The nucleus of the Sgr dSph galaxy and M54: A window on the process of galaxy nucleation

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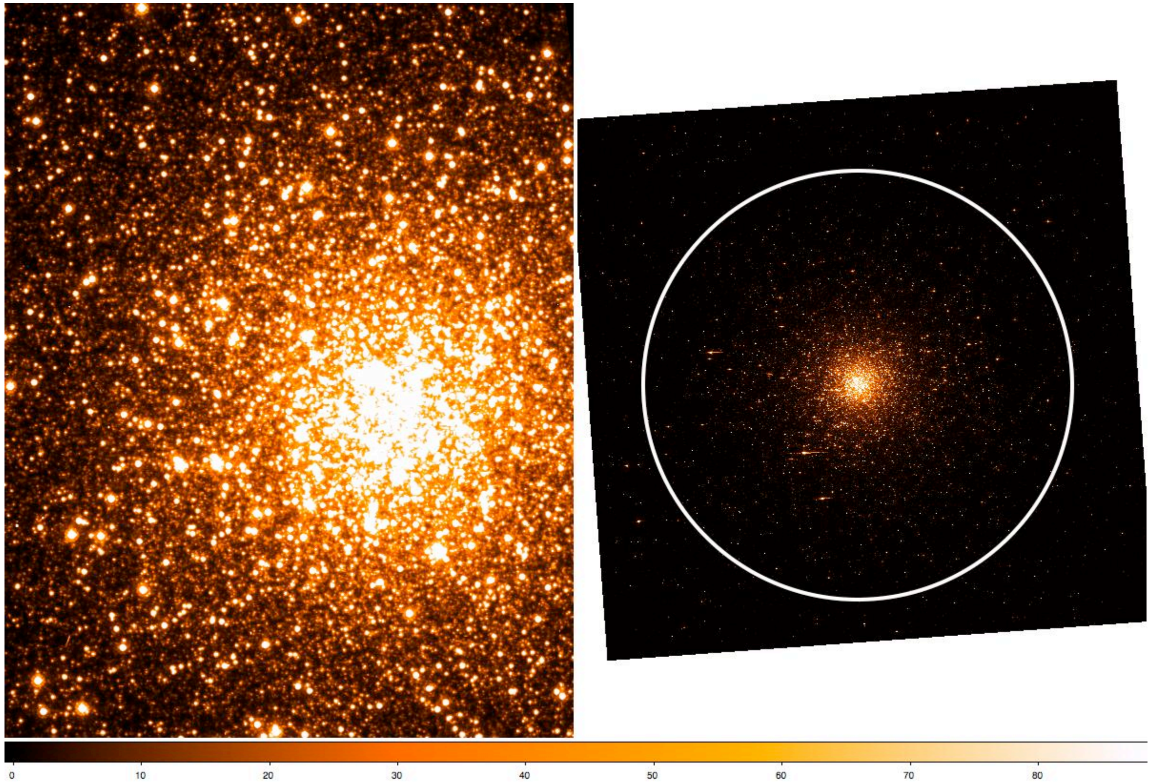


Looking into a nucleus with unprecedented detail (structure & kinematics): the case of the Sgr dSph.

Results from:

Monaco et al. 2005, MNRAS, 356, 1396 (M05)

Bellazzini et al. 2008, AJ, 136, 1147 (B08)

Ibata et al. 2009, ApJ, 699, L169 (I09)

Carretta et al., 2010, ApJ, 714, L7 (C10)

Involved in this project (at large):

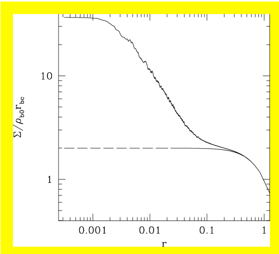
Ibata,R.A.; Chapman,S.C.; Mackey A.D.; Monaco,L.; Irwin, M.J.; Martin,N.F.; Lewis,G.F.; Dalessandro, E.; Ferraro, F.R., Lanzoni, B.; Miocchi, P.; Varghese, A.; E. Carretta; A. Bragaglia; *R. Gratton; S. Lucatello et al.*

ESO Workshop:
"CMO: The Stellar Nuclei – Black Hole Connection"
Garching, June 22-25, 2010

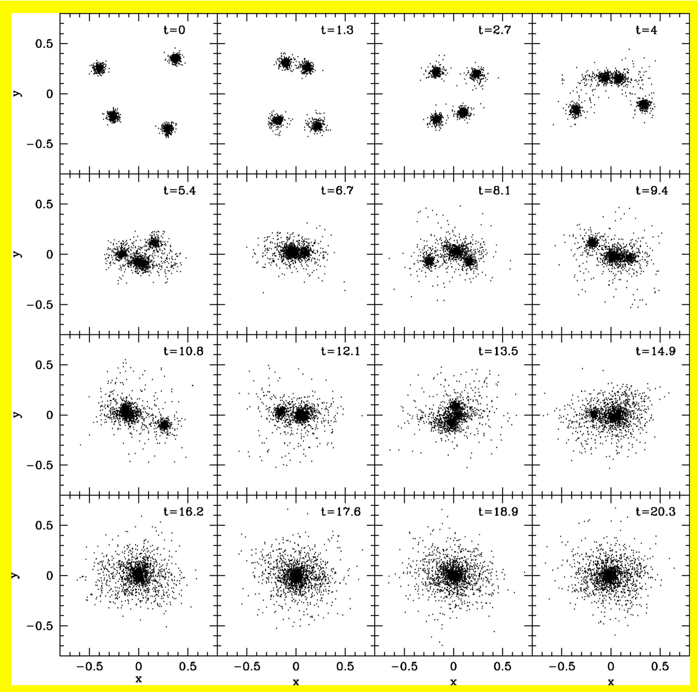
Stellar nuclei are ubiquitous in $M_B>-20.5$ galaxies: how do they form?

Two proposed channels

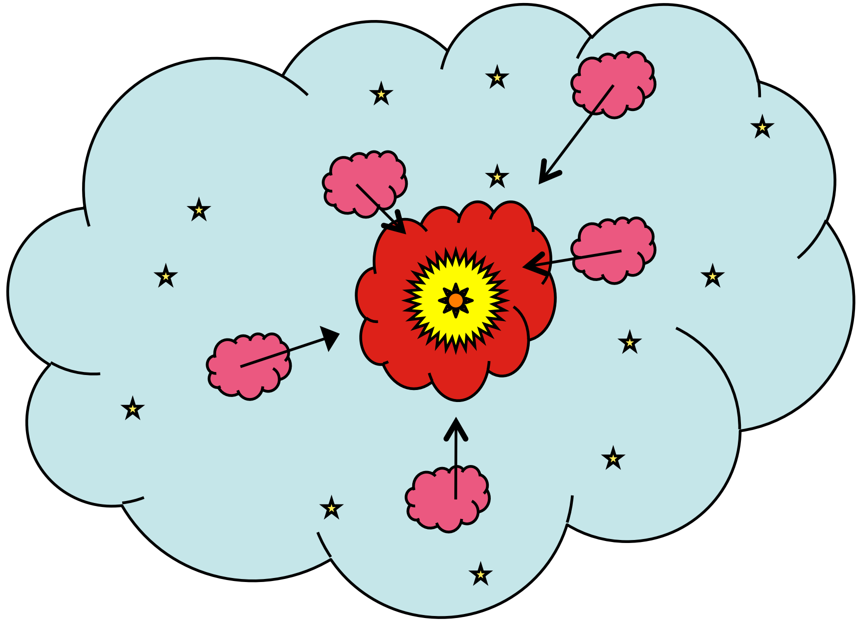
Orbital decaying and merging Globular Clusters



Capuzzo-Dolcetta & Miocchi (2008)



In situ: processed gas piles up at the bottom of the galaxy potential well until star formation is ignited and a compact stellar system is formed



See Grant et al. 2005 for a thorough discussion of formation models

Stellar nuclei: how do they form?

Evidences supporting both scenarios, for instance

-Lotz et al. (2004) found that nuclei of dEs have the same color of typical metal poor globular clusters

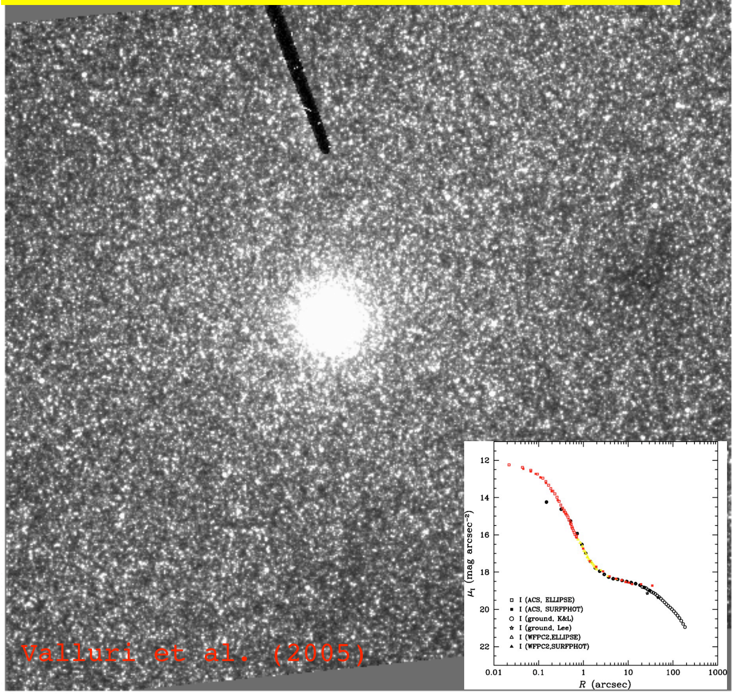
-Rossa et al. (2006) claims that the spectra of most of the nuclei of spirals show evidence of the occurrence of subsequent episodes of SF

-Barazza et al. (2003), Cote' et al. (2006): off-centered nuclei

-Geha et al. (2003): nuclei share FP properties of GCs

Can we get a deeper insight from local systems?

NGC 205 ACS-HRC. FoV = 29" X 26"



M33. FoV = 70" X 113"

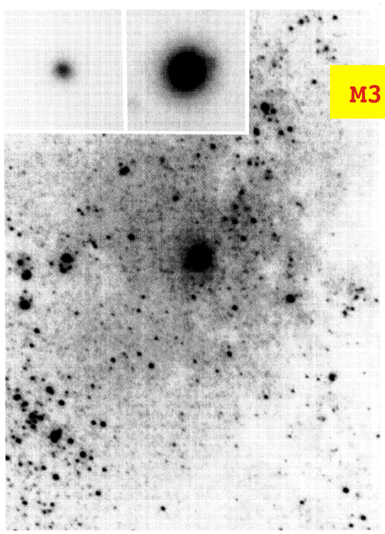
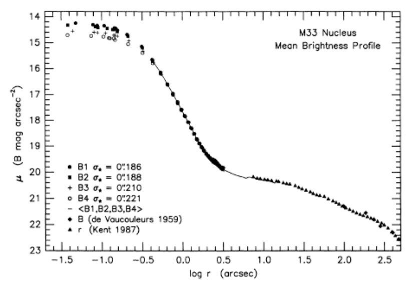


FIG. 1. Central 70"×113" of M33. This is a 150 s, B-band image taken with the CFHT and HR Cam; the seeing is $\sigma_* = 0.''188$ (image B2 in Tables 1 and 2). Northeast is at the top. The insets show the nucleus at four times the scale of the main figure and at two levels of lower contrast.

