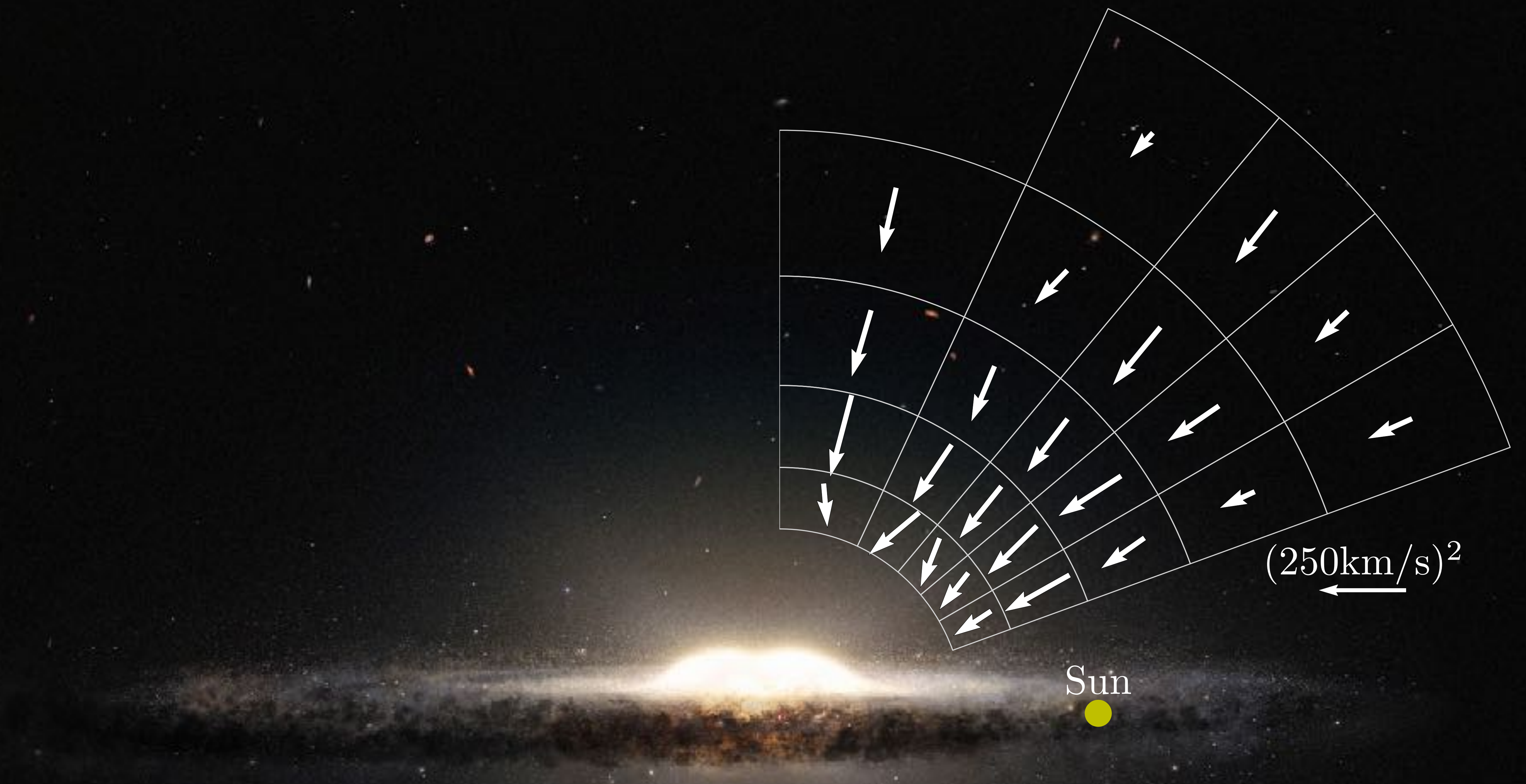
The Shape of the Inner Milky Way in Stars and Dark Matter



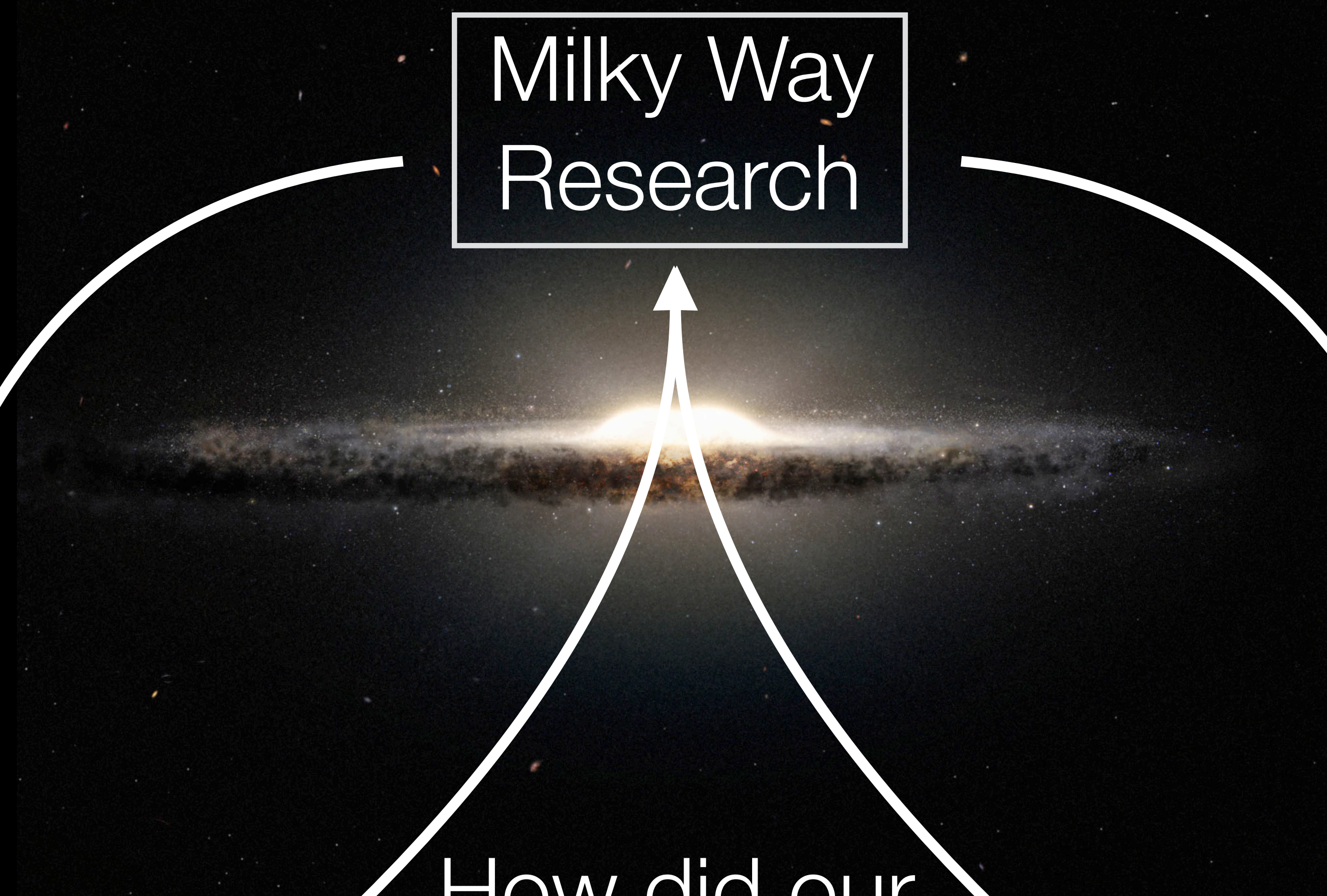
Chris Wegg
with Ortwin Gerhard, Matthieu Portail and Marie Bieth

26/6/2018

Outline

- Shape of the bulge in stars
- Shape of the bar in stars
- Making dynamical models of the inner Galaxy
- Using the kinematics of the stellar halo to measure the dark matter shape

Milky Way Research



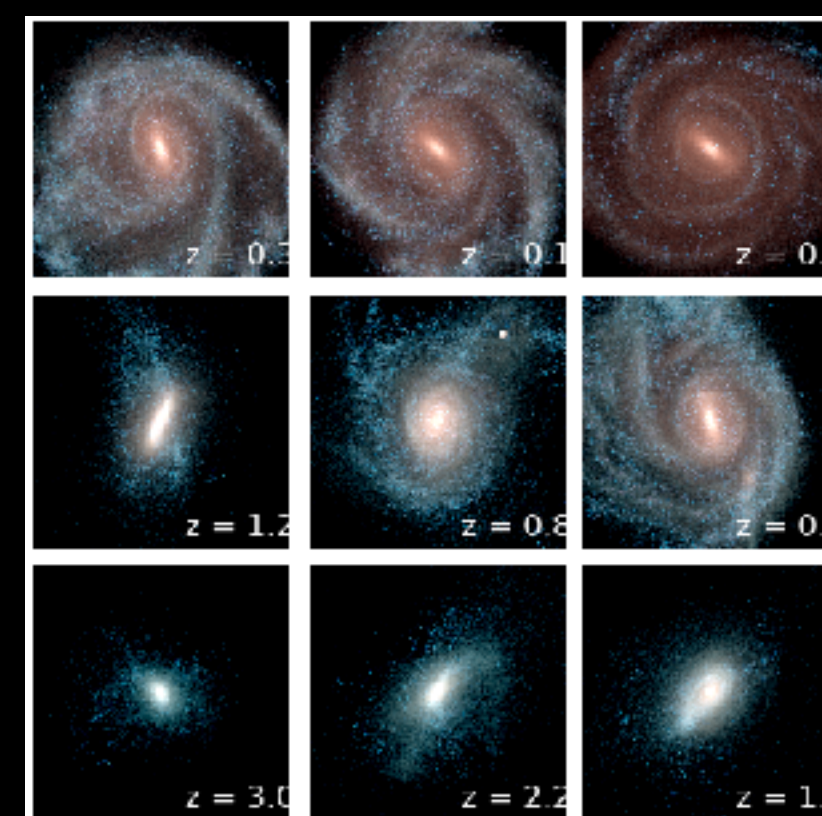
How do individual building blocks form?

Is Physics Correctly Modelled?

How did our Galaxy form?

External Galaxies

Simulations



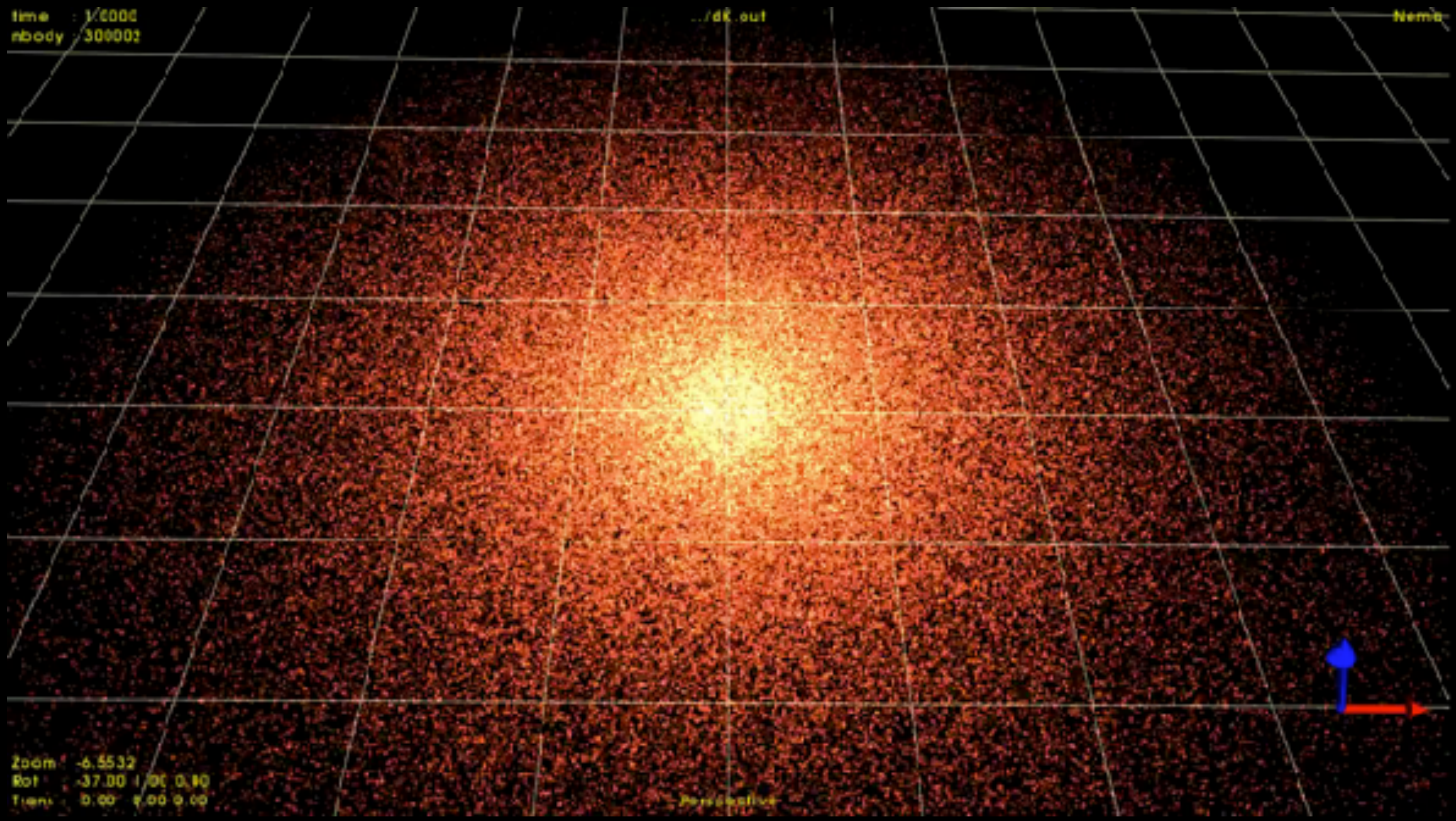
Classical Bulge vs Box/Peanut Bulge

vs

Accretion/mergers vs disk instability formation

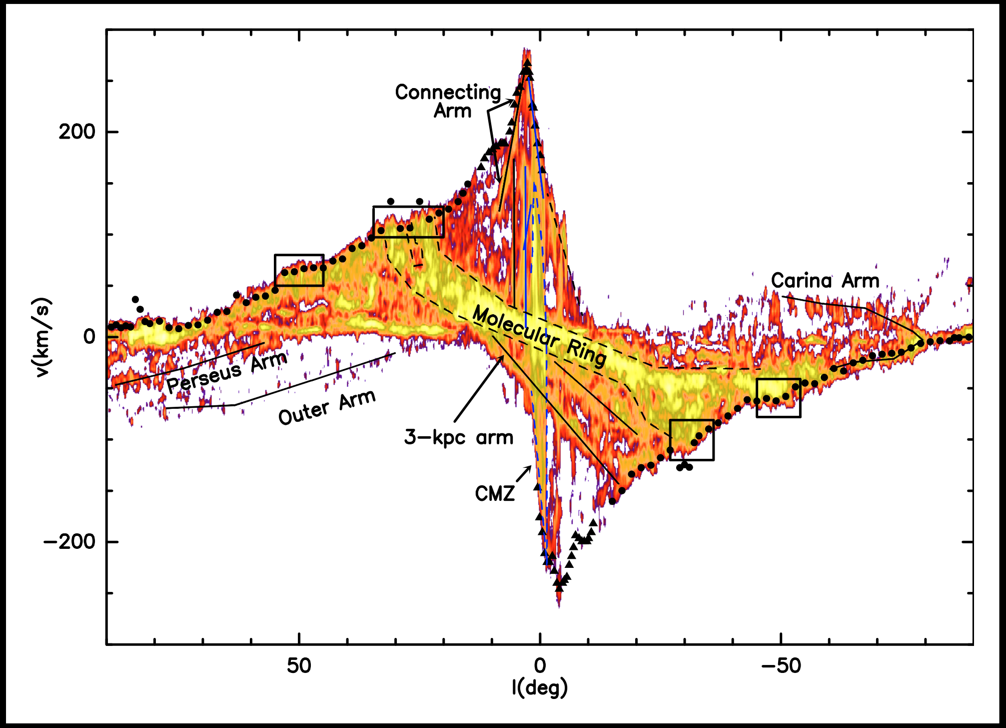
Box/Peanut Bulges

- Inner parts of bars — External galaxies & Simulations
- Formed by rearranging a kinematically cold disk into a bar. Central part subsequently buckles.



