introduction

- **Milky Way is spiral galaxy, type: Sbc**
- **~2 x 10^{11} stars + dm,**
- **Diameter 30-55 kpc**
- **Sun’s distance 8.1 ± 0.4 kpc**
- **Escape velocity $\odot$ 550 km/s**



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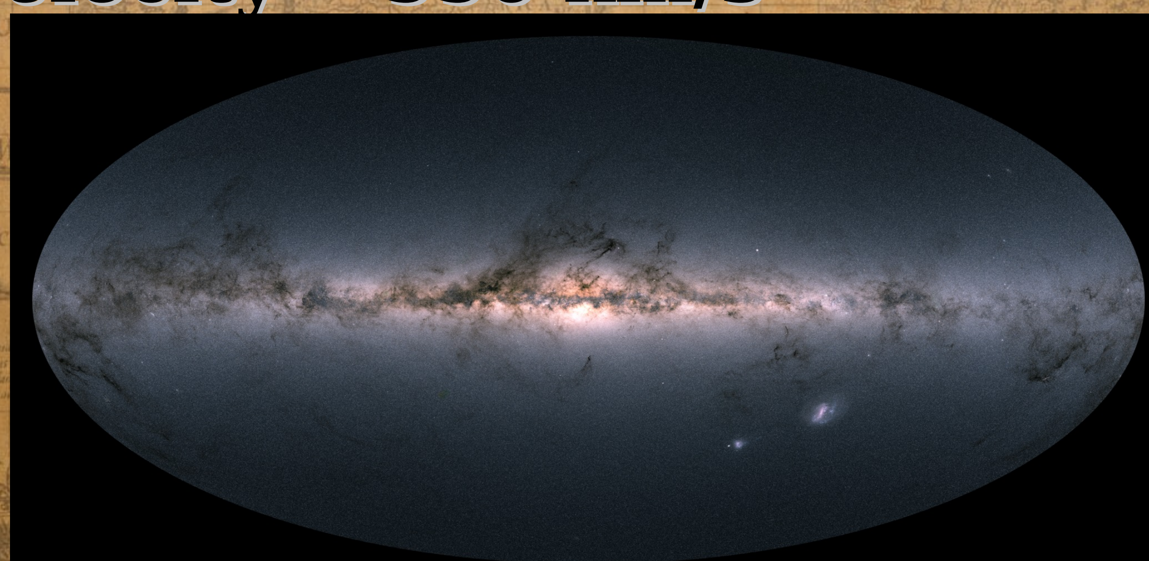
  - Disc (thin & thick)
  - Bulge
  - Dark matter halo



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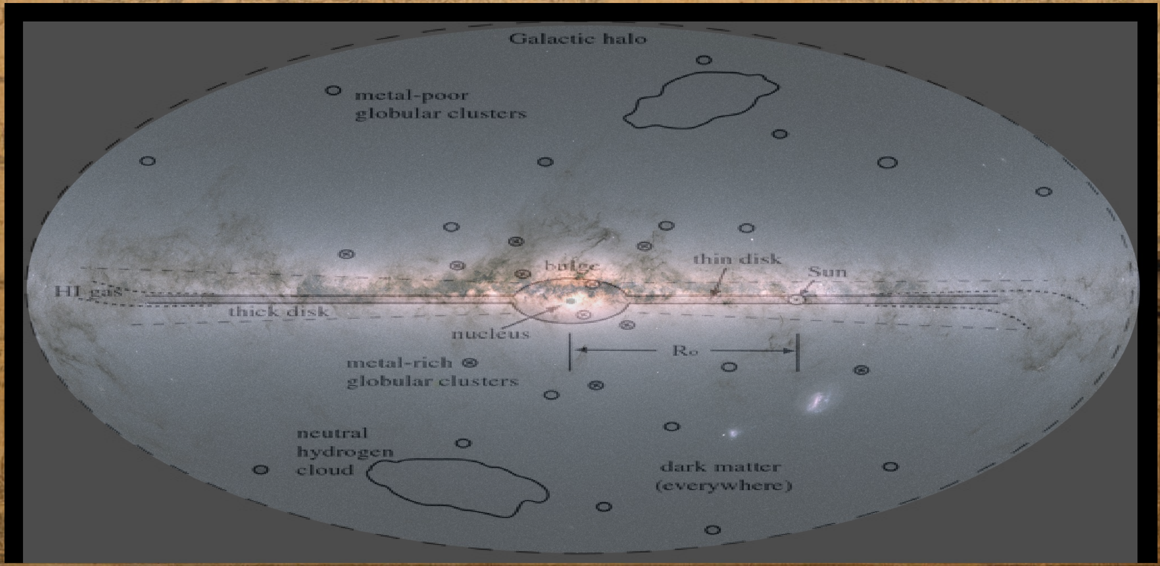
- **Mass ??**

