Determining the Local Dark Matter Density

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

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APS Paris, 2016.

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Why do we care about local DM density?

Direct Detection (e.g. Xenon1T, LUX...)

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

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

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

→ Scans of theoretical parameter space, eg Supersymmetry

How do we measure local DM density?

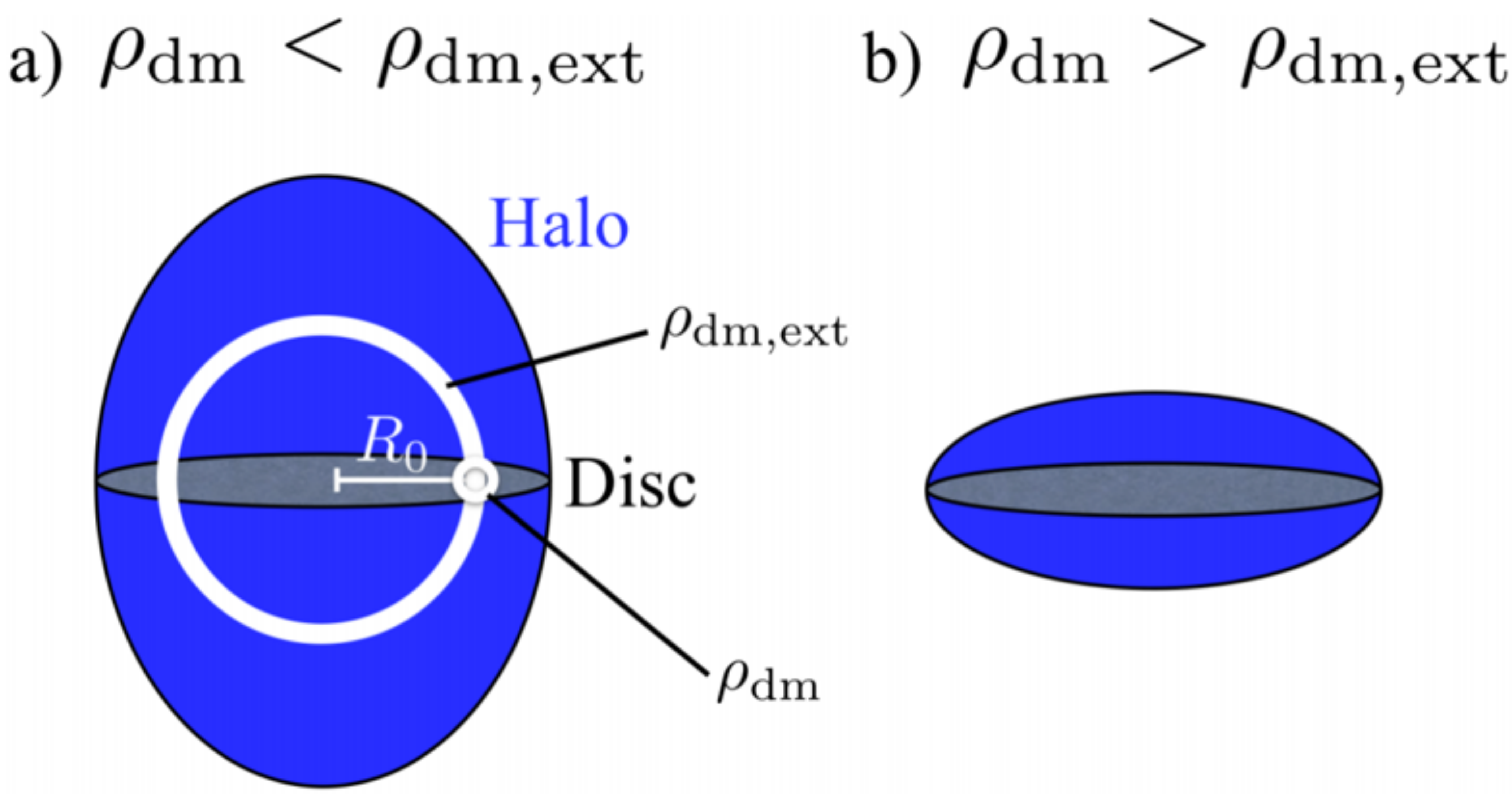
- **Global measurements (rotation curves):**
  powerful, but have to assume global properties of the halo.
  e.g. Dehnen & Binney 1998; Weber & de Boer 2010; Catena & Ullio 2010; Salucci et al. 2010; McMillan 2011; Nesti & Salucci 2013; Piffl et al. 2014; Pato & Iocco 2015; Pato et al. 2015

- **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

Combination of Local and Global Measurements

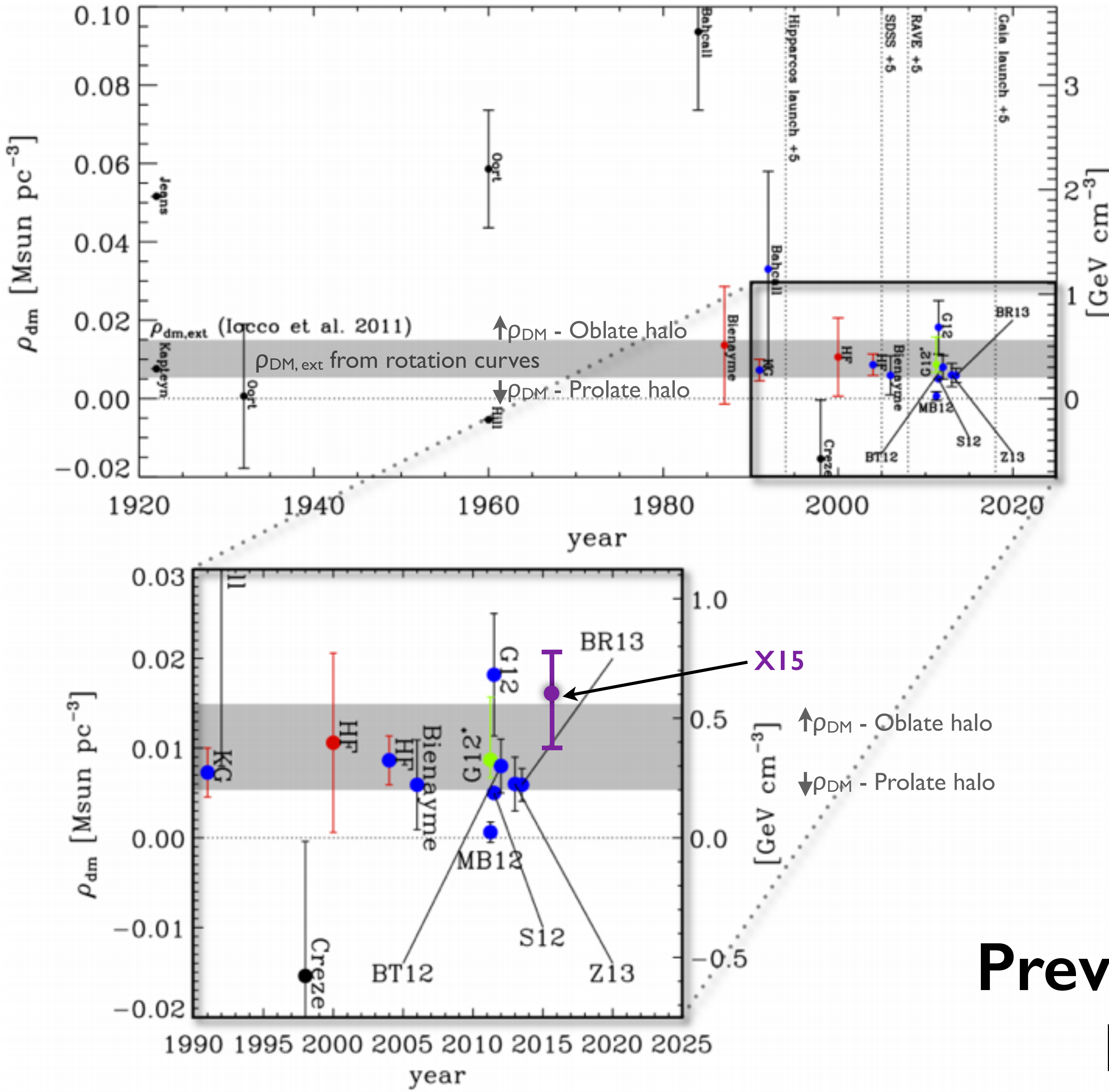
Justin Read,
The Local Dark Matter Density, 2014.
J. Phys. G: Nucl. Part. Phys. 41 063101.
arXiv: 1404.1938

