Galaxy Formation and Evolution: from the Outside

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and

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CASE WESTERN RESERVE UNIVERSITY

NOAO

NSF

Near-field cosmology

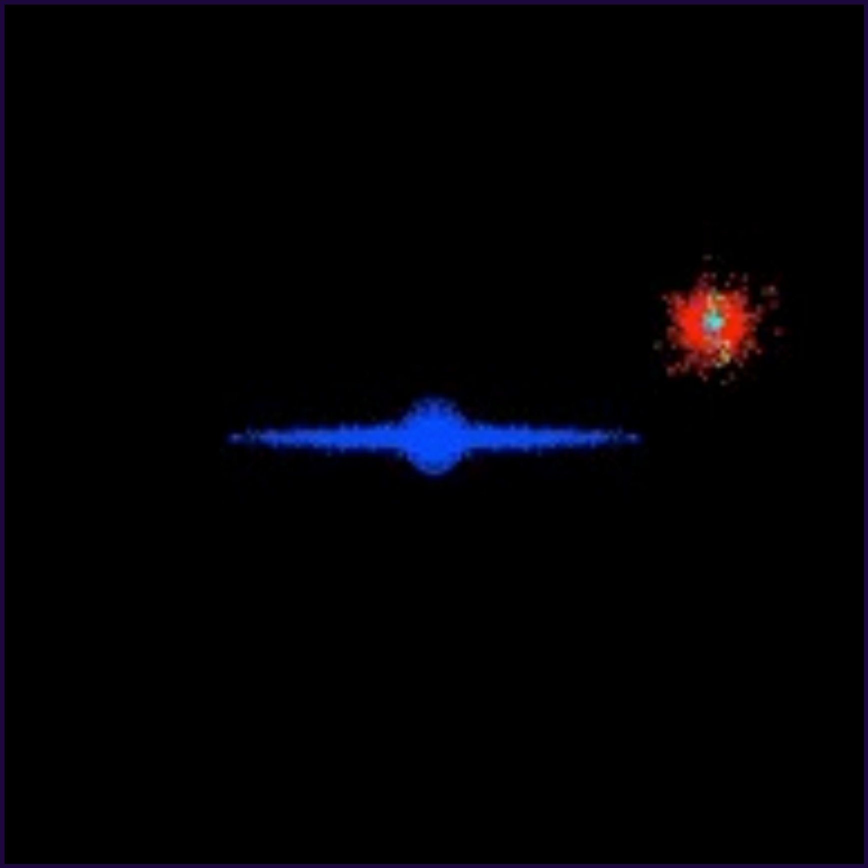
- The outer parts of galaxies (in particular, the Milky Way's halo) can make strong connections to galaxy formation in bottom-up picture (LCDM)
- Here I'll focus in particular on research using NOAO telescopes that has played an important role

Talk plan

1. Star streams and tidal distortions
2. Links to cosmological simulations and dark matter:
    a. Inner vs outer halo
    b. Number of progenitors of inner halo

3. New results on the Milky Way's outer limits

1. Star streams: minor, minor mergers

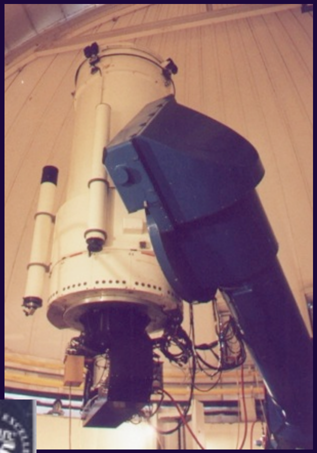


Movie from Kathryn Johnston

Tidal disruption of infalling satellite by larger galaxy leaves star streams

This is an important way the galaxy builds up its halo, expected from LCDM simulations of structure growth

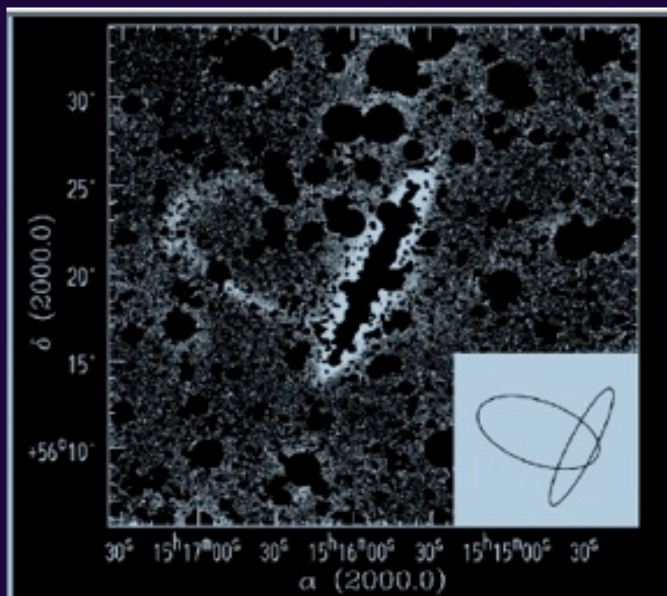
Large format CCDs come to KPNO:



- Deep surface photometry with 0.9m detects faint halo around edge-on galaxy NGC5907

(Morrison, Boroson and Harding 1994; Sackett et al 1994)

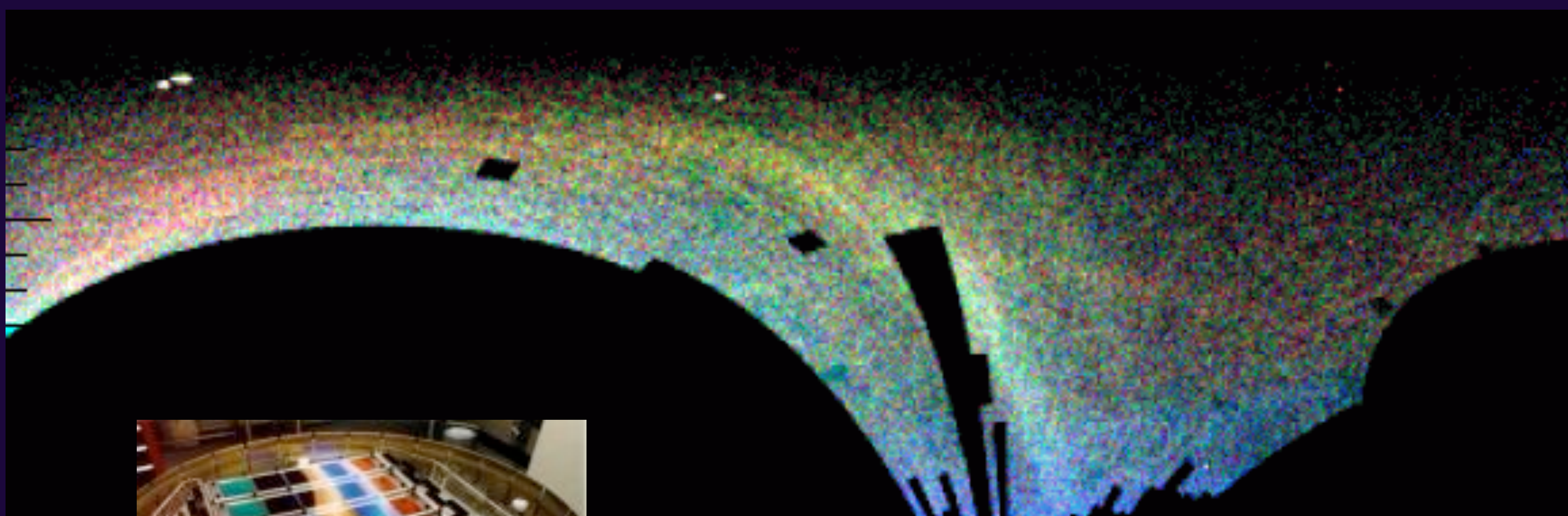
Later work finds star streams in 5907 halo!



