

„Disks in Galaxies“  
Munich, 14. July 2016



# Action-based Dynamical Modelling for the Milky Way Disk

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# Questions about the Milky Way

Distribution of...  
... dark matter  
... baryonic matter

Formation  
& dynamics of...  
... halo streams  
... spiral arms


How many stars...  
... are on which orbit?  
... have what chemical  
abundances?

➔ How and where  
were the stars born?  
➔ How did they get  
where they are now?

 First step

Axisymmetric gravitational  
potential

First step

Orbit distribution function for  
stellar mono-abundance  
populations (MAPs) 



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

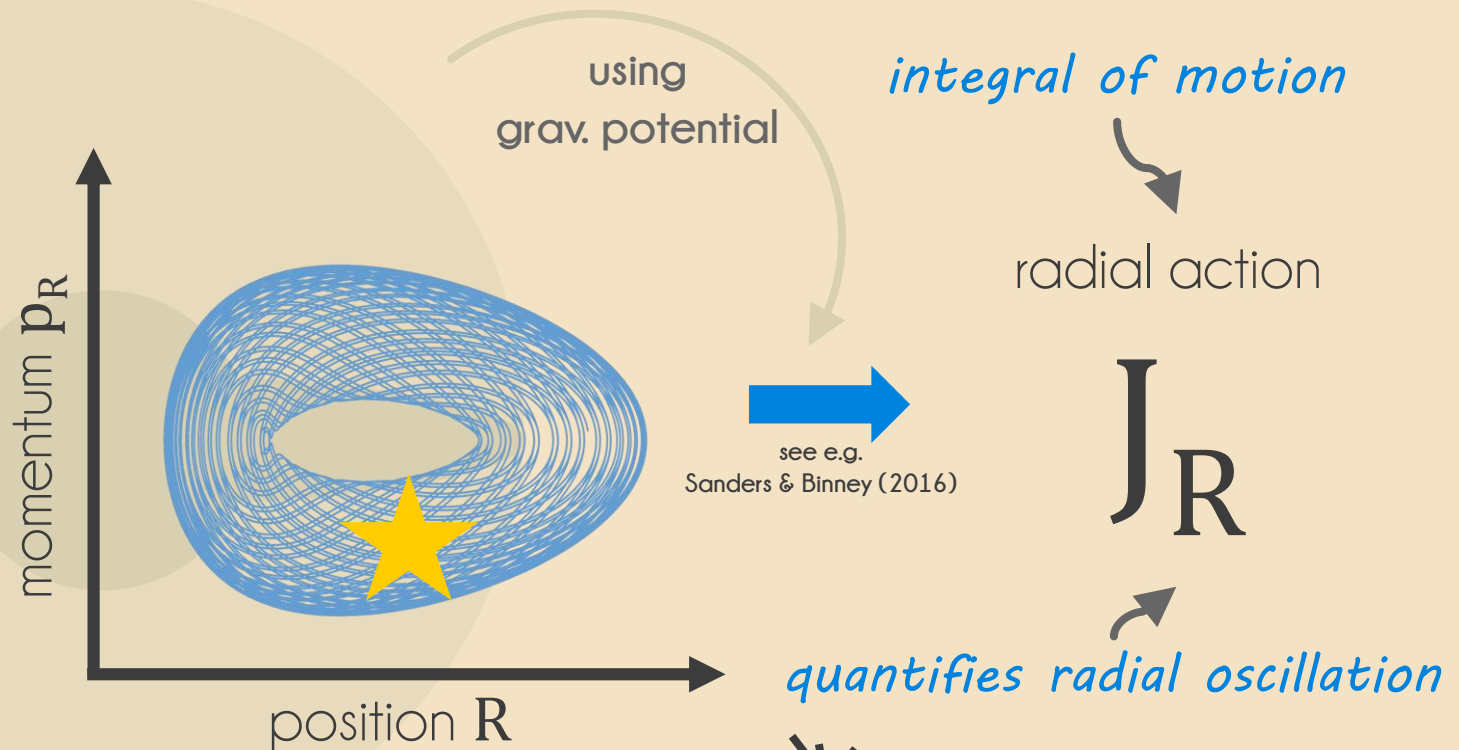
Trick, Bovy & Rix (2016)

Trick, Bovy & Rix in prep.

Bovy & Rix (2013), Binney & McMillan (2011), Binney (2012)



# What are actions?



... analogous for

- vertical action  $J_z$
- azimuthal action  $J_\phi = L_z$  (angular momentum)

