Sowing the seeds of dust

What does it take to make a giant star dusty?

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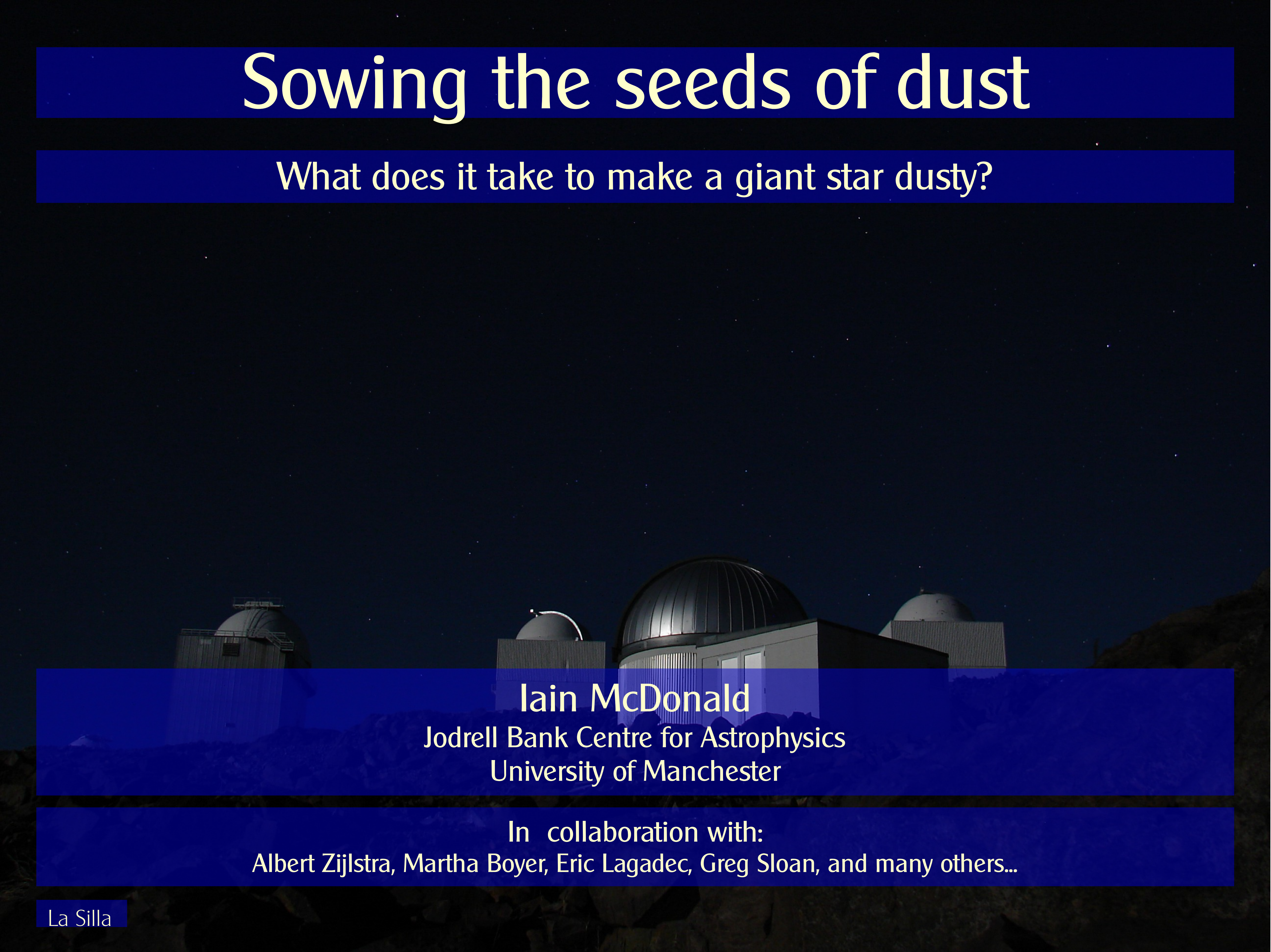
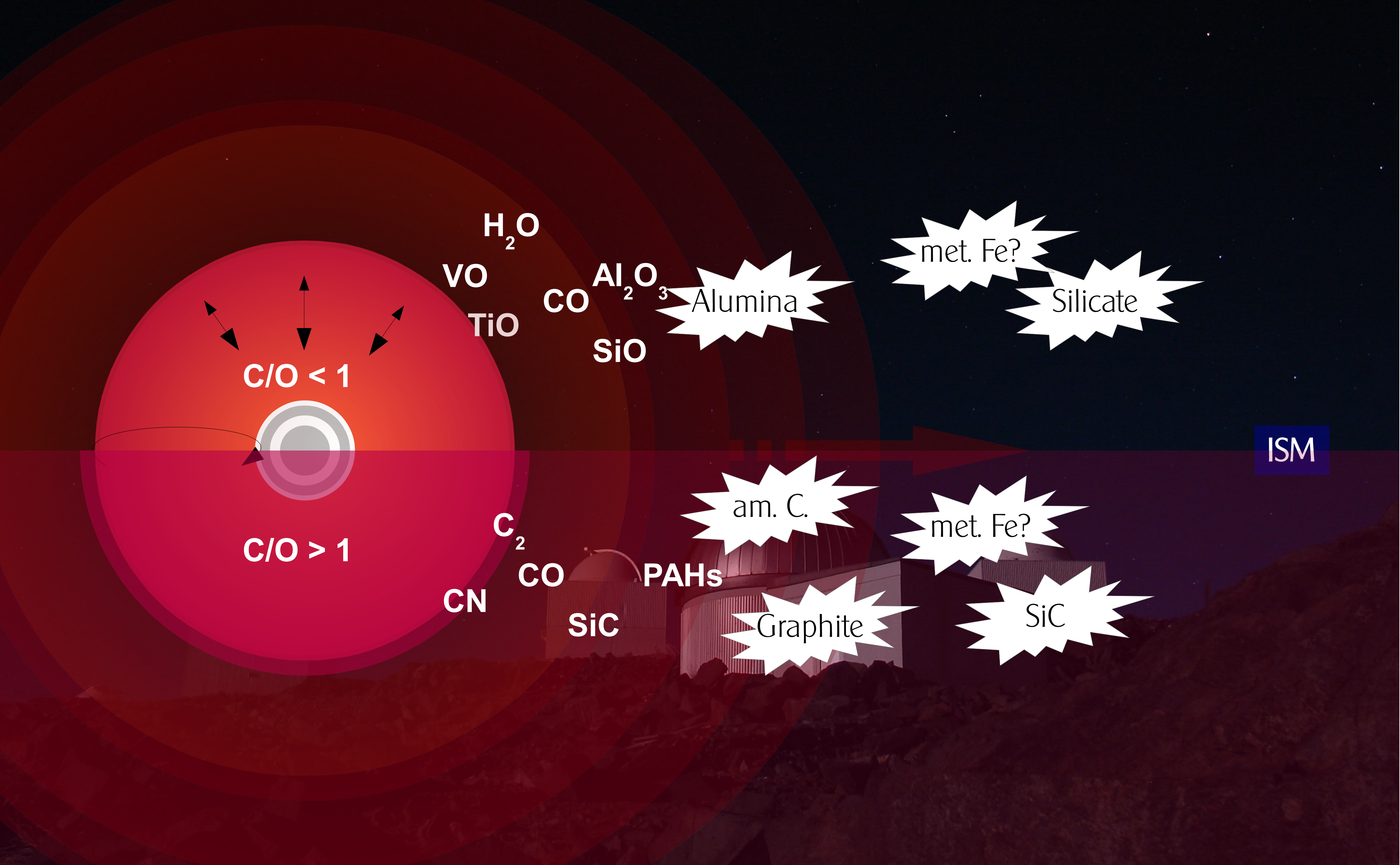
University of Manchester

In collaboration with:
Albert Zijlstra, Martha Boyer, Eric Lagadec, Greg Sloan, and many others...


La Silla

Pulsation-enhanced radiatively-driven winds



C/O < 1

H_2O

VO

TiO

CO

Al_2O_3

SiO

Alumina

met. Fe?

Silicate

ISM

C/O > 1

C_2

CO

CN

SiC

PAHs

am. C.

met. Fe?

Graphite

SiC

following Le Bertre (1997)

Which stars are dusty?

Luminous metal-poor AGB star

DUSTY

Luminous metal-rich AGB star

Faint metal-poor AGB star

DUSTY

Faint metal-rich AGB star

Who cares?

What happens if metal-poor stars lose mass more slowly?

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More nuclear fusion on the AGB

Brighter AGB tip

Core growth

Less mass lost

More dredge-up

More dust made

More near-IR flux

Who cares?

