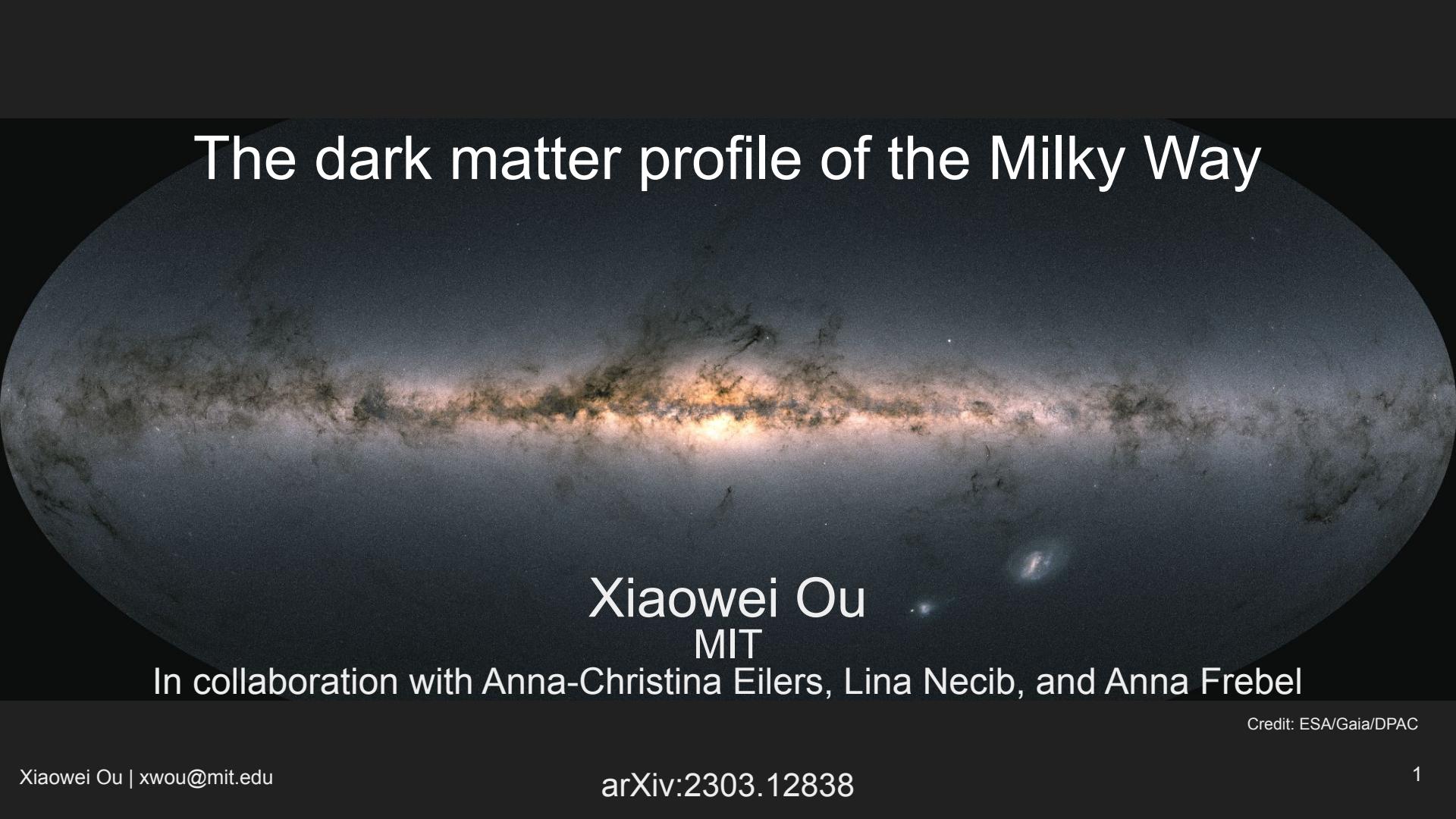


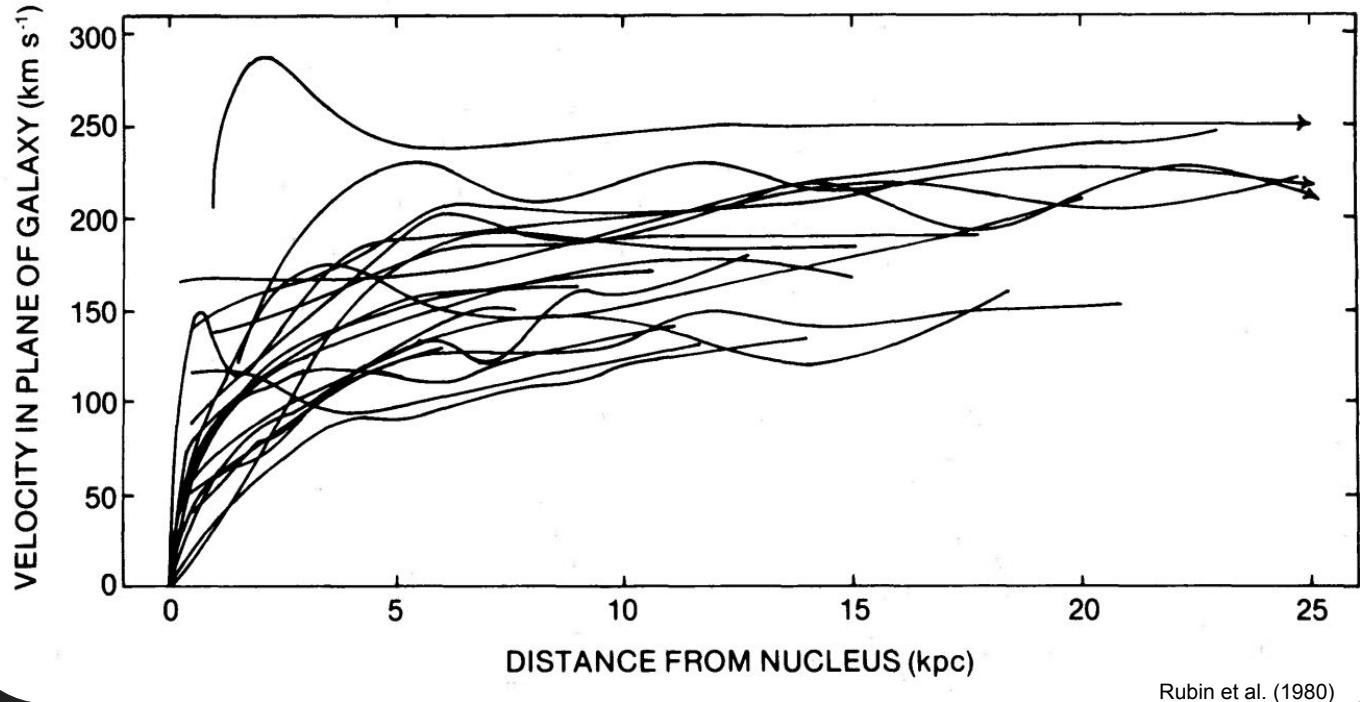
The dark matter profile of the Milky Way



Xiaowei Ou
MIT

In collaboration with Anna-Christina Eilers, Lina Necib, and Anna Frebel

Credit: ESA/Gaia/DPAC

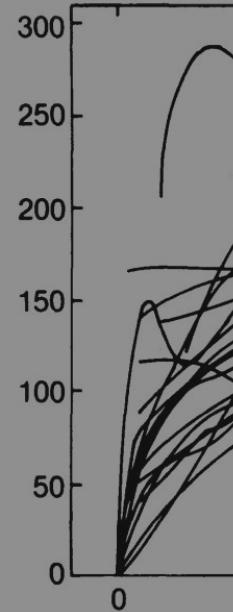


Vera Rubin

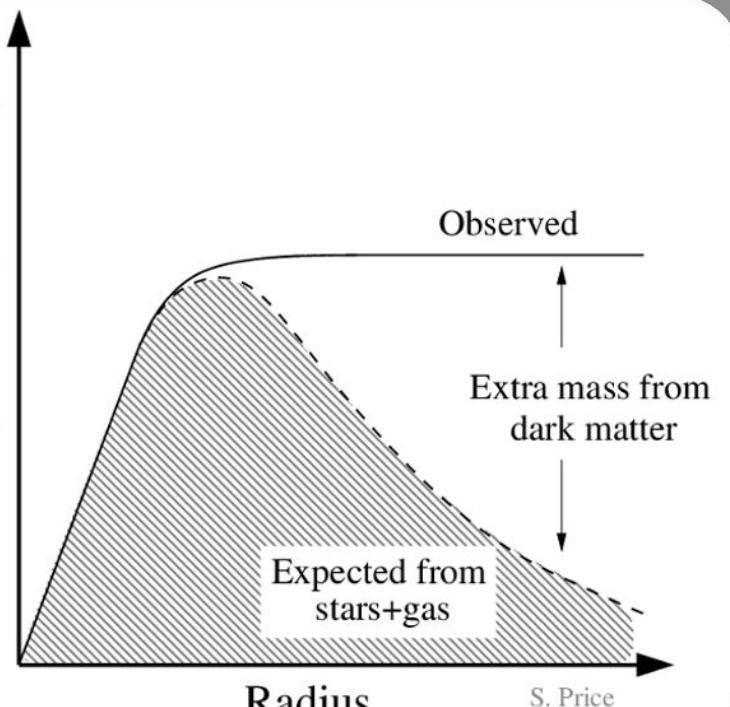
Credit: NASA/NOIRLab



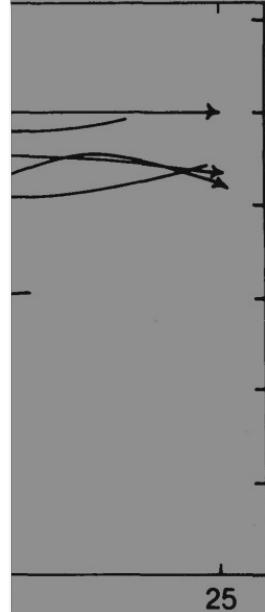
VELOCITY IN PLANE OF GALAXY (km s⁻¹)



Rotation (Circular) Velocity

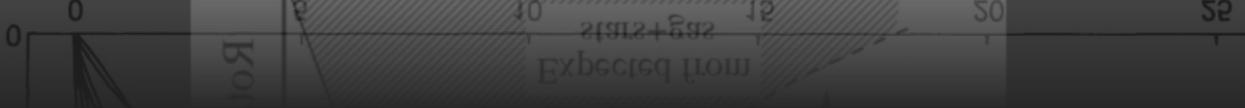


Rubin et al. (1980)

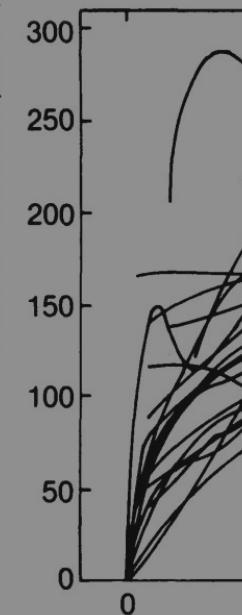


Credit: NASA/NOIRLab

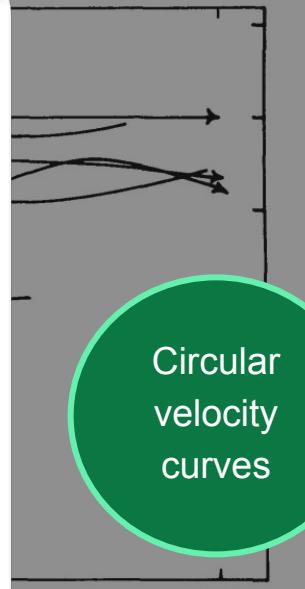
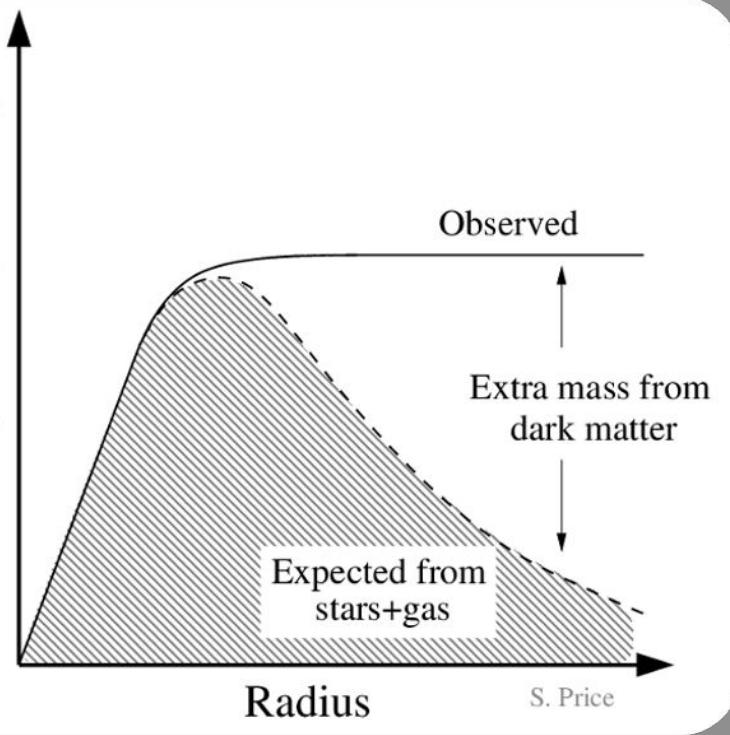
VELOC



VELOCITY IN PLANE OF GALAXY (km s⁻¹)



Rotation (Circular) Velocity



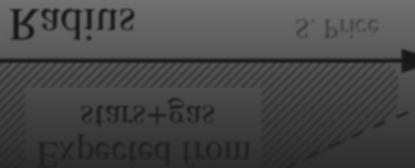
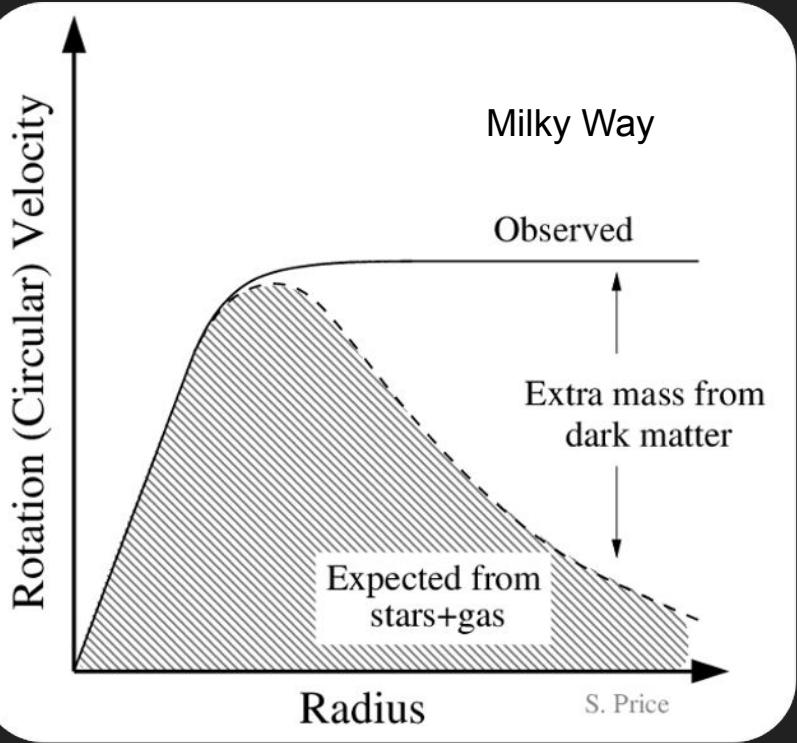
Probe

