Estimating the local DM content using *Gaia* DR2

(based on 1807.xxxxx w/ JiJi Fan and John Leung)

Jatan Buch

(Brown U.)

Contents:

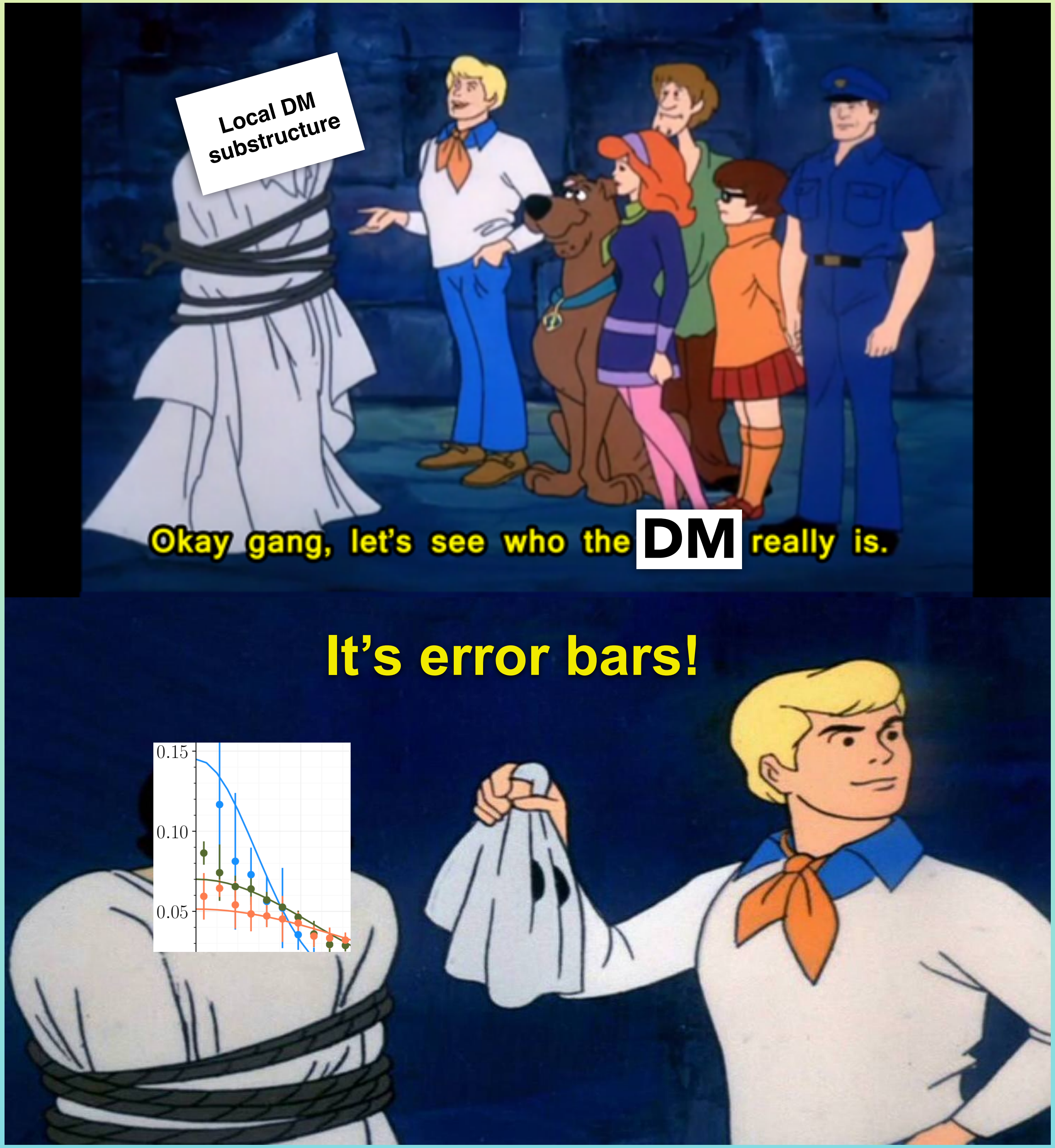
- Overview
- *Gaia* Data Release 2 (DR2): data, number density, velocity distribution
- Kinematic analysis
- Results: local DM density, dark disks (DD)?!
- Takeaways

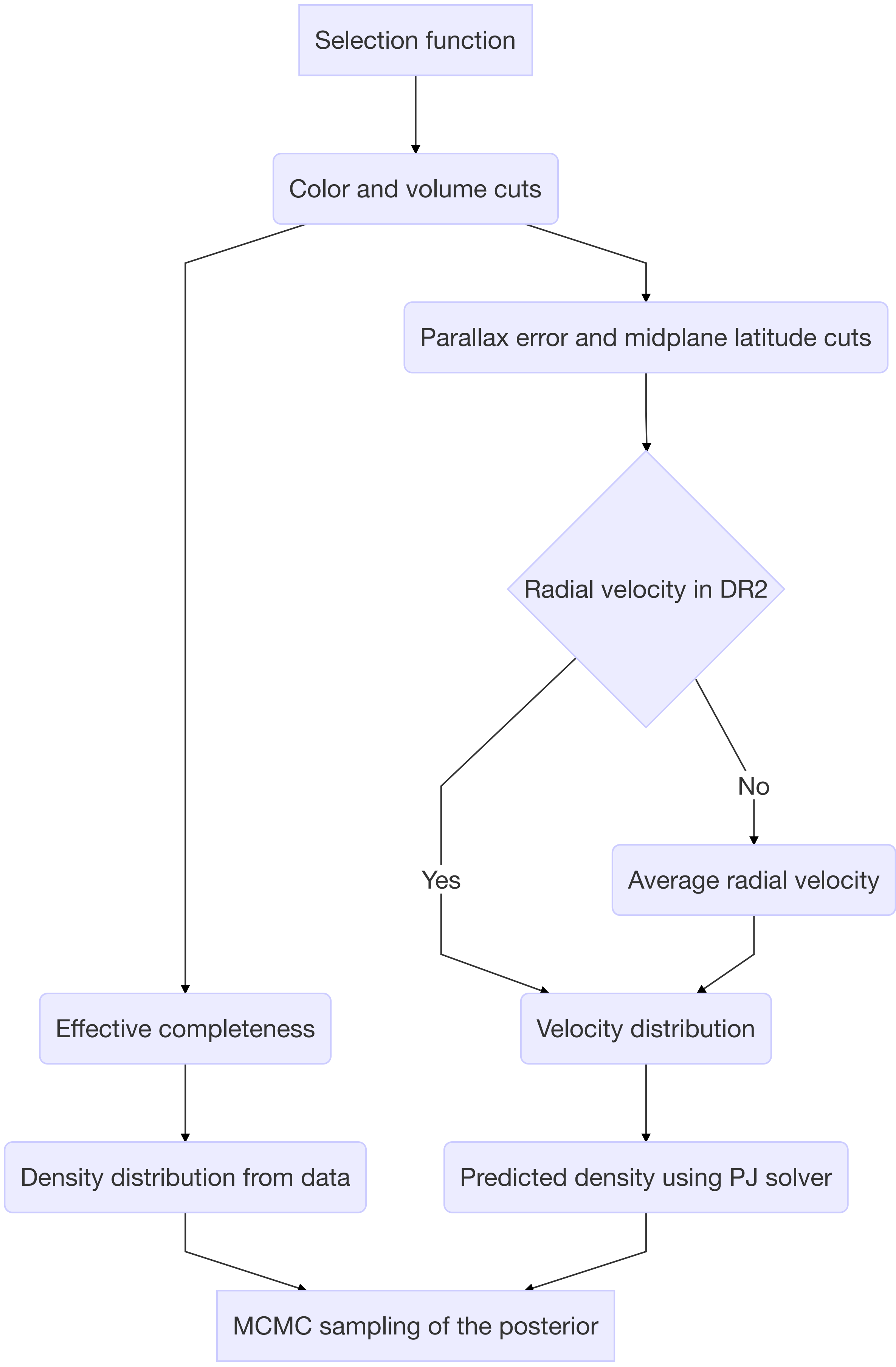
Overview

Motivation

- Density and morphology of local DM density is an important ingredient in direct detection searches on Earth: LZ, Xenon1T, PandaX …
- Also plays a crucial role in computing the flux of charged cosmic rays produced in DM annihilations. Of course, there's other complicating factors as well [talks by Perez & Cholis on Friday].
- From a theoretical perspective, DM with dissipative self-interactions, for instance $U(1)_D$, can cool down like baryons and form compact objects (substructure). Depending on the specifics of the astrophysical modeling, various signatures have been proposed: [Fan et al '13; Agrawal & Randall '16; Ghalasi & McQuinn '17; Buckley & DiFranzo '17]

Central question: Can we set *realistic* constraints on the density in DM substructure in the solar neighborhood using current dynamical methods?


