# Non-Parametric Spherical Jeans Mass Estimation with B-Splines

Nabeel Rehemtulla[1], Monica Valluri[1], Eugene Vasiliev[2, 3]

[1] Department of Astronomy, University of Michigan, Ann Arbor, MI, USA
[2] Institute of Astronomy, University of Cambridge, Cambridge, UK
[3] Lebedev Physical Institute, Moscow, Russia

MIDAS annual symposium 2020

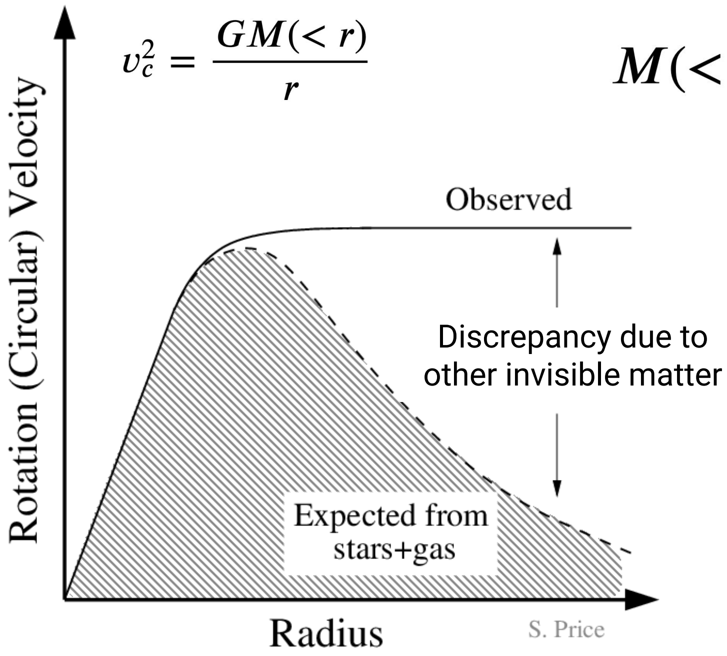
# Overview

- Background
  - Dark matter
  - Spherical Jeans equation and modeling
- Our novel routine
- Results of testing our routine
- Application to the Milky Way

# Background: Dark matter

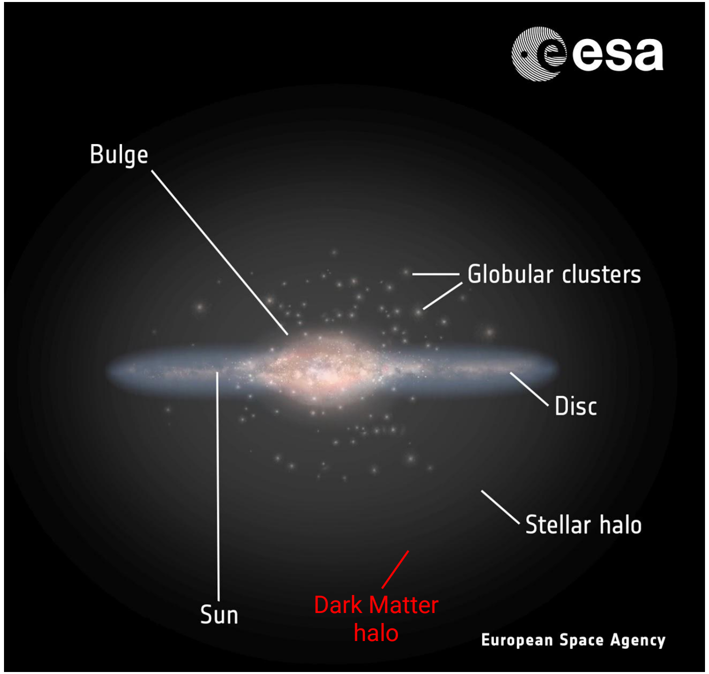
## What exactly is dark matter?