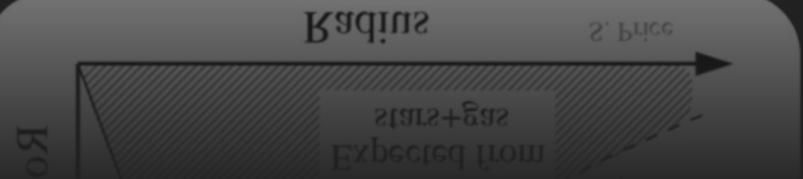
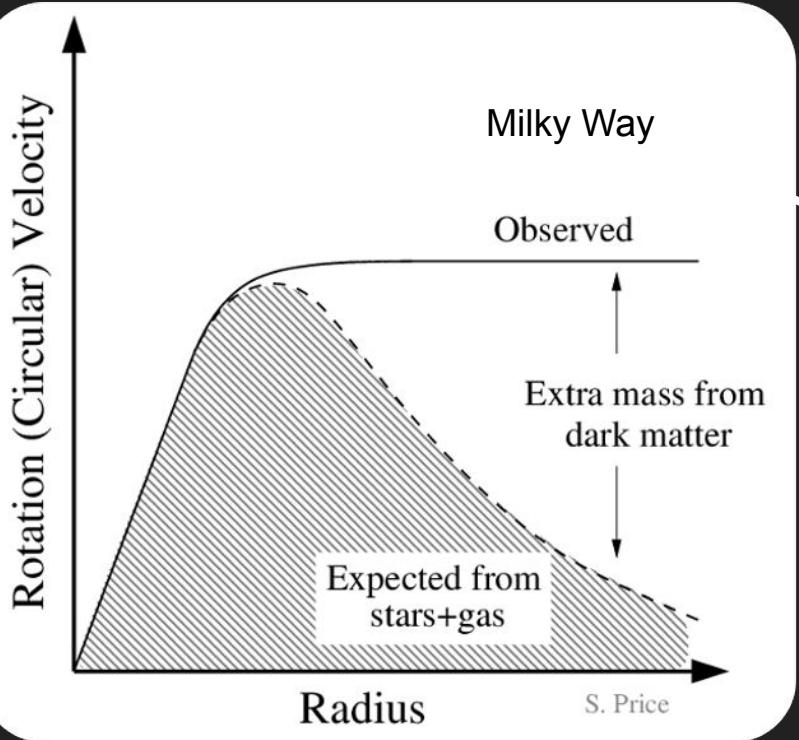


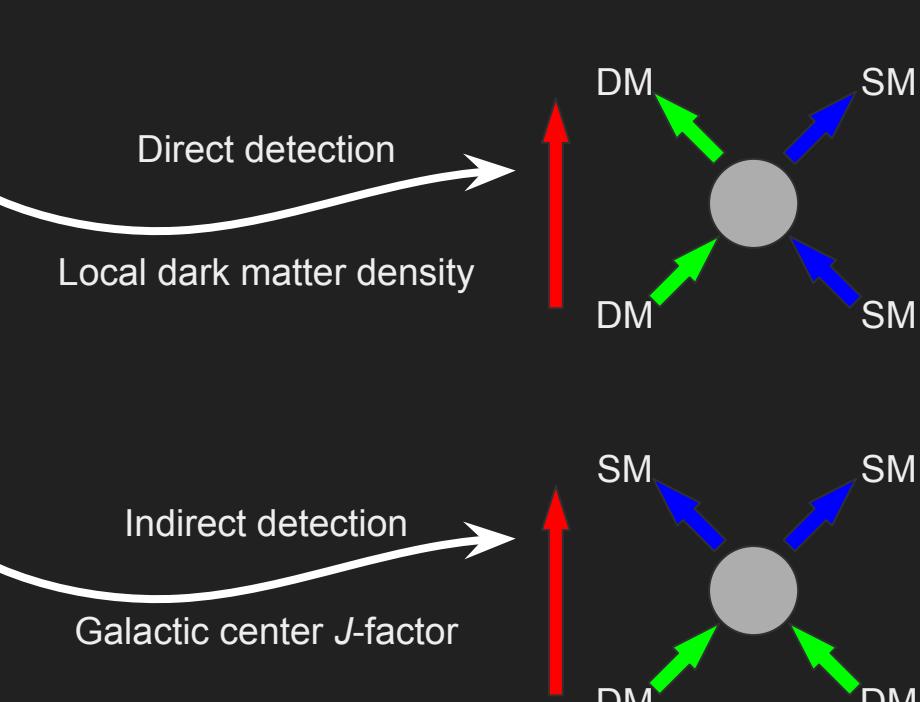
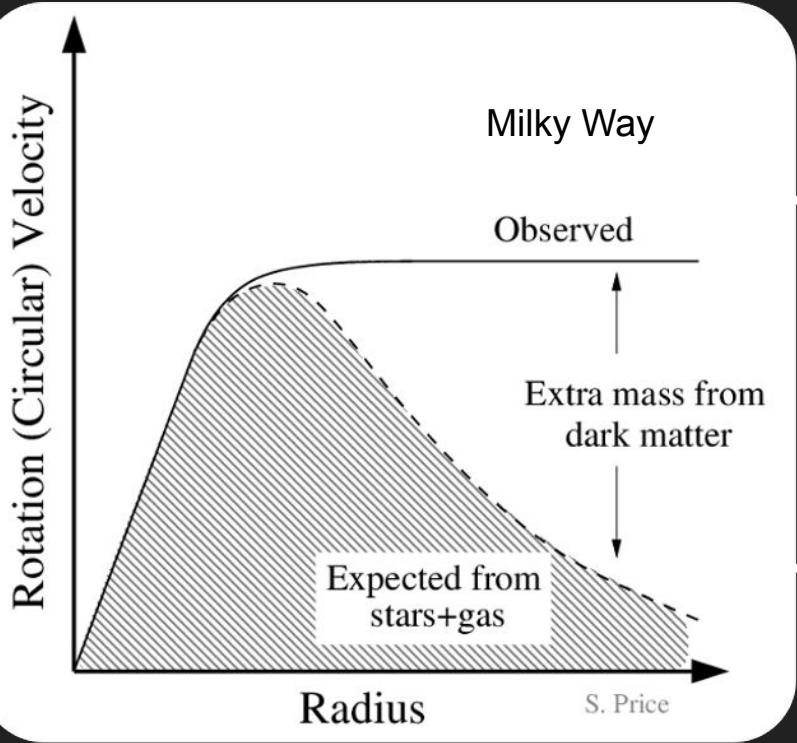
Evidence

Dark matter

Velocity

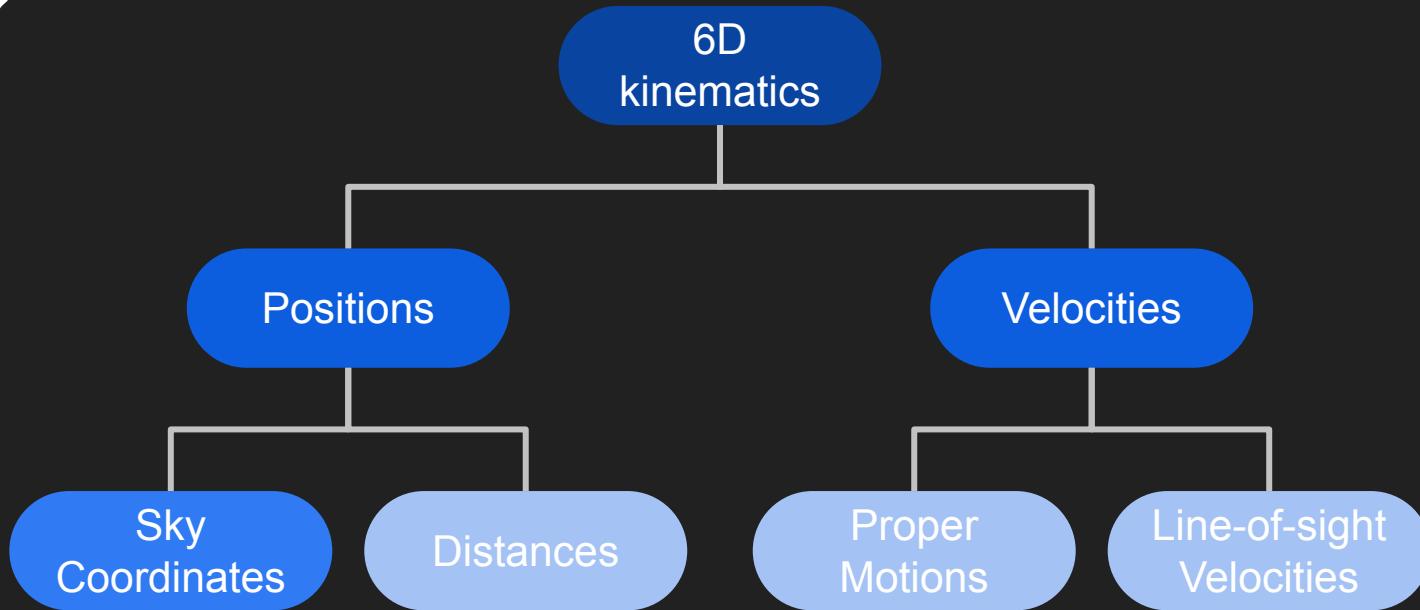




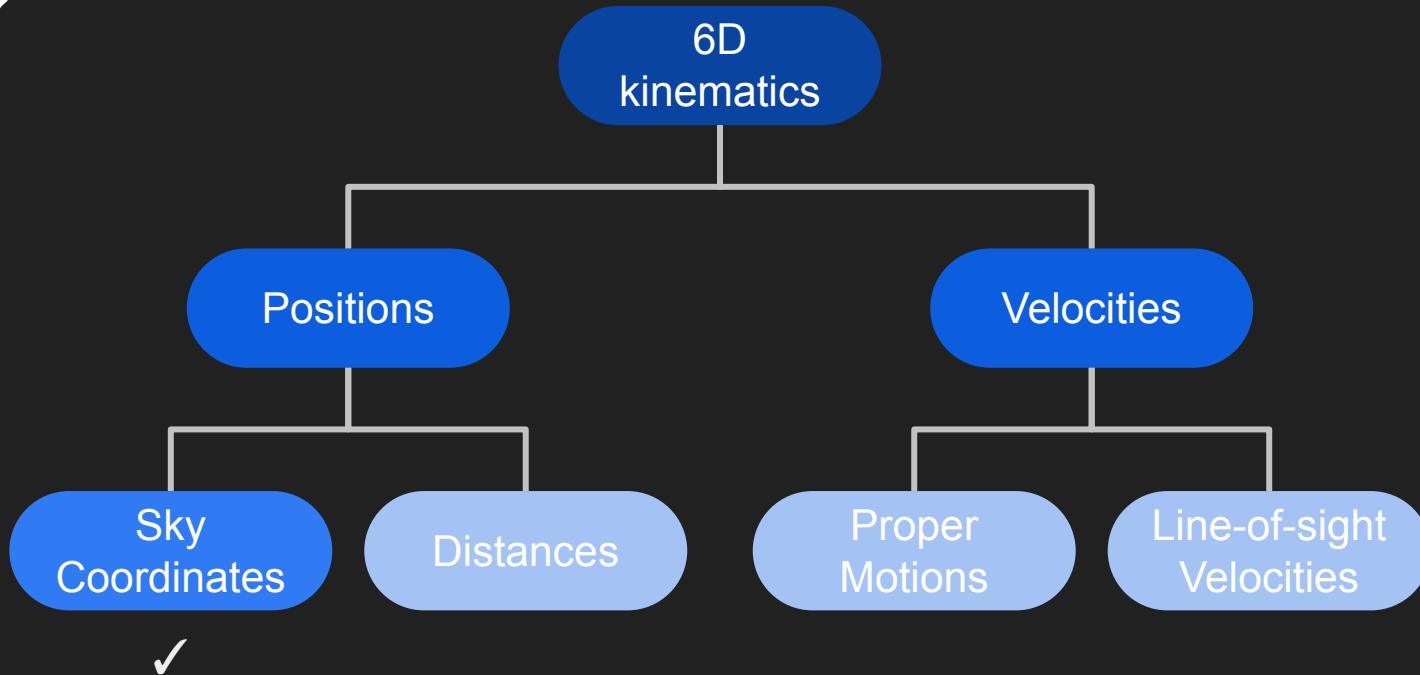


Goal: Measure the circular velocity curve
for the Milky Way

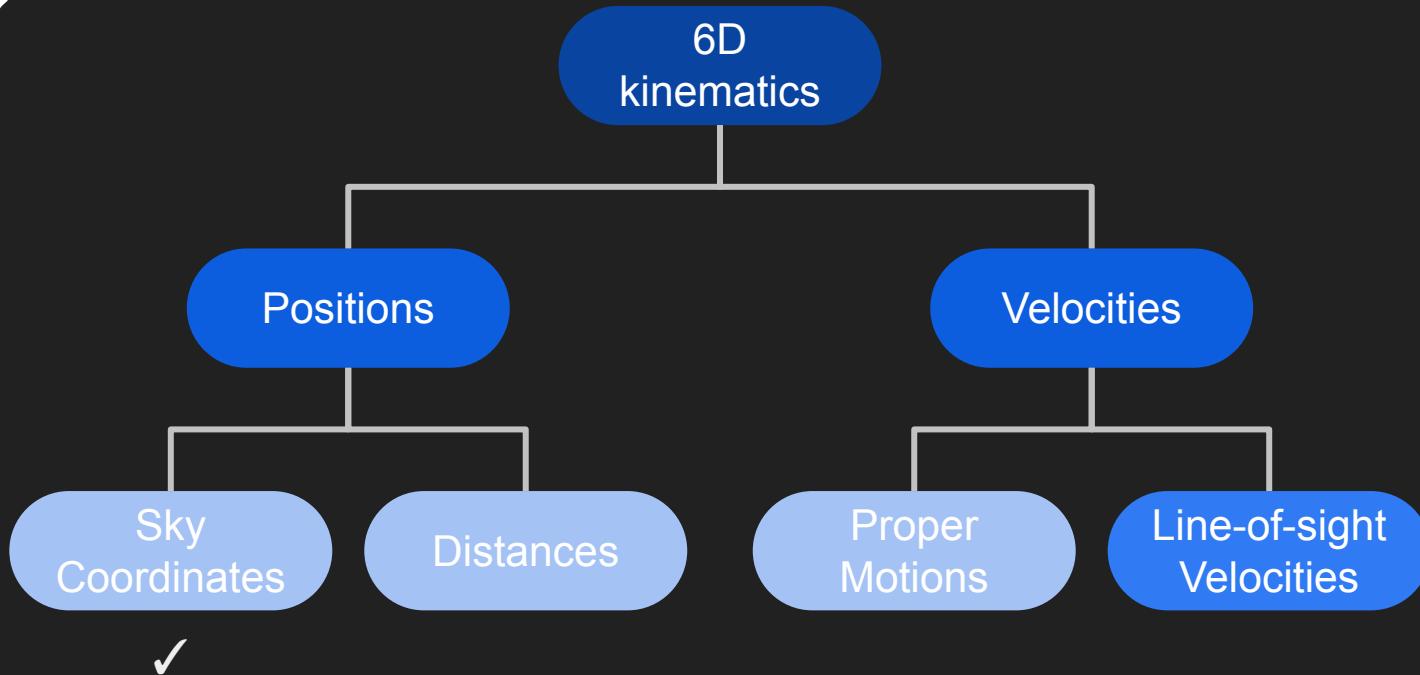
How?



