The Local Group: Then, Now, Forever, and Always

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THE GREAT ANDROMEDA GALAXY

Princeton

June 18, 2012

Acknowledgements

Pan-Andromeda Archæological Survey (PAndAS) Collaboration

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Aaron Dotter
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Pauline Barmby
Olivier Bienayme
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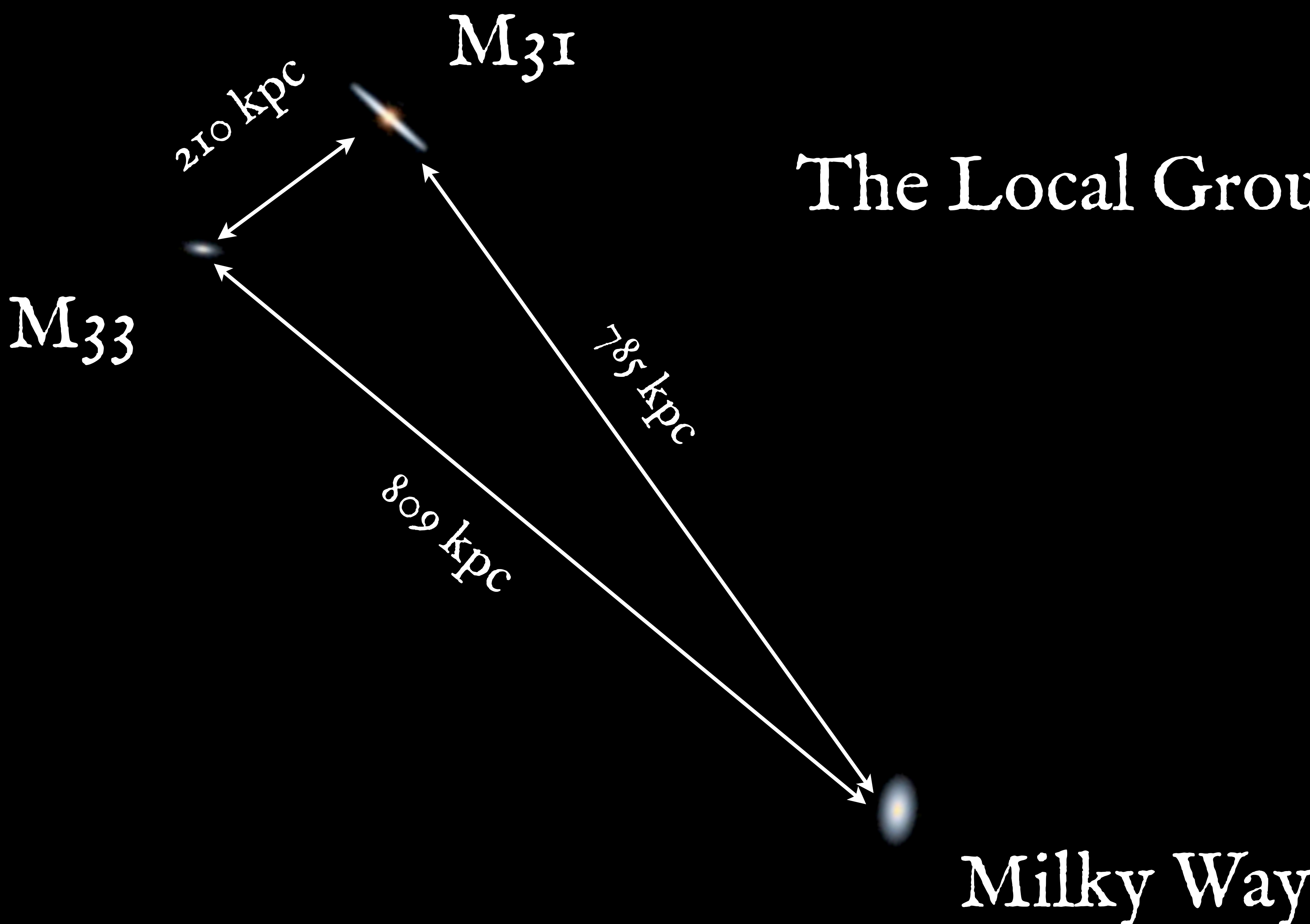
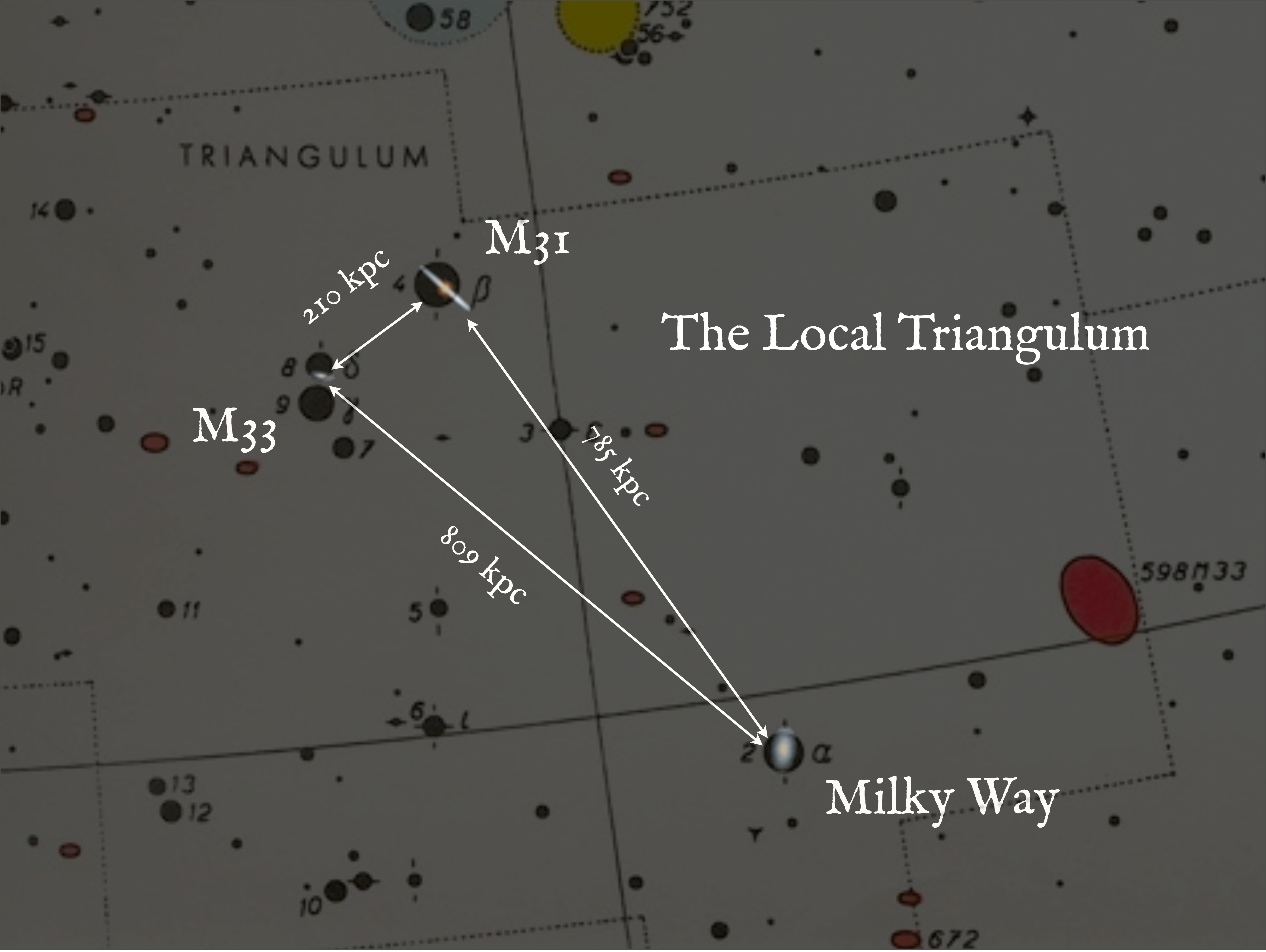
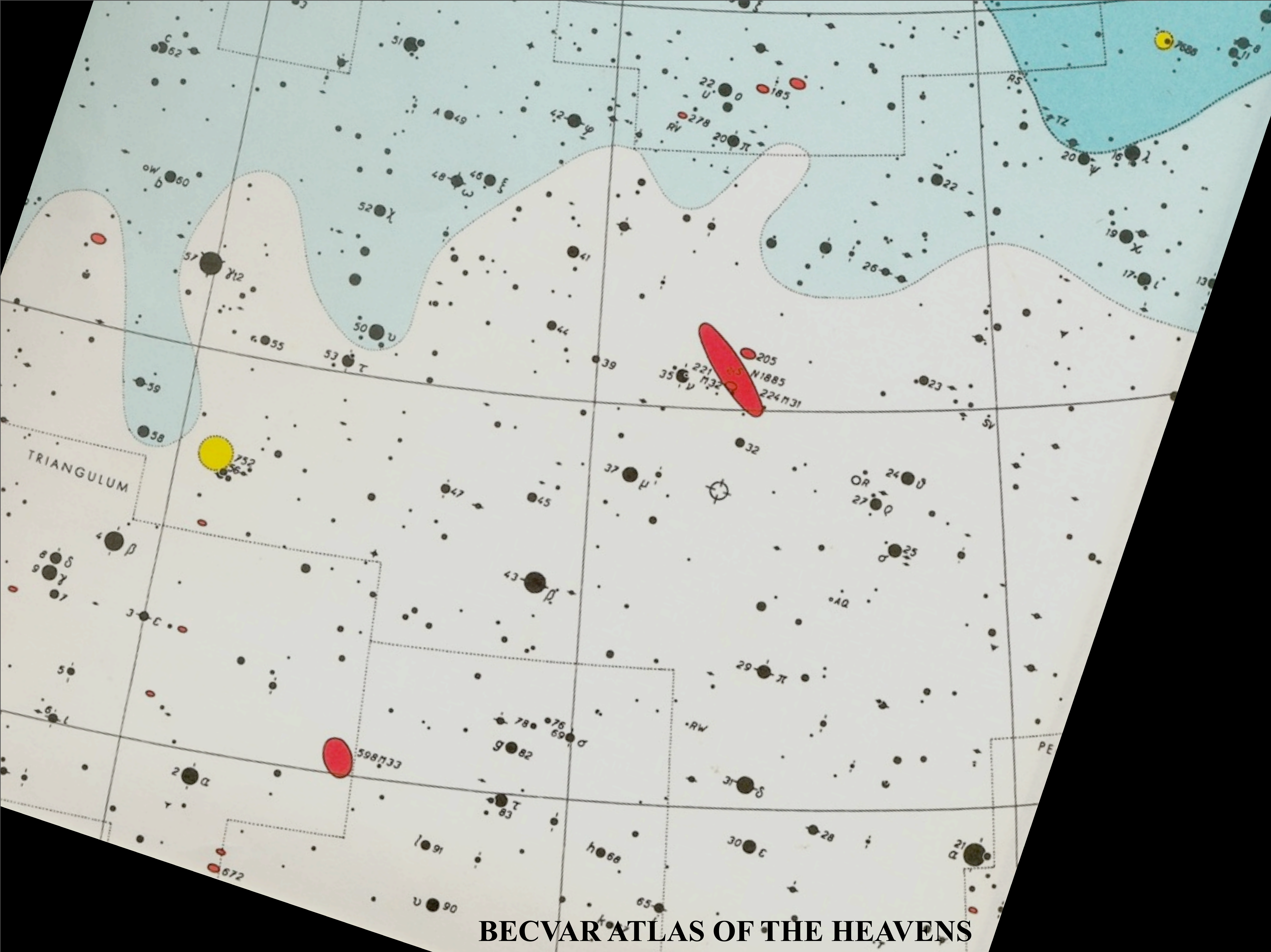
Scott Chapman
Robert Cockcroft
Michelle Collins
Mark Fardal
William Harris
Avon Huxor
A. Dougal Mackey
Jorge Penarrubia
R. Michael Rich
Harvey Richer
Arnaud Siebert
Nial Tanvir
David Valls-Gabaud
Kimberly Venn