What happens if metal-poor stars lose mass more slowly?

More nuclear fusion on the AGB

Brighter AGB tip

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Less mass lost

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More near-IR flux

SNe rate

WD bigger

Less ISM

Greater C/O

Higher dust:gas ratio

[α/Fe]

[K, U, ... /Fe]

Less star formation

Carbon-rich ISM?

Affects galaxy SED

Radiogenic heating in planets

Fewer planets?

Diamond planets?

[O/Fe]

[Si/Fe]

ISM cools efficiently

Jeans mass lower

Metallicity measures

Planetary core masses

More planets?

Bottom-heavy IMF

Affects population modelling

Interstellar extinction curve

Fewer giant planets

Cosmological foregrounds

Some expectations

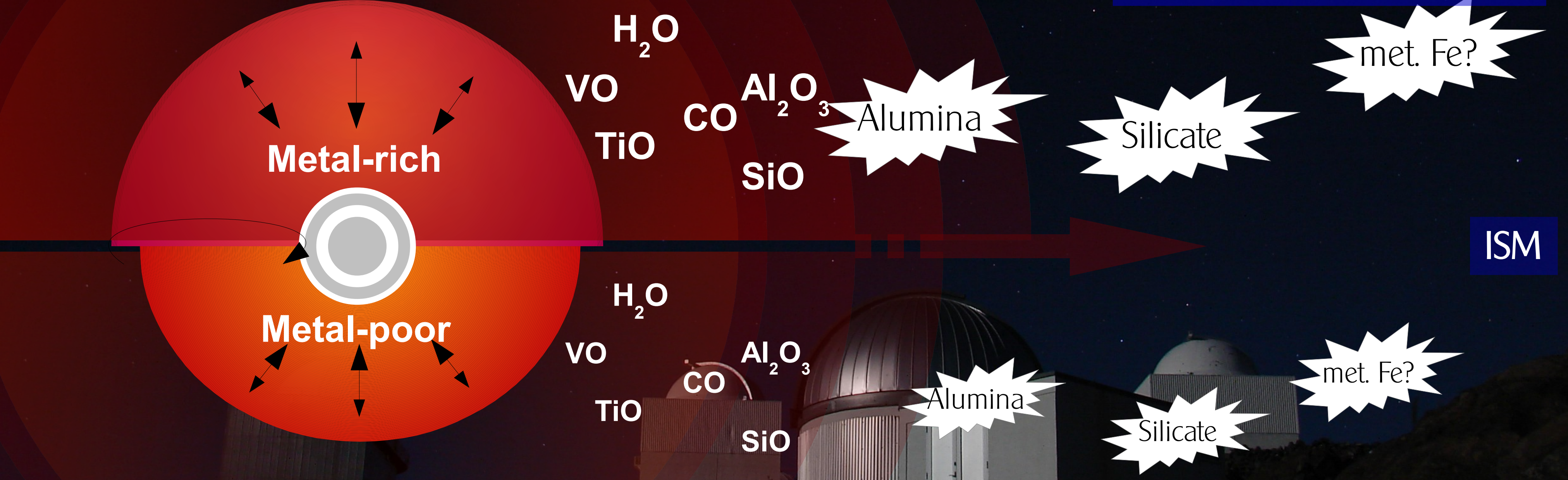
1. Smaller stars → material leviated further before condensation

2. Pulsations weaker → harder to levitate material

Kjeldsen & Bedding (1995)

5. Radiation driving less effective → slower outflow?

6. Different dust formation pathways (different chemistry, conditions)?



3. Fewer metals → fewer molecules (but alpha-element enhanced.)

4. Less dust but fewer dust seeds → fewer grains or smaller grains?

McDonald et al. (2012)

7. Dust shielding less effective? Gas may be dissociated closer to the star.

Which stars are dusty?

DUSTY?

Luminous metal-poor AGB star

DUSTY

Luminous metal-rich AGB star

DUSTY?

Faint metal-poor AGB star

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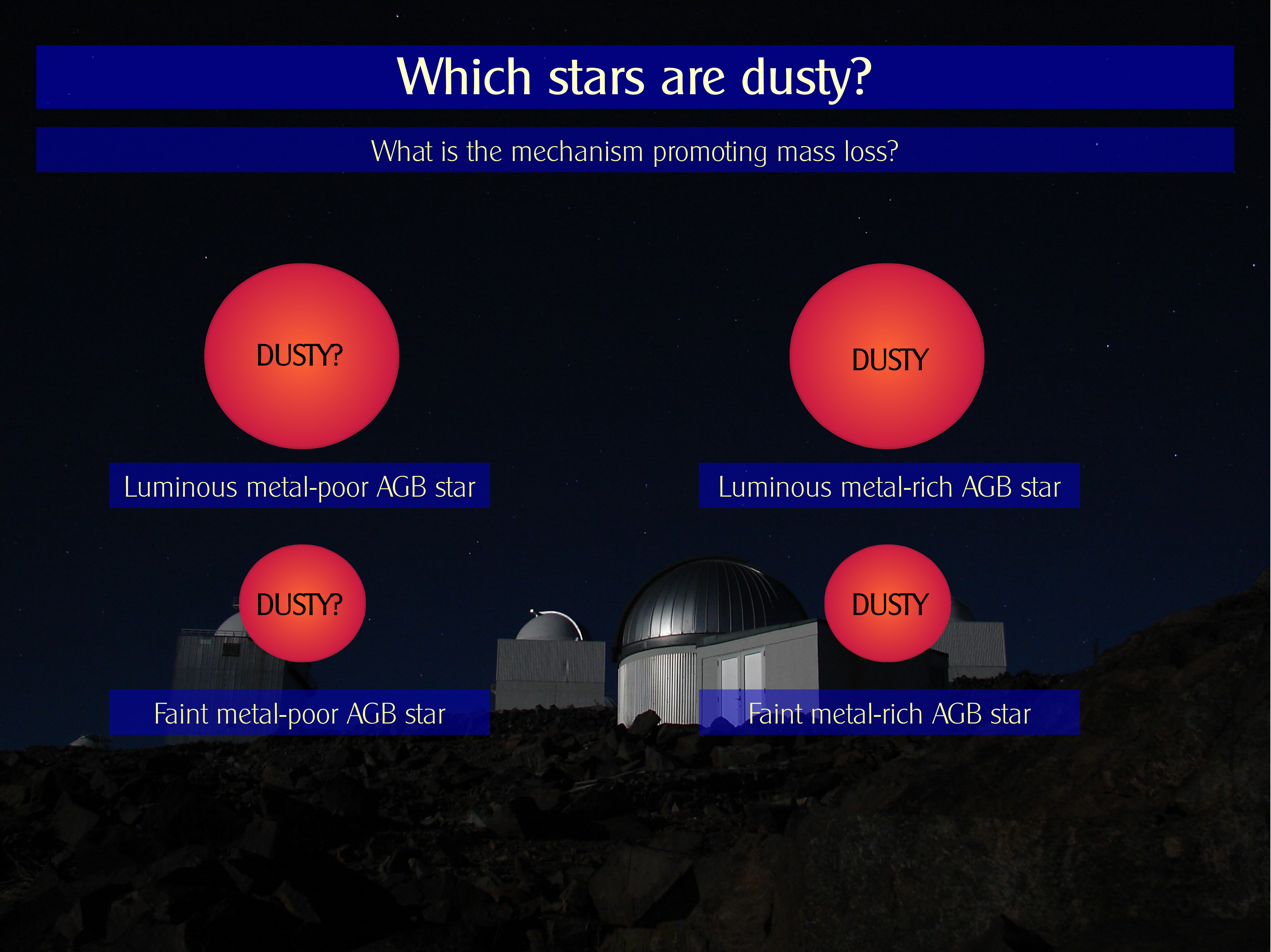
Faint metal-rich AGB star

Which stars are dusty?

What is the mechanism promoting mass loss?



DUSTY?