Local Global Local Global



Prolate Halo Oblate Halo

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



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

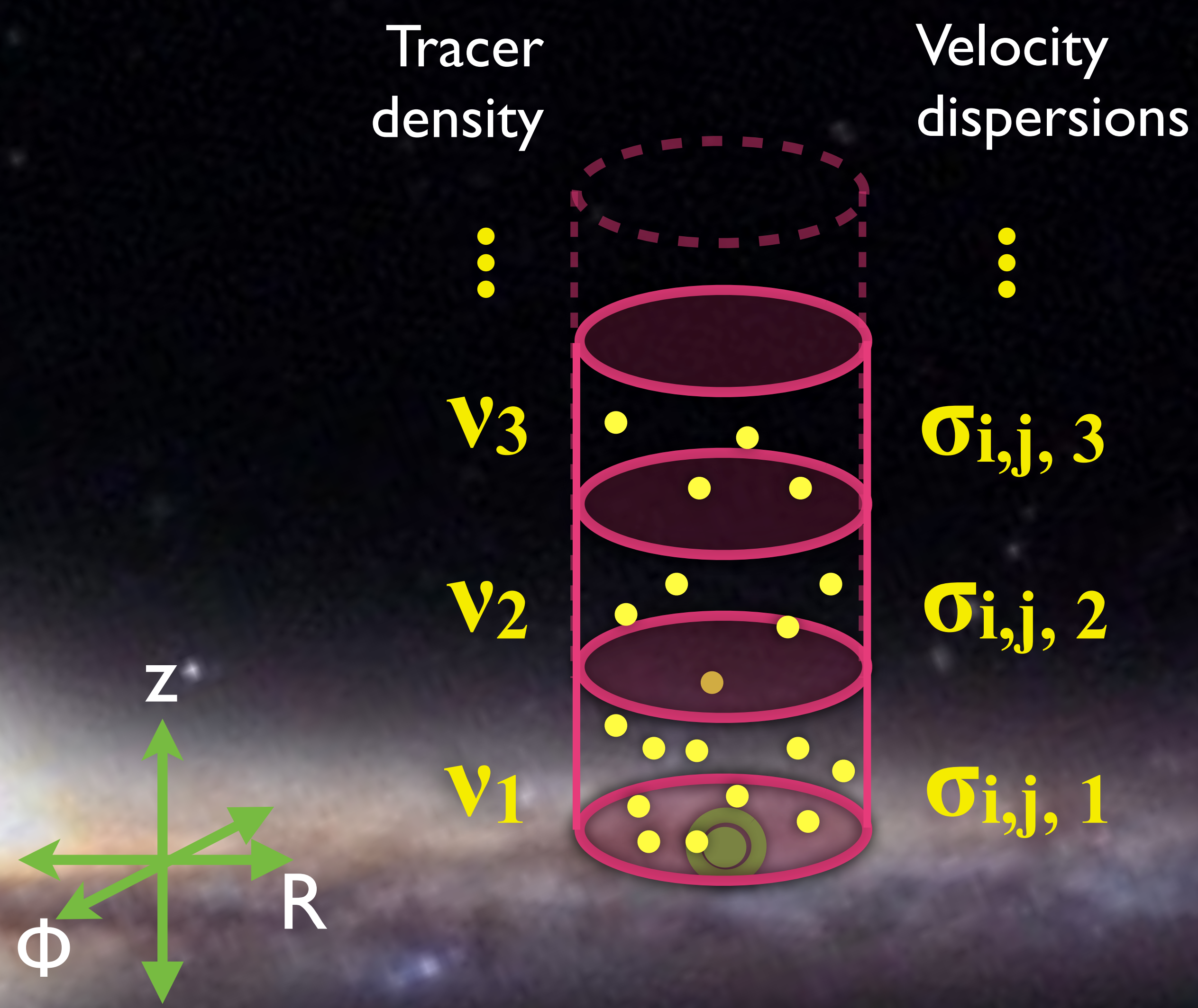
X15 - Xia et al., released last week, 1427 G & K type MS stars from LAMOST survey

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 spherical-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 $\Sigma_z(z) = \frac{|K_z|}{2\pi G}$

