Searching for IMBH in Local Volume Globular clusters and Nuclei

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Importance To Astronomy

Two types of black holes are known:

1. Stellar Mass black holes - formed in SNe, ~10Msun

2. Supermassive black holes – in bulges, AGN ~10^6 – 10^9 Msun

The discovery of supermassive black holes in a ``simple’’ stellar population (globular clusters may give insight into their formation.

TMT Science Case for IMBH:

6.2.3 Intermediate-mass black holes

Intermediate-mass black holes (IMBHs), with masses between 10^2 and 10^6 $M_\odot$, are a missing link between stellar-mass BHs and SMBHs. Determining the demographics of IMBHs in nearby, low-mass galaxies is of great importance since these objects are much closer to the mass scale of their original "seeds", unlike high-mass SMBHs which have essentially lost any physical "memory" of their original seed masses and environments. Theoretical models suggest that the occupation fraction and M_{BH}-σ relation of IMBHs may contain unique clues to the distribution of BH seed masses and the efficiency of their formation (Volonteri et al. 2008). IMBHs are also of great interest as sources of gravitational waves, either from binary BH mergers or from extreme mass-ratio inspiral events (in which a stellar-mass compact object inspirals into a low-mass nuclear BH). The probable hosts of these intermediate-mass objects are globular and other massive star clusters, and the nuclei of late-type bulgeless spirals and dwarf galaxies.

Some dynamical evidence has been reported for the existence of intermediate-mass black holes in globular clusters such as G1 (Gebhardt, Rich & Ho 2005). However, the existence of intermediate-mass black holes is still controversial partly due to the insufficient spatial resolution and sensitivity of current telescopes. Some late-type galaxies, even those that are completely bulgeless, host a central black hole with a mass as low as $M_{BH} = 10^5\ M_\odot$ (Filippenko & Ho 2003; Greene & Ho 2007), but all such estimates are based on secondary methods of mass determination that rely on AGN broad emission lines. At the same time, HST stellar-dynamical observations have been used to set an astonishingly-tight upper limit of 1500 $M_\odot$ to the mass of any BH in the nucleus of the Local Group Spiral M33 (Gebhardt et al. 2001). This observation provides the best demonstration that not all galaxies contain a central BH, but the occupation fraction of BHs as a function of galaxy mass remains almost entirely unconstrained by available data for late-type and dwarf galaxies. There is tantalizing evidence for IMBHs in a small number of low-mass dwarf galaxies from X-ray observations (such as the dwarf galaxy Henize 2-10; Reines et al. 2011), but the critical confirmation via spatially resolved dynamics is still lacking. At present, direct dynamical searches for IMBHs are restricted to the Local Group and its closest neighbors.

Nuclear star clusters in dwarf and late-type galaxies are the likely homes of IMBHs (if they indeed exist), and will be high-priority targets for IMBH searches in the TMT era. These clusters typically have stellar velocity dispersions of 15-30 km s^{-1}, and the need for simultaneously high angular resolution and high spectral resolution to resolve the kinematic structure of these objects is the primary factor limiting observational progress at present. The proposed high spectral resolution mode for IRIS ($R \sim$ 8,000-10,000) will be critically important for carrying out IMBH searches in nearby low-mass galaxies, and it will be a uniquely powerful capability for TMT. At a resolving power of R=8000, it becomes possible for IRIS to deliver accurate measurements of mean velocity, velocity dispersion, and higher-order moments of the line-of-sight velocity profile in individual spaxels for observations of central star clusters in galactic centers (Do et al. 2014) and for objects such as the M31 globular cluster G1. Other targets for IMBH searches with TMT will include ultra-compact dwarf galaxies (UCDs) in nearby groups and clusters; these objects may be the remnant nuclear clusters of tidally stripped low-mass galaxies and could host BHs in the range 10^5-$10^7\ M_\odot$ (Mieske et al. 2013). IRIS data will revolutionize the search for IMBHs, making it possible to detect IMBHs or set highly constraining limits for targets out to several Mpc distance.

Overview for TMT science

Other than M31-G1, there are no undisputed candidates for IMBH in globular clusters

Searches for IMBH in Milky Way clusters have been done using existing IFUs (e.g. Lanzoni, Ferraro, COSMIC-LAB) but no convincing detections

IMBH of ~10^5 Msun found in an ultracompact Dwarf (Seth et al. 2015)

Connection between internal population/composition complexity in globular clusters, Galactic nuclei, IMBH ?

IMBH in Milky Way GC searches likely to be settled by TMT first light. IRIS FOV likely too small for this project One hope: mosaic GC cores and use main sequence turnoff stars to map the velocity field (IRIS)

TMT Science

Extragalactic searches using WFOS possible (R~8000)

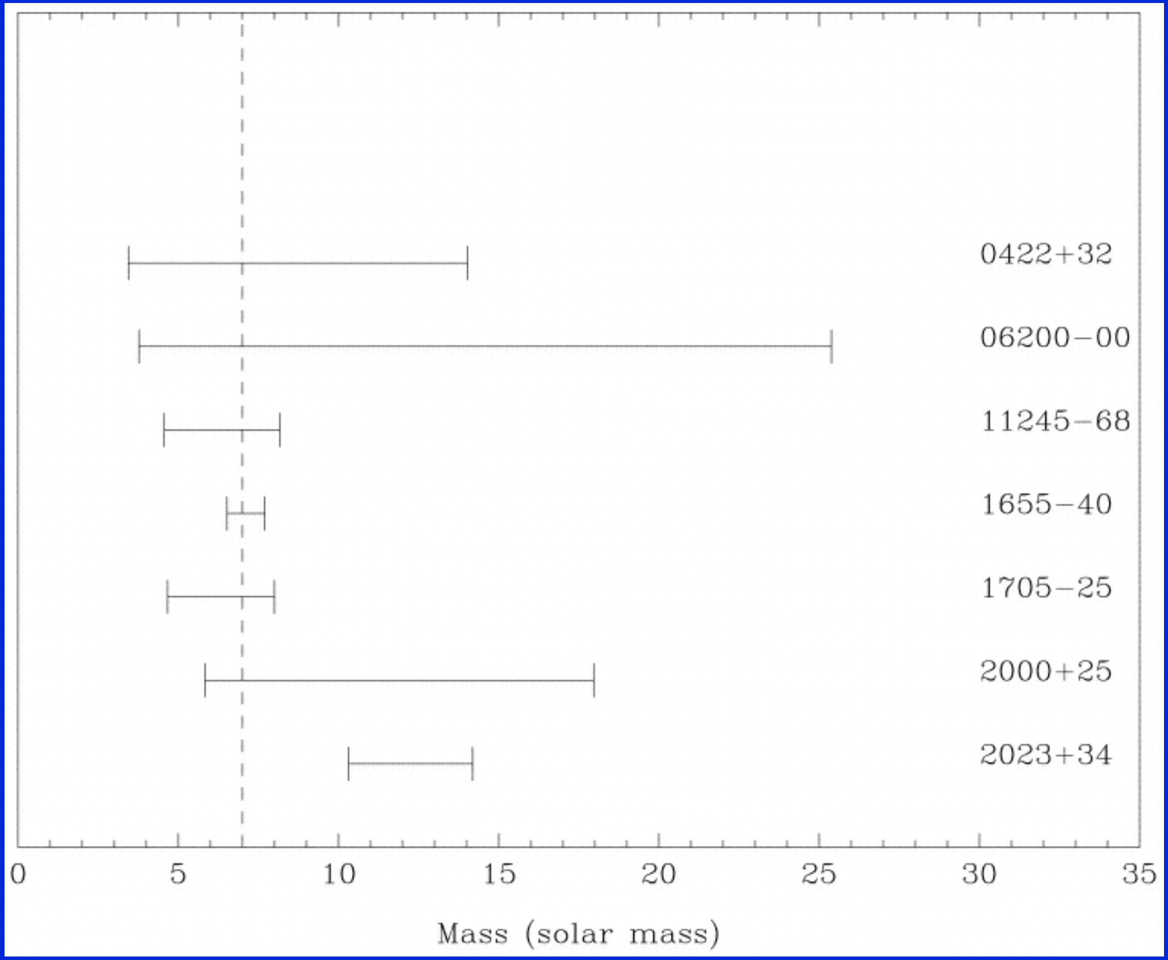
“Zoom in” on promising candidates with IRIS

IRMS for long slit (need to map the orbital asymmetry)

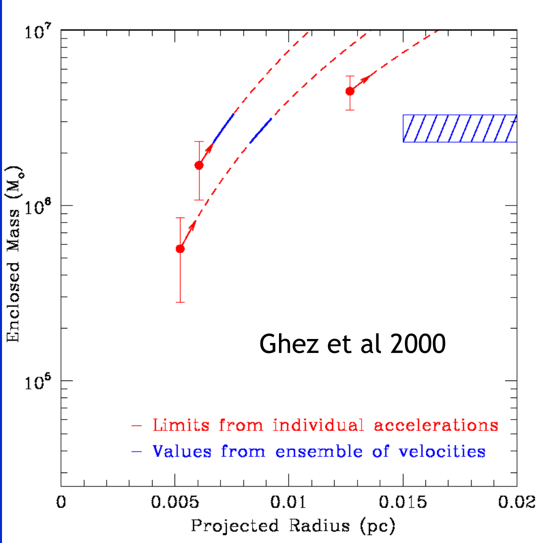
Abundances, kinematics of stars in M31, M32, M33, NGC 205
Color-magnitude diagrams of these nuclei using IRIS

Do the nuclei have same internal abundance spreads as complex GC (see talk by Pilachowski)

Stellar-mass black holes well measured from binary orbits (Bailyn et al. 1998) gives compilation below



Strong evidence for the reality of supermassive black holes



Galactic Center: Ghez et al. 2000
Eckart et al. 2002

X-ray variability: Baganaoff et al. 2001

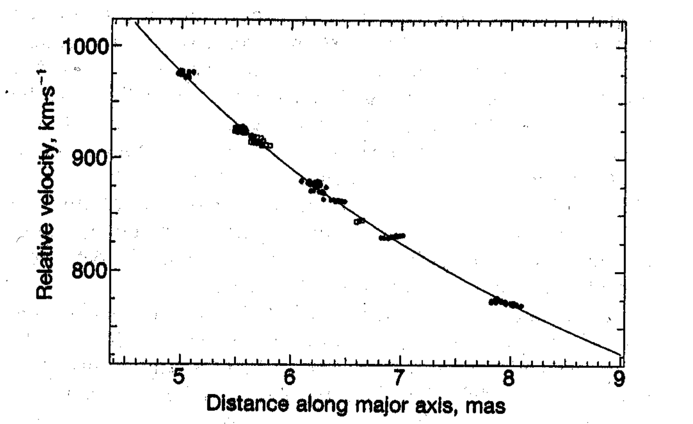


FIG. 2. Keplerian rotation curve displayed by high-velocity maser features. Velocities and radii are with respect to the systemic velocity of the galaxy (476 $km \cdot s^{-1}$ Local Standard of Rest) and position of the central massive object, respectively. The magnitude of the velocities is shown so that the redshifted (●) and blueshifted (□) emission are overlaid. The velocity range of the emission has been roughly the same as shown here since its discovery.

Keplerian orbit of OH masers in NGC 4258: Miyoshi et al. 1995

.. But note cautionary concern of Maoz (1998)

Black Holes in Globular Clusters: A Brief History I.

- X-rays detected from globulars, in particular M15 (Giaconni et al. 1974
- King (1975) notes high central surf. Brightnesss M15
- Accretion and X-ray flux of black holes in GC: Bahcall & Ostriker, 1975, Nature 256, 23
- Stellar distribution due to BH: Bahcall & Wolf 1976, ApJ 209, 214
- Identification of the X-ray sources with LMXBs quiets the subject
- HST imagery (as early as Bahcall projects) finds no clear evidence.

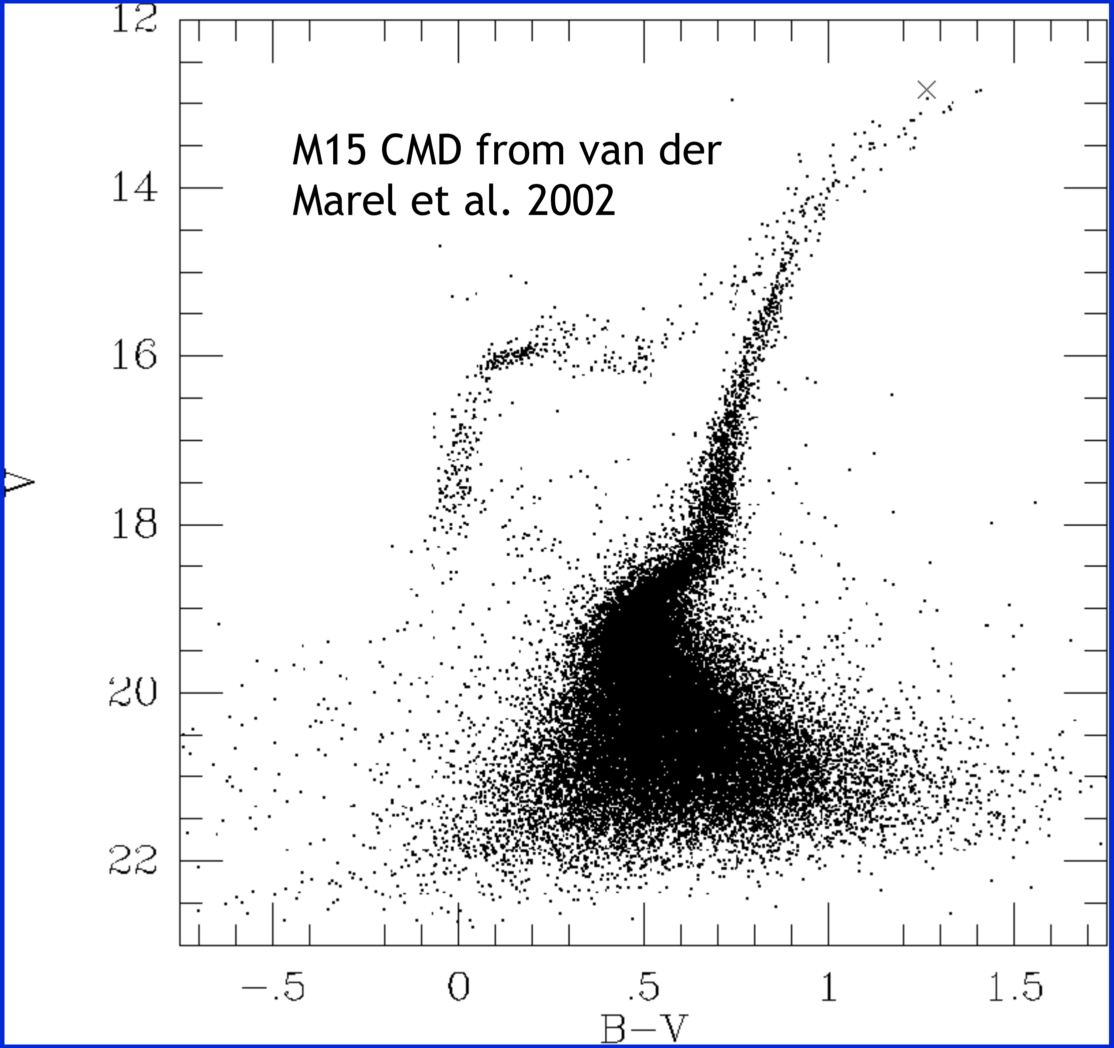
- Lee & Goodman (1989) show that BH would increase v/sigma
- M15 spect. Search by Peterson, Seitzer, Cudworth 1989 ApJ 347, 251
- Sosin & King 1997 show profile M15 neither Bahcall-Wolf nor Post core-collapse.
- Kulkarni, Hut, McMillan 1993 argue that population of 10Msun remnant BH cannot grow into supermassive BH (hard binaries eject)
- Phinney (1993) uses pulsar timing to estimate central mass

