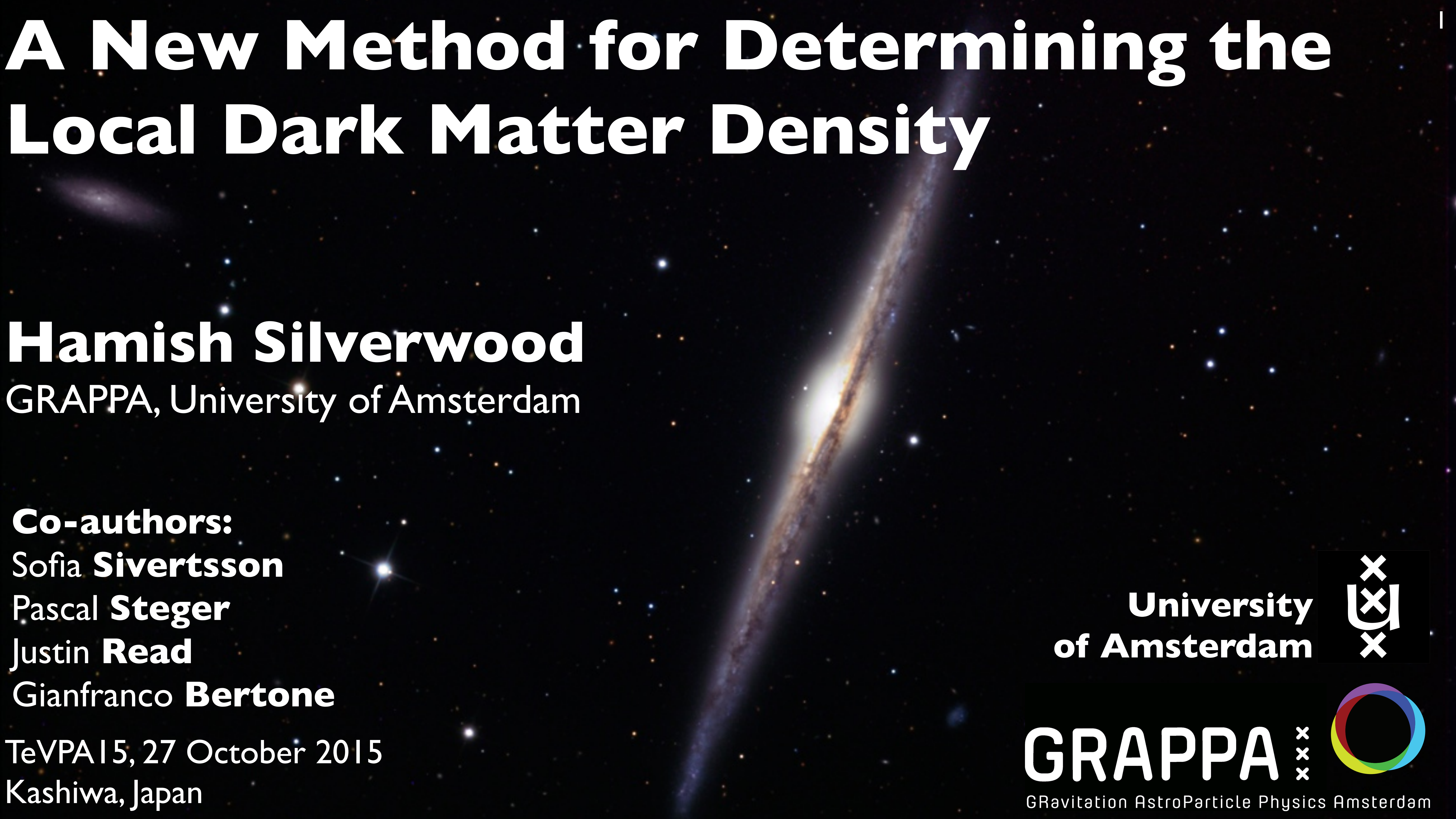
A New Method for Determining the Local Dark Matter Density



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TeVPA15, 27 October 2015
Kashiwa, Japan

