Title: Constraining a Thin Dark Matter Disk with Gaia

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Abstract: <p>If a component of the dark matter has dissipative interactions, it could collapse to form a thin dark disk in our Galaxy coincident with the baryonic disk. It has been suggested that dark disks could explain a variety of observed phenomena, including periodic comet impacts. Using the first data release from the Gaia mission, we search for a dark disk via its effect on stellar kinematics in the Milky Way. I will present new limits on the presence of a thin dark matter disk, as well as measurements on the matter density in the solar neighborhood.</p>

Constraining a thin dark matter disk with Gaia

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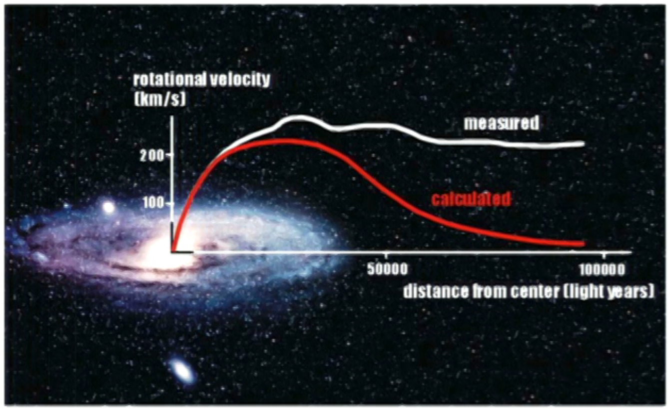
December 12, 2017
PI Seminar

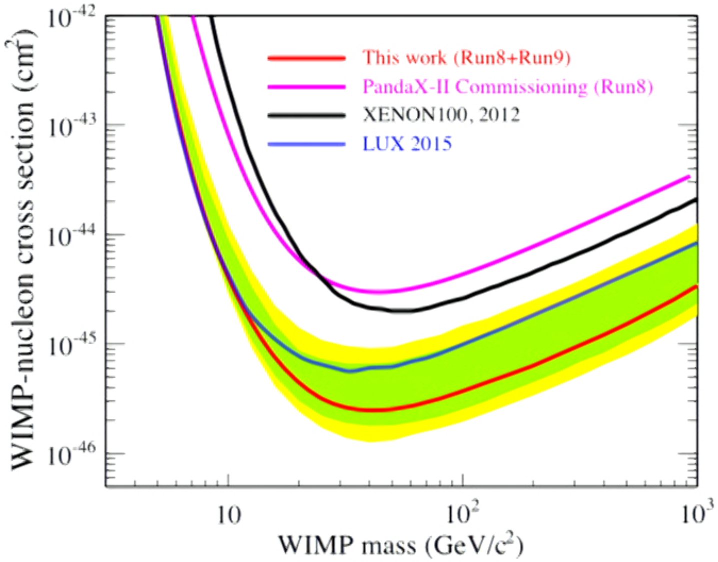
1711.03103 with Katelin Schutz, Ben Safdi, and Chih-Liang Wu

Particle models for dark matter

Evidence for gravitation interactions



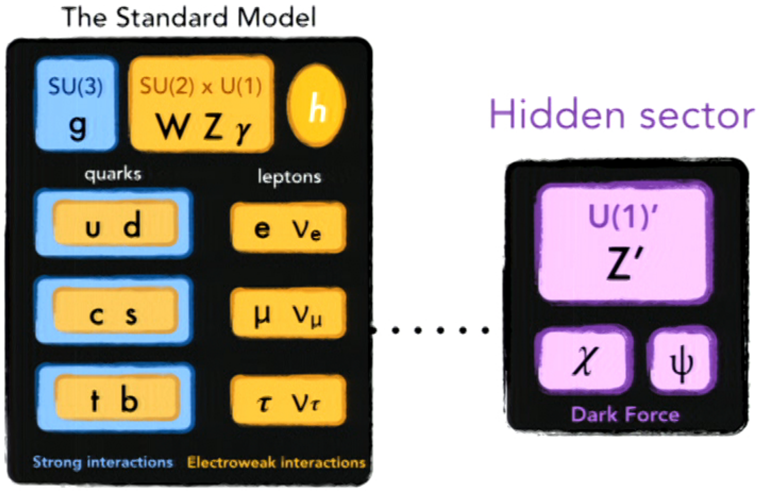
Non-evidence for SM gauge interactions



We can also use gravitational interactions
to test gauge interactions of DM

Hidden Sectors

By analogy with the SM, a compelling possibility that dark matter has its own gauge interactions

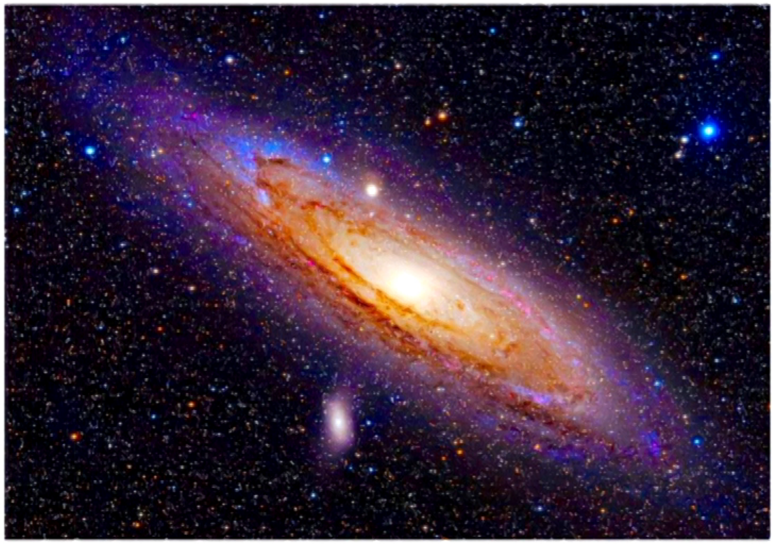


Models containing new light mediators (Z′) could explain:

- small scale structure and SIDM
- large scale structure and H0
- Galactic center GeV excess
- …

where the interacting hidden sector may be a fraction of the total DM

Why dark disks?



Disk shapes form due to cooling…

By analogy with the Standard Model, if some of the dark matter interacts with "dark forces", this could also lead to cooling and flattening

Very rough estimate:

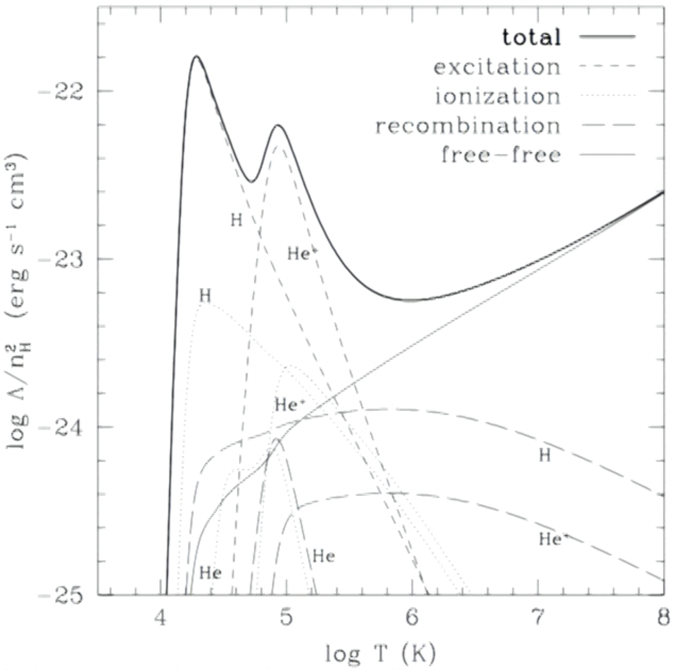
$$z_d \approx 2.5 \text{ pc} \left(\frac{\alpha_D}{0.02}\right)^2 \frac{m_C}{1 \text{ MeV}} \frac{100 \text{ GeV}}{m_X}$$

<u>Thin</u> dark matter disks?

