Determining the Local Dark Matter Density

Hamish Silverwood
GRAPPA, University of Amsterdam

Collaborators:
Sofia Sivertsson (OKC Stockholm)
Pascal Steger (ETH Zurich)
Justin Read (U Surrey)
Gianfranco Bertone (GRAPPA)

Including additional Rotation Curve material from:
Fabio Iocco (ICTP-SAIFR Sao Paolo),
Miguel Pato (OKC Stockholm),
Gianfranco Bertone (GRAPPA)

Based on:
Silverwood et al., MNRAS 469, 2016,
arXiv:1507:08581
Sivertsson et al., in preparation

University of Amsterdam

GRAPPA
GRavitation AstroParticle Physics Amsterdam

TeVPA 2016, CERN.

Why do we care about local DM density?

Direct Detection (e.g. PandaX, XENON1T, LUX, DEAP3600…)

$$\frac{\mathrm{d}R}{\mathrm{d}E} = \frac{\rho_\odot}{m_{\mathrm{DM}} m_{\mathcal{N}}} \int_{v>v_{\min}} \mathrm{d}^3 v \, \frac{\mathrm{d}\sigma}{\mathrm{d}E}(E,v)\, v\, f(\vec{v}(t))$$

Indirect Detection through Solar Capture and annihilation to neutrinos (IceCube, Antares, KM3NeT, Super-Kamiokande)

$$C^\odot \approx 1.3\times 10^{21} s^{-1} \left(\frac{\rho_{local}}{0.3\mathrm{GeV\ cm}^{-3}}\right)\left(\frac{270\mathrm{km\ s}^{-1}}{v_{local}}\right) \times \left(\frac{100\mathrm{GeV}}{m_\chi}\right)\sum_i \left(\frac{A_i(\sigma_{\chi i,SD}+\sigma_{\chi i,SI})S(m_\chi/m_i)}{10^{-6}\mathrm{pb}}\right)$$

Scans of theoretical parameter space, eg Supersymmetry

Relic Axion Searches (ADMX, CULTASK, CAST, RADES, CASPEr…)

$$P = \frac{2\pi\hbar^2 g_{a\gamma\gamma}^2 \rho_{\mathrm{DM}}}{m_a^2 c}\cdot f_\gamma \cdot \frac{1}{\mu_0} B^2 V_{nlm}\cdot Q$$

1403.3121

How do we measure local DM density?

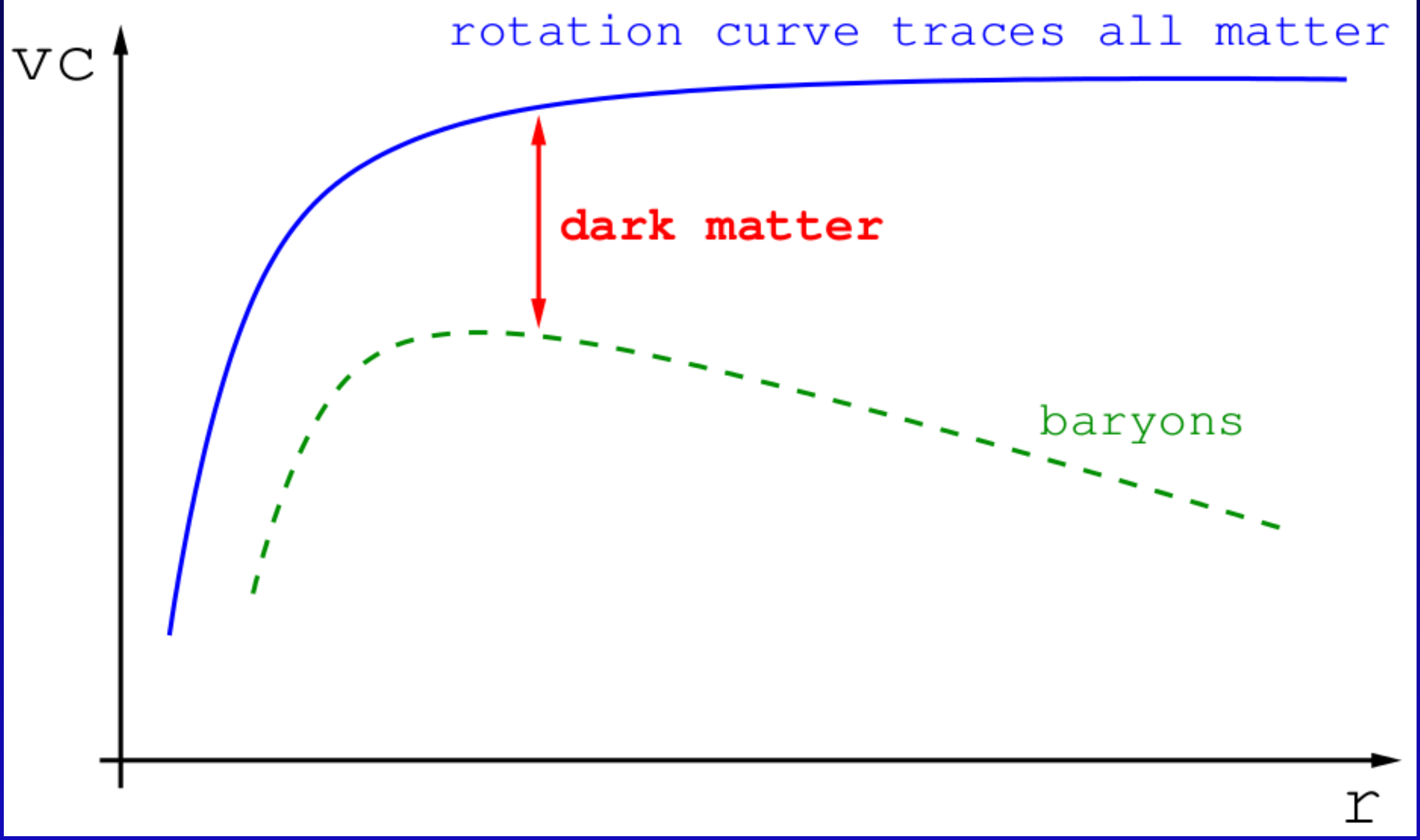
- **Global measurements (rotation curves)**:
  powerful, but have to assume global properties of the halo.
  e.g. Dehnen & Binney 1998; Weber & de Boer 2010; Catena & Ullio 2010; Salucci et al. 2010; McMillan 2011; Nesti & Salucci 2013; Piffl et al. 2014; Pato & Iocco 2015; Pato et al. 2015

- **Local measurements:**
  larger uncertainties but fewer assumptions
  e.g. Jeans 1922; Oort 1932; Bahcall 1984; Kuijken & Gilmore 1989b, 1991; Creze et al. 1998; Garbari et al. 2012; Bovy & Tremaine 2012; Smith et al. 2012; Zhang et al. 2013; Bienaymé et al. 2014

Iocco, Pato, Bertone:

Global methods

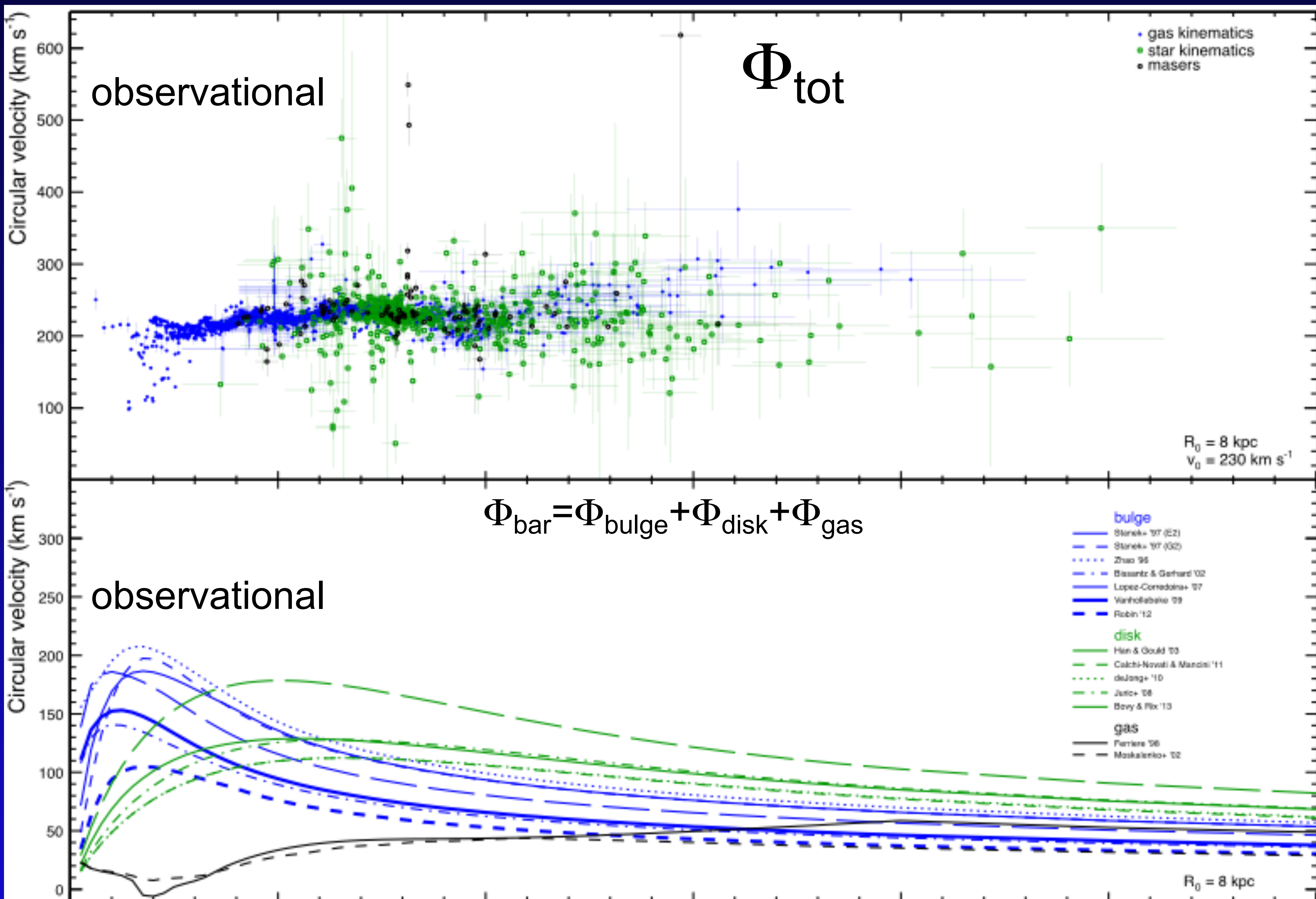
$$\phi_{\rm tot} = \phi_{\rm bulge} + \phi_{\rm disc} + \phi_{\rm gas} + \phi_{\rm dm}$$



Fitting a DM profile on top of baryons

Iocco, Pato, Bertone:

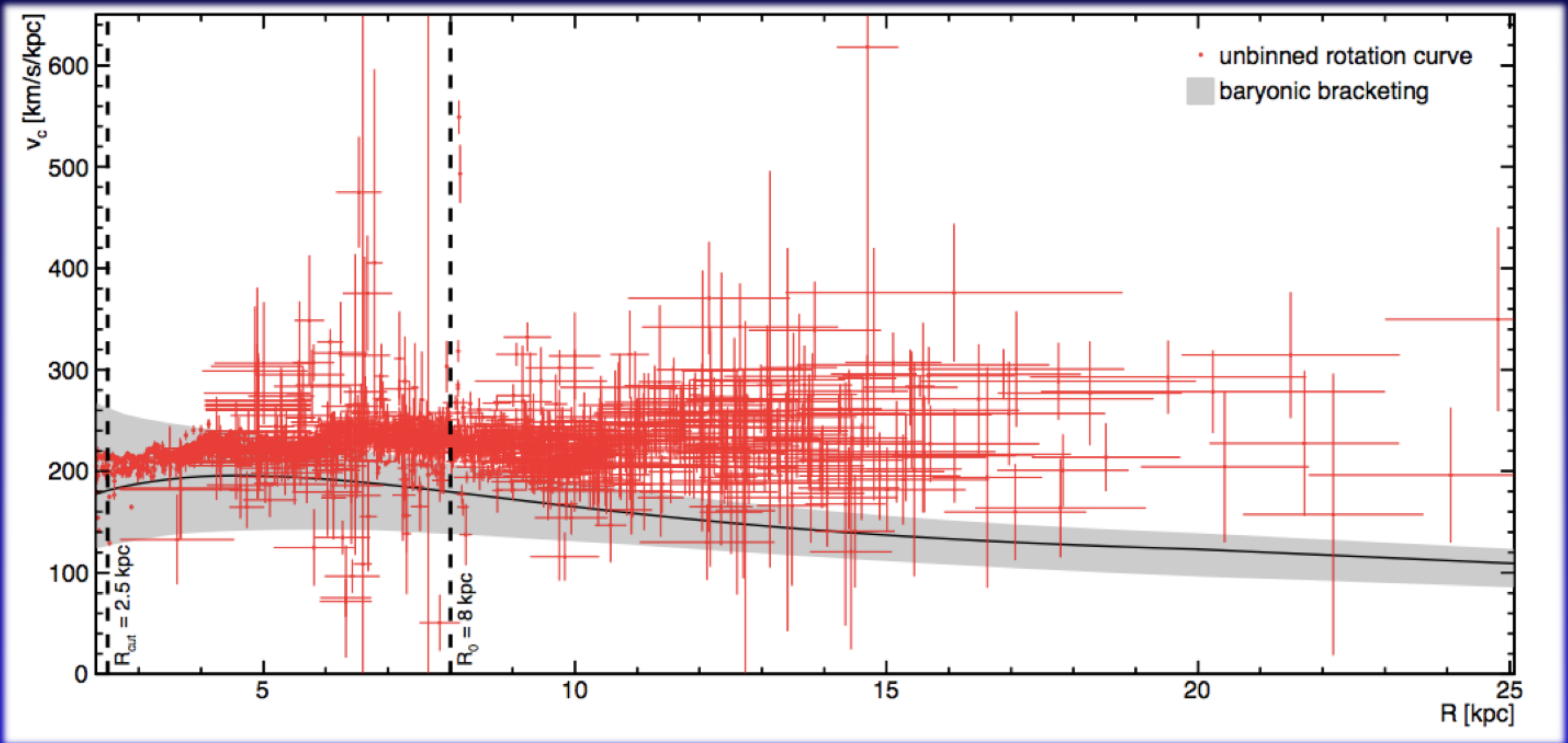
The Milky Way: testing expectactions



[Iocco, Pato, Bertone, Nature Physics 2015]

Iocco, Pato, Bertone:

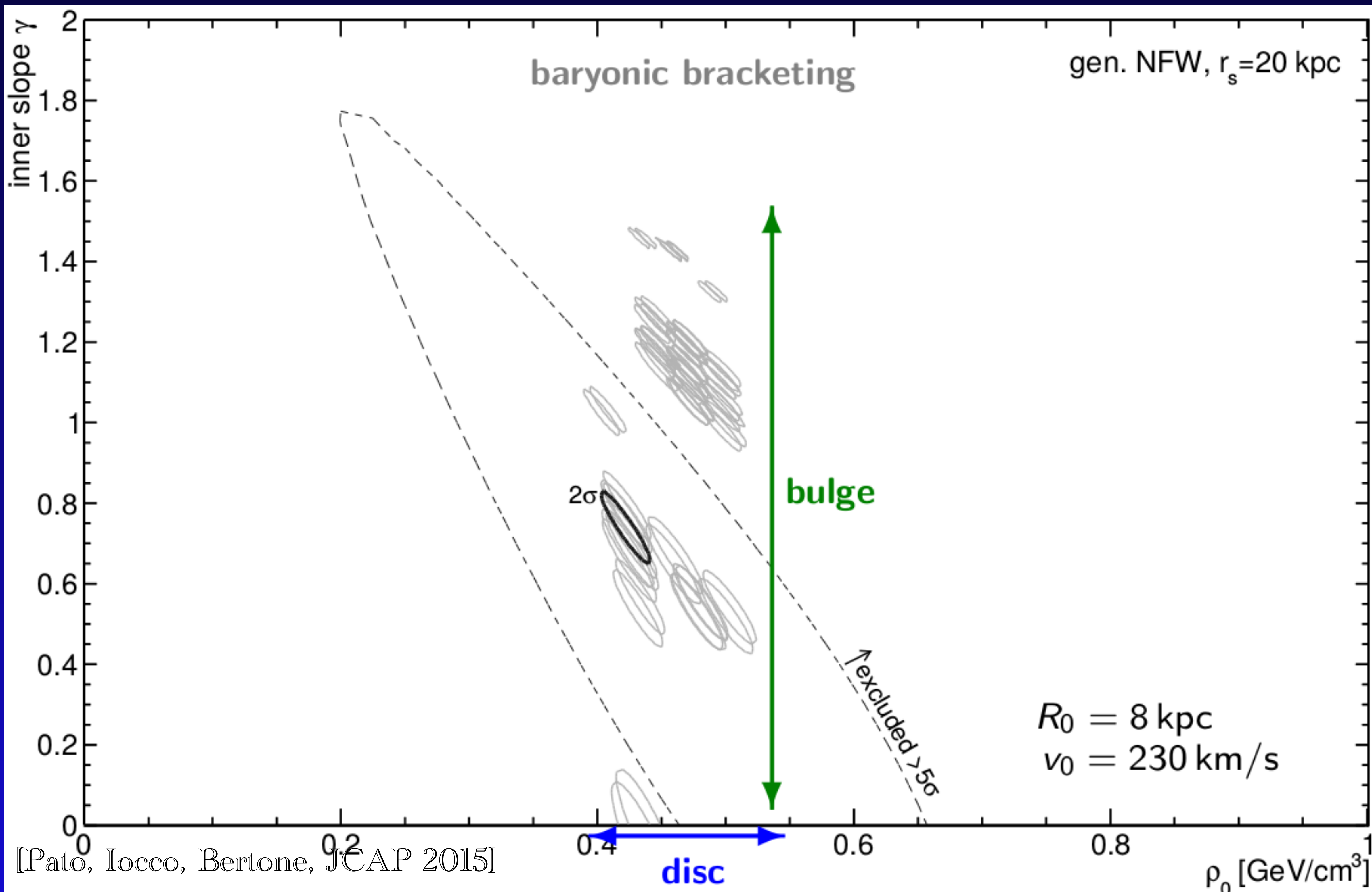
The Milky Way: testing expectactions (with no additional assumptions)



[Iocco, Pato, Bertone, Nature Physics 2015]

Iocco, Pato, Bertone:

The Milky Way: the importance of baryon modelling



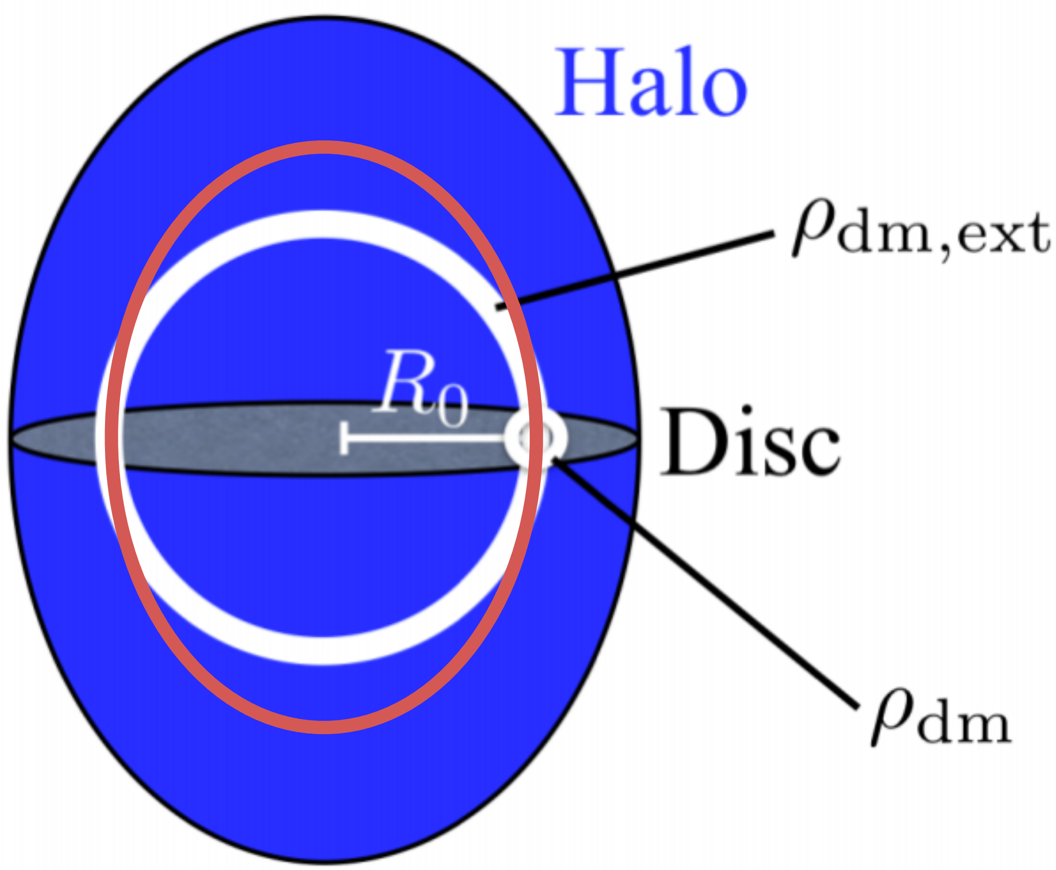
[Pato, Iocco, Bertone, JCAP 2015]