Shang et al 1998

Martinez Delgado et al 2008

Surface photometry limited – star counts go fainter

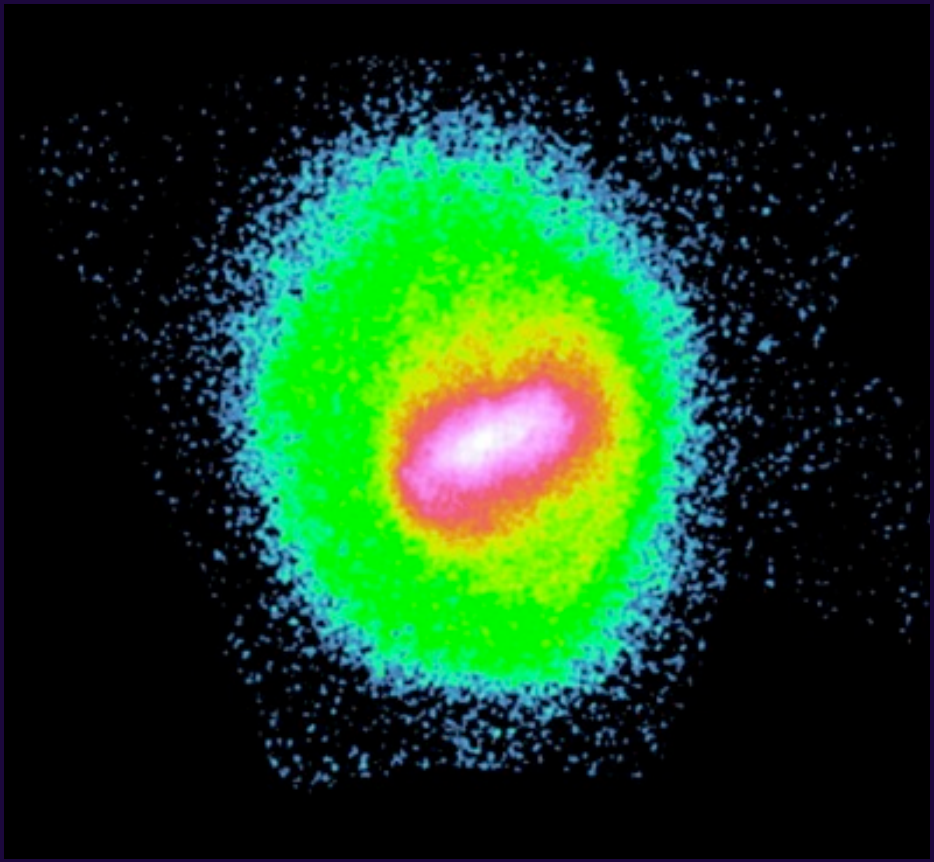


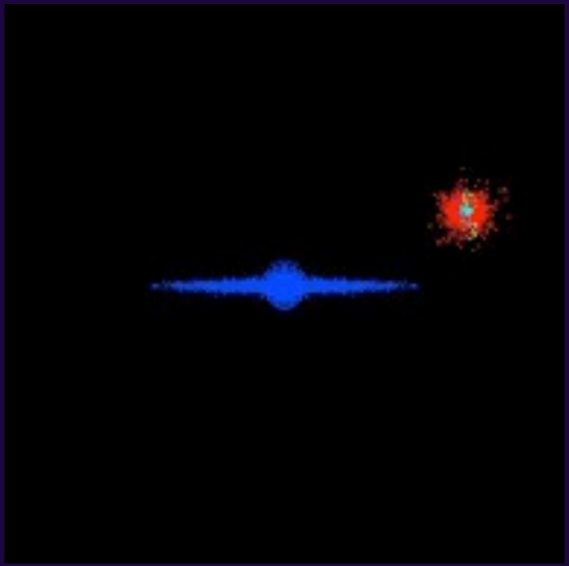
SDSS imager

Belokurov et al 2006

LMC disk elongation – tidal effect of MW?

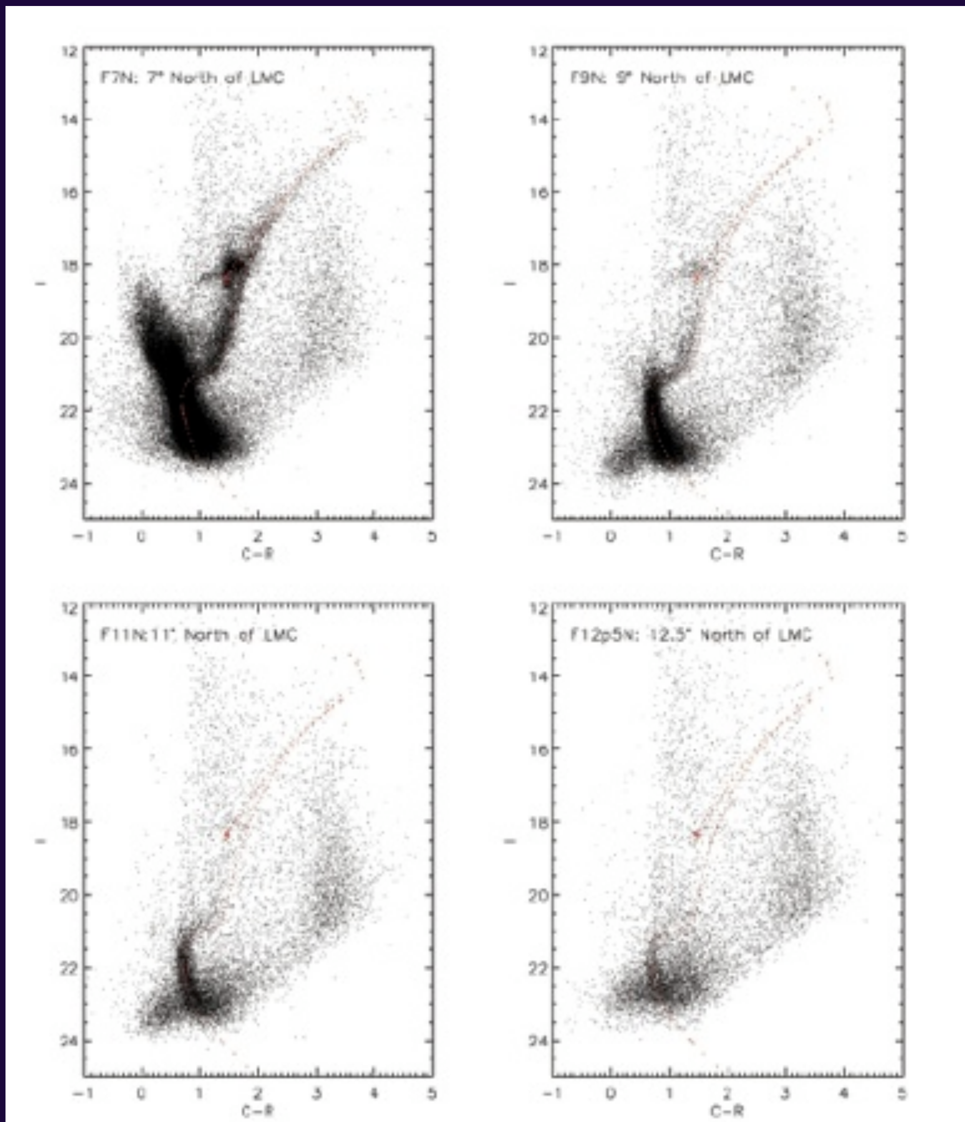
2MASS telescope at CTIO



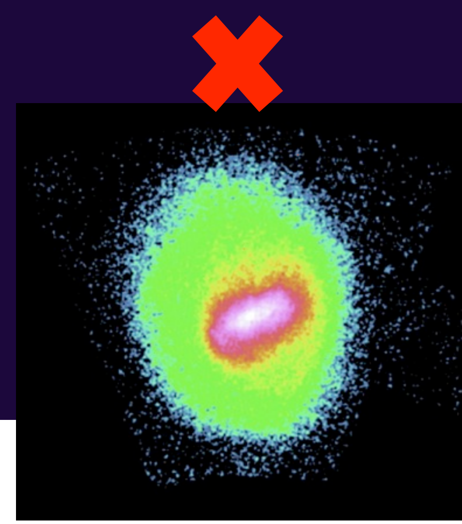


Van der Marel 2001

Outer limits survey



Deep imaging of LMC outer limits by Saha et al (2010) shows old population more than 12 degrees N of LMC!
Fits disk scale length derived by van der Marel from 2MASS giants.
Where is LMC halo?



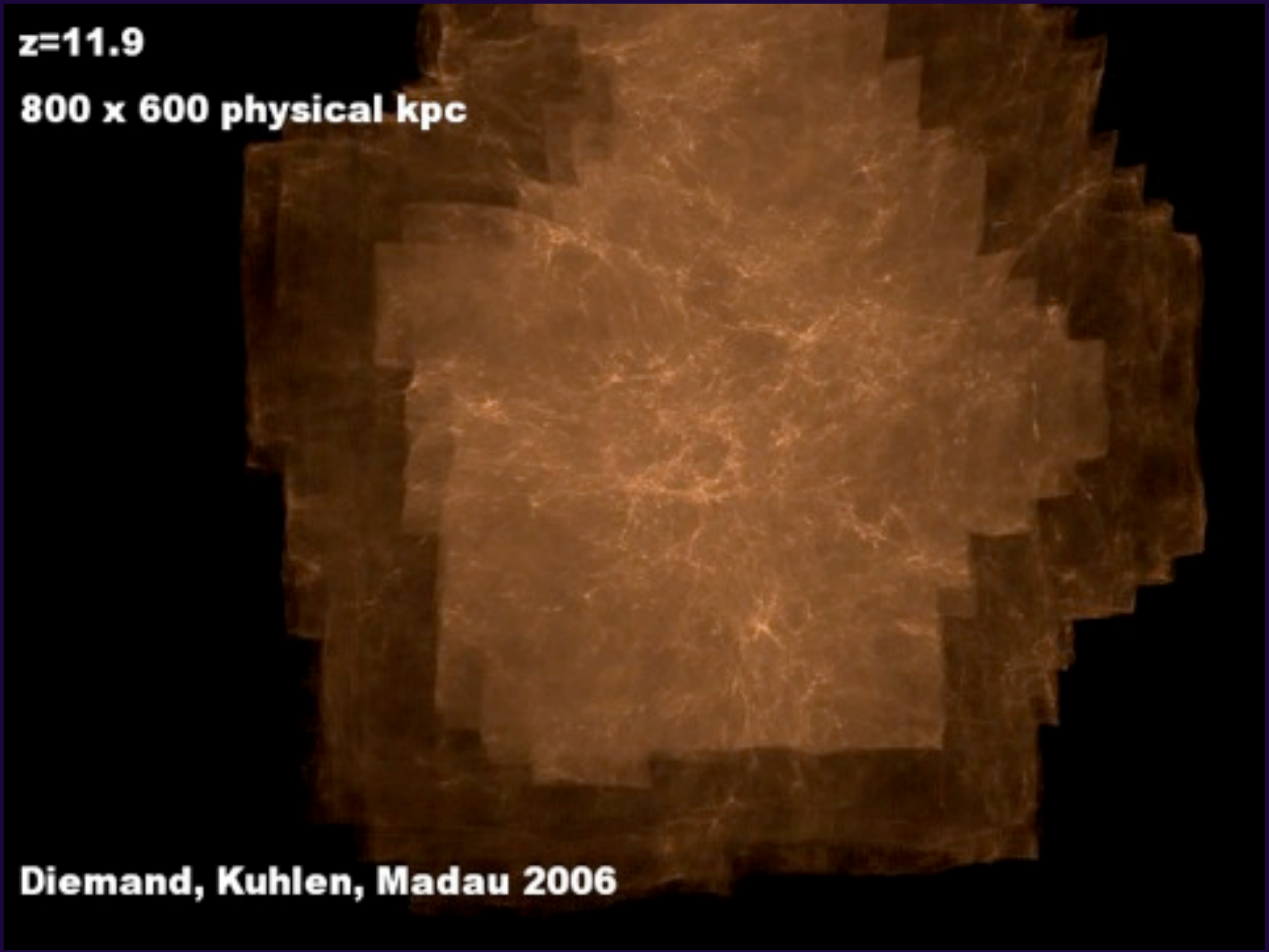
Summary 1: star streams

- We are learning how galaxies grow by accreting small satellites via detecting their remains: star streams
- Although deep surface photometry has produced some stunning images, MUCH deeper images can be made with wide field star counts
- LSST should produce remarkable results here

