Chasing Ghosts in the Galactic Halo

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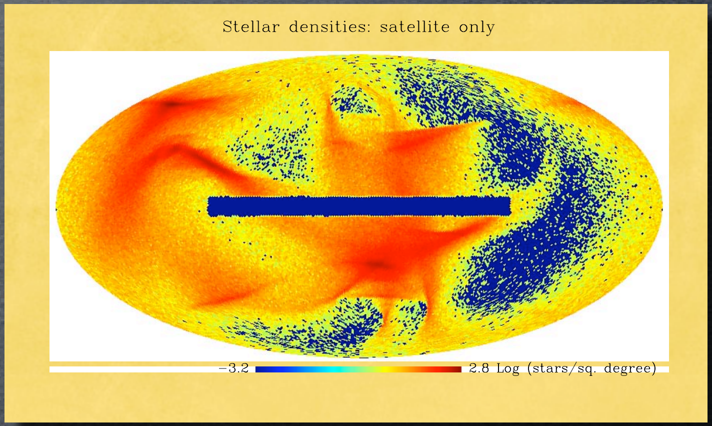
The punch line ...

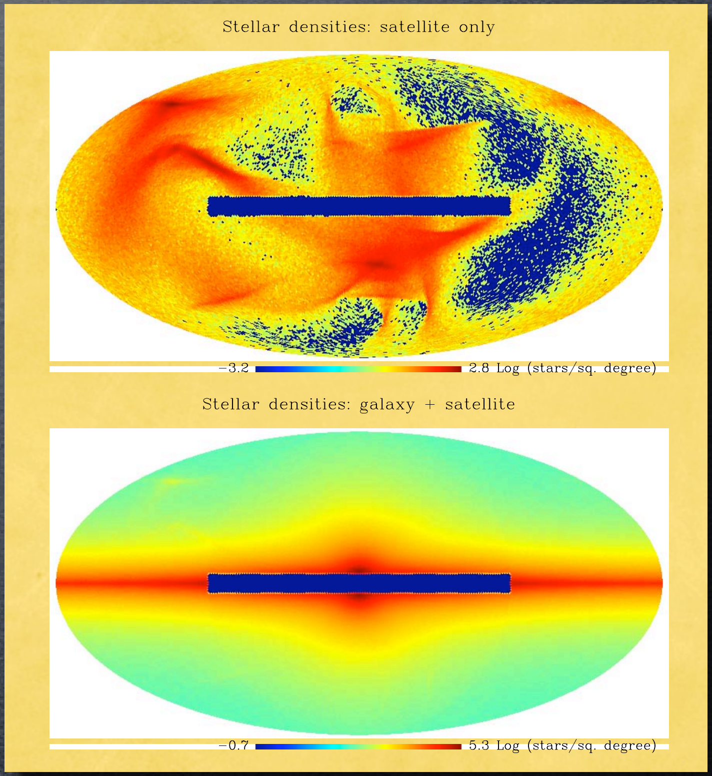
When looking for something,
sometimes what you get,
is not what you thought you
would see.



The punch line ...

When looking for something, sometimes what you get, is not what you thought you would see.

Issues: Observational errors, selection effects, background.



Outline

Why search ?
How to search ?
The promise of Gaia
This work:
Questions of background
Questions of sampling
Questions of accuracy
Expected results
The future

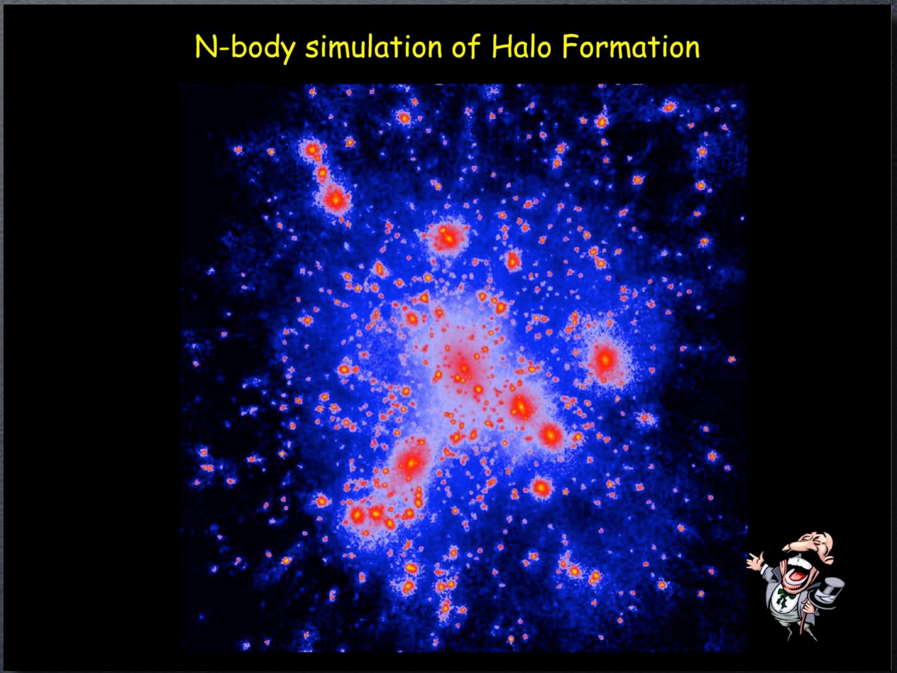
Why search?

Why search?

Current cosmological models envisage the formation of large luminous galaxies as a long process of merging of smaller structures.

This process must have left an imprint on halos of galaxies like ours, where long dynamical time scales preserve remnants of old mergers.

By probing the structure of our galaxy´s halo, we do “in situ” cosmology.



www.iap.fr

But remember Zel’dovich:
“Cosmology, often in error, never in doubt”

Why search?

We actually see evidence of structure in our galactic halo

Why search?

We actually see evidence of structure in our galactic halo

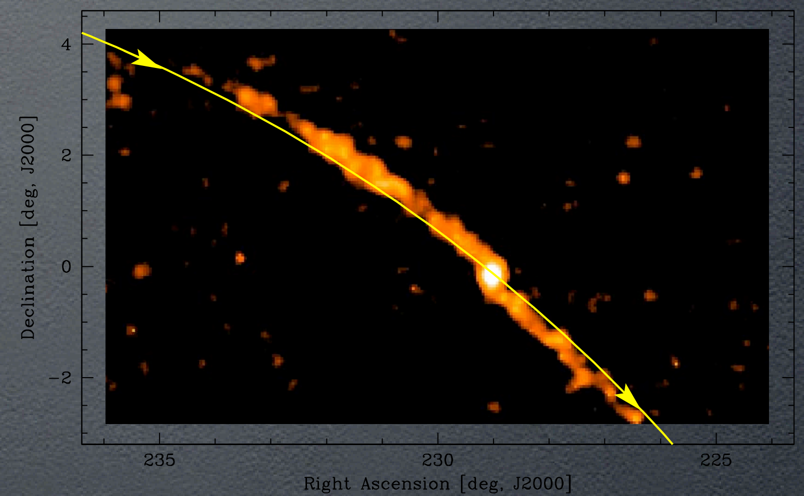
The Sagittarius dwarf spheroidal galaxy (Ibata, Gilmore & Irwin, 1994)

Ibata, Wyse and Sword

Why search?

We actually see evidence of structure in our galactic halo

The tidal disruption of Palomar 5
(Odenkirchen et al., 2002)

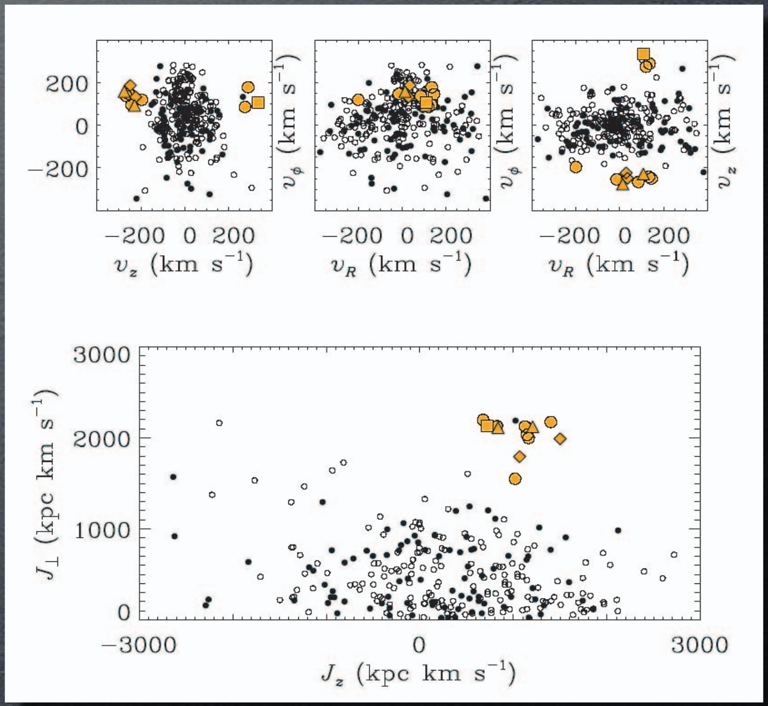


Oderkirchen et al. (MPIA) & SDSS collaboration (2002)

Why search?

We actually see evidence of structure in our galactic halo

Groups in the velocity space of a solar neighborhood halo sample (Helmi et al., 2002)



Helmi et al. *Nat.* 402, 53 (2002)

Why search?

We actually see evidence of structure in our galactic halo

and many more ...

Eggen (1965),
Lynden-Bell (1976),
Rodgers and Paltoglou (1984),
Ratnatunga and Freeman (1985),
Dionidis and Beers (1989),
Arnold and Gilmore (1992),
Majewski, Munn and Hawley (1996),
Ibata et al. (2003),
Martin et al. (2004), ...

Mon. Not. R. astr. Soc. (1976) **174**, 695–710.

DWARF GALAXIES AND GLOBULAR CLUSTERS IN HIGH VELOCITY HYDROGEN STREAMS

D. Lynden-Bell
Institute of Astronomy, The Observatories, Madingley Road, Cambridge

(Received 1975 July 11)

THE ASTROPHYSICAL JOURNAL, **291**:260–269, 1985 April 1

KINEMATICS OF K GIANTS IN THE OUTER GALACTIC HALO

KAVAN U. RATNATUNGA[1] AND K. C. FREEMAN
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Received 1984 August 6; accepted 1984 October 1

THE ASTROPHYSICAL JOURNAL, 459:L73–L77, 1996 March 10

ABSOLUTE PROPER MOTIONS TO $B \sim 22.5$: LARGE-SCALE STREAMING MOTIONS AND THE STRUCTURE AND ORIGIN OF THE GALACTIC HALO

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Received 1995 July 6; accepted 1995 November 27

How to search?

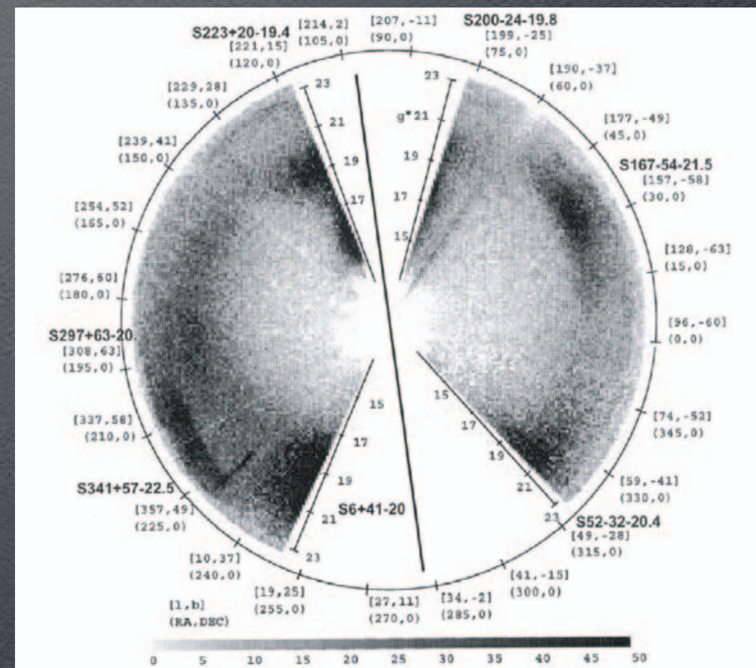
How to search?

Spatial information from photometry

How to search?

Spatial information from photometry

Large scale photometric surveys (SDSS, 2MASS).



Newberg et al. *ApJ*, 569, 245 (2002)
Polar plot of *g* vs. R.A.*
$0.1 < (g^*-r^*) < 0.3 \quad M_V \sim +4.2$

How to search?

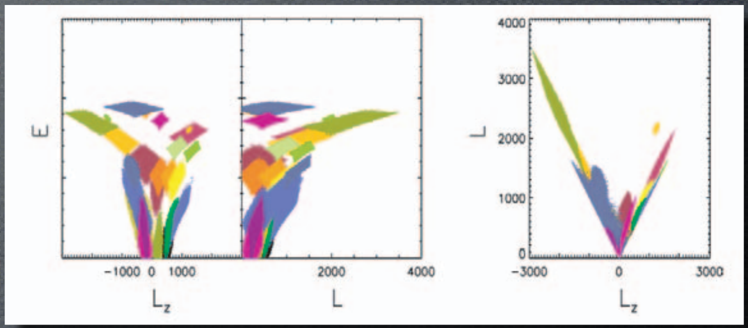
Search in E vs L and L_z space

How to search?

