Can Gaia conclude the local dark matter density problem?

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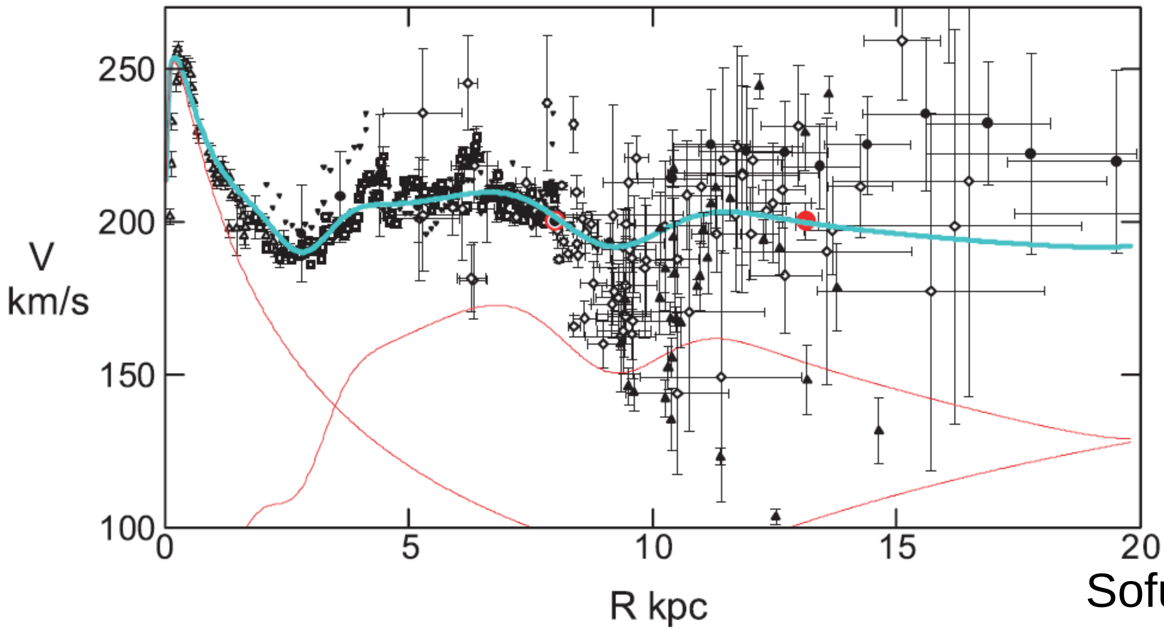
"Astrometric mock observations for determining the local dark matter density"

Inoue & Gouda (2013) A&A, 555, A105

The Galactic DM halo



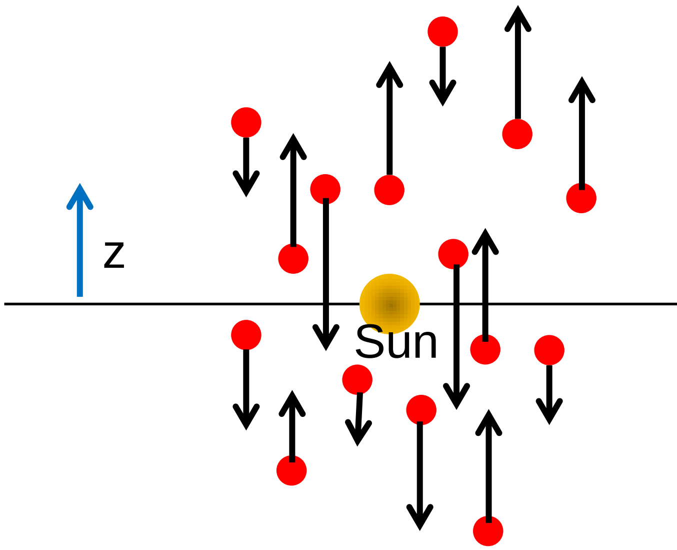
Sofue et al. (2009)

- The Galactic rotation curve
  - The analysis has to assume spherical symmetry.
    - The DM density at the solar radius
      - e.g. Sofue (2012) $\rho_{DM,RC} \cong 0.006\ M_{\odot}/pc^3$

    - However, the Galactic halo may not be spherical.

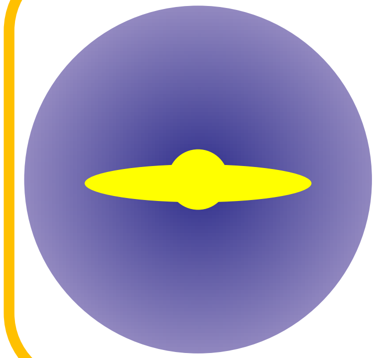
LDMD determination by vertical motions

- How is the LDMD determined?
    - an old problem; since Oort (1932, 1960), Hill (1960)
  - z-Jeans eq. for dynamical tracers
    - $\frac{\partial}{\partial z}(\rho {\sigma_z}^2) + \rho \frac{\partial \Phi}{\partial z} = 0$
    - or Boltzmann eq.



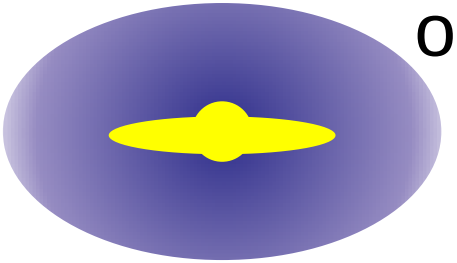
  - If we know (or assume) ρ and σ_z, Φ can be derived.
  - Baryonic density can be subtracted, then we can determine the DM density.

