Selfconsistent Modelling of the Milky Way using Gaia data

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Astrometry and Astrophysics in the Gaia sky
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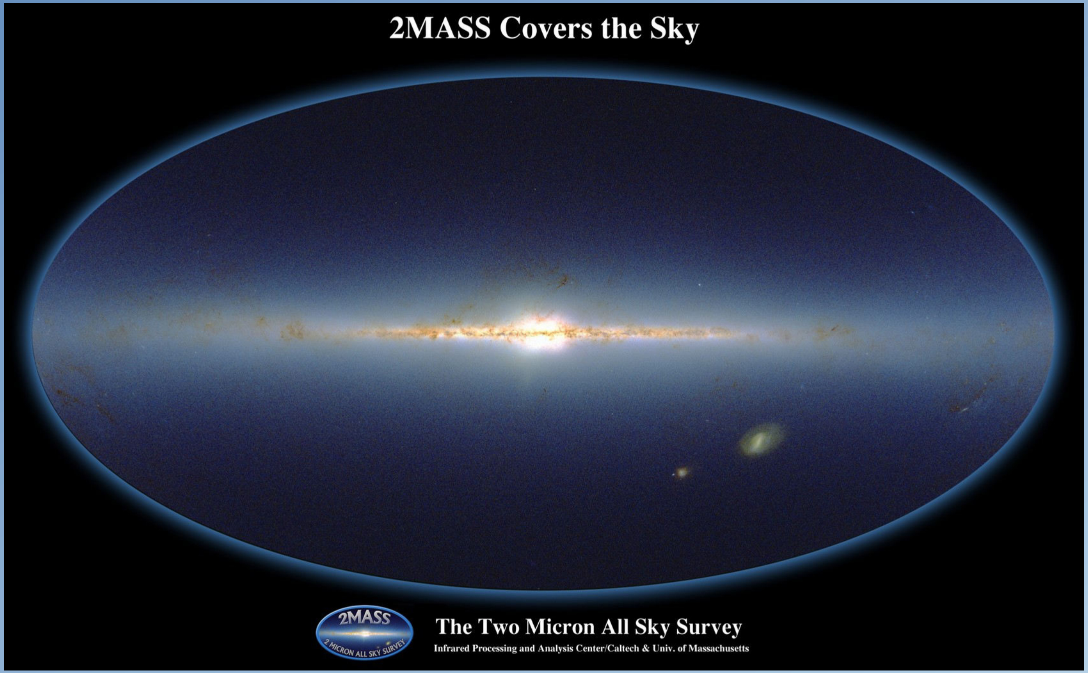
Models to compare to surveys

- Our knowledge of how baryons were accreted by galaxies such as the Milky Way is limited
- So how can we make best use of large surveys to discover the distribution of dark matter in the Galaxy?
- We have to use stars as tracer particles
- Must assume statistical equilibrium
- Exploit Jeans theorem and make DFs analytic functions of three constants of orbital motion, actions J_i

Self-consistent models

- Density models
  - Bulge
  - Gas disc
- DF based models
  - Dark halo
  - Thin and thick disc
  - Stellar halo