See McConnachie et al. 2009 and many others

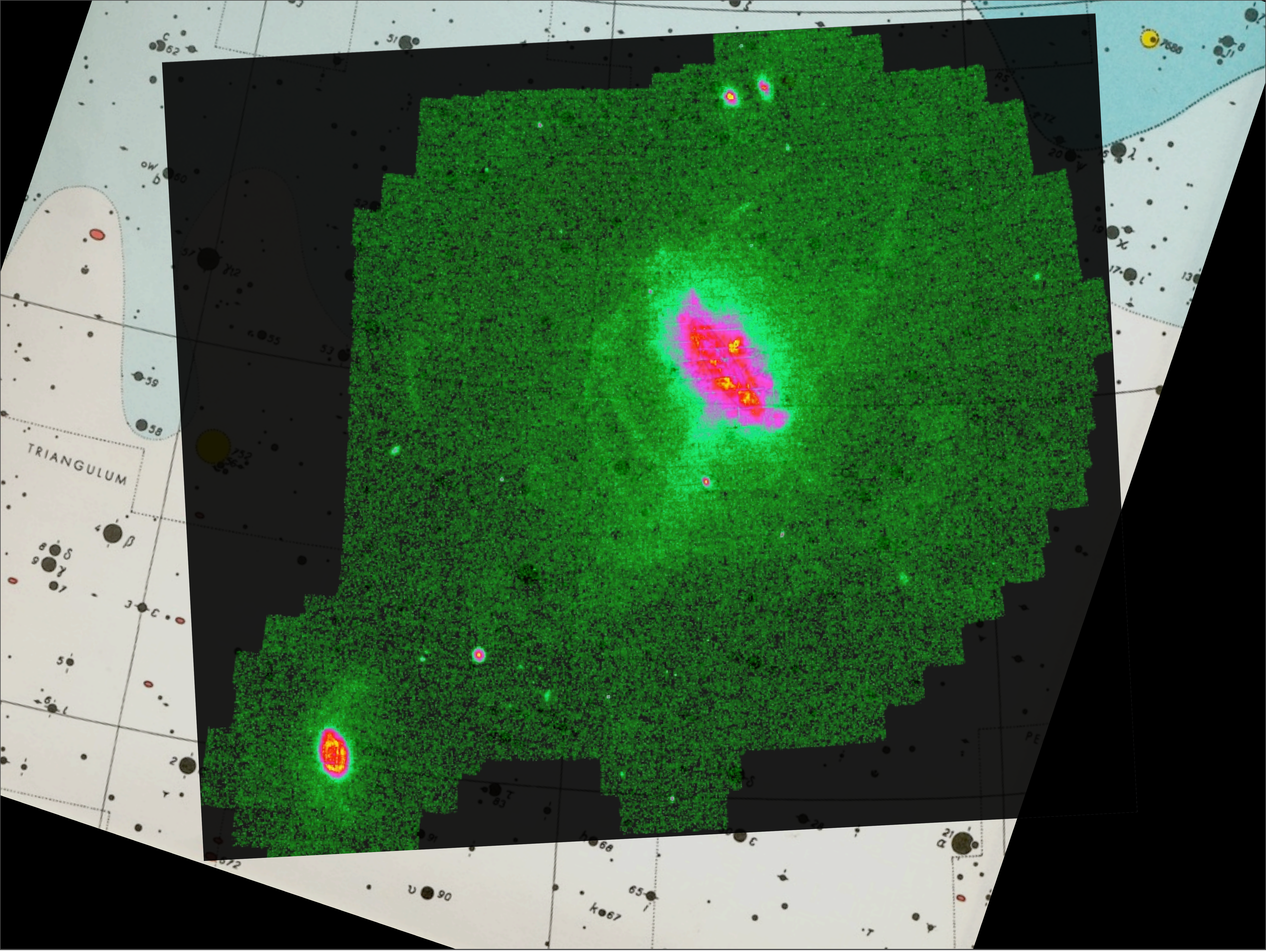
The Local Group

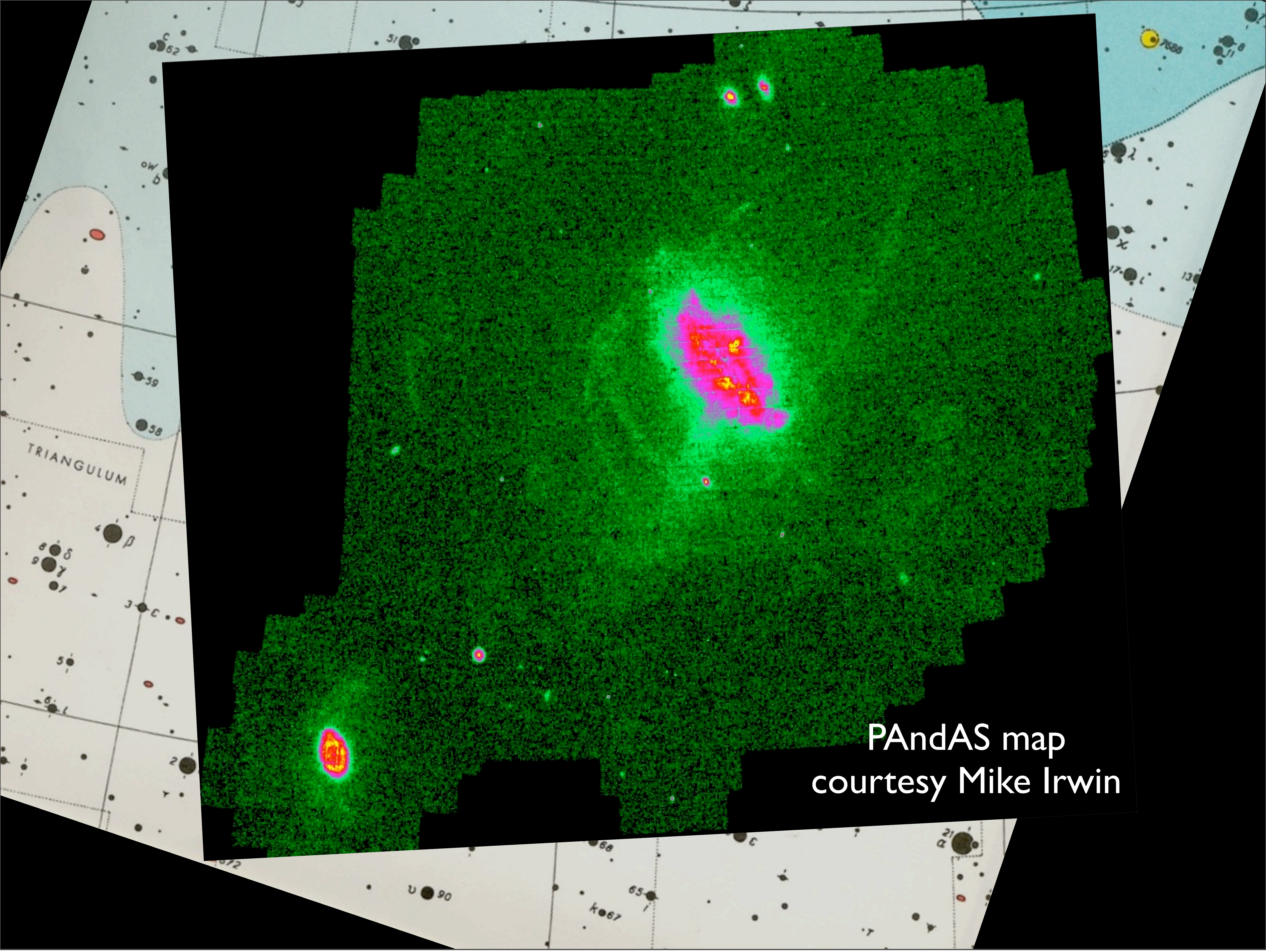



The Local Triangulum
TRIANGULUM
M31
M33
Milky Way
210 kpc
785 kpc
809 kpc
598M33



BECVAR ATLAS OF THE HEAVENS


TRIANGULUM


TRIANGULUM
PAndAS map
courtesy Mike Irwin

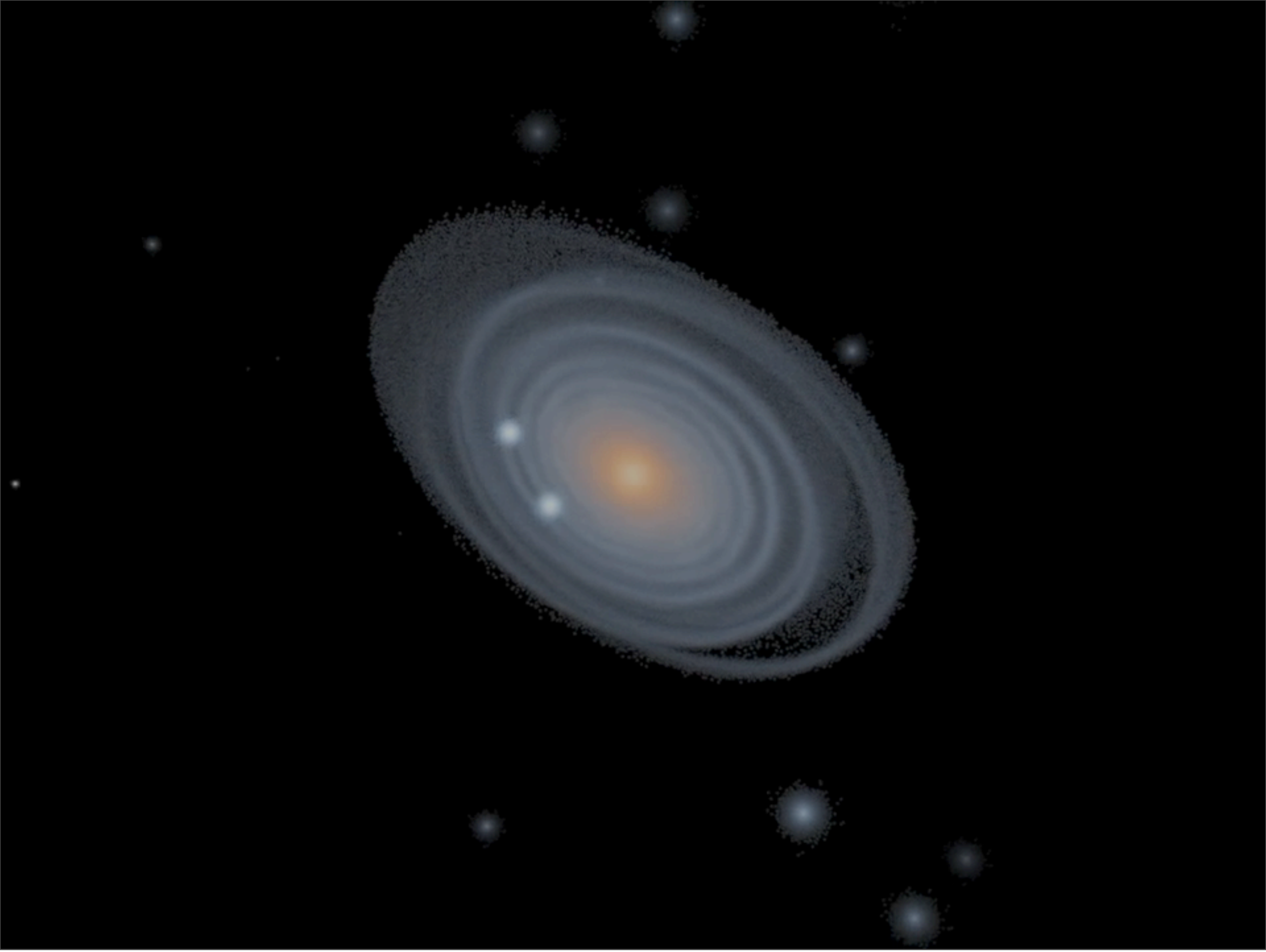
From Crumb's Illustrated Book of Genesis

Modeling Goals

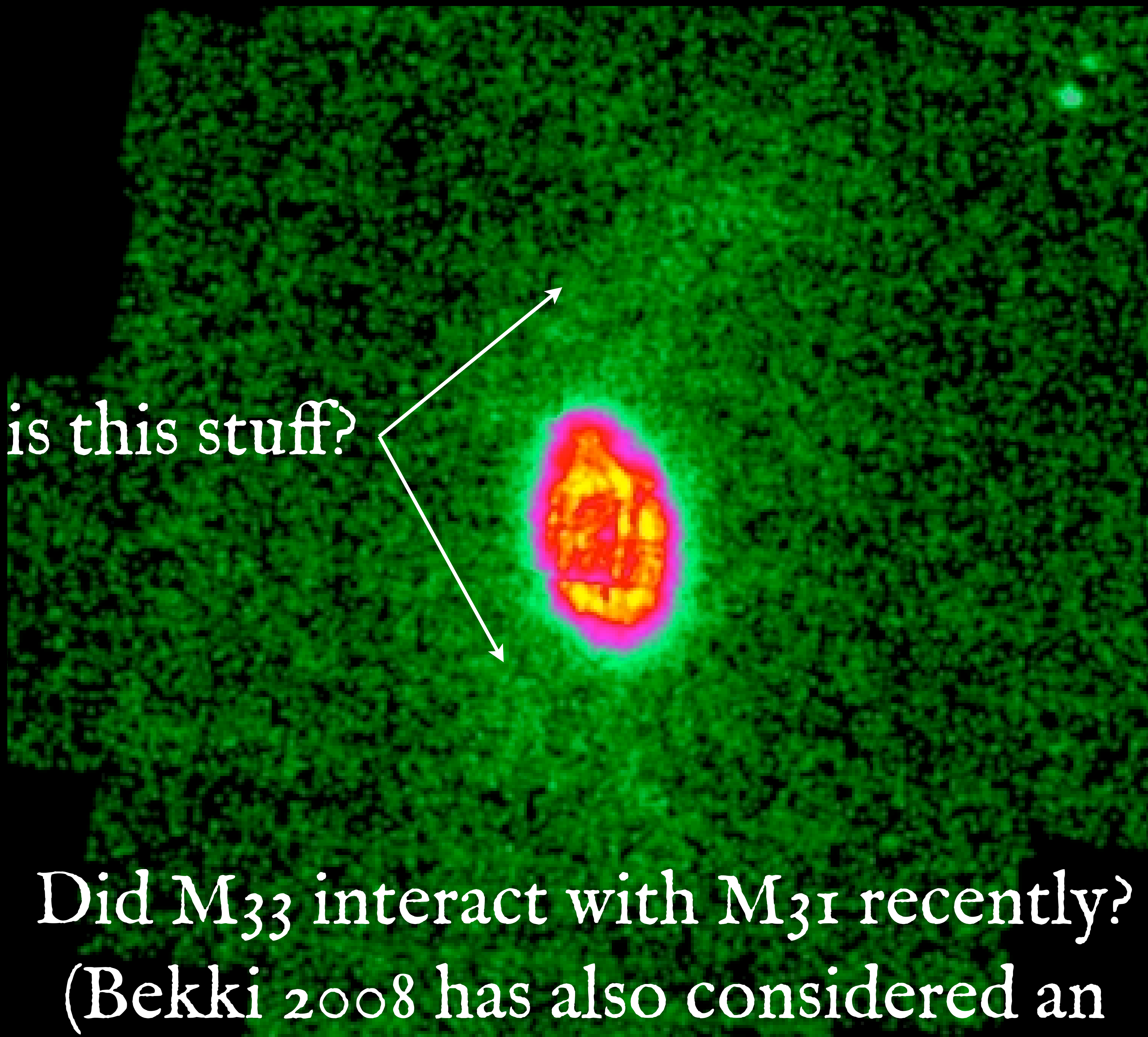
Construct a Realistic Model of The Local Group Including the M31, M33, the Milky Way and Satellites

Use This Experimental Platform to Investigate The Dynamics of the Local Group Including Interactions and Satellite Tidal Disruption And Stream/Shell creation
(In Progress...)

Galaxy models: Widrow et al. 2008
N-body: Dubinski 1996
Satellite data: Brasseur, Collins, McConnachie

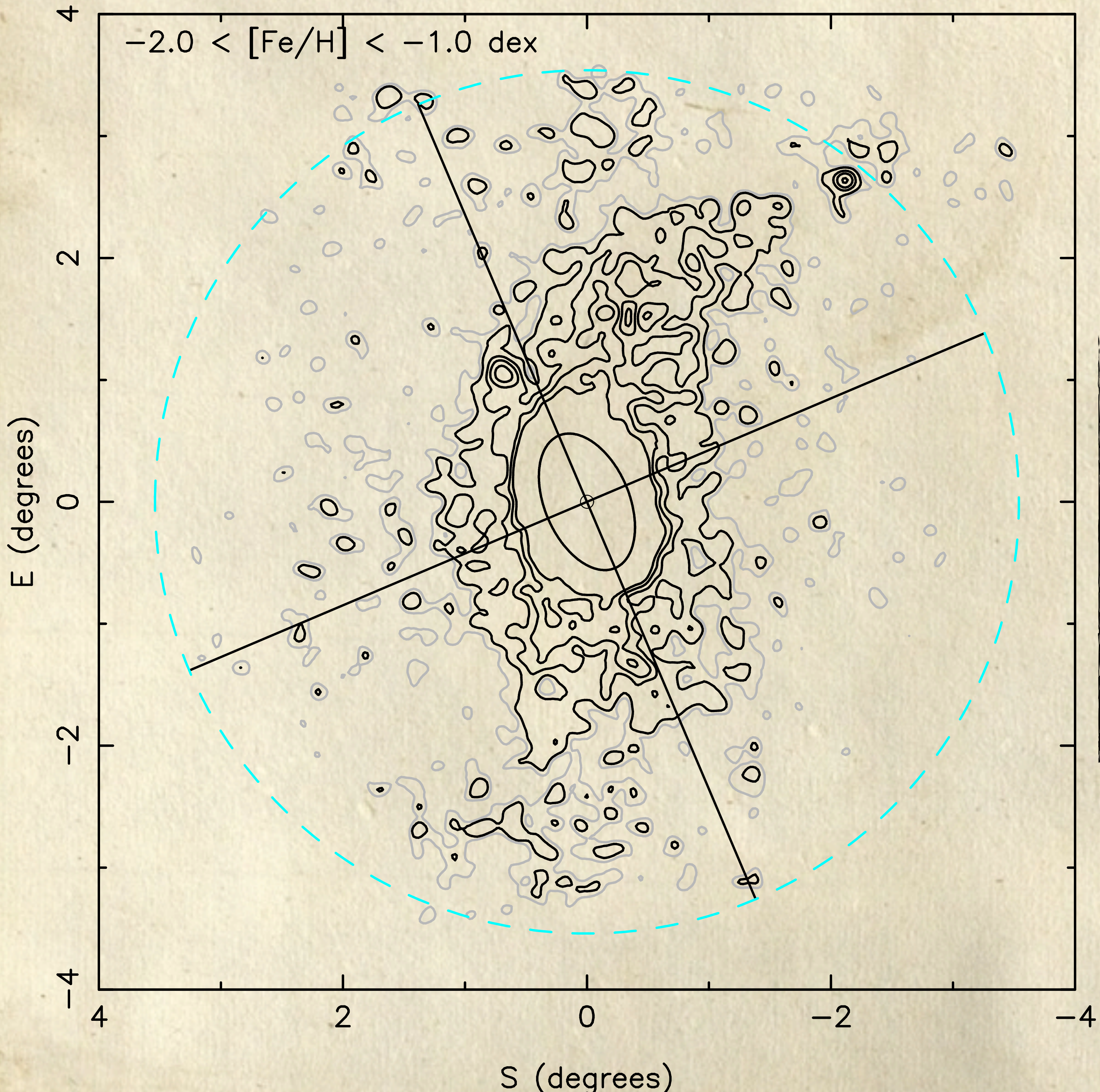


Tidal Distortion of M33?



