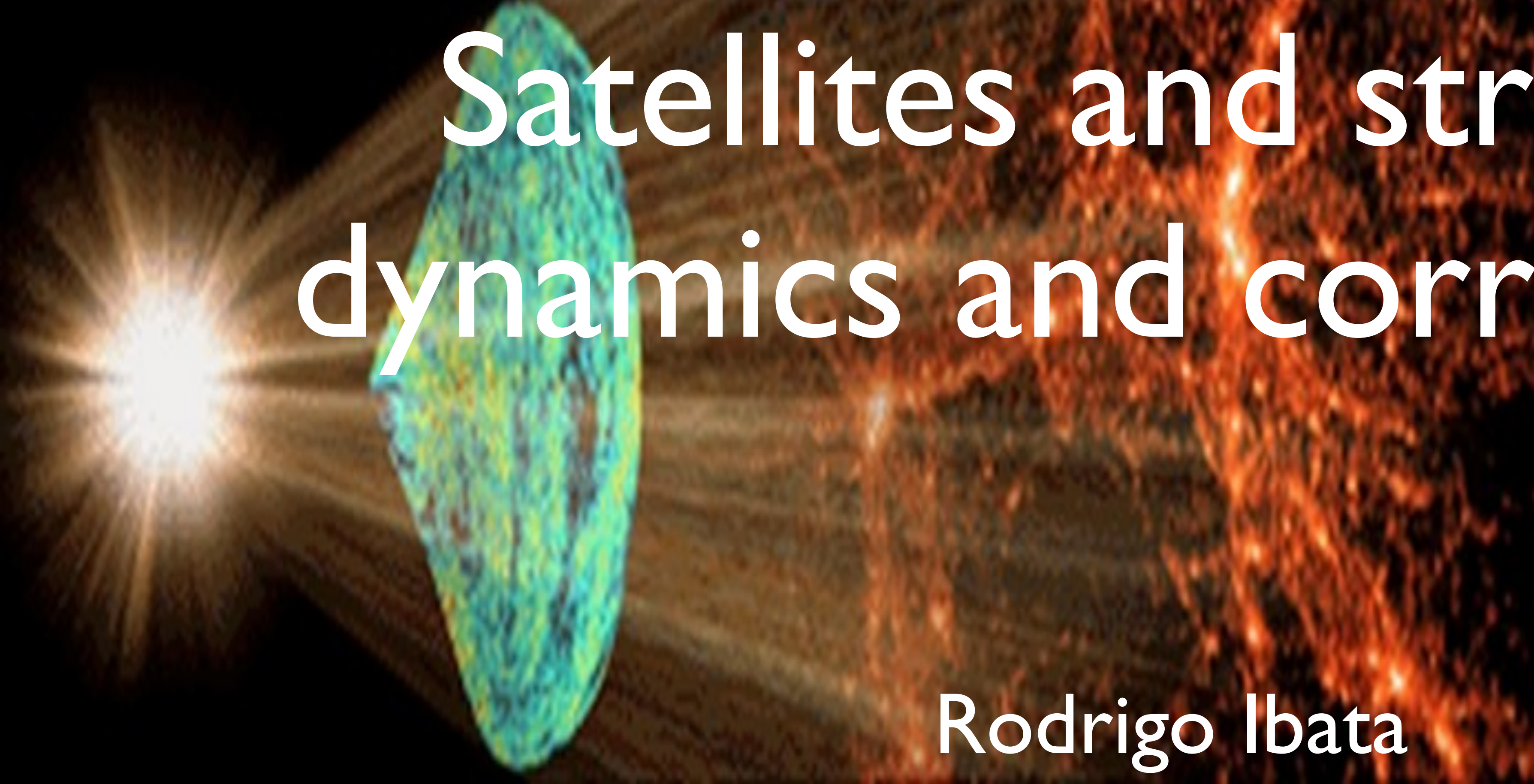
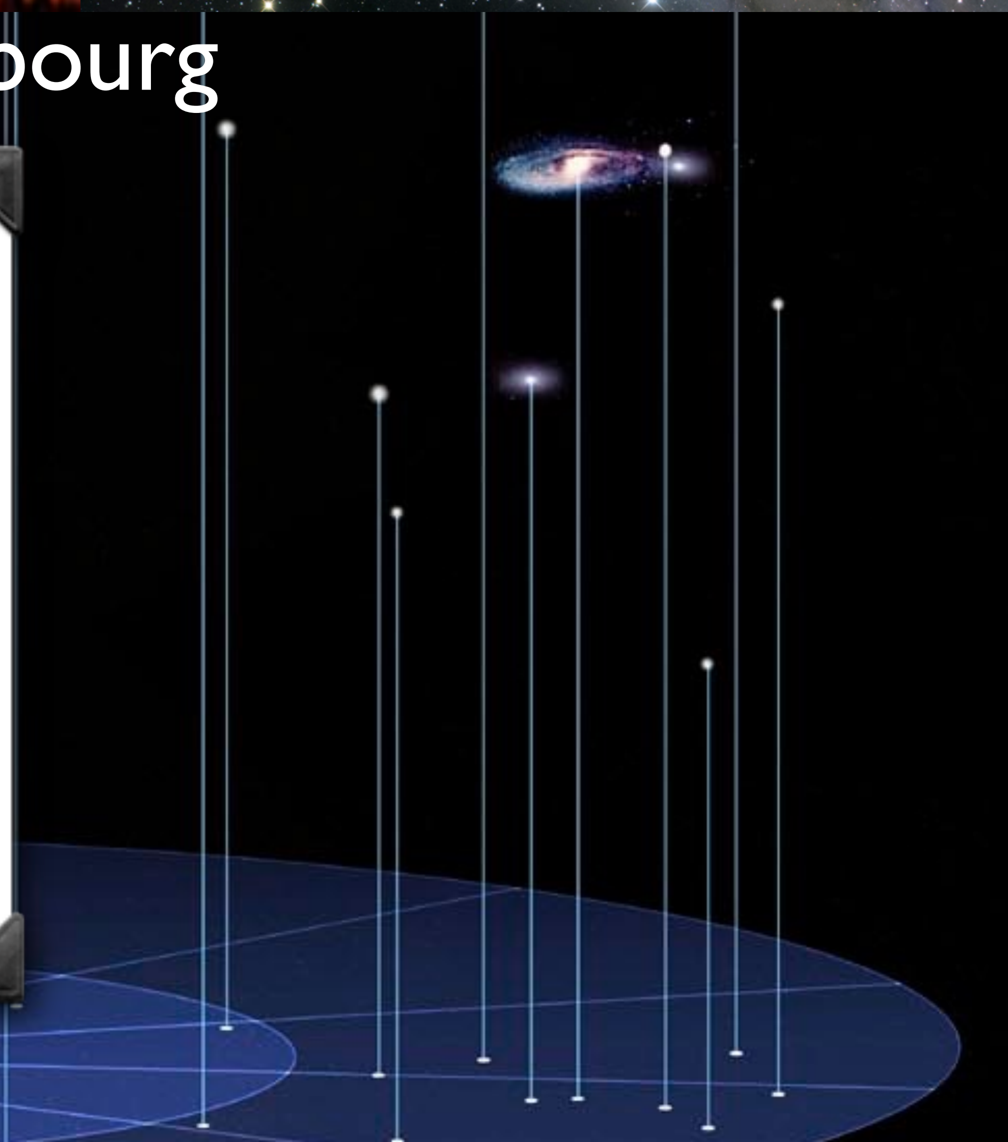
Satellites and streams: dynamics and correlations



Rodrigo Ibata

Observatoire de Strasbourg

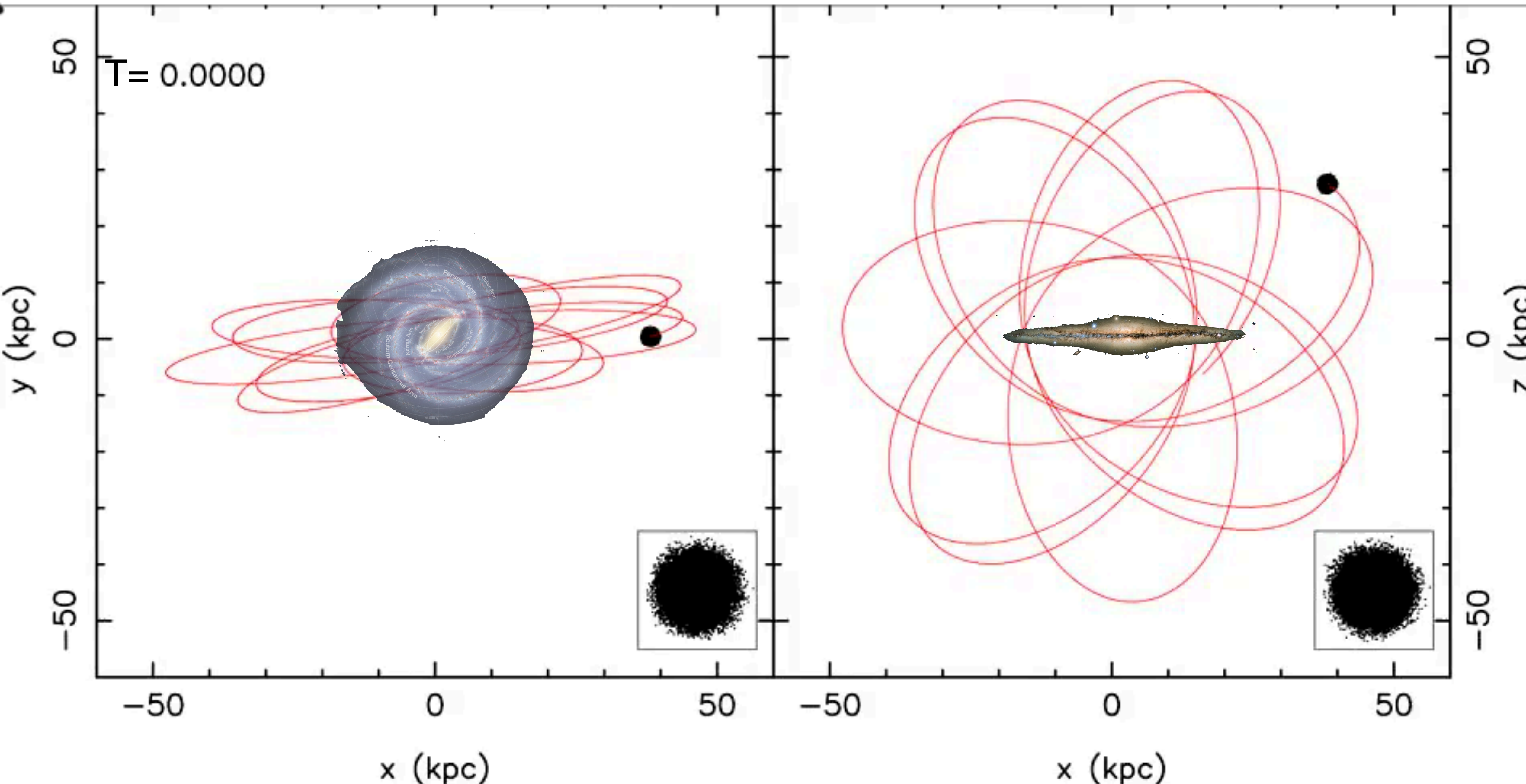


+ Benoit Famaey, Guillaume Thomas & Neil Ibata

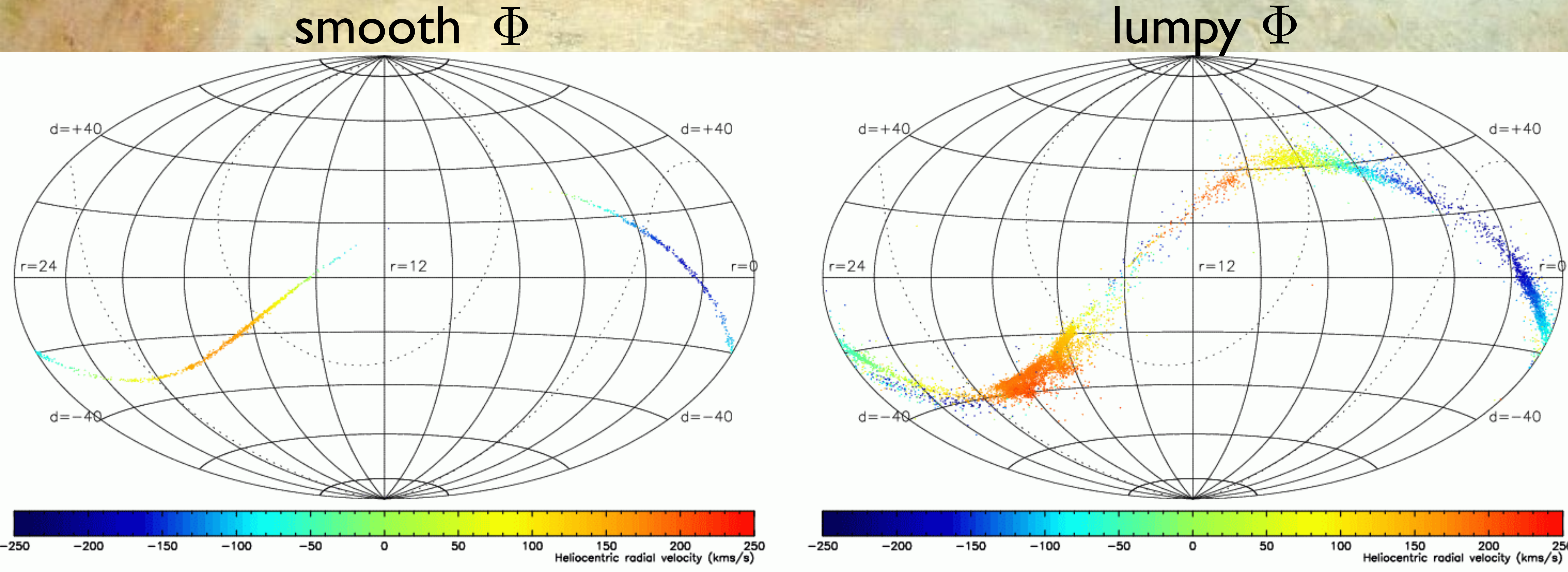
Streams are about the only reliable means to measure mass at large distances…

cf.

$$\frac{GM(r)}{r} = -\overline{v_r^2}\left[\frac{\mathrm{d}\ln\rho}{\mathrm{d}\ln r} + \frac{\mathrm{d}\ln\overline{v_r^2}}{\mathrm{d}\ln r} + 2\left(1 - \frac{\overline{v_\theta^2}}{\overline{v_r^2}}\right)\right],$$



Stellar streams as seismometers



Ibata, Lewis, Irwin, Quinn (2002)
Johnston et al. (2002)
Dalal & Kochanek (2002)
Carlberg (2012, 2013)

Or probes of exotic dark matter (Kesden & Kamionkowski 2006)

What information can we recover from stellar streams?