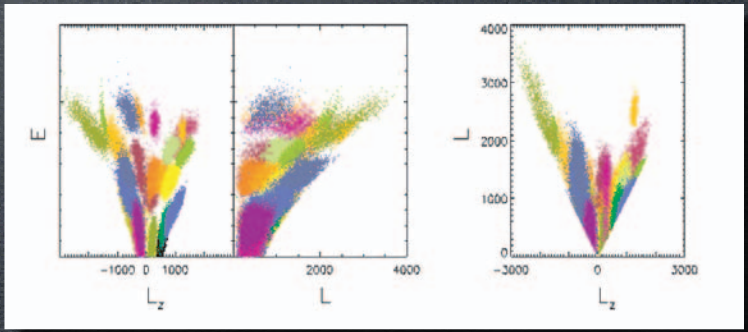
Search in *E vs L* and L_z space

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

But where is the galactic background?



Initial conditions



Final frame

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 Gyrs* time span, simulated *Gaia* errors.

How to search?

Use *N*-body simulations
to look for clues

How to search?

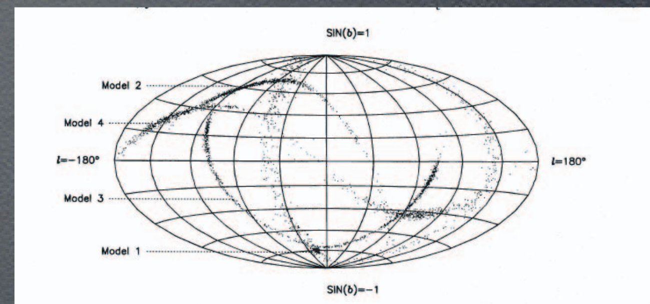
Use *N*-body simulations to look for clues

N-body simulations can reveal characteristics of the debris that can be used to devise a search method

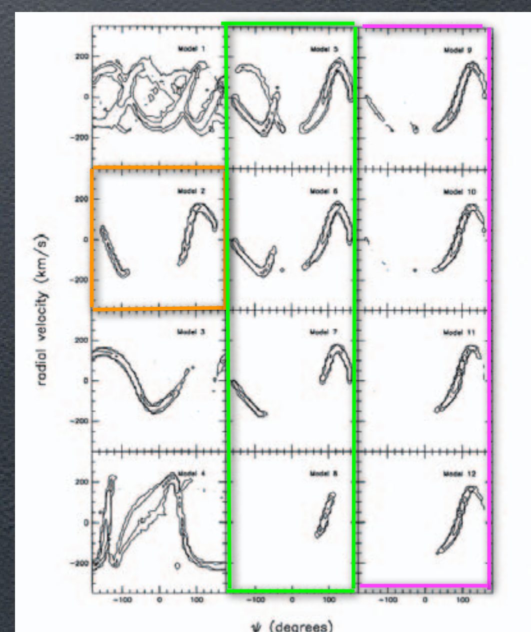
Johnston, Hernquist and Bolte, *ApJ*, 465, 278 (1996)

Great Circle Cell Count Method

Simulations: Self-consistent field code, fixed *spherical* galactic potential, 10^4 particle Plummer model satellites, *10 Gyrs* time span.



Sky projections



Arc on the sky *vs.* radial velocity

Fiducial case

Effect of decreasing velocity dispersion ↓

Effect of increasing central density ↓

But it's a spherical halo!

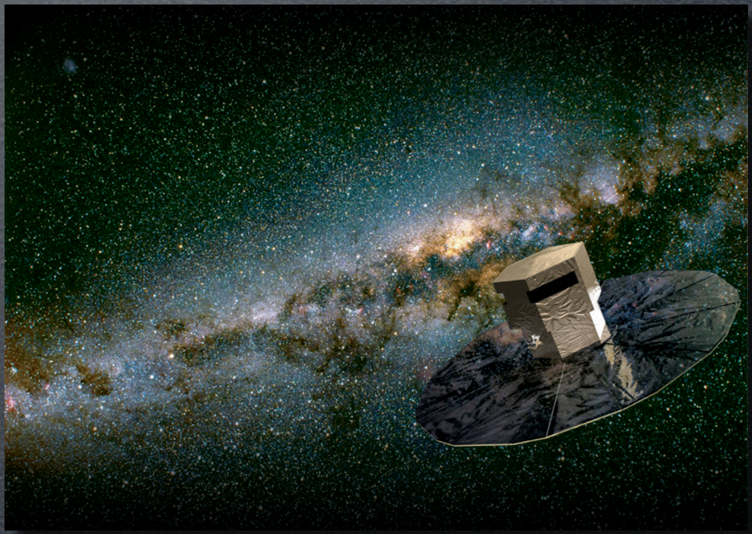
The promise of Gaia

The promise of Gaia

The Gaia Mission

A stereoscopic census of our Galaxy:

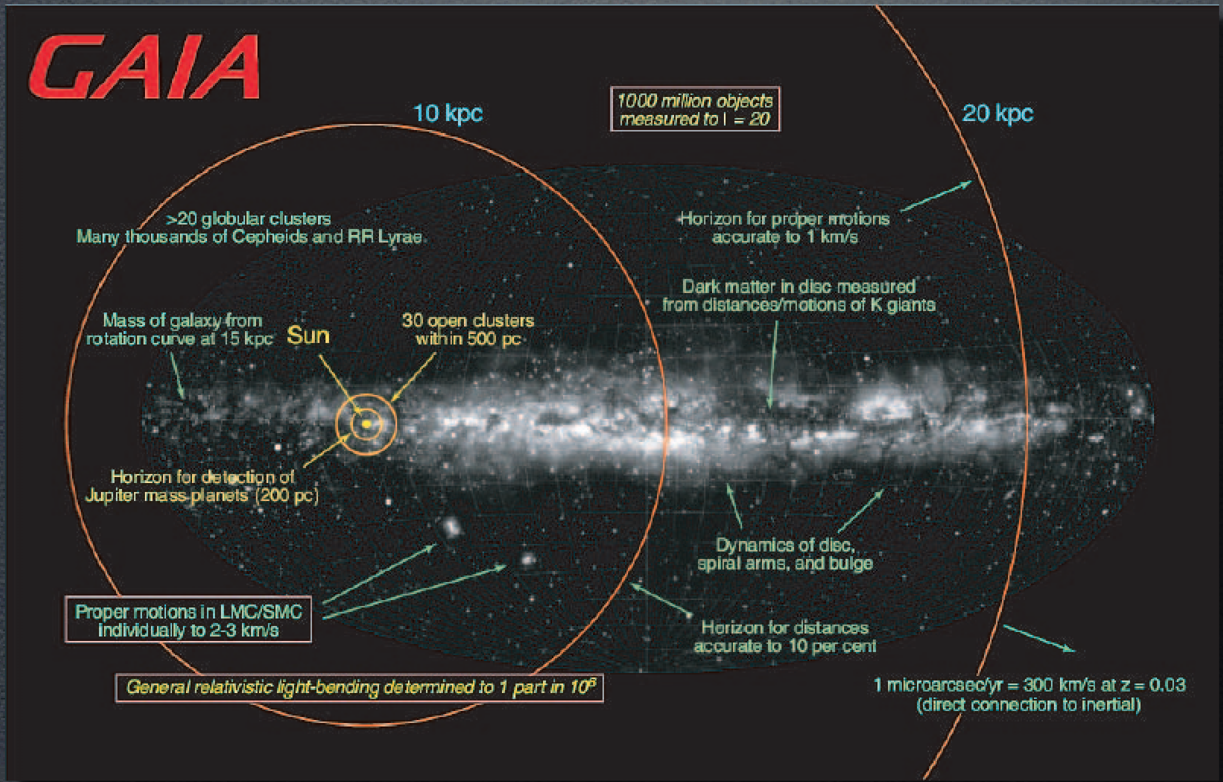
Magnitude limit:	20-21 mag
Completness:	20 mag
Number of objects:	26 million to *V*=15
	250 million to *V*=18
	1,000 million to *V*=20
Astrometric accuracy:	4 μarcsec at *V*=10
	10 μarcsec at *V*=15
	200 μarcsec at *V*=20
Photometry:	4 broad band to *V*=20
	11 medium band to *V*=20
Radial velocities:	1-10 *km/s* at *V*=16-17
Observing program:	On-board and unbiased
Expected launch year:	2011
Space agency:	ESA



ESA and Medialab

The promise of Gaia

The Gaia Mission



ESA and Medialab

10 μ*arcsec* ⇒10% accuracy in distances at *10 kpc*

10 μ*arcsec/yr* ⇒ 1 *km/s* accuracy at 20 *kpc*

This work

This work

What sets this work apart?

Realistic modeling of galactic background

We address sampling issues

Realistic modeling of the observational errors

This work

Key ingredients

Realistic modeling of the dynamical process of satellite destruction:

- ✔ Mass model of the Galaxy with non-spherical halo
- ✔ N-body simulation with self-gravity and large number of particles

Mass model of the Galaxy

Bulge:

Spherical Hernquist

$$\rho_b(r) = \frac{M_b}{2\pi} \frac{a}{r(r+a)^3}$$

Disk:

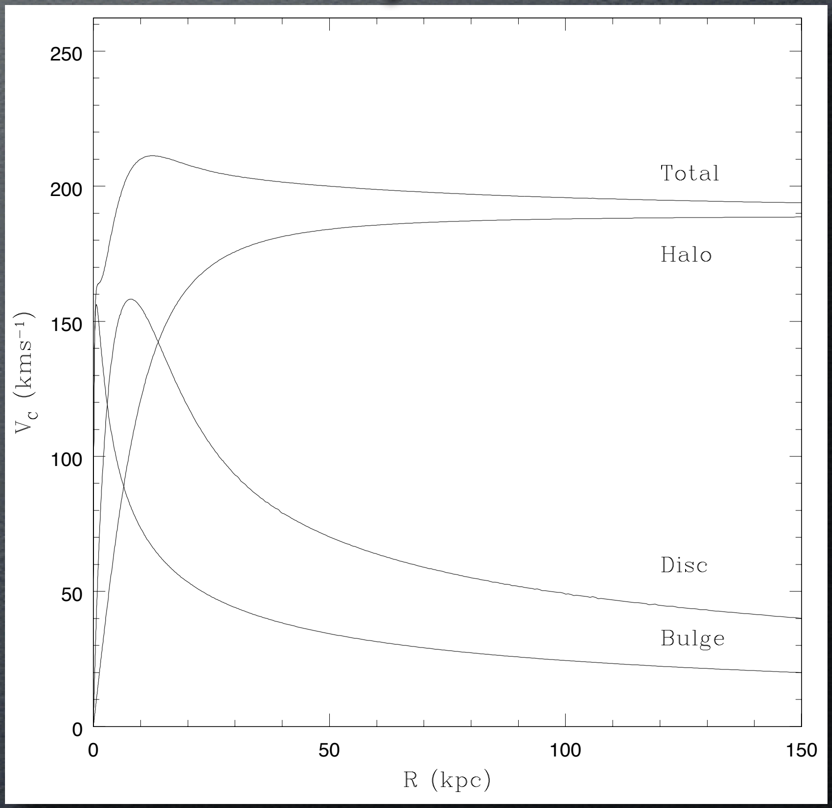
Double exponential

$$\rho_d(R,z) = \frac{M_d \beta}{4\pi R_d^2} \exp[-R/R_d - \beta|z|]$$

Halo:

Logarithmic

$$\Phi_h(R,z) = v_h^2 \ln[R_c^2 + R^2 + z^2/q_h^2]$$



Bulge	Disk	Halo
$M_b = 1.4 \times 10^{10} M_o$	$M_d = 5.6 \times 10^{10} M_o$	$v_h = 186$ km/s
$a = 630$ pc	$R_d = 3.5$ kpc	$R_c = 12$ kpc
	$\beta^{-1} = 700$ pc	$q_h = 0.8$

Mass model of satellites

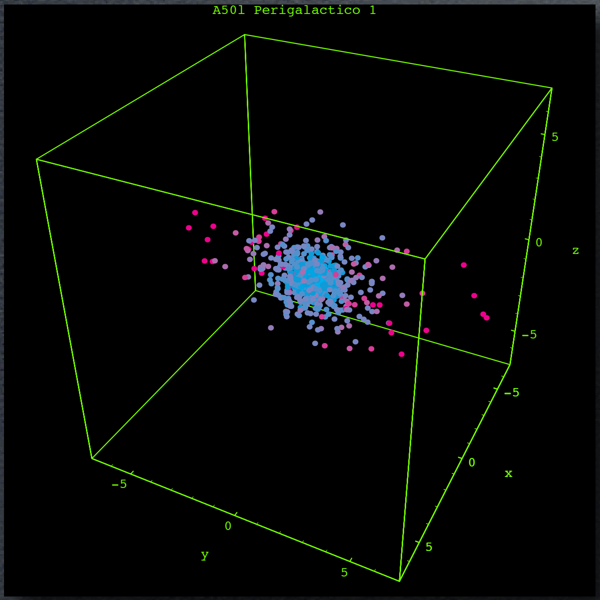
King models:

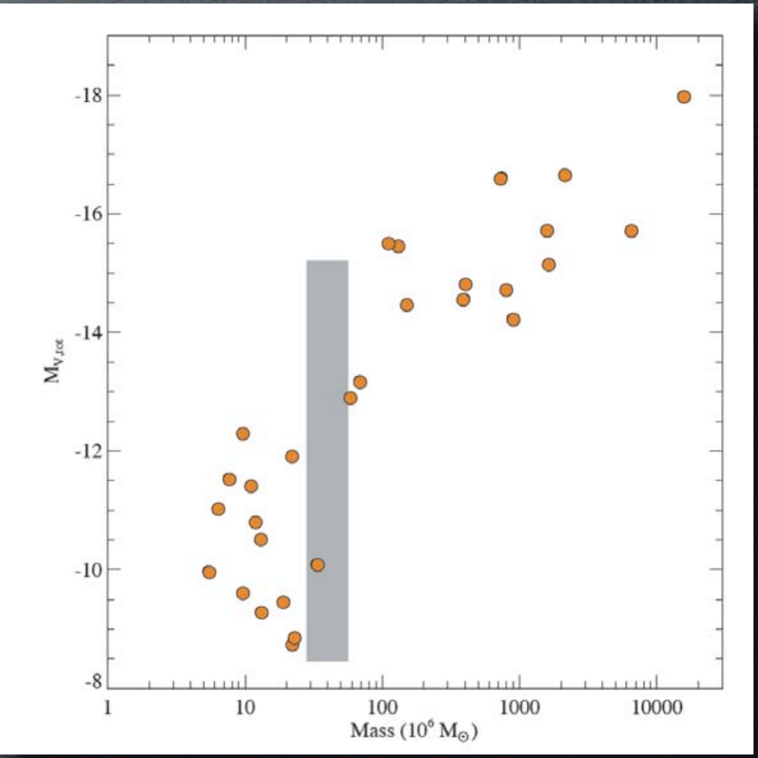
$N = 10^6$

$M = 2.8 \times 10^7\ M_o$ and $5.6 \times 10^7\ M_o$

$r_t = 3.15\ kpc$

$c = 0.9$



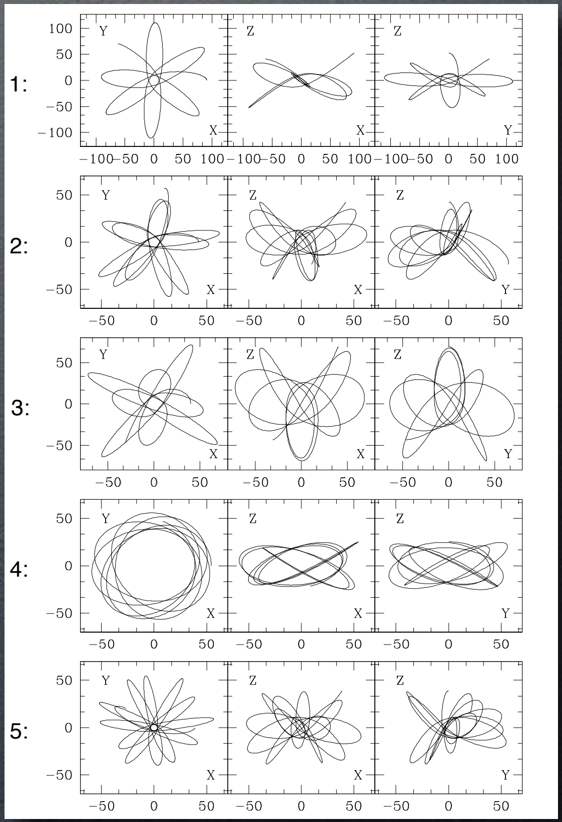


M. Mateo, 1998, *ARA&A*, 36, 435

N-body simulations

Simulation specs:

Code: Tree (Dubinski)
Runs: 5
CPU per run: 4 days
Time span: 10 Gyrs
Energy error < 0.1%
Computer: 32 processor Beowulf
"La Granja"



Orthogonal projections of 5 runs


"La Granja"

Run	Satellite	Peri	*(kpc)* Apo	θ
1	High mass	*8.75*	*105*	*30º*
2	High mass	*7*	*60*	*45º*
3	Low mass	*7*	*80*	*60º*
4	Low mass	*40*	*60*	*25º*
5	Low mass	*3.5*	*55*	*45º*

This work

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Realistic modeling of galactic background:

- ✔ Luminosity model of the Galaxy
- ✔ Efficient Monte Carlo realization

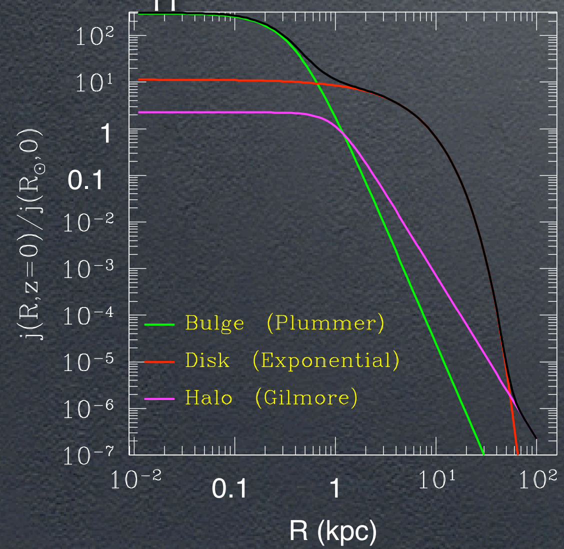
Luminosity model of the Galaxy

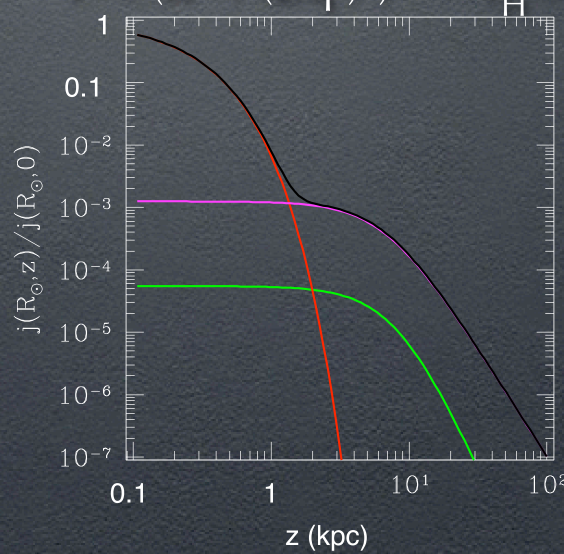
3 components:

Bulge $\propto (r_B^{\,2} + r^2)^{-5/2}$ $r_B = 0.38\ kpc$

Disk $\propto exp[- ((R-R_o)/R_D + |z|/z_D]$ Ro = 8.5 kpc $R_D = 3.5\ kpc$ zD = 0.2 *kpc*

Halo $\propto 1/(r_H^{\,7/2} + r'^{\,7/2})$ $r' = (R^2 + (z/q')^2)^{1/2}$ $r_H = 1\ kpc$ $q' = 0.8$





Photometric Model of the Galaxy

Normalization at solar neighborhood: 0.067 $L_\odot/pc^3$

$L_{Gal} = 3.2\times10^{10}\ L_\odot$

$L_B = 4.7\times10^{9}\ L_\odot$ (14.6 %)

$L_D = 2.3\times10^{10}\ L_\odot$ (73.2 %)

$L_H = 3.9\times10^{9}\ L_\odot$ (12.2 %)

q_H: 0.8

r_B: 0.383 R_D: 3.5 z_D: 0.2 r_H: 1 $R_\odot$: 8.5

$(j_H/j_D)_\odot = 0.00125$ $(L_H/L_D) = 0.1667$

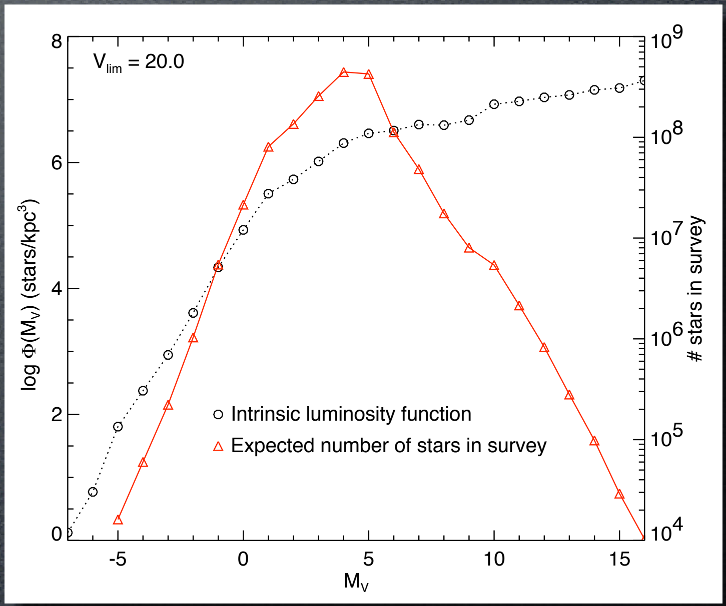
$(j_B/j_D)_\odot = 5.5\times10^{-5}$ $(L_B/L_D) = 0.200$

Efficient Monte Carlo realization

Luminosity function:

We first calculate the weighted luminosity function for a survey limited to *V*=20 (Gaia)

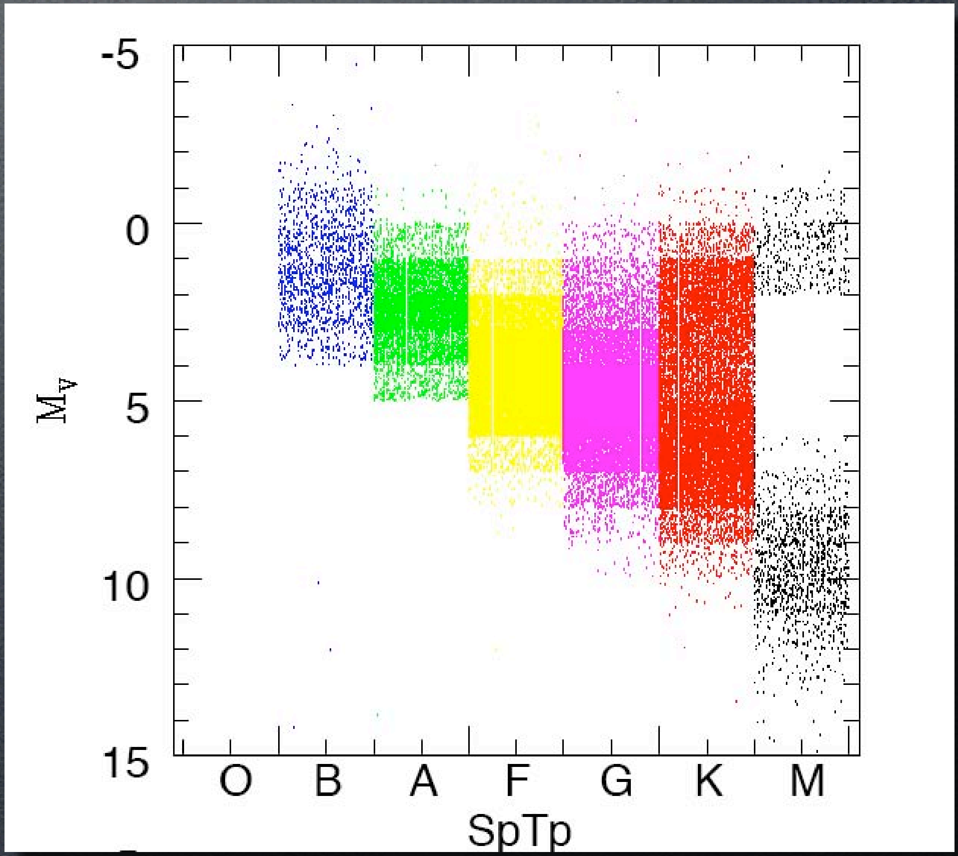
Integrated over the whole galaxy, the weighted luminosity function results in ~1.5 × 10^9 stars!

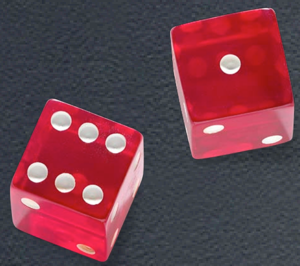


Efficient Monte Carlo realization

Then for each individual star:

- ✔ Choose Mv from weighted luminosity function
- ✔ Choose spectral type from Hess diagram
- ✔ Compute maximum visible distance dmax
- ✔ Generate random position within sun-centered sphere of radius dmax using Von Neumann rejection technique
- ✔ Assign galactic component from local relative densities





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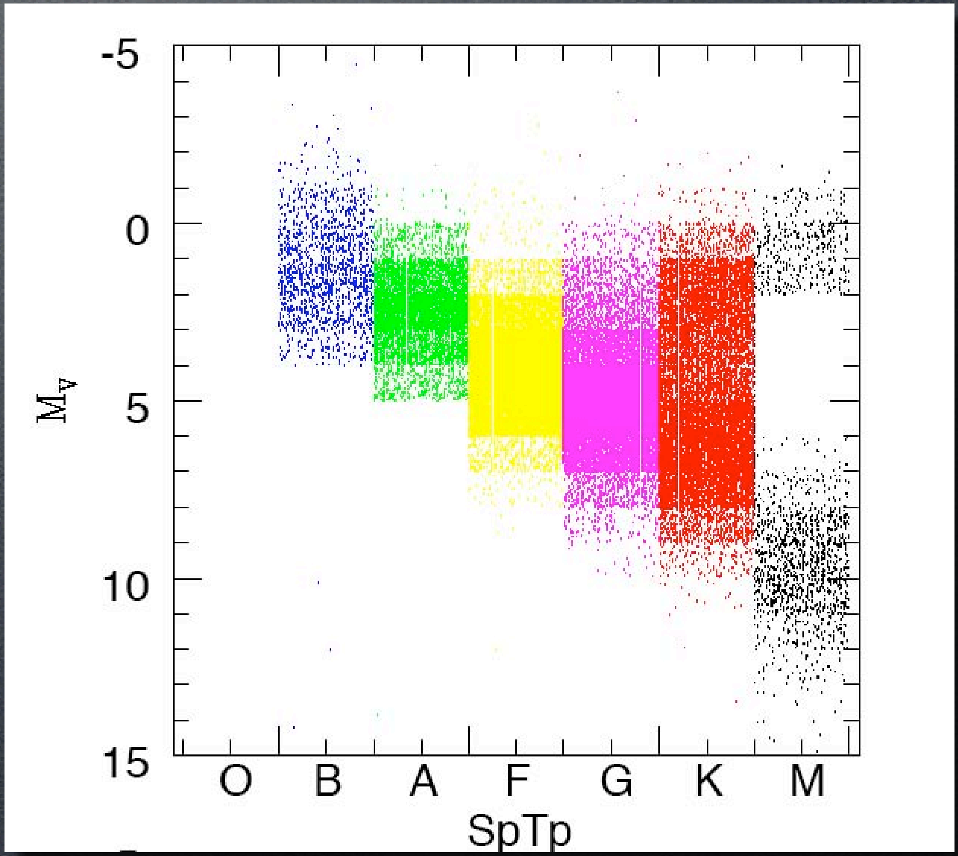
We have avoided the galactic plane:

$-90^o < l < +90^o$ and $-5^o < b < +5^o$

This reduces the number of stars to be generated to 3.1×10^8 stars.