$$v_c^2 = \frac{GM(< r)}{r}$$




$$M(< r) = \frac{v_c^2 r}{G}$$

## How is it distributed in a galaxy?



# Background:
# Spherical Jeans Equation and Modeling

$$M(< r) = \frac{v_c^2 r}{G}$$

$$M(< r) = \frac{\overline{v_r^2} r}{G}\left( - \frac{\mathrm{d} \ln \rho}{\mathrm{d} \ln r} - \frac{\mathrm{d} \ln \overline{v_r^2}}{\mathrm{d} \ln r} - 2\beta \right)$$

$$\beta = 1 - \frac{v_\theta^2 + v_\phi^2}{2v_r^2}$$

- Apply to halo stars (tracers)
    - Kinematics to get mass profile, M( < r)
- Not a new method (Jeans 1915)
- **Assumptions**
    - Spherical symmetry
    - Dynamical equilibrium

Description of terms

$\mathrm{M}(<\mathrm{r})$ : Mass enclosed

$r$ : spherical radius from galactic center

$G$ : Gravitational constant

$v_r, v_\phi, v_\theta$ : spherical velocity components

$\varrho$ : number density of tracers

$\beta$ : velocity anisotropy

# Our Novel Routine

$$M(<r) = \frac{\overline{v_r^2} r}{G}\left(-\frac{\mathrm{d}\ln\rho}{\mathrm{d}\ln r} - \frac{\mathrm{d}\ln\overline{v_r^2}}{\mathrm{d}\ln r} - 2\beta\right)$$

$$\beta = 1 - \frac{v_\theta^2 + v_\phi^2}{2v_r^2}$$

- Uses **B-Splines**
  - **Unbinned, Non-parametric**
  - Accurate, convenient derivatives
- Calculation of velocity terms
  - Fit B-Splines to spherical velocity components, $v_r^2, v_\phi^2, v_\theta^2$
- Calculation of density $\rho$ term
  - Fit B-Spline to tracer count, C(ln r)
  - Numerical derivative
    - Richardson's method