Local DM substructure
Okay gang, let's see who the DM really is.
It's error bars!
0.15
0.10
0.05


Selection function
Color and volume cuts
Parallax error and midplane latitude cuts
Radial velocity in DR2
Yes
No
Average radial velocity
Effective completeness
Velocity distribution
Density distribution from data
Predicted density using PJ solver
MCMC sampling of the posterior

Gaia DR2:

Data, number density, velocity distribution

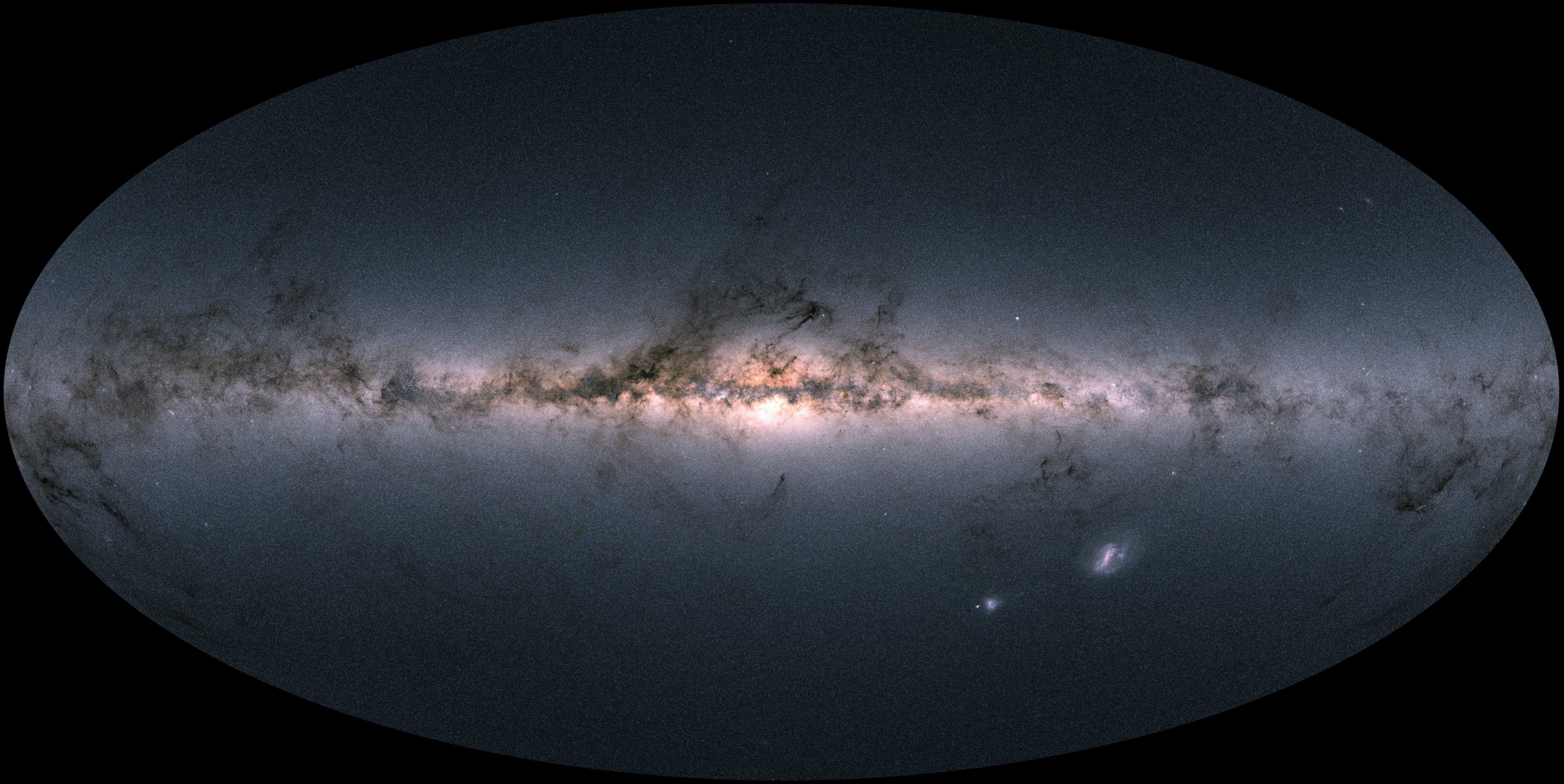


Image Credit: ESA

➔ GAIA'S HERTZSPRUNG-RUSSELL DIAGRAM

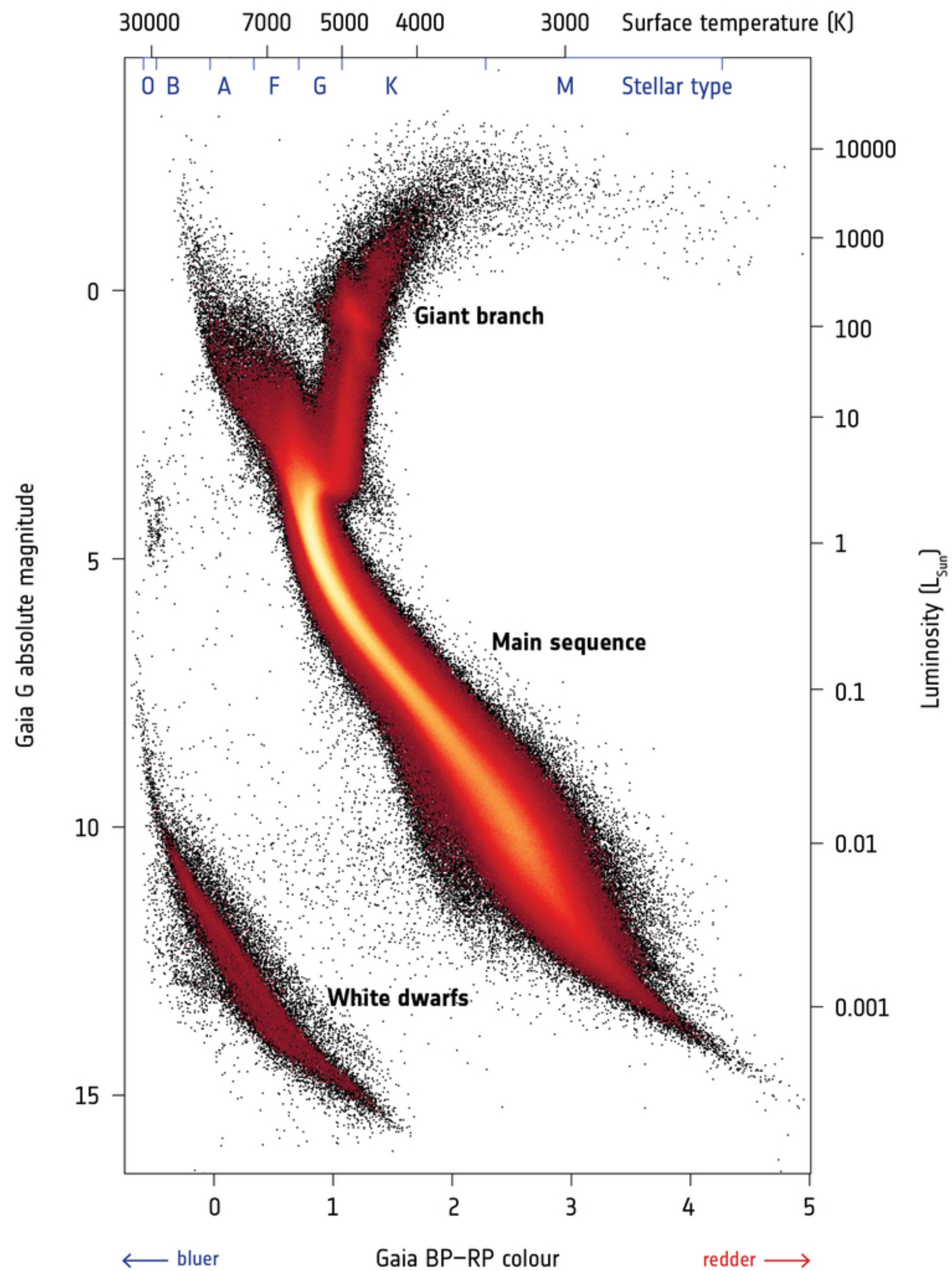


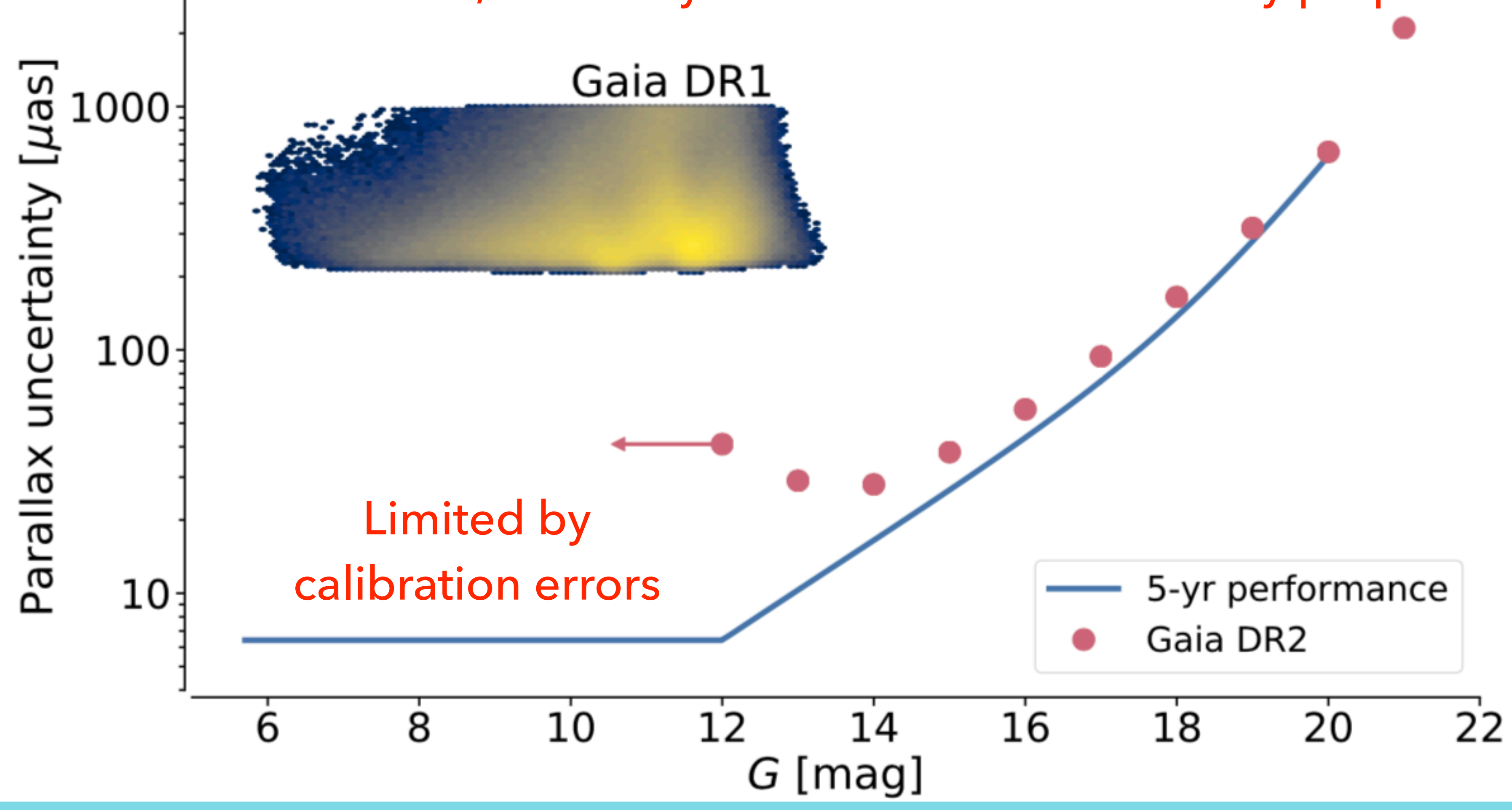
Image Credit: ESA

Some numbers…

- *Gaia* DR2 provides photometry, and high-precision astrometric data for ≈1.7 billion sources. The 5-parameter astrometric solution $(\alpha, \delta, \mu_{\tilde{\alpha}}, \mu_{\delta}, \varpi)$ is available for ≈1.3 billion sources.

- How much has the precision improved over DR1?

[*Gaia* Collaboration et al., Summary of the contents and survey properties]



Effective completeness

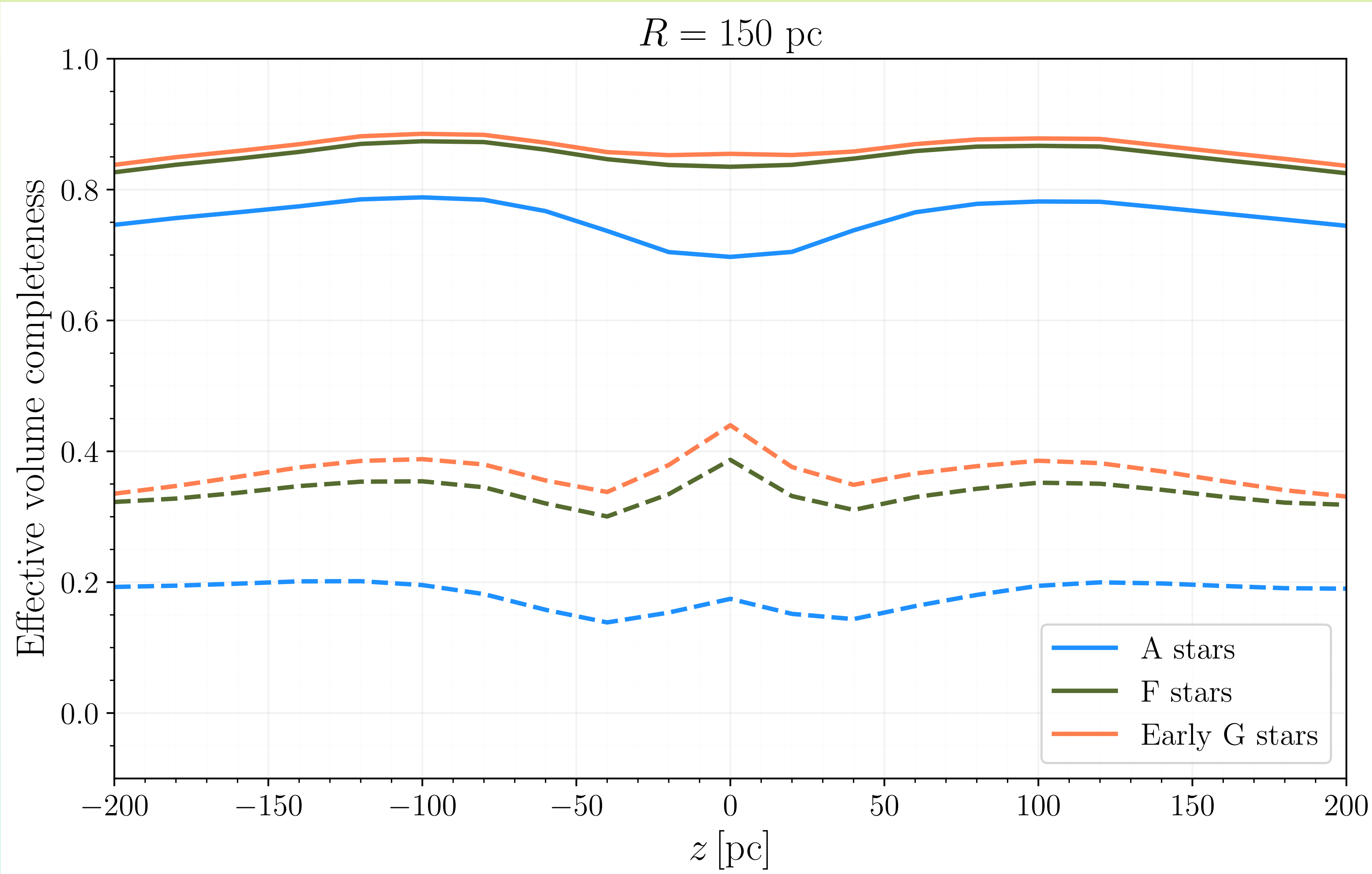