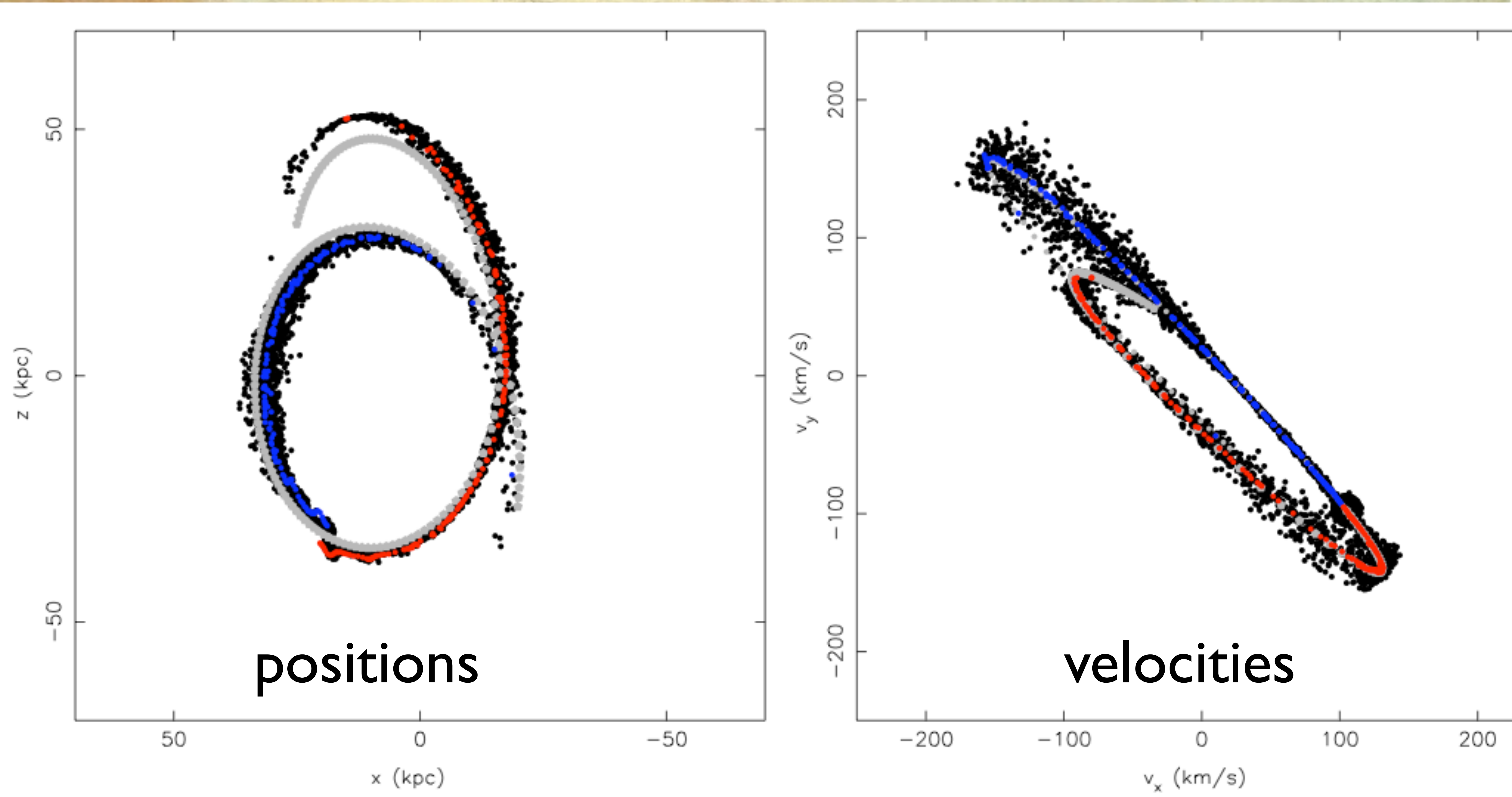
- How unique is this stream?
- What can we derive about the dark mass distribution from this image?
- Can we derive any information about the progenitor orbit?

distributions

costly...

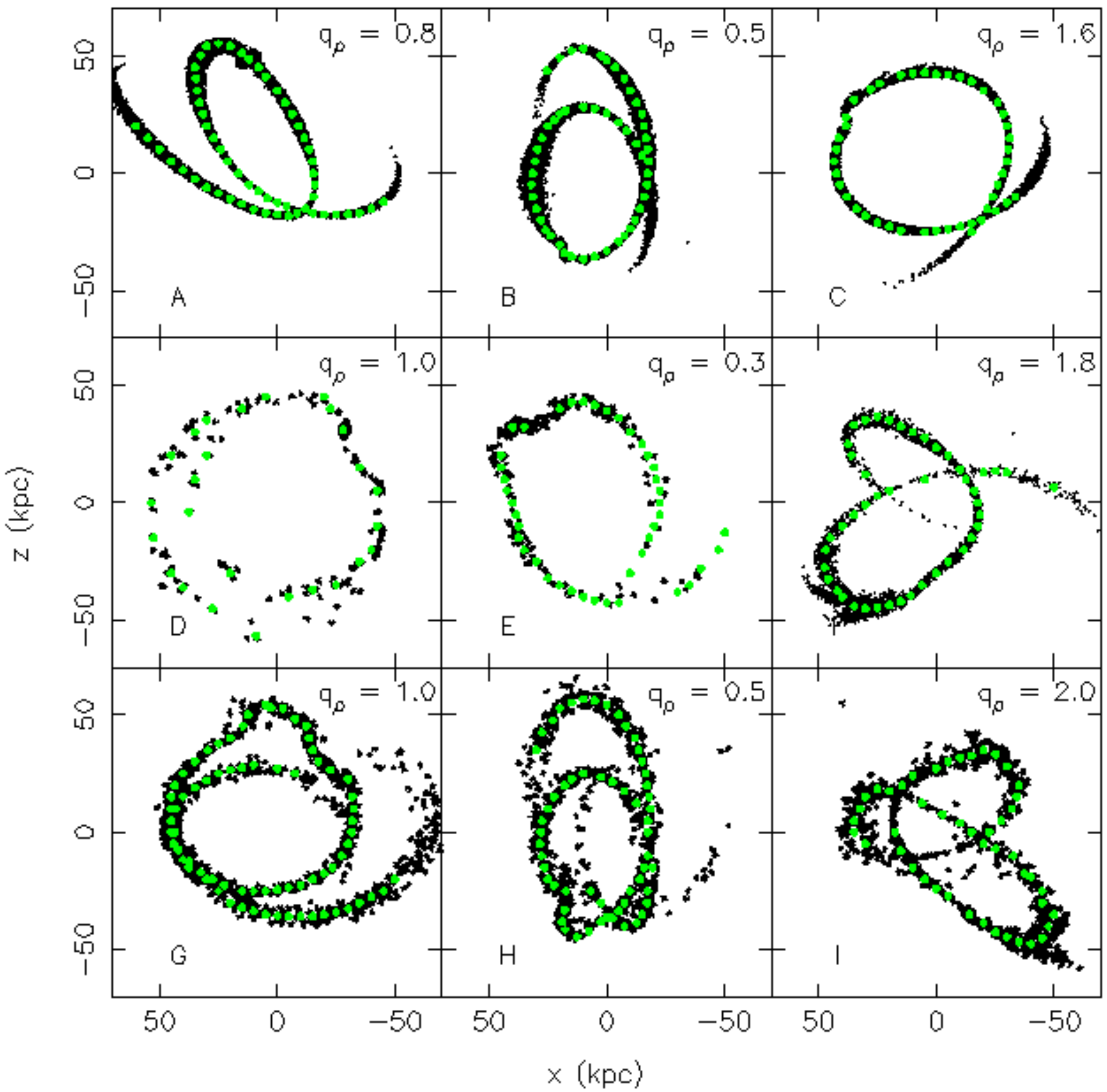
Modelling escape from satellites...

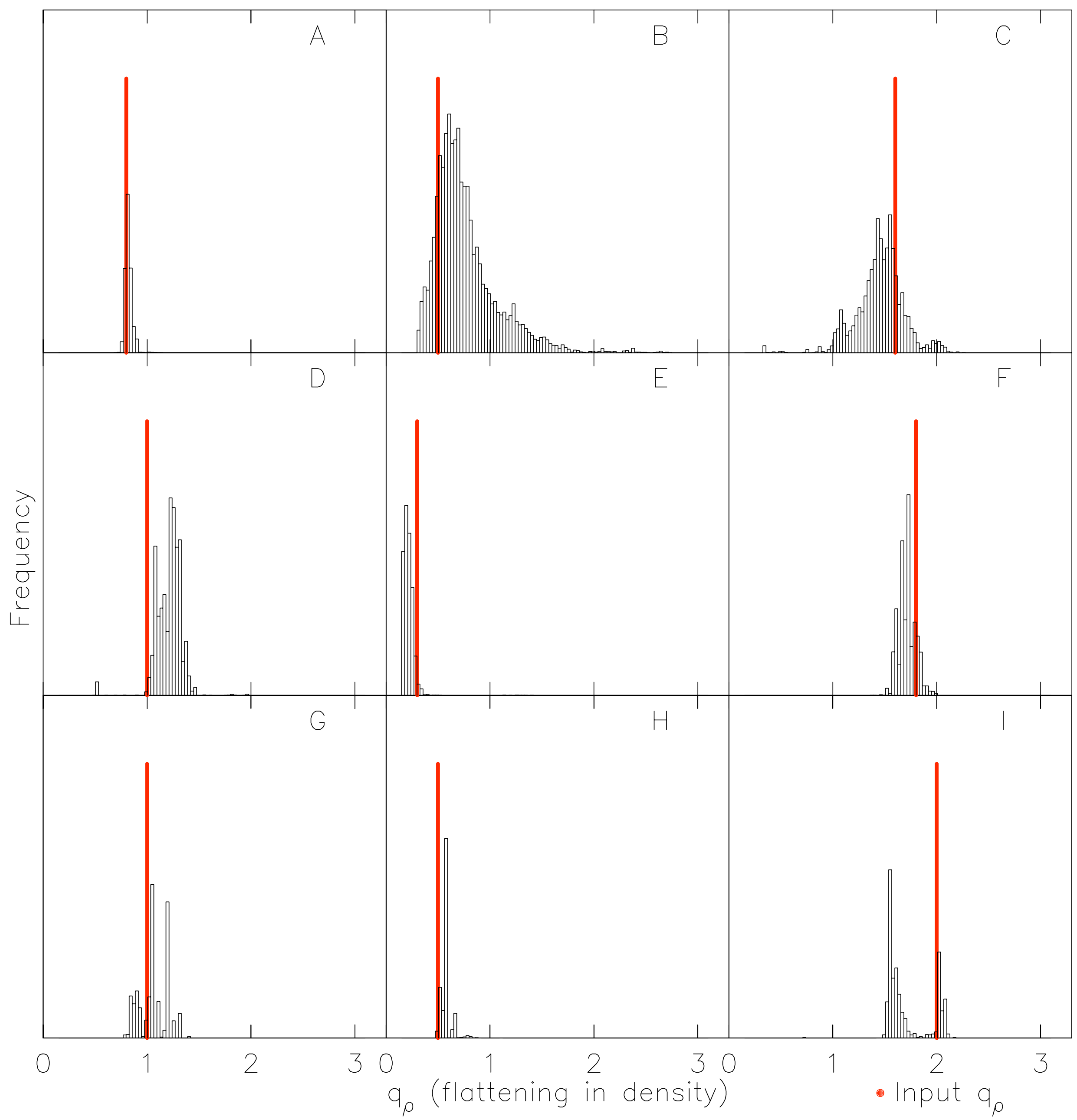
(Varghese, Ibata & Lewis 2011)



