Mapping Dark Matter: Non-Parametric Spherical Jeans Mass Estimation with B-Splines

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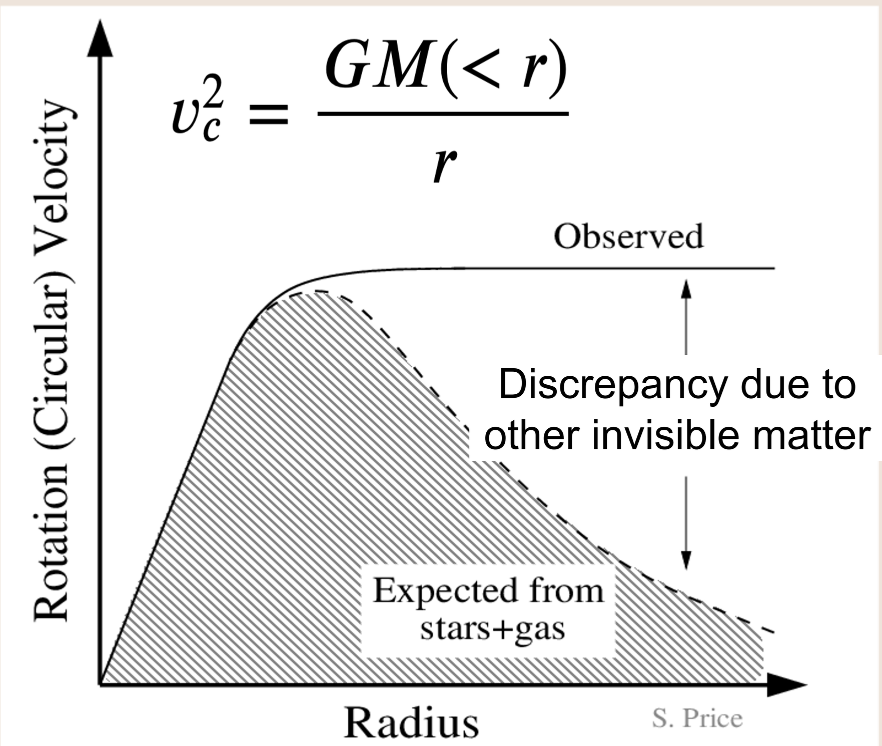
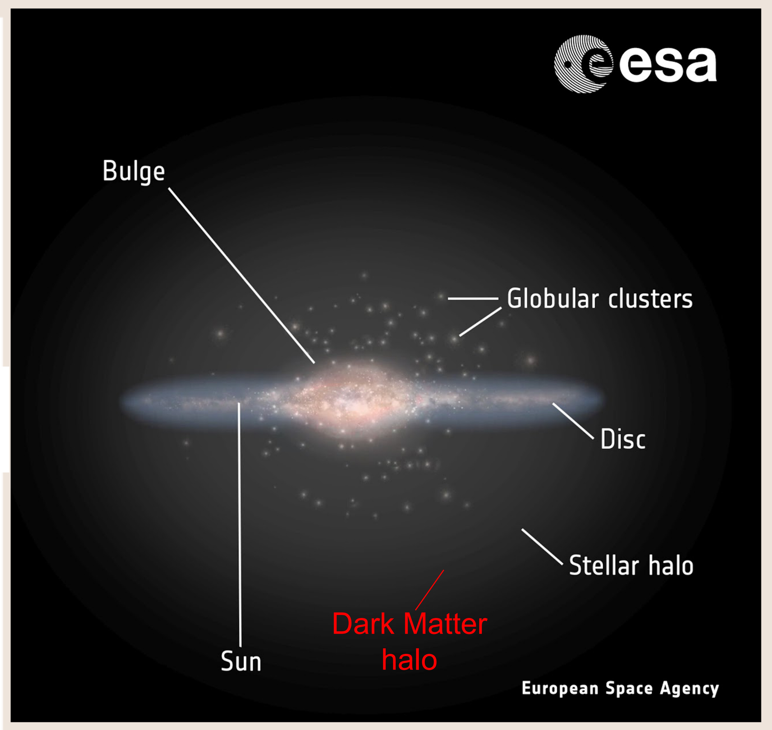
Background: Dark Matter





What exactly is dark matter?