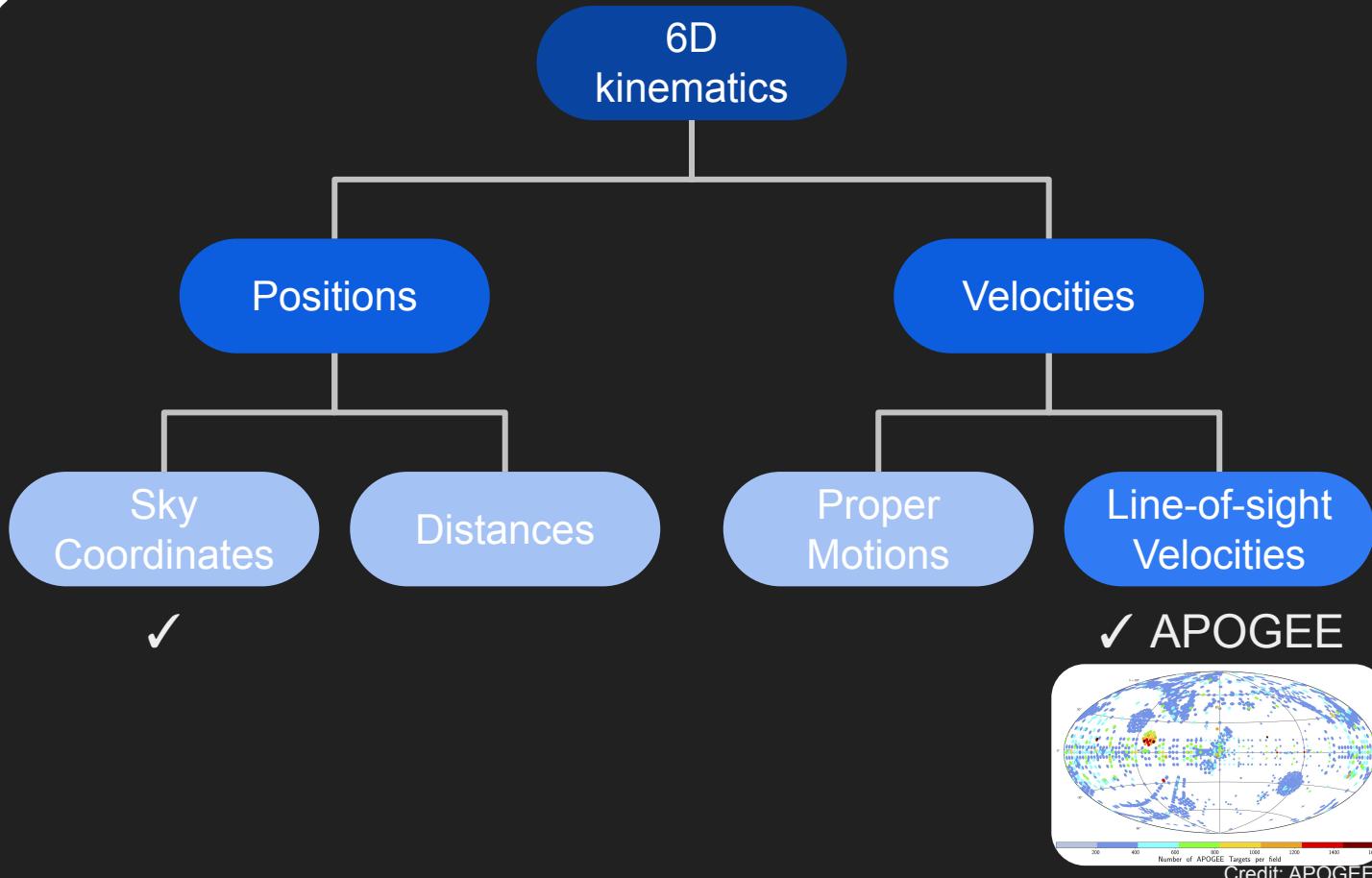
How?



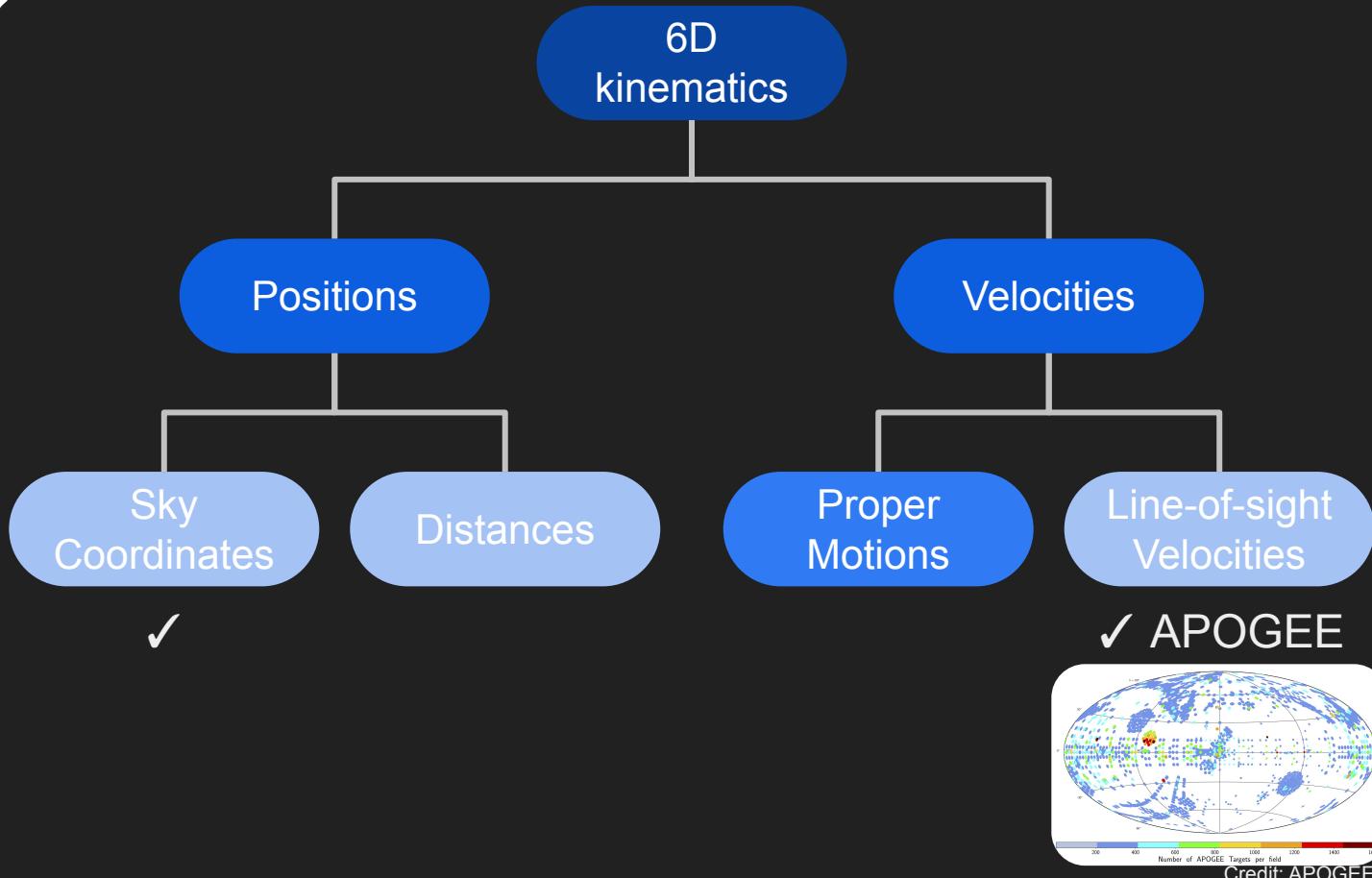
How?



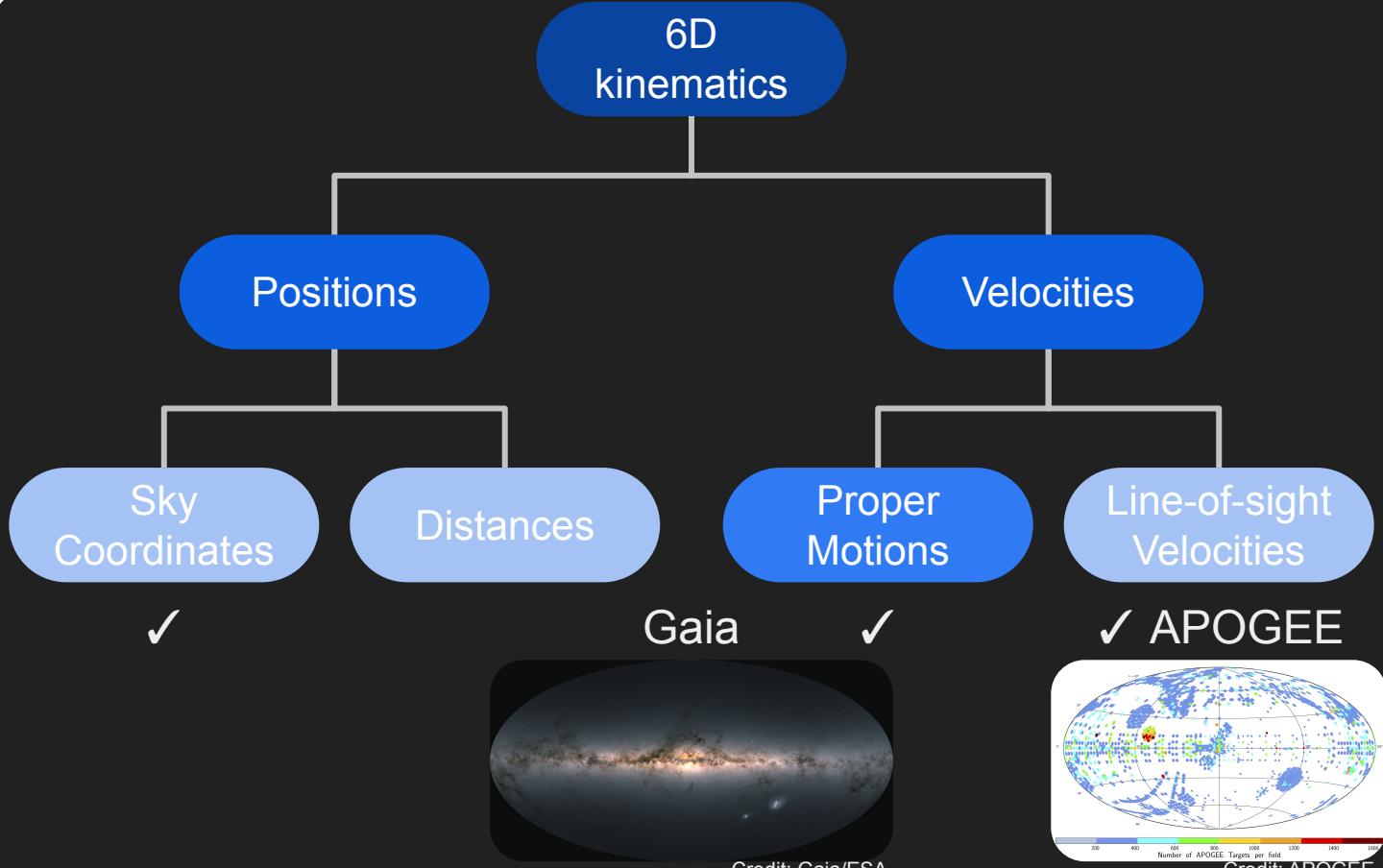
How?



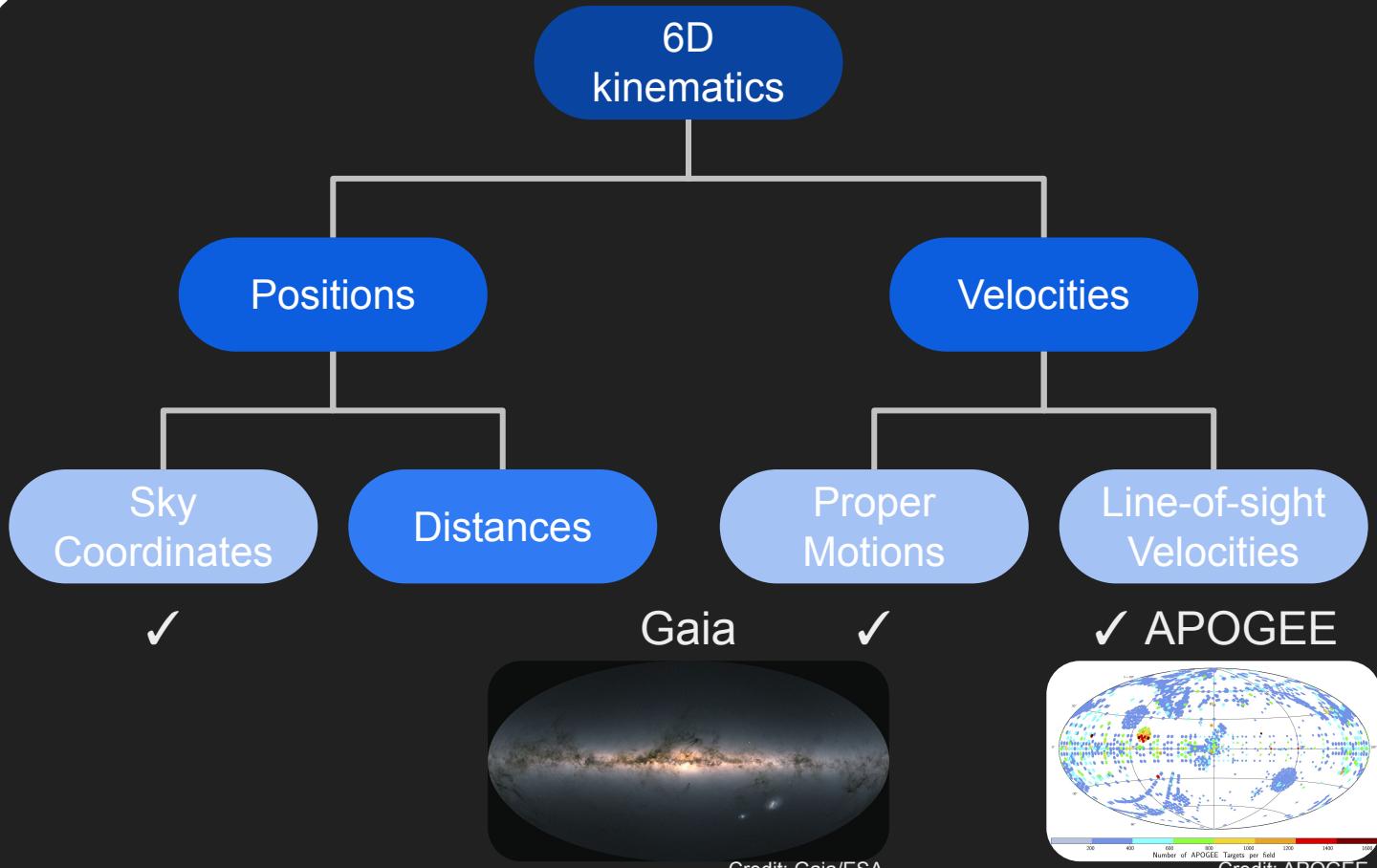
How?