…enables the exploration of parameter space

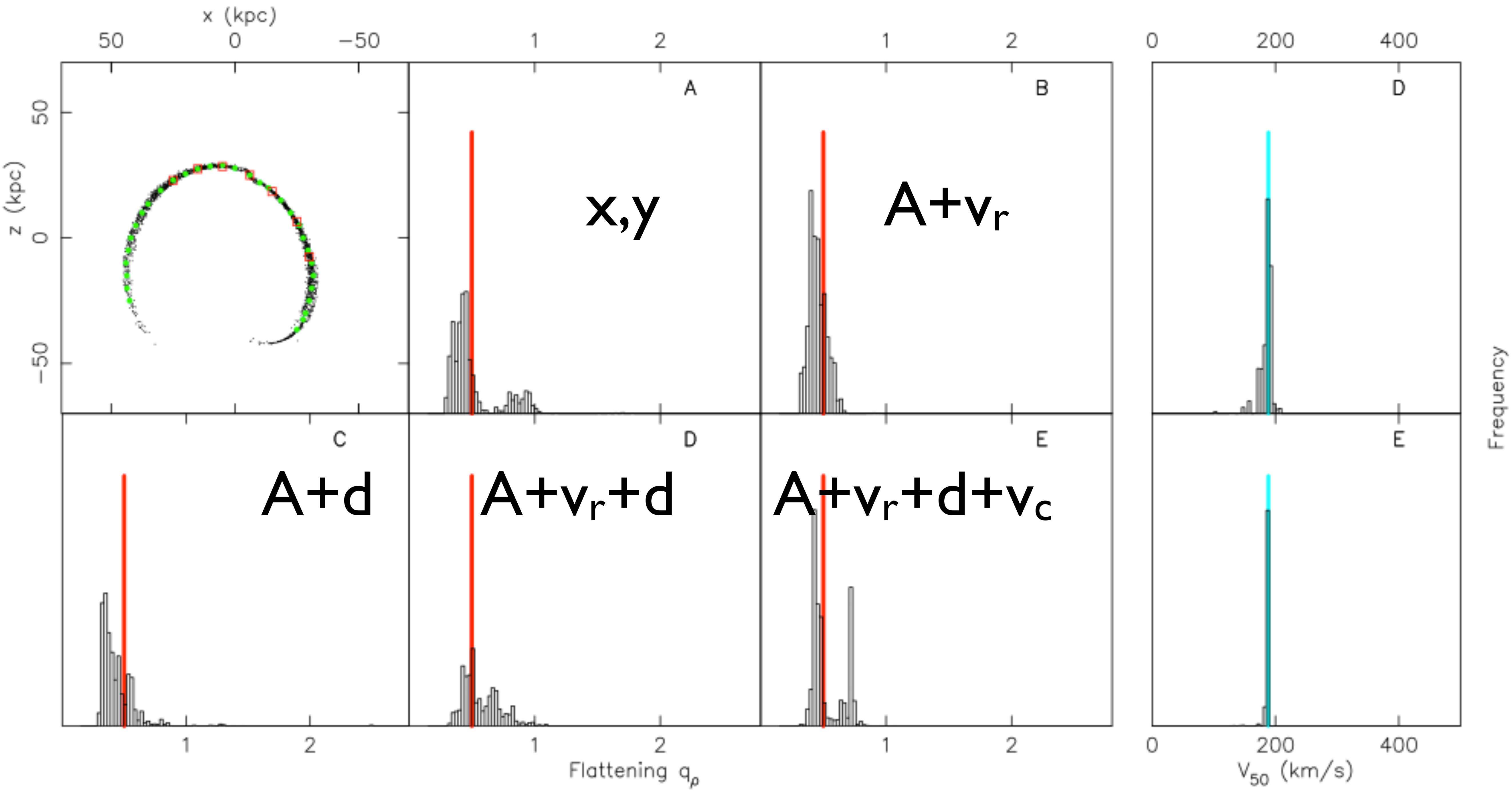
Test streams (in axisymmetric hosts)





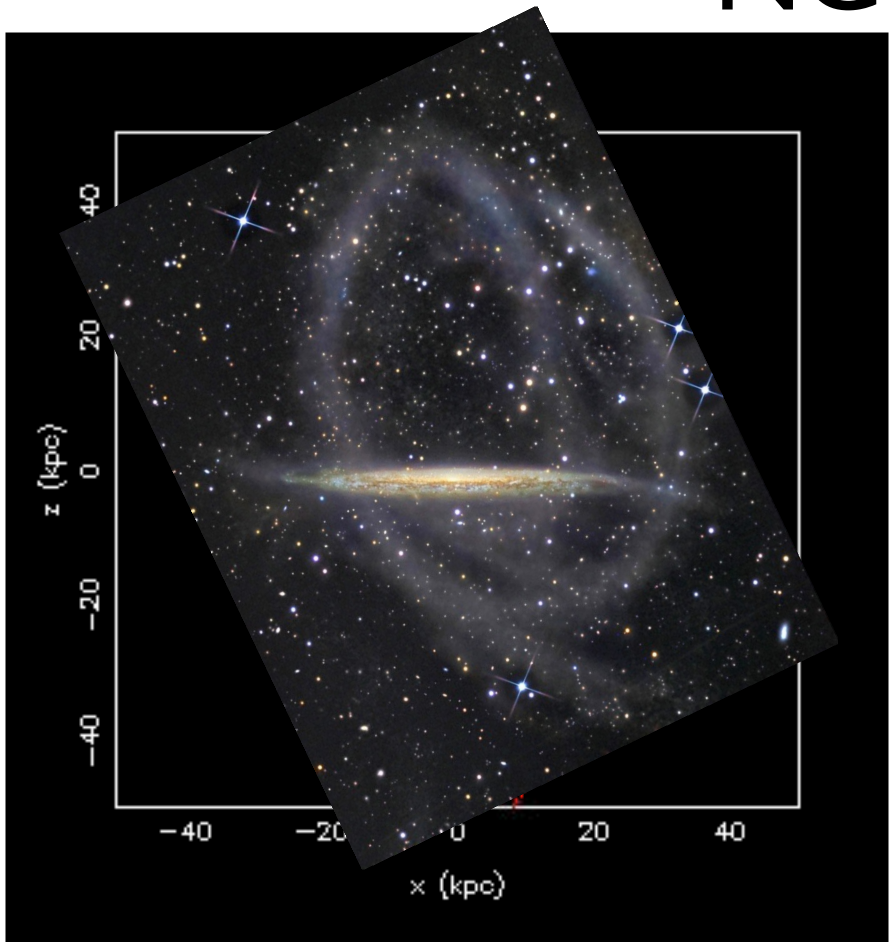
MCMC solutions

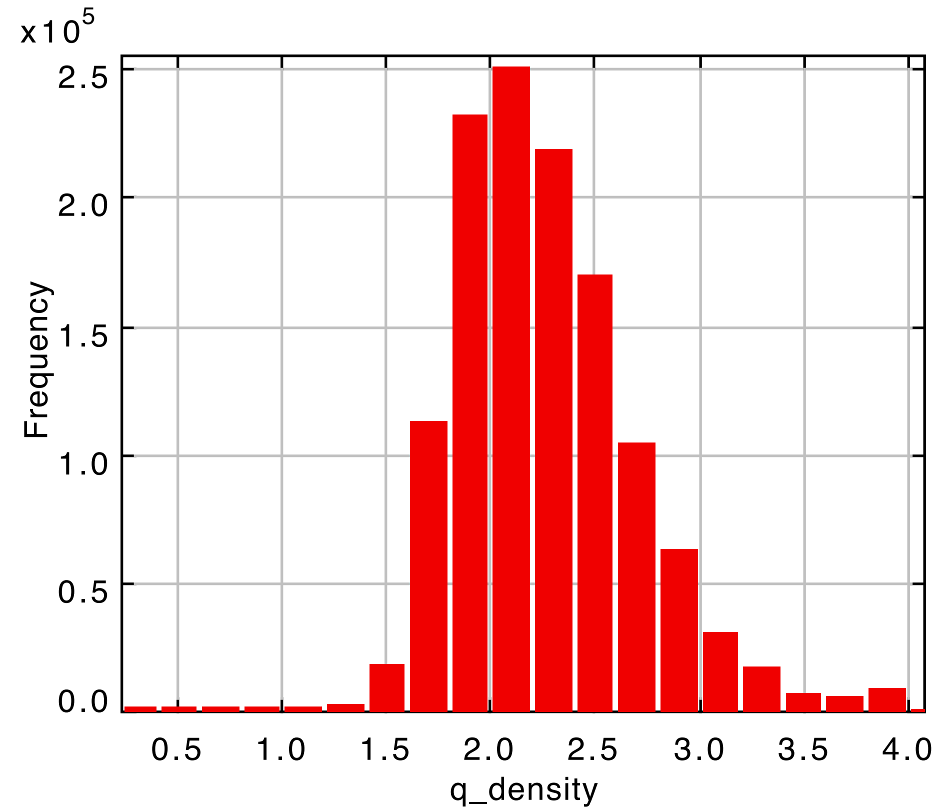
The shorter the stream the more difficult things become