DM halo shape and the LDMD



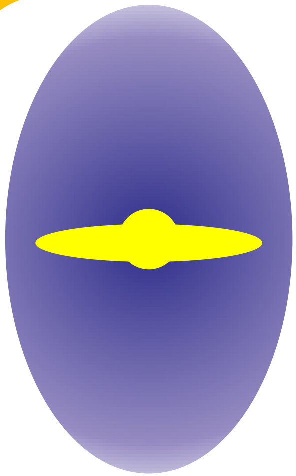
spherical

LDMD= $\rho_{DM,RC}$



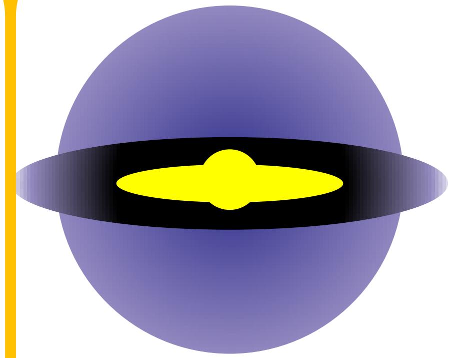
oblate

LDMD > $\rho_{DM,RC}$



prolate

LDMD < $\rho_{DM,RC}$



dark disc

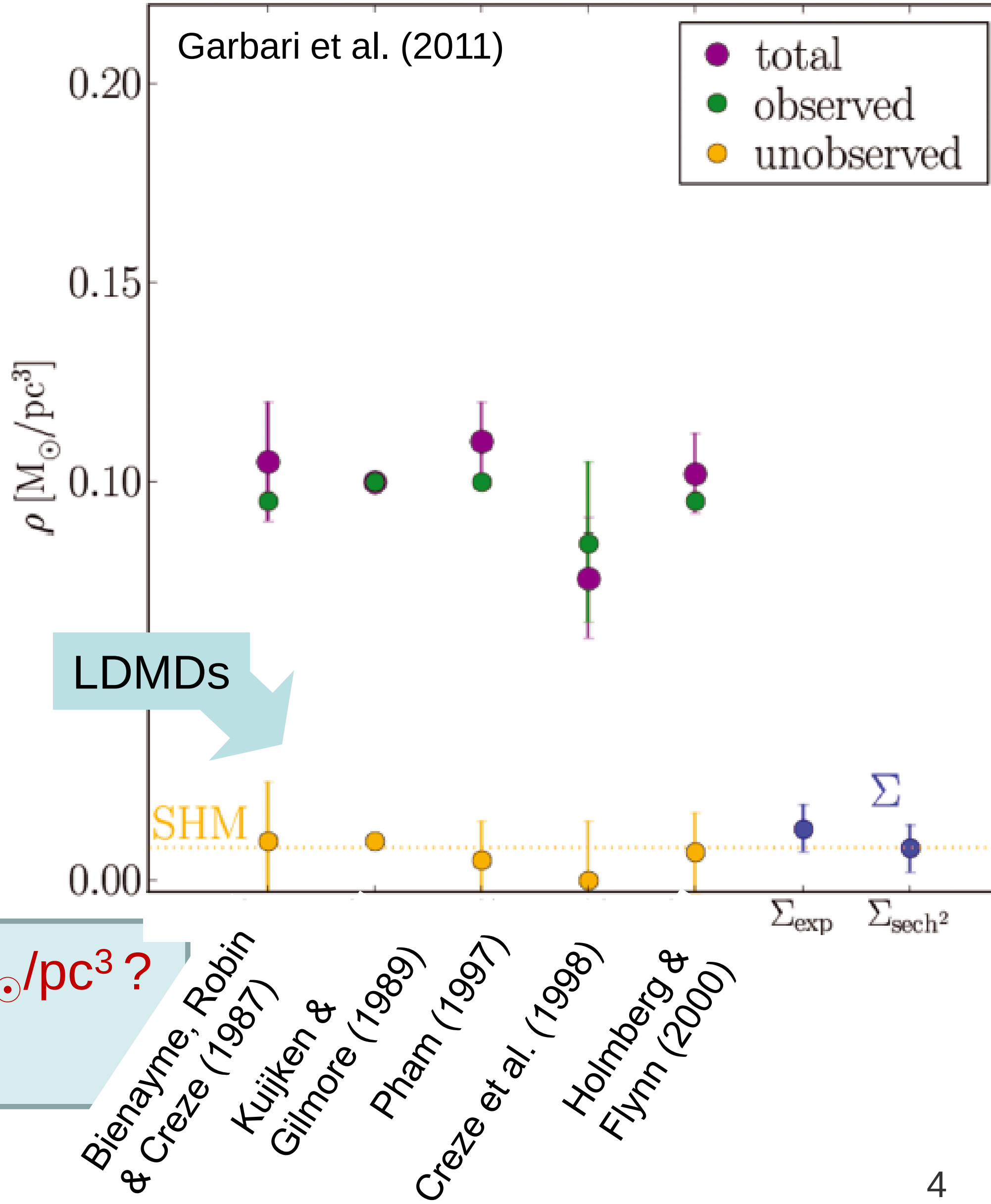
(Read et al. 2009)

LDMD > $\rho_{DM,RC}$

It may give us a hint on the DM halo shape to compare the $\rho_{DM,RC}$ with the LDMD.

LDMDs in previous studies

- Garbari et al. (2011)
  - LDMD ≅ 0.033 $M_\odot/pc^3$
- Garbari et al. (2012)
  - LDMD ≅ 0.022 $M_\odot/pc^3$
- Bovy & Tremaine (2012)
  - LDMD ≅ 0.008 $M_\odot/pc^3$
- Smith et al. (2012)
  - LDMD ≅ 0.015 $M_\odot/pc^3$
- Zhan et al. (2013)
  - LDMD ≅ 0.006 $M_\odot/pc^3$



- conversing on ~0.006 – 0.033 $M_\odot/pc^3$?
- higher than $\rho_{DM,RC}$? or similar?

The aim of this study

- This study performs **"mock"** observations of astrometry.
  - to scrutinize a method
    - Minimal Assumption method (Garbari et al. 2011, 2012)
    - Are there intrinsic systematic errors in the method?
  - to estimate observational precisions required to determine the LDMD with accuracy.
    - Were the Hipparcos observations precise enough?
    - Are the Gaia observations precise enough?

- the Minimal Assumption method
  - *cf. Garbari et al. (2011, 2012)*

The MA method by Gairbari et al. (2011, 2012)

- **The Minimal Assumption (MA) method**

- Assumptions
  1. The system is in equilibrium
  2. DM density is constant in the region we consider ($z < 1.2$ kpc)
  3. The "tilt" term is negligible in Jeans equation

◆ *Step1* Choose trial parameters

- the LDMD; ρ_{DM}
- 15 baryon components; $\rho_{i,0}$, $\sigma_{z,i}$ at $z = 0$

◆ *Step2* Solve the equations below, compute the trial potential $\Phi(z)$

- $\frac{\partial^2 \Phi}{\partial z^2} = 4\pi G(\rho_b + \rho_{DM})$
- $\rho_b = \sum \rho_{i,0} exp\left(-\frac{\Phi(z)}{\sigma_{z,i}{}^2}\right)$ ← isothermal disc model

The MA method (galaxy model)

Flynn et al. (2006)

#	Component	$\rho_i^{\mathrm{ass}}(0)$ [$M_\odot$ pc^{-3}] (observation)		$\sigma_{z,i}(0)$ [km s^{-1}] (observation)
1	H_2	0.021	50% error	4.0 ±1.0
2	HI(1)	0.016		7.0 ±1.0
3	HI(2)	0.012		9.0 ±1.0
4	Warm gas	0.0009		40.0±2.0
5	Giants	0.0006	20% error	20.0±2.0
6	$M_v < 2.5$	0.0031		7.5 ±2.0
7	$2.5 < M_v < 3.0$	0.0015		10.5±2.0
8	$3.0 < M_v < 4.0$	0.0020		14.0±2.0
9	$4.0 < M_v < 5.0$	0.0022		18.0±2.0
10	$5.0 < M_v < 8.0$	0.007		18.5±2.0
11	$M_v > 8.0$	0.0135		18.5±2.0
12	White dwarfs	0.006		20.0±5.0
13	Brown dwarfs	0.002		20.0±5.0
14	Thick disk	0.0035		37.0±5.0
15	Stellar halo	0.0001		100.0±10.0

- Densities and velocity dispersions at z=0

The MA method by Gairbari et al. (2011, 2012)

- Necessary observations of tracer stars
  - density profile: $\rho_{trac}(z)$
  - velocity dispersion profile: ${\sigma_{z,trac}}^2(z)$

◆ *Step3* predict the tracer density profile

- input ${\sigma_{z,trac}}^2(z)$ and the trial potential $\Phi(z)$ into Jeans equation,
  - $\rho_{pred}(z) = \rho_{pred}(z_{min}) \frac{{\sigma_{z,trac}}^2(z_{min})}{{\sigma_{z,trac}}^2(z)} exp\left\{- \int_{z_{min}}^{z} \frac{1}{{\sigma_{z,trac}}^2(z\prime)} dz'\right\}$

non-isothermal

◆ *Step4* compare the predicted and the observed density fall-off

- evaluate goodness-of-fit
- MCMC: go back to step1

see Garbari et al. (2011, 2012)

- Mock galaxy model

    Mock tracer model

Mock galaxy and tracer models

- I assume "**mock**" density distributions for a galaxy model.
- Density profiles for the 15 baryon components and DM
  - baryon $\rho_i(z) = \rho_{0,i}\,\mathrm{sech}^2(z/h_{z,i})$
    - for each of the 15 components with each scale height
  - dark matter $\rho_{DM} = 0.01\ M_\odot/pc^3$