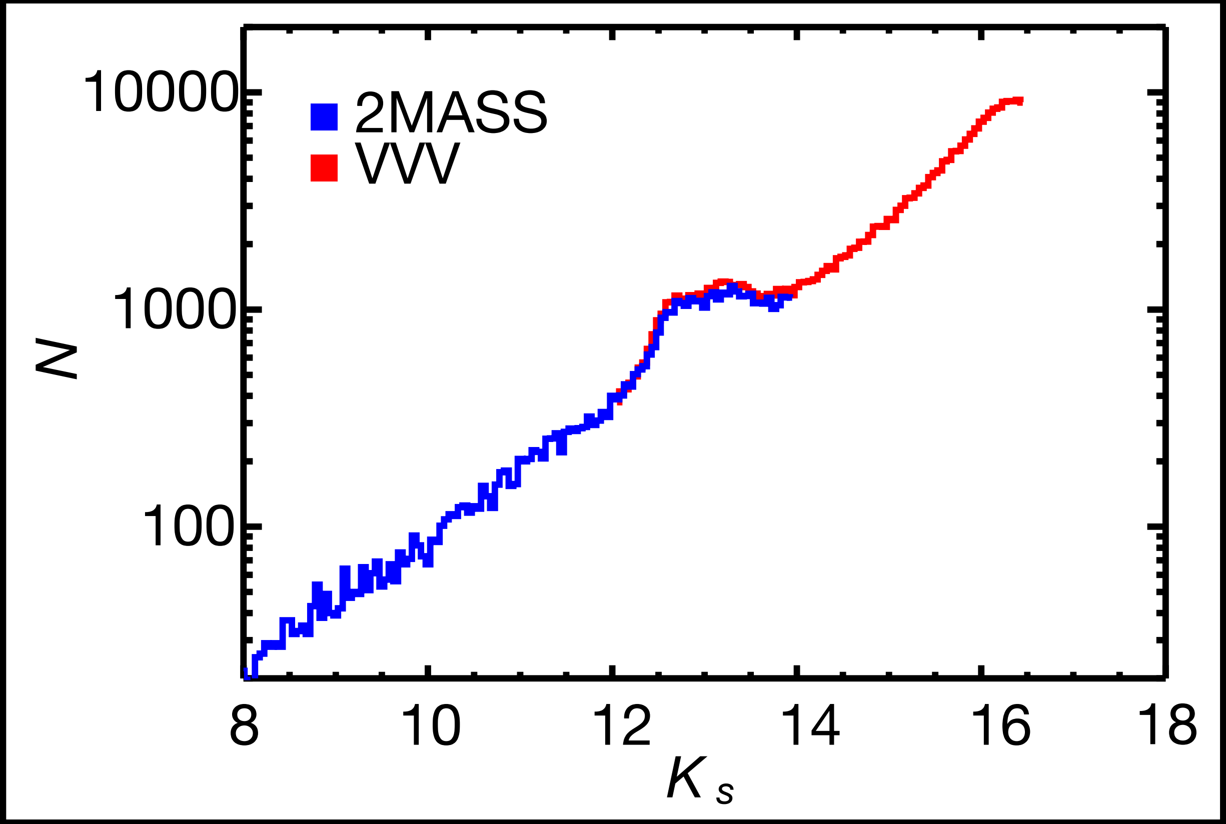
The Galaxies Bulge: Classical vs Box/Peanut

- Surprisingly difficult to resolve — argument persisted until recently
- Traditional evidence for B/P bulge:
  - Boxy shape in e.g. COBE images
  - Gas dynamics
- Traditional for classical bulge:
  - Metallicity gradient in the bulge
  - Photometrically apparently very old population
- Recent developments:
  - Metallicity gradients in the disk are mapped into gradients in the bulge (Martinez-Valpuesta et al 2013, Debatista et al 2016)
  - Microlensed stars show range of ages (Bensby et al 2017)
  - Bulge cylindrically rotates (Kunder et al 2012)
  - We now know the shape of the bar and bulge



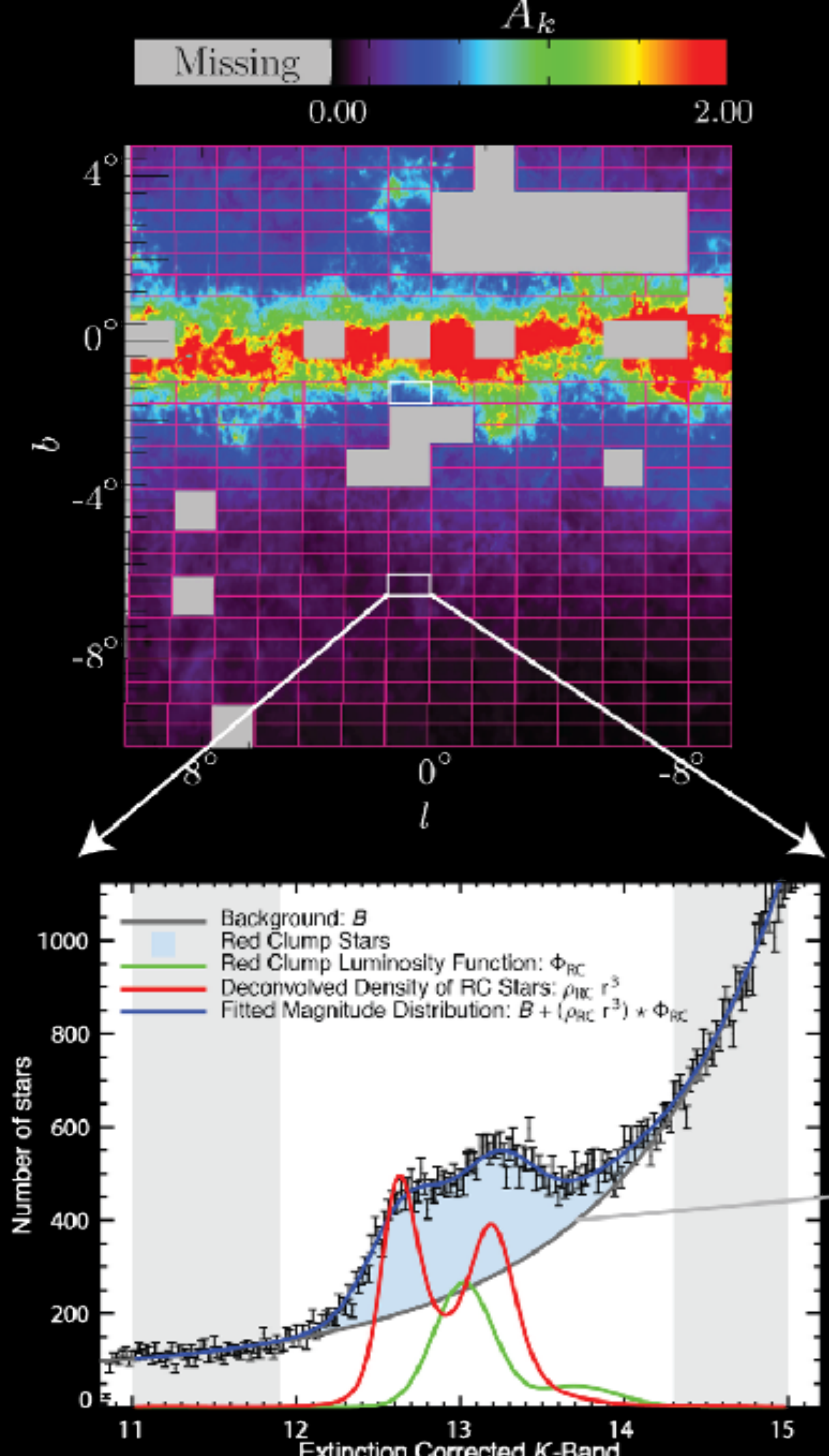
Red clump stars

- Helium Core Burning Stars
- Standard Candle with: $\sigma(K_s) \sim 0.17$
- Given bulge MDF 90% of stars will become RCGs
  ⇒ they are good tracers of the underlying stellar distribution

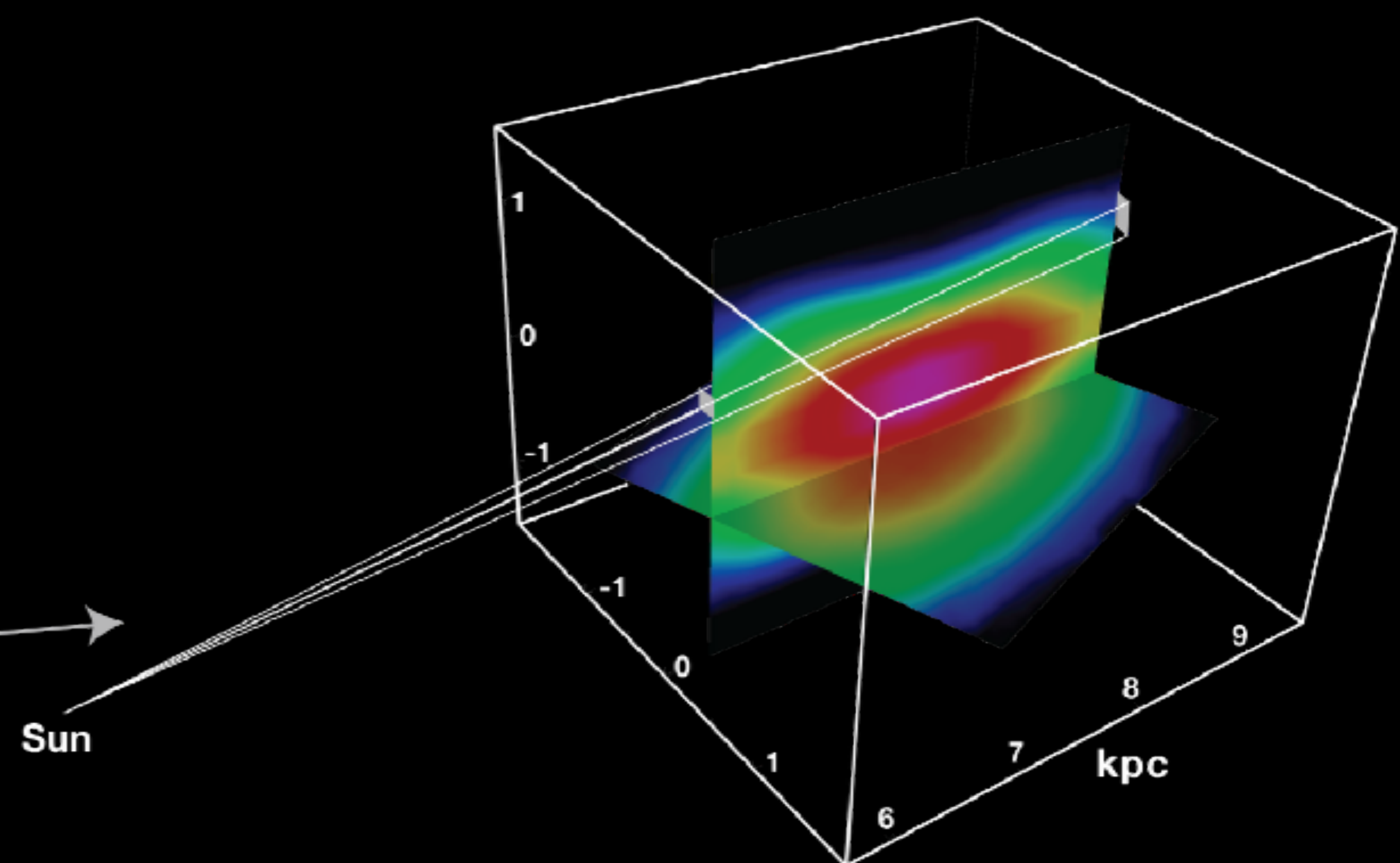


- Used by Stanek ('94 & '97) to show bulge hosts triaxial bar-like structure
- X-shape by McWilliam & Zoccali (2010), Nataf *et al.* (2010), Saito *et al.* (2011), Ness *et al.* (2012)

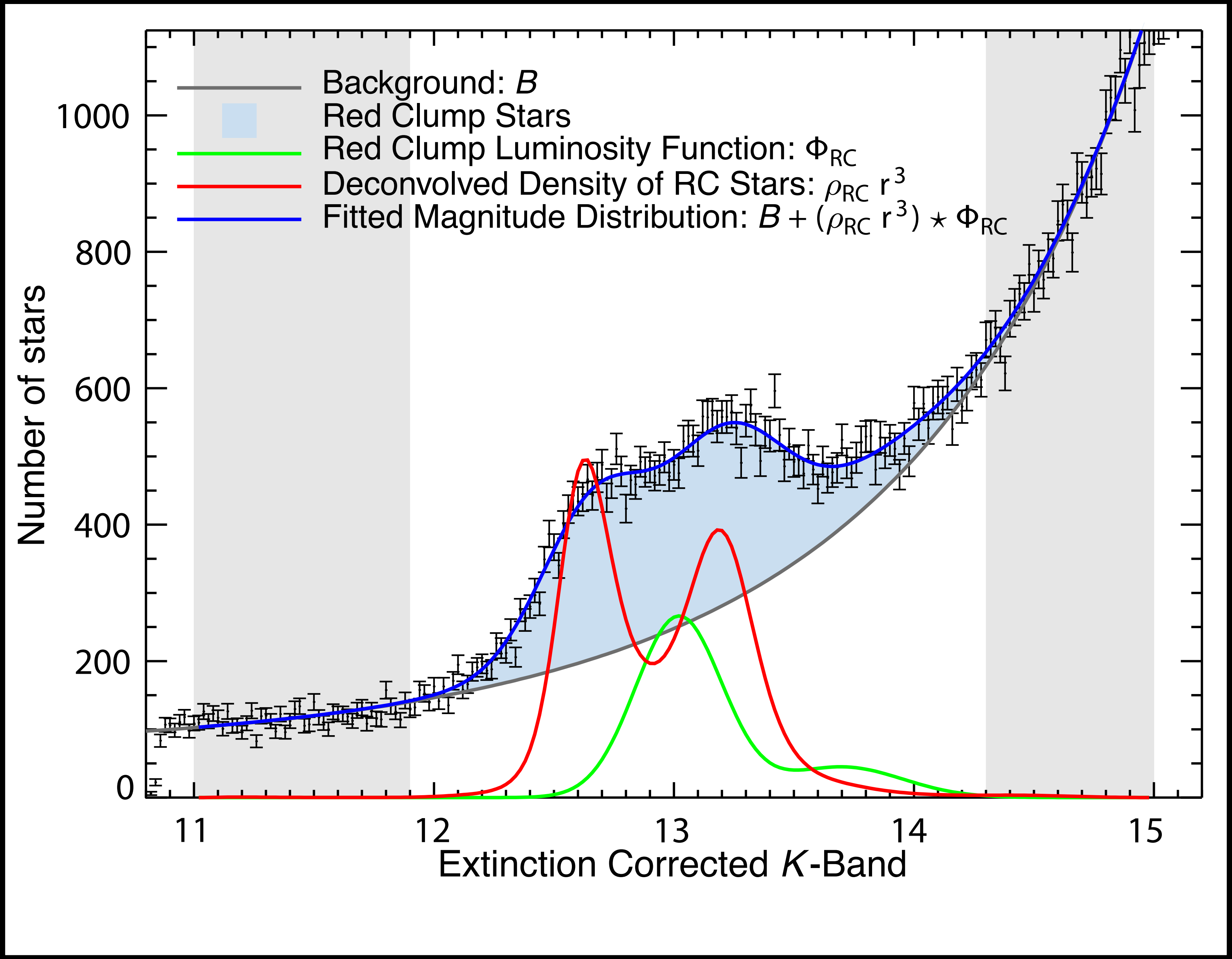
The Structure of the Inner Galaxy



- Combine ~300 line-of-sight density estimates into 3D density
- 3D map non-parametric, assuming only 8-fold mirror symmetry, with small departures

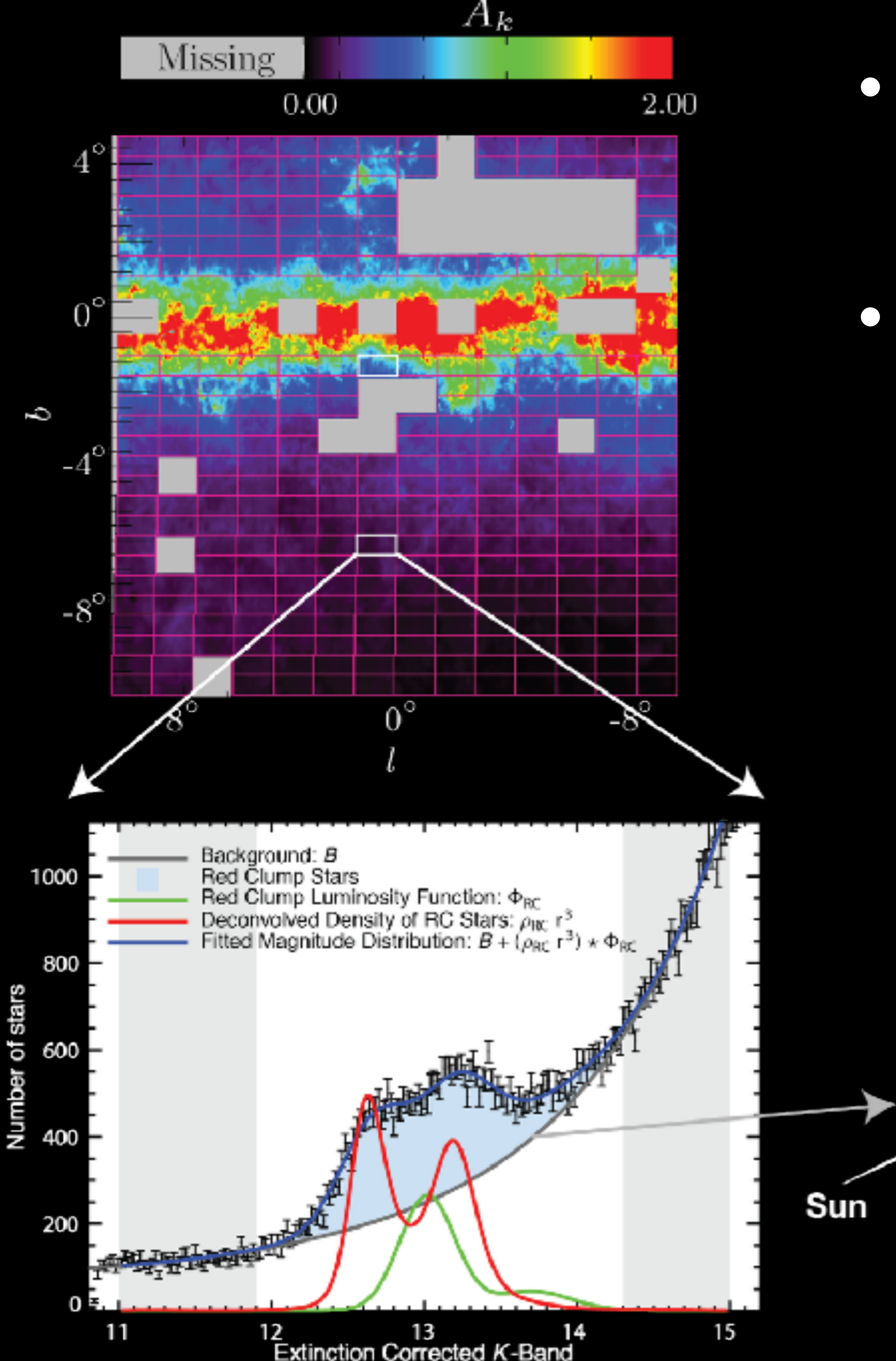


Line-of-sight density estimation



- Fit background to region outside Bulge's RC stars
- Statistically identified red clump stars are convolution of line-of-sight density with luminosity function.
- Deconvolve to estimate density using a slight variation on Lucy-Richardson algorithm

