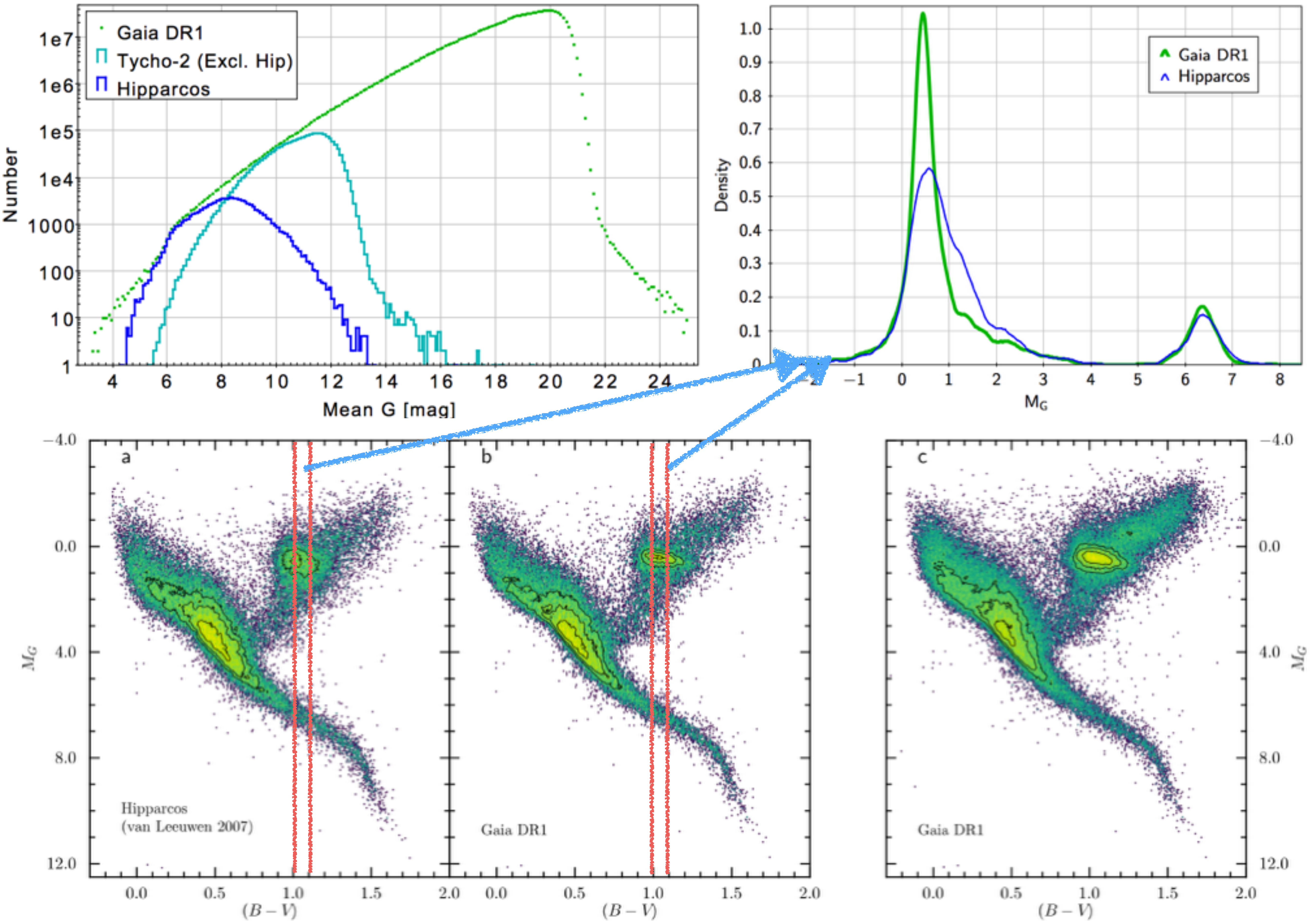
The stellar content and dynamics of the solar neighborhood in *Gaia* DR1

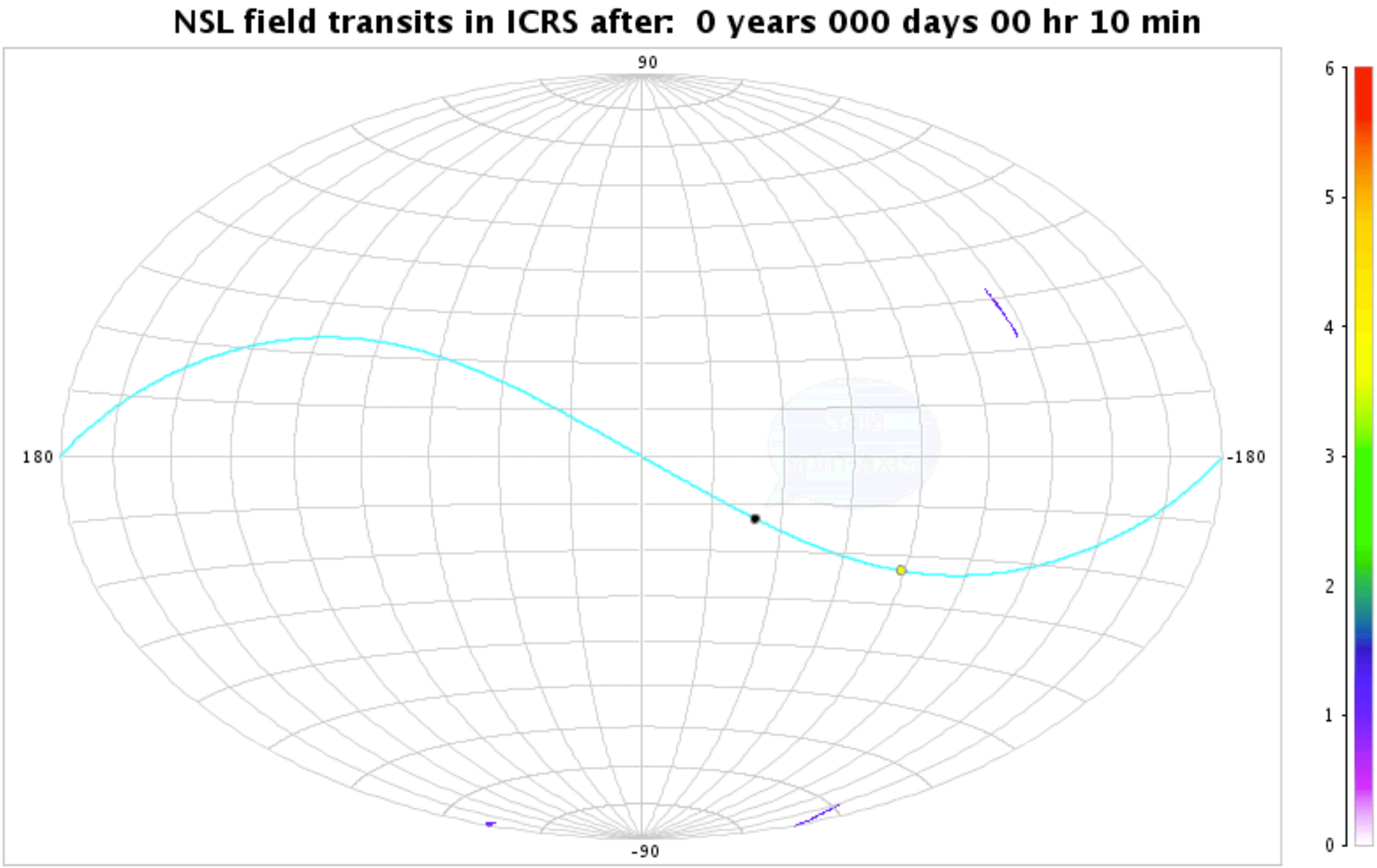
Jo Bovy (University of Toronto; Canada Research Chair / Simons Center for Computational Astrophysics)