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

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

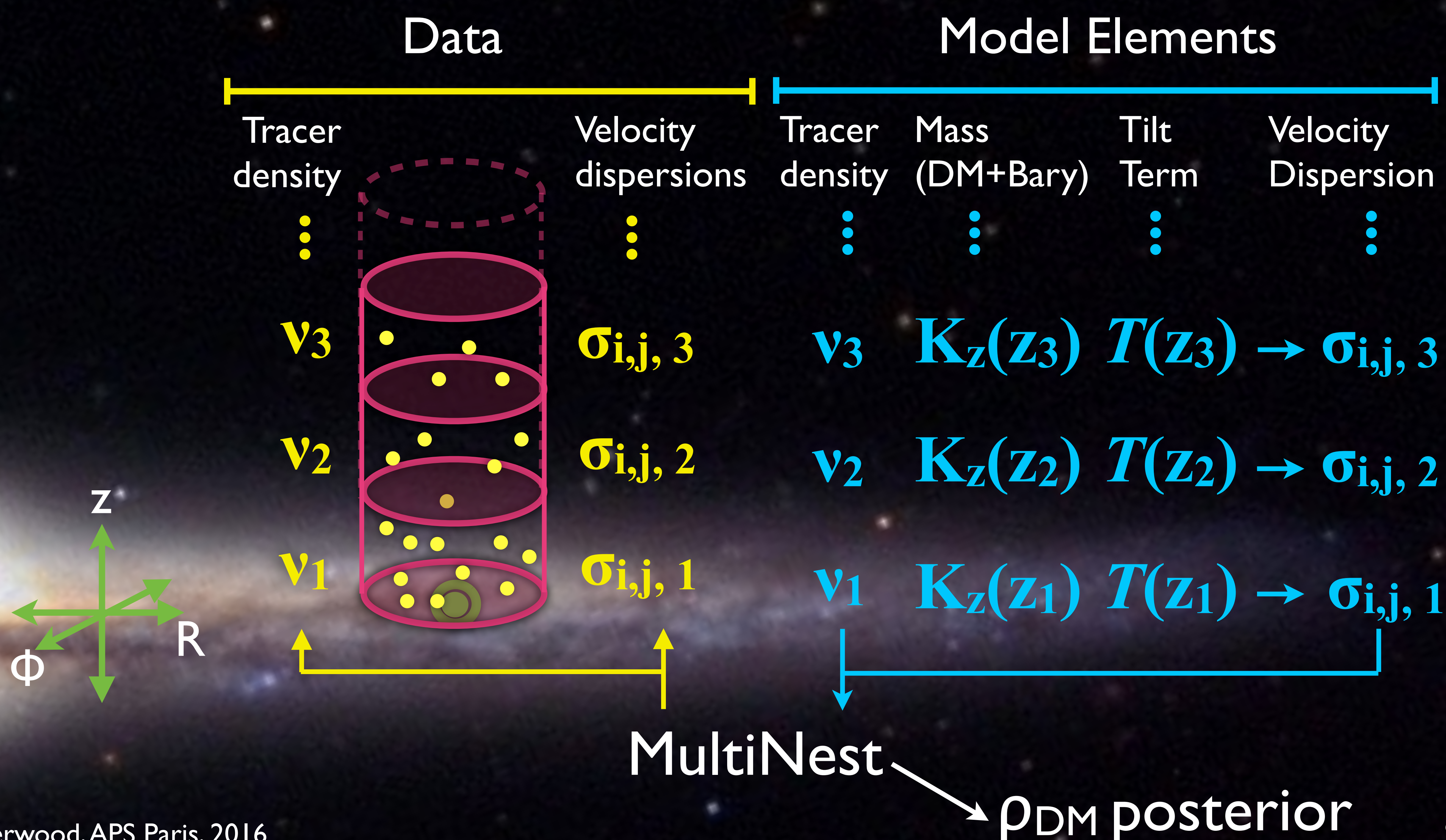
Construct model for

- **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 - Modeling 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



Modeling the Components:

Mass profile - K_z term

$$K_z = -\frac{d\Phi}{dz}$$

- 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.

Modeling the Components:

Tilt Term

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

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

- 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

- Traditionally (e.g. Binney & Tremaine) tracer density ν is a exponential **falling** with radius, eg:

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

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

$R_0 = R_1$

- Model σ_{Rz}^2 as a power law:

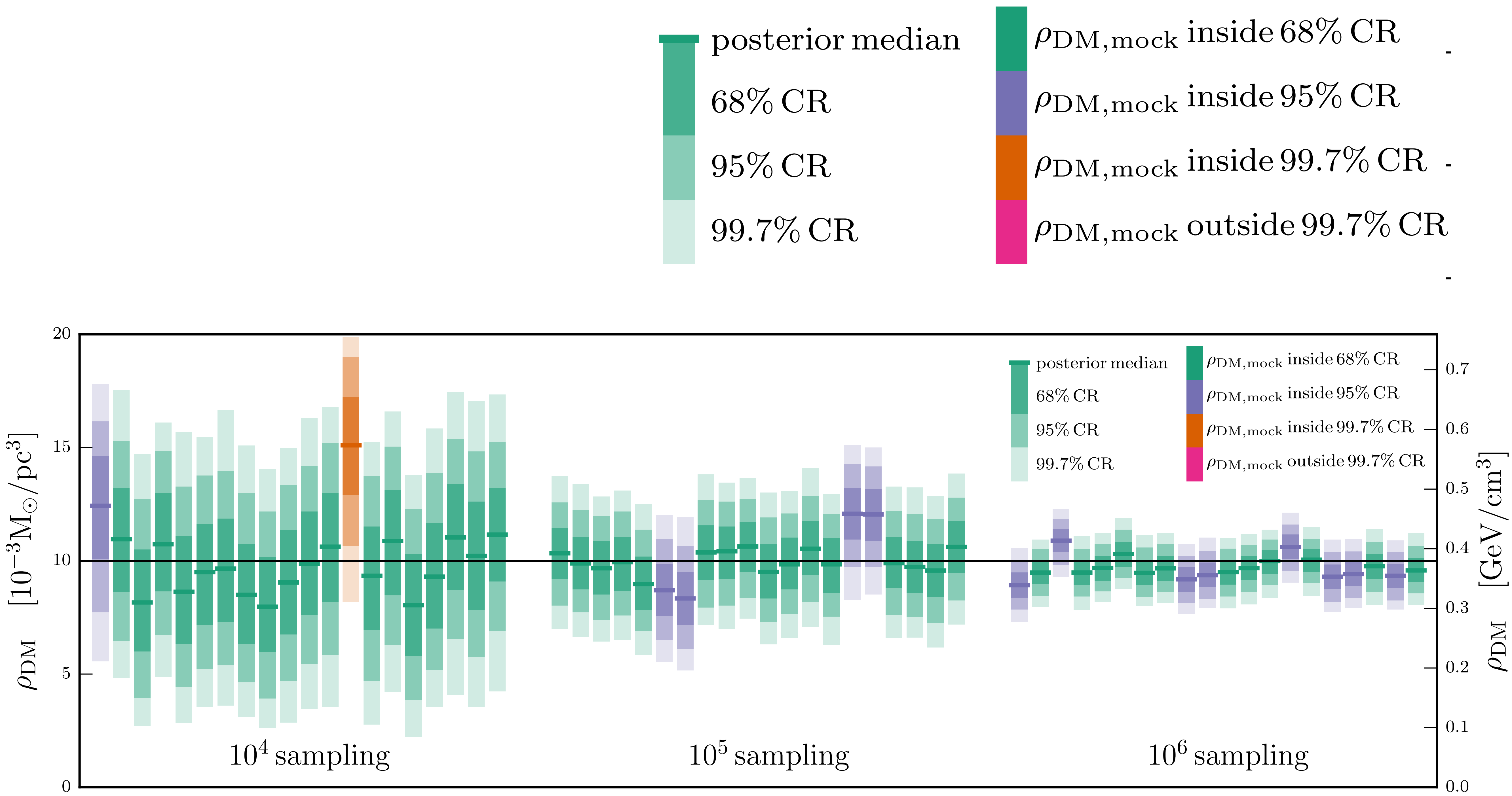
$$\sigma_{Rz}^2(z)\big|_R = A\left(\frac{z}{\text{kpc}}\right)^n\Big|_R$$

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

Silverwood et al. arXiv:1507:08581

Testing with 20 Simple Mock Data Sets

Sampling: More data points (stars) = better result.

