H_0 and the Age of the Universe

Cosmology and fundamental physics with current and future ESO facilities

Massimo Dall'Ora, Italian Institute for Astrophysics

On behalf of Giuseppe Bono, Giuliana Fiorentino, Matteo Monelli, Clara Martinez-Vazquez, Peter Stetson, and many other colleagues

How old is the universe?

Till the end of XVIII, the Universe was ~6,000 yrs old

According to the Irish Cardinal Ussher in his treatise:

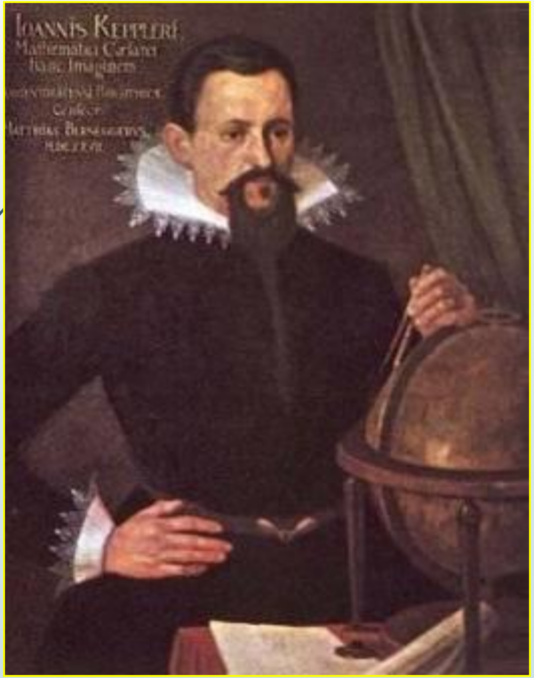
Annales veteris testamenti, a prima mundi origine deducti (1650)

Sunday, 23 October 4004 BC

J. Ussher, Cardinal of Armagh (1581-1656)

To complete the Copernican "**Revolution**"

.....



Johannes Kepler
1571-1630

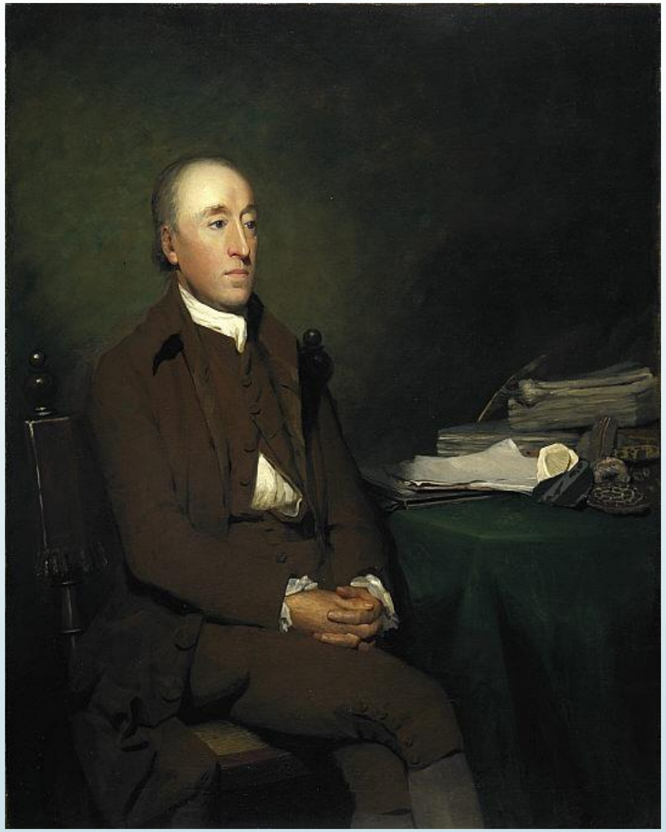
Galileo Galilei
1564-1642

Isaac Newton
1642-1727

We have to wait for three key characters

The opening of the dark abyss of time

Buffon 1683–1775



Hutton 1726-1797

Darwin 1809-1882

How old is the universe?

Count Buffon in his Les Epoques de la Nature (1778) published a summary of History of the Earth and History of the Civilization: The former is boundless times longer than the former

Geological Empirical Evidence

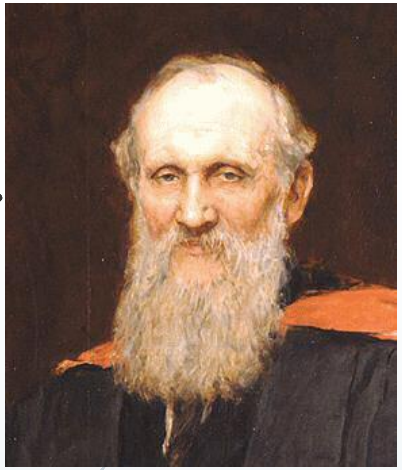
J. Hutton → *Theory of the Earth (1785), R. S. of Edinburg*:

the Earth has to be very old in order to erode mountains and to form new rocks (sediments/fossils).

Biological Empirical Evidence

C.R. Darwin –> On the Origin of Species (1859)

Natural selection as a basic mechanism (lengthy evolution)



Thompson/Lord Kelvin (1824-1907) **Age<30 Myr**

"Whitin a finite period of time the earth must have been, and within a finite period of time to come, the earth must be again, unfit for the abitation of man" (1852, On the universal tendency in nature to the dissipation of mechanical energy)

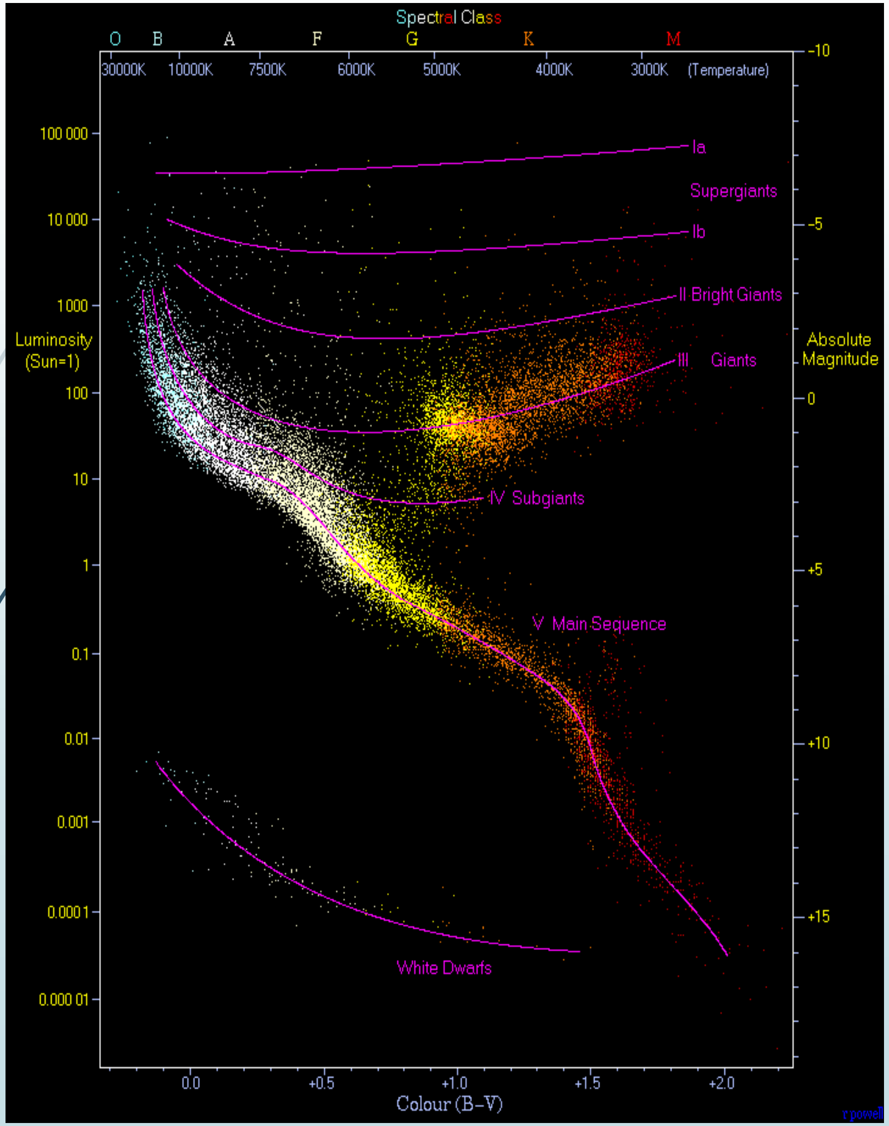
Radiometric dating

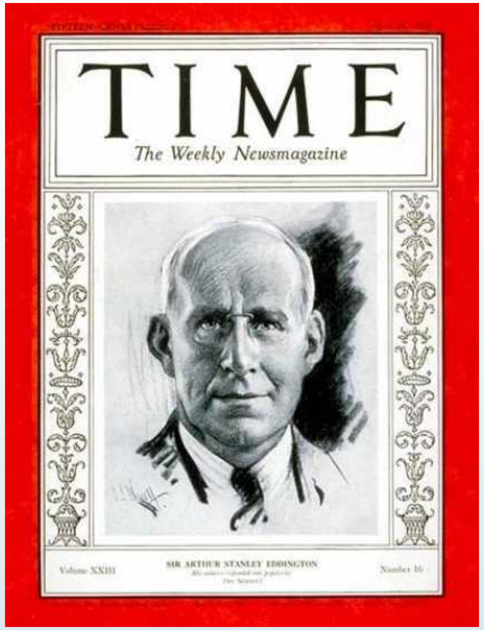
Rutherford & Boltwood (1907) 0.3—1.3 Gyr

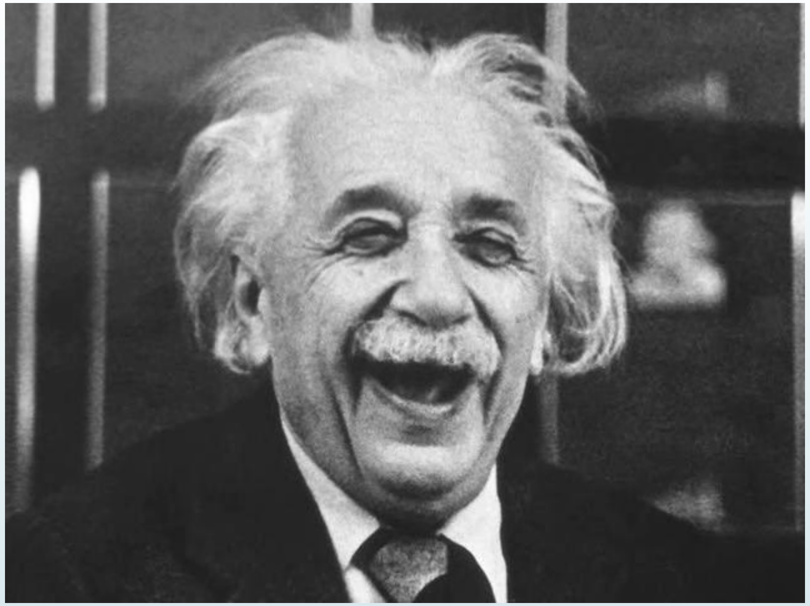
Arthur Holmes (in 1911, 1.5 Gyr)

The Age of the Earth, an Introduction to Geological Ideas (1927) 1.5--3.0 Gyr

EVOLUTIONARY PROPERTIES OF THE STARS

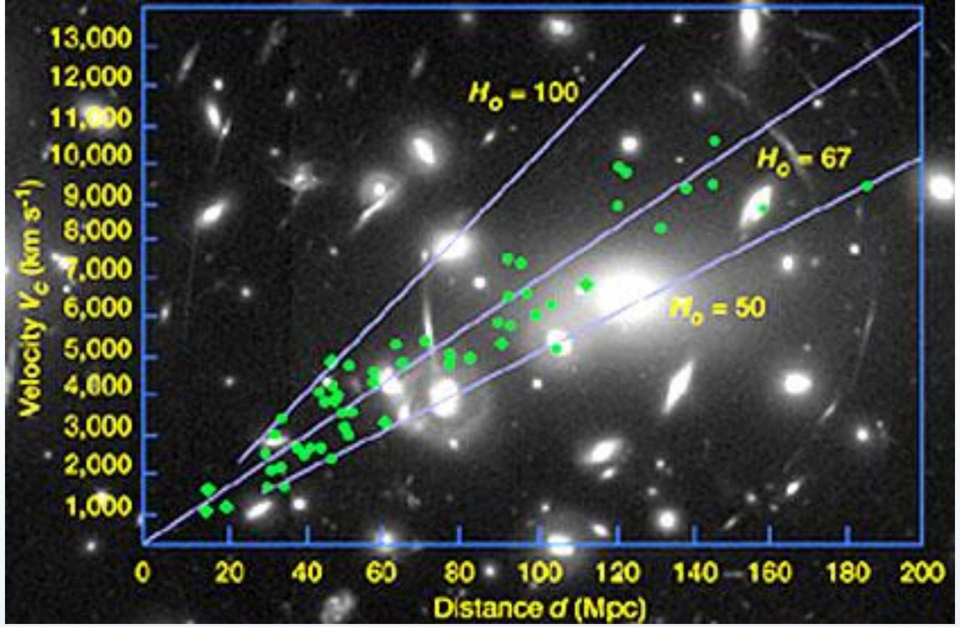






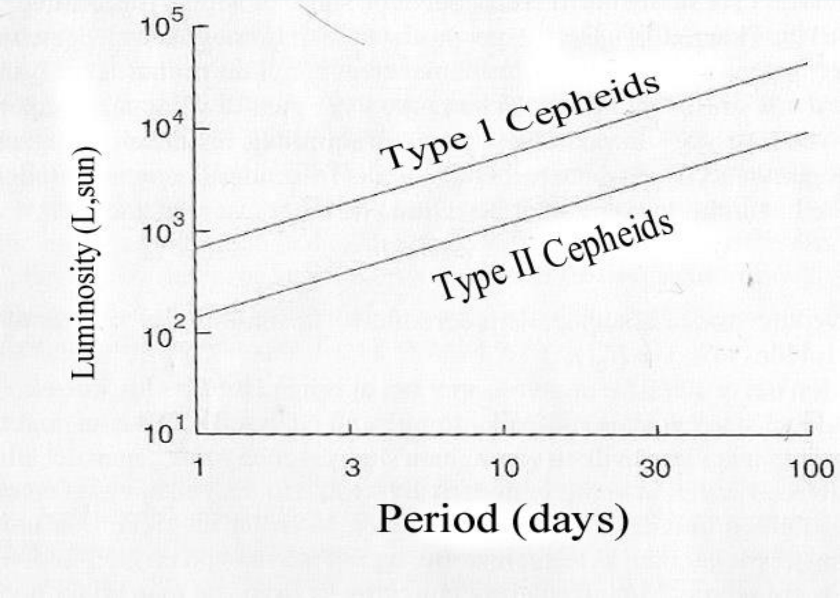
General Relativity

HR DIAGRAM → FUNDAMENTAL PLANE OF THE STARS



E. Hubble → Universe is expanding

The MW IS NOT the center of the Universe



Baade → Existence of two different stellar populations

The sun is a common dwarf of the MW disc → **Solving the problem with geologists**

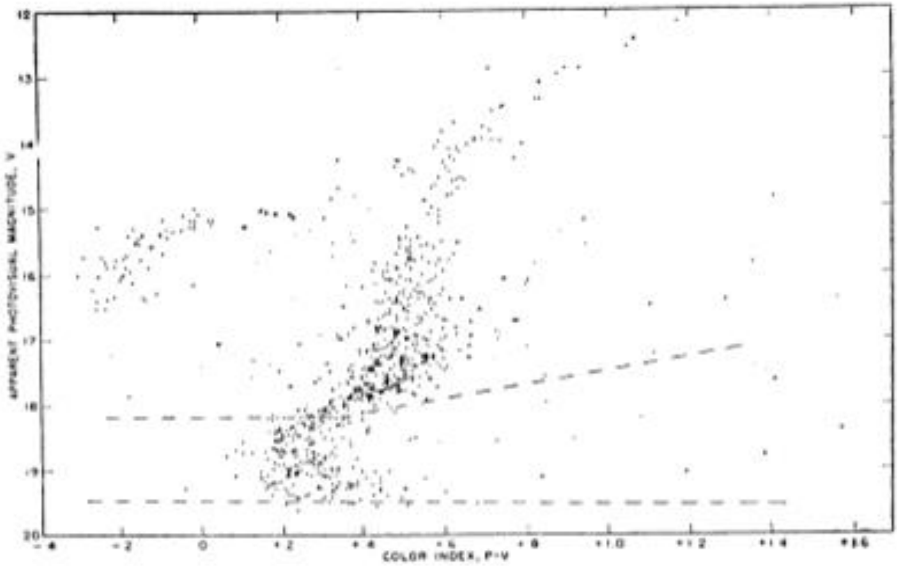
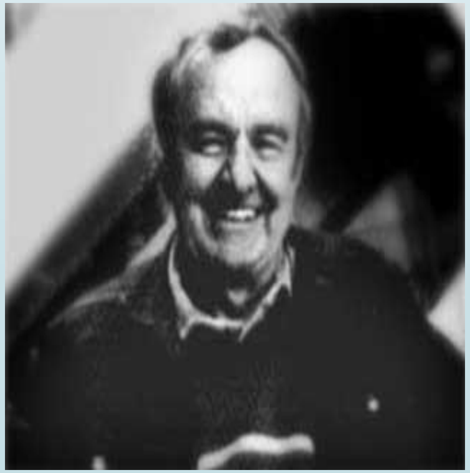


Fig. 1. Color-magnitude array for the globular cluster M92.

Arp, Baum, Sandage (1950)



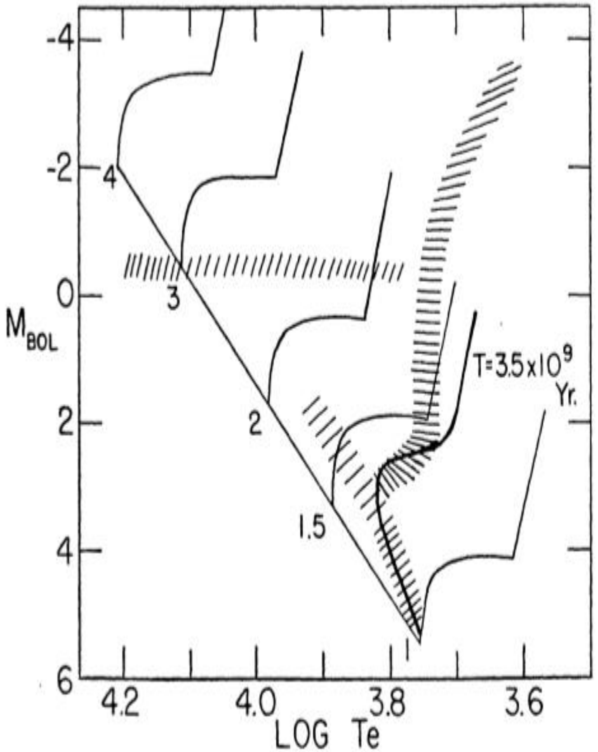


FIG. 4.—Speculative evolutionary tracks for stars of various masses with an assumed temperature of 1.1×10^{8} °K for the helium burning. The schematic globular cluster H–R diagram is shown for comparison. The heavy line is the theoretical appearance of the diagram 3.5×10^{9} years after the formation of the stars.