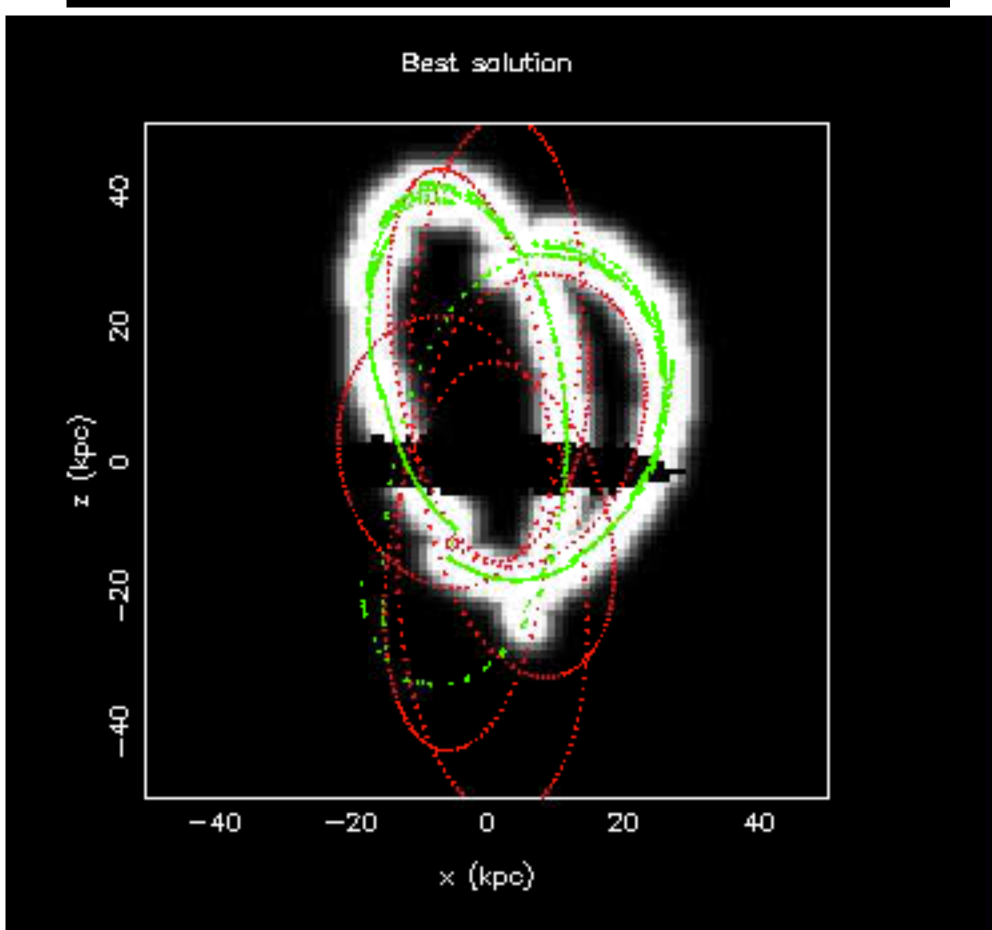


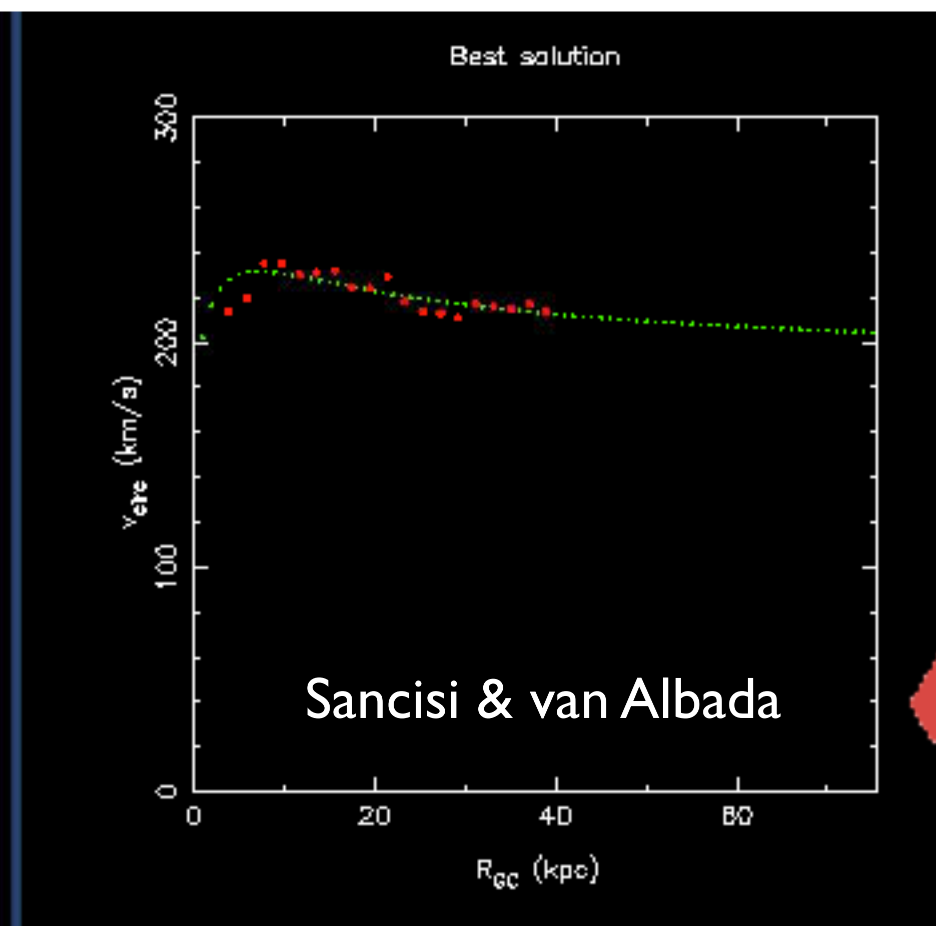
its the number of turning points that really matter.

NGC 5907 (difficult as progenitor not visible)





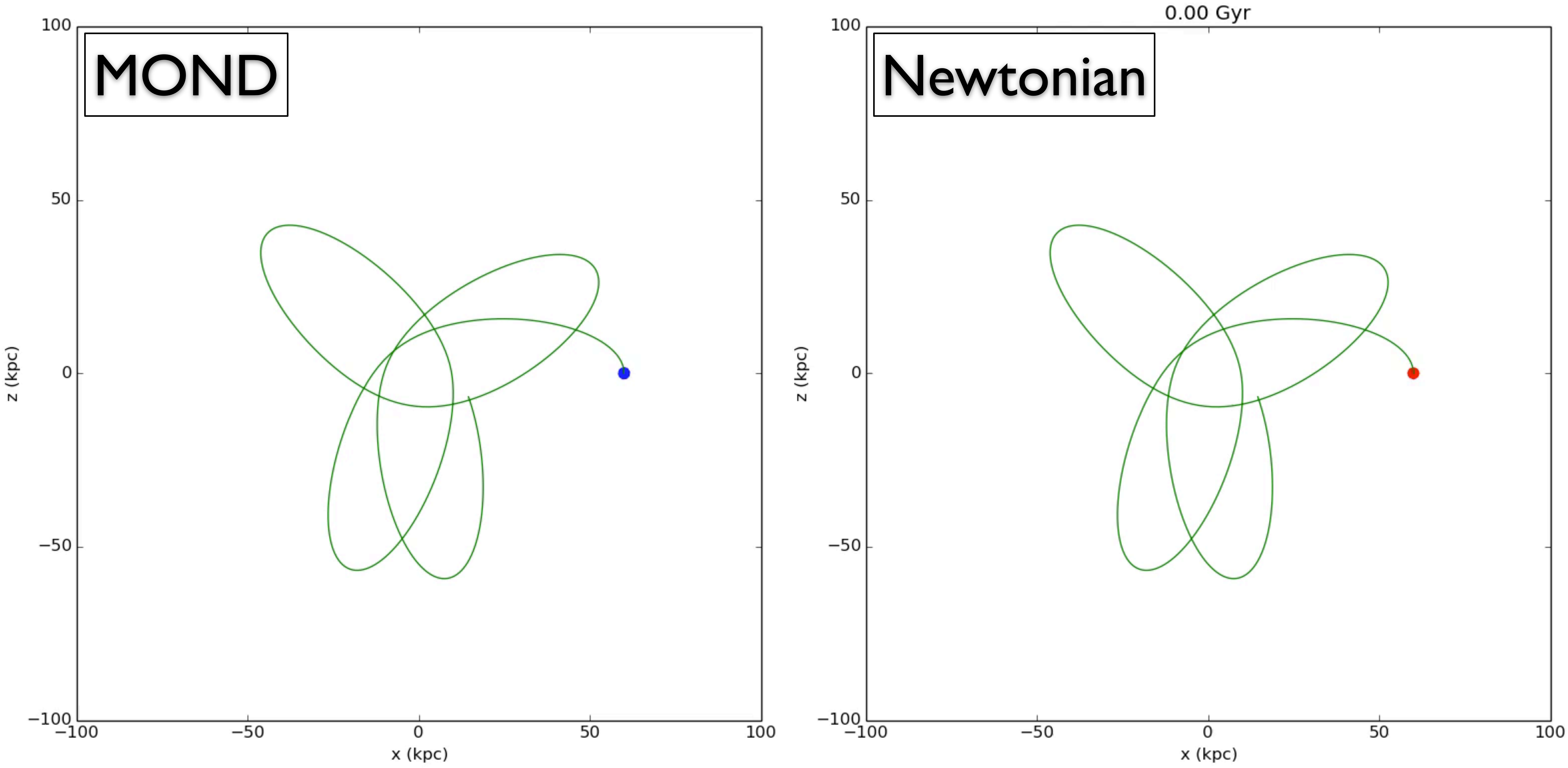




MCMC stream path fitting...

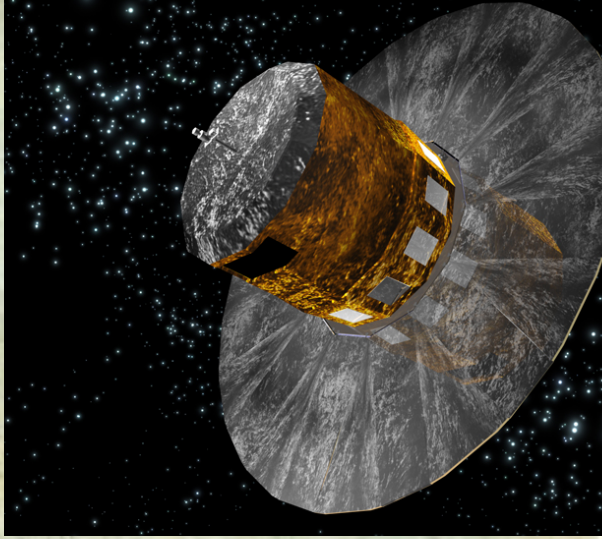
- Even pure projections of some stream systems allow us to uncover the shape of the dark matter distribution. Very promising for next-generation surveys!
- With additional kinematic and/or distance information, we can recover the density profile in a particularly interesting radial range where there are virtually no other tracers.
- Can switch on dynamical friction
- Works also for triaxial systems...
- Have implemented MOND option

with Guillaume Thomas & Benoit Famaey:



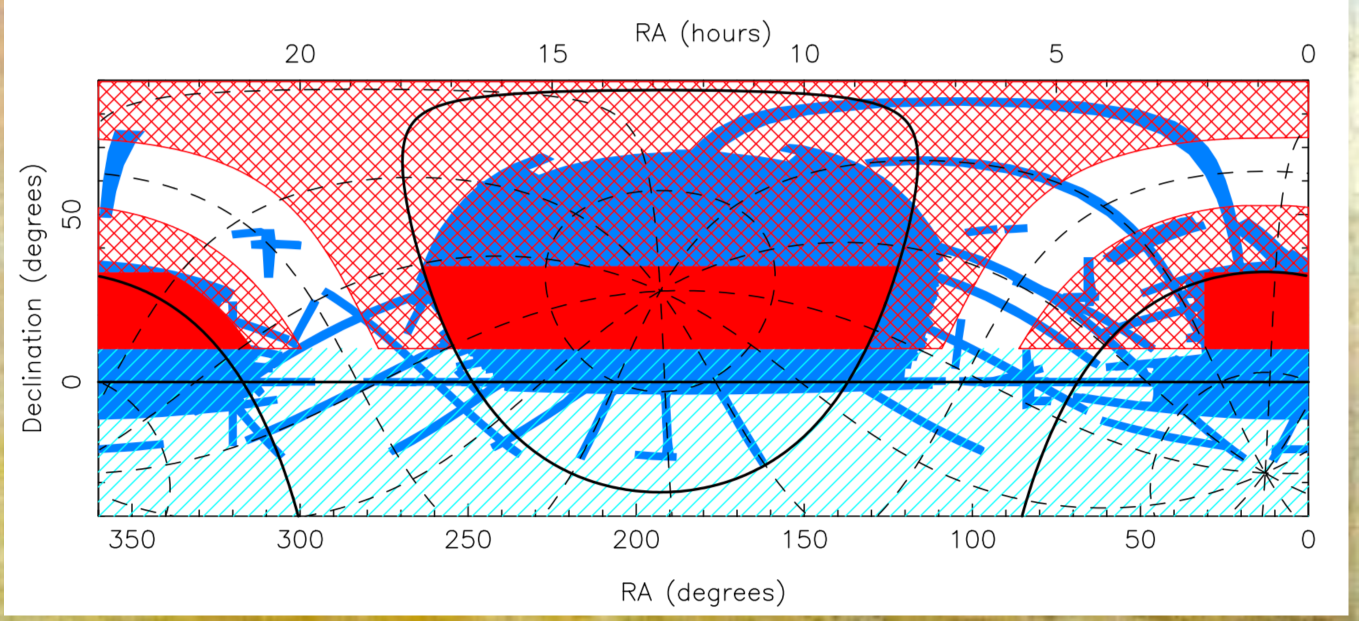
using “Phantom of Ramses” code by Lüghausen, Kroupa & Famaey

Modelling the Milky Way with Gaia



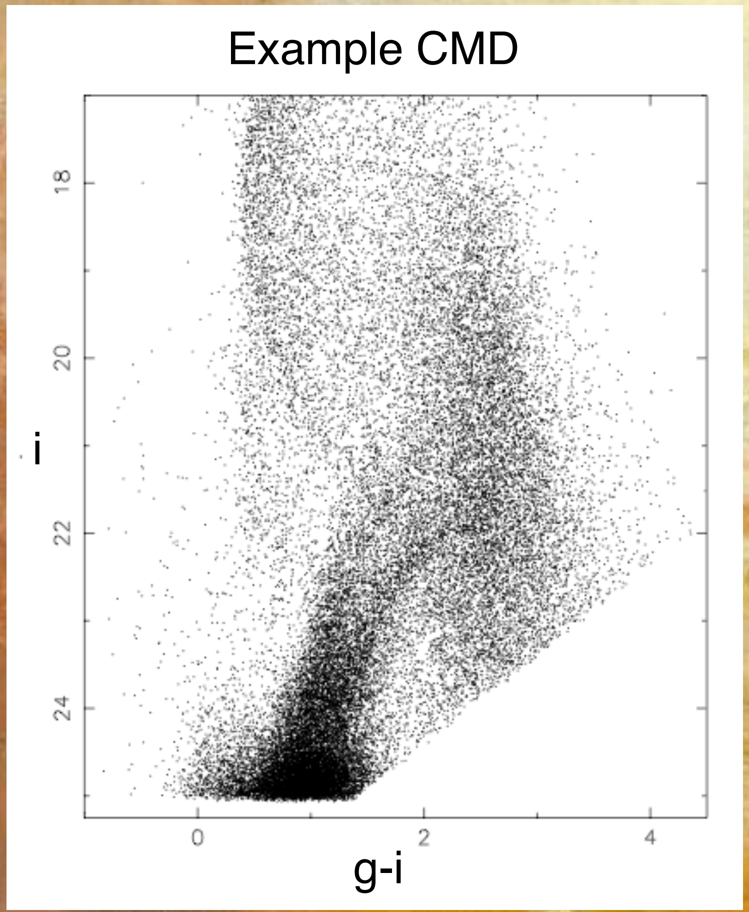
- For all but the nearest stars, certain phase-space measures will have large uncertainties.
- Stream fitting works transparently with any combination of data. Advantage over other approaches is the ease with which we can include uncertainty estimates.
- Currently developing an iterative outside-in scheme. Stream detection and halo fitting can go hand-in-hand.
- Complementary survey:

CFHT-Luau:
u-band for photometric
metallicities & distances

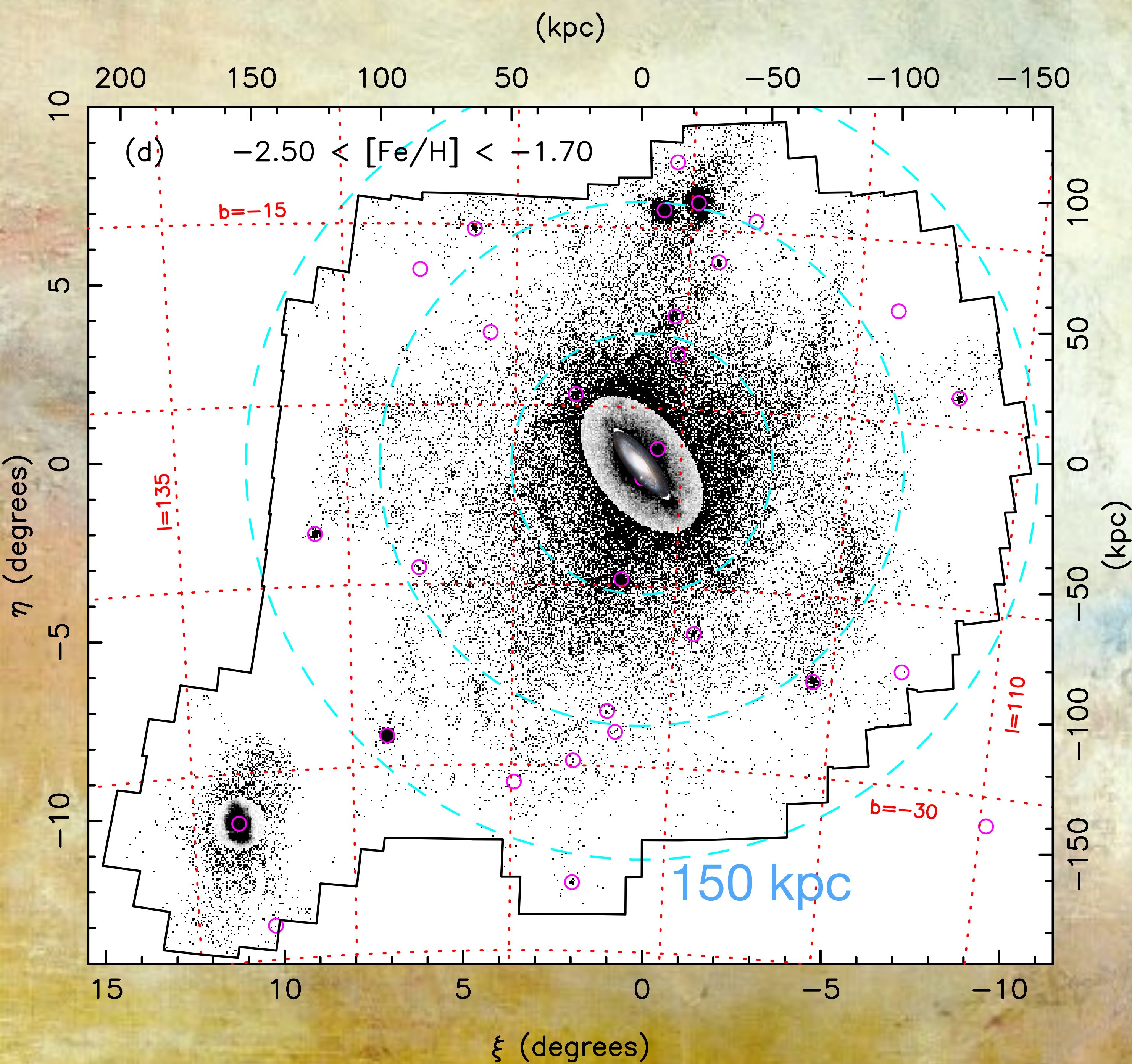


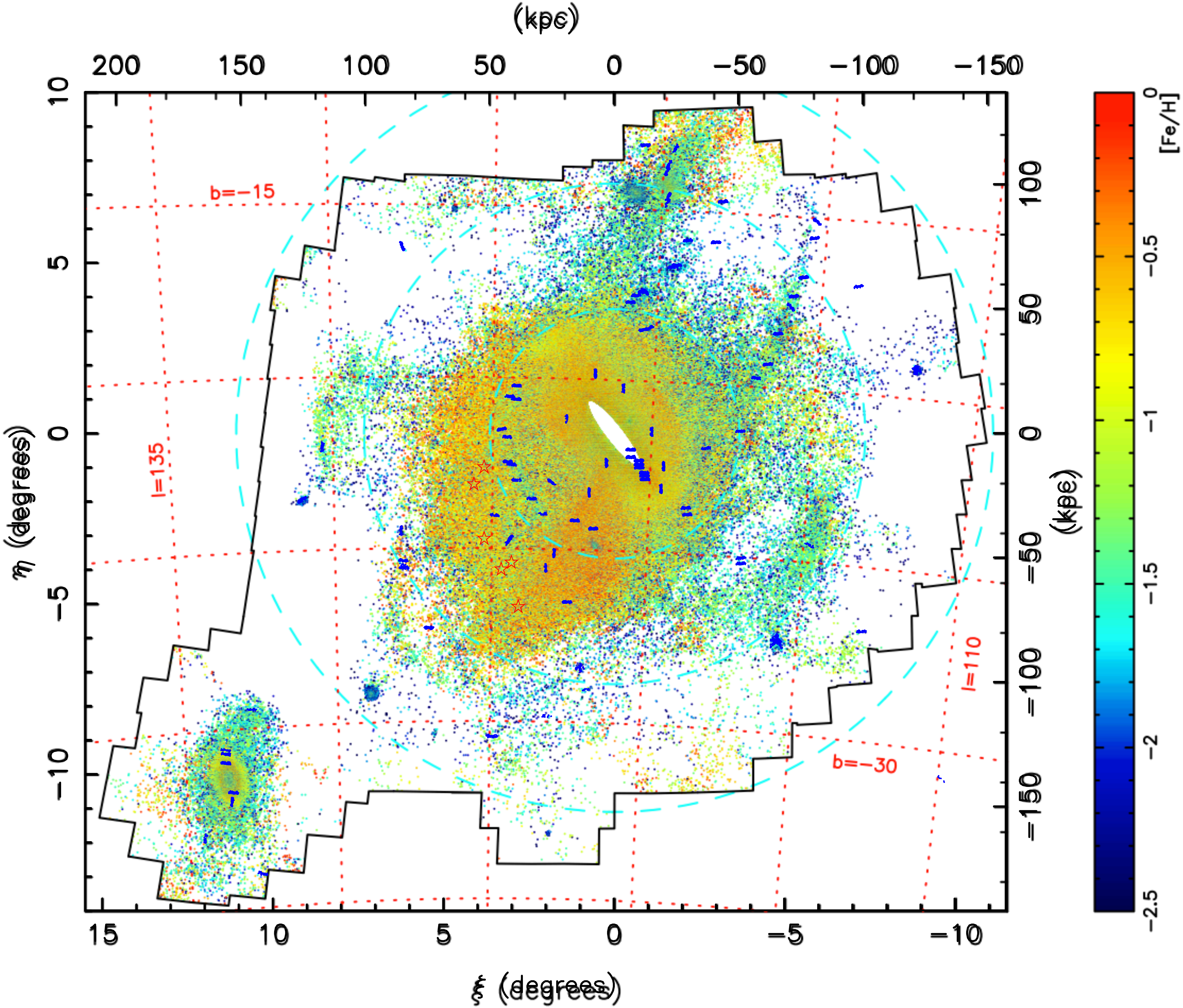
Streams & satellites in Andromeda

The Pan-Andromeda Archaeological Survey (PAndAS)



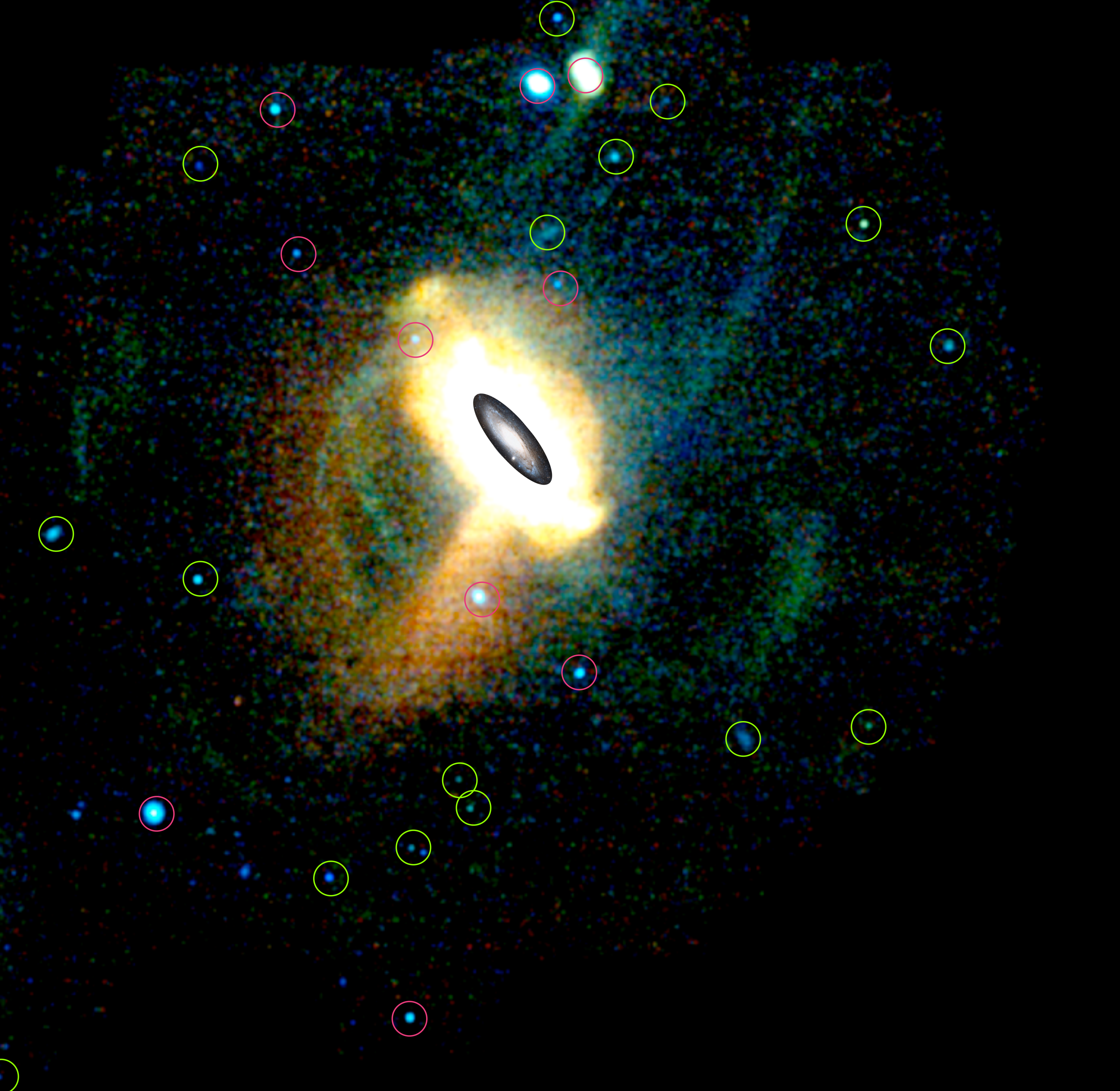
- g,i ➔ [Fe/H]
- foreground & background contamination model (Martin et al. 2013)





(kpc)
200
150
100
50
0
−50
−100
−150
10
5
0
−5
−10
η (degrees)
ξ (degrees)
15
10
5
0
−5
−10
100
50
0
−50
−100
−150
(kpc)
b=−15
b=−30
l=135
l=110
0
−0.5
−1
−1.5
−2
−2.5
[Fe/H]