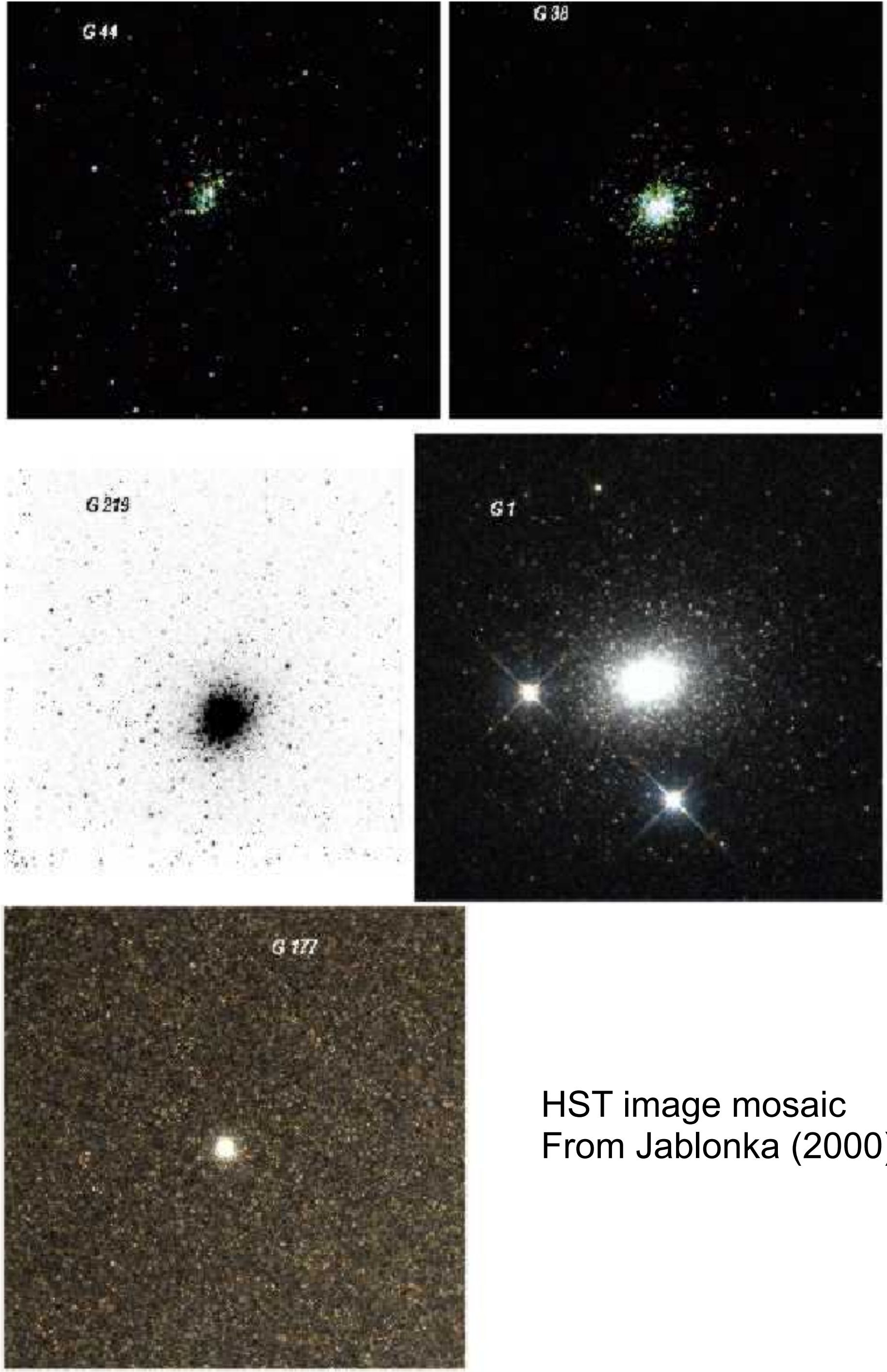
Modeling approach we use was first applied to case of M87 by Sargent et al. 1978, ApJ 221, 731

Black Holes in Globular Clusters:
A Brief History II.

- M15 IMBH claim withdrawn after uncertainty
- ω Cen very promising; Gebhardt; Noyola spectroscopy
- Anderson claims no PM support
- Lutzgendorf, Lanzoni recent work Feldmeier + 2013 claim IMBH of 2+/-1000 Msun IMBH in NGC 5286
- Wrobel has coadded both MW and exgal GCs using VLA (flat spectrum search) – nothing.
- Strader has stellar mass BH in binaries but no IMBH

While there are good reasons to believe that bulges are old (Ortolani et al. 1995; Zoccali et al. 2002) Globular clusters are simple stellar populations with a well defined age and abundance.





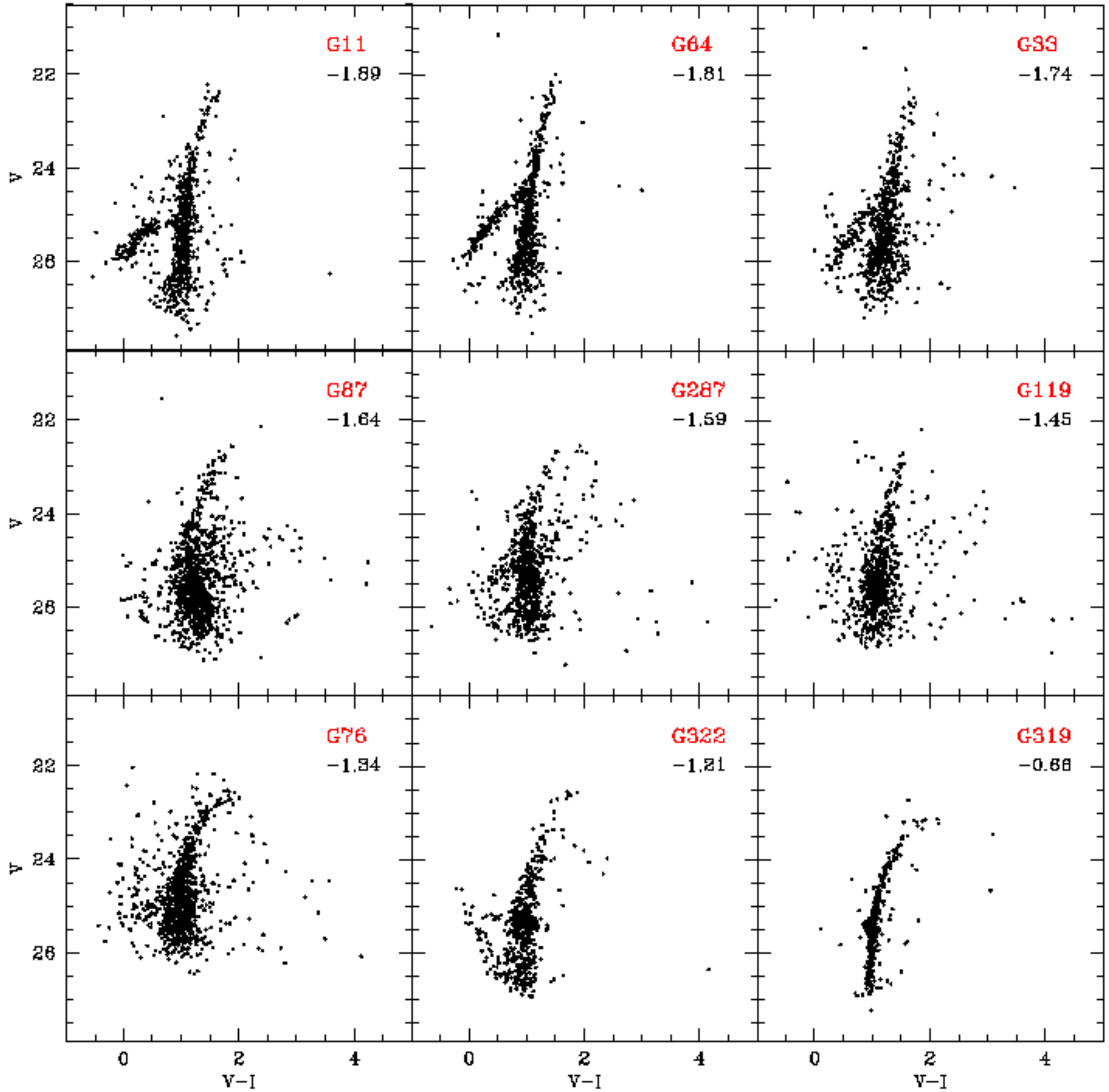
HST image mosaic
From Jablonka (2000)

Only a relatively small number of M31 clusters are well enough resolved for HST color-magnitude diagram studies.

G1 among the best cases, Leading Rich et al. to propose WFPC2 study in 1994

First CMD from Ground by Christian & Heasley 1991; HST: Rich et al. 1996 Ajhar et al. 1996 (shows metallicity spread).

Fusi Pecci et al. 1996 AJ (8 clusters)



Rich, Fusi Pecci,Cacciari, FedericiCorsi, Freedman,Djorgovski 2002 in prep.

9 new clusters With WFPC2 (romafot reduction)

- [Fe/H] as in Milky Way
- RGB slope vs [Fe/H] OK
- HB morpholog vs
- Full range of HB type

Strong indications that the M31 cluster system Is as old as the Milky Way

G1 has a normal luminosity function Like 47 Tuc (Rich et al. 1996)

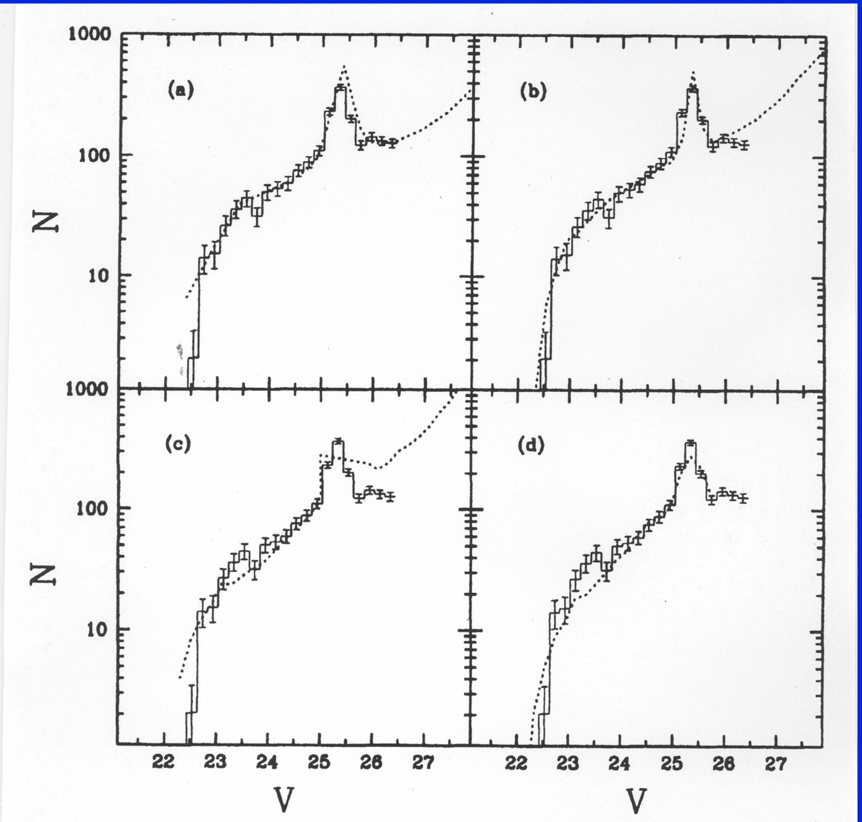
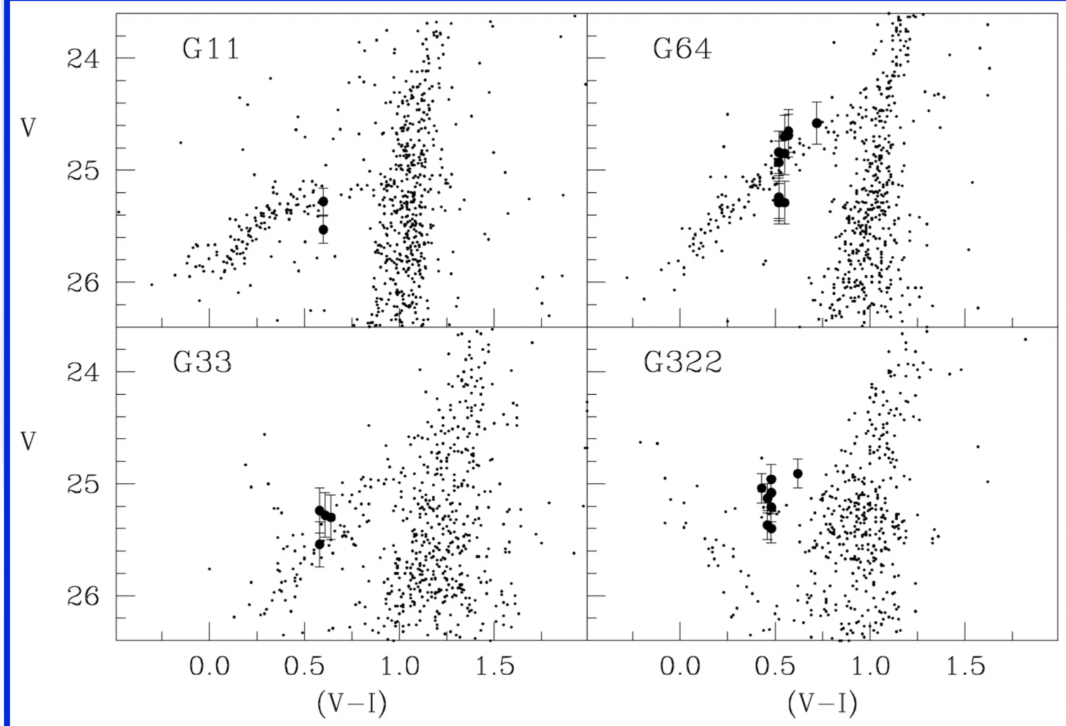


FIG. 5. Comparison of the G1 V stellar luminosity function with published stellar luminosity functions (see text for sources). (a) G1vs 47 Tuc, at $(m-M)_0=24.4$; (b) G1 vs M3, modulus of 25.35; (c) G1 vs M13, modulus 25.0; (d) G1 vs Fornax, modulus 24.8. We conclude that 47 Tuc fits the G1 luminosity function best.

Rich, Mighell, Freedman 1996 AJ

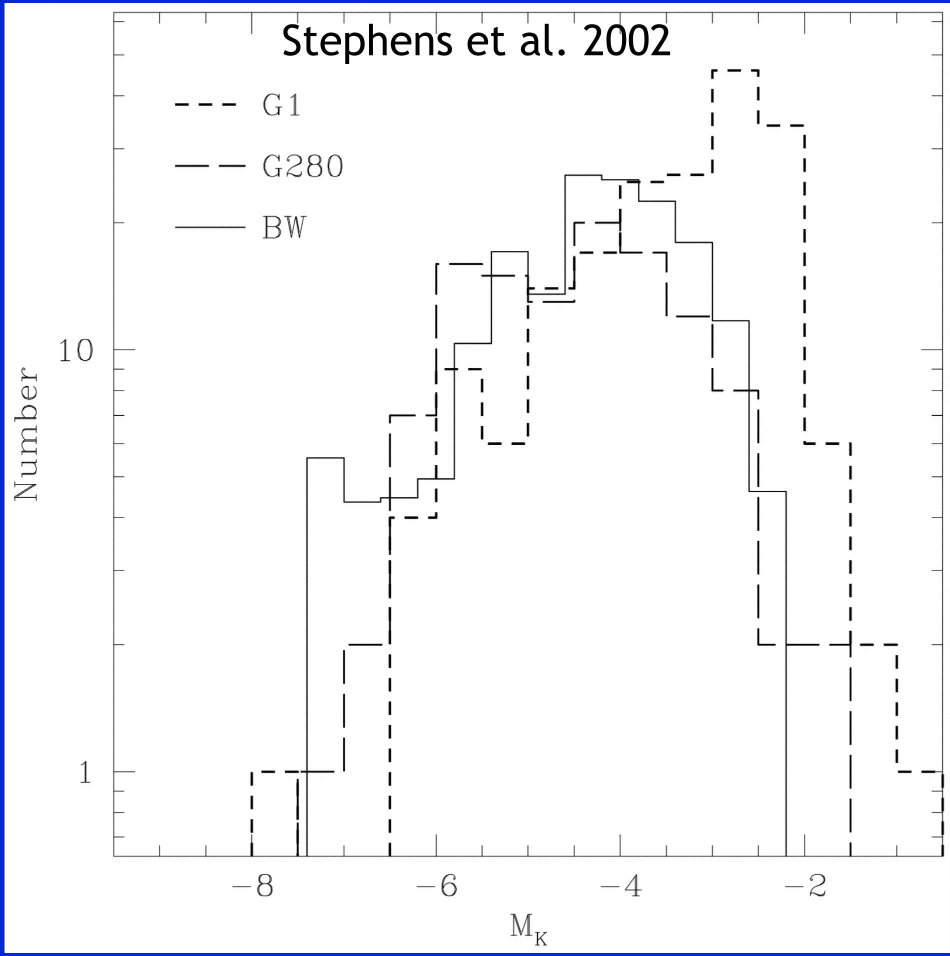
Long standing high HBeta and CN controversy (Burstein et al. 1988)may be solved: M31 clusters old, and have BHB stars (see poster by Peterson 102)

