Digging out Substructure in the Halo with Gaia

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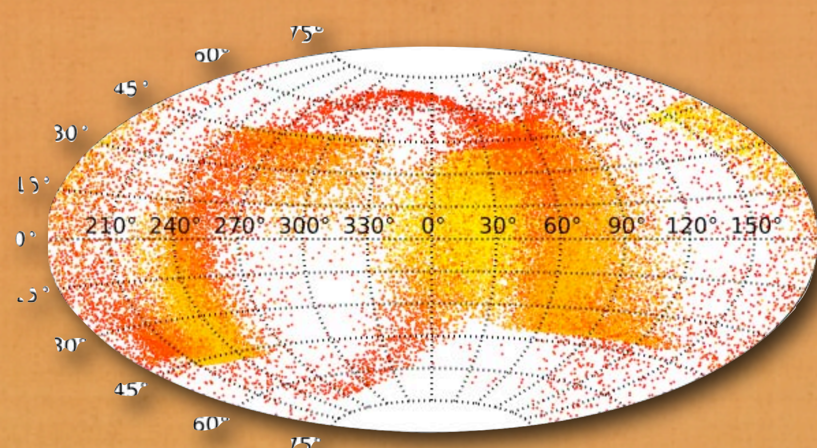
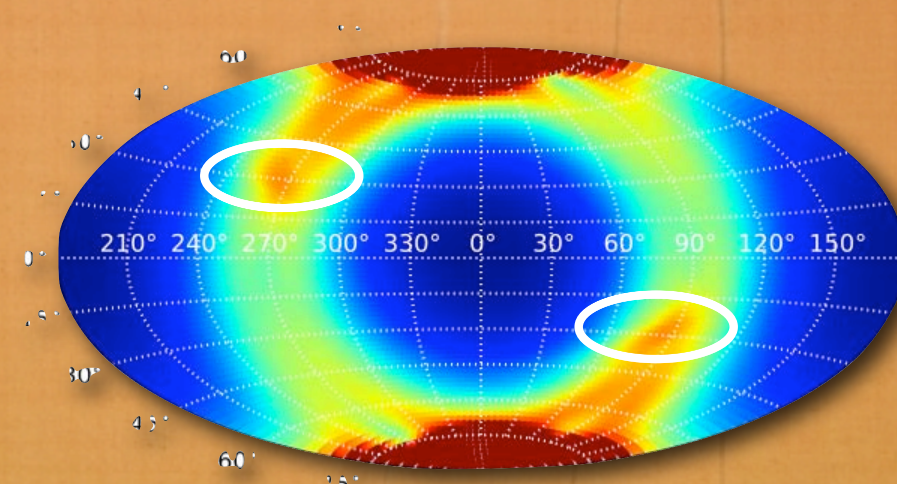
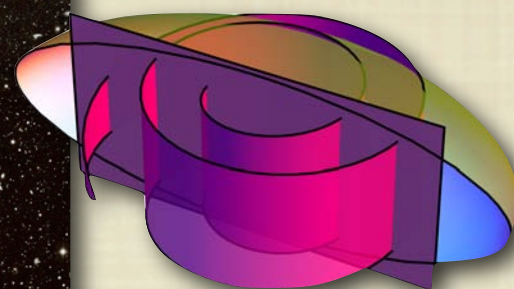
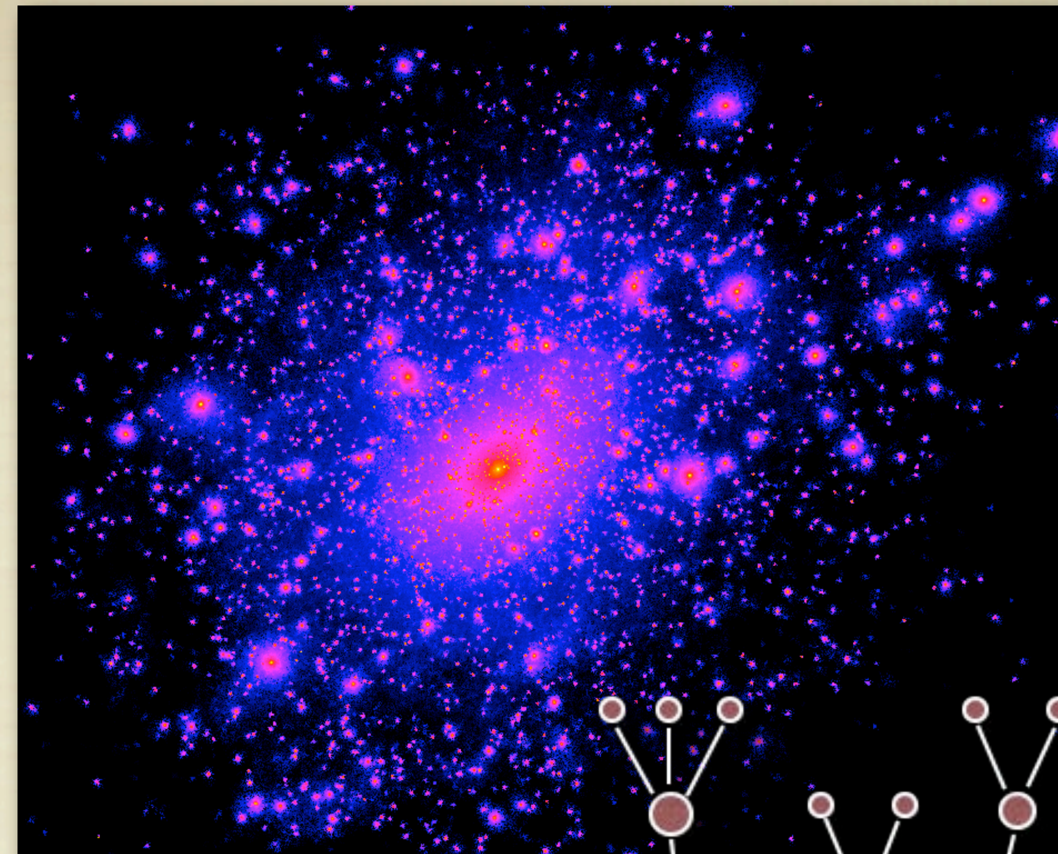
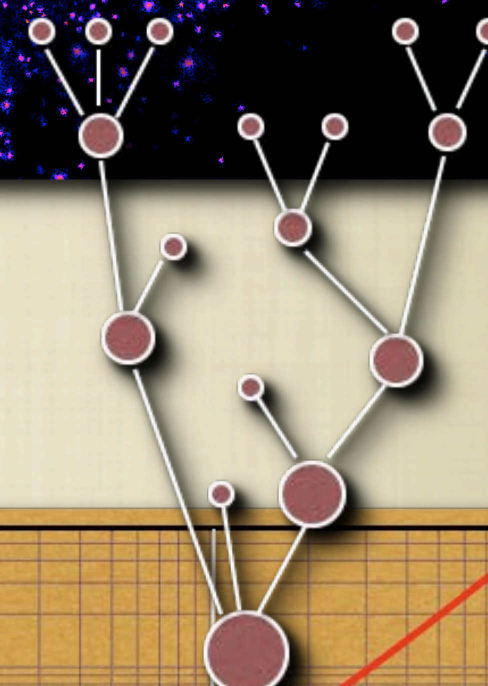


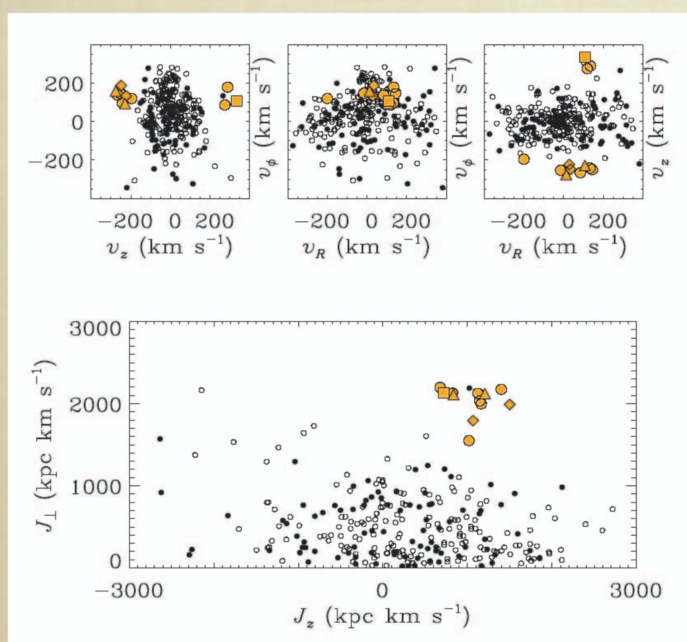


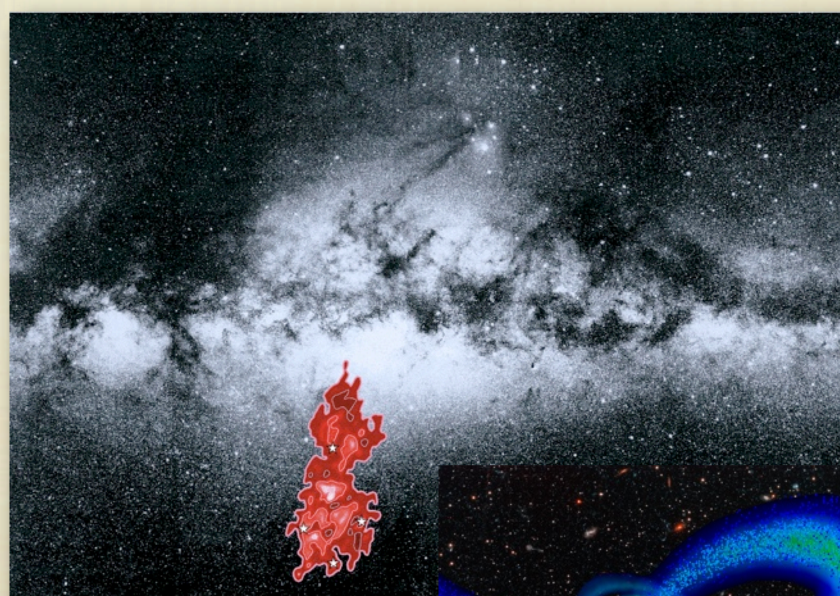
Why dig?

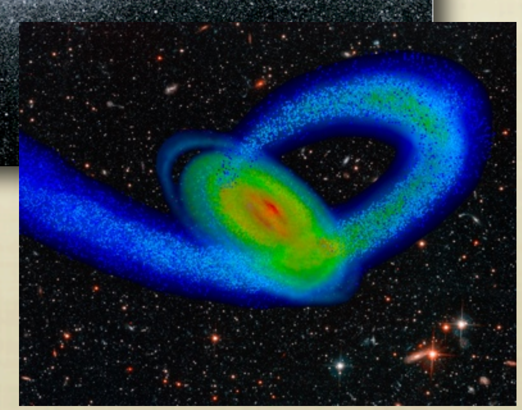


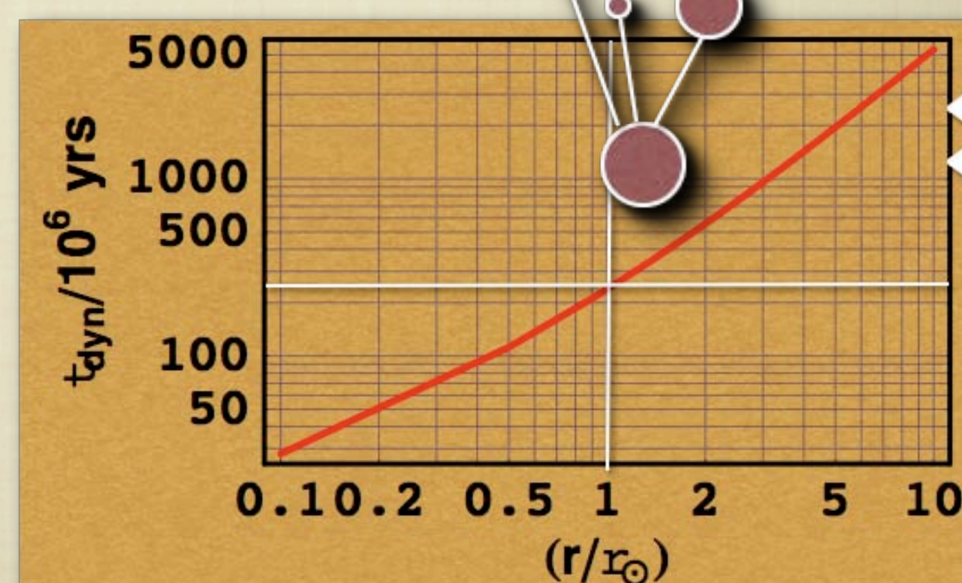





200
0
−200
−200 0 200
v_z (km s^{-1})
v_ϕ (km s^{-1})
v_R (km s^{-1})
v_z (km s^{-1})
3000
2000
1000
0
$J_\perp$ (kpc km s^{-1})
−3000
3000
J_z (kpc km s^{-1})