*with angles  $\vec{\theta}$ :  
canonical coordinates*

**Actions are  
excellent  
orbit labels.**

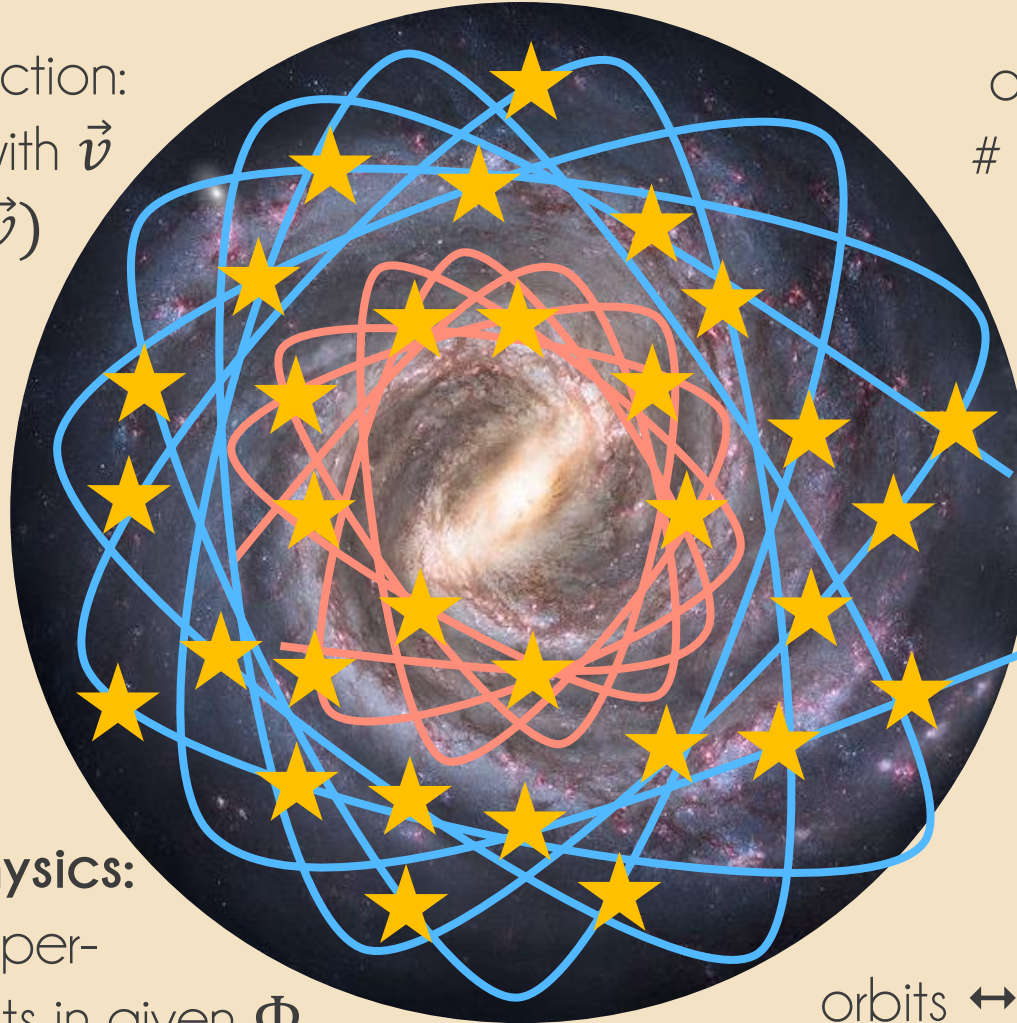




# What is an orbit DF?

Stellar  
distribution function:  
# stars at  $\vec{x}$  with  $\vec{v}$   
 $= DF(\vec{x}, \vec{v})$

Stellar orbit  
distribution function:  
# stars on given orbit  
 $= DF(\vec{J})$



**Underlying physics:**  
MW disk is a super-  
position of orbits in given  $\Phi$ .

orbits  $\leftrightarrow$  actions  $\vec{J}(\vec{x}, \vec{v}|\Phi)$

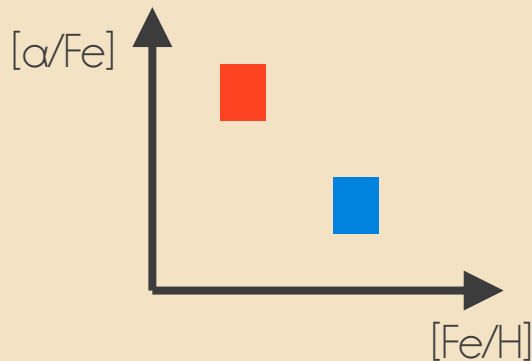


# Why use Mono-Abundance Populations?

complex kinematic structure;  
depends strongly  
on abundances

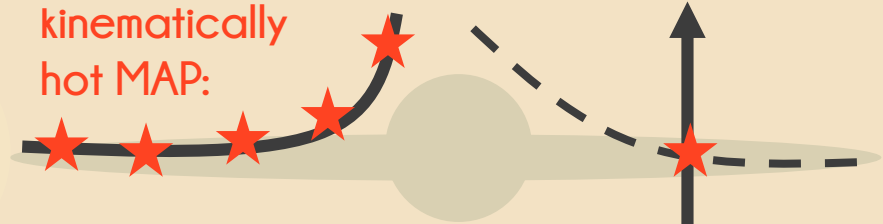
(e.g., Chiba & Beers 2000, Feltzing et al. 2003, Lee et al. 2011, Schönrich & Binney 2009, Sanders & Binney 2015)

Mono-Abundance  
Populations (MAP)

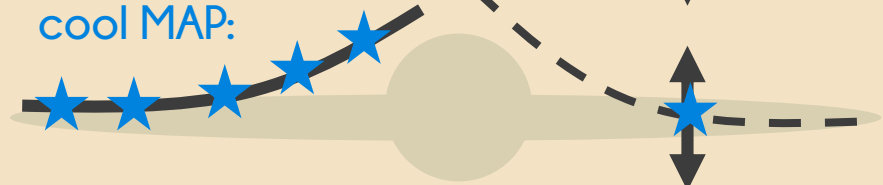


Bovy et al. (2012a,b,c):

kinematically  
hot MAP:



kinematically  
cool MAP:



exponential disk

quasi-isothermal  
velocity distribution

Ting et al. (2013):

MAPs are well described by  
quasi-isothermal DF  
 $q\text{DF}(\mathbf{J} | p_{\text{DF}})$   
by Binney & McMillan (2011)