  $0.5x10^{12}$

  $2x10^{12}$



Inspiration – *Iocco et al. 2015* *Li 2016*

nature physics

LETTERS

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Evidence for dark matter in the inner Milky Way

Fabio Iocco[1,2]*, Miguel Pato[3,4] and Gianfranco Bertone[5]

The ubiquitous presence of dark matter in the Universe is today a central tenet in modern cosmology and astrophysics[1]. Throughout the Universe, the evidence for dark matter is compelling in dwarfs, spiral galaxies, galaxy clusters as well as at cosmological scales. However, it has been historically difficult to pin down the dark matter contribution to the total mass density in the Milky Way, particularly in the innermost regions of the Galaxy and in the solar neighbourhood[2]. Here we present an up-to-date compilation of Milky Way rotation curve measurements[3–13], and compare it with state-of-the-art baryonic mass distribution models[14–26]. We show that current data strongly disfavour baryons as the sole contribution to the Galactic mass budget, even inside the solar circle. Our findings demonstrate the existence of dark matter in the inner Galaxy without making any assumptions about its distribution. We anticipate that this result will compel new model-independent constraints on the dark matter local density and profile, thus reducing uncertainties on direct and indirect dark matter searches, and will help reveal the structure and evolution of the Galaxy.

Existing studies of the dark matter density in the inner Galaxy fall into two categories: mass modelling and local measurements. In mass modelling, the distribution of dark matter is assumed to follow a density profile inspired by numerical simulations, typically an analytic fit such as the well-known Navarro–Frenk–White[27] or Einasto[28] profiles, with two or more free parameters whose best-fit values are then determined from dynamical constraints. The weak constraints in the innermost regions of the Milky Way, due to a combination of poor rotation curve data and large uncertainties associated with the distribution of baryons. We show that recent improvements on both fronts allow us to obtain a convincing proof of the existence of dark matter inside the solar circle.

We start by presenting a new, comprehensive compilation of rotation curve data derived from kinematic tracers of the Galactic potential, which considerably improves on earlier (partial) compilations[30,31]. Optimized to Galactocentric radii $R = 3$–20 kpc, our database includes gas kinematics (HI terminal velocities[3,4], CO terminal velocities[5], HI thickness[6], HII regions[7,8], giant molecular clouds[8]), star kinematics (open clusters[9], planetary nebulae[10], classical cepheids[11], carbon stars[12]) and masers[13]. This represents an exhaustive survey of the literature that intentionally excludes objects with only kinematic distances, and those for which asymmetric drift or large random motions are relevant. In total we have compiled 2,780 measurements, of which 2,174, 506 and 100 are from gas kinematics, star kinematics and masers, respectively (see Supplementary Text). For each measurement, we translate the kinematic data into a constraint on the angular velocity $\omega_c = v_c/R$ and on the Galactocentric radius R. The upper panel of Fig. 1 shows the rotation curve $v_c(R)$ for the full compilation of data, including only statistical uncertainties (see Supplementary Text for a test of systematics on observational data).