Fan, Katz, Randall, and Reece 2013

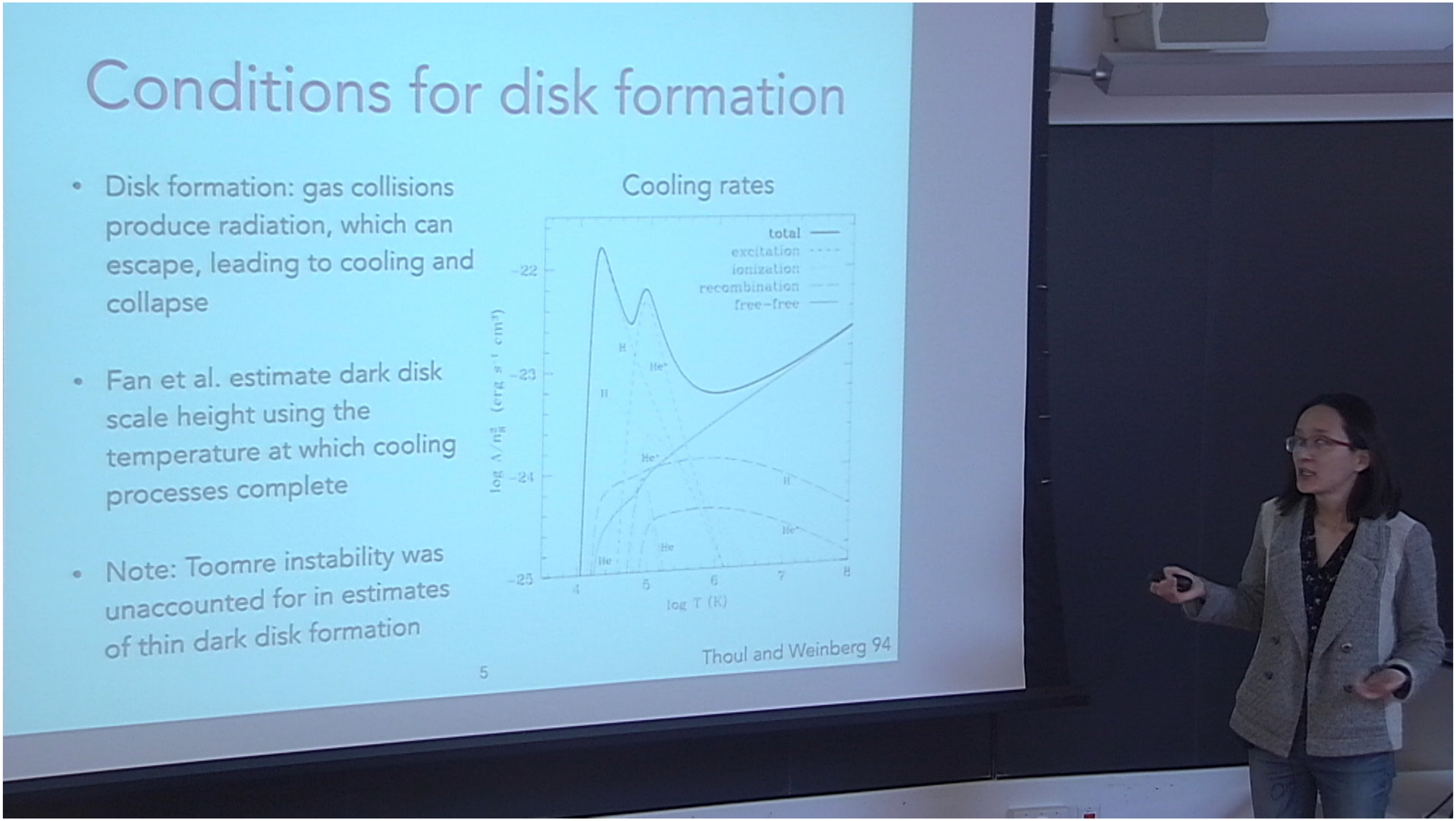
Conditions for disk formation

- Disk formation: gas collisions produce radiation, which can escape, leading to cooling and collapse
- Fan et al. estimate dark disk scale height using the temperature at which cooling processes complete
- Note: Toomre instability was unaccounted for in estimates of thin dark disk formation



Cooling rates

Thoul and Weinberg 94



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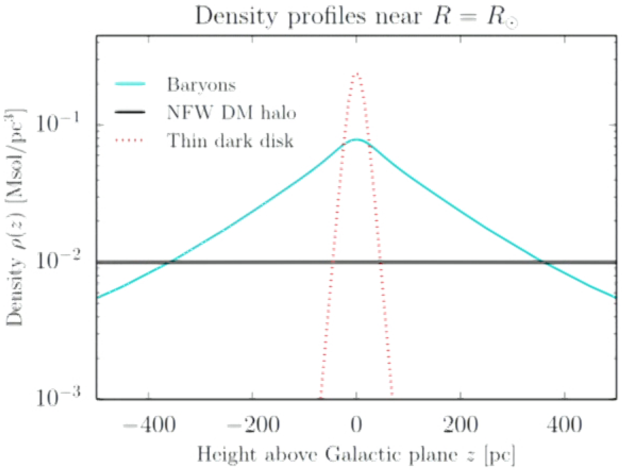
Thoul and Weinberg 94

Implications of dark disks

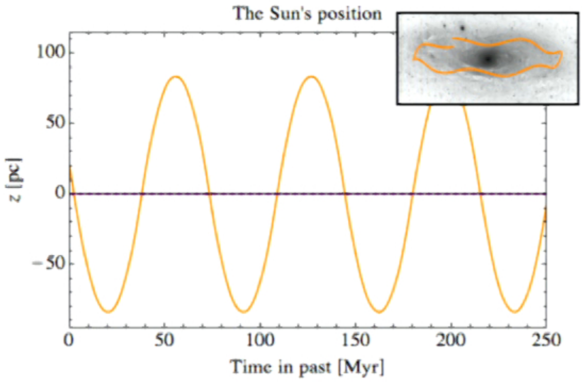
- Implications for (in)direct detection (McCullough & Randall, Fan, Katz & Shelton)
- Co-rotation of Andromeda satellites (Randall & Scholtz)
- Periodic disruption of comet trajectories causing mass extinction events (Randall & Reece, Shaviv, Kramer & Ramon)
- Collapsed dark matter objects can account for the point-like nature of the inner galaxy GeV excess (Agrawal & Randall)
- Massive black hole formation (D'Amico et al.)



High density dark disk considered for these!

Periodic Comet Impacts

Oscillation of sun about thin dark disk
can perturb Oort cloud…



Randall and Reece 2014
Kramer and Rowan 2016
Shaviv 2016

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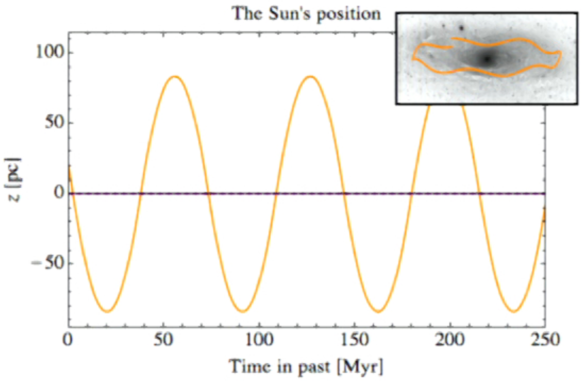

Randall and Reece 2014
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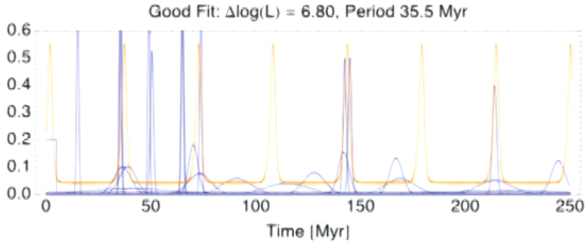
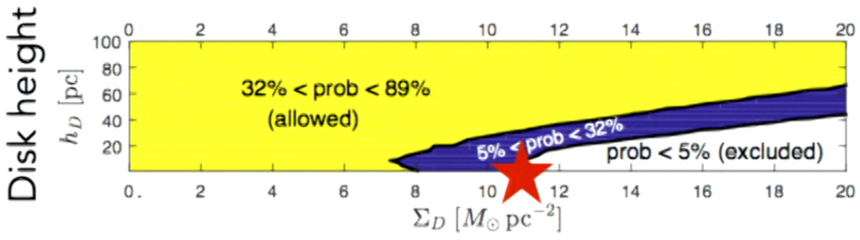
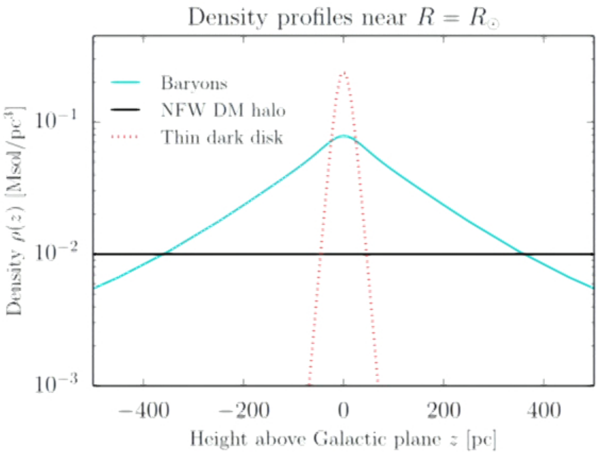
Leading to periodic comet impacts