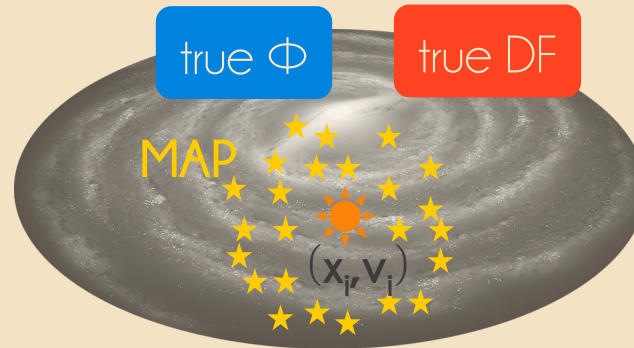


# Idea behind ROADMAPPING

1. Pick stellar population.

2. Try all potentials and calculate stellar actions.

3. Try all qDFs and test if one fits.

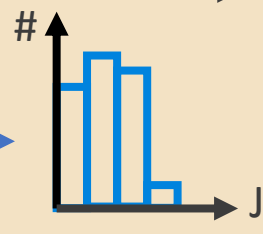
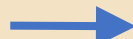
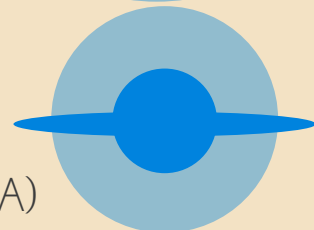
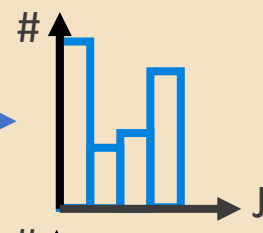
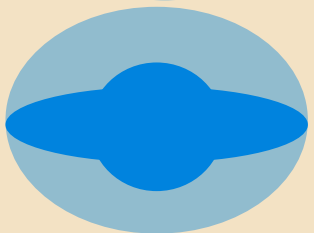
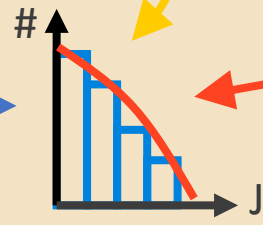
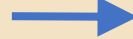
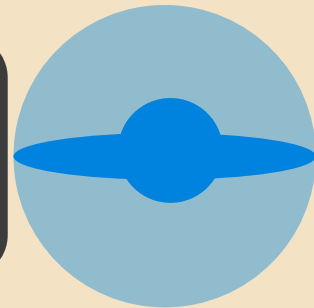


fast & approx.  
action calculation  
(Binney 2012)

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

$qDF(\mathbf{J} | p_{DF})$   
*Binney & McMillan 2012*

*Only in the true  $\Phi$   
do we have a  
realistic orbit DF.*

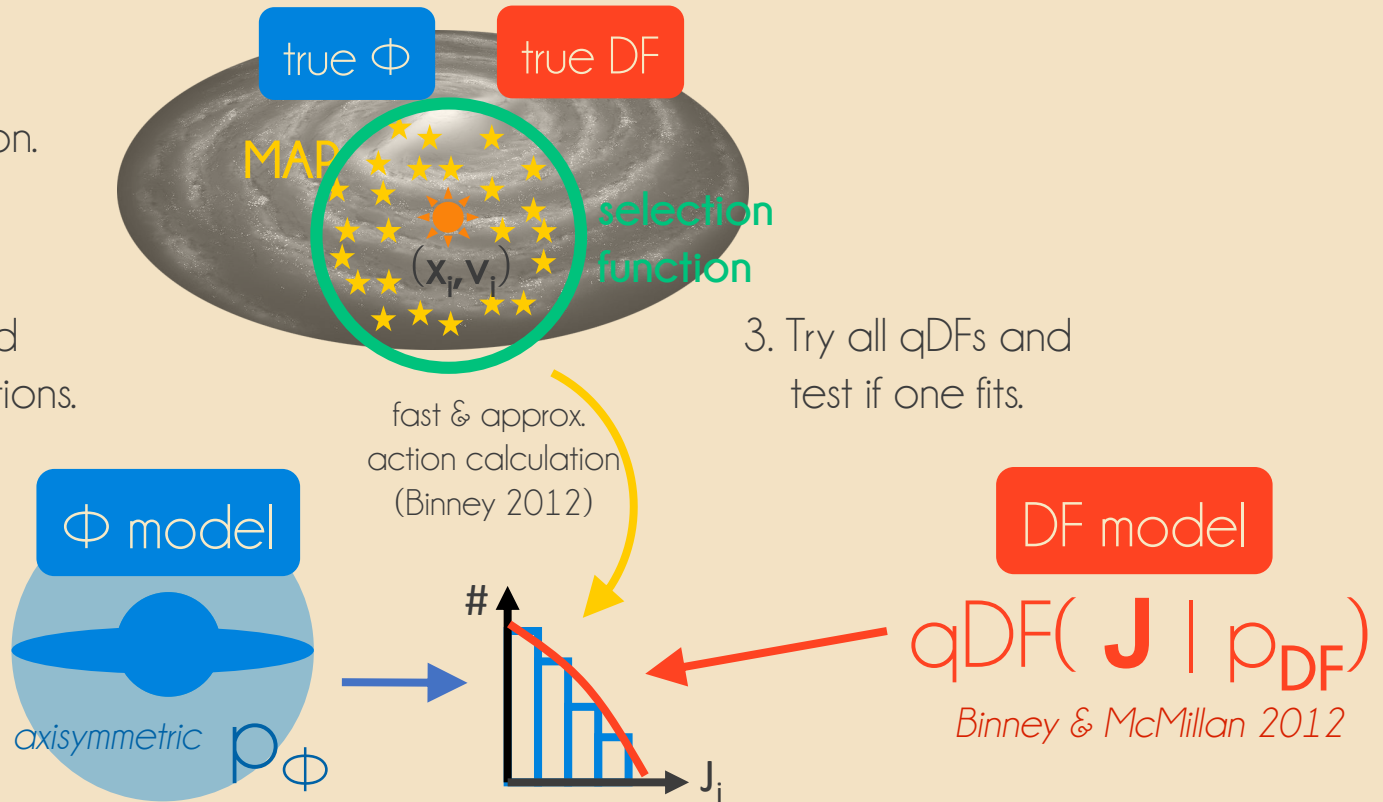


# Idea behind ROADMAPPING

1. Pick stellar population.

2. Try all potentials and calculate stellar actions.

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$$\mathcal{L} = \prod_i \frac{sf(\mathbf{x}_i) \cdot qDF(\mathbf{J}(\mathbf{x}_i, \mathbf{v}_i) | p_\Phi) | p_{DF}}{\int sf(\mathbf{x}) \cdot qDF(\mathbf{J}(\mathbf{x}, \mathbf{v}) | p_\Phi) | p_{DF} d^3x d^3v}$$



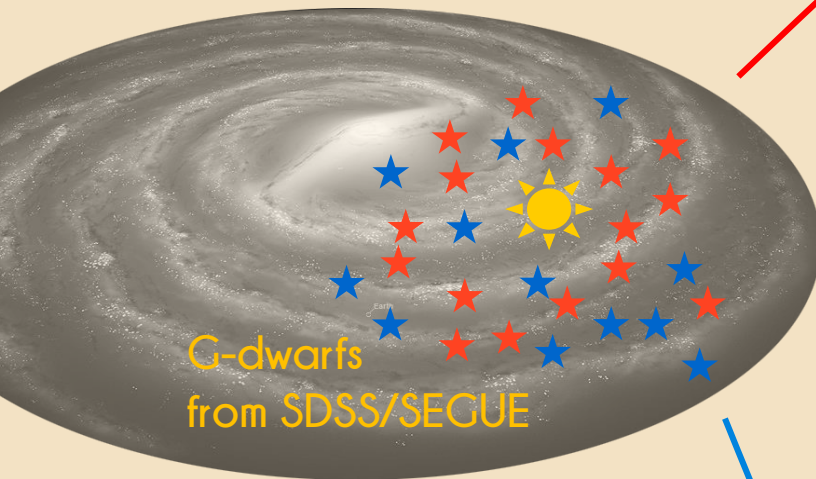


# First Application

Bovy & Rix (2013)