Gaia Collaboration, Brown et al. (2016)



TGAS selection function:

The scanning law



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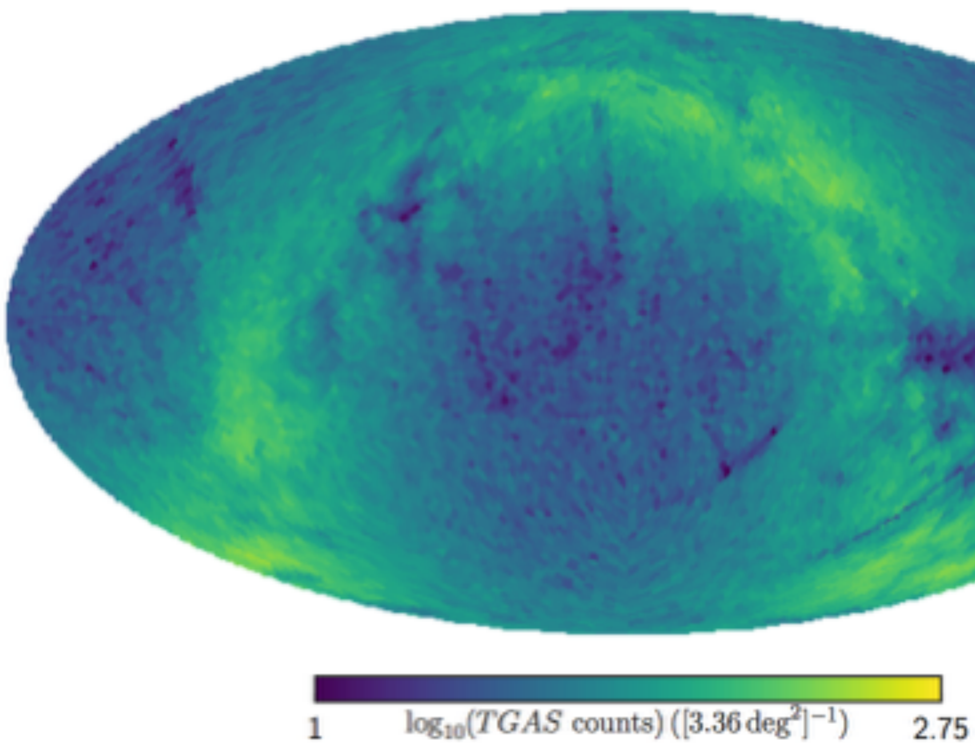
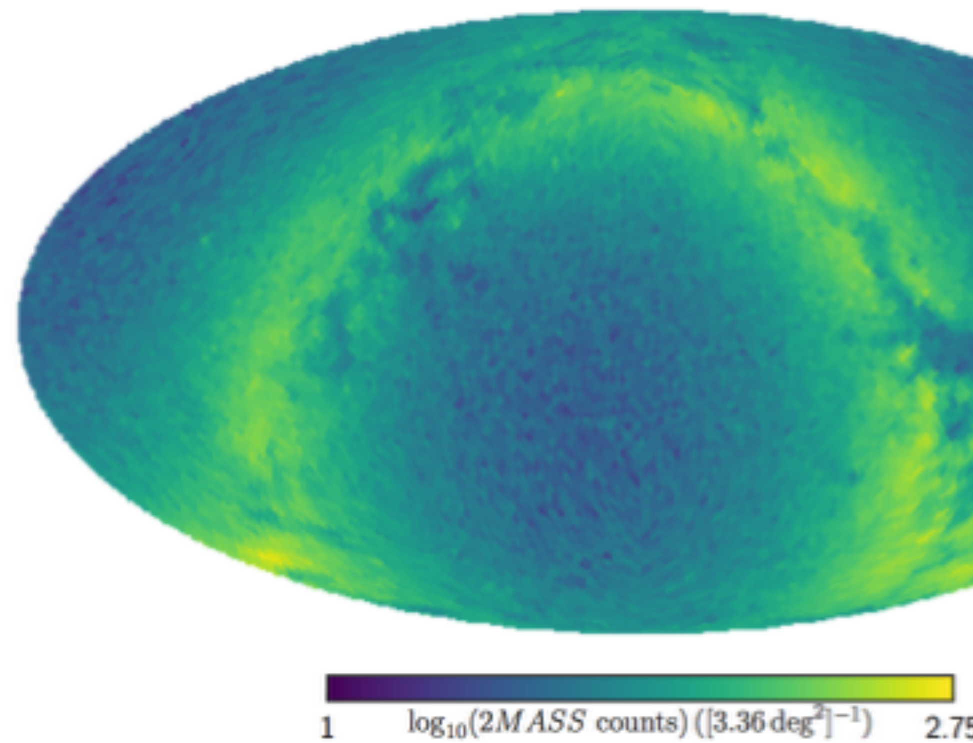