University of Amsterdam

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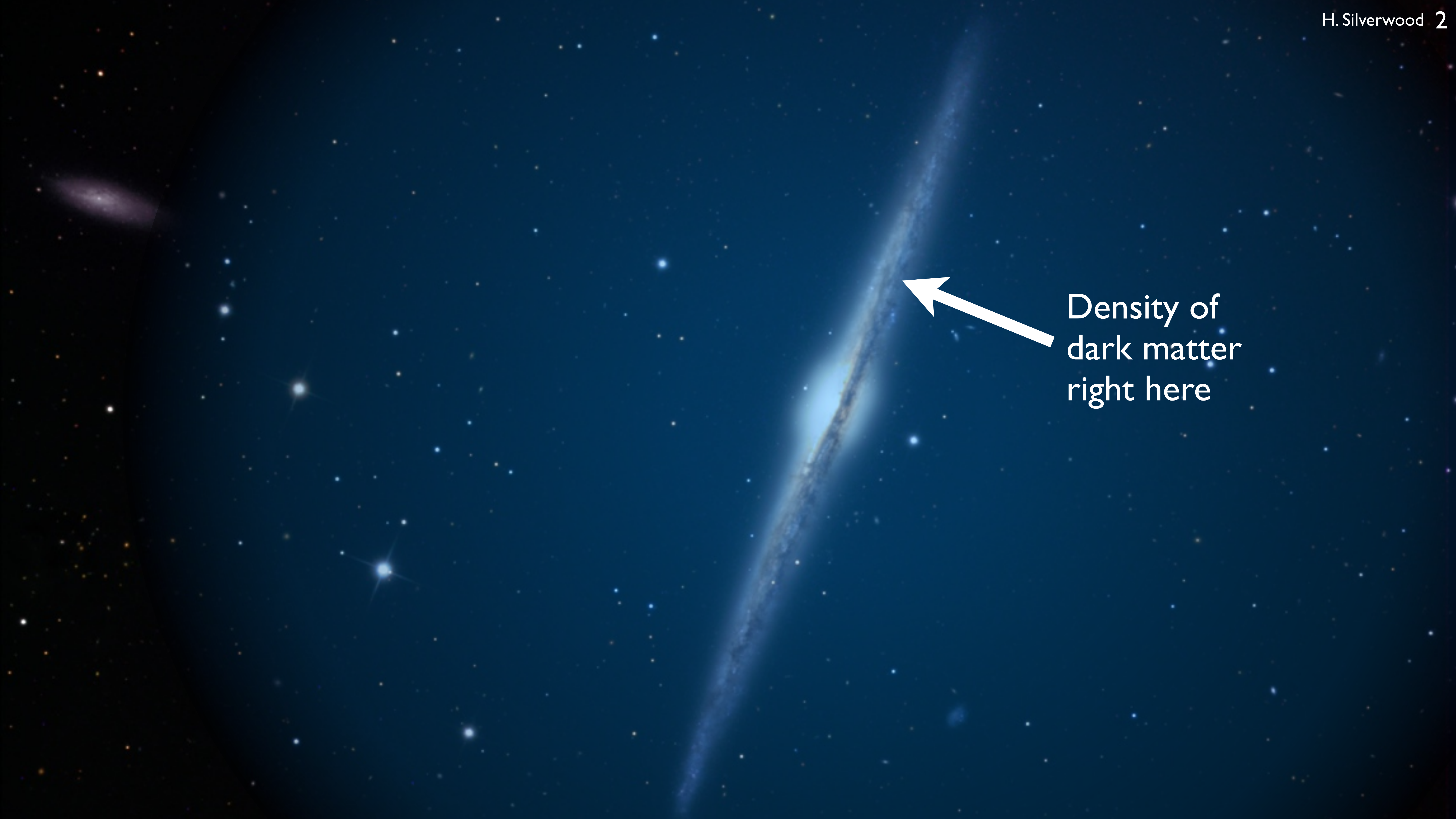
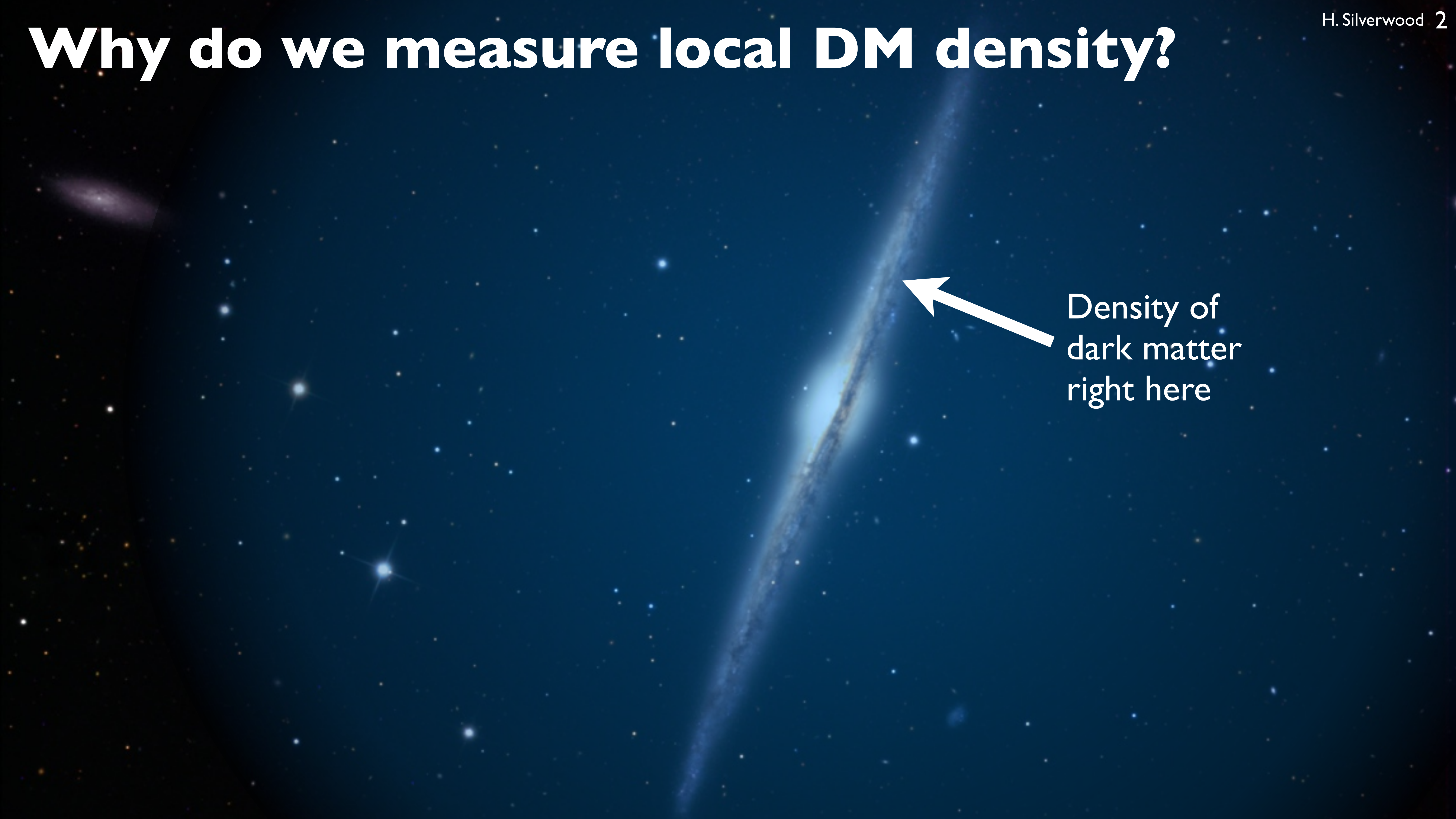


Density of
dark matter
right here

Why do we measure local DM density?



Density of
dark matter
right here

Why do we measure local DM density?

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

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

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

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

Density of
dark matter
right here

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,
  see Miguel Pato’s talk on Friday morning
  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

Our Method

- Local measurements in z-direction
- Data points are **positions** and **velocities** for a set of tracer stars

You are here.

- bin the data to get **tracer density ν**
  and **velocity dispersion** $\sigma_{ij}^2(\mathbf{x}) = \overline{v_i v_j} - \overline{v}_i \overline{v}_j$
- Focus on making as **few assumptions as possible**

Link kinematic data to mass density via Jeans Equations

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

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

Integrate

= 0 from axisymmetry

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

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**.

Key equation assumes only dynamical equilibrium. Can use almost any model to describe tracer density, mass density and tilt term. We can in principle have more parameters than data points, hence we call it **Non-Parametric Method.**