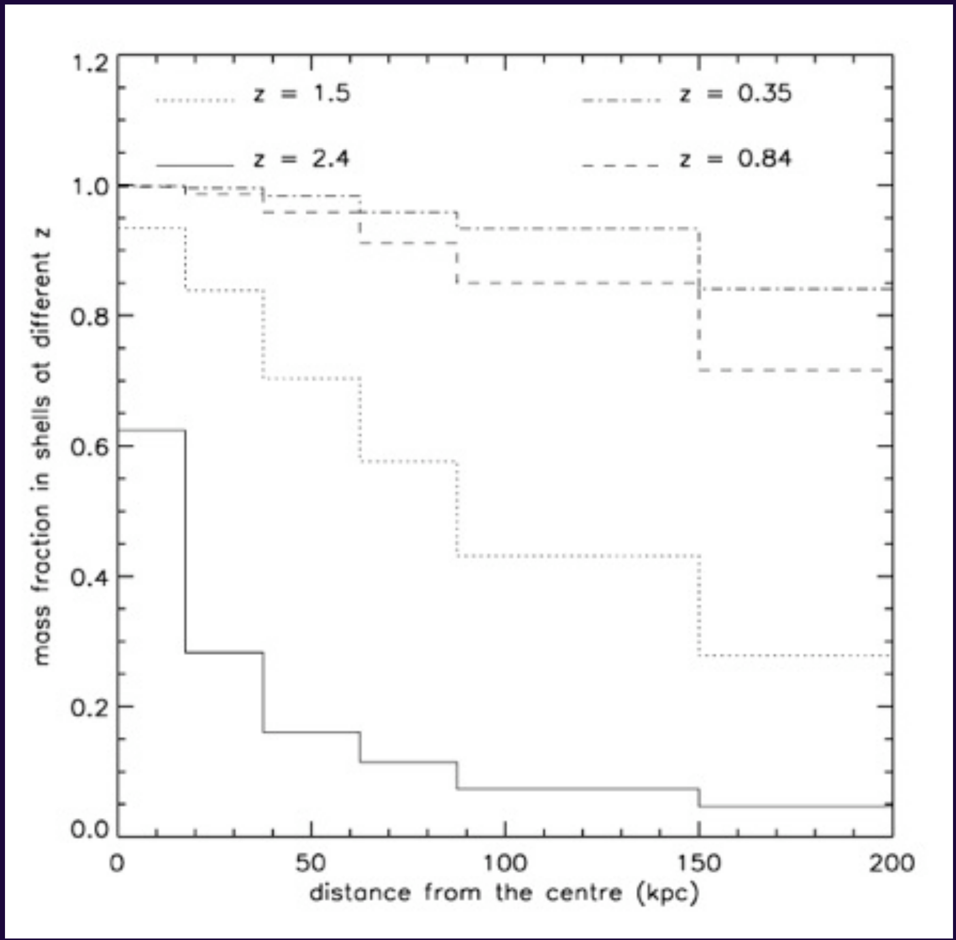
“Yet another star stream”

- Remark made by Michael Strauss, SDSS Spokeperson, in his presentation at an SDSS meeting around 2006.
- Where do you go after you have found a number of star streams?
- …… use them, and the rest of the halo, to constrain LCDM-based theories of the growth of galaxies

Growth of Milky Way dark halo



Most of inner dark halo in place very early



More than 60% of halo within 20 kpc is in place before z=2.4 (2 Gyr after Big Bang)

Outer halo takes much longer to assemble and is still growing today

(Helmi, White, Springel 2003)

What about the stars?

- Density matters: expect earliest star formation in densest regions
- Expect star formation to start more slowly and take longer in lowest density regions

=>Expect oldest stars in inner halo, younger stars in outer halo

Structure of the halo from globular clusters

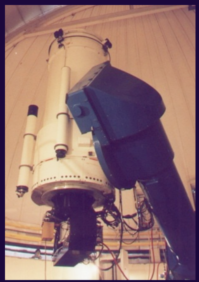
- Outer halo globular clusters have wider range of ages (Searle and Zinn 1978)
- Old Halo clusters in inner halo; Younger halo clusters in outer halo; different kinematics (Zinn 1993)

Field stars: inner vs outer halo

- Horizontal branch morphology indicates age (Lee et al 1994) --- at fixed metallicity, BHB stars will be older than RR Lyraes
- BHB stars stars more centrally concentrated than RR Lyraes (Preston et al 1991; confirmed by Kinman, Suntzeff, Kraft 1994)
- Older stars ARE more centrally concentrated, as expected from early assembly and formation of inner halo

A special local halo sample

- Halo giants (Bond 1980: Curtis Schmidt at CTIO; uvby from CTIO/KPNO .4m,.6m,.9m - used Crawford and Barnes uvby standards)
- Very accurate distances (Anthony-Twarog and Twarog 1994 from CTIO 1m,1.5m,KPNO 1.3m)
- RR Lyrae variables (Morrison et al 2009: Kinman's exquisite light curves using KPNO .9m,1.3m; Morrison velocities using KPNO 2.1m)



NOAO has a big stake in these stars!

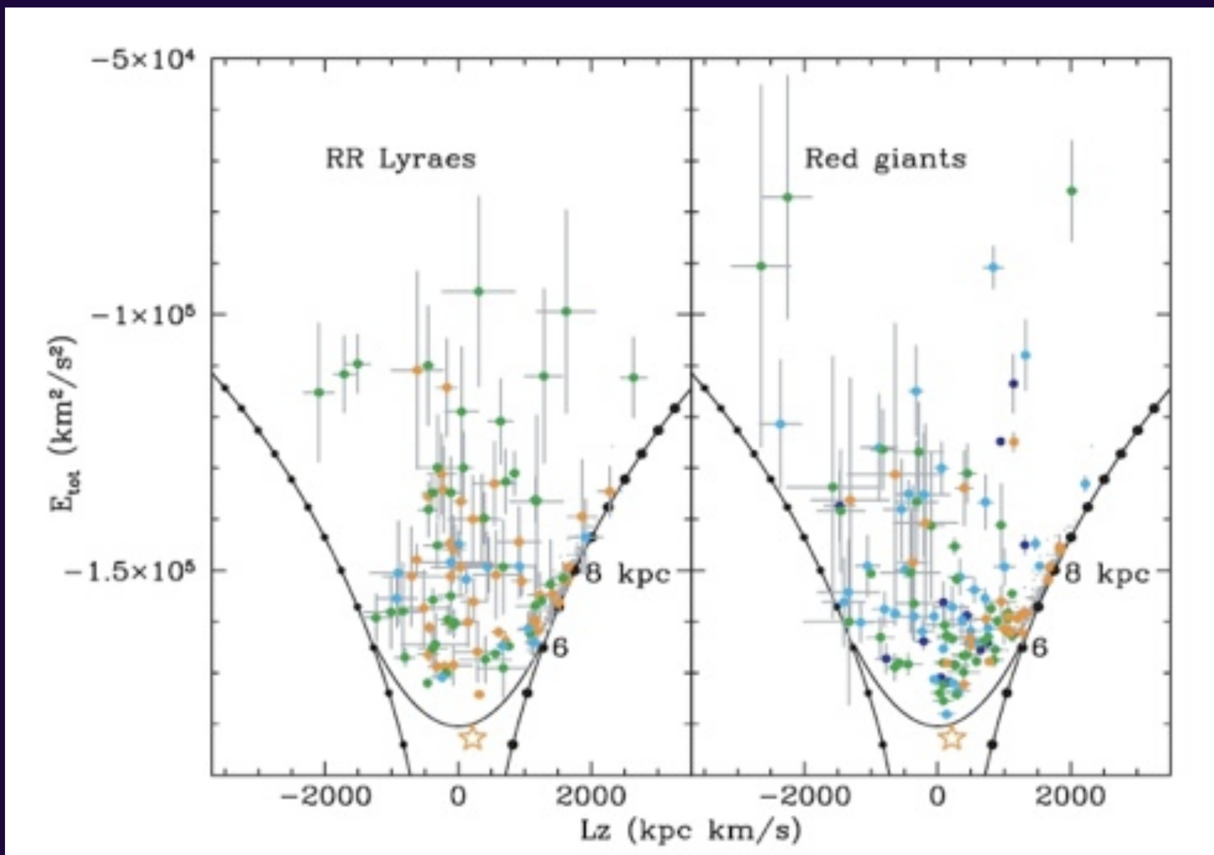
- Well-quantified, small, distance errors (a remarkable median 7% error)

- 250 stars: [Fe/H] -1.0 to -4.0
- Median distance 1 kpc

What do halo stars remember about their birth?