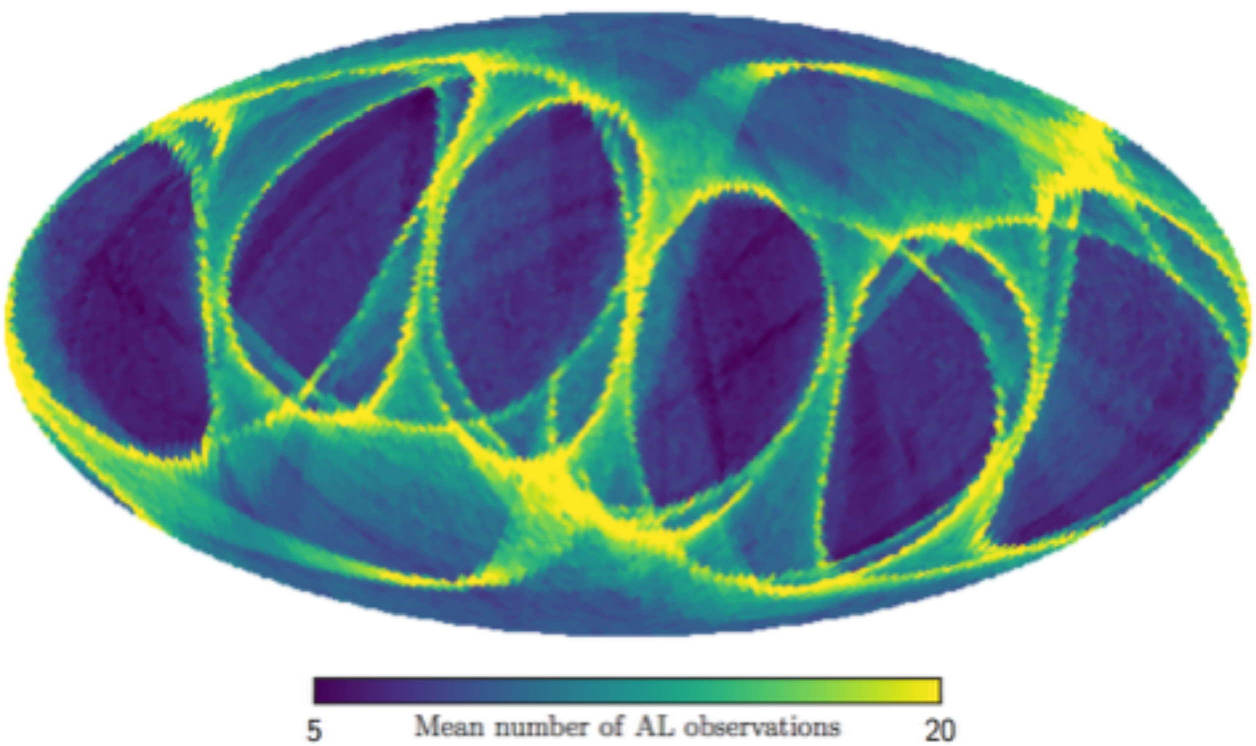
TGAS



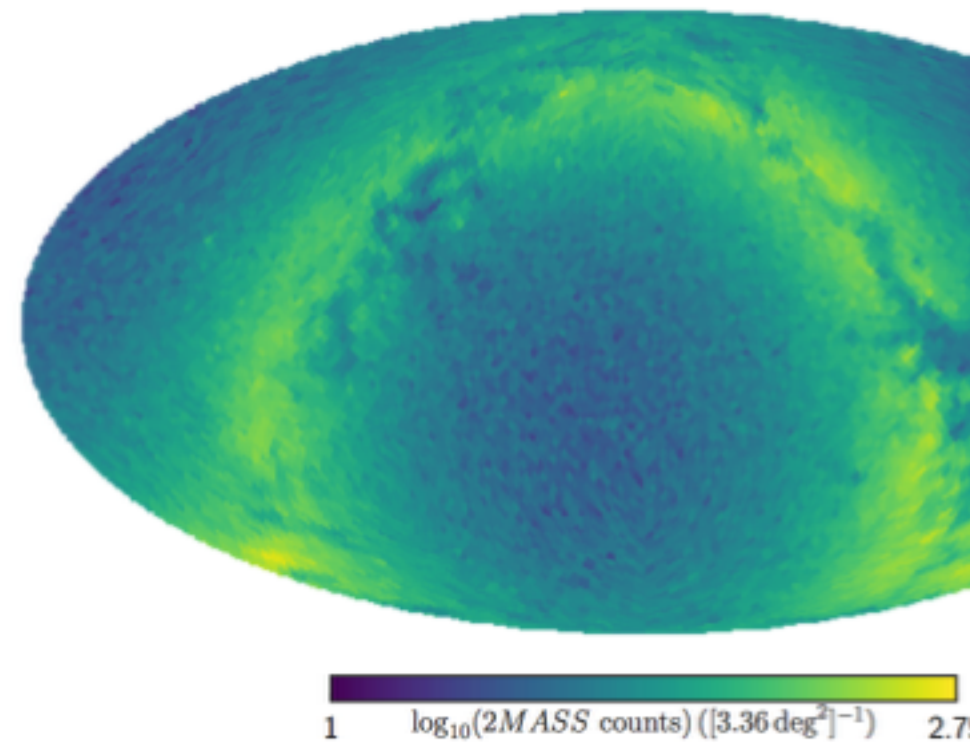
2MASS

TGAS selection function:

The scanning law



TGAS



2MASS

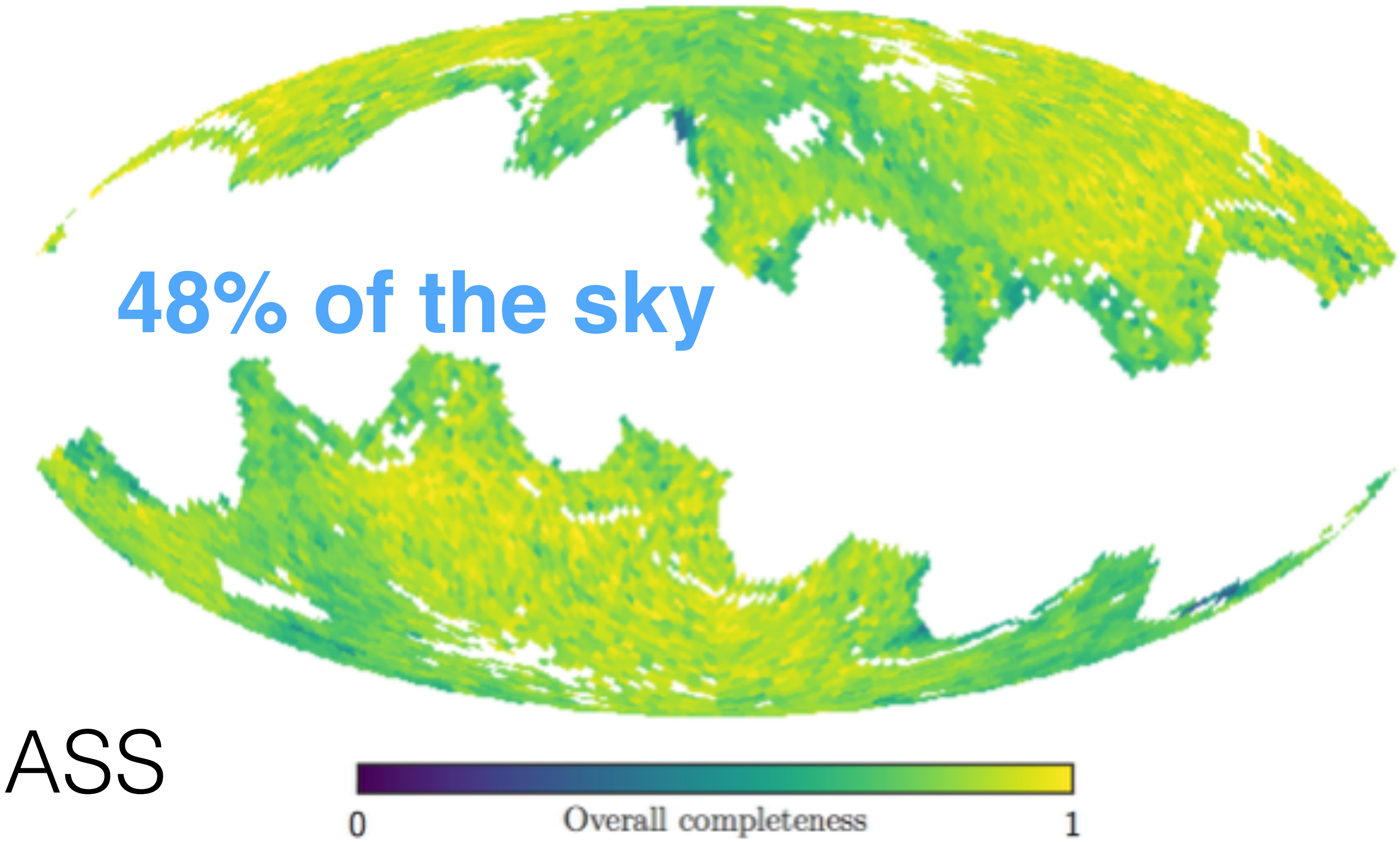
TGAS selection function:

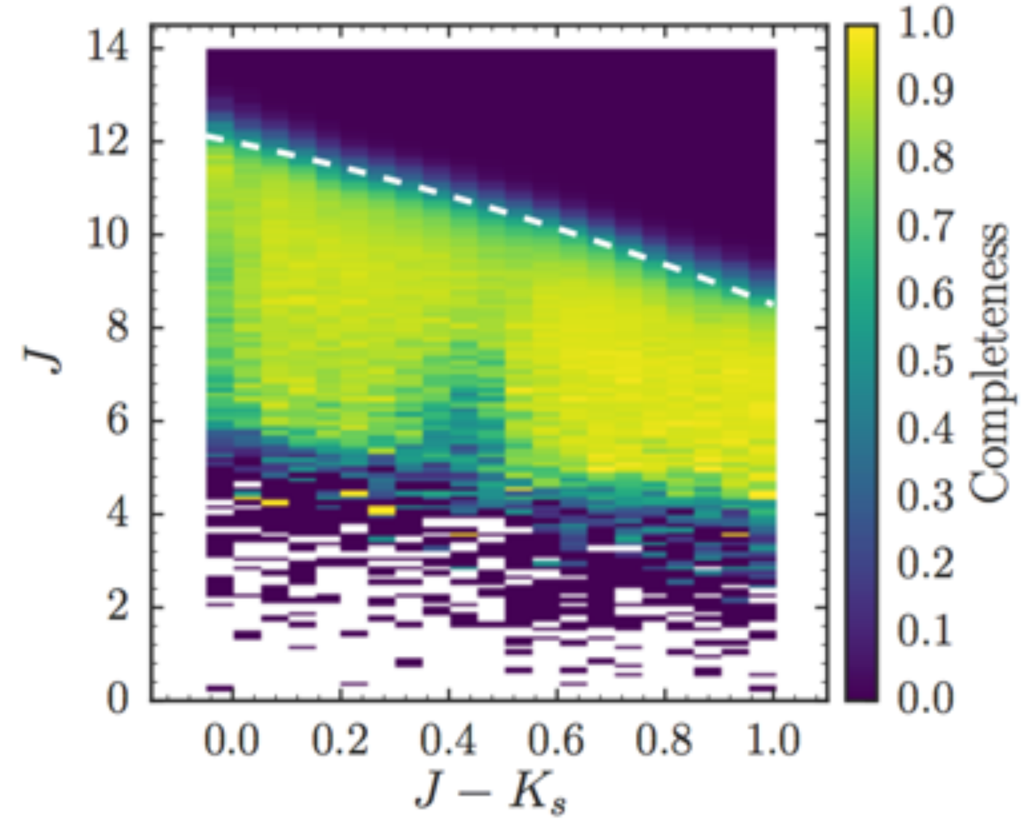
- Smooth function:

  S(J,J-K_S,RA,Dec) =

  # in TGAS / # in 2MASS

- https://github.com/jobovy/gaia_tools





Measuring stellar densities with *TGAS*

Complete survey:

$$n = \frac{N}{V}$$

Measuring stellar densities with *TGAS*

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$$n = \frac{N}{V} = \frac{\text{Number of stars in a volume } \Pi}{\text{Volume of } \Pi}$$

Measuring stellar densities with *TGAS*

Incomplete survey:

$$n = \frac{N}{\Xi(\Pi)\,V(\Pi)} = \frac{\text{Number of stars in a volume }\Pi}{\text{Effective Volume of }\Pi}$$

Measuring stellar densities with *TGAS*

Incomplete survey:

$$n = \frac{N}{\Xi(\Pi)\,V(\Pi)} = \frac{\text{Number of stars in a volume }\Pi}{\text{Effective Volume of }\Pi}$$

$\Xi(\Pi) =$ Effective volume completeness

Measuring stellar densities with *TGAS*

Incomplete survey: examples

- Only observe 80% of all stars: $\Xi\left(\prod\right)$= 0.80
- $\prod$ = sphere with radius 100 pc, only observe stars to 80 pc: $\Xi\left(\prod\right)$= $(100/80)^3$

Measuring stellar densities with *TGAS*

Incomplete survey: how to compute $\Xi(\Pi)$

- Depends on
    - (a) survey through selection function S(J,J-K_s,RA,Dec)
    - (b) stellar type through (M_J,[J-K_s]$_0$)
    - (c) 3D extinction A_λ(RA,Dec,*D*) for (M_J,[J-K_s]$_0$) —> (J,J-K_s,RA,Dec)
- Intermediate: Effective (distance) completeness

$\mathfrak{S}(\alpha, \delta, D)$ = fraction of stars of given type observed at (RA,Dec,*D*)

Measuring stellar densities with *TGAS*

Incomplete survey: how to compute $\mathfrak{S}(\alpha, \delta, D)$

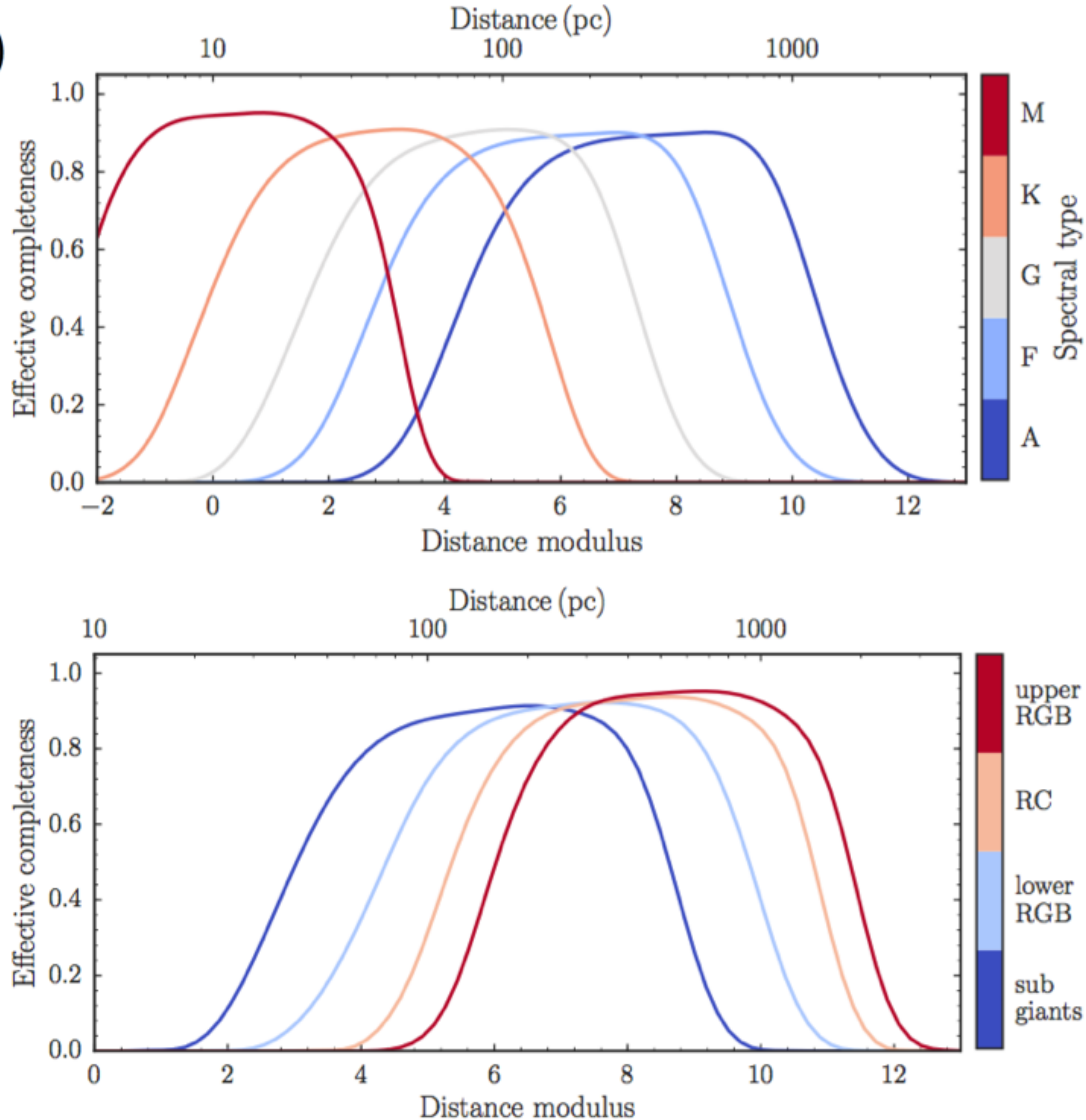
- Example: standard candle and crayon (M_J,J-K_s), no extinction