Complementarity of Local and Global Measurements

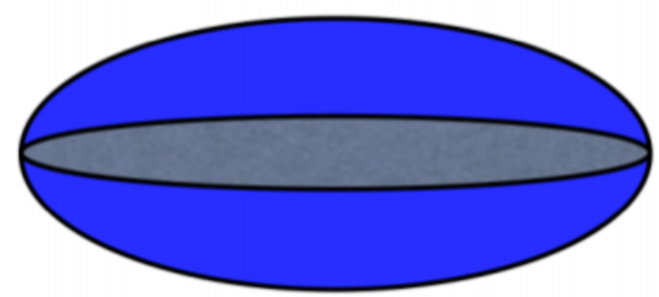
Local	Global	Local	Global

a) $\rho_{\rm dm} < \rho_{\rm dm,ext}$ b) $\rho_{\rm dm} > \rho_{\rm dm,ext}$

Constant density curve



Prolate Halo



Oblate Halo

Justin Read, *The Local Dark Matter Density*, 2014.
J. Phys. G: Nucl. Part. Phys. 41 063101. arXiv: 1404.1938

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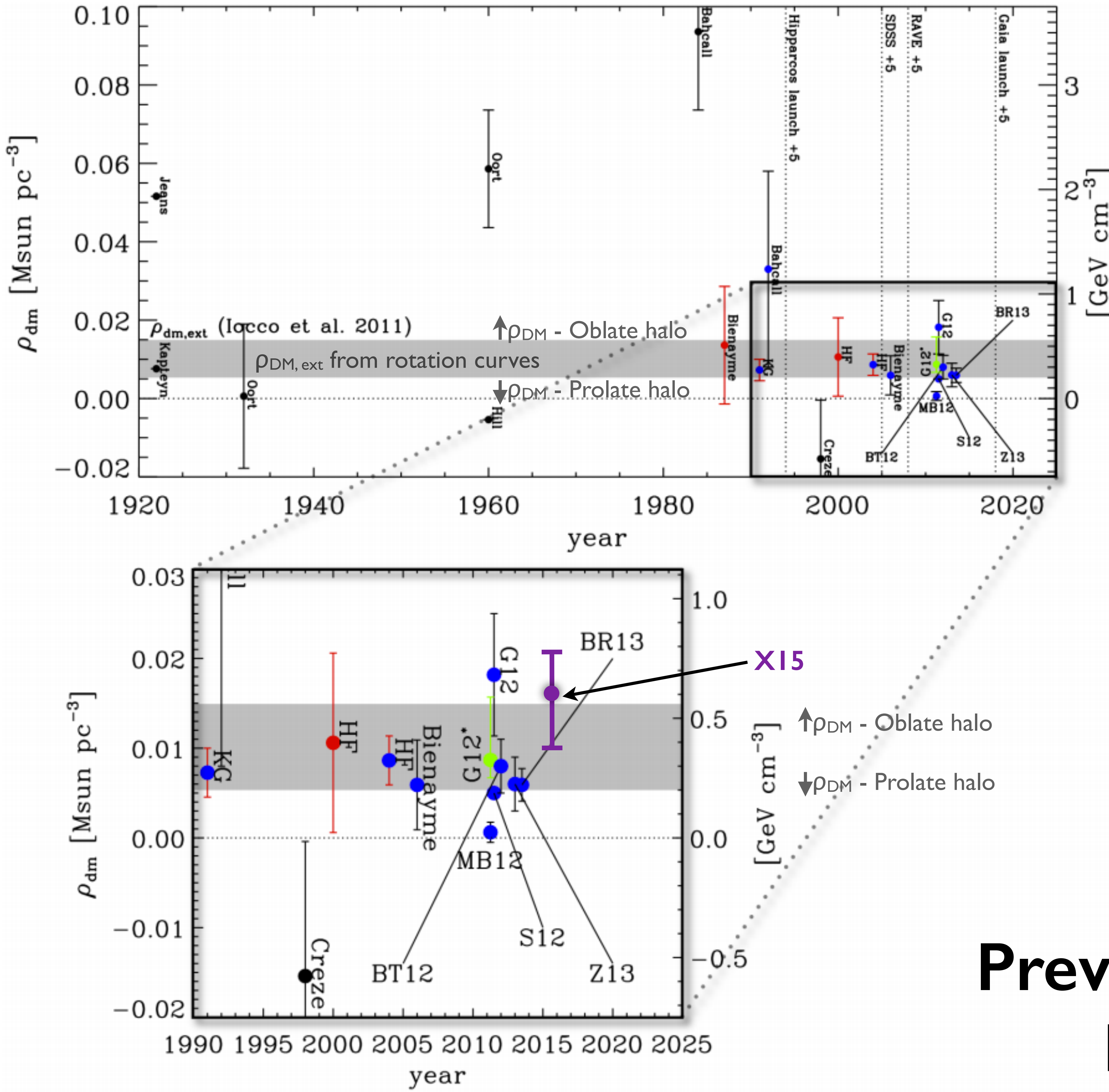


S12 - Smith et al., SDSS
Z13 - Zhang et al., SDSS
BR13 - Bovy & Rix, SDSS

MB12 - Moni Bidin et al., 412 red giants towards South Galactic Pole
BT12 - Bovy & Tremaine, reanalysis of MB12 data set

G12 - Garbari et al., ~2000 K-dwarfs from Kuijken & Gilmore 1989

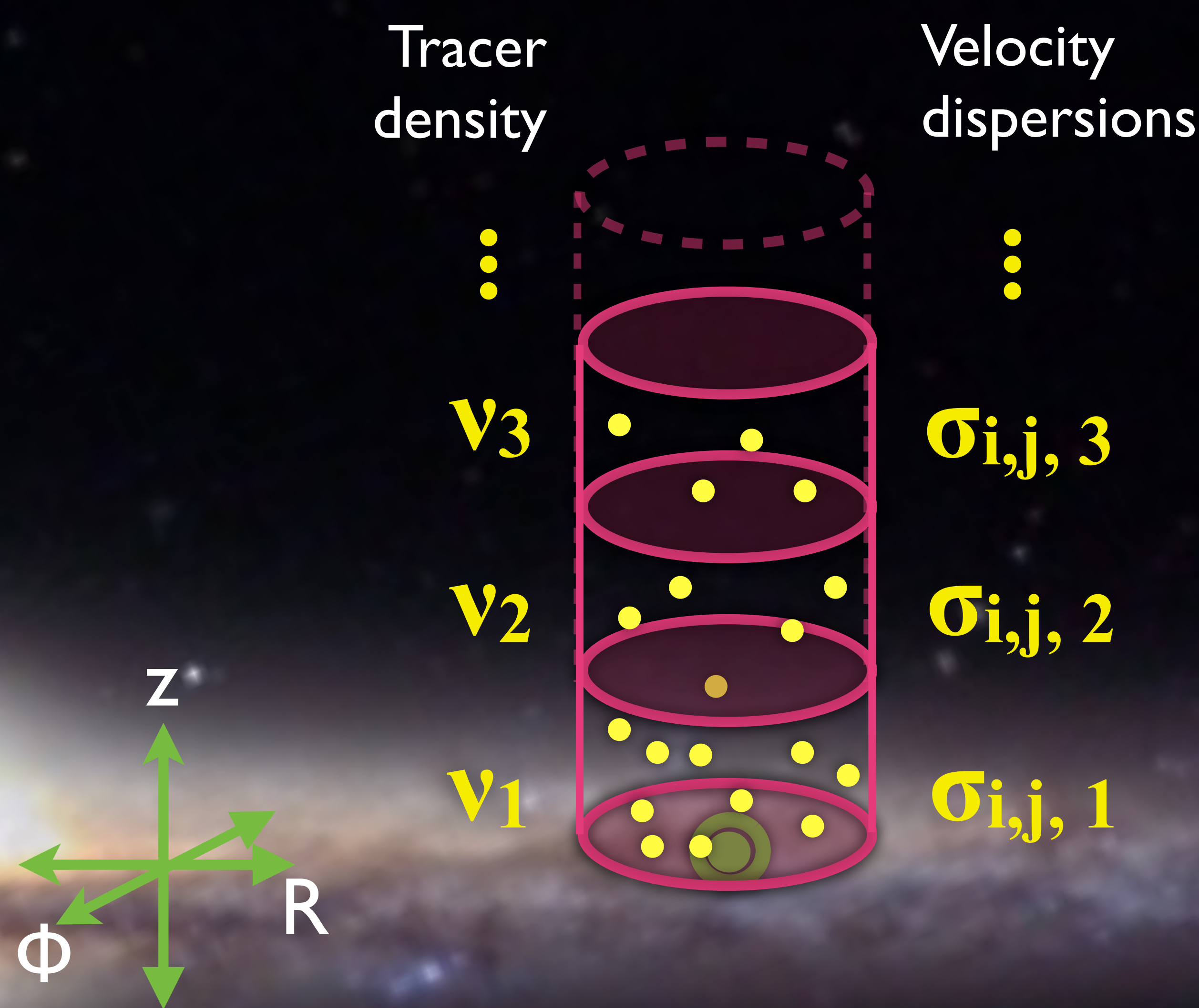
X15 - Xia et al., released last week, 1427 G & K type MS stars from LAMOST survey

Previous Local DM Measurements

Our Method - Basics

- Local measurements in z-direction and R-direction
- Data points are positions and velocities for a set of tracer stars in a cylindrical volume.
- data is binned to get tracer density and velocity dispersions

$$\sigma_{ij}^2(\mathbf{x}) = \overline{v_i v_j} - \overline{v}_i \overline{v}_j$$



Our Method - Integrated Jeans Equations

- We need to link positions and velocities to the mass distribution
- Tracer stars follow the Collisionless Boltzman Equation:

$$\frac{df}{dt} = \frac{\partial f}{\partial t} + \nabla_x f \cdot \mathbf{v} - \nabla_v f \cdot \nabla_x \Phi = 0$$

- f(**x**,**v**) - stellar distribution function, positions **x**, velocities **v**, gravitational potential **Φ**
- Integrate over velocities, switch to cylindrical-polar co-ordinates, and get the **Jeans Equation in z.**

$$\underbrace{\frac{1}{R\nu}\frac{\partial}{\partial R}\left(R\nu\sigma_{Rz}\right)}_{\text{'tilt' term: }\mathcal{T}} + \underbrace{\frac{1}{R\nu}\frac{\partial}{\partial \phi}\left(\nu\sigma_{\phi z}\right)}_{\text{'axial' term: }\mathcal{A}} + \frac{1}{\nu}\frac{d}{dz}\left(\nu\sigma_z^2\right) = \underbrace{-\frac{d\Phi}{dz}}_{K_z}$$

Surface Density $\Sigma_z(z) = \frac{|K_z|}{2\pi G}$

$$\underbrace{\frac{1}{R\nu}\frac{\partial}{\partial R}(R\nu\sigma_{Rz})}_{\text{`tilt' term: }\mathcal{T}} + \underbrace{\frac{1}{R\nu}\frac{\partial}{\partial \phi}(\nu\sigma_{\phi z})}_{\text{`axial' term: }\mathcal{A}} + \frac{1}{\nu}\frac{d}{dz}\left(\nu\sigma_z^2\right) = \underbrace{-\frac{d\Phi}{dz}}_{K_z}$$