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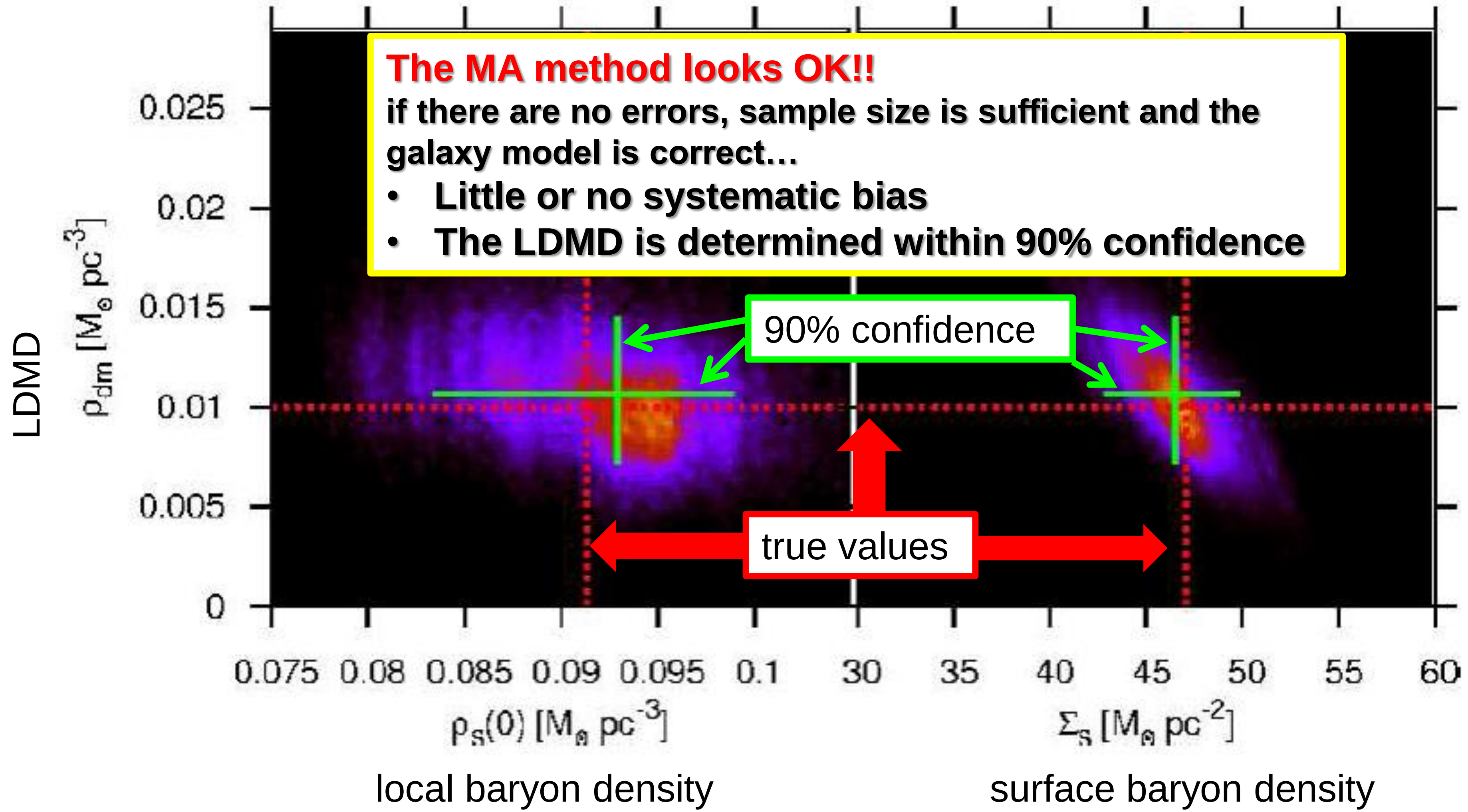
11	$M_v > 8.0$	0.0135
12	White dwarfs	0.006
13	Brown dwarfs	0.002
14	Thick disk	0.0035
15	Stellar halo	0.0001

- If a tracer density profile is assumed, ${\sigma_{z,trac}}^2(z)$ can be calculated.
  - $\rho_{trac}(z) \propto \mathrm{sech}^2(z/400\ pc)$
  - ${\sigma_{z,trac}}^2(z) = \frac{1}{\rho_{trac}} \int_z^\infty \rho_{trac} \frac{d\Phi}{dz'} dz'$

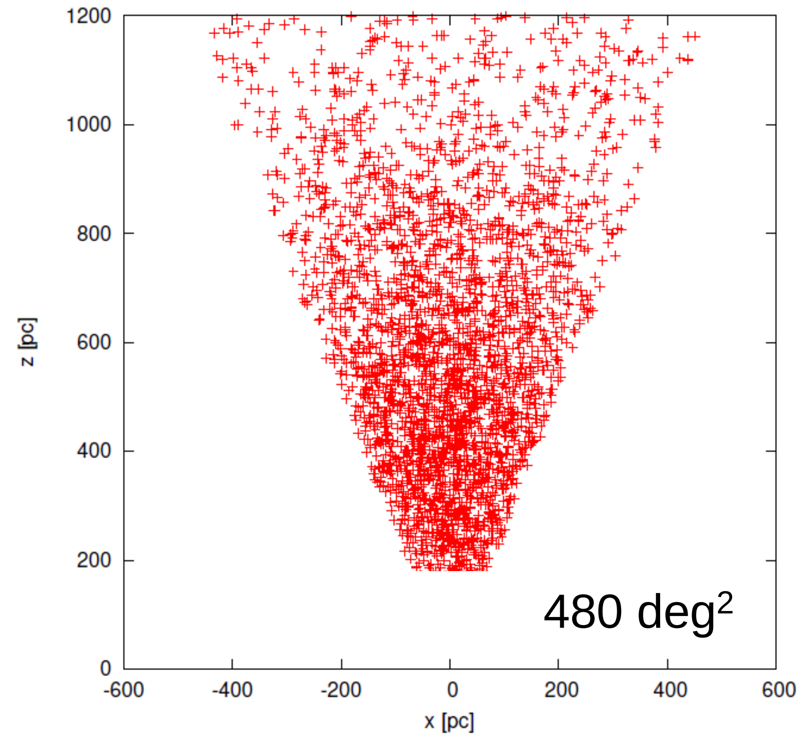
test of the MA method with the analytic solutions

- MCMC outputs: PDFs of the parameters.



Mock tracer model & observations

- tracer density distribution
  - $\rho_{trac}(z) \propto \mathrm{sech}^2(z/400\ pc)$
    - $z_{min} = 200$ pc, $z_{max} = 1.2$ kpc



- velocity distributions (Gaussian)
  - $\sigma_{z,trac}{}^2(z) = \frac{1}{\rho_{trac}} \int_z^\infty \rho_{trac} \frac{d\Phi}{dz'} dz'$
  - $\sigma_{R,trac}(z) = 40 + 5 \left|\frac{z}{kpc}\right|^{1.5}$ [km/s]
  - $\overline{v_{\phi,trac}}(z) = -19.2 \left|\frac{z}{kpc}\right|^{1.25}$ [km/s]
  - $\sigma_{\phi,trac}(z) = 30 + 3 \left|\frac{z}{kpc}\right|^{2}$ [km/s]

from observations of Bond et al. (2010)

The mock observations are 3D, but the variations of ρ_{trac} and σ_{trac} are 1D.

Mock tracer model & observations

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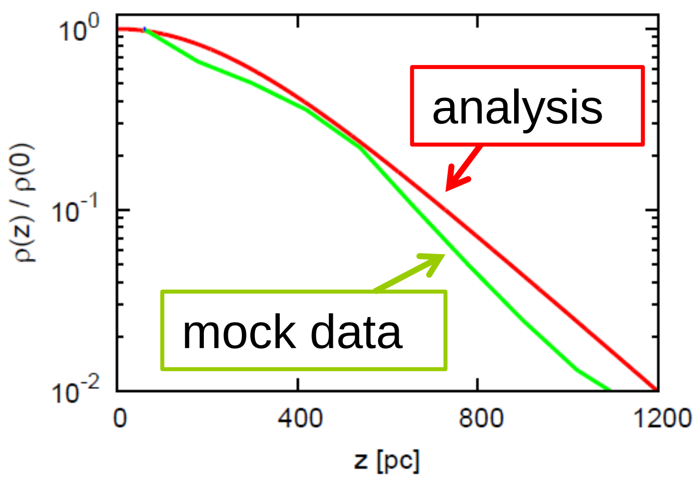

