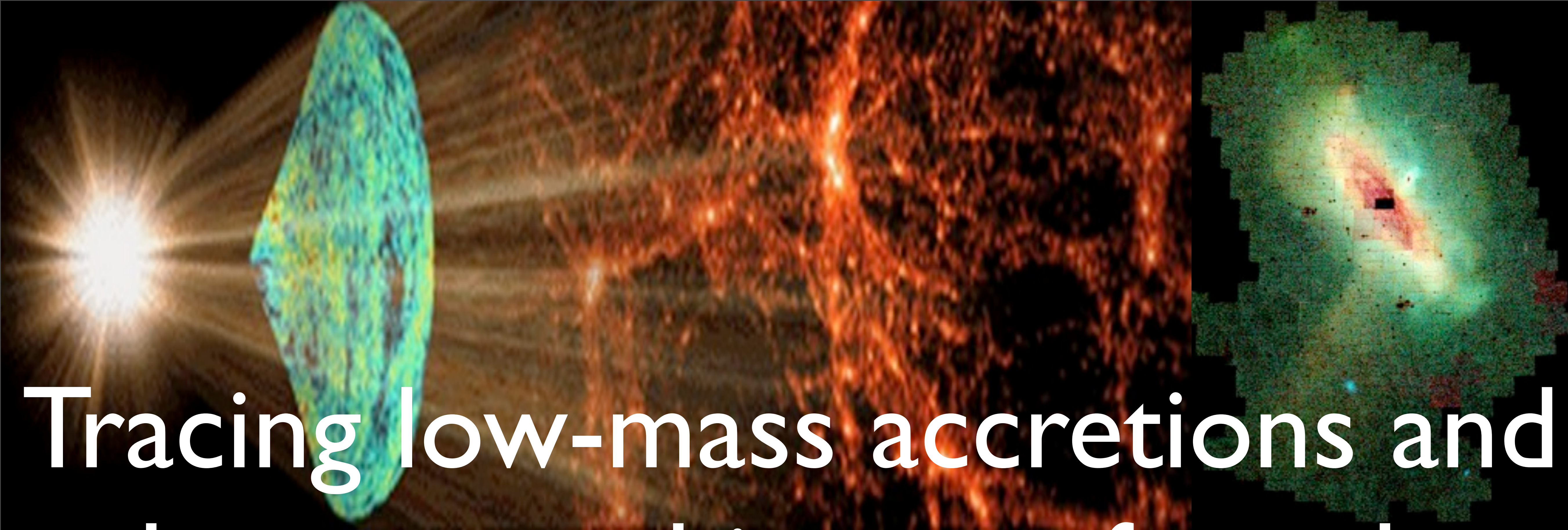
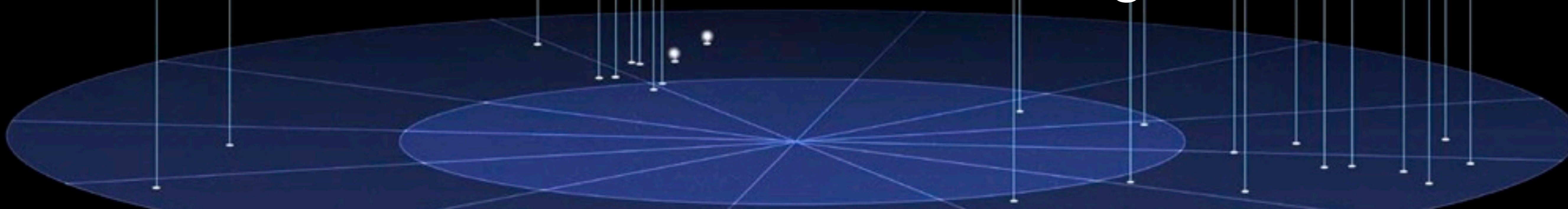


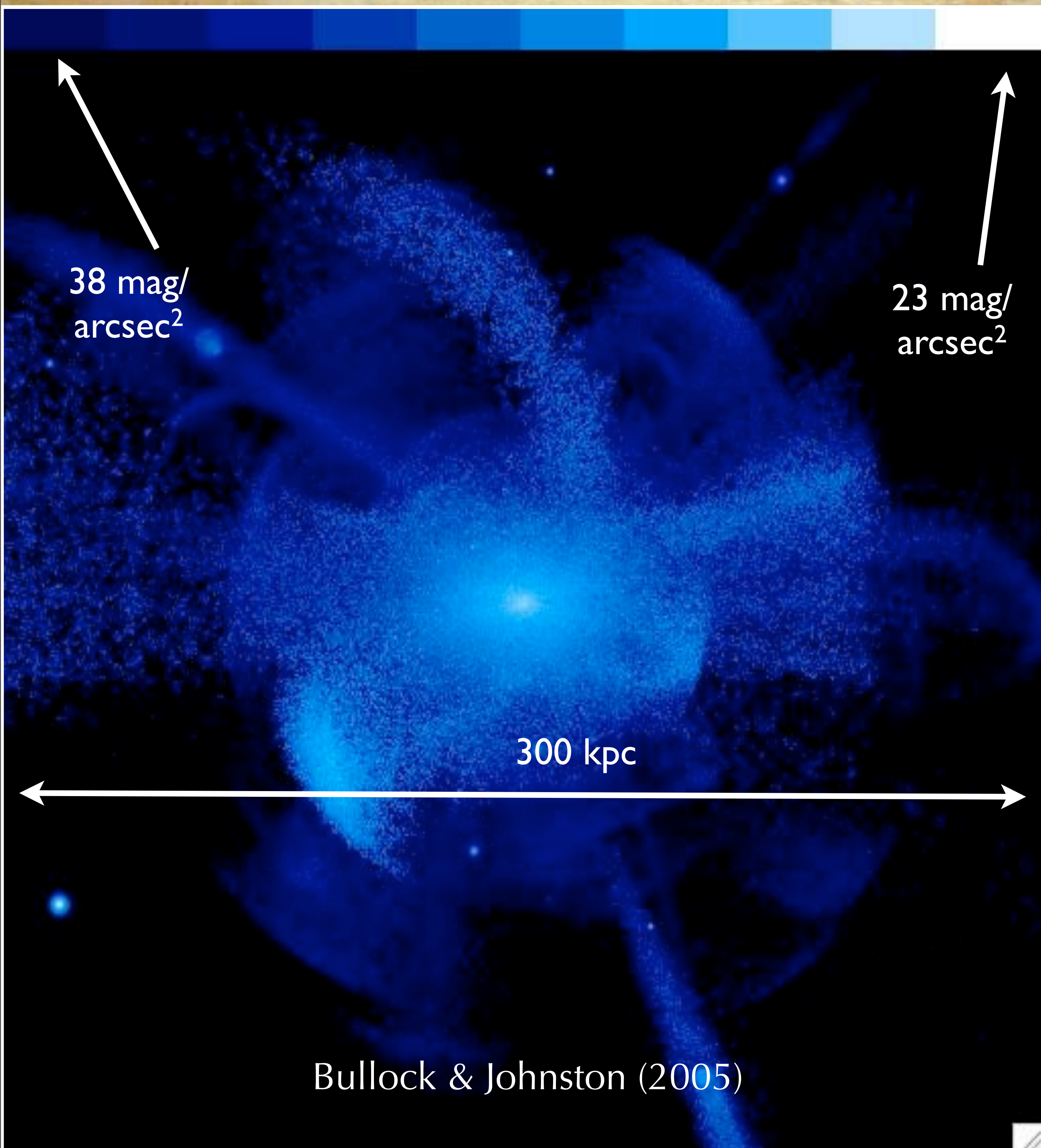
Tracing low-mass accretions and the merger history of nearby galaxies with stellar streams

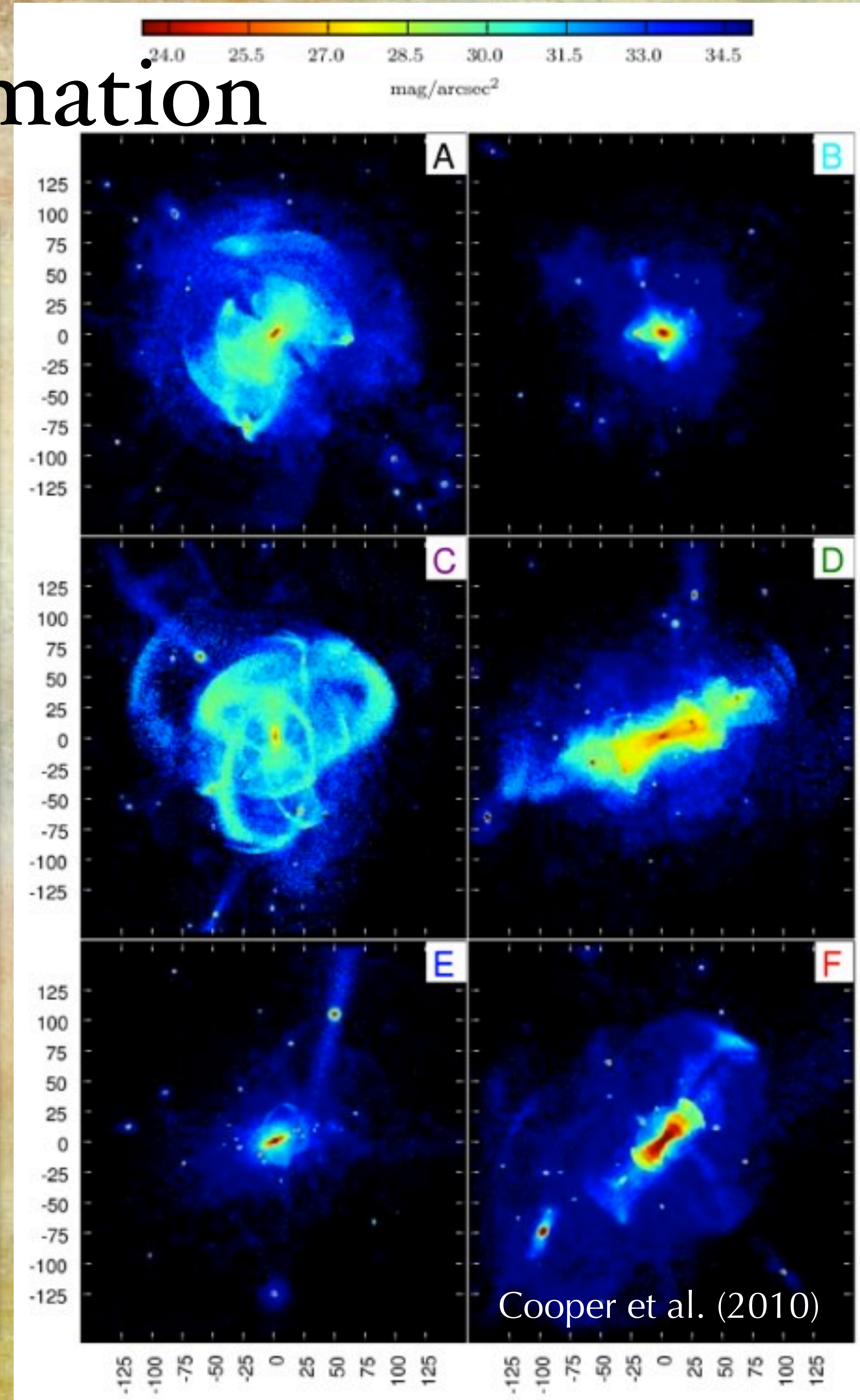
Rodrigo Ibata

Observatoire de Strasbourg

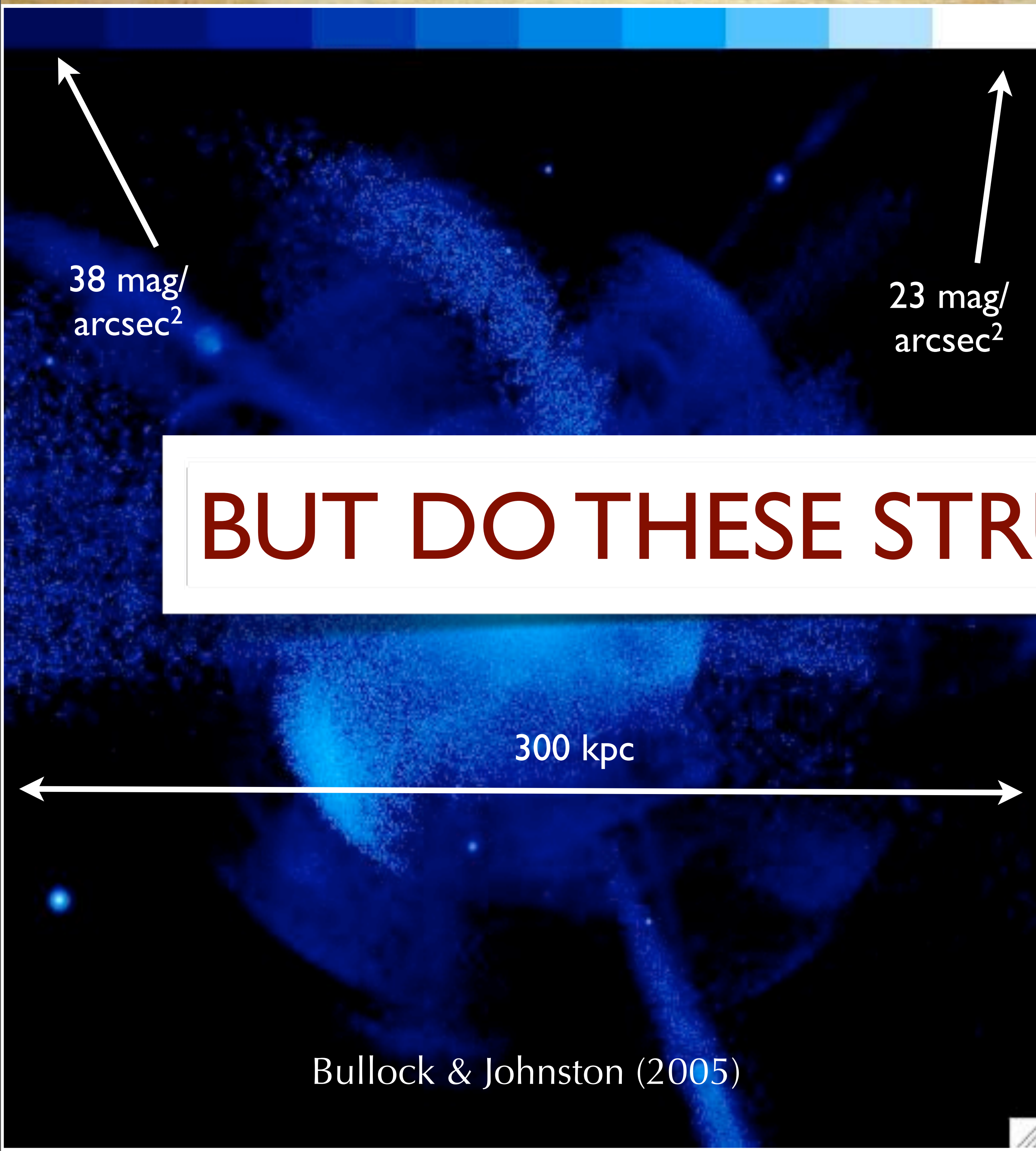


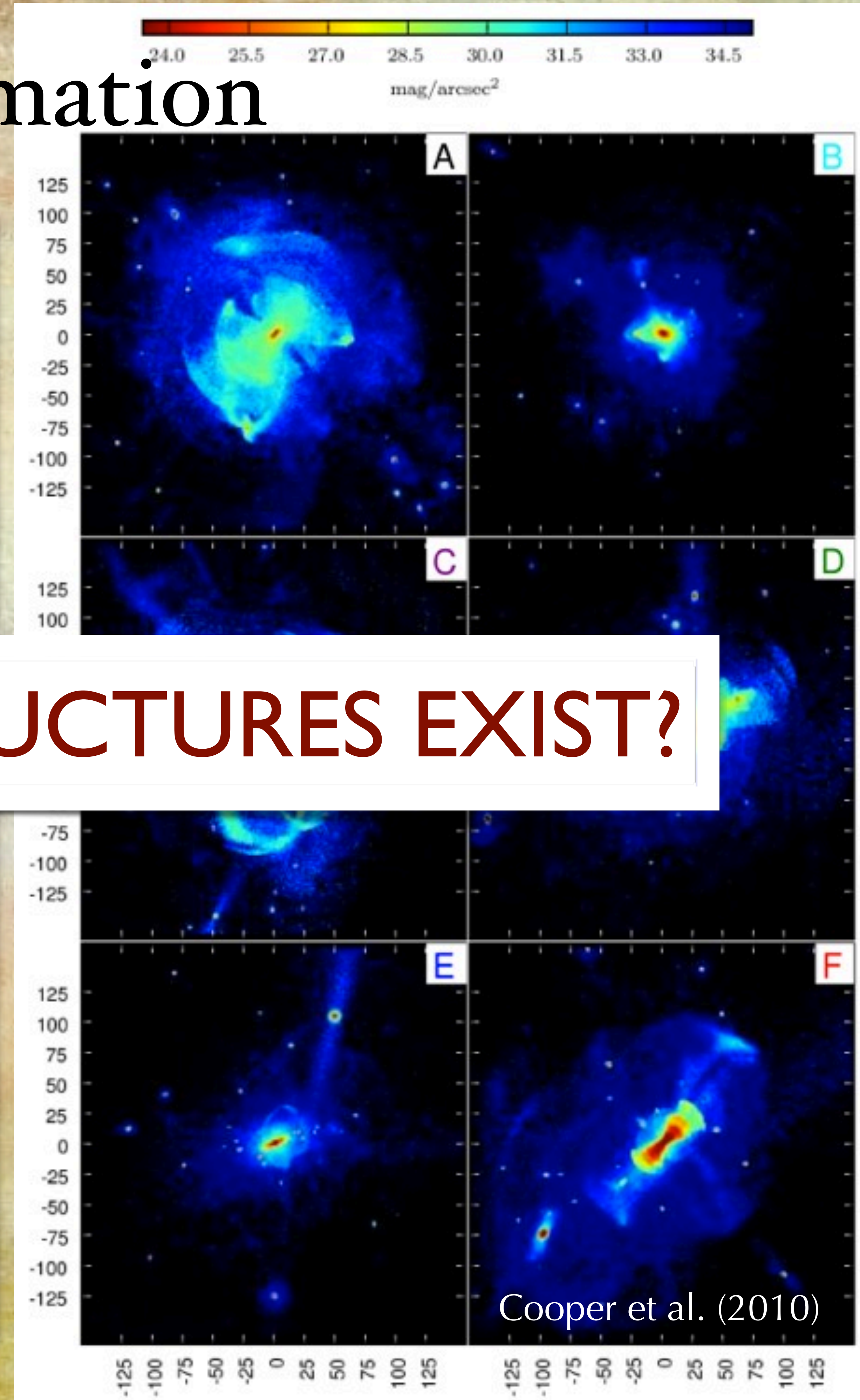
Streams as fossils of formation



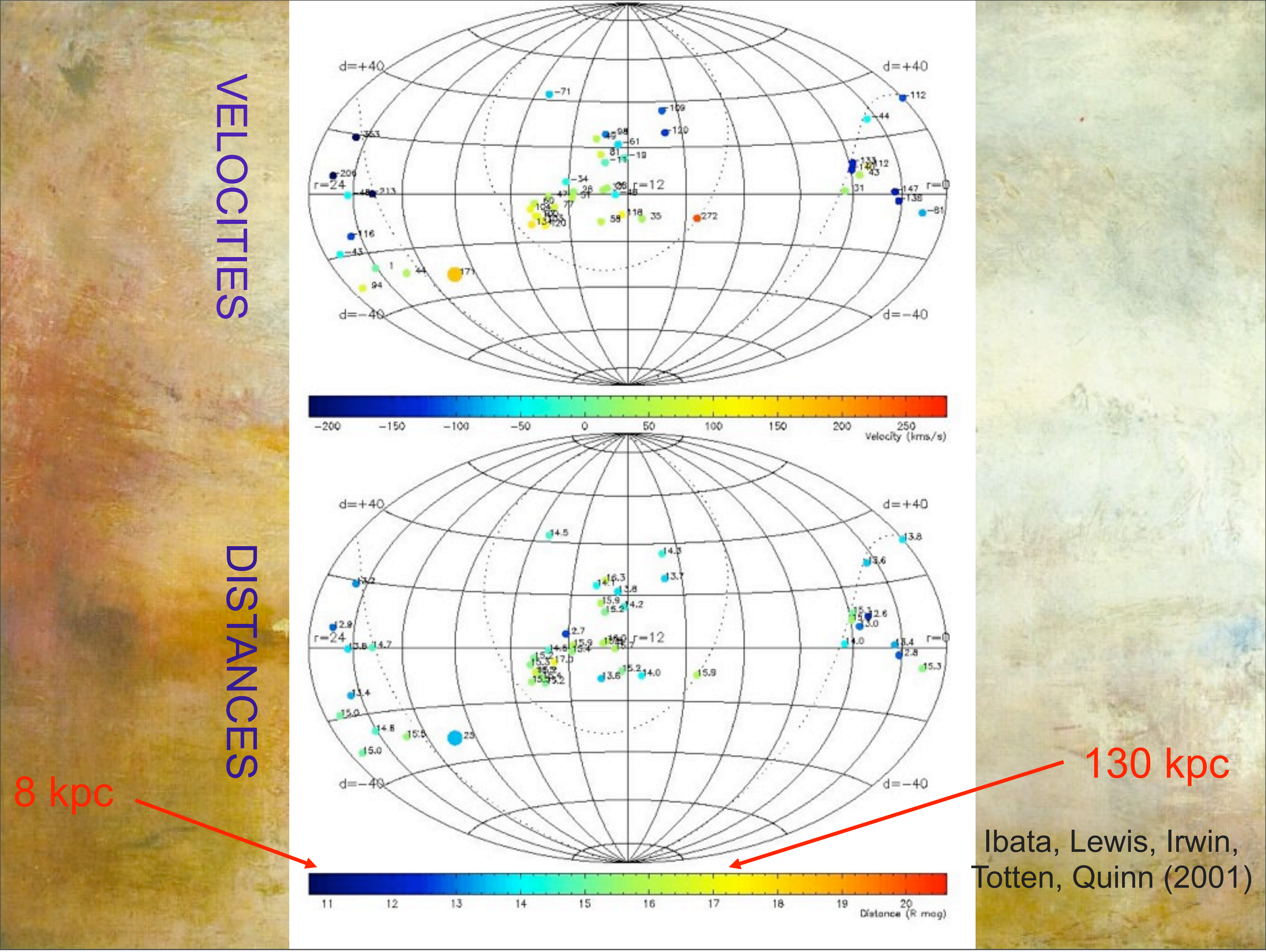


Streams as fossils of formation





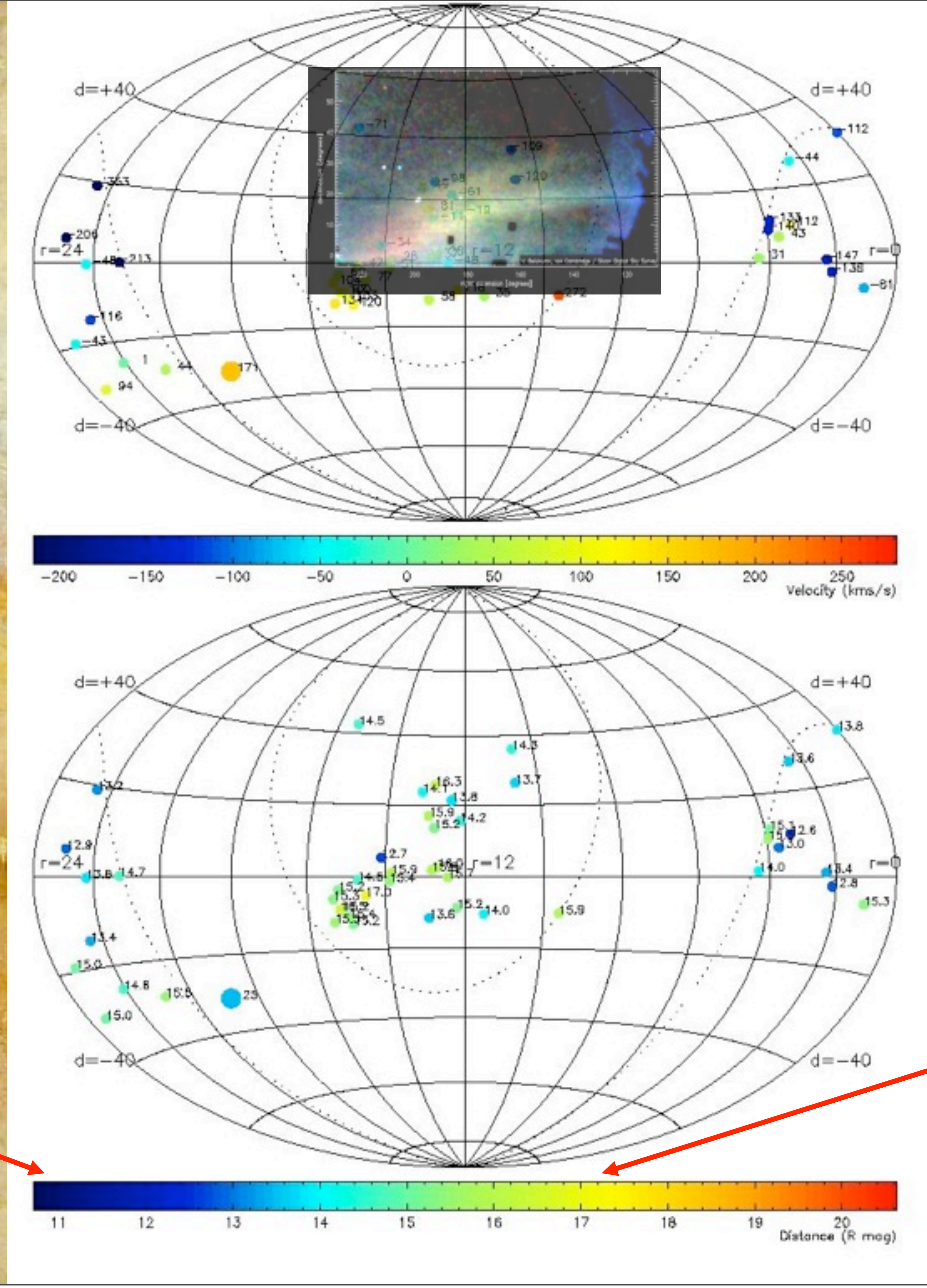
BUT DO THESE STRUCTURES EXIST?