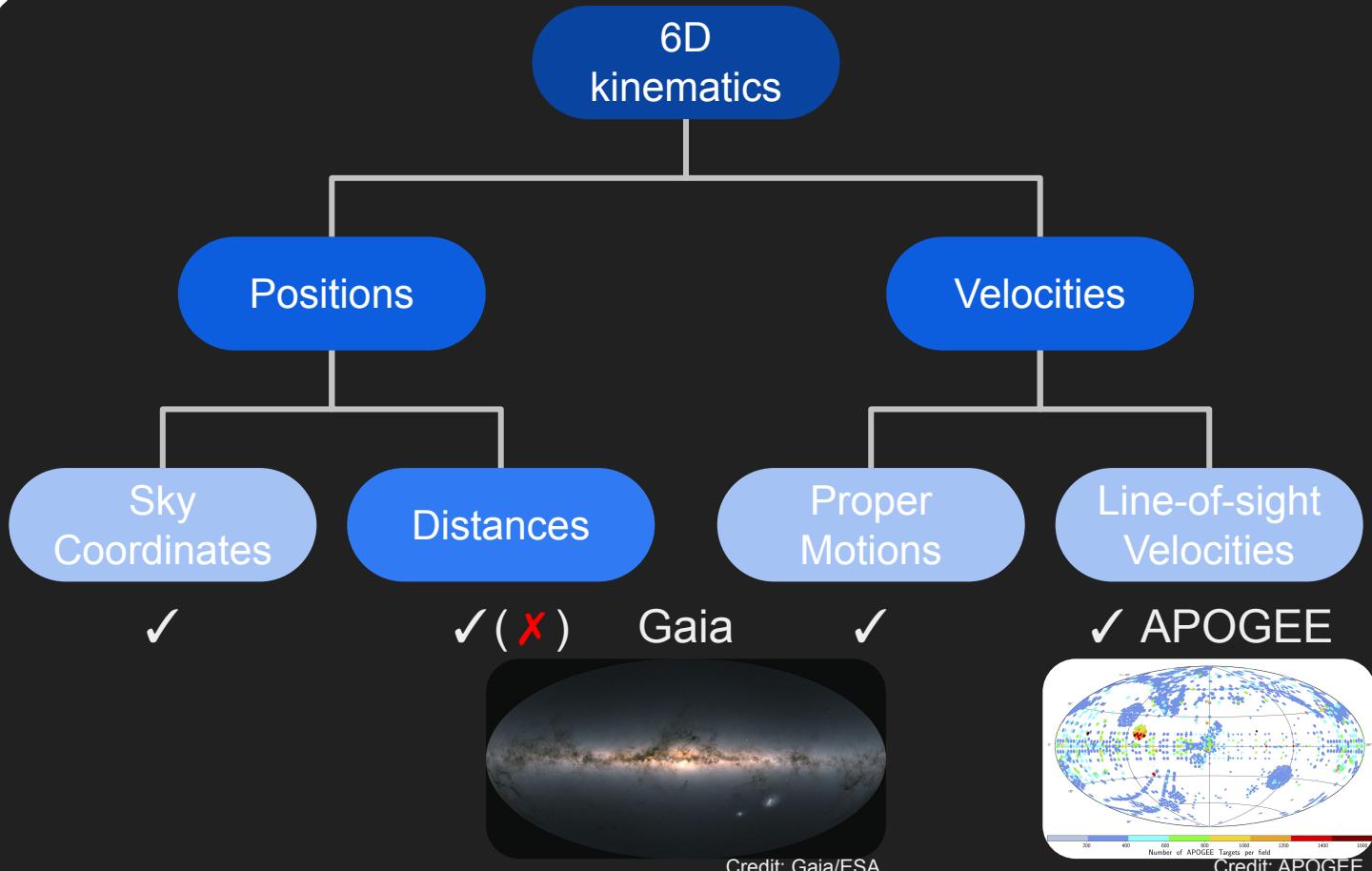
How?



How?



How?



A data-driven model for more precise distances*

Photometry

Spectroscopy

Astrometry

*: parallax

A data-driven model for more precise distances*

Features

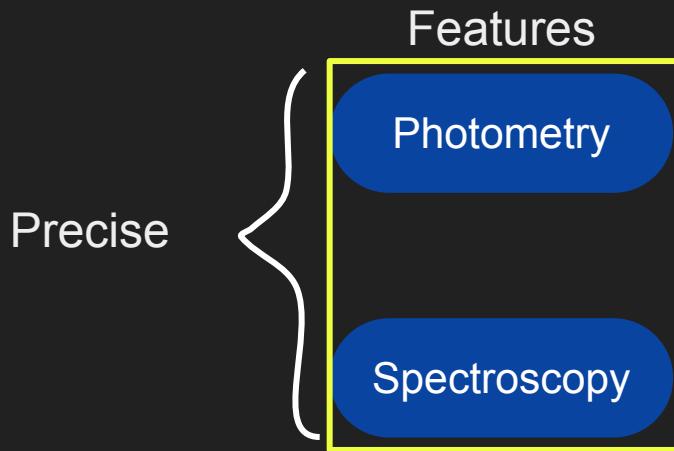
Photometry

Spectroscopy

Astrometry

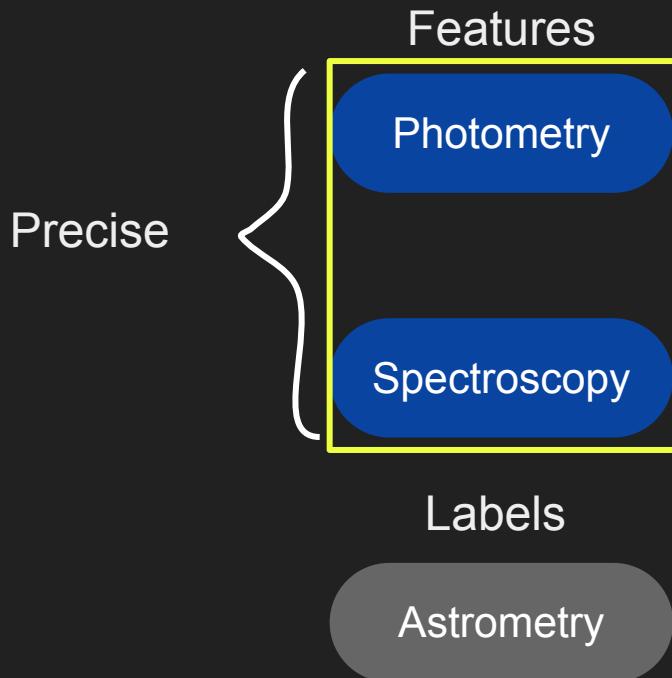
*: parallax

A data-driven model for more precise distances*



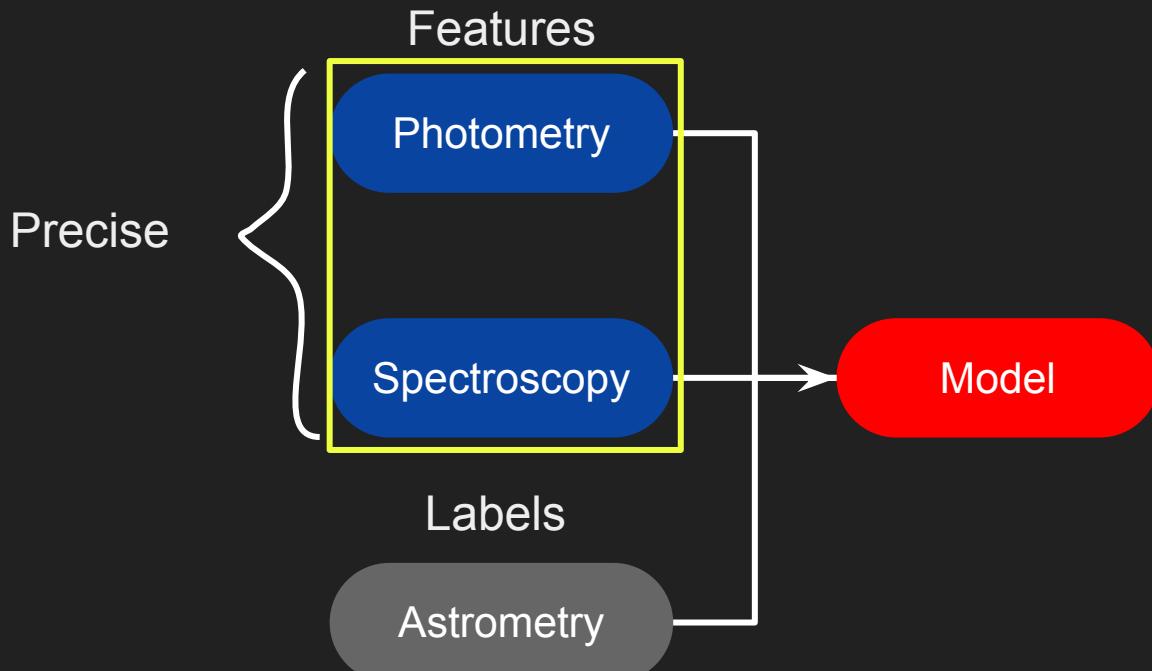
*: parallax

A data-driven model for more precise distances*



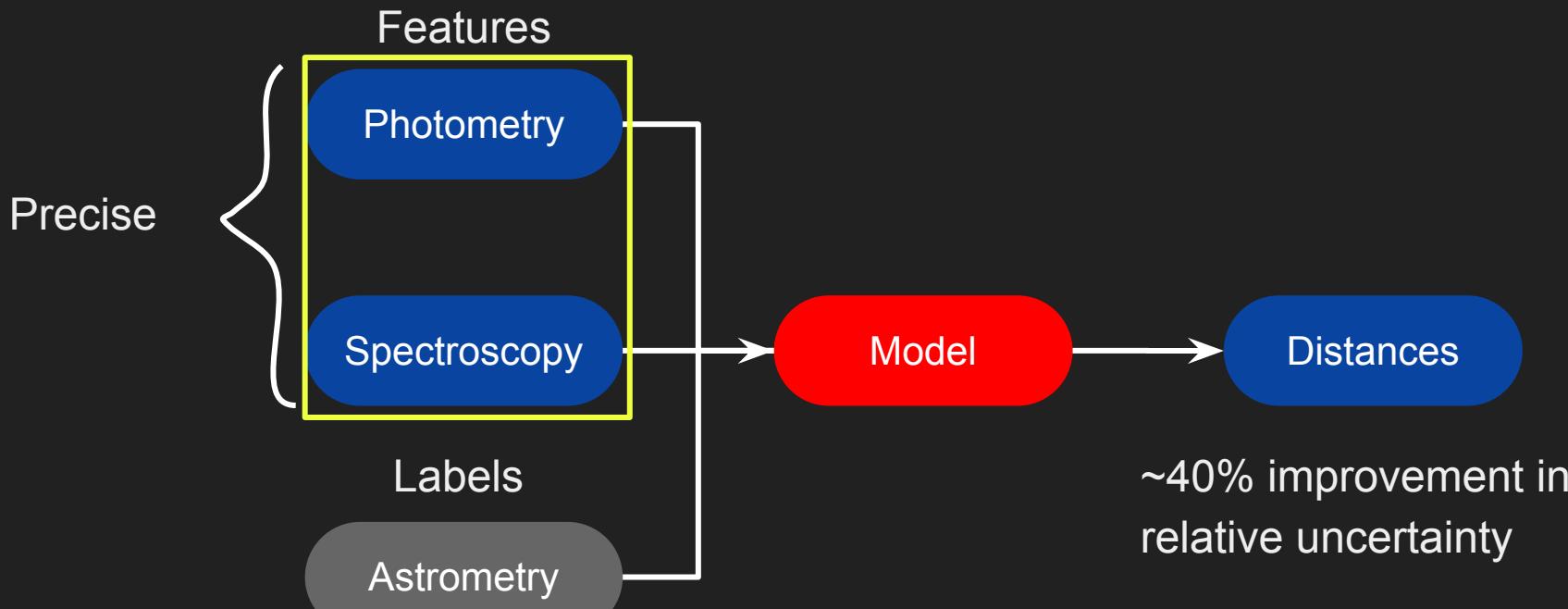
*: parallax

A data-driven model for more precise distances*

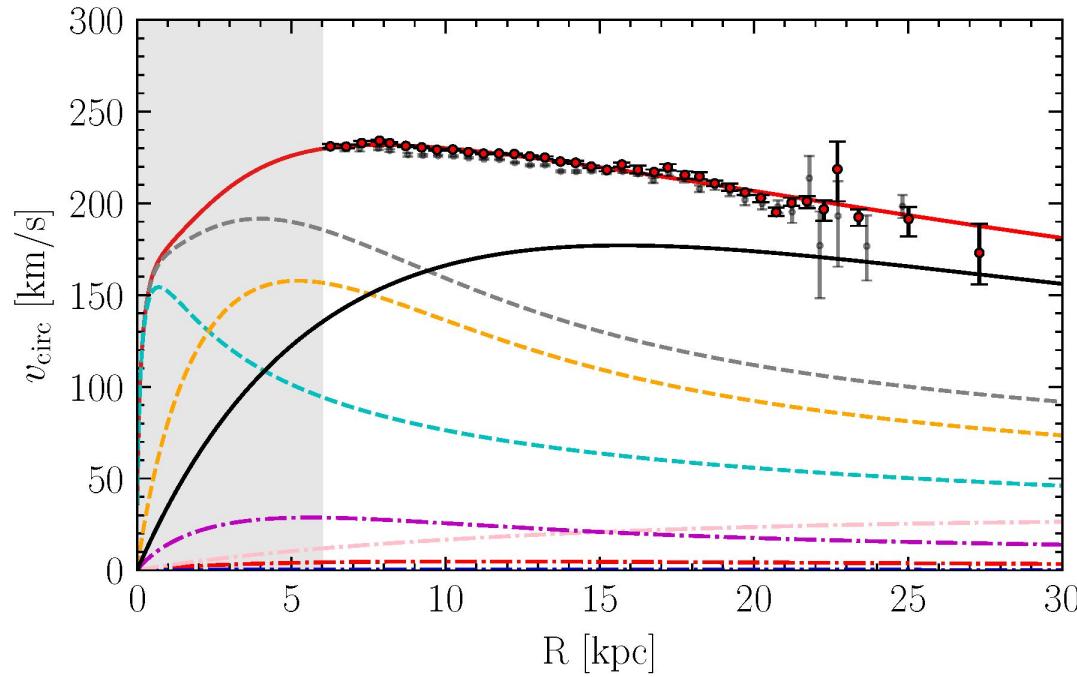
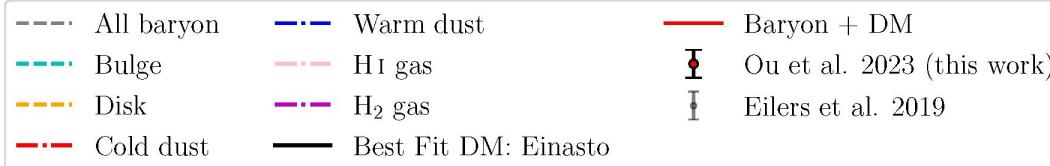