RR Lyrae candidates are present: Clementini et al. 2001

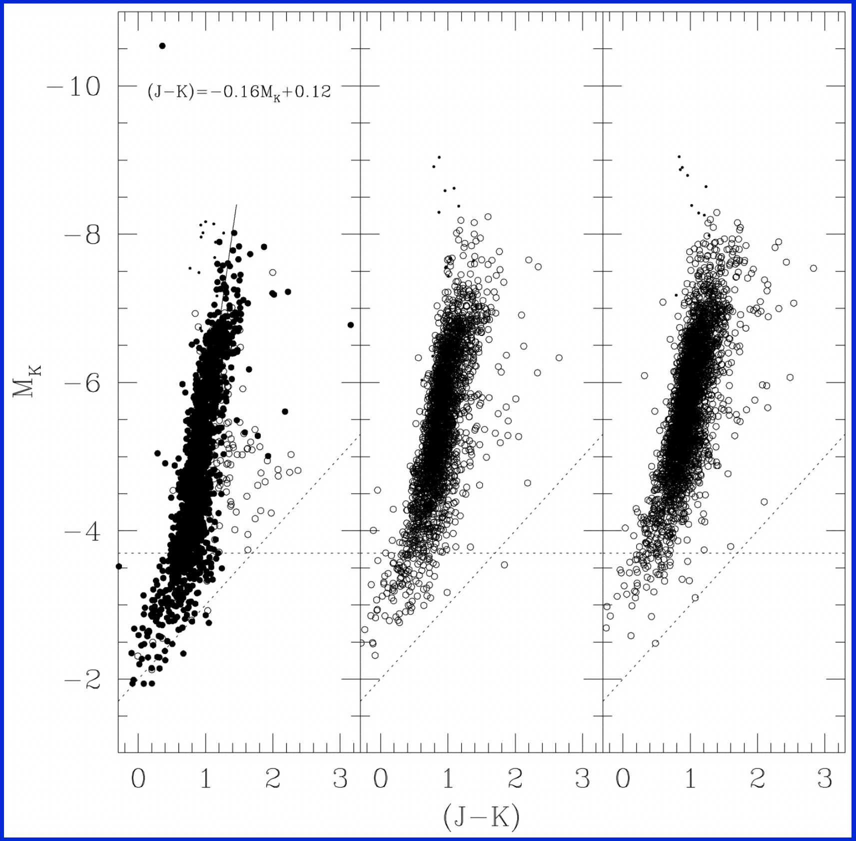


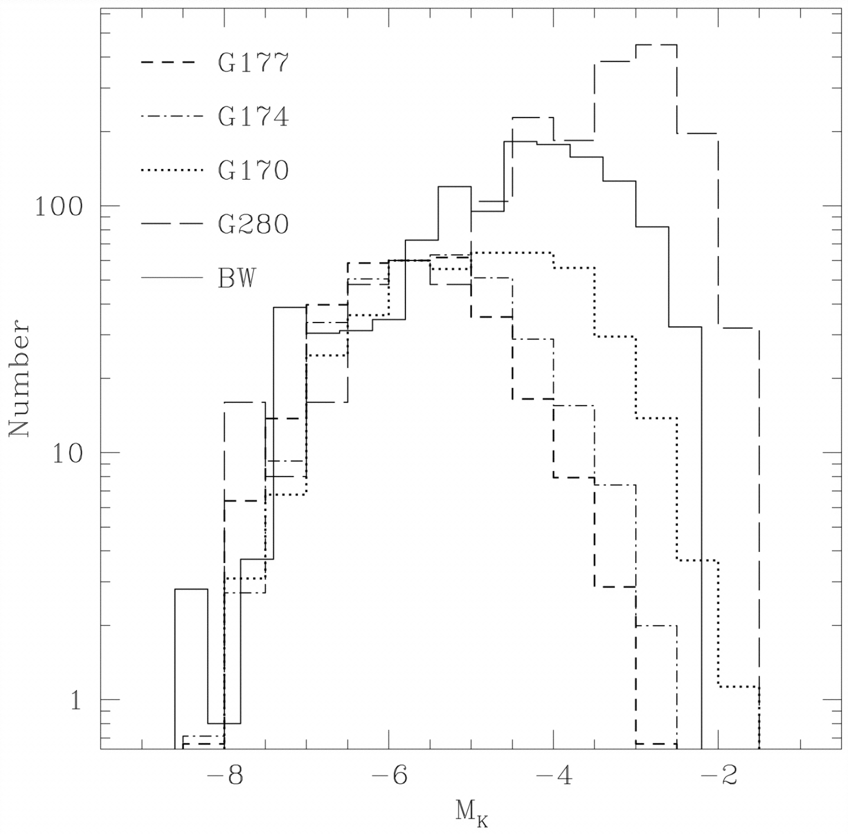
The infrared luminosity functions look similar,
Like old MW clusters and like the bulge luminosity
Function in Baade's Window (BW).

No evidence for intermediate-age clusters



M31 bulge fields are old, as well, but do have
Stars reaching M_bol=-5.   Guarnieri et al. show
such bright AGB stars, even to -6, found in N6553, an old metal
rich globular cluster.





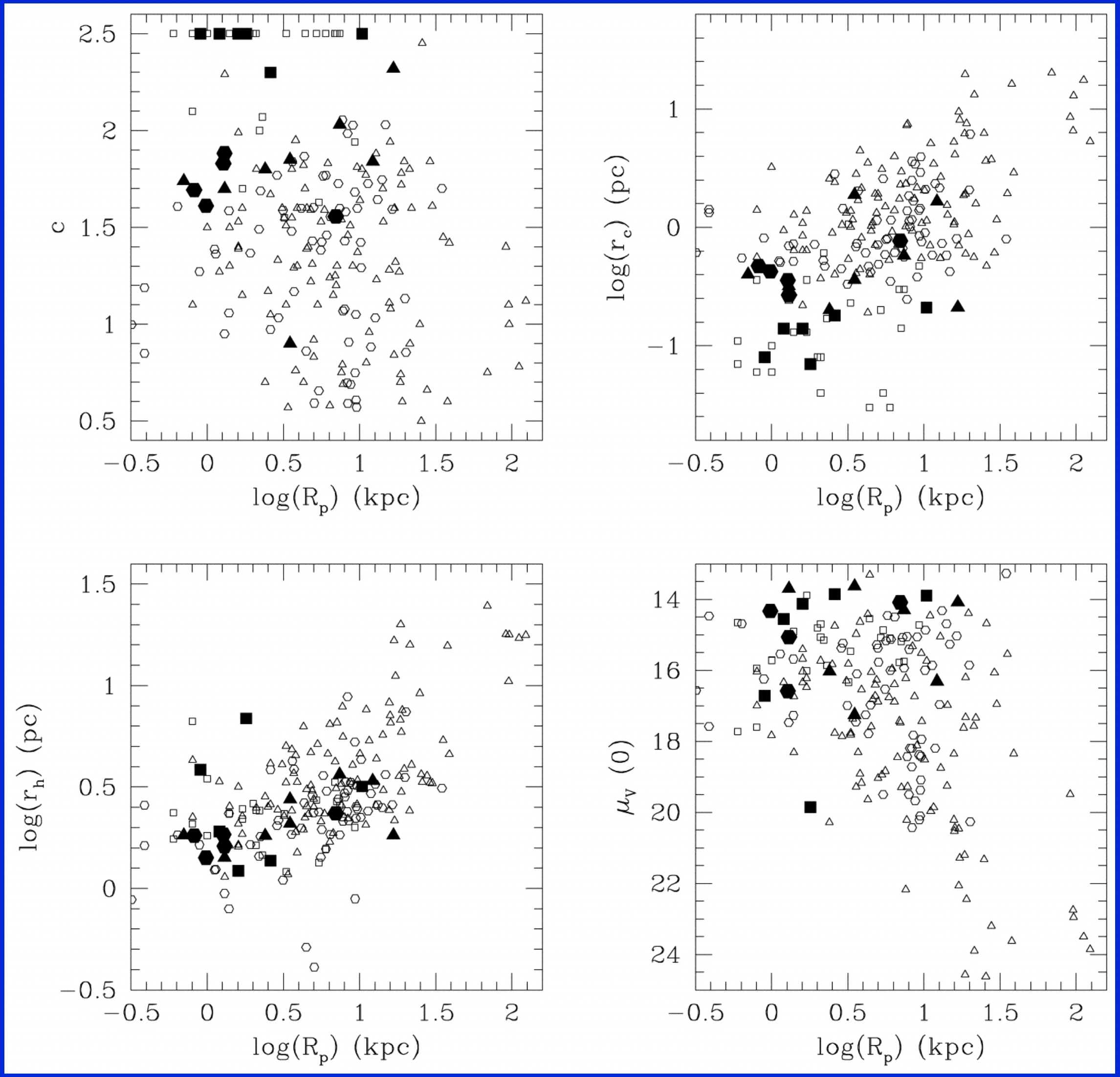
Dynamical effects might be more important in M31, though no apparent effect on correlations

Nuclear bulge ~7xMW, velocity dispersion 150 vs 120 km/sec, Rotation speed 260 vs 220 km/sec

Are clusters destroyed more quickly? No additional collapsed cores

Di Stefano et al. 2002 find that very X-ray luminous $L_x > 10^{37}$ erg/sec are a larger fraction of GC sources than in the Galaxy.

Di Stefano et al. find the most compact clusters have luminous X-ray sources (filled symbols). G1 is not yet observed.



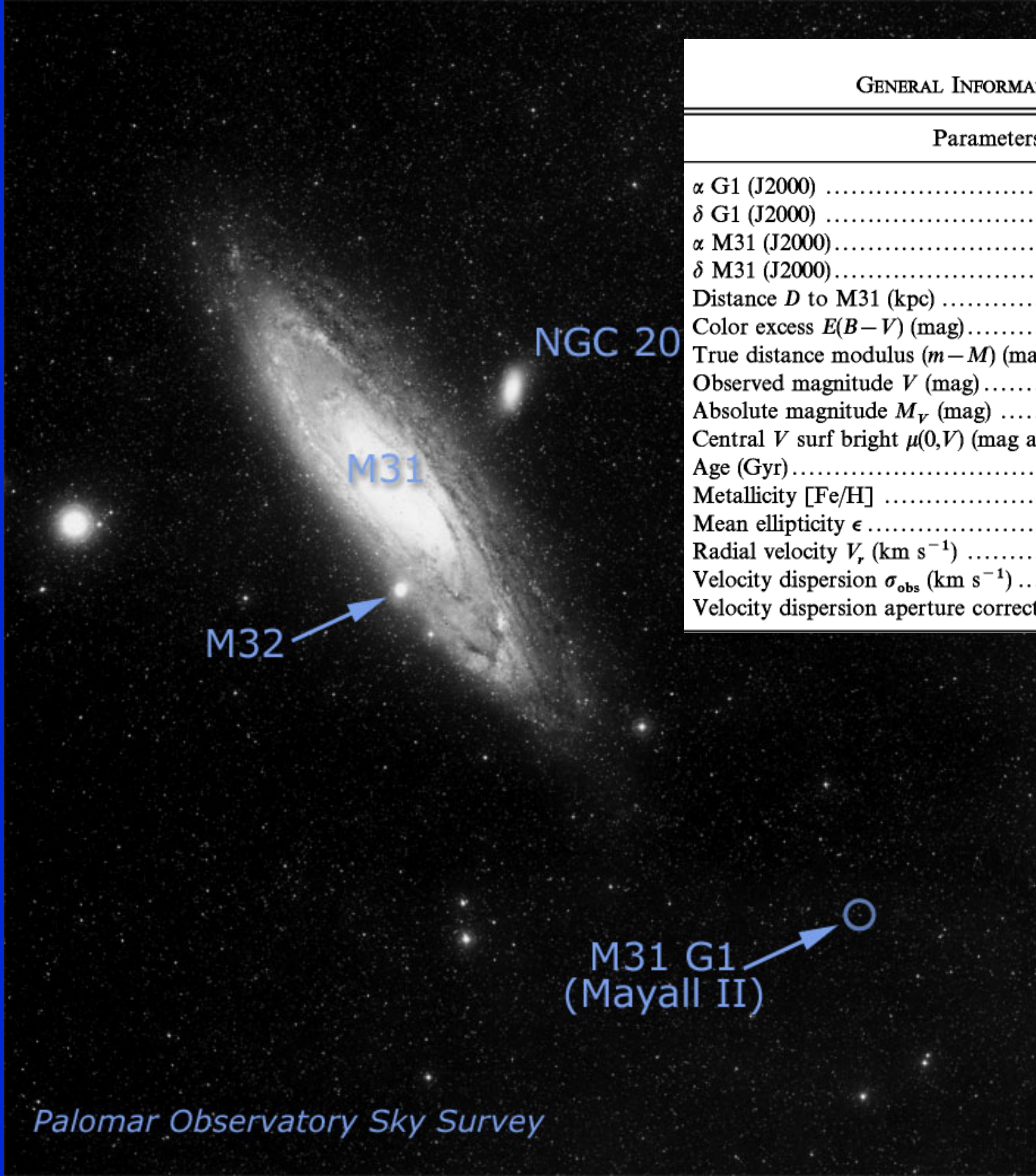
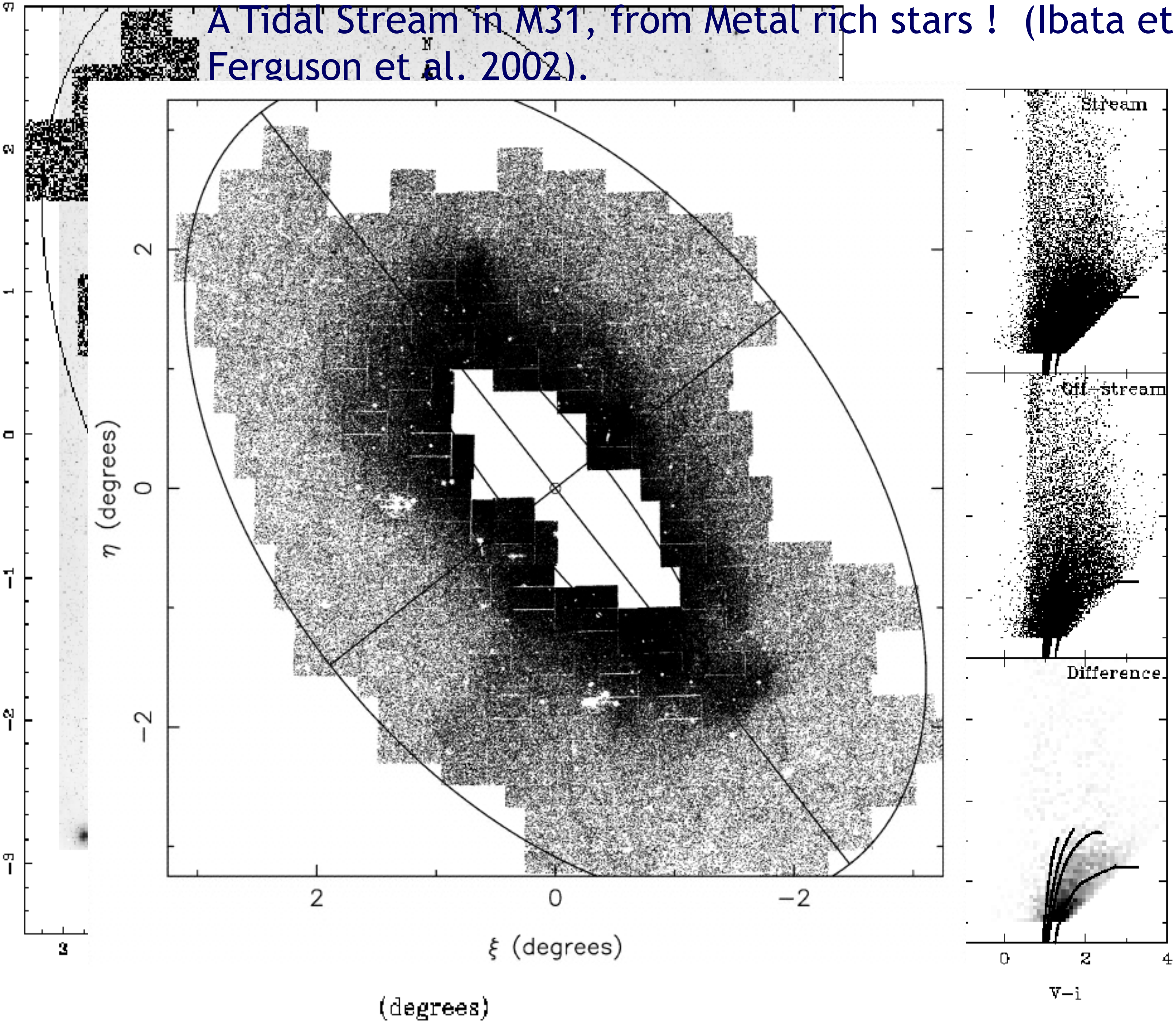