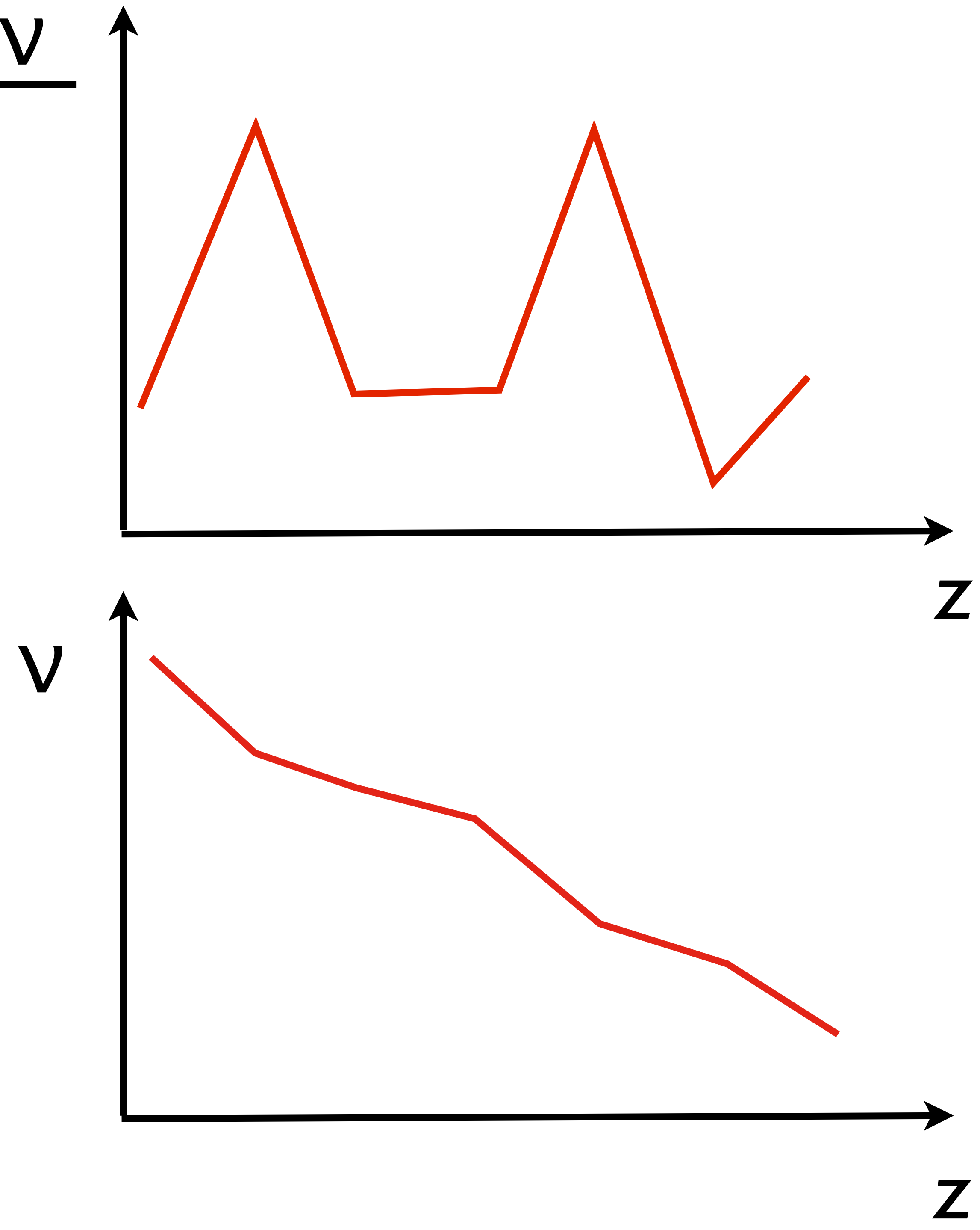
Modelling the Components:

Tracer Density with the k_z parameterization

We want to **discard the assumption of exponential tracer density ν.**

k_z allows for sufficient freedom to yield good fit to data. Integration of k_z yields smoother **ν** profile. Priors on k_z can further limit fitting to noise in data.

$$k_z = - \frac{d\ ln\ \nu}{dz}$$



Modelling the Components:

Tracer Density with the k_z parameterization

We want to **di**

assumption

tracer densi

k_z allows for su

yield good fit to

yields smoothe

k_z can further li

data.

Non-parametric model for tracer density.

Discard usual assumption of exponential tracer density.

Modelling the Components:

Tilt Term

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

Tilt term links vertical and radial motion.

T ~ 0 at low z, becomes larger at higher z where DM becomes dominant part of total density profile.

Would normally require moving to 2D Jeans equations, but with a few simplifying assumptions we can model the Tilt Term and remain in 1D.

$$\nu(R,z) = \nu(z)\exp(-R/R_0)$$
$$\sigma_{Rz}(R,z) = \sigma_{Rz}(z)\exp(-R/R_1)$$

$$\mathcal{T}(R_\odot, z) = \sigma_{Rz}(R_\odot, z)\left[\frac{1}{R_\odot} - \frac{1}{R_0} - \frac{1}{R_1}\right]$$

$$\sigma_{Rz}(R_\odot, z) = Az^n\big|_{R_\odot}$$

Parameters:

- A,
- n,
- R_0=R_1

Modelling the Components:

Dark Matter Density profile

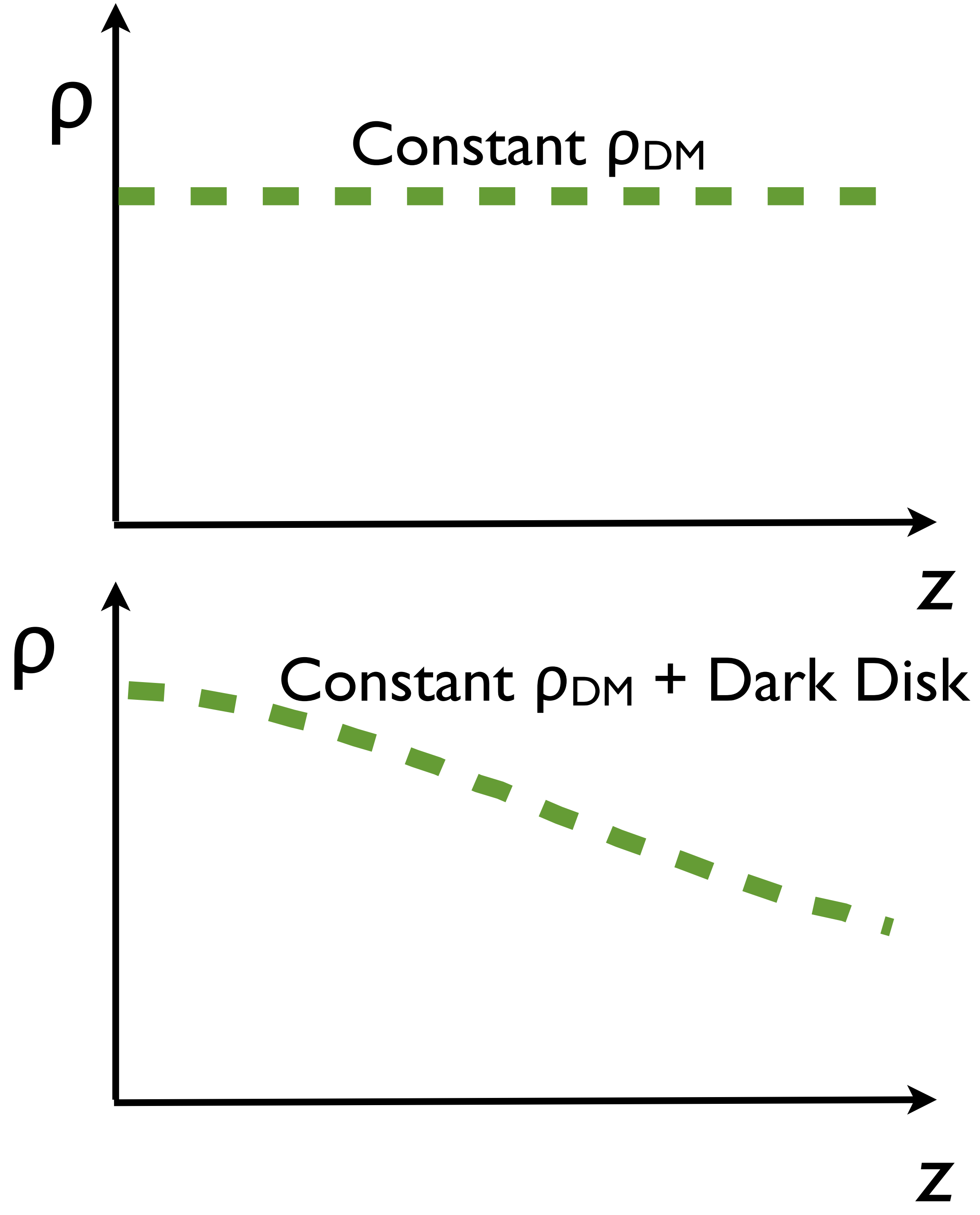
Constant ρ_{DM}

Within 10% of correct spherical halo density up to z ~ 3kpc

Constant ρ_{DM} + Dark Disc

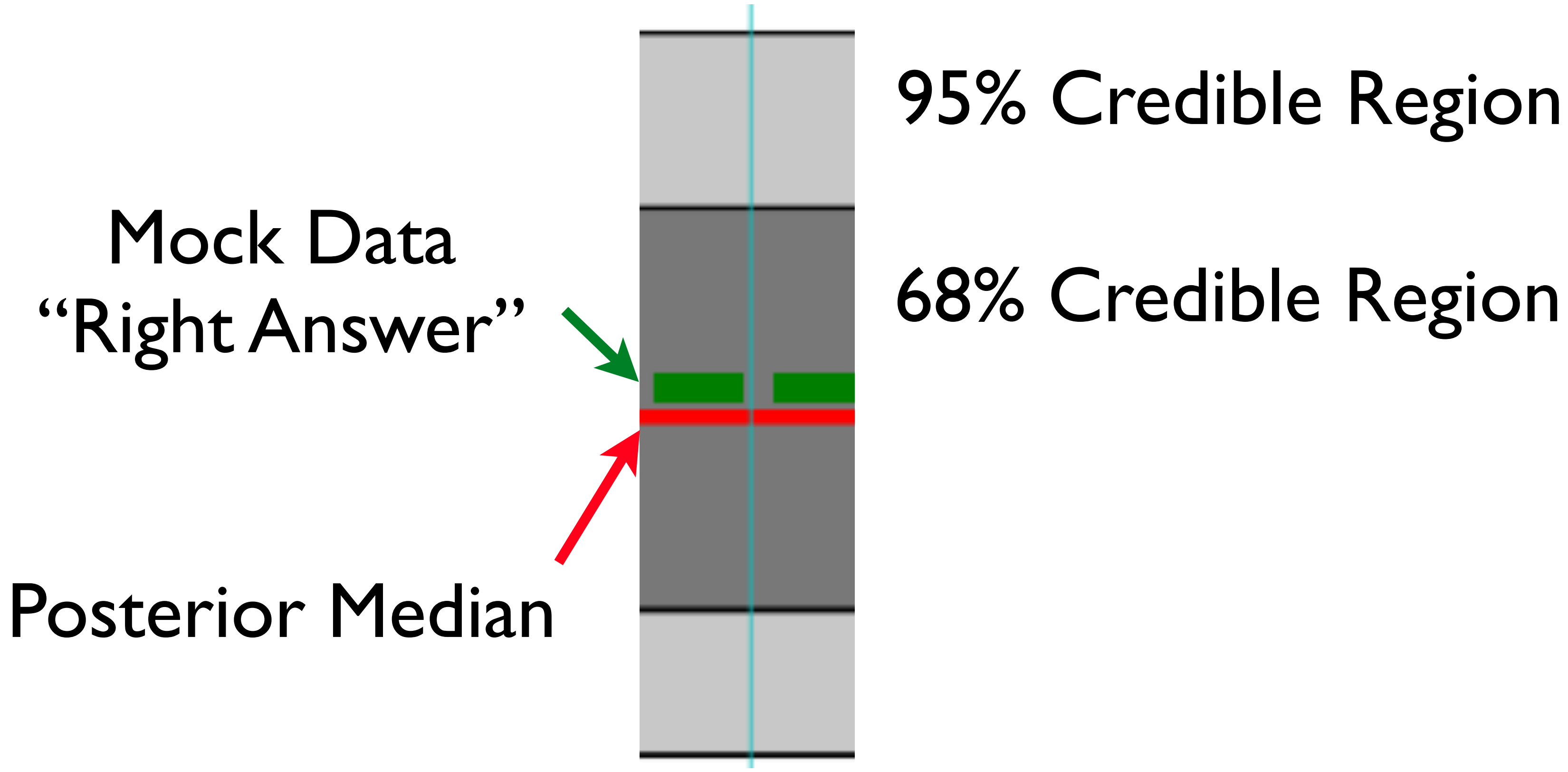
Dark Discs from e.g. accretion of subhalos, Partially Interacting DM.

Similar vertical profile from flattened, oblate halo.



Results:

- Initial testing on **Mock Data** sets generated from distribution functions
- varying numbers of tracer stars
- With & without effects of **tilt** (radial-vertical motion coupling)
- With & without **dark discs**



95% Credible Region

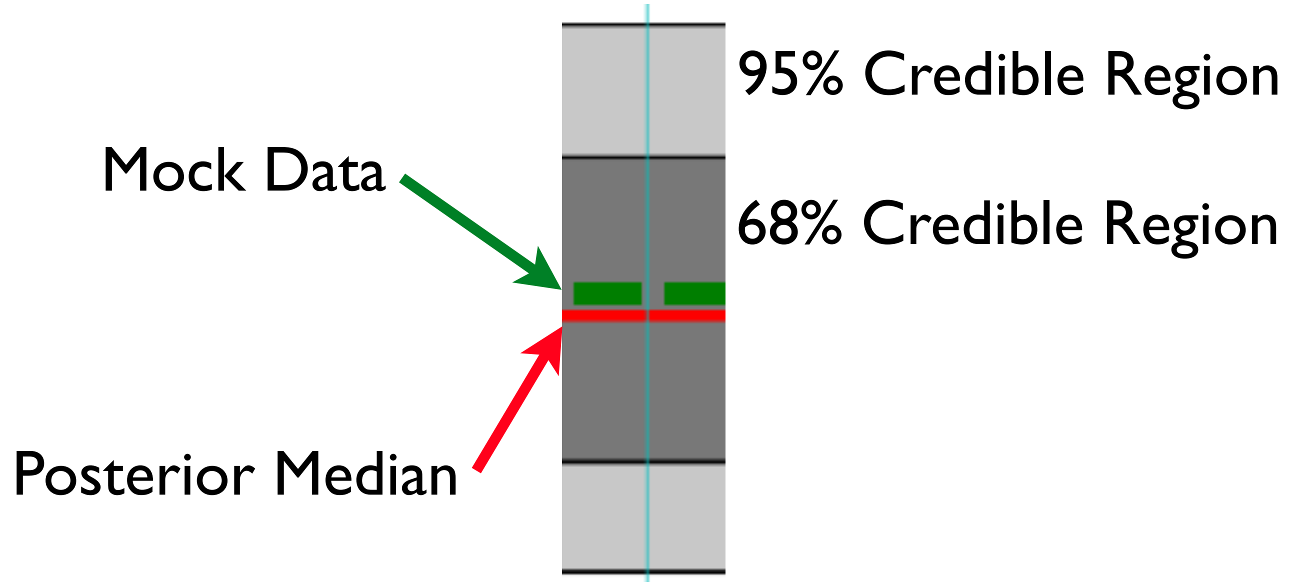
68% Credible Region

Mock Data “Right Answer”

Posterior Median

Results: Sampling

More data points = better result.