$$\mathfrak{S}(\alpha, \delta, D) = S(M_J + \mu, J - K_s, \alpha, \delta)$$

- General: distribution of (M_J,J-K_s)$_j$, extinction

$$\mathfrak{S}(\alpha, \delta, D) \approx \sum_j S(M_{J,j} + \mu + A_J, [J - K_s]_{0,j} + E(J - K_s), \alpha, \delta)$$

$\mathfrak{S}(\alpha, \delta, D)$

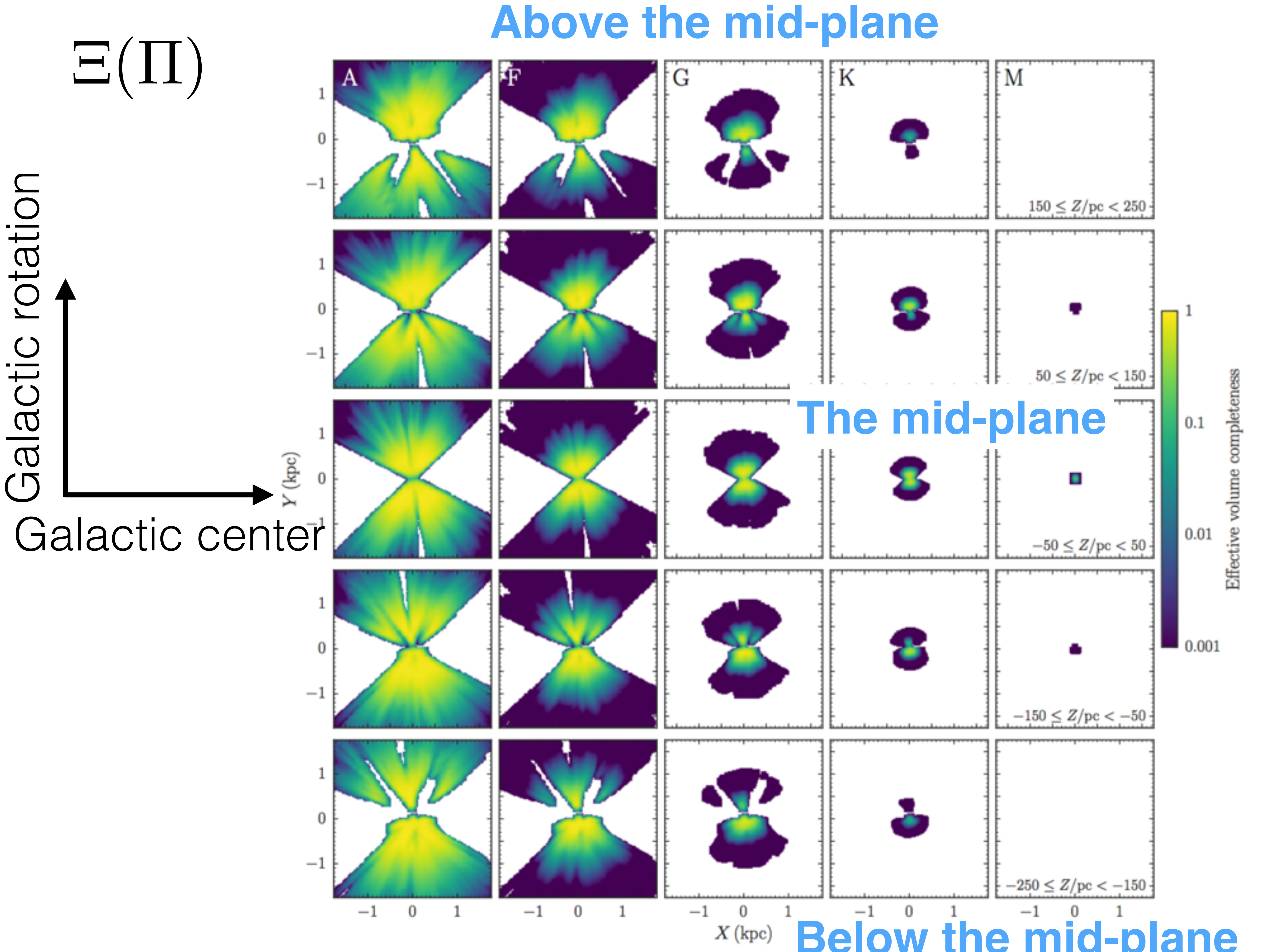


Measuring stellar densities with *TGAS*

Incomplete survey: how to compute $\Xi(\Pi)$

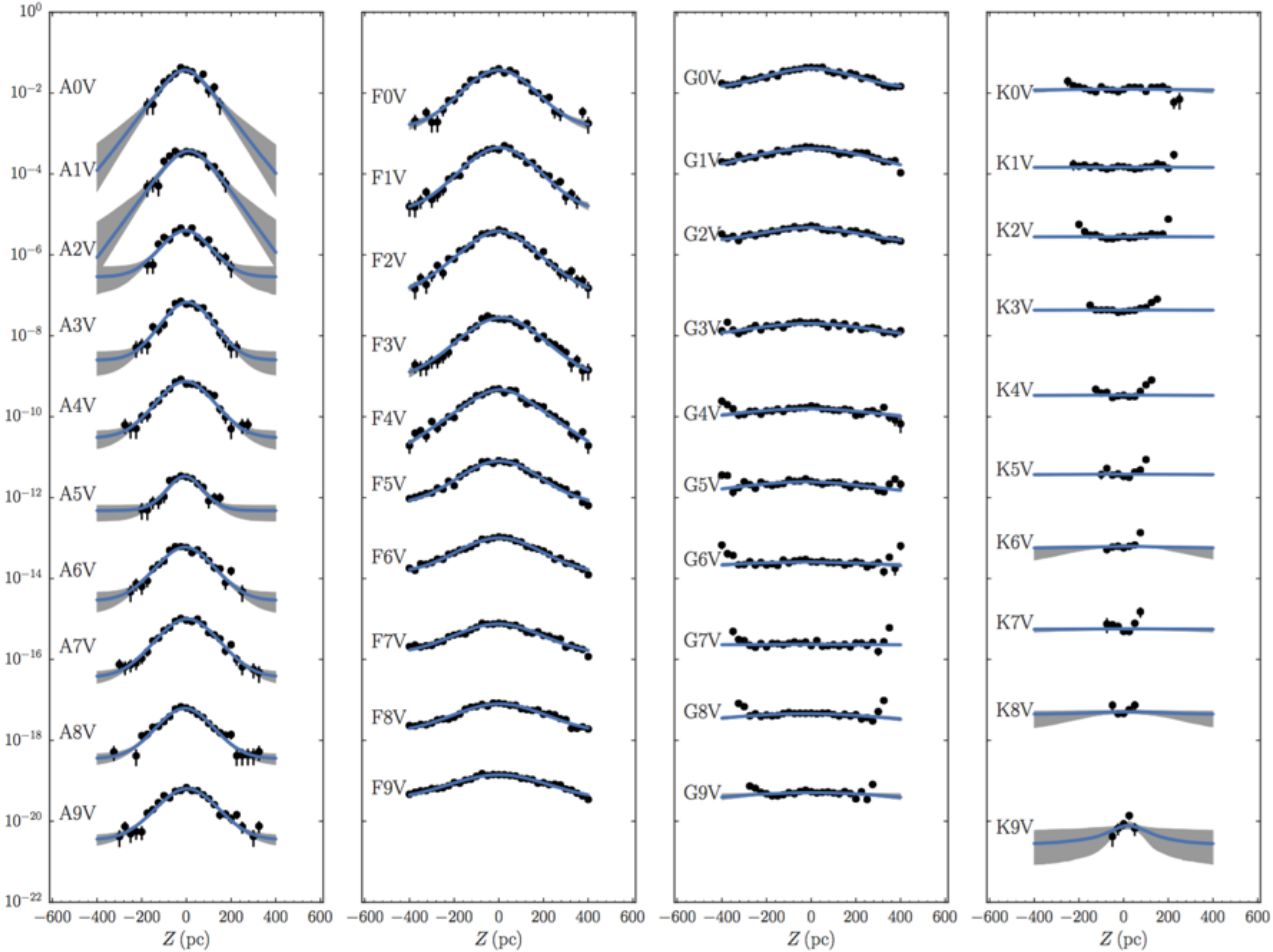
- Depends on
  - (a) survey through selection function S(J,J-K_S,RA,Dec)
  - (b) stellar type through (M_J,[J-K_S]$_0$)
  - (c) 3D extinction for (M_J,[J-K_S]$_0$) —> (J,J-K_S,RA,Dec)
- Compute as