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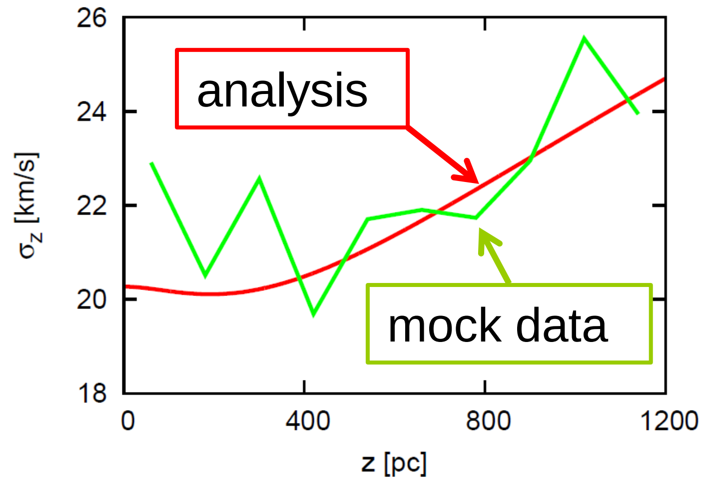
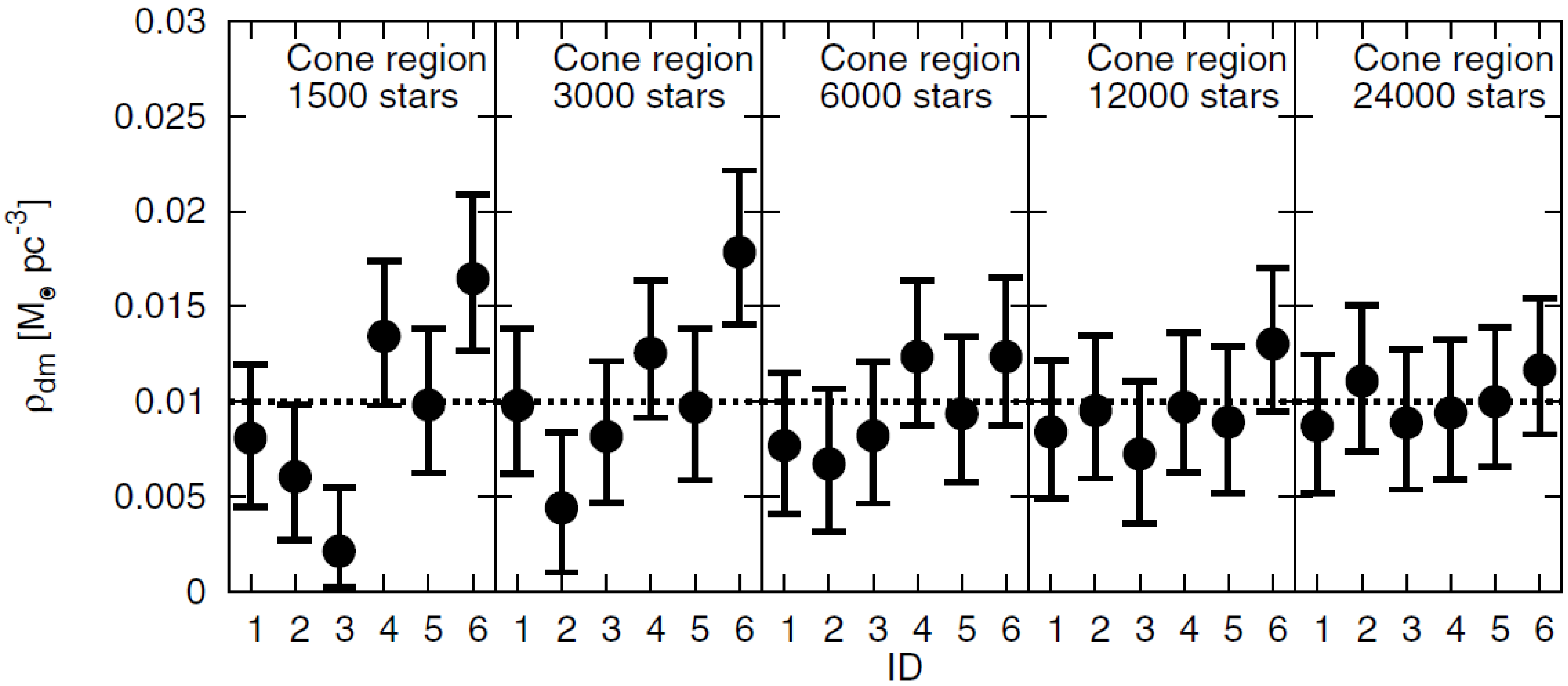


- Mock observations
  - required sample size

Required sample sizes

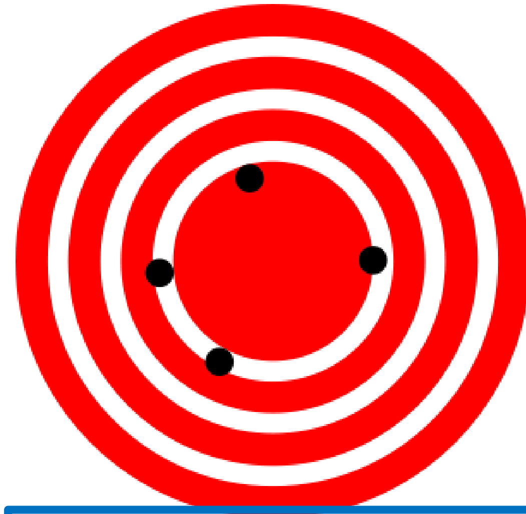
- ~>6000 stars are required to determine the LDMD



The error bars are indicating 90% confidence levels.

- Mock observations
  - required observational precisions

What is advantage of astrometry?



imprecise but accurate

inaccurate but precise

- Astrometry is imprecise, but accurate.
  - systematic errors << random errors
  - The errors are already-know.
- In this study, observational uncertainties are assumed to be random Gaussian errors.

Mock distance errors

- In astrometry, distance errors can be formalized as follows:
  - Stellar image centroids are determined by photon statistics
    - $\sigma_{\varpi} \propto 1/\sqrt{f} \propto d$
  - fractional parallax error
    - $\sigma_{\varpi}/\varpi \propto d^2$
  - fractional parallax error is equal to fractional distance error (FDE).

$$\varepsilon_{\mathrm{FDE}} = A \left(\frac{d}{\mathrm{kpc}} \right)^2$$

  - A corresponds to parallax precision in mas at $d = 1$ kpc.

Mock distance errors

- Applying the distance errors to the mock data with Gaussian.