Integrate to avoid noise

$$\sigma_z^2(z) = \frac{1}{\nu(z)}\int_0^z \nu(z')\left[K_z(z') - \mathcal{T}(z') - \mathcal{A}(z')\right]dz' + \frac{C}{\nu(z)}$$

= 0 from axisymmetry

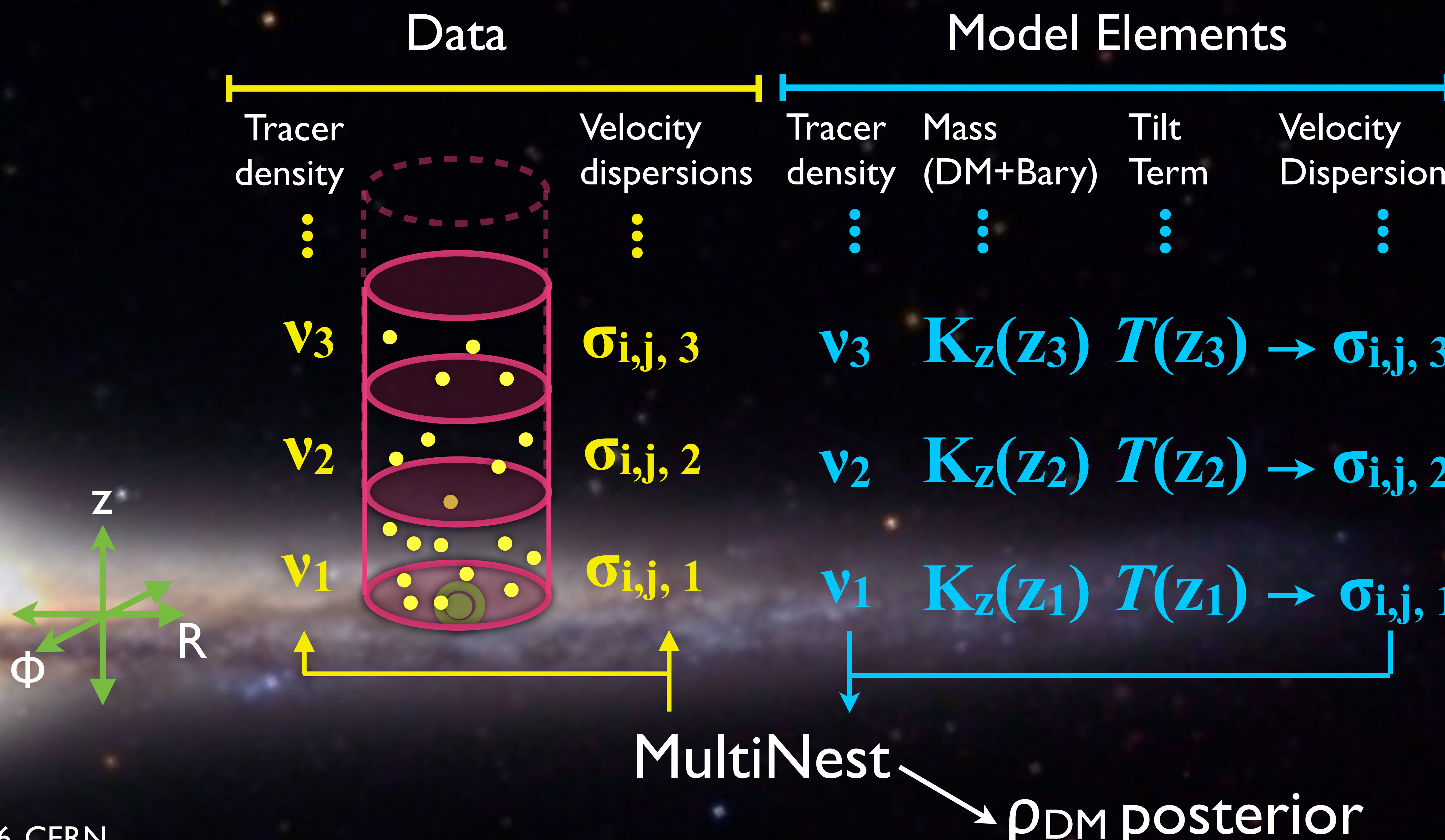
Construct model for

- **tracer density ν,**
- **Dark Matter + Baryon density → K_z,**
- **tilt term T(z).**

Calculate **velocity dispersion σ_z**, then fit the model to velocity dispersion, tracer density & tilt term to data. Use **MultiNest** to derive **posterior distribution on DM**.

Our Method - Modelling and MultiNest

- Construct models for the tracer density, baryon+DM mass, tilt term
- Calculate z velocity dispersion
- Fit tracer density and z-velocity dispersion to data with MultiNest



Modelling the Components:

Mass profile - K_z term

$$K_z = -\frac{\mathrm{d}\Phi}{\mathrm{d}z}$$

- We assume constant DM density going up in z
- Simplified two-parameter baryon profile for mock data testing.

- Poisson Equation in Cylindrical Coordinates picks up a Rotation Curve term

$$\nabla^2\Phi = \frac{\partial^2\Phi}{\partial z^2} + \underbrace{\frac{1}{R}\frac{\partial V_c^2(R)}{\partial R}}_{\text{'rotation curve' term: } \mathcal{R}} = 4\pi G\rho$$

- Flat rotation curve makes rotation curve term disappear.
- Rotation curve term becomes a shift in the density.

$$\frac{\partial^2\Phi}{\partial z^2} = 4\pi G\rho(z)_{\rm eff} \qquad \rho(z)_{\rm eff} = \rho(z) - \frac{1}{4\pi GR}\frac{\partial V_c^2(R)}{\partial R}$$

- We assume a locally flat RC, but from Oort constants we can estimate the systematic uncertainty from this to be on the order of **0.1 GeV/cm^3**.

Modelling the Components:

Tilt Term

$$\underbrace{\frac{1}{R\nu}\frac{\partial}{\partial R}\left(R\nu\sigma^2_{Rz}\right)}_{\text{'tilt' term: } \mathcal{T}}$$

$$\mathcal{T}(R_\odot, z) =$$

- Tilt term links vertical and radial motion of a set of stars.
- Tilt becomes larger and thus more important at higher z.
- Require information about the radial variation of σ_{Rz}^2 which we currently do not have.
- Thus we assume it has the same dependence as the tracer density ν
- for instance the traditional model is a falling exponential

$R_0 = R_1$

$$\nu(R,z) = \nu(z)|_{R_\odot} \exp\left(-\frac{R-R_\odot}{R_0}\right),$$

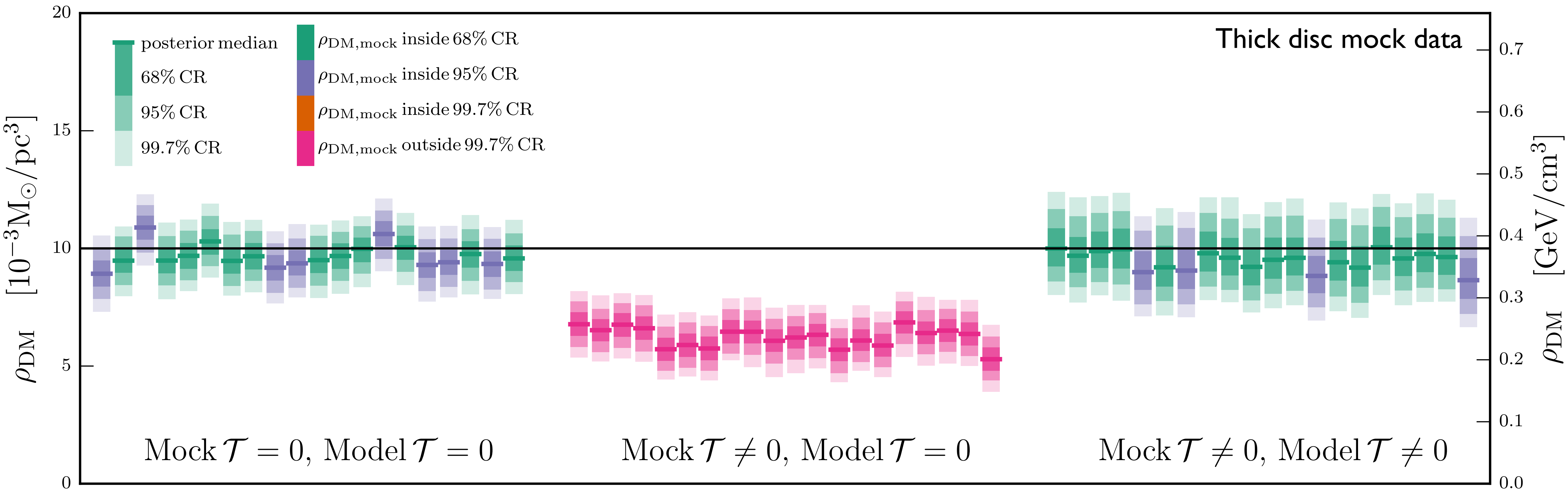
$$\Longrightarrow \sigma^2_{Rz}(R,z) = \sigma^2_{Rz}(z)|_{R_\odot} \exp\left(-\frac{R-R_\odot}{R_1}\right)$$

$$\sigma^2_{Rz}(z)|_R = A\left(\frac{z}{\mathrm{kpc}}\right)^n\Big|_R$$

$$\Longrightarrow \boxed{\mathcal{T}(R_\odot, z) = A\left(\frac{z}{\mathrm{kpc}}\right)^n\Big|_{R_\odot}\left[\frac{1}{R_\odot} - \frac{2}{R_0}\right]}$$

