The Local Dark Matter Density

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Sivertsson et al., arXiv:1705:XXXXX

Why do we care about local DM density?

WIMP, sterile neutrino & axion direct detection via nuclear/electron recoils (e.g. XENON1T, LUX)

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

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

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

Relic Axion Searches via conversion to photons (e.g. ADMX)

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

→ Scans of theoretical parameter space, eg Supersymmetry

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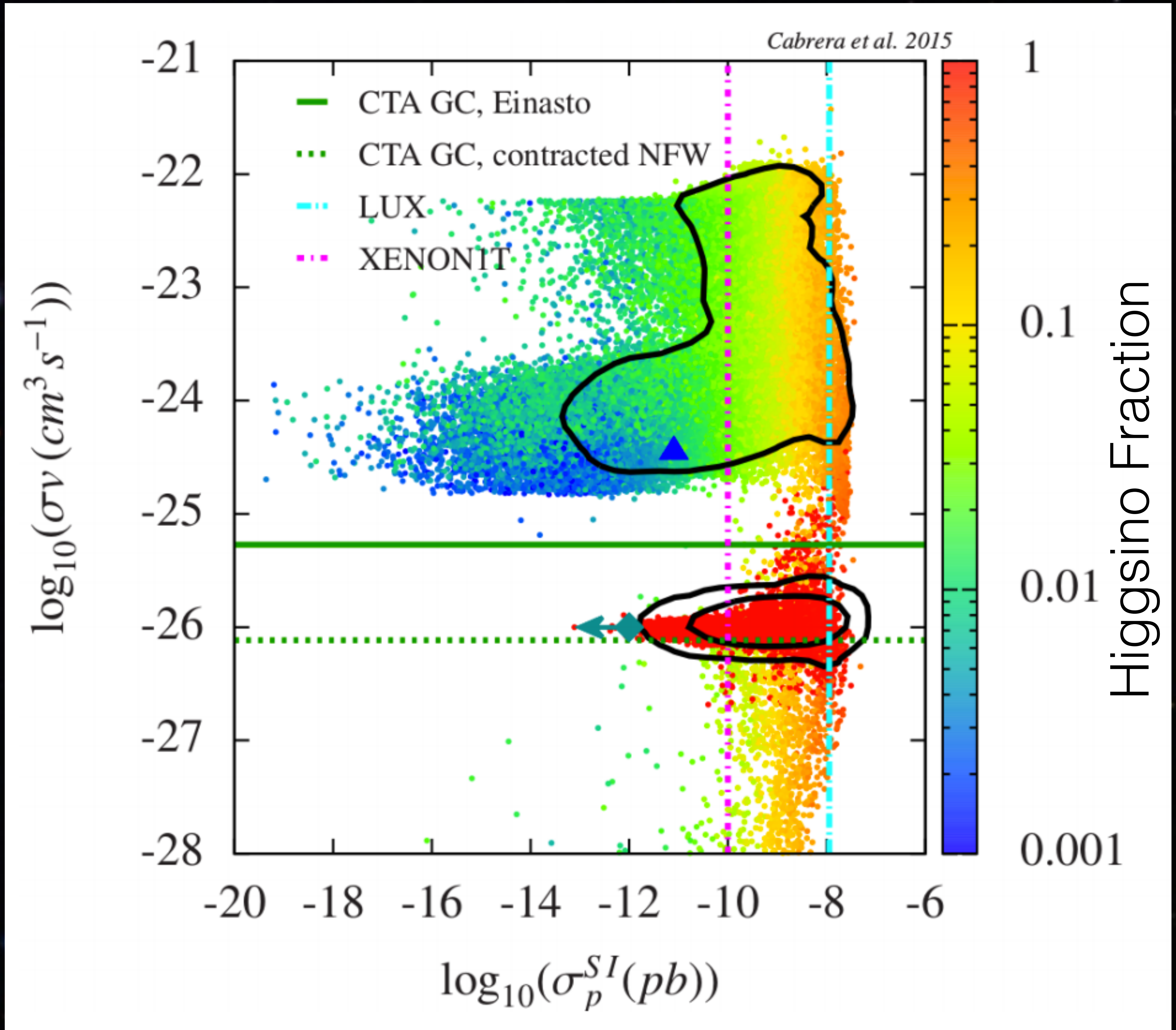
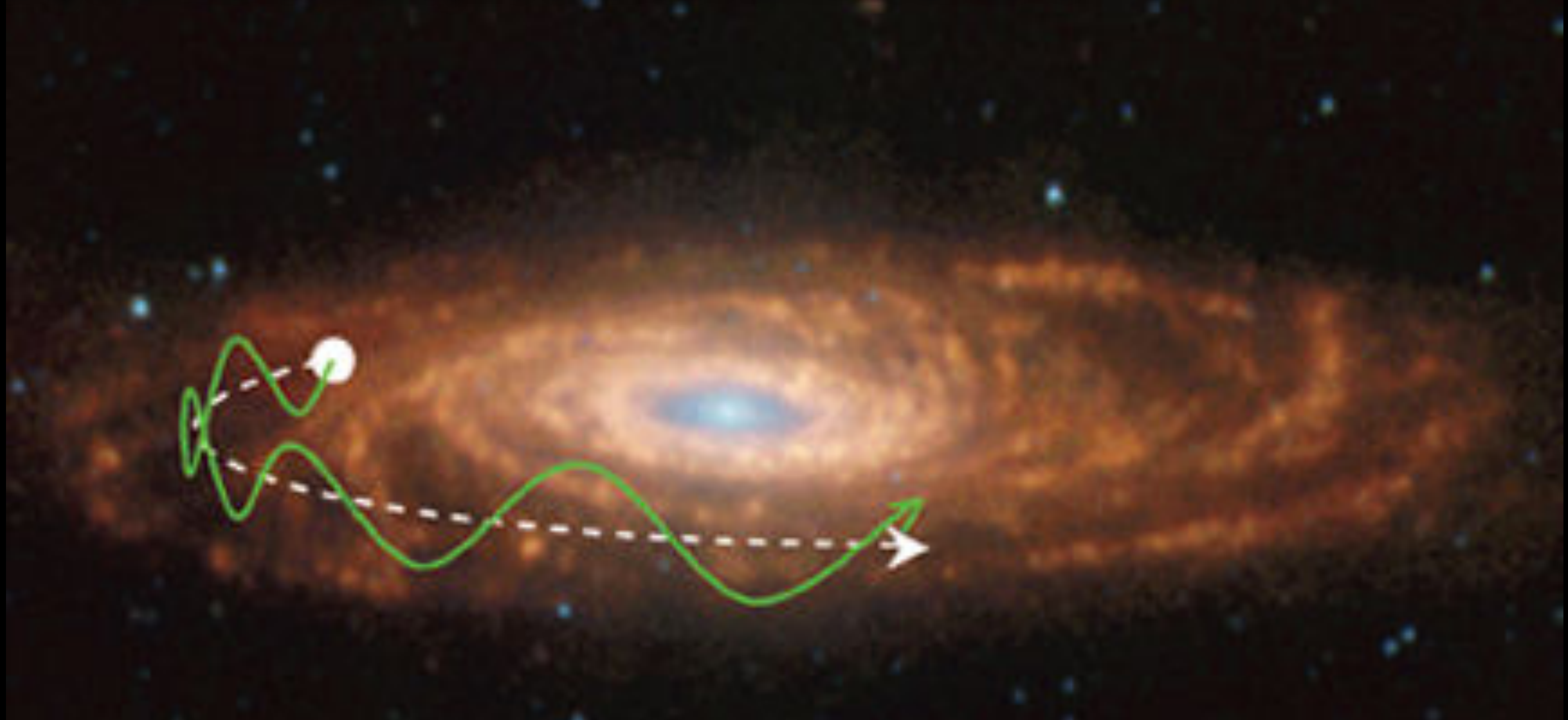


MSSM9 scans, Cabrera+ 2015, 1503.00599v2

How do we measure the local DM density?