$\Phi$  model:

with only two  
free parameters

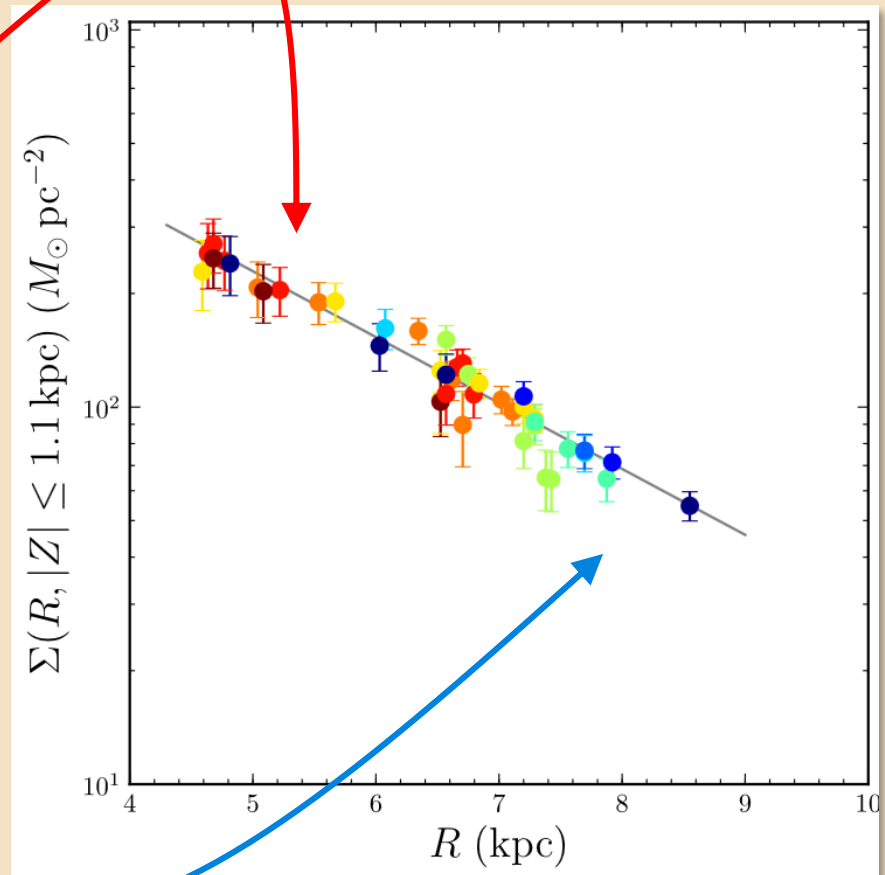


G-dwarfs  
from SDSS/SEGUE

surface density

cool MAPs with longer  
tracer scale length

hot MAPs with shorter  
tracer scale length



Galactocentric radius



# Investigation of ROADMAPPING

Trick, Bovy, & Rix (2016)

## Modelling Characteristics

more free model parameters &  
speed up of algorithm

influence of the MAPs'  
kinematic temperature

shape & position  
of survey volume

measurement  
uncertainties in  
stellar distances

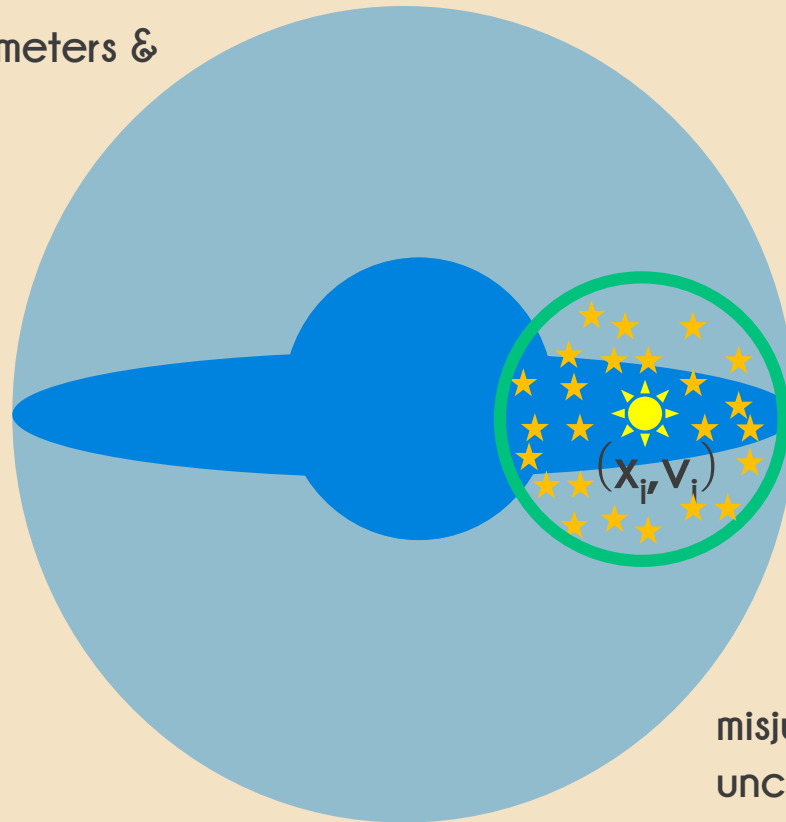
## Breakdown of Assumptions

using a too  
restrictive  
potential model

misjudgement of  
distribution function (DF)

misjudgement of  
selection function (SF)