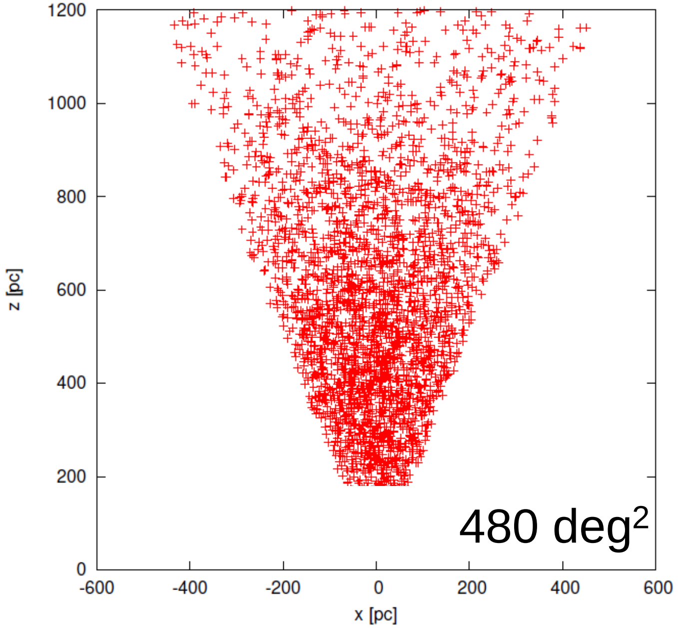
$$(x, y, z, v_x, v_y, v_z)$$

$$\Downarrow$$

$$(d, \theta, \phi, v_{\rm los}, v_\theta, v_\phi)$$ + errors

$$\Downarrow$$

$$(x', y', z', v'_x, v'_y, v'_z)$$

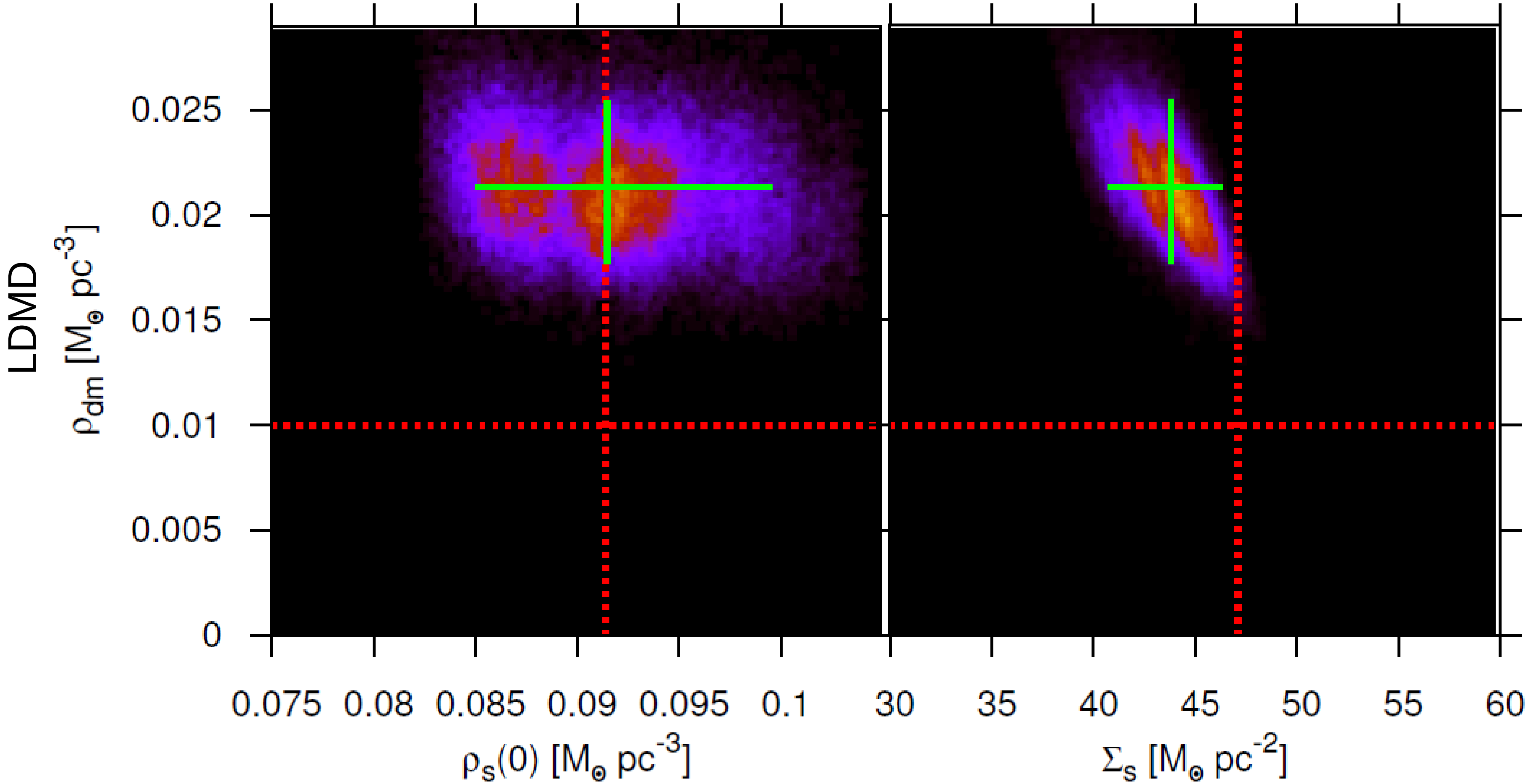


- Moreover, the distance errors propagete to transverse velocities.

$$v_\theta = d \times \mu_\theta \qquad v'_\theta = v_\theta \frac{d'}{d}$$

Mock distance errors

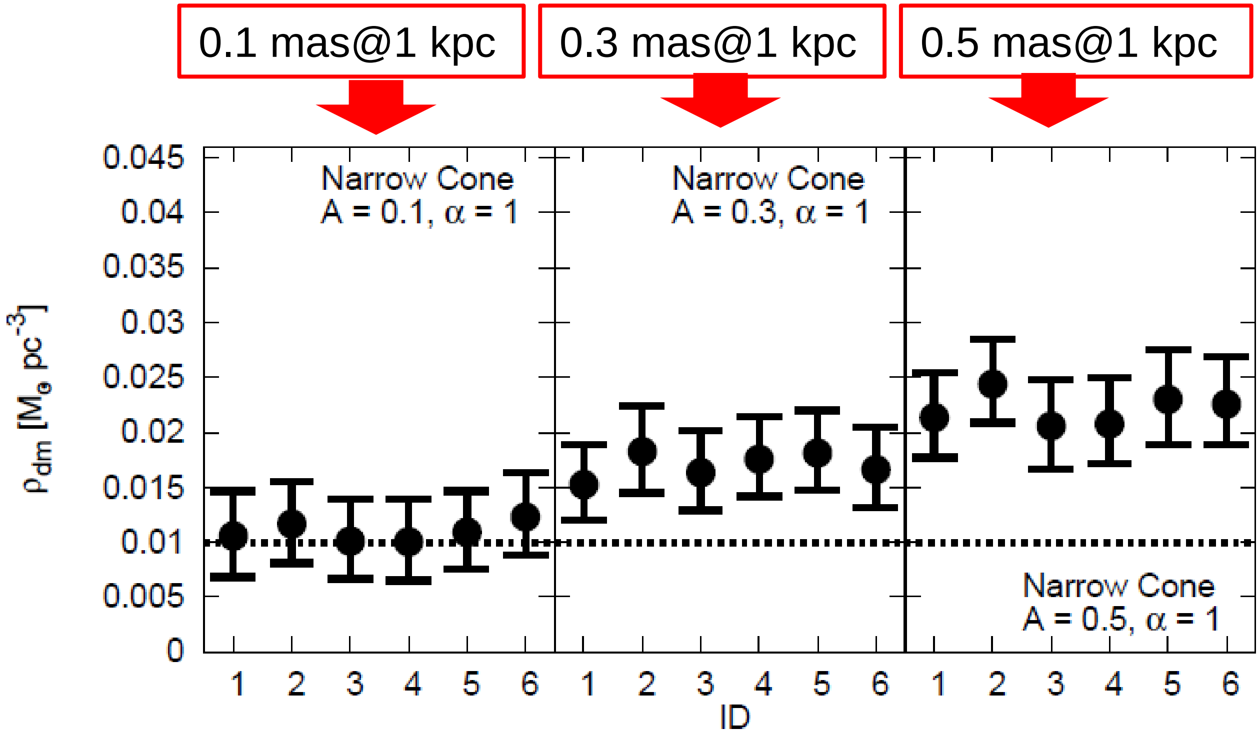
0.5 mas@d=1 kpc
24,000 stars



local baryon density

surface baryon density

Mock distance errors

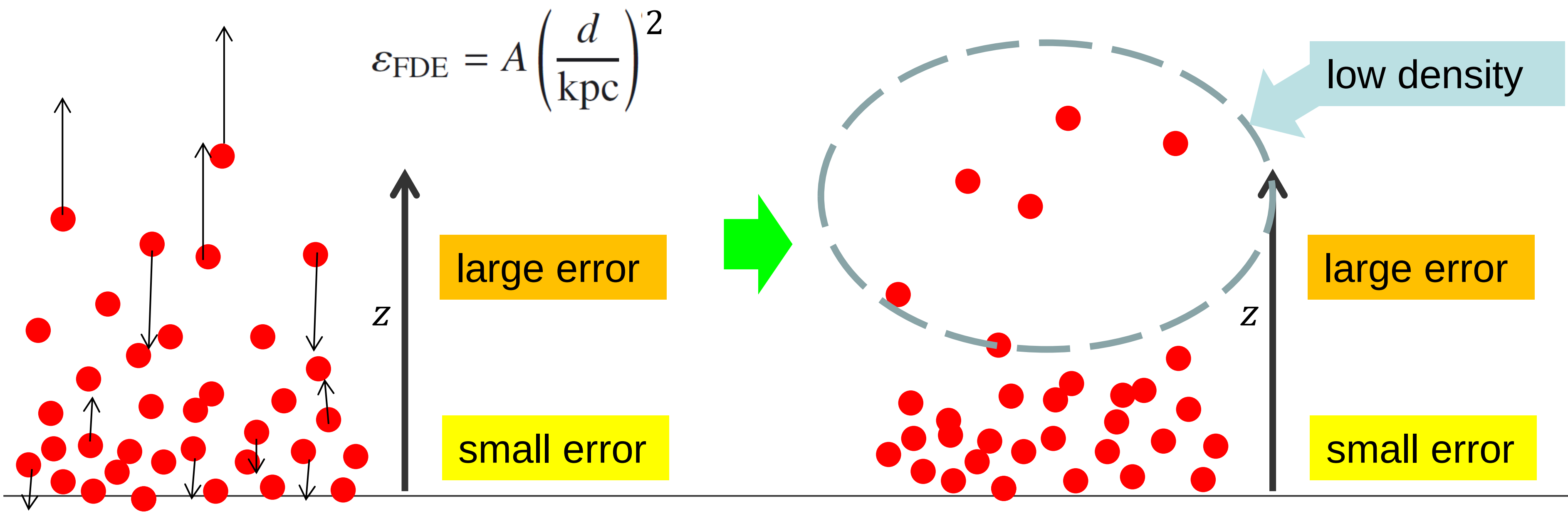


- **The parallax errors can cause a systematic overestimate of the LDMD.**
- **Required parallax precision is <u>0. 1- 0. 3 mas @ *d*=1 kpc</u>**

  - ***Hipparcos*** **~1mas @ *d*=100 pc**
  - **Gaia** **~0.06 mas @ d= 1kpc for K stars**

Why overestimate?