Bounds on a thin dark disk



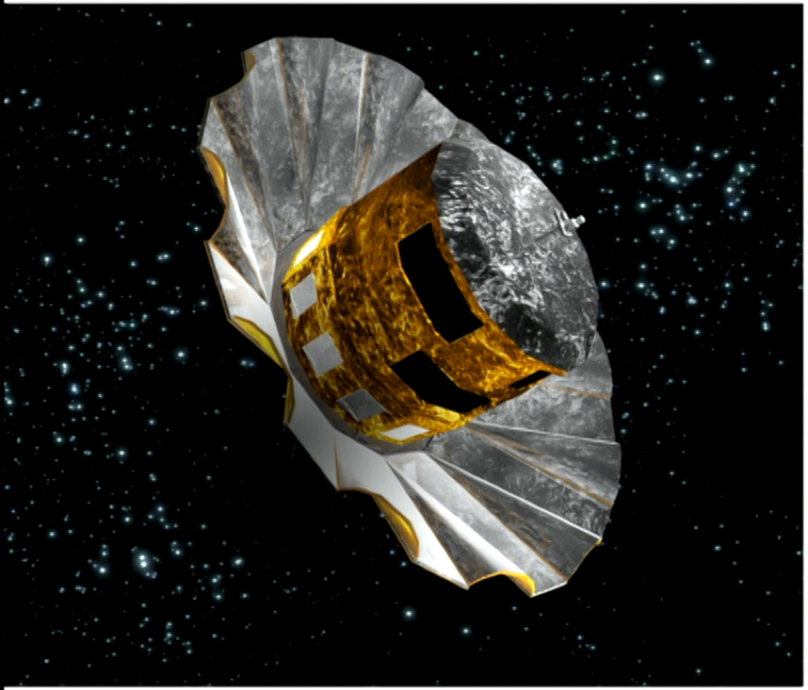
Disk Surface Density



1604.01407 Eric Kramer and Lisa Randall

Using kinematics of ~2000 stars from Hipparcos

Gaia satellite



- Full sky view of stellar positions, distances, and velocities

- Launched 2013

- First data release (DR1): September 2016 ~ 10^6 stars

- Next release (DR2): April 2018 ~ 10^9 stars

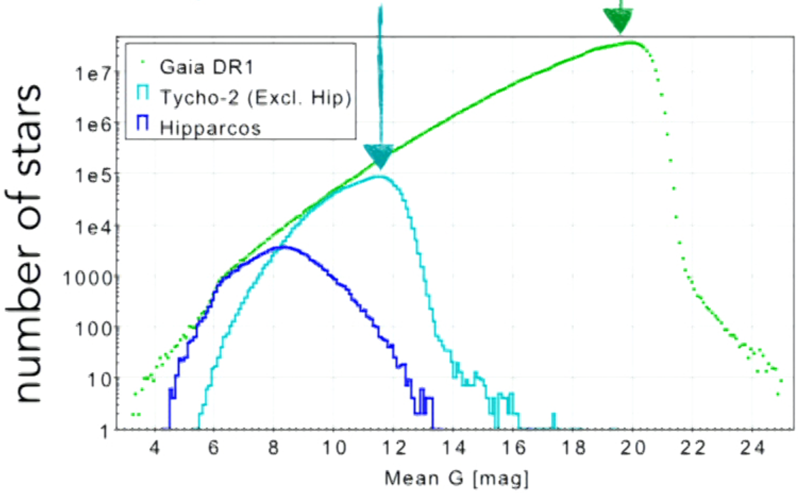
Gaia astrometry

With 15 µas resolution you can see a quarter on the surface of the moon

Gaia astrometry

Next data release:
astrometry for
~10^9 stars

TGAS: subsample of DR2
with parallaxes, vel's



← brightness

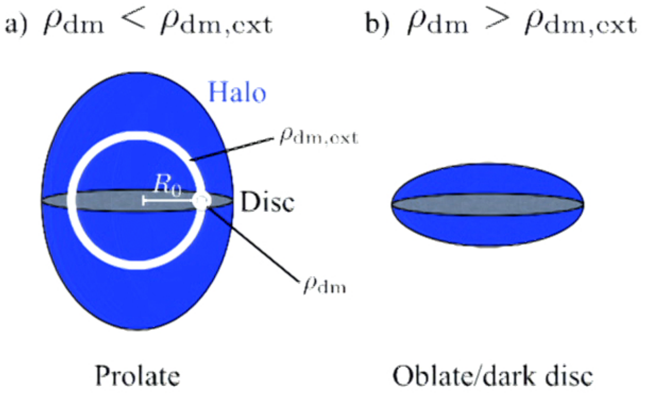
See also: MacMillan et al. 2017
Anderson et al. 2017

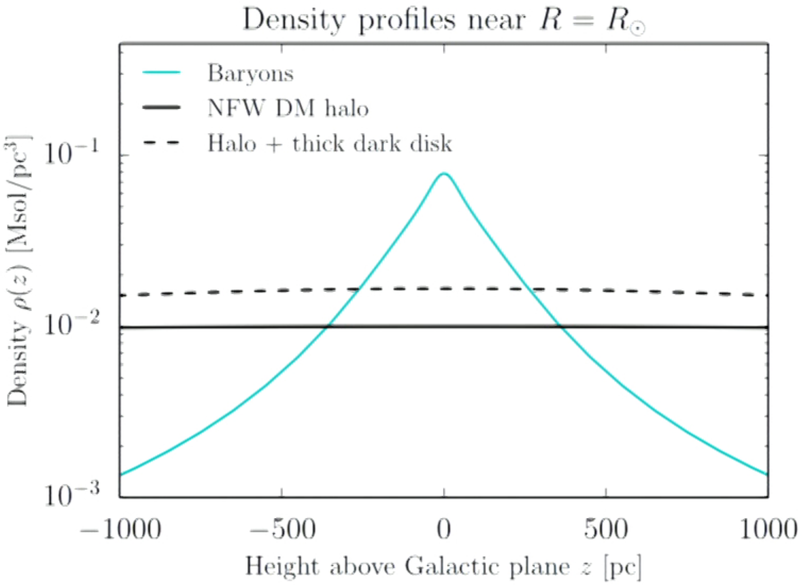
Dark matter applications

- Local dark matter density — *Read 2014, Silverwood et al. 2015*
- Local velocity distribution — *Herzog-Arbeitman, Lisanti, Necib 2017*
- Dark matter halo profile — *Bovy & Rix 2013 + followups*
- Substructure — dark disks, thick dark matter disks, dark matter subhalos

All important inputs for dark matter
direct detection, indirect detection

Thick dark disk





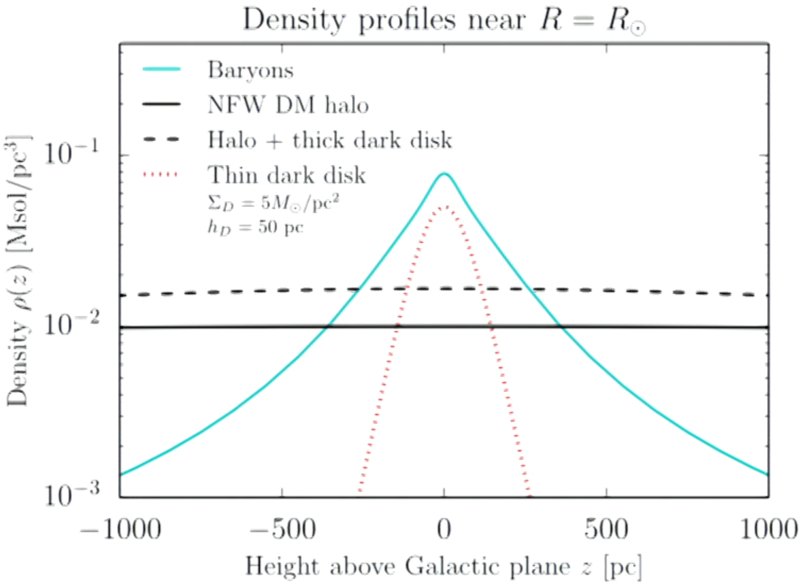
Read et al. 2009
Silverwood et al. 2015

Thin dark disk

Surface density

$$\rho_{DD}(R_\odot, z) = \frac{\Sigma_D}{4h_D}\mathrm{sech}^2\left(\frac{z}{2h_D}\right)$$

Scale height

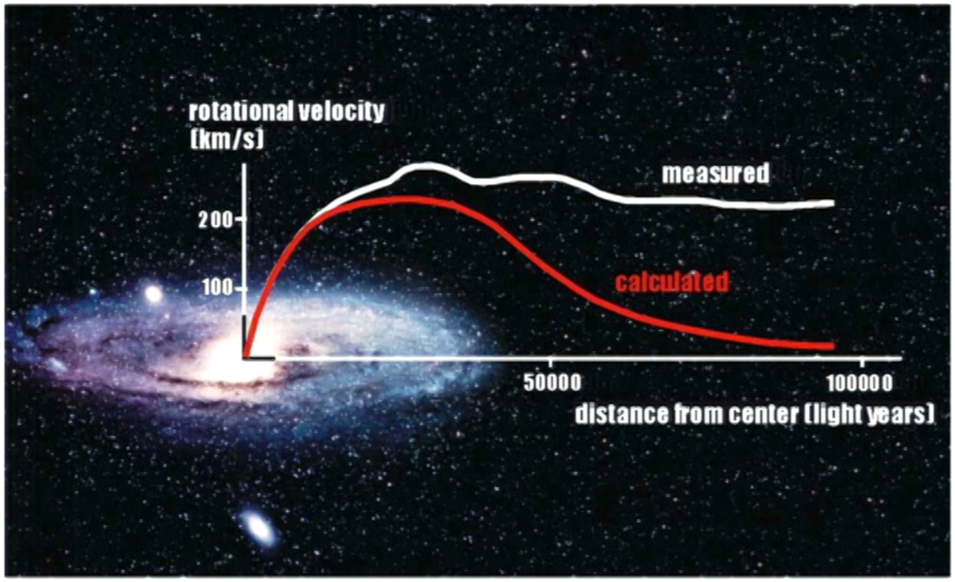


I. Constraining a dark disk and the local DM density

Basic idea

Tracer populations (of stars) are sensitive to the total gravitating mass.