misjudgement of measurement  
uncertainties in proper motions

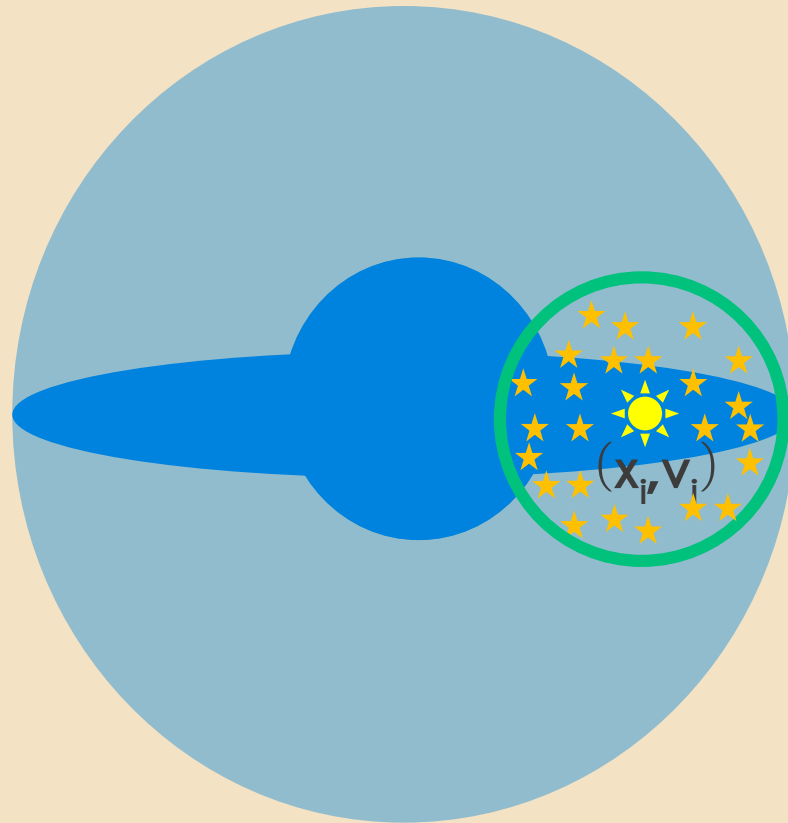


# Investigation of ROADMAPPING

Trick, Bovy, & Rix (2016)

## Test Procedure

1. Draw mock data from given DF & SF in given  $\Phi$ .
2. Try to recover true model parameters with ROADMAPPING.



## Overall Result

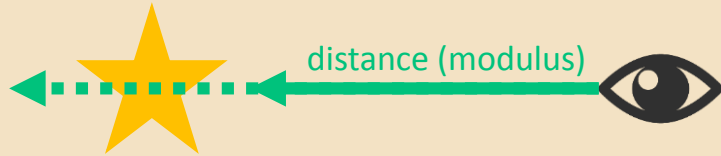
ROADMAPPING is ...

...robust against modest deviations from the model assumptions \*

...well-suited to making precise measurements of the MW potential with Gaia data. \*



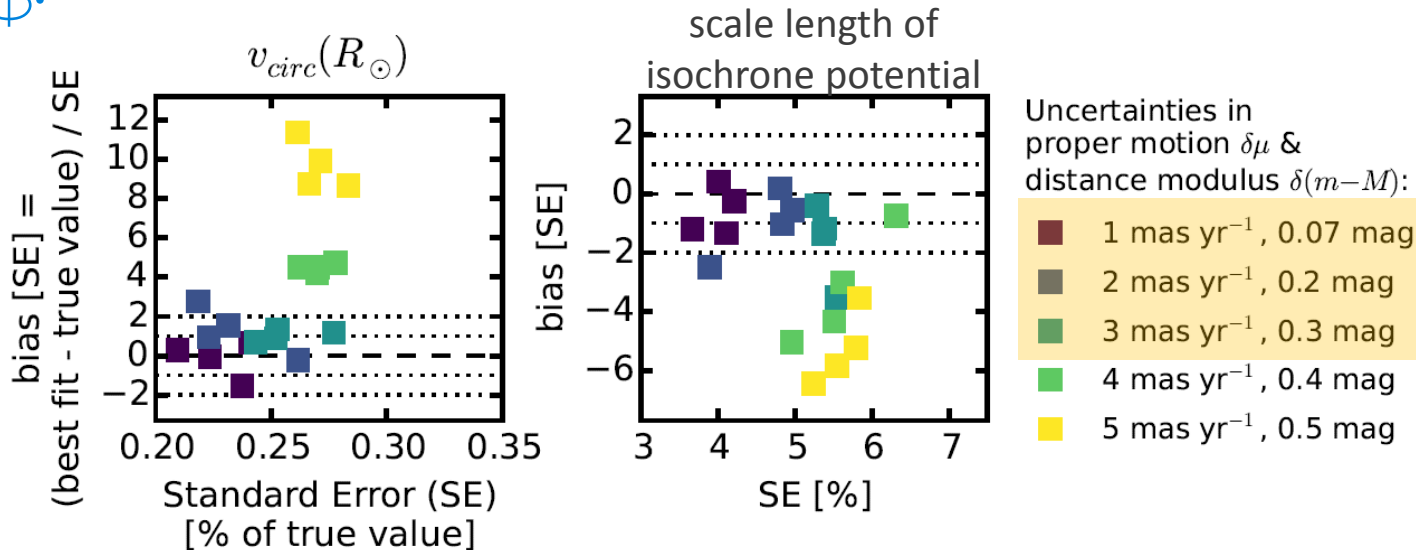
# Measurement Uncertainties in Stellar Distance



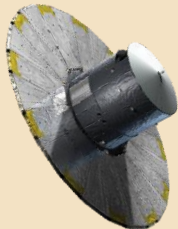
For speed reasons, ROAD/MAPPING uses an approximation when including distance uncertainties.

➡ How well does this approximation work?

$p_\phi$ :



at  $d=3\text{kpc}$   
➡  $<10\%$   
distance error



Typical red clump giant in Gaia:  
at  $d=3\text{kpc}$  ➡ 5% distance error  
(de Bruijne et al. 2014)

Result

ROAD/MAPPING will work for  
bright ( $<15\text{ mag}$ ) stars at  
 $d<3\text{kpc}$  in Gaia!



