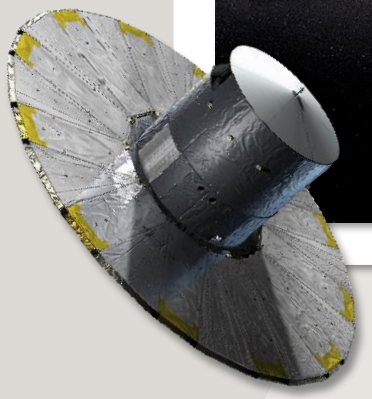
IAU Symposium 330
Nice, 27. April 2017



Action-based Dynamical Modeling of the Milky Way Disk with Gaia & RAVE

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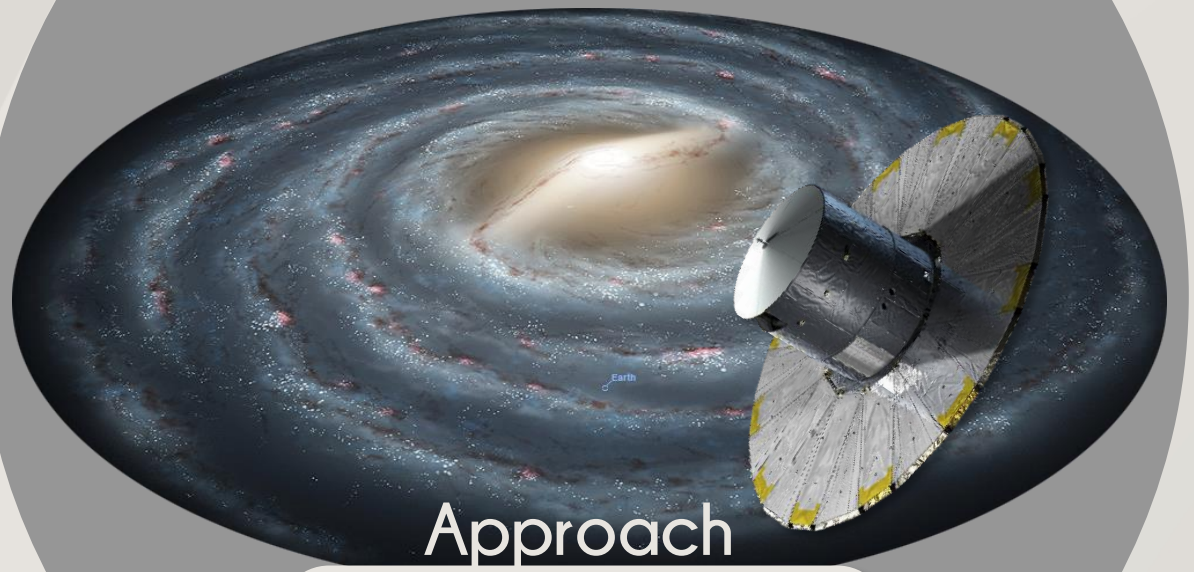
Hans-Walter Rix (MPIA)
Jo Bovy (Uni Toronto)

Open Questions of Galaxy Formation

Can we answer them with Gaia in our Milky Way (MW)?

- Core/cusp problem & shape of the **dark matter halo**?
- Is there a **dark disk**?
- Mass contrast of **spiral arms**?



- Formation of the disk: Relation between **stellar orbits**, their abundances and ages?
- Characterizing infall/**sub-structure**? Need smooth model…

Approach

Solving simultaneously for **Φ** and DF by rigorous fitting to discrete Gaia data

Gravitational Potential Φ

Stellar orbit distribution function (DF)

Recovery of the Orbit Action Distribution of Mono-Abundance Populations & Potential INference for our Galaxy

THE ROADMAPPING CODE

Trick, Bovy, D'Onghia & Rix (2017)
Trick, Bovy & Rix (2016)
Bovy & Rix (2013)
Binney (2012)
Binney & McMillan (2011)

RoadMapping Modeling

The gravitational potential Φ
- relates a star's obs. 6D (**x,v**) to its orbit within the Galaxy

Recovery of the
Orbit **A**ction **D**istribution of
Mono-**A**bundance
Population
&
Potential **IN**f
for our G

The actions

$\mathbf{J} = (J_R, J_\varphi = L_z, J_z)$

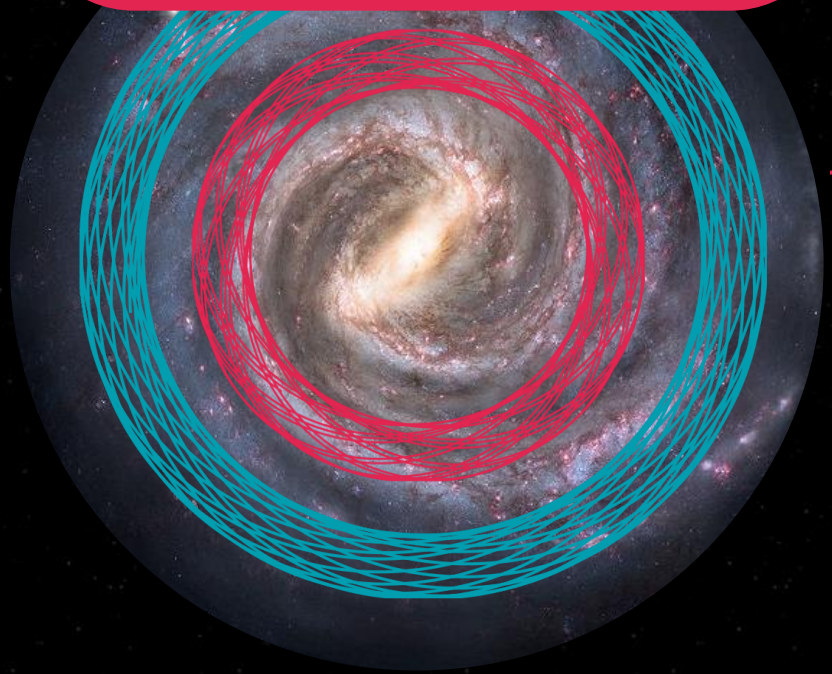
- are integrals of motions
- label orbits in a given **Φ**
- hard to calculate, except for axisymm. **Φ** (e.g. Sanders & Binney 2016)