The Structure of the Inner Galaxy



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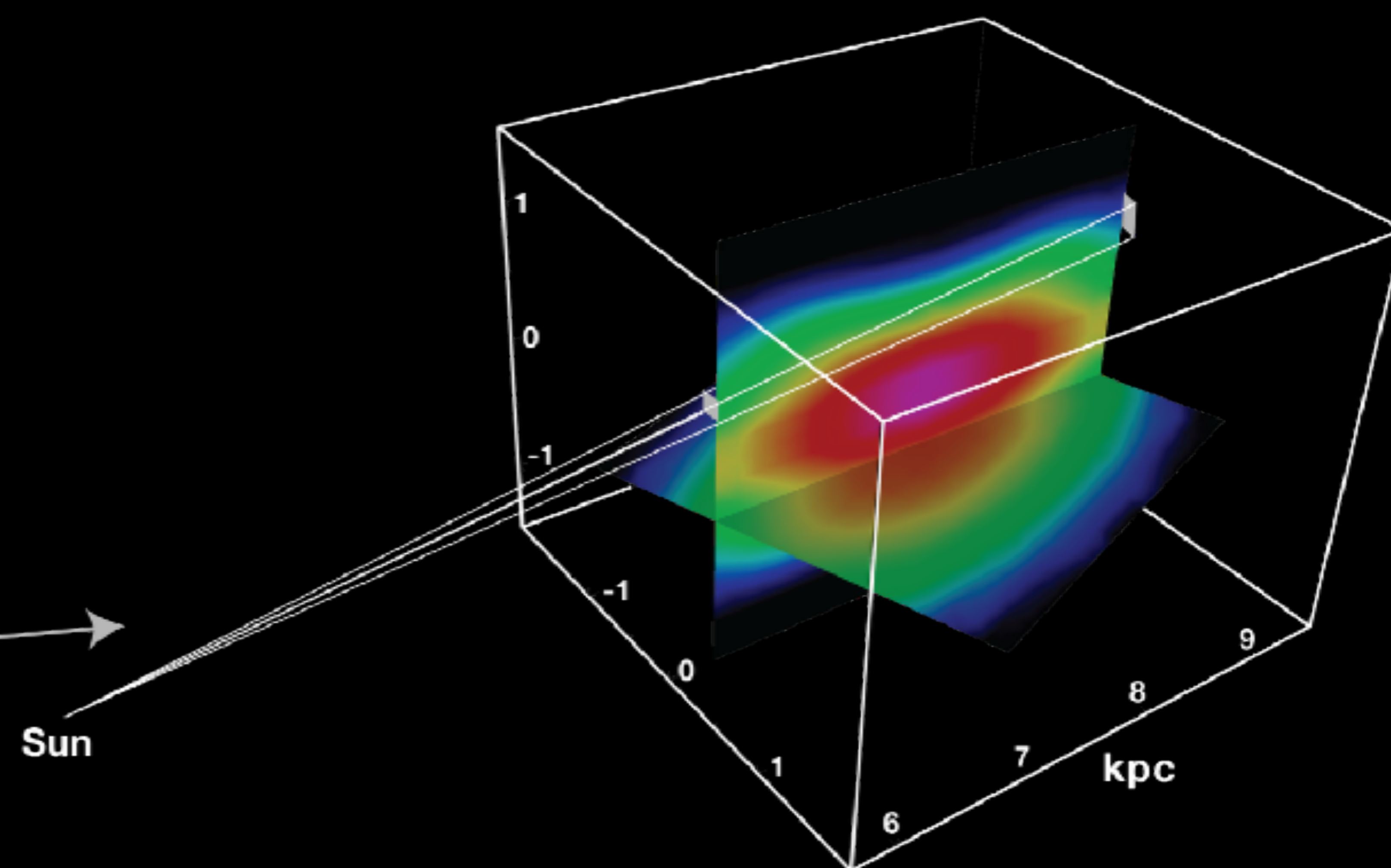
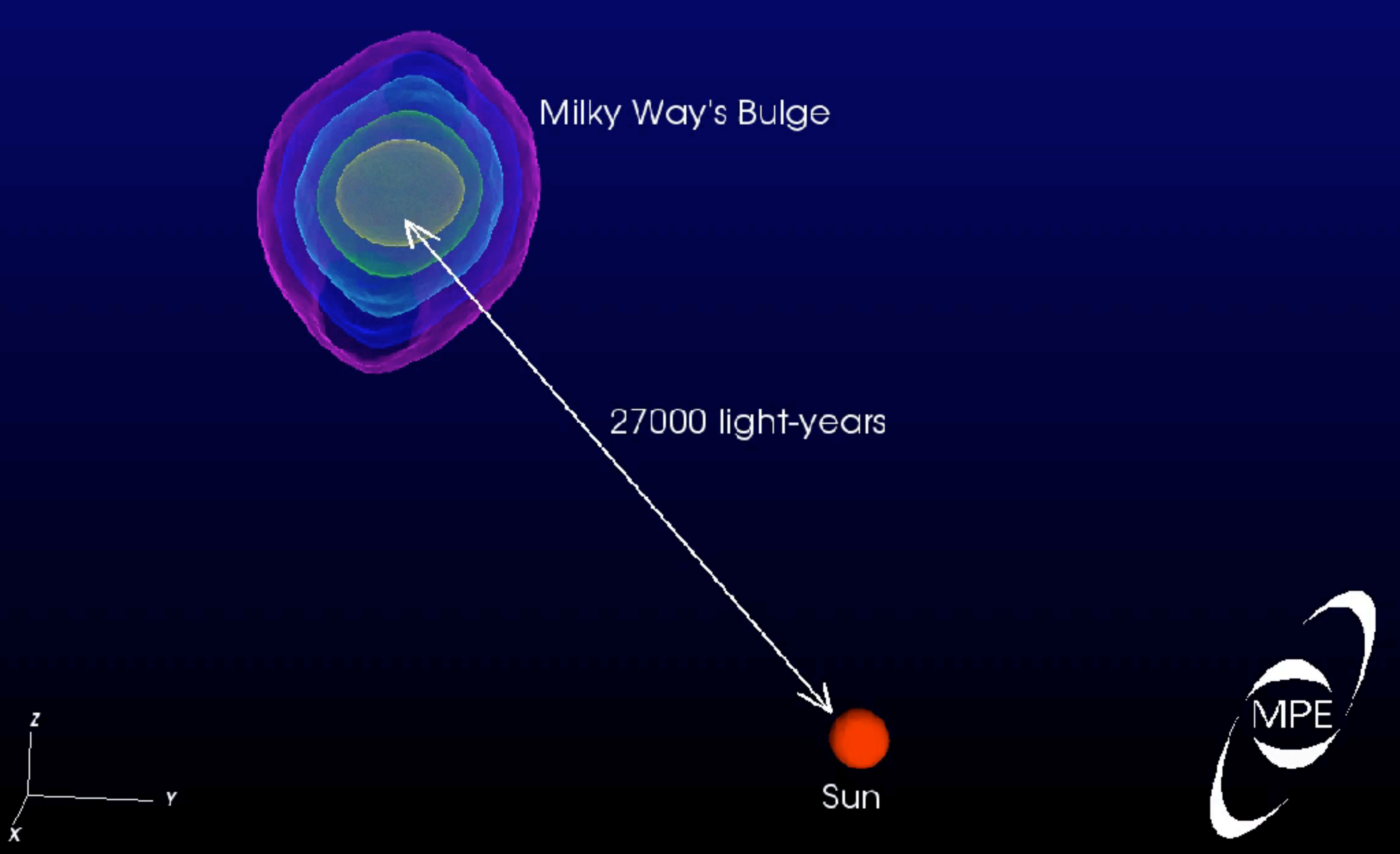
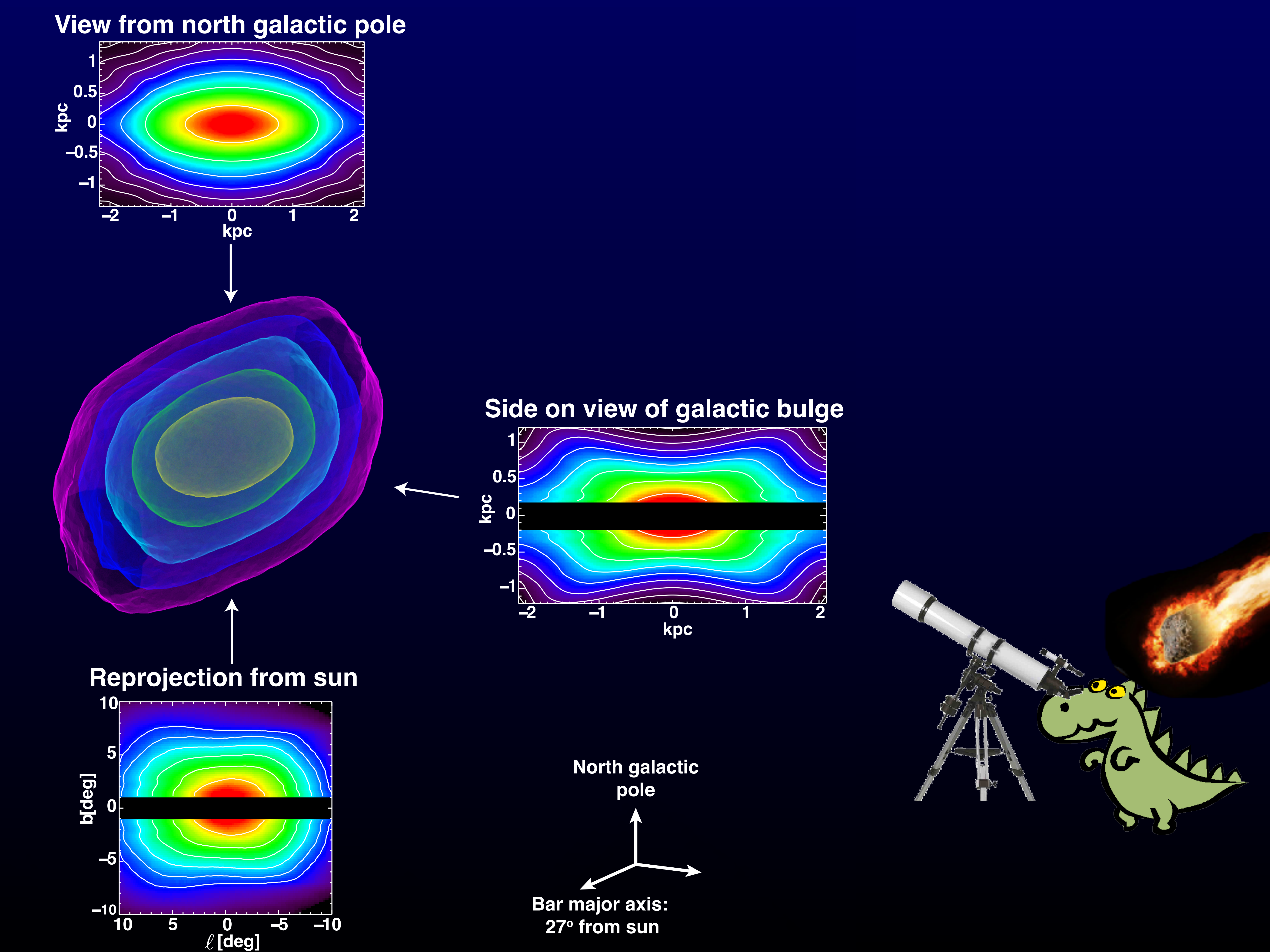
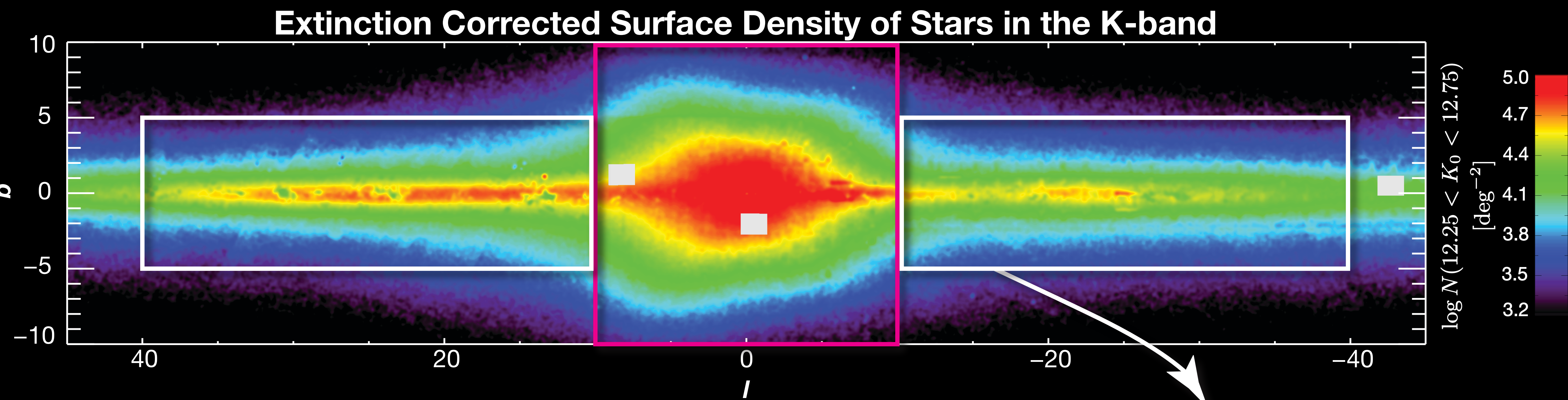




Shape of the bulge: **CW** & Gerhard (2013)

Shape of the bar outside the bulge: **CW**, Gerhard & Portail (2015)

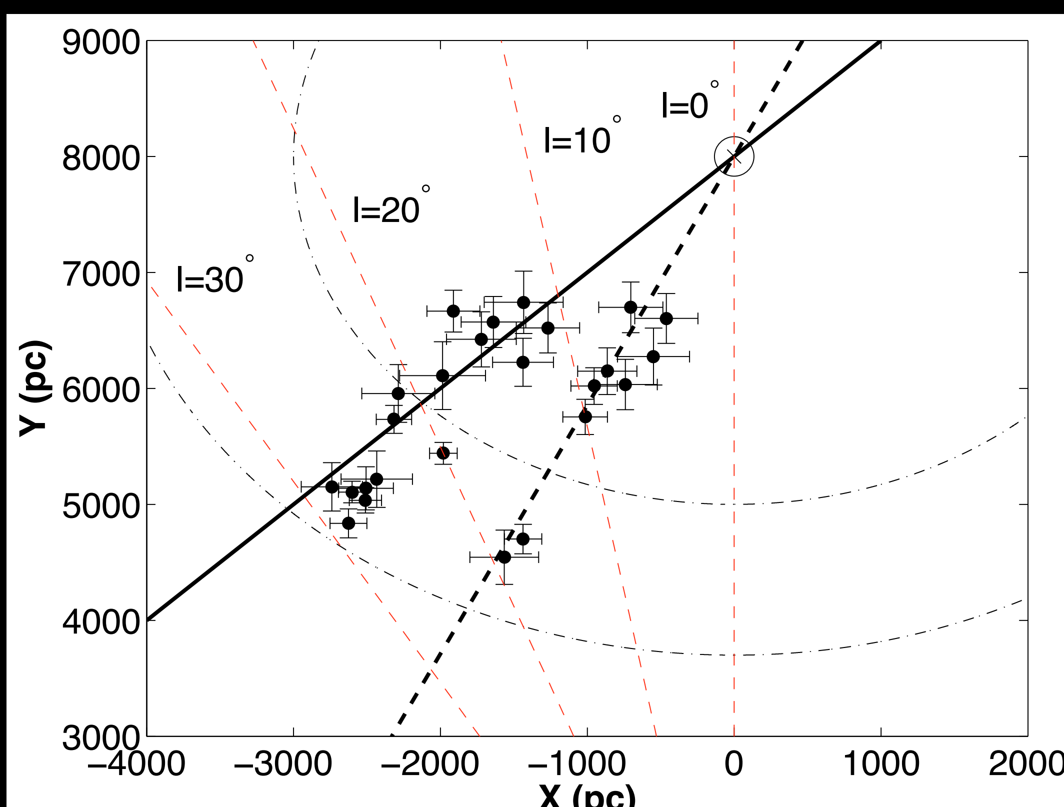

View from north galactic pole
kpc
1
0.5
0
–0.5
–1
–2
–1
0
1
2
kpc
Side on view of galactic bulge
1
0.5
kpc
0
–0.5
–1
–2
–1
0
1
2
kpc
Reprojection from sun
10
5
b[deg]
0
–5
–10
10
5
0
–5
–10
ℓ [deg]
North galactic pole
Bar major axis: 27° from sun



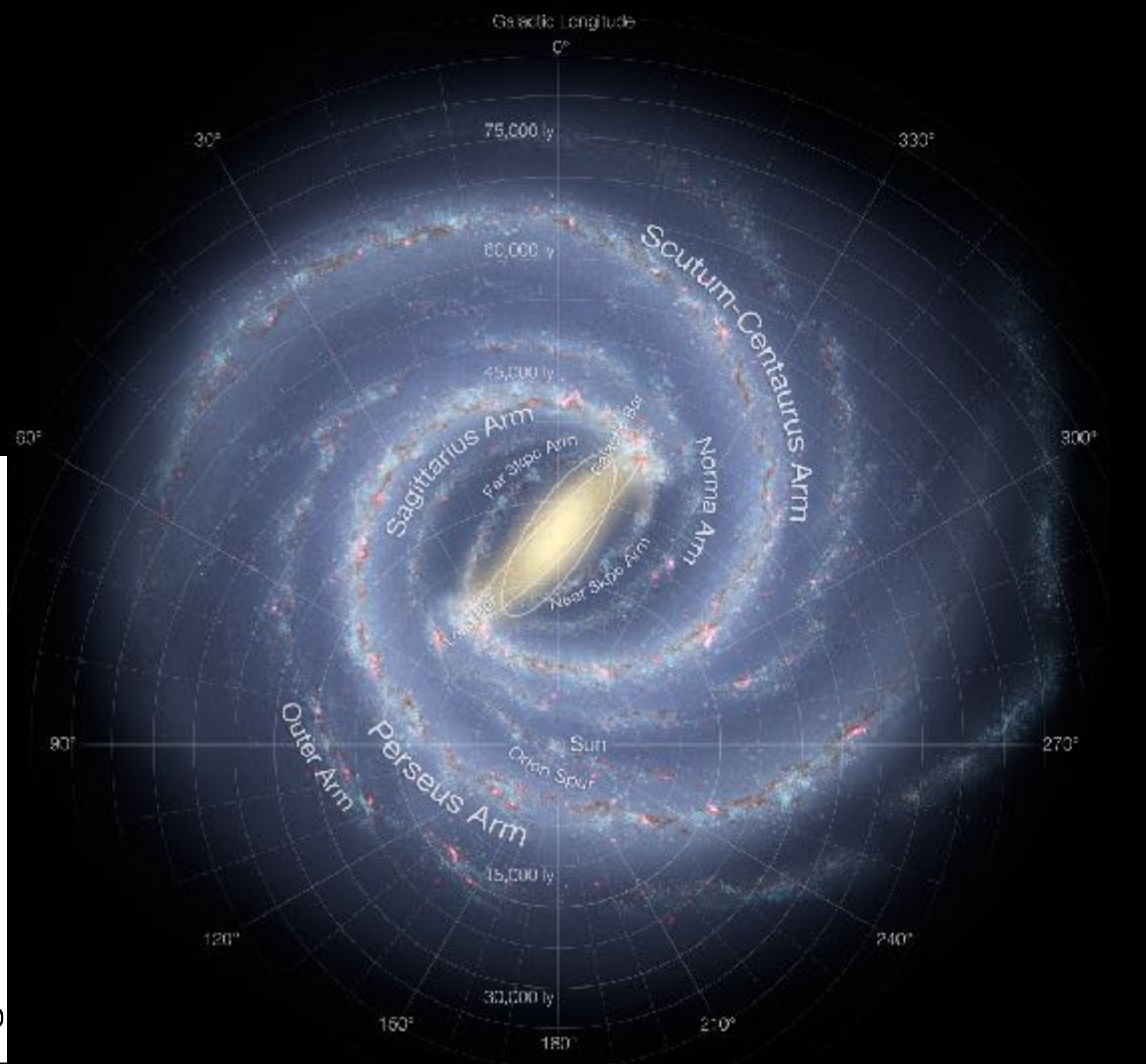
Structure of the Galactic Bar at $|l| > 10°$