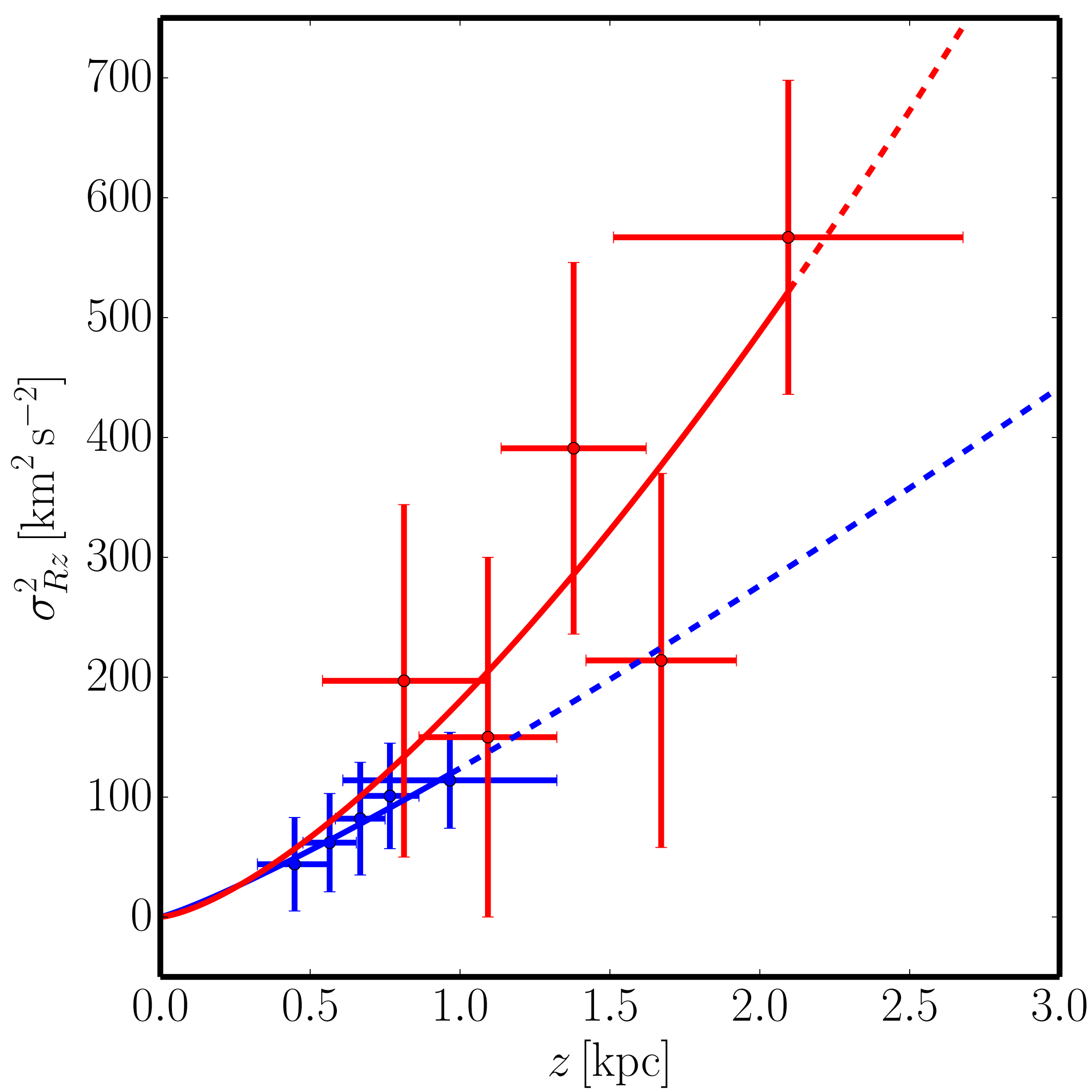


10^4 tracer stars 10^5 tracer stars 10^6 tracer stars

Testing with 20 Simple Mock Data Sets

The Importance of the Tilt Term

We generate out tilt mock data by fitting our tilt model to σ_{Rz}^2 data from Budenbender et al. 2014.



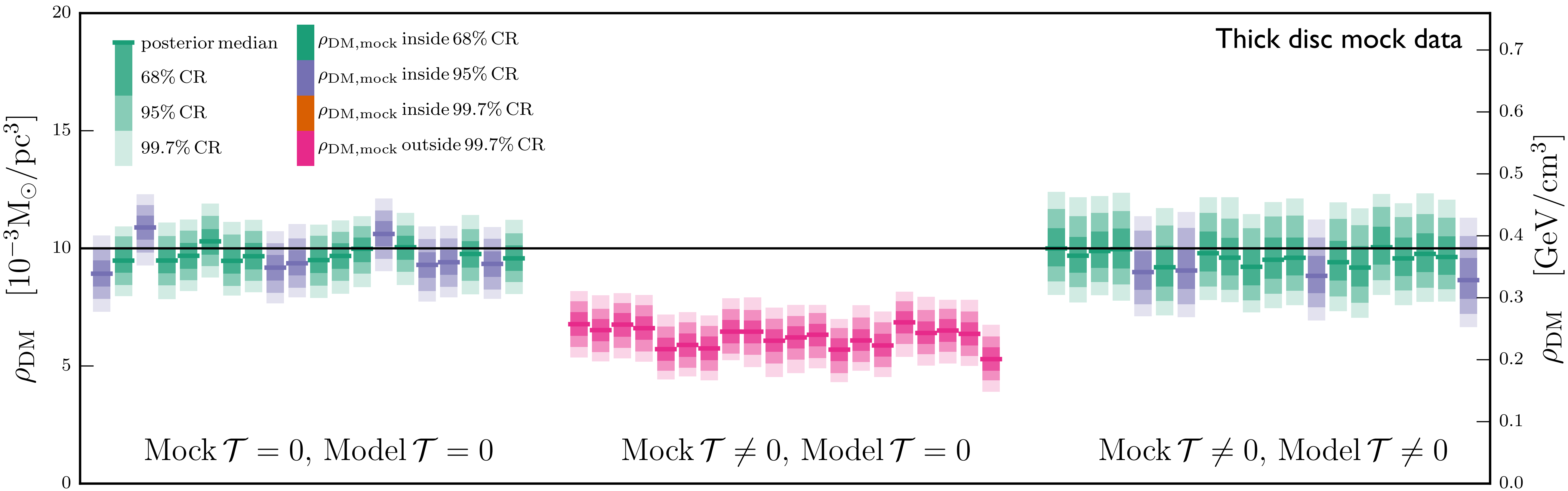
$$\sigma^2_{Rz}(z)\big|_R = A\left(\frac{z}{\text{kpc}}\right)^n\Bigg|_R$$ **Positive**