- The survey has a limiting magnitude $G \approx 21$, bright limit $G \approx 2$, and is essentially complete between $G \approx 12$ and $G \approx 17$. While this is definitely an improvement over TGAS, we still need to use an external catalog for constructing a volume complete number density of stars.

- We query the *Gaia* archive for stars in DR2 (full data is ~550 GB*) cross-matched with *2MASS* and apparent magnitude $J < 14$, and calculate the effective completeness using the `gaia_tools` package [Bovy '17].

- *2MASS* also provides color information (J, K_s) for DR2 stars, which we use for classifying stars into different spectral types: A, F, early G. An advantage of using (J-K_s) instead of *Gaia* colors (G_{BP} - G_{RP}) is that these are in the infrared spectrum and only weakly affected by scattering due to interstellar dust.

* If you're interested in working with DR2, I'd be happy to share ideas about handling data.

Effective completeness



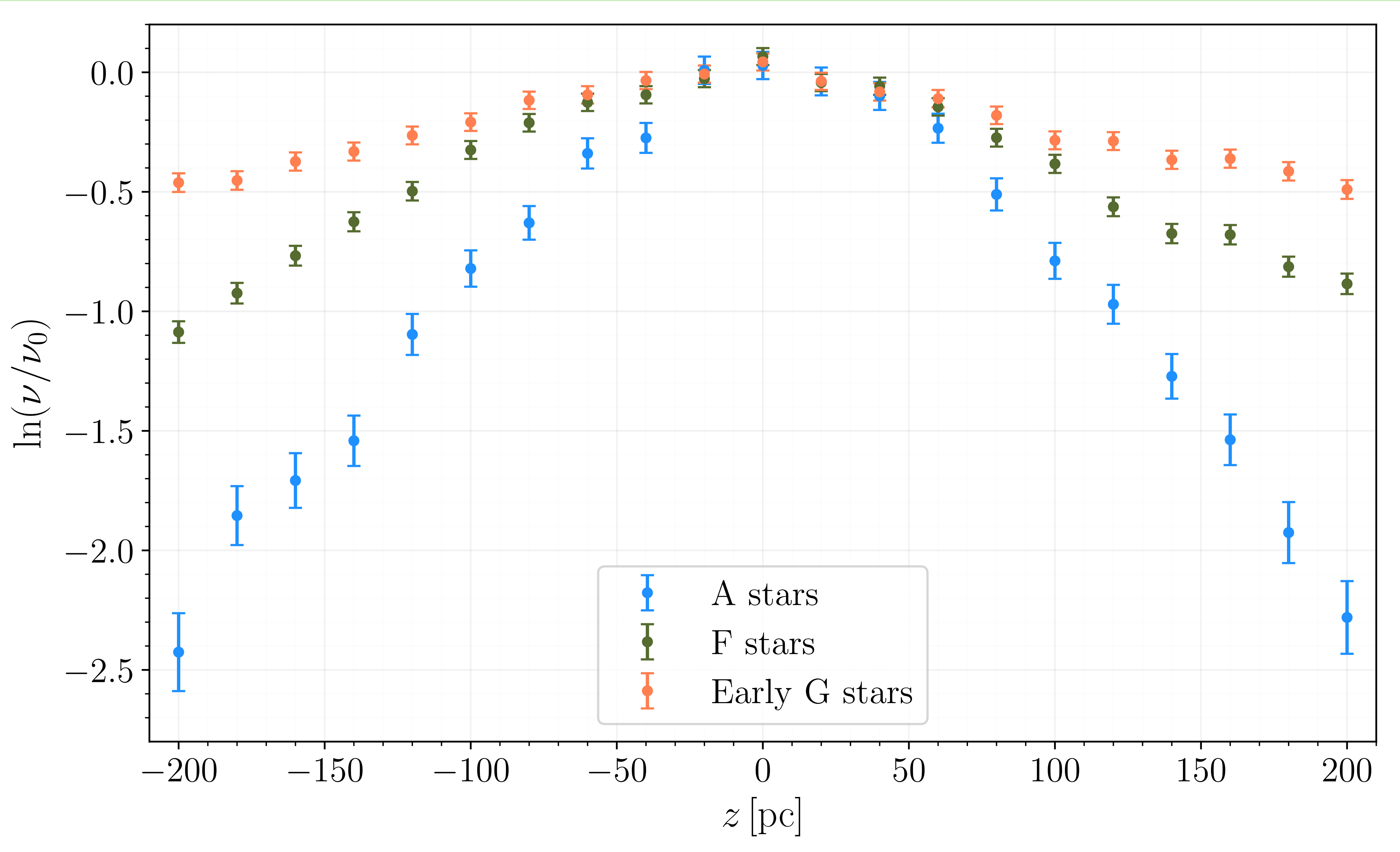
We define the local solar neighborhood as a heliocentric cylinder of radius R=150 pc and half-height z=200 pc.