Wilma Trick (MPIA)

Trick, Bowy, & Rix (2016)

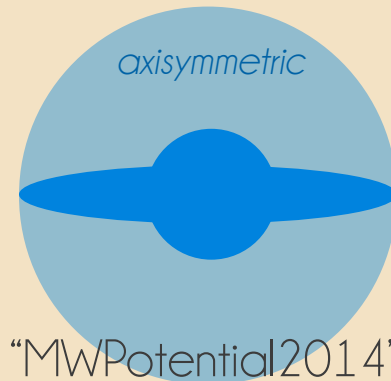
„Disks in Galaxies“, Munich, 14. July 2016

# Potential with Restrictive Parametric Form

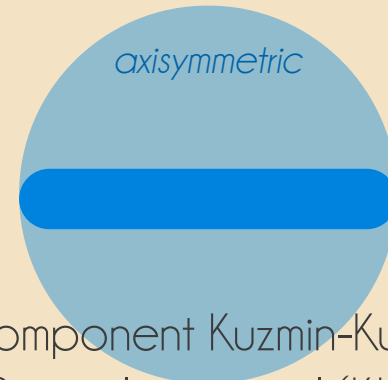
In mock data creation:

In ROADMAPPING analysis:

$\Phi$  model:

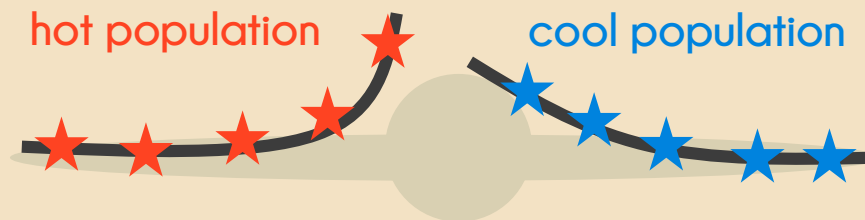


"MWPotential2014"  
(Bovy 2015)



2-component Kuzmin-Kutuzov  
Stäckel potential (KKS)  
(Batsleer & Dejonghe 1994)

DF model:



qDF

following qDF  
in given  $\Phi$

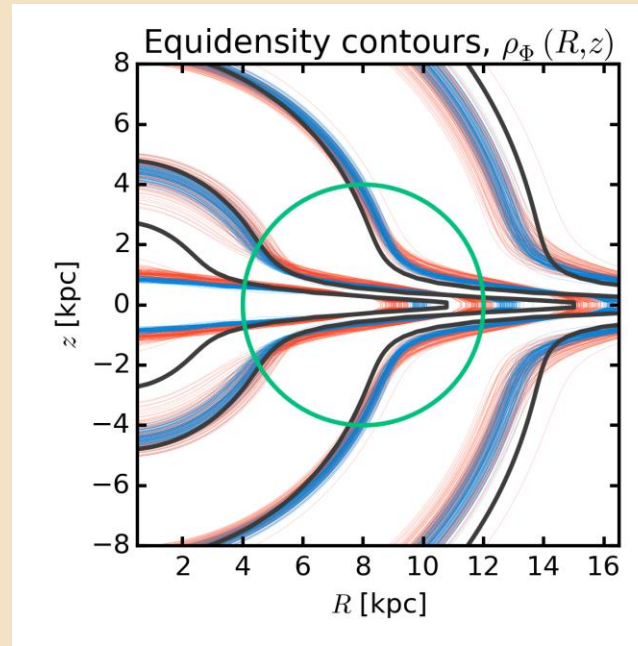




# Potential with Restrictive Parametric Form

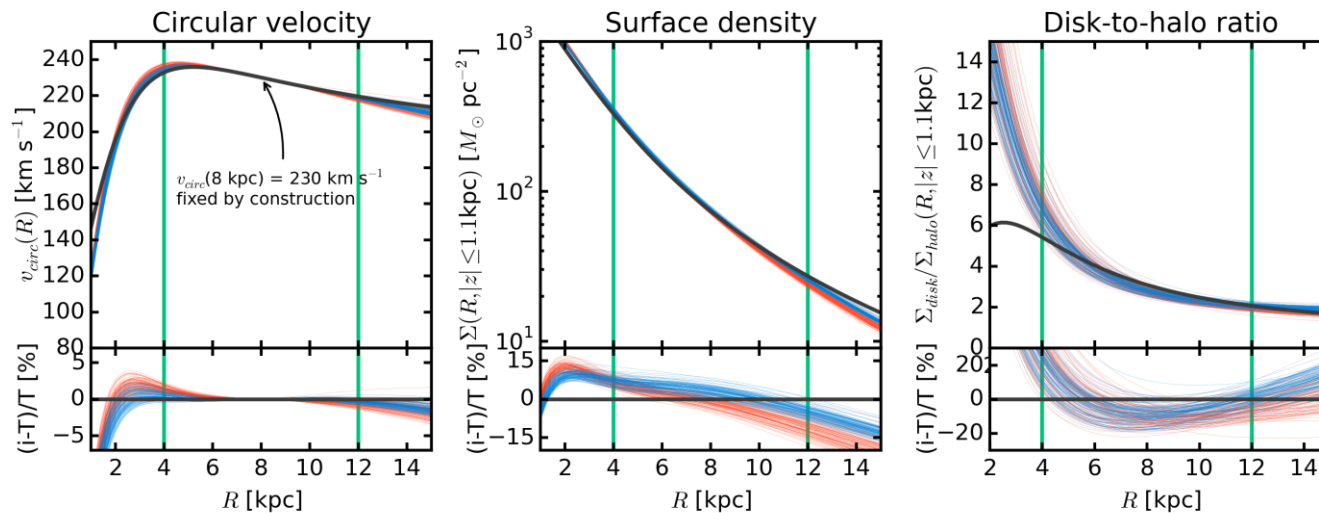
## Result

We find a reliable best fit to the data – given the limitations of the model.