- While satellites can be completely disrupted spatially, properties such as orbital energy or angular momentum may not change; or change slowly; or in predictable ways
- So calculating these properties can give us insight into formation history
- Accurate distances are vital!!

Binding energy vs angular momentum Lz



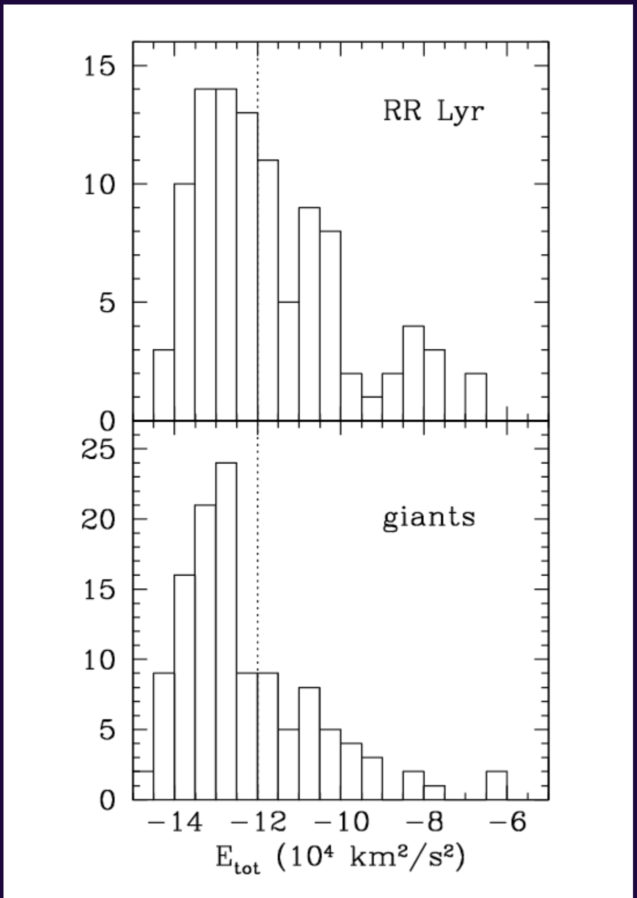
Distribution quite clumpy!

Different for RR Lyraes and giants

Morrison et al 2009

Younger RR Lyraes less tightly bound to Milky Way

- RR Lyraes less bound than giants
- Local halo HB morphology blue (Kinman et al 1994), so most giants will become BHB stars
- HB morphology <=>age
- Local confirmation from kinematics that younger halo stars are less centrally concentrated



Morrison et al 2009

Summary 2a: confirmation of LCDM predictions

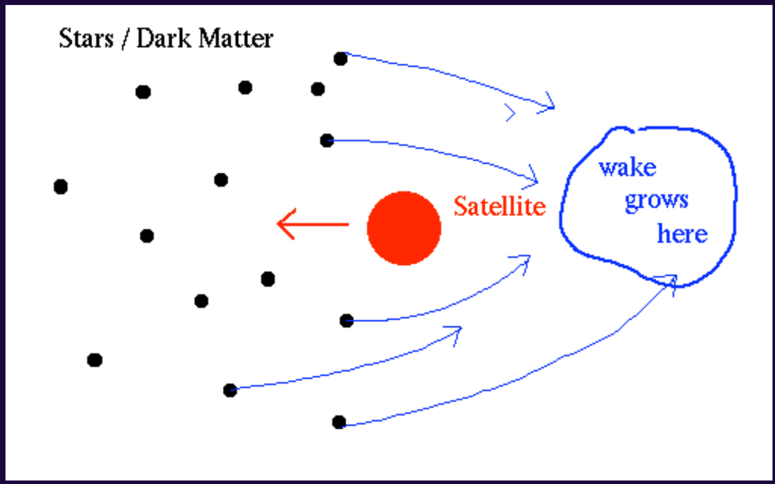
- From globular cluster horizontal-branch morphology;
- From in-situ studies of the spatial distribution of RR Lyraes and BHB field stars
- From the different binding energy distribution of a very well-studied local halo sample:
- We find confirmation of a centrally concentrated, very old inner halo and a less concentrated, somewhat younger outer halo

2b: Number of progenitors of inner halo

- Inner dark halo assembles first: what were its progenitors like?
- Although dark matter is collisionless, sub-halos can transfer energy and angular momentum via dynamical friction, and sink to center

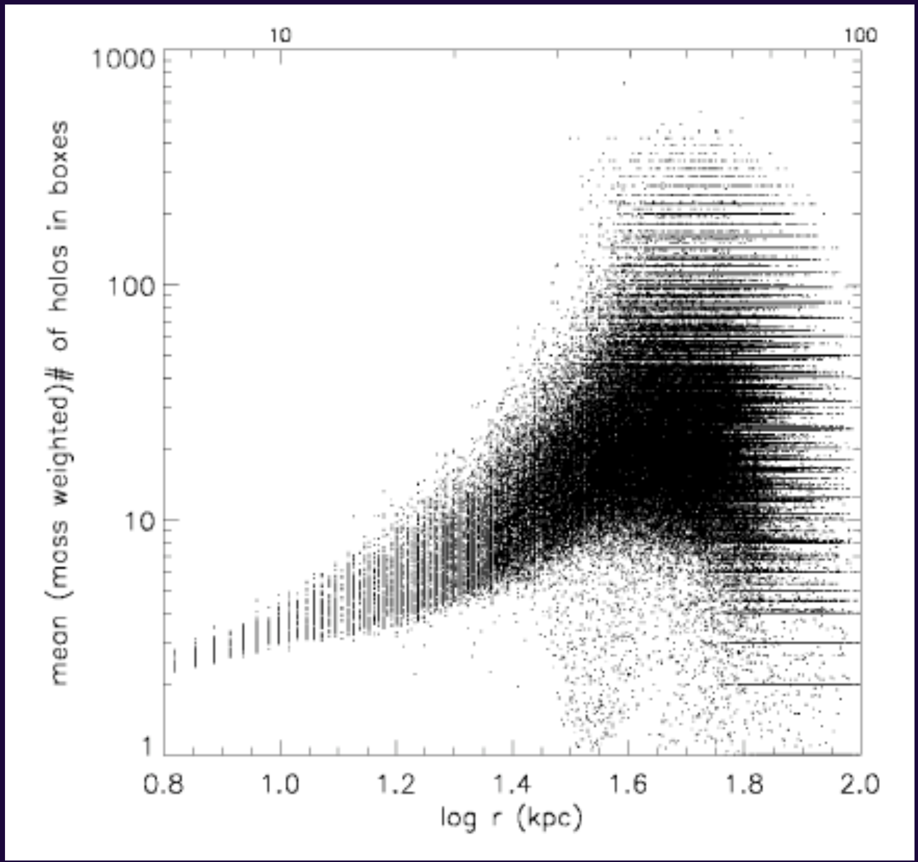
Mihos javalab: http://burro.case.edu

Dynamical friction



- As an object moves through the halo, it creates a gravitational wake which pulls backwards
- Energy, angular momentum is lost to background particles
- Dynamical friction works best for massive subhalos (which create bigger wakes)

Inner dark halo comes from a few progenitors only

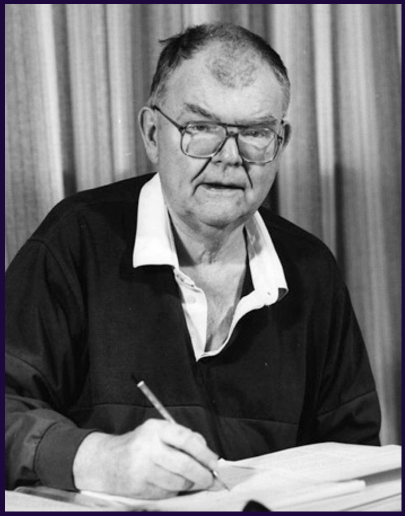


Helmi et al 2003

- Massive sub-halos are rare
- They will sink to the center of the halo via dynamical friction
- Outer halo has many different progenitors, inner halo only a few

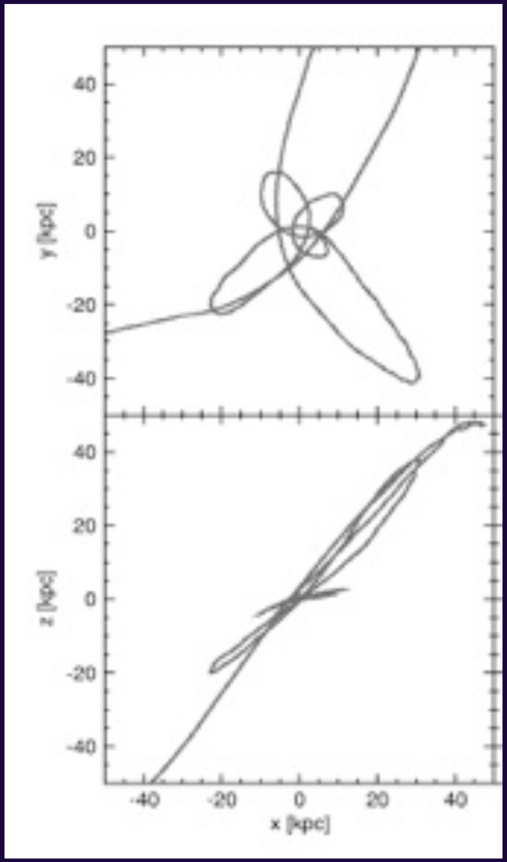
Can we see evidence in stellar orbital properties?