$$\Xi(\Pi_k) = \frac{\int_{\Pi_k} \mathrm{d}^3x\, \mathfrak{S}(\alpha, \delta, D)}{\int_{\Pi_k} \mathrm{d}^3x}$$

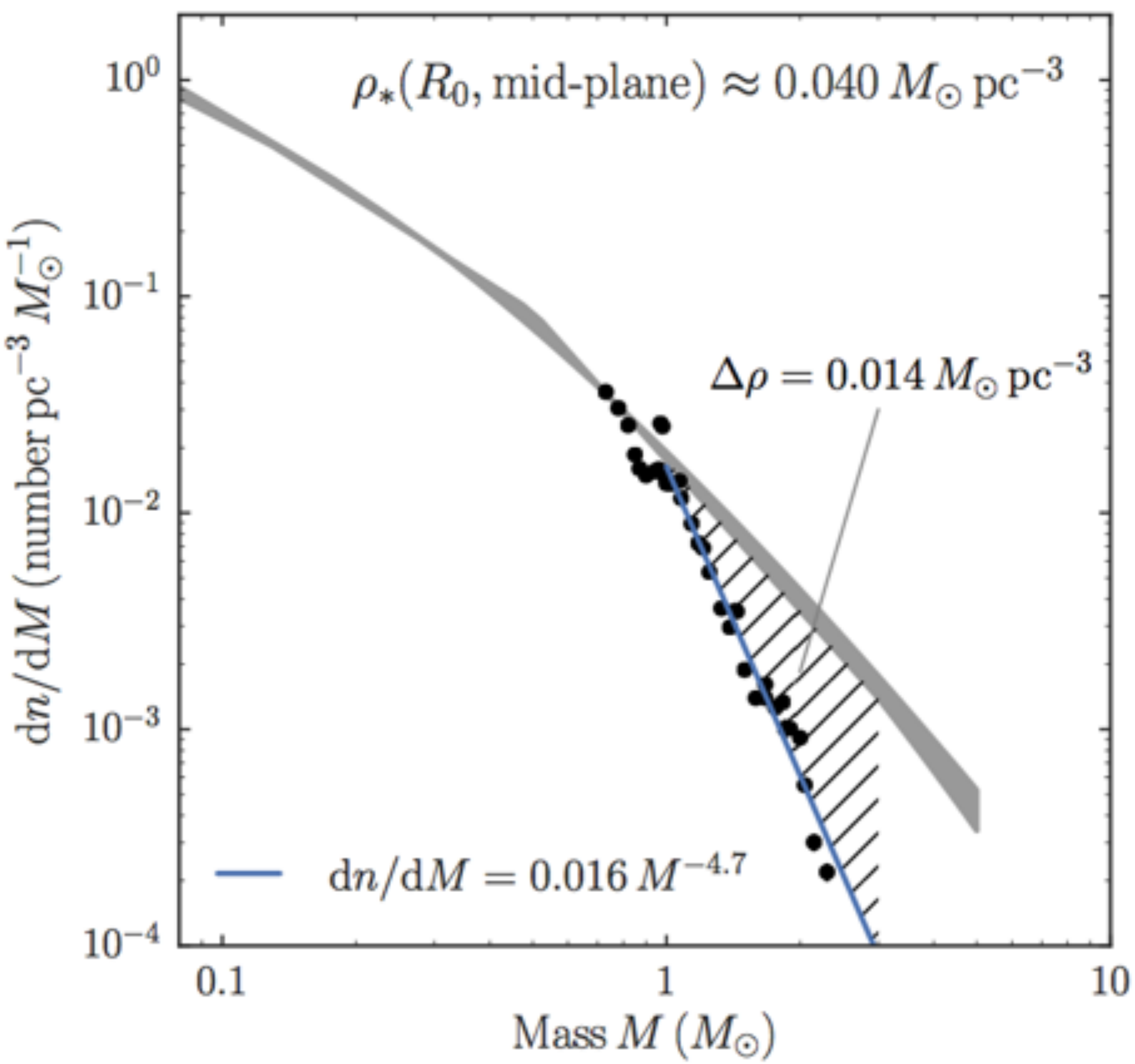


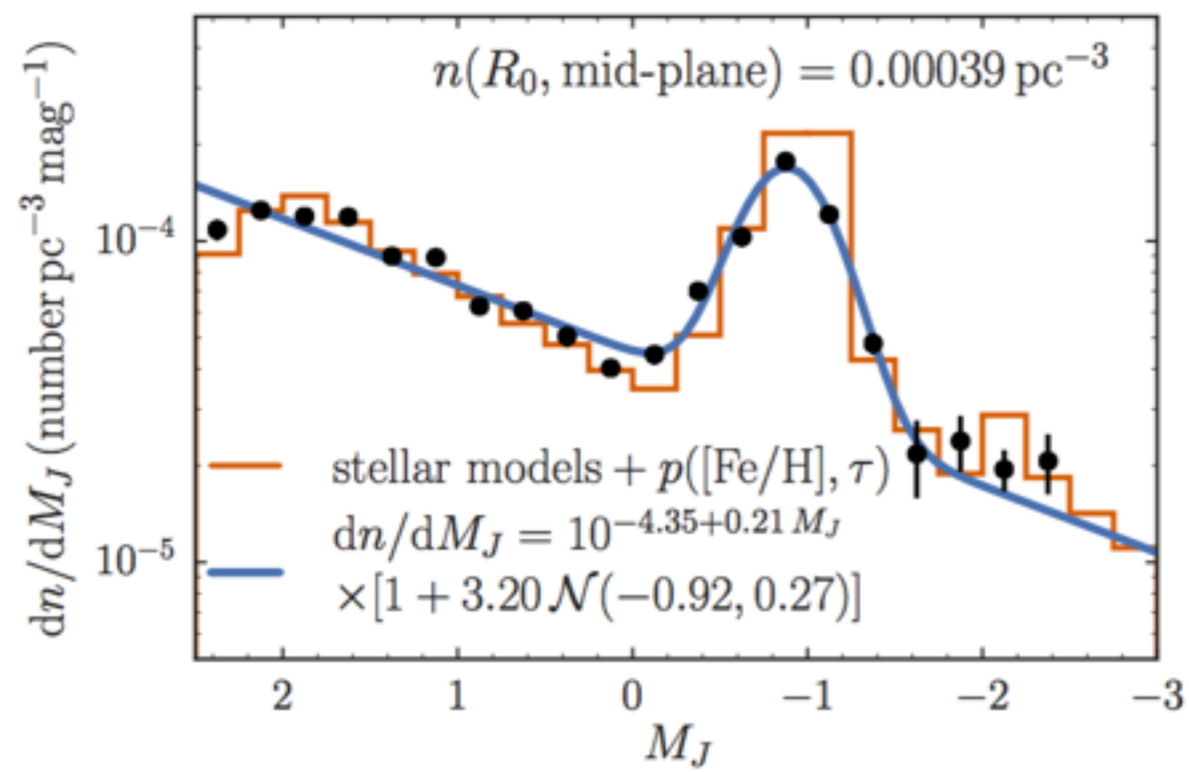
Above the mid-plane
Ξ(Π)
Galactic rotation
Galactic center
A
F
G
K
M
150 ≤ Z/pc < 250
50 ≤ Z/pc < 150
The mid-plane
−50 ≤ Z/pc < 50
−150 ≤ Z/pc < −50
−250 ≤ Z/pc < −150
Y (kpc)
X (kpc)
Effective volume completeness
1
0.1
0.01
0.001
Below the mid-plane

Vertical stellar densities with *TGAS*



Mid-plane mass and luminosity function of dwarfs and giants





$$\rho_*^{\text{MS}} = 0.040 \pm 0.002\, \text{M}_\odot\, \text{pc}^{-3}$$

$$\rho_*^{\text{giants}} = 0.00046 \pm 0.00005\ \text{M}_\odot\, \text{pc}^{-3}$$

Going forward: *need selection function!*

- Selection function = crucial part of the data, should be a data-release product

- A *function*: Need to be able to evaluate whether hypothetical object *i* with observables O_i could have been observed, ended up in the catalog

- Most basic: S(RA,Dec,G,G_{BP}-G_{RP})

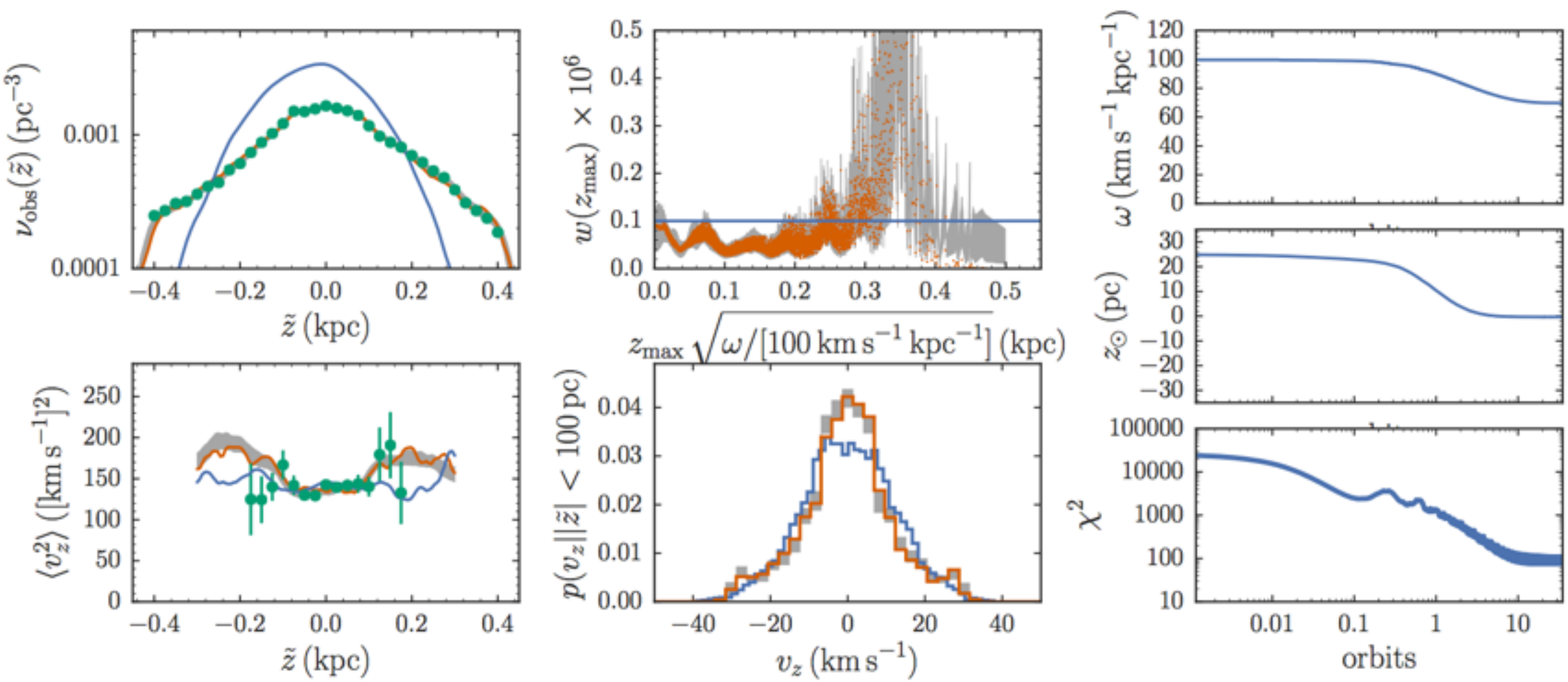
- Not content with '99% complete': *huge* number of stars and amount of science at G > 20, even at low completeness *as long as it's known*

Little bit of dynamics

Made-to-measure modeling of the vertical dynamics with *TGAS*

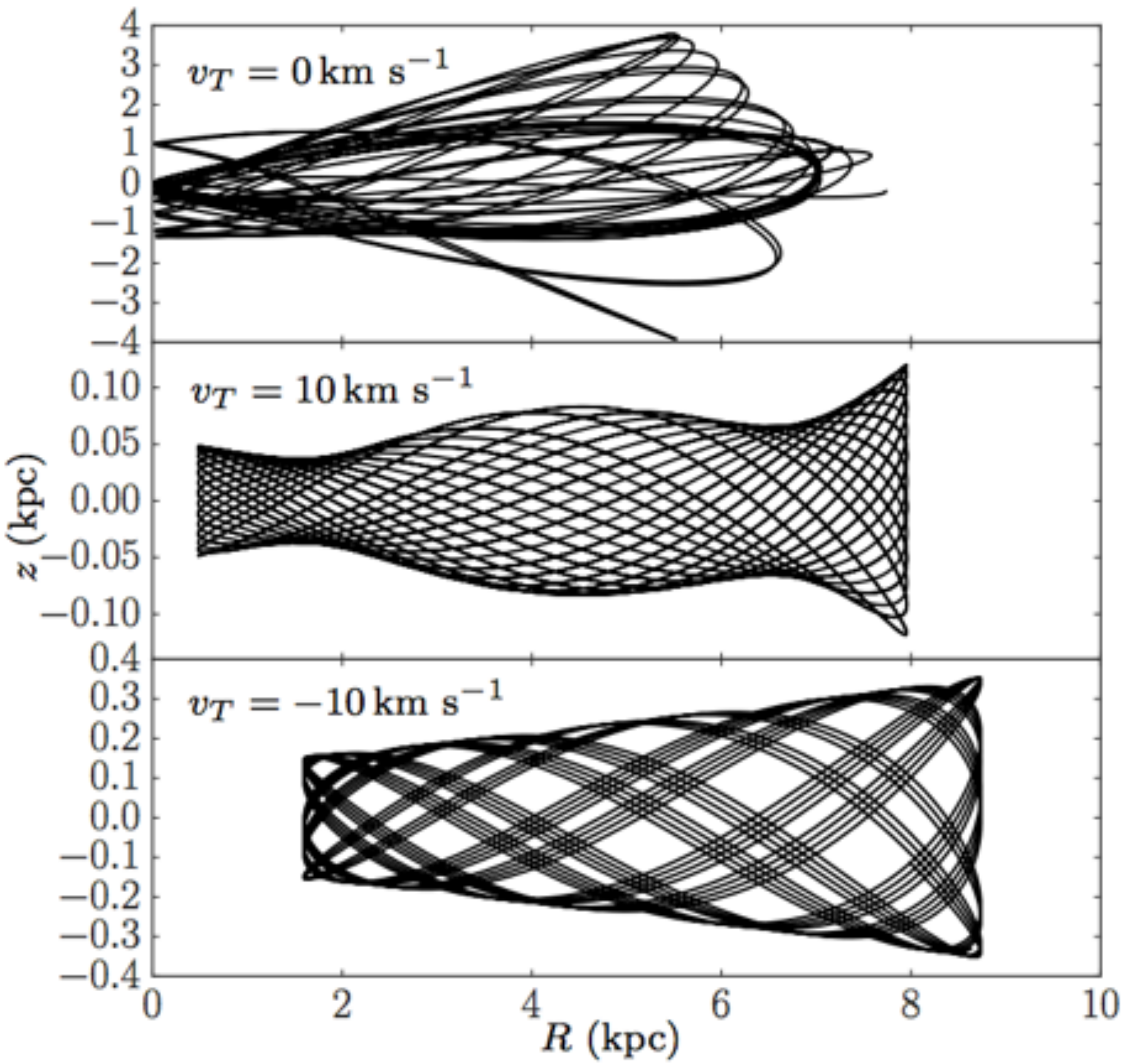
- M2M: Flexible, non-parametric dynamical modeling
- Improvements: Fit for external gravitational field, nuisance parameters + uncertainties in particle weights
- Simple 10,002 parameter model of the vertical dynamics of F-type dwarfs in *TGAS:*

Bovy, Kawata, & Hunt (2017, subm.), Hunt et al. in prep.

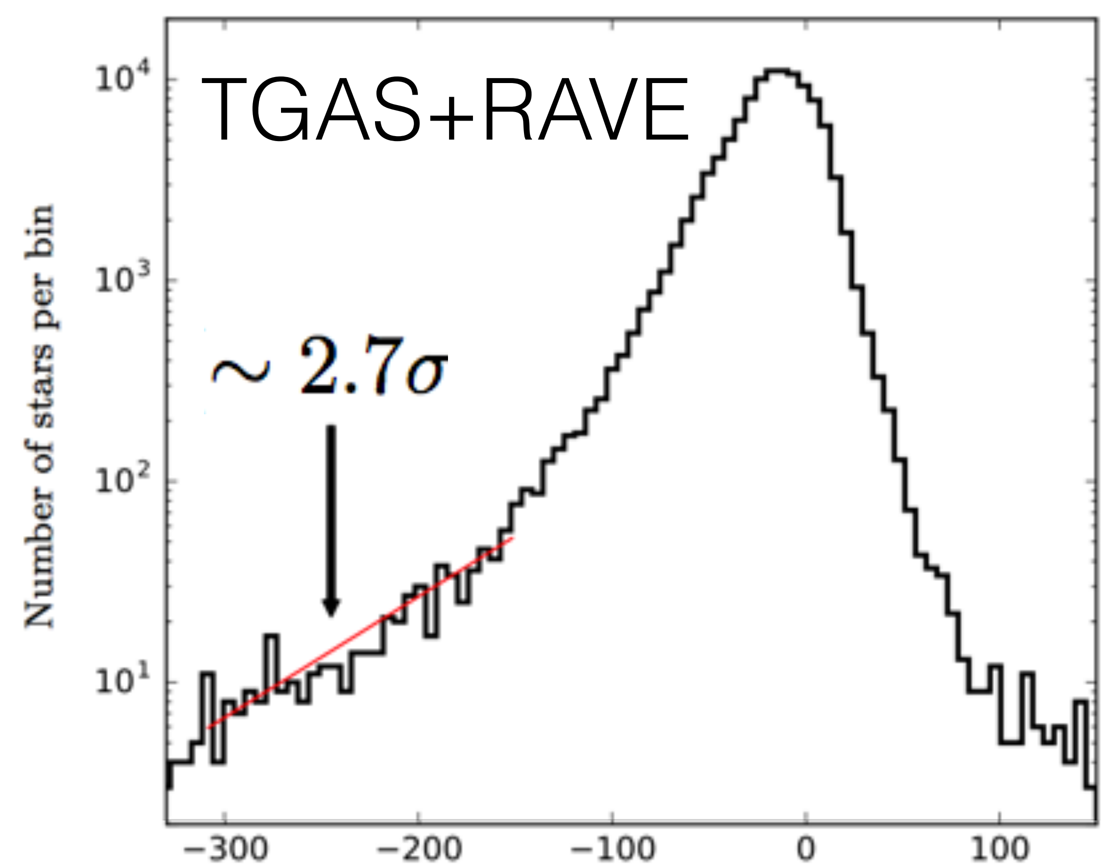


Detection of a dearth of zero angular-momentum stars in the solar neighborhood (Hunt, Bovy, & Carlberg, 2016)

- Stars on orbits plunging towards the Galactic center should be scattered out of the disk plane
- Can measure solar reflex motion, properties of inner galaxy
- May lead to most precise measurement of R_0 from *Gaia* data



$$v_\odot = 239 \pm 9\,\mathrm{km\ s^{-1}}$$
$$R_0 = 7.9 \pm 0.3\,\mathrm{kpc}.$$



Conclusions

- *TGAS* selection function $S(J,J\text{-}K_s,\mathrm{RA},\mathrm{Dec})$ covering the 'well-observed' 48% of the sky:

- Effective completeness in distance and volume for different stellar types: tools also available in `gaia_tools`

- Detailed new stellar inventory of solar neighborhood
  a) along the main sequence $0.7 \lesssim M/M_\odot \lesssim 2.2$
  b) along the giant branch

- Total stellar mid-plane density = $0.04 \pm 0.002\ M_\odot/\mathrm{pc}^3$

- Good agreement between observed and predicted giant luminosity function

- + measurements of vertical profile, scale heights, Sun's position wrt the mid-plane, star-formation history

- Code:
  https://github.com/jobovy/gaia_tools
  https://github.com/jobovy/tgas-completeness