- Fit **global** model to **global** measurements, extrapolate local value: powerful, but we have to assume global properties of the halo, e.g. rotation curves, distribution function modelling
  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; Binney & Piffl 2015,

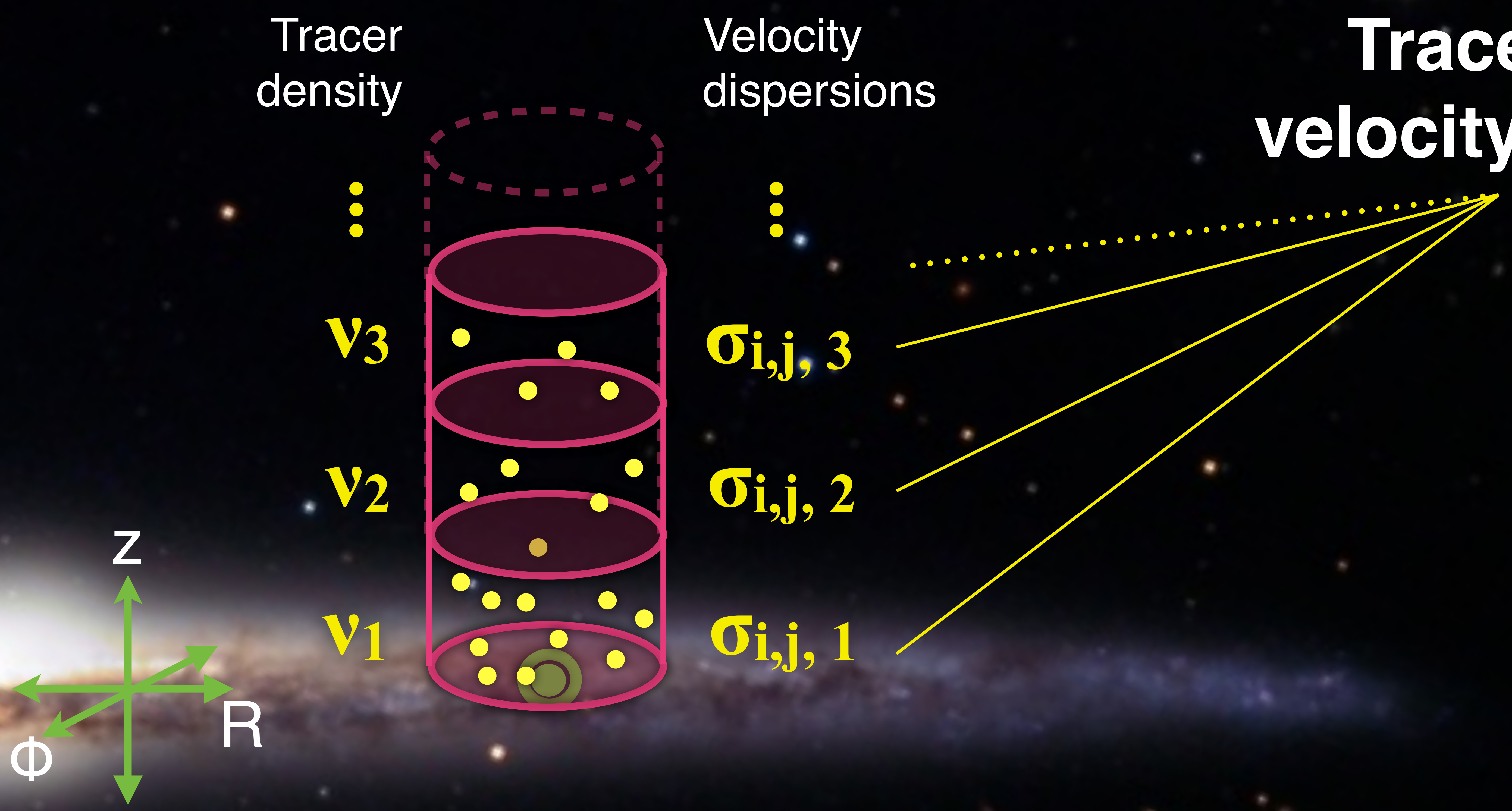
- **Local** model and **local** measurements: larger uncertainties but fewer assumptions, e.g. vertical motions of stars in the disc
  e.g. Jeans 1922; Oort 1932; Bahcall 1984; Kuijken & Gilmore 1989b, 1991; Creze et al. 1998; Garbari et al. 2012; Bovy & Tremaine 2012; Smith et al. 2012; Zhang et al. 2013; Bienaymé et al. 2014, Xia et al. 2016