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

Negative **Positive** **Negative**

Testing with 20 Simple Mock Data Sets

The Importance of the Tilt Term

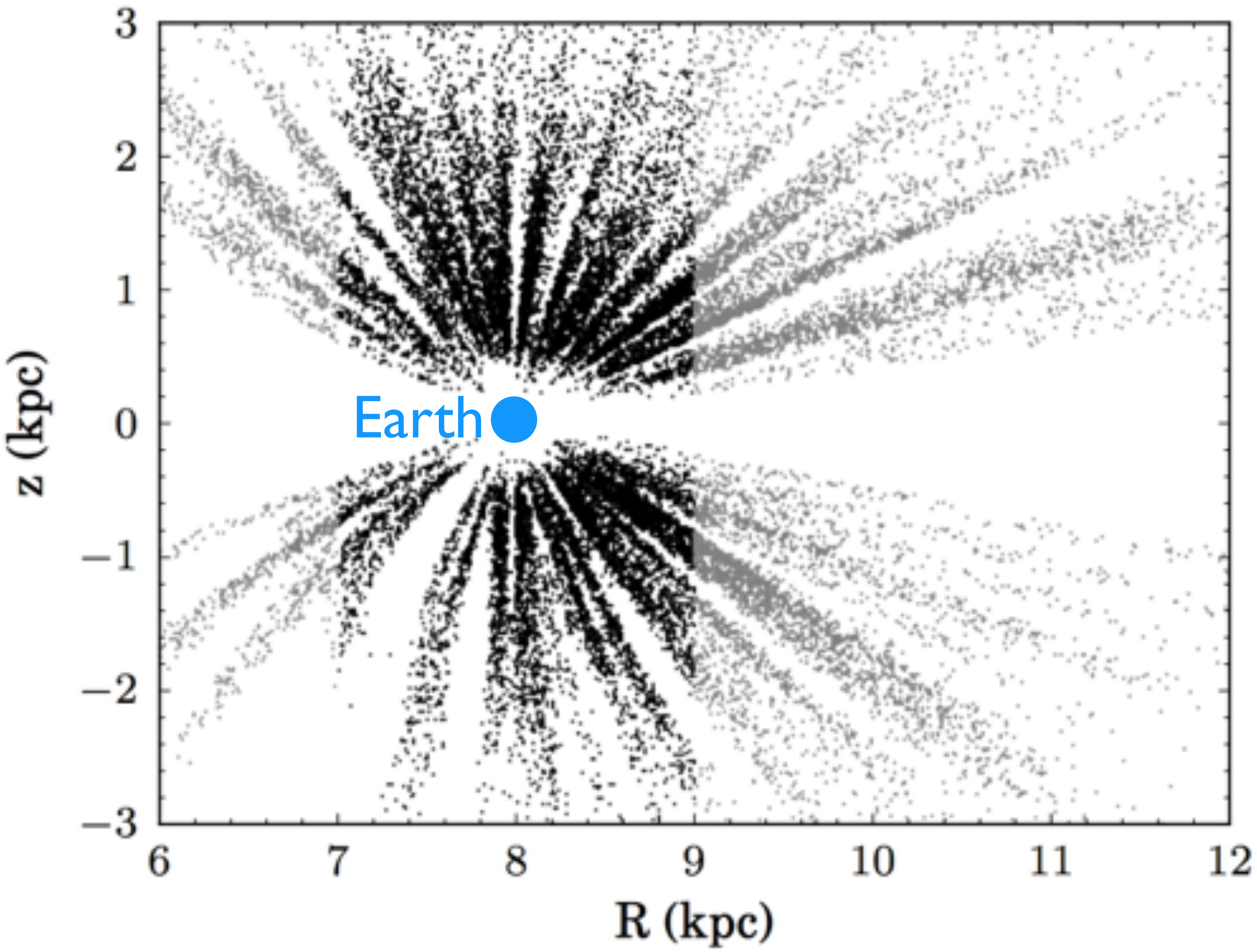


Mock: No tilt Recon: No tilt	Mock: Tilt Recon: No tilt	Mock: Tilt Recon: Tilt

Tilt is the coupling between **Radial** and **Vertical** motions

Neglecting tilt leads to a **systematic** underestimation of the **dark matter density** when the **tilt term** is negative.

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

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:

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

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

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

$R_0 = R_1$

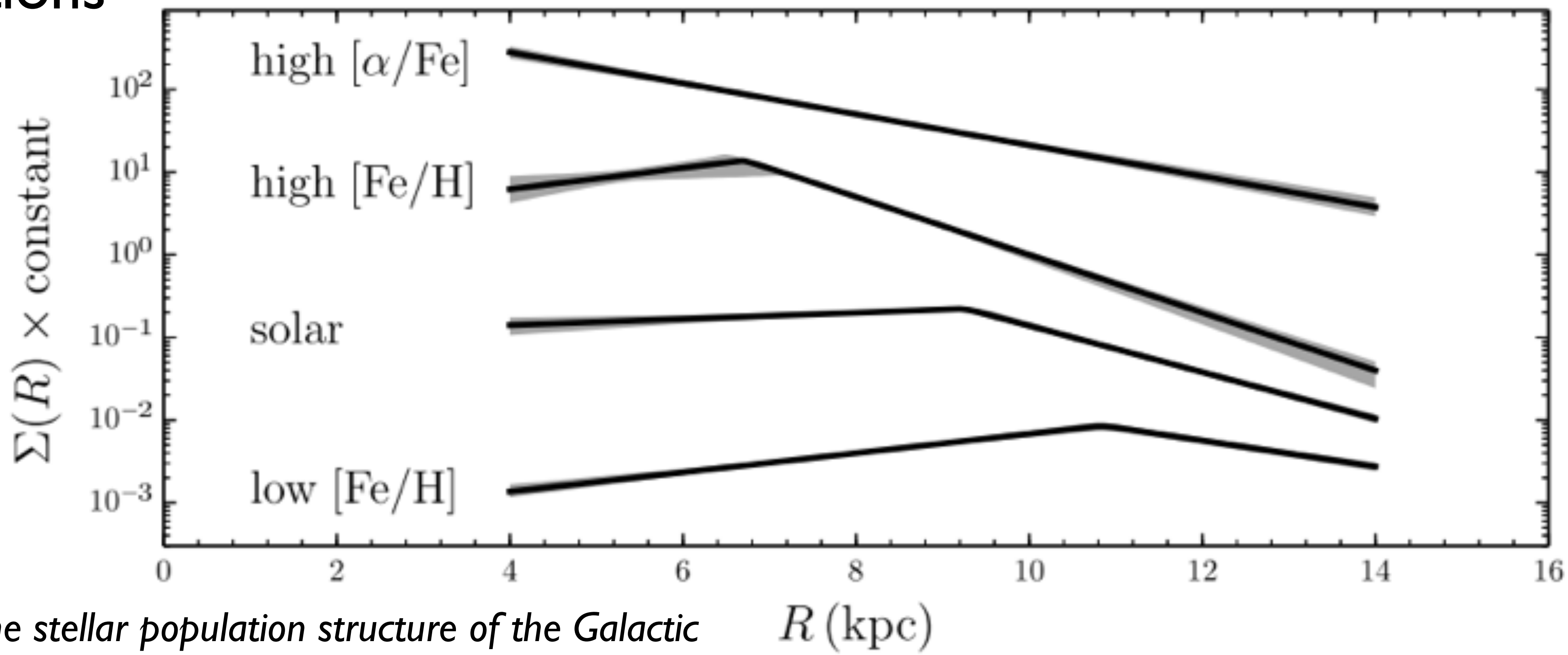
$$\mathcal{T}(R_\odot, z) = A\left(\frac{z}{\text{kpc}}\right)^n\Big|_{R_\odot}\left[\frac{1}{R_\odot} - \frac{2}{R_0}\right]$$

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

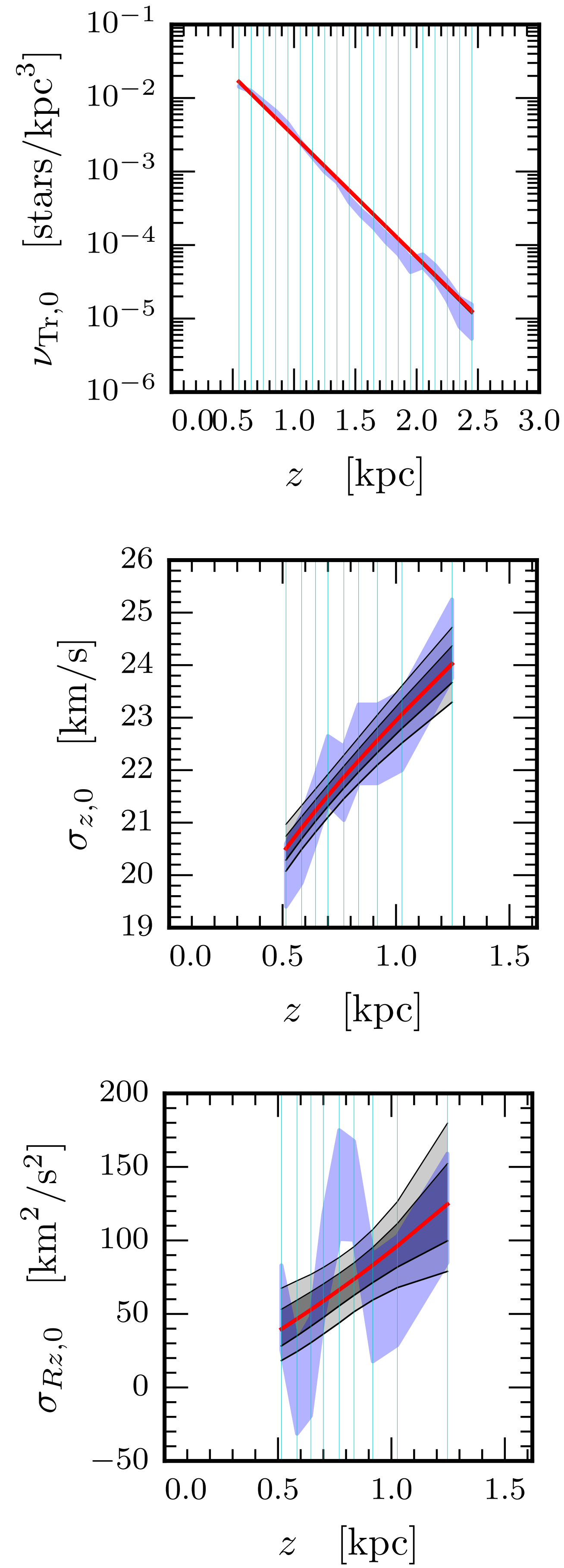
Preliminary Results.