Familiar example:



Basic idea

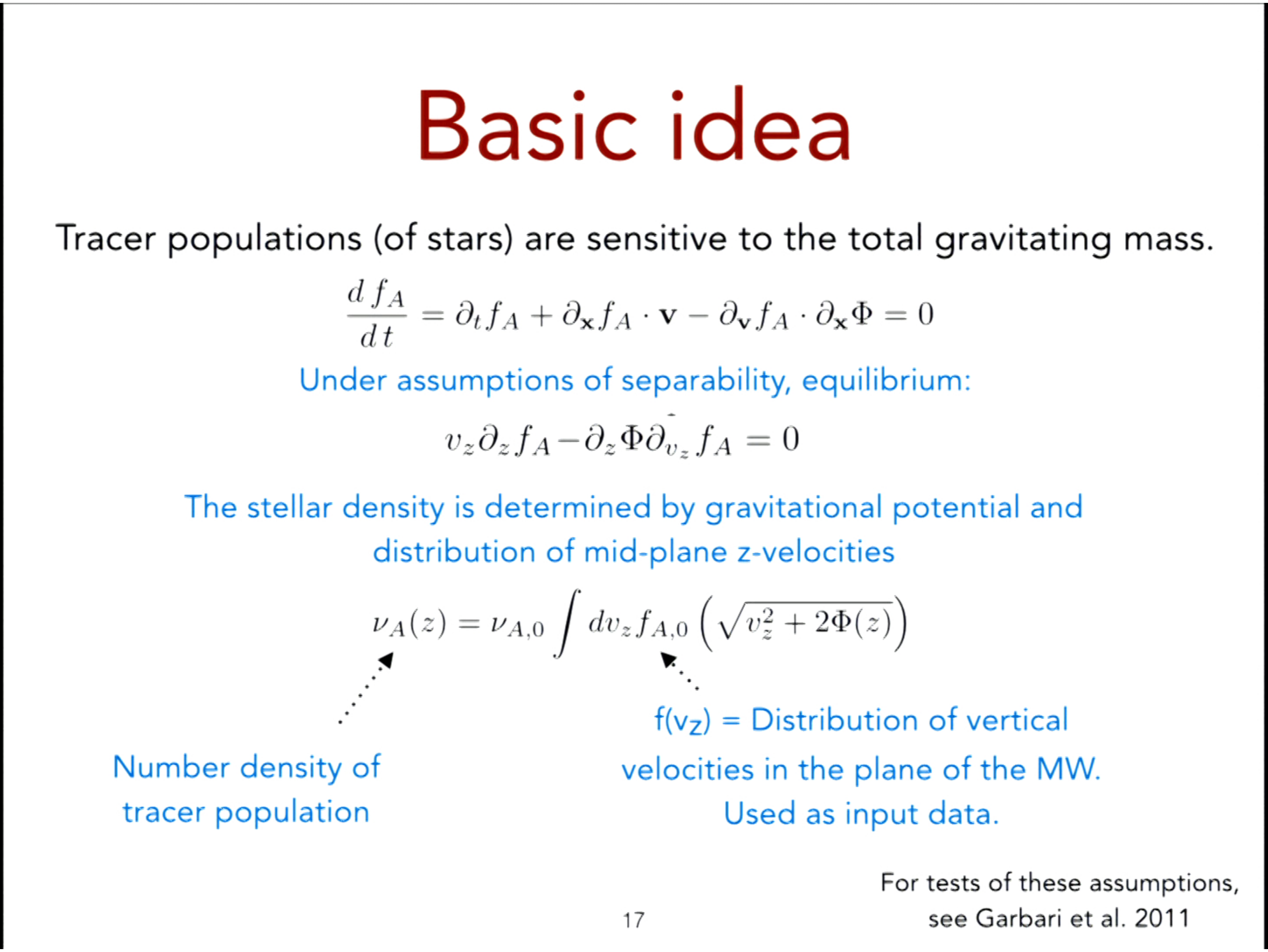
Tracer populations (of stars) are sensitive to the total gravitating mass.

$$\frac{d\,f_A}{d\,t} = \partial_t f_A + \partial_{\mathbf{x}} f_A \cdot \mathbf{v} - \partial_{\mathbf{v}} f_A \cdot \partial_{\mathbf{x}} \Phi = 0$$

Under assumptions of separability, equilibrium:

$$v_z \partial_z f_A - \partial_z \Phi \partial_{v_z} f_A = 0$$

For tests of these assumptions,
see Garbari et al. 2011



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Under assumptions of separability, equilibrium:

$$v_z \partial_z f_A - \partial_z \Phi \partial_{v_z} f_A = 0$$

The stellar density is determined by gravitational potential and distribution of mid-plane z-velocities

$$\nu_A(z) = \nu_{A,0} \int dv_z f_{A,0} \left(\sqrt{v_z^2 + 2\Phi(z)} \right)$$

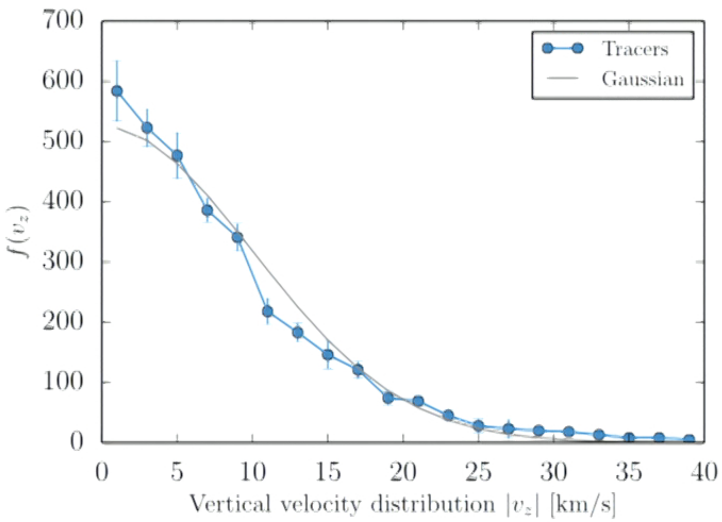
Number density of tracer population

$f(v_Z)$ = Distribution of vertical velocities in the plane of the MW. Used as input data.

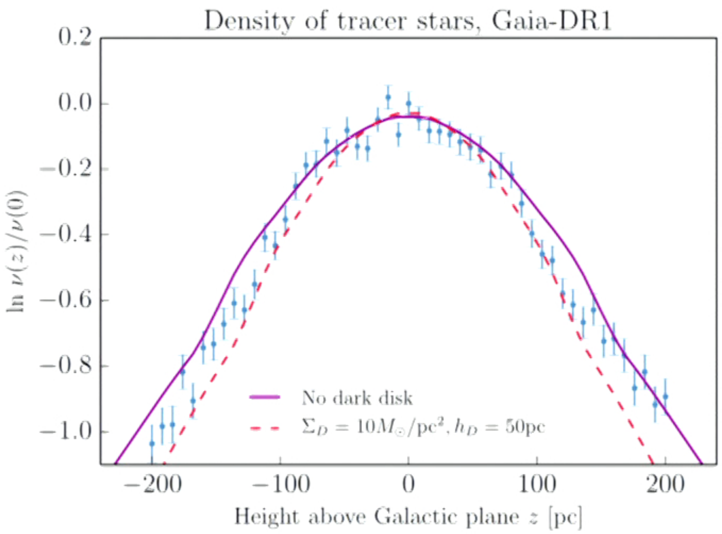
For tests of these assumptions, see Garbari et al. 2011

Tracer stars

Midplane velocity distribution f(v)



Density fall-off ν(z)



Gravitational Potential

Determining the gravitational potential requires a mass model

Model baryonic mass as a number of isothermal* components ν_A

Vertical Jeans equation: $$\frac{\sigma_A^2}{\nu_A}\partial_z \nu_A + \partial_z \Phi = 0 \longrightarrow \nu_A(z) = \nu_A(0)\, e^{-\Phi(z)/\sigma_A^2}$$

*Velocity dispersion doesn't depend on z

Connect this to the mass density profile with Poisson equation

$$\partial_z^2 \Phi = 4\pi G \rho$$

Inject: baryons, smooth dark matter halo, and dark disk

For tests of these assumptions,
see Garbari et al. 2011

Baryons

Biggest uncertainties are in the gas density

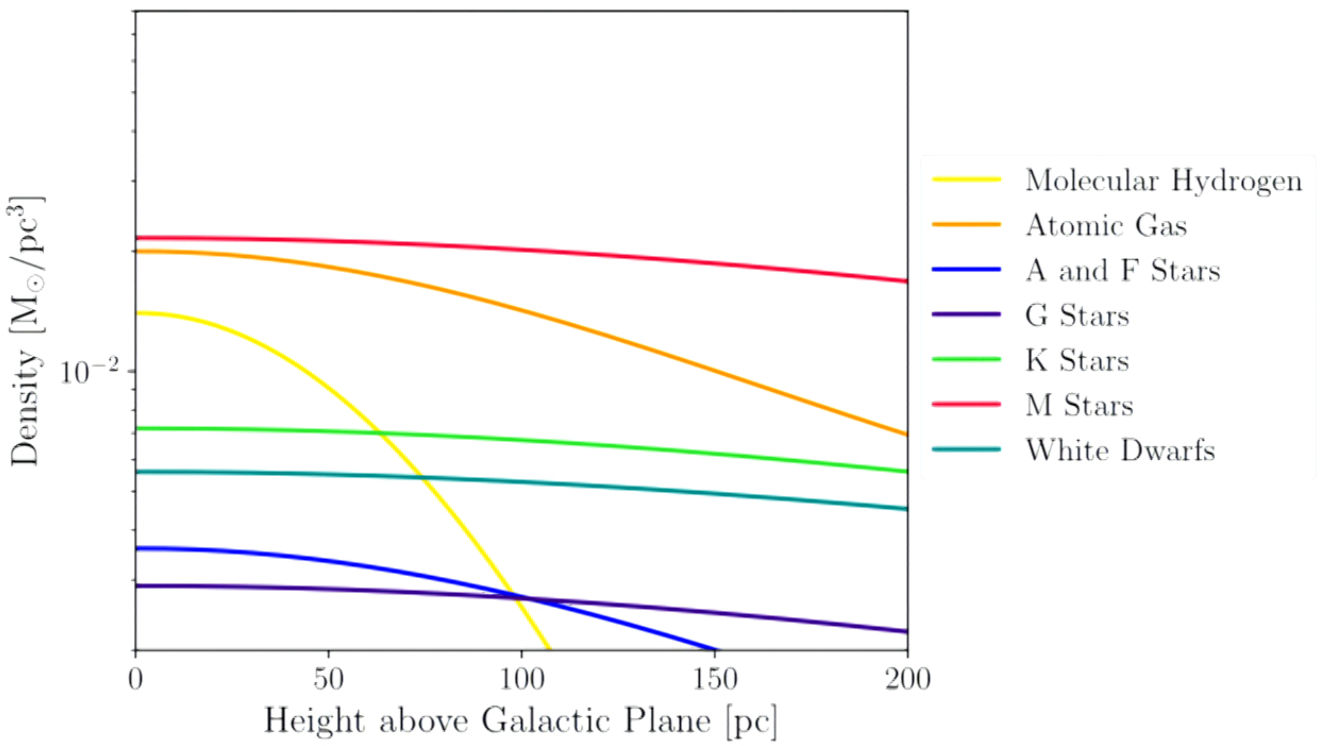
Stellar midplane densities are improving with Gaia (Bovy 2017)