Testing with 20 Simple Mock Data Sets

The Importance of the Tilt Term



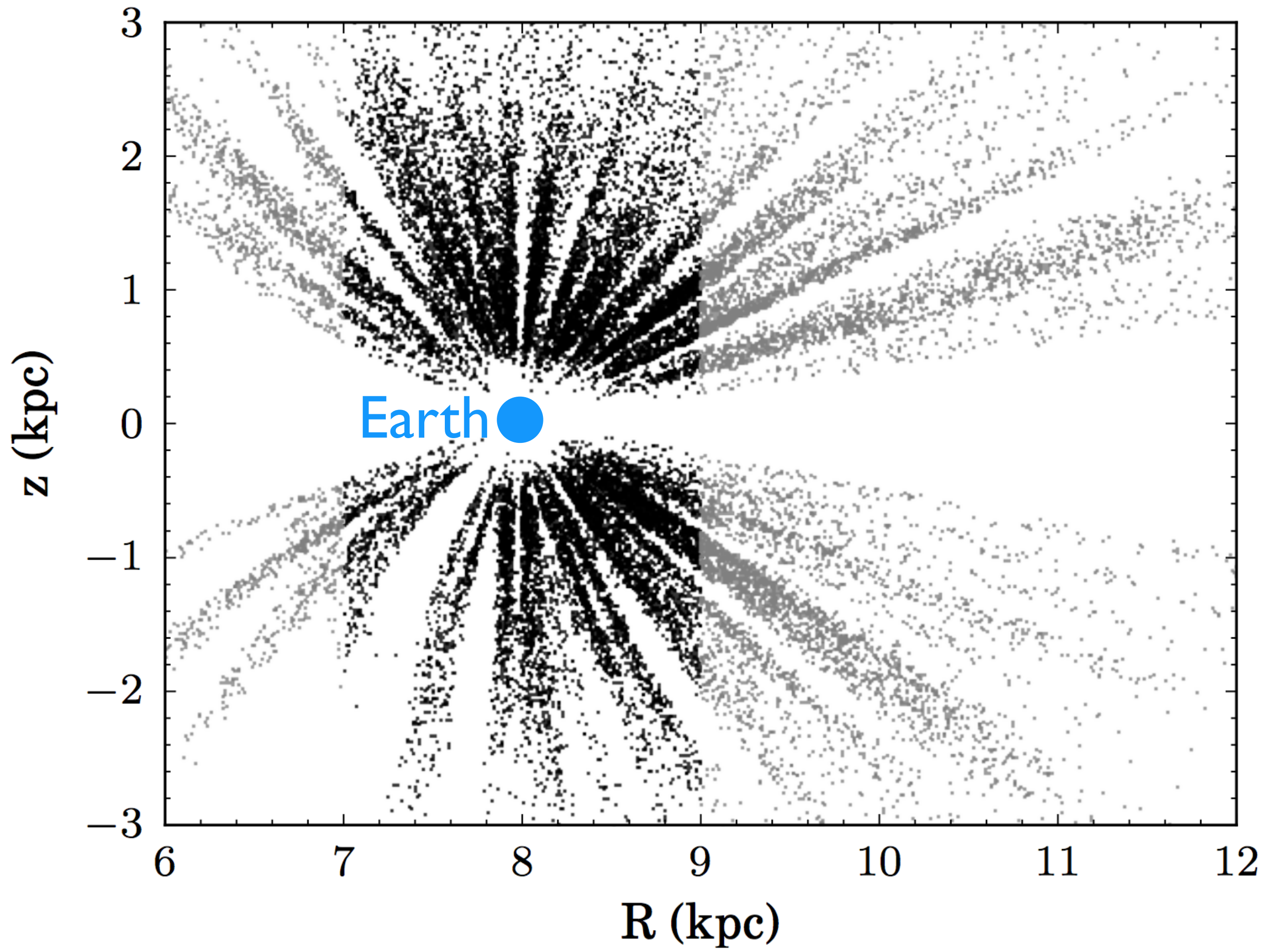
Mock: No tilt
Recon: No tilt

Mock: Tilt
Recon: No tilt

Mock: Tilt
Recon: Tilt

Tilt is the coupling between **Radial** and **Vertical** motions. **Neglecting tilt** leads to a **systematic bias** of the **dark matter density.**

Initial Tests with SDSS Data from Budenbender et al.



- Stellar kinematics data from SDSS G-dwarfs from Budenbender et al.,
  MNRAS 452 (2015) 956–968, arXiv:1407.4808.

- Observational baryon profile derived from McKee et al.,
  ApJ 814 (2015) 13, arXiv:1509.05334

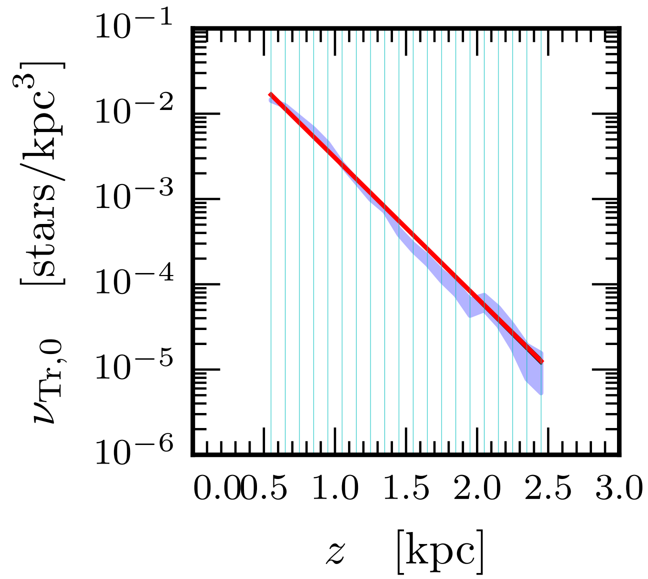
- Modified Tilt model to allow for stellar populations which rise with radius

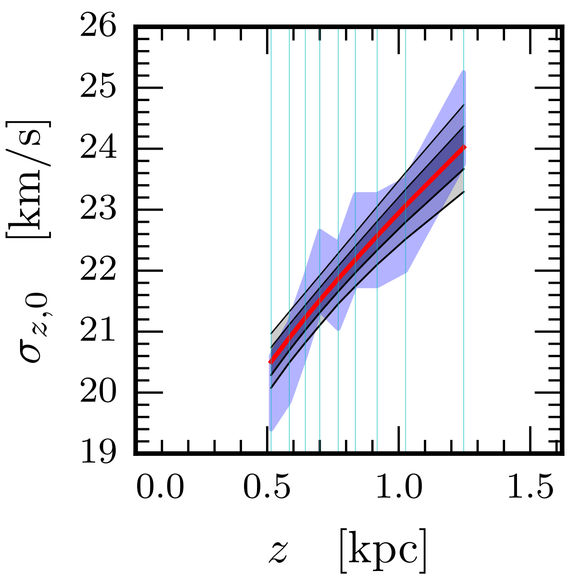
$$\mathcal{T}(R_\odot, z) = \sigma^2_{Rz}(R_\odot, z)\left[\frac{1}{R_\odot} - 2k\right]$$

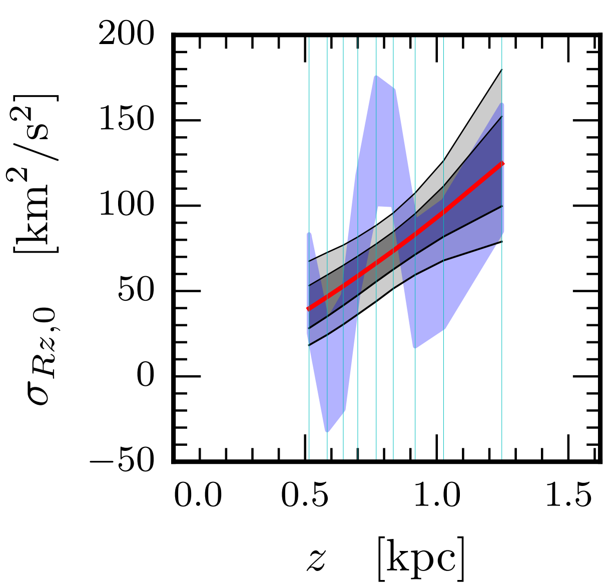
Alpha-young population
('thin disc')

Preliminary Results.

Alpha-old population
('thick disc')

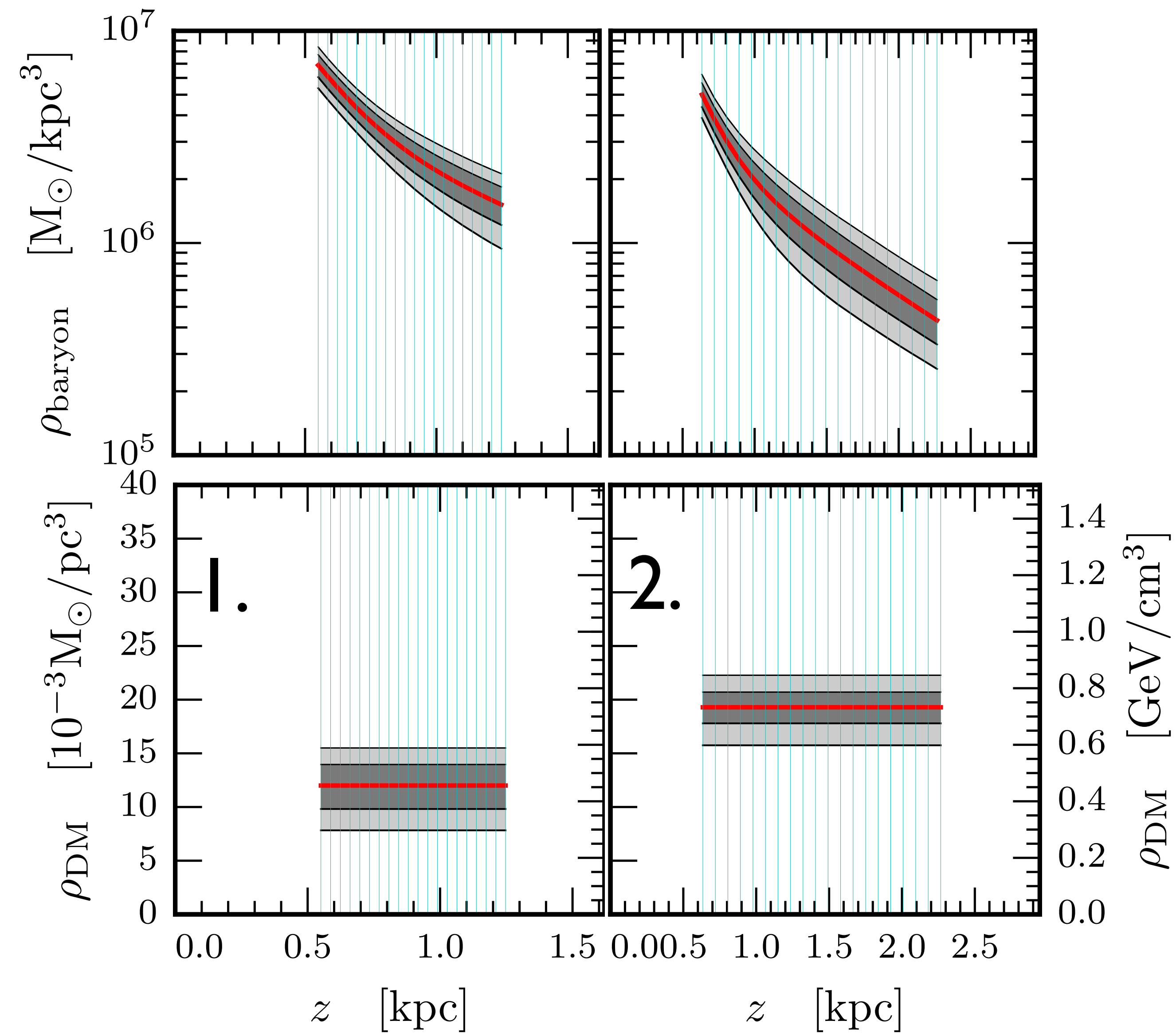






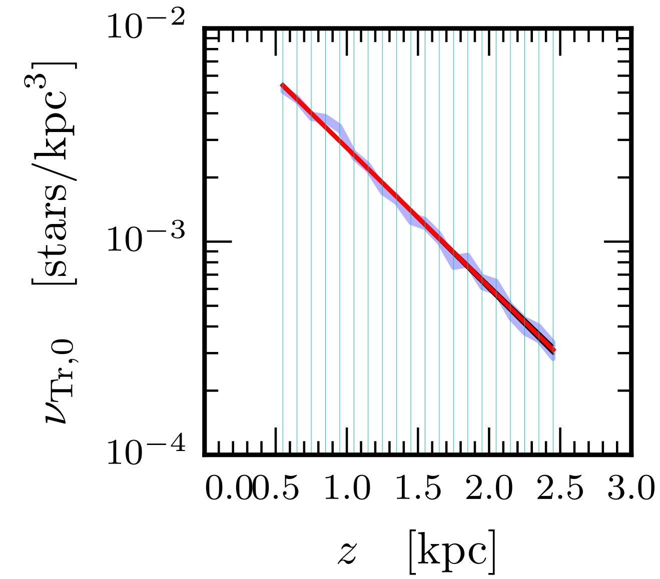
SDSS-SEGUE G-dwarf data from Budenbender et al. 2014 1407.4808v2. Tilt priors informed by data from SDSS-APOGEE, Bovy et al. 1509.05796.