- true MWPotential2014 ( $i=T$ ) (Bovy 2015)
- recovered KKS potential with ROADMAPPING ( $i=R$ )
- ... from a **hot** population
- ... from a **cool** population
- survey volume

residuals

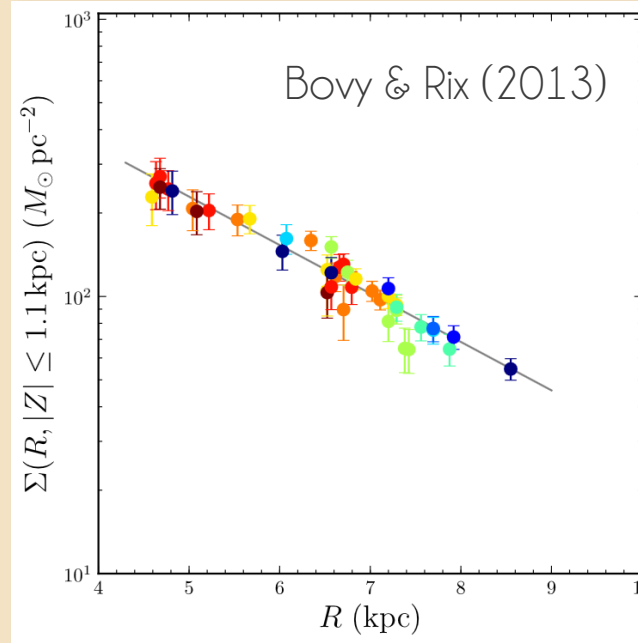


# Potential with Restrictive Parametric Form

## Result

We find a reliable best fit to the data – given the limitations of the model.

Populations with smaller scale lengths constrain surf. density at smaller radii best (and vice versa). Justifies Bovy & Rix (2013).



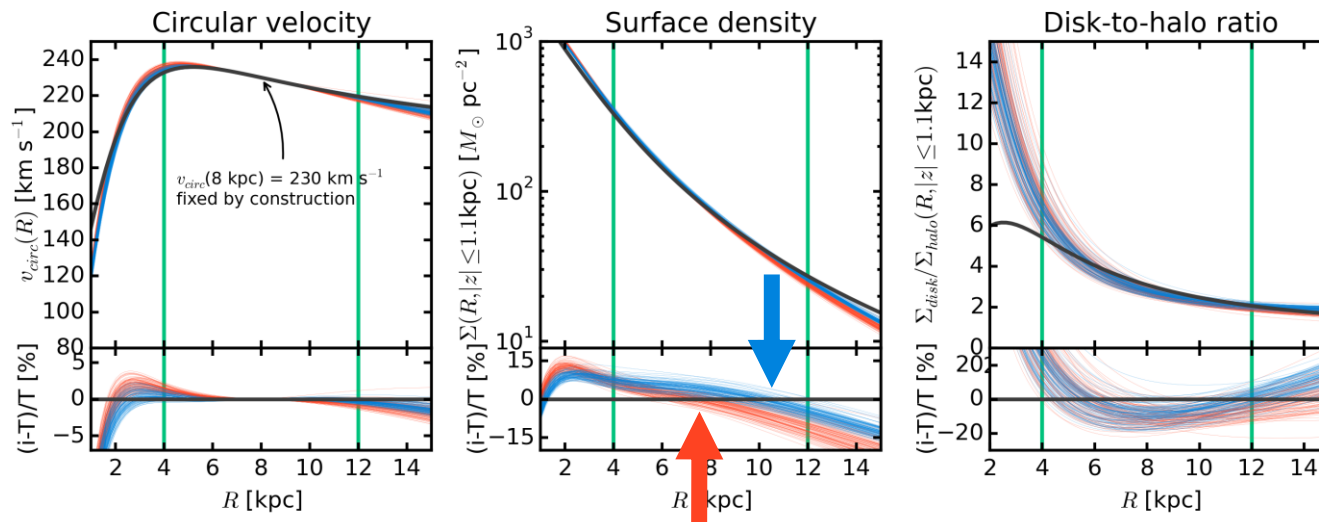
— true MWPotential2014 (i=T)  
(Bovy 2015)

recovered KKS potential  
with ROAD MAPPING (i=R)

— ... from a hot population  
— ... from a cool population

— survey volume

residuals



# Recovering the Potential in a Spiral Galaxy

Trick, Bovy, D'Onghia, & Rix (in prep.)

Breakdown  
of several  
assumptions:

## Data:

affected by strong  
non-axisymm. spiral arms

vs.

## Model in general:

axisymmetric!!!

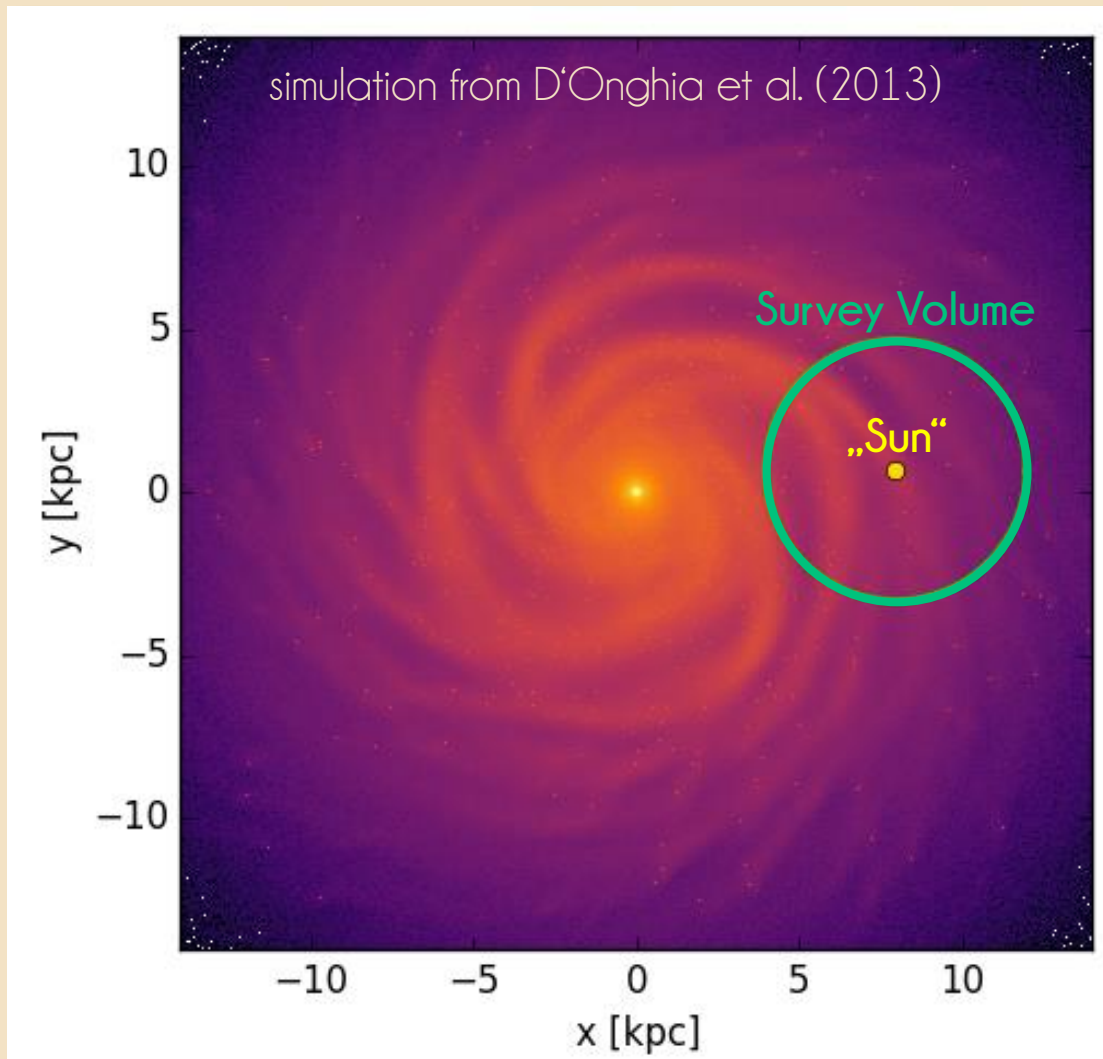
## DF model:

most simple: single qDF

## Potential model:

halo, bulge &  
„wrong“ disk

in ROADMAPPING



# Recovering the Potential in a Spiral Galaxy

Even though...

**Data:**

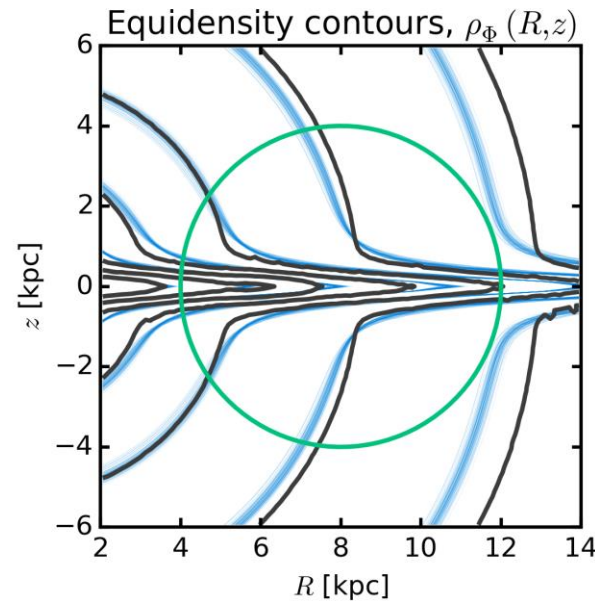
affected by spiral arms

**DF model:**

most simple

**Potential model:**

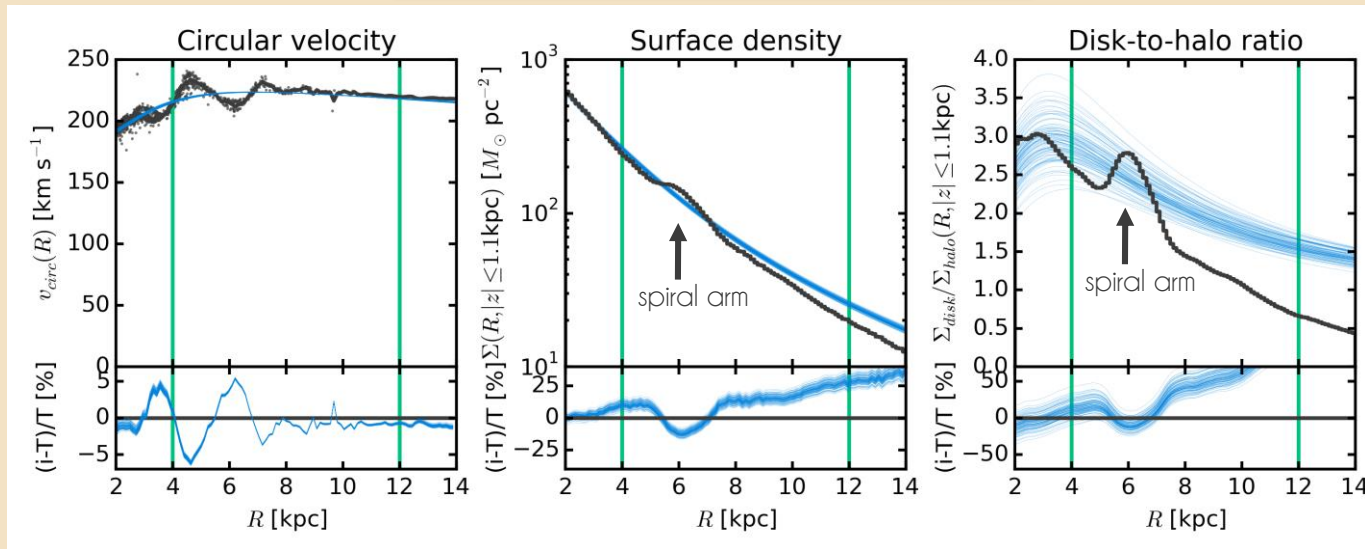
axisymmetric



Result

Recovered potential is good average model where most of the stars are located.

— true from galaxy simulation ( $i=T$ )  
— recovered with ROAD-MAPPING ( $i=R$ )  
— survey volume



residuals



# Ready for Gaia!

**ROADMAPPING:** an action-based dynamical modelling machinery to recover the Milky Way's gravitational potential from discrete 6D measurements. \*

**ROADMAPPING** is robust against modest deviations from the model assumptions. \*

**ROADMAPPING** is well-suited to making precise new measurements of the MW potential with data from the upcoming Gaia data releases (including TGAS/DR1). \*

see also: \*

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





„Disks in Galaxies“  
Munich, 14. July 2016



Thank you for your attention!

# Action-based Dynamical Modelling for the Milky Way Disk

with ROADMAPPING

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