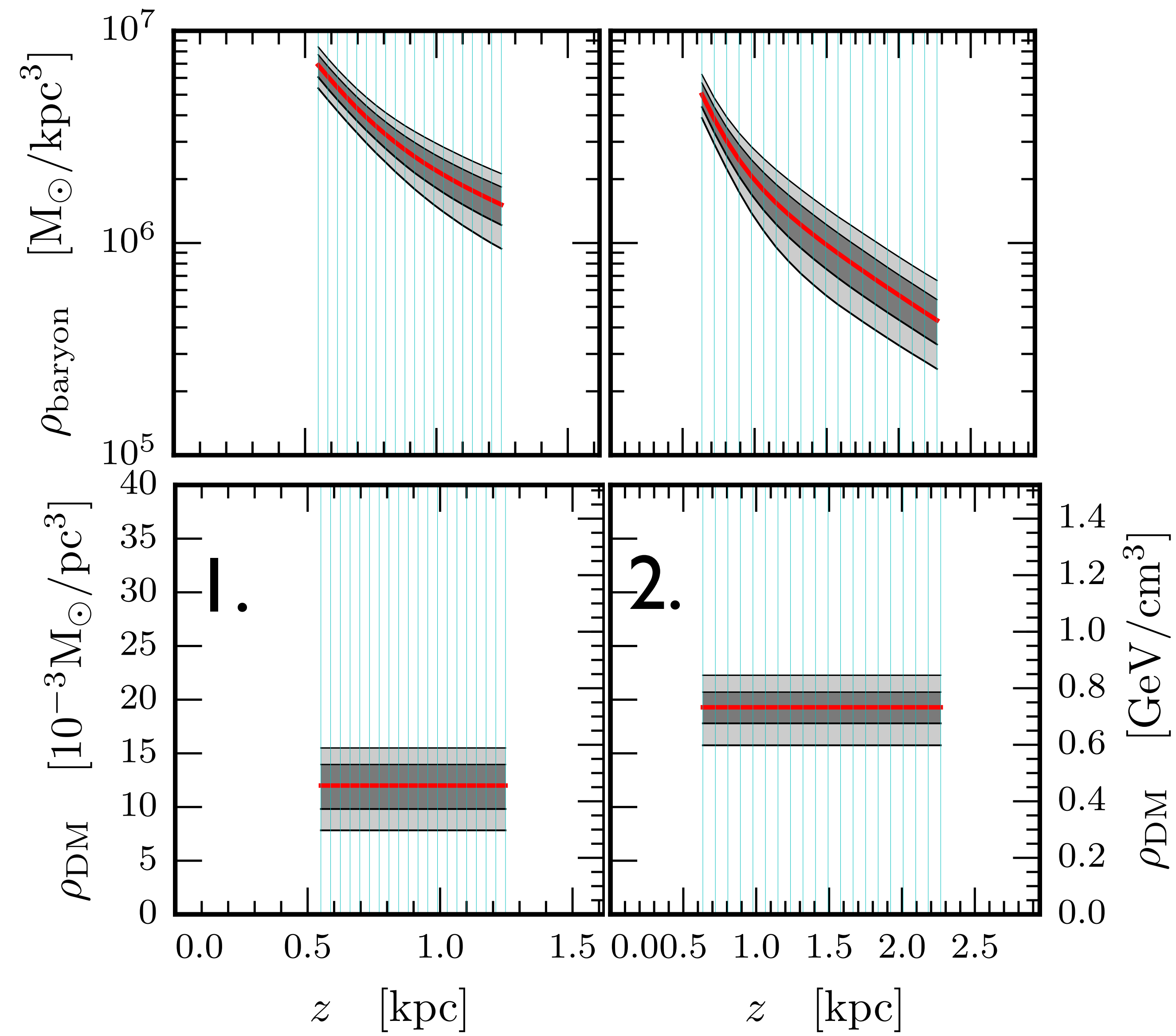
Alpha-young population ('thin disc')

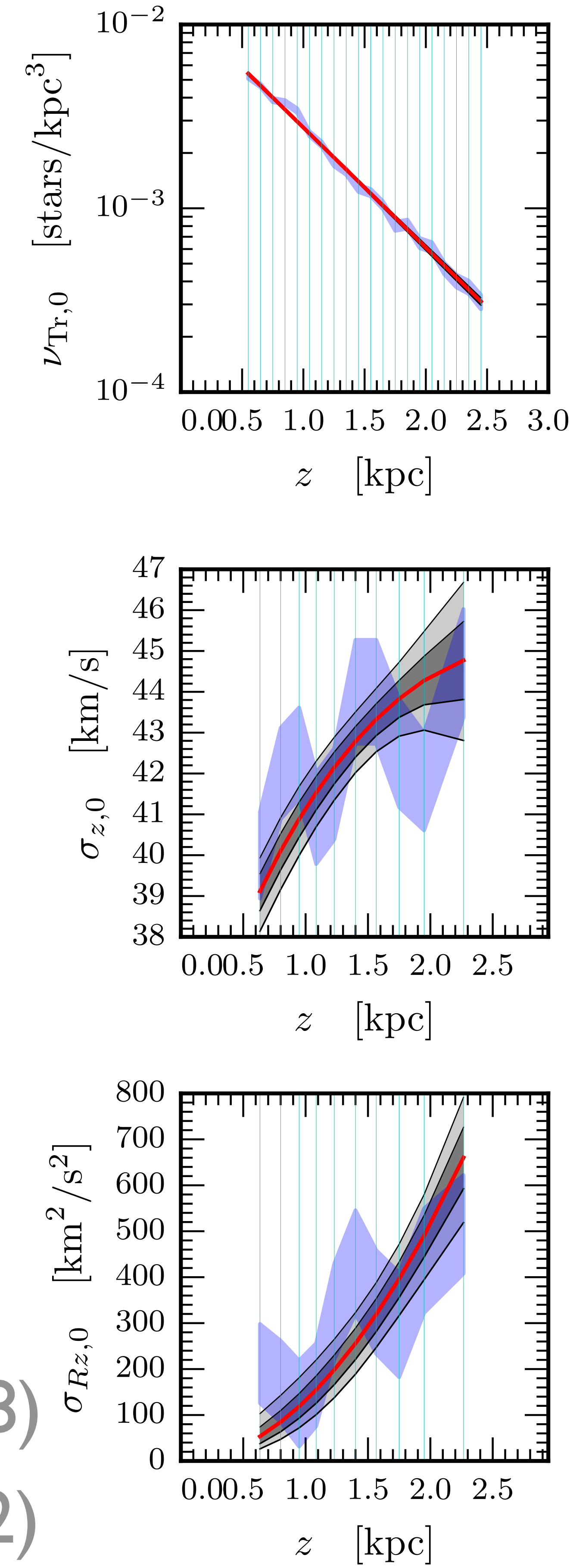
Alpha-old population ('thick disc')

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)

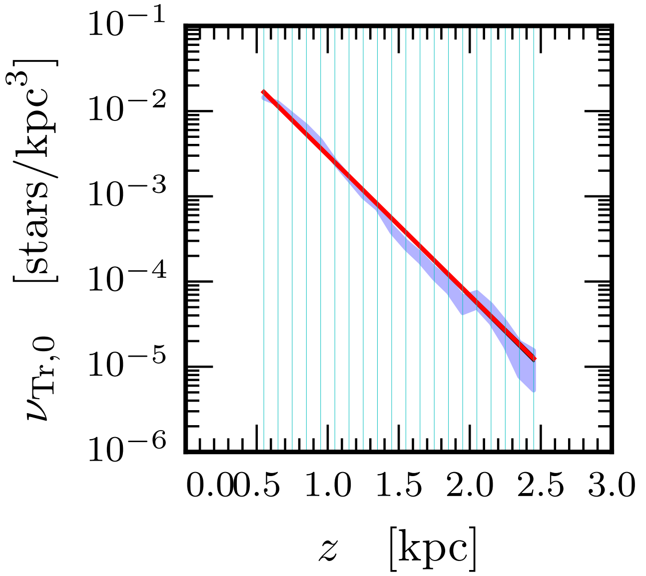
2. $\rho_{DM} = 0.73^{+0.13}_{-0.13}$ GeV/cm^3 (~~tilt~~: 0.42)