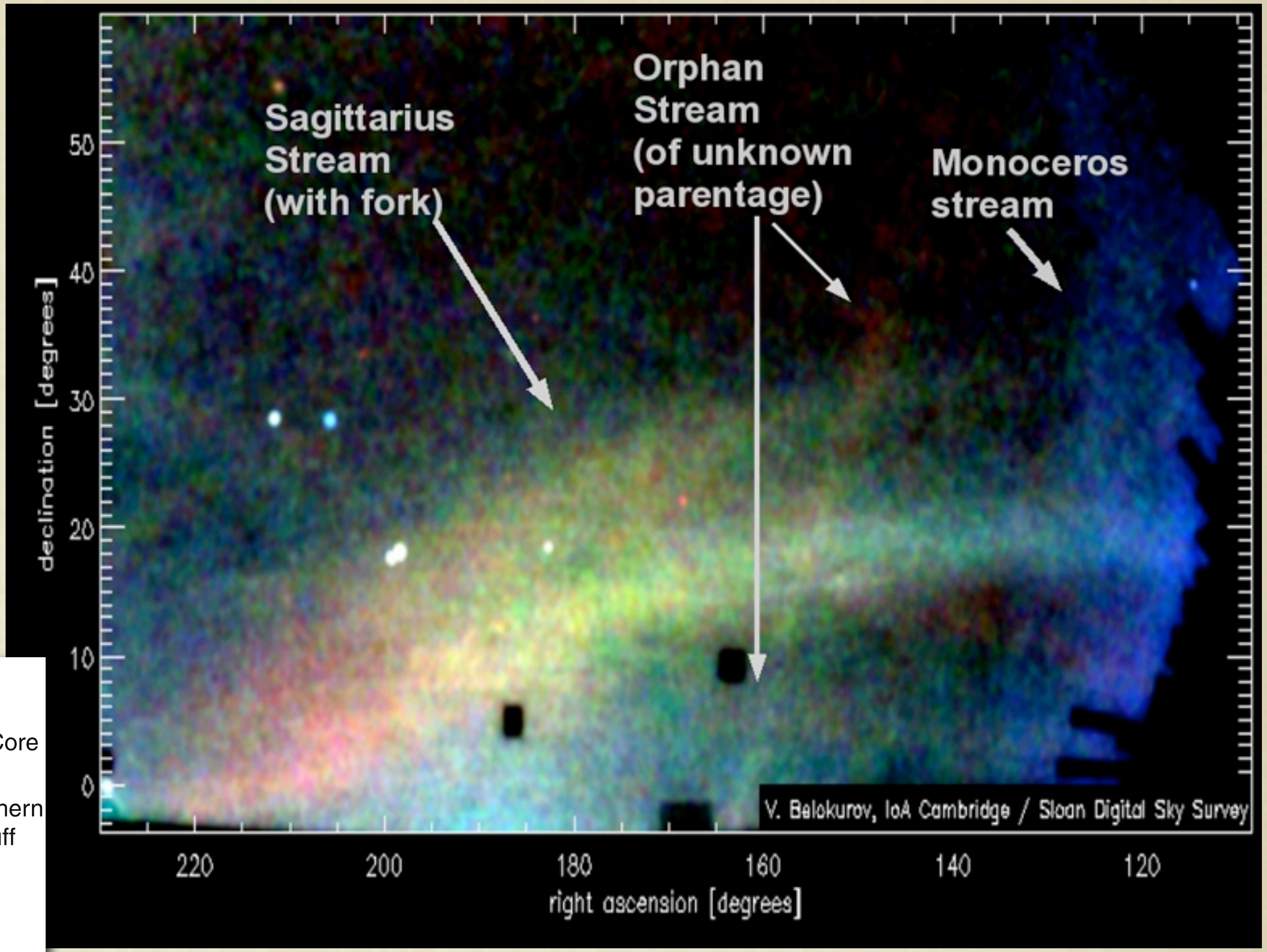



5000
1000
500
100
50
$t_{dyn}/10^6$ yrs
0.1 0.2 0.5 1 2 5 10
$(r/r_\odot)$

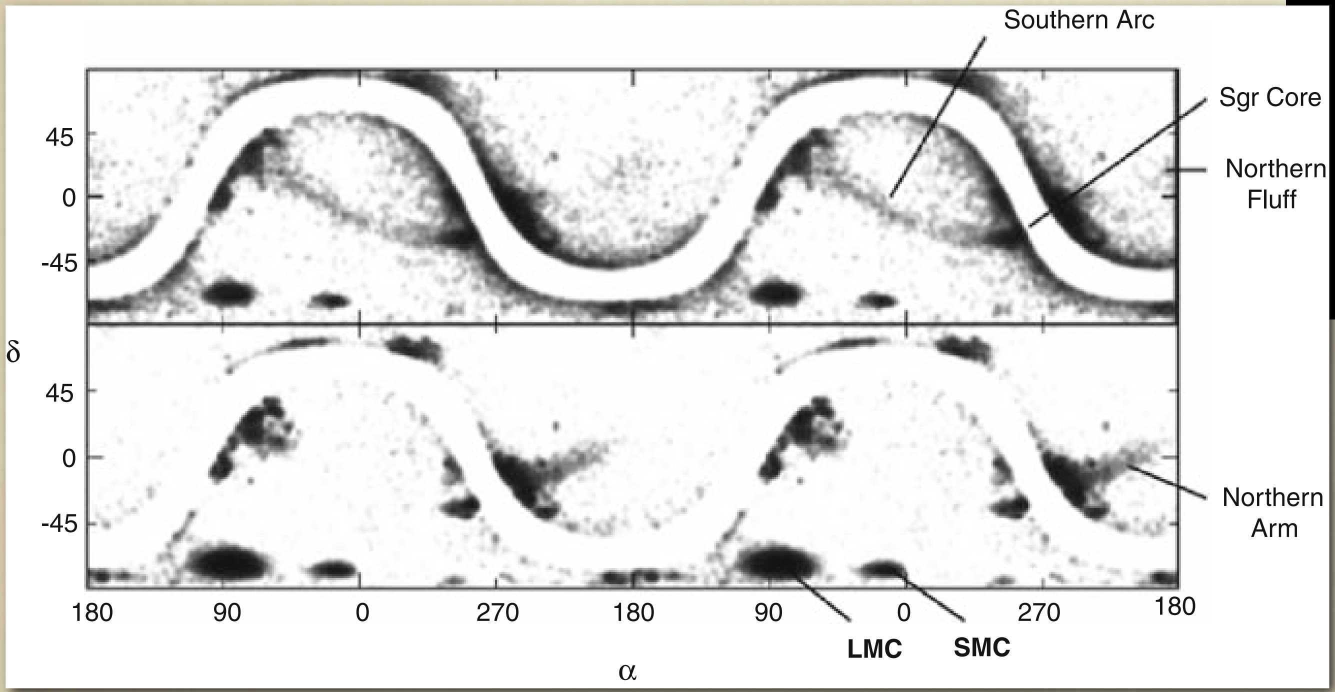
Where to dig?

Spatial information from photometry

Large scale photometric surveys (SDSS, 2MASS).



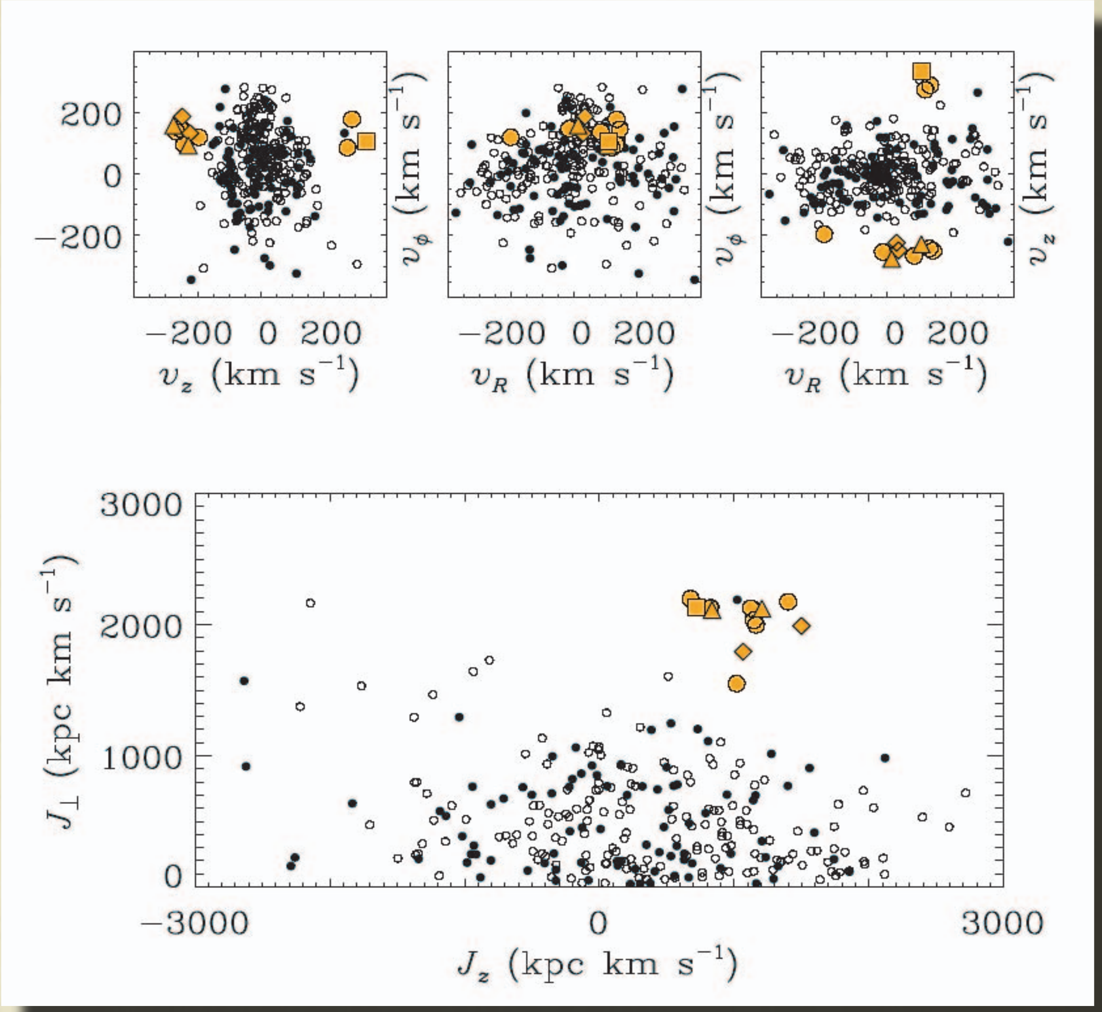
"Field of Streams"
Belokurov et al. *ApJ*, 642, L137 (2006)
SDSS sky plot for
$g - r < 0.4$
$B: \quad 20.00 < r \leq 20.66$
$G: \quad 20.66 < r \leq 21.33$
$R: \quad 21.33 < r \leq 22.00$



Majewski et al. *ApJ*, 599, 1082 (2003)
2MASS sky plot for.
11 < Ks < 12 1.00 < J-Ks < 1.05 (top)
12 < Ks < 13 1.05 < J-Ks < 1.15 (bottom)

Where to dig?

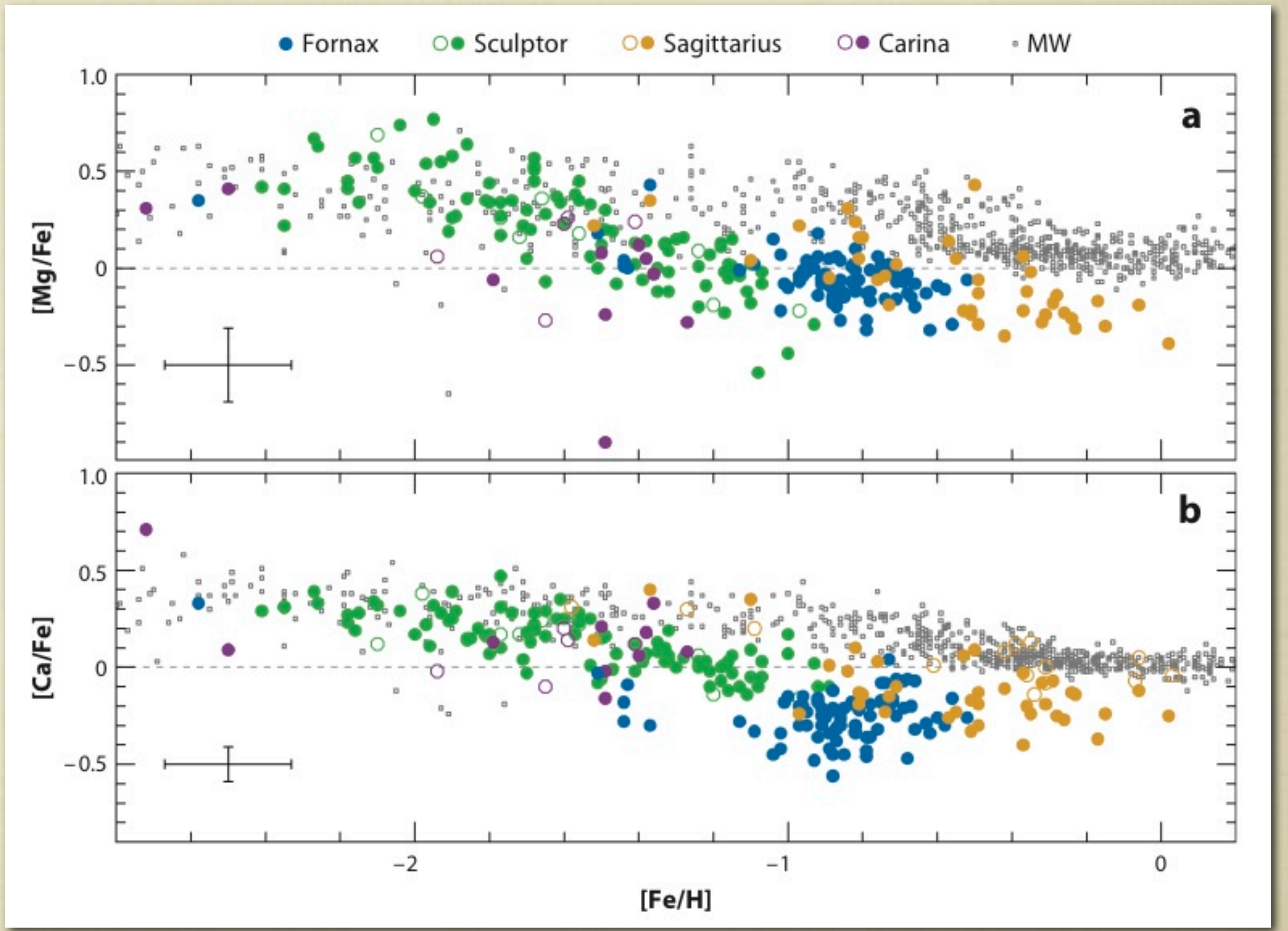
Adding kinematical information



Helmi, et al. *Nat* **402**, 53 (2002)
Sample of 97 metal poor red giants and RR-Lyrae stars with radial velocities and Hipparcos astrometry.

Where to dig?

Adding metallicity information

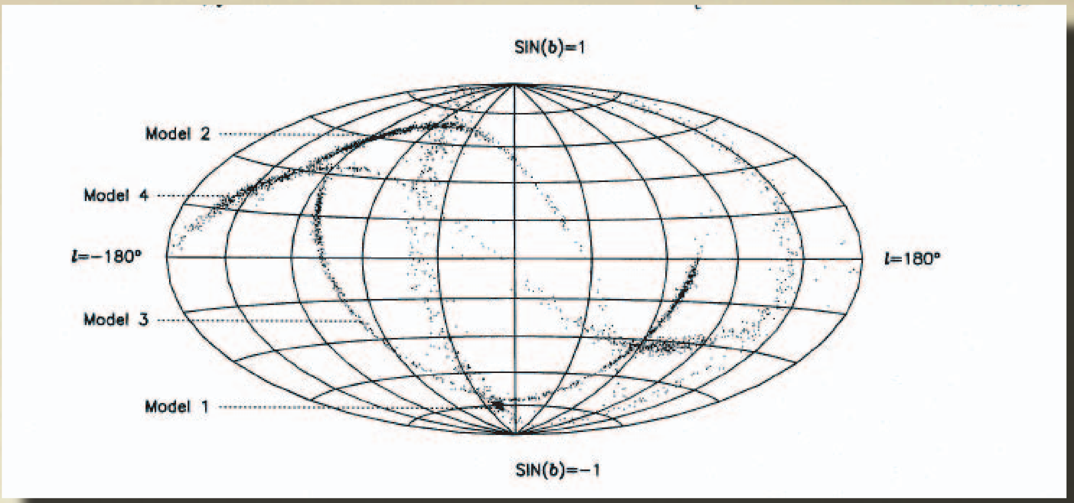


Tolstoy, et al. *ARAA* **47**, 371 (2009)

α-element metallicities for 4 nearby dwarf spheroidal galaxies compared with our Galaxy.

How to dig?

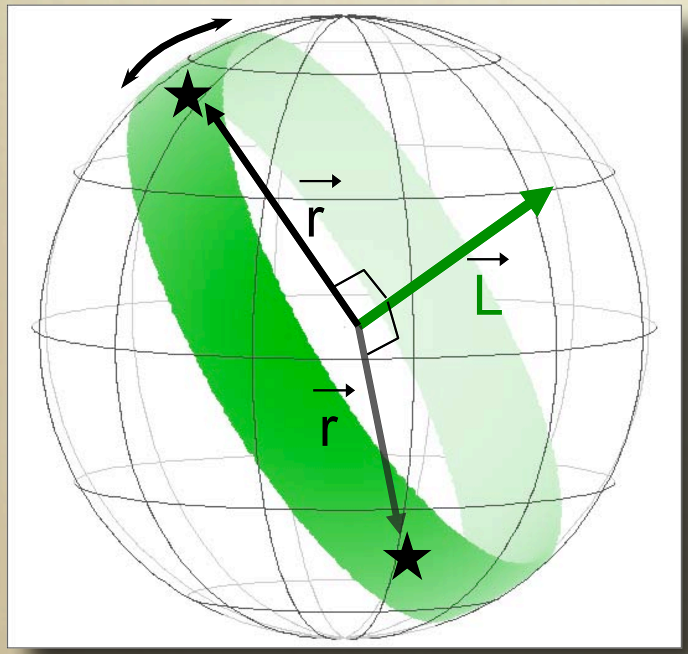
N-body simulations as guides

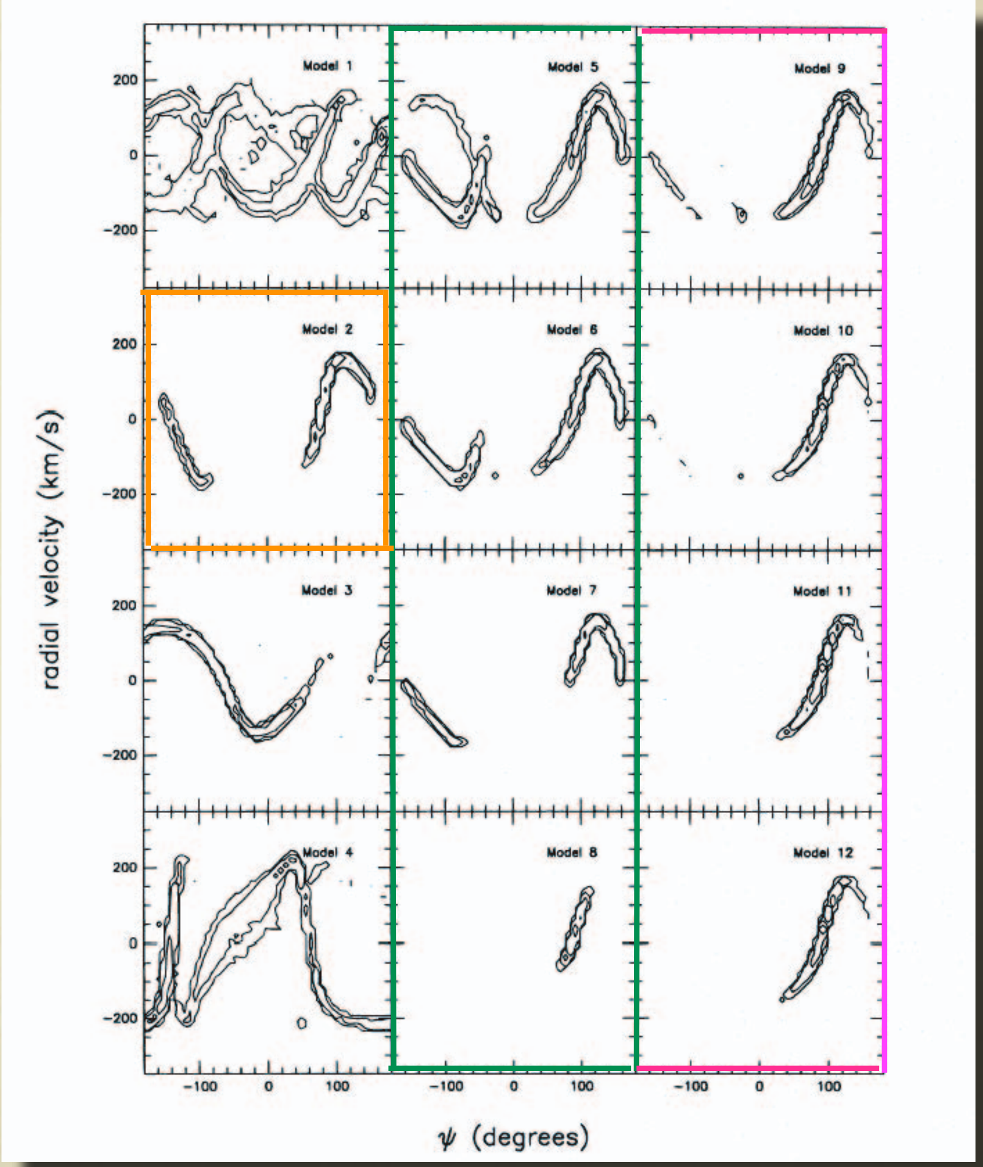


Sky projections

Systematic experiments that can help us design search strategies.