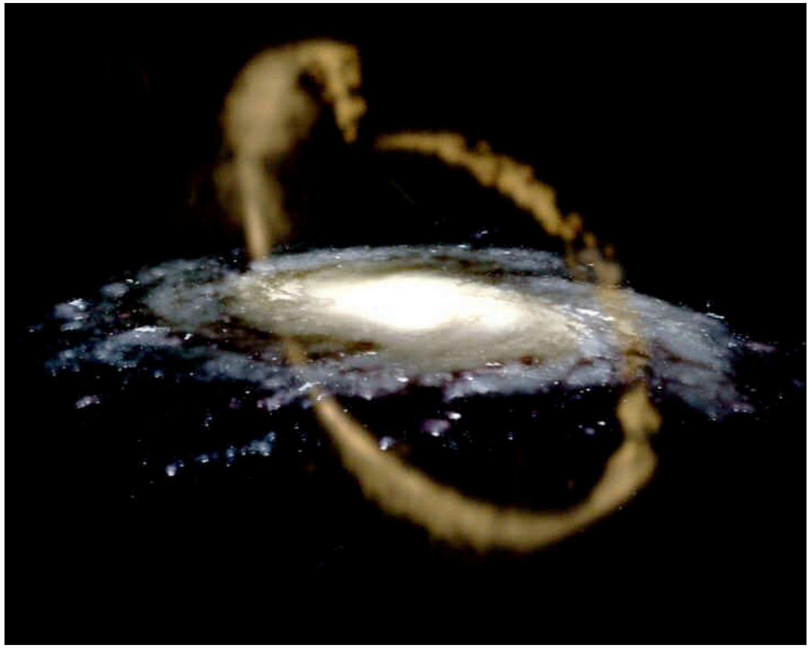
J. KORMENDY AND R. D. MCCLURE: THE NUCLEUS OF M33

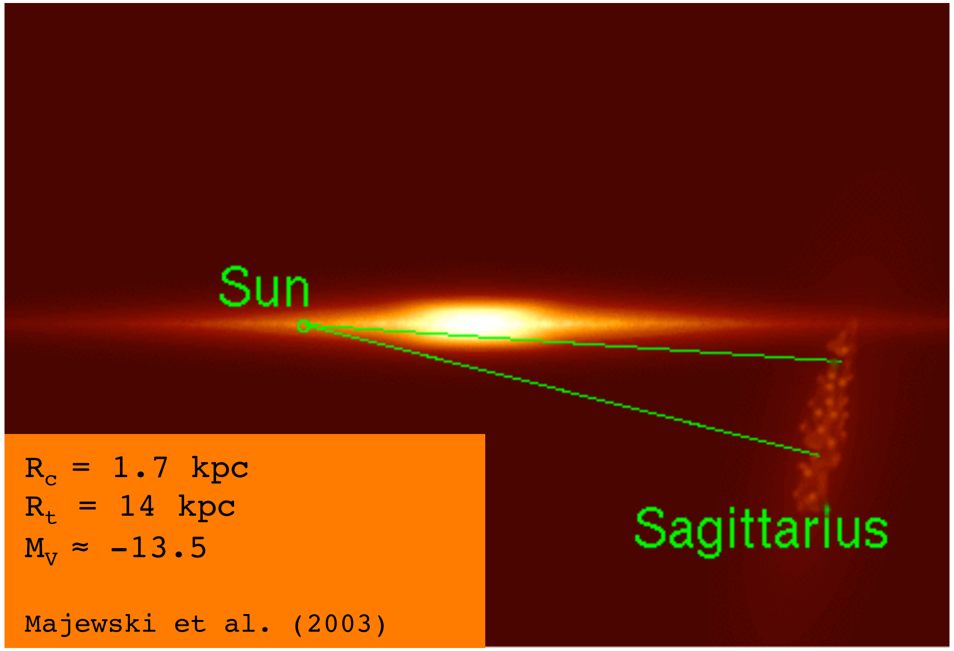


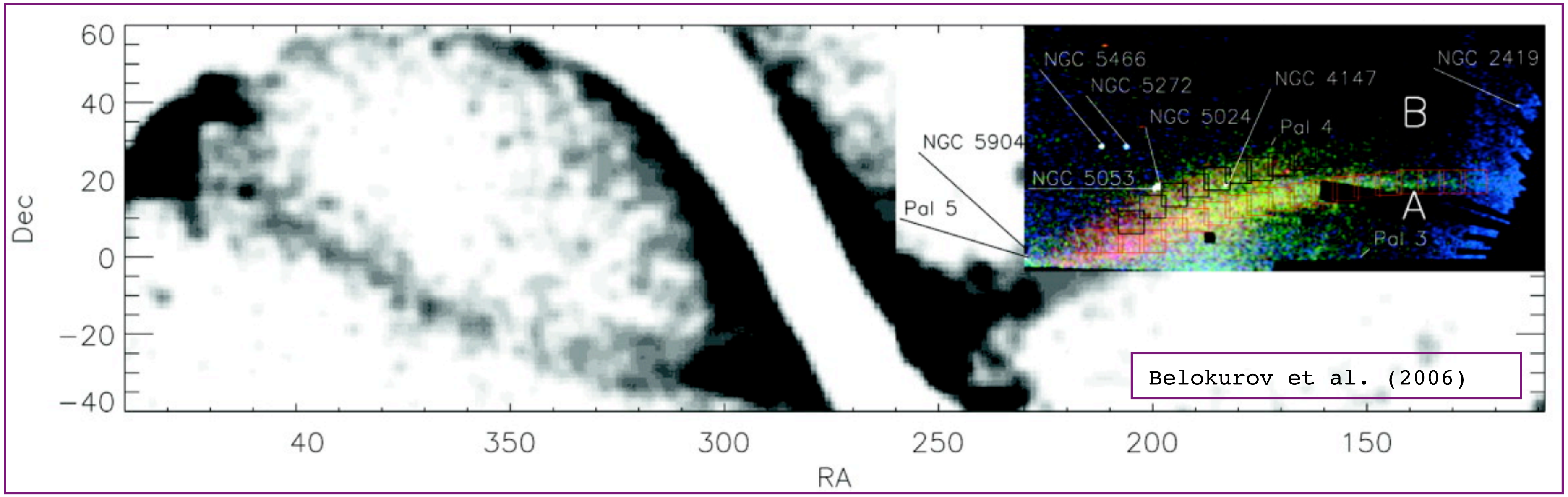
The nearest nuclei (NGC205, M33) are unresolved even with the highest resolution cameras of HST
The nuclear cluster of the MW is
Affected by strong extinction

Here comes Sagittarius dSph !

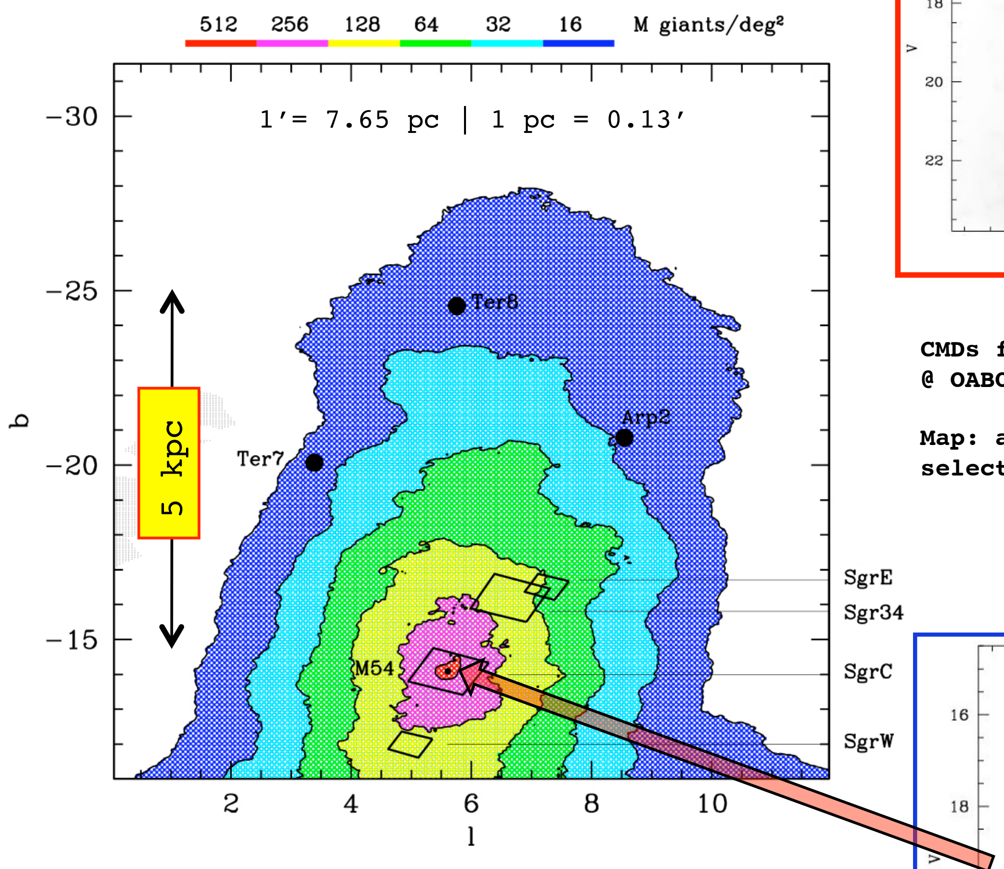
Sgr dSph: a disrupting dwarf satellite of the Milky Way at 26.3 Kpc from us