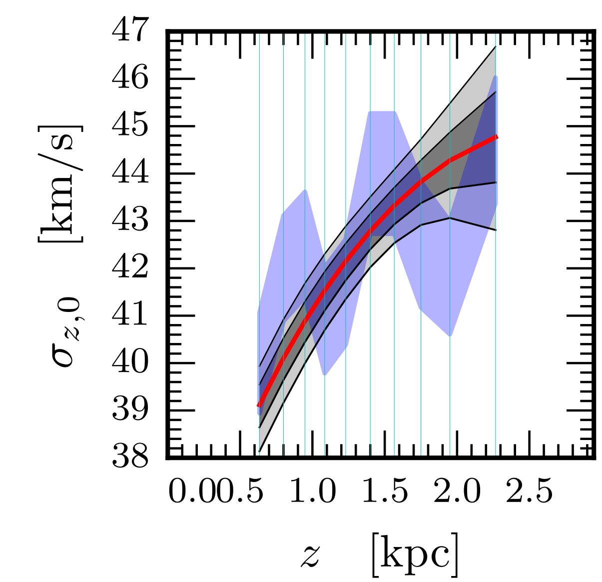
Analyzed separately, 2σ uncertainties quoted.

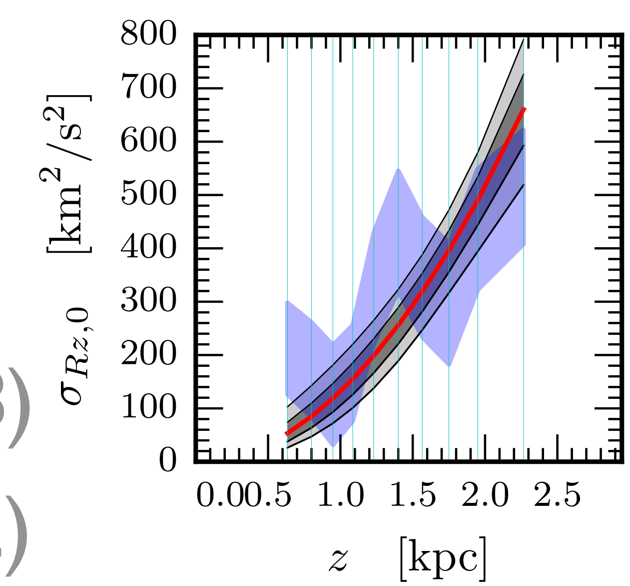


1. $\rho_{DM} = 0.46^{+0.13}_{-0.16}$ GeV/cm^3 (~~tilt~~: 0.48)

2. $\rho_{DM} = 0.73^{+0.13}_{-0.13}$ GeV/cm^3 (~~tilt~~: 0.42)



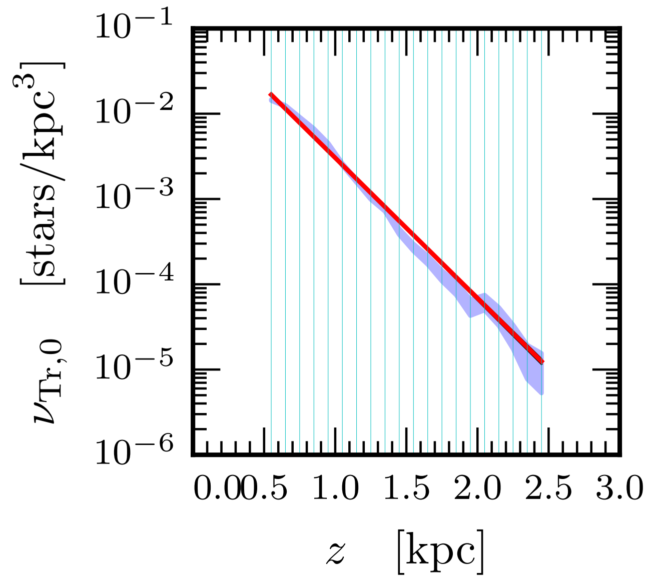


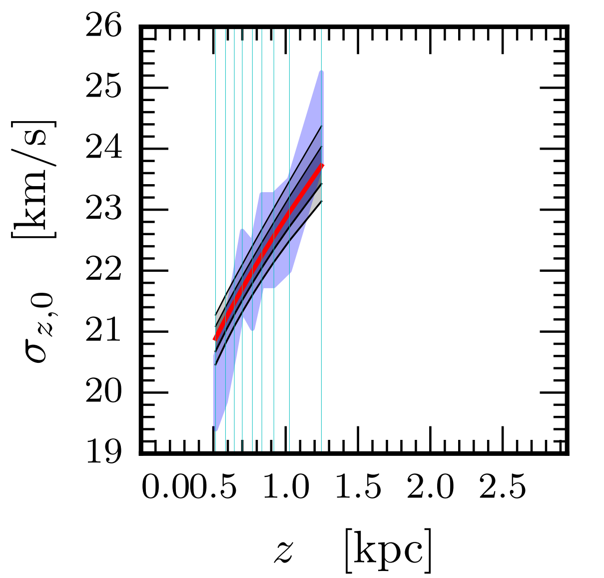


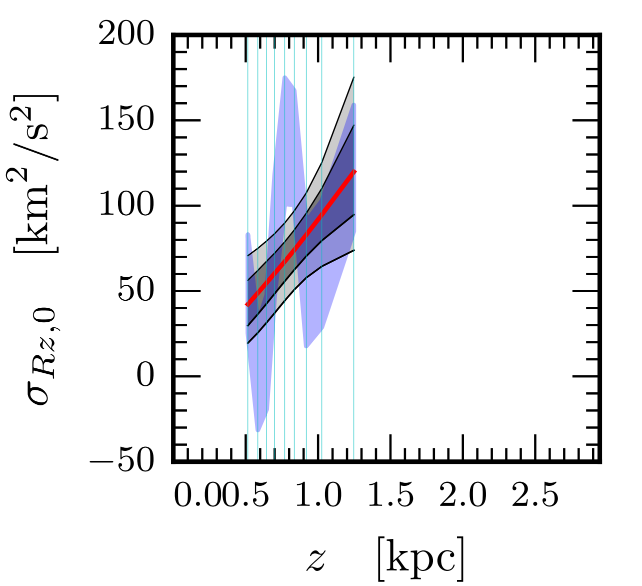
TeVPA 2016, CERN.

Preliminary Results.

Alpha-young population
('thin disc')







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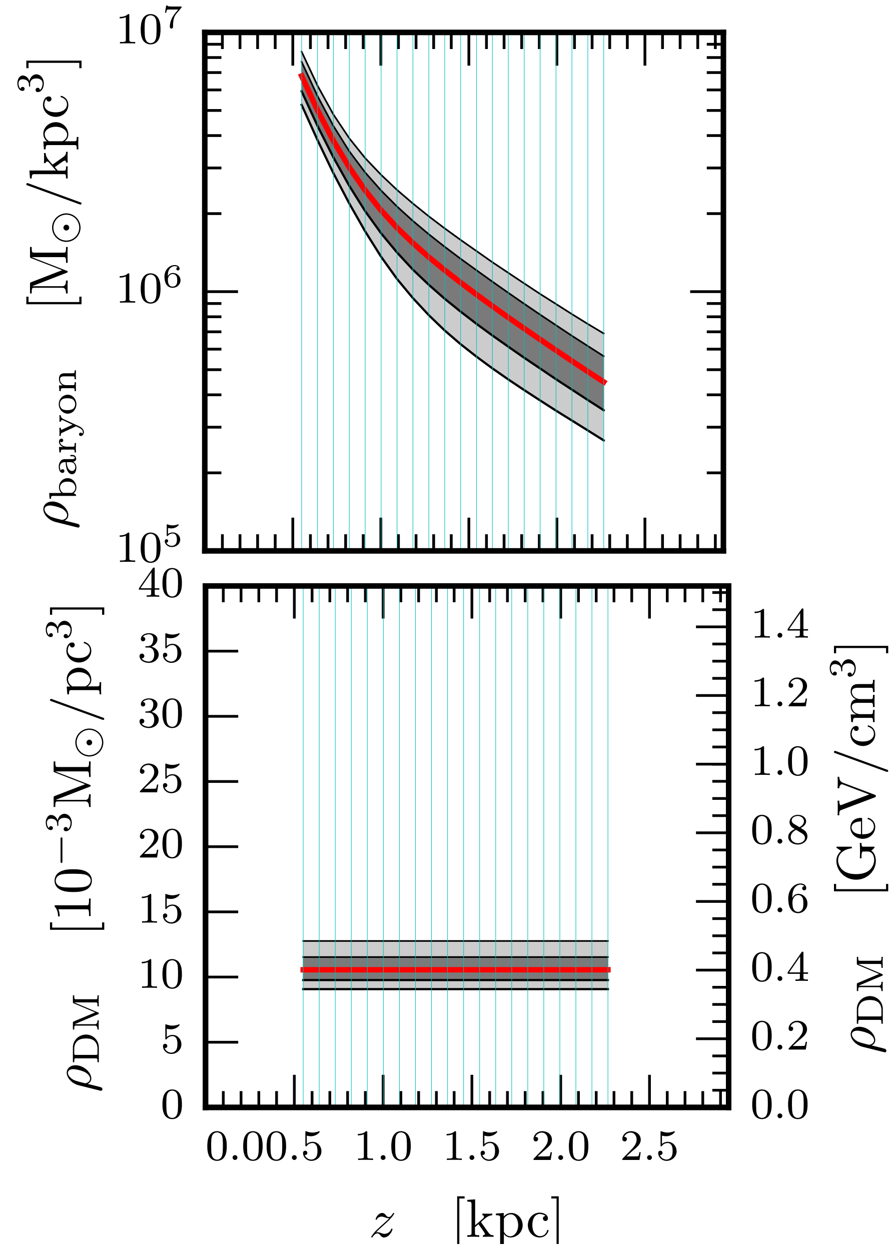
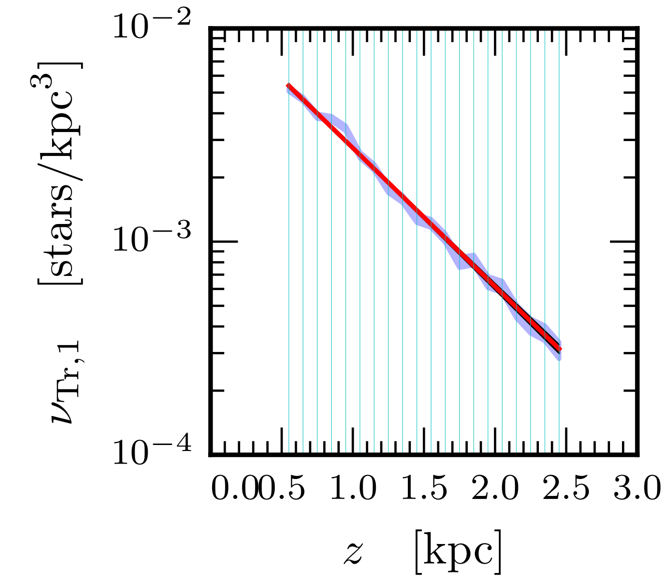
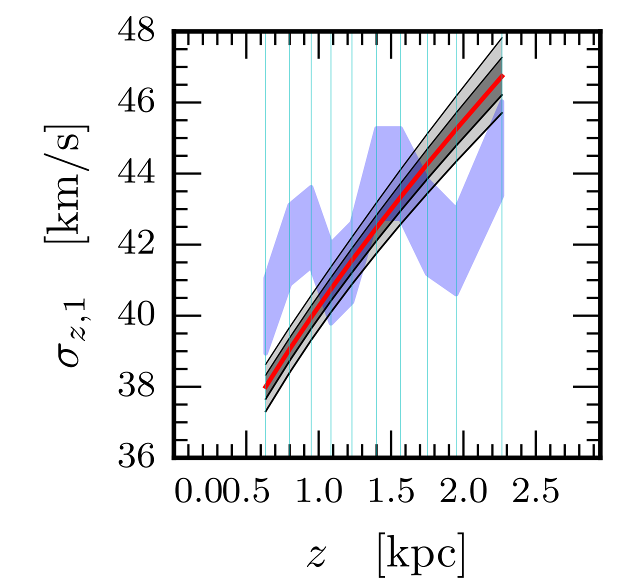
Combined Analysis, 2σ uncertainties quoted.