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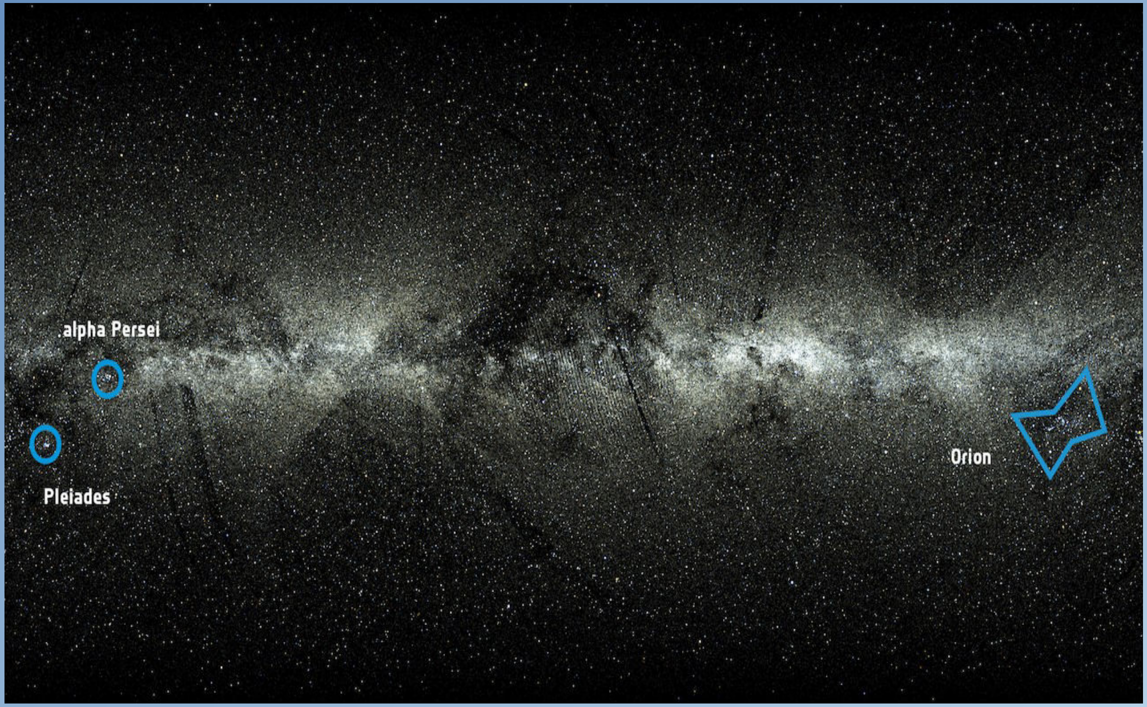


Iterative scheme

- Initial estimate for potential Φ
- Evaluate actions J(**x**,**v**) using Φ_{TOT} and Stäckel Fudge (Binney 2012,2014)
- Compute density by integrating over v

$$\rho_{DM}(x)=\int d^3 v\, f[J(x,v)]$$

- Solve Poisson's equation for new Φ

Disc DF

- A quasi-isothermal f(J) for each cohort of coeval stars
- Parameters:

$$DF \equiv f(J_r, J_z, L_z) = f_{\sigma_r}(J_r, J_z, L_z) f_{\sigma_z}(J_r, J_z, L_z)$$

$$f_{\sigma_r}(J_r, L_z) = \frac{\Omega \Sigma}{\pi \sigma_r^2 \chi} [1 + \tanh(L_z / L_0)] e^{-\frac{\chi J_r}{\sigma_r^2}}$$

$$f_{\sigma_z}(J_z, L_z) = \frac{\nu}{2\pi \sigma_z^2} e^{-\frac{\nu J_z}{\sigma_z^2}}$$