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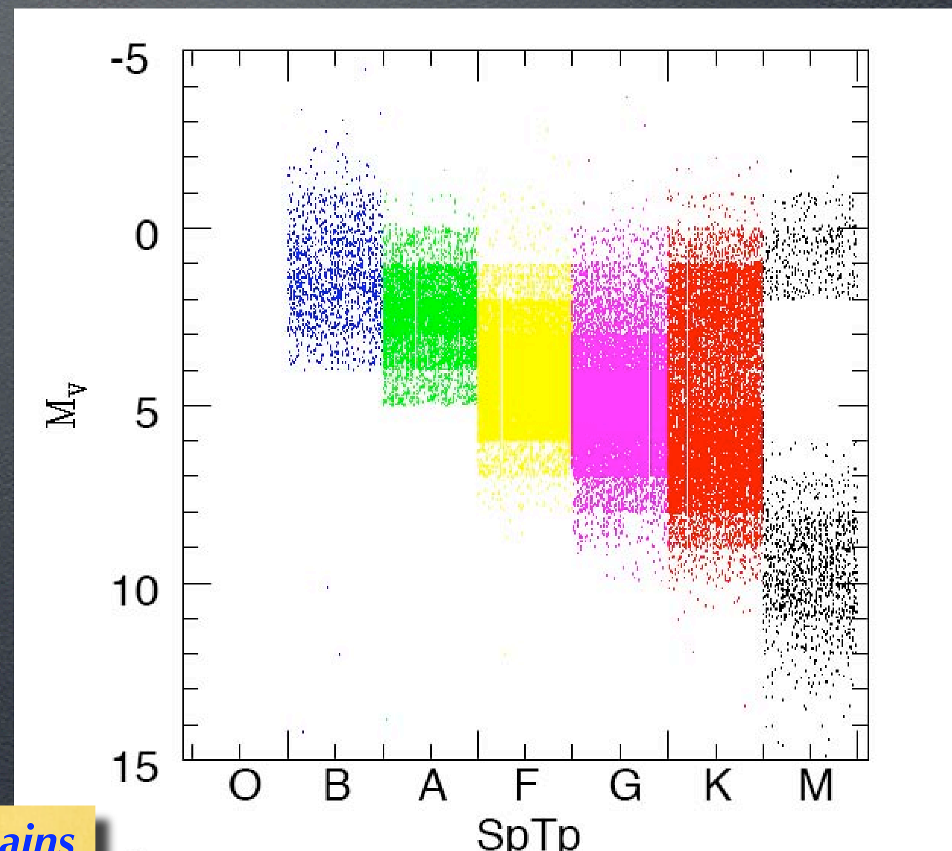

We have avoided the galactic plane:

$-90^o < l < +90^o$ and $-5^o < b < +5^o$

This reduces the number of stars to be generated to 3.1×10^8 stars.

Our simulated survey contains every single one of those!

This work

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Realistic modeling of galactic background:

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Realistic modeling of Gaia errors:

- ✔ Simulate dependency on apparent magnitude, color and ecliptic latitude

Simulating Gaia astrometry

We need to add kinematics to our Galaxy model

Bulge:	Non-rotating	Isotropic velocity dispersion
Disk:	Rotating	Velocity ellipsoids for each spectral type
Halo:	Rotating	Single velocity ellipsoid

Simulating Gaia astrometry

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Bulge:	Non-rotating	Isotropic velocity dispersion
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Component	v_{rot}	σ (km/s)			
Bulge	0	110			
Disk	220	Sp. Type	σ_R	σ_θ	σ_z
		O	10	9	6
		B	10	9	6
		A	20	9	9
		F	27	17	17
		G	32	17	15
		K	35	20	16
		M	31	23	16
Halo	35		135	105	90

Simulating Gaia astrometry

We also need to add photometric information to our simulated satellites

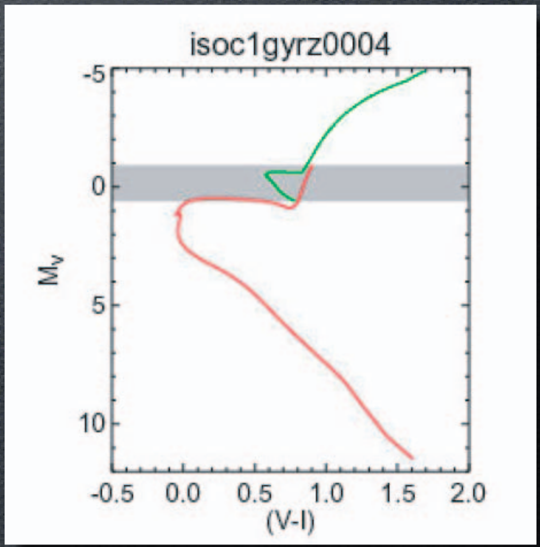
Assume all stars on a single isochrone (*Girardi et al. 2000*):

- Low metallicity
- Age corresponds to simulation snapshot

Assume power law mass function:

$\xi(m) \propto m^{-1.5}$

Get M_V and $(V - I)$ from assumed isochrone



Girardi et al. *A&AS* 141, 371 (2000)

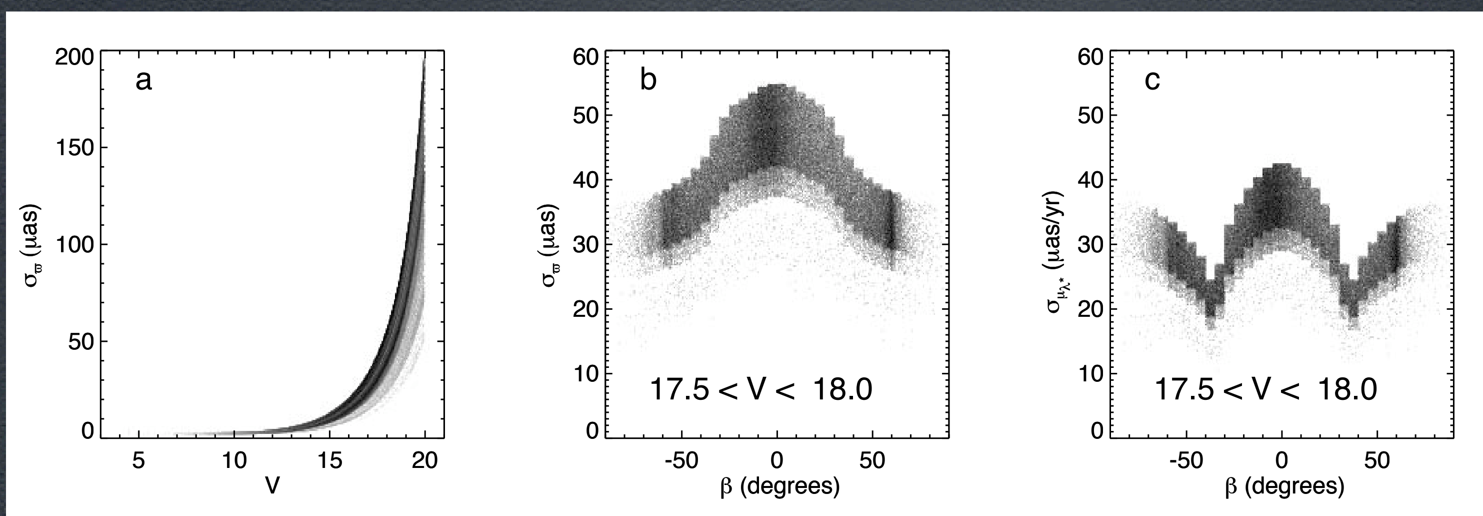
Simulating Gaia astrometry

We can now simulate the astrometry and its errors

Convert phase space information to astrometric observables: proper motion, parallax and radial velocity

Add astrometric errors as a function of Gaia *G* magnitude, *(V - I)* color and ecliptic latitude

Add radial velocity errors as a function of apparent magnitude



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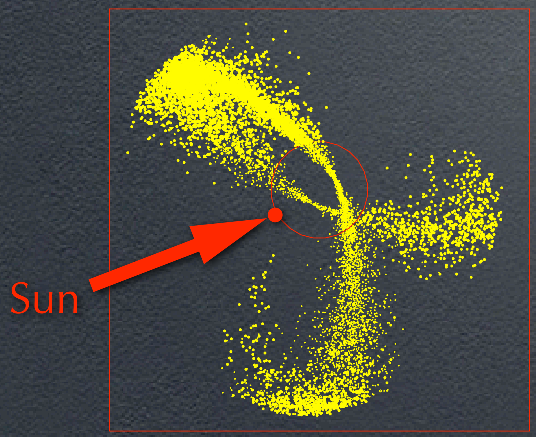
Realistic modeling of sampling limitations and bias:

- ✔ Variation in probing of satellite luminosity function along streamer
- ✔ Proper matching of star counts for background and satellite

Variation in depth of probing of streamer

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

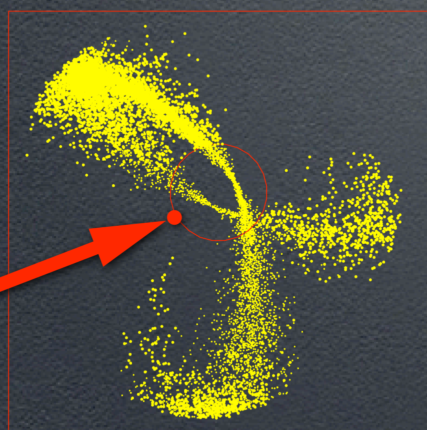


Simulation #1

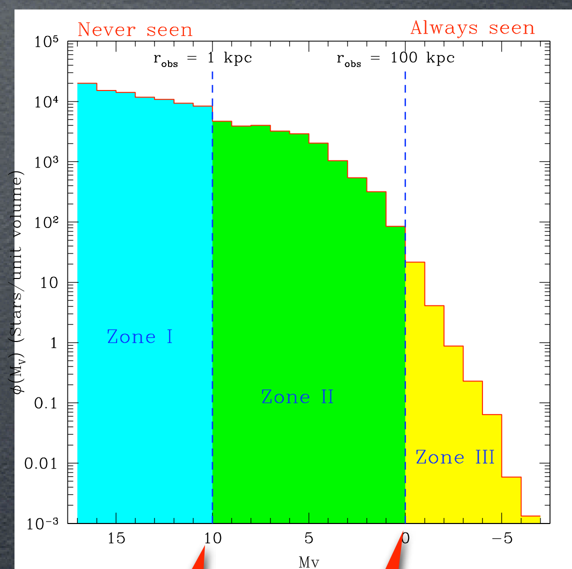
Variation in depth of probing of streamer

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

Sun



Simulation #1



Brighter →

Faintest star seen at closest distance

Faintest star seen at largest distance

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

Variation in depth of probing of streamer

Given an assumed isochrone, metallicity and mass function for the satellite, we can compute the fraction of stars visible along the streamer

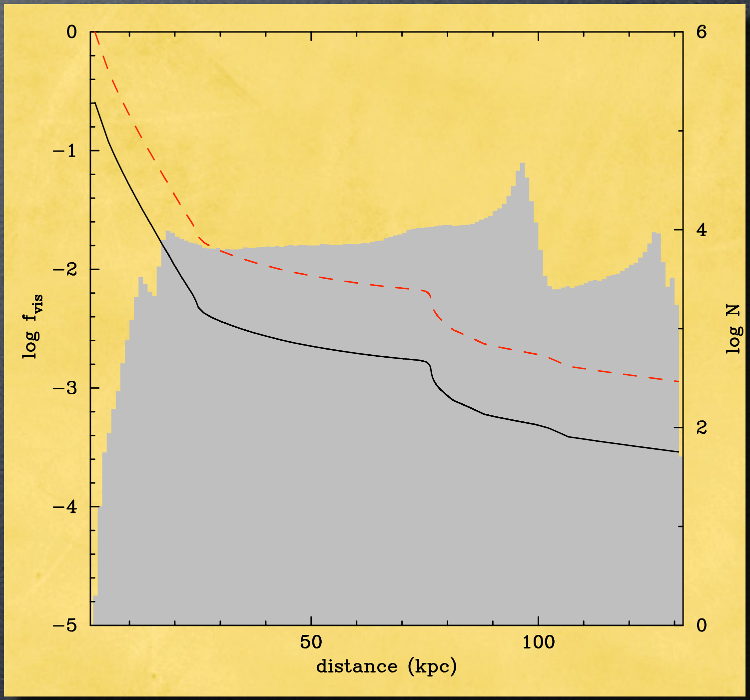
Histogram: Distribution of distances to observer (right vertical axis)

Black line: Visible fraction of simulated satellite stars (left vertical axis)

Overall fraction of visible stars: 0.0025!