There's ~2.5x improvement in statistics in the local neighborhood using DR2.

Data set		*Gaia* DR2		TGAS	
Type	Subtype	Total	Midplane	Total	Midplane
A	A0-A9	4544	310	1729	182
F	F0-F9	38431	2213	16789	1308
Early G	G0-G3	44075	2166	18653	1205

Vertical Number Density

$$z\,(\text{kpc}) = \frac{\sin b}{\varpi\,(\text{mas})}$$



Midplane velocity distribution

- Meanwhile, the vertical velocity of a star is given by,

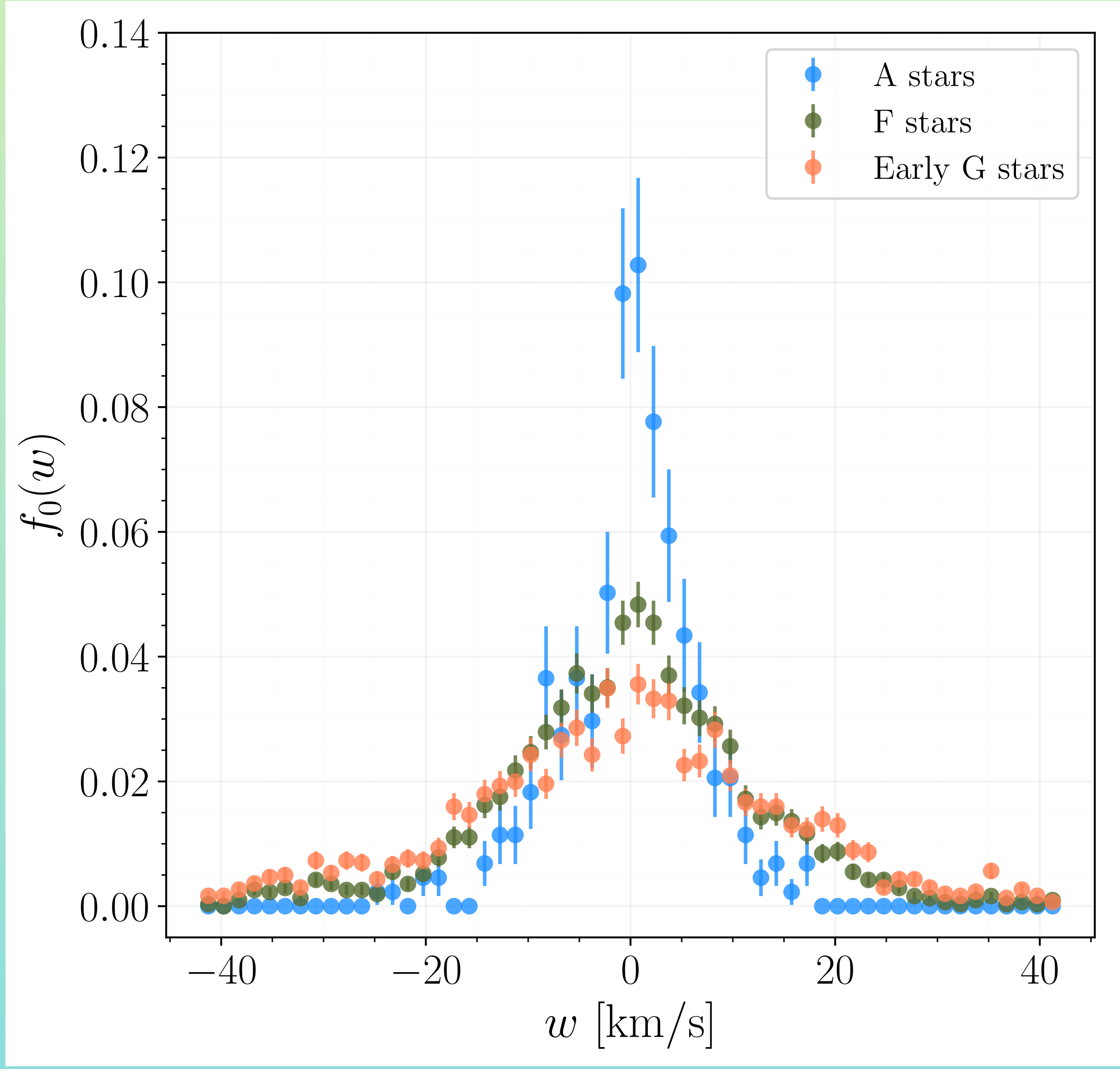
$$w = w_\odot + \frac{\kappa \mu_b}{\varpi} \cos b + v_R \sin b,$$

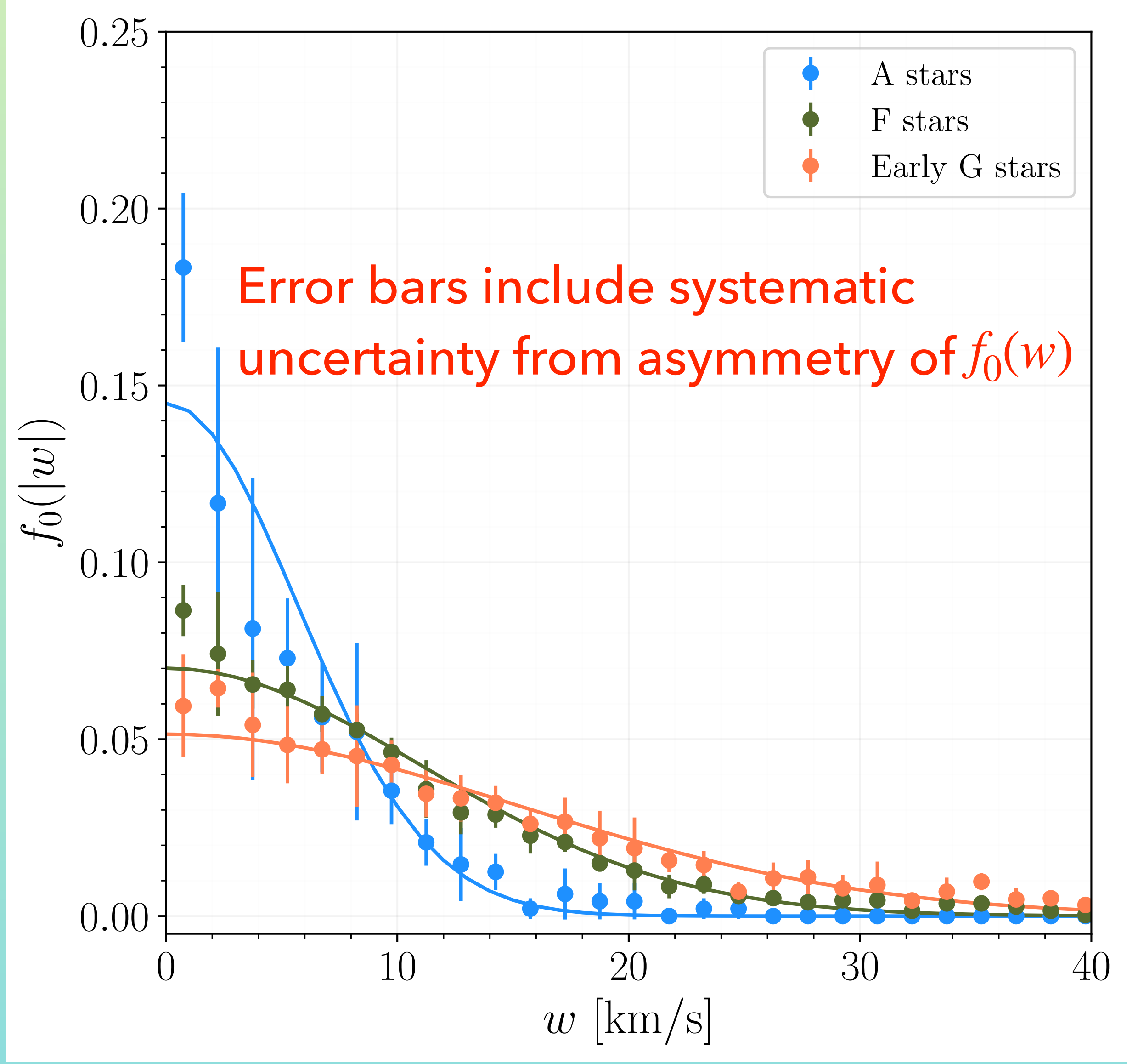
- DR2 also contains line-of-sight radial velocities (RVs) for ≈7.2 million stars measured by its on-board spectrometer. For context, RAVE DR5 presented spectra for ≈450,000 stars.

