



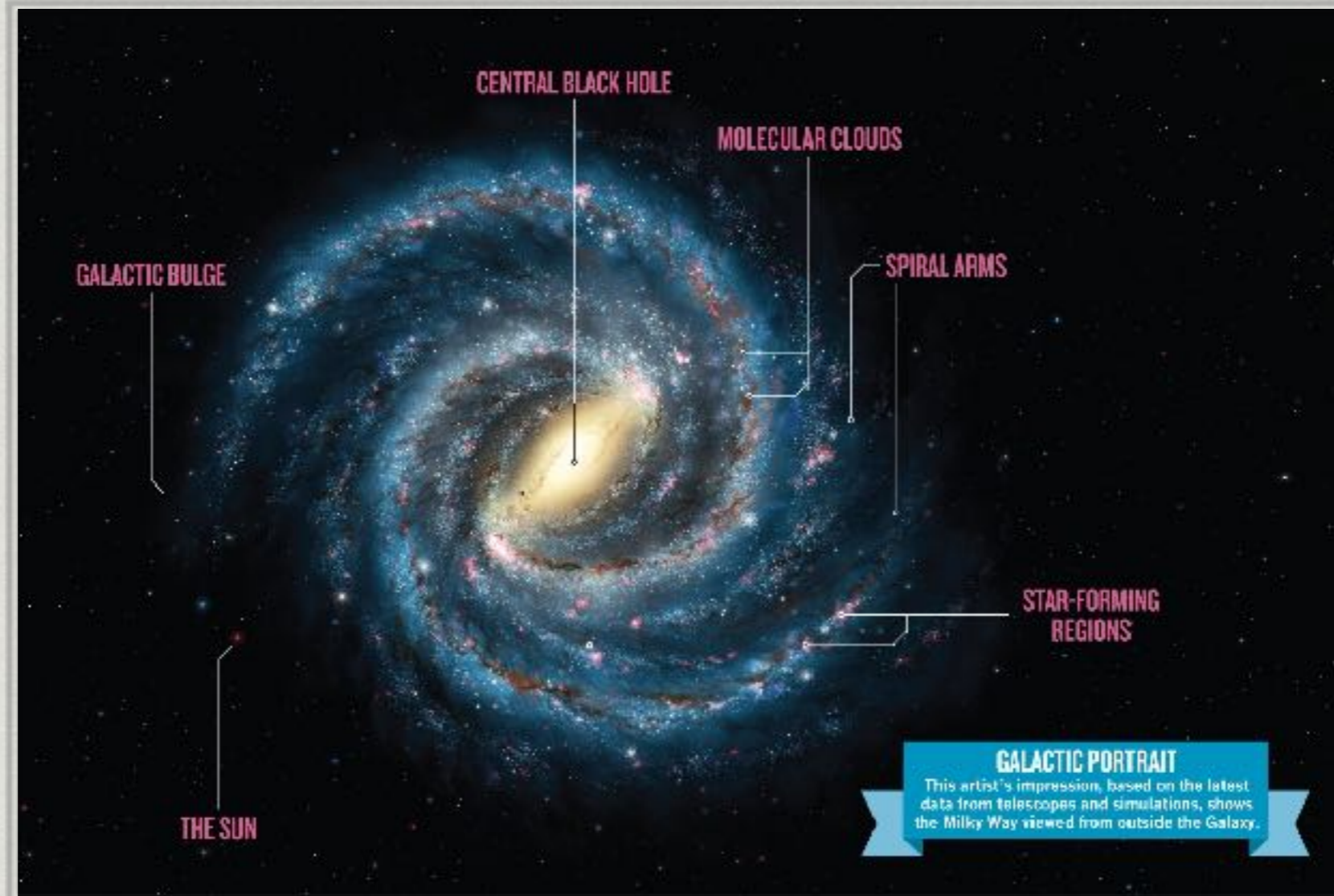
THE NEW BULGE

ROBERTO DE PROPRIS (ESO-SUOMEN KESKUS,
UNIVERSITY OF TURKU, FINLAND)

The Cabal...

- * R. Michael Rich (UCLA), Andrea Kunder (Potsdam), Juntai Shen (Shanghai), Andreas Koch (Lancaster), David Nataf (Baltimore), Christian Johnson (CfA) ...

The Hubble Type of the Milky Way

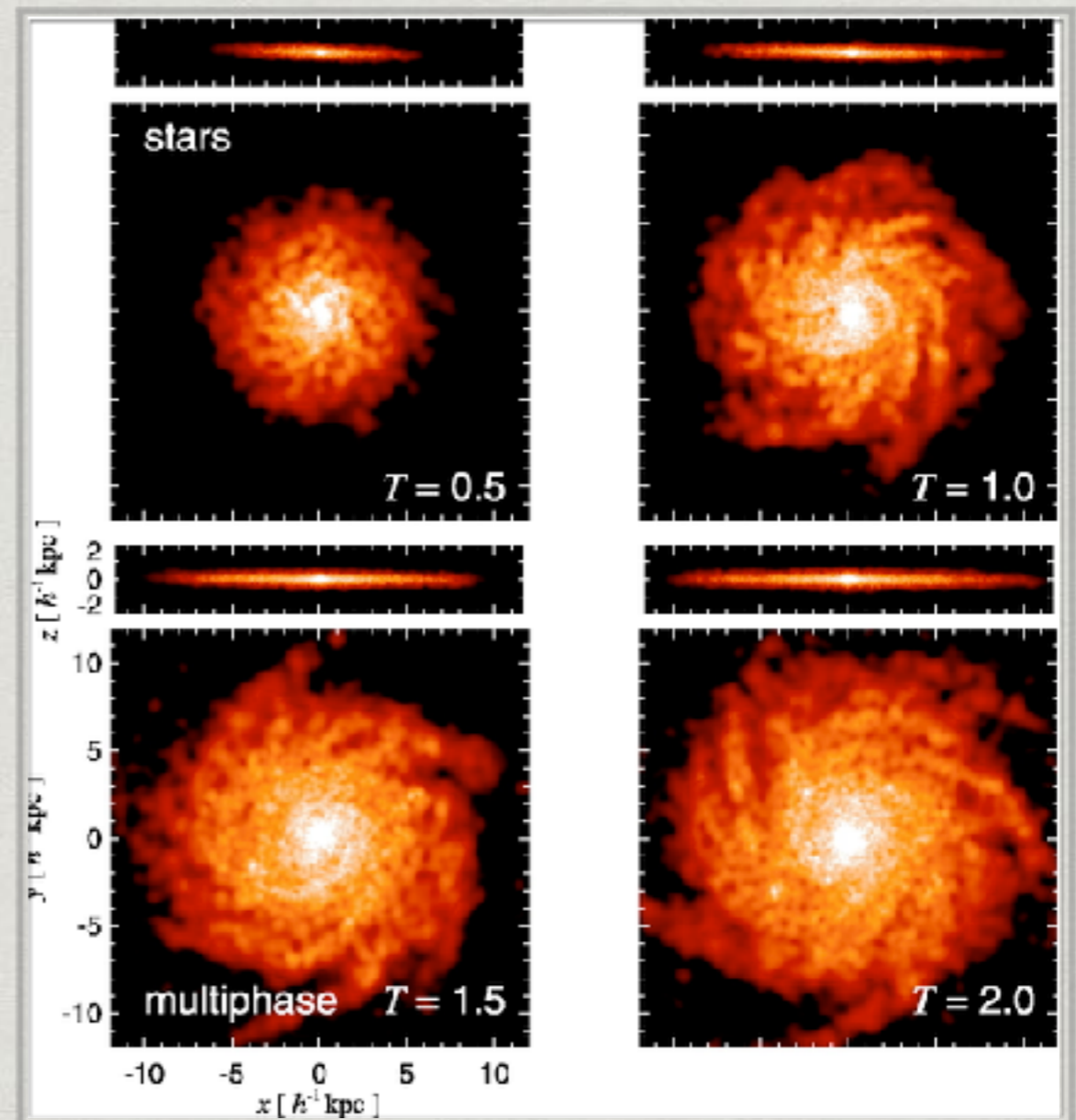


- * Our Galaxy is a relatively late-type multi-armed spiral galaxy
- * Like all spirals it contains an inner bulge/spheroid component

The Importance of the Bulge

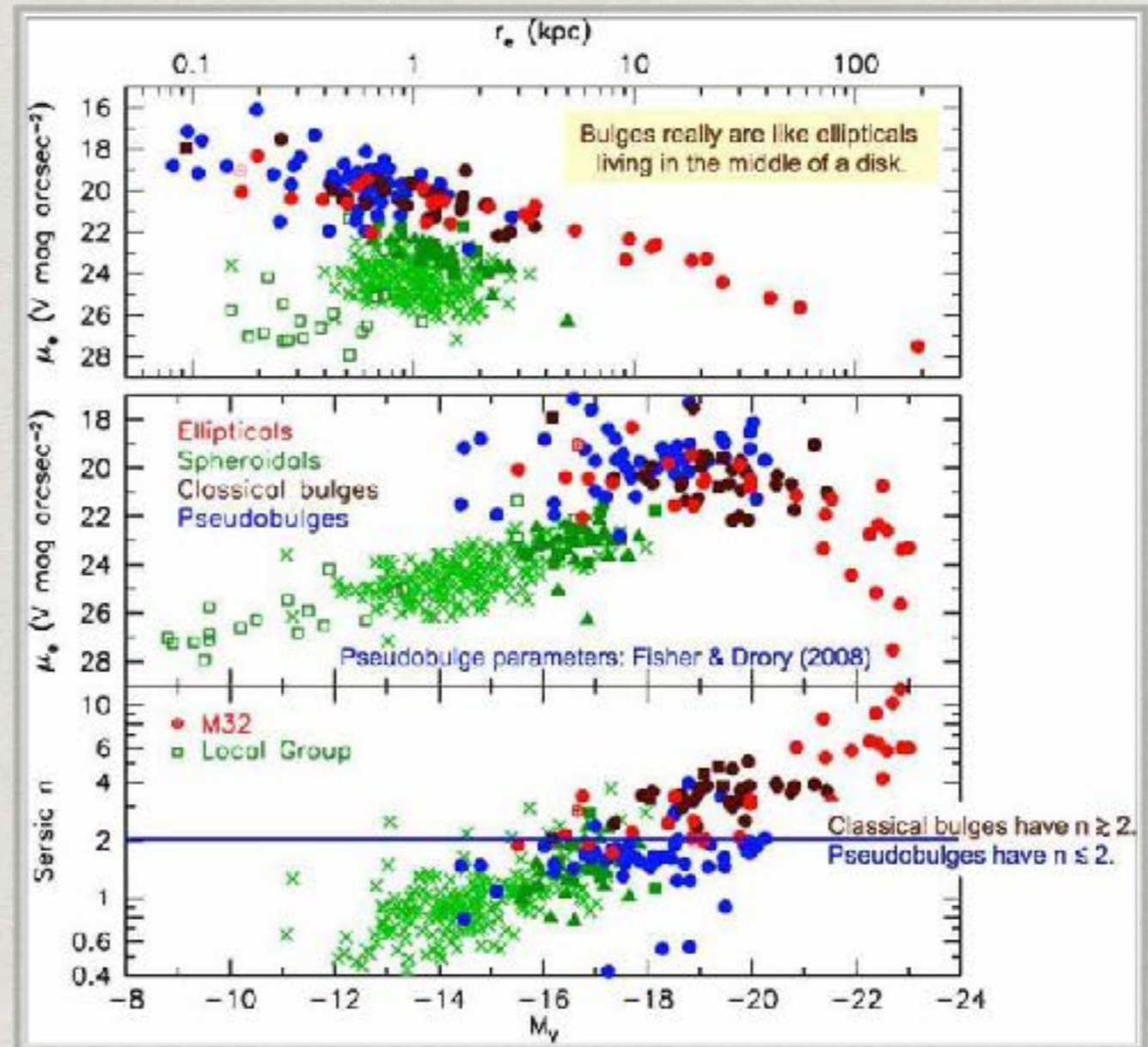
- * It is the only spheroidal-like population that we can resolve into stars to the level of the main sequence turnoff
- * Models show bulges to be connected to the early phases of galaxy formation via mergers

Robertson+ 2003

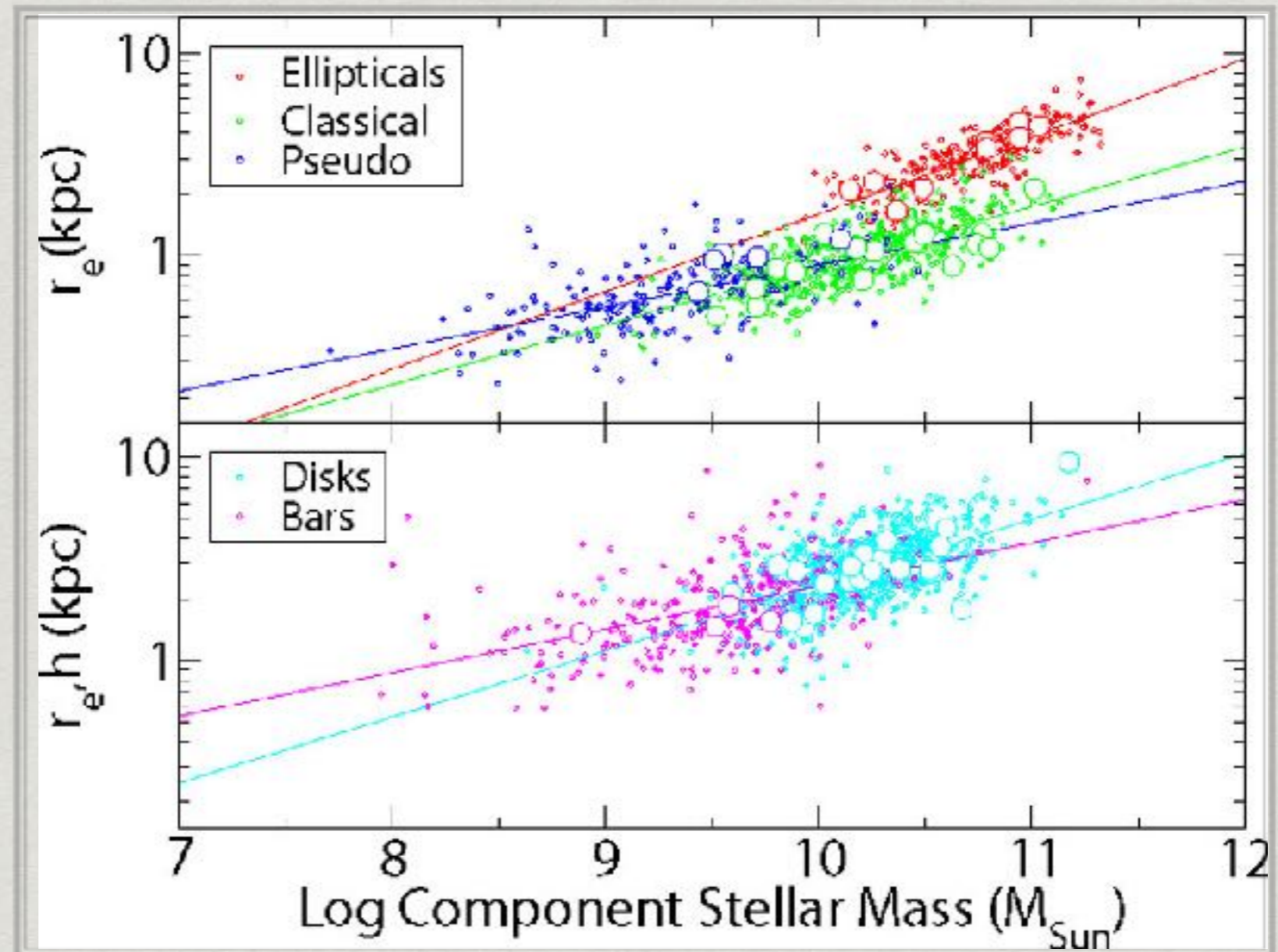


Bulges as small ellipticals

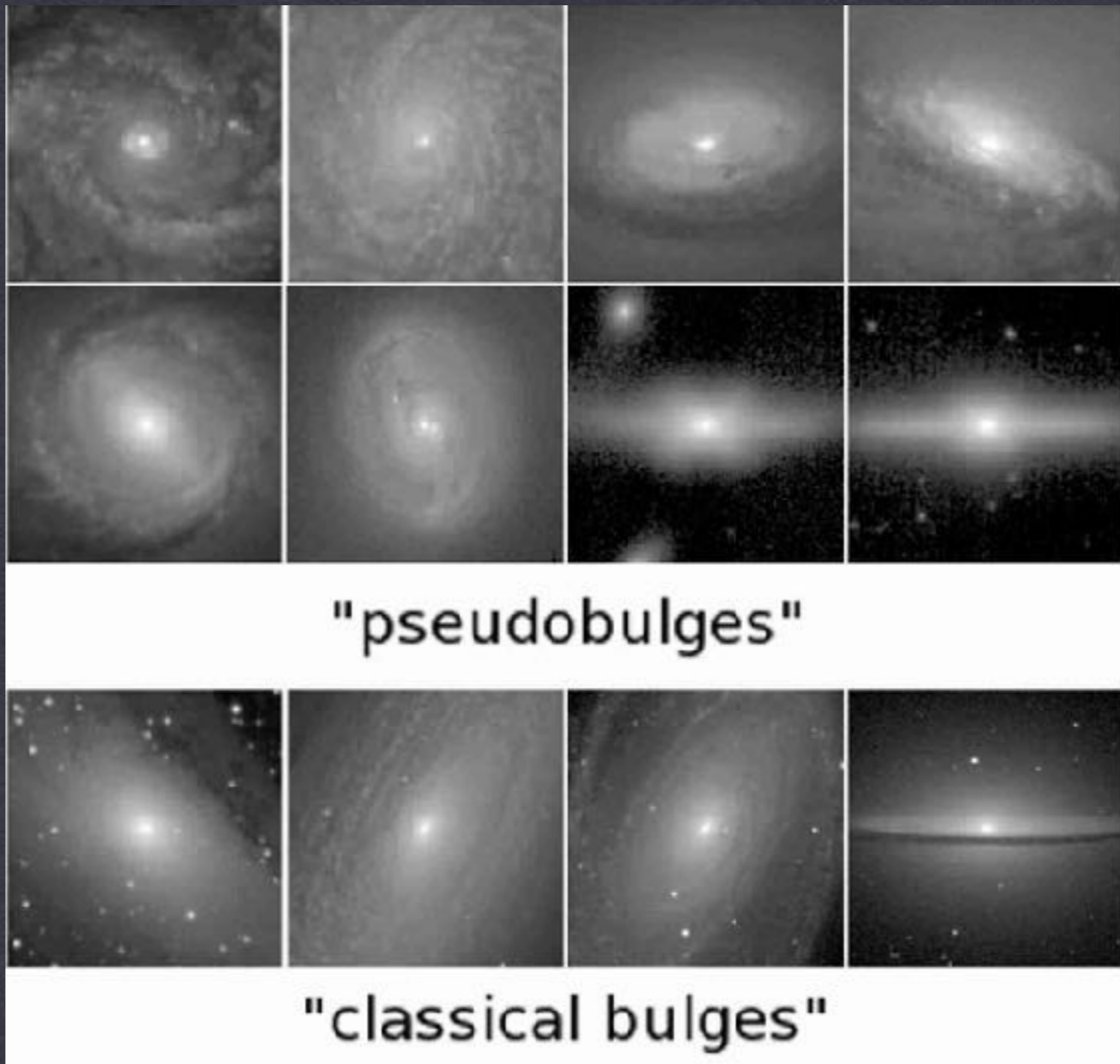
- * Fundamental plane seems to indicate that bulges are like small ellipticals living in a disk



However...



- * There seems to be a fundamental difference between actual spheroids and bulges, with spiral bulges being more similar to disks and pseudobulges

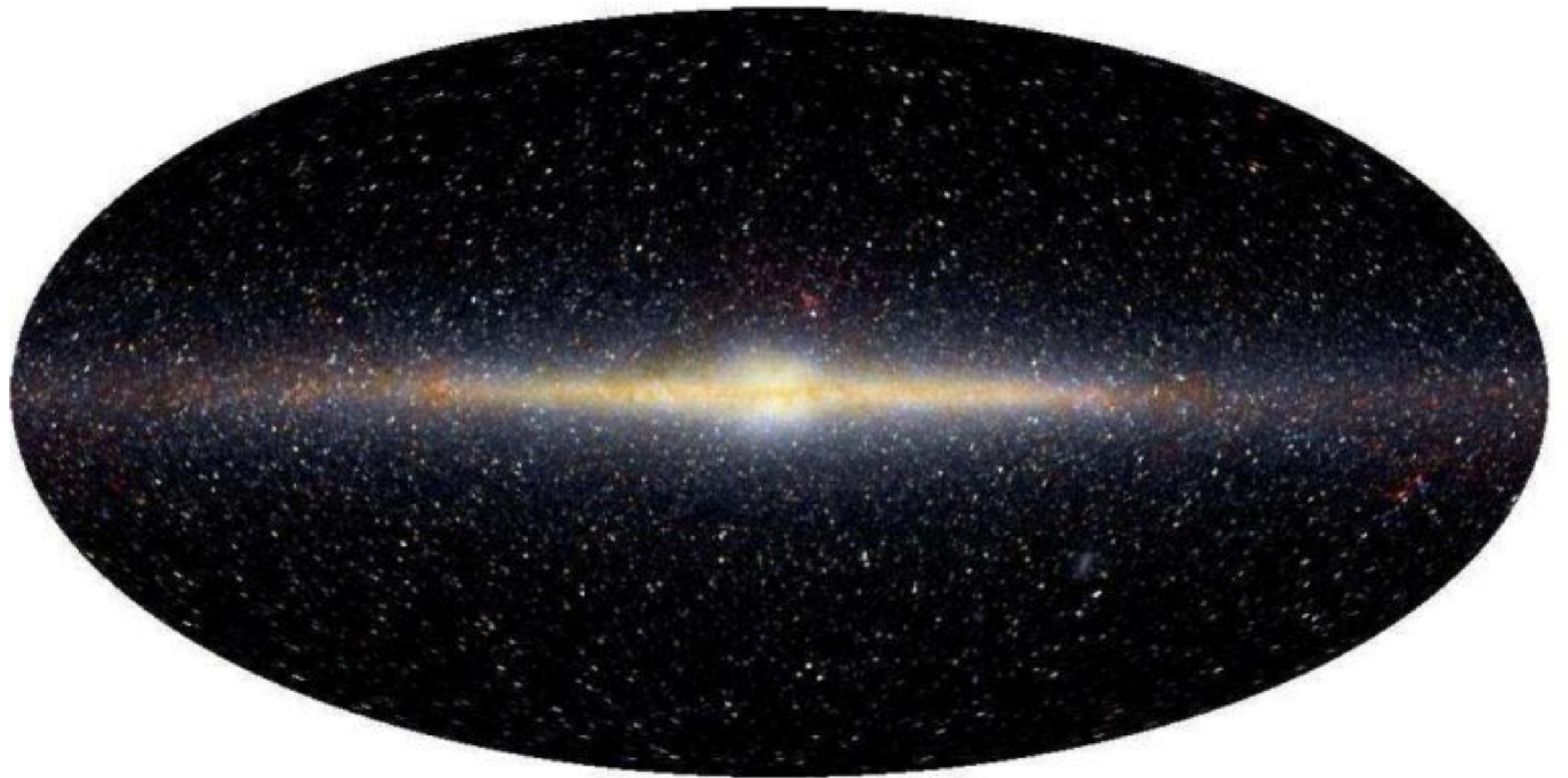


BULGE TYPES

CLASSICAL VS. **PSEUDOBULGES**

DE VAUCOULEURS

EXPONENTIALS



COBE

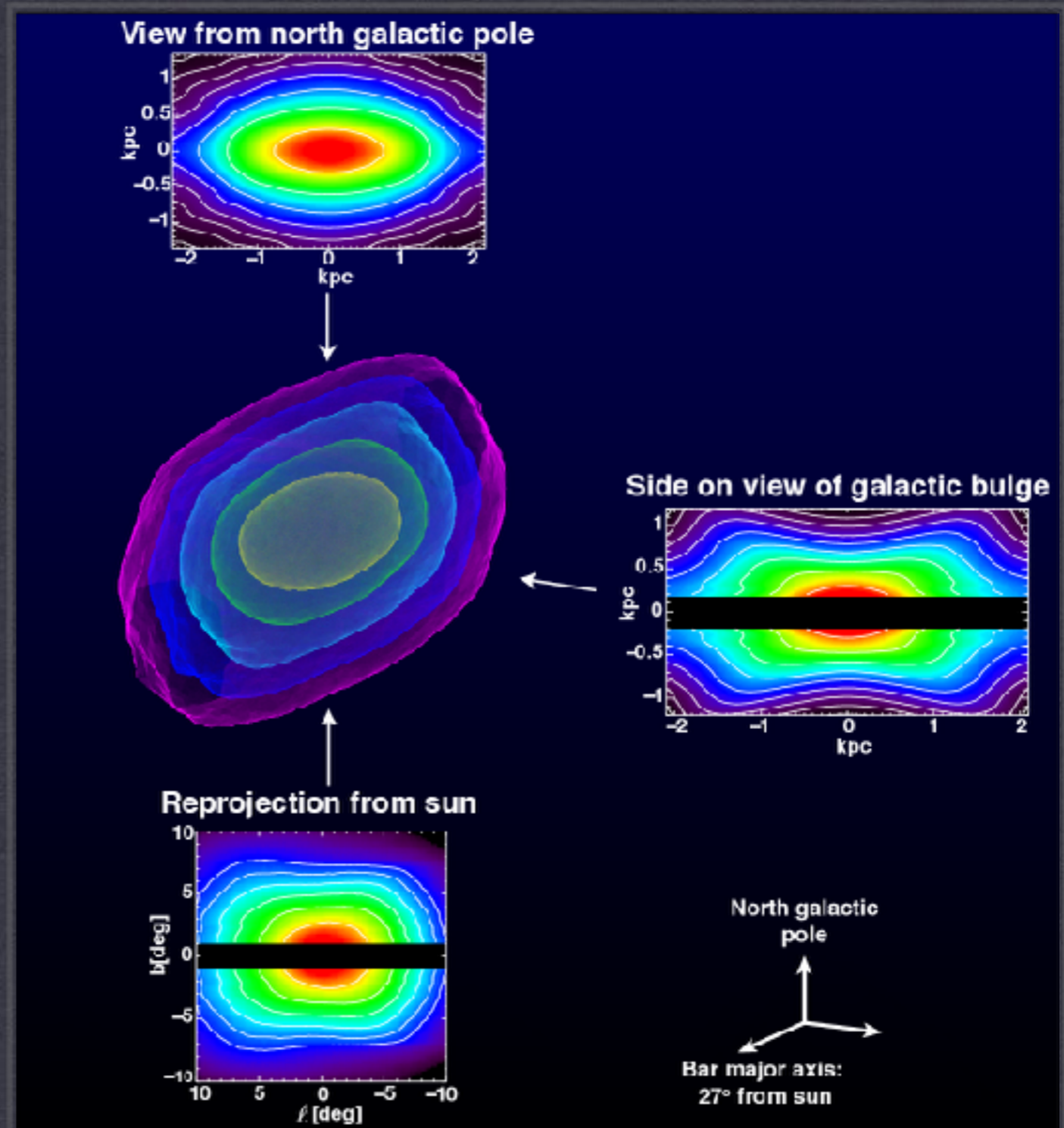
BOXY/PEANUT BULGE

HIGH EXTINCTION

INFRARED IMAGING

GALACTIC BAR

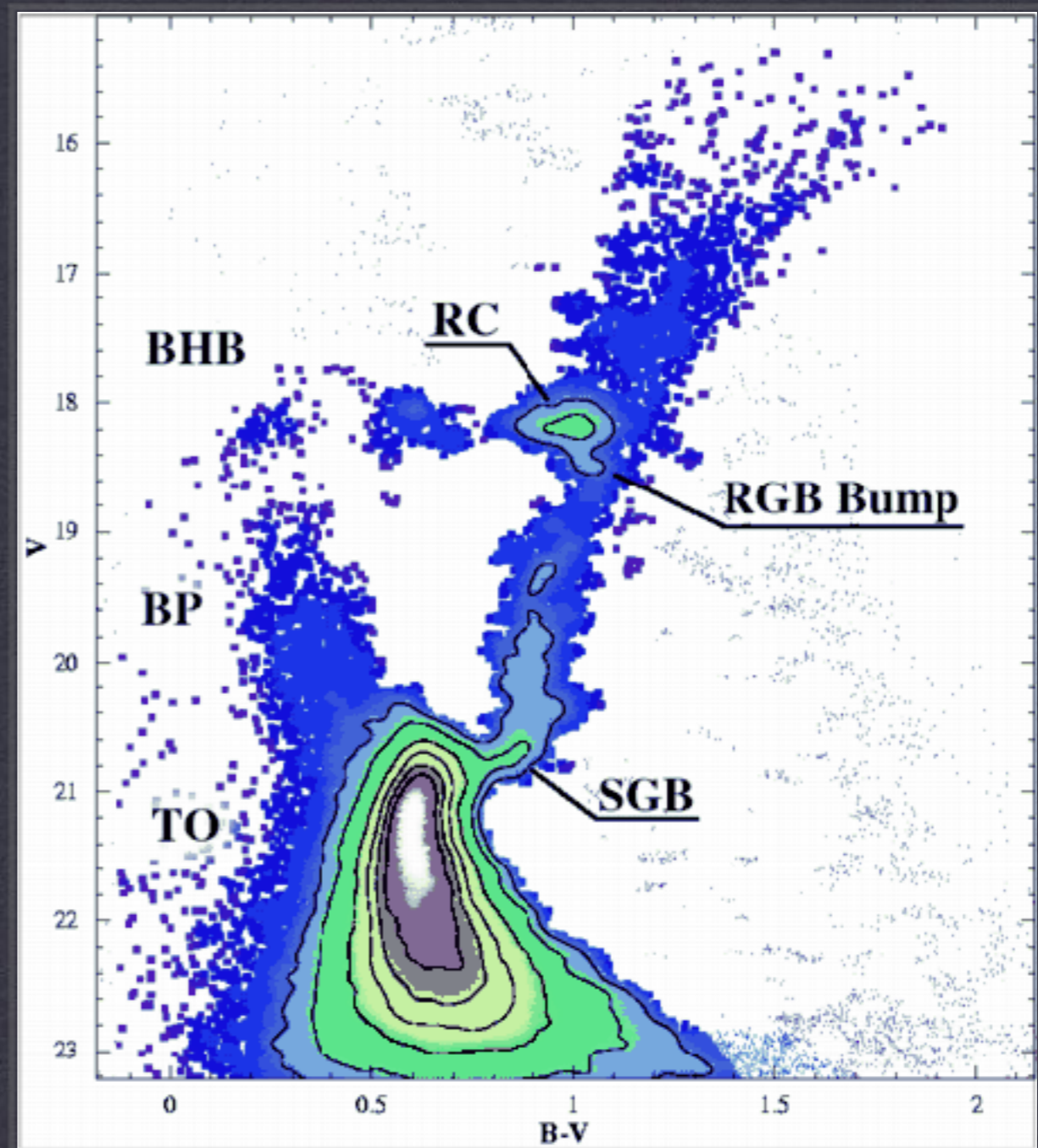
FROM GAS MOTIONS AND LATER STELLAR COUNTS IN THE IR, THE MILKY WAY IS KNOWN TO CONTAIN A STELLAR BAR AS WELL

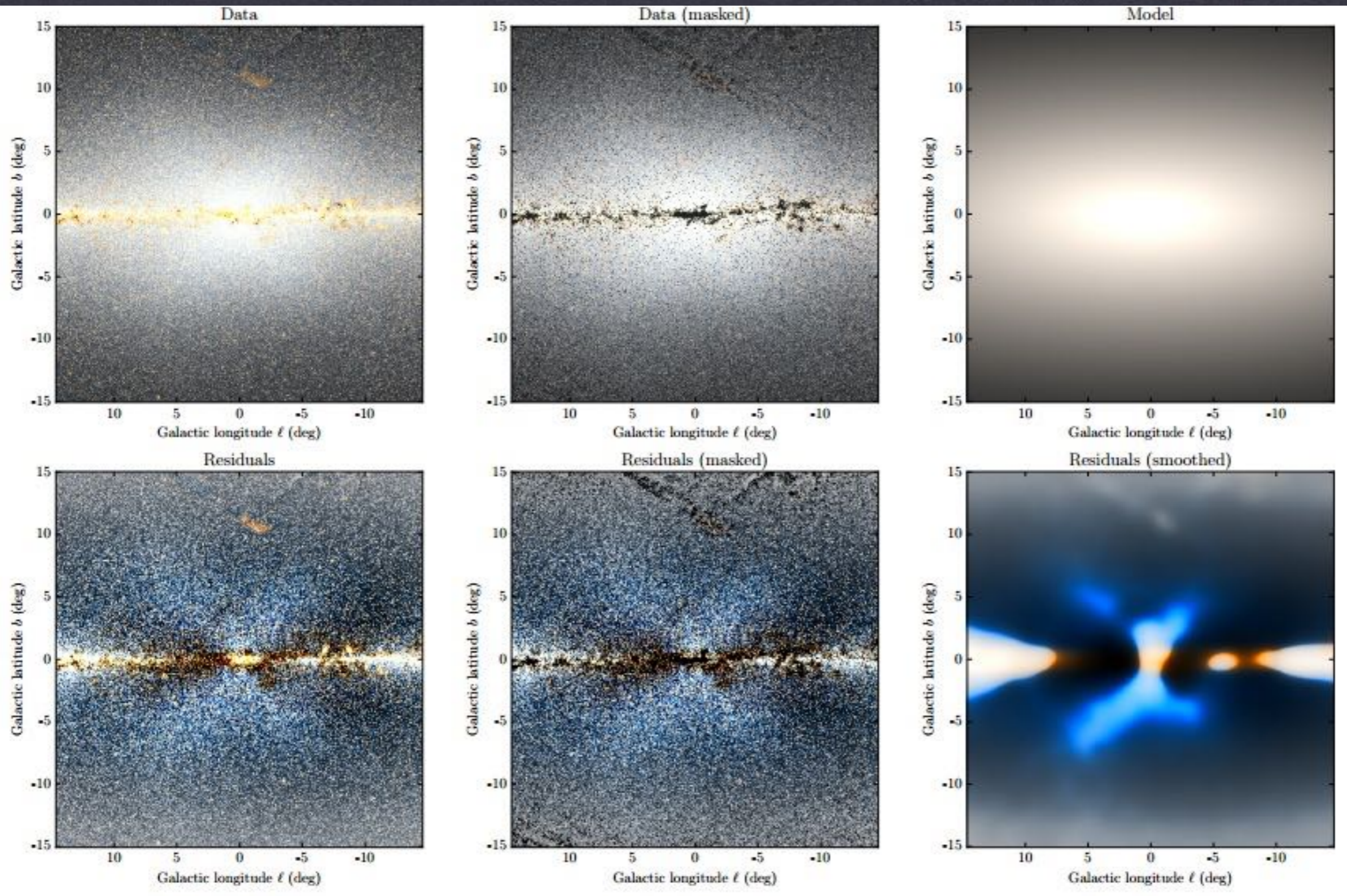


RED CLUMP STARS

USED AS DISTANCE INDICATORS

MEAN LUMINOSITY OF RED CLUMP BRIGHTER AT $L=+5$ THAN AT $L=-5$





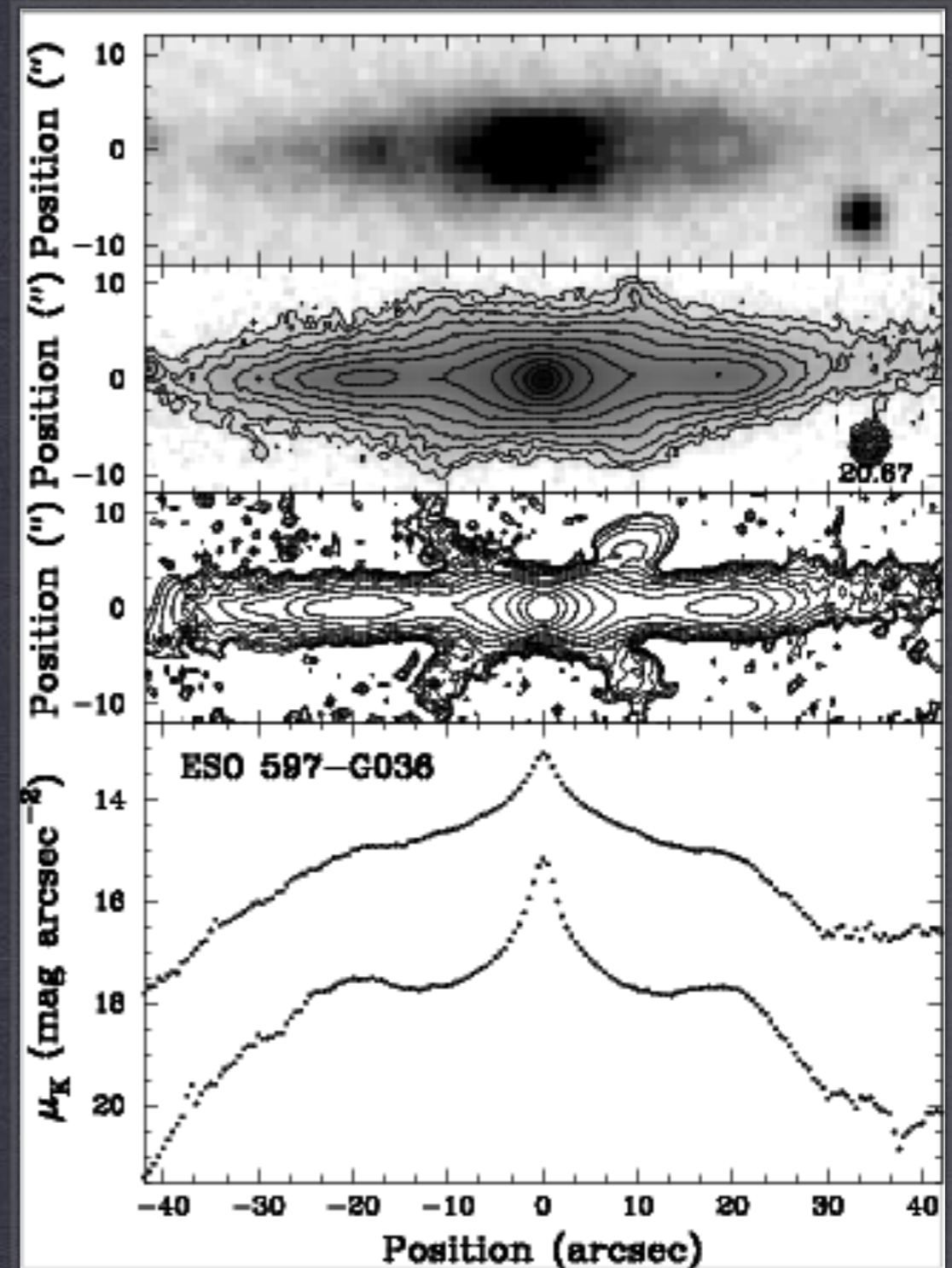
X-SHAPED STRUCTURE

ORIGINALLY FROM DOUBLE RED CLUMP

X-SHAPES

SEEN IN EXTERNAL GALAXIES

MOST COMMONLY
ASSOCIATED WITH
PSEDOBULGES





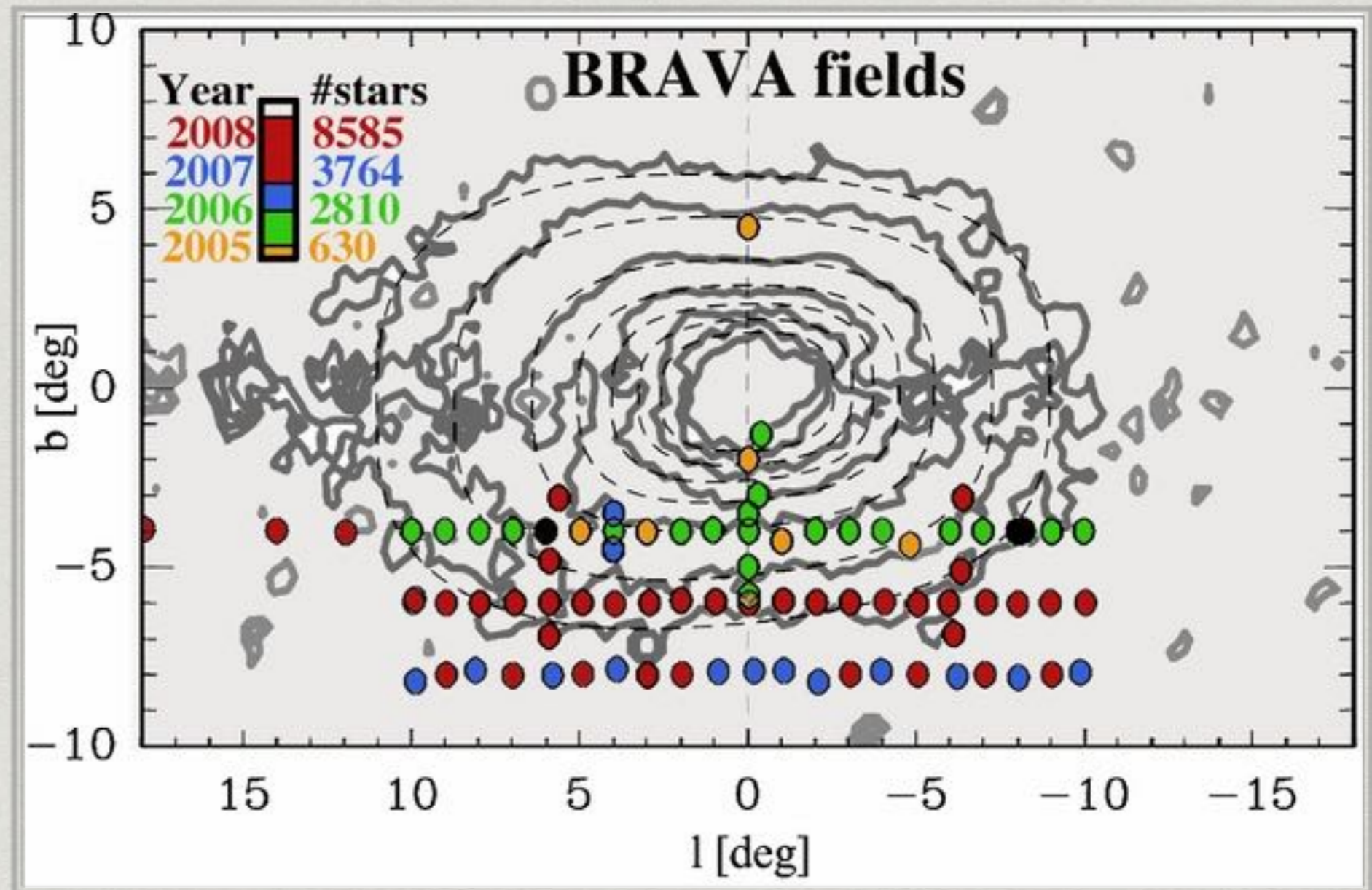
OUR GALAXY HAS A BAR AND X-SHAPE AND B/P BULGE

LIKELY TO CONTAIN A PSEUDO BULGE. HOW IS EVERYTHING RELATED ?

The Bulge Radial Velocity Assay

- * Is there a bar ?
- * Is there a classical bulge ?
- * Are there any cold substructures (dwarfs, mergers) ?
- * Radial velocity survey of the Galactic bulge

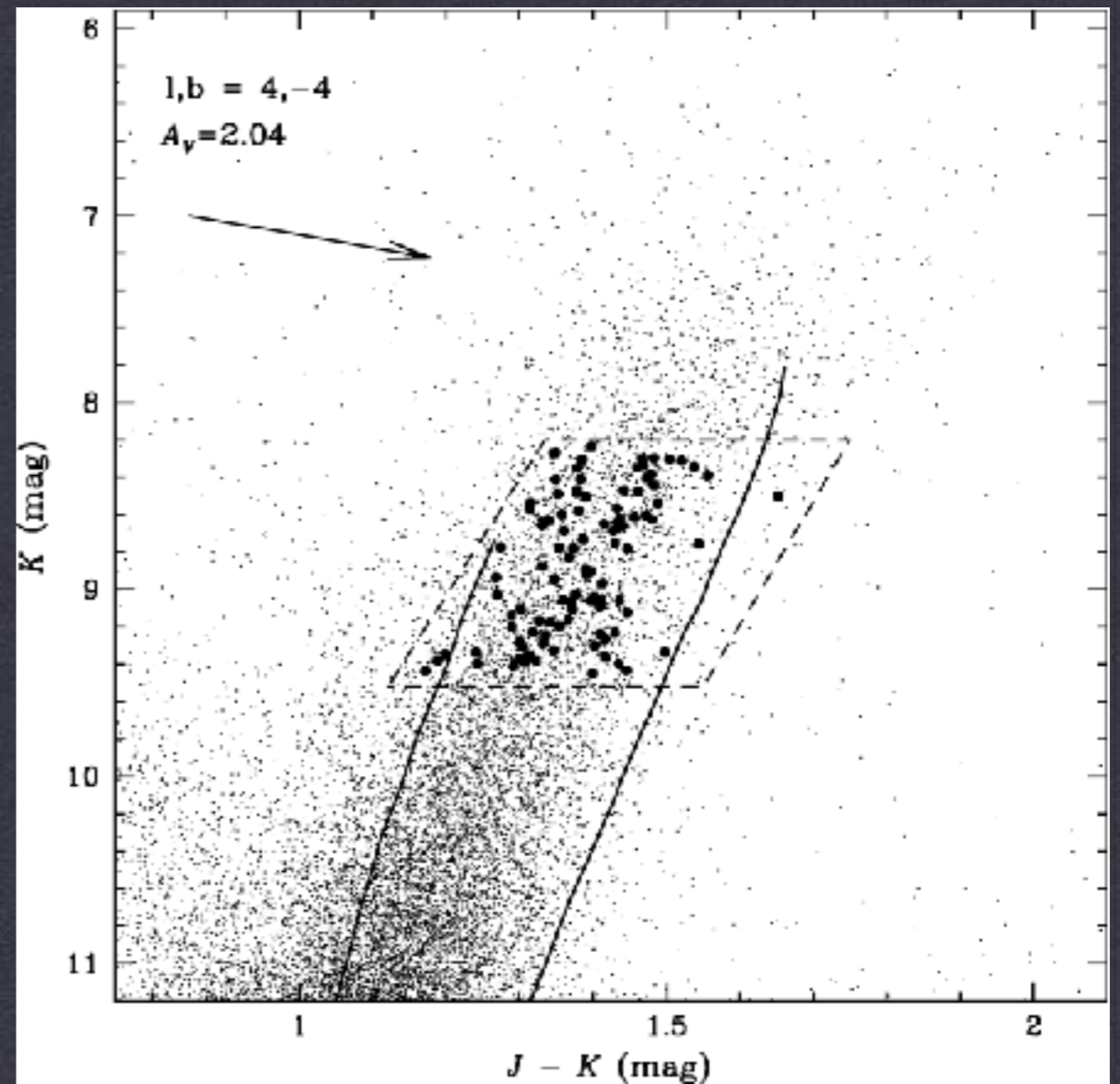
BRAVA



- * 9500 M giants ~ 100 per field
- * Spectra from CTIO with Hydra multi-fiber spectrograph

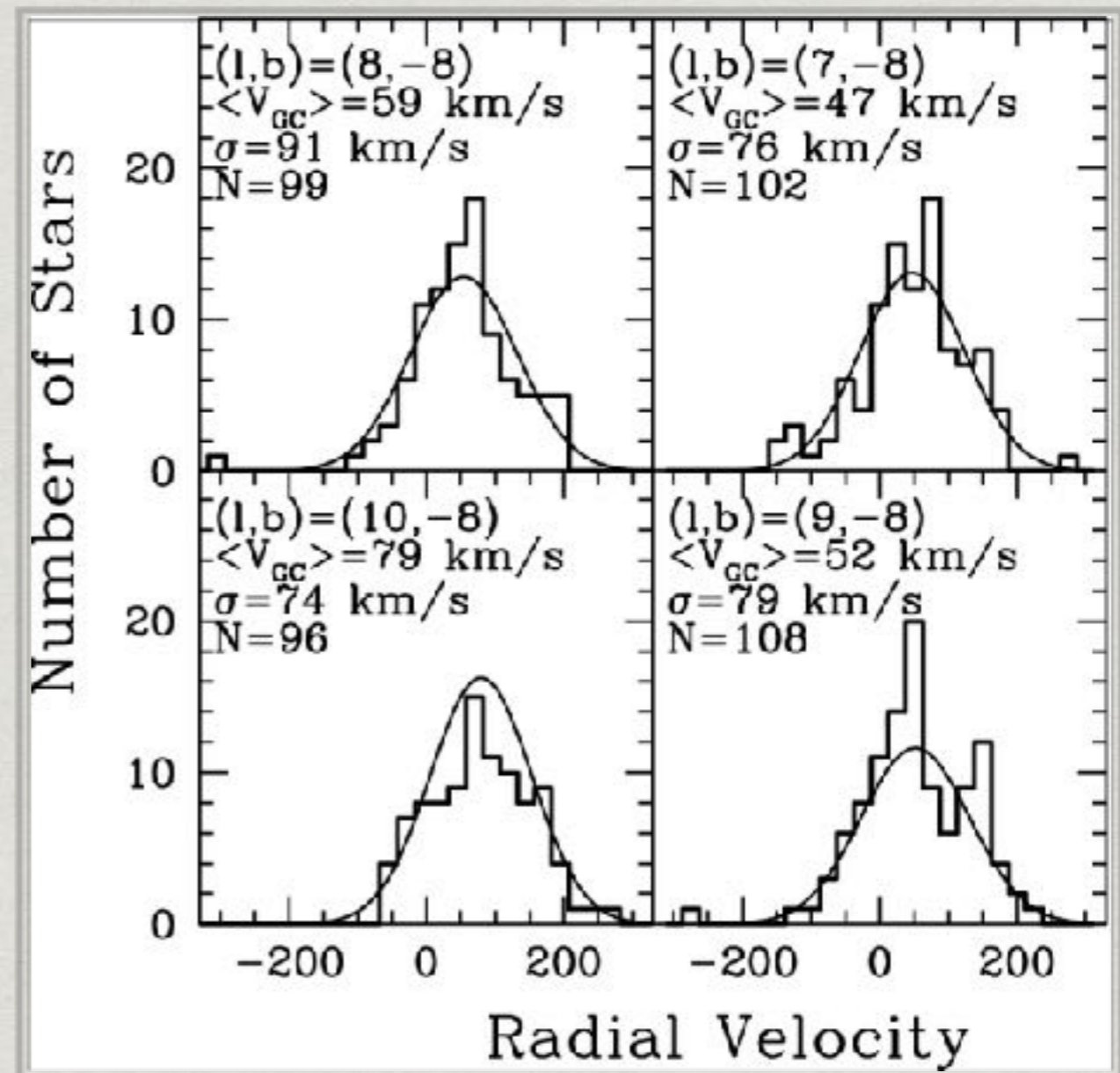
BRAVA STARS

SELECTED FROM 2MASS
WITH COLOURS AND
LUMINOSITIES CONSISTENT
WITH BULGE MEMBERSHIP



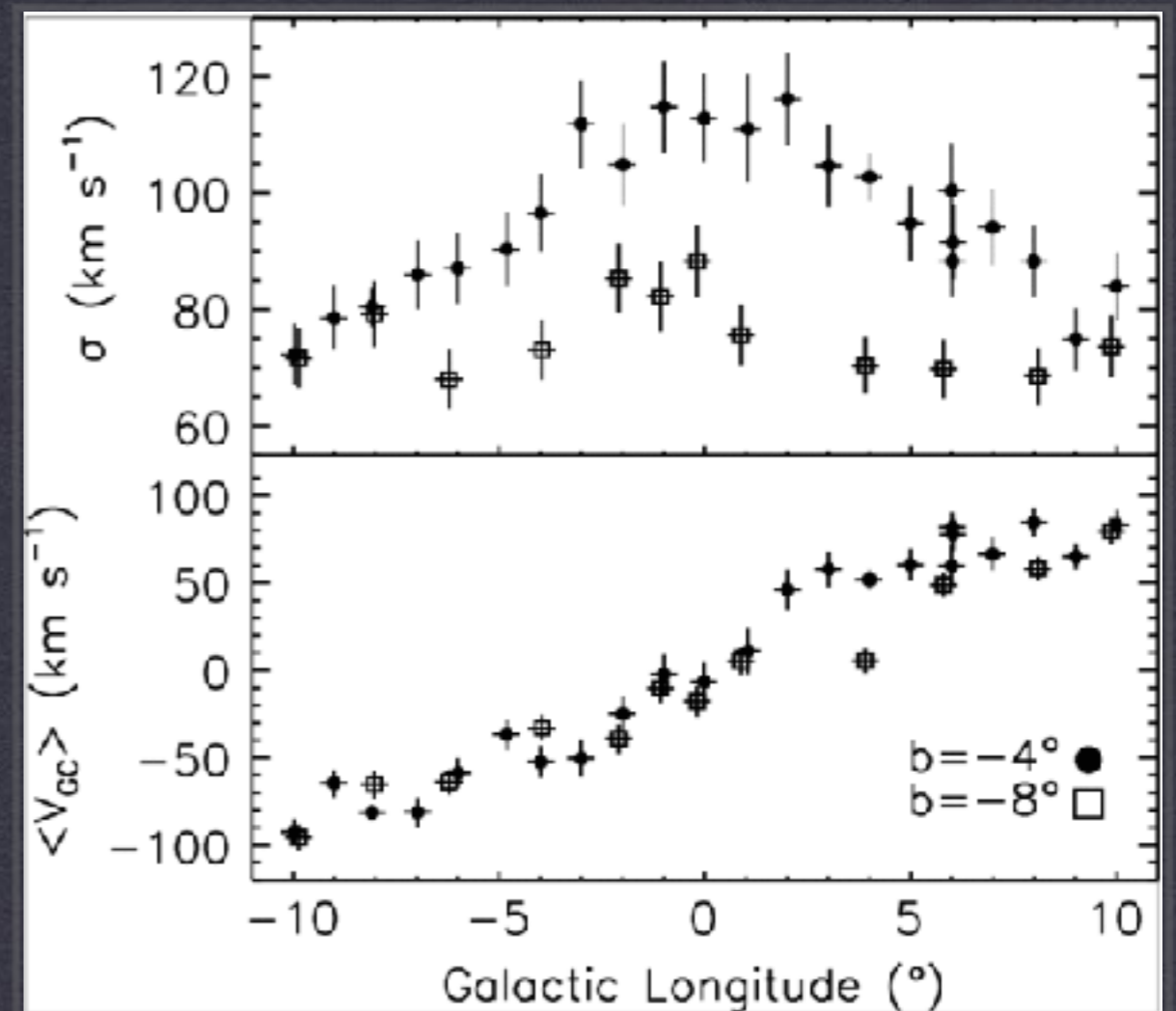
No stellar streams

- * No evidence of significant deviations from Gaussian mean in any of the BRAVA fields
- * Suggests that there is no evidence of substructure in the Bulge and therefore no recent mergers large enough to detect

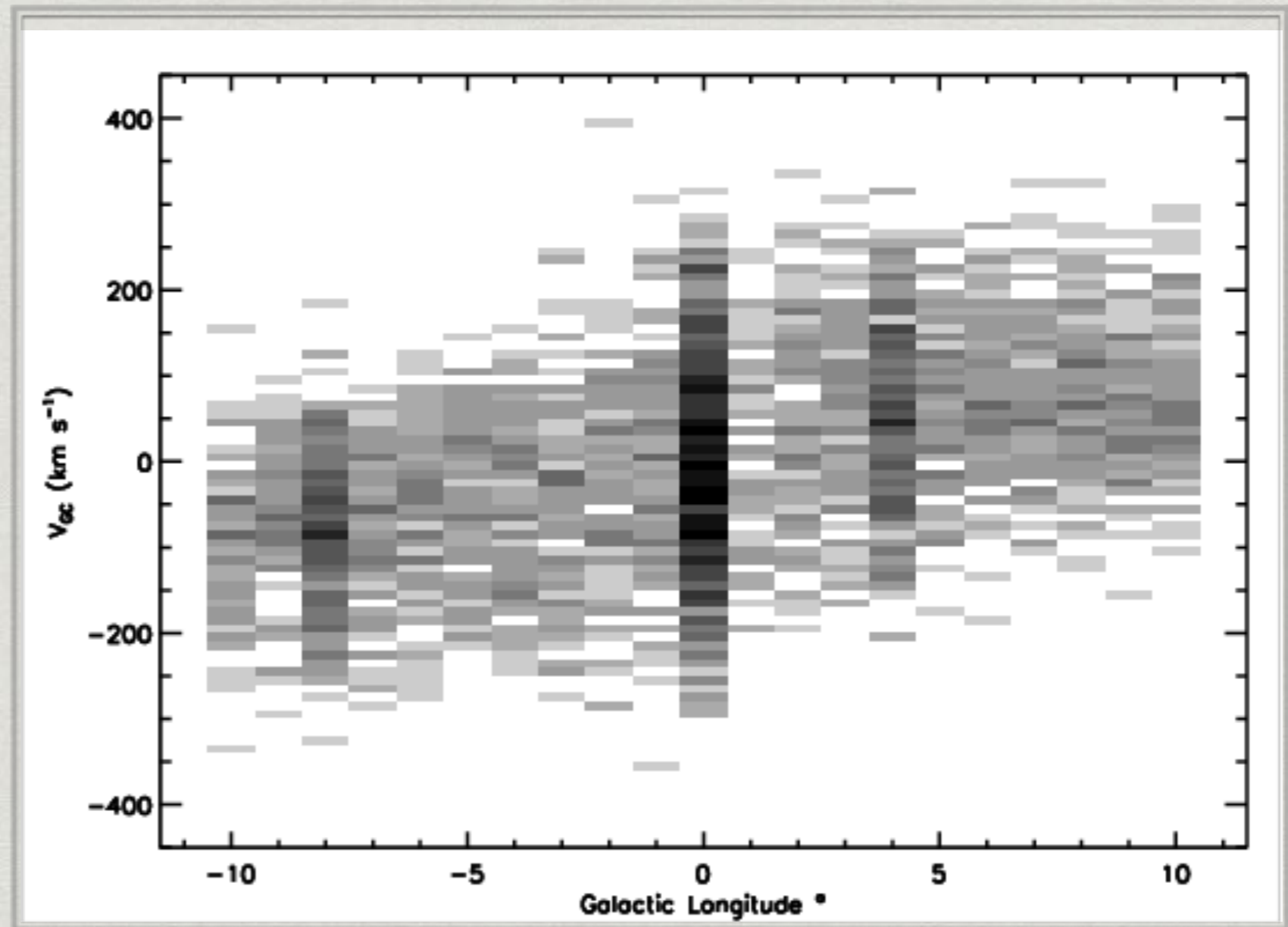


BRAVA

THE MAIN OUTCOME OF THE SURVEY IS A ROTATION CURVE AND A VELOCITY DISPERSION PROFILE FOR THE GALACTIC BULGE



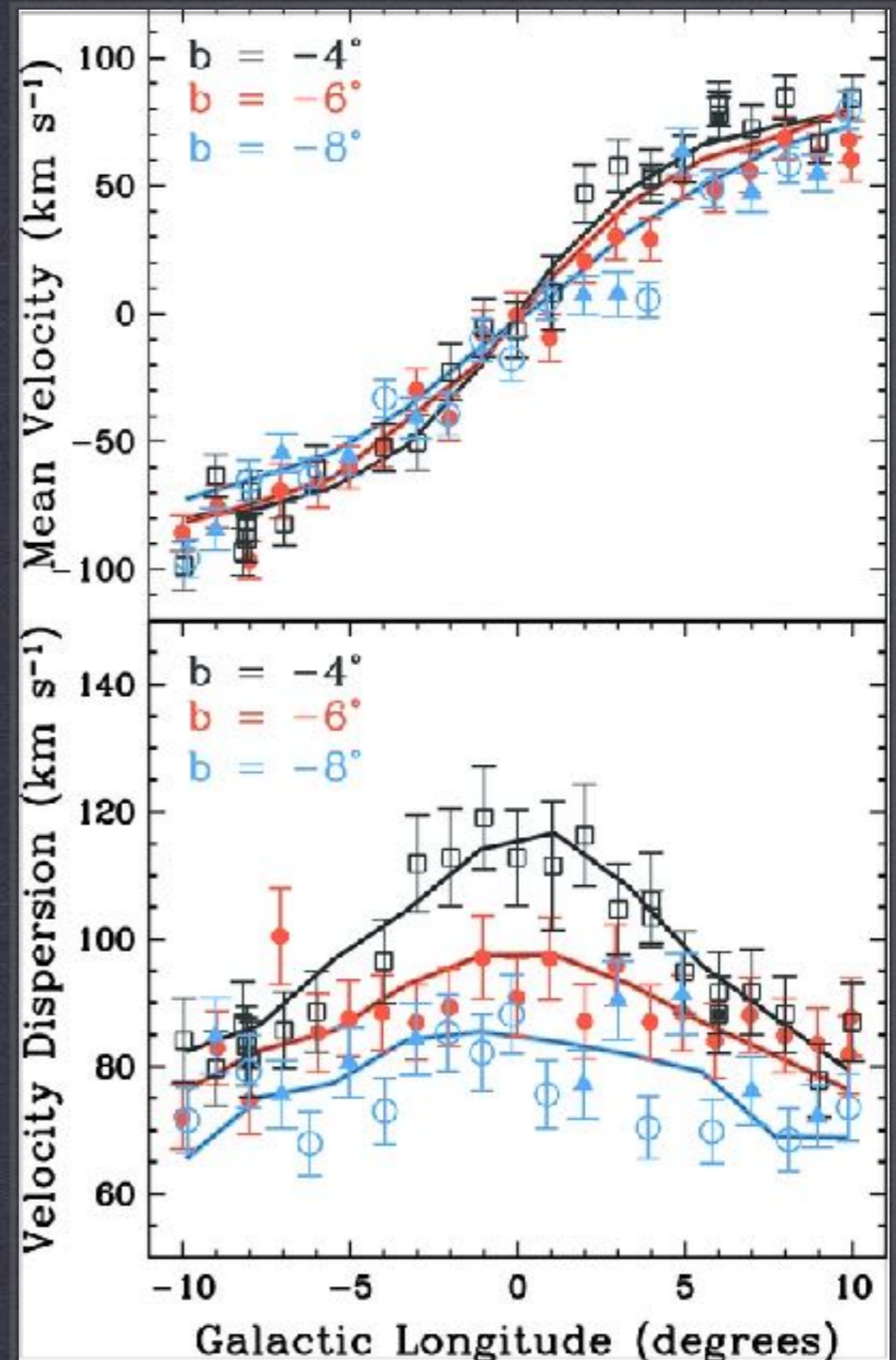
A pure bar



- * The rotation speed of the bulge is consistent with pure cylindrical rotation and no evidence of cold disk components or a pressure supported bulge

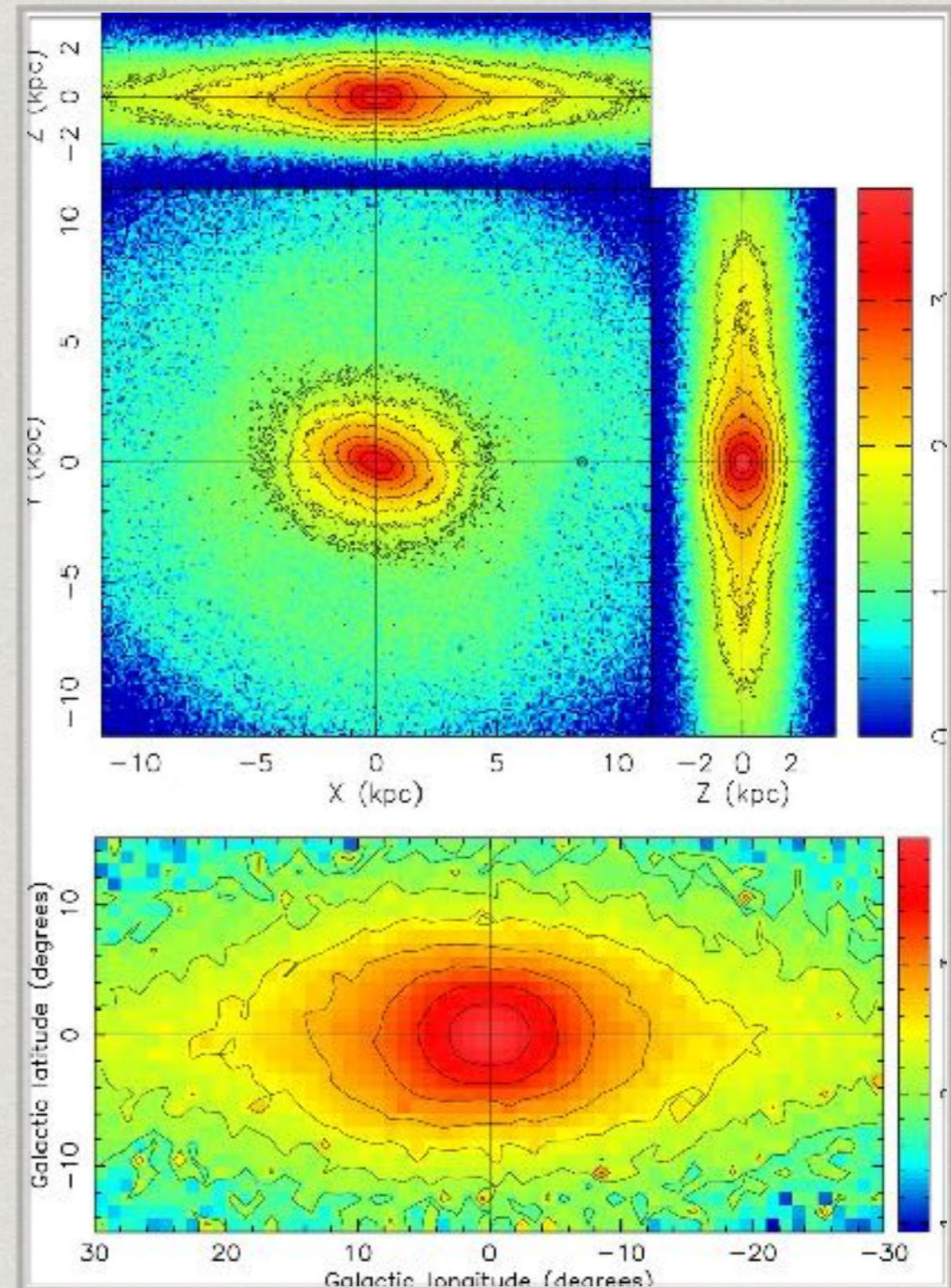
CYLINDRICAL ROTATION

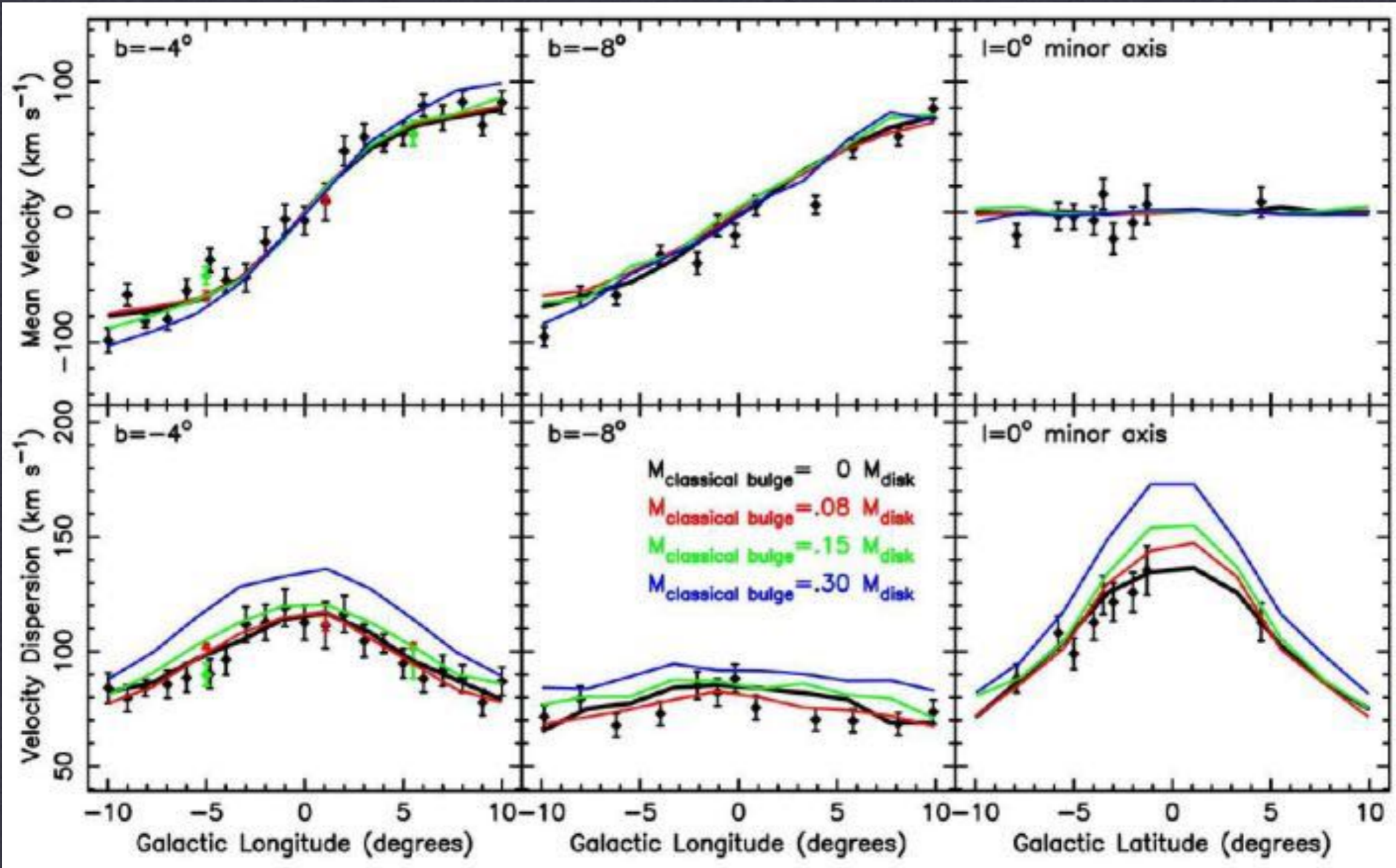
CONSISTENT WITH THE
VELOCITY FIELD OF A PURE
STELLAR BAR



Model

- * A simple model accounts for all observations
- * It consists of a single massive bar comprising the entirety of the bulge



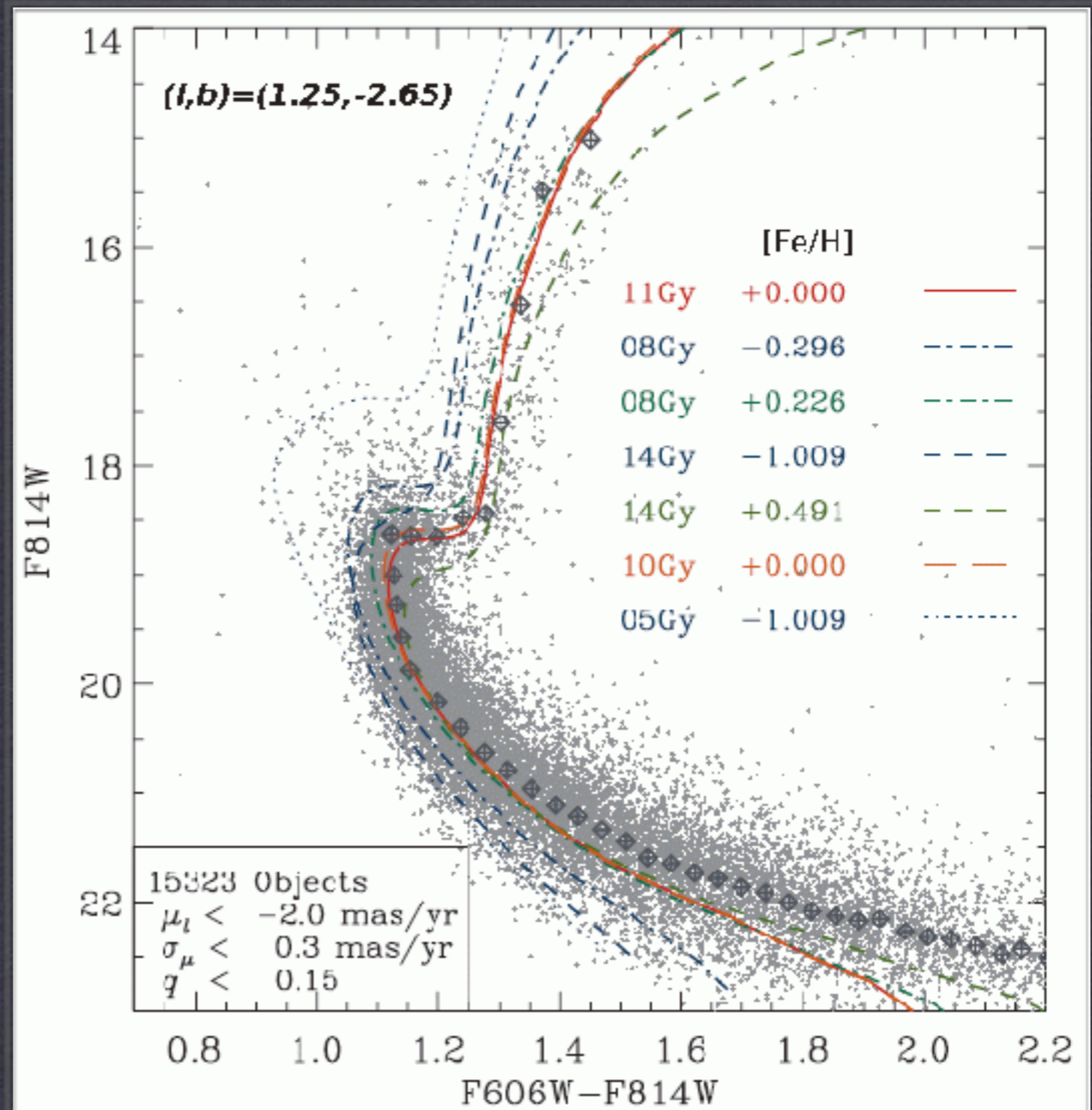


LIMITS TO CLASSICAL COMPONENT

< 8% OF THE DISK MASS

AGE OF BULGE STARS

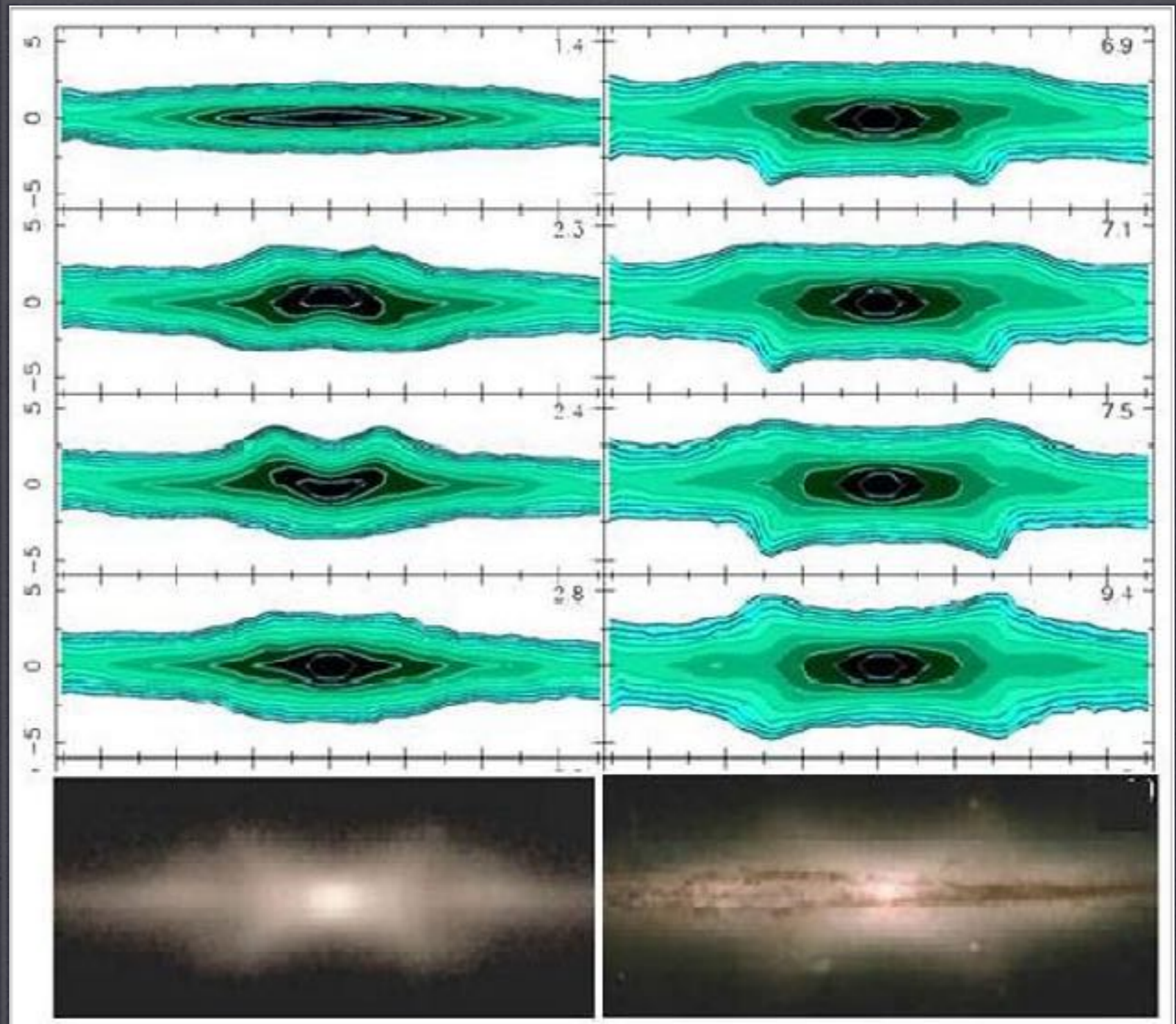
OLD AND METAL-RICH
 $Z \sim 3$

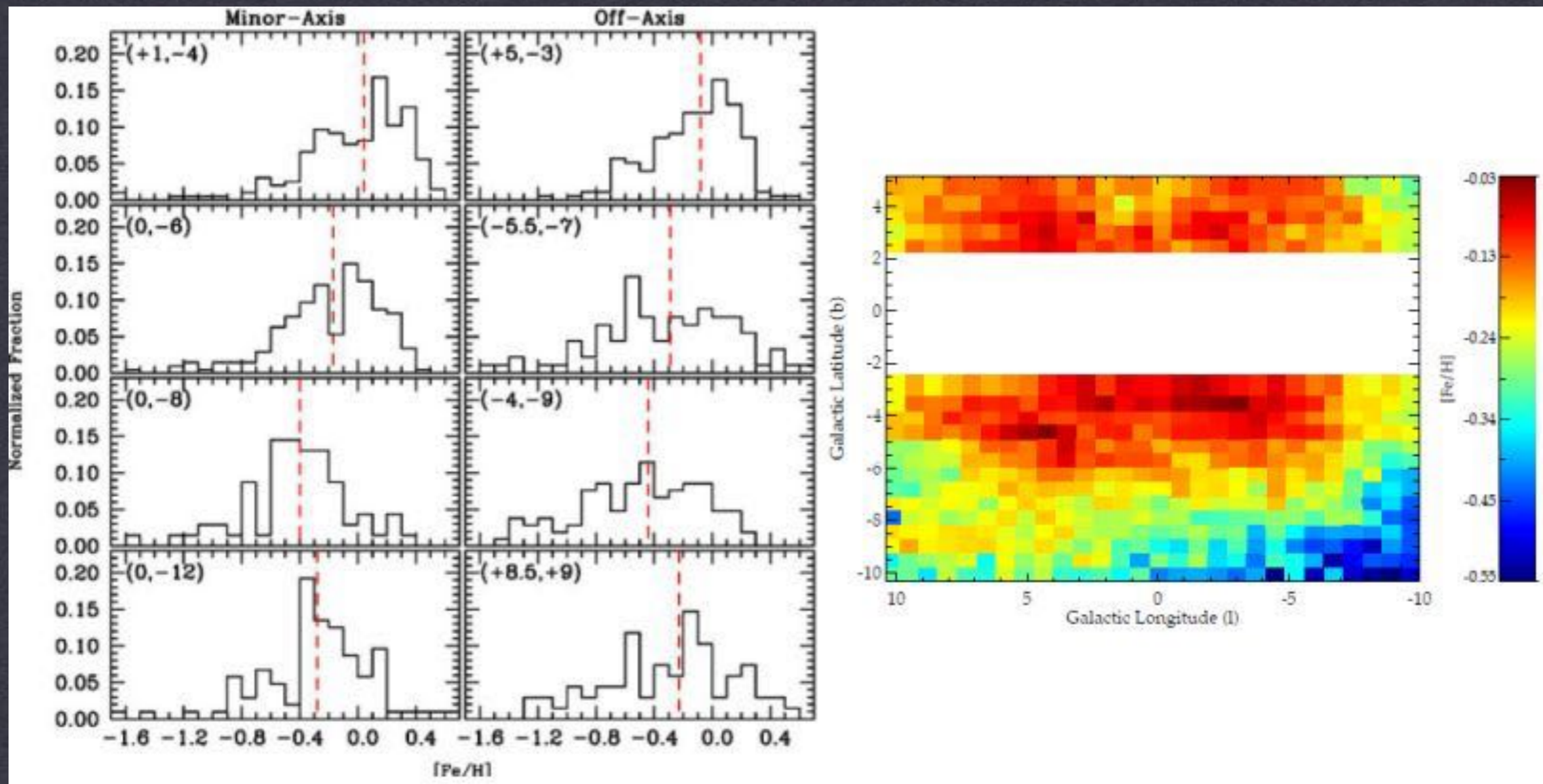


FIREHOSE INSTABILITY

BULGE FORMS
FROM BAR-
LIKE
INSTABILITY OF
MASSIVE
EARLY DISK

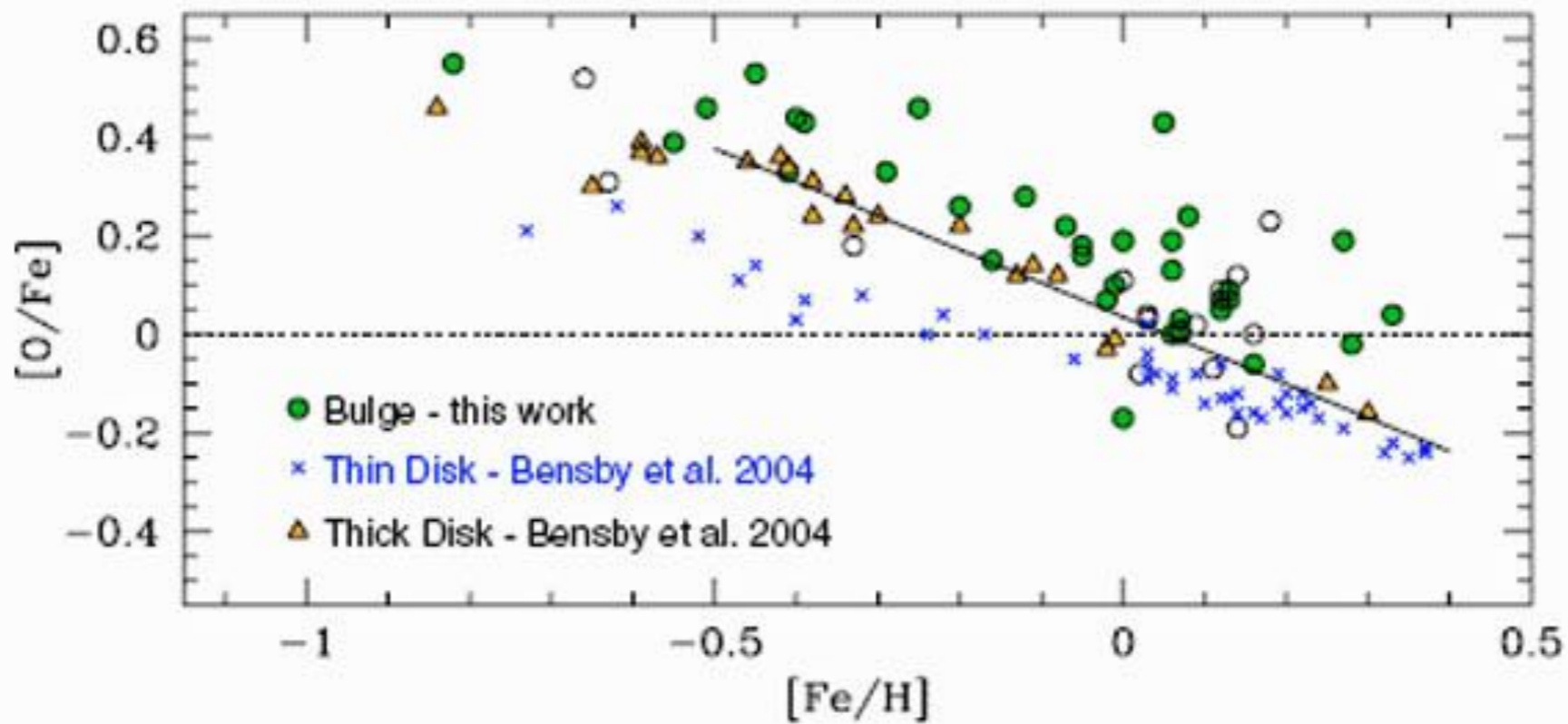
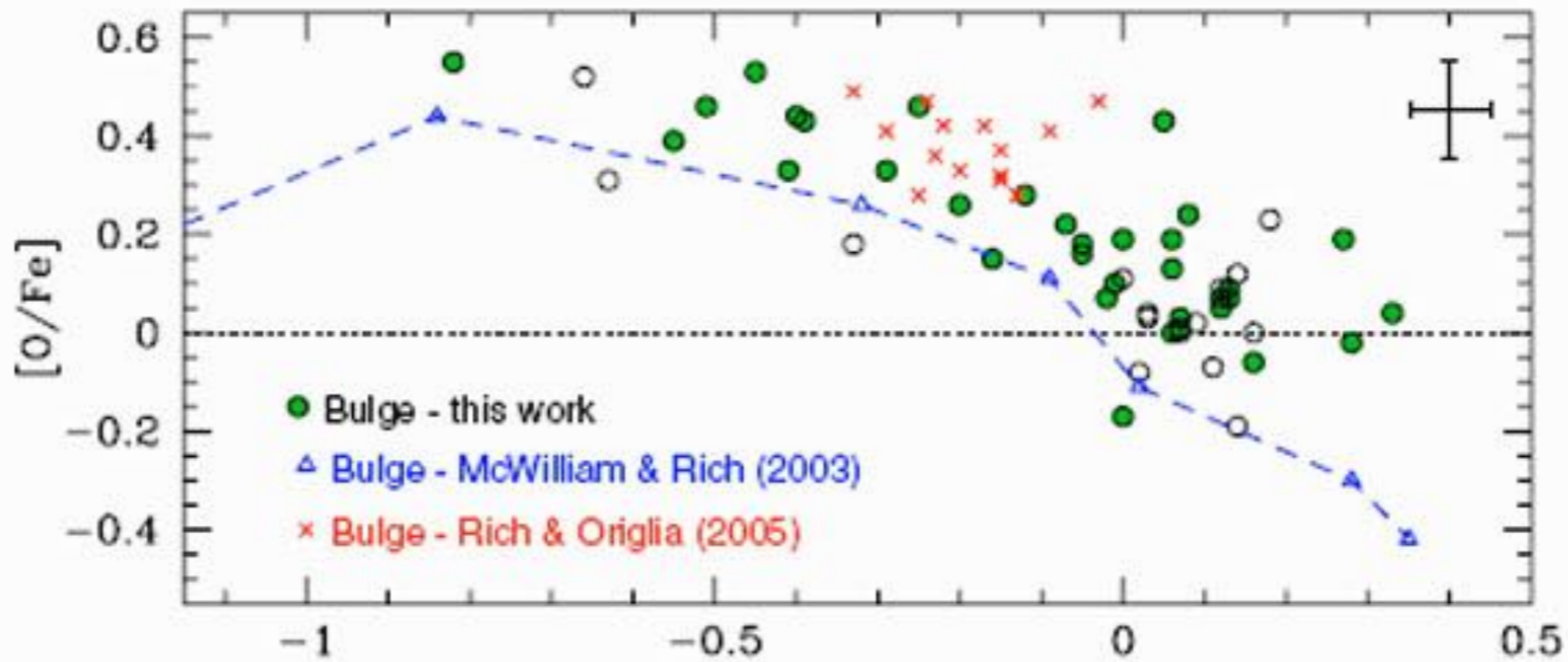
OLD AGE SO NO
MERGERS
SINCE $Z \sim 3$





METALLICITY GRADIENT IN BULGE STARS

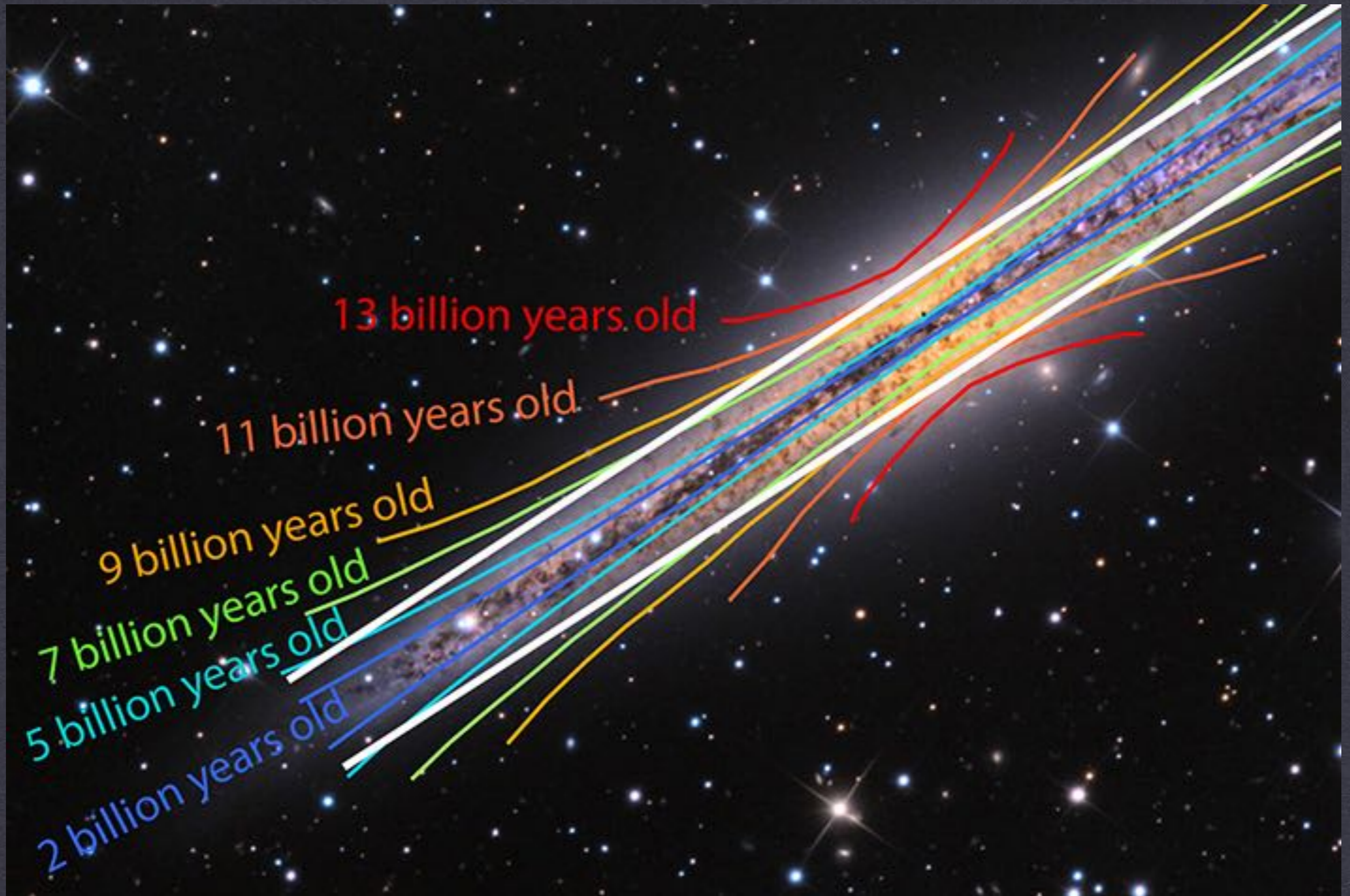
LIKE SMALL ELLIPTICAL ?



α -elements are enhanced among bulge stars

SUGGESTS RAPID STAR FORMATION AND QUENCHING AT HIGH REDSHIFT

- * The bulge appears to be a stellar bar formed from the instability of a massive disk at very early times
- * Old stellar ages and α -enhanced abundances imply rapid early star formation and quiescent evolution
- * Difficult to explain the abundance gradients in this fashion
- * Unless bulge evolves from an early thick disk

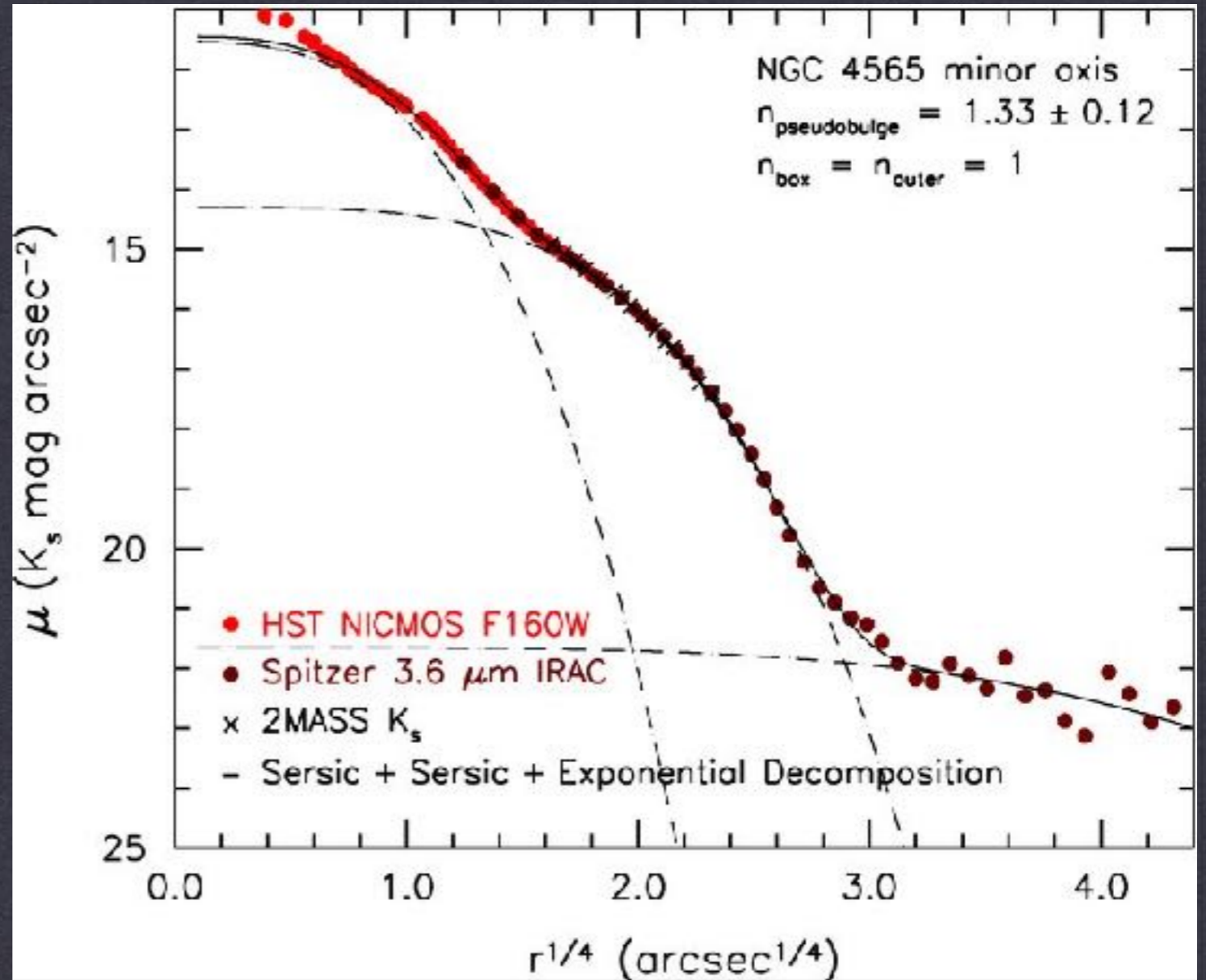


HEATED DISK

LEADS TO AGE AND METALLICITY GRADIENTS IN BULGE

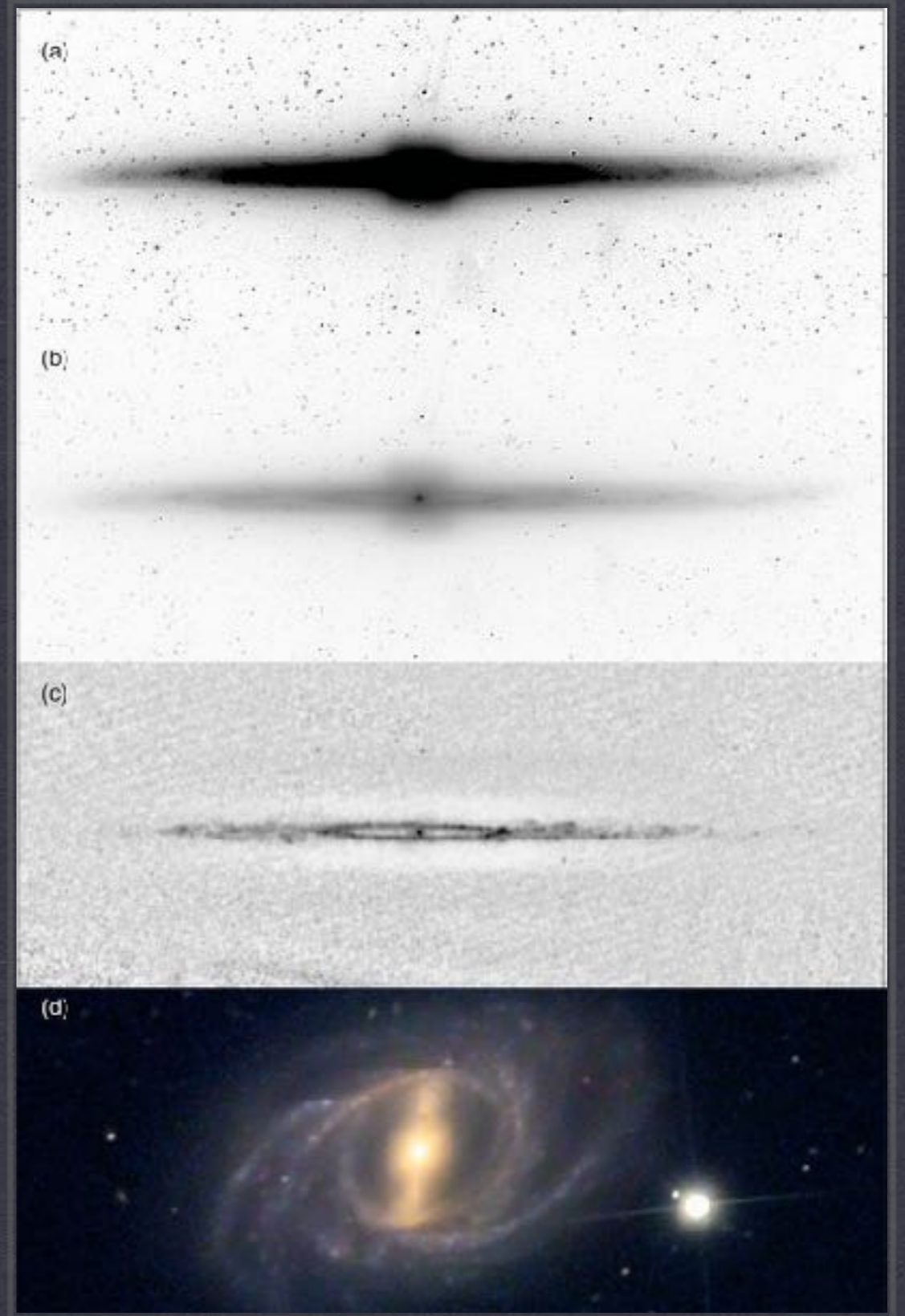
PSEUDO BULGES

NGC 4565 CAN BE
MODELLED WITH A
DOUBLE SERSIC
PROFILE OF INDEX
 ~ 1.3



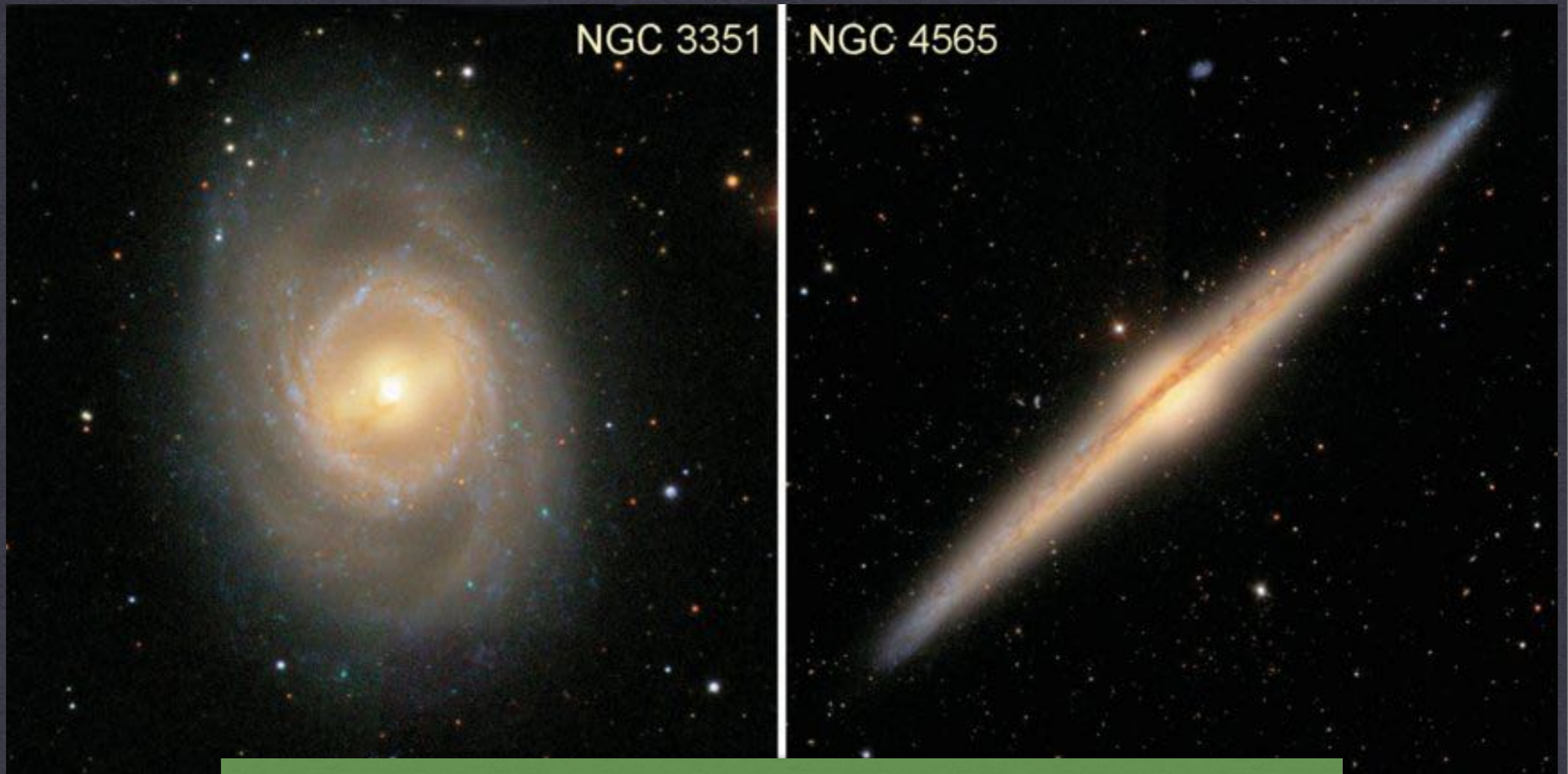
PSEUDO BULGE OF NGC 4565

LIKELY A COUNTERPART OF
OUR GALAXY, BULGE IS
ACTUALLY A PROMINENT
BAR WITH NO CLASSICAL
COMPONENT





DOES THE MILKY WAY LOOK LIKE THIS ?



NGC 3351

NGC 4565

In 11 Mpc sample 3/4 of all spirals are bulgeless or have B/P bulges

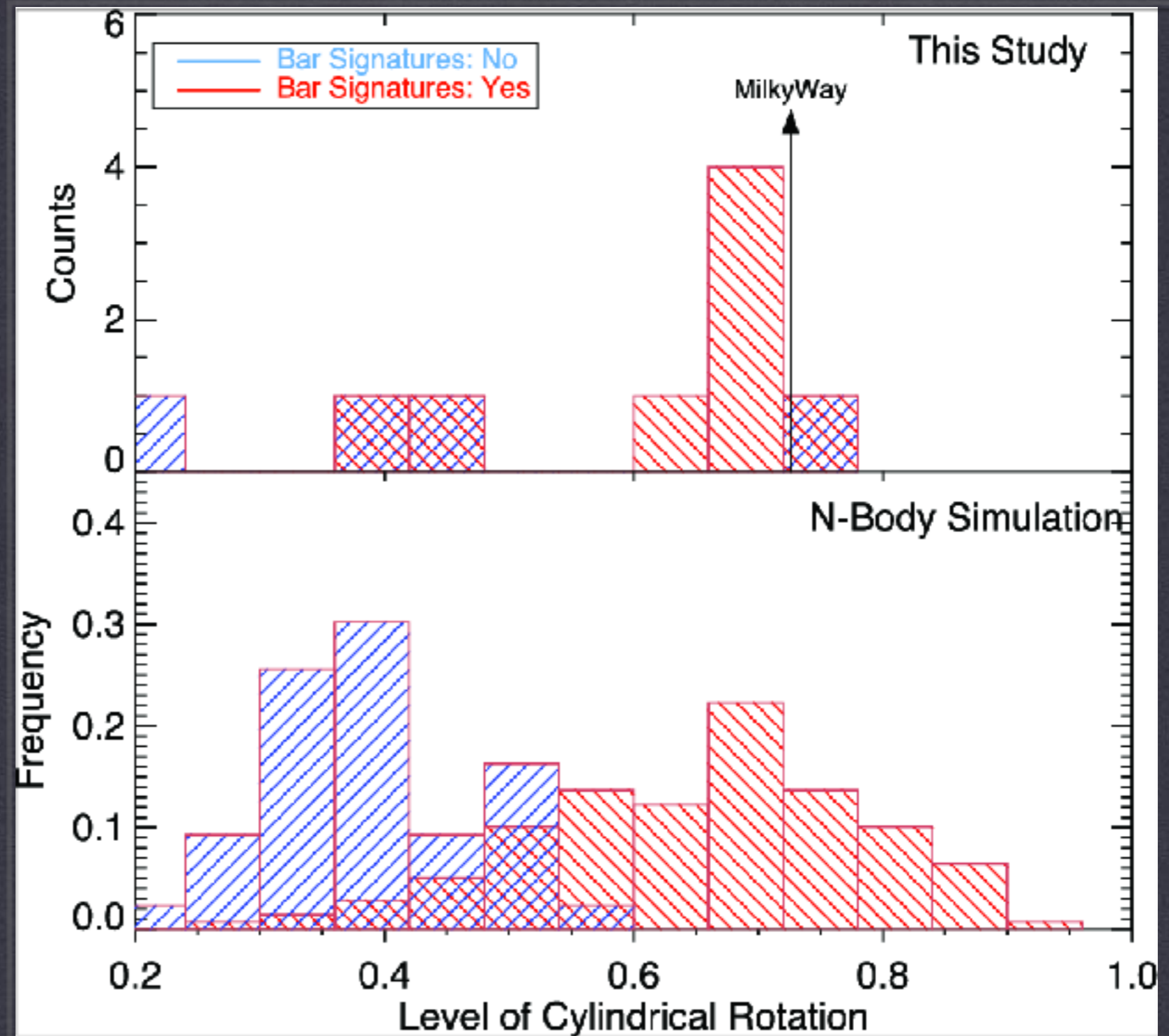
BARLENSES IN FACE ON GALAXIES

ARE LIKELY TO BE BOXY/PEANUT BULGES OR BARS AS WELL

OTHER BULGES

Moleainezhad et al. 2016

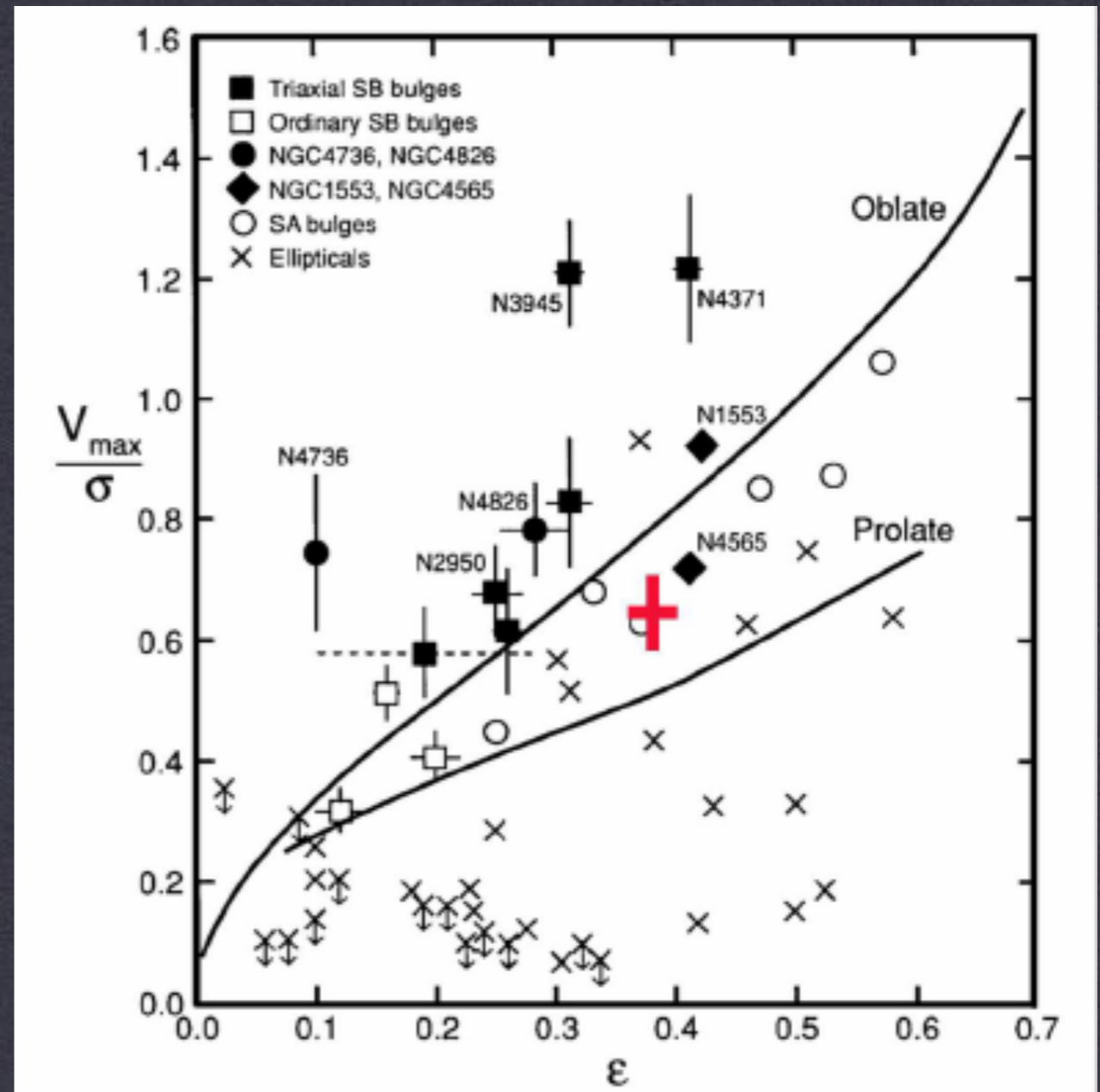
CYLINDRICAL
ROTATION IS
COMMON
AMONG B/P
BULGES
SUGGESTING
THEY ARE ALL
BARS



- * This poses an interesting problem for theoretical models
- * Milky Way sized halos in cosmological simulations tend to form classical bulges via mergers
- * While the Galaxy seems to have had a quiet merging history this cannot be true of all galaxies
- * Yet most local bulges seem to originate from buckled disks and therefore no mergers since high z .

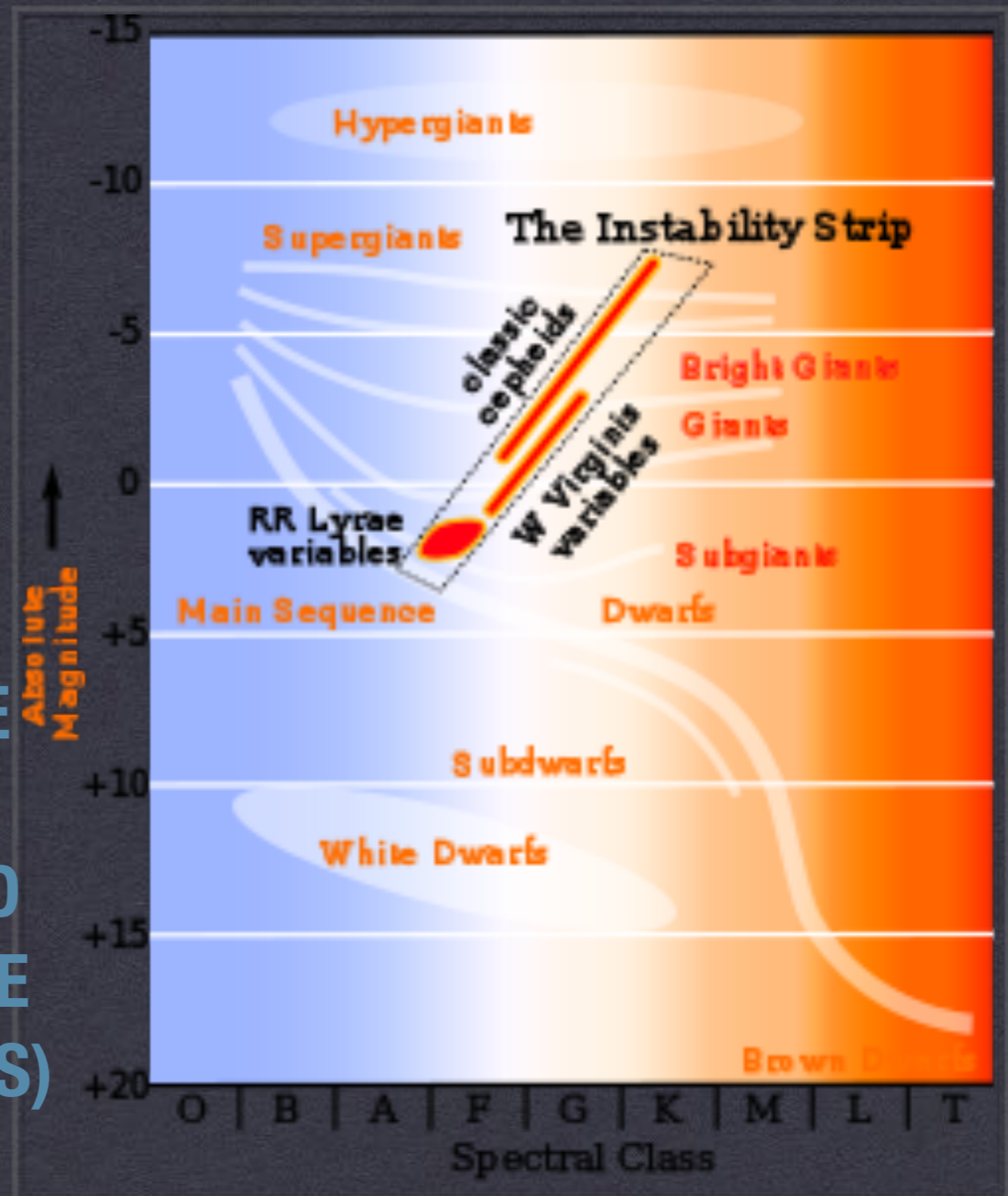
OUR BULGE

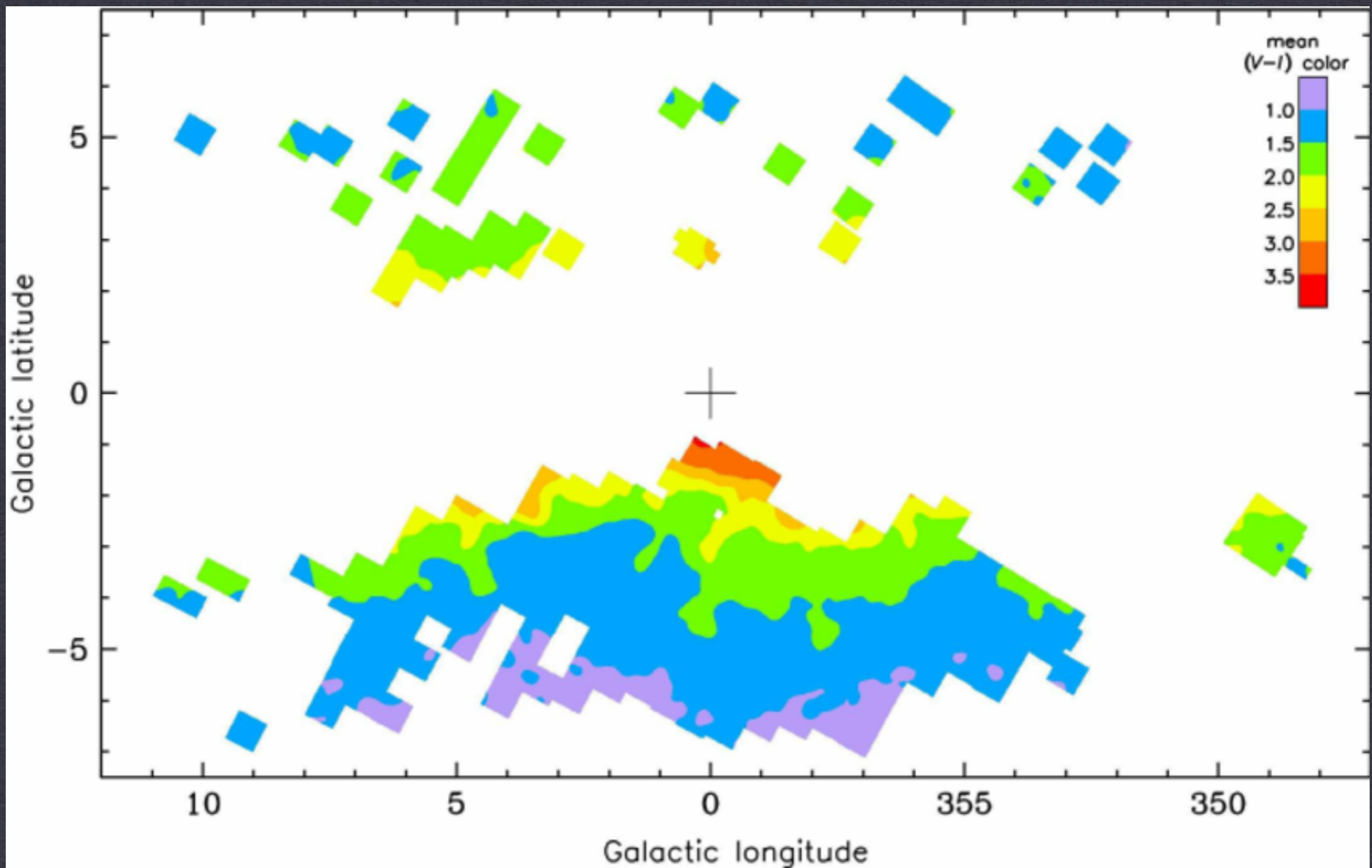
NORMAL PARAMETERS SO
ALL BULGES MAY BE BARS



RR LYRAE

CAN BE ISOLATED AS A TRUE BULGE COMPONENT (DISTANCE INDICATORS) AND AS THE OLDEST STARS (CORE HELIUM-BURNING LOW MASS)



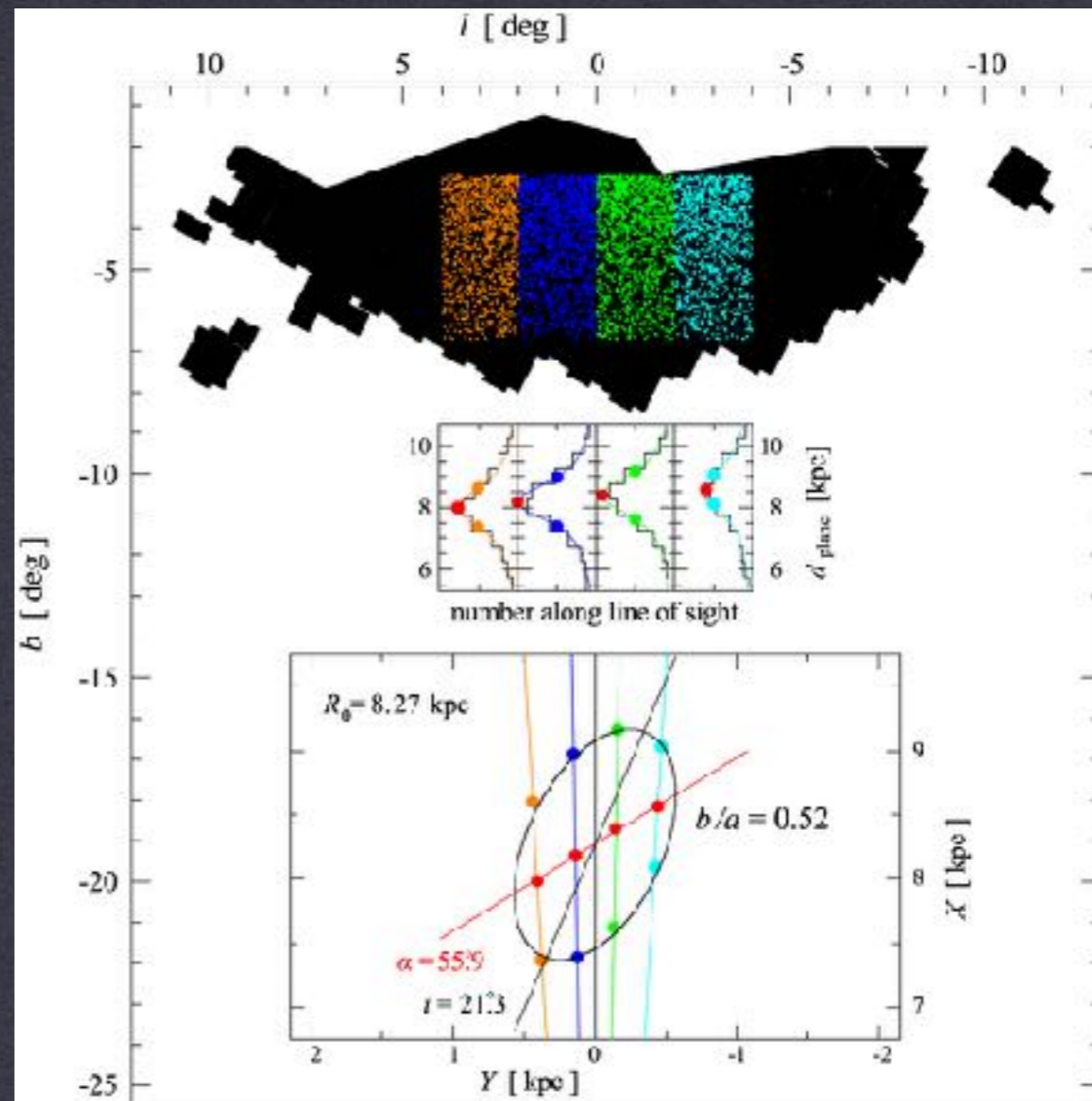


OGLE SURVEY

40,000 RR LYRAE IN SOUTHERN BULGE

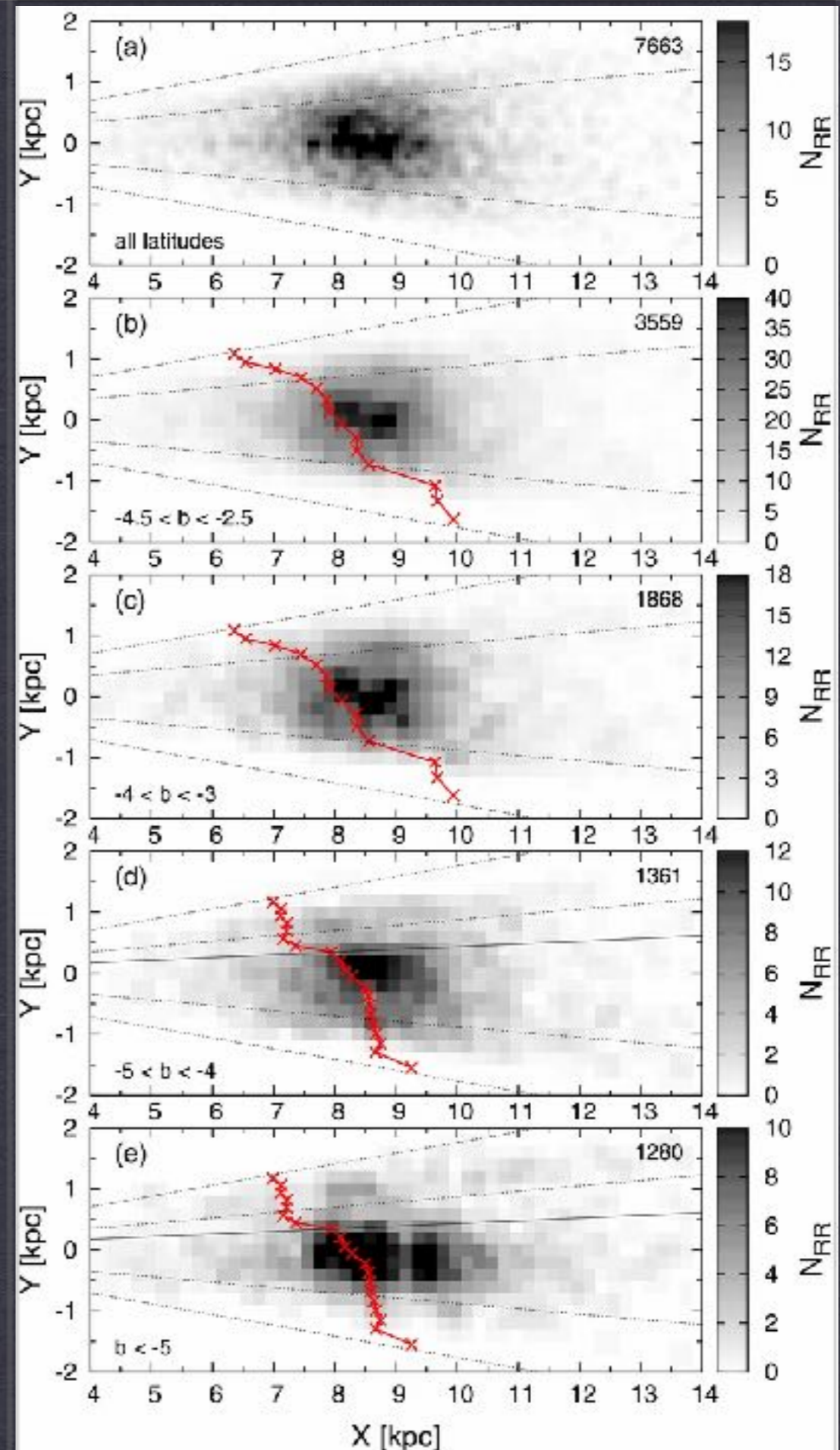
PIETRUKOWICZ ET AL. 2015

CLAIM TO HAVE DETECTED
THE BAR IN OGLE RR LYRAE



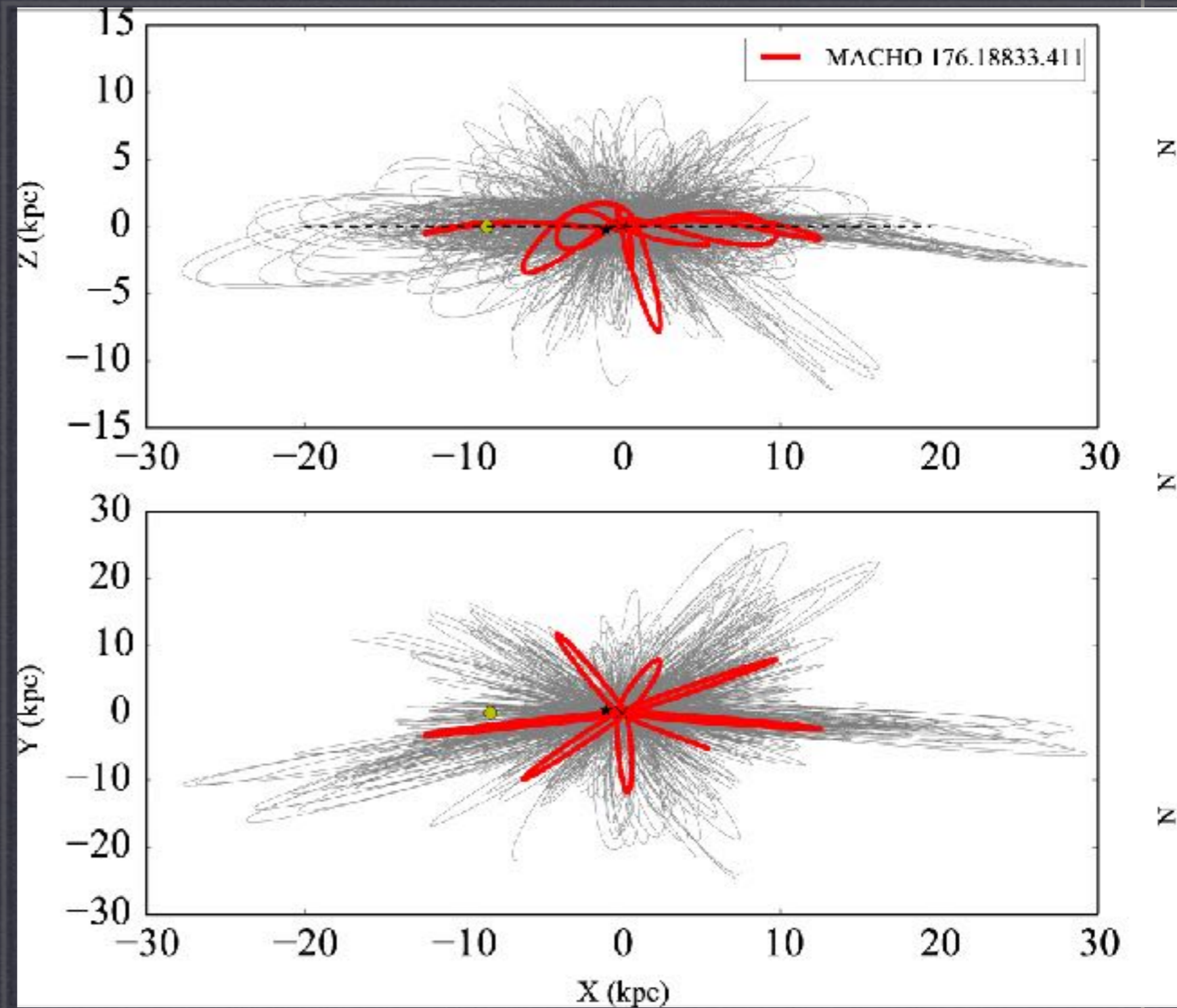
VVV SURVEY

NO DETECTION OF BAR BUT
SPHEROIDAL-LIKE
DISTRIBUTION
EITHER OLD BULGE OR
INNER HALO REGIONS



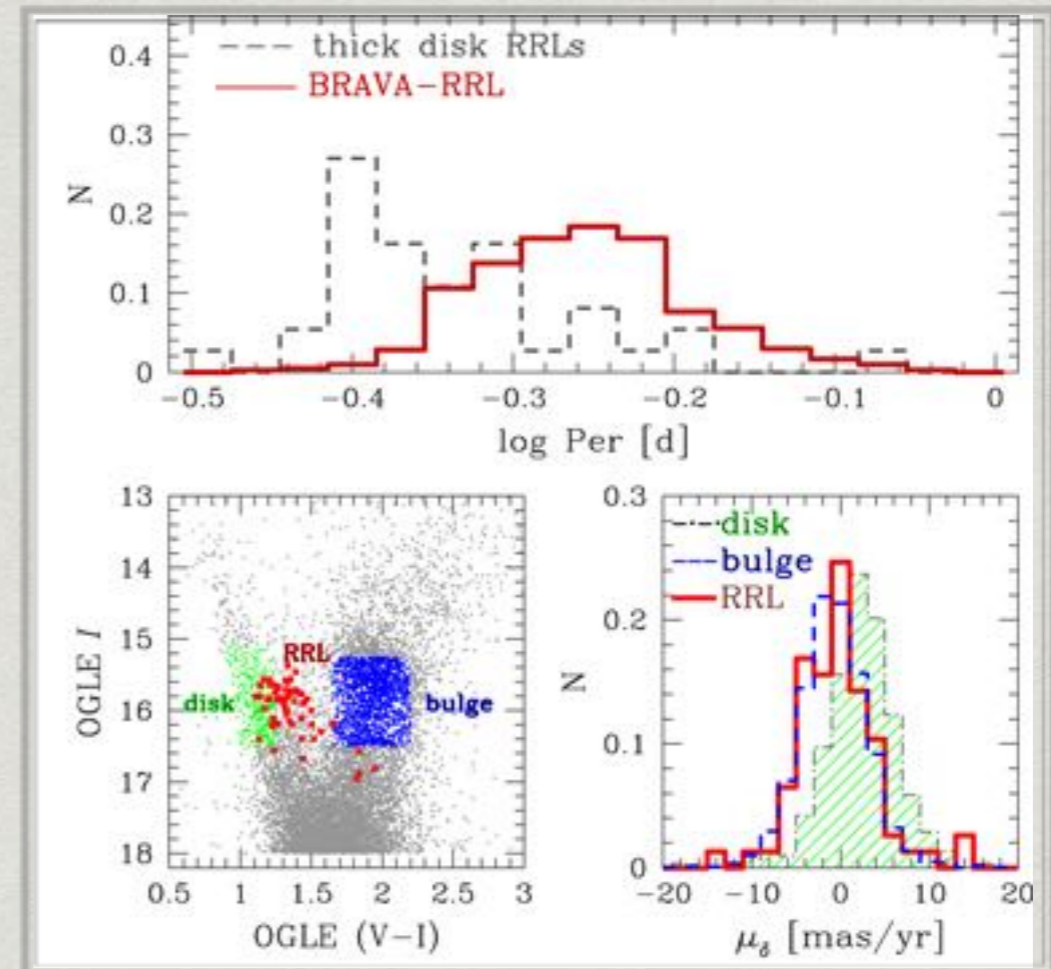
KUNDER ET AL. 2015

A BULGE RR LYRA
WITH A HALO-LIKE
ORBIT



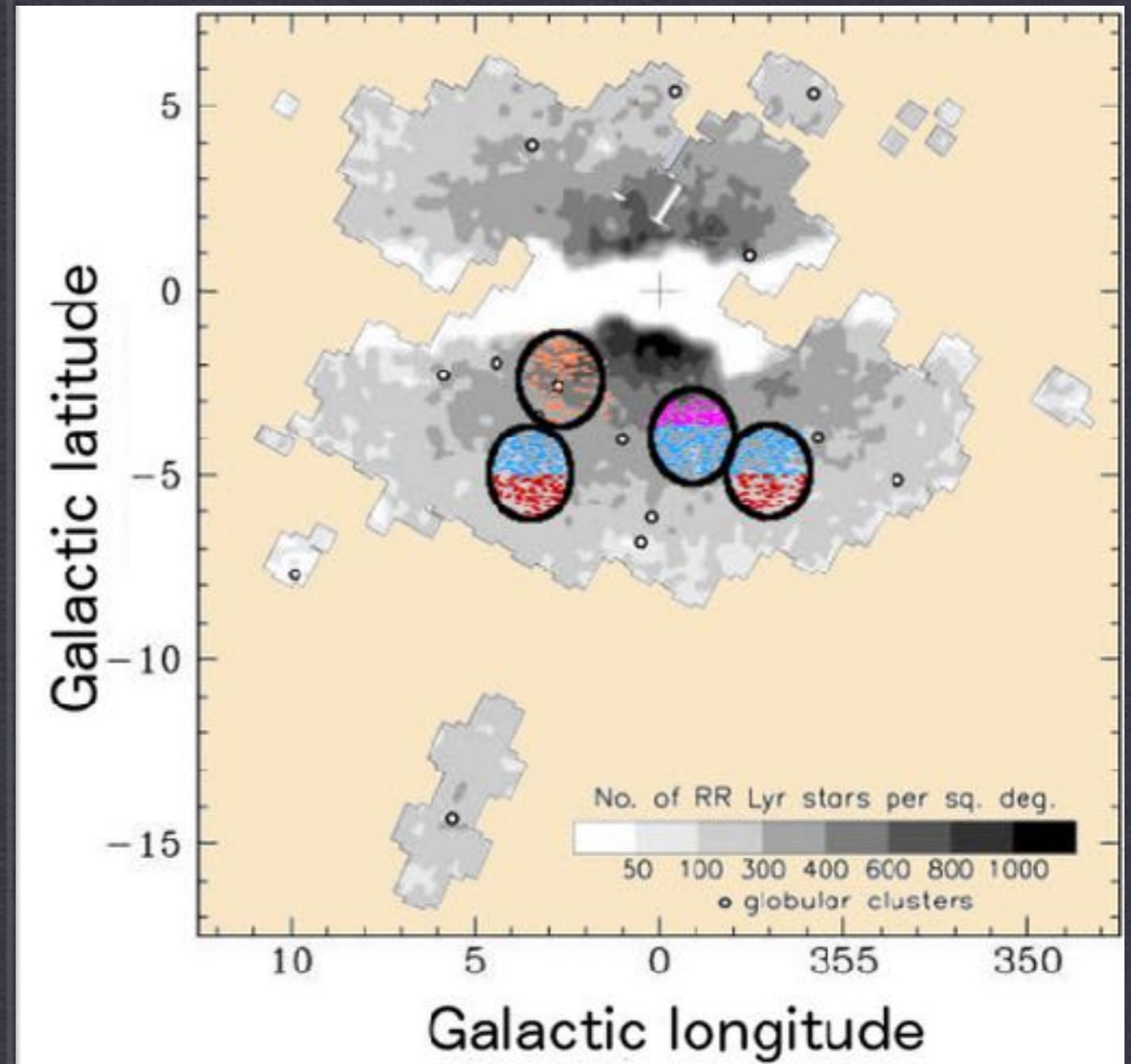
BRAVA RR Lyrae survey

- * Radial velocity survey of OGLE RR Lyrae
- * Colours and luminosities and periods are typical of what expected from a bulge population



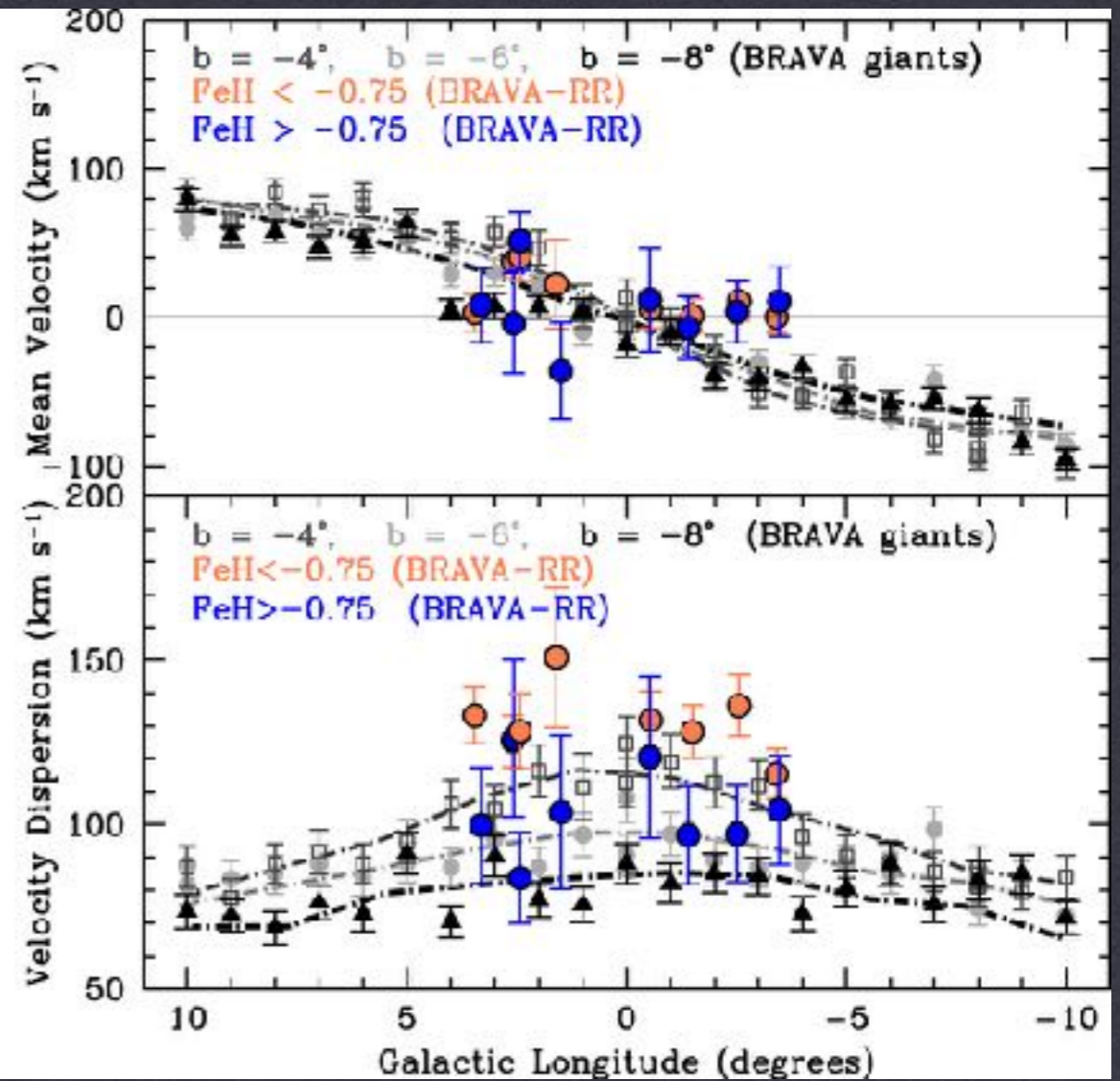
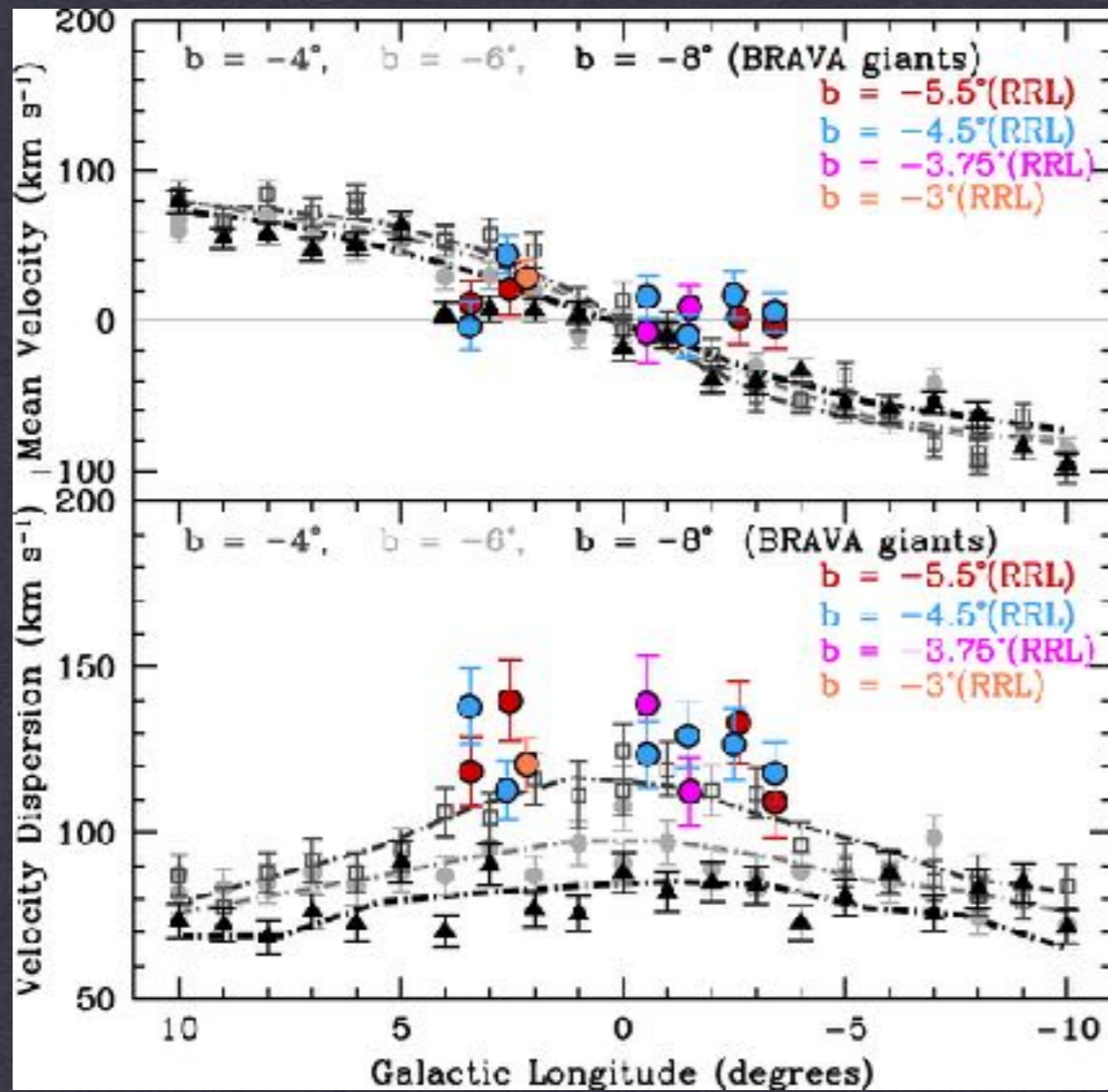
947 RR LYRAE

4 FIELDS OBSERVED FROM
THE CAT WITH THE AA Ω
MULTI-FIBER
SPECTROGRAPH



BRAVA RR

- * Our RR Lyrae do not trace a rotating component
- * They appear to lie within an approximately spheroidal component supported by pressure
- * About 1% of the mass in the bulge

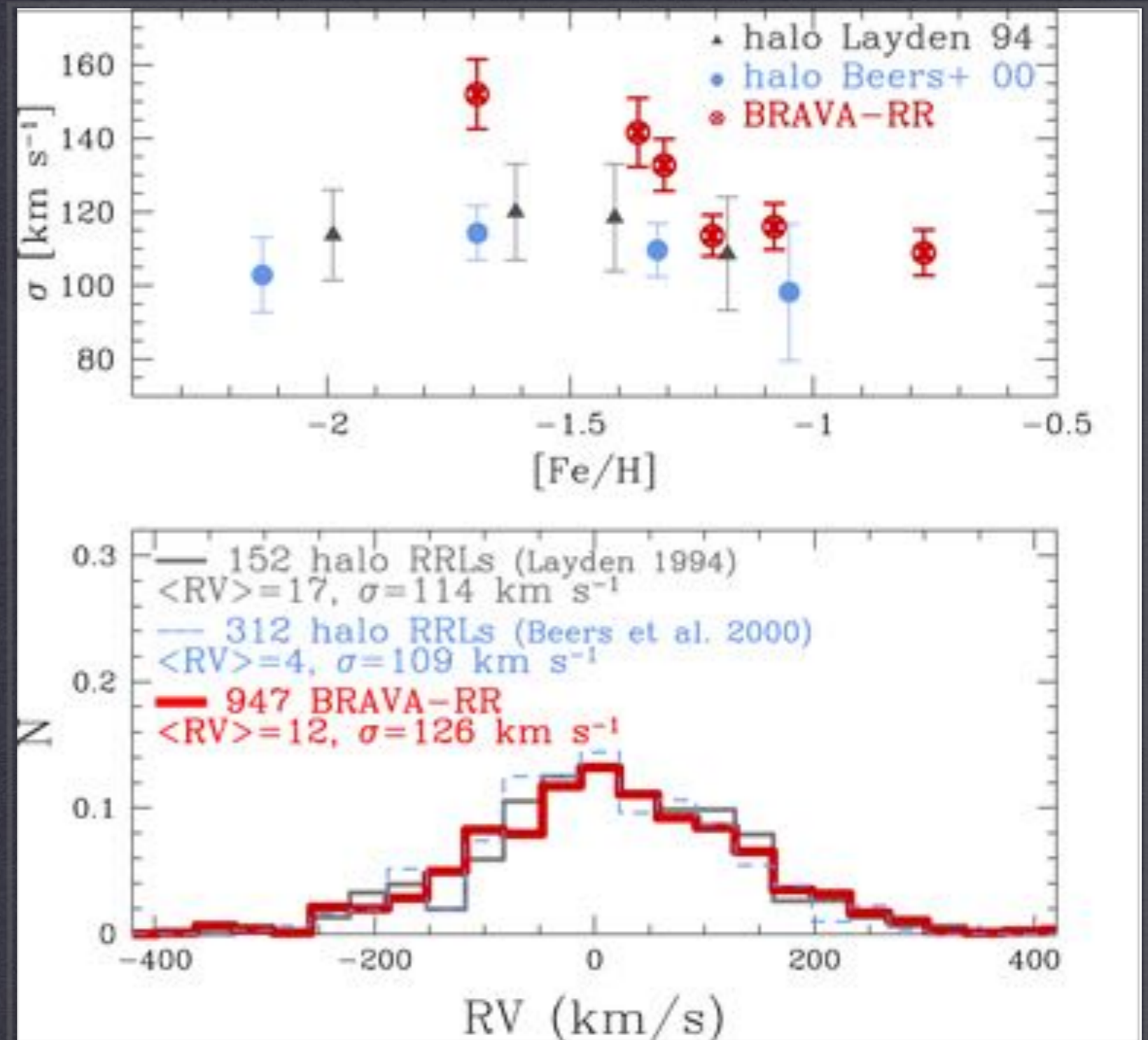


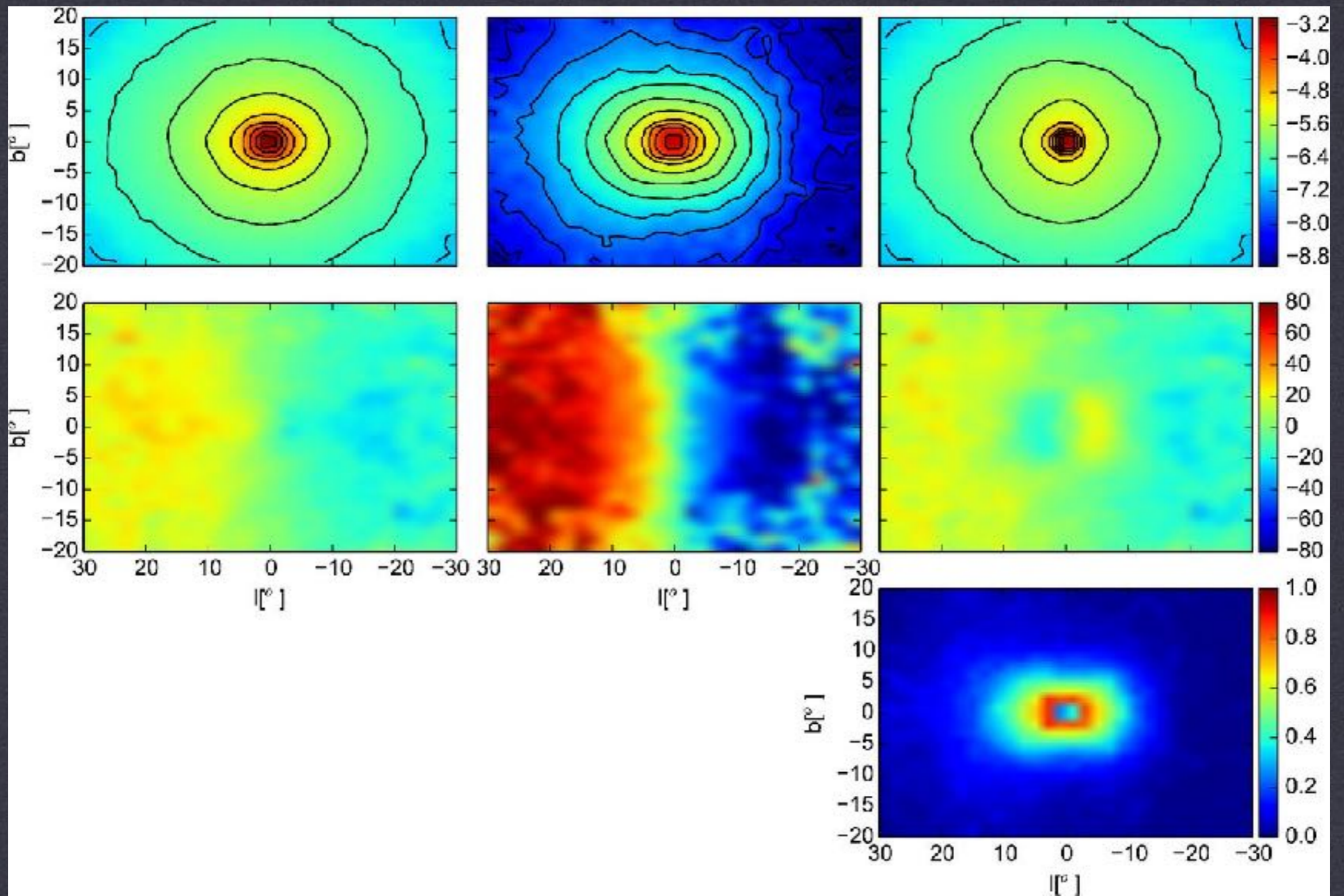
BRAVA RR LYRAE

HALO MEMBERS

UNLIKELY GIVEN THE VELOCITY DISPERSION

HOWEVER MODELS INDICATE THAT THE INNER HALO MAY ONLY BE SPUN UP AT LARGE RADII





KINEMATICS OF RR LYRAE IN MODEL

PEREZ-VILLEGAS ET AL. 2017

A residual bulge

- * 1% of the mass of the bar
- * It is predicted that the earliest epoch of star formation may take place in the bulge but not be of the bulge
- * Relics of the oldest star formation episode in the galaxy should be found in the centre

Conclusions

- * The Milky Way is a bulgeless spiral dominated by a massive stellar bar
- * There is no significant pressure-supported component
- * Bar is very old and implies no significant merging for the Milky Way since $z \sim 3$

- * Nearly all bulges in the nearby universe also seem to be pseudo bulges and stellar bars
- * This is in very severe contrast to models of galaxy formation in CDM where a bulge must always form
- * A small residual bulge may be present in the inner kpc.



SMITTEN

RACHAEL HALE

BULFINCH

RACHAEL HALE

CAT'S PAJAMAS

B

101 CATAclysms

101
KITTENS
&
CATS

RACHAEL HALE

BULFINCH

101 CATAclysms

101
KITTENS
&
CATS

RACHAEL HALE

BULFINCH