Red line: Visible fraction of simulated satellite stars, eliminating those that are never seen

Overall fraction of visible stars: 0.01!



Simulation #1
10 Gyr isochrone, Z=0.004, $\xi \propto m^{-1.5}$

It is clear that the answer is to simulate a tracer bright population only.

But how to choose a proper luminosity cut-off ?

Proper matching of star counts for background and satellite

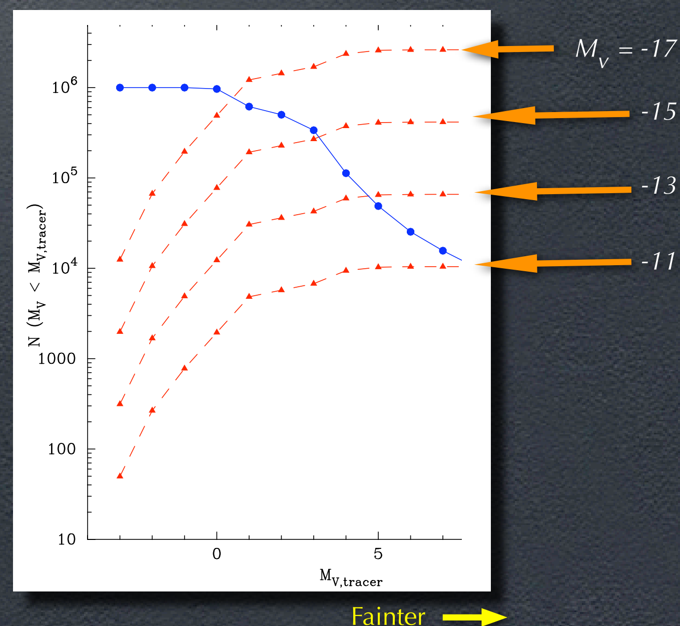
Given a dwarf galaxy with an assumed luminosity function and simulated orbit, we can compute the fraction of stars brighter than a given absolute magnitude, that will visible by Gaia.

Proper matching of star counts for background and satellite

Given a dwarf galaxy with an assumed luminosity function and simulated orbit, we can compute the fraction of stars brighter than a given absolute magnitude, that will visible by Gaia.

The answer obviously depends on the total luminosity of the dwarf galaxy.

As we dim the faint luminosity cut-off, more stars become visible, until we reach the total number that can be seen given the Gaia apparent magnitude limit.



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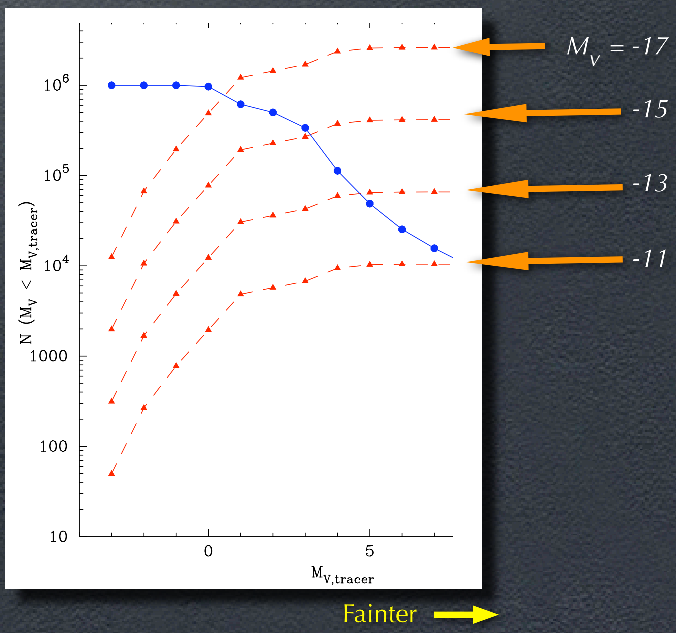
Given a simulated satellite we can compute the number of particles that will be seen if we assume that all are brighter than a given absolute magnitude.



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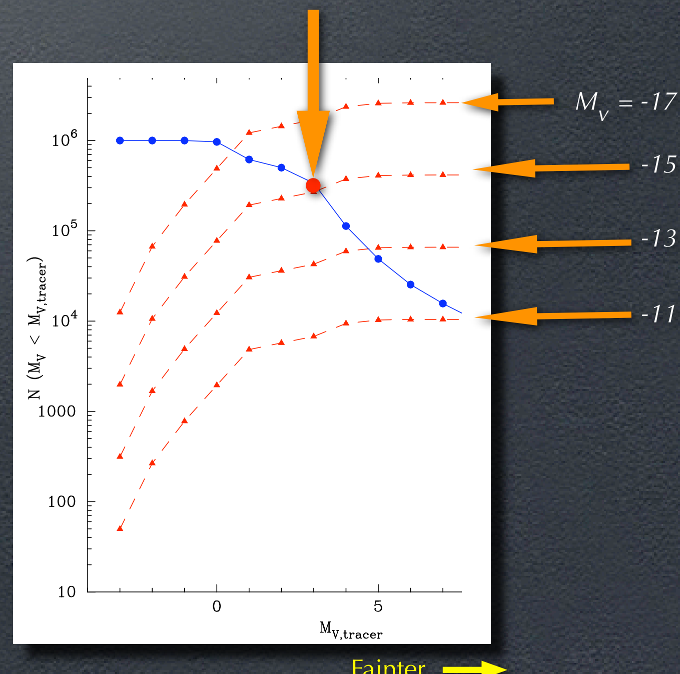
The point where these two curves intersect defines the correct number of particles that should be considered.

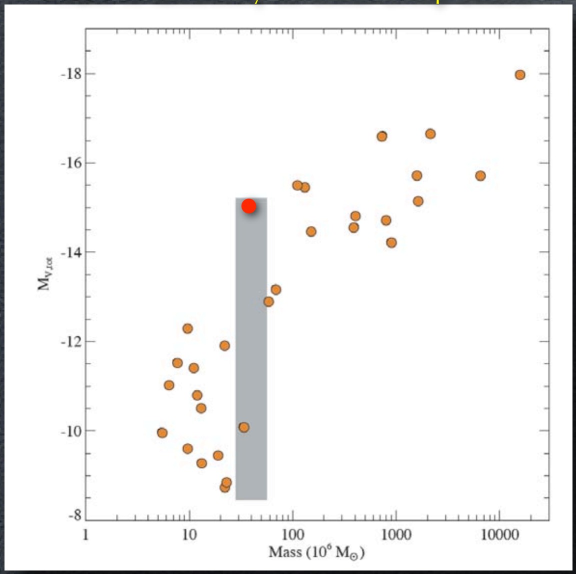


Proper matching of star counts for background and satellite

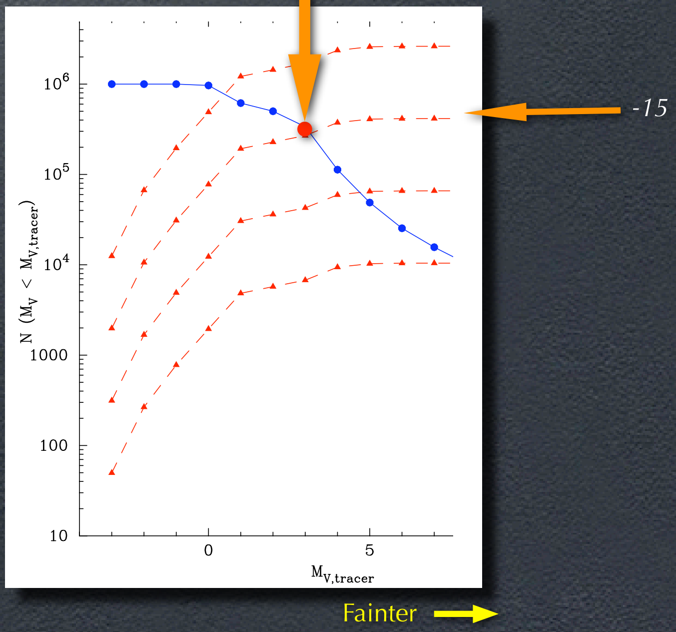
For a $M_v = -15$ dwarf galaxy, a 10^6 particle simulation results in $3{\times}10^5$ that should be considered (*30%*).

This wastes precious simulated particles, but ensures the correct inclusion of the varying depth of sampling along the orbit and the proper matching of satellite and galactic background.

Mass *vs* luminosity for Local Group dwarfs



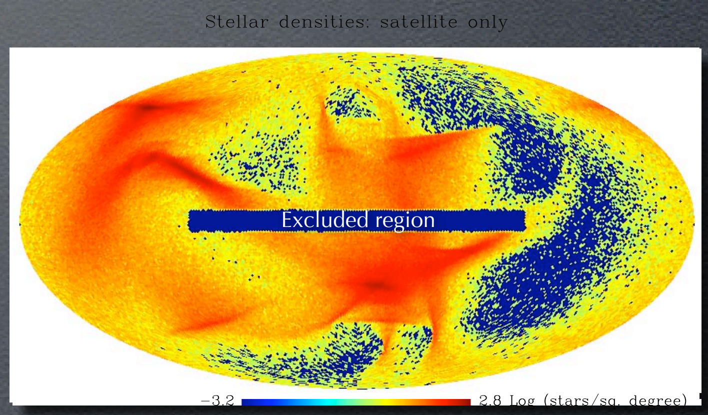
M. Mateo, 1998, *ARA&A*, 36, 435



Expected results

Gauging the galactic background problem

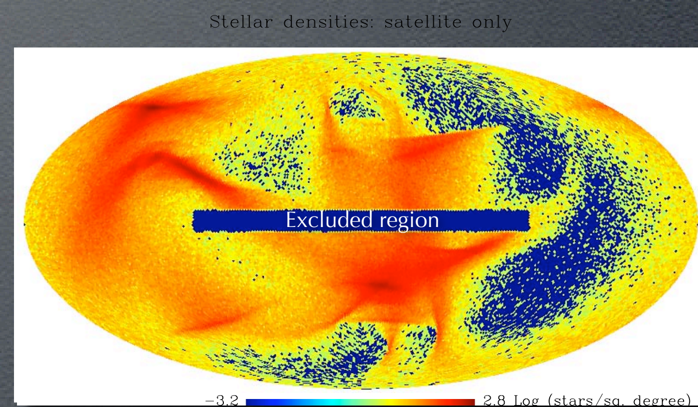
Star counts on an equal area projection on the sky of two simulated satellites



Mollwide projection on the sky of runs 1 and 5

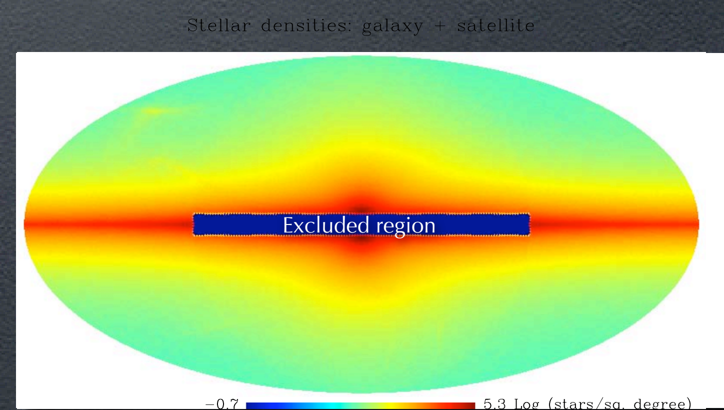
Gauging the galactic background problem

Star counts on an equal area projection on the sky of two simulated satellites



Mollwide projection on the sky of runs 1 and 5

Adding the proper galactic background swamps all but the densest parts of the remnant



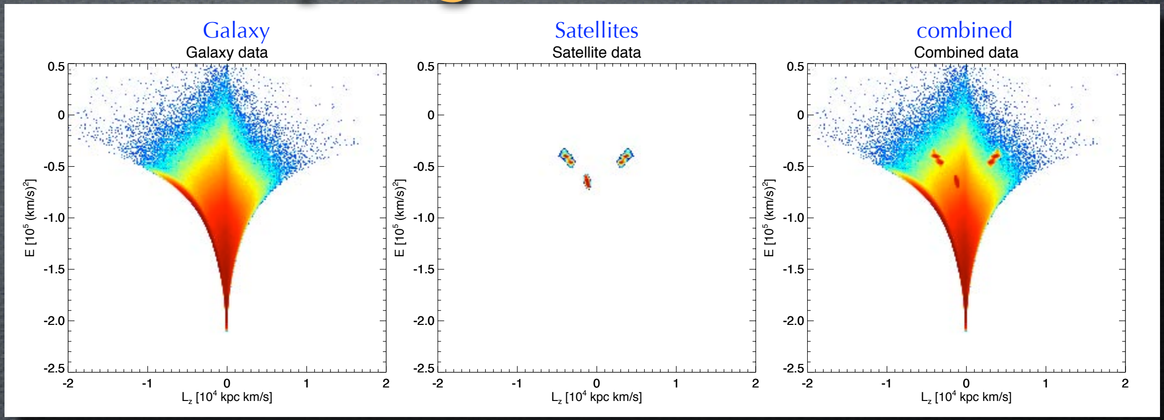
Same as above but with inclusion of galactic background