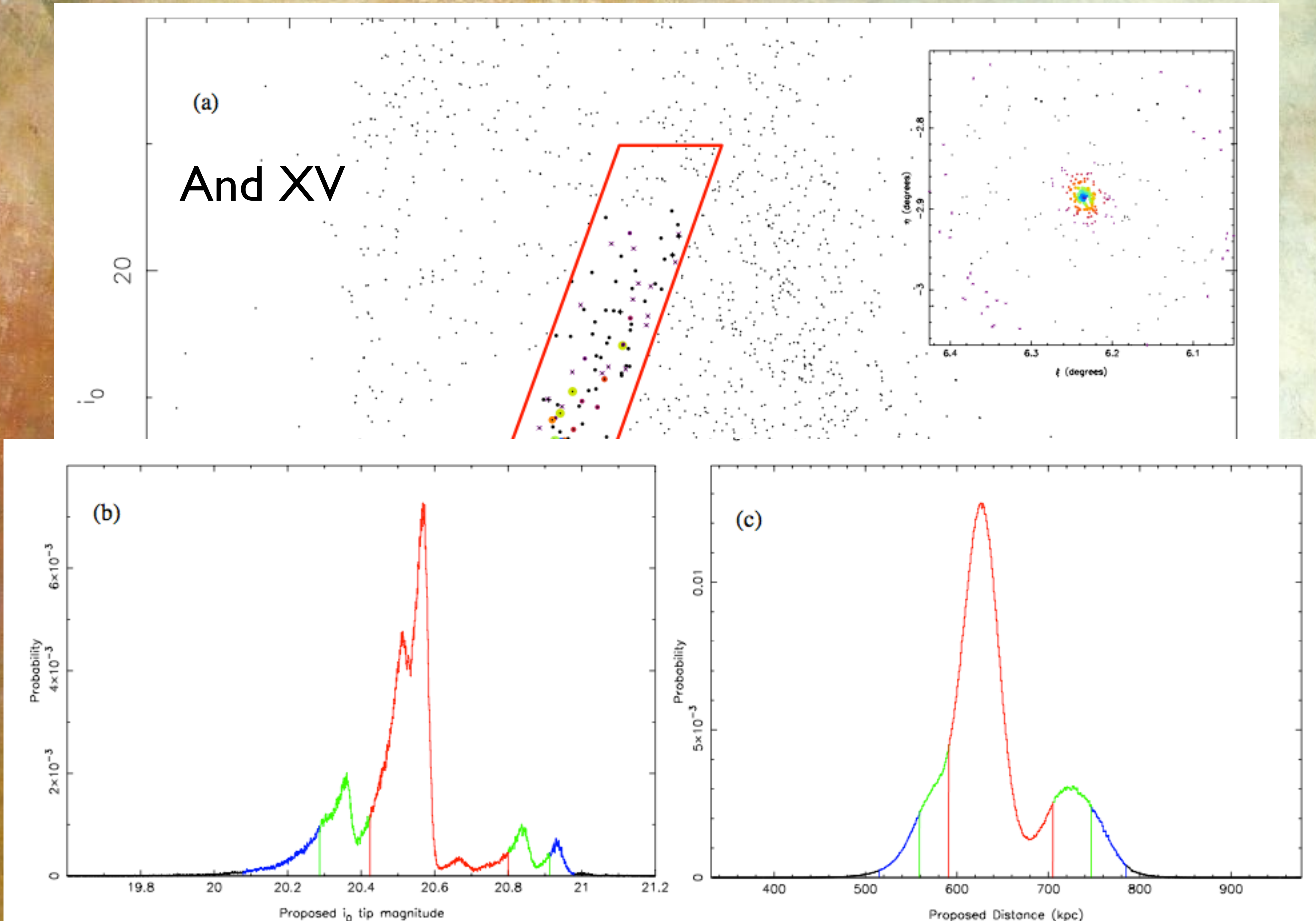
CFHT



MCMC fitting of RGB tip mag.

Anthony Conn et al. 2011,2012,2013

- Previous TRGB algorithms were not appropriate for task
- Model for the background CMD + spatial distribution
- Model for the satellite RGB LF
- Prior fit on spatial distribution of satellite
- Naturally accounts for discreteness of stars

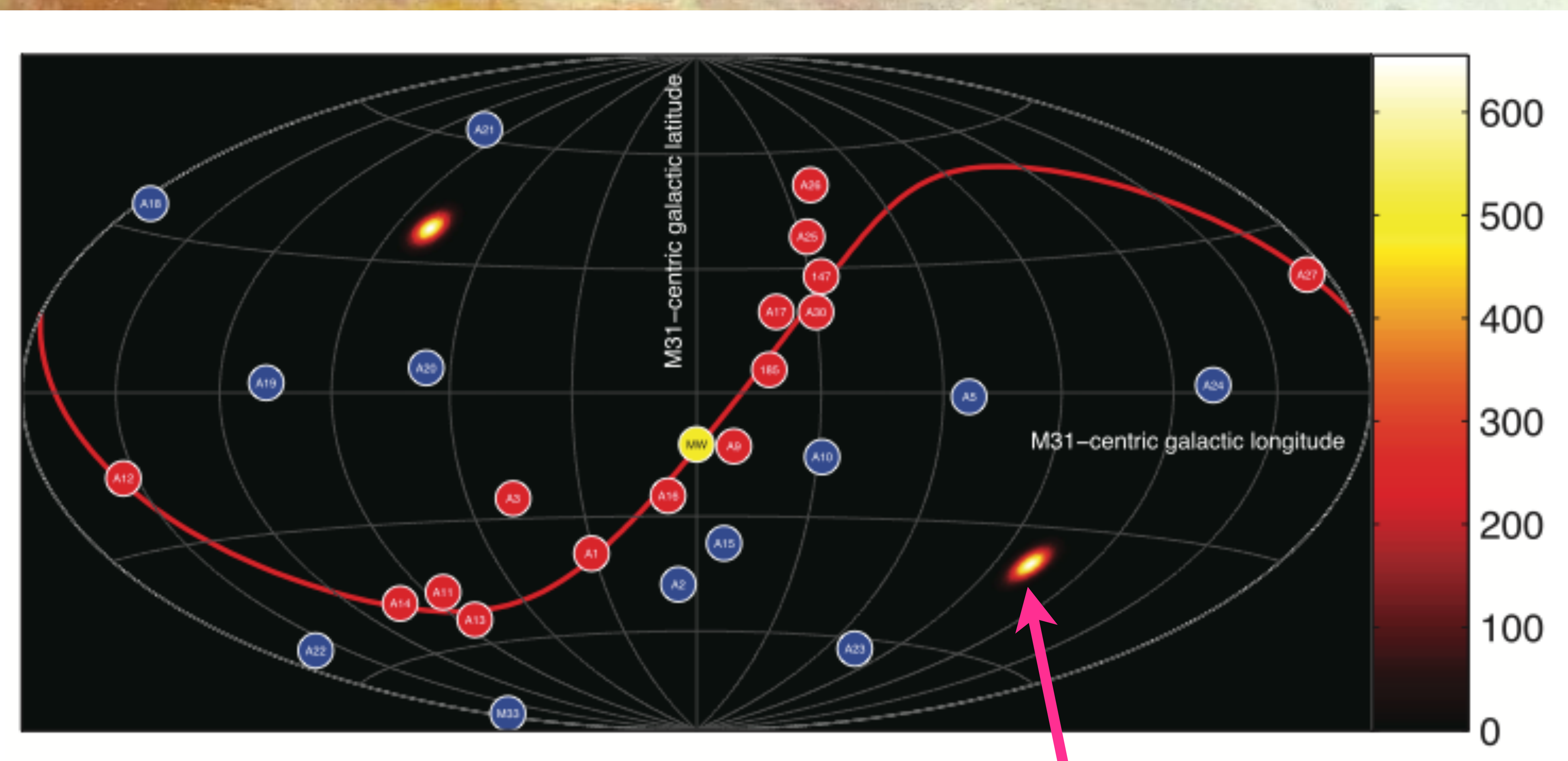


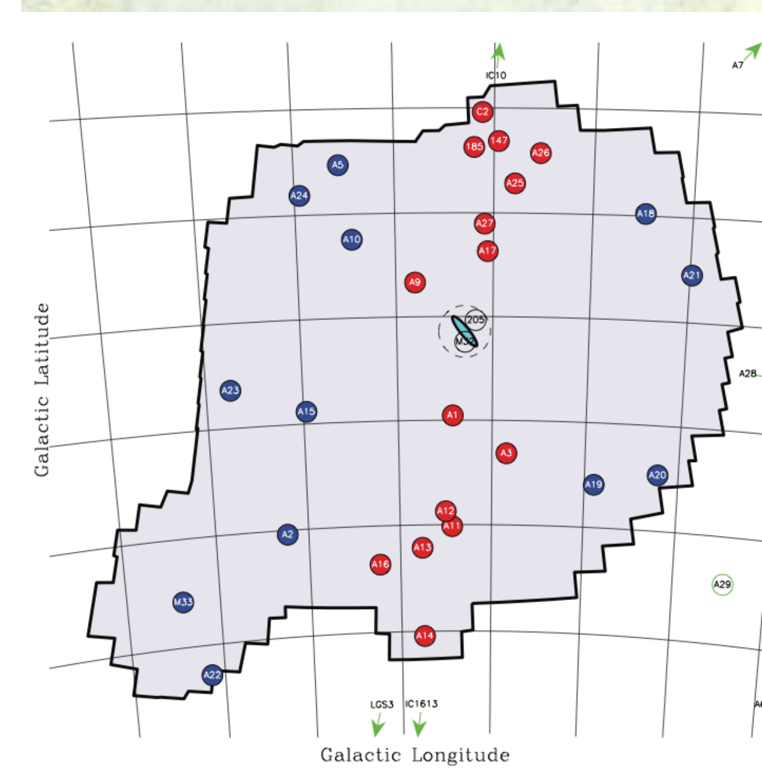
And XV
(a)
20
i0
η (degrees)
−2.8
−2.9
−3
6.4
6.3
6.2
6.1
ξ (degrees)
(b)
Probability
6×10−3
4×10−3
2×10−3
0
19.8
20
20.2
20.4
20.6
20.8
21
21.2
Proposed i0 tip magnitude
(c)
Probability
0.01
5×10−3
0
400
500
600
700
800
900
Proposed Distance (kpc)

Are M31 satellites spatially aligned?

- generate 27 galaxies at random from distance PDFs, and find plane containing lowest rms to sub-sample of 15
- repeat 1000 times to find PDF of rms thickness

rms thickness: 12.6±0.6kpc (<14.1kpc 99% conf.)



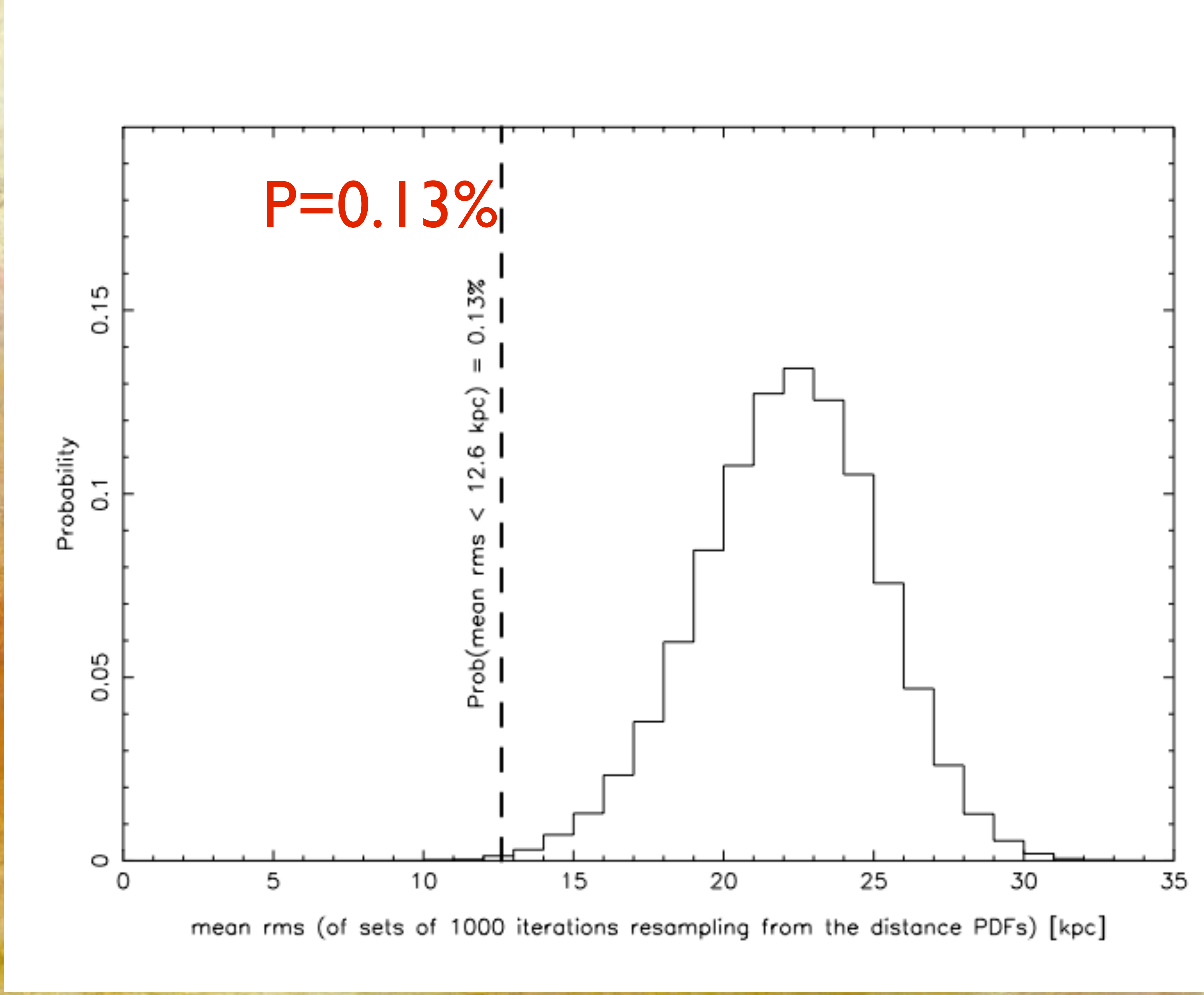


$(\ell_{M31} = 100\overset{\circ}{.}9 \pm 0\overset{\circ}{.}9, b_{M31} = -38\overset{\circ}{.}2 \pm 1\overset{\circ}{.}4)$

Monte Carlo experiments

What is the probability of the spatial alignment?