Sandage & Schwarzschild (1952)

Setting the stage

Sandage (1953)

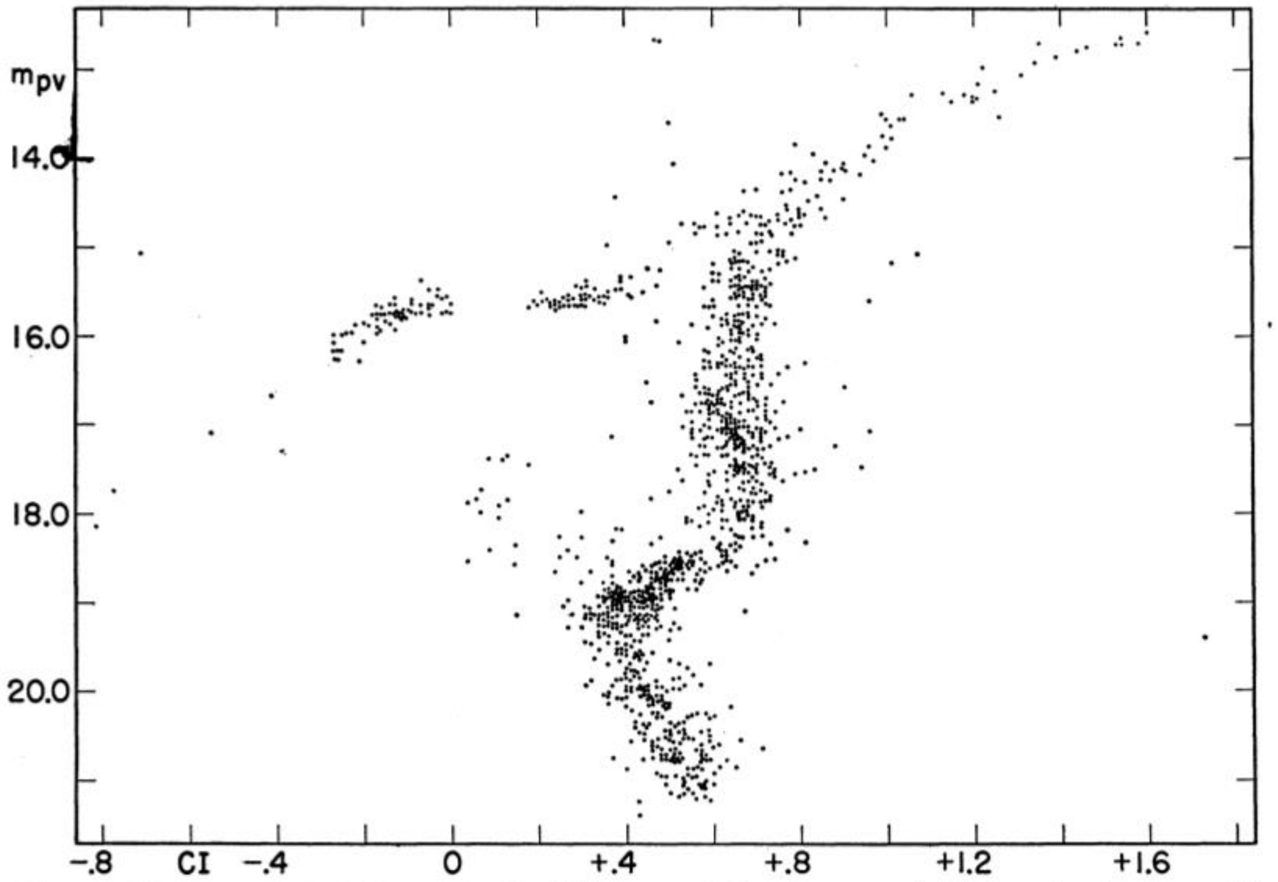
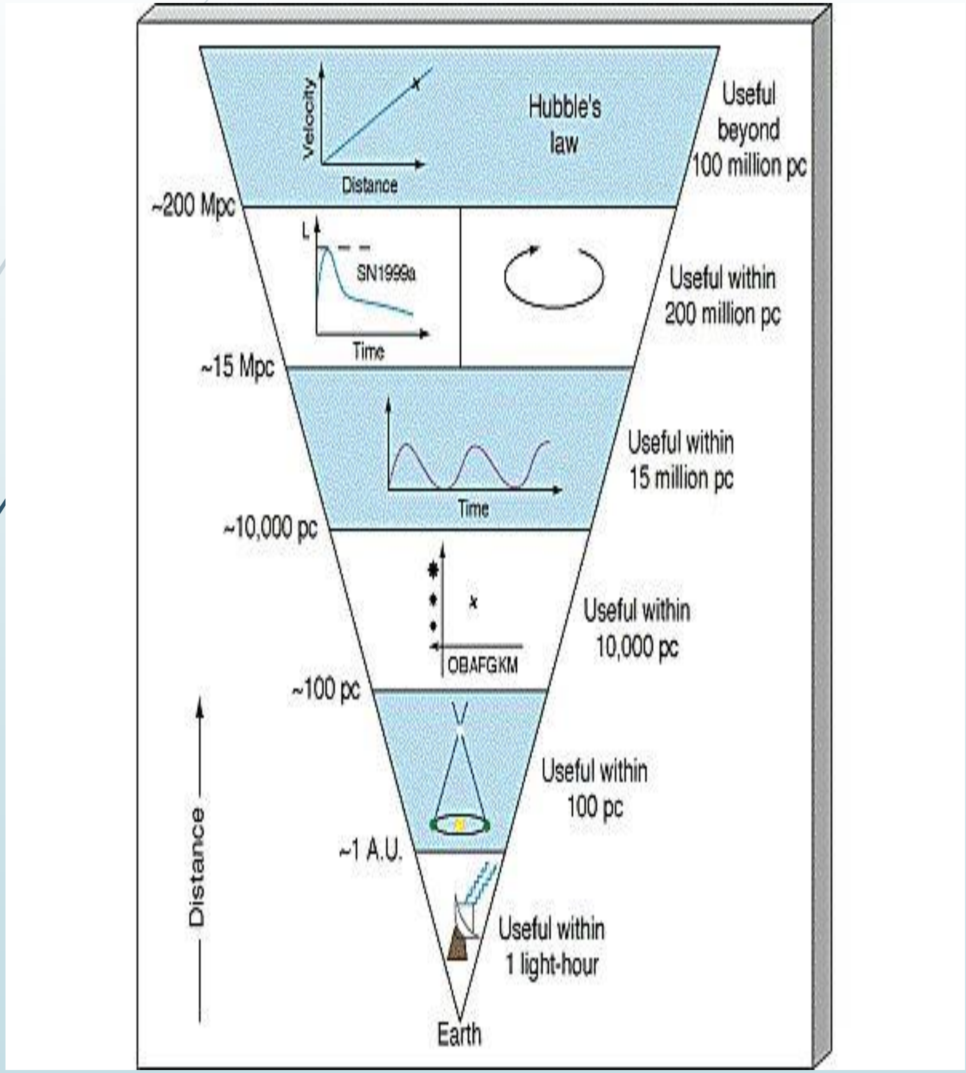


Figure 1. The color-magnitude diagram for M3. All known variable stars were excluded from the photometry. The ordinate and abscissa are on the magnitude and color system of the photographic materials. The transformation to the *P* and *V* system of Stebbins, Whitford, and Johnson may be made by use of the color equations 1, 2, and 3 given in the text. The diagram does not represent a homogeneous sample. The density of points does not, therefore, give a relative luminosity function.

"The application of an evolutionary theory to M3 & M92 Gives 5 Gyr, since the formation of the main sequence"

Setting of primary and secondary distance indicators



Ho~ 56 (km/sec)/Mpc

t_o ~ 18 Gyrs

Absolute age of GCs (Renzini 1993)

$$\log t_9 \cong -0.51 + 0.37 M_V(TO) + -0.13[Fe/H]$$

- M_V(TO) affected by uncertainties in μ and in E(B-V)

  ~0.2 mag means an uncertainty of ~2 Gyr on the age

- Uncertainties on [Fe/H], [α/Fe] and on the metallicity (scale)

  ~0.2 dex → ~ 0.1mag on M_V(TO) and ~1 Gyr on the age

- Y_P ~ 0.245 (WMAP) with an uncertainty ΔY_P < 0.03 mag

Uncertainties affecting current estimates of GC absolute ages

$$\log t_9 = \alpha + \beta M_V(TO) + \gamma[Fe/H] + \delta Y_P$$

⇧ Evol. models

⇧ Photometry
Evol. models
Atm. models
Reddenings
Distances

⇧ ⇧ Spectroscopy
Atm. models

[Fe/H]=log Z - **log Zo**

A new spin on stellar opacity

LETTER

doi:10.1038/nature14048

A higher-than-predicted measurement of iron opacity at solar interior temperatures

J. E. Bailey[1], T. Nagayama[1], G. P. Loisel[1], G. A. Rochau[1], C. Blancard[2], J. Colgan[3], Ph. Cosse[2], G. Faussurier[2], C. J. Fontes[3], F. Gilleron[2], I. Golovkin[4], S. B. Hansen[1], C. A. Iglesias[5], D. P. Kilcrease[3], J. J. MacFarlane[4], R. C. Mancini[6], S. N. Nahar[7], C. Orban[7], J.-C. Pain[2], A. K. Pradhan[7], M. Sherrill[3] & B. G. Wilson[5]

Here we report measurements of iron opacity at electron temperatures of 1.9–2.3 million kelvin and electron densities of (0.7–4.0)10^22 per cubic cm, conditions very similar to those in the solar region at radiation/convection boundary.

The measured opacity is 30–400% higher than predicted.

This represents roughly half the change in the mean opacity needed to resolve the solar discrepancy …..

Relative Ages: vertical method

PROS

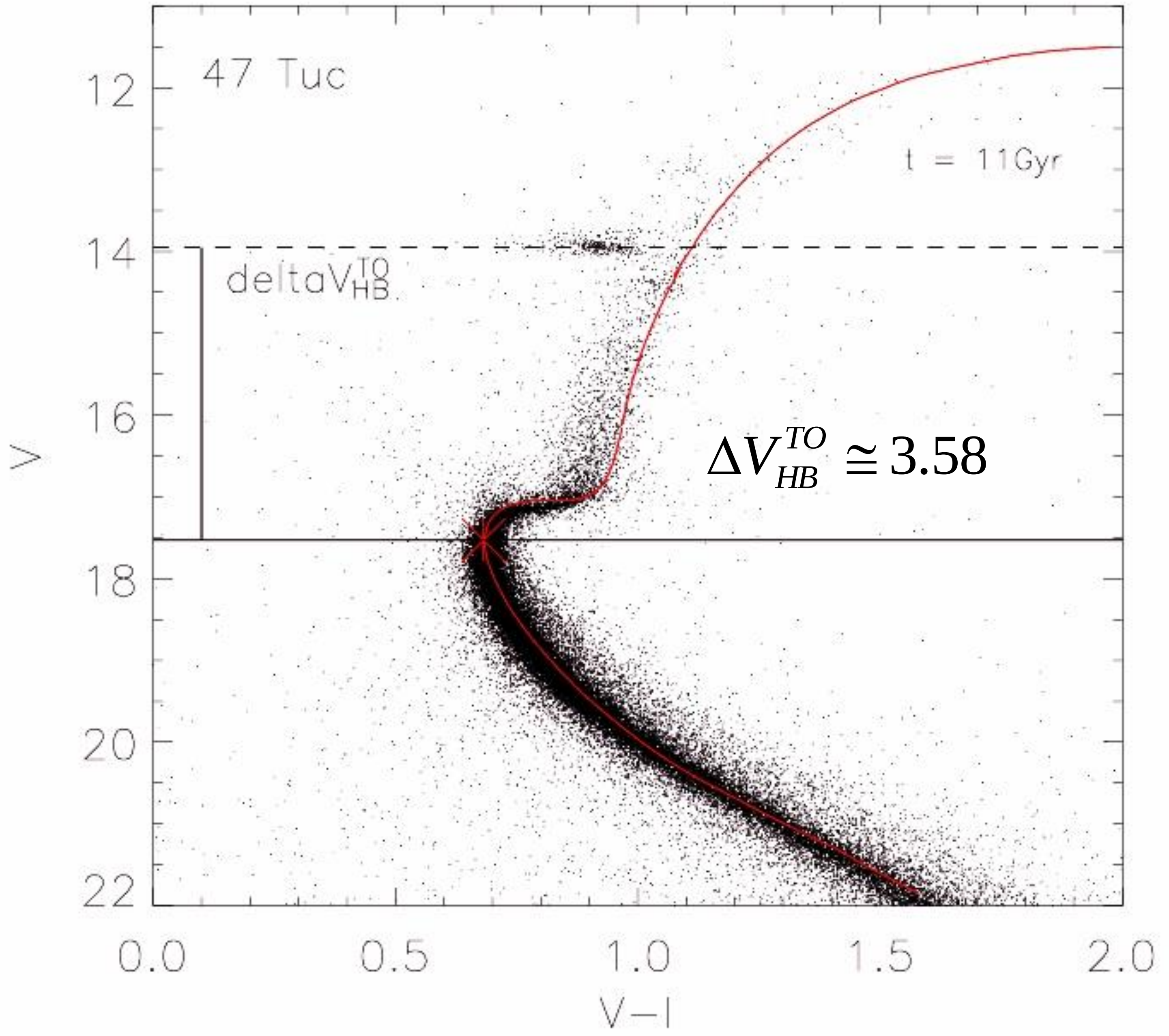
→ Independent of distance and reddening

→Accuracy of the order of ~1 Gyr → Crucial to constrain the formation of both the Galactic Halo and bulge

CONS

→The HB might depend on age (2nd parameter)

→HB morphology and ZAHB luminosity level



Relative ages: horizontal method

PROS

→ **Independent of distance and reddening**

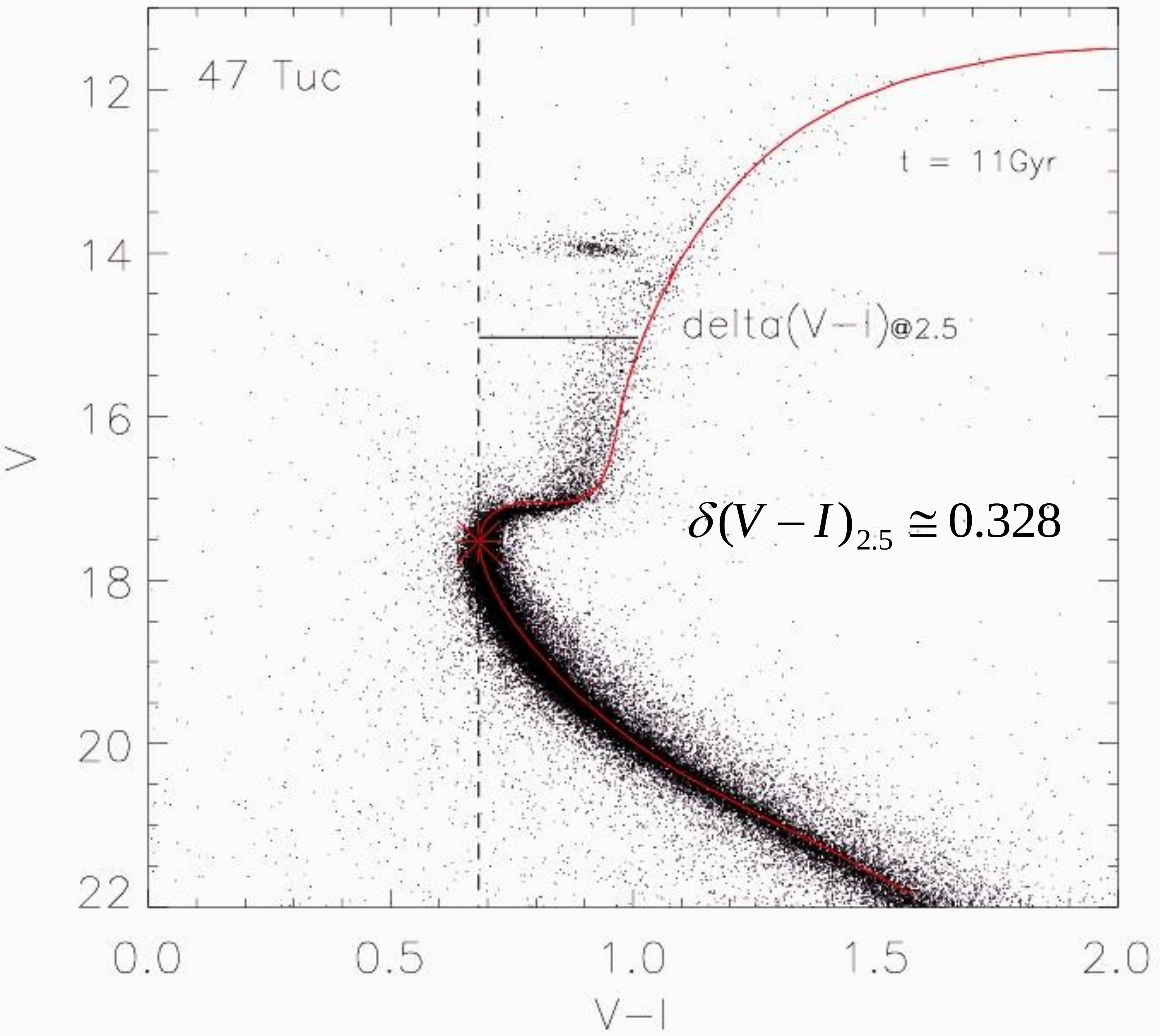
→ **Accuracy of the order of ~1 Gyr → Crucial to constrain the formation of both the Galactic Halo and bulge**

CONS

→ **Strong sensitivity to color**

→ **Age estimates are affected by the adopted mixing length**

→ **The TO color and the RGB color are different**



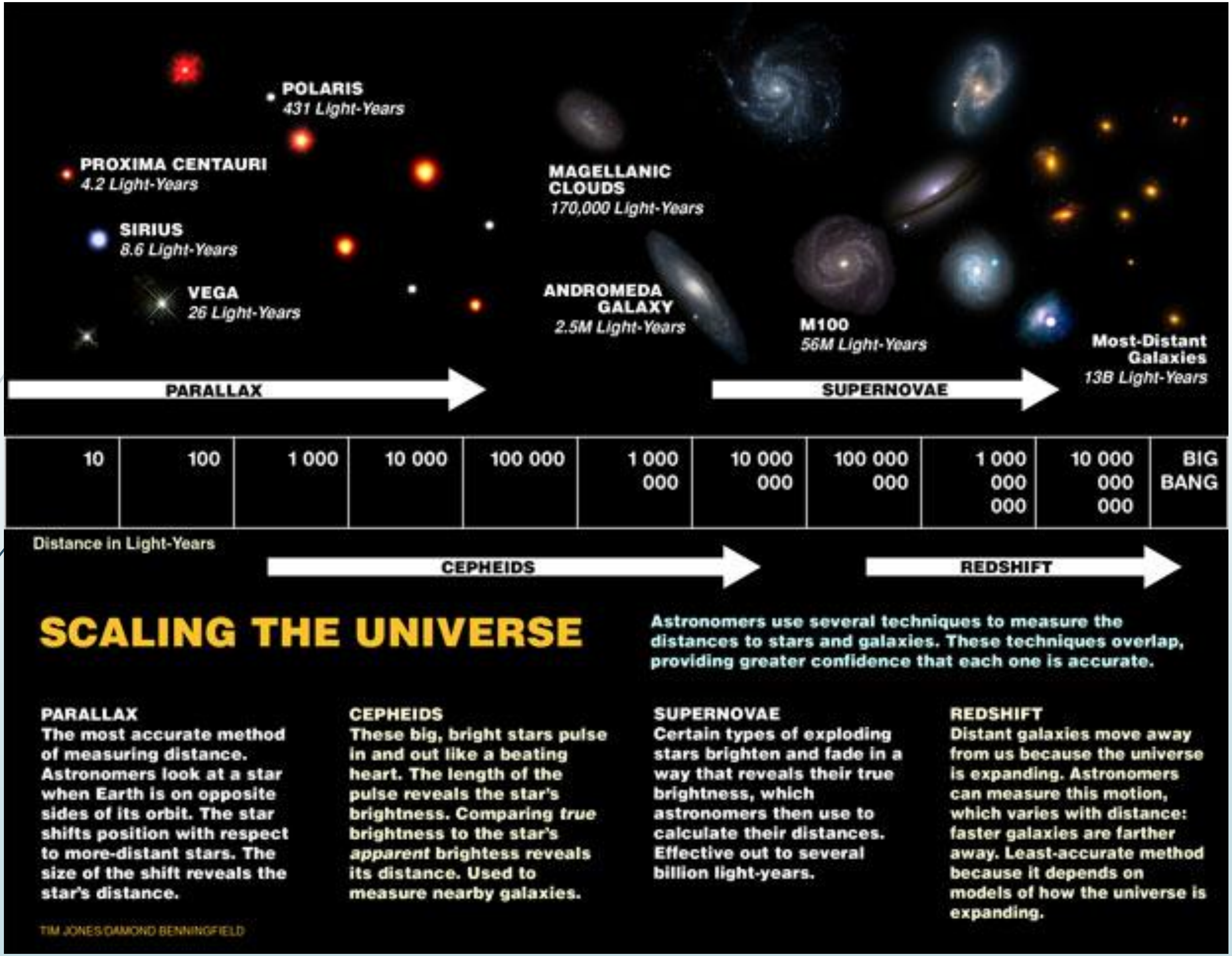
Skeletons in the closet

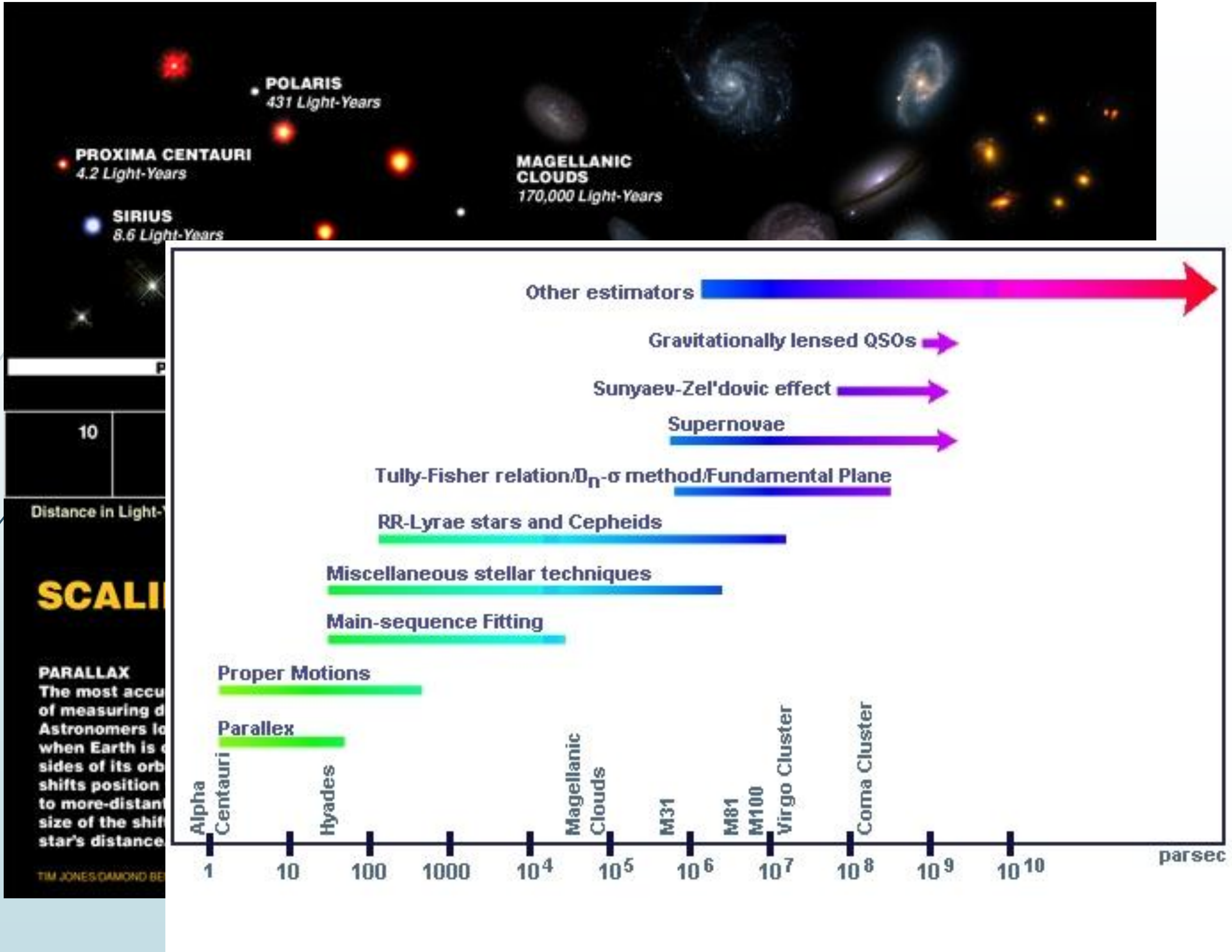
Relative ages accurate at 10%
GGCs are coeval within 1 Gyr