- Unfortunately, we only have RVs for ≈2% A, ≈53% F, and ≈62% G stars near the midplane (|*z*| < 20 pc). Thus, we define the midplane using a latitude cut, |*b*| < 5^0, and use an approximation for the mean RV when a star has no RV data in DR2,

$$\langle v_R \rangle = - u_\odot \cos l \cos b - v_\odot \sin l \sin b - w_\odot \sin b,$$

Midplane velocity distribution





Kinematic analysis

Discussion based on: [Flynn & Fuchs ’92; Holmberg & Flynn ’98; Kramer & Randall ’16; Schutz et al. ’17]

Poisson-Jeans theory

- The procedure for obtaining the tracer density is straightforward:

  a) choose a mass model for baryons (gas, stars, and stellar remnants), DM contribution from the halo, and other exotic DM component,

  b) calculate the local galactic potential of these ingredients, and

  c) compute the tracer density as a function of the potential.

- To obtain the potential in part *b),* we solve the Poisson eq.

$$\nabla^2\Phi = \frac{\partial^2\Phi}{\partial z^2} + \frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial\Phi}{\partial r}\right) = 4\pi G\rho_{\rm tot},$$

with,

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial\Phi}{\partial r}\right) \approx (3.4 \pm 0.6)\times 10^{-3}\ {\rm M}_\odot/{\rm pc}^3$$

[Bovy '16]

Poisson-Jeans theory

- The total mass density is given by,

$$\rho_{\rm tot} = \sum_{i=1}^{N_b} \rho_i(0) e^{-\Phi/\sigma_{z;i}^2} + \rho_{\rm DM} + \rho_{\rm substructure}(z)$$

where the sum is over N_b components of the Bahcall model that consists of a set of *isothermal* components of baryons characterized by their midplane densities $\rho_i(0)$ and vertical velocity dispersion $\sigma_{z;i}^2$.

The exponential dependence on the potential is due to the vertical Jeans equation, derived by integrating the Boltzmann equation assuming each population is in *equilibrium*,

$$\frac{1}{r\nu_i}\frac{\partial}{\partial r}\left(r\nu_i\sigma_{rz;i}\right) + \frac{1}{r\nu_i}\frac{\partial}{\partial \phi}\left(\nu_i\sigma_{\phi z;i}\right) + \boxed{\frac{1}{\nu_i}\frac{d}{dz}\left(\nu_i\sigma_{z;i}^2\right) = -\frac{d\Phi}{dz}}$$

"Tilt" term

"Axial" term

Poisson-Jeans theory

- We can put all these ingredients together by solving the Boltzmann equation in the *z* direction for each tracer population,

$$w\frac{\partial f_i}{\partial z} - \frac{\partial \Phi}{\partial z}\frac{\partial f_i}{\partial w} = 0.$$

where $f_i(z, w)$ is the distribution function. Assuming separability of phase space, we can integrate over the velocity to obtain the normalized tracer density,

$$\frac{\nu_i(z)}{\nu_i(0)} = 2\int_0^\infty dw f_{i,z=0}(\sqrt{w^2 + 2\Phi(z)})$$

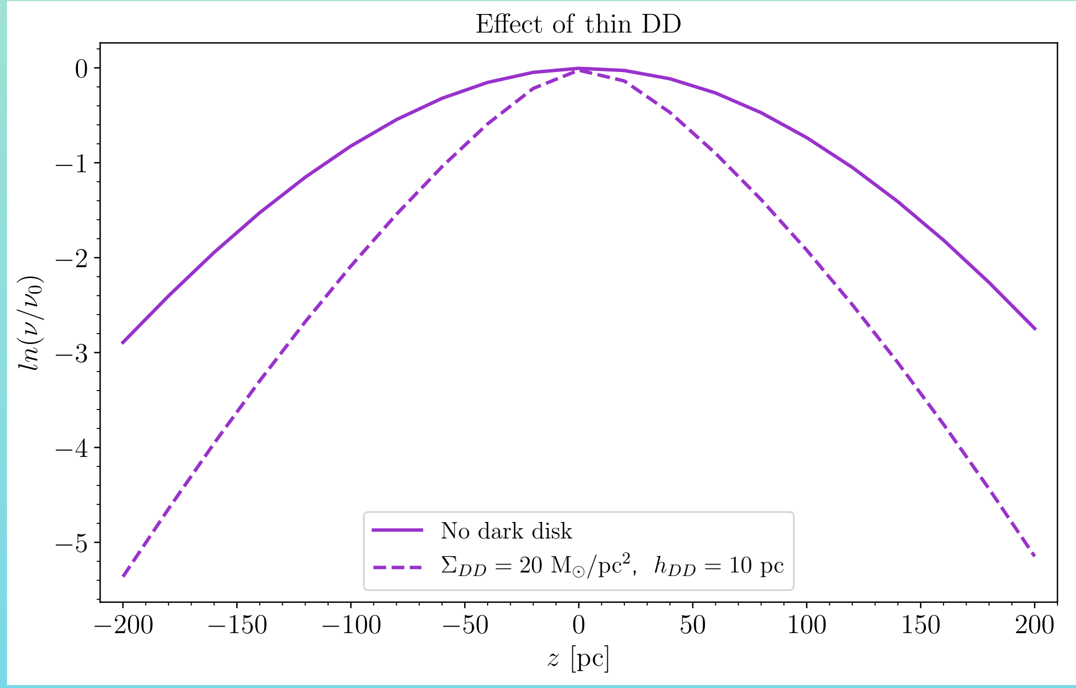
Results

Data analysis

- We constrain the total matter density by including with the Bahcall model:
  a) Local DM density $\rho_{\rm DM}$,

  b) Local DM content: $\rho_{\rm DM}$ + thin DD parametrized by,

$$\rho_{DD}(z) = \frac{\Sigma_{DD}}{4h_{DD}} \operatorname{sech}^2\left(\frac{z}{2h_{DD}}\right)$$



Parameters	Prior type	Range	Total
$\rho_k(0)$, $\sigma_{z;k}$	Gaussian	Eq. (4.1)	24
N_{ν_i}	Uniform	$[0.9, 2.0]$	3
$z_\odot$	Uniform	$[-30.0, 30.0]$ pc	1
h_{DD}	Uniform	$[0.0, 100.0]$ pc	1
$\rho_{\rm DM}$	Uniform	$[0.0, 0.06]$ $\mathrm{M}_\odot/\mathrm{pc}^3$	1
Σ_{DD}	Uniform	$[0.0, 30.0]$ $\mathrm{M}_\odot/\mathrm{pc}^2$	1

- Our model $\mathscr{M}$ is characterized by $\boldsymbol{\theta} = \{\boldsymbol{\psi}, \boldsymbol{\xi}\}$, where

  $\boldsymbol{\psi} = \{\rho_{\rm DM}, \Sigma_{DD}, h_{DD}\}$ are the parameters of interest

  $\boldsymbol{\xi}$ are the nuisance parameters, including height of the sun, baryonic uncertainties, …

Data analysis

- Performing parameter estimation in a Bayesian framework, we sample from the posterior,

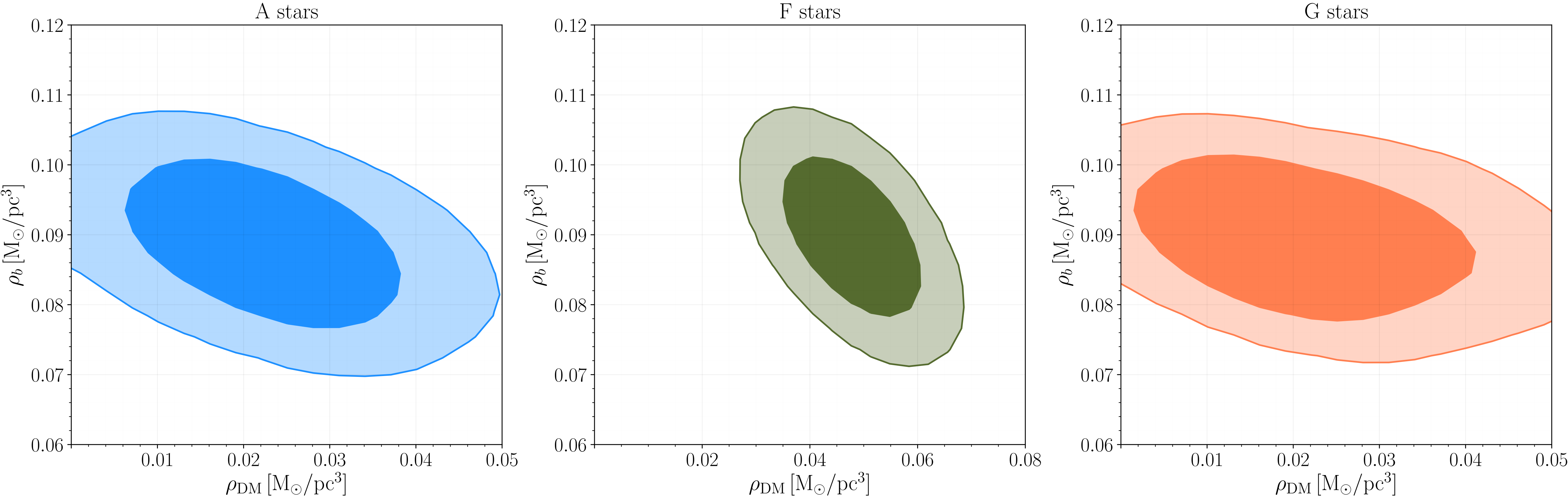
$$p(\boldsymbol{\theta}\,|\,d) = \frac{p(d\,|\,\mathscr{M},\boldsymbol{\theta})\,p(\boldsymbol{\theta}\,|\,\mathscr{M})}{Z\,*}$$