Motivations for studying the Long Bar

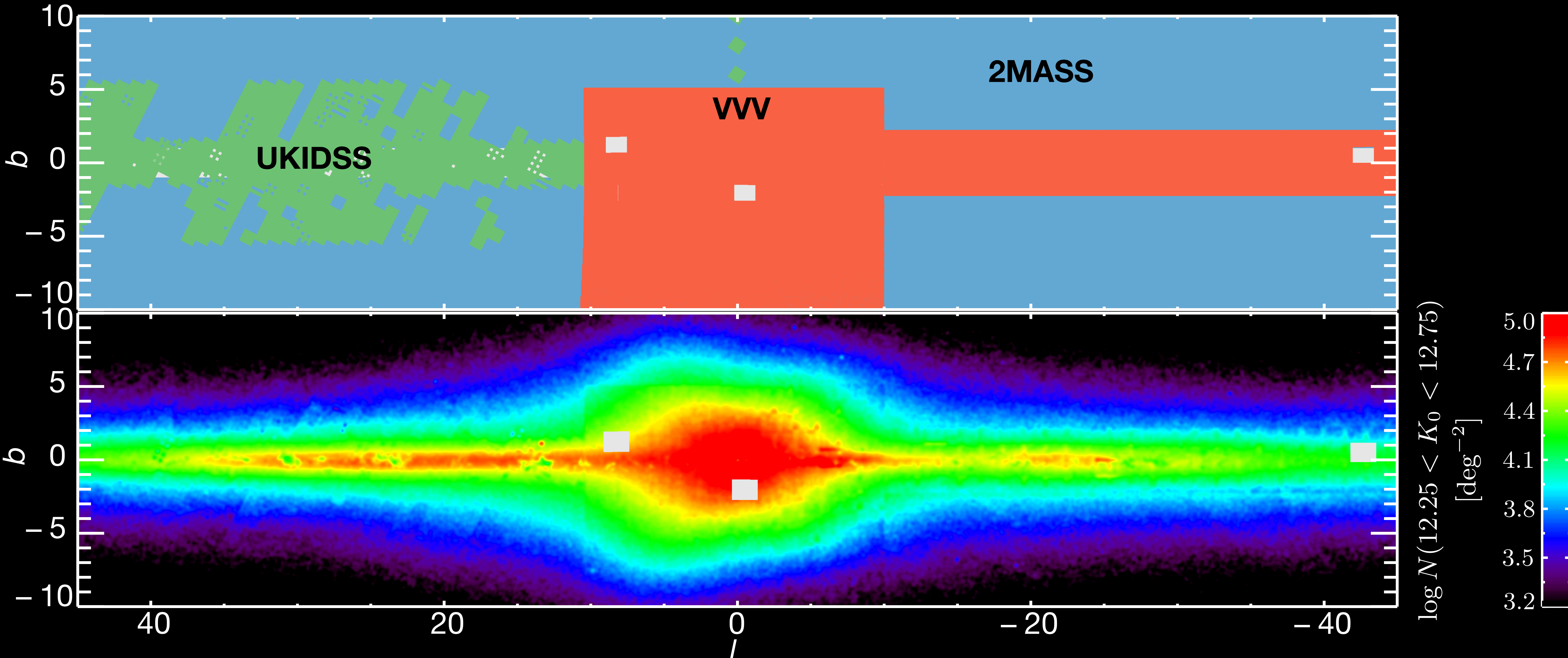
- The bar outside the bulge called the ***long bar*** was found by Hammersley et al. (1994).
- But we still have very few details or understanding!
- Best investigation below. Long bar seems misaligned to bulge. Do we have two bars in the Milky Way?
- Seems unlikely:
  - Theoretically: Strong mutual torques
  - Observationally: External Galaxies
  - Philosophically: Connected 3D bulge+long bar arises naturally in simulations



Cabrera-Lavers *et al.* (2008)



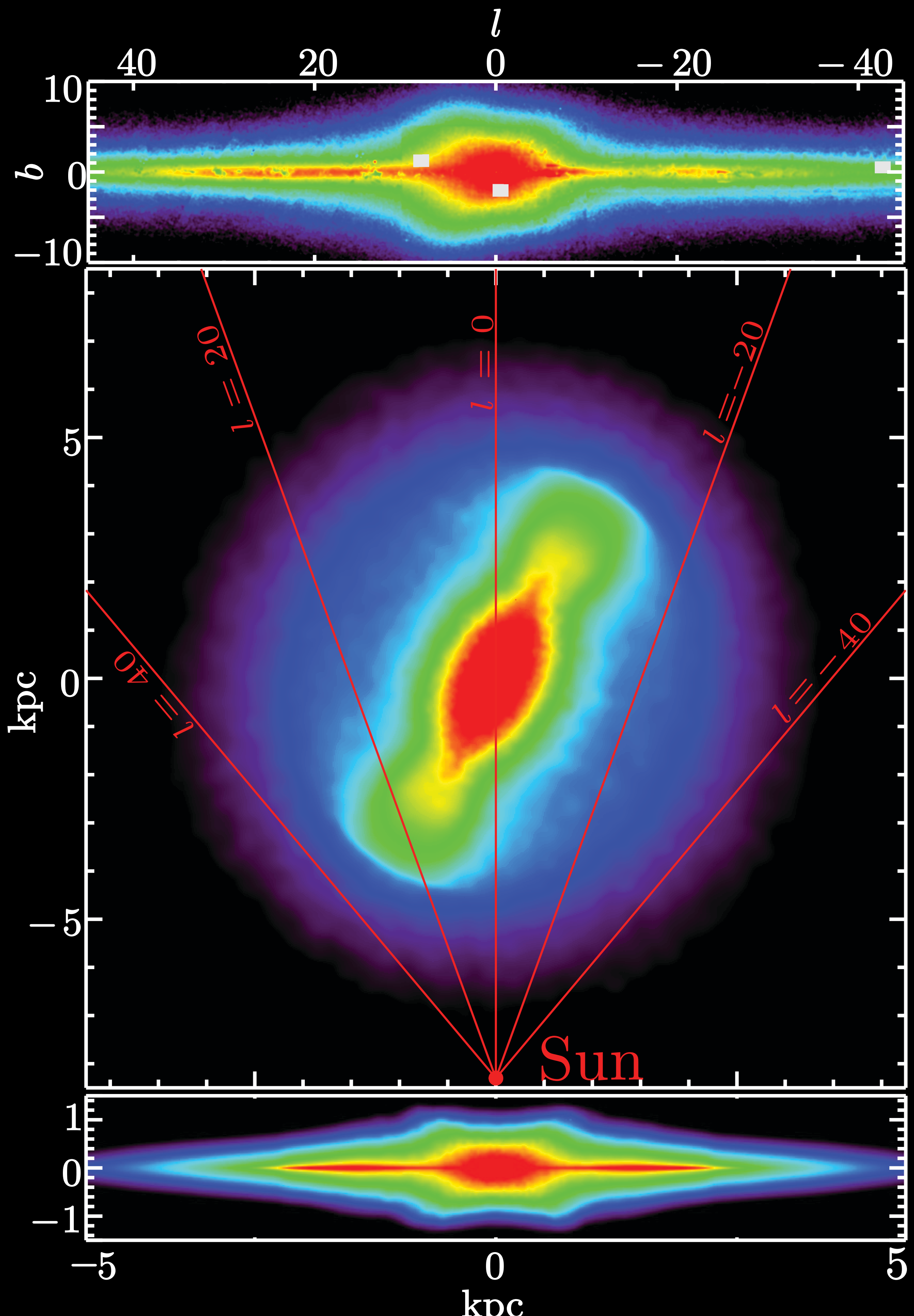
Data Sources



- Signal-to-noise of RCGs is smaller *i.e.* background of foreground disk stars is higher, number of RCGs lower.

  ⇒ Can't field-by-field non-parametrically estimate density.

The Structure of the Inner Galaxy



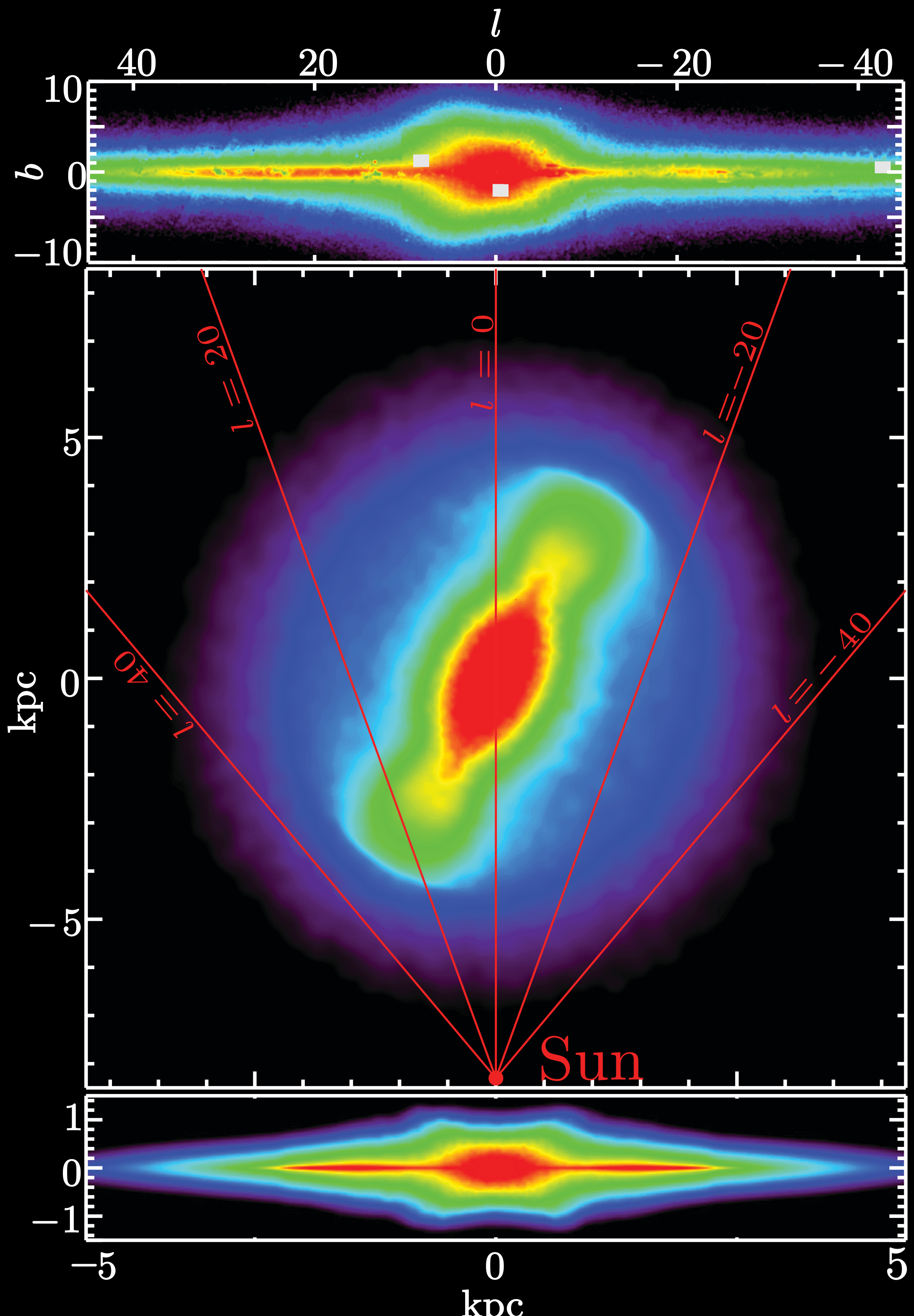
Parametric model tells us:

- Long bar angle is (28-33)° - Aligned with the bulge!
- Bar half length is 5.0±0.2 kpc.

Shape of the bulge: **CW** & Gerhard (2013)

Shape of the bar outside the bulge: **CW**, Gerhard & Portail (2015)

The Structure of the Inner Galaxy

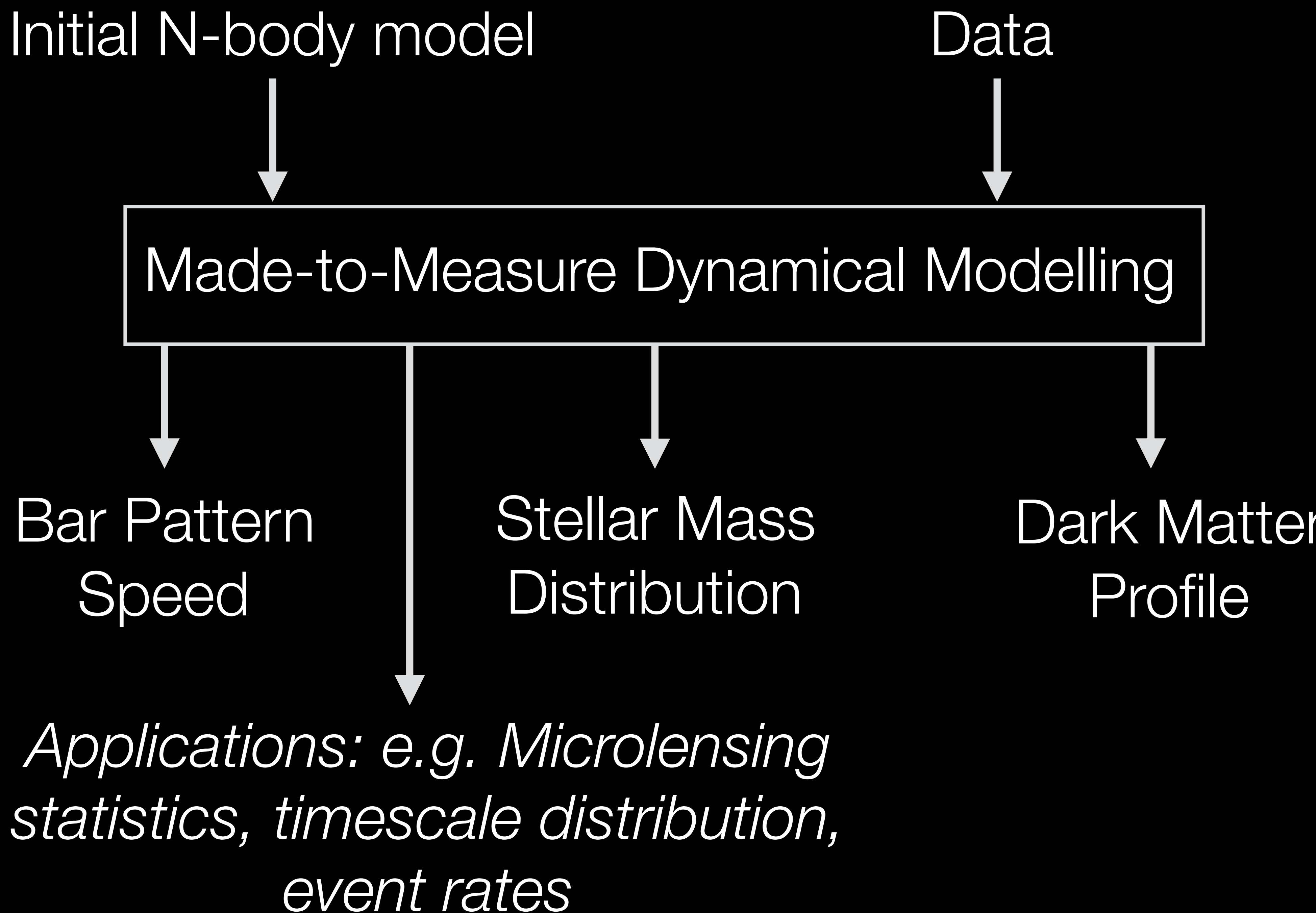


- Bulge looks like a typical Box/Peanut bulge.
- Looks just like other peanut bulges side-on.
- Shape naturally similar to N-body simulations of bars where the central part buckles into a B/P-bulge leaving a thinner 'long bar' outside.
- Most of the bulge evolved secularly from the disk, there can only a sub-dominant classical bulge

Shape of the bulge: **CW** & Gerhard (2013)

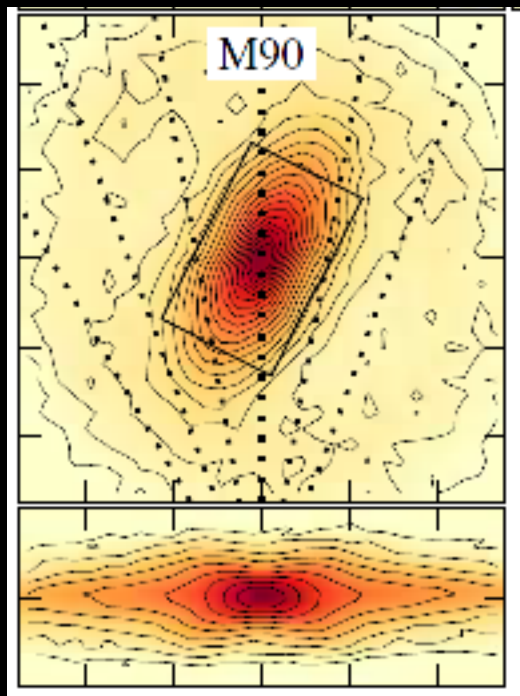
Shape of the bar outside the bulge: **CW**, Gerhard & Portail (2015)

Made-to-measure N-body models of the Inner Galaxy



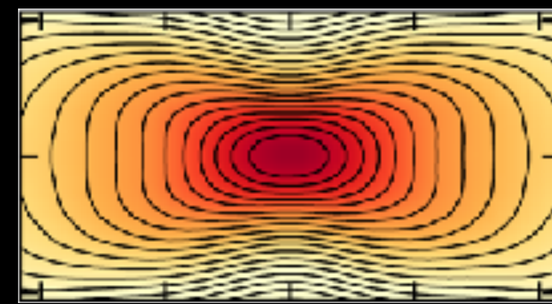
Application to Bulge: Portail, CW & Gerhard (2015)
Application to Entire Inner Galaxy: Portail, Gehard, CW & Ness (2017)

Made-to-measure N-body models of the Inner Galaxy

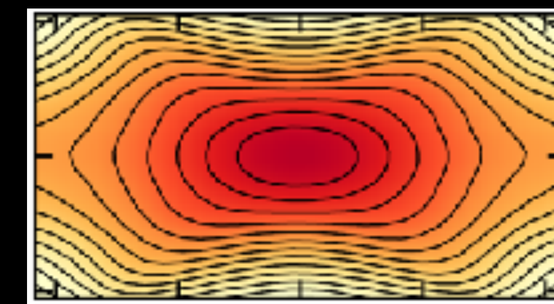


Self-graviting N-body model

Model observables



Real data with errors



Compare

$$\frac{dw_i}{dt} = \epsilon w_i \frac{\partial F}{\partial w_i}$$

Update the particle masses

Syer & Tremaine (1996), De Lorenzi et al. (2007)

