Observationally decoding the mechanisms driving mass-loss from AGB stars

Or: *"So you think you're using the right mass-loss rate?"*

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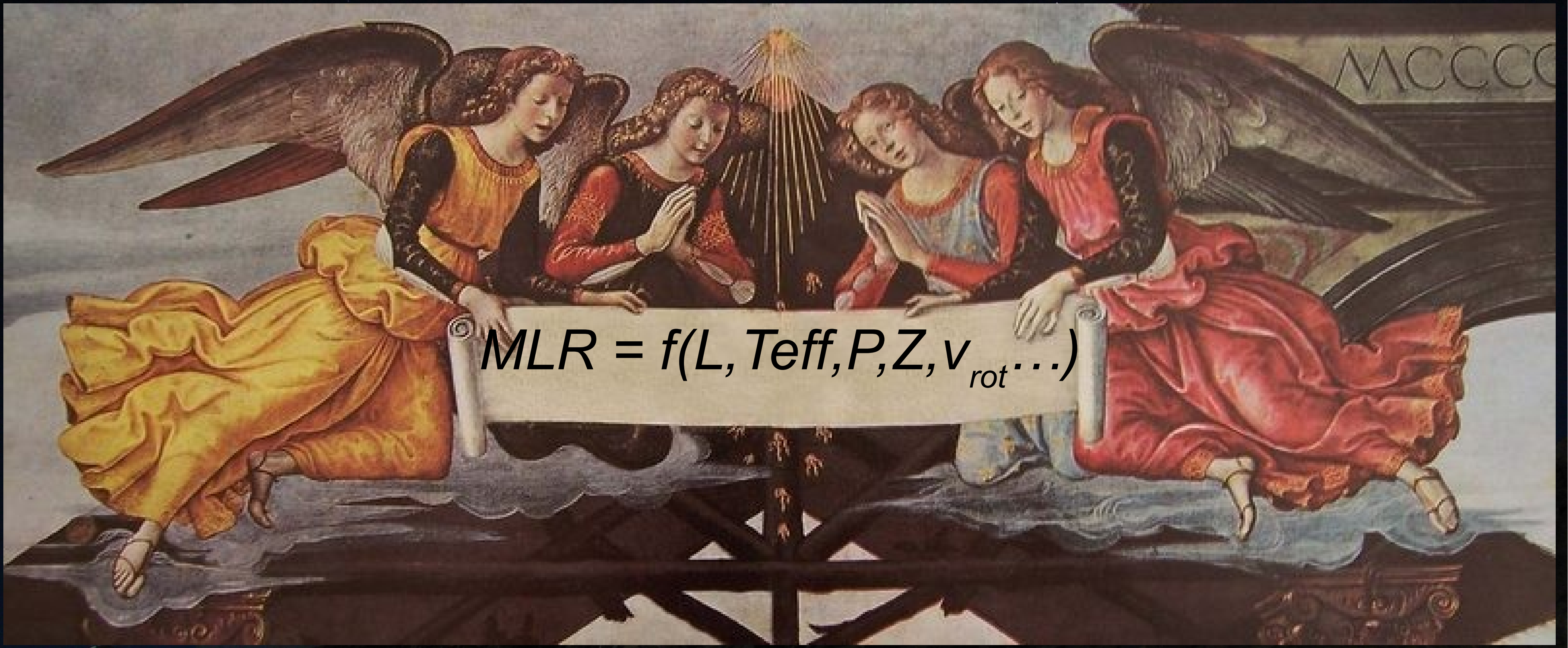
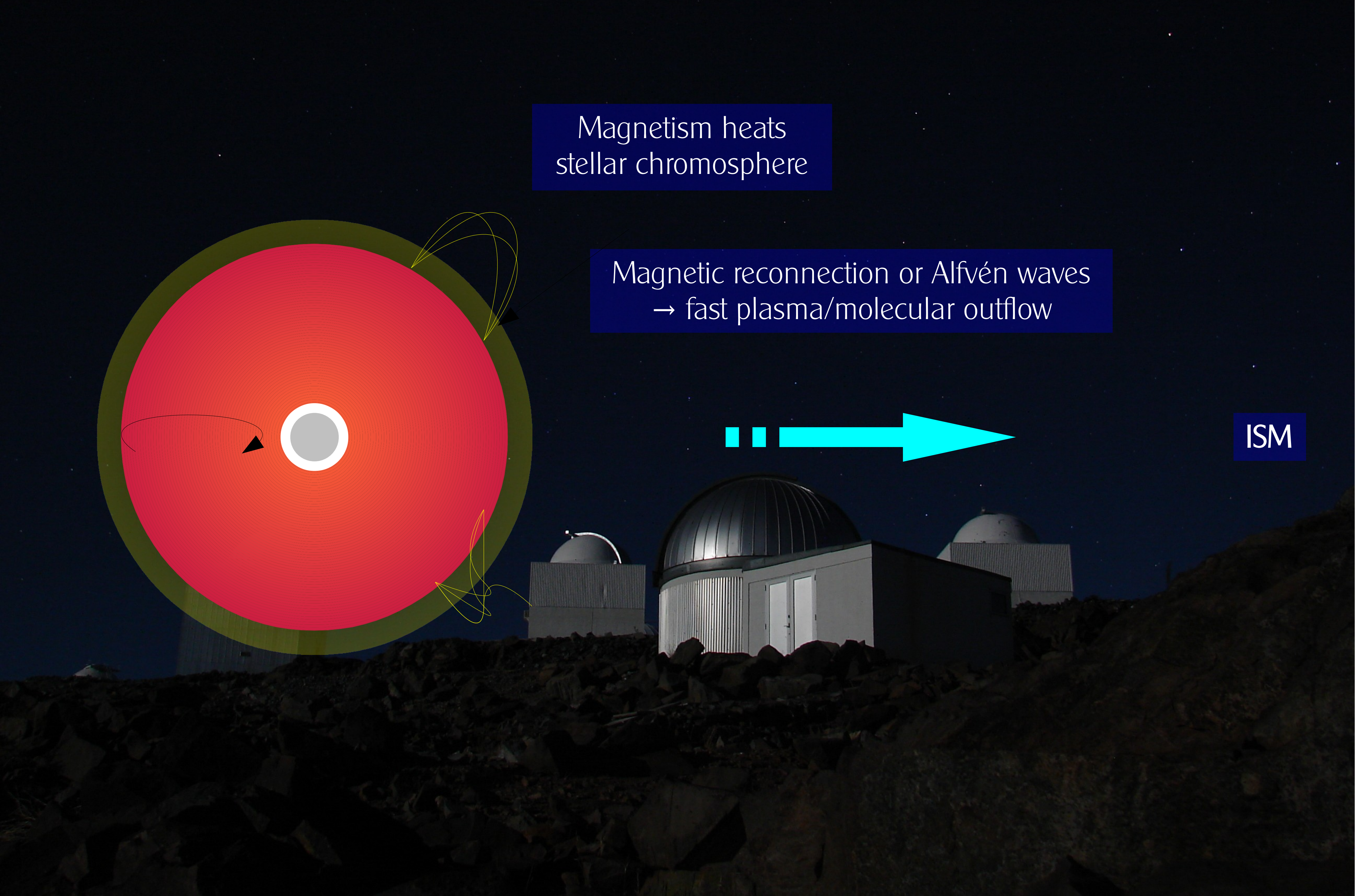
La Silla

Why it matters

Why it matters



Magneto-acoustically driven mass loss

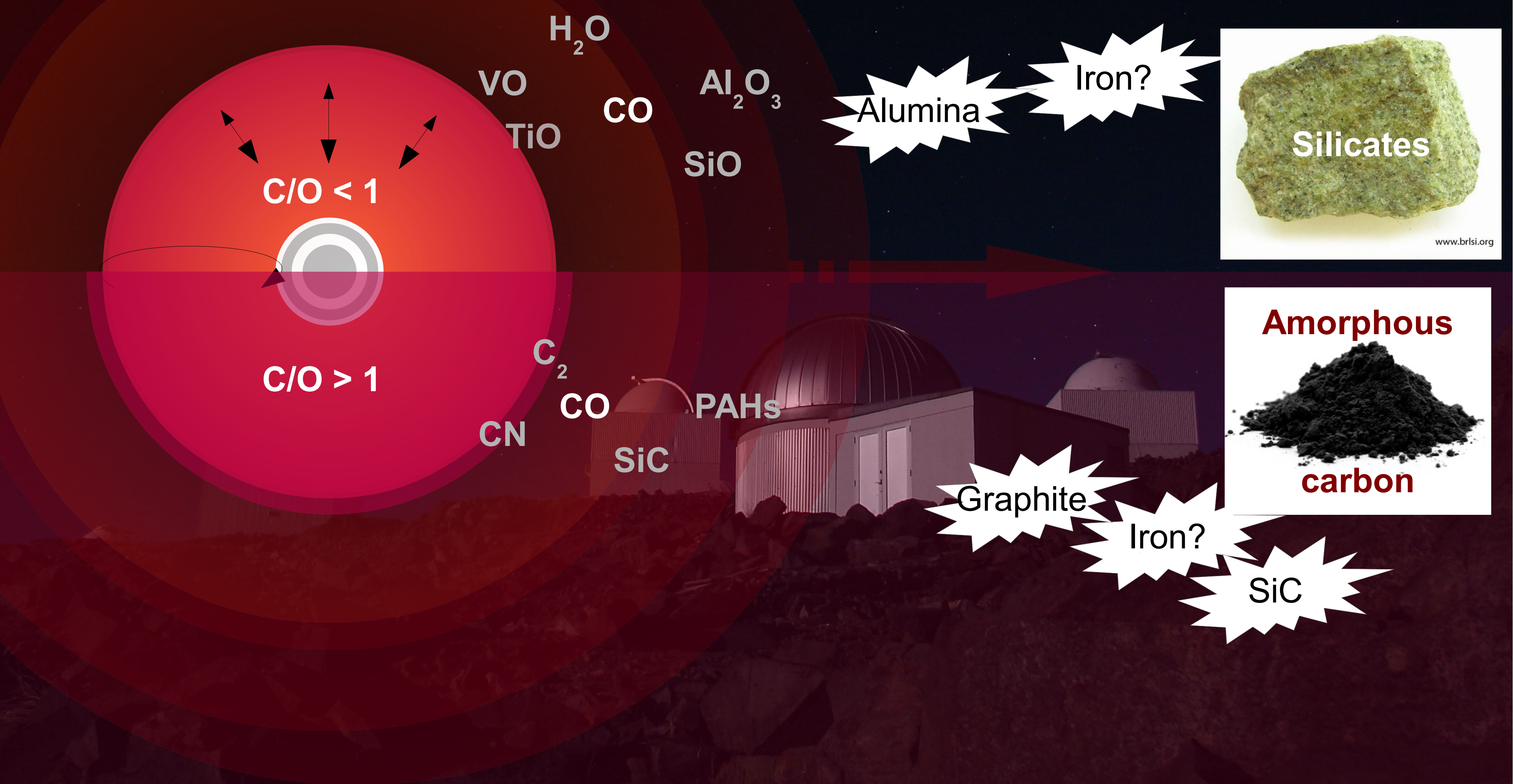


Pulsation-driven mass loss

Pulsation levitates the outer atmosphere.

Which condenses into molecules and small dust grains.

But radiation pressure is ineffective.

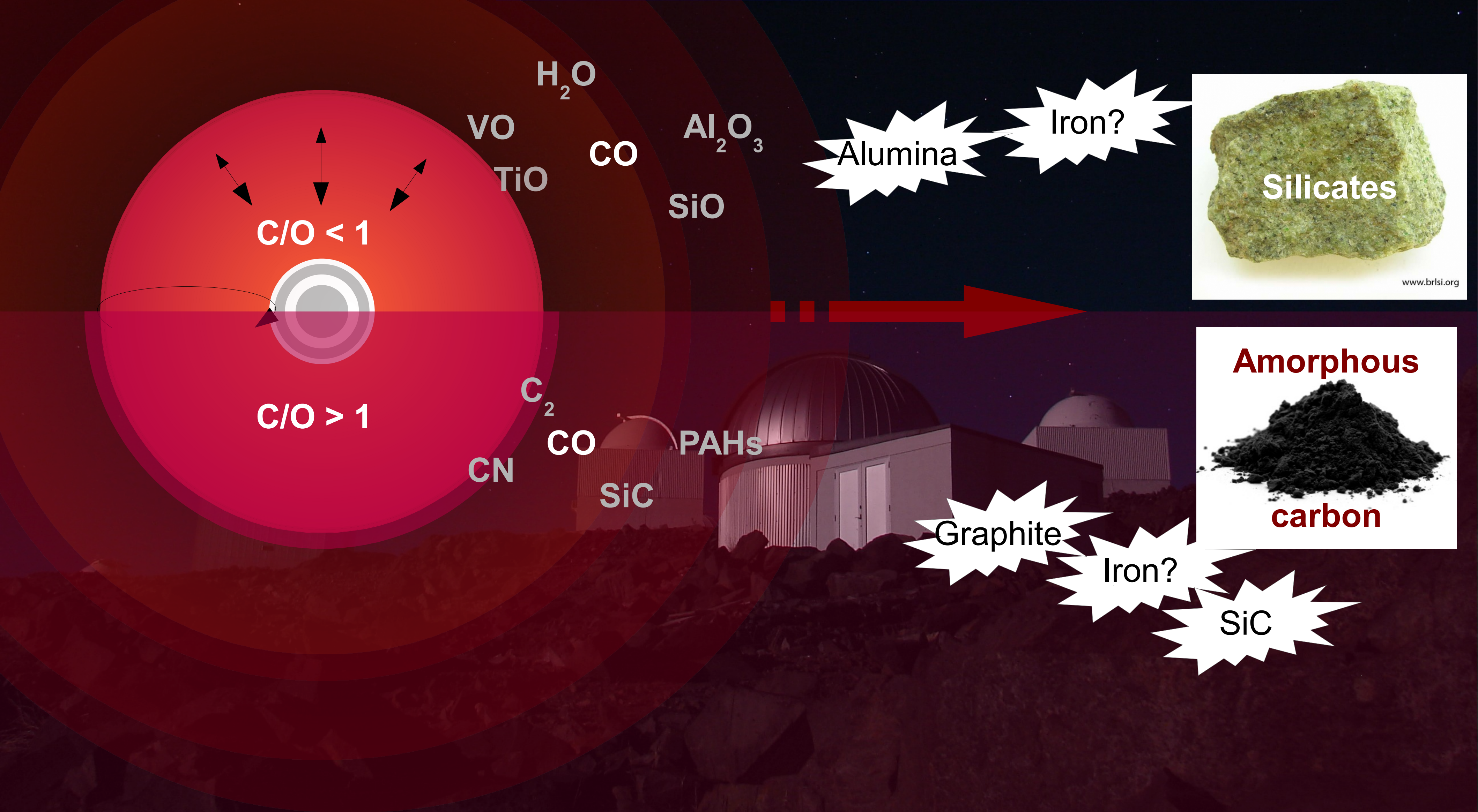


Radiation-driven mass loss

Same but radiation pressure on dust grains is effective.

Could be because grains are larger, so scatter light...

...or are made of more opaque minerals.



Expectations

At solar metallicity…

Magneto-acoustic

Magnetic energy fixed by core. As radius grows:

(1) surface area grows → MLR grows

(2) chromosphere cools → v_{wind} drops

Pulsation

Pulsation provides the energy

(1) MLR / v_{wind} related to pulsation amplitude (& period?)

MLR & v_{wind} should not vary with luminosity

Radiation

If acceleration occurs below the wind's sonic point
→ MLR increases with L

otherwise
→ v_{wind} increases with L

At sub-solar metallicity…

Magneto-acoustic

Probably little change in B with metallicity.

At the same luminosity:
stars are warmer and more compact
→ MLR slightly lower?

→ Little change in MLR or v_{wind}

Pulsation

Stars warmer, so pulsation slightly weaker.
→ MLR slightly lower?

→ Little change in MLR or v_{wind}

Radiation

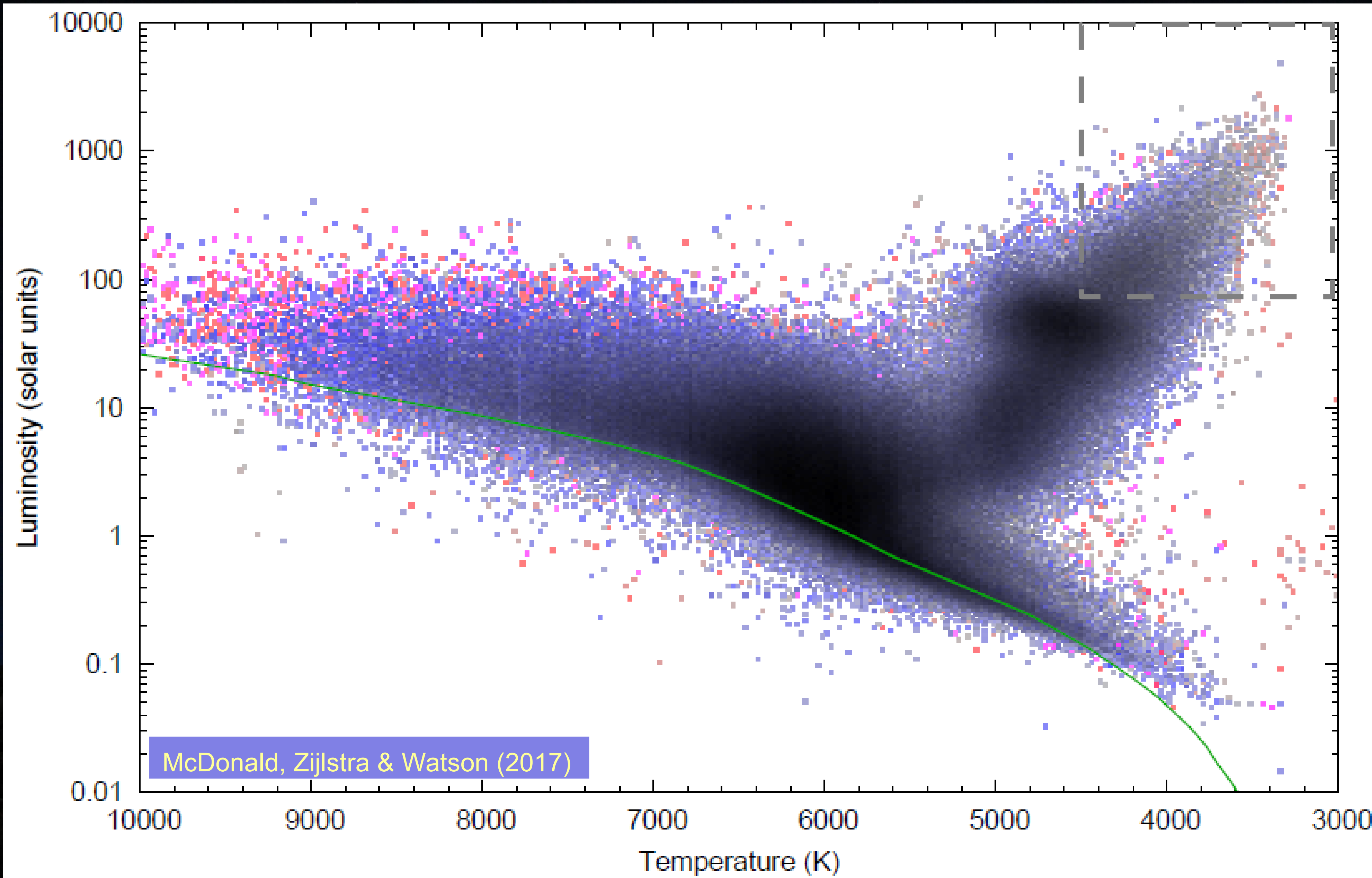
Lower dust:gas
→ MLR or v_{wind} should drop

→ Drop is proportional to metallicity for O-rich stars
(C stars produce their own dust)
(Different efficiencies in C & O star winds?)

What happens at solar metallicity?

Nearby stars

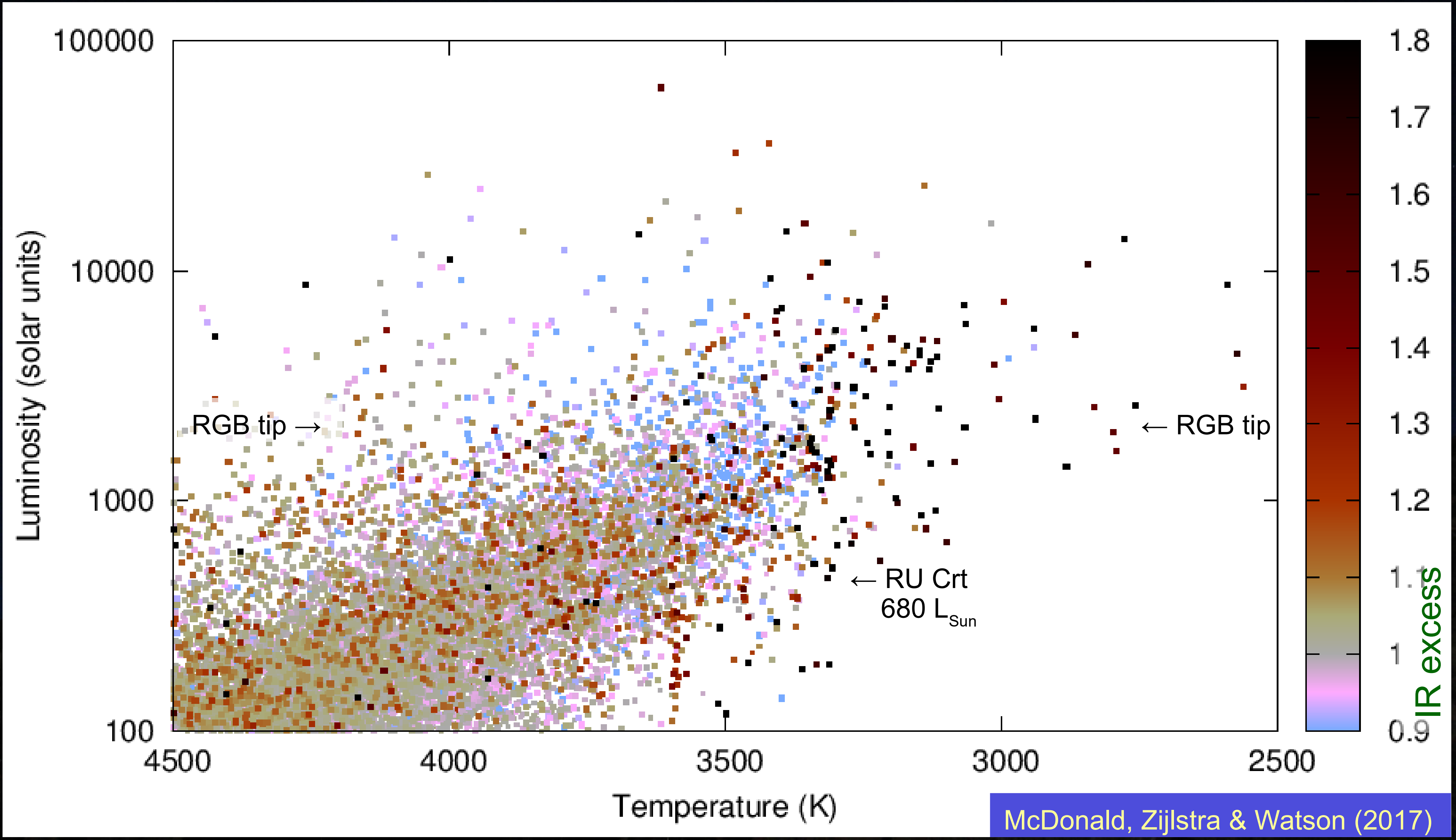
Gaia DR1 Hertzsprung–Russell diagram...



Nearby stars

Dust production (and third dredge-up) in AGB stars typically starts near the RGB tip

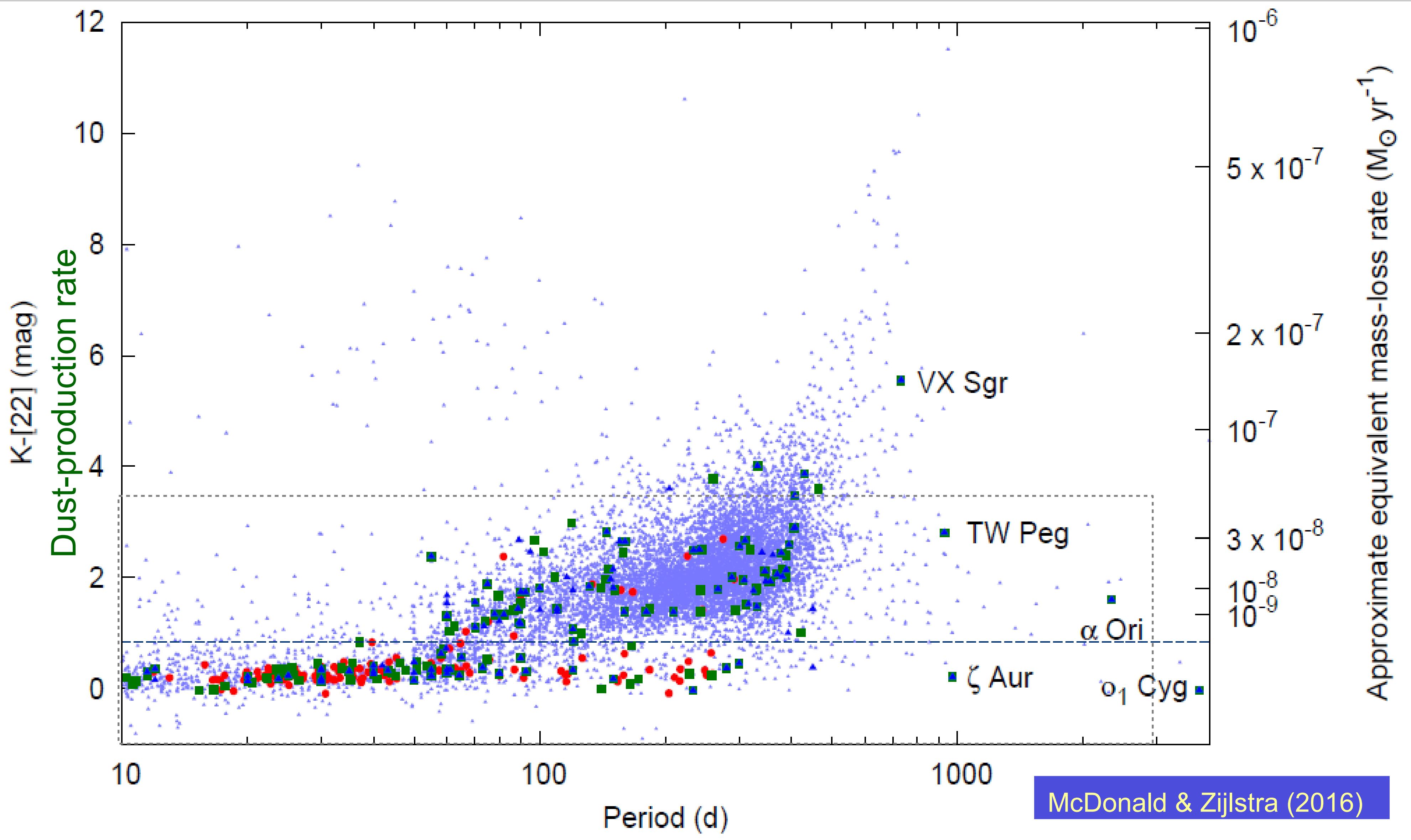
No clear relation between IR excess and luminosity



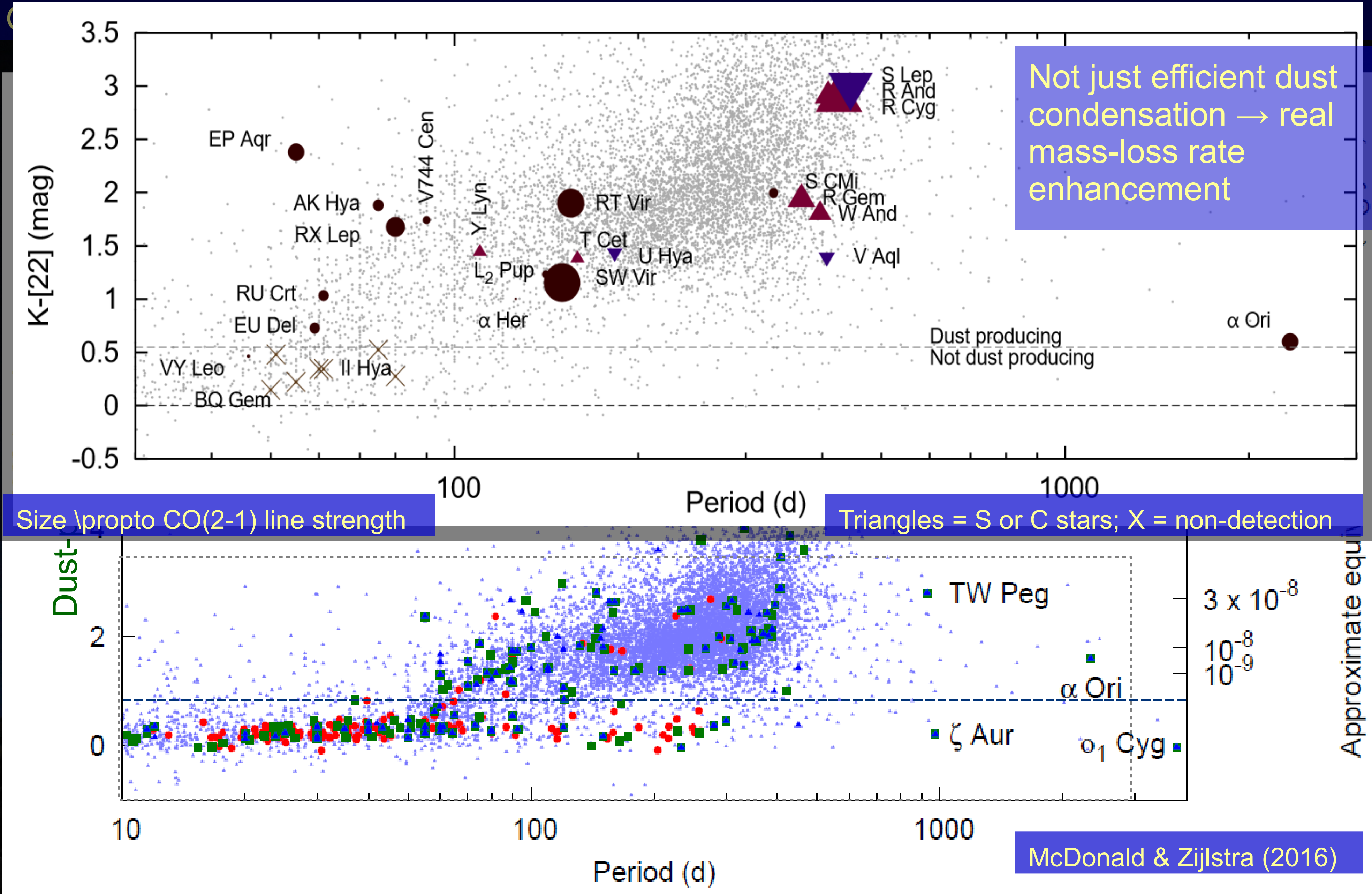
McDonald, Zijlstra & Watson (2017)

Nearby stars

Onset of dust production correlates with pulsation period: steps at 60 and 300 days



Nearby stars



Not just efficient dust condensation → real mass-loss rate enhancement

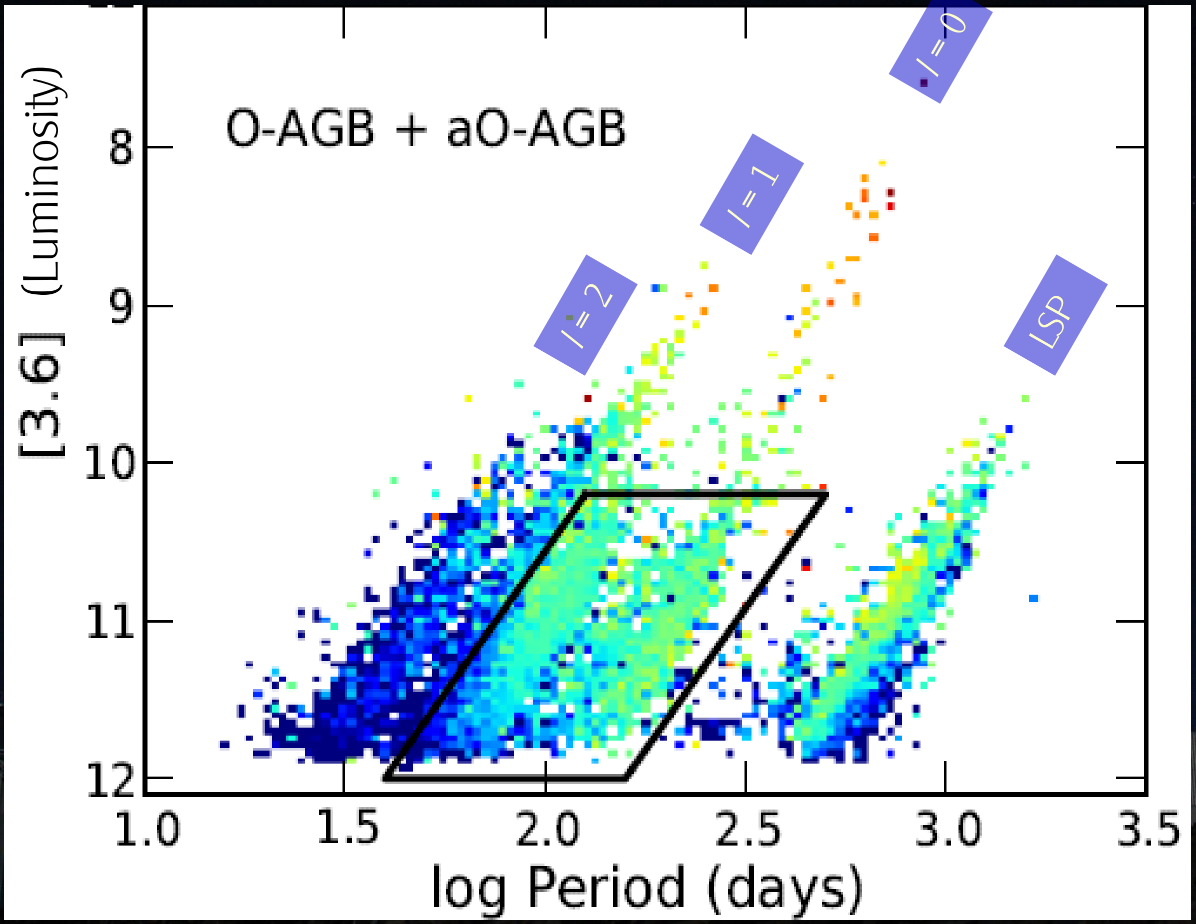
Size \propto CO(2-1) line strength

Triangles = S or C stars; X = non-detection

McDonald & Zijlstra (2016)

Nearby stars (& Magellanic Clouds)

LMC: IR colours linked to the **pulsation mode**.

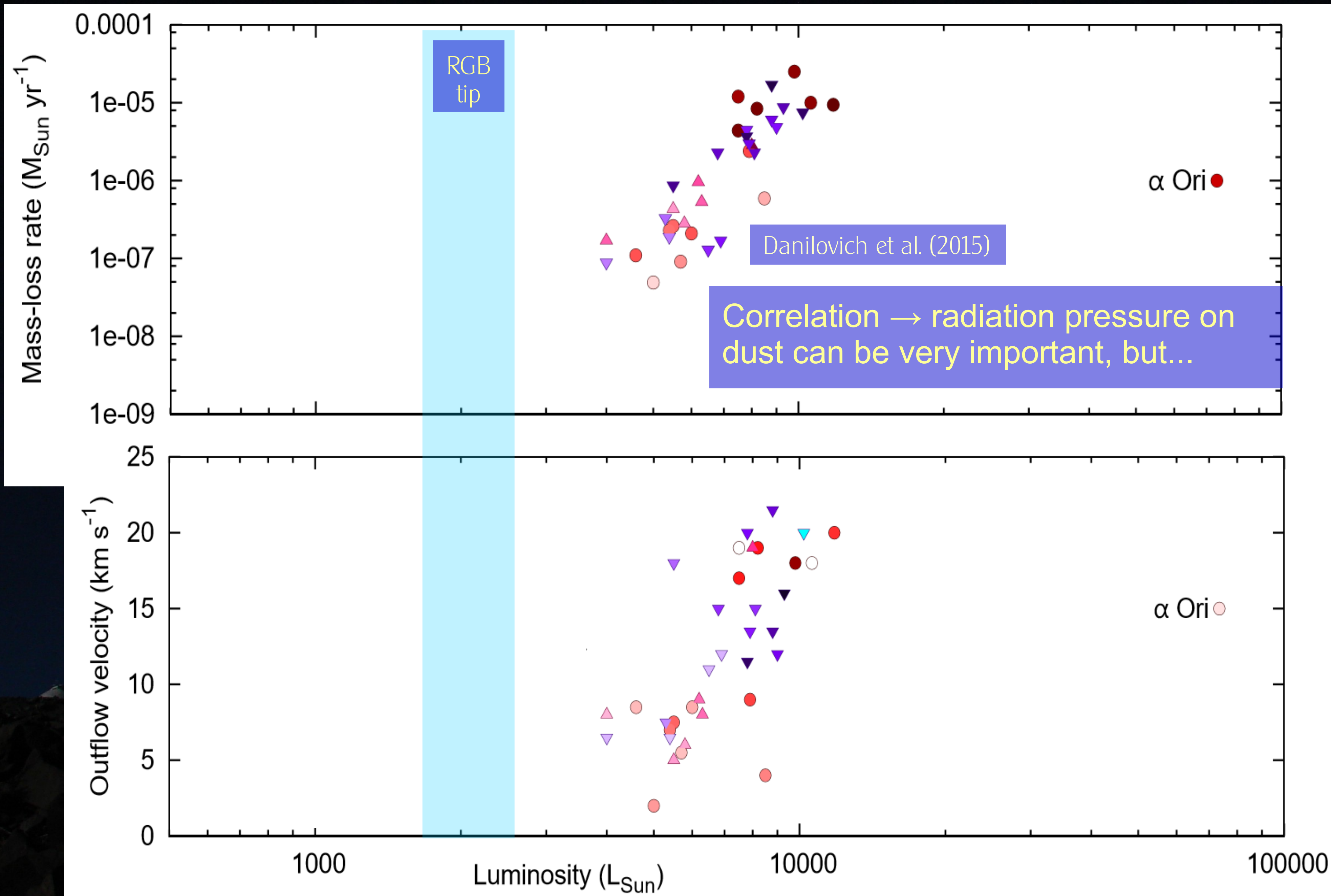


Boyer et al. (2015)

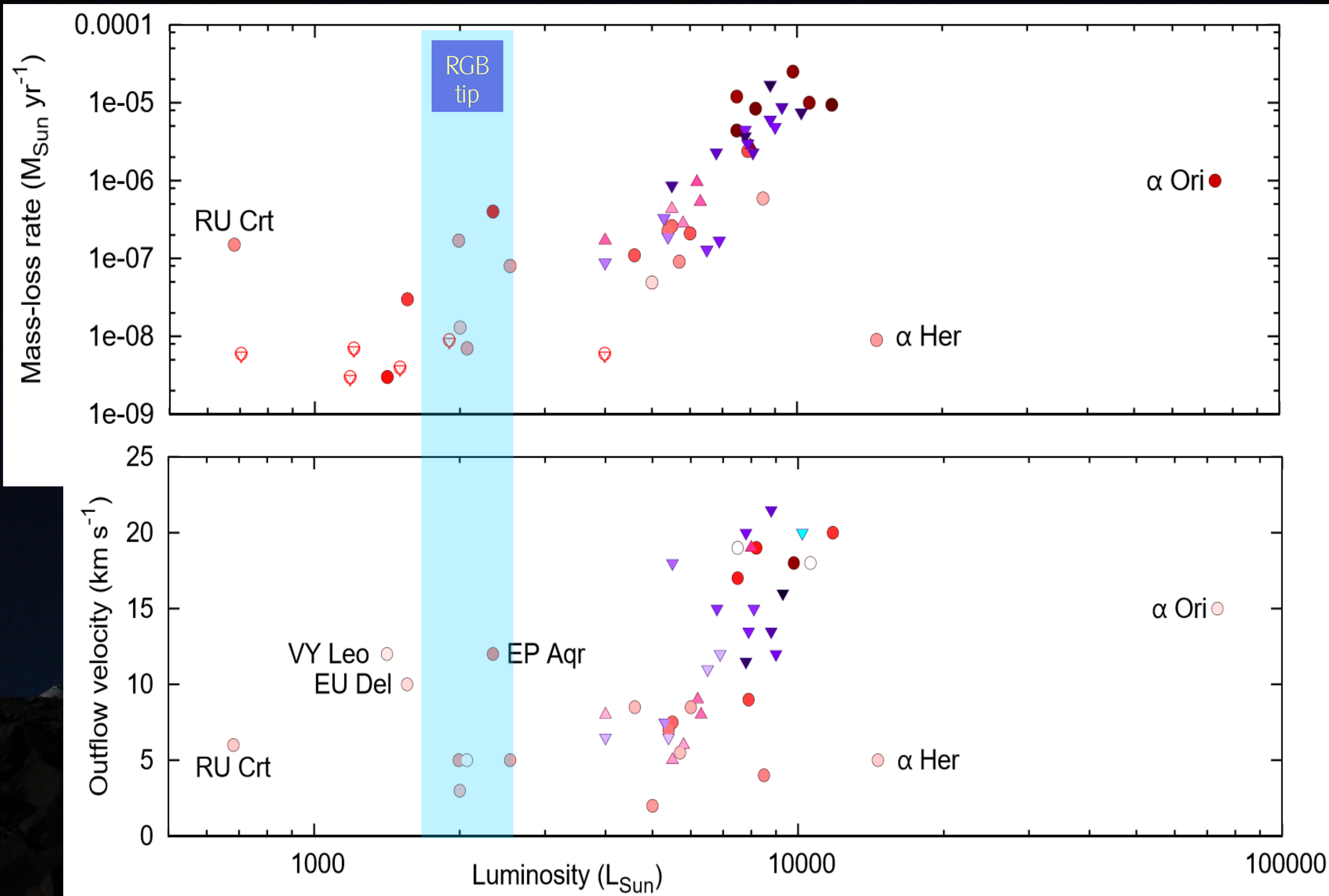
Low-order modes → higher amplitudes, but period seems important too.

→ Pulsation important for dust production

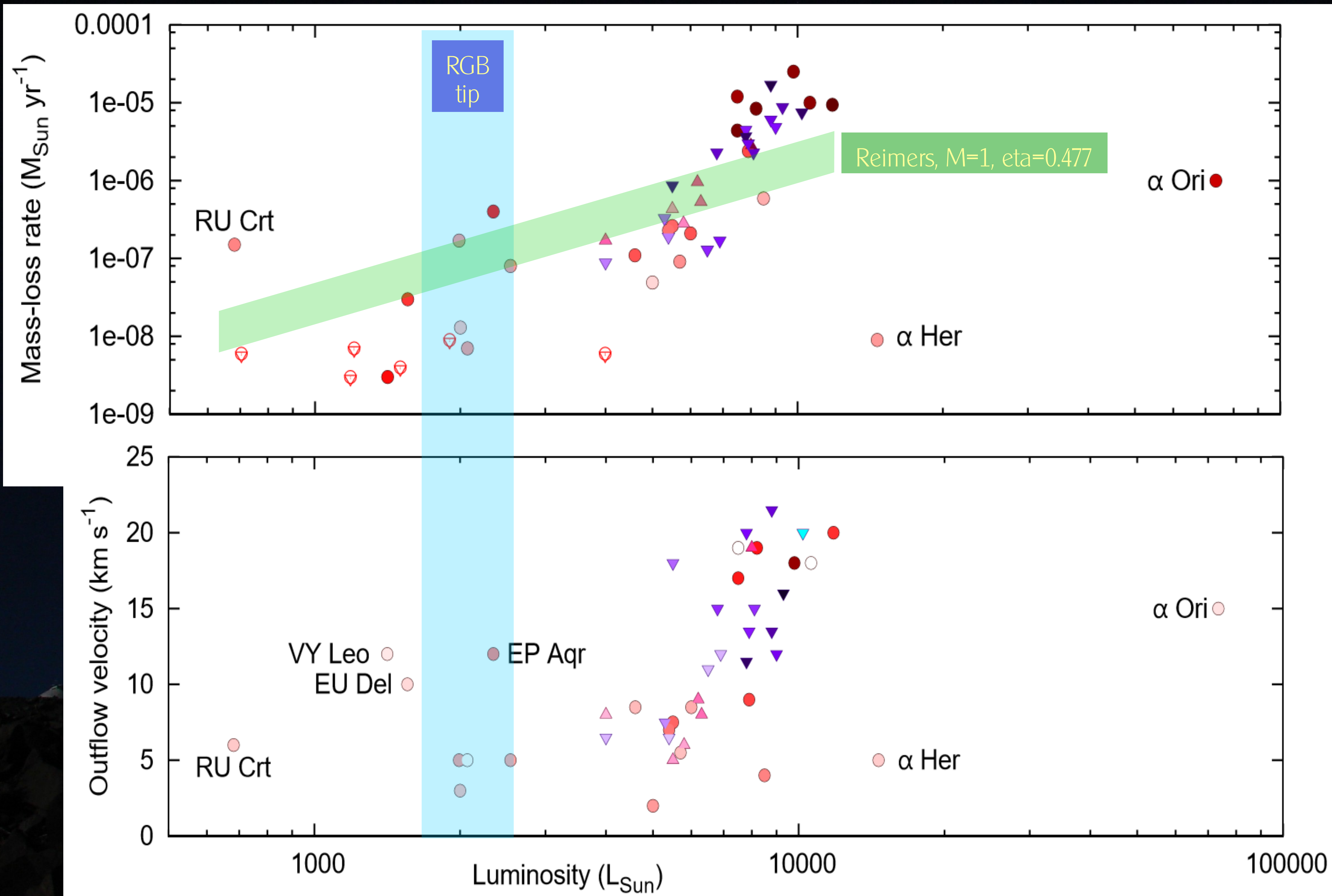
Nearby stars



Nearby stars



Nearby stars



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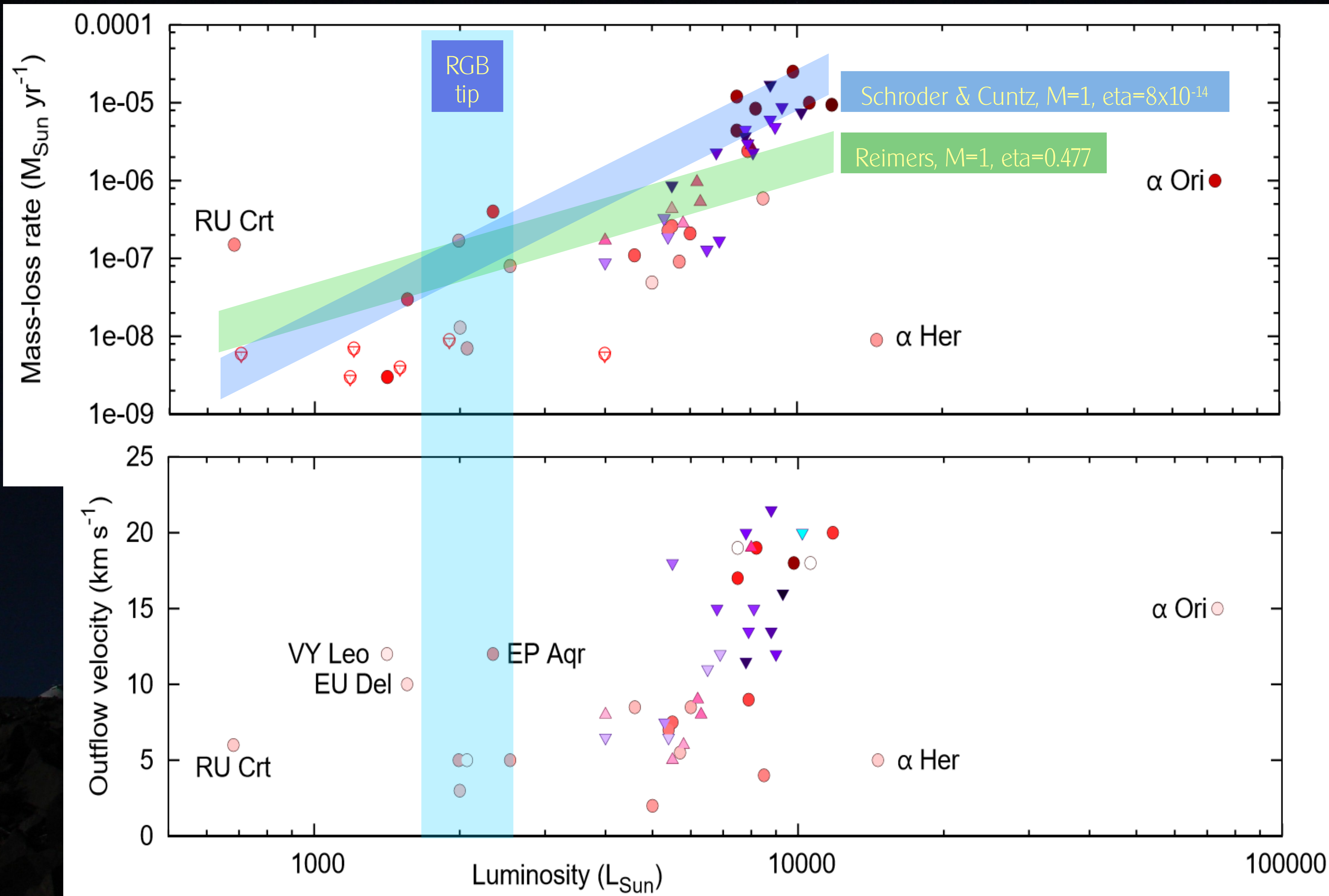
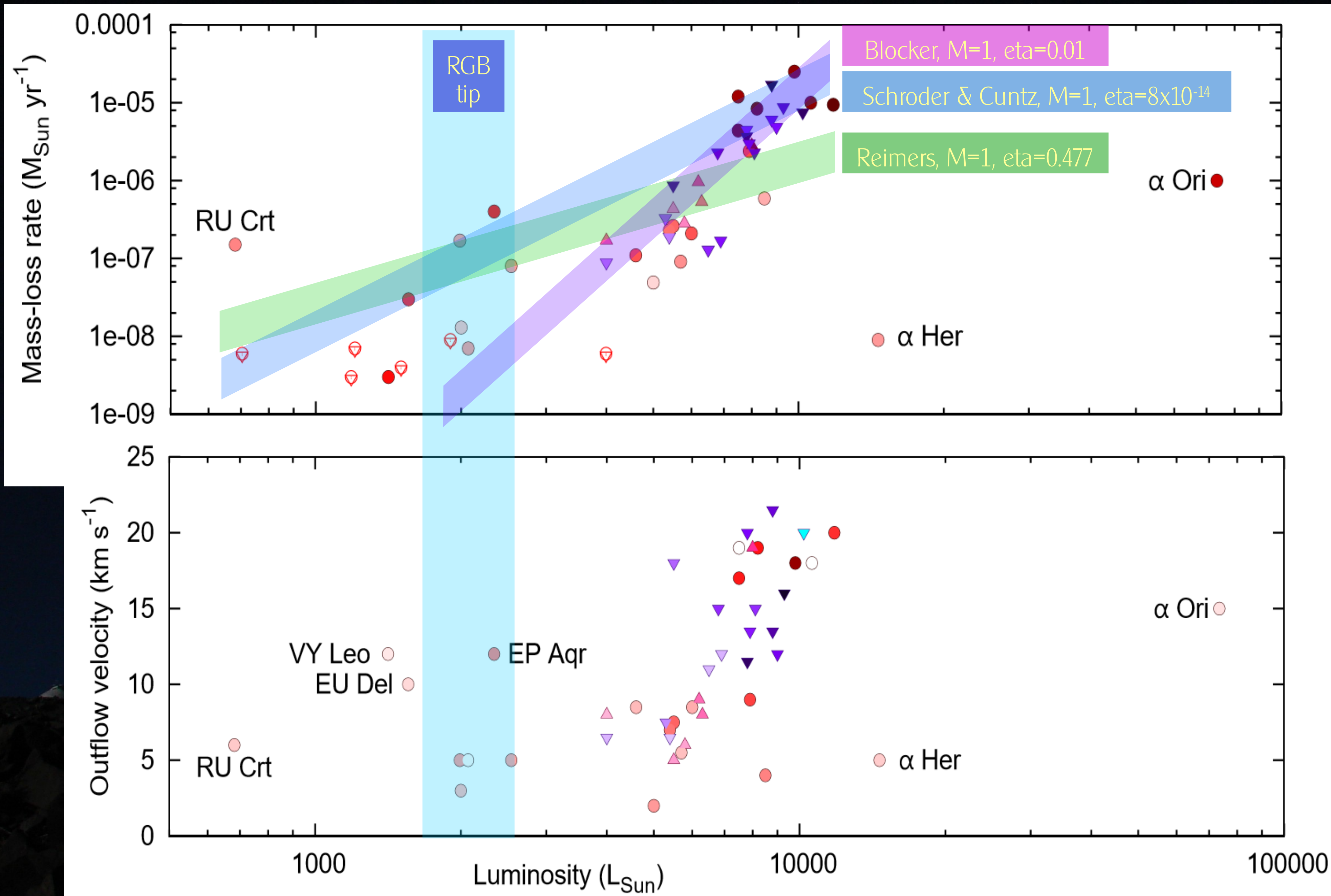
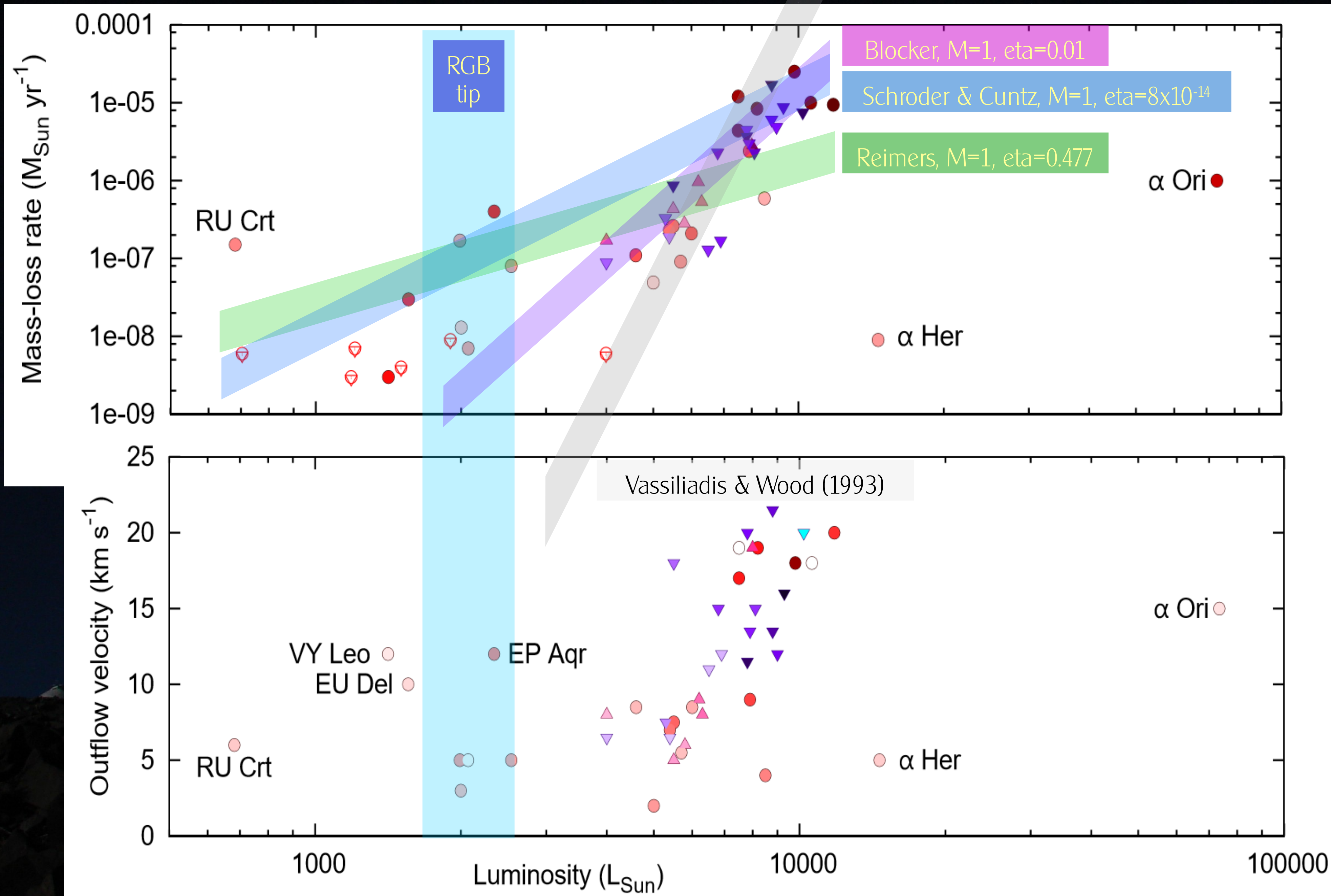


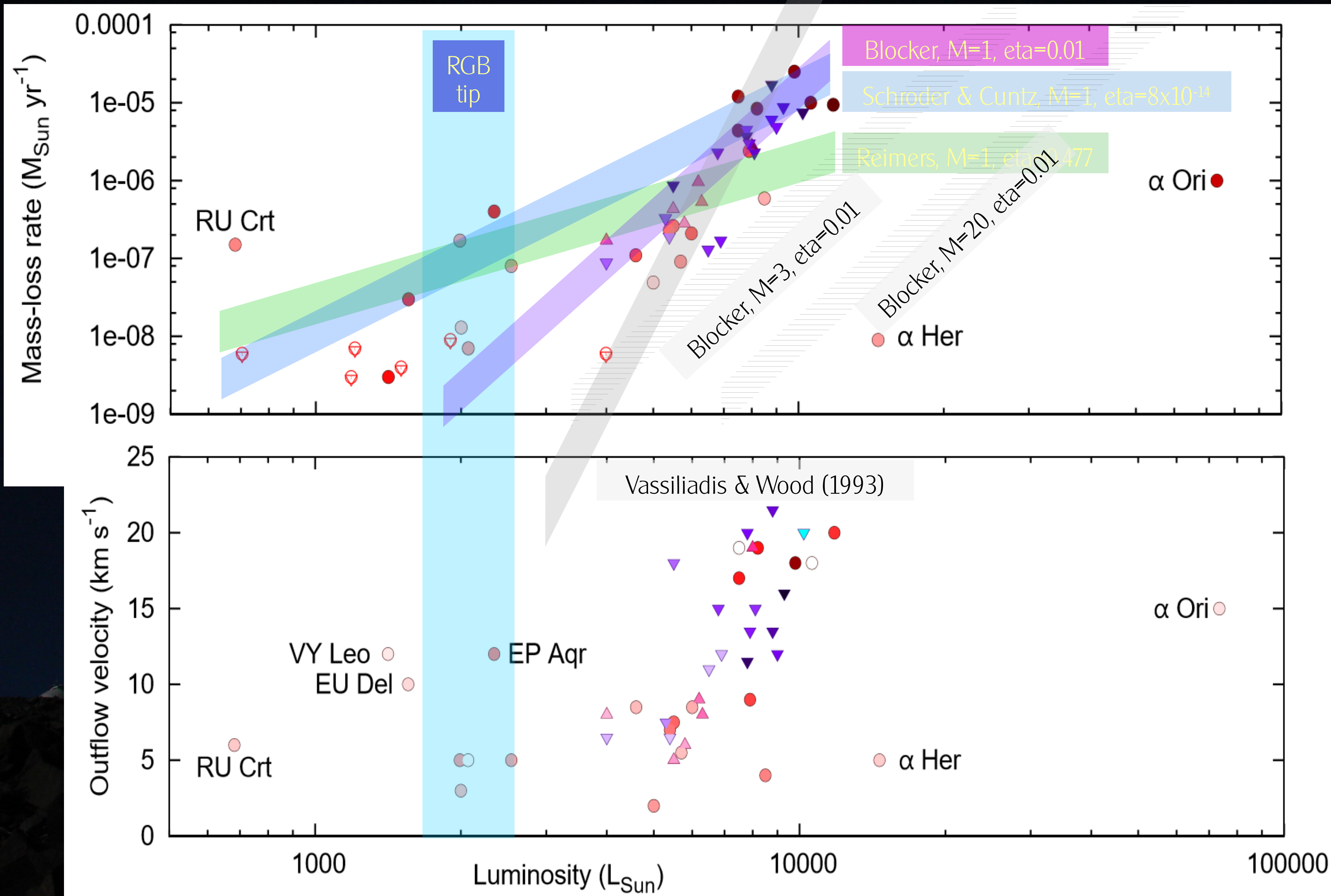
Nearby stars



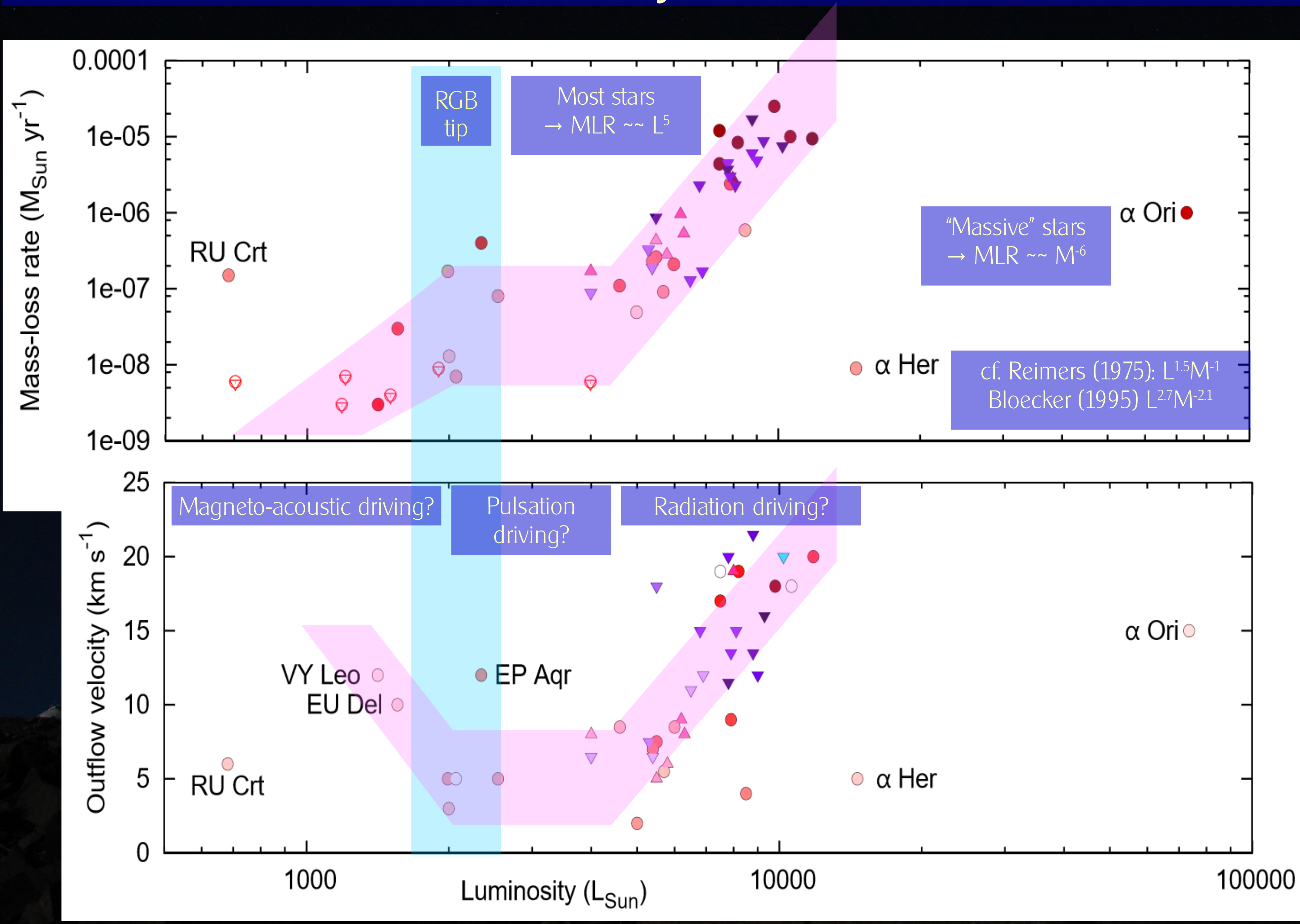
Nearby stars



Nearby stars



Nearby stars



What happens in metal-poor stars?

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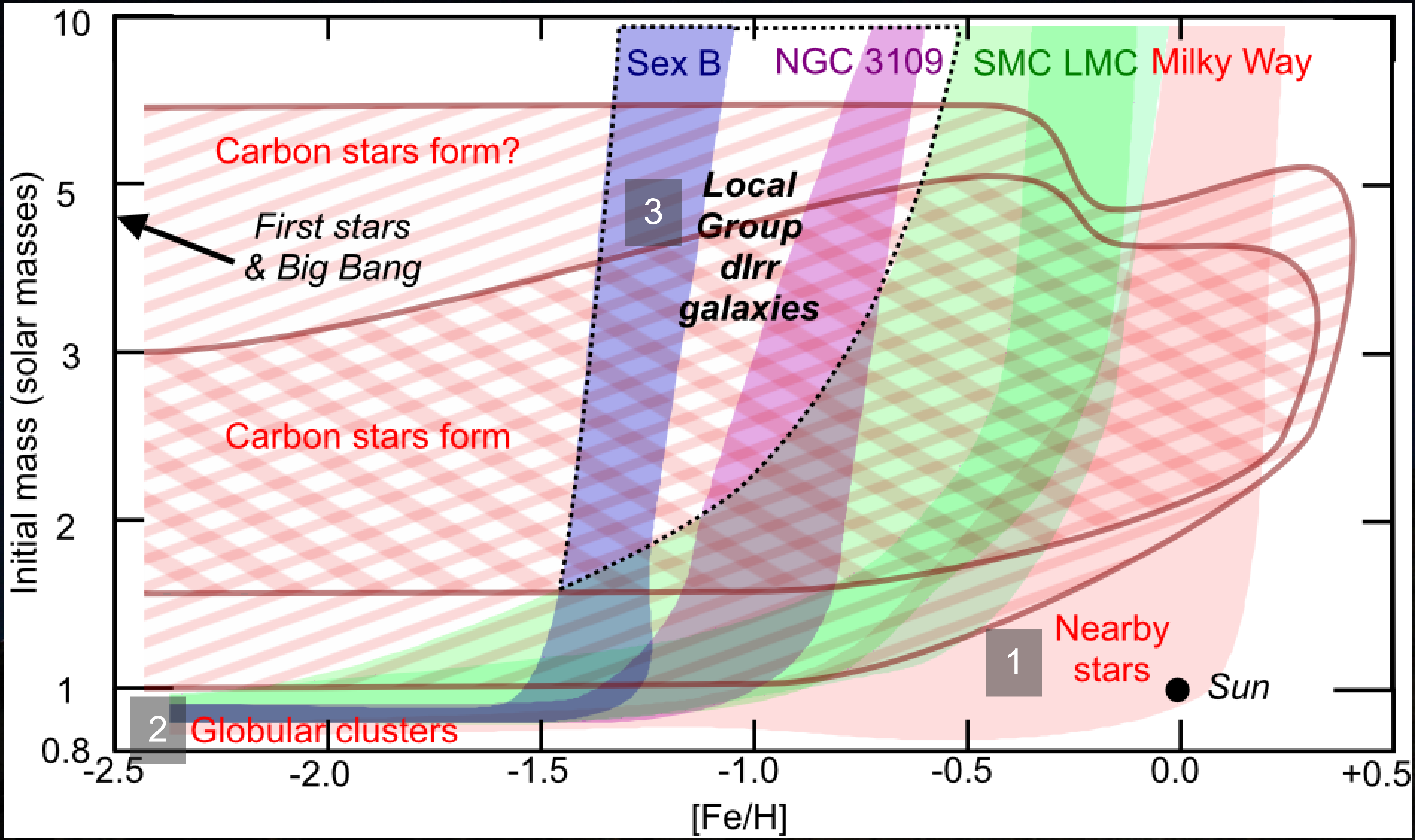
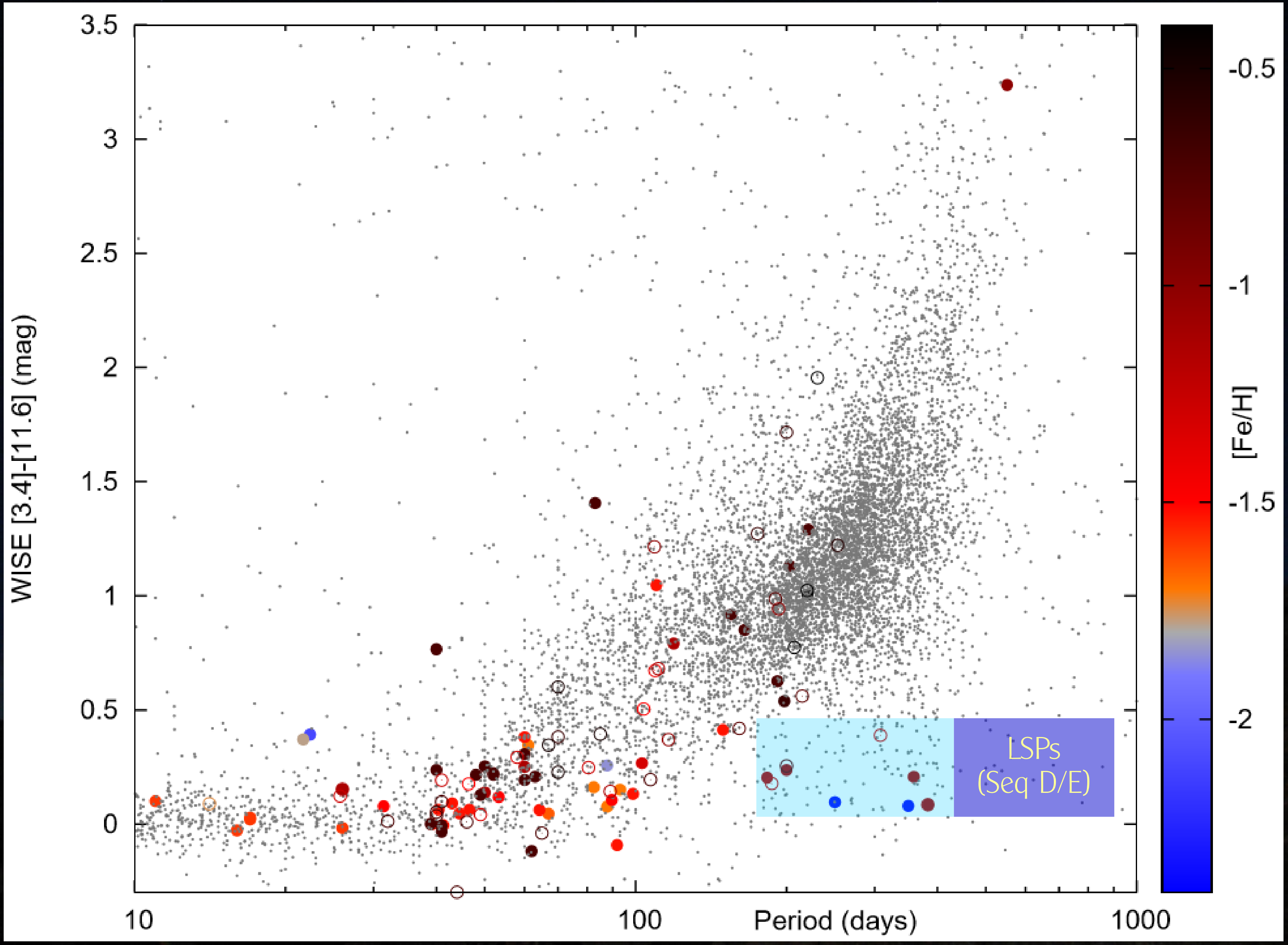
Local dIrr galaxies and globular clusters are the only places to study metal-poor stars.

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



What happens in metal-poor stars?

Metal-poor stars reach the same IR colours, despite their lower metallicity. Implies *larger* mass-loss rate at a given period / luminosity. Radiation pressure on dust not important?



Expectations for massive, metal-poor stars

Massive stars:

Pulsation and radiation driving of winds probably delayed to higher luminosities.

Metal-poor stars:

Pulsation-driven wind still appears effective.
Radiation-driven superwind *may* happen later, but maybe not.
No major decrease of any relation between mass-loss rate and metallicity?

Massive, metal-poor stars:

???
But maybe mass is more important than metallicity?

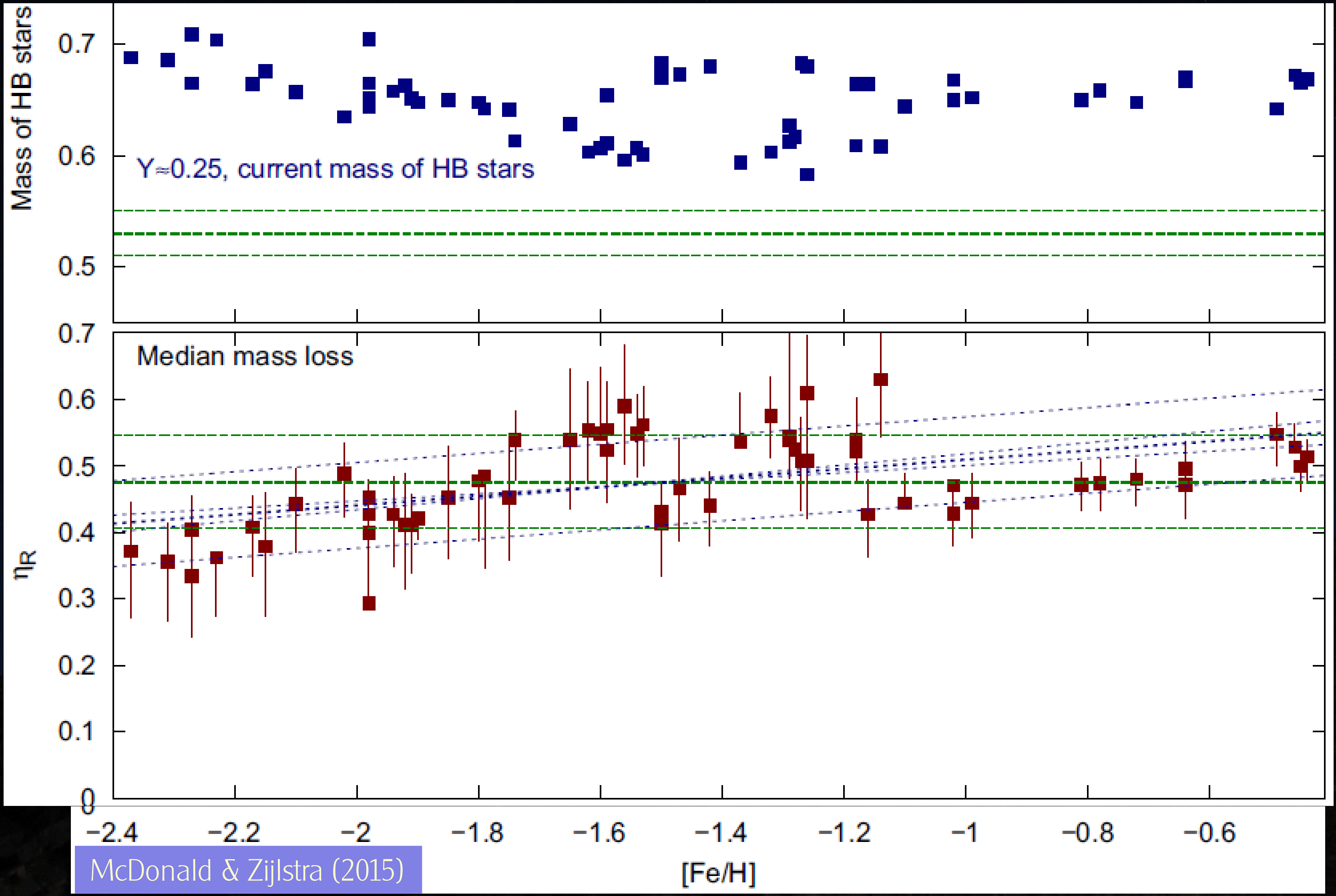
Need further IR & pulsation data on higher-mass stars → DUSTiNGS and *JWST*


FIN
2
2

What happens in metal-poor stars?

Magnetically-driven mass-loss is important in **low** mass stars: can remove entire envelope!

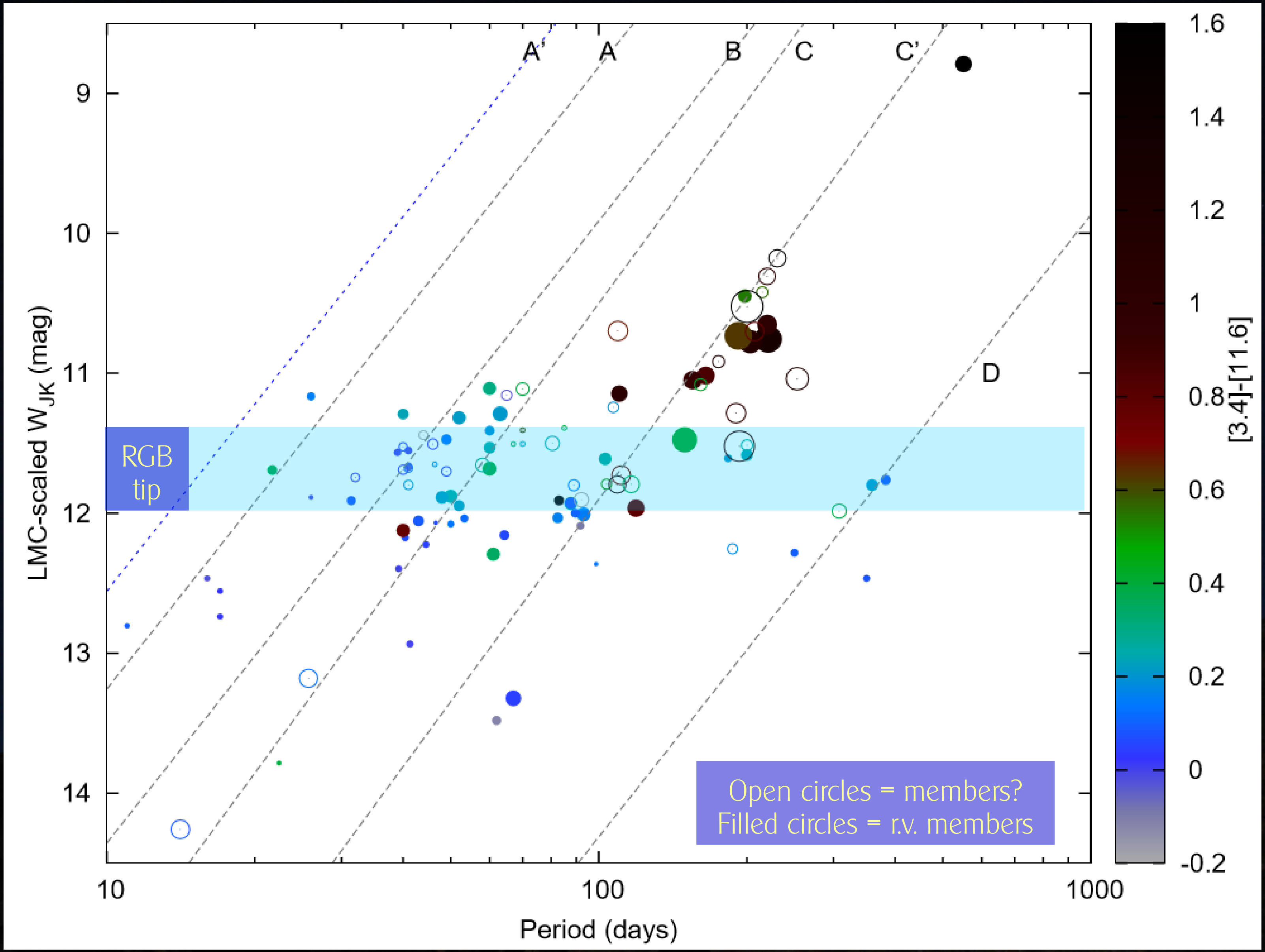
Very little metallicity variation (~20% over factor 100 in metallicity).



McDonald & Zijlstra (2015)

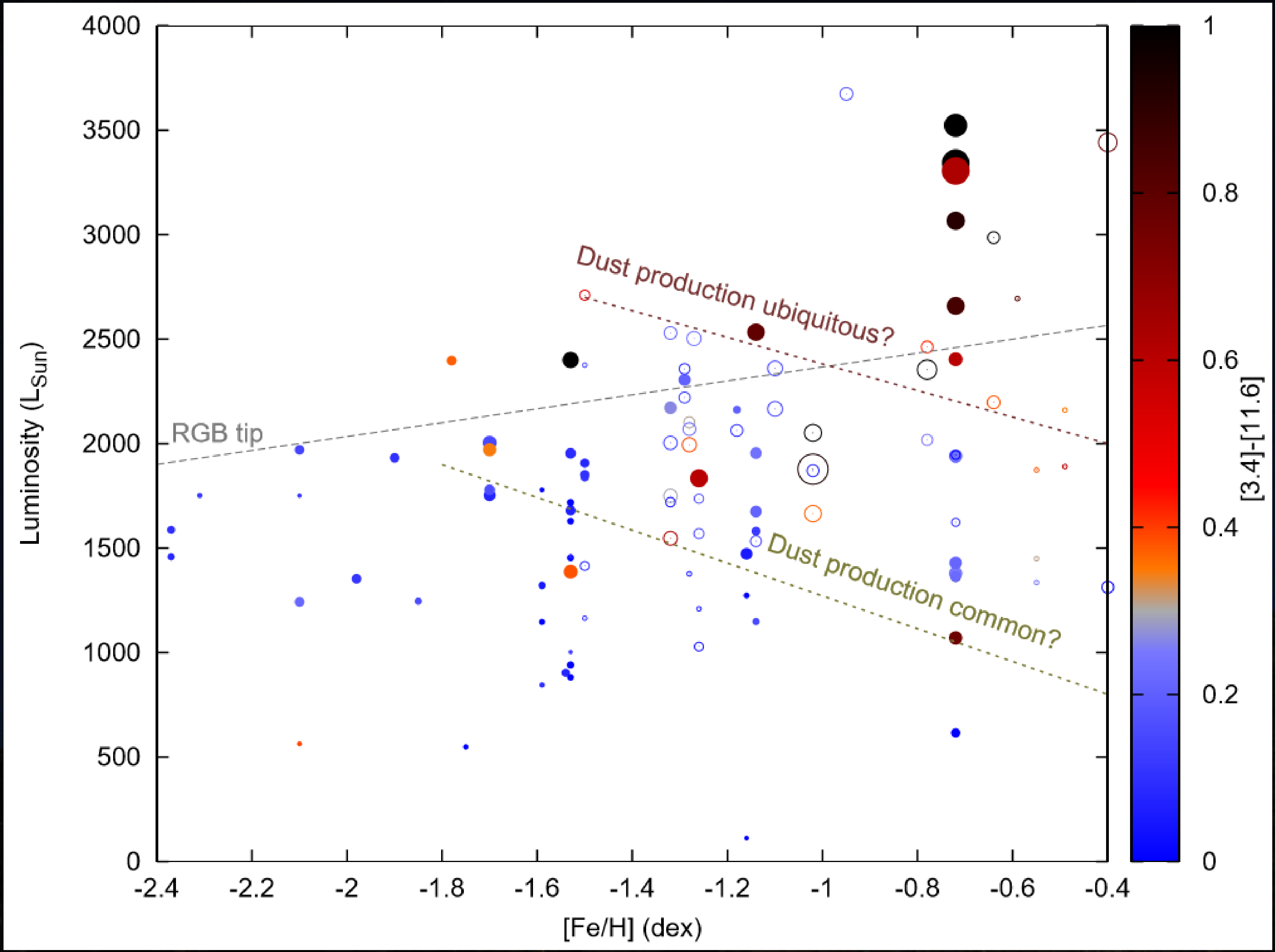
What happens in metal-poor stars?

Similar effects seen in P-L diagram: fundamental mode pulsators are dustiest.



What happens in metal-poor stars?

Mass loss has some luminosity variation. Tends to kick in about 120 R_{Sun}.



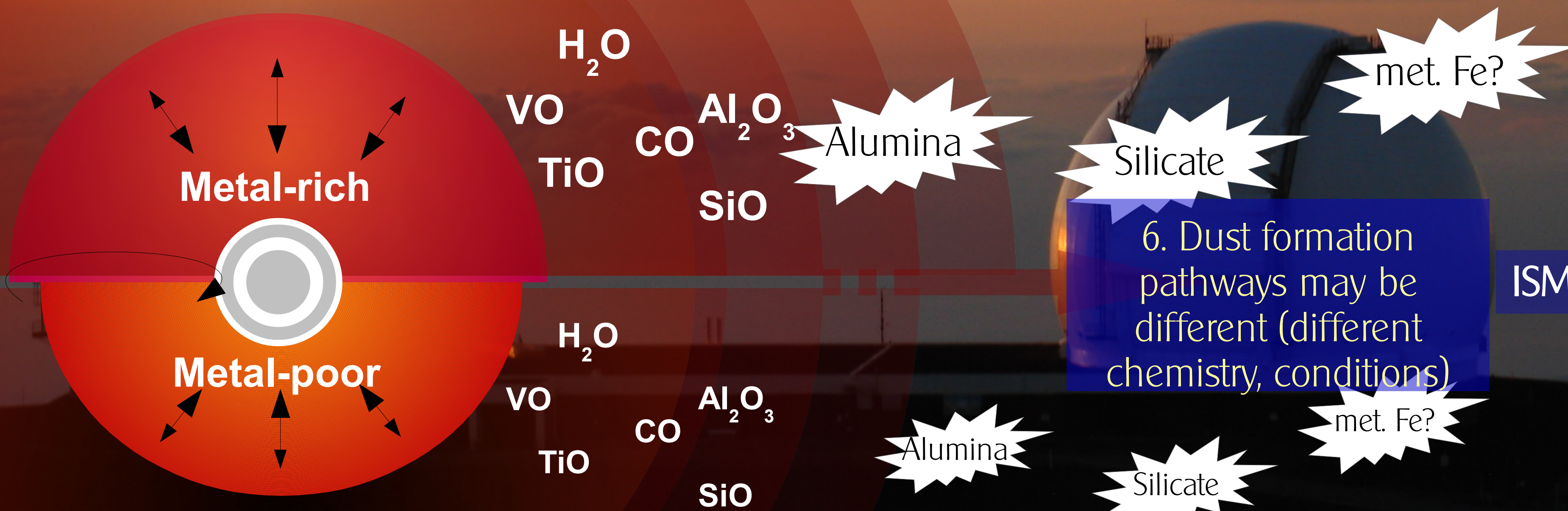
Differences: metal-poor stars are hotter

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)

ISM

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

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)

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

Observations

1. Dust is produced at very low metallicities.

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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

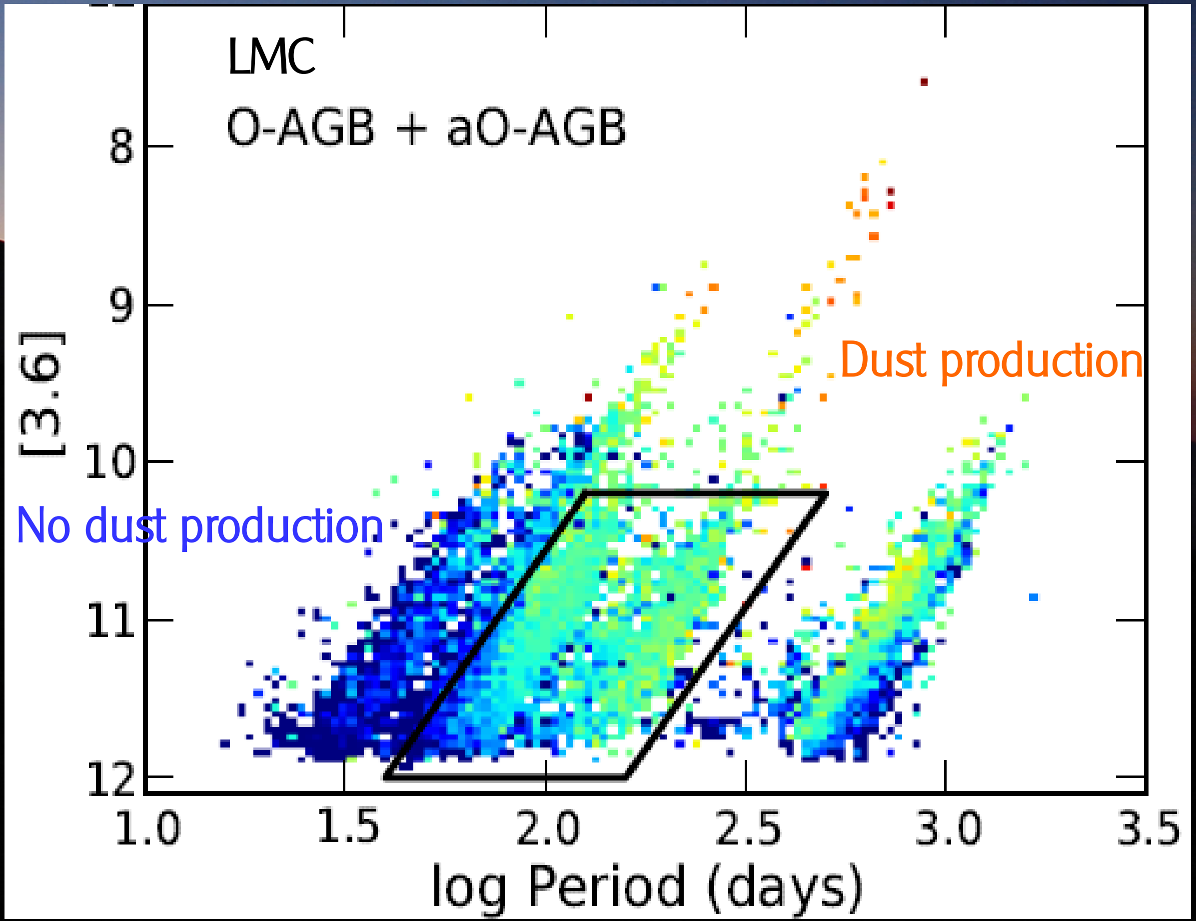
1. Dust is produced at very low metallicities.

2. Dust production starts at higher luminosities.

   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)

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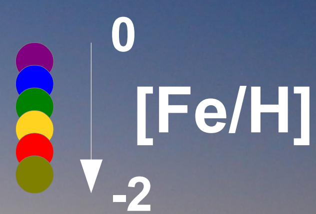
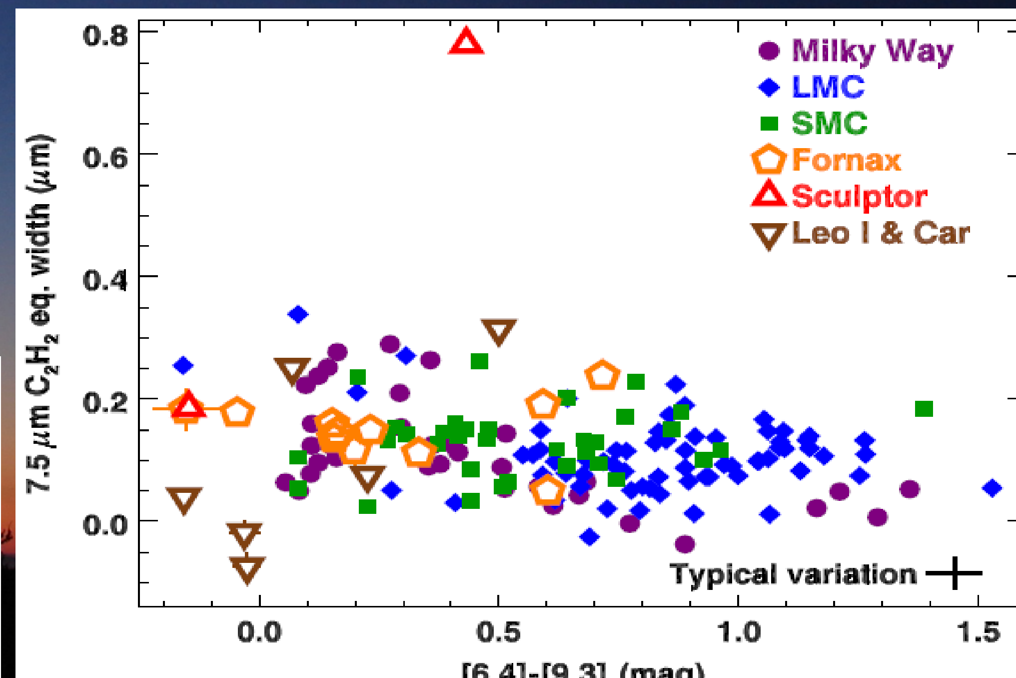
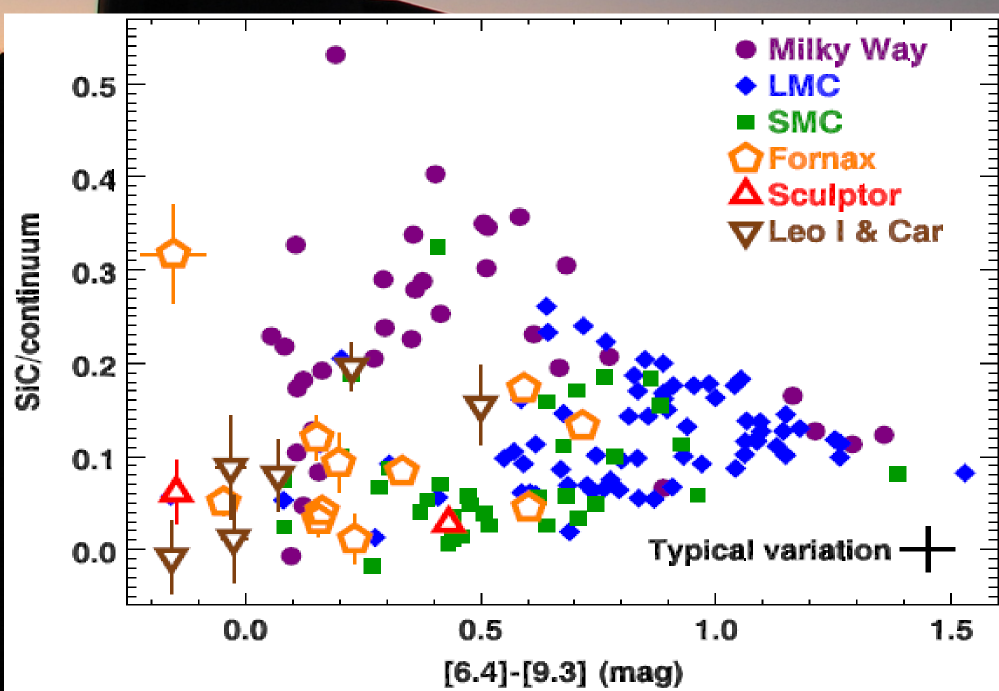
(They produce their own carbon!)







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

Sloan et al. (2012)

Observations

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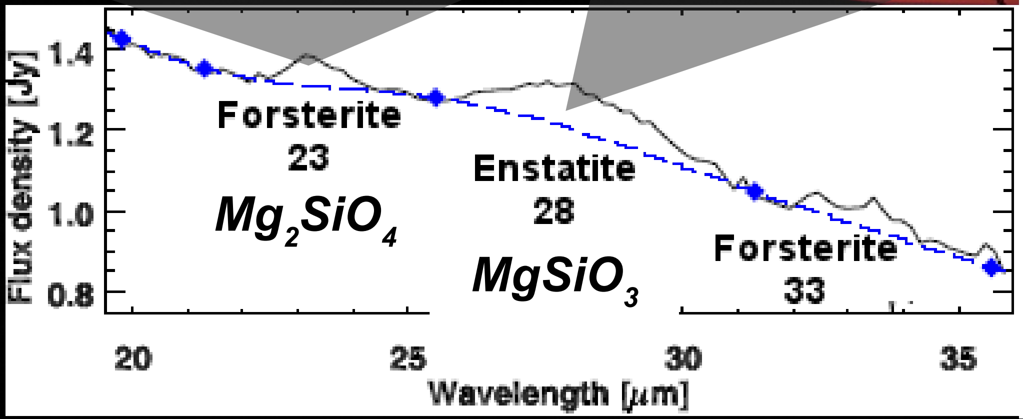
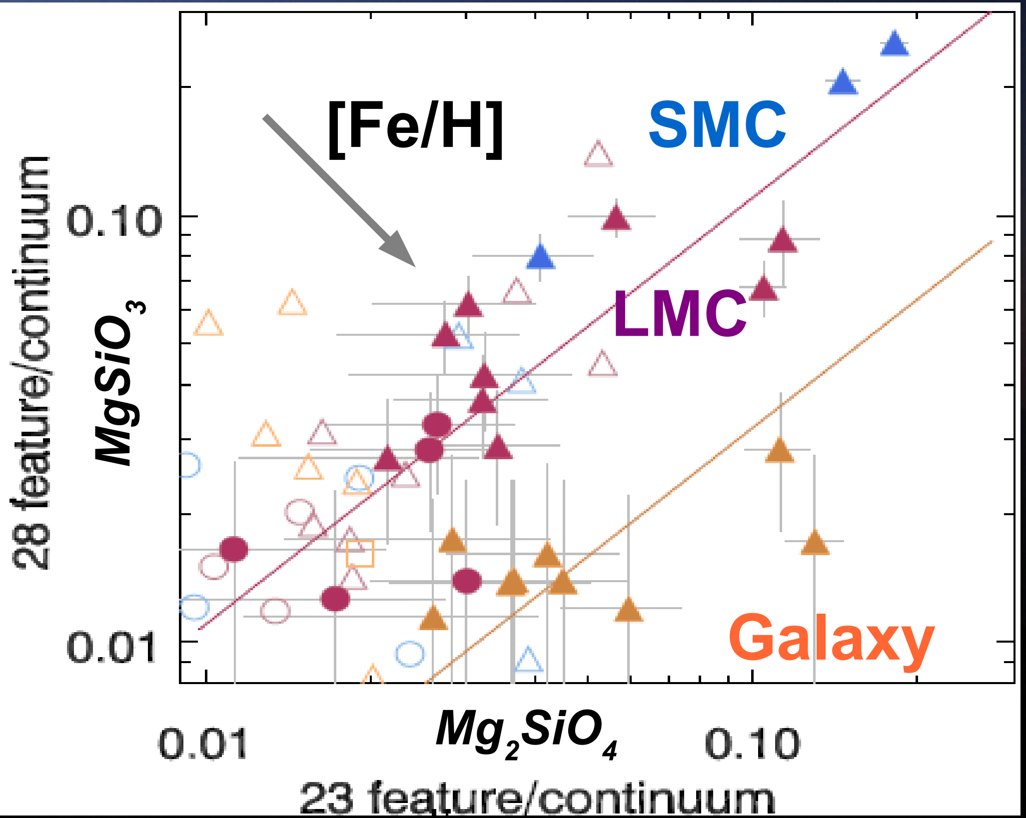
Change in entstatite/forsterite ratio of crystalline silicates as metallicity decreases





Jones et al. (2012)

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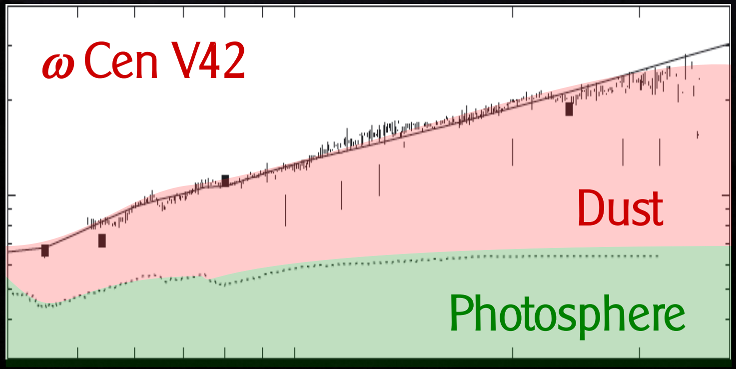
Parameter	$\delta \dot{M}$
Grain size[1]	$\pm 10\%$
Grain density	-50%
Dust formation temperature	$\pm 10\%$
Dust:gas ratio	-55% $+125\%$
Velocity distribution	$\sim +500\%$
Photosphere	$\pm 12\%$ $\pm 15\%$
Calculation error[2]	$\pm 30\%$
Total	$\sim^{+7}_{-4} \times$

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.
    - 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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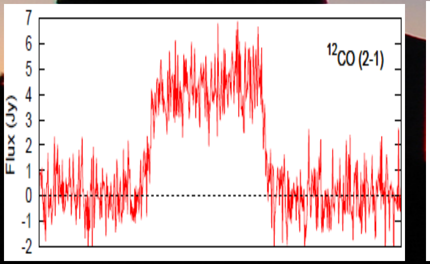
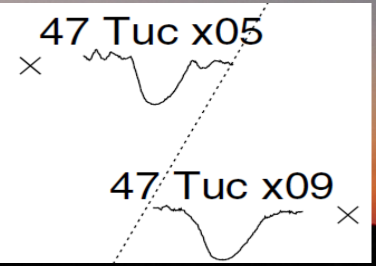
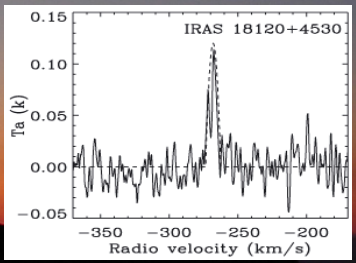
Mixed observational data on metal-poor stars



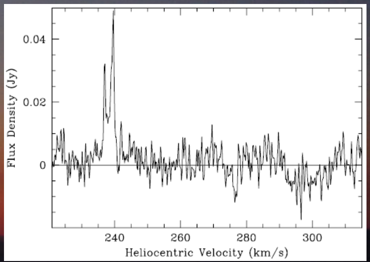
McDonald et al. (in prep.)
CO (3-2, 2-1)
EU Del
Oxygen-rich SRV
Probable thick disk star
9.5 km/s outflow



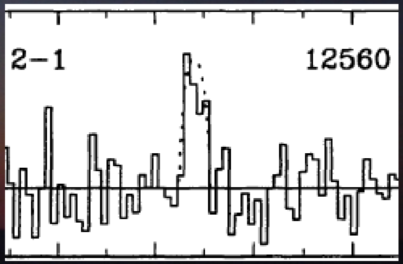
McD & van Loon (2007)
Hα bisectors
Globular clusters
Oxygen-rich
SRVs+Miras
5-20 km/s outflow



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?

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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)

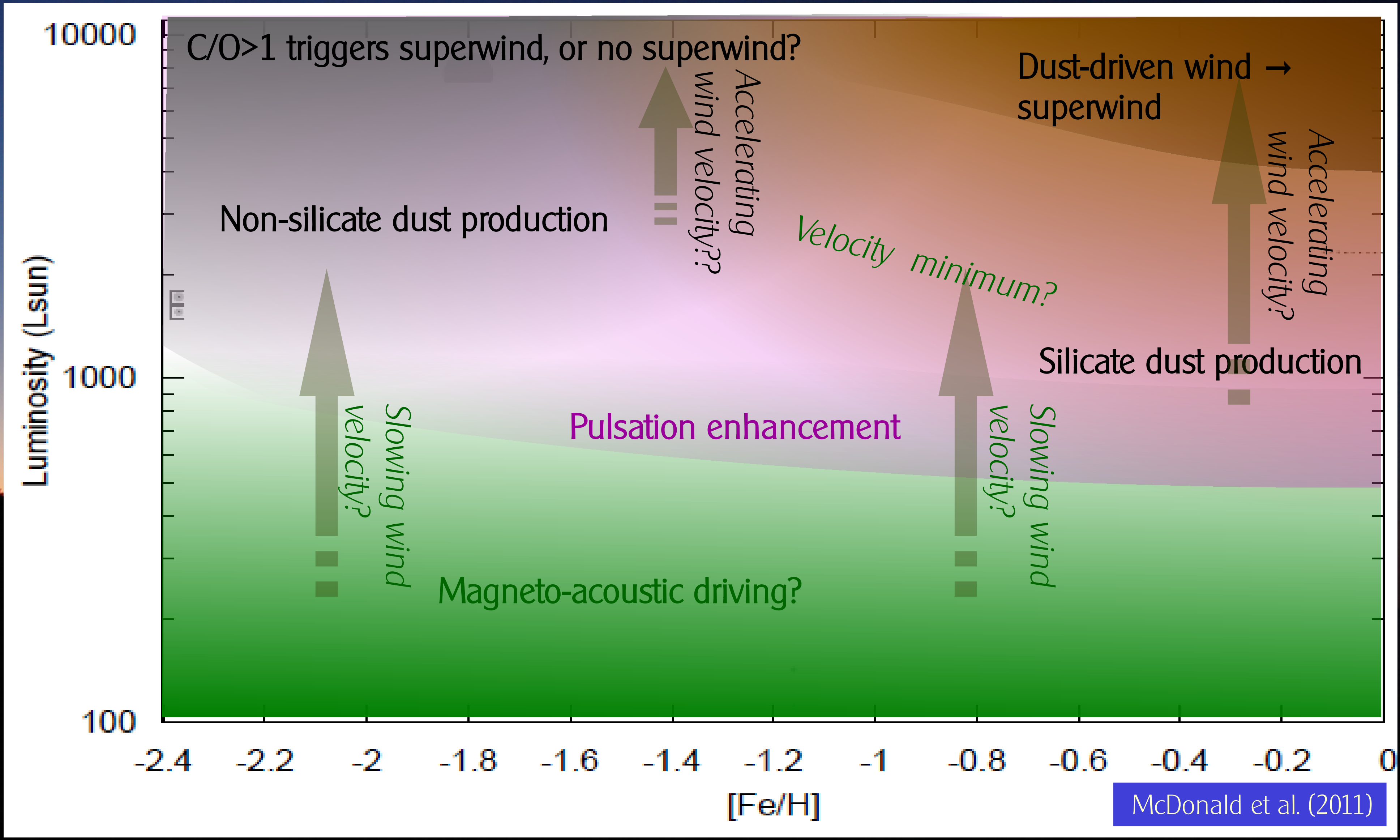
→ Mass-loss may be magneto-acoustically driven, later enhanced by pulsation?

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

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

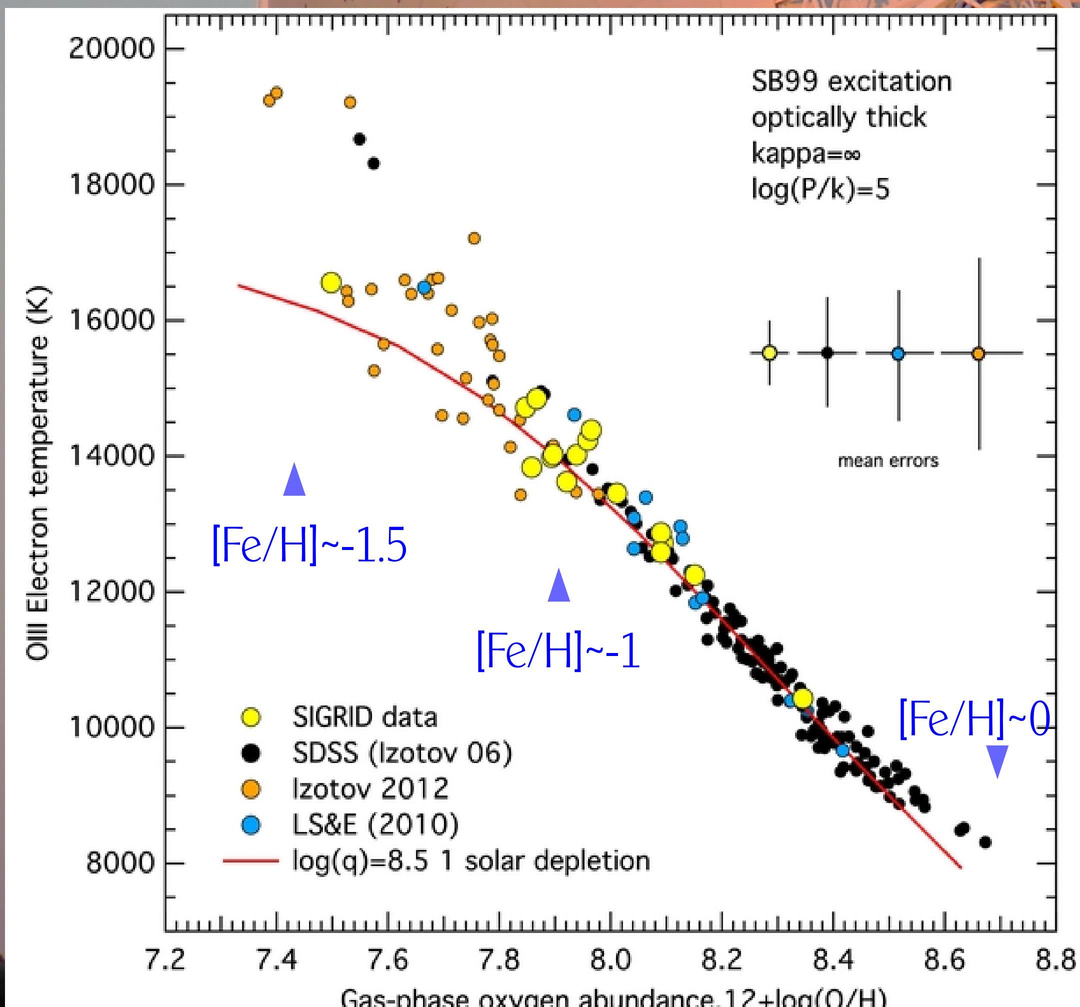
Lagadec & Zijlstra (2008)

Observations



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



Nichols et al. 2014

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

Breaking dust

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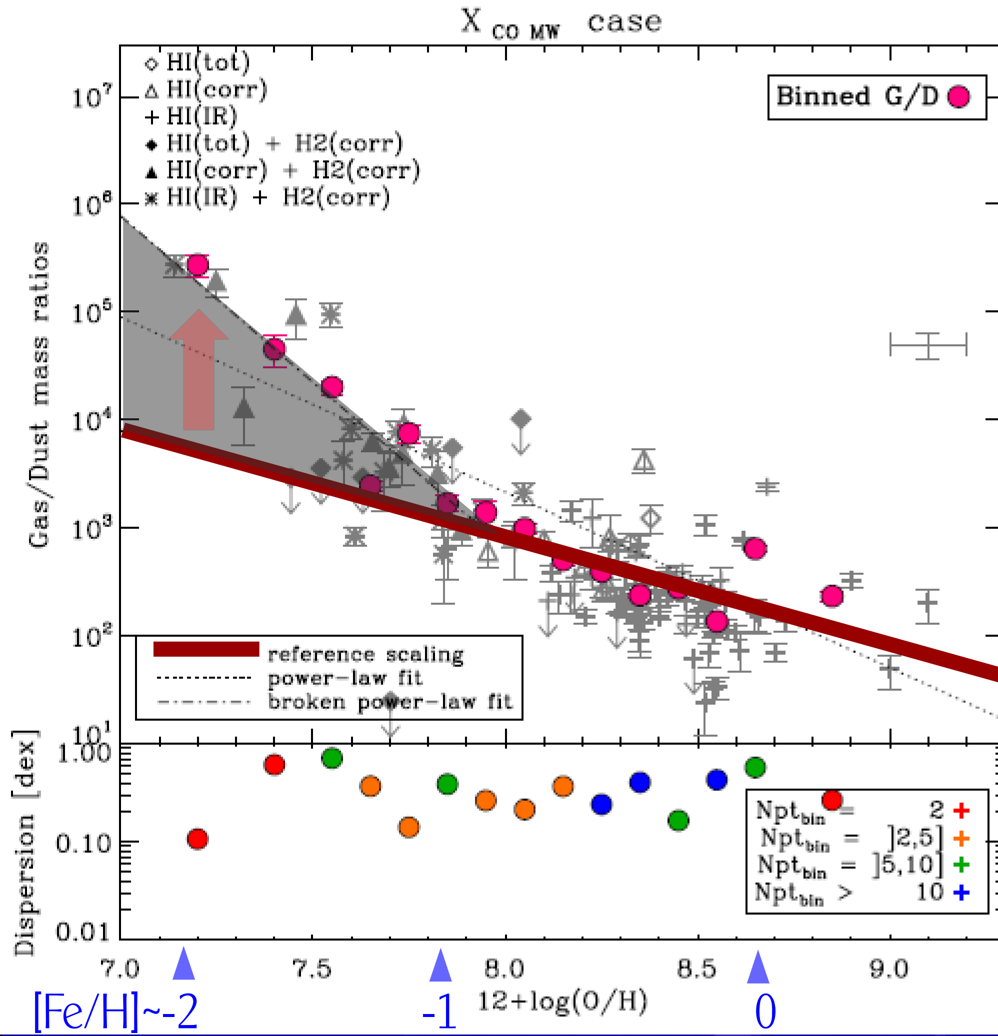
(2) Sputtering: dust grain – ion collisions
(3) Photo-desorption: dust grain – photon interactions

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.



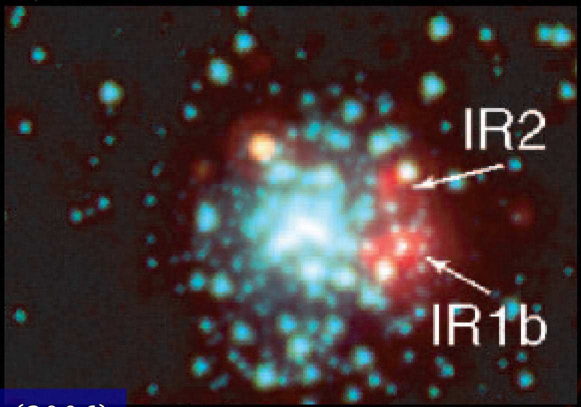
Rémy-Ruyer et al. 2014; see also Galametz+11, Draine+07

Radiation on ISM in globular clusters

Only two detections of ISM in globular clusters:

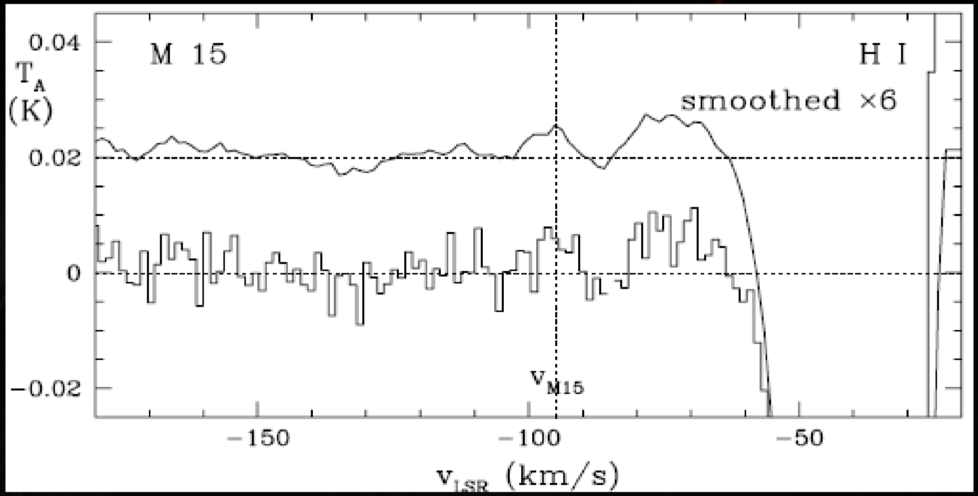
M15
0.3 $M_{\odot}$ of dusty neutral ISM

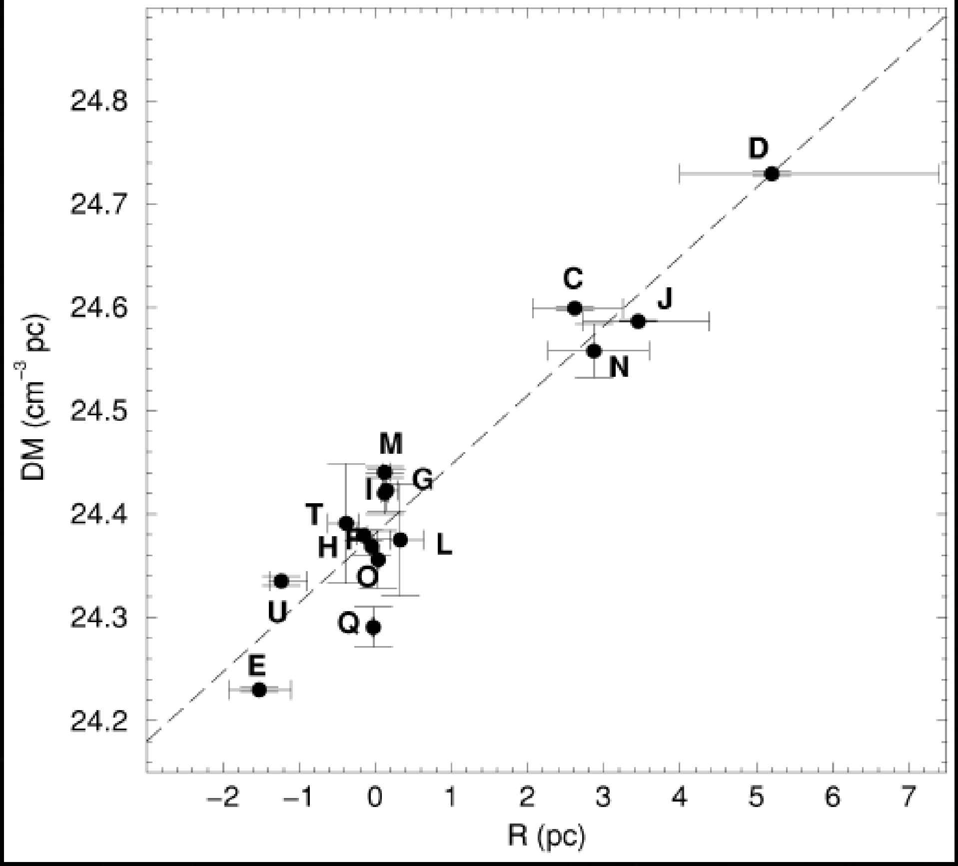
47 Tuc
0.1 $M_{\odot}$ of ionised ISM in core



Boyer et al. (2006)

Van Loon et al. (2006)



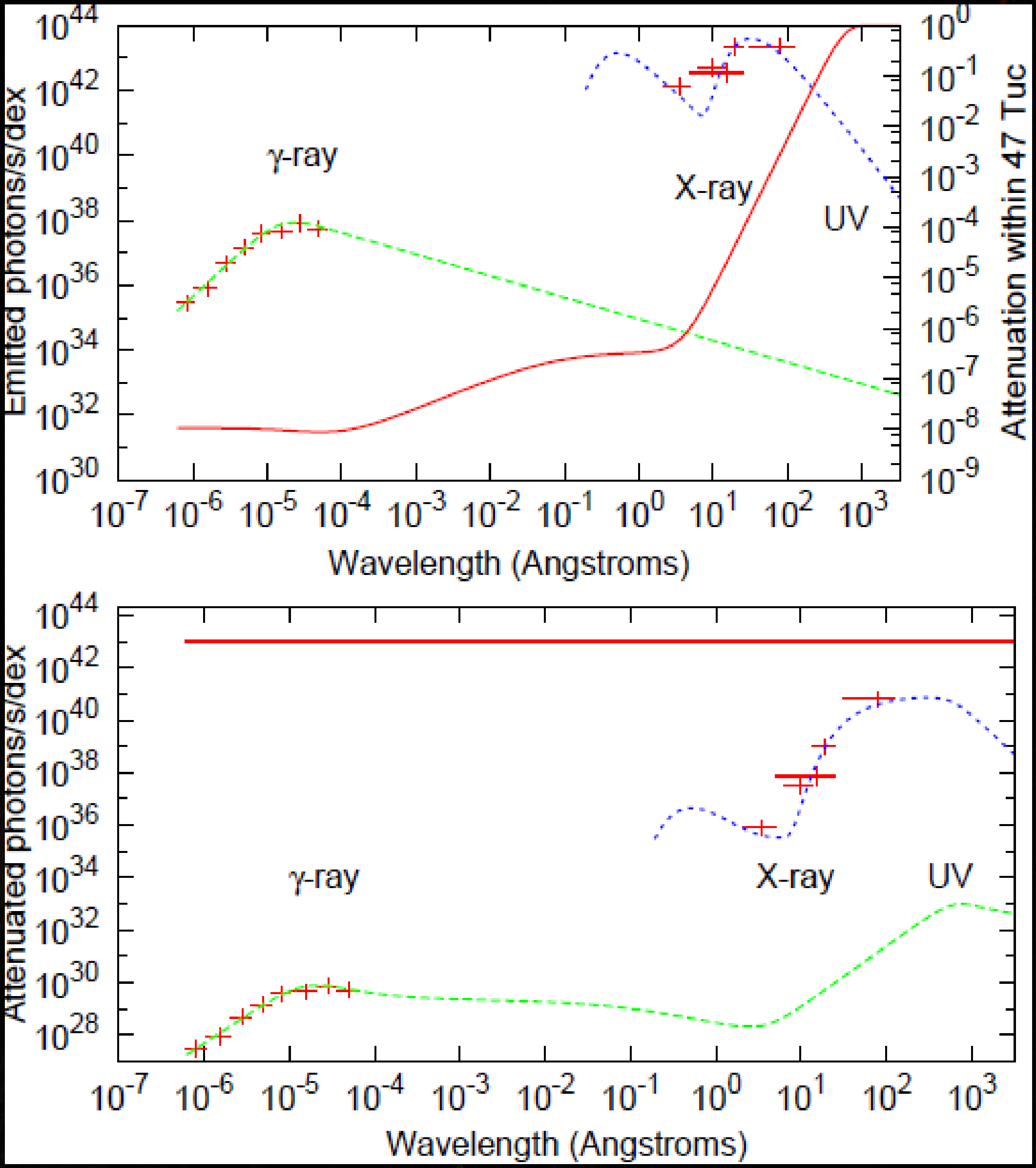


Freire et al. (2001)

Dust is probably cleared within ~1 Myr.

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.

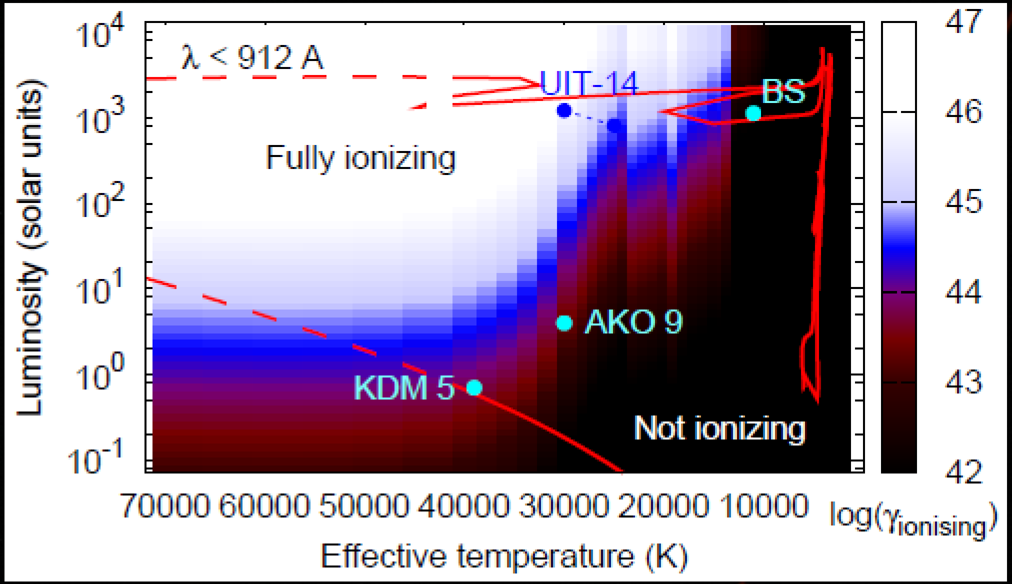
Need a UV source.

Invisible to us: absorbed by Galactic hydrogen

McDonald & Zijlstra (2015a)

Radiation on ISM in globular clusters

Need hot sources to emit enough UV...

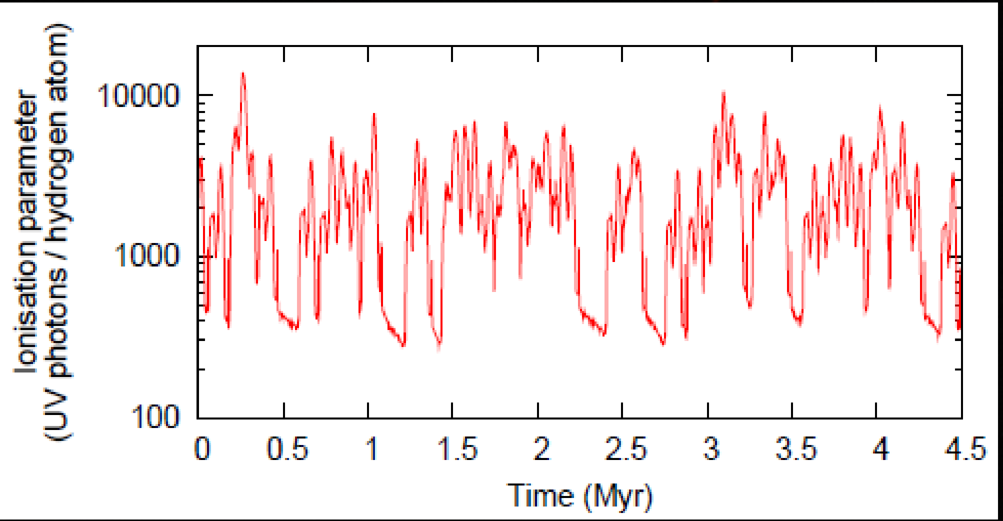


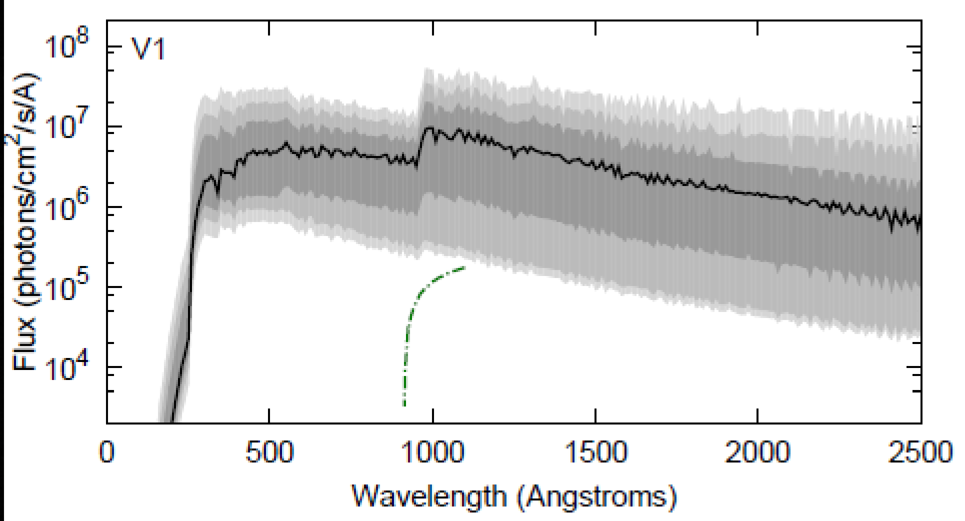
A single post-AGB star produces enough UV photons to ionise the cluster ISM for 4 Myr of its white dwarf evolution.

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.

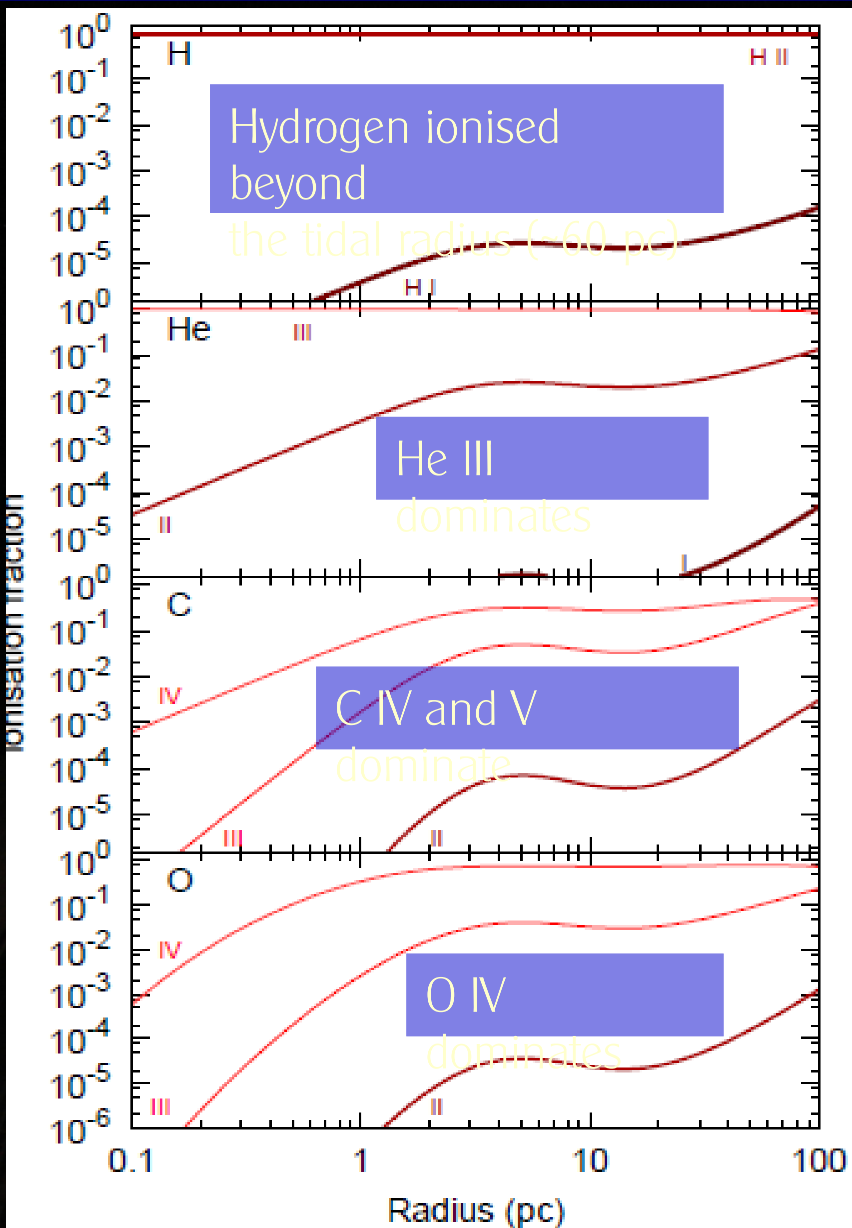




McDonald & Zijlstra (2015a)

Radiation on ISM in globular clusters

Conditions in the ISM are harsh

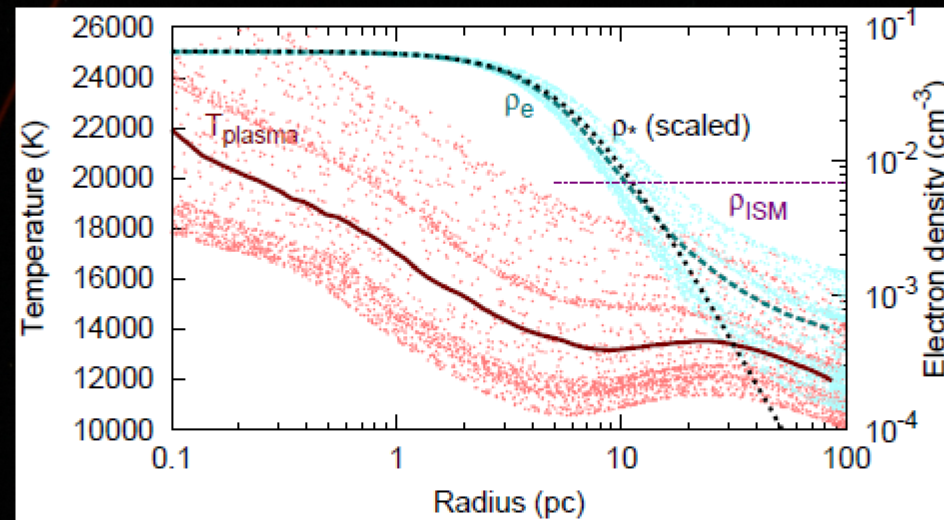


Hydrogen ionised beyond the tidal radius (~60 pc)

He III dominates

C IV and V dominate

O IV dominates



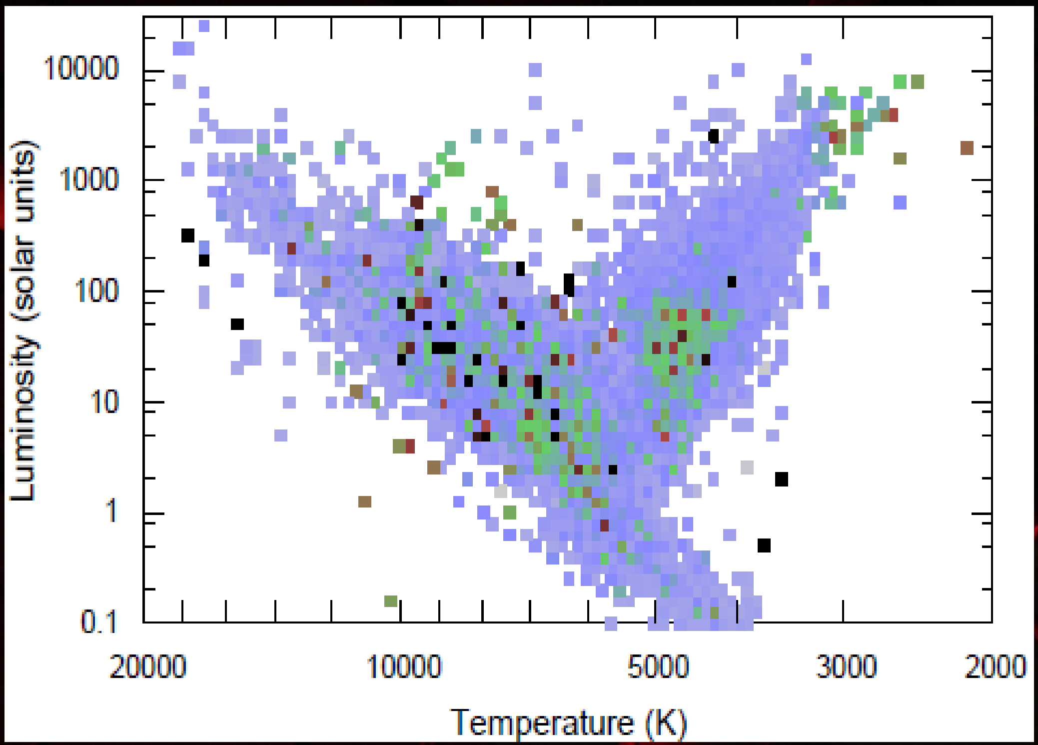
Plasma temperatures are 10000-20000 K

This gives the plasma enough energy to overflow the cluster

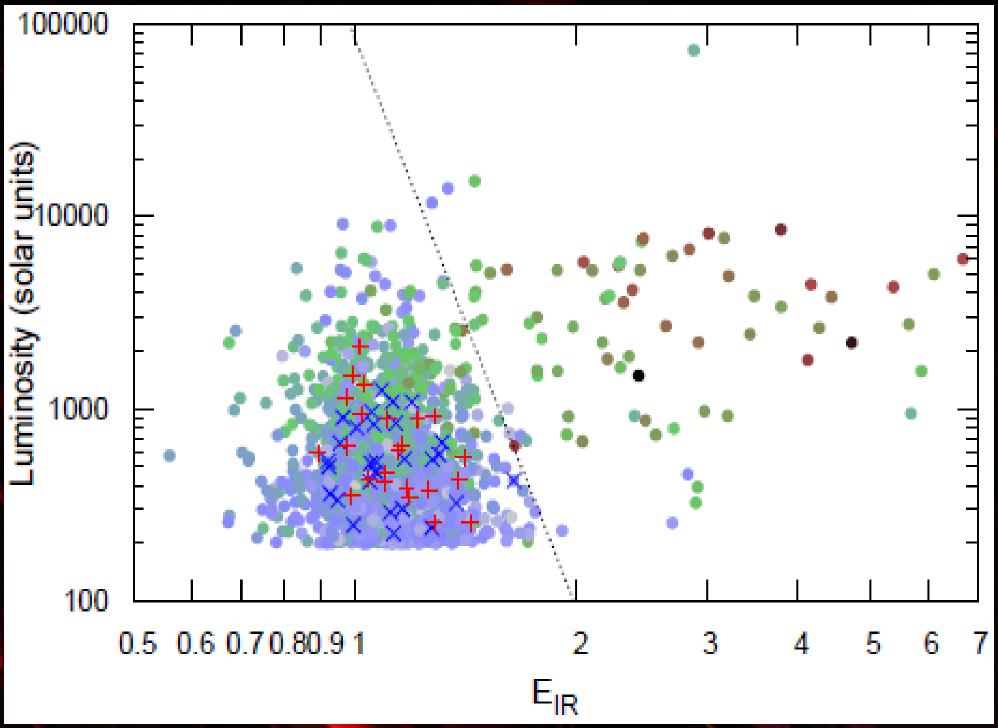
McDonald & Zijlstra (2015a)

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.

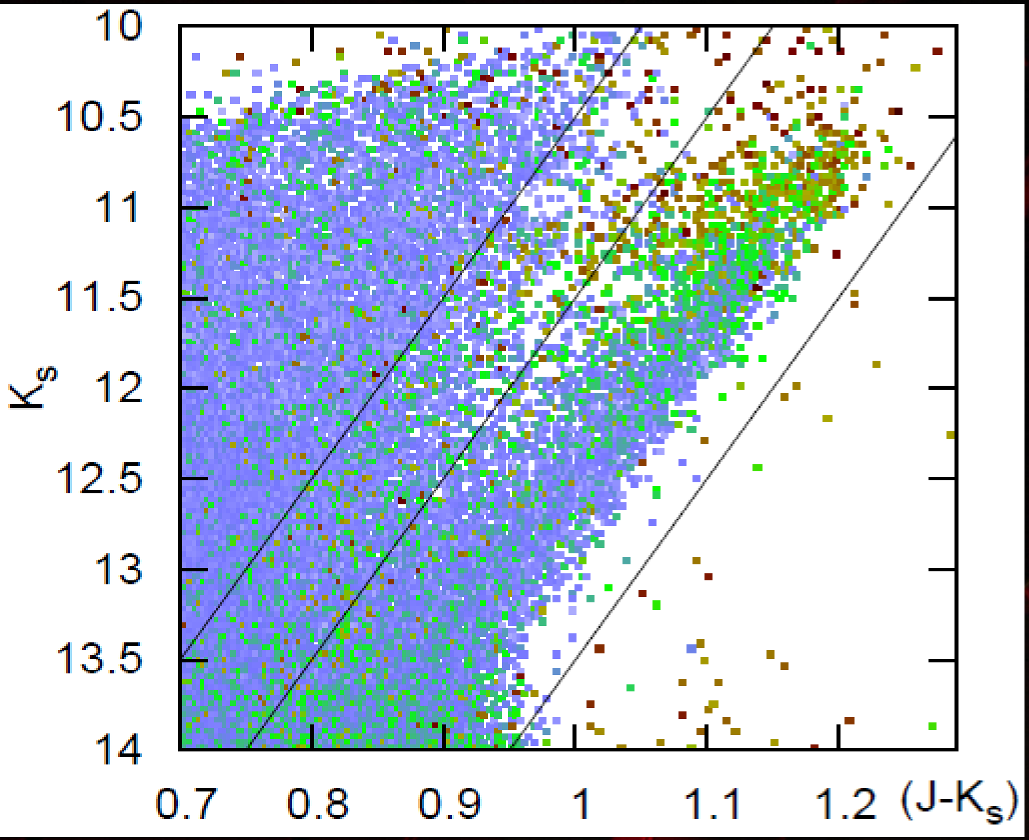
62 dusty giant stars with accurate distances, almost all known variables

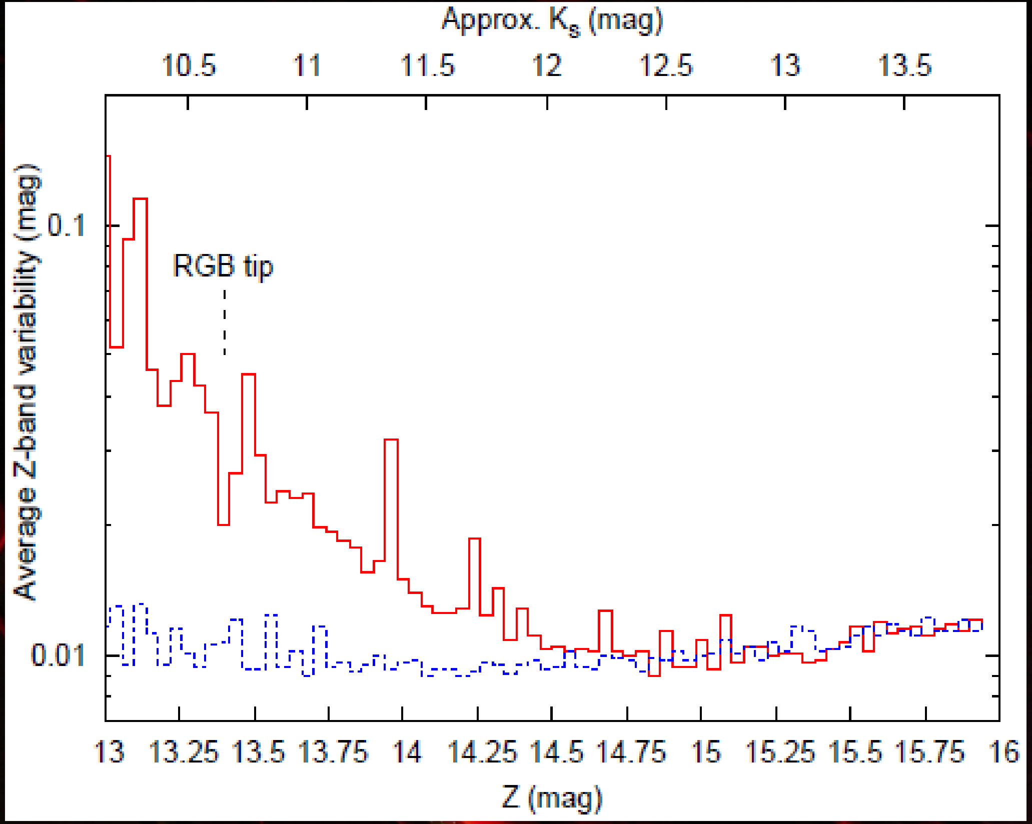
→ Pulsation comes before dust production

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.

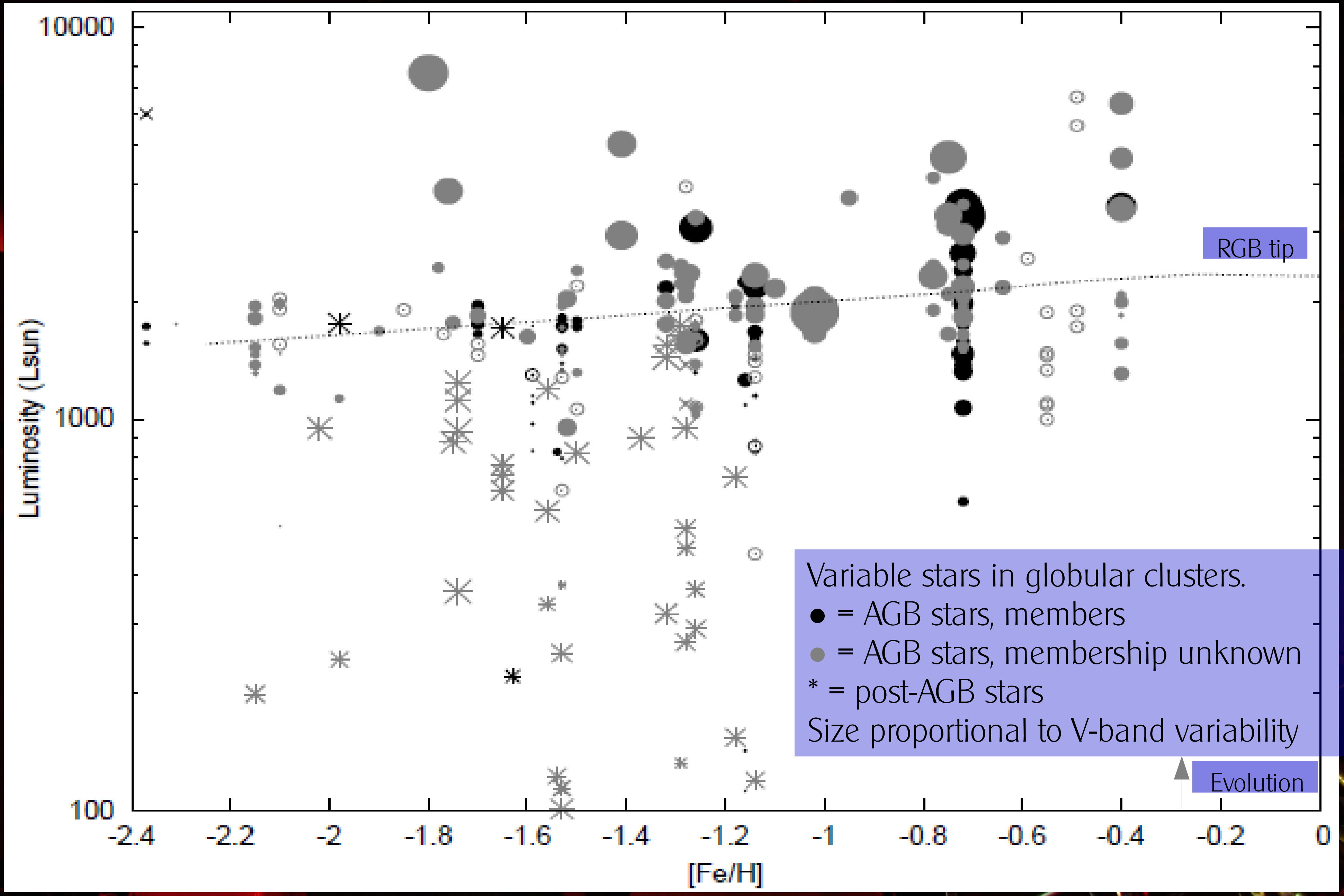




Every star is variable at some level (as *Kepler* tells us too)
No correlation of pulsation amplitude with dust production in *oxygen-rich* stars
→ Pulsation alone is not enough for dust production
RGB stars pulsate the same as AGB stars but don't tend to produce dust – a clue in the pulsation period

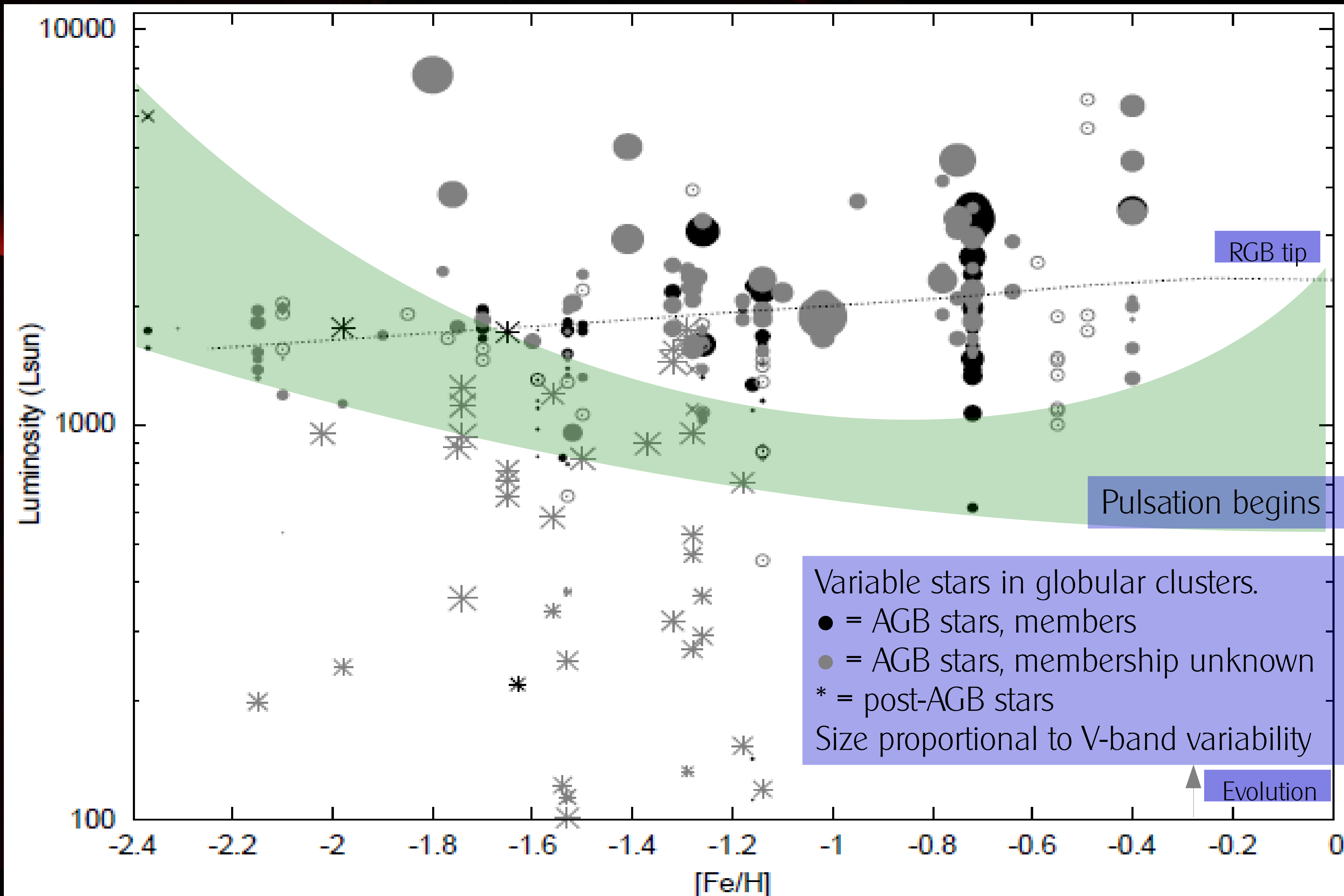
McDonald et al. (2013,2014,2016)

Asymptotic giant branch mass loss: globular clusters



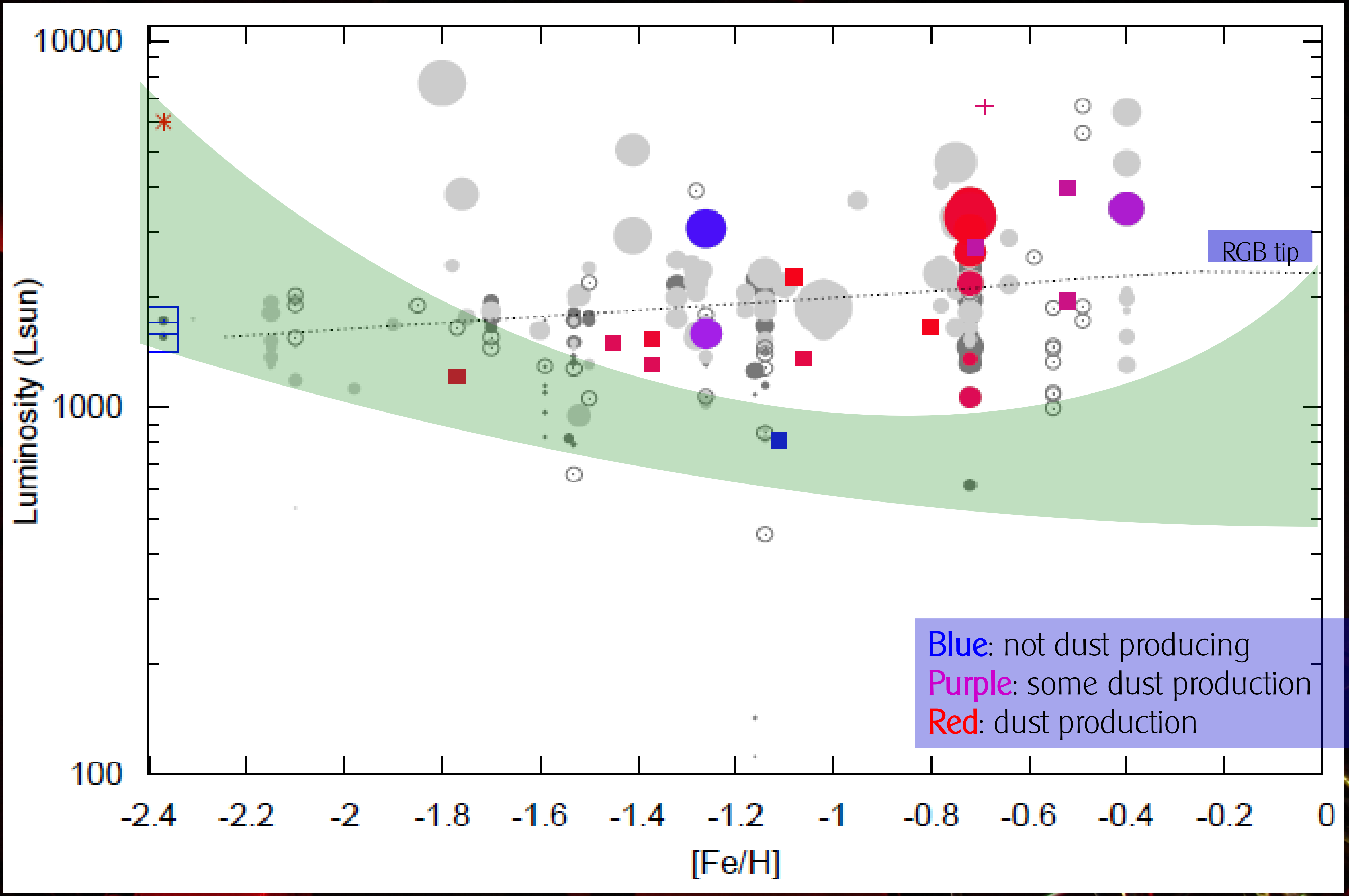
McDonald et al. (2011)

Asymptotic giant branch mass loss: globular clusters



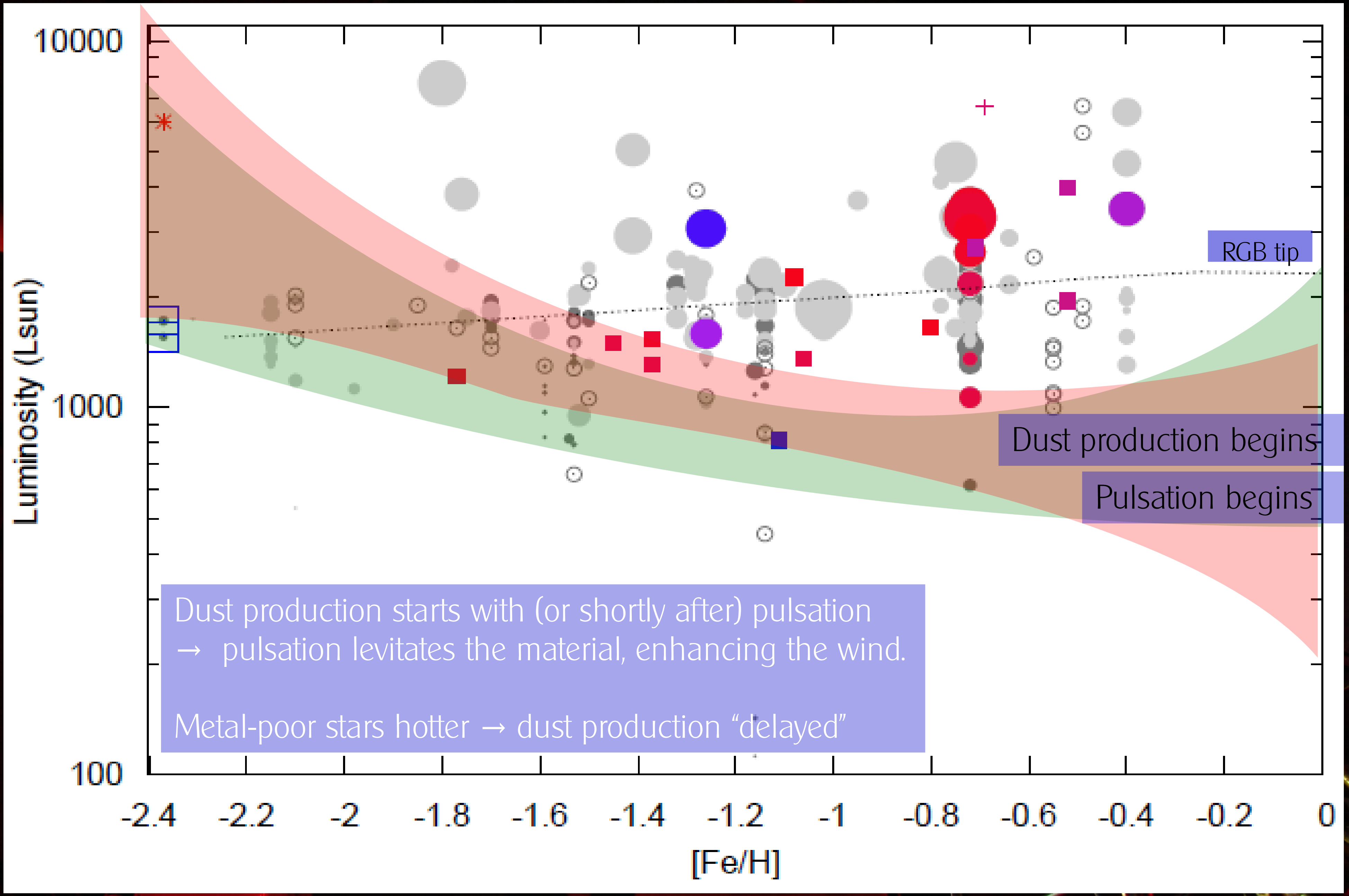
McDonald et al. (2011)

Asymptotic giant branch mass loss: globular clusters



McDonald et al. (2011)

Asymptotic giant branch mass loss: globular clusters



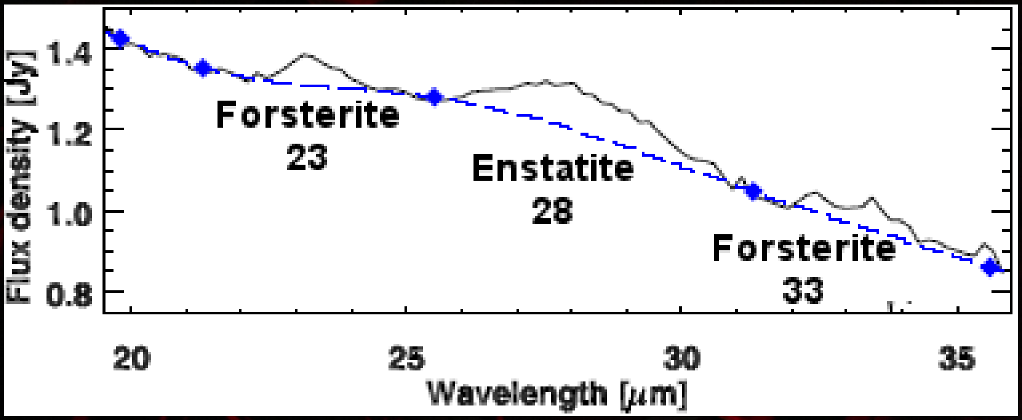
McDonald et al. (2011)

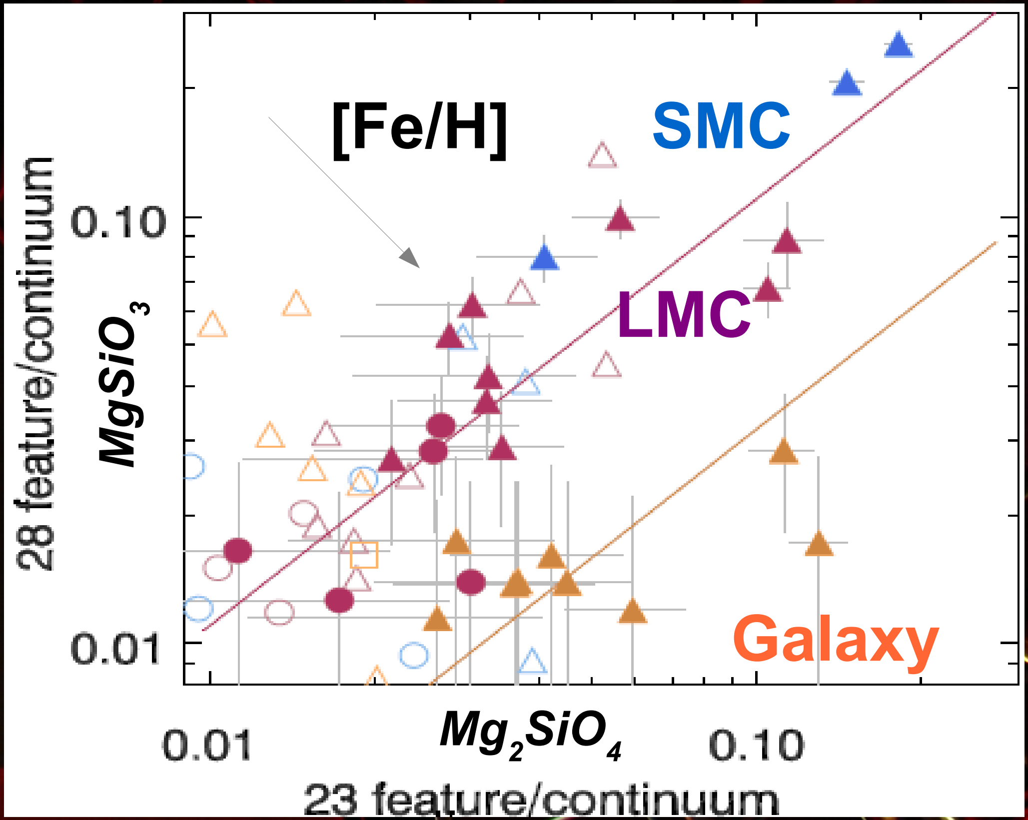
AGB dust production

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)

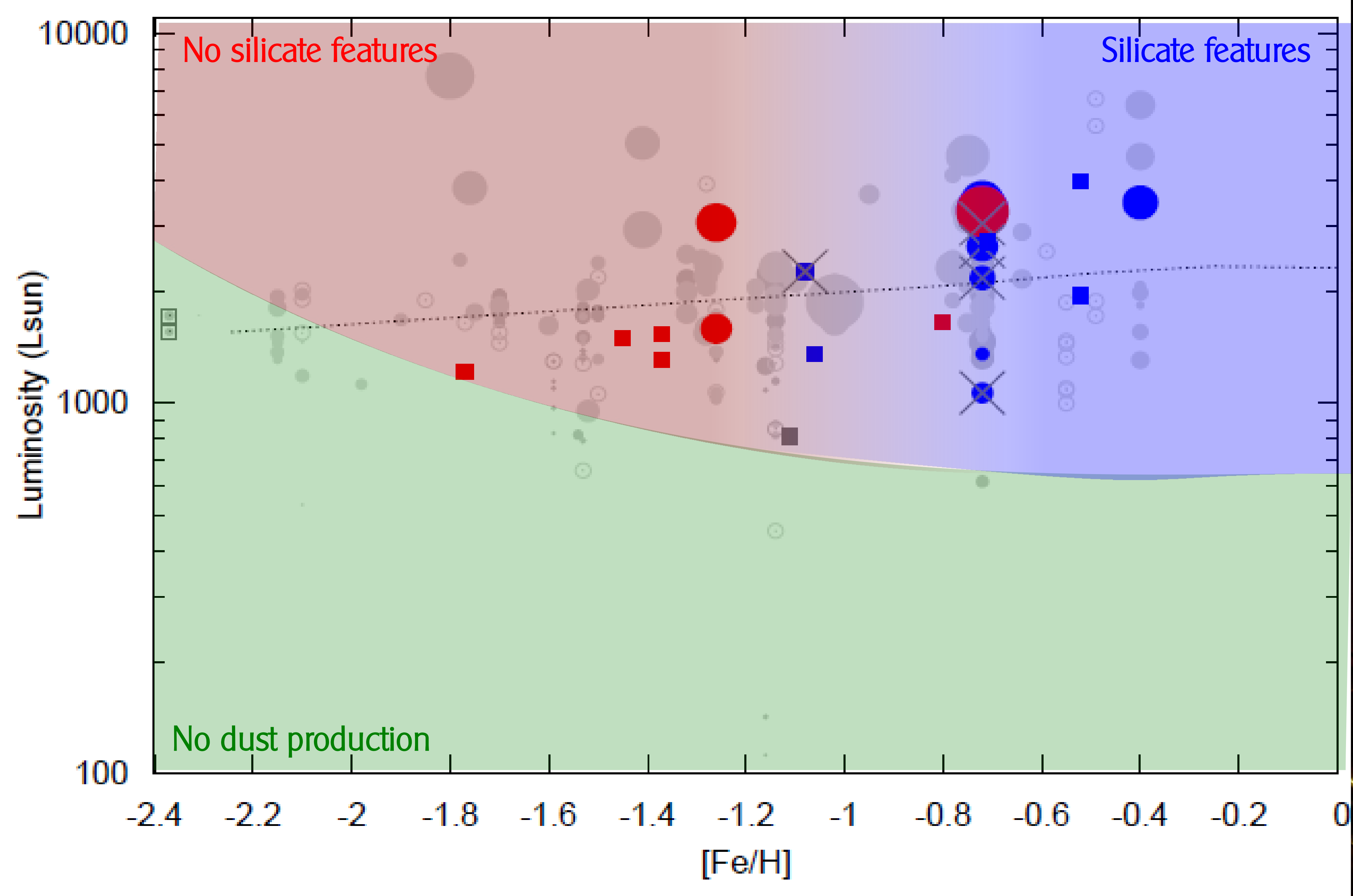
Some evidence to suggest **crystalline** silicates become simpler at low metallicity.



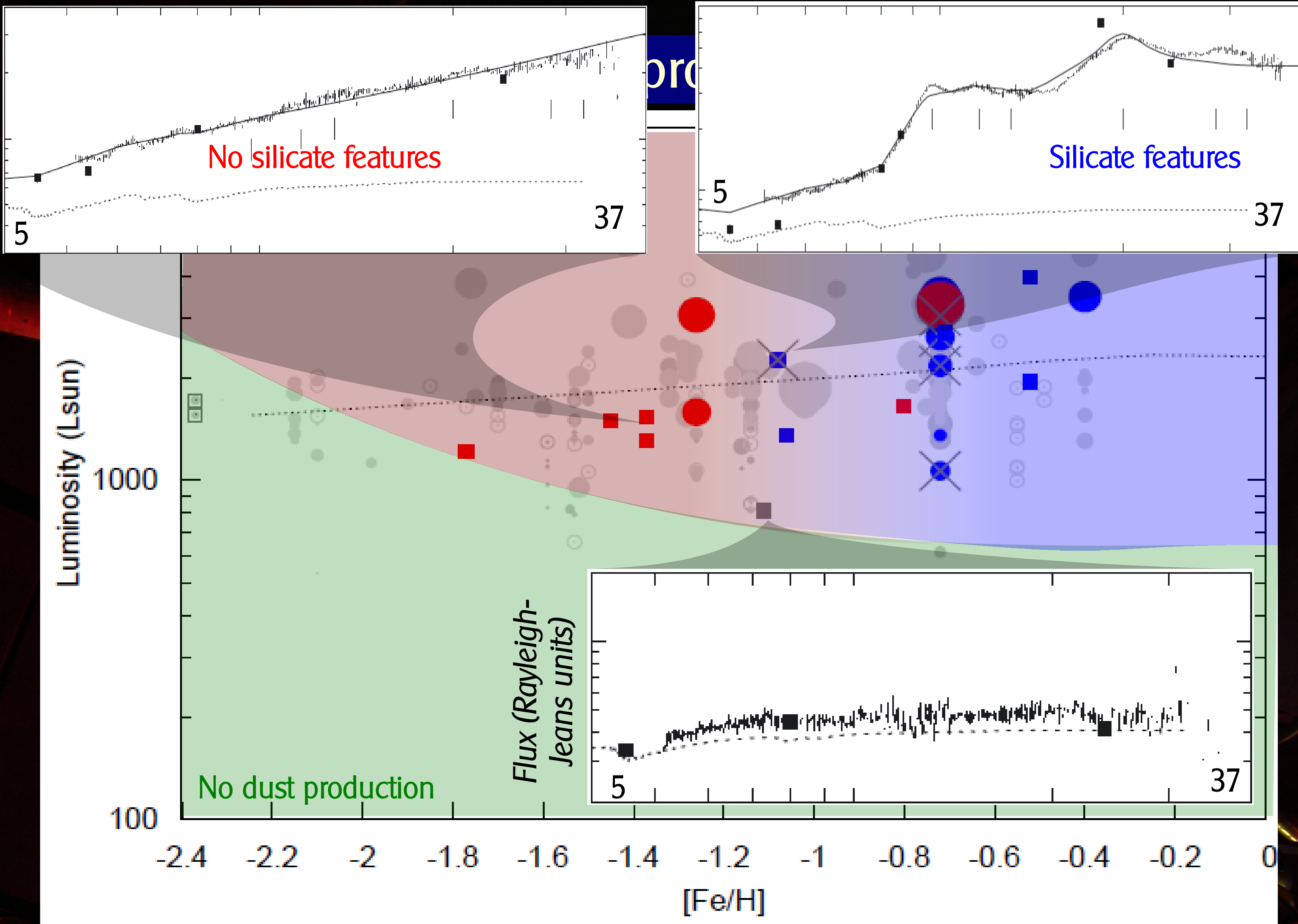


Jones et al. (2012)

AGB dust production



McDonald et al. (2010-2013)



McDonald et al. (2010-2013)