TABLE 1

General Information about Mayall II = G1

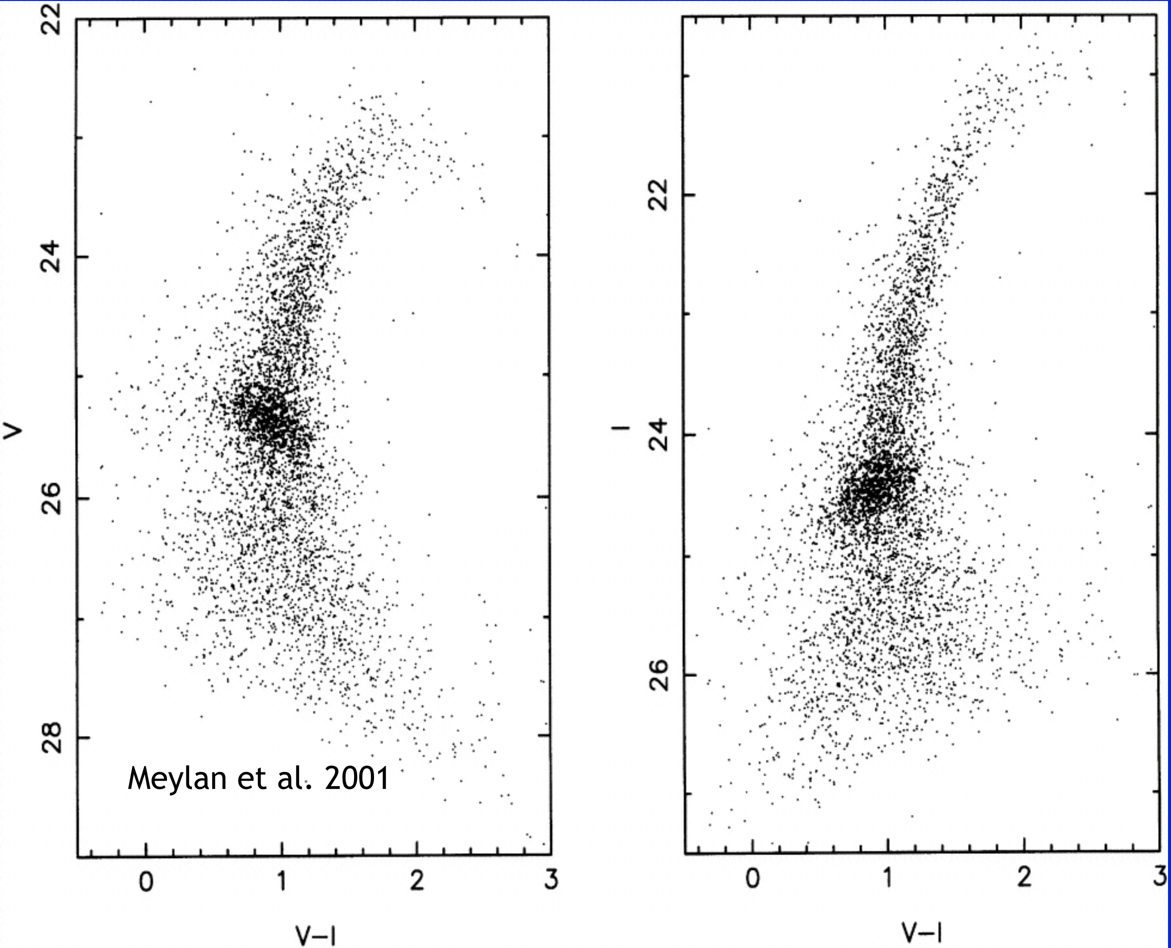
Parameters	Mayall II = G1
α G1 (J2000)	00 32 46.6
δ G1 (J2000)	+39 34 40
α M31 (J2000)	00 42 44.5
δ M31 (J2000)	+41 16 29
Distance D to M31 (kpc)	770
Color excess $E(B-V)$ (mag)	0.06
True distance modulus $(m-M)$ (mag)	24.42
Observed magnitude V (mag)	13.48
Absolute magnitude M_V (mag)	−10.94
Central V surf bright $\mu(0,V)$ (mag arcsec^{-2})	13.47
Age (Gyr)	~15
Metallicity [Fe/H]	−0.95
Mean ellipticity ϵ	0.2
Radial velocity V_r (km s^{-1})	-331 ± 24
Velocity dispersion σ_{obs} (km s^{-1})	25.1
Velocity dispersion aperture corrected $\sigma(0)$ (km s^{-1})	27.8

A Tidal Stream in M31, from Metal rich stars ! (Ibata et al. 2001; Ferguson et al. 2002).

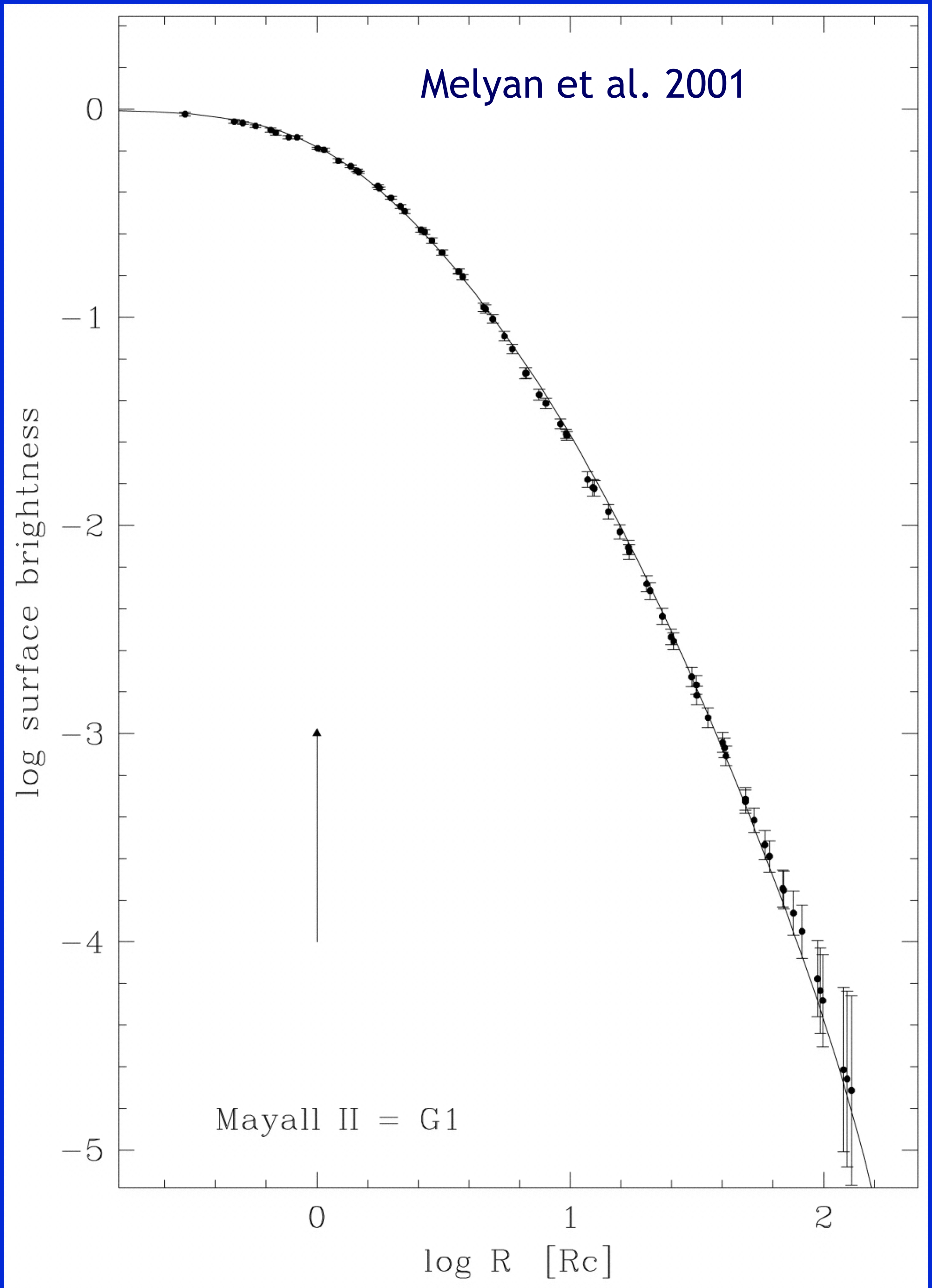


G1 is one of the most luminous globular clusters in the Local Group

- r_c=0.54 pc, V(cent)=13.5 mag/sq. arcsec (Rich et al. 1996)
- Virial mass=15x10^6 Msun, M/L_v=7.5, sigma(obs)=25.1 km/sec (highest globular cluster dispersion) (Meylan et al. 2001)
- Although G1 falls on the usual globular cluster surface brightness relations, intuition leads one to suspect HST spectroscopy interesting



Metal rich giant branch
And abundance spread
(Rich et al. 1996;
Meylan et al. 2001).
[Fe/H]~47 Tuc
(also halo field)



G1 follows King profile

r_c= 0.53 pc

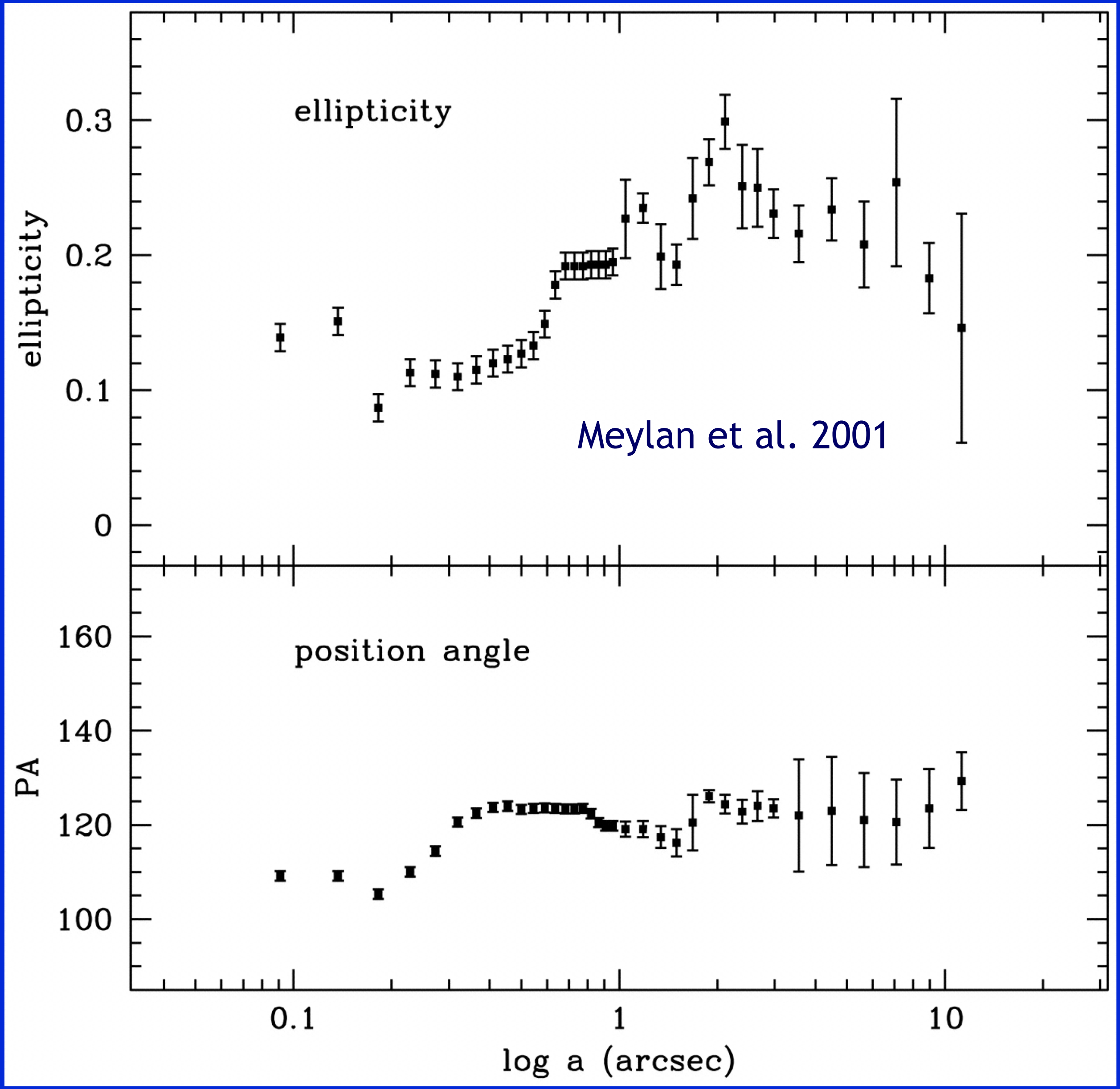
r_h=14 pc

r_t= 200 pc

rho_c = 4.9x10^5 Msun/pc^3

13.5 mag /sq. arcsec
Central surf. Brightness

(almost appears nucleated)



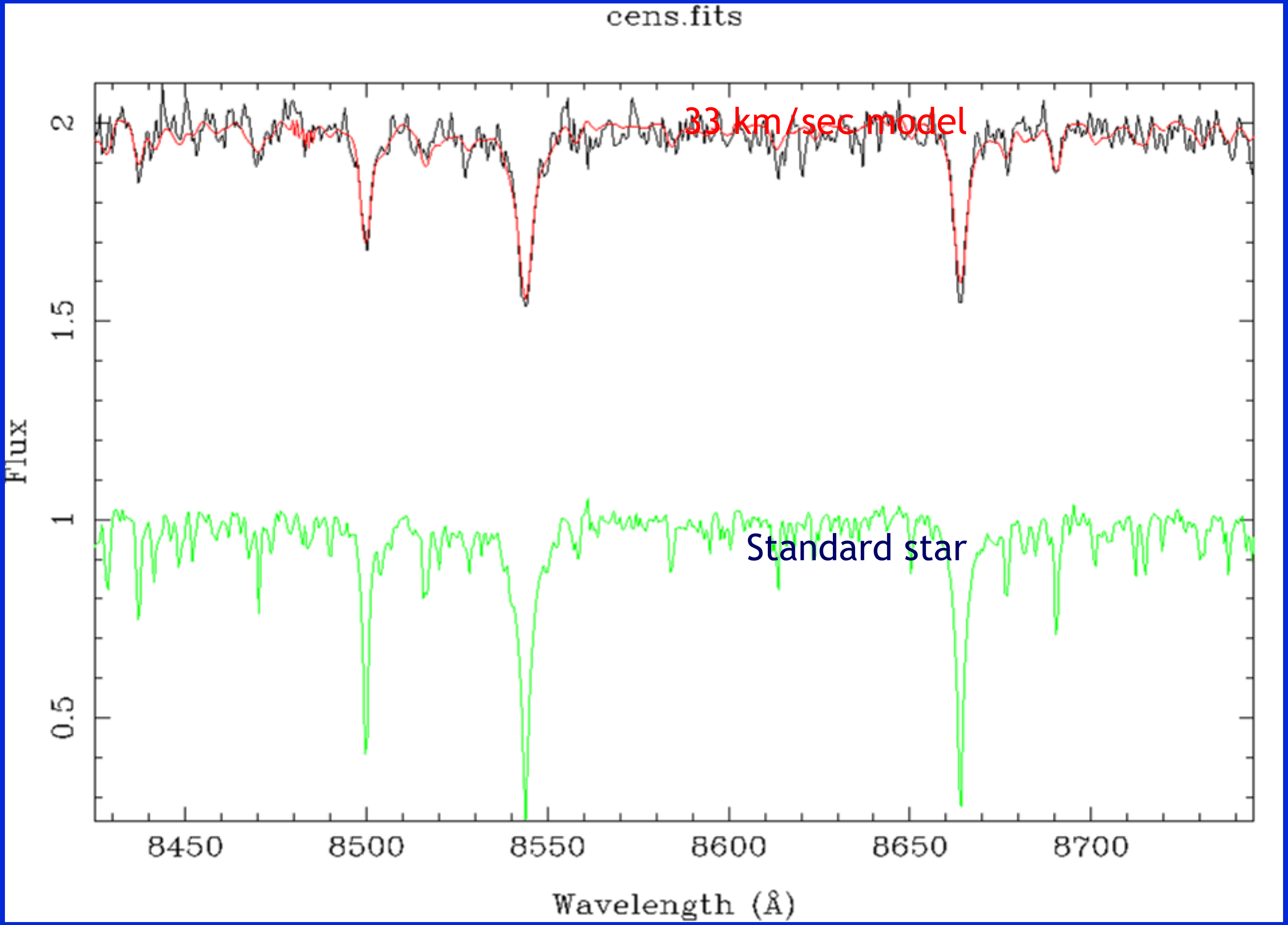
No strong indications of of triaxiality.