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Iocco et al. 2015

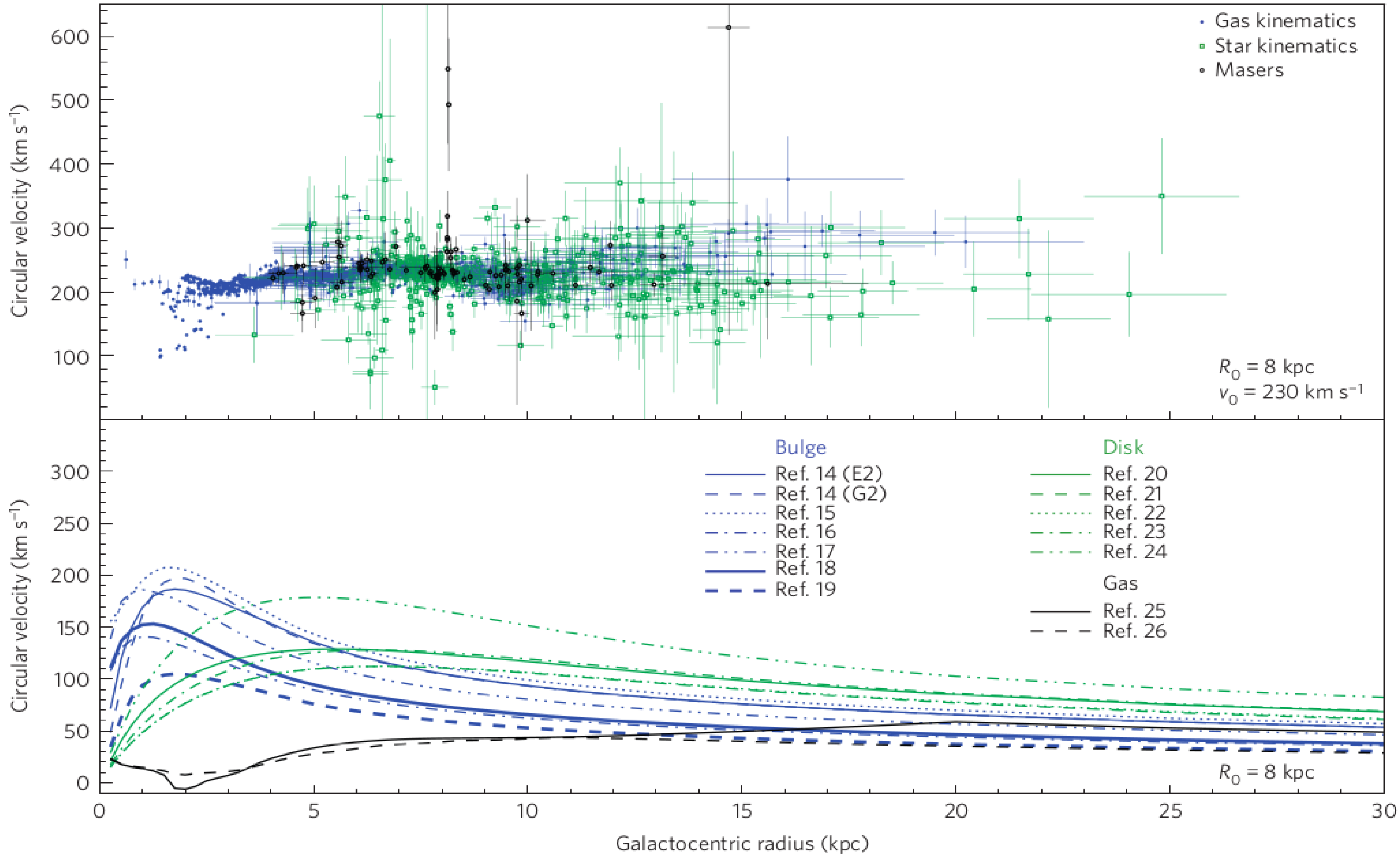

Figure 1 | The rotation curve of the Milky Way. In the top panel we show our compilation of rotation curve measurements as a function of Galactocentric radius, including data from gas kinematics (blue dots; HI terminal velocities, CO terminal velocities, HI thickness, HII regions, giant molecular clouds), star kinematics (open green squares; open clusters, planetary nebulae, classical cepheids, carbon stars) and masers (open black circles). Error bars correspond to 1σ uncertainties. The bottom panel shows the contribution to the rotation curve as predicted from different models for the stellar bulge (blue), stellar disk (green) and gas (black). We assume a distance to the Galactic Centre $R_0 = 8$ kpc in both panels, and a local circular velocity $v_0 = 230$ km s^{-1} in the top panel.

Milky Way potential
Four subsystems

- **Potential is assumed to be stationary and axially simmetric**
  - **Bulge (b) - Hernquist model**
  - **Innermost dark matter (idm) – spherical symmetry**
  - **Disc (d) – *PASA, vol. 32, 2015***
  - **Outer dark corona (odm) – *Open Ast. Vol. 26, 2017***
- **For each of them, potential is given analytically by using only elementary functions**
- **Model parameters are specified by fitting an assumed rotation curve.**