Using photometric information to isolate particular sets of stars will greatly help the identification of remnants on the sky

The *E* vs L_z diagram

These figures show error-free data

Despite the background, the three satellites are clearly visible



The *E vs L_z* diagram

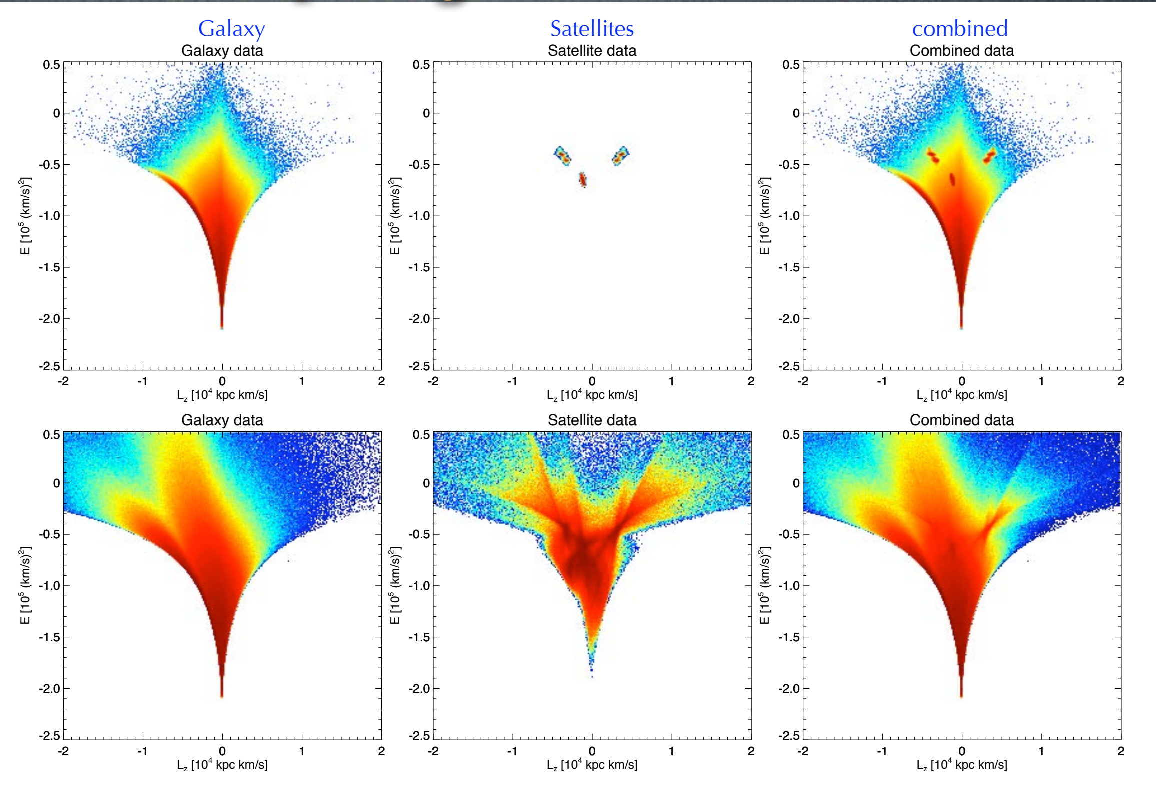
These figures show error-free data

Despite the background, the three satellites are clearly visible

These figures show data with errors

The satellites are smeared over a large region, but are still seen

Notice that errors produce caustic-like structures, with several emanating from each satellite



The E vs L_z diagram

These figures show error-free data

Despite the background, the three satellites are clearly visible

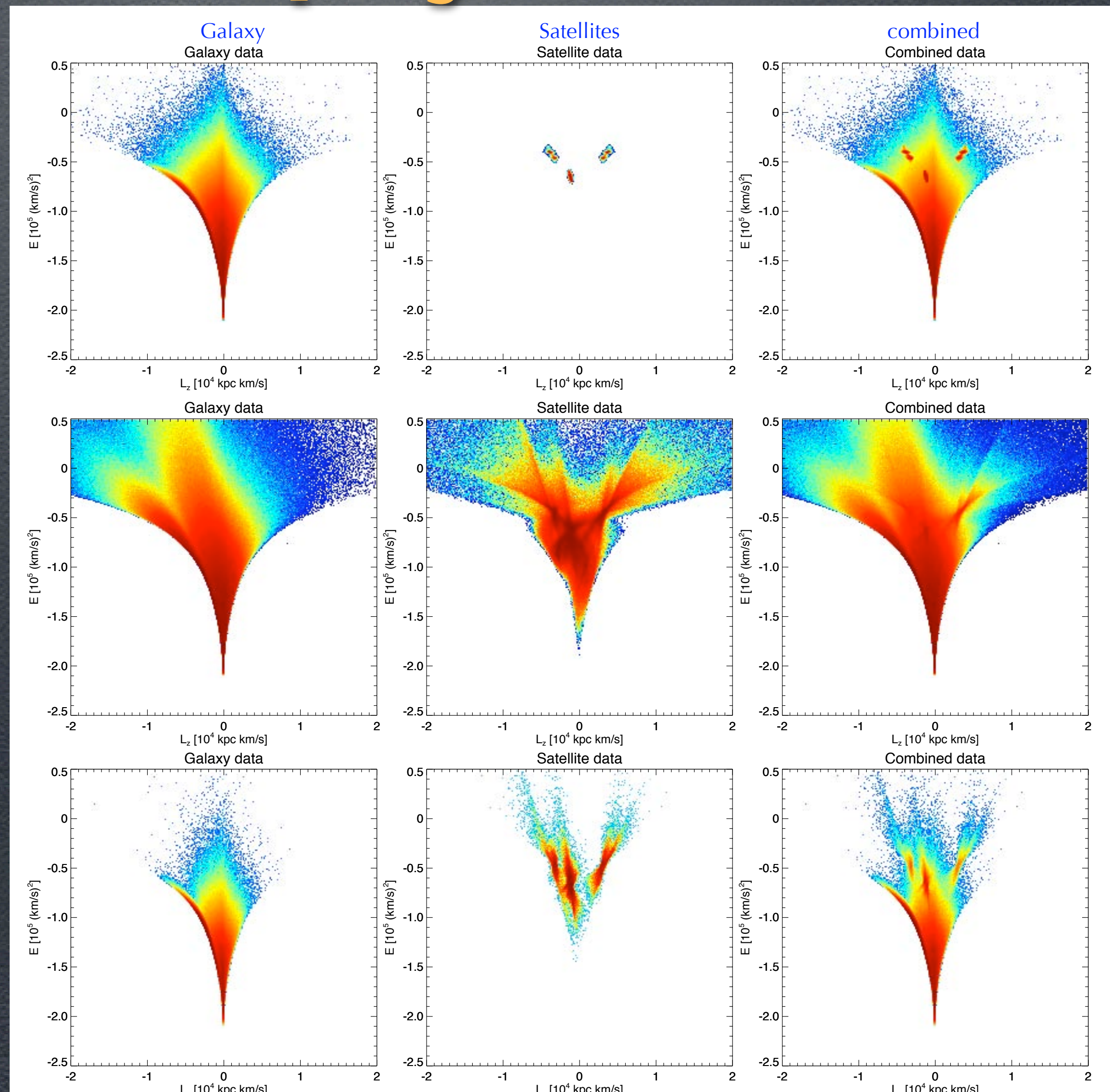
These figures show data with errors

The satellites are smeared over a large region, but are still seen

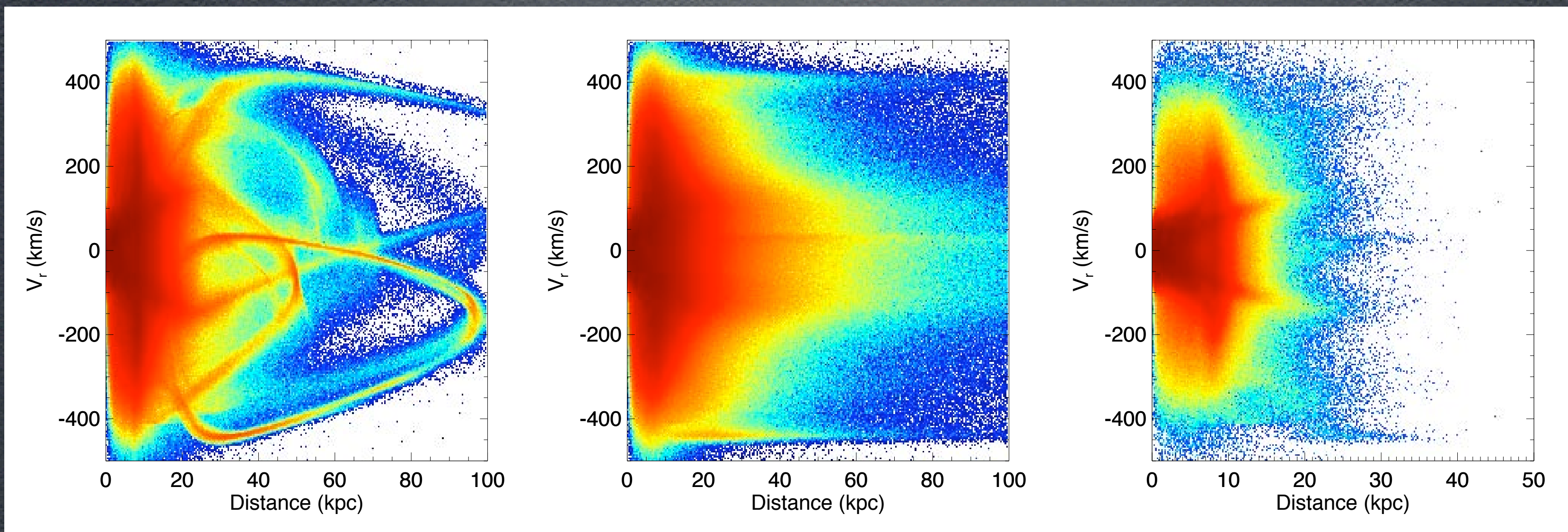
These figures show high quality data

Restricting to a high quality sample improves the detection.

$V < 15, \quad \varpi/\sigma_{\varpi} > 5$



The *d* vs v_r diagram



Similar searches can be made in other diagrams, like distance vs radial velocity

In all cases, the conclusion is that the picture becomes quite fuzzy, and high quality data must be used

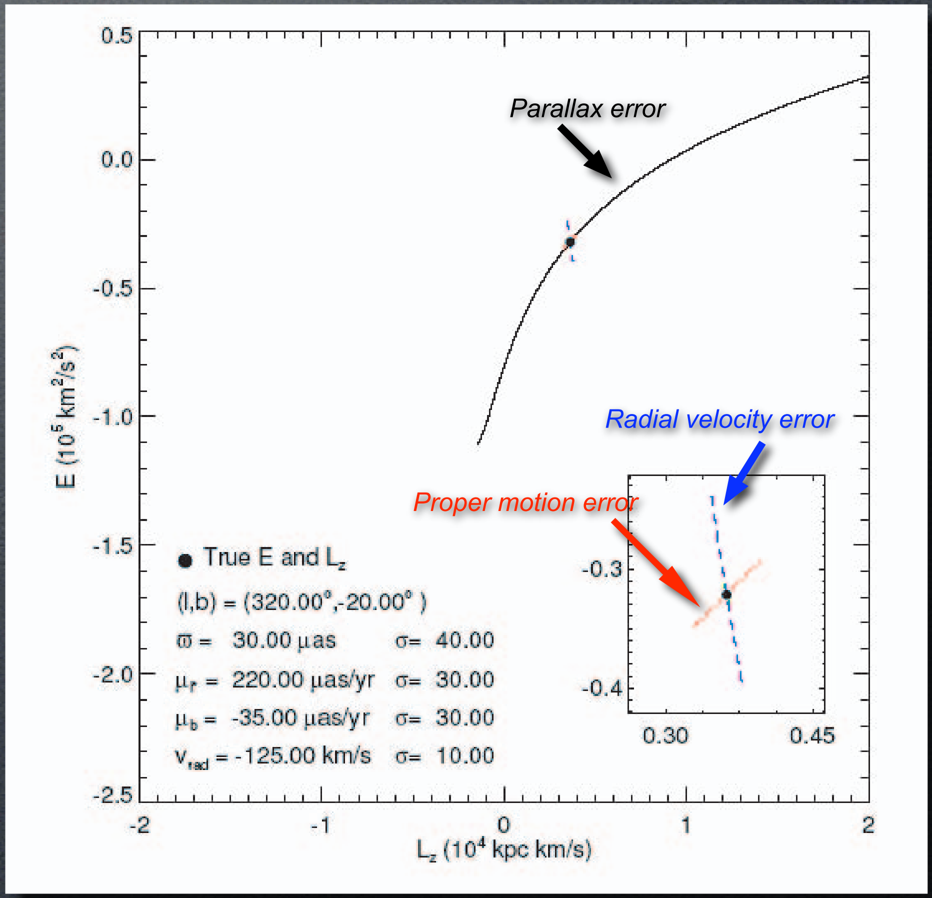
The use of photometry to restrict the sample to particular stellar populations will be very important

Why the huge spread?

This figure illustrates the effect of 3σ errors in the astrometry and radial velocity for a particular star in the *E*-L_Z plane.