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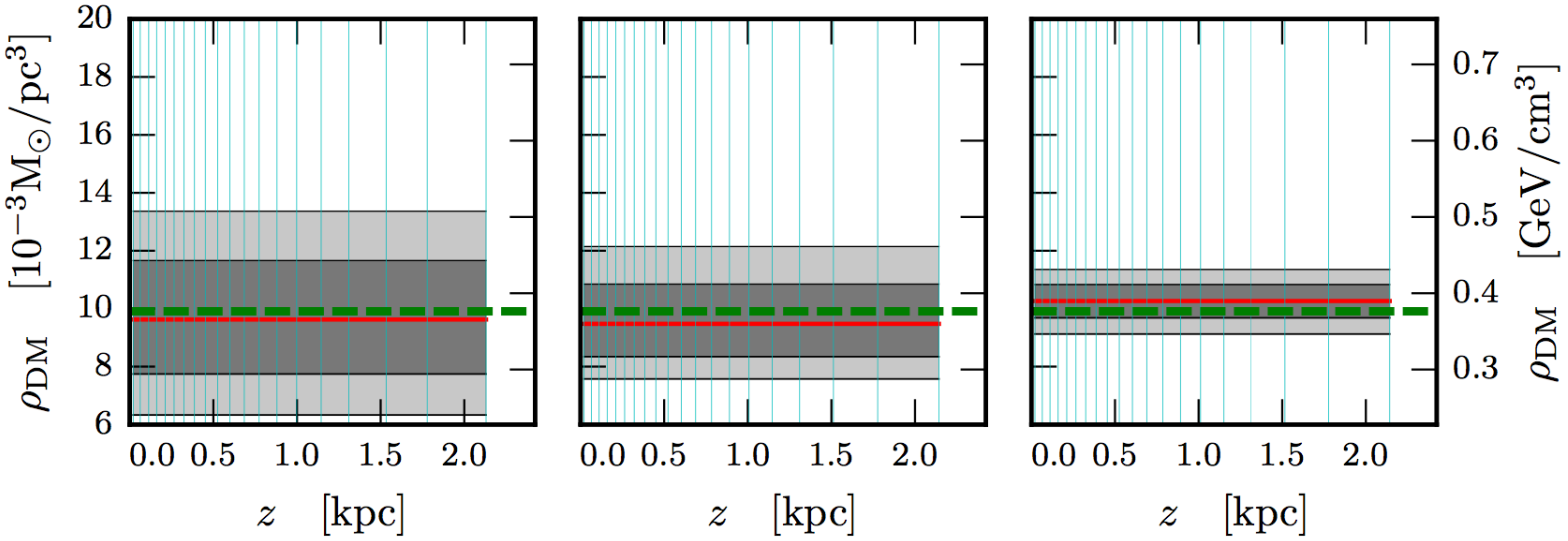
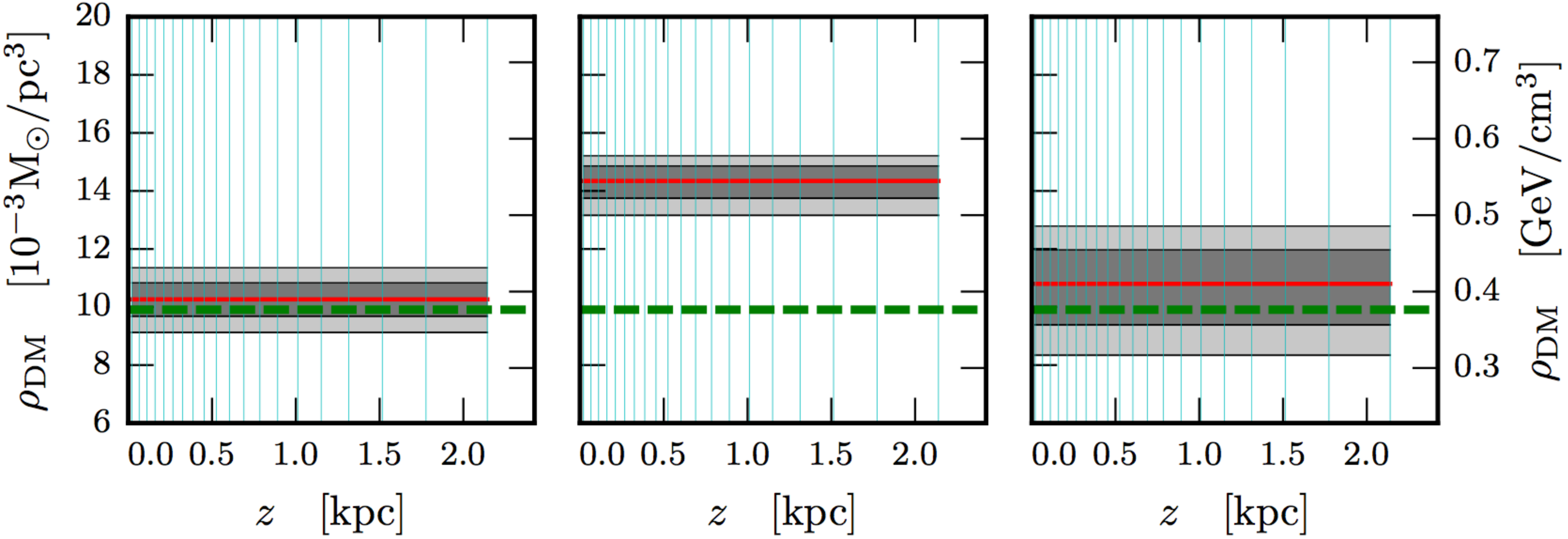