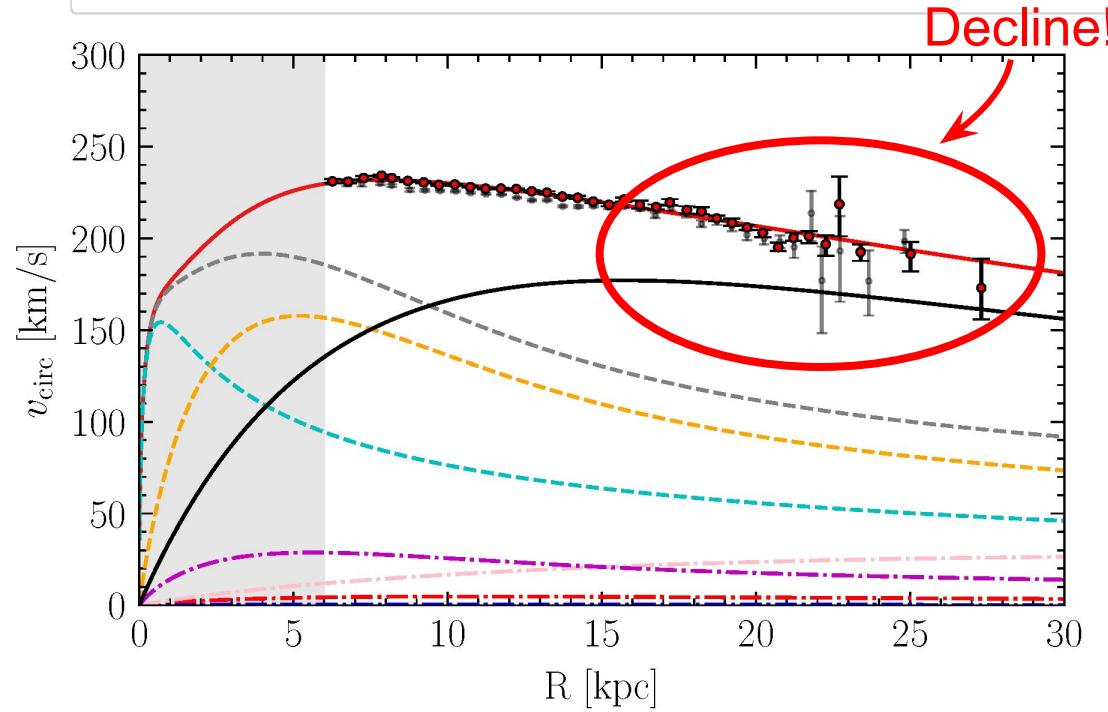
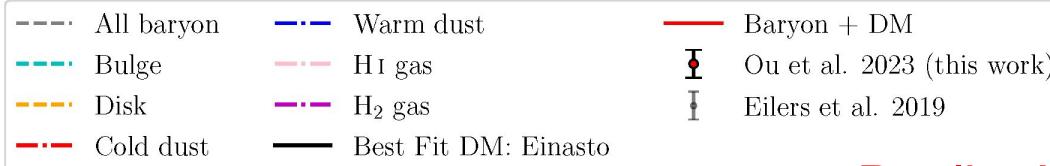
*: parallax

A data-driven model for more precise distances*

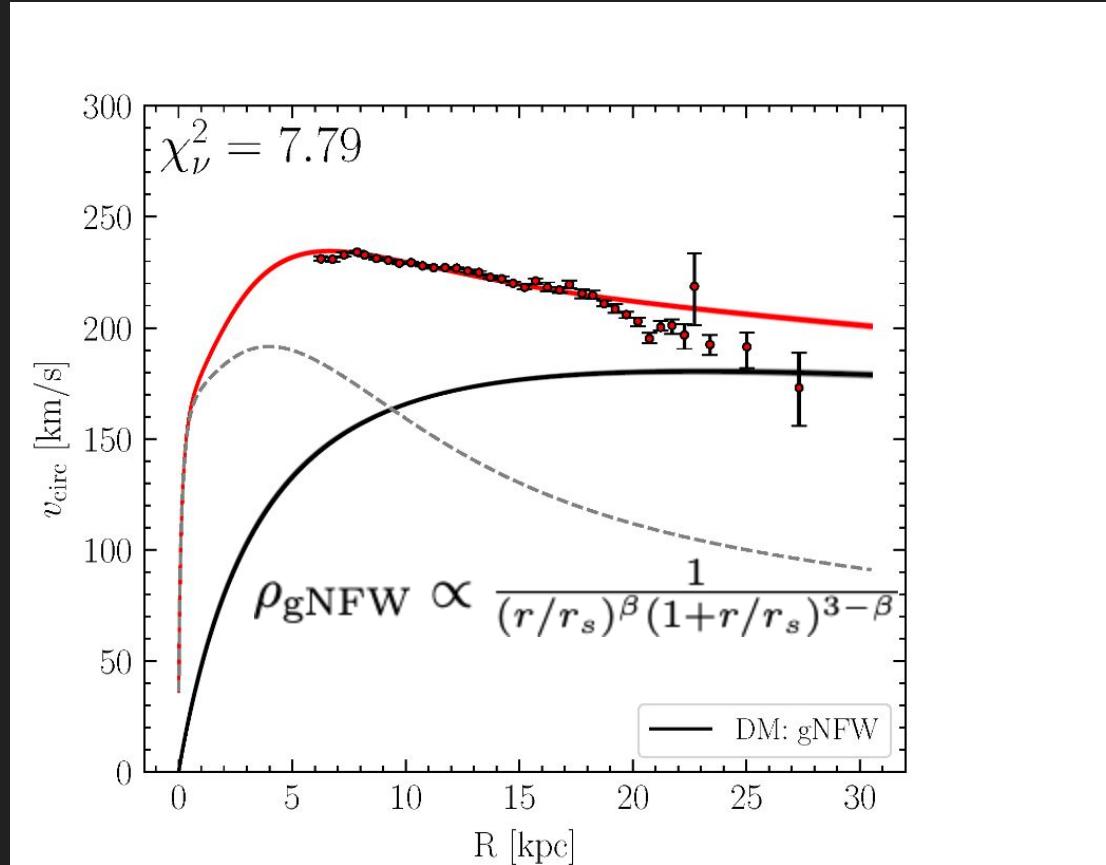


*: parallax

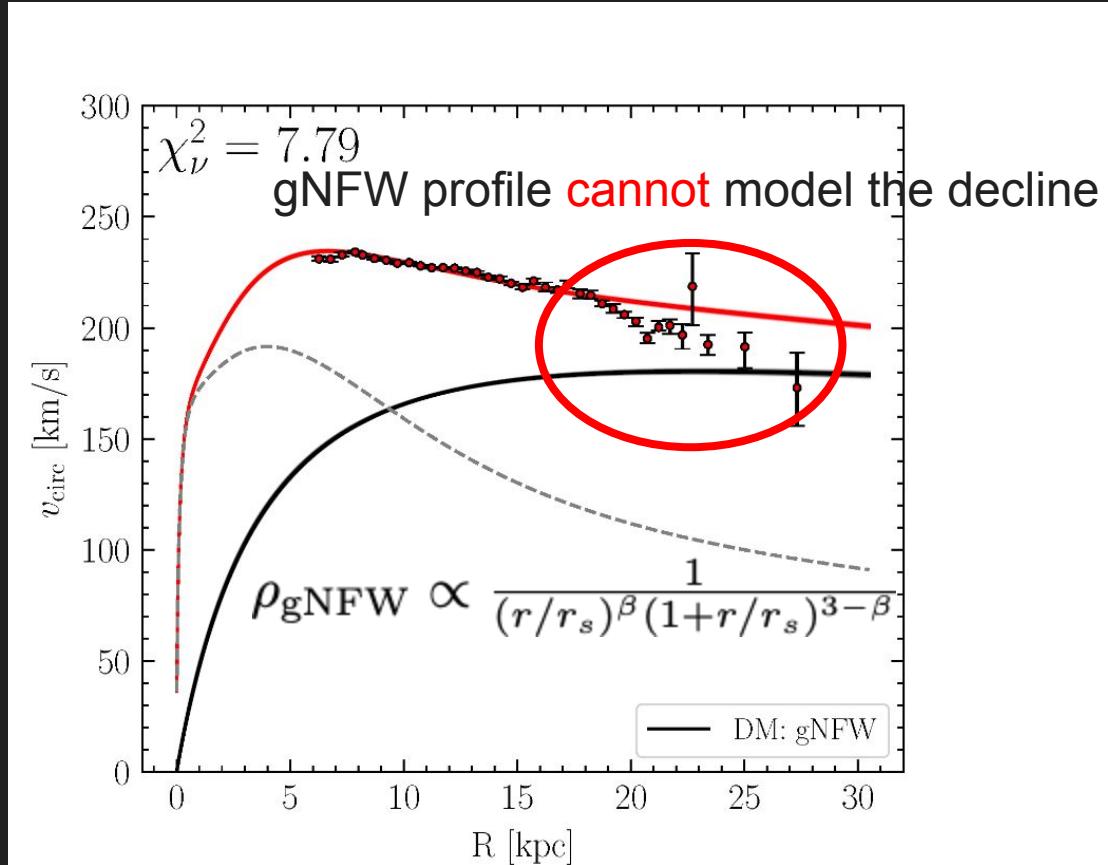




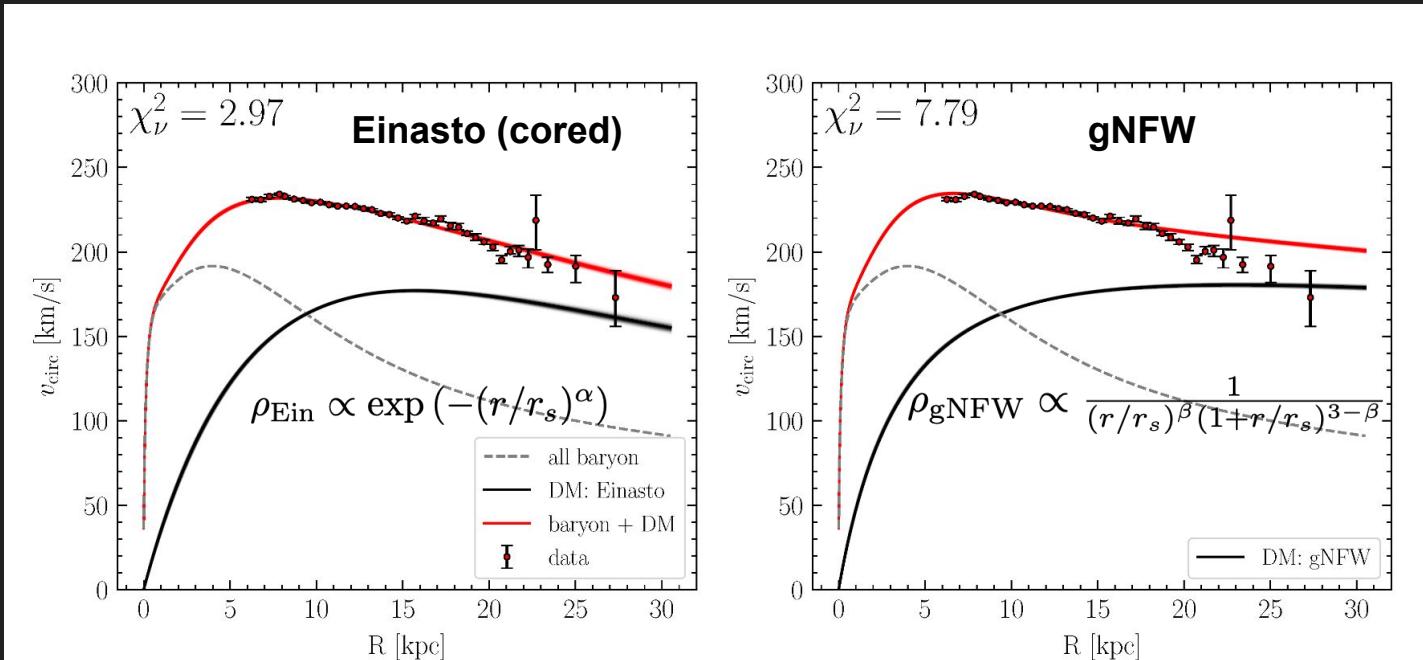
Modeling the curve: generalized NFW vs. Einasto



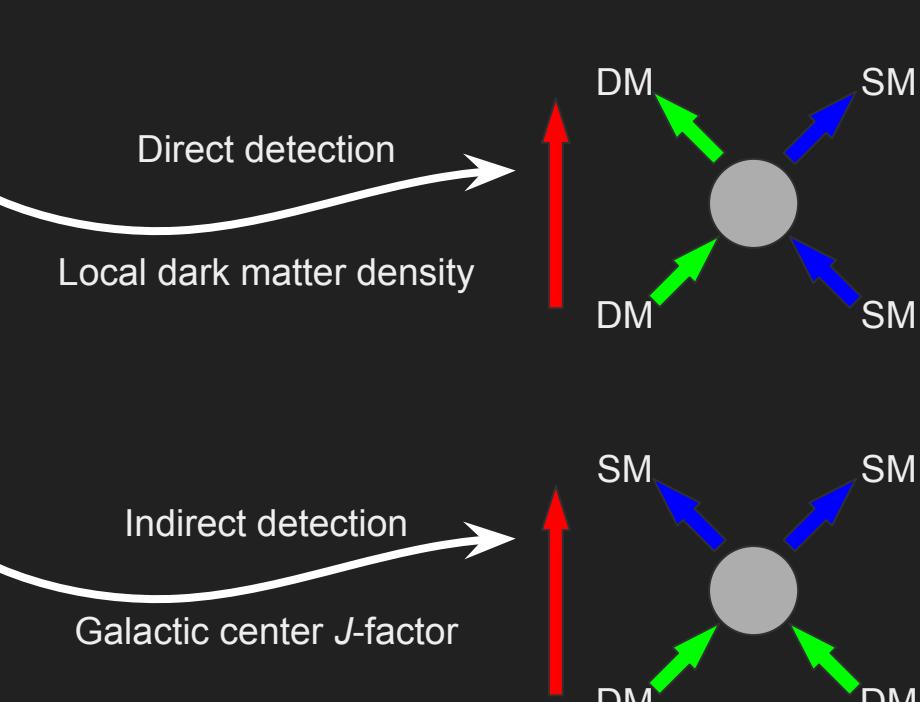
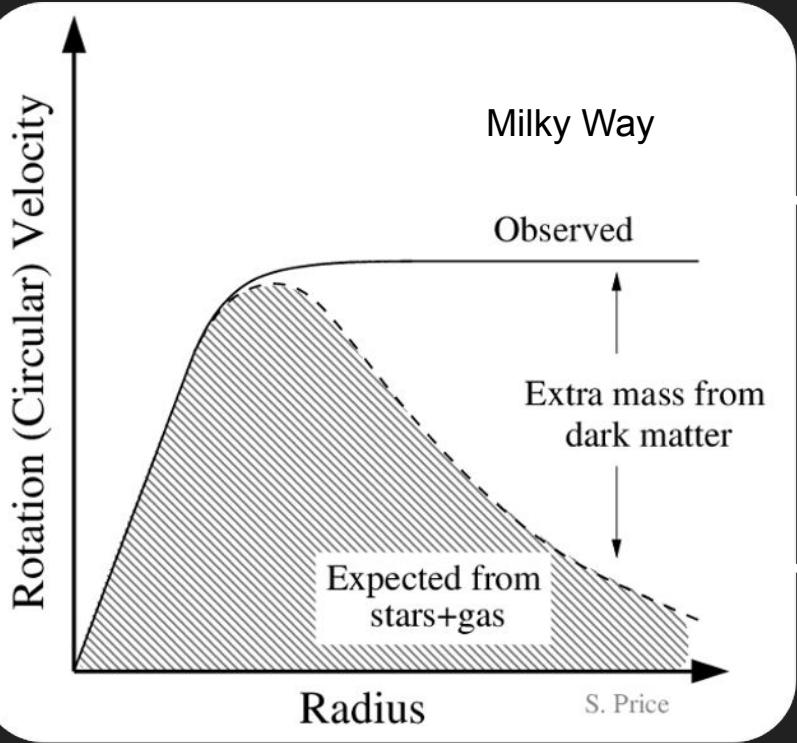
Modeling the curve: generalized NFW vs. Einasto