Did M33 interact with M31 recently?
(Bekki 2008 has also considered an interaction re: the gas “bridge”)

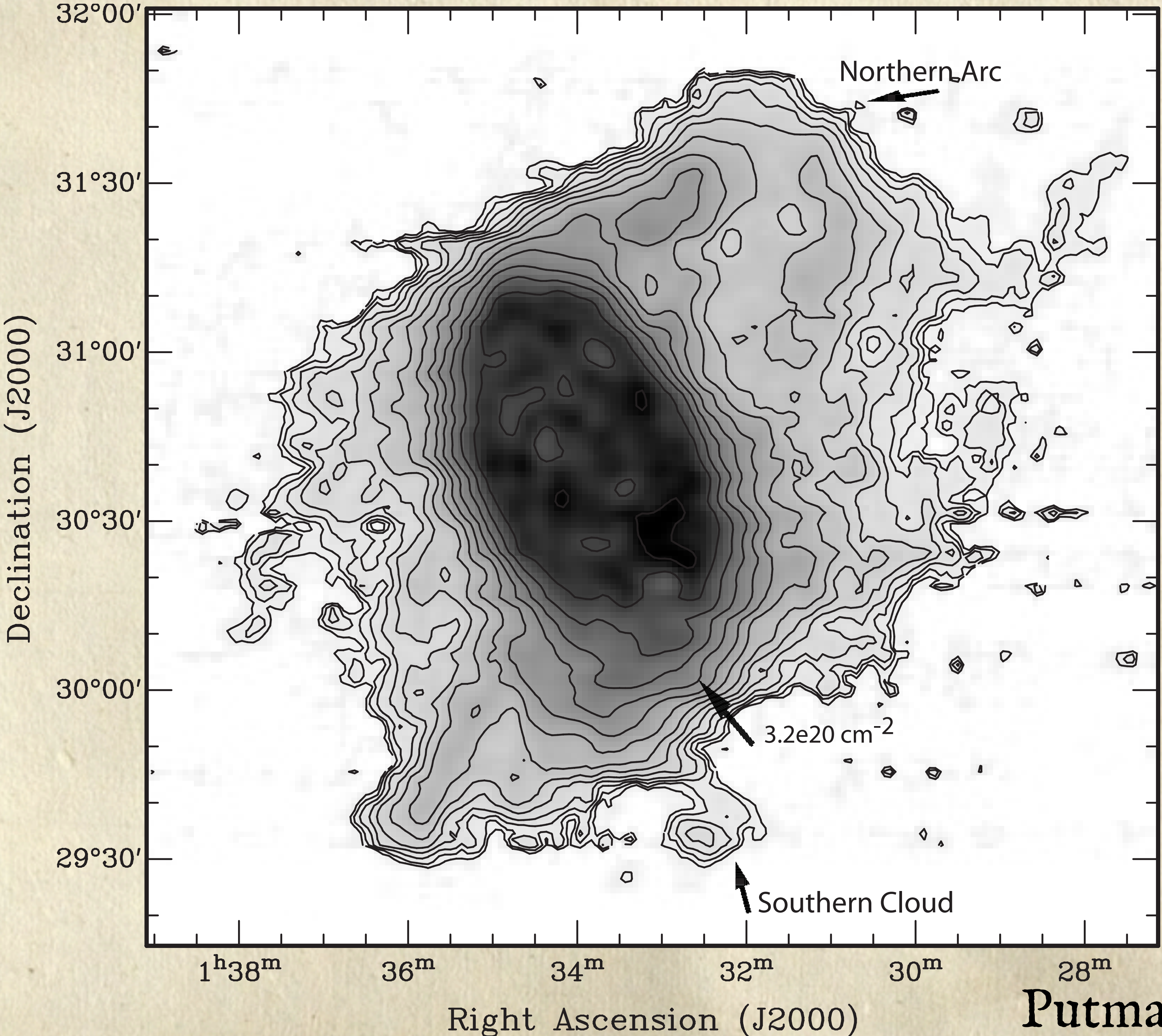
Stellar Distribution Around M33



- ~1% in tidal extensions
- very low surface brightness
- low metallicity

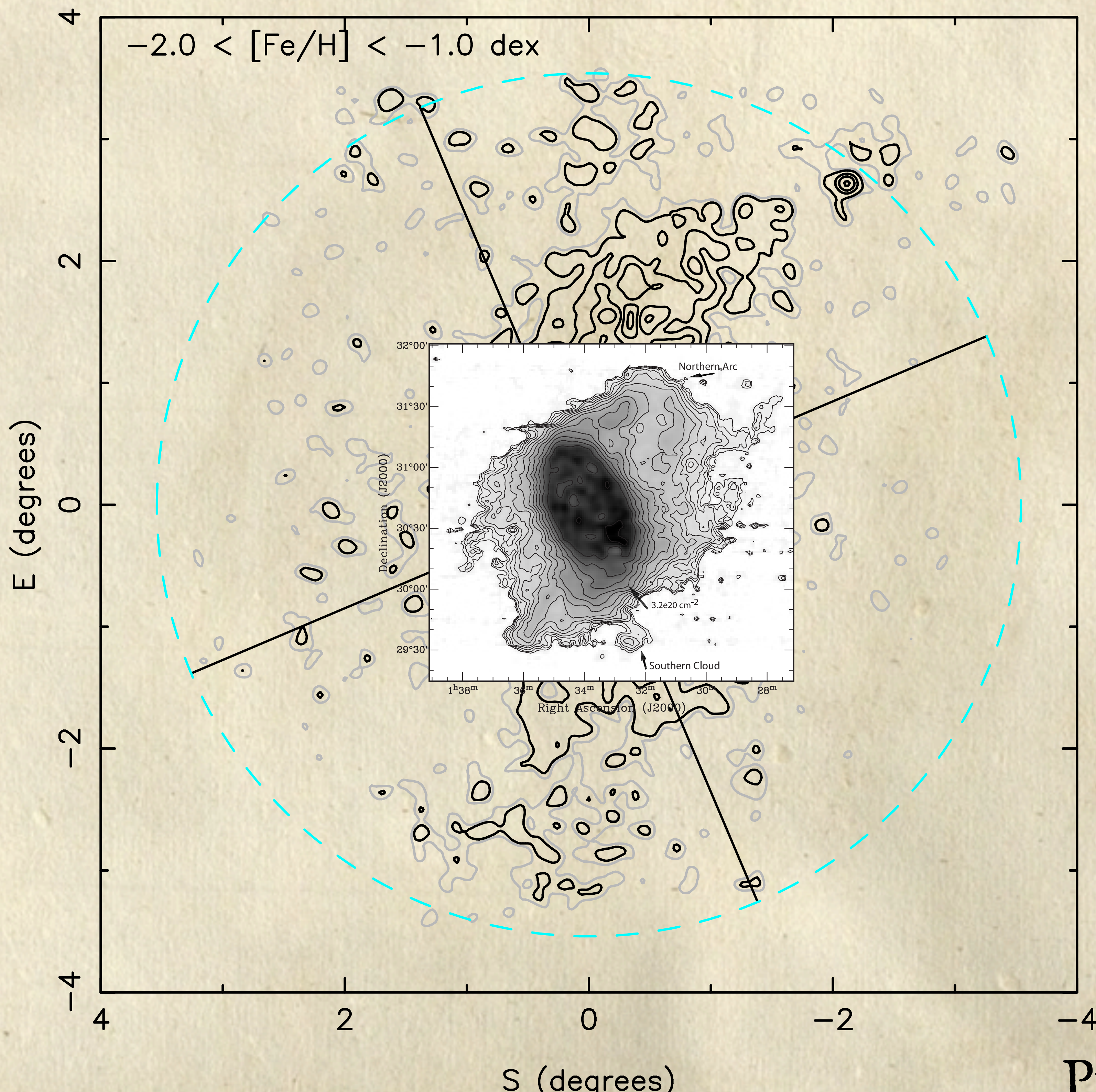
McConnachie et al. 2010

HI Distribution



Putman et al. 2009

HI Distribution



Putman et al. 2009

The Warped Disk of M33

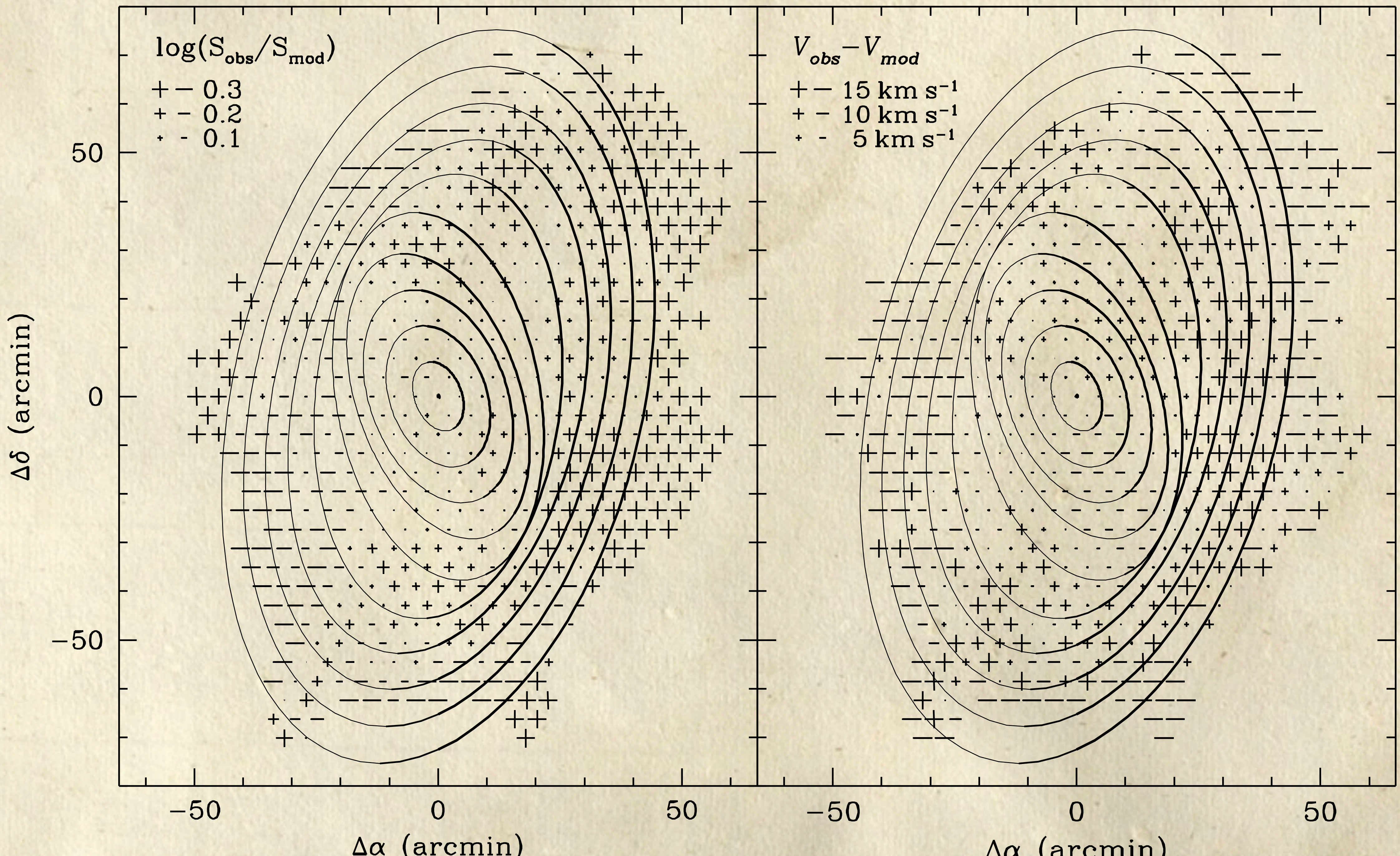


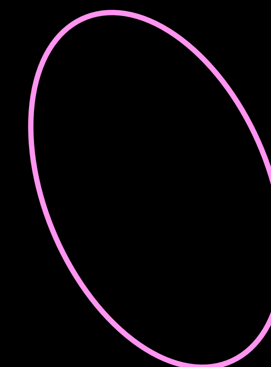
FIG. 4.—Maps of flux and velocity residuals for the basic model

Corbelli & Schneider 1997

M33

M31-M33 Interaction

Panoramic View



10 kpc

M31

100 kpc

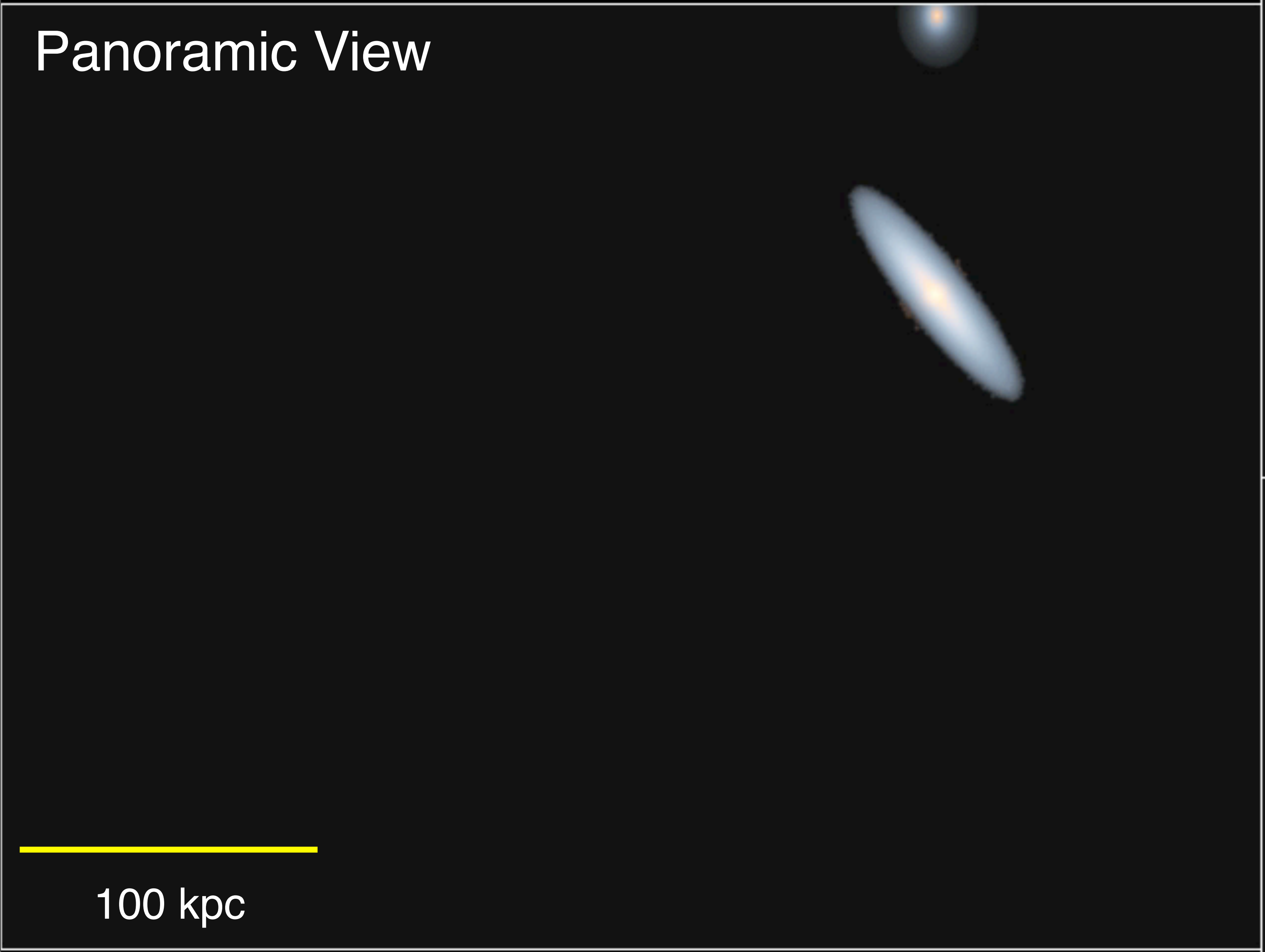
Elapsed time 3.4 Gyr (70 Myr/s)