Input Data Set:

Astrometric observations
SDSS-SEGUE G-dwarfs **+**
USNO obs. for proper motions
α-old (“thick”) & α-young (“thin”)
↓
z, R, v_z, v_R data
↓
Tracer density & velocity dispersion

} Budenbender, van de Ven, Watkins, 2014 1407.4808



Our Method - Integrated Jeans Equation

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

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

= 0 from assumption of time independence

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

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

Integrate 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

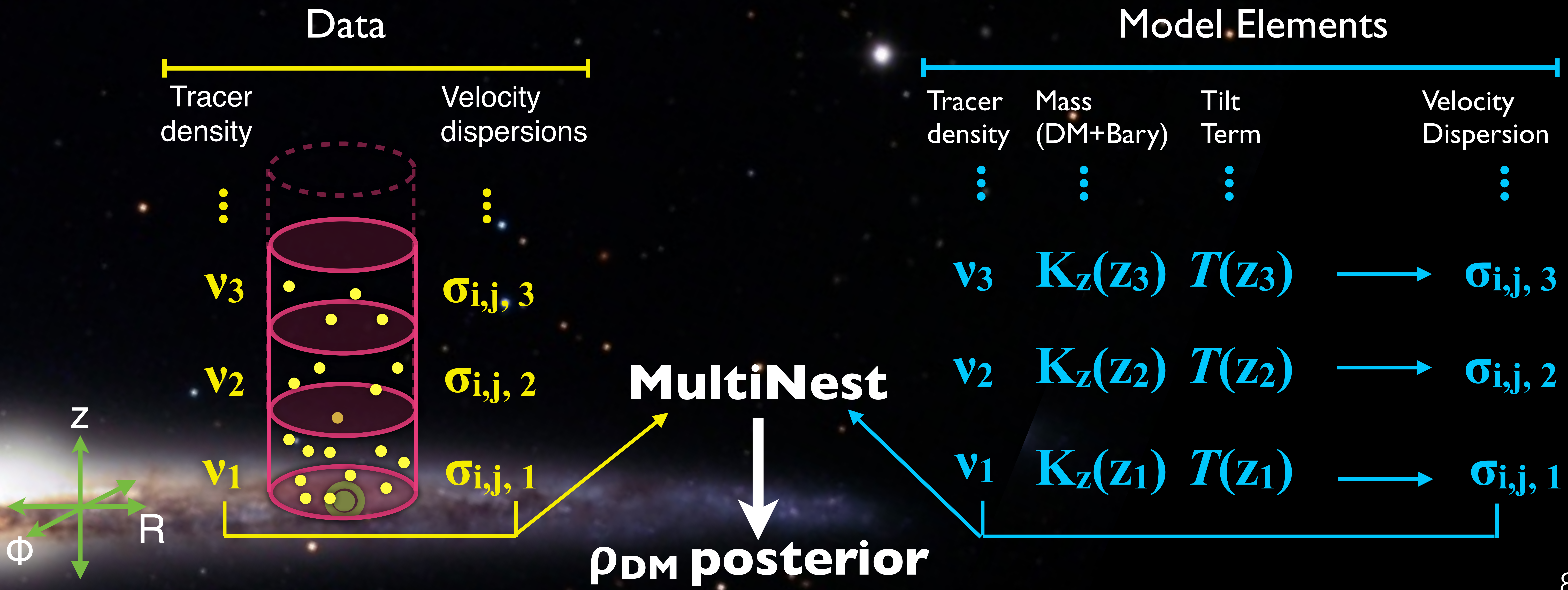
Construct model for

- **tracer density v,**
- **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 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
- 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.