Johnston, Hernquist and Bolte, *ApJ*, 465, 278 (1996)
Great Circle Cell Count Method
Simulations: Self-consistent field code, fixed, spherical galactic potential,
10^4 particle Plummer model satellites,
10 Gyrs time span.





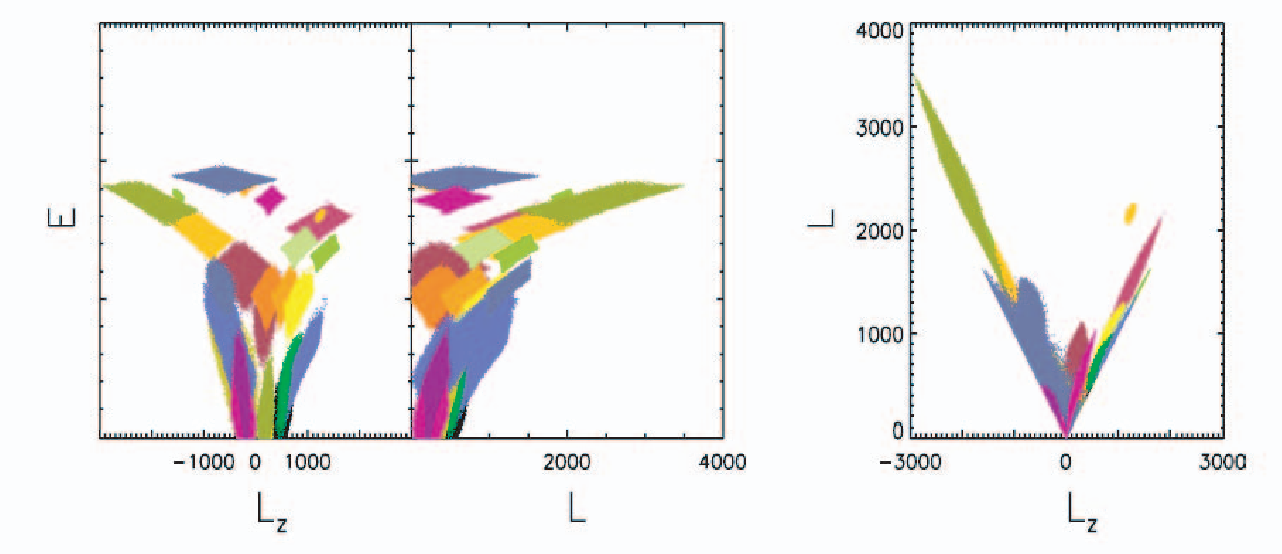
Fiducial case
Effect of decreasing velocity dispersion ↓
Effect of increasing central density ↓

How to dig?

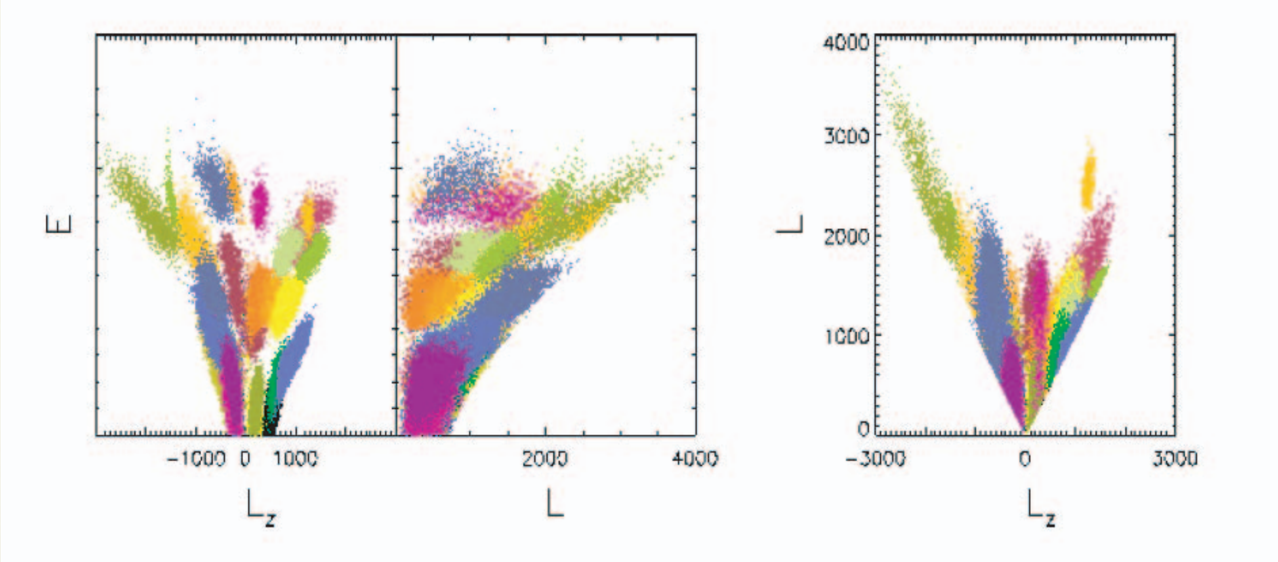
Theoretical spaces

Searches in the space of integrals of motion.

A steady state potential preserves E,
a spherical potential preserves L,
an axisymmetric potential preserves L_z



Helmi and de Zeeuw, *MNRAS*, 319, 657 (2000)
Space of conserved quantities
Simulations: Multipolar code,
fixed galactic potential,
10^5 particle King model satellites,
12 *Gyr* time span,
simulated *Gaia* errors.

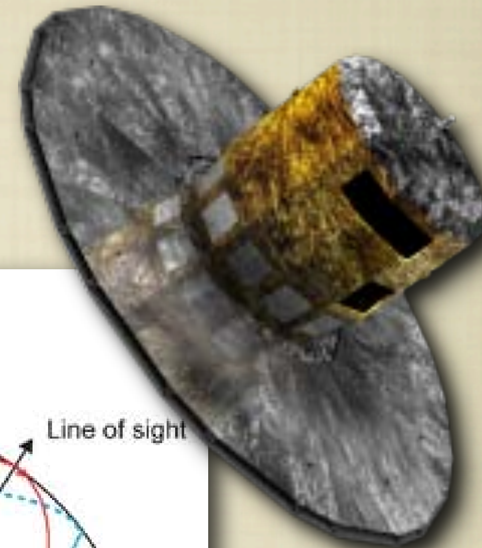


J. Vermeer "The Astronomer" (~1668)

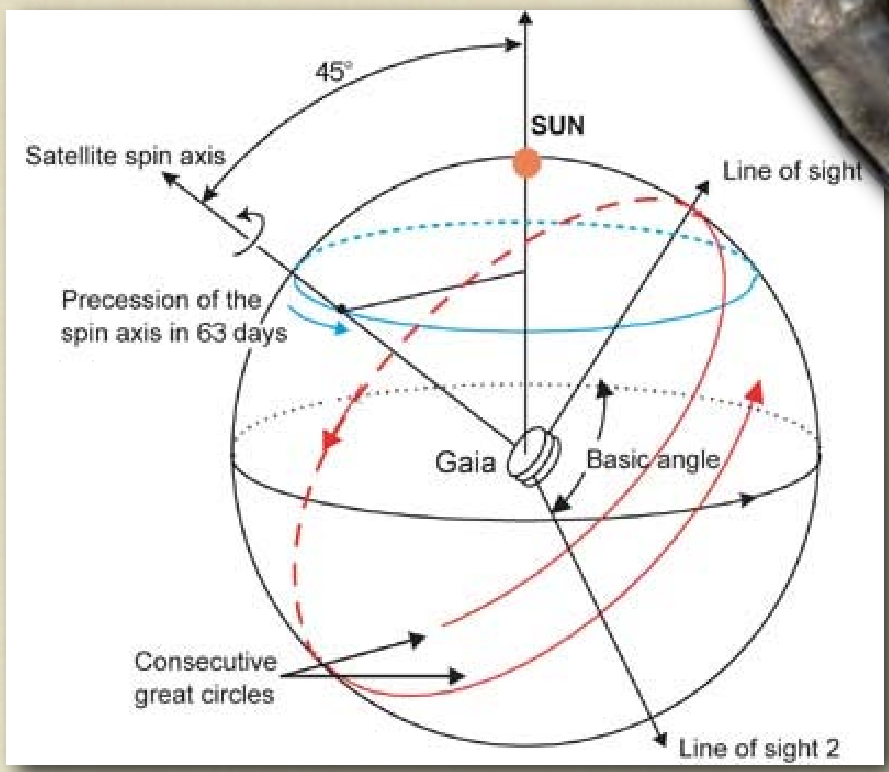
What would you do with a catalogue with 3D info for 10^9 stars?

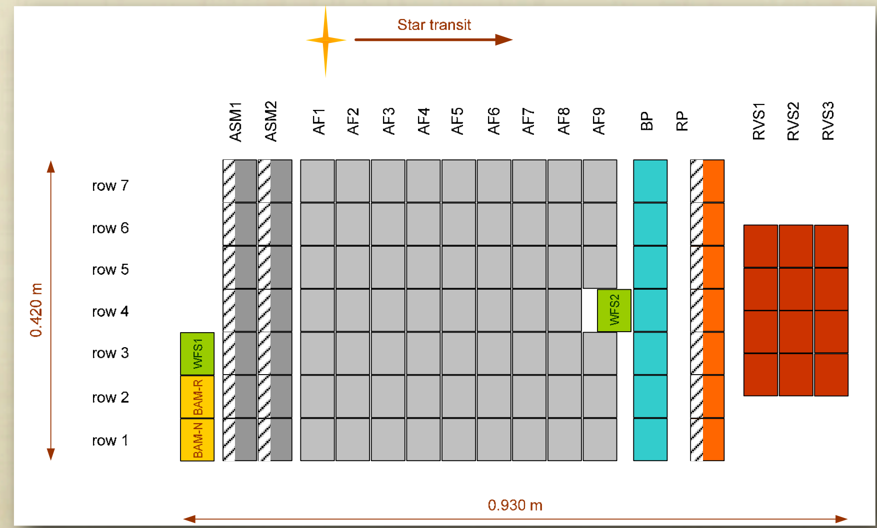
The promise of Gaia

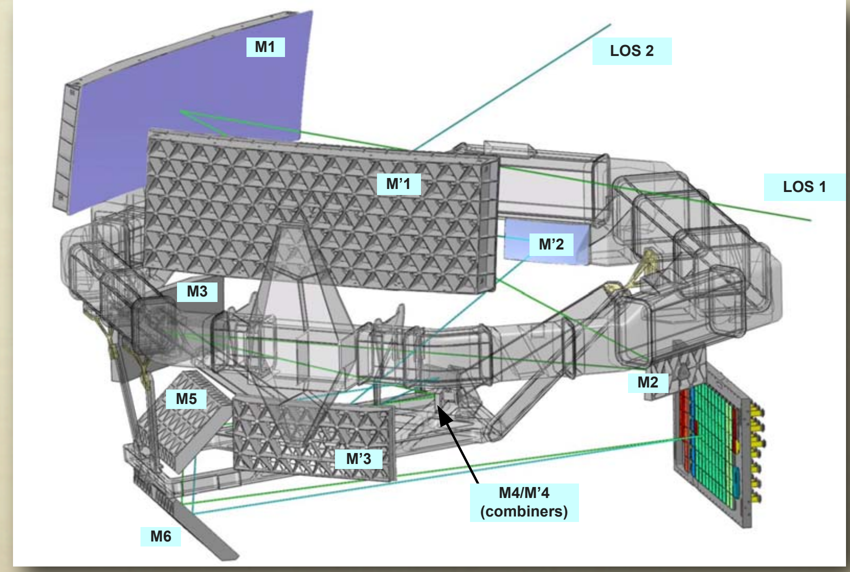
Launch date: August 2013
Mission span: 5 years
Orbit: Lissajous type around L2
Mission capabilities: Astrometry, Photometry, spectroscopy



Magnitude limit:	20-21 mag
Completeness:	20 mag
Number of objects:	26 million to *V*=15
	250 million to *V*=18
	1,000 million to *V*=20
Astrometric accuracy:	7 μarcsec at *V*=10
	10 μarcsec at *V*=15
	200 μarcsec at *V*=20
Photometry:	4 broad band to *V*=20
Radial velocities:	1-10 *km/s* at *V*=16-17
Observing program:	On-board and unbiased