Isothermal components of Baryonic mass

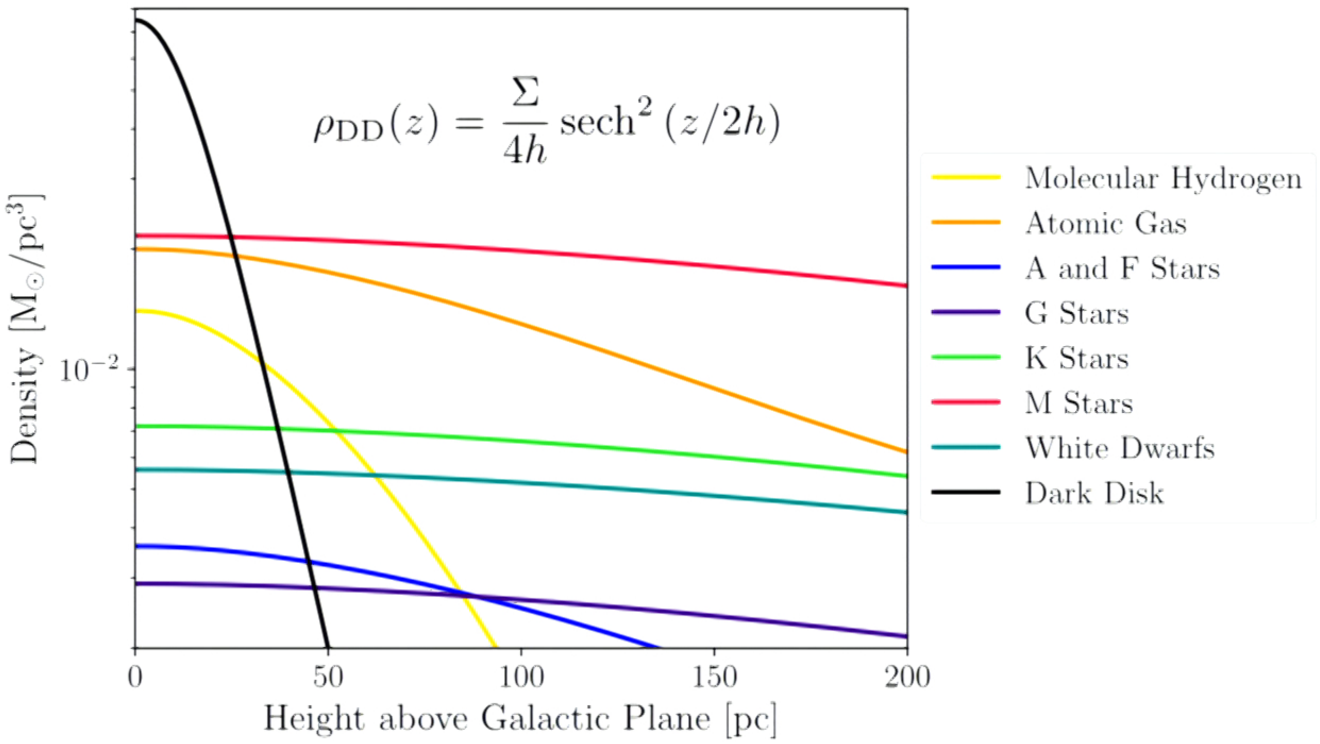
Baryonic Component	$\rho(0)$ [$M_\odot/pc^3$]	σ [km/s]
Molecular Gas (H_2)	0.0104 ± 0.00312	3.7 ± 0.2
Cold Atomic Gas ($H_I(1)$)	0.0277 ± 0.00554	7.1 ± 0.5
Warm Atomic Gas ($H_I(2)$)	0.0073 ± 0.0007	22.1 ± 2.4
Hot Ionized Gas (H_{II})	0.0005 ± 0.00003	39.0 ± 4.0
Giant Stars	0.0006 ± 0.00006	15.5 ± 1.6
$M_V < 3$	0.0018 ± 0.00018	7.5 ± 2.0
$3 < M_V < 4$	0.0018 ± 0.00018	12.0 ± 2.4
$4 < M_V < 5$	0.0029 ± 0.00029	18.0 ± 1.8
$5 < M_V < 8$	0.0072 ± 0.00072	18.5 ± 1.9
$M_V > 8$ (M Dwarfs)	0.0216 ± 0.0028	18.5 ± 4.0
White Dwarfs	0.0056 ± 0.001	20.0 ± 5.0
Brown Dwarfs	0.0015 ± 0.0005	20.0 ± 5.0
Total	0.0889 ± 0.0071	—

collected from: Flynn et al. 2006, Read 2014, McKee et al. 2015, Kramer+Randall 2015, Bovy 2017

Density profiles



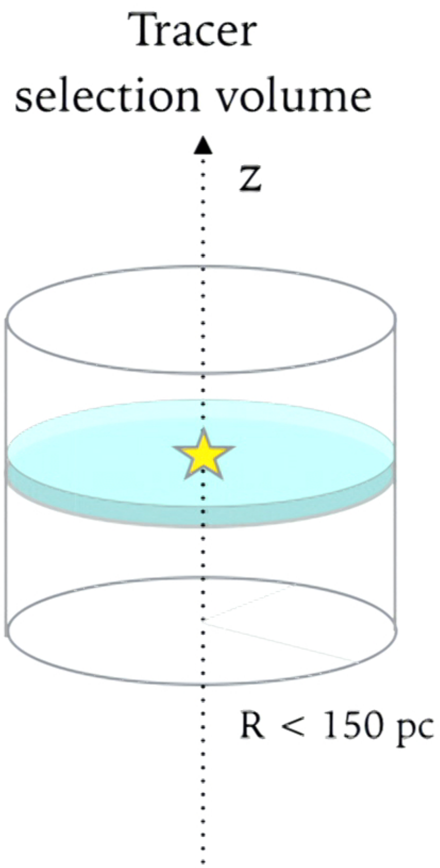
Density profiles



$$\rho_{\mathrm{DD}}(z) = \frac{\Sigma}{4h}\,\mathrm{sech}^2\left(z/2h\right)$$

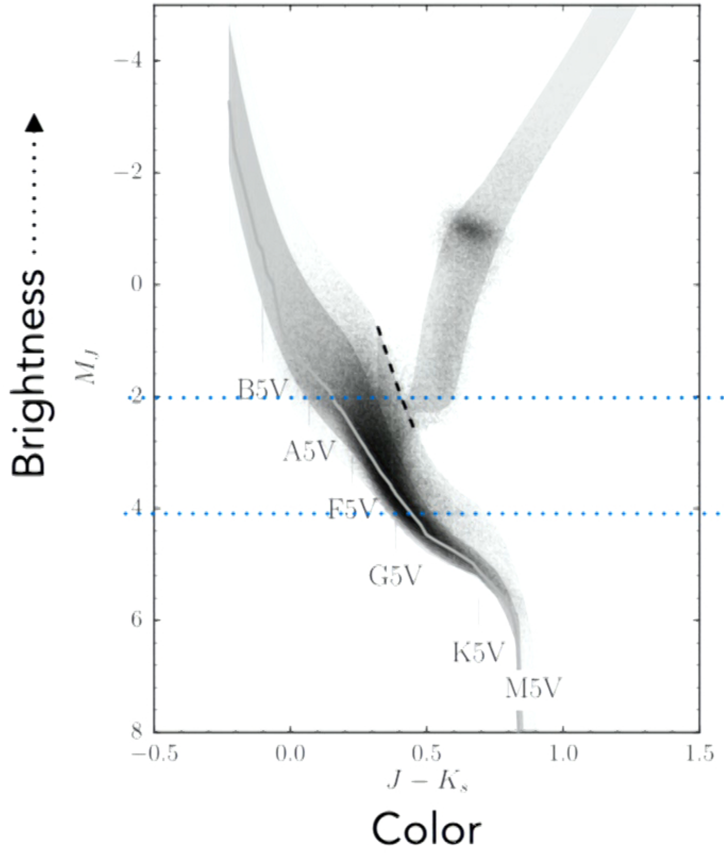
Analysis

1. Model the baryons at the plane
2. Solve Poisson-Jeans equations for the gravitational potential Φ, including dark matter and dark disks
3. Selecting a tracer population of stars, determine the vertical fall-off of stars (using Φ and f(v))
4. Fit to data, marginalizing over many nuisance parameters



see also: Kramer and Randall, Holmberg and Flynn 2000

Tracer stars



Gaia measures fainter stars out to larger distances

Hipparcos survey (~1990)