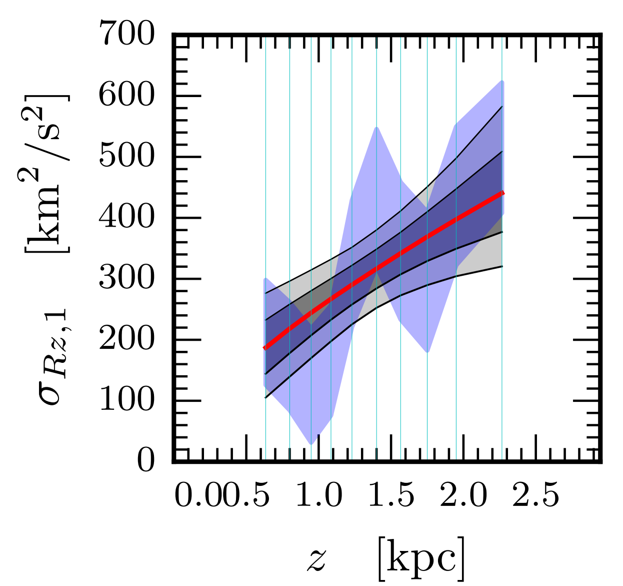


$$\rho_{\mathrm{DM}} = 0.40^{+0.08}_{-0.06}\ \mathrm{GeV/cm^3}$$

Alpha-old population
('thick disc')







SDSS Preliminary Results: Summary

Thin Disk only: $\rho_{DM} = 0.46^{+0.13}_{-0.16}$ GeV/cm^3 (2σ) (0.48 w/out tilt)
Thick Disc only: $\rho_{DM} = 0.73^{+0.13}_{-0.13}$ GeV/cm^3 (2σ) (0.42 w/out tilt)

Thin+Thick Disc: $\rho_{DM} = 0.40^{+0.08}_{-0.06}$ GeV/cm^3 (2σ)

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2. Combining thick and thin data gives a result that is lower than either separate result - still under investigation.

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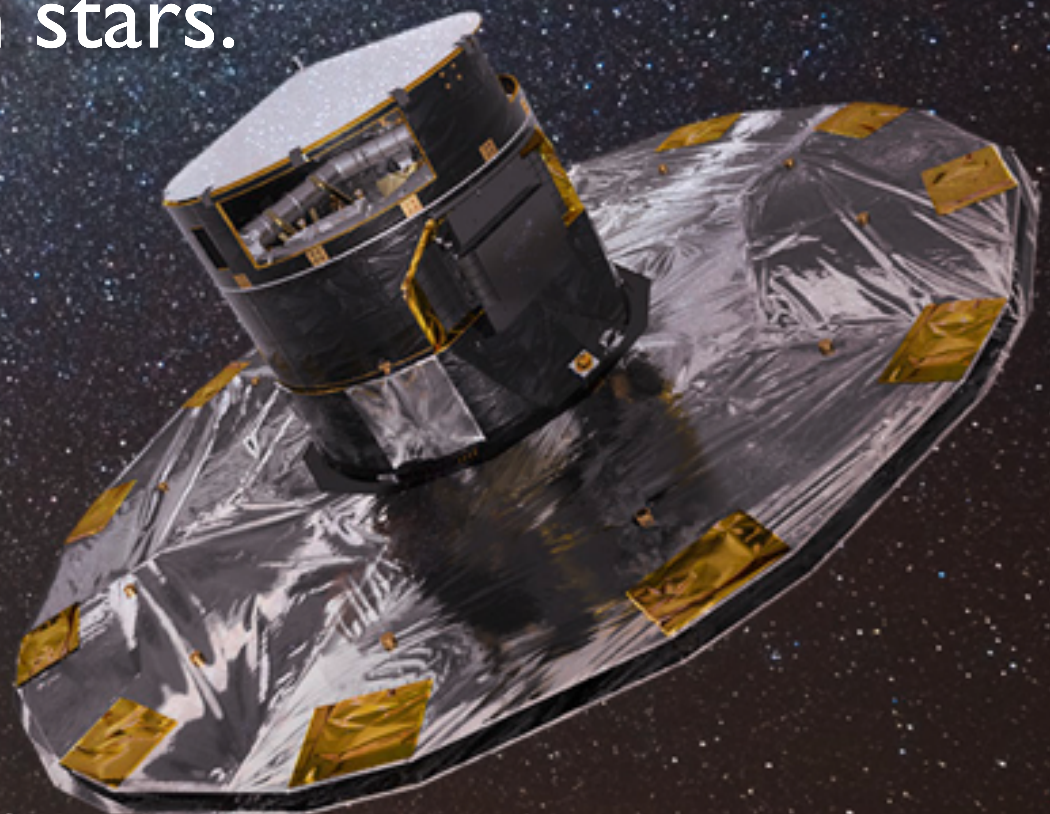
2. Combining thick and thin data gives a result that is lower than either separate result - still under investigation.
3. Statistical uncertainty is now less than the systematic uncertainty arising from the rotation curve term - this needs to be tackled.
4. We assume the radial variation of σ_{Rz}^2 matches that of the tracer density - we need to measure the σ_{Rz}^2 radial variation…

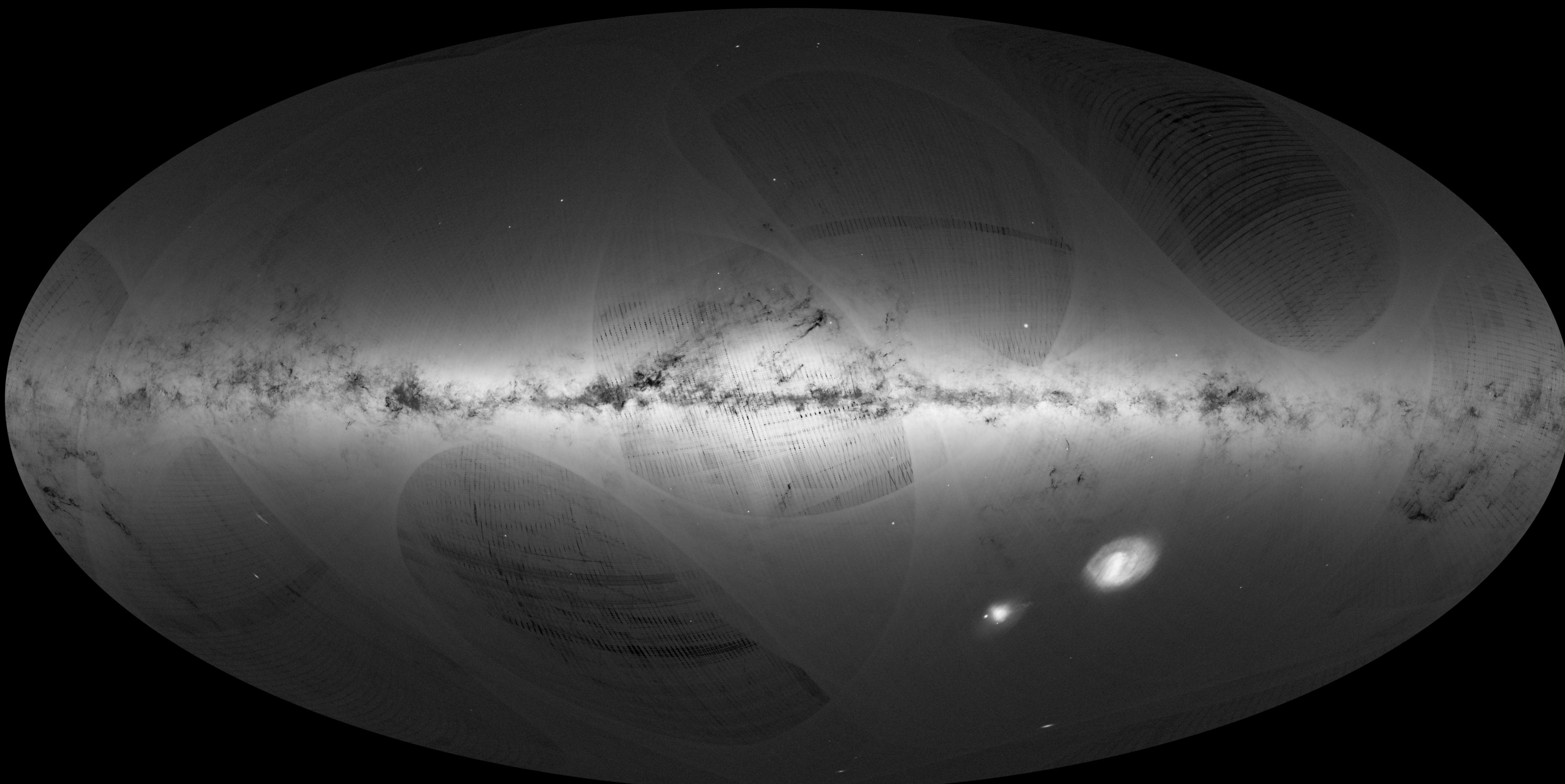
Gaia Satellite, 2013-

- Astrometrics mission, successor to Hipparcos (1989-1993)
- 10^4 times more stars with factor 50-100 higher accuracy compared to Hipparcos.
- Full data set will include 5D data for ~1 billion stars
    - sky positions (α, δ),
    - parallaxes (ω),
    - proper motions (μ_α,μ_δ)
- Radial velocities μ_r for ~150 million stars.