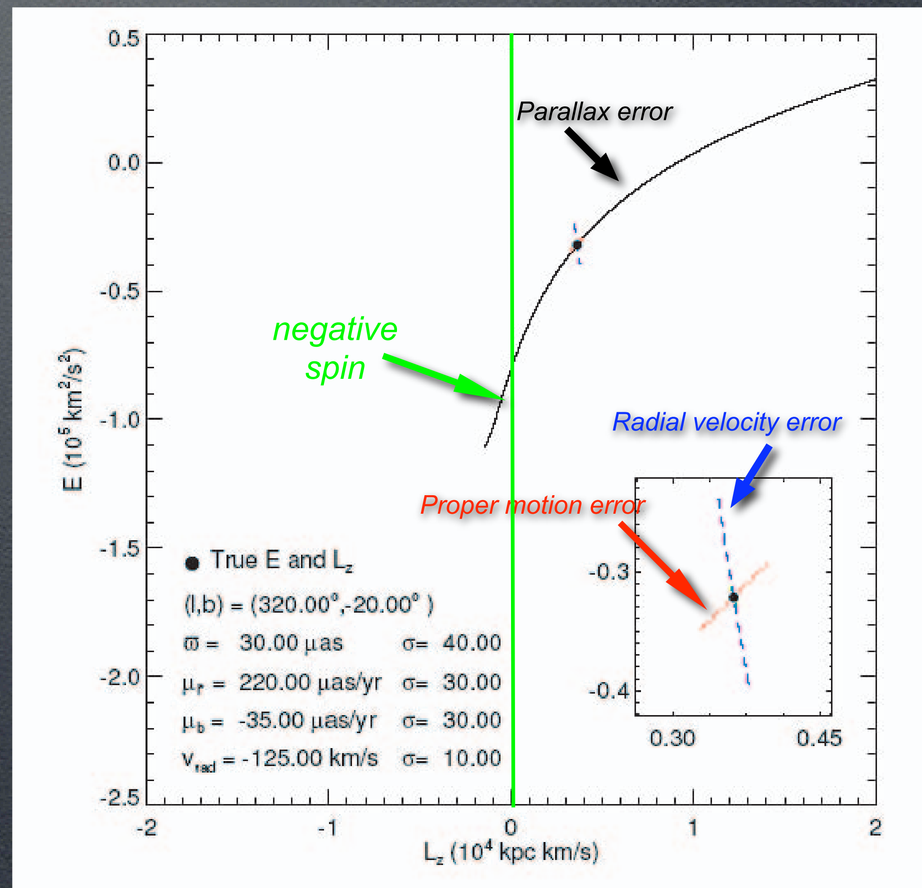
The largest spread is due to the parallax error, which produces the caustic-like structures in this diagram.

After the parallax, the radial velocity and the proper motion errors in turn, have decreasing effects.
The errors are correlated and it is necessary to propagate them from observables to derived quantities.



Why the huge spread?

Notice that the parallax error, if severe enough, may not even allow us to determine whether the star is rotating or counterotating around the Galaxy.



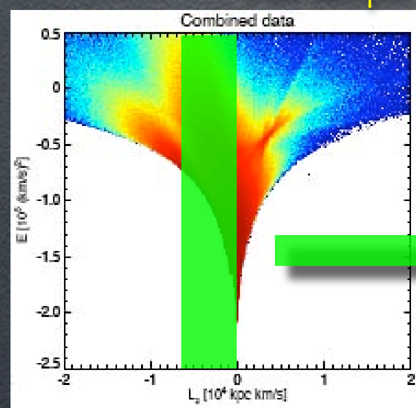
Slices in the *E vs* L_z diagram

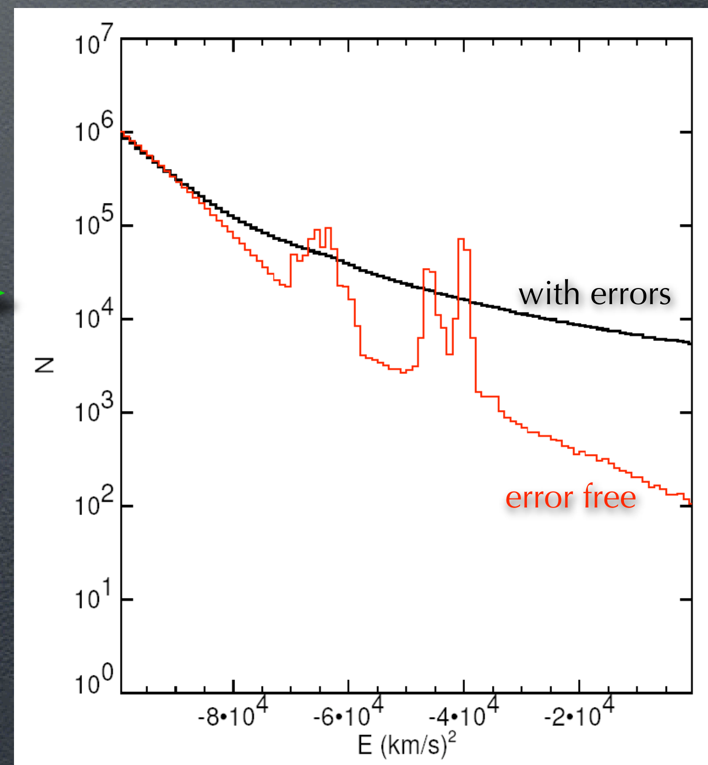
Another approach is to take slices in the *E vs* L_z diagram and plot the resulting histograms

Slices in the *E vs L_z* diagram

Another approach is to take slices in the *E vs L_z* diagram and plot the resulting histograms

Full sample



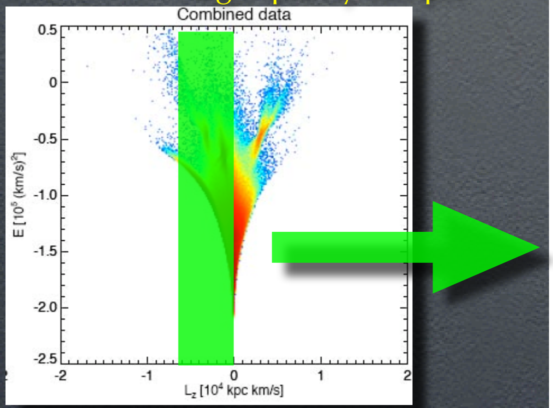


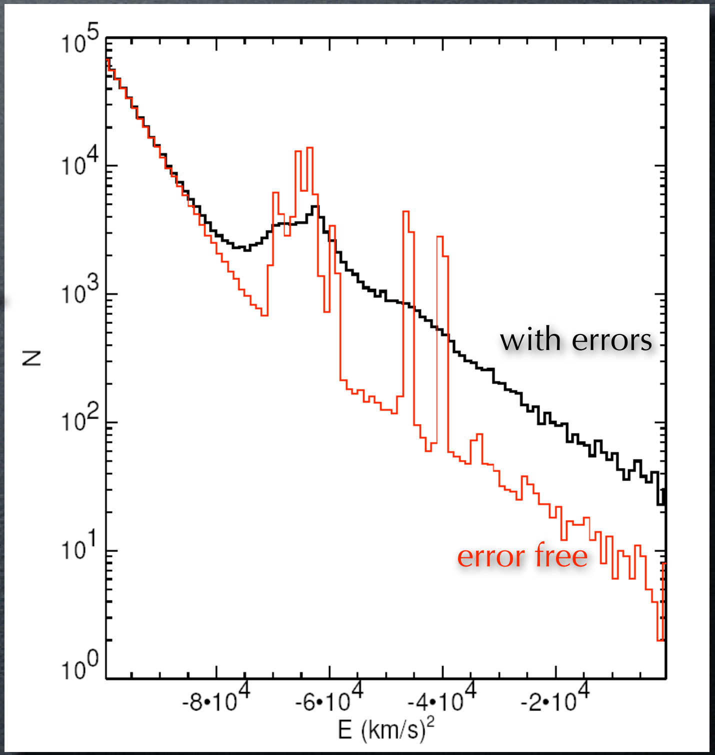
The satellites, wich are clarely visible in the error-free data, are completely swamped out by the errors

Slices in the *E vs L_z* diagram

Another approach is to take slices in the *E vs L_z* diagram and plot the resulting histograms

High quality sample

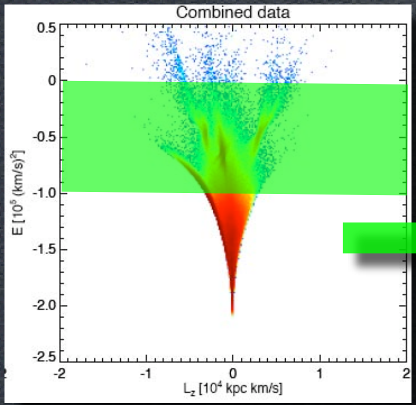




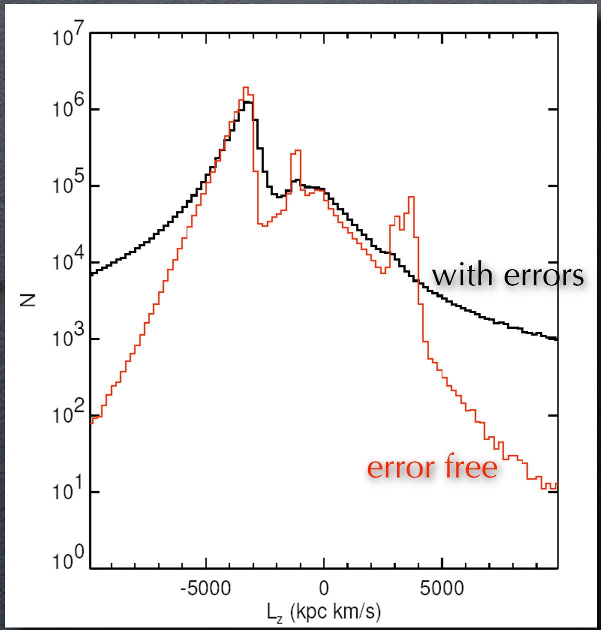
Using the high quality sample (V<15, ϖ/σ_{ϖ} >5) recovers the signal for the satellites, but it will be difficult to isolate them based on dynamics alone.

Slices in the *E vs L_z* diagram

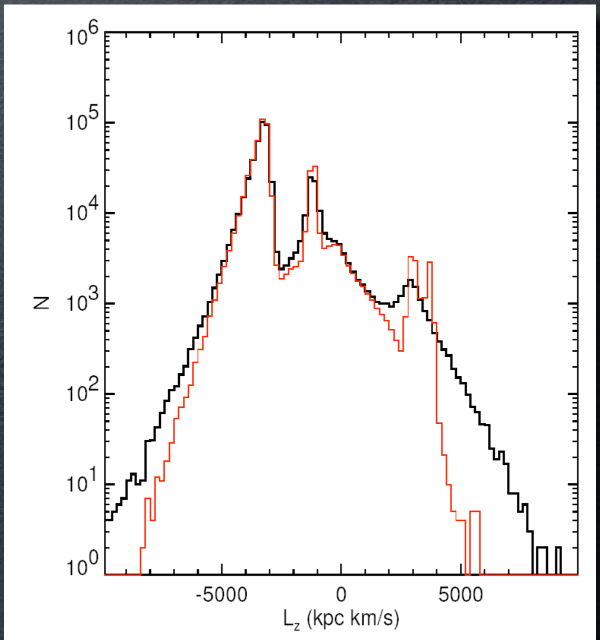
Another approach is to take slices in the *E vs L_z* diagram and plot the resulting histograms



Full sample



High quality sample



In this case we fare better, since most of disk stars are left behind.

The *E-L_z* technique is a good starting point, but it needs to be complemented with further criteria

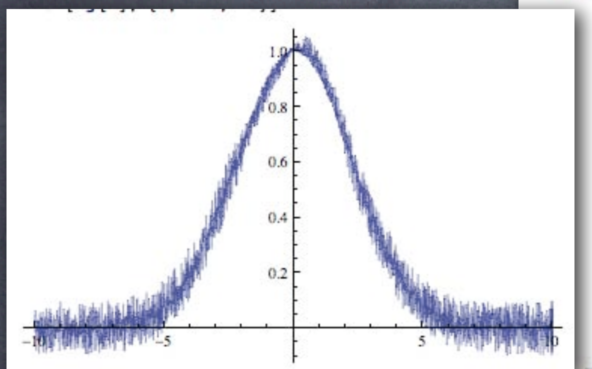
The future

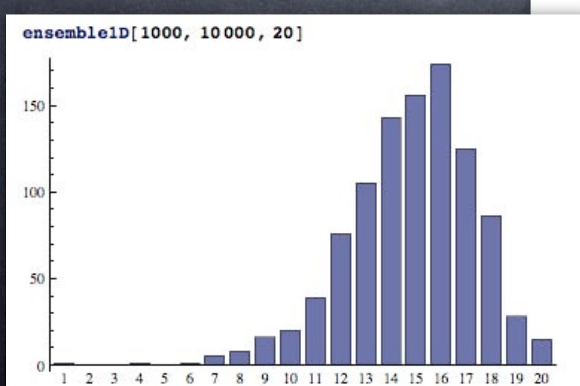
Things to do

- ✔ Model improvements
  - ✔ Improve Gaia astrometry model
  - ☛ Improve Gaia photometry model
- ✔ Search techniques
  - ☛ Try global diagnostics of substructure: entropy
  - ☛ Contrast enhancement techniques: unsharp masking
  - Simulate restricted searches: "pencil beams"
  - ✔ Revisit previous schemes: Great Circle Method
- ✔ Astronomy
  - Use a "cosmological halo" with remnants in various stages of relaxation and diverse stellar populations

Search Techniques

Entropy methods





Entropy methods

L. Boltzmann introduced in 1872 what is now called the *Boltzmann entropy* for an ideal gas.
This entropy is of the form:

$$S_B = -k_B \ln(W),$$

where k_B is Boltzmann's constant and W is the number of microstates associated to a given macroscopic configuration.
Boltzmann's entropy assumes that all microstates are equally probable, which in most cases is not true. When each microstate has a different probability p_i, then the *Gibb's entropy* should be used:

$$S_G = -k_B \sum p_i \ln(p_i)$$

We will use a Gibb's type of entropy as a diagnostic for structure. In our case, the summation will be over all the partitions in which we subdivide the observable space and the p_i are the occupation numbers for each partition. We will omit Boltzmann's constant.