Cluster	M_v	Surf(0) mag/sq”	Sigma Km/sec	[Fe/H]
G1	-10.9	13.5	25	-0.7
M15	-9.0	14.2	10	-2.2
ω Cen	-10.1	16.3	16	-1.6
47 Tuc	-9.4	14.1	11.5	11.5

Source: Djorgovski & Meylan, Structure & Dynamics of Glob. Clusters ASP 50

HST spectroscopy: 25º off of major axis (due to guide star)
Ca triplet 0.554A (19 km/sec/pix) 0.1x52" slit
7.06 hr total exposure. + WFPC2 parallels: deep imaging of M31 halo

Large dithers of +/- 1 " give hot pixel map from data.
Spectra cover 8276-8843A
0.554A = 19 km/s per pixel, FWHM resol. Element=1.06A = 37 km/s



3-integral models (Gebhardt et al. 2000, 2002 (see also Verolme & De Zeeuw aph/0112185

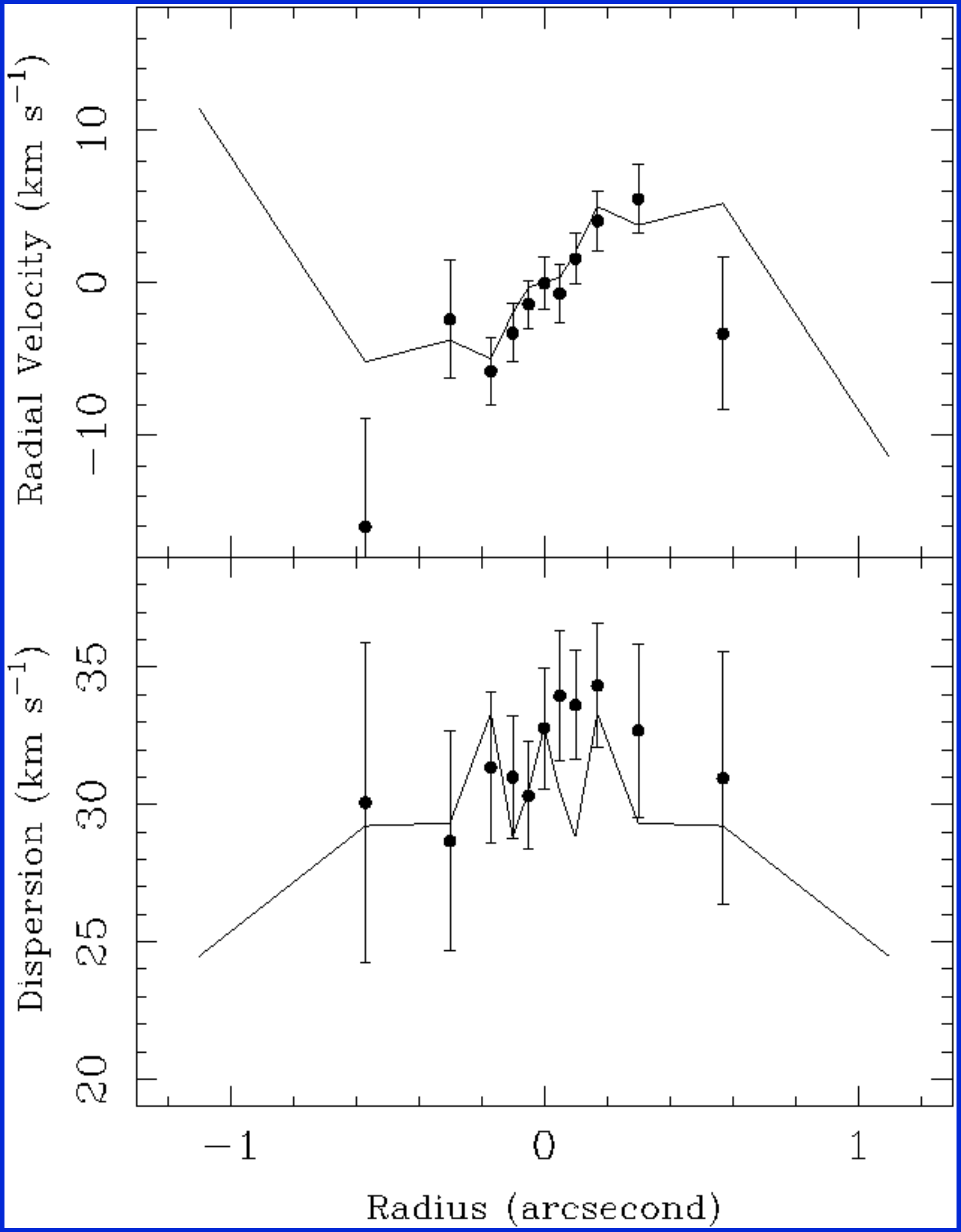
Use surf. Brightness profile of Rich et al. 1996, no deconvolution (resolved stars near 1 " complicate this

Axisymmetric orbit based models, no specified form for the distribution function

Input potential, integrate set of orbits covering phase space
Find non-negative set of orbital weights that best matches
BOTH photometry and kinematics (Schwarzschild method)
(Like HongSheng Zhao's bulge models). Only free parameters
Are M/L and black hole mass.

Results are stored both in kinematic and photometry bins
12 radial, 4 angular, 13 velocity bins.

Luminosity density of G1 reproduced to 0.5% everywhere



Kinematics to +/- 1.1”

Lines show first two
Moments of Gauss-Hermite
Poly expansion of the velocity
Dispersion profile.

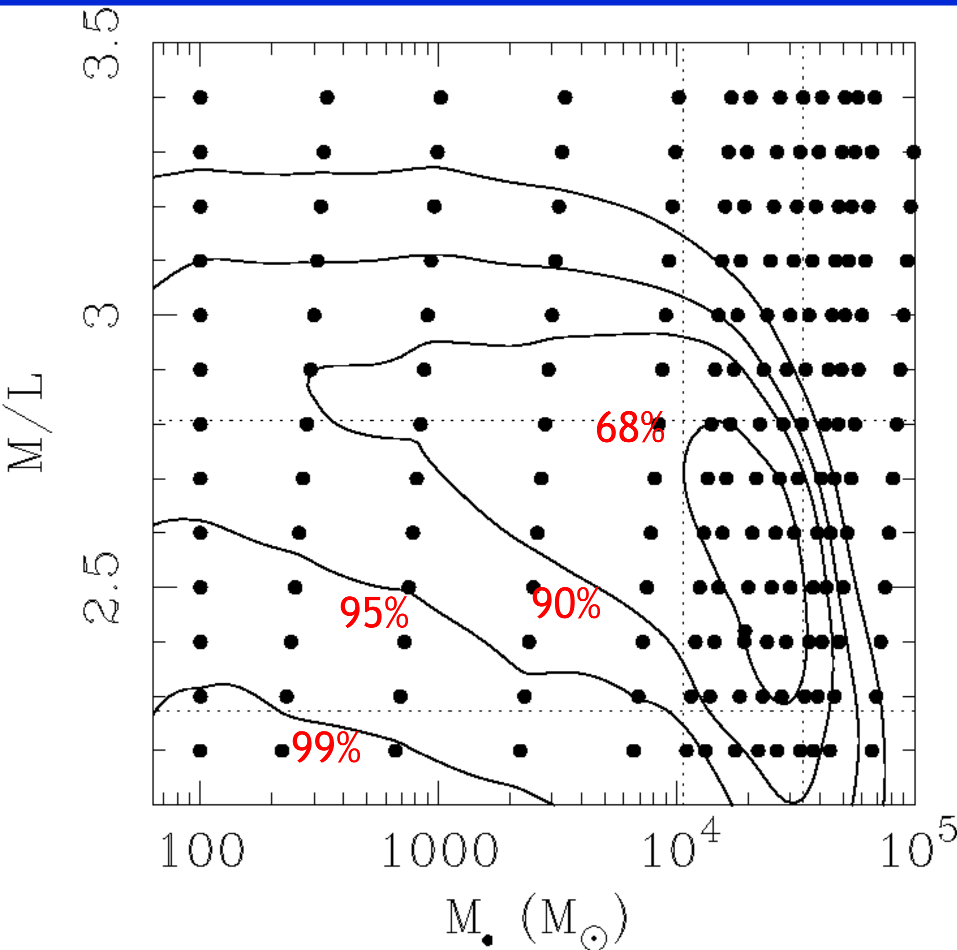
Sampling noise not a problem
central spatial resolution
element has light from
30-100 stars.

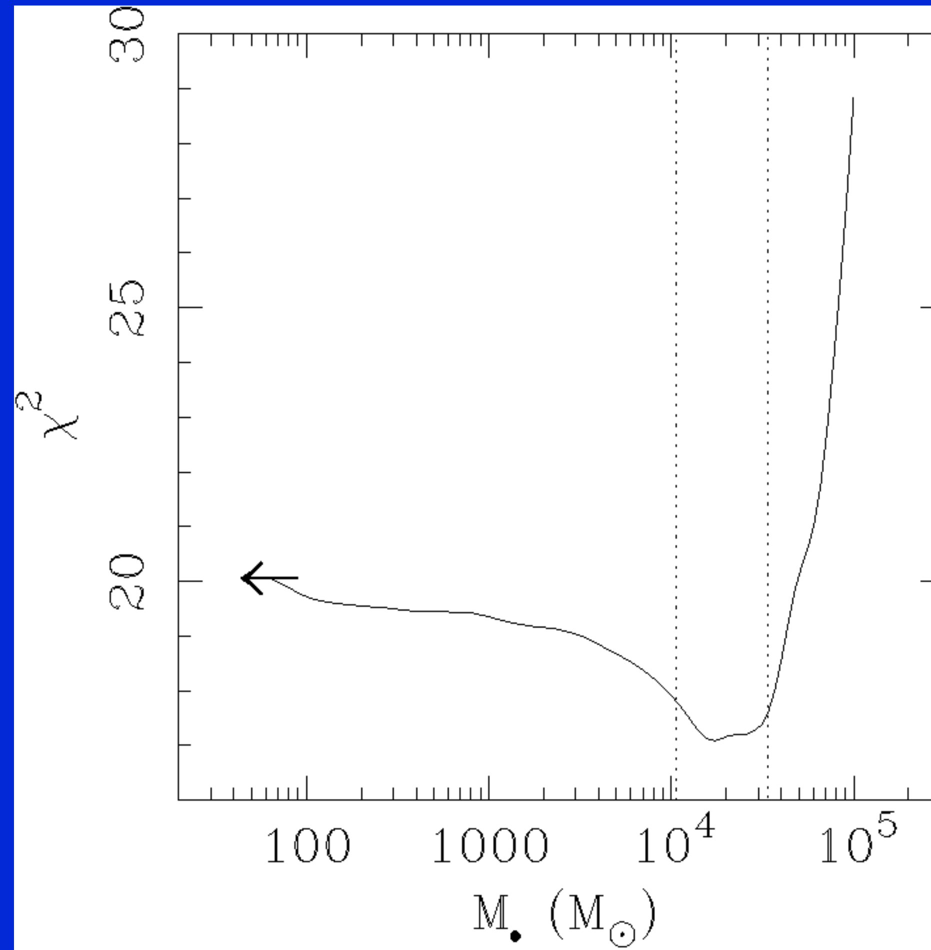
Rapidly rotating core
And high central velocity
Dispersion!

Rapid rotation > little radial
anisotropy

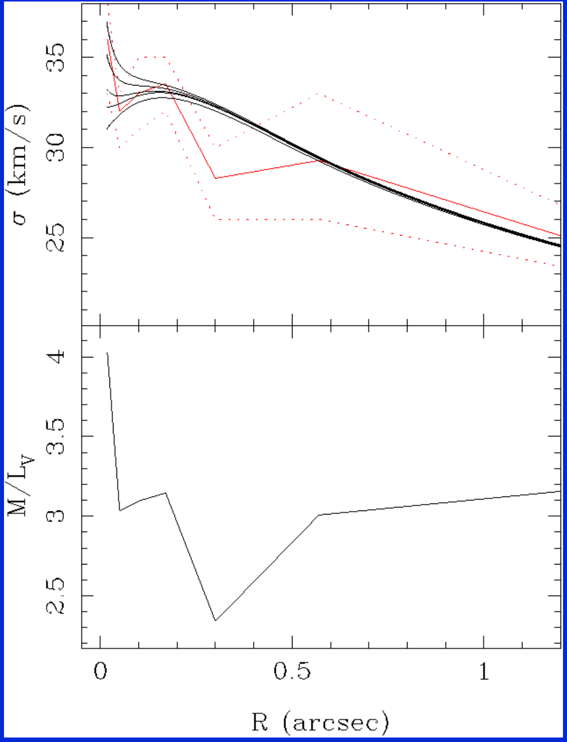
Modeling technique as in Gebhardt et al. (2000 AJ 119): axisymmetric 3 integral models. Populate orbits using Schwarzschild's method (non-negative orbital weights to self-consistently fit luminosity profile and kinematics, Satisfy Poisson and Jeans equations. Central point mass is varied until the best fit is found. About 3000 orbits per model.

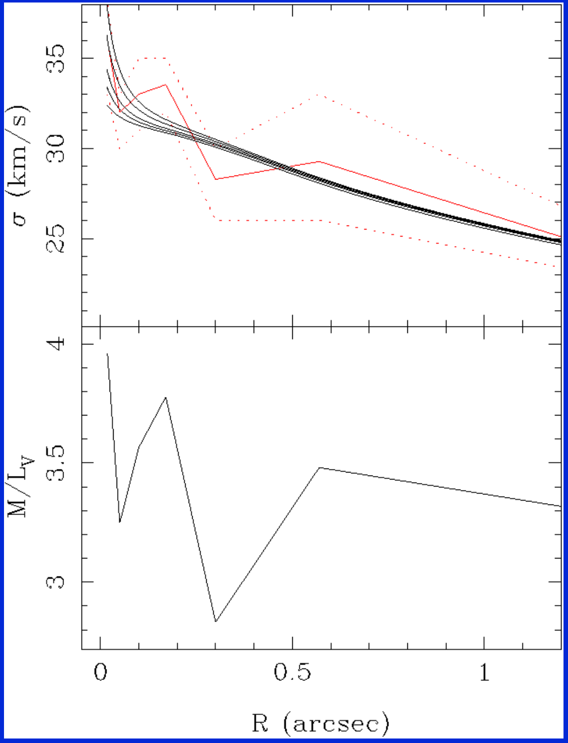
M(central) = 2.0(+1.4, -0.8) Msun M/L_V=2.6 Varying β gives no fit.

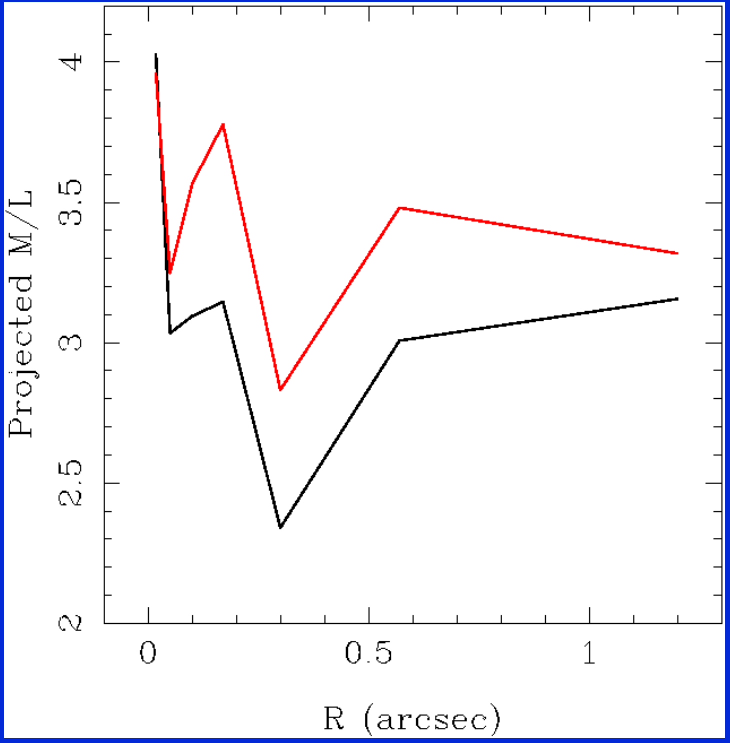




Dynamical models also show a rise in M/L, but
More ground-based data are needed.