Innermost dm and bulge

- **We use (modification of) Hernquist model**

$$\Pi(r) = \frac{G\mathcal{M}}{r_1 + \sqrt{r_2^2 + r^2}} \,.$$

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M=11, r=2.05

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↓ **bulge**

$$\mathcal{M}_r = \mathcal{M}\frac{r^3}{(r_1 + \sqrt{r_2^2 + r^2})^2\sqrt{r_2^2 + r^2}} \; .$$

$$\rho = \frac{\mathcal{M}}{4\pi}\frac{3r_1 r_2^2 + 2r_1 r^2 + 3r_2^2\sqrt{r_2^2 + r^2}}{(r_1 + \sqrt{r_2^2 + r^2})^3(r_2^2 + r^2)^{3/2}} \; .$$

$10.5<M<13$
$0.3<r<0.5$

M in 10^9 solar masses
r in kpc

Disc

- **Observational constraints**

  (Deg & Widrow 2013)

$$\rho(R,z) = \rho(0)exp\left(-\frac{R}{R_d}\right)sech^2\left(\frac{z}{z_d}\right),$$

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- **We start with famous Miyamoto-Nagai formula**

$$\Phi = \frac{G\mathcal{M}}{\mathcal{R}_{MN} - \mathcal{R}_N}.$$

$$\mathcal{R}_{MN} = \left[R^2 + \left(a + \sqrt{z^2 + b^2}\right)^2\right]^{1/2}.$$

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$$\mathcal{R}_N = \frac{1}{2} R_d \left[\left(1 + \frac{R^2}{c_1^2}\right)^{\gamma_1} + \left(1 + \frac{z^2}{c_2^2}\right)^{\gamma_2}\right],$$

$$u_c = \sqrt{\frac{G\mathcal{M}R}{\left[\sqrt{R^2 + (a+b)^2} - \frac{1}{2}R_d\left(1 + \left(1 + \frac{R^2}{R_d^2}\right)^{\gamma_1}\right)\right]^2}} \cdot \sqrt{\frac{R}{\sqrt{R^2 + (a+b)^2}} - \gamma_1 \frac{R}{R_d}\left(1 + \frac{R^2}{R_d^2}\right)^{\gamma_1 - 1}}.$$

(Ninkovic 2015)

Disc

- **Three parameters are important:**
  - **Total mass *M*, exp. scale length R_d and scale len. b**
- **Since disc is flattened it must be *a>>b* and *$\gamma_1,\gamma_2<0.5$.***
- **We have chosen *$a+b=2.1R_d$* and *$7.8x10^{10}<M<9x10^{10}$***
- **And *$\gamma_1=-0.3$, $\gamma_2=0.3$, $c_1=c_2=R_d$* and *$a\approx 2R_d$***

Outer dark corona

- **The assumed model density & cumulative mass**

$$\rho = \rho_0 \left(\frac{1}{1+\xi^3} - \frac{1}{1+\xi_l^3} \right) .$$

$$\mathfrak{M}_\xi = 4\pi \rho_0 \mathfrak{R}_c^3 \left[\frac{\ln(1+\xi^3)}{3} - \frac{\xi^3}{3(1+\xi_l^3)} \right] .$$

Designations: $\mathfrak{R}$ - distance to the Milky Way centre, $\mathfrak{R}_c$ - corona scale length, $\mathfrak{R}_l$ - corona limiting radius, $\xi = \mathfrak{R}/\mathfrak{R}_c$, $\xi_l = \mathfrak{R}_l/\mathfrak{R}_c$.