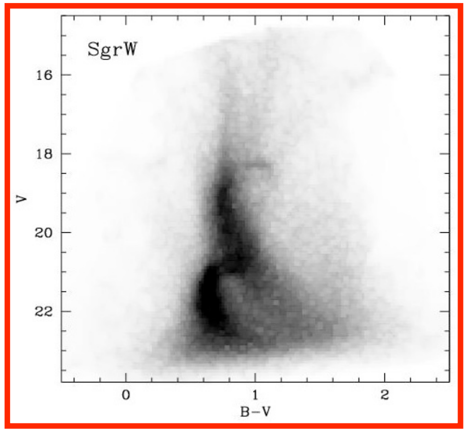


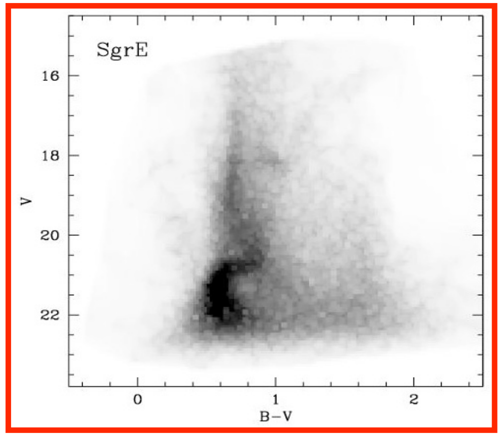




Sgr dSph: The Main Body

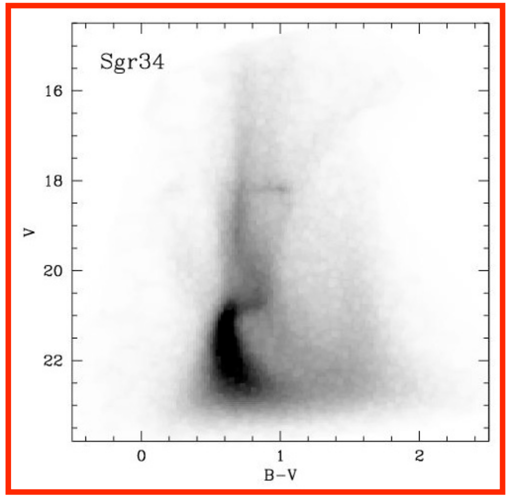


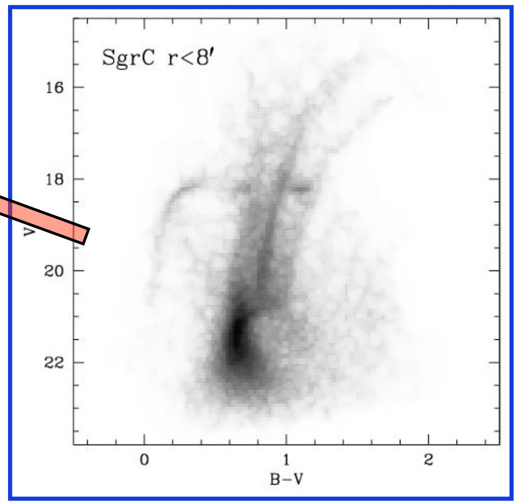


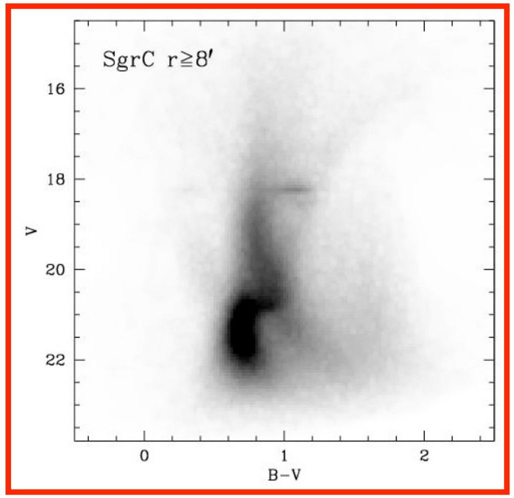


CMDs from the Sgr WF survey @ OABO: Bellazzini et al. 2006

Map: adaptive density on color selected M-giants from 2MASS





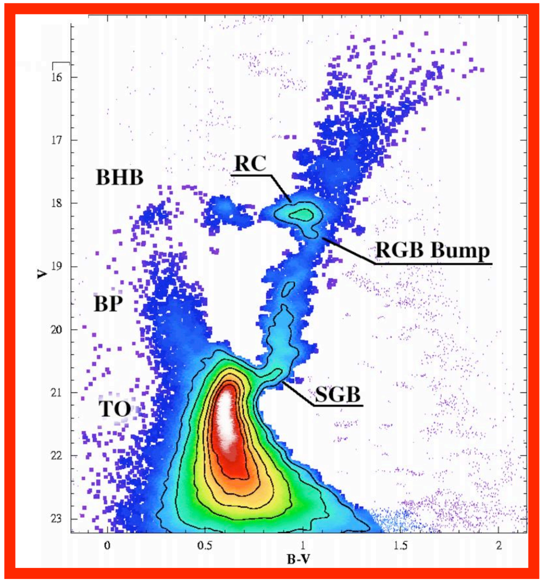


The Main Body is huge, several kpc; the Core Radius is 1.7 kpc

We focus on the innermost 70 pc

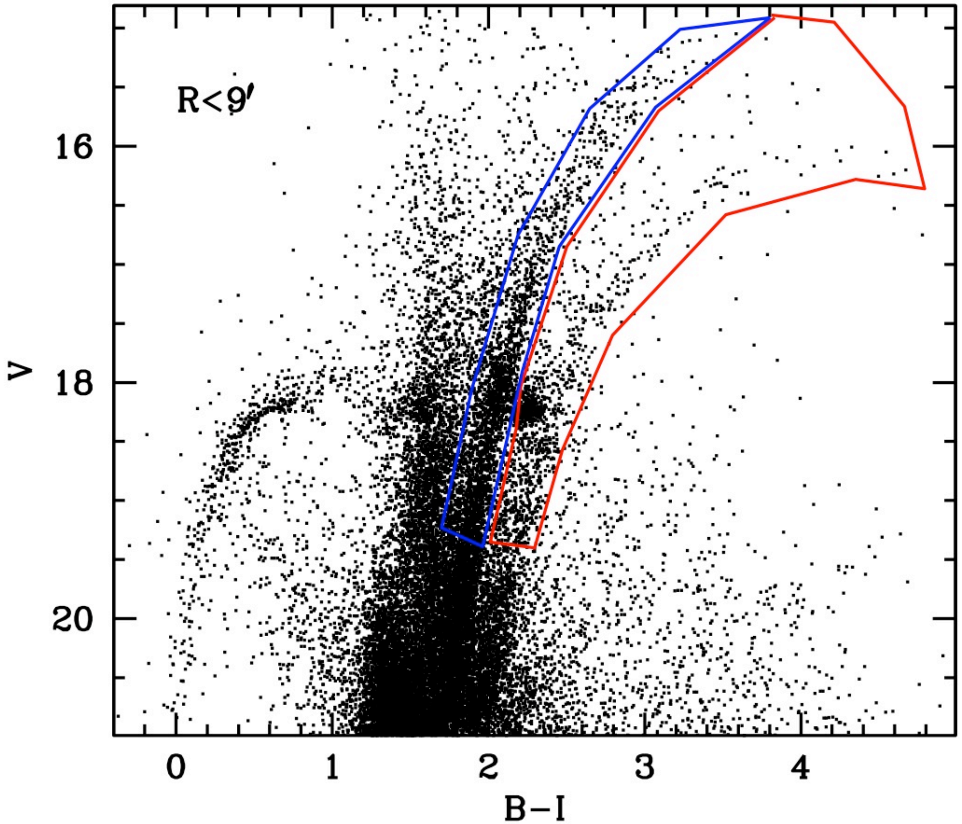
Sgr is dominated by an
intermediate-age metal-rich population;
M54 is old and metal-poor:
they can be disentangled

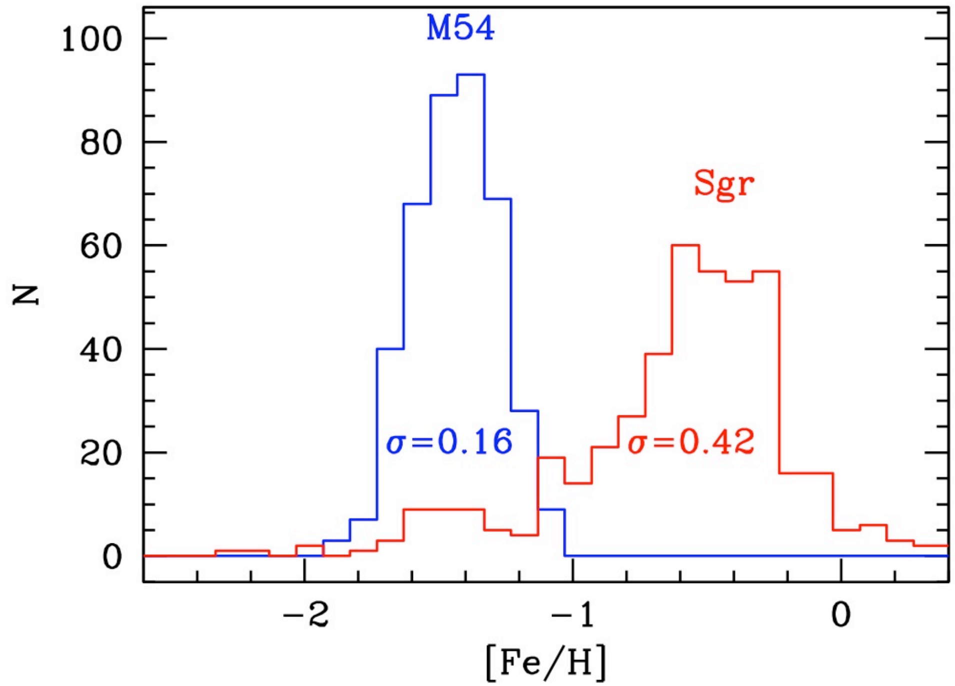
**Layden & Sarajedini 2000, and
Majewski et al. 2003 already noted
The presence of a central overdensity
Of Sgr stars (red RGB, Red Clump).**



From Monaco et al. 2001

M54 Sgr





Bellazzini et al. 2008

Sgr has its own nucleus (Sgr,N): even removing M54 by magic Sgr would appear as a nucleated galaxy [with a red nucleus]

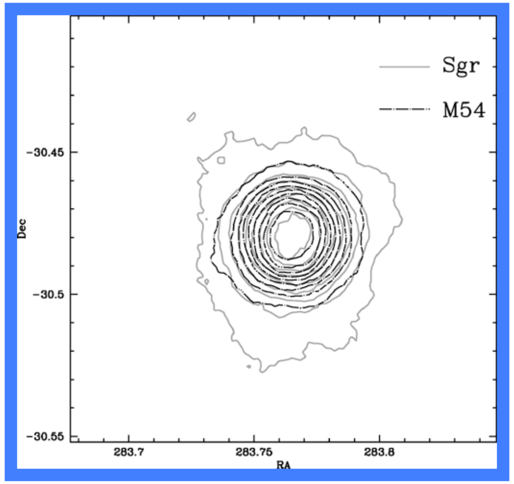
Sgr,N and M54 appear concentric, within the uncertainties (a few arcsec)

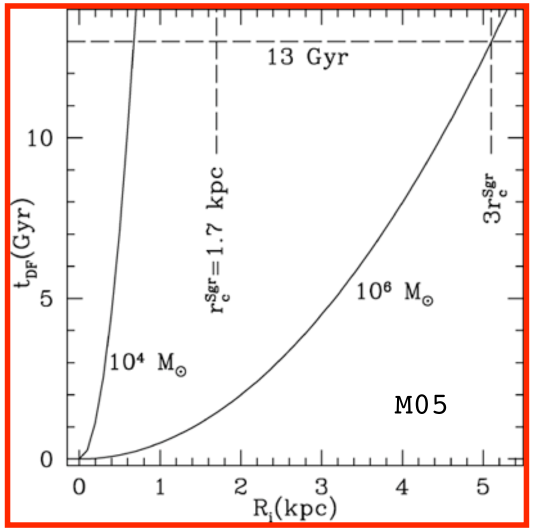
At the center of the system the light surface density of M54 is ≈ 3 times that of Sgr,N, r_h of the best-fit KM is 2 times as large

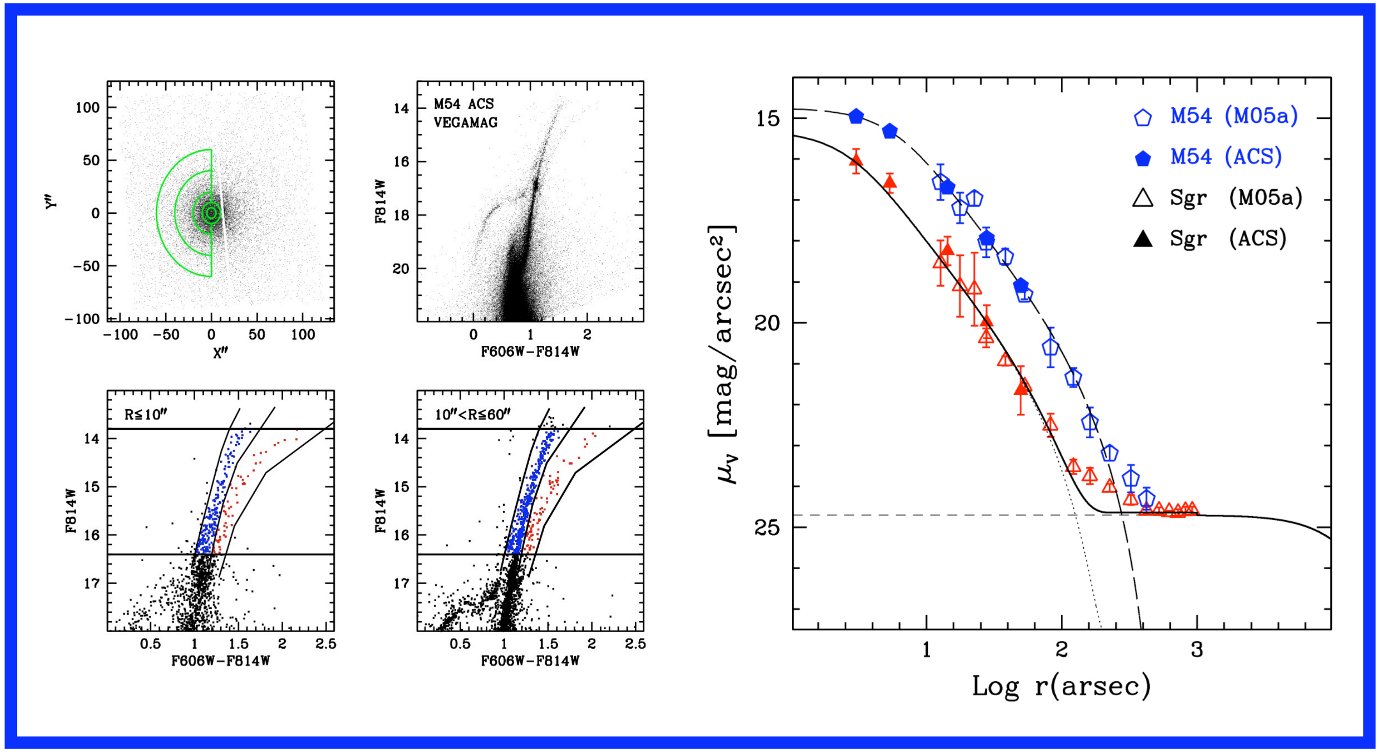
The total luminosity of M54 is ≈ 7 times that of Sgr,N

The coincident position requires an explanation:

1) Two subsequent epochs of SF on similar spatial scale
2) M54 was driven there by Dynamical Friction (compatible)