Ibata, Lewis, Irwin, Totten, Quinn (2001)

VELOCITIES

DISTANCES

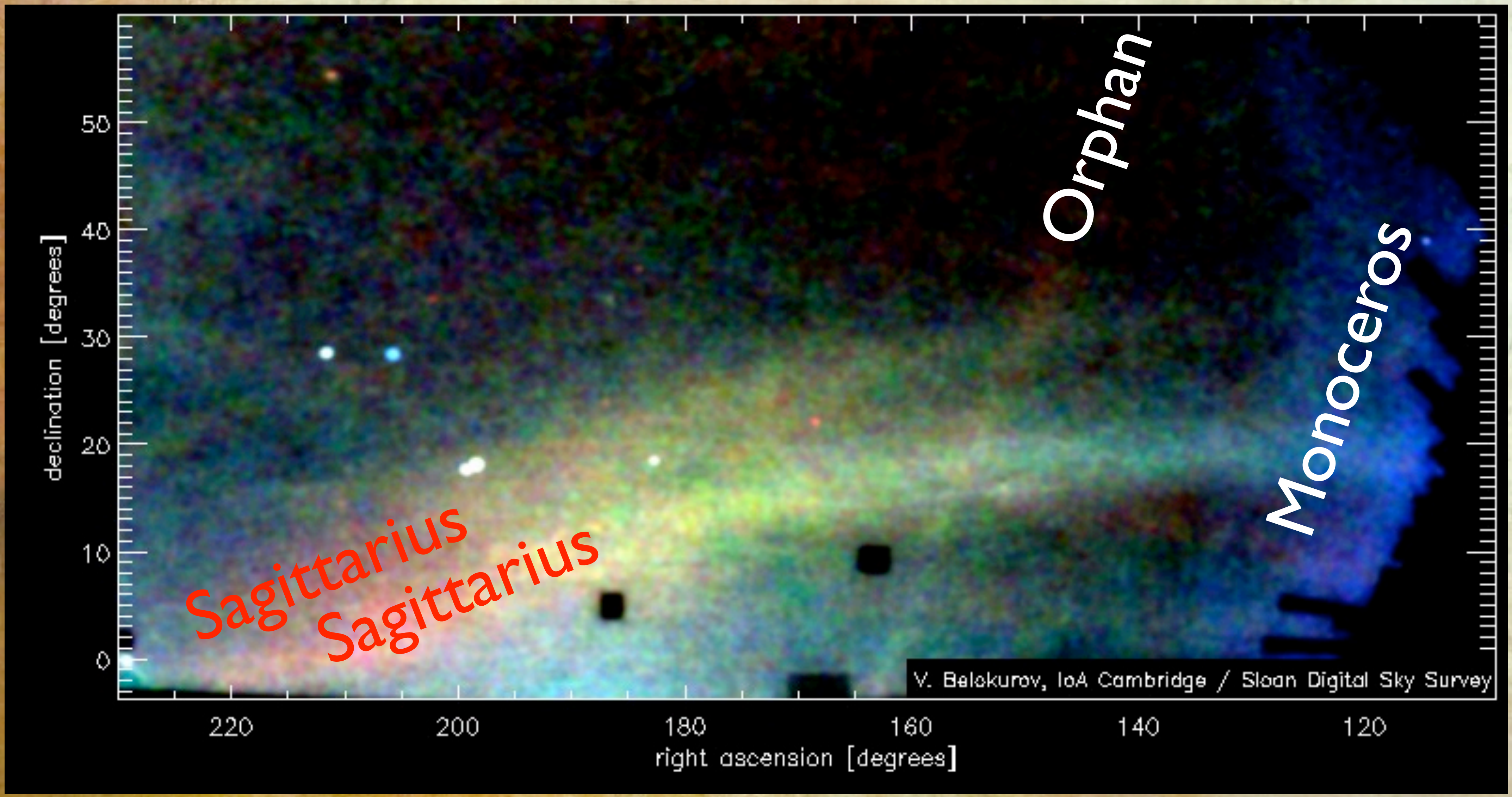


8 kpc

130 kpc

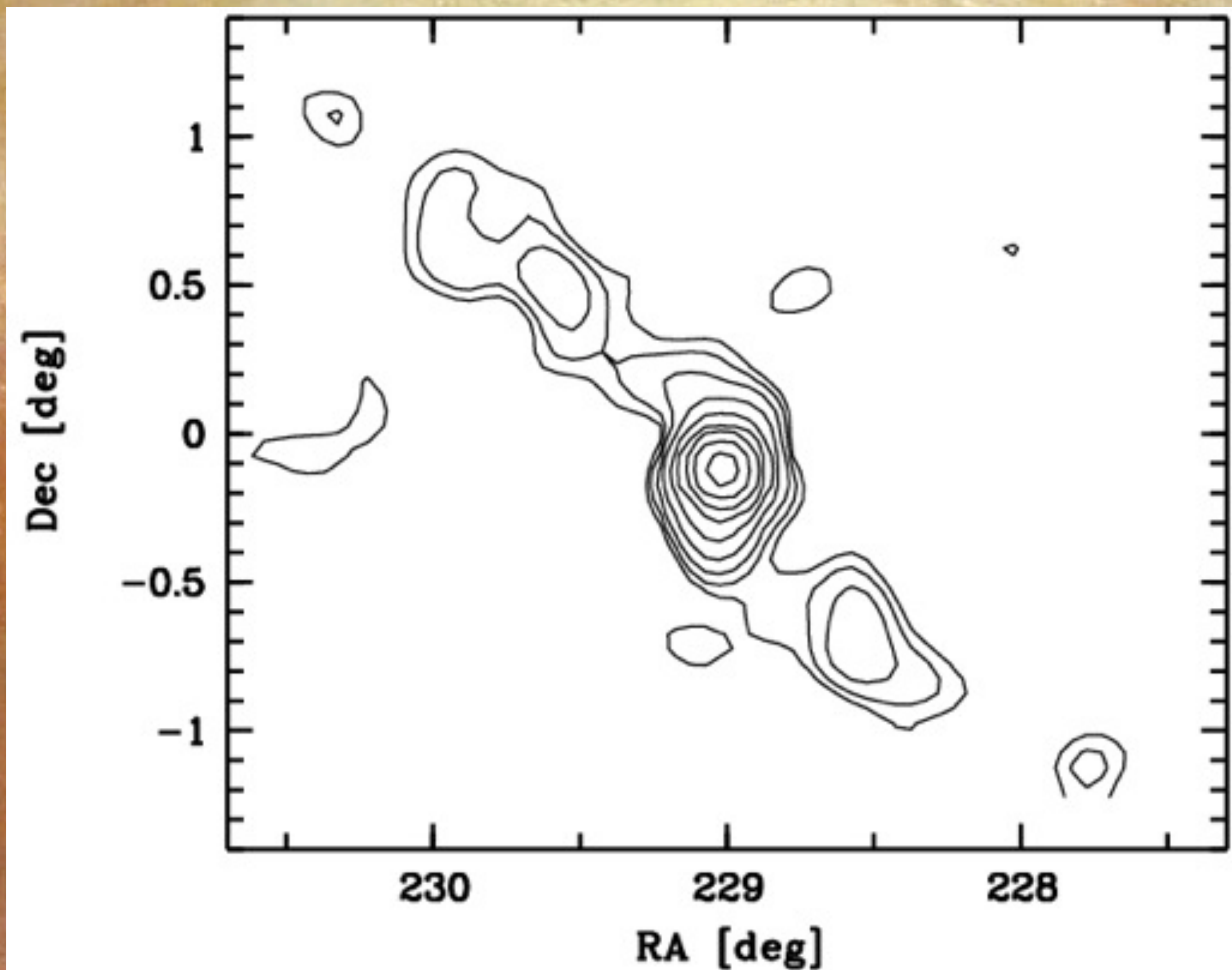
Ibata, Lewis, Irwin, Totten, Quinn (2001)

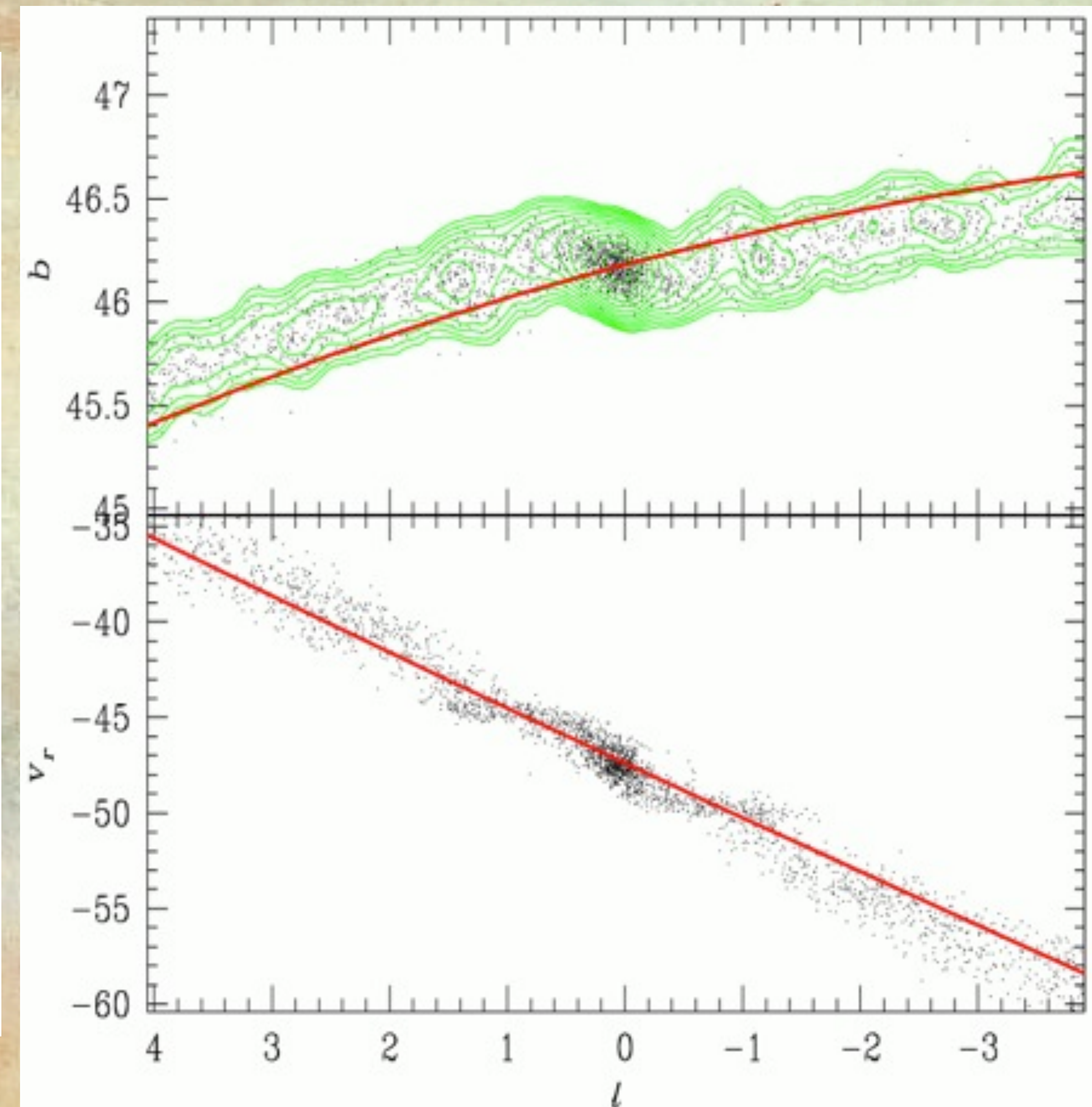
Field of Streams...



Belokurov et al 2006

The globular cluster Palomar 5





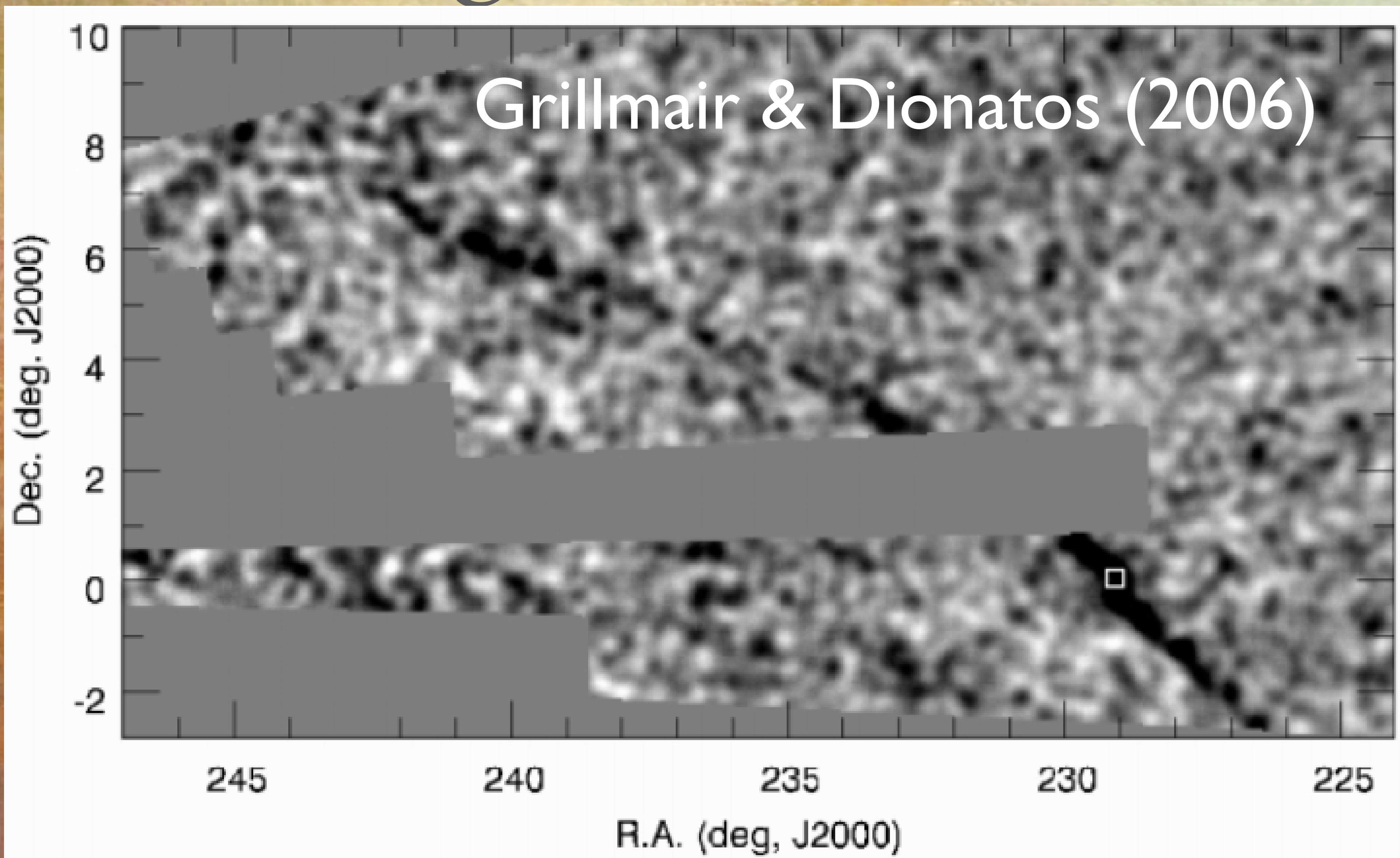
Pal5 : Odenkirchen et al (2001)

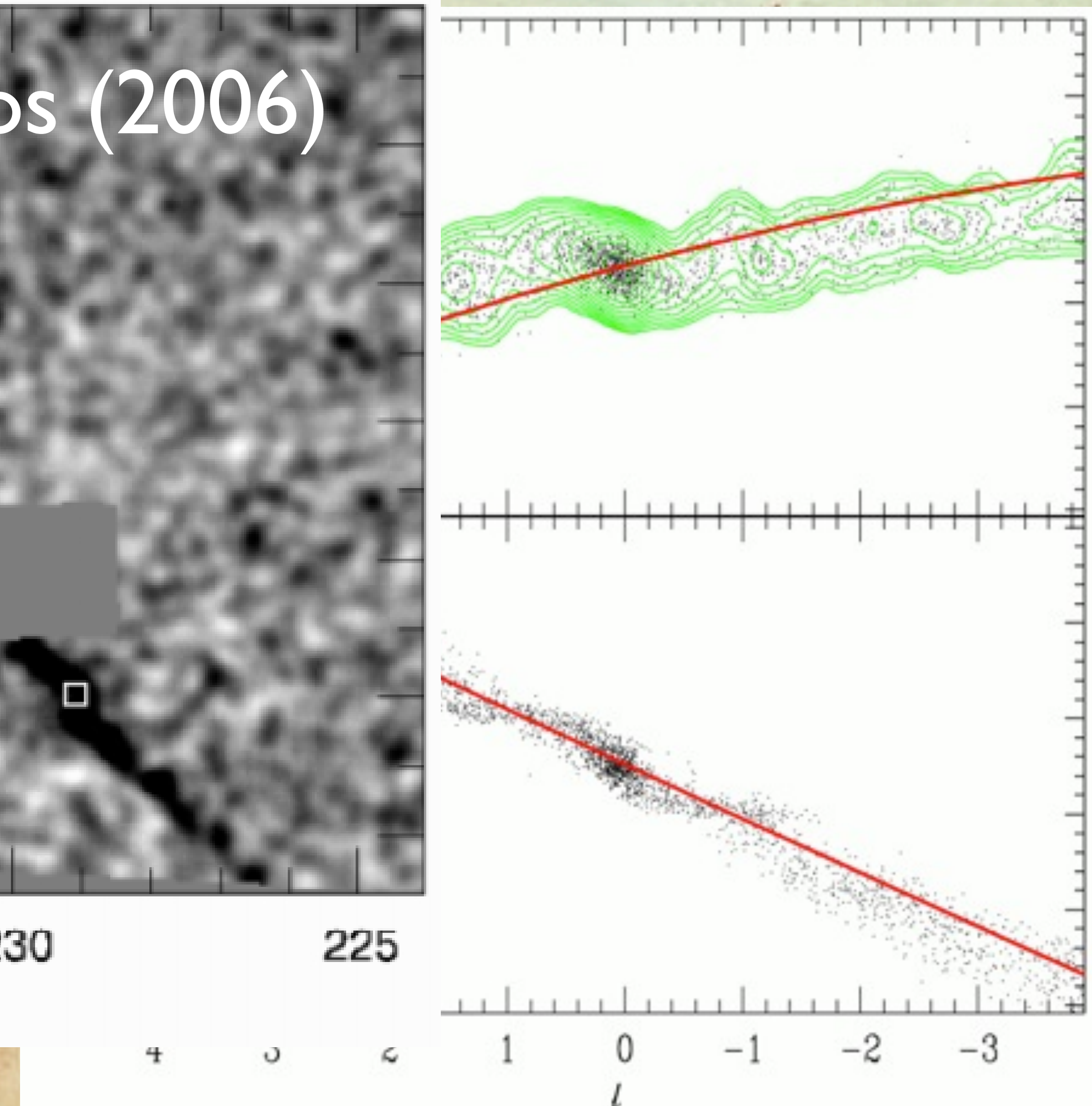
Dehnen et al. 2004

Disk shocks dominate evolution

Will disappear next disk passage; 1% of its lifetime

The globular cluster Palomar 5



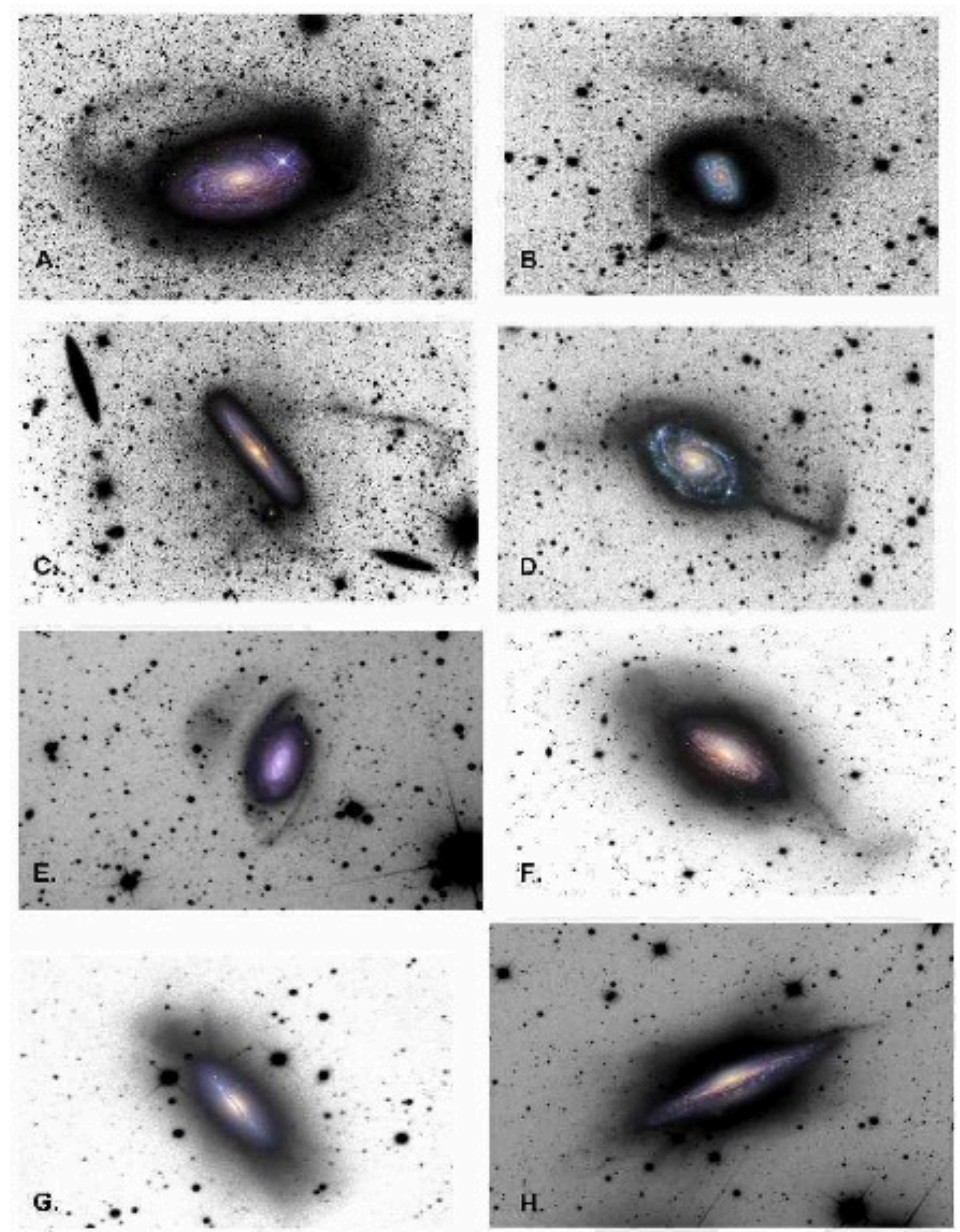


Pal5 : Odenkirchen et al (2001)

Dehnen et al. 2004

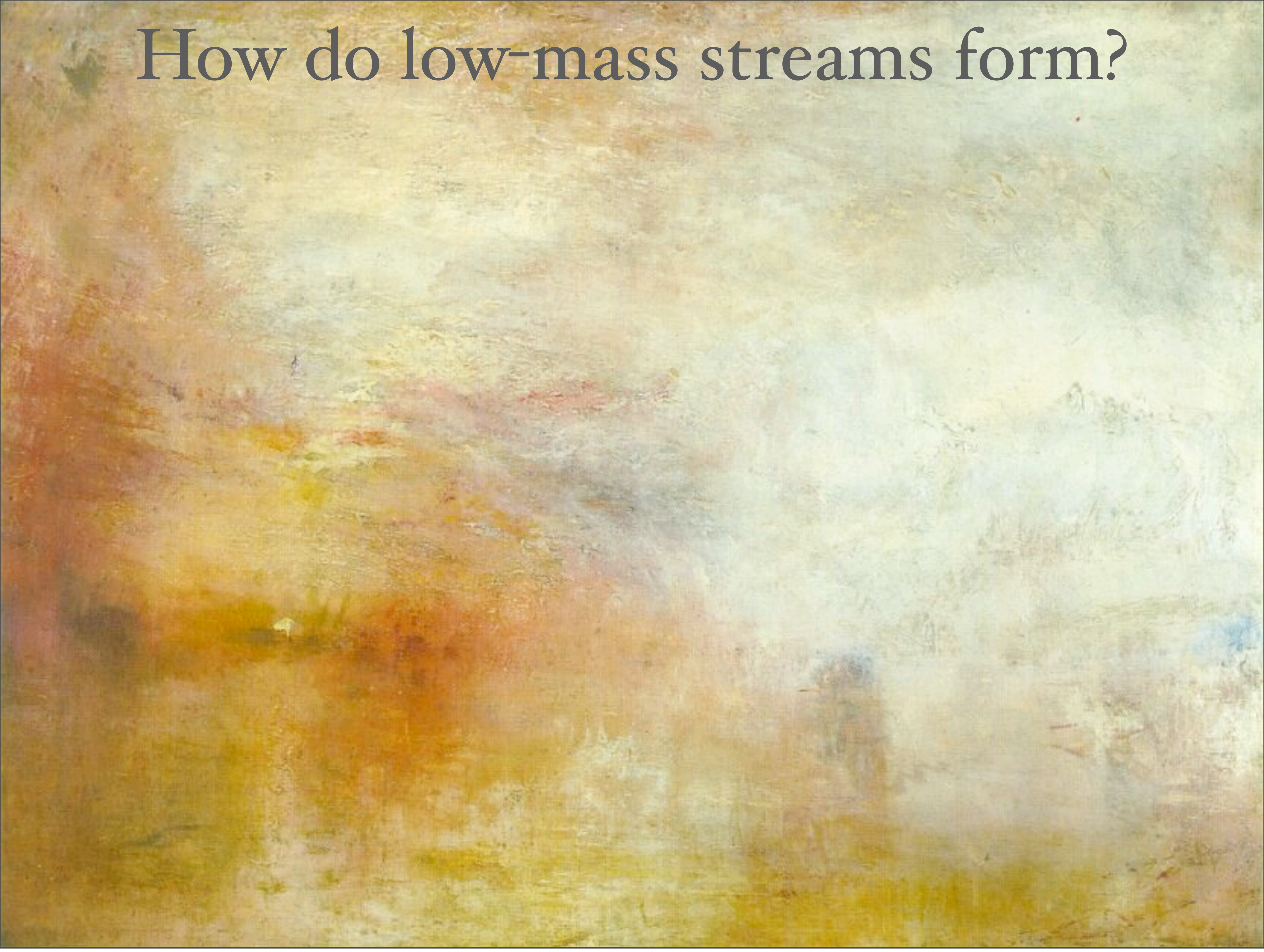
Disk shocks dominate evolution

Will disappear next disk passage; 1% of its lifetime

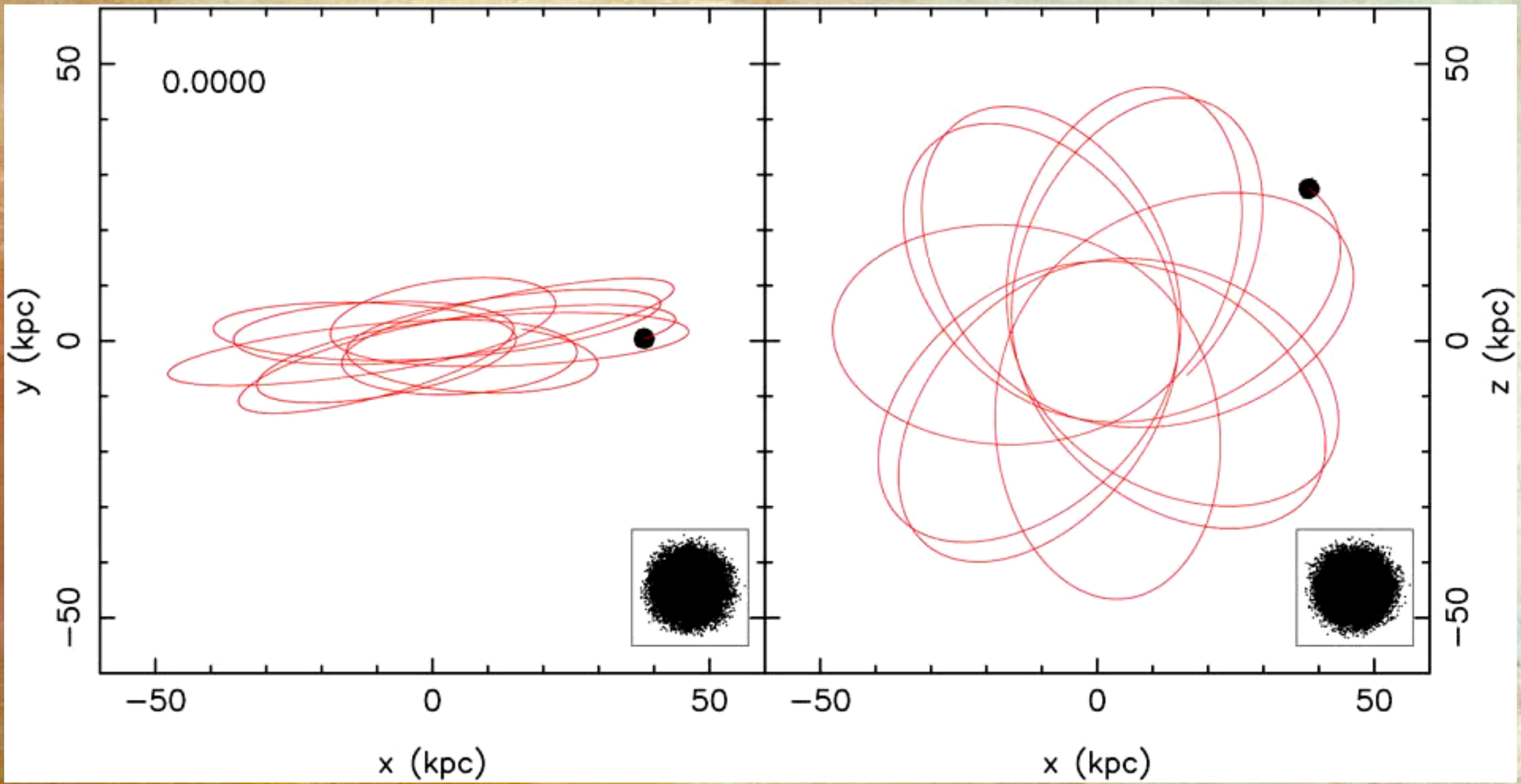


Martinez-Delgado et al. 2010

How do low-mass streams form?



How do low-mass streams form?



How do low-mass streams form?