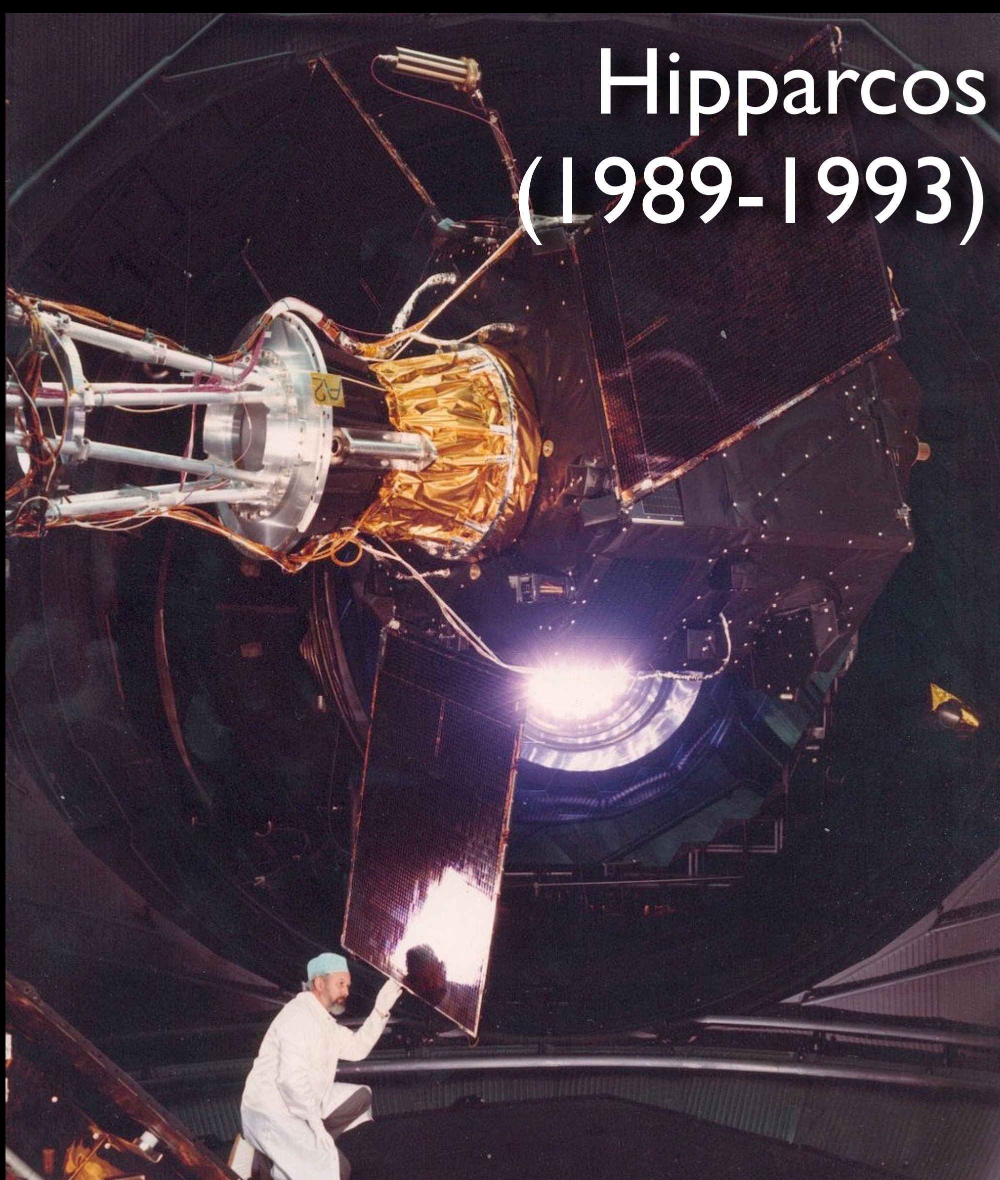
Data Release 1 was on Wednesday 14/9

- Observations taken between July 2014 and September 2015
- Sky positions (α, δ) and G-magnitude for ~ 1.14 billion stars
- TGAS solution for 2.05 million stars…



Tycho-Gaia Astrometric Solution (TGAS)

- Hipparcos astrometric satellite produced the Tycho catalogue of 2.5 million stars.
- TGAS combines sky position (α, δ) from Tycho with initial data from Gaia to produce 5D astrometric data.



Radial Measurements

- Ideally we need full 6D information.
- Both TGAS and final Gaia data release have a radial velocity deficit:
    - TGAS: No radial data
    - Full Gaia data release: radial data for only 150m of 1b stars
- Near term: TGAS + RAVE radial data
- Long term: Gaia + WEAVE + 4MOST spectrographic surveys

RAVE, 2003-13
UK Schmidt Telescope, Australia

WEAVE, 2018-
William Herschel Telescope, La Palma

4MOST, 2021-
VISTA Telescope, Paranal, Chile

Conclusions

- Tilt term is important - ignore at your peril!
- We still need more data on the tilt term - namely radial variation of σ_{Rz}^2
- Preliminary analysis of thin disc and thin+thick disc Budenbender SDSS data yield a local dark matter density inline with previous estimates, but analysis is ongoing.
- Statistical uncertainty is now less than the systematic uncertainty arising from the rotation curve term.

- Gaia Data Release 1 is **out now:**

https://gea.esac.esa.int/archive/

Backup Slides

SDSS/Budenbender:

Tilt Term Redux

$$\underbrace{\frac{1}{R\nu}\frac{\partial}{\partial R}\left(R\nu\sigma^2_{Rz}\right)}_{\text{'tilt' term: }\mathcal{T}}$$

- We assume σ_{Rz}^2 has the same radial dependence as the tracer density ν
- **Traditionally** (e.g. Binney & Tremaine) tracer density ν is a exponential **falling** with radius, eg:

$$\nu(R,z) = \nu(z)|_{R_\odot} \exp\left(-\frac{R-R_\odot}{R_0}\right),$$

$$\Longrightarrow \sigma^2_{Rz}(R,z) = \sigma^2_{Rz}(z)|_{R_\odot} \exp\left(-\frac{R-R_\odot}{R_1}\right)$$

$$\sigma^2_{Rz}(z)|_R = A\left(\frac{z}{\text{kpc}}\right)^n\Big|_R$$

$R_0 = R_1$

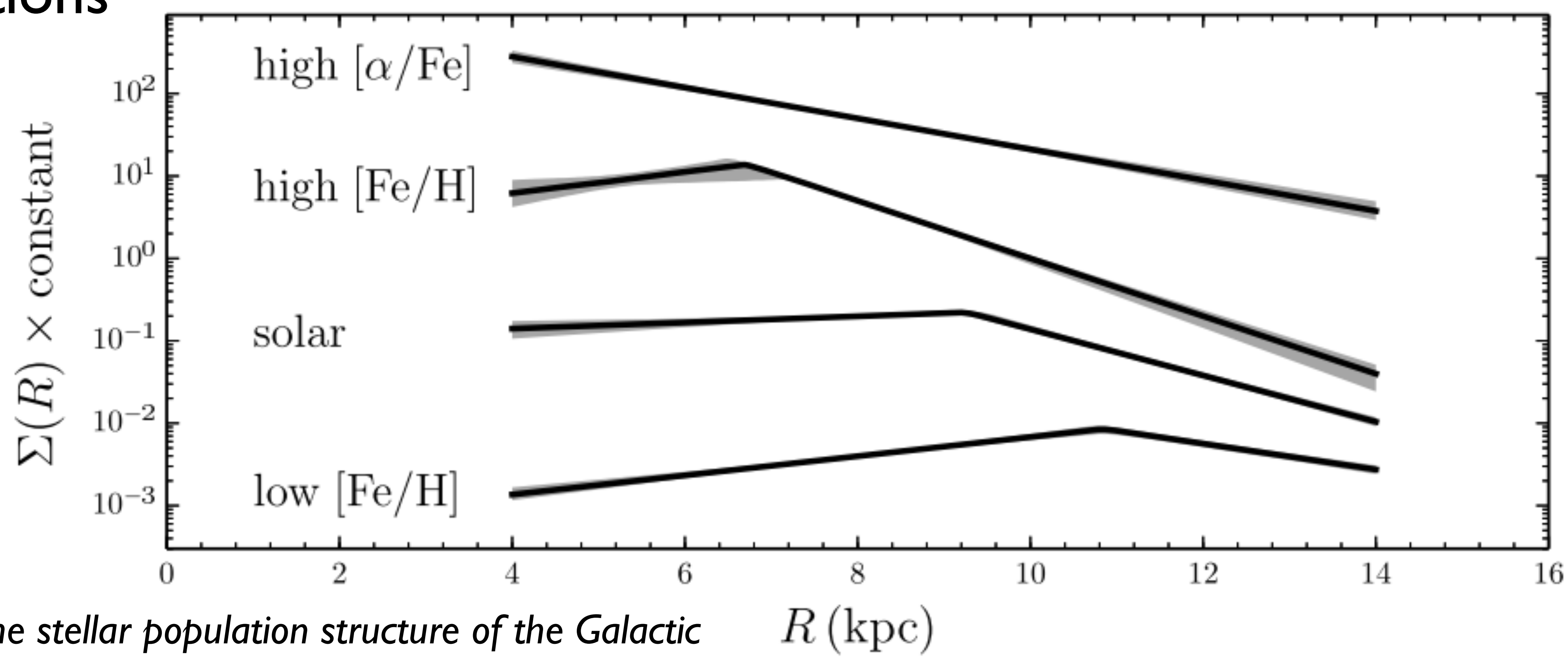
$$\boxed{\mathcal{T}(R_\odot,z) = A\left(\frac{z}{\text{kpc}}\right)^n\Big|_{R_\odot}\left[\frac{1}{R_\odot} - \frac{2}{R_0}\right]}$$

Negative Positive Negative

SDSS/Budenbender:

Tilt Term Redux

- **But** recent SDSS results show a surface density **rising** with radius for some populations



Bovy et al., *The stellar population structure of the Galactic disk*, Astrophys.J.823:30, 2016, arXiv: 1509.05796

- Thus we model the tilt term as the following, with a flat prior on k that ranges from negative to positive values.

$$\mathcal{T}(R_\odot, z) = \sigma^2_{Rz}(R_\odot, z)\left[\frac{1}{R_\odot} - 2k\right]$$

alpha-young k = [-1.3, 1.0]
alpha-old k = [-0.5, 1.5]

Positive or Negative Positive Positive or Negative