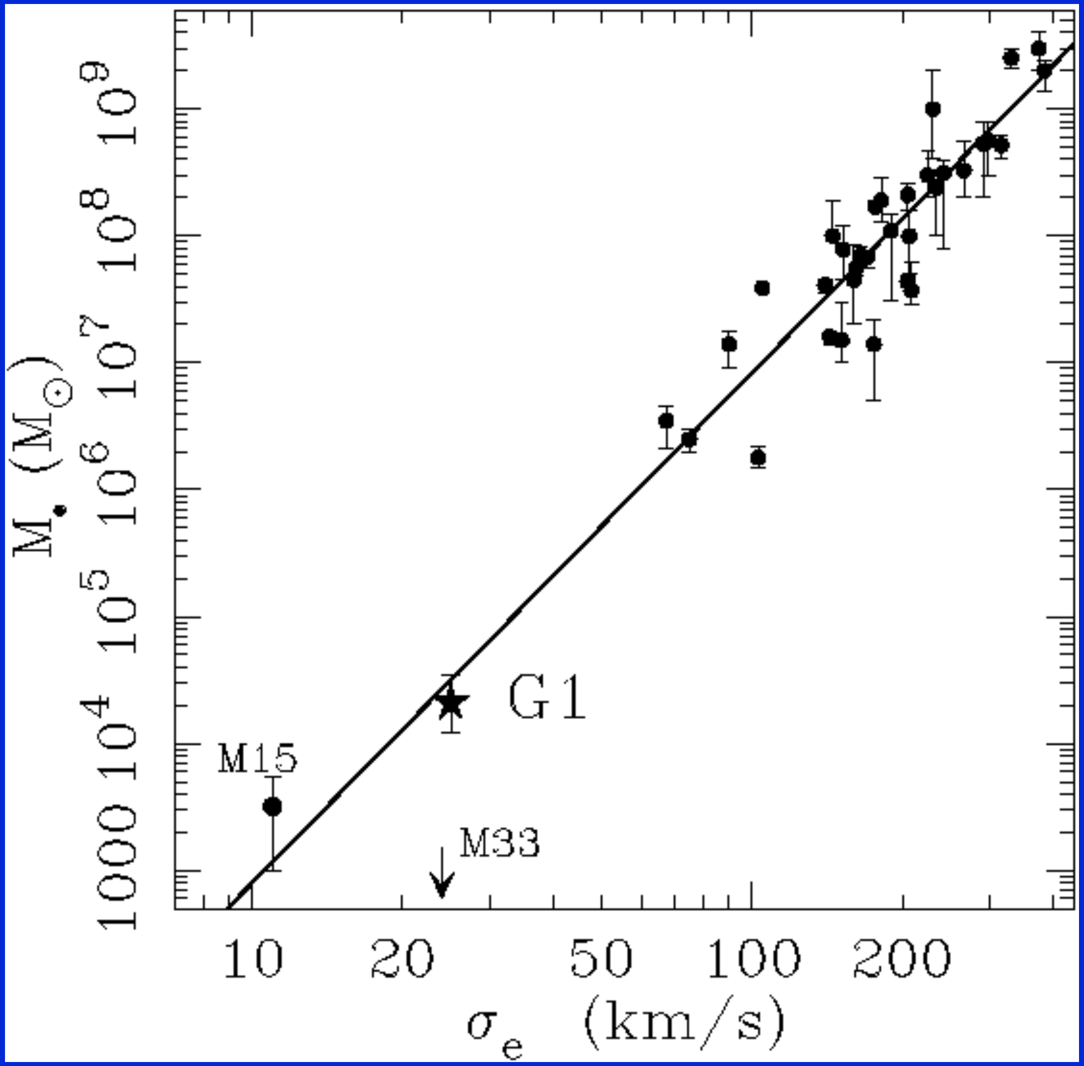






G1 falls on the Tremaine et al. (2002) [Ferrarese & Merritt; Gebhardt et al.] Relationship between BH mass and "bulge" velocity dispersion.

The modeling techniques we use are identical to those applied to nuclear Point masses (putative nuclear black holes) found in more massive galaxies.



Linear fit is from Tremaine et al. 2002 Not including clusters.

Globular cluster black Holes would be in the category of supermassive black holes

Implications

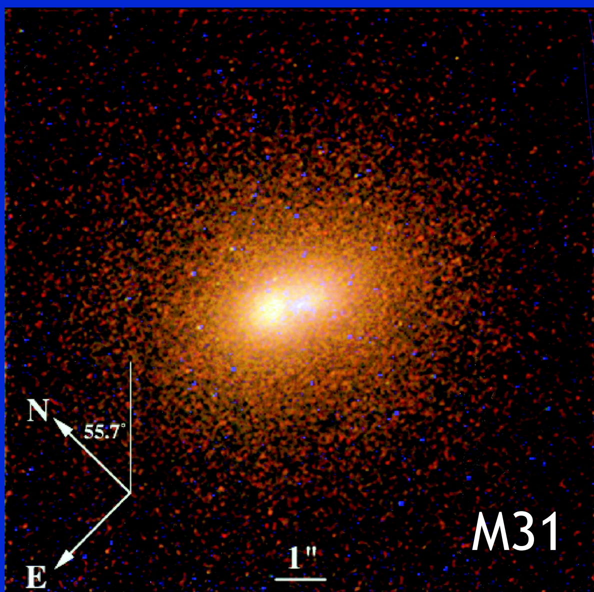
Is the central mass a core of remnants? Dull (1997) use Fokker-Planck models for M15 and get 1000 Msun remnants. G1 is 5x more massive, implies 5000 Msun in remnants. But G1 central relaxation time ~10^7 yr (longer than M15)

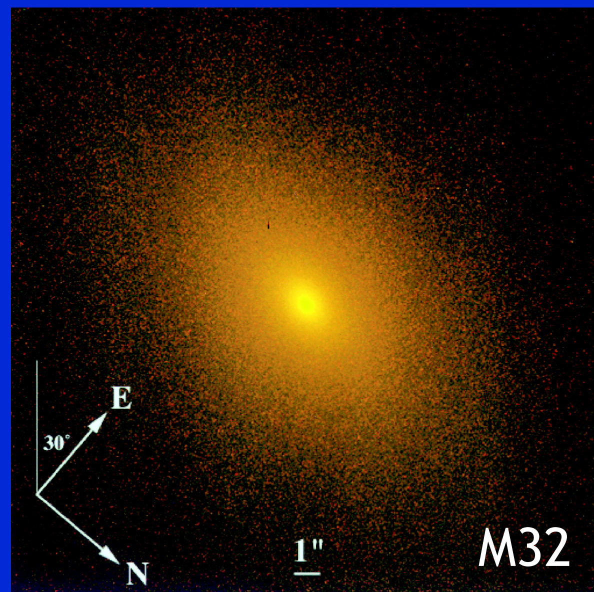
Not all compact nuclei have central point masses: counterexample Is M33 (Gebhardt et al. 2001). If the central mass of G1 is confirmed, may suggest that massive globular clusters are building blocks of nuclei, or that Galactic nuclei share some of the globular cluster formation mechanisms. G1 may be a fossil nucleus, or perhaps nucleus of long lost dwarf galaxy.

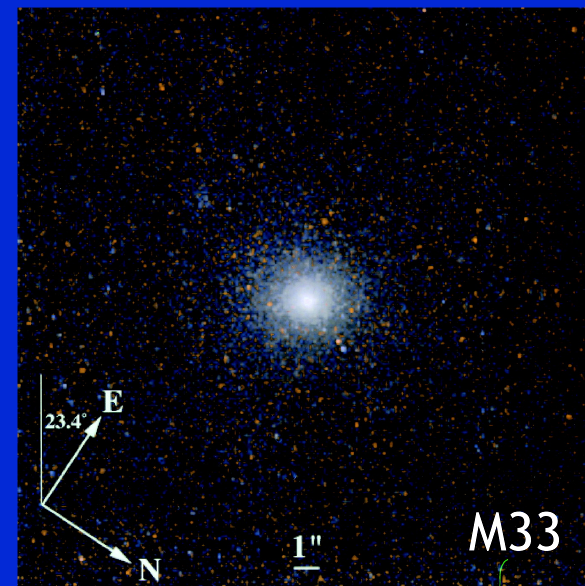
Due to its high central surface brightness and 33 km/sec dispersion,
G1 may be different from other clusters with central masses.

M33: A Nucleus with No central Black hole

Gebhardt et al. 2001, AJ, 122, 2469







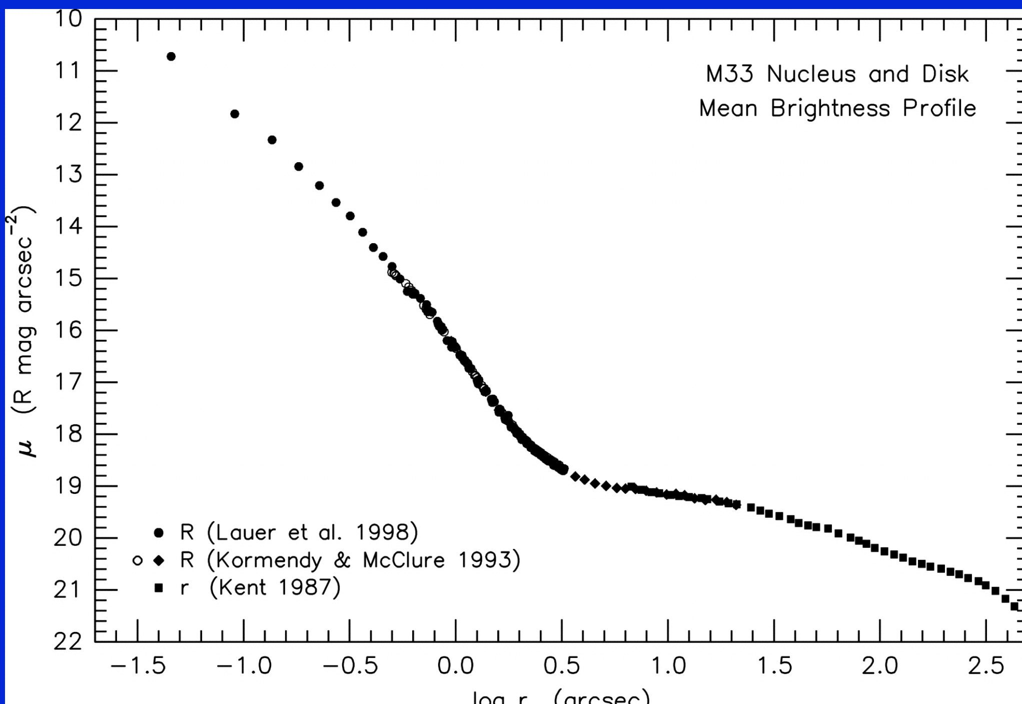
Lauer, T.R. et al. 1998, AJ, 116, 2263

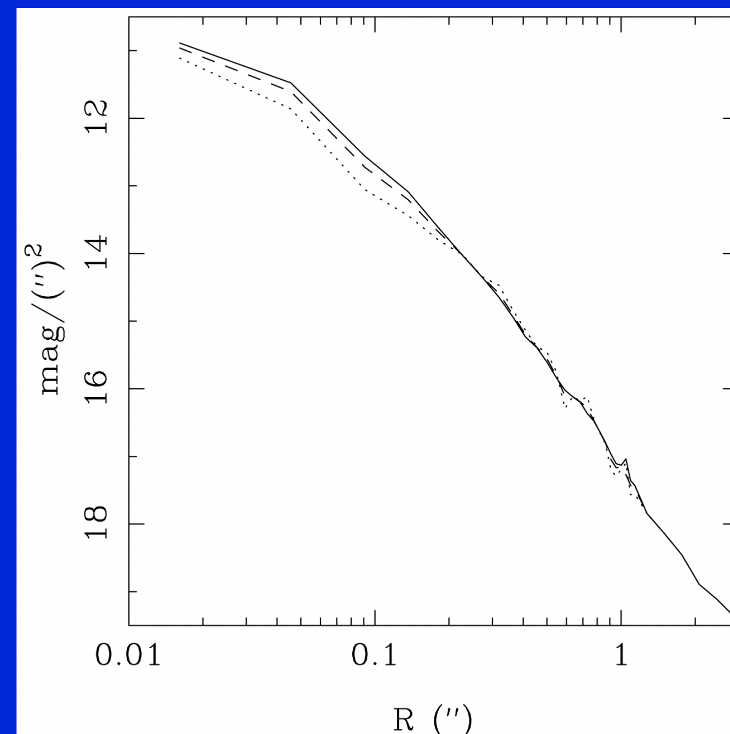
The nucleus of M33 is a distinct system from the "disk"
M_v=-10.2 , sig(V)=24 km/sec, almost the same as G1

M33 nucleus is younger than G1 (~1 Gyr vs >10 Gyr)

M33 analysis identical to that for G1

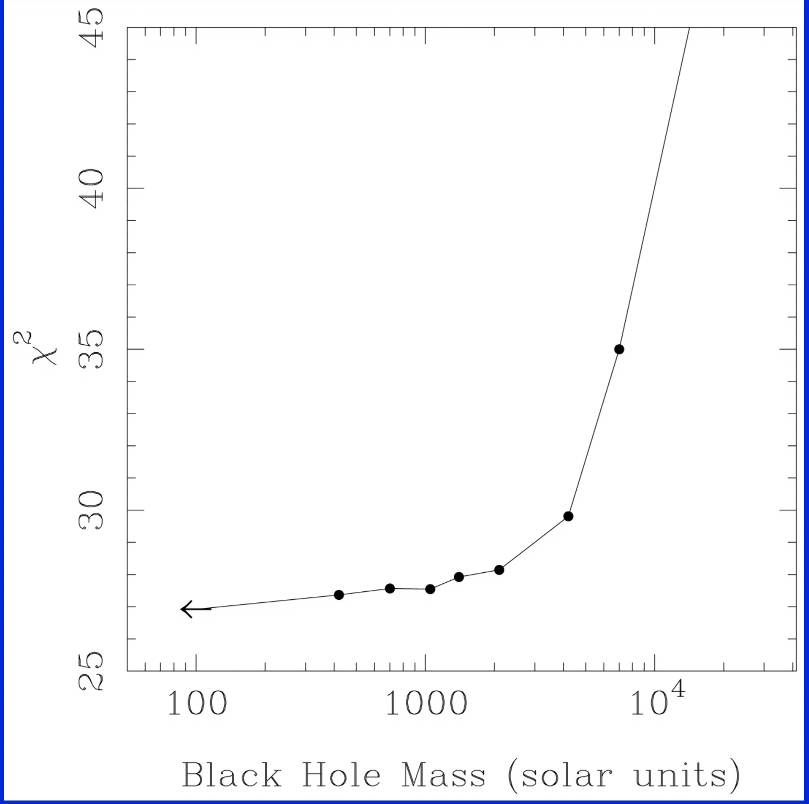
Nucleus of M33 reaches 1 mag brighter than G1
(but stellar population is younger)

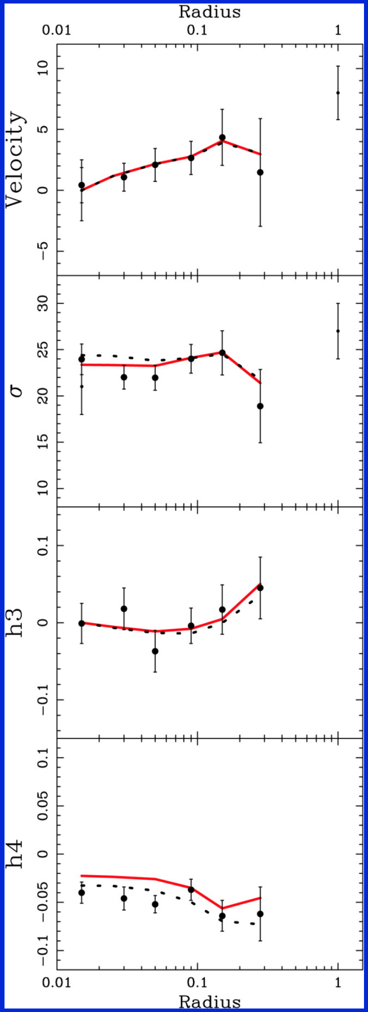


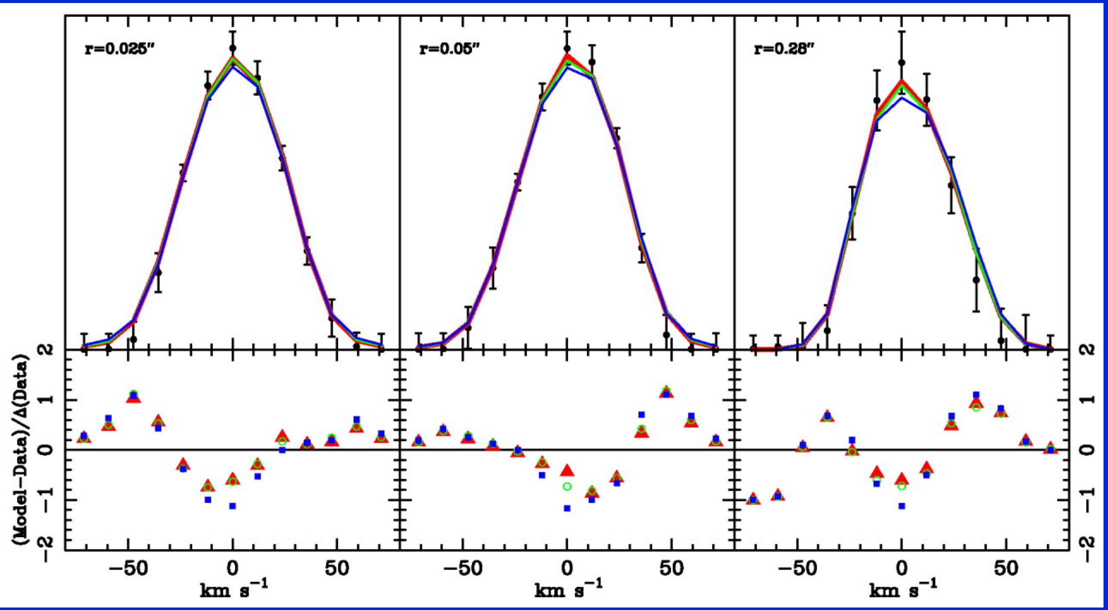


The identical analysis applied to M33 finds the best fit to be no central black hole.
STIS wavelength (Ca Triplet) the same..