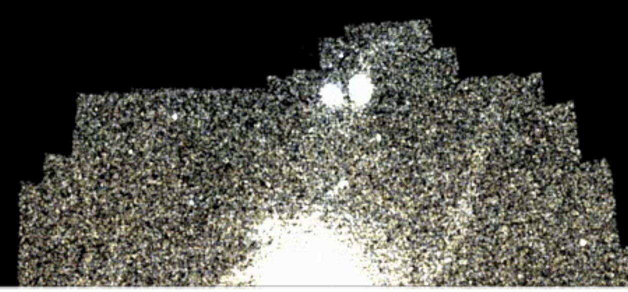
- generate 27 fake satellites:
  - select satellite at random
  - select random orientation wrt M31
  - keep if within PAndAS
- treat as if real data (i.e. draw 1000 times from distance PDF and measure rms)
- repeat 100000 times



In PAndAS survey we find a planar alignment:

~50% of satellites
~300 kpc diameter
12.6 kpc rms thickness
co-rotating structure

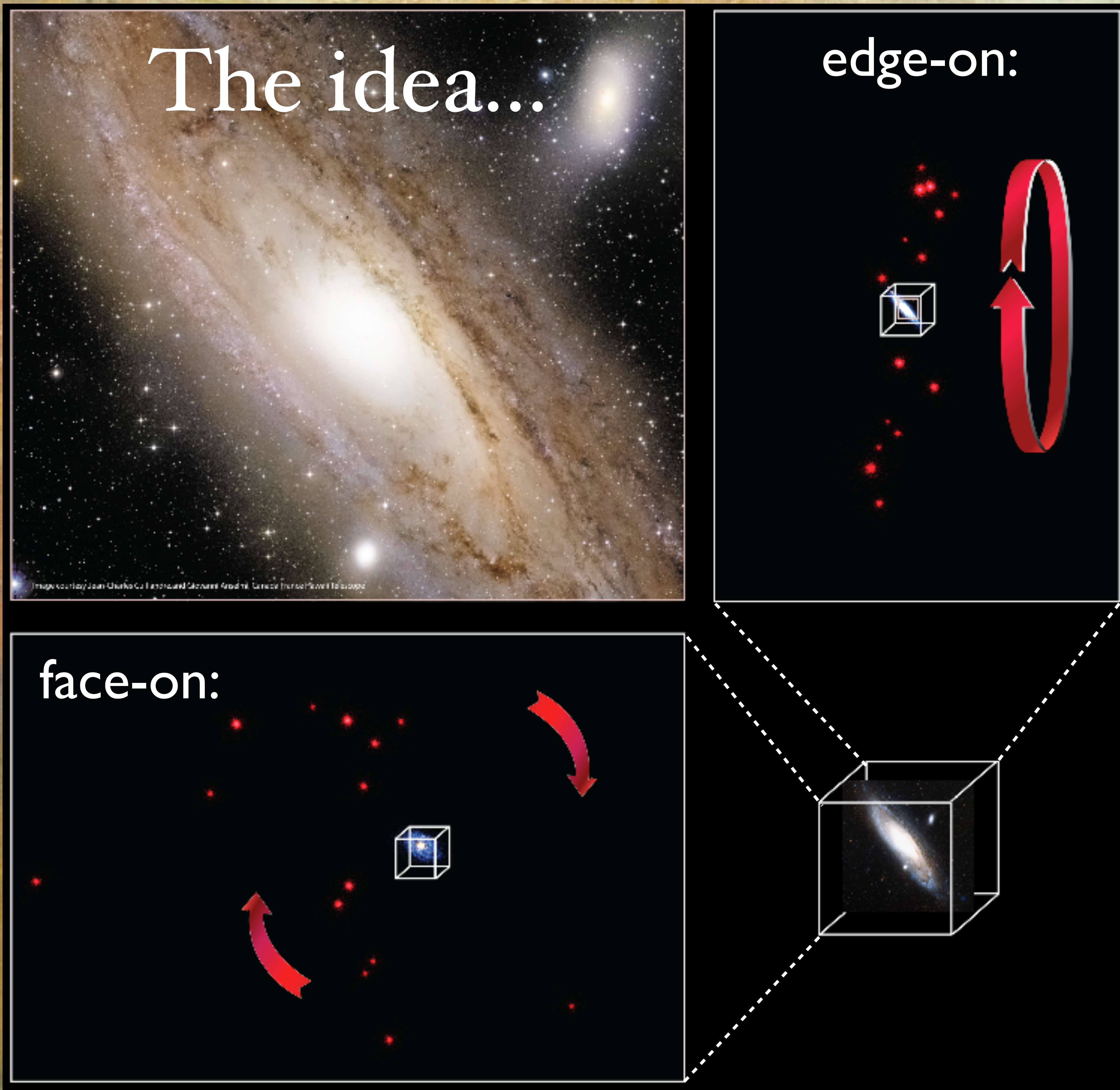
Prob(13 or more/15 sharing same sense of rotation)=0.7%
Total significance = 99.998%



Milky Way: Lynden-Bell (1976), Kroupa (2005), Metz et al. (2007,2008); Pawlowski et al. (2012a,2012b, 2013, 2014)

Is this a peculiarity of the Local Group?

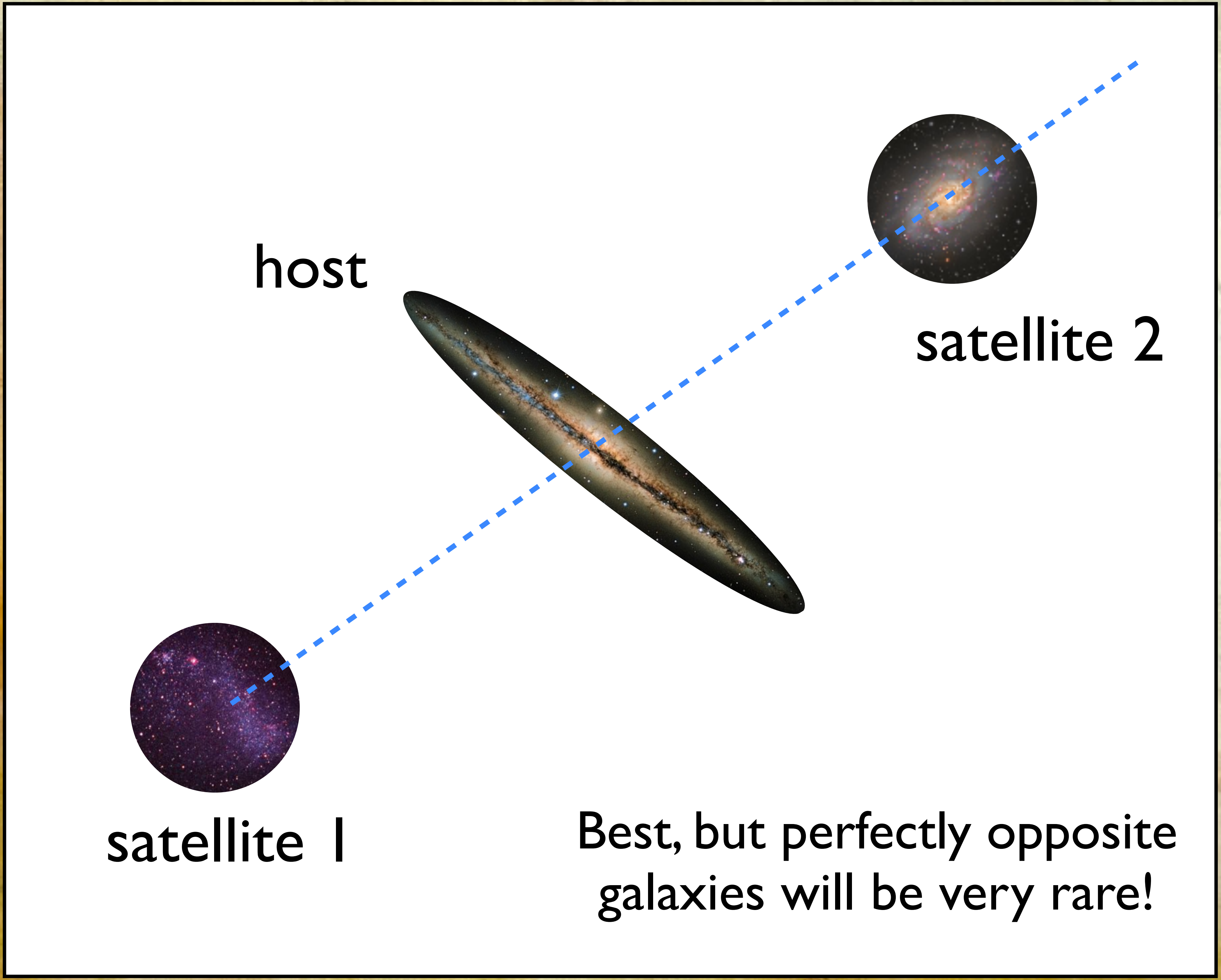
The idea...



effect will be most pronounced for edge-on configurations

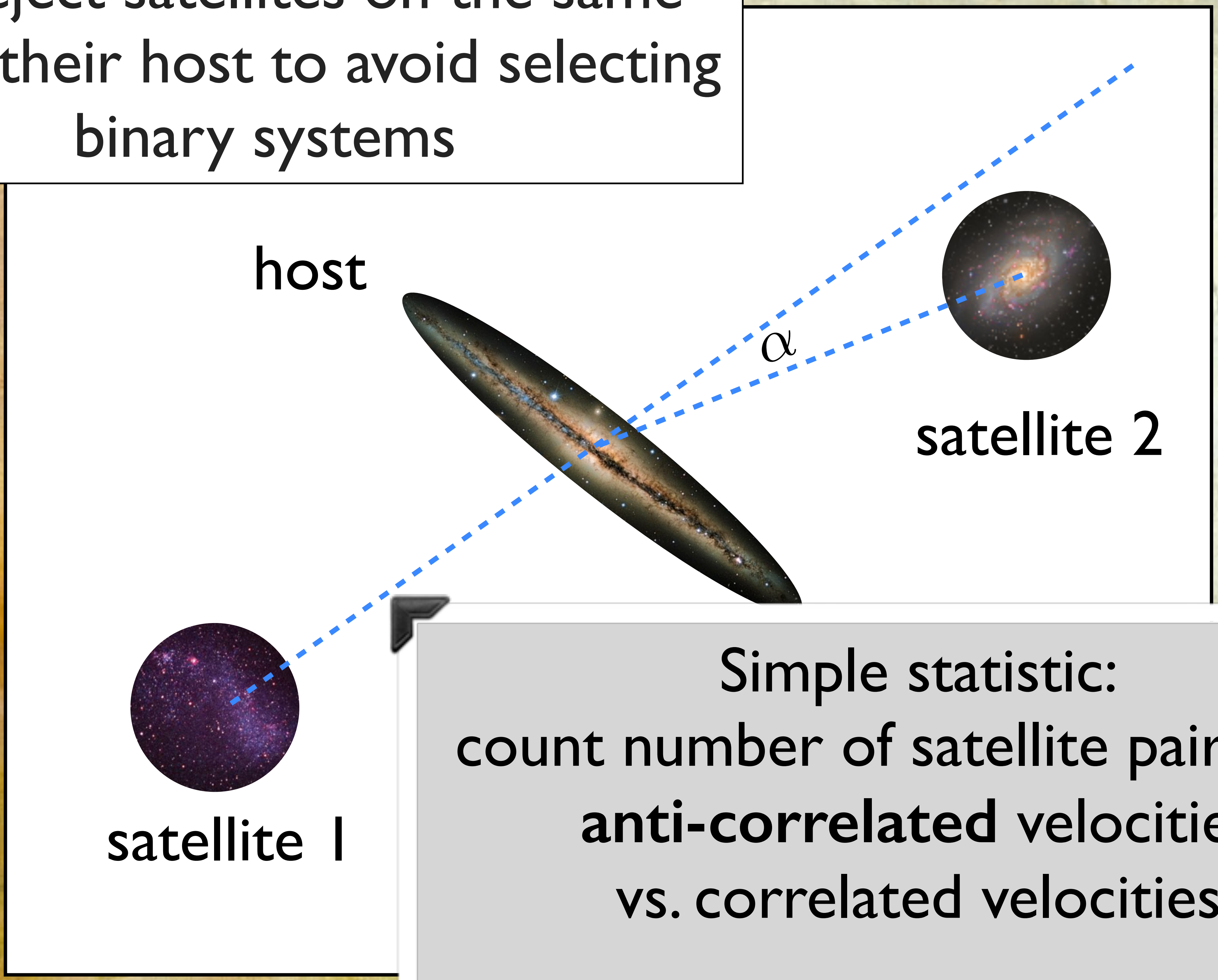
satellites on opposite sides of their host will have anti-correlated velocities