10^4 tracer stars

10^5 tracer stars

10^6 tracer stars

Results: The Importance of Tilt



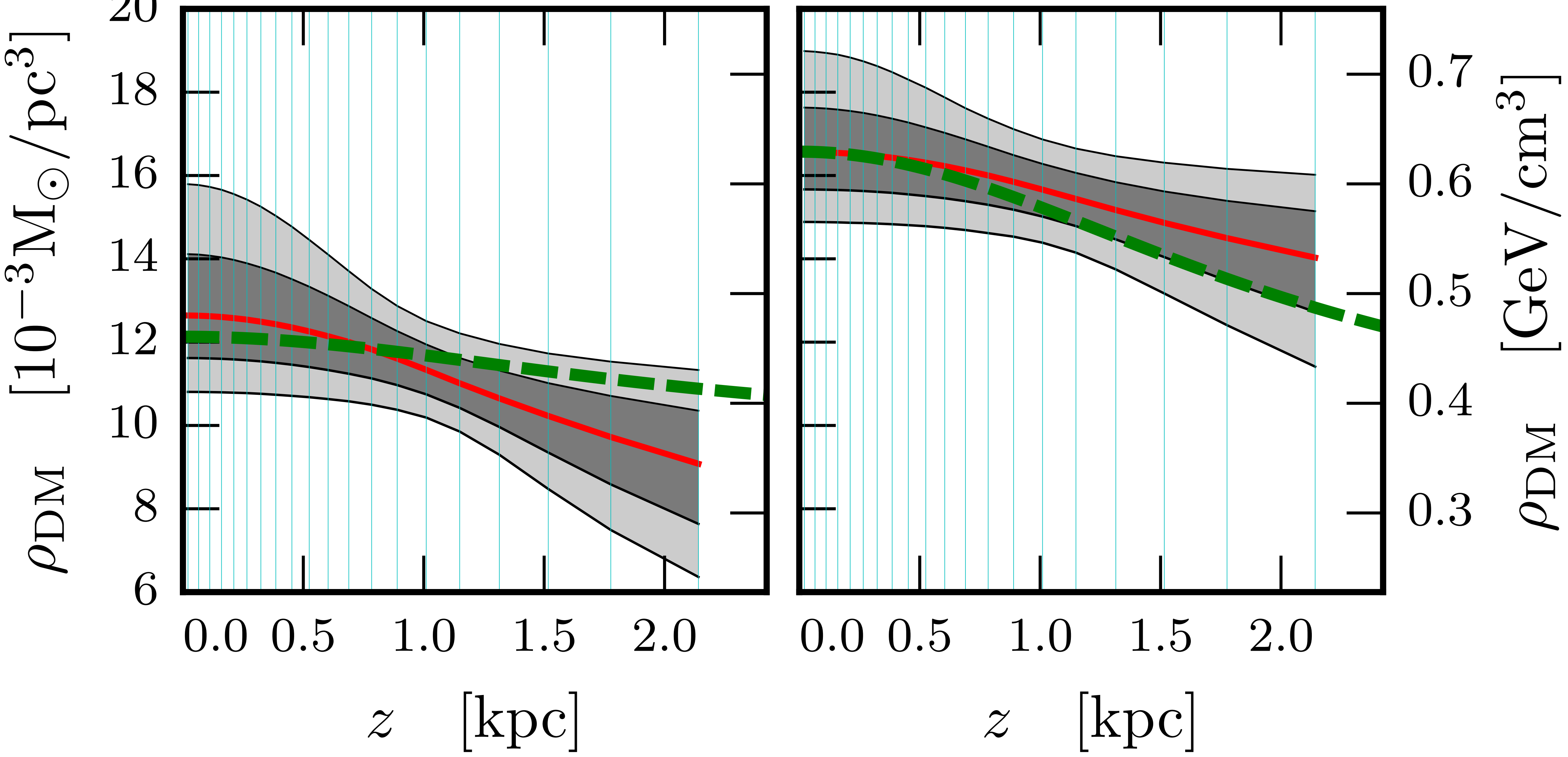
Mock: No tilt
Recon: No tilt

Mock: Tilt
Recon: No tilt

Mock: Tilt
Recon: Tilt

Neglecting tilt leads to a **systematic bias** of the **dark matter density,** given fixed baryon density profile.

Results: Dark Discs



Dark Disc

Big Dark Disc

Method is able to reconstruct a Dark Disc structure.

Ongoing Work:

- Testing on mock data sets generated from N-body simulations.
- Updating baryon model
- Working with G-dwarf measurements from the Sloan Digital Sky Survey (SDSS)

Future Work

- **2016:** Tycho-Gaia Astrometric Solution: combine data from Tycho catalogue (from Hipparcos, 1993) with first Gaia data, leverage 24 year time difference.
- Incorporate axial term and expand method to two and three dimensions
- **2016-2022**: **Gaia data releases**

arXiv:1507:08581

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Conclusions

- **New method** to reconstruct vertical Dark Matter density profile and Local Dark Matter Density
- **Enormous freedom** in describing the input models: we can move beyond constant Dark Matter density profile and exponential tracer density profile
- **Tilt term** is very important for local Dark Matter measurements - ignoring it will yield systematic bias. Our method can deal with tilt term within a 1D approach.

Thank you.

arXiv:1507:08581

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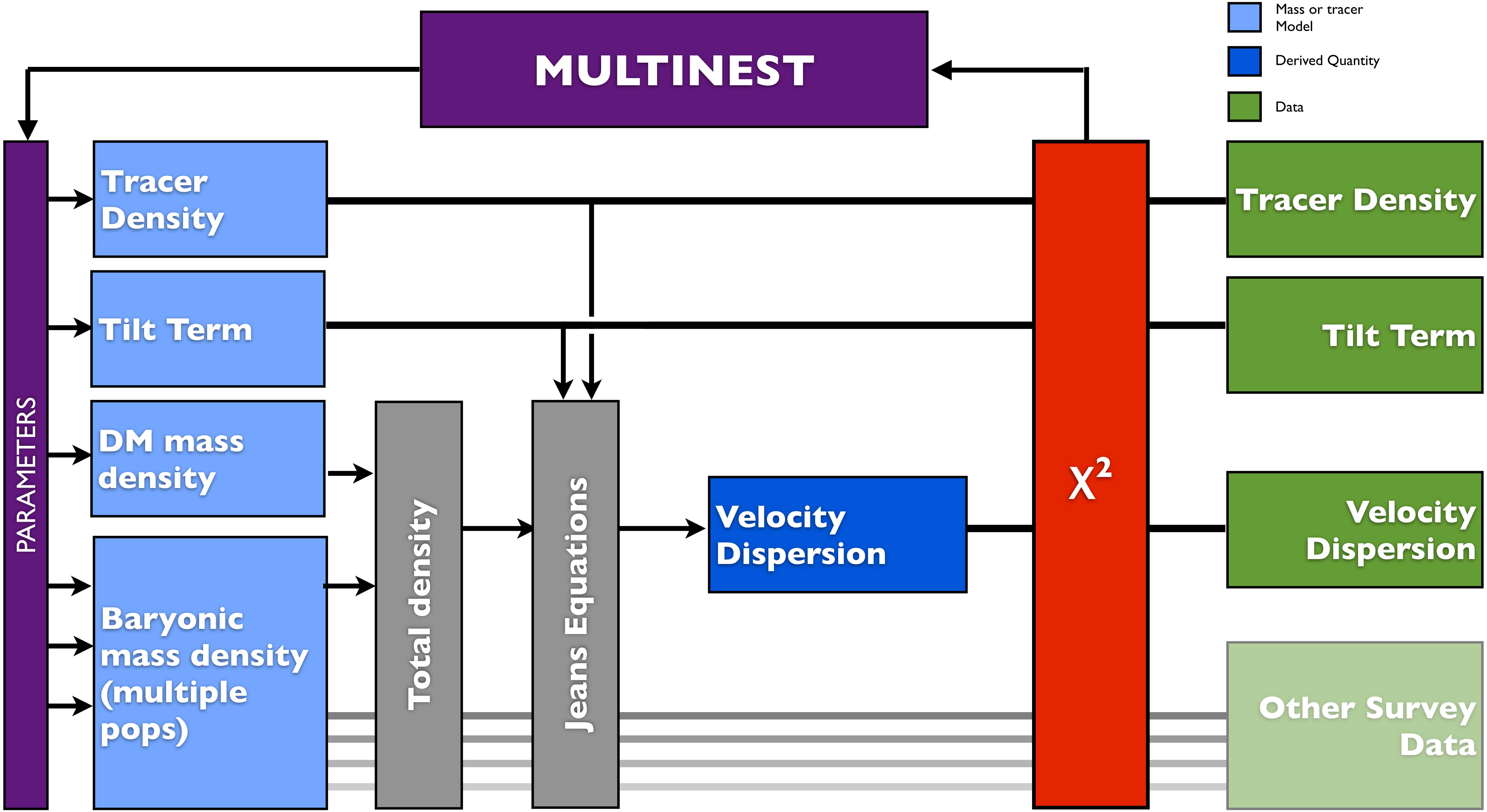
Backup Slides