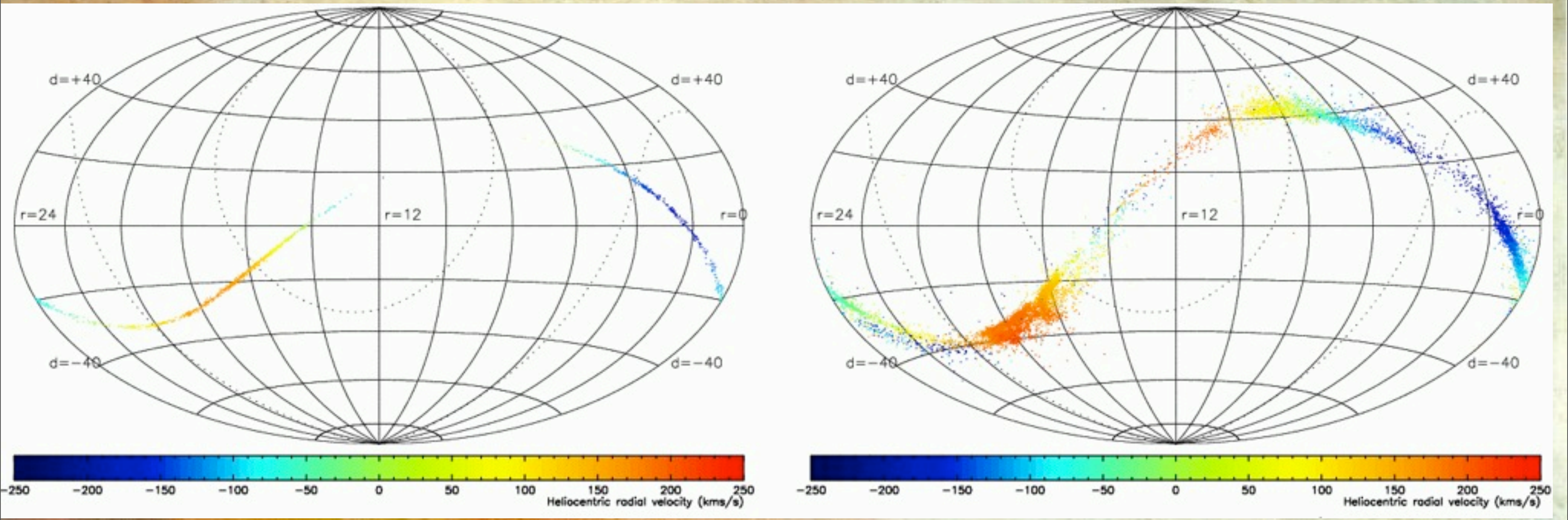
- Baryons in dark matter satellite collapse, forming stars
- Satellite orbit decays via dynamical friction
- Tidal sculpting then tidal disruption simultaneously with internal dynamical evolution
- Slow case: stars lost though Lagrange points L1 & L2 of satellite: so get two tidal arms
- L1 is deeper in potential, so stars escape from it with larger v, causing leading arm
- But not all unbound stars are lost
- Phase-mixing leads to lower vel dispersion of stream with time

How do low-mass streams form?

- Baryons in dark matter satellite collapse, forming stars
- Satellite orbit decays via dynamical friction
- Tidal sculpting then tidal disruption simultaneously with internal dynamical evolution
- Slow case: stars lost though Lagrange points L1 & L2 of satellite: so get two tidal arms
- L1 is deeper in potential, so stars escape from it with larger v, causing leading arm
- But not all unbound stars are lost
- Phase-mixing leads to lower vel dispersion of stream with time

But these streams are just icing on the cake -
why should we care?

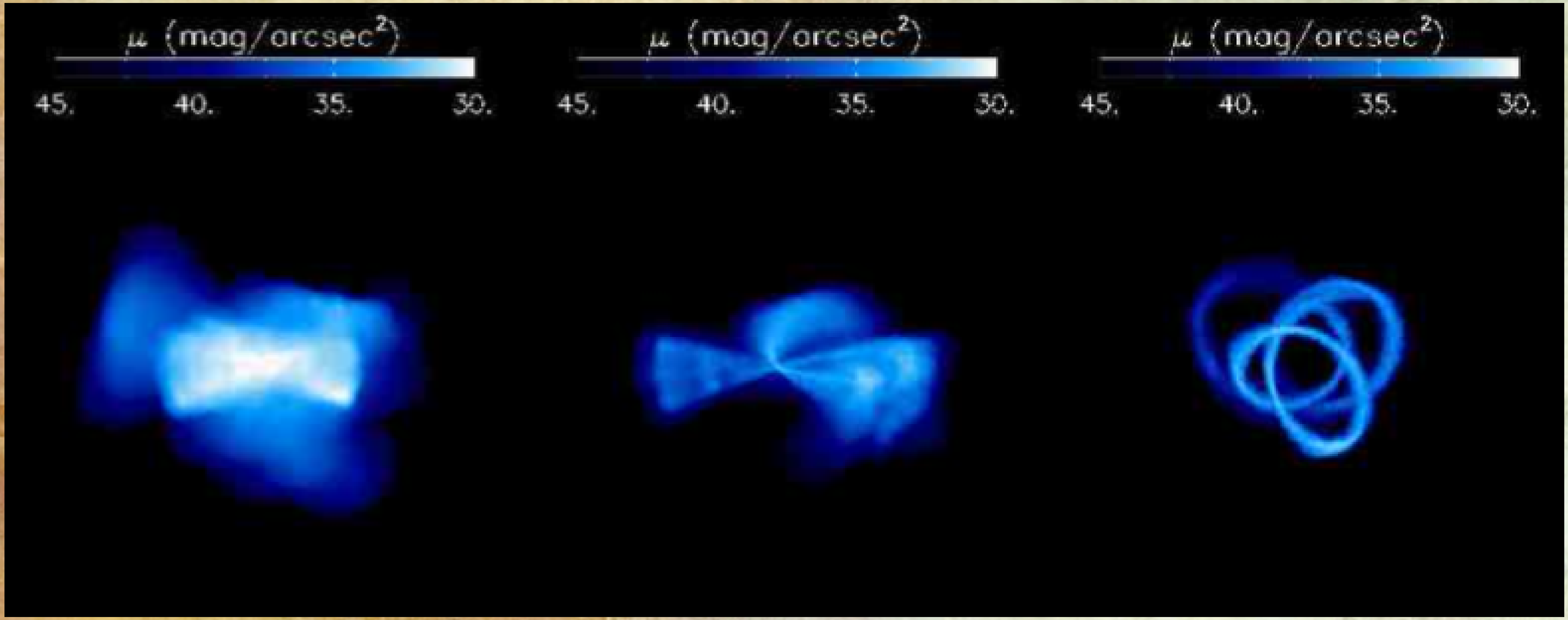
Stellar streams as seismometers



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

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

Statistics of streams



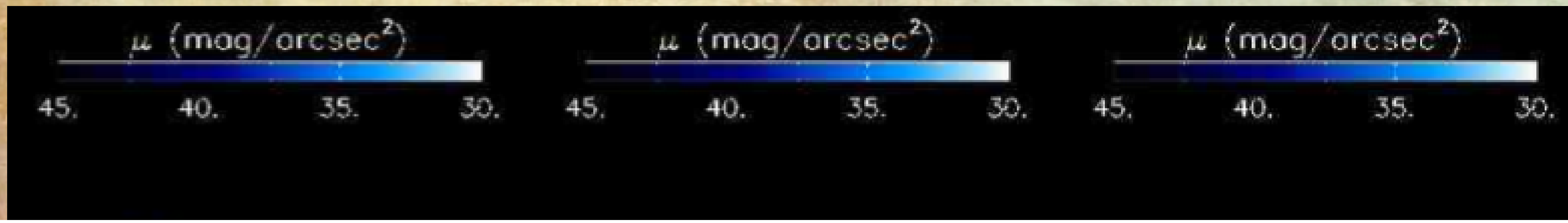
"Mixed"

"Great circle"

"Shell/Plumes/Clouds"

Johnston et al. 2008

Statistics of streams



Observable property	Interpretation	Implication
fraction in substructure	recent accretions	high fraction $\Rightarrow$ many recent events low fraction $\Rightarrow$ few recent events
scales in substructure	luminosity function (and orbit type) of recent events	large $\Rightarrow$ high luminosity events small $\Rightarrow$ low luminosity events
number of features	number of recent events	large $\Rightarrow$ many events small $\Rightarrow$ few events
morphology of substructure	orbit distribution	clouds/plumes/shells $\Rightarrow$ radial orbits great circles $\Rightarrow$ circular orbits
[Fe/H]	luminosity function	metal-rich $\Rightarrow$ high luminosity events metal-poor $\Rightarrow$ low luminosity events
[α/Fe]	accretion epoch	α-rich $\Rightarrow$ early accretion epoch α-poor $\Rightarrow$ late accretion epoch

Johnston et al. 2008

What additional 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?
- Clearly (somewhat) degenerate, so we aim to get likelihood distributions

Method:

Stellar Streams as Probes of Dark Halo Mass and Morphology: A Bayesian Reconstruction
Varghese, Ibata & Lewis arXiv:1106.1765, MNRAS in press

Markov-chain Monte Carlo

Typically run 10^5 to 10^6 iterations

1. Choose initial trial potential, choose initial trial **x**,**v**
2. Integrate orbit
3. Calculate likelihood by comparing to stream data
4. Resample new parameters
5. if chain well-mixed: stop
6. go to (2)

Technically very challenging MCMC problem
(use population of affine samplers [Goodman & Weare 2010] and parallel tempering)

First test for orbits (not streams), purely with projected positions and toy galaxy model

Logarithmic potential: $\Phi_{halo} = \frac{1}{2} V_0^2 \ln \left(R_c^2 + R^2 + \frac{z^2}{q_\phi^2} \right)$

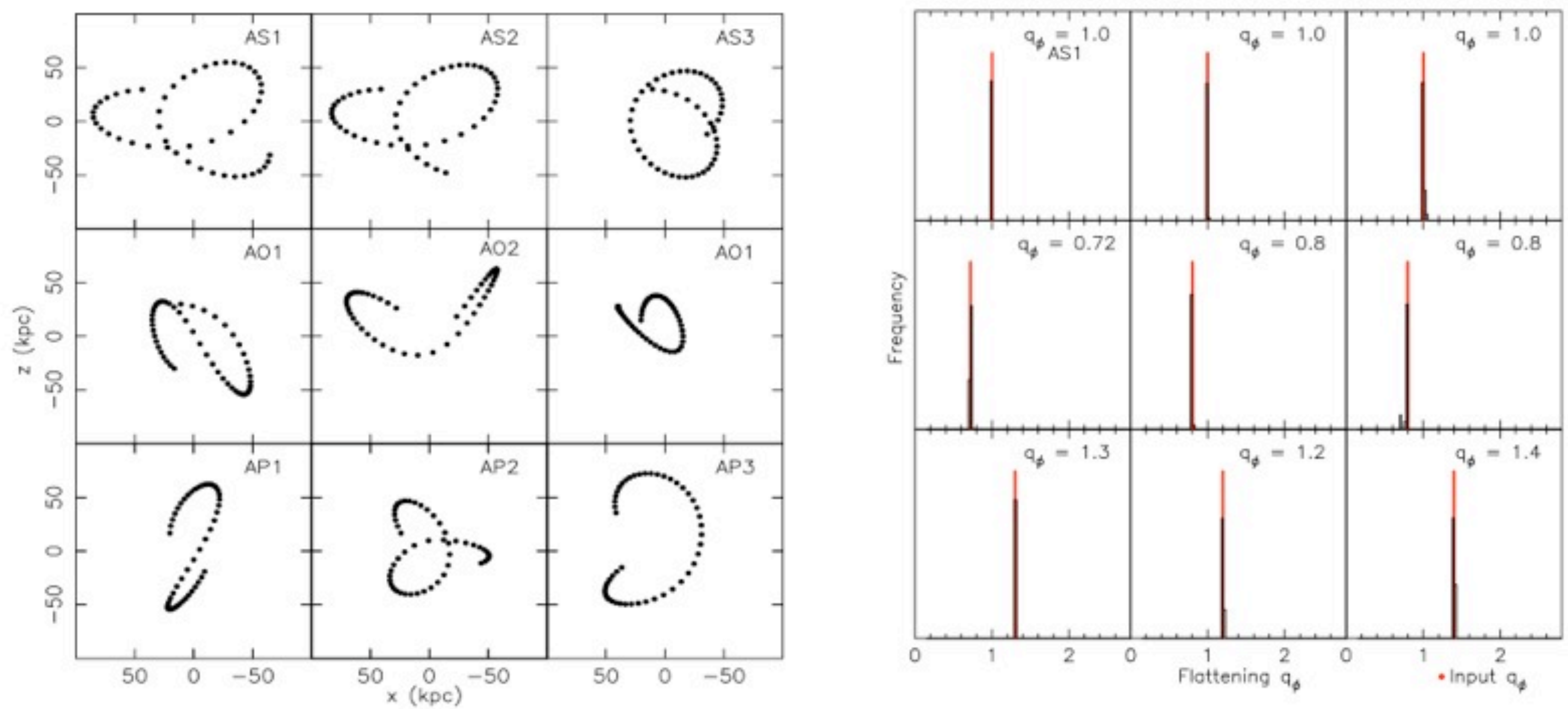


Figure 1. Projection in the xz plane of orbits integrated in a logarithmic potential using a Runge-Kutta scheme. The top, middle and bottom panels show orbits in spherical, oblate and prolate potentials respectively. The parameters of each orbit are listed in Table 1.

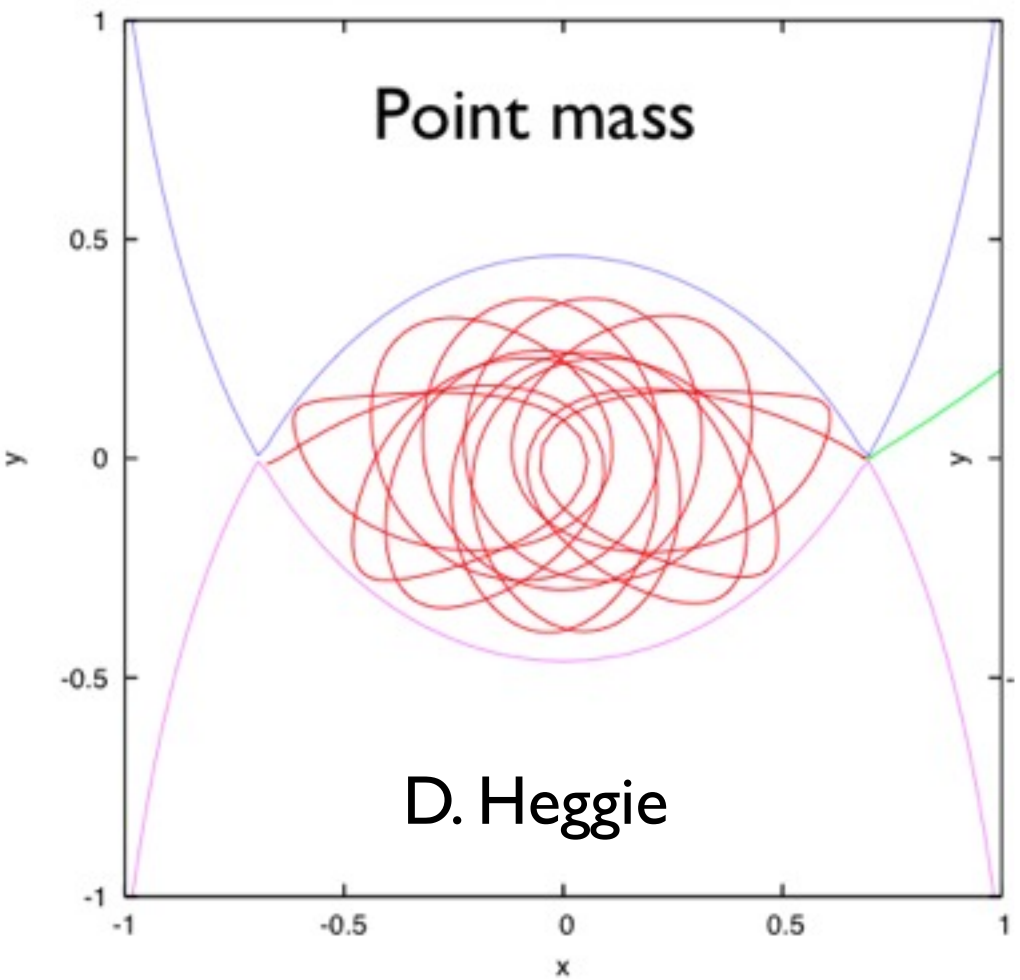
Figure 2. Estimation of q for the orbits shown in Figure 1. The input value of q in each case is shown. This distribution is drawn from 100,000 steps of the coldest Monte Carlo Markov chain.

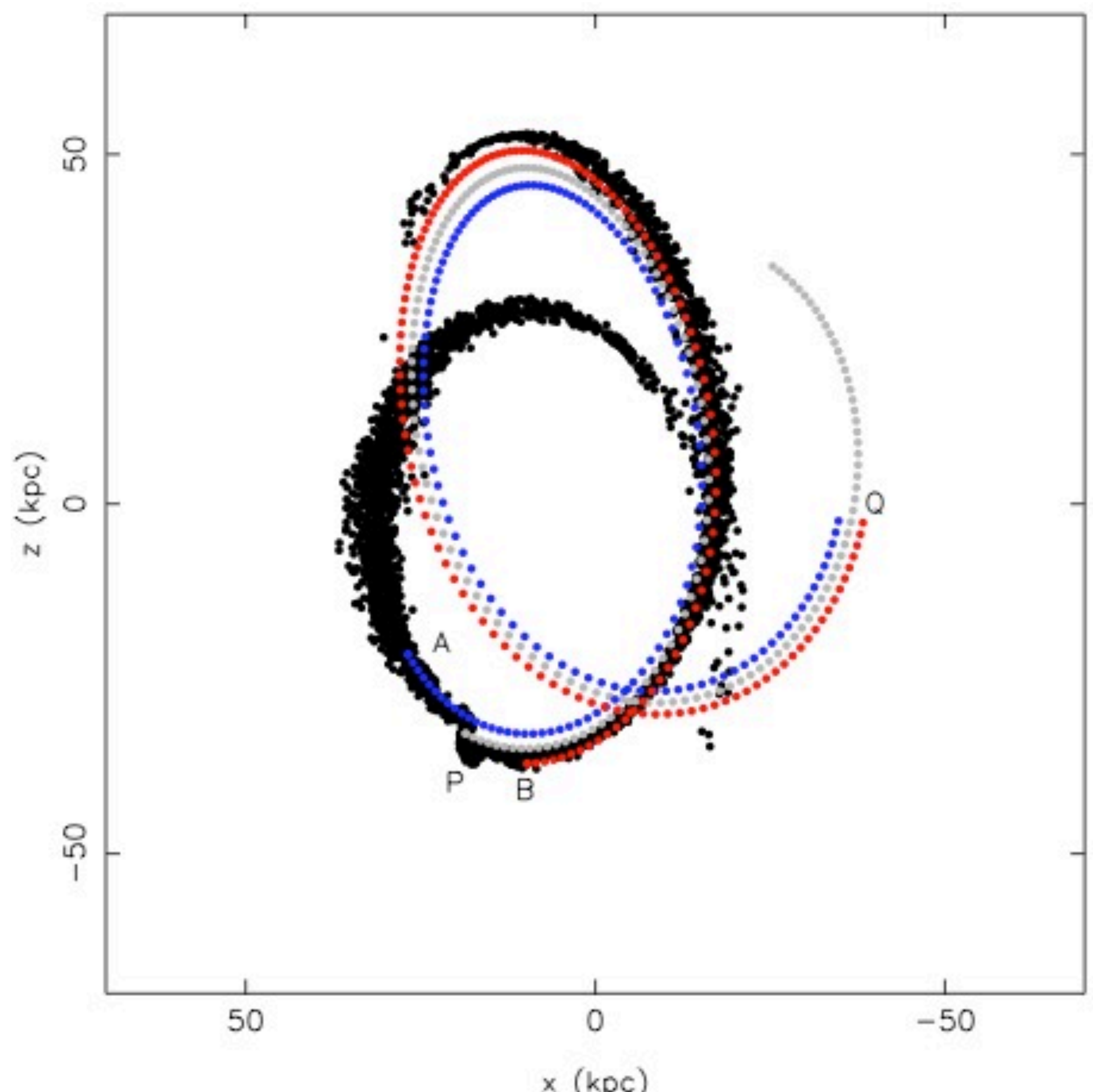
line of sight distance also recovered similarly well

The stream of stars closely follows the orbit of the satellite (if low mass) BUT DOES NOT delineate its orbit.

So we cannot fit the streams with orbits.

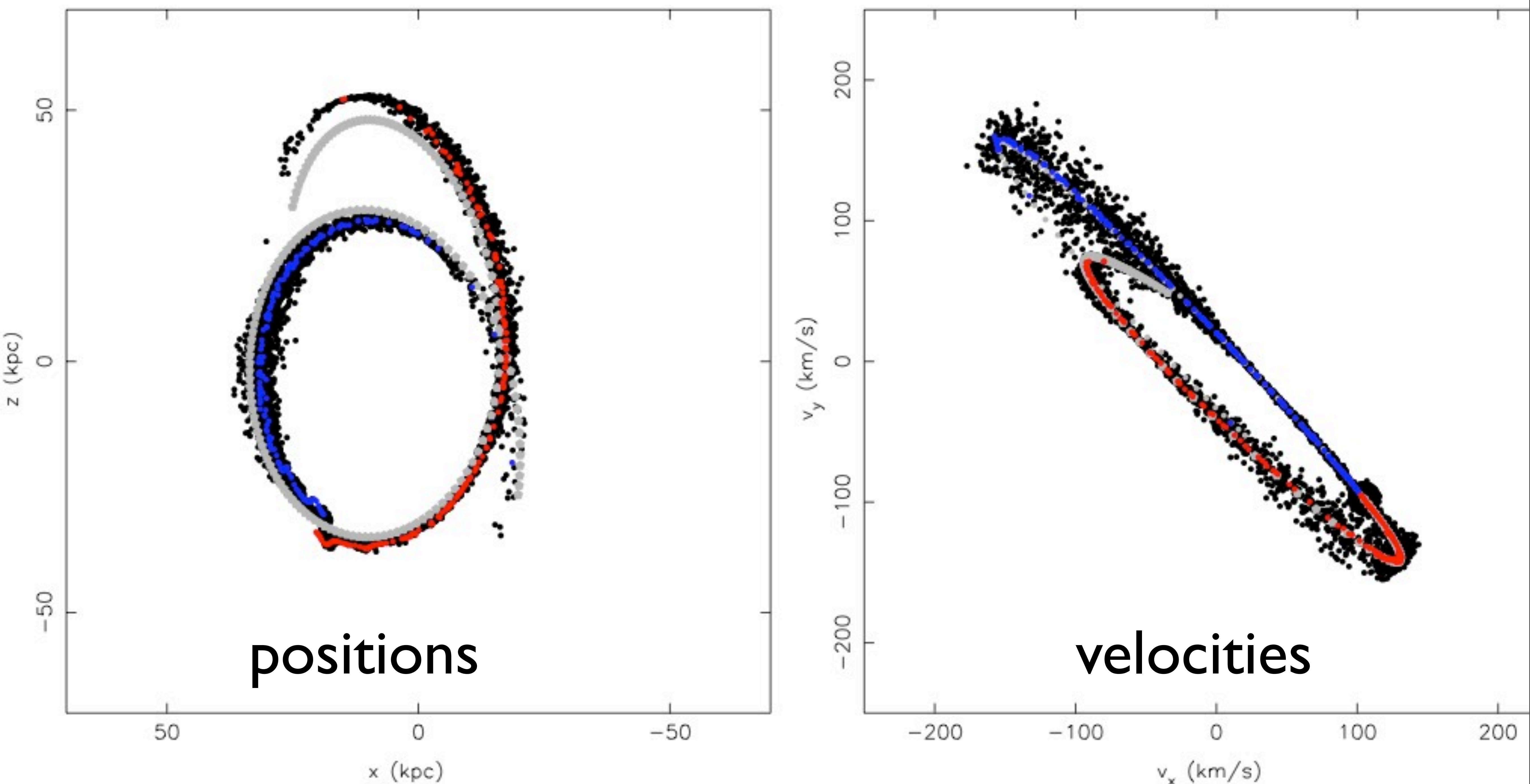
Good news: There is a simple correction by which we can obtain the stream for a given orbit (without N-body integrations!)





take simply: $r_{escape} \sim 2.8 * r_{Jacoby}$

Correction from centre of mass orbit to stream



Use a more realistic galaxy model

Modelling Galactic potential (Dehnen & Binney 1998):

$$\rho_{\rm d}(R,z) = \frac{\Sigma_{\rm d}}{2z_{\rm d}} \exp\left(-\frac{R_m}{R} - \frac{R}{R_{\rm d}} - \frac{|z|}{z_{\rm d}}\right)$$ thin, thick disks & ISM

$$\rho(R,z) = \rho_0 \left(\frac{s}{r_0}\right)^{-\gamma} \left(1 + \frac{s}{r_0}\right)^{\gamma-\beta} e^{-s^2/r_t^2}$$ Bulge, Halo

where

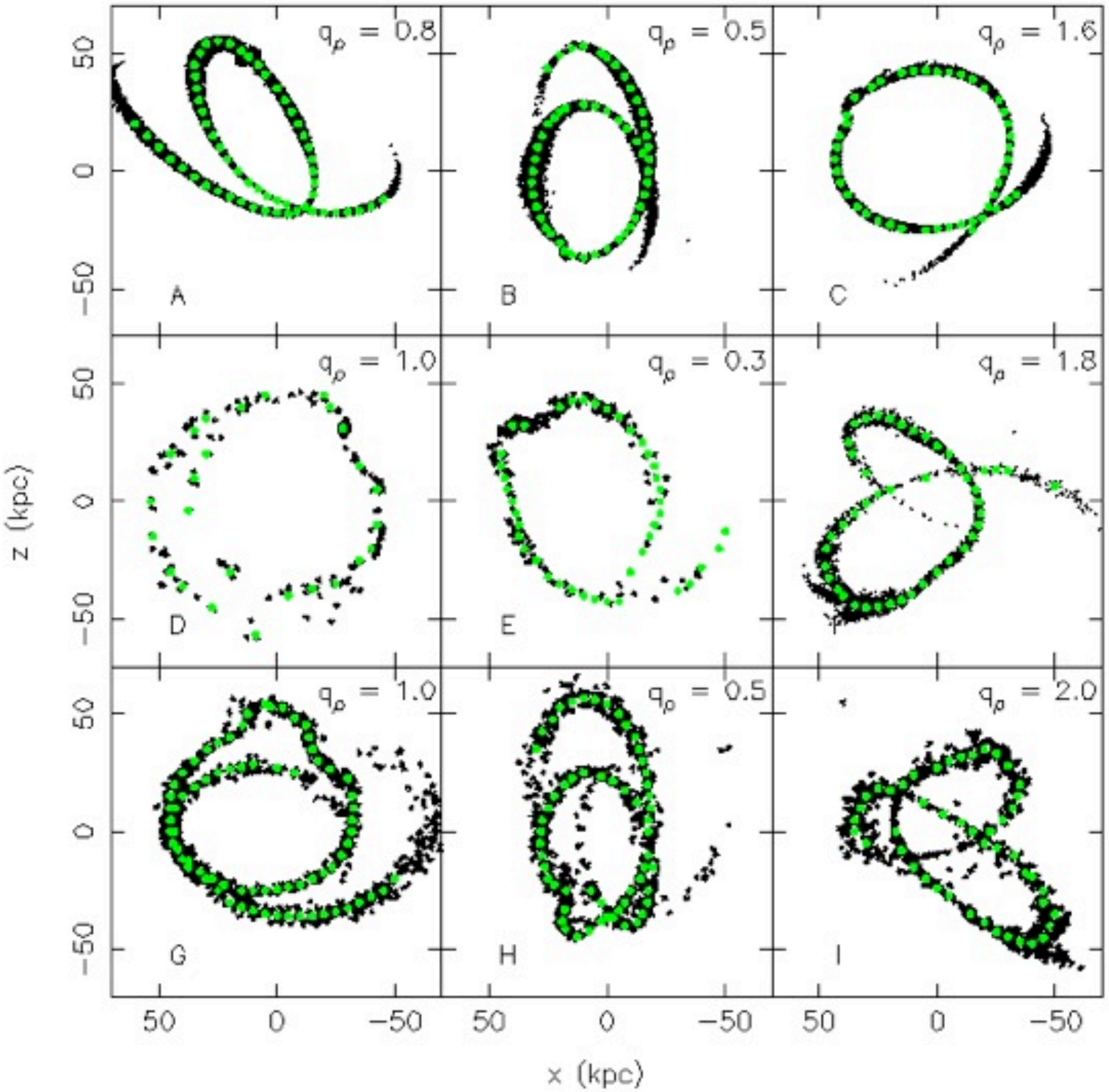
$$s \equiv (R^2 + q_m^{-2} z^2)^{1/2}$$ (q_m is density flattening)

$$\rho \propto \begin{cases} r^{-\gamma} & \text{for } r \ll r_0 \\ r^{-\beta} & \text{for } r_0 \ll r \ll r_t \\ \text{softly truncated} & \text{at } r = r_t \end{cases}$$