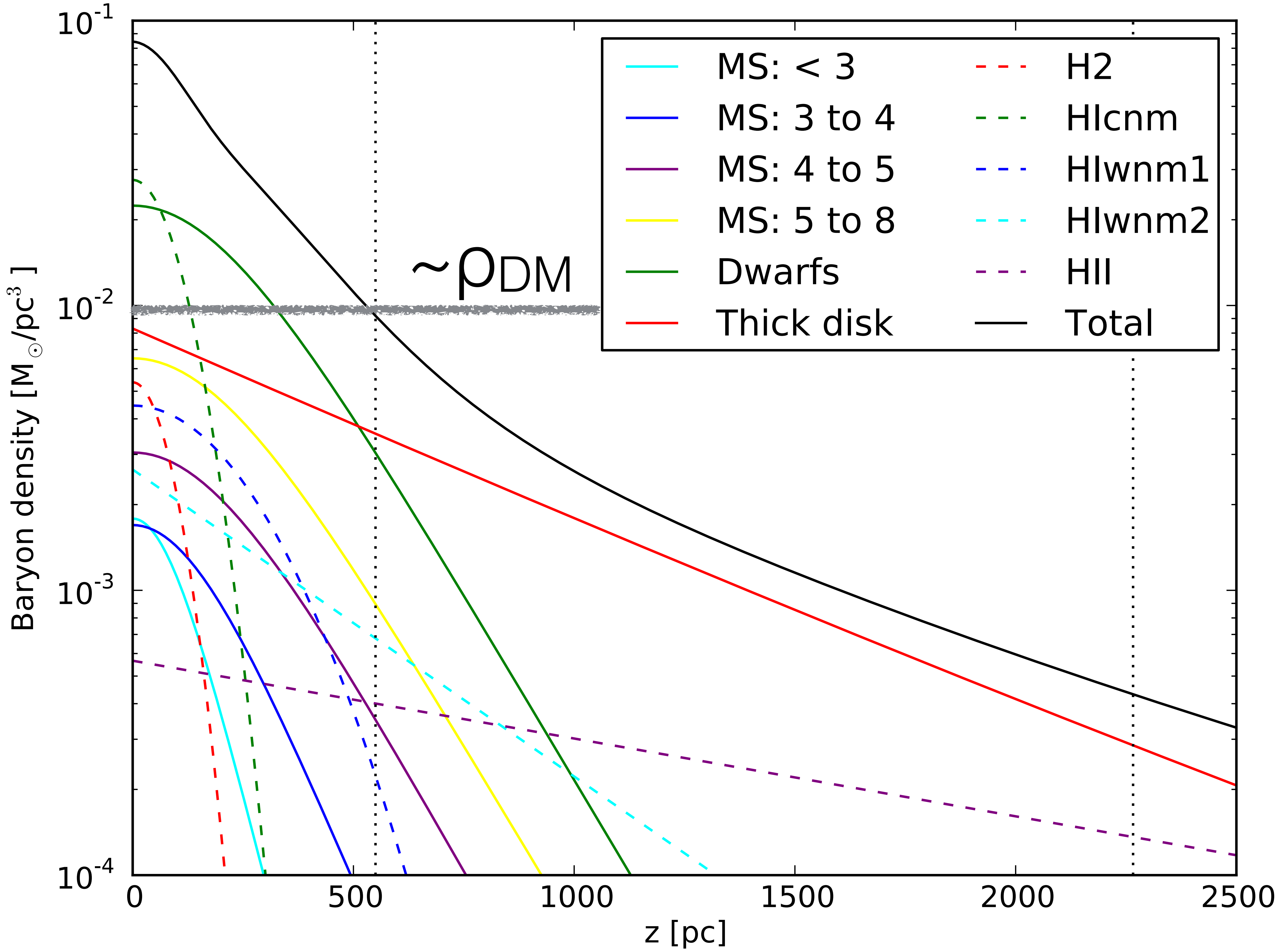
$$\frac{\partial^2\Phi}{\partial z^2} = 4\pi G\rho(z)_{\rm eff} \qquad \rho(z)_{\rm eff} = \rho(z) - \frac{1}{4\pi G R}\frac{\partial V_c^2(R)}{\partial R}$$

- 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** or **0.003 Msun/pc^3**.