RoadMapping Modeling

Galactic disk

- is superposition of stellar orbits in Φ
- ➡ action-based distribution function

$DF(J, [X/H], t_{age}, ...)$



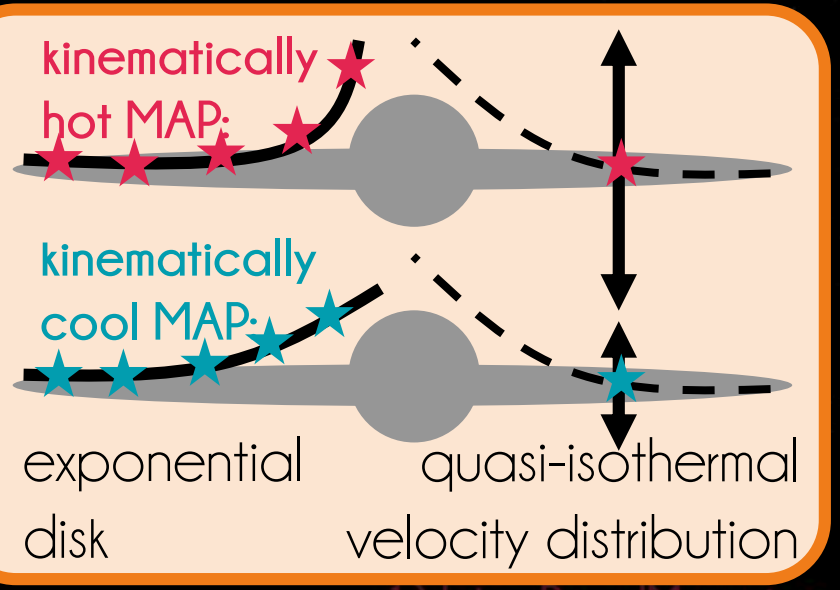
see, e.g., talks by Rosemary Wyse, Carlos Allende Prieto, James Binney,…

Recovery of the **O**rbit **A**ction **D**istribution of **M**ono-**A**bundance **P**opulations & **P**otential **IN**ference for our **G**alaxy

RoadMapping Modeling

DF model:
„quasi-isothermal DF“:
qDF(J)
(Binney & McMillan 2012)

Recovery of the
Orbit **A**ction **D**istribution of
Mono-**A**bundance
Populations



Stellar Mono-Abundance Sub-Populations (MAPs)

- disk stars with same [Fe/H] & [α/Fe]
- simple phase-space structure

(Bovy et al. 2012a,b,c ; Ting et al. 2013)

RoadMapping Modeling

DF model:
„quasi-isothermal DF“:
$\mathbf{qDF(J)}$
(Binney & McMillan 2012)

parame-
trized by

Recovery of the
Orbit **A**ction **D**istribution of
Mono-**A**bundance
Populations
&
Potential **IN**ferenc
for our **G**alaxy

observed

(x,v) data

fitting to

Φ model:
axisymmetric, analytic
disk+halo+bulge

parame-
trized by

shaped by

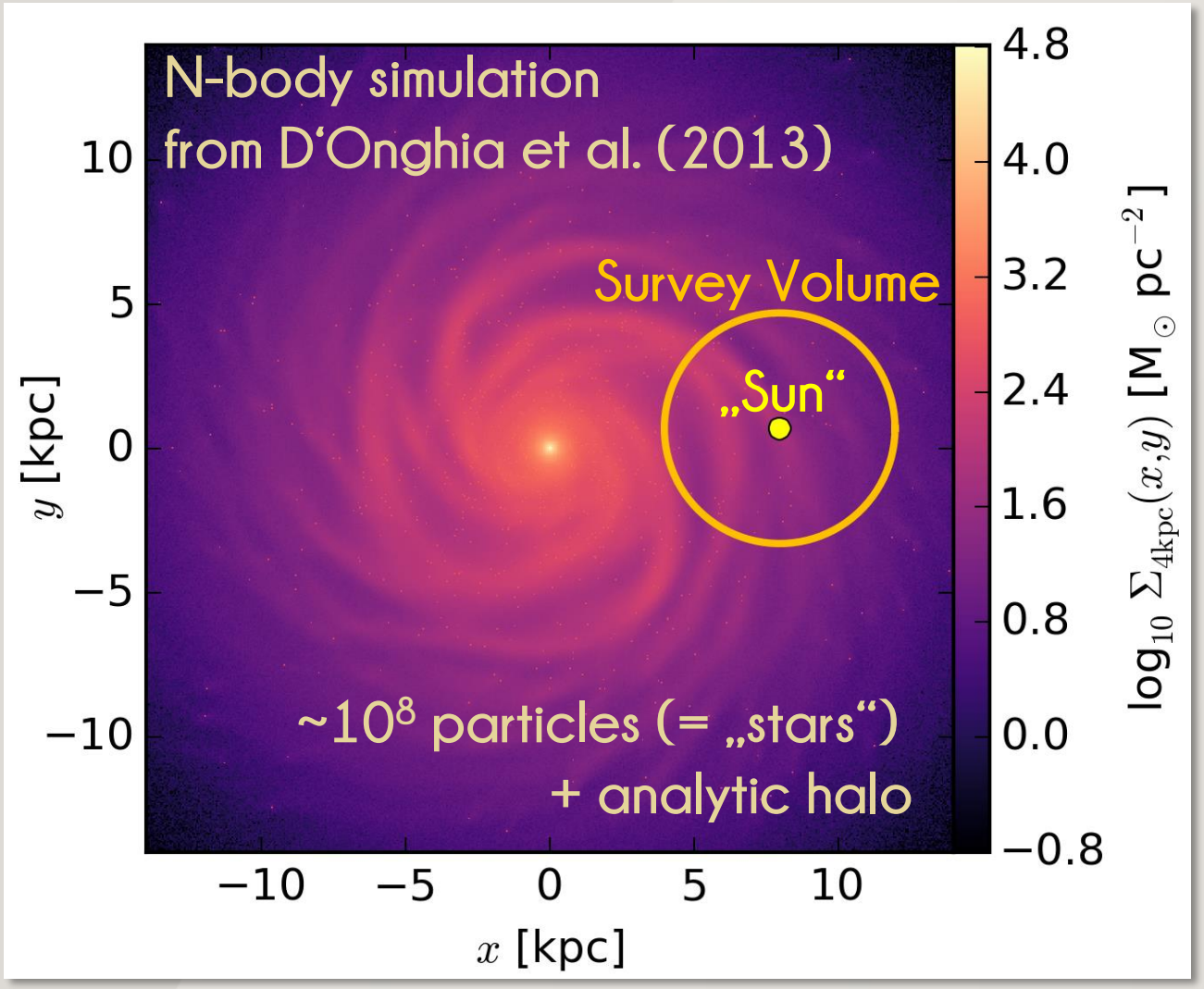
Selection Function
of the survey

Advantage of using MAPs:

- implicit treatment of chemical abundances in the modeling
- the MAPs are independent tracers for the same **Φ**

RoadMapping in a Spiral Galaxy Simulation

Trick, Bovy, D'Onghia, & Rix (2017)



Breakdown of several modeling assumptions:

Data:
affected by strong non-axisymm. spiral arms

vs.