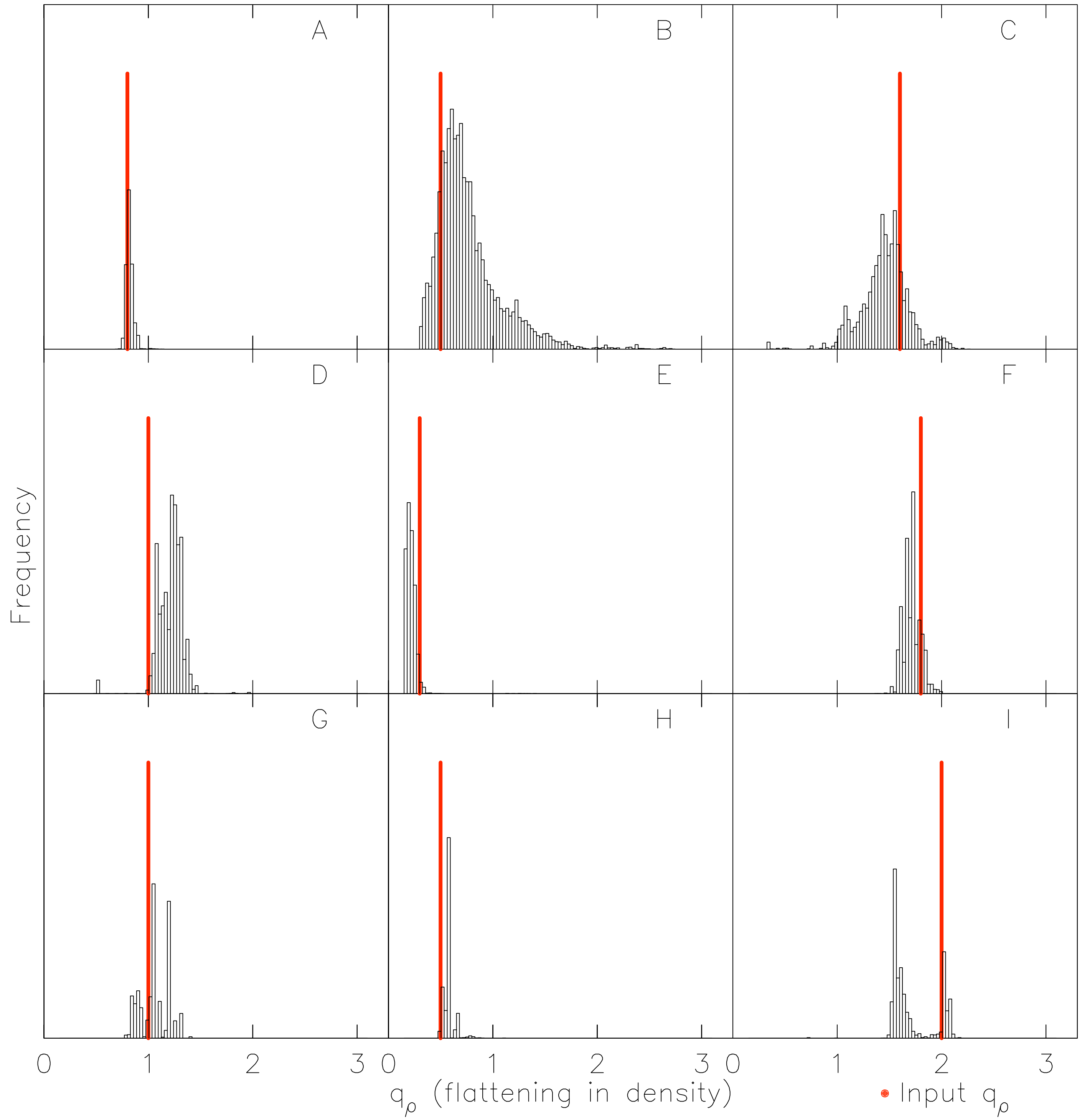
Forces calculated by multipole expansion

Have also implemented a "non-parametric" halo

Test Streams



RESULTS:
Fitting using only projection of the stream



1. **Flattening in density is well constrained:** Projections of streams in far away systems as well as nearby ones with no kinematic information can reveal the shapes of halos.

Adding the inner rotational curve:

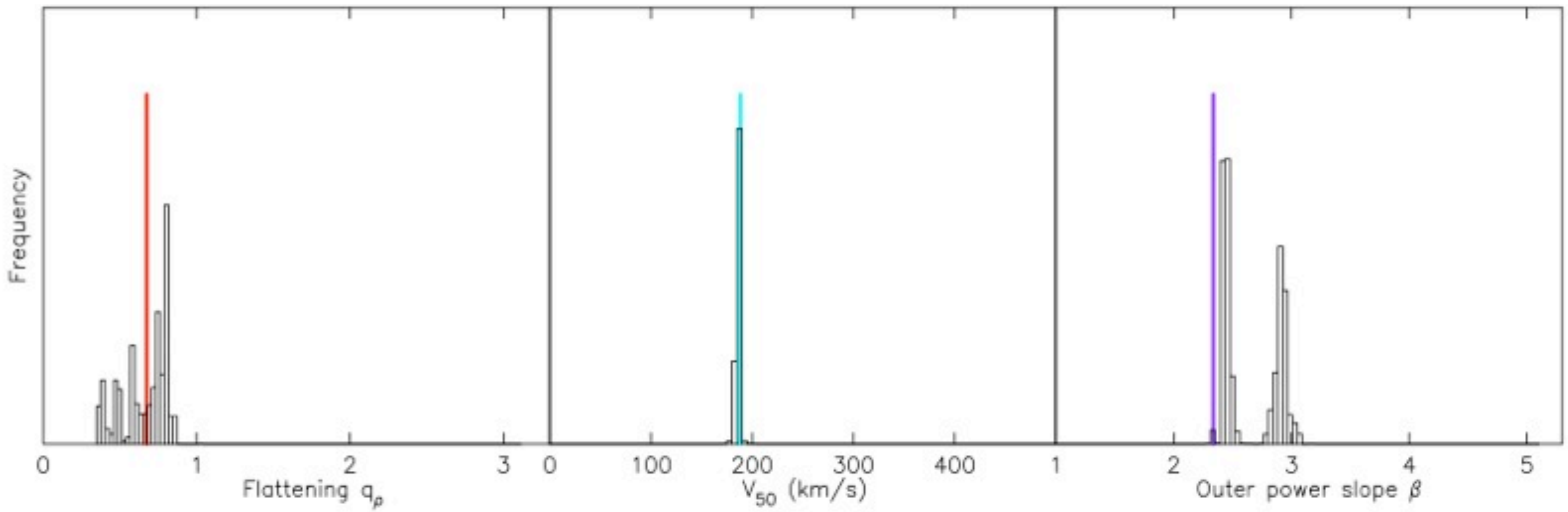
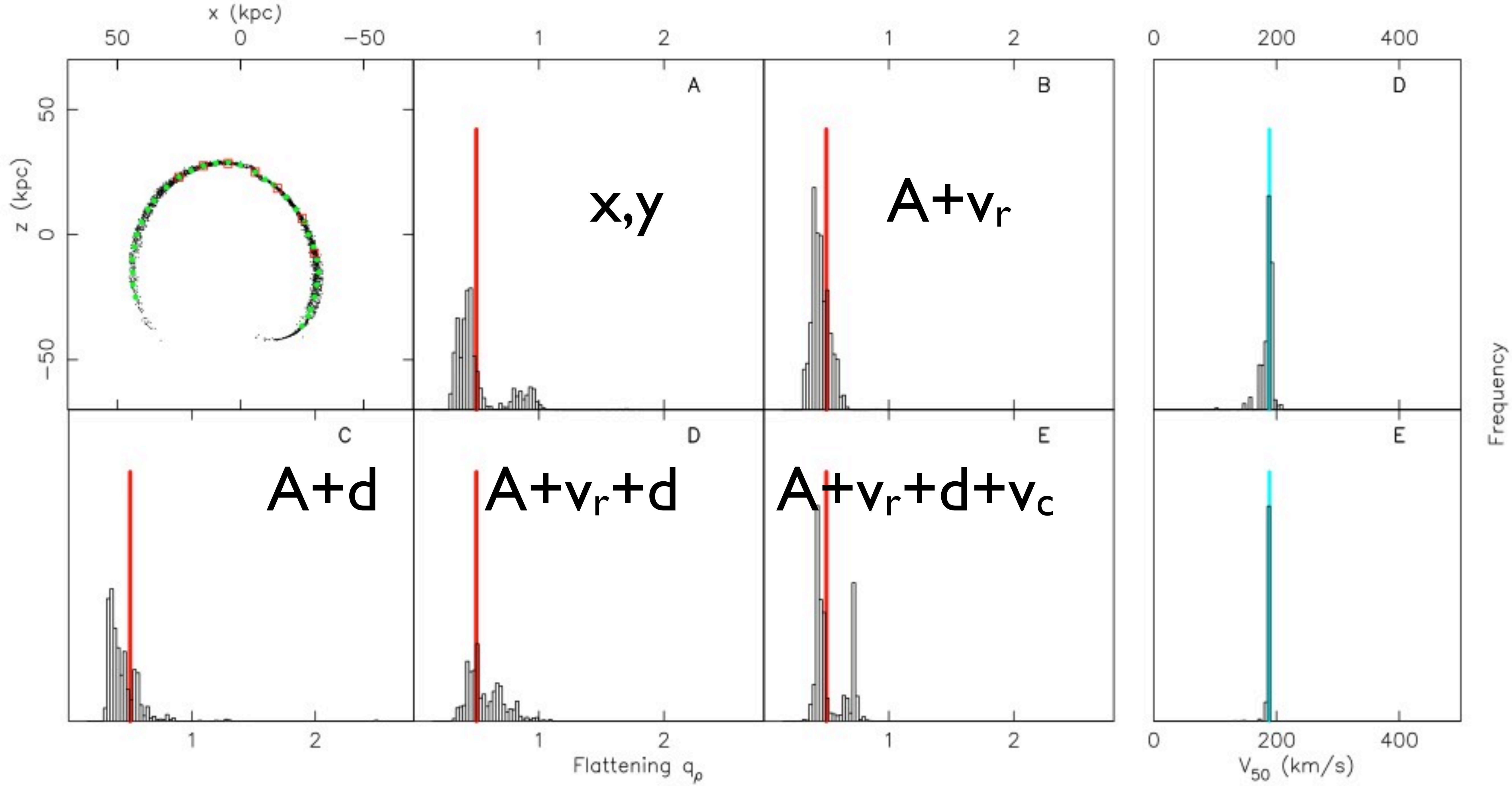


Figure 13. The distributions in q_ρ, V_{50} and β for **stream B** when the inner rotational velocity curve is also provided in addition to the projected positions. The true values of each of these are marked in red, cyan and violet respectively.

Estimates of flattening q do not improve markedly.
Improves estimates on all other parameters.
Mass can be constrained (as expected).
Distance and velocities of progenitor are recovered too!

If we have a long stream with some kinematic information (l.o.s velocities or rot. curve) all the parameters (except inner power slope) can be constrained.

The shorter the stream the more difficult things become

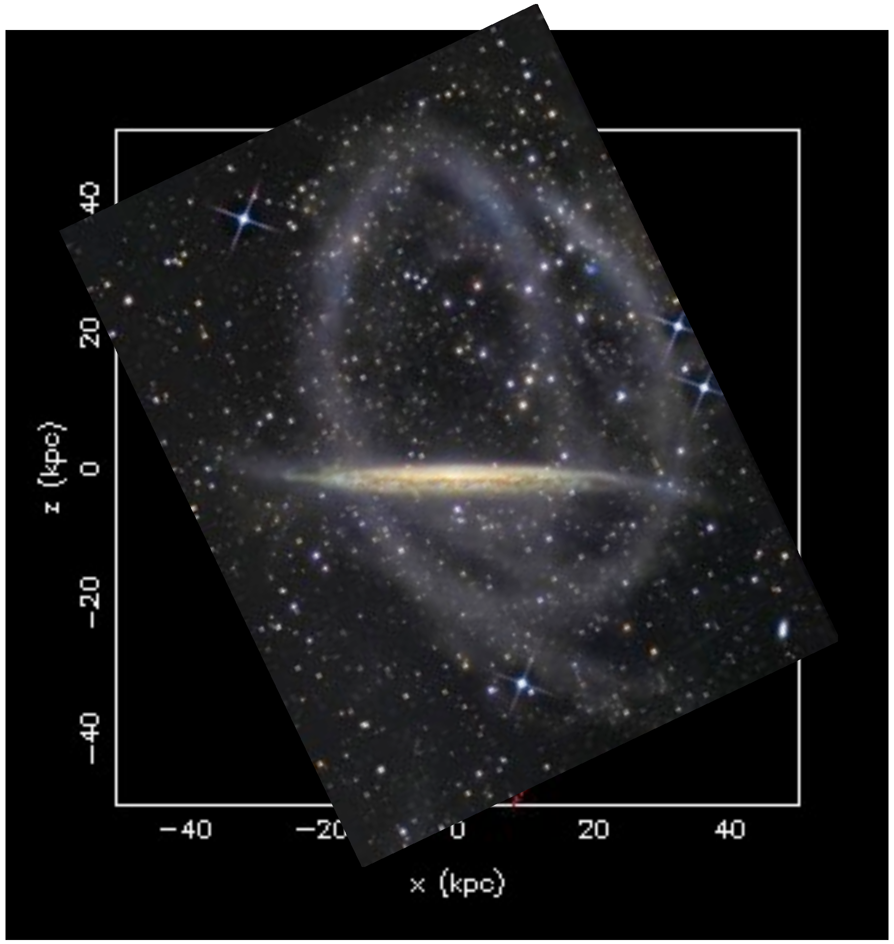


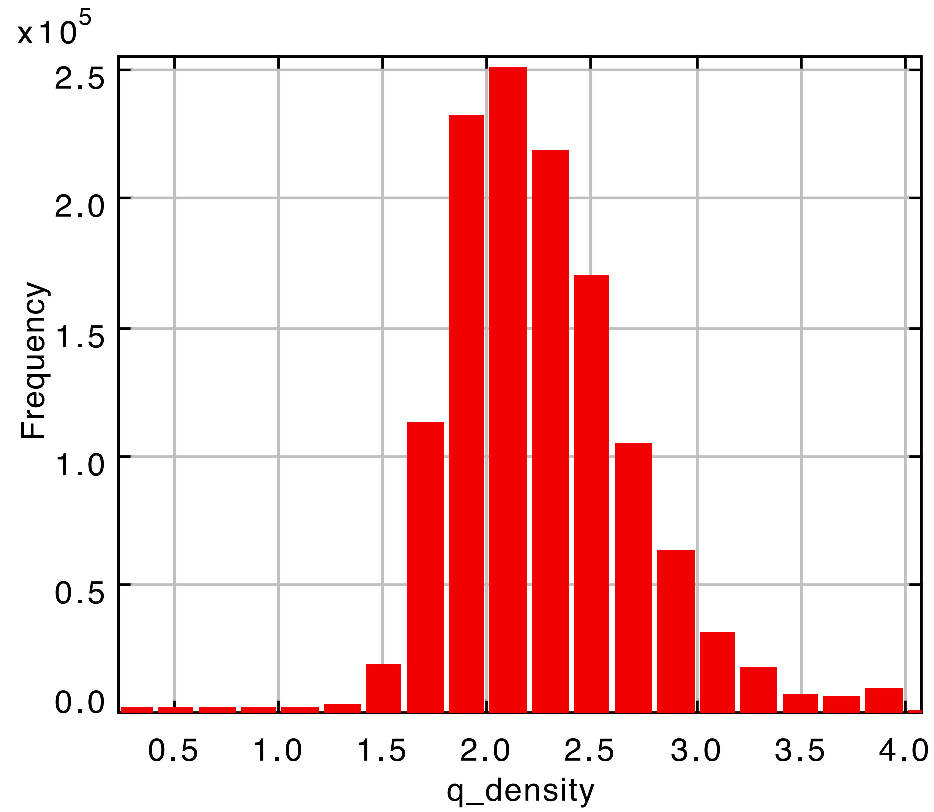
Its the number of turning points that really matter.

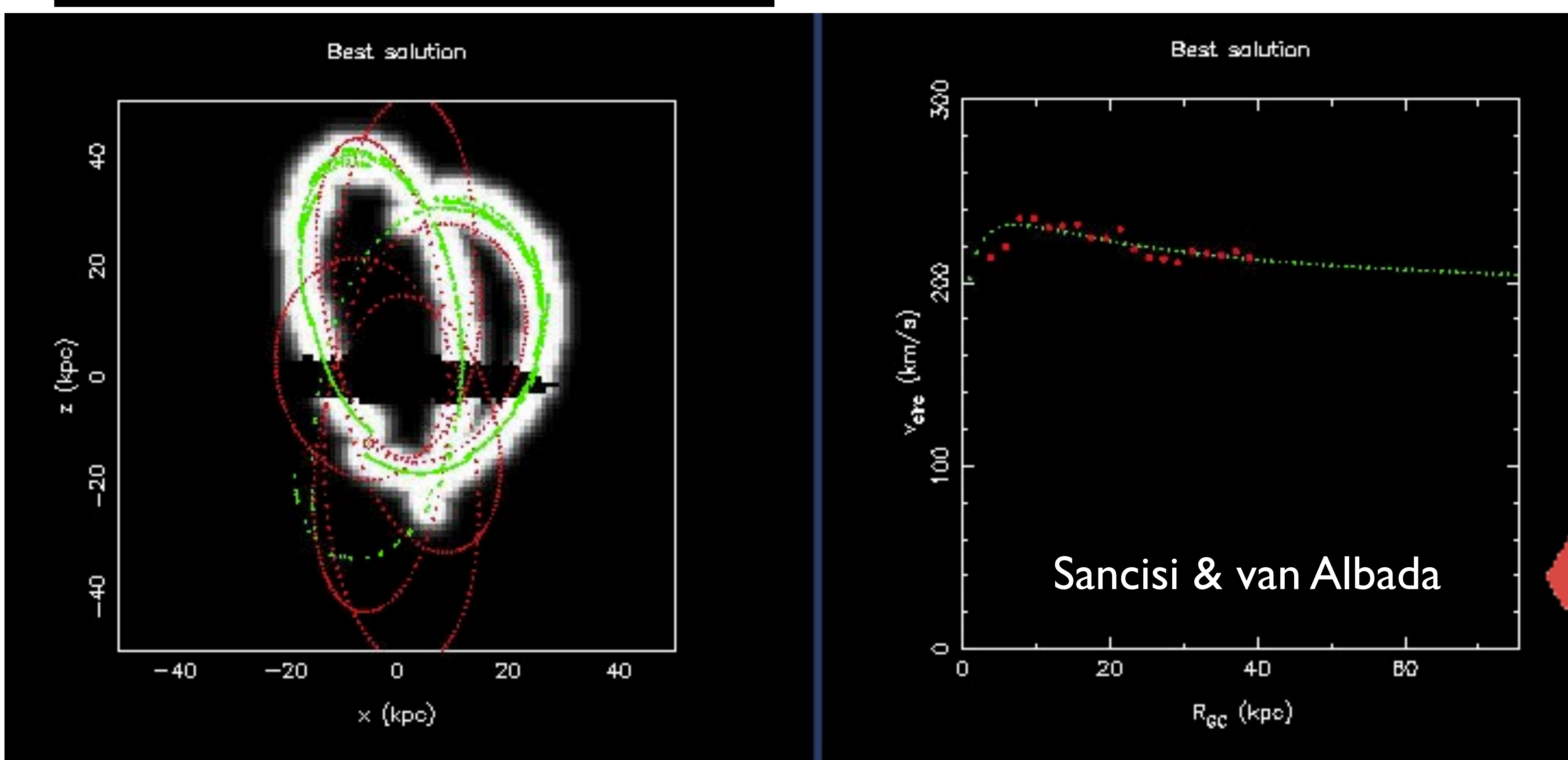
Bottom line:

- Pure projections of stream systems allow us to uncover the shape of the dark matter distribution. Very promising for next-generation instruments!
- 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.
- Works also for triaxial systems... but harder...
- Have implemented MOND gravity (with Benoit Famaey)... very interesting test!
- Can add in dynamical friction

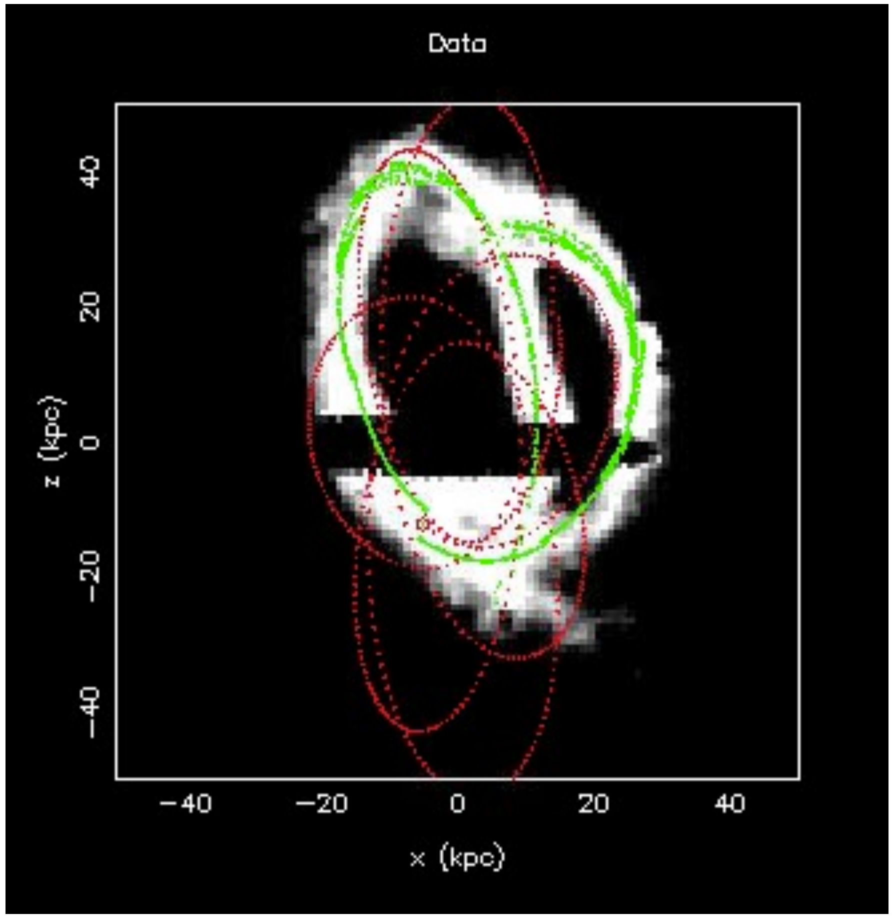
NGC 5907


z (kpc)
x (kpc)

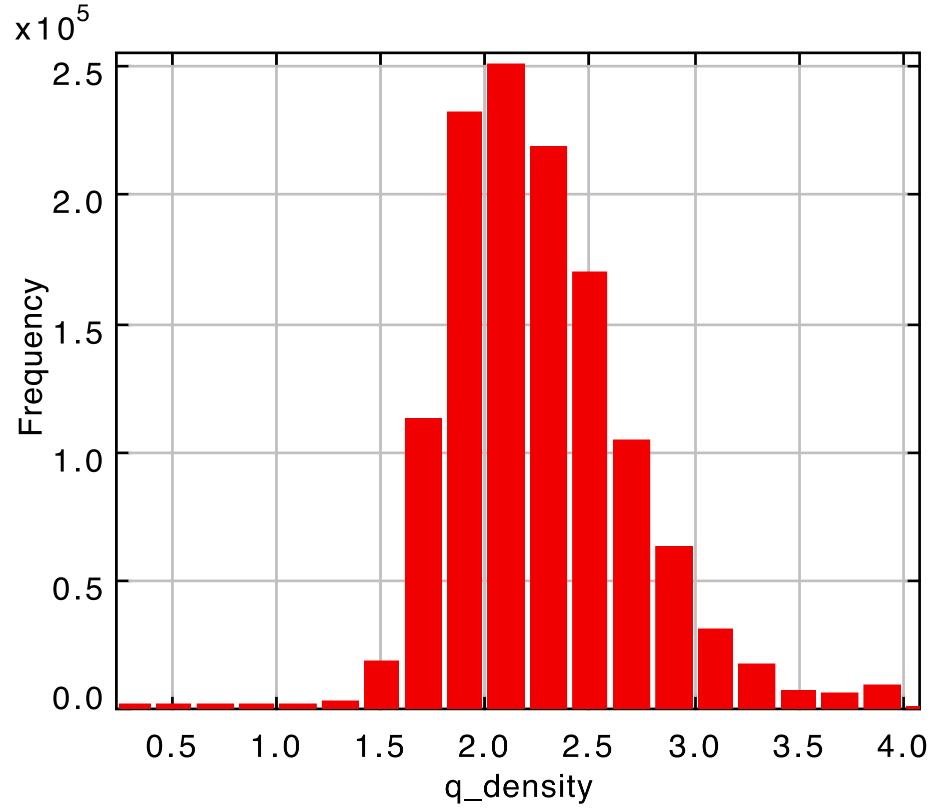

x10^5
Frequency
q_density


Best solution
z (kpc)
x (kpc)
Best solution
v_{circ} (km/s)
R_{GC} (kpc)
Sancisi & van Albada