Modelling the components:

Baryon Modelling

- Compiled from McKee+ ApJ 814(2015)13, arXiv:1509.05334
- Marginalize over the total surface density and the underlying shape (e.g. thicker vs thinner baryonic disc).
- Σ_{baryon} $(z \rightarrow \infty) = 46.95\ M_\odot\ pc^{-2} \pm 13\%$.



Modelling the components:

Tilt Term:

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

Vertical behaviour of σ_{Rz}^2 at the solar radius

Encodes information on the radial behaviour of ν and σ_{Rz}^2

Fit to data from Budenbender+

No radial information from Budenbender+, so we impose priors on k based on Bovy et al. 2016:

α-young k = [-1.3, -1.0]

α-old k = [-0.5, 1.5]

Results: α-young vs α-old

- α-young ("thin disc") not as sensitive to tilt term as the α-old ("thick disc")
- mismatch between α-young and α-old results…

		α-young		α-old		Combined analysis
		Tilt	No Tilt	Tilt	No Tilt	Tilt
95% CR upper	$\mathrm{GeV\,cm^{-3}}$	**0.59**	0.57	0.85	0.51	0.48
	$\mathrm{M_\odot\,pc^{-3}}$	**0.016**	0.015	0.022	0.013	0.013
68% CR upper	$\mathrm{GeV\,cm^{-3}}$	**0.53**	0.53	0.79	0.48	0.43
	$\mathrm{M_\odot\,pc^{-3}}$	**0.013**	0.014	0.021	0.013	0.012
Median	$\mathrm{GeV\,cm^{-3}}$	**0.46**	0.48	0.73	0.46	0.40
	$\mathrm{M_\odot\,pc^{-3}}$	**0.012**	0.013	0.019	0.012	0.011
68% CR lower	$\mathrm{GeV\,cm^{-3}}$	**0.37**	0.42	0.68	0.44	0.37
	$\mathrm{M_\odot\,pc^{-3}}$	**0.0098**	0.011	0.017	0.012	0.0097
95% CR lower	$\mathrm{GeV\,cm^{-3}}$	**0.30**	0.35	0.60	0.42	0.34
	$\mathrm{M_\odot\,pc^{-3}}$	**0.0078**	0.0092	0.016	0.011	0.0091

Results: We don't trust α-old…

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- α-old (thick disc) results favour a very high baryon density e.g. large amounts of mass at low z.

- α-old data has more unknowns and potential problems:
  - more sensitive to tilt and hence our assumptions on the tilt model
  - more contamination from stellar halo
  - stars are further away, increasing measurement errors
  - previous assumptions on the impact of the rotation curve term are derived close to the disc, may not be applicable at larger z
  - thick disc has longer vertical equilibration time, so might still be oscillating from prior satellite merger

What we trust: α-young ("thin disc") with tilt.

$$\rho_{\rm DM} = 0.46^{+0.07}_{-0.09}\,{\rm GeV\,cm^{-3}}$$
$$= 0.012^{+0.001}_{-0.002}\,{\rm M_\odot\,pc^{-3}}$$

The Hopes for Gaia…

- We need more data on the **radial variation** of **tracer density** ν and **velocity dispersion** σ_{Rz} to better model the tilt term.
- We need more data on the **impact of the rotation curve**, including at high-z

So we will do what we can with TGAS and other cross matches, and wait for DR2…

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Conclusions

- $$\rho_{\rm DM} = 0.46\,^{+0.07}_{-0.09}\,{\rm GeV\,cm^{-3}}$$
  $$= 0.012\,^{+0.001}_{-0.002}\,{\rm M_\odot\,pc^{-3}}$$

- We need more data on the radial variation of σ_{Rz}^2, and the rotation curve term at higher z…

… and so on to Gaia DR2!