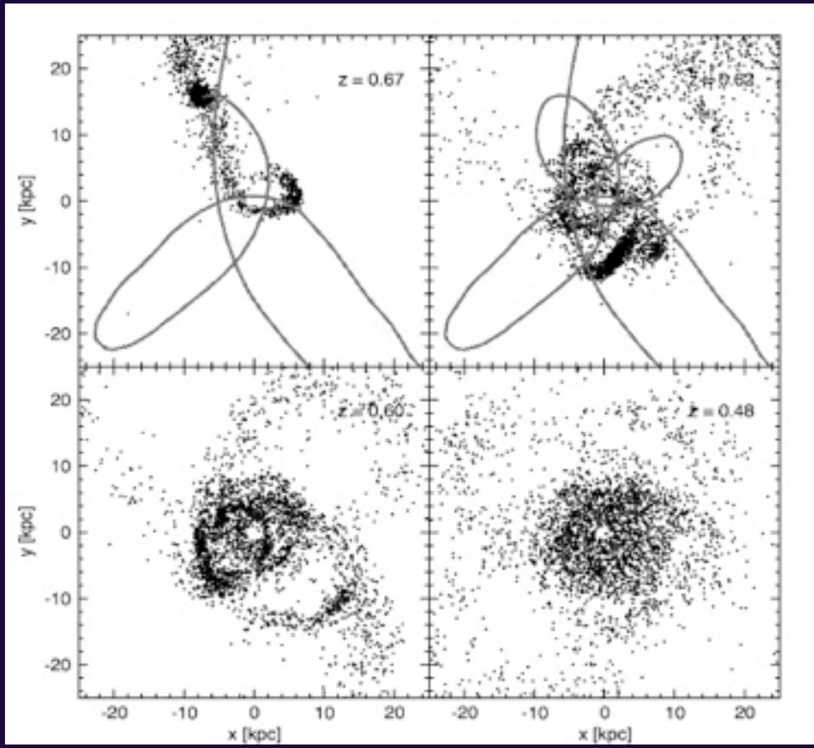
- Seminal paper on galaxy formation in 1962 by Eggen, Lynden-Bell and Sandage …. stellar halo formed by rapid, smooth collapse.
- BUT Eggen subsequently spent much of his career studying another formation scenario, “moving groups” of stars which are spatially mixed but have similar velocities.



Olin Eggen

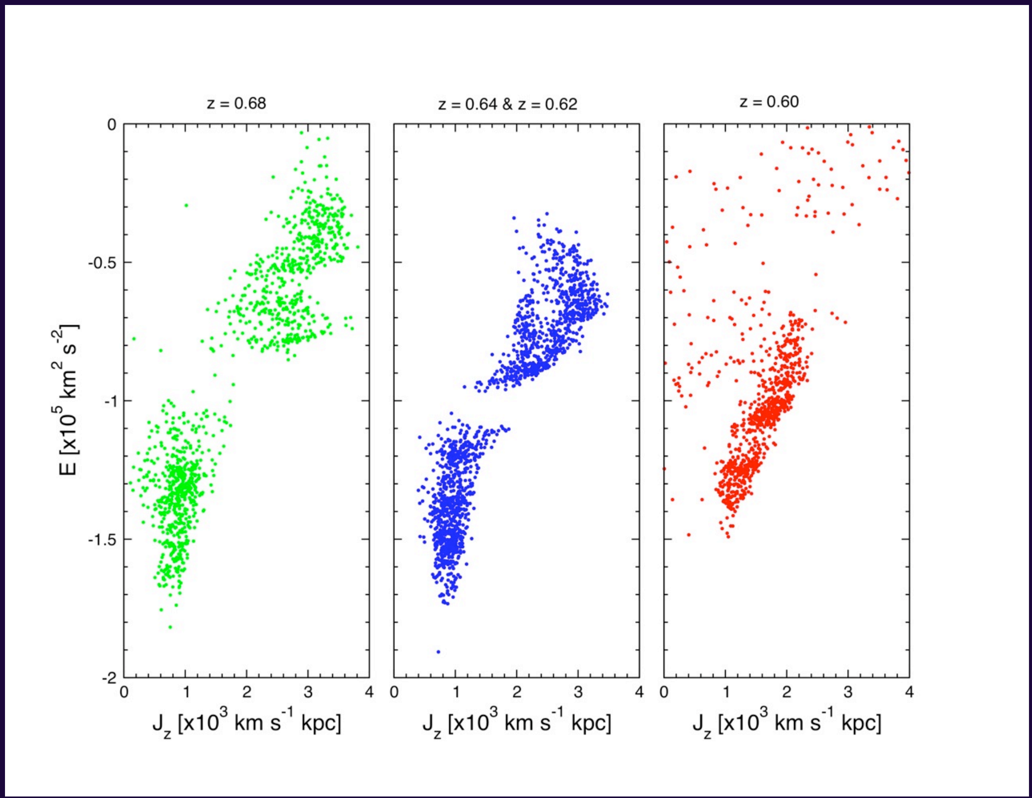
An example: model of accretion of a large satellite whose core becomes the cluster Omega Cen

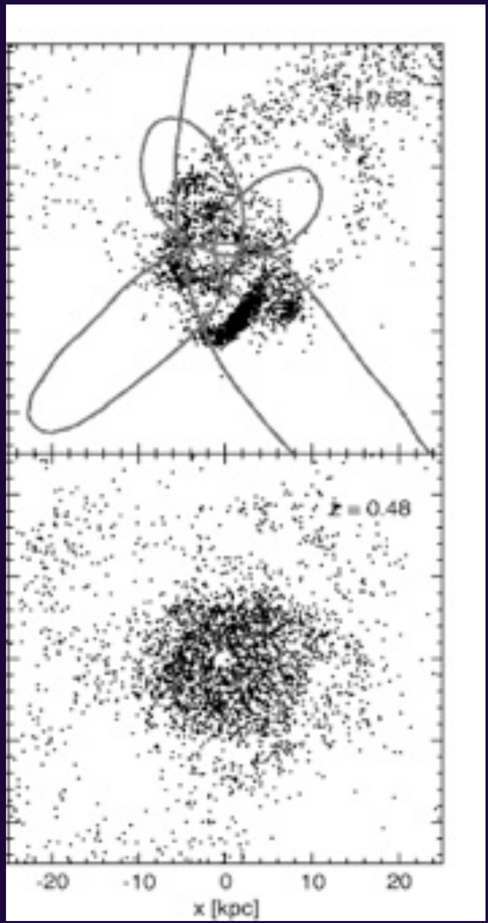




Meza et al 2005

Spatially mixed, but clumping in energy and angular momentum remains

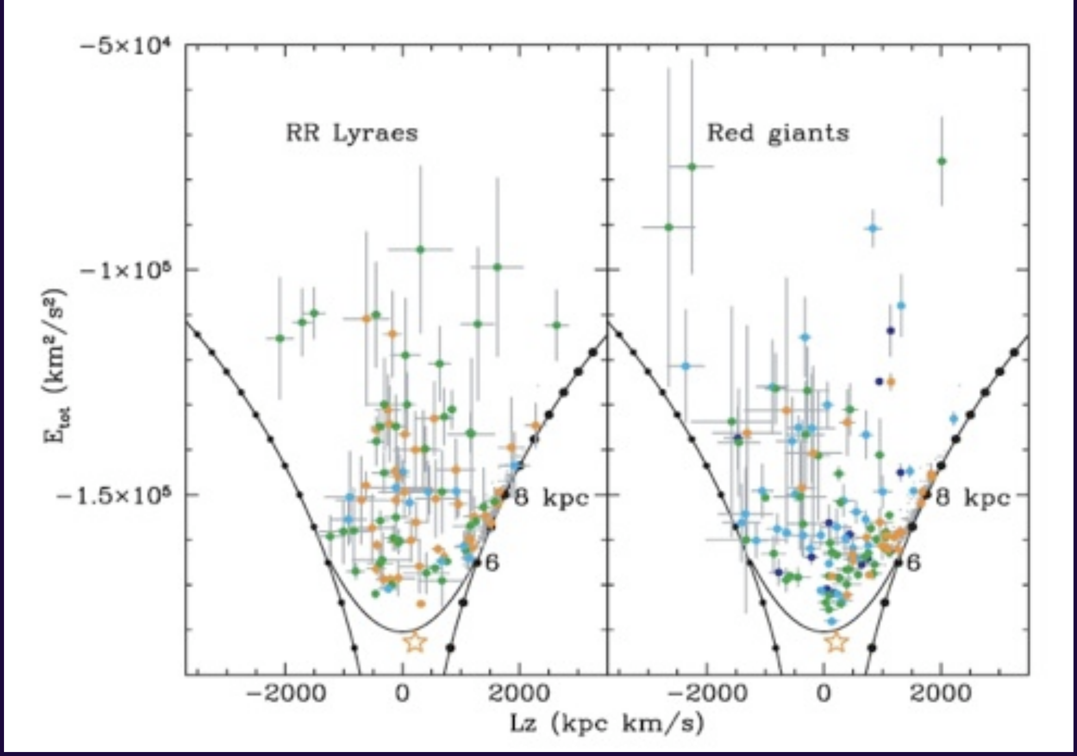




Simulation from Meza et al 2005

Energy/angular momentum diagrams

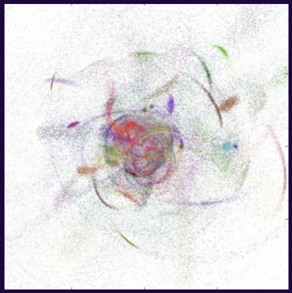
Significant structure seen
.... stars are not evenly distributed
.... traces of clumpy origins