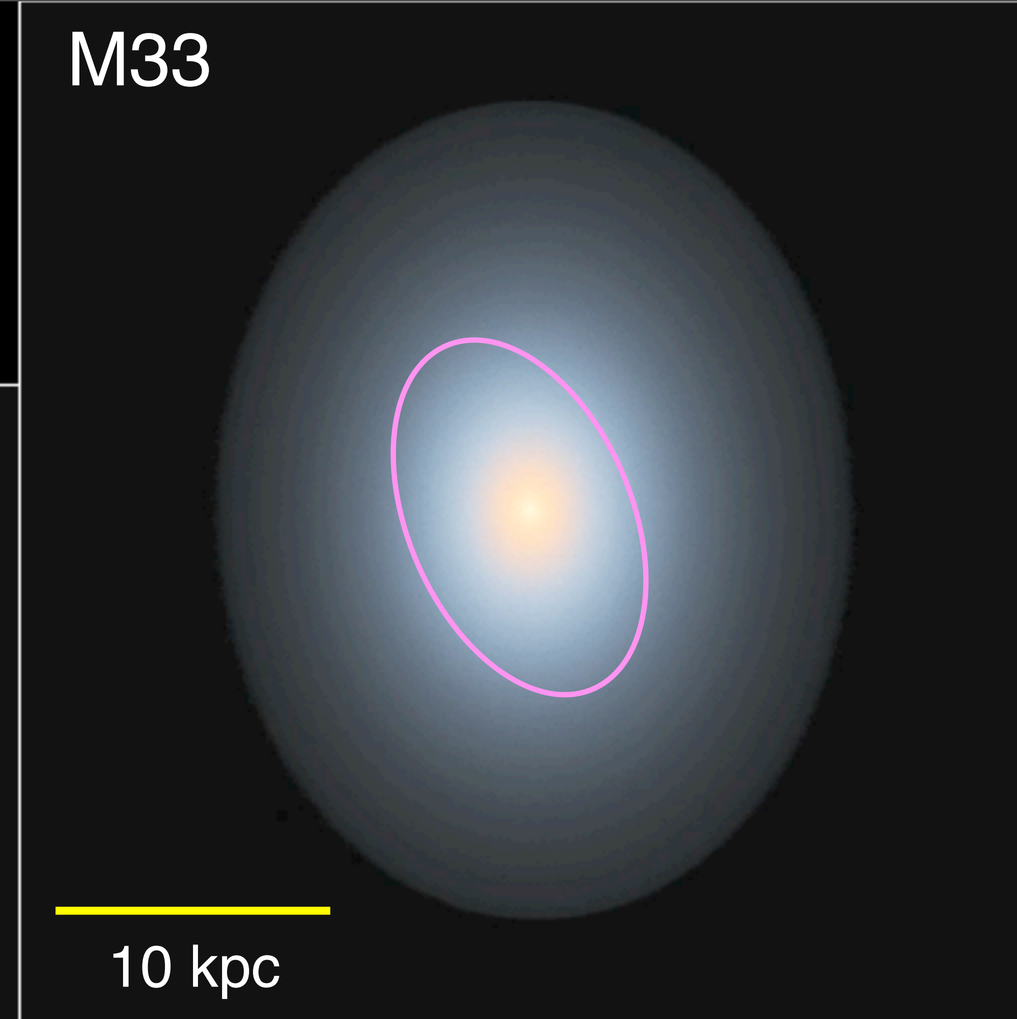
M33 interaction occurs about 2.5 Gyr ago

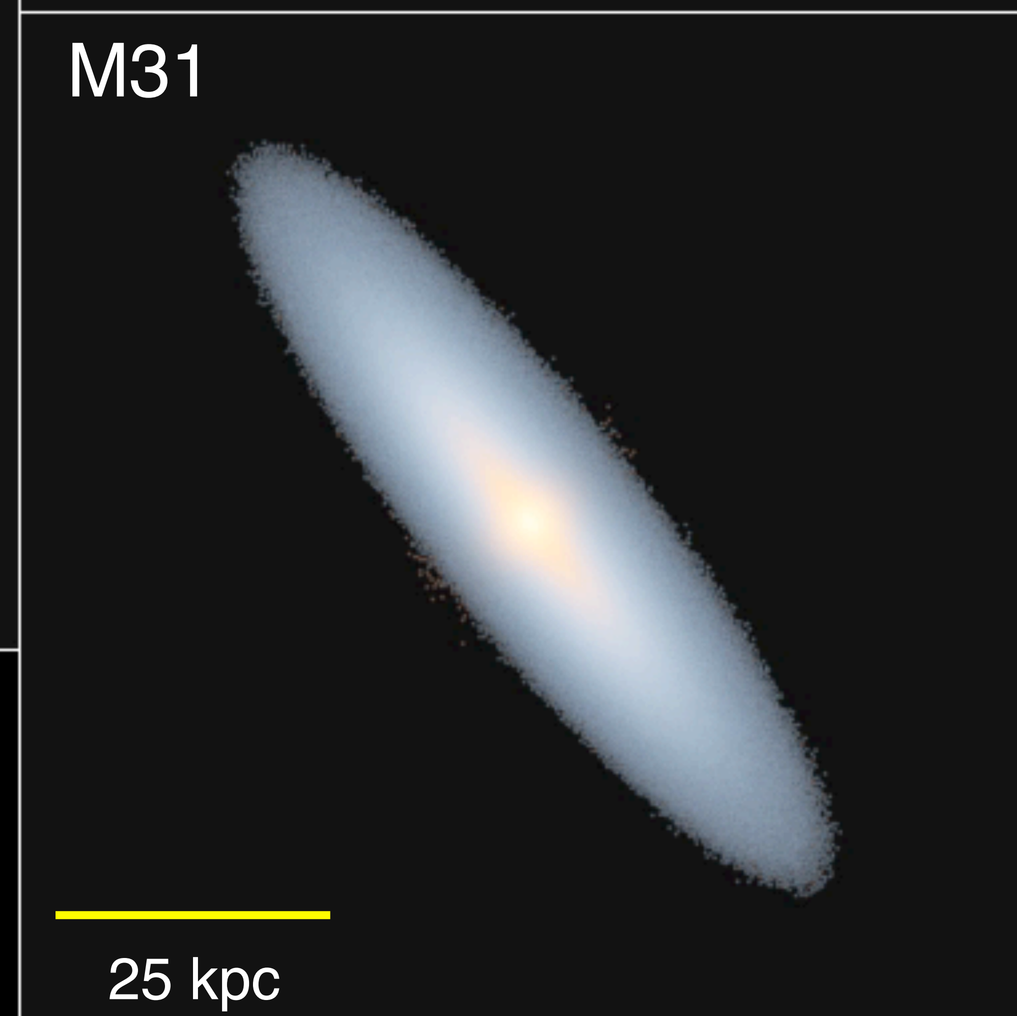
Orbital pericentre 50 kpc

25 kpc

M31-M33 Interaction

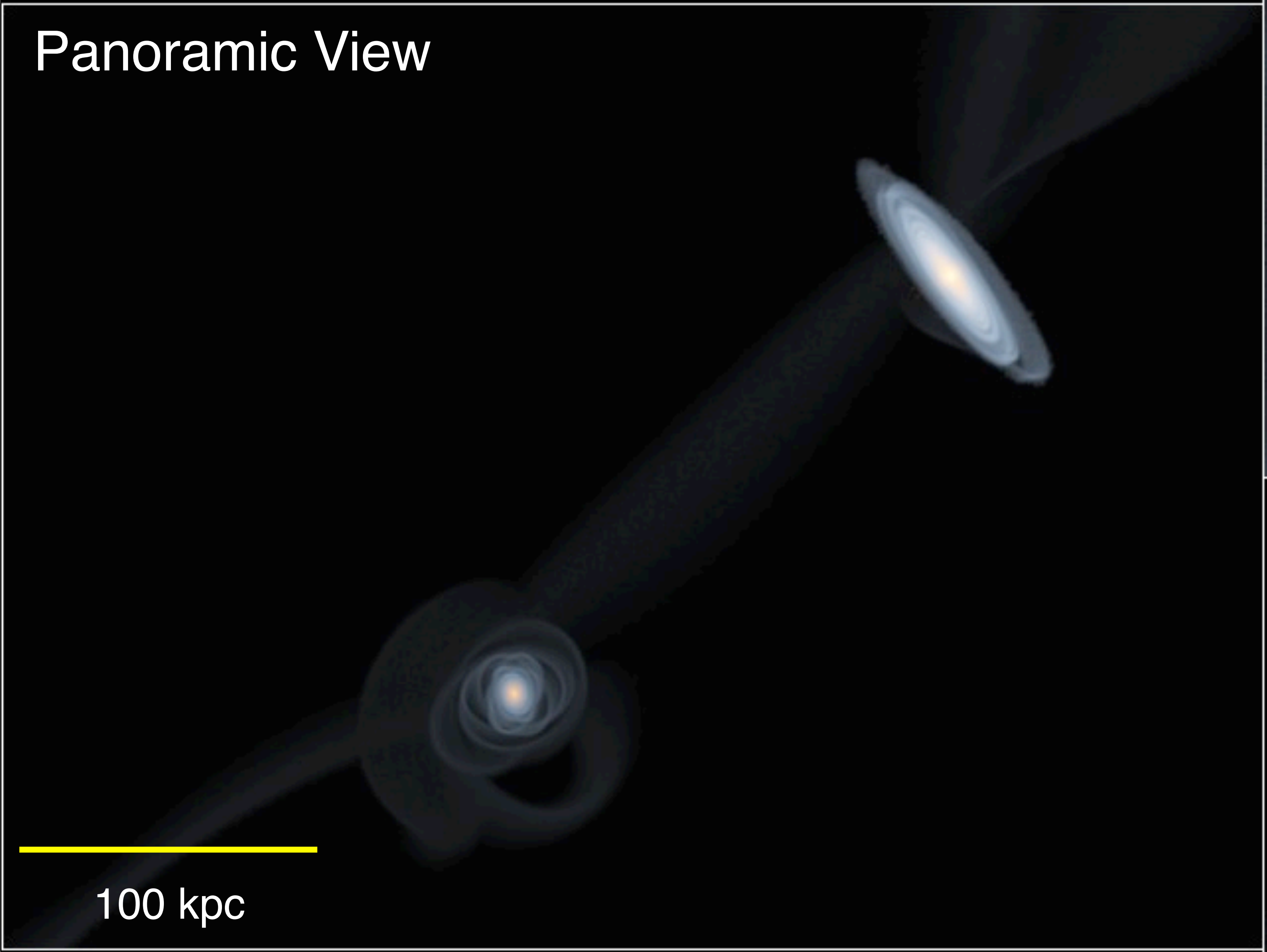


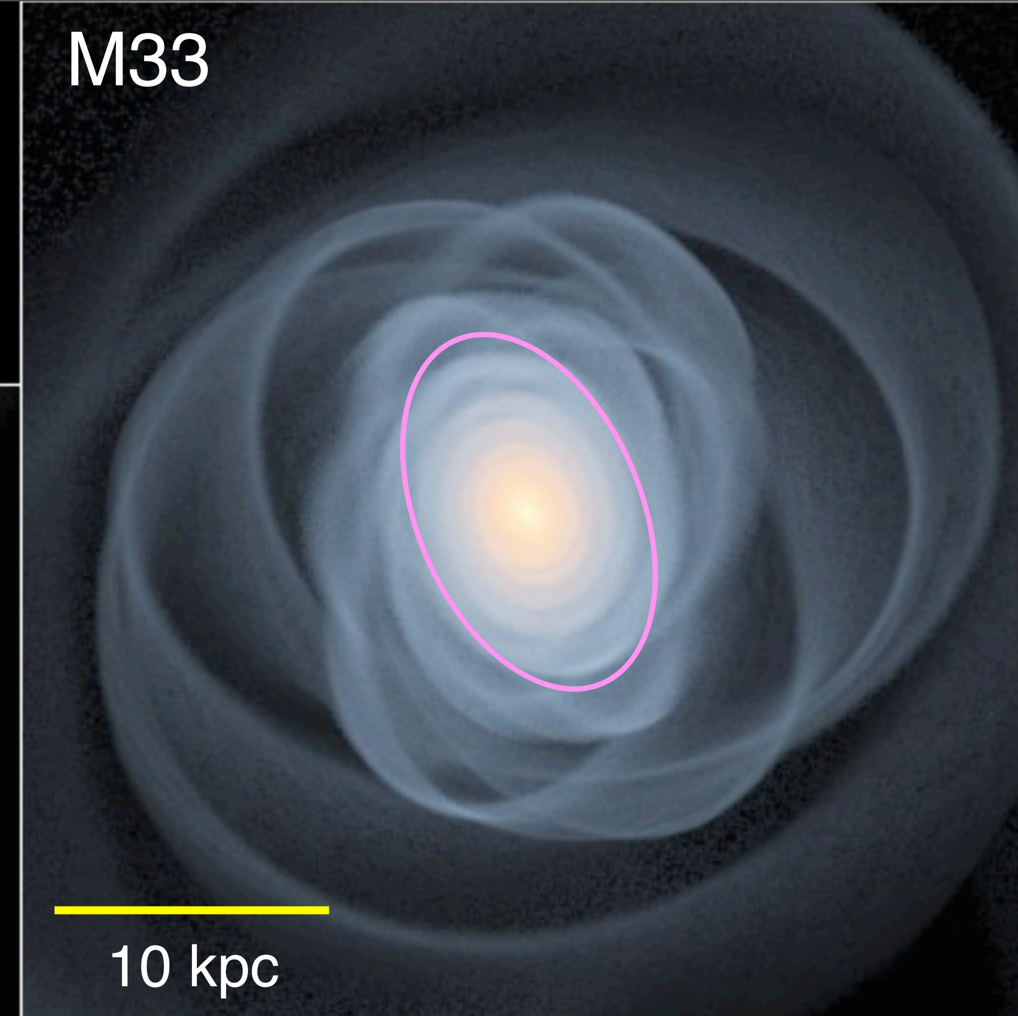


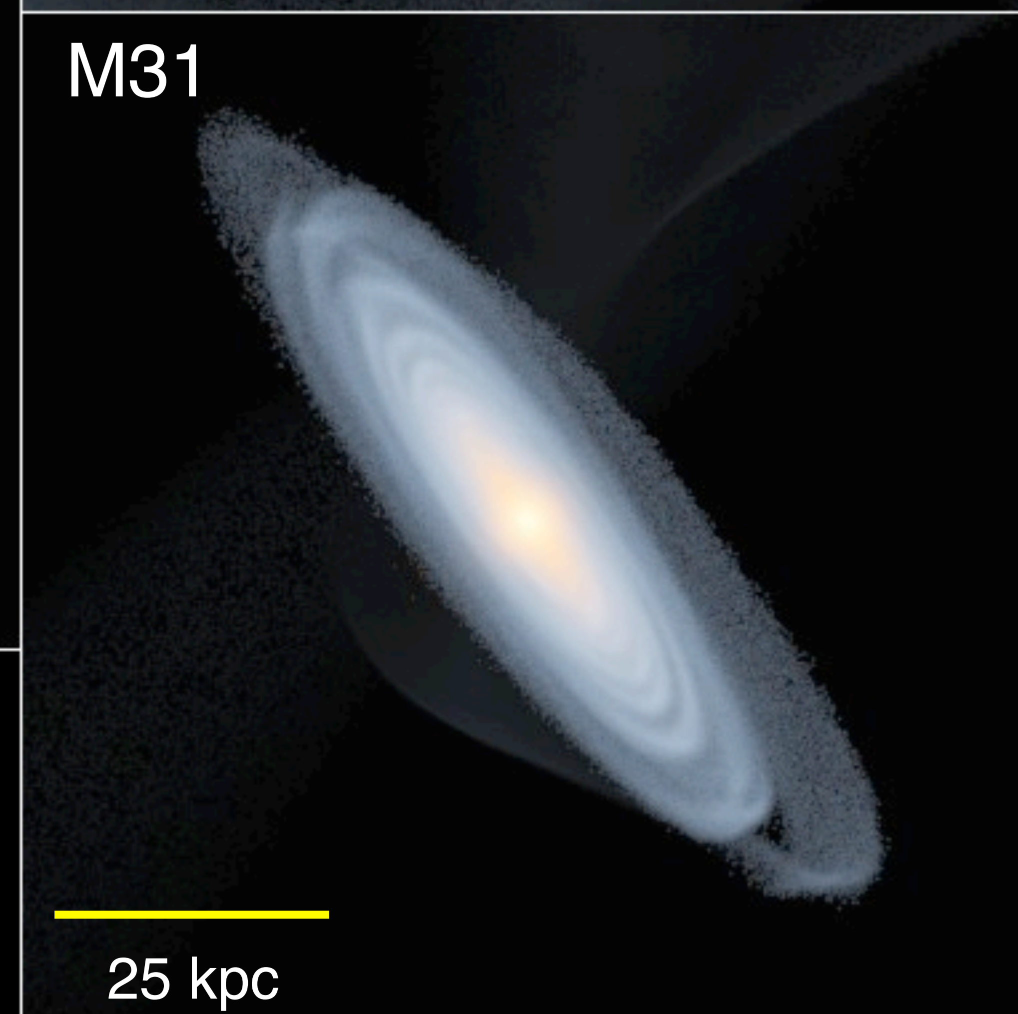


Elapsed time 3.4 Gyr (70 Myr/s)
M33 interaction occurs about 2.5 Gyr ago
Orbital pericentre 50 kpc

