Evolved stars in a new era of space-based infrared spectroscopy

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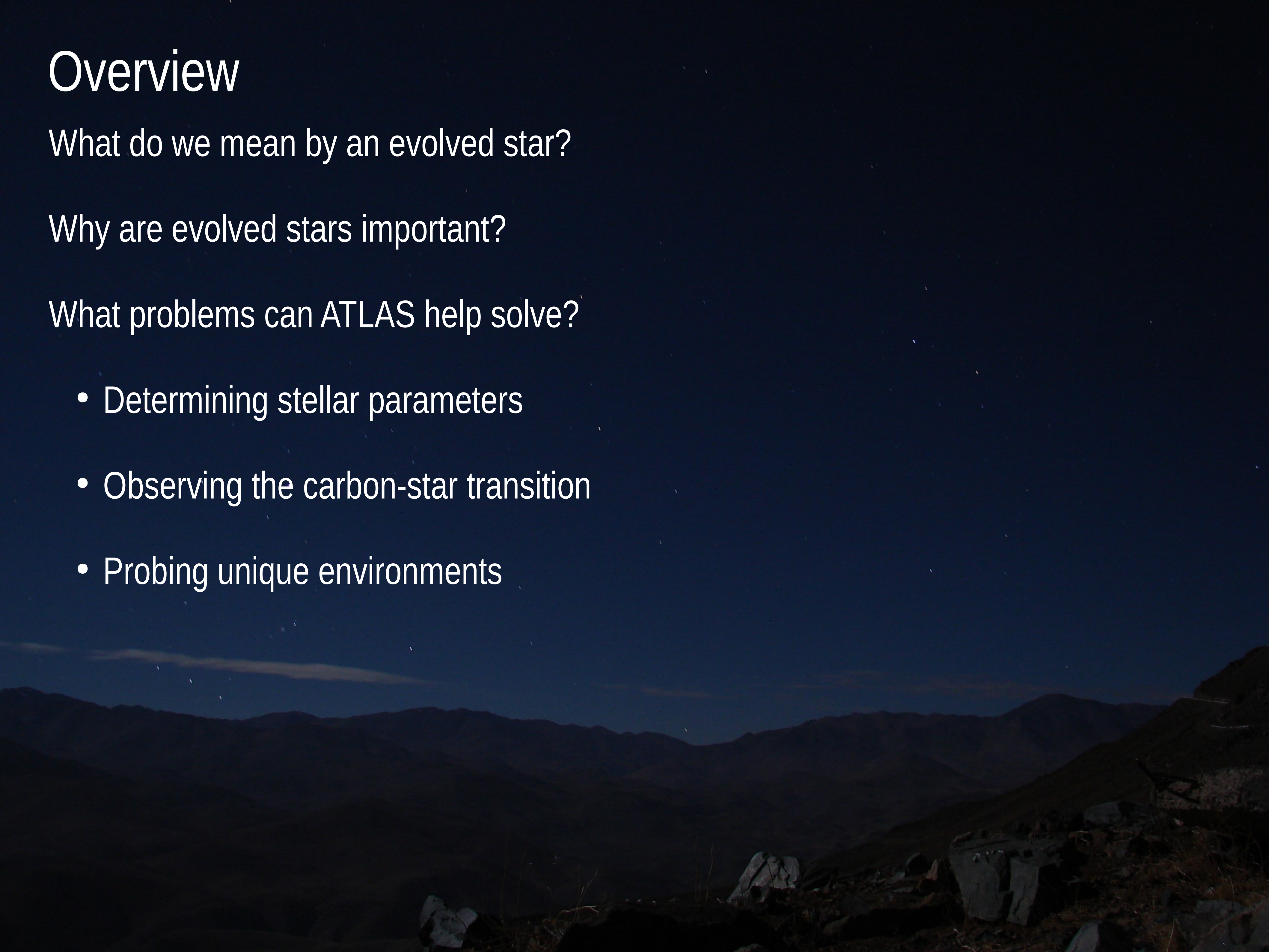


Overview

What do we mean by an evolved star?

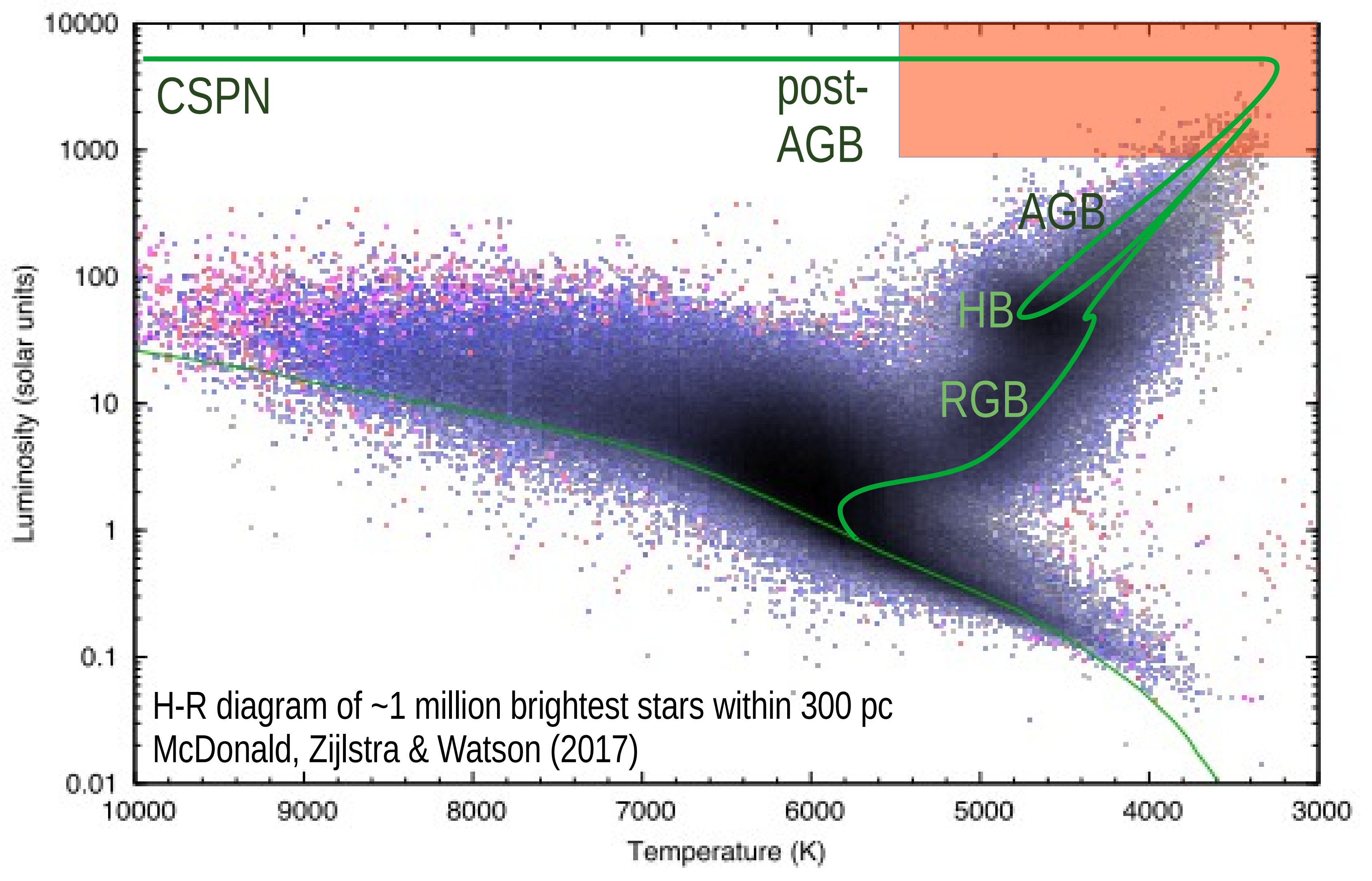
Why are evolved stars important?

What problems can ATLAS help solve?

- Determining stellar parameters
- Observing the carbon-star transition
- Probing unique environments

What do we mean by an evolved star?

Mainly: Luminous asymptotic giant branch (AGB) stars
Also: Luminous red giant branch (RGB) stars
Post-AGB stars
Central stars of planetary nebulae
Young white dwarfs



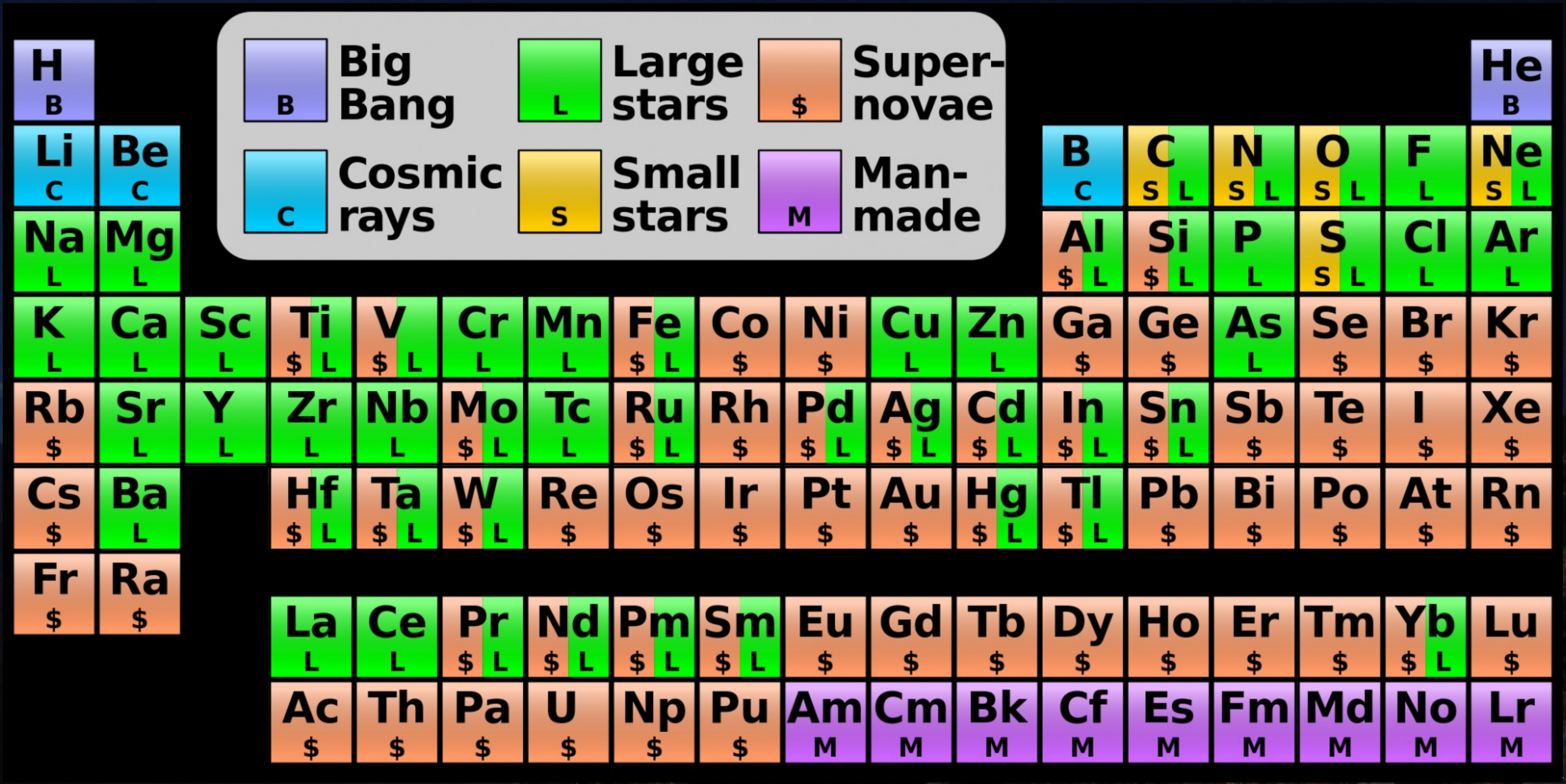
H-R diagram of ~1 million brightest stars within 300 pc
McDonald, Zijlstra & Watson (2017)

Why are evolved stars so important?

Dominant sources of gas and dust to continue star formation at low redshift

Important drivers of chemical evolution

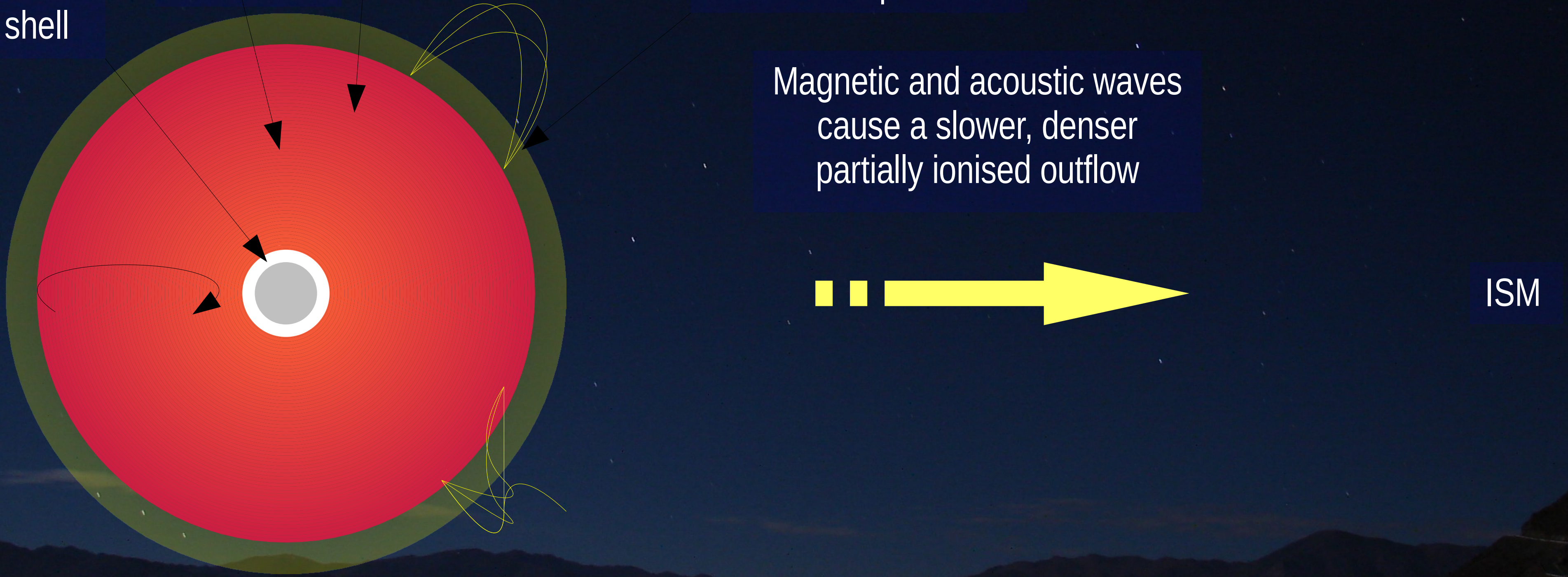
Important sources of molecular chemistry, especially carbon-based chemistry



B Big Bang
L Large stars
$ Supernovae
C Cosmic rays
S Small stars
M Man-made

H B																	He B
Li C	Be C											B C	C S L	N S L	O S L	F L	Ne S L
Na L	Mg L											Al $ L	Si $ L	P L	S S L	Cl L	Ar L
K L	Ca L	Sc L	Ti $ L	V $ L	Cr L	Mn L	Fe $ L	Co $	Ni $	Cu L	Zn L	Ga $	Ge $	As L	Se $	Br $	Kr $
Rb $	Sr L	Y L	Zr L	Nb L	Mo $ L	Tc L	Ru $ L	Rh $	Pd $ L	Ag $ L	Cd $ L	In $ L	Sn $ L	Sb $	Te $	I $	Xe $
Cs $	Ba L		Hf $ L	Ta $ L	W $ L	Re $	Os $	Ir $	Pt $	Au $	Hg $ L	Tl $ L	Pb $	Bi $	Po $	At $	Rn $
Fr $	Ra $																
			La L	Ce L	Pr $ L	Nd $ L	Pm $ L	Sm $ L	Eu $	Gd $	Tb $	Dy $	Ho $	Er $	Tm $	Yb $ L	Lu $
			Ac $	Th $	Pa $	U $	Np $	Pu $	Am M	Cm M	Bk M	Cf M	Es M	Fm M	Md M	No M	Lr M

Why are evolved stars so important?



RGB / early-AGB star

H → He shell

Large convective envelope

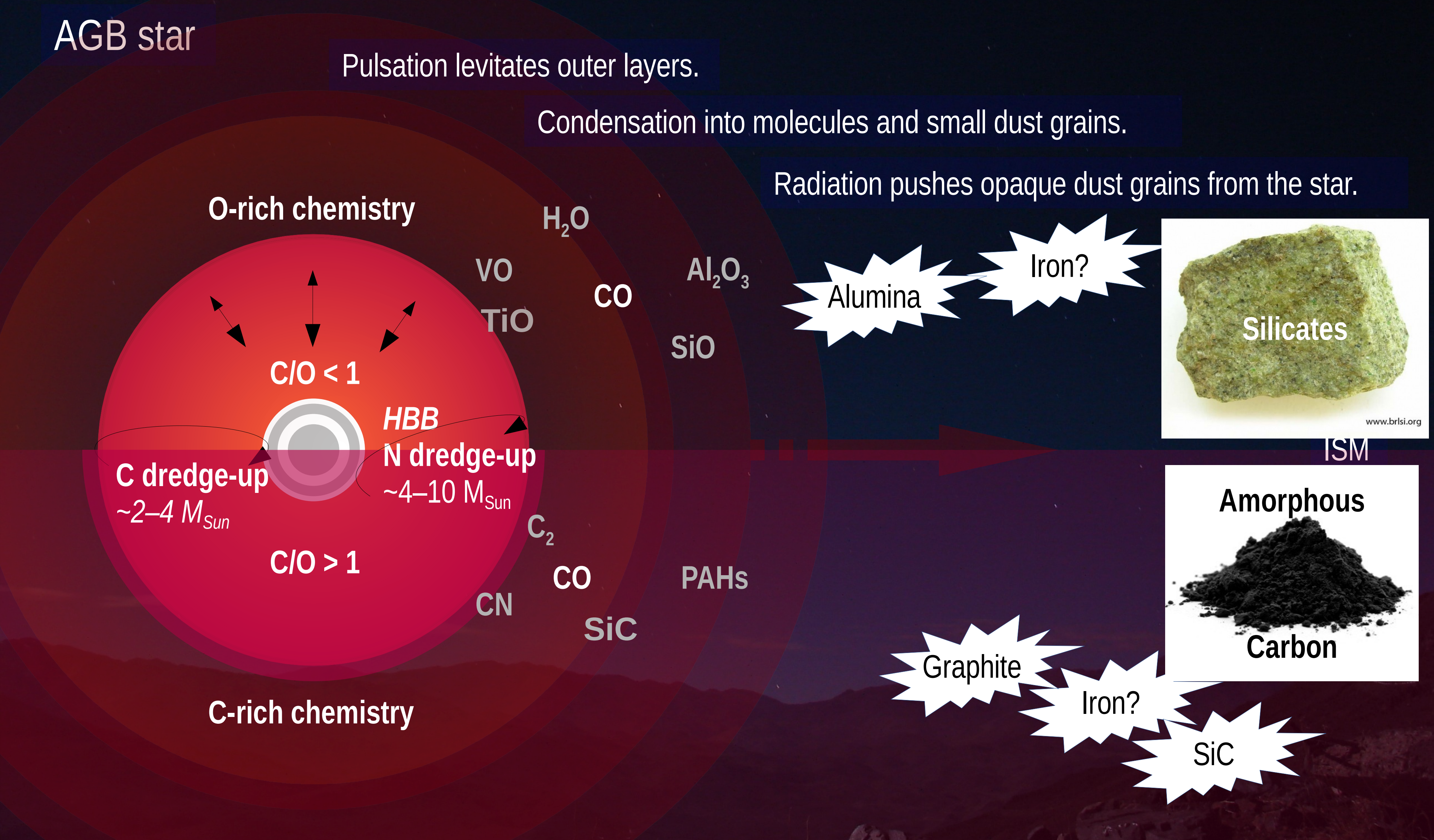
Large convective cells → weak pulsation

Magnetic energy excites stellar chromosphere

Magnetic and acoustic waves cause a slower, denser partially ionised outflow

ISM

Why are evolved stars so important?



AGB star

Pulsation levitates outer layers.

Condensation into molecules and small dust grains.

Radiation pushes opaque dust grains from the star.

O-rich chemistry

H_2O

VO

TiO

CO

Al_2O_3

SiO

C/O < 1

HBB

N dredge-up

~4–10 M_{Sun}

C dredge-up

~2–4 M_{Sun}

C/O > 1

C_2

CO

CN

SiC

PAHs

C-rich chemistry

Alumina

Iron?

Silicates

www.brlsi.org

ISM

Amorphous

Carbon

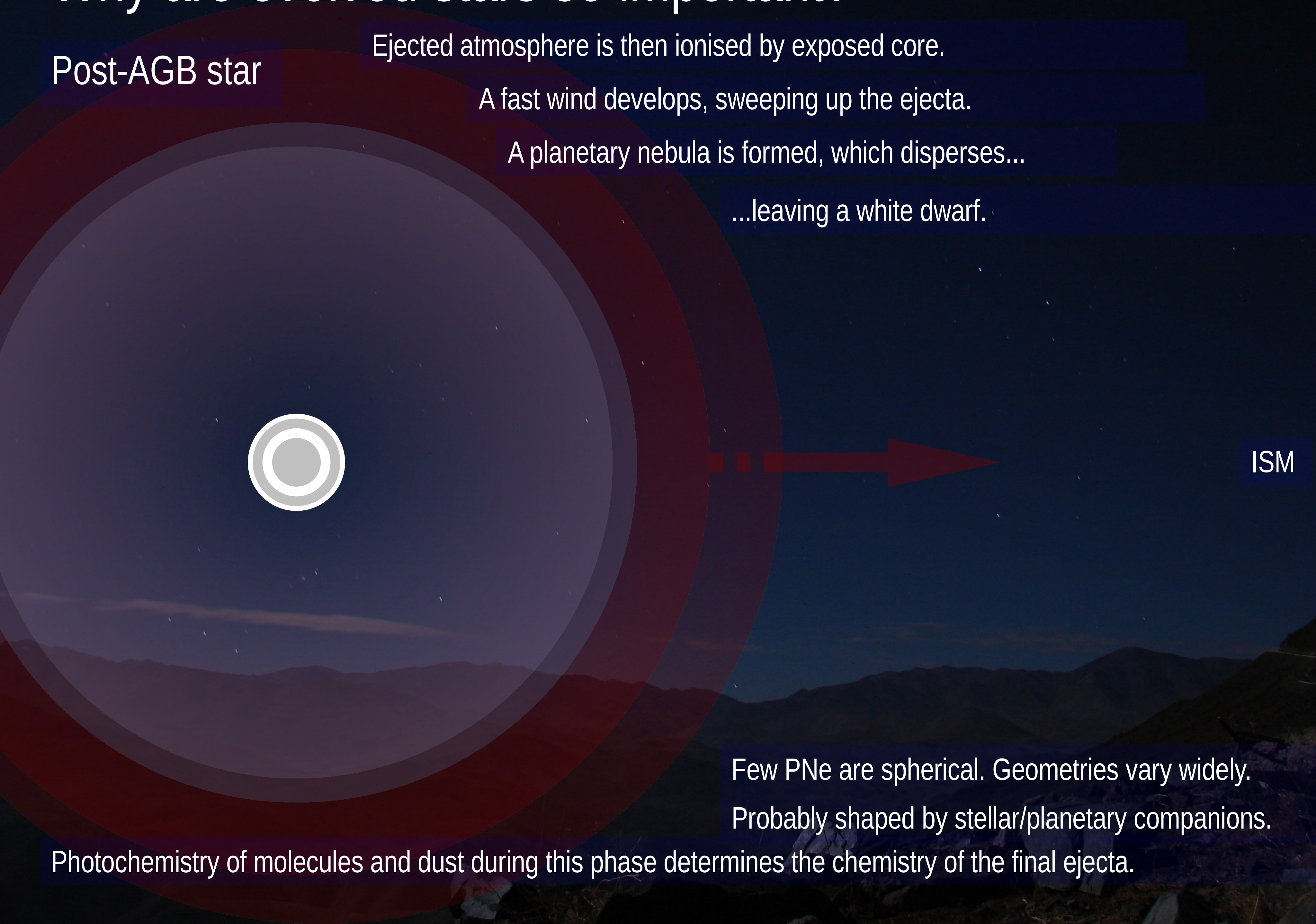
Graphite

Iron?

SiC

The ejecta are some of the most chemically rich locations in the Universe.

Why are evolved stars so important?



Post-AGB star

Ejected atmosphere is then ionised by exposed core.

A fast wind develops, sweeping up the ejecta.

A planetary nebula is formed, which disperses...

...leaving a white dwarf.

ISM

Few PNe are spherical. Geometries vary widely.

Probably shaped by stellar/planetary companions.

Photochemistry of molecules and dust during this phase determines the chemistry of the final ejecta.

Why are evolved stars so important?

Main unknowns in late-stage stellar evolution:

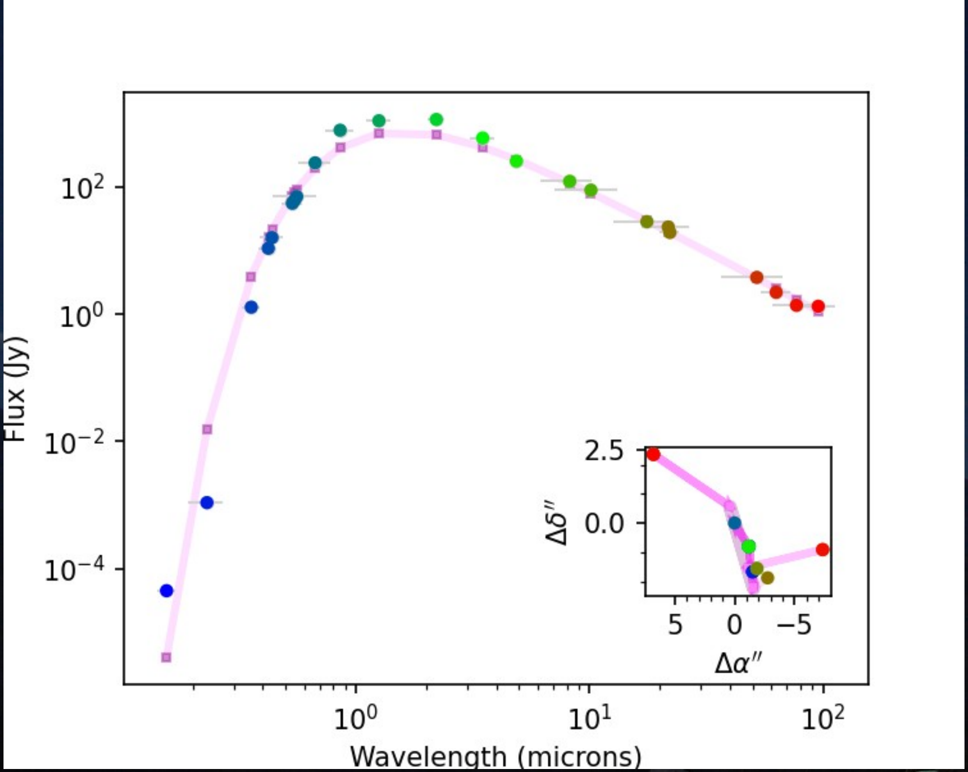
- How efficient is the convective dredge-up process that brings material from the stellar core to the stellar surface?
- How efficient is the mass-loss process that ejects material from the stellar surface?
- How is the ejected dust and gas shaped and reprocessed before entering the ISM?
- ...and what the underlying properties of the stars are!

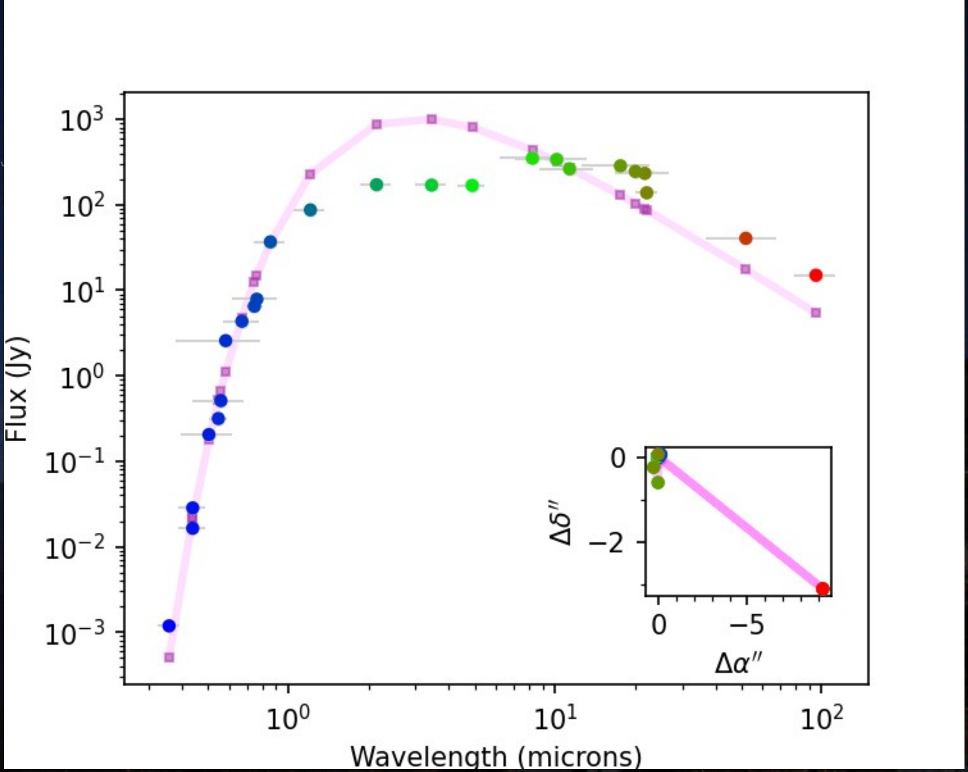
These processes are too complex to model from first principles. We need an *empirical*, *statistical*, *comprehensive* approach to understand evolved stars.

Determining stellar parameters

Evolved stars are brightest in the 1-4 μm range → best sensitivity for large distances

Spectra are dominated by molecular bands.
Optical spectra are mostly TiO for oxygen-rich stars, and C_2 and CN for carbon stars.
Mid-infrared spectra show broadband dust features.
Near-infrared spectra show mostly molecular features but also some atomic lines.
Dust can obscure the optical spectrum, necessitating IR observations.





Determining stellar parameters

Problem: evolved stars pulsate.

Optical brightness can very from a few percent to factors of ~400,000.

→ Temperature and radius constantly vary – the star has no clearly defined surface

→ Standard assumptions of LTE apply poorly, if at all

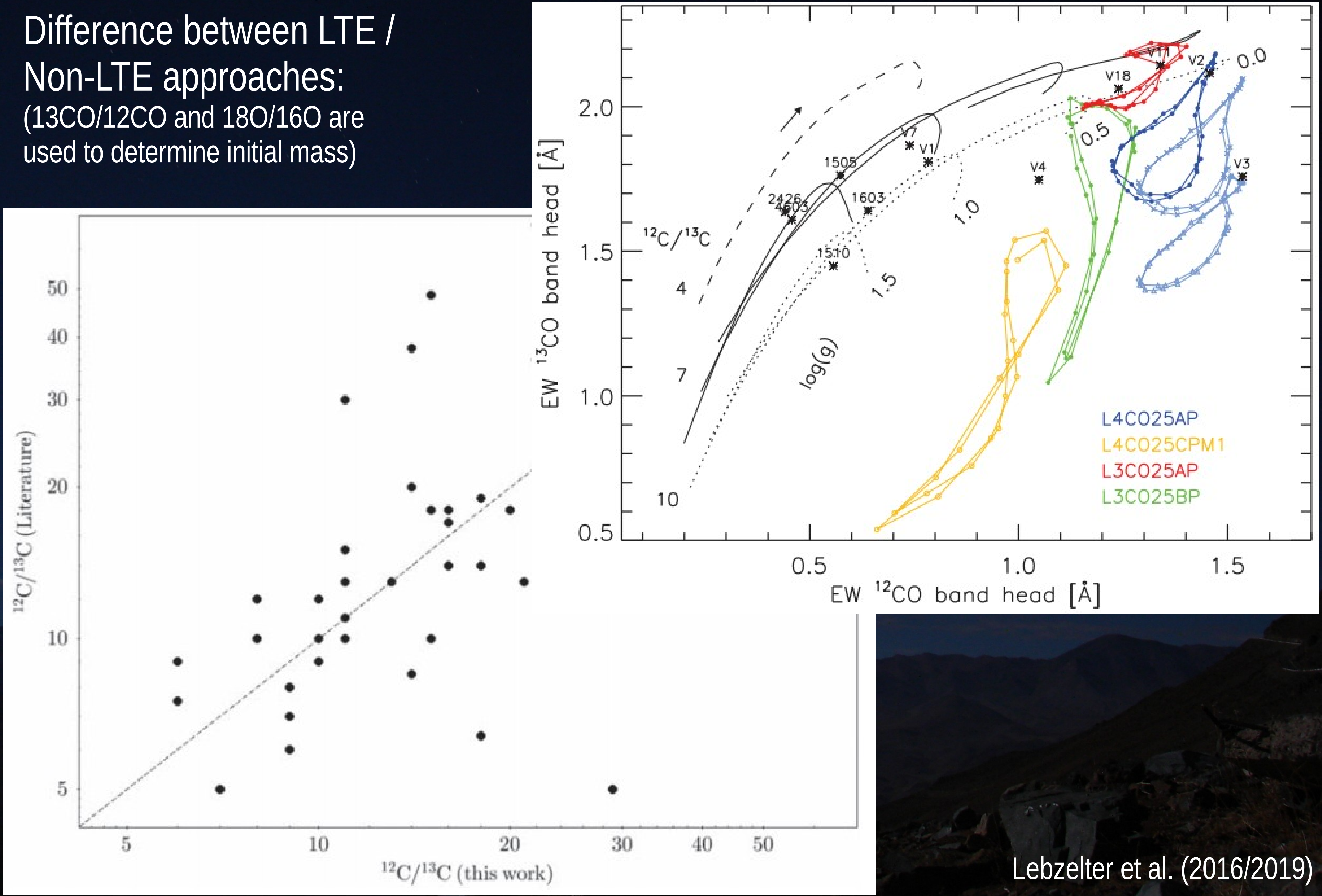
→ Hard to measure even average spectroscopic parameters

Models: Bernard Freytag, astro.uu.se/~bf/

Determining stellar parameters

Difference between LTE / Non-LTE approaches:

(13CO/12CO and 18O/16O are used to determine initial mass)

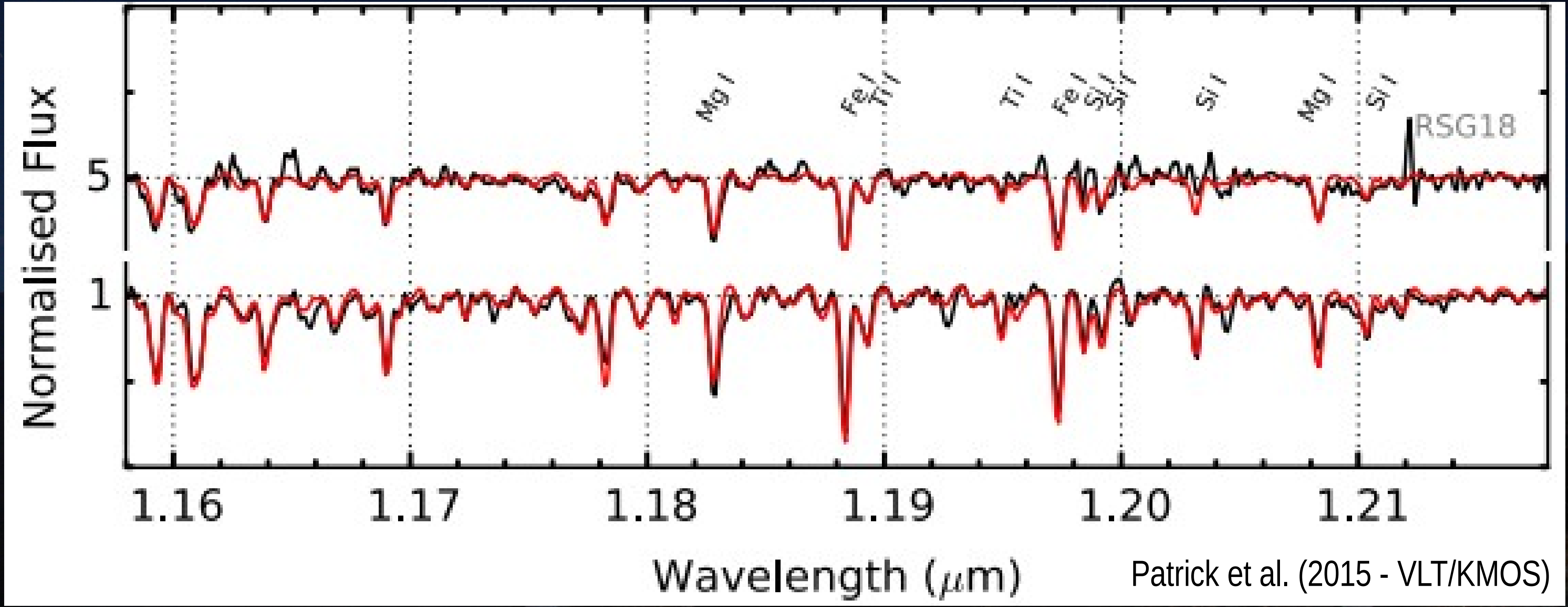


Lebzelter et al. (2016/2019)

Determining stellar parameters

Atomic lines are less affected, but normally swamped by molecular absoprtion.
However, some near-IR lines could be used for metallicity estimates.
Combination of isotopic (molecular) and metal-line estimates gives mass + metallicity.

Difficult at R ~ 1000 but not impossible.
Ground-based data suffer poor calibration due to atmospheric conditions
→ How much could ATLAS improve on these estimates?



Patrick et al. (2015 - VLT/KMOS)

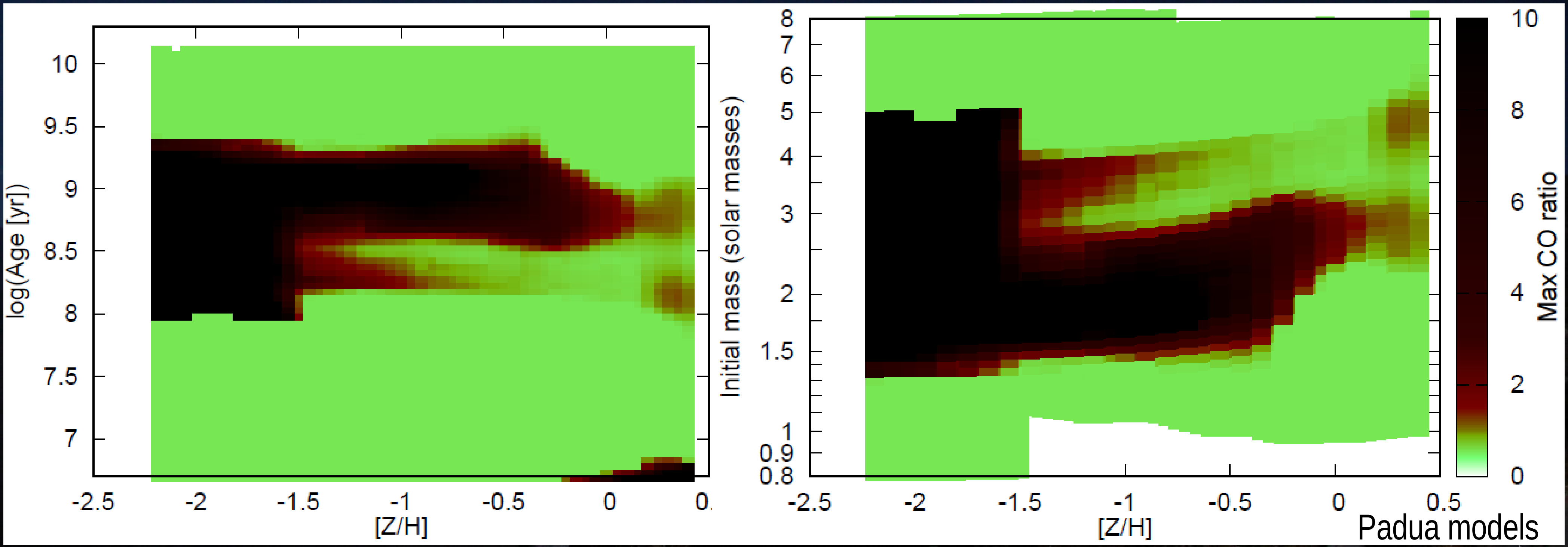
Observing surface enrichment via convective dredge-up

Sporadic helium burning (*thermal pulses*) lead to material being dredged up from the core to the surface.

- Stars between ~1–4 M_{Sun} dredge up C-rich material → carbon stars.
- Above ~5–10 M_{Sun} process C → N: only M-type stars.
- Metal-rich stars never dredge up enough to become carbon-rich.

This causes a fundamental metallicity-based difference to how stars evolve.

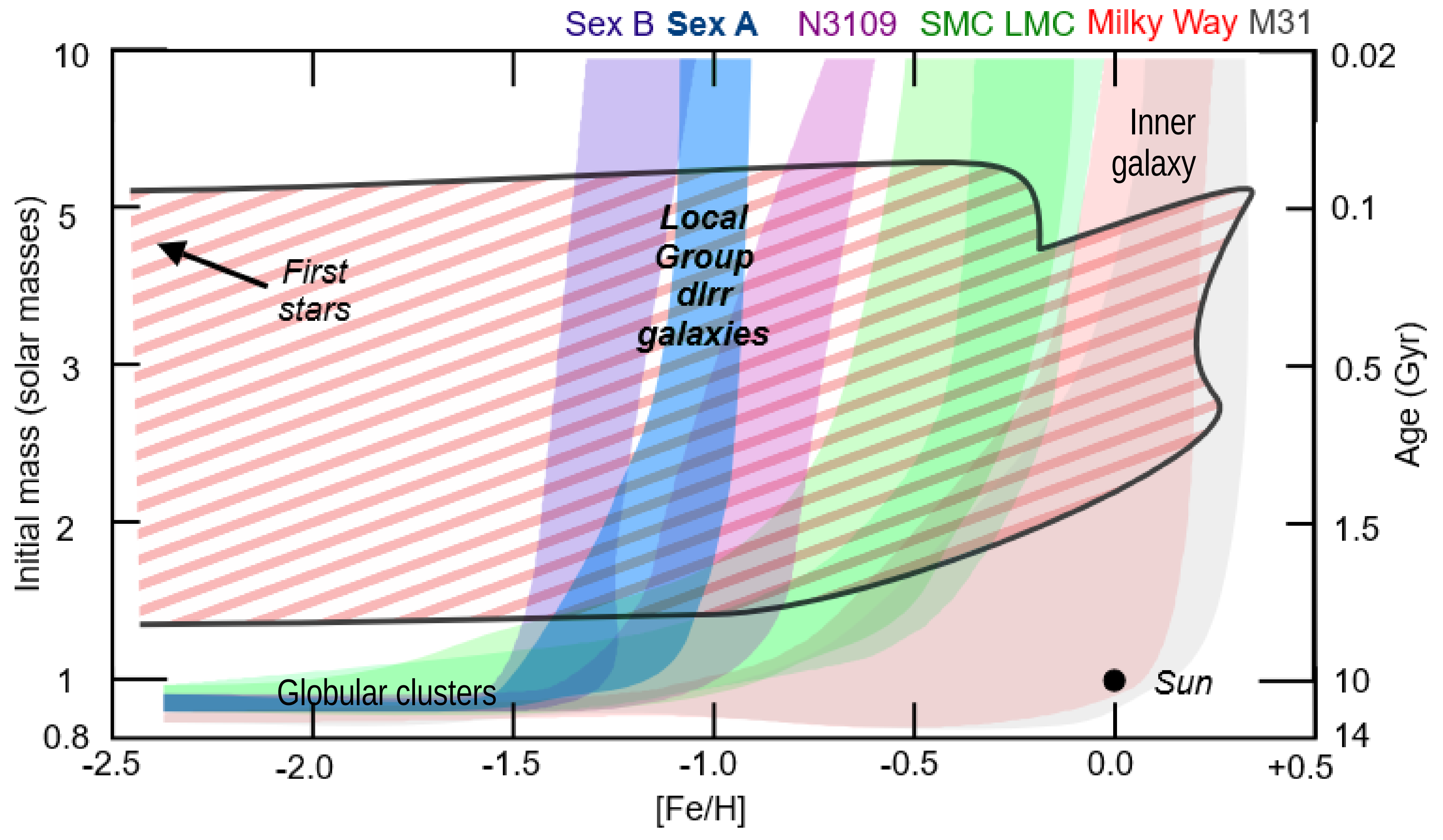
The efficiency of this process is poorly known, but the ratio of C to M stars measures a body's star-formation history.



Padua models

Observing surface enrichment via convective dredge-up

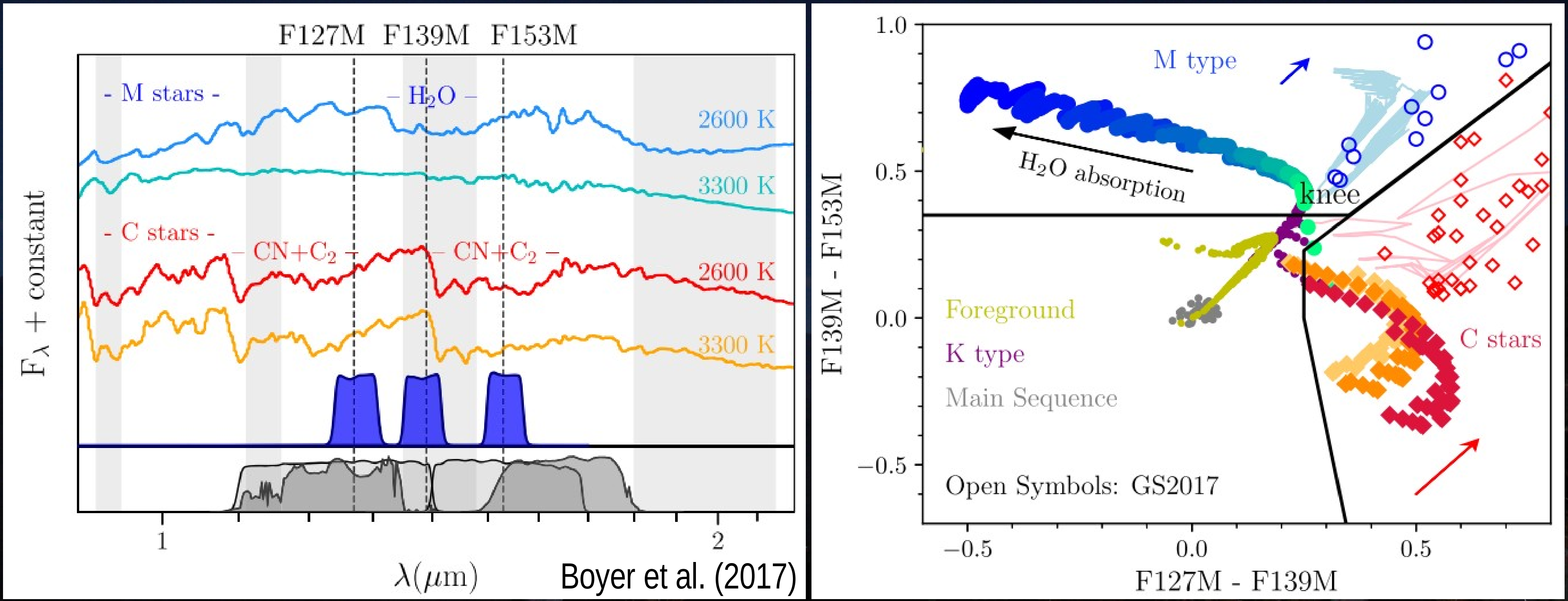
We can observe these differences by looking at populations outside the Milky Way.



Observing surface enrichment via convective dredge-up

Separation of C-rich and O-rich stars can sometimes be done from photometry, but normally requires coarse spectroscopy.

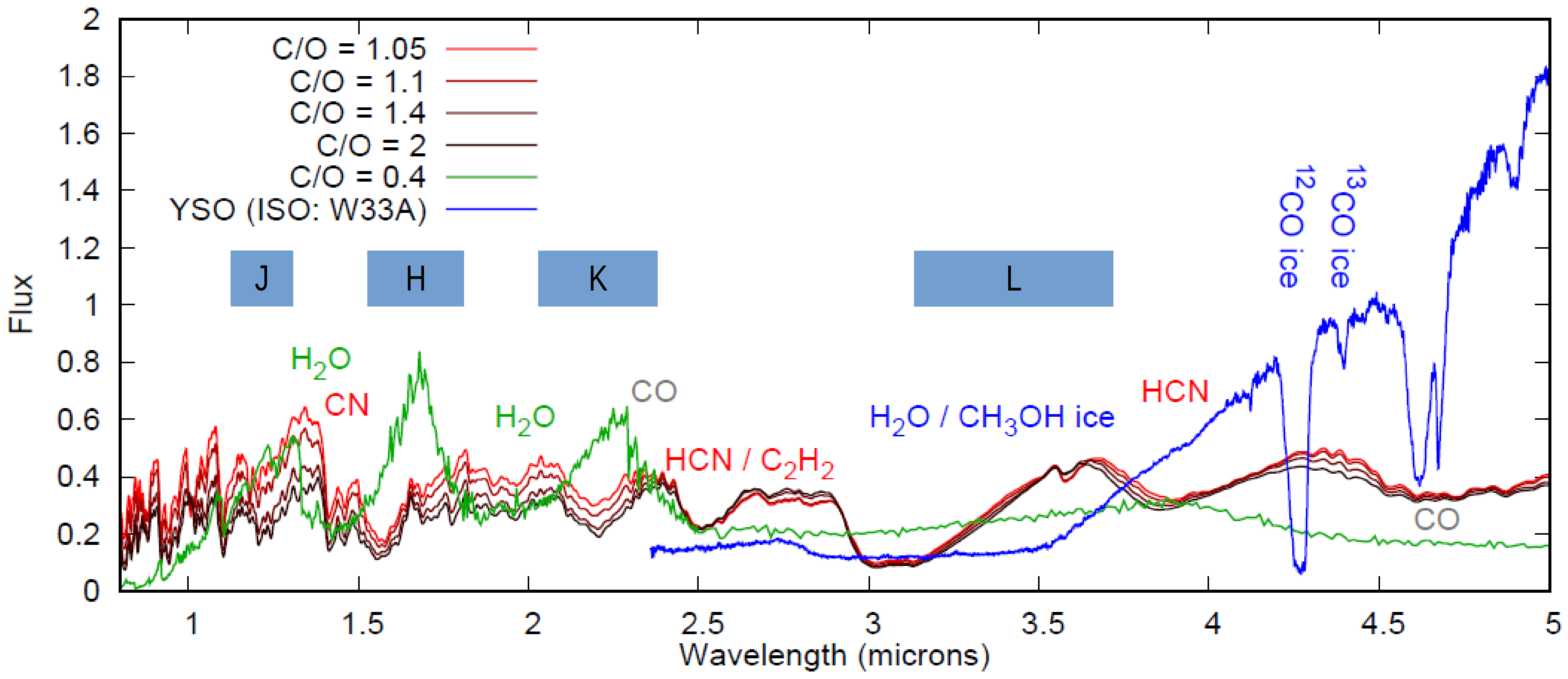
Obscured AGB stars require near-IR molecular lines or mid-IR dust to distinguish. Water lines are crucial determinants for M-type stars, so can’t be done from ground. Currently done with broad-band *HST* photometry.



Boyer et al. (2017)

Observing surface enrichment via convective dredge-up

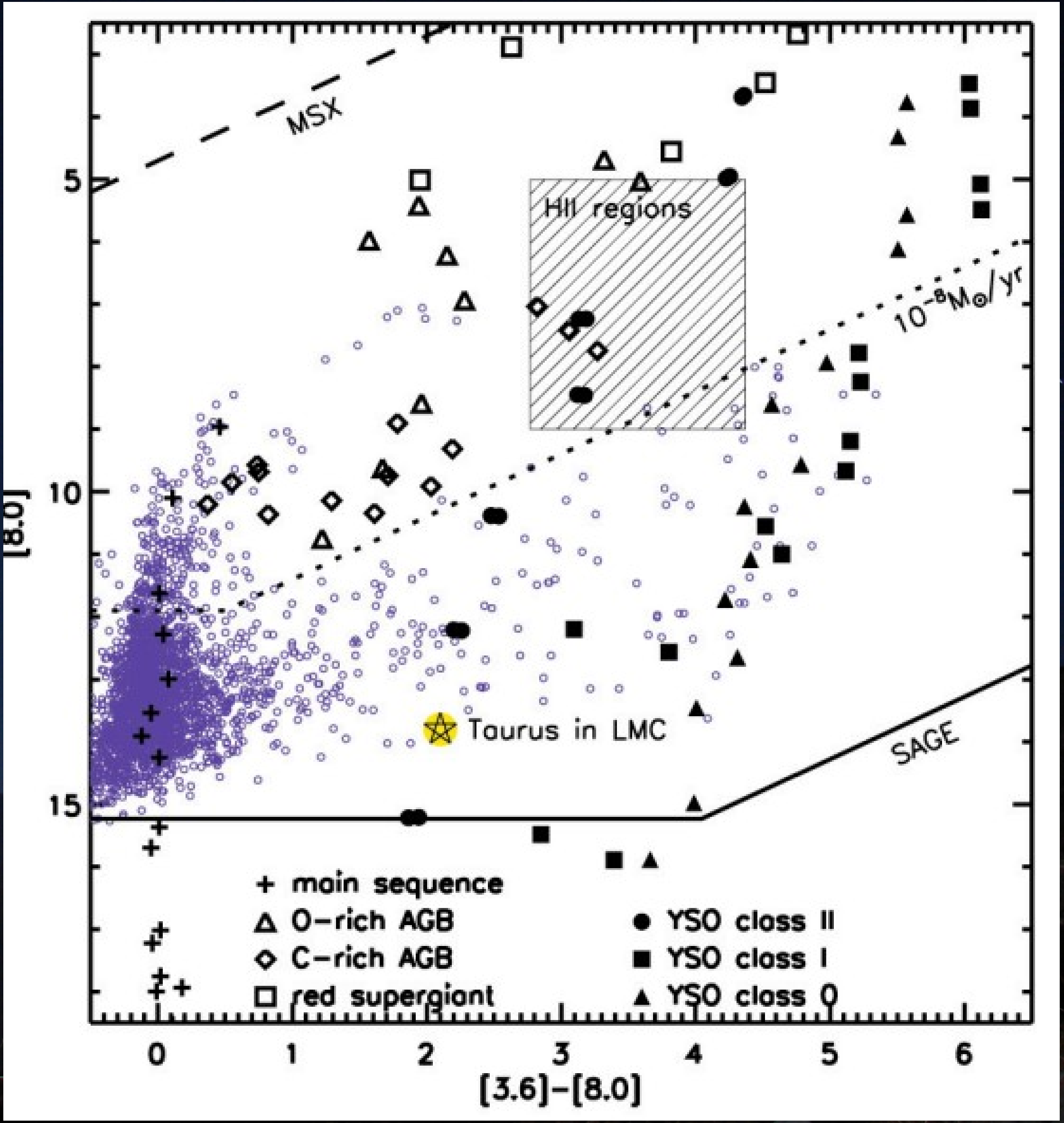
Shape of spectral features can also betray the C/O ratio, so the total amount of carbon that has been dredged up.



Observing surface enrichment via convective dredge-up

Ratios of C/M stars can be used to diagnose a population’s star-formation history.
But dusty, evolved stars can be photometrically confused with young stellar objects.

(and background galaxies)



Meixner et al., SAGE observing proposal

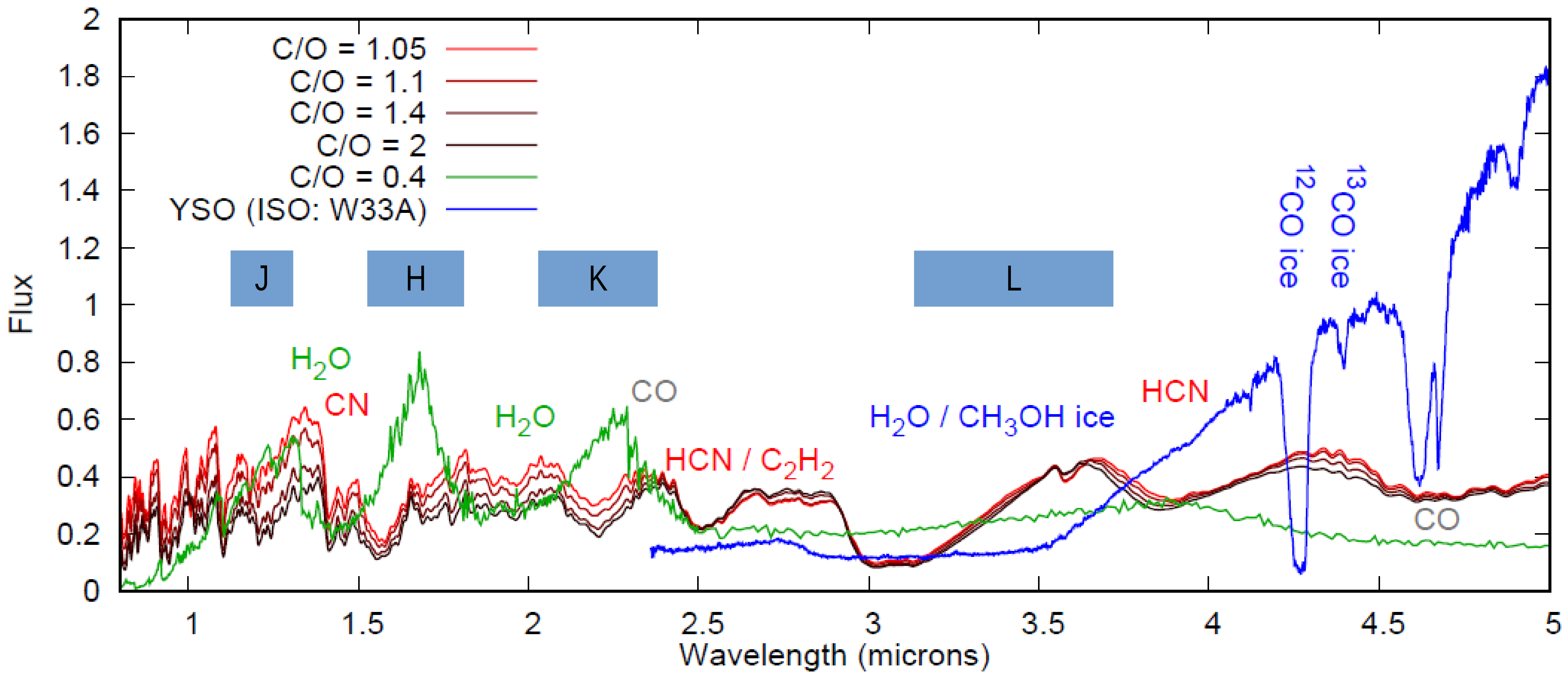
YSO separation and carbon star classification

YSOs can be differentiated from dusty AGB stars because YSOs exhibit:

- Mixed chemical features
- Strong ice bands around 3-5 μm.

Presence of these ice bands can be used to classify an object as an interloping YSO.

- AGB/YSO/galaxy and C/M spectral type classifications will be done by *SPHEREX*.
- But *ATLAS* could go much deeper and be targetted.



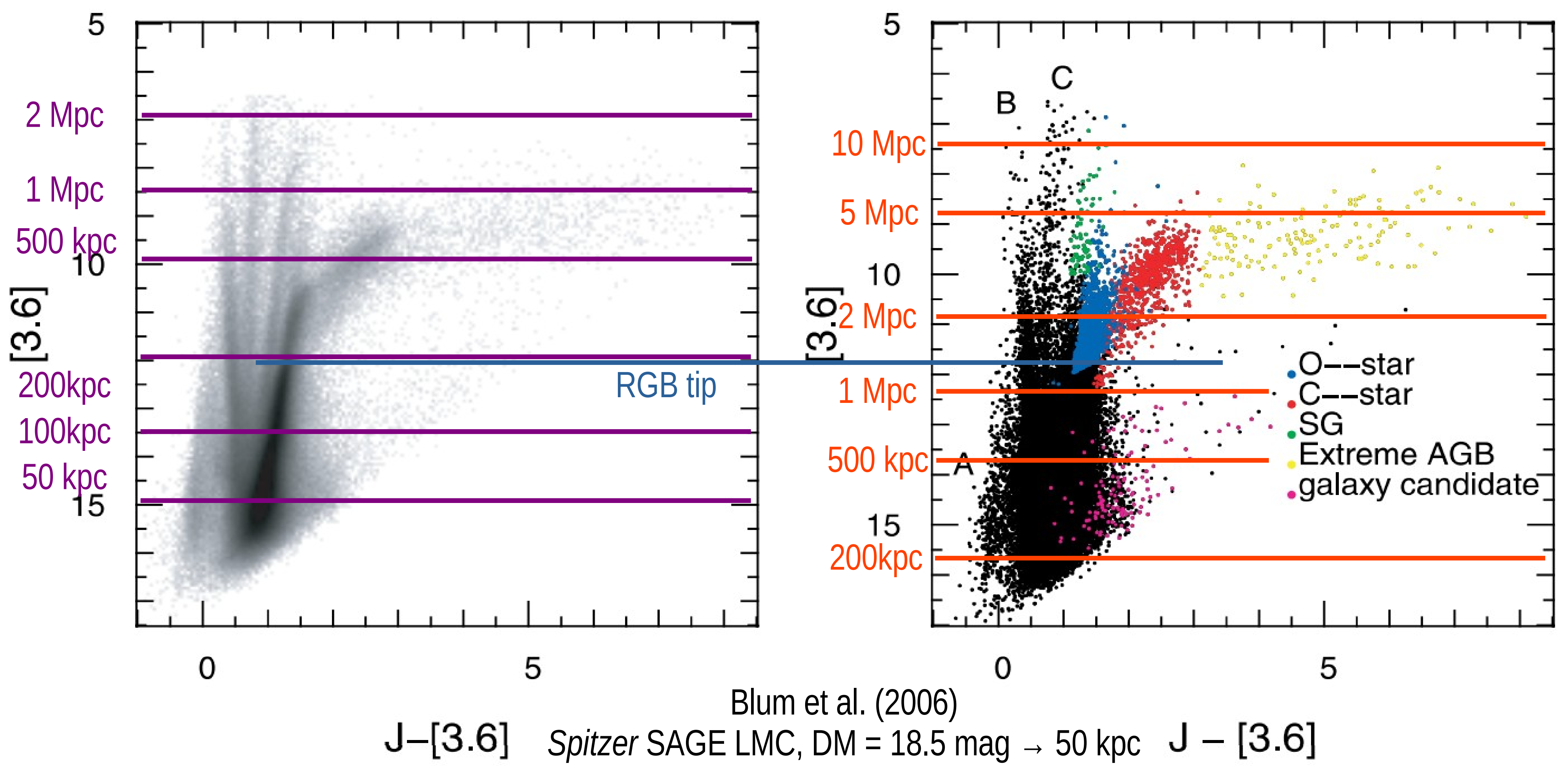
YSO separation and carbon star classification

SPHEREX all-sky → m_{AB}(3 μm) ~ 19.3 mag @ 6” resolution @ 5σ @ *R*=35.

ATLAS targetted → m_{AB}(3 μm) ~ 23 mag @ 0.75” resolution @ 5σ @ *R*~35 (binned).

Primary benefits are *distance* and *resolution*.

Allows us to explore chemically very different environments.

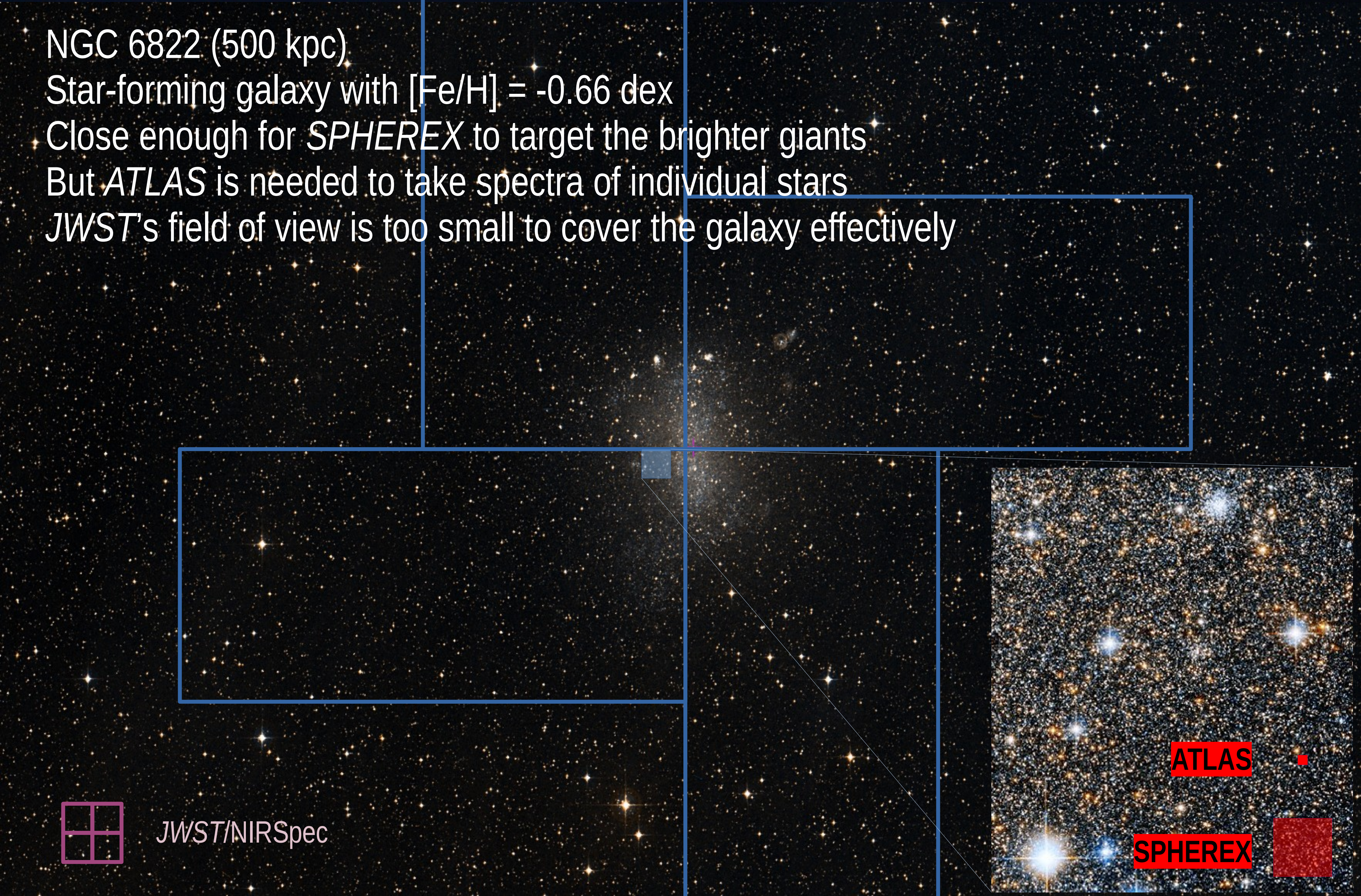


Blum et al. (2006)

Spitzer SAGE LMC, DM = 18.5 mag → 50 kpc

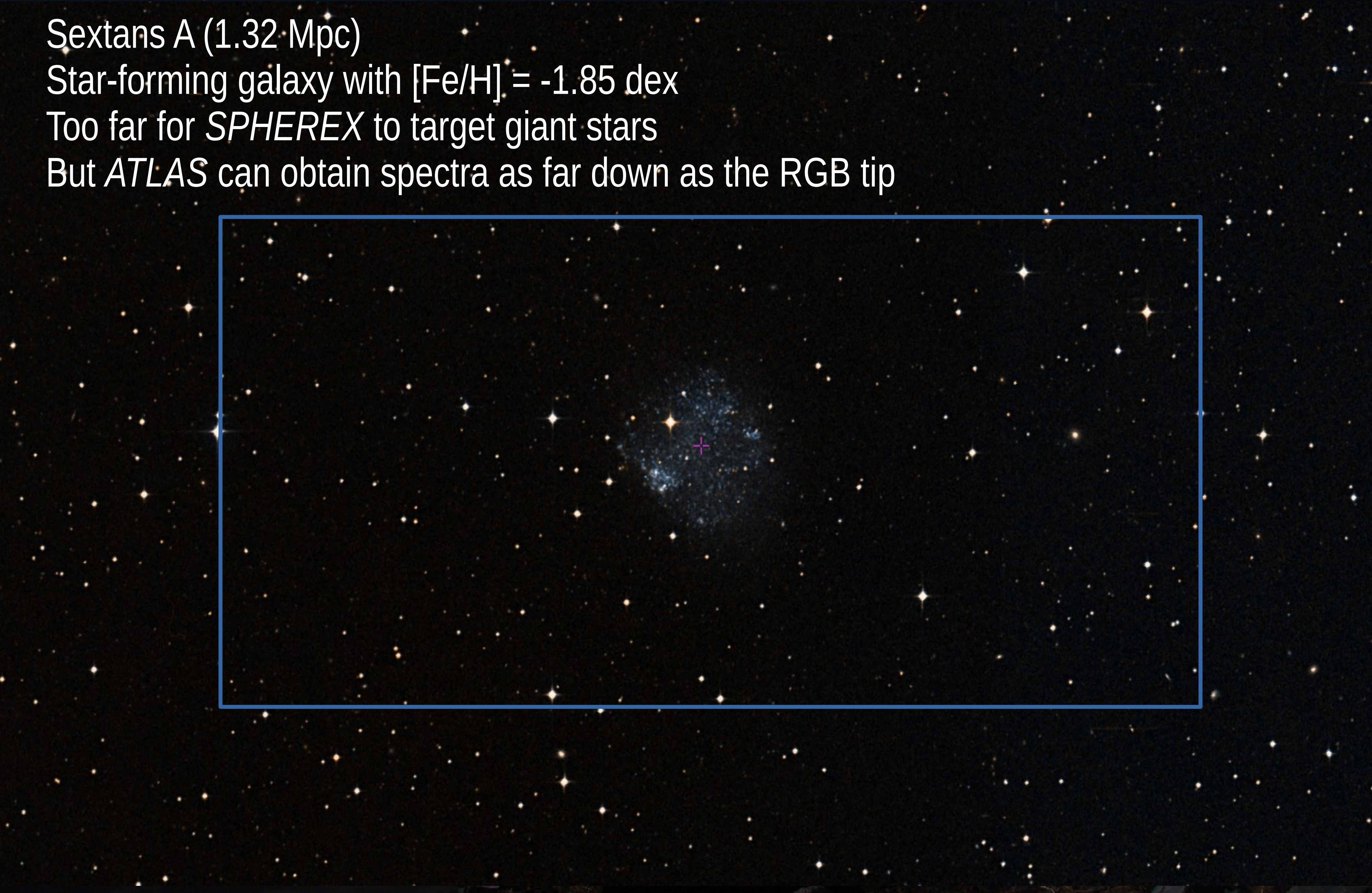
YSO separation and carbon star classification

NGC 6822 (500 kpc)
Star-forming galaxy with [Fe/H] = -0.66 dex
Close enough for *SPHEREX* to target the brighter giants
But *ATLAS* is needed to take spectra of individual stars
JWST's field of view is too small to cover the galaxy effectively



YSO separation and carbon star classification

Sextans A (1.32 Mpc)
Star-forming galaxy with [Fe/H] = -1.85 dex
Too far for *SPHEREX* to target giant stars
But *ATLAS* can obtain spectra as far down as the RGB tip



Inner galaxy and Sgr dSph galaxy

2MASS

Inner galaxy and Sgr dSph galaxy

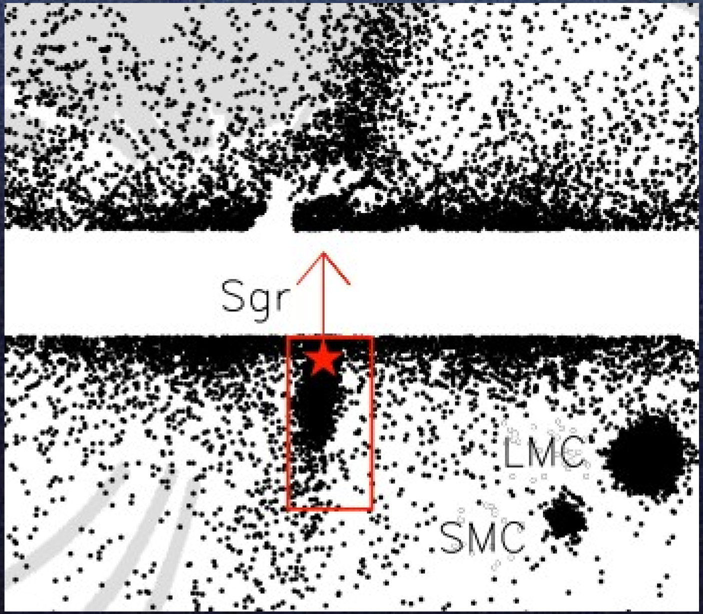
Sgr dSph (26 kpc)

- Hidden behind the Milky Way and undergoing tidal destruction
- Search for metal-poor and obscured components

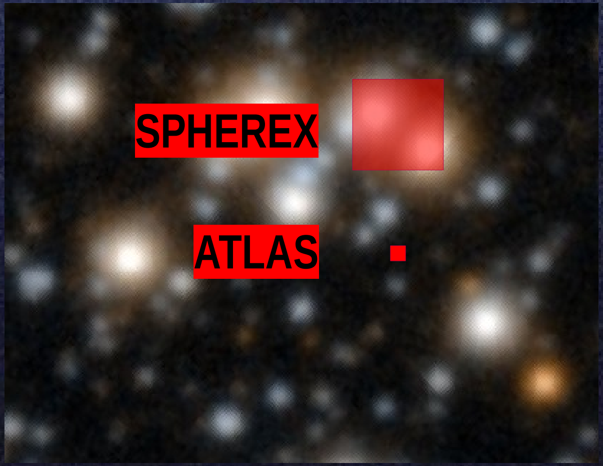
Inner galaxy and bulge contains many evolved stars with well-constrained properties

ATLAS benefits from small pixel size in both cases

Niederste-Ostholt et al. (2010)



Sample field, *b* = -8



2MASS

Stellar clusters

Dense environments, but key for studying stellar evolution processes

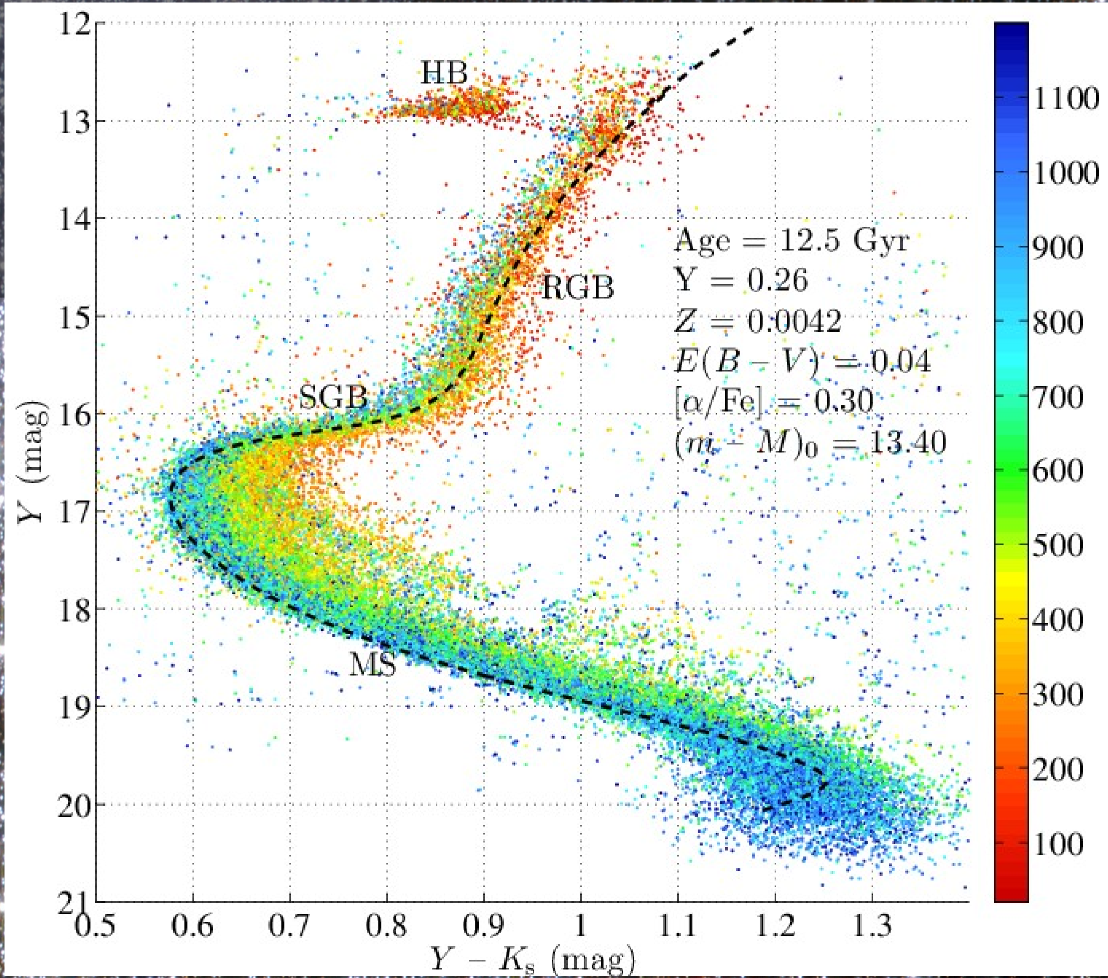
SPHEREX lacks resolution to observe stars in dense clusters, esp. globular clusters.

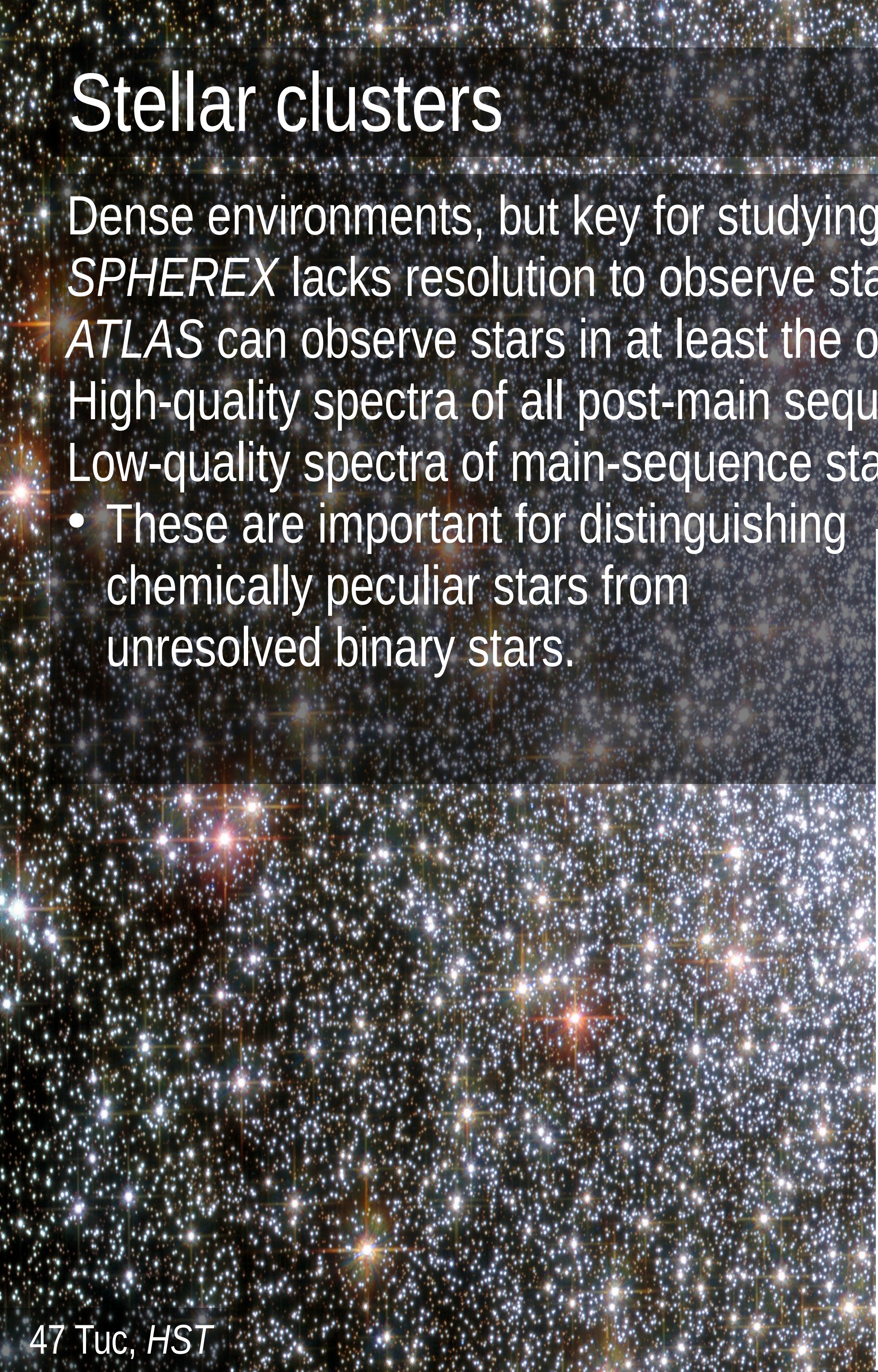
ATLAS can observe stars in at least the outer parts of the clusters

High-quality spectra of all post-main sequence stars

Low-quality spectra of main-sequence stars

- These are important for distinguishing chemically peculiar stars from unresolved binary stars.





47 Tuc, *HST*

Summary

ATLAS offers many unique prospects for research into evolved stars

It's main benefits are:

- Greater depth than *SPHEREX*
  - Invaluable for exploring stellar evolution in metal-poor environments
  - Allows us to explore galaxies ~10x more metal-poor
- Finer resolution than *SPHEREX*
  - Can observe individual stars in nearby galaxies, stellar clusters, inner Galaxy
- Lack of terrestrial contamination for key molecular transitions
  - Can observe H_2O bands in oxygen-rich stars
  - Can measure C/O ratios in carbon-rich stars
  - Can better separate YSOs and galaxies from evolved stars

JWST/NIRSpec will do many of these things first but

- High pressure will prevent all but the most important observations being taken
- The field of view of *ATLAS* allows true surveys not possible with *JWST*
  - Important for statistical astronomy needed for evolved-star research

The end