in RoadMapping

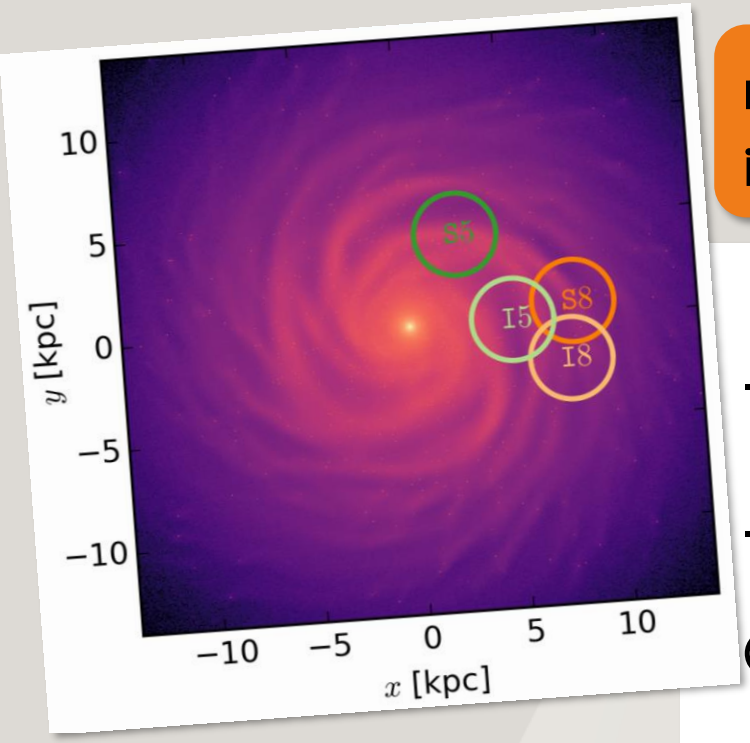
Model in general:
axisymmetric!!!

DF model:
most simple: single qDF

Potential model:
halo, bulge & „wrong" disk

RoadMapping in a Spiral Galaxy Simulation

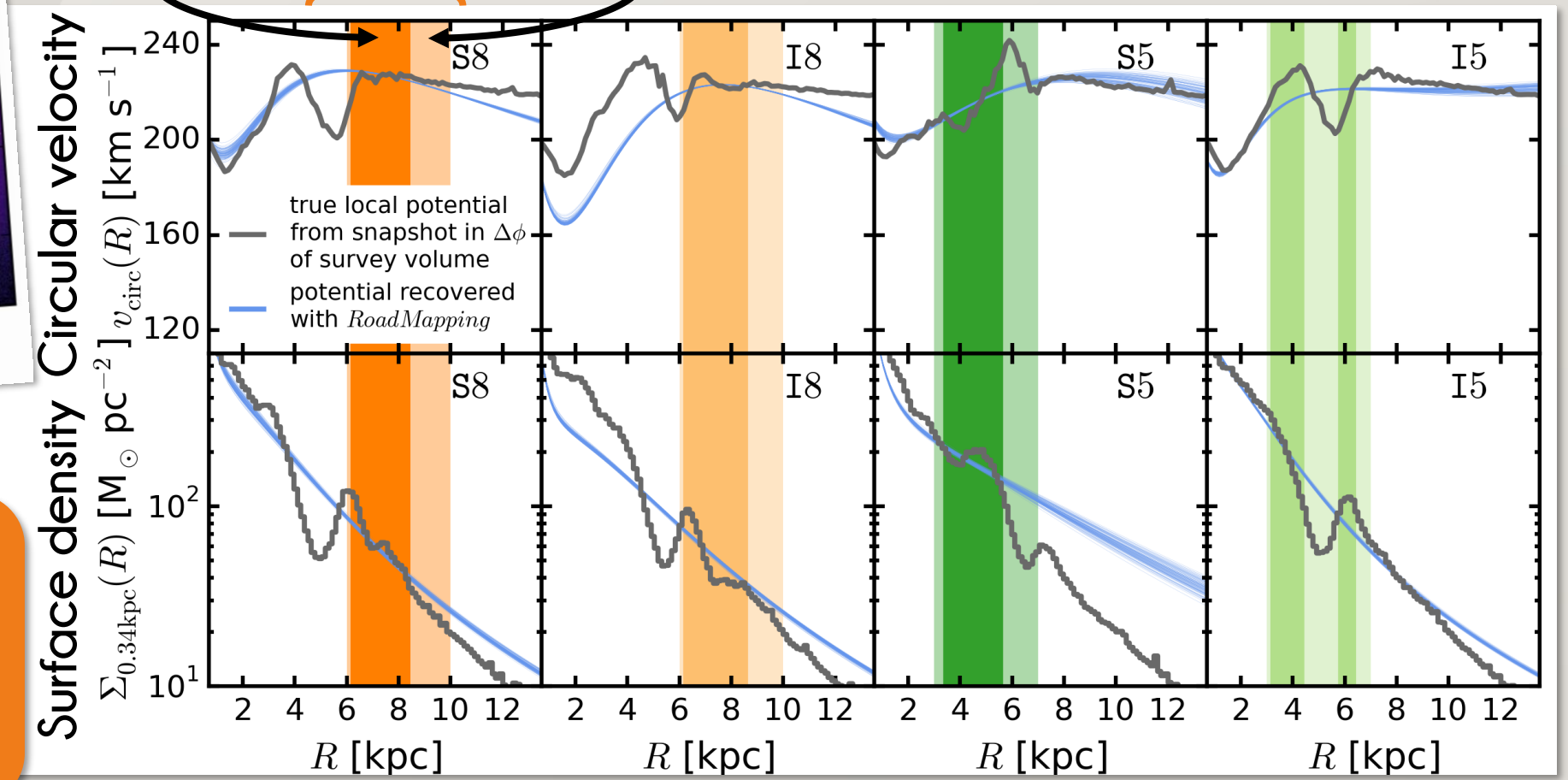
Trick, Bovy, D'Onghia, & Rix (2017)



more stars in data set

survey volume

less stars in data set



Result

Where most of the stars are located, RoadMapping recovers the local gravitational forces.

Application To Data from Gaia & RAVE

Gaia
(DR1, Lindegren et al. 2016)

Radial Velocity Experiment
(DR5, Kunder et al. 2016)

NIR spectroscopy
(Majewski et al. 2015)

NIR photometry
(Skrutskie et al. 2006)

TGAS
Tycho-Gaia Astrometric Solution
(Michalik et al. 2015)

RAVE-on
re-analysis of RAVE spectra
(Casey et al. 2016)

APOGEE-Red Clump
Red clump star identification
& precise photometric distances
(Bovy et al. 2014)

see poster by **Johanna Coronado** on the callibration of photometric distances

R.A., Dec., &
$\mu_{R.A.}$, $\mu_{Dec.}$, ~~ϖ~~

for ~$2 \cdot 10^6$ stars

v_{los}

for ~200,000 stars on southern sky / in TGAS

T_{eff}, log g, [Fe/H], [Mg/Fe]

for ~80,000 giant stars in RAVE / TGAS; labels on APOGEE scale

d_{phot}

for ~20,000 red clump stars in RAVE / TGAS

Trick et al. (in prep.)