  using the Markov Chain Monte Carlo (MCMC) sampler `emcee` [D. Foreman-Mackey et al. '13]

- Note that MCMC methods are samplers and not optimizers, so there is no one 'true' value for each parameter. Instead, results are quoted using marginalized posteriors of parameters.

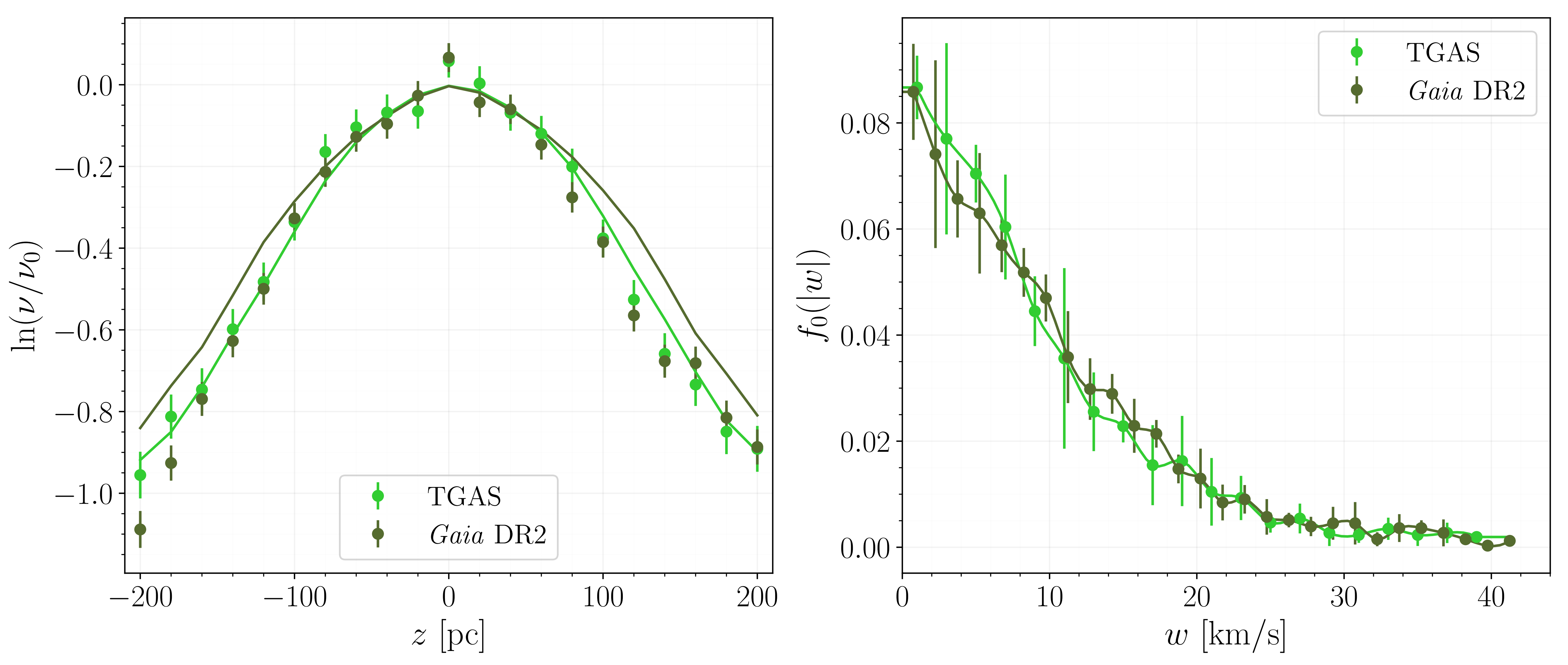
* MCMC samplers don't care about Z, and if you're a Bayesian neither should you! Would love to debate this point in more detail if anyone is interested.

Local DM density



Stellar type	ρ_{DM} [$M_\odot/pc^3$]	ρ_{DM} [GeV/cm^3]	ρ_b [$M_\odot/pc^3$]	$z_\odot$ [pc]
A stars	$0.023^{+0.010}_{-0.010}$	$0.874^{+0.380}_{-0.380}$	$0.089^{+0.007}_{-0.007}$	$4.95^{+3.78}_{-4.15}$
F stars	$0.047^{+0.006}_{-0.007}$	$1.786^{+0.228}_{-0.266}$	$0.091^{+0.007}_{-0.006}$	$2.52^{+2.58}_{-2.74}$
G stars	$0.021^{+0.014}_{-0.011}$	$0.798^{+0.532}_{-0.418}$	$0.090^{+0.007}_{-0.007}$	$-8.46^{+4.61}_{-4.09}$

Local DM density



- The DR2 midplane velocity distribution has a more gradual falloff as compared to TGAS that results in a broader predicted density. Raises issues regarding the robustness of the method!
- Broader prediction –> accommodates more matter –> weaker constraints

Local DM density

- Our results are consistent with previous measurements:

  $\rho_{\rm DM} = 0.012^{+0.001}_{-0.002}\ {\rm M_\odot/pc^3}$ (within 1σ) [Sivertsson et al. '17]

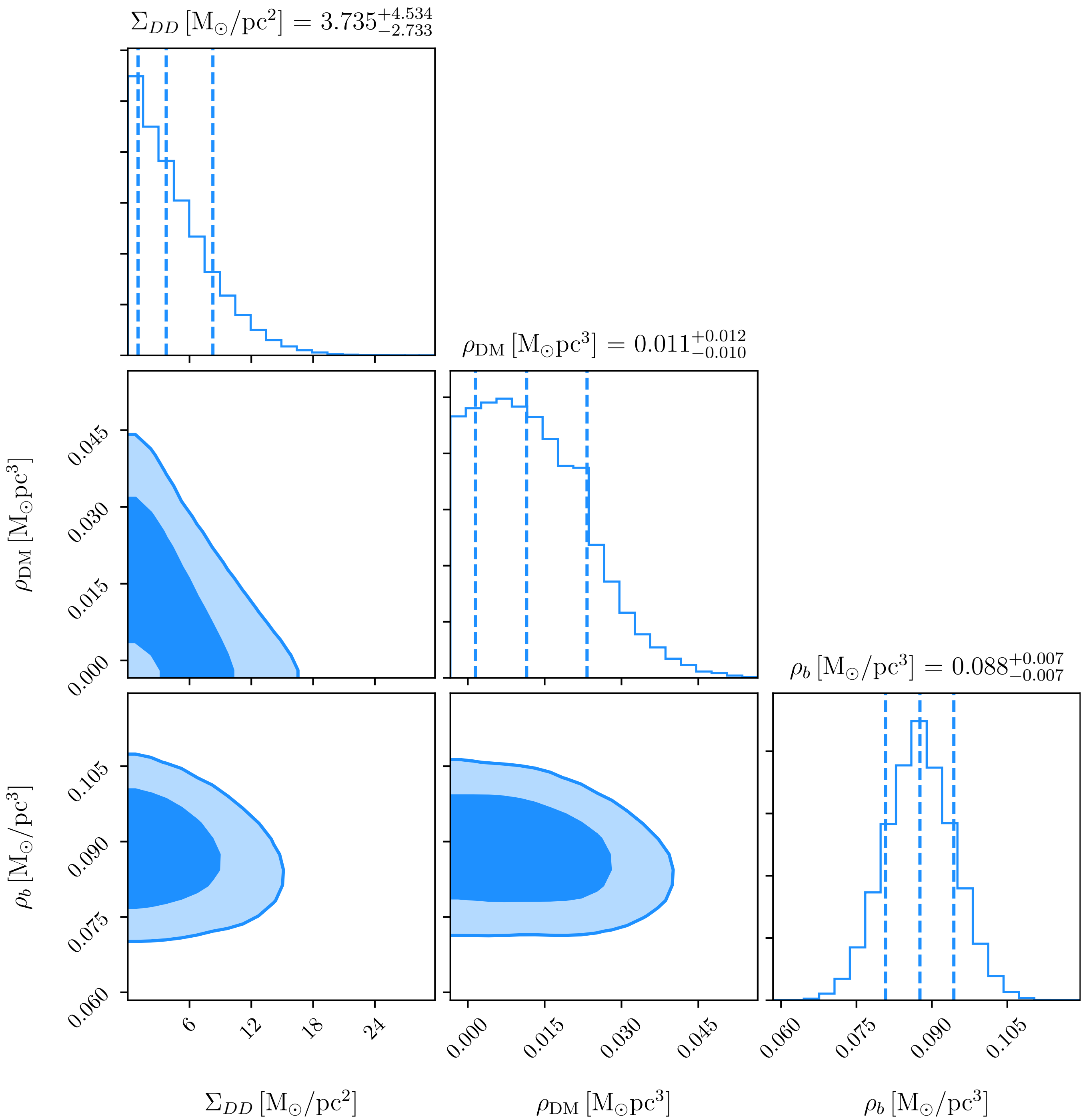
  $\rho_{\rm DM} = 0.008^{+0.003}_{-0.003}\ {\rm M_\odot/pc^3}$ (within 2σ) [Bovy & Tremaine '12]