Summary 2b: clumpy inner halo

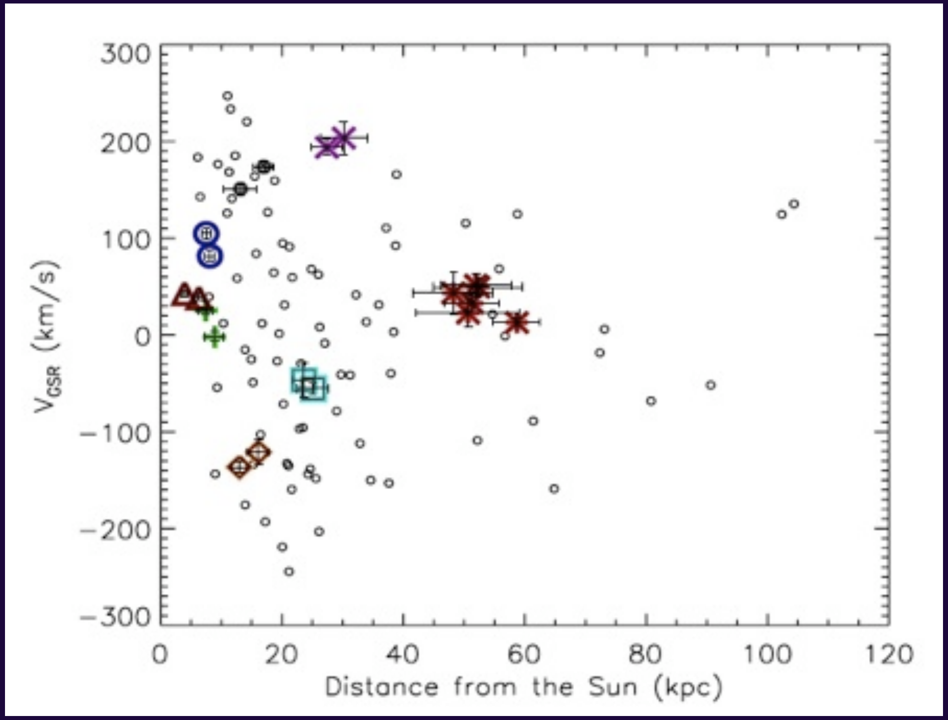
- Clumping we see in our energy/angular momentum diagram (first time!) is expected when only a few progenitors contribute most of inner halo
- We currently see no evidence of a smooth, well-mixed halo near the Sun …. despite short dynamical times in inner halo (ELS were wrong….)

3. New results on Milky Way outer halo



- Spaghetti survey …. used Washington photometric system (Geisler) for survey for halo giants with KPNO/CWRU Burrell Schmidt and BTC mosaic on CTIO 4m

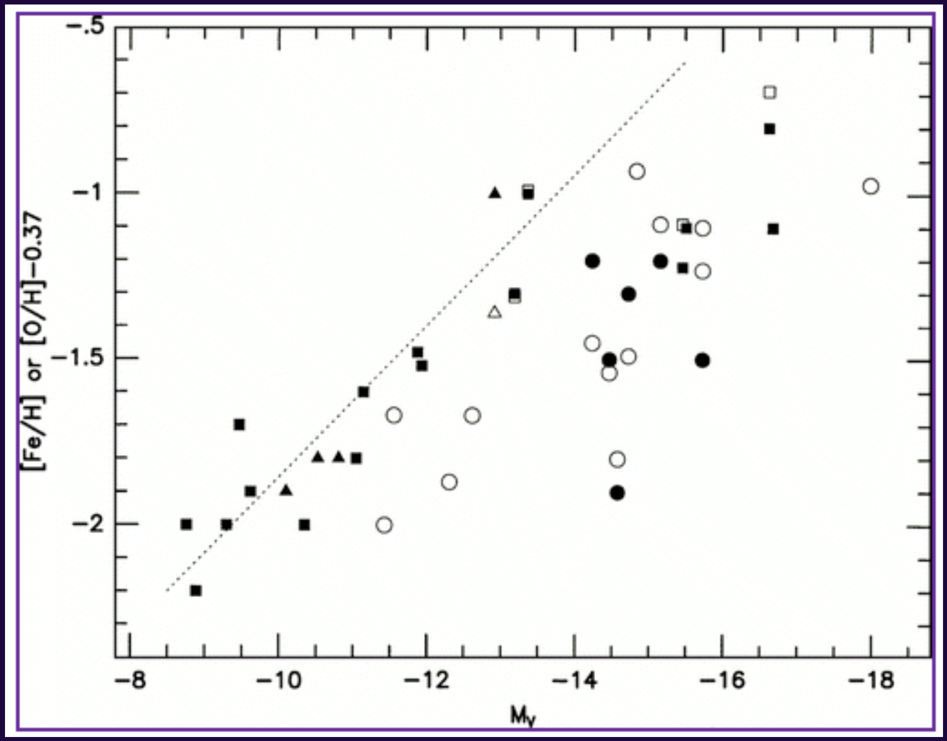
101 halo giants….



- Spectroscopic followup with KPNO and CTIO 4m (+Magellan and WHT and AAT)
- Clumping in velocity (star streams, moving groups)

Starkenburg et al 2009

What can metallicity teach us?



Mateo 1998 – Local group dwarfs

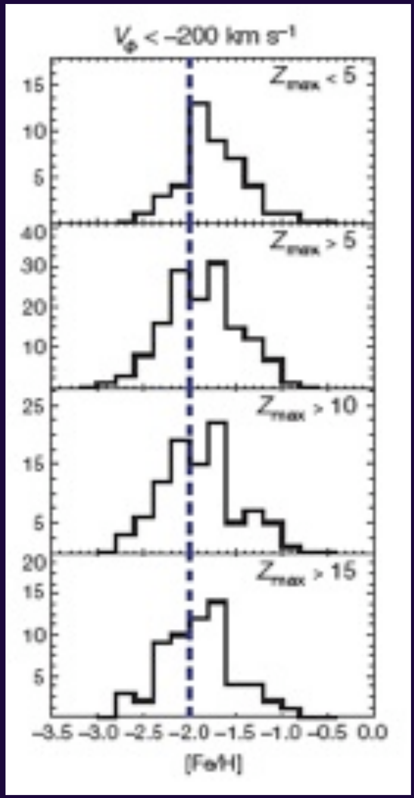
Low luminosity (mass) satellites tend to have low metallicity.

So [Fe/H] in halo can give information on mass of progenitors

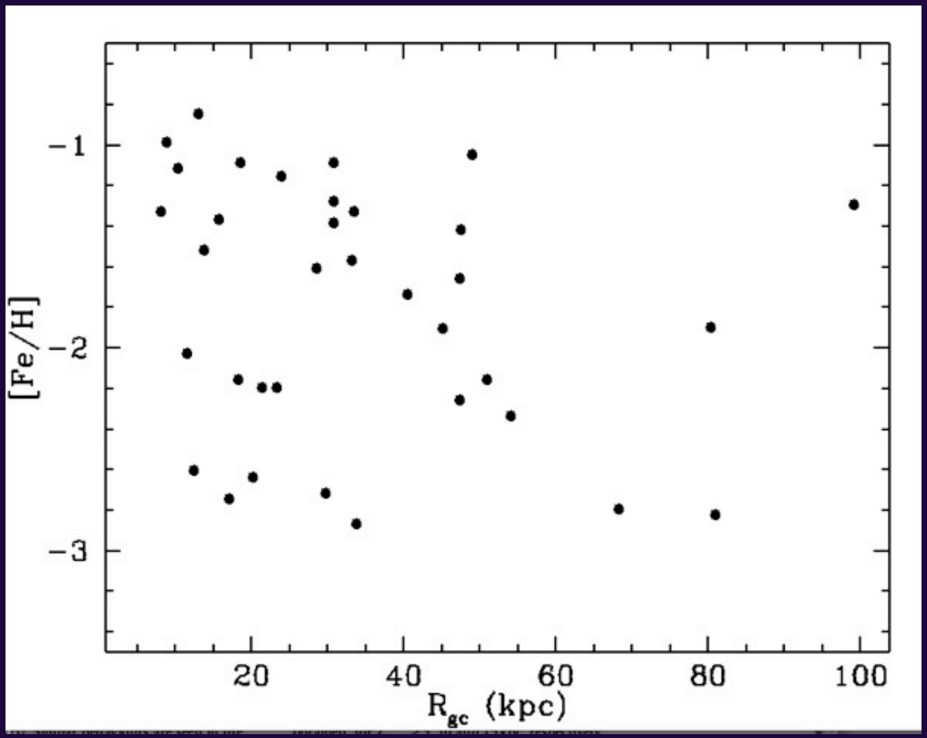
Metallicity distribution in outer halo

- Zinn (1993) finds a metallicity gradient in old halo clusters

- Carollo et al (2007) infer a similar gradient in halo field stars using a large local sample from SDSS/SEGUE. But not all halo orbits will reach solar neighborhood (eg Sgr streams)