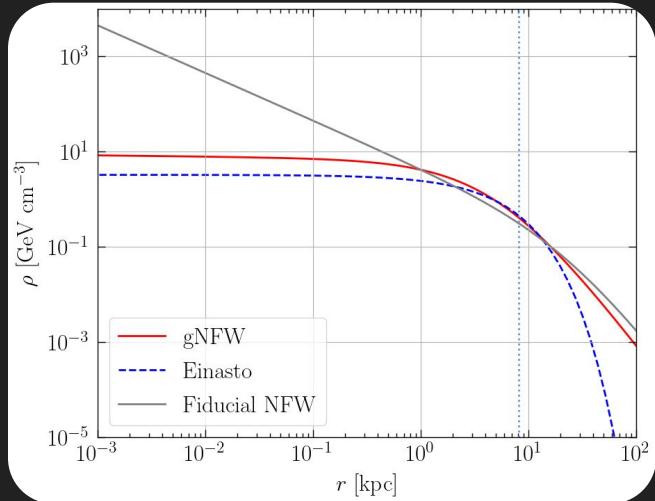
Modeling the curve: generalized NFW vs. Einasto



Exponential drop-off in DM density outside of $R \sim 10$ kpc needed to explain the decline*

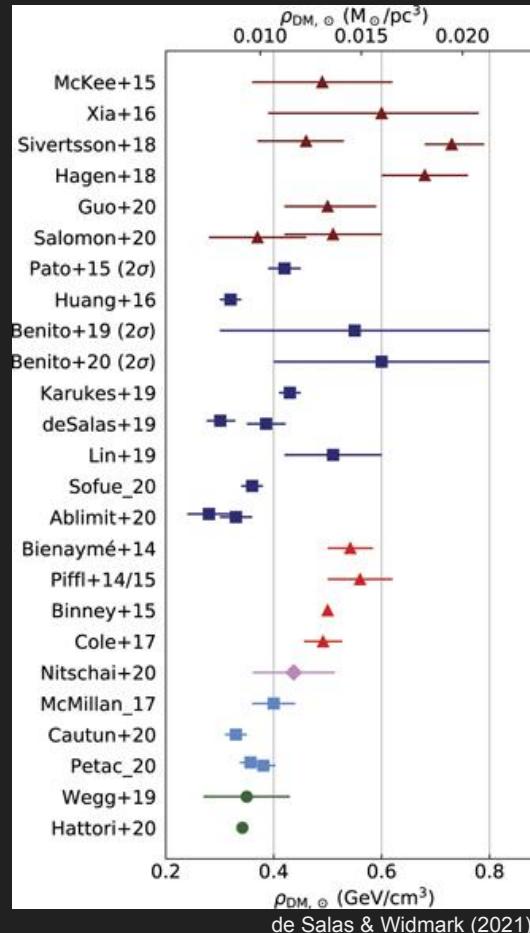


Local dark matter density

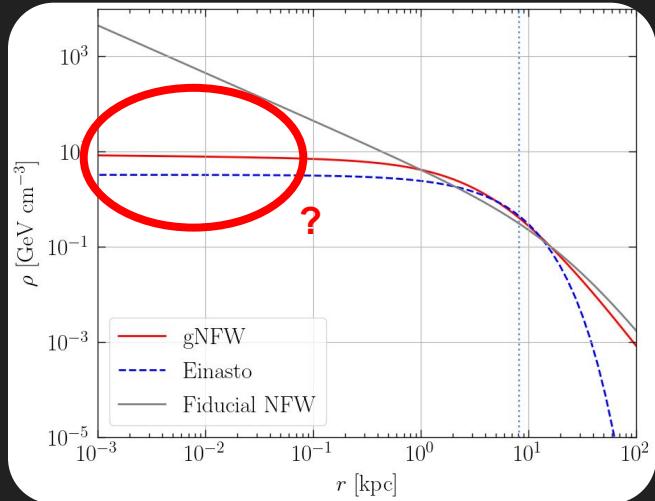


Both gNFW and Einasto results are consistent with literature

0.45 GeV/cm³

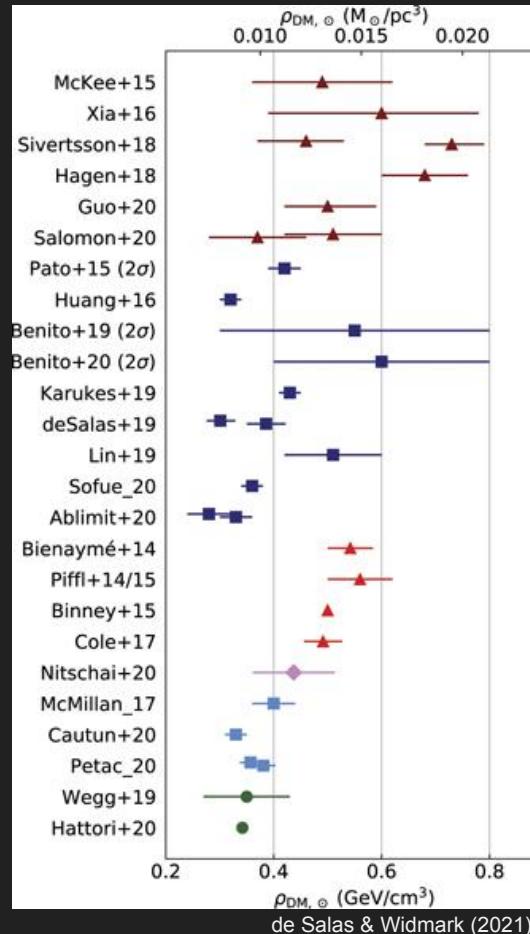


Local dark matter density

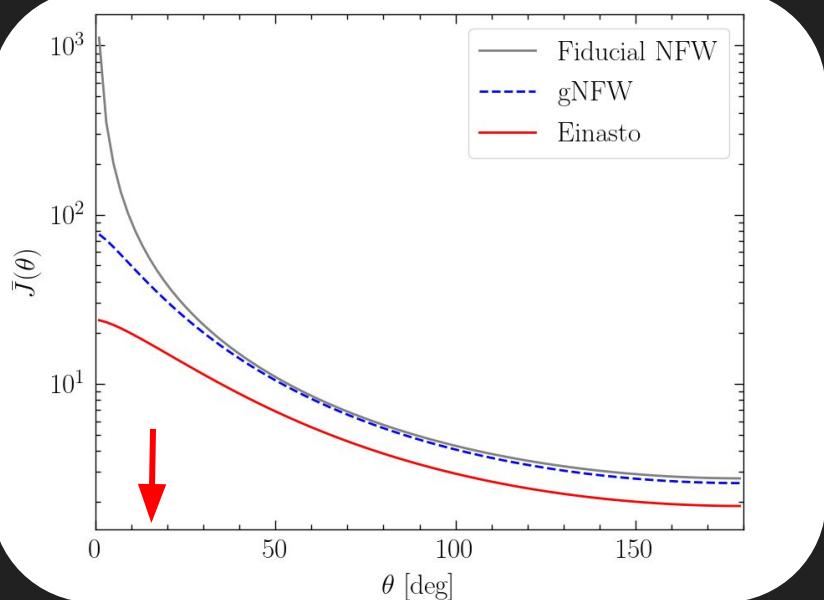


Both gNFW and Einasto results are consistent with literature

0.45 GeV/cm³



Galactic center J -factor

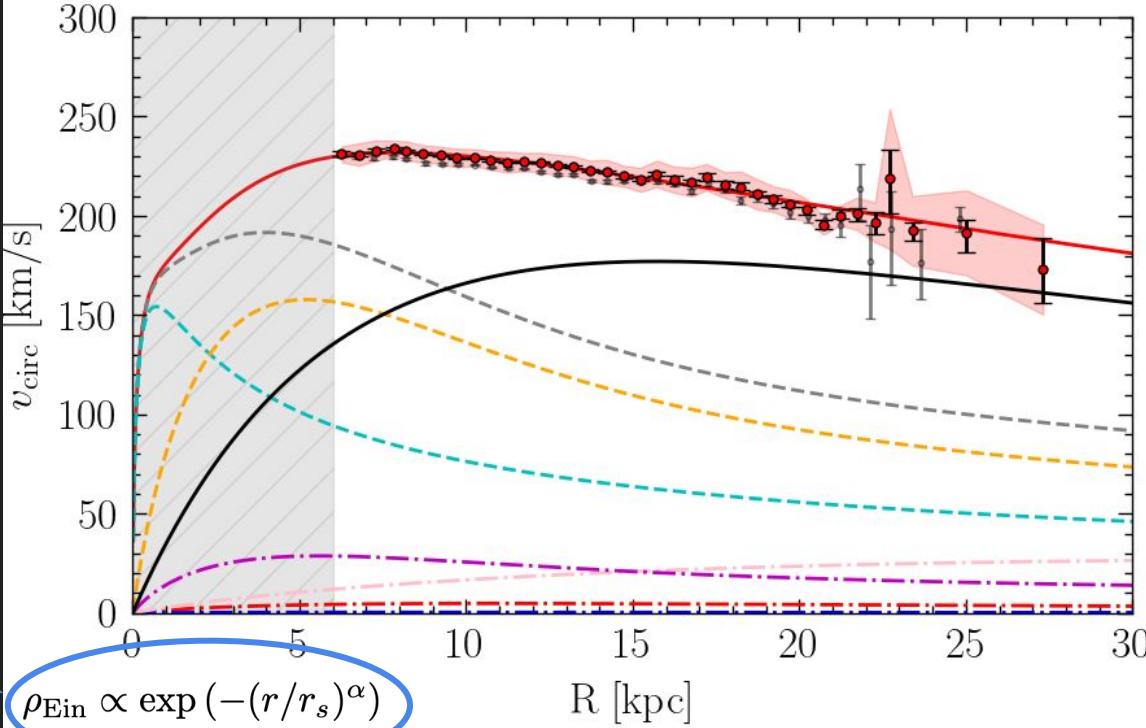
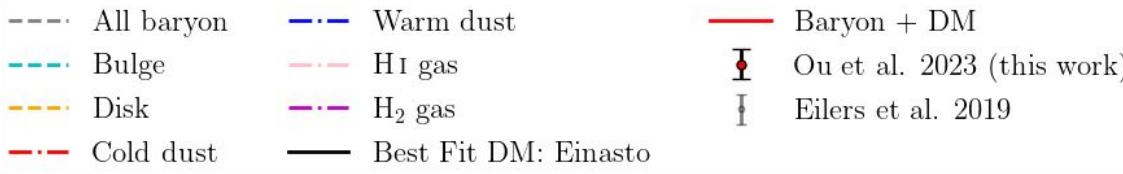


Consistently lower normalized average
 J -factor

$$J = \int \rho^2 ds$$

Integrated J -factor at 15° from the Einasto
an order of magnitude lower than from the
fiducial NFW profile