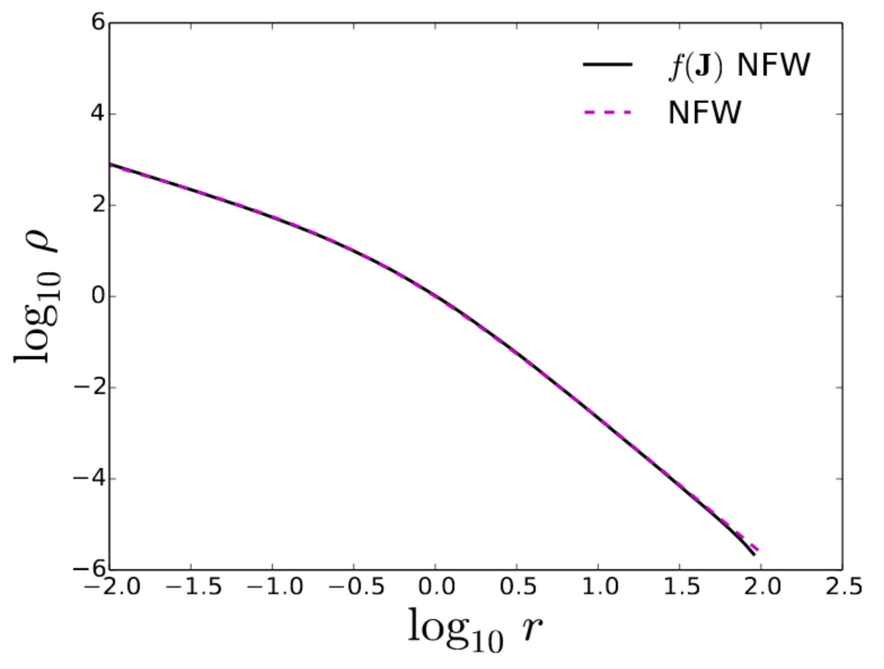
$$\Sigma(L_z) = \Sigma_0 e^{-\frac{R}{R_d}}$$

Self-consistent NFW halo DF

- Self-consistently generates NFW profile in absence of a disc
- h(**J**) (almost) linear in Js

$$f(J)=\frac{N}{J_0^3}\frac{\left(1+J_0/h(J)\right)^{5/3}}{\left(1+h(J)/J_0\right)^{2.9}}$$

- Isotropic centrally and mildly radial $r>r_s$
- Closely resembles haloes formed in dark matter only simulations

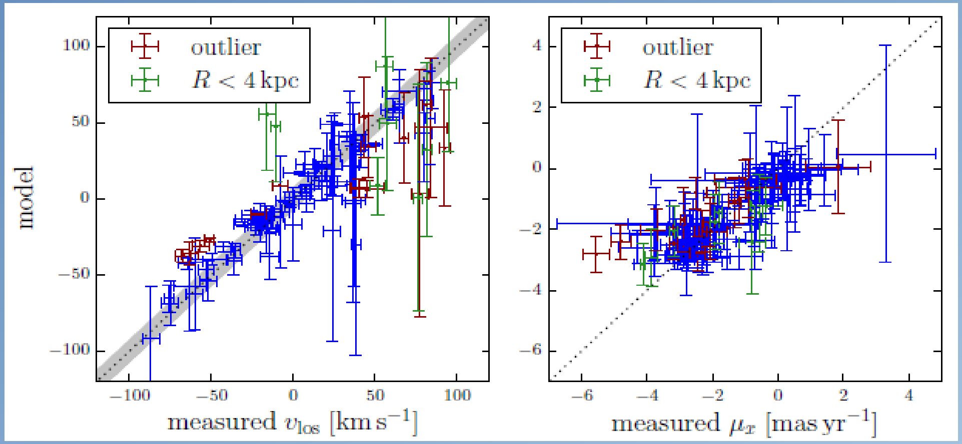


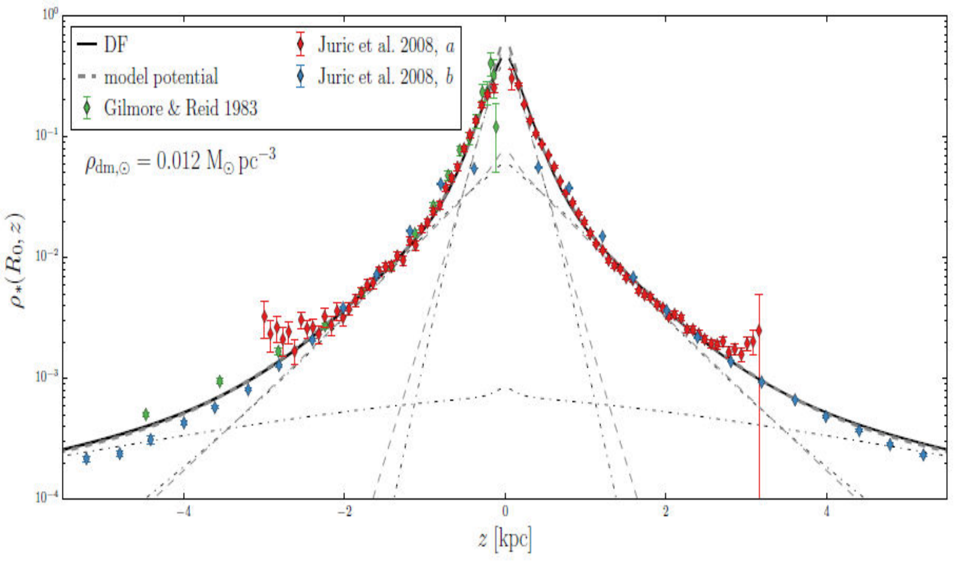
DF for the dark halo (Posti et al 2015)