Mbh<1500Msun







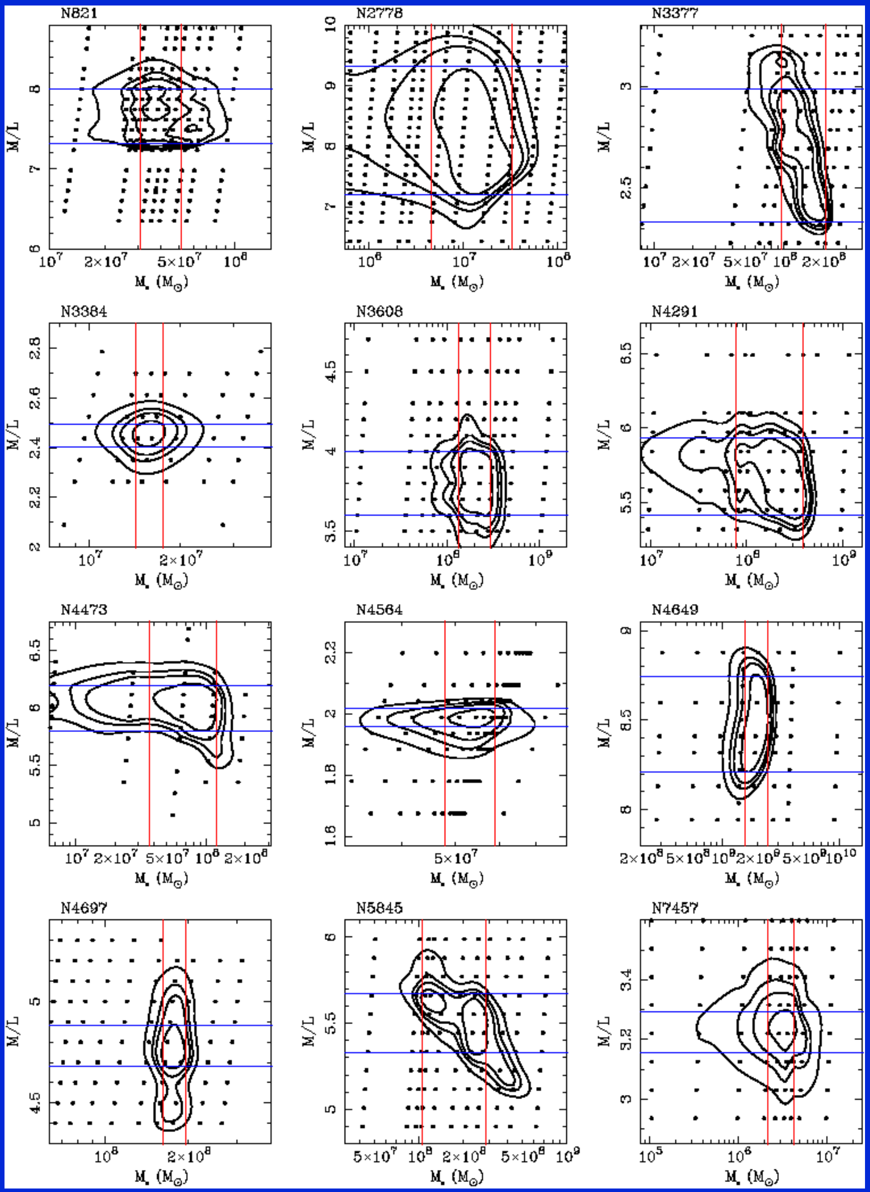
3-integral axisymmetric models have been widely applied and tested

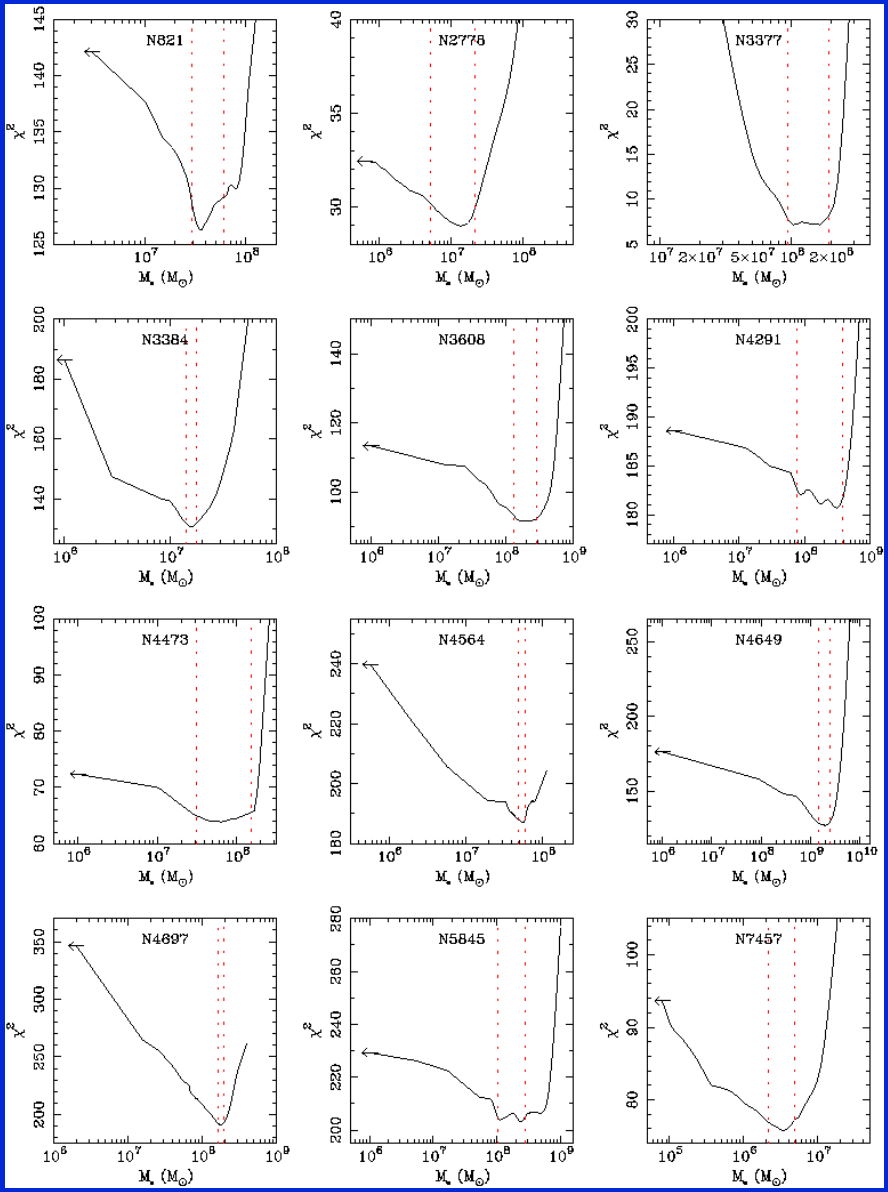
Axisymmetric Models applied to the black hole in NGC 3379:
Gebhardt + NUKER collab. 2000 AJ 119, 1157
(This paper explains models in detail; Richstone et al. 2002 Forthcoming also).

Axisymmetric Dynamical Models of the Central Regions of Galaxies: Gebhardt et al. 2002 astro-ph 0209483

The method is the one used by the "NUKER" collaboration that has derived the largest number of HST-measured central Black holes from stellar velocity dispersions.

Gebhardt et al. 2002 applied to bulges





G1 is likely NOT the nucleus of a dwarf galaxy. Probably is a luminous, massive, but bona fide globular cluster in M31. No evidence for dark matter.. but needs confirmation.

Keck/OSIRIS Spectroscopy of the M31 nucleus and bulge

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M31 nucleus at K with NIRC2, LGSAO: Wizinowich et al. 2006 PASP and A. Bouche

Background

M31 nucleus has Mbh = 1-2.3 $\times 10^8 M_\odot$ (Kormendy 1980s; Bender et al. 2005

3 nuclear components: P1 - brightest, P2- dynamical center (Bacon et al.); P3-blue nucleus dominated by A stars (Bender et al. 2005); P3 nearly coincident with P2. Dynamics consistent with Keplerian disk and velocity dispersion ~ 1000 km/s.

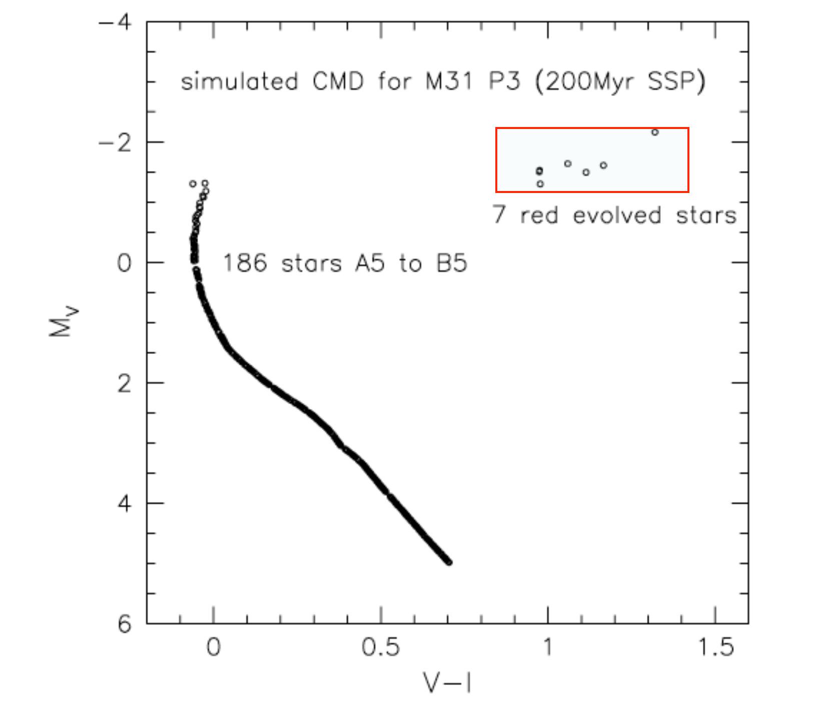
Lauer et al. 1998, Rich et al. 1996 made optical color maps of the nucleus and find no optical/near-IR color gradient; King et al. 1994 observed blue P3 with FOC.

Elliptical stellar disk, with stars lingering at apocenter, is model for P1 offset.

Motivation: Detection of A star disk implies an evolved stellar population (possibly with extreme kinematics) present.

Unusual metallicities? Metallicities of P1, P2? Spatial variations.

CO bands in K band gravity sensitive;
Some atomic features there.
H-band has OH features near 1.6um

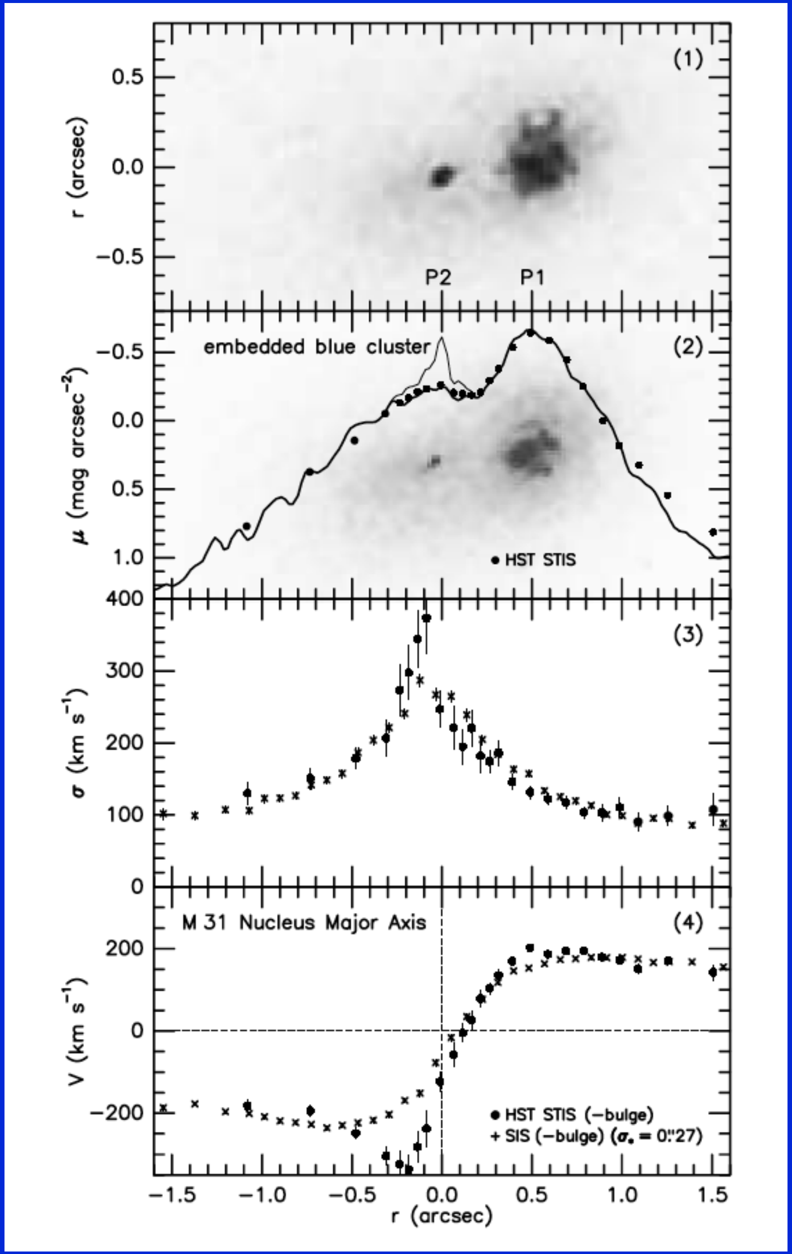


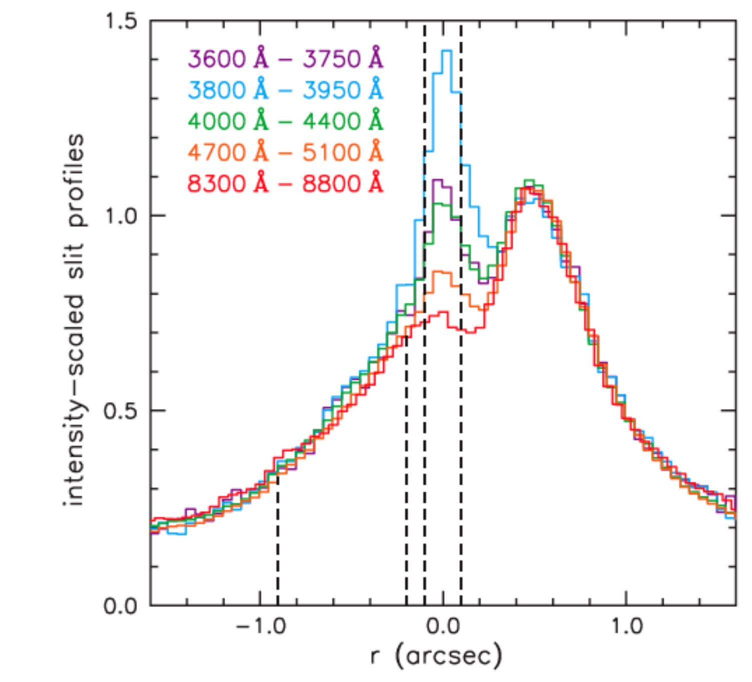
A map of the nucleus based on line strengths offers the most sensitive test of population and metallicity gradients. Our goal is to characterize any gradients relative to the structure of the nucleus.