M31-M33 Interaction







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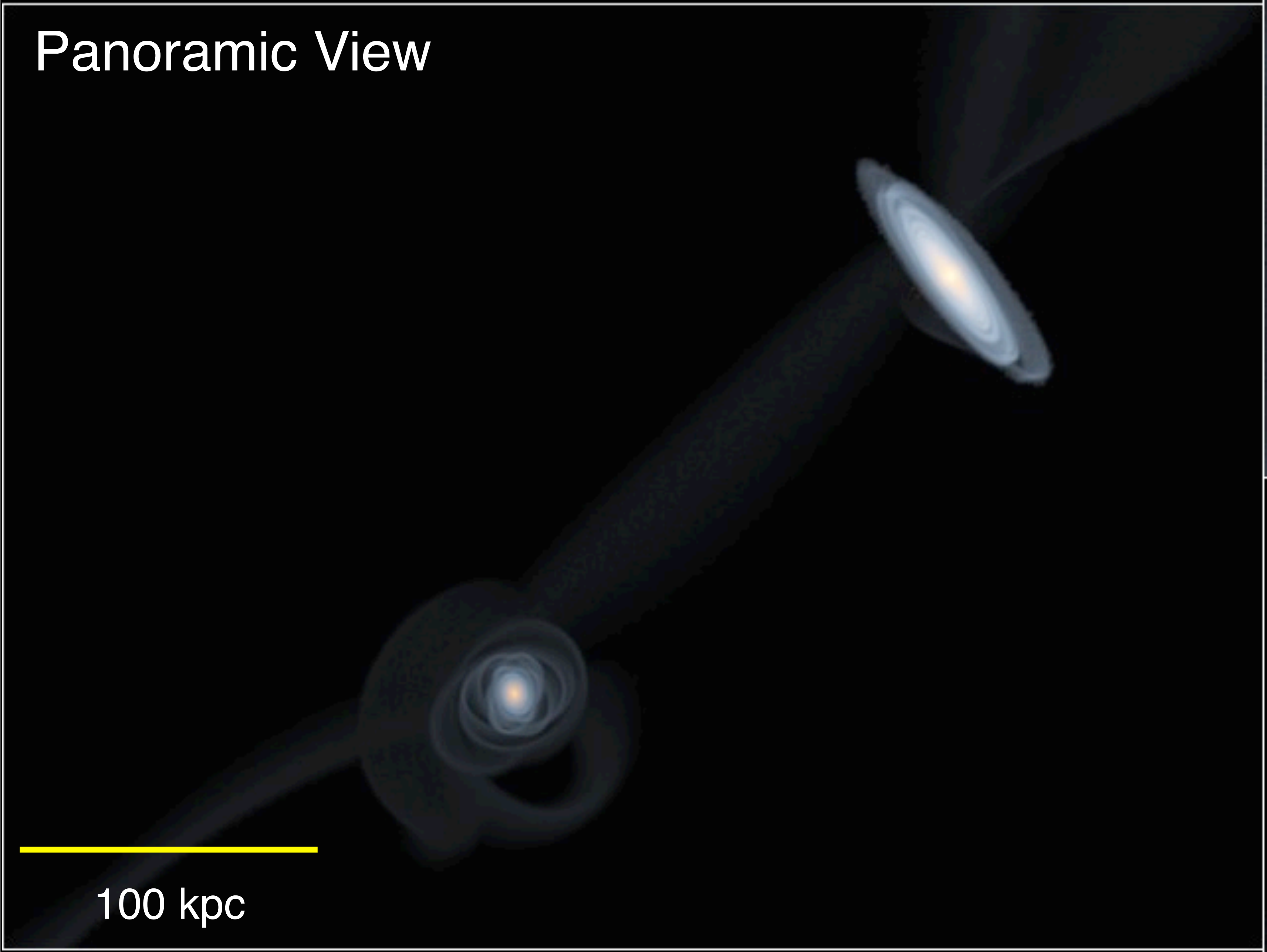
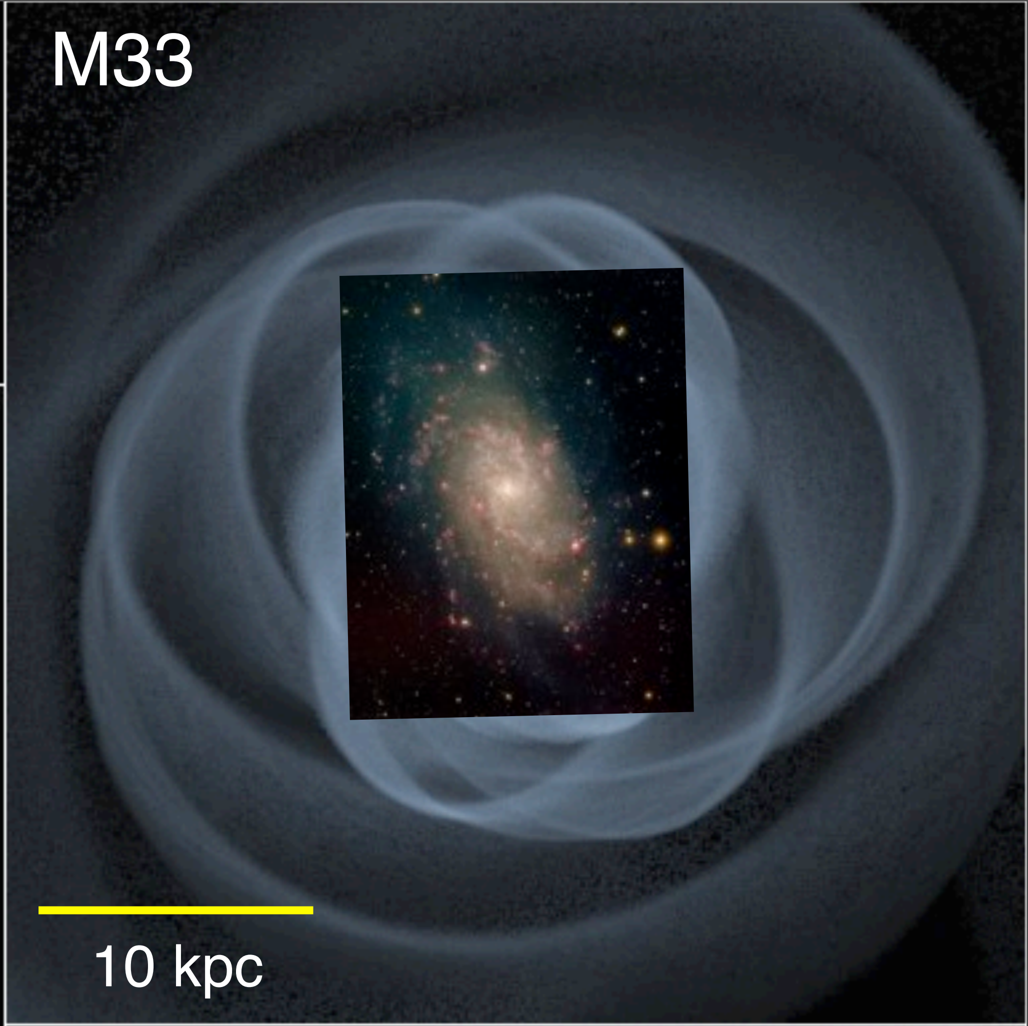
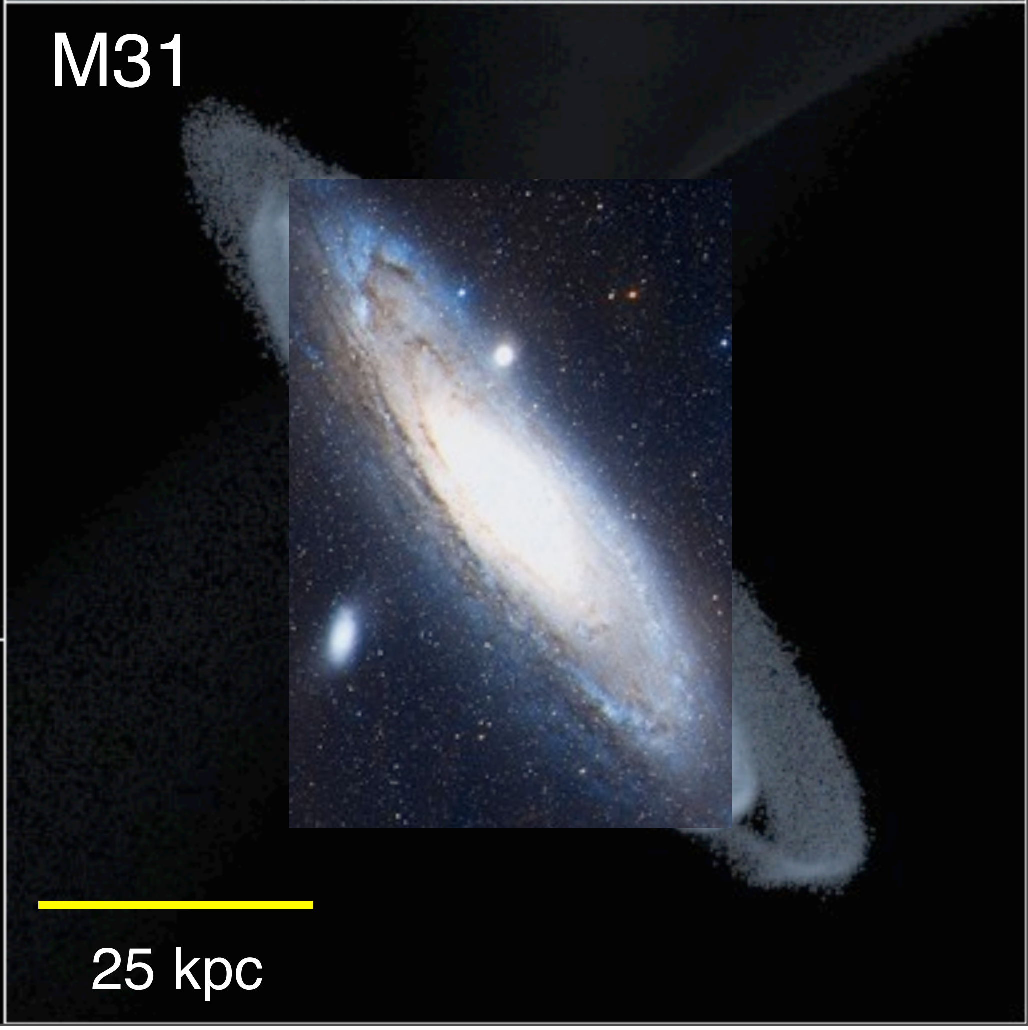
M31-M33 Interaction







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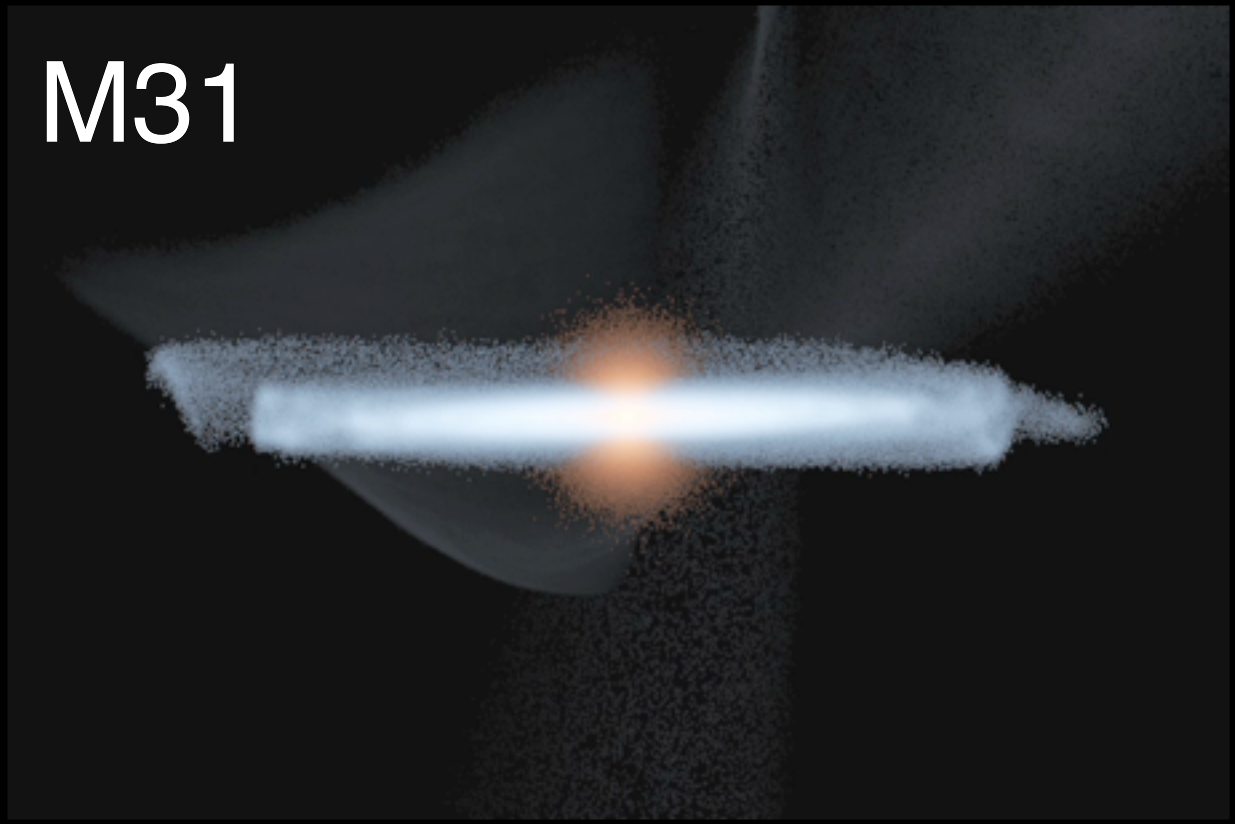
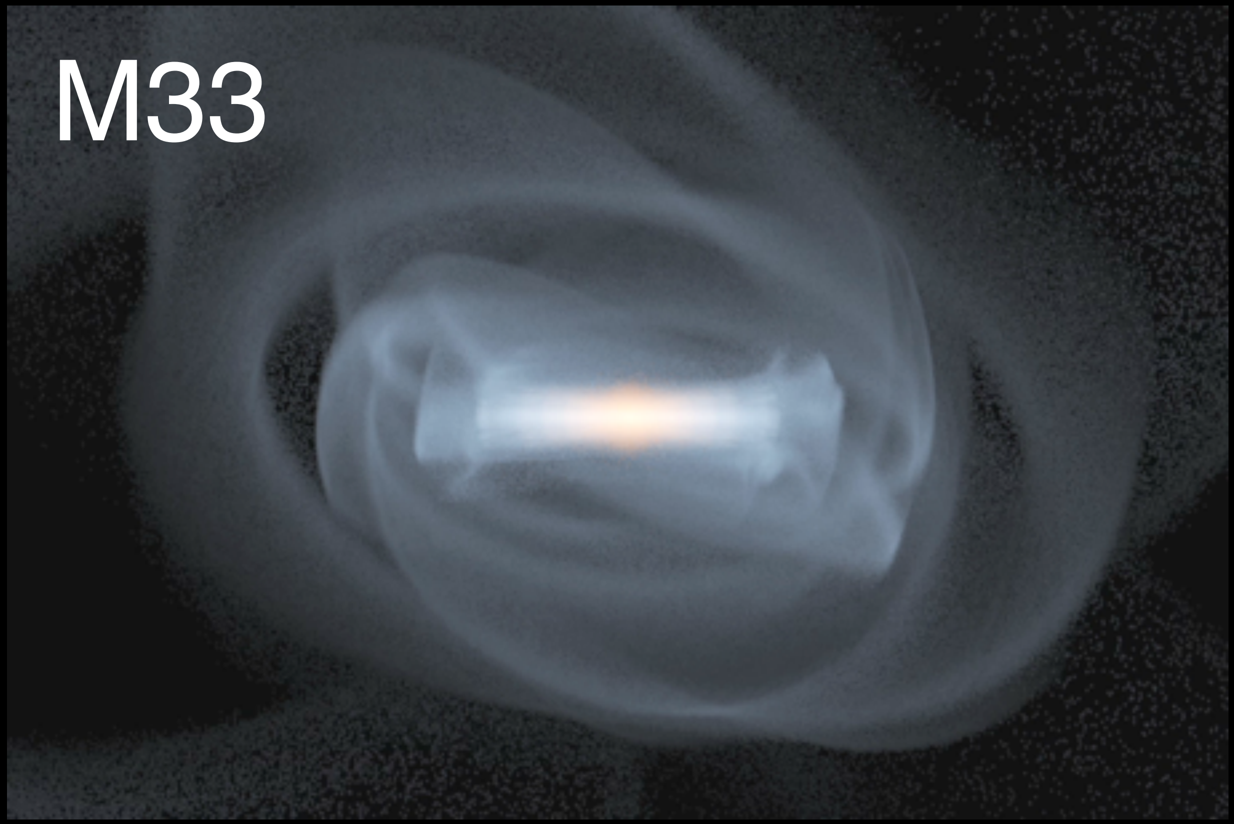
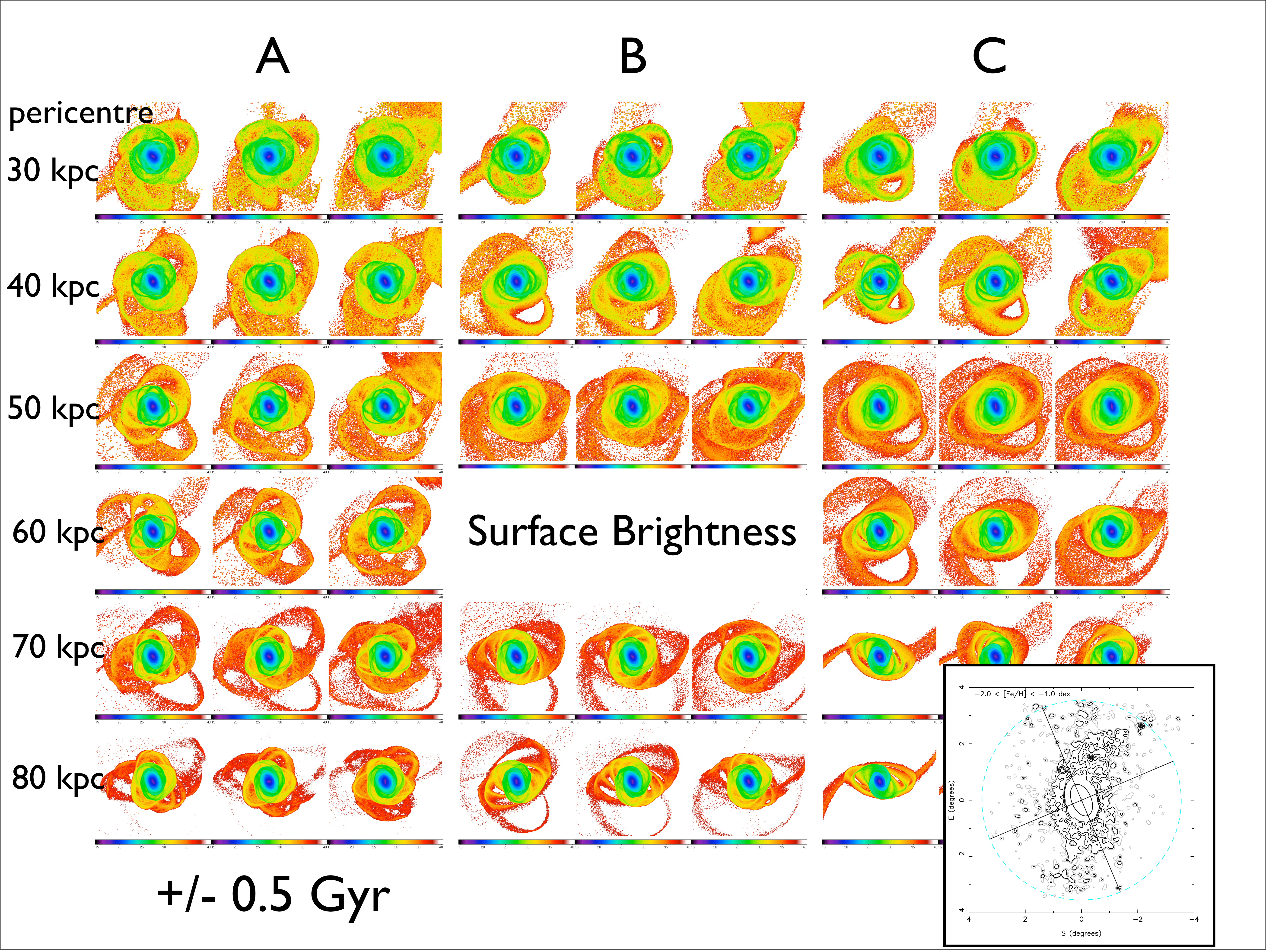