→ Zero-point absolute age affected
by uncertainty on μ & E(B-V)
at the 0.1-0.2 mag level

→The problem becomes even more
severe for old open clusters no HB

Classical age dating methods can hardly be popular among Galactic stellar systems


POLARIS
431 Light-Years
PROXIMA CENTAURI
4.2 Light-Years
SIRIUS
8.6 Light-Years
VEGA
26 Light-Years
MAGELLANIC CLOUDS
170,000 Light-Years
ANDROMEDA GALAXY
2.5M Light-Years
M100
56M Light-Years
Most-Distant Galaxies
13B Light-Years
PARALLAX
SUPERNOVAE
10
100
1 000
10 000
100 000
1 000 000
10 000 000
100 000 000
1 000 000 000
10 000 000 000
BIG BANG
Distance in Light-Years
CEPHEIDS
REDSHIFT
SCALING THE UNIVERSE
Astronomers use several techniques to measure the distances to stars and galaxies. These techniques overlap, providing greater confidence that each one is accurate.
PARALLAX
The most accurate method of measuring distance. Astronomers look at a star when Earth is on opposite sides of its orbit. The star shifts position with respect to more-distant stars. The size of the shift reveals the star's distance.
CEPHEIDS
These big, bright stars pulse in and out like a beating heart. The length of the pulse reveals the star's brightness. Comparing true brightness to the star's apparent brightess reveals its distance. Used to measure nearby galaxies.
SUPERNOVAE
Certain types of exploding stars brighten and fade in a way that reveals their true brightness, which astronomers then use to calculate their distances. Effective out to several billion light-years.
REDSHIFT
Distant galaxies move away from us because the universe is expanding. Astronomers can measure this motion, which varies with distance: faster galaxies are farther away. Least-accurate method because it depends on models of how the universe is expanding.
TIM JONES/DAMOND BENNINGFIELD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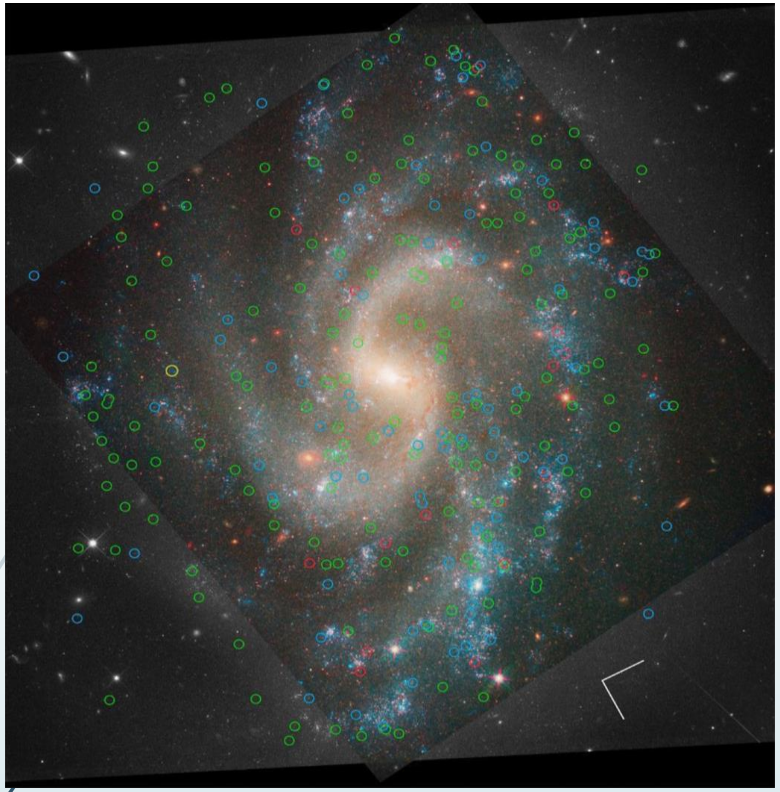
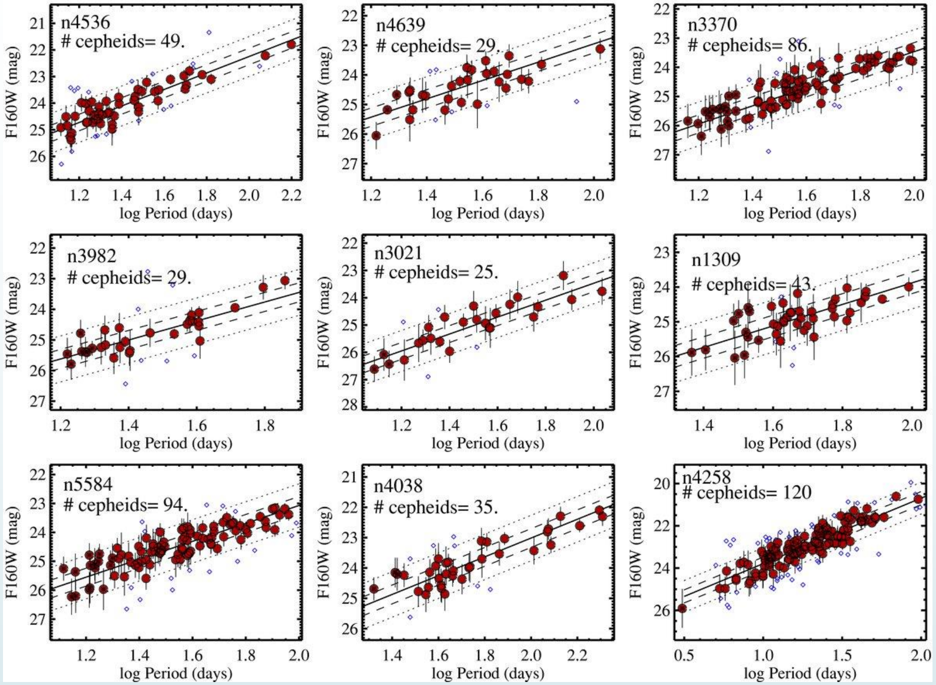
170,000 Light-Years
10
Distance in Light-
SCALI
PARALLAX
The most accu
of measuring d
Astronomers lo
when Earth is o
sides of its orb
shifts position
to more-distant
size of the shif
star's distance
Other estimators
Gravitationally lensed QSOs
Sunyaev-Zel'dovic effect
Supernovae
Tully-Fisher relation/Dn-σ method/Fundamental Plane
RR-Lyrae stars and Cepheids
Miscellaneous stellar techniques
Main-sequence Fitting
Proper Motions
Parallex
Alpha Centauri
Hyades
Magellanic Clouds
M31
M81
M100
Virgo Cluster
Coma Cluster
1
10
100
1000
10 4
10 5
10 6
10 7
10 8
10 9
10 10
parsec

Riess et al. 2011 -- SHOES



NGC 5584 SN Ia + Cepheids



NIR PL relations external galaxies

8 (6) calibrating SN Ia

NIR phot. of external Cepheids

Homogeneous optical/NIR Phot. (WFC3)

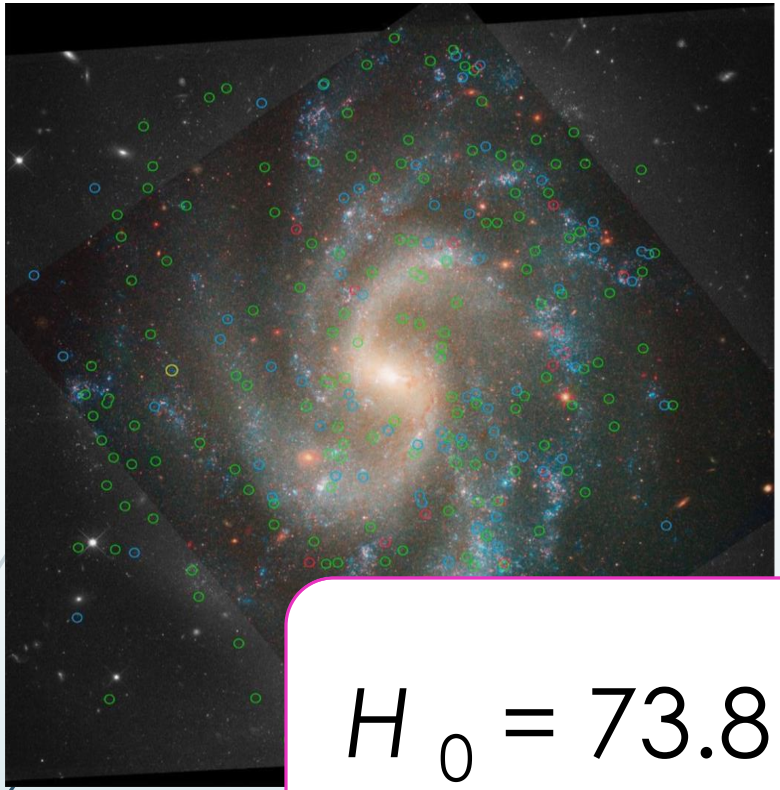
Three independent zero-points:

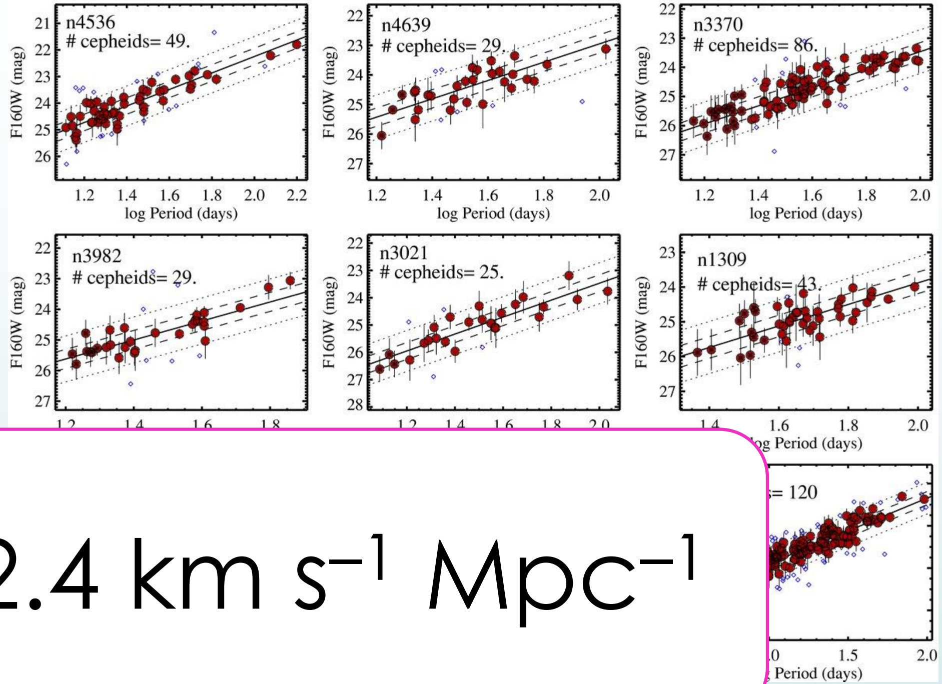
NGC4258 (geometric/maser distance)

9 Gal. Ceph. Trigonometric parallaxes

92 LMC Cepheids

Riess et al. 2011 -- SHOES





$$H_0 = 73.8 \pm 2.4 \text{ km s}^{-1} \text{ Mpc}^{-1}$$

NGC 5584

NIR PL relations external galaxies

8 (6) calibrating SN Ia

NIR phot. of external Cepheids

Homogeneous optical/NIR Phot. (WFC3)

Three independent zero-points:

NGC4258 (geometric/maser distance)

9 Gal. Ceph. Trigonometric parallaxes

92 LMC Cepheids

WMAP + PLANCK

$H_o = 67.8 \pm 0.9$ km / (s Mpc)

Tension or not tension?

Resolved sources → 2.5σ level

Re-analysis by Efstathiou (2014) using a new maser distance to NGC4258 → 1.9σ

New calibration by Riess + (2016)

Using new optical & NIR photometry WFC3@HST for Cepheids in 10 new galaxies hosting Sne Ia
(18 calibrators) + 300 SN Ia at a redshift z≤0.15

Geometrical calibrators

→Maser galaxy NGC4258 (33% improvement)
→Larger sample of LMC Cepheids + 8 double eclipsing binary
→Larger sample of M31 Cepheids + 2 double eclipsing binary
→HST rigonometric parallaxes from 9 to 12

Ho = 73.02 ± 1.79 km / (s Mpc)
final uncertainties from 3.3% to 2.4%

PLANCK CMB DATA (2015)

+ ΛCDM + 3 neutrino flavors (0.06 eV)

Ho = 67.27 ± 0.66 km / (s Mpc)

Tension or not tension? 3.3 σ level

WMAP9+ACT+SPT → Ho=70.9 ± 1.6 km / (s Mpc)

Tension or not tension? 0.9σ level (Calabrese + 2015)

WMAP9+ACT+SPT+BAO (BOSS DR11+6dFGS)

→ Ho=69.3 ± 0.7 km / (s Mpc)

Tension or not tension? 2σ level

WHO CARES?

gest, that in a flat Universe, the age of the Universe $-t_0-$ is connected with the Hubble constant $-H_0-$, the matter density parameter $-\Omega_m-$ and with the dark energy density $-\Omega_\Lambda-$ by the following relation (Dekel et al. 1997):

$$t_0 = [1 - (\Omega_m - 0.7\Omega_\Lambda)/5.8]/(1.3 \times h_0) \qquad (1)$$

where $h_0 = H_0/100$ km s^{-1}Mpc^{-1} is the current espansion rate of the universe and t_0 is the age of the Universe today in units of 10^{10} Gyr.

Monelli et al. (2016)

The current uncertainty on Ho
→ an uncertainty of 2 Gyr on to

A new spin on the absolute ages of GCs: optical vs NIR

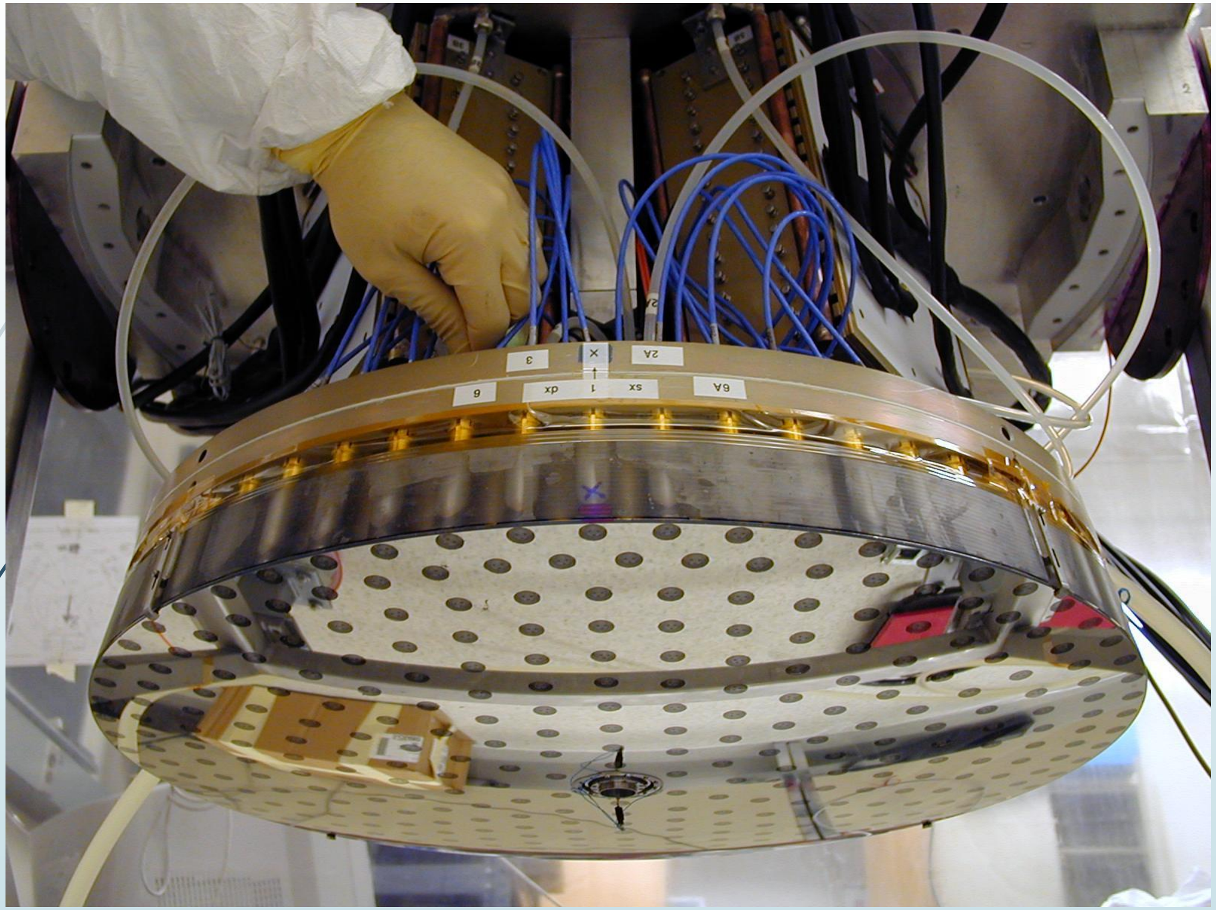
NIR CONS

→ Photometric precision (repeatability)
→ Sky subtraction (T←→S) in crowding regions
→ NIR bands are twice less sensitive to T_{eff} of TO stars than BVI bands

NIR PROS

→Minimally affected by reddening & diff. redd.
→Faint MS stars are brighter (NIR vs optical)
→Calibration: 2MASS
→Intrinsic features of the MS

Adaptive optics

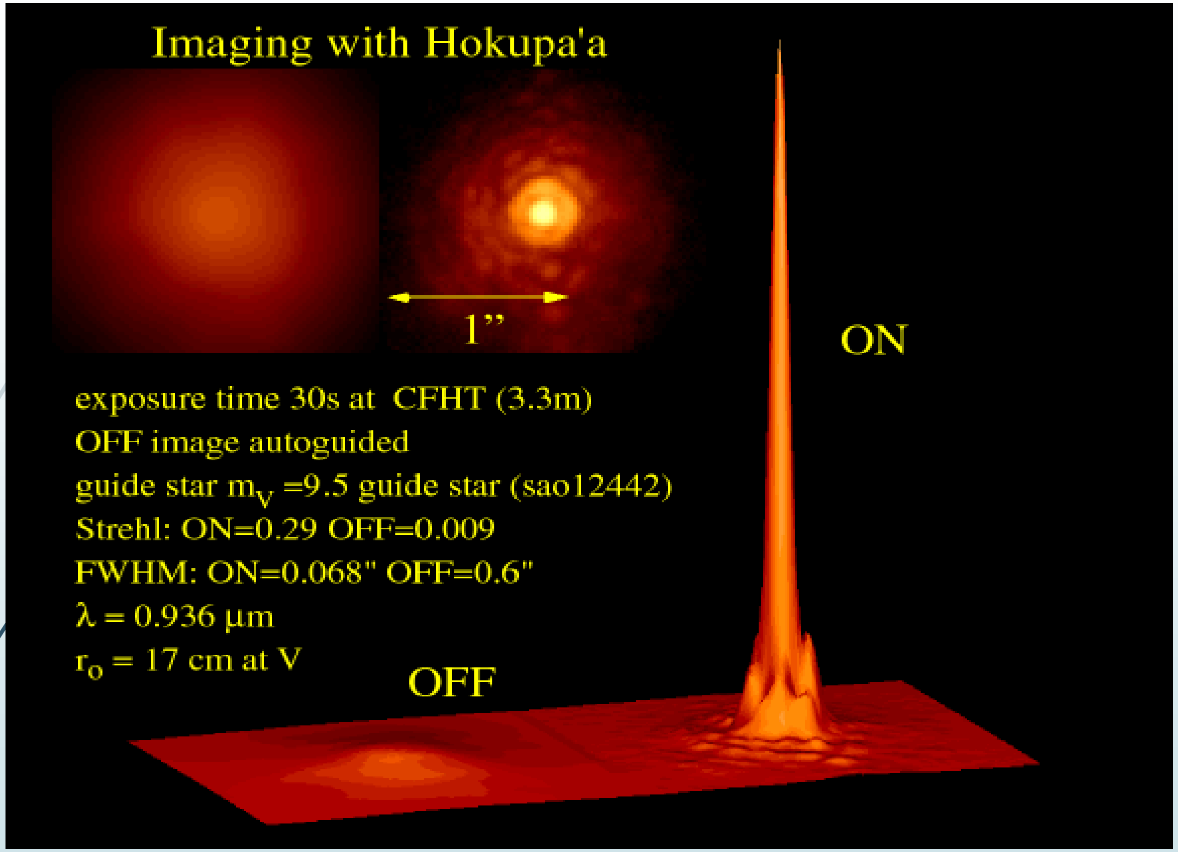


Secondary adaptive mirrors at 4-10m class telescopes

TNG -- MMT pioneering

Opening a new path!!

Image Quality



Strehl ratio

Isoplanatic angle

PSF stability
time & space

Optical vs NIR

It is mainly applied to NIR
due to technological limits

density of actuators

frequency of actuators

Adaptive Optics: MCAO

→ Very good Strehl ratio ~20-40%

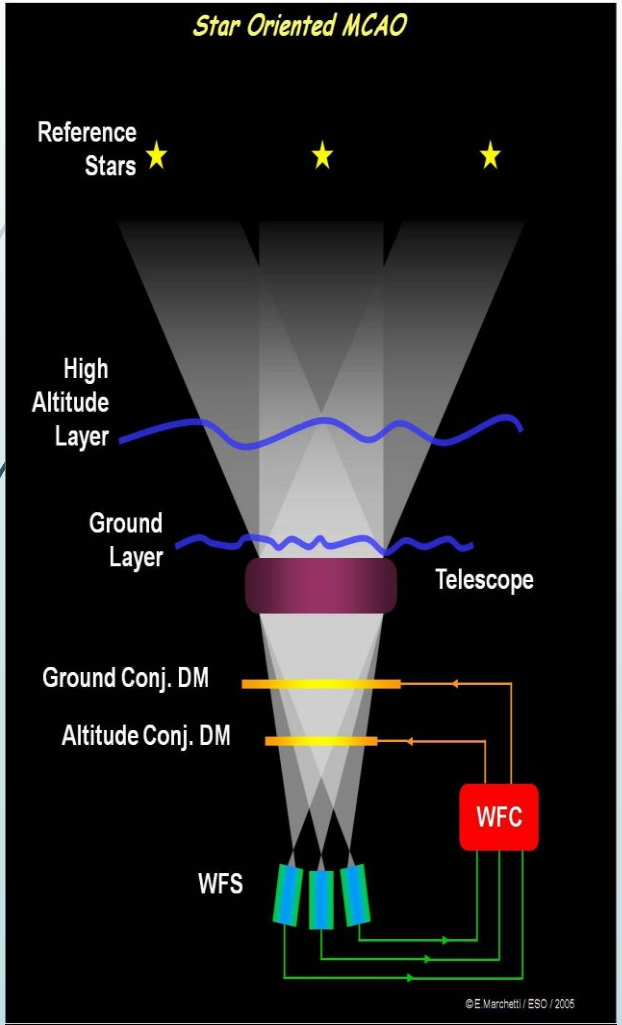
→ Modest isoplanatic angle

→ Large FoV: ~ 1'

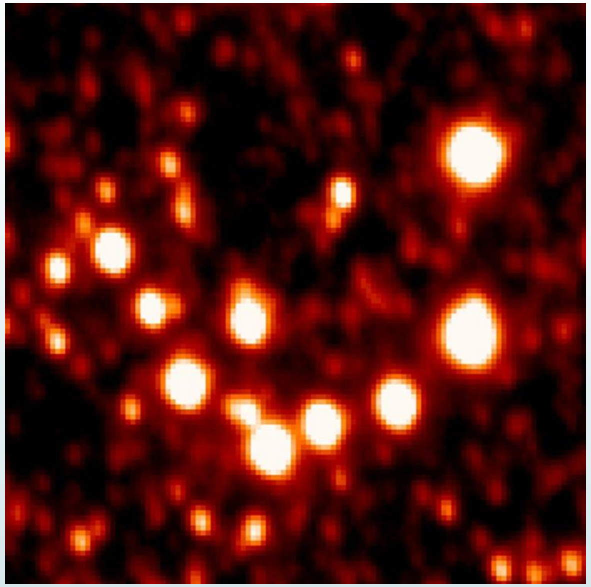
→ PSF quite stable across the FoV

Bright (V≤13-15) NGSs (three) either the targets or inside the scientific FoV
Sky coverage
Asterism → [stellar vs extragalactic]

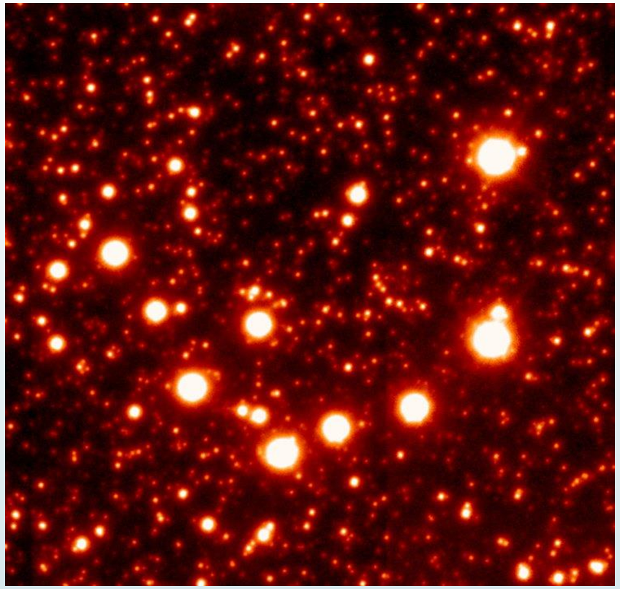
In the beginning was …. MAD@VLT



ISAAC@VLT



MAD@VLT

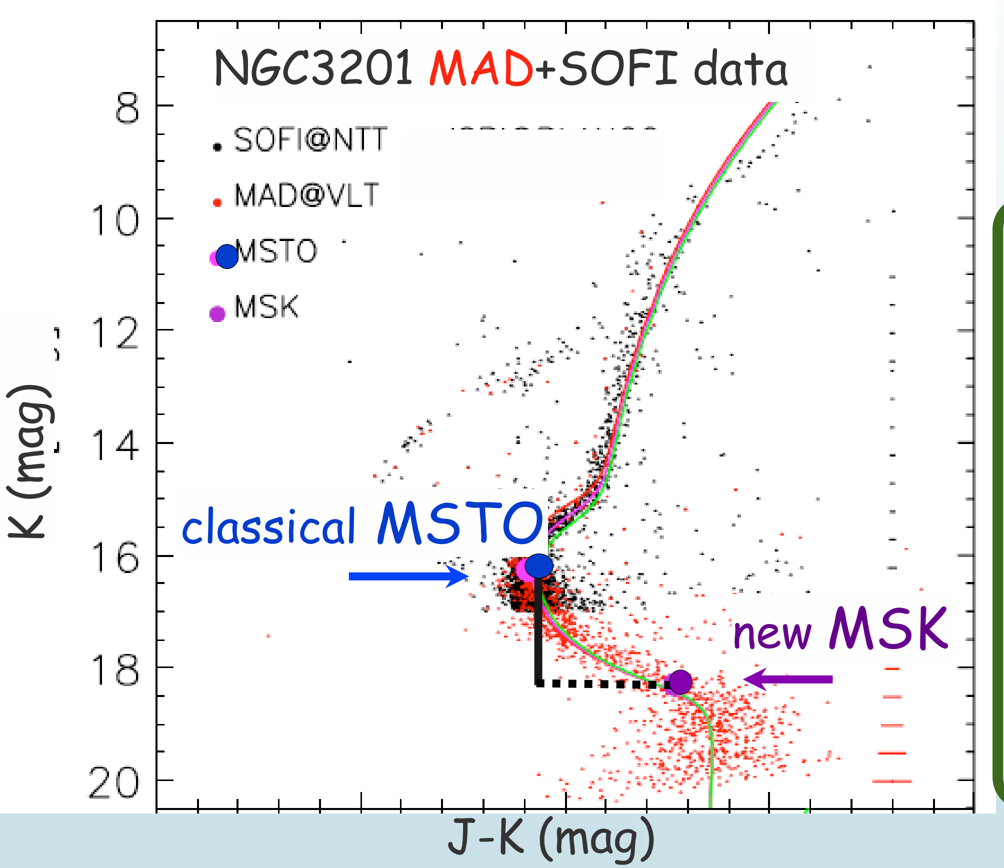


ω Centauri the very center crowded field!!

Log ρ = 3.5

Photometric & astrometric precision similar to HST!!! Marchetti et al. (2008)

NGC3201 as seen by MAD



NIR CMD of NGC3201 as provided by the combination of MAD (red dots) and SOFI (black dots). The blue and purple points highlight the Main Sequence Turn Off (MSTO) and the Main Sequence Knee (MSK) locations.

Bono et al. 2010, ApJL

NGC3201
d~5Kpc
E(B-V)~0.25-0.30

1) MSK better shows-up in NIR-filters

2) the MSK is almost independent on age

3) Based on a different physics: for M≤0.4Mo, due to CIA of H2 molecules

4) Independent of Reddening and Distance

The absolute age of NGC3201: NIR

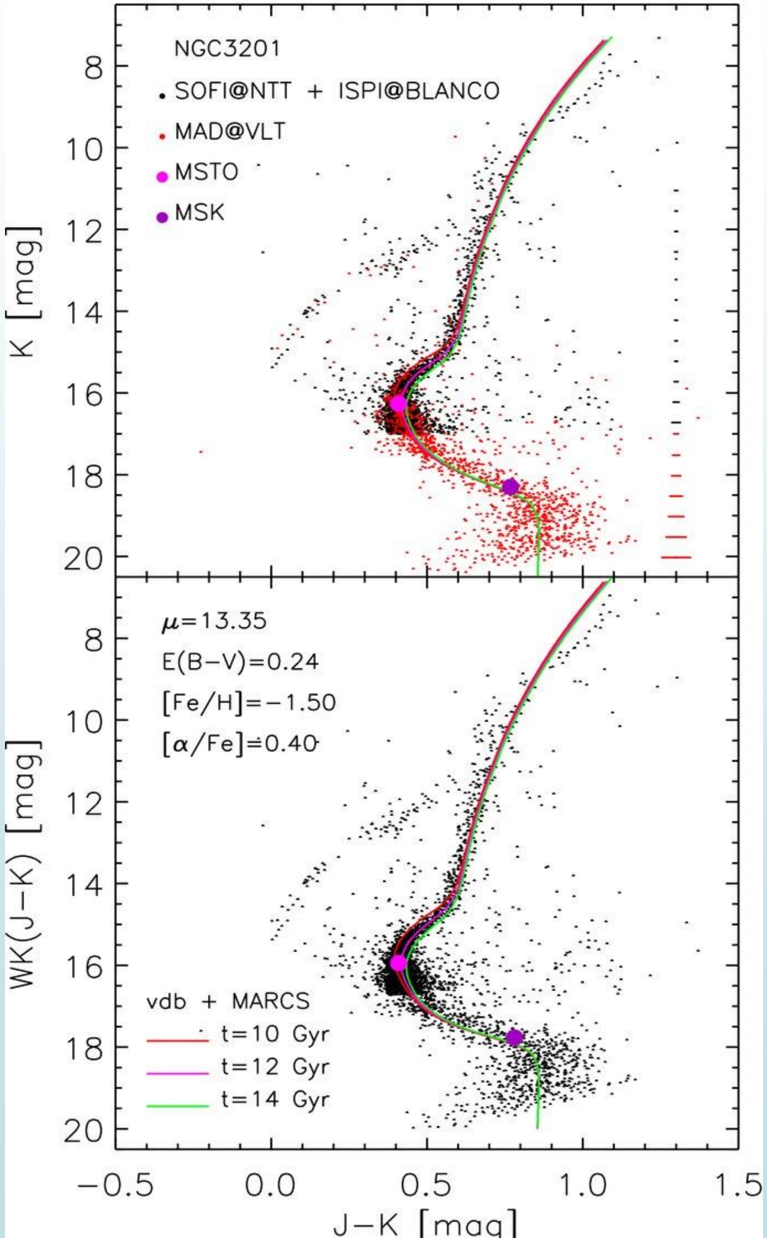
A new method to estimate the Absolute age of stellar systems

the difference in magnitude and/or in color between the TO and the NIR MS knee

t~11±1 Gyr [GB +2010]

See Di Cecco et al. (2015)
For an extension into UV-optical.

Wesenheit (V,V-I)



Adaptive Optics: SCAO

→Very good Strehl ratio ~60%

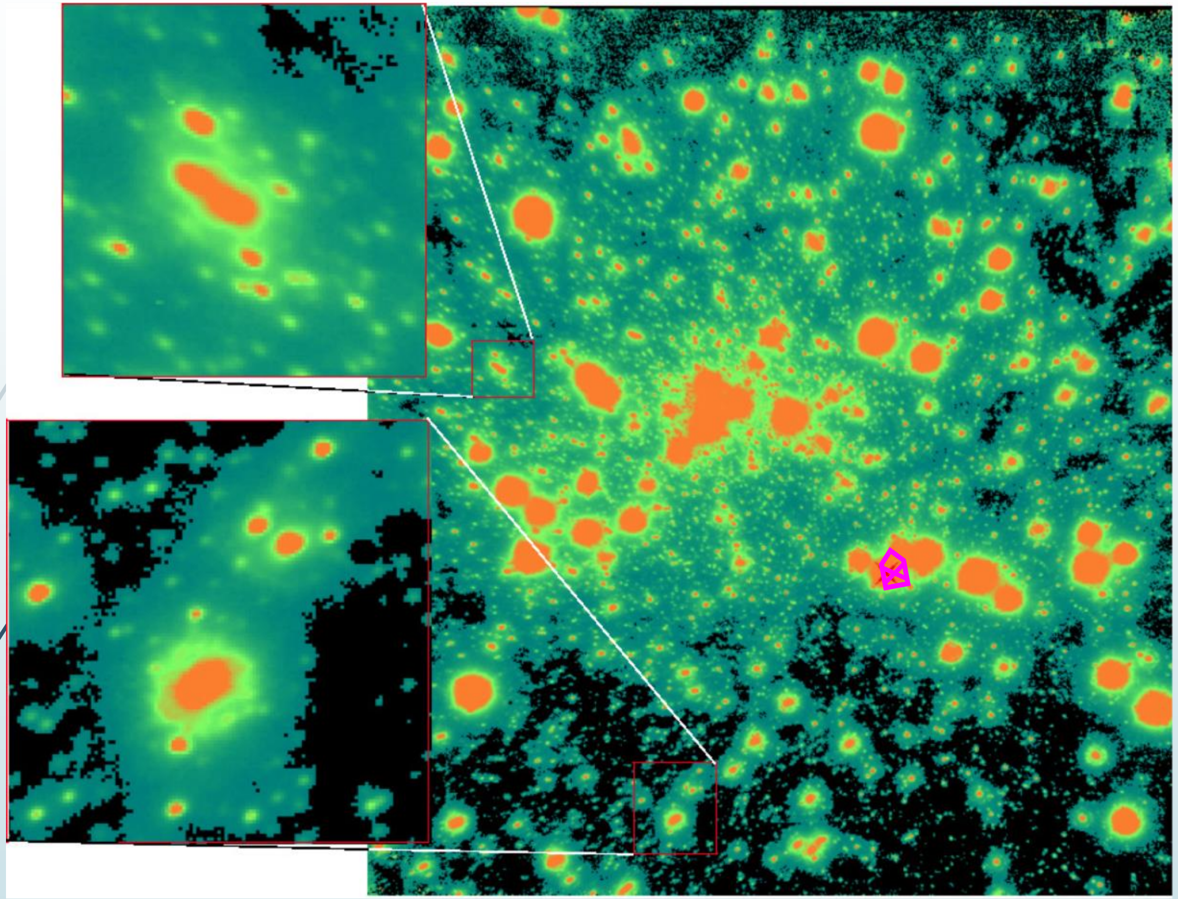
→ Good isoplanatic angle

→Modest FoV: ~10”

→ PSF strong radial dependence

Bright (V≤13-15) NGS either the target or inside the scientific FoV
Sky coverage [stellar vs extragalactic]

Later on was FLAO@LBT



J-band image

Drift of the PSF shape at larger
Distances from the NGS

SCAO

M15 core (pcc)

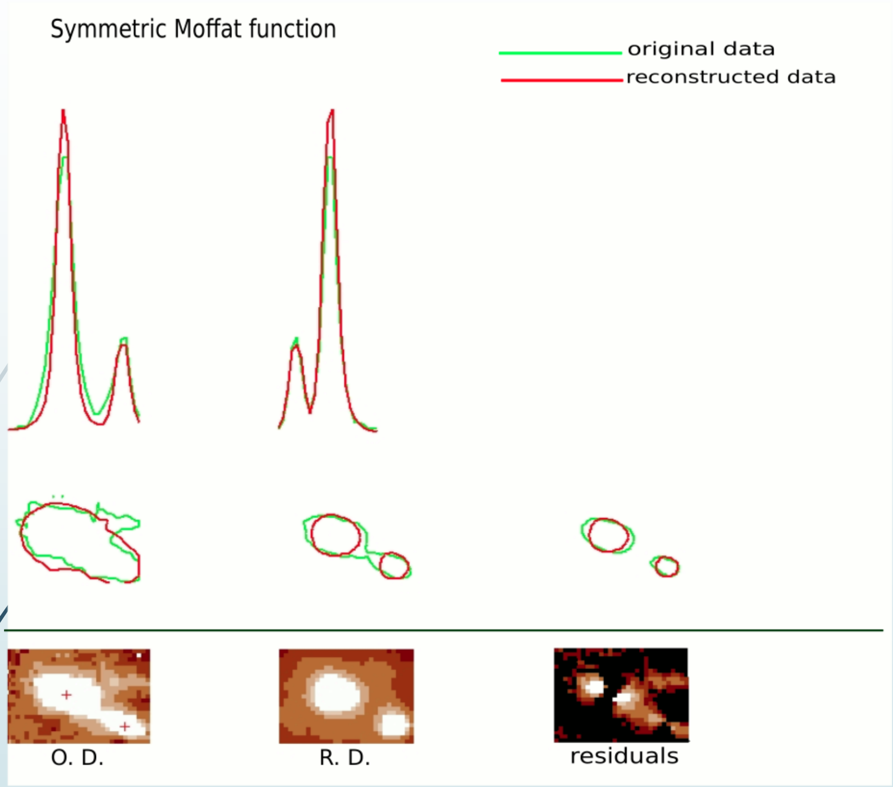
FWHM of 0.05 (J) &
0.06 (Ks) arcsec.

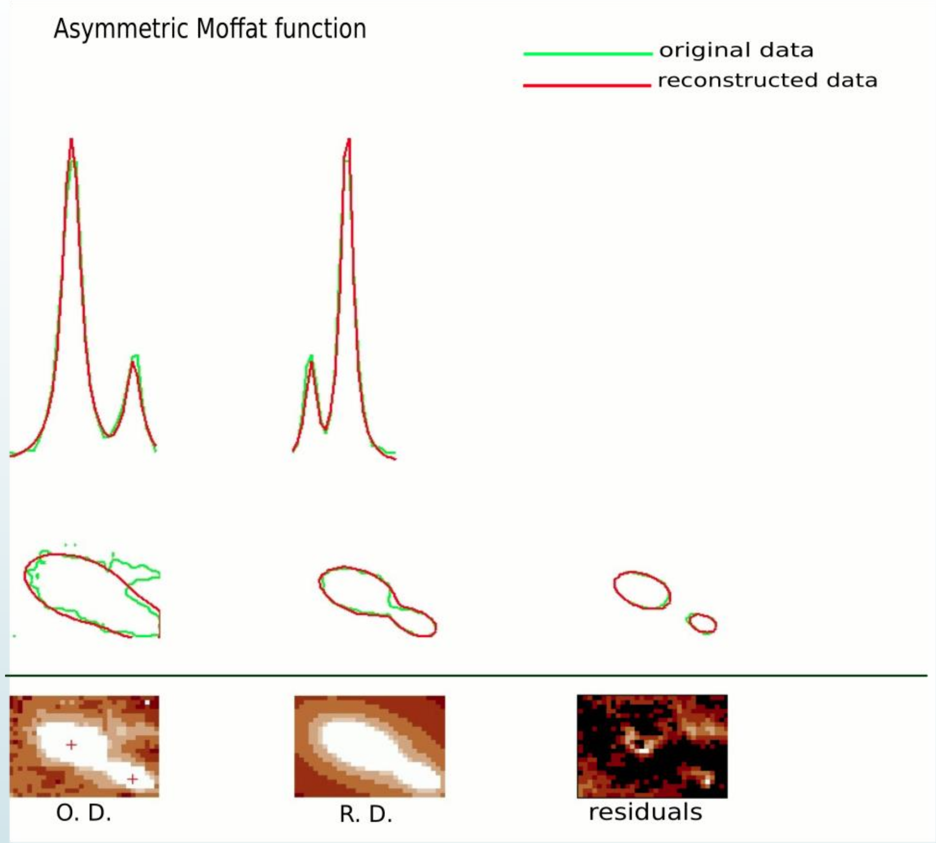
Strehl ratio
13–30% (J), 50–65% (Ks)

Limiting magnitudes:
J~22.5 mag
Ks~23 mag

Esposito + (2010)

Symmetric vs asymmetric PSF





Increase in the number of unknowns (8 vs 4), but *AO* images are oversampled … (ROMAFOT environment)

Fiorentino et al. (2014)

The absolute age of M15

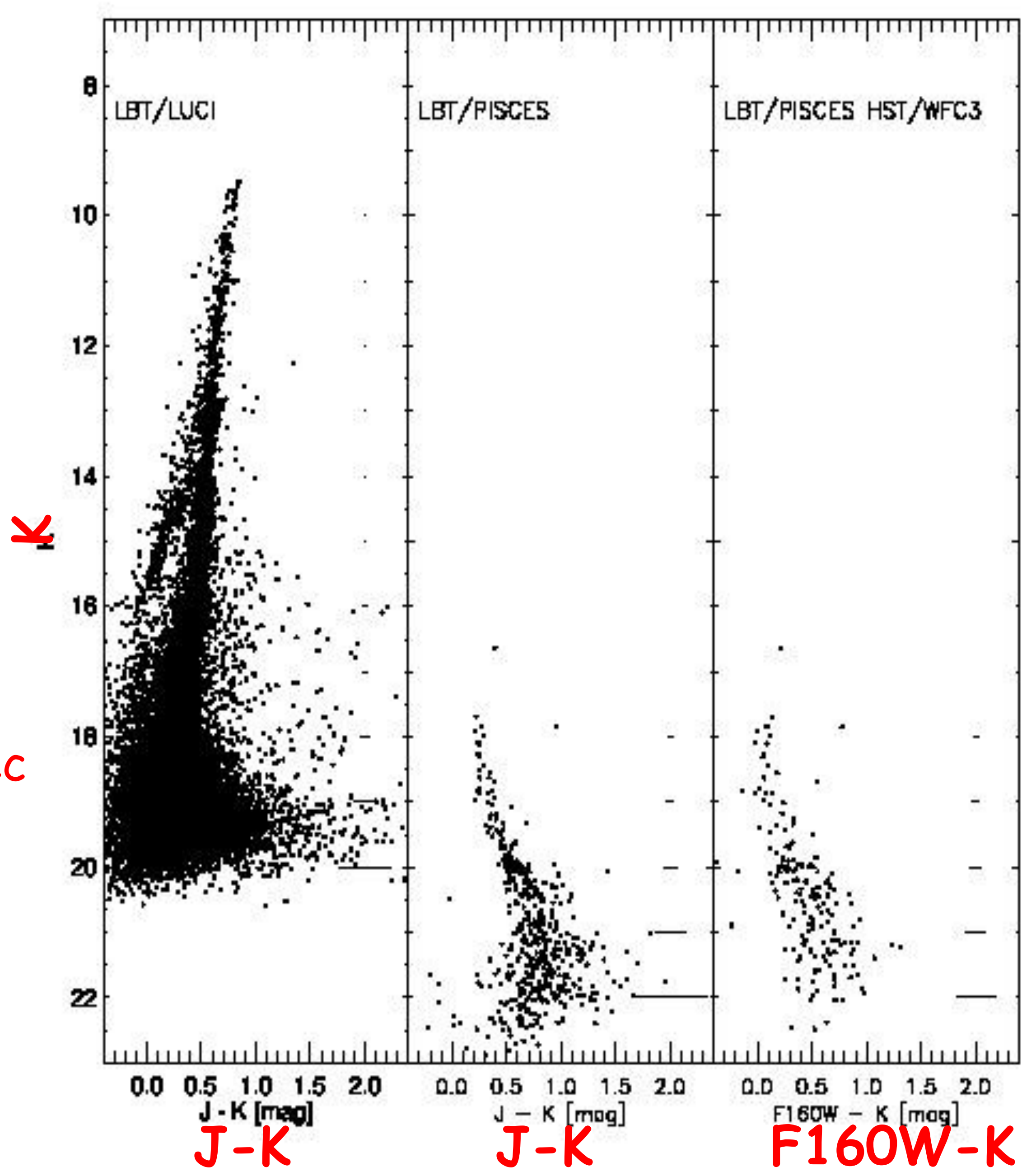
LUCI (4x4arcmin):
19J 20-40 sec
20K 20 sec

PISCES (26X26arcsec):
30J 30 sec
30K 15 sec

WFC3:
F160W(H) 3X200+6X250sec

t= 13±1 Gyr

Monelli et al. (2015)



Adaptive Optics: LTAO

→ Very good Strehl ratio ~20-40%

→ Modest isoplanatic angle

→ Large FoV: ~ 1.5’

→ PSF quite stable across the FoV

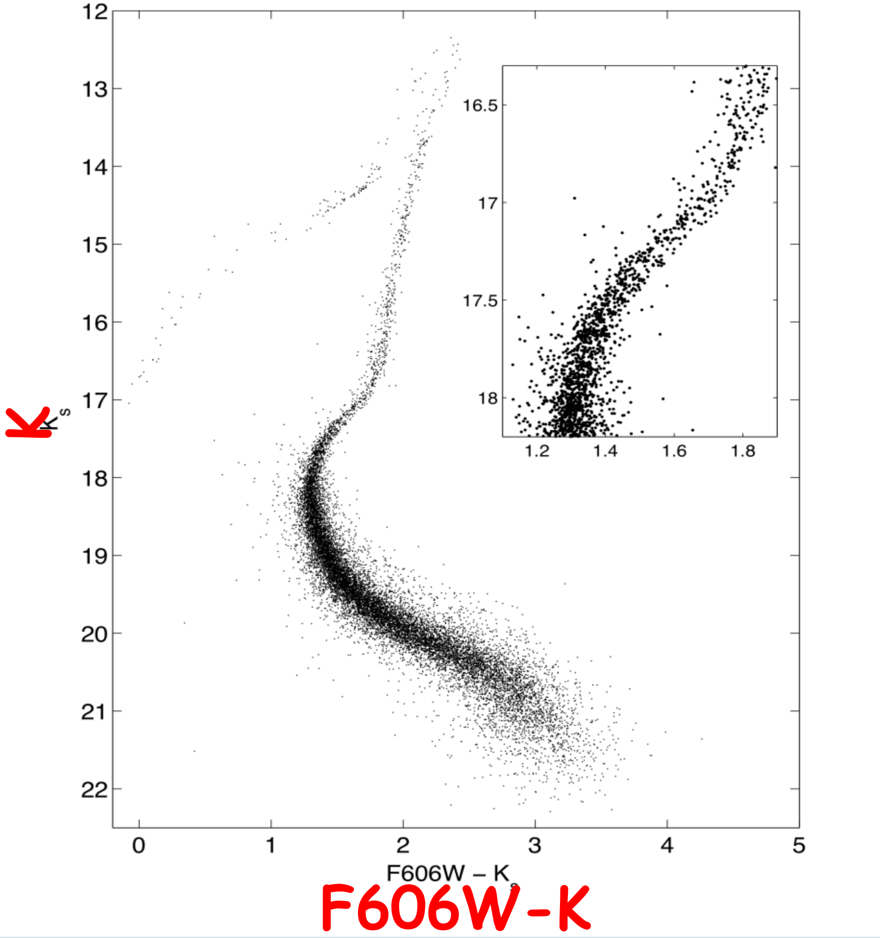
Bright (V≤13-15) NGS inside the scientific FoV → Tip Tilt correction

Sky coverage QUITE GOOD!!

… and more recently GEMs@Gemini

Rigaut + (2014)
Turri + (2015)

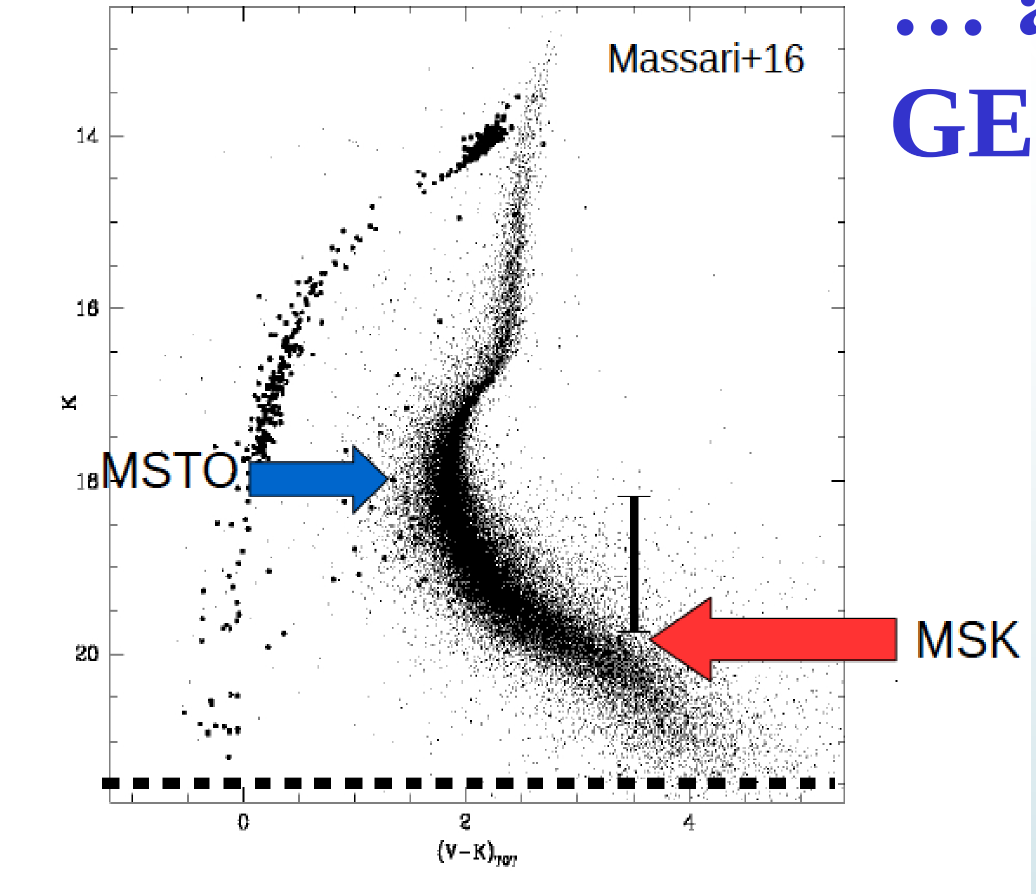
NGC1851 core



Two DMs + 5 Na LGS to deliver a FoV of 83" X 83"

Detection of multiple populations in the SGB confirming opt. findings

… and more recently GEMs@Gemini



age(MSK-MSTO)=10.9 Gyr±0.6(intrinsic)
±0.45(metallicity uncertainty)
+0.25 Gyr (He abundance)

age(MSTO)=11Gyr±2.7(intrinsic)
±0.05(metallicity uncertainty)

INDEPENDENT OBSERVATIONS

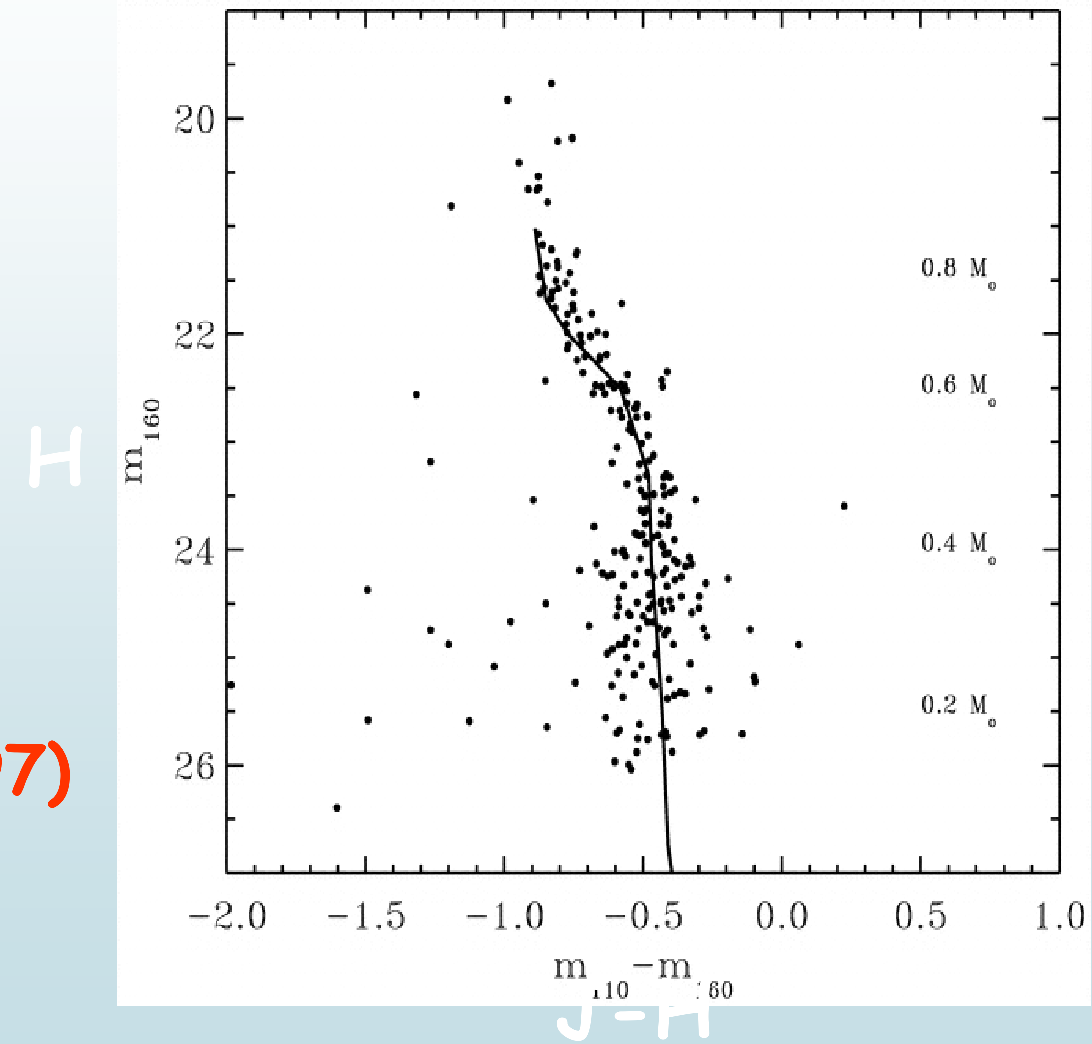
NICMOS J,H data for ω Cen

Pulone et al. (1998)

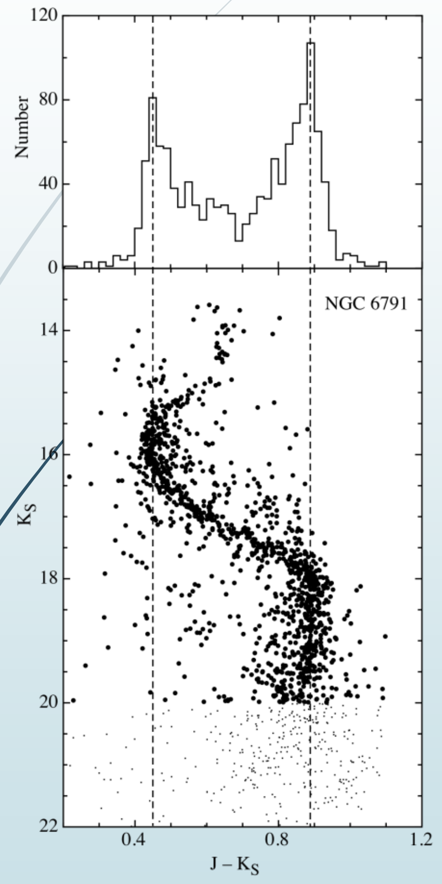
TO stars saturated
μ=13.45
E(B-V)=0.15

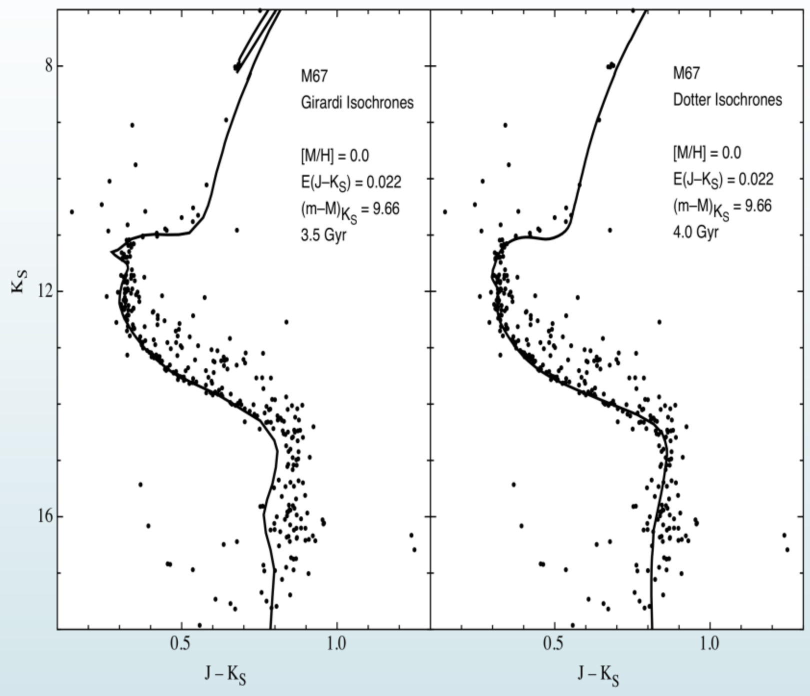
t=10 Gyr
[M/H]=-1.3
(Chabrier, Baraffe 1997)

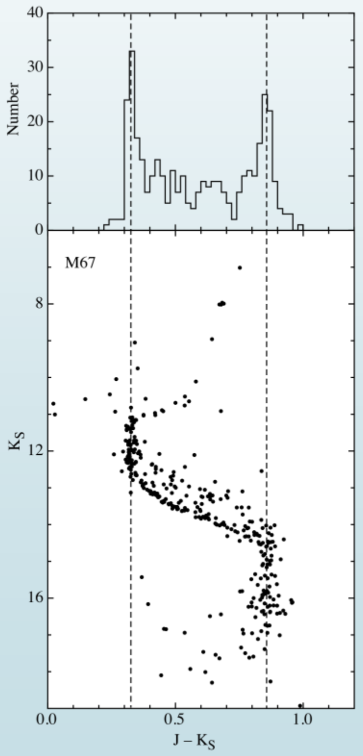
FOV=20”X20” pixel scale=0.075”



INDEPENDENT OBSERVATIONS

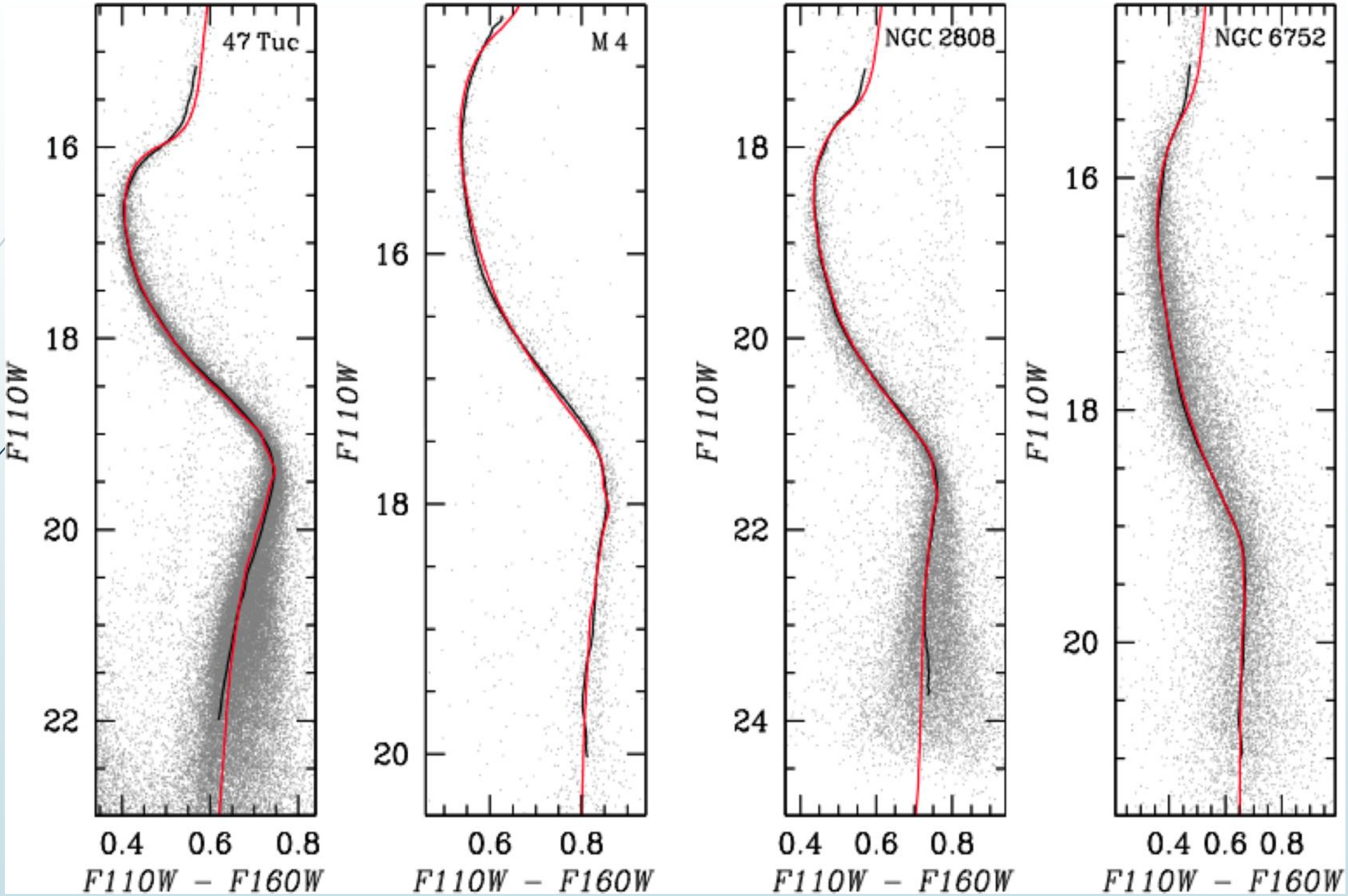






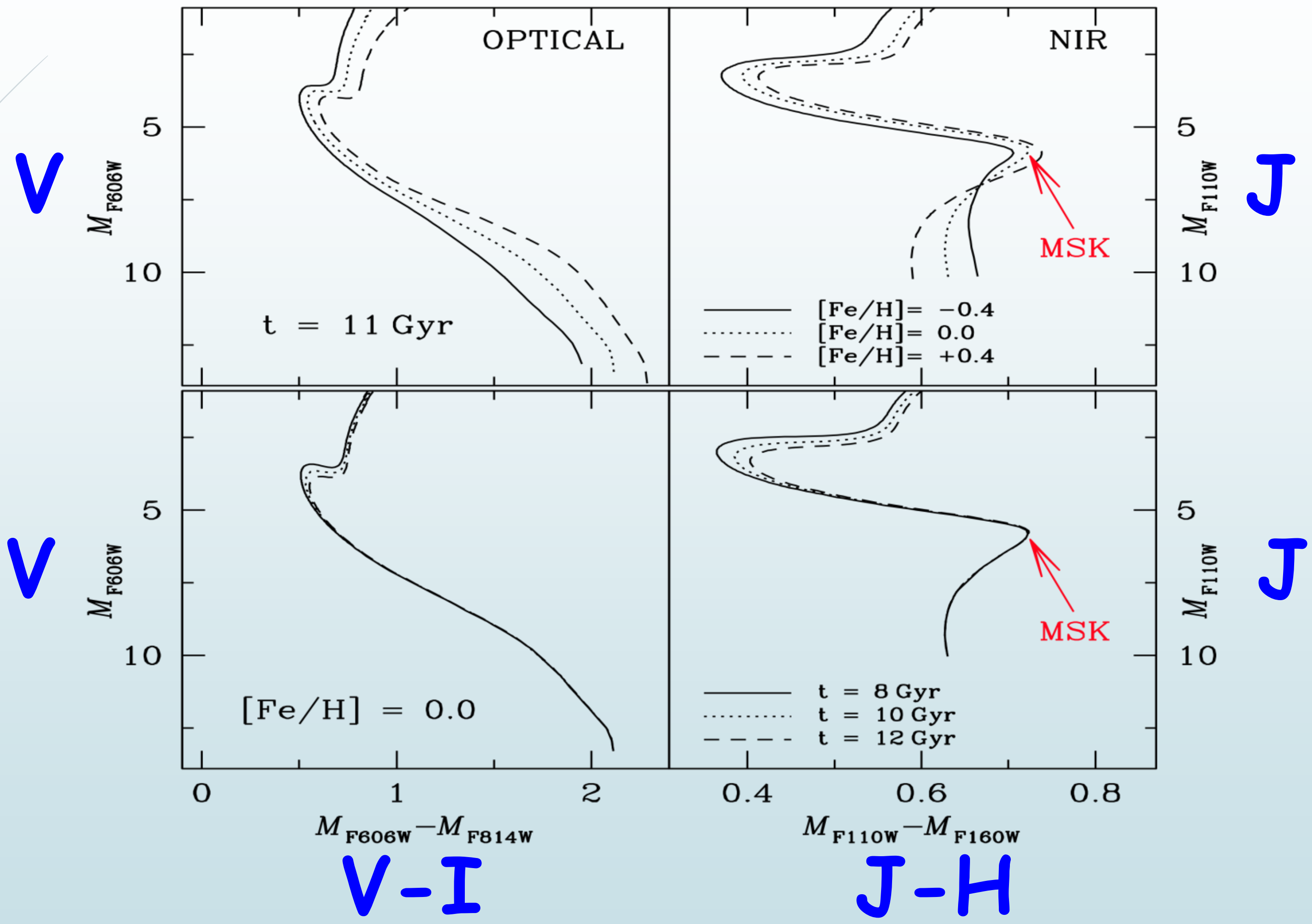
Sarajedini et al. (2009)

INDEPENDENT OBSERVATIONS



WFC3 at HST → Correnti et al. (2016)

WHY IT WORKS?

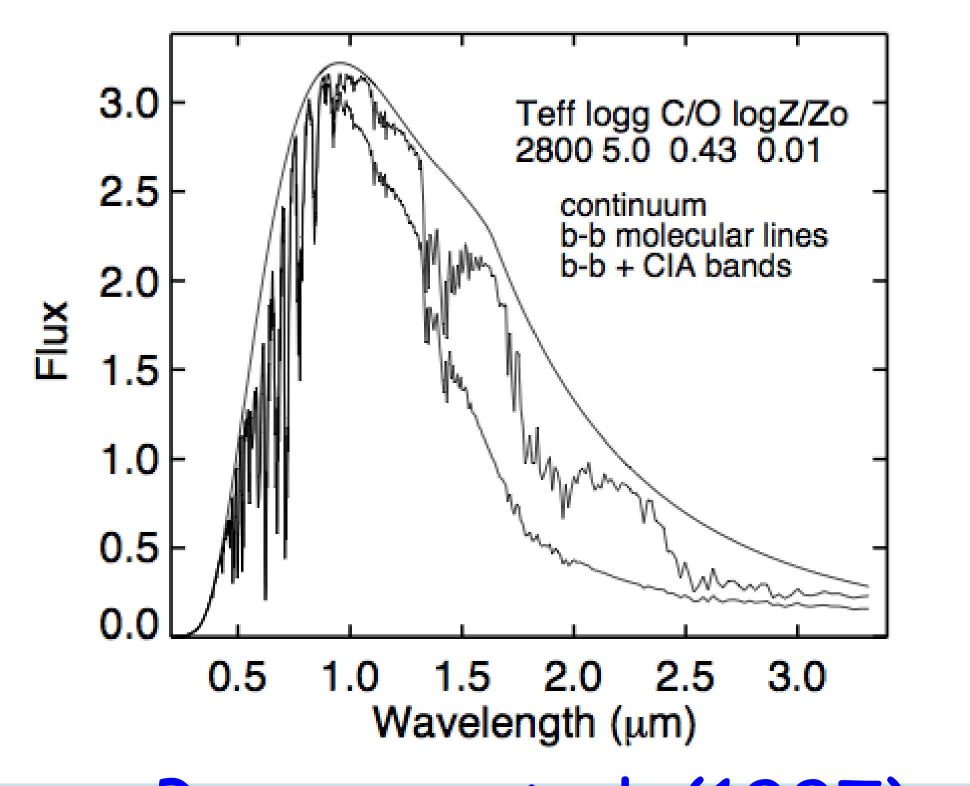


OPTICAL
NIR
V
V
J
J
M_{F606W}
M_{F110W}
5
10
t = 11 Gyr
MSK
[Fe/H]= −0.4
[Fe/H]= 0.0
[Fe/H]= +0.4
[Fe/H] = 0.0
t = 8 Gyr
t = 10 Gyr
t = 12 Gyr
0
1
2
0.4
0.6
0.8
$M_{F606W} - M_{F814W}$
$M_{F110W} - M_{F160W}$
V-I
J-H

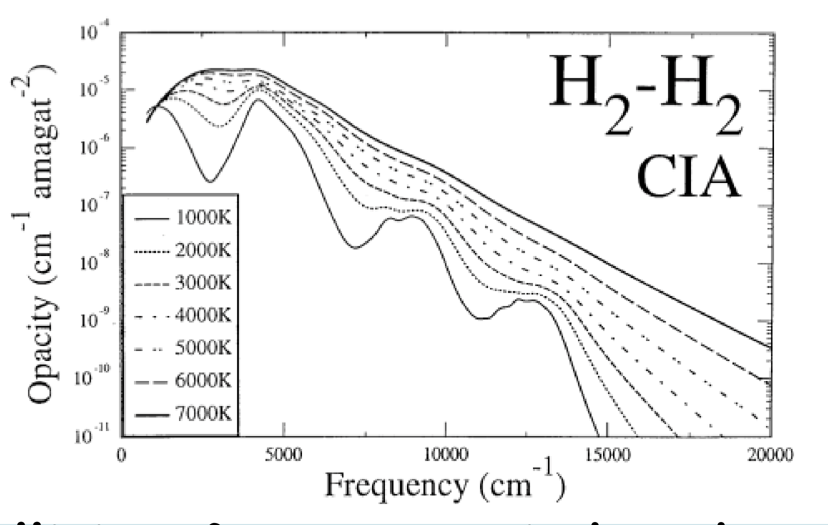
Who is the culprit??

Formation of H_2 → temp. gradient → in optical MS bending
in NIR Collisional Induced Absorption (H_2-H_2 & H_2-He) MS knee

Homonuclear molecules (such as H_2 are non-polar) do not absorb/emit dipole radiation, but during transient interactions a temporary dipole moment is induced

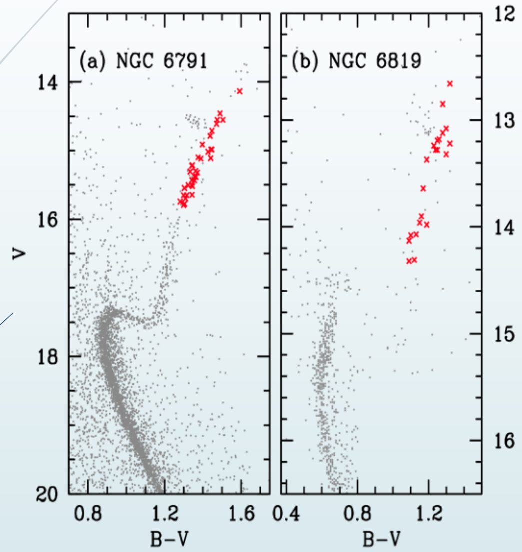


Borysow et al. (1997)

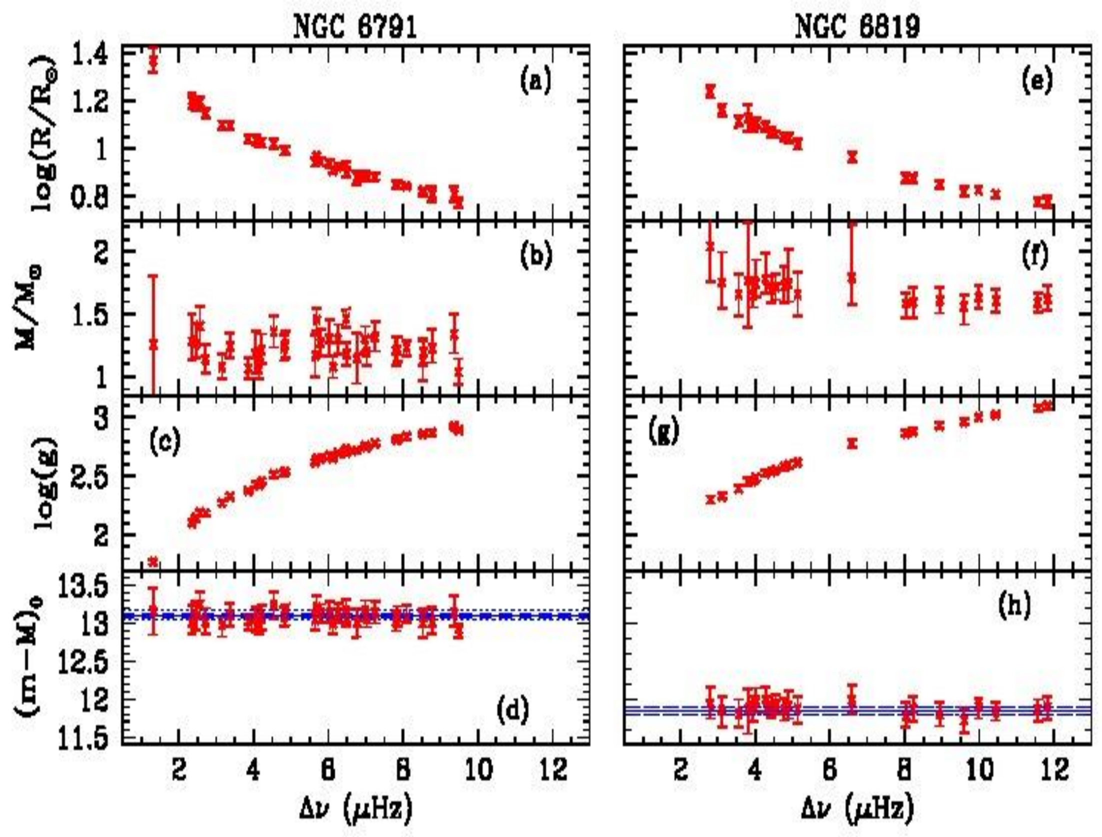


Collision & pressure induced opacities were suggested by Herzberg (1952) to explain a band observed in Uranus & Neptune by Kuiper!!

Let's follow different Paths e.g. Asteroseismology



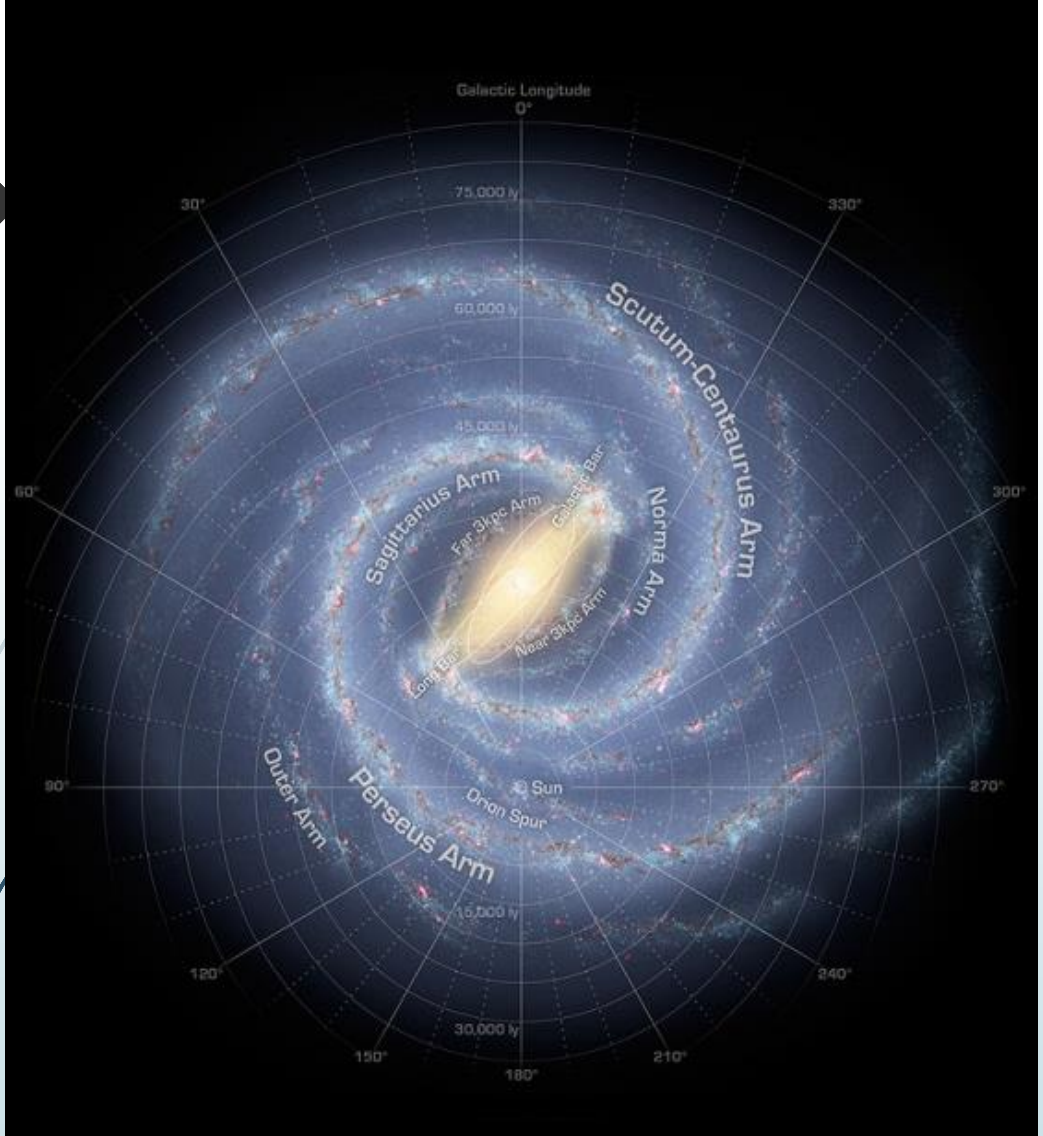
Kepler observations
Basu et al. (2011)



Δν, νmax

Large separation → ρ
Frequency of max power
No direct dependence on age → it depends on models

Precision of the order 10-20%



Annotated Roadmap to the Milky Way
(artist's concept)

NASA / JPL-Caltech / R. Hurt (SSC-Caltech) ssc2008-10b

Galaxy inventory:

Total mass 8x10^11Mo
(Vera-Ciro + 2013)

Disk → M~3x 10^10 Mo

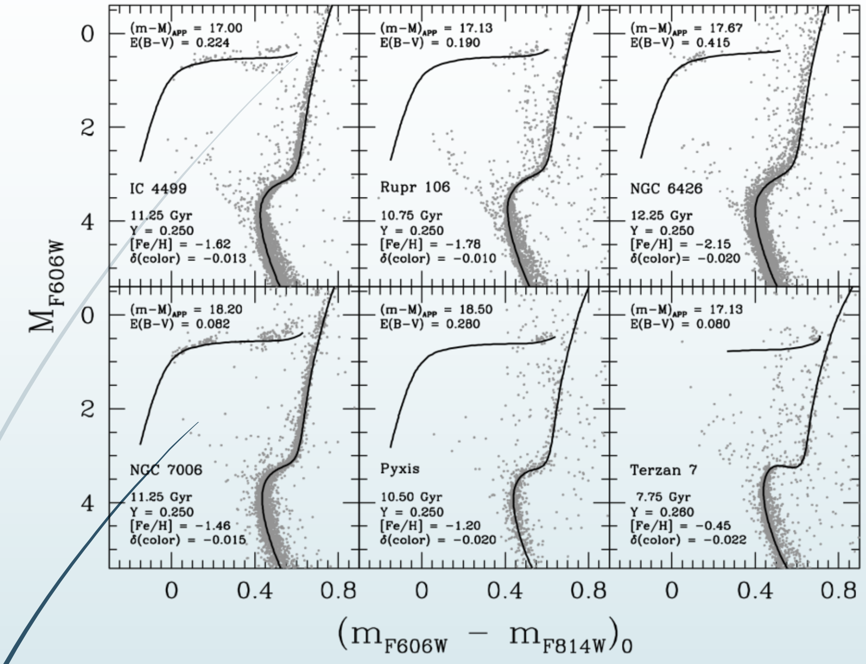
Bulge → M~1x 10^10 Mo
(McMillan + 2011)

Halo→ M~1±0.4 x10^9 Mo
(Deason + 2011)

Ngc(disk)/Ngc(halo)=20-30%

Total mass 10^7-10^8 Mo
A few percents

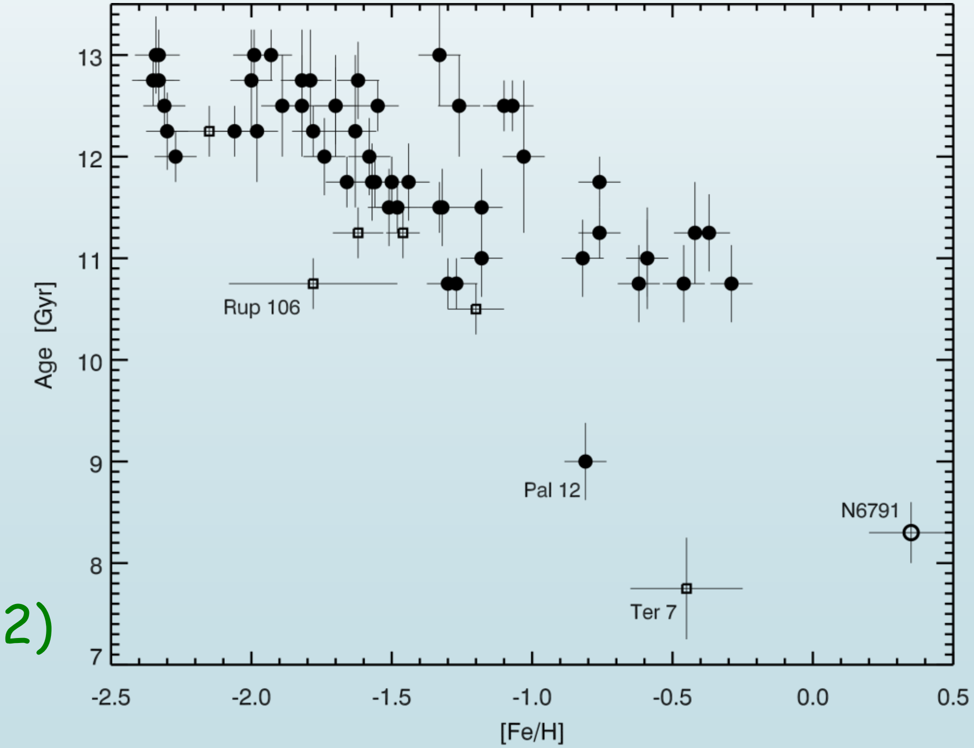
GCs as tracers of the Halo



Leaman + (2013): 61 GGCs

Absolute & relative ages

Two AMRs for [Fe/H]≥-1.8

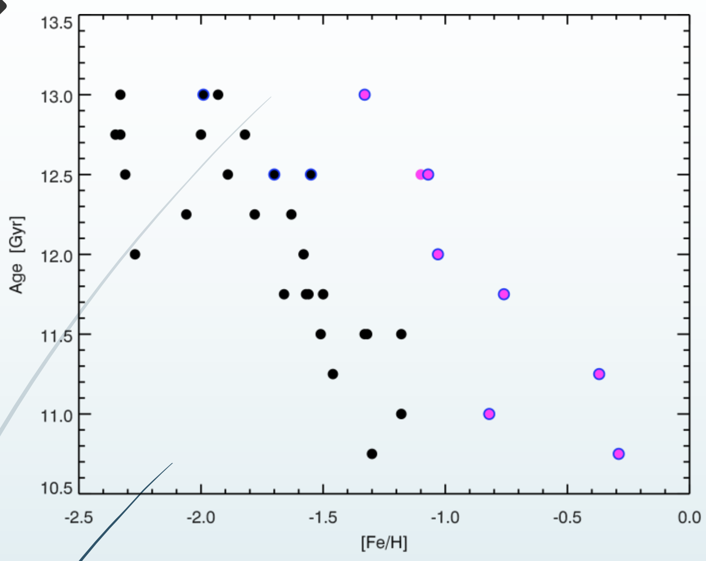


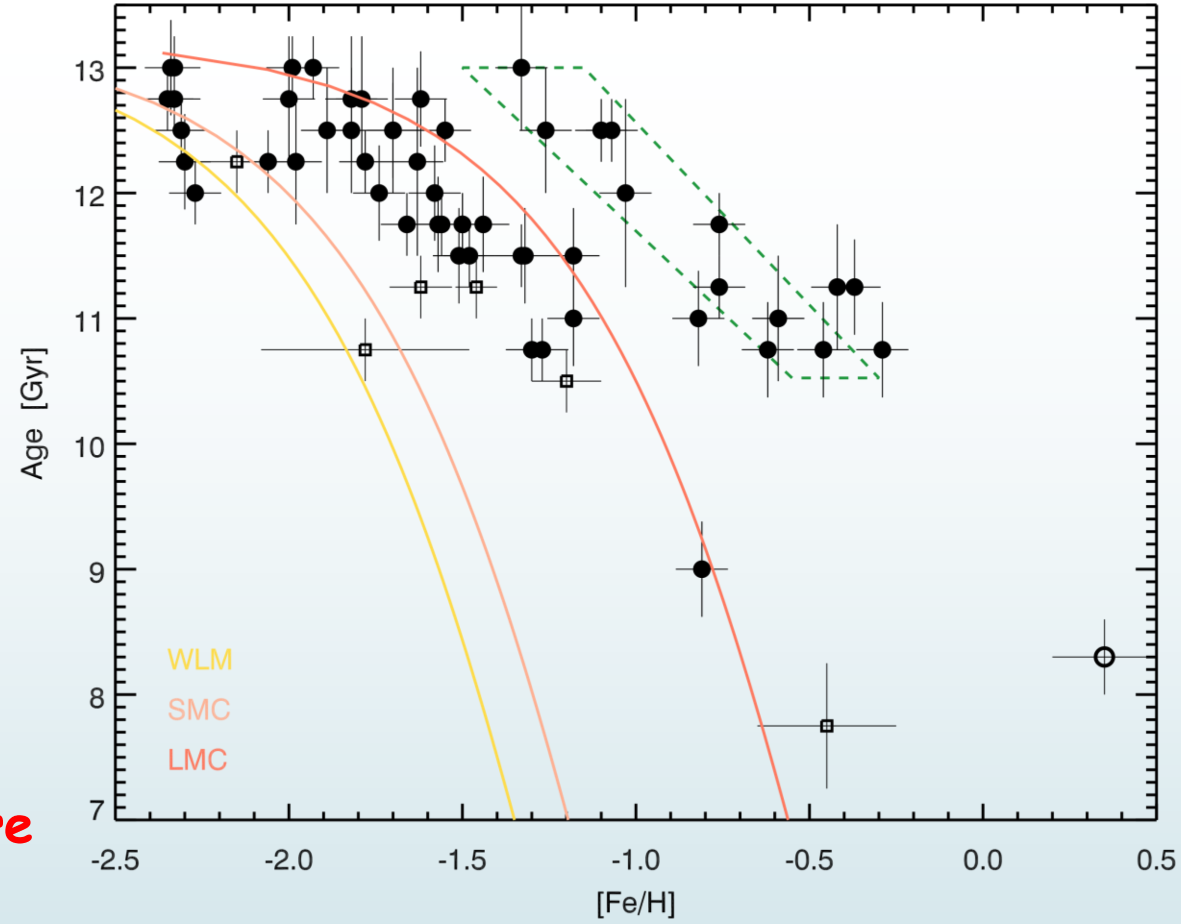
1/3 of the sample is, at fixed age, 0.6 dex more metal-rich

Eggen, Lynden-Bell & Sandage (1962)

Searle & Zinn (1978)

Leaman + (2013)





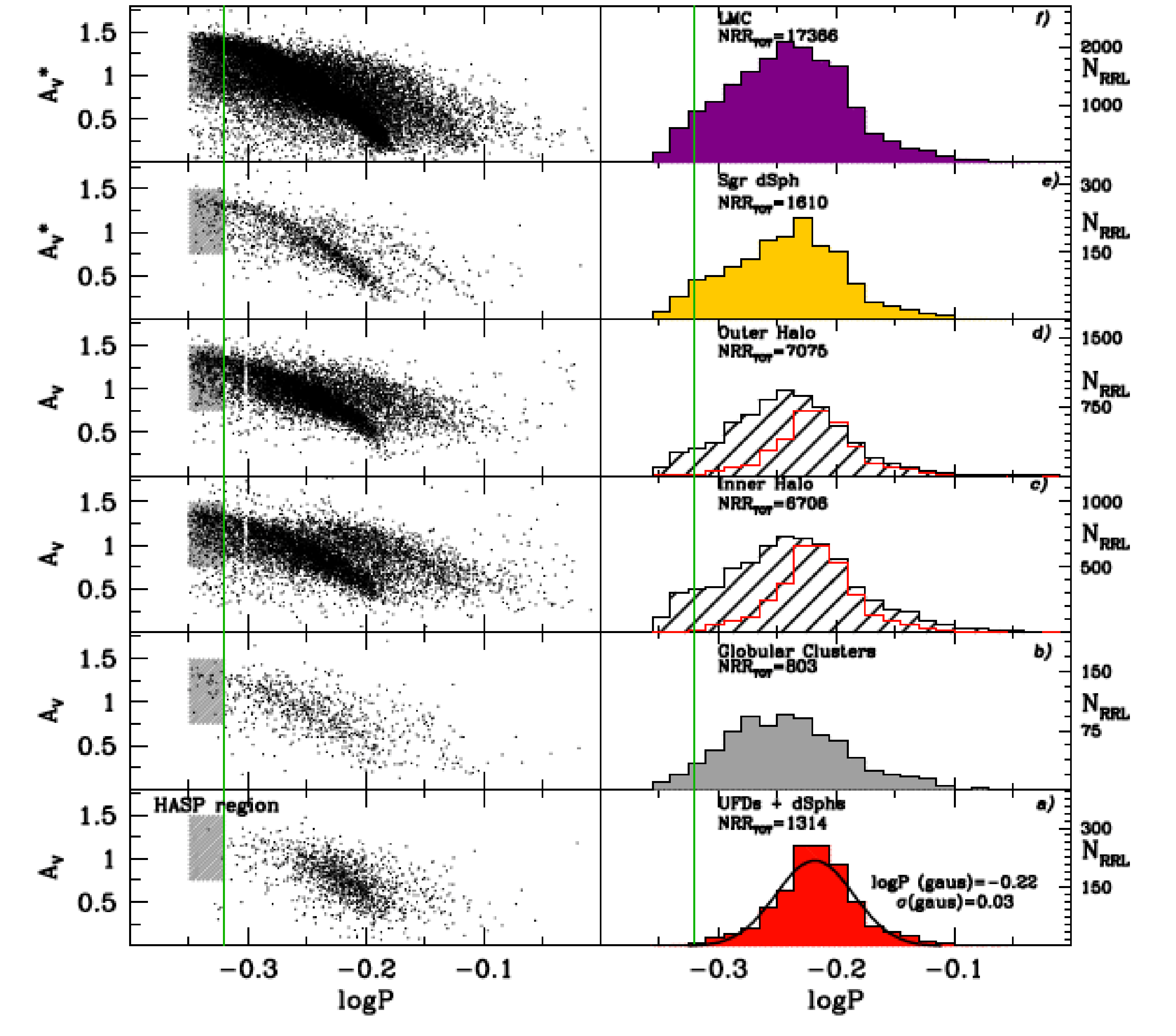
Their orbital properties are typical of disk/bulge GCs.

The bulk of the M.-R. sequence formed in the Galactic disk

A significant fraction of the M.-P. ones formed in dwarf galaxies that have been accreted by the MW.

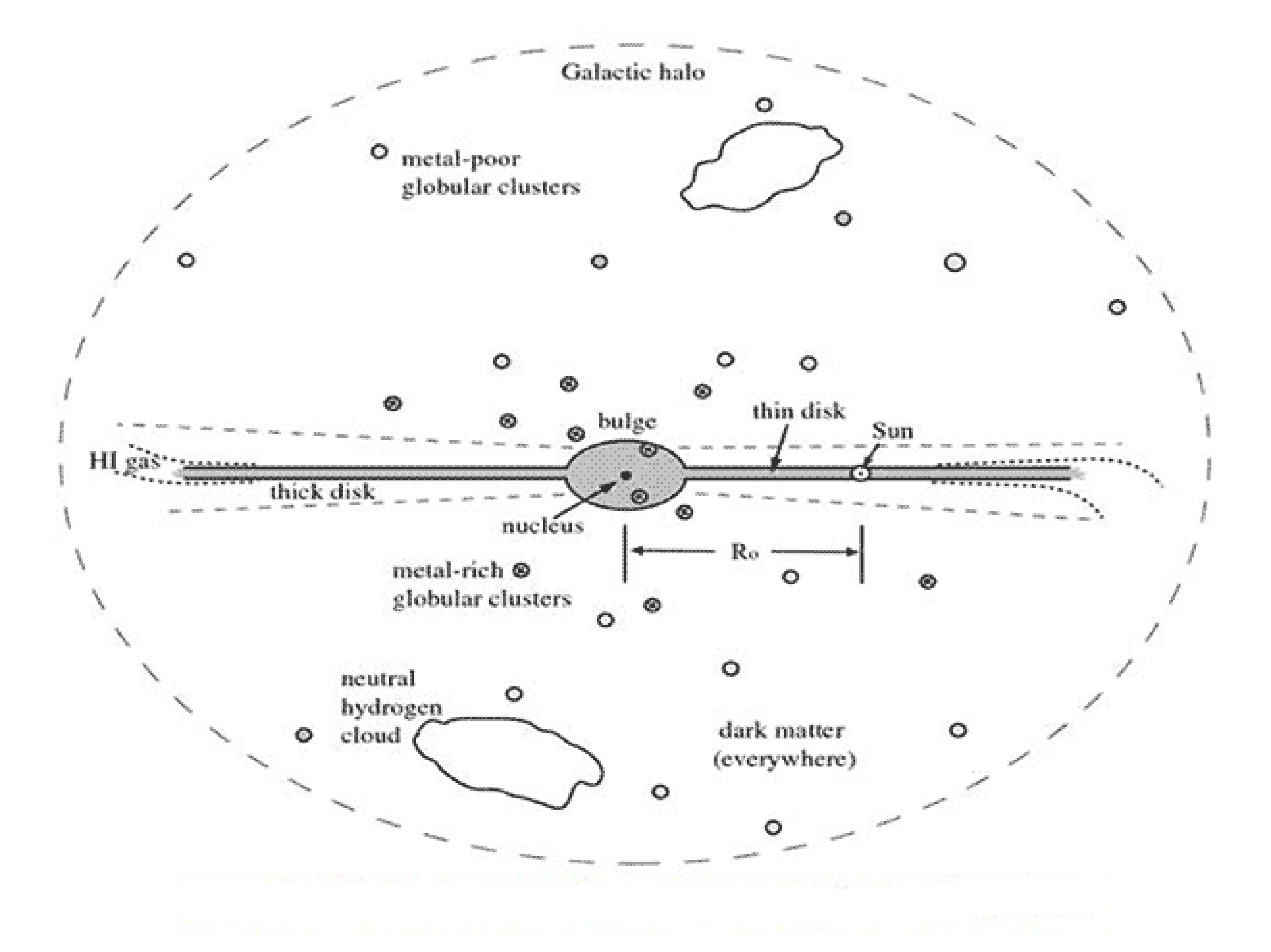
A New Spin!

We support the major merging scenario!!

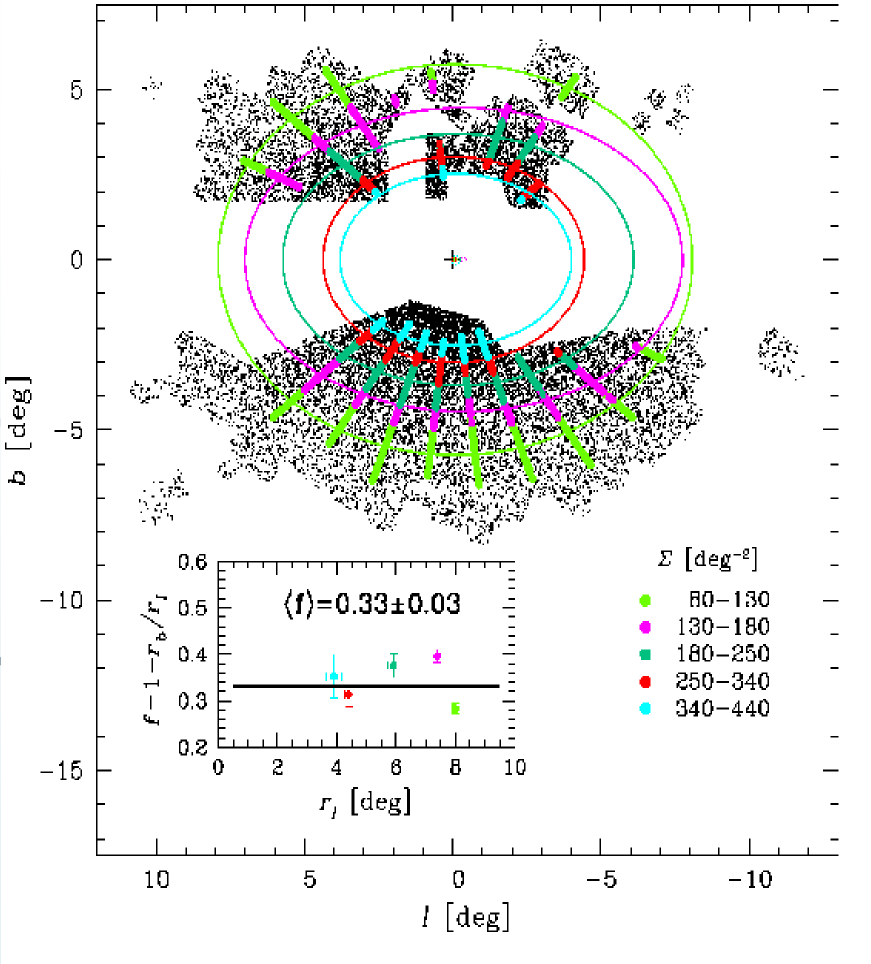


Fiorentino et al. (2014)

The Galactic Bulge

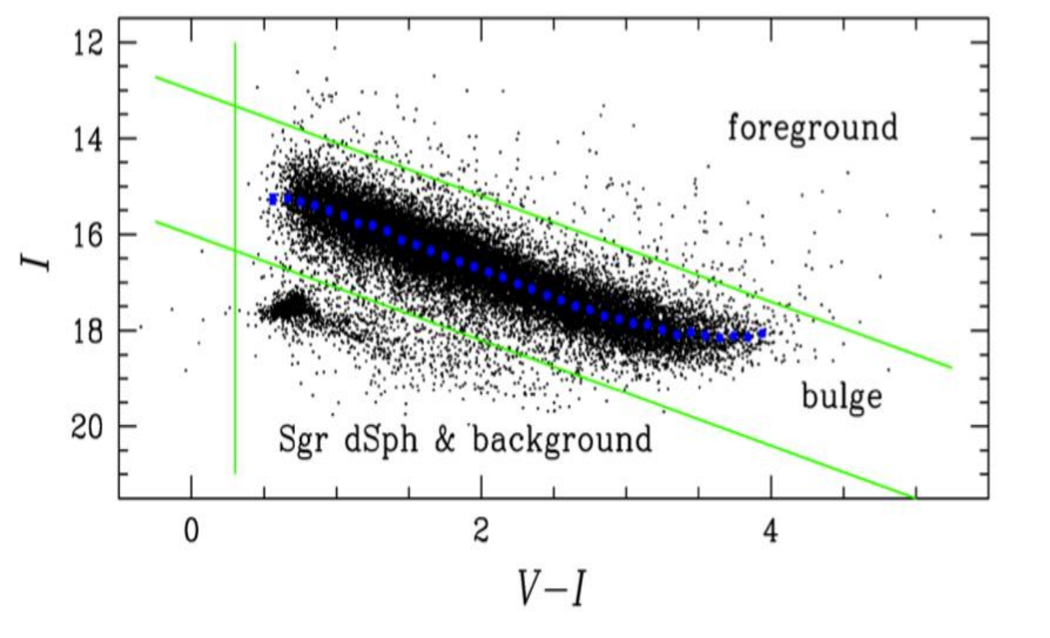


Unveiling the inner bulge



~25,000 RR Lyrae by OGLE IV

Census far from being complete!



Pietrukowicz + (2015)

VVV → JHK~16-18

Dust under the carpet

Age metallicity relation only relies on bulge GCs

Reddening law: low & high-reddening regions (BW, …) inner vs outer bulge (Valenti/Zoccali + 2015/2016)

Proper motion cleaning
Gaia Legacy

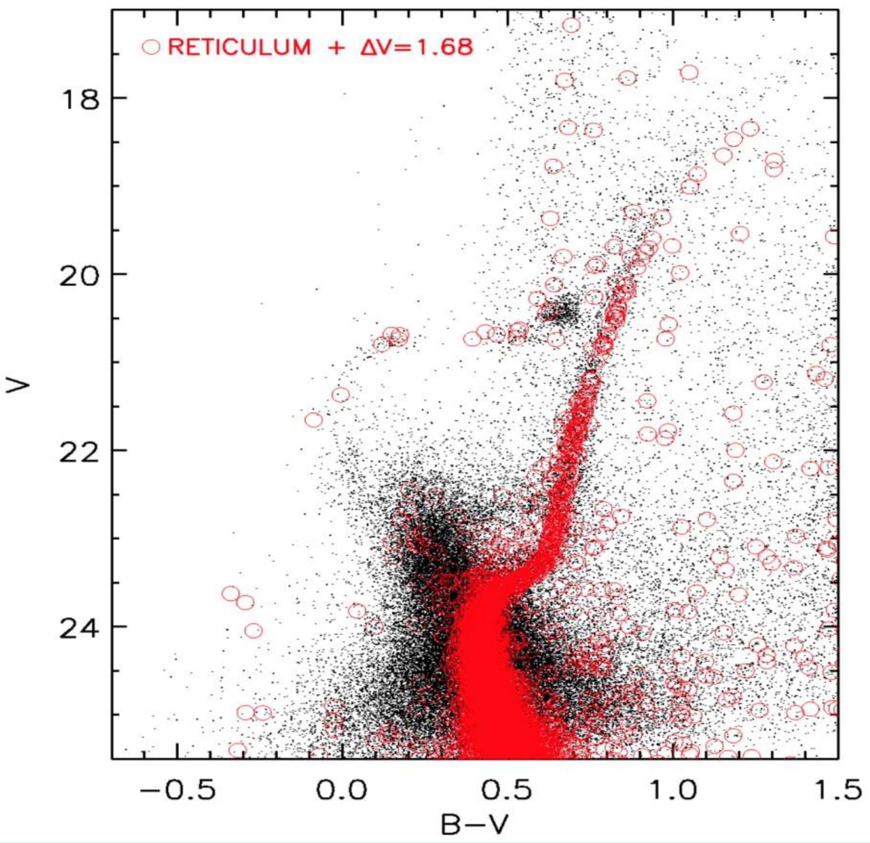
Chemical distribution

→ Fe abundance (gradients?)