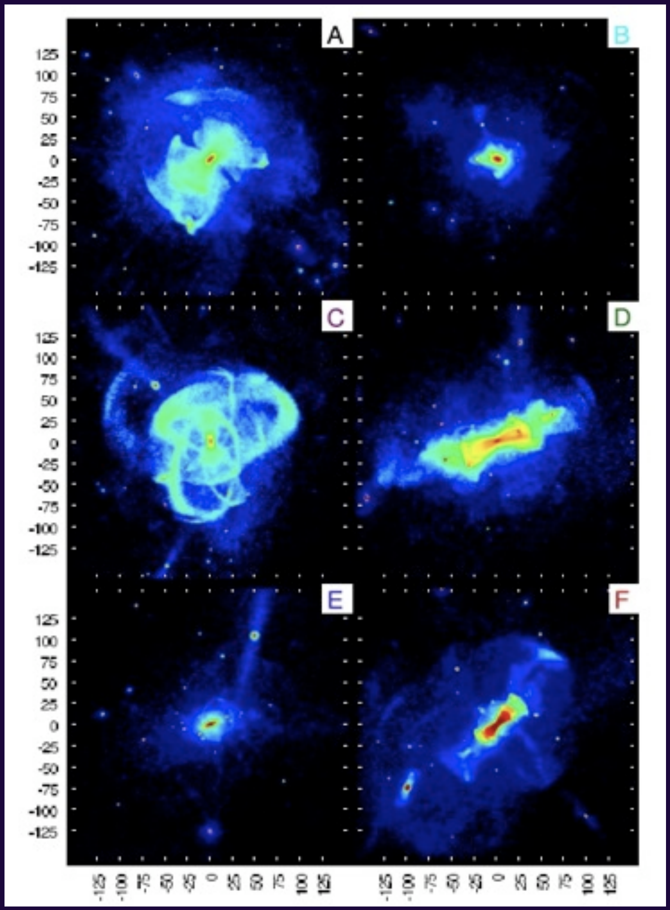
Spaghetti giant [Fe/H] distribution

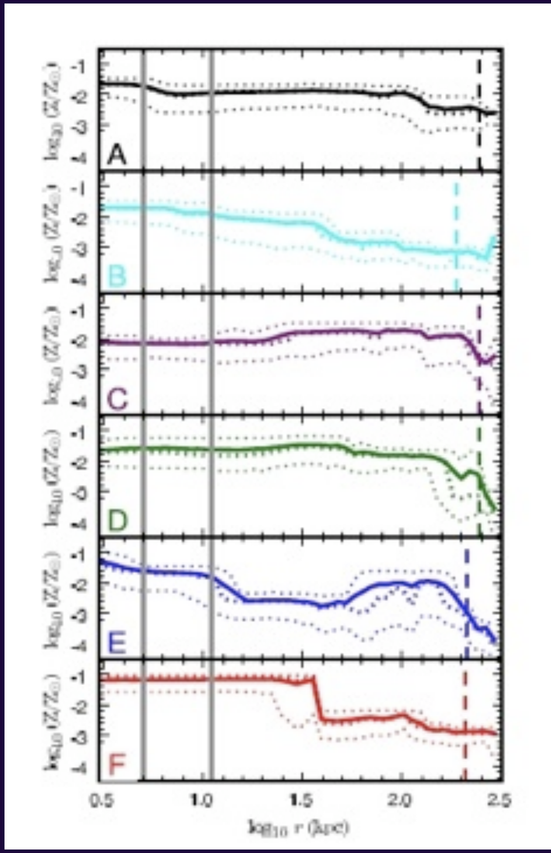


Small sample, but no strong trend with distance from galactic center….

Extrapolations from local samples dangerous…. Outer halo quite complex

Aquarius simulates 6 halos: rich variety of metallicity gradients





Cooper et al 2009

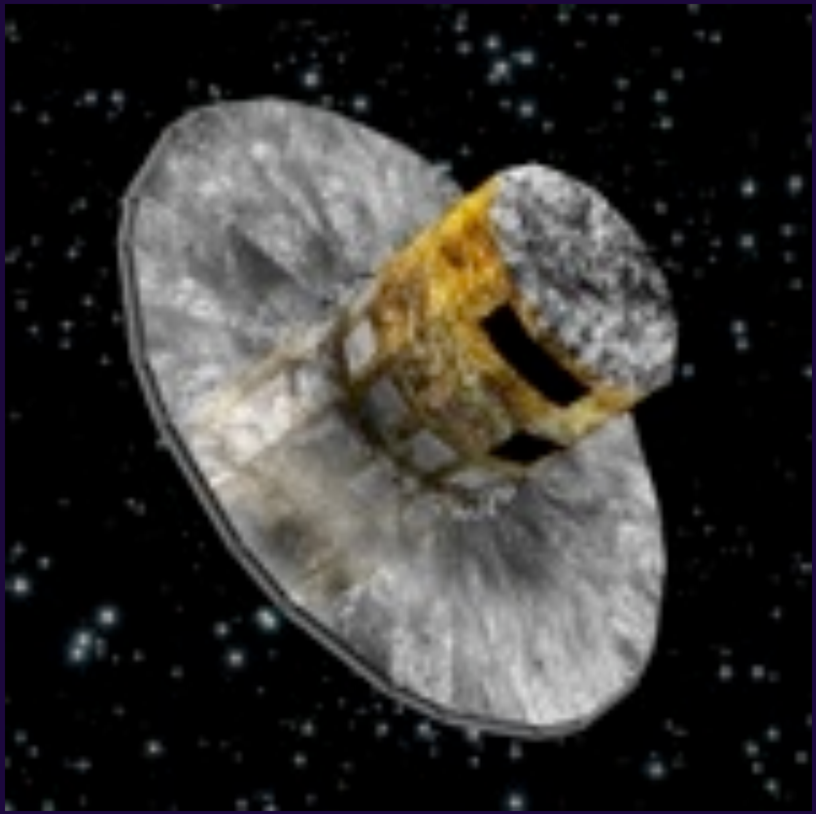
3. Outer halo summary

- Metallicities can help constrain the properties of the progenitors of the Milky Way halo
- Clusters and extrapolation from orbits of nearby halo stars show expected gradient: more massive progenitors make metal-richer stars
- New in-situ data show some quite metal-rich stars in the outer halo – pointing out the diversity of accretion origins of outer halo

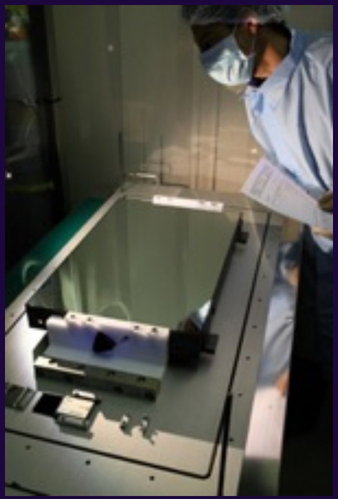
The future: GAIA

GAIA will provide parallax distances accurate to 10% out to 10 kpc for halo stars ….. Will enable accurate orbital properties to be calculated for enormous sample of halo stars

GAIA launch August 2012



Torus now assembled; 3 of 10 mirrors delivered



However ……

- Although GAIA will give proper motion measurements for stars all through the halo, it will only deliver velocity measurements for stars brighter than V=16 - 17.
- There is a real need for velocity measurements for large numbers of stars to allow accurate 3D velocities to be computed further into the halo

The future: LAMOST

Telescope is currently being commissioned: ~4m aperture, 20 square degree field, 4000 fibers, galactic survey (LEGUE) planned, not so vulnerable to poor site at Xinglong observatory ….. good complement to GAIA for velocities

The Ground-Based Stage IV BAO Experiment

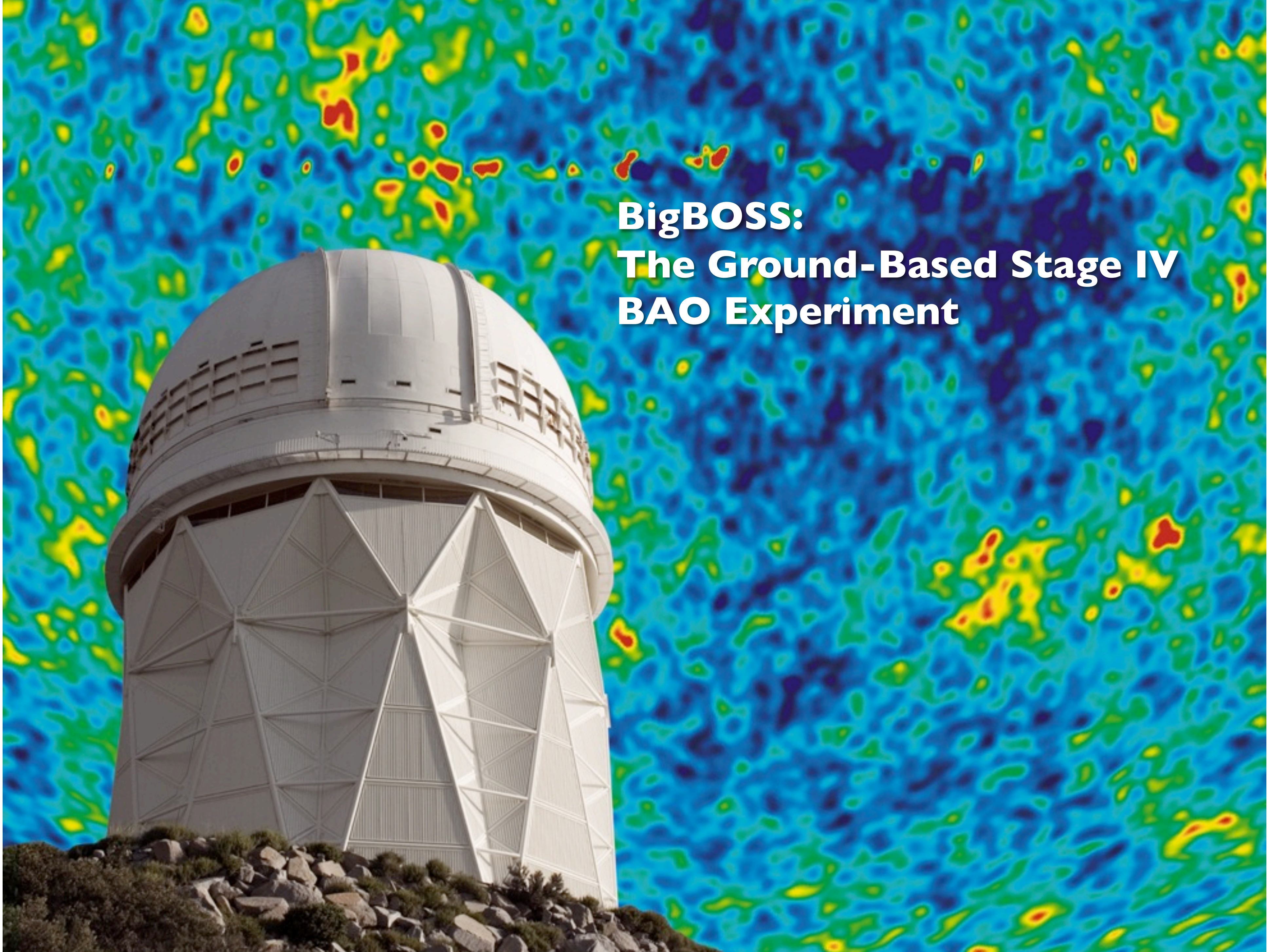
BigBOSS

NOAO > KPNO Home

Announcement of Opportunity for Large Science Programs Providing New Observing Capabilities for the Mayall 4m Telescope on Kitt Peak