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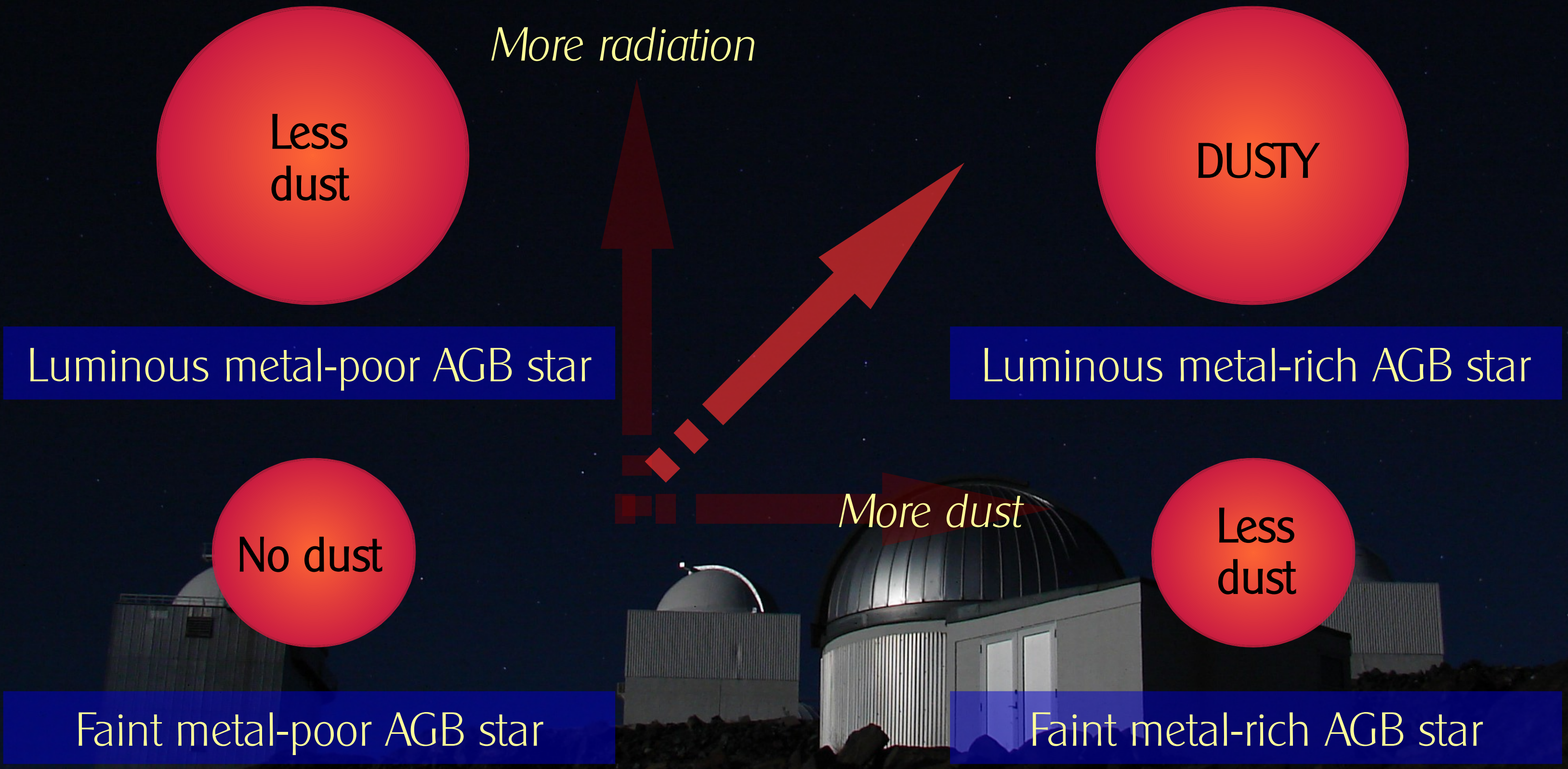
Which stars are dusty?

What is the mechanism promoting mass loss?

Radiation pressure on dust?



Less dust

Luminous metal-poor AGB star

More radiation

DUSTY

Luminous metal-rich AGB star

No dust

Faint metal-poor AGB star

More dust

Less dust

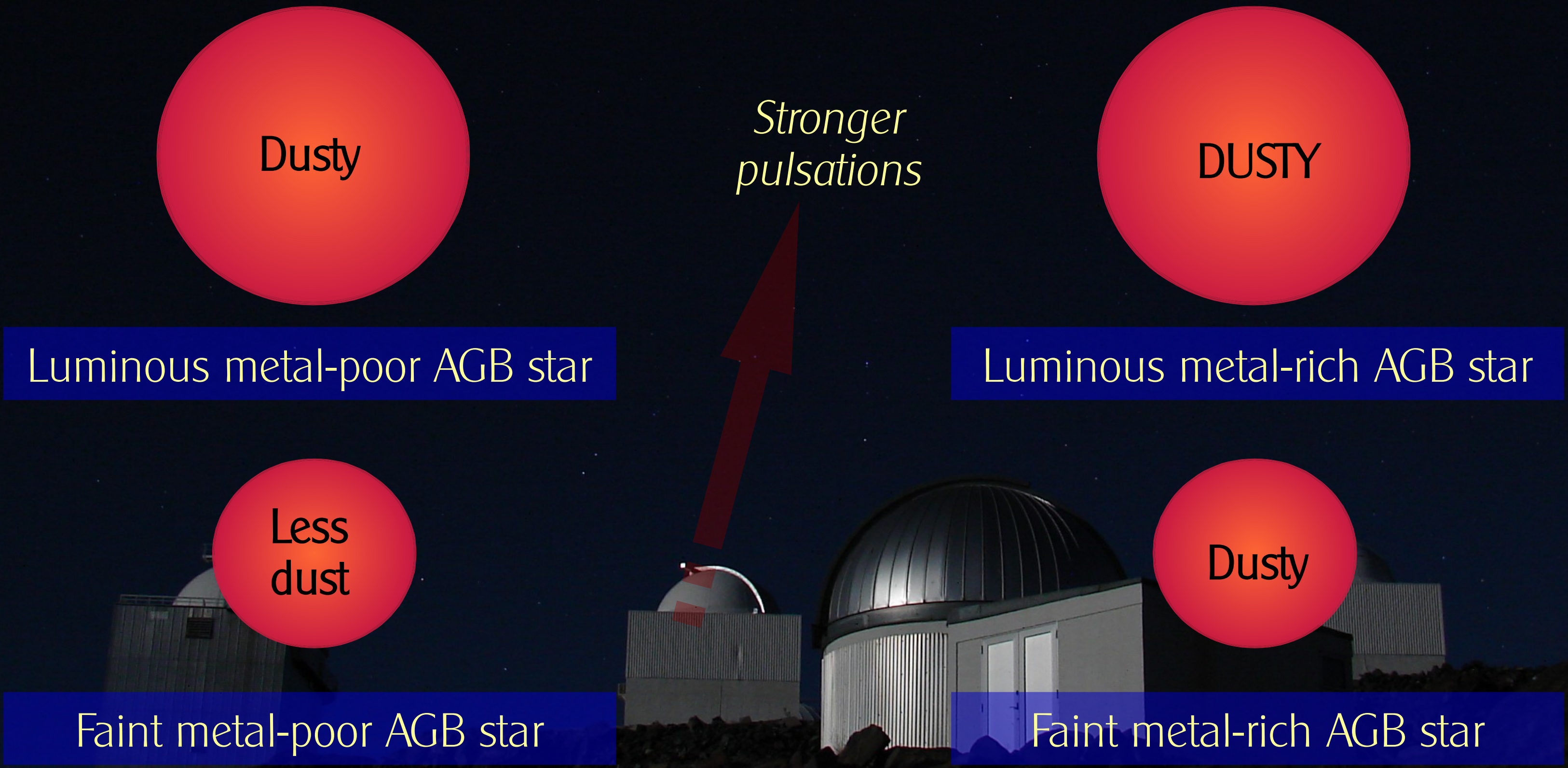
Faint metal-rich AGB star

Which stars are dusty?

What is the mechanism promoting mass loss?

Radiation pressure on dust?

Stellar pulsation?



Dusty

Luminous metal-poor AGB star

Less dust

Faint metal-poor AGB star

Stronger pulsations

DUSTY

Luminous metal-rich AGB star

Dusty

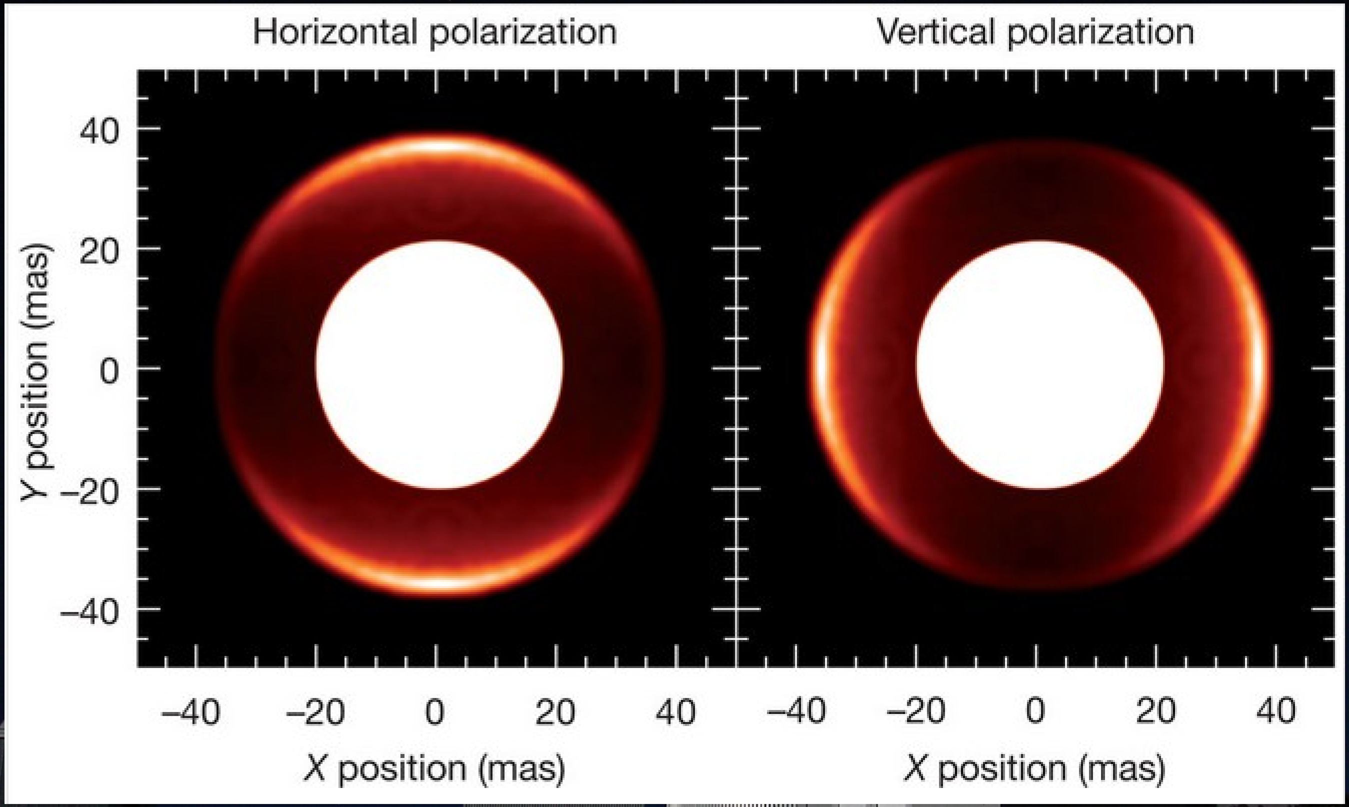
Faint metal-rich AGB star

If radiation pressure dictates the mass-loss rate → strong (~linear) dependence on [Fe/H] & luminosity

If pulsation dictates the mass-loss rate → weak dependence on [Fe/H] & luminosity

Local observations support radiation pressure

Winds are momentum driven as starlight is scattered off large grains




Winds of M-type AGB stars driven by micron-sized grains

S. Höfner

Norris et al. (2012), Hoefner et al. (2008)

Local observations support radiation pressure

Evidence for strong acceleration after a few stellar radii, consistent with dust formation

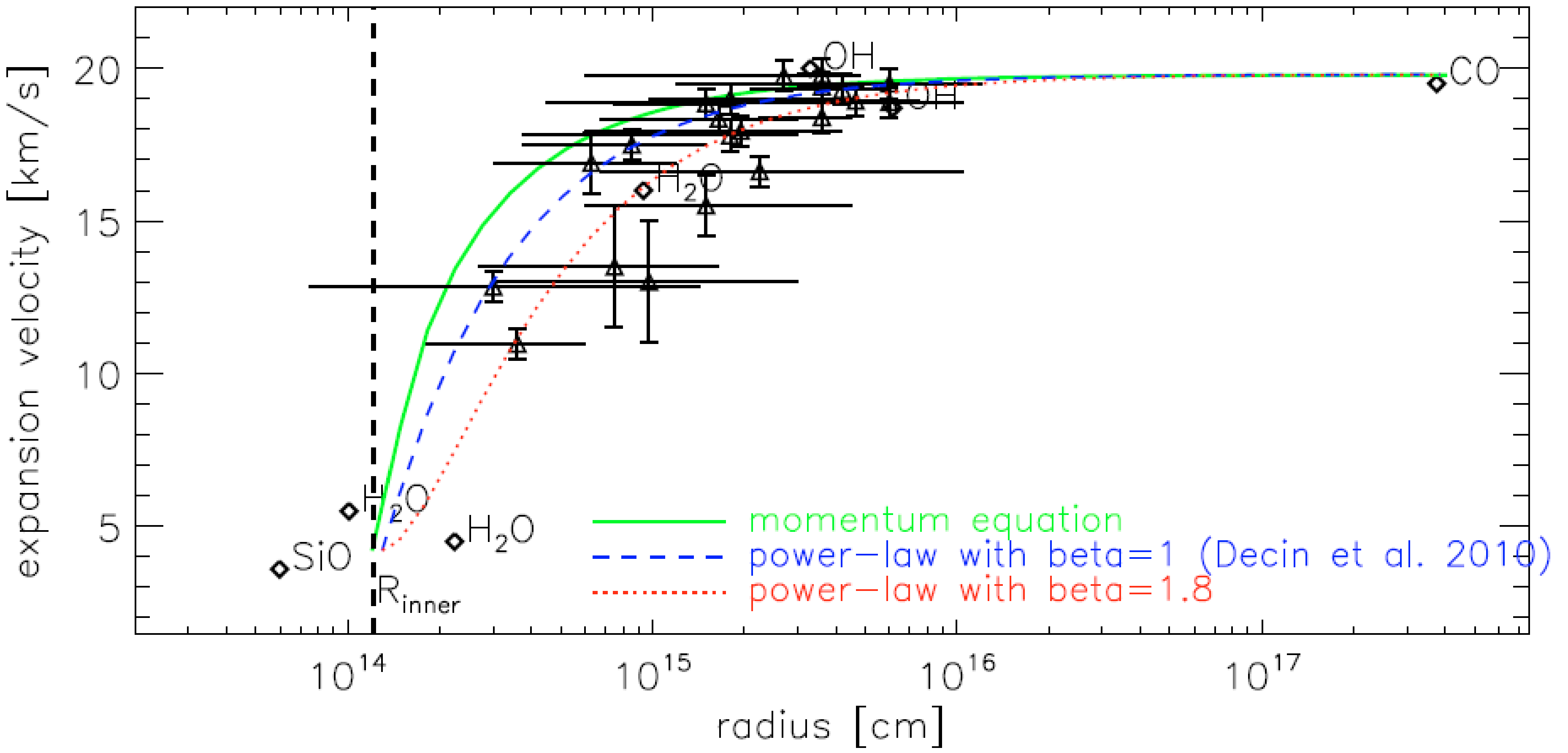
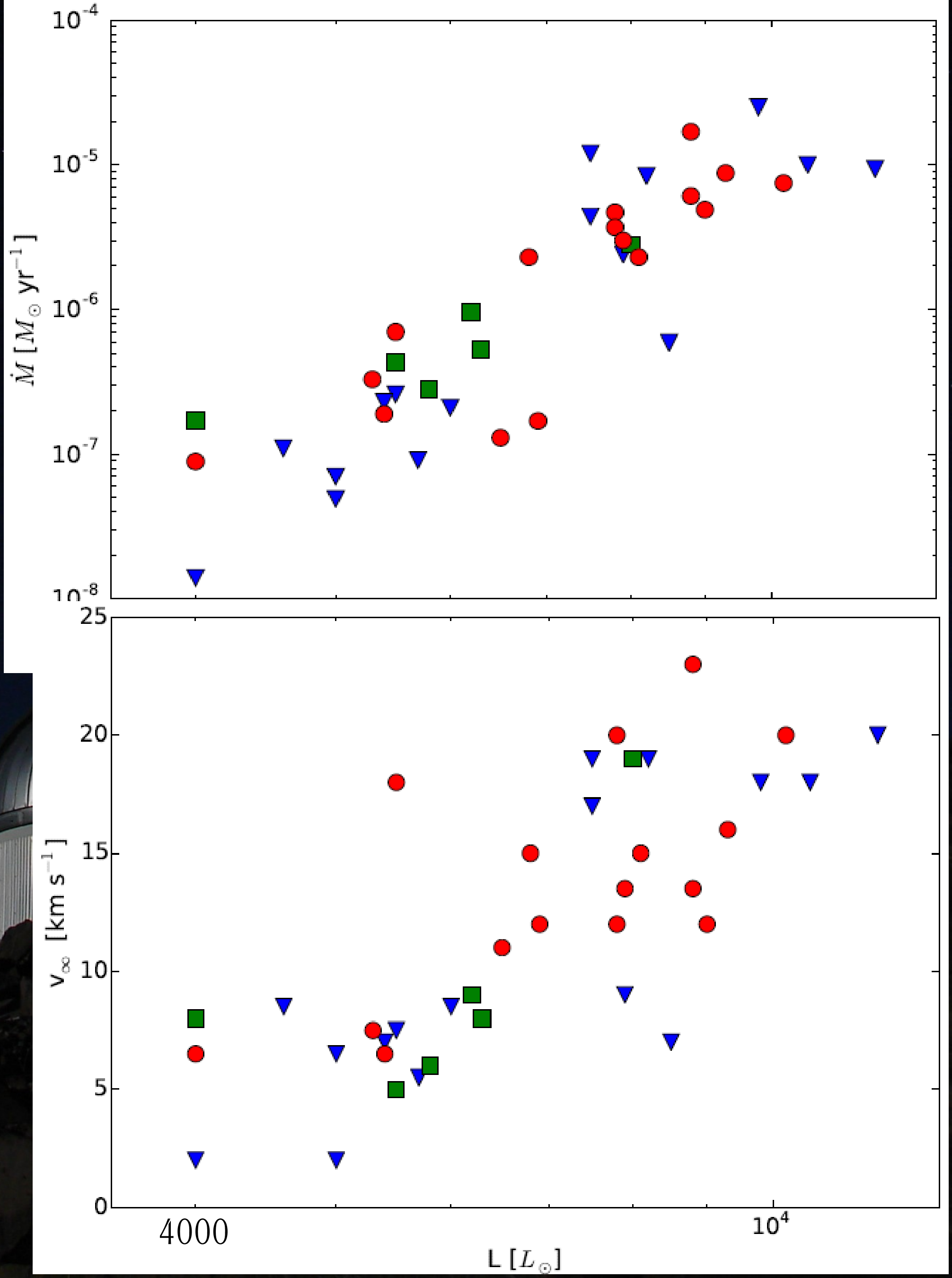


Fig. 3. Velocity profile of IK Tau.

Decin et al. (2010)

Local observations support radiation pressure

Increasing luminosity →
increasing mass-loss rate and outflow velocity



Danilovich et al. (2015)

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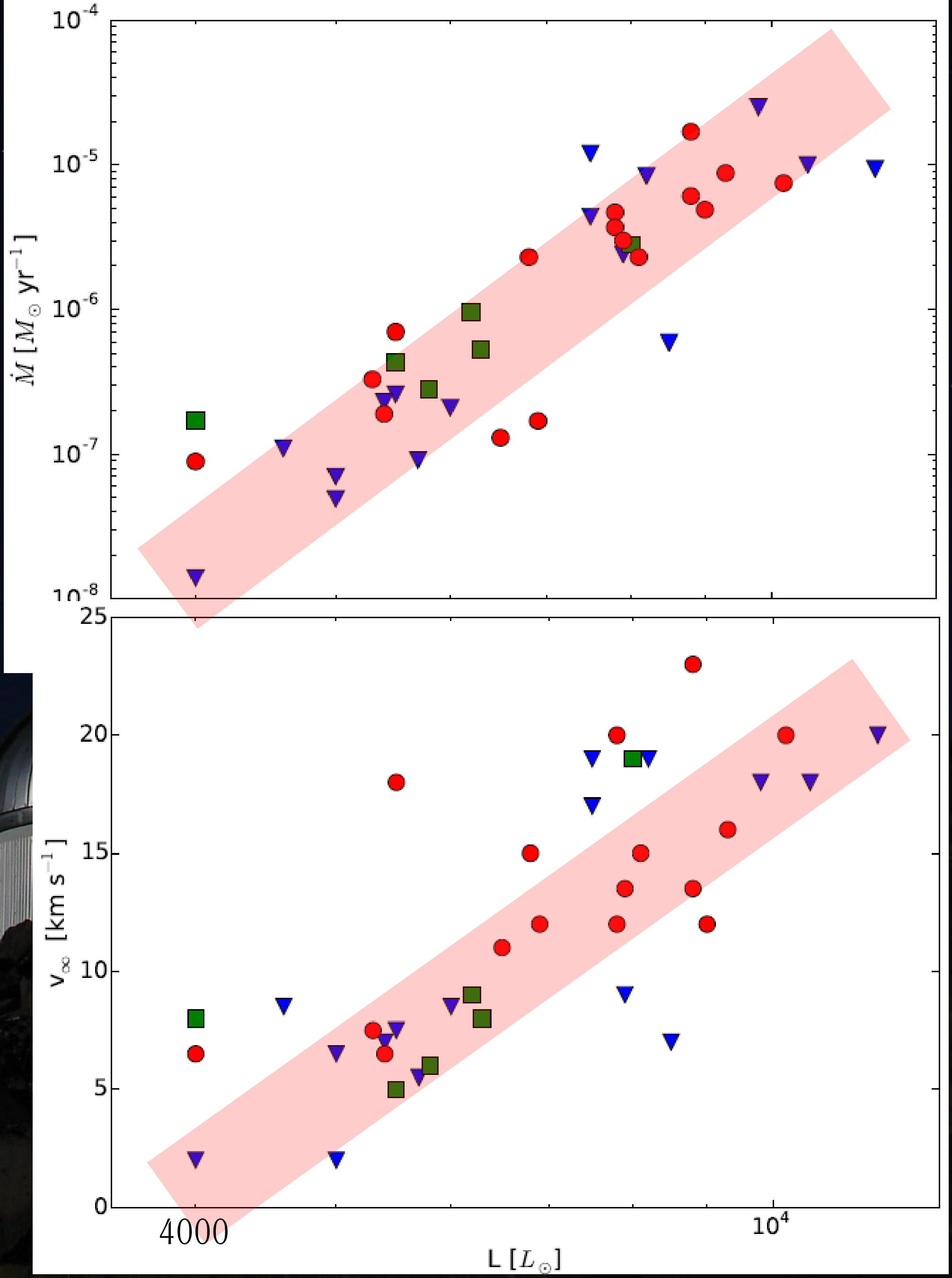
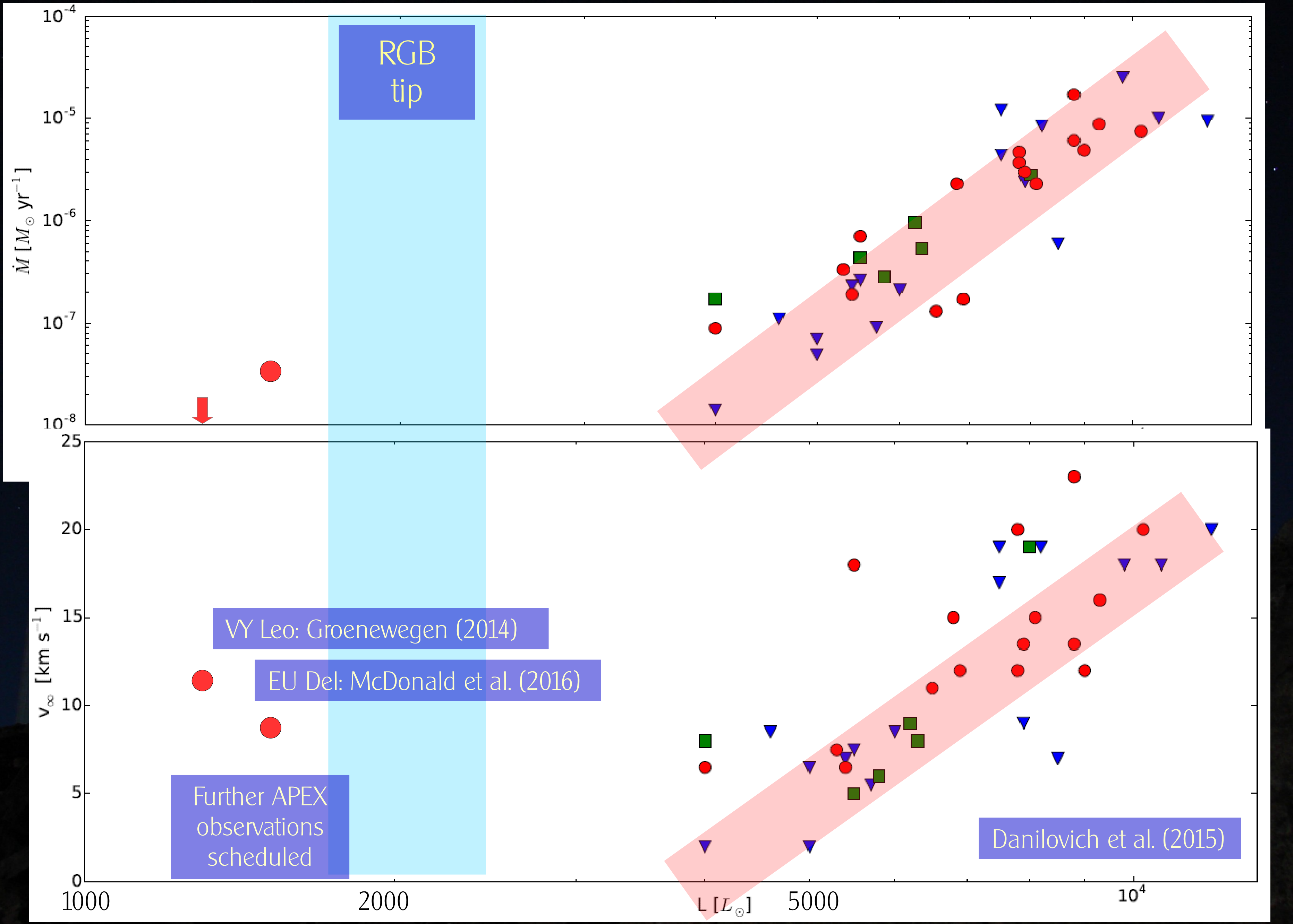


Danilovich et al. (2015)

Lower-luminosity giant stars



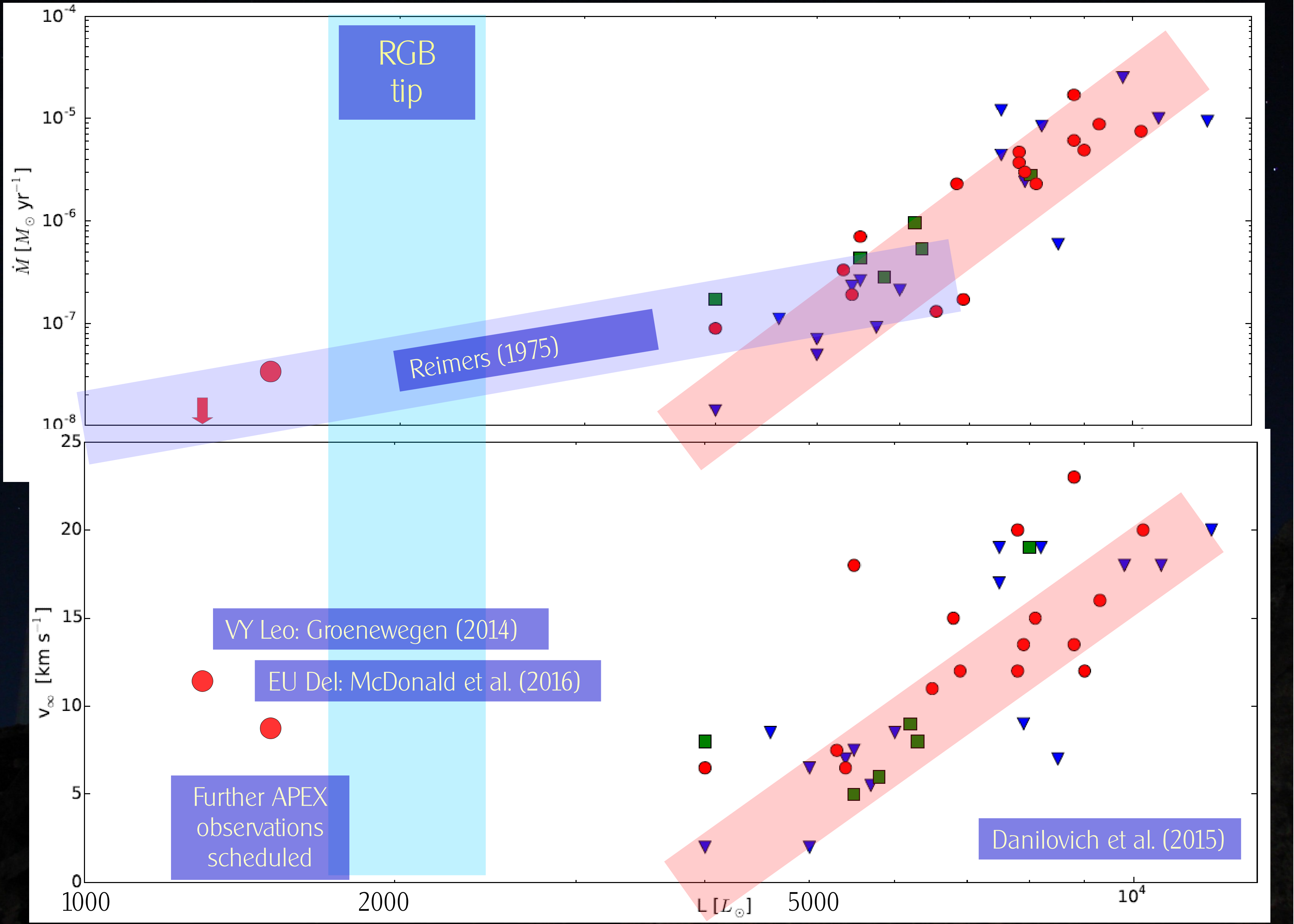
VY Leo: Groenewegen (2014)

EU Del: McDonald et al. (2016)

Further APEX observations scheduled

Danilovich et al. (2015)

Lower-luminosity giant stars


RGB tip

Reimers (1975)

VY Leo: Groenewegen (2014)

EU Del: McDonald et al. (2016)

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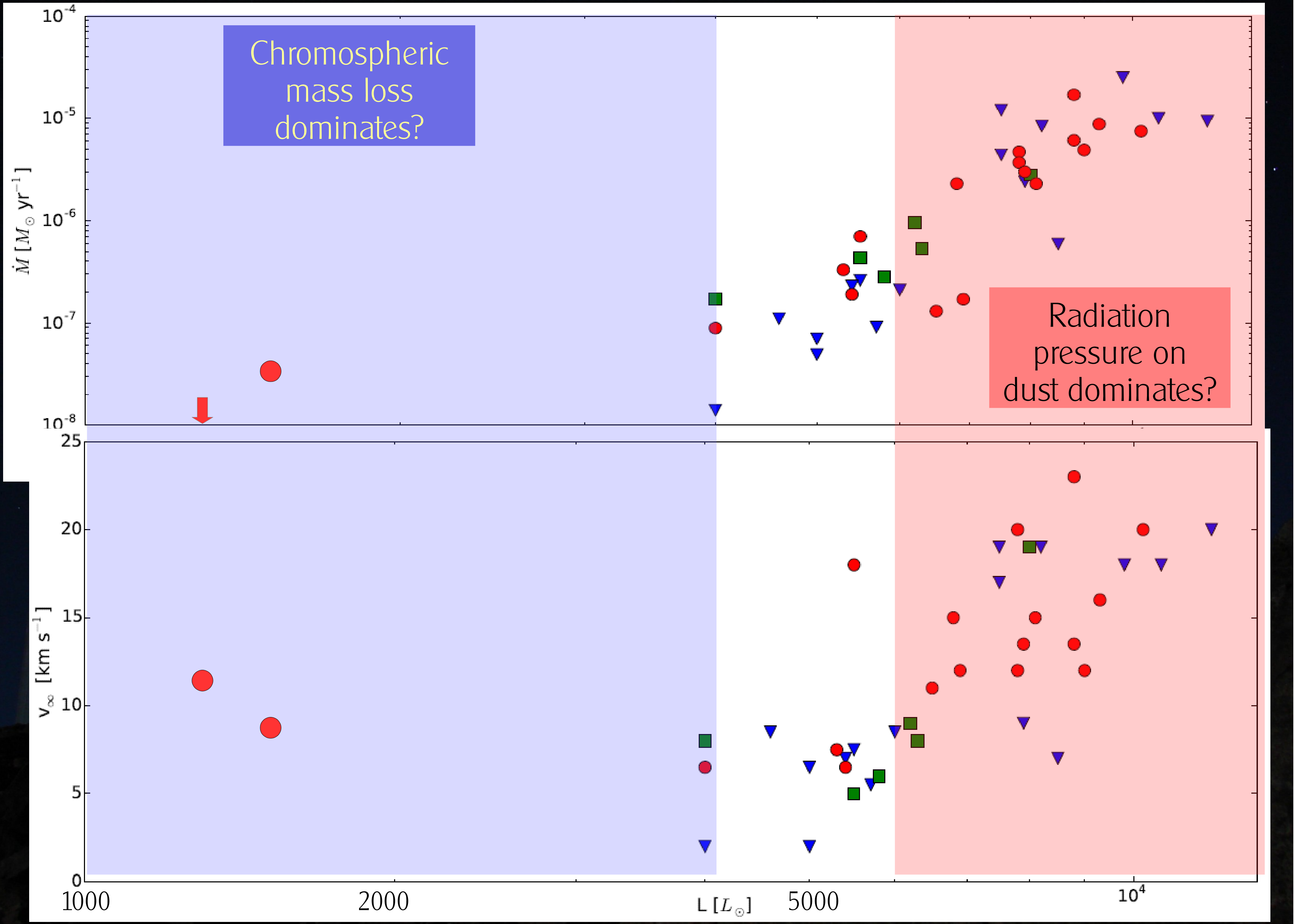
Lower-luminosity giant stars



What about pulsation?