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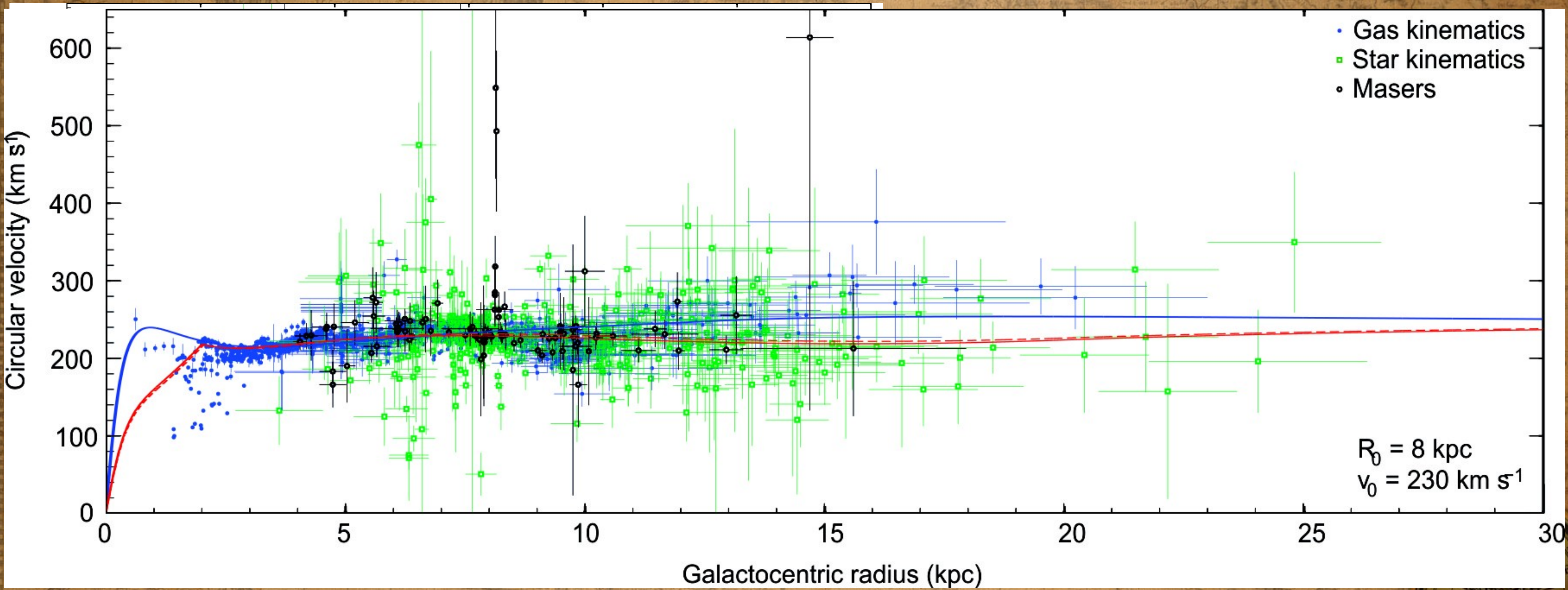
- **We can now obtain potential *(Ninkovic 2017)***

$$\Pi(\mathfrak{R}) = \frac{G\mathfrak{M}_\mathfrak{R}}{\mathfrak{R}} + 4\pi G \rho_0 \mathfrak{R}_c^2 \left\{ \frac{1}{6} \ln \frac{\frac{4}{3}\left(\xi_l - {}^1\!/_2\right)^2 + 1}{\frac{4}{3}\left(\xi - {}^1\!/_2\right)^2 + 1} + \frac{\sqrt{3}}{3} \mathrm{arctg}\left[\frac{2\sqrt{3}}{3} \left(\xi_l - {}^1\!/_2\right) \right] \right.$$

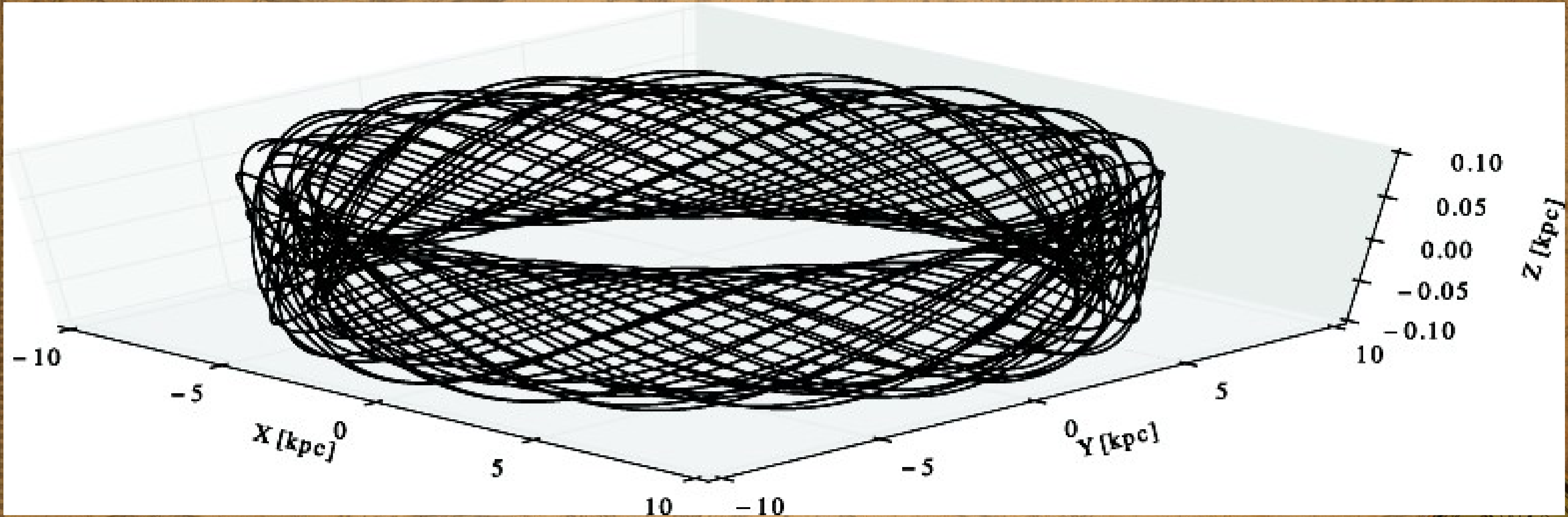
$$\left. - \frac{\sqrt{3}}{3} \mathrm{arctg}\left[\frac{2\sqrt{3}}{3} \left(\xi - {}^1\!/_2\right) \right] - \frac{1}{3} \ln \frac{\xi_l + 1}{\xi + 1} - \frac{\xi_l^2 - \xi^2}{2(1+\xi_l^3)} \right\} .$$