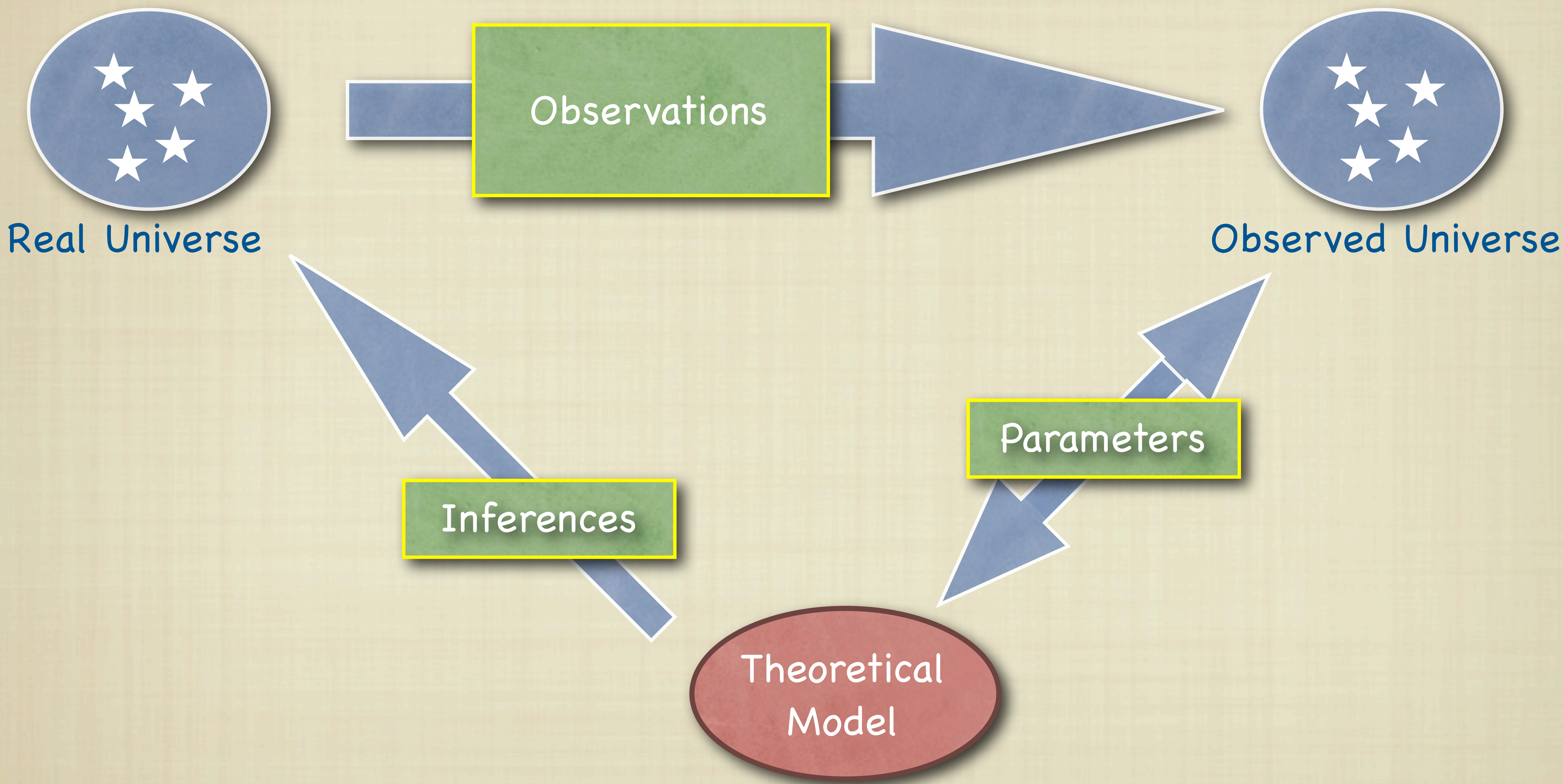




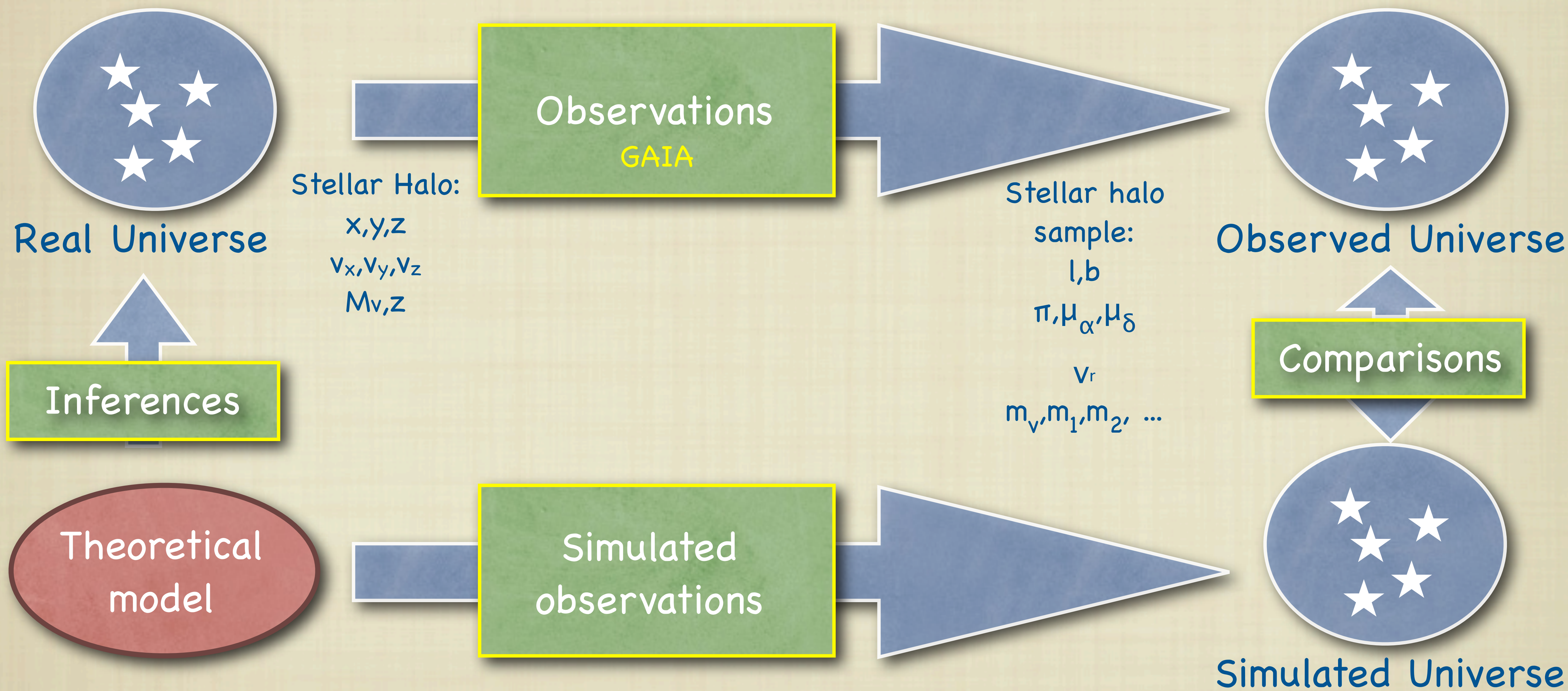


A different way of looking at things

Mock catalogues



Mock catalogues



General layout

Sources

- Galaxy model
- Satellite models
- N-Body models
- Stellar population models

Simulators

- Random realization generator
- Photometry simulator
- Astrometry simulator
- Catalogue simulator

Diagnostics

- Accretion event Identifiers
- Substructure quantifiers

A lot of work
We need to pool efforts

Our example

We developed:

- Mass model of the Galaxy
- Light model of the Galaxy
- Dynamical and stellar pop. satellite models.

- Gaia mock catalogue generator
- Tool to insert N-body simulations within mock catalogue.

Advantages:

- Freedom to test our ideas in a realistic framework
- Have all tools ready before first data release.

Disadvantages:

- Lots of preparatory work
- Models not as sophisticated as some already available.

UNIVERSITAT DE BARCELONA

Mon. Not. R. Astron. Soc. **359,** 1287–1305 (2005) doi:10.1111/j.1365-2966.2005.09013.x

Detection of satellite remnants in the Galactic Halo with *Gaia* – I. The effect of the Galactic background, observational errors and sampling

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[2]*Instituto de Astronomía, UNAM, Apartado Postal 877, Ensenada, 22800, Baja California, Mexico*

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY
Mon. Not. R. Astron. Soc. **415,** 214–224 (2011) doi:10.1111/j.1365-2966.2011.18690.x

Detection of satellite remnants in the Galactic Halo with *Gaia* – II. A modified great circle cell method

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[1]*Centro de Investigaciones de Astronomía, AP 264, Mérida 5101-A, Venezuela*
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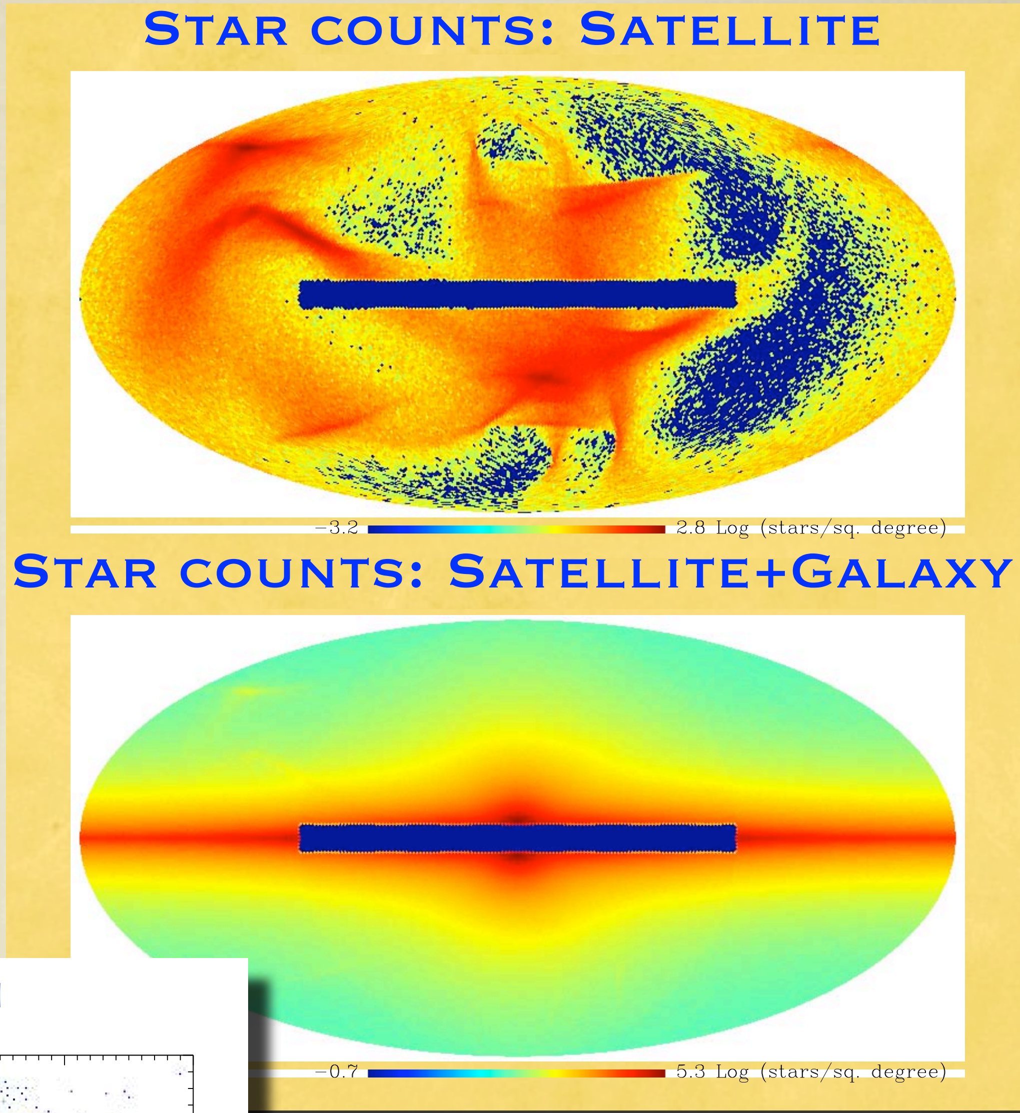
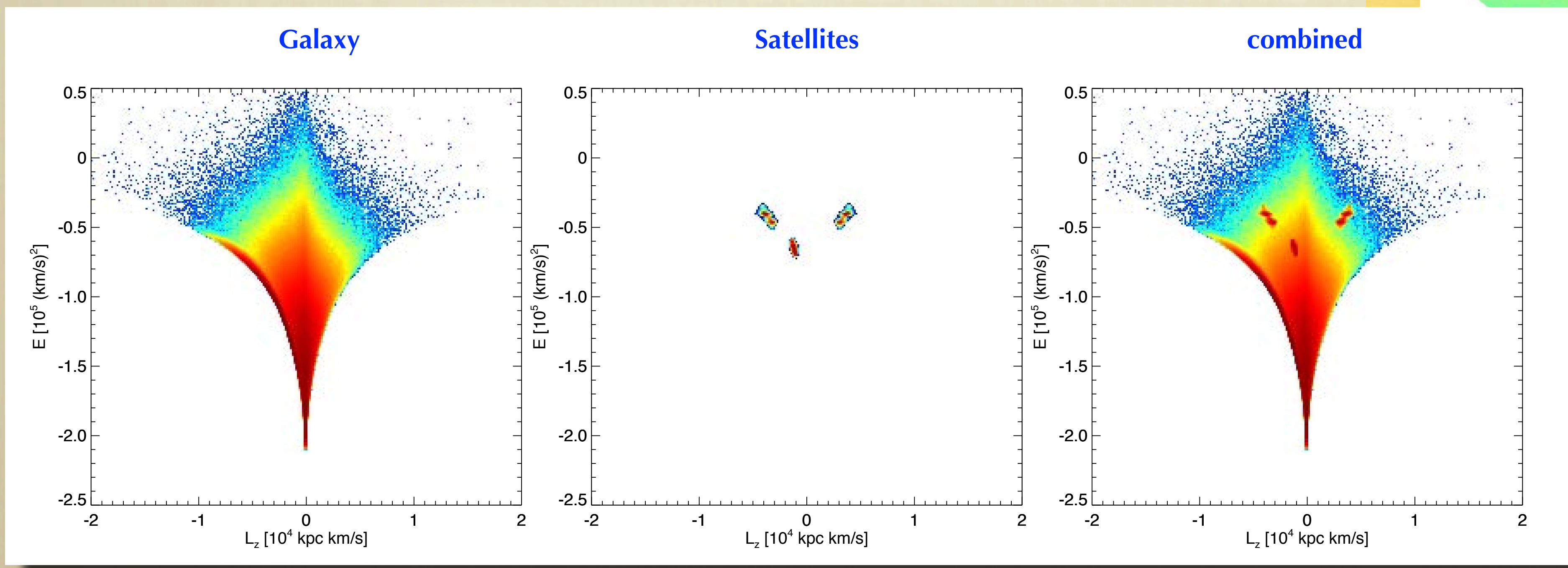
... More in the pipeline

Some lessons learned

Realistic background

Adding a realistic background, with the proper star counts is very important





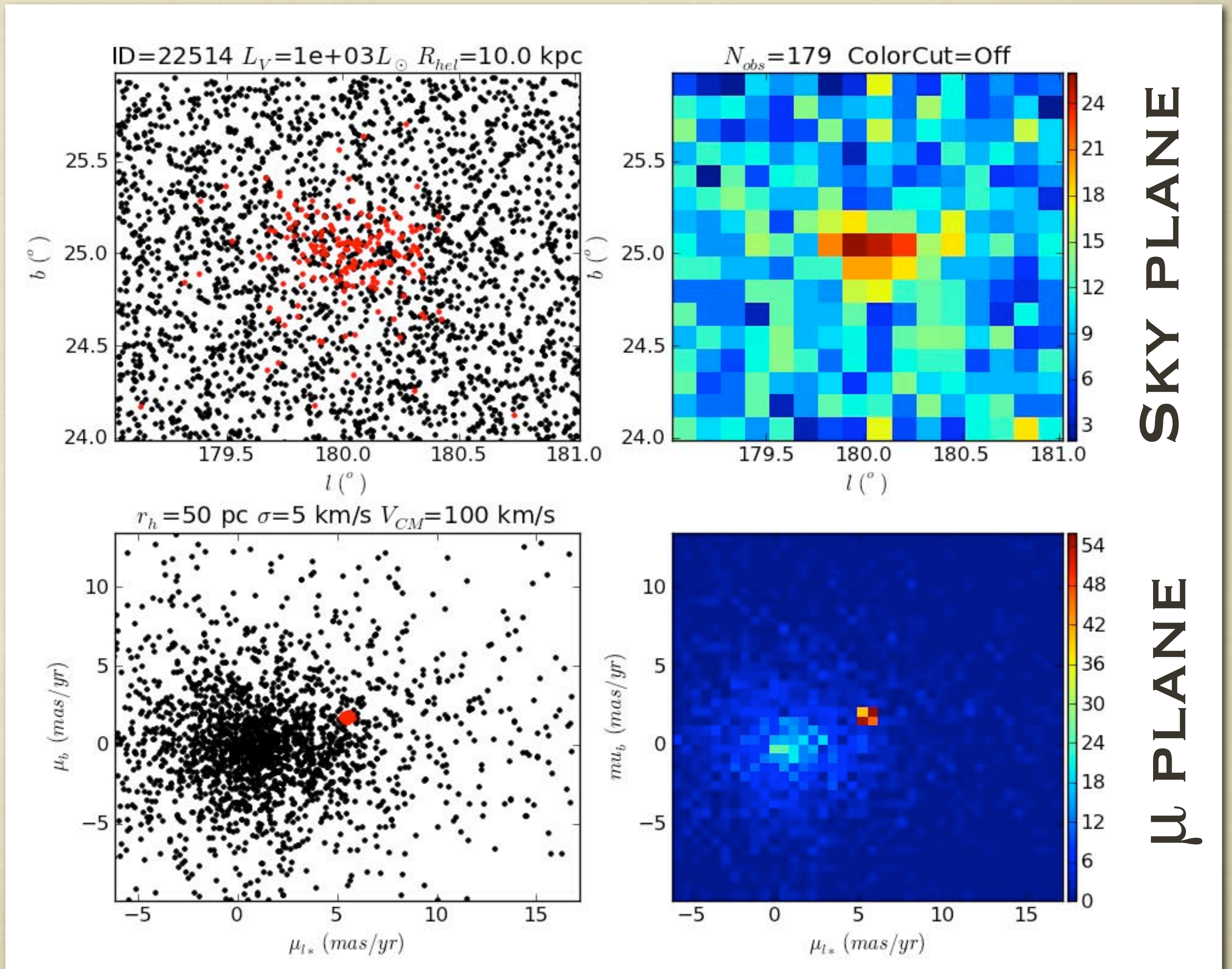
Realistic background

UFGX simulation:

$L_V = 10^3\ L_\odot$
$r_h = 50\ pc$
$\sigma = 5\ km/s$

$d = 10\ kpc$
$v_{cm} = 100\ km/s$

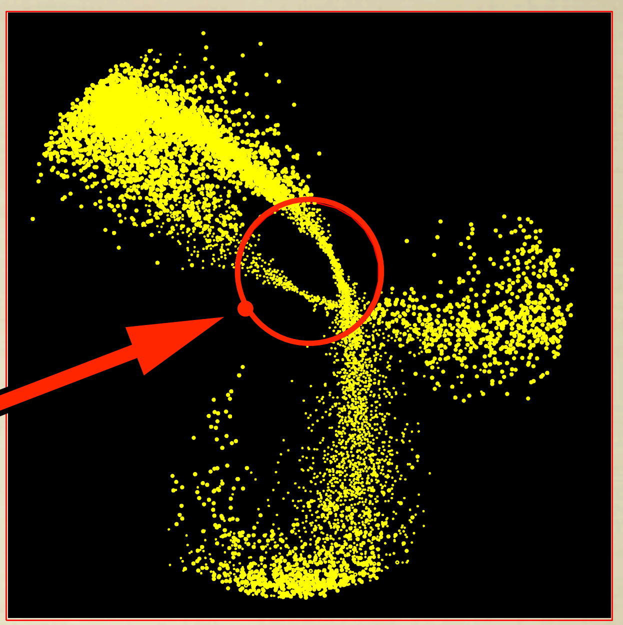
$l = 180°$
$b = 25°$



Insertion in mock catalogue

A proper way to incorporate an N-body simulation in a mock catalogue is fundamental

Sun

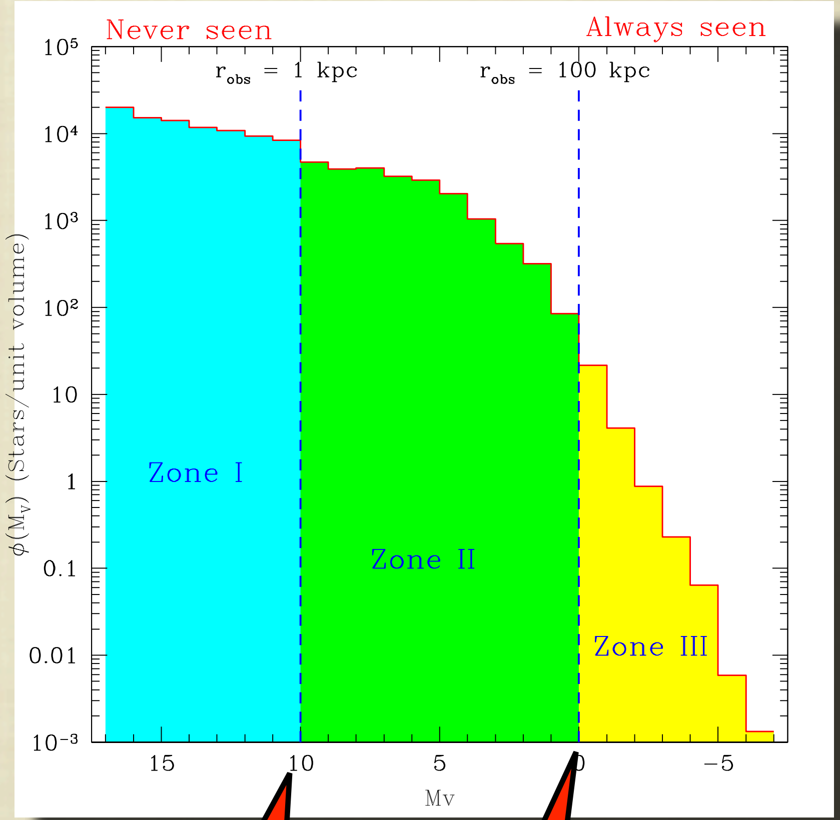


Simulation #1

Variation in depth of probing of streamer

A dissolving satellite is spread along a streamer with varying distance to the observer.

And this results in stars that are always seen,
others that are seen sometimes
and other that are never seen



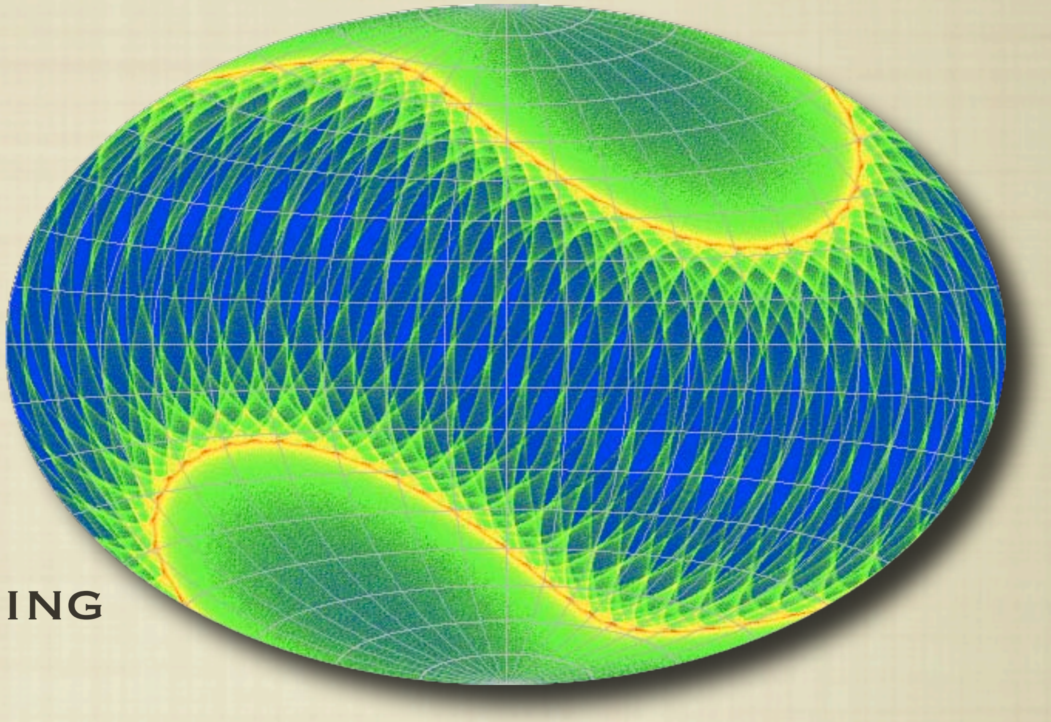
Brighter

Faintest star seen at closest distance

Faintest star seen at largest distance

Adding realistic errors

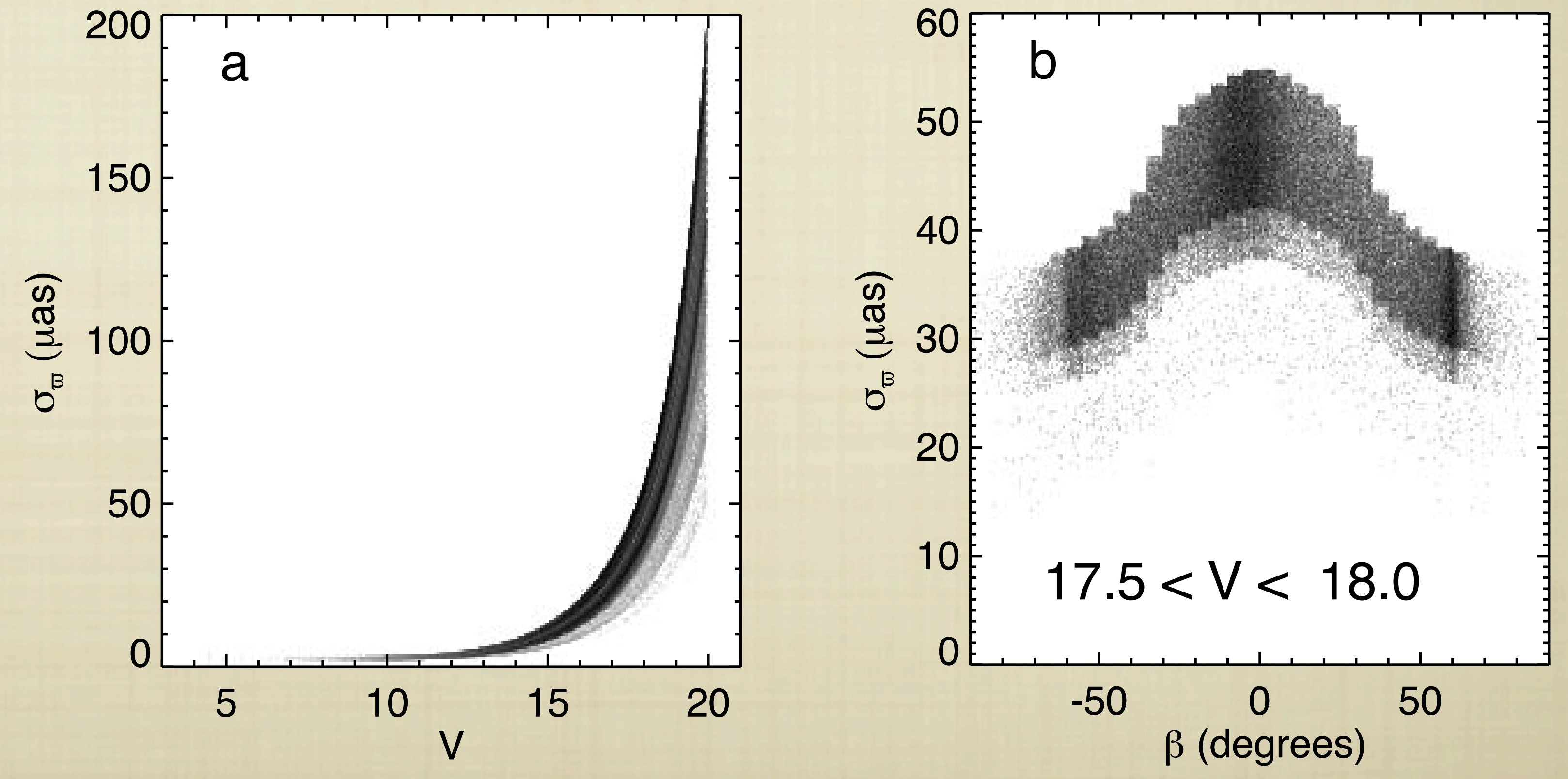
Errors depend not only on apparent brightness, but also on position in the sky, color, etc.



Gaia scanning

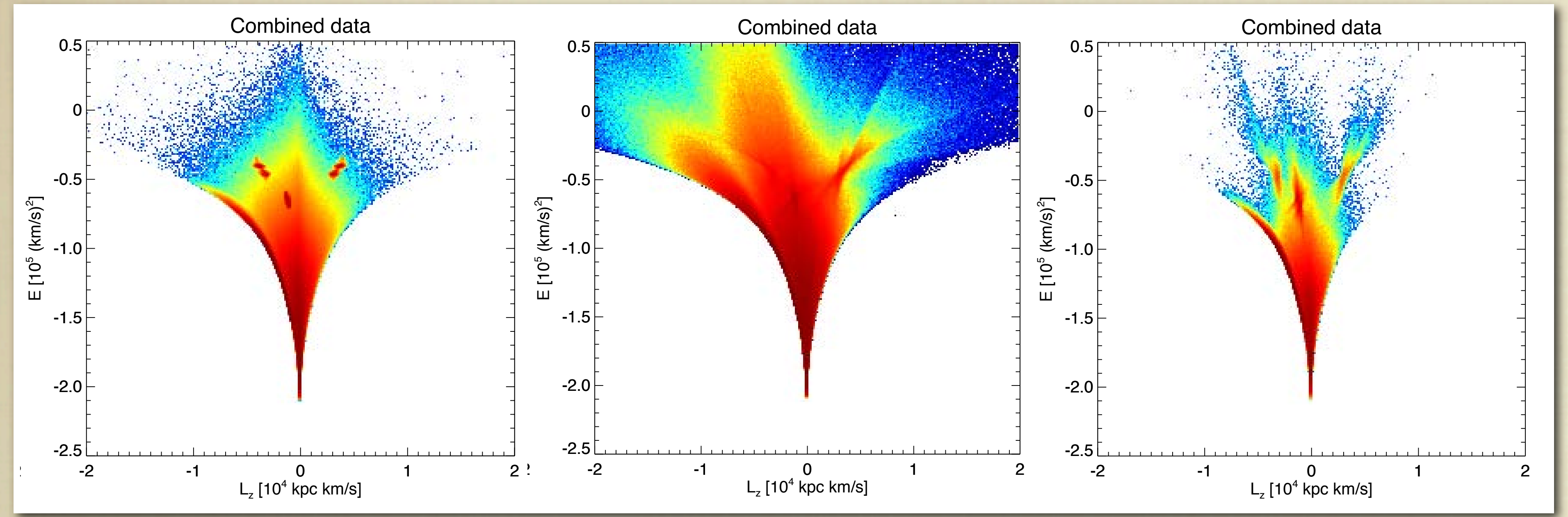
Radial velocity errors

OBA		FGKM	
V	$\sigma(v_r)$	V	$\sigma(v_r)$
10	0.25	10	0.1
15	4	16	1
16	10	17	2
17	50	18	6



