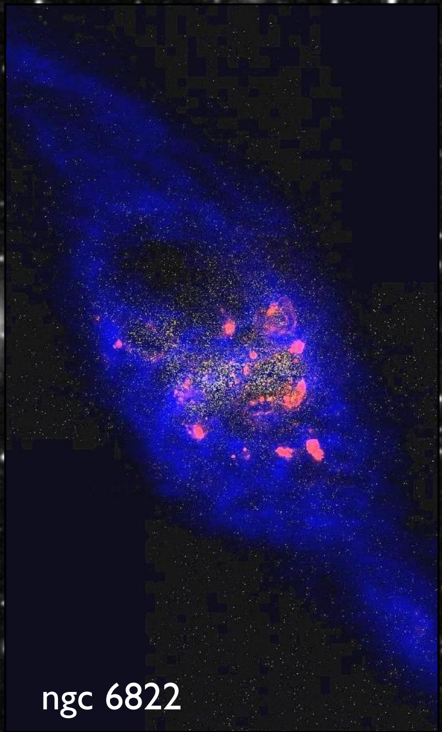
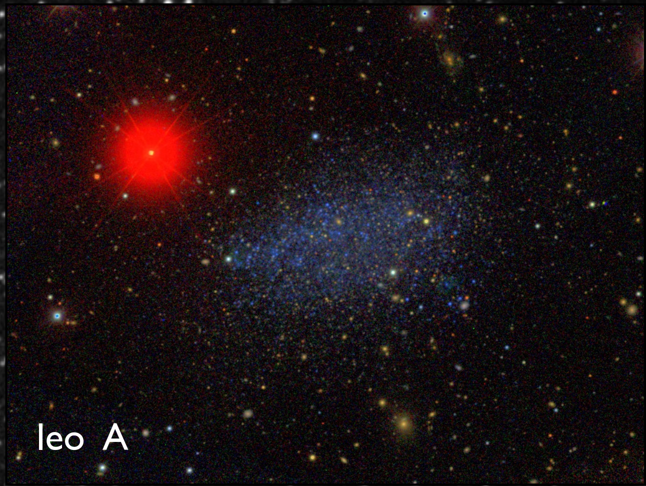
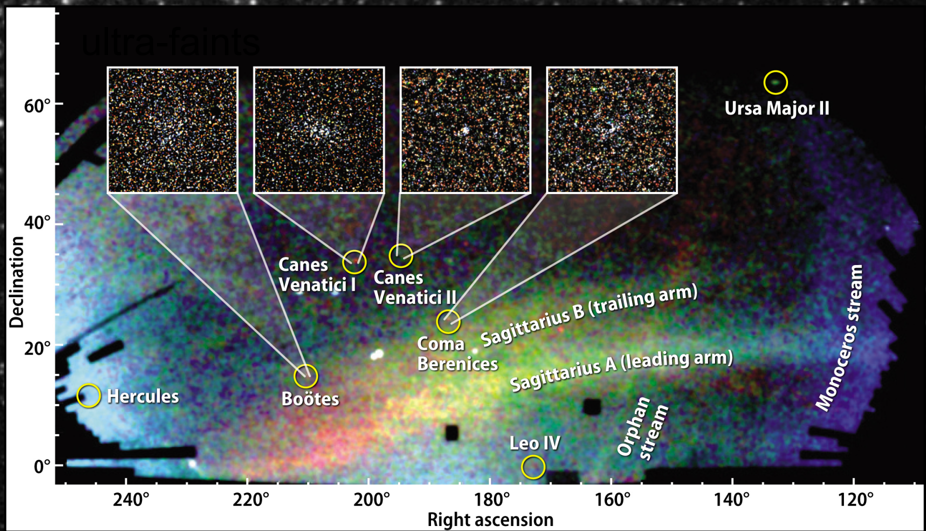
Chemical Evolution of the Milky Way and Local Group Galaxies

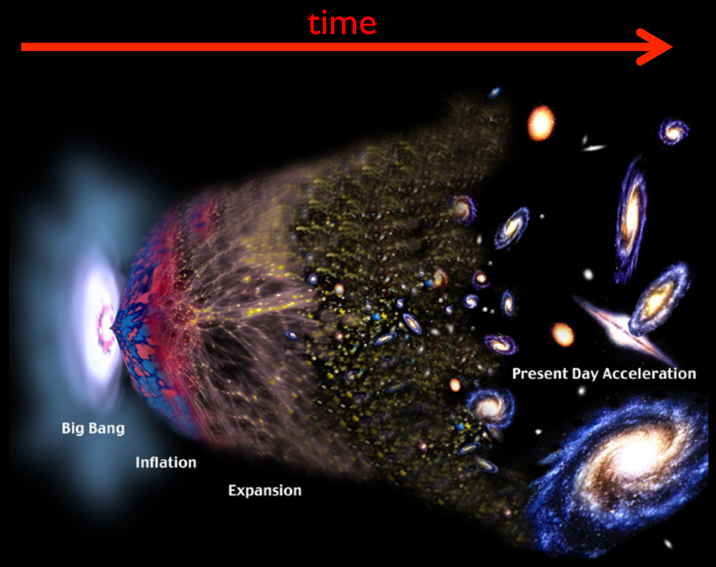






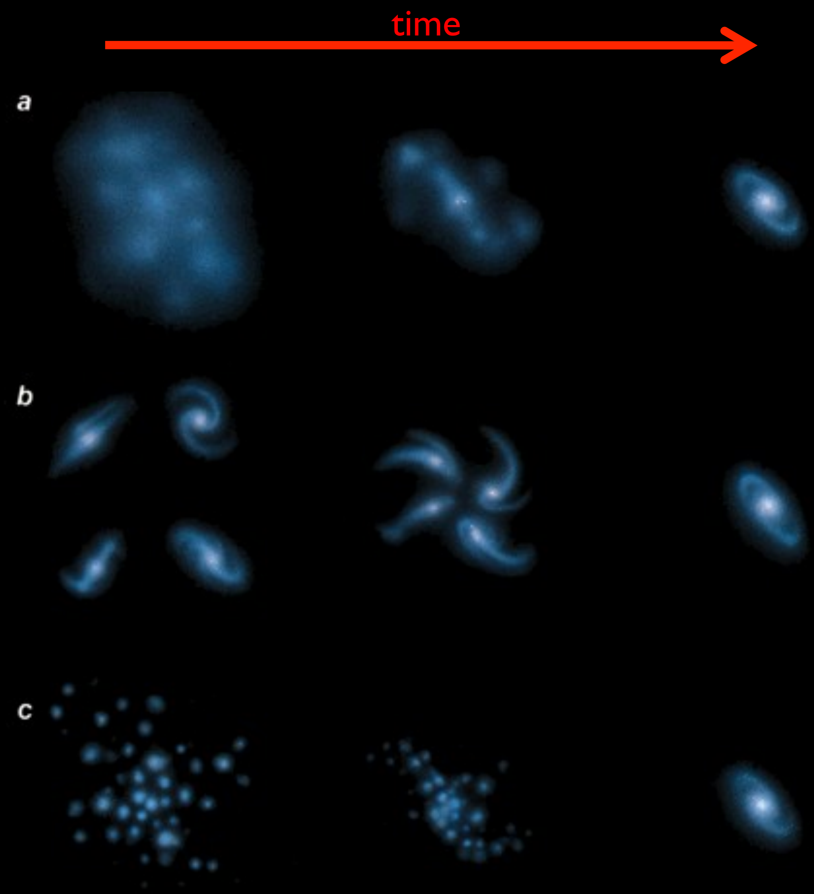
Eline Tolstoy
Kapteyn Institute
University of Groningen
the Netherlands

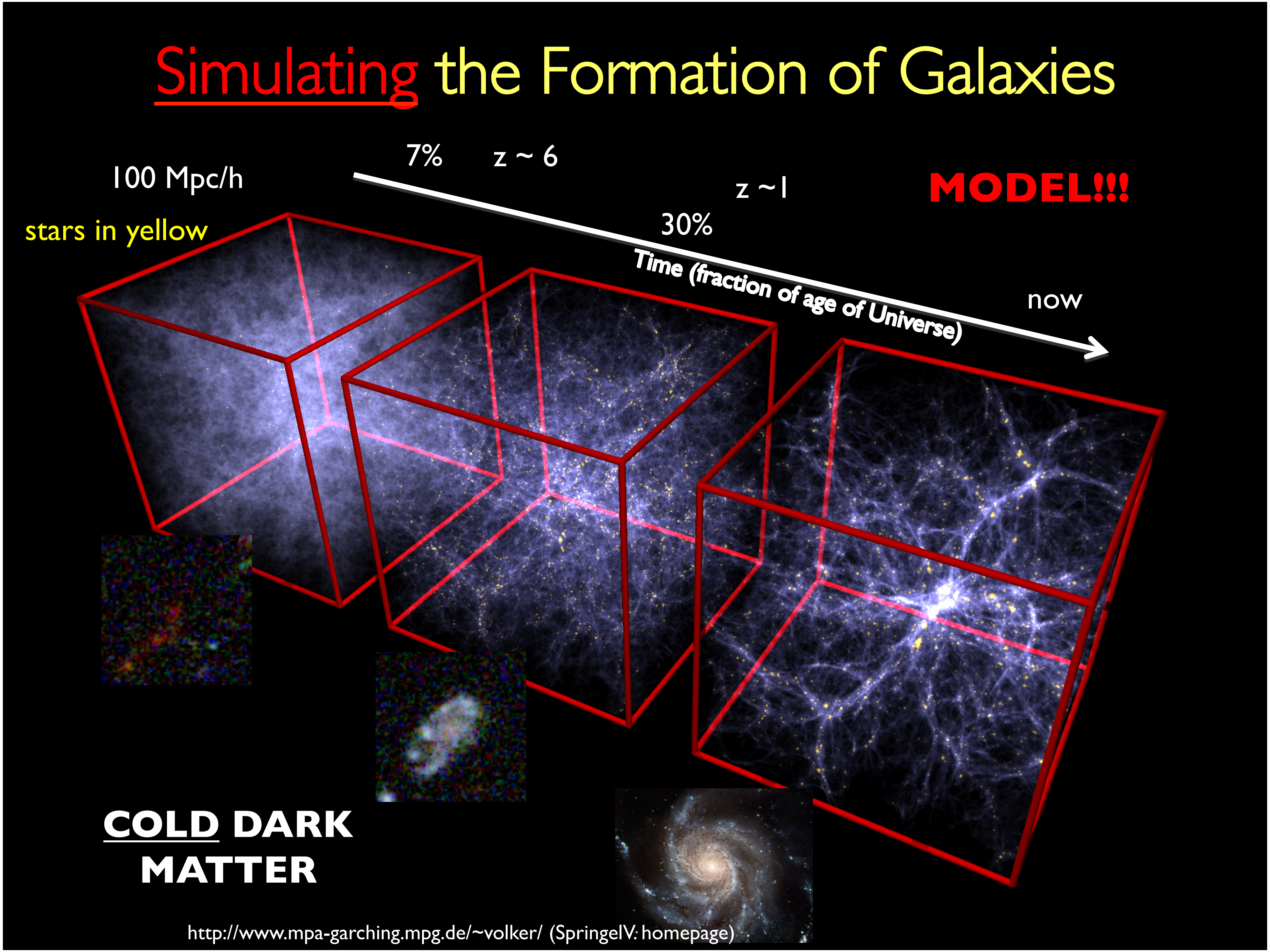
The History of the Universe



In the beginning there was… Hydrogen, Helium and a little bit of Lithium plus a lot of other strange things… like dark matter… the Universe was very smooth & uniform

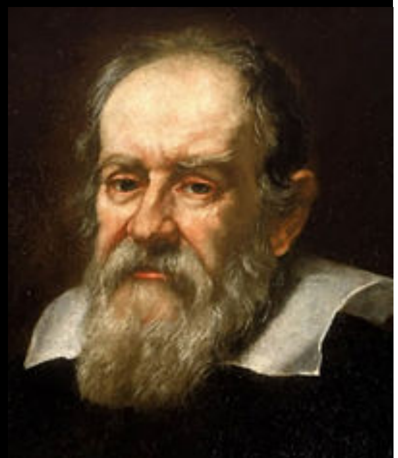
… we see today a complex and dynamic universe full of galaxies and stars – how did this happen?




Simulating the Formation of Galaxies
100 Mpc/h
stars in yellow
7%
z ~ 6
z ~ 1
30%
MODEL!!!
Time (fraction of age of Universe)
now
COLD DARK MATTER
http://www.mpa-garching.mpg.de/~volker/ (SpringelV: homepage)

The Nearest Galaxy...

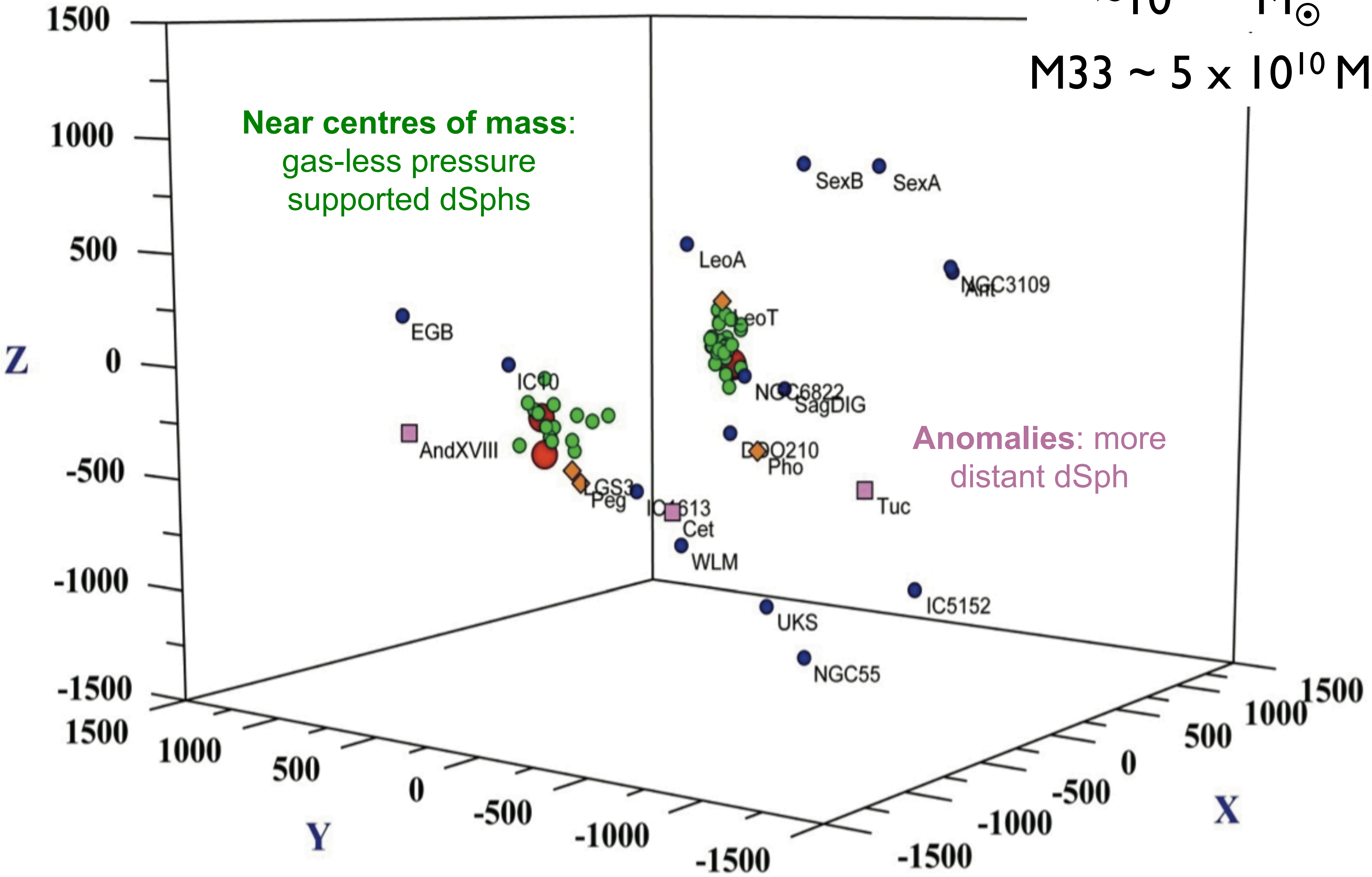
...congeries
stellularum...



Galileo Galilei (1609)

The Local Group

M31, MW
$\sim 10^{11-12} M_\odot$
M33 ~ 5 x $10^{10} M_\odot$



Outer regions: dominated by gas rich quiescently evolving dwarf irregulars

Mateo 2008, Garching workshop

Milky Way - Halo

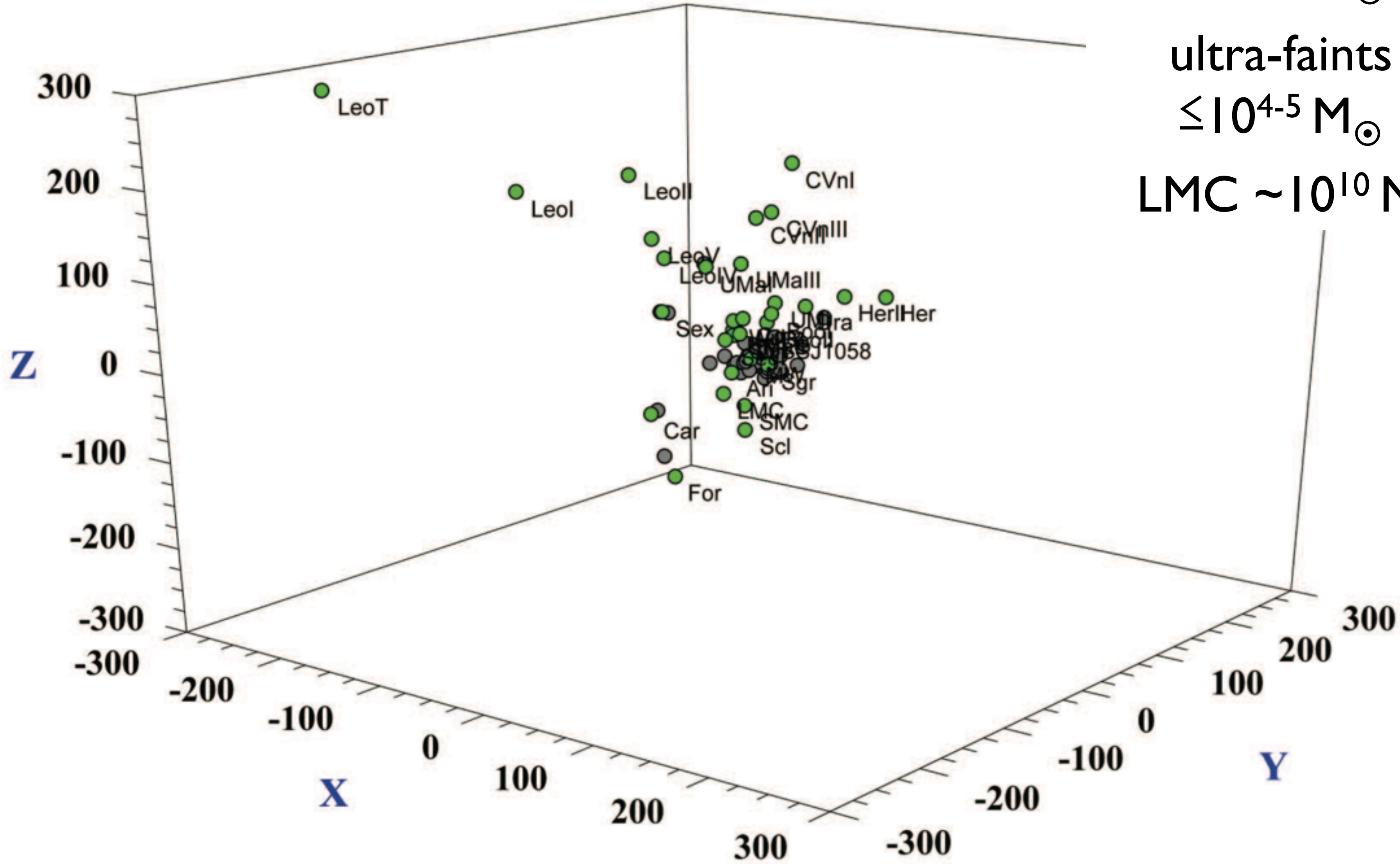
dwarfs

$\sim 10^{8\text{-}9}\, M_\odot$

ultra-faints

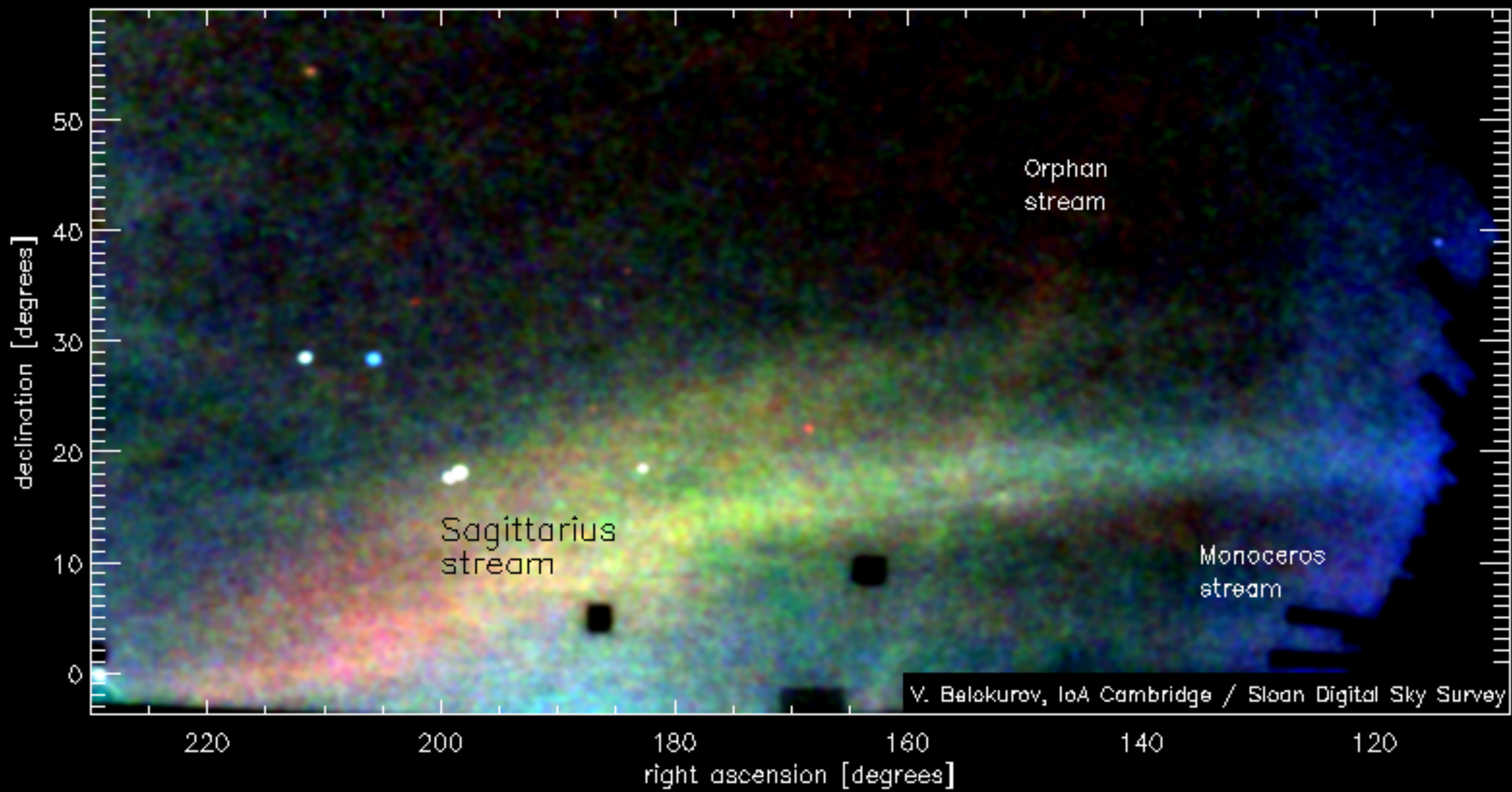
$\leq 10^{4\text{-}5}\, M_\odot$

LMC $\sim 10^{10}\, M_\odot$



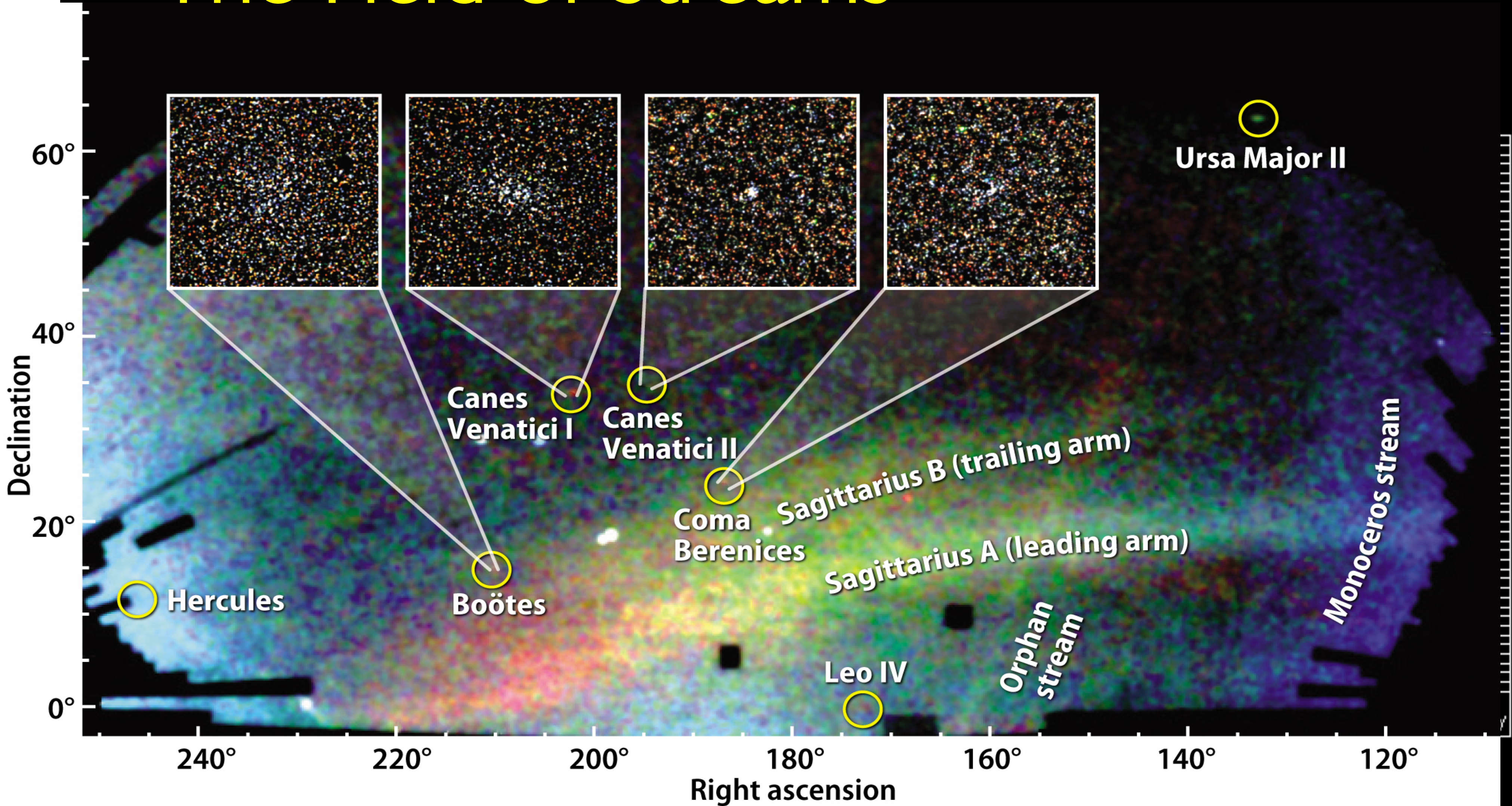
Mateo 2008, Garching workshop

The Field of Streams



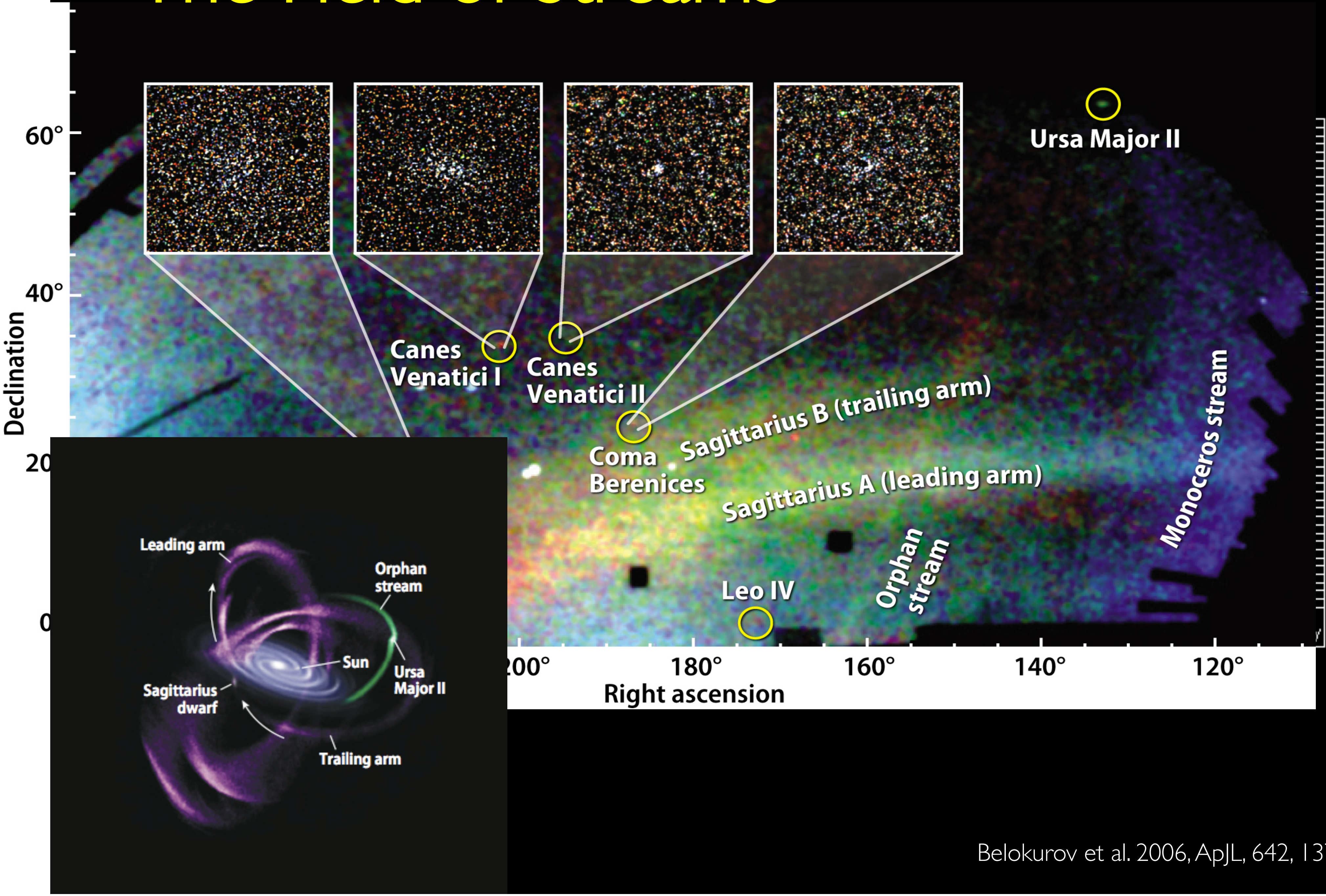
Belokurov et al. 2006, ApJL, 642, 137

The Field of Streams



Belokurov et al. 2006, ApJL, 642, 137

The Field of Streams

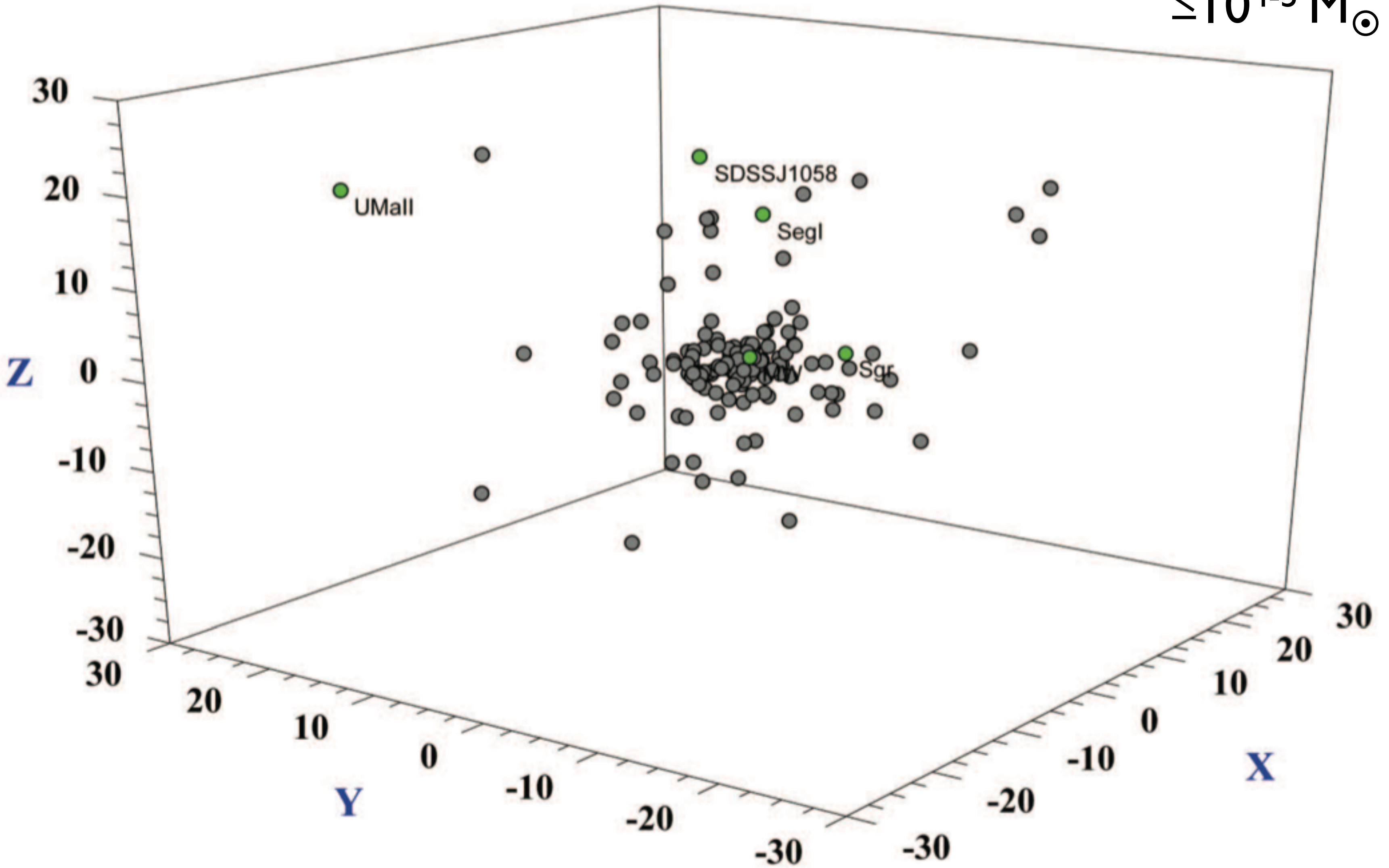


Belokurov et al. 2006, ApJL, 642, 137

Globular Clusters

(and a few ultra-faints)

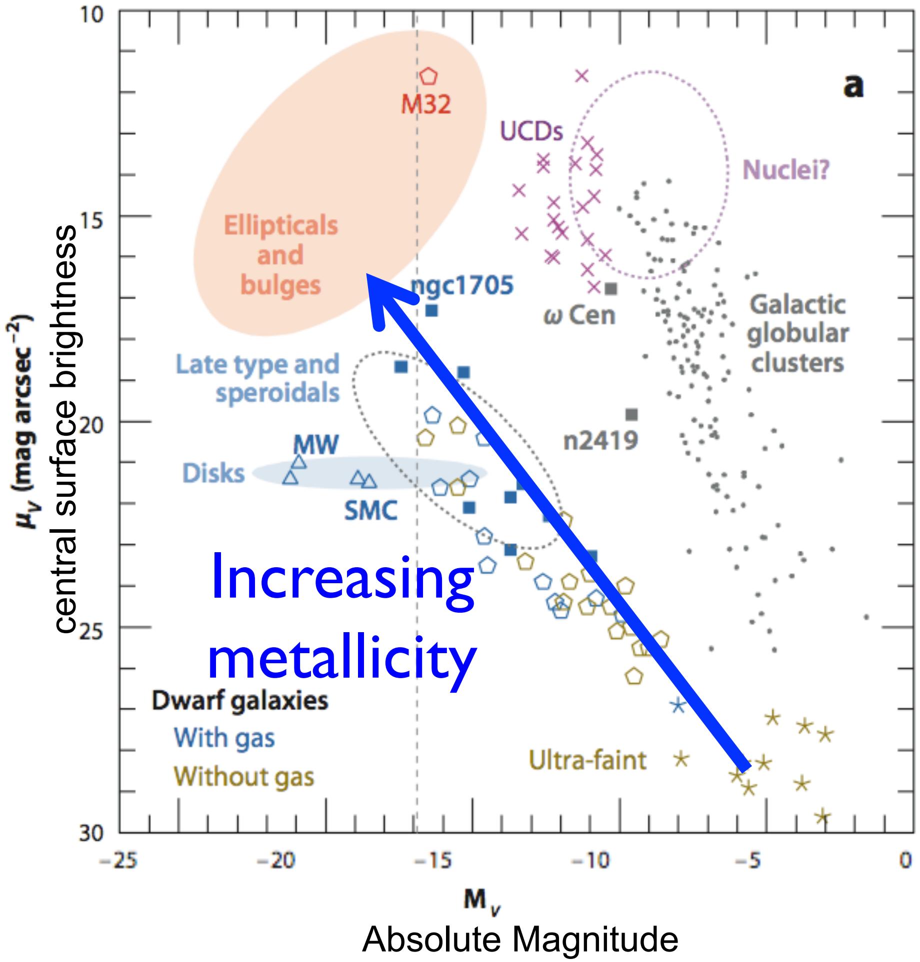
≤$10^{4\text{-}5}$ $M_\odot$

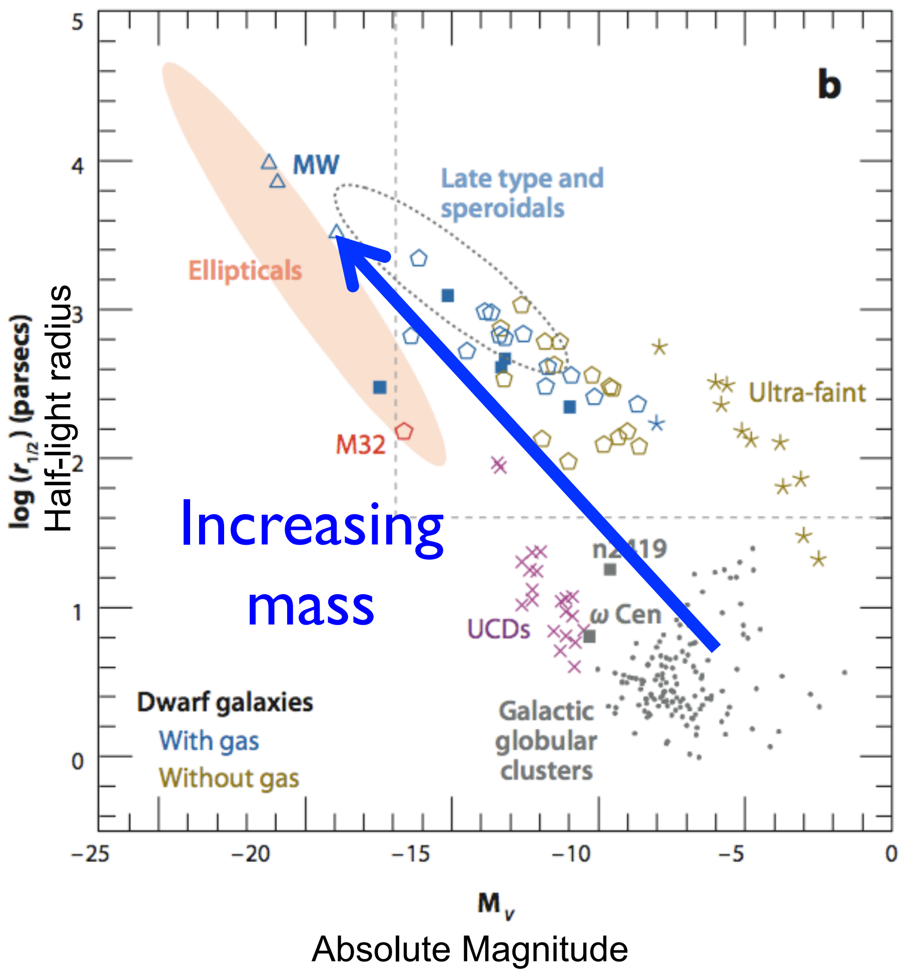


~140 globular clusters, 65% <8kpc from centre

Mateo 2008, Garching workshop

Global Properties of Galaxies





based on Kormendy 1985; Binggeli 1994

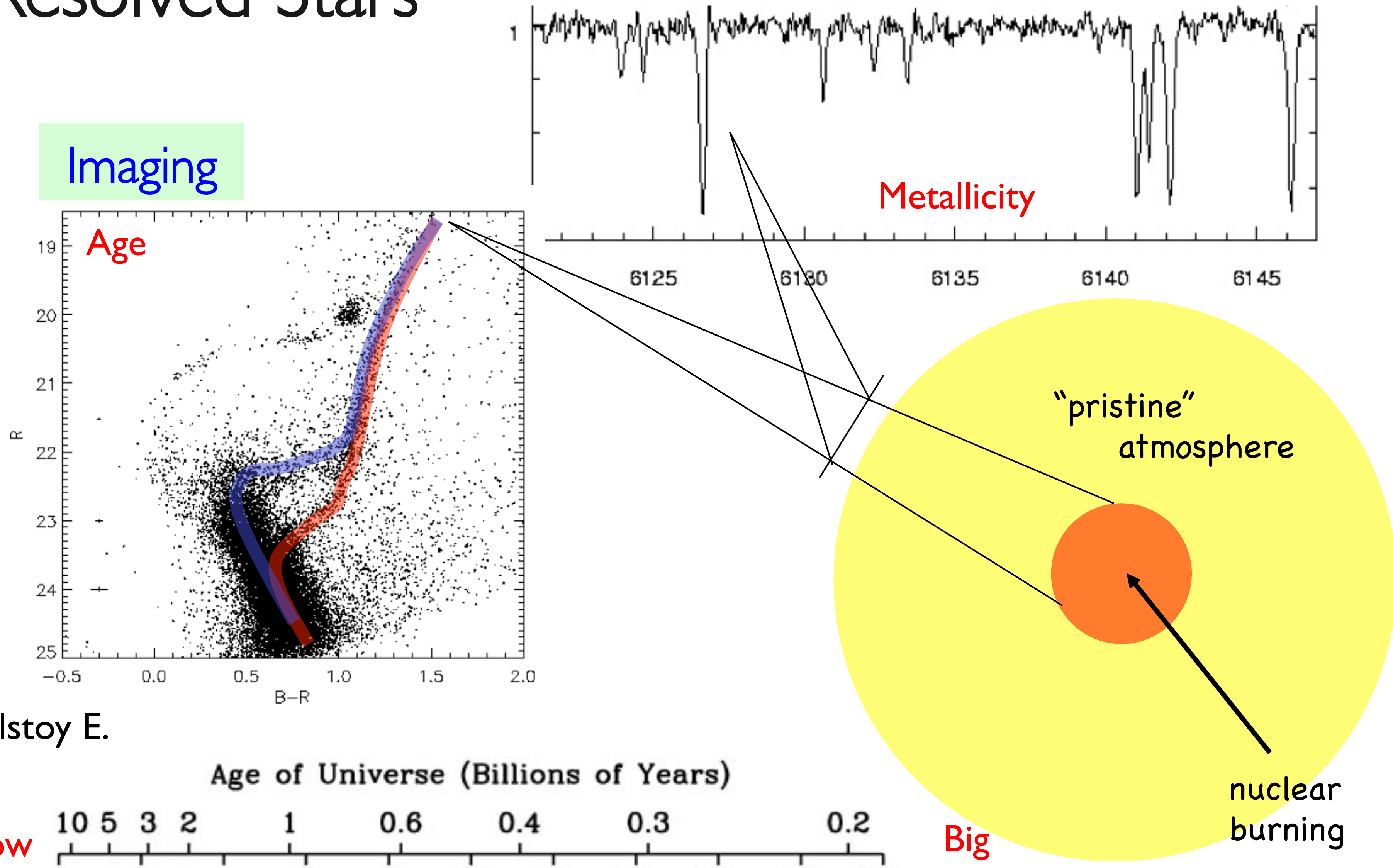
see also Belokurov et al. 2007

Tolstoy, Hill & Tosi 2009, ARAA, 47, 371

Resolved Stars

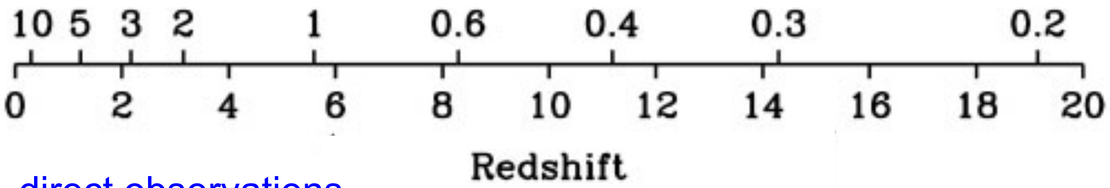
Spectroscopy

Tolstoy E.



Tolstoy E.

now



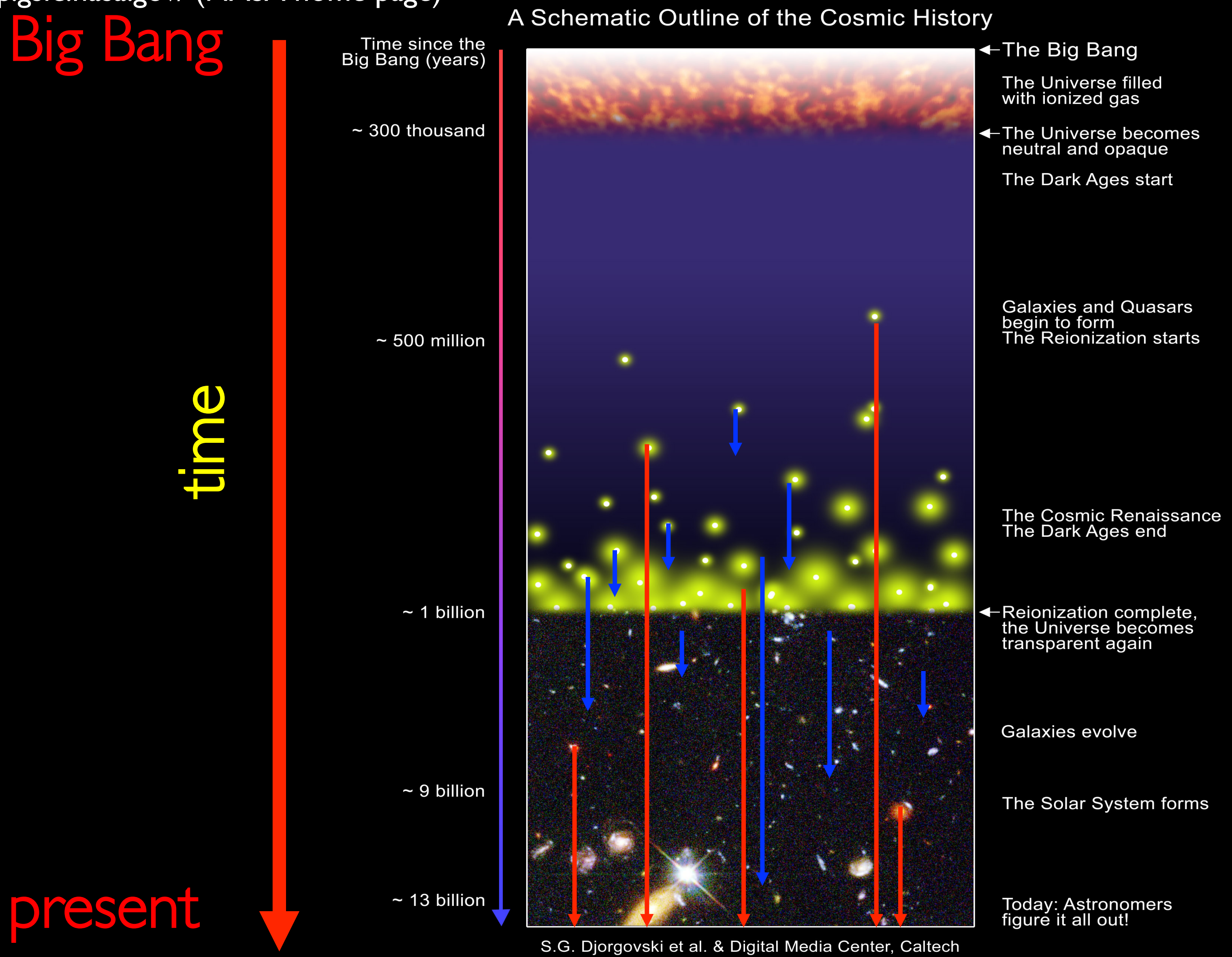
Big Bang

direct observations of galaxies

Low mass stars < $1M_{\odot}$

Cosmic History

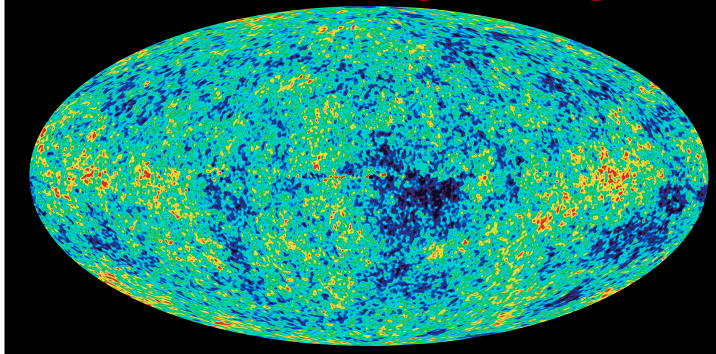
http://wmap.gsfc.nasa.gov/ (NASA home page)



Cosmic History

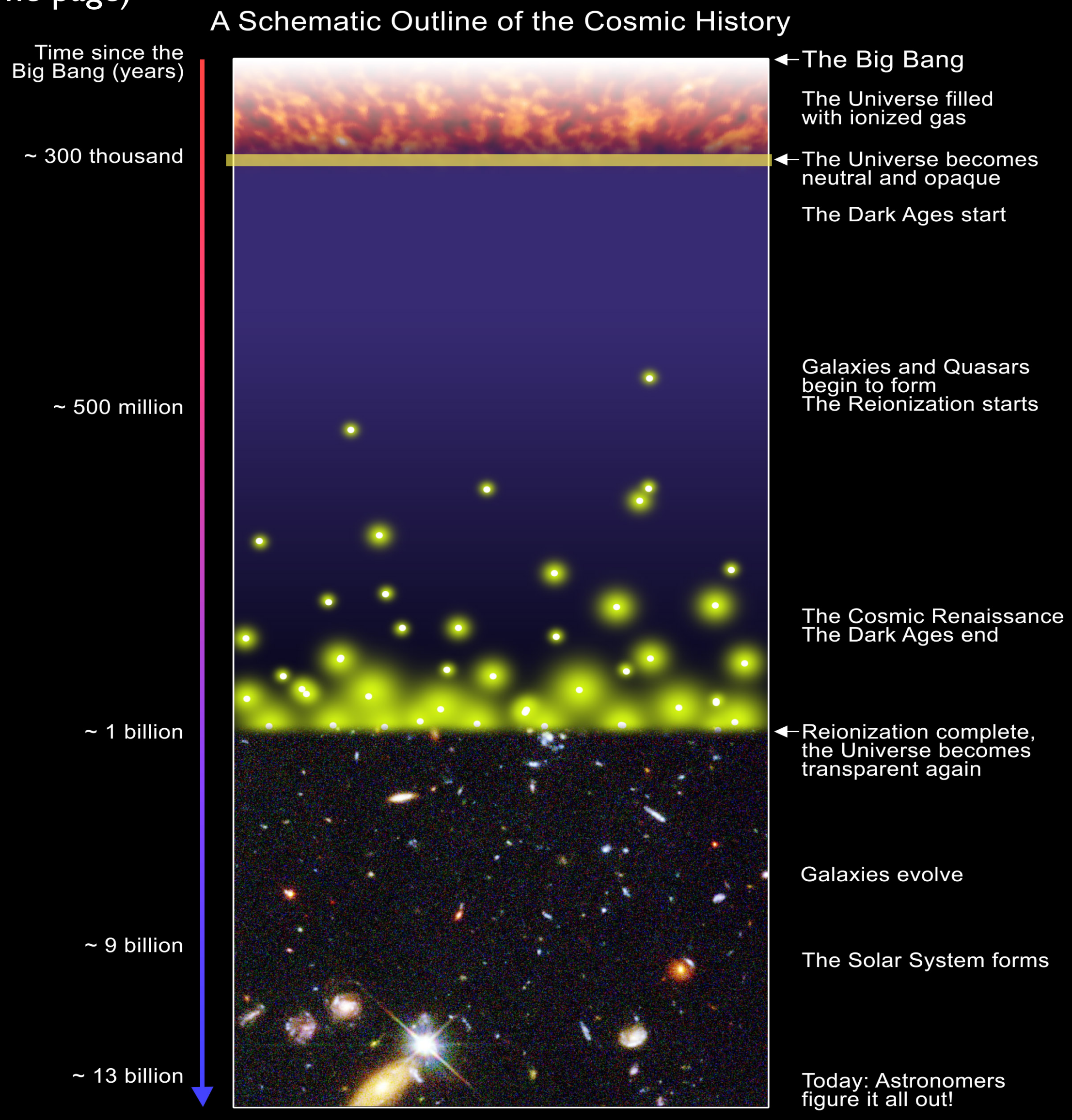
http://wmap.gsfc.nasa.gov/ (NASA home page)

Big Bang -



time

present

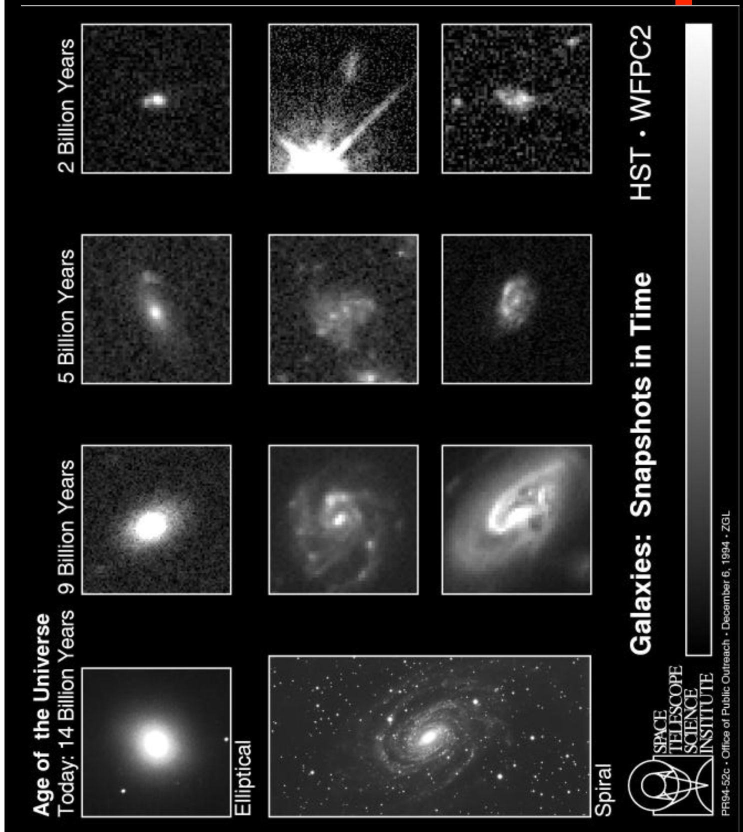


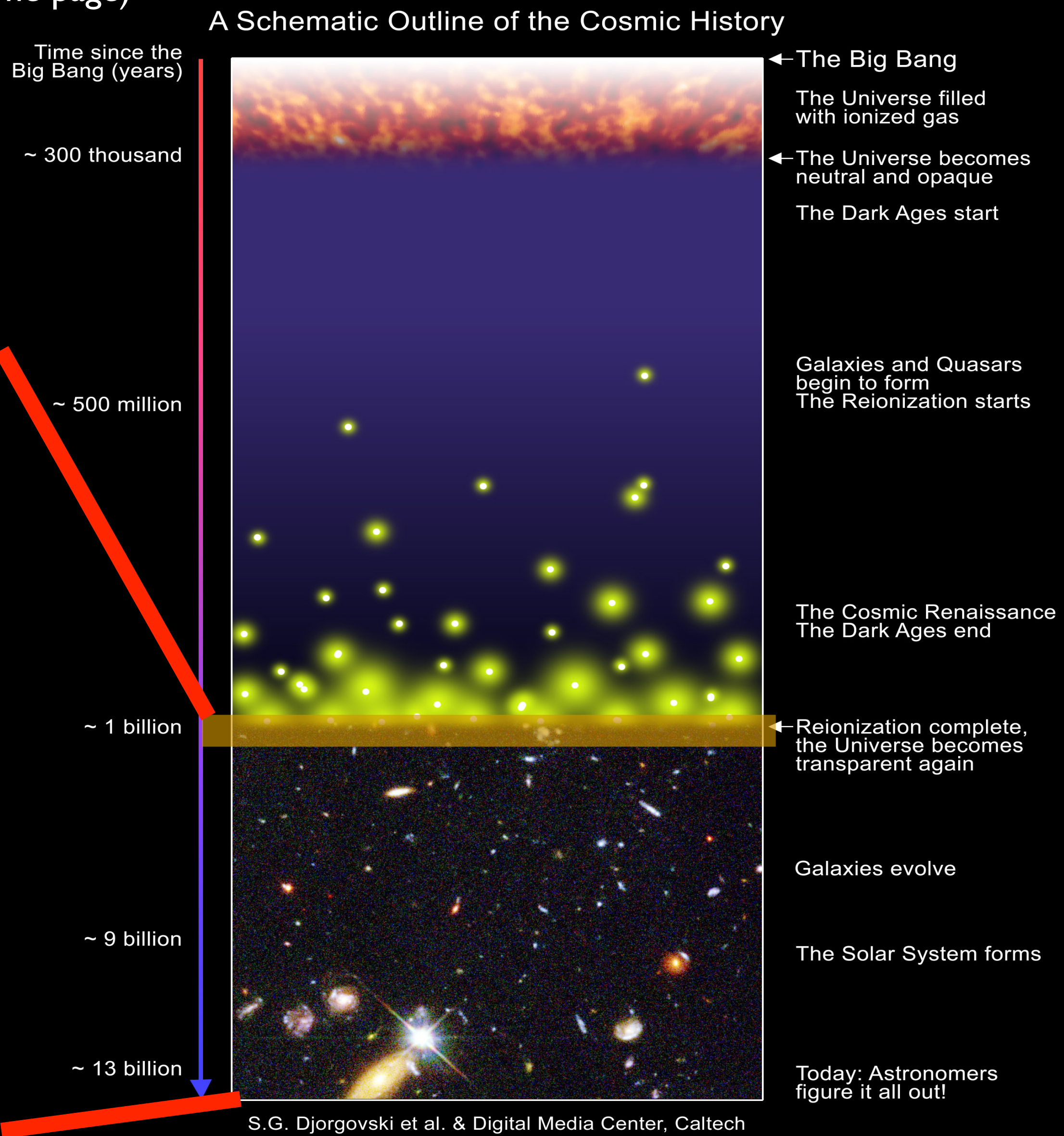
S.G. Djorgovski et al. & Digital Media Center, Caltech

Cosmic History

http://wmap.gsfc.nasa.gov/ (NASA home page)

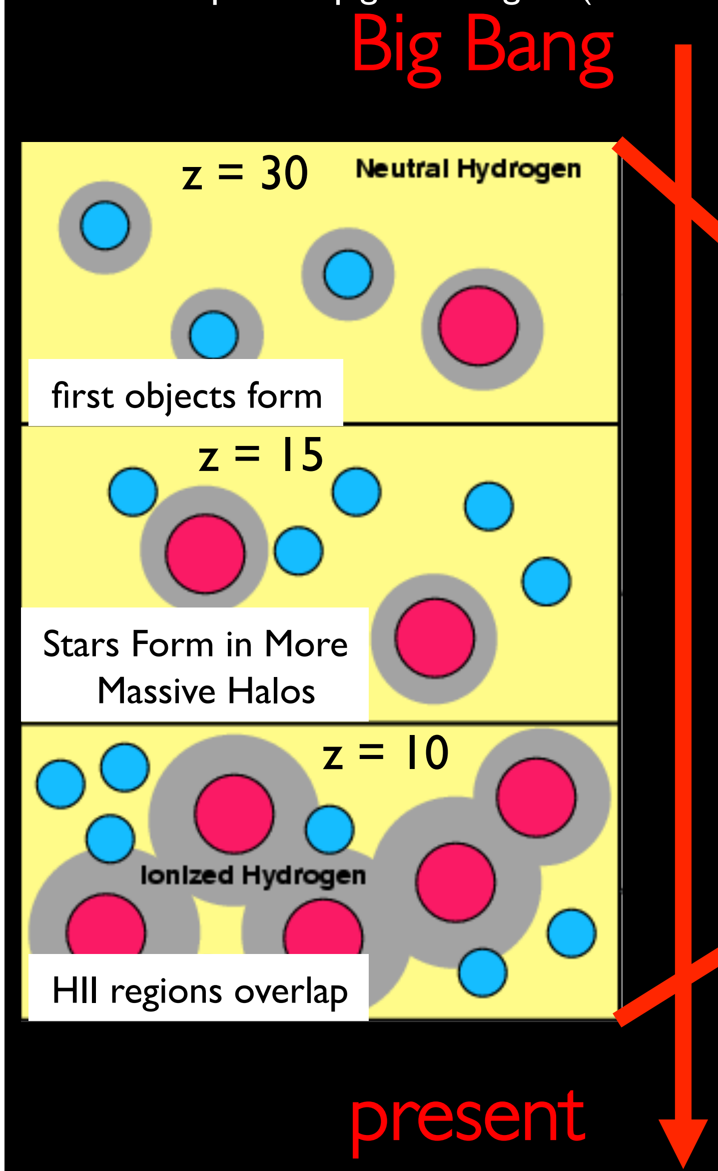
Big Bang

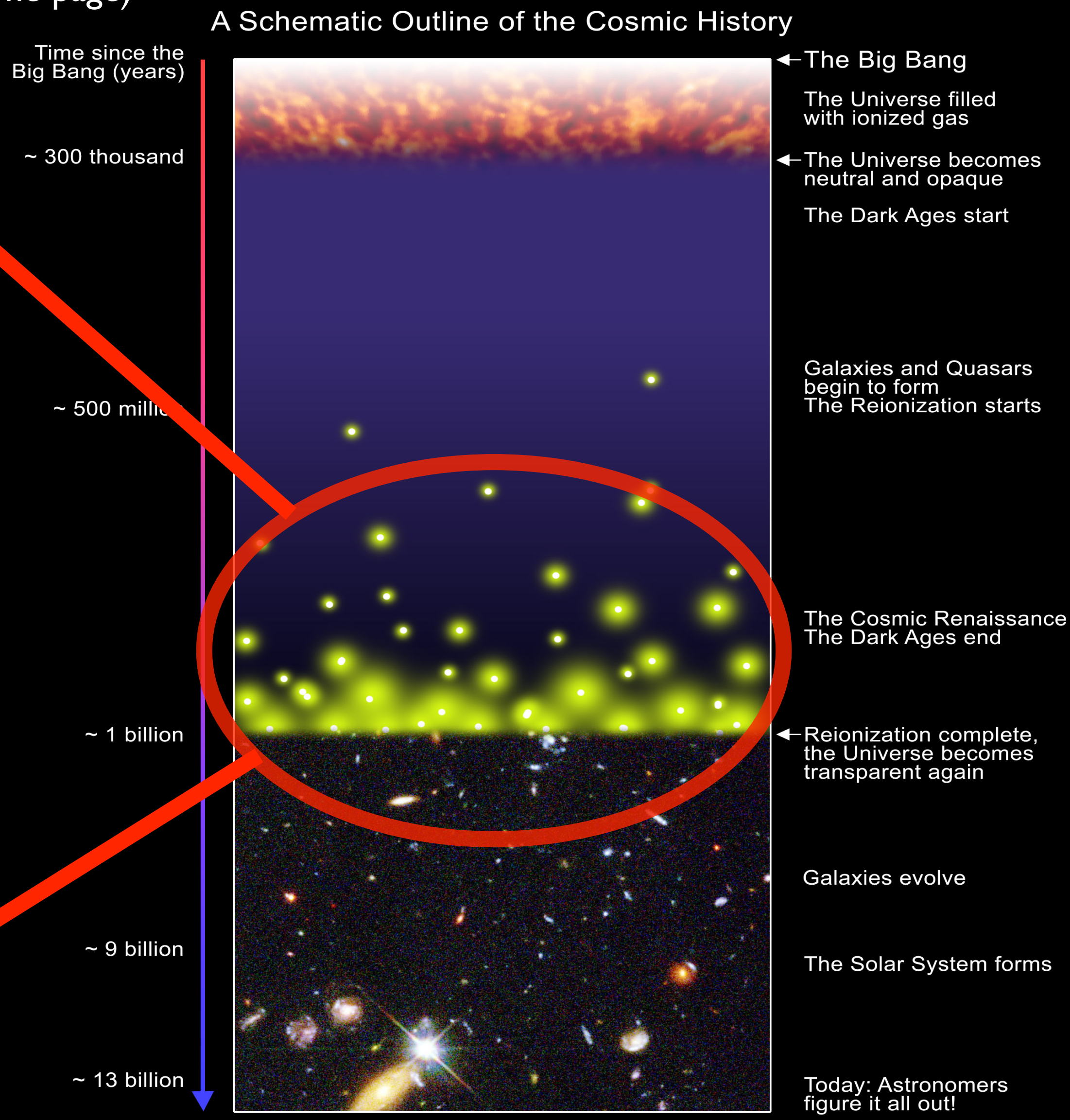




Cosmic History

http://wmap.gsfc.nasa.gov/ (NASA home page)

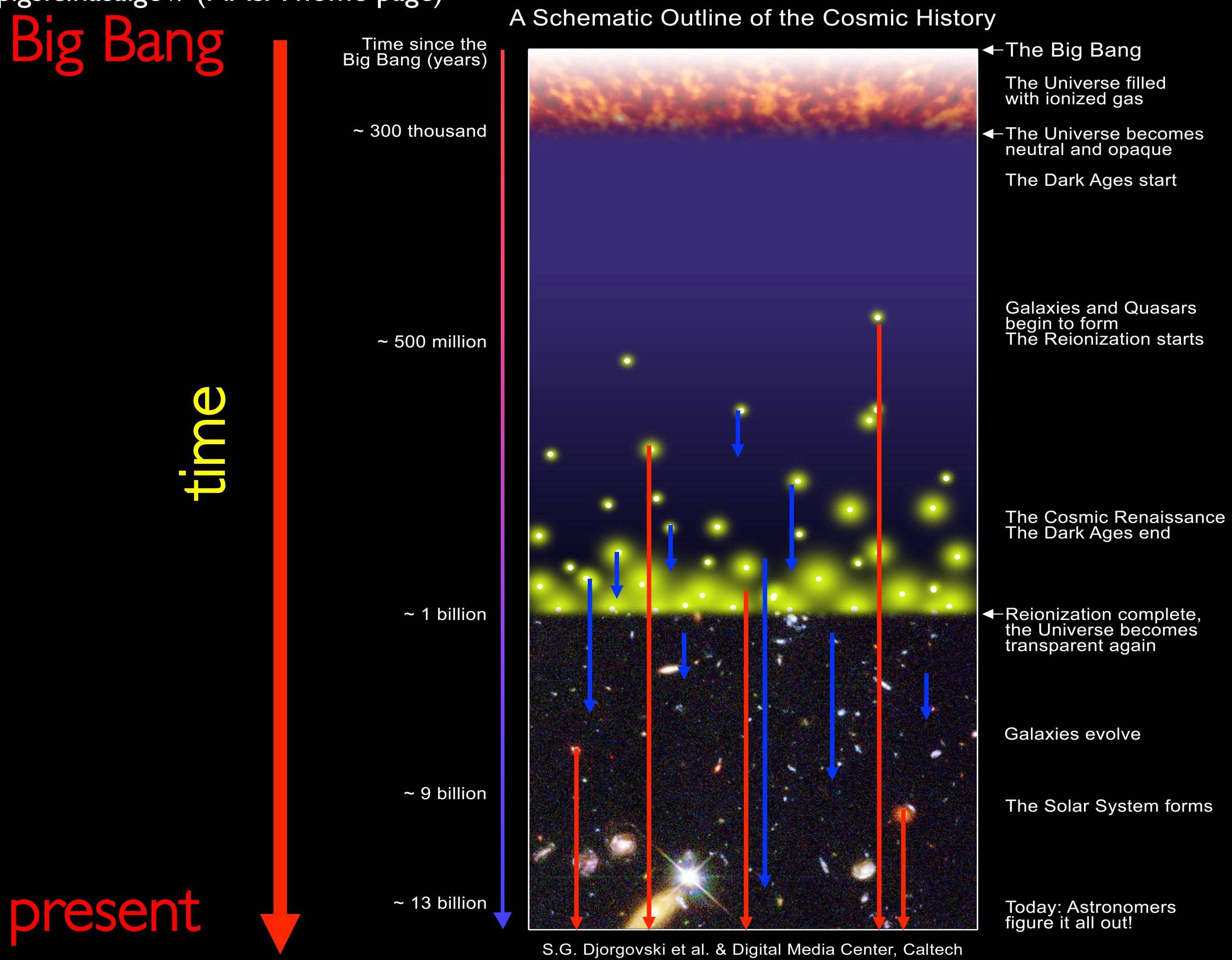




S.G. Djorgovski et al. & Digital Media Center, Caltech

Cosmic History

http://wmap.gsfc.nasa.gov/ (NASA home page)



Galactic Archaeology…

We want to study how the properties of the universe change – but it is difficult to do it directly – so we can try indirectly:

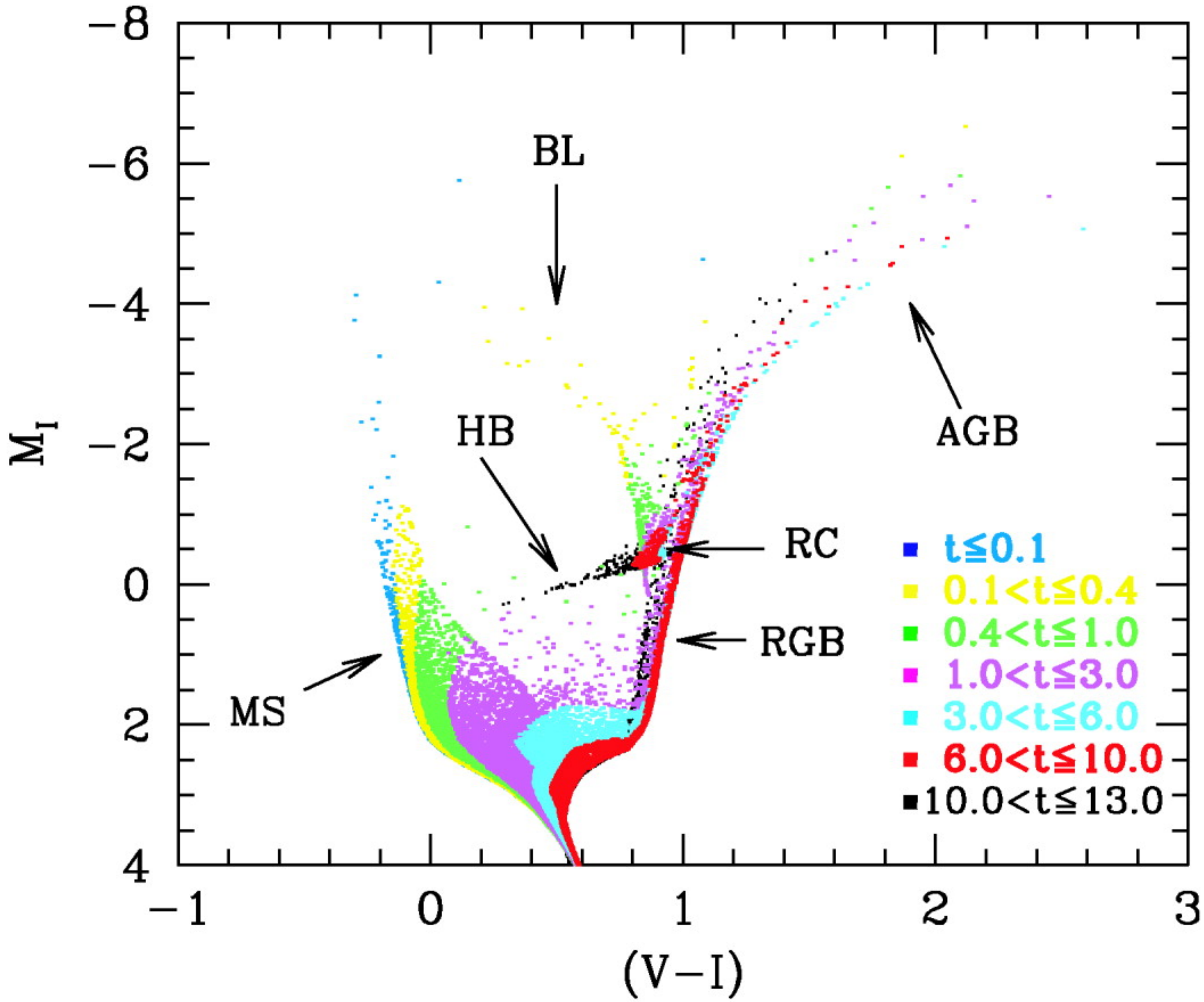
Stars form from gas through time – they live a long time – and if we can measure their properties at different ages we learn about galaxy formation & evolution

Part I

Resolved Imaging

- Star Formation Histories -

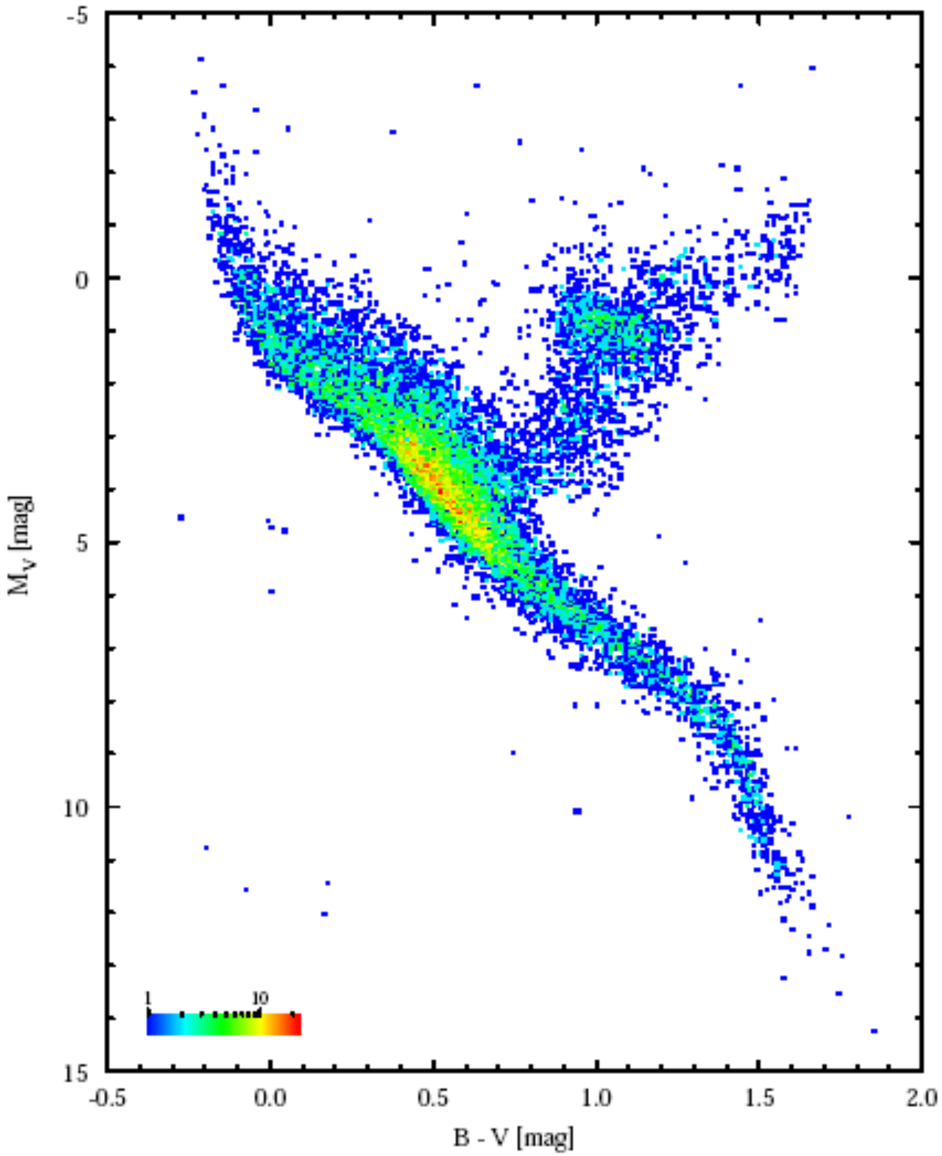
Colour-Magnitude Diagram (CMD)



Tosi et al. 1991; Aparicio et al. 1996; Tolstoy & Saha 1996; Dolphin 1997, 2002; Hernandez et al. 2000; Ikuta & Arimoto 2002; Gallart et al. 2005

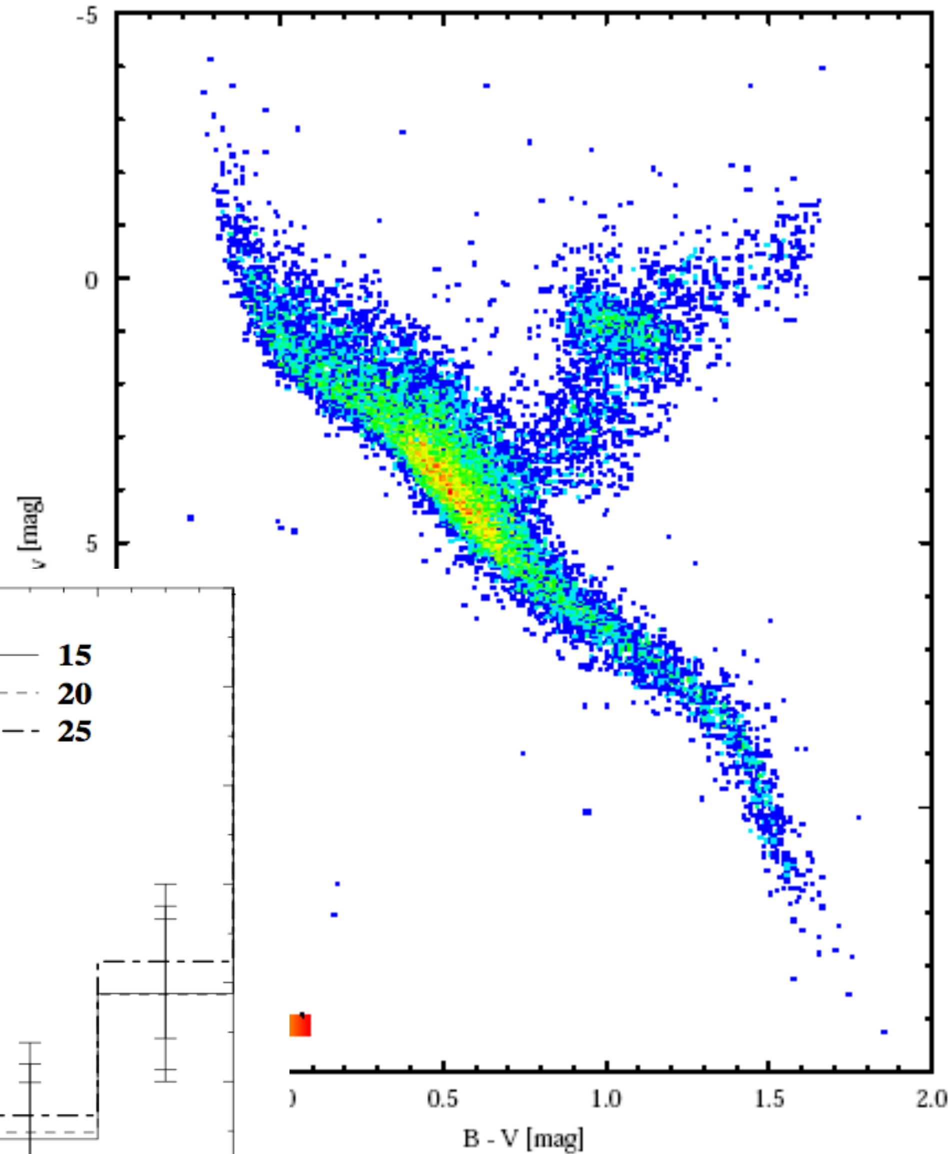
Aparicio & Gallart 2004

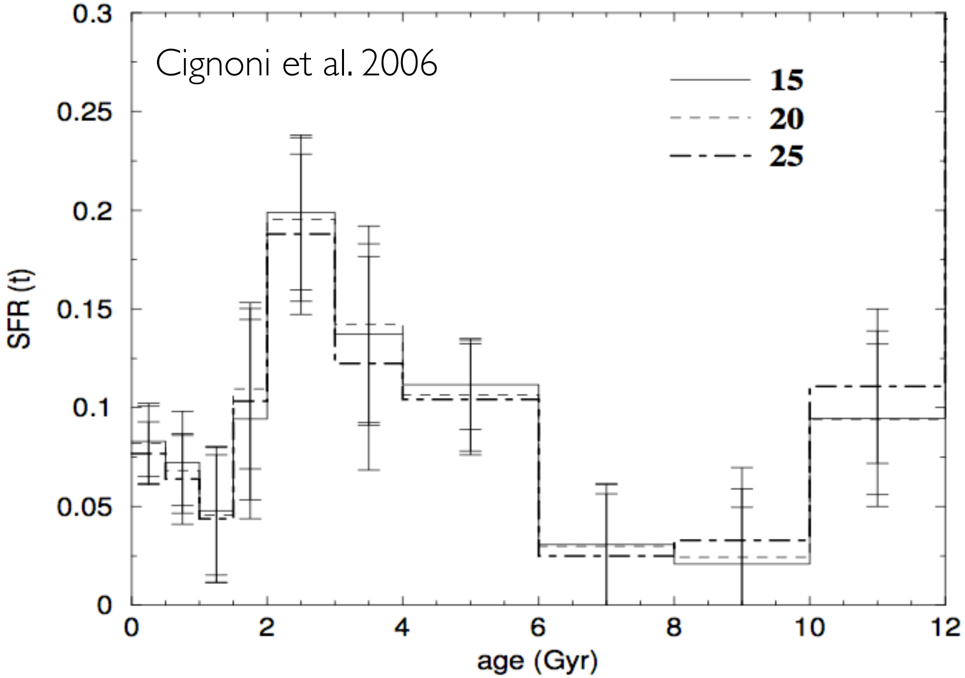
Hipparcos CMD of Milky Way



Perryman et al. 1995, A&A, 304, 69

Hipparcos CMD of Milky Way





Perryman et al. 1995, A&A, 304, 69

SFHs in the Local Group

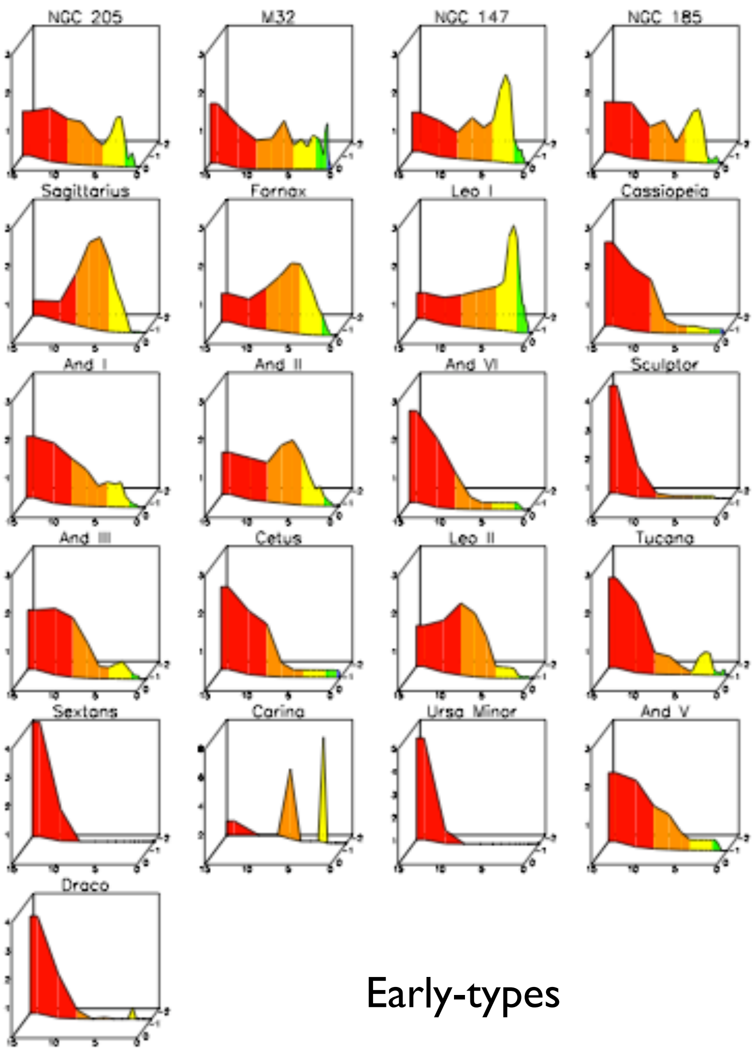


Figure 43. Star formation histories of elliptical and spheroidal galaxies. Colors correspond to the CMD features generated by each age. Red: RGB plus full HB. Orange: RGB plus red HB. Yellow: RGB plus red clump. Green: bright red clump. Blue: young MS and blue helium-burning stars. Ages are given in Gyr, and star formation rates are normalized to the lifetime averages.

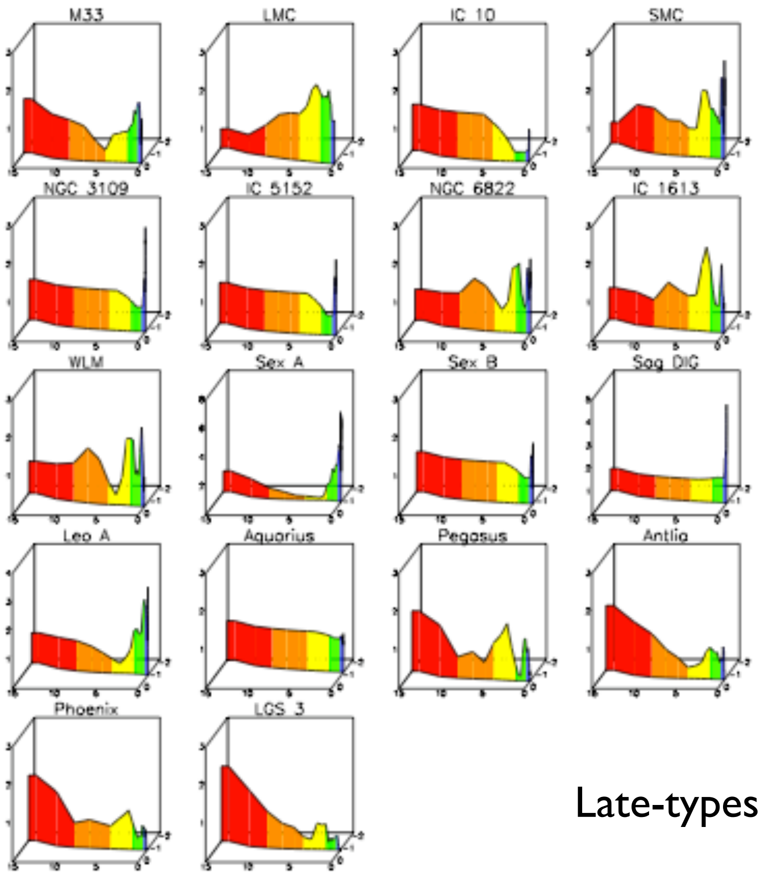
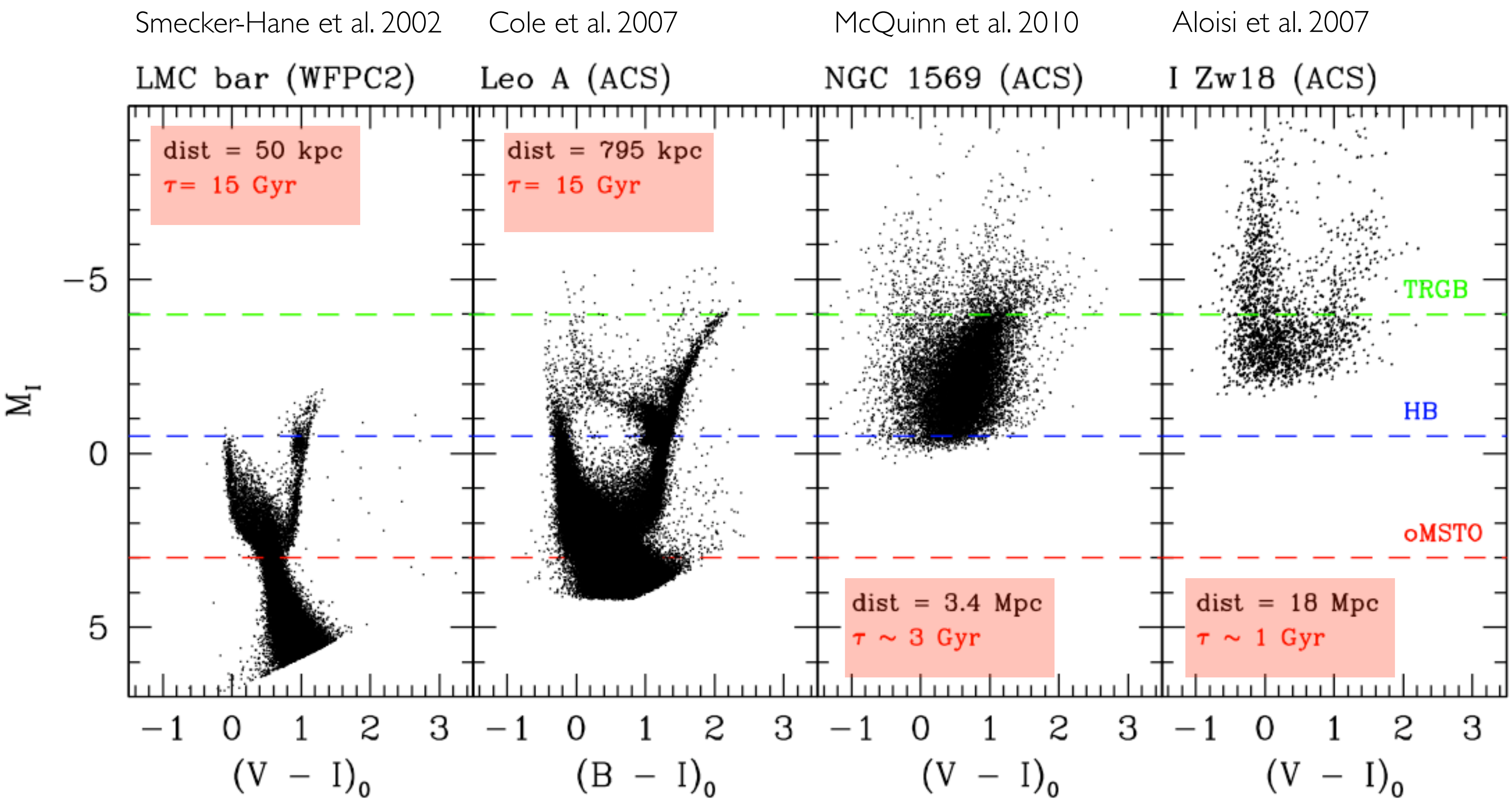


Figure 44. Star formation histories of irregular and transition-type galaxies. Colors correspond to the CMD features generated by each age. Red: RGB plus full HB. Orange: RGB plus red HB. Yellow: RGB plus red clump. Green: bright red clump. Blue: young MS and blue helium-burning stars. Ages are given in Gyr, and star formation rates are normalized to the lifetime averages.

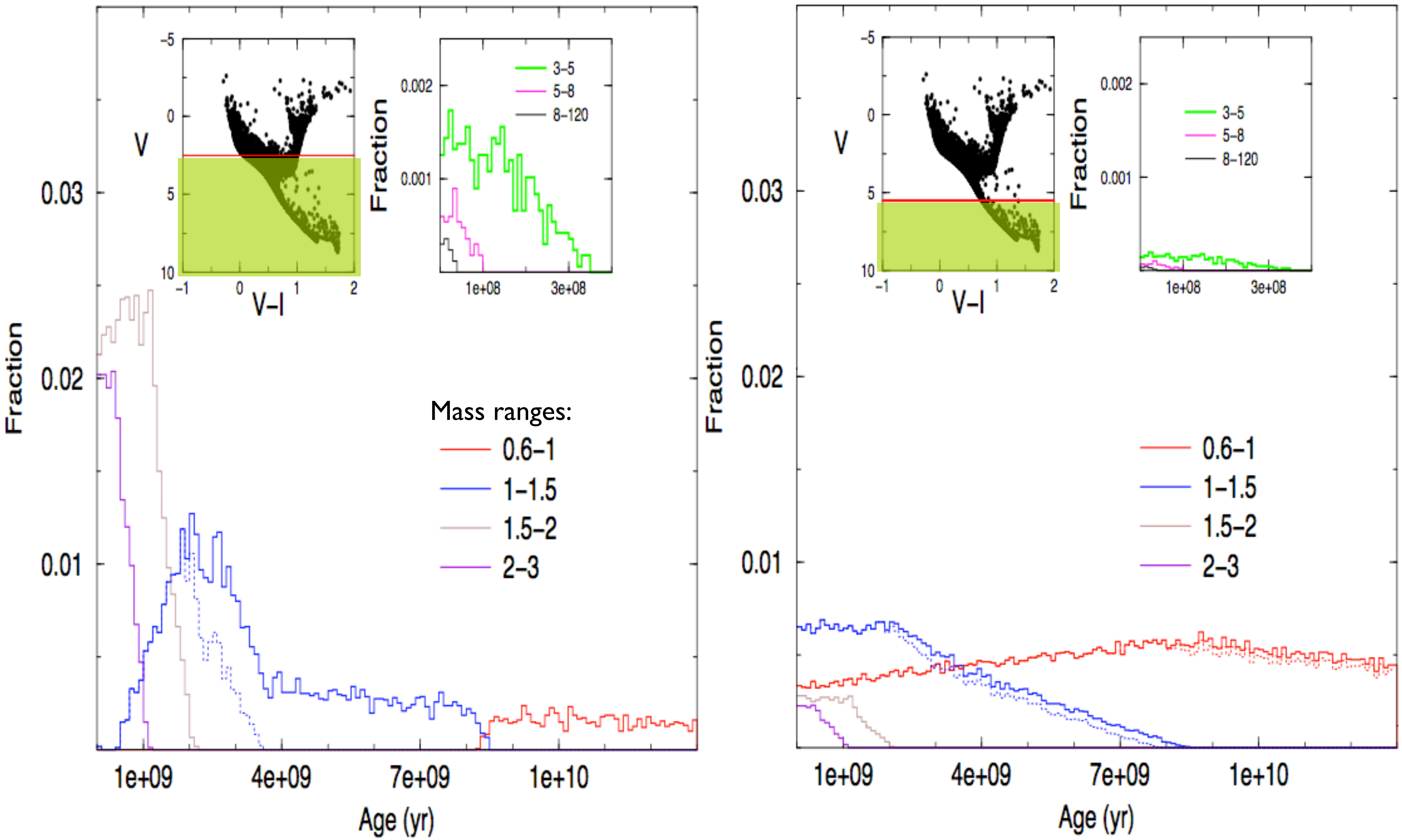
Dolphin et al. 2005 astro-ph/0506430

Probing Different Environments



We can't study all galaxies with the same detail and beyond the Local Group it becomes particularly difficult with current facilities.

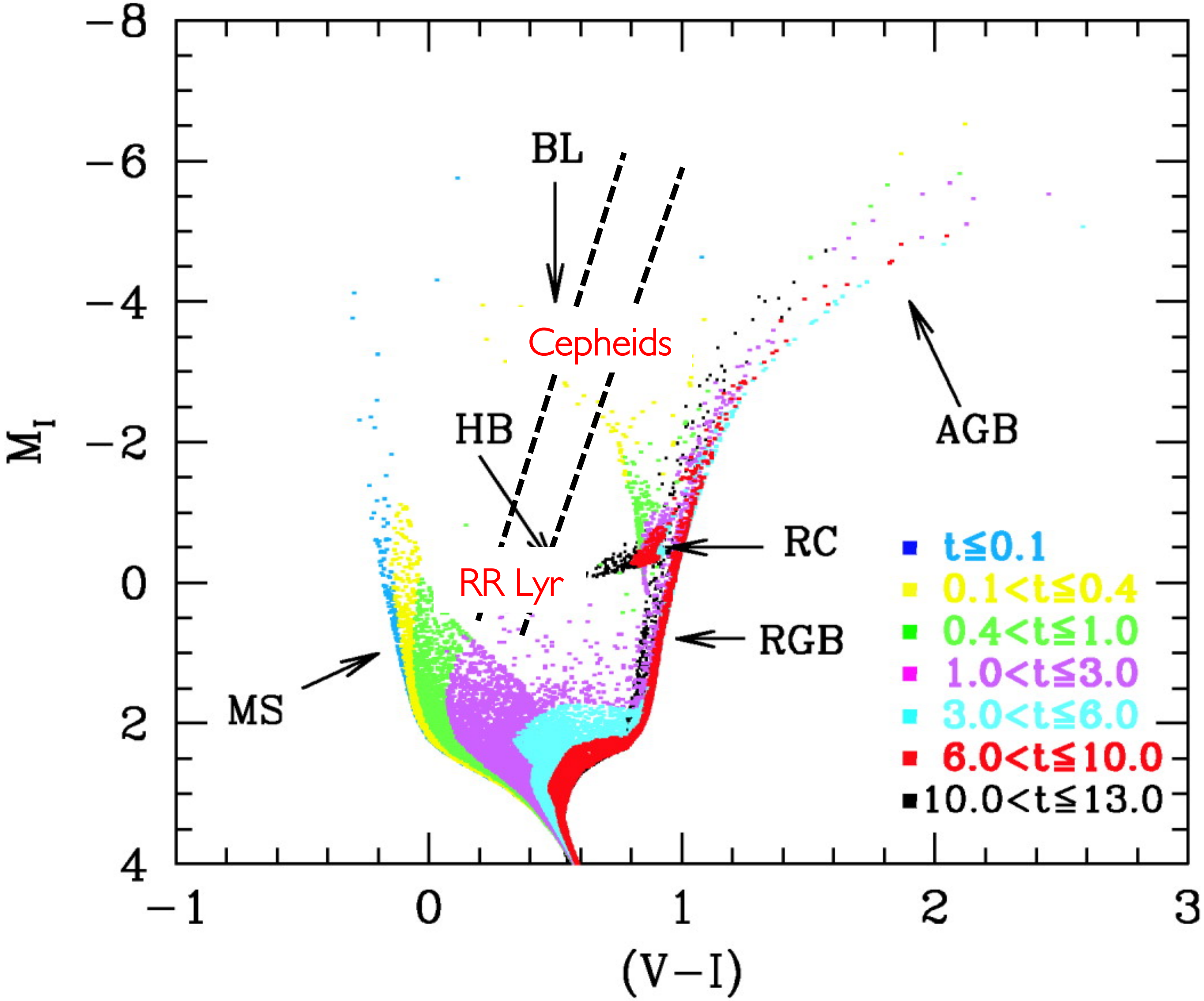
Fractional age distributions



Assuming constant SFR over 13Gyr

Cignoni & Tosi 2010, *Advances in Astronomy, pp.1-26*

Variable Stars

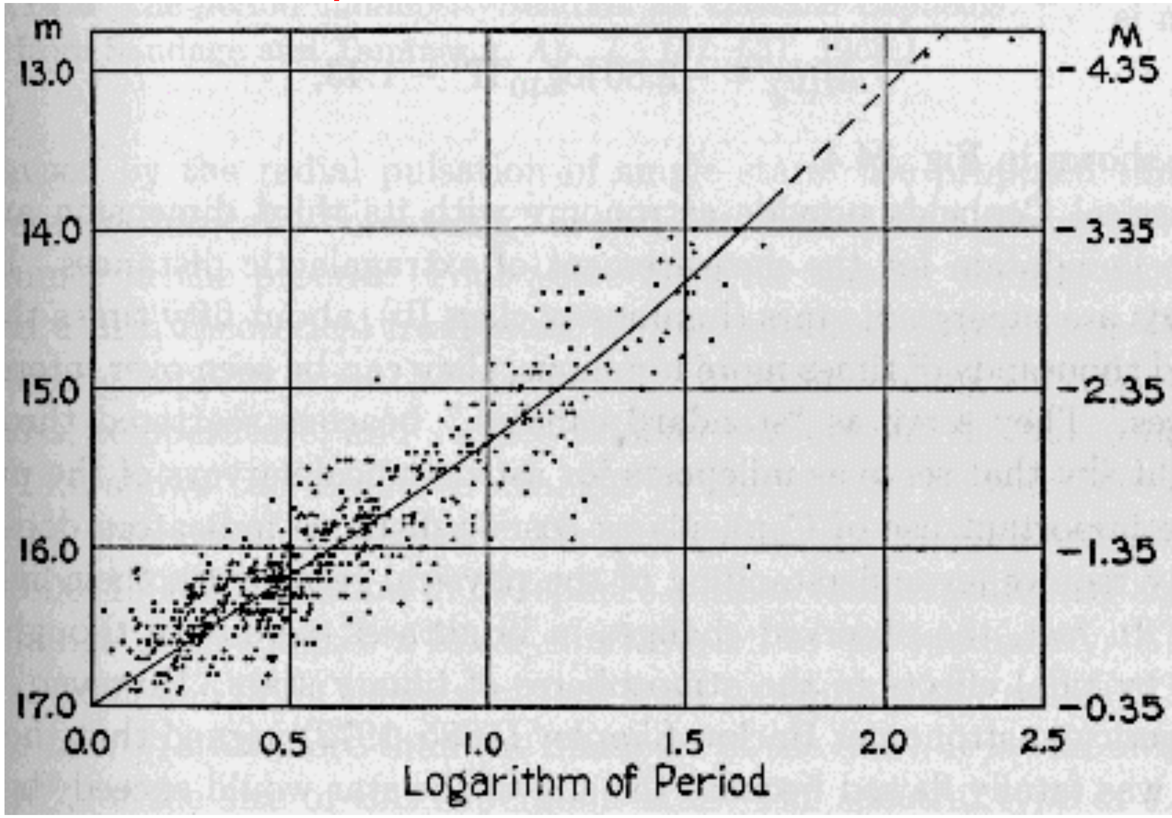


AparicioA.,GallartC.,,AJ,128,1465

Cepheid Variable Stars

Period-Luminosity relation

Harlow S.,1961, Harvard University Press



Accurate DISTANCES

$$M_V = -2.80 \, Log_{10} P - 1.43$$

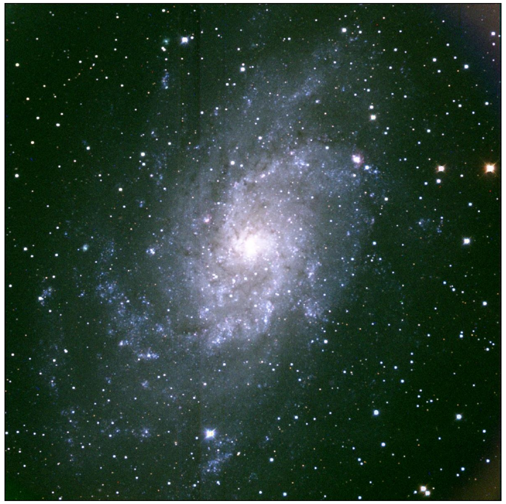
$$(m-M_V)_0 = 5log_{10}d(pc) - 5 \; (+A)$$

Henrietta Leavitt (1912)

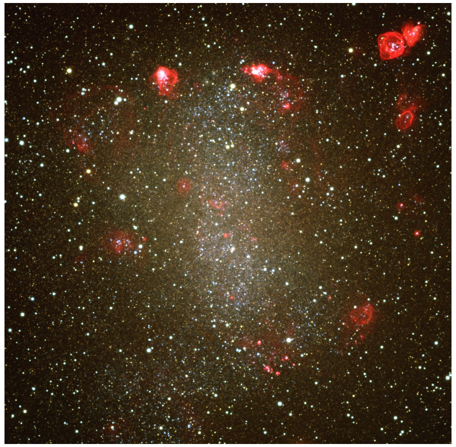
Birth of Extragalactic Astronomy

Hubble (1926) ApJ, 64, 321 *Extragalactic nebulae*

M31



M33



NGC6822

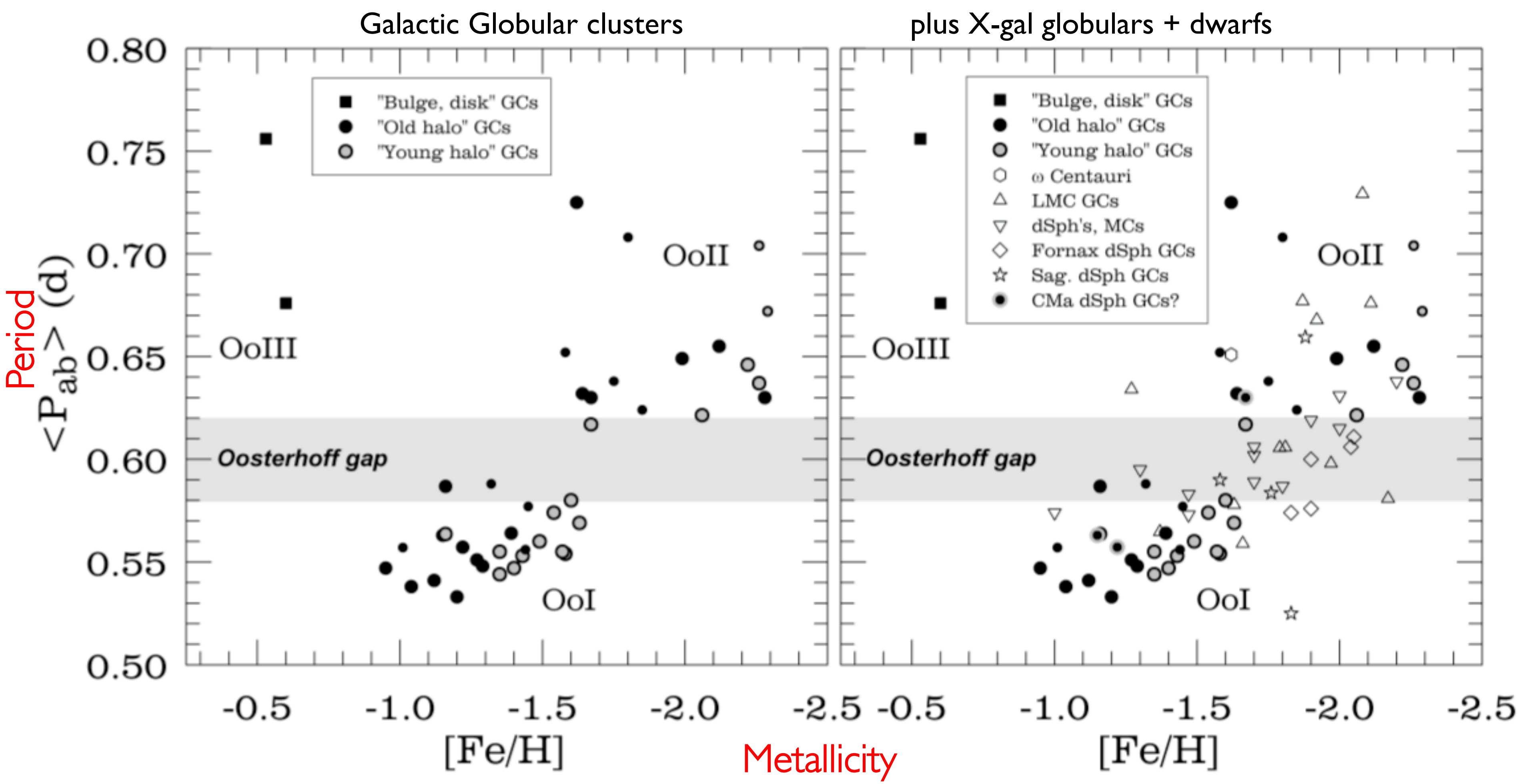
Hubble used Cepheid variable stars to show that distances to M31, M33 and NGC6822 are without doubt BEYOND our own Galaxy

Edwin Hubble

RR Lyr Variable Stars

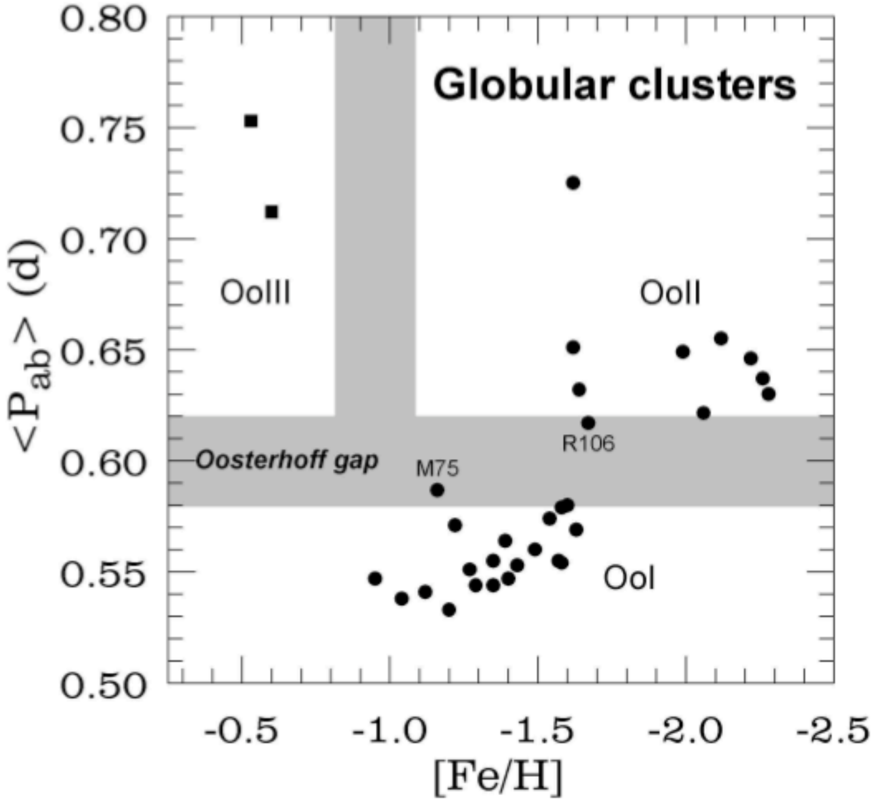
Oosterhoff Dicotomy

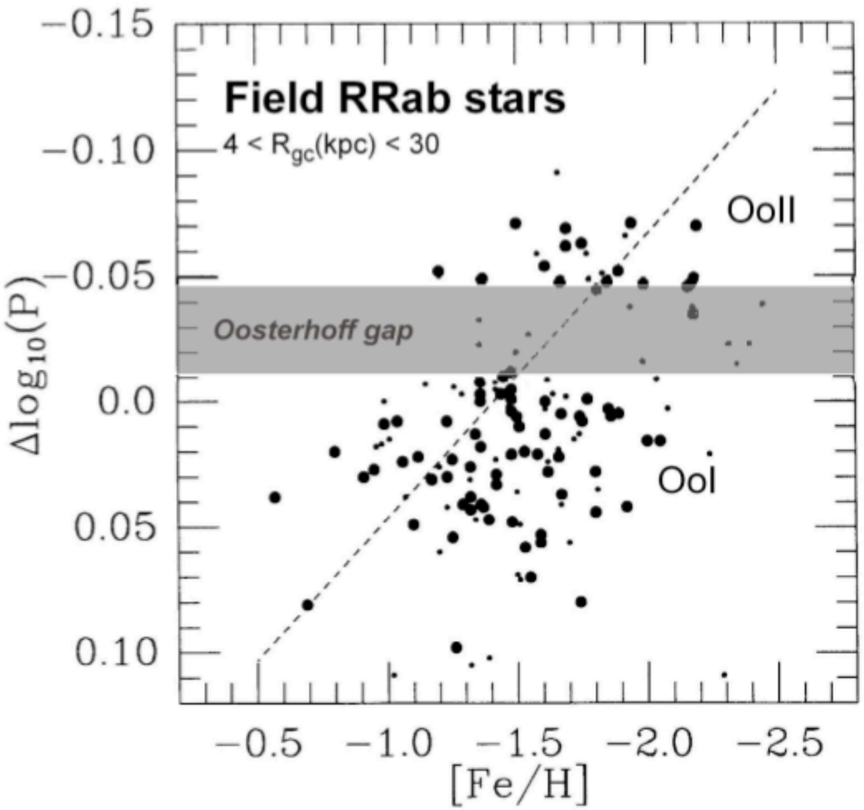
Oosterhoff (1939)



Catelan 2009

RR Lyr Variable Stars





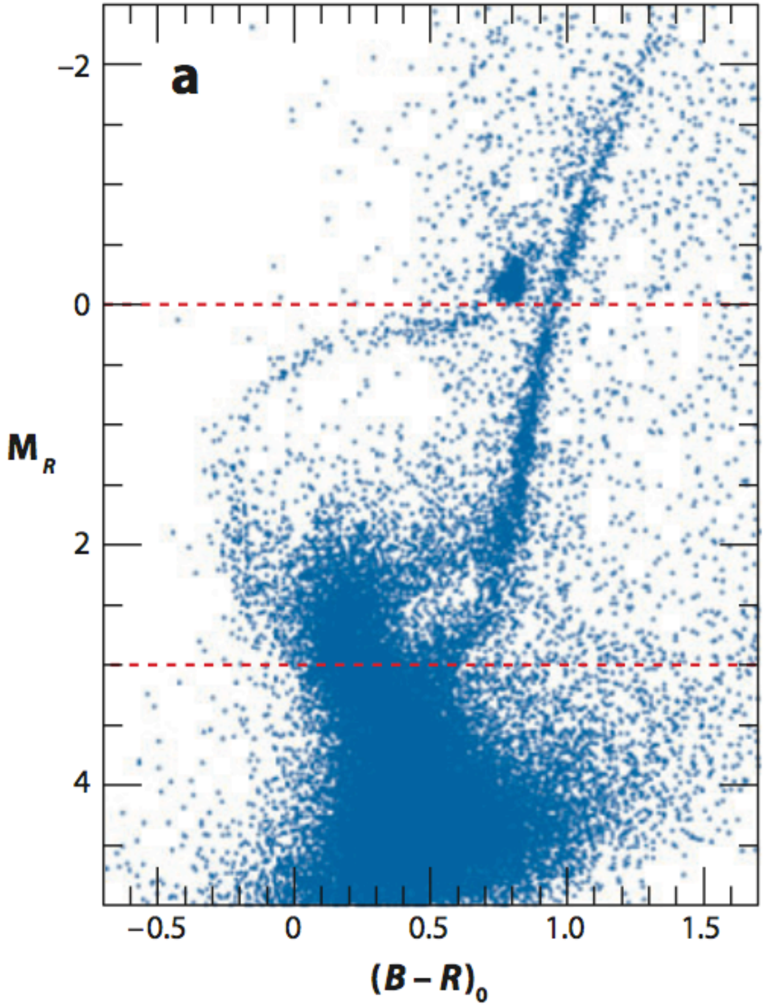
Suntzeff, Kinman & Kraft 1991

Dichotomy also present in field stars….

Catelan 2004

Carina Dwarf Spheroidal Galaxy

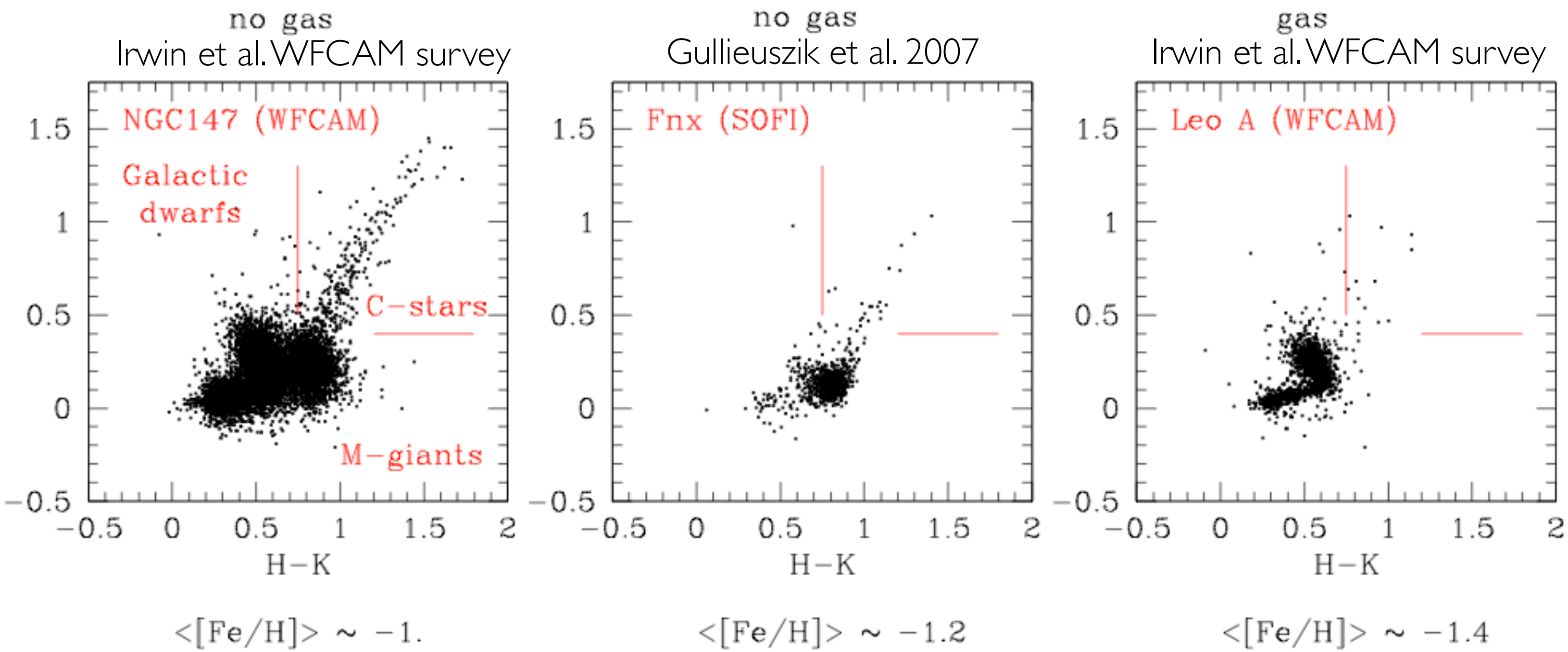
Tolstoy F., Hill V., TosiM.,,ARA&A,46,371



Mario Mateo

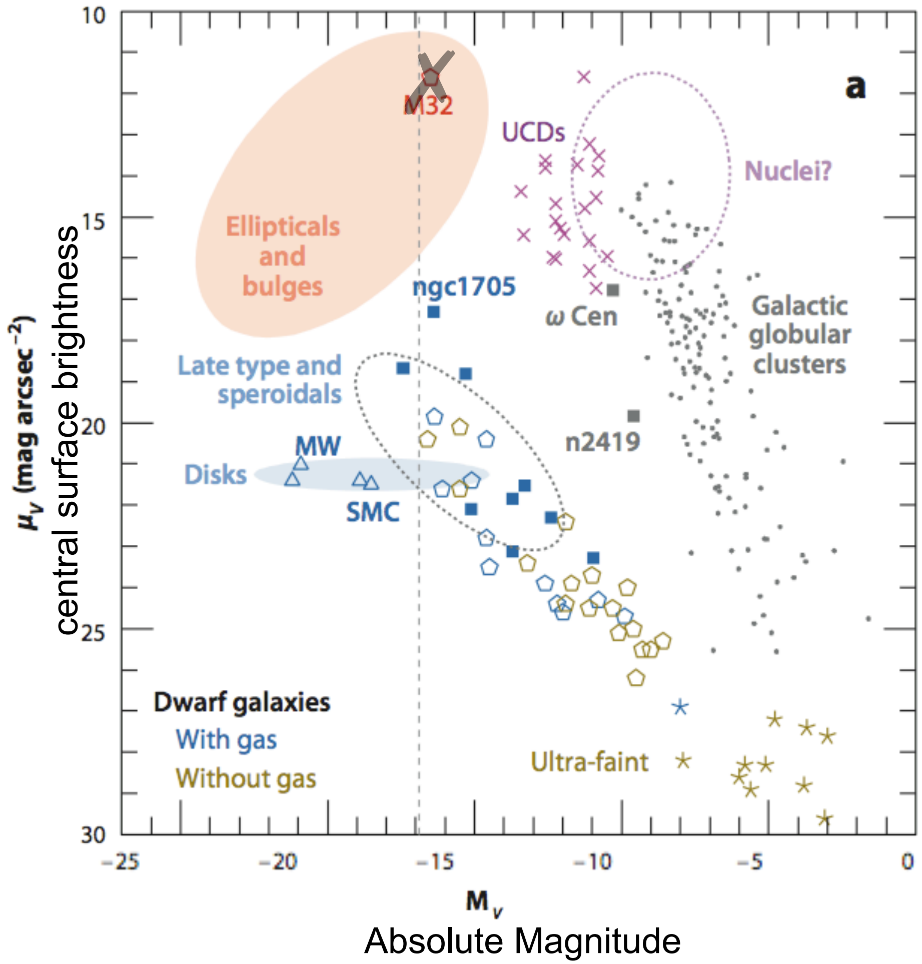
Some hints about evolved populations

Compilation by Tolstoy (2010) arXiv:1012.2229



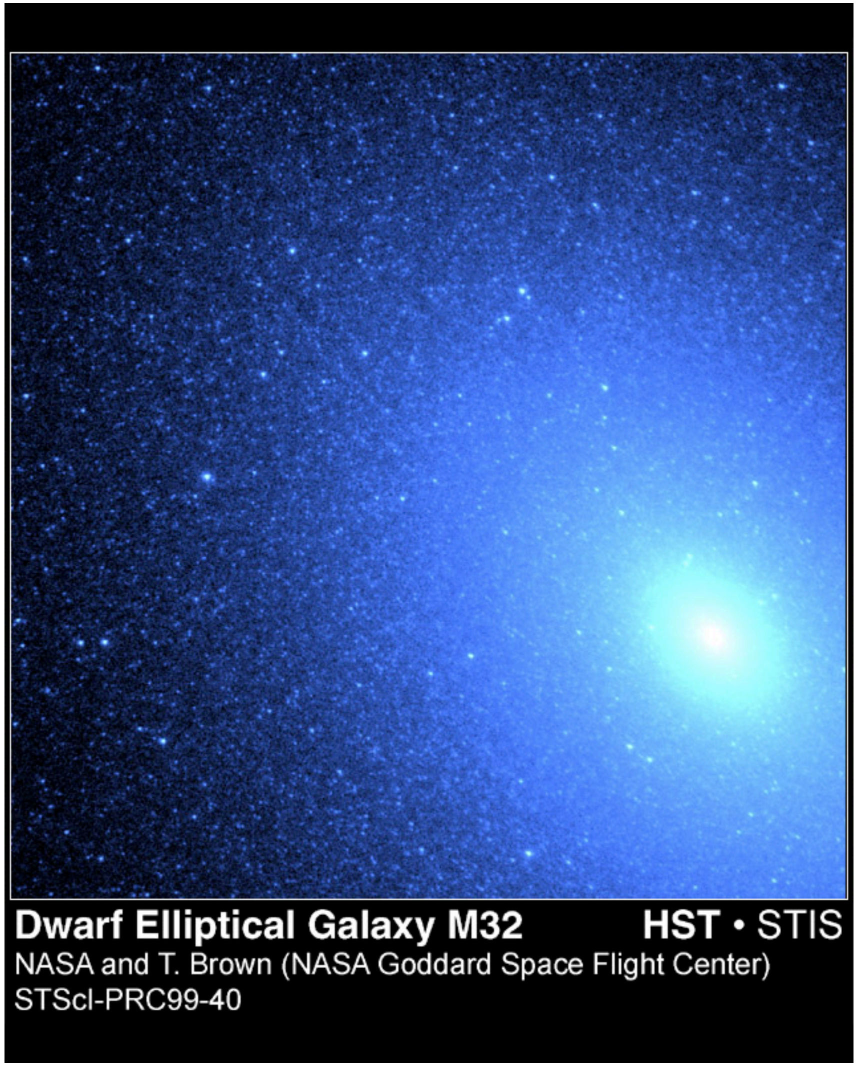
See also Tolstoy F.,, 2010arXiv1012.2229

Global Properties



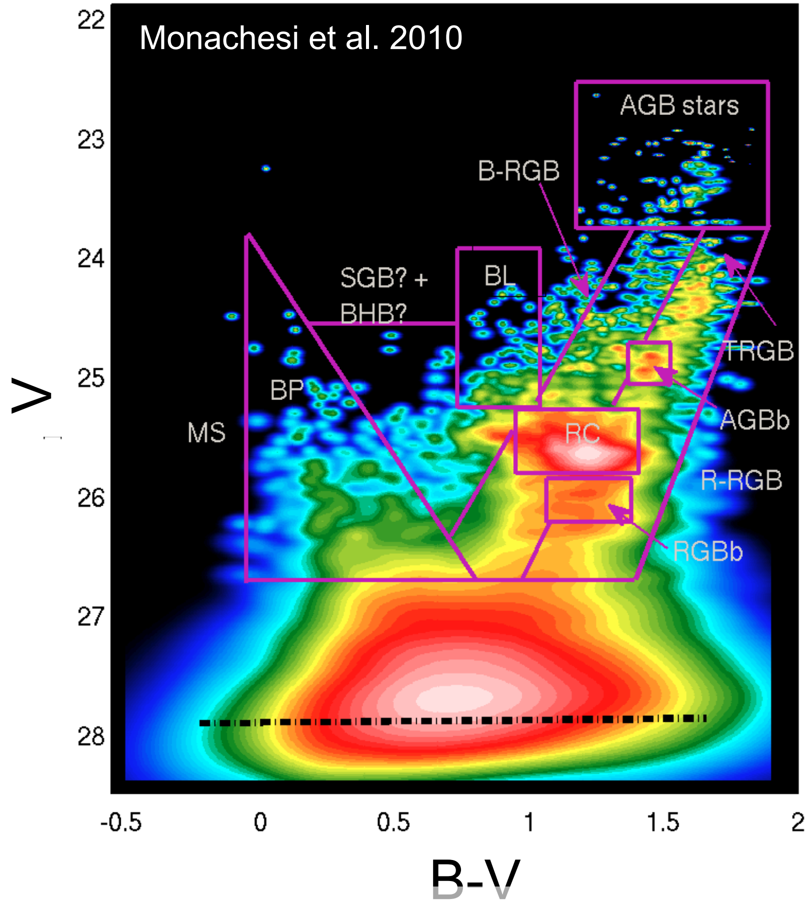
Tolstoy, Hill & Tosi 2009, ARAA, 47, 371

M32 – an elliptical in the Local Group



Intermediate age, metal rich system

<u>+ ancient metal poor component</u>

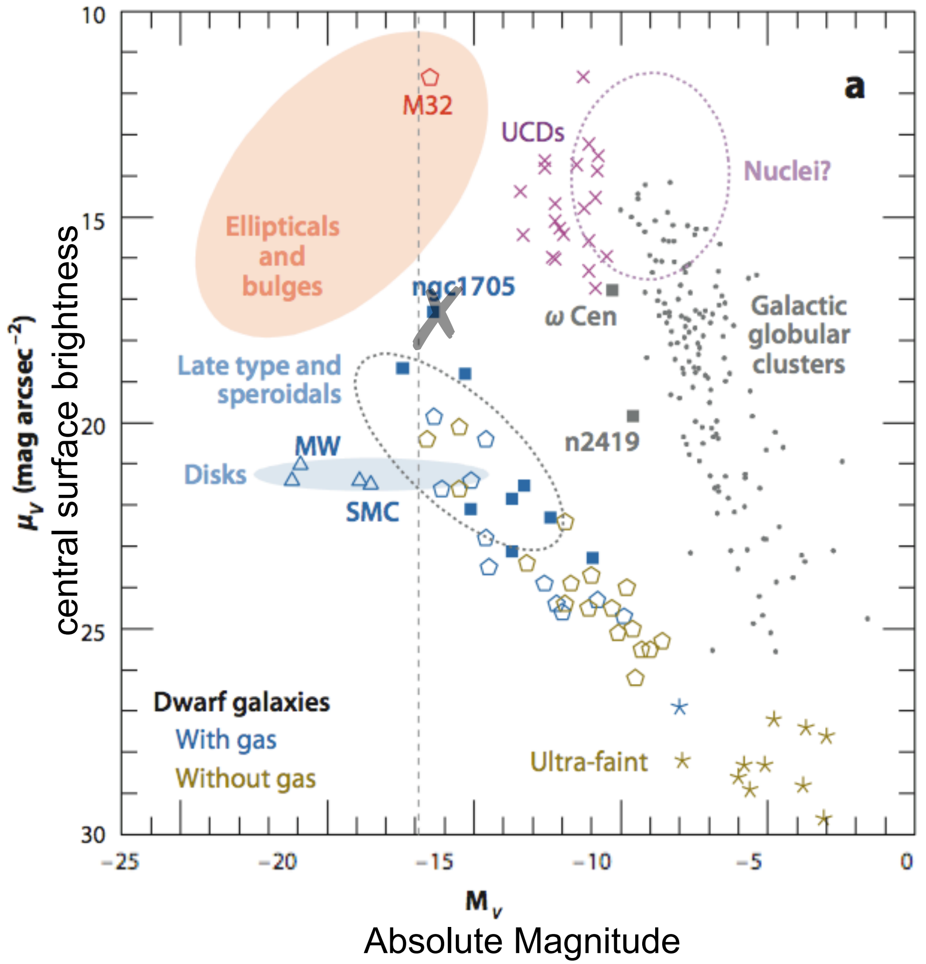


Monachesi et al. 2011, ApJ, 727, 55

M32 – NGC221 (~760kpc)

Fiorentino et al. 2010 ApJ, 708, 817

Global Properties



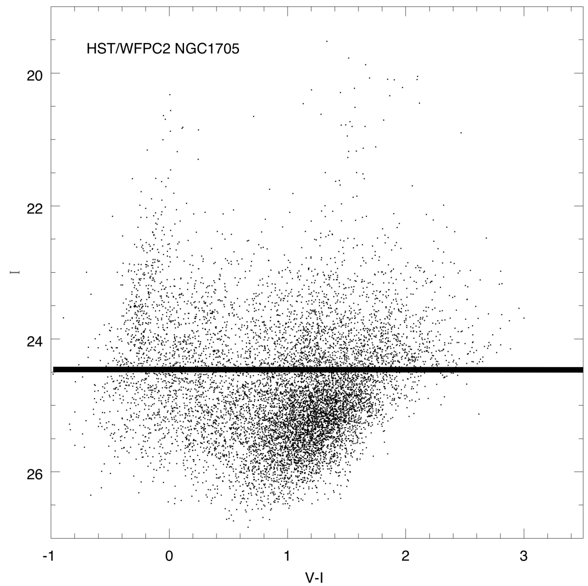
Tolstoy, Hill & Tosi 2009, ARAA, 47, 371

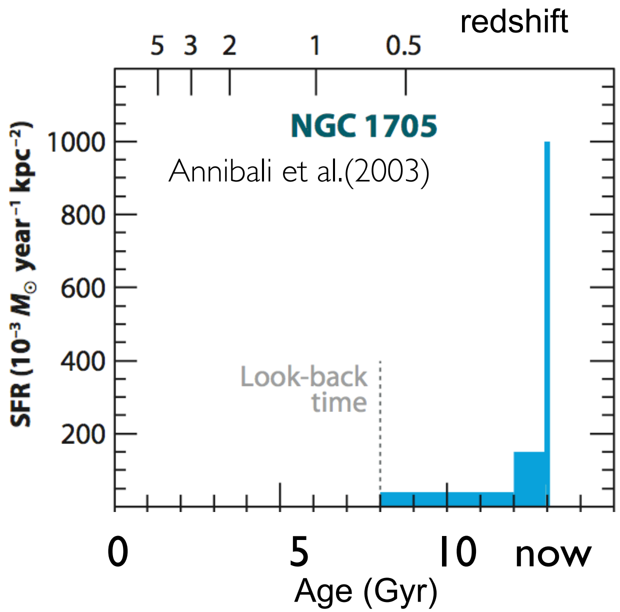
NGC1705: a Blue Compact Dwarf

HST/ACS image

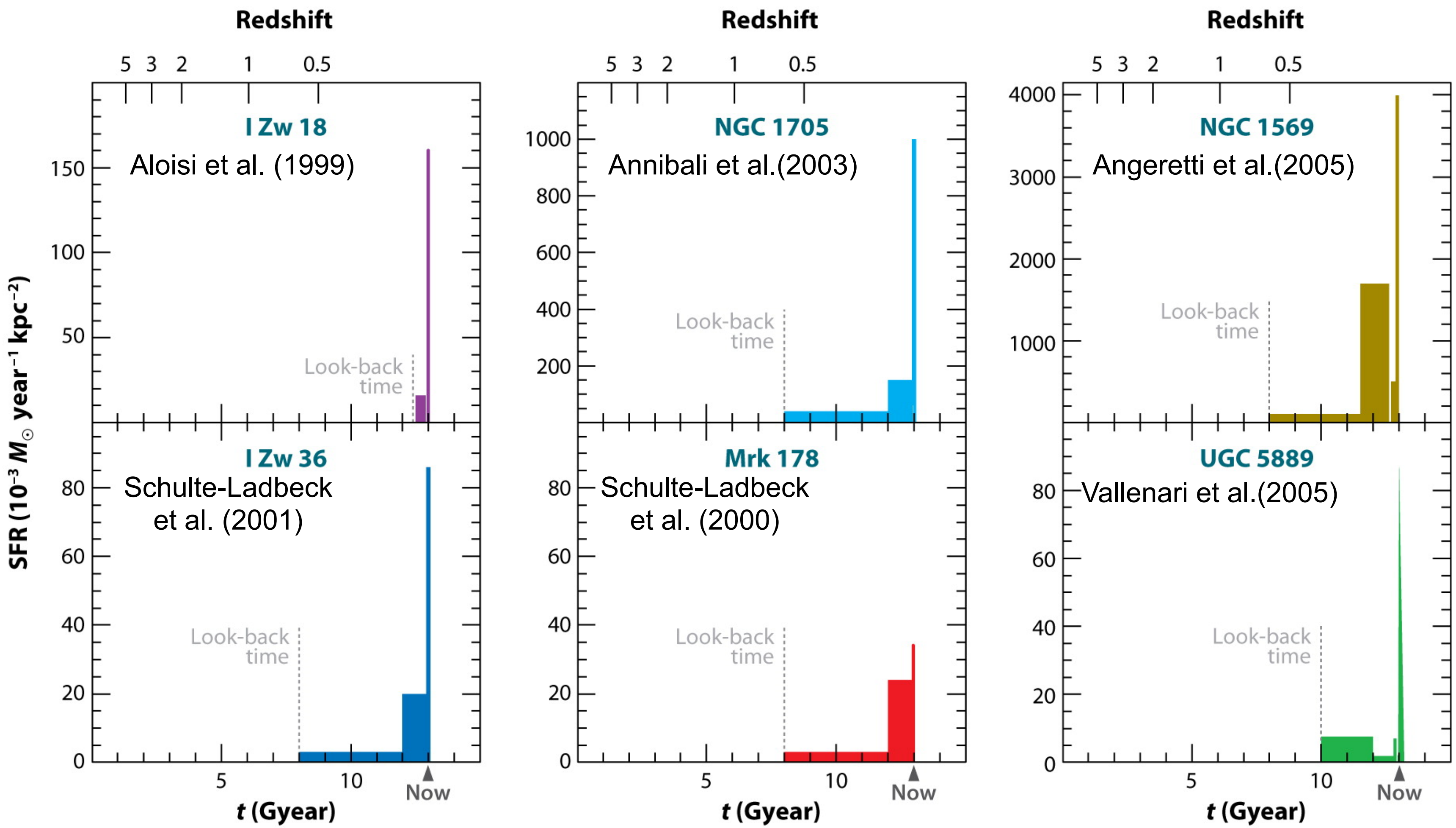
NGC1705 (~5Mpc)

Annibali et al.(2003)



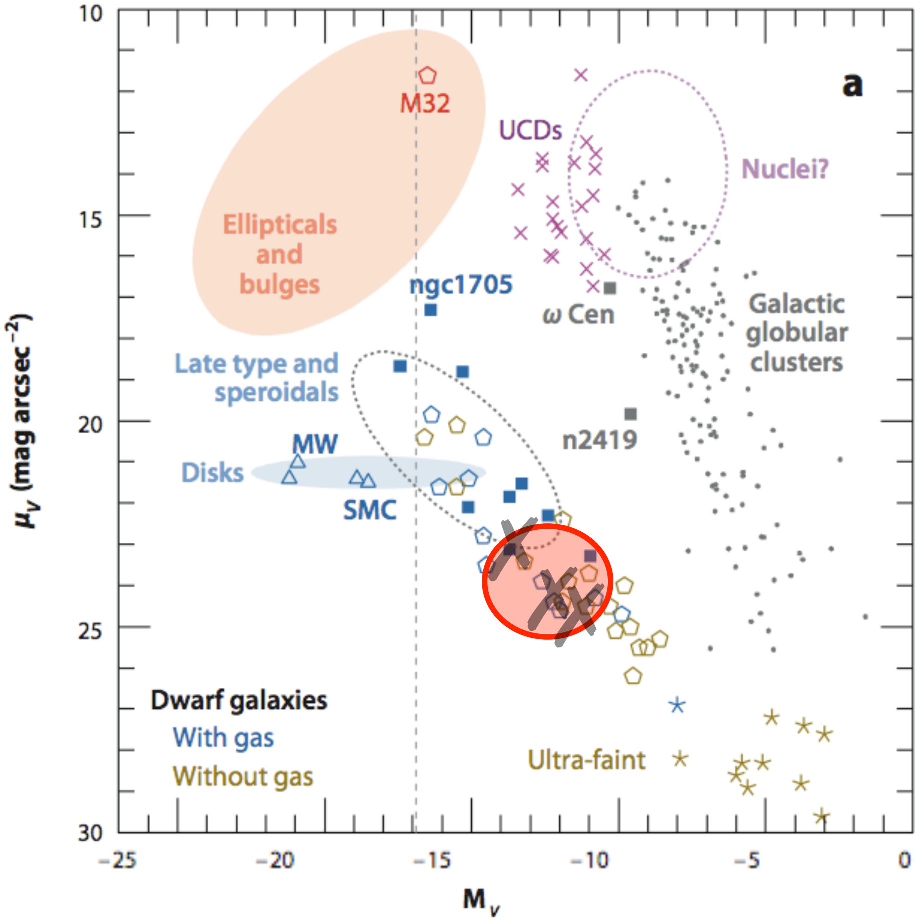


Summary of BCD SFHs



from Tolstoy, Hill & Tosi 2009

Comparing different types in one "region"

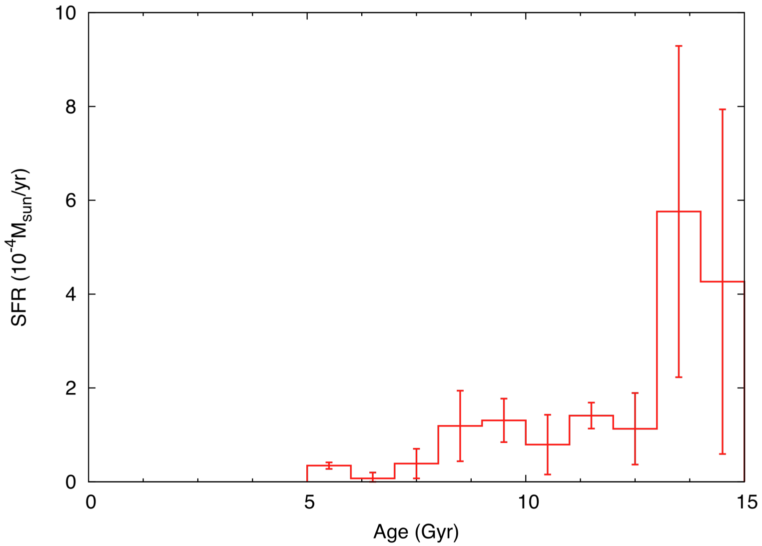


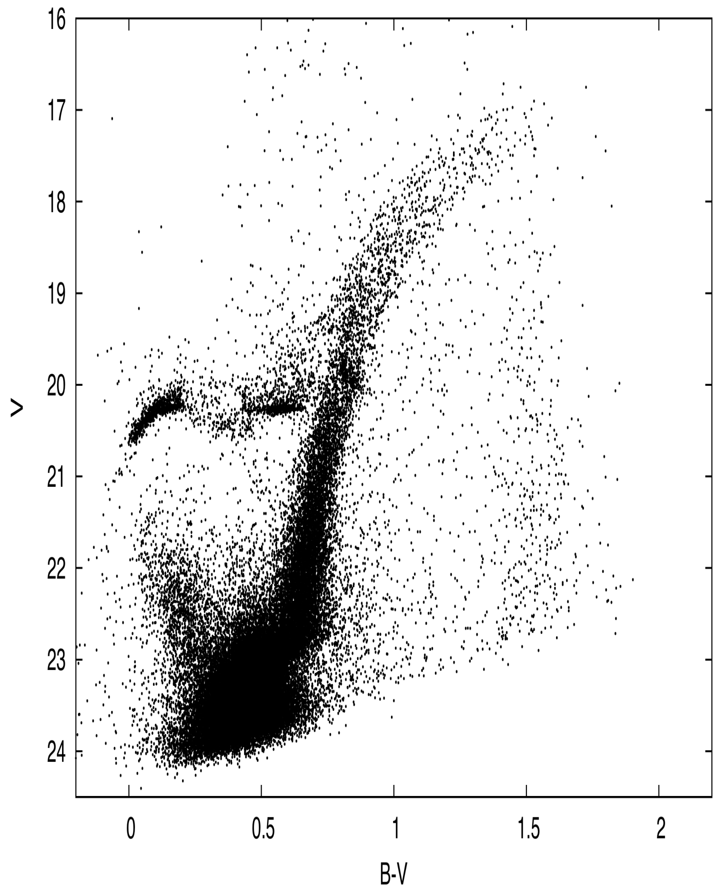
Tolstoy, Hill & Tosi 2009, ARAA, 47, 371

Scl dSph

86 kpc distance

M_v = -11.2



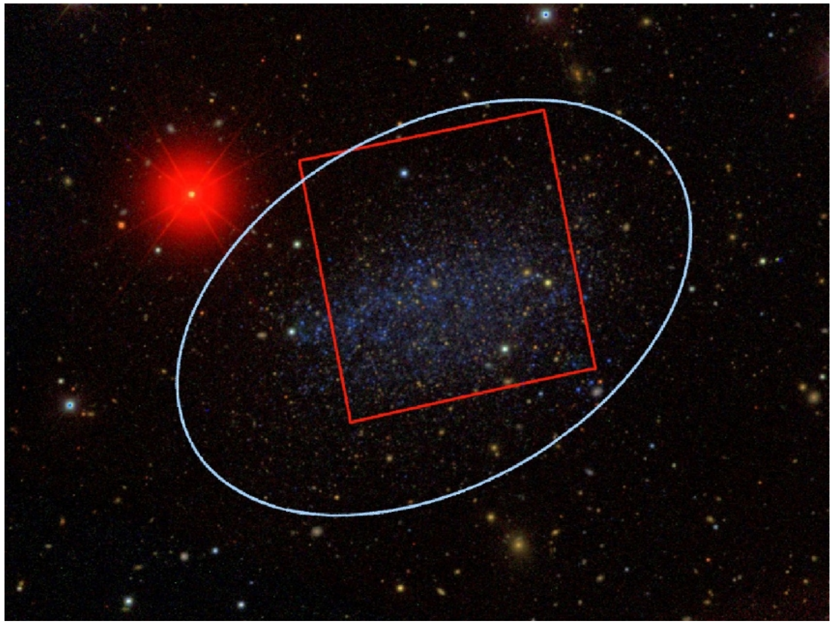


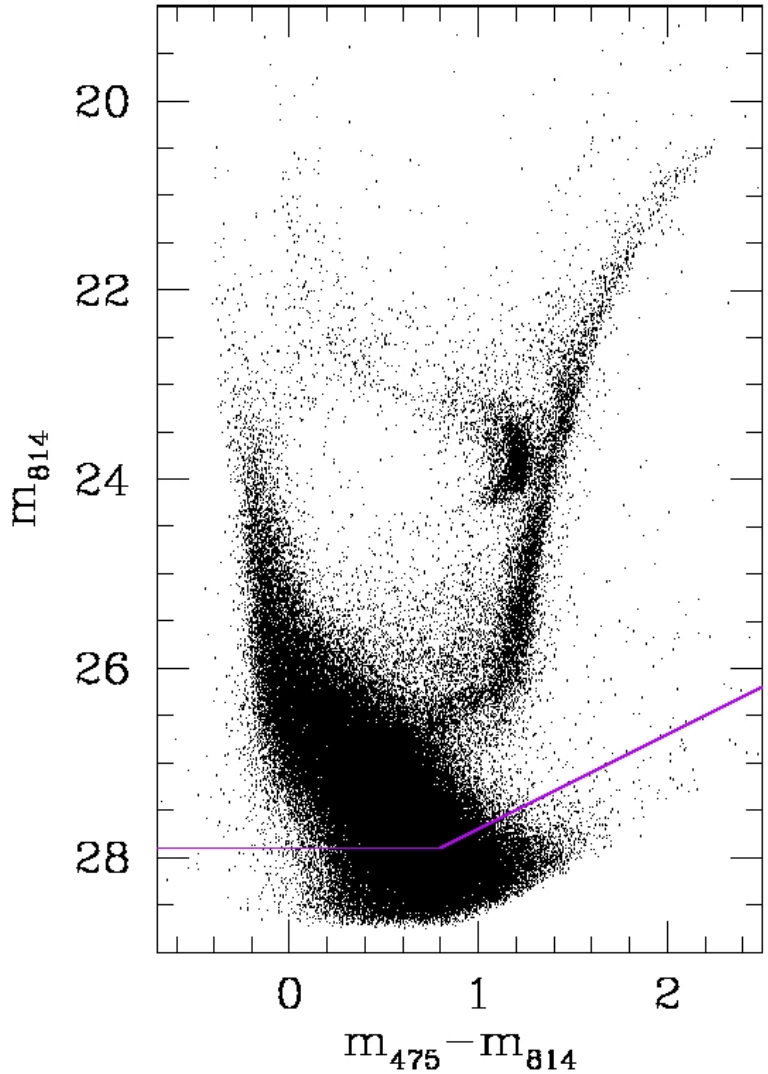
de Boer et al. 2011 A&A, in press

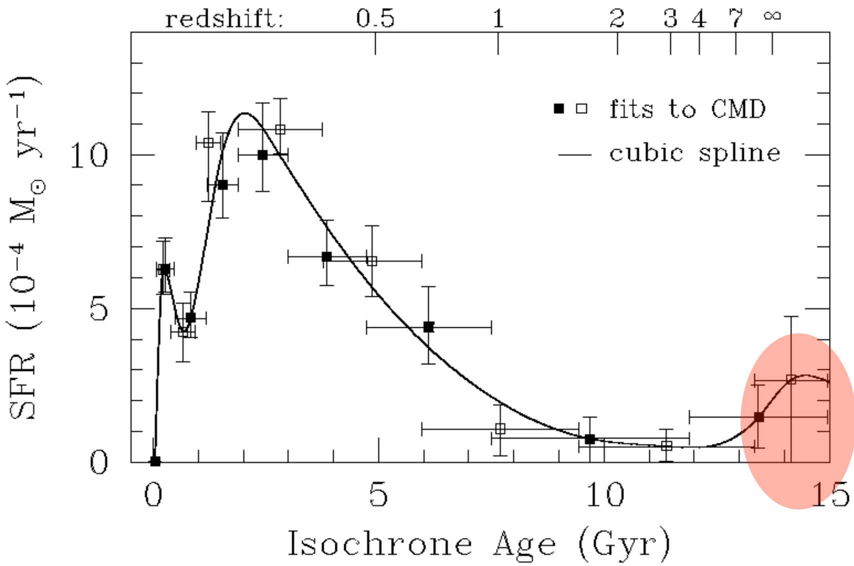
Leo A dI

800 kpc distance

M_v = -11.7







8 candidate RR Lyraes (Dolphin et al. 2002); Fiorentino et al., in prep.

Cole et al. 2007

VII Zw 403: a Blue Compact Dwarf

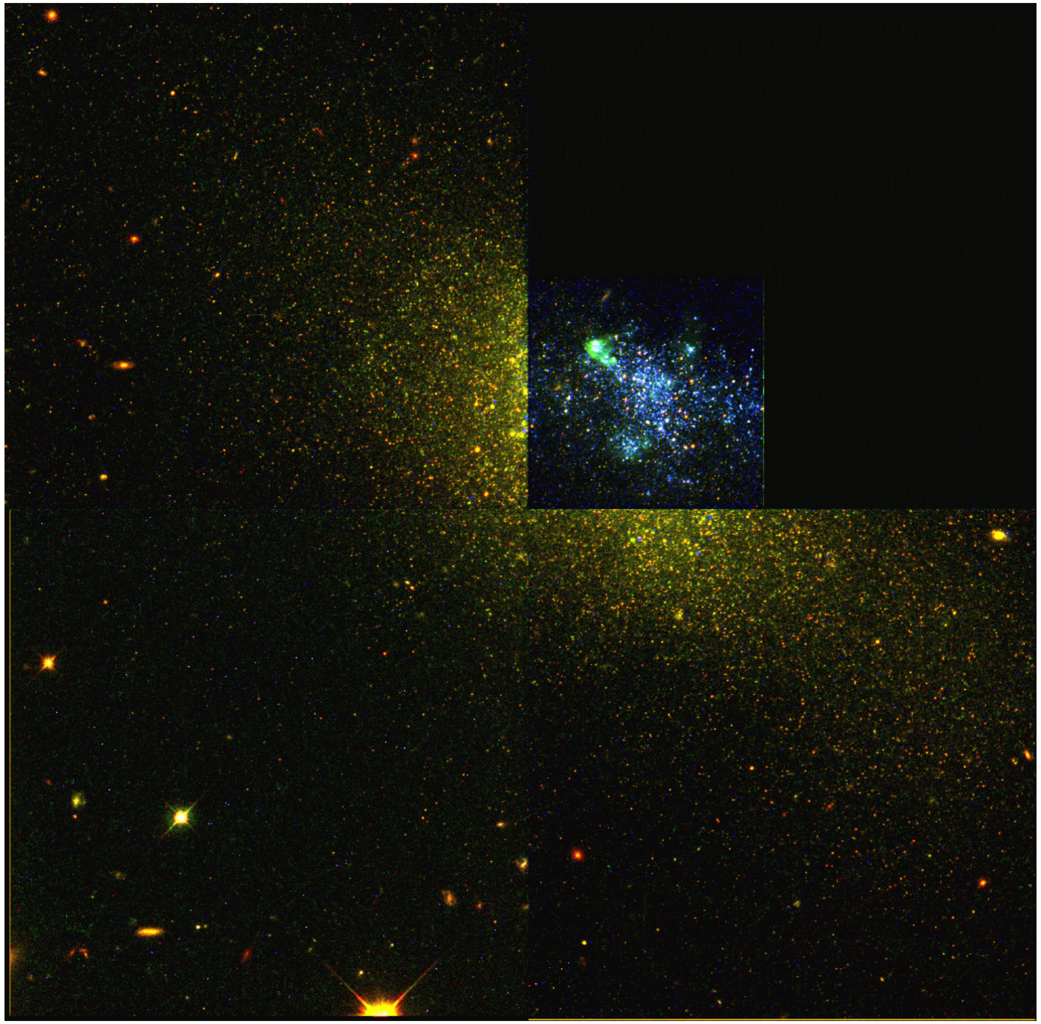
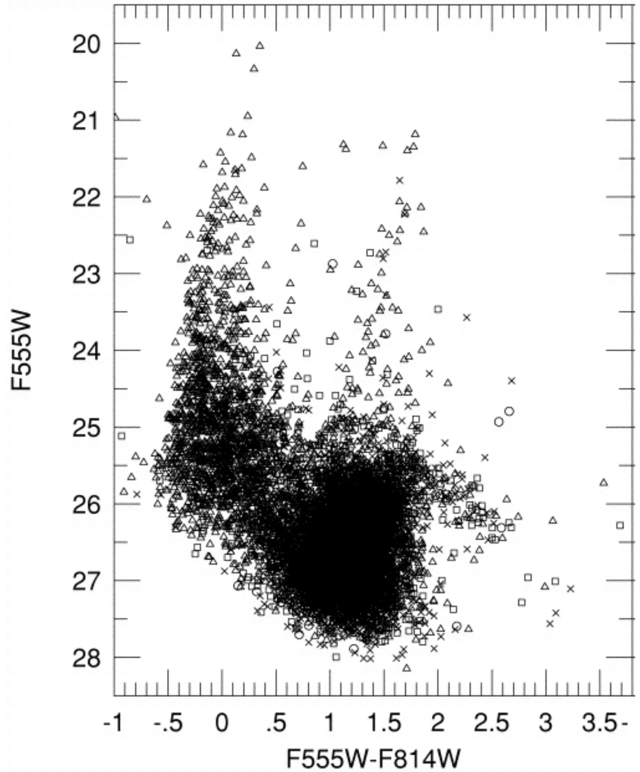
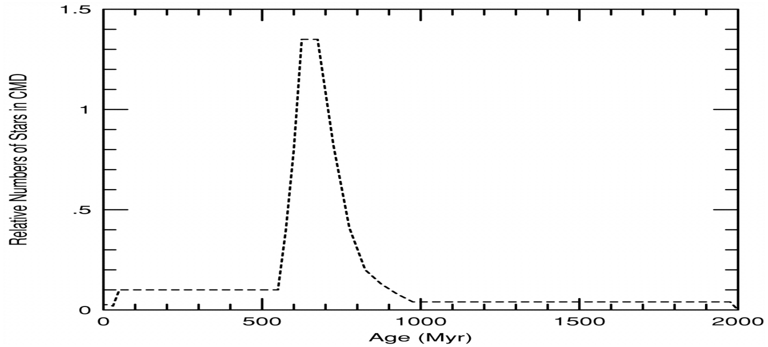


Image: multi-colour HST/WFPC2, credit D. Hunter

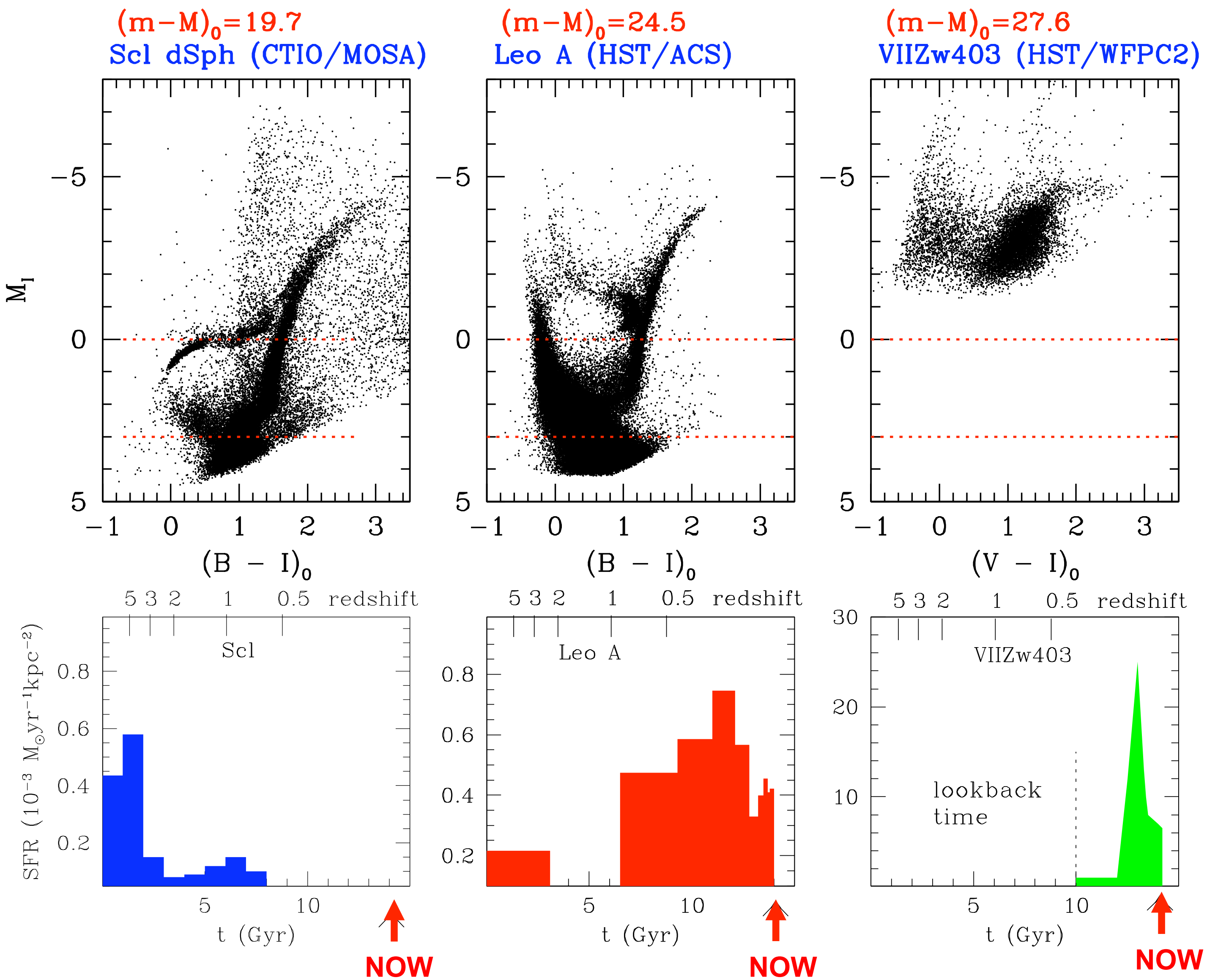




VII Zw 403 – UGC 6456 (~4.5Mpc)

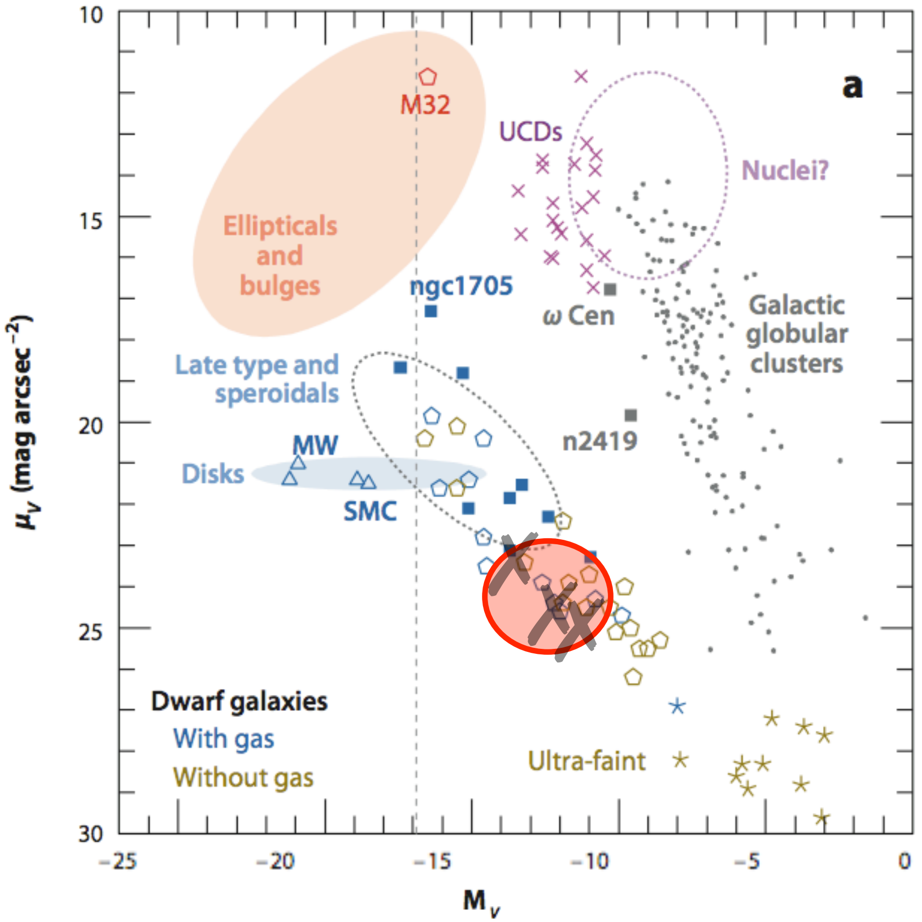
Lynds et al. 1998

Comparing the different types



de Boer et al. 2011 | Cole et al. 2007 | Lynds et al. 1998

Comparing different types in the transition region



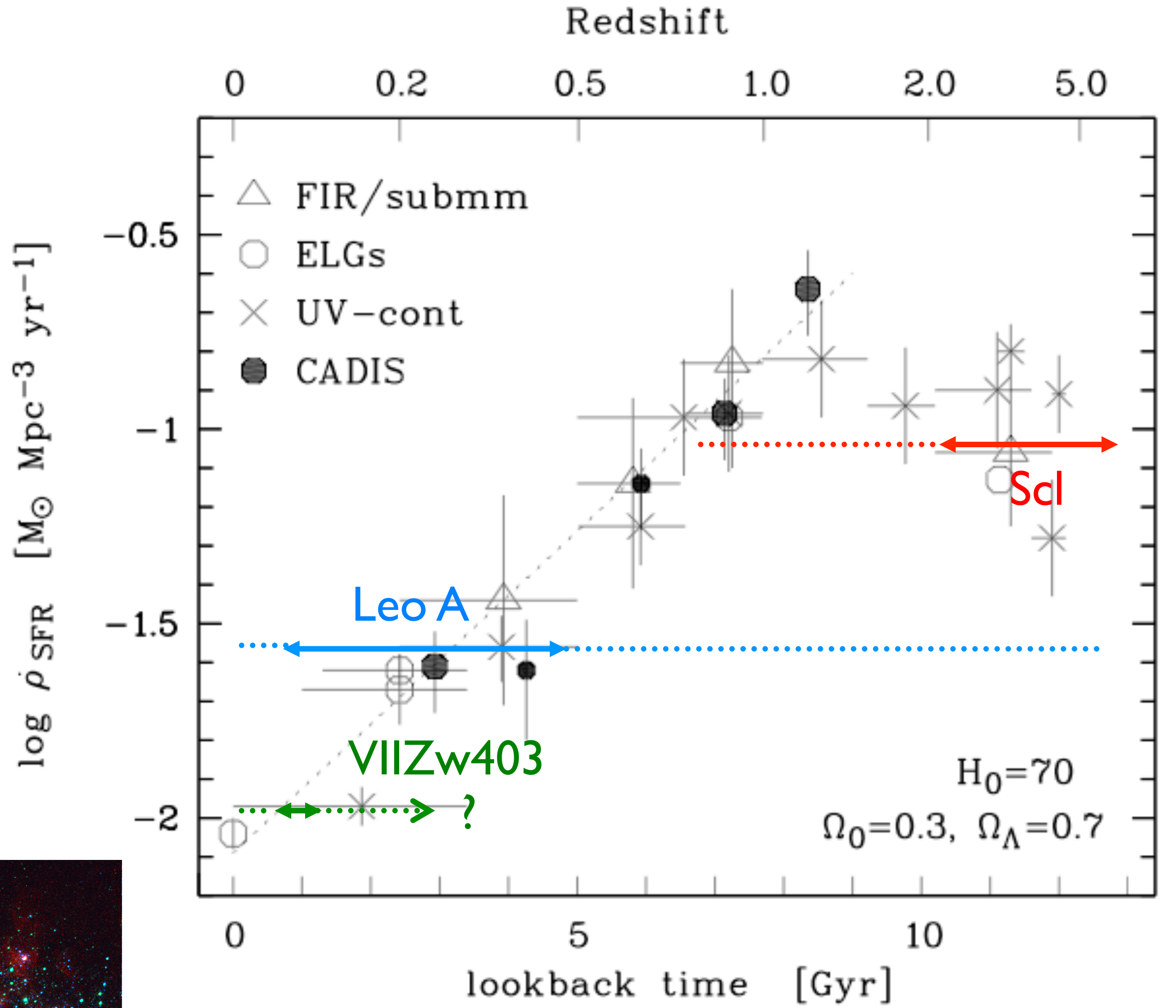
Different SFHs - yet global properties still correlate

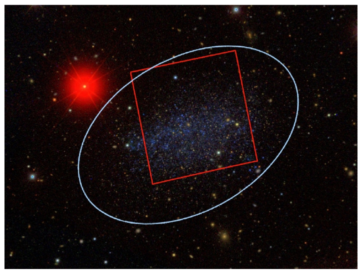
dSph, dI & BCDs differ only in that dI & BCD have on-going star formation

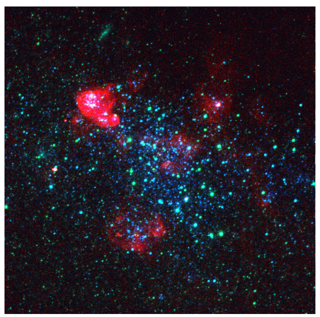
Tolstoy, Hill & Tosi 2009, ARAA, 47, 371

Cosmological Context

Evolution of SFR density

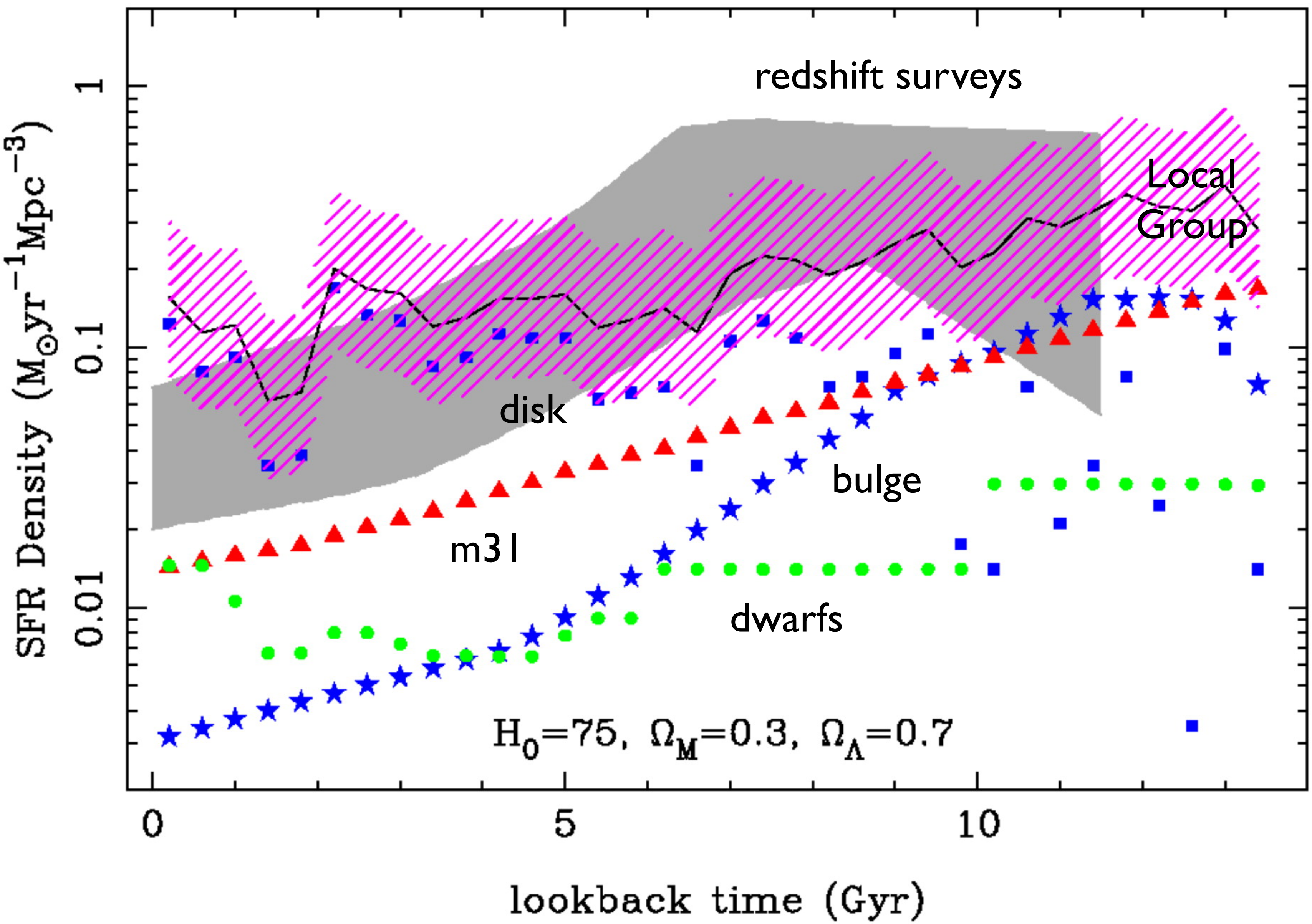






Hippelein et al. 2003

Star Formation Density in Local Group



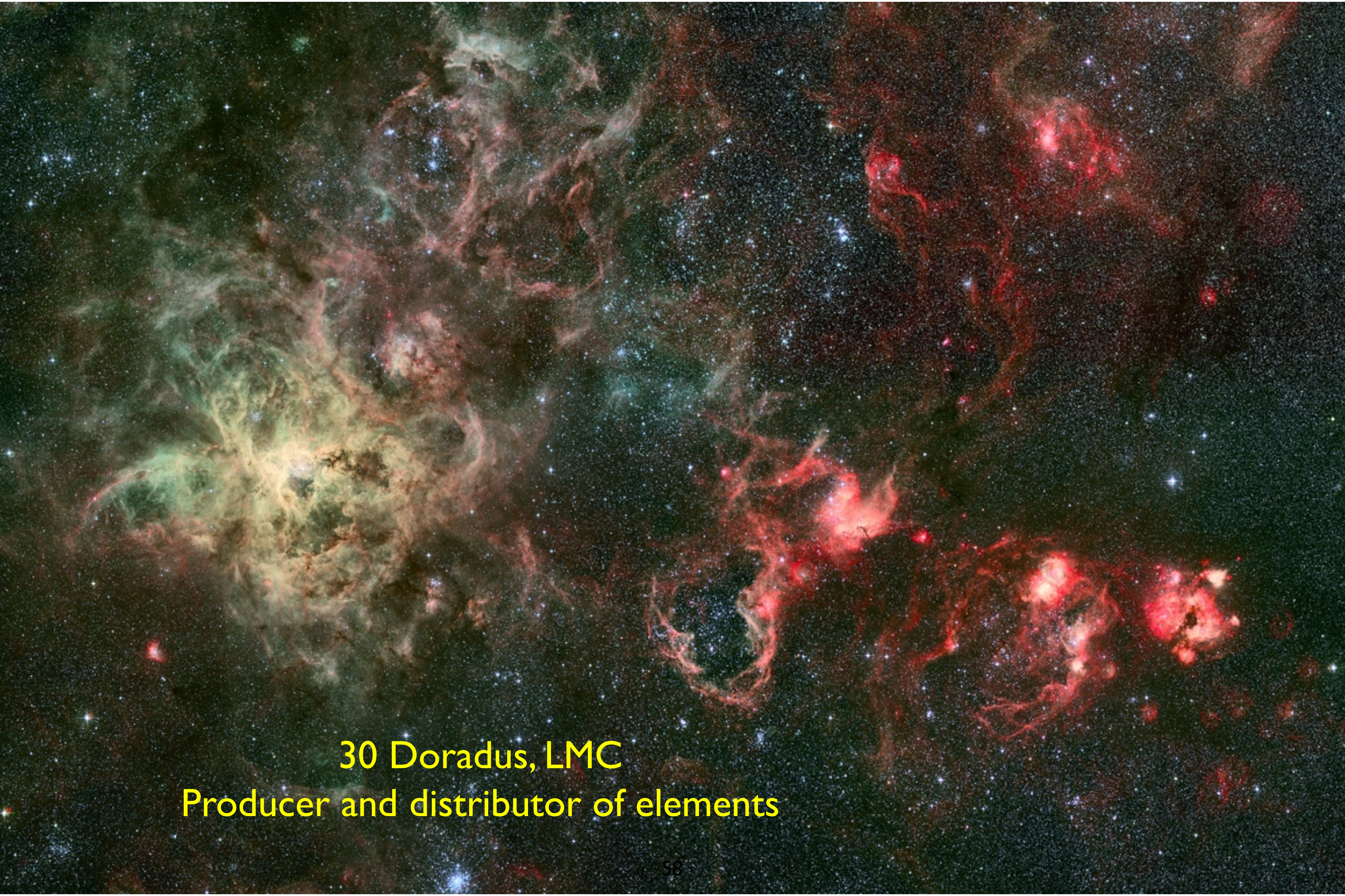
Hopkins et al. 2001

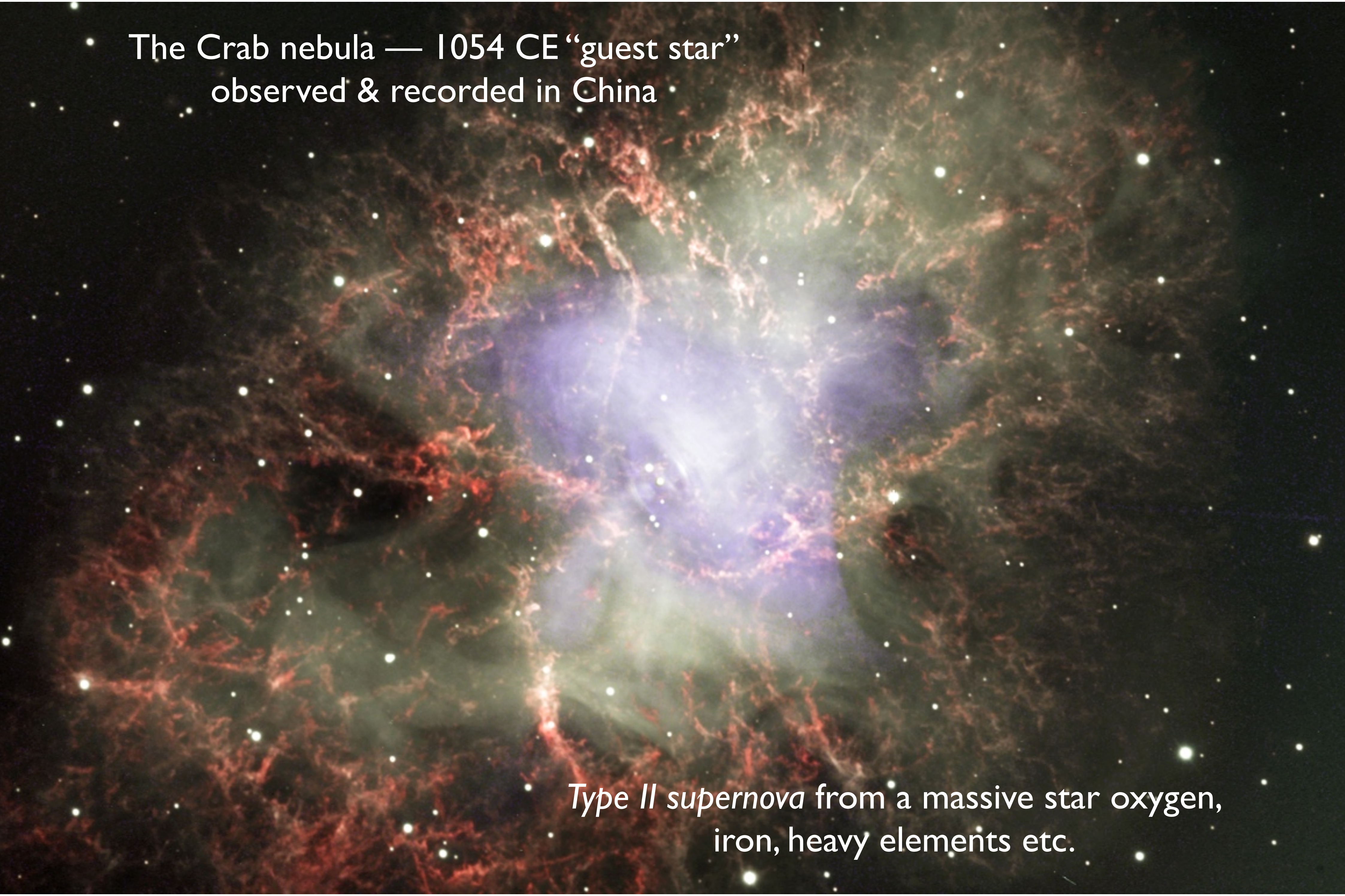
Next lecture I tell you about metallicites and spectroscopy

Part II

- Spectroscopy –

metallicities, abundances &
kinematics

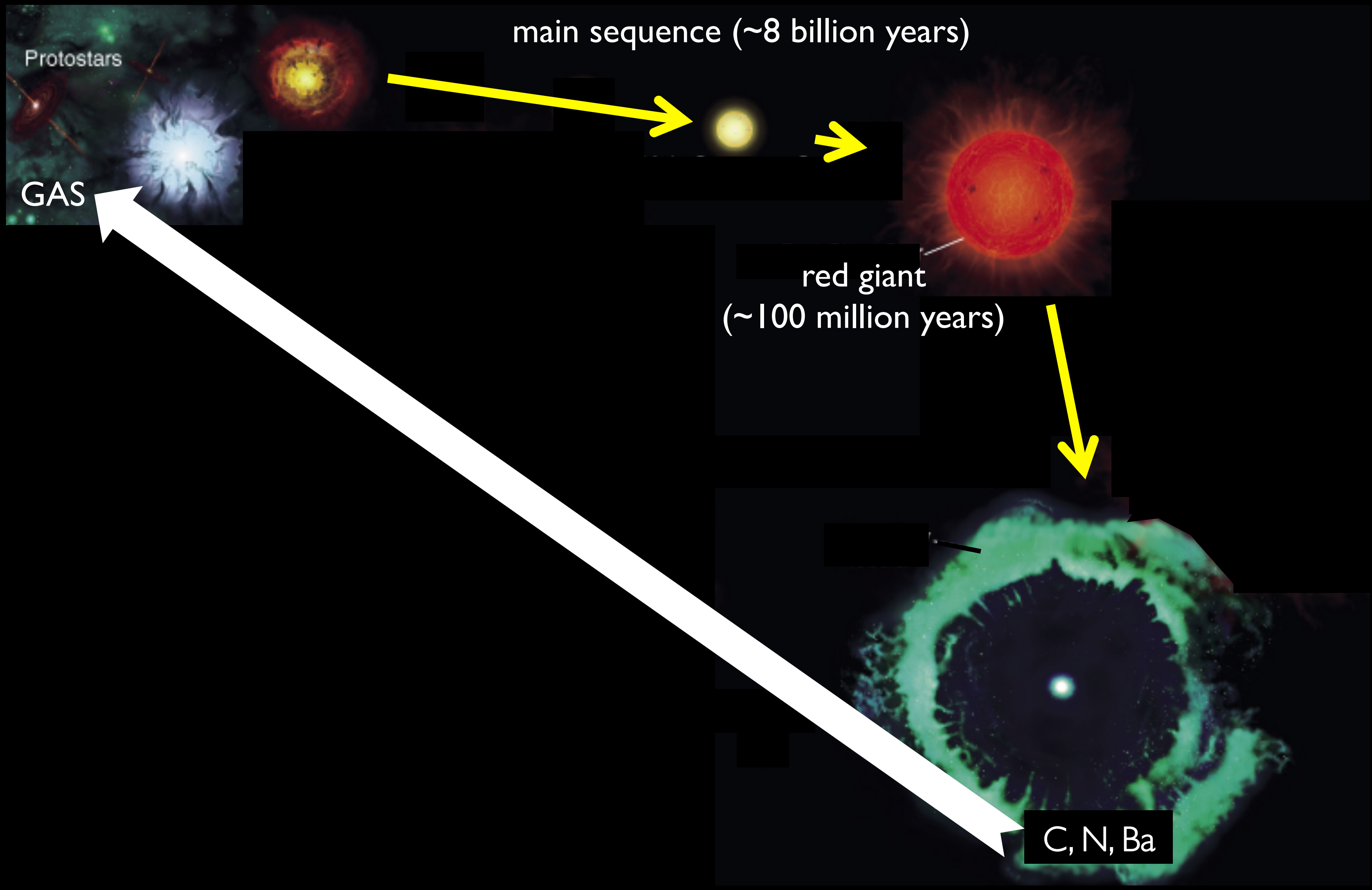

30 Doradus, LMC
Producer and distributor of elements


The Crab nebula — 1054 CE "guest star"
observed & recorded in China
Type II supernova from a massive star oxygen,
iron, heavy elements etc.


…and most stars lose their mass more slowly….
The Helix: a planetary nebula from a Sun-like star, producing carbon, nitrogen etc.

Nucleosynthesis

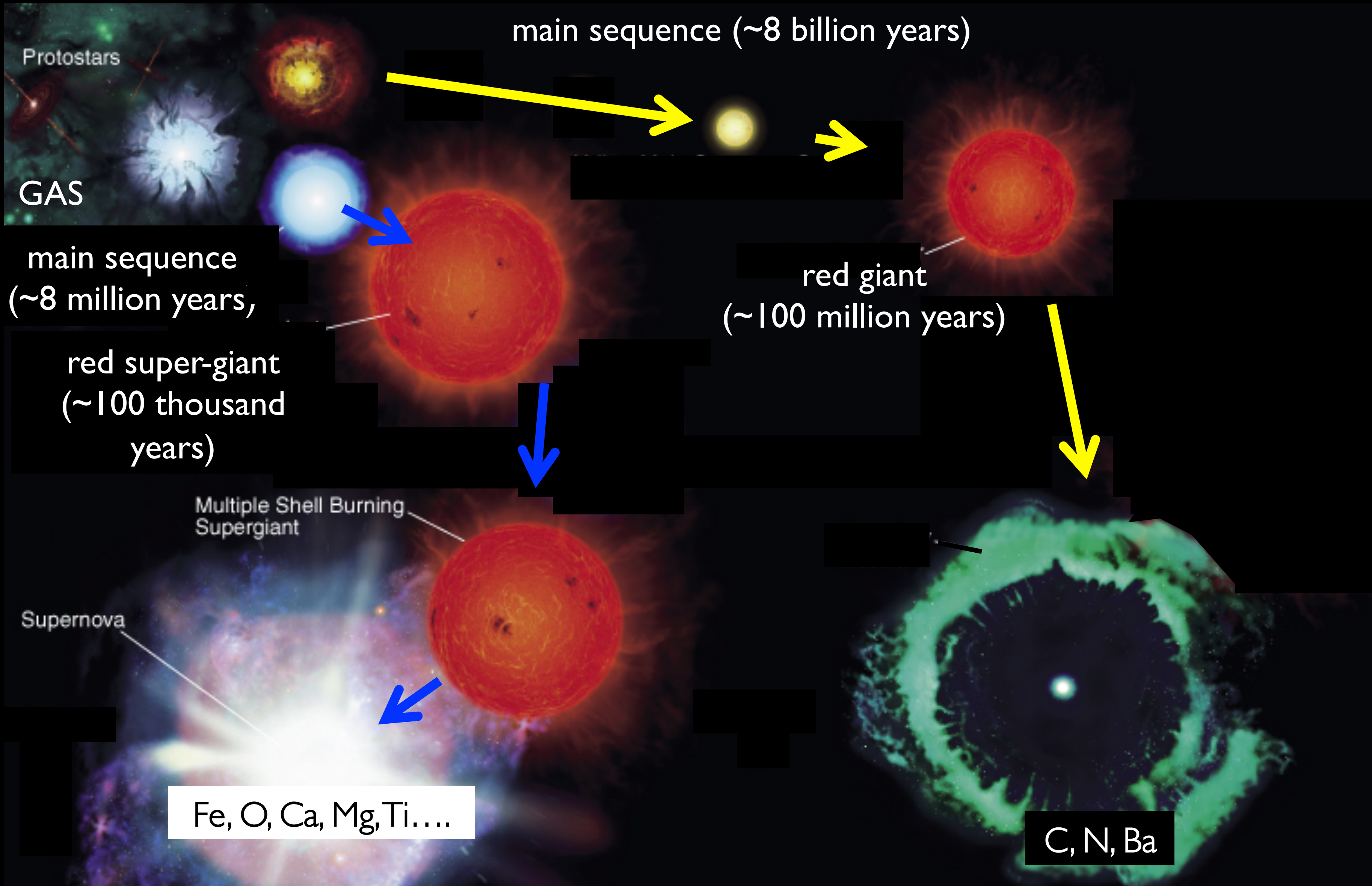
LOW MASS STAR (the Sun)



Planetary nebula (100 thousand years)

Nucleosynthesis

LOW MASS STAR (the Sun)

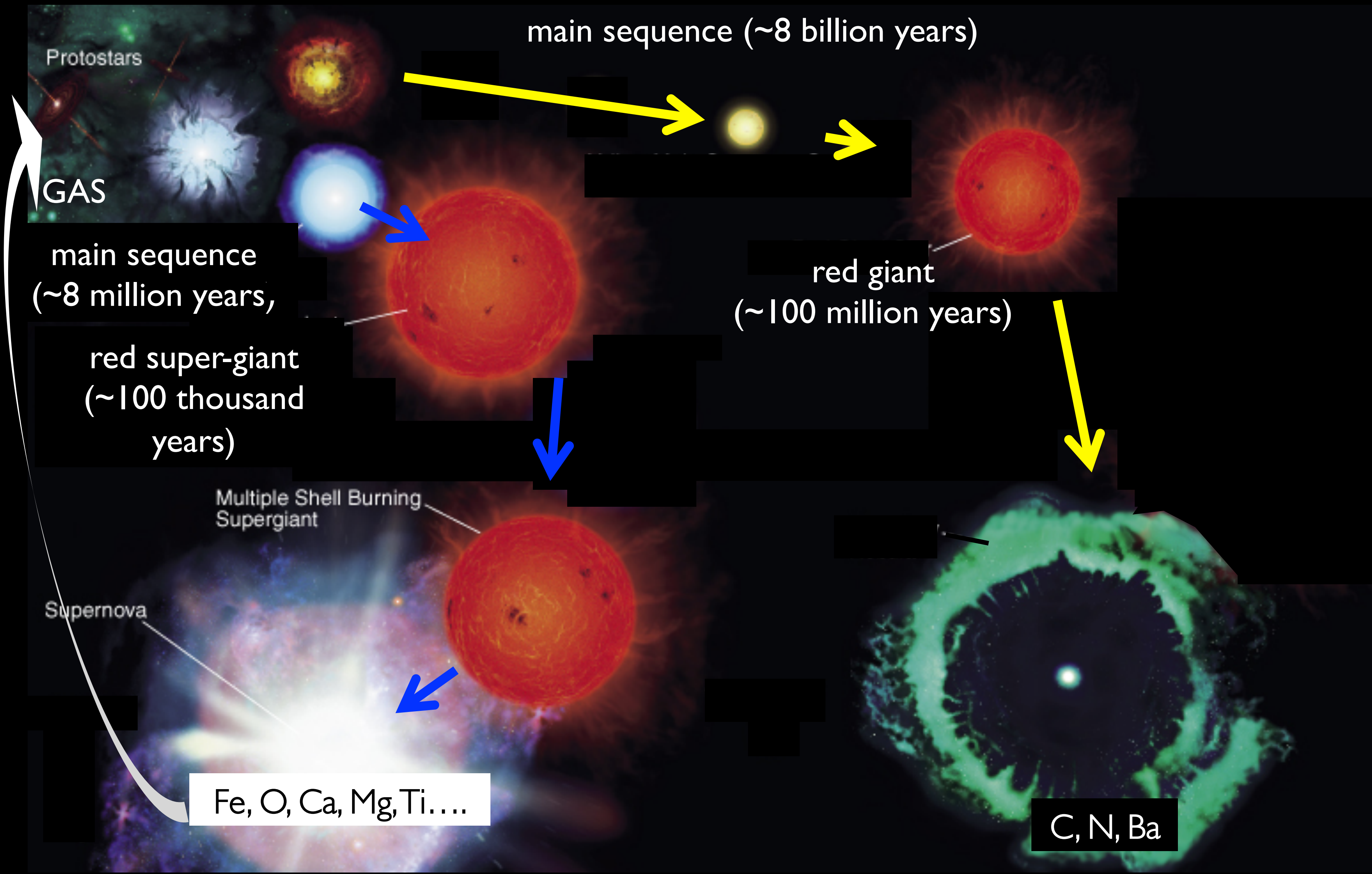


HIGH MASS STAR (20 x Sun)

Planetary nebula (100 thousand years)

Nucleosynthesis

LOW MASS STAR (the Sun)



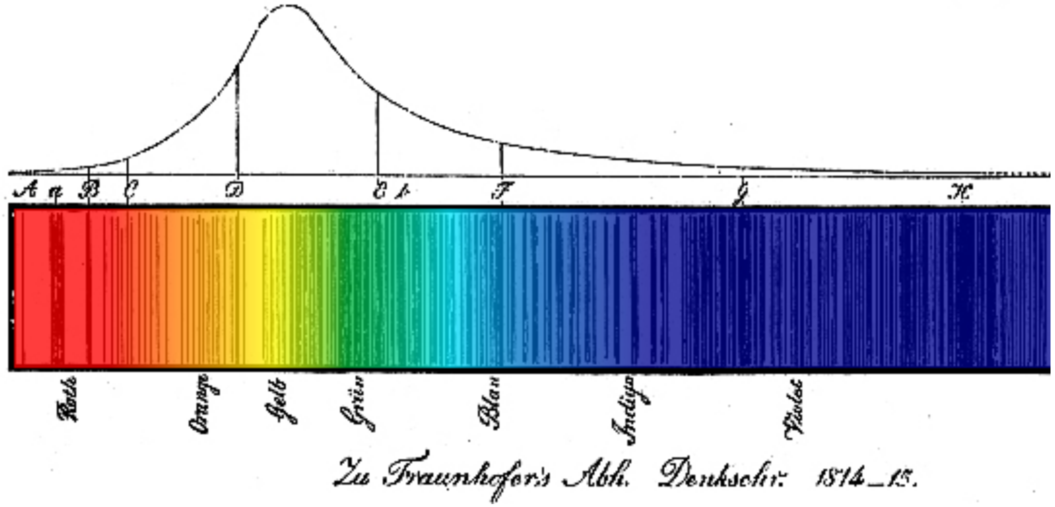
HIGH MASS STAR (20 x Sun)

Planetary nebula (100 thousand years)

A spectrum...

Kirchhoff

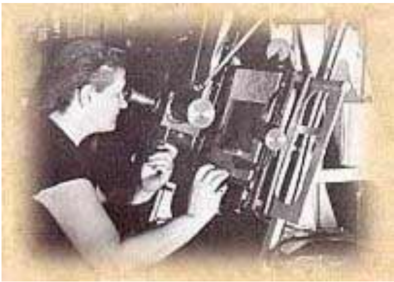
Fraunhofer



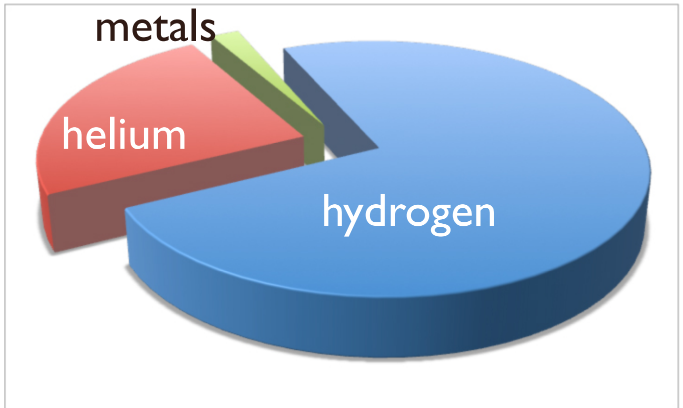
- Fraunhofer (1817) absorption lines in the solar spectrum.

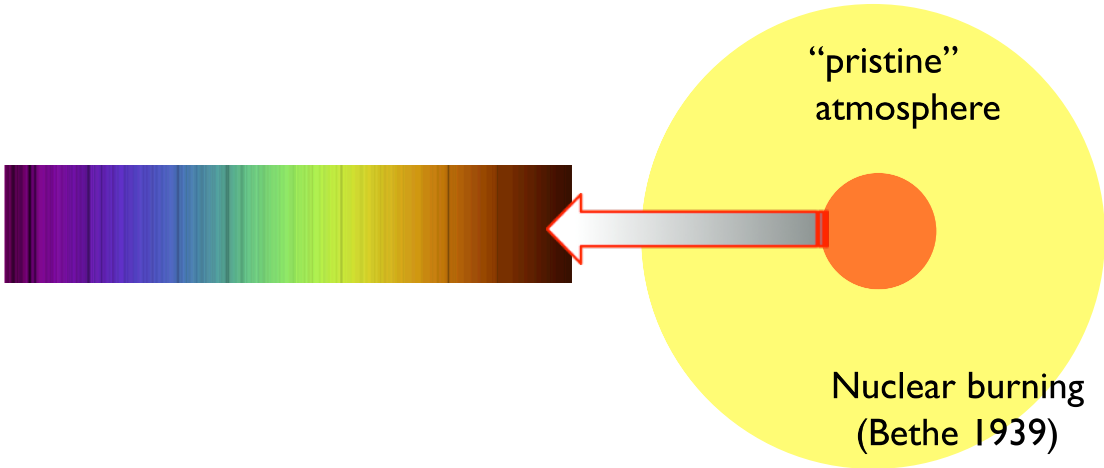
- Kirchhoff (1859) every chemical element has its own spectral lines (a DNA fingerprint).

- Payne[-Gaposchkin] (1925) stars are mostly Hydrogen and Helium



Cecilia Payne-Gaposchkin

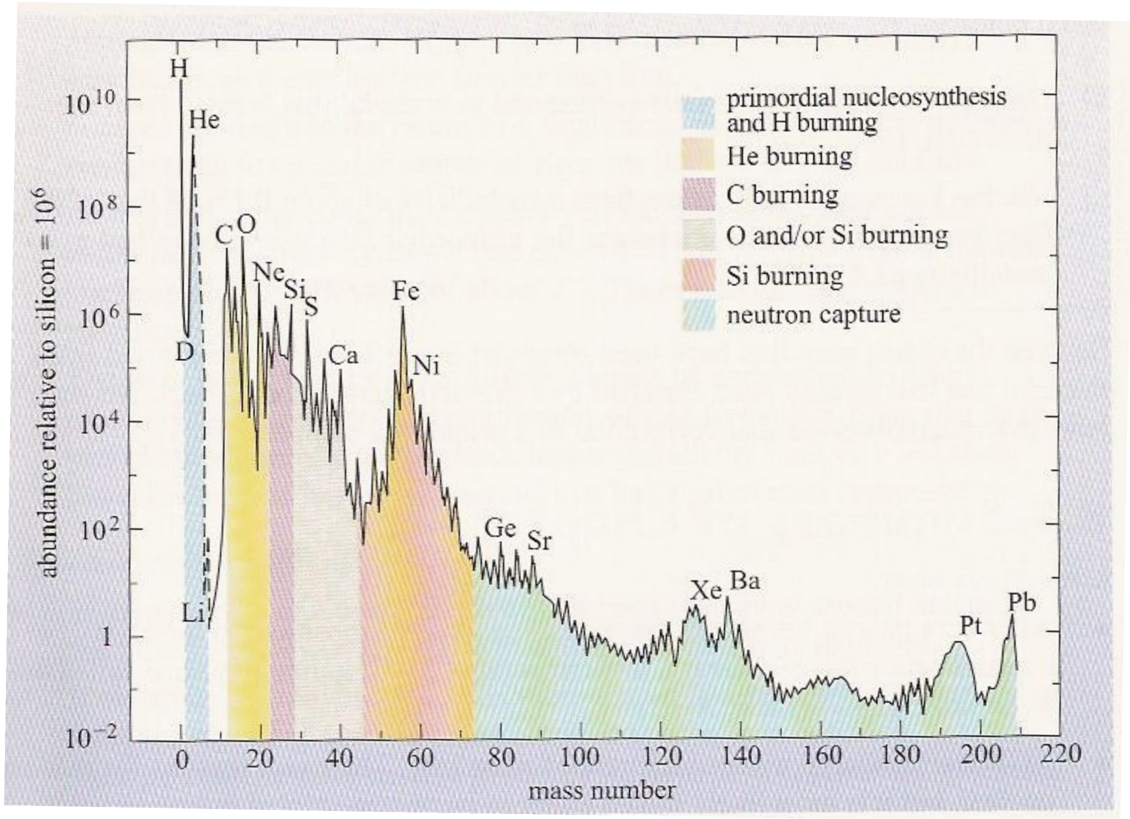




- nucleosynthesis, Burbidge, Burbidge, Fowler & Hoyle (1957)

We are all made of stardust....

All elements in the Universe heavier than He & Li are formed within stars: NUCLEOSYNTHESIS



Burbidge, Burbidge, Fowler & Hoyle 1957

These are the abundances in the gas out of which our Sun and our Solar System was formed about 4Gyr ago; other stars formed at other times will be different: CHEMICAL TAGGING

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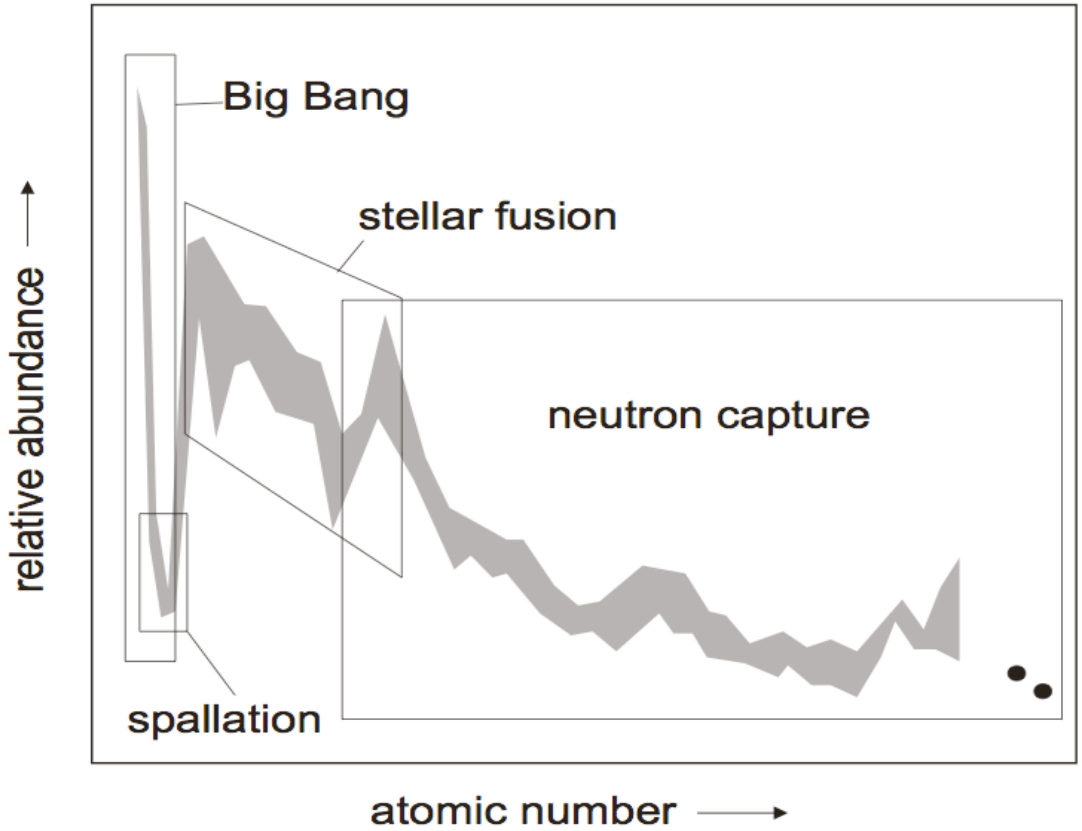


Burbidge, Burbidge, Fowler & Hoyle 1957

These are the abundances in the gas out of which our Sun and our Solar System was formed about 4Gyr ago; other stars formed at other times will be different: CHEMICAL TAGGING

Chemical Tagging

- Light Elements – e.g., O Na Mg Al
  tracers of deep mixing abundances patterns
  (globular clusters versus field stars)

- α- Elements – e.g., O Mg Si Ca Ti
  dominated by products of Supernovae II

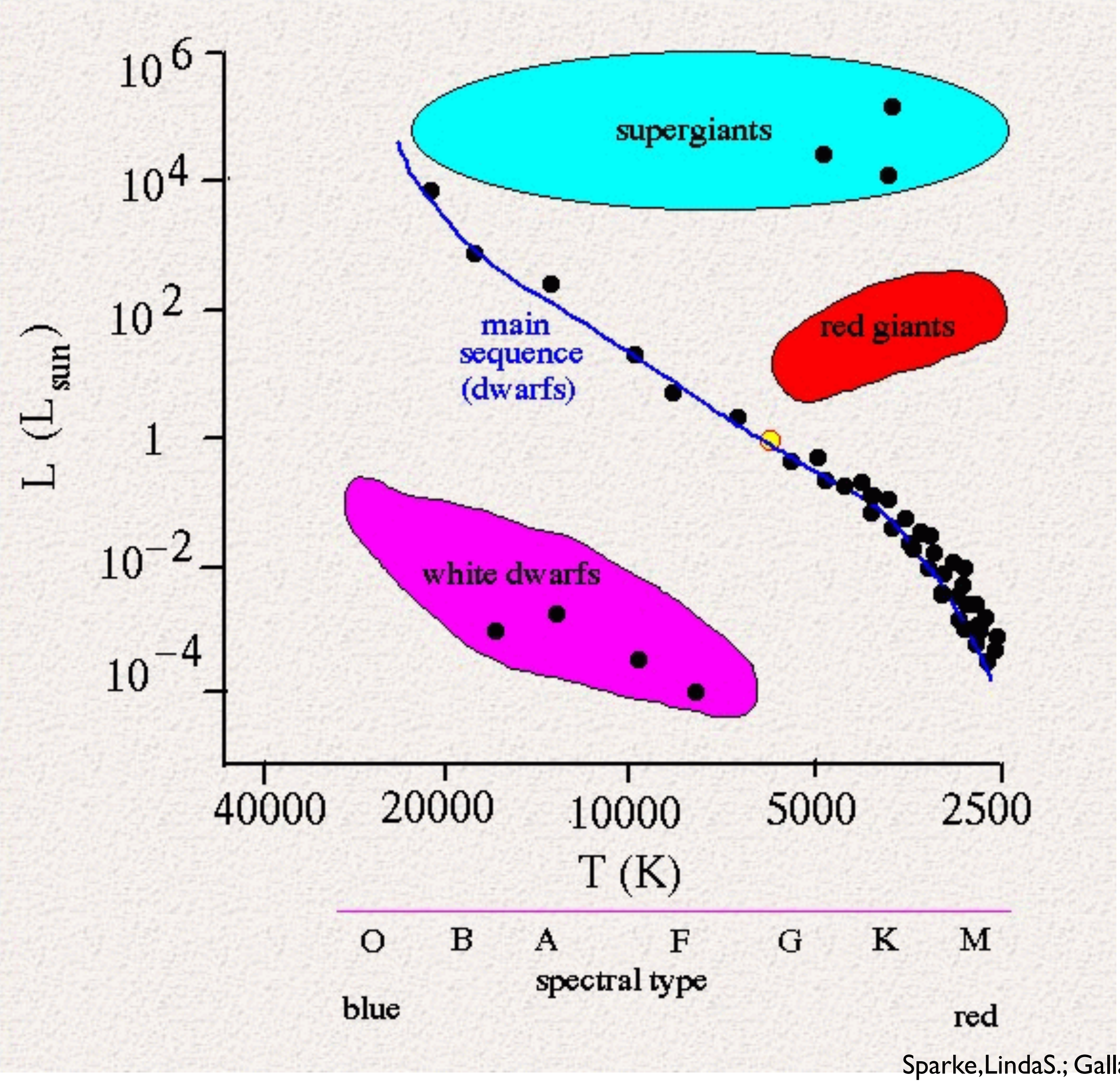
- Iron-peak Elements e.g., V Cr Mn Co Ni Cu Zn
  explosive nucleosynthesis (supernovae I)

- Heavy Elements (Z > 30)
  mix of r- and s- process elements
  e.g., s-process e.g., Ba, La (low mass stellar winds)
  r-process e.g., Eu (supernovae?)

McWilliam 1997 ARAA, 35, 503
Freeman & Bland-Hawthorn 2002 ARAA, 40, 487

Spectral Types: temperature sequence

O B A F G K M



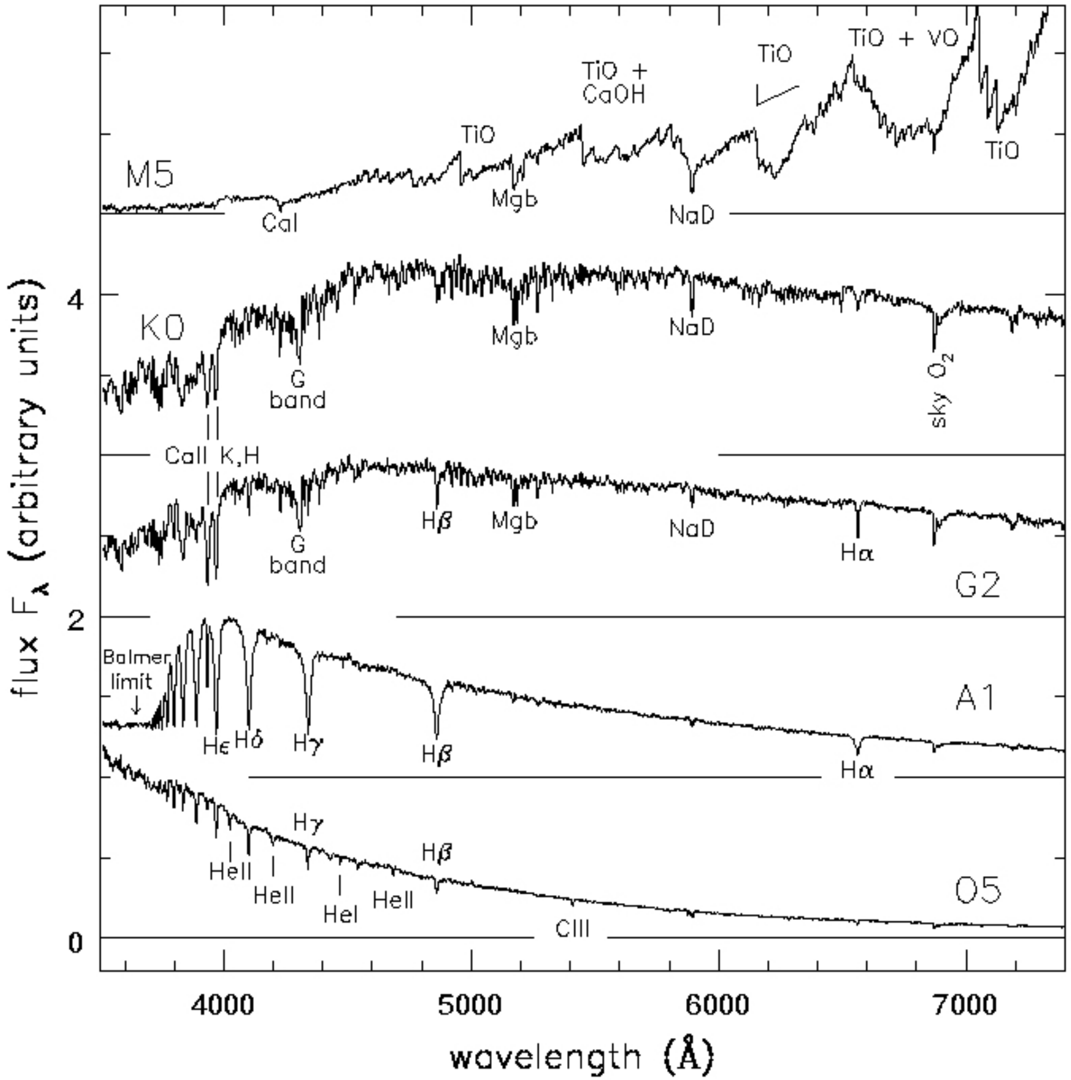
Sparke,LindaS.; Gallagher,JohnS.,III,2007: Galaxies in the Universe: An Introduction, Cambridge University Press

Spectral Types: temperature sequence

O B A F G K M

<u>Metal lines</u>: Strongest when temperature is low enough that lower ionization stages are populated.

The metal lines become progressively stronger as the temperature cools and dominate in the F, G, K stars.



T ~ 4000K

Molecules!

Mainly neutral metal lines

T ~ 6000K

Ionised Metal lines

T < 11 000K

Dominated by neutral H

T ~ 30 000K

Highly ionised species

Sparke, Linda S.; Gallagher, John S., III, 2007: Galaxies in the Universe: An Introduction, Cambridge University Press

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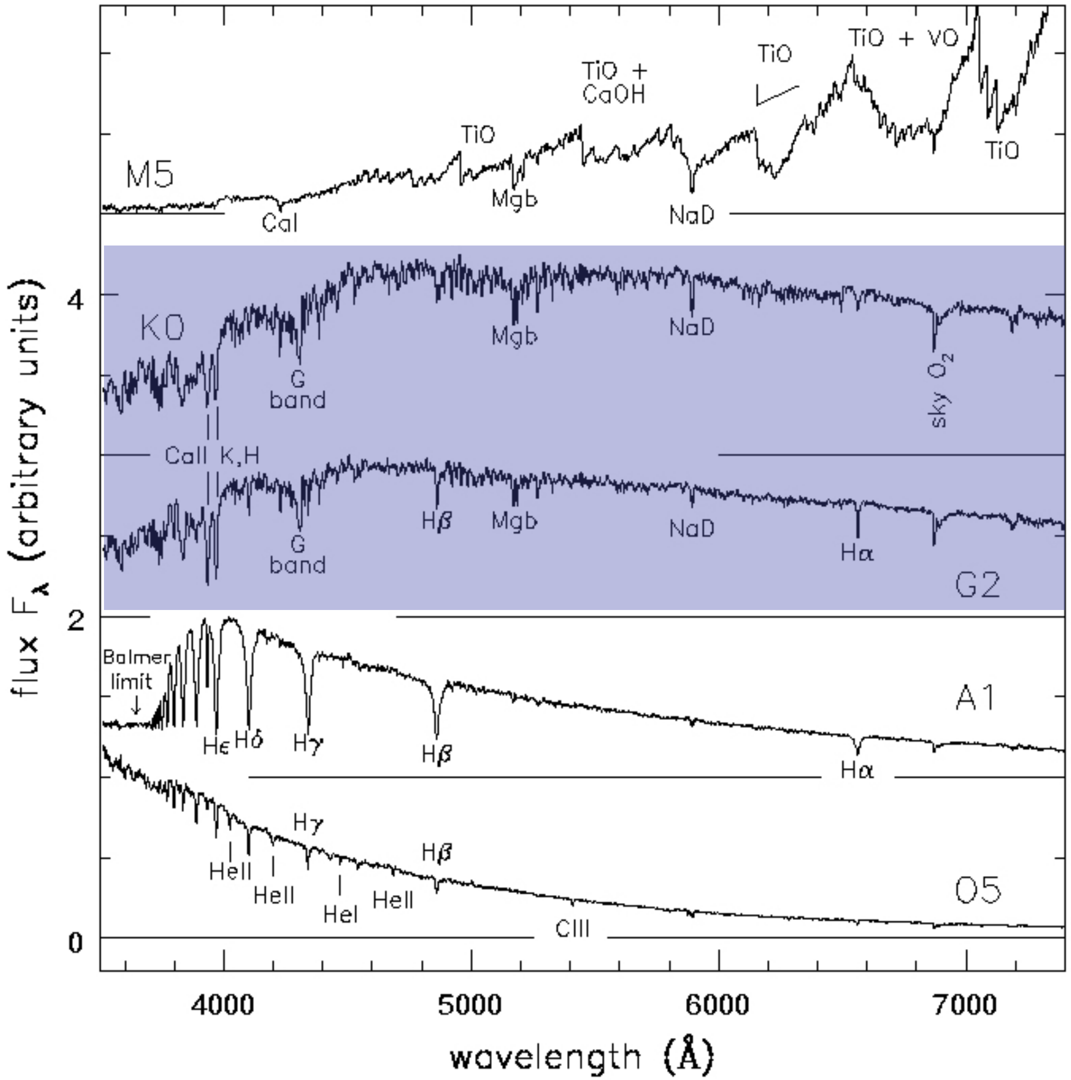

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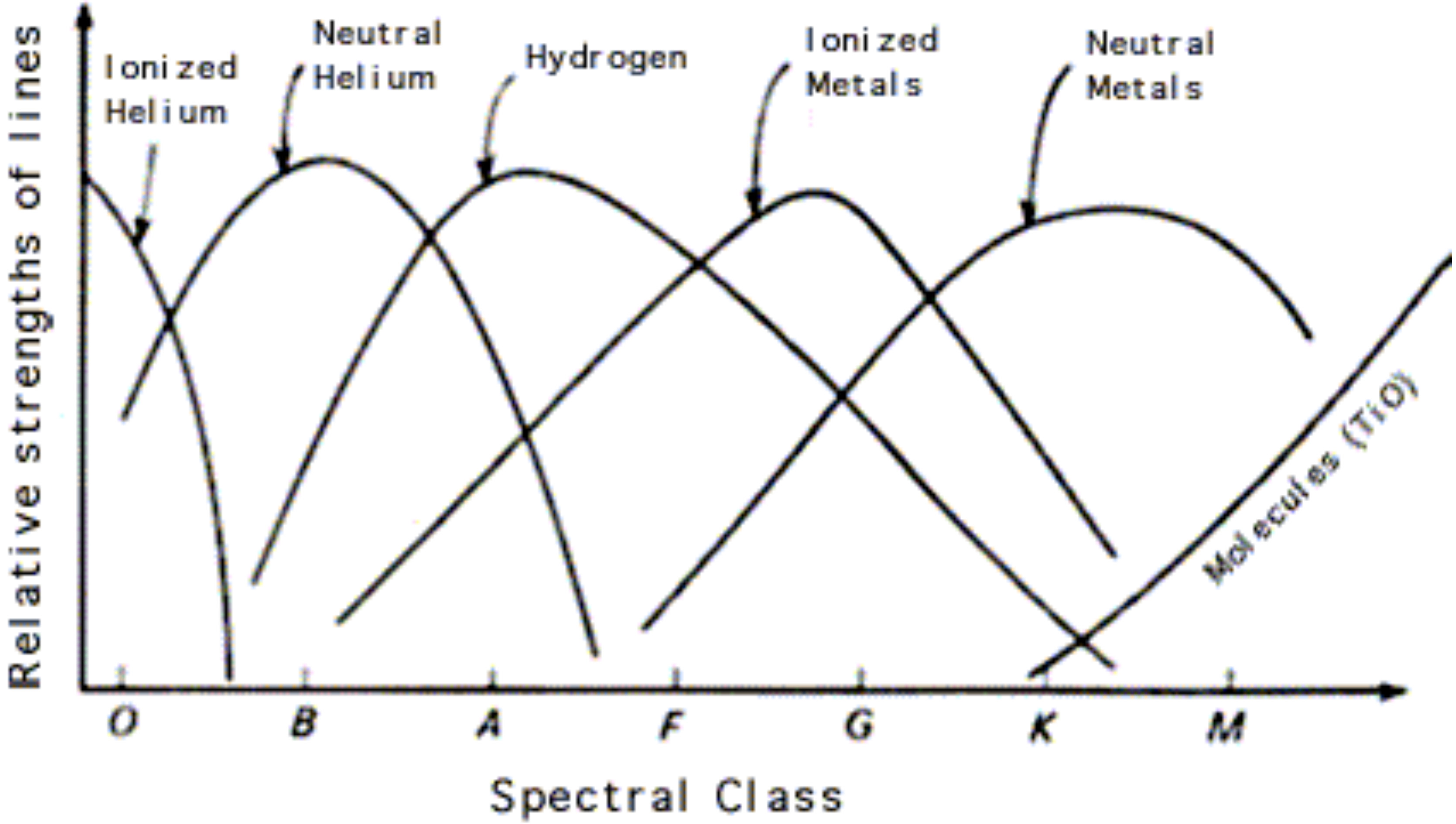
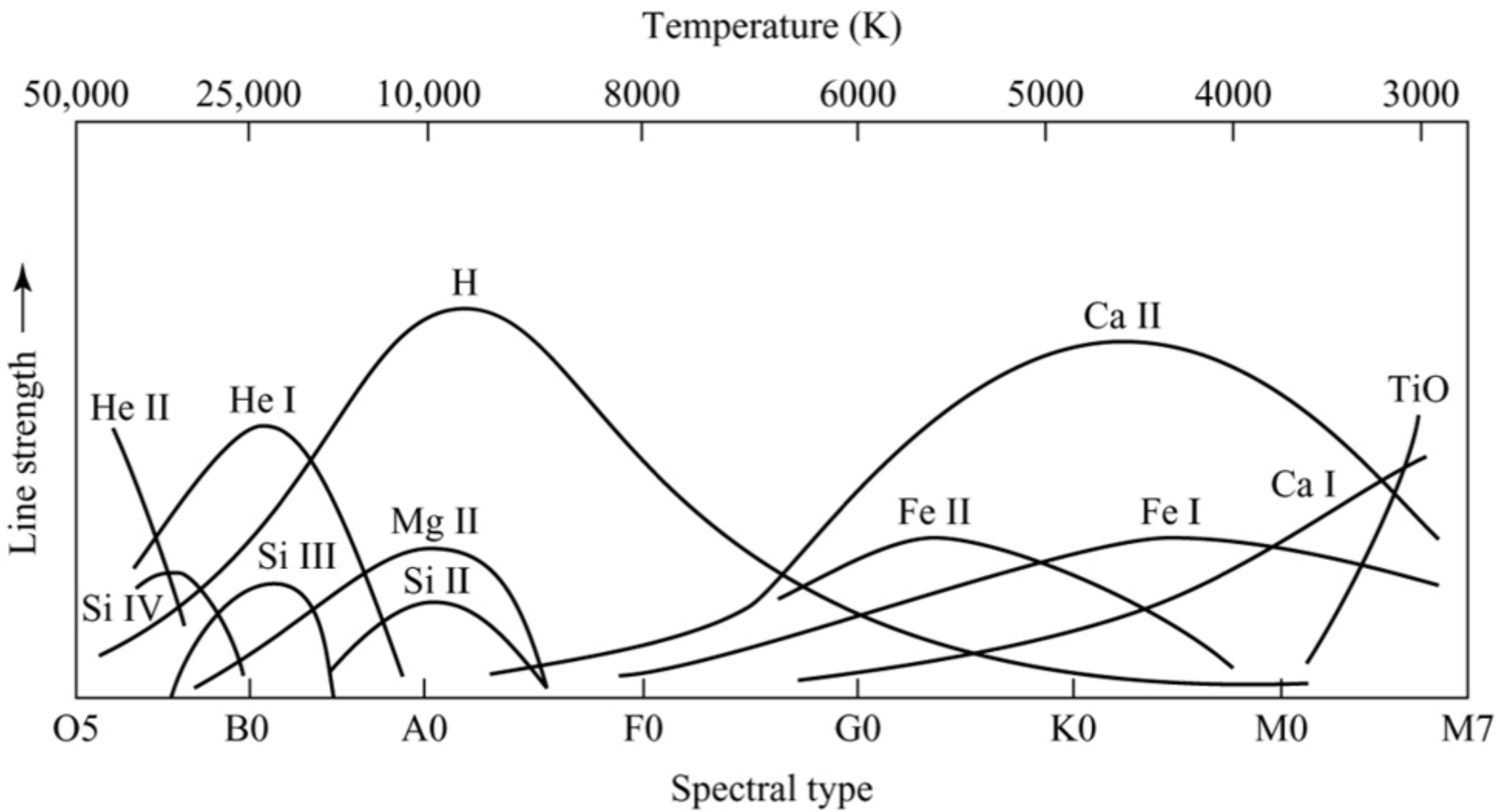
Sparke,LindaS.; Gallagher,JohnS.,III,2007: Galaxies in the Universe: An Introduction, Cambridge University Press

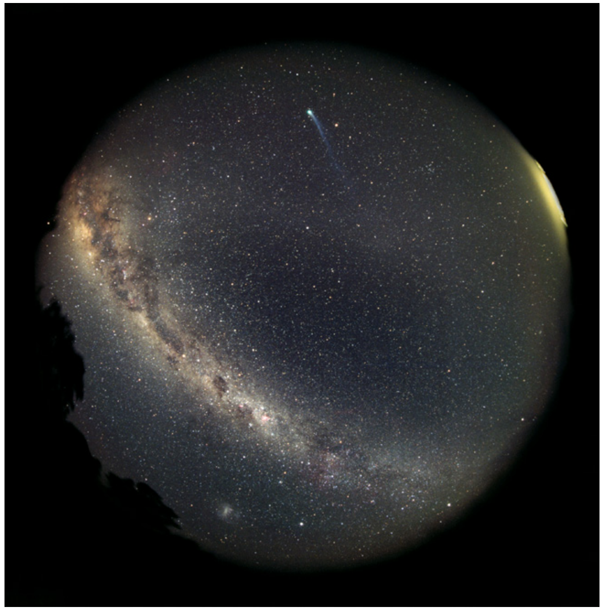
Relative Strength of Spectral Lines



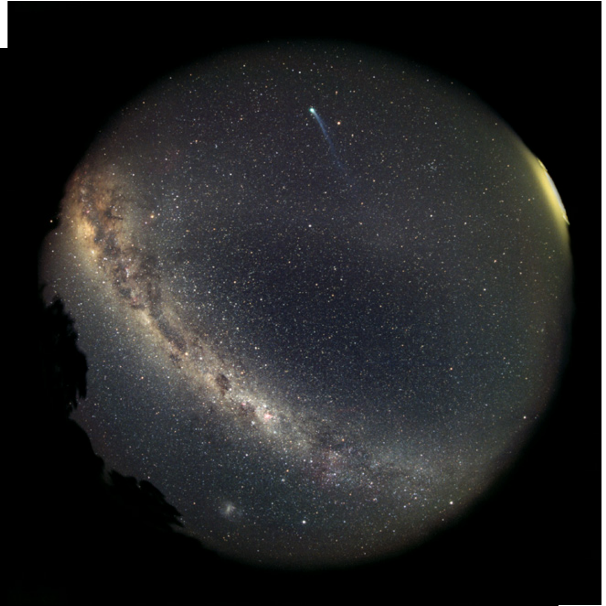
Dominant Features in the Spectra of Stars

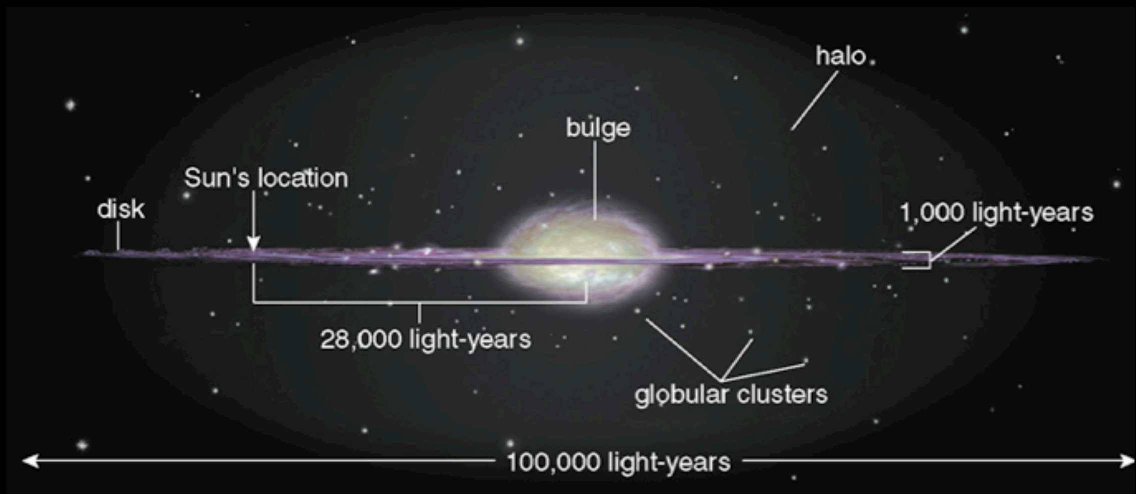


The Milky Way



Properties of Milky Way…

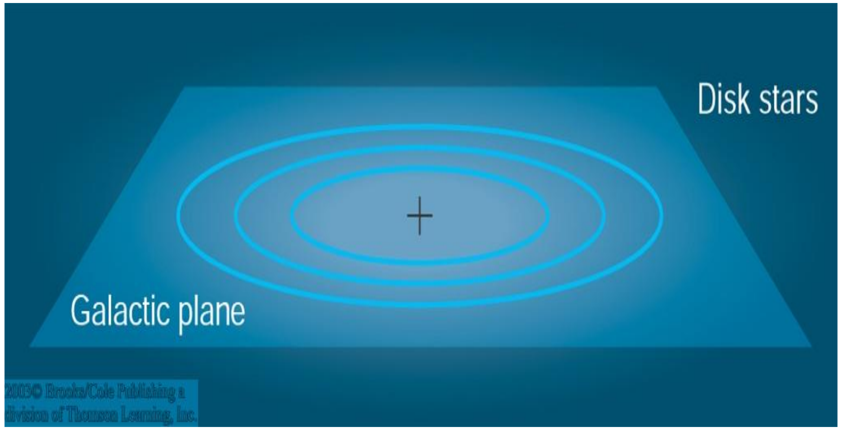




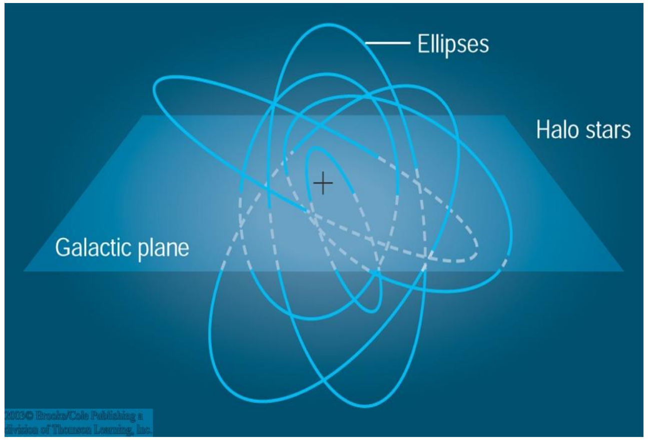
Disentangling the Galaxy

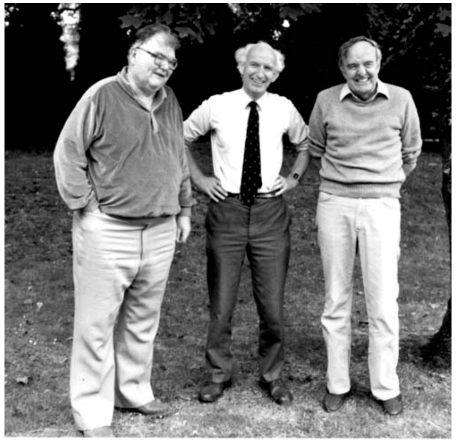
stellar abundances and kinematics are
excellent tools for galactic archaeology.

Slow, uniform

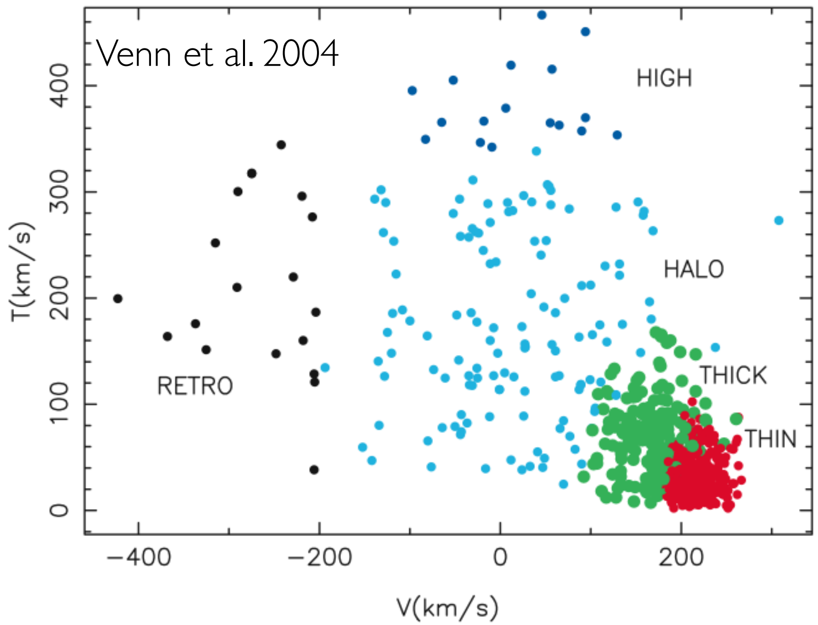


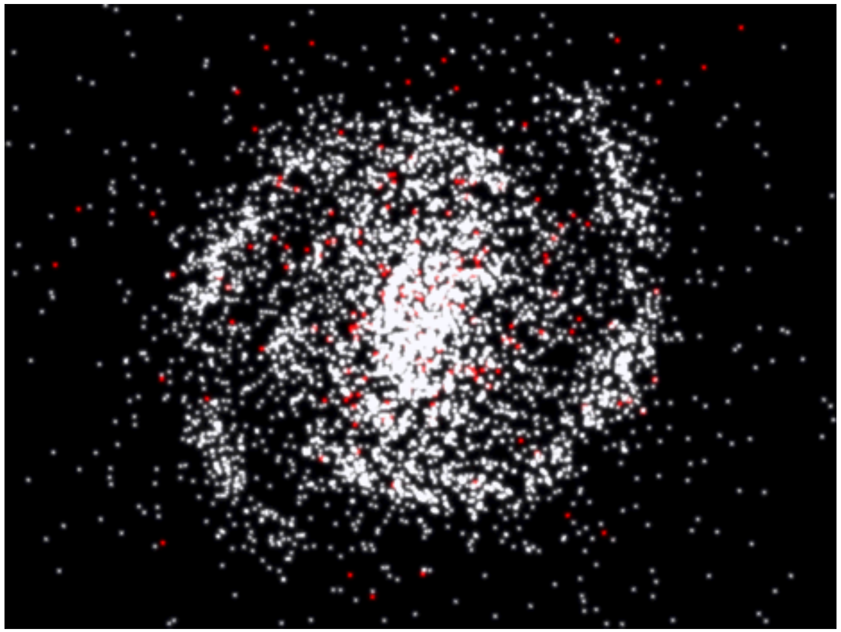
Fast, chaotic



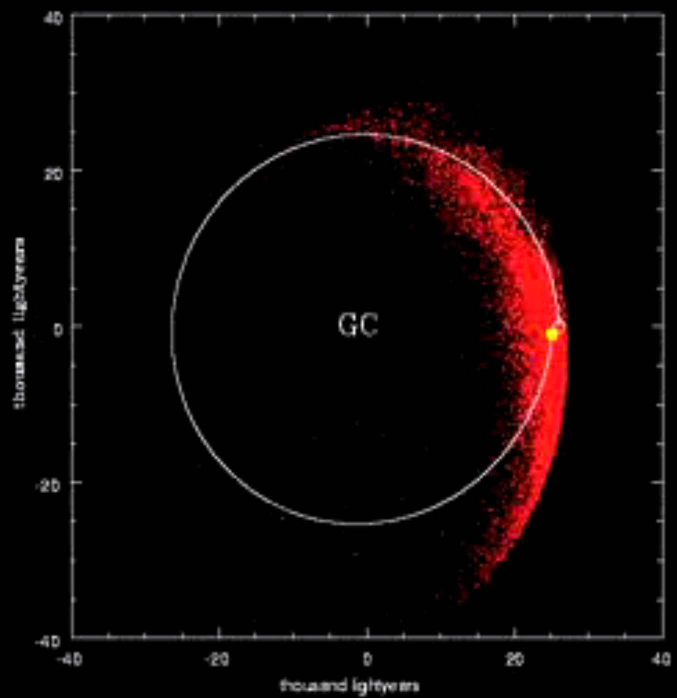


Eggen, Lynden-Bell & Sandage





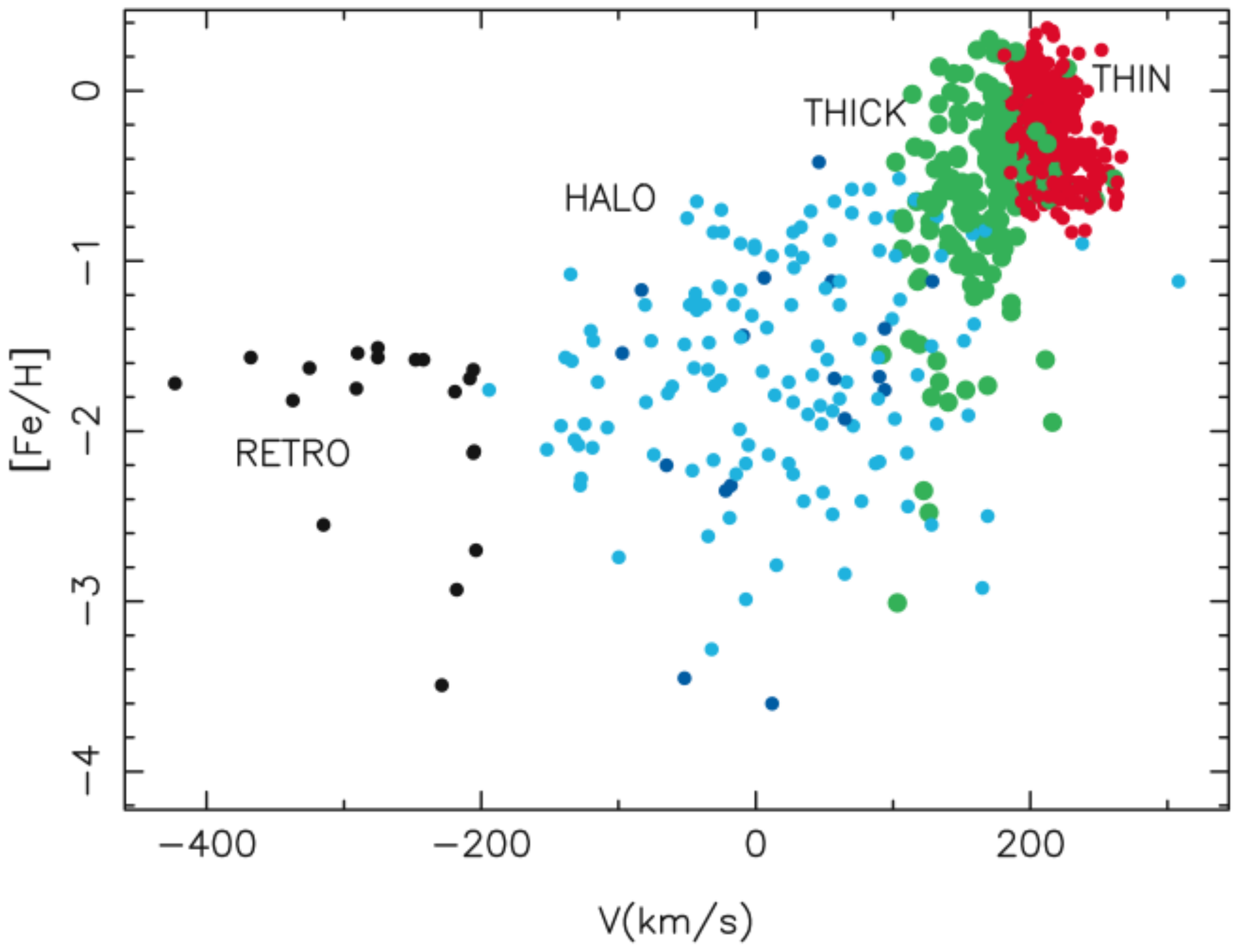
Copenhagen-Geneva Survey of stars in Solar Neighbourhood



Motions during last 250 million years

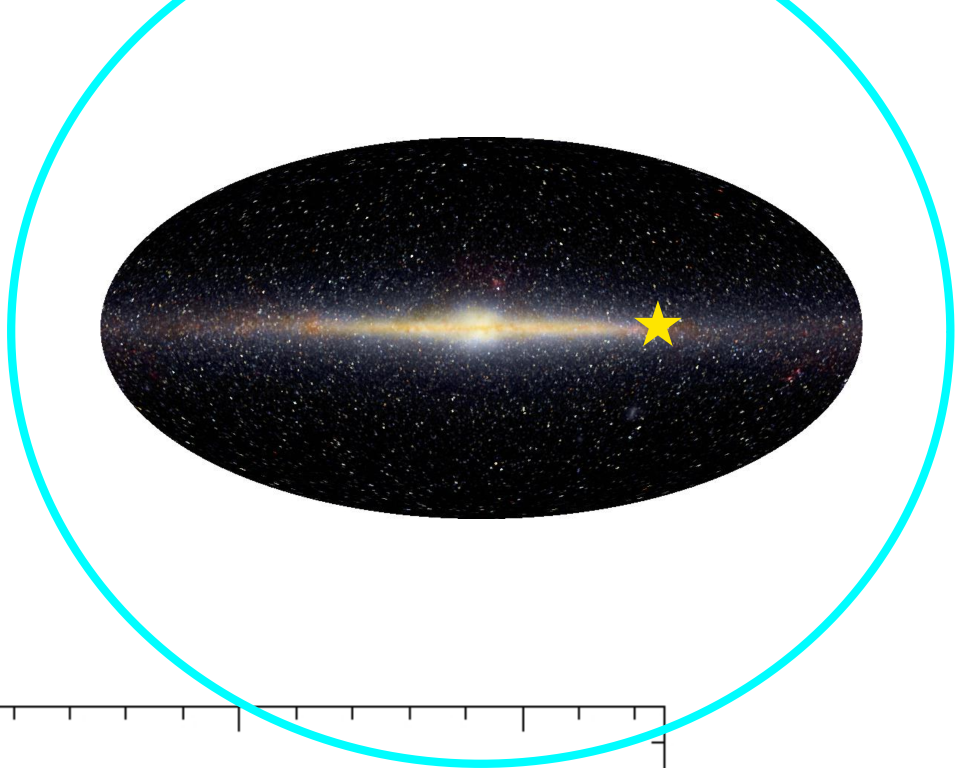
Nordstrom et al. 2004

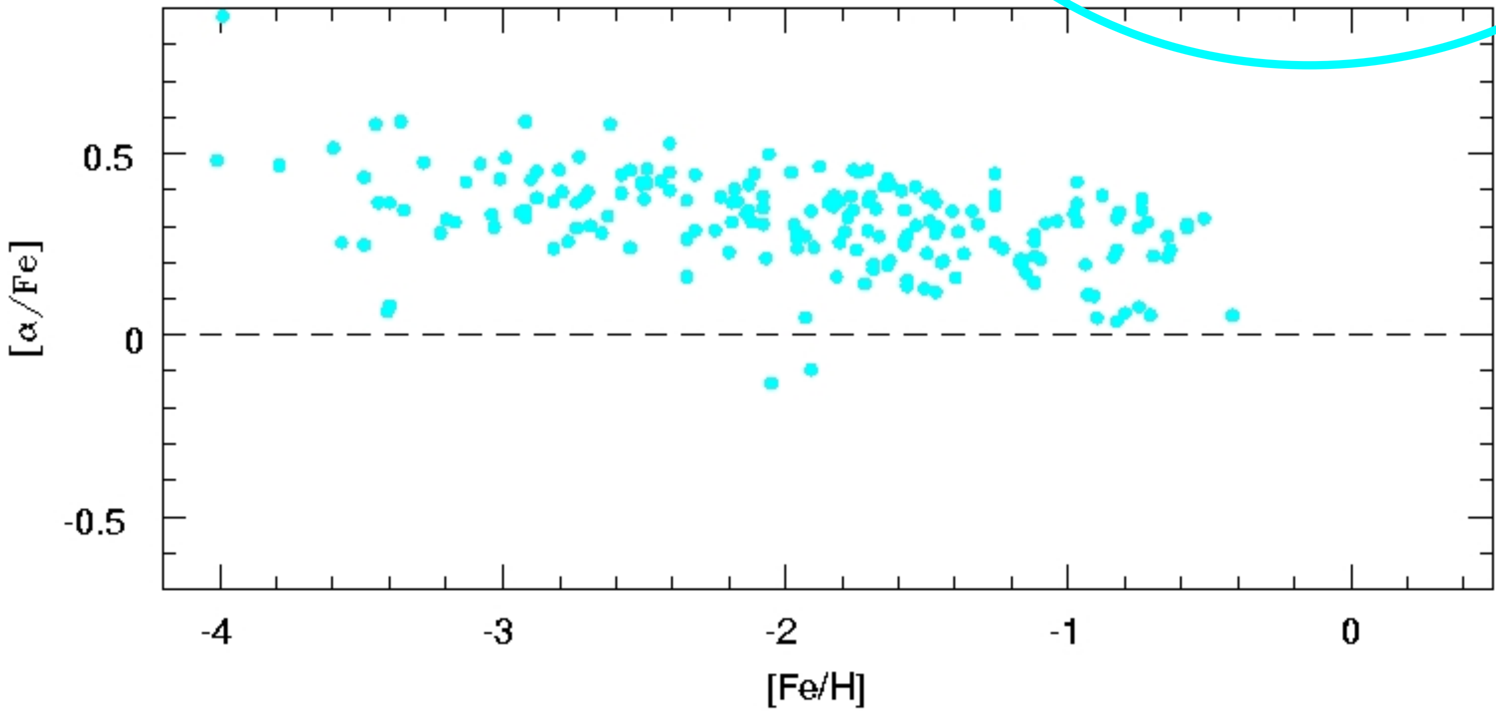
Properties of different components



Venn et al. 2004

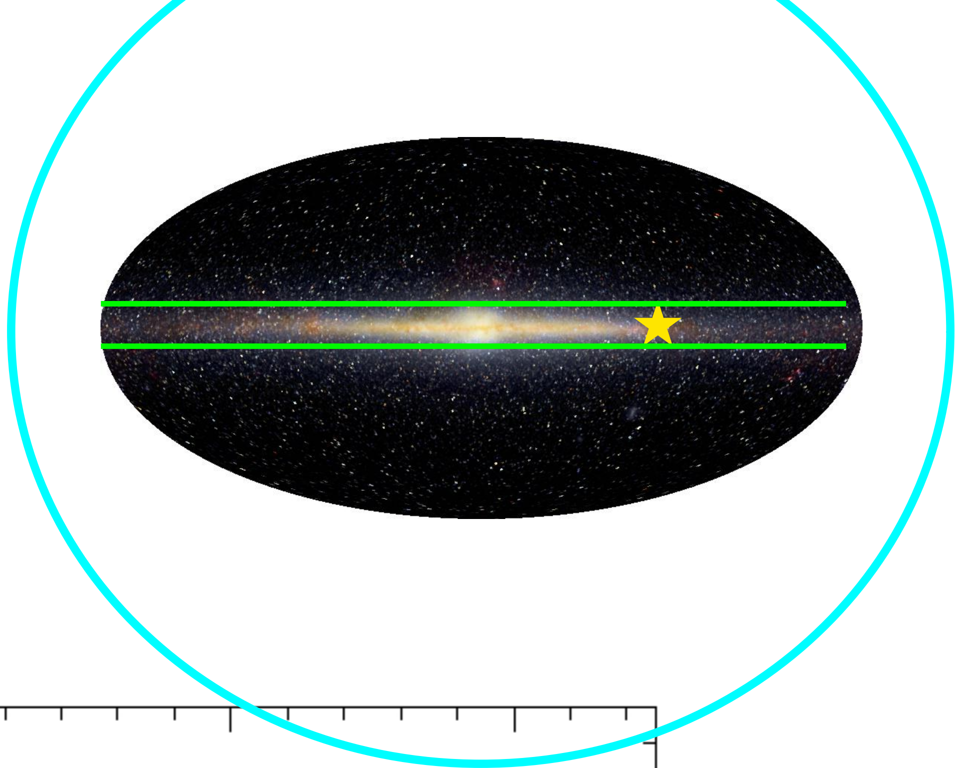
Stellar Abundances in the Milky Way

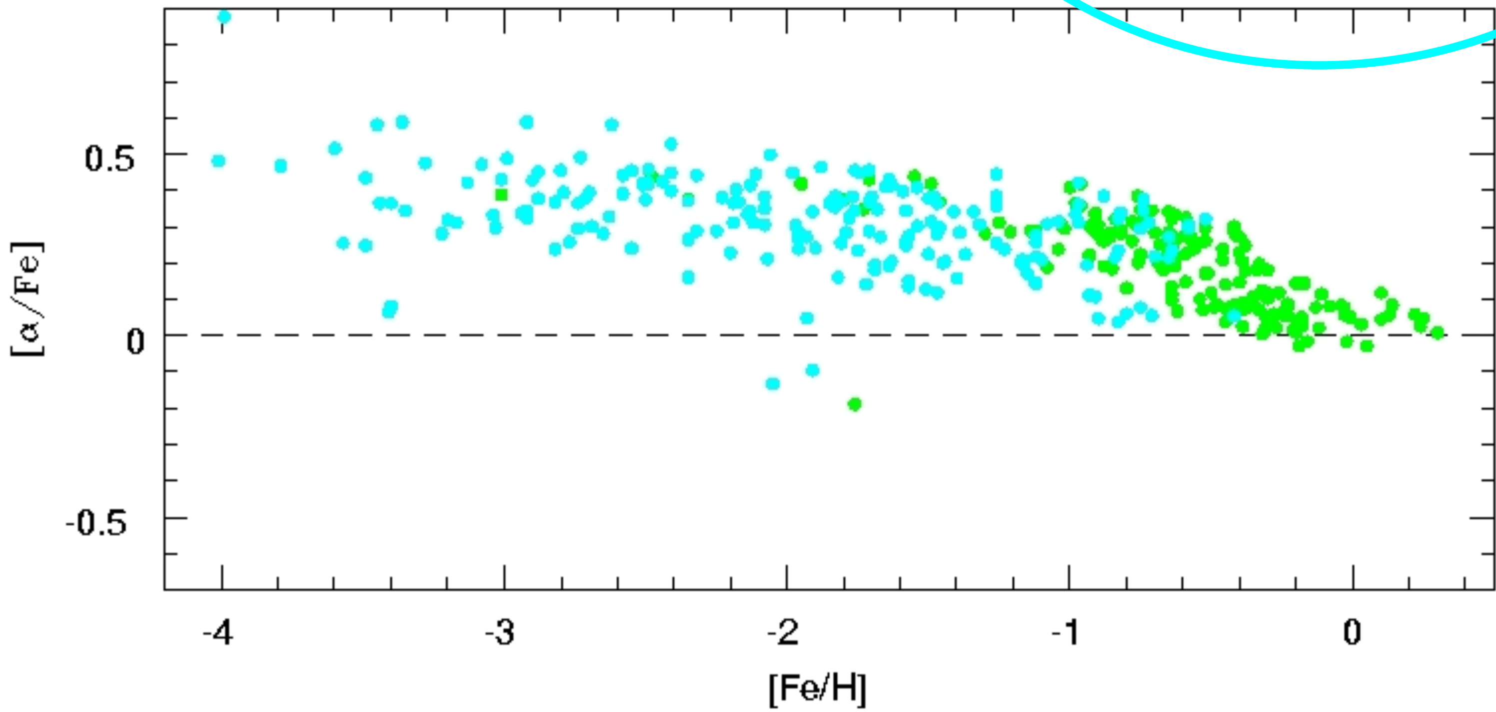




compilation by Venn et al. 2004

Stellar Abundances in the Milky Way





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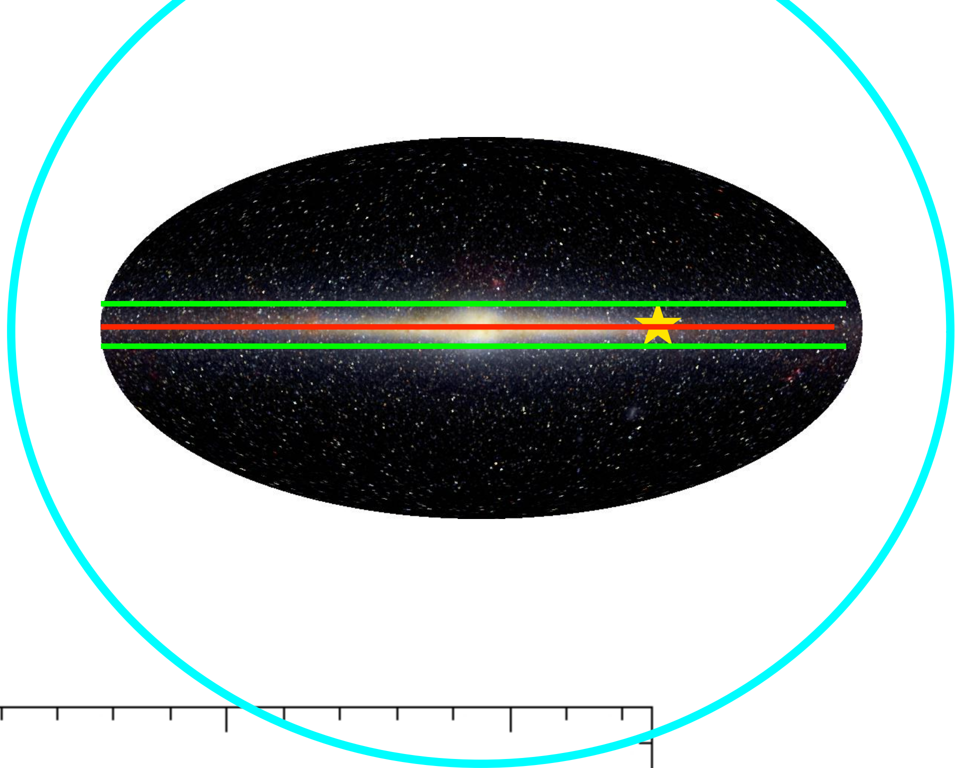
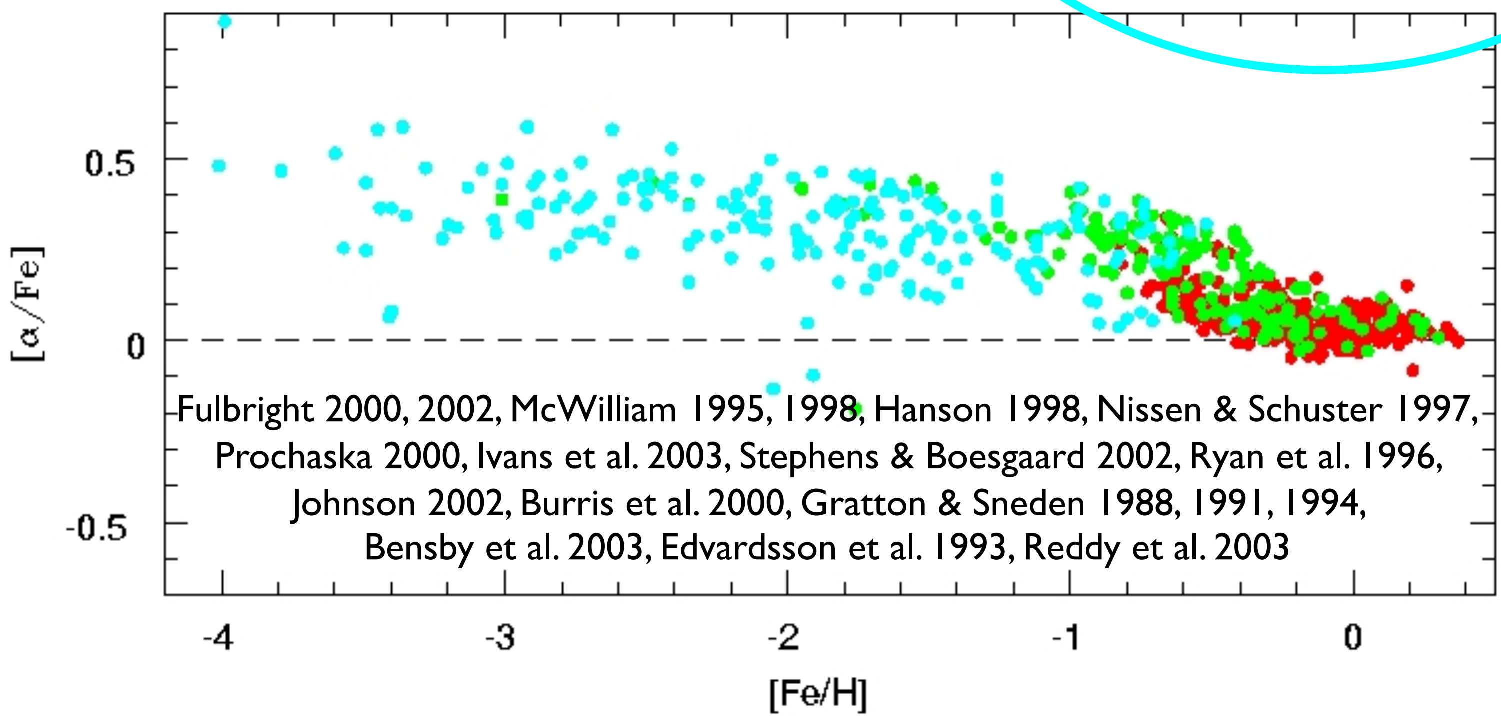
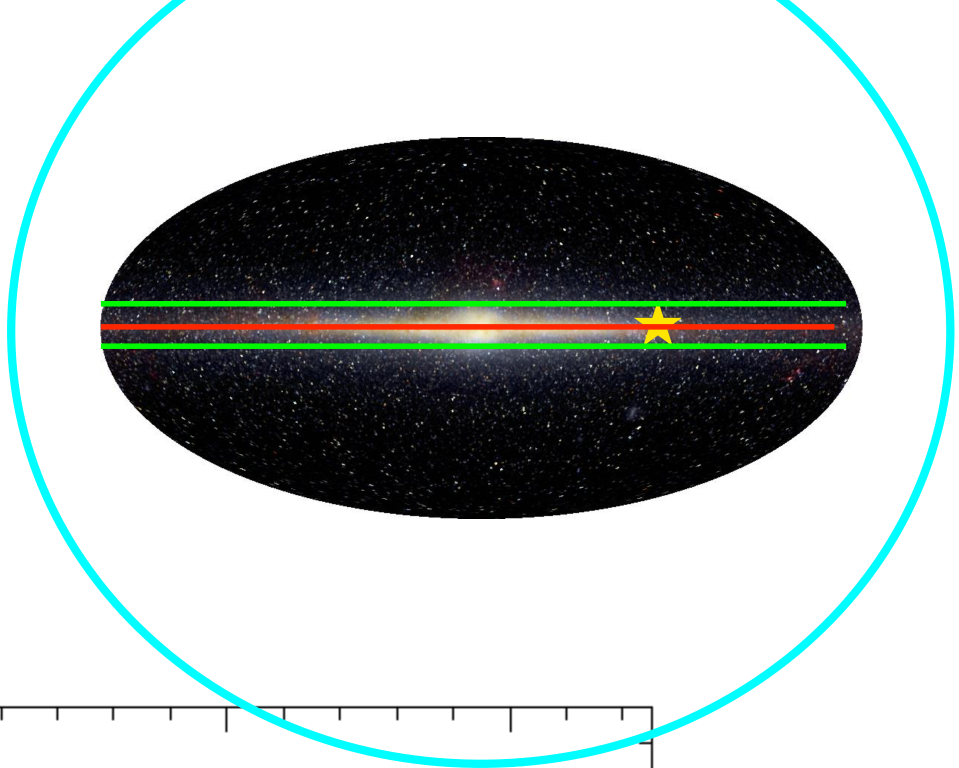
Stellar Abundances in the Milky Way

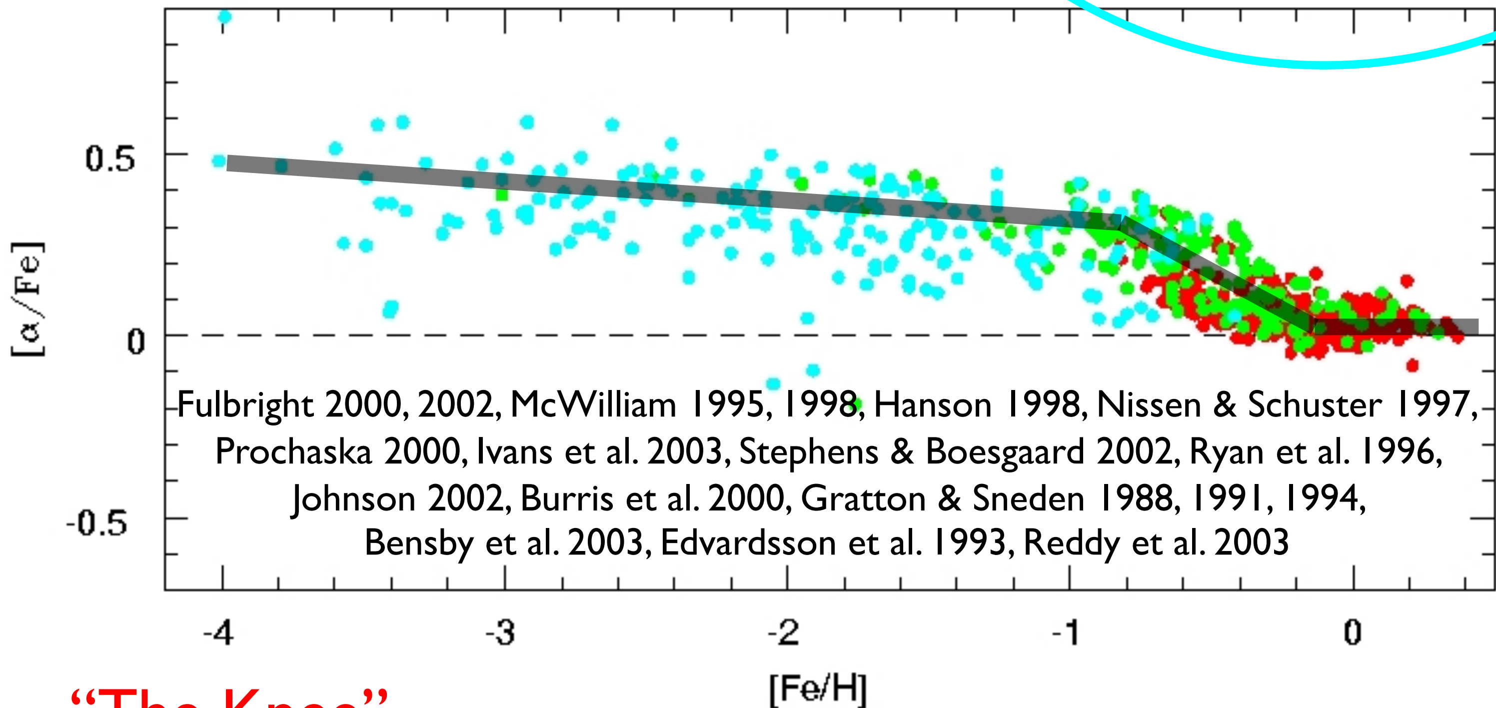




compilation by Venn et al. 2004

Stellar Abundances in the Milky Way





"The Knee"

compilation by Venn et al. 2004

Stellar Abundances in the Milky Way

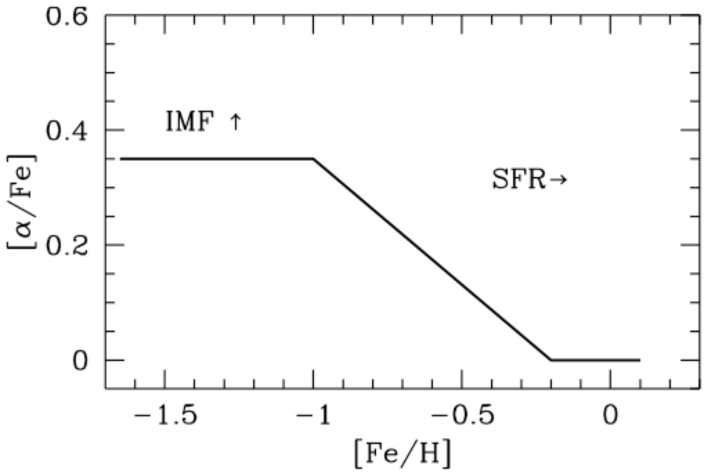
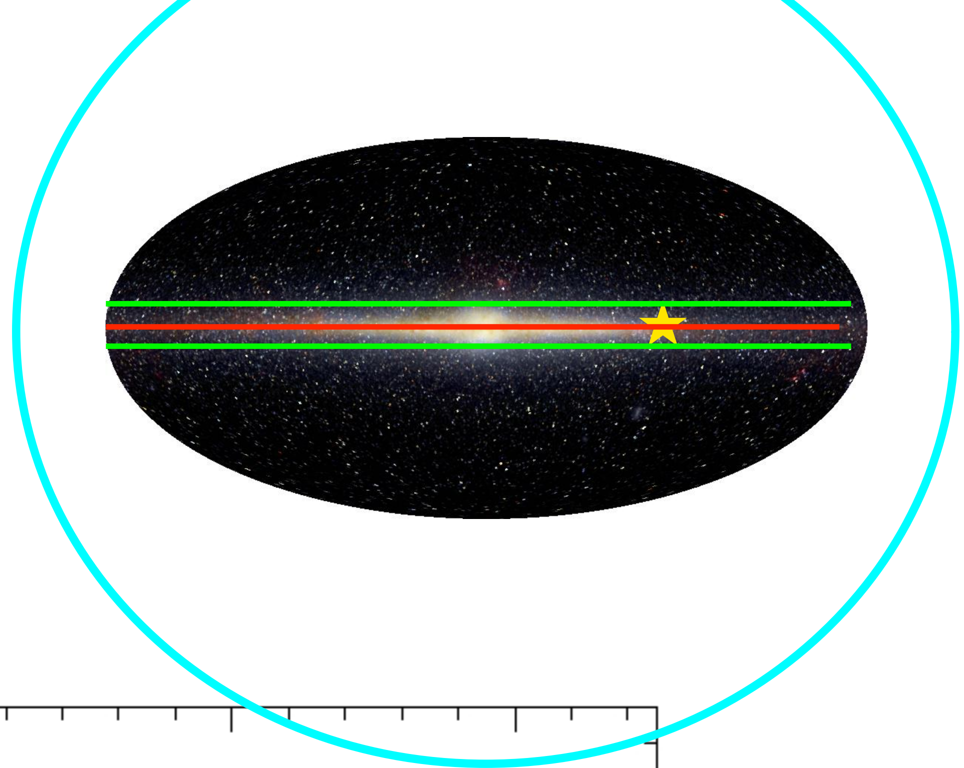
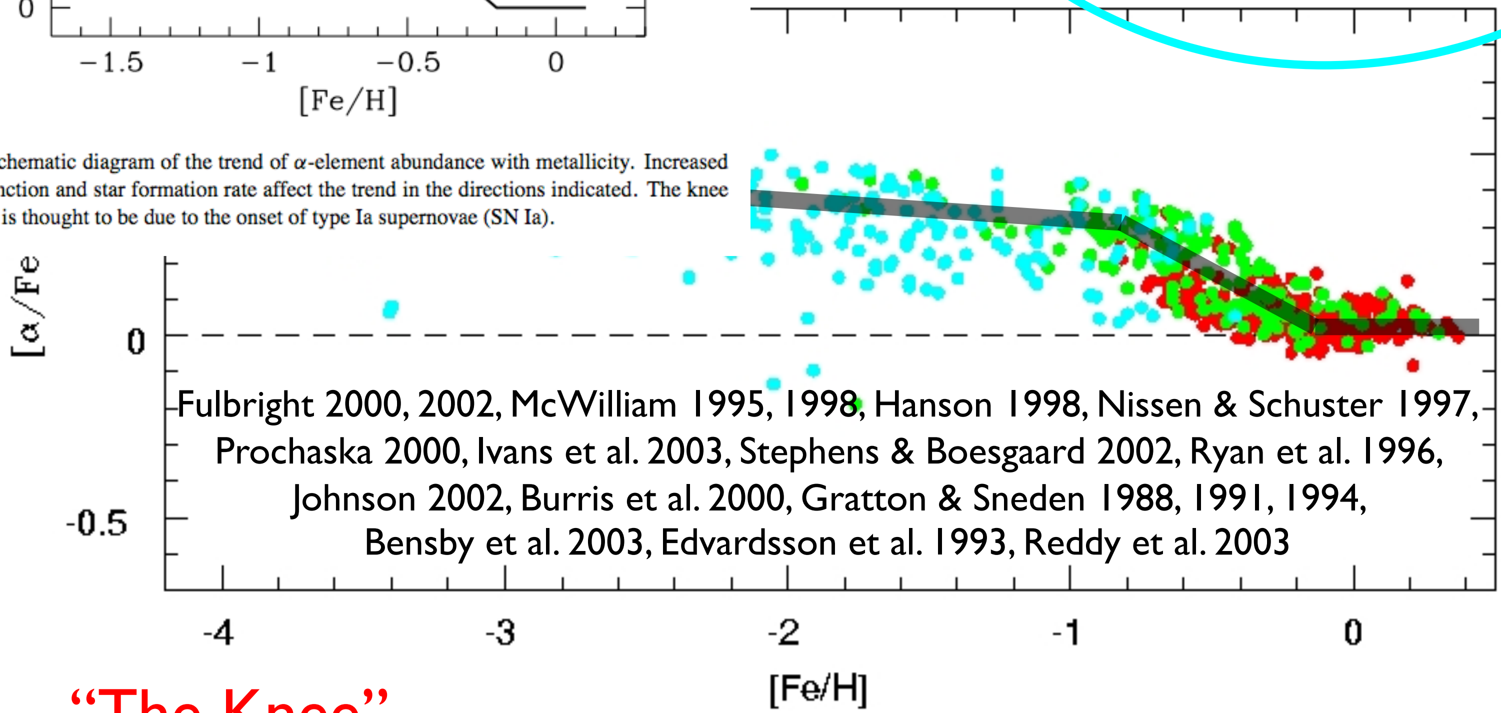


Figure 1 A schematic diagram of the trend of α-element abundance with metallicity. Increased initial mass function and star formation rate affect the trend in the directions indicated. The knee in the diagram is thought to be due to the onset of type Ia supernovae (SN Ia).





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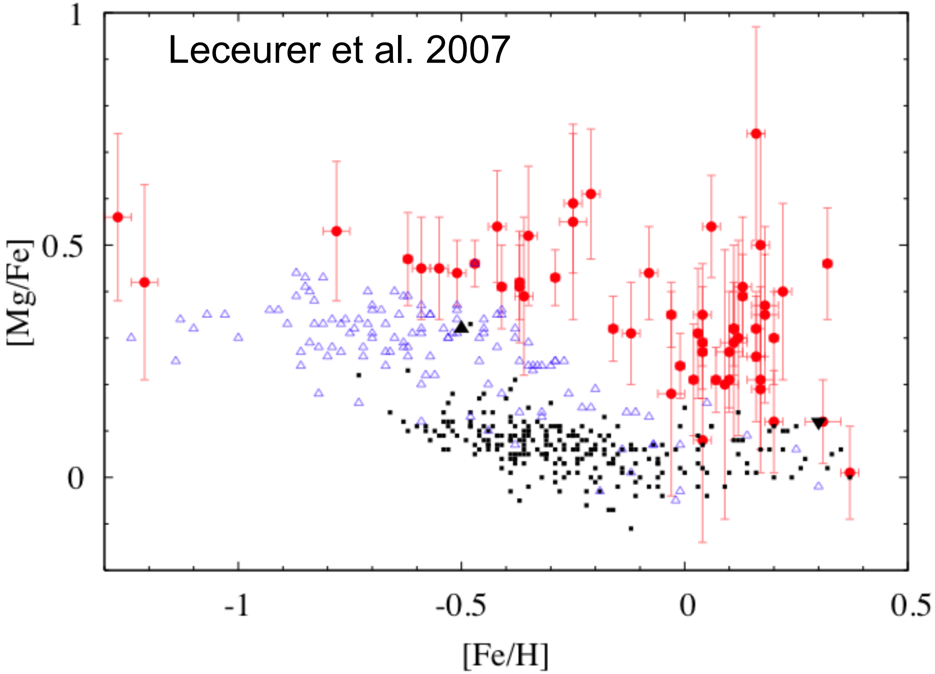
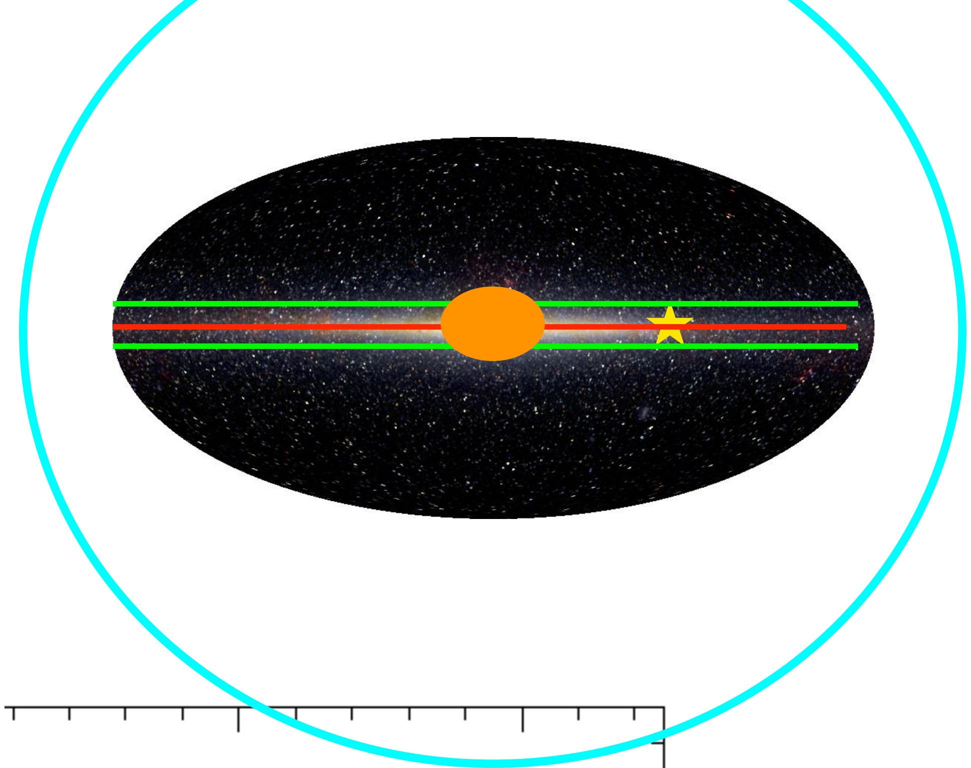
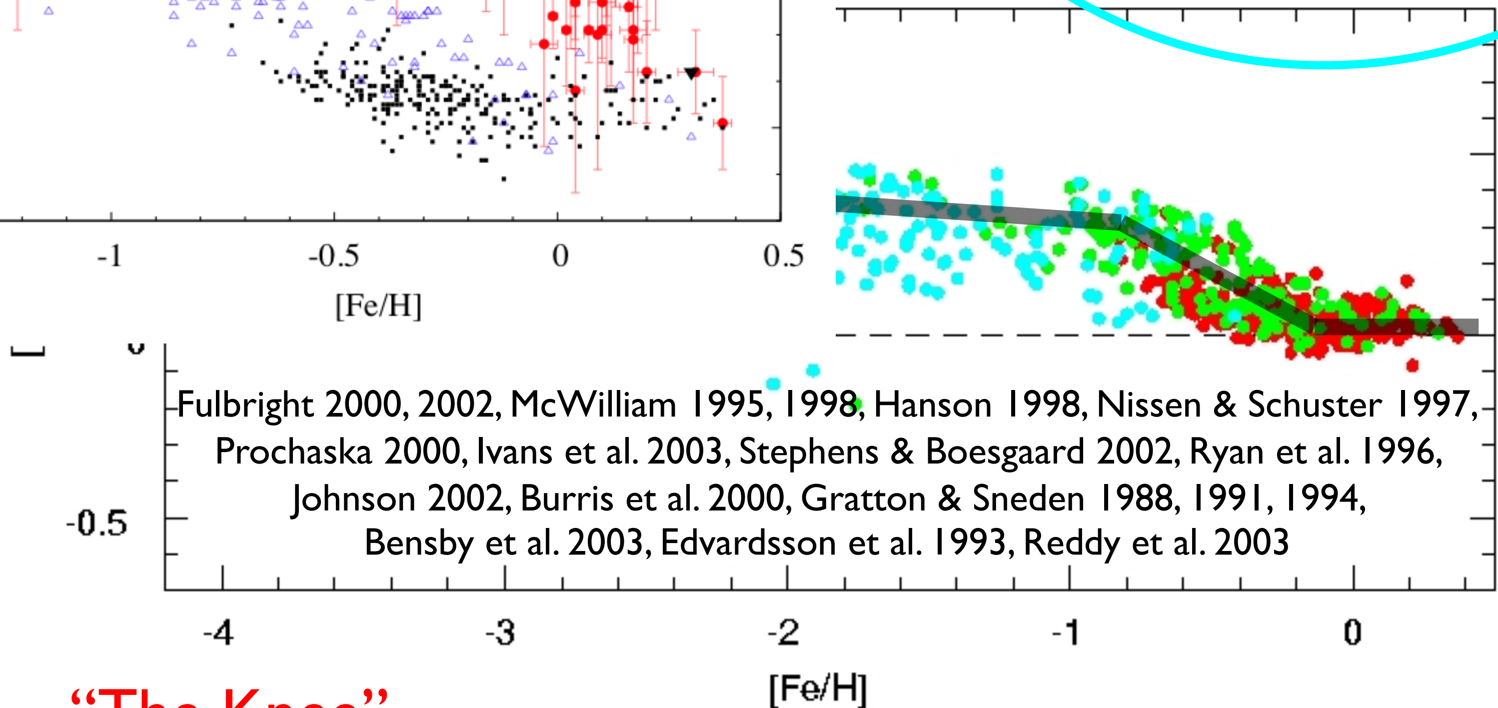
Stellar Abundances in the Milky Way







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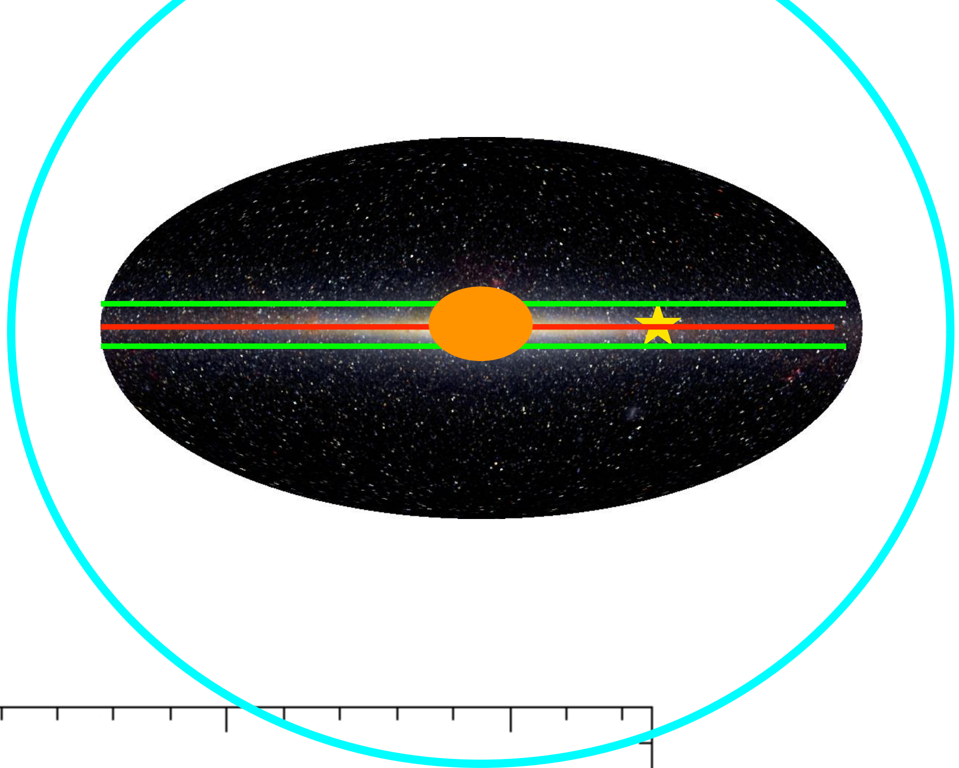
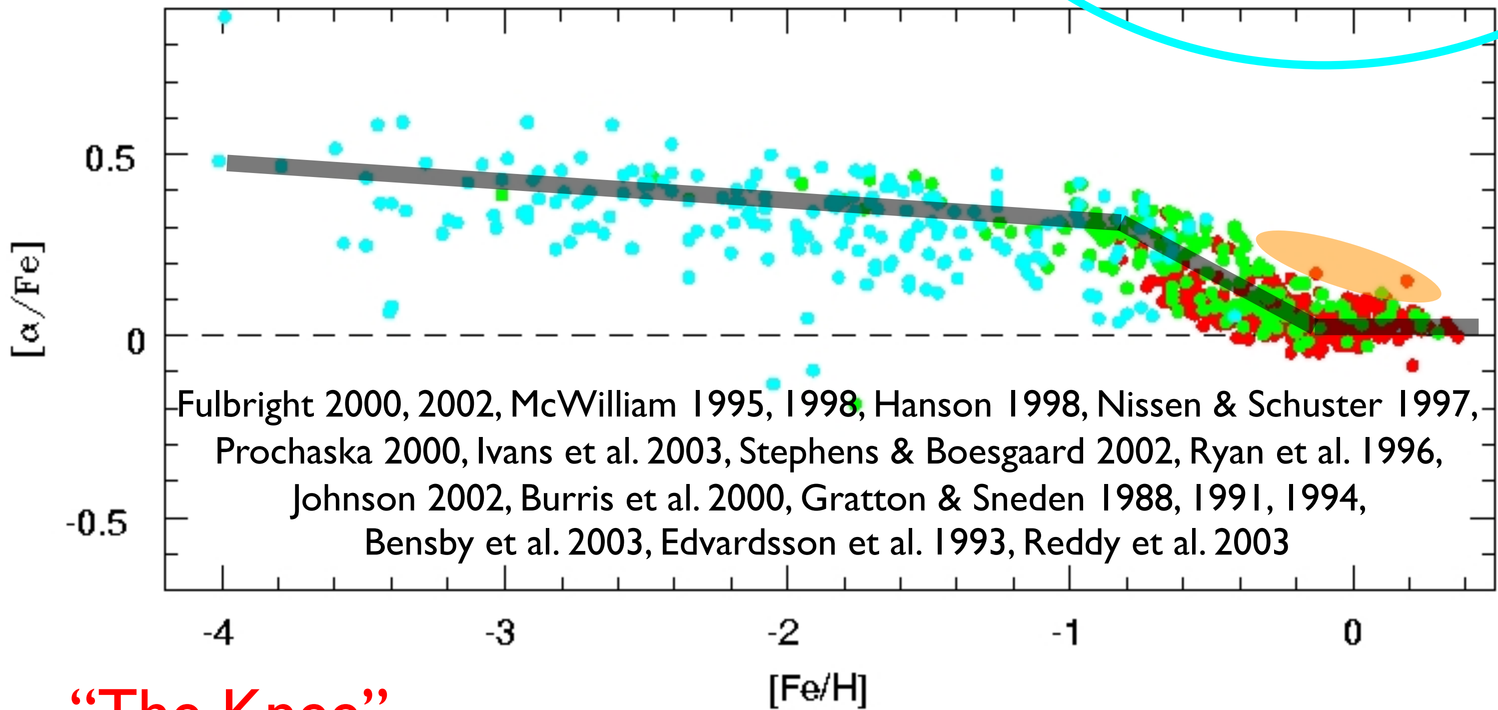
Stellar Abundances in the Milky Way





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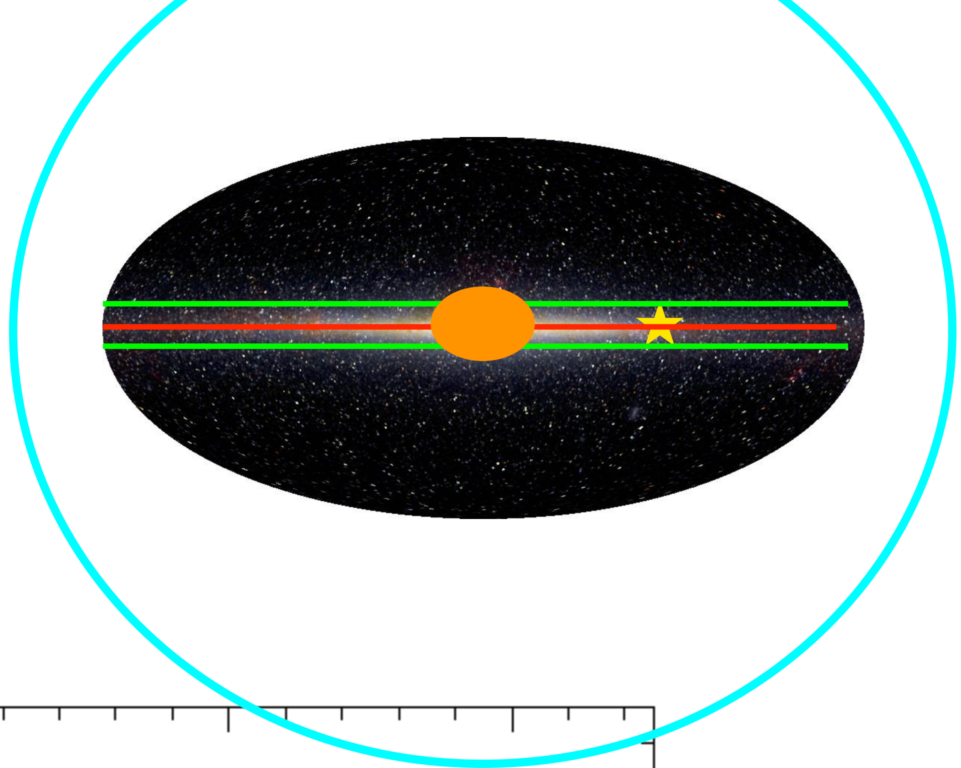
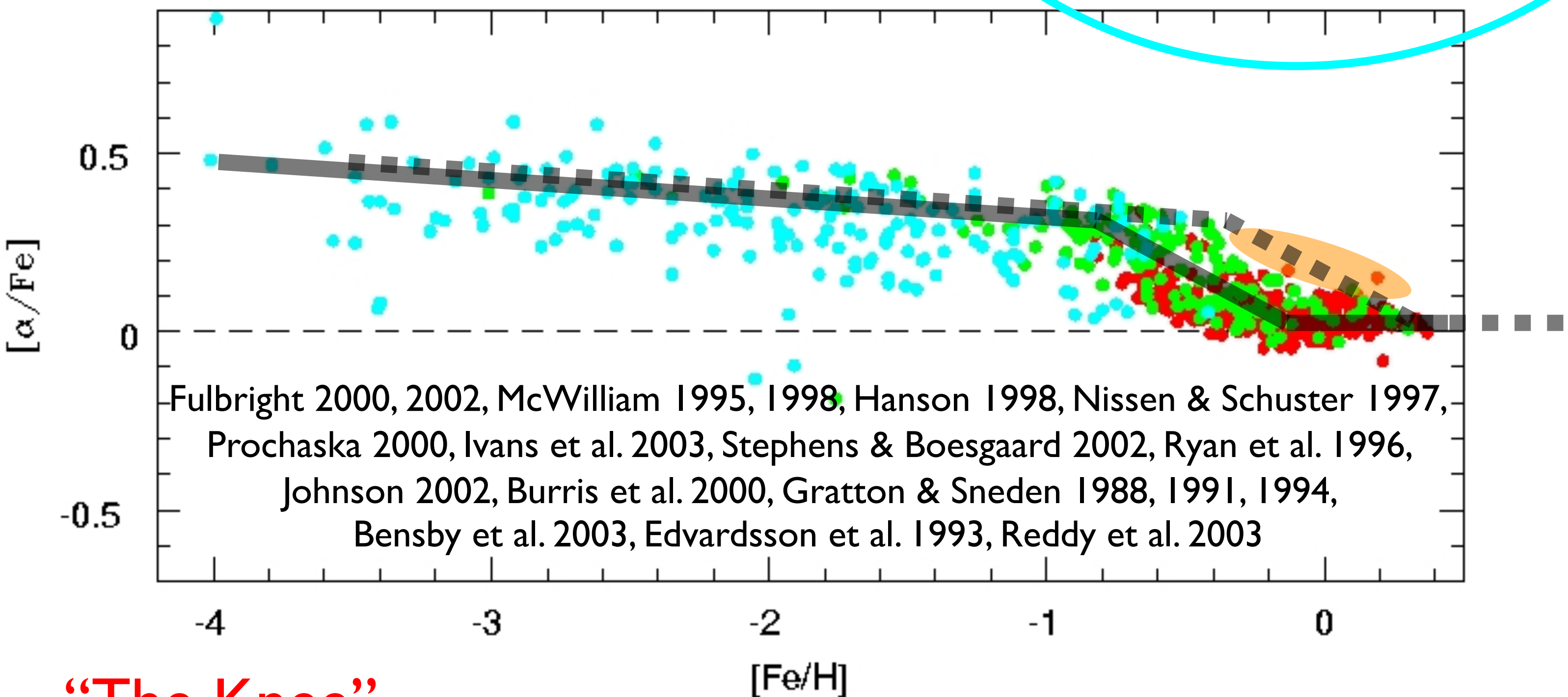
compilation by Venn et al. 2004

Stellar Abundances
in the Milky Way





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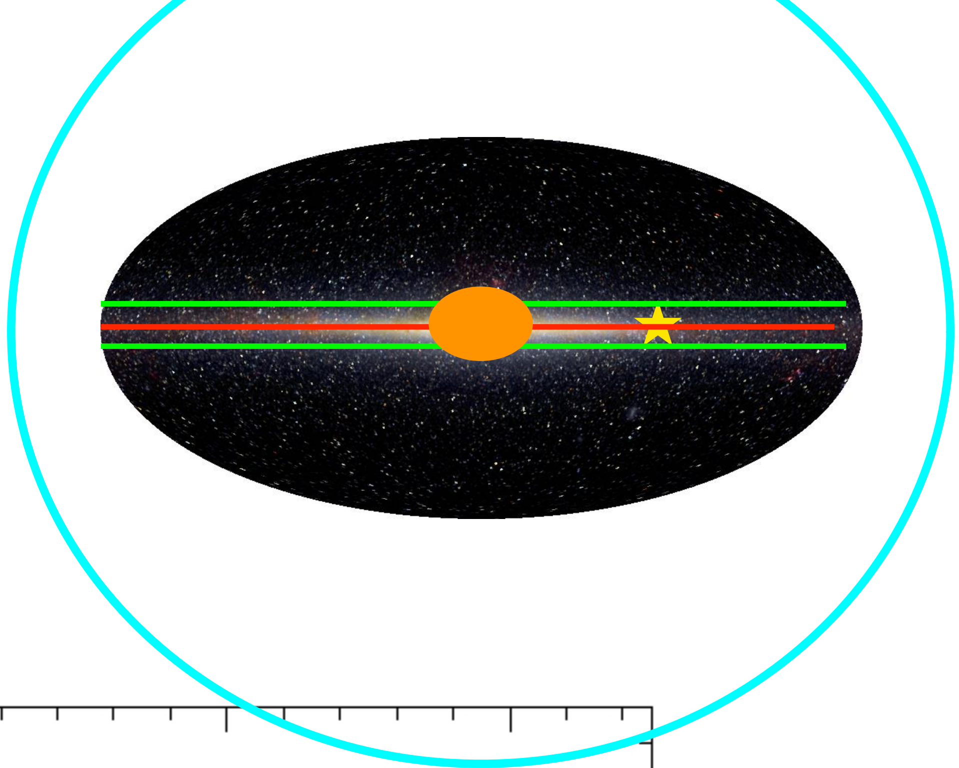
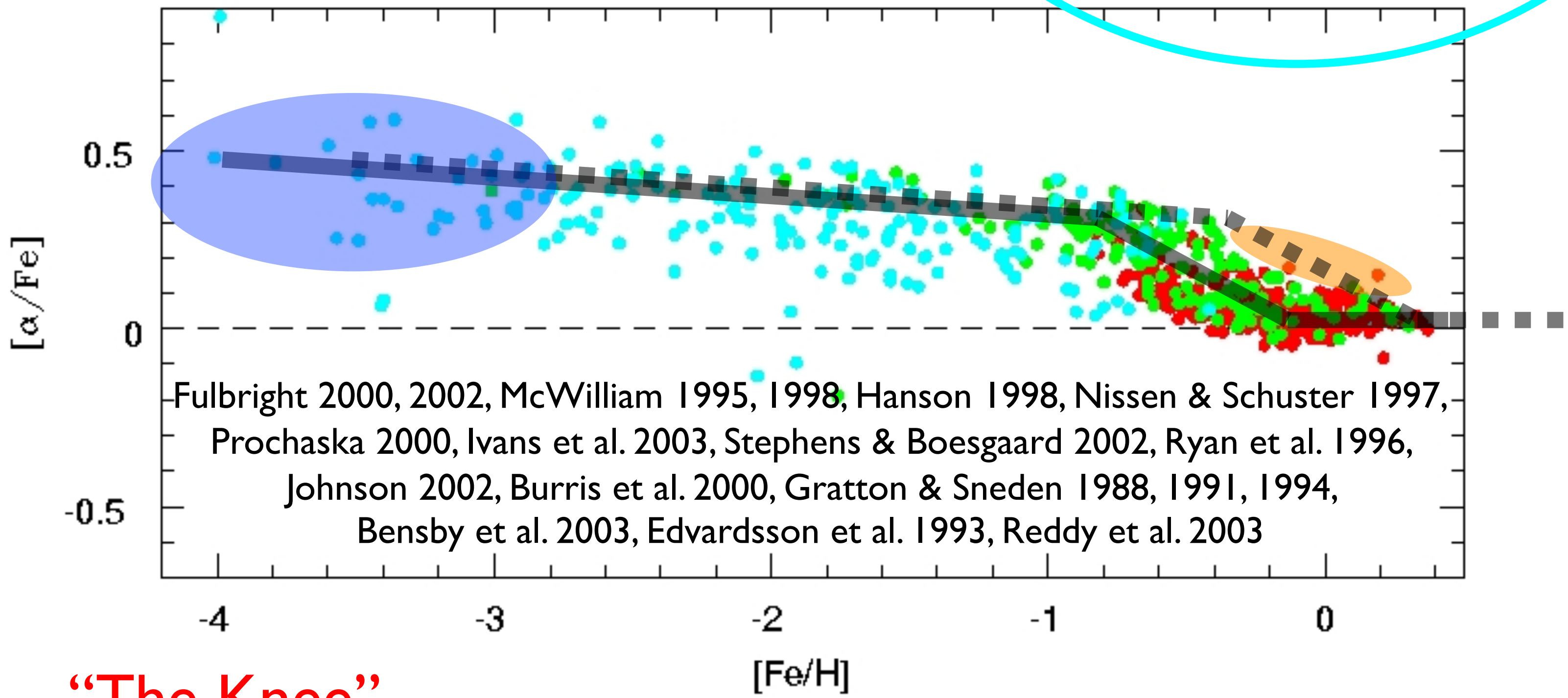
Stellar Abundances in the Milky Way



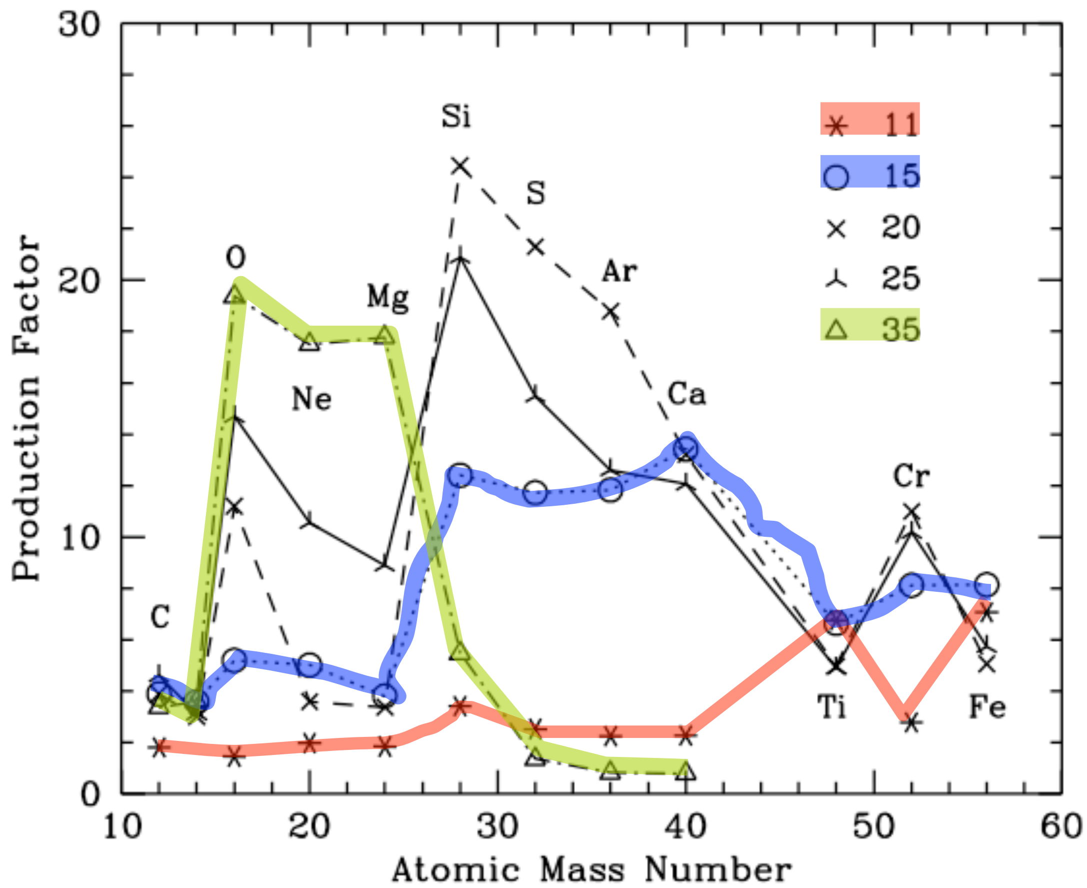


"The Knee"

compilation by Venn et al. 2004

Production factors of SNII

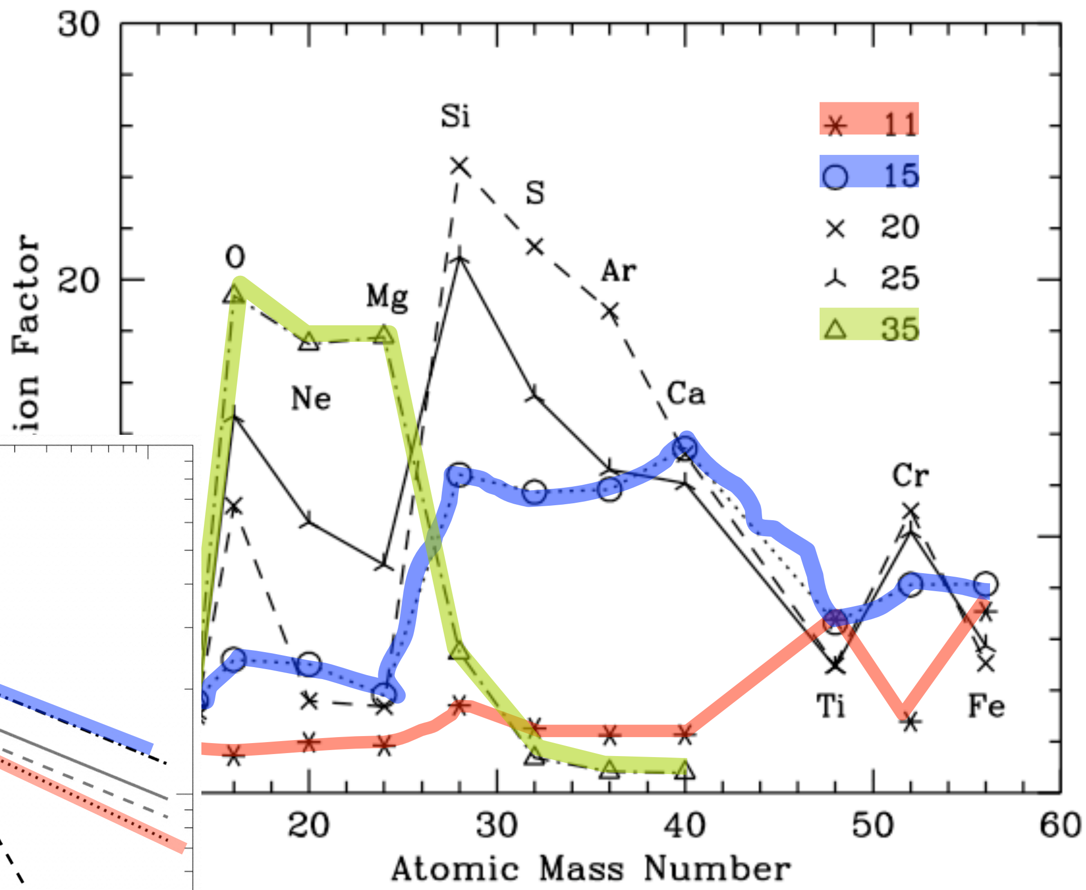
Baldry,IvanK,,Apj,593,258



Woosley & Weaver 1995

the indicated elements is given in the key in the upper right.

Production factors of SNII



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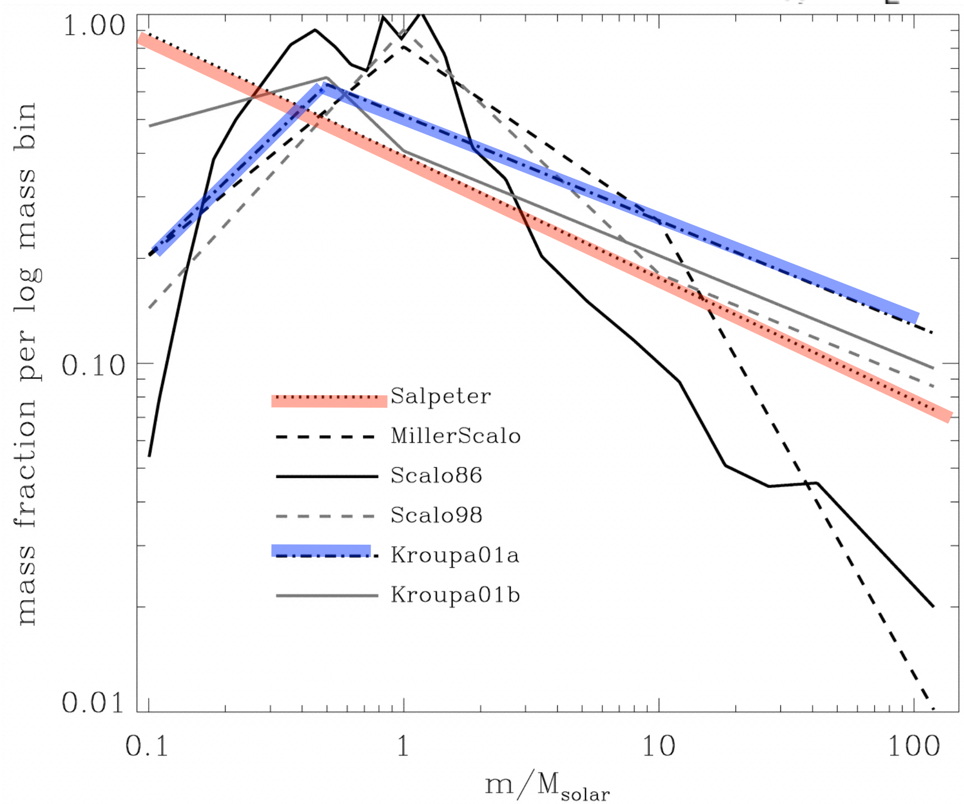
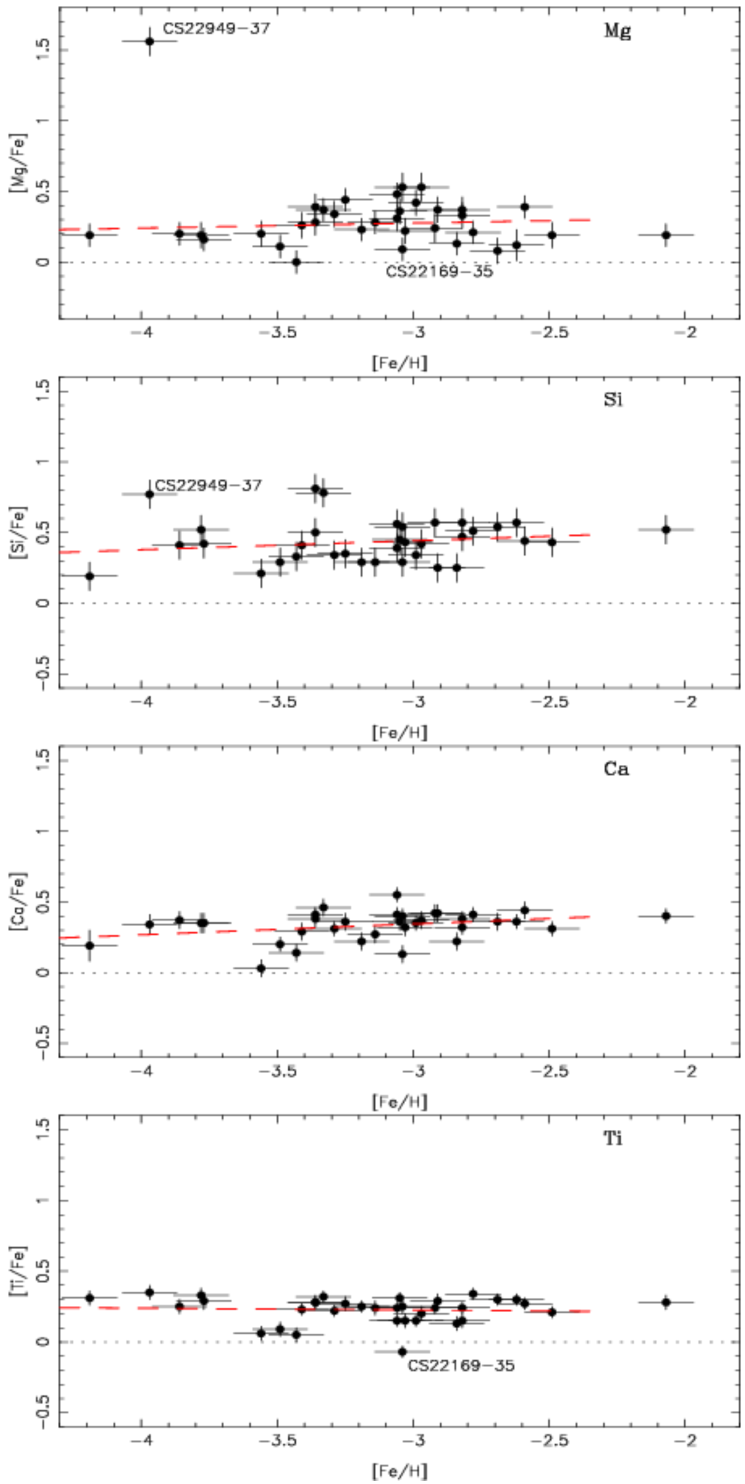


the indicated elements is given in the key in the upper right.

EMPS in Galactic halo

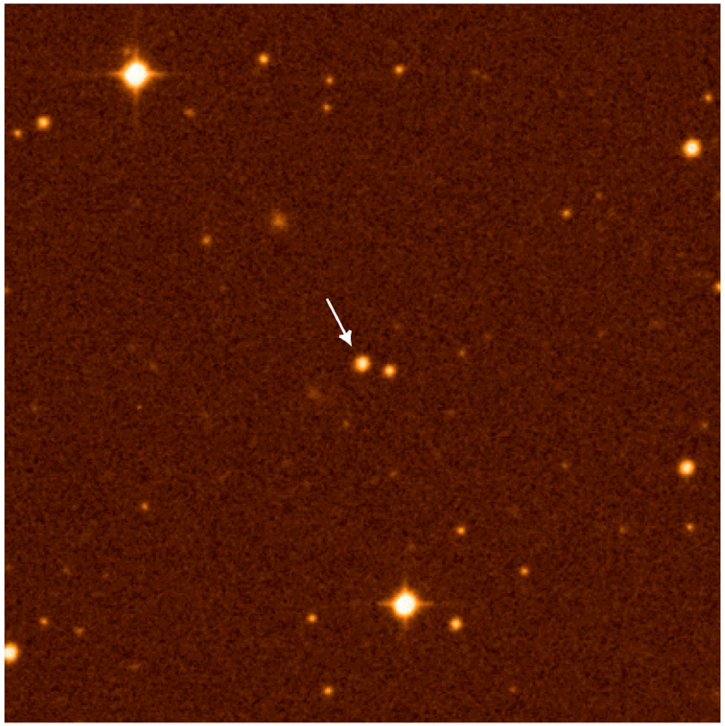
ESO Large Programme:
"The First Stars"
30 giants:

-4.1 < [Fe/H] < -2.7



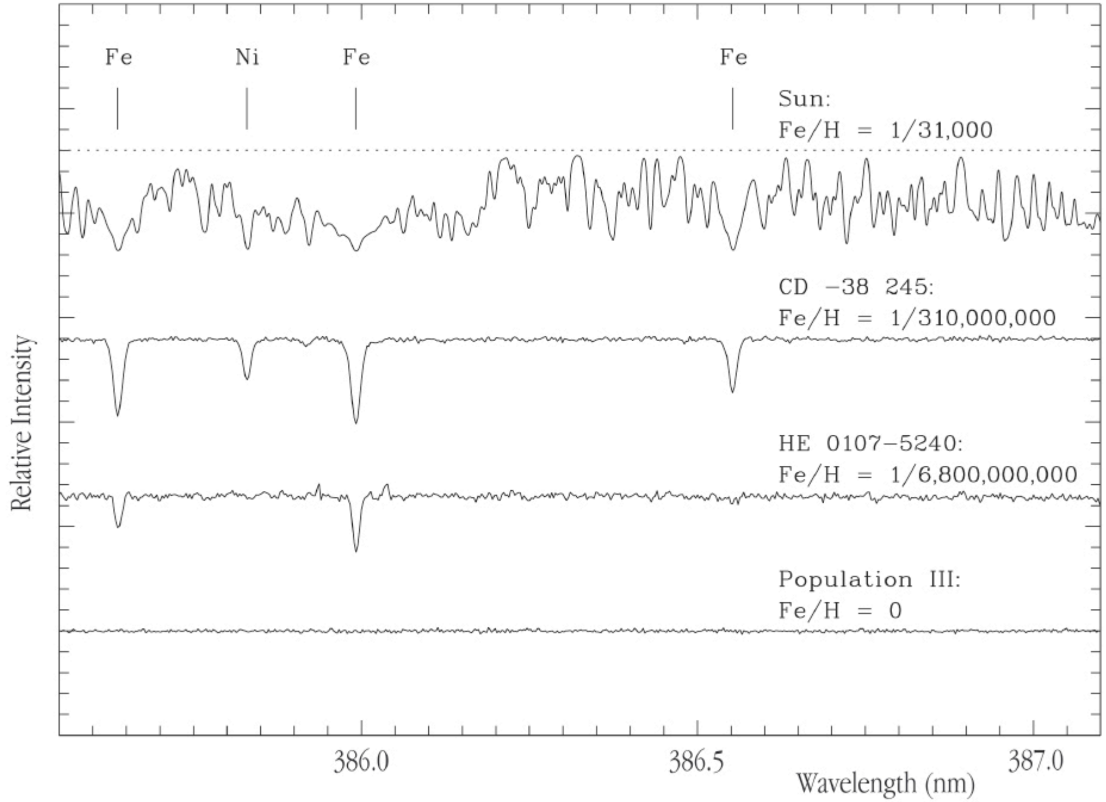
Cayrel et al. 2004

The most ancient object we know of ?



The Very Metal-Deficient Star HE 0107-5240

ESO PR Photo 25a/02 (30 October 2002)



Spectra of Stars with Different Metal Content

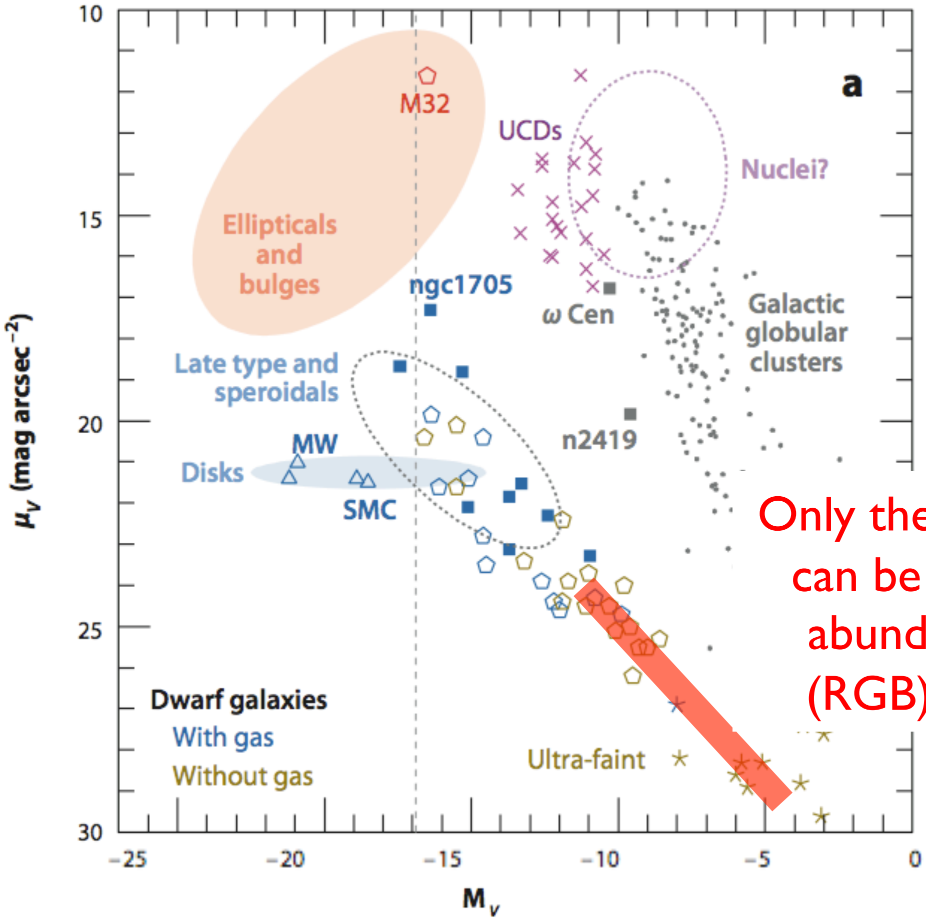
ESO PR Photo 25b/02 (30 October 2002)

[Fe/H] = -5.4

Christlieb & HES

Dwarf Galaxies

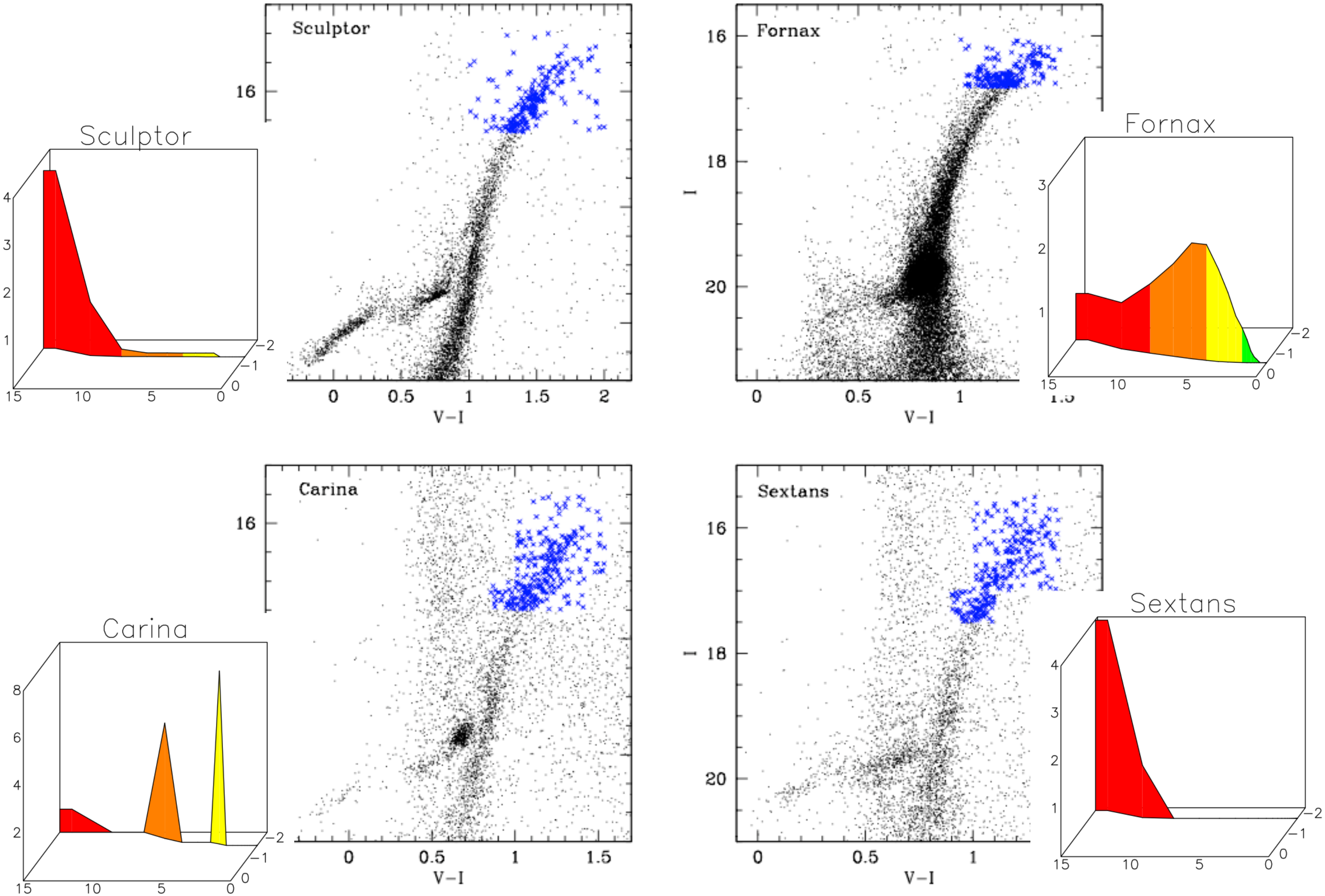
Understanding Galaxies



Only the very closest galaxies can be subjects of detailed abundance studies of old (RGB) stars: mostly dSph

Tolstoy, Hill & Tosi 2009, ARAA, 47, 371

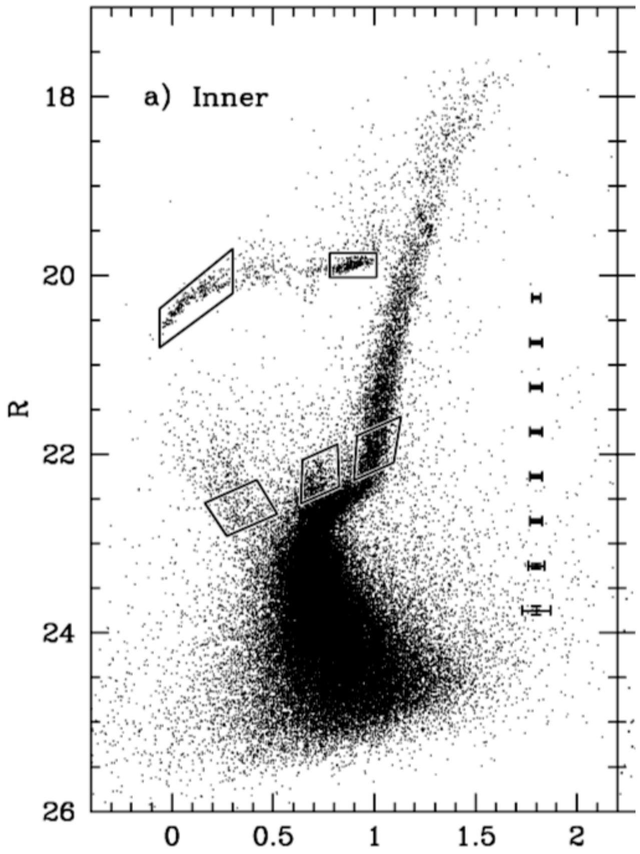
Spectroscopic Targets



Dolphin A.E., Weisz, D.R., Skillman, E.D., Holtzman, J.A., 2005, arXiv:astro-ph/0506430

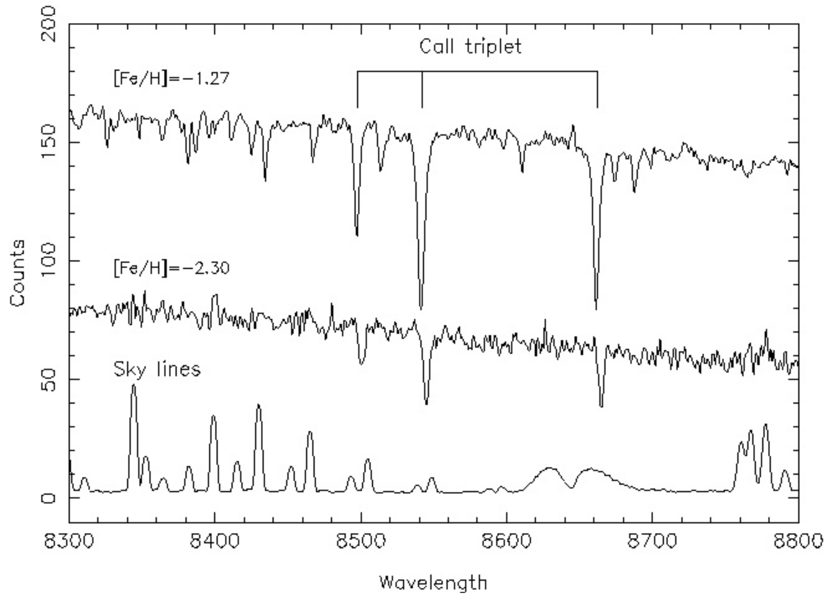
Metallicity Indictor

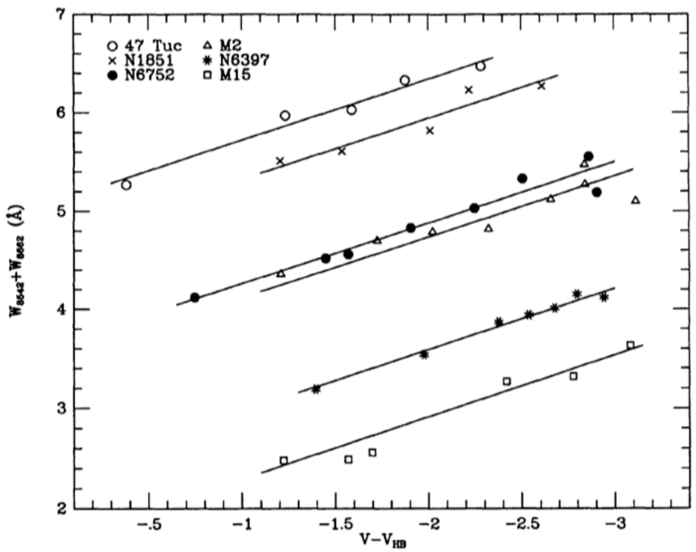
SPECTRA!



Hurley-Keller D., Mateo M., GrebelE.K.,Apj,523,25

Call Triplet R~6000



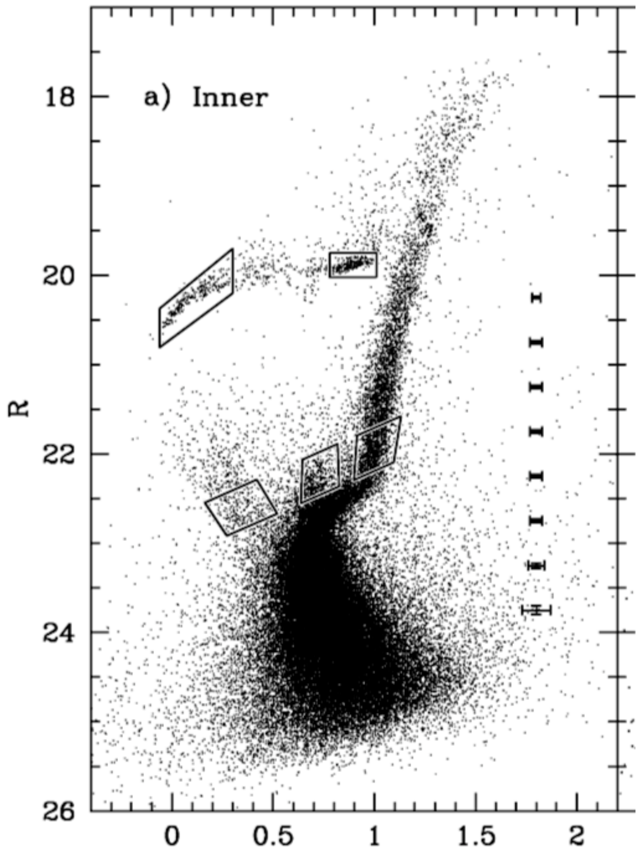


Only valid for RGB stars!!

Armandroff & Da Costa 1991

Detailed Abundances

SPECTRA!

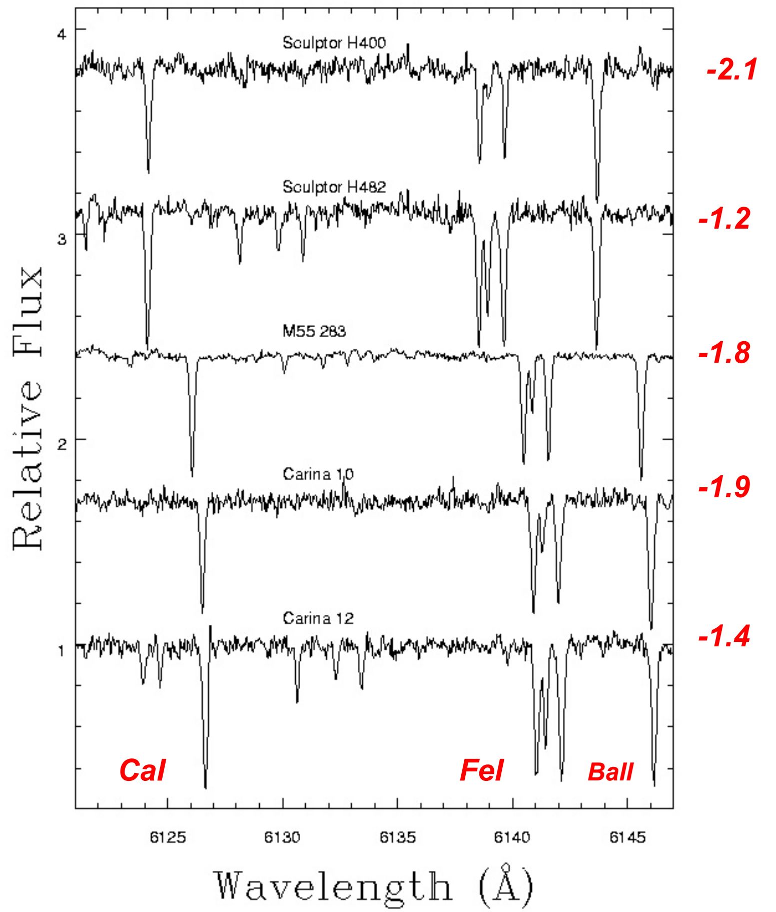


Hurley-Keller D., Mateo M., GrebelE.K., Apj,523,25

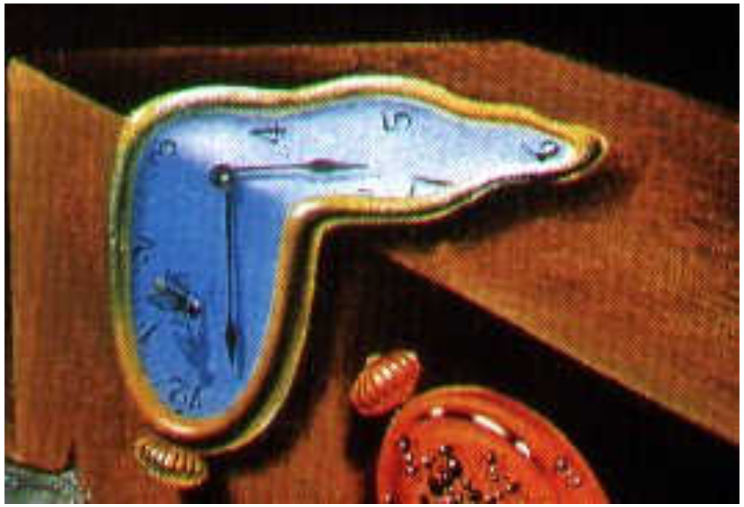
Fe 80, 20	
O 2	
Na 5	Cu 2
Mg 3	Zn 1
Al 2	Y 4
Si 5	Ba 3
Ca 9	Nd 2
Sc 1	La 3
Ti 9, 6	Eu 1
Cr 2	
Mn 6	
Co 2	
Ni 3	

Direct Measurement

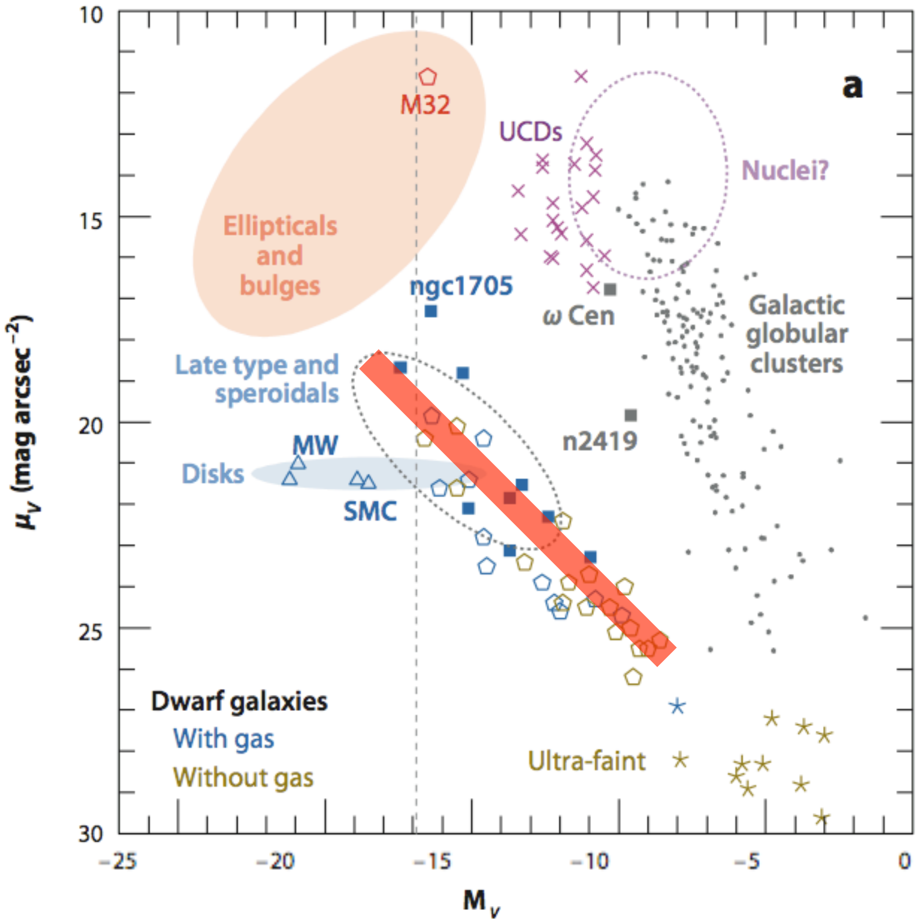
e.g., UVES R~40 000



Metallicity Indicators

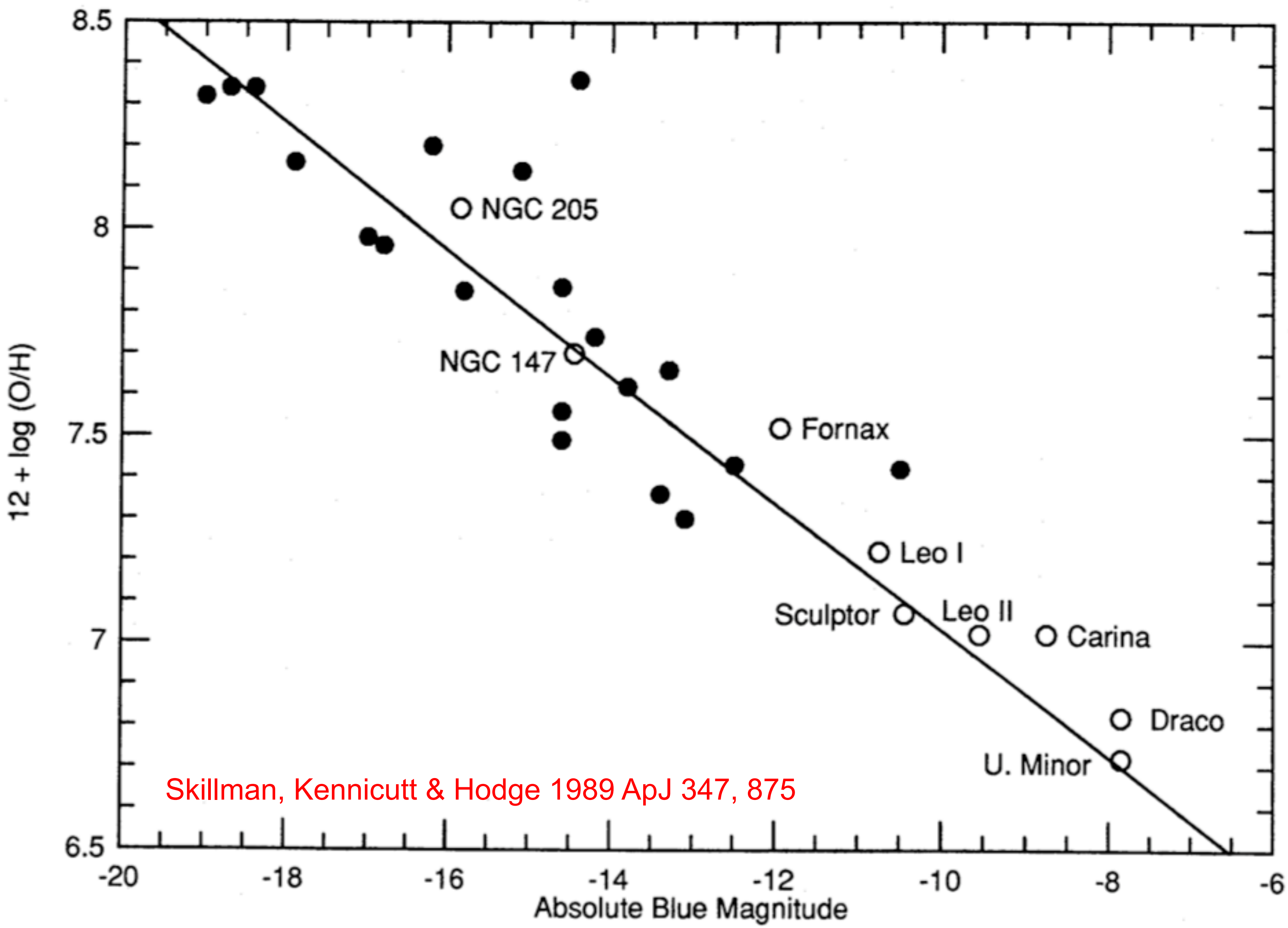


Global Properties

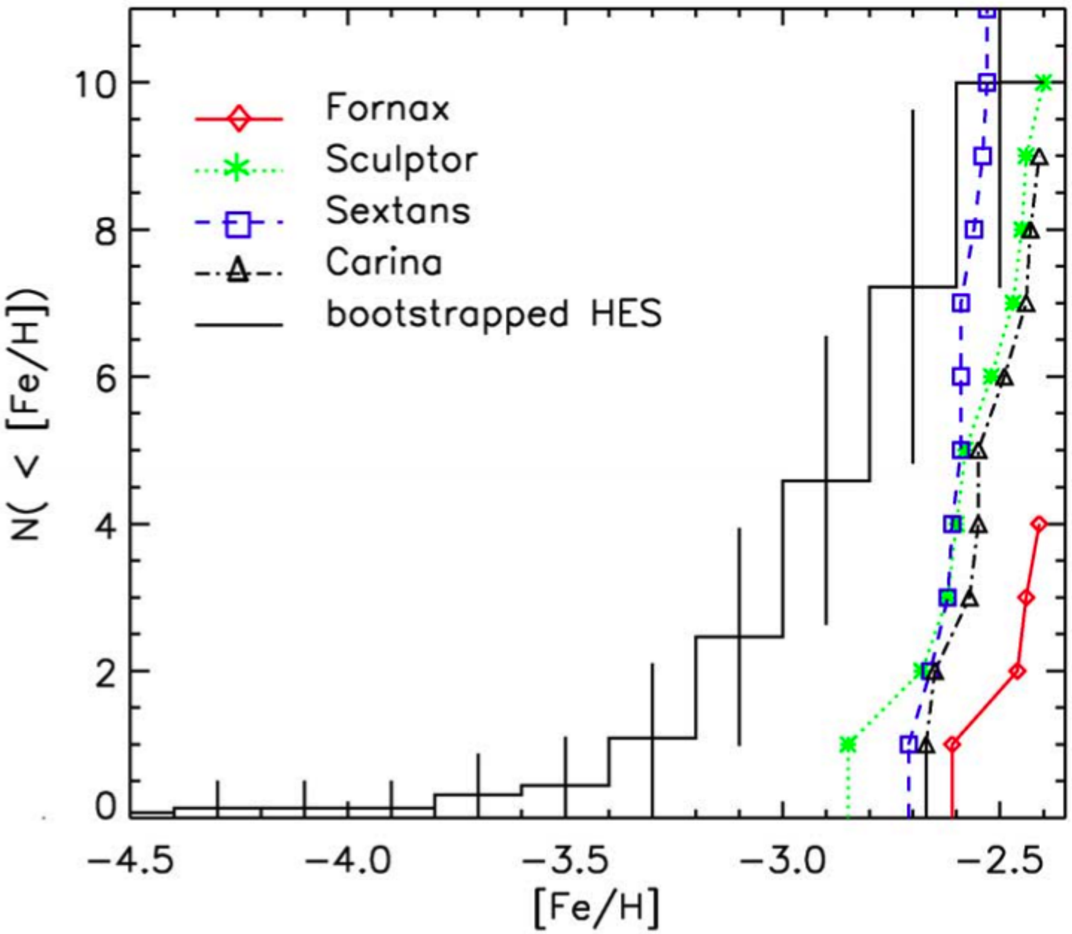


Tolstoy, Hill & Tosi 2009, ARAA, 47, 371

Global Metallicity Correlation



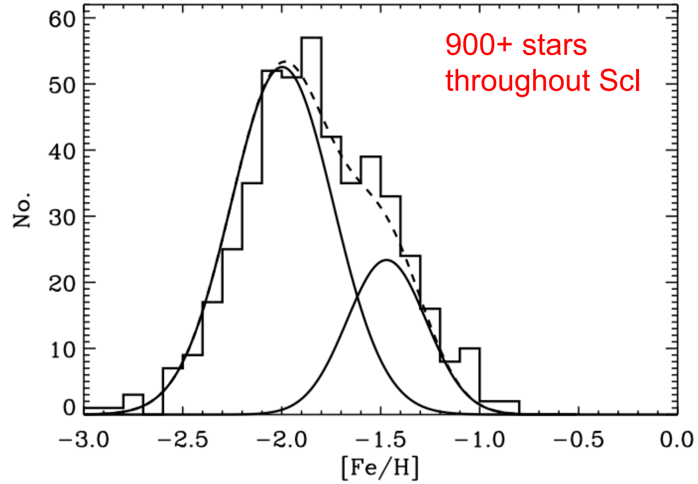
Metallicity Distribution

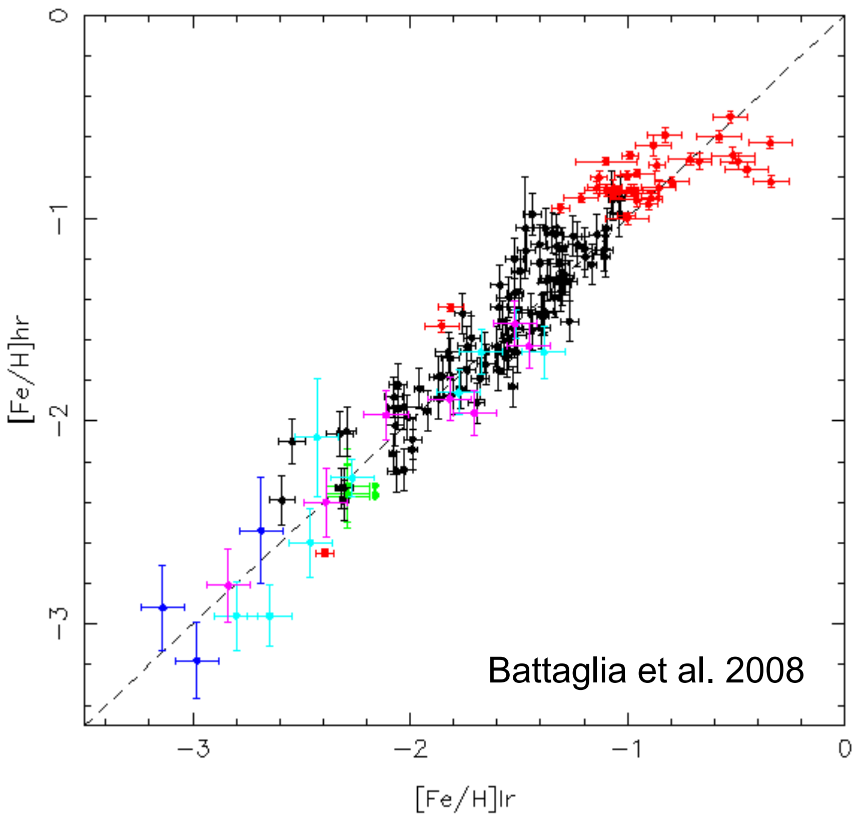


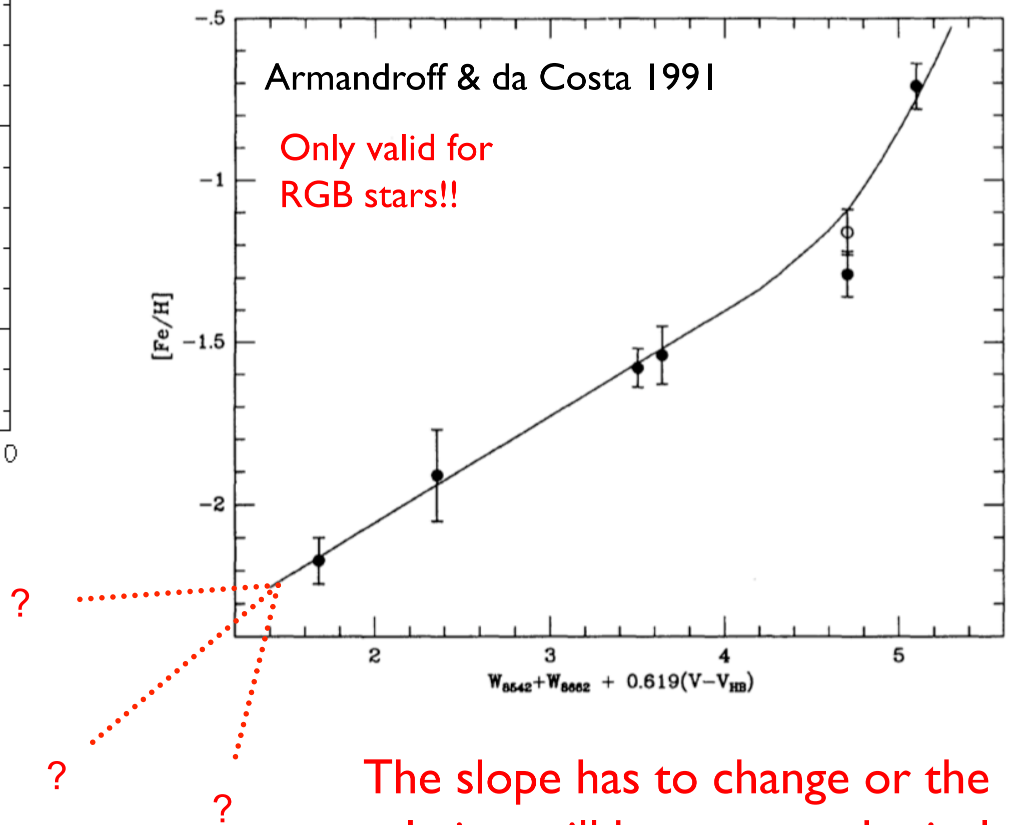
Helmi et al. 2006, ApJL

Do Galactic halo & dSph metallicity distributions differ significantly?

Ca II triplet calibration...







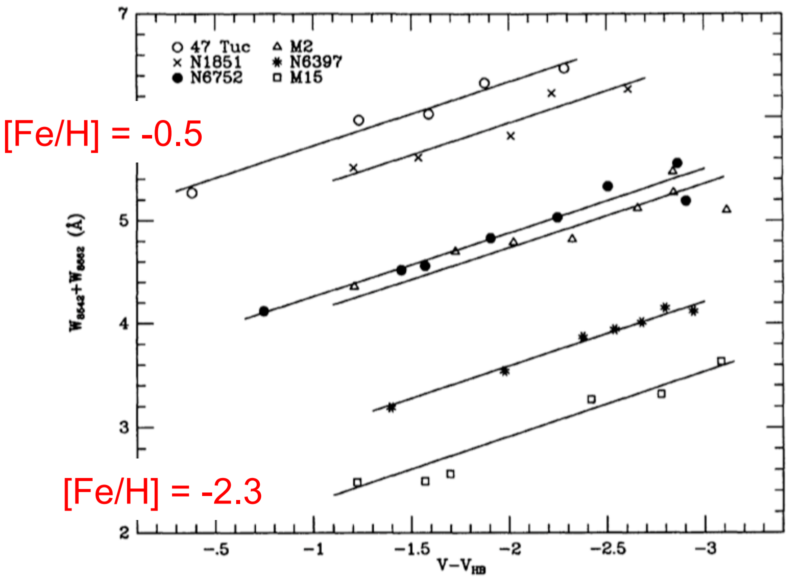
Extra points from analyses by Shetrone with HET (Draco & Umin), Venn with Magellan (Car)

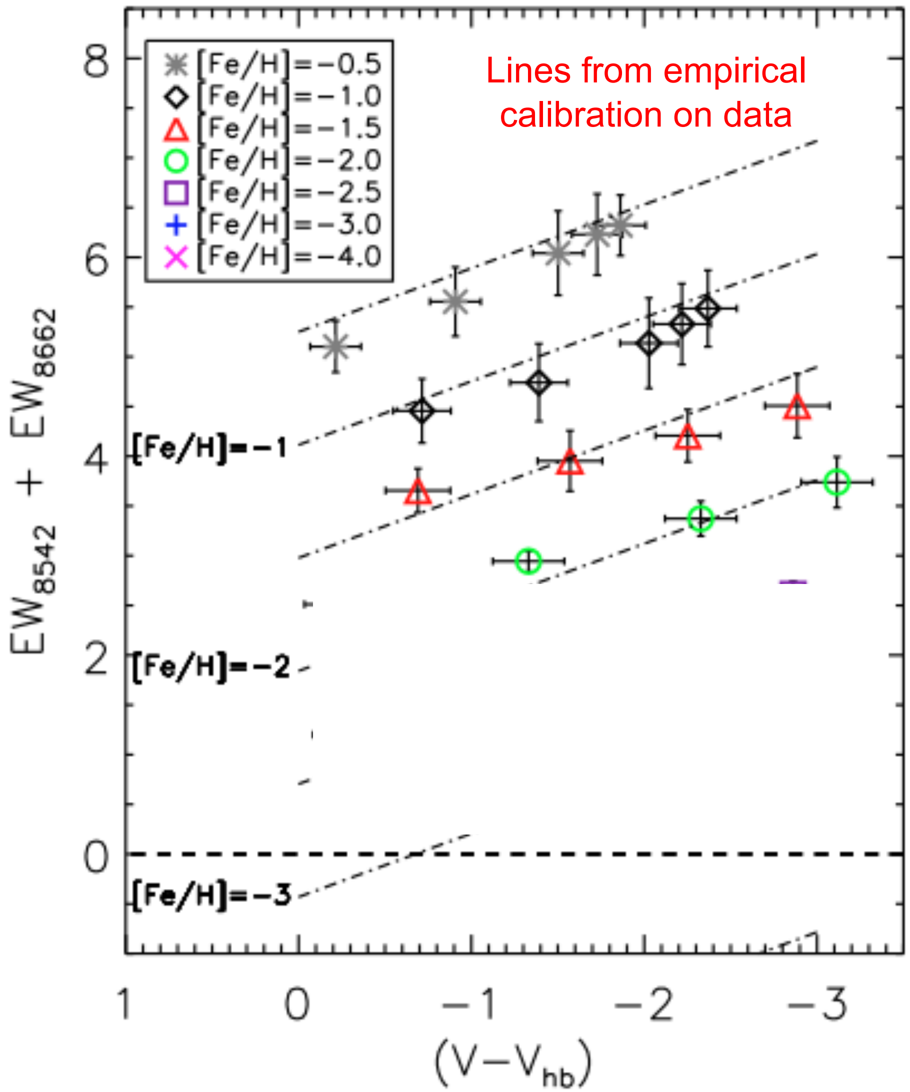
The slope has to change or the relation will become unphysical around [Fe/H] ~ -3

Modelling the CaT

Model points

DATA

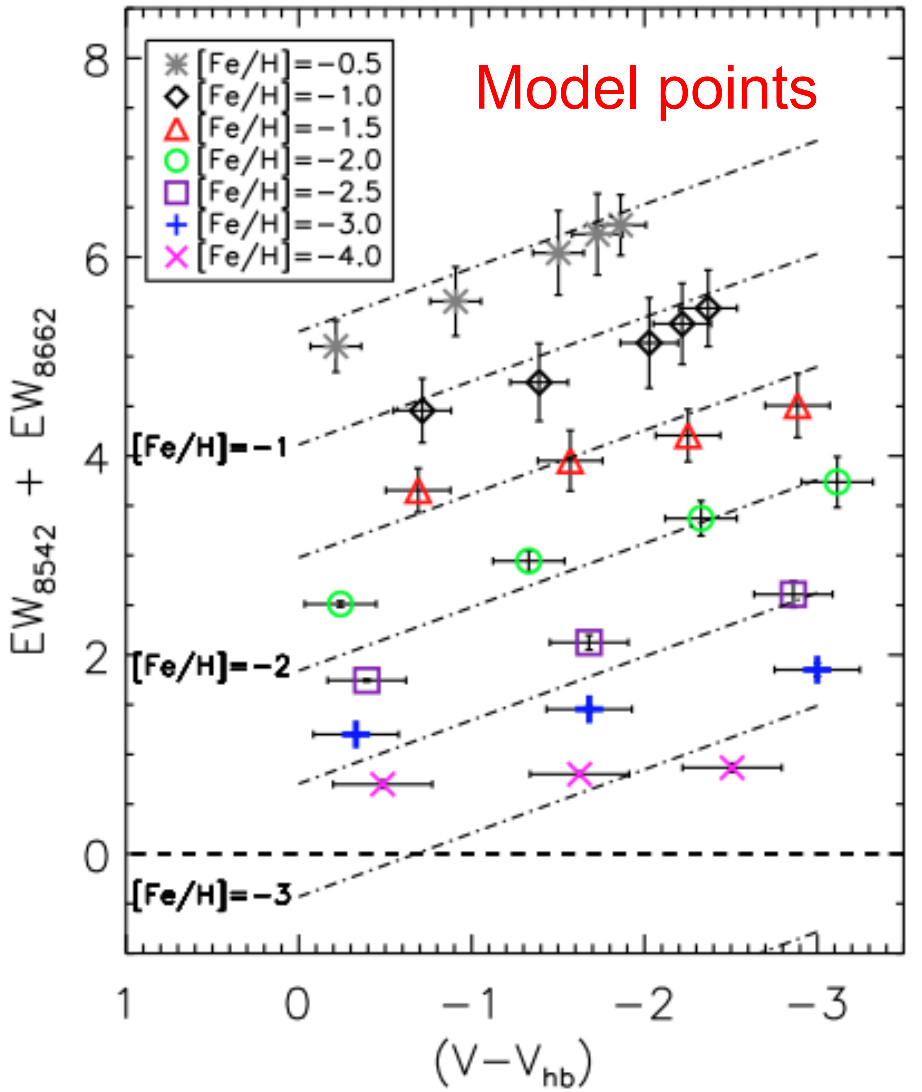




Globular cluster stars of "known" metallicity (from HR spectroscopy) compared to CaT line widths

Starkenburg et al. 2009

Modelling the CaT

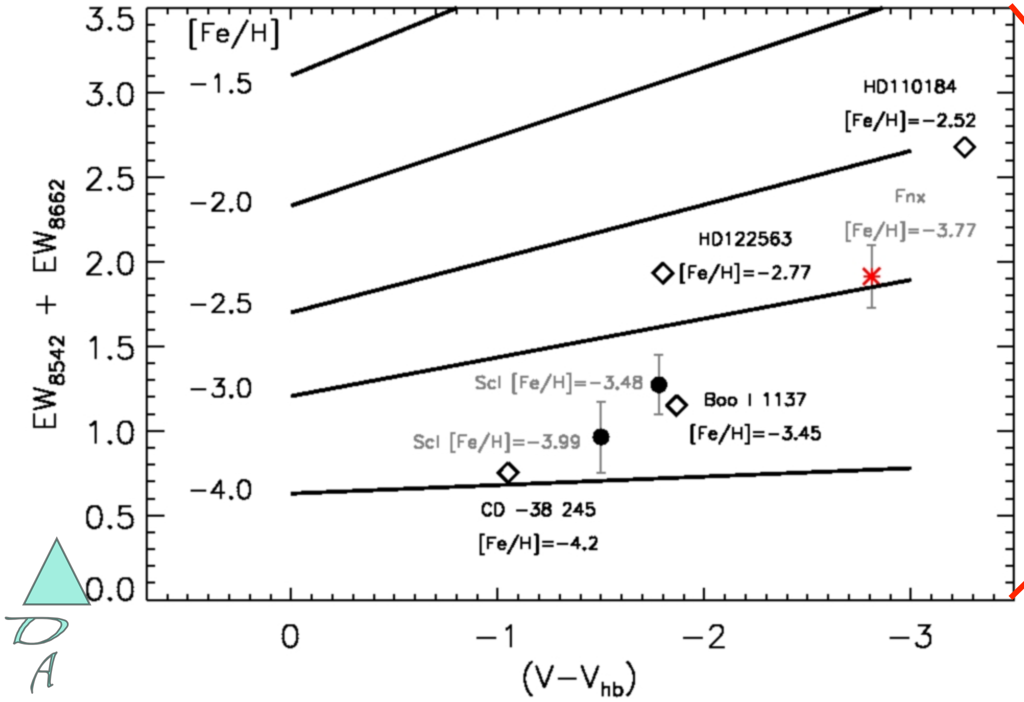


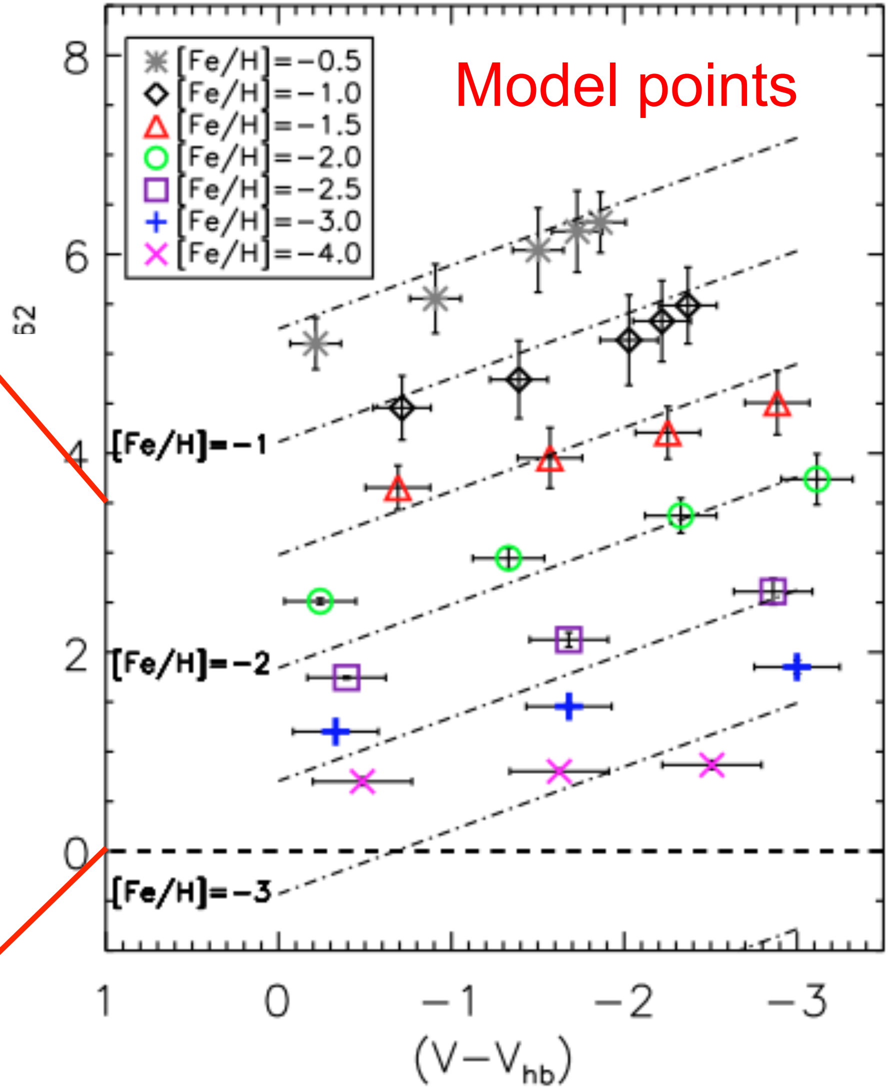
Starkenburg et al. 2010

Modelling the CaT

Tafelmeyer et al. 2010
Aoki, halo stars priv. comm. Norris et al. 2007 (Boo)
X-shooter comissioning data

Model vs. Data





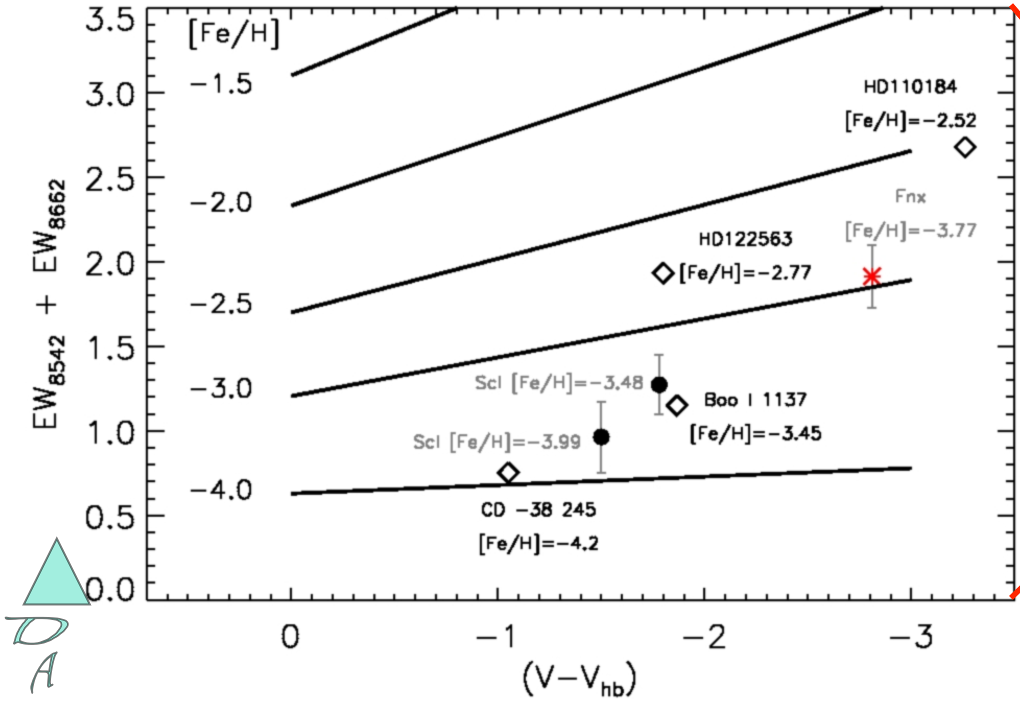
Starkenburg et al. 2010

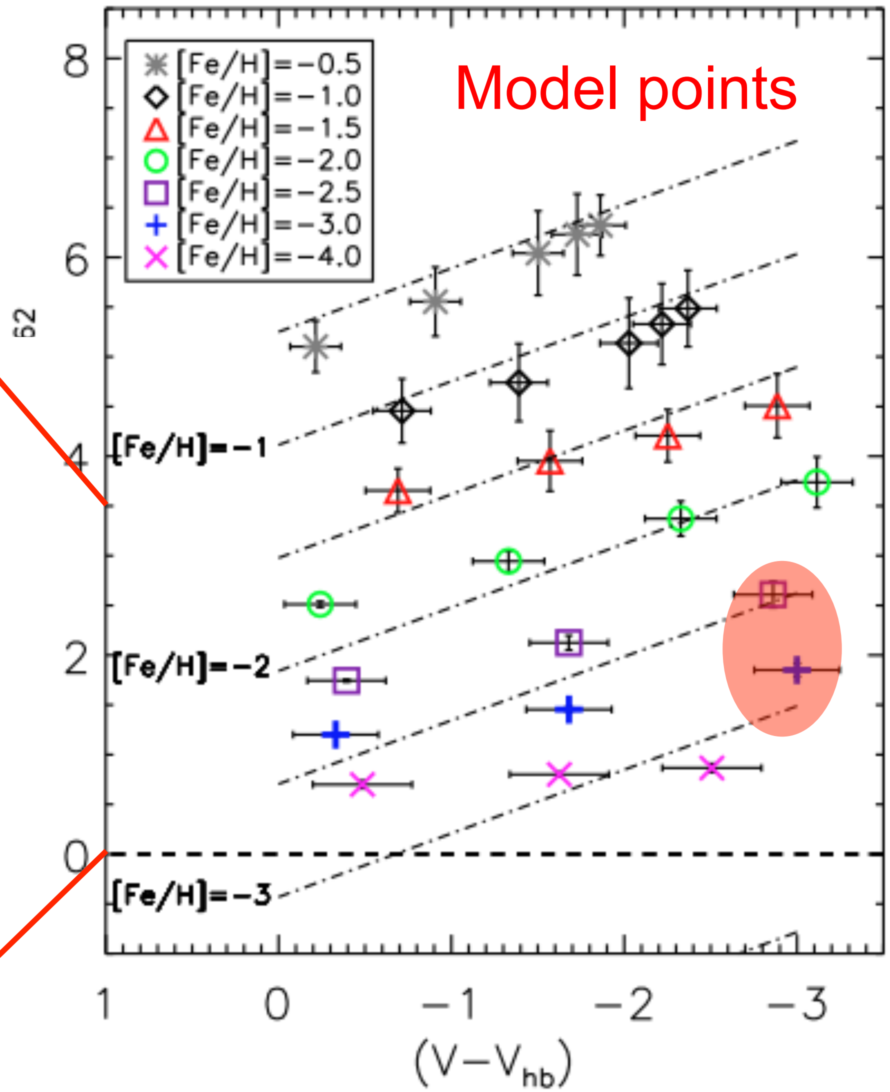
Modelling the CaT

Stars near the TRGB are the last to leave the correlation

Tafelmeyer et al. 2010
Aoki, halo stars priv. comm. Norris et al. 2007 (Boo)
X-shooter comissioning data

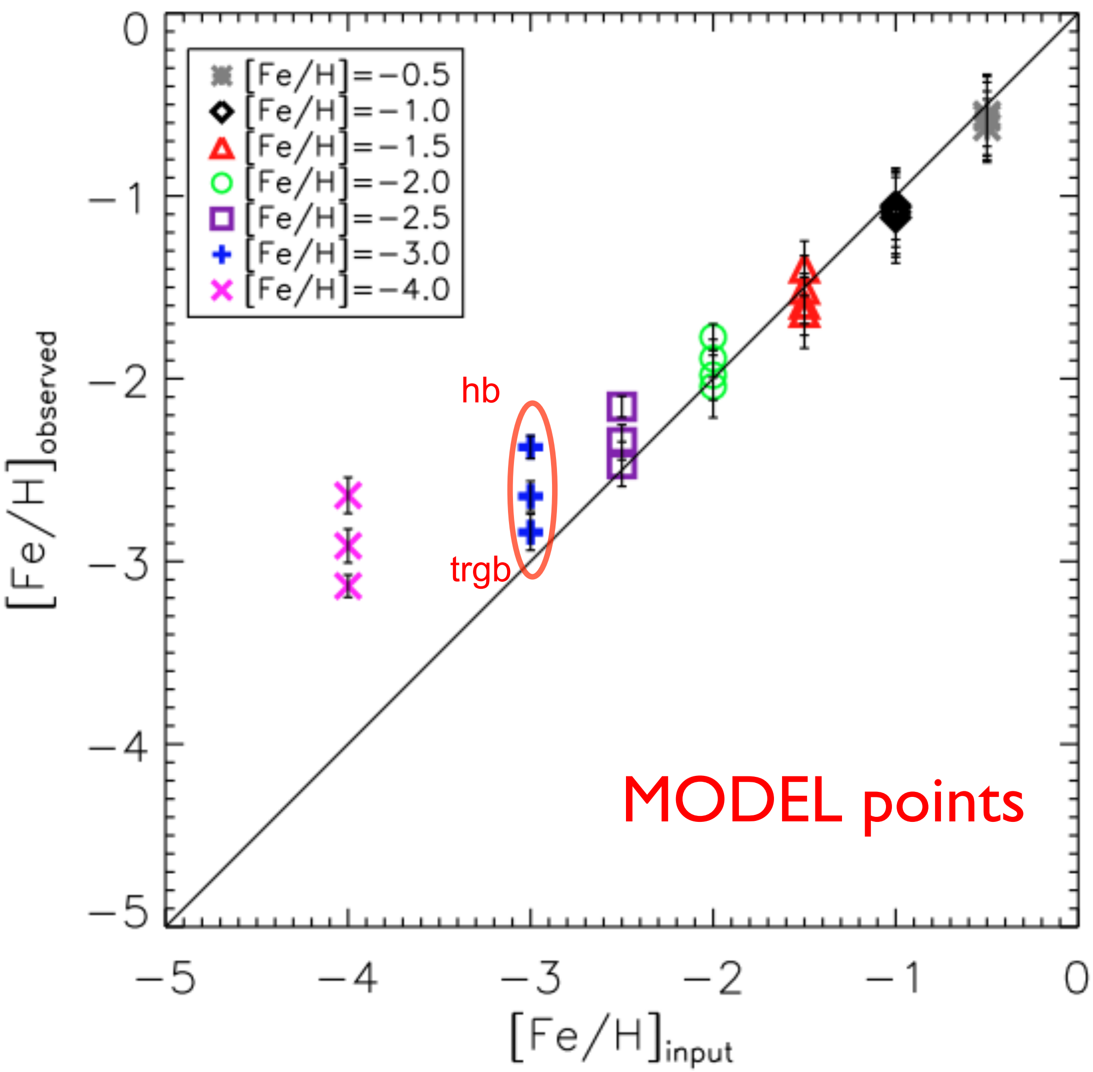
Model vs. Data





Starkenburg et al. 2010

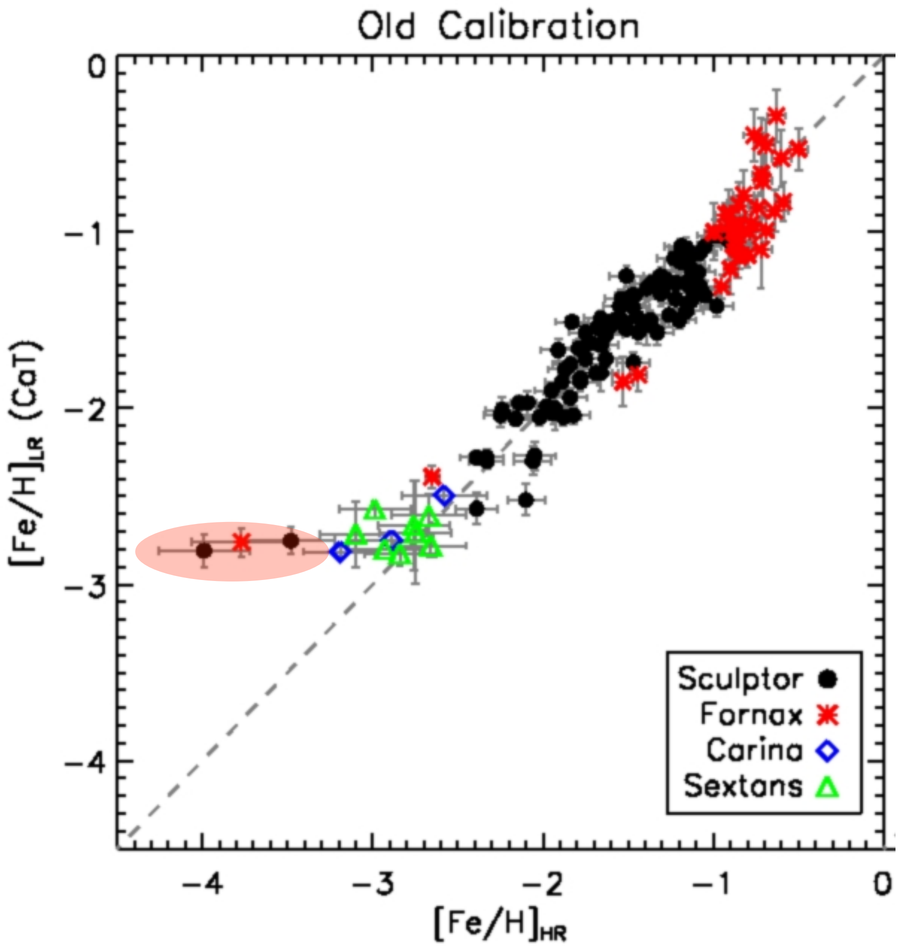
Call triplet accuracy at low metallicity



Based on synthetic spectra can re-determine the CaT calibration at low [Fe/H]

Starkenburg et al. 2009

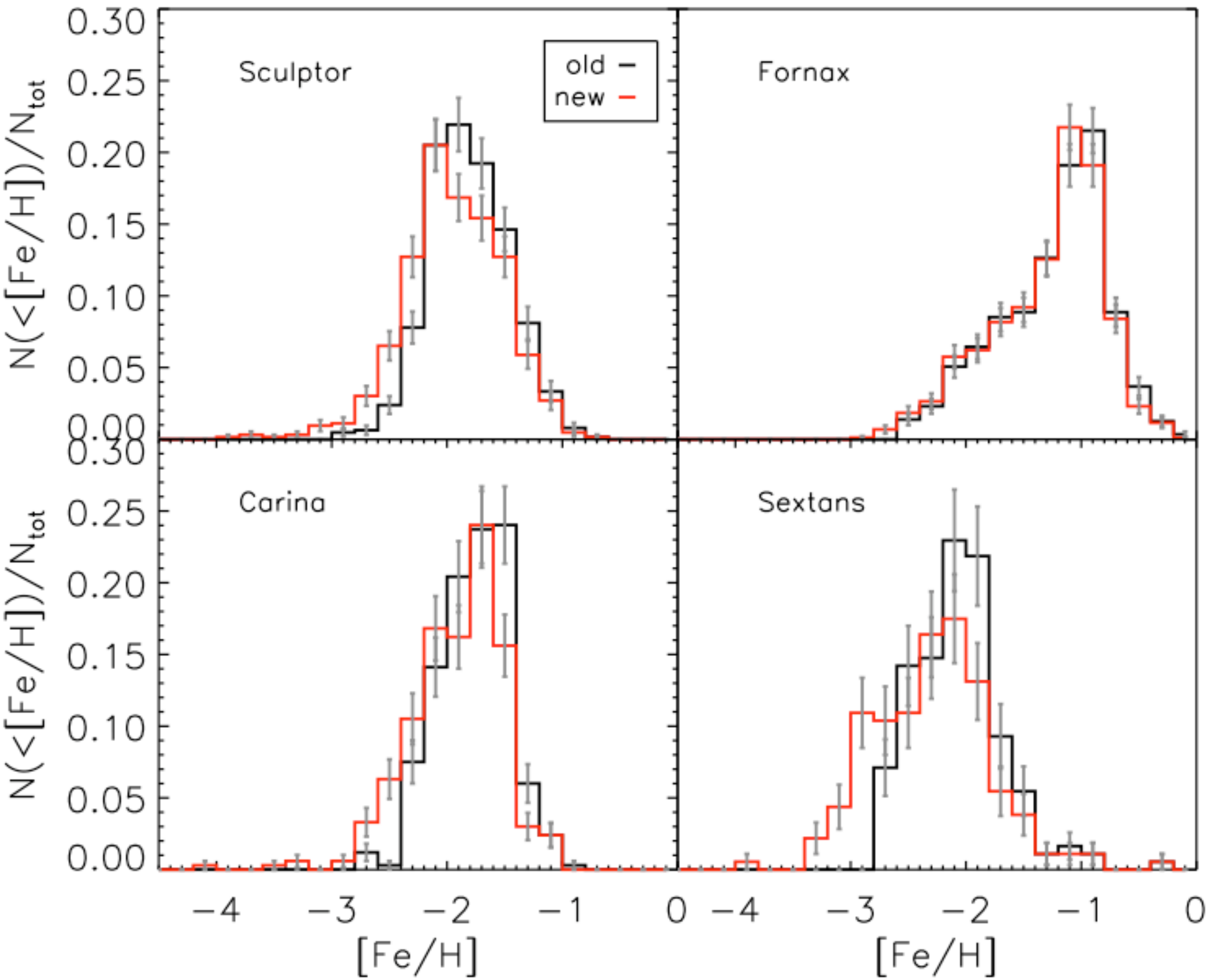
Testing the New Calibration



Tafelmeyer et al. 2010
Venn et al. 2011 in prep
Aoki et al. 2009 A&A
Battaglia et al. 2008

Starkenburg et al. 2010

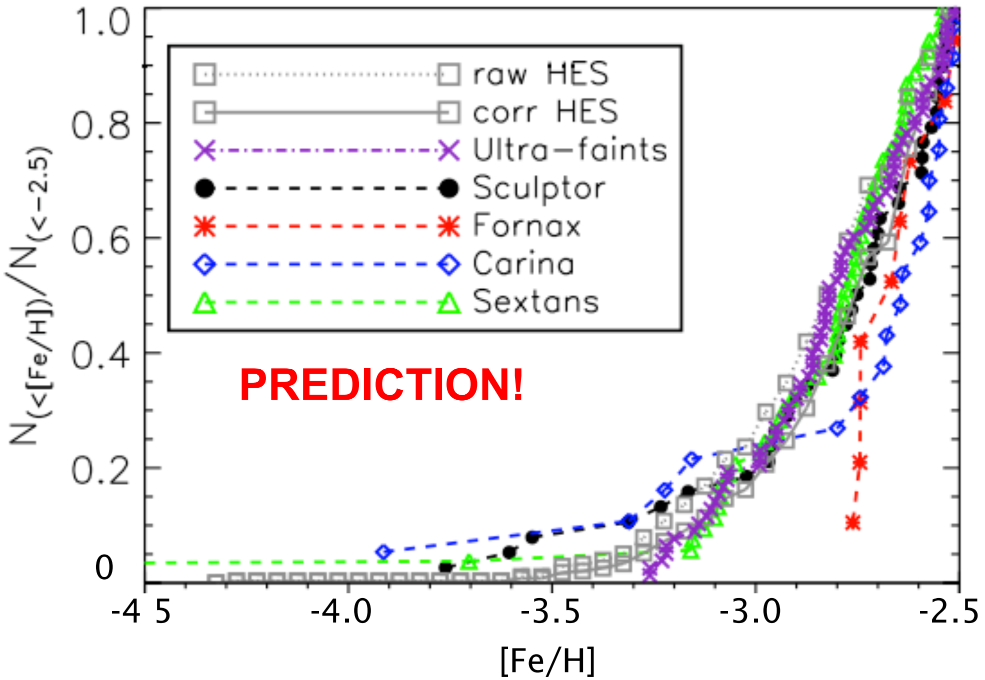
CaII triplet metallicity indicator



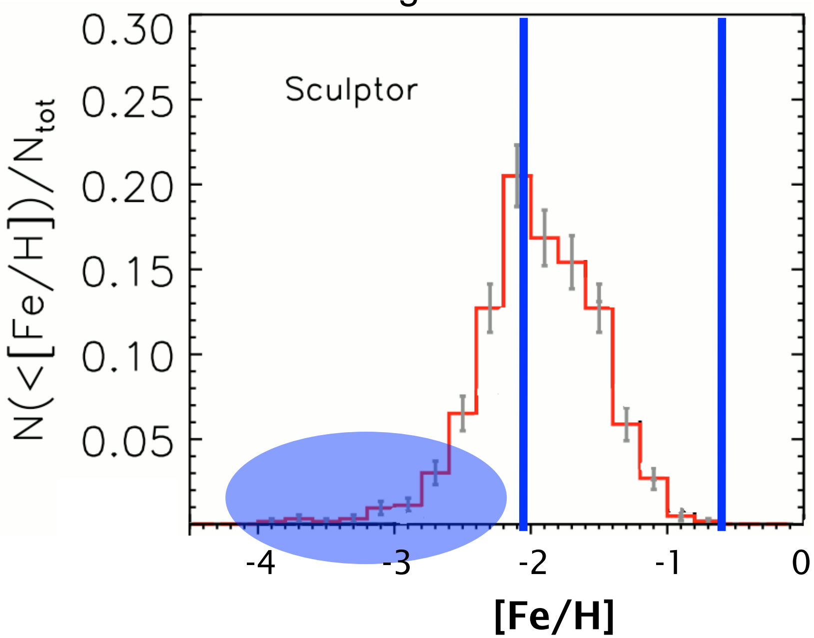
Starkenburg et al. 2010

Metal Poor stars…

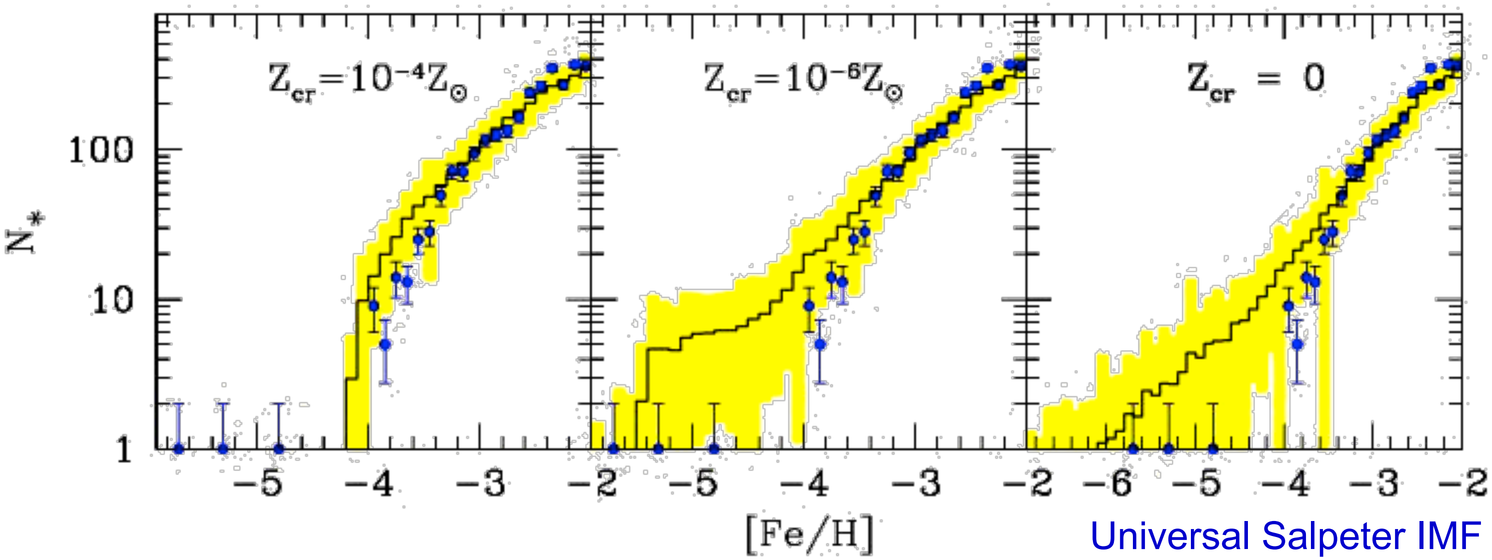
Starkenburg et al. 2010



Starkenburg et al. 2010



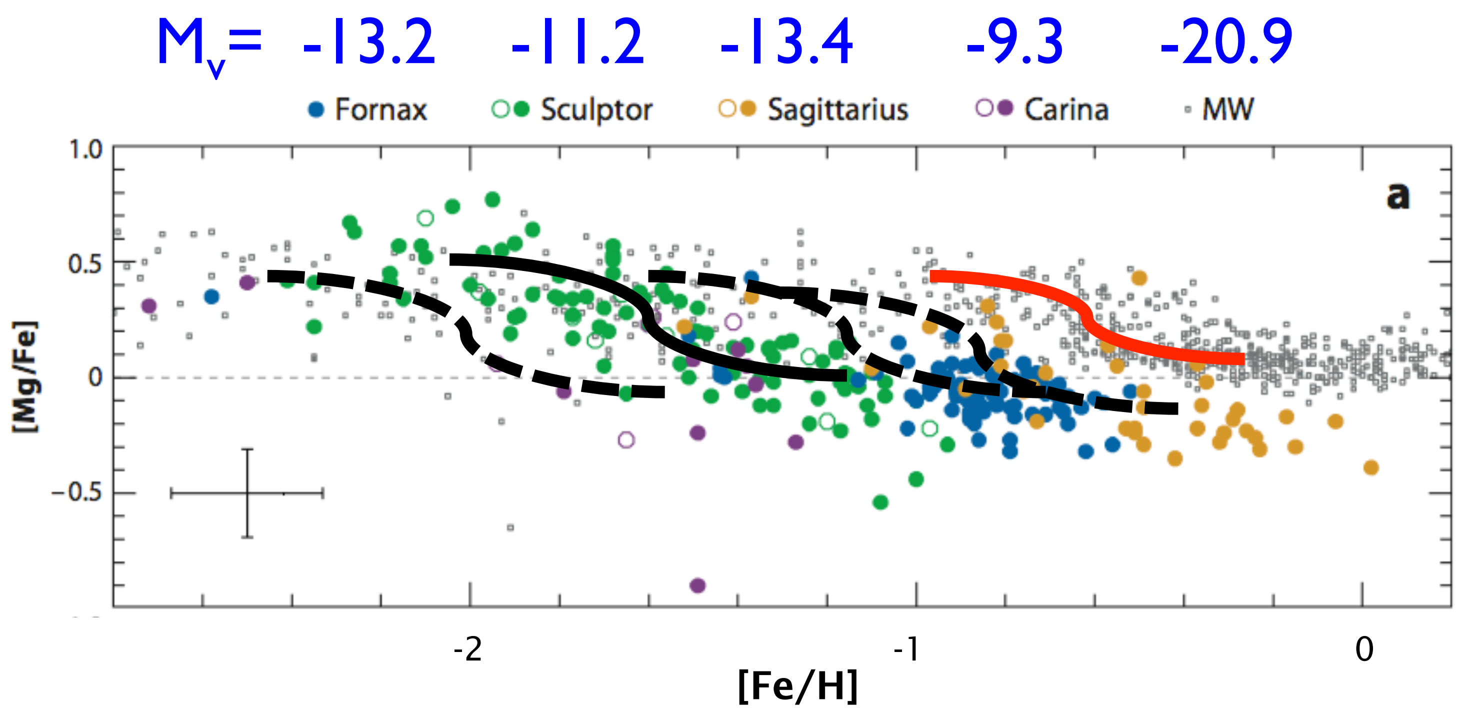
Salvadori, Schneider & Ferrara 2007



Universal Salpeter IMF

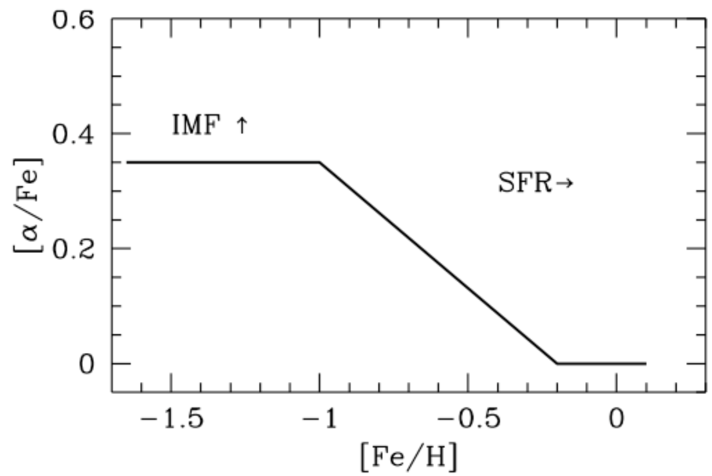
Detailed Abundances

α-element abundances in dSph



"The Knee"

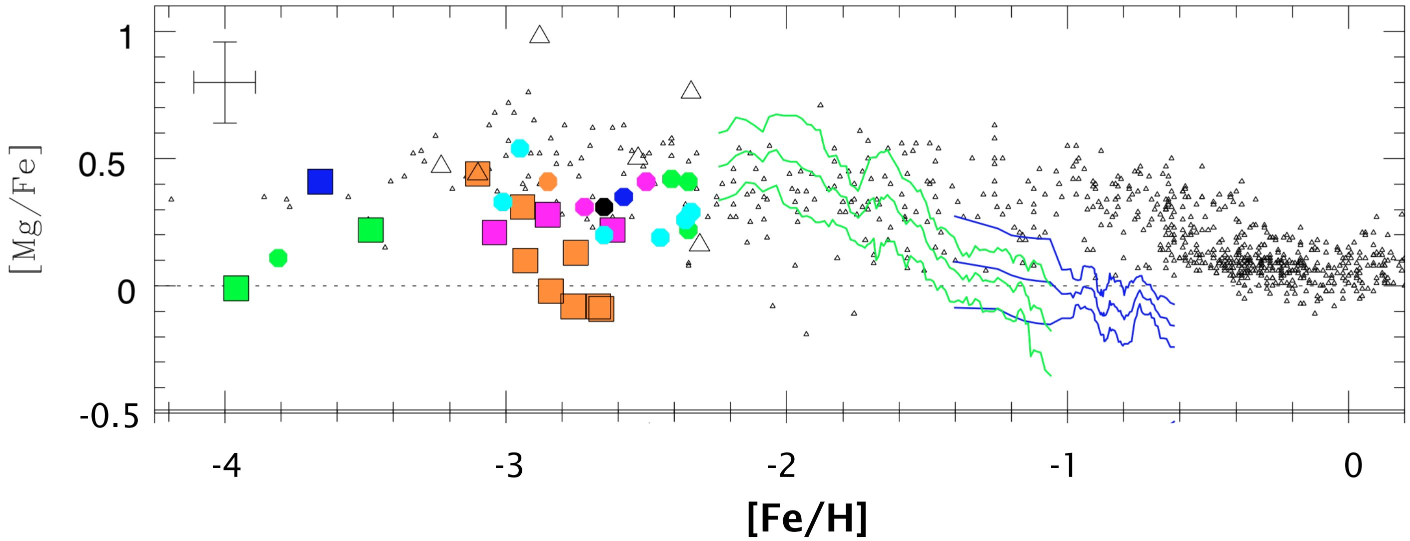
Hill et al. 2010
Letarte et al. 2010
Koch et al. 2008
Venn et al. 2011
Sbordone et al. 2007

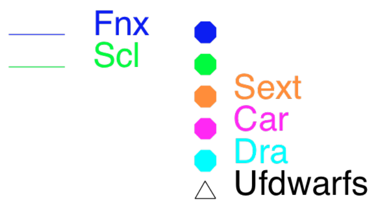


Tolstoy, Hill & Tosi 2009

Figure 1 A schematic diagram of the trend of α-element abundance with metallicity. Increased

Extremely Metal Poor stars: clues to formation

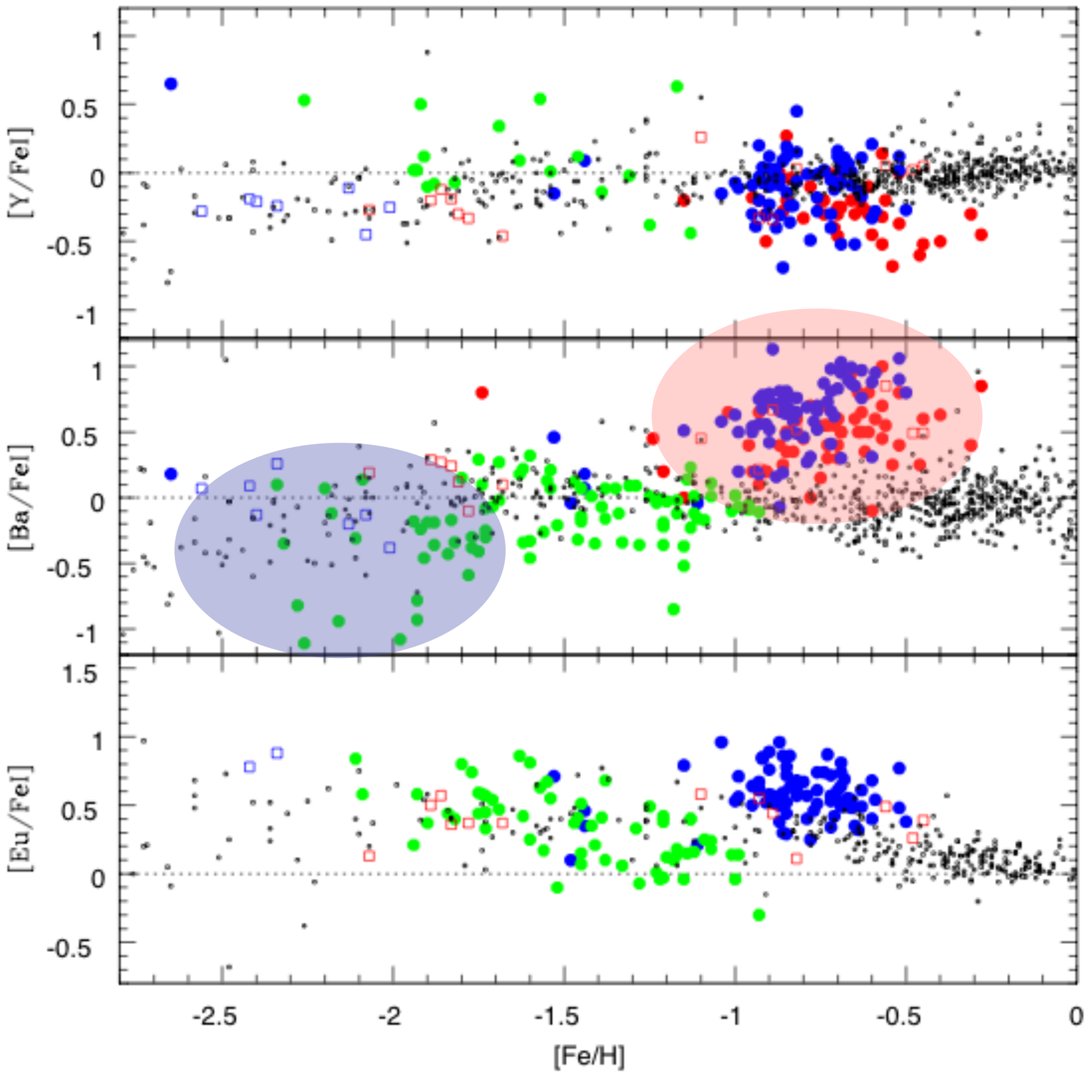




Tafelmeyer et al. 2010
Shetrone et al. 2001, 2003
Frebel et al. 2010
Koch et al. 2008
Aoki et al. 2009
Letarte et al. 2010
Hill et al. 2011

Tafelmeyer et al. 2010

heavy elements



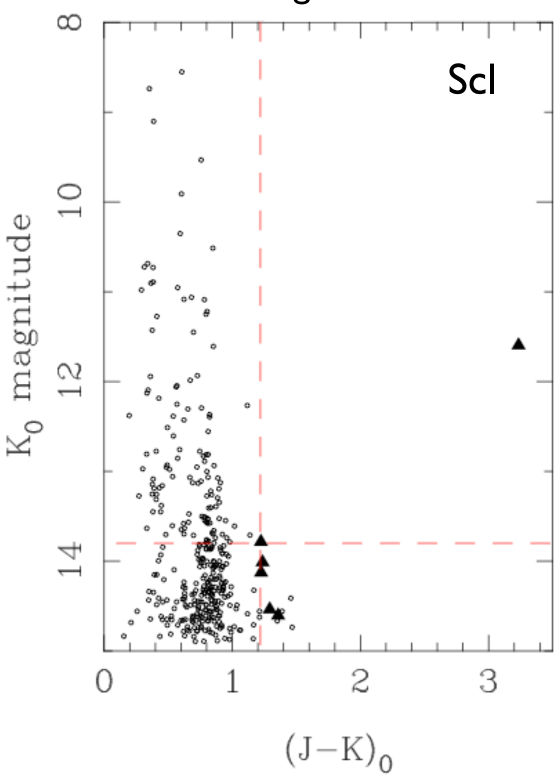
Sculptor dSph
Hill et al. 2011, in prep
Tolstoy, Hill & Tosi 2009

Fornax dSph
Letarte et al. 2010

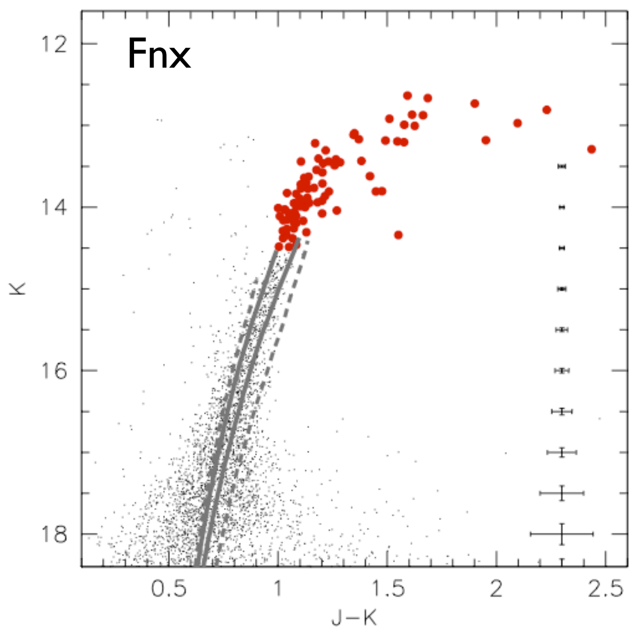
Large Magellanic Cloud
Pompeia et al. 2008

Evolved stars in CMDs

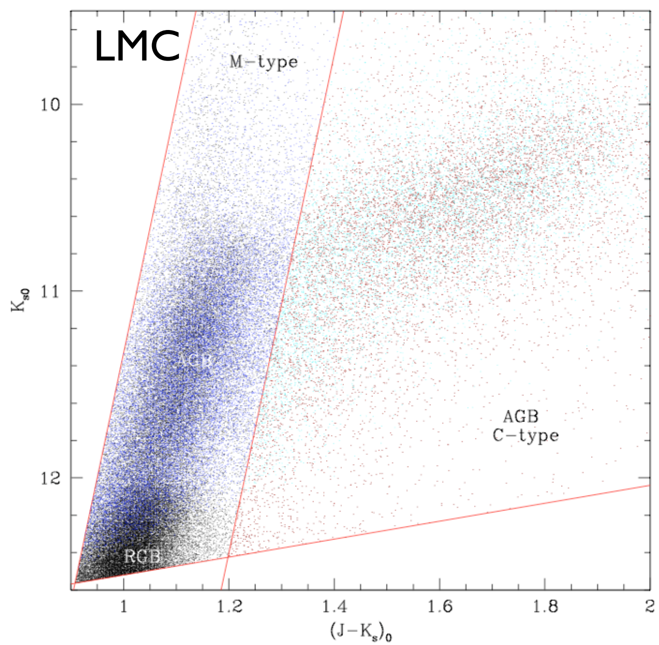
Groenewegen et al. 2009



Gullieuszik et al. 2007

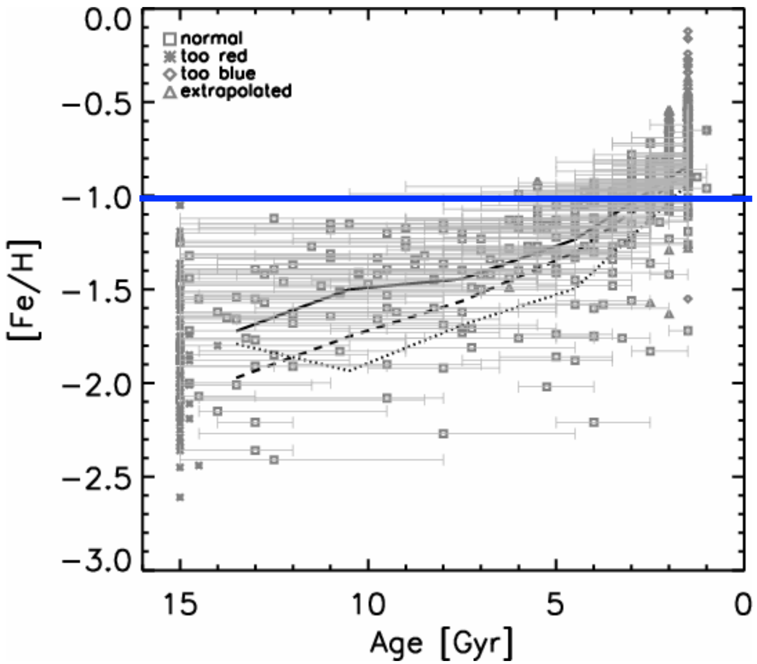


Cioni et al. 2006

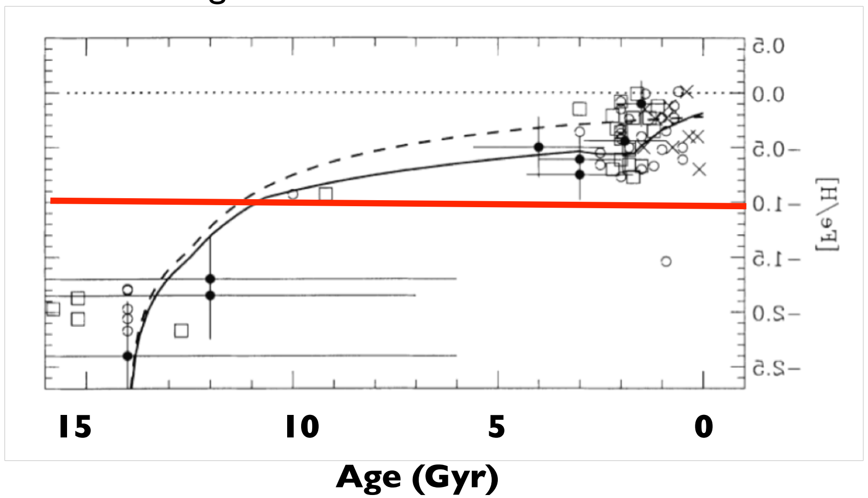


Age -Metallicity

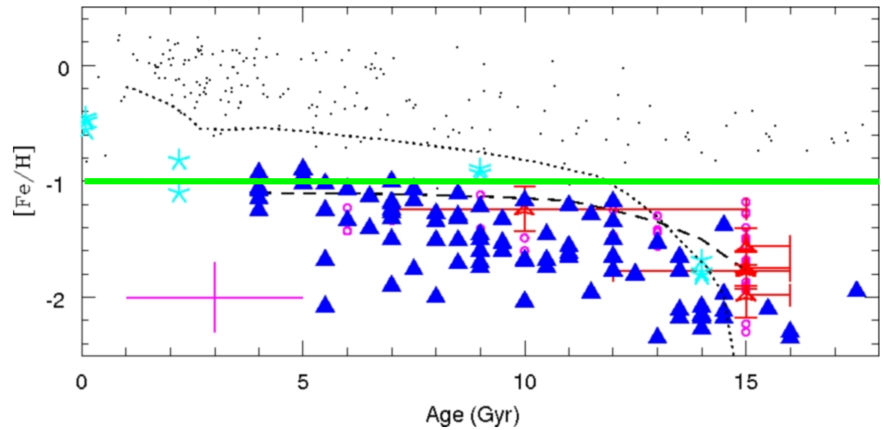
Fnx: Battaglia et al. 2006 A&A

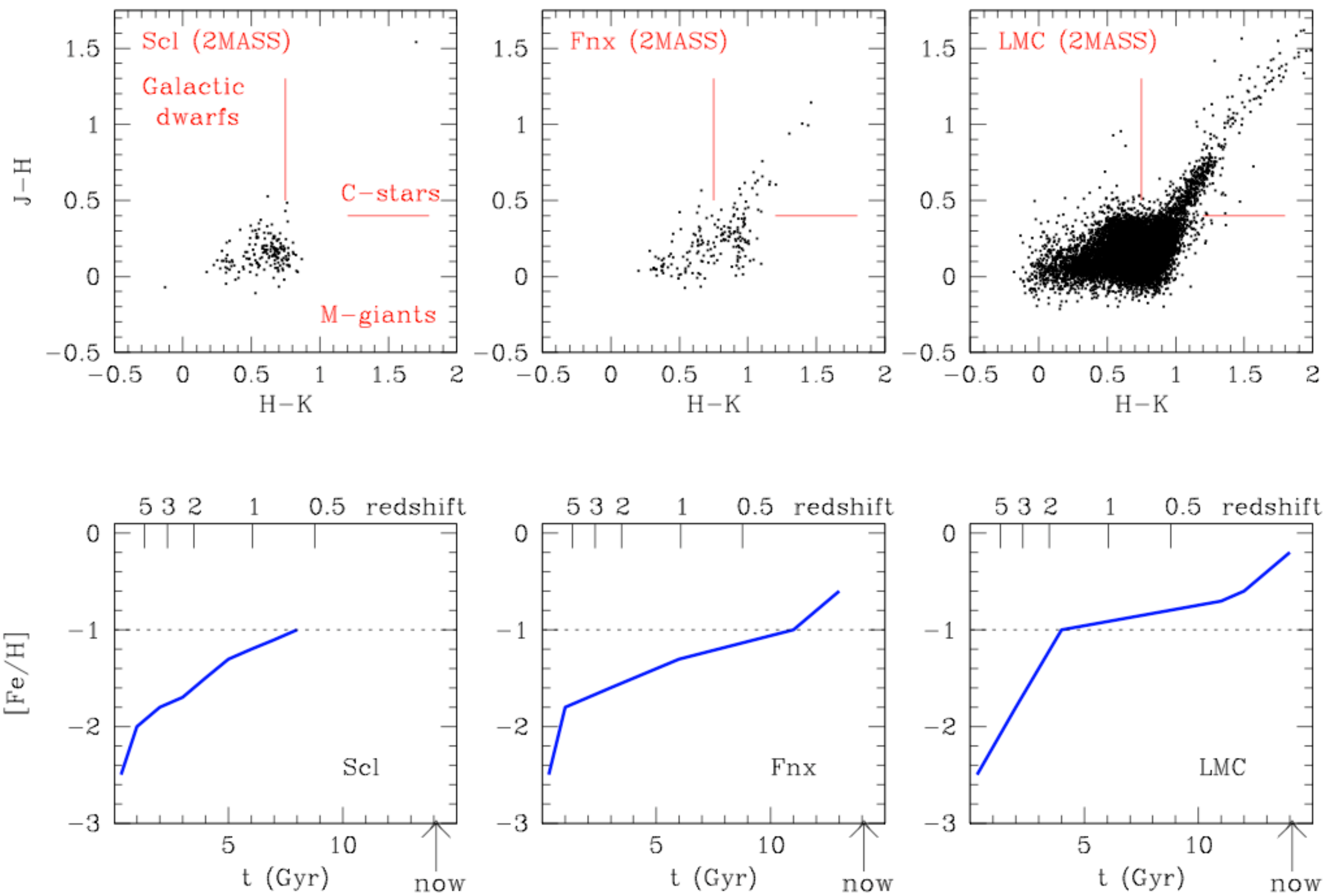


LMC: Pagel & Tautvaisiene 1998 MNRAS



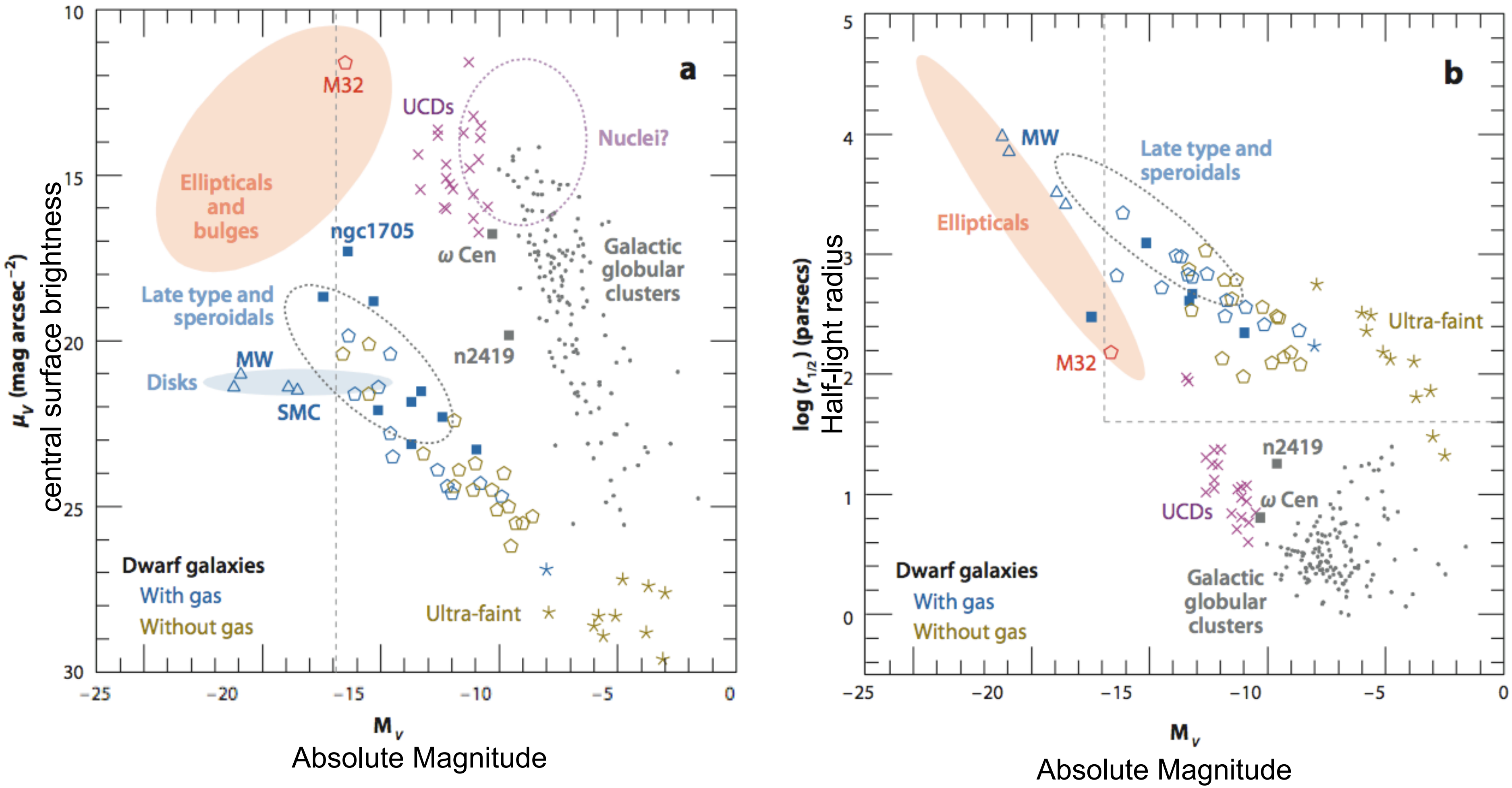
Scl: de Boer et al., in prep





Tolstoy F.,, 2010arXiv1012.2229

signatures of formation & evolution?

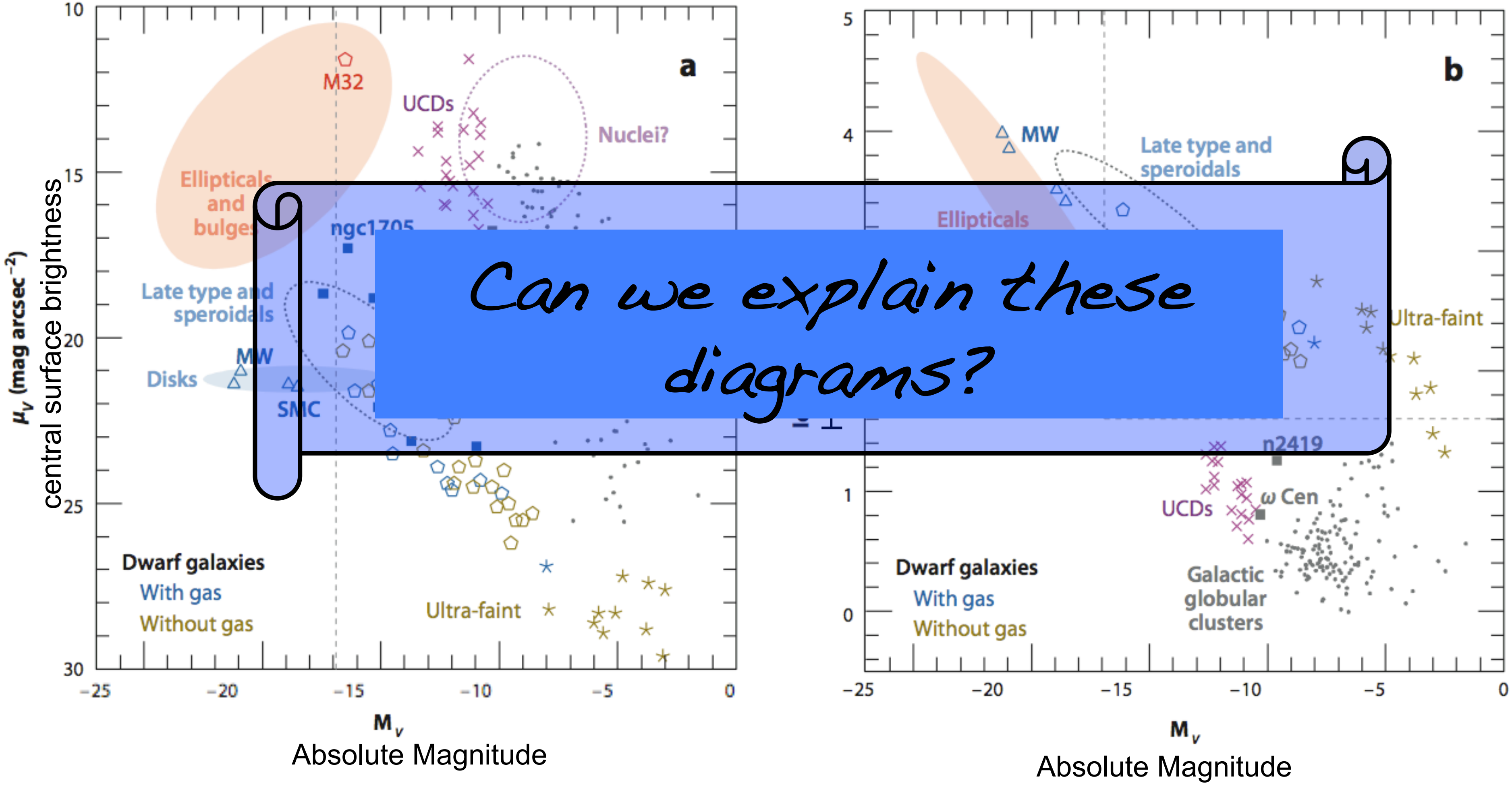


based on Kormendy 1985; Binggeli 1994

see also Belokurov et al. 2007

Tolstoy, Hill & Tosi 2009, ARAA, 47, 371

signatures of formation & evolution?



based on Kormendy 1985; Binggeli 1994

see also Belokurov et al. 2007

Tolstoy, Hill & Tosi 2009, ARAA, 47, 371

Conclusions

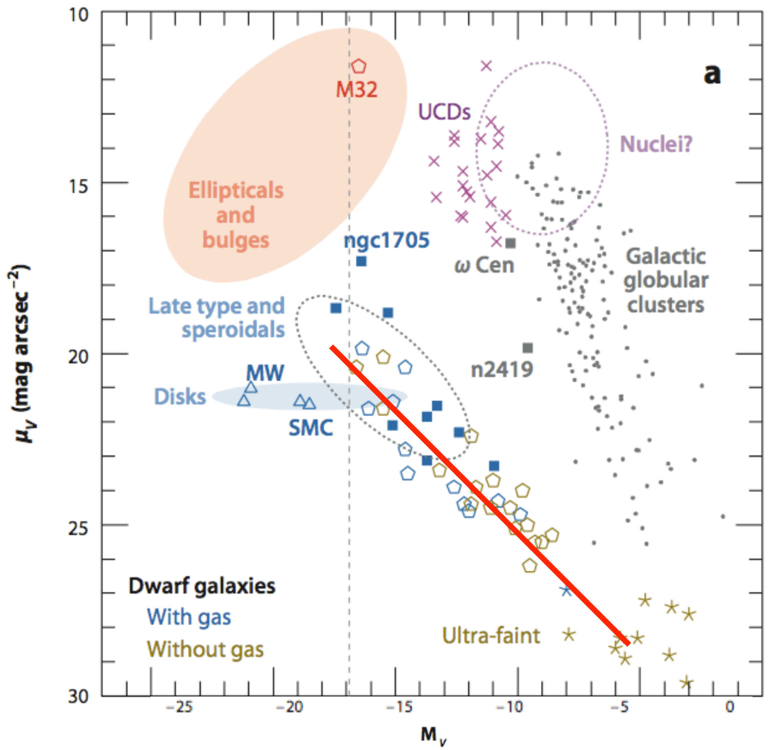
dSph contain stars with [Fe/H] < -3 (one has now been found at [Fe/H] = -4 !)

dSph, dI & Ufds show consistent abundance patterns

Most stars in dwarf galaxies are different from those in the Milky Way (!)

All dwarf galaxies (with the exception of M32) seem to follow a continuum of properties **suggesting** a common progenitor/formation & evolution processes which is still apparent even when all the gas has been removed.

This relation likely indicates the ability of galaxies of increasing mass to be increasingly stable against disruption from either surrounding galaxies or their own star formation processes (test: changing position of “knee” in alpha-elements). But they are still subject to variety of evolutionary influences….



Thanks to...

Nobuo Arimoto

Wako Aoki

Mike Irwin

Vanessa Hill

Else Starkenburg

Giuseppina Battaglia

Andrew Cole

Thomas de Boer

Pascale Jablonka

Martin Tafelmeyer

Bertrand Lemasle

Giuliana Fiorentino

Stefania Salvadori

Abhijit Saha

Monica Tosi

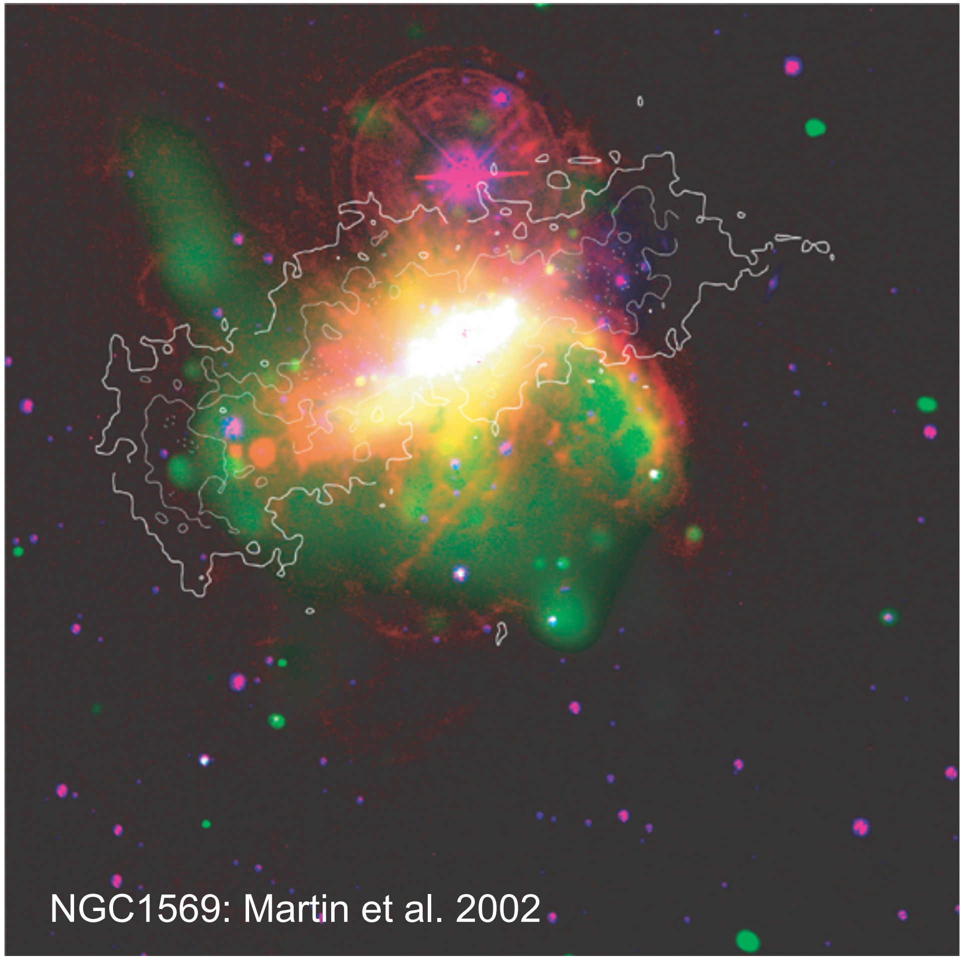
Matthew Shetrone

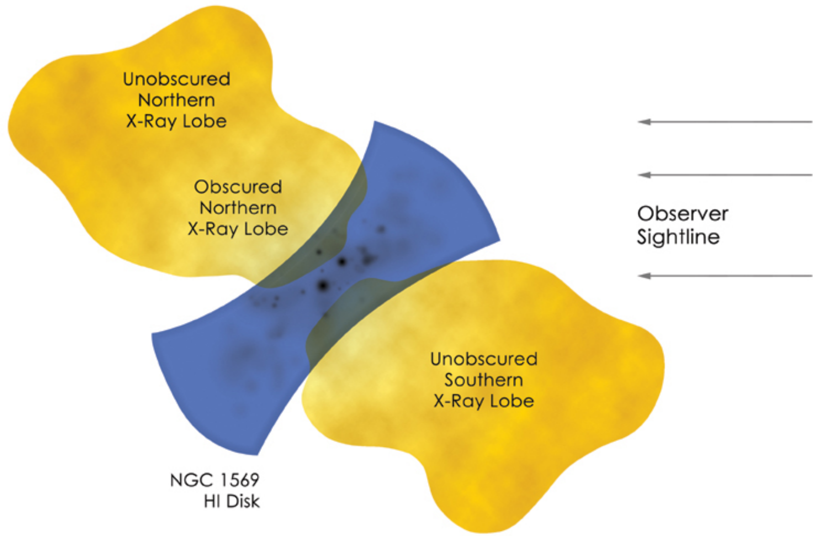
Kim Venn

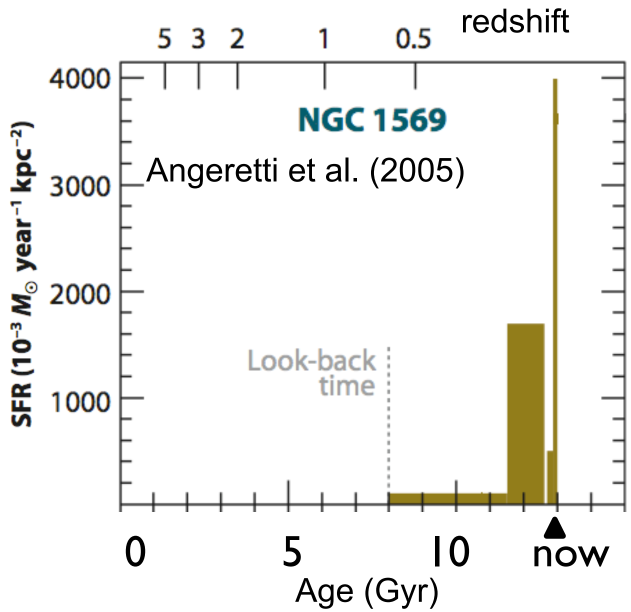
Amina Helmi

Kozo Sadakane

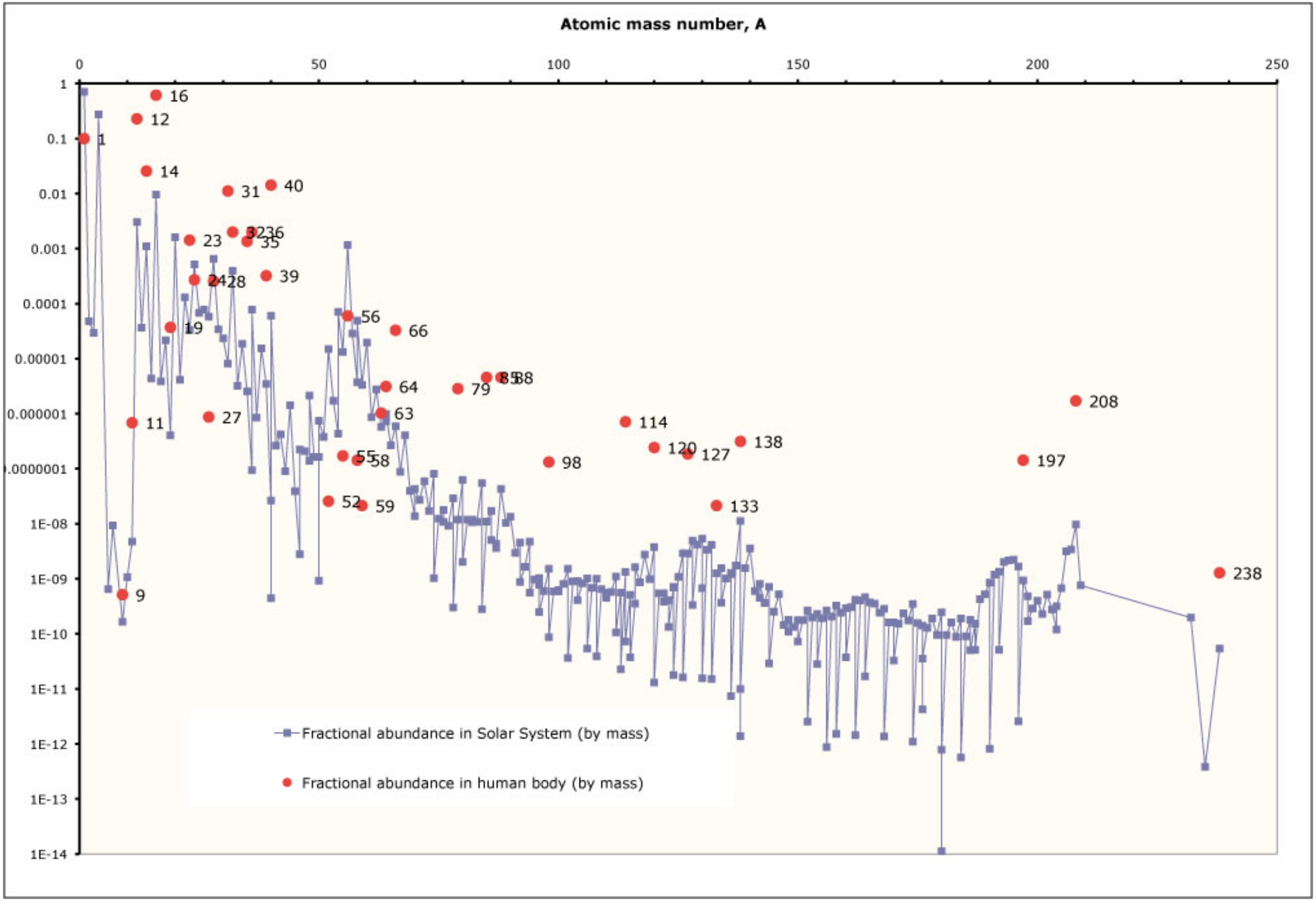
Galactic Outflows (& Infall?)



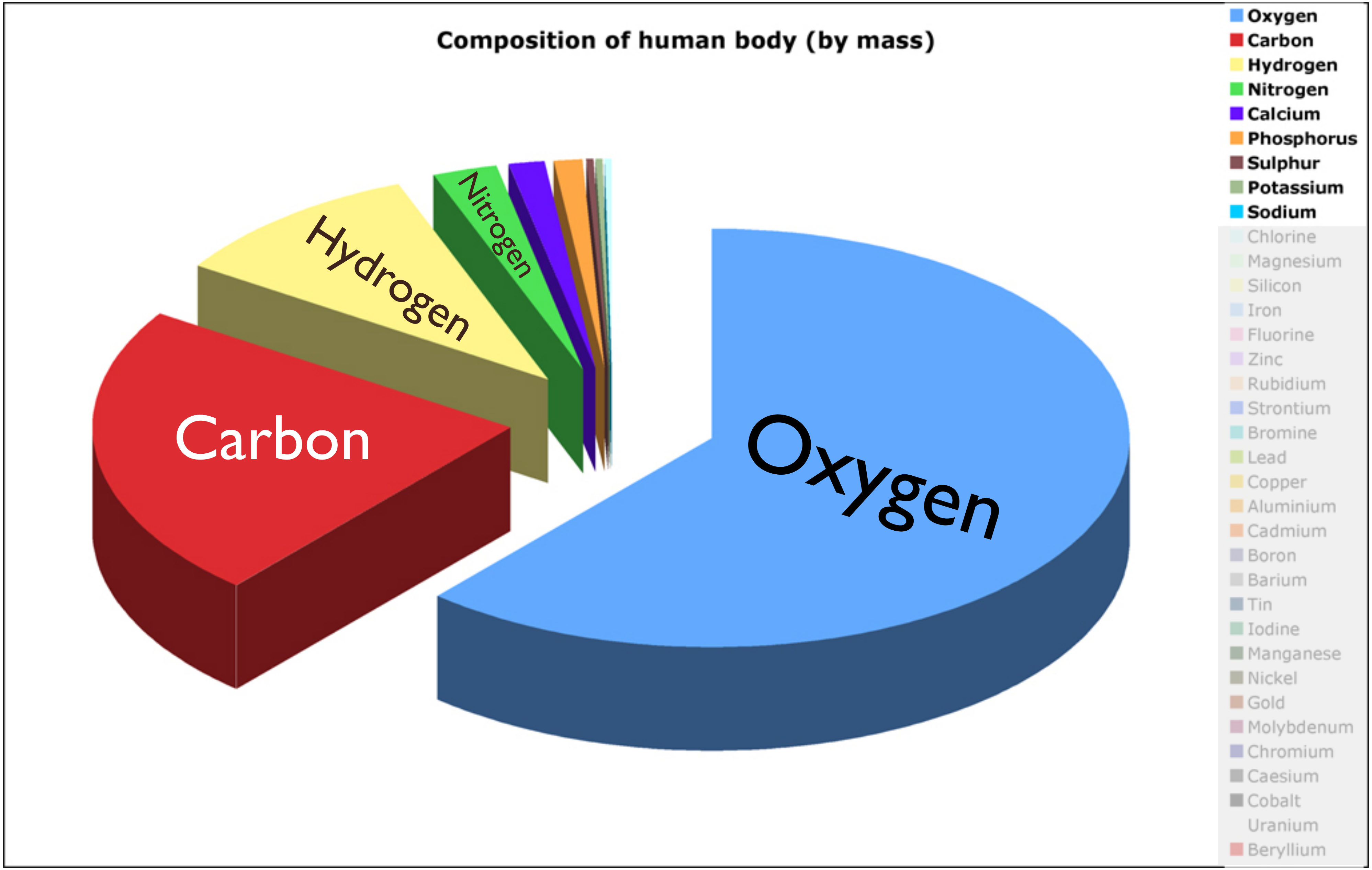




Gas circulation!



99% of the mass of the human body is made up of the six elements: oxygen, carbon, hydrogen, nitrogen, calcium, and phosphorus.


Composition of human body (by mass)
Oxygen
Carbon
Hydrogen
Nitrogen
Oxygen
Carbon
Hydrogen
Nitrogen
Calcium
Phosphorus
Sulphur
Potassium
Sodium
Chlorine
Magnesium
Silicon
Iron
Fluorine
Zinc
Rubidium
Strontium
Bromine
Lead
Copper
Aluminium
Cadmium
Boron
Barium
Tin
Iodine
Manganese
Nickel
Gold
Molybdenum
Chromium
Caesium
Cobalt
Uranium
Beryllium

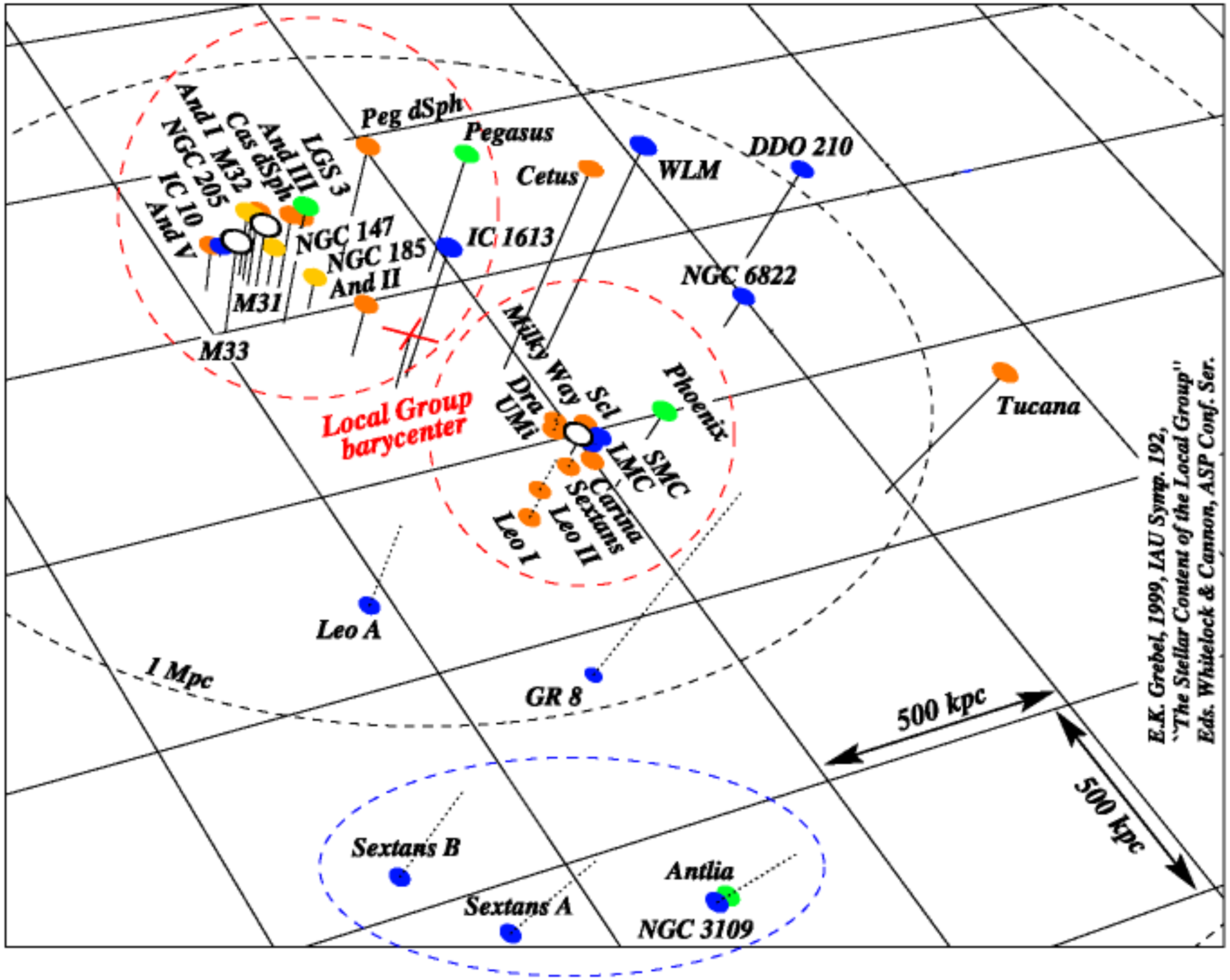
Where did it all come from?

- hydrogen (in water) — Big Bang (17 minutes)

- oxygen, carbon, nitrogen, calcium, phosphorous, sulphur, potassium, sodium etc. — gradual (millions to billions of years) fusion reactions in stars: spread by planetary nebulae and supernovæ

- iron — supernovæ: creation and distribution

The Local Group



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