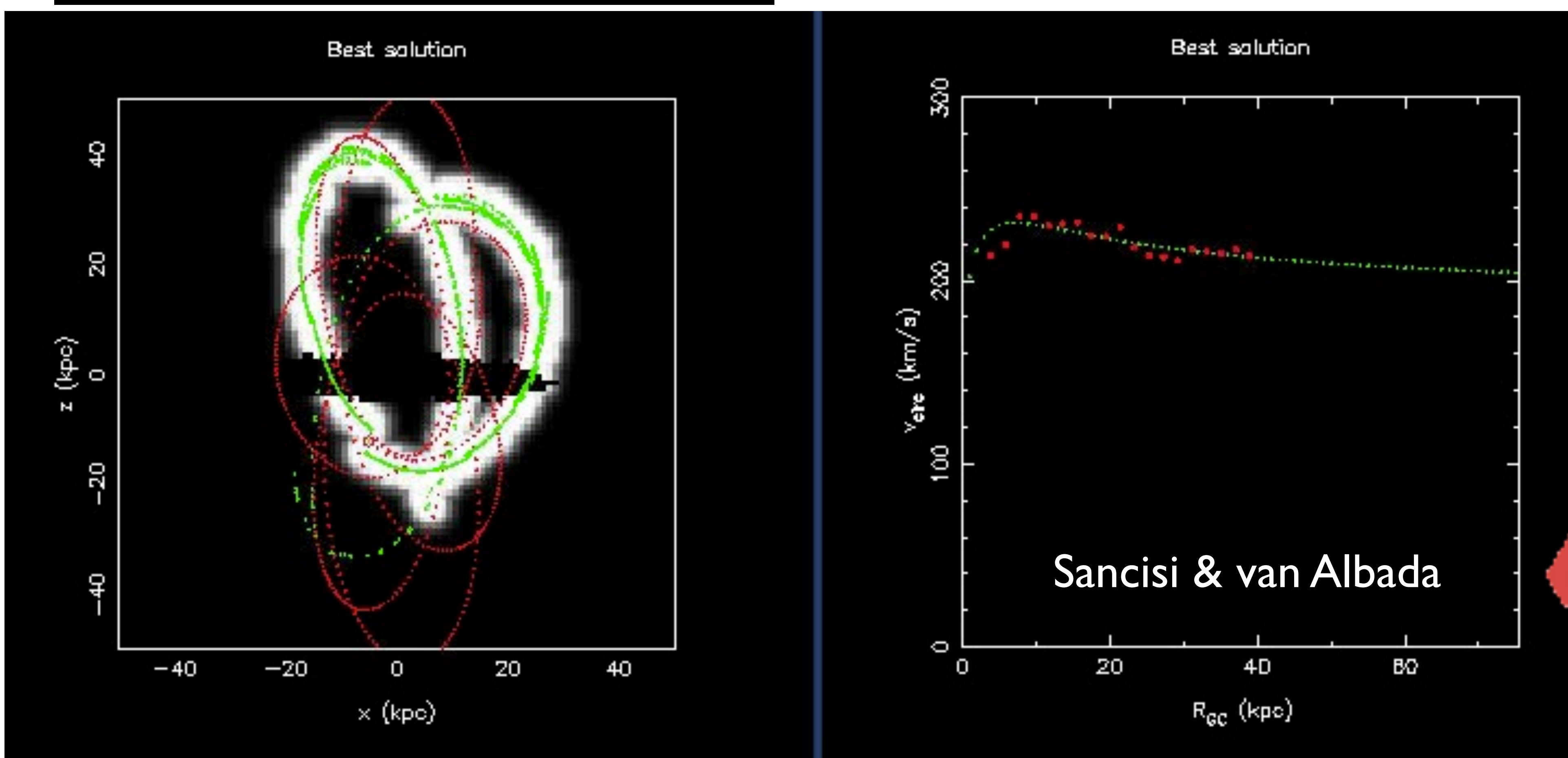
NGC 5907



Data
z (kpc)
x (kpc)
−40
−20
0
20
40



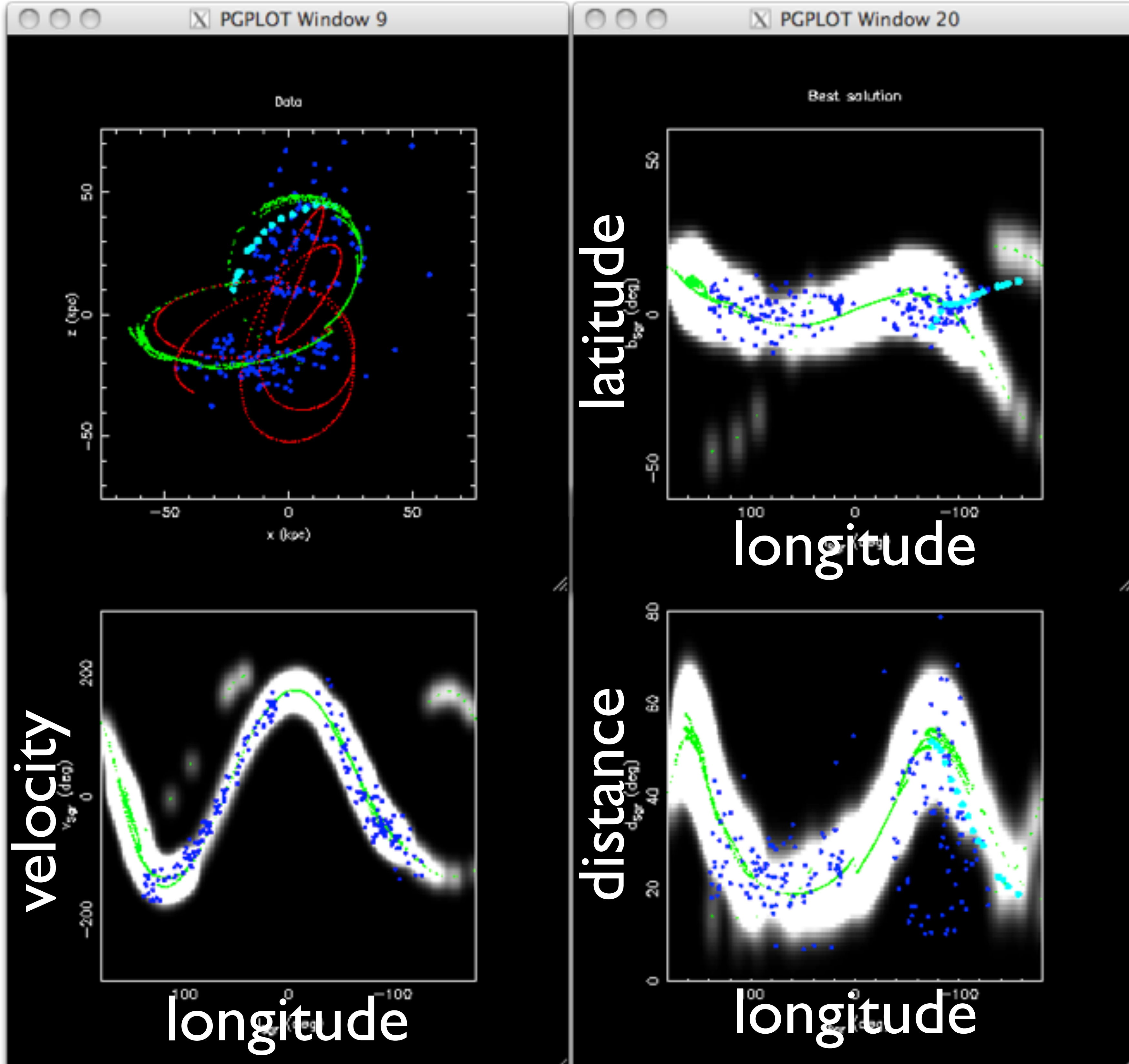
x10^5
Frequency
q_density
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0

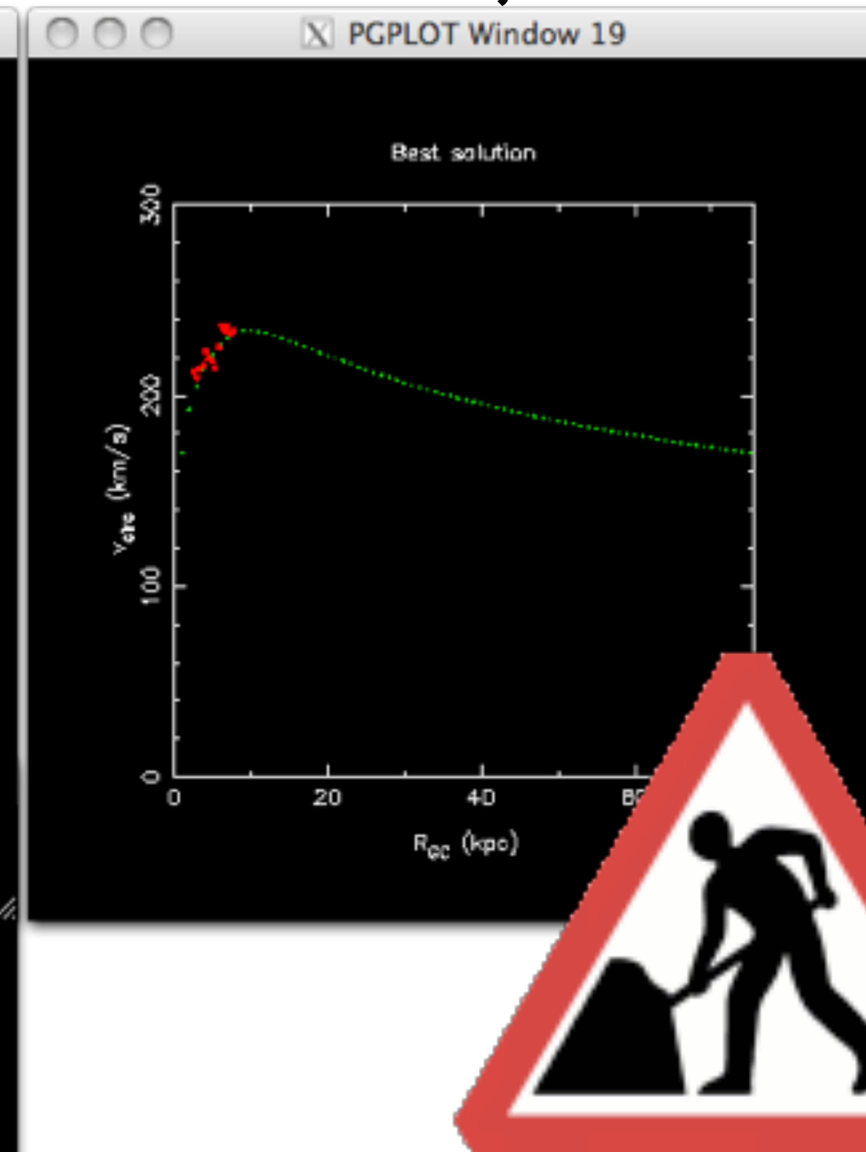


Best solution
z (kpc)
x (kpc)
Best solution
v_circ (km/s)
R_GC (kpc)
0
100
200
300
20
40
60
Sancisi & van Albada

Sagittarius stream in Milky Way with MOND

Data from Law & Majewski 2010





with Benoit Famaey, Arnaud Siebert, Dan Zucker, Elaina Hyde, Anthony Conn

AAT + CFHT

With Gaia

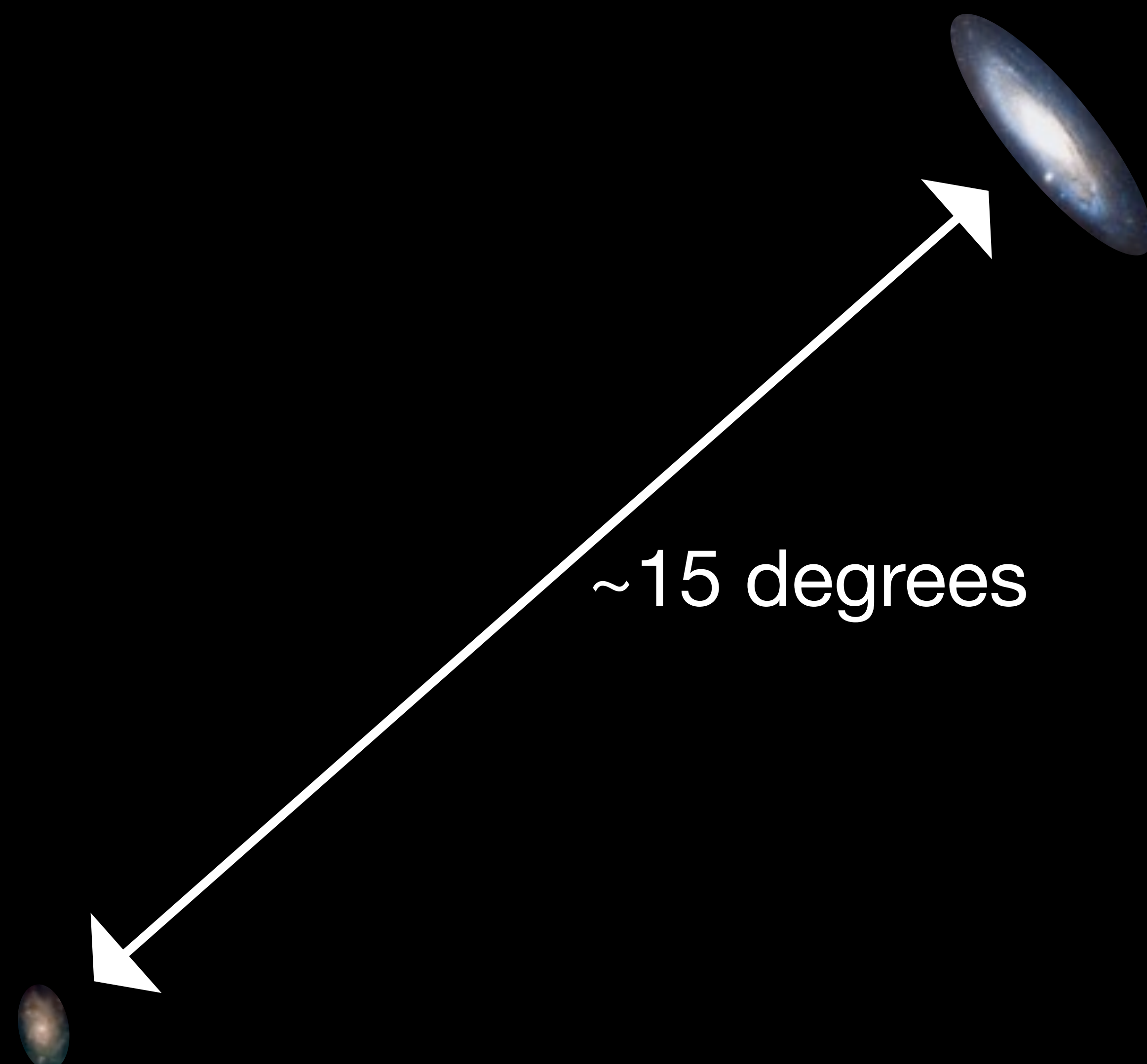
- Direct method probably too inefficient to serve for detection, but useful for characterisation.
- e.g.: have a tentative (~3 sigma?) local stream detection (phase-space correlation) with Gaia, and wish to constrain global orbit and properties of population.
- This technique can work transparently with any additional data.
- Advantage over other approaches is the ease with which we can include uncertainty estimates.
- For stream detection, may work if shifted to space of integrals of motion... TBC

The Pan-Andromeda Archaeological Survey (PAndAS)

P.I. Alan McConnachie

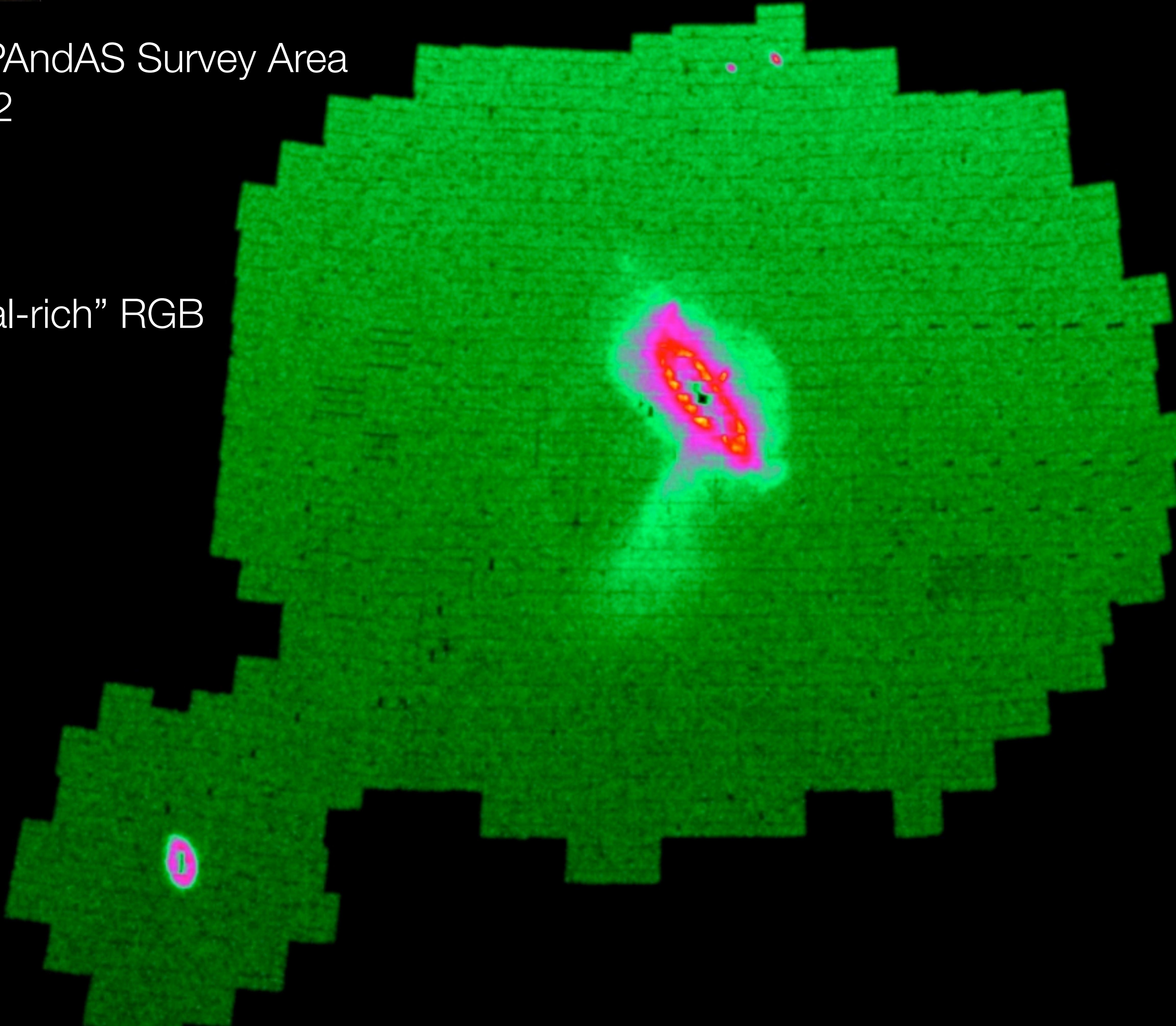
Arif Babul, Mike Barker, Pauline Barmby, Edouard Bernard, Olivier Bienayme, Scott Chapman, Robert Cockcroft, Michelle Collins, Anthony Conn, Pat Cote, Tim Davidge, Anjali Doney, Aaron Dotter, John Dubinski, Greg Fahlman, Mark Fardal, Annette Ferguson, Jurgen Fliri, Bill Harris, Avon Huxor, Rodrigo Ibata, Mike Irwin, Geraint Lewis, Dougal Mackay, Nicolas Martin, Mustapha Moucine, Julio Navarro, Jorge Penarrubia, Thomas Puzia, Mike Rich, Jenny Richardson, Harvey Richer, Arnaud Siebert, Nial Tanvir, David Valls-Gabaud, Kim Venn, Larry Widrow, Kristin Woodley