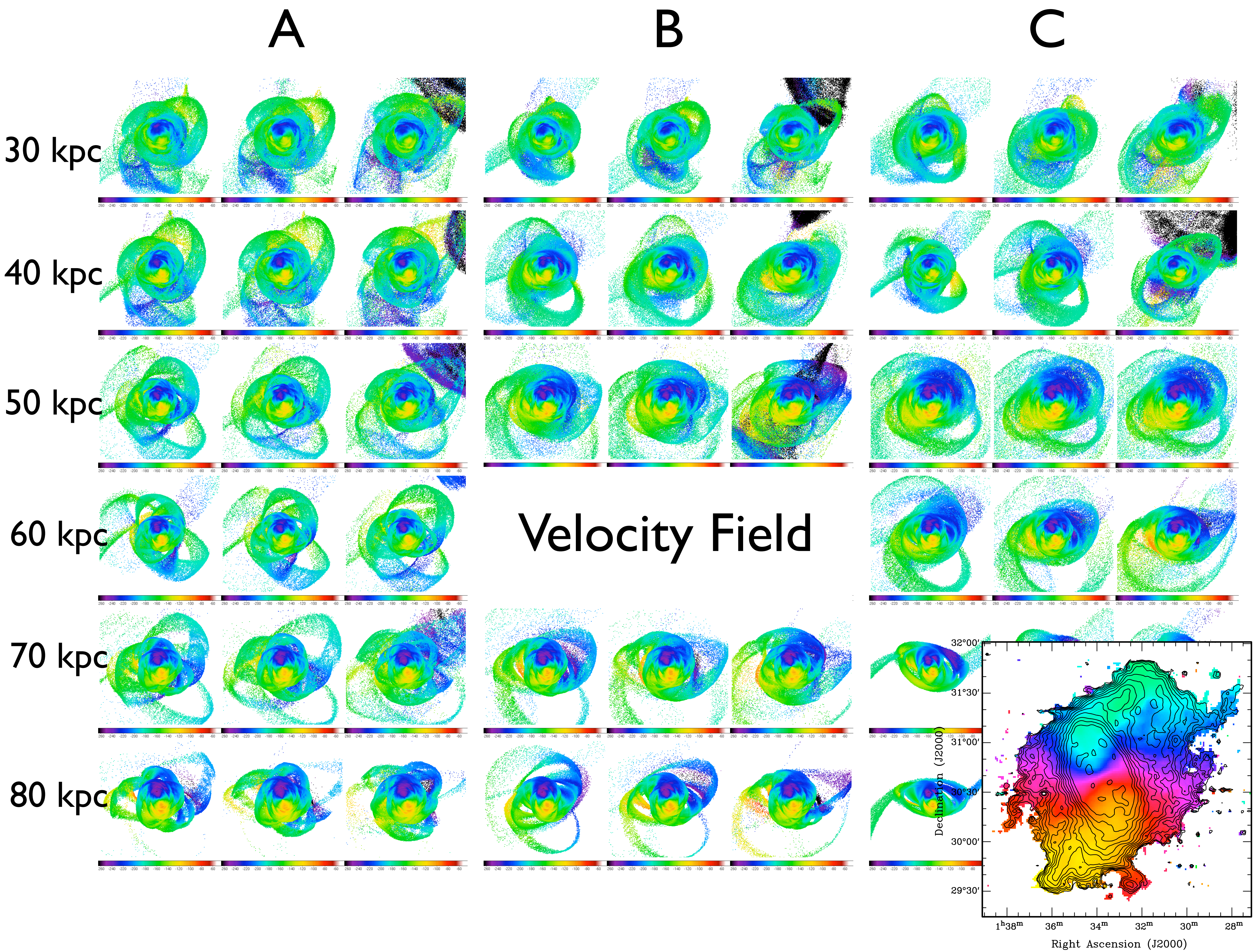


Edge-on Views

M31 is mildly warped by encounter - maybe explains the observed warp?

M33 - outer disk is pulled into the orbital plane
- strongly warped disk
- consistent with the inferred gas warp

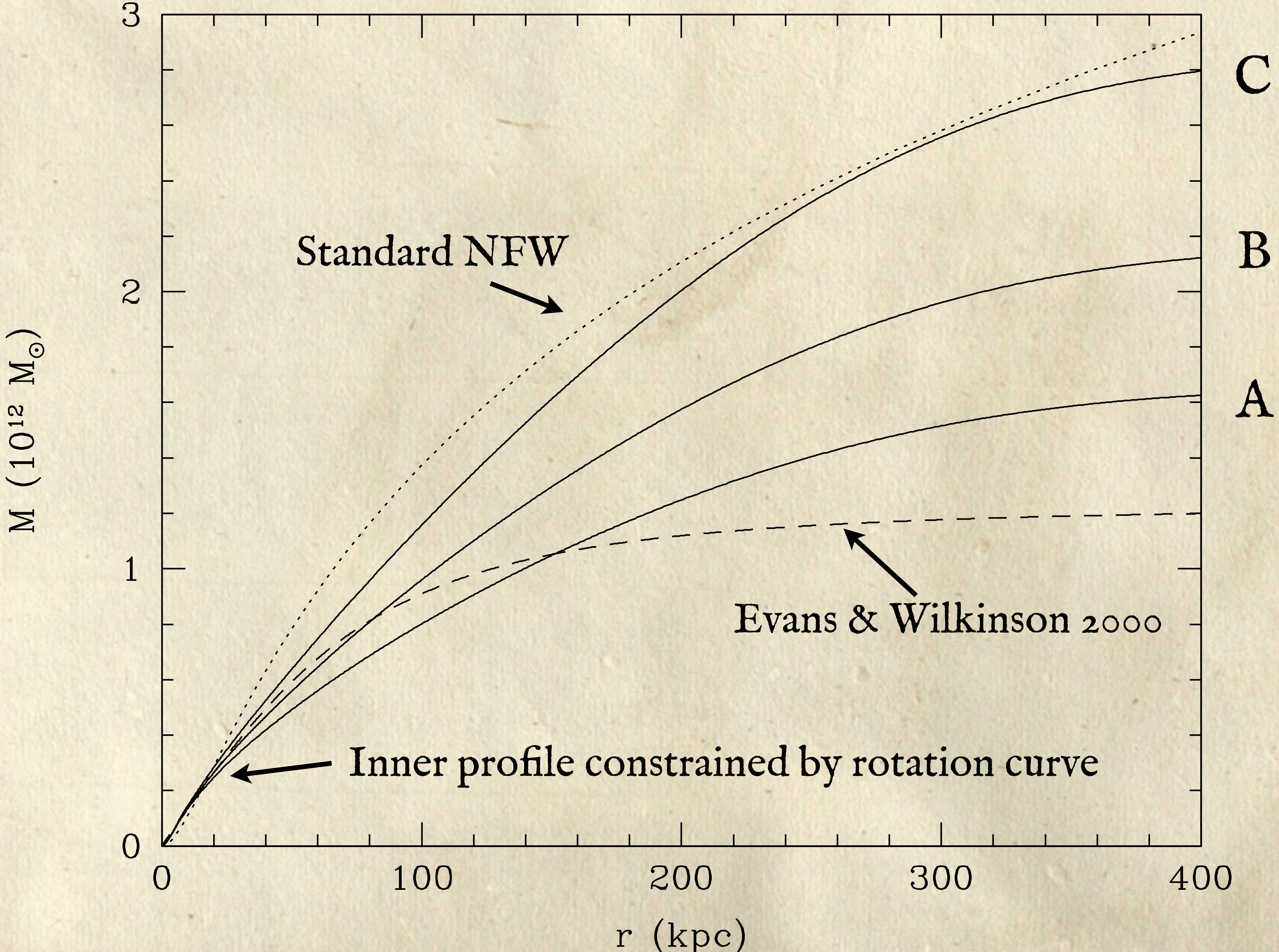

A
B
C
pericentre
30 kpc
40 kpc
50 kpc
60 kpc
70 kpc
80 kpc
Surface Brightness
+/- 0.5 Gyr
−2.0 < [Fe/H] < −1.0 dex
E (degrees)
S (degrees)


A
B
C
30 kpc
40 kpc
50 kpc
60 kpc
70 kpc
80 kpc
Velocity Field
Declination (J2000)
Right Ascension (J2000)
KM/S
32°00′
31°30′
31°00′
30°30′
30°00′
29°30′
1h38m
36m
34m
32m
30m
28m
−100
−150
−200
−250
−300

M33 and the Local Group

- M33 interaction seems plausible but is the model unique?
- How can this interaction constrain the structure and dynamics of the Local Group?
- We perform a Bayesian analysis of possible M33 orbits assuming different M31 potentials and M33 orbital parameters constrained by observations

Consider different M31 potentials with varying mass and halo extent



Local Group Data (Priors)

$$D_{M31} = 785 \text{ kpc}$$
$$D_{M33} = 809 \text{ kpc}$$

errors +/- 25 kpc
McConnachie TRGB distances

$$v_{r,M31,helio} = -301 \text{ km/s}$$
$$v_{r,M33,helio} = -179 \text{ km/s}$$

errors +/- 1 km/s

$$v_{r,M31,G} = -115 \text{ km/s}$$
$$v_{r,M33,G} = -42 \text{ km/s}$$

errors +/- 15 km/s
LSR uncertainty

$$v_{\alpha,M33} = -70 \text{ km/s}$$
$$v_{\delta,M33} = 140 \text{ km/s}$$

errors +/- 50 km/s
Brunthaler et al. 2005

$$v_{\alpha,M31} = ?$$
$$v_{\delta,M31} = ?$$

In this analysis, these are posteriors but now there is a measurement

Relative Orbital Velocity in terms of galactocentric transverse and radial velocity components of M31 and M33

$\mathbf{v}_f = \mathbf{v}_{M33} - \mathbf{v}_{M31}$ (M33 orbital velocity wrt M31 now)

T_A - rotation matrix from M33 to M31 tangent plane coordinates

$$v_{f,x} = T_{A,11} v_{\alpha,M33} + T_{A,21} v_{\delta,M33} + T_{A,13} v_{r,M33} - v_{\alpha,M31}$$

$$v_{f,y} = T_{A,21} v_{\alpha,M33} + T_{A,22} v_{\delta,M33} + T_{A,23} v_{r,M33} - v_{\delta,M31}$$

$$v_{f,z} = T_{A,31} v_{\alpha,M33} + T_{A,32} v_{\delta,M33} + T_{A,33} v_{r,M33} - v_{r,M31}$$

$$\chi^2 = (v_{f,z,obs} - v_{f,z,orbit})^2 / \sigma_v^2$$

$$L \propto e^{-\chi^2/2}$$

Likelihood Function Involves the *z* component of final orbital velocity in M31 tangent plane coordinates

$$\mathbf{v}_f = \mathbf{v}_{M33} - \mathbf{v}_{M31}$$ (relative velocity)