$\rho_0 = 0.0058\ \mathfrak{M}_\odot \mathrm{pc}^{-3}$, $\mathfrak{R}_c = 2R_\odot = 17\mathrm{kpc}$ ($\xi = 0.5$) and $\xi_l = 5.665$.

What? (do we get when we combine everything)



Why?



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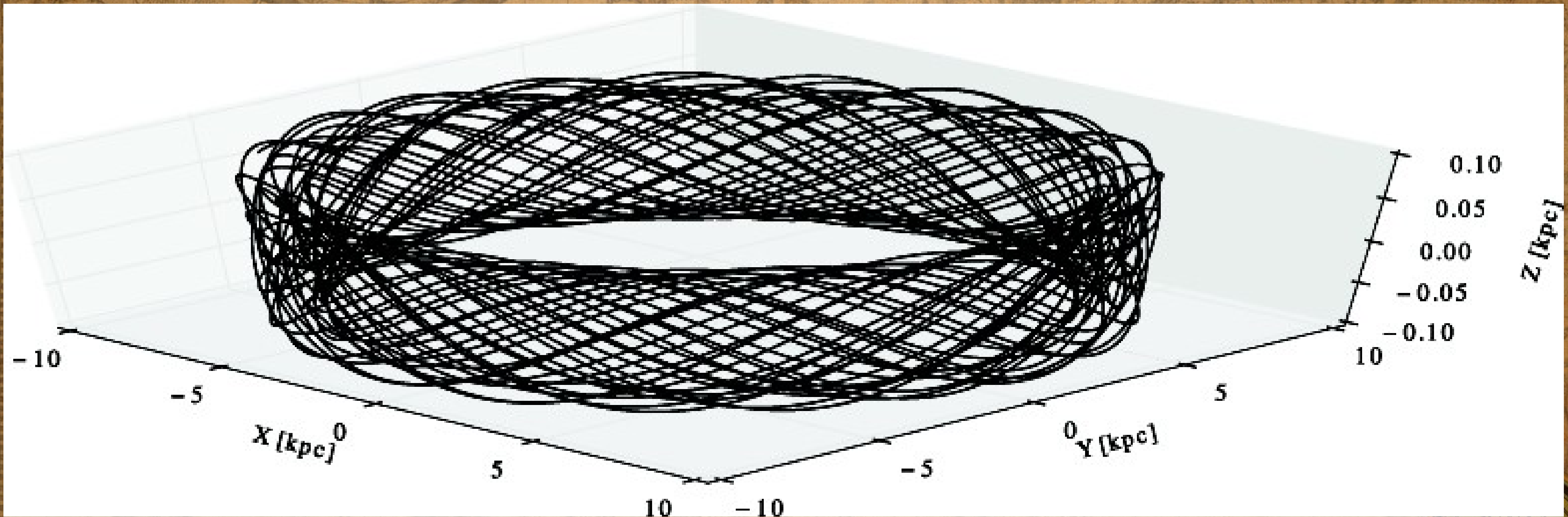

Thank you!