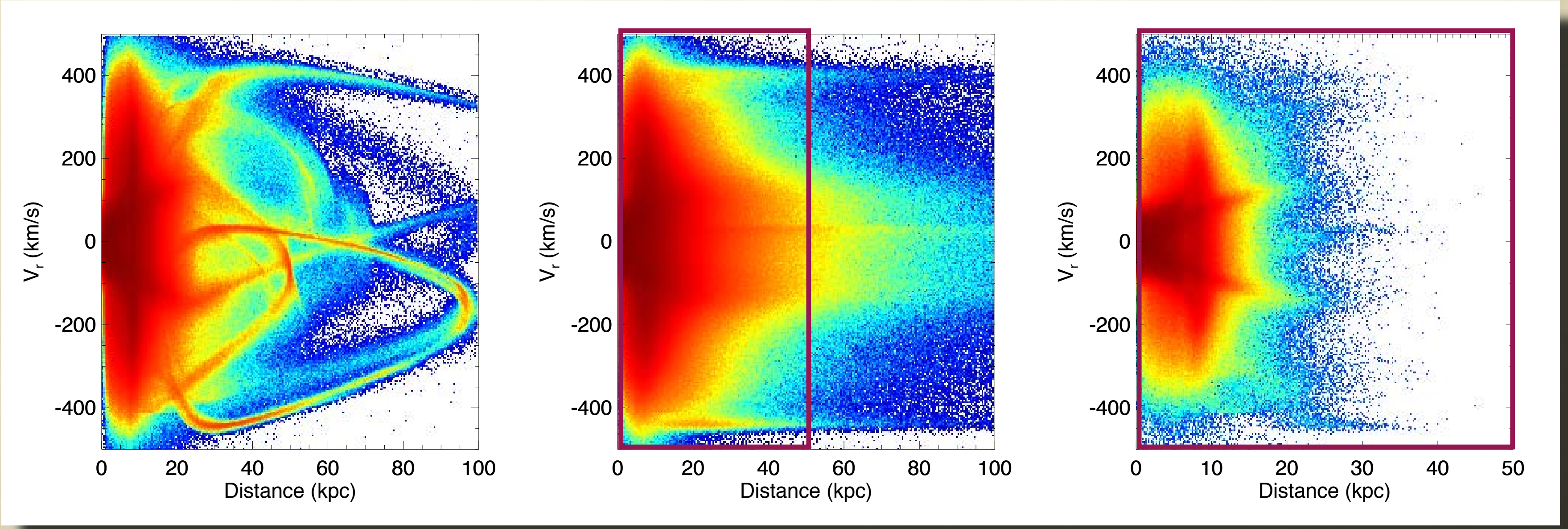
Adding realistic errors

The E vs L_z diagram



Error free — With errors — Good astrometry

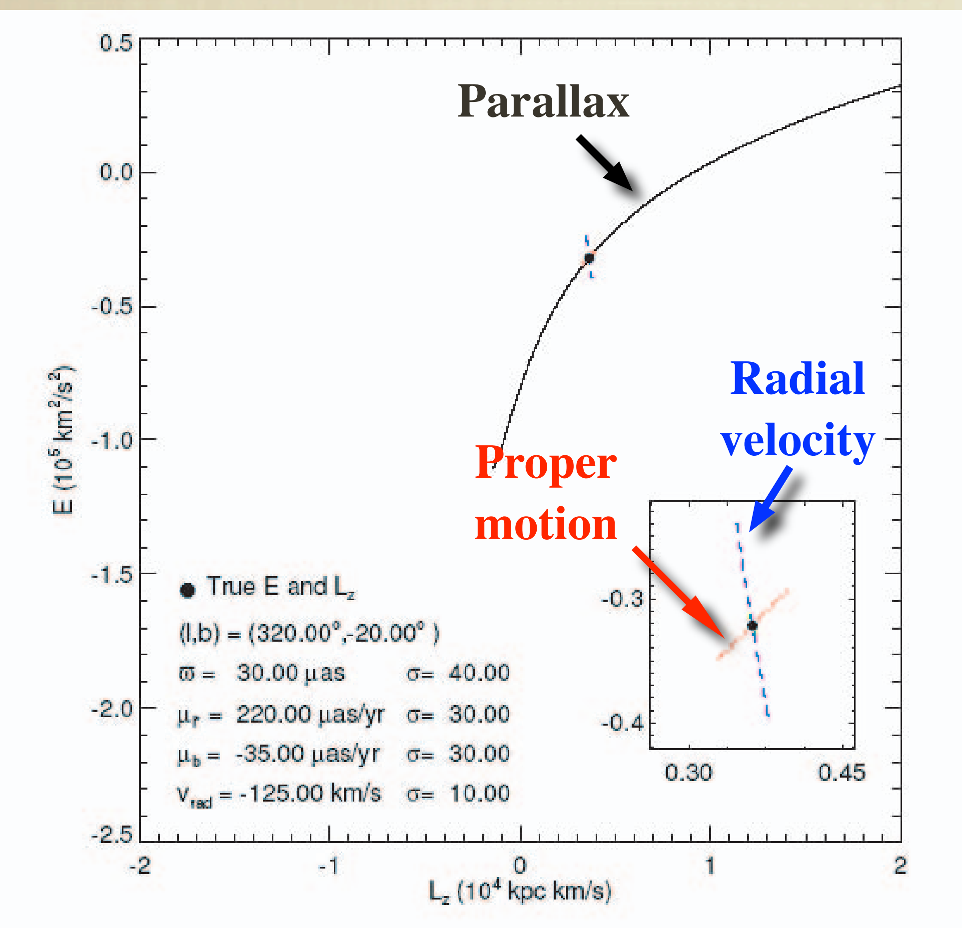
The d vs v_r diagram

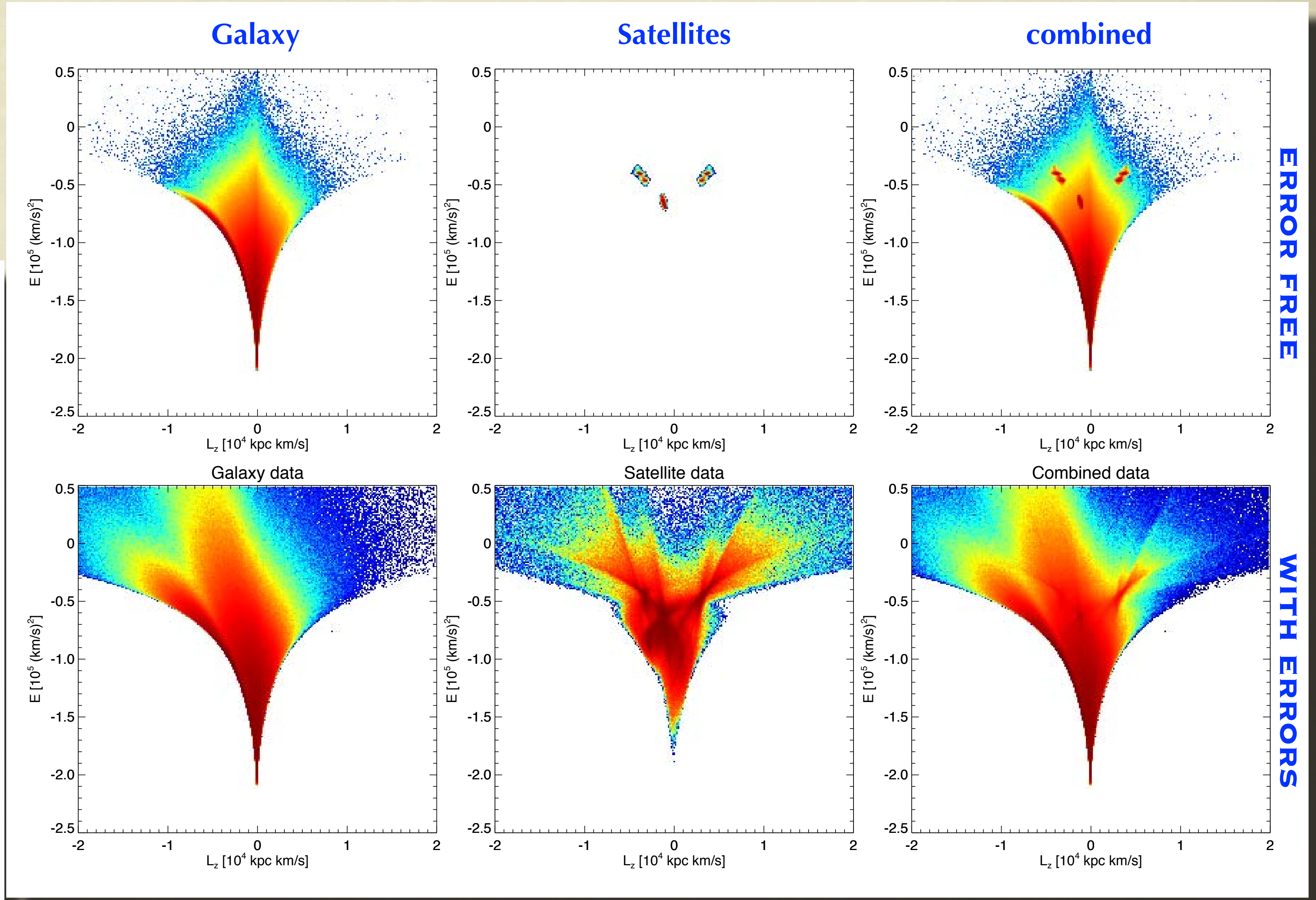


Error free — With errors — Good astrometry

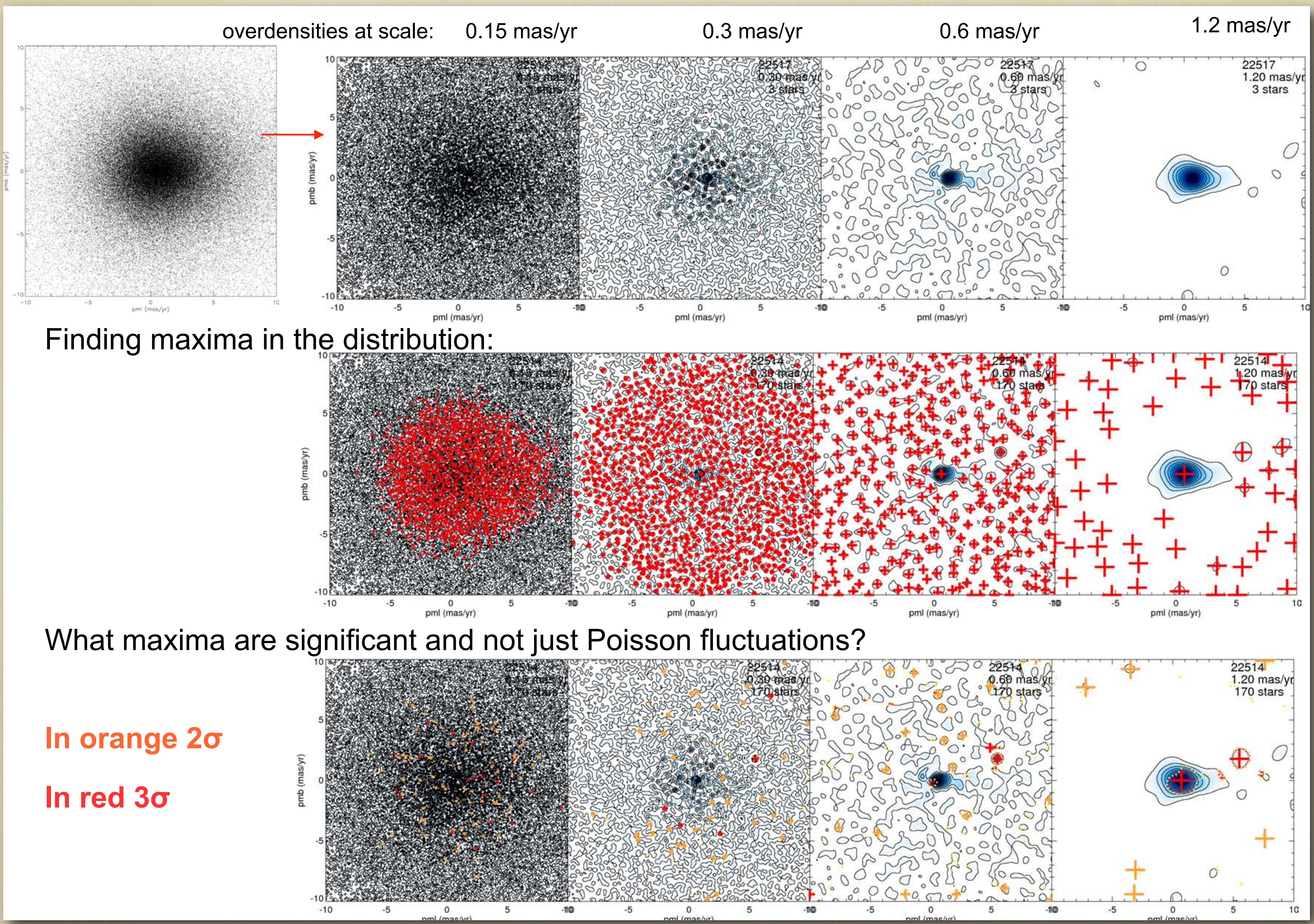
Understand the source of errors

Figuring out the contribution of each error source and the way they map onto your final diagnostics space is crucial

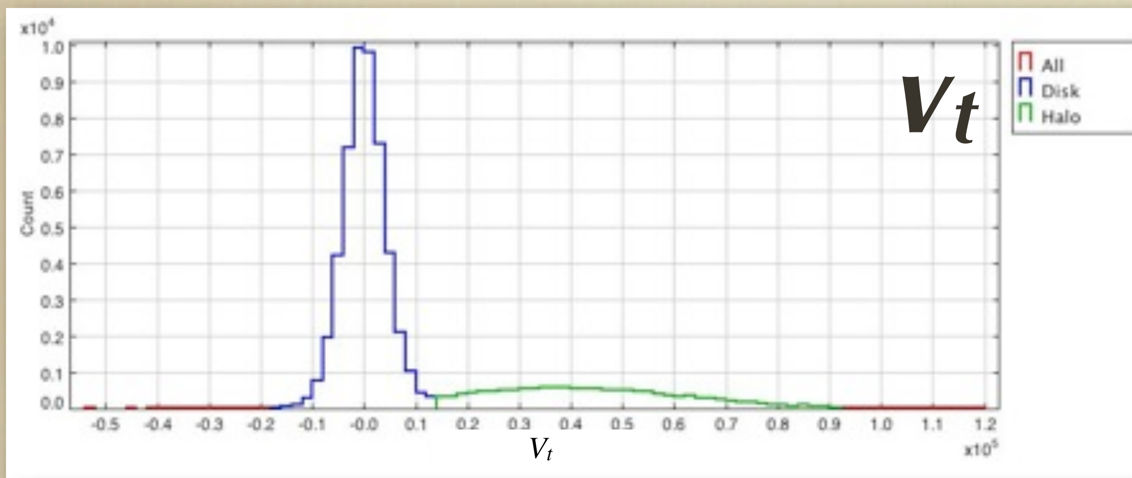


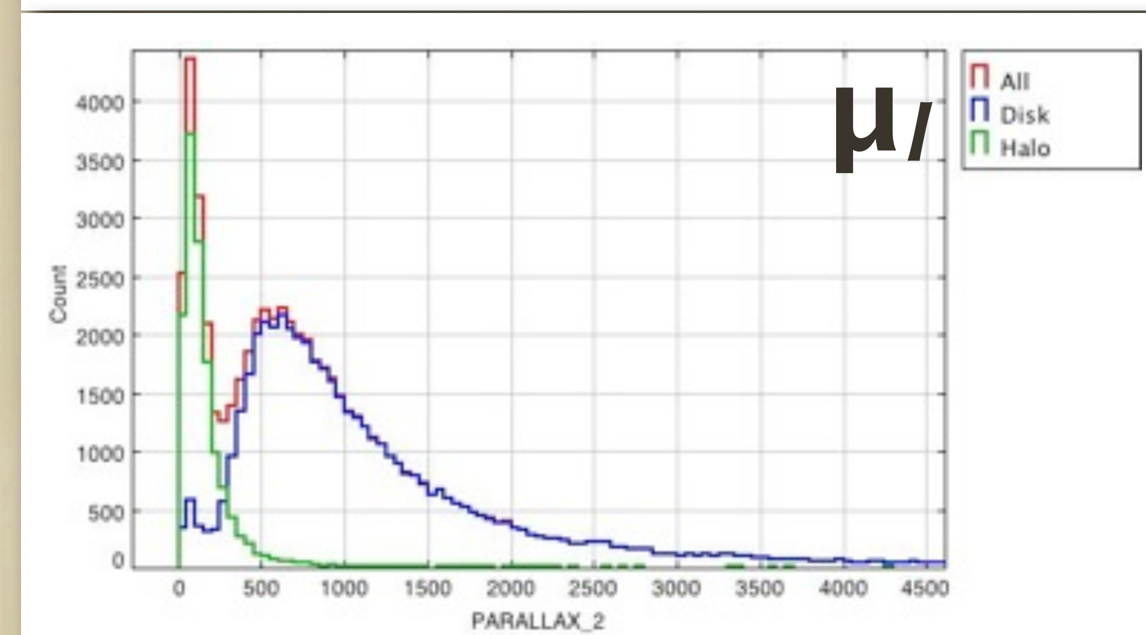


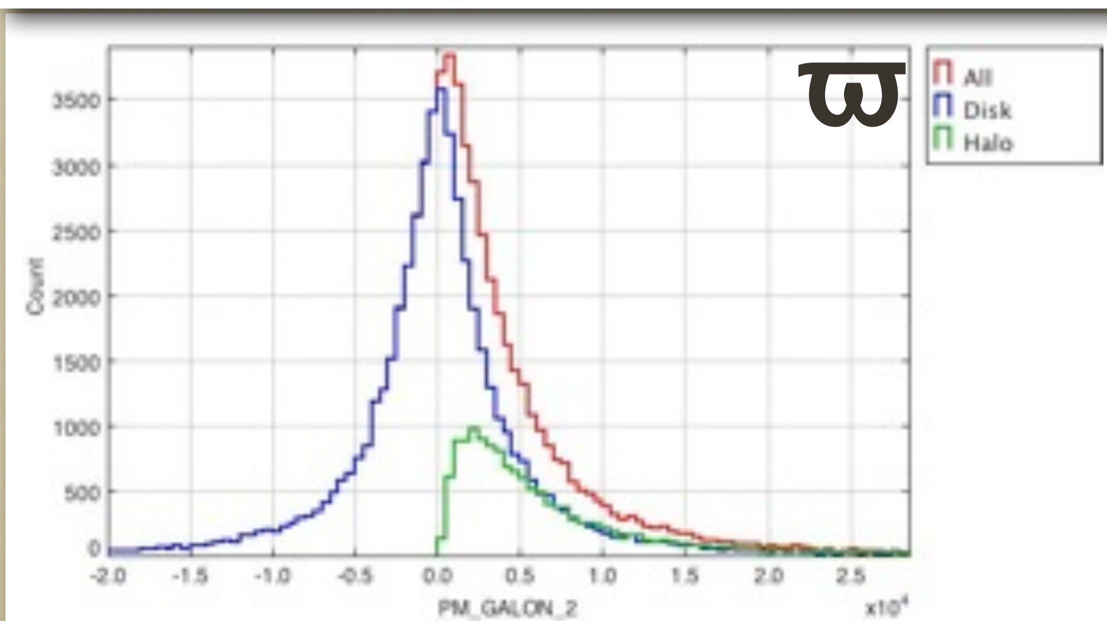
Tool to conduct experiments

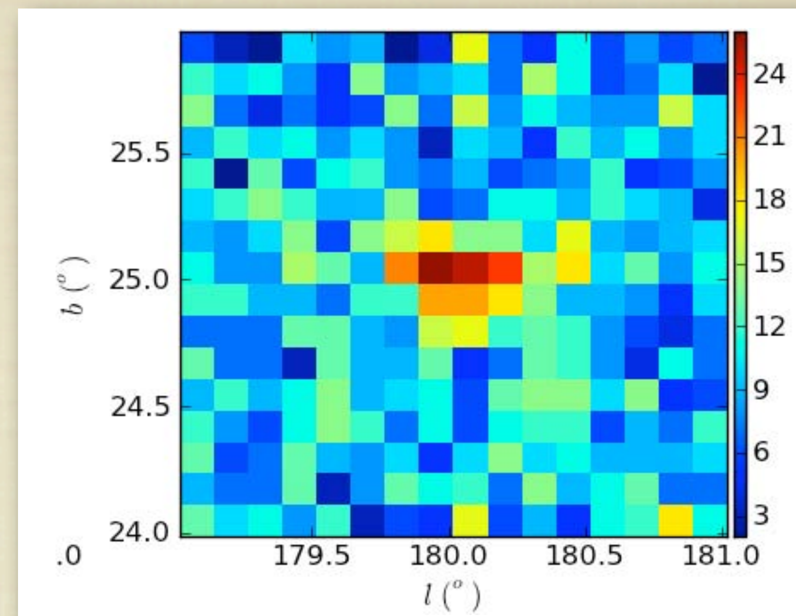


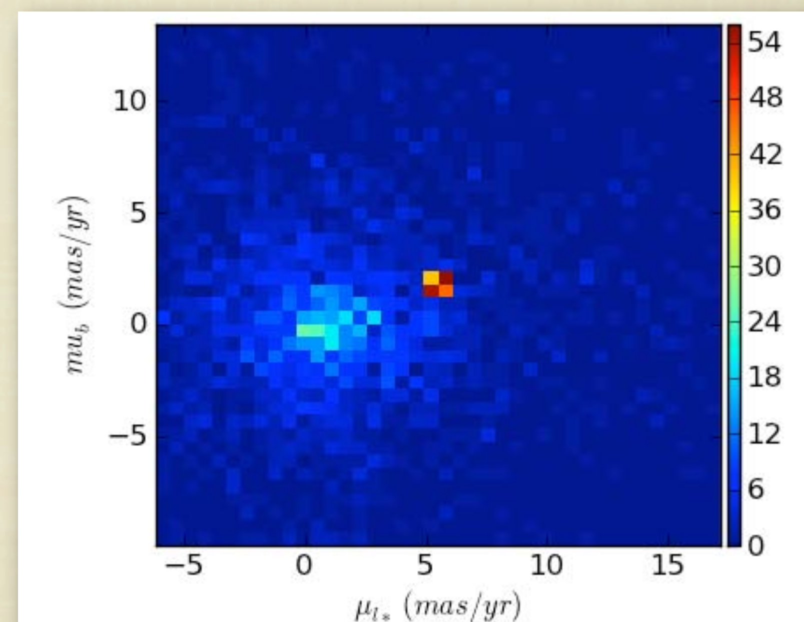
Tool to conduct experiments











WORK IN OBSERVABLE SPACE

UFGX simulation:

Model: Plummer

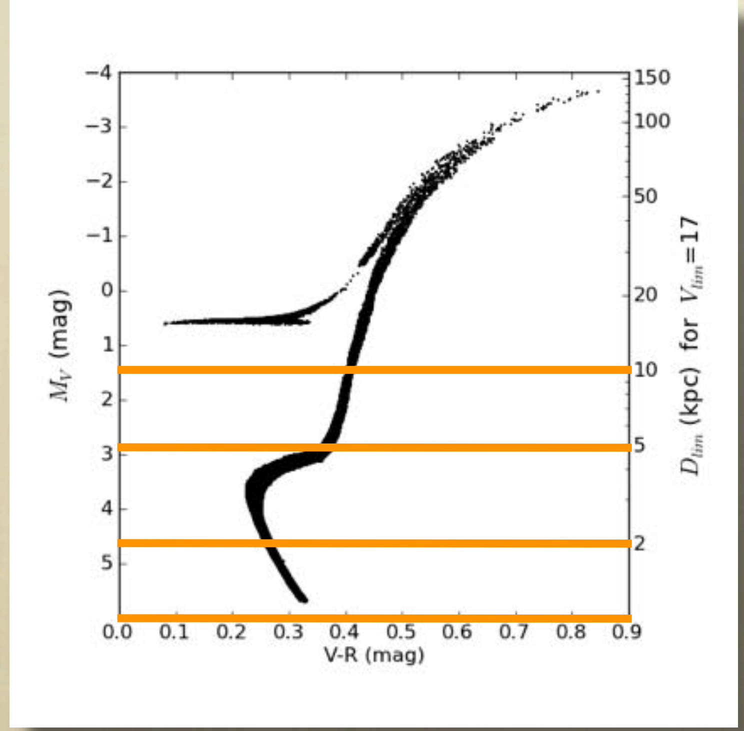
R_H = 20 pc, σ=3km/s

$L_V = 3.5\times10^3 L_\odot$

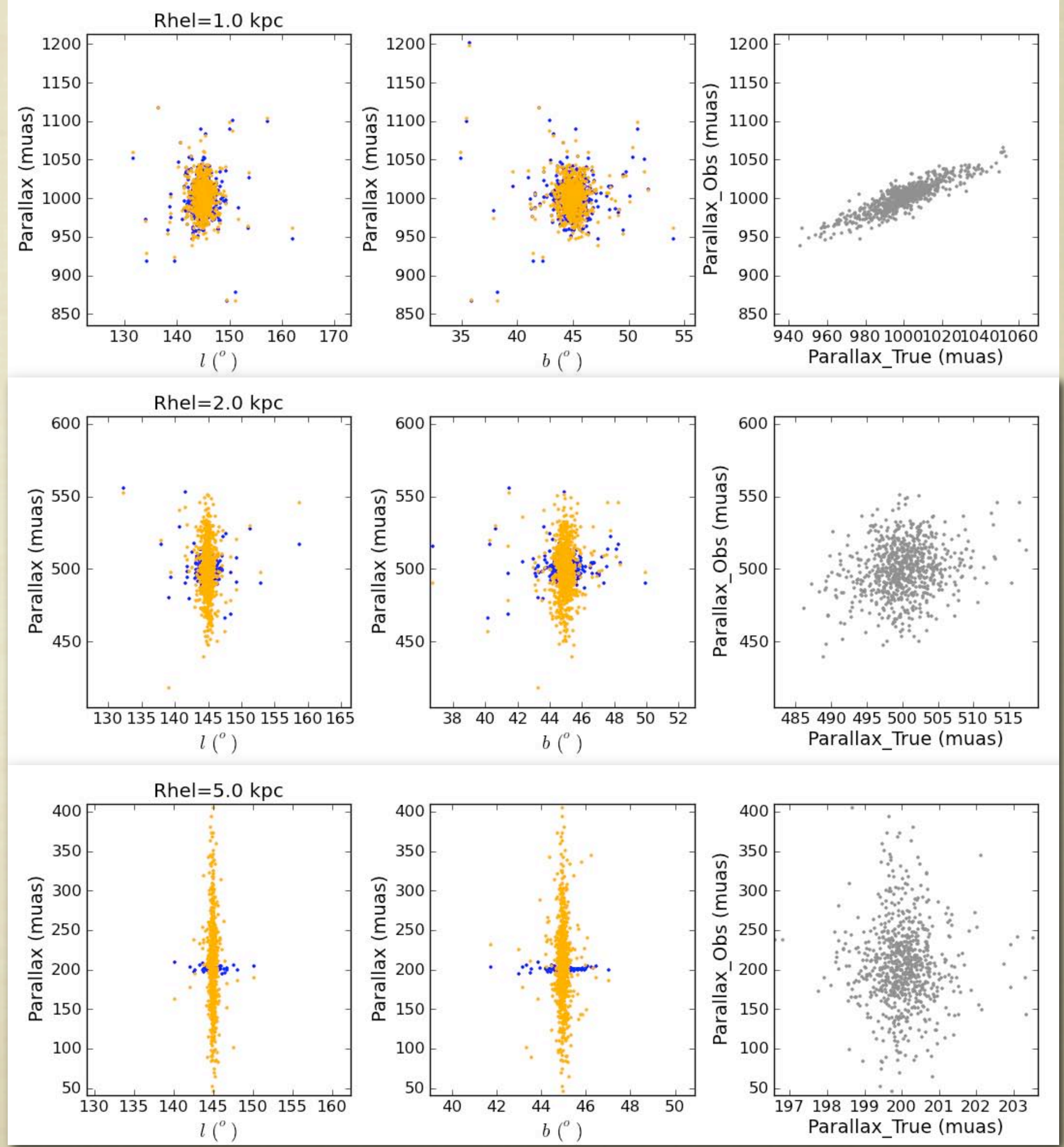
743 stars down to M_V=+5, which is the faint limit of the photometry random realization.

Position: l=145°, b=45°

Distances to observer:
1, 2, 5, 10 & 15 kpc.



Parallax vs. Position in the Sky



WORK IN OBSERVABLE SPACE

Parallax vs. distance

UFGX simulation:

Model: Plummer

R_H = 20 pc, σ=3km/s

$L_V = 3.5\times10^3\ L_\odot$

743 stars down to M_V=+5,
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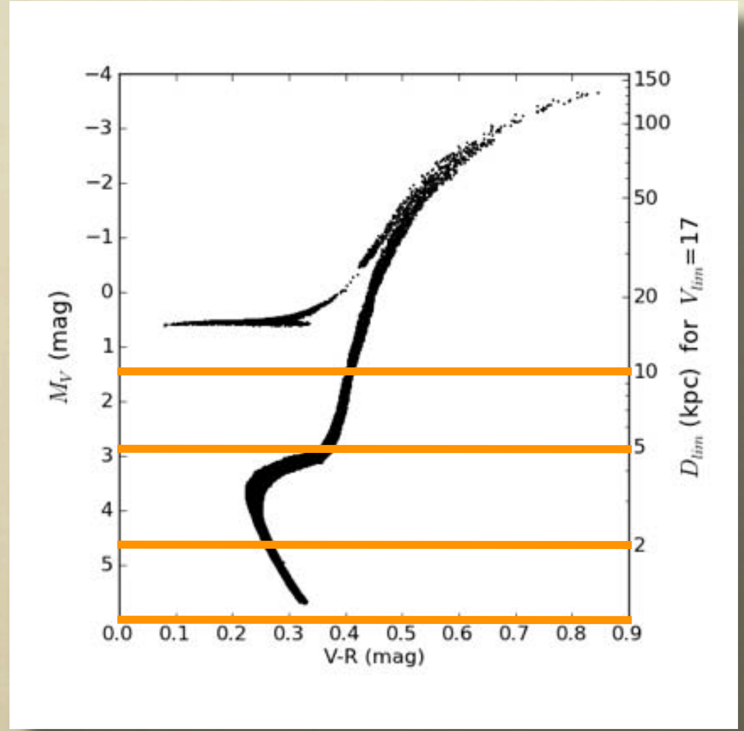
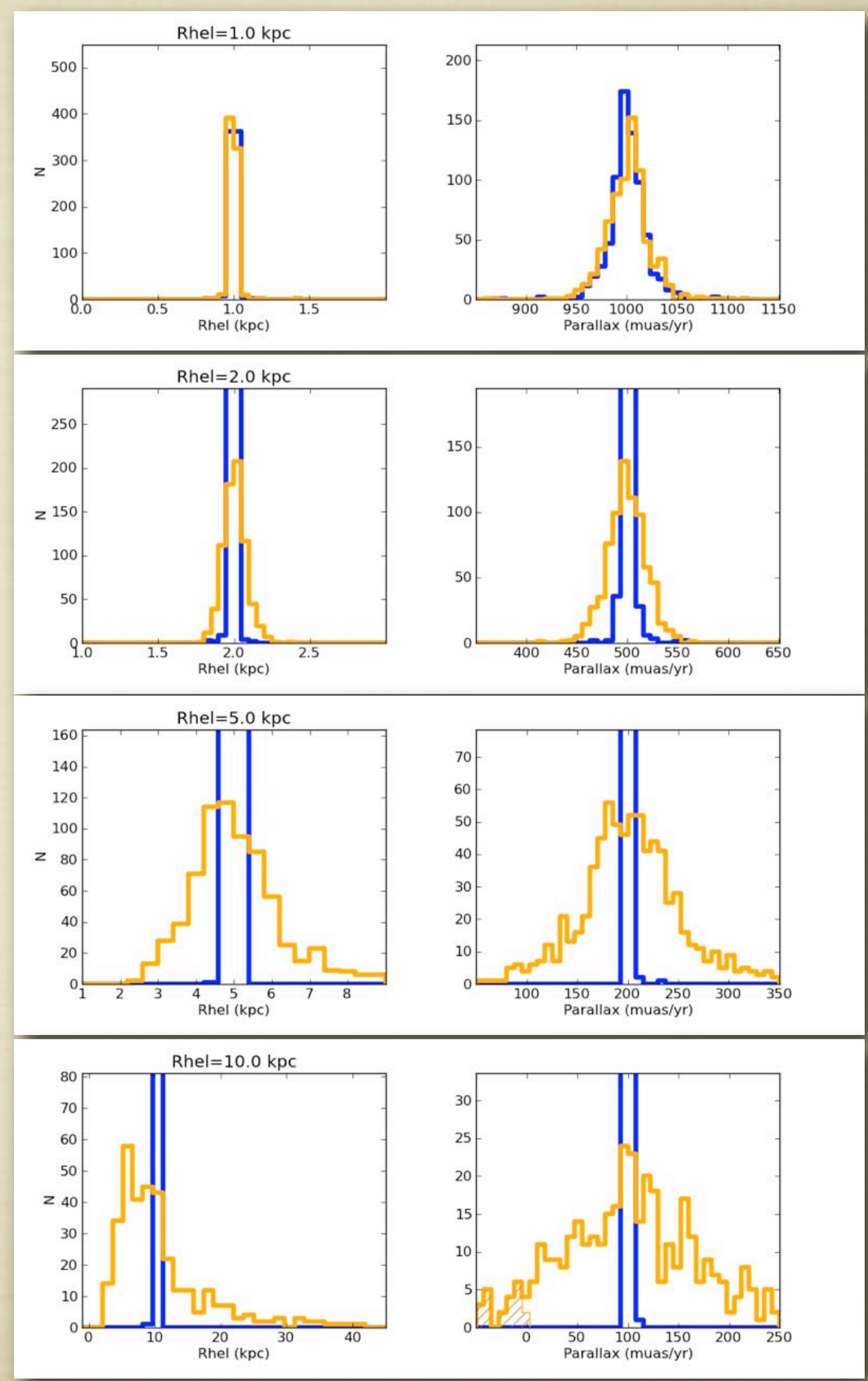
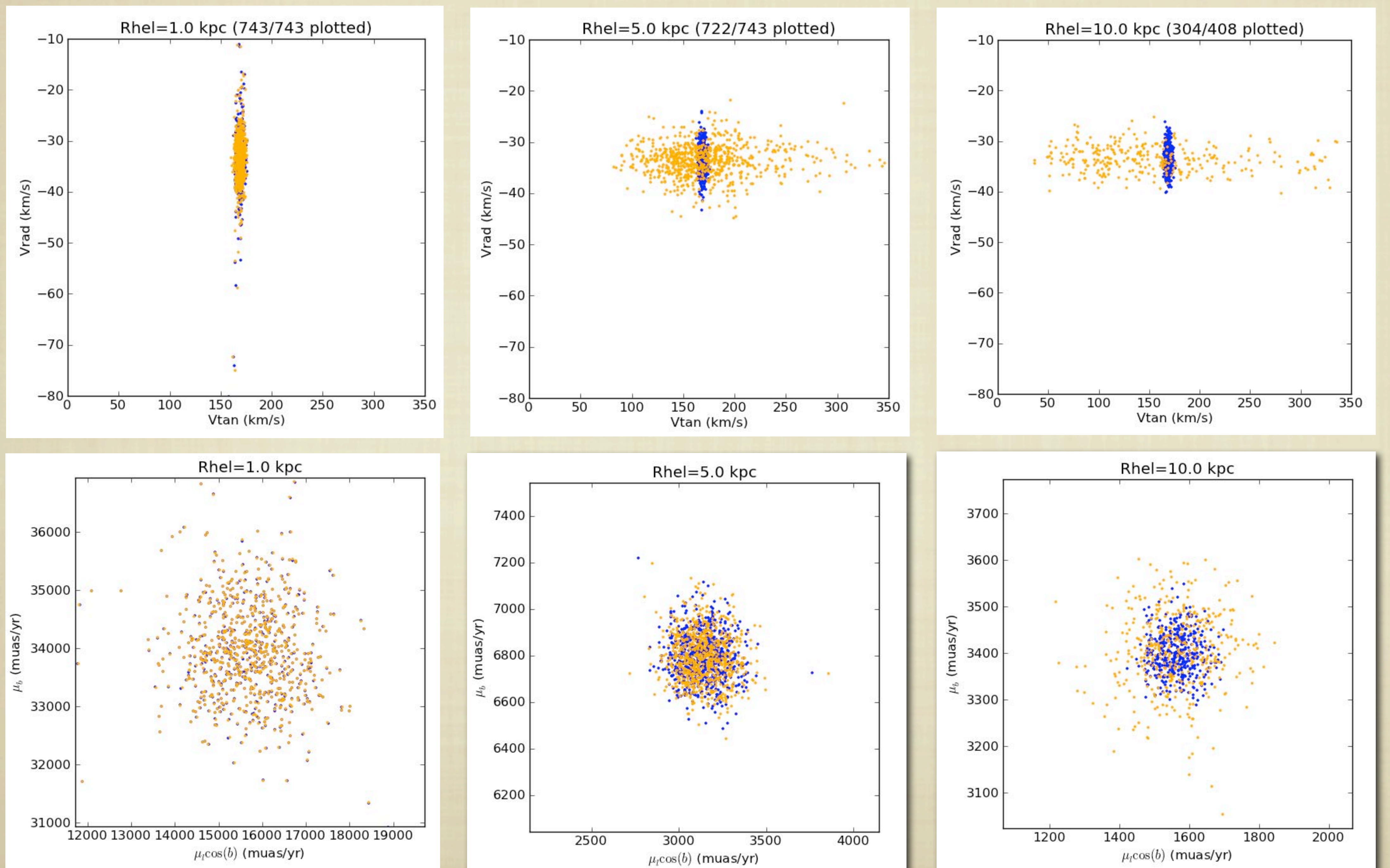