- The distance errors are *random* Gaussian.
  - However, the LDMD was systematically overestimated.



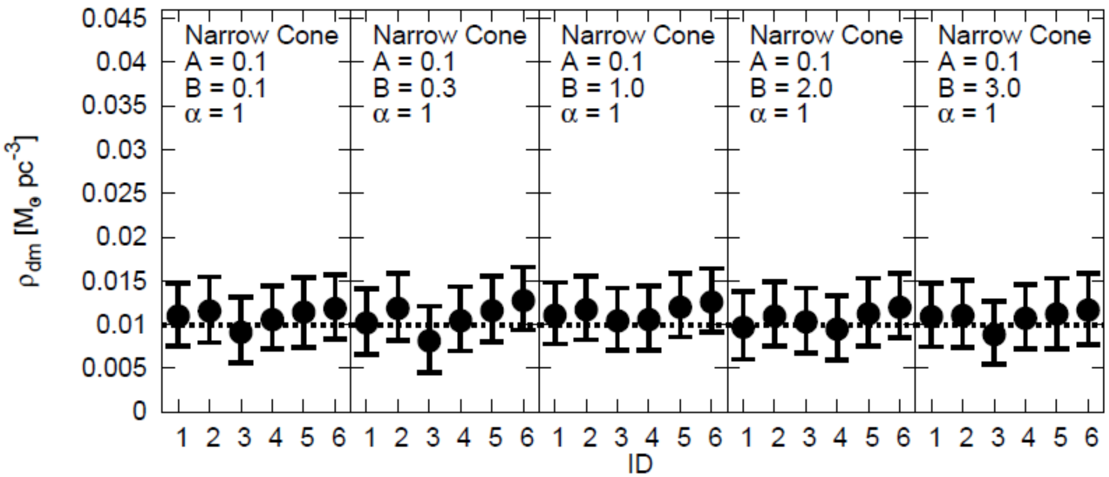
- Large distance errors in high-z region makes the disc thinner than the real.
- The thinner disc prefers a deeper potential.
- The deeper potential means a higher LDMD.

Proper motion errors

- Proper motion errors also vary with distance in the same way as parallaxes.

$$\varepsilon_\mu = B\left(\frac{d}{\mathrm{kpc}}\right) \quad \mathrm{mas\ yr}^{-1}$$

3 mas/yr @1 kpc



- The proper motion errors little affect the LDMD determinations.

- It is because proper motions have little information about v_z

Mock line-of-sight velocity errors

- LOSV measurements are independent from astrometric observations.
  - *Gaia* is designed to measure LOSVs simultaneously.

- Distance-dependence of LOSV errors is highly complicated.

$$\varepsilon_{losv} = C \left(\frac{d}{\mathrm{kpc}} \right)^{\beta} \mathrm{km\ s}^{-1} \qquad \beta = 0,1,2 \ or\ 3$$

  - $\beta = 2 - 3$ is the most likely for *Gaia*.