How is it distributed in a galaxy?

- Can only see through gravitational influence on visible matter
  - Galactic rotation curve (Vera Rubin)
- DM in nearly spherical 'Dark Matter Halo'
- Intertwined with Stellar Halo
  - Halo stars trace DM gravitational potential

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

- Use **halo star kinematics to infer DM distribution**

Background: Spherical Jeans Equation

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

- Reminiscent of circular velocity equation
- Halo stars kinematics to get M(<r)
  - Observe visible for information on invisible

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

- Not a new method (Jeans 1915)
- **Assumptions**
  - **Spherical symmetry**
  - Dynamical equilibrium
- Widely used, but errors poorly understood
- Constrain errors for application to MW

M(<r) : Mass enclosed
r : galactocentric radius
v_r, v_ϕ, v_θ : spherical velocity
ρ : number density of tracers
β : velocity anisotropy

Our Novel Routine

- Uses **B-Splines**
  - **Unbinned, Non-parametric**

Fit B-Splines to, v_r, v_ϕ, v_θ & tracer count, C(r) $\rho = C/4\pi r^3$
- Numerical derivative
  - Richardson's method

Why B-Splines?
- Analytical derivatives
- No error from radial binning or forcing curve shape
- Refine implementation decisions with extensive testing

First implementation with this methodology

Testing our routine

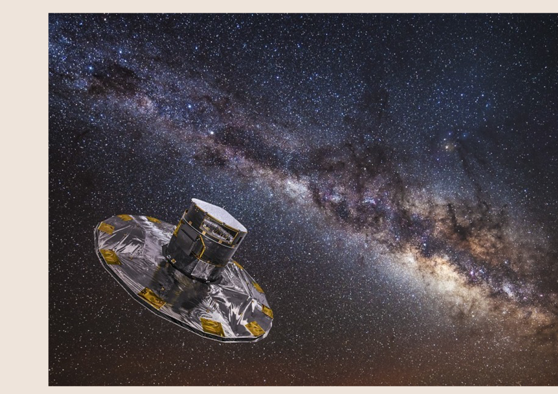
- Why use mock data (simulations)?
  - True cumulative profile
  - Control how we break assumptions
- **Quantify errors introduced when breaking assumptions**
  - Currently, poorly understood
- Run our own simulations with AGAMA (Vasiliev 2019)

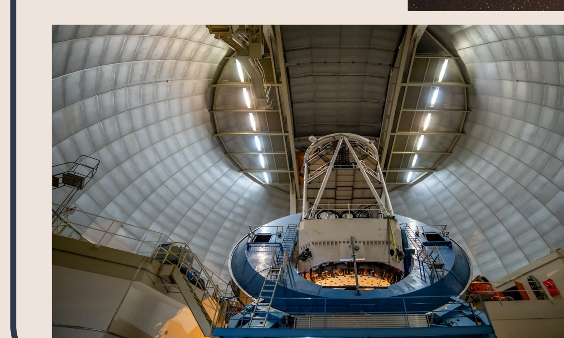
Progression of datasets
1. Spherical halo
2. Flattened halo (6 variants)
3. Spherical halo with disk and bulge

Application to Milky Way

- Preparation for MW Halo data from Gaia and DESI
- **We will map real dark matter in the Milky Way**