The PAndAS Survey Area
Year 2



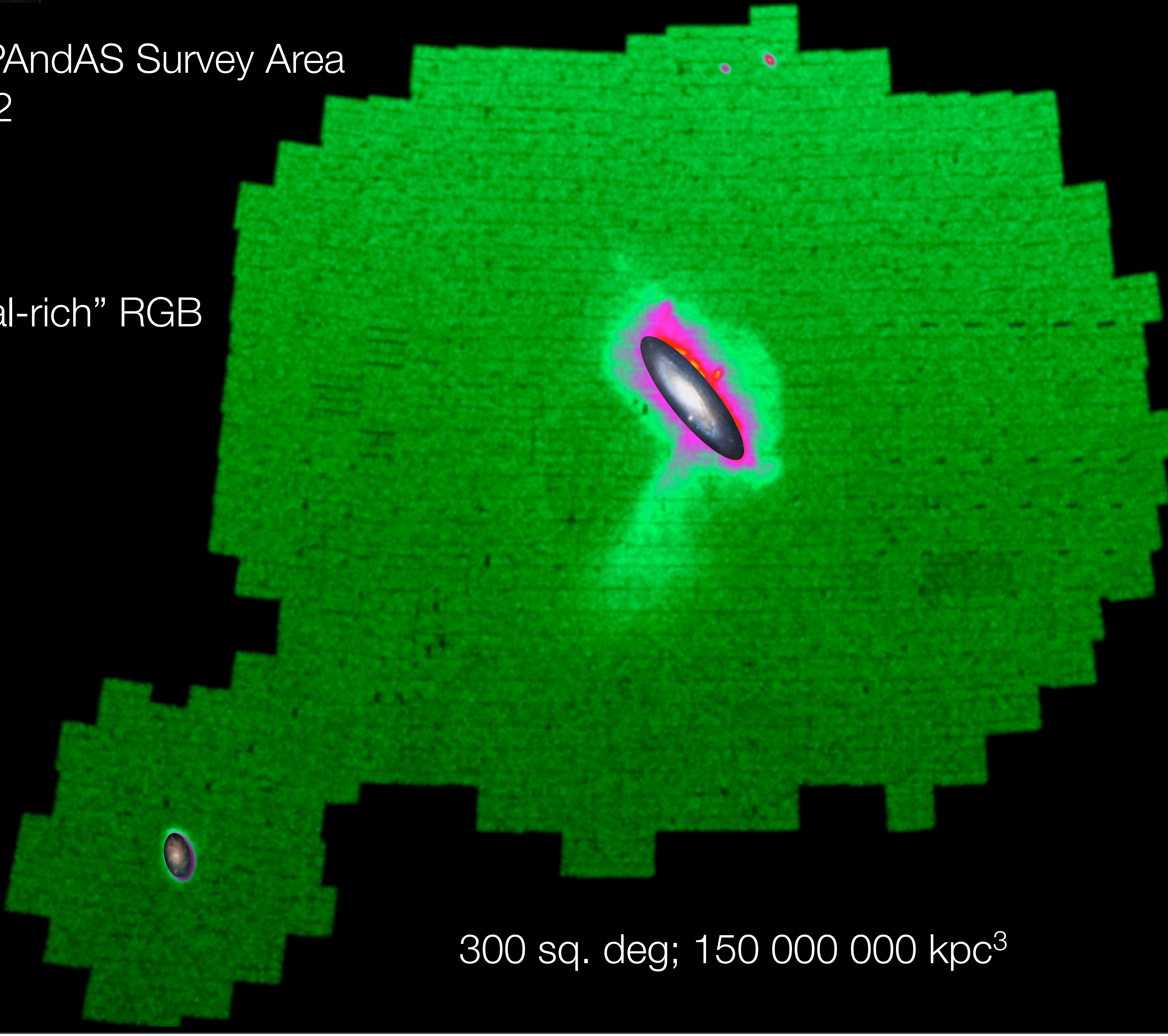
The PAndAS Survey Area
Year 2

“Metal-rich” RGB



The PAndAS Survey Area
Year 2

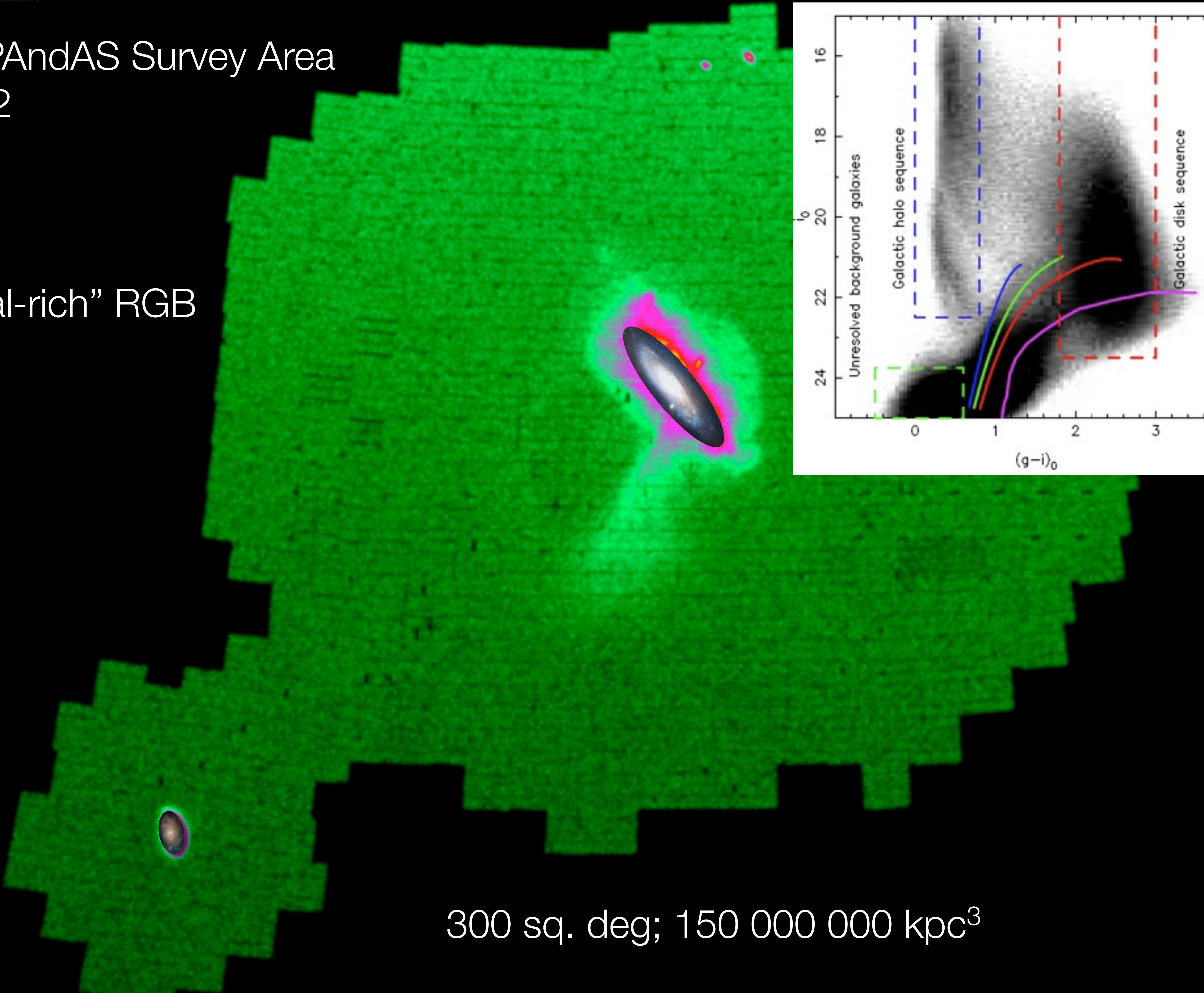
“Metal-rich” RGB



300 sq. deg; 150 000 000 kpc^3

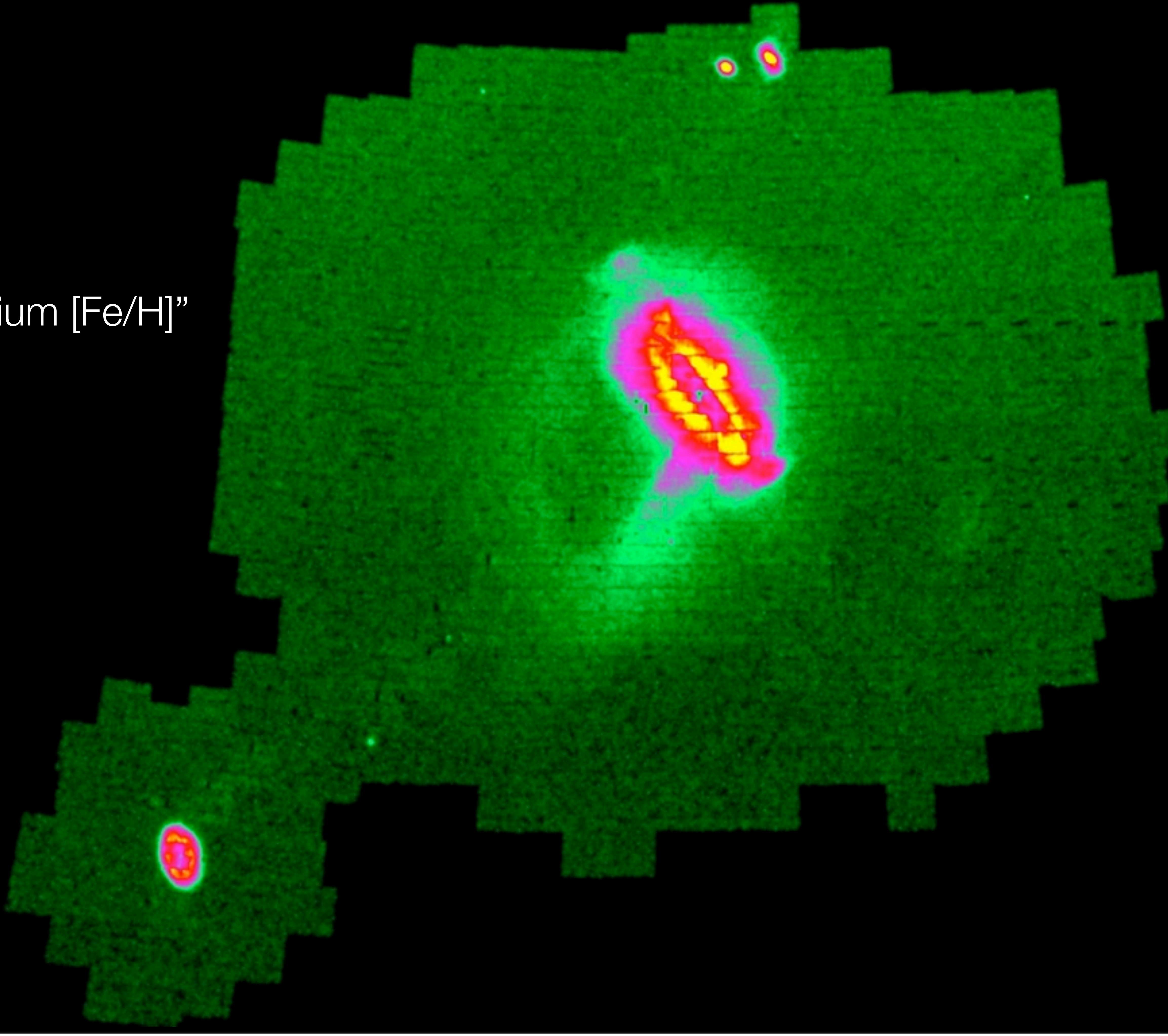
The PAndAS Survey Area
Year 2

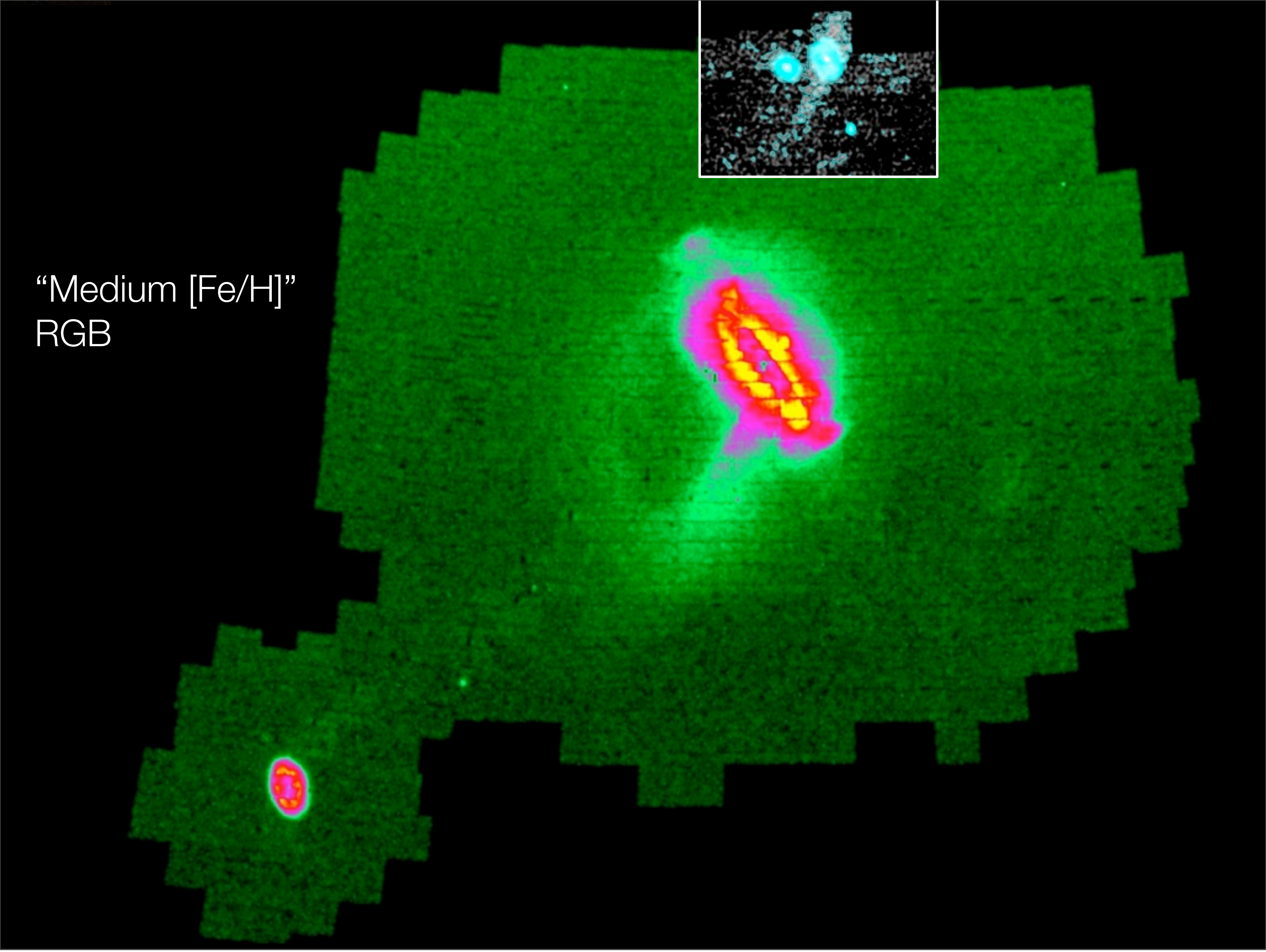
“Metal-rich” RGB



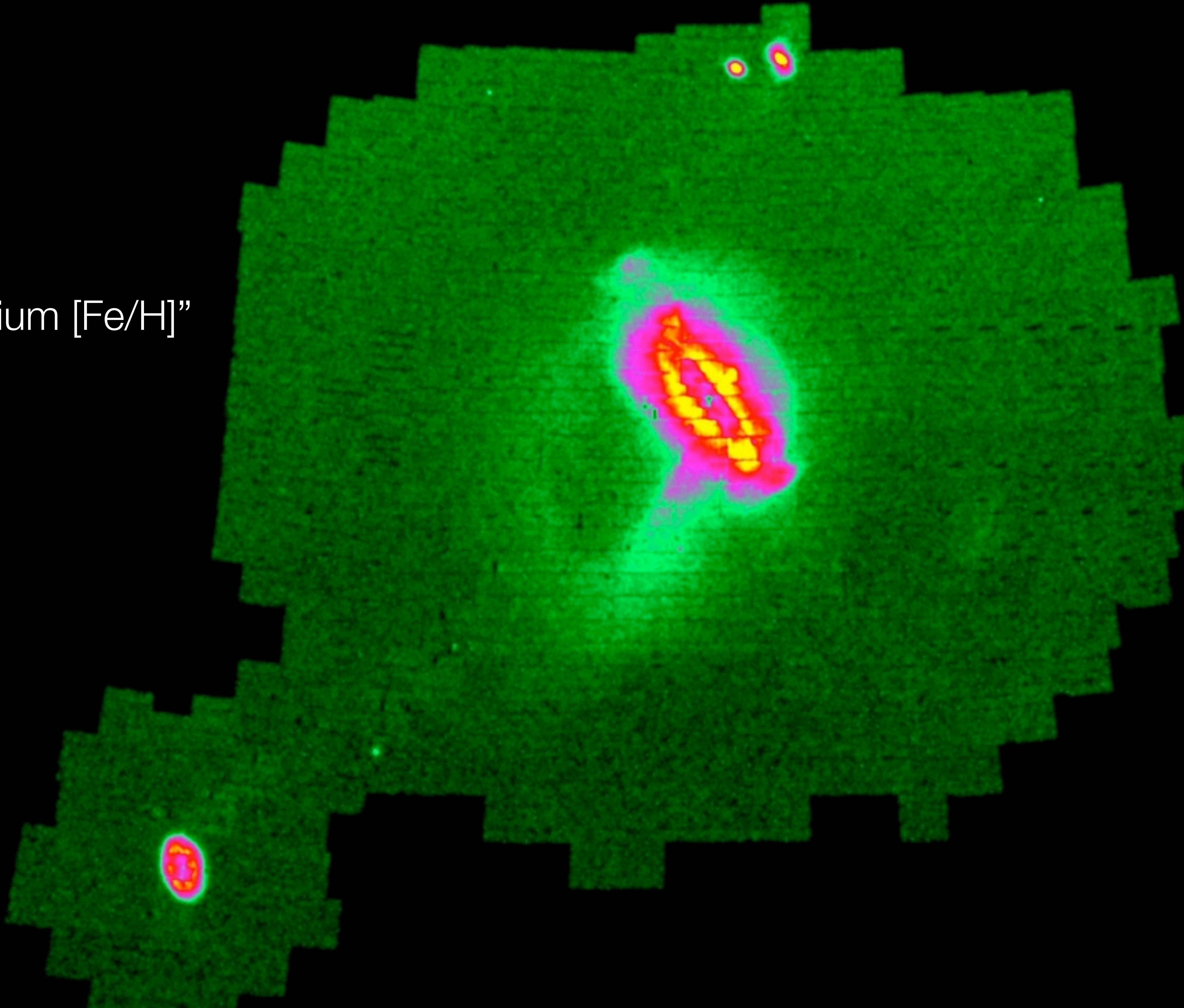
300 sq. deg; 150 000 000 kpc^3

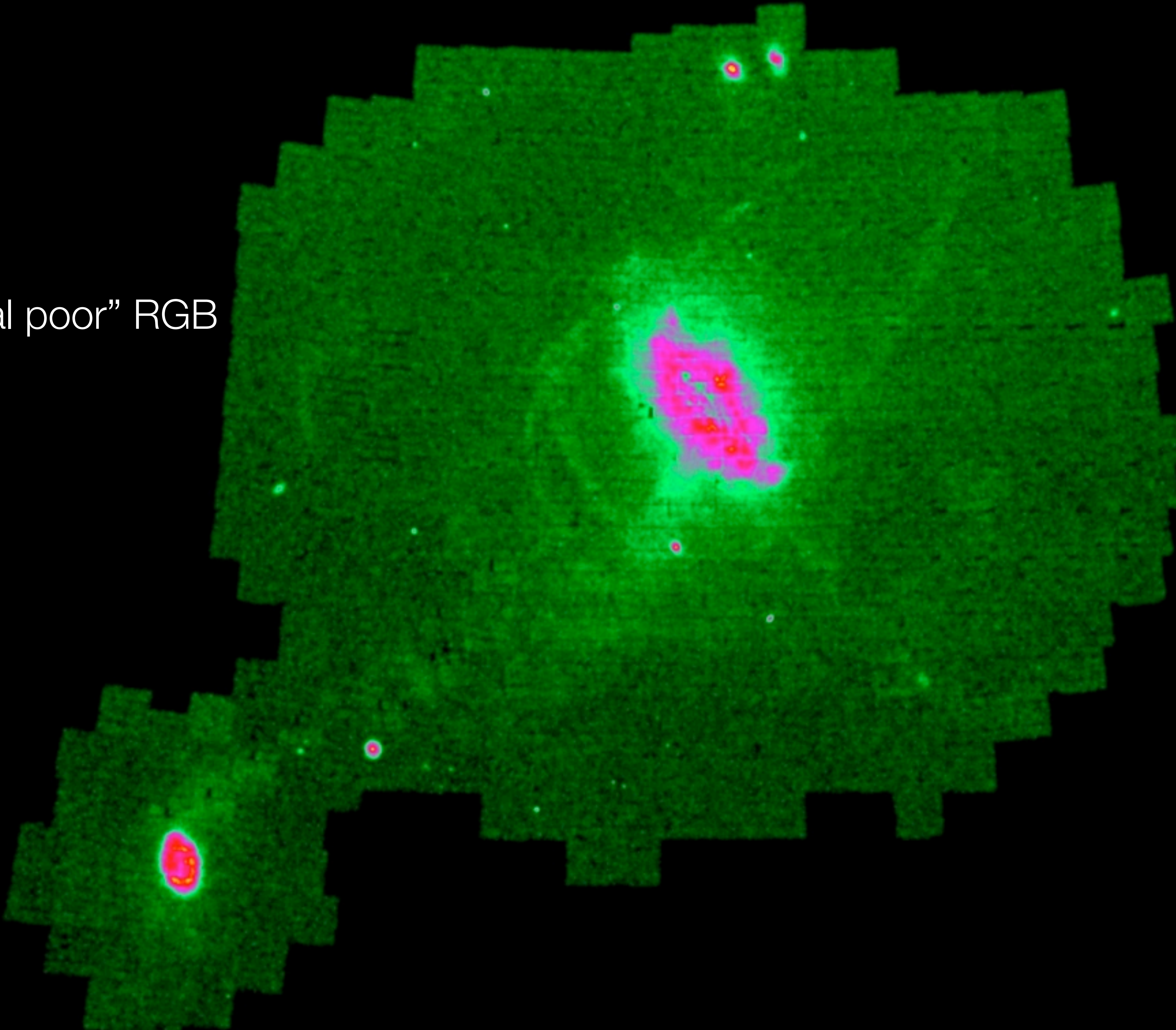
“Medium [Fe/H]”
RGB



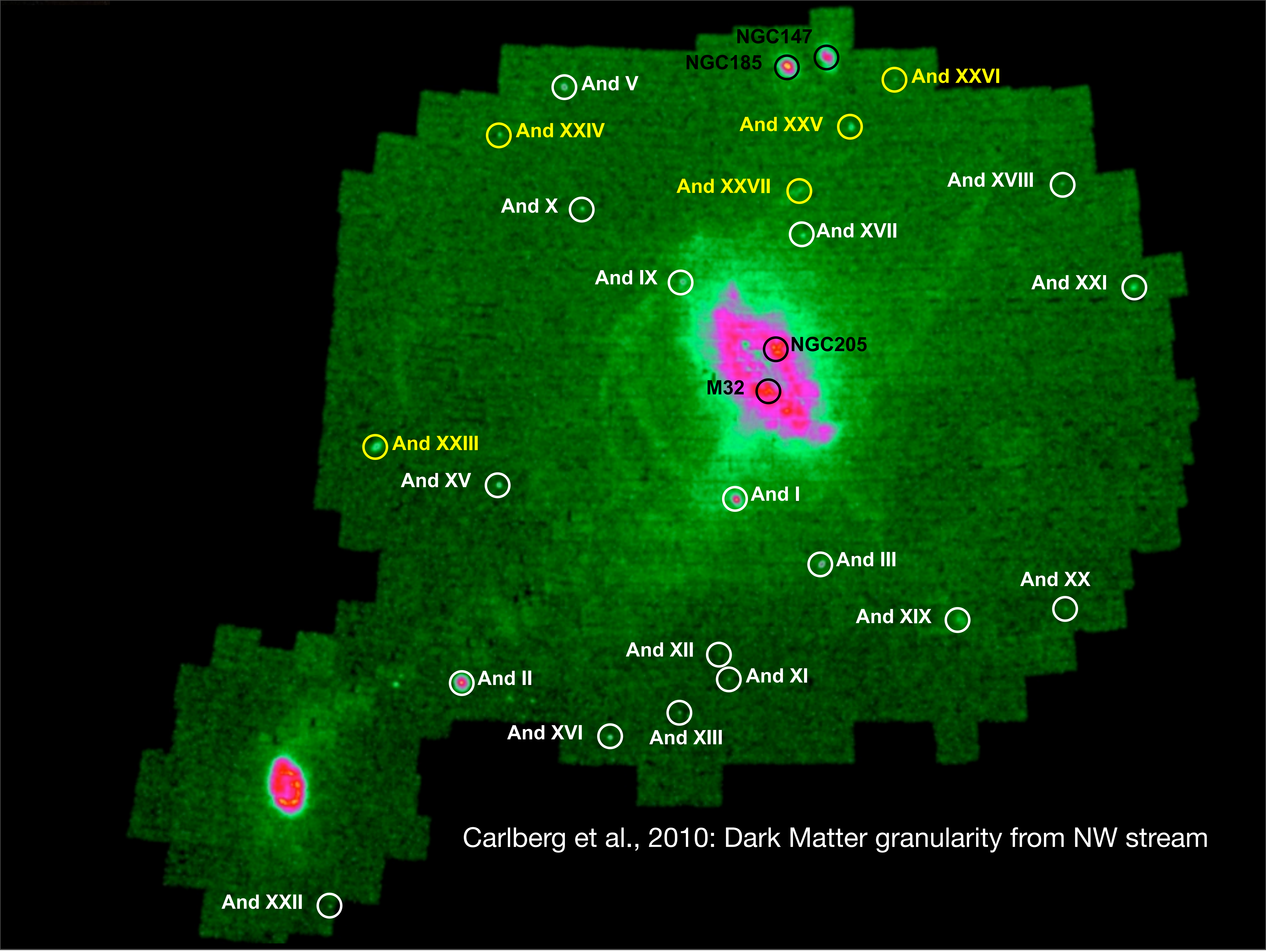

“Medium [Fe/H]”
RGB

“Medium [Fe/H]”
RGB

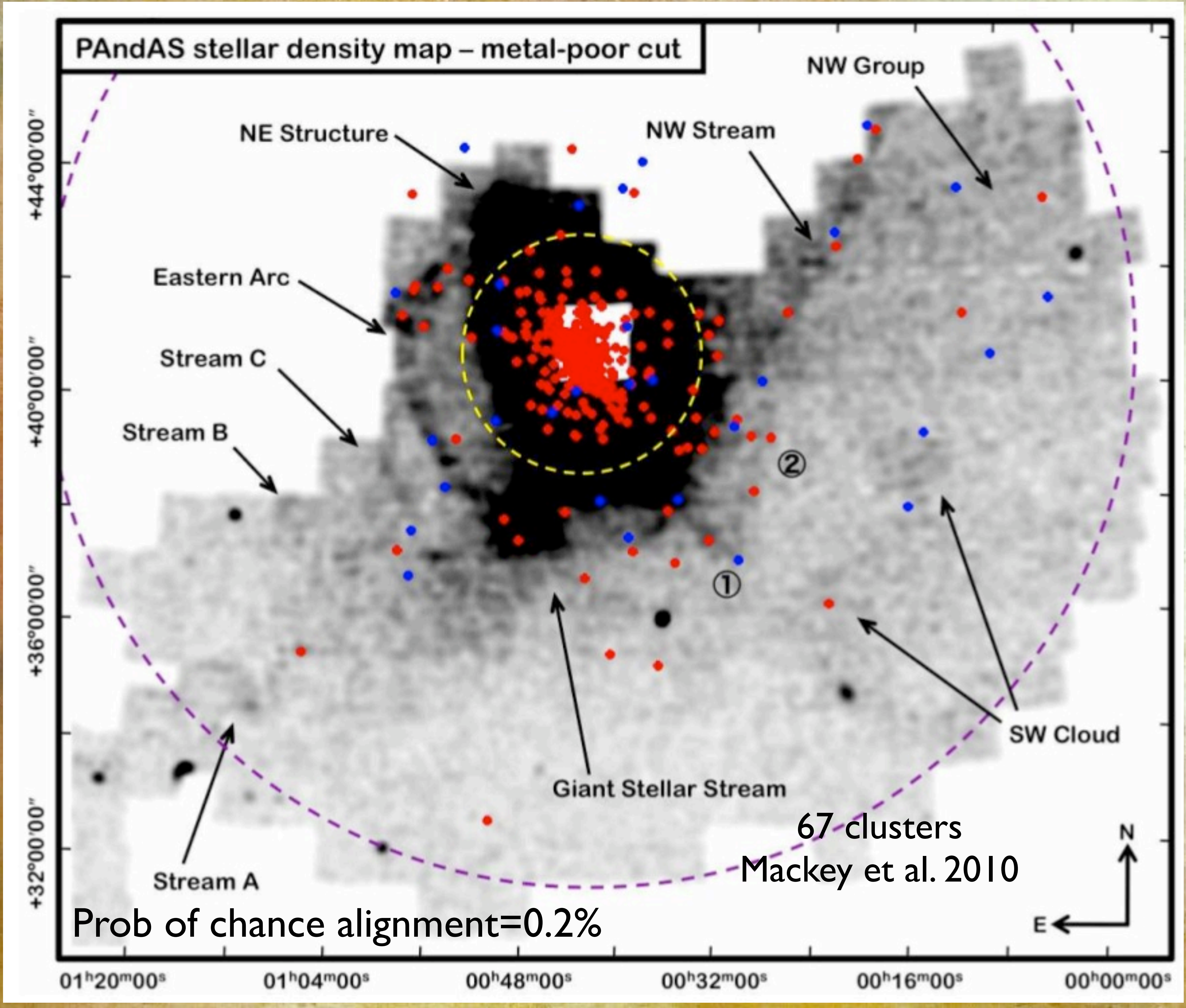


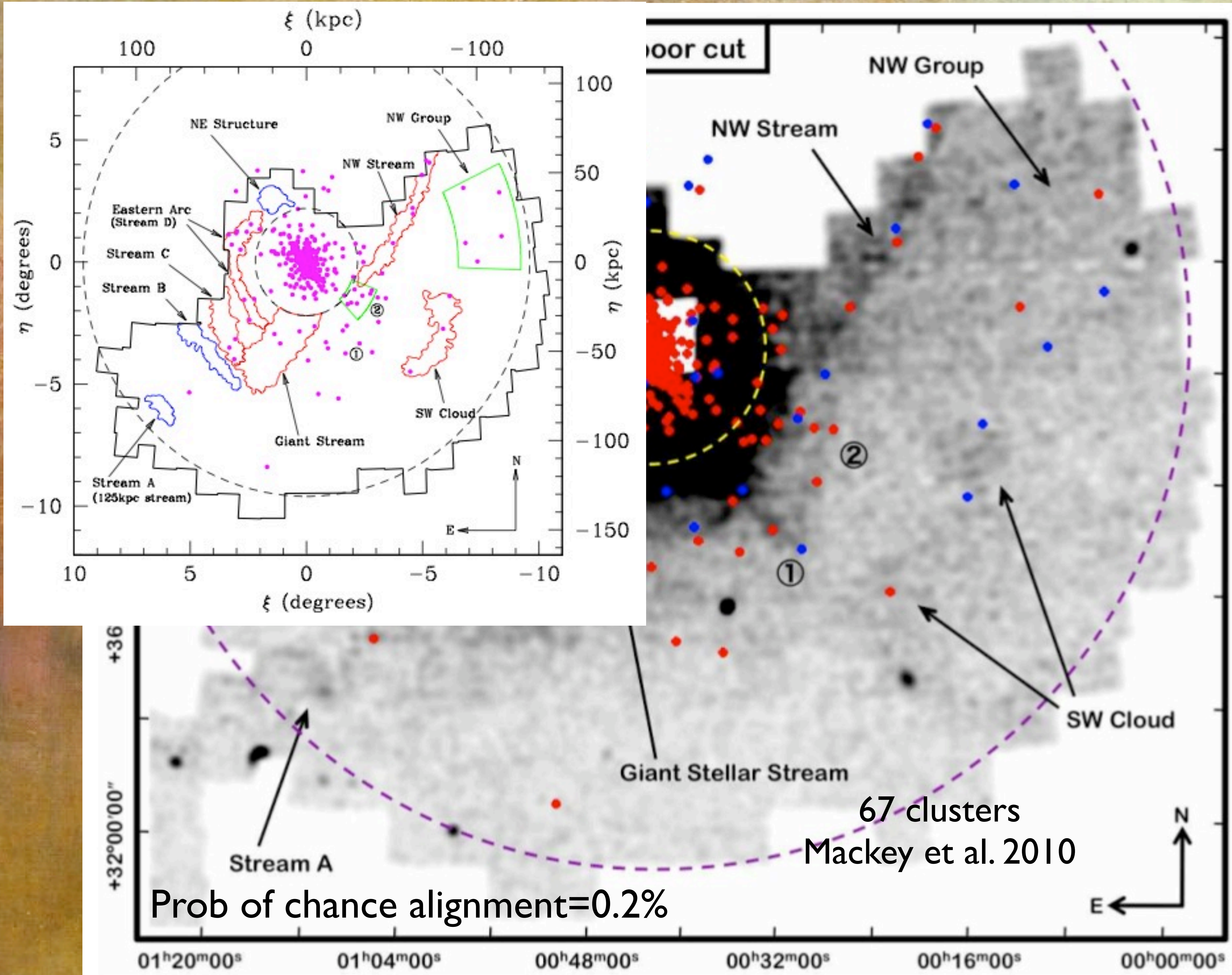


“Metal poor” RGB



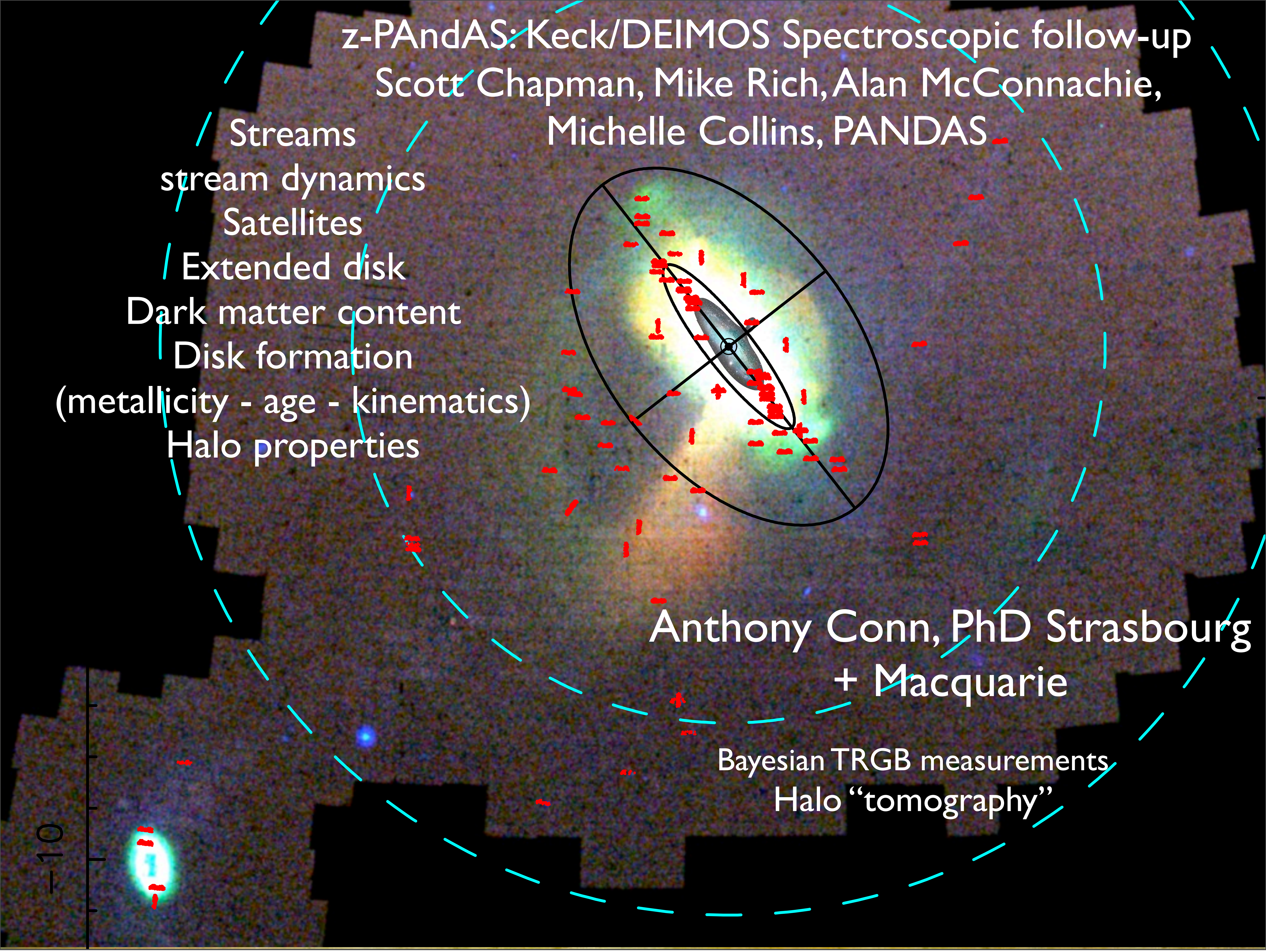
Monday, 20 June 2011


PAndAS stellar density map – metal-poor cut
NW Group
NE Structure
NW Stream
Eastern Arc
Stream C
Stream B
②
①
SW Cloud
Giant Stellar Stream
Stream A
67 clusters
Mackey et al. 2010
Prob of chance alignment=0.2%
N
E
+44°00'00"
+40°00'00"
+36°00'00"
+32°00'00"
01ʰ20ᵐ00ˢ
01ʰ04ᵐ00ˢ
00ʰ48ᵐ00ˢ
00ʰ32ᵐ00ˢ
00ʰ16ᵐ00ˢ
00ʰ00ᵐ00ˢ