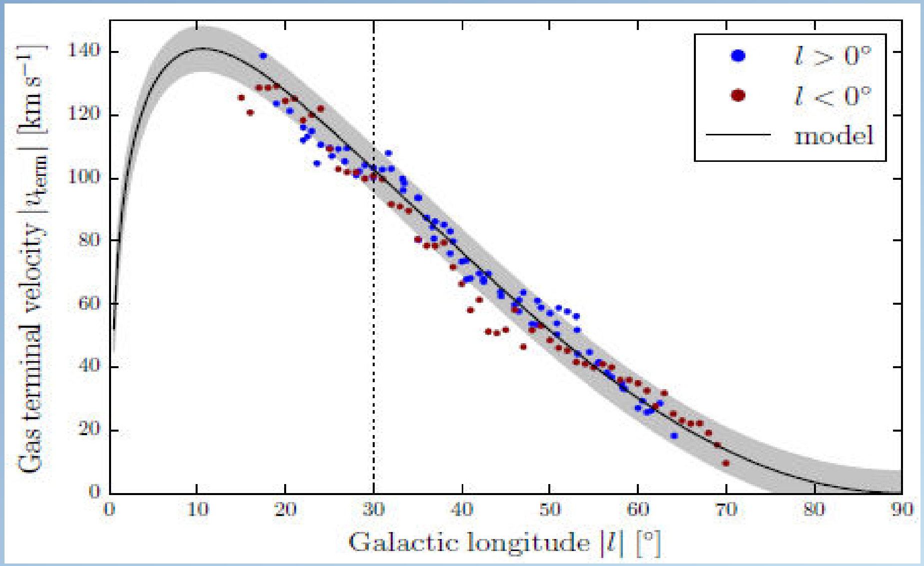
Modelling

We use constraints on $V_c(R)$ from

- Astrometry of H_2O and SiO masing stars
- radio-frequency lines of HI and CO
- The density of stars $\rho(z)$ at (R_0,z)