Ingredients for the TGAS/RAVE RoadMapping Analysis

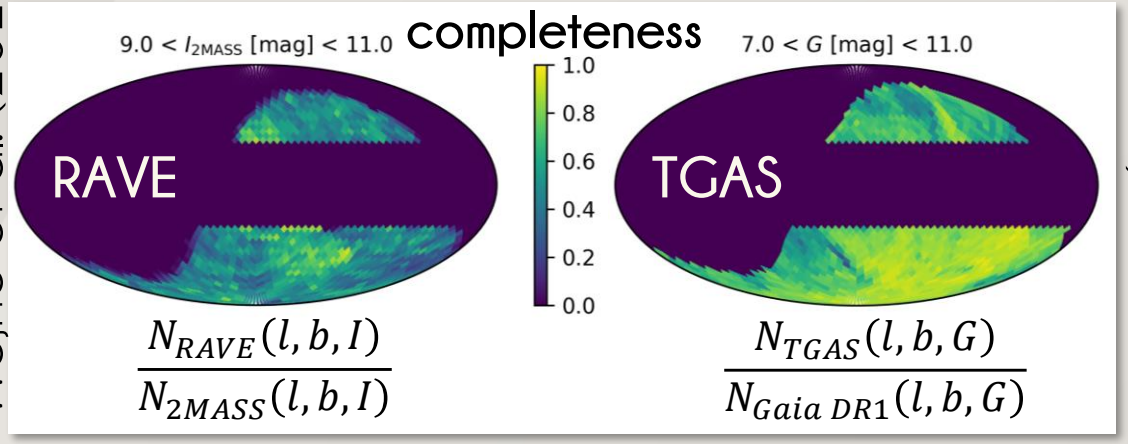
Potential model:

- Exponential disk
  (Smith et al. 2015)
- NFW halo
  (Navarro, Frenk, & White 1997)
- Hernquist bulge
  (Hernquist 1990)

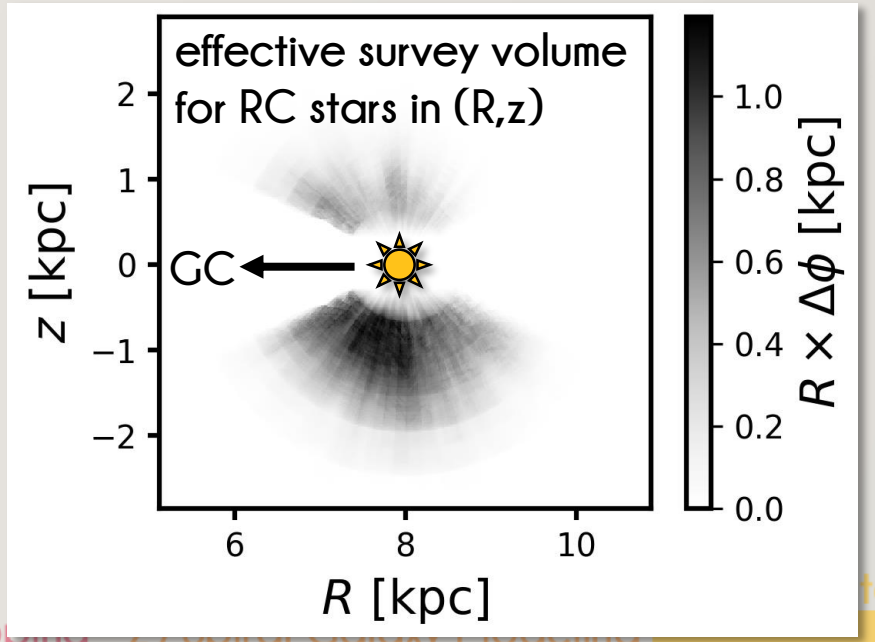
Trick et al. (in prep.)

Selection Function:

Wojno et al. (2017)



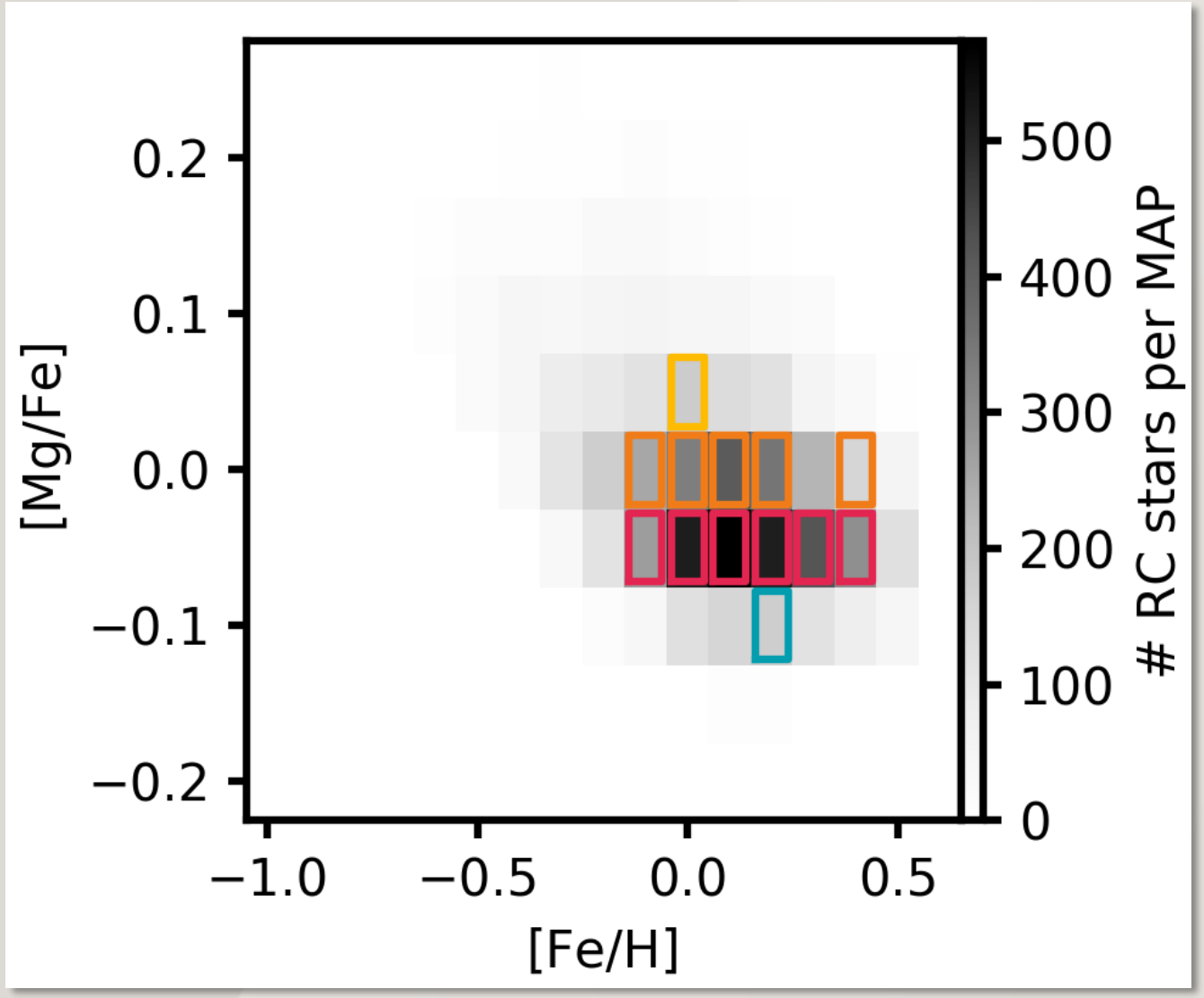
Trick et al. (in prep.)