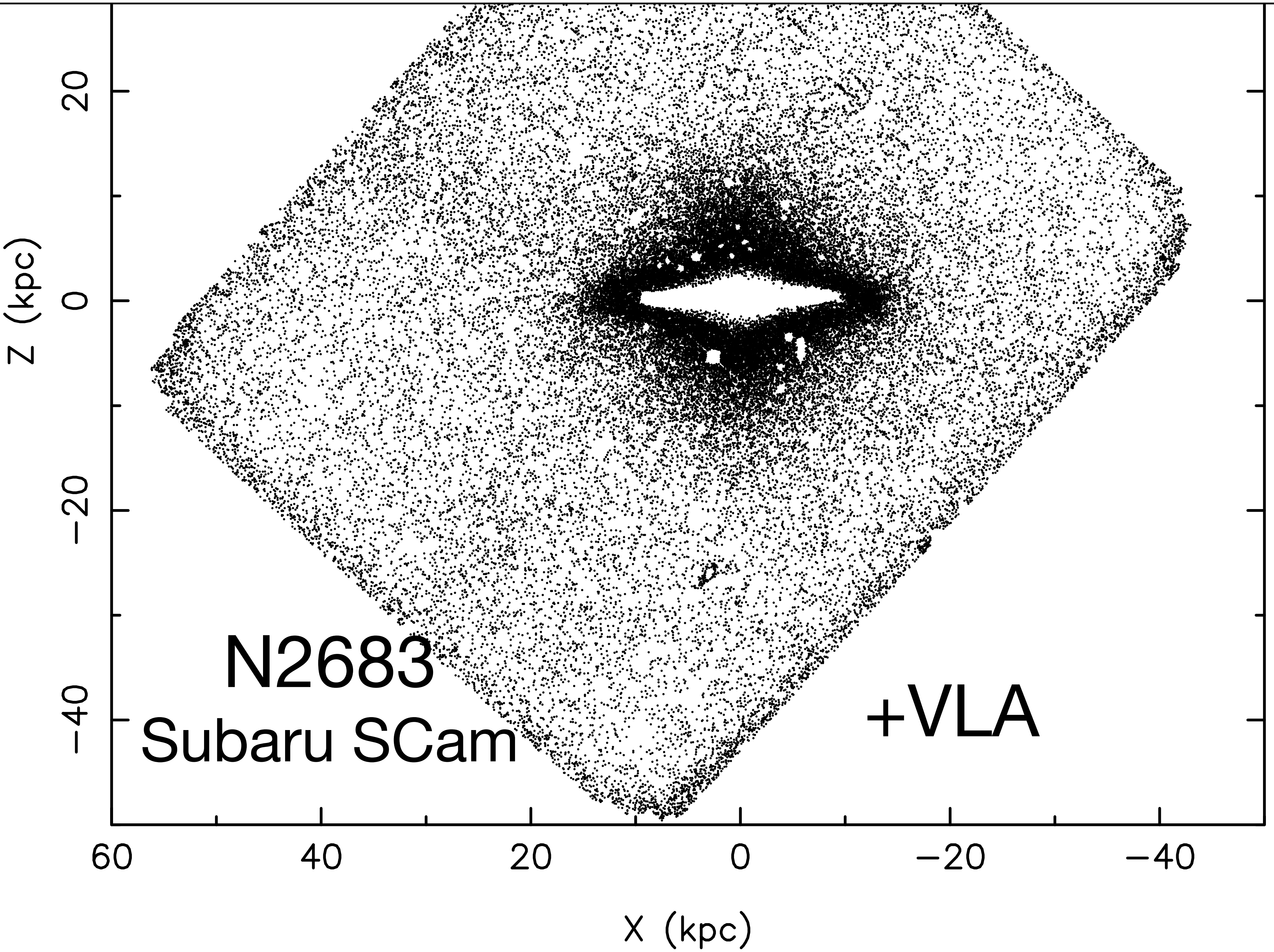
67 clusters
Mackey et al. 2010

Prob of chance alignment=0.2%


z-PAndAS: Keck/DEIMOS Spectroscopic follow-up
Scott Chapman, Mike Rich, Alan McConnachie,
Michelle Collins, PANDAS
Streams
stream dynamics
Satellites
Extended disk
Dark matter content
Disk formation
(metallicity - age - kinematics)
Halo properties
Anthony Conn, PhD Strasbourg
+ Macquarie
Bayesian TRGB measurements
Halo "tomography"
−10

PLANS (Panoramic Landscape of Spirals)

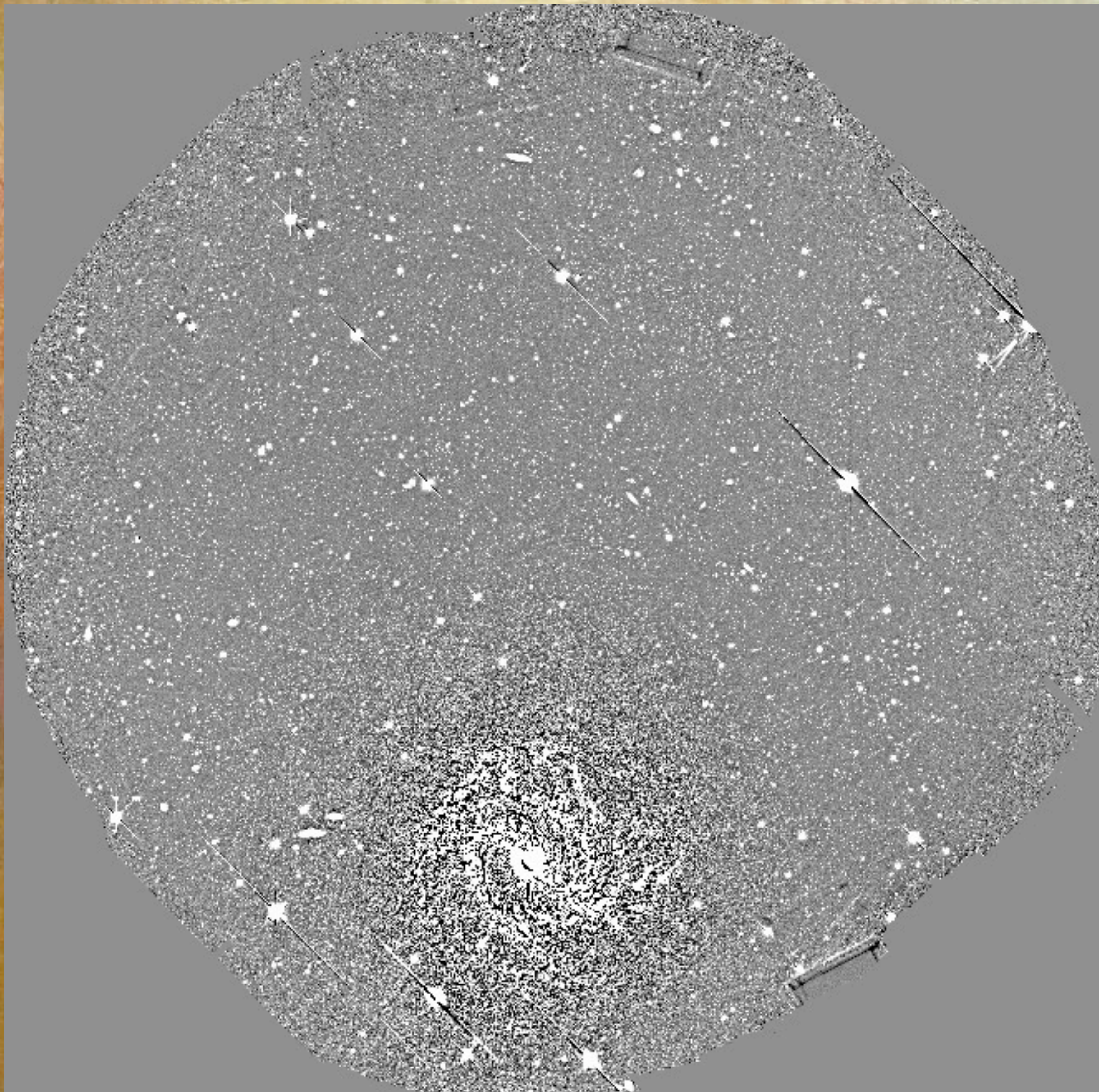
Mustapha Mouhcine, Marina Rejkuba, Barry Madore,
Matias Gomez, Lorenzo Monaco, Ata Sarajedini,
Bernd Vollmer, Anjali Varghese



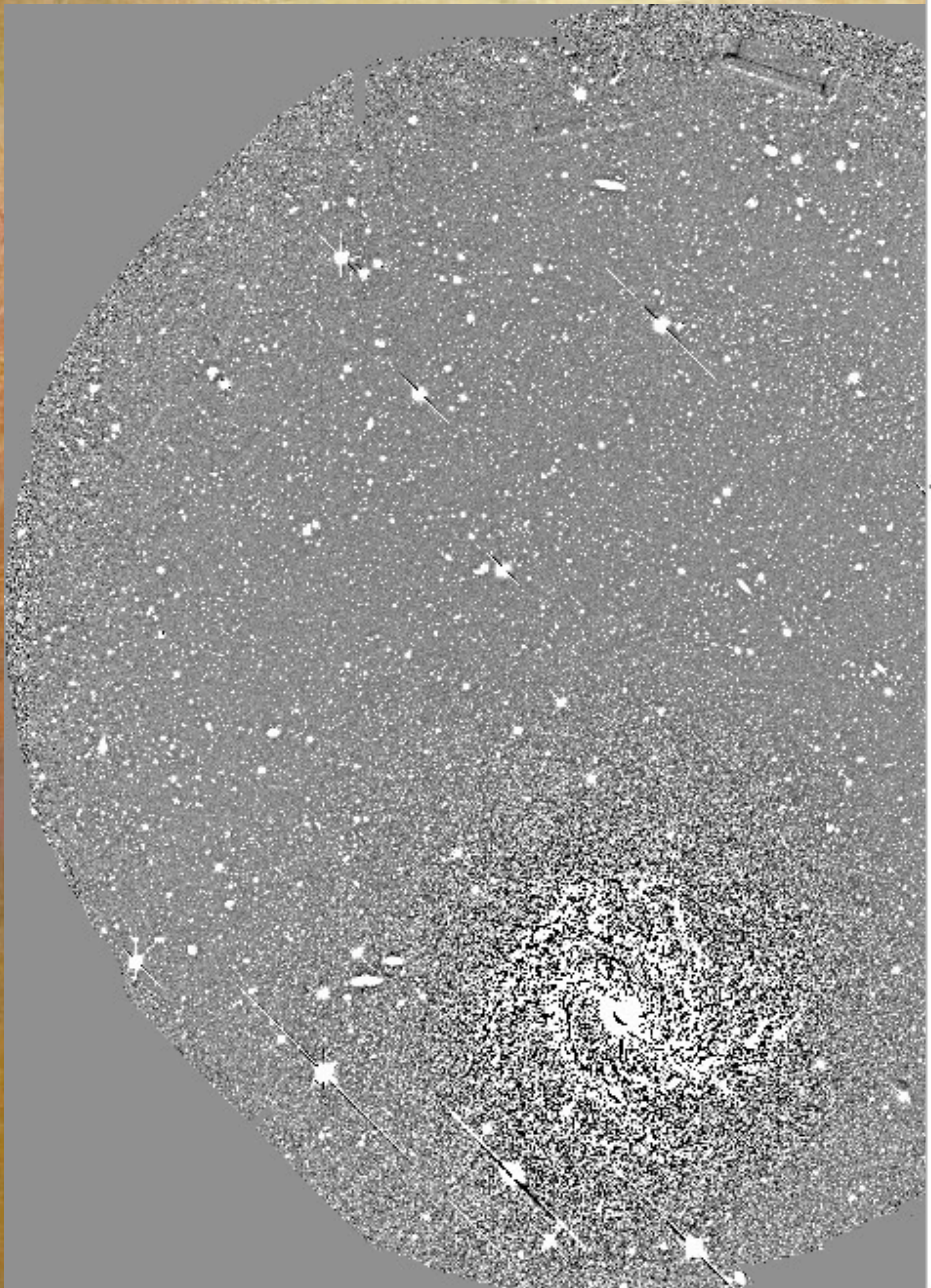
Current sample:

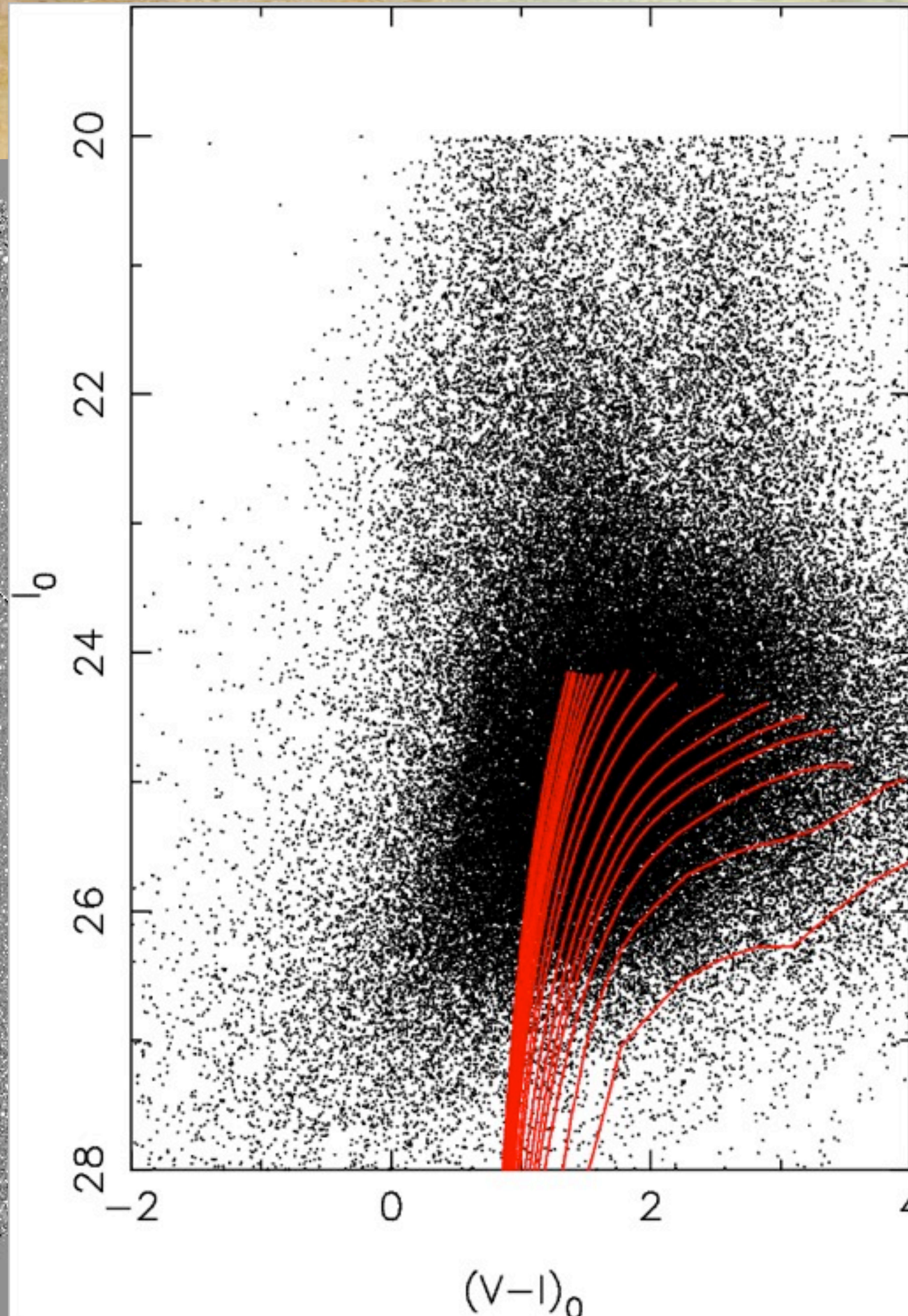
N253
N300
N55
M81
M83
N5128
N4945
N2683
N891