T_A - rotation matrix from M33 to M31 tangent plane coordinates

$$v_{f,x} = T_{A,11} v_{\alpha,M33} + T_{A,21} v_{\delta,M33} + T_{A,13} v_{r,M33} - v_{\alpha,M31}$$

$$v_{f,y} = T_{A,21} v_{\alpha,M33} + T_{A,22} v_{\delta,M33} + T_{A,23} v_{r,M33} - v_{\delta,M31}$$

$$v_{f,z} = T_{A,31} v_{\alpha,M33} + T_{A,32} v_{\delta,M33} + T_{A,33} v_{r,M33} - v_{r,M31}$$

$$\chi^2 = (v_{f,z,obs} - v_{f,z,orbit})^2 / \sigma_v^2$$

$$L \propto e^{-\chi^2/2}$$

Derive a marginal posterior pdf for M31 transverse velocities

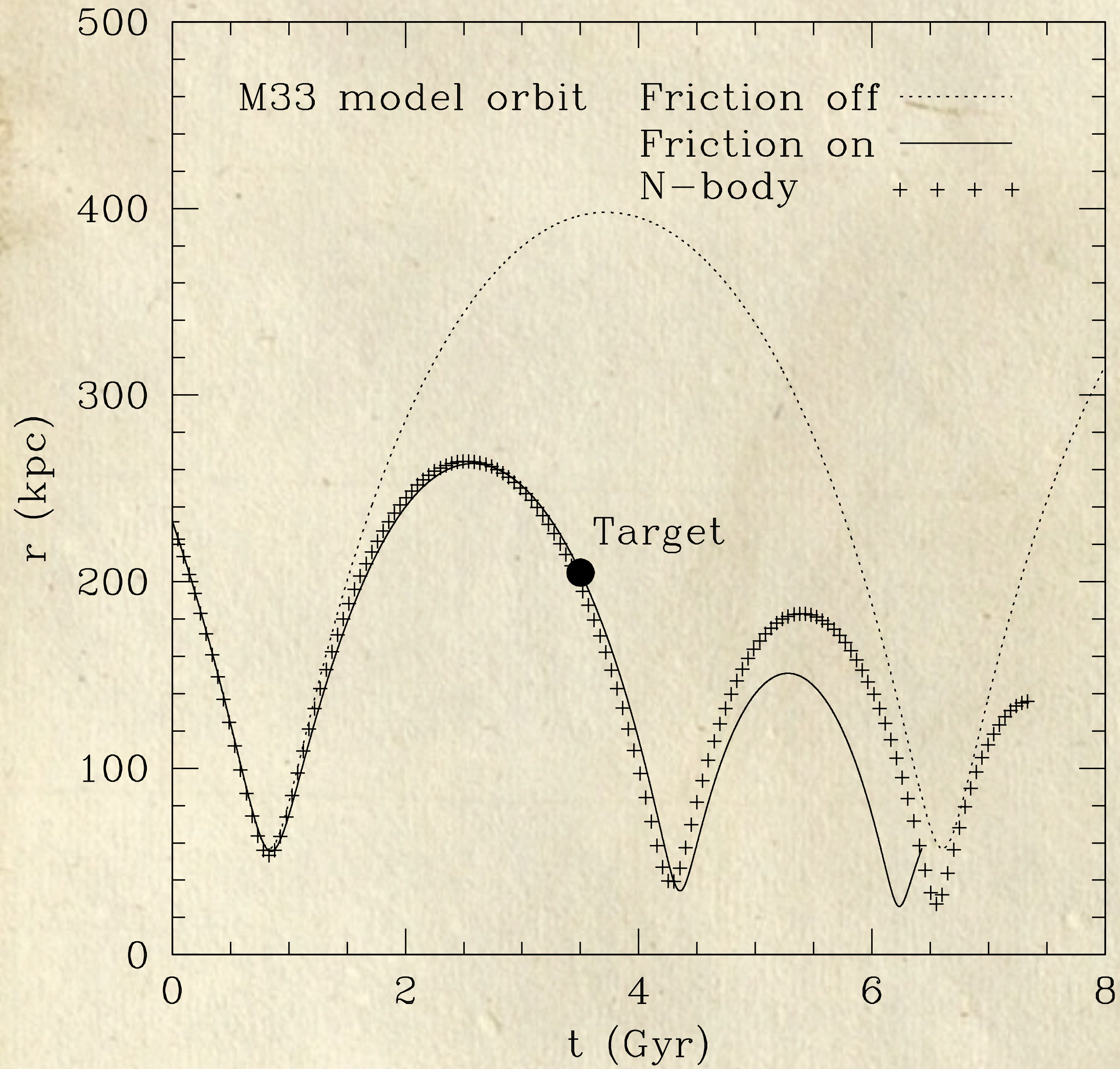
$$v_{f,x} = T_{A,11} v_{\alpha,M33} + T_{A,21} v_{\delta,M33} + T_{A,13} v_{r,M33} - v_{\alpha,M31}$$

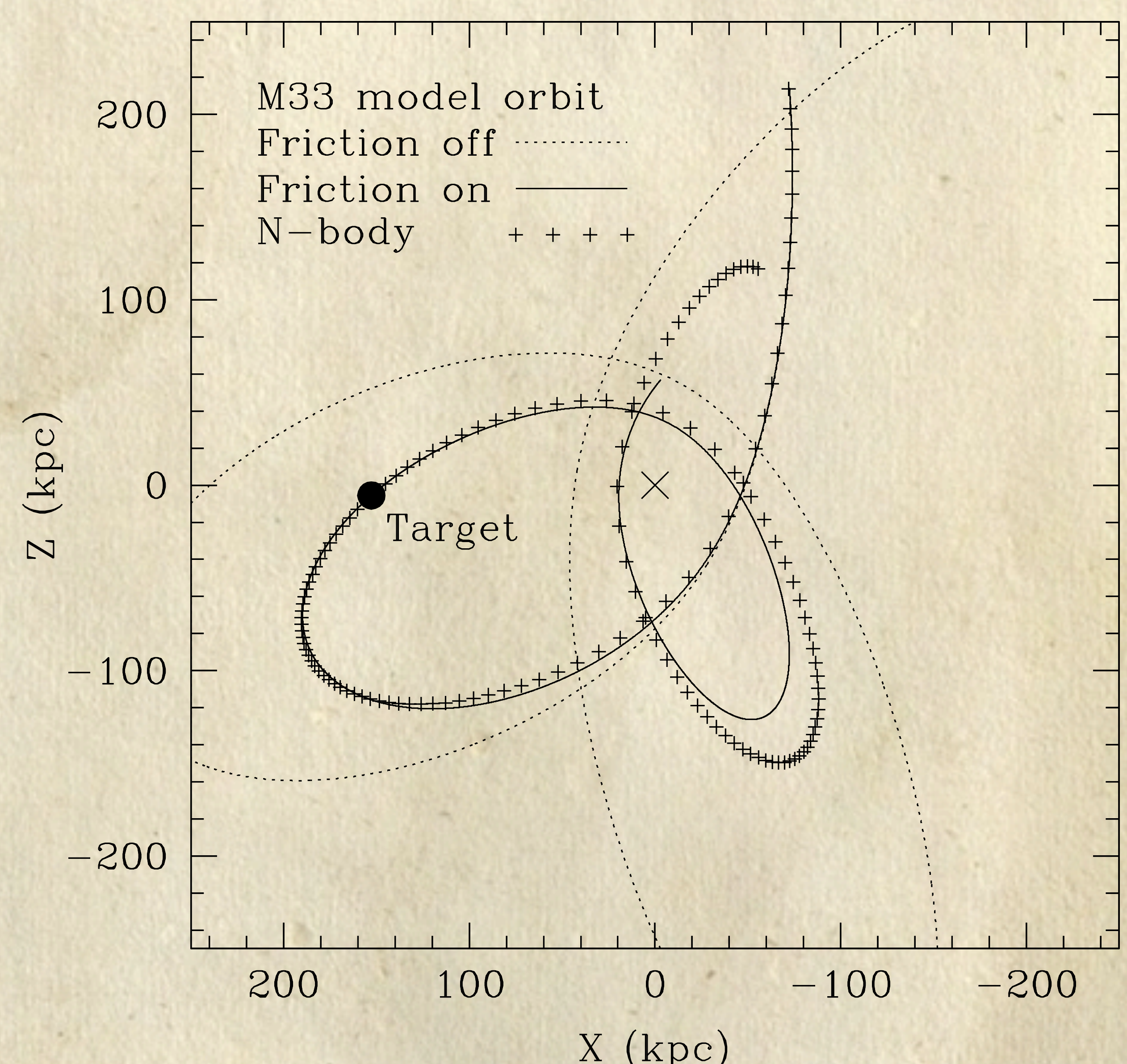
$$v_{f,y} = T_{A,21} v_{\alpha,M33} + T_{A,22} v_{\delta,M33} + T_{A,23} v_{r,M33} - v_{\delta,M31}$$

$$v_{f,z} = T_{A,31} v_{\alpha,M33} + T_{A,32} v_{\delta,M33} + T_{A,33} v_{r,M33} - v_{r,M31}$$

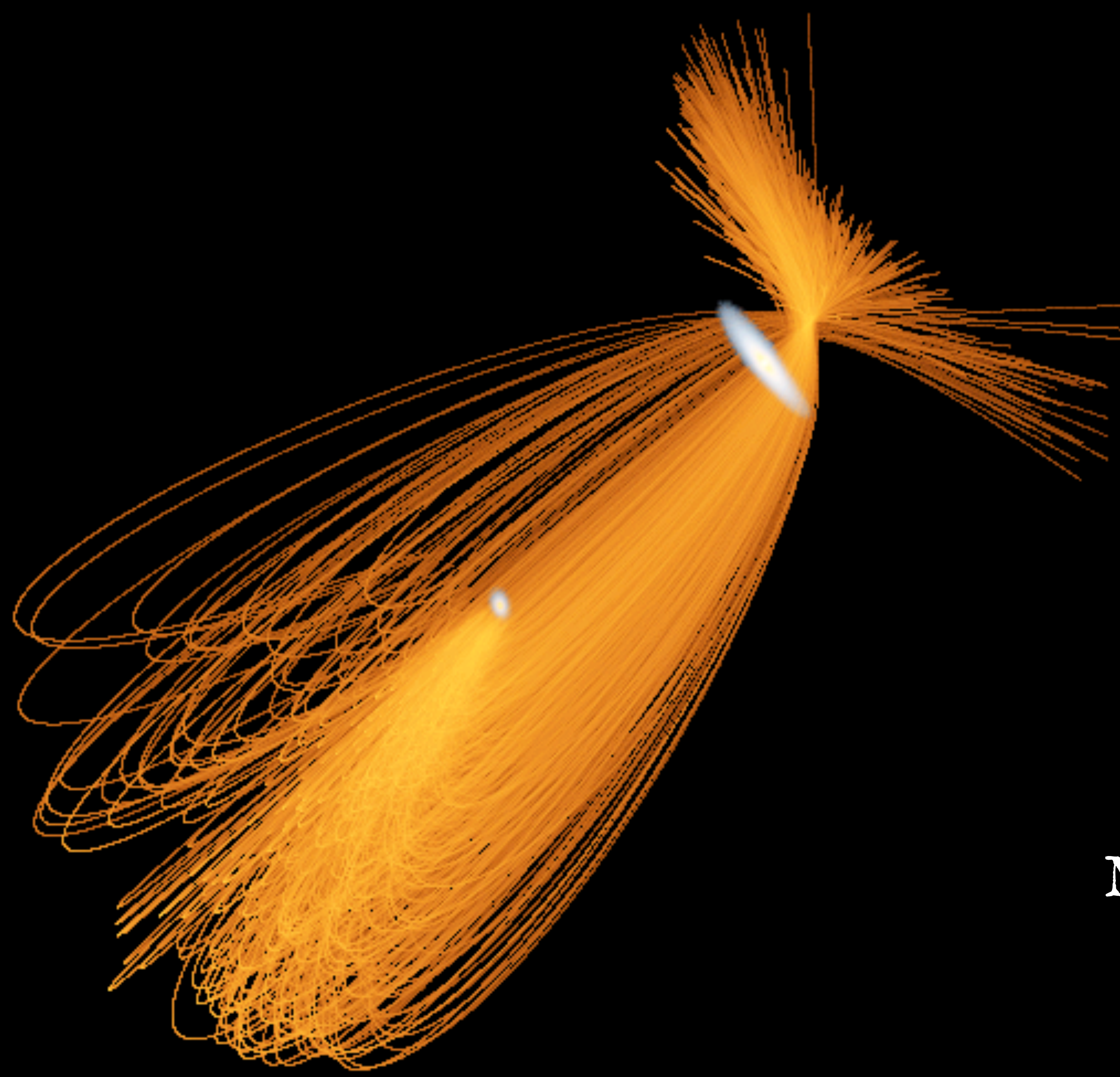
For a given orbit, solve for M31 transverse components and use its derived Bayesian probability to determine a pdf

The Importance of Dynamical Friction





Compute orbits in M31 potential that are consistent with Local Group priors - *must* include Chandra friction calibrated to N-body simulations



Likely M33 orbits for the case:

$$t_{peri} < 4 \text{ Gyr}$$

$$30 \text{ kpc} < r_{peri} < 60 \text{ kpc}$$

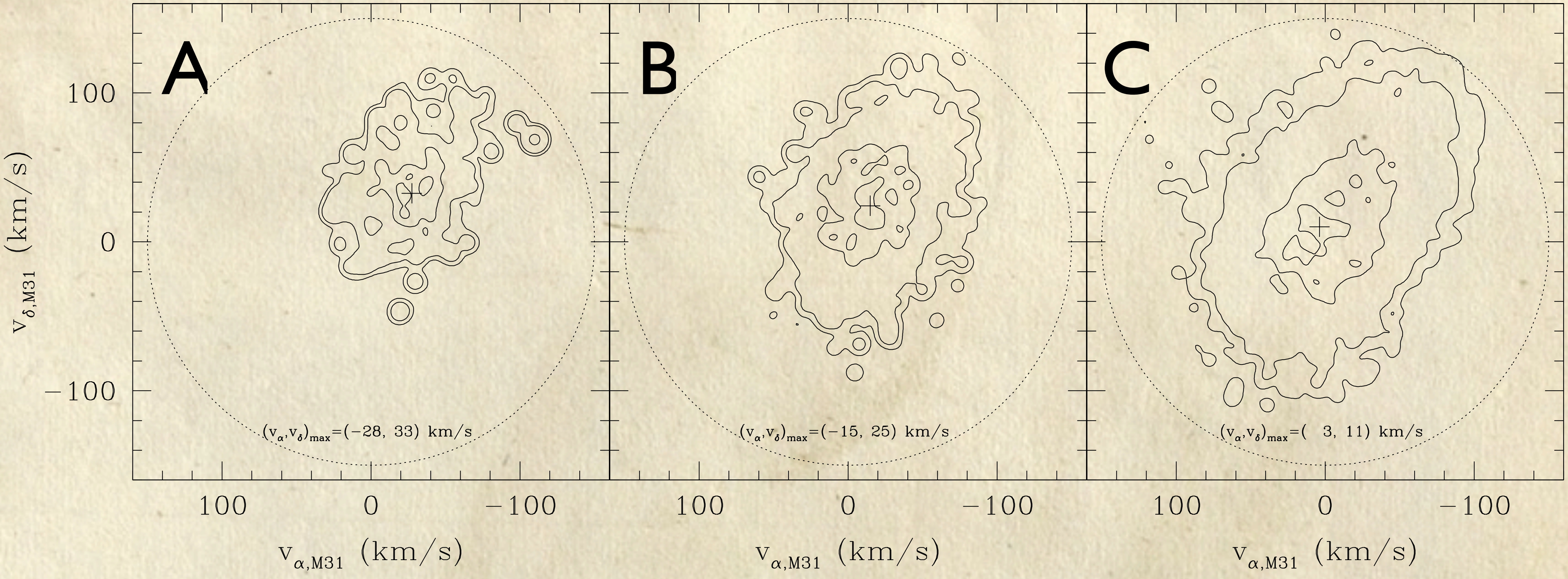
M33 initially falls from behind M31 towards us

Apocentre ~200-400 kpc

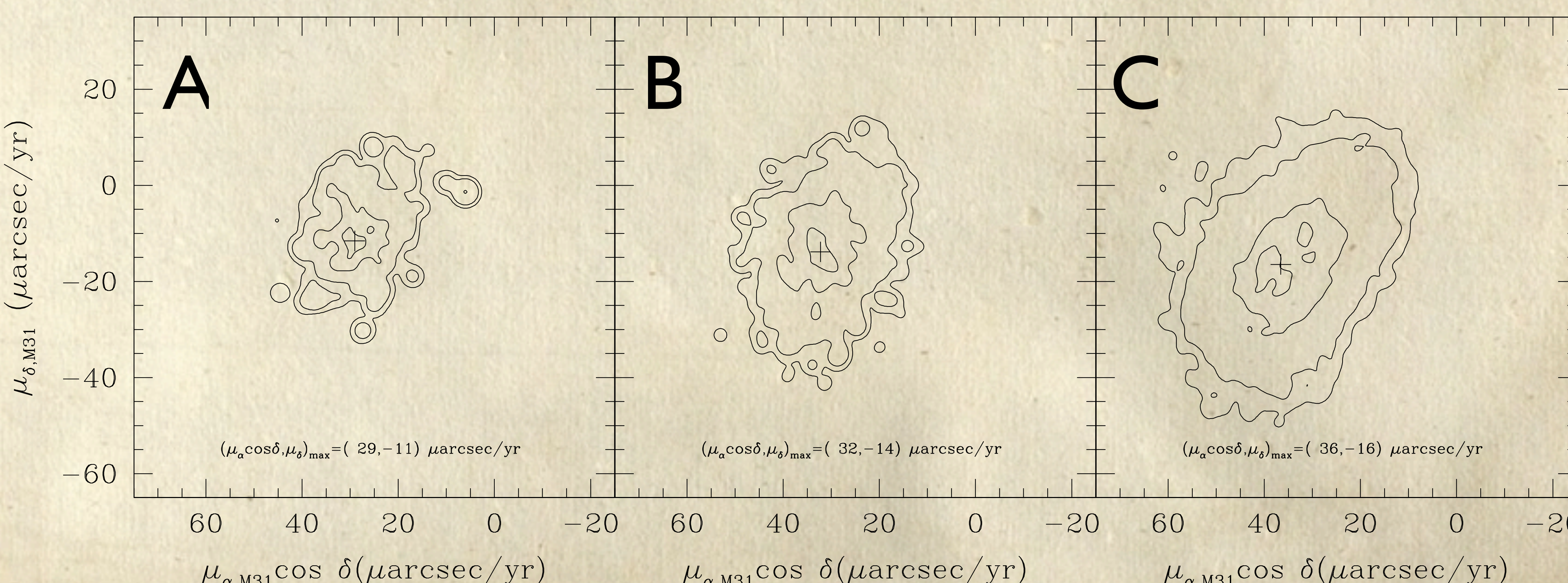
M33 is currently falling towards M31 - collision within < 1 Gyr