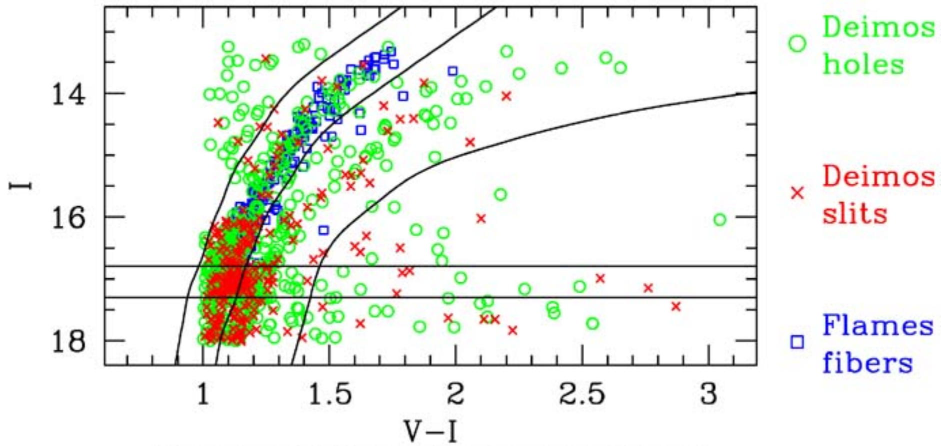


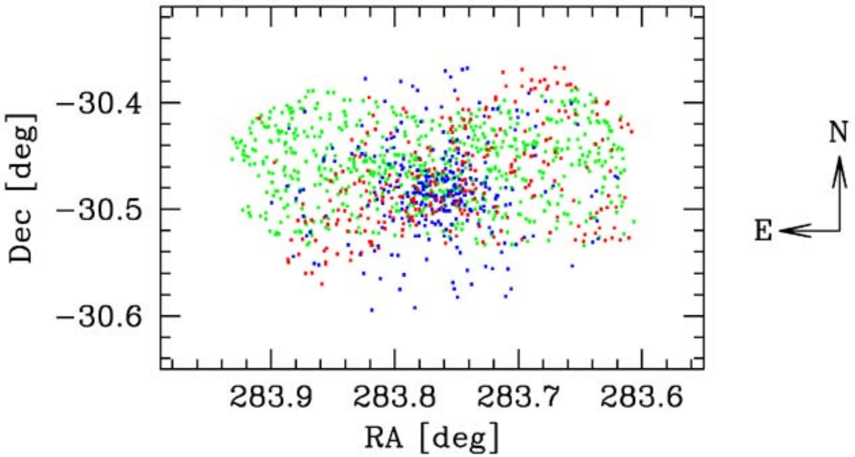


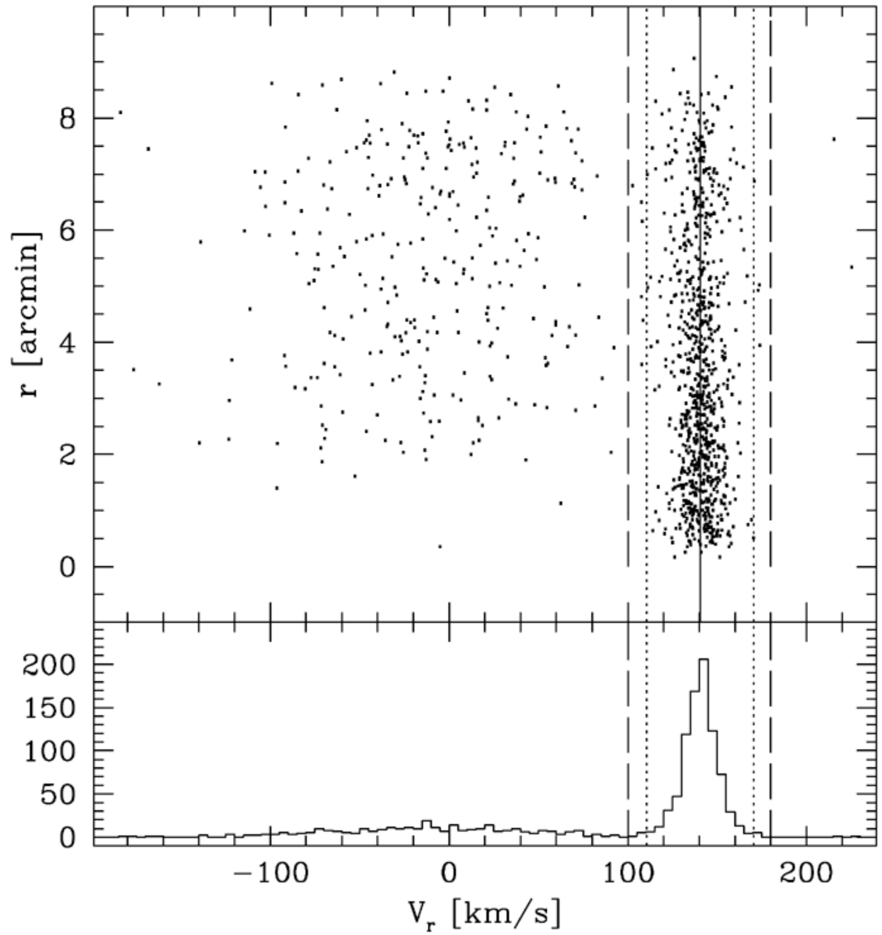


In Monaco et al. (2005) we concluded that the observational scenario was compatible with the sinking of M54 into the Sgr Nucleus by Dynamical Friction. Let’s have a look at kinematics!

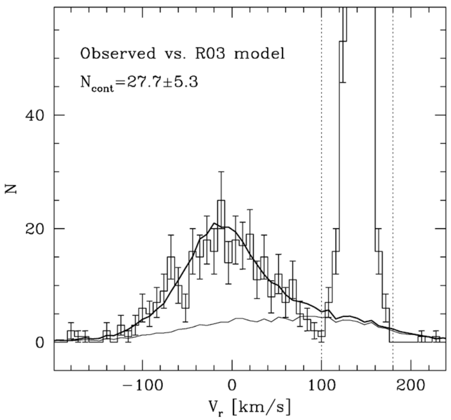
We got Vr (<2 km/s accuracy) for 1152 candidate M54 & Sgr,N stars (within ~9’ ~70 pc) from CaT spectra taken with DEIMOS@Keck and FLAMES@VLT (B08)

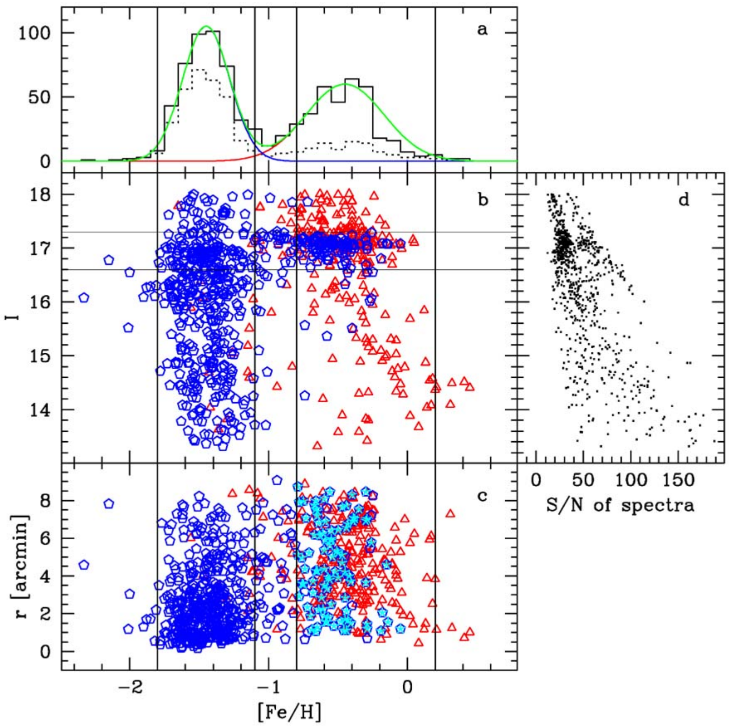


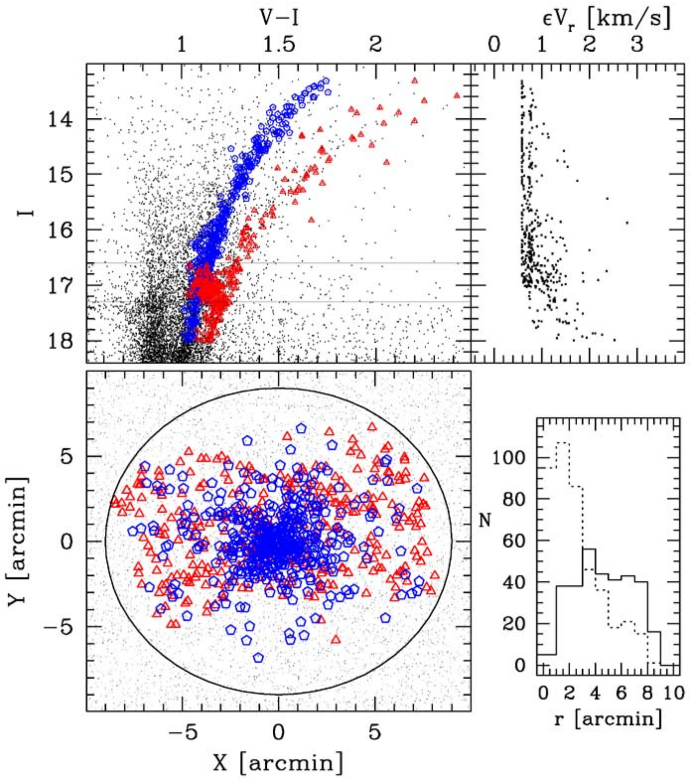




We made many internal and external checks on our Vr.
We used the CMD, Vr and metallicities from CaT to select (conservatively) two samples as cleanest as possible of *bona fide* M54 (425 stars) and Sgr,N (321) members.





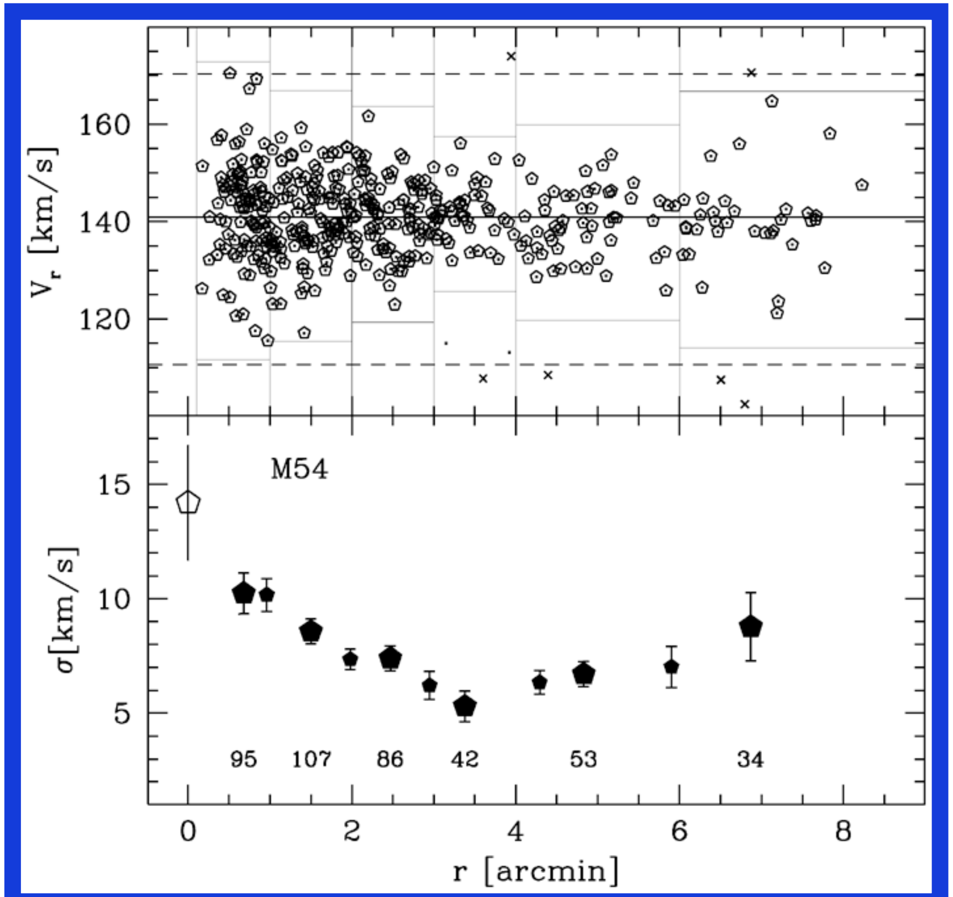


The first relevant result is that the mean systemic velocities of the two systems concide within <1 km/s