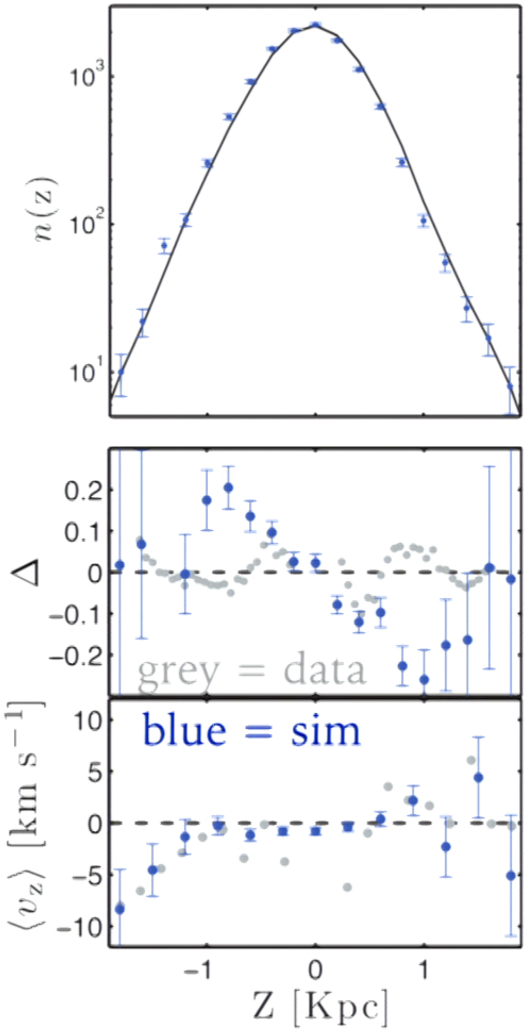
Our cuts for Gaia DR1

We divide up tracers into three populations:
A, F, and Early G stars

Bovy 2017

Equilibrium?

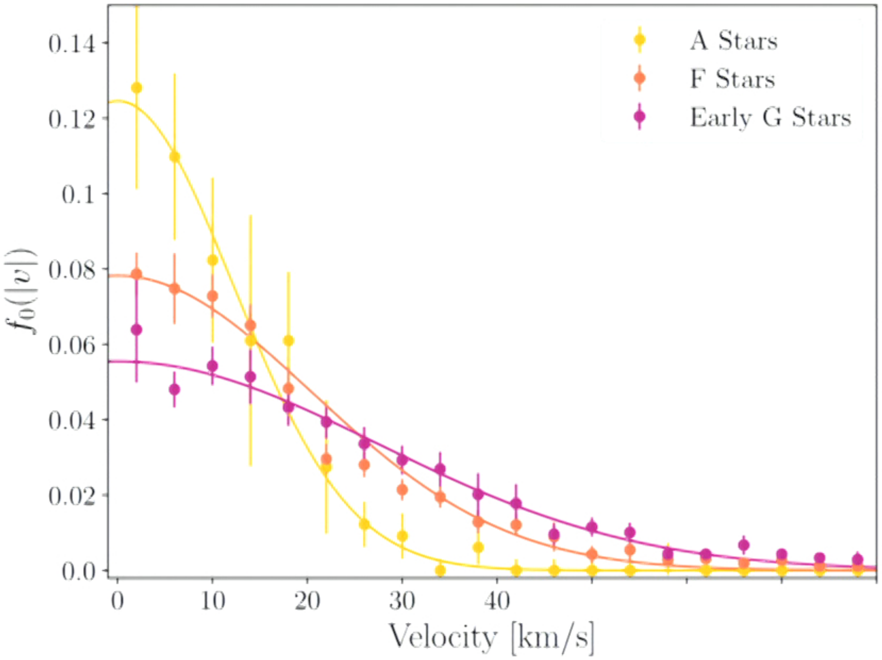
- The basis of our analysis is that the stellar populations and mass components are close to equilibrium near the mid-plane
- Stellar populations have different lifetimes, and display different departures from equilibrium
- To be conservative, we also include a systematic from asymmetries in f(v)



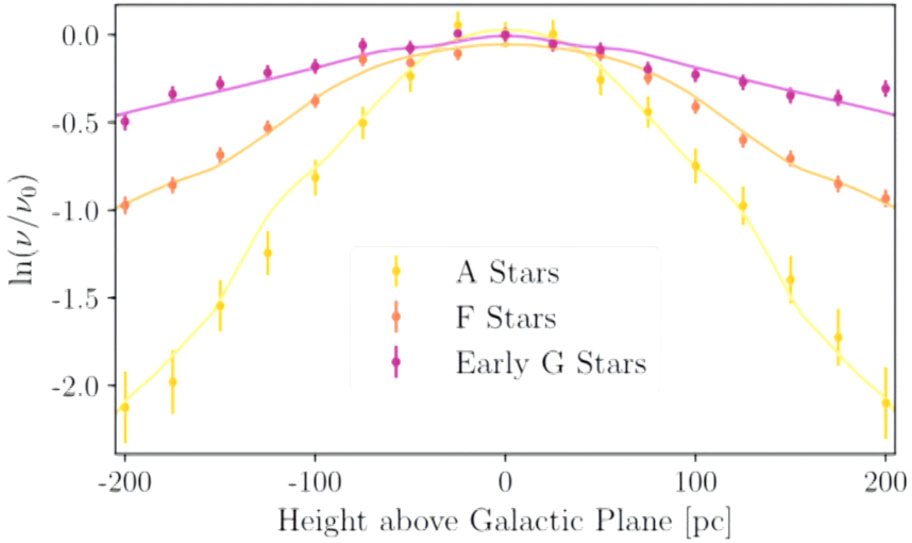
data from Widrow et al. 2012
Figure from Gomez et al. 2013

Velocity distributions

- Best fit $v_{z,sun}$ = 6.8 ± 0.2 km/s consistent with independent determinations
- Good fit to Gaussians
- Final systematics are: ~15%, 5%, 7% for AFG stars

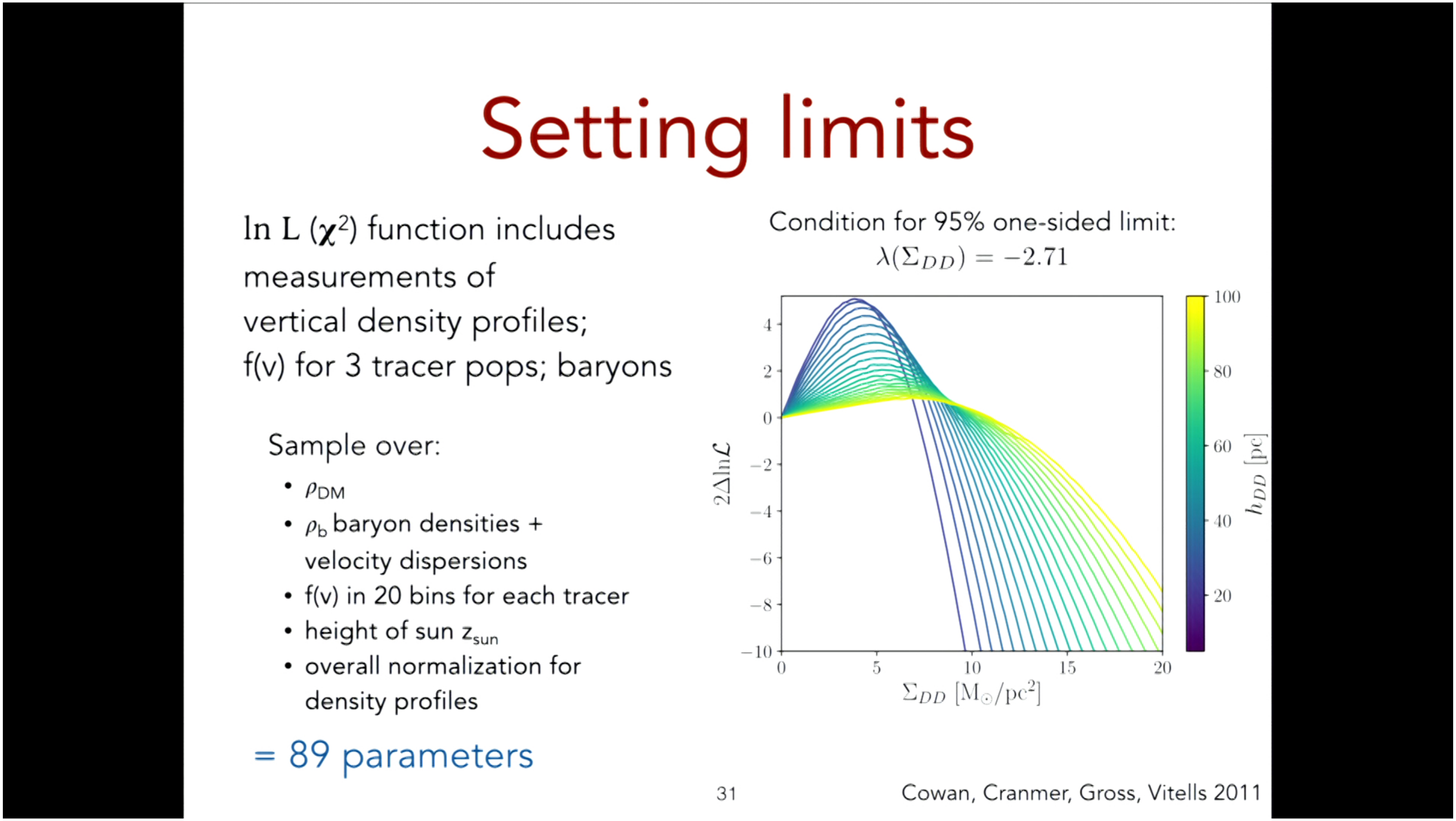


Number density of tracers



Best fit assuming no dark disk.