Increasing M31 Halo Mass and Extent →

Expected M31 Galactocentric Transverse Velocity $30 < r_p < 60$ kpc

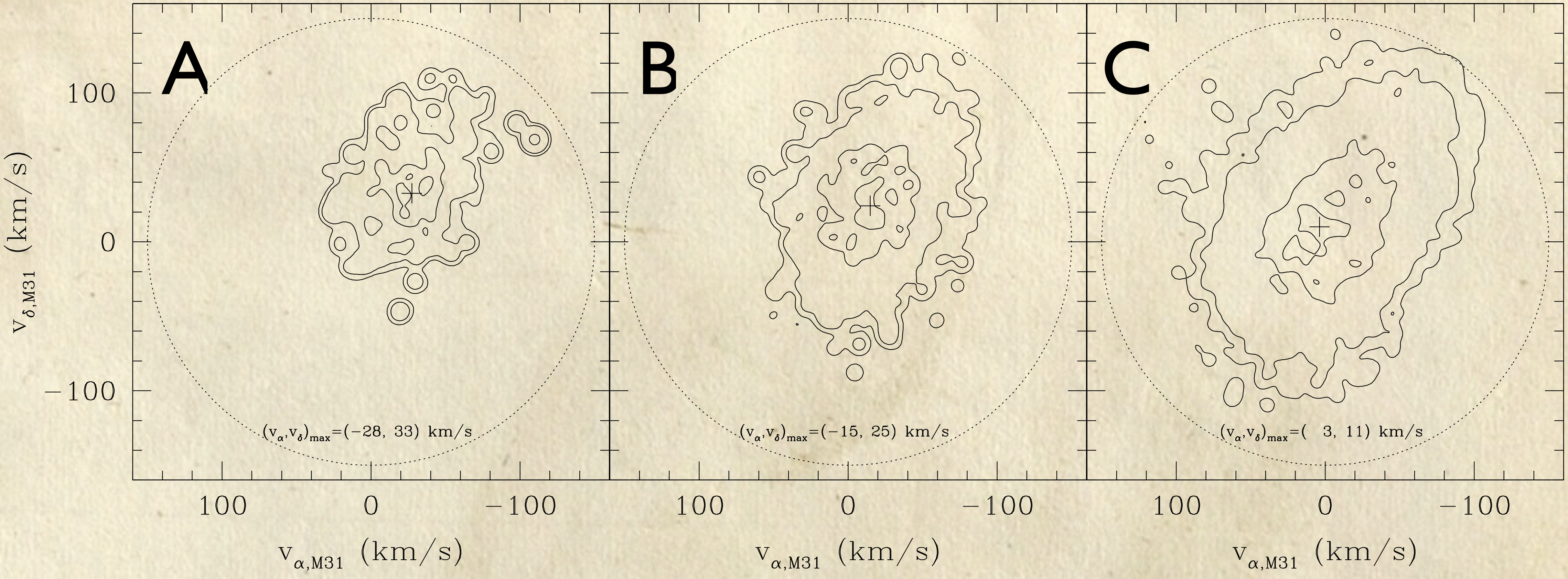


"Predicted" proper motion for M31 pdf Contours: 10% 50% 95% 99%

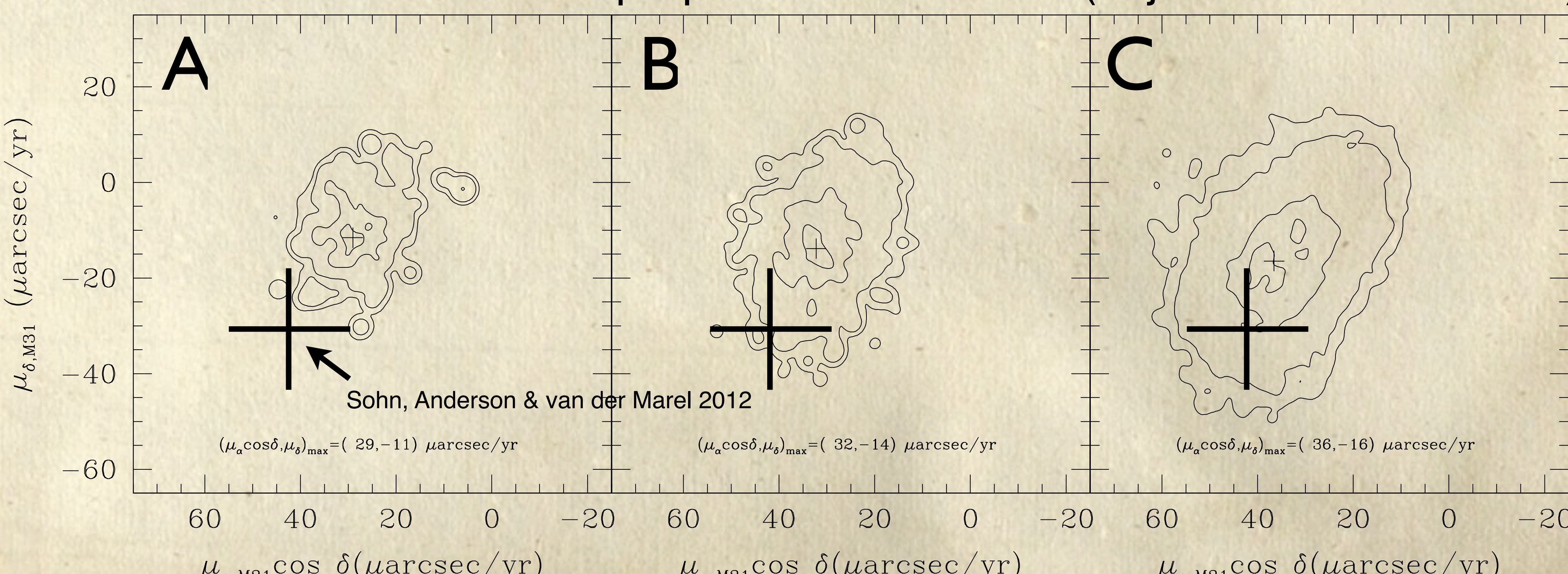


Expected M31 Galactocentric Transverse Velocity

Increasing M31 Halo Mass and Extent →

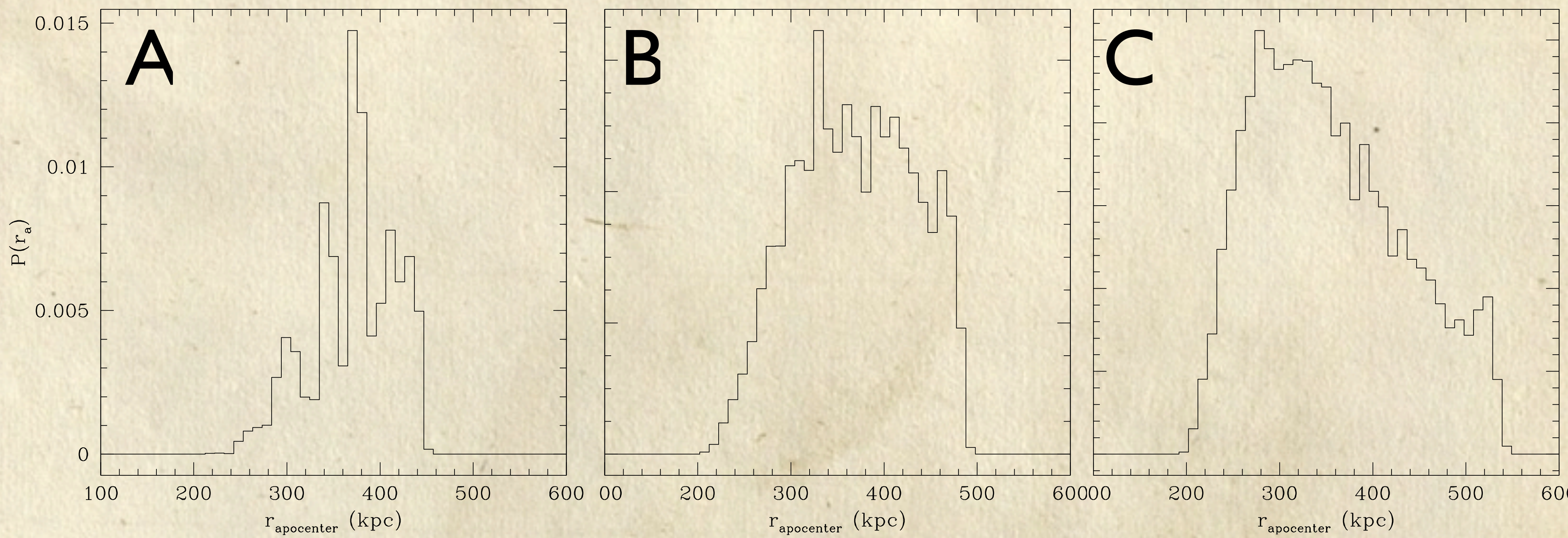


"Predicted" heliocentric proper motion for M31 (adjust for Sun's motion)



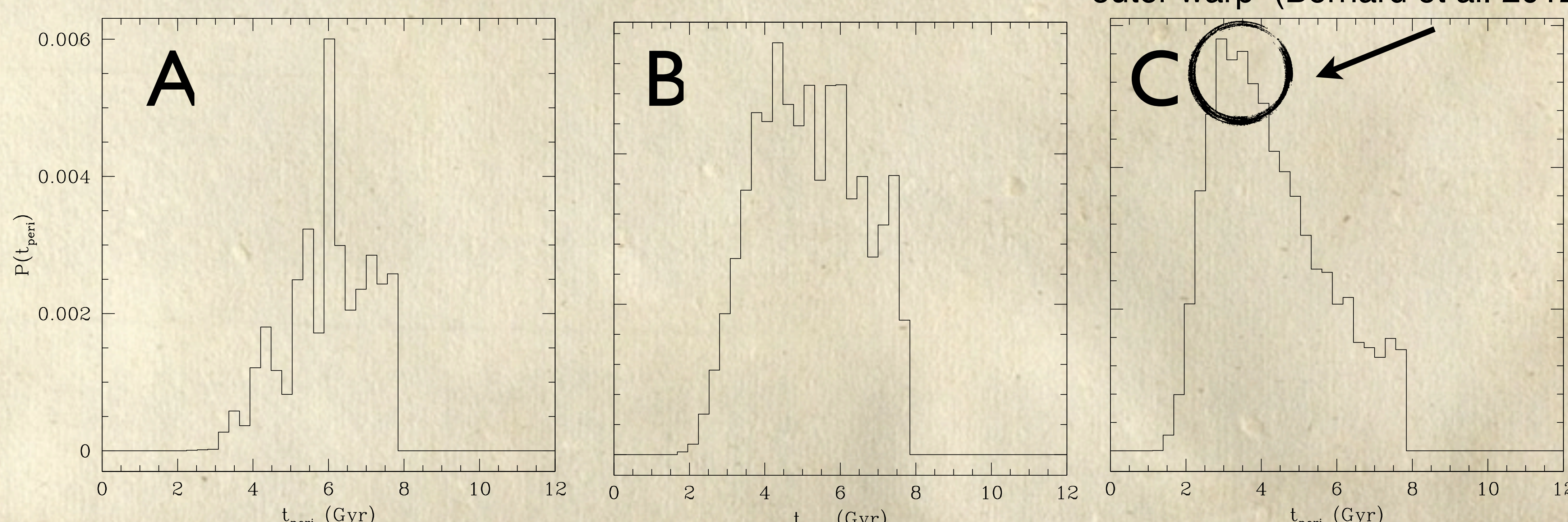
Increasing M31 Halo Mass and Extent

M33 apocentre

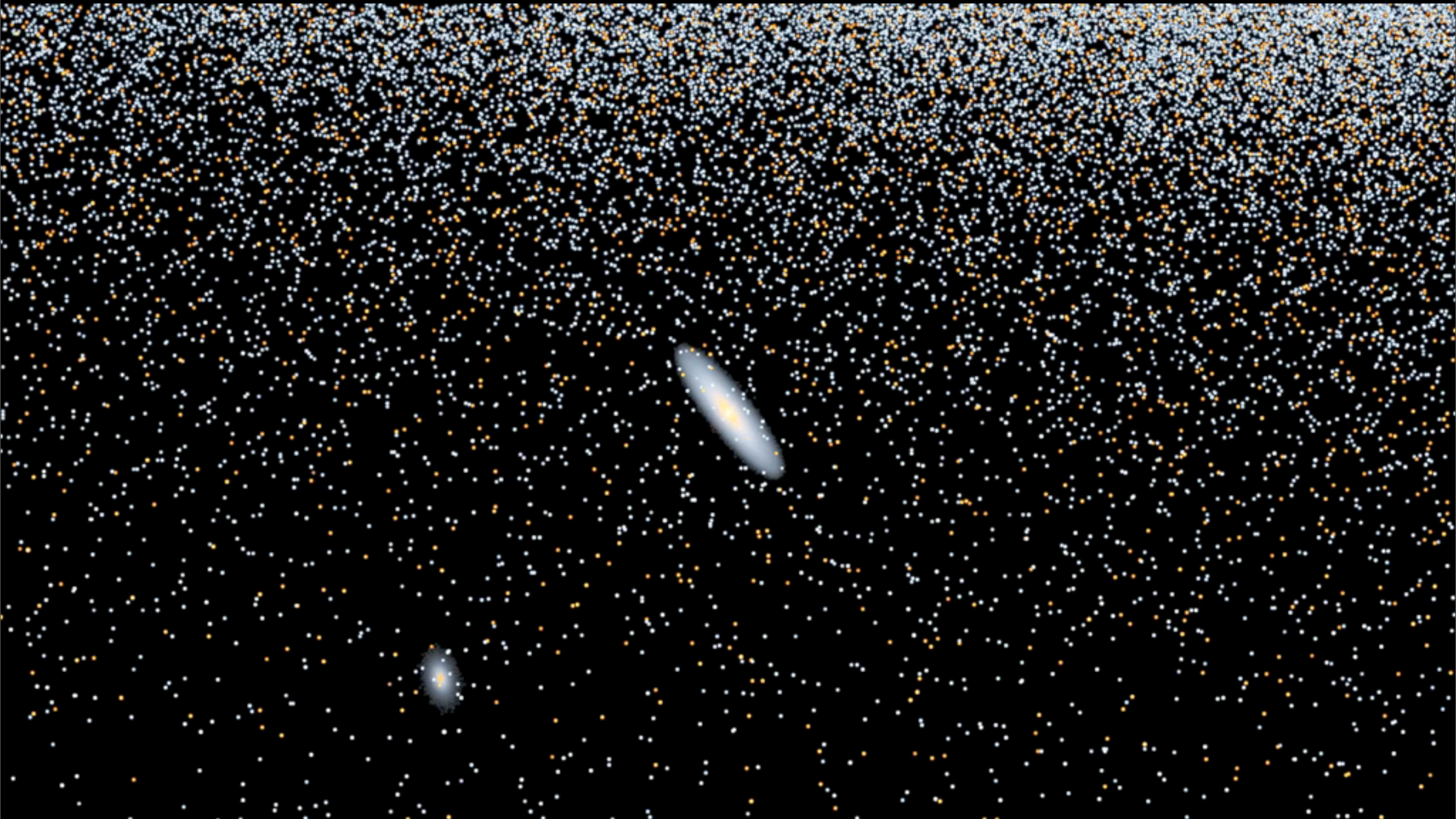


Time since M33 pericentre passage

A starburst event occurred 2.6 Gyr ago in M31 outer warp (Bernard et al. 2012)!



Local Group evolution as viewed from Sun's current position fixed in inertial space 785 kpc from M31 - grazing collision



The Milky Way recedes into the distance towards encounter with M31+M33 and merger and transformation into an elliptical.