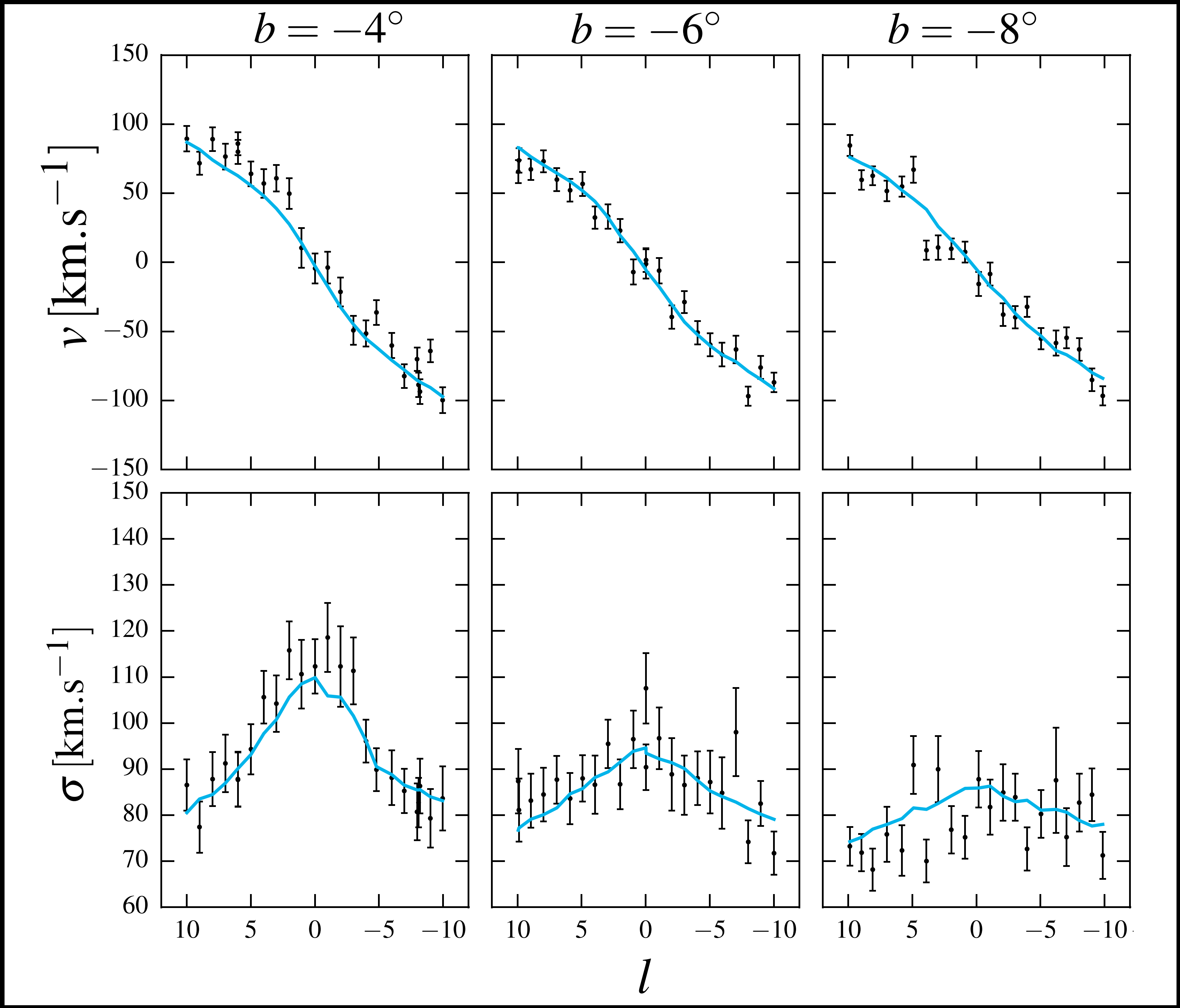
Models fitted to a range of data on the inner Galaxy:

- Density maps: Bulge
- Star counts: Bar
- Radial Velocities from spectroscopic surveys: BRAVA & ARGOS

Portail, **CW**, Gehard & Ness MNRAS (2015)
Portail, Gehard, **CW** & Ness MNRAS (2017)

Made-to-measure N-body models of the Inner Galaxy

Fit to BRAVA radial velocities in the bulge



Reproduce quantitatively:

- The cylindrical rotation
- The dispersion profiles

Portail, Gehard, CW & Ness MNRAS (2017)

Made-to-measure N-body models of the Inner Galaxy

Initial N-body model → Made-to-Measure Dynamical Modelling

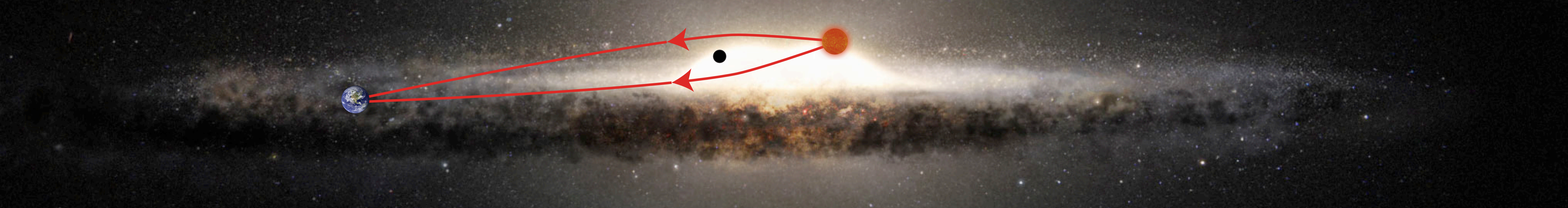
Data → Made-to-Measure Dynamical Modelling

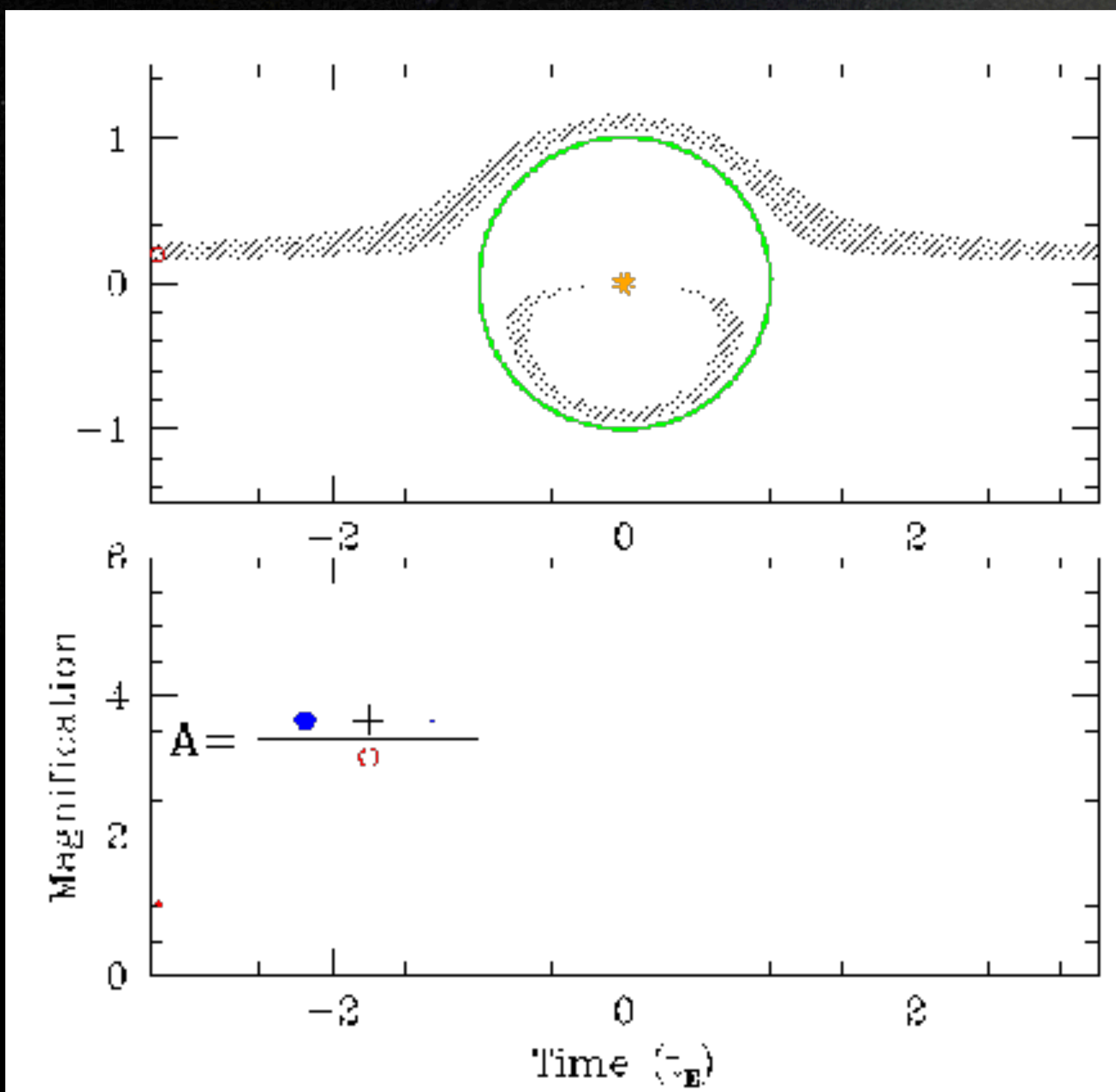
Made-to-Measure Dynamical Modelling →

- Bar Pattern Speed: corotation @ 6.2kpc
- Applications: Microlensing Low DM fraction in inner Galaxy, IMF is ~Kroupa/Chabrier in Bulge
- Stellar Mass Distribution: 70% of stars inside corotation
- Dark Matter Profile: Milky Way has core not NFW

Application to Bulge: Portail, CW & Gerhard (2015)
Application to Entire Inner Galaxy: Portail, Gehard, CW & Ness (2017)

IMF in the Inner Milky Way





- The time axis stretch of the curves is called the timescale
- It depends on lens mass, but also lens geometry and kinematics
- Model provides these statistically ⇒ ***Can statistically measure lens mass function and infer IMF***

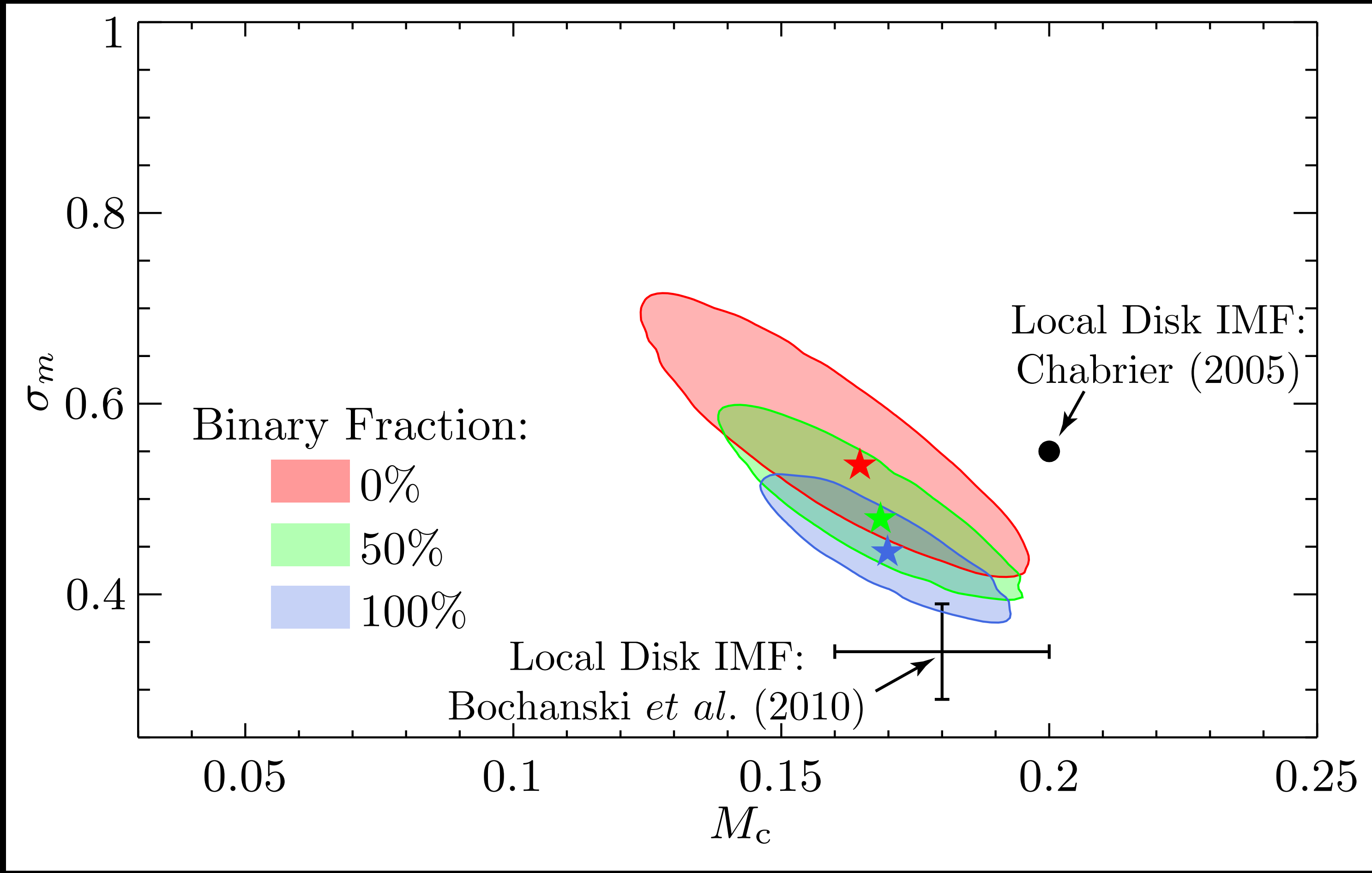
CW, Gerhard & Portail ApJL, 843, 1 (2017)

The IMF of the Inner Galaxy

- IMF in the inner galaxy very similar to the local IMF. Indistinguishable because of the uncertain binary fraction.
- These stars lie 2kpc from the galactic centre and are therefore mostly 10Gyr old and mostly formed on a short α-enhanced timescale of formation.
- Therefore places stringent constraints on star formation models where the IMF varies according to the properties of the the parent molecular gas cloud.

Use log-normal IMF:

$$dN/dM \propto \exp\left\{\frac{-(\log M - \log M_c)^2}{2\sigma_m}\right\} \text{ for } M < 1.0M_\odot$$
$$\propto M^{-2.3} \text{ for } 1.0M_\odot \leq M < 100M_\odot \ .$$



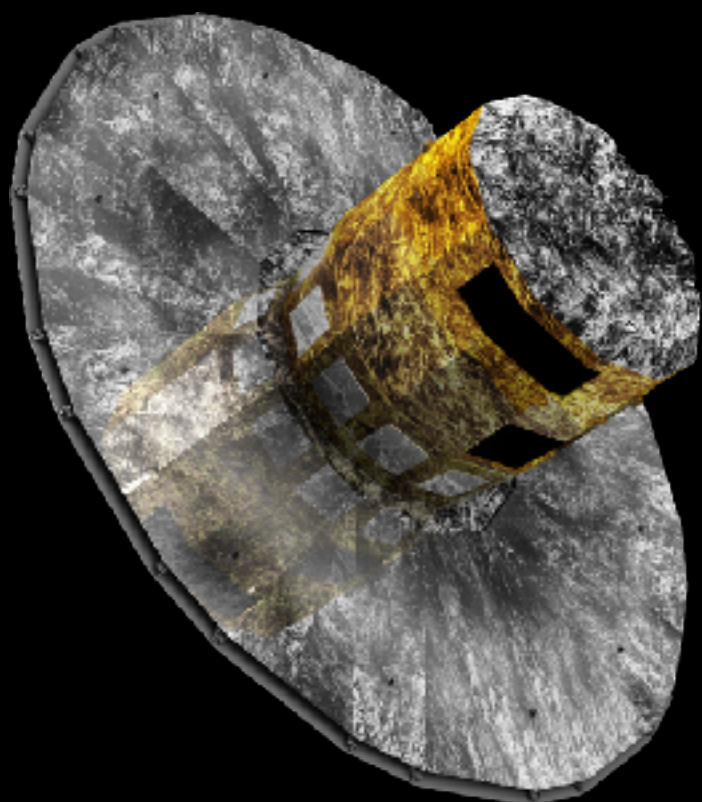
We find:

$$M_c = (0.17 \pm 0.02|_{\text{stat}} \pm 0.01|_{\text{sys}})M_\odot$$
$$\sigma_m = 0.49 \pm 0.07|_{\text{stat}} \pm 0.06|_{\text{sys}}$$

CW, Gerhard & Portail ApJL, 843, 1 (2017)

A New Era in Milky Way Science

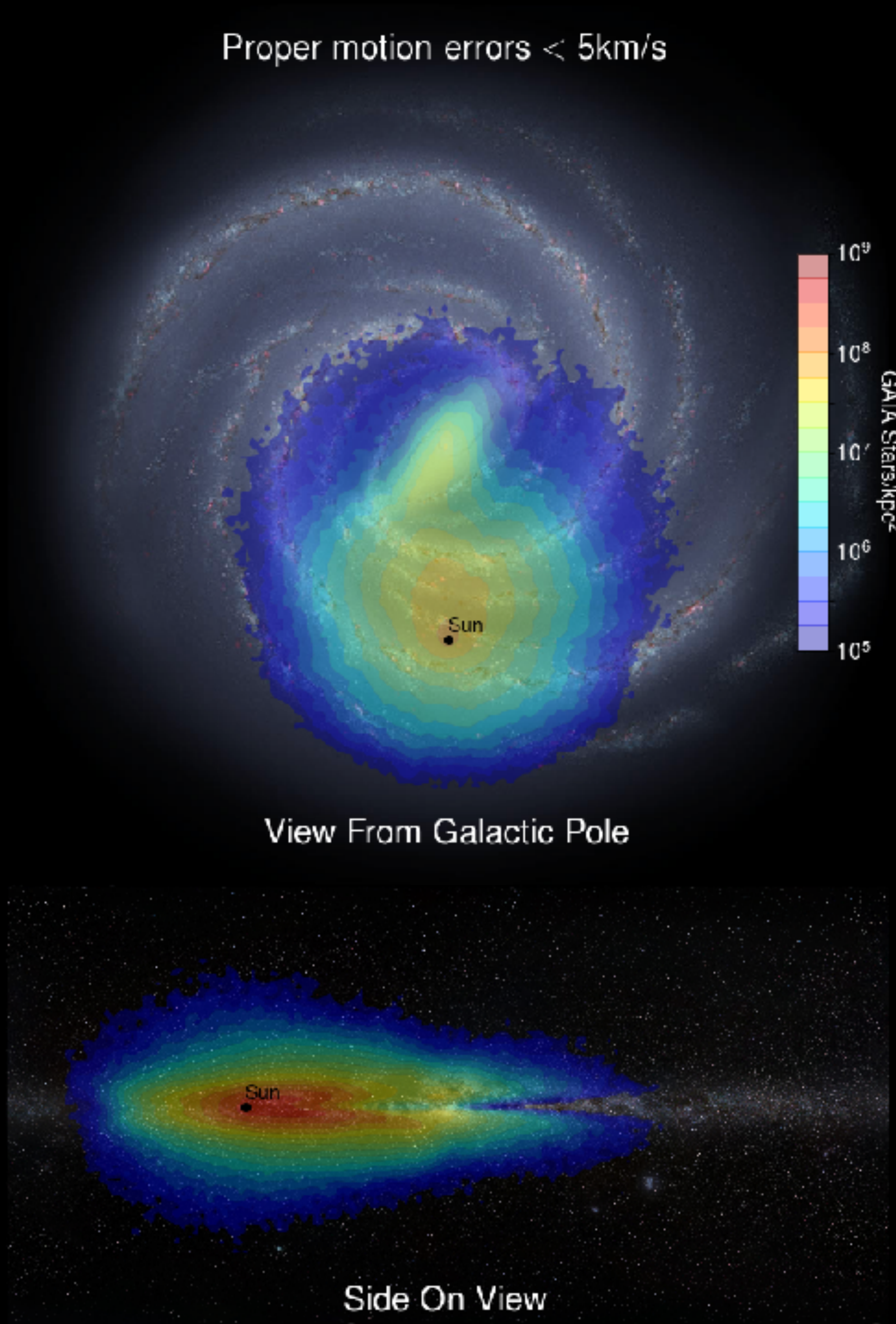
Driven by data from GAIA in space



DR2 released in April 2018 contains astrometry of ~10^9 stars

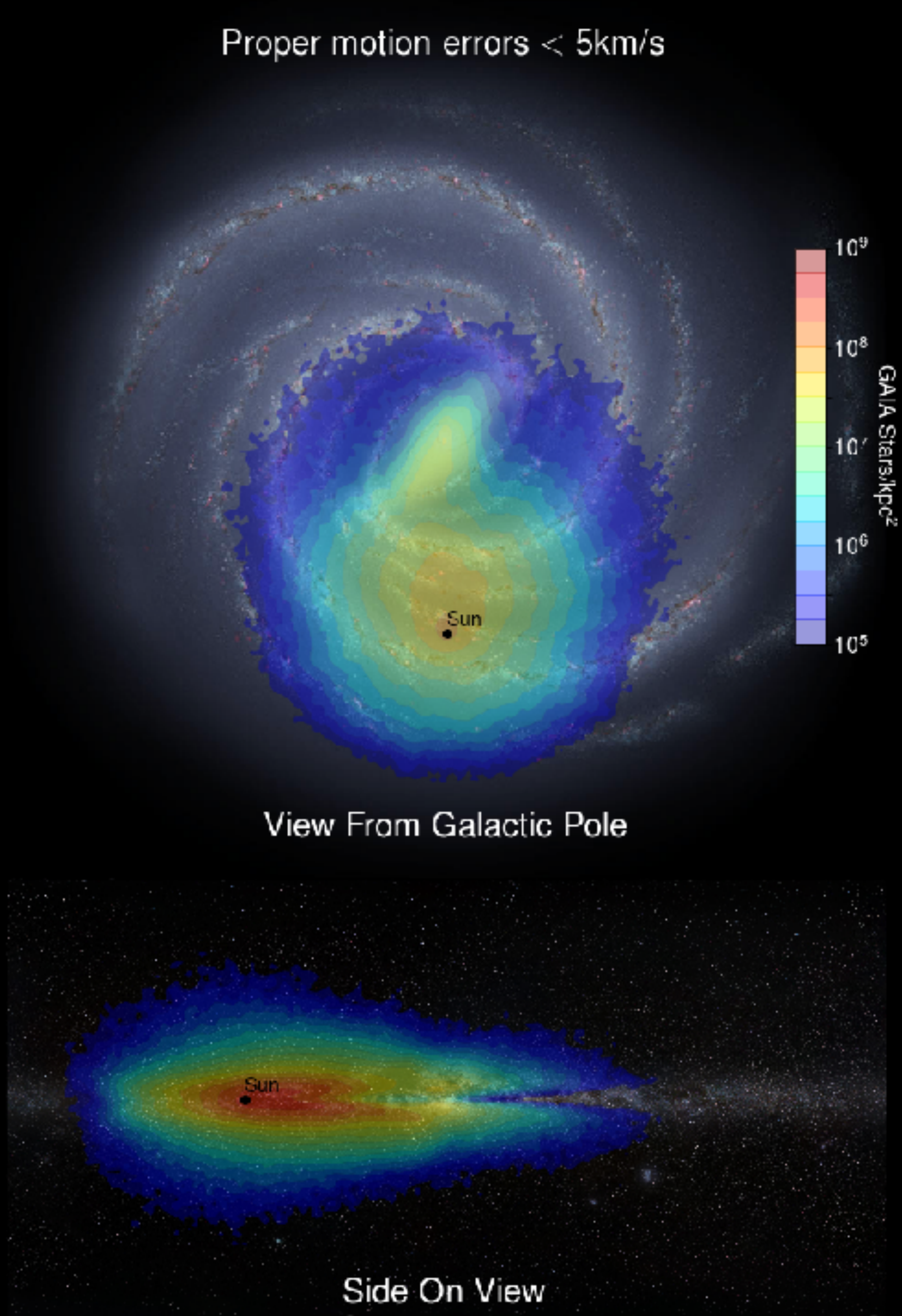
Together with complementary ground based surveys

A New Era in Milky Way Science



- Gaia will detect stars over a large fraction of the Galactic disk
- But view is obscured in the Galactic plane
- Gaia's horizon for accurate parallaxes lies in front of the Galactic centre
- But we can still measure very accurate proper motions – can make exquisite dynamical models

A New Era in Milky Way Science



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- But view is obscured in the Galactic plane
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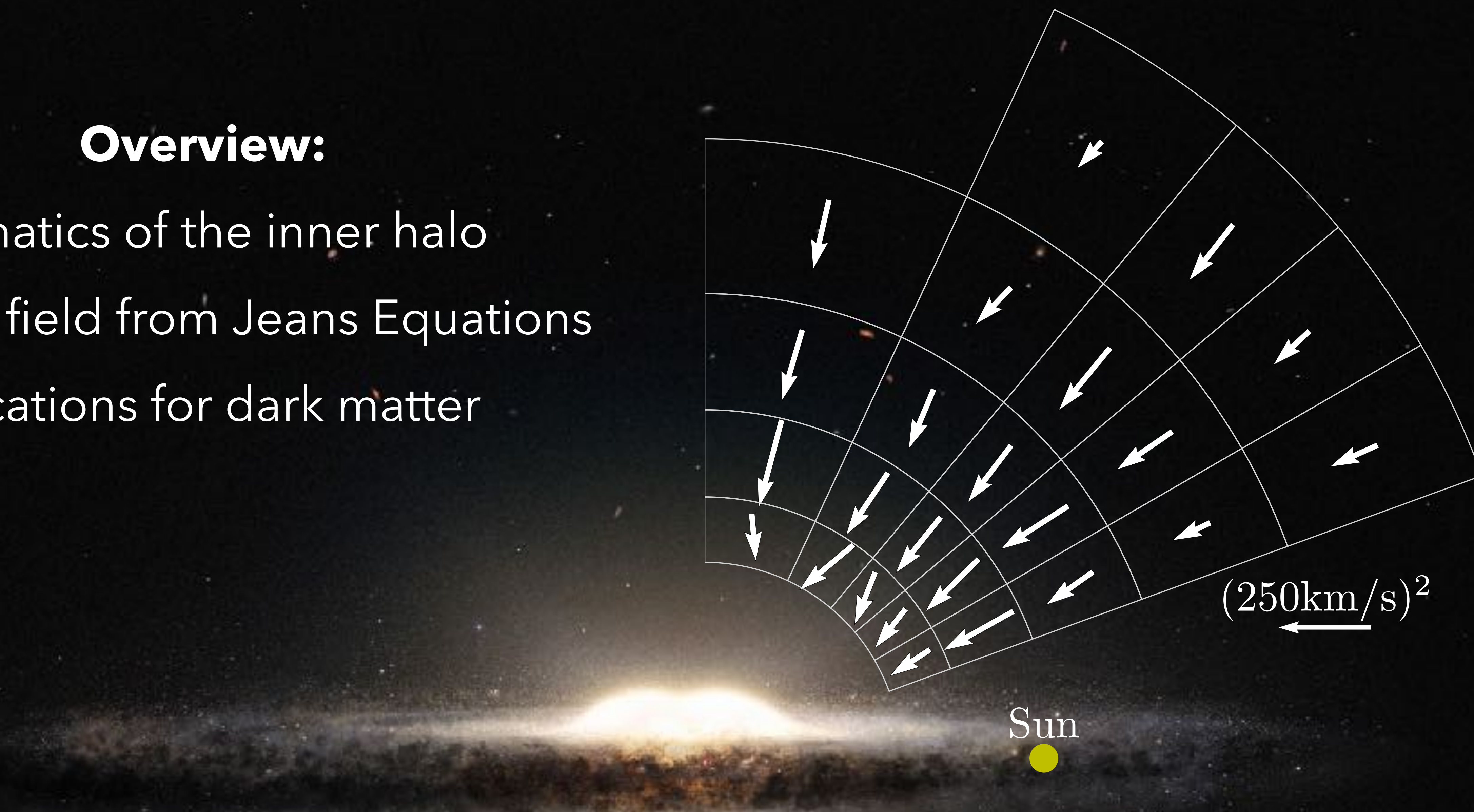
The Gravitational Force Field of the Galaxy Measured From the Kinematics of RR Lyrae in Gaia DR2

Overview:

- Kinematics of the inner halo
- Force field from Jeans Equations
- Implications for dark matter

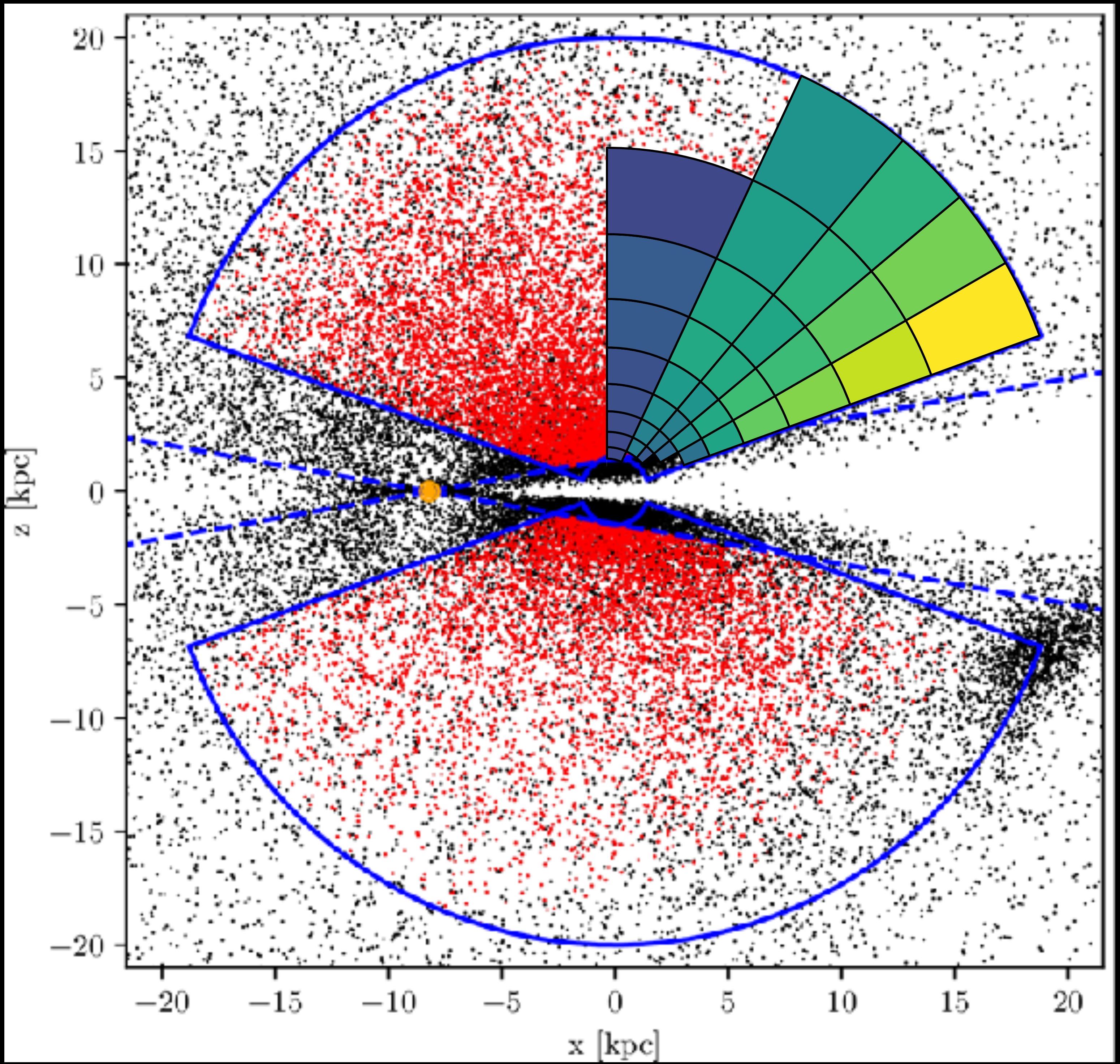


Chris Wegg
Ortwin Gerhard and Marie Bieth

Submitted to MNRAS and arXiv (will appear tomorrow morning)

Halo RR Lyrae in Gaia DR2

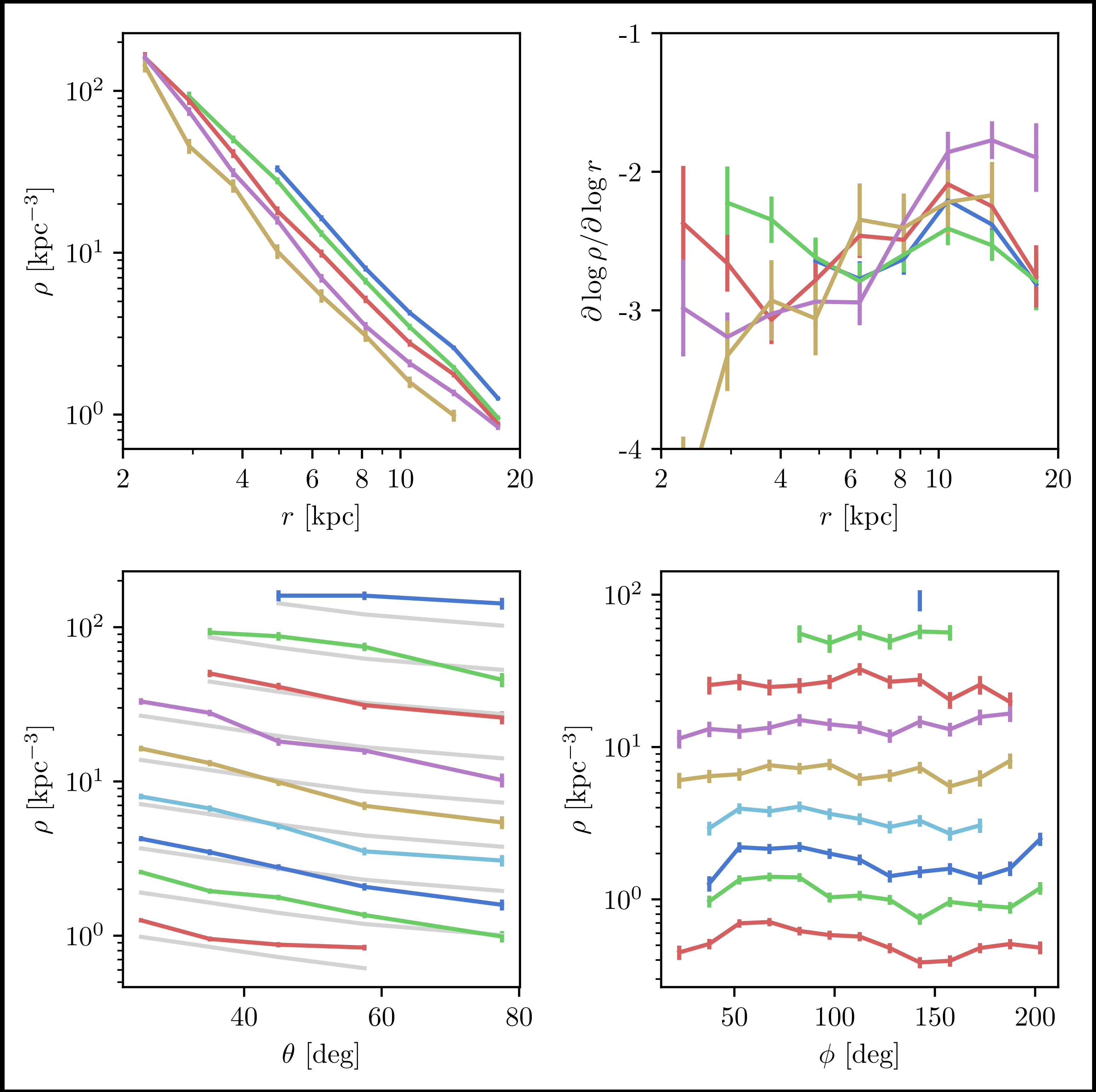
- Use catalogue of RR Lyrae produced by Sesar *et al.* (2017) using Pan-Starrs 3π survey
- We make sample of RR Lyrae stars with galactocentric radii between 1.5kpc and 20kpc, avoiding the Galactic plane
- About 16,000 RR Lyrae over this volume
- Each has a distance to about 3%
- Cross matching to Gaia DR2 we get an accurate transverse velocity for almost all of them



We use 9 bins in log r and 5 bins in θ

Halo RR Lyrae in Gaia DR2

- RR Lyrae are strongly centrally concentrated with $\rho \propto r^{-3}$
- Mildly flattened with $q \approx 0.7$
- But structure in detail is complicated - both flattening and density gradient vary with radius
- Making parametric models that fit this data will be difficult, so we make ***non-parametric models***



Kinematics of Halo RR Lyrae in Gaia DR2

- We have transverse velocities, but no radial velocities i.e. we have measurements of only 5D of the 6D *(x,v)* phase space

- Each measured transverse velocity is the projection of the (unknown real velocity):

$$\mathbf{p} = \mathbf{A}.\mathbf{v}$$

- $\mathbf{A}$ is a projection matrix so we can't invert this…

- But if we take the mean in one of our bins, and assume that positions and velocities are uncorrelated we can!

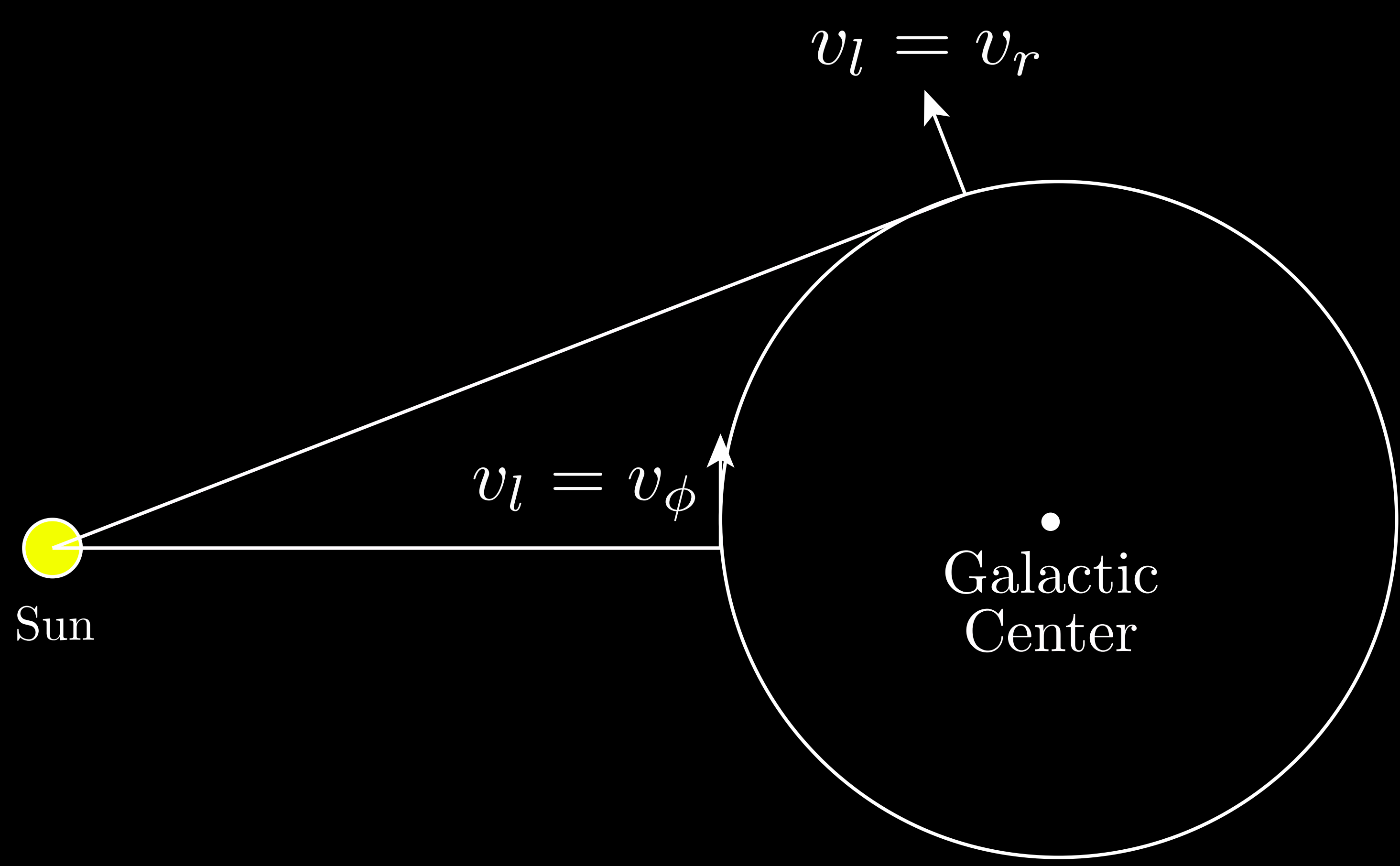
$$\langle\mathbf{p}\rangle = \langle\mathbf{A}\rangle.\langle\mathbf{v}\rangle \quad \rightarrow \quad \langle\mathbf{v}\rangle = \langle\mathbf{A}\rangle^{-1}.\langle\mathbf{p}\rangle$$

- Only tricky part is finding $\mathbf{A}$ since our assumption is that position and velocity in ***spherical coordinates*** is uncorrelated

- Can construct similar estimators for dispersions

Kinematics of Halo RR Lyrae in Gaia DR2

- Concrete example – a bin of stars with constant (r, θ) near the Galactic plane

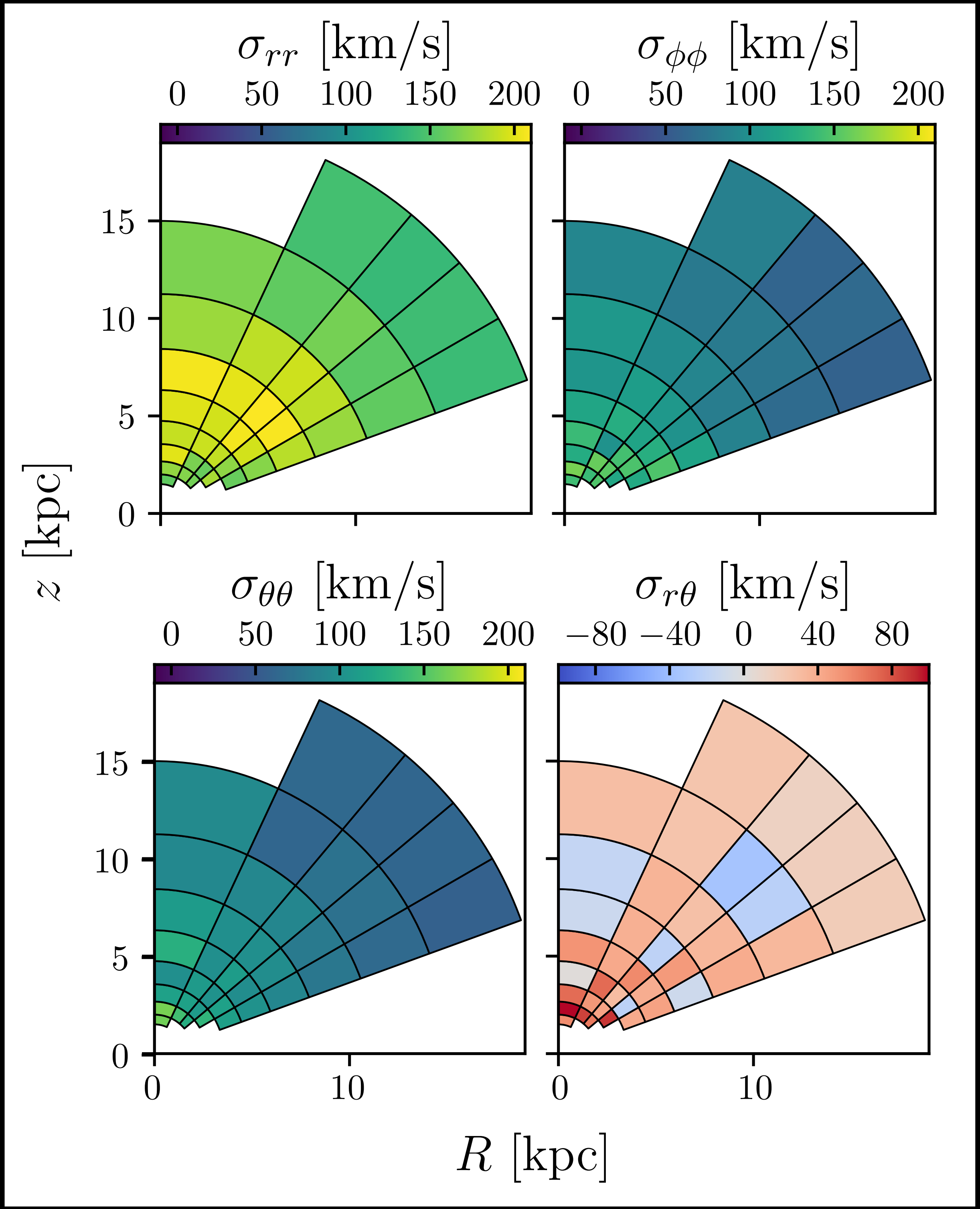


- Because in each bin of (r, θ) stars with different ϕ have projections of the velocity (v_r, v_θ, v_ϕ) we can measure the 3D velocity distribution

Kinematics of Halo RR Lyrae in Gaia DR2

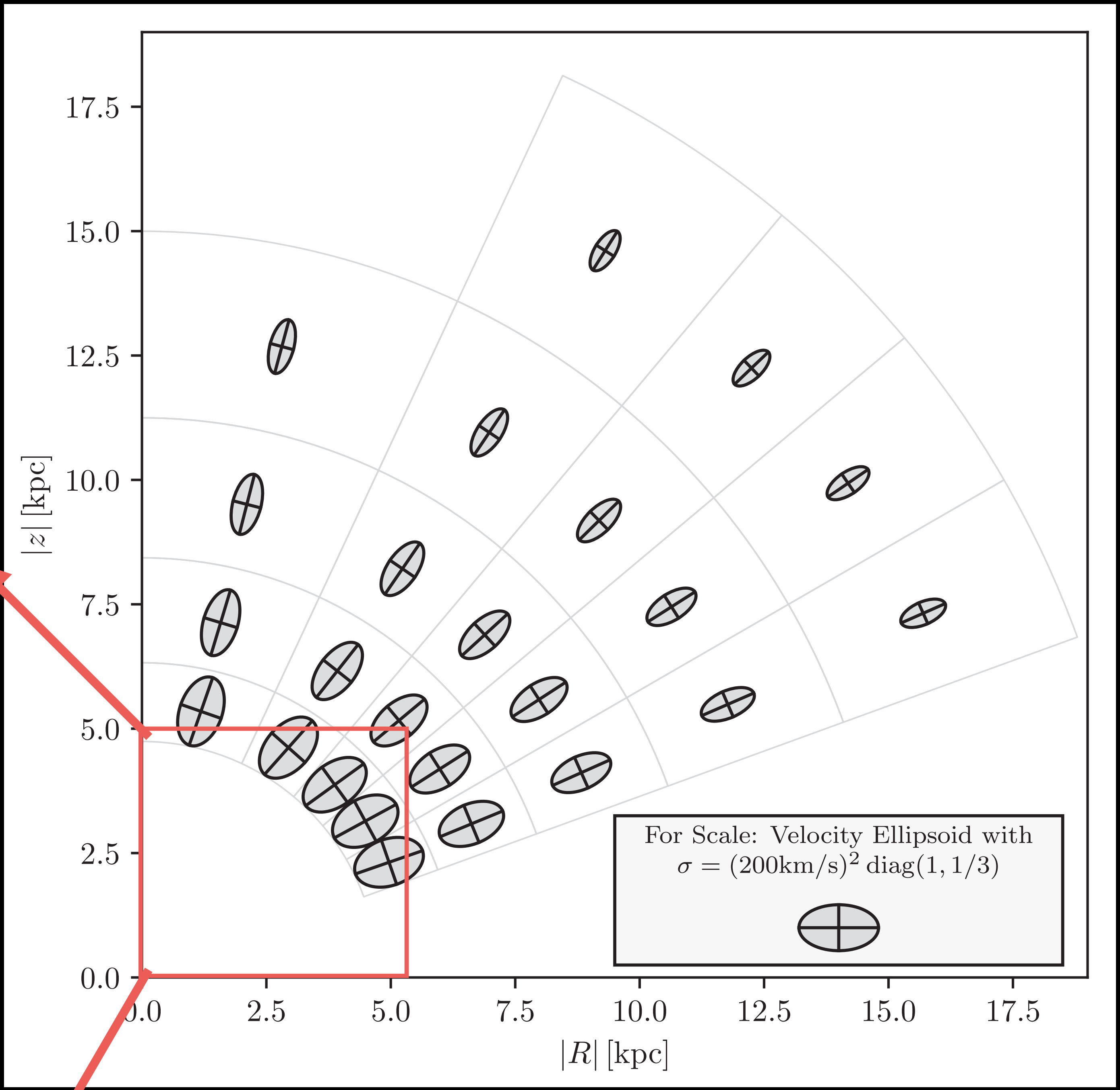
- What do the reconstructed kinematics look like?
- Velocity dispersion tensor σ – like the covariance
- $\sigma_{rr} > \sigma_{\theta\theta} \approx \sigma_{\phi\phi}$
- $\sigma_{r\theta}$ Small

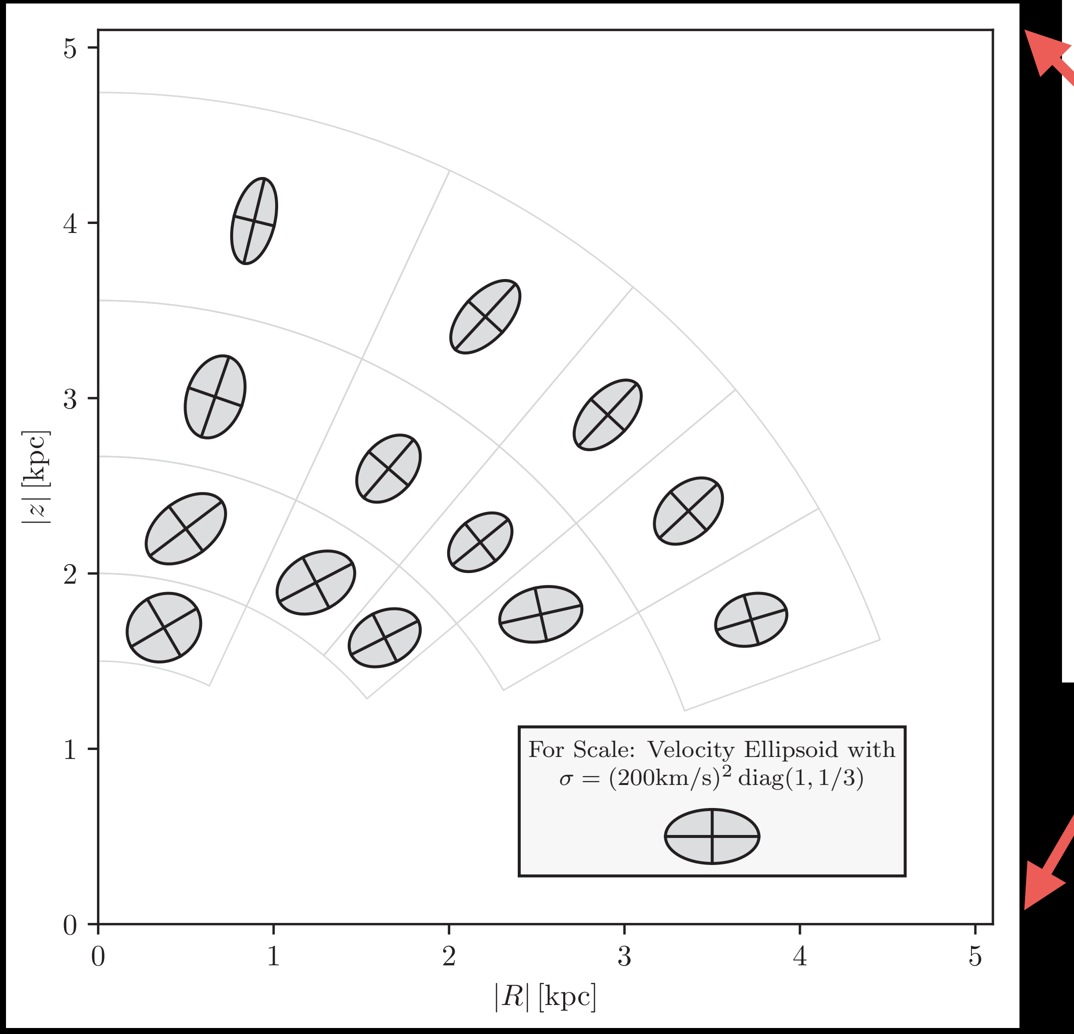
But what does this mean?



Kinematics of Halo RR Lyrae in Gaia DR2

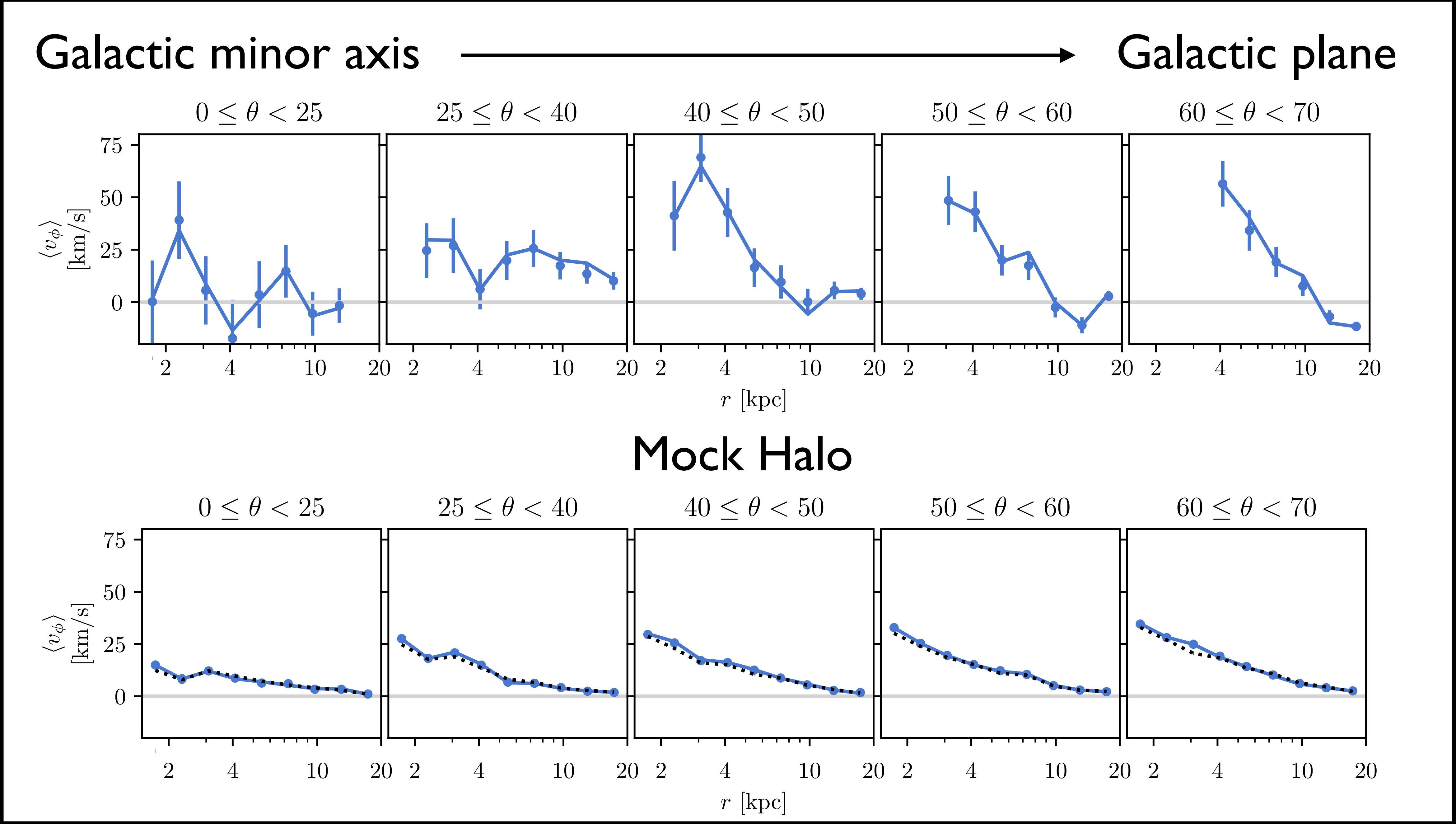
- The inner halo is strongly radially anisotropic
- The velocity ellipsoid is nearly aligned in to spherical coordinates everywhere





Kinematics of Halo RR Lyrae in Gaia DR2

- We knew that the halo near the the sun is rotating (e.g. Beers *et al* 2012, Kafle *et al* 2017, Helmi *et al* 2018)
- The inner halo is rotating even faster



- The rotation could reflect early formation history of the Milky Way, but there is also significant angular momentum transfer from the bar

The Gravitational Force Field of The Milky Way

- We have kinematics in 3D across a large fraction of the inner Galaxy. We can put these into the Jeans Equations to learn about the forces!
- If everything was isotropic things would be easy