M83 - IMACS

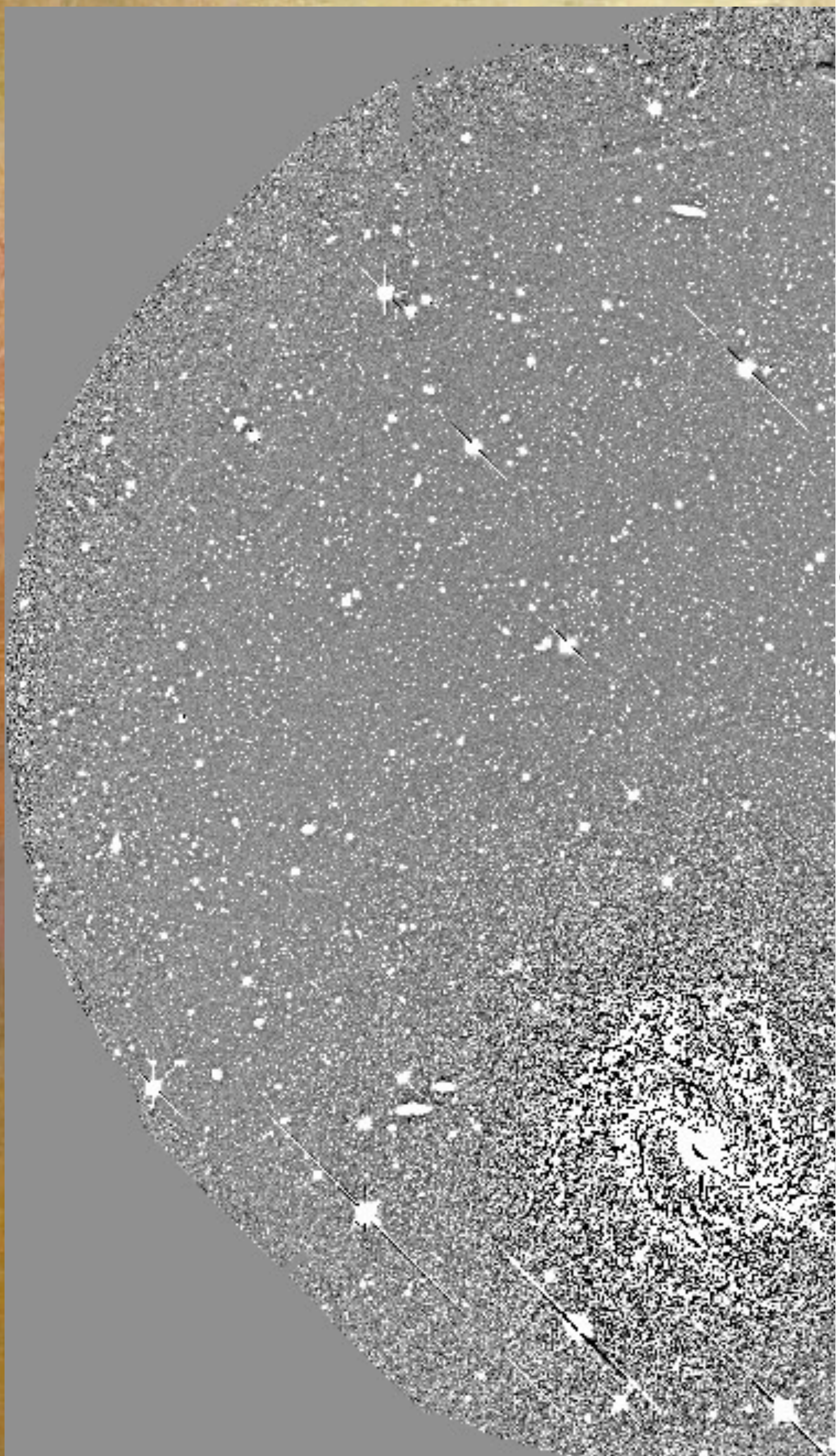


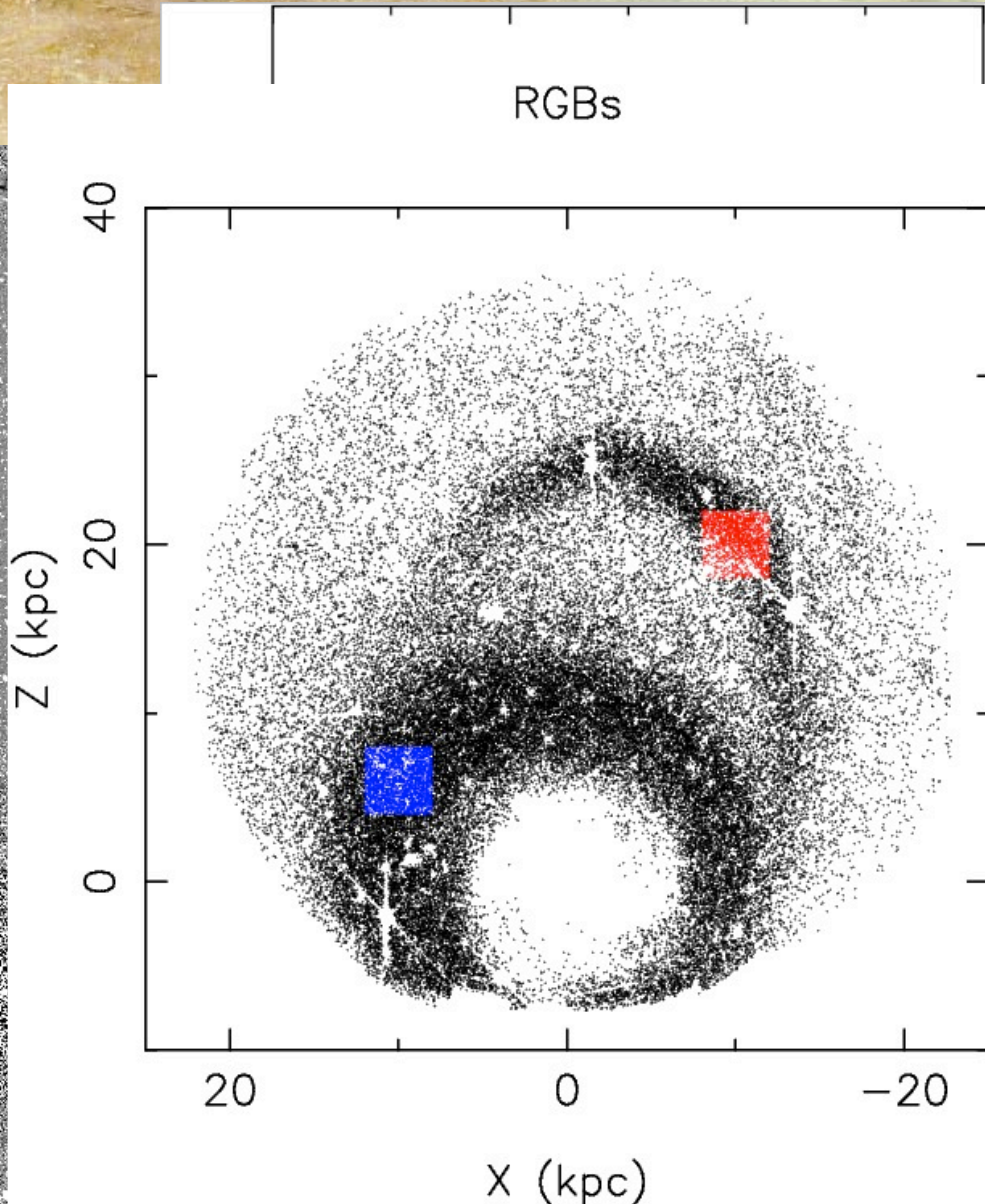
M83 - IMACS



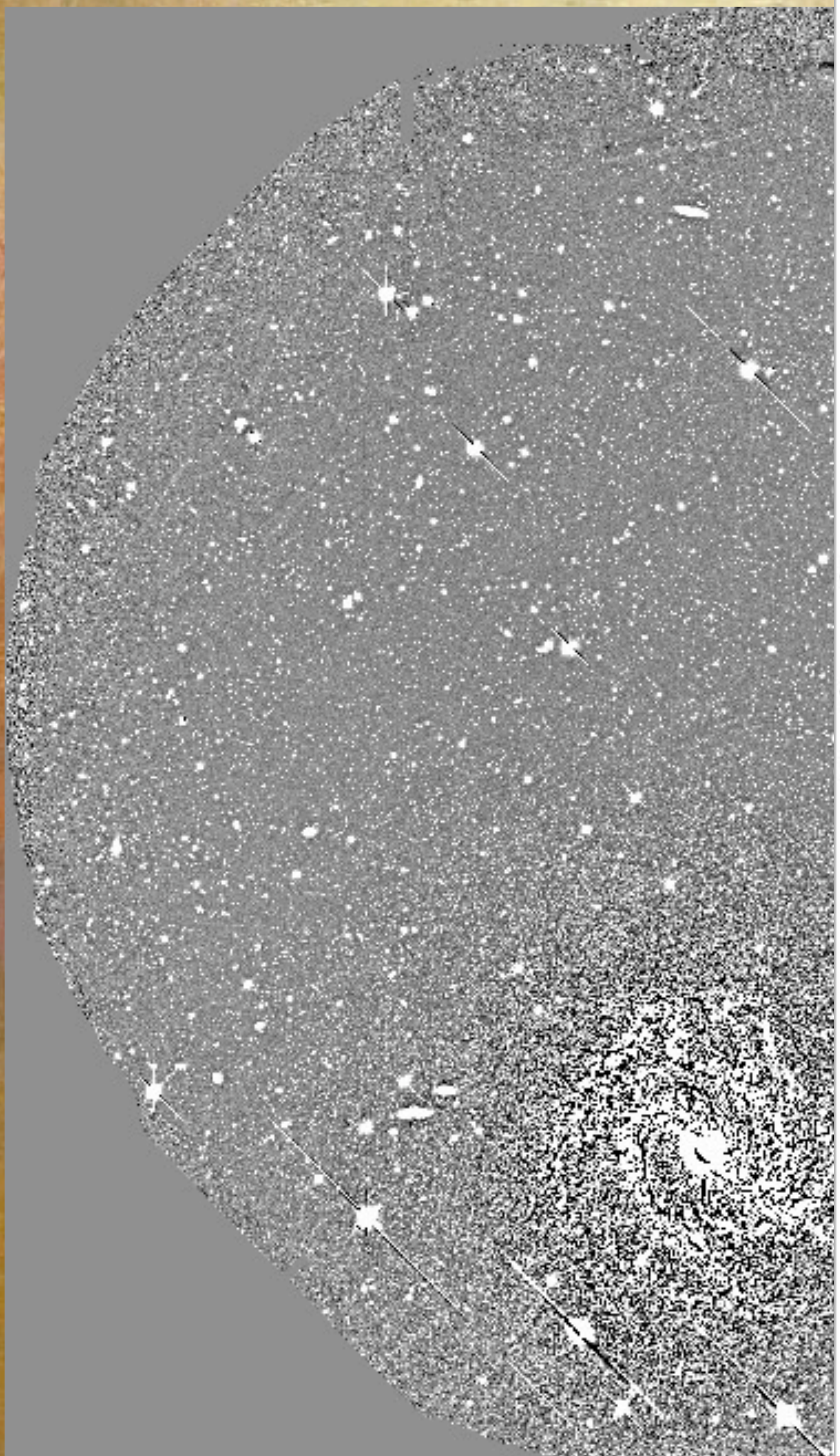


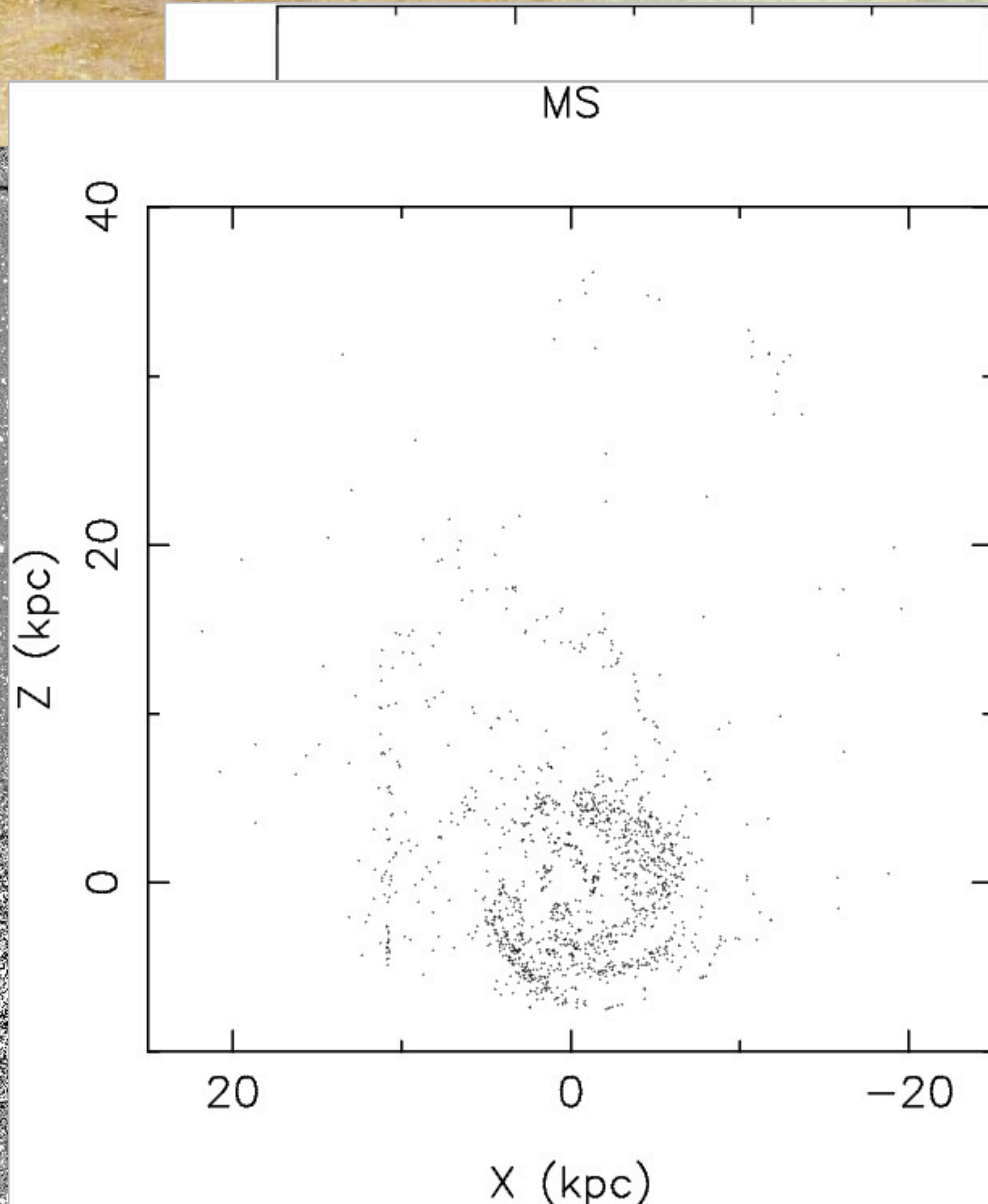
M83 - IMACS

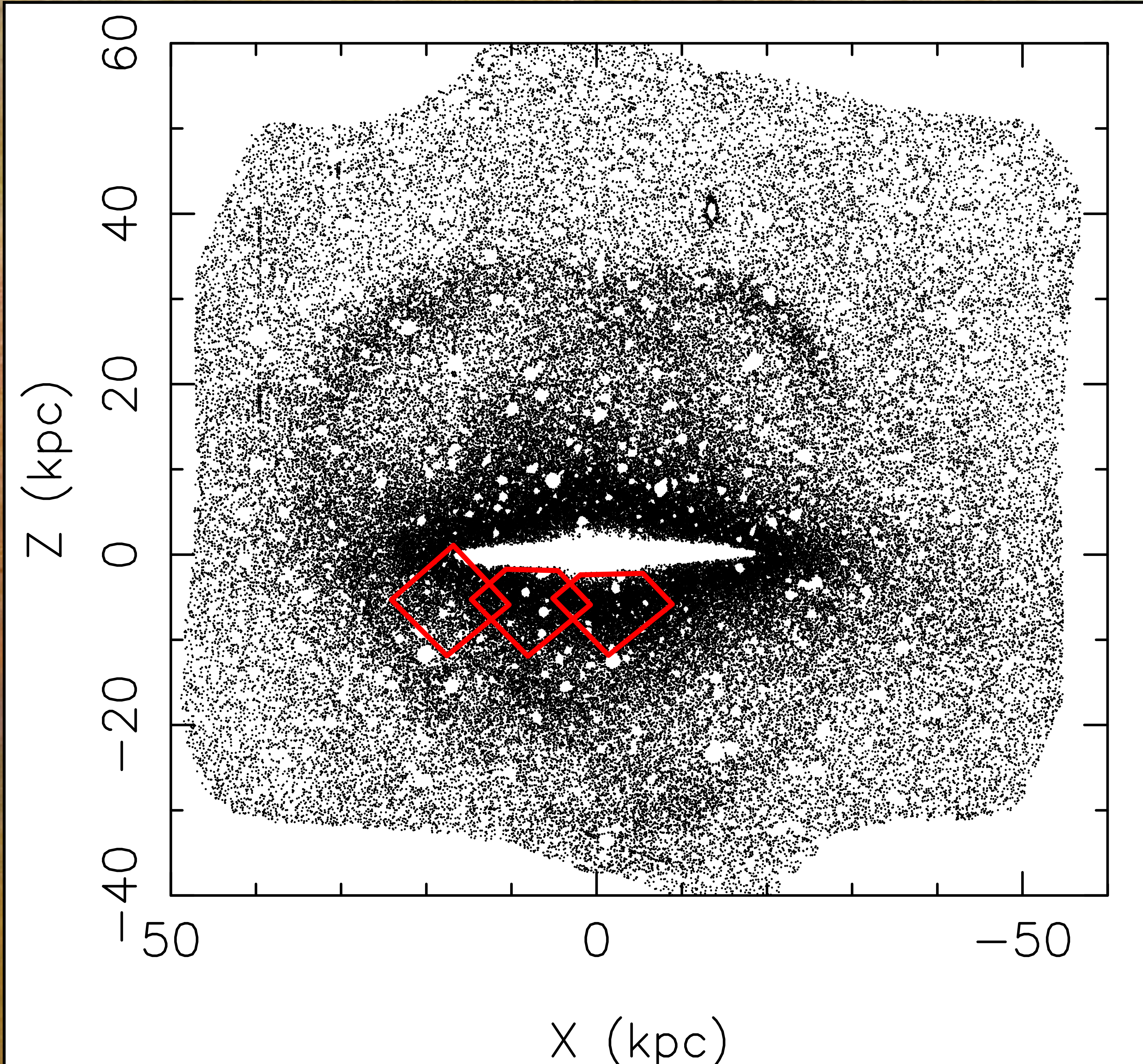




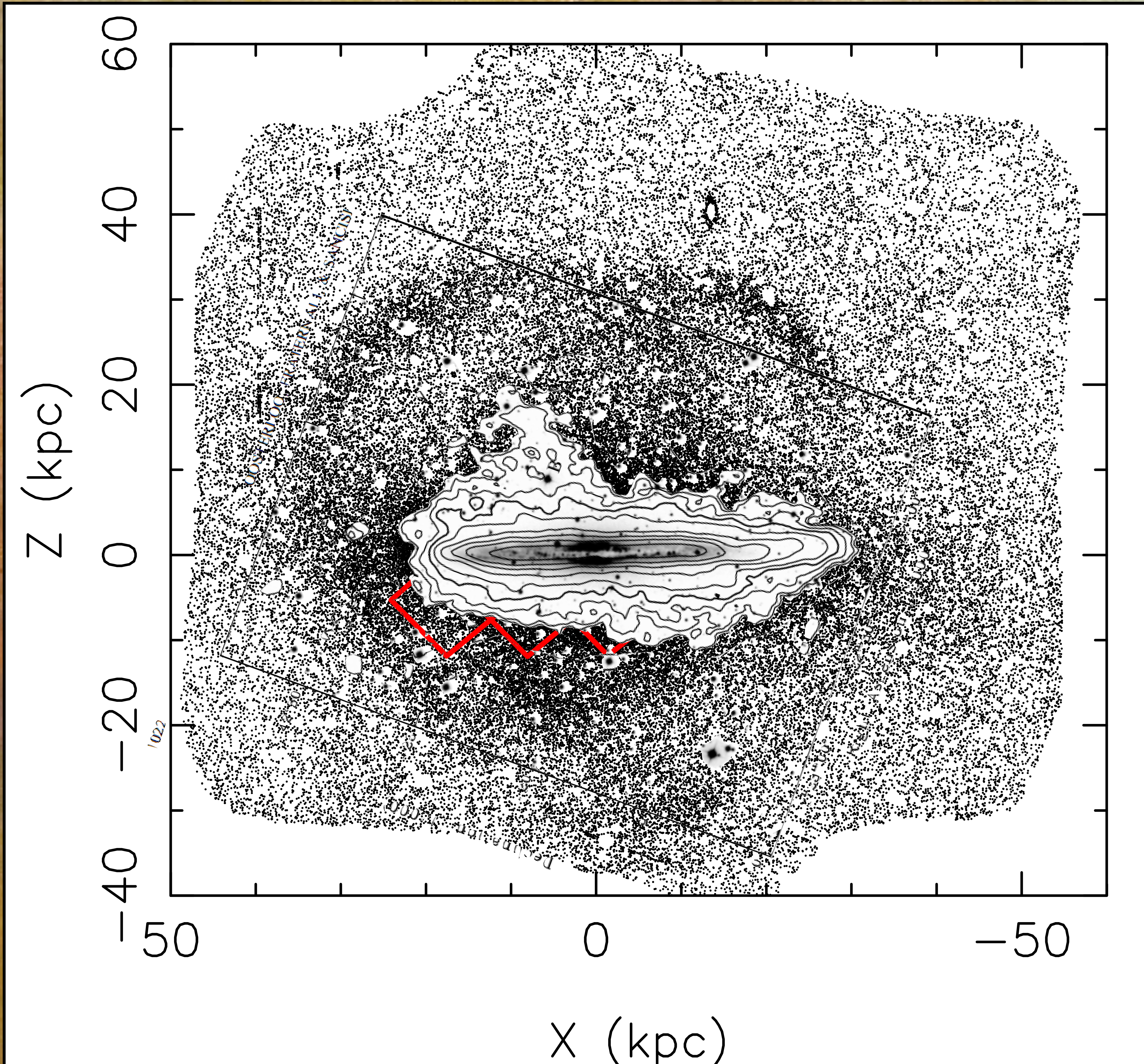
M83 - IMACS







Mouhcine, Ibata & Rejkuba (2010)



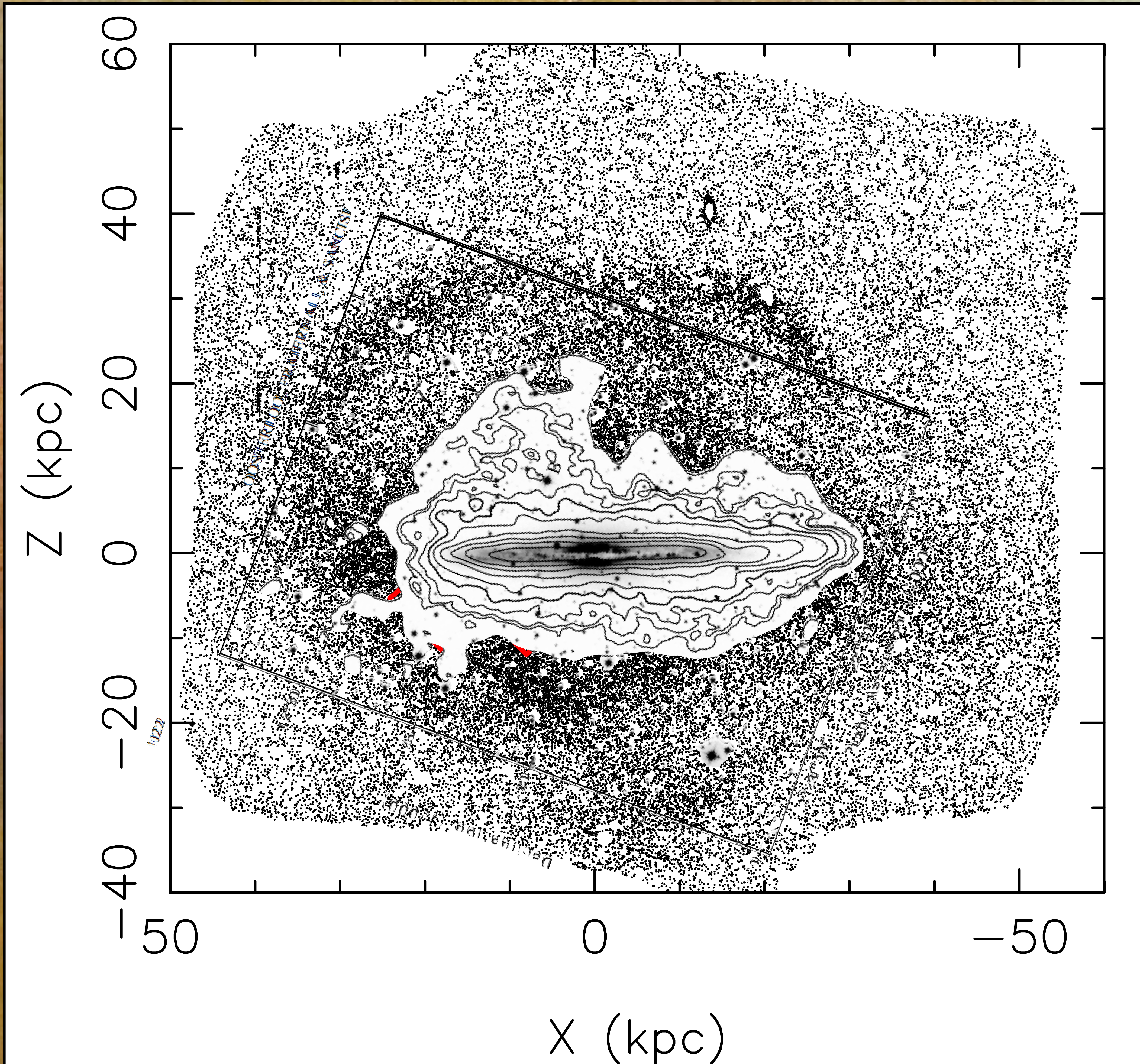
$1.6\times10^{7} M_{o}$

in infalling HI

Oosterloo et al.

(2007)

Mouhcine, Ibata & Rejkuba (2010)



1.6x10^{7}M$_o$

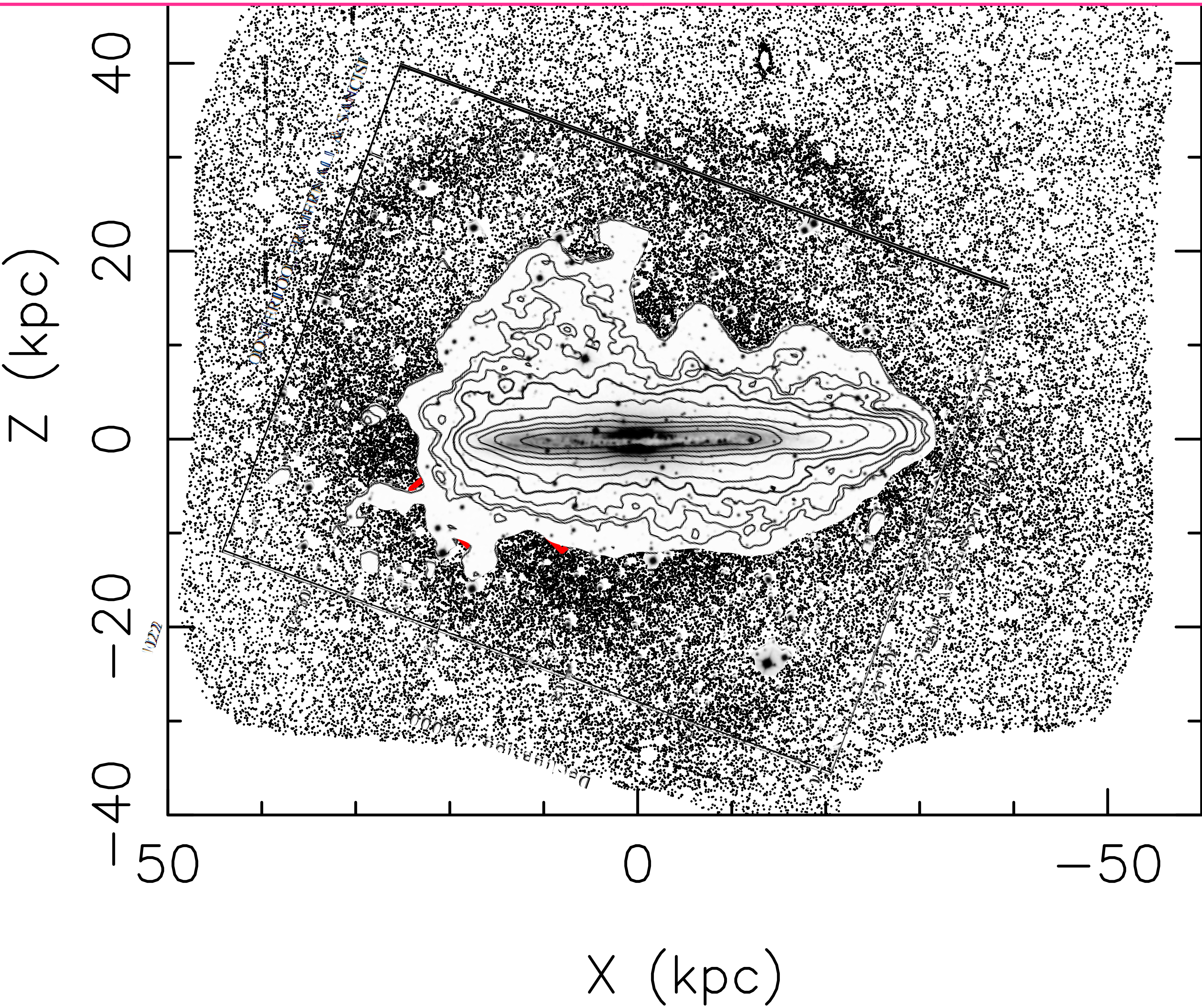
in infalling HI

Oosterloo et al.

(2007)

Mouhcine, Ibata & Rejkuba (2010)

First detailed panoramic view of a halo beyond the Local Group



$1.6\times10^{7}M_{o}$

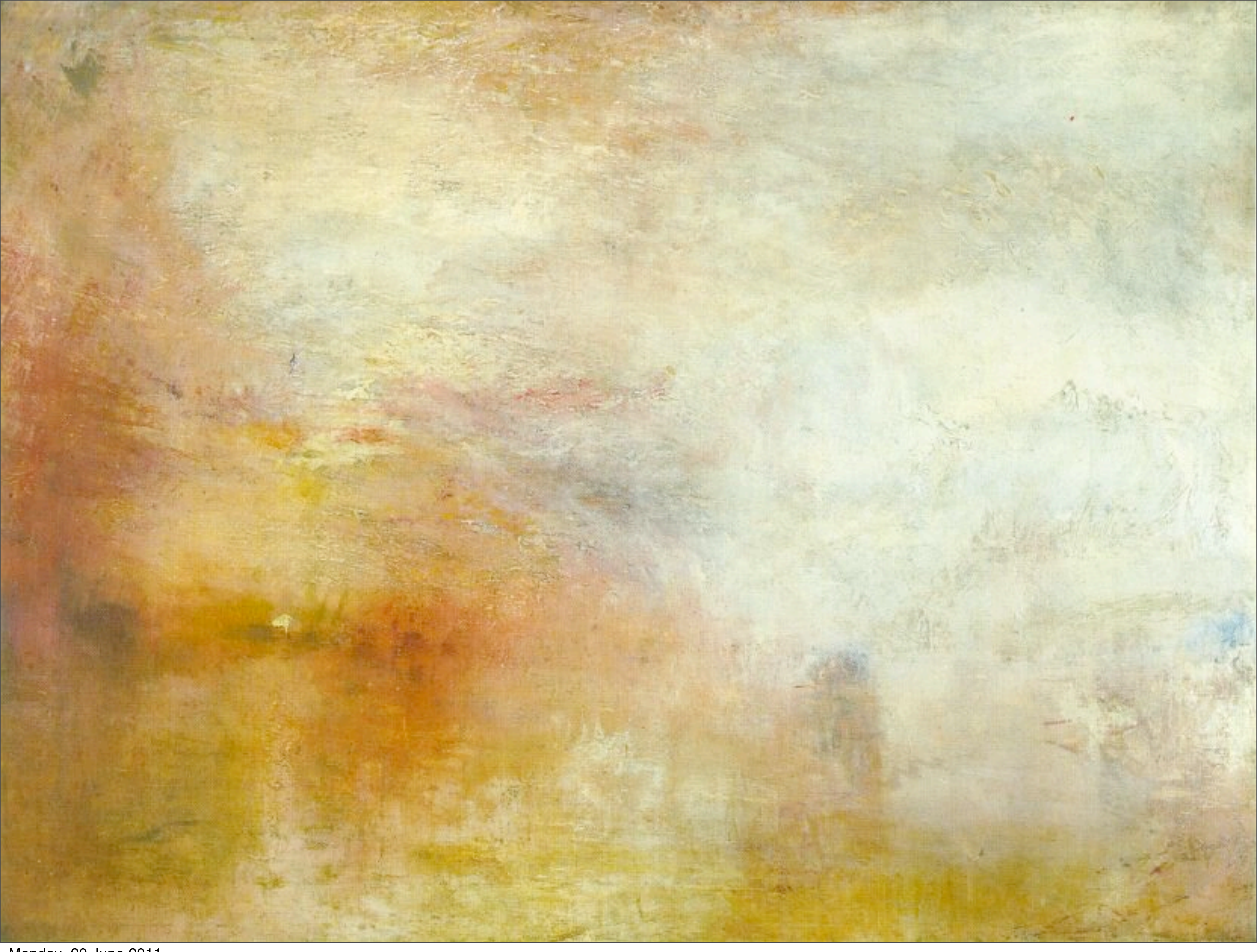
in infalling HI

Oosterloo et al. (2007)

Mouhcine, Ibata & Rejkuba (2010)

Prospects

- Exquisite new panoramic data is being obtained in the halos of many nearby galaxies. PAndAS (M31 & M33) provides the best reference halo for comparison to halo formation simulations.
- Many long streams have just been discovered. These are excellent dynamical probes situated at radial locations where we have few constraints.
- Even more distant systems with only projected stream morphologies can be used to derive dark halo properties.
- With very deep images (from a dedicated small telescope?) we can hope to uncover the numerous very low mass accretions, study their orbital properties, and build up the accretion history of such structures.
- In Milky Way - Gaia!!!



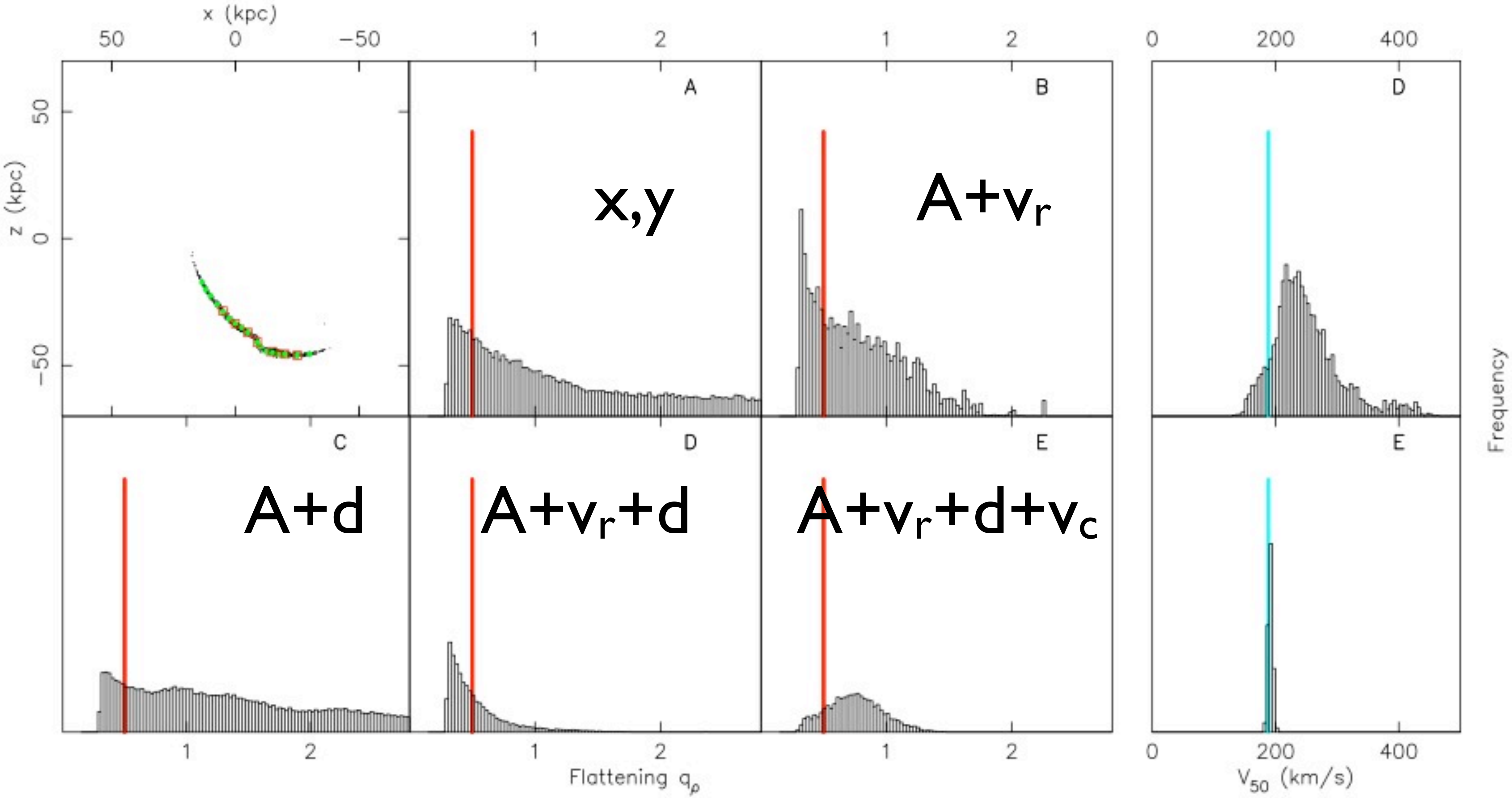
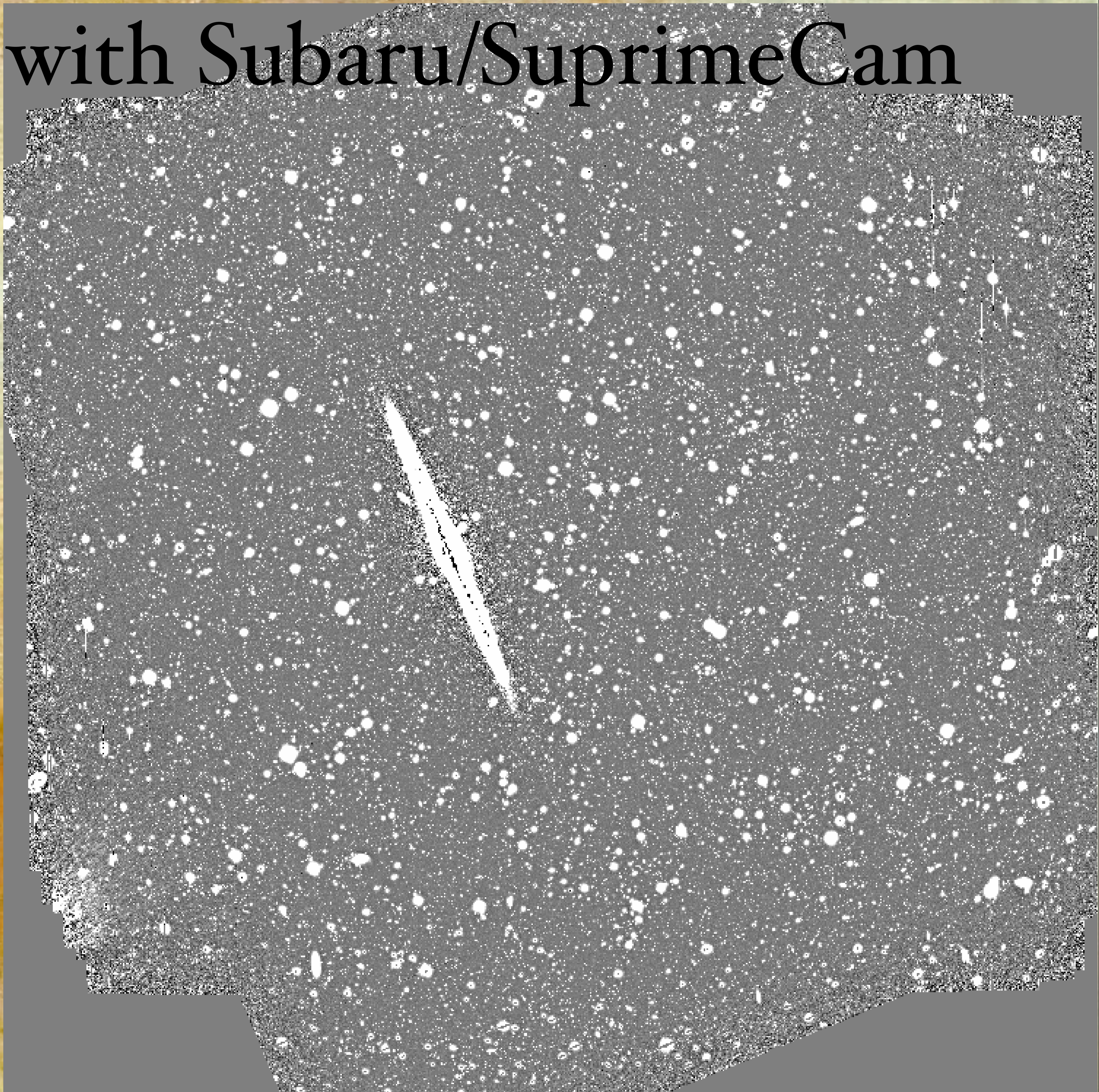


Figure 17. Estimation of q_ρ and V_{50} for a Palomar 5-like stream with no turning point. The red line shows the input value of q_ρ. The distributions are drawn from 500,000 steps of the coldest Monte Carlo Markov chain. Case A: only projected positions. Case B: projected positions and l.o.s velocities at red squares. Case C: projected positions and distance to the progenitor. Case D: projected positions, distance to the progenitor and l.o.s velocities at red squares. Case E: Same as Case D but with the rotational velocity curve given. The rightmost panels show the estimation of the circular velocity at 50 kpc for case D and E, the cyan lines indicating its true value. It is not possible to constrain V_{50} without any velocity information, but if l.o.s velocities are provided (case D), it can be estimated even with a short stream like the one above. It is not surprising that V_{50} is very well constrained in case E as the circular velocities up to 30 kpc are given.

N891 with Subaru/SuprimeCam



- 4 nights Nov 2008
- 0.4” to 0.8” seeing!
- +3 nights Oct 2009

N891: