Killing me softly: the death of low- and intermediate-mass stars

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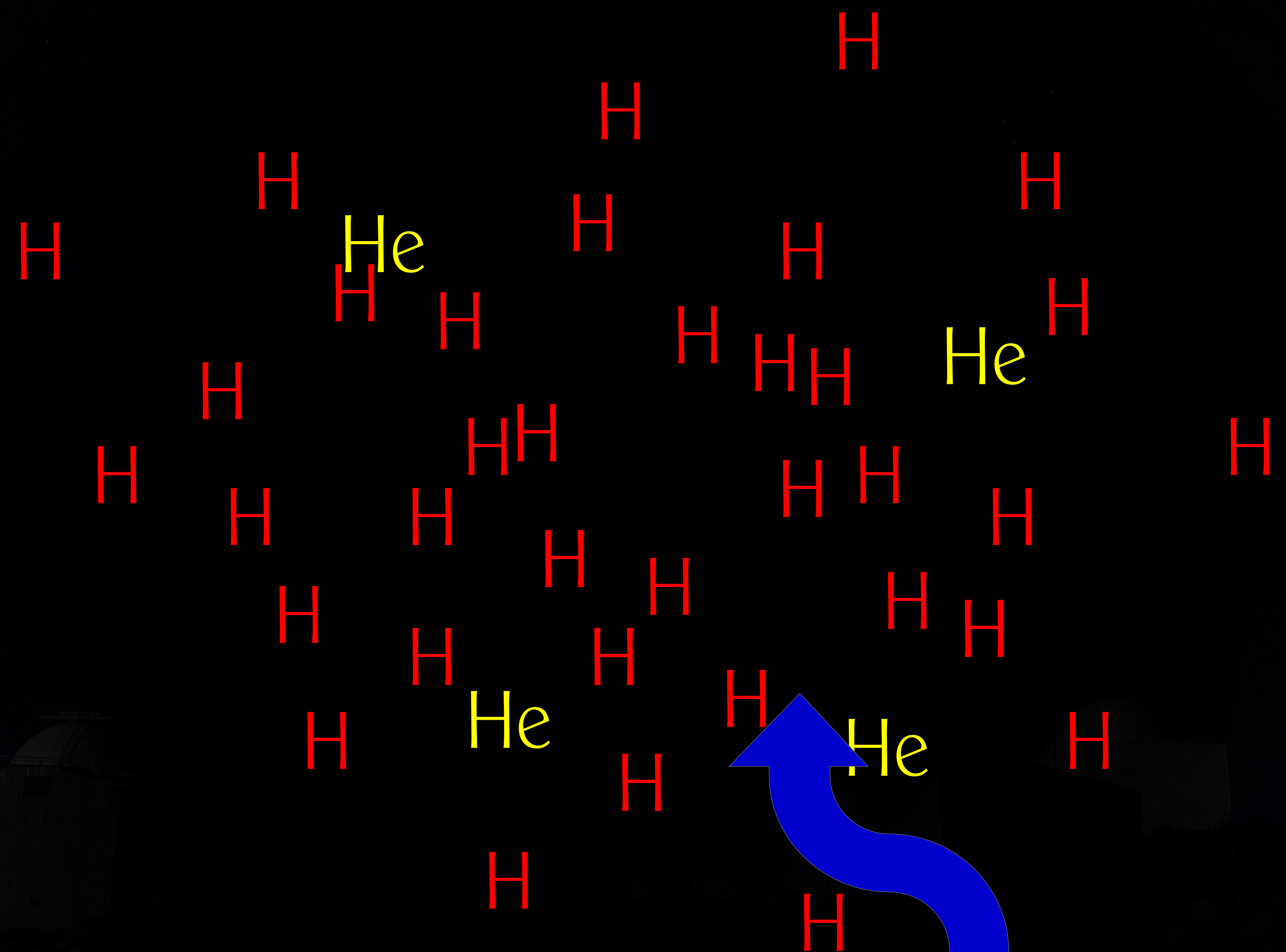
La Silla

In the beginning...

"Anon"

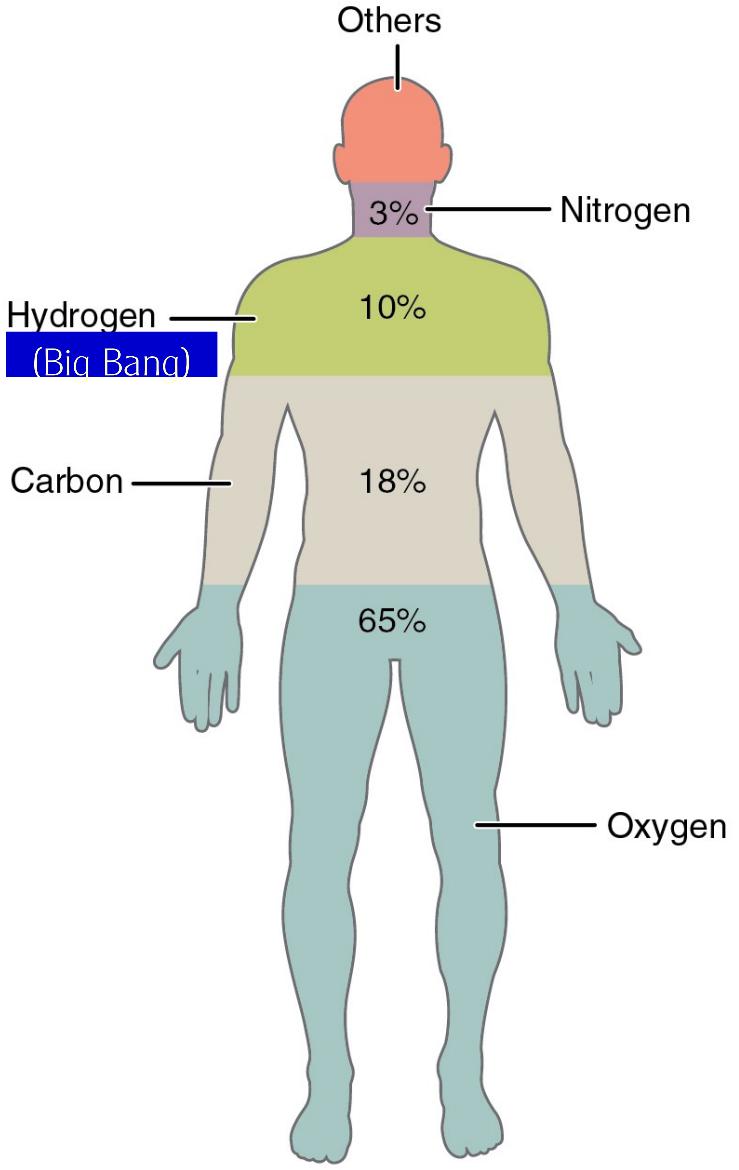
In the beginning...

"Anon"



Quite hard to make anything interesting out of this

90% of the human body isn't hydrogen or helium



Element	Symbol	Percentage in Body by mass
Oxygen	O	65.0
Carbon	C	18.5
Hydrogen	H	9.5
Nitrogen	N	3.2
Calcium	Ca	1.5
Phosphorus	P	1.0
Potassium	K	0.4
Sulfur	S	0.3
Sodium	Na	0.2
Chlorine	Cl	0.2
Magnesium	Mg	0.1
Trace elements include boron (B), chromium (Cr), cobalt (Co), copper (Cu), fluorine (F), iodine (I), iron (Fe), manganese (Mn), molybdenum (Mo), selenium (Se), silicon (Si), tin (Sn), vanadium (V), and zinc (Zn).		less than 1.0

Wikipedia!

99.97% of the Earth isn't hydrogen or helium

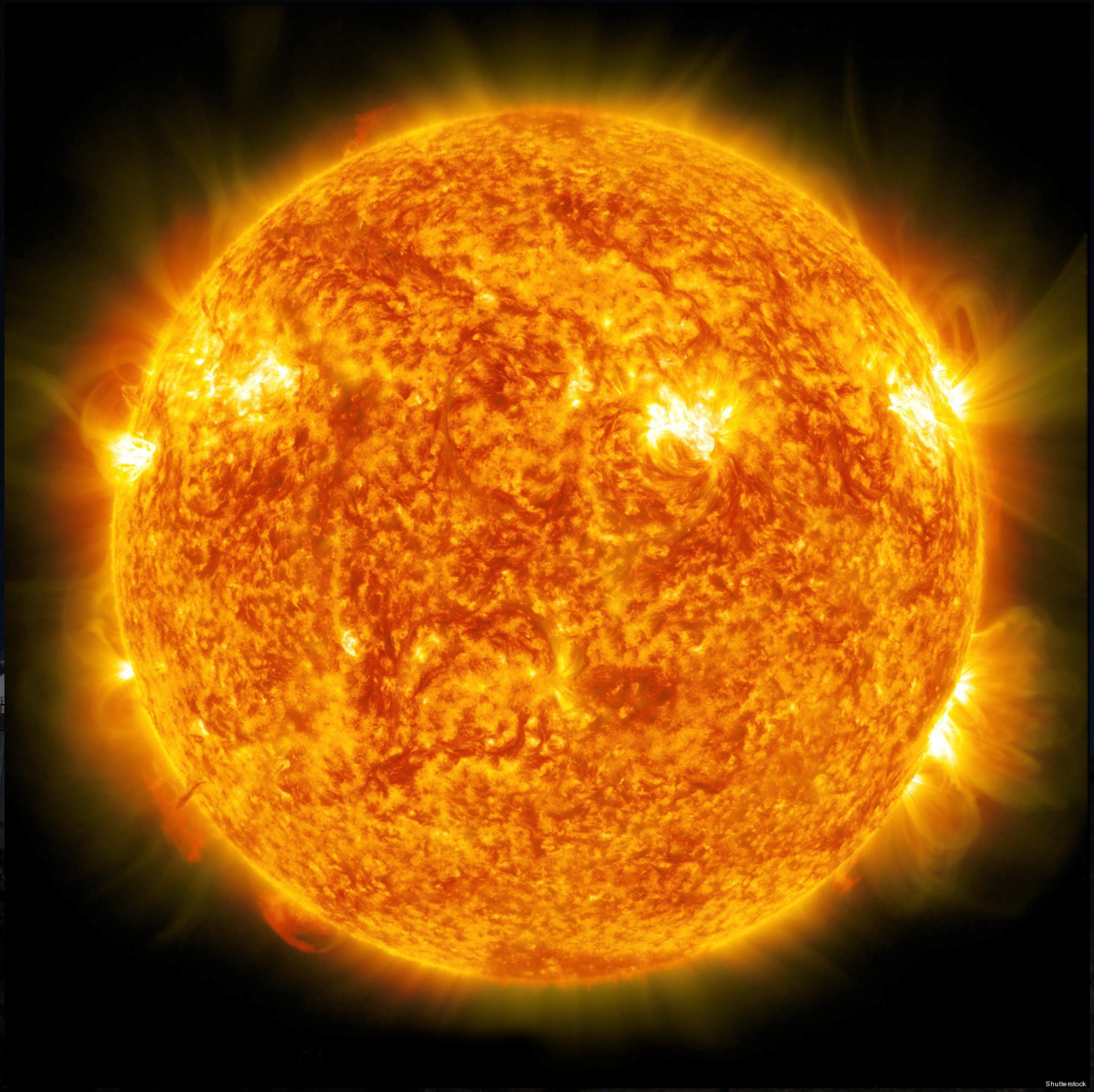
Z	Species	Symbol	%
26	iron	Fe	31.9%
8	oxygen	O	29.7%
14	silicon	Si	16.1%
12	magnesium	Mg	15.4%
28	nickel	Ni	1.822%
20	calcium	Ca	1.710%
13	aluminum	Al	1.590%
16	sulfur	S	0.635%
24	chromium	Cr	0.470%
11	sodium	Na	0.180%
25	manganese	Mn	0.170%
15	phosphorus	P	0.121%
27	cobalt	Co	0.088%
22	titanium	Ti	0.081%
6	carbon	C	0.073%
1	hydrogen	H	0.026%
…	…	…	...
2	helium	He	0.000%

Earth from the Galileo spacecraft

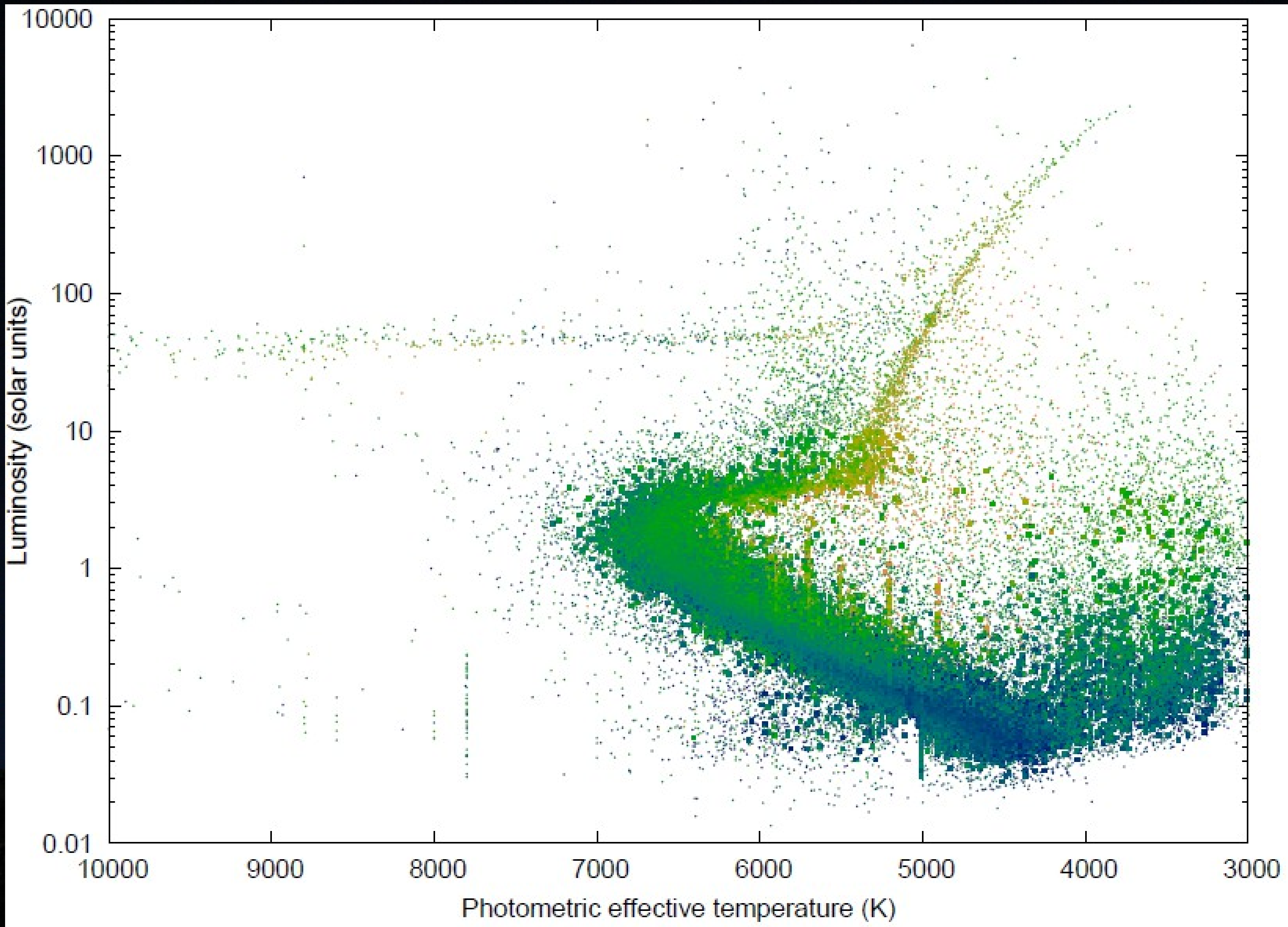
Galactic chemical enrichment

- Astronomical metals are needed to produce the interesting parts of the cosmos (rocky planets, life, etc.)
- These are made in the cores of stars.
- But to be useful, we also need them to be ejected from the stars.
- How does this happen?

This is a star



There are many stars

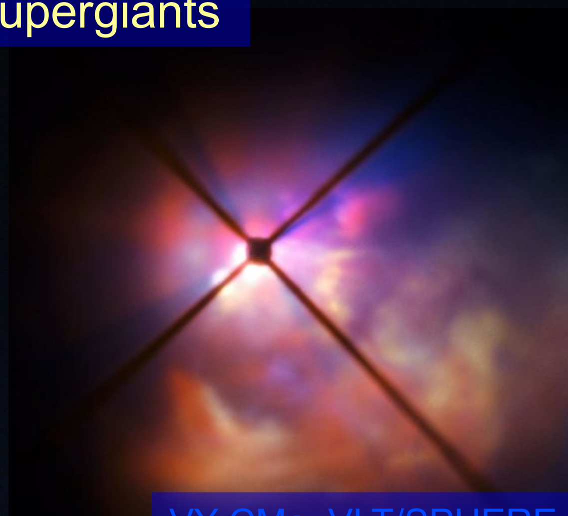


M5; McDonald et al. (2017)

Origins of the elements

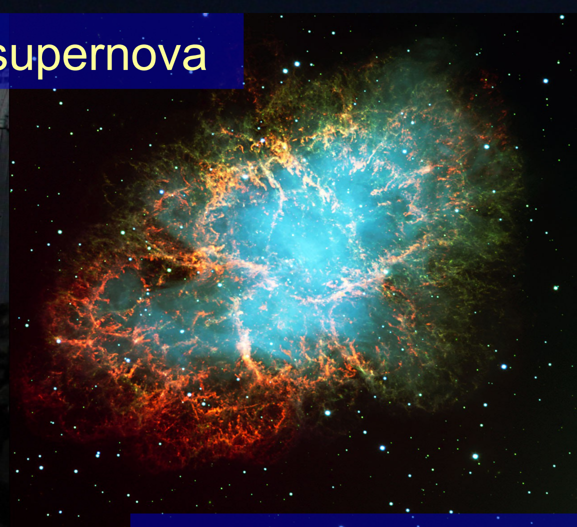
Massive stars (>8x Sun's mass)

Lose mass as supergiants



VY CMa; VLT/SPHERE

Then undergo supernova



Crab Nebula; VLT/FORS2

Low-mass stars (0.8-8x Sun's mass)

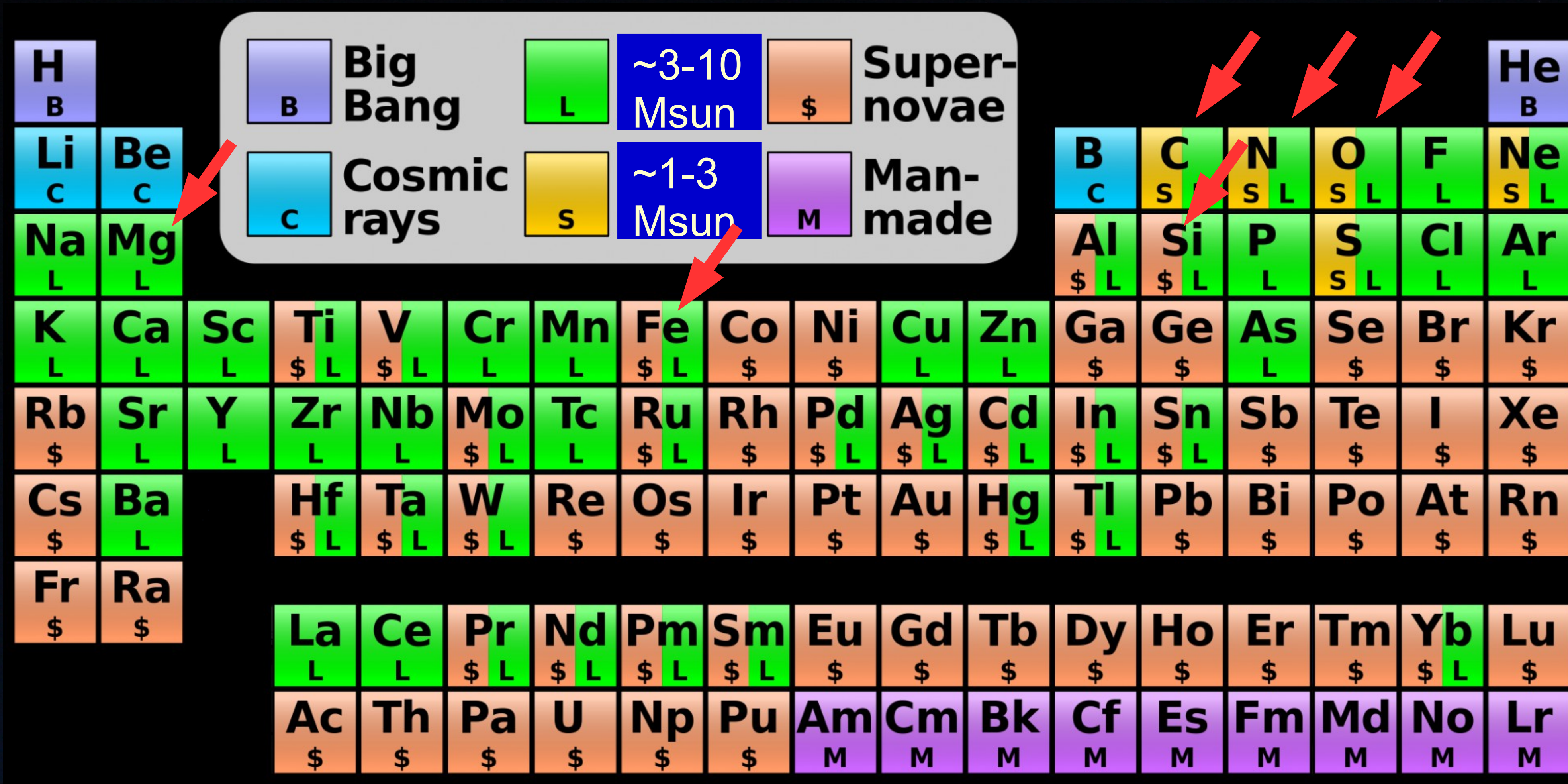
Lose mass as AGB stars

R Scl; ALMA

Then become planetary nebulae

Owl Nebula (ESO)

Origins of the elements



Wikipedia!

Origins of the elements

How does the mass loss from low- and intermediate-mass stars change from star to star?

Has it changed over the history of the Universe?

Origins of the elements

What happens if mass loss is slower than we model?

Origins of the elements

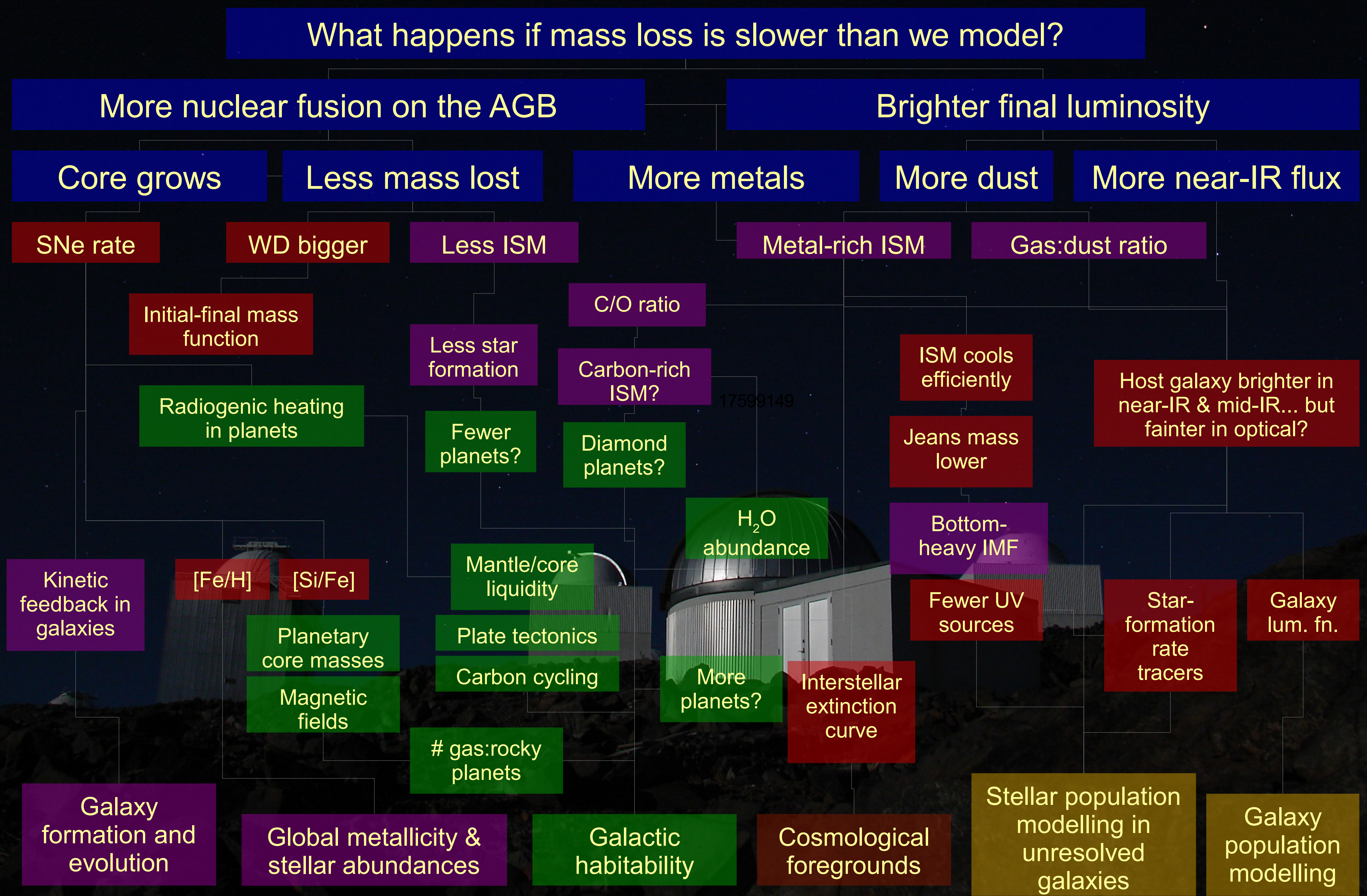
What happens if mass loss is slower than we model?

- More nuclear fusion on the AGB
  - Core grows
  - Less mass lost
- More metals
- Brighter final luminosity
  - More dust
  - More near-IR flux

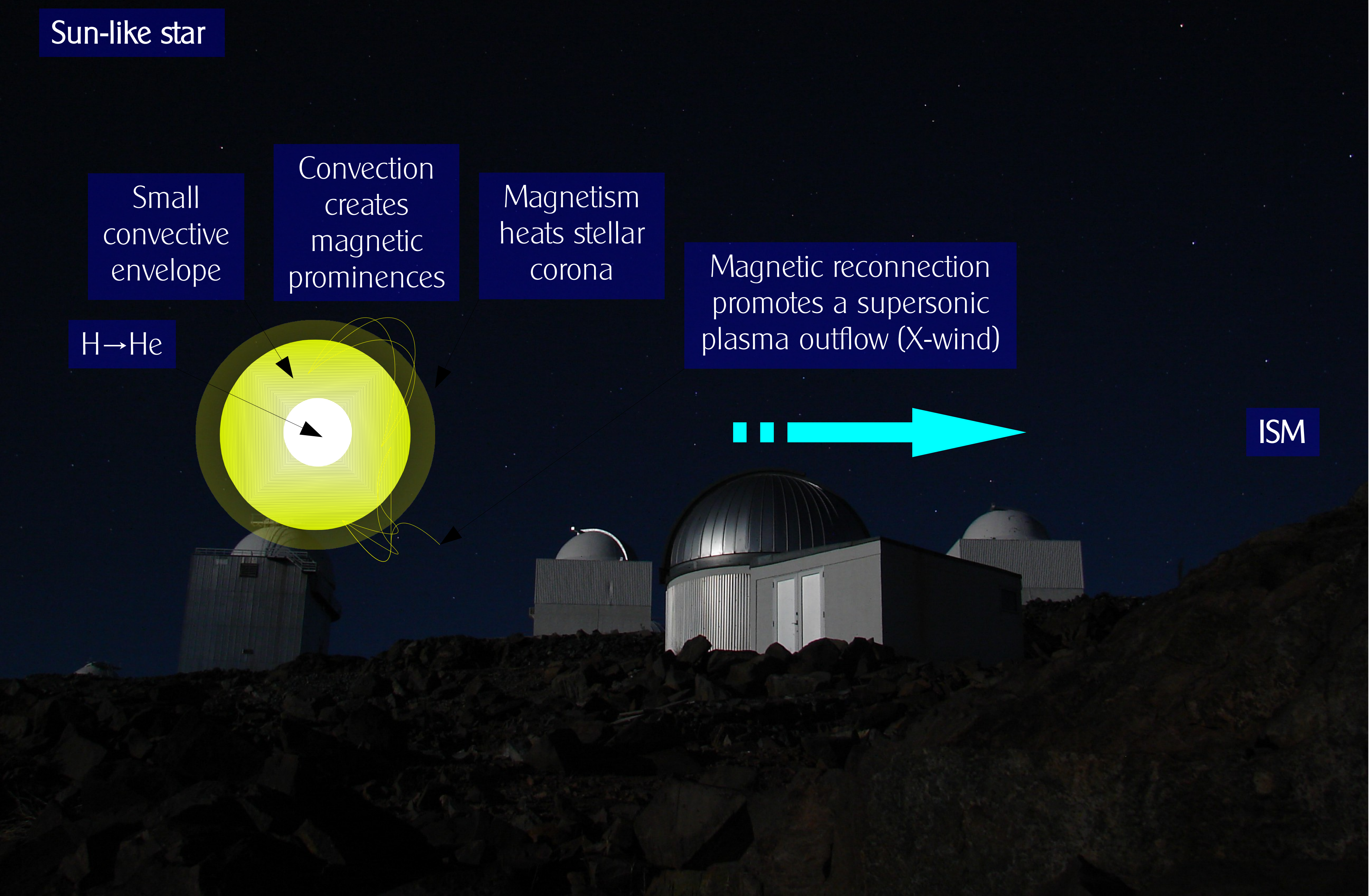
Origins of the elements

- What happens if mass loss is slower than we model?
  - More nuclear fusion on the AGB
    - Core grows
      - SNe rate
    - Less mass lost
      - WD bigger
      - Less ISM
  - More metals
    - Metal-rich ISM
  - Brighter final luminosity
    - More dust
      - Metal-rich ISM
      - Gas:dust ratio
    - More near-IR flux

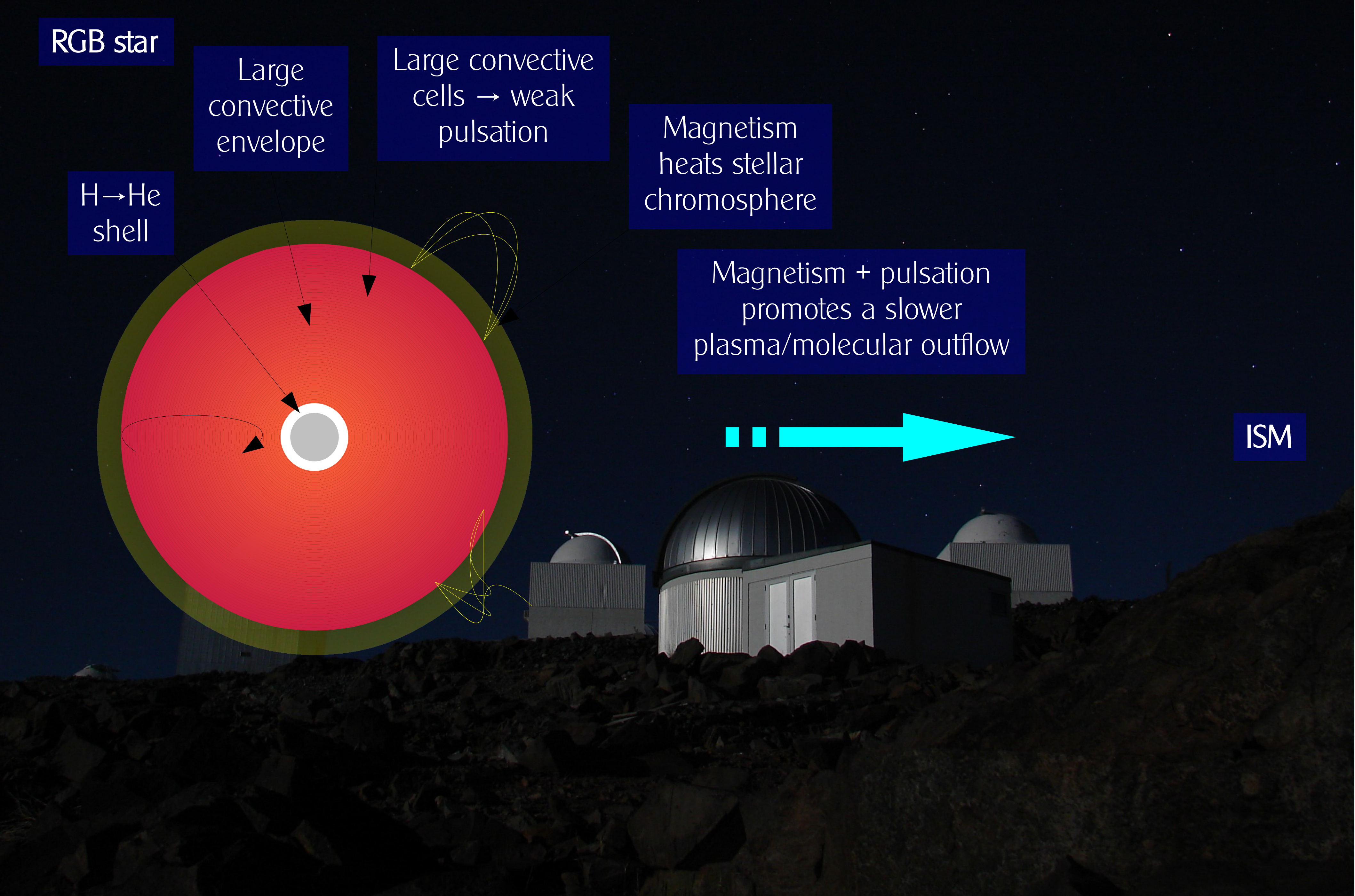
Origins of the elements



Mass loss from evolved stars



Mass loss from evolved stars



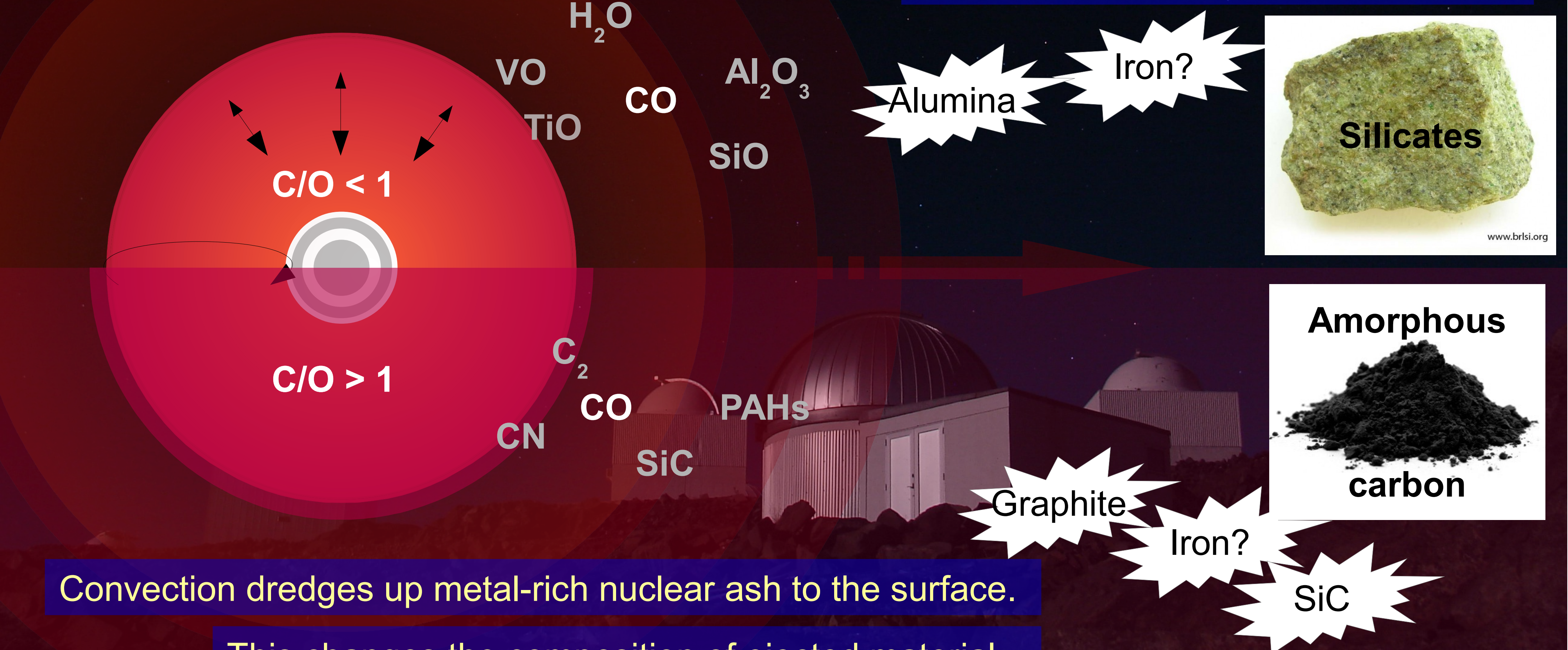
Mass loss from evolved stars

AGB stars expand to about 200x Sun's radius.

They pulsate, levitating their outer layers.

These condense into molecules and small dust grains.

Radiation pushes dust from the star.



Convection dredges up metal-rich nuclear ash to the surface.

This changes the composition of ejected material.

Bottom line: We don't know how this process changes from star to star.

Primary research topics

How fast do stars lose mass? → A mass-loss law for stellar evolution modellers

Which stars become carbon-rich? → Constraint of non-standard convection parameters

→ Model for galactic chemical enrichment

How fast do stars lose mass?

How do stars lose mass?

Pulsation-enhanced radiation-driven wind.

How do stars lose mass?

Pulsation-/magnetism- enhanced radiation-/**dust-**driven wind.

Magnetism

Mass-loss rate (dM/dt) should depend on **magnetic field*** but not strongly depend on other observable properties.

Magnetic field declines with stellar **age** and **evolution**.

(* Can't be measured in highly evolved stars)

Pulsation

dM/dt and wind expansion velocity ($v_{\rm exp}$) should scale with **pulsation amplitude** and/or **period**.

dM/dt should not strongly depend on other factors* (e.g. $\boldsymbol{T_{\rm eff}}$, $\boldsymbol{L}$ or **[Fe/H]**).

(* But pulsation properties depend on temperature, luminosity and metallicity)

Dust

dM/dt and $v_{\rm exp}$ should scale with $\boldsymbol{L}$ and **[Fe/H]**.

dM/dt should not strongly depend on **pulsation properties***.

S stars have low dust:gas ratios, so should have low dM/dt and $v_{\rm exp}$.

C stars have high opacity, so should have high dM/dt and $v_{\rm exp}$.

(* But pulsation properties depend on luminosity and metallicity.)

We need to observe a variety of stars with different properties to disentangle these effects.

Programme of work

We need to observe a variety of stars with different properties to disentangle these effects.

Dependent variables

Mass-loss rate
Dust-production rate
Wind-expansion velocity

Independent variables

Stellar age
Stellar evolution
(Surface magnetic field)
Pulsation amplitude
Pulsation period
Temperature
Luminosity
[Fe/H]
M → S → C transition (C/O)

Observations/computations

Optical/near-IR spectra → abundances

Full SED fitting → T_{eff}, L

Infrared spectrophotometry → dust

CO sub-mm spectra → dM/dt, v_{exp} [nearby stars]

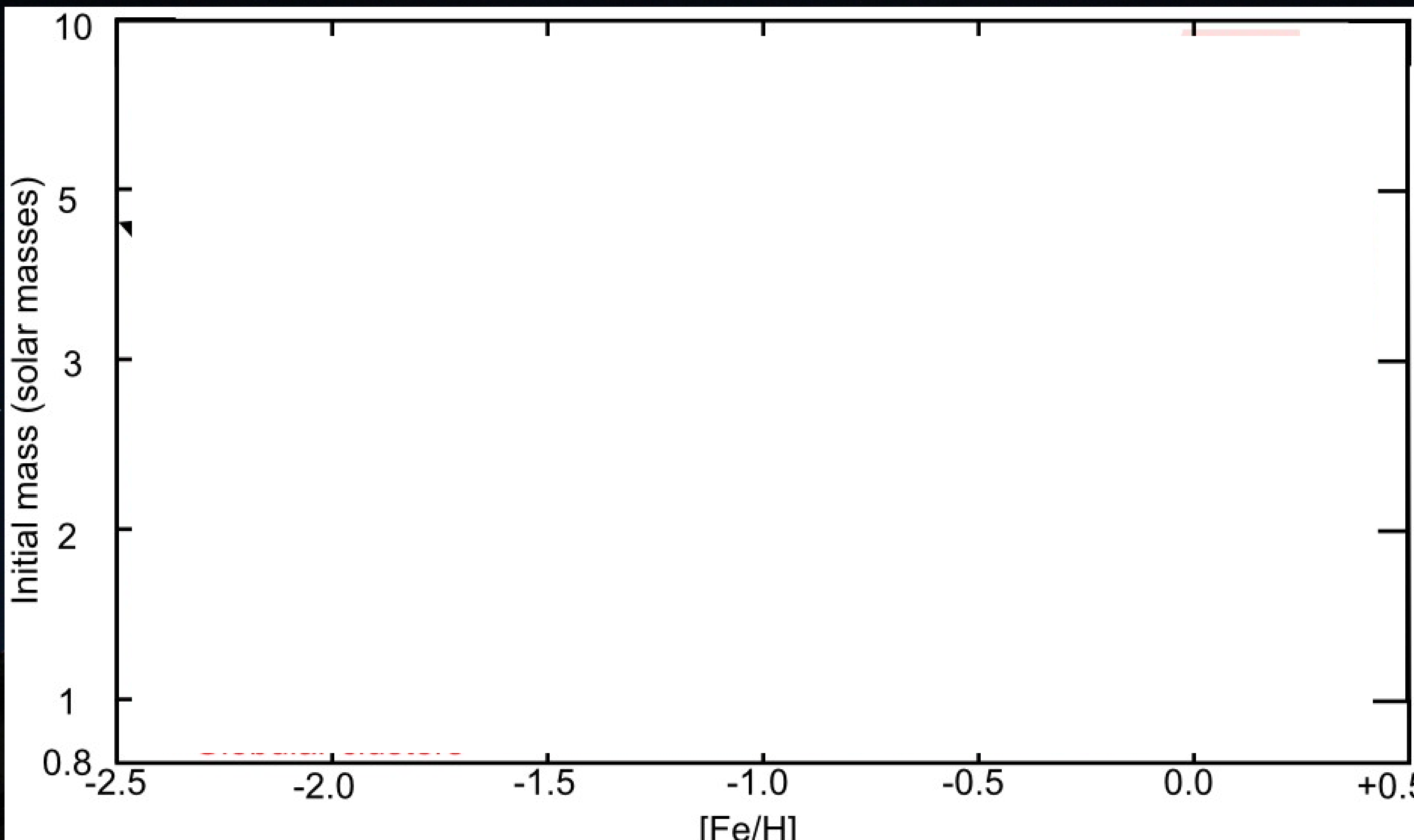
Photometric monitoring → pulsation

Population modelling → age, evolution

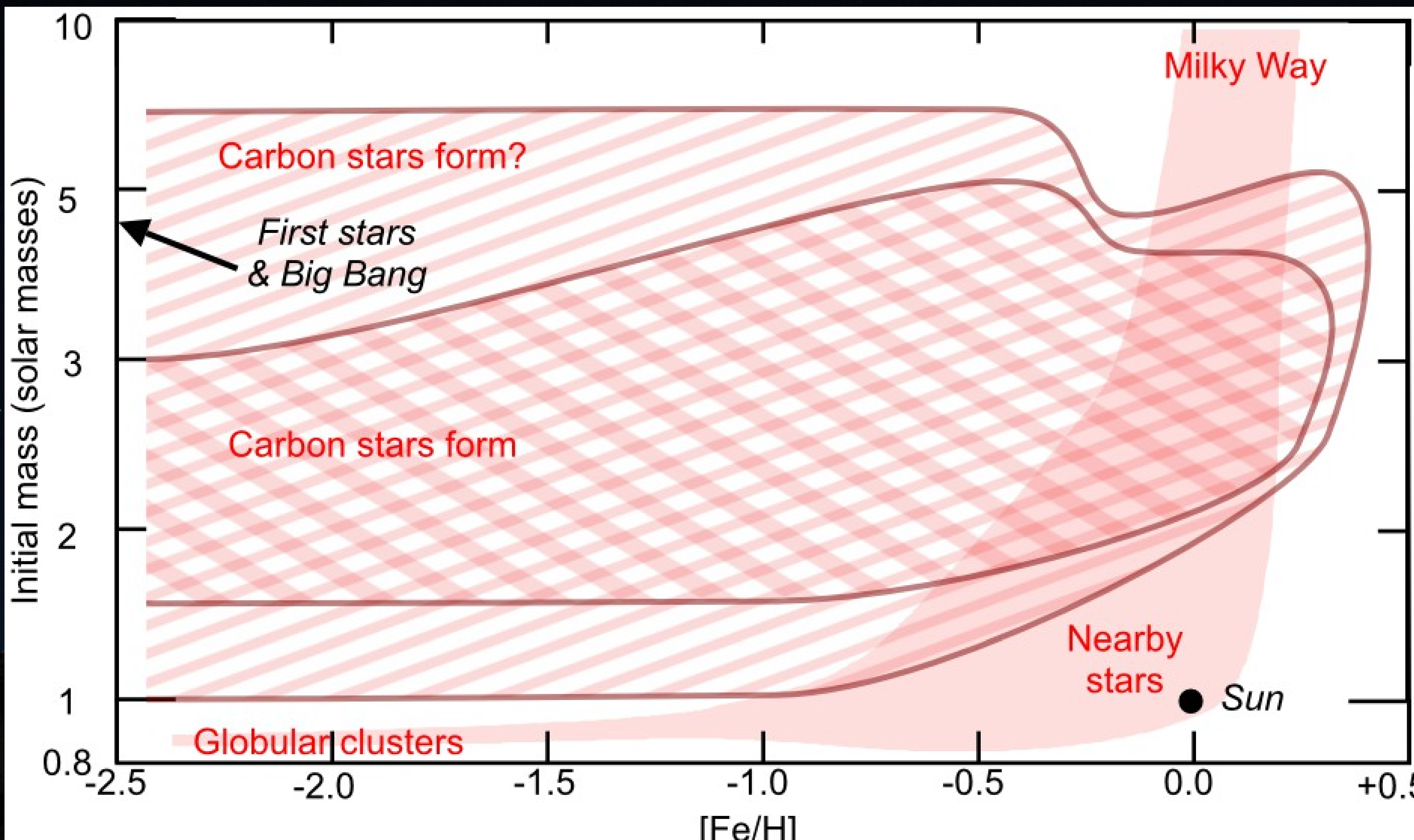
...in populations of differing ages and metallicities...

Targets

A.k.a.: which stars become carbon-rich?

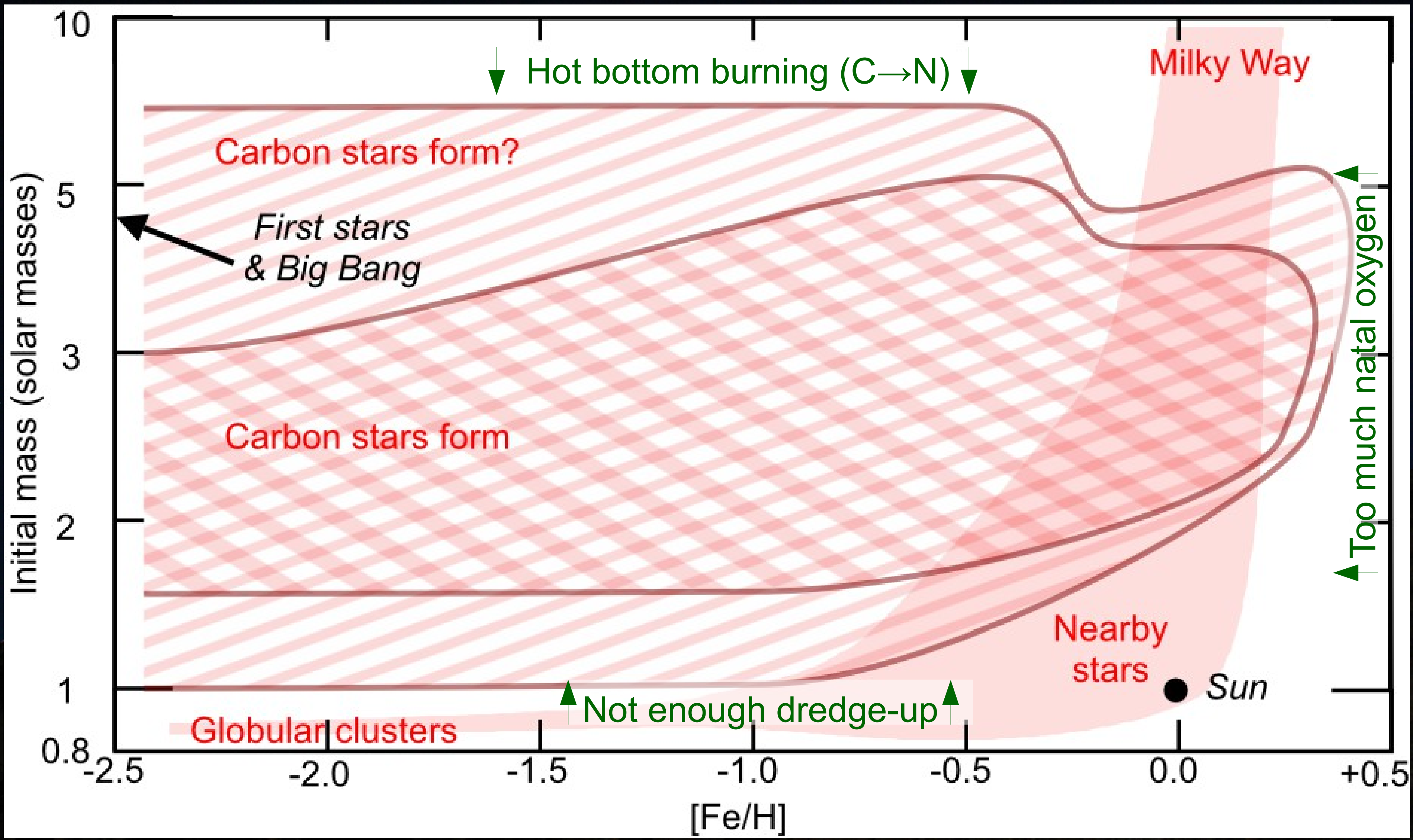


Targets



Milky Way
Carbon stars form?
First stars
& Big Bang
Carbon stars form
Nearby
stars
Sun
Globular clusters
Initial mass (solar masses)
10
5
3
2
1
0.8
-2.5
-2.0
-1.5
-1.0
-0.5
0.0
+0.5
[Fe/H]

Targets

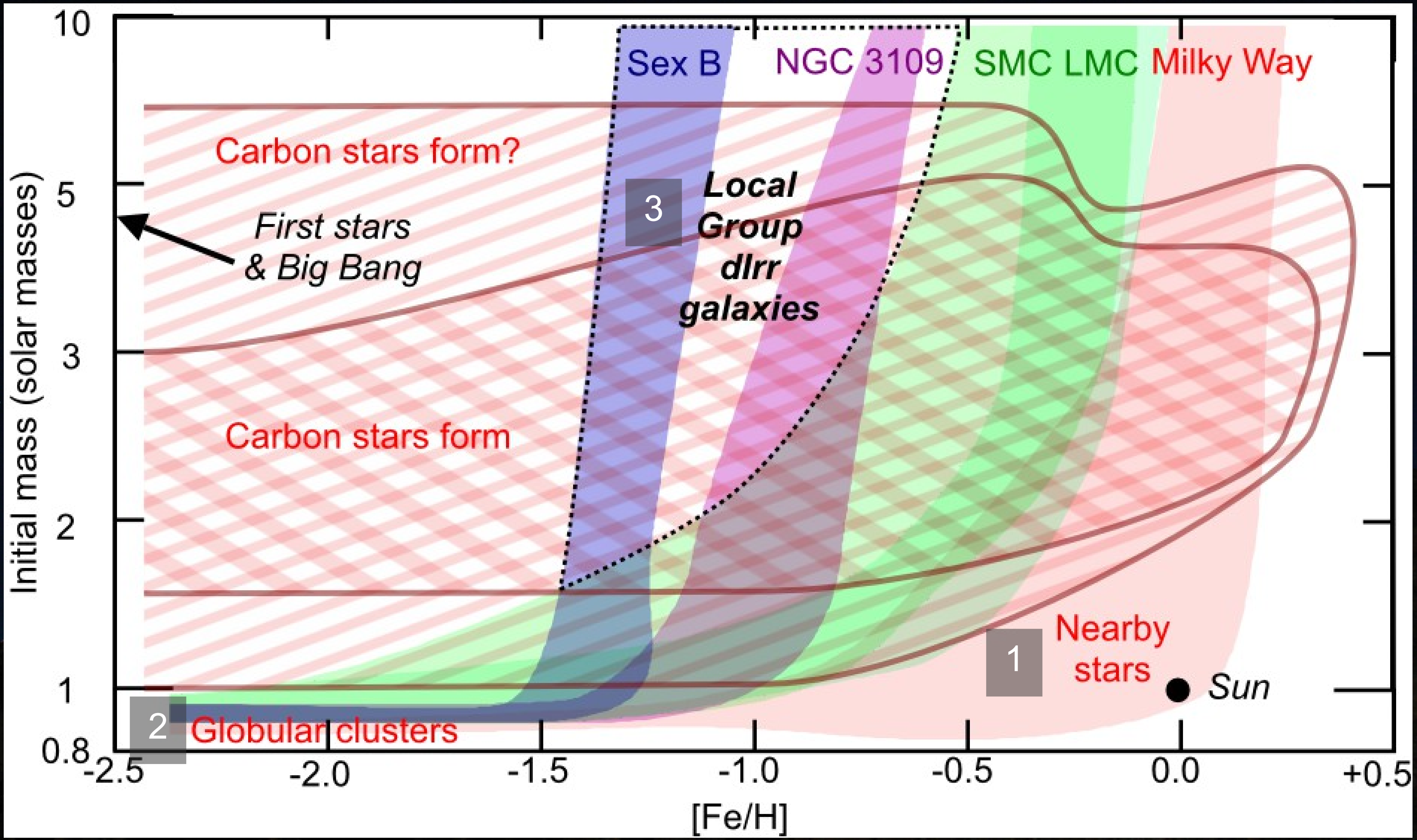


Hot bottom burning (C→N)
Milky Way
Carbon stars form?
First stars
& Big Bang
Carbon stars form
Too much natal oxygen
Nearby
stars
Sun
Not enough dredge-up
Globular clusters
Initial mass (solar masses)
10
5
3
2
1
0.8
-2.5
-2.0
-1.5
-1.0
-0.5
0.0
+0.5
[Fe/H]

Targets

Local dIrr galaxies are the only places we can observe massive, metal-poor stars.

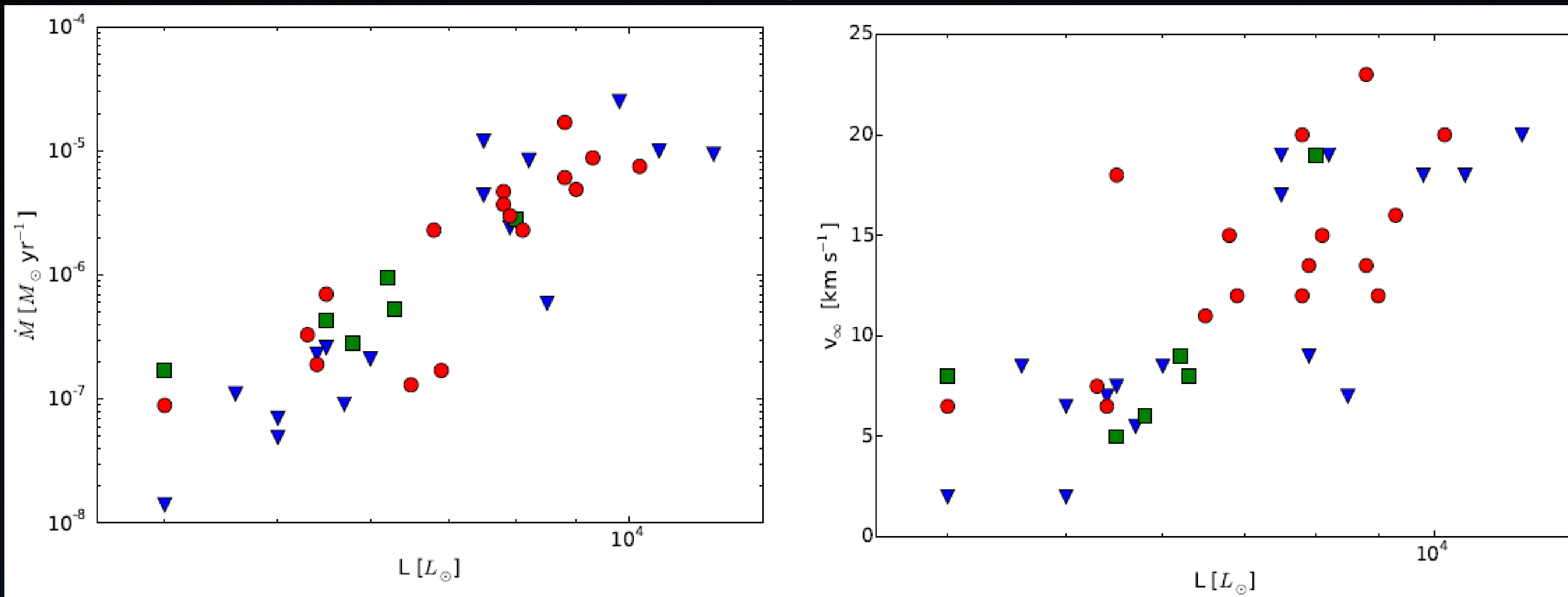
The Magellanic Clouds are not metal-poor enough for this work.