Gaia will provide proper motions





DESI will provide radial velocities and distances

References

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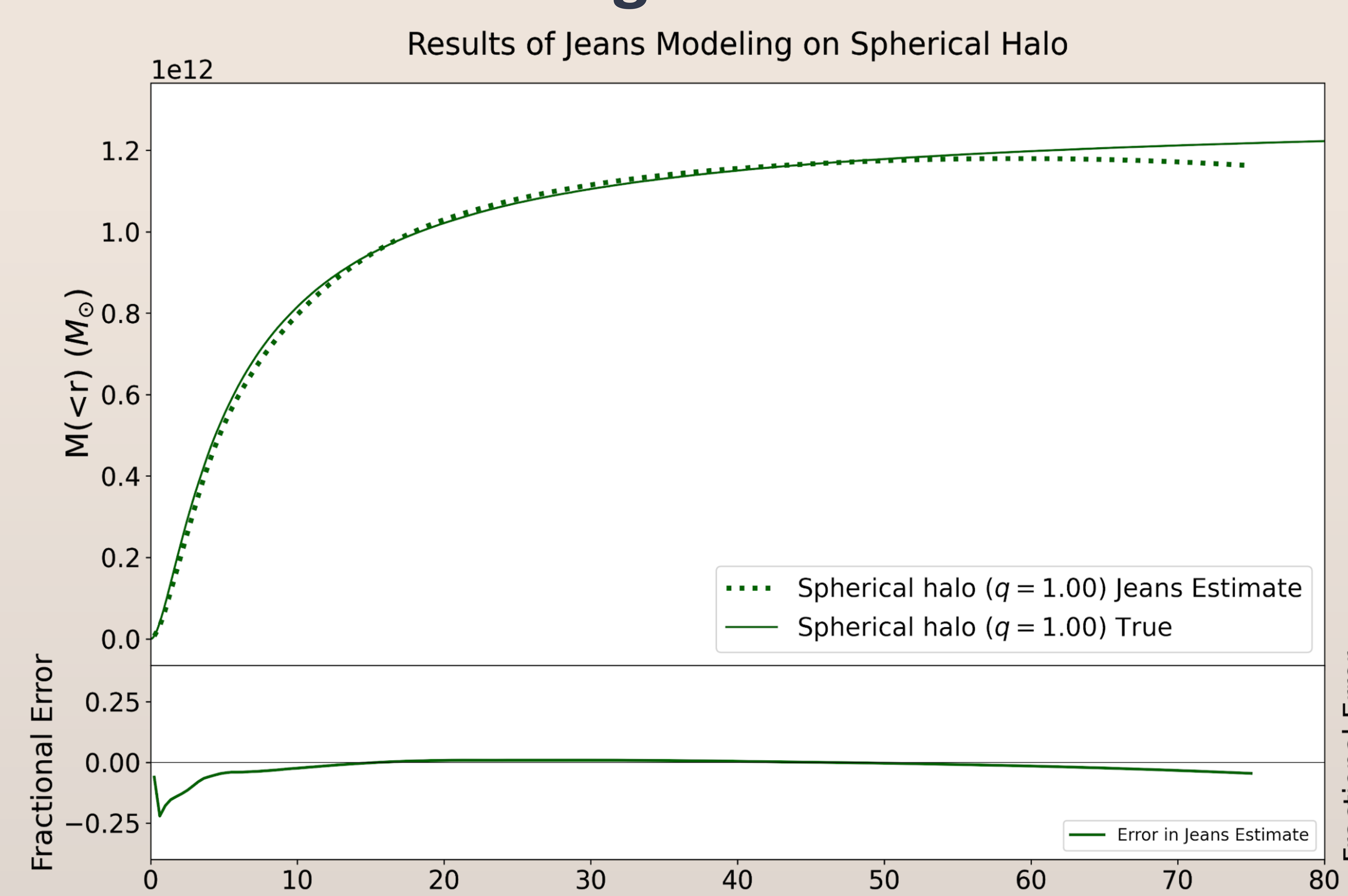
Jeans, J. H., 1915, MNRAS, 76, 70

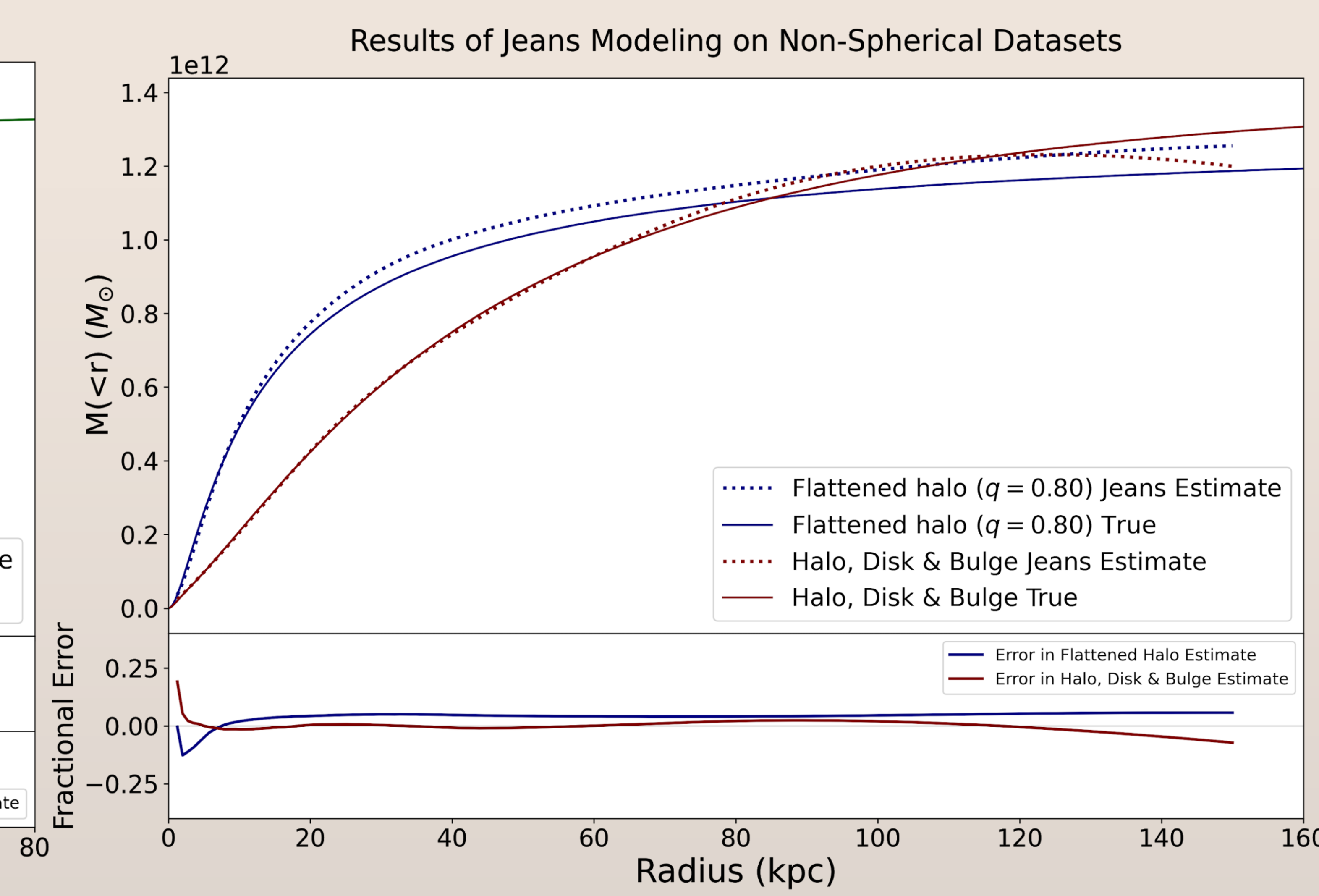
Vasiliev, E., 2019, MNRAS, 482, 1525

Results of testing



Spherical halo (axis ratio=1.00) - Satisfies both assumptions - Expect near perfect estimation

Error at small radii due to extremely high density in simulation, inconsequential to MW application



Flattened halo - (axis ratio=0.80) & Halo, Disk & Bulge Both break assumption of spherical symmetry

Mass estimation on both is very good; **breaking spherical symmetry does not introduce large errors**