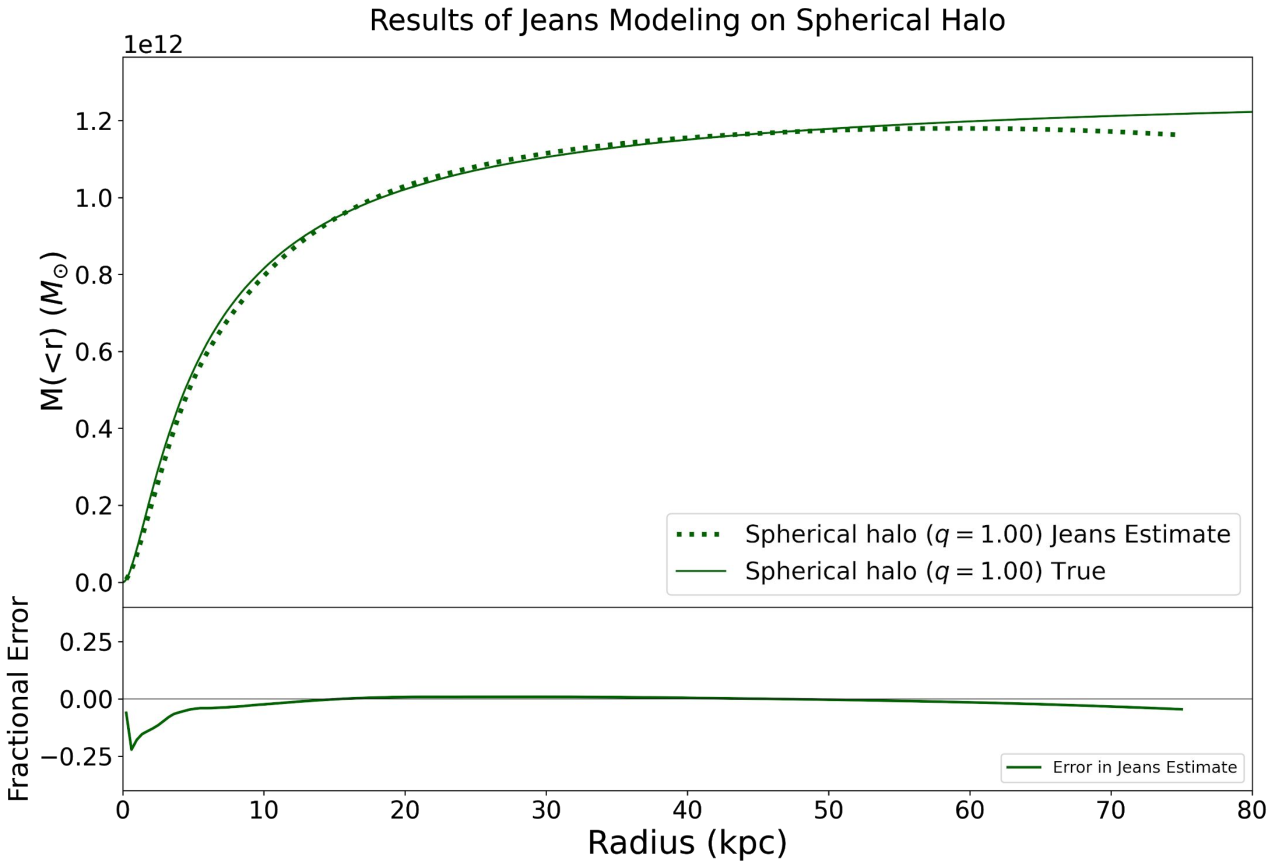
$\rho(r) = C(\ln r) / 4\pi r^3$

# Testing with mock datasets

- Why use mock data (simulations)?
    - True cumulative profile
    - Control how assumptions are broken
- **Quantify errors introduced when breaking assumptions**
- AGAMA (Vasiliev 2019)