Hamish Silverwood, APS Paris, 2016

Alpha-young population
('thin disc')

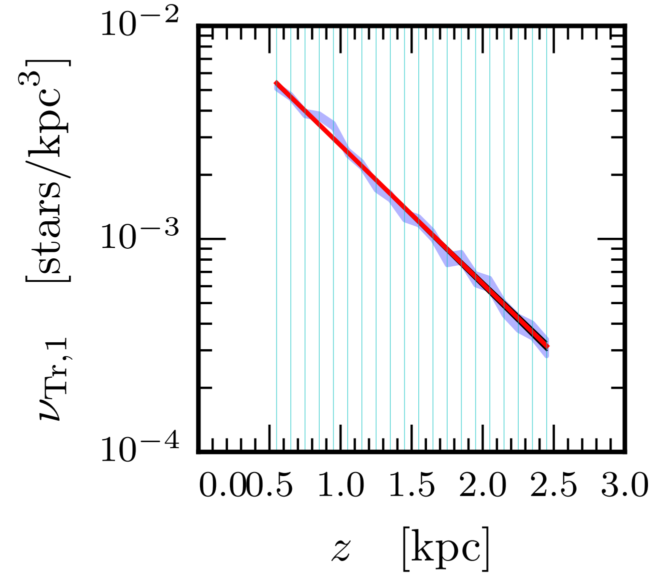
Preliminary Results.

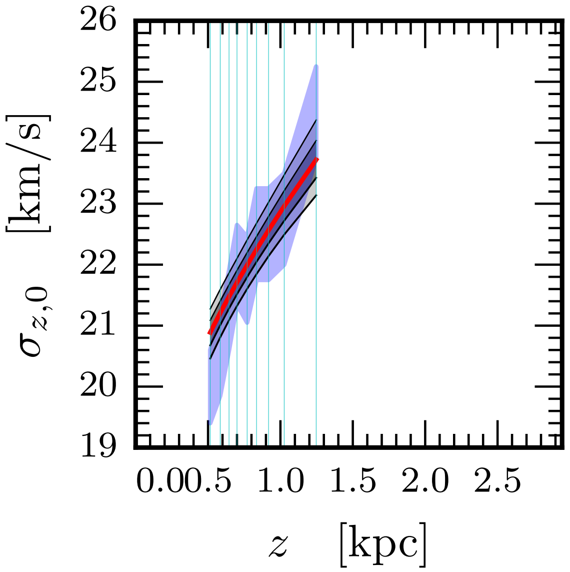
Alpha-old population
('thick disc')

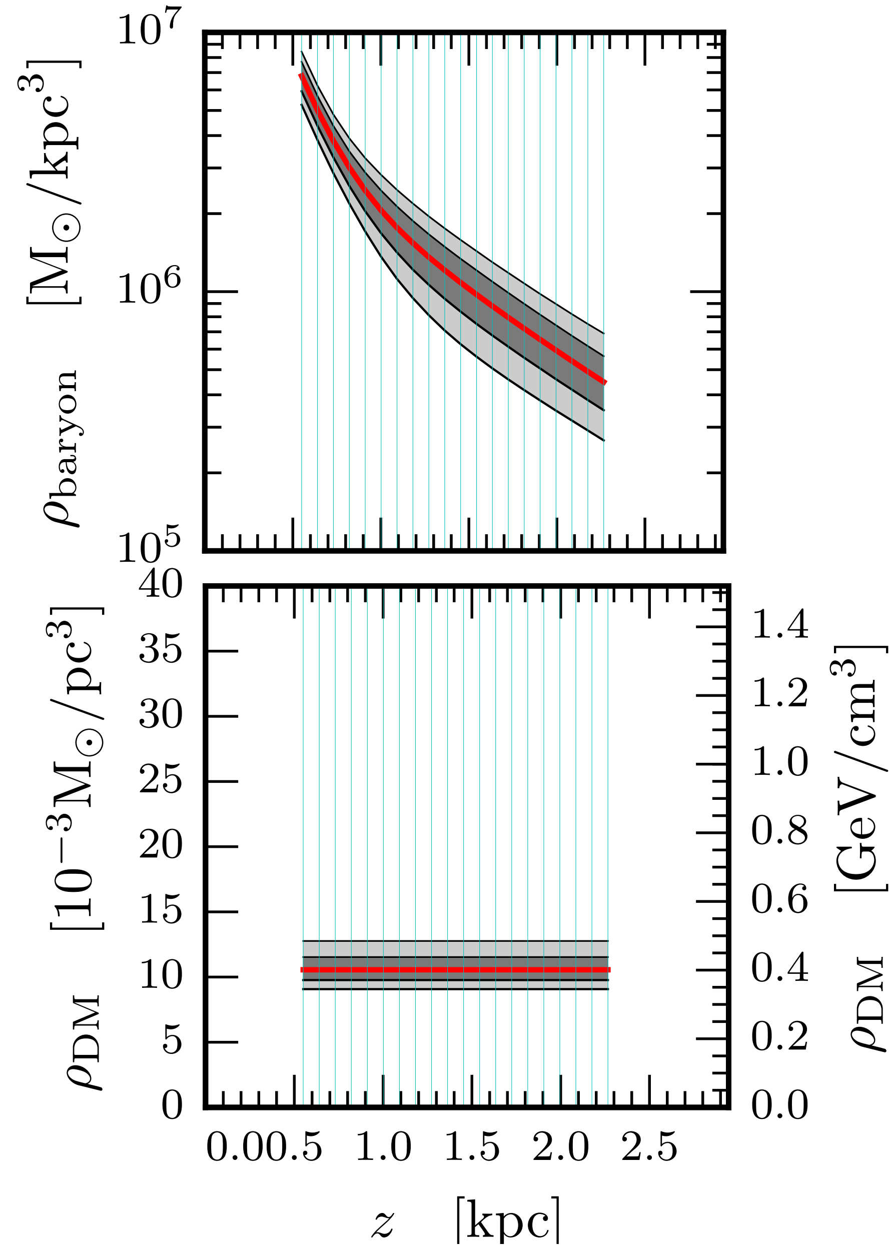


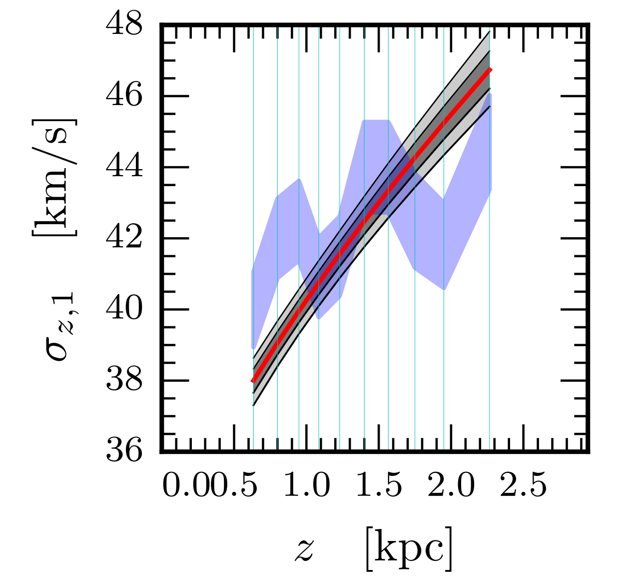
SDSS-SEGUE G-dwarf data from Budenbender et al. 2014 1407.4808v2. Tilt priors informed by data from SDSS-APOGEE, Bovy et al. 1509.05796.