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Pulsation is linked to luminosity (P–L relationship) → two factors hard to disentangle

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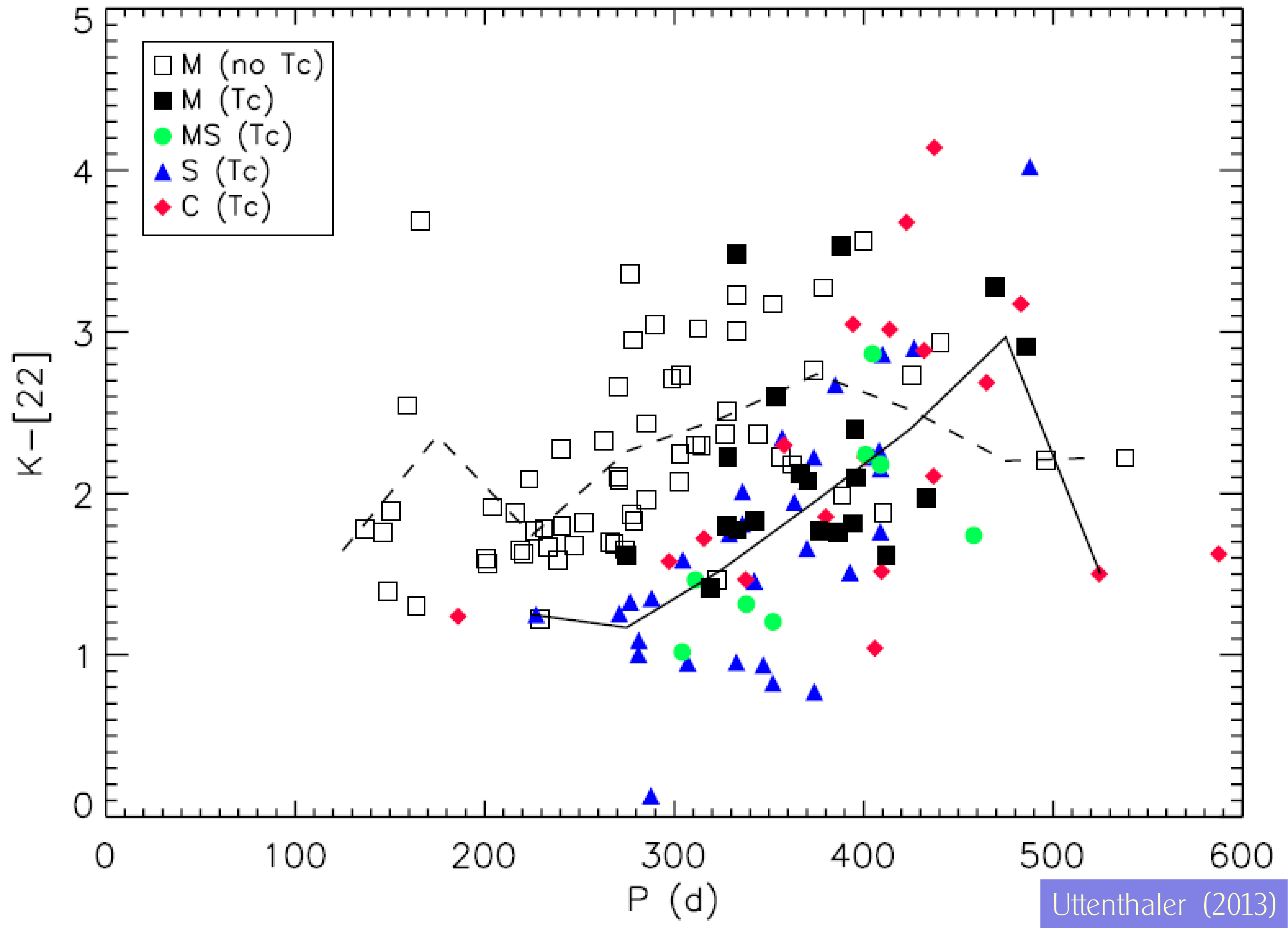
Long-period variables (LPVs) show weak relations between period and wind density (~ mass-loss rate)



Uttenthaler (2013)

What about pulsation?

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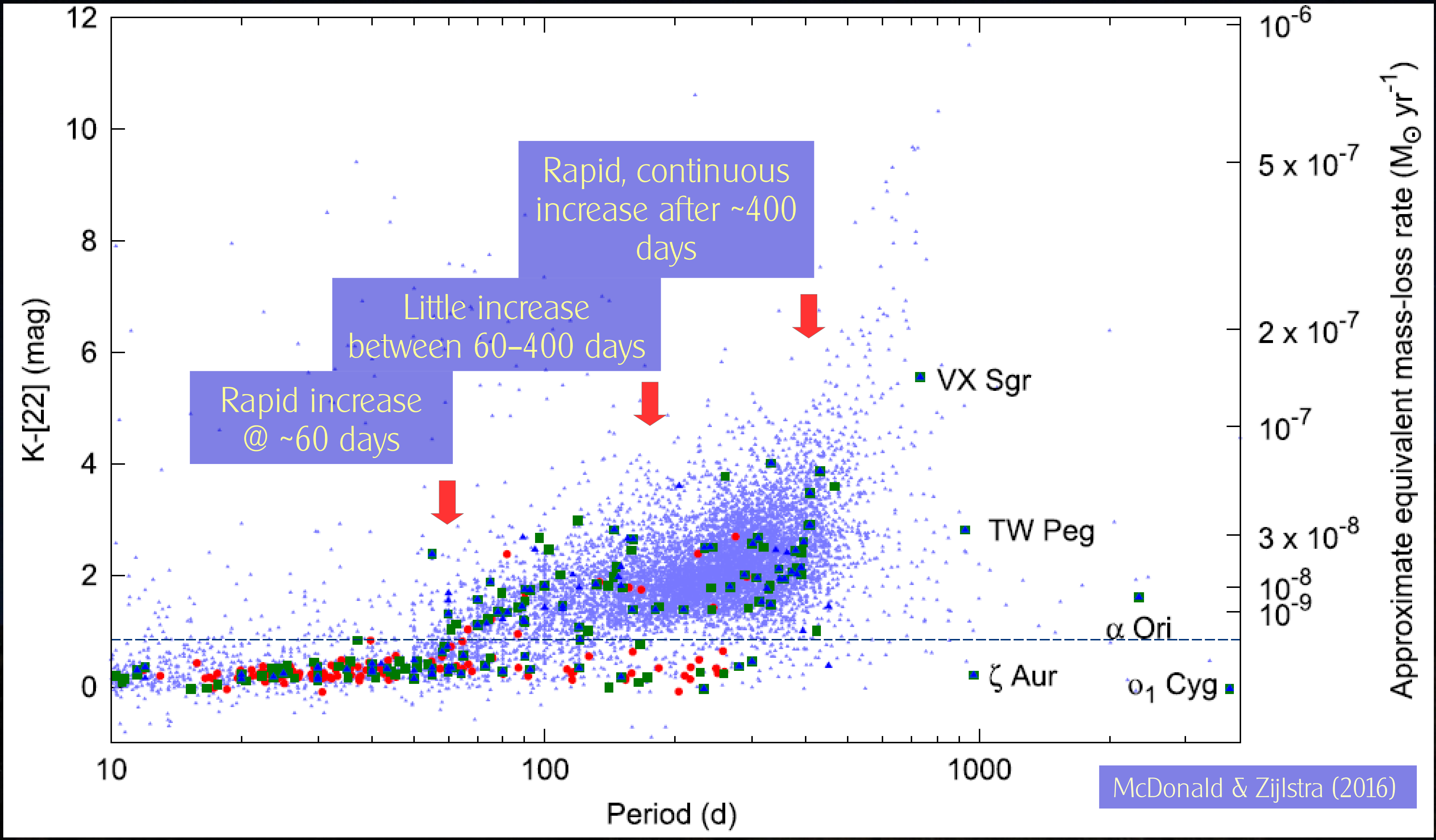
But a clear relationship exists for shorter period variables, with a 60 (& 400-day) critical period