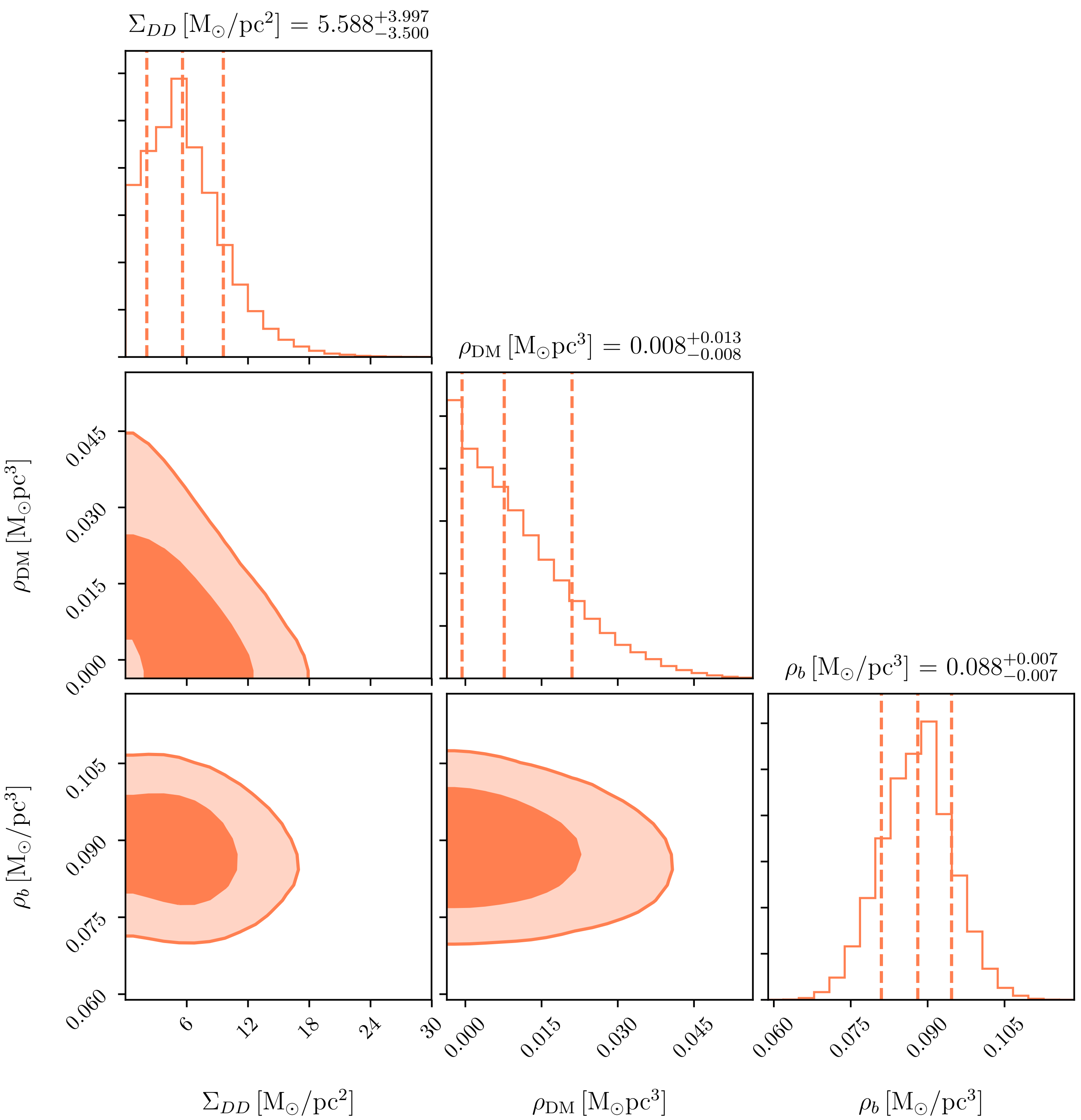
- Notice that the error bars are fairly large in our case. While poorly modeled systematics can be a culprit, the posteriors indicate a high level of degeneracy between baryons and DM.

- Indeed, as first pointed out by Bahcall (1992) and shown via detailed N-body simulations by Garbari et al. (2011), this degeneracy can only be broken by including the density falloff at $z > 1$ kpc.

- Since the baryons are mostly confined to the stellar disk with a scale height of ~kpc, any falloff at high z can be attributed to (atleast at leading order) to DM, leading to a more precise measurement with smaller error bars.

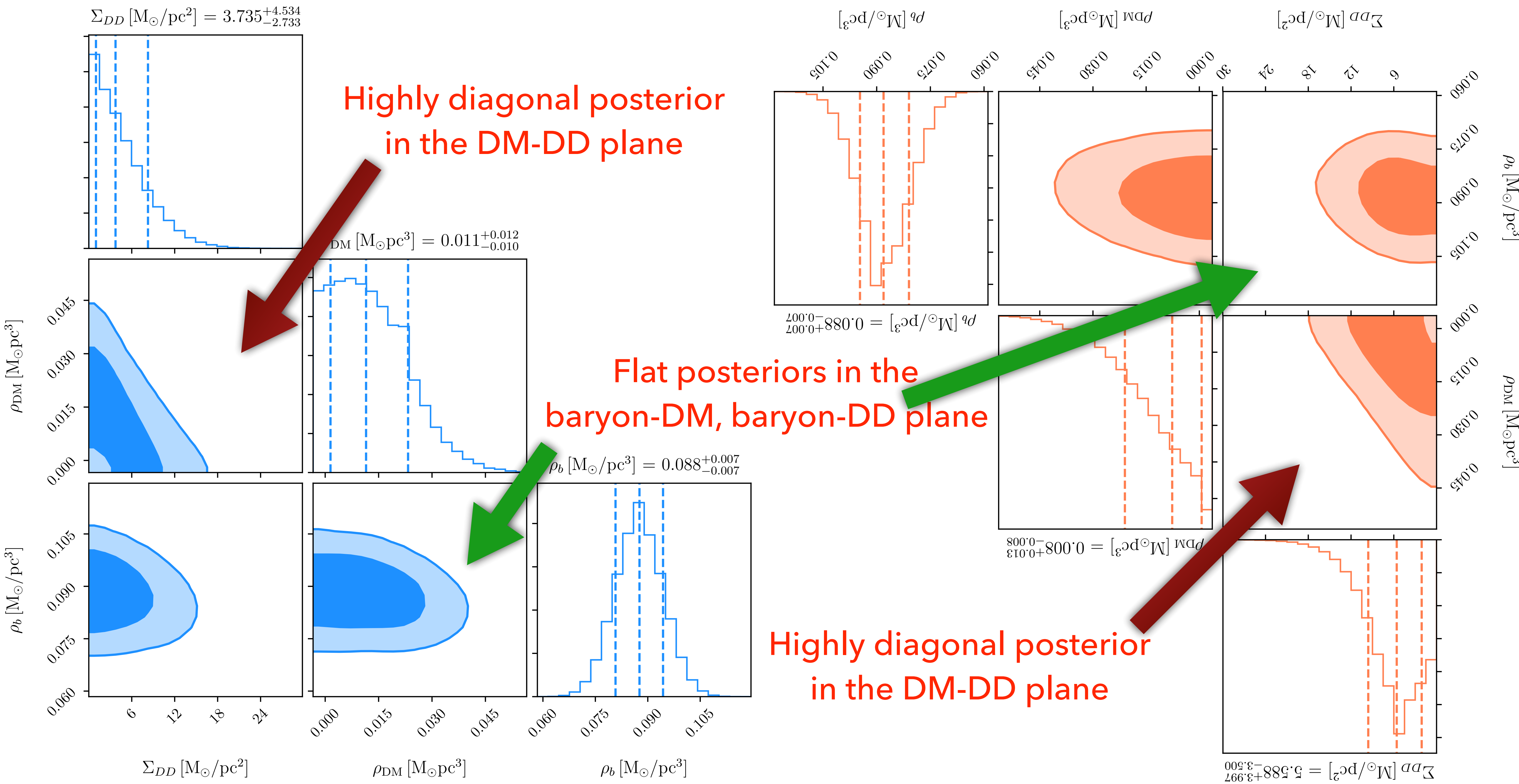
Local DM content





Central question: Can we set *realistic* constraints on the density in DM substructure in the solar neighborhood using current dynamical methods?

Local DM content



Answer: Maybe, but ...