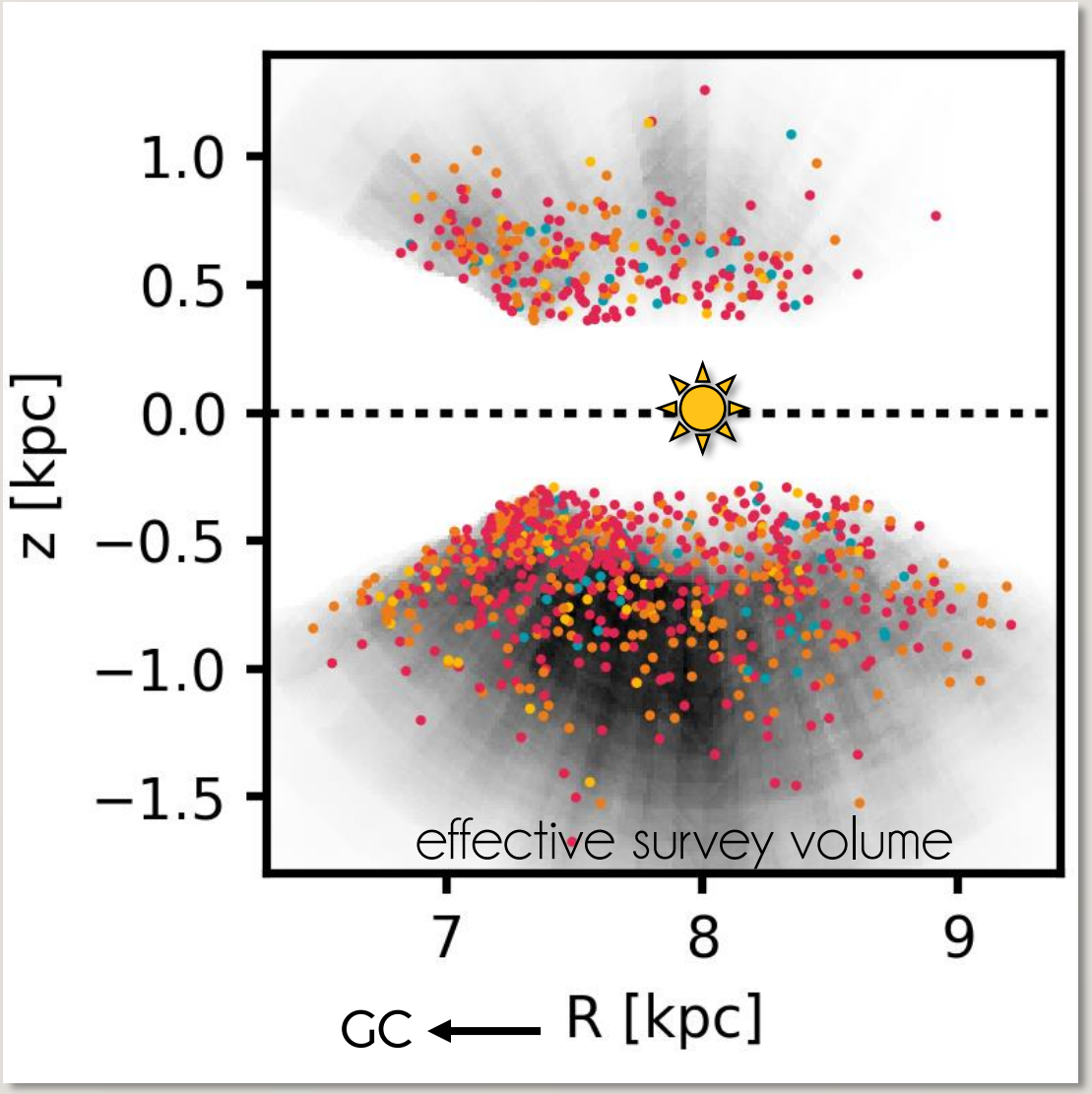


Further ingredients:

- outlier model for halo stars
- prior information on flat slope of rotation curve
  (Bovy et al. 2012a)
- convolution with corell. measurement uncertainties