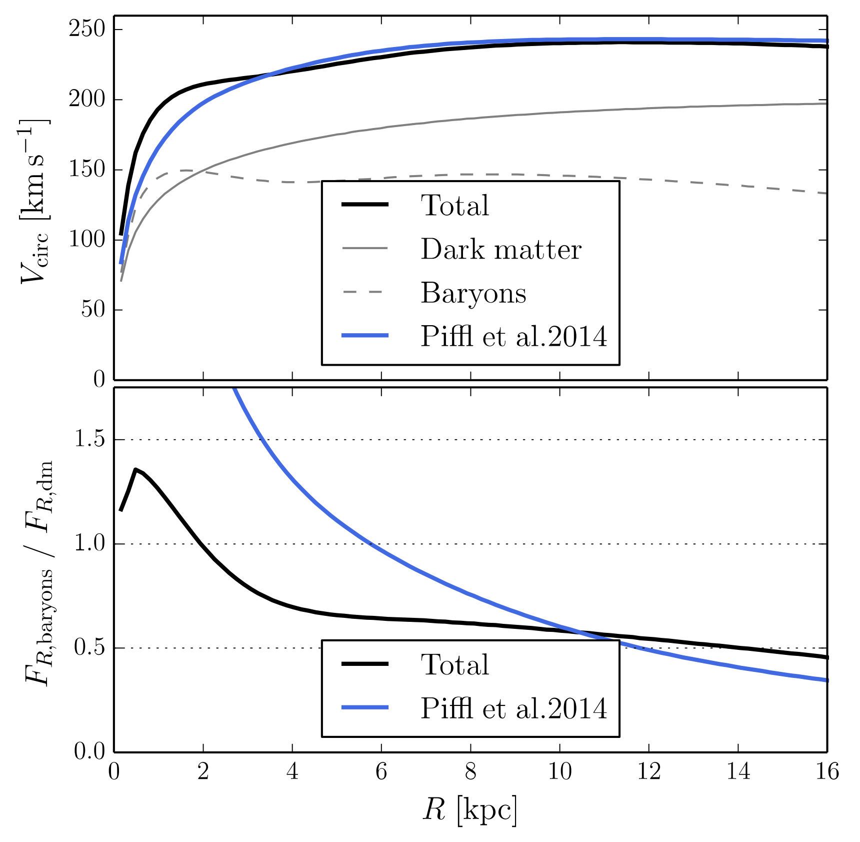






Adiabatic Dark Halo, results

- Piffl 2014 used RAVE data and SDSS Juric 2008 data to constrain mass of DM within solar radius, R_o
- Dark halo included as a potential not a DF
- Binney and Piffl 2015 use a DF for the dark halo
- A dark matter halo distorts adiabatically in response to the quiescent growth of the baryons
- Adiabatically compressed NFW halo
- Too much dark matter at low radii



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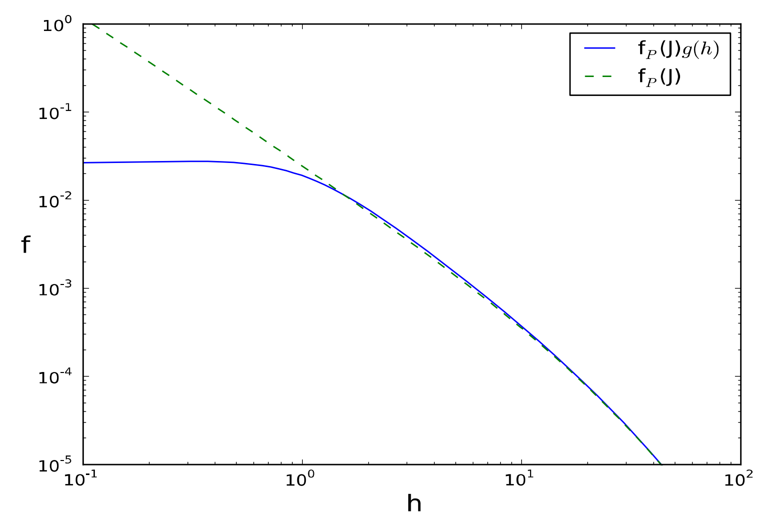
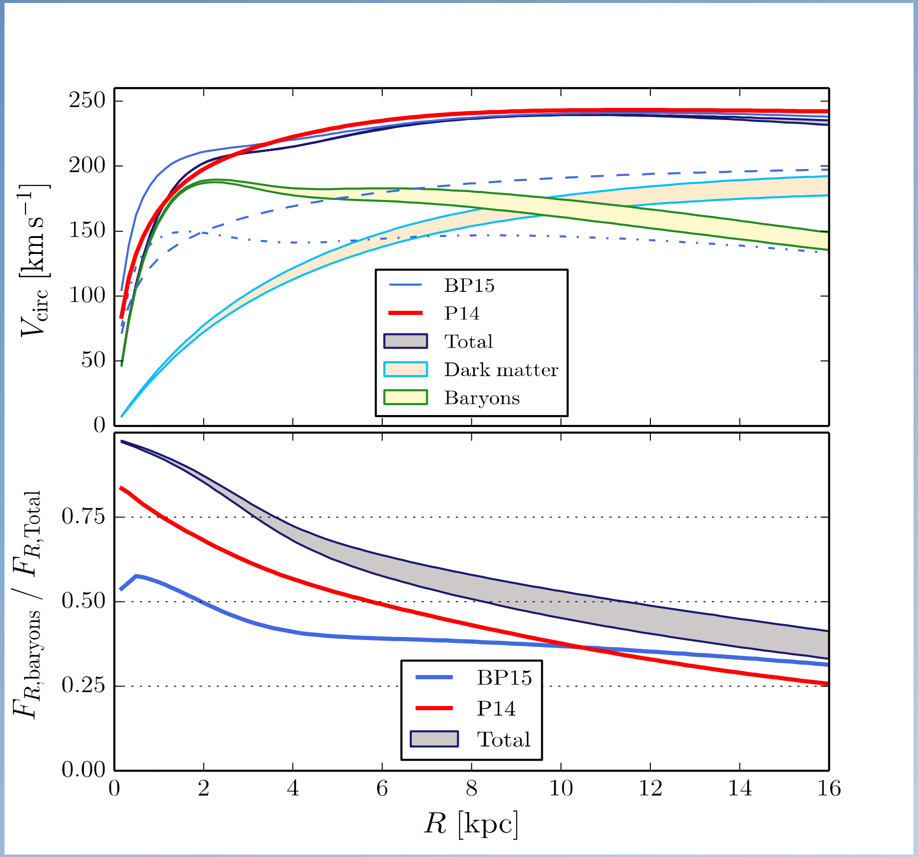
Impact of Baryons on DM

- In NFW DF there's an infinite phase-space density of particles at J=0
- Scattering of DM particles by baryons will reduce phase-space density of DM
- Reduction will have greatest impact near J=0
- So we modify NFW DF by shifting particles from very low J to higher J
- $f(J) = g(h)\, f_{NFW}(h)$ with $h(J)$ and g small at low h

Dark Matter core





$$DF = f(h)g(h) \quad f(J) = \frac{N}{J_0^3}\frac{(1+J_0/(h(J)))^{5/3}}{[1+h(J)/J_0]^{2.9}}$$

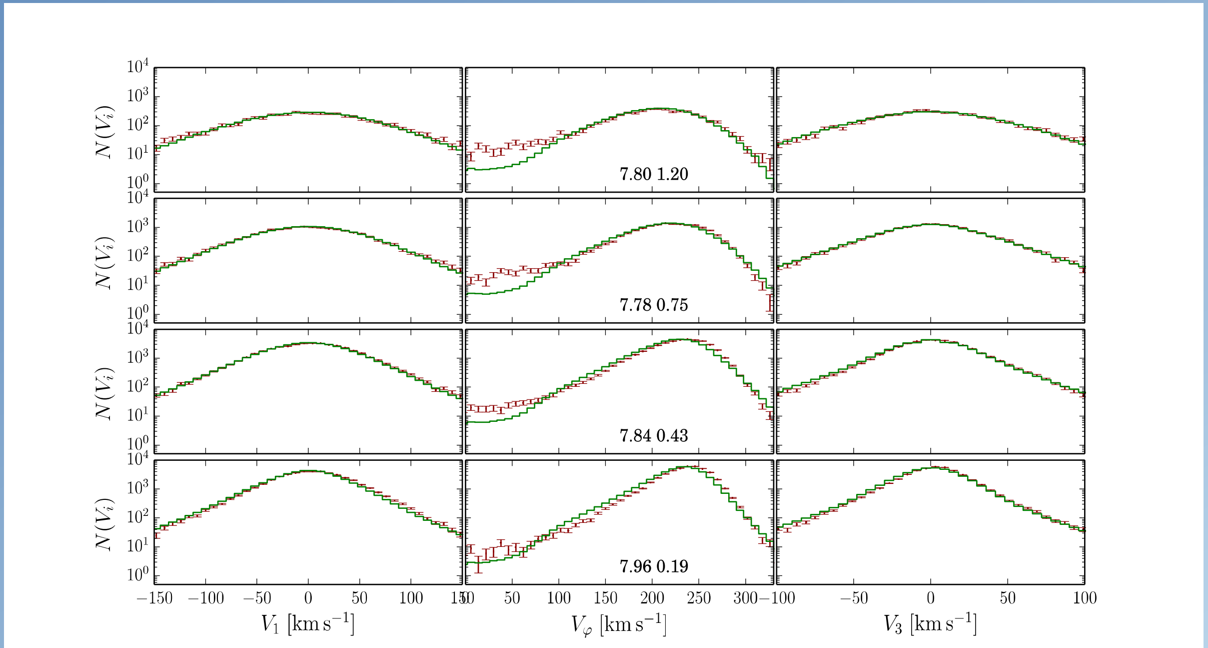
$$g(h) = \left[\frac{h_0^2}{h^2} - \beta(h_0)\frac{h_0}{h} + 1\right]^{-5/6}$$

$\rho_{\rm DM} \sim 0.012\text{-}3\ M_{\rm sun}\ {\rm pc}^{-3}$; R_d approx 2.9 kpc;

M_d higher 4 x 10^{10} M_sun

RAVE kinematics

- Define 8 spatial bins
  - R_0 ± 1 kpc in R
  - 0,0.3,0.6,1.0,1.5 kpc in |z|
- Compute velocity distributions predicted by the DF at the mean positions
- Accumulate chi^2 for 24 histograms
- Take into account velocity ellipsoid in solar neighbourhood, uncertainties of the binned stars velocities, uncertainties in RAVE distances



The RAVE-TGAS selection function S(s)

- Full a priori calculation of S(s) needs:
  - Full chemodynamical model of the MW disc S(s,τ,[Fe/H])
  - Know/model exact distribution of stars in age and metallicity in Solar neighbourhood
- Population synthesis (Schönrich et al 2014) & T_{eff} >4200 K
- Schönrich and Aumer 2017; S(s,τ) is a steep selection function in distance and age
- S(s) at fixed metallicity falls off approximately exponentially with scale 0.12 kpc at s > 0.2 kpc

Including the selection function

- Selection function for TGAS is biased
  - Younger stars are more likely to be seen so kinematics appear cooler that realy are
- Our models have age but not metallicity
- We can add metallicity
- Then we can compute likelihoods based of model based on selection function

AGAMA (Action-based Galaxy Modelling Architecture) library

- Low-level interfaces and generic routines, not particularly tied to stellar dynamics: various mathematical tasks, coordinate systems, unit conversion, input/output of particle collections and configuration data, and other utilities.
- Gravitational potential and density interface: the hierarchy of classes representing density and potential models, including two very general and powerful approximations of any user-defined profile, and associated utility functions.
- Routines for numerical computation of orbits and their classification.
- Action/angle interface: classes and routines for conversion between position/velocity and action/angle variables.
- Distribution functions expressed in terms of actions.
- Galaxy modelling framework: computation of moments of distribution functions, interface for creating gravitationally self-consistent multicomponent galaxy models, construction of N-body models and mock data catalogues.
- Data handling interface, selection functions, etc.
- The code can be downloaded from https://github.com/GalacticDynamics-Oxford/Agama

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Conclusions

- Self-consistent modelling is a powerful and flexible tool for discovering the structure of the Milky Way
- It can use the rich data becoming available from large surveys to test our models of galactic structure
- Combing TGAS with spectrascopic surveys such as RAVE and LAMOST can provide improved matches of model to surveys