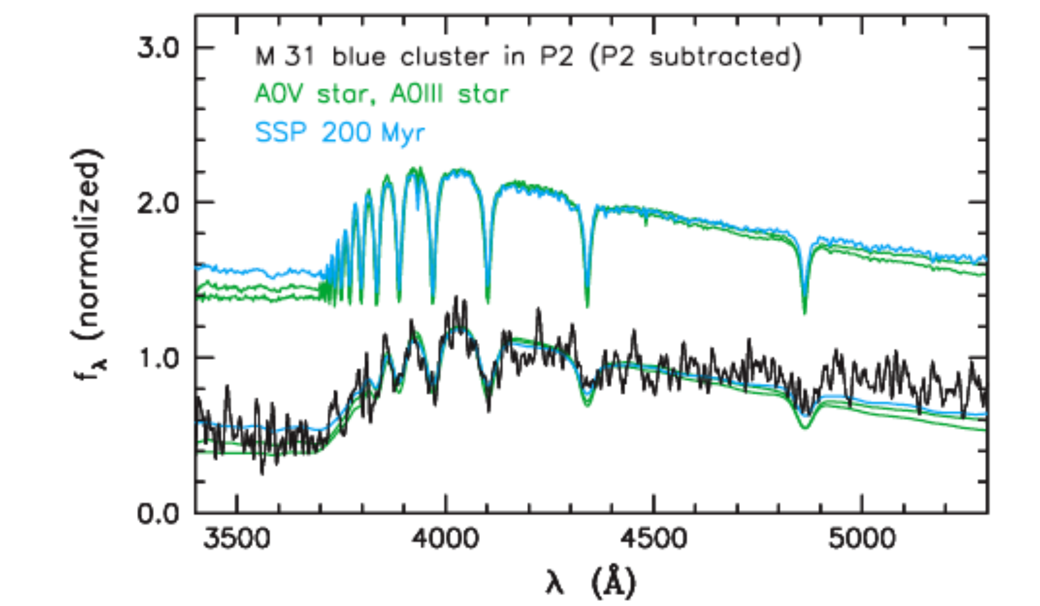
Does the P3 location have any luminous evolved red giants?

M31 triple nucleus

Bender et al. 2005







Discussion: G1

Even if G1 is a "nucleus" note that globular clusters are found in dwarf sperhoidal galaxies (5 in Fornax, of order 5 assoc. with the Sgr dwarf. Fornax cluster 4 may be a nucleus.

We find no evidence for dwarf sph nucleus; we argue that G1 is a bona fide luminous globular cluster.

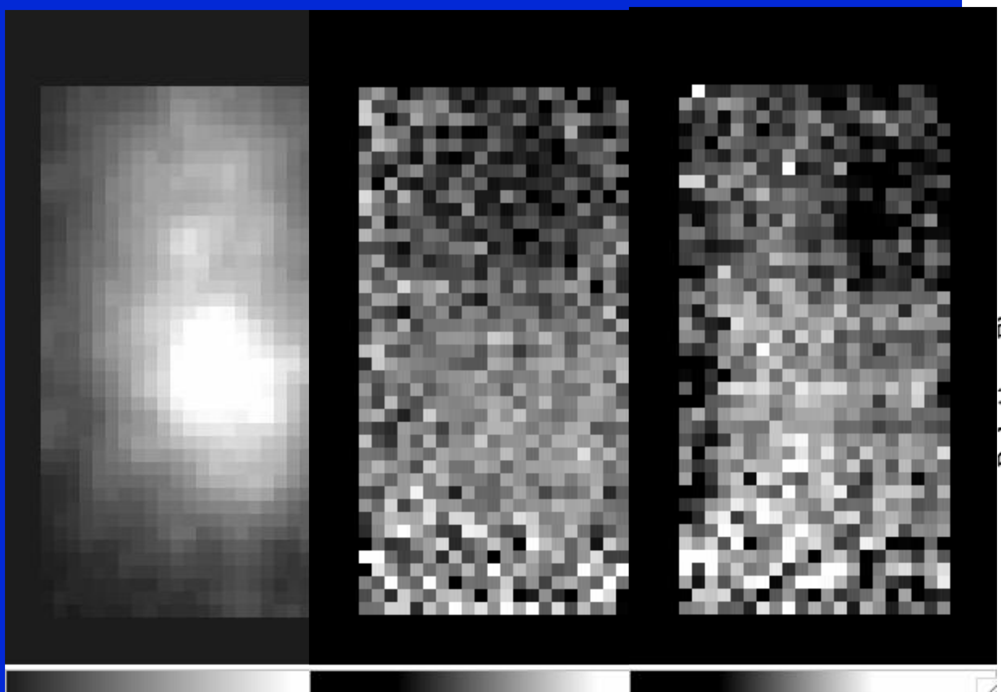
Low escape velocity in G1 (<100 km/sec) makes it difficult to grow a BH slowly over time. Since cluster could not retain much gas, difficult to grow by accretion.

If from accretion of stars and remnants, require a very massive "seed" black hole (equal mass BH ejected). (Portugies-Zwart & McMillan 2002)

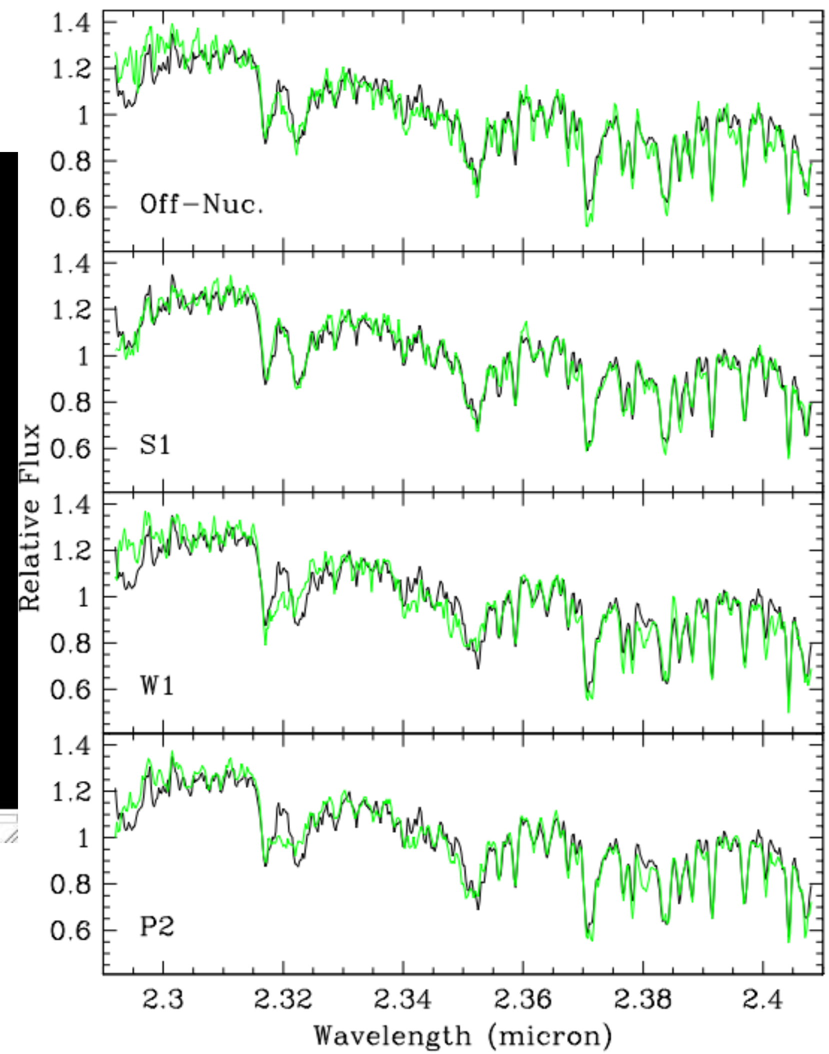
M15 is old, with no abundance spread. G1, omega Cen have abundance spread (multiple SNe, evidence that metal rich gas is retained).

No evidence for dark matter in either M15 or G1

Spectroscopy: subtle spatial variat



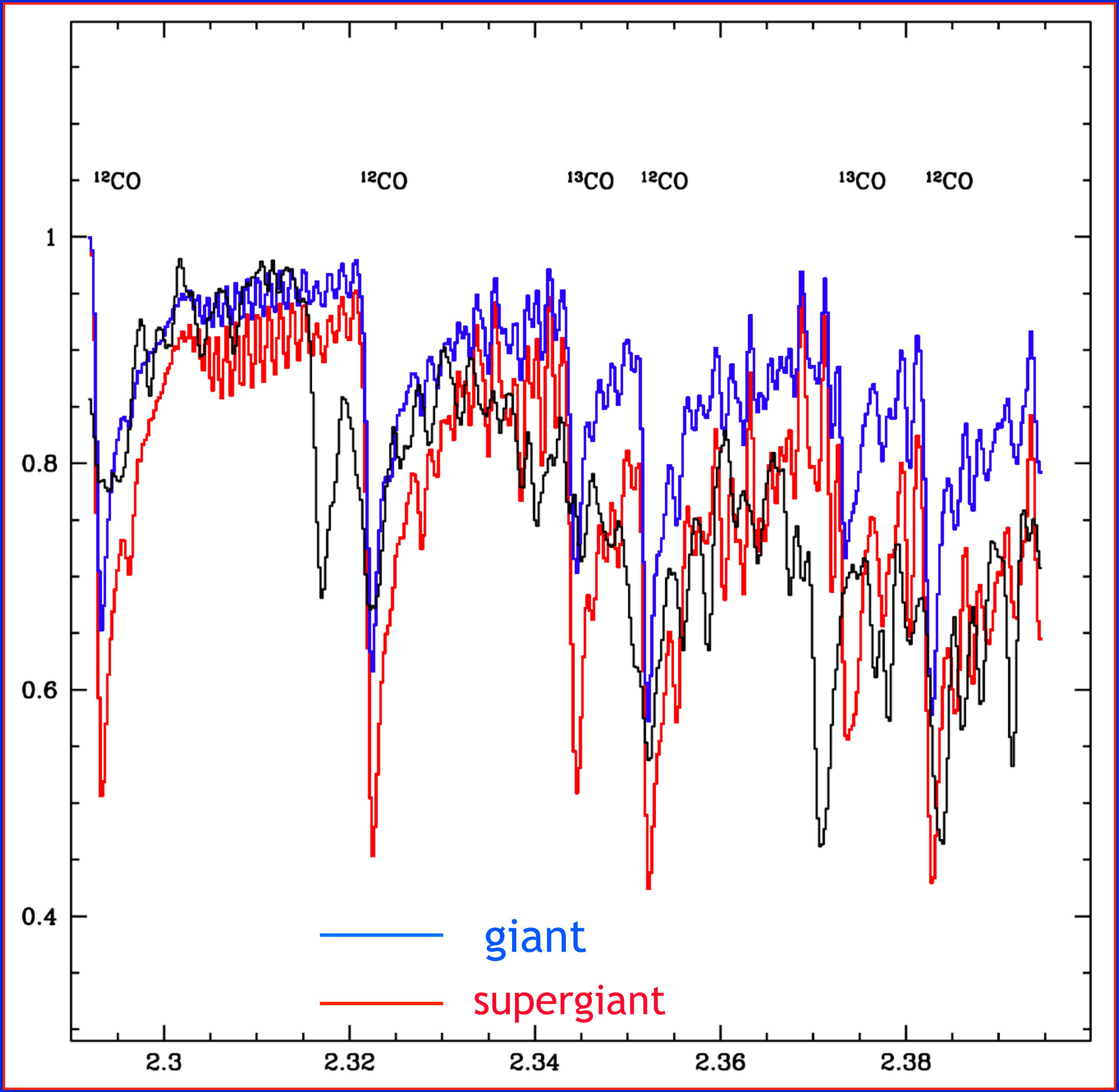
CO 2.32 + 2.385 um   2.29um



Off-nuclear decline not expected as int. age pop
Should have stronger CO lines.

Preliminary fit finds a composite spectrum for nucleus, not consistent with supergiants. Very bright supergiants would have been discovered with imaging.

Atmosph correction in progress.



AAS meeting, Austin, Jan 2008

Lu, Rich et al. in prep

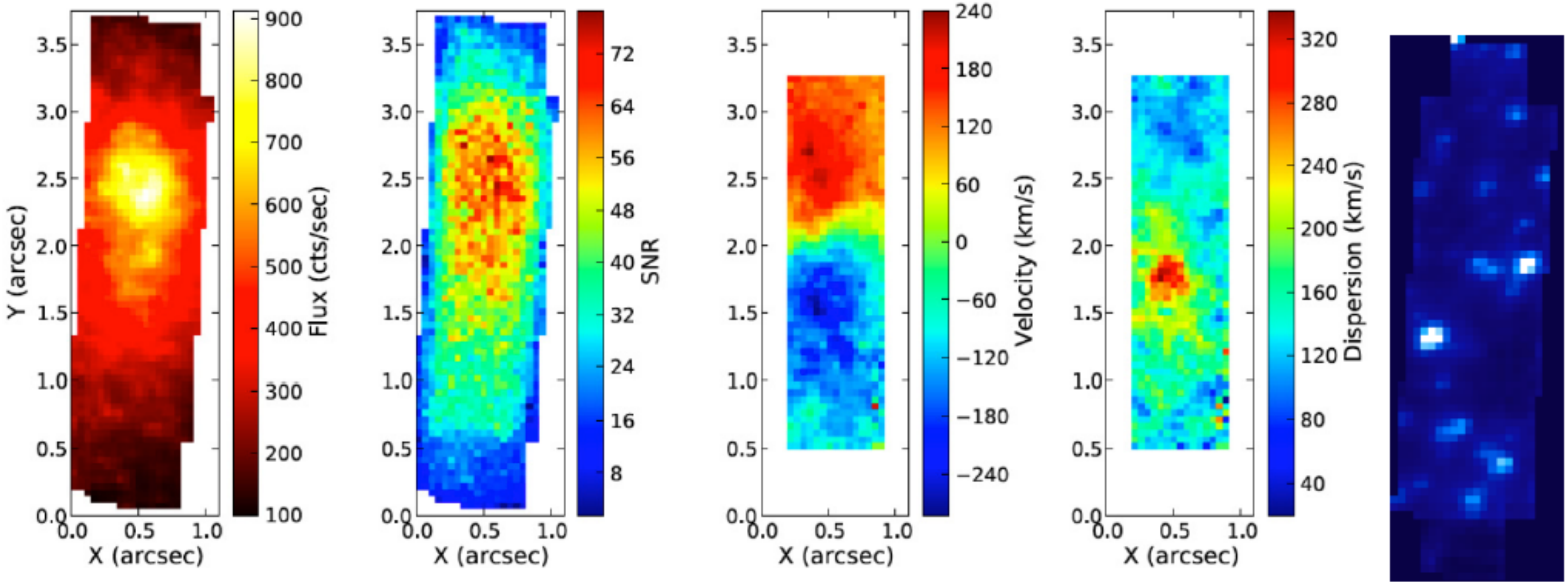


Figure 9- Infrared (2um K band) integral field spectroscopy of the M31 nucleus, obtained using OSIRIS at Keck II under this project (Lu and Rich et al. 2011, in prep). The field of view is aligned with the major axis of the M31 nucleus eccentric disk. Reading from left to right: image plane (all wavelengths collapsed together), S/N map, line-of-sight velocity field (with evident rotation), velocity dispersion field (notice the spike to 320 km/s at the position of nucleus P2 cf. Bender et al. 2005) where the black hole is proposed to reside. This is the first 2D velocity field of M31 obtained at this spatial resolution. Each pixel is an integrated light spectrum; these are being modeled for metallicity (Rich & Origlia in prep). (Far Right) Resolved red giants in the M31 bulge, only 200 pc from the nucleus, using Keck II/OSIRIS and laser guide star; unfortunately S/N~3 per spectral resolution element; spectroscopy of individual M31 red giants impossible at present.