NOAO announces an opportunity to partner with NOAO and the National Science Foundation to pursue a large science program with the Mayall 4-meter telescope on Kitt Peak and to develop a major observing capability (instrument, software, and archival plans) for the Mayall 4-meter telescope of the Kitt Peak National Observatory for the purpose of enabling large, high impact science programs and improving the capabilities provided as part of the U.S. System of ground-based optical and near-IR telescopes. Projects that use a diverse range of observing requirements (e.g. time of year, lunar phase, etc.) are encouraged. The dual goals of the large science program, as discussed in a recent edition of NOAO Currents are to enable frontier science and to improve the U.S. system of ground-based ØIR facilities. Although there are no restrictions on the type or scale of instrument, NOAO encourages proposals that will build on the Mayall telescope's strengths, utilizing its unique wide-field capabilities. NOAO has investigated potential wide-field options at both the Cassegrain and Prime foci, and these designs are available to aid those planning proposals.

BigBOSS: The Ground-Based Stage IV BAO Experiment

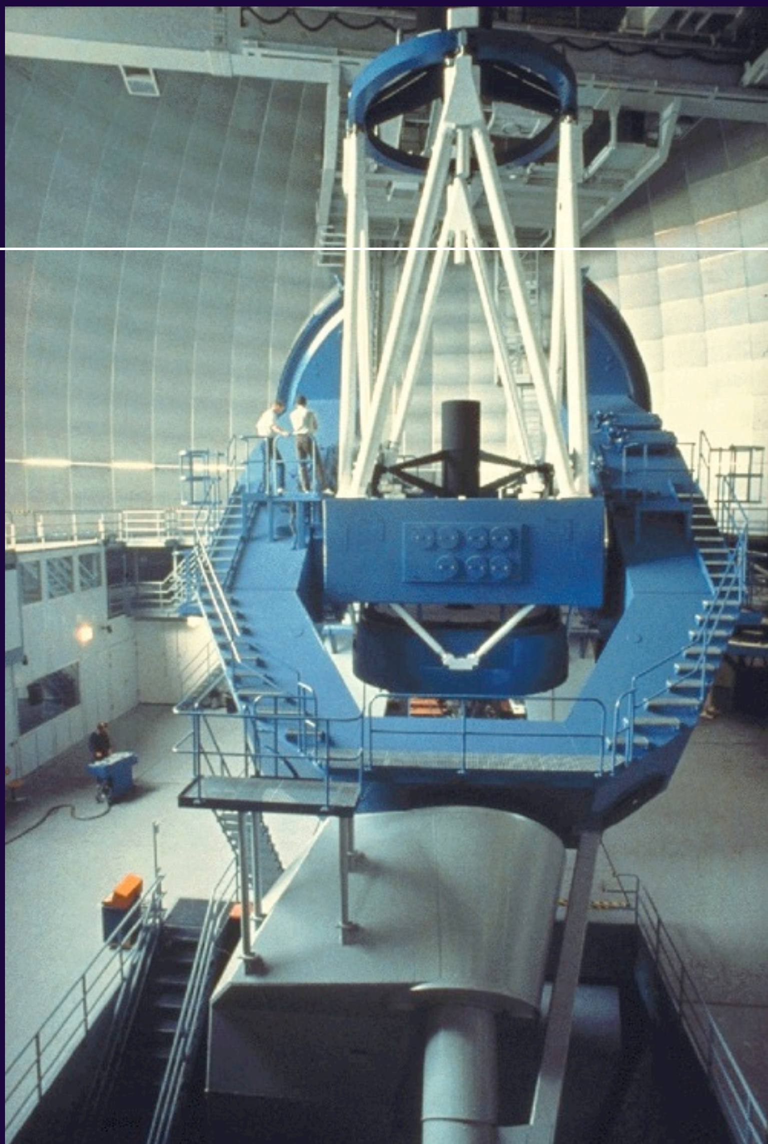


From David Schlegel

http://bigboss.lbl.gov

The Ground-Based Stage IV BAO Experiment

BigBOSS



Which 4m-class telescopes could have 3-deg multi-object system?

KPNO 4-m
CTIO 4-m
CFHT 3.6-m
Calar Alto 3.5-m
ARC 3.5-m (Apache Point)
WIYN 3.5-m (Kitt Peak)
Discovery Channel 4.2-m
WHT 4.2-m
ESO 3.6-m
SOAR 4.2-m
UKIRT 3.8-m
Galileo 3.58-m
ESO NNT 3.58-m
VISTA 4-m
AAT 3.9-m

3-deg possible (KPNO 4-m, CTIO 4-m, Calar Alto 3.5-m)

2-deg exists (AAT 3.9-m)

From David Schlegel

http://bigboss.lbl.gov

The Ground-Based Stage IV BAO Experiment
BigBOSS

Kitt Peak 4-m (Mayall)

1.5-m f/5 secondary enables 3° FOV

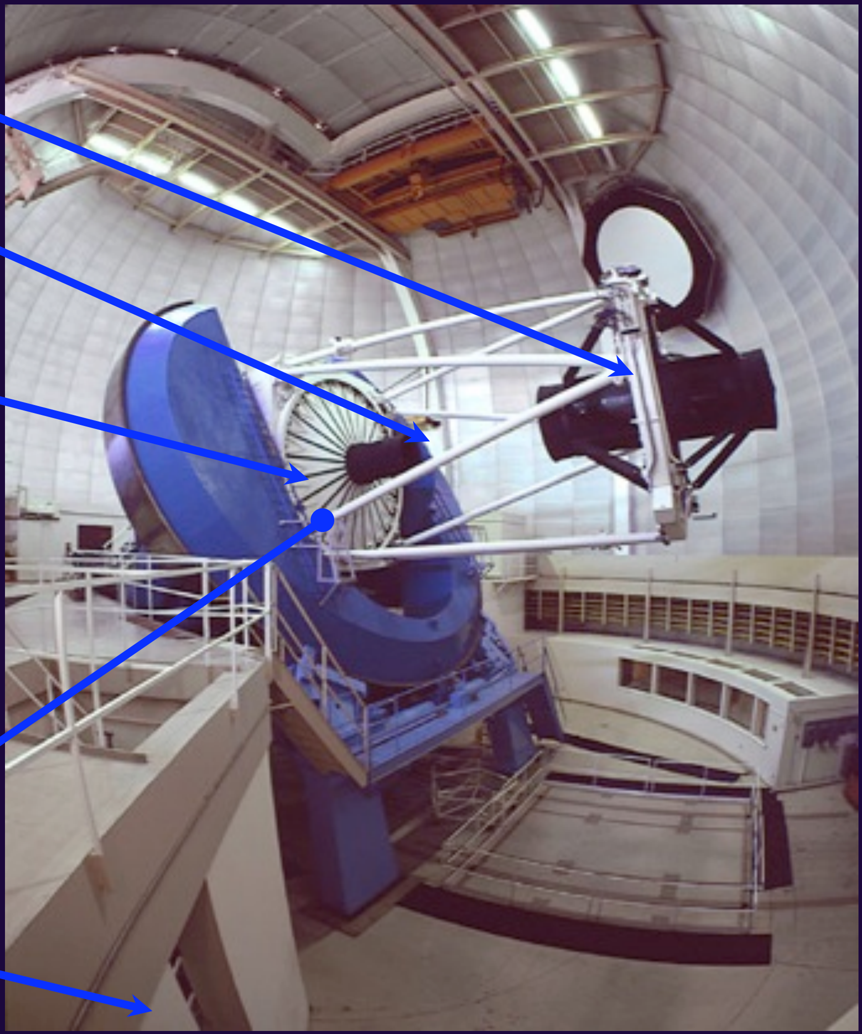
3-element corrector

5000 fiber positioners on 99-cm focal plane

SDSS-inspired: simple, high-throughput

Fiber run (bare fibers)

10 spectrographs



From David Schlegel

http://bigboss.lbl.gov

The future: BigBOSS

- BigBOSS on KPNO 4m has potential for several exciting galactic structure programs:
- a spatially complete survey for outer halo giants (for the first time: SEGUE and spaghetti were pencil beams)
- Radial velocities for large number of stars to complement GAIA’s rich picture of inner Galaxy

Summary

- The NOAO telescopes;
- The remarkable astronomers who use them;
- Have taught us (and will continue to teach us) about the formation of our Galaxy, and how it is shaped by the properties of the Universe