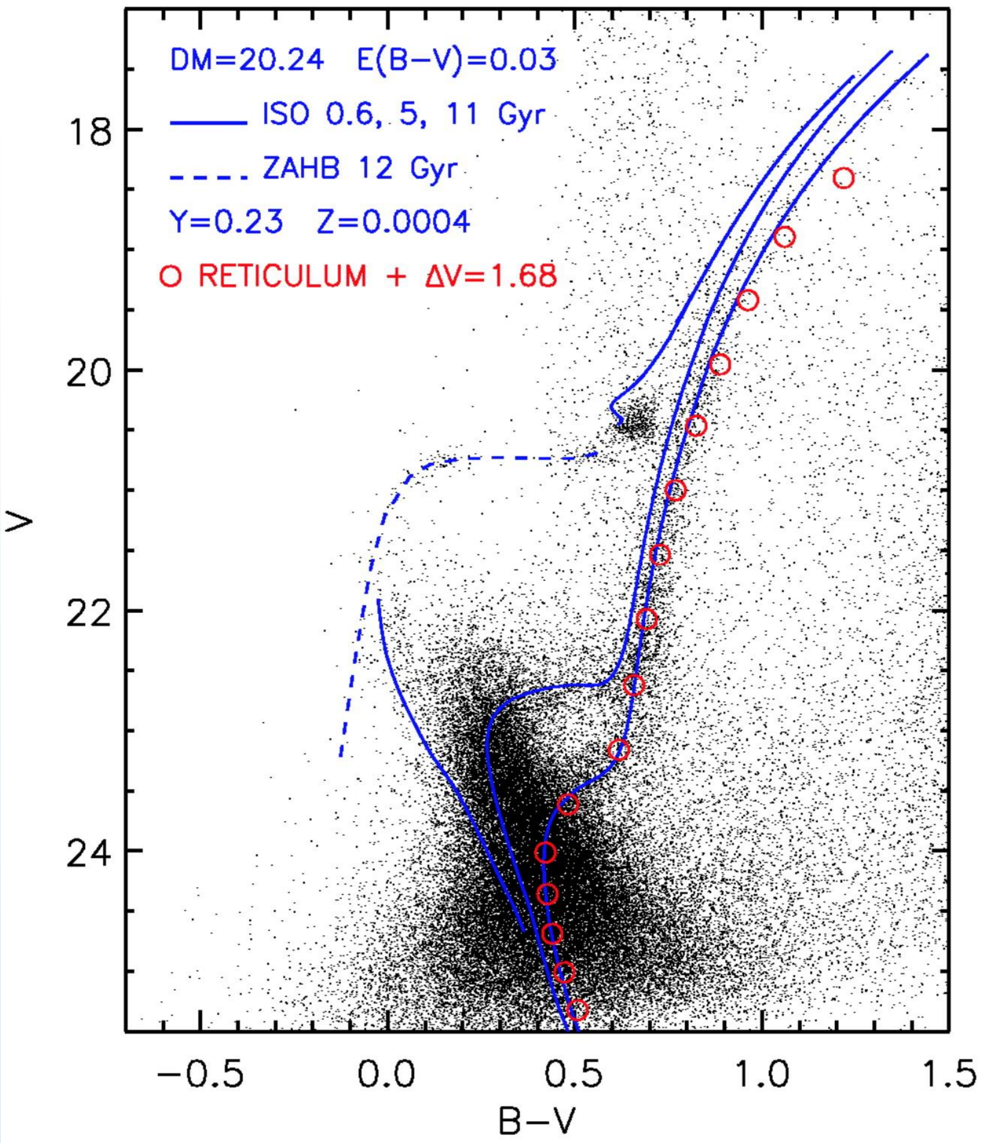
→ α-element abundances (gradients?)

→ Galactic center

Carina dSph



The age-metallicity degeneracy



A clear separation
old & intermediate-age

Monelli+ (2003)

Carina dSph: metallicity distribution
Old & intermediate-age stars

[Fe/H]

μ(int) =-1.74±0.38±0.20

μ(old)=-2.13±0.06±0.28

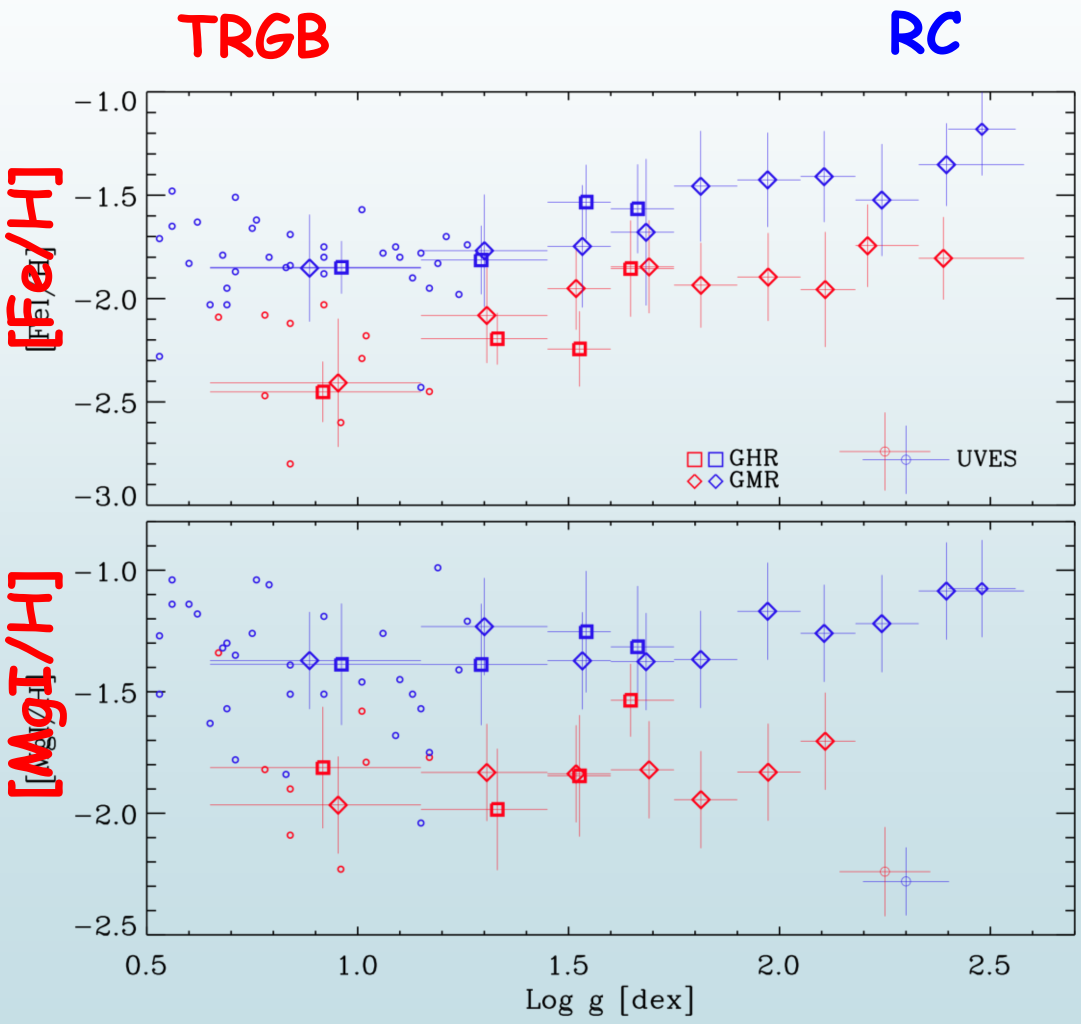
They differ 75% c.l.

[Mg/H]

μ(int) =-1.37±0.04±0.27

μ(old)=-1.77±0.08±0.36

They differ 83% c.l.



Fabrizio + 2015

GLOBAL GROWTH

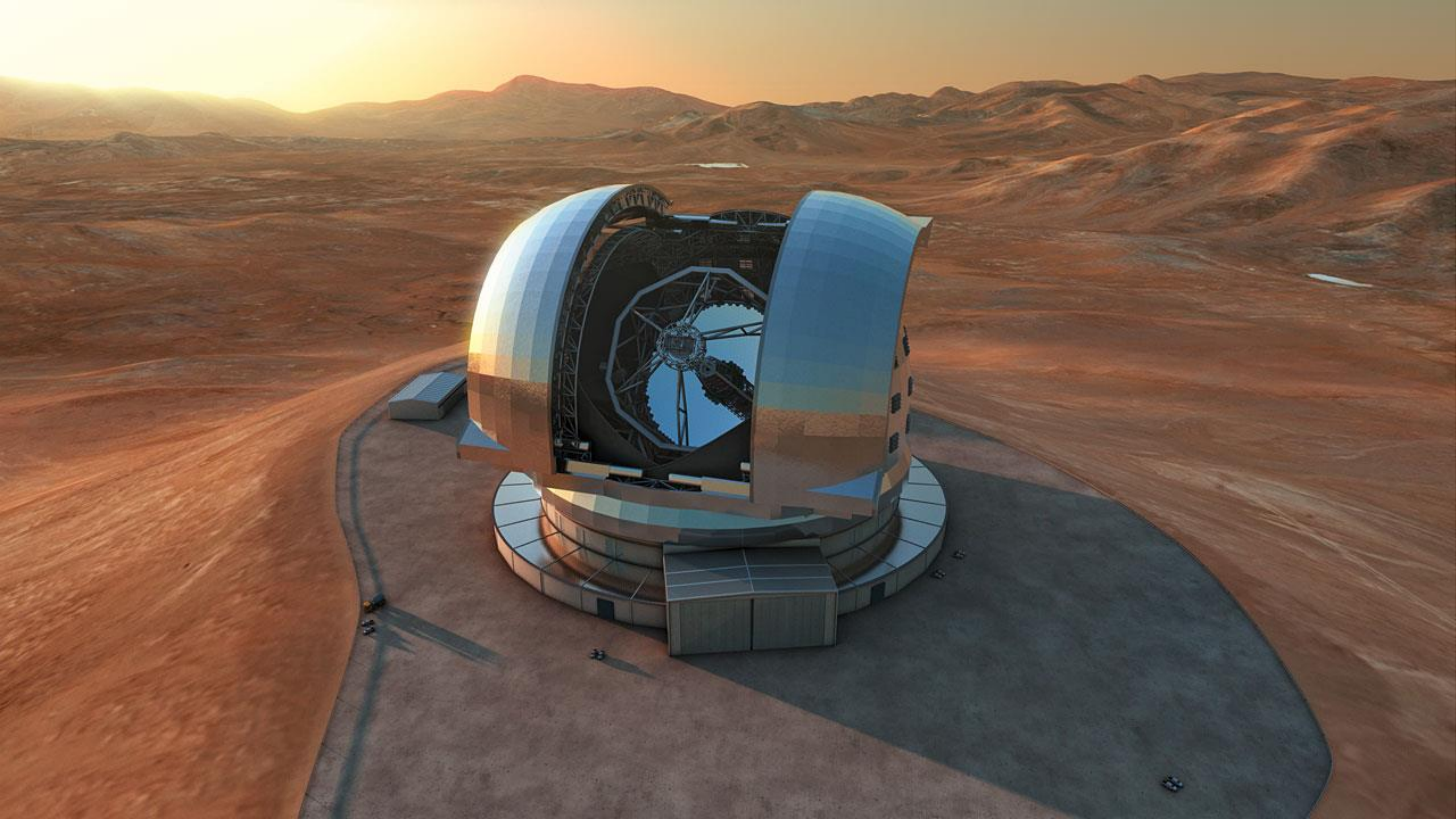
Evolutionary, Pulsation, Atmosphere models → 1D vs 3D

Opacity, EOS, line identifications, molecules (NIR)

Multiband Asymmetric PSF

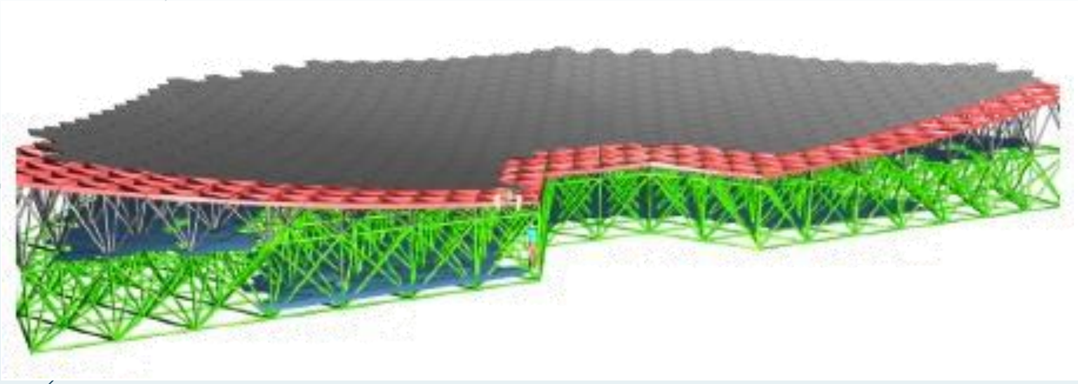
Integral field spectroscopy

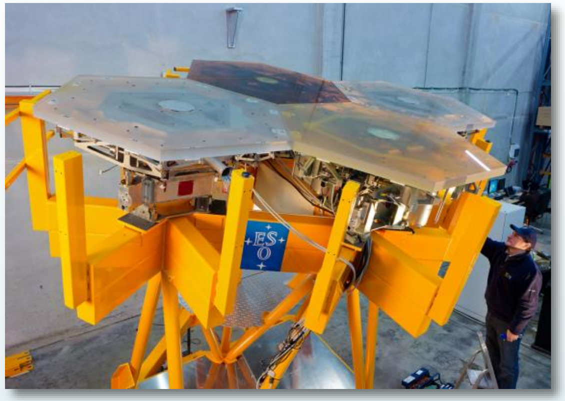
Gaia + LSST

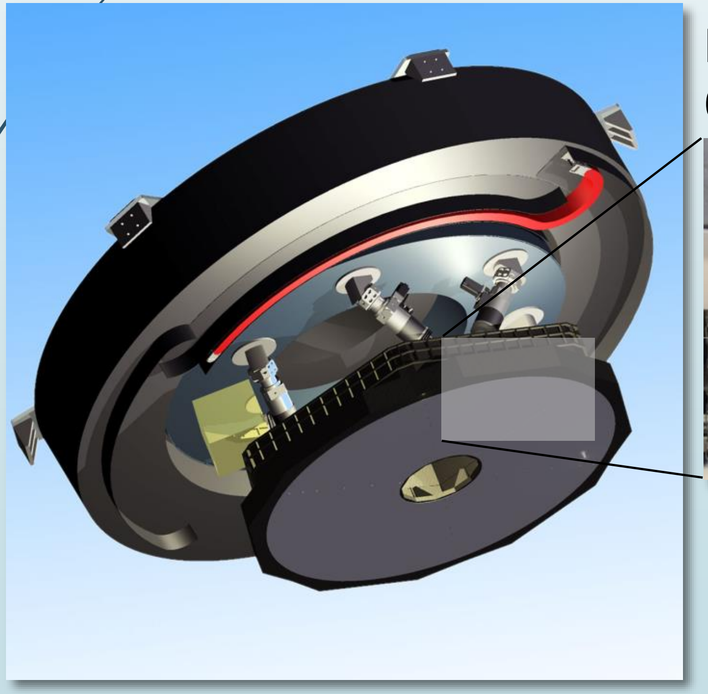


E-ELT in a nutshell: The Mirrors

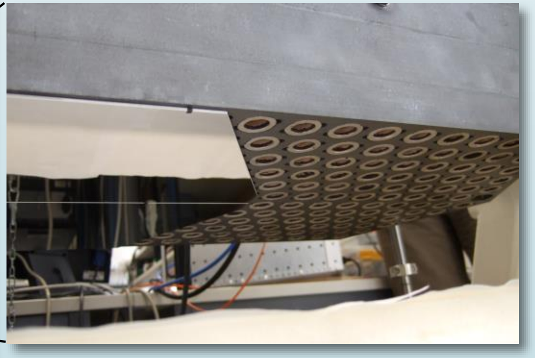
M1: 39.3 m, 798 hexagonal segments of 1.45 m tip-to-tip: 978 m² collecting area





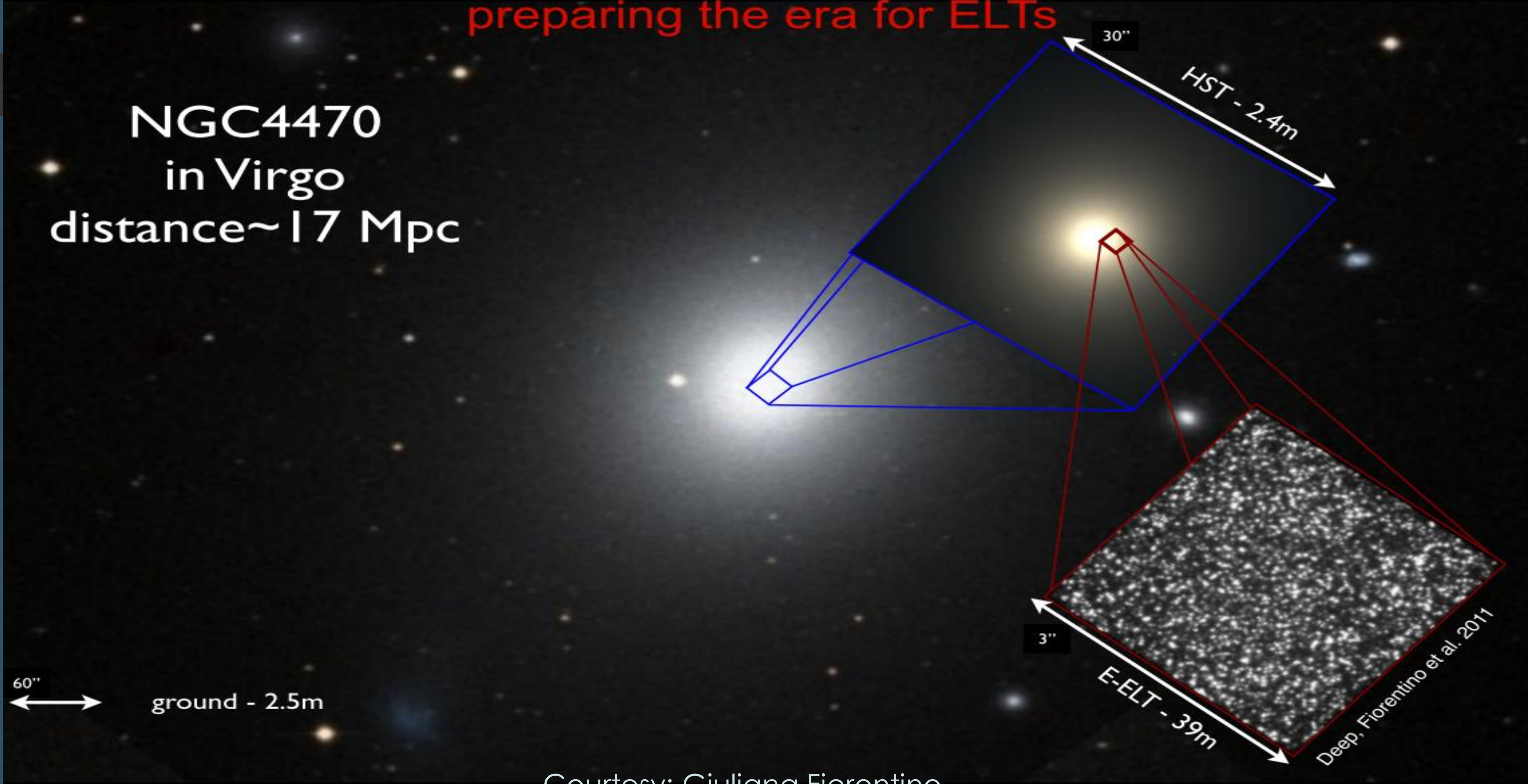


M4: 2.4 m, flat, adaptive
6000 to 8000 actuators



M5: 2.6 x 2.1 m, flat,
provides tip-tilt correction

preparing the era for ELTs



Courtesy: Giuliana Fiorentino

First Generation E-ELT Instruments

First Light

E-ELT -- CAM (MICADO): R. Davies

E-ELT -- IFS (HARMONI): N. Thatte

E-ELT – MIR: L, M, N: B. Brandl

MAORY (AO module) E. Diolaiti

4) E-ELT – HIRES (Optical – NIR)

5) E-ELT – MOS: Fibers + IFUs (optical, NIR)

CONCLUSIONS

→ Facing a golden age for Stellar Astrophysics:
The near future appears very promising
Gaia + 8-10m AOs ground-based + ELTs

→ A new spin on uncertainties affecting absolute ages of stellar systems

→Astroseismic age dating