🟦 Mass or tracer Model

🟦 Derived Quantity

🟩 Data



MULTINEST

PARAMETERS

Tracer Density

Tilt Term

DM mass density

Baryonic mass density (multiple pops)

Total density

Jeans Equations

Velocity Dispersion

X^2

Tracer Density

Tilt Term

Velocity Dispersion

Other Survey Data

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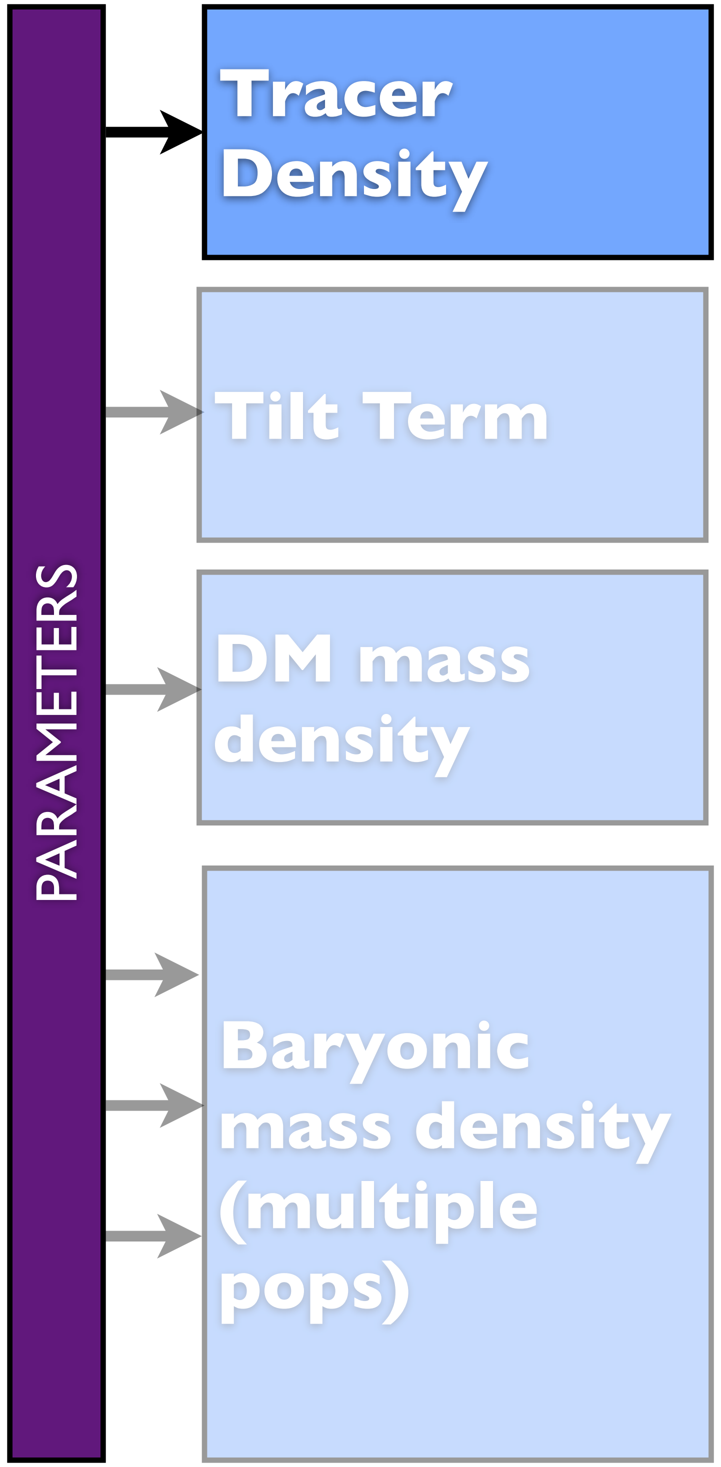

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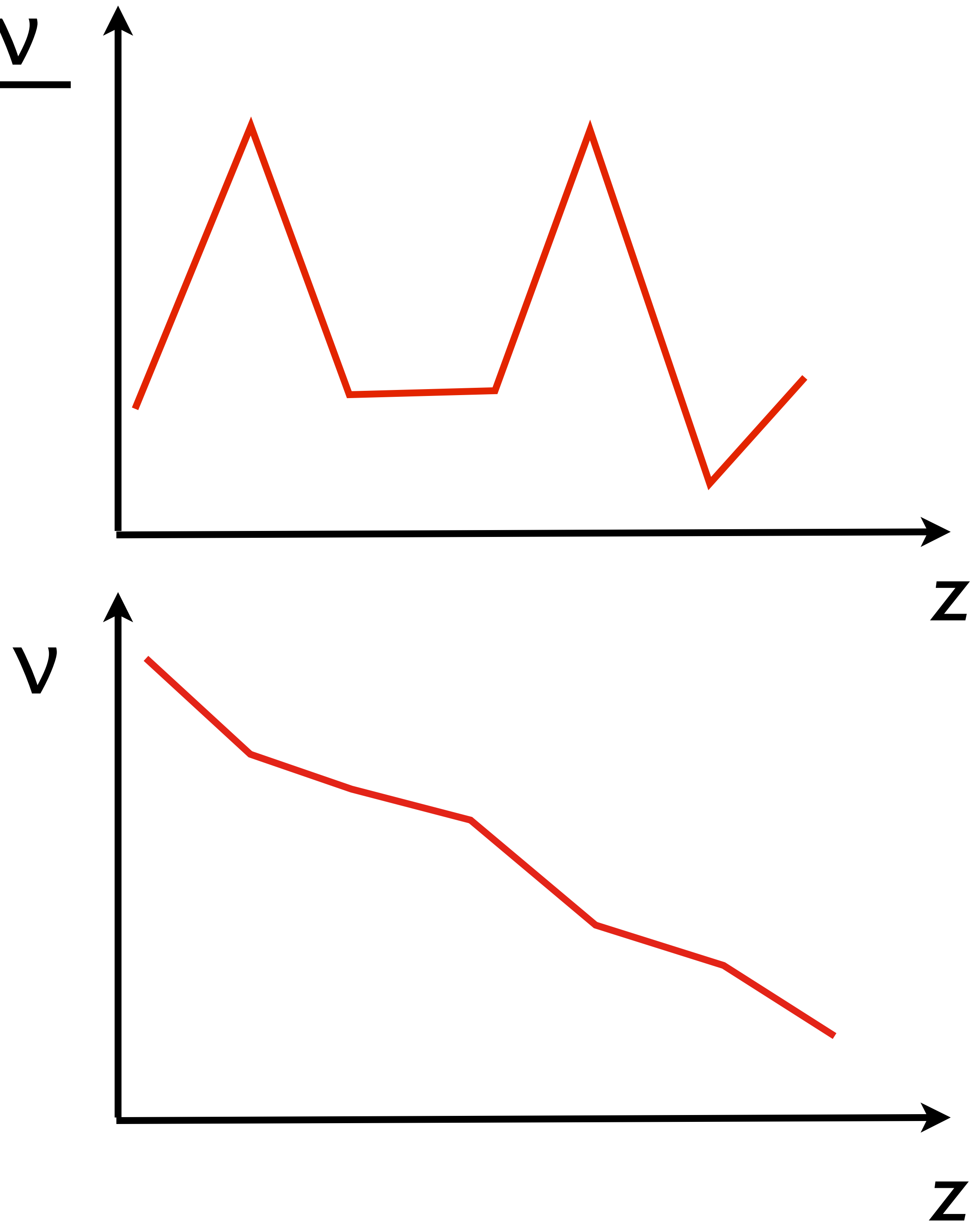