Nearby stars

Nearby stars

Radiation pressure on dust is clearly important: strong link between luminosity and both mass-loss rate and outflow velocity. But something else is going on too...



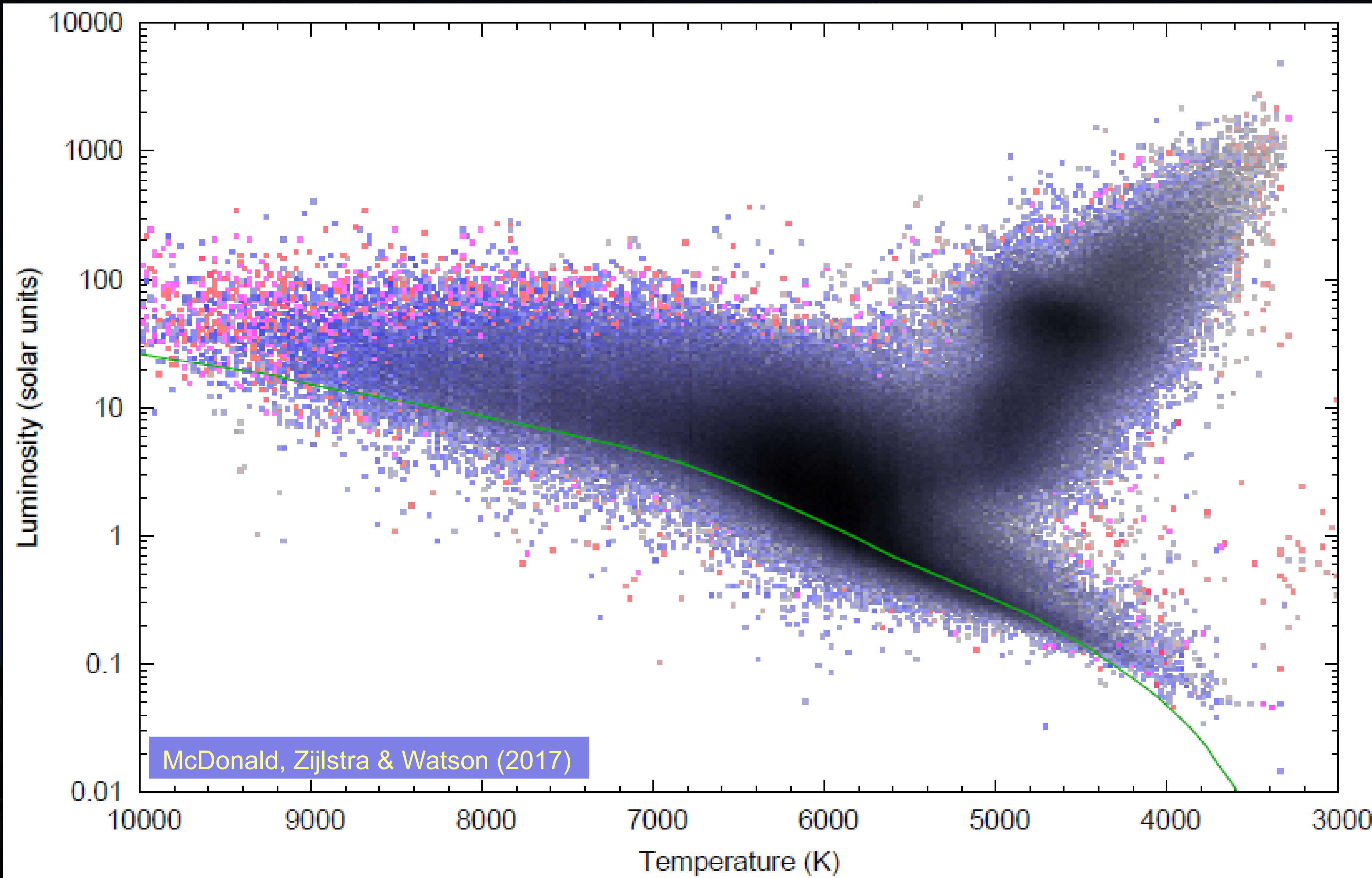
Danilovich et al. (2015)

Nearby stars

Gaia DR1: distances to ~1.6 million stars. Add literature photometry...

Nearby stars

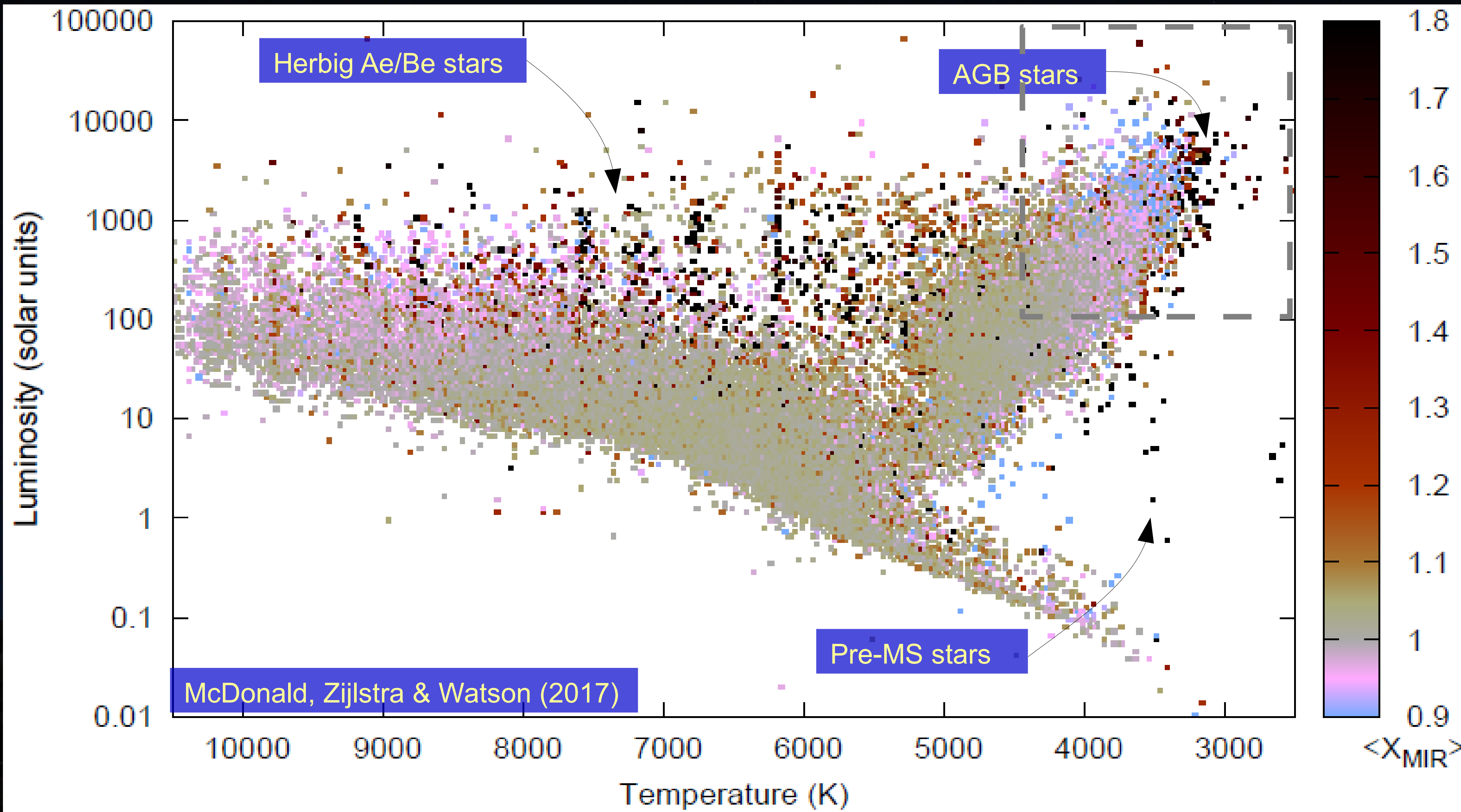
Gaia DR1: distances to ~1.6 million stars. Add literature photometry...



Nearby stars

Gaia DR1: distances to ~1.6 million stars. Add literature photometry...

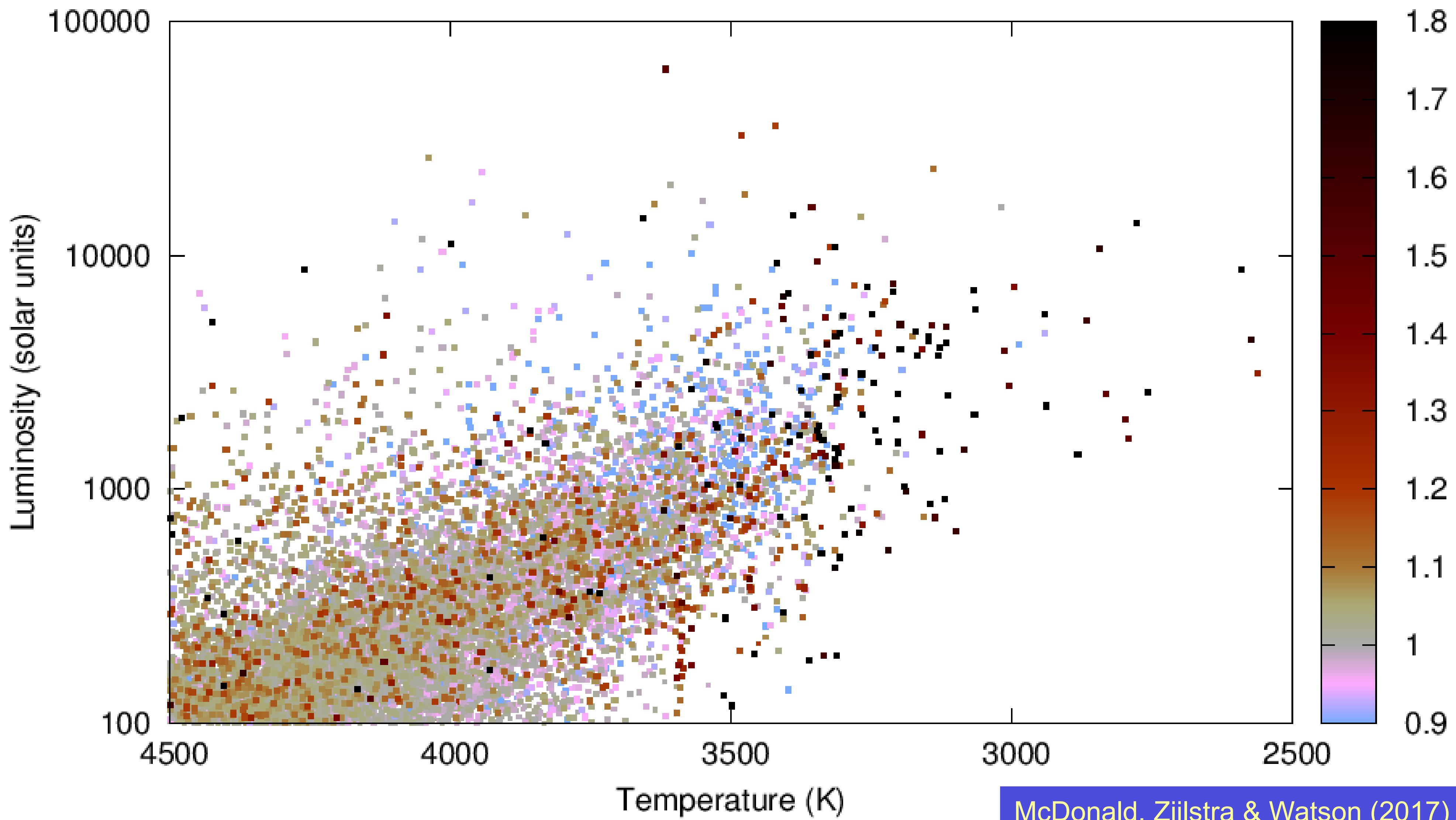
...and colour-code by infrared excess (dust-production rate)...



Nearby stars

Some, but not all giant lose mass at a given luminosity

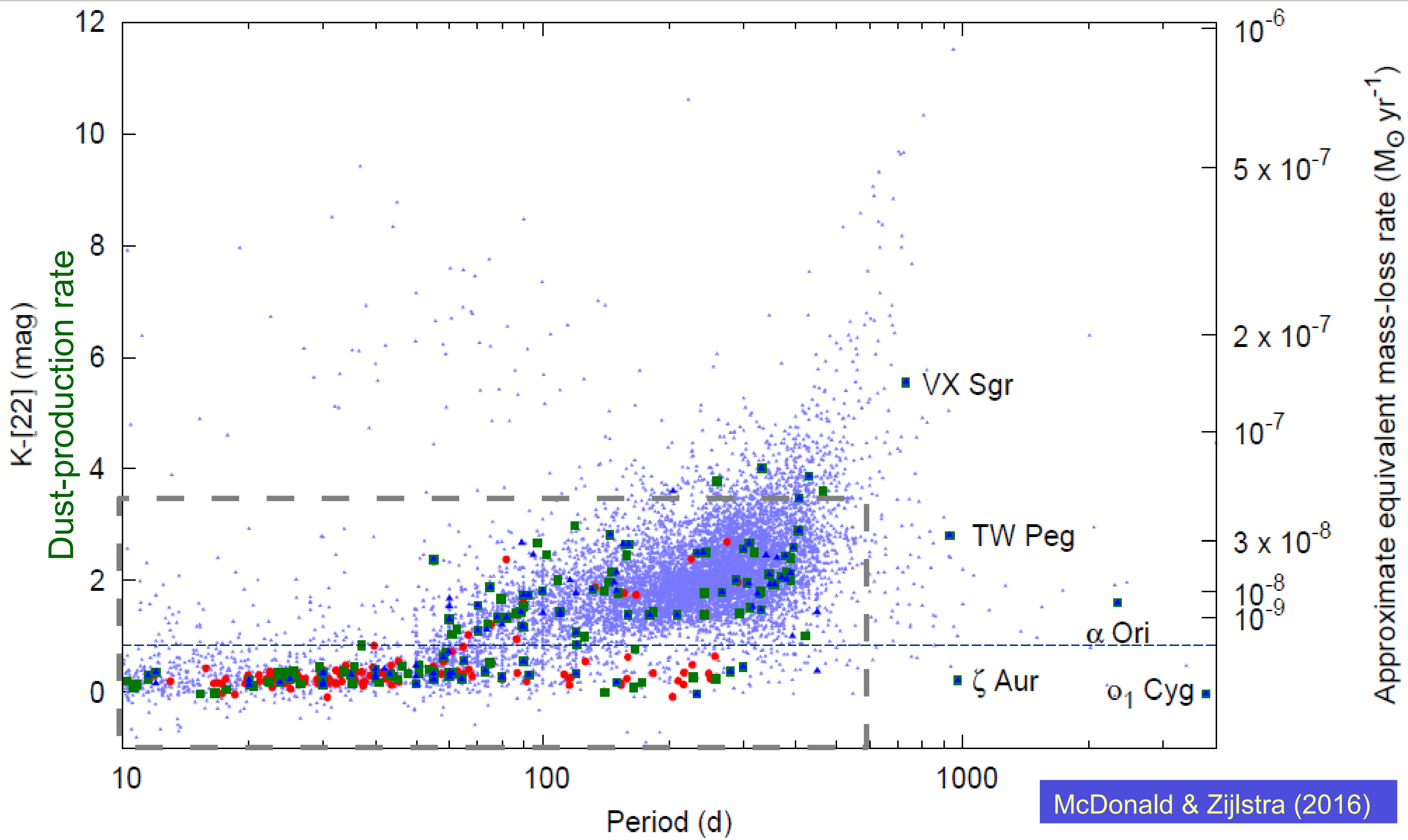
→ Radiation pressure on dust isn't the only variable (perhaps temperature is important?)



McDonald, Zijlstra & Watson (2017)

Nearby stars

Pulsation initiates dust-production, and continues to be important until the final AGB stages.

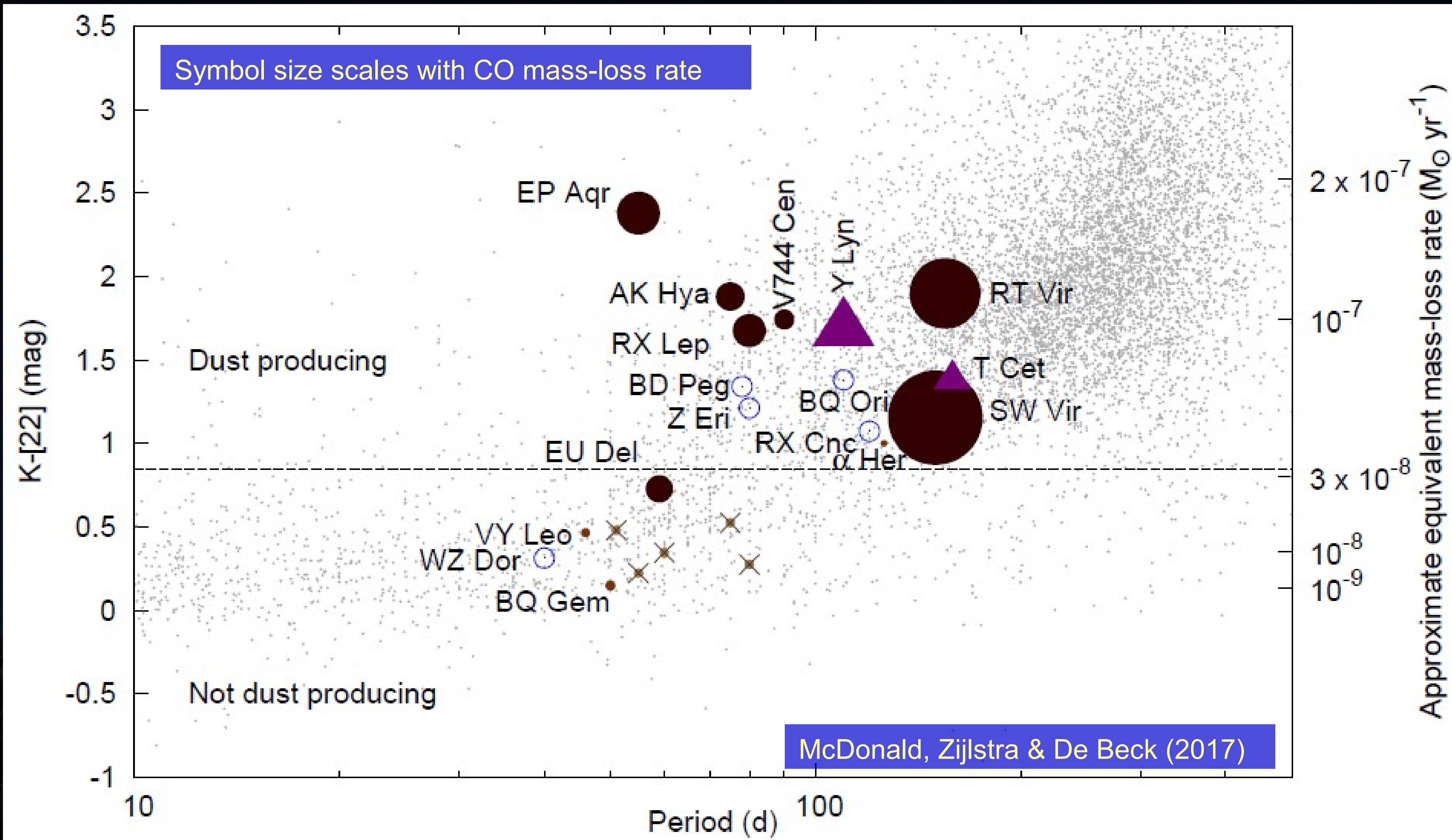


McDonald & Zijlstra (2016)

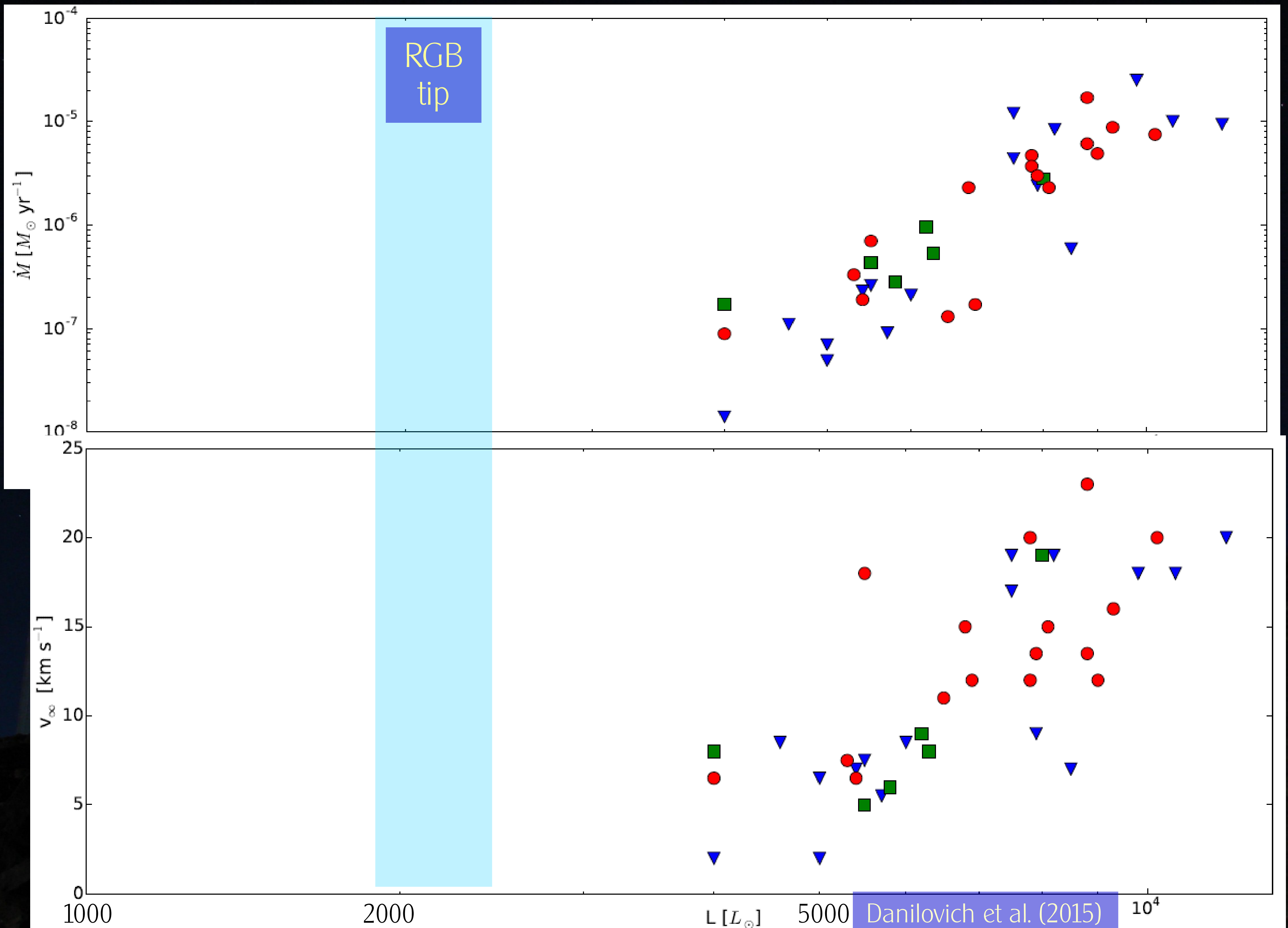
Nearby stars

Pulsation initiates dust-production, and continues to be important until the final AGB stages.

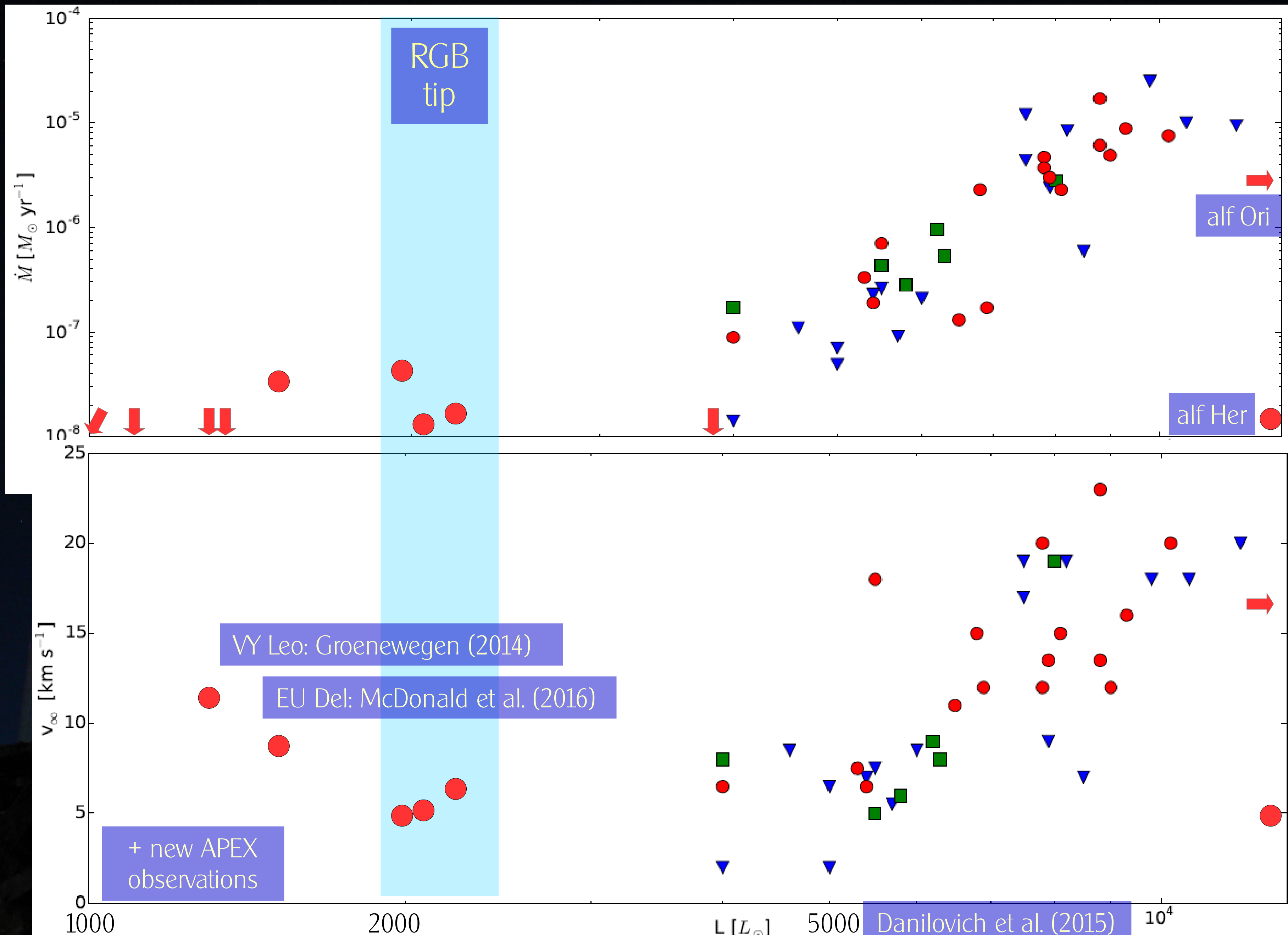
This is a real mass-loss rate enhancement, not just dust condensation in an existing wind.