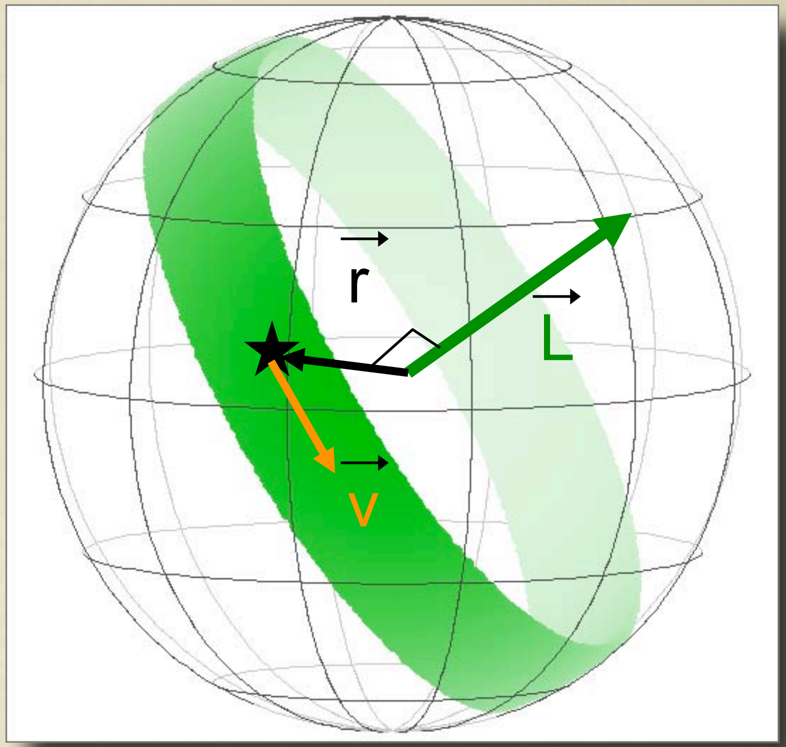
WORK IN OBSERVABLE SPACE

Tangential velocities vs proper motions



Devise methods that work best in observable space

MGC3: Modified Great Circle Cell Counts Method
Mateu, et al., 2011, MNRAS, 415, 214.



We add the extra requirement that the velocity vector lies within the great circle band.

$$|\hat{L} \cdot \hat{\mathbf{r}}_\star| \leq \delta_r \qquad |\hat{\mathbf{L}} \cdot \hat{\mathbf{v}}_\star| \leq \delta_v$$

$$\mathbf{r}_{gal} = \mathbf{r}_\odot + A_p \varpi^{-1} \left[(\cos l \, \cos b)\hat{\mathbf{x}} + (\sin l \, \cos b)\hat{\mathbf{y}} + (\sin b)\hat{\mathbf{z}}\right]$$

$$\mathbf{v}_{gal} = \mathbf{v}_\odot + v_r \hat{\mathbf{r}} + A_v \varpi^{-1} \left[(\mu_l \cos b)\hat{\mathbf{l}} + \mu_b \hat{\mathbf{b}}\right]$$

$$\mathbf{r}'_{gal} = \varpi \mathbf{r}_{gal} = \varpi \mathbf{r}_\odot + A_p \left[(\cos l \, \cos b)\hat{\mathbf{x}} + (\sin l \, \cos b)\hat{\mathbf{y}} + (\sin b)\hat{\mathbf{z}}\right]$$

$$\mathbf{v}'_{gal} = \varpi \mathbf{v}_{gal} = \varpi \mathbf{v}_\odot + \varpi v_r \hat{\mathbf{r}} + A_v \left[(\mu_l \cos b)\hat{\mathbf{l}} + \mu_b \hat{\mathbf{b}}\right]$$

Now the reciprocal of the parallax is gone!

Theoretical vs observable space

Theoretical space	Observable space
- Models simply defined	- Models difficult to work with
- Errors and survey limits difficult to work with	- Errors and survey limits easier to model
- Models have infinite "signal to noise" ratio	- Observations have finite "signal to noise" ratio

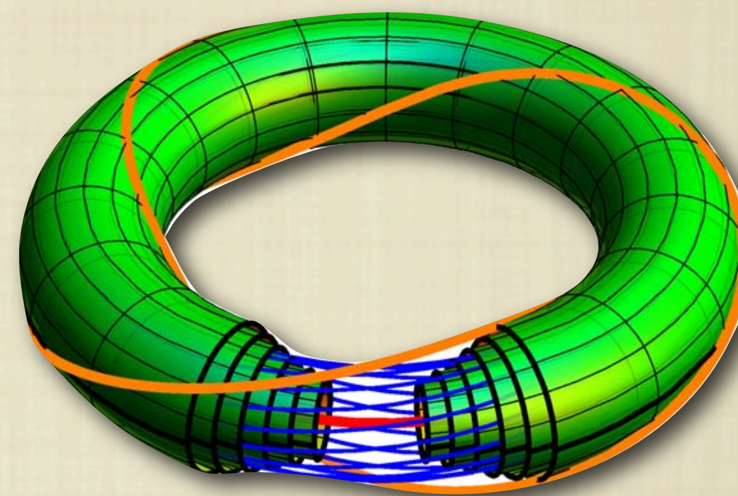
In the end, it is better to manipulate models rather than data

New tools for a new era

Theory:

e.g. Torus model of the Galaxy (Binney)

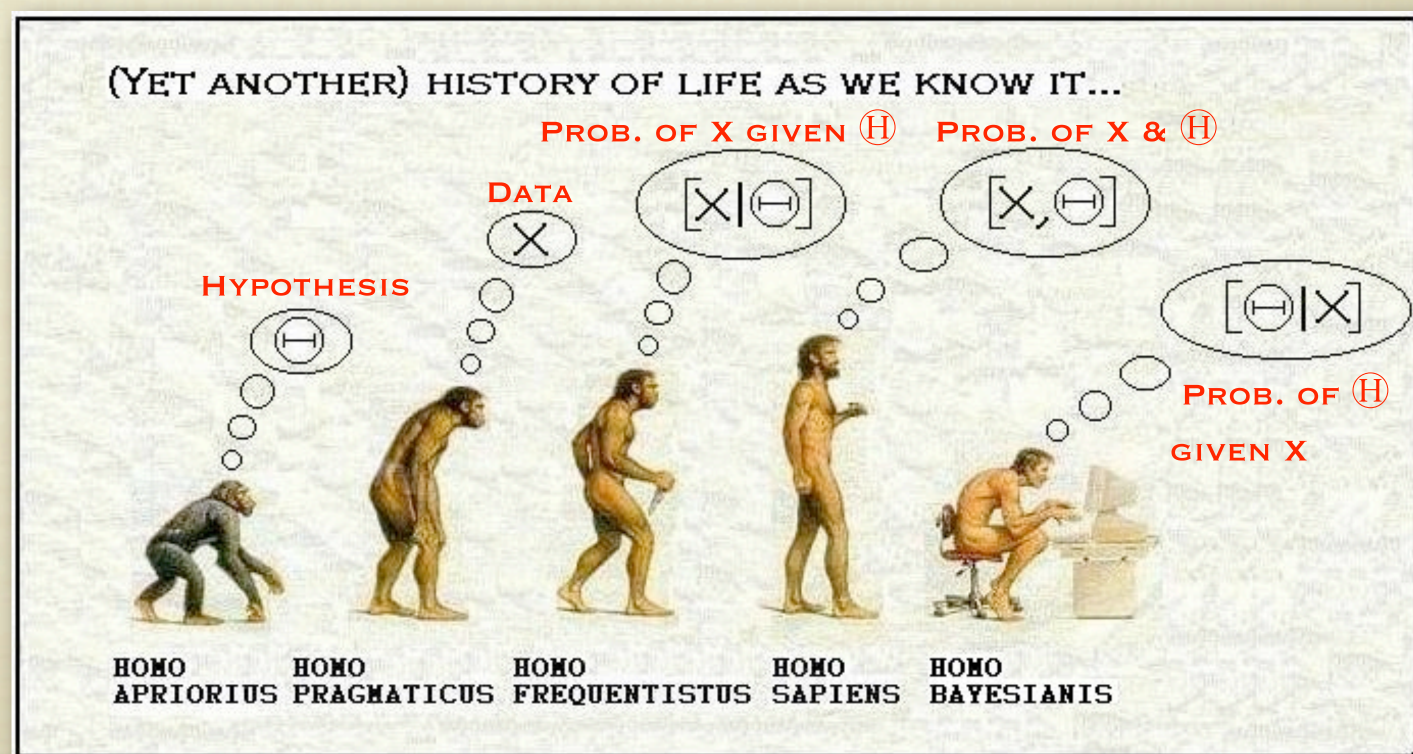
$$\mathcal{H}_o \xrightarrow{\mathcal{S}(\theta, J')} \mathcal{H}$$



Data analysis:

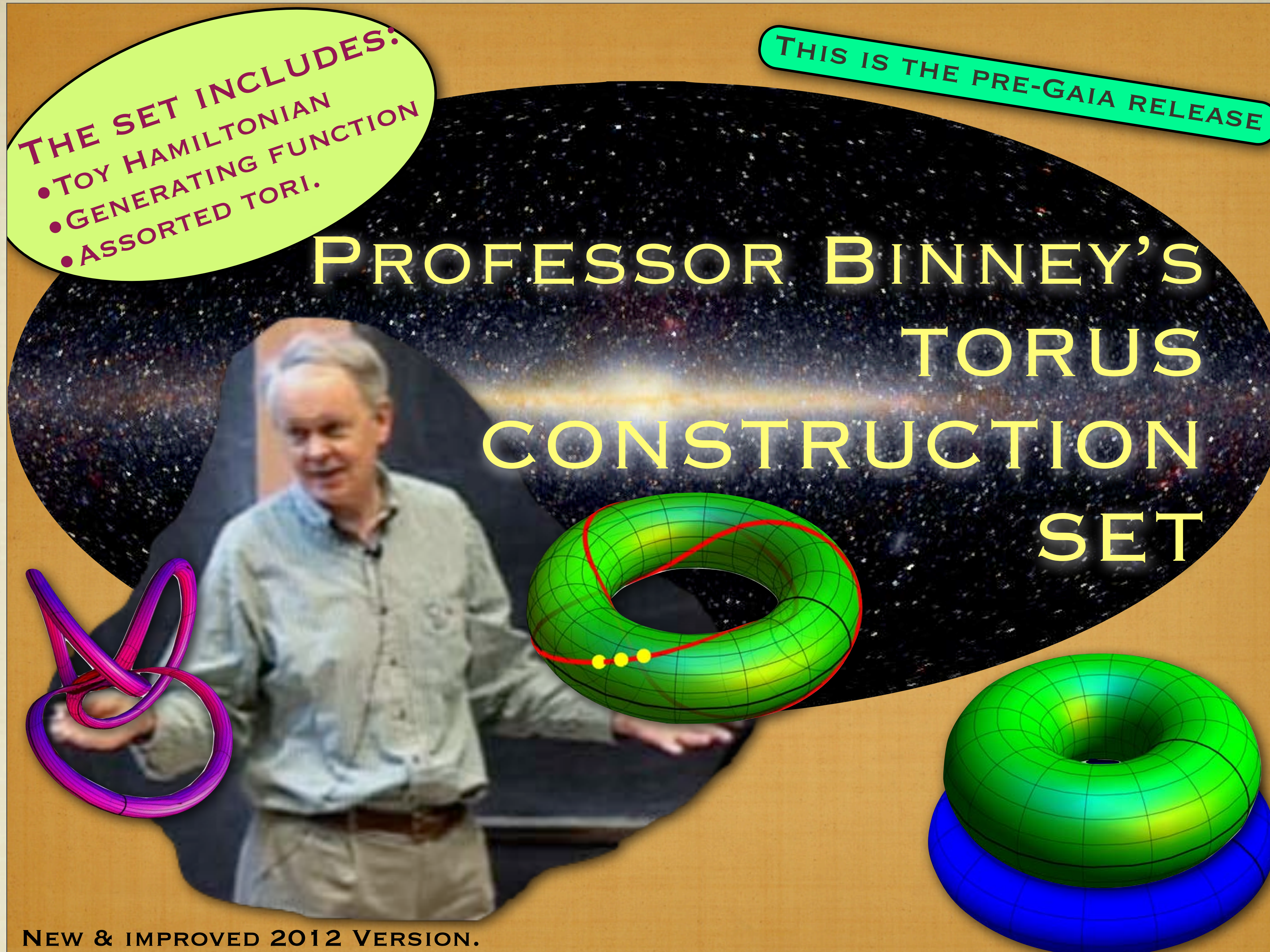
e.g. Bayesian inference

$$p(P|E) = \frac{p(E|P)}{p(E)}\, p(P)$$

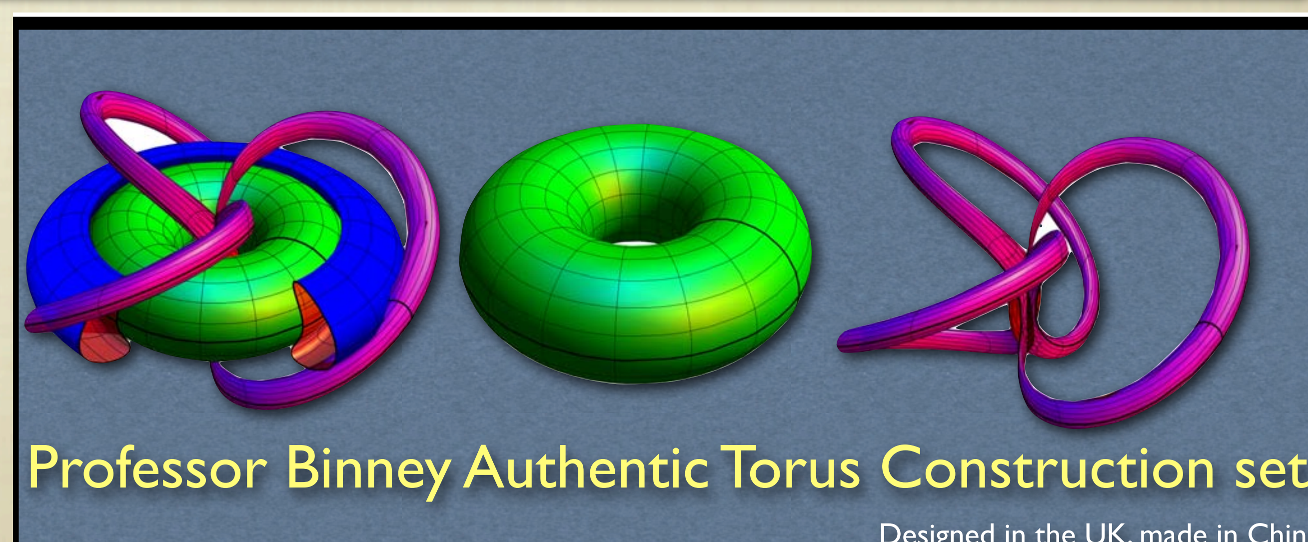


M. West (Duke Univ.)


THE SET INCLUDES:
•TOY HAMILTONIAN
•GENERATING FUNCTION
•ASSORTED TORI.
THIS IS THE PRE-GAIA RELEASE
PROFESSOR BINNEY'S
TORUS
CONSTRUCTION
SET
NEW & IMPROVED 2012 VERSION.
Professor Binney Authentic Torus Construction set
S
H


The set includes:
•Toy Hamiltonian
•Generating function
•Assorted tori.
This is the pre-Gaia release
Professor Binney's
torus
construction
set
New & improved 2012 Version.


Professor Binney Authentic
Torus Construction set
It contains:
• Toy torus
• Generating function
• Assorted tori
• Illustrated cards
Designed in the UK, made in China


Professor Binney Authentic Torus Construction set
Designed in the UK, made in China

Wish List

- Gaia mock catalogue without errors
- Gaia mock catalogue with errors
- Tool to extract user-defined subsample
- Tool to add Gaia errors to own data
- Ability to modify base galactic model

GUMS: Gaia Universe Model Snaphot
GOG: Gaia Object generator
$\sim 10^9$ stars
(~600 GB each file)

Our mock Gaia catalogue
All stars except: $|b|<10°$ & $-90° < l < +90°$
3.4×10^8 stars
(~50 GB)

Time is running down ...