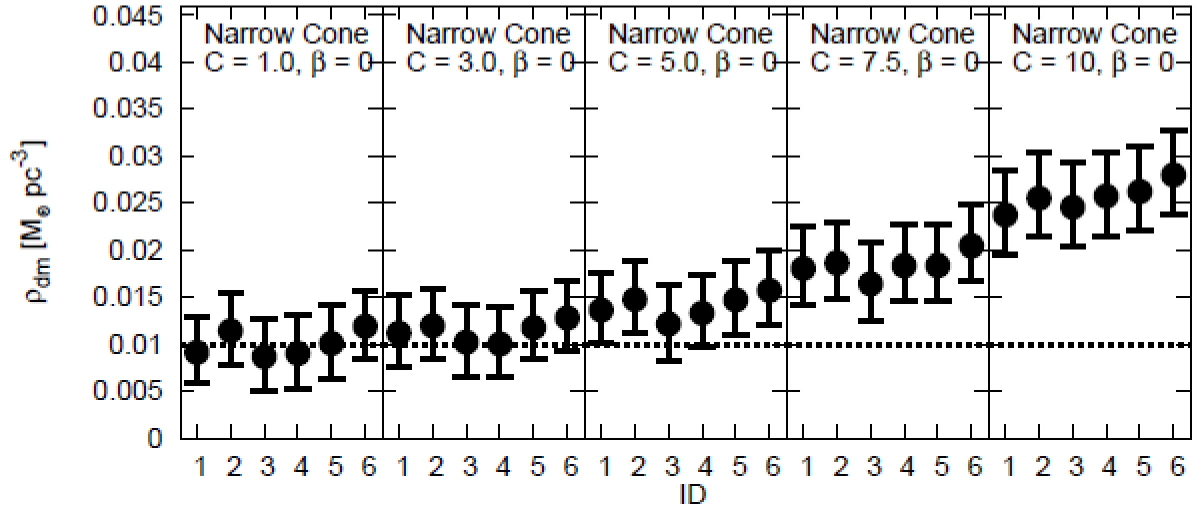
Mock line-of-sight velocity errors

1 km/s @1 kpc

5 km/s @1 kpc

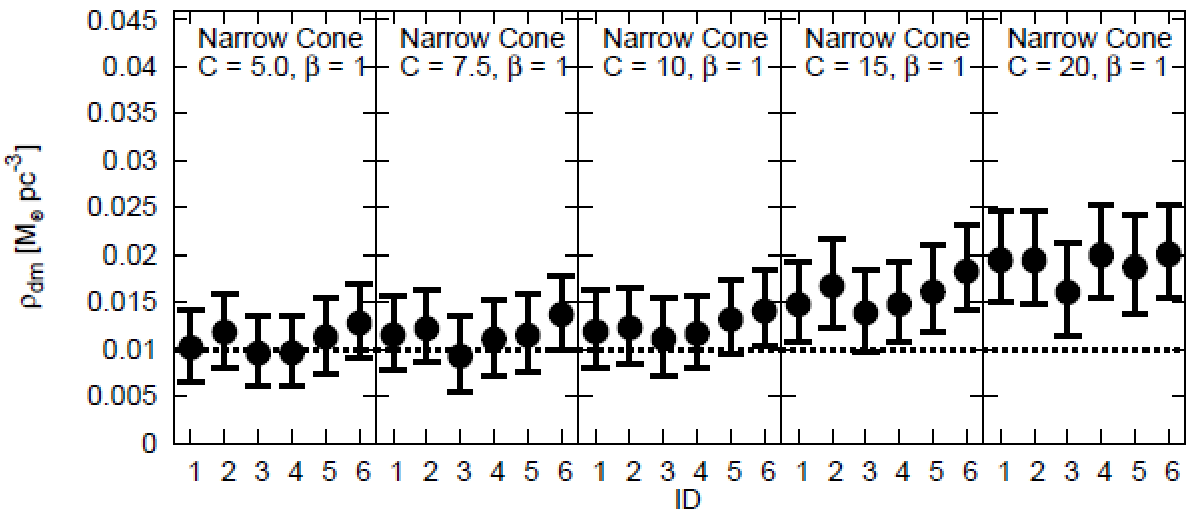
10 km/s @1 kpc

β= 0



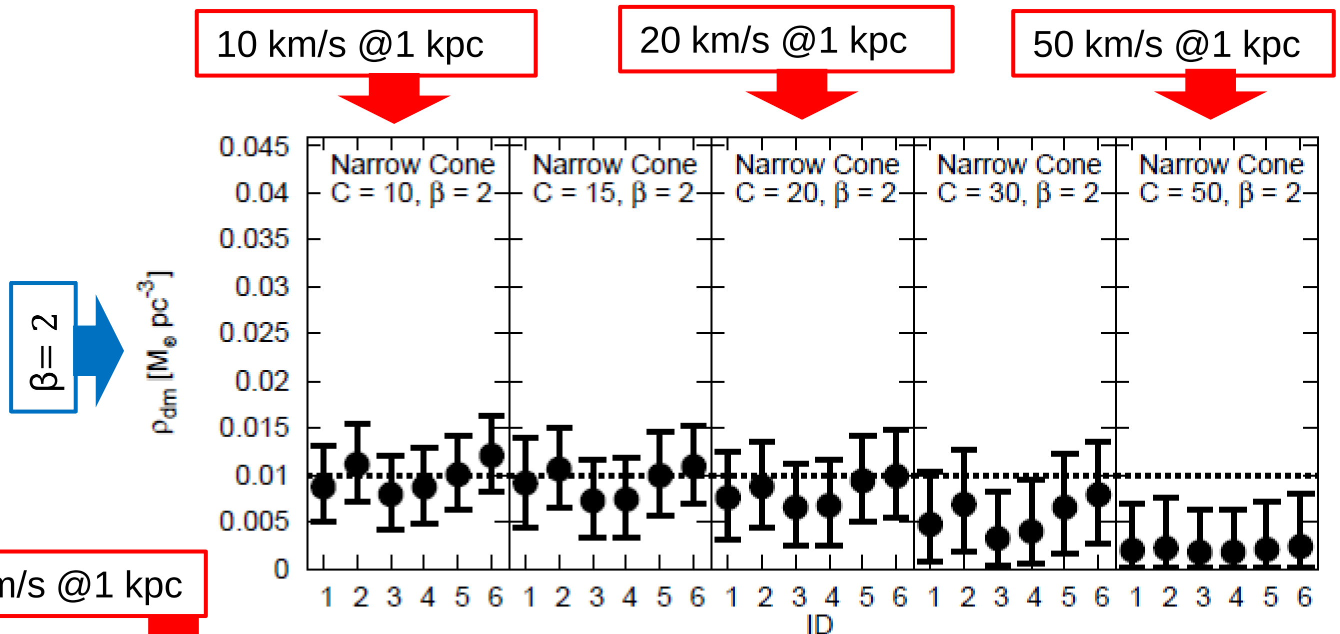
20 km/s @1 kpc

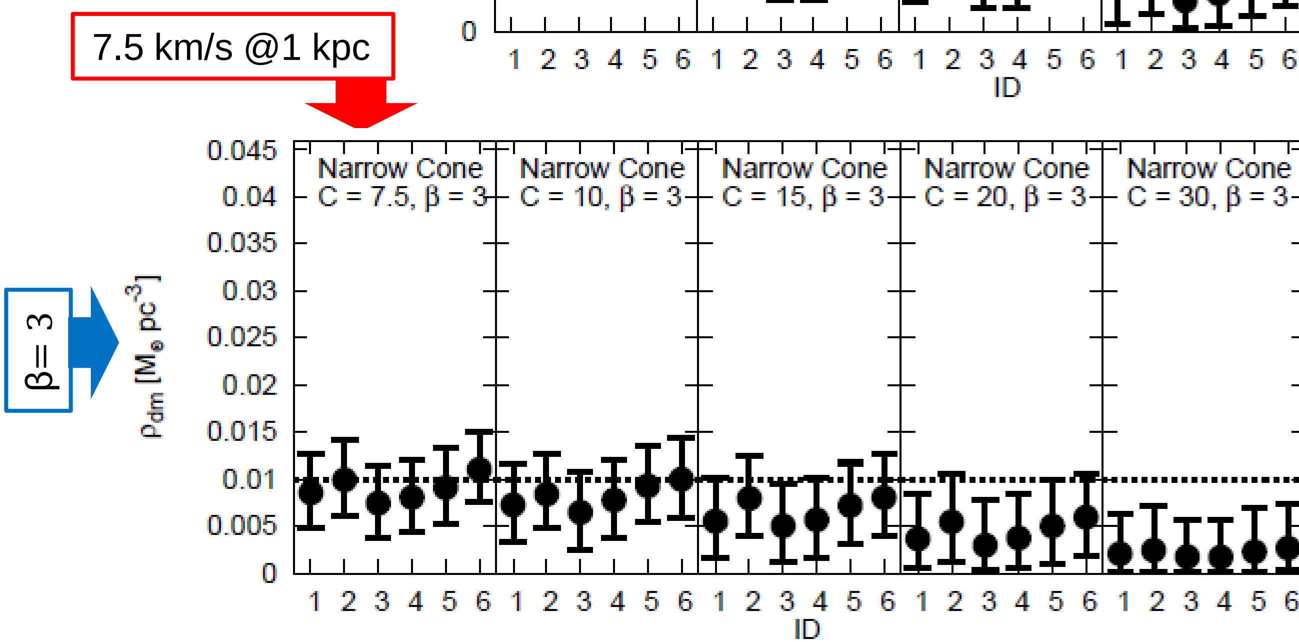
β= 1



The LOSV errors can overeste the LDMD when β=0-1.

Mock line-of-sight velocity errors

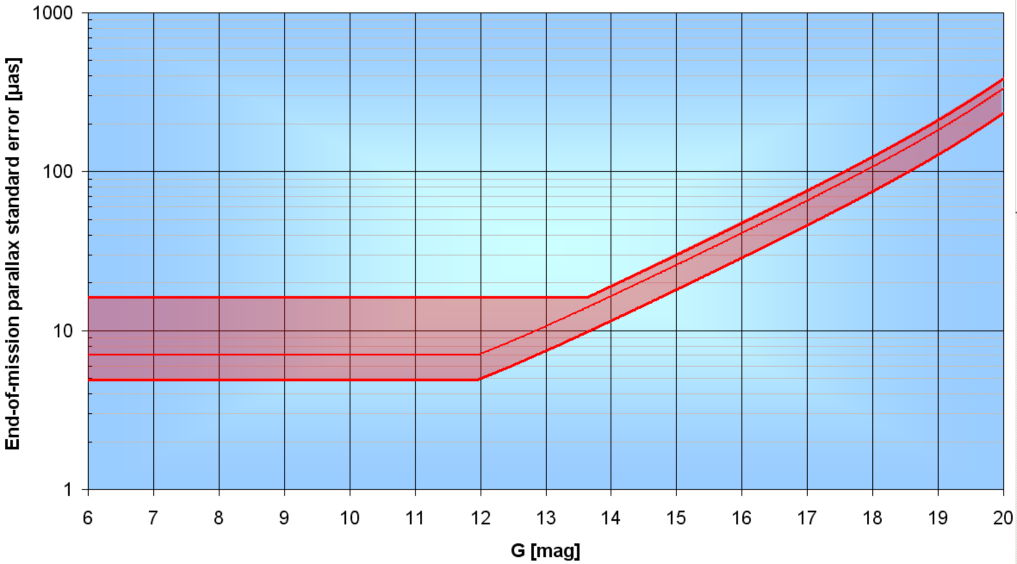


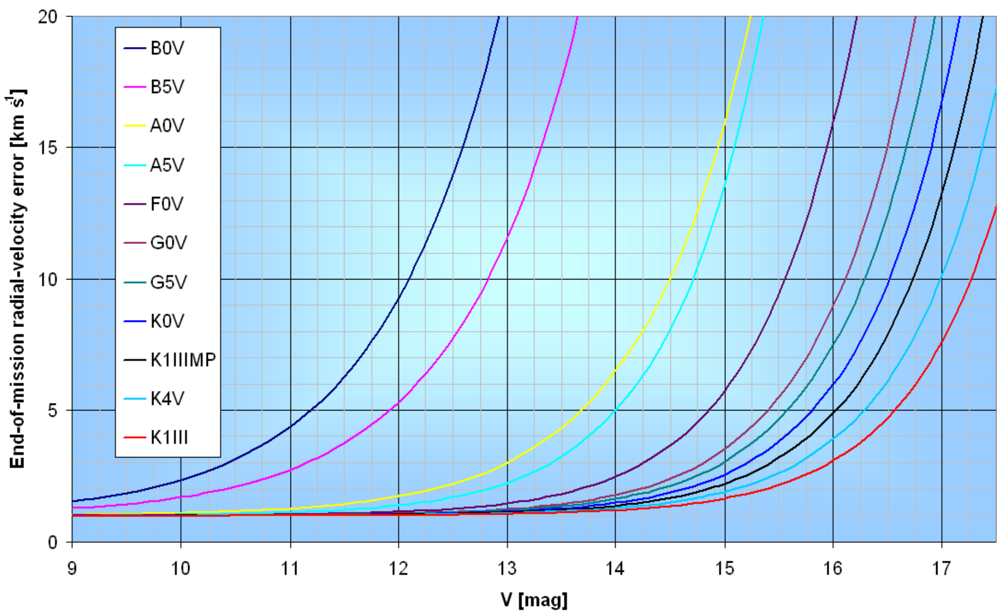


The LOSV errors can undereste the LDMD when β=2-3.