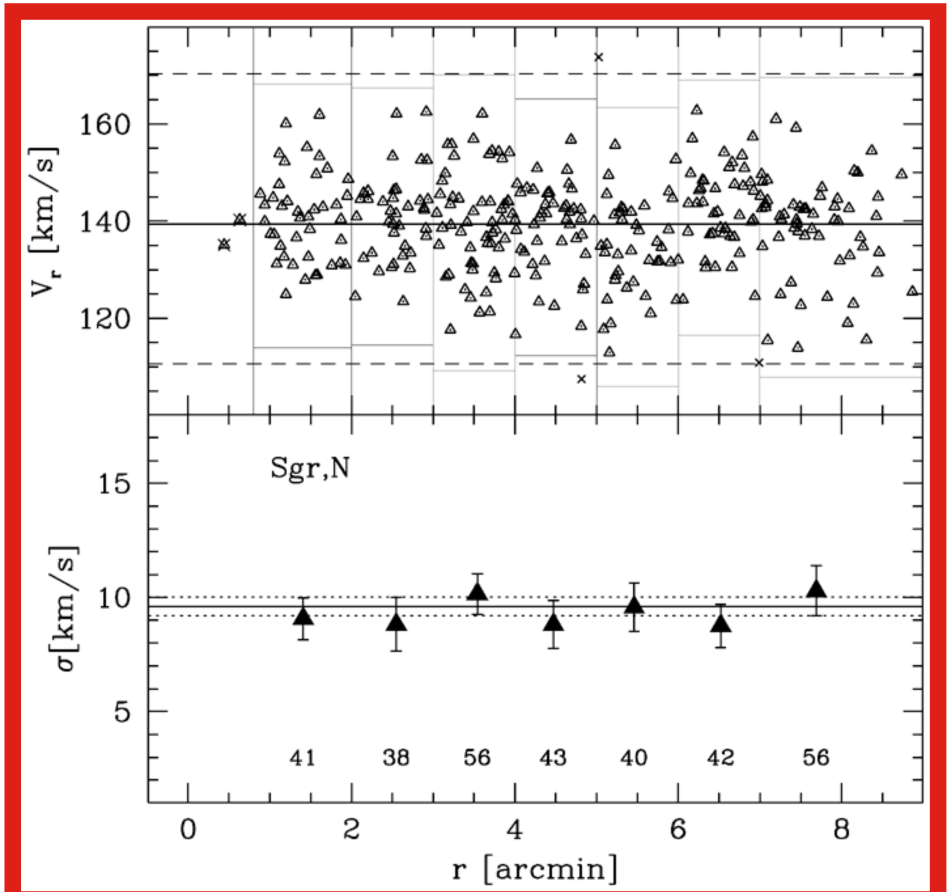
They are in the same place AND they have the same V_r

We used the clean samples to obtain robust velocity dispersion profiles: they are clearly different

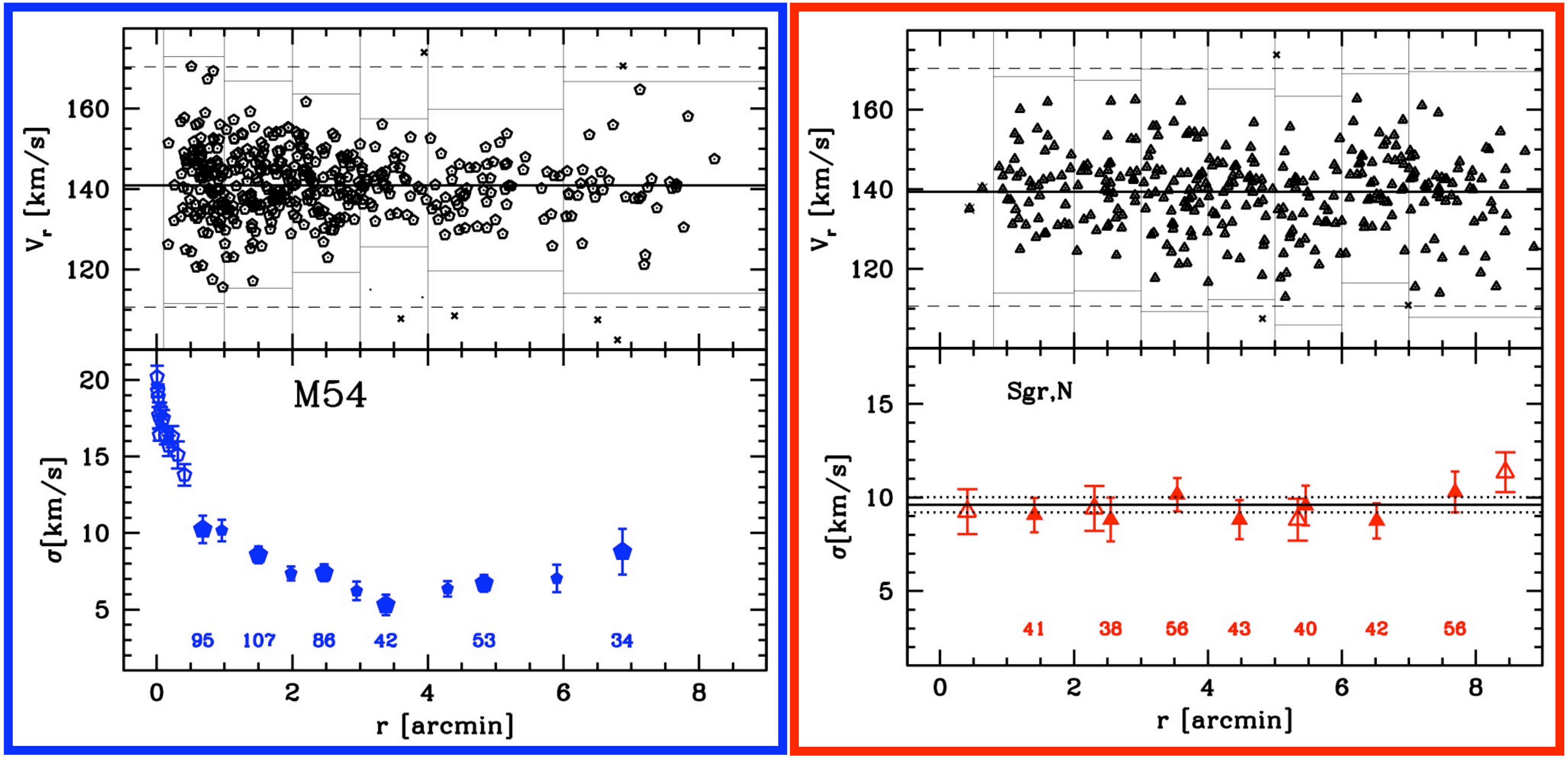
M54



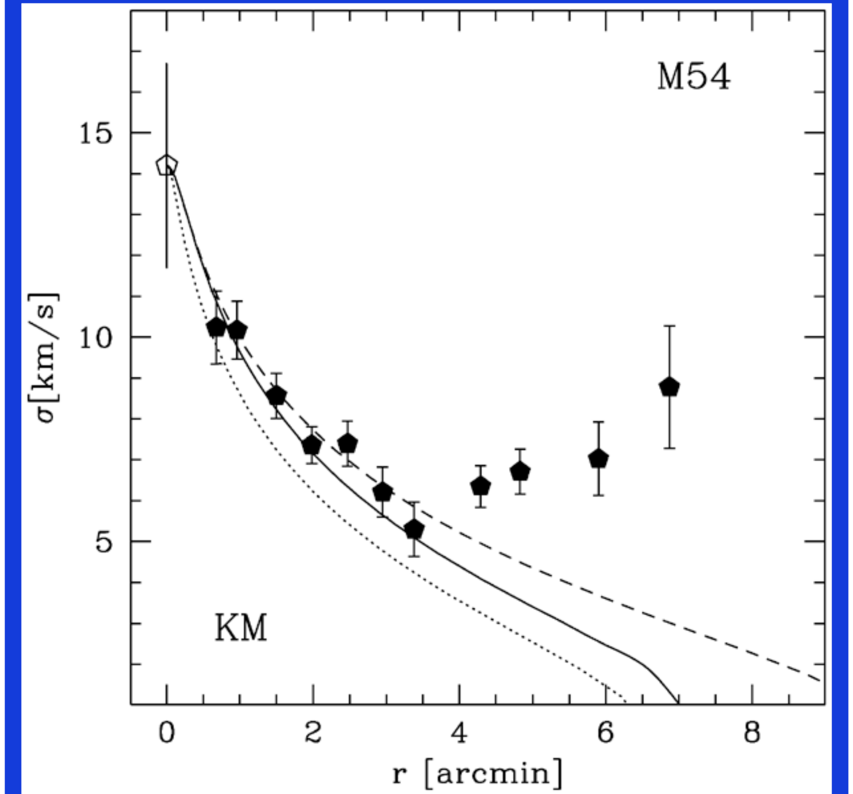
Sgr,N

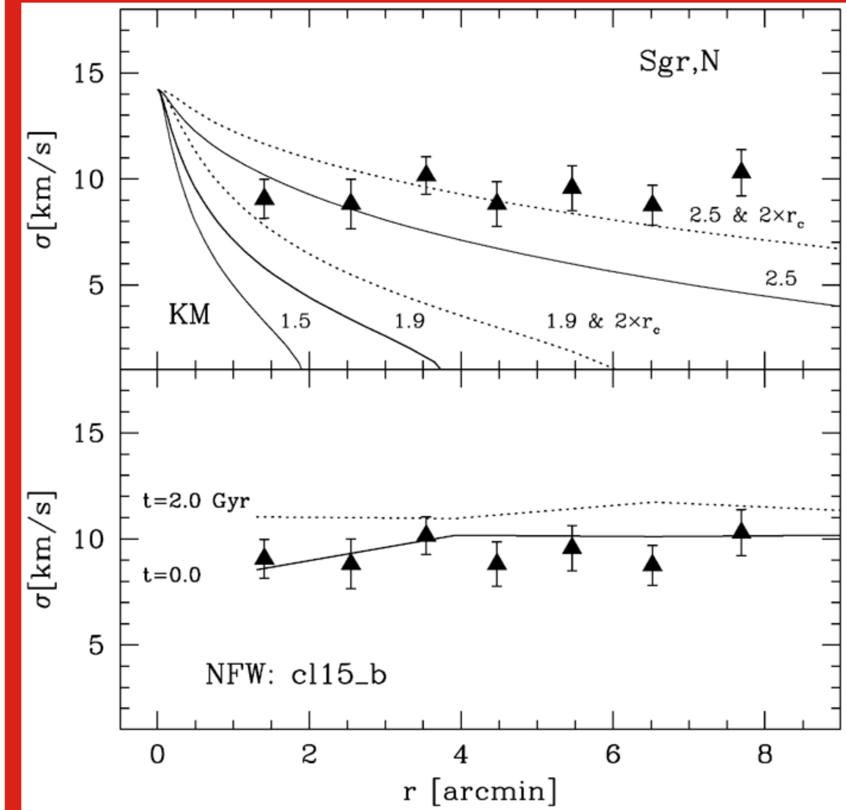


Adding a new set of FLAMES spectra of single stars + a tile of ARGUS IFUs at the center of M54 from I09



Comparison with models



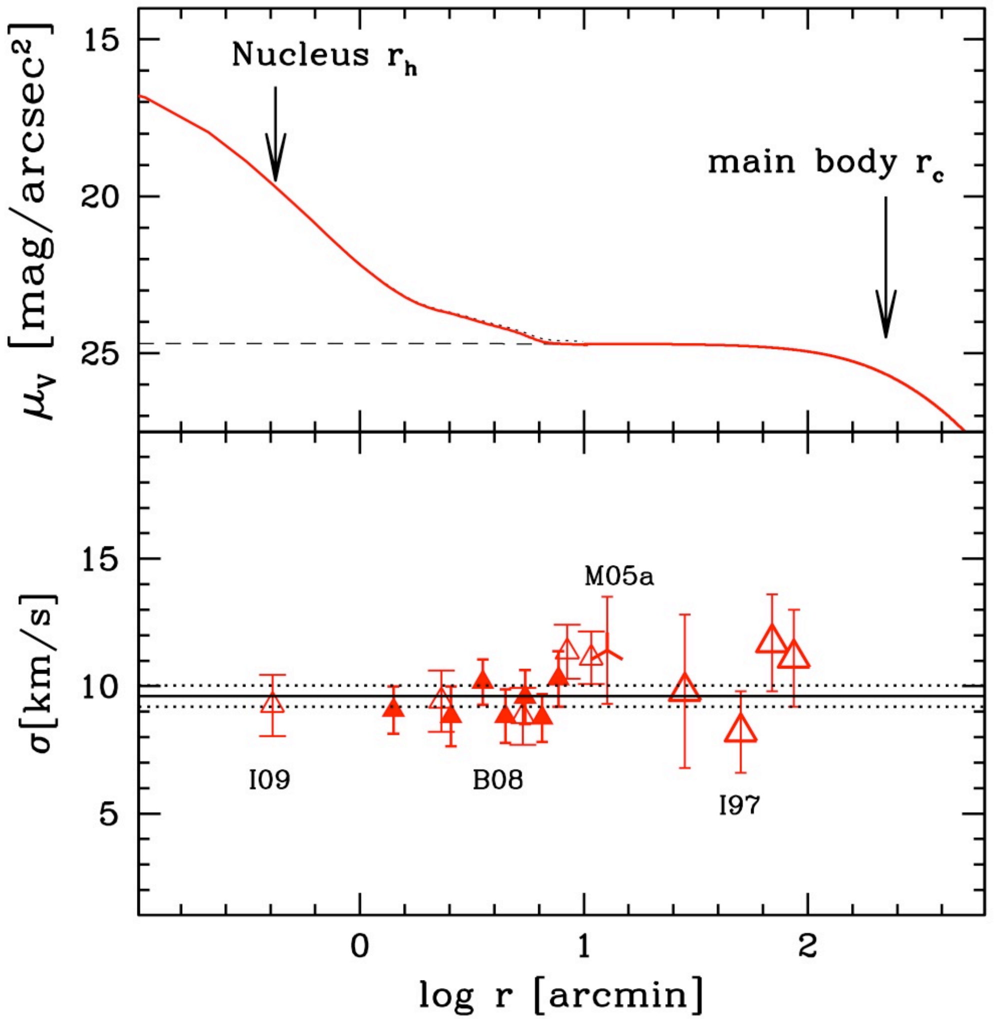


The velocity dispersion profile of M54 is very well fitted by the King (1966) model that best-fits also the SB profile out to a radius (3.3′=25 pc) including 90% of the cluster light/mass. A classical GC Mass-follow-light model is OK!

The velocity dispersion profile of Sgr,N is consistent with a NFW model roughly appropriate for the whole body of the galaxy (V_c=17 km/s).
A King model can't do the job

Does the velocity profile of Sgr change Within the nucleus?

We merged together all the velocity measures available in the literature for the Sgr galaxy



The >3000× nuclear increase in luminosity density
Does not correspond to a change in the kinematics:

the velocity profile inside and outside the nucleus is the same.

Clearly NOT consistent with (isotropic) mass-follows-light models

Two stellar systems lying in the same place, feeling the same potential and having widely different kinematics

↓

Different equilibria

↓

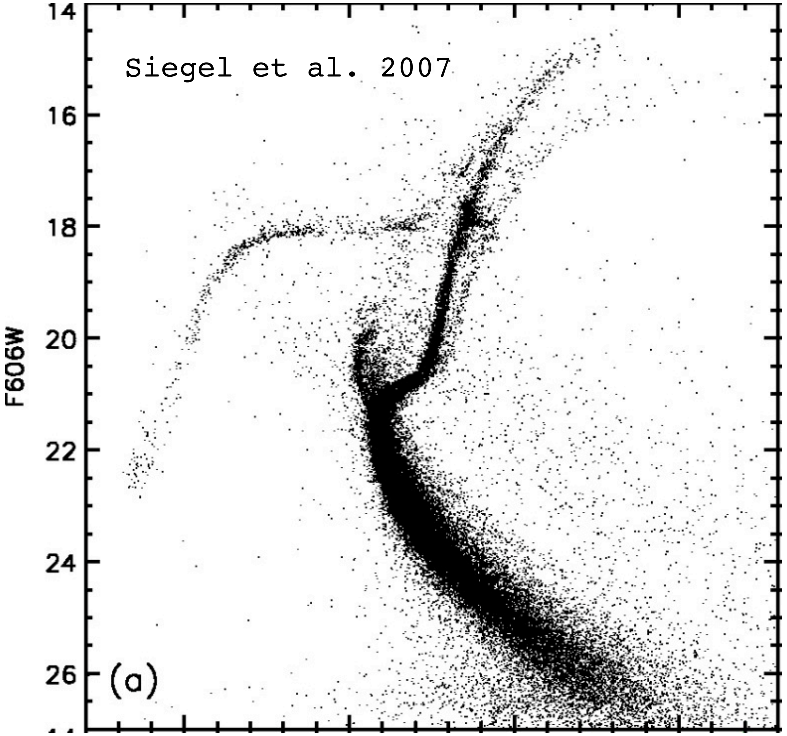
Different initial conditions

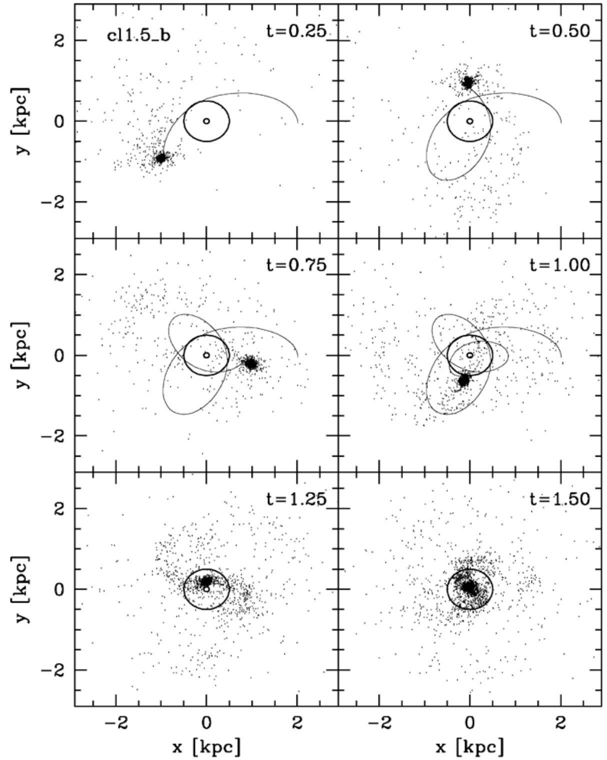
↓

Different origin

Attempting an interpretation:

Probably non the only one but the most convincing
(in our view! See the papers)

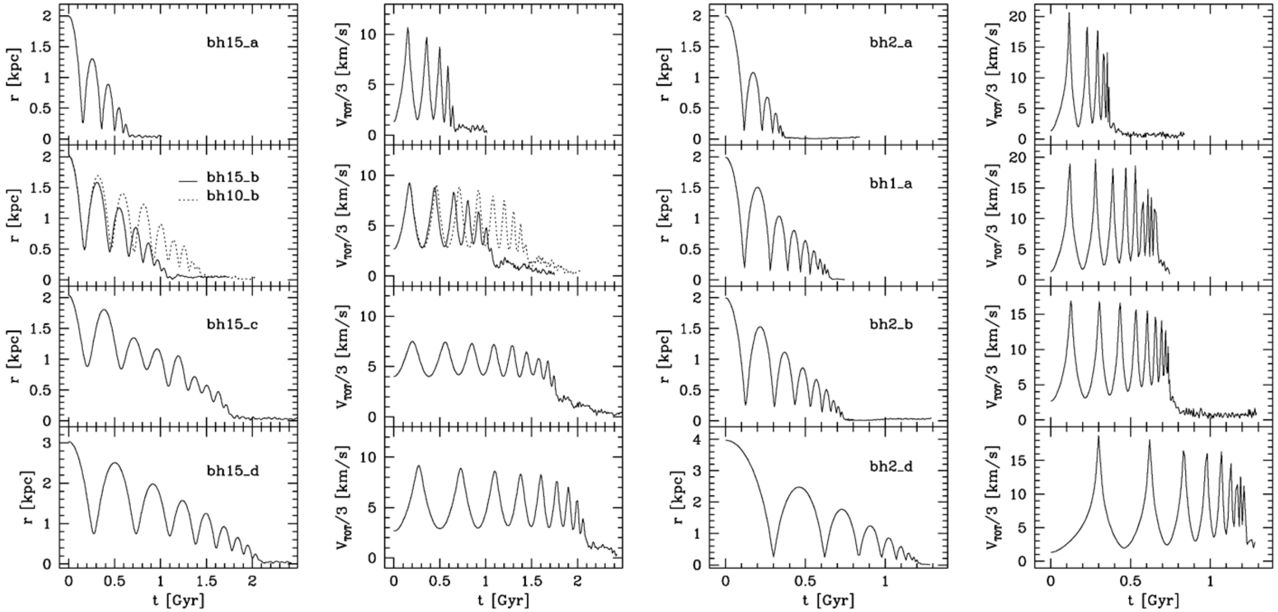


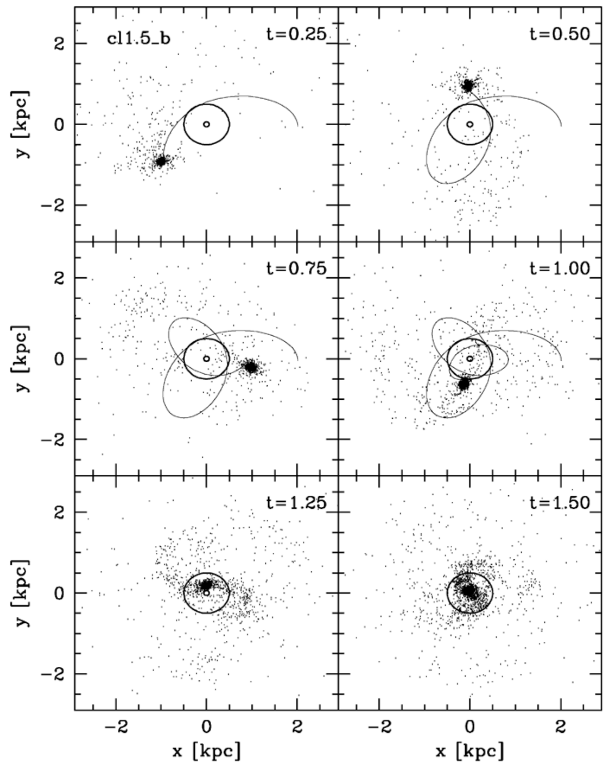


Sgr,N formed in situ from the piling up of gas processed by the various generations of stars at the very bottom of the Sgr potential well. In line with this it hosts the youngest stars of the whole Sgr galaxy.

M54 born somewhere within the Sgr galaxy as a classical massive metal-poor GC, and (later)it was driven to the center of Sgr by dynamical friction. An extensive set of dedicated N-body simulations indicates that this is realistic.

Driving M54 at the (very) center of Sgr





M54 reaches the center of Sgr
($r_{apo} \leq 30$ pc)
With velocity difference < 2 Km/s

in less than 3 Gyr from a range of
Realistic initial conditions (if a
NFW halo is assumed as the model for
Sgr

A suite of N-body experiments with
falcON (Dehnen 2000, 2002)

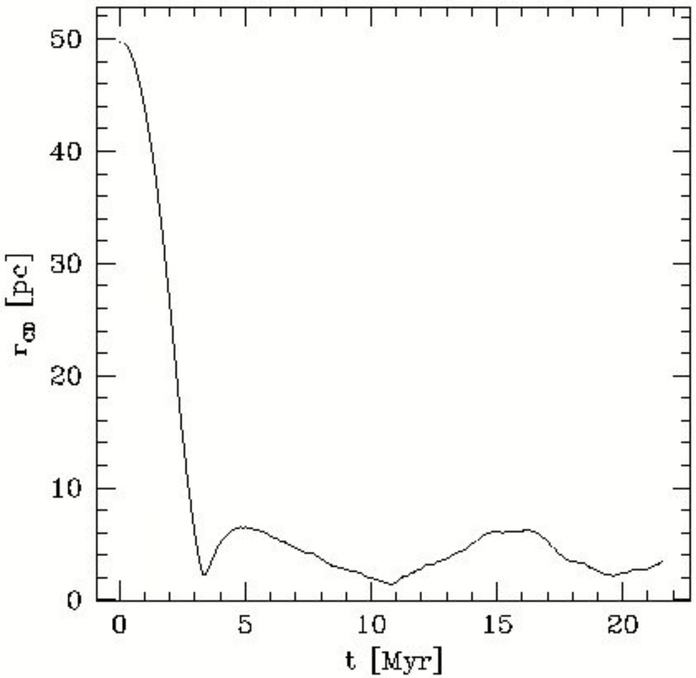
Sgr: NFW 10^5 particles

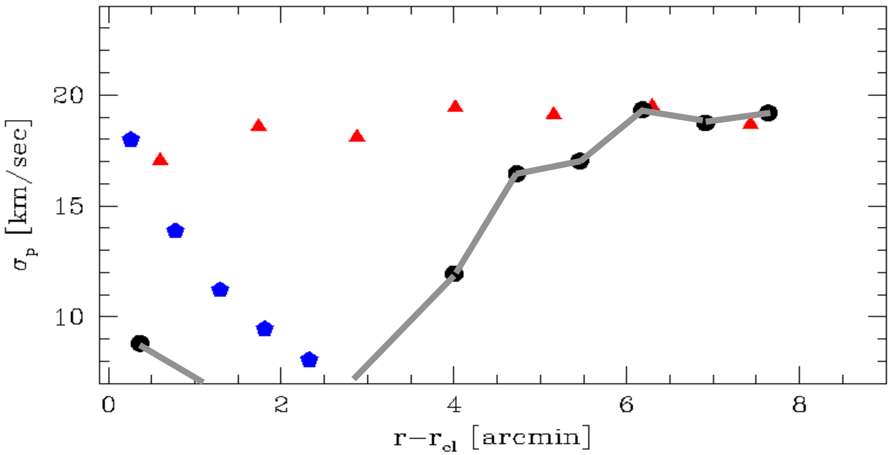
M54: 1 massive particle / 10^4 particles

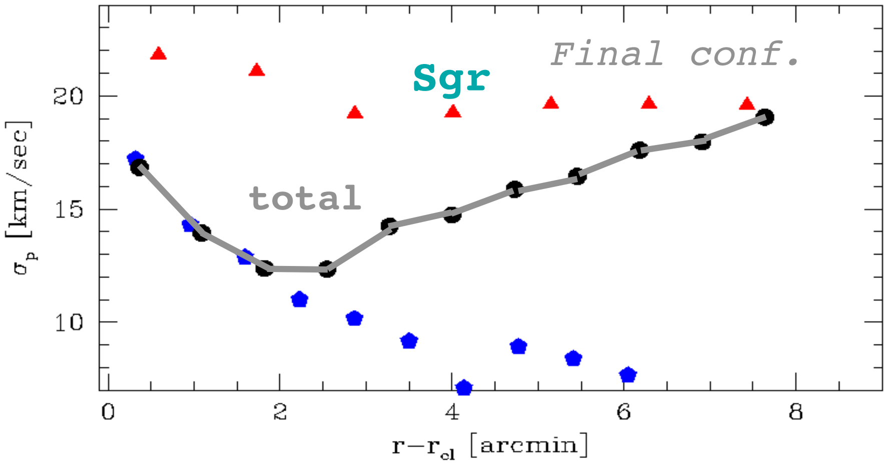
Wide range of initial conditions

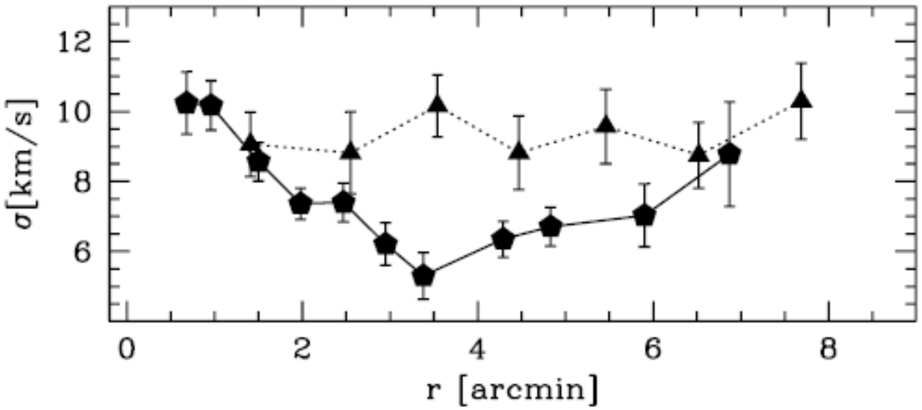
A higher resolution simulation of the latest phases by Paolo Miocchi.
- Initial conditions from one of the B08 experiments
- 10^5 (M54) + 10^5 (Sgr) particles; evolved using the treecode by Miocchi & Capuzzo Dolcetta (2002)

Driving M54 at the (very) center of Sgr

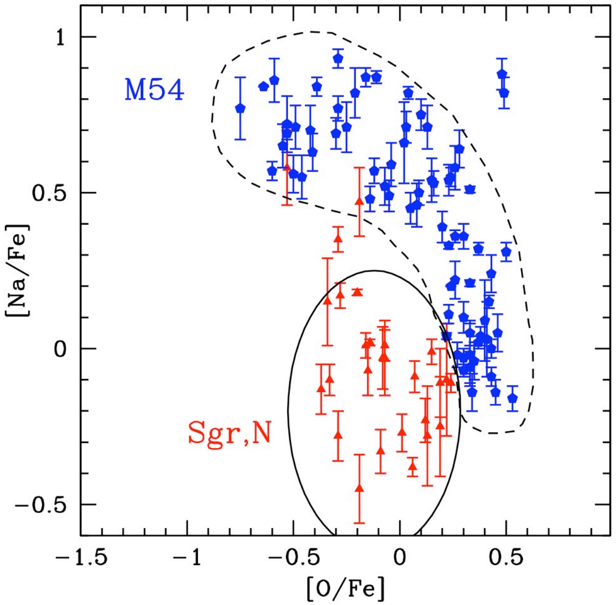








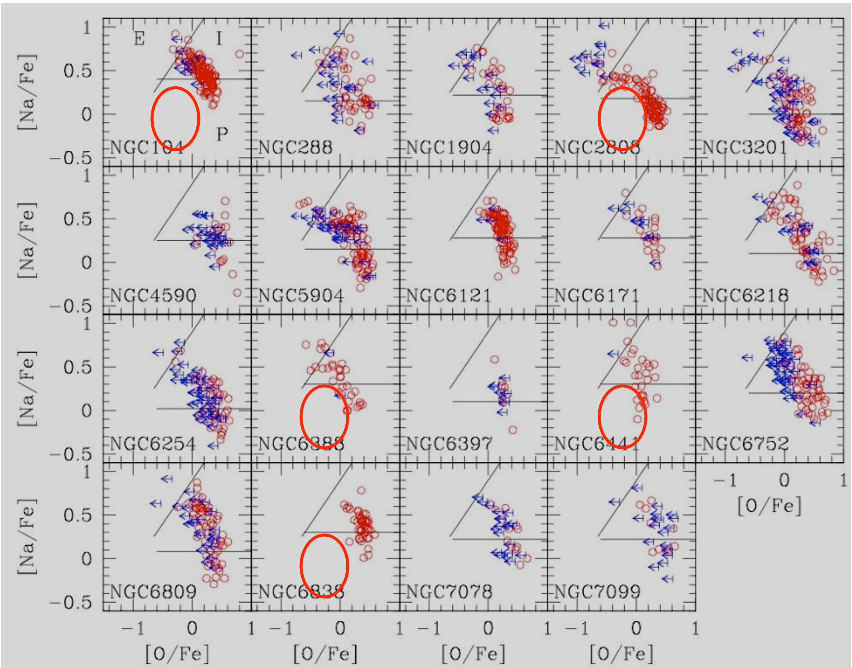
Independent support from Chemical Evidence (C10)

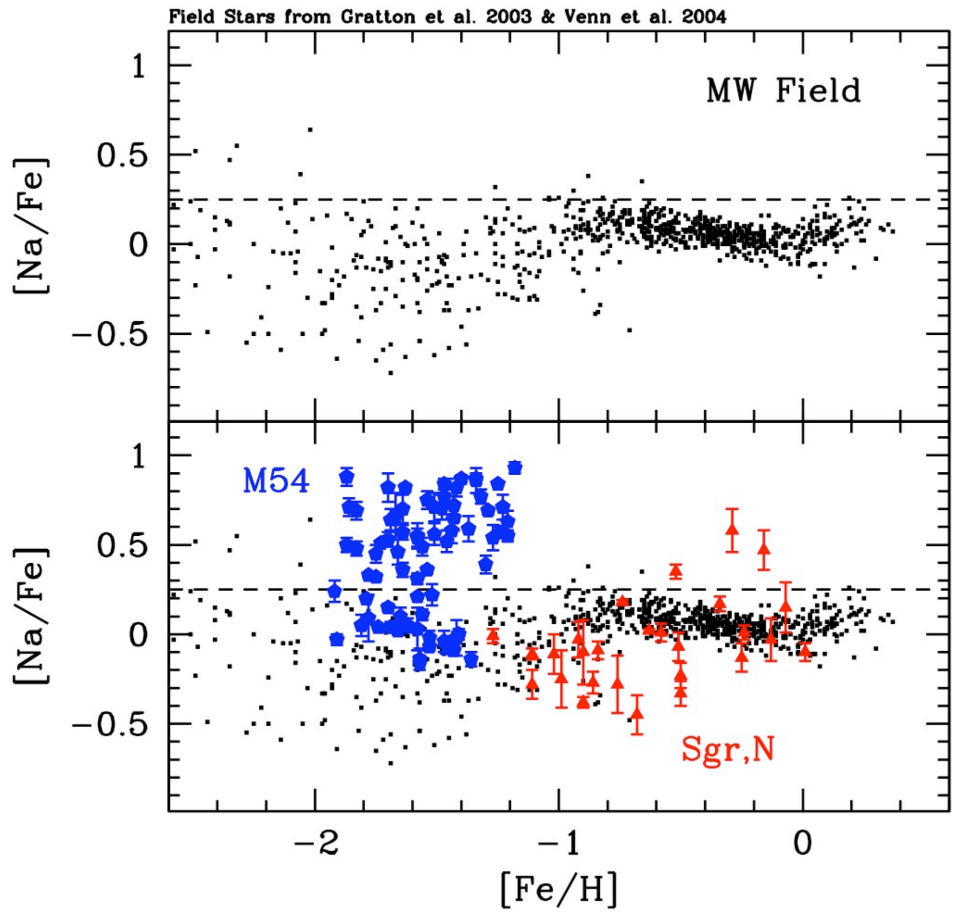


M54 stars display the wide spread in Na abundances, reaching [Ne/Fe]≈+1.0 that is DISTINCTIVE of globular clusters, while the LARGE majority of Sgr,N stars have [Na/Fe]<0.25, resembling Galactic Field stars.

M54 present a large-amplitude Na-O anti-correlation typical of GCs

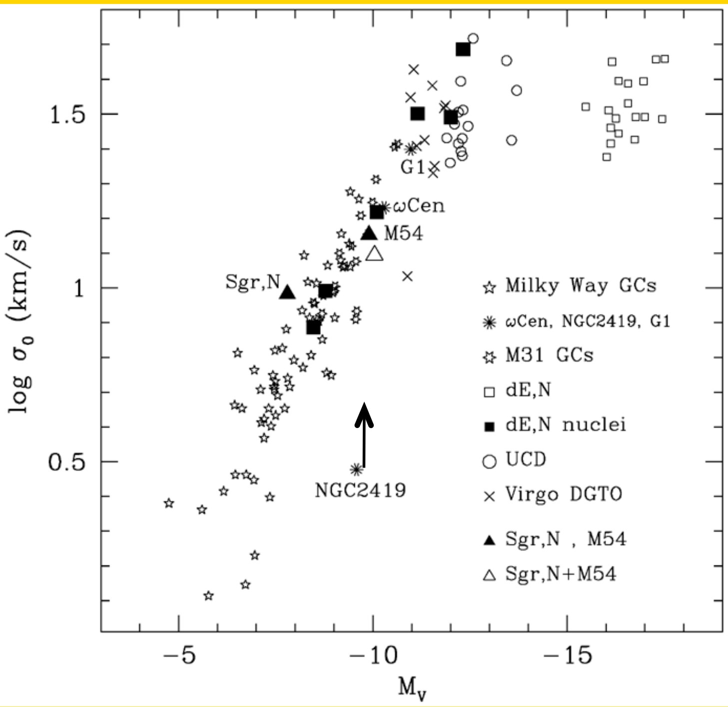
The bulk of Sgr,N stars lie in a region of the [O/Fe] vs [Na/Fe] plane where NO GC star lies





What we have learned about galaxy nucleation from this case ?

both formation channels are viable.
In the Sgr galaxy both actually succeeded in forming a nucleus!
This may be an explanation to the ubiquity of stellar nuclei in (faint) galaxies: both the proposed channels are so naturally efficient that the typical galaxy has more than one opportunity to form a nucleus.



Analogy with ω Centauri:
In a couple of Gyr the main body of Sgr will be dissolved: we will observe a metal-poor bright globular clusters with a minor population of residual metal-rich stars, with abundance and kinematic anomalies.

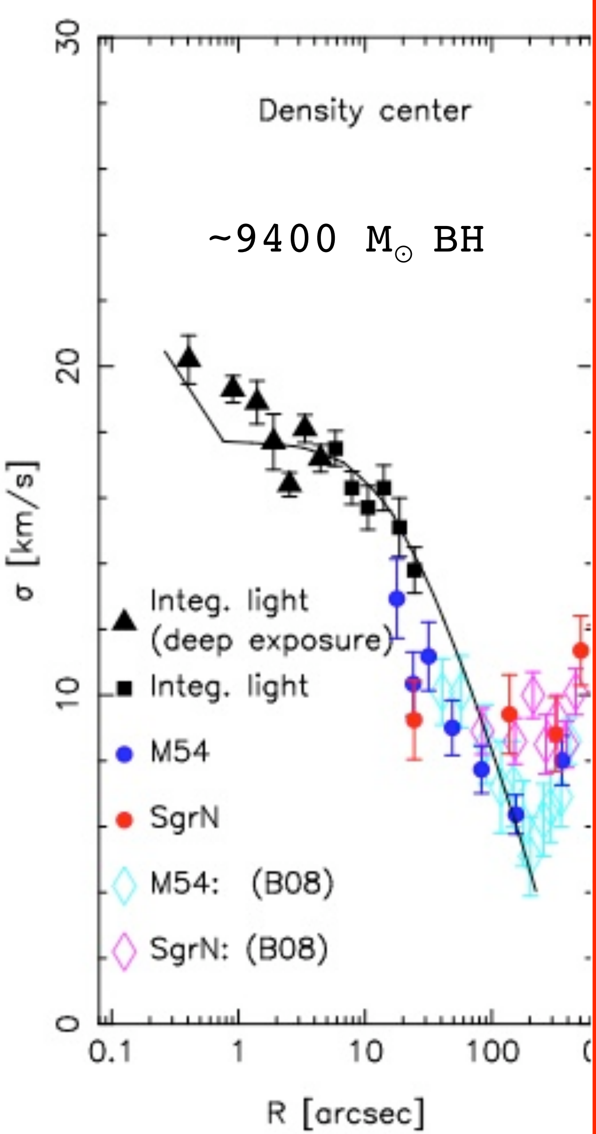
More details and discussion in: Bellazzini et al. (2008) and Carretta et al. 2010

A further step: more radial velocity and IFUs in the innermost 30″

A Surface Brightness & velocity dispersion cusp

A new VLT / FLAMES + ARGUS run in 2008 (I09)

- Including the sample discussed above we end up with V_r for 944 individual members of Sgr/M54 within 0.5′ ≤ r ≤ 12.5′
- The innermost region within r ≤ 0.6′ is covered with 51 overlapping ARGUS fields (each ARGUS field is a raster of 22×14 pixels covering 11.4″×7.7″. Each 0.5″ px is an HR21 spectrum R~20000



2 Ibata et al.

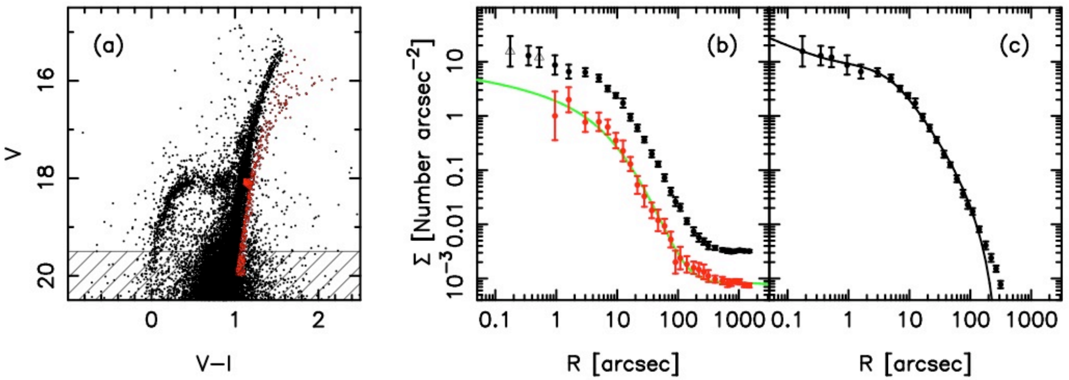


FIG. 1.— (a) ACS color-magnitude diagram (CMD). Sources are classified into likely M54 (heavy black), Sgr (red), and foreground (light black), according to CMD location. (b) Corresponding star counts profiles for M54 (black) and Sgr (red), with respect to the M54 density center and as a function of (projected) radius R. Towards the centre of M54 we detect a sharp rise in the stellar surface density, at odds with a flat distribution expected from a King model. The green line shows a Hernquist model fit to the Sgr profile (with background given by the King model of Majewski et al. 2003, also displayed in Fig. 2 of B08). The background-subtracted profile M54 is presented in (c), together with a composite model comprising a King model and a central IMBH.

A IMBH at the center of M54?

-The Surface Brightness & Velocity Dispersion Cusps are compatible with the presence of a 9400 $M_{\odot}$ Black Hole at the center of M54

-A relatively modest degree of radial anisotropy in the central 2″ (σ_r/σ_θ=1.25) can also produce the observed velocity cusp

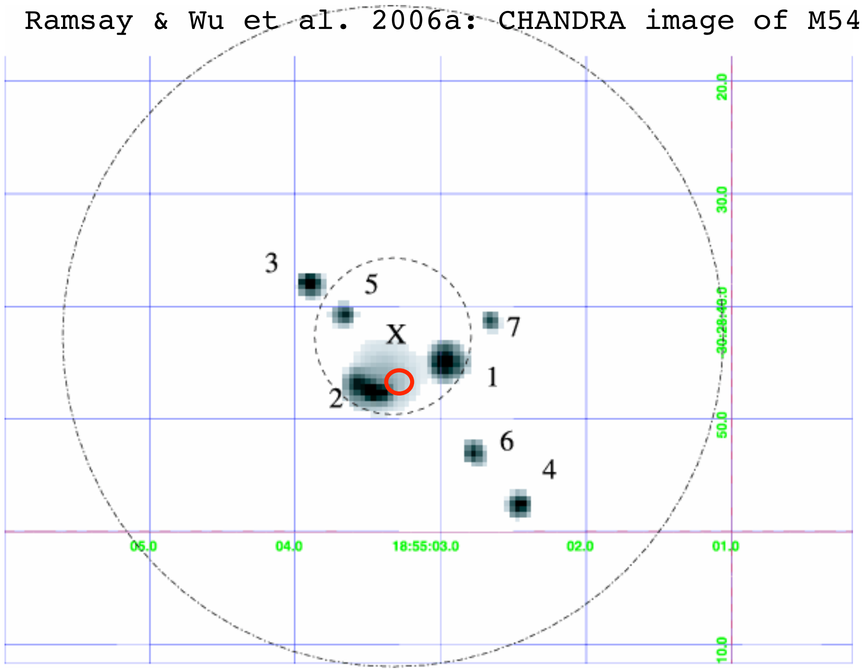
-Within 1″ of our center there is an X-ray source with L_X=0.72×10^{33} erg/s at the lower limit of the range of X luminosities predicted for IMBH in GCs (Maccarone & Servillat 2008).

-In the framework of the CMO hypothesis:

Mass(M54+Sgr,N) ≈ 0.03% Mass(Sgr)
Mass(IMBH) ≈ 0.03% Mass(M54)

They fit into the scheme:
A matrioska-like set of CMOs…

Ramsay & Wu et al. 2006a: CHANDRA image of M54



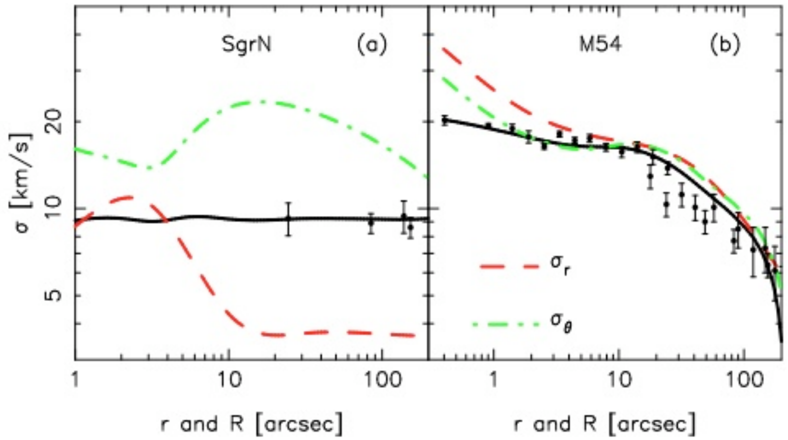


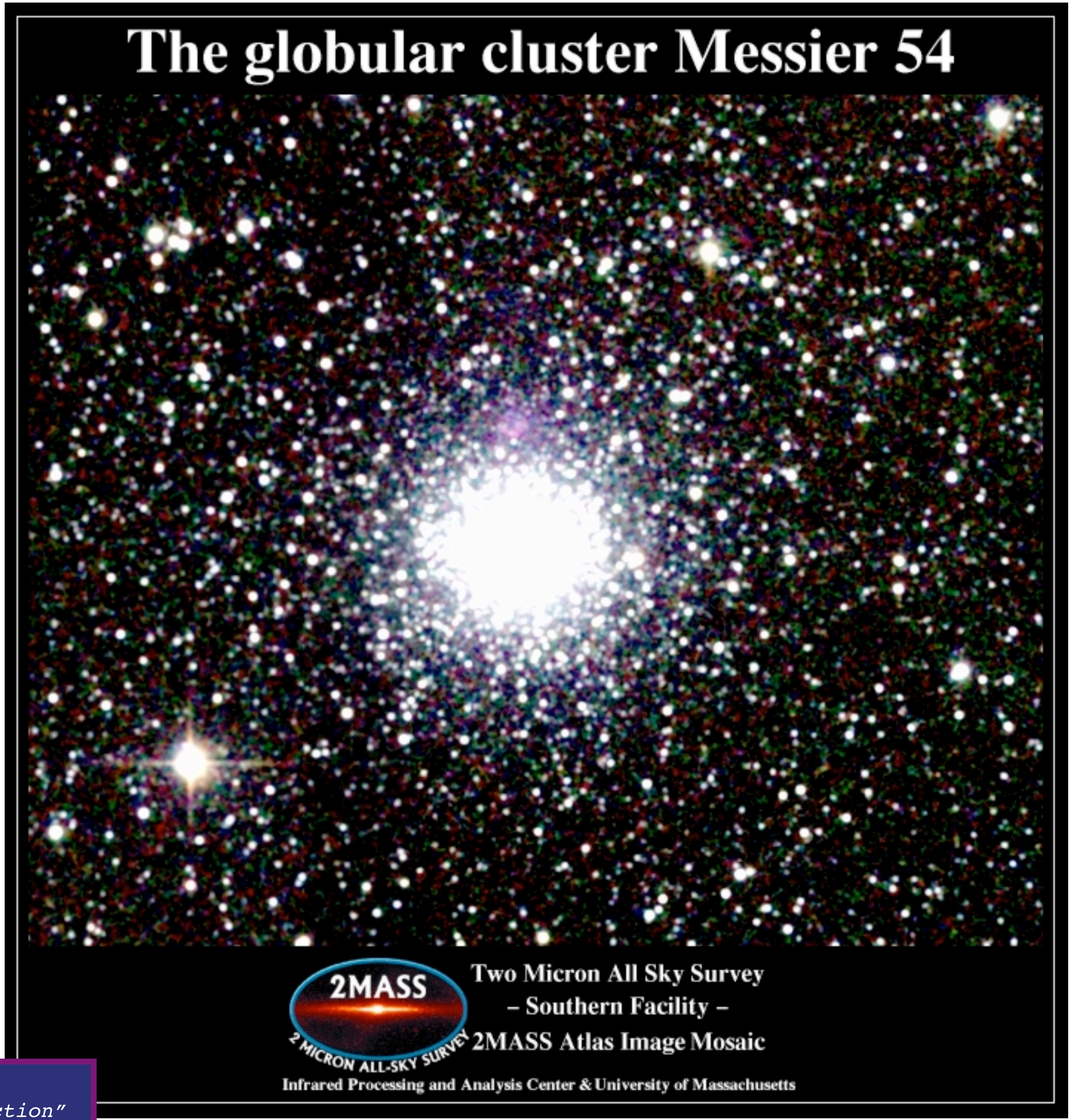
FIG. 4.— (a) An MCMC scheme was used to find the most likely profiles for the radial (red) and tangential (green) components of σ (as a function of radius r) of the Sgr,N population that give rise to a projected σ that is flat as a function of projected radius R. (b) The components of σ required of the M54 population if no BH is present. (Data points are reproduced from Fig. 3).

Detailed analysis of the whole B08+I09 sample

(944 Sgr/M54 member stars within 9')

is ongoing…

Stay tuned!



Thank you

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