Caveats

- Better understanding and modeling of how disequilibria [talk by Necib today] affects dynamics in the solar neighborhood.
- Identifying good tracers that incorporate information about age, and sensitivity to non-equilibrium dynamics: using mono-abundant populations (MAPs) [Lee et al. '11, Bovy et al. '12 , Banik et al. '16].
- Need physical observable(s) to break the degeneracy between DM and substructure; ratios, hierarchical modeling?
- Exploring the effect of dissipative DM interactions using cooling prescriptions [Fan & Rosenberg '17] in simulations—semi-analytic or numerical—is still lacking. For discovery or constraining many dissipative DM scenarios listed in the Overview, their input will be key.

Takeaways

(or what you should be able to remember after the cocktail hour tonight!)

- We estimate, using A stars as tracers, the value of local DM density to be $\rho_{\rm DM} = 0.023 \pm 0.01\ {\rm M_{\odot}/pc^3}$, and exclude a thin DD with Σ_{DD} greater than $(5 - 15)\ {\rm M_{\odot}/pc^2}$ at the 95% confidence level.

- Due to the latent degeneracy between baryons and DM (substructure or otherwise) in the solar neighborhood, hard to match the precision (given unknown systematics) of DM density measurements at high z. This also leads to only *weak* upper bounds on the thin DD parameters.

- Studying (sub)structure in phase space could shed light on (sub)structure in theory space: *e.g*: multicomponent DM sector, tweaks to the CDM paradigm etc. Developing creative and *robust* dynamical methods for their study will be crucial.

- We've only begun to tap the potential of *Gaia*; there's a lot more to look forward to in the coming years!

Thank you.

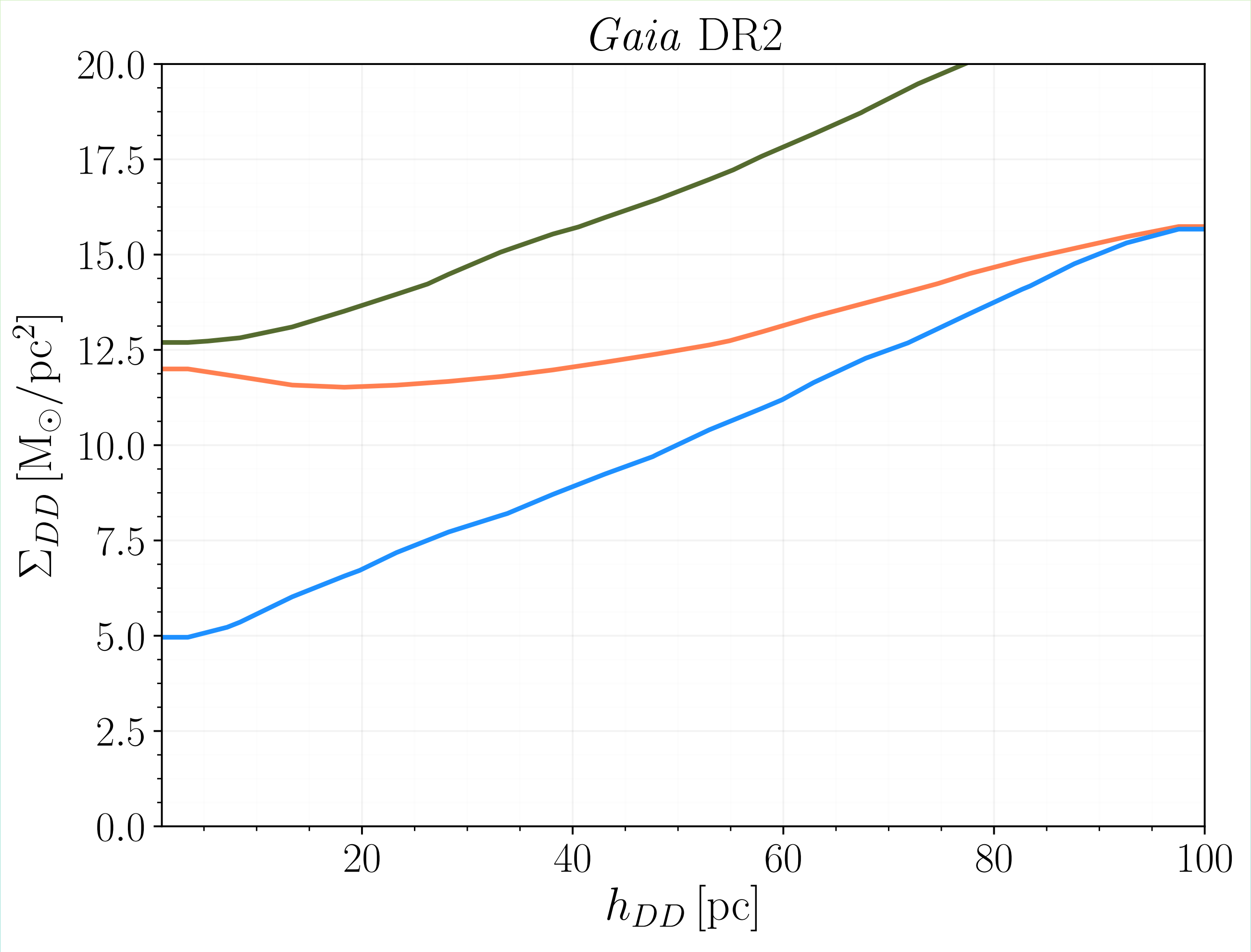
Comments & criticisms welcome!

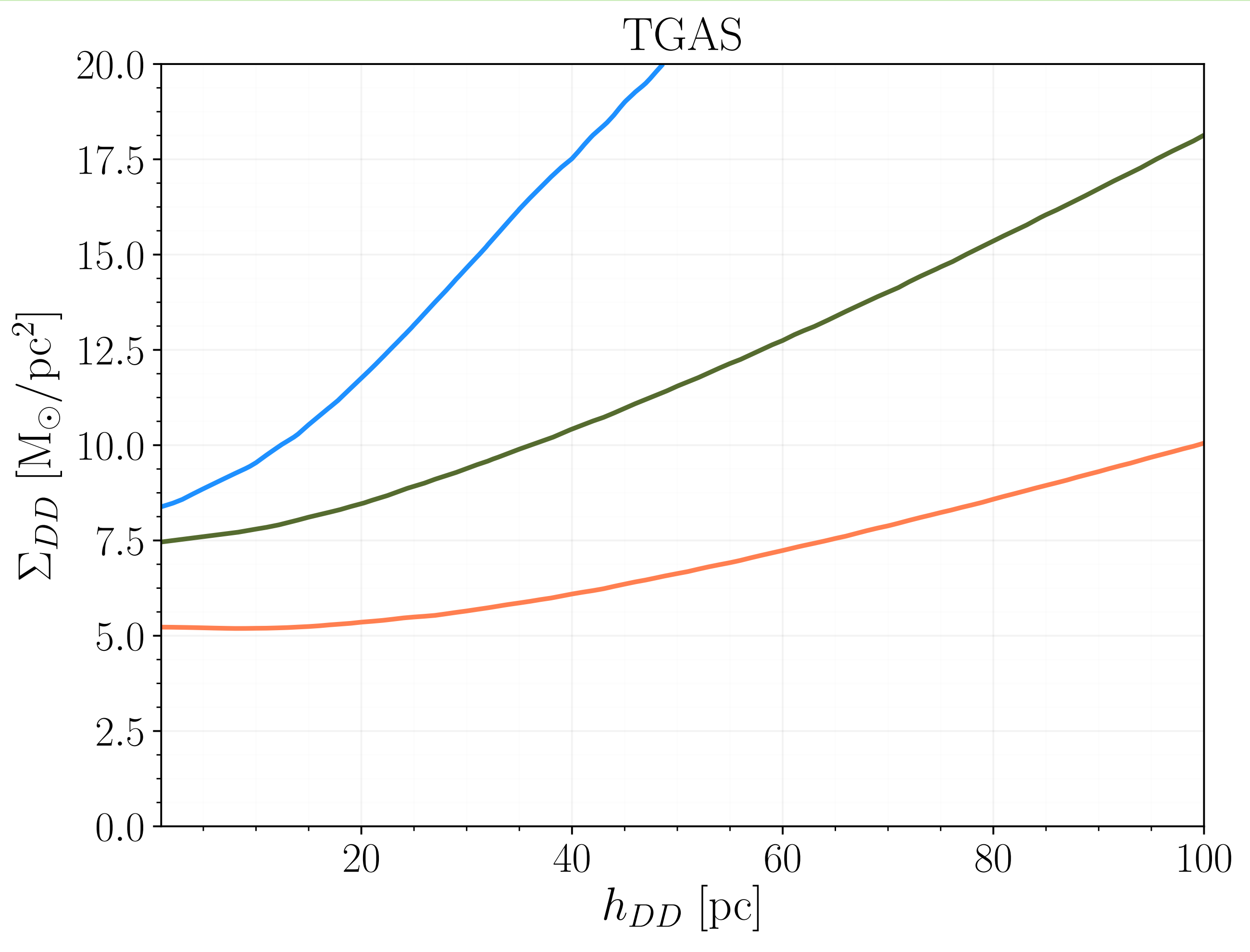
Extra slides

Bahcall model

Baryonic components	$\rho(0)$ [$M_\odot/pc^3$]	σ_z [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

Consistency with TGAS





- DR2 catalog should be treated as independent from DR1! In particular, there may be significant differences between observations in DR2 and the *Tycho-Gaia Astrometric Solution* (TGAS) subset of DR1 for some sources.