Here ρ_{DM} = 0.014 $M_\odot/\mathrm{pc}^3$ = 0.5 GeV/cm^3



Setting limits

ln L (χ^2) function includes measurements of
vertical density profiles;
f(v) for 3 tracer pops; baryons

Sample over:

- ρ_{DM}
- ρ_{b} baryon densities + velocity dispersions
- f(v) in 20 bins for each tracer
- height of sun z_{sun}
- overall normalization for density profiles

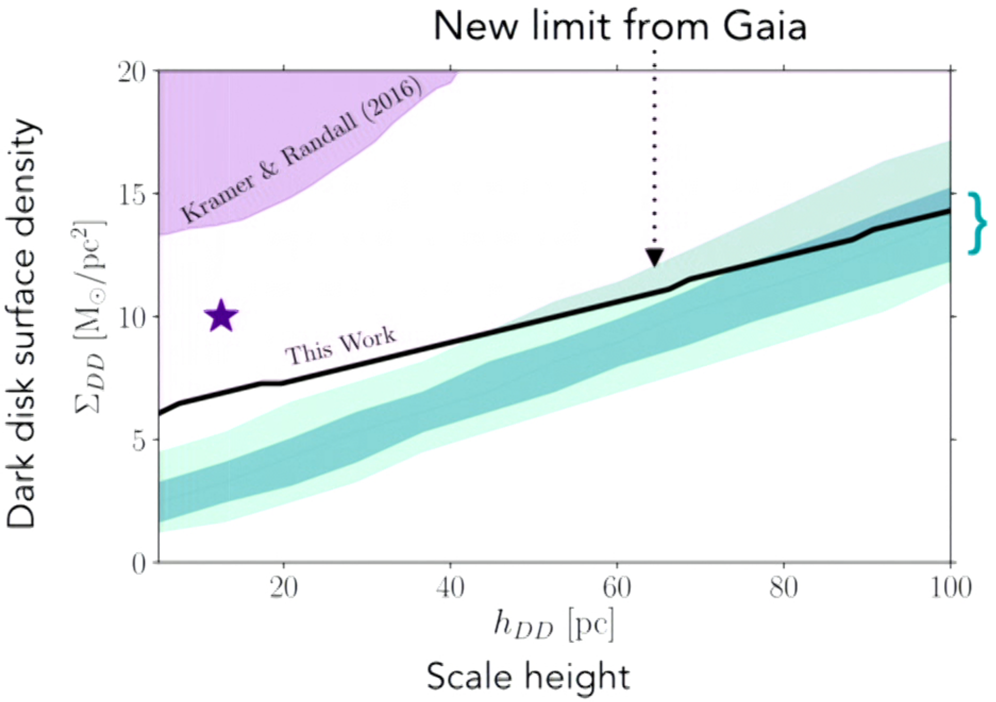
= 89 parameters

Condition for 95% one-sided limit:

$$\lambda(\Sigma_{DD}) = -2.71$$

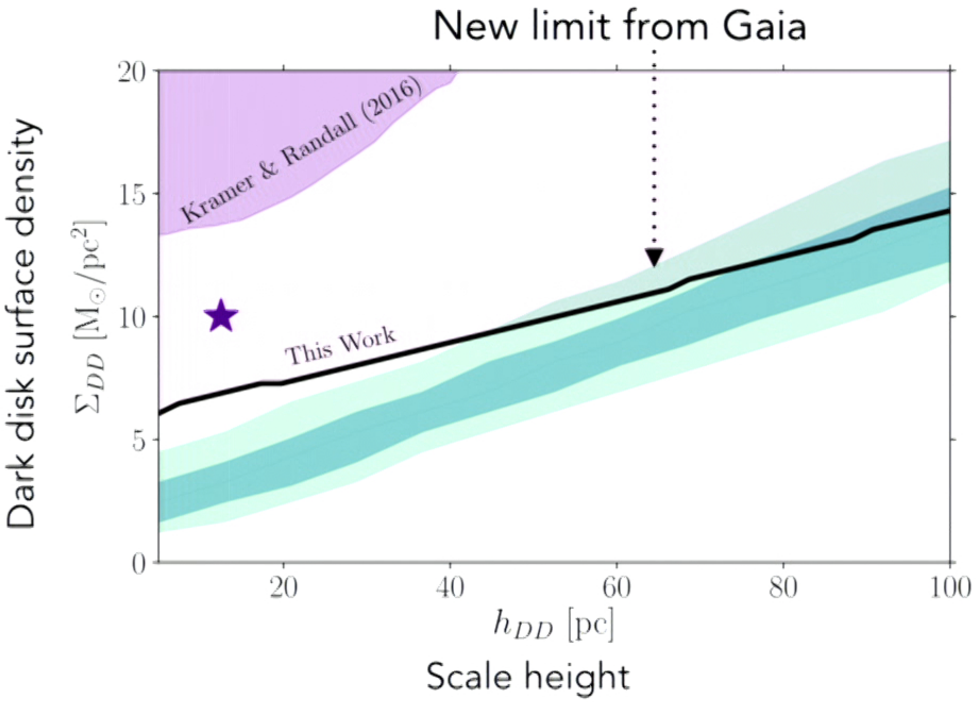
Cowan, Cranmer, Gross, Vitells 2011

Dark disk bounds



Expectation from mock data catalogs, assuming default baryon mass model and $\rho_{\mathrm{DM}} = 0.015\ \mathrm{M}_\odot/\mathrm{pc}^3$

Dark disk bounds



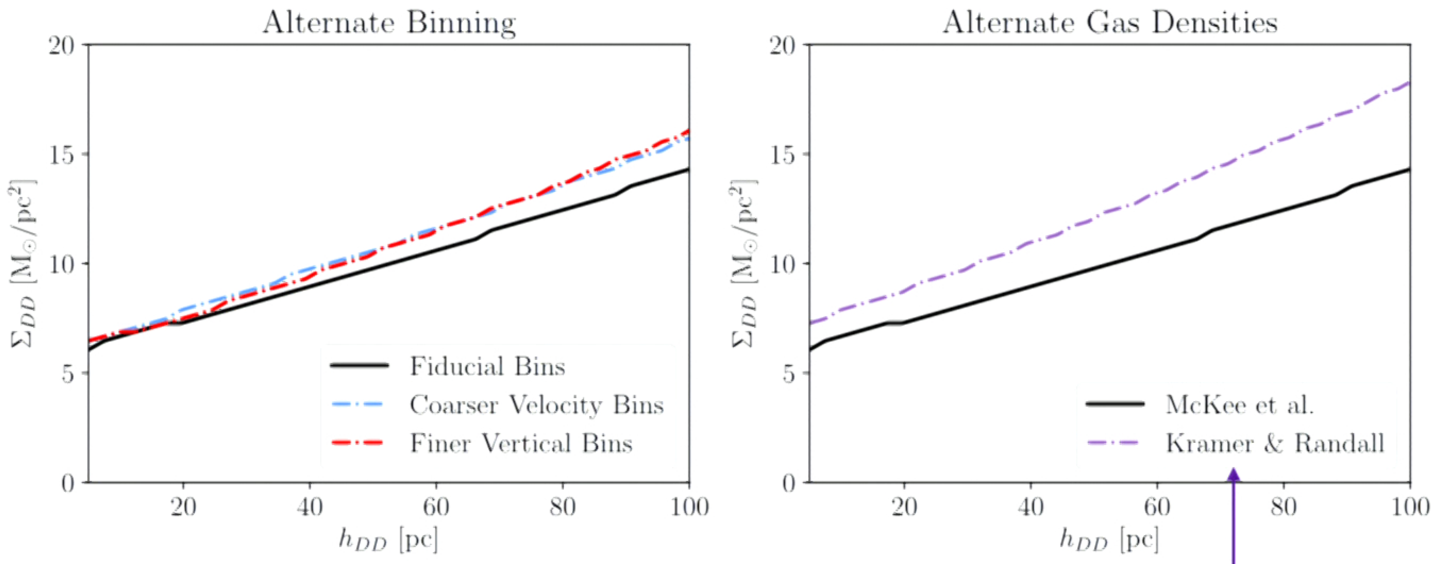
Improvements

Statistics:
~38,000 vs. 2000 stars

Longer lever arm:
max z = 200 pc vs. 150 pc

Nuisance parameters:
marginalize over many nuisance parameters vs. ``non-equilibrium" method