- **1 D - Case**

- **Introduction**

For simplicity, we will begin with the 1 - dimensional case.
Let's assume we have N_p points distributed among N_b cells in a 1-D space. The entropy is then:

$$S = -\sum_{i=1}^{N_b} n_i \ln(n_i),$$

where the occupation numbers satisfy the following restrictions:

$$N_p = \sum_{i=1}^{N_b} n_i \,, \quad n_i \geq 0 \text{ for all } i=1, \ldots, N_b.$$

We will now prove that the most featureless distribution is an extrema for the entropy.
Let us assume that,

$$n_1 = n_2 = \ldots = n_{N_b} = N_p / N_b$$

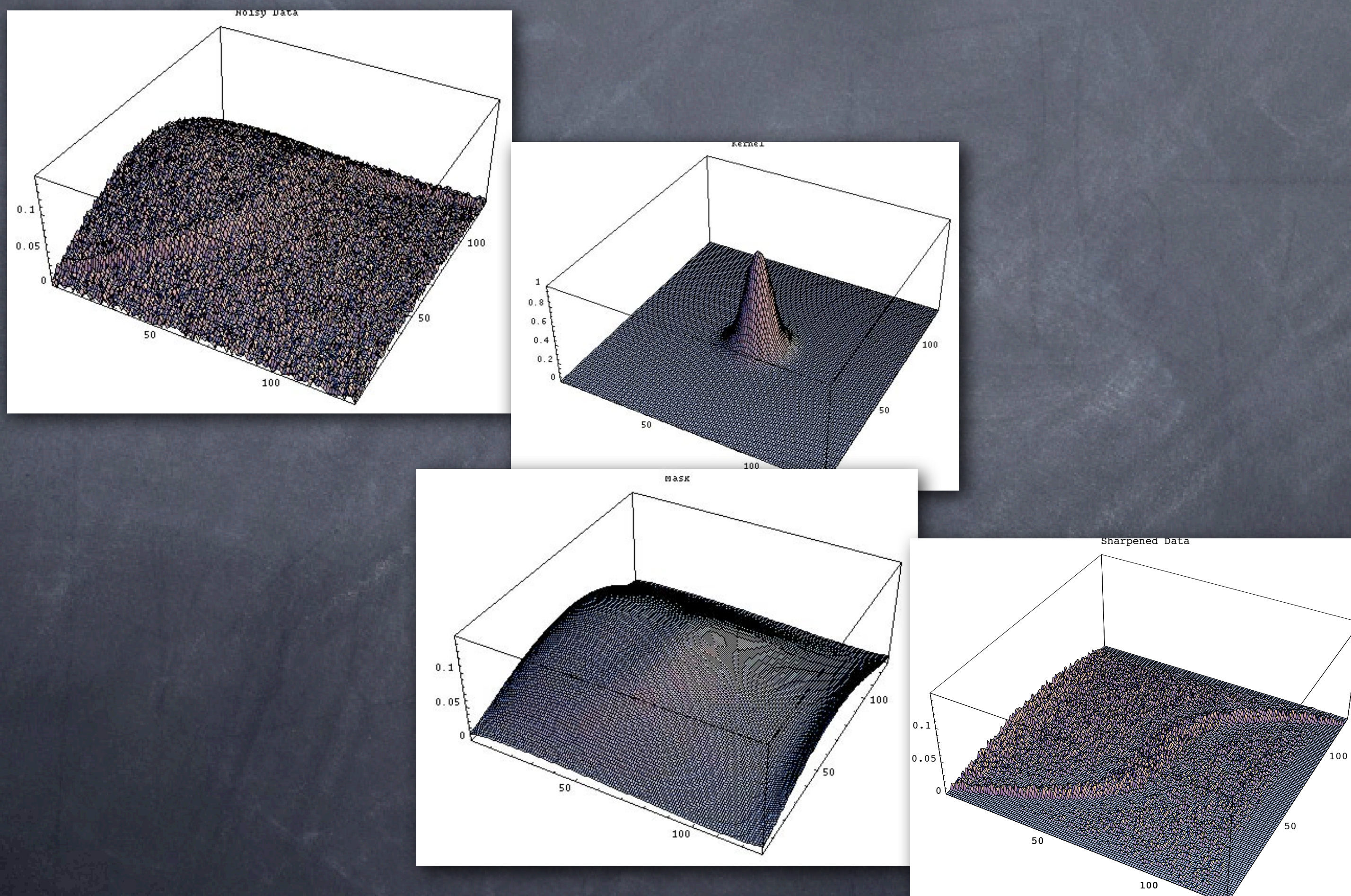
The entropy is then,

$$S_U = -N_b \times (N_p / N_b) \ln(N_p / N_b) = -N_p \ln (N_p / N_b) = N_p \ln(N_b) - N_p \ln(N_p)$$

As we can see, the entropy value for the uniform configuration depends on both, the number of points and bins.

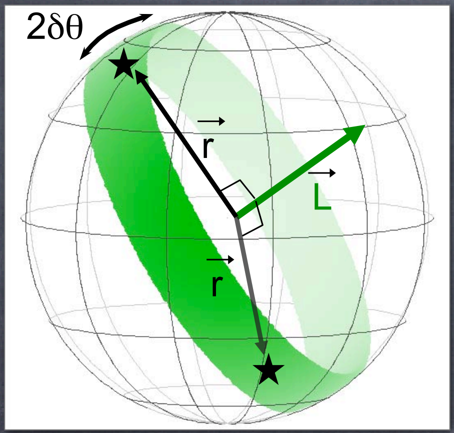
Search Techniques

Unsharp masking

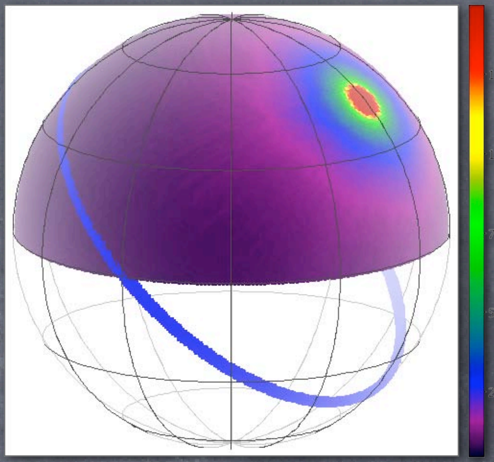


Search Techniques

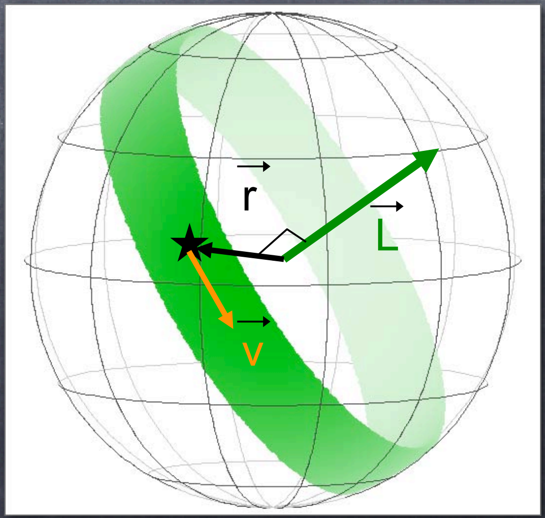
Modified Great Circle Method



Original method



Polar count map



Modified method

Basic Lessons

- ✔ We have to be clever

  The Gaia database will be a treasure trove of information about our Galaxy, but extracting knowledge from it won't be straightforward.

- ✔ Use a "holisitc" approach

  Devise search strategies that employ as much of Gaia information at once, don't throw away useful information.

- ✔ Learn to live in observable space

  As much as it is possible, we should conduct our studies directly in the space of observables. Models have infinite signal to noise ratio, observations don't.

MNRAS (2005) 359, 1287

"A theoretical work is a well thought chain of logic reasonings, that are believed by no one, except the work's author.
An observational work is a collection of noisy measurements, that are believed by everybody, except the work's author".

Harlow Shapley

End of the story!

(at least for now)

MNRAS (2005) 359, 1287

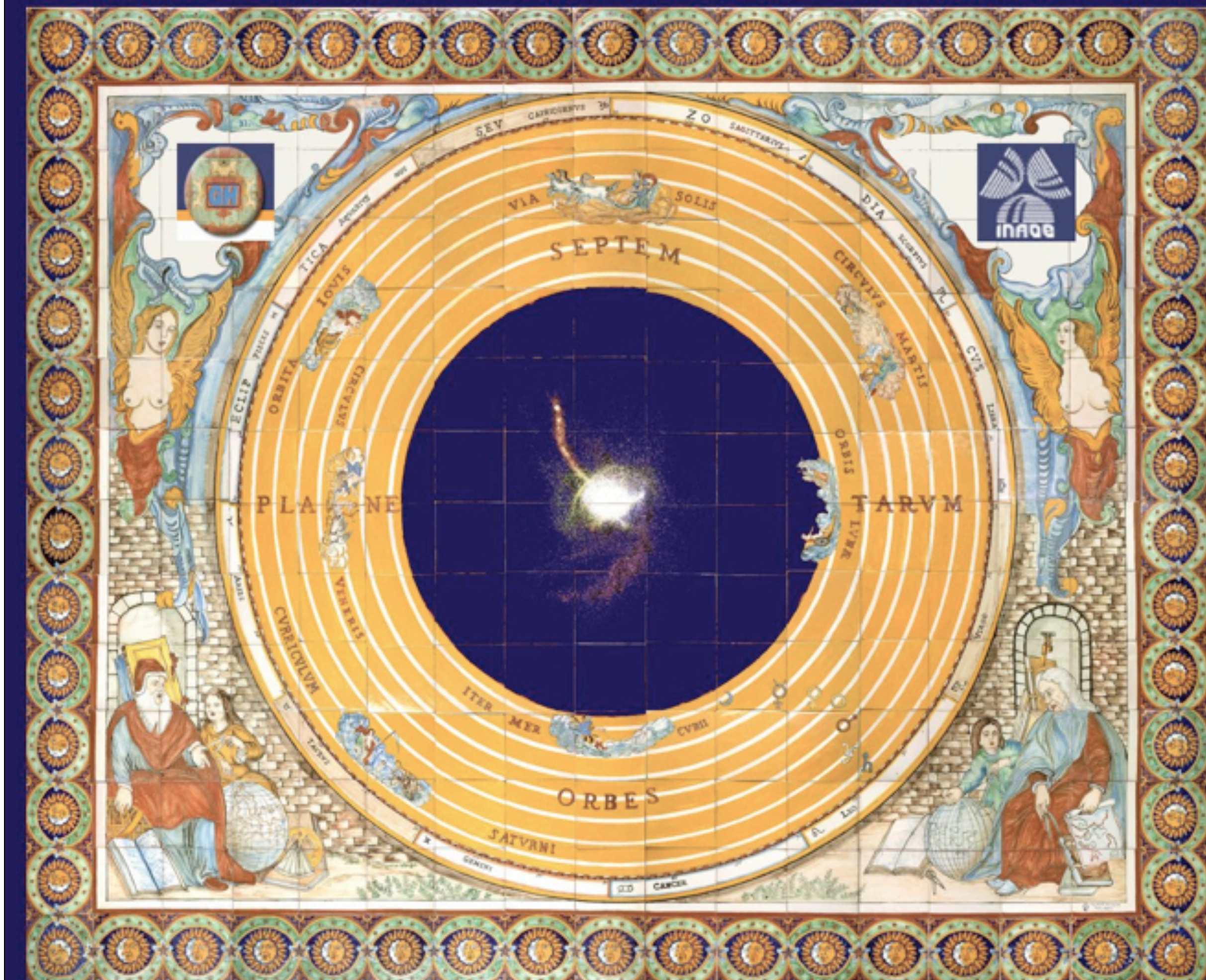
End of the story!

(at least for now)

International School on Galactic and Cosmological N-Body Simulations

July 23 – August 5, 2006 Tonantzintla – Puebla, México

http://www.inaoep.mx/gh2006/



Lecturers:

Luis Aguilar(UNAM/México)
Lia Athanassoula(Marseille/France)
Walter Dehnen(Leicester/UK)
Julio Navarro(Victoria/Canada)
Peter Teuben(Maryland/USA)

Topics

- Introduction: The Art of N-body simulationns
- A good beginning: The art of setting up inital conditions
- N-body codes: The garden of parallel trees
- Making sense of all: Analysis tools
- Is this of any use?: Modeling galactic and cosmological phenomena

Local Organizing Committee

Luis Aguilar
Alberto Carramiñana
Omar López Cruz
Raúl Mújica
Ivanio Puerari
Jean Charles Lambert

Tile Mosaic: Ptolemaic System, ca. 1661
Mexican Talavera tile mosaic by: *Talavera de la Luz*, Puebla, México
Poster design: *Alejandro González, Liliana Hernández and Luis Aguilar*

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