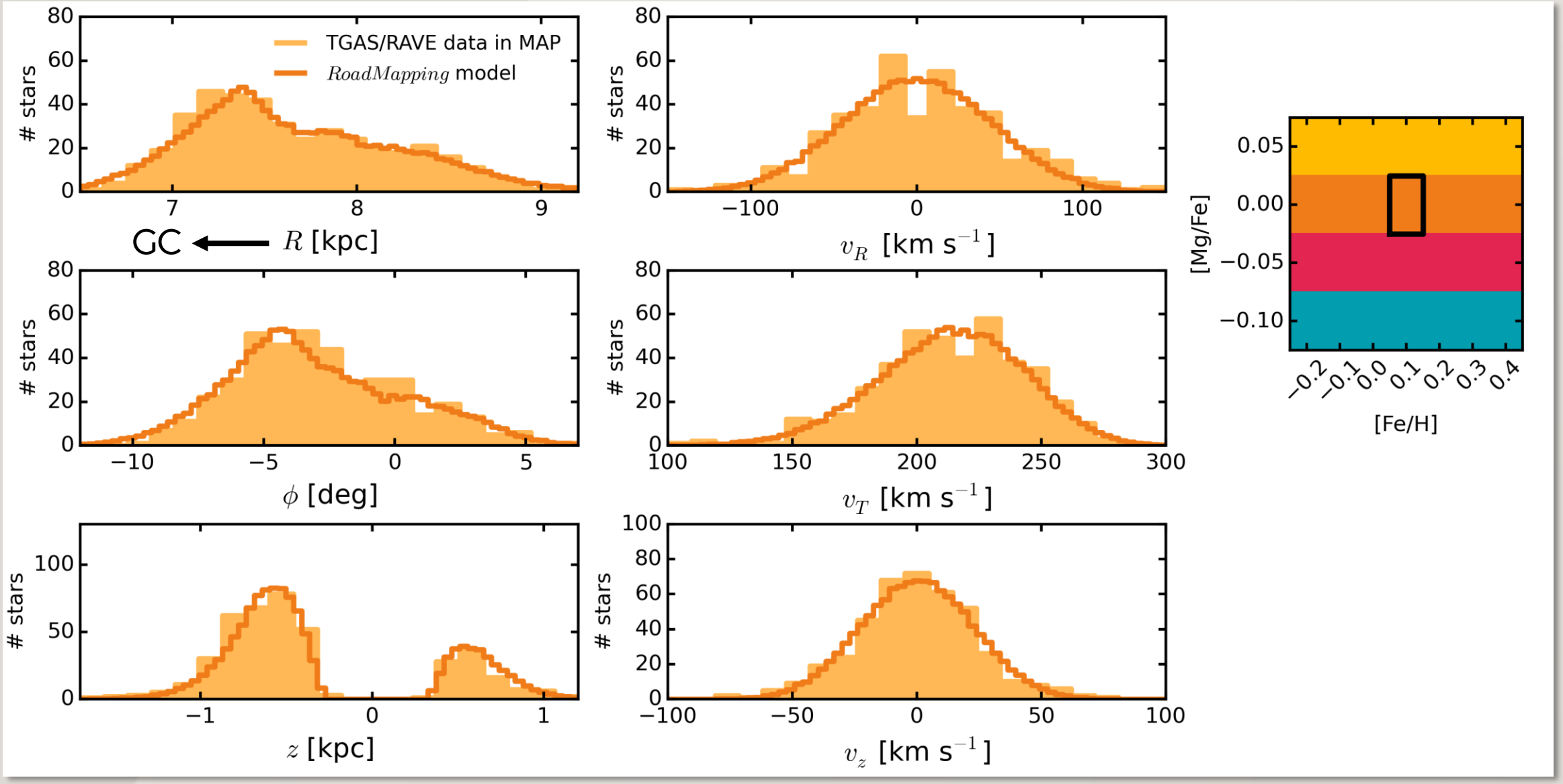
Red Clump Stars from 13 MAPs in TGAS/RAVE





Trick et al. (in prep.)

The DF Model describes the galactocentric Data Well



Trick et al. (in prep.)

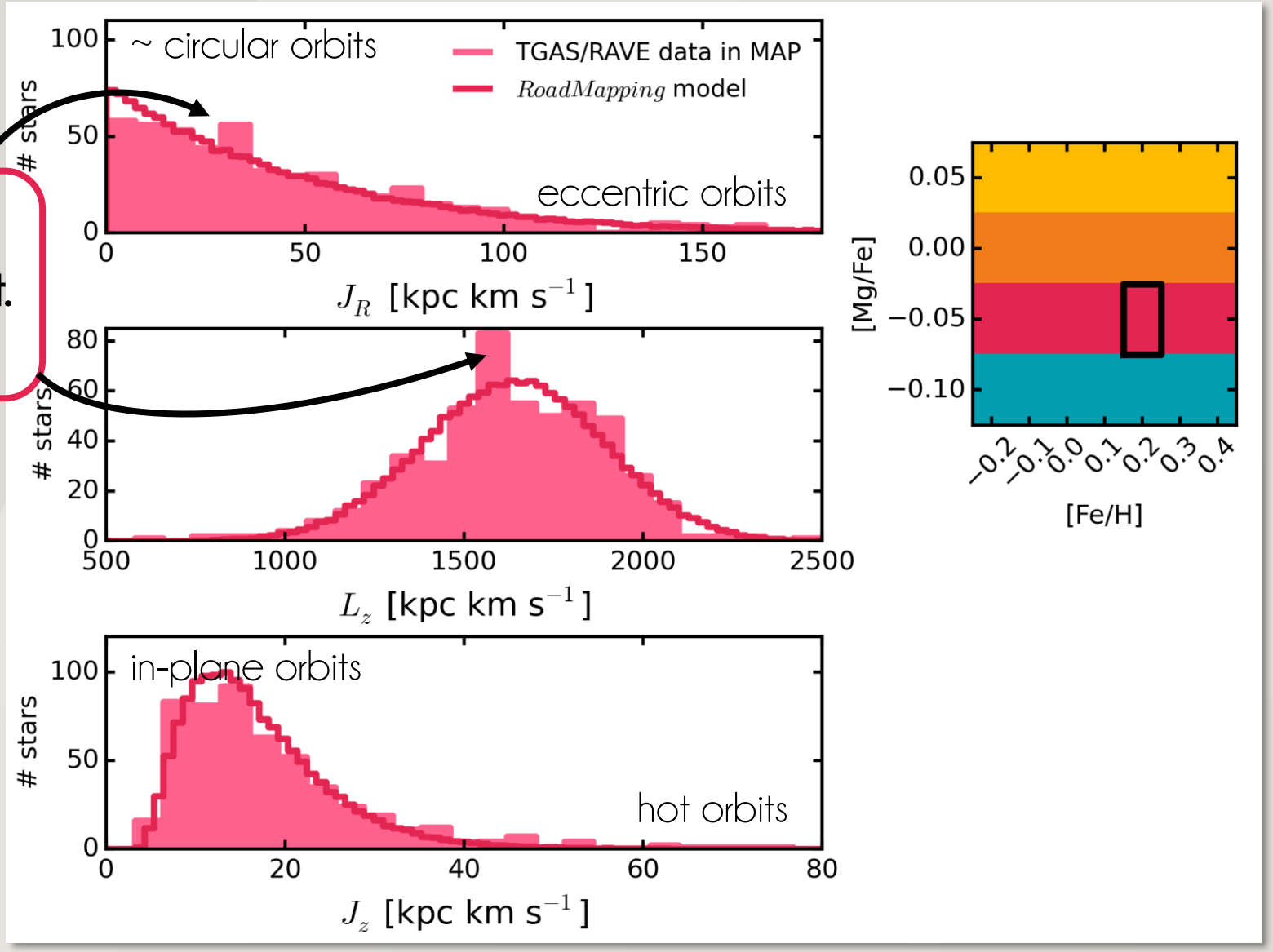
A Smooth Model in Orbit Space Will Help to Find Disk Sub-Structure

radial action

Sub-structure?
Not yet significant.
Wait for DR2…

angular momentum

vertical action



Trick et al. (in prep.)