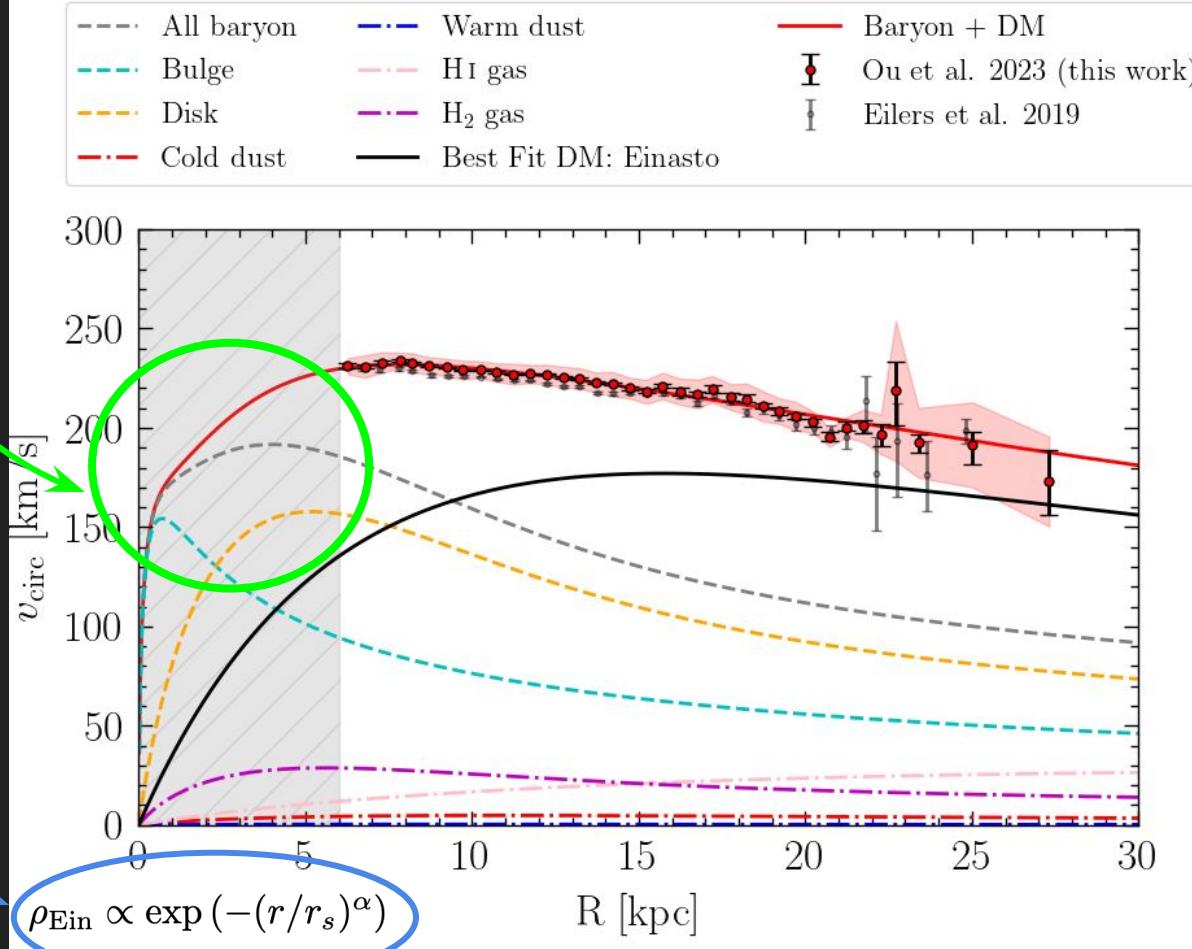
Caveats



Caveats

Galactic bar model
+
Non-axisymmetric
assumption

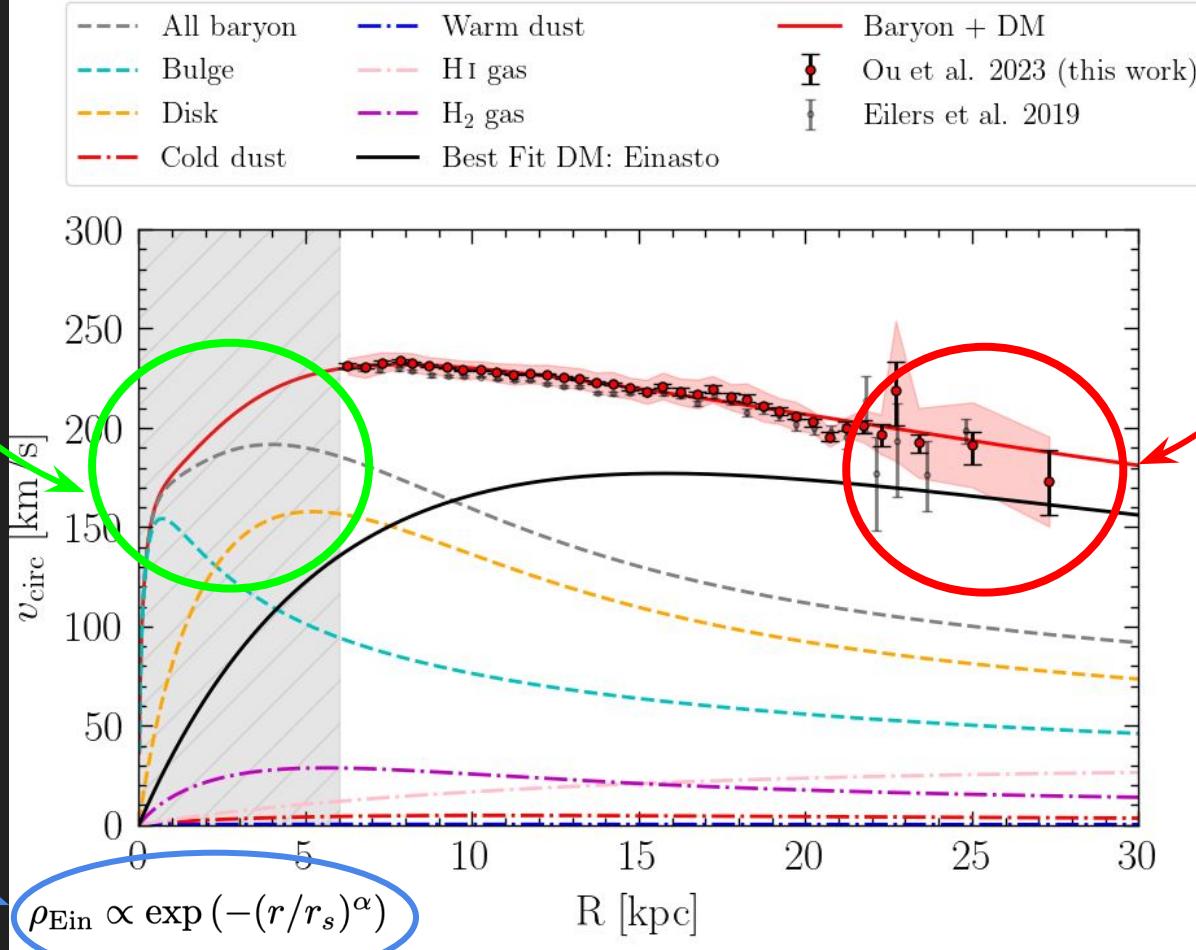
Non-parametric
model



Caveats

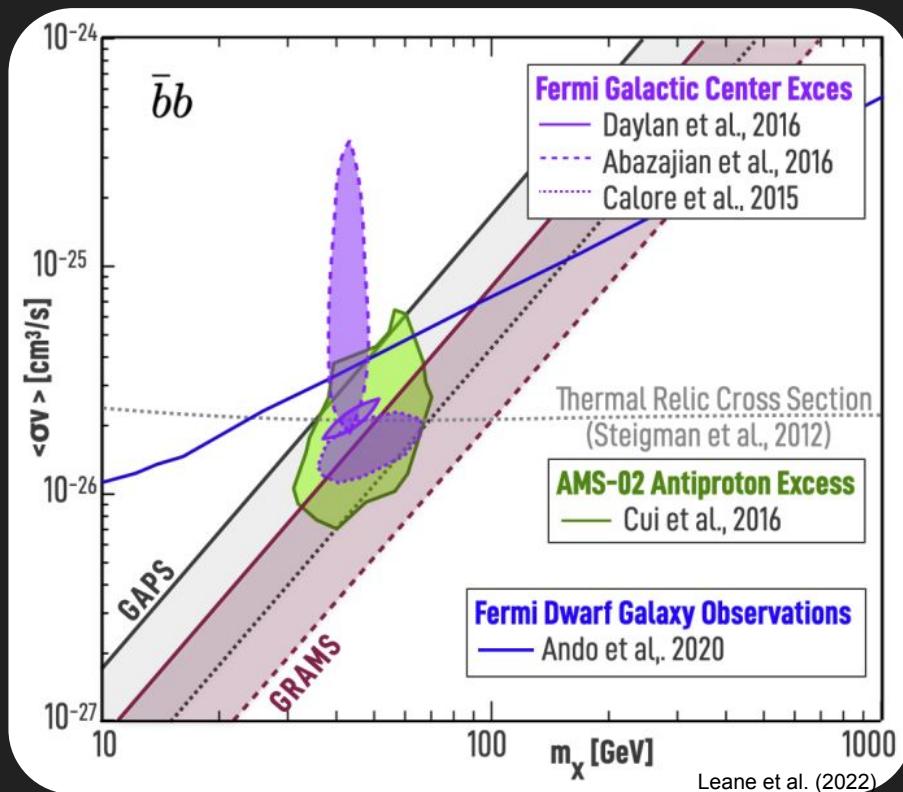
Galactic bar model
+
Non-axisymmetric
assumption

Non-parametric
model



Future
observation

Annihilation cross section



Lower J -factor ***increases*** the inferred annihilation cross section

Tension with dwarf galaxy constraint!

Dark matter models in general

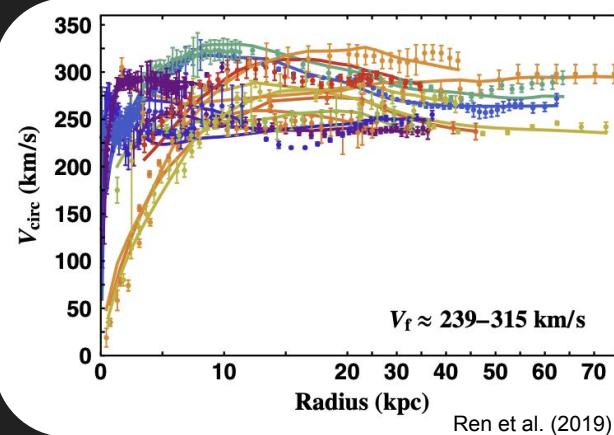
Baryonic feedback

- intense star formation episodes with decreased rate of dark matter accretion rate at the center

Astro**physics**

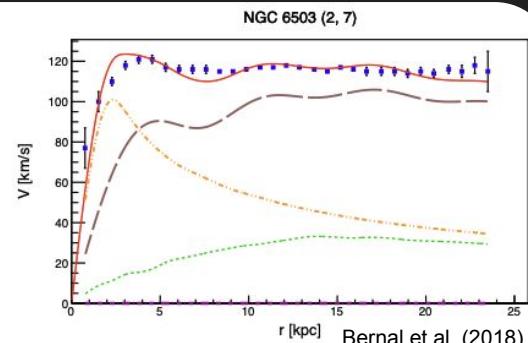
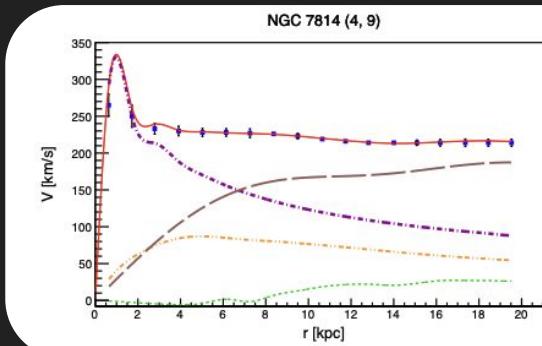
Non-equilibrium stellar kinematics

- non-axisymmetric potential;
- recent mergers;
- tracer population profile;
- underestimated asymmetric drift correction from vertical motion

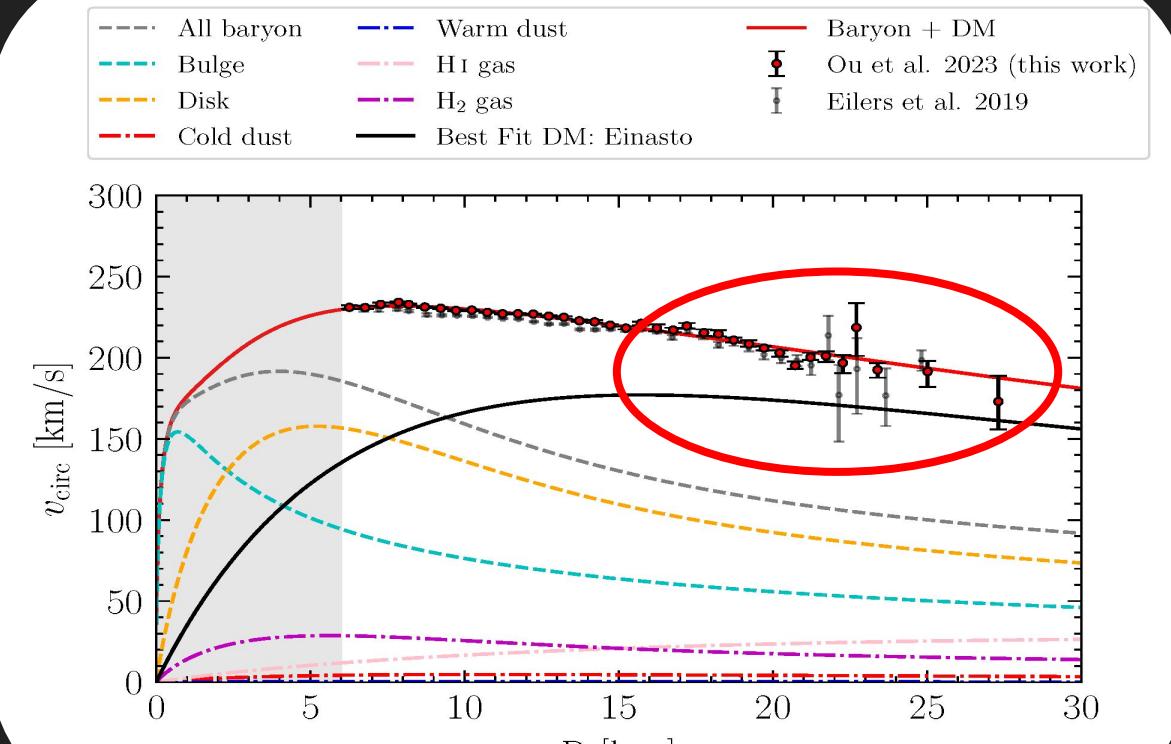


Self-interacting dark matter

Fuzzy dark matter



Summary



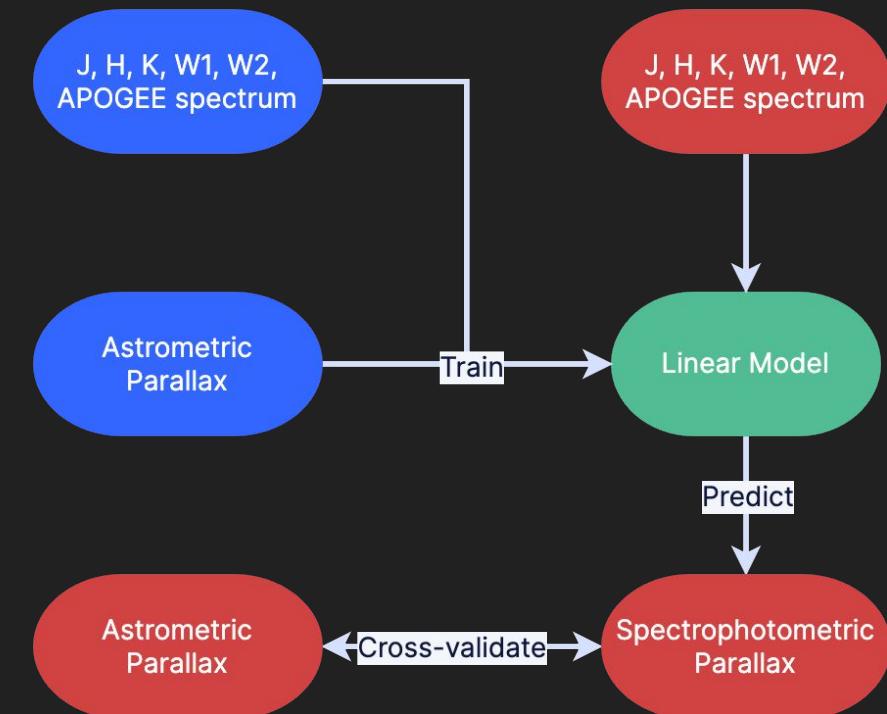
The Milky Way circular velocity curve has a faster decline at $R > 15$ kpc → a potential cored center?