Progression of datasets

1. Spherical halo
2. Flattened halo (6 variants)
3. Spherical halo with disk and bulge

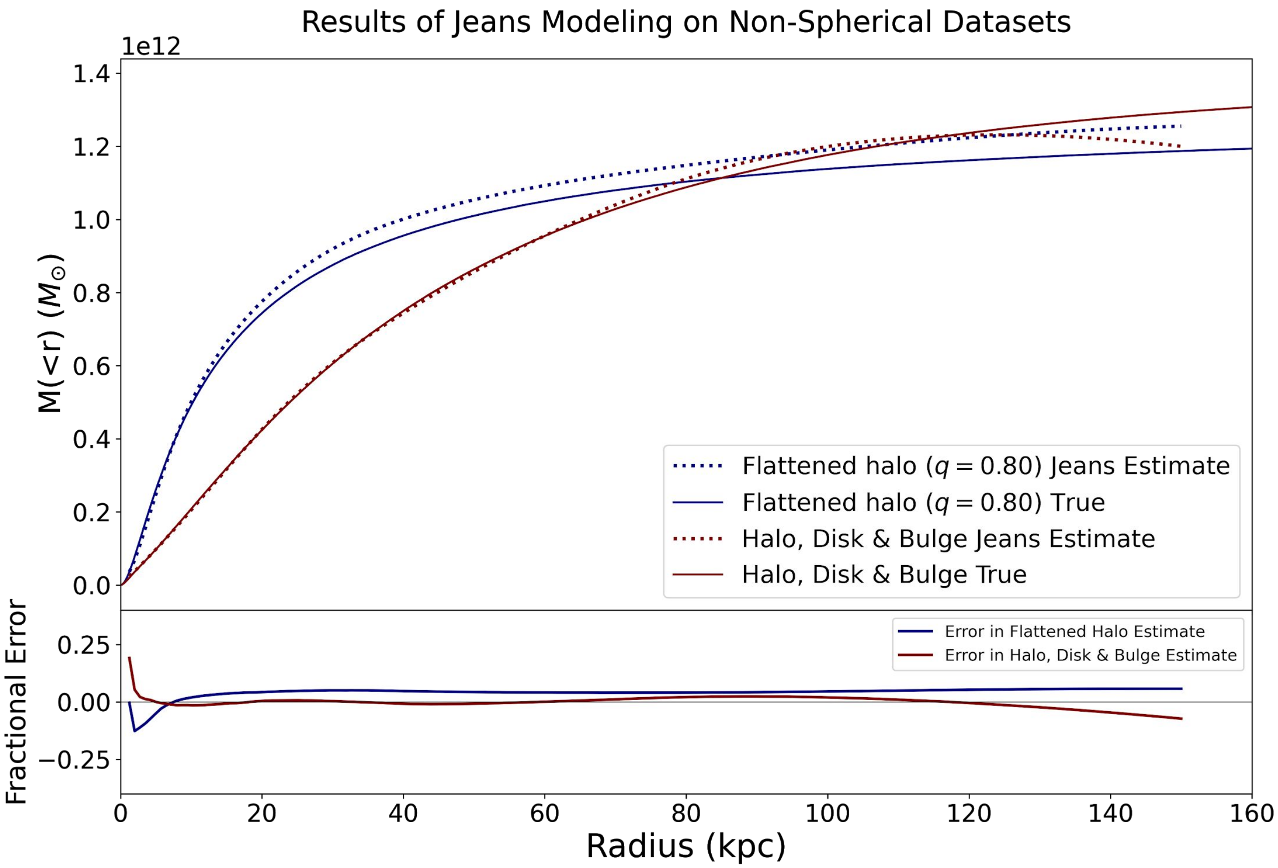



Spherical halo (axis ratio=1.00)

Satisfies both assumptions

Expect near perfect estimation

# Results from testing a spherical halo




Flattened halo
(axis ratio=0.80)
-and-
Halo, Disk & Bulge

Both break assumption of spherical symmetry

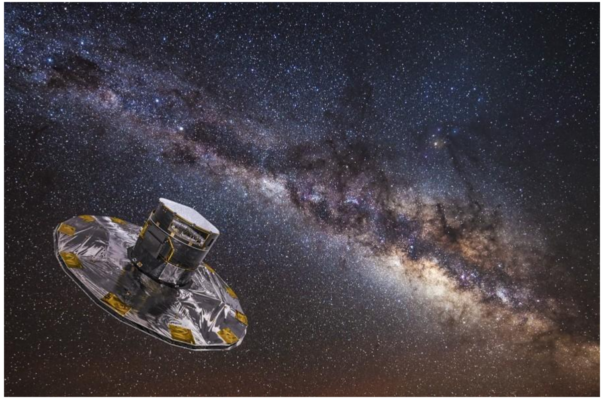
# Results from testing non-spherical datasets

# Application to the Milky Way

- Current work is preparation for real data
  - Test assumption of dynamical equilibrium

- Milky Way data from
  - Gaia
  - Dark Energy Spectroscopic Instrument (DESI)

- Implications for “Jeans-users”



# Overview

- Background
    - Dark matter
    - Spherical Jeans modeling
- Our novel routine
- Results of testing our routine
- Application to the Milky Way

# Questions and comments

Contact us:

**nabeelr@umich.edu**
mvalluri@umich.edu

This work is funded by NASA grants NNX15AK79G and 80NSSC20K0509 and a Catalyst Grant from MICDE.

# Thank you!

## References:


Jeans, J. H., 1915, MNRAS, 76, 70

Vasiliev, E., 2019, MNRAS, 482, 1525


## Image Sources:

http://mosdef.astro.berkeley.edu/wp-content/uploads/2015/12/rot_curve.png
https://www.esa.int/ESA_Multimedia/Images/2018/05/Anatomy_of_the_Milky_Way
https://solarsystem.nasa.gov/system/content_pages/main_images/1698_Gaia_mapping_the_stars_of_the_Milky_Way-900x597.jpg
https://news.fnal.gov/wp-content/uploads/2020/05/mayall-telescope-interior-berkeley.jpg