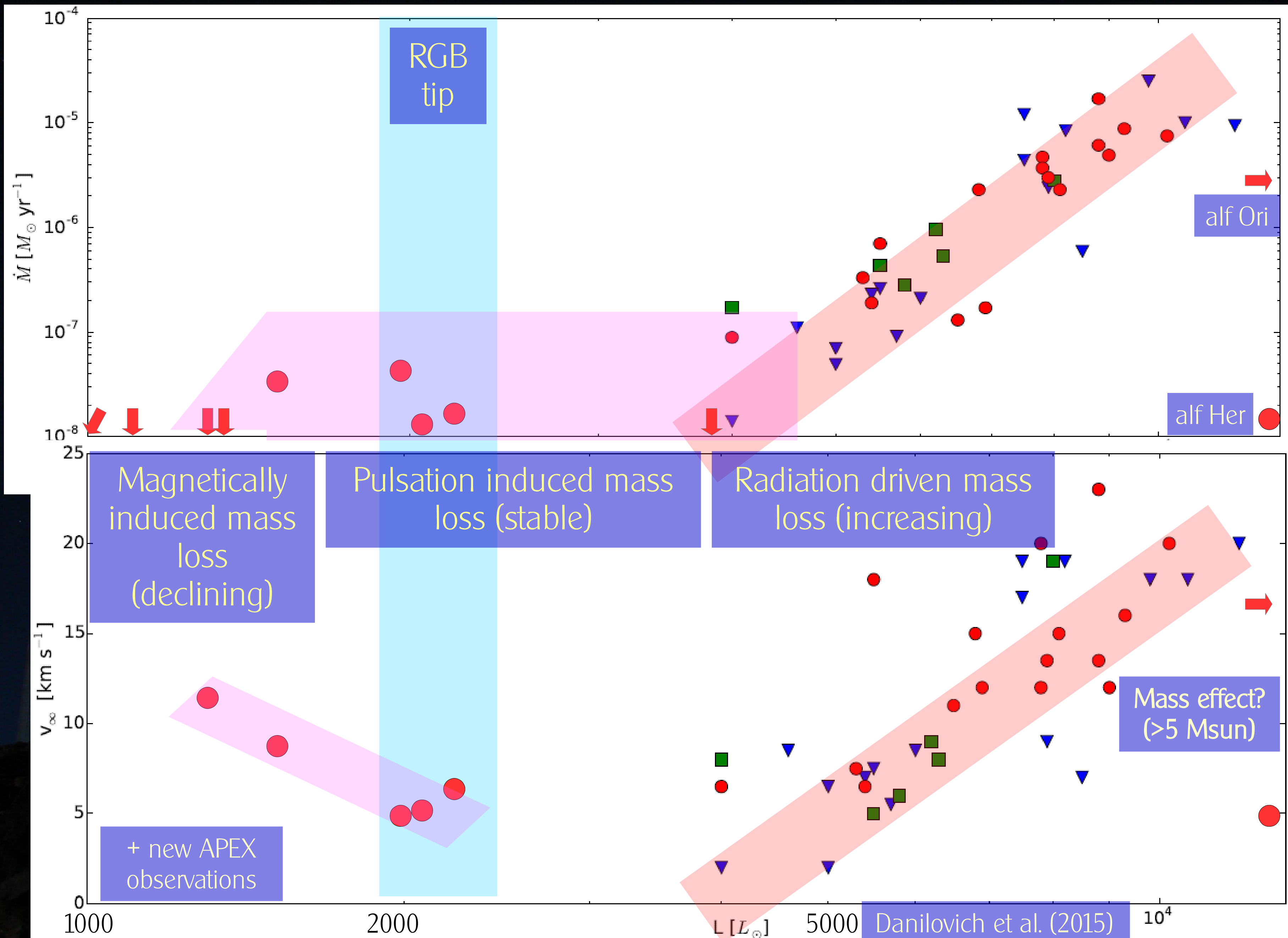
Nearby stars



Nearby stars

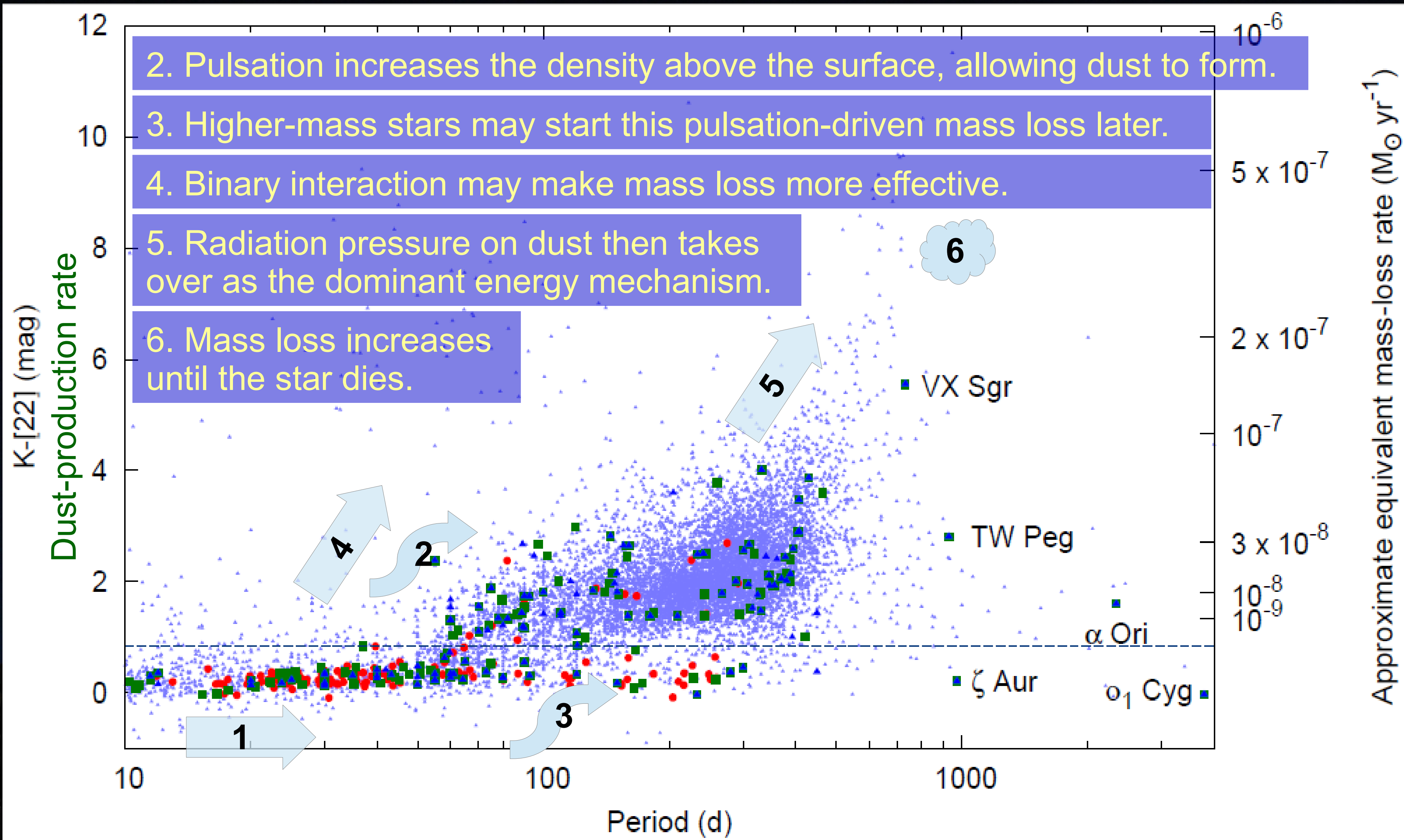


Nearby stars



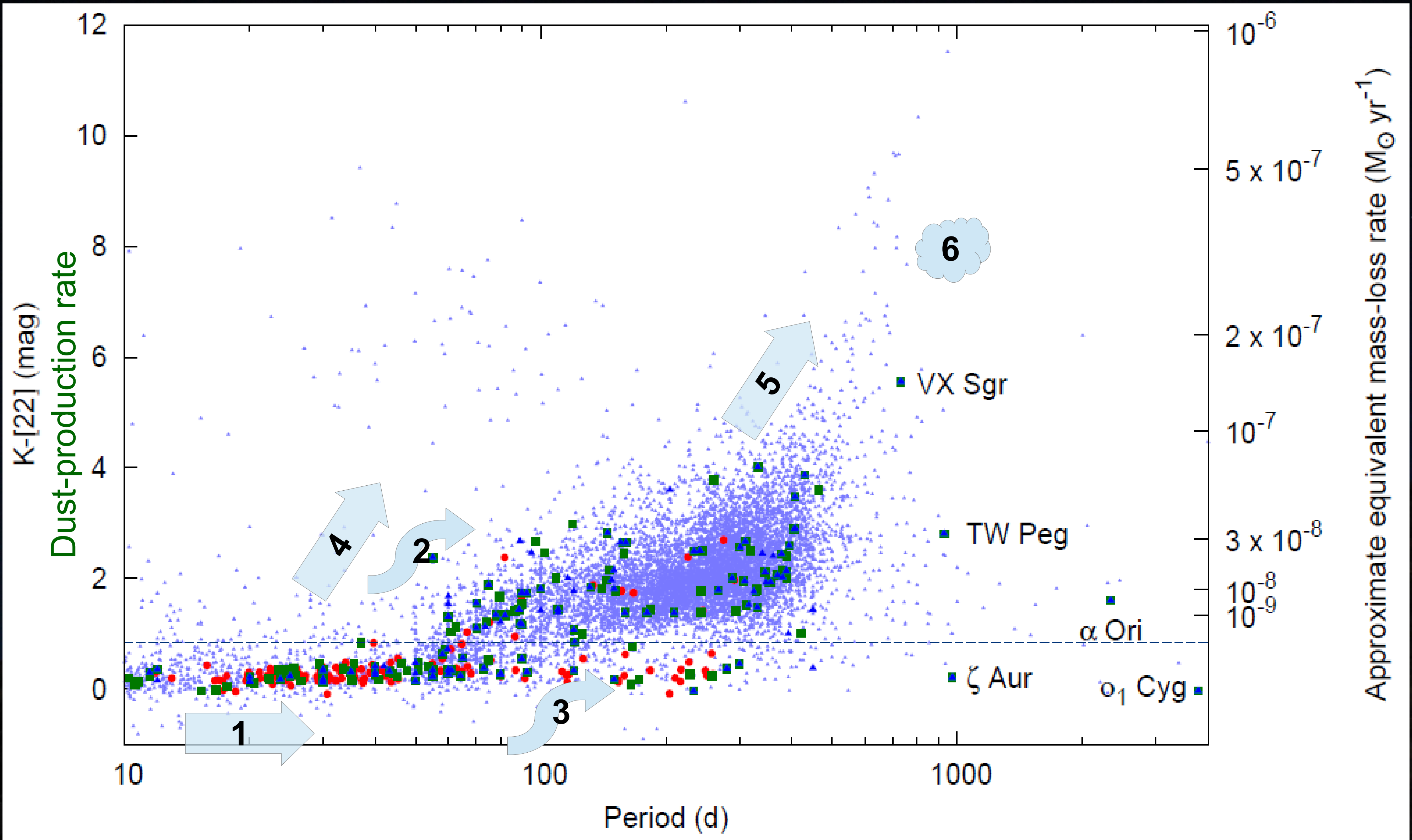
Nearby stars

1. Declining magnetic activity slows the hot, low-density outflow from the star.



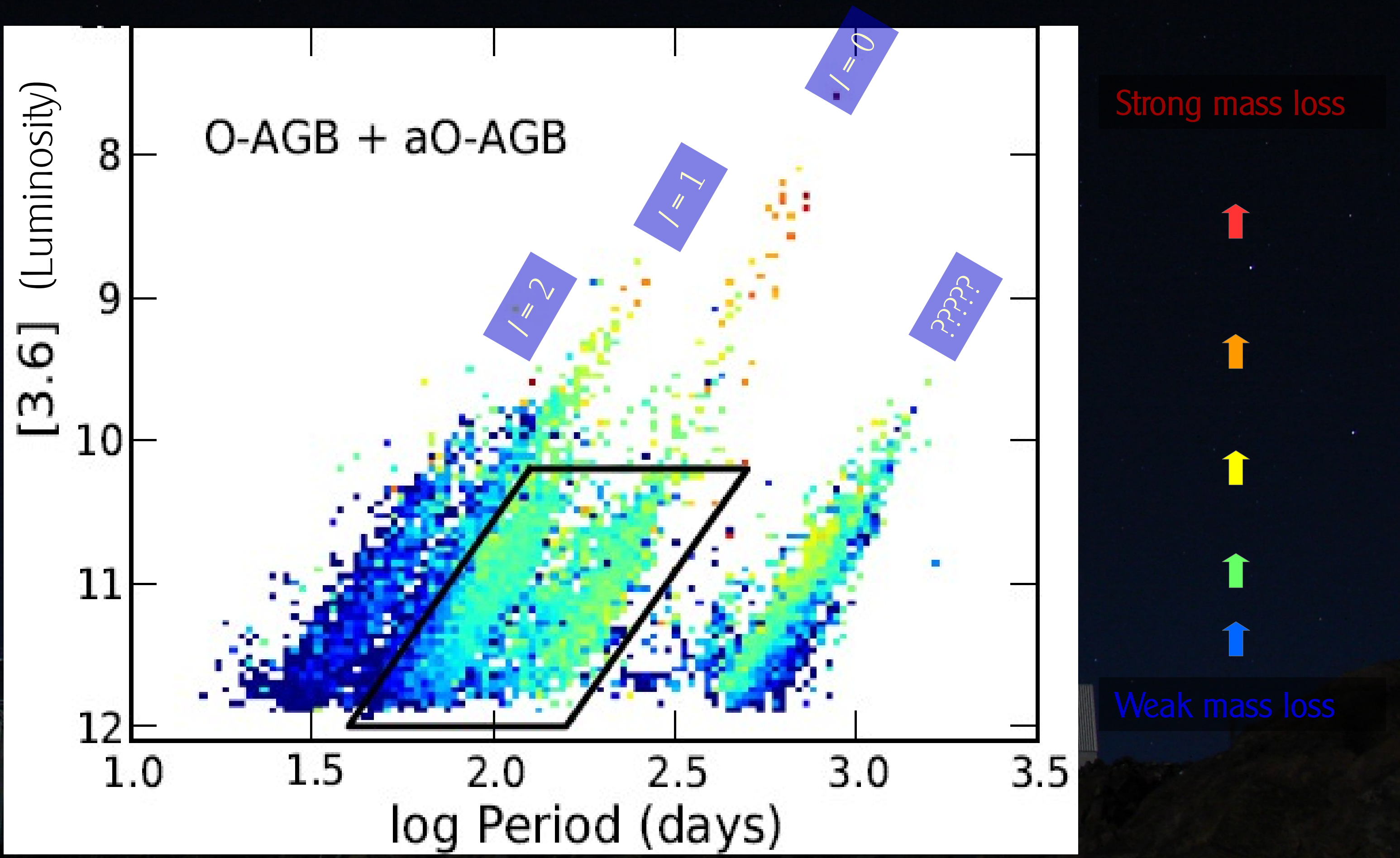
Nearby stars

Physically, what does this correspond to?



Nearby stars (& Magellanic Clouds)

Physically, what does this correspond to?



Boyer et al. (2015)

Changes in the wind-driving mechanism seem to be linked to the pulsation mode.

Pulsation mode is dictated by radius (T_{eff}, L) and density (mass).

Globular clusters

Do these hypotheses hold if we look at globular clusters?

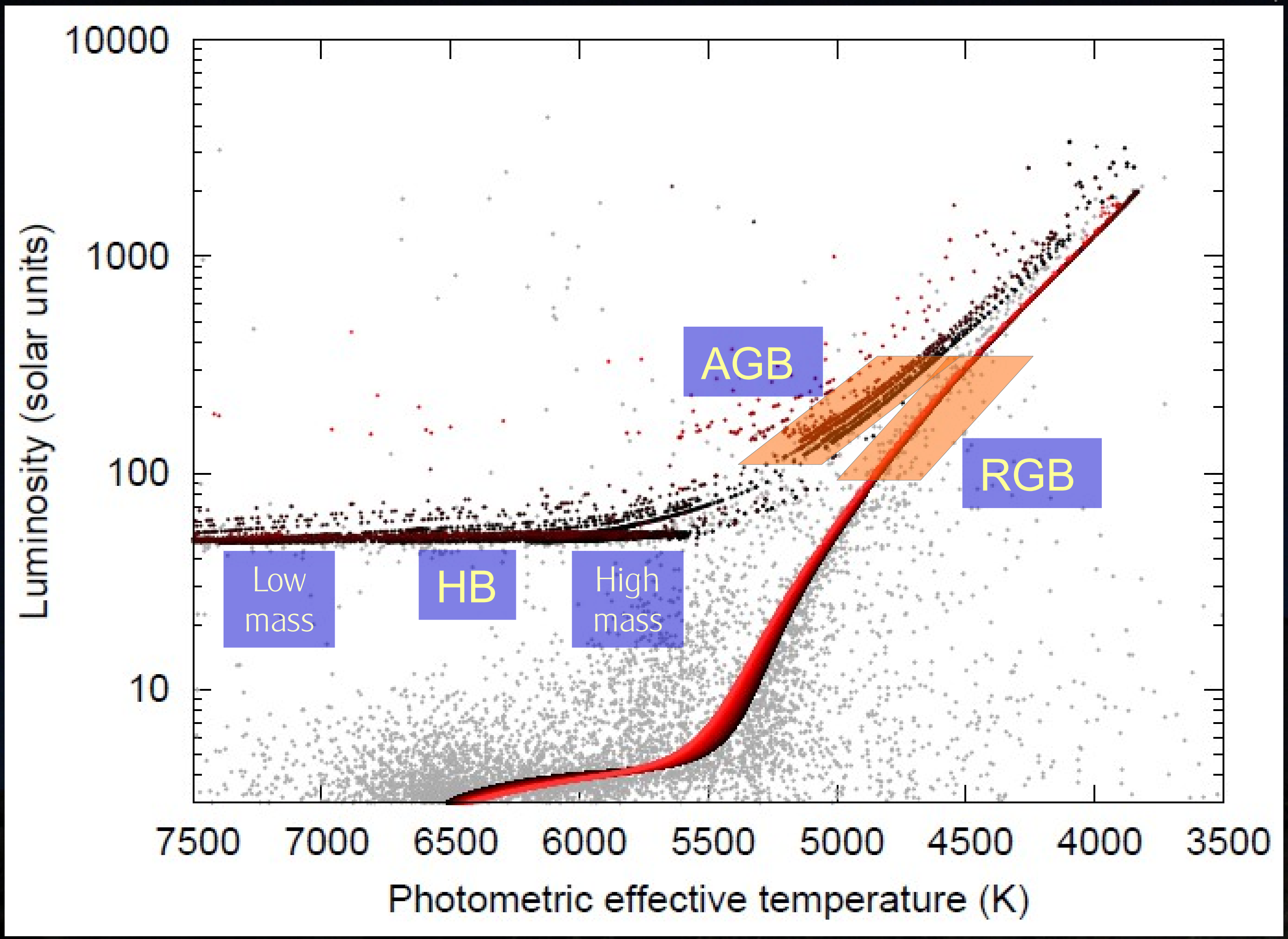
Metal-poor stars ([Fe/H] = -2.4 to 0.0) at 0.8-0.9 M_{Sun}.

Can't make CO measurements, but we do have infrared excess and evolutionary models.

Globular clusters

Magnetically-driven mass-loss in metal-poor stars:

Globular clusters have clean H-R diagrams and good evolutionary models.



M5; McDonald et al. (2017)

Main seq.: M = 0.85 M_{Sun}

$M_{RGB} \sim M_{MS}$

$M_{HB} \sim M_{AGB}$

M_{AGB}:

Photometry → T_{eff}, L

Spectra → T_{eff}, log g

$$M = \frac{gL}{4\pi\sigma T_{\rm eff}^4 G}$$

M_{RGB} - M_{HB}

M_{HB}:

Fitting evolutionary models to HB

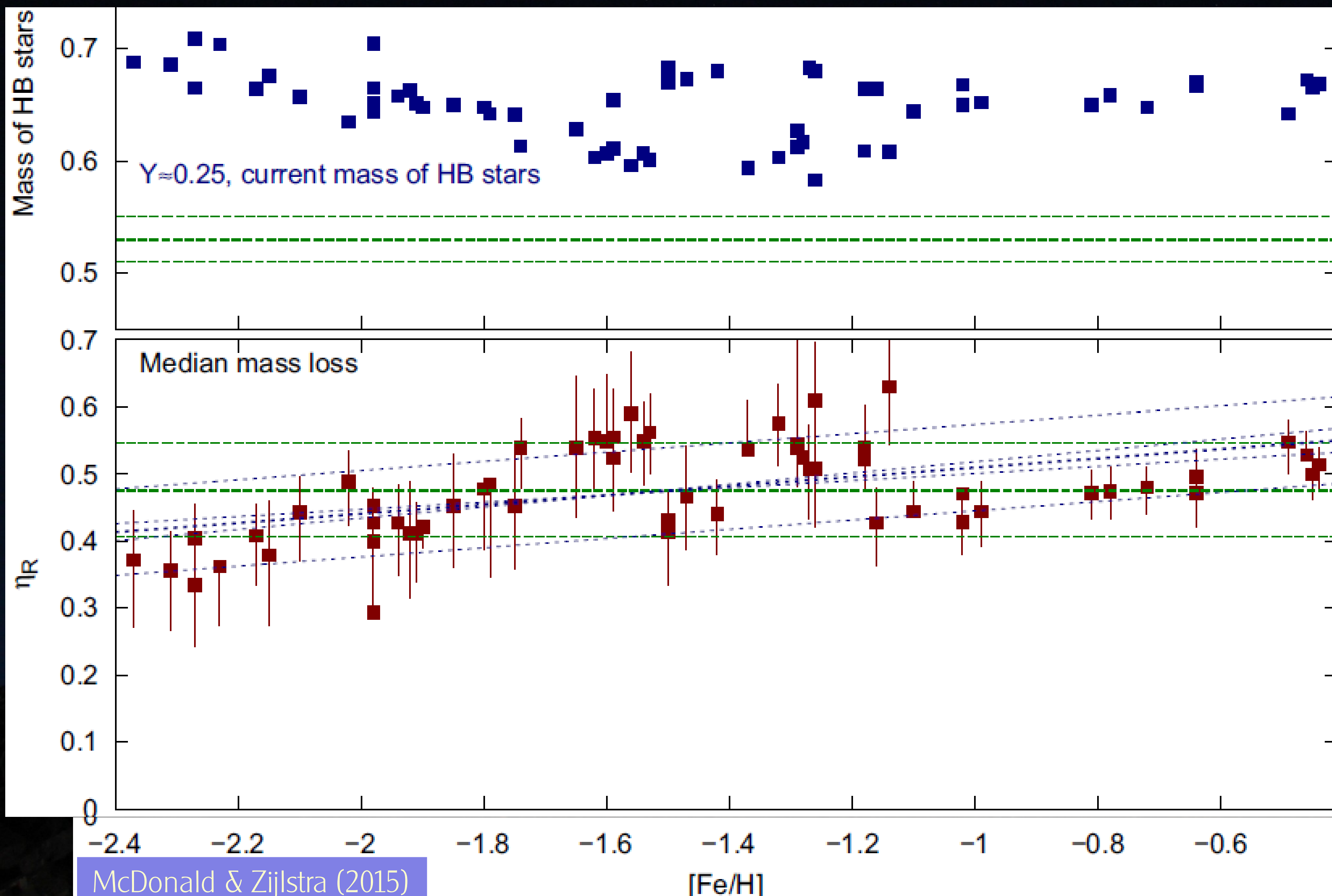
M_{final}:

White dwarf masses

Globular clusters: RGB - HB

Magnetically-driven mass-loss in metal-poor stars:

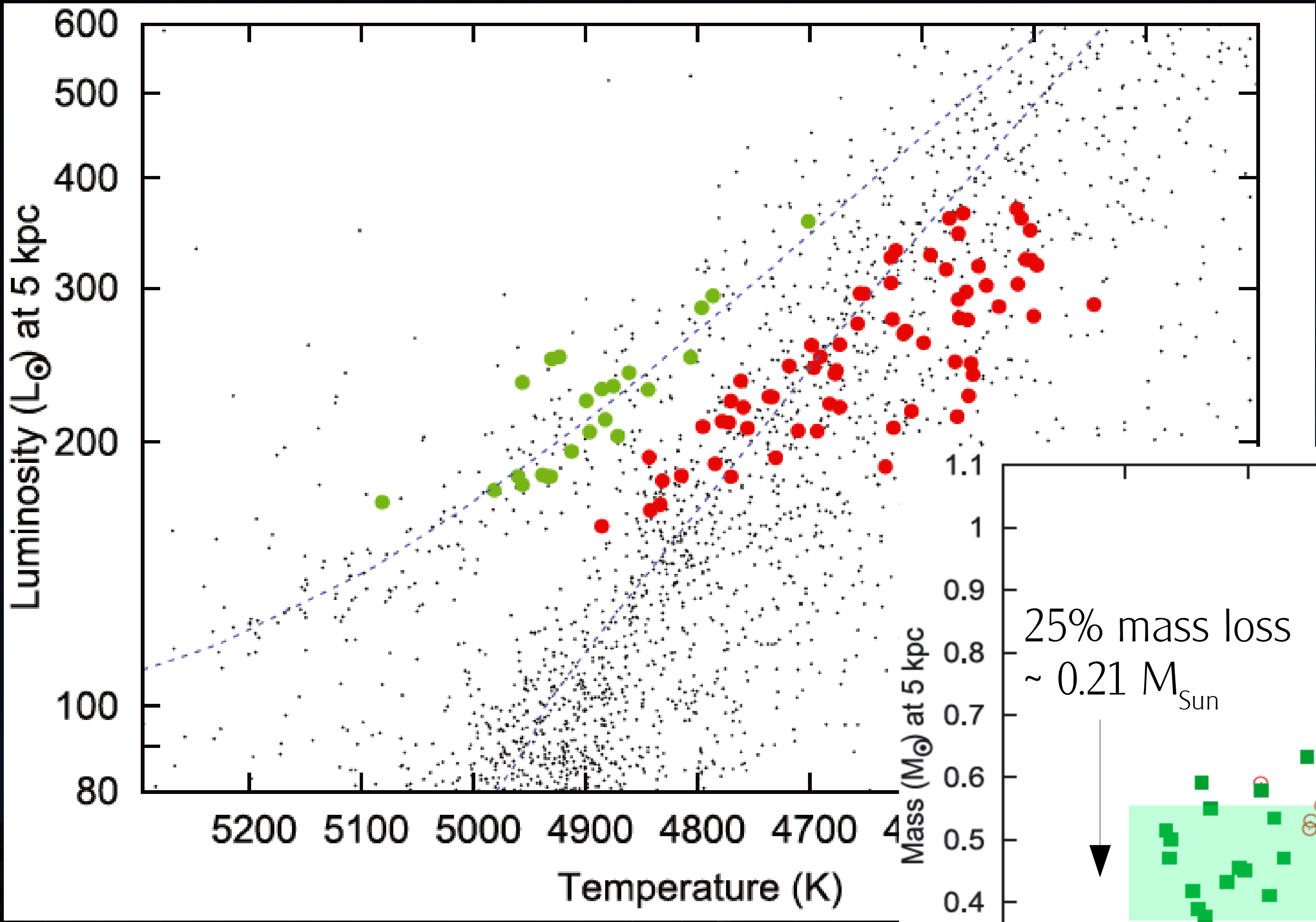
HB stellar masses and mass-loss efficiencies vary negligibly with metallicity.



Globular clusters: RGB - HB

Magnetically-driven mass-loss in metal-poor stars:

We can confirm this by looking at AGB stellar masses.

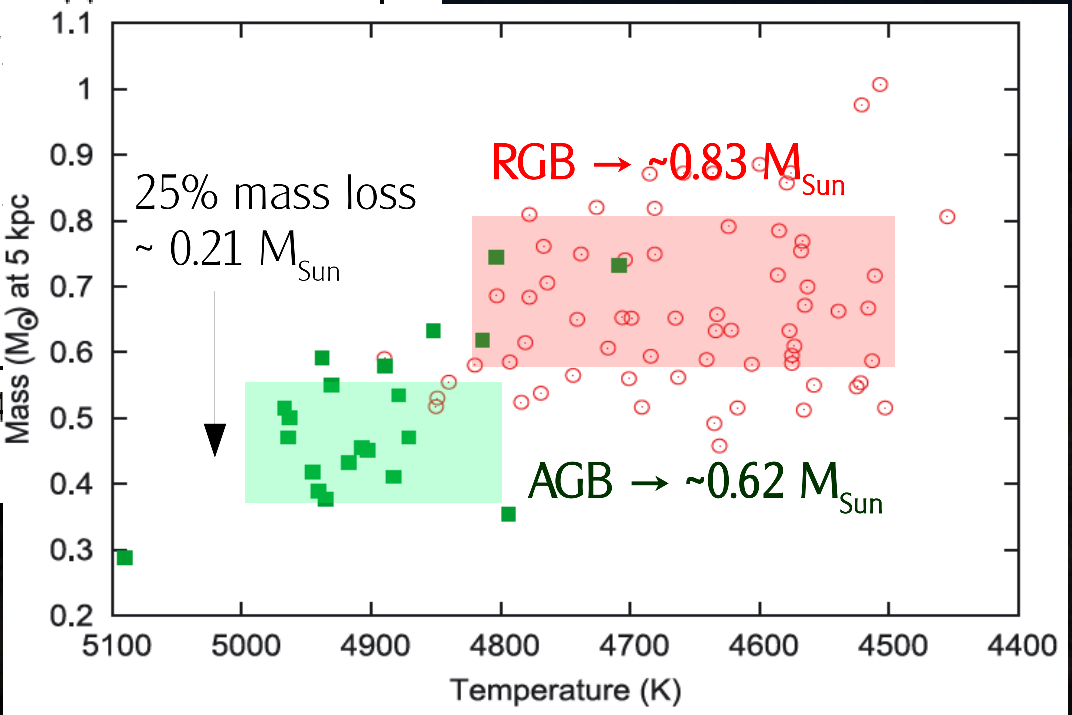


M_{AGB}:

Photometry → T_{eff}, L

Spectra → T_{eff}, log g

$$M = \frac{gL}{4\pi\sigma T_{eff}^4 G}$$

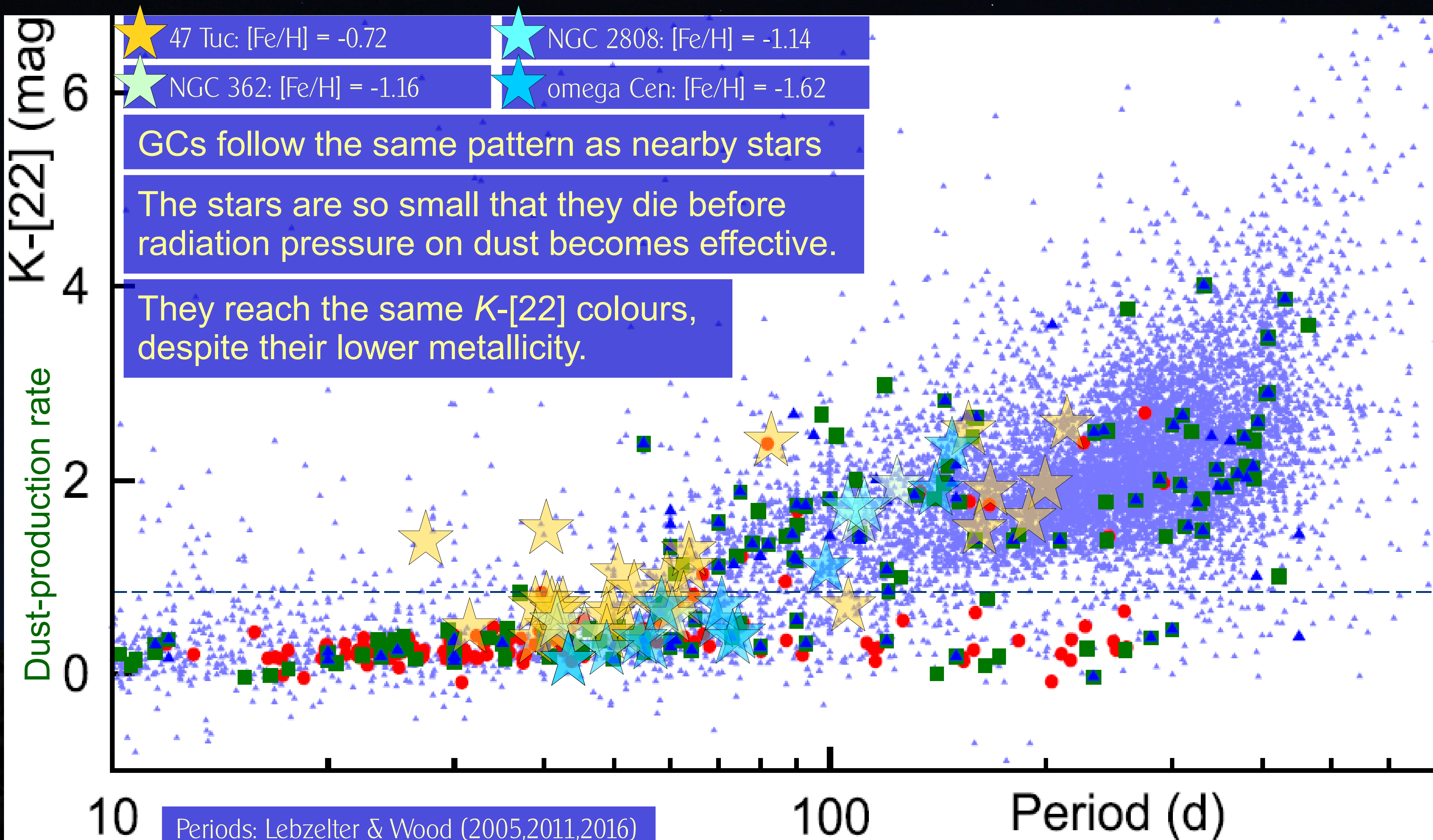


McDonald & Zijlstra (2011d)

Globular clusters

Magnetically-driven mass loss in metal-poor stars ~ metallicity independent.

Pulsation-driven mass loss:



Globular clusters

Magnetically-driven mass loss in metal-poor stars ~ metallicity independent.

Pulsation-driven mass loss ~ metallicity independent.

Radiation-enhanced mass loss ~ ?

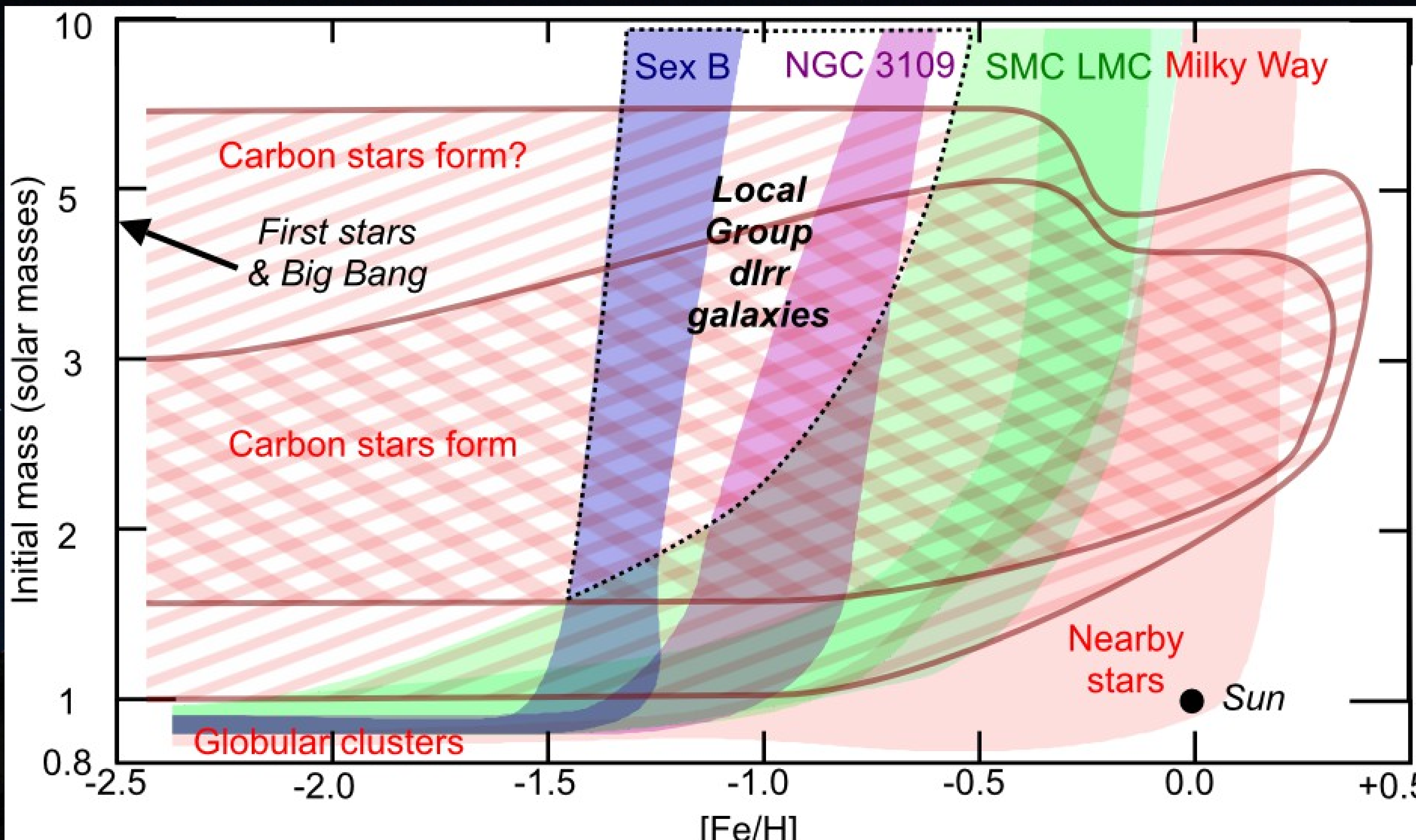
We know that metal-poor stars behave much like metal-rich stars, but globular clusters don't contain stars with high enough mass to hold radiation-enhanced dust-driven winds.

Radiation pressure should be less effective in metal-poor stars.
Does this slow down mass loss?

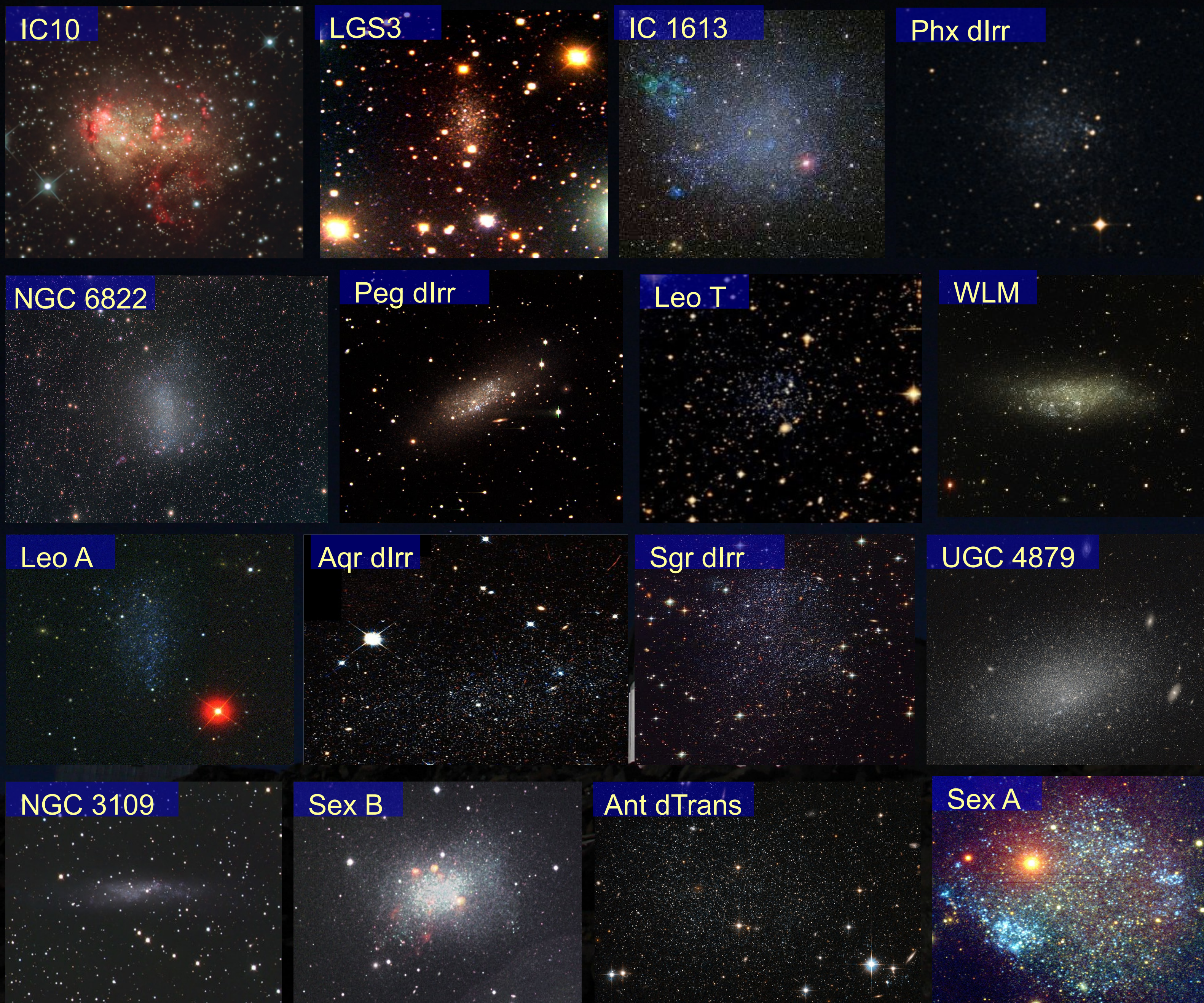
Local Group dwarf irregular galaxies

Local dIrr galaxies are the only places we can observe massive, metal-poor stars.

The Magellanic Clouds are not metal-poor enough for this work.



Local Group dwarf irregular galaxies



Local Group dwarf irregular galaxies

DUSTiNGS: Dust in Nearby Galaxies (with *Spitzer*) : P.I. Martha Boyer

Survey of 50 nearby dwarf galaxies, including 11 dIrr galaxies, at 3.6 & 4.5 um.
Multi-epoch photometry → basic variability information, including some pulsation periods.

HST near-IR medium-band survey
PI: M. Boyer
Purpose: To separate carbon-rich from oxygen-rich stars

INT optical survey (Northern)
PI: J. Th. van Loon
Purpose: Multi-wavelength survey to obtain deep, high-quality photometry & variability

VLT optical survey (Sorthern)
PI: I. McDonald
Purpose: Multi-wavelength survey to obtain deep, high-quality photometry

JWST ERS proposal (PI: C. Kemper): a 100+ team targetting ~two of these dIrr galaxies for comprehensive infrared observation.

First three DUSTiNGS papers published: Boyer et al. 2016 a/b, McQuinn et al. 2016.
More to come in the future!

Conclusions

Mass loss from stars is the primary mechanism that sets the chemistry of the Universe.

Low-mass (0.8-8 M_{Sun}) stars are more numerous, so have as much effect as supernovae.

Mass loss is driven by magnetism, pulsation and radiation pressure on dust.

It now seems likely that these become important in this sequence.

The transition between these phases seems linked to the harmonic of the pulsation.

Pulsation and radiation pressure on dust become effective later in higher-mass stars.

Metal-poor stars behave (more or less) the same as metal-rich stars for magnetically and pulsationally driven winds.

The transitions in metal-poor stars may occur at different times, as metal-poor stars evolve faster and have different properties (temperature/radii/gravity) to metal-richstars.

We don't know how effective radiation pressure on dust is in metal-poor stars, because those we have observed don't reach the phase where radiation pressure is important.

New and upcoming observations of high-mass, metal-poor stars in nearby dwarf galaxies should help us understand this “final” problem.

FIN


2
2

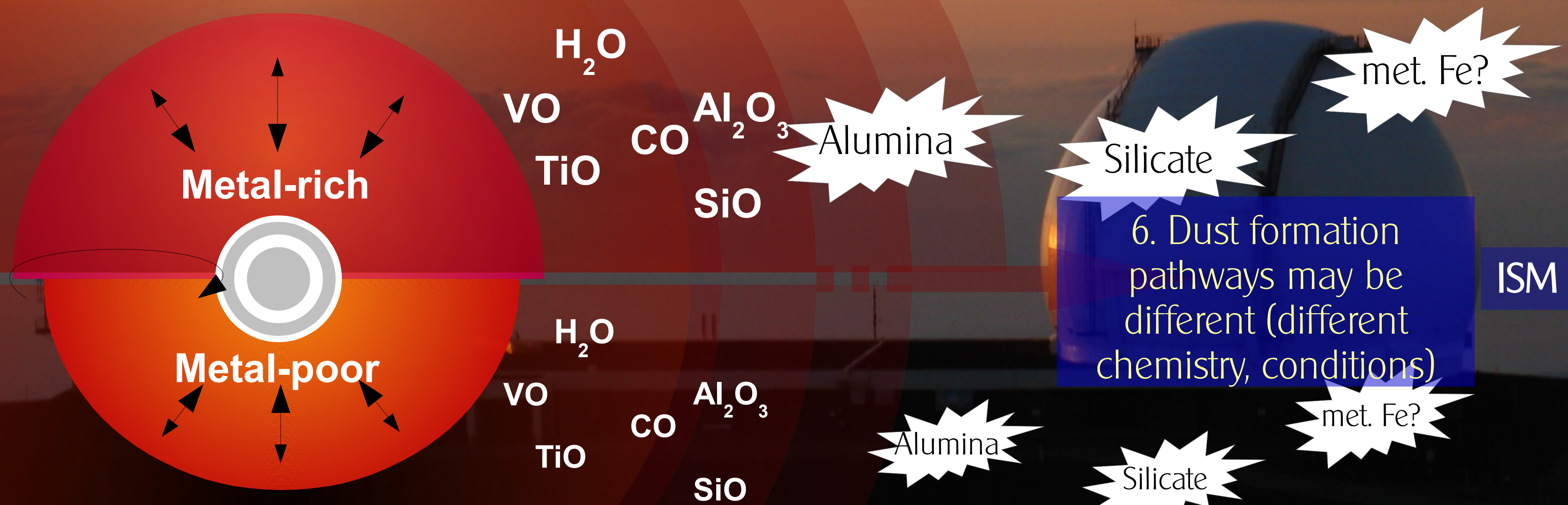
Differences: metal-poor stars are hotter

1. Smaller stars must leviate material further before it condenses

2. Pulsations are generally weaker, making it harder to levitate material

Kjeldsen & Bedding (1995)

5. Radiation pressure on dust is less effective at driving the wind → slower outflow?



6. Dust formation pathways may be different (different chemistry, conditions)

3. Fewer metals → fewer molecules. Stars typically alpha-enhanced, so composition is different

4. Fewer molecules means less dust but also fewer dust seeds → fewer grains or smaller grains?

McDonald et al. (2012)

7. Gas may be dissociated closer to the star, as self-shielding is less effective.

→ Can't trust mass-loss rates currently derived for individual metal-poor stars.

Observations

1. Dust is produced at very low metallicities.

Observations

1. Dust is produced at very low metallicities.

Oxygen-rich stars: dust production may be delayed until the "superwind" phase:

[Fe/H]=-1.26: V2 & V16, AGB in NGC362; *

** [Fe/H] ~ -1.45: V394, AGB in ω Cen; McD+ (2011)

[Fe/H] ~ -1.59: RU Vul; see poster by Stefan Uttenthaler

[Fe/H] ~ -1.77: V1, post-AGB in ω Cen; McDonald et al. (2011)

[Fe/H] = -2.37: Pease 1 (PN) and ISM in M15; Boyer et al. (2006)

Claimed around RGB/AGB (Boyer+2006, Origlia+2014) but unlikely to be real (Boyer+2010; McDonald+2011)

Carbon stars: still produce carbon at very low metallicities

[Fe/H] ~ -2.2: probable carbon stars in And IX; Boyer et al. (2015)

[Fe/H] ~ -2.1: probable carbon stars in LGS 3, Sag DIG; Boyer+ (2015)

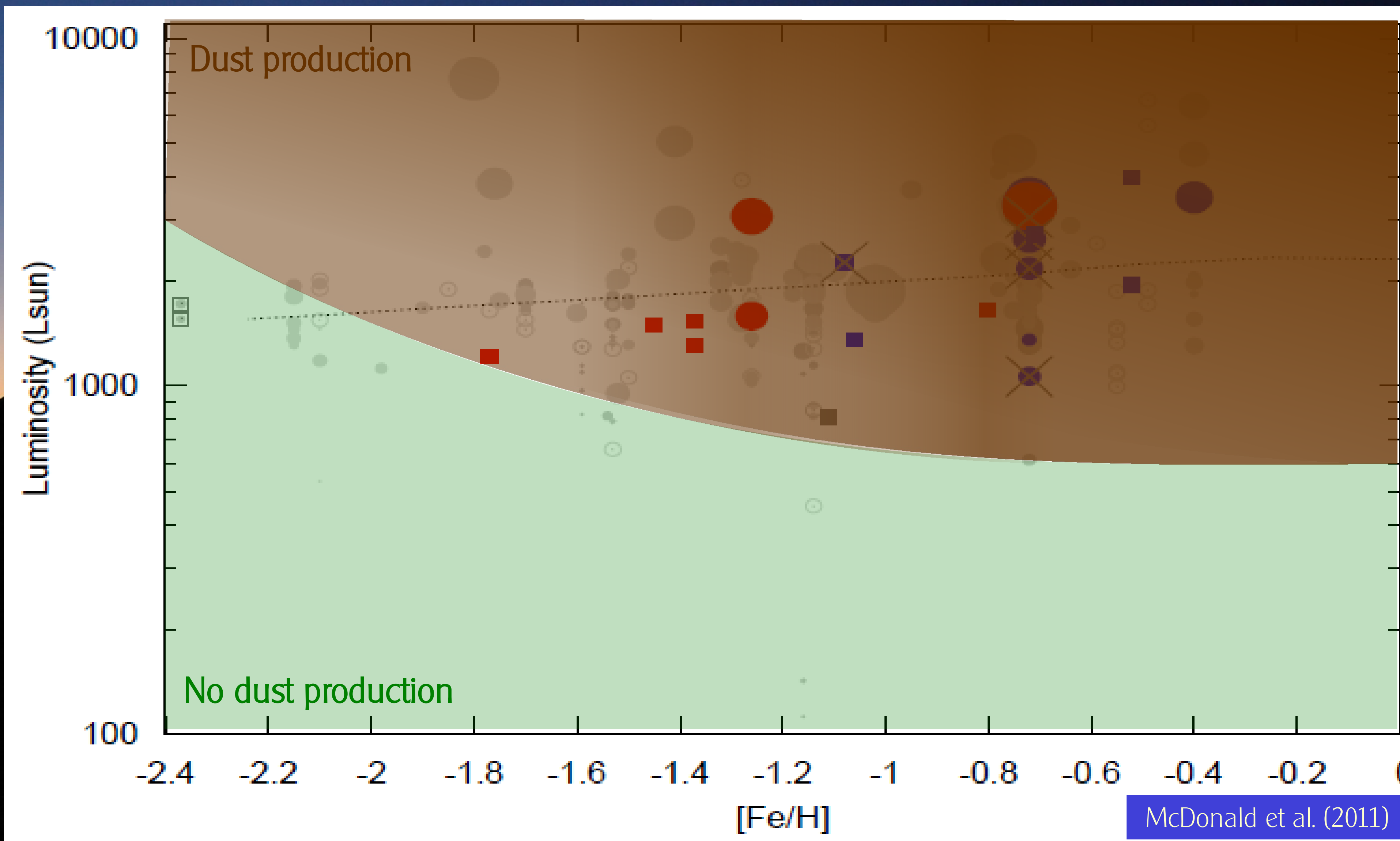
*Boyer et al. (2009); Sloan et al. (2010)
**Other dust producing stars in ω Cen down to [Fe/H] ~ -1.8?

[Fe/H] = -2.5 | -2.0 | -1.5 | -1.0 | -0.5 | 0.0

Observations

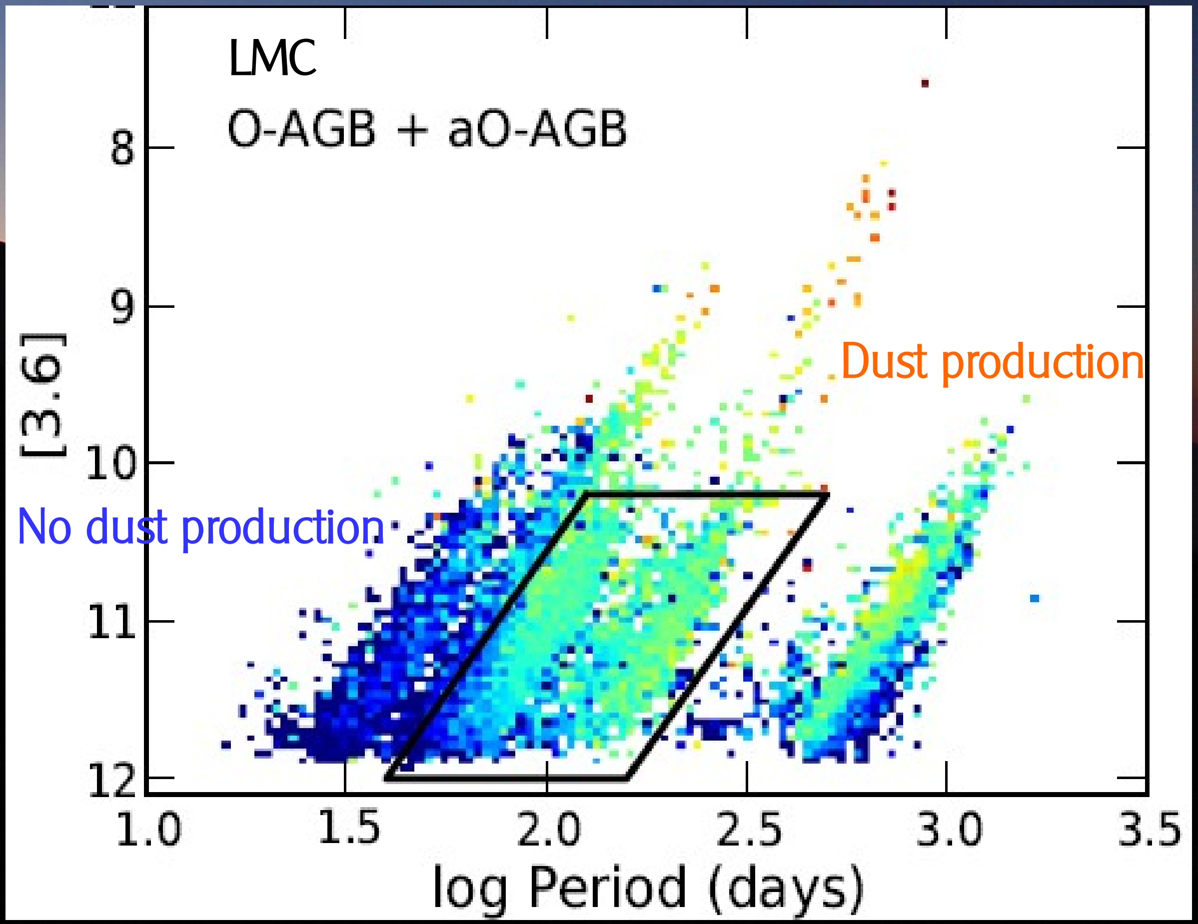
1. Dust is produced at very low metallicities.

2. Dust production starts at higher luminosities.



Observations

1. Dust is produced at very low metallicities.
2. Dust production starts at higher luminosities.
   - Stars are hotter with weaker pulsations...
   - ...but metal-poor stars are smaller → shorter-period pulsations
   - Long-period pulsations needed to produce dust



Boyer et al. (2015)

Observations

1. Dust is produced at very low metallicities.
2. Dust production starts at higher luminosities.
3. Carbon stars look almost the same at all metallicities

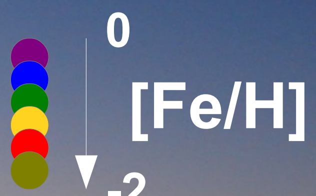
Observations

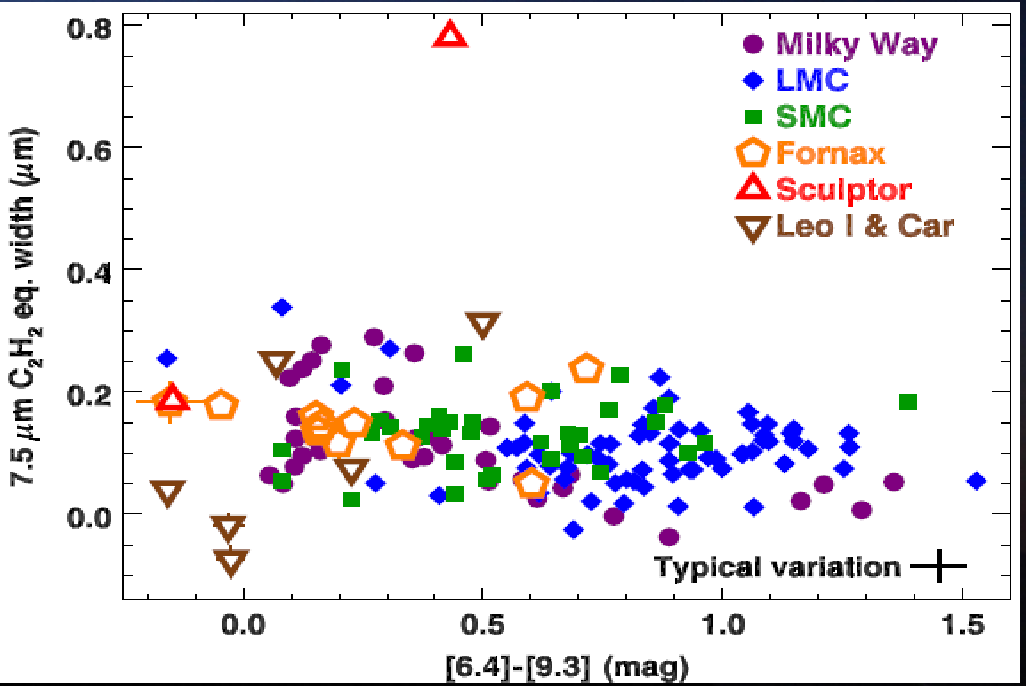
1. Dust is produced at very low metallicities.

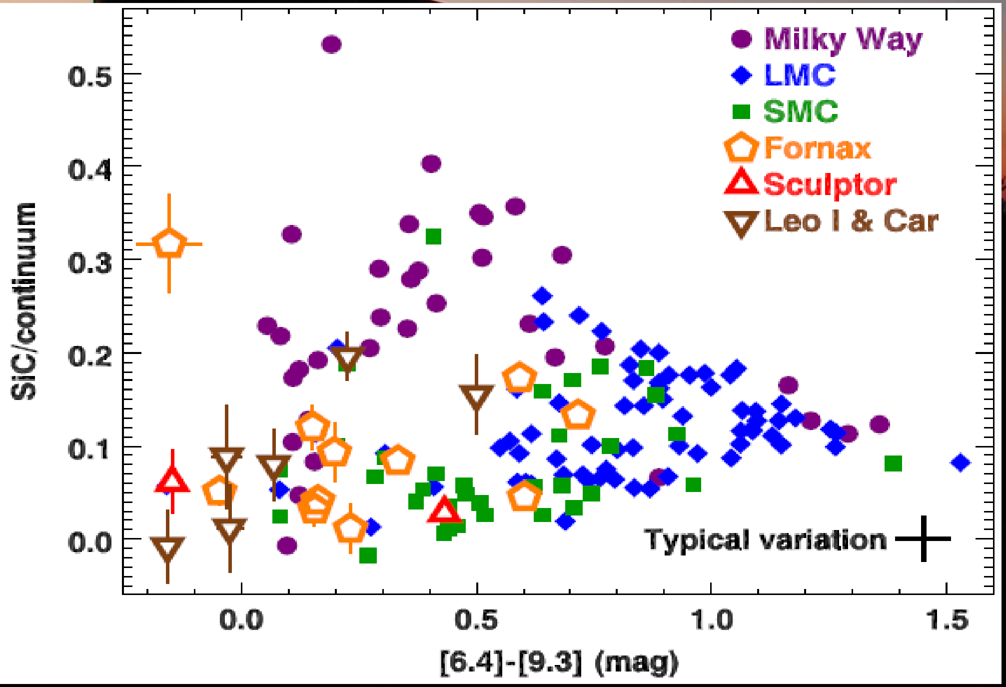
2. Dust production starts at higher luminosities.

3. Carbon stars look almost the same at all metallicities

(They produce their own carbon!)







Subtle differences in metal-poor C stars.
E.g.: Slight decrease in SiC contribution

Sloan et al. (2012)

Observations

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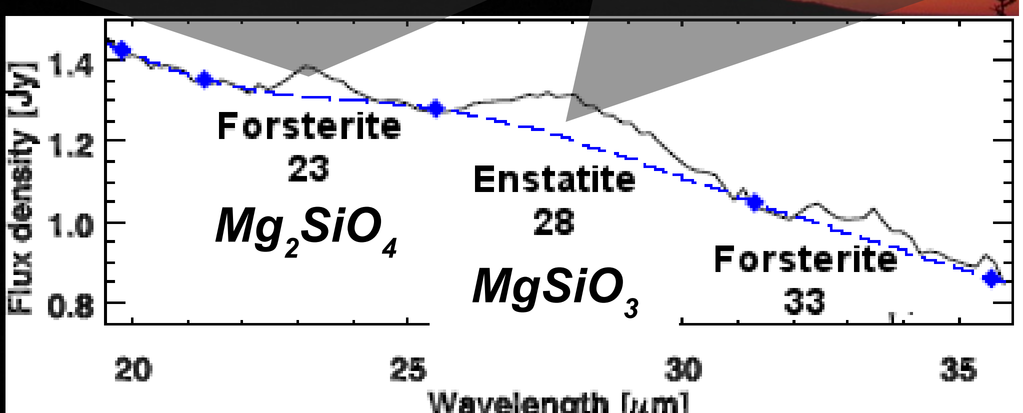
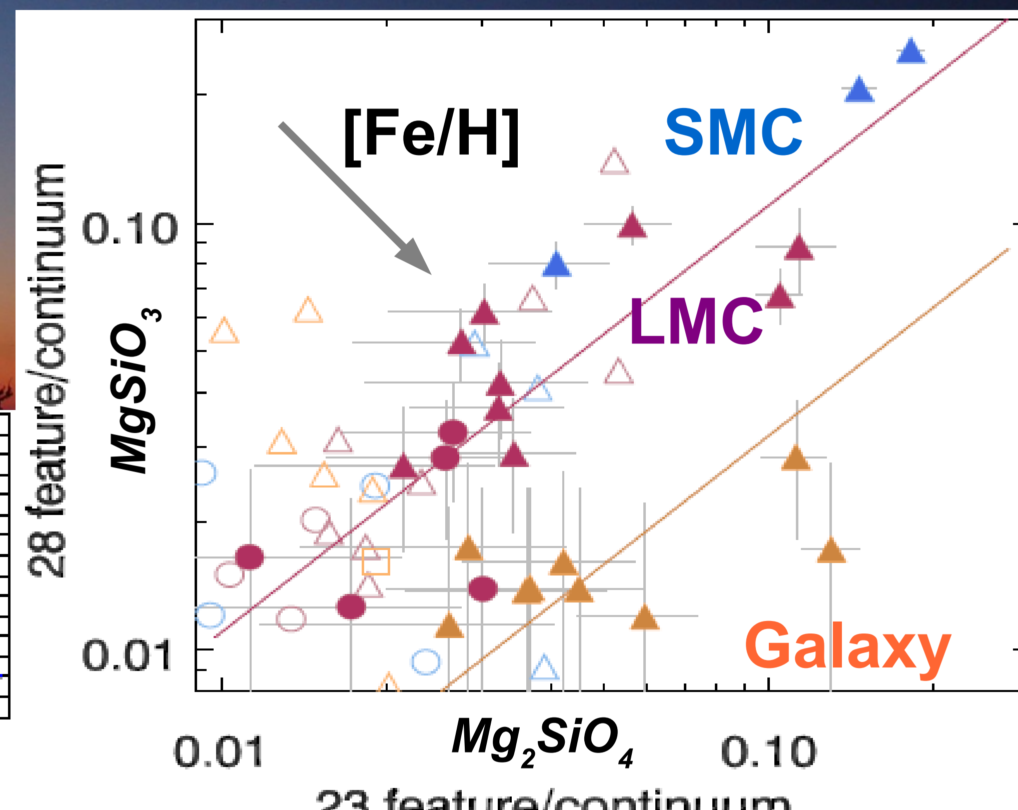
Change in entstatite/forsterite ratio of crystalline silicates as metallicity decreases





Jones et al. (2012)

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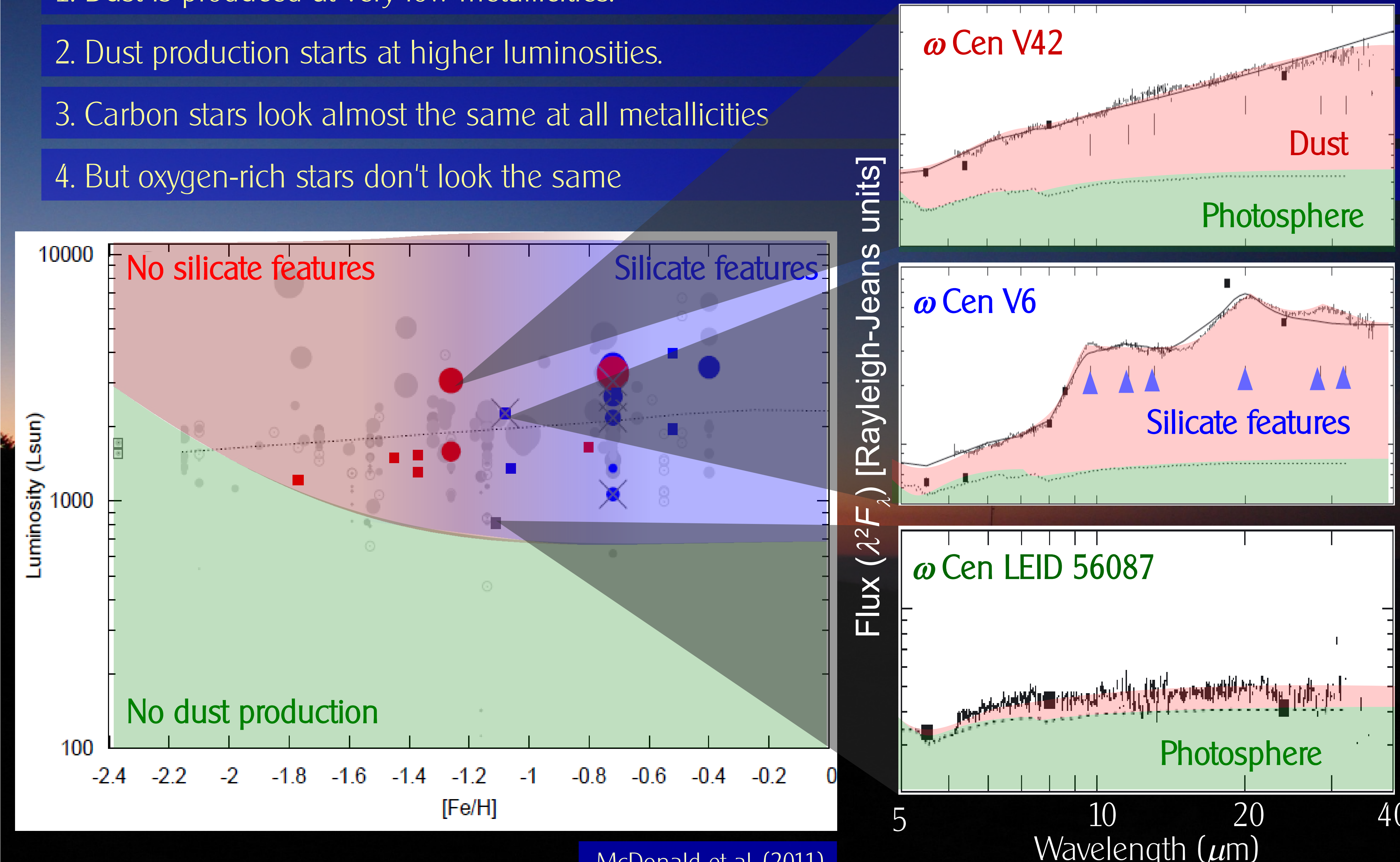

McDonald et al. (2011)

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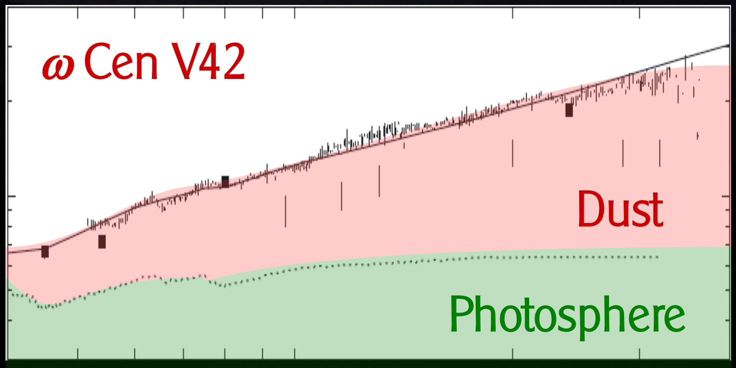
Parameter	$\delta \dot{M}$
Grain size[1]	$\pm10\%$
Grain density	-50%
Dust formation temperature	$\pm10\%$
Dust:gas ratio	-55% $+125\%$
Velocity distribution	$\sim+500\%$
Photosphere	$\pm12\%$ $\pm15\%$
Calculation error[2]	$\pm30\%$
Total	$\sim^{+7}_{-4}\times$

McDonald et al. (2011)

Uncertainties in the dust-based mass-loss rate for a well-parameterised, metal-poor star.

Optical properties of the "peculiar" dust are well matched by amorphous carbon or metallic iron. Suspect the dust is of very high opacity per unit mass.



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6. ...because we know so little about the outflow velocity.

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6. ...because we know so little about the outflow velocity.
    - Canonically expected to be ~10 km/s (~20 km/s for very luminous stars)
    - If wind is dust driven, metal-poor stars should have slower winds
    - If pulsation driven, slightly slower winds
    - If magneto-acoustically driven, winds of the same speed

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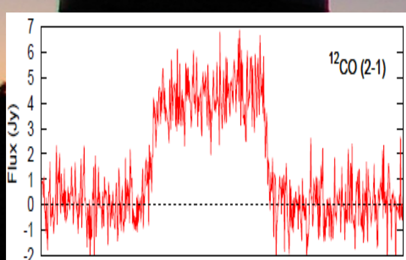
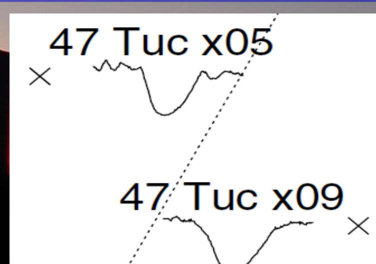
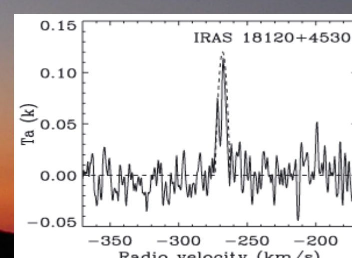
Mixed observational data on metal-poor stars



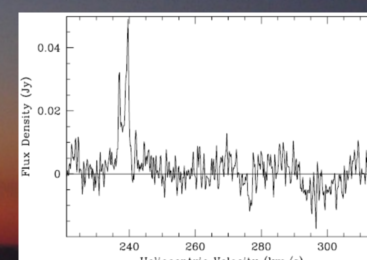
McDonald et al. (in prep.)
CO (3-2, 2-1)
EU Del
Oxygen-rich SRV
Probable thick disk star
9.5 km/s outflow



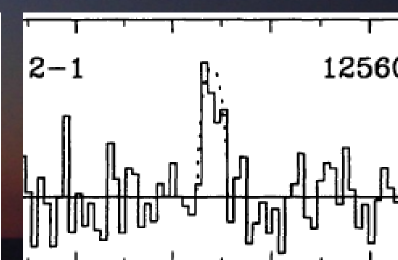
McD & van Loon (2007)
Hα bisectors
Globular clusters
Oxygen-rich
SRVs+Miras
5-20 km/s outflow



Lagadec et al. (2010)
CO (3-2)
Obscured Halo stars
Carbon-rich
3-17 km/s outflow



Marshall et al. (2004)
& Goldman (poster 13)
OH masers
O-rich LMC stars
Undergoing superwind
6-24 km/s outflow



Groenewegen+ (1997)
CO (2-1)
Halo carbon star
Undergoing superwind?
Carbon-rich
3.2 km/s outflow

High luminosity (>~5000 L_{Sun}): Slightly slower? Possibly consistent with lack of dust driving?
Low luminosity: Same velocity? Possibly consistent with a metal-independent energy source?

Observations

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Mixed observational data on metal-poor stars

High luminosity: Slightly slower? Low luminosity: Same velocity?

Globular clusters: mass-loss efficiency* before the dust producing phase is metal-independent.

*Defined by Reimers (1975) law; McDonald & Zijlstra (2015b)

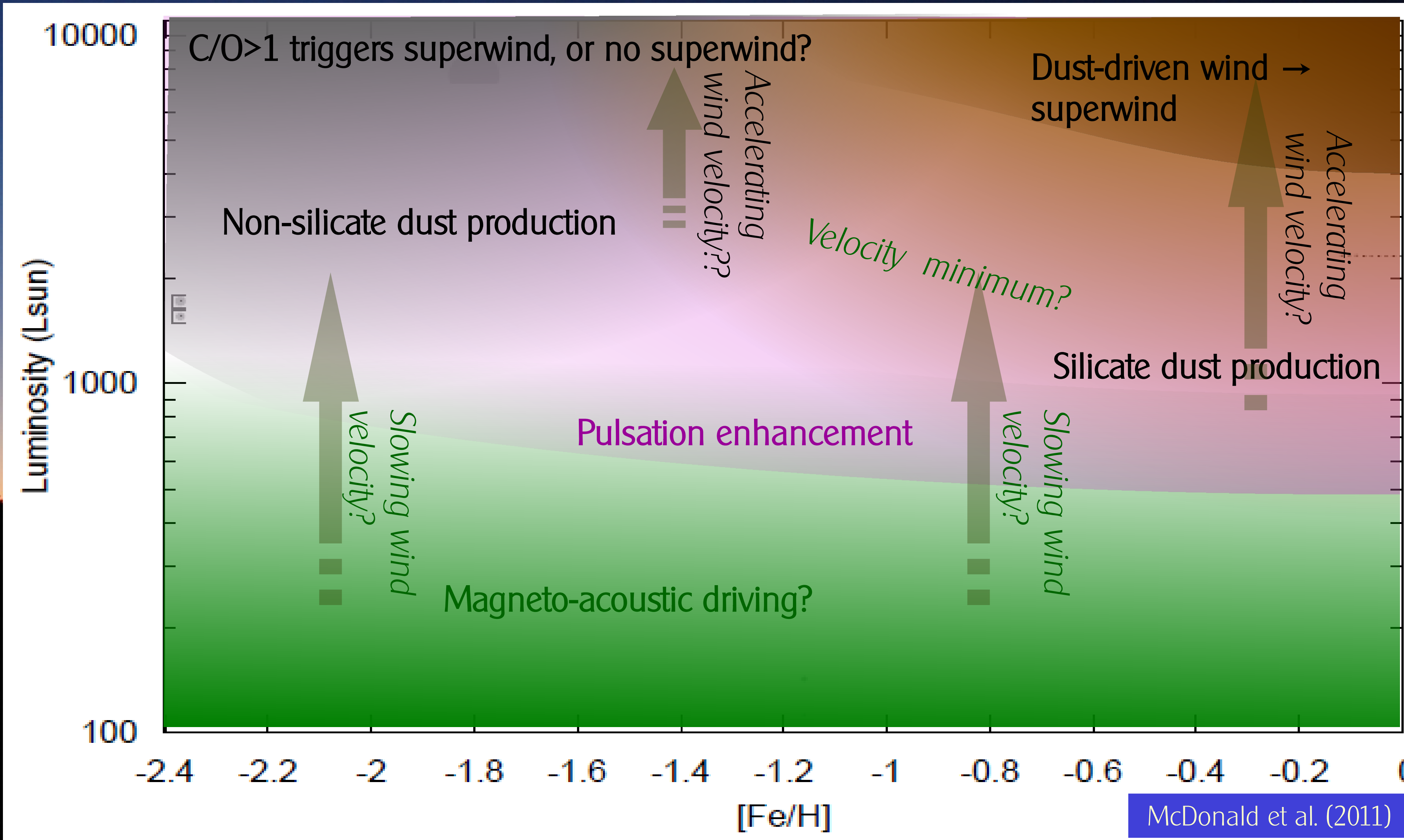
→ Mass-loss may be magneto-acoustically driven, later enhanced by pulsation?

See, e.g., Bowen & Willson (1991)

Difference between C & O-rich stars may mean the O→C transition triggers the superwind

Lagadec & Zijlstra (2008)

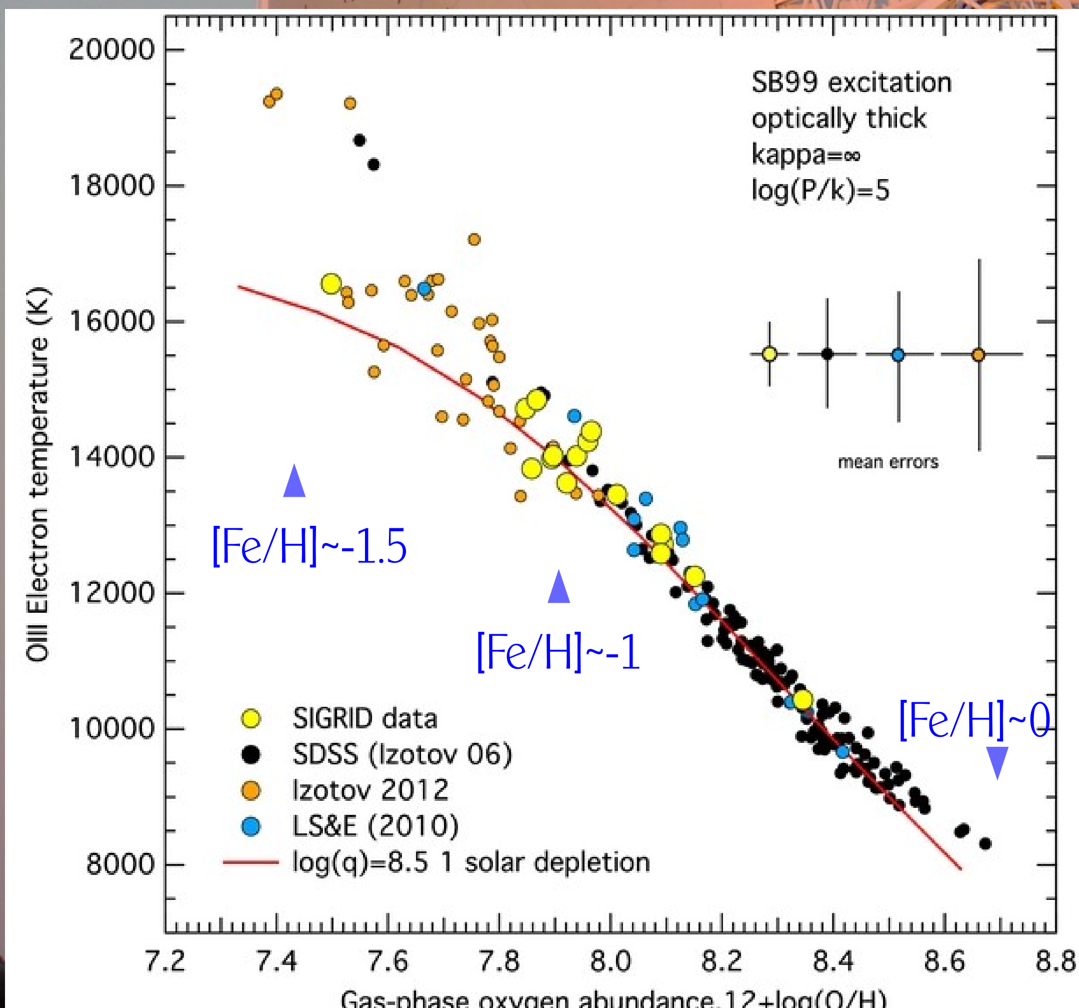
Observations



McDonald et al. (2011)

Breaking dust

Three main dust destruction mechanisms:
~~(1) Shattering: dust grain – dust grain collisions~~
(2) Sputtering: dust grain – ion collisions
(3) Photo-desorption: dust grain – photon interactions



Metal-poor stars:
Fewer or smaller dust grains, so shattering should be less common

Observed gas-phase temperatures are higher because the radiation field is stronger, particularly at [Fe/H] <~ -1

Should increase sputtering and photo-desorption efficiency

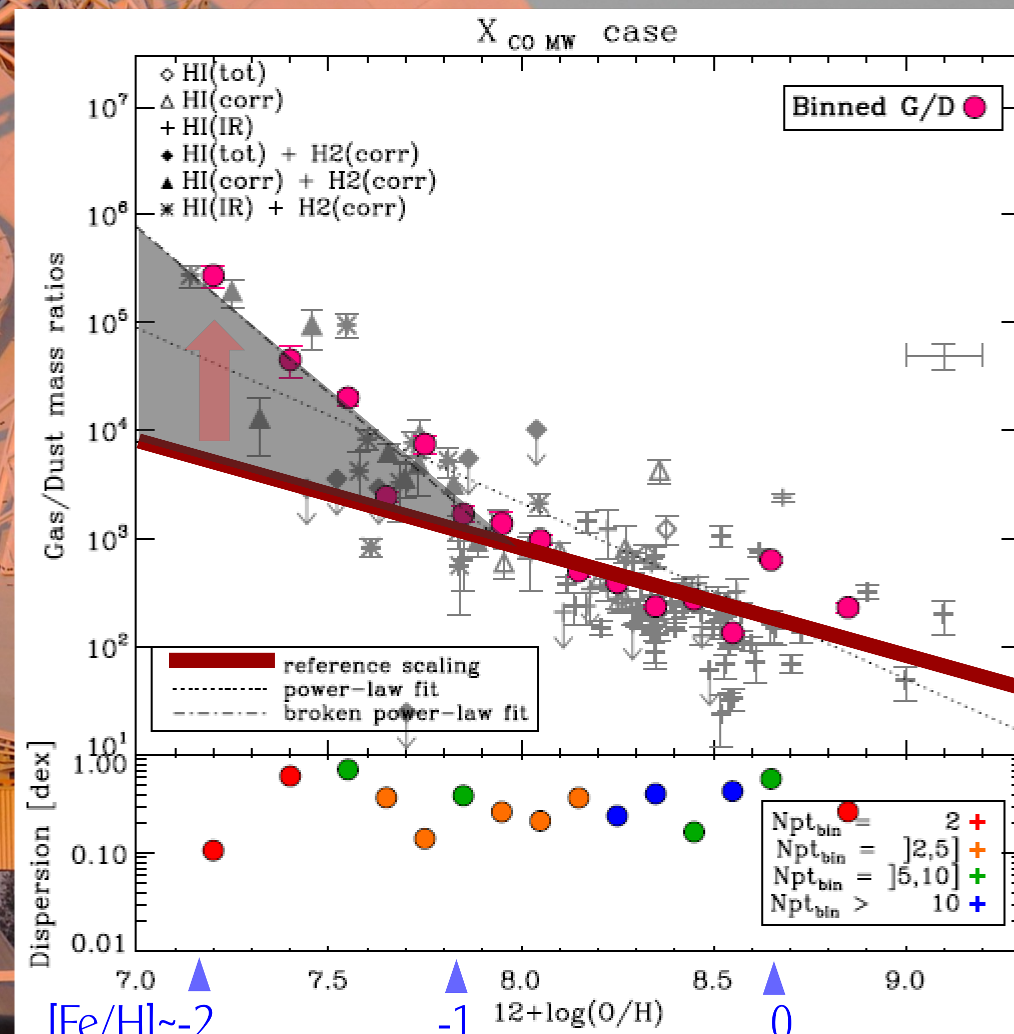
Nichols et al. 2014

Breaking dust

Three main dust destruction mechanisms:
~~(1) Shattering: dust grain – dust grain collisions~~
(2) Sputtering: dust grain – ion collisions
(3) Photo-desorption: dust grain – photon interactions

Decrease in dust condensation efficiency, or faster dust destruction rate, at [Fe/H] <~ -1.

Co-incident with lack of silicates seen in globular cluster stars with [Fe/H] <~ -1.

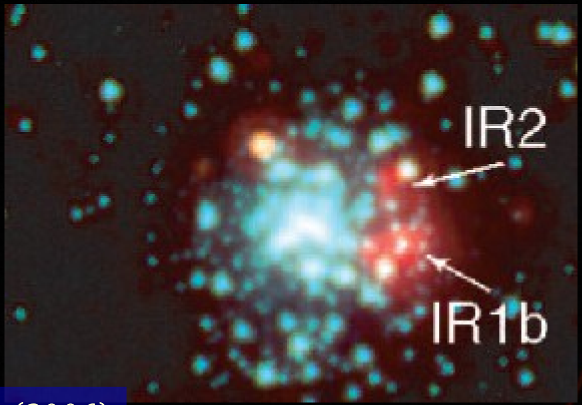


Rémy-Ruyer et al. 2014; see also Galametz+11, Draine+07

Radiation on ISM in globular clusters

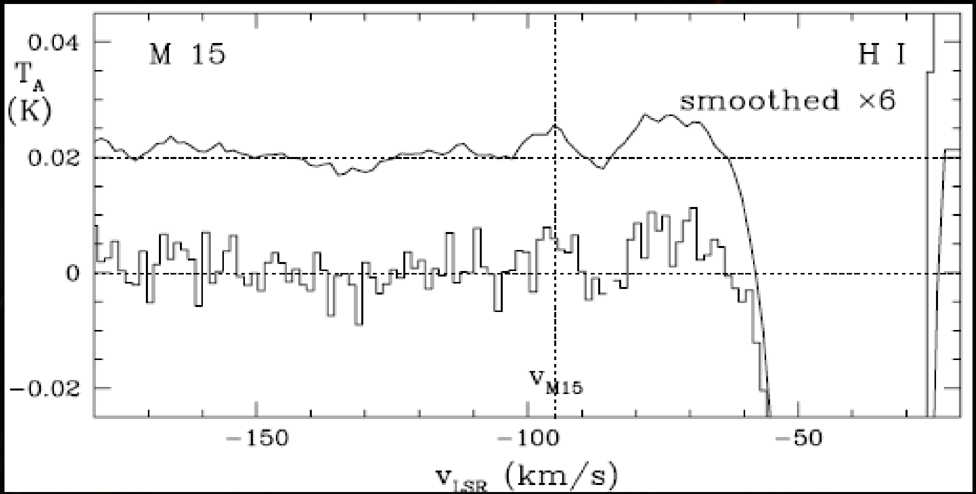
Only two detections of ISM in globular clusters:

M15	47 Tuc
0.3 $M_{\odot}$ of dusty neutral ISM	0.1 $M_{\odot}$ of ionised ISM in core

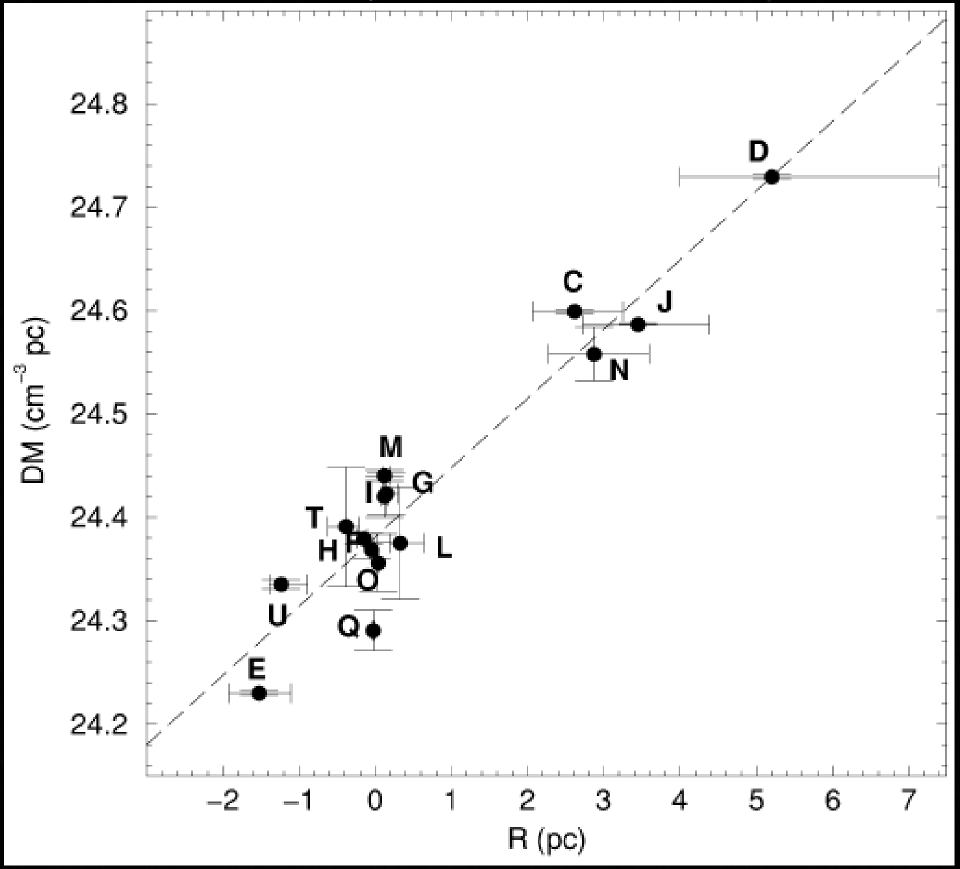


Boyer et al. (2006)

Van Loon et al. (2006)



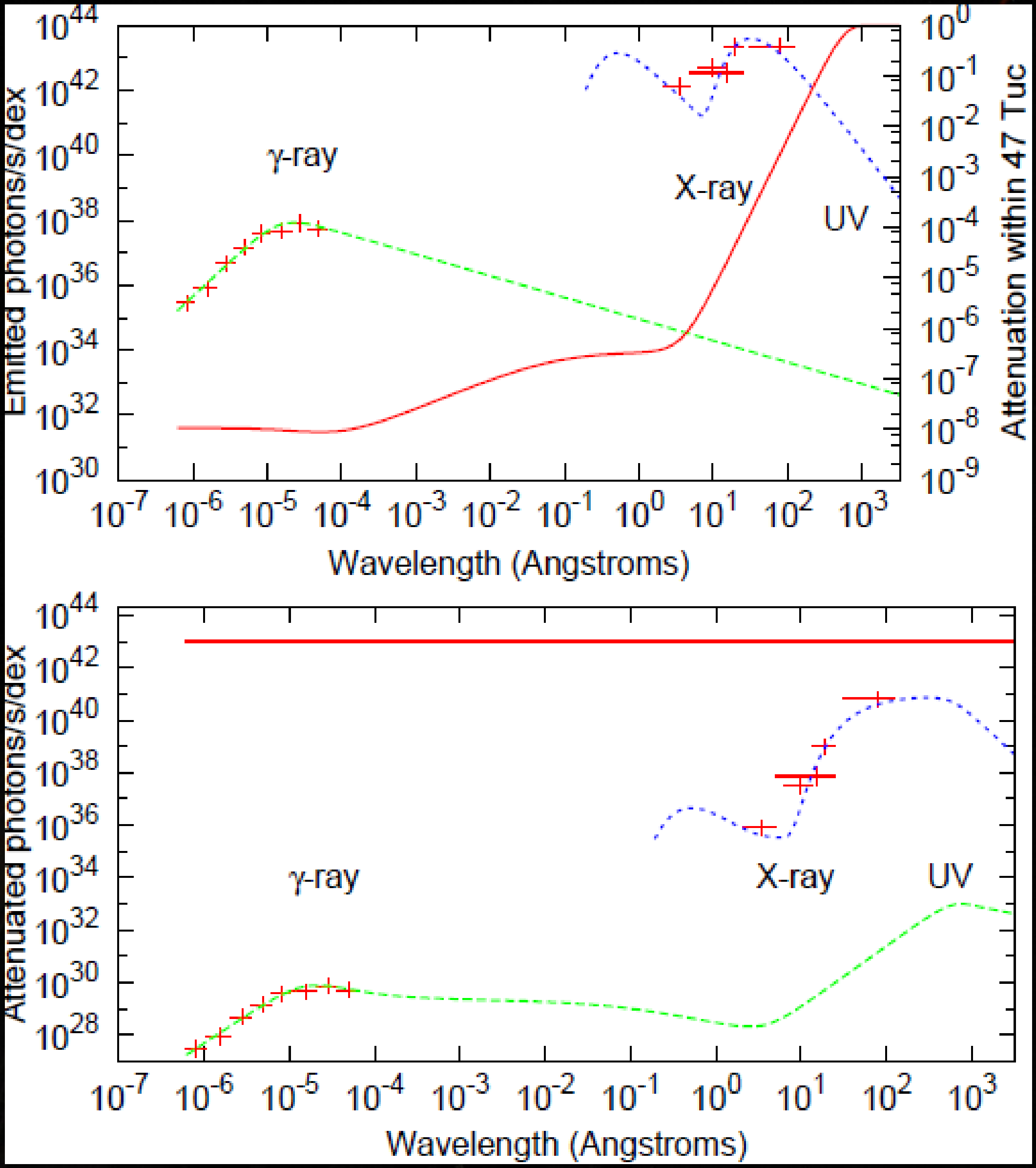
Dust is probably cleared within ~1 Myr.



Freire et al. (2001)

Radiation on ISM in globular clusters

47 Tuc in detail:



Recombination rate: 10^{43} atoms s^{-1}

Stellar mass-loss rate rate: 10^{44} atoms s^{-1}

Need to absorb ~10^{44} photons s^{-1} to ionise ISM

Gamma-/X-rays not sufficiently attenuated.

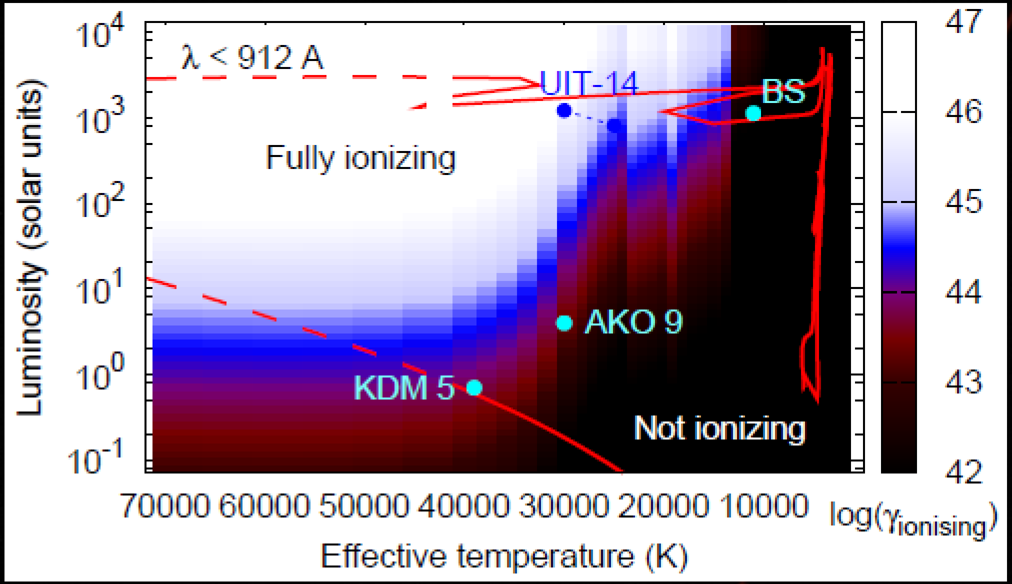
Need a UV source.

Invisible to us: absorbed by Galactic hydrogen

McDonald & Zijlstra (2015a)

Radiation on ISM in globular clusters

Need hot sources to emit enough UV...

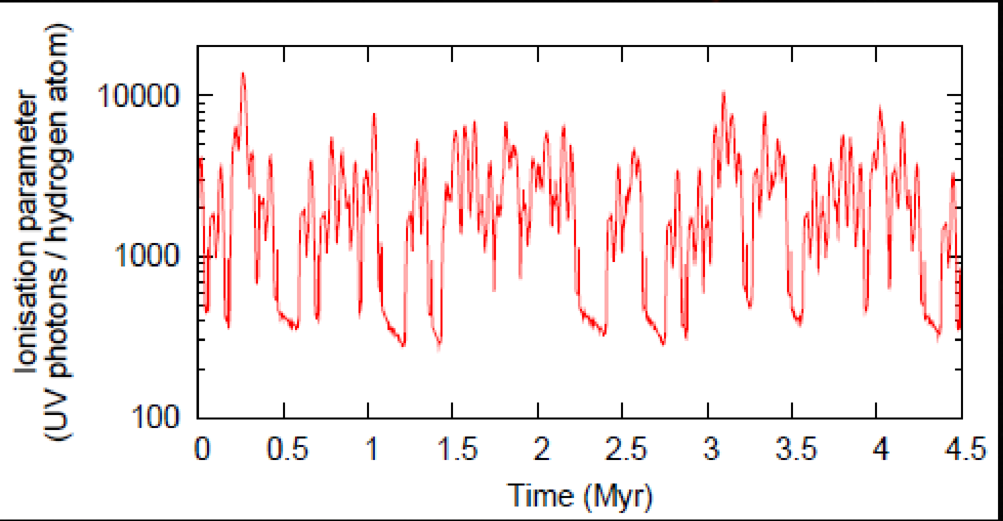


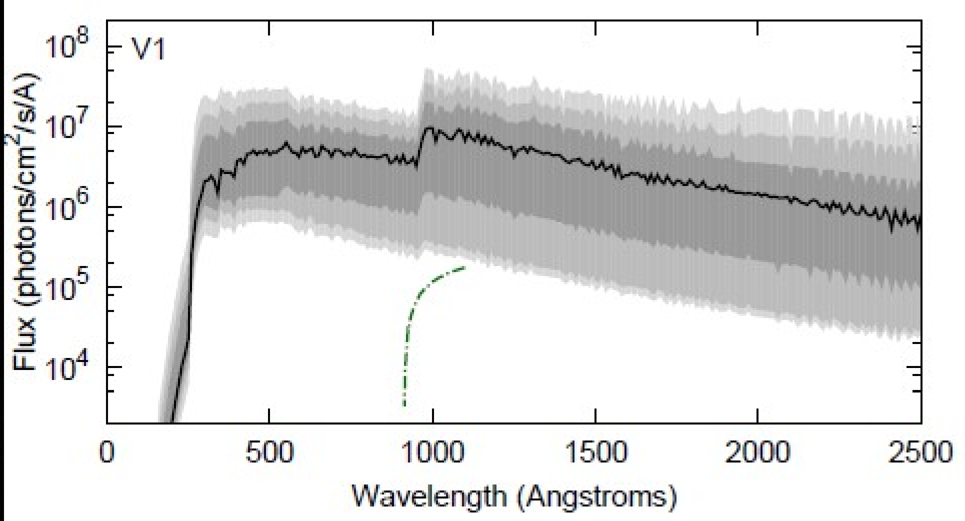
A single post-AGB star produces enough UV photons to ionise the cluster ISM for 4 Myr of its white dwarf evolution.

One star dies in 47 Tuc every 80,000 years.

Should always be enough radiation to ionise the ISM of 47 Tuc.

The same should be true of all clusters with *M* >~ 10^5 Msun.

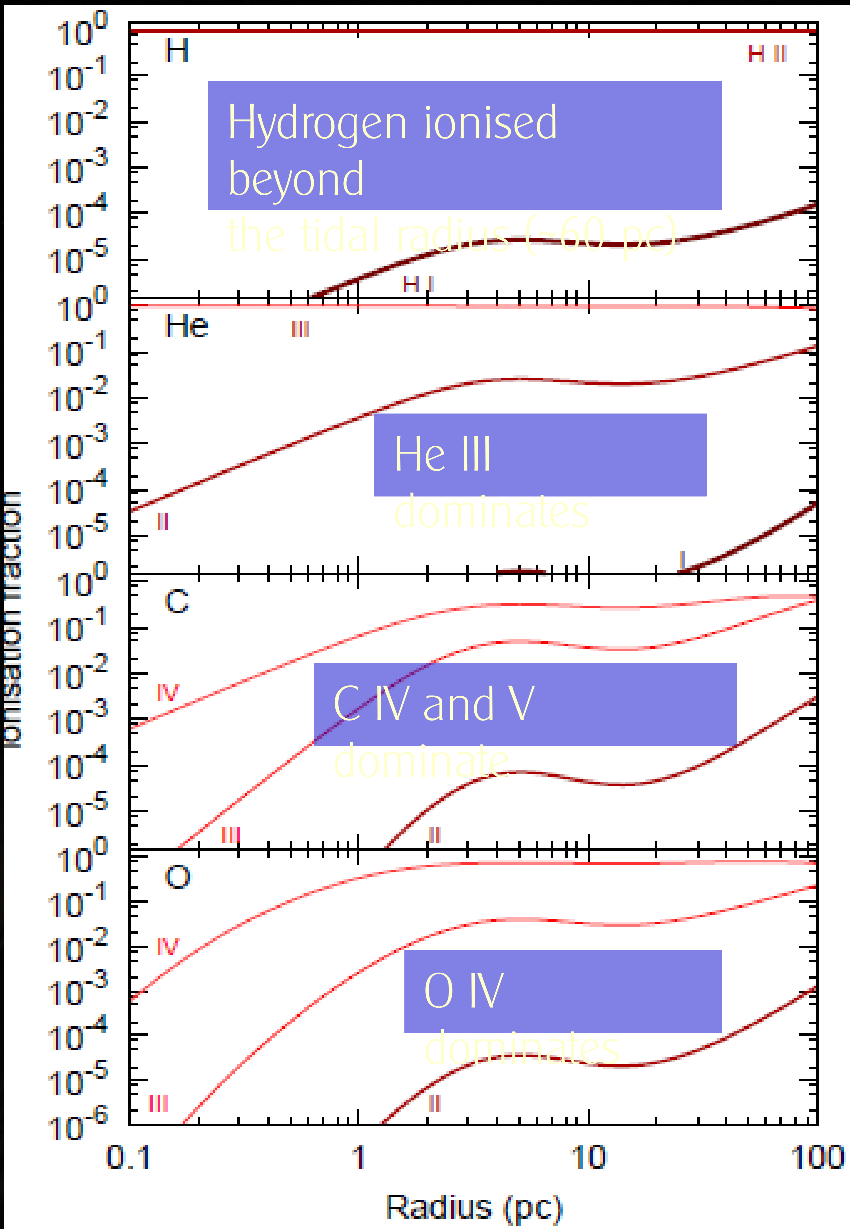




McDonald & Zijlstra (2015a)

Radiation on ISM in globular clusters

Conditions in the ISM are harsh

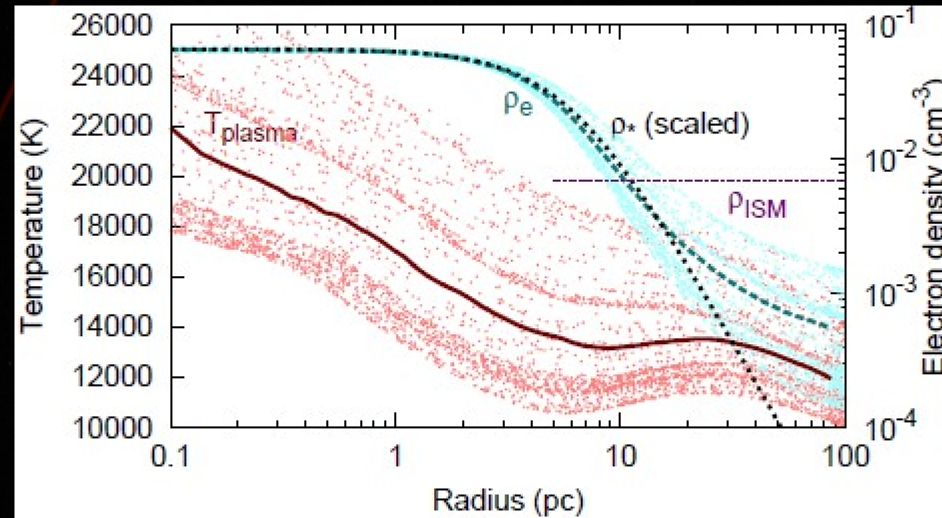


Hydrogen ionised beyond the tidal radius (~60 pc)

He III dominates

C IV and V dominate

O IV dominates



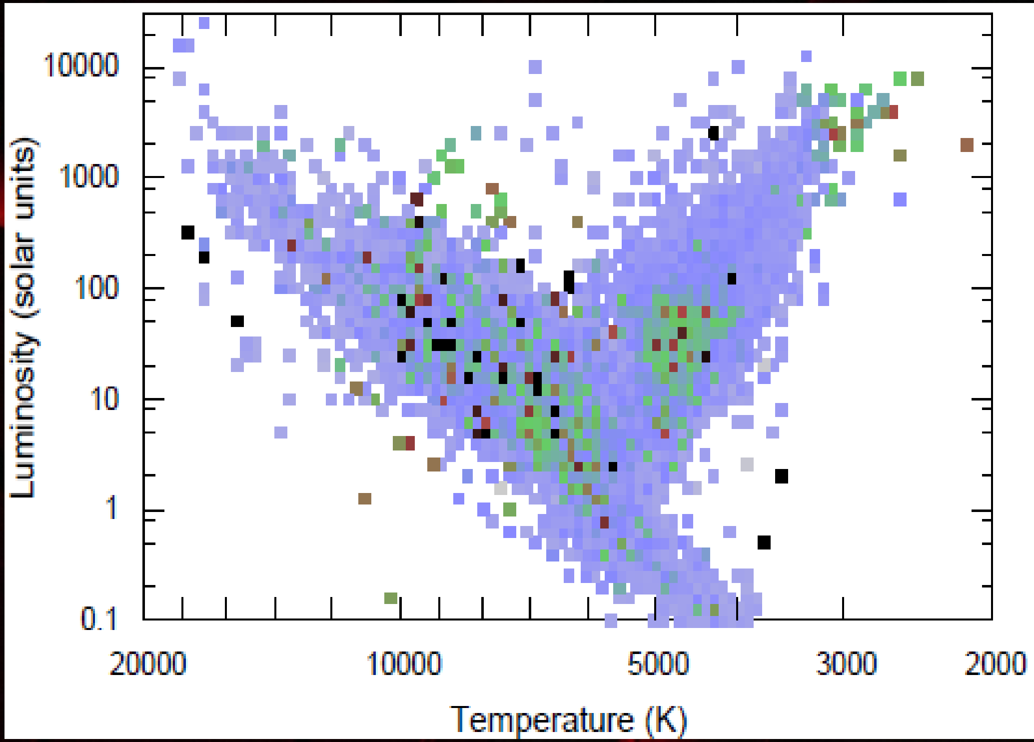
Plasma temperatures are 10000-20000 K

This gives the plasma enough energy to overflow the cluster

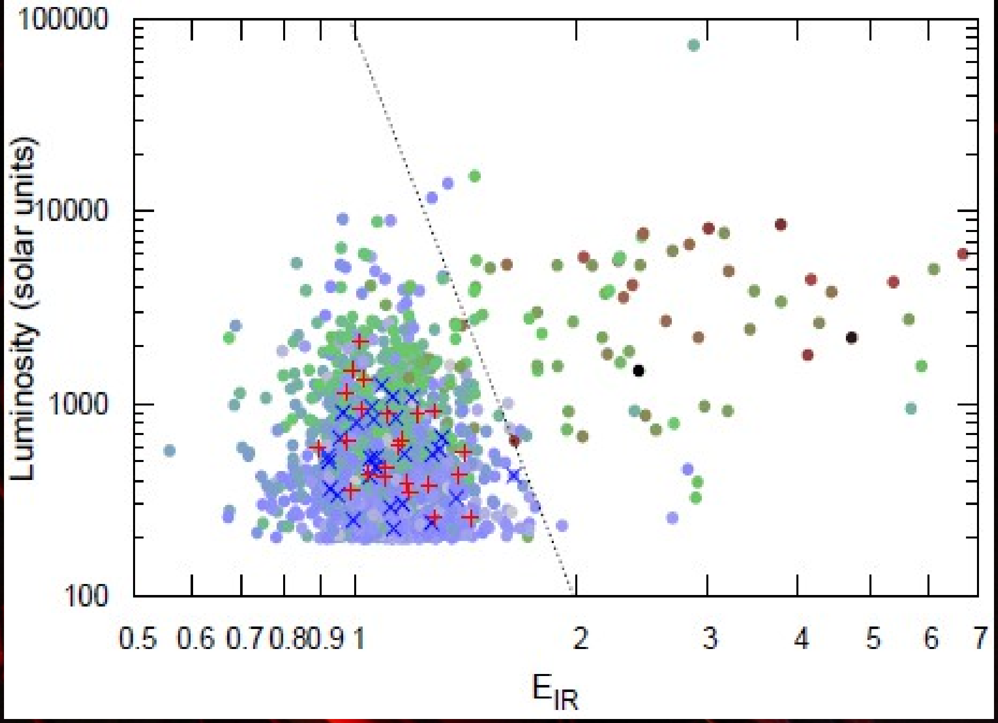
McDonald & Zijlstra (2015a)

Asymptotic giant branch mass loss

Hipparcos: modelled SED of 110,000 stars; made an H-R diagram and looked for infrared excess (dust)



Bins are colour-coded by infrared excess (E_{IR})



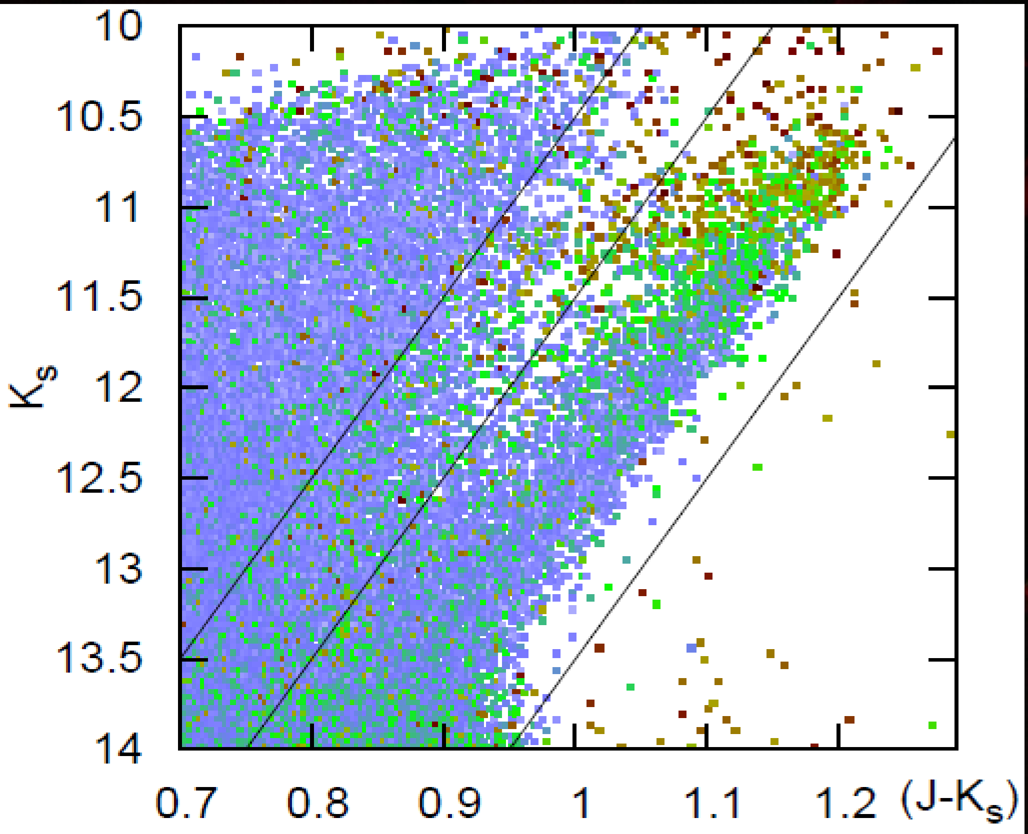
Excess among giant stars.

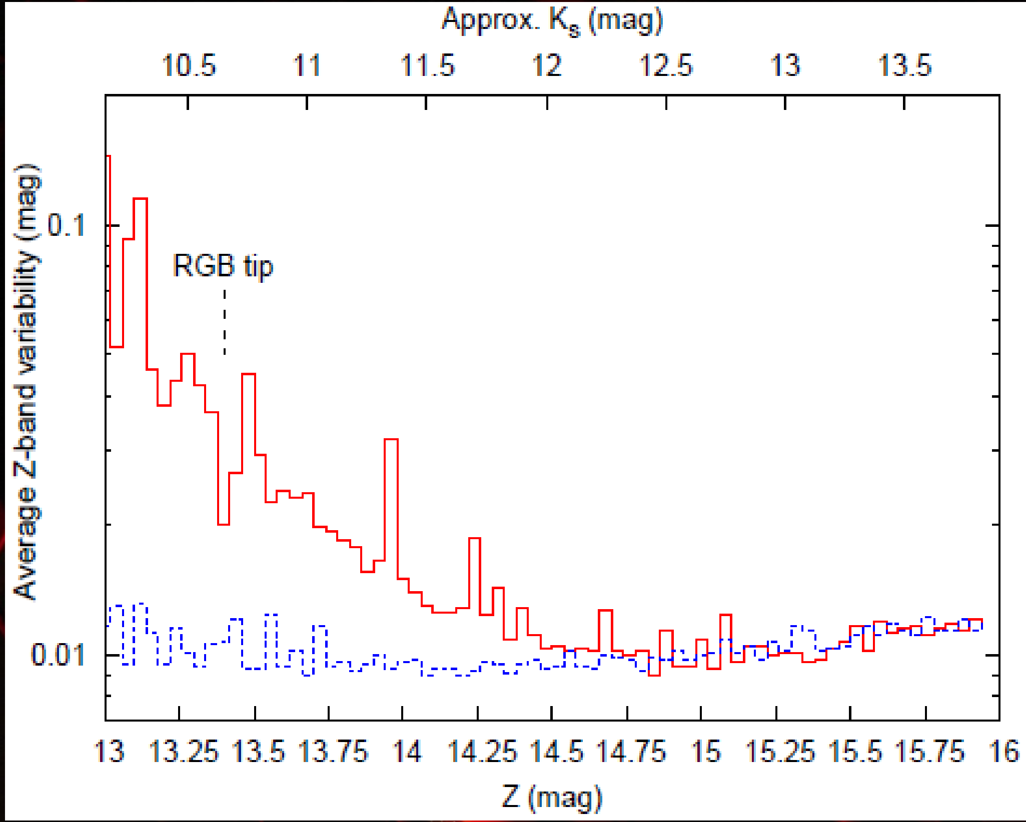
62 dusty giant stars with accurate distances, almost all known variables
→ Pulsation comes before dust production

McDonald et al. (2012)

Asymptotic giant branch mass loss

Sgr dSph with VISTA: 12 epochs of Z-band images, looking for variability among 4 million stars.

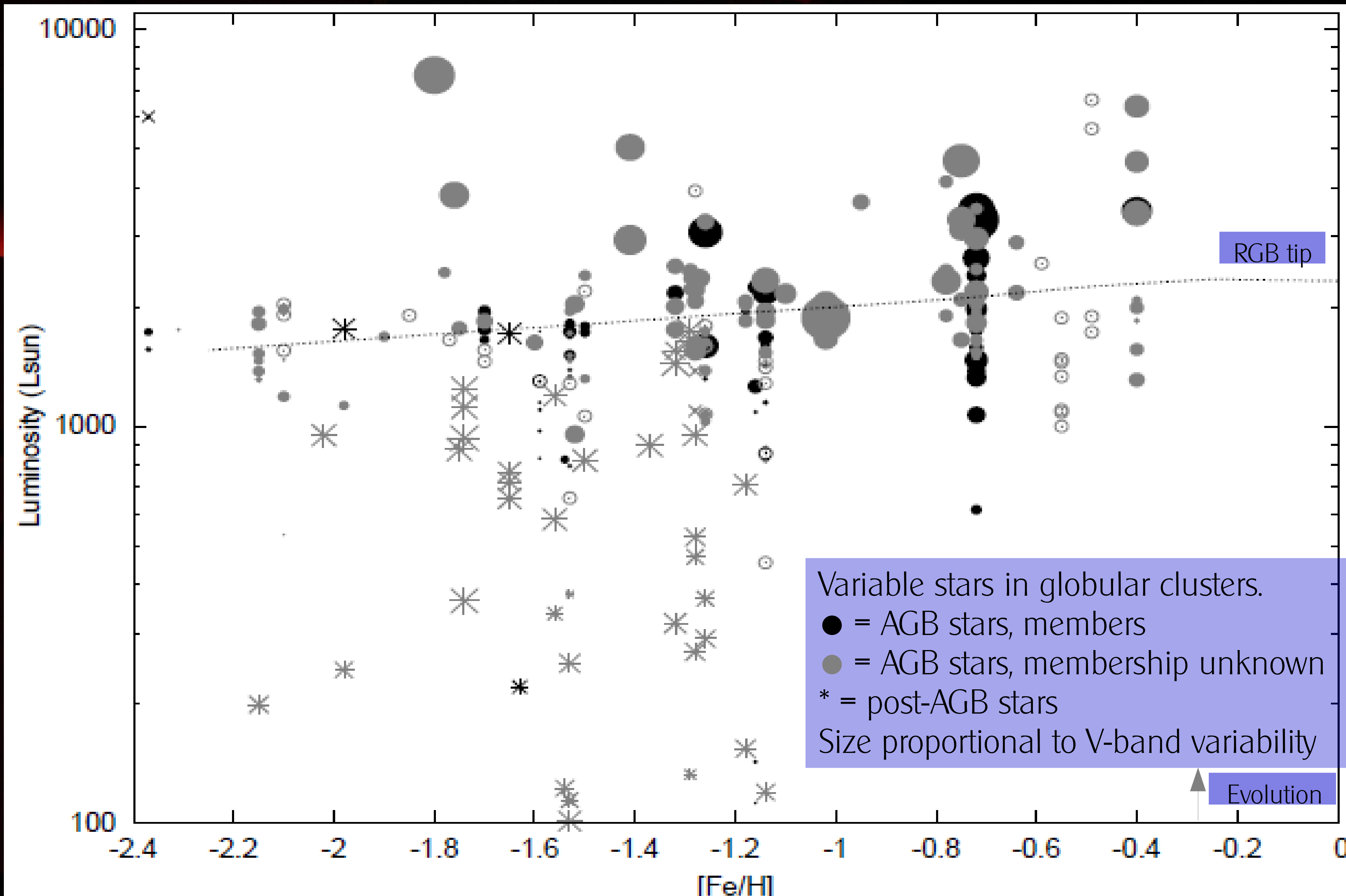




Every star is variable at some level (as *Kepler* tells us too)
No correlation of pulsation amplitude with dust production in *oxygen-rich* stars
→ Pulsation alone is not enough for dust production
RGB stars pulsate the same as AGB stars but don't tend to produce dust – a clue in the pulsation period

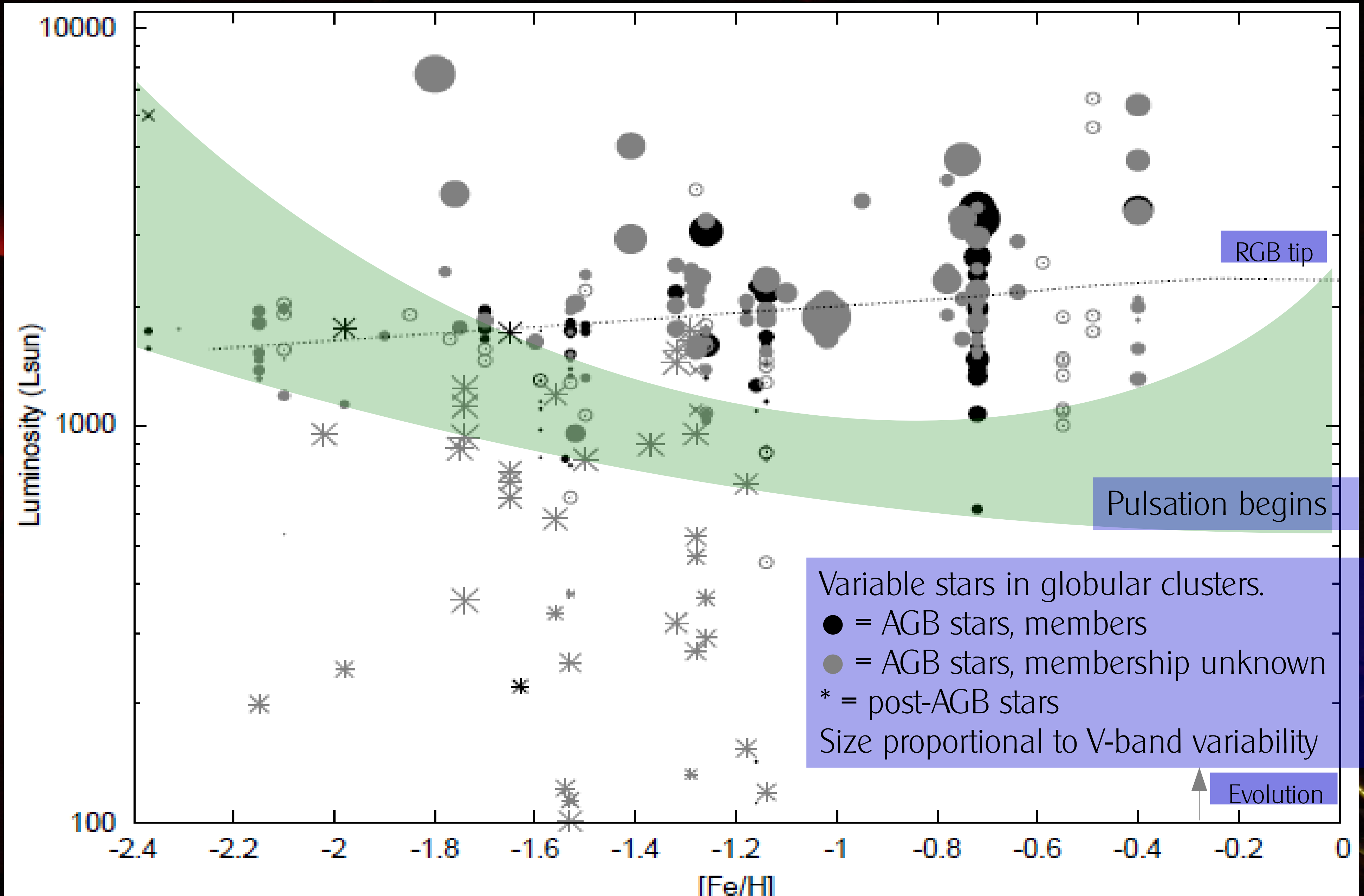
McDonald et al. (2013,2014,2016)

Asymptotic giant branch mass loss: globular clusters



McDonald et al. (2011)

Asymptotic giant branch mass loss: globular clusters



McDonald et al. (2011)

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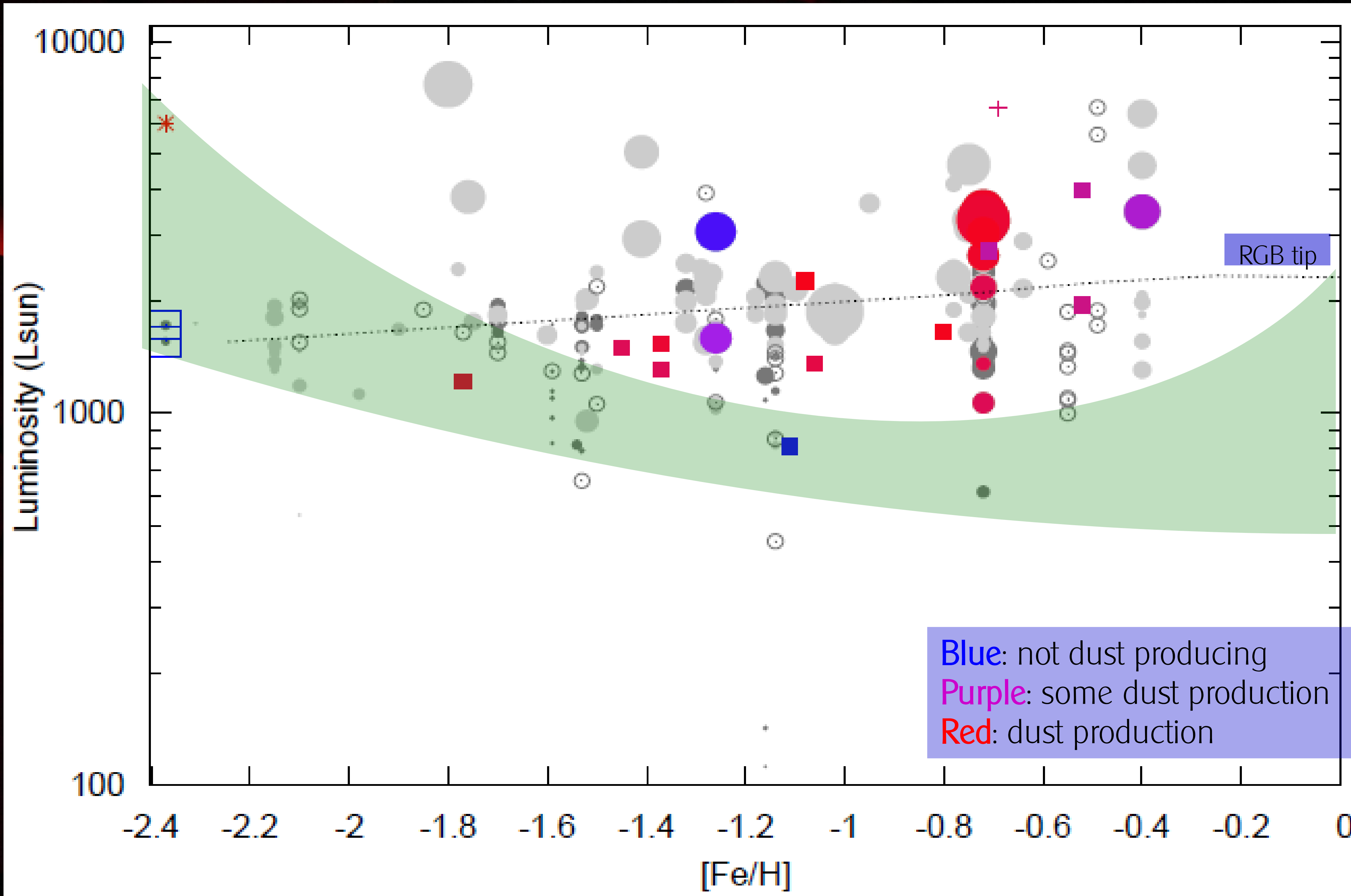

McDonald et al. (2011)

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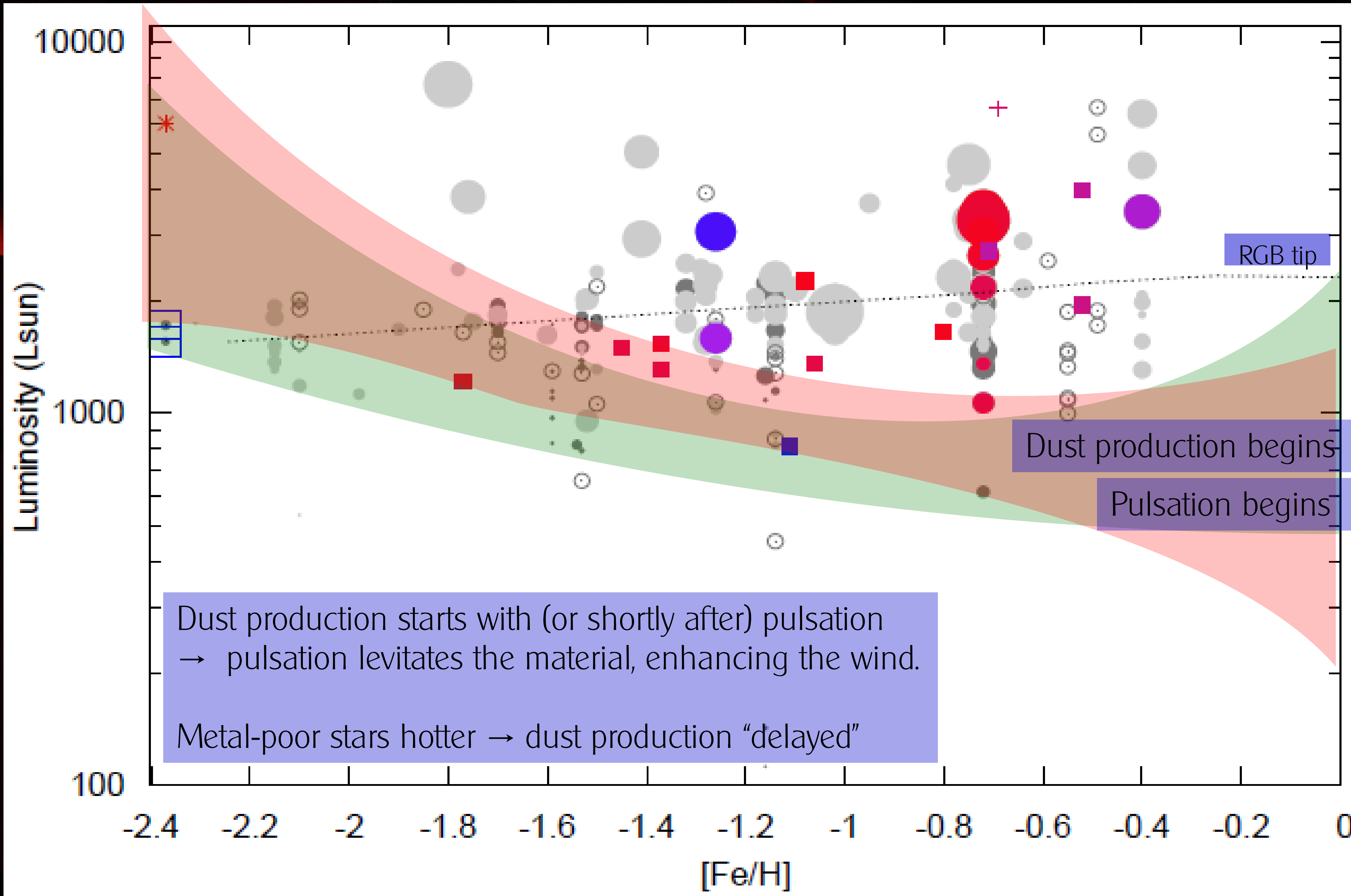


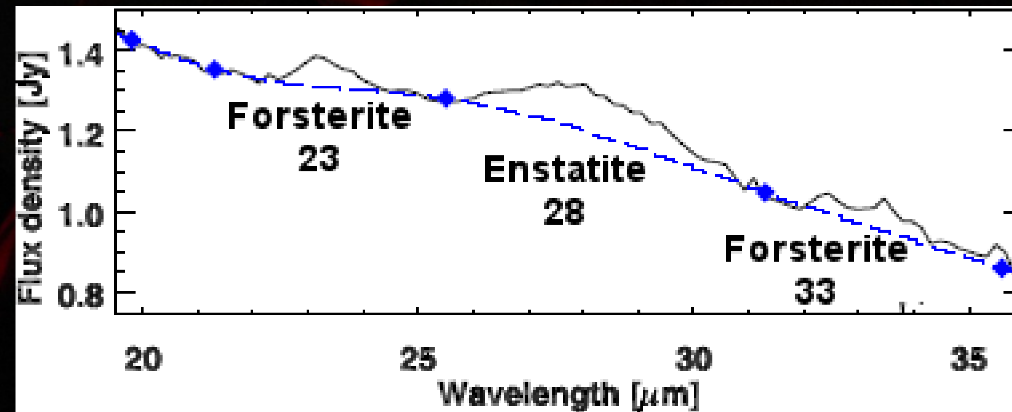
McDonald et al. (2011)

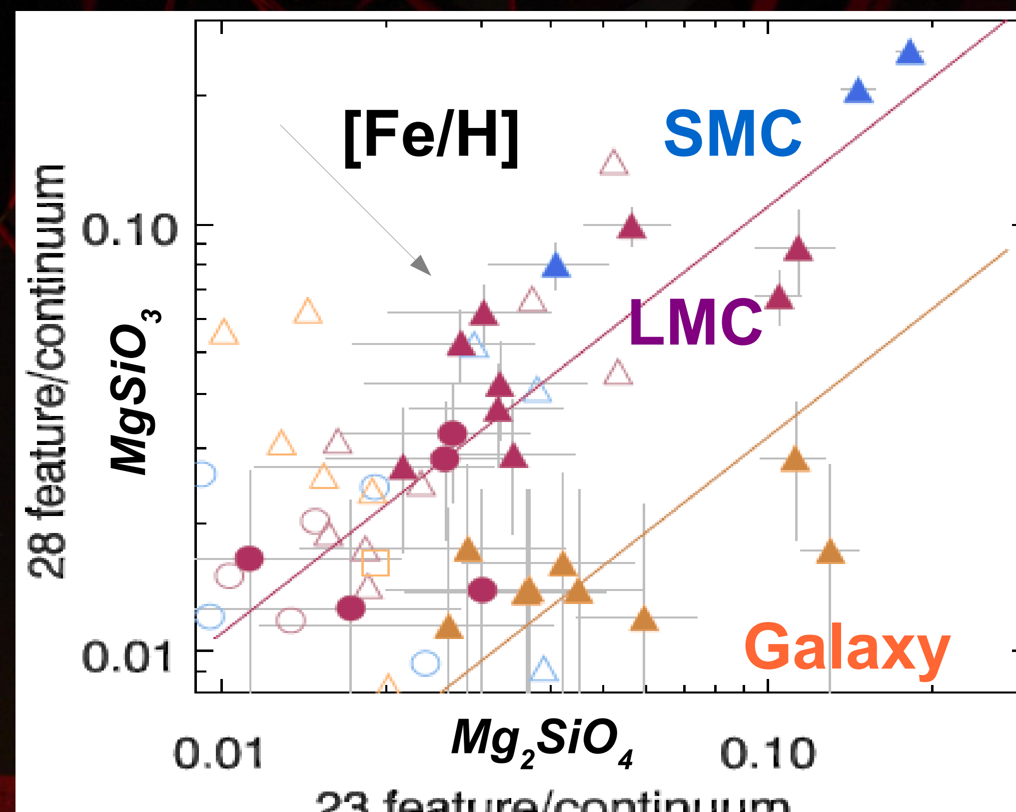
AGB dust production

Oxygen-rich stars have less condensible material so dust production is expected to be different at low metallicity.

Most common oxygen-rich dust species is **amorphous** silicate (shows 10 & 20 um features)

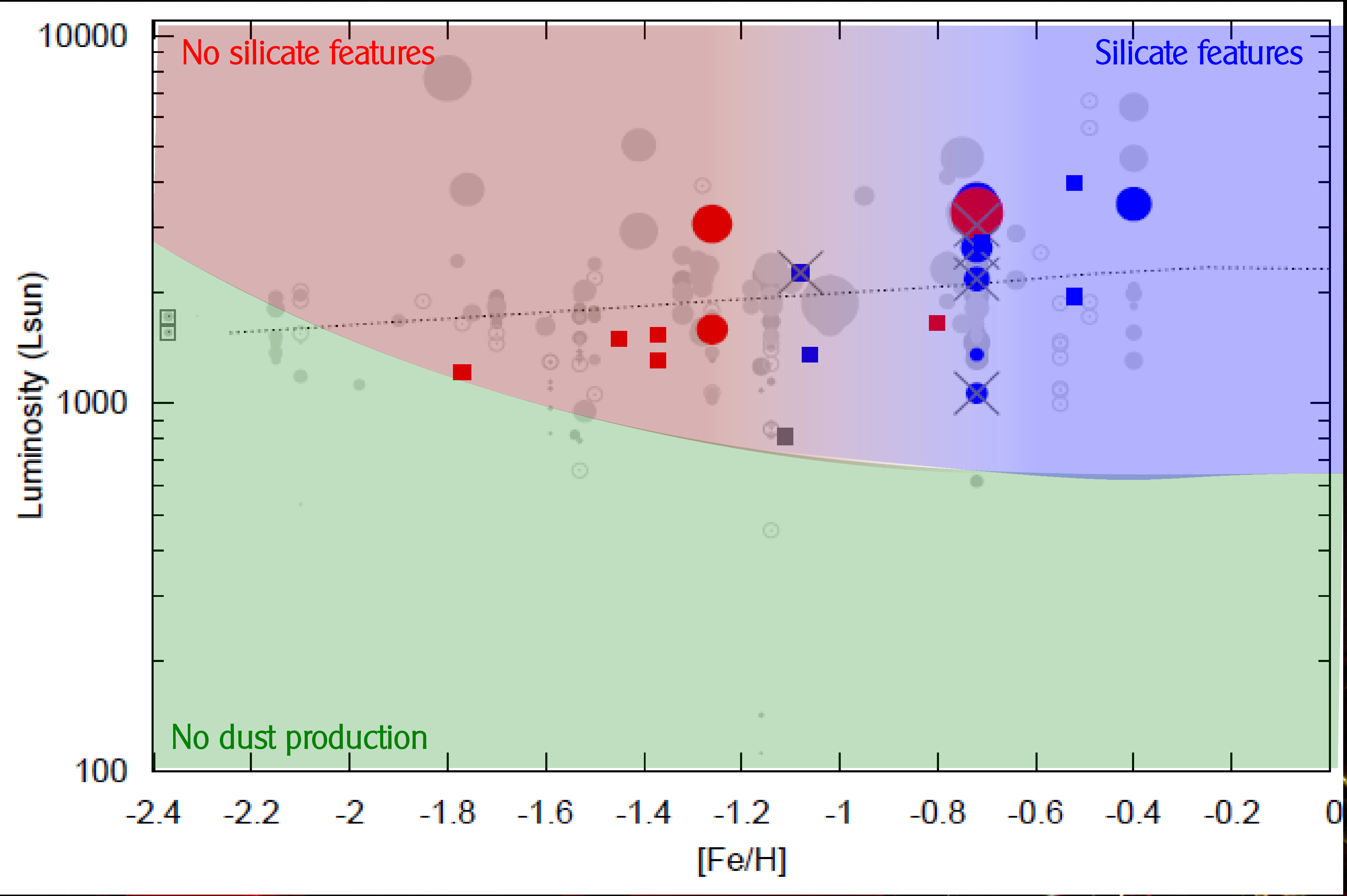
Some evidence to suggest **crystalline** silicates become simpler at low metallicity.



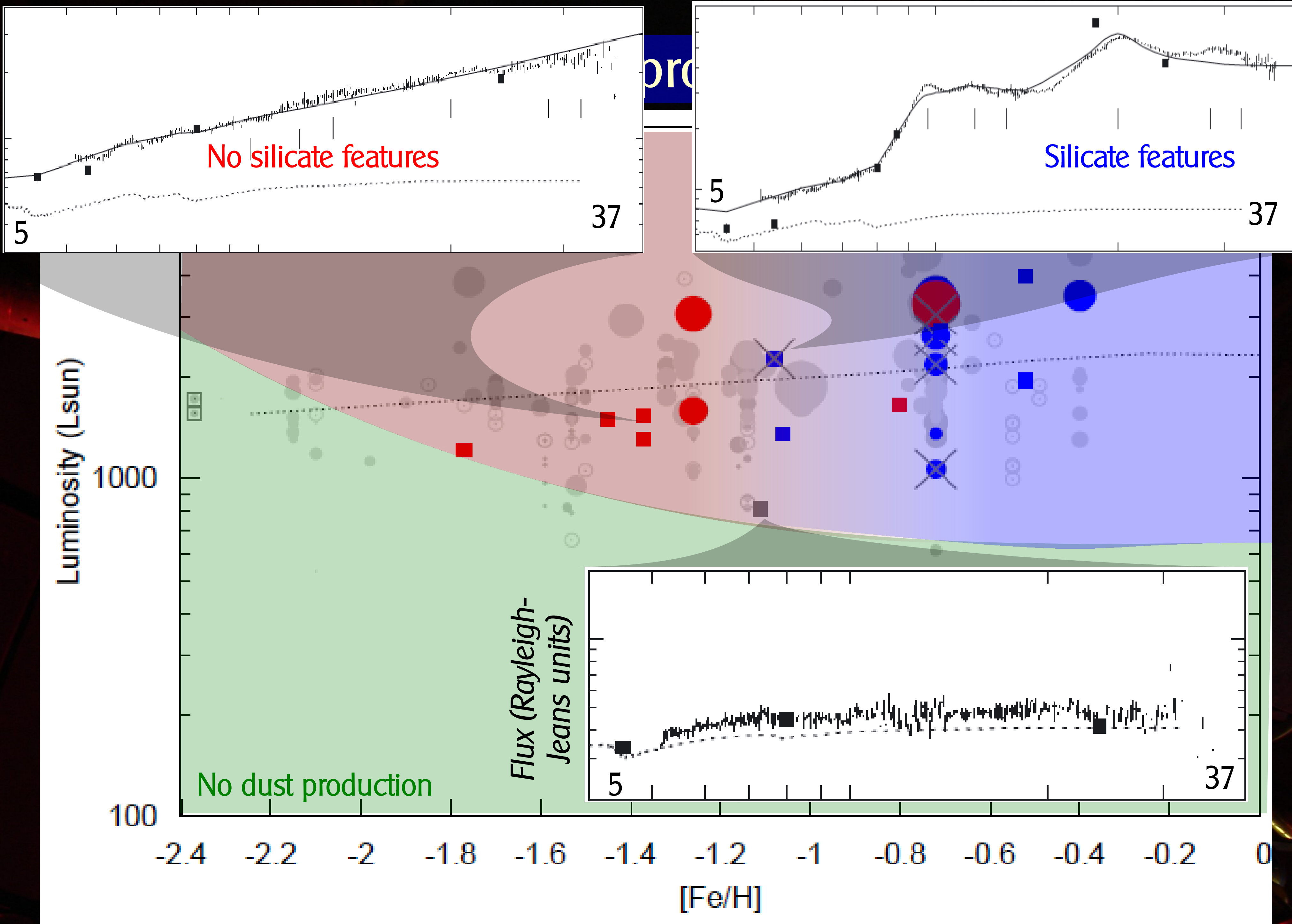


Jones et al. (2012)

AGB dust production



McDonald et al. (2010-2013)



McDonald et al. (2010-2013)