Backup slides

Conclusion in text

- We derive precise parallaxes for 120,309 stars with a data-driven model
 - using APOGEE spectra combined with photometry measurements from Gaia, 2MASS, and WISE
 - ~40% improvement in relative uncertainty for parallax
- We measure the circular velocity curve of the Milky Way out to \sim 30 kpc
 - find a significantly faster decline in the circular velocity curve at outer galactic radii
- A cored Einasto profile is a better fit to the data than an NFW profile
 - local dark matter density is $0.447\pm0.004 \text{ GeV cm}^{-3}$
 - J -factor for annihilating dark matter at a 15 degree view angle towards the galactic center is $15.8+1.08-0.93 \times 10^{22} \text{ GeV}^2 \text{ cm}^{-5}$
- Future study on examining both particle and astrophysical effects
 - Better modeling of the galactic bar and bulge will allow a direct constraint on the core density in the future

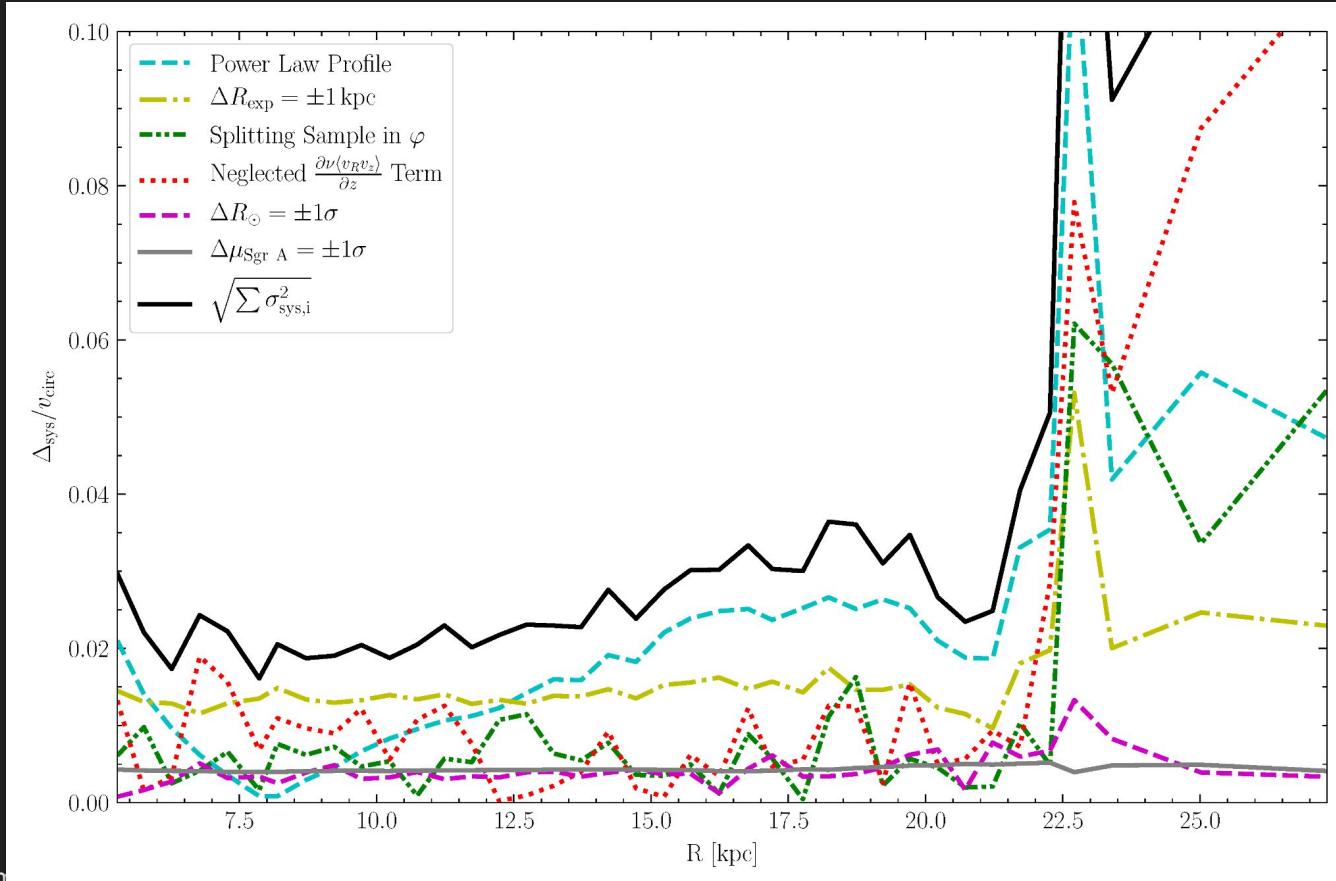
Spectrophotometric parallaxes – Red Giant Branch stars



Assumption: parallaxes (label) of all RGB stars selected can be completely described by photometric and spectroscopic information (feature) using a linear model.

Learn patterns in the data set and discover the relationships between spectral features in the spectra of the stars, photometry (including colours), and parallax (or distance).

Systematic uncertainties



All those equations

$$\rho_{\text{gNFW}}(r) = \frac{M_0}{4\pi r_s^3} \frac{1}{(r/r_s)^\beta (1+r/r_s)^{3-\beta}}$$

$$\rho_{\text{Ein}}(r) = \frac{M_0}{4\pi r_s^3} \exp(-(r/r_s)^\alpha)$$

$$4\pi G\rho = \nabla^2\Phi$$

$$\frac{\partial f}{\partial t} + \vec{v}\frac{\partial f}{\partial \vec{r}} - \nabla\Phi\frac{\partial f}{\partial \vec{v}} = 0$$

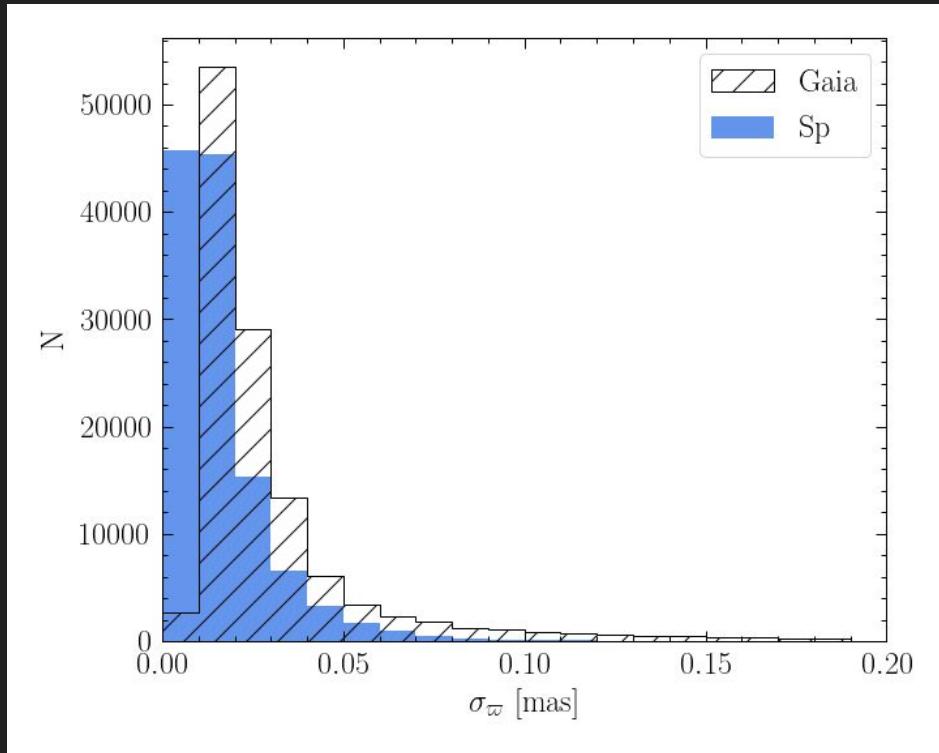
$$v_c^2(R) = \langle v_\varphi^2 \rangle - \langle v_R^2 \rangle \left(1 + \frac{\partial \ln \nu}{\partial \ln R} + \frac{\partial \ln \langle v_R^2 \rangle}{\partial \ln R} \right)$$

Model likelihood function

$$\log \mathcal{L} = -\frac{1}{2}\chi^2(\vec{\theta}) = -\sum_{n=1}^N \frac{[\varpi_n^{(a)} - \exp(\vec{\theta} \cdot \vec{x}_n)]^2}{2\sigma_n^{(a)2}}$$

$$\varpi_n^{(a)} = \exp(\vec{\theta} \cdot \vec{x}_n) + \text{noise}$$

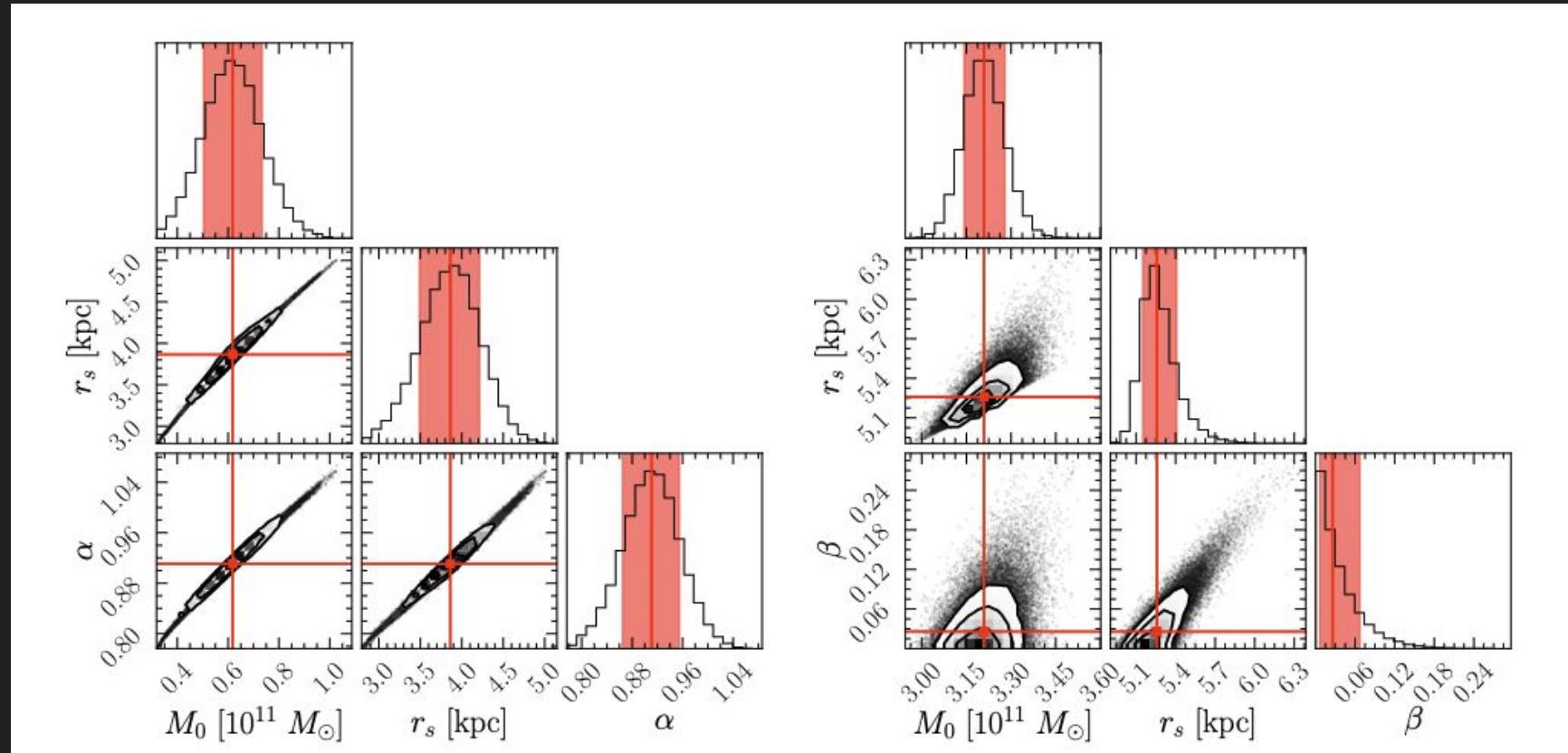
Astrometric & Spectrophotometric parallaxes



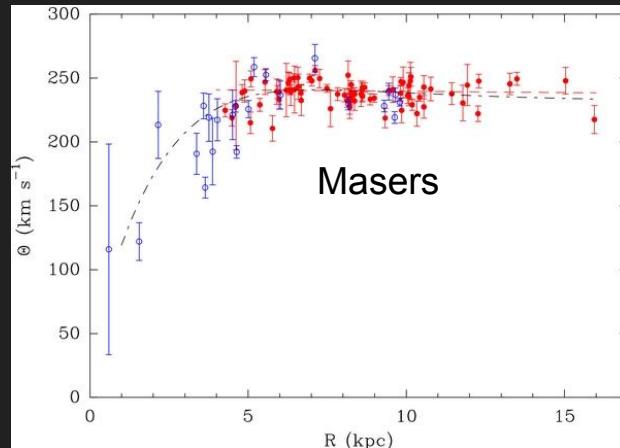
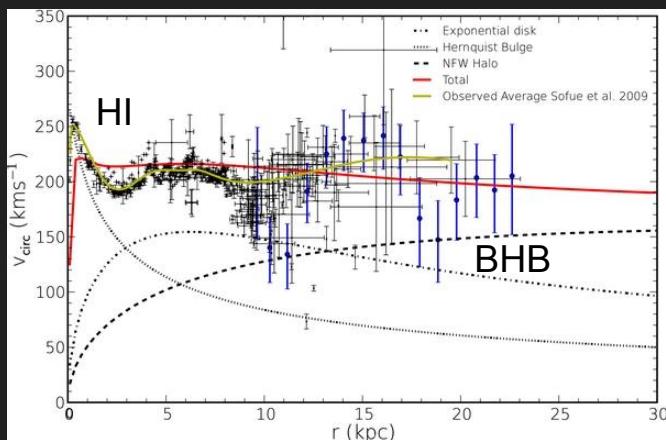
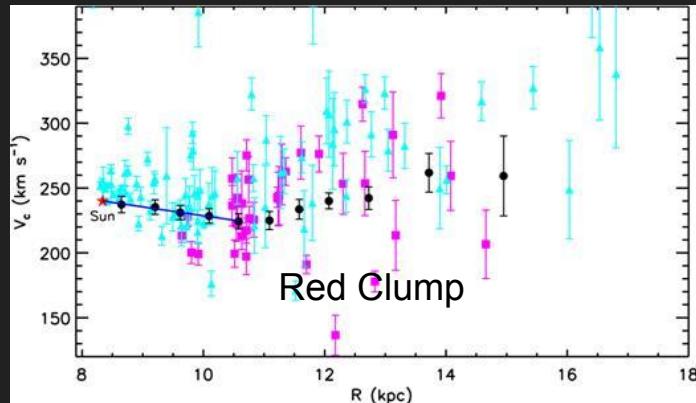
~40% improvement in relative uncertainty for full sample (120309 stars)

At heliocentric distance greater than 3(18) kpc, ~ 2.5(10) times as precise as Gaia parallaxes

Corner plots for model fitting



Milky Way circular velocity curve - past



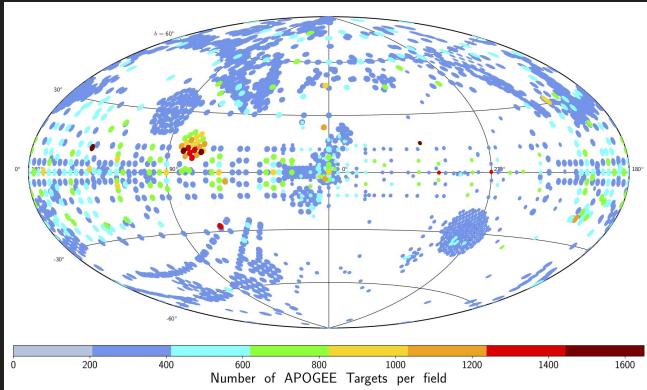
6D information:

RA & DEC ✓

Line of sight velocity ✓

Distance & proper motion ✗

APOGEE & GAIA footprint



APOGEE: LOS velocity for 10^5 stars with 0.02 km/s uncertainty

GAIA: parallax and PM for 10^9 stars with 0.02 mas uncertainty



6D information:

RA & DEC ✓

Line of sight velocity (✓) → More stars to come

Distance & proper motion (✓) → Higher precision ✓