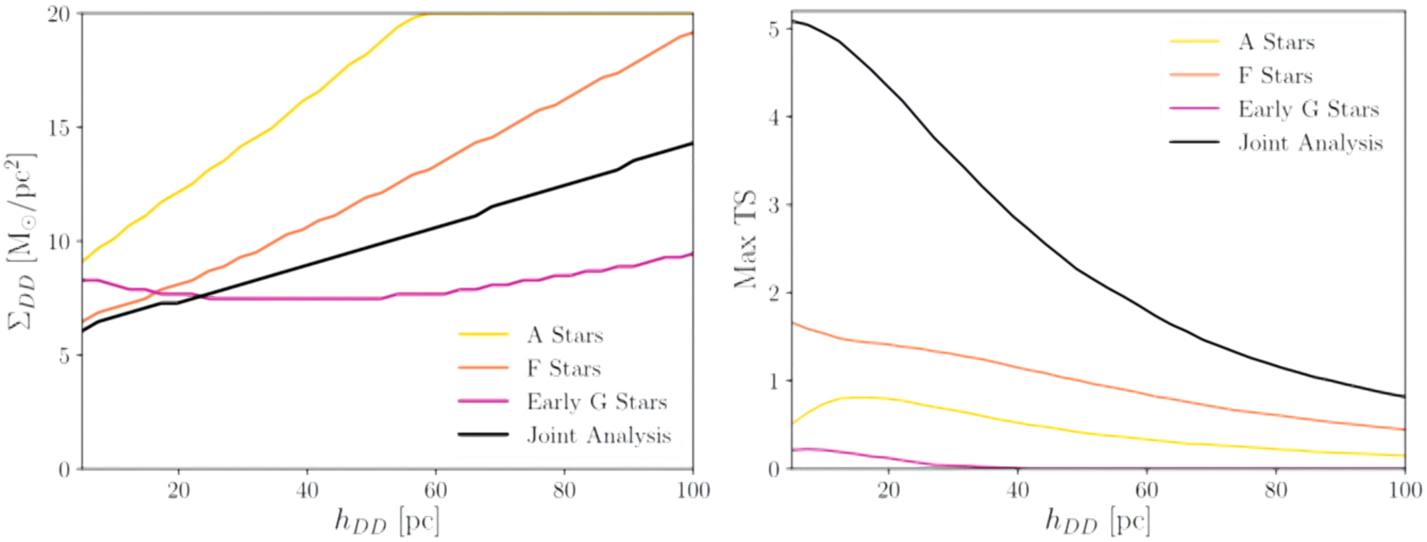
Robustness of bounds



Gas Component	Kramer & Randall $\rho(0)$ [M$_\odot$/pc^3]	McKee et al. $\rho(0)$ [M$_\odot$/pc^3]
Molecular Gas (H_2)	0.014 ± 0.005	0.01 ± 0.003
Cold Atomic Gas ($H_I(1)$)	0.015 ± 0.003	0.028 ± 0.006
Warm Atomic Gas ($H_I(2)$)	0.005 ± 0.001	0.007 ± 0.001
Hot Ionized Gas (H_{II})	0.0011 ± 0.0003	0.0005 ± 0.00002

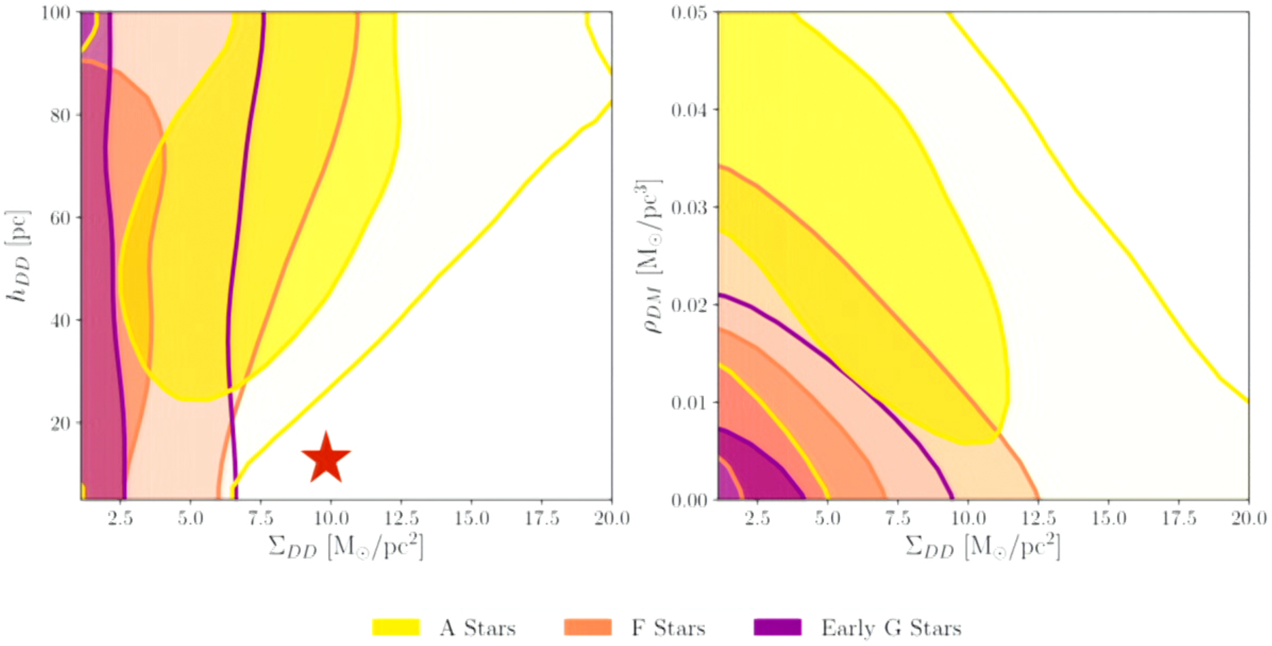
Kramer & Randall gas densities lower by ~25%

Bounds by population



F and Early G stars have similar statistics: differences may be due to statistical fluctuations, measurement error, different dynamical densities seen by older stars, effect of non-equilibrium perturbations?

Dark disk parameters



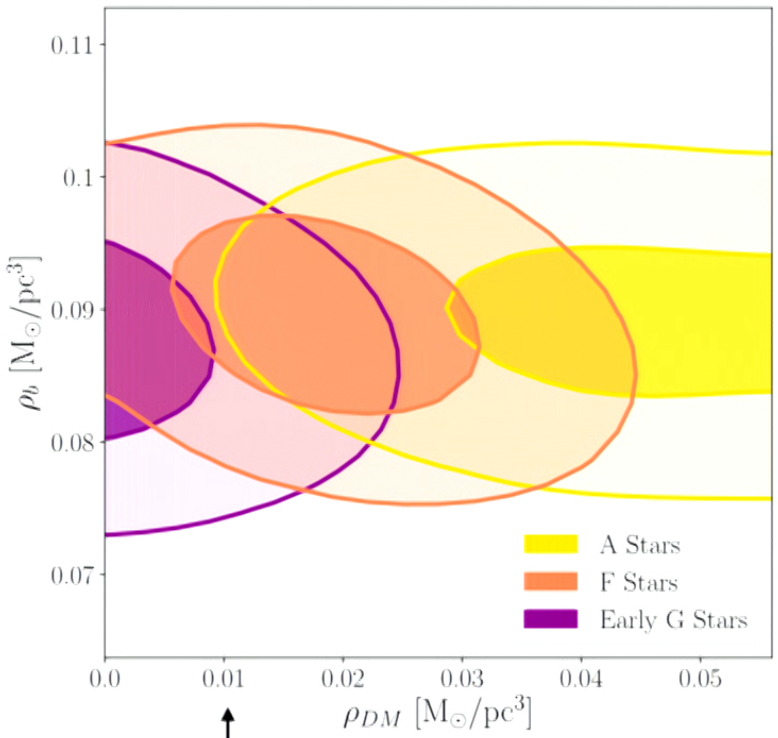
Bayesian analysis gives similar results on the dark disk posterior distributions for 3 tracer populations

Local dark matter density

Measurements of midplane density in $M_\odot/\mathrm{pc}^3$

Component	A Stars	F Stars	Early G Stars
baryons	$0.088^{+0.006}_{-0.006}$	$0.088^{+0.007}_{-0.007}$	$0.085^{+0.007}_{-0.006}$
DM	$0.038^{+0.012}_{-0.015}$	$0.019^{+0.012}_{-0.011}$	$0.004^{+0.01}_{-0.004}$

First measurements of *local* DM density (usually obtained at 1.1 kpc).



↑ 0.4 GeV/cm^3 in particle physics units

Dark disk implications, revisited

- Dynamical influence on local stars in the Milky Way (Kramer/Randall non-equilibrium method): $\Sigma \sim 12\ M_{\odot}/pc^2$, h~10 pc
- Enhanced direct detection signal: O(1) level
- Periodic disruption of comet trajectories causing mass extinction events:

  $\Sigma \sim 10\text{-}20\ M_{\odot}/pc^2$, h~10-30 pc
- Collapsed dark matter objects can account for the point-like nature of the inner galaxy GeV excess:

  $\Sigma \sim 10\ M_{\odot}/pc^2$, h~10 pc
- Co-rotation of Andromeda satellites

  $\Sigma \sim 10\ M_{\odot}/pc^2$, h~50 pc

New constraints on these scenarios

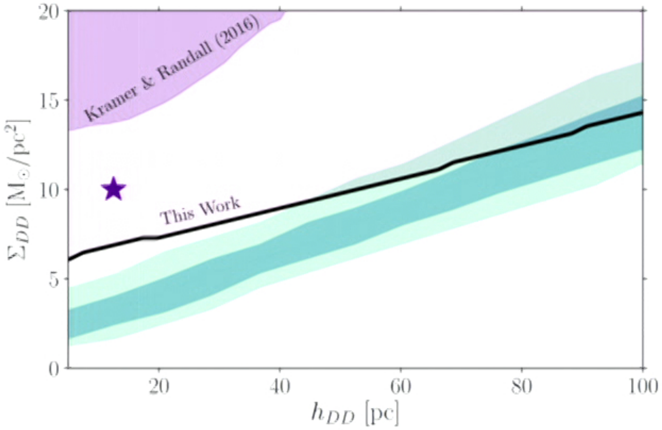
Important to note that dissipative DM is not ruled out!

Conclusions

- Dark disks can arise in models of dissipative dark matter

- Using Gaia TGAS data, we obtain
  - + new bounds on the presence of thin dark matter disks
  - + measurements of midplane densities and first <u>local</u> dark matter density

- Exciting time to better understand dark matter in the Milky Way with Gaia data!



Thanks!