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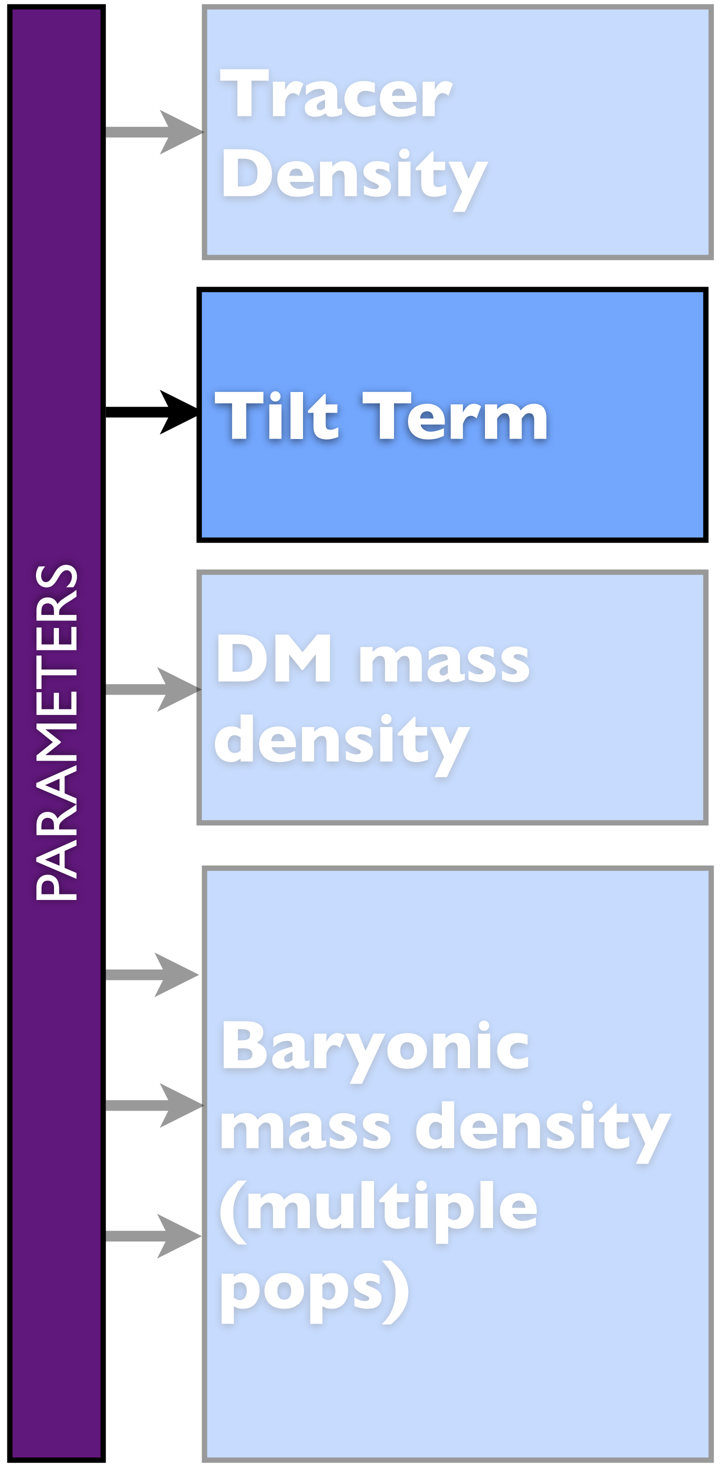
Tilt Term



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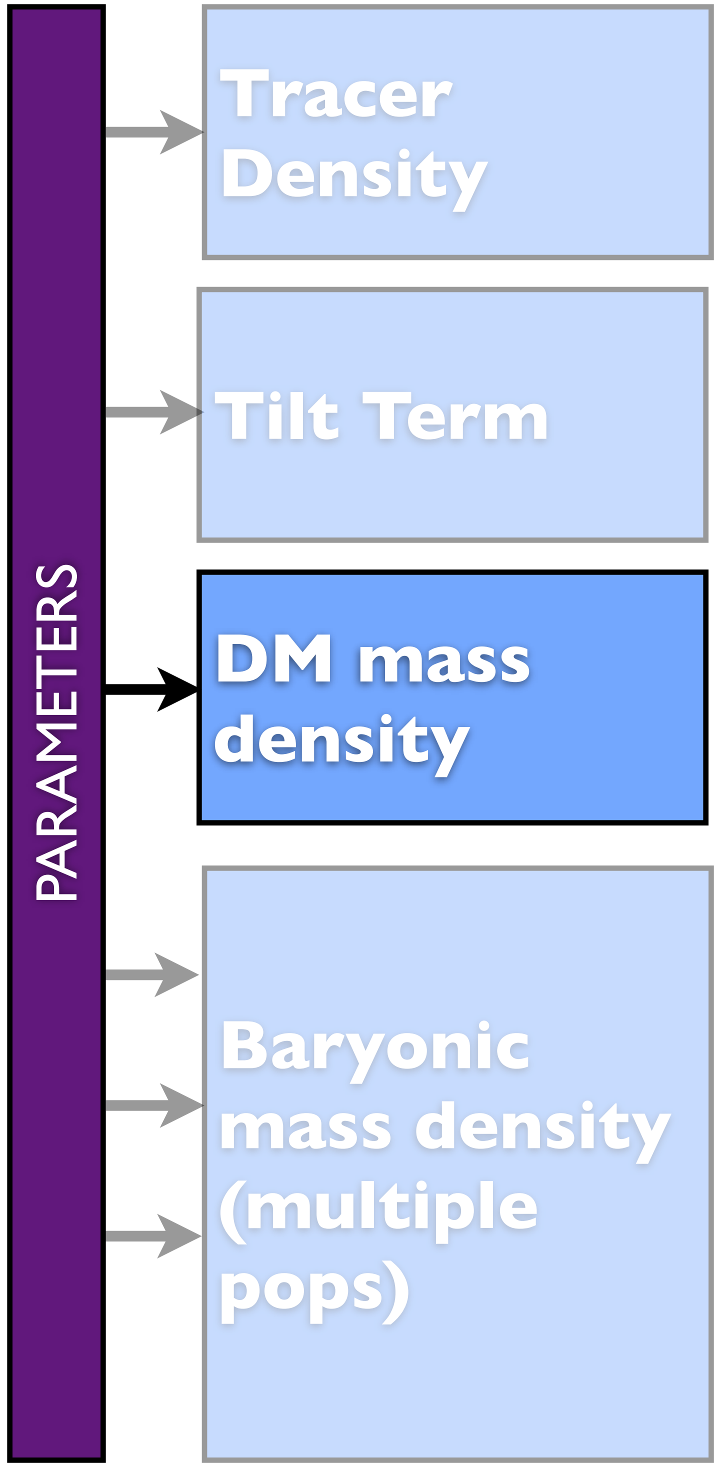

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