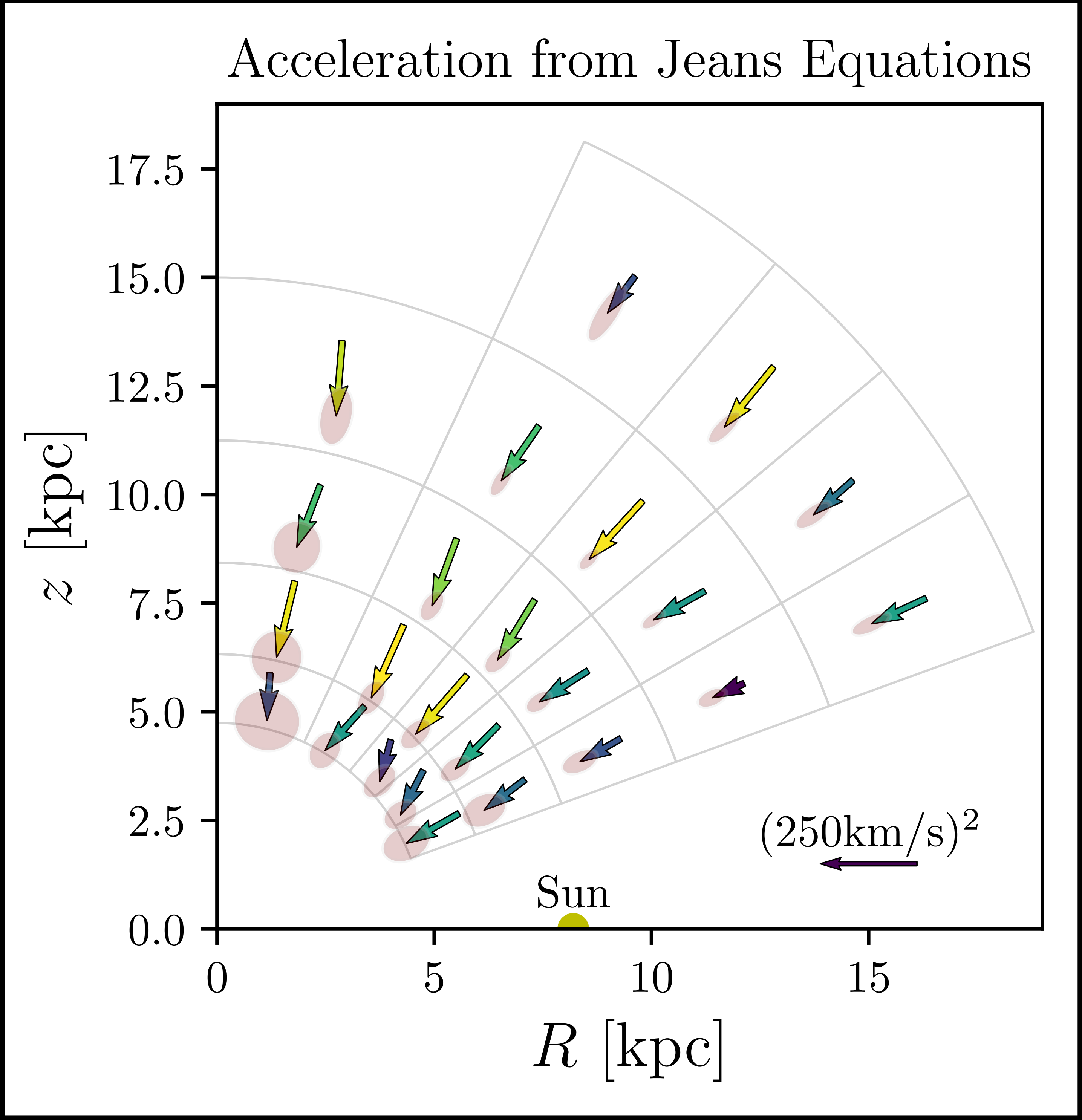
$$\frac{1}{\rho}\frac{\partial \rho\sigma^2}{\partial r} = -F_r$$

- But galaxies aren't isotropic, and so there's extra terms that we can't usually measure
- But the Milky Way is different
- Equations are long, but straightforward… and we have all the kinematic measurements we need from Gaia

$$\frac{\partial \rho\langle v_r^2\rangle}{\partial r} + \frac{1}{r}\frac{\partial \rho\langle v_r v_\theta\rangle}{\partial \theta} + \frac{\rho}{r}\left[2\langle v_r^2\rangle - \langle v_\theta^2\rangle - \langle v_\phi^2\rangle + \langle v_r v_\theta\rangle \cot\theta\right] = -\rho\langle F_r\rangle$$

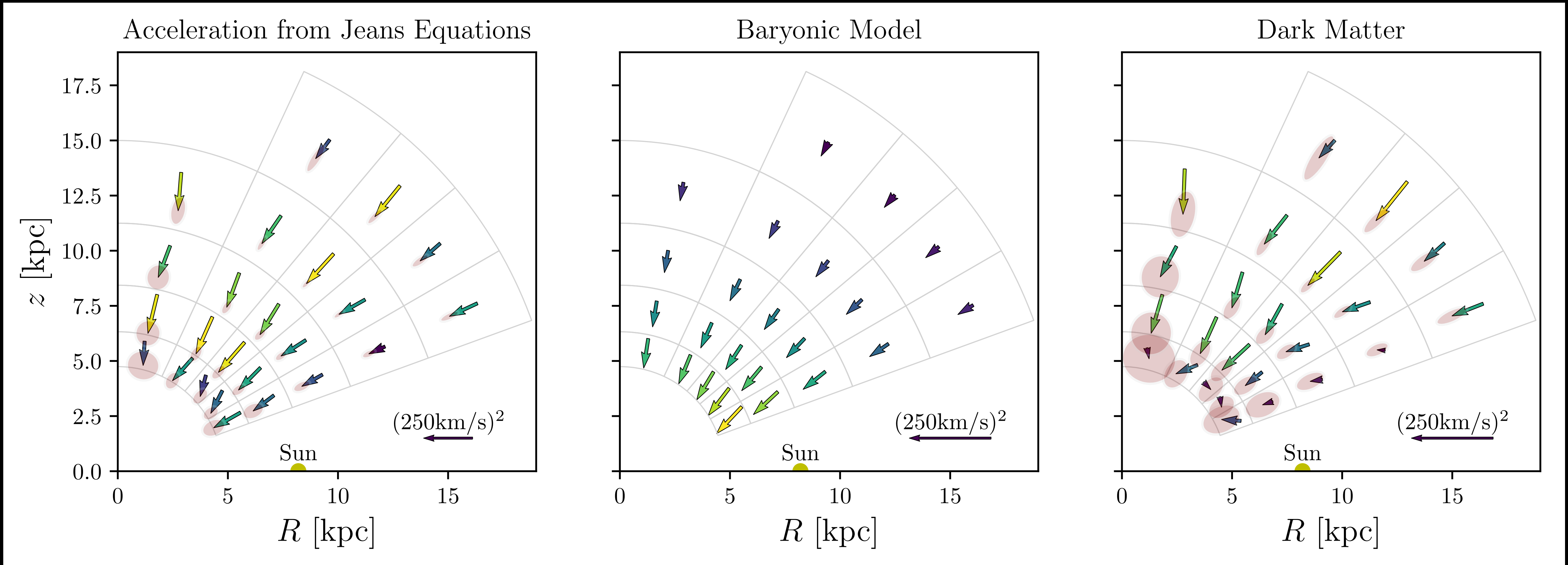
The Gravitational Force Field of The Milky Way

- Each arrow is a force measurement
- The pink ellipses have show the 1 sigma errors *ie* each arrow head can lie anywhere within the ellipse
- We can already see that the forces in the Milky Way are mostly radial



The Gravitational Force Field of The Milky Way

- Can subtract the baryonic part to see the contribution from the dark matter



- For the baryonic part uses the made-to-measure model of the inner Galaxy with exponential star/gas disks outside

The Shape of the Milky Way's Dark Matter Halo

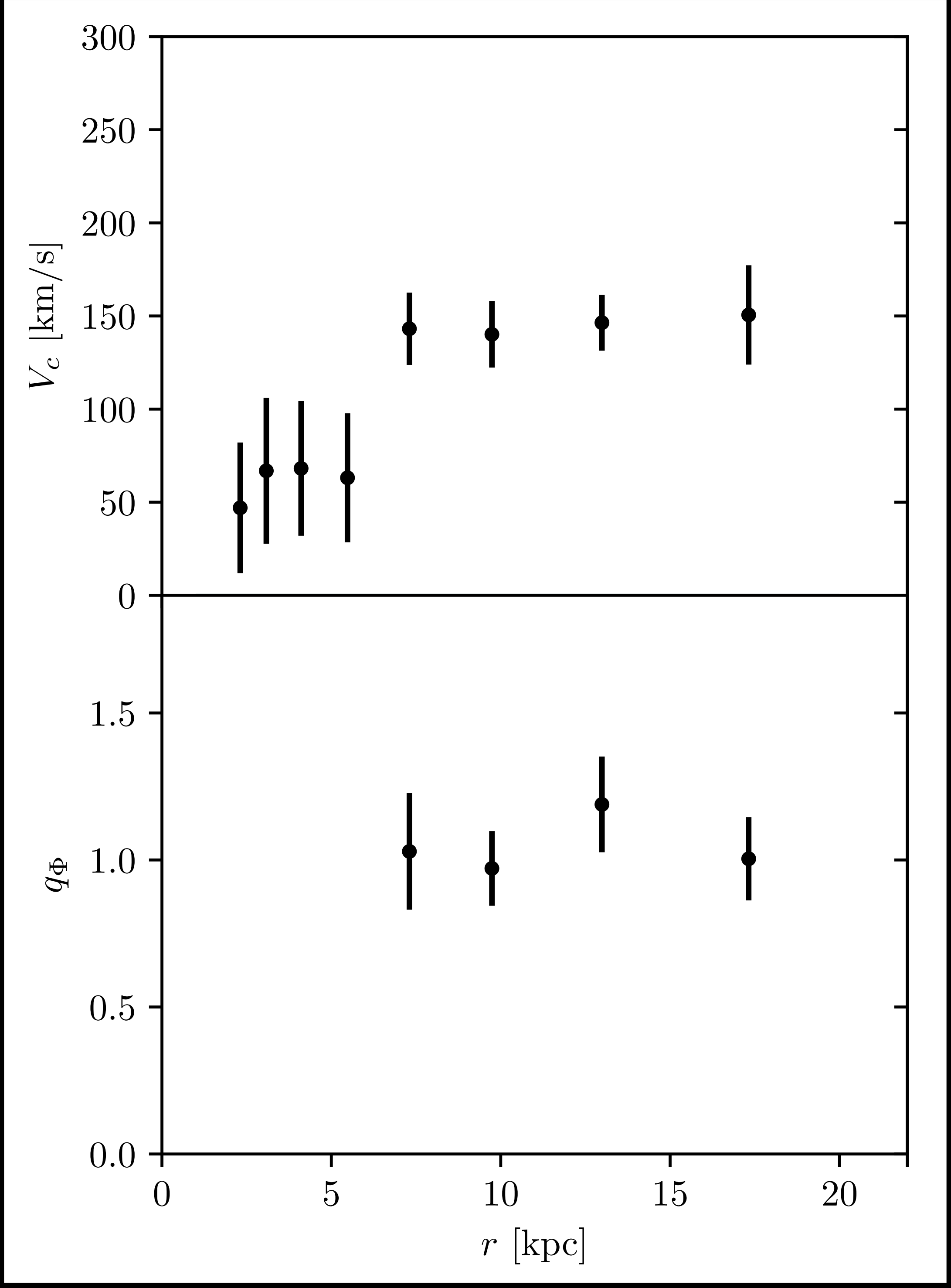
- If we assume that the dark matter potential is ellipsoidal:

$$\Phi_{\rm dm}(m) = \Phi_{\rm dm}\left(\left[R^2 + z^2/q_\Phi^2\right]^{1/2}\right) \quad \text{and}$$

$$\frac{\partial \Phi_{\rm dm}}{\partial \log m} = V_c^2$$

- We can use the forces to measure the flattening q_Φ and circular velocity V_c
- For the first time we have the profile of the flattening of the dark matter in the Milky Way
- Consistent with spherical:

$$q_\Phi = 1.03 \pm 0.08$$

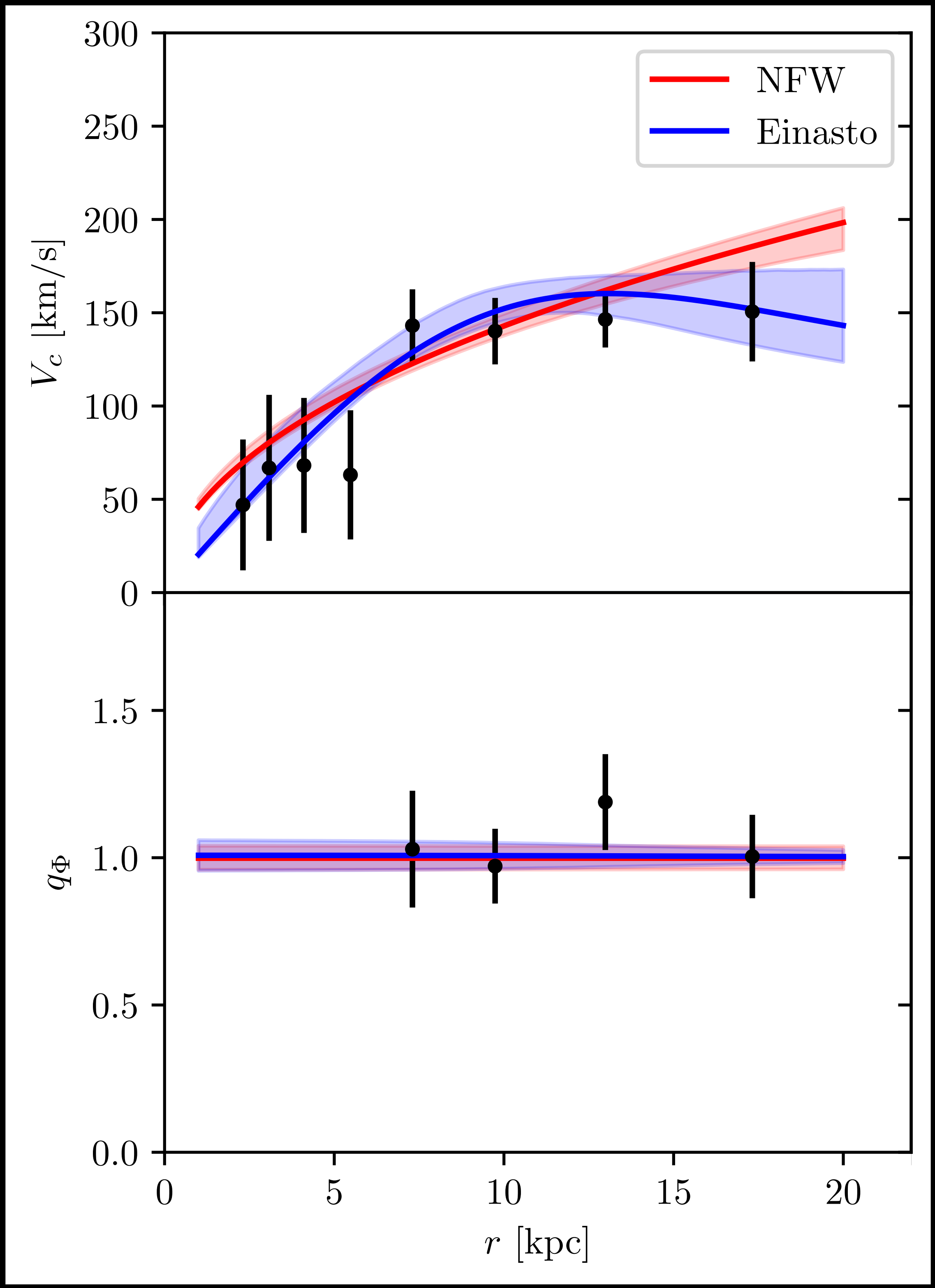


The Shape of the Milky Way's Dark Matter Halo

- We have also fit parametric dark matter models to the force field
- A range of dark matter profiles fit the data, but all agree on the flattening

$$q_\rho = 1.00 \pm 0.09$$

- $q_\rho < 0.8$ is ruled out at 99% significance



The Shape of the Milky Way's Dark Matter Halo

What does it mean?

- Our flattening value of $q_\rho = 1.00 \pm 0.09$ agrees with two other recent measurements of a near spherical halo
- Modelling streams in the halo Bovy (2016) finds $q_\rho = 1.05 \pm 0.14$
- Modelling ~100 globular clusters with 6D velocities Posti & Helmi (2018) find $q_\rho = 1.30 \pm 0.25$

- Such a spherical halo appears in tension with current LCDM simulations:
  - Dark Matter only simulations predict $\langle q_\rho \rangle \approx 0.5$
  - Baryons increase this, but in most simulations only by 0.1-0.3 e.g. Kazantzidis+04/10
  - Could be a very exciting tension - clear example of near-field cosmology

Milky Way Research

How do individual building blocks form?

IMF is constant across disk, even in α-enhanced old populations

Is Physics Correctly Modelled?

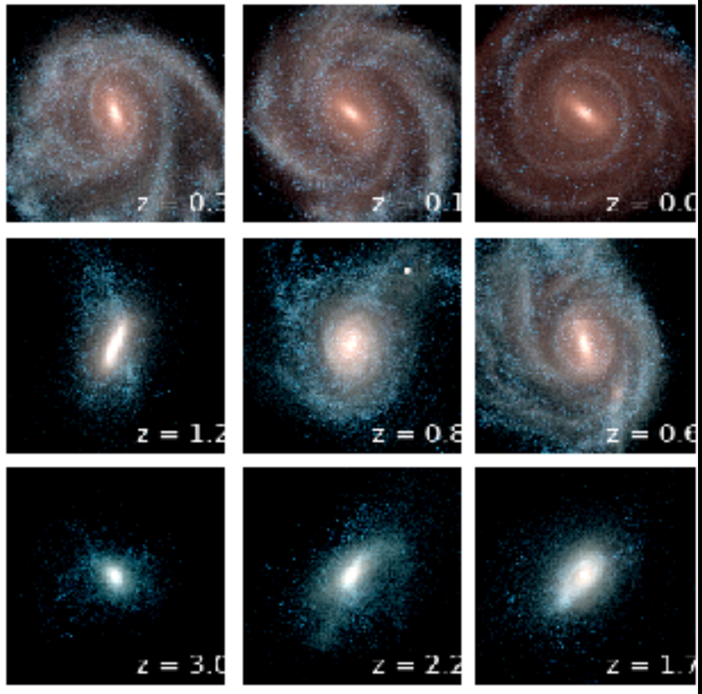
DM is spherical inside 20kpc

How did our Galaxy form?

B/P-bulge and bar ⇒ secular evolution shaped the inner MW

External Galaxies

Simulations



This is an hugely exciting time for Milky Way research — many of our long standing questions about the Milky Way, its assembly, and its place in the universe will be answered