Rapid, continuous increase after ~400 days

Little increase between 60–400 days

Rapid increase @ ~60 days

McDonald & Zijlstra (2016)

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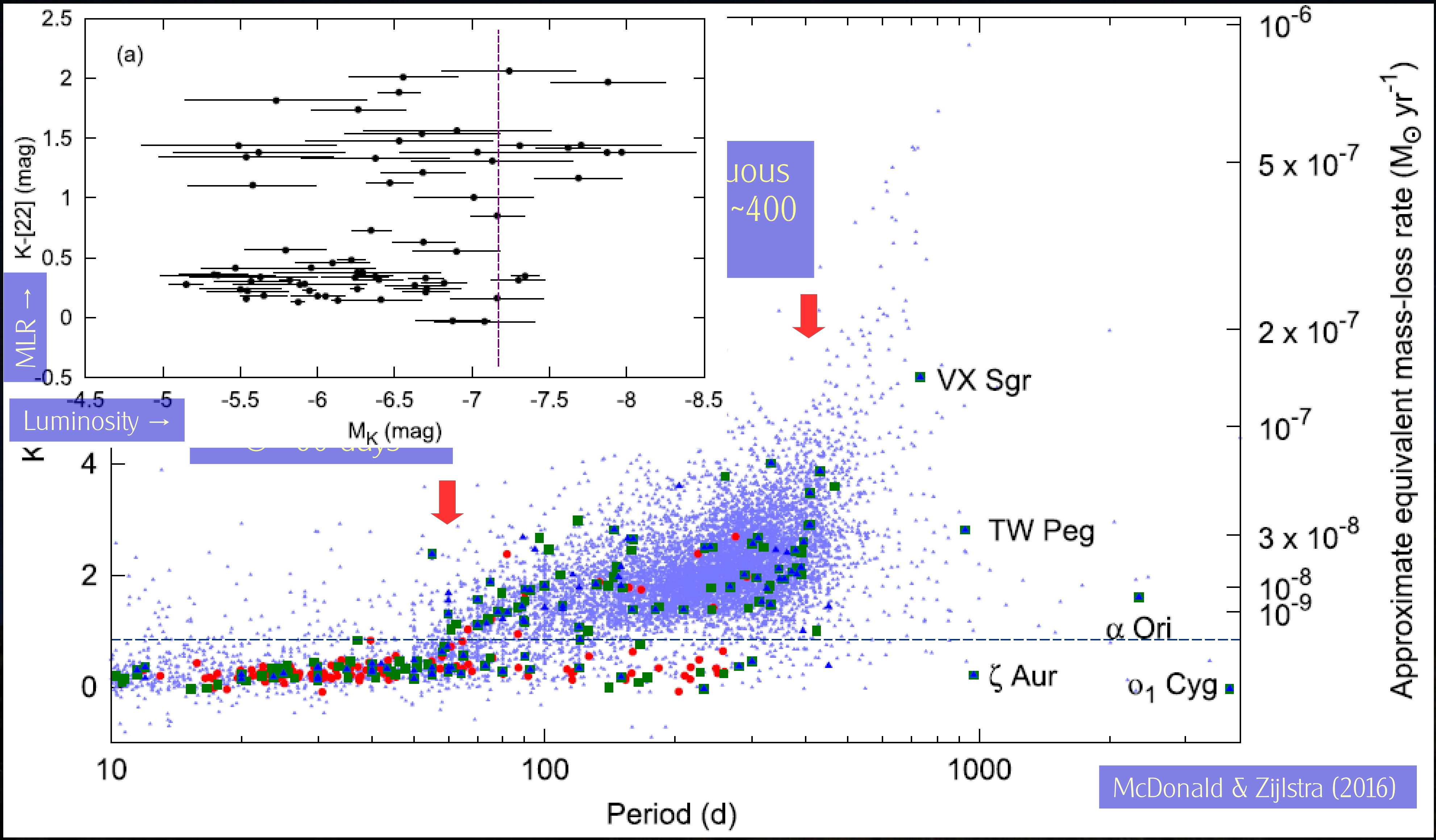


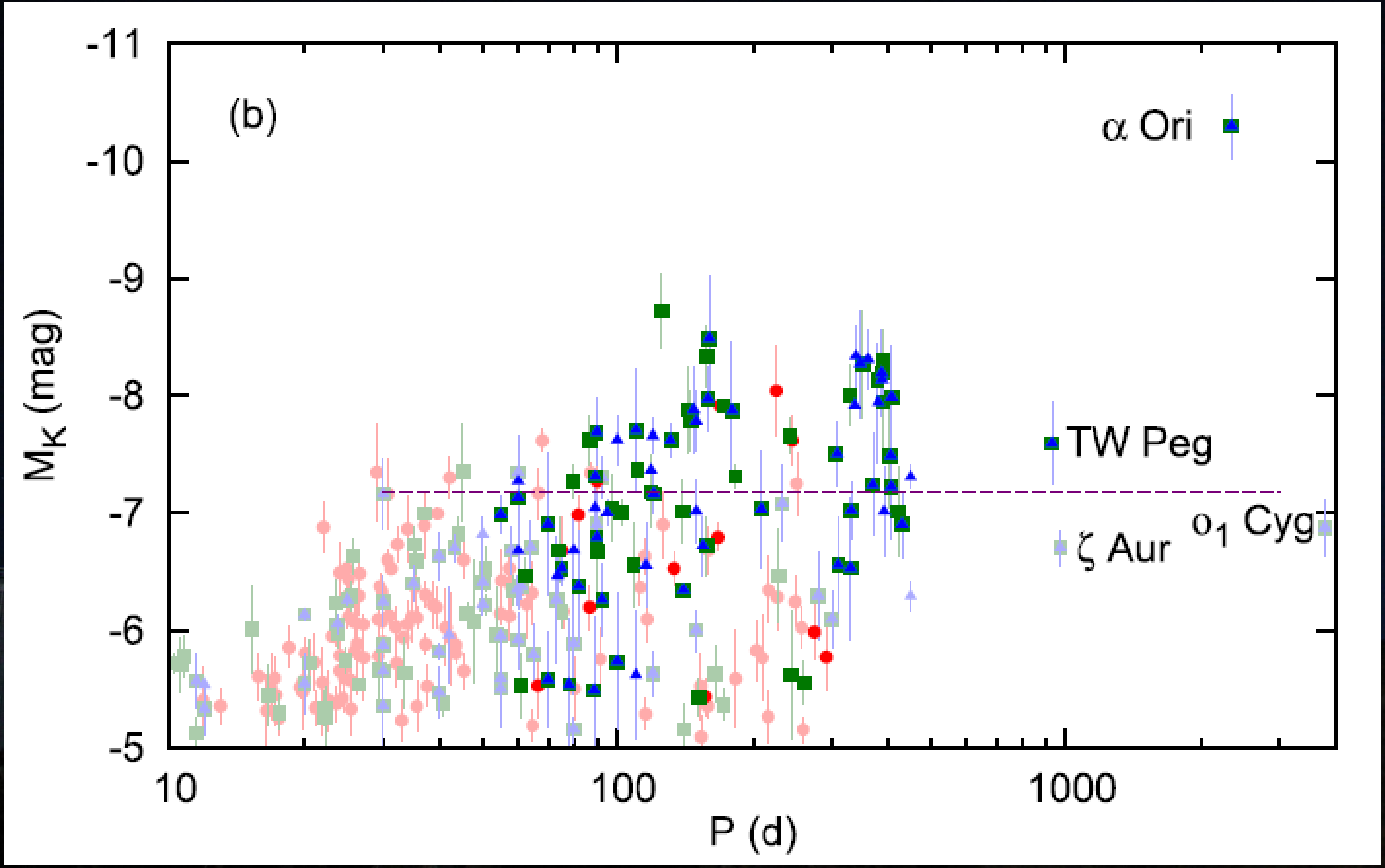
McDonald & Zijlstra (2016)

What about pulsation?

Pulsation is linked to luminosity (P–L relationship) → two factors hard to disentangle

P–L diagram shows that this is not a luminosity effect.

Linked to the pulsation mode? Dusty stars mostly fundamental + 1st overtone pulsators.



Higher-overtone RGB & massive stars tend to