To select edge-on alignments



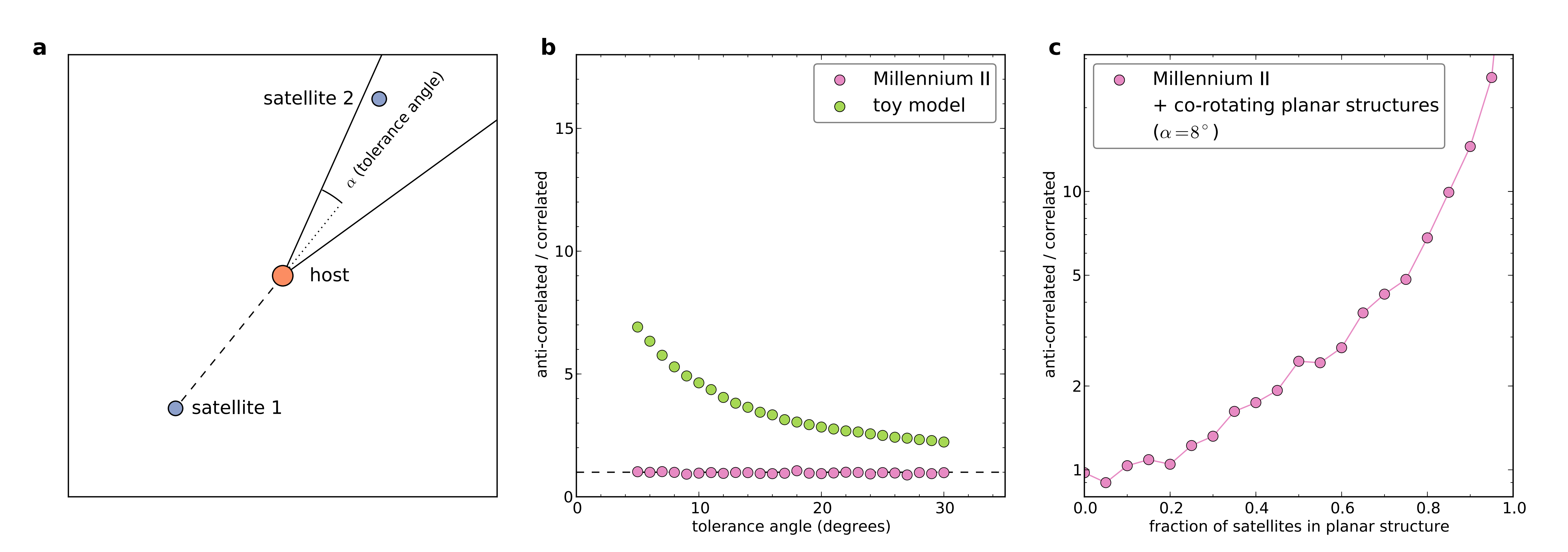
To select edge-on alignments

We reject satellites on the same side of their host to avoid selecting binary systems



Simple statistic:
count number of satellite pairs with **anti-correlated** velocities vs. correlated velocities

How does this statistic behave?

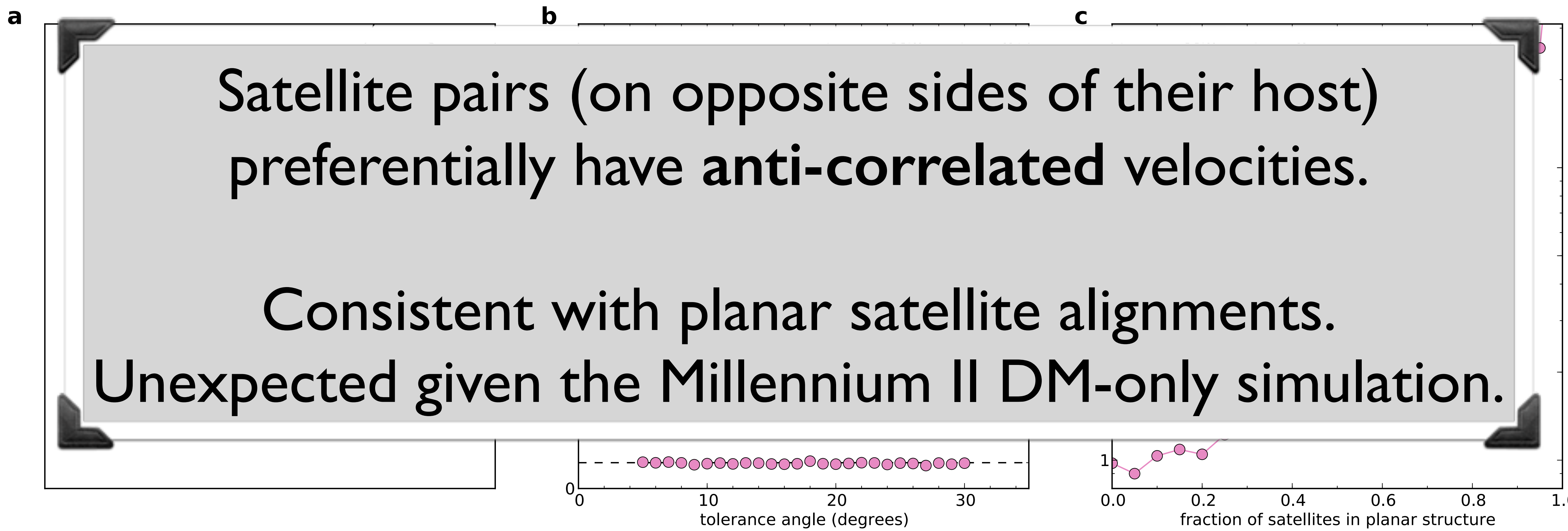


- Toy model:
  - 50% of satellites in isotropic distribution + 50% in flat, rotating structure
- Millennium II:
  - use **same** selection criteria as for SDSS hosts (abs. magnitude, isolation, etc), choose 2 brightest satellites

The galaxy sample

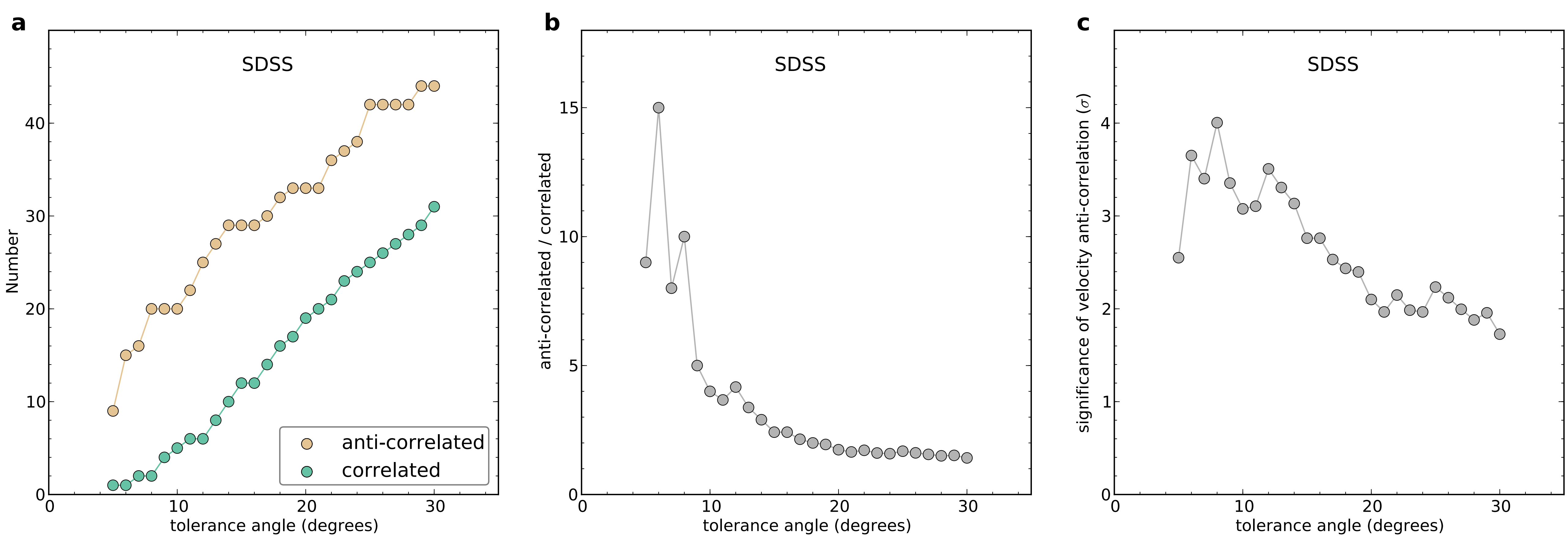
- NYU Value Added Galaxy Catalog (SDSS DR7, update to Blanton et al. 2005)
  - 2.5 million sources, gives estimates of absolute mag (and stellar mass)
- Select M31 and Milky Way-like hosts
  - $-23 < M_r < -20$
  - Isolated: No brighter neighbour within 0.5 Mpc, and 1500 km/s
  - $z < 0.05$ (very few satellite pairs beyond this redshift)
  - sample contains: 24772 hosts
- Satellites
  - at least 1 mag fainter than host, but brighter than $M_r = -16$
  - distance from host: $20 < R < 150$ kpc (like PAndAS) , and within $300 \exp(-(R/300\text{kpc})^{0.8})$ km/s
  - max velocity error: 25 km/s (typical error 15 km/s)
  - velocity direction wrt host resolved: $|v - v_{host}| > \text{error}(|v - v_{host}|)$
  - final sample: 380 **pairs** of satellites

How does our statistic behave in reality?

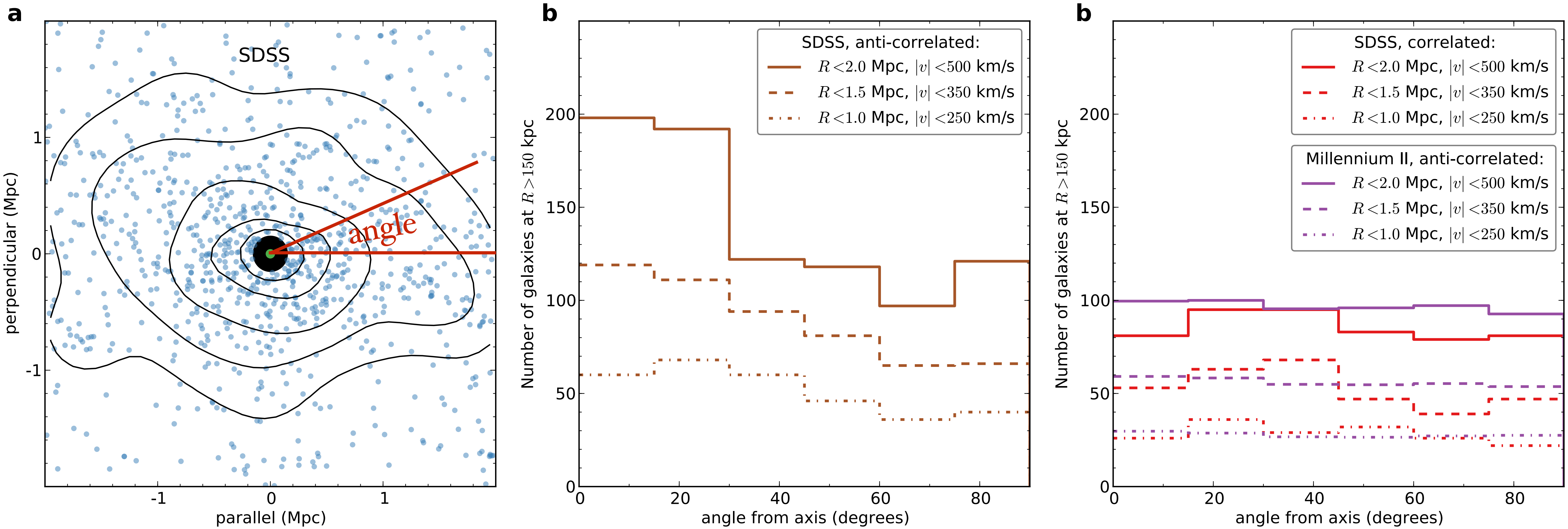


Satellite pairs (on opposite sides of their host) preferentially have **anti-correlated** velocities.

Consistent with planar satellite alignments.
Unexpected given the Millennium II DM-only simulation.



The large-scale environment



- SDSS anti-correlated pairs (alpha=15deg, 30 galaxy pairs):
  - large-scale structure elongated along line connecting satellites (7 sigma)
- SDSS correlated pairs and Millennium:
  - no significant alignment with LSS

Discussion Cautun et al. 2015 vs. RI et al. 2015

- C15 critique:
  - different parameter selections lower the significance
  - same-side satellites show no signal
  - photometrically-selected satellites behave as expected by MS2
- We respond:
  - parameter selection variations behave as expected
  - same-side satellites do show signal if quality cuts are applied
  - C15's photometrically-selected satellites are 95-98% contaminated in radial range 100-150kpc
  - satellites selected by *photometric metallicity* independently confirm our earlier result.

Conclusions & prospects

- Satellite alignments are real and common. A substantial fraction of satellite galaxies did not form independently.
- Appears consistent with ~50% of satellites around giant field galaxies belonging to thin co-rotating planar structures (similar to what we find in M31 & Milky Way).
- Such spatial & kinematic correlation is not (as yet) produced in any cosmological simulations.
- Long streams are excellent dynamical probes situated at radial locations where we have few constraints. We can uncover the numerous very low mass accretions, study their orbital properties, and build up the accretion history of such structures.
- Even distant systems with only projected stream morphologies can be used to derive dark halo properties. (But better with more information!)
- Milky Way: developing outside-in stream+potential fitting for Gaia.