- Gaia simulation

Gaia simulation





Prusti (2012)

Tracer stars used frequently are K dwarf stars.

– K stars
  - $M \cong 7 \;\Rightarrow\; m \cong 17$ @ 1 kpc

– parallax error = 0.06 mas

– PM error = 0.06 mas/yr

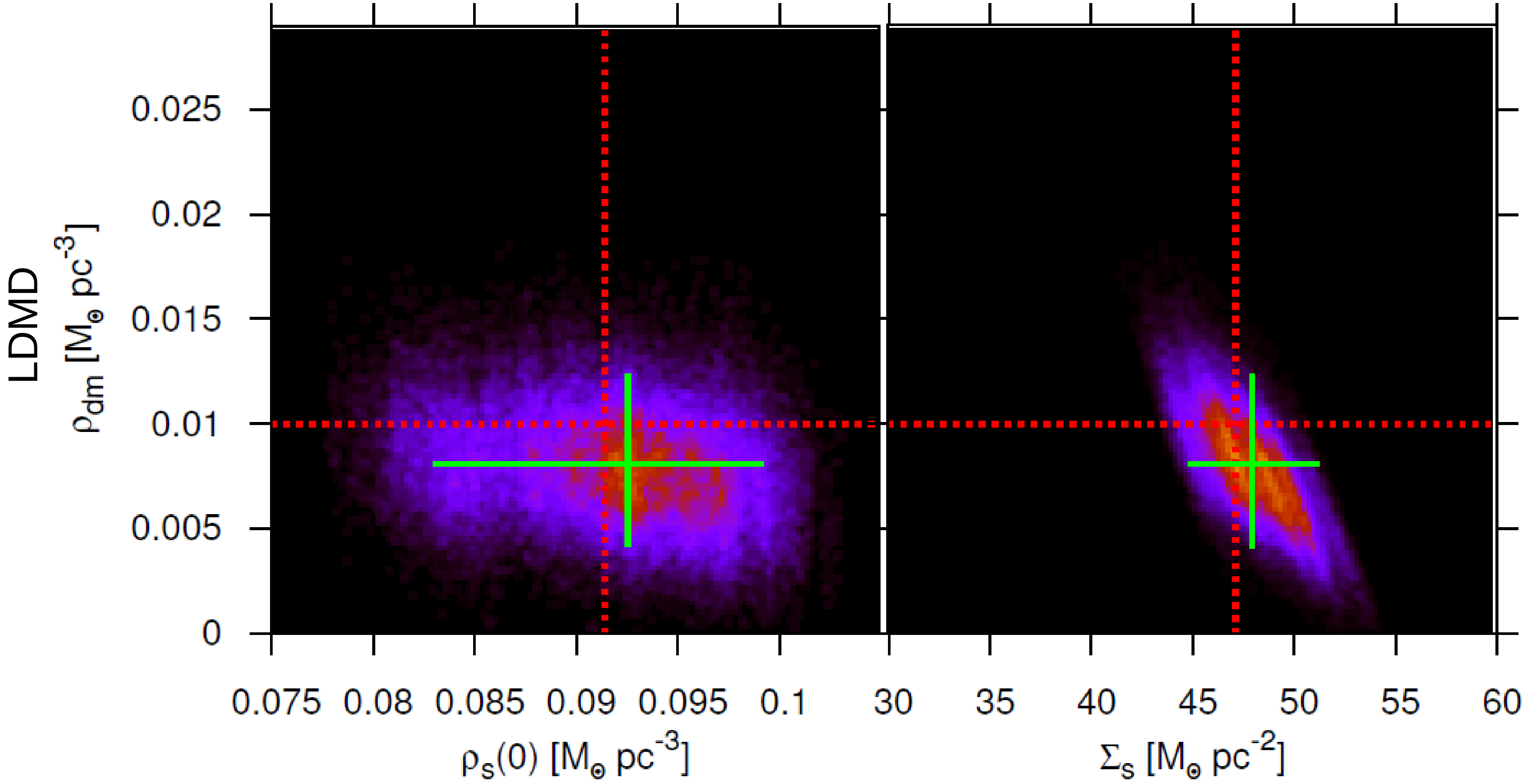
– LOSV error = 10 – 17 km/s
  - β=2-3

– $z_{min} = 200$ pc, $z_{max} = 1.2$ kpc

– conical region   480 deg^2

– sample size = 24,000 stars

Gaia simulation



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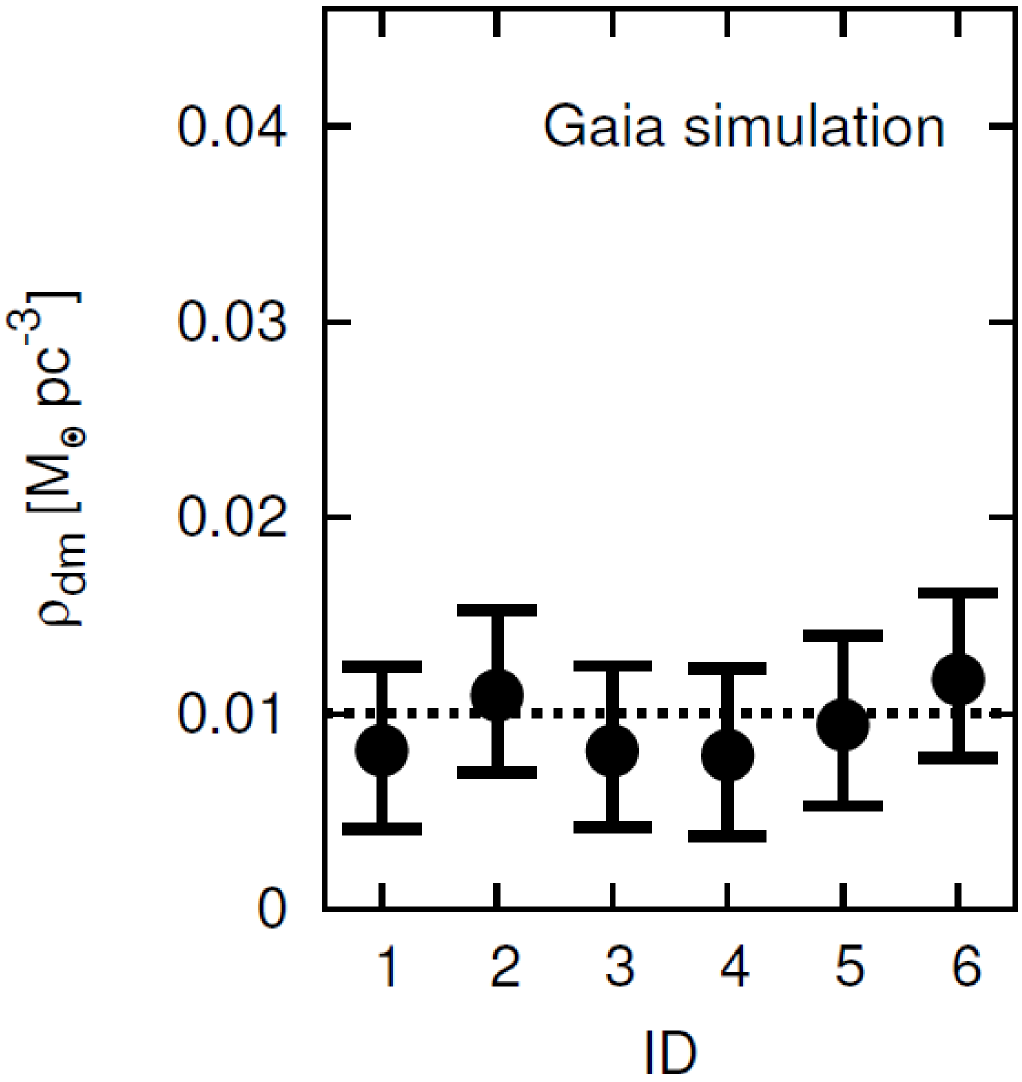

Summary

- method
  - The MA method seems promising.
    - little or no systematic errors
      - if sample size and observational precisions are sufficient.
- required observational precisions
  - Parallax precision must be < 0.1-0.3 mas @ d=1 kpc (would be a necessary condition)
    - Otherwise, distance errors can cause overestimation.
- *Gaia & Hipparcos*
  - Gaia can exceed the required precisions.
    - Hipparcos catalogue is not sufficient.

- **more calculations → Inoue & Gouda (2013) A&A, 555, A105**