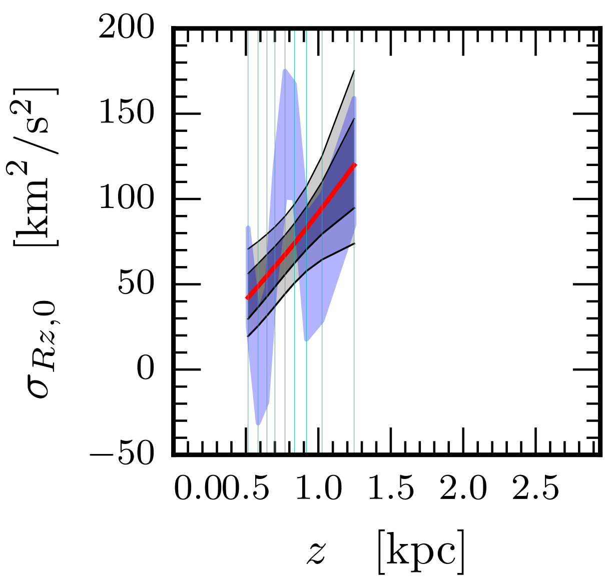
Combined Analysis, 2σ uncertainties quoted.

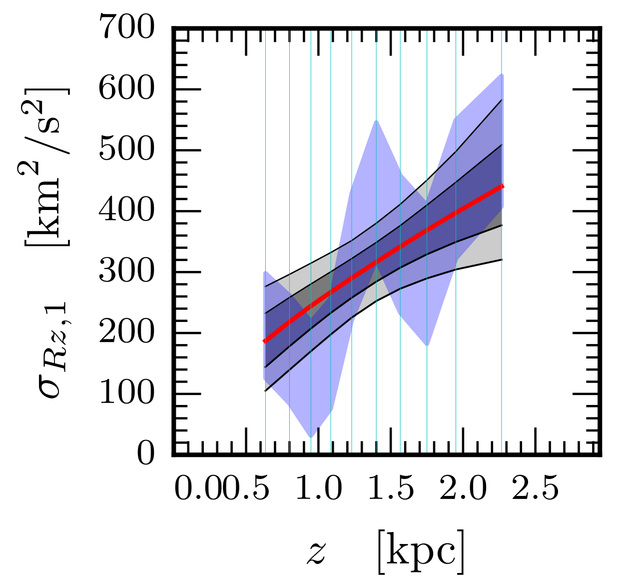












$\rho_{DM} = 0.40^{+0.08}_{-0.06}$ GeV/cm^3

Hamish Silverwood, APS Paris, 2016

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)

1. Thin disk result less sensitive to tilt term than the thick disc
2. Combining thick and thin 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.
5. Tilt term can now be negative or positive, giving a systematic under- **or** over-estimation of the local DM density if ignored.

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: 14 September

- Observations taken between July 2014 and September 2015
- Sky positions (α, δ) and G-magnitude for ~ 1 billion stars
- TGAS solution for 2.5 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 5D data from Gaia to produce improved 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

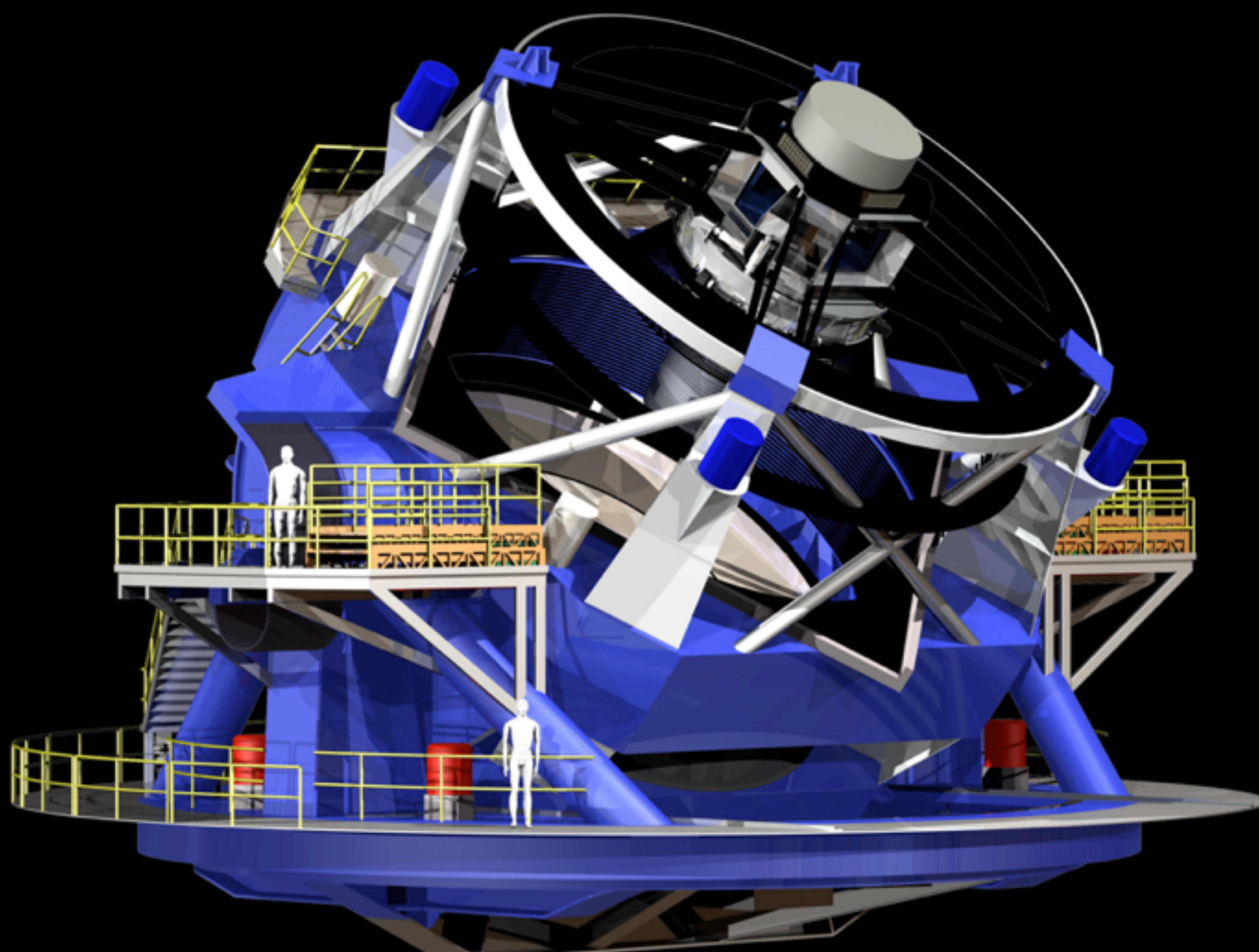
RAVE, 2003-13
UK Schmidt Telescope, Australia

WEAVE, 2018-
William Herschel Telescope, La Palma

4MOST, 2021-
VISTA Telescope, Paranal, Chile

LSST 2019-

Deep complement to Gaia survey, seeing dimmer stars and reaching further out into the halo.



Conclusions

- Tilt term is important (ignore at your peril!), and can now potentially be positive or negative.
- 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: 14 September
- TGAS + RAVE 6D will be very exciting.