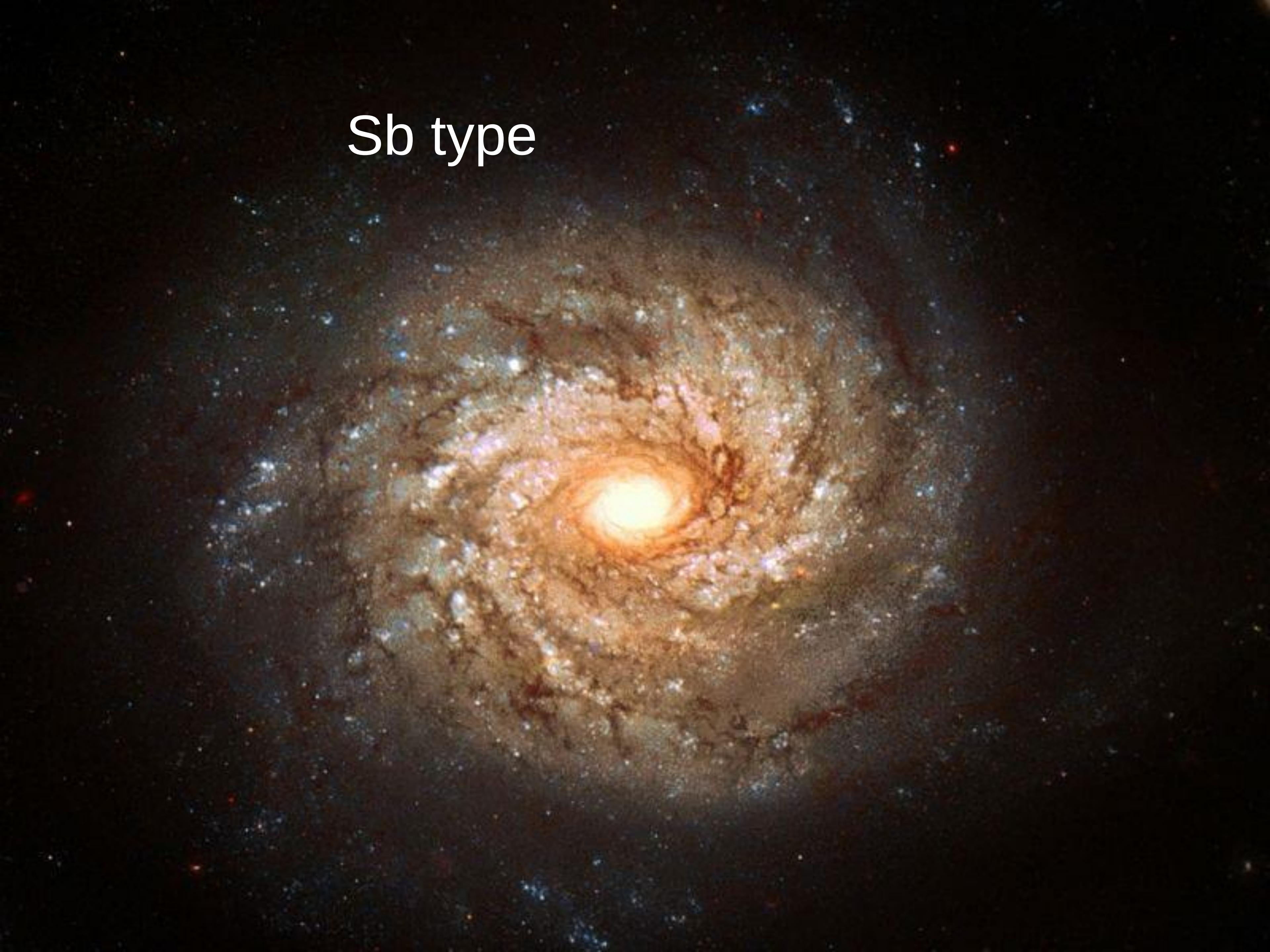
THE GALACTIC BULGE

Beatriz Barbuy

IAG - Universidade de São Paulo

SOMBRERO - Sa


Sb type

M101 – Sc type

M33 - Sc


M33 © IAC/RGO/Malin
Photo from Isaac Newton Telescope plates by David Malin

Kormendy & Kennicutt 2004:

BULGES OF SPIRALS:

Sa, Sb = high mass = bulges

Sc = pseudobulges formed from the bar

Milky Way

Barred:

SABbc(rs) ➔ SABb(rs)

Classical bulge or

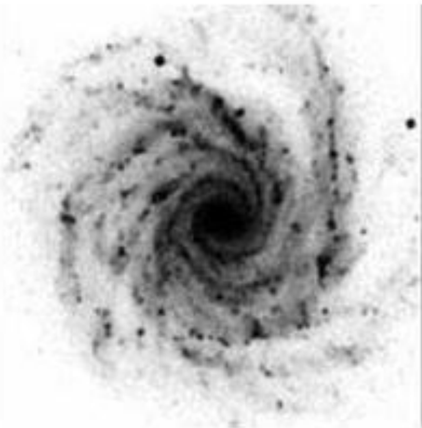
Pseudobulge formed entirely

from the bar?

NGC 1300 – SBb(s) - prototype

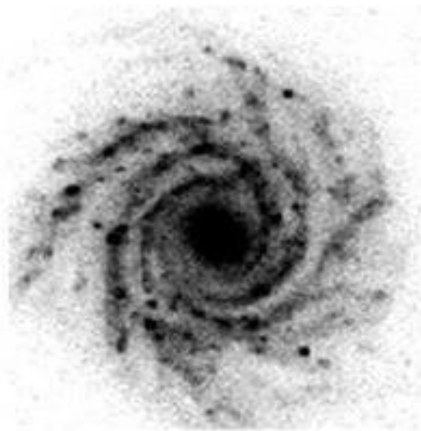
NGC
4394
SBb(r)

Sc(rs)



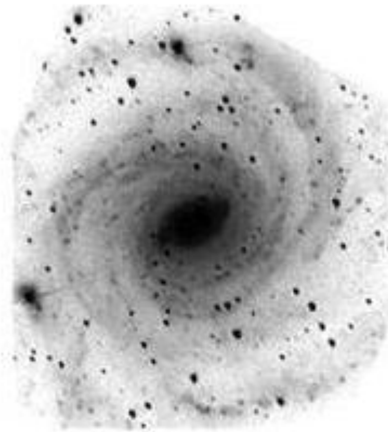
NGC 1232

Sb(r)



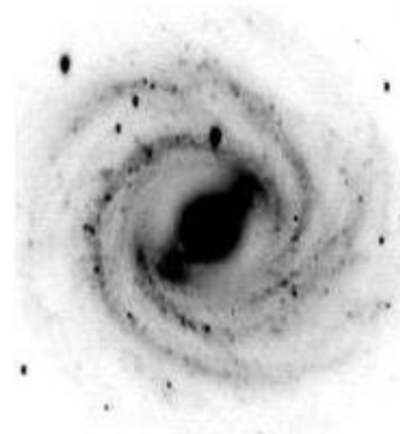
NGC 1288

Sb(r)



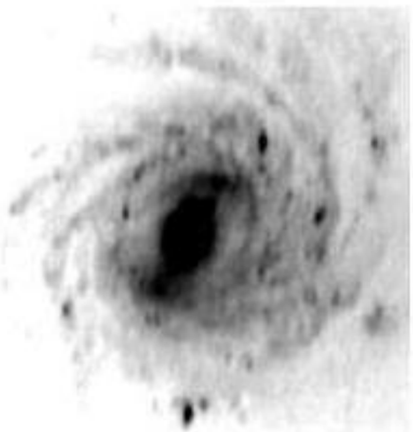
NGC 6384

SBb(rs)



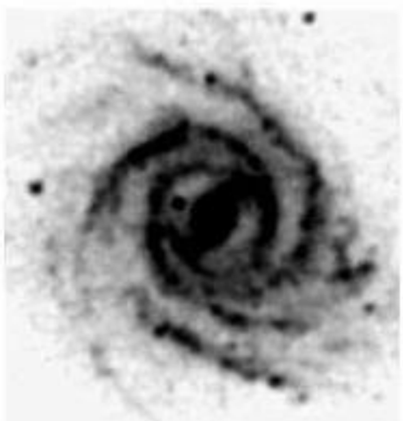
NGC 3992

SBbc(r)



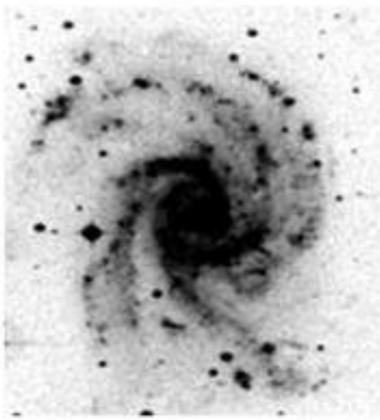
NGC 3953

SBbc(r)



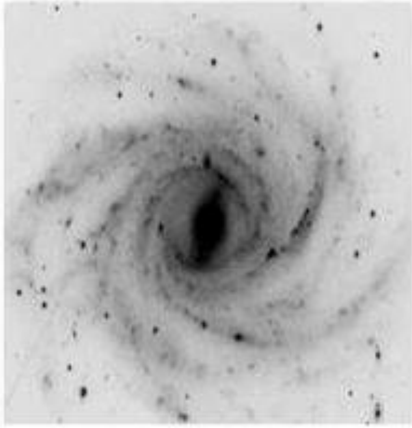
NGC 3124

SBc(rs)

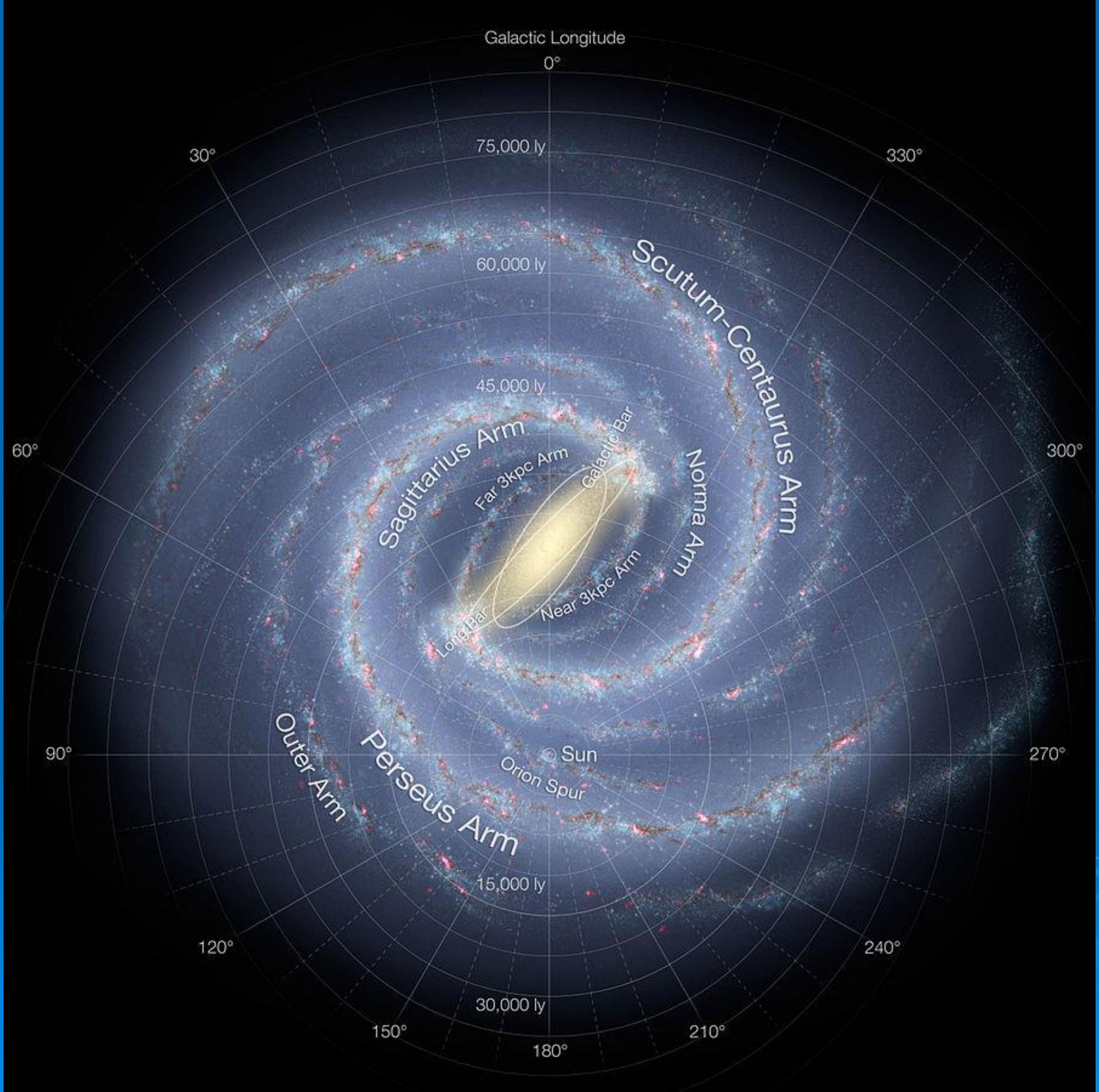


NGC 2835

SBbc(r)

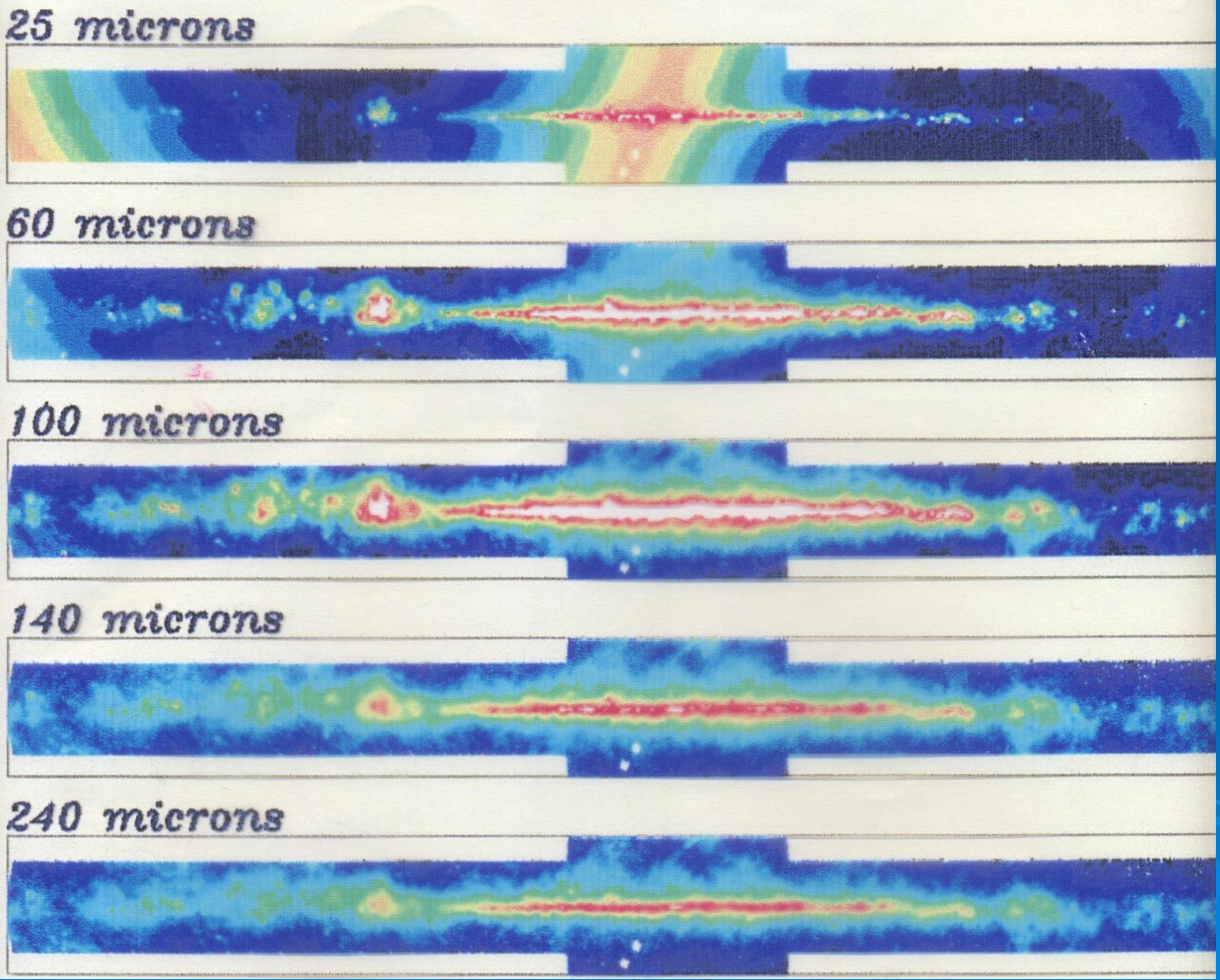


NGC 2336



Galactic Longitude
0°
30°
330°
60°
300°
90°
270°
120°
240°
150°
180°
210°
75,000 ly
60,000 ly
45,000 ly
15,000 ly
30,000 ly
Scutum-Centaurus Arm
Sagittarius Arm
Far 3kpc Arm
Galactic Bar
Norma Arm
Near 3kpc Arm
Long Bar
Outer Arm
Perseus Arm
Sun
Orion Spur

DIRBE Galactic Plane Maps



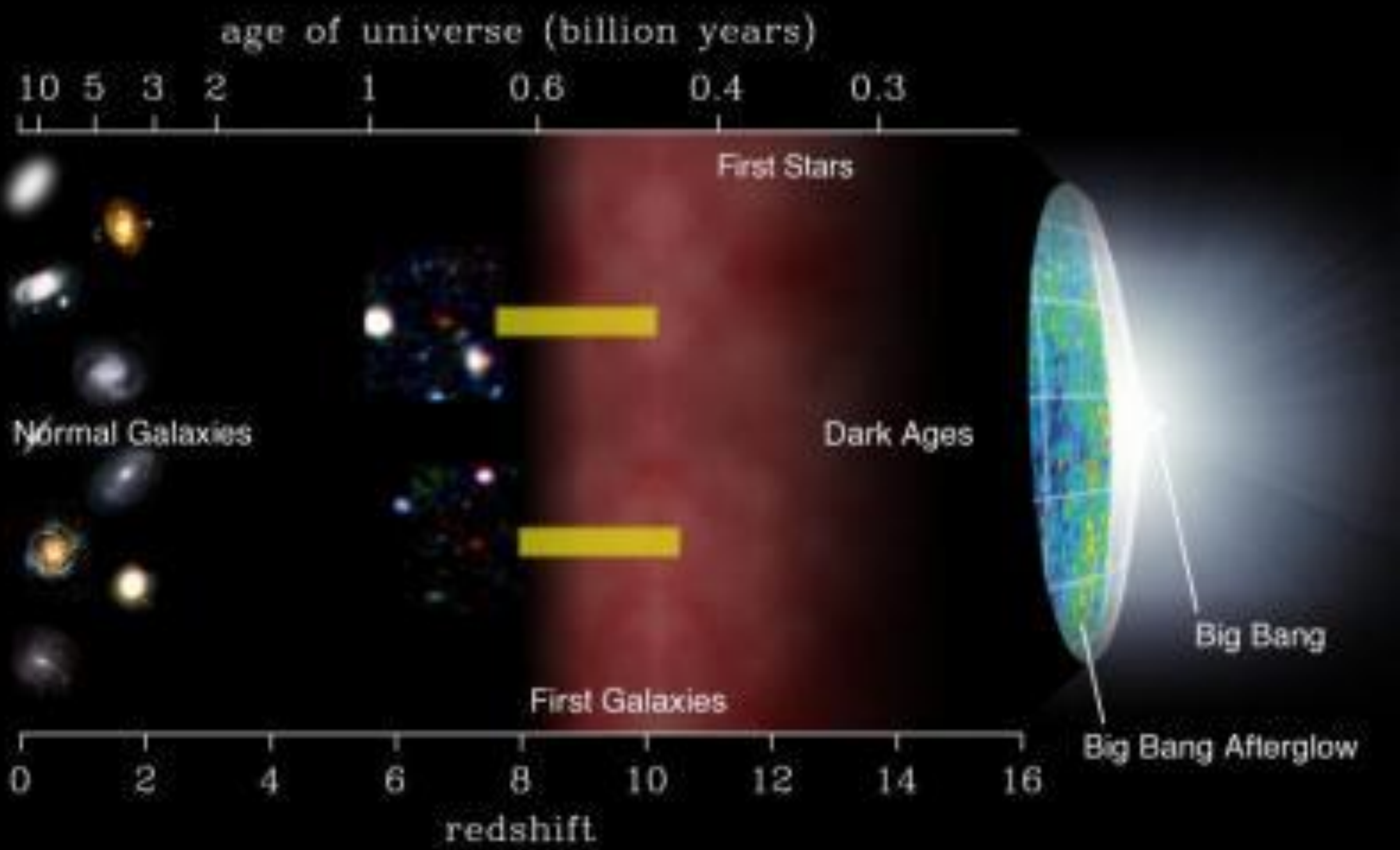
Redshift z~2 → 10 Gyr →

bulges in formation

Evidence show bulges already formed,
with no star formation in the center,
only in the surrounding disk
(Tacchella+15, Nelson+16)

Disks had much more gas than now,
of the order of 50% →

Evolution of Universe vs. redshift



Tacconi+18: quantity of gas scales with redshift: $(1+z)^{2.6}$

and effective radius scaling with $(1+z)^{-1}$ (Newman+12)

Therefore surface gas density scales with: $(1+z)^{4.6}$

➔ Probably the property of galaxies that evolve most rapidly (Renzini+18).

Scenarios of bulge formation

1. Classical = central collapse

$t_{free\text{-}fall} \sim (G\rho)^{-1/2}$

→ bulge forms first, in $\sim 10^8$ yr

→ super-simplification → several models are acceptable and still rather similar

2. Evolution of the bar → transfer of gas and stars to the center of the Galaxy, causing bulge formation

Several models in the lines of option 1:

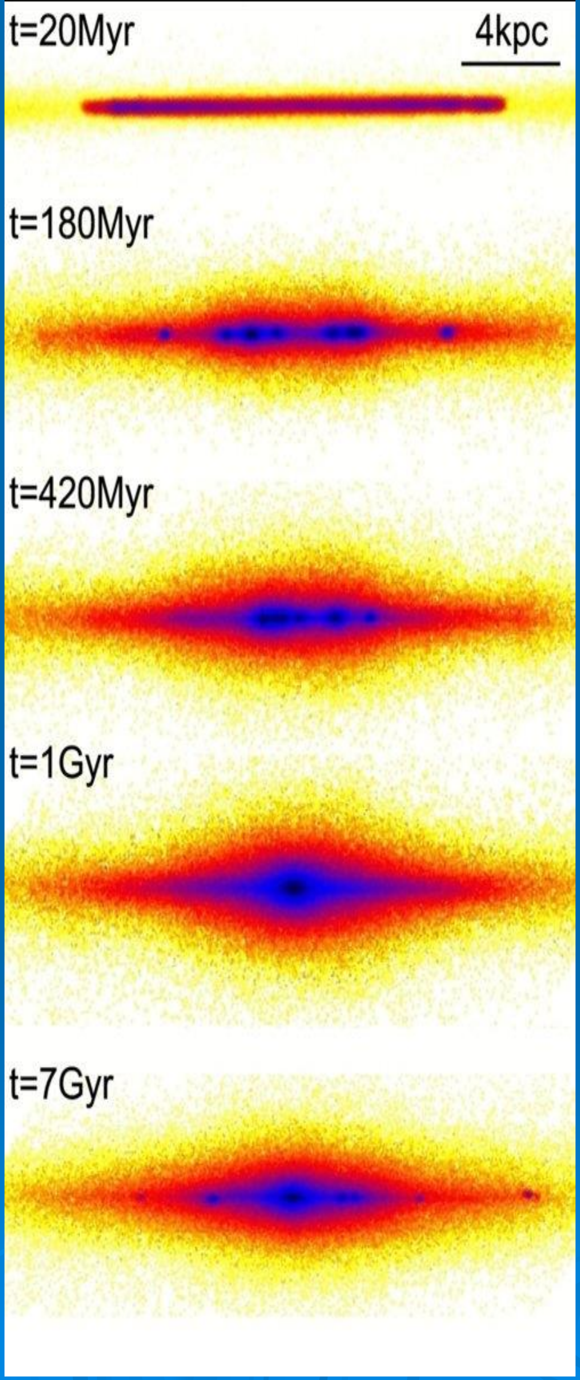
formation of bulge first
➔ old bulge (13 Gyr)

Clumps migrate and coalesce in the centers of protogalaxies (Bournaud)

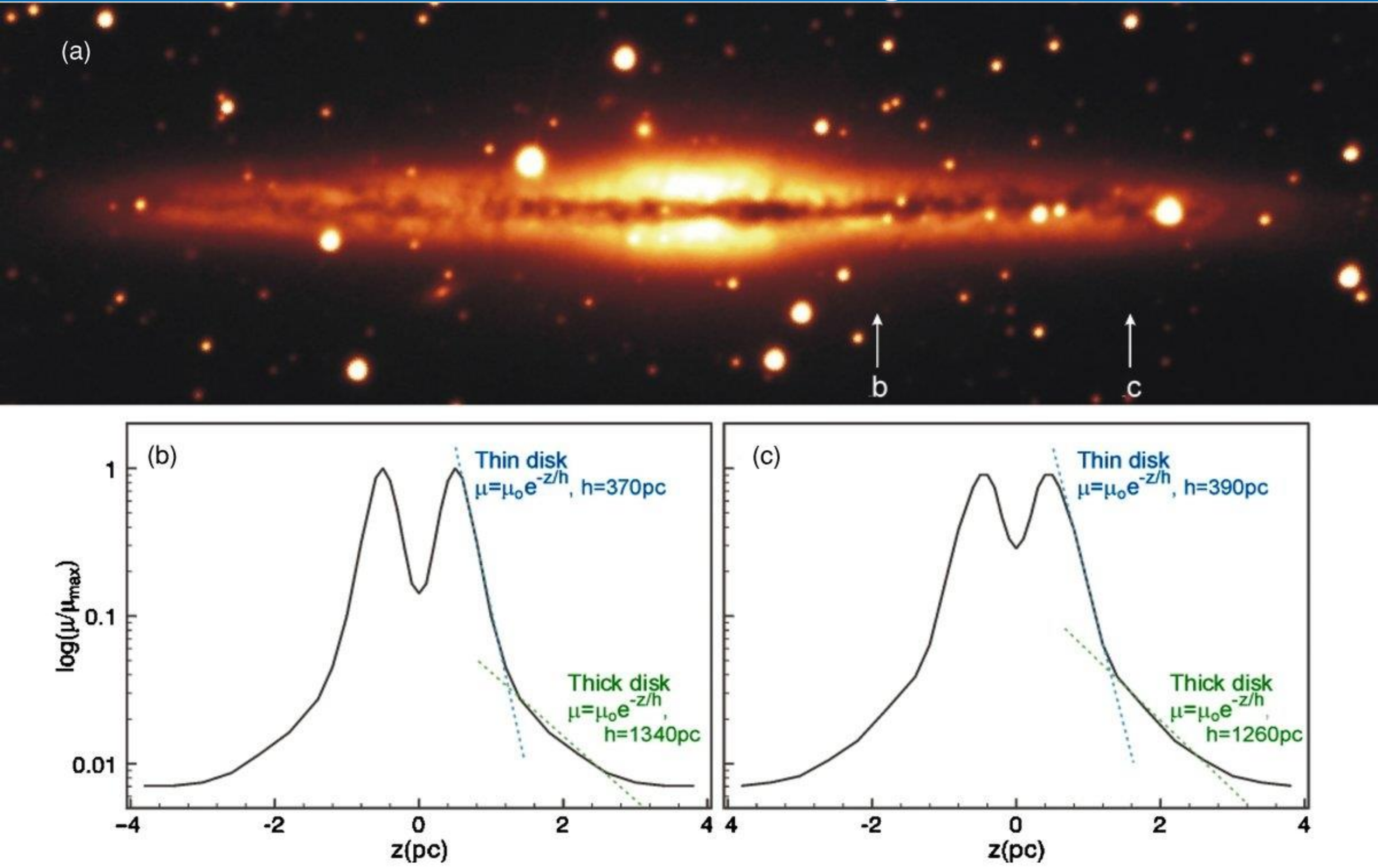
Turbulent instabilities of disks, leading to intense star formation (Dekel & Burkert14, Tacchella+16).

Bournaud et al. 2009

Clouds of gas coalesce



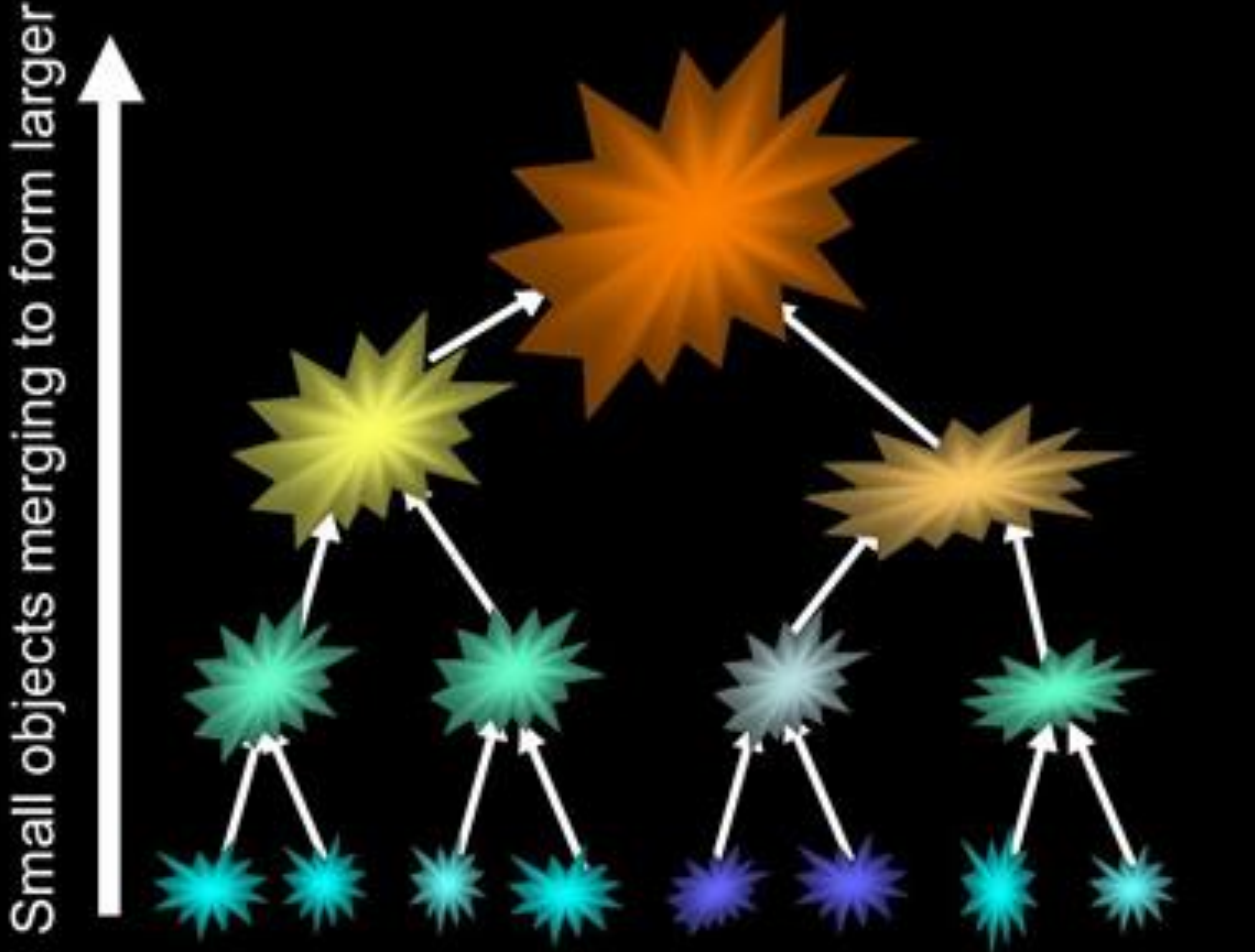
Bournaud, Elmegreen, Martig 2009, ApJ 707, L1
NGC 891 – analog to Via Lactea

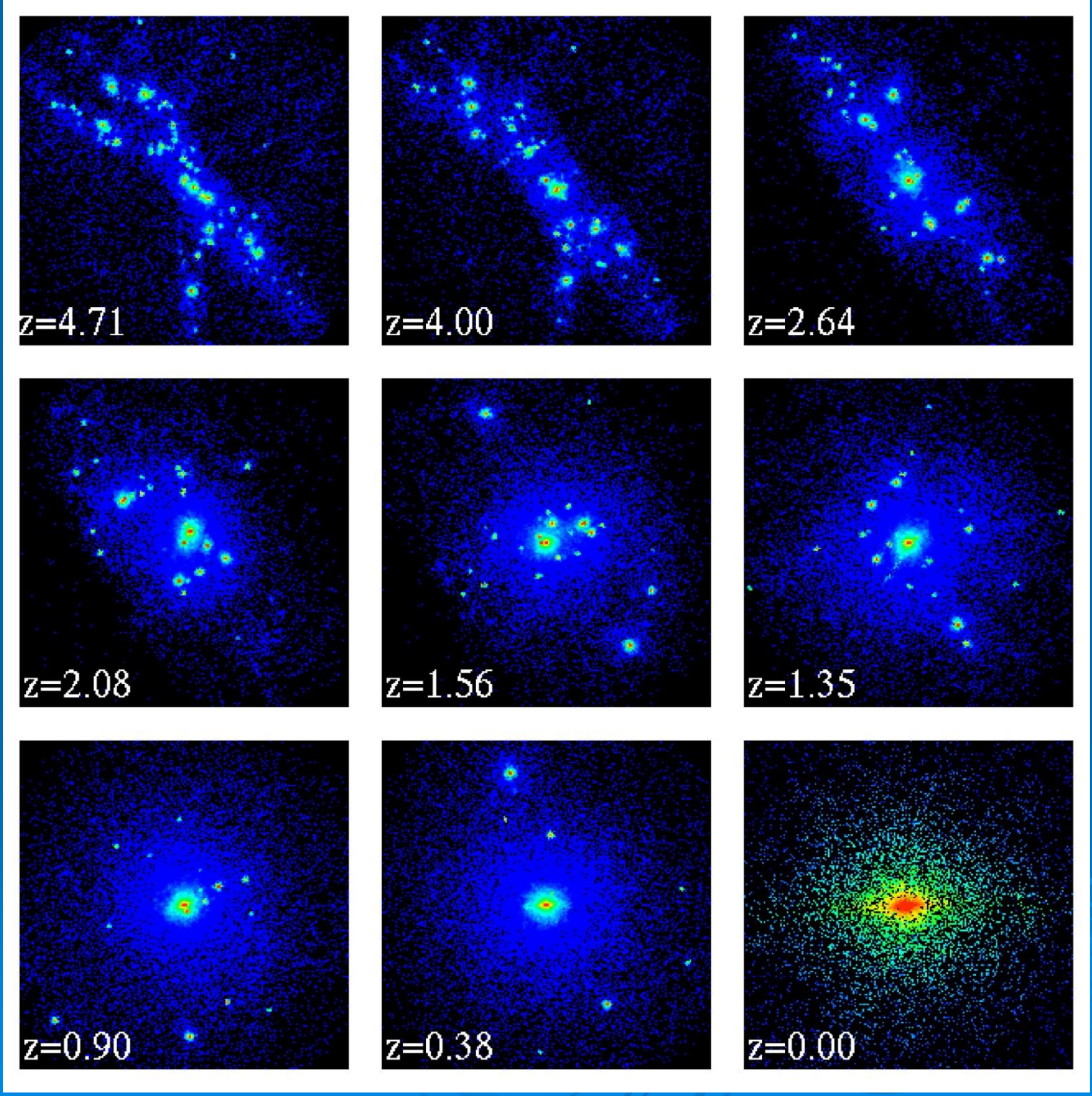


Cosmological simulations with dark matter and dark energy Λ (so-called model ΛCDM) :

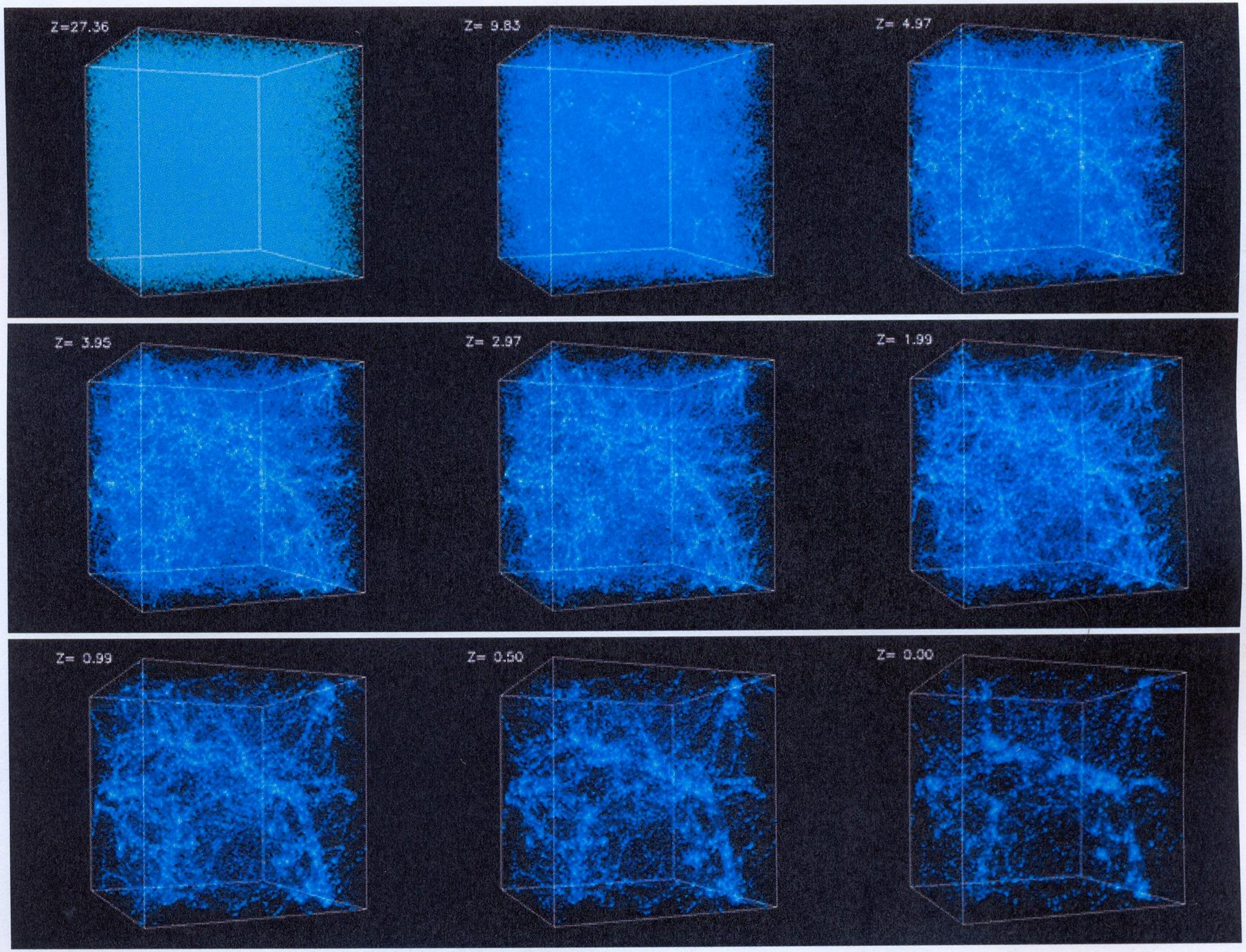
Formation of small disks of dark matter:

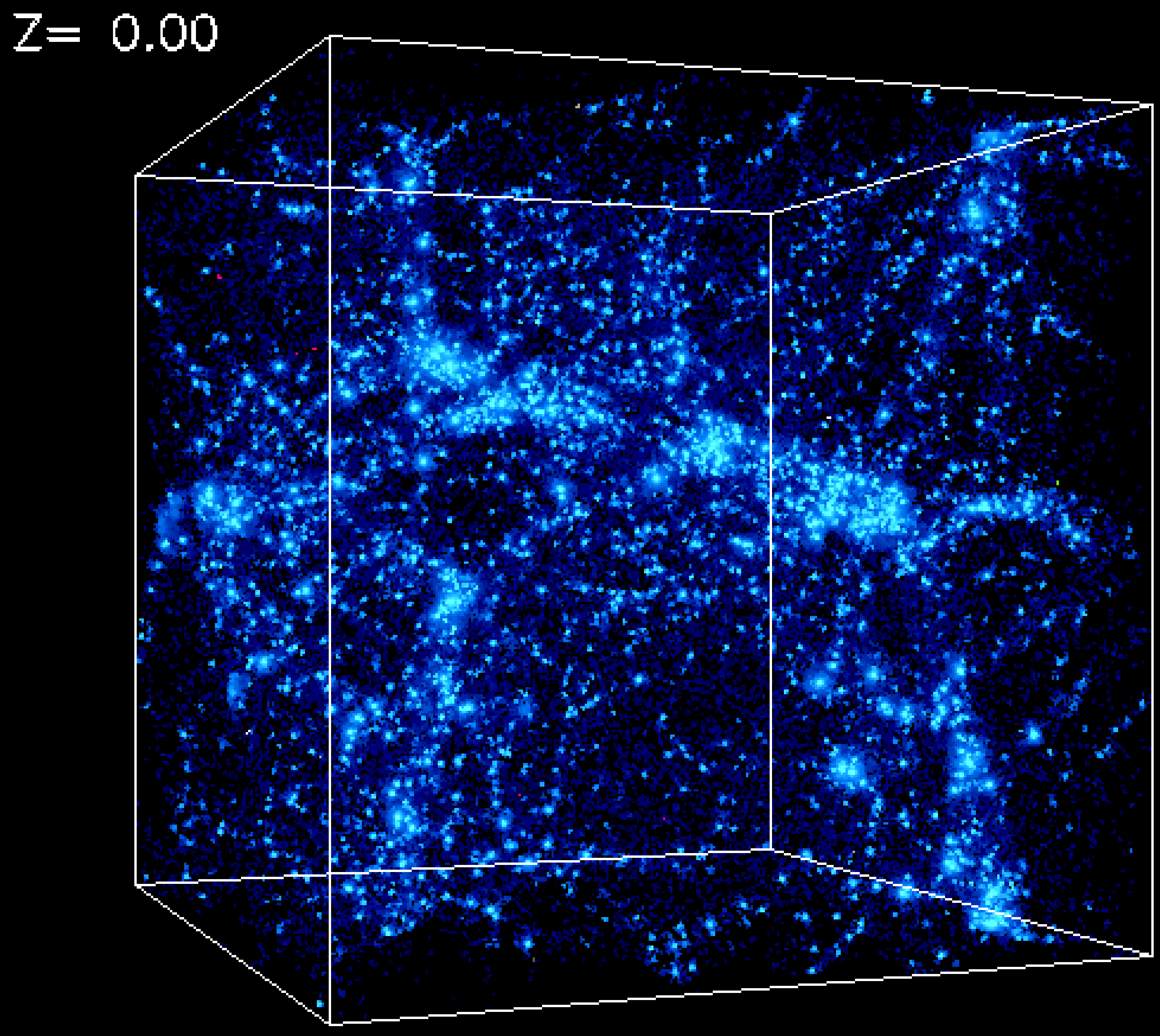
→ these disks coalesce
→ gas falls in these potential wells due to gravity
→ bulges form first

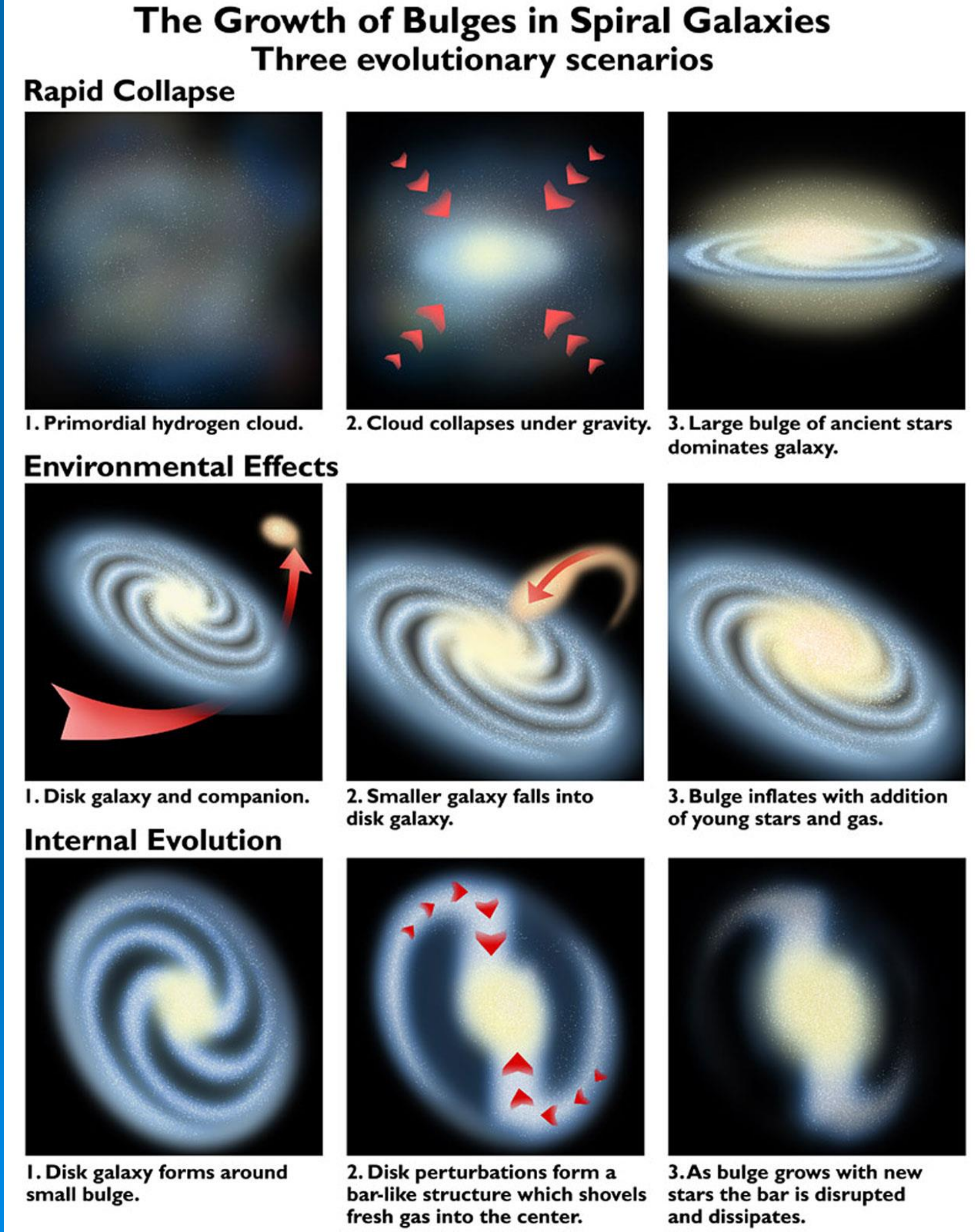

Small objects merging to form larger


z=4.71
z=4.00
z=2.64
z=2.08
z=1.56
z=1.35
z=0.90
z=0.38
z=0.00

Formation of the large-scale structure in the Universe: filaments

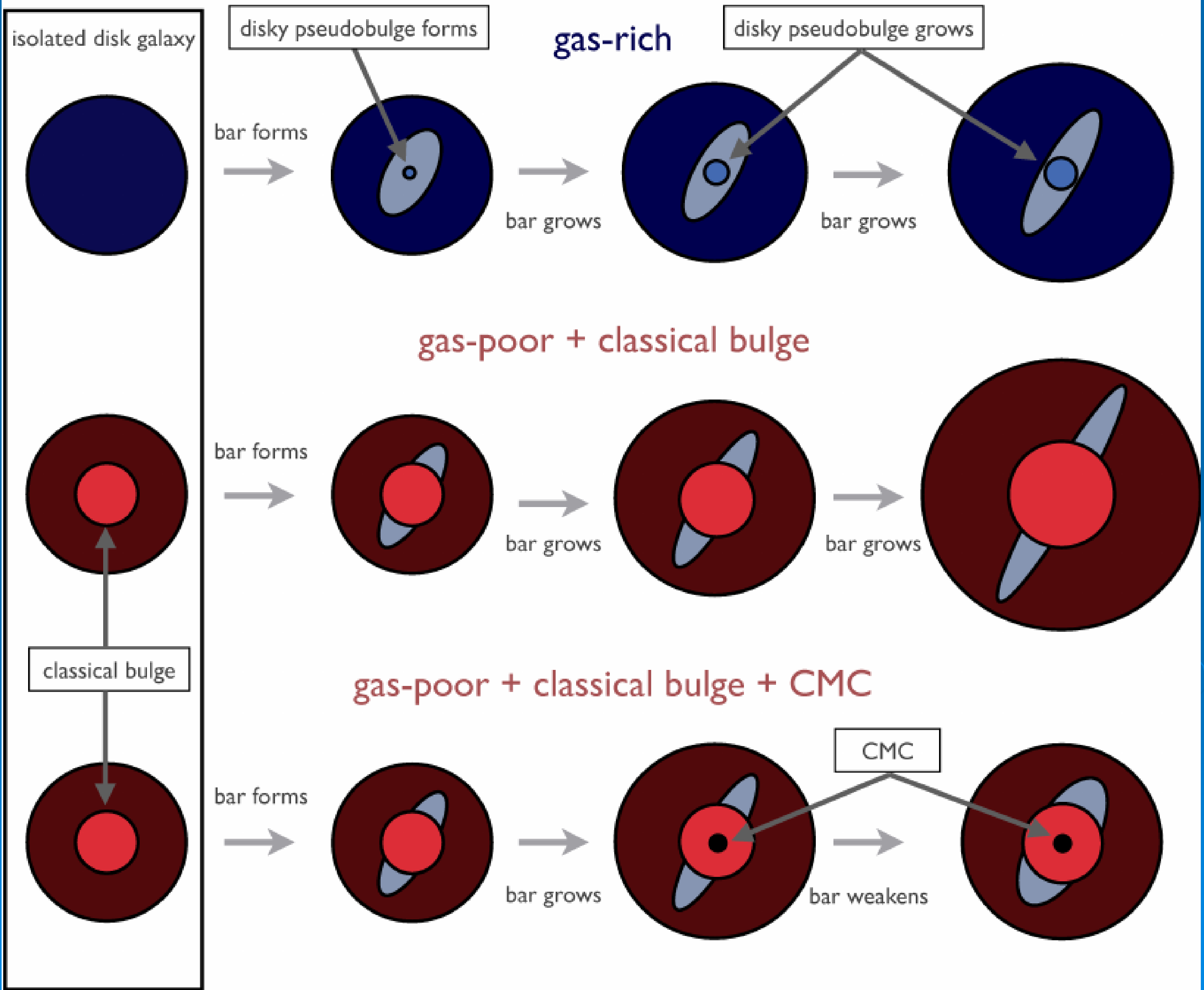



Z= 0.00


The Growth of Bulges in Spiral Galaxies
Three evolutionary scenarios
Rapid Collapse
1. Primordial hydrogen cloud.
2. Cloud collapses under gravity.
3. Large bulge of ancient stars dominates galaxy.
Environmental Effects
1. Disk galaxy and companion.
2. Smaller galaxy falls into disk galaxy.
3. Bulge inflates with addition of young stars and gas.
Internal Evolution
1. Disk galaxy forms around small bulge.
2. Disk perturbations form a bar-like structure which shovels fresh gas into the center.
3. As bulge grows with new stars the bar is disrupted and dissipates.

CMC = Central Mass Concen-tration

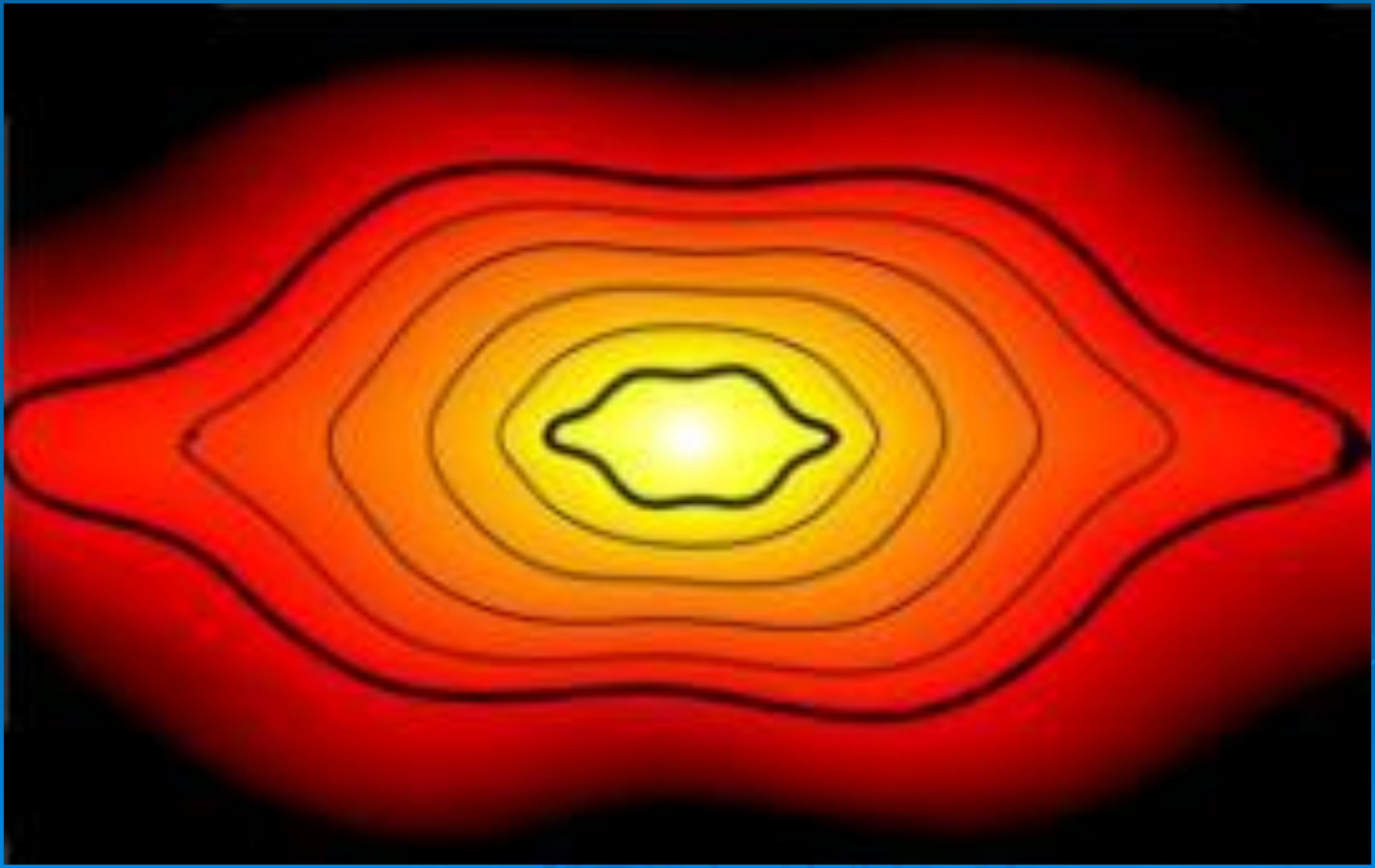
Schematic of Bar Formation and Evolution



Buckling: in simulations, galactic bars can buckle, due to a vertical instability that can occur in the bar shortly after its formation.

When this asymmetric buckling eventually ends, the inner part of the bar settles into a vertically symmetric structure again: B/P bulge = bar/peanut bulge

Bar/peanut shape



The formation of the bar and buckling in the MW are confirmed, given its box/peanut shape.

But this has probably occurred more recently, when there was already little gas → in this case bulge was already formed (Renzini+18)

Age of bar in the MW:
8 Gyr (Buck et al. 2018)

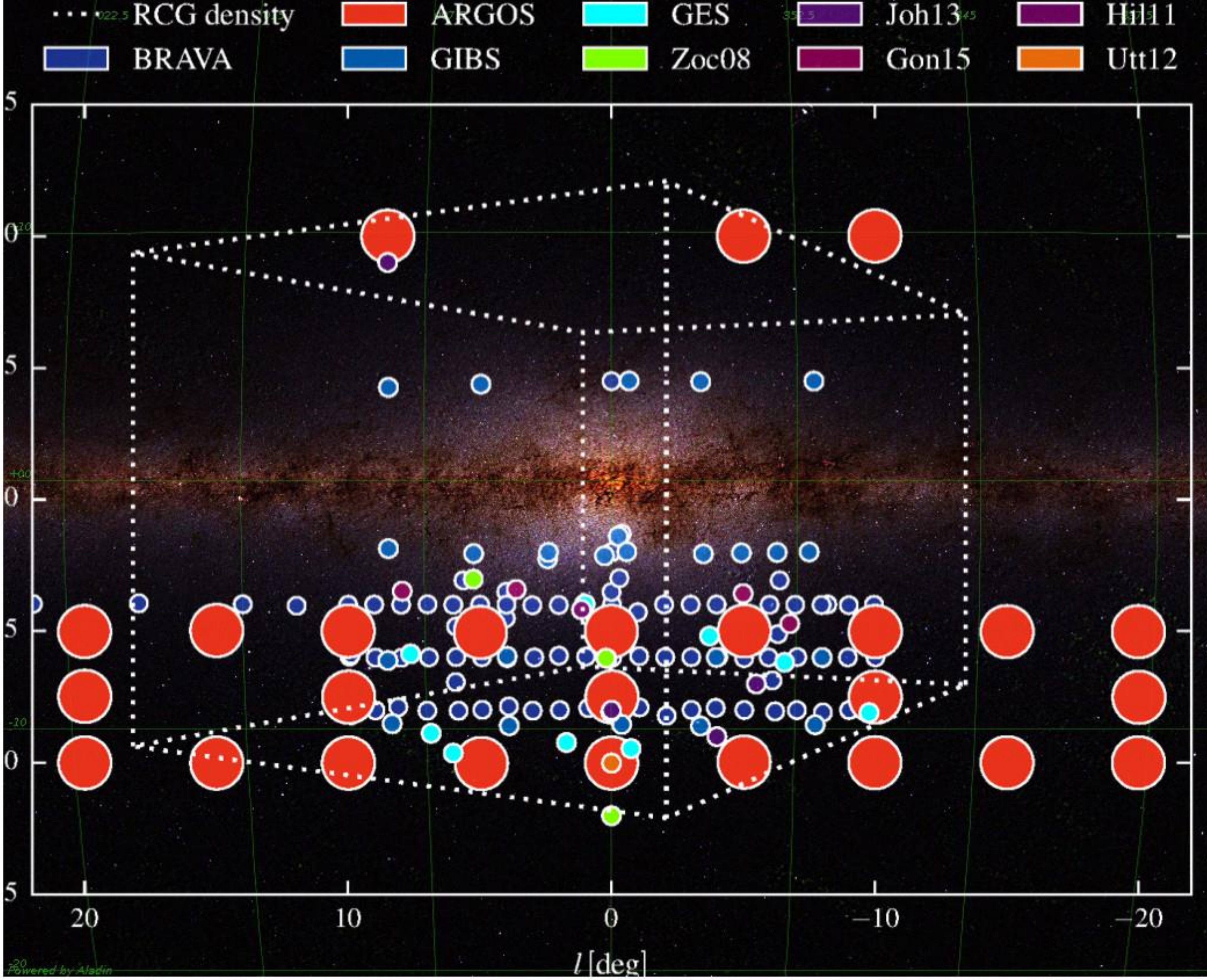
Oldest stars: 13 Gyr

➔ Ages of younger stars in the bulge – its verification in the future is an importante project

Observations

Field in
the
Galactic
bulge

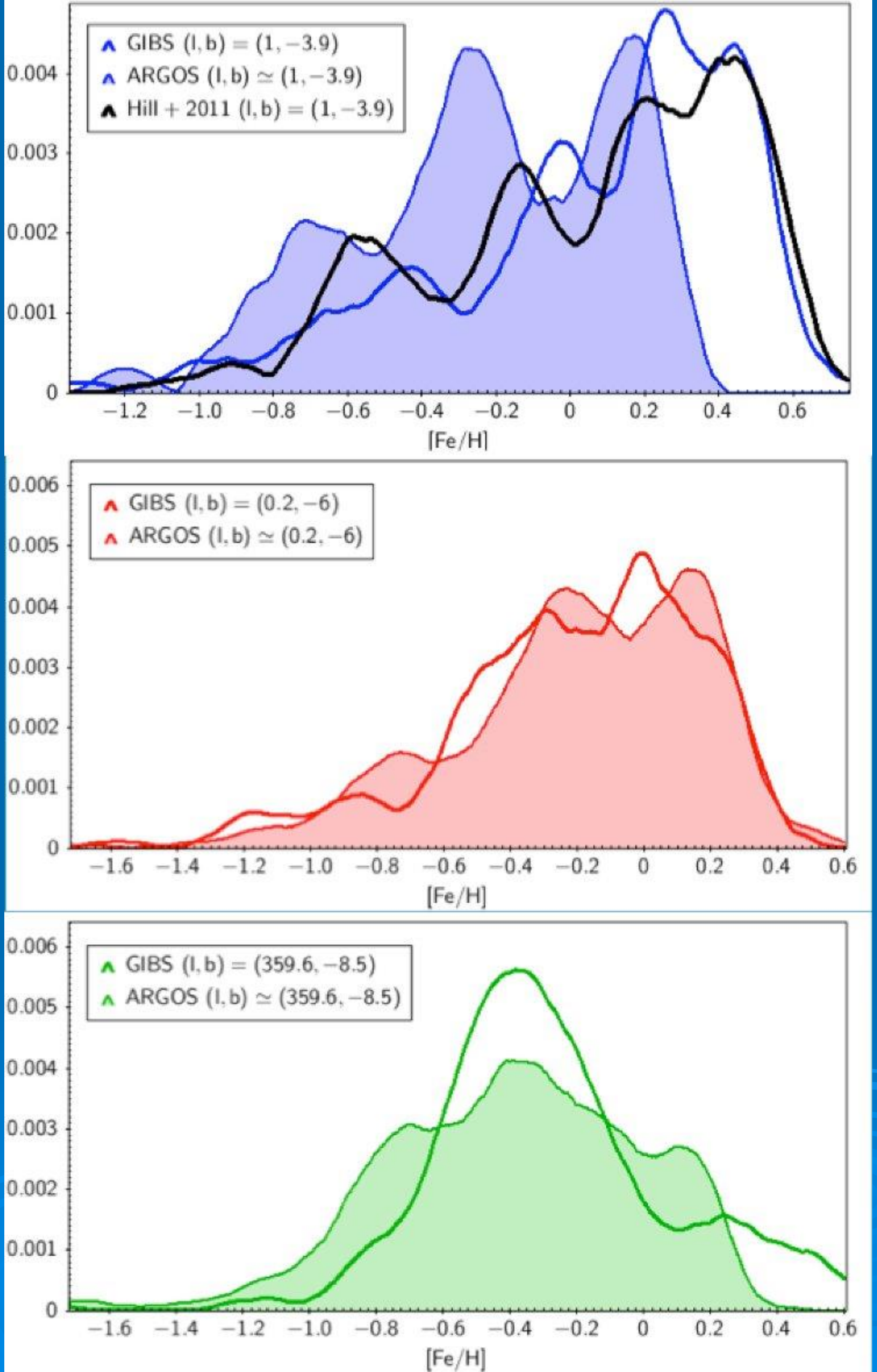
NGC 6528



RCG density
ARGOS
GES
Joh13
Hill1
BRAVA
GIBS
Zoc08
Gon15
Utt12
5
0
5
0
5
0
5
20
10
0
−10
−20
l [deg]
Powered by Aladin

ARA&A
2018

Barbuy,
Chiappini
Gerhard



Why oxygen abundances are important ➔ high oxygen-to-iron ➔ fast enrichment by the first supernovae – Fe comes later from SNIa

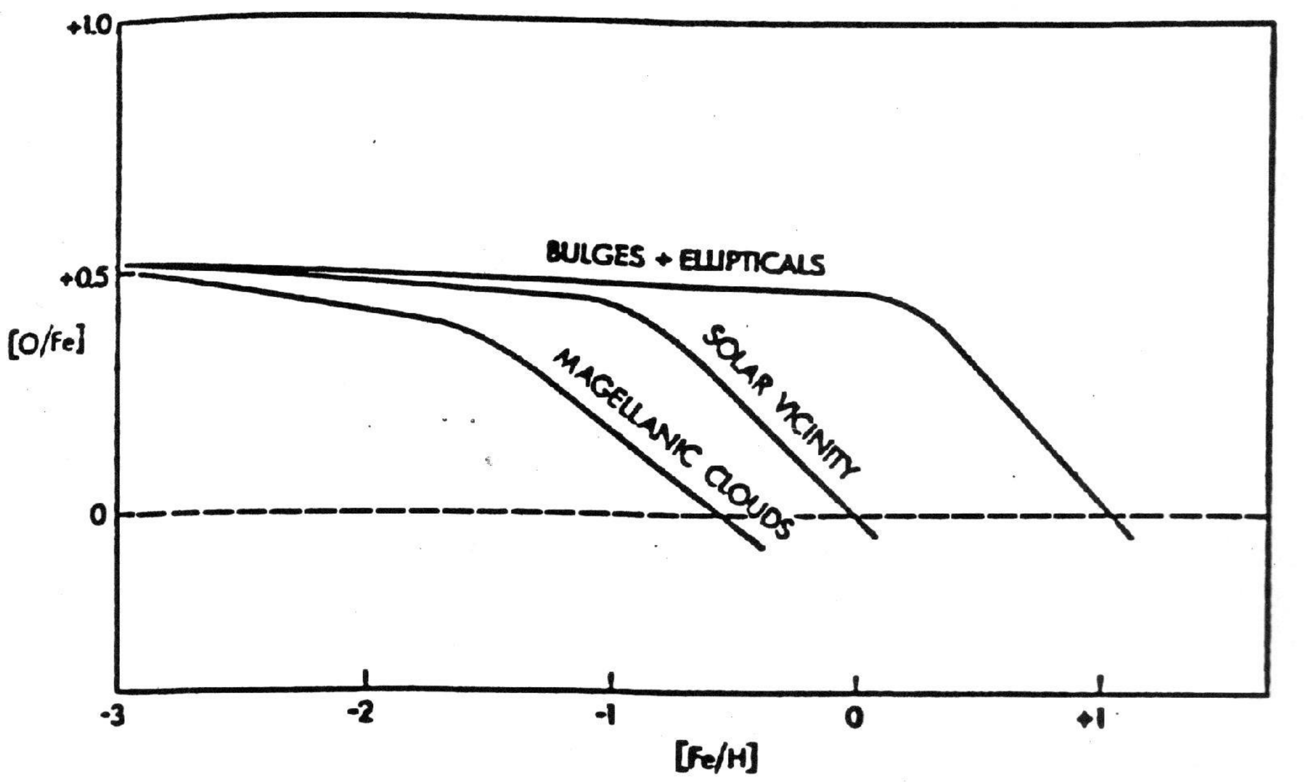
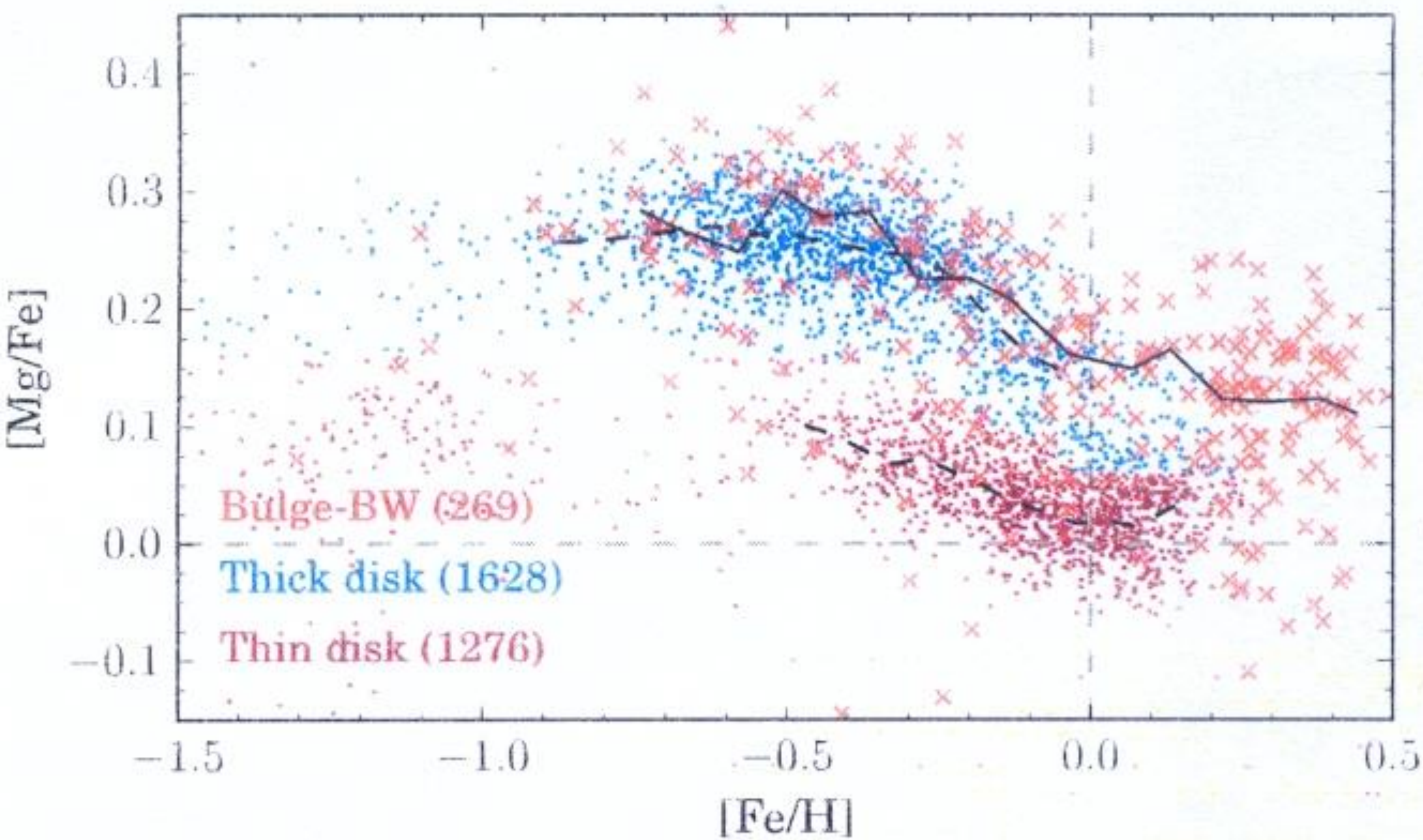


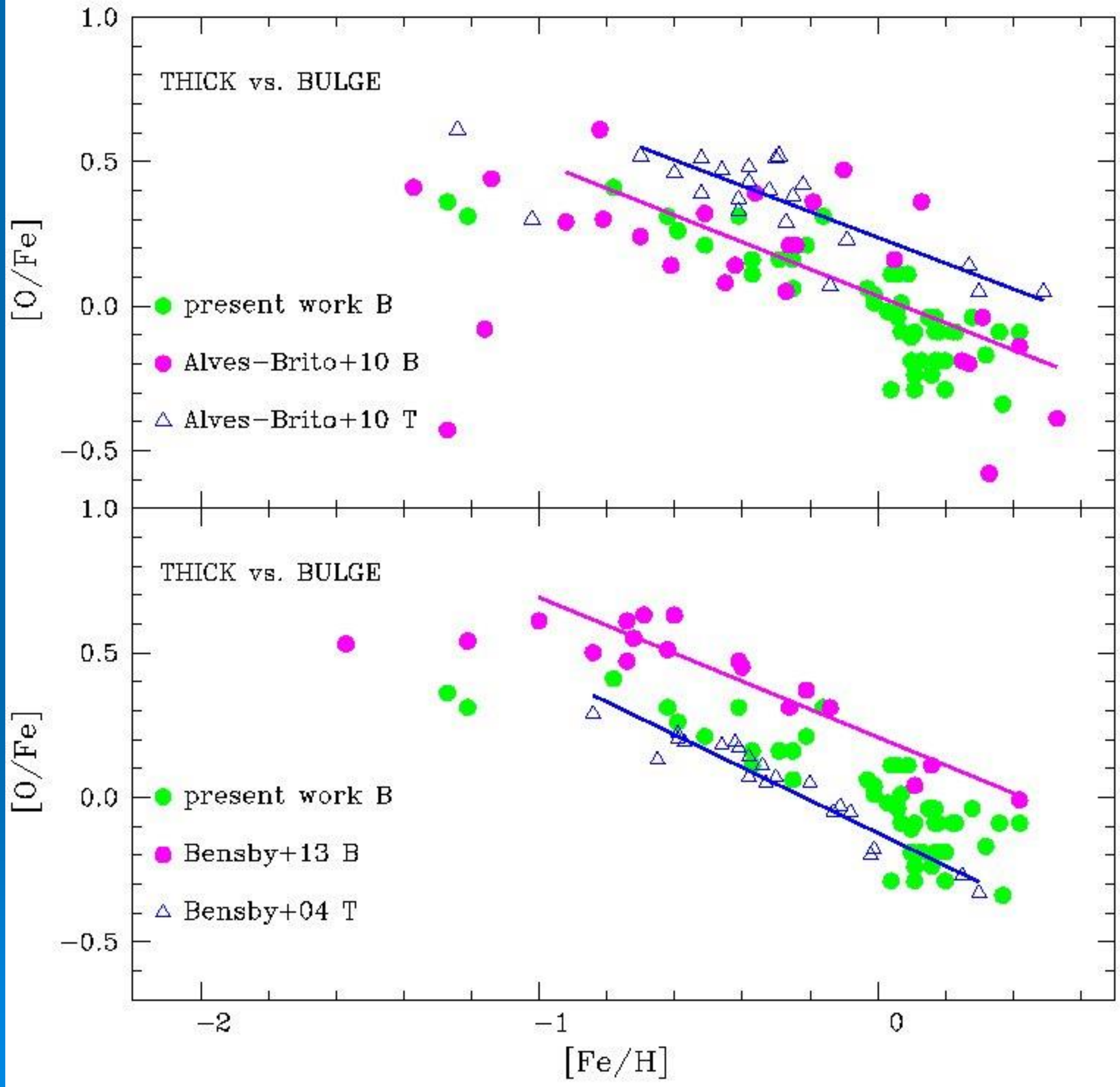
FIG. 4.—A sketch of the predicted [O/Fe] vs. [Fe/H] relations in different systems as a consequence of their different [Fe/H]-*t* relations.

Matteucci & Brocato 1990, ApJ, 365, 539

Bulge vs. Thick disk – different or the same?



Friaça
Barbuy
2017

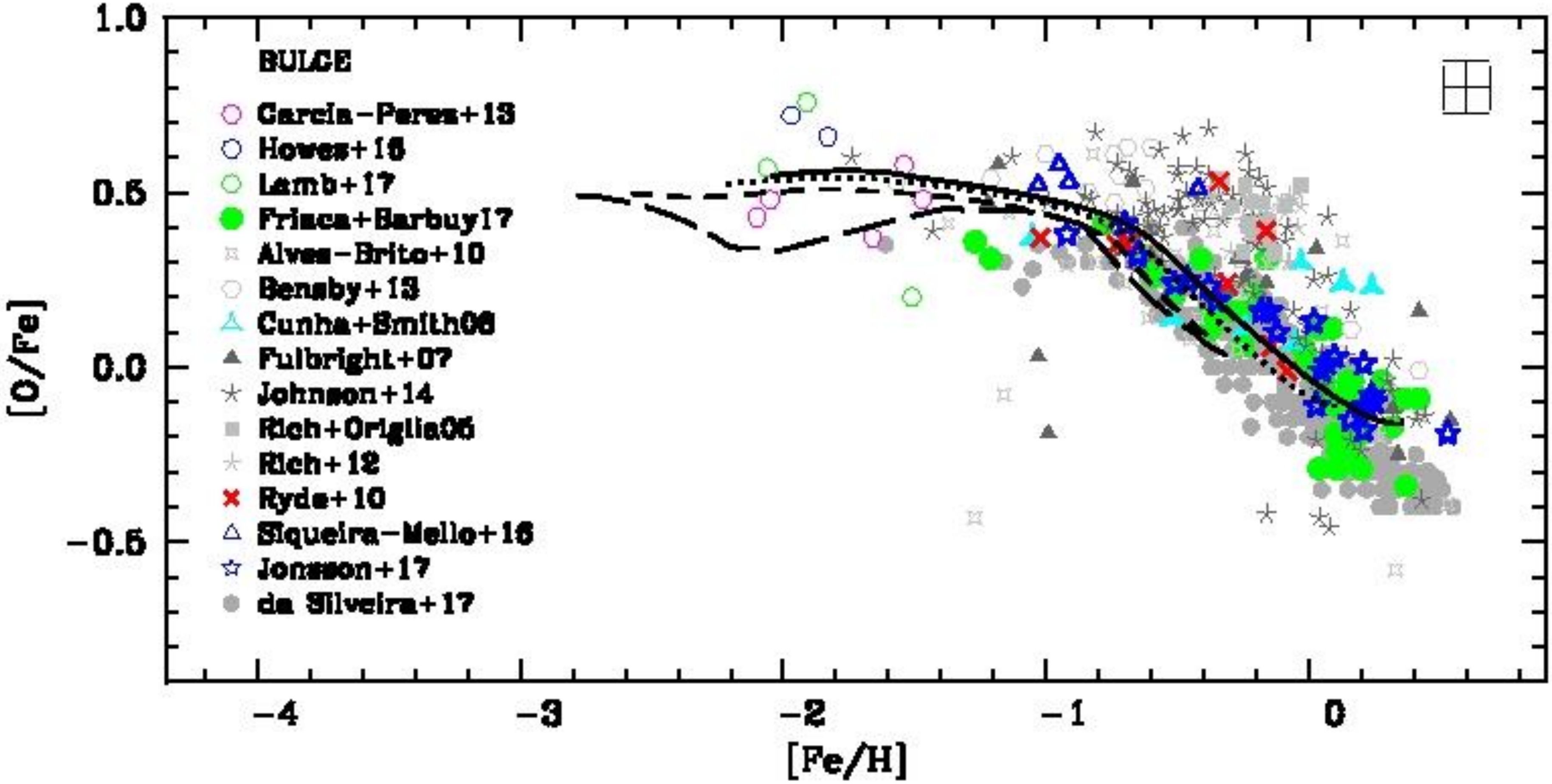


Differences Bulge vs. Thick Disk

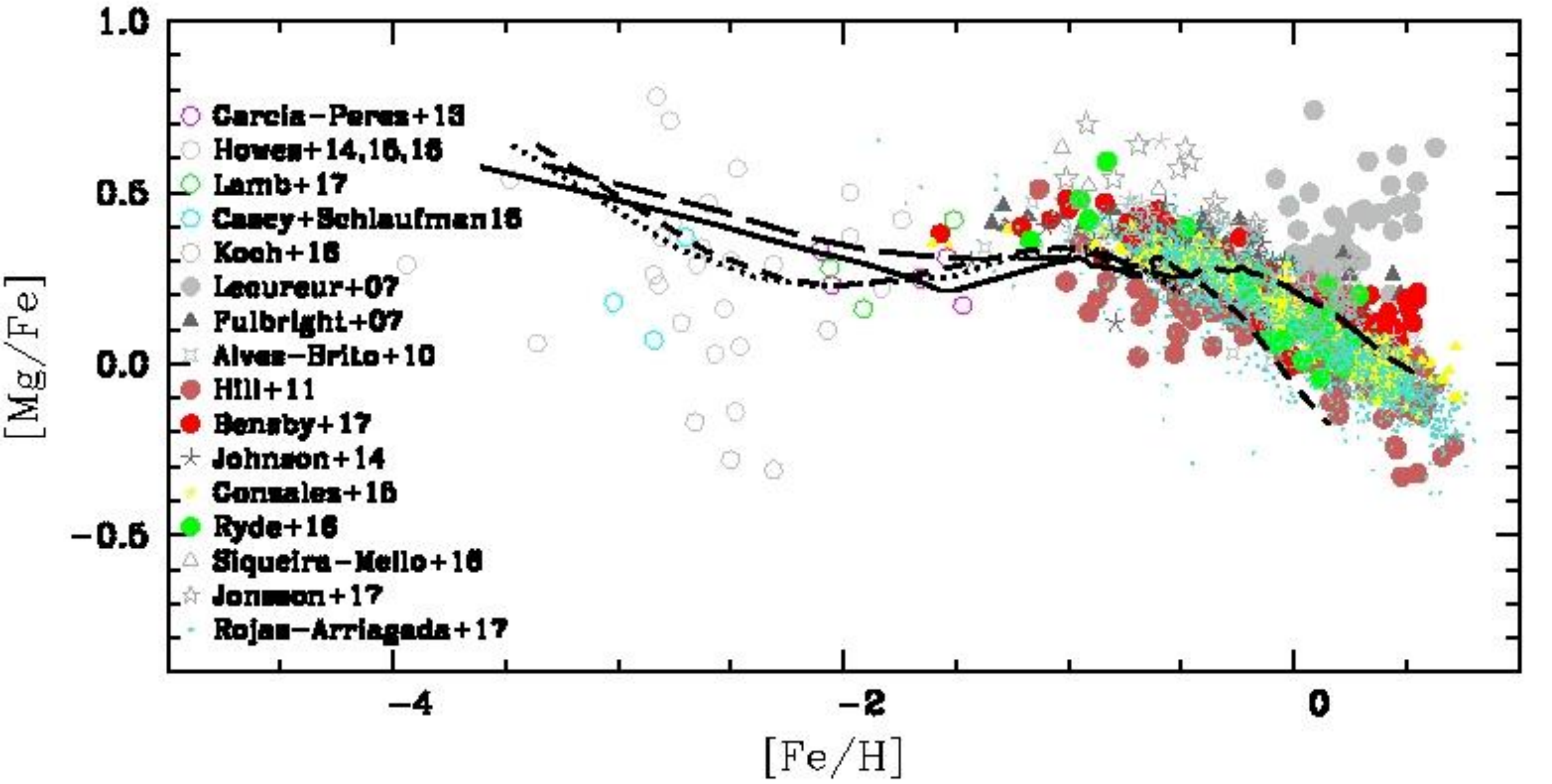
Table 3 Level of abundance ratio plateau, and knee when it starts to drop, for comparable populations of Bulge (B) and thick-disk (TD) stars

Reference	Stars B/TD	[O, Mg/Fe] Plateau	[Fe/H] Knee	Reference	Stars B/TD	[Mg/Fe] Plateau	[Fe/H] Knee
Friaça & Barbuy (2017)	B	+0.30	-0.55 ± 0.03	Hill et al. (2011)	B	+0.36	−0.4 to −0.5
Bensby et al. (2013, 2017)	B	+0.41	−0.45 to −0.05	Bensby et al. (2017)	TD	+0.36	−0.6
Rojas-Arriagada et al. (2017)	B	$+0.310 \pm 0.11$	−0.37	Rojas-Arriagada et al. (2017)	TD	$+0.304 \pm 0.07$	−0.43

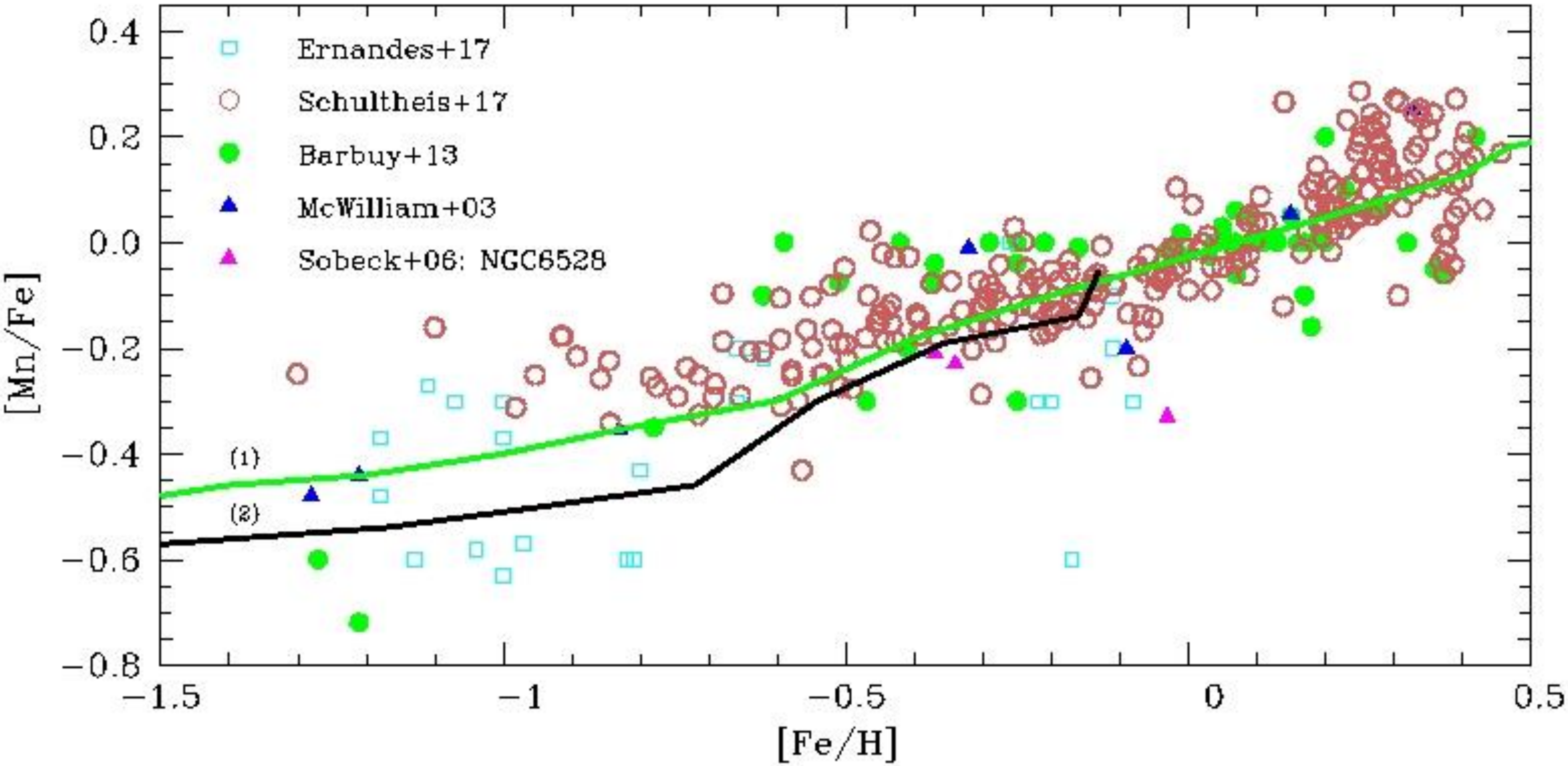
Barbuy, Chiappini, Gerhard 2018



BULGE
Garcia-Perez+13
Howes+16
Lamb+17
Friaca+Barbuy17
Alves-Brito+10
Bensby+13
Cunha+Smith06
Fulbright+07
Johnson+14
Rich+Origlia05
Rich+12
Ryde+10
Siqueira-Mello+16
Jonsson+17
da Silveira+17
[O/Fe]
[Fe/H]
1.0
0.5
0.0
−0.5
−4
−3
−2
−1
0

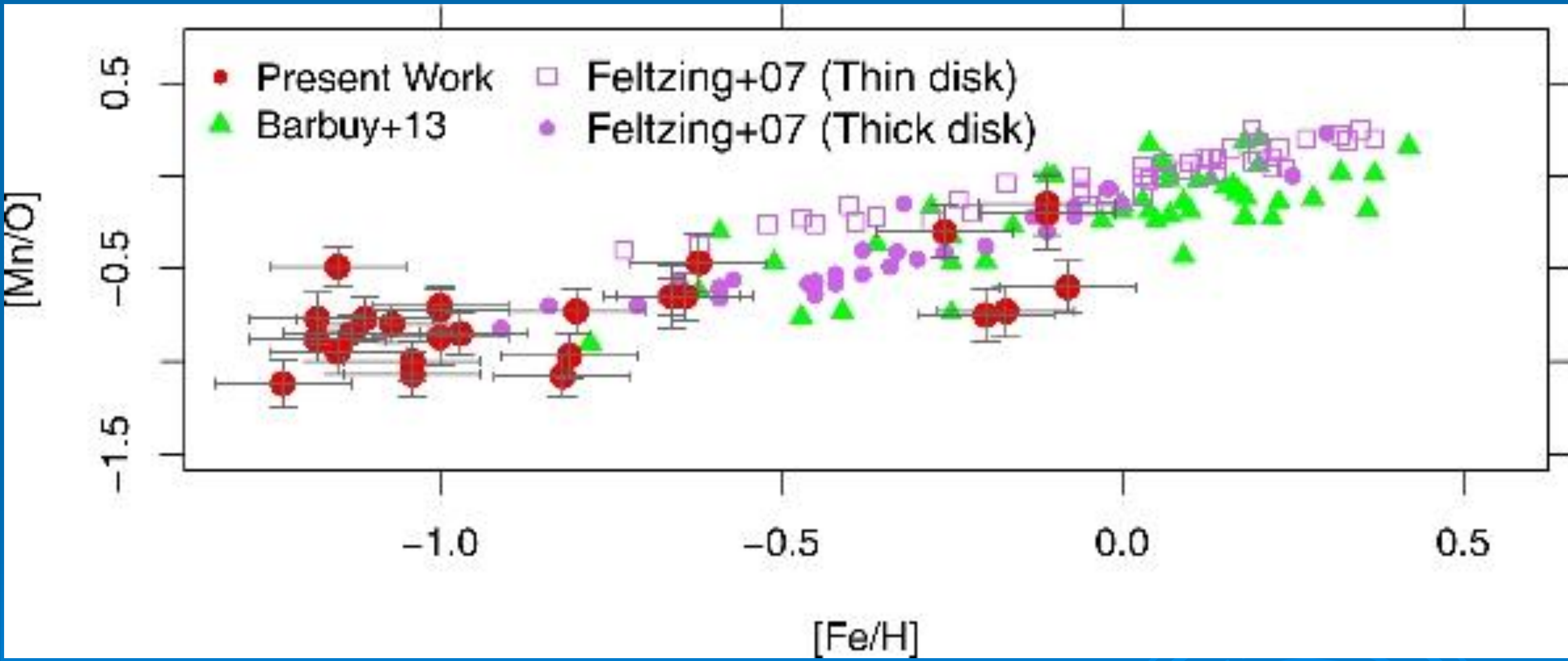


1.0
0.5
0.0
−0.5
[Mg/Fe]
−4
−2
0
[Fe/H]
Garcia−Perez+13
Howes+14,15,16
Lamb+17
Casey+Schlaufman15
Koch+16
Lecureur+07
Fulbright+07
Alves−Brito+10
Hill+11
Bensby+17
Johnson+14
Gonzales+15
Ryde+16
Siqueira−Mello+16
Jonsson+17
Rojas−Arriagada+17

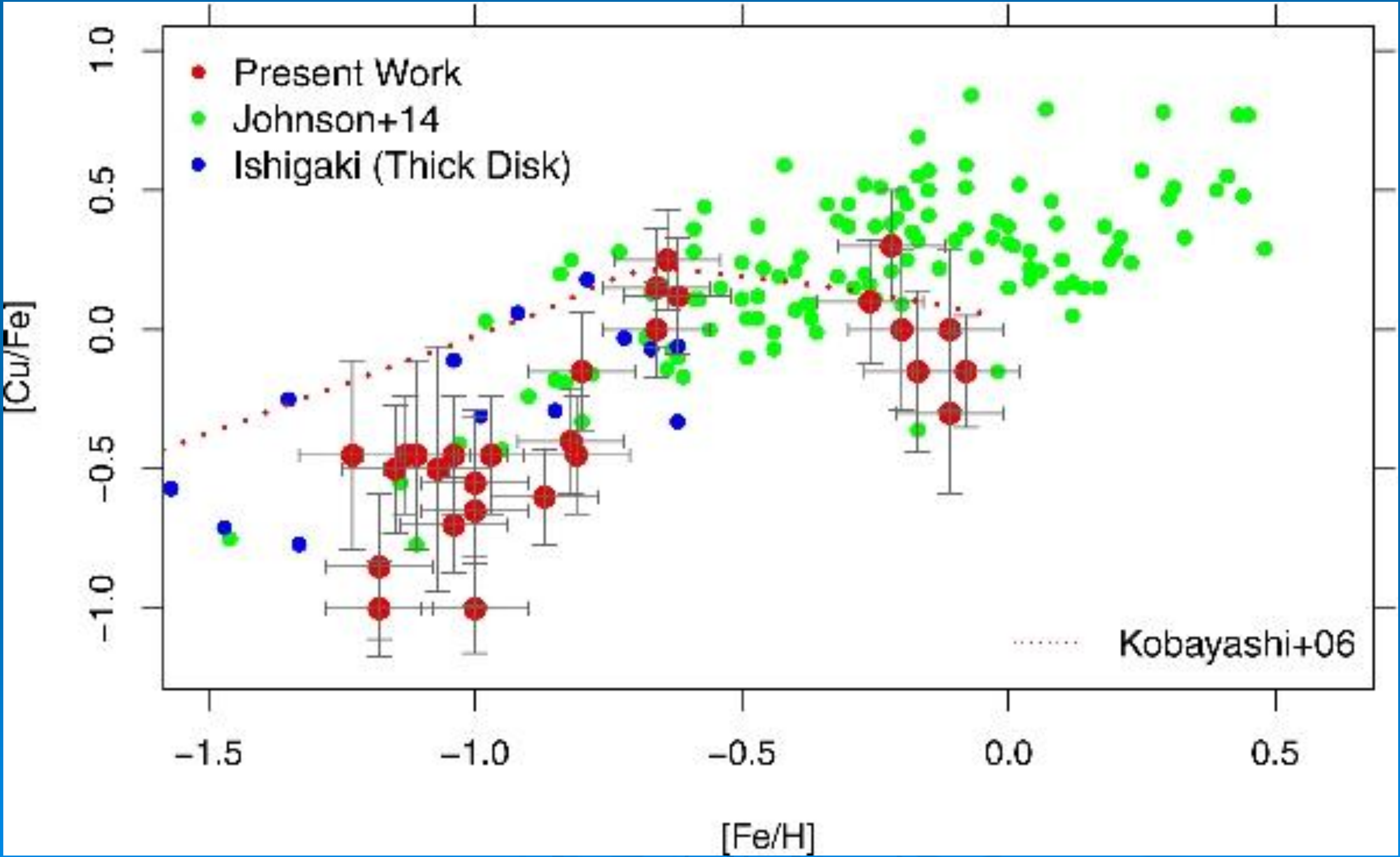


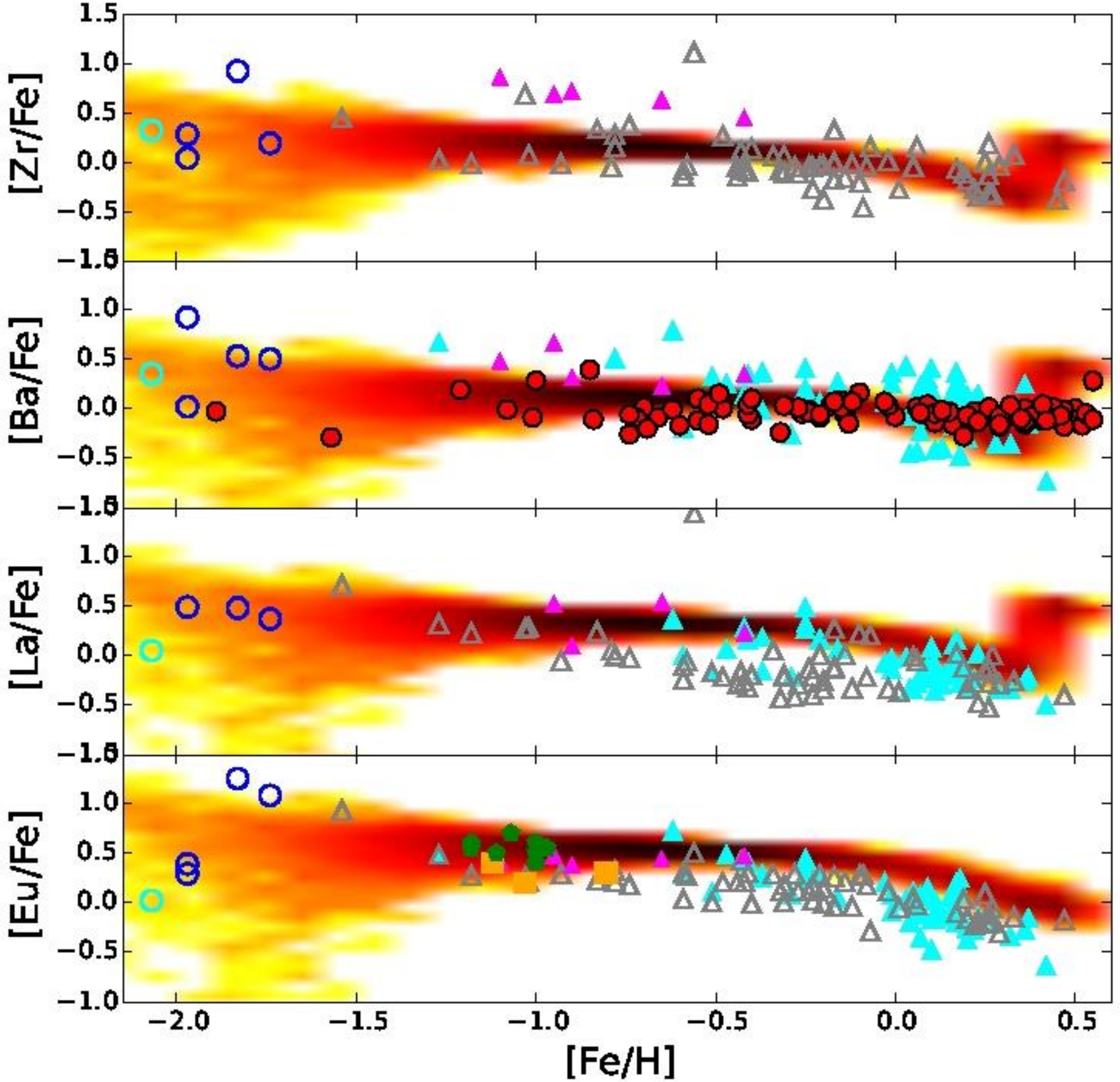
Ernandes+17
Schultheis+17
Barbuy+13
McWilliam+03
Sobeck+06: NGC6528
(1)
(2)
[Mn/Fe]
[Fe/H]
0.4
0.2
0.0
−0.2
−0.4
−0.6
−0.8
−1.5
−1
−0.5
0
0.5

Ernandes+18; [Mn/O] distinguishes thin-thick disk field bulge + GCs slightly more [Mn/O]-poor



Ernandes+18: GCs more Cu-poor





[Zr/Fe]
[Ba/Fe]
[La/Fe]
[Eu/Fe]
[Fe/H]
−2.0
−1.5
−1.0
−0.5
0.0
0.5
1.5
1.0
−1.0

Globular clusters in the bulge

Hansen et al. 2013 (Nature): difference of 2 Gyr between blue globular clusters (metarl-poor), and red (metal-rich).

Red: formed in situ, or in mergers

Blue: formed very early, and they are not produced in mergers

Formation of globular clusters

Forbes+18:

WHEN did GCs form?:

>12.8 Gyr (z>~6) before the end of reionisation

or

z~2 closer to the peak in cosmic star formation:

Most GCs are very old, younger branch associated with disrupted Sgr dwarf and other accreted GCs

WHERE:

Forbes+18:

Two-phase galaxy formation:

Large galaxies: initial in-situ

+ satellite accretion

or

Choksi et al. 2018 ➔

Choksi, Gnedin & Liu (2018): all GCs result from accretion of satellite galaxies.

DM halos from Millenium-II → bimodality arises from hierarchical mergers.

Blue GCs form from **many mergers of low-mass haloes at high redshift**

Red GCs form from **a few high-mass mergers at low redshift**.

Half of GCs form at $5 < z < 2.3$ or

10.8 to 12.5 Gyr

Renaud et al. 2017:

Cosmological hydrodynamic + N-body zoom-in simulation of a Milky Way galaxy

Blue globulars: accreted satellite galaxies

Red globulars: in situ, or major merger with MW

→ Assumes a major (larger than 1:10) merger at z~2

Assume early enrichment by pop. III to $Z \sim 10^{-3}$

Renaud et al. 2017:

Cosmological hydrodynamic + N-body zoom-in simulation of a Milky Way galaxy

Blue globulars: accreted satellite galaxies

Red globulars: in situ, or major merger with MW

→ Assumes a major (larger than 1:10) merger at z~2

Assume early enrichment by pop. III to $Z\sim10^{-3}$

Renzini 2017

Formation of GCs at $3 < z < 8$, (peak at z~5?), preceding the bulk of stars in galaxies

NIRCam onboard JWST:
FoV: 10 arcmin^2 → ~60 GCs

→ direct detection of GC formation,
→ info on redshift formation, +1G/2G

Formation of globular clusters

Blue GCs ([Fe/H]<~-0.9), from their ages, suggest their formation before collapse (formation) of the Galaxy

Boley et al. 2009: model ΛCDM, with formation of BGCs before reionization: with 10% formed at z~18, and the rest at z~13, and at z~10, formation truncated by reionization.

Renaud, Agertz & Gieles (2017):
BCGs form in satellite galaxies and are
later accreted

Perspectives to get answers:

Springel:´´ to check how many of their bulges
originate in major mergers vs. Disk instability
in their simulations´´

Renzini (2017): GCs 12.5 Gyr, z~5
→ JWST NIRCam, NIRSpec.

Globular Clusters in the Galactic bulge

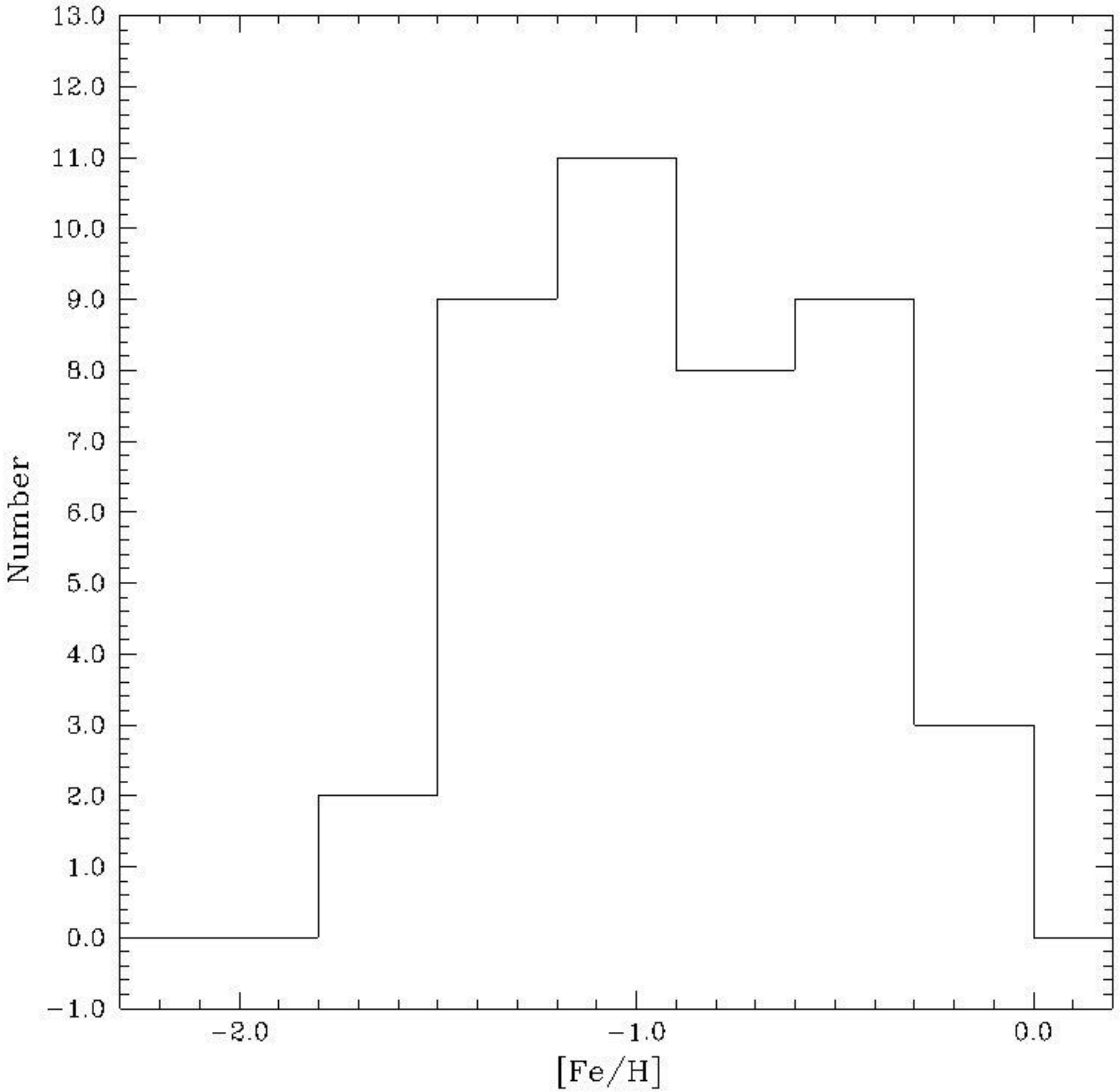
Bica, Ortolani, Barbuy 2016, PASA, 33, 16

43 genuine bulge globular clusters (RGC<3.5 kpc, l,b< 20º)

plus:
40 including halo intruders, outer bulge shell, ¨disk¨ clusters (metal-rich, R>4.5kpc)

Bica+16

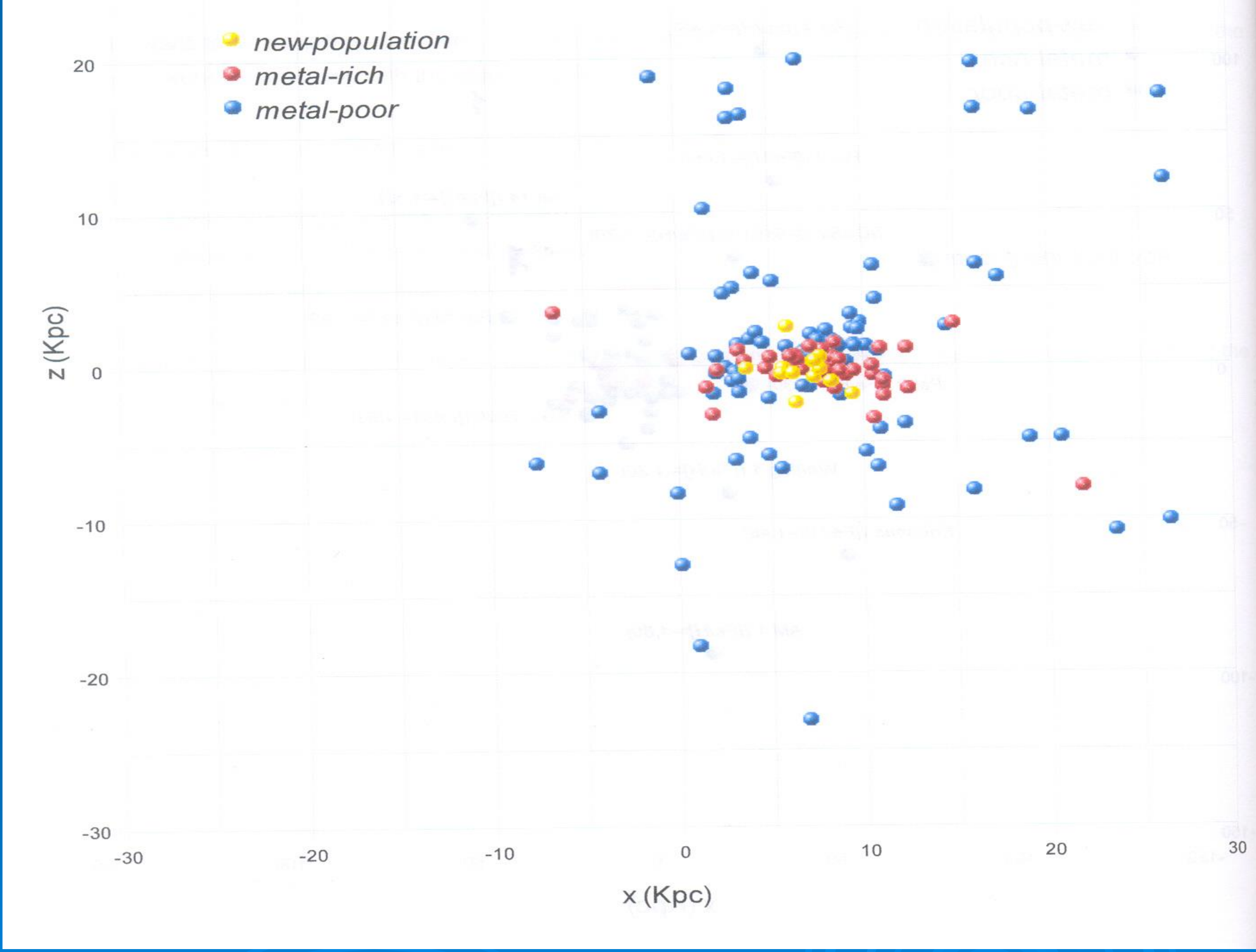
MDF



Galactic center:

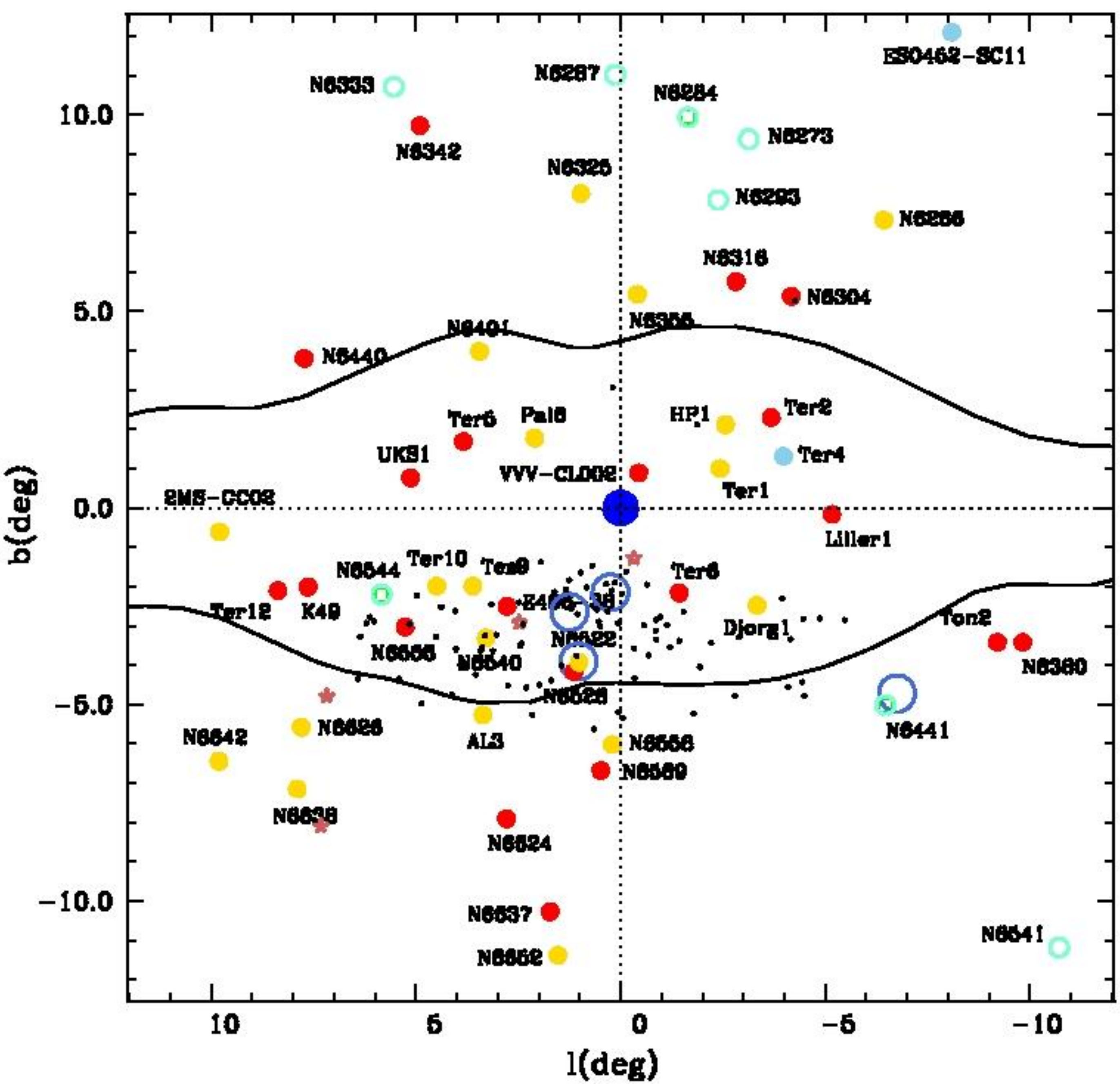
Very old GCs

13 Gyr



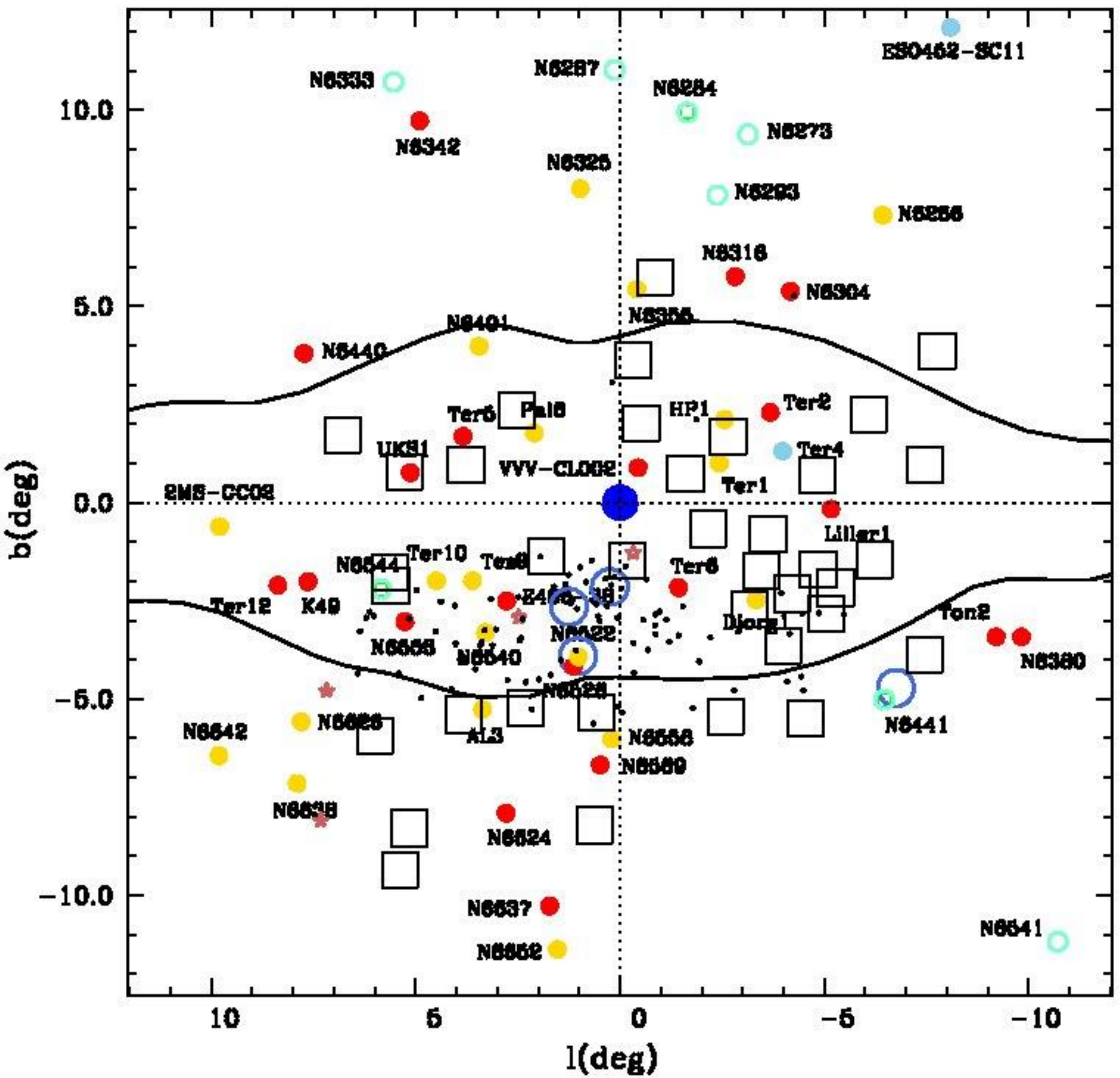
Barbuy
Chiappini
Gerhard
2018

ARA&A

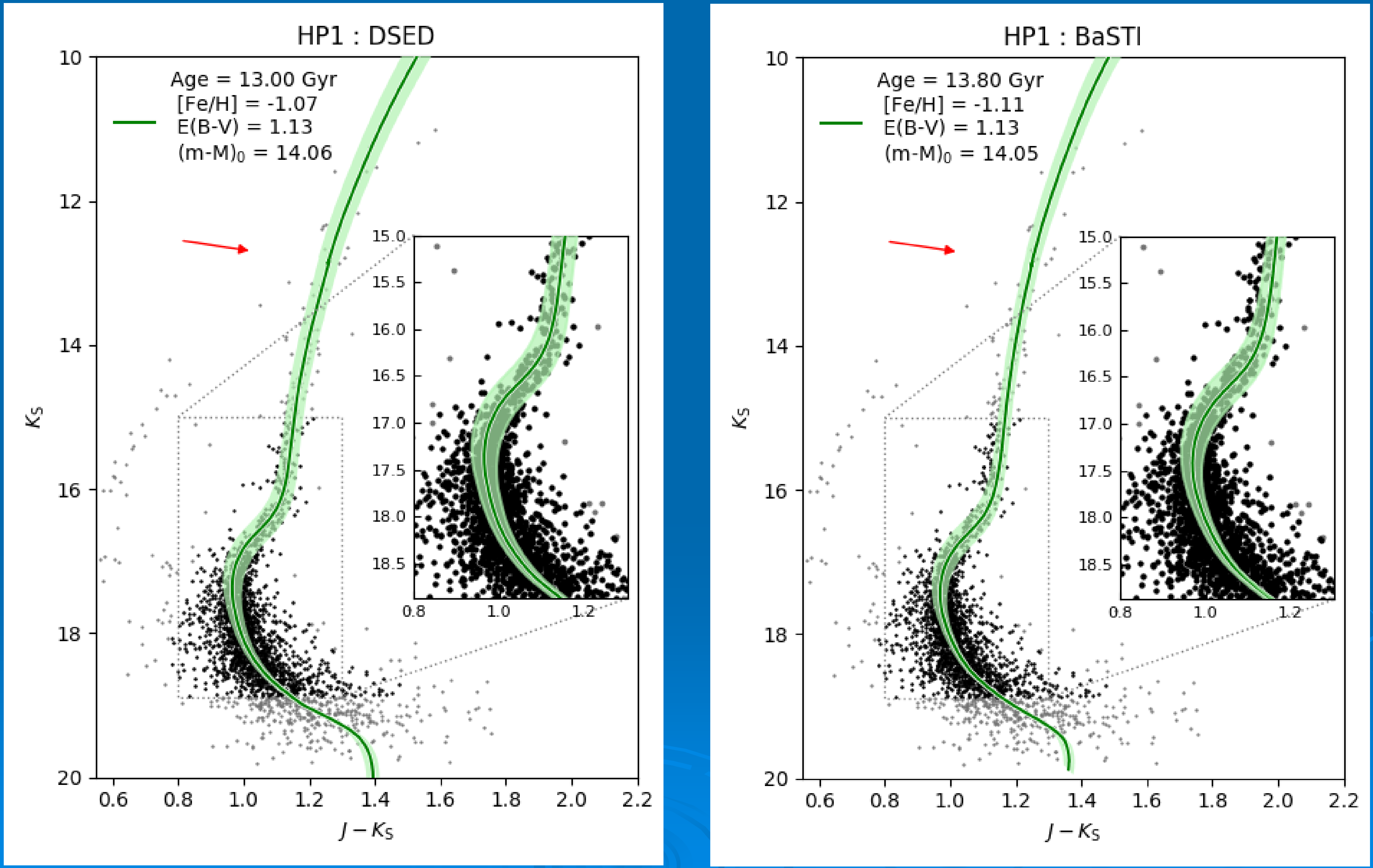


squares:

newly identified GCs
or
candidates



AGES: HP1: 13 GYR (Kerber+19)



REDSHIFT	AGE
z = 2	10.6 Gyr
z = 4	12.4 Gyr
z = 7	13.2 Gyr

Reionization:

z=8.8 (Planck)	13.4 Gyr
z = 10	13.5 Gyr

2 fronts of work:

- Spectroscopy → abundance pattern

- Colour-Magnitude Diagrams → distances, proper motions and orbits, ages

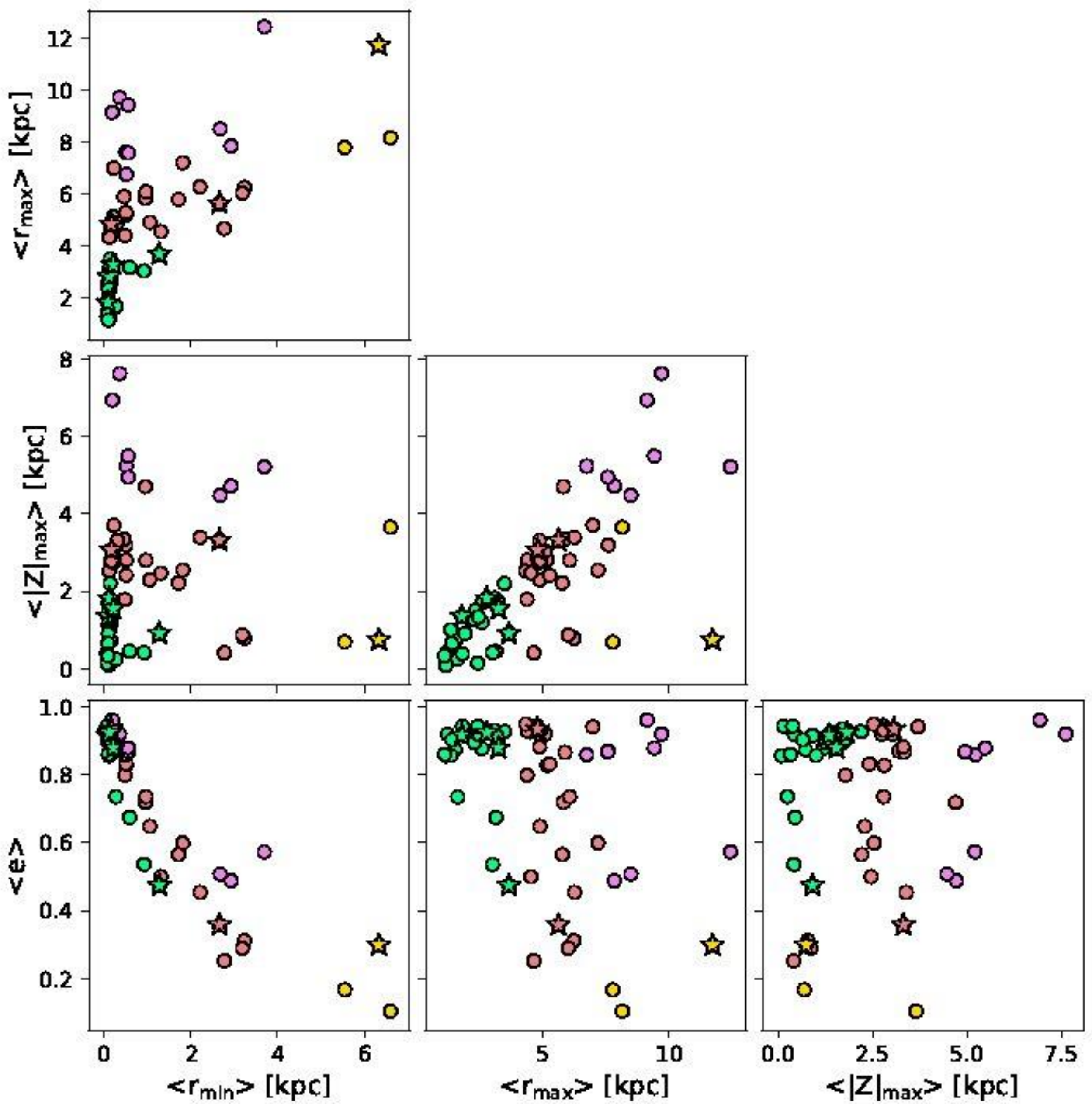
RECENT ORBITS, ABUNDANCES:

Terzan 10, Djorgovski 1
→New radial velocities, and proper motions -> Halo intruders (Ortolani+18, A&A)

Terzan 9: [Fe/H]=-1.3 (Ernandes+19)

Gaia DR2
pm
+ radial
Velocity
+ distance

➔ classi-
fication
from
orbits



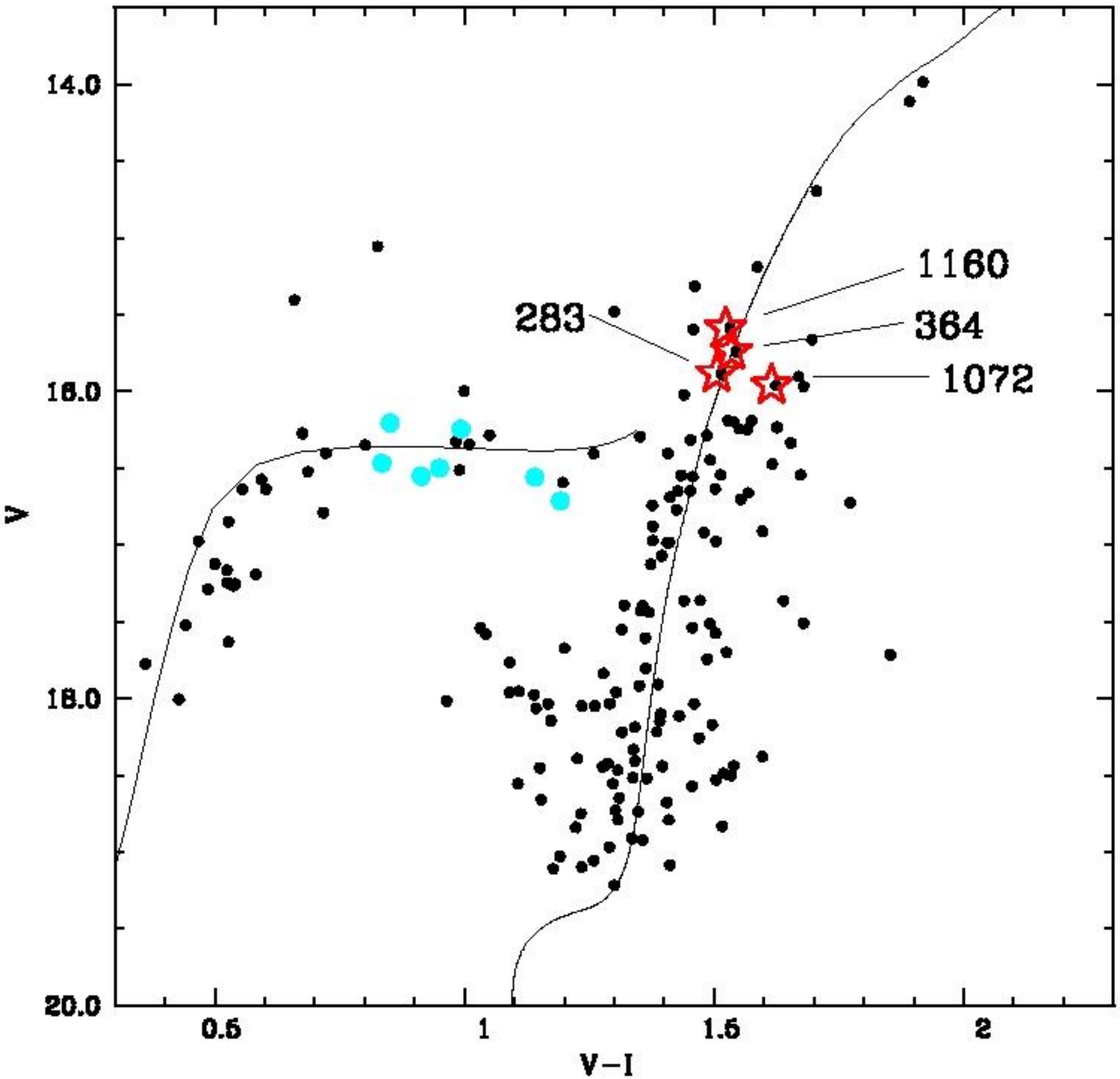
And element abundances:

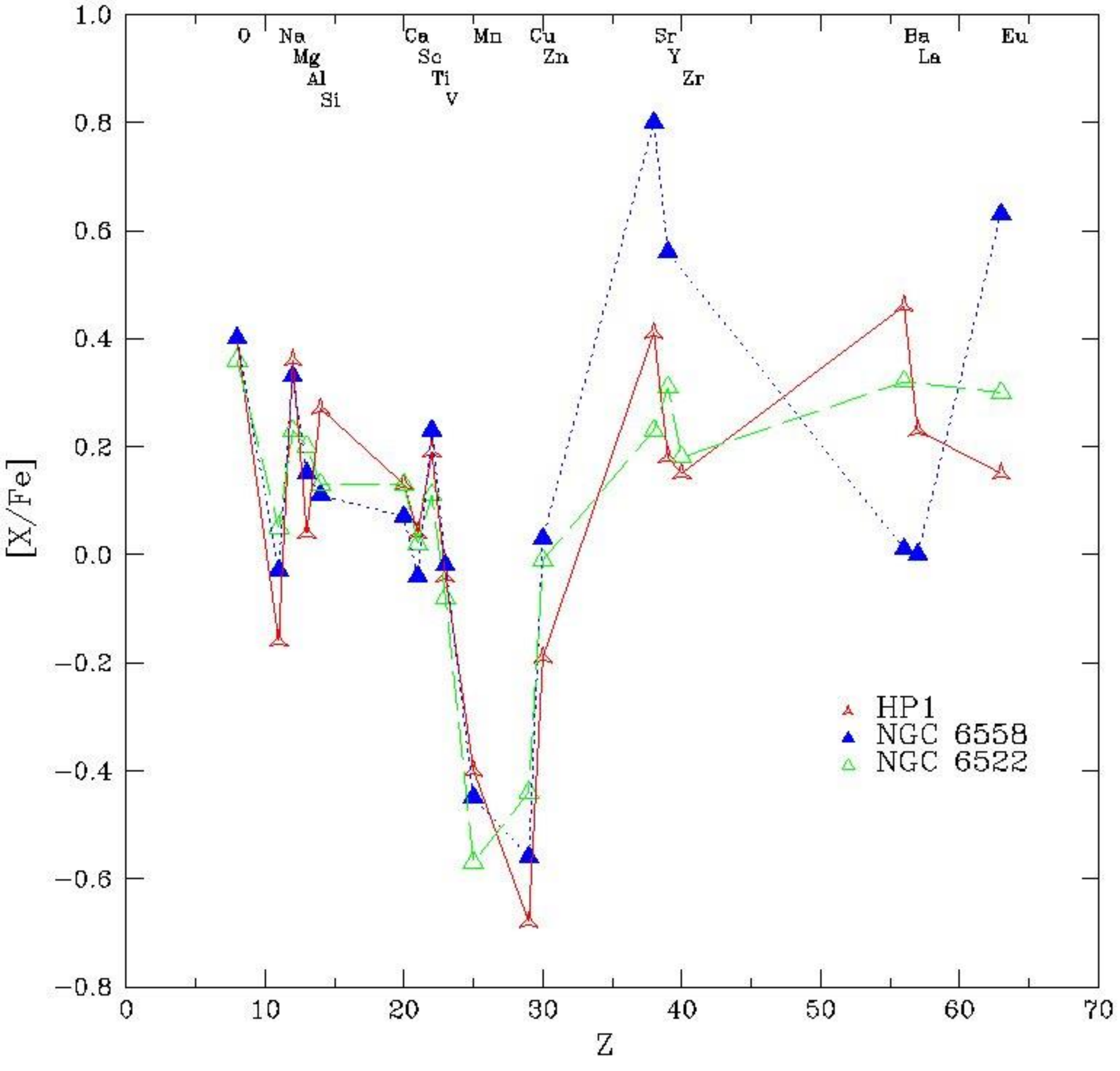
→ we have been looking for:

Bulge GCs characterized by:

- [Fe/H] ~ -1.0
- BHB (and/or + RHB)
- Old age (~13Gyr)

A typical abundance pattern?


14.0
16.0
18.0
20.0
V
0.5
1
1.5
2
V−I
283
1160
364
1072



O
Na
Mg
Al
Si
Ca
Sc
Ti
V
Mn
Cu
Zn
Sr
Y
Zr
Ba
La
Eu
HP1
NGC 6558
NGC 6522
[X/Fe]
Z

Conclusions from GCs:

Bulge is old → GCs can be as old as 13 Gyr.
→ formed at redshifts z~3 to 8. Formed in an early bulge in situ, or accreted?

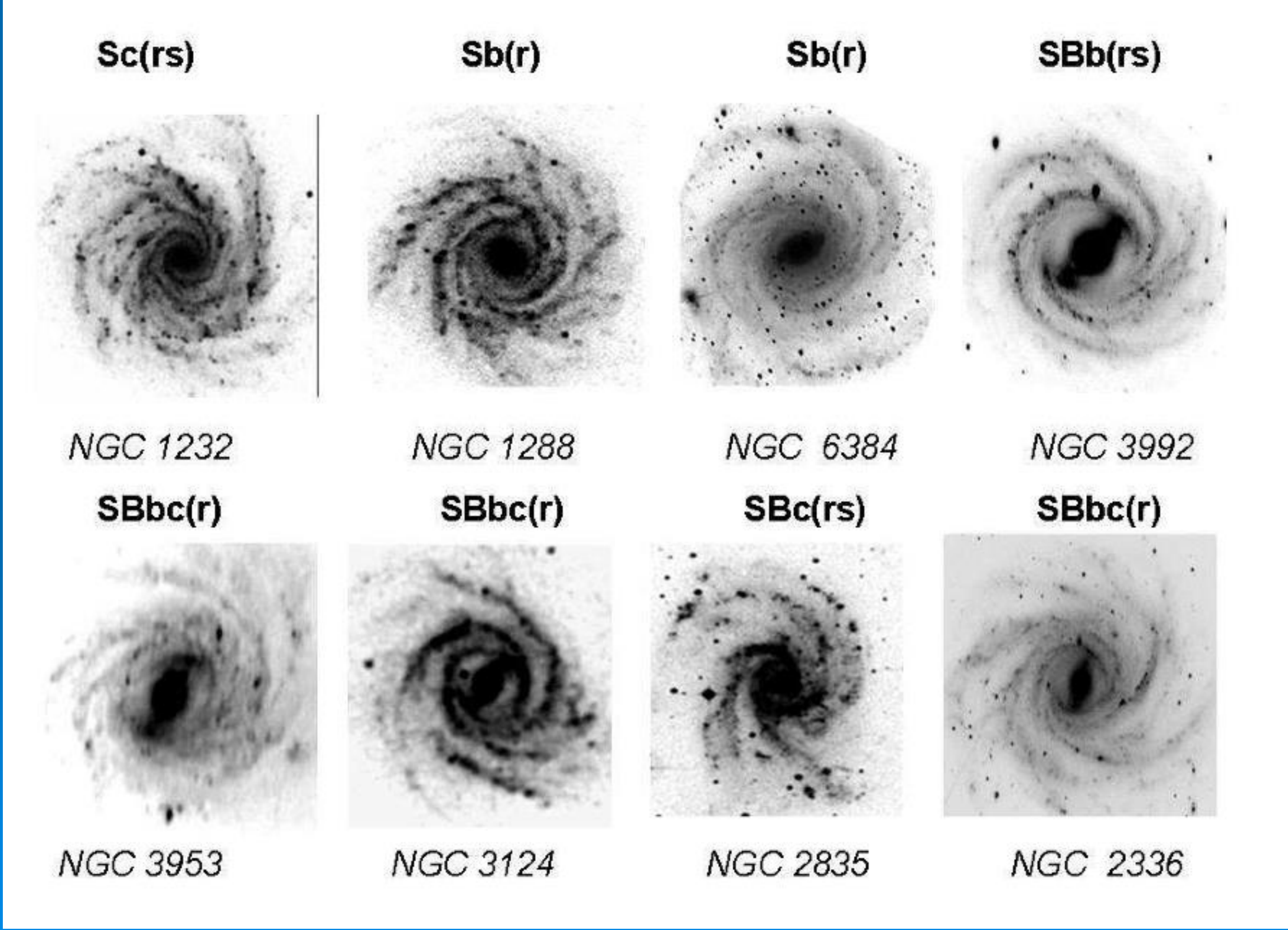
Old globular clusters:
trapped in the bar (Pérez-Villegas et al.)
➔ is there a possibility to have formed the GCs in the bar? ➔ pseudo-bulge →
only if bar formed very early ➔ not possible

Conclusions ARA&A: Facts

1.Most stellar mass in the bulge is in the bar.
2. Rotation is cylindrical
3. MDF -1.3 < [Fe/H] < +0.5
4. Predominantly old – fraction of young
   < 3.5 % → controversies
5. [alpha/Fe],[Al/Fe],[Eu/Fe]=+0.4 dex
   → enrichment by SN II
6. Small differences in abundance ratios
   with thick disk – significant or not?

MW:
Sb ?

Bland-Hawthorn+Gerhard ARA&A 2017



The End