Our Estimate for the Milky Way Potential

Result

Joint constraint from all MAPs:

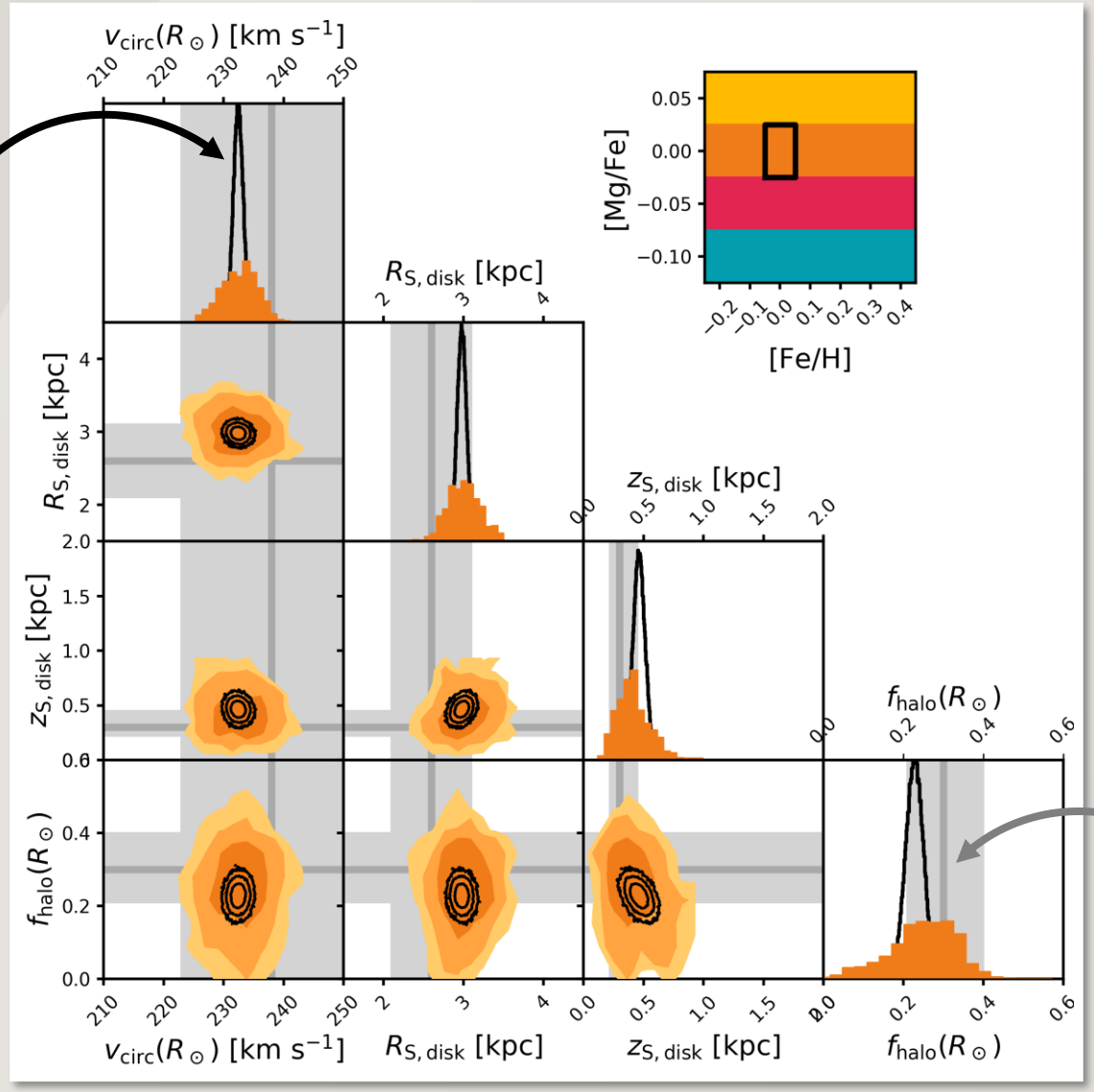
Circular velocity @Sun:
$v_{circ}(R_\odot)$ = (**232.5** ± 0.8) km s^{-1}

Disk scale length:
$R_{S,disk}$ = (**2.98** ± 0.06) kpc

Disk scale height:
$z_{S,disk}$ = (**460** ± 50) pc

Halo fraction @Sun:
$f_{halo}(R_\odot) = (v_{circ,halo}/v_{circ,tot})^2 \, |_{R=R\odot}$
= **0.23** ± 0.02

Trick et al. (in prep.)



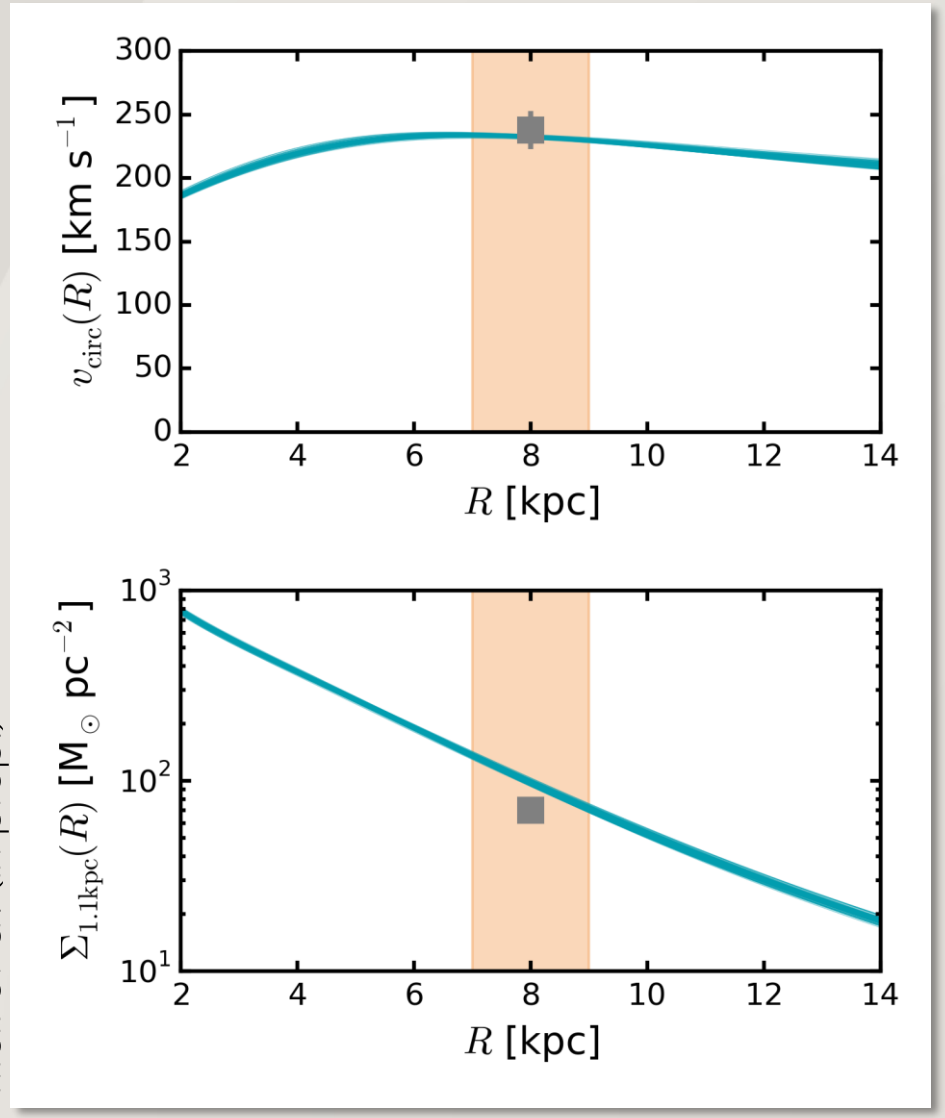
Current best estimates from literature:
review by
Bland-Hawthorn
& Gerhard (2016)

$f_{halo}(R_\odot)$ from Bovy & Rix (2013)

Our Estimate for the Milky Way Potential

circular velocity curve

surface density profile



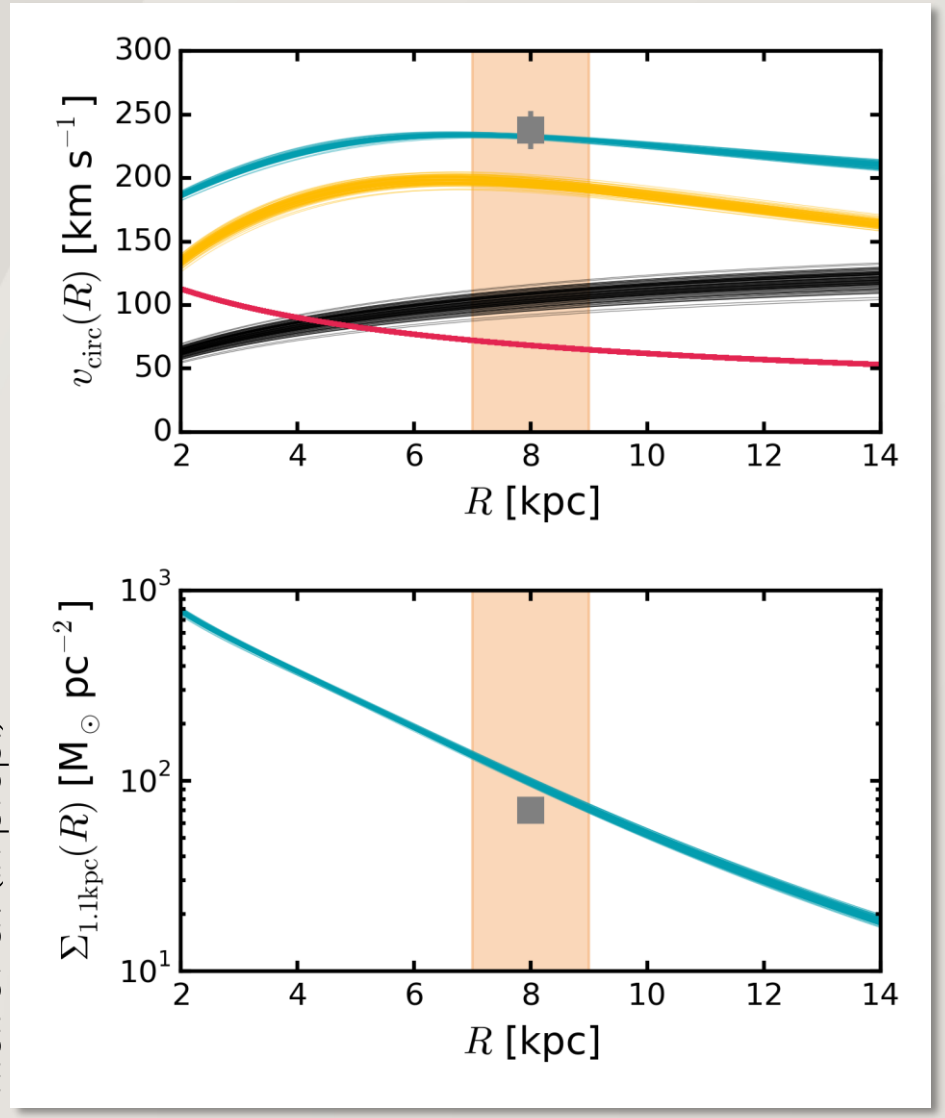
Trick et al. (in prep.)

- model from RoadMapping
- radial extent of the TGAS/RAVE data
- measurements from literature:
  - $v_{circ}(R_\odot)$: see review by Bland-Hawthorn & Gerhard 2016
  - $\Sigma_{1.1kpc}$: e.g., Kuijken & Gilmore 1989; Catena & Ullio 2010; McMillan 2011; Bovy & Rix 2013; Piffl et al. 2014a

Our Estimate for the Milky Way Potential

circular velocity curve

surface density profile



Trick et al. (in prep.)

- total
- exponential disk
- NFW halo (fixed scale radius a_{halo})
- Hernquist bulge (fixed)

Result

rotational support of disk: ~75%

➡ disk is maximal!

(Sackett 1997; Gerhard 1999; Bovy & Rix 2013; Piffl et al. 2014)

Constraining the Milky Way with Gaia

RoadMapping action-based **dynamical modeling**:

- . . . robust & well-tested machinery
- . . . using discrete 6D stellar (**x**,**v**)
- . . . recovering the MW grav. potential

RoadMapping promises:

. . . constraints on Galaxy formation from future Gaia DRs.

RoadMapping application to **TGAS/RAVE**:

- . . . new & very precise measurements of the MW potential parameters
- . . . survey selection function is crucial

Trick, Bovy & Rix (2016),
Trick, Bovy, D'Onghia & Rix (2017),
Bovy & Rix (2013), Ting et al. (2013), Binney (2012), Bovy et al. (2012a,b,c), Binney & McMillan (2011)

Thanks also to Jennifer Wojno (AIP Potsdam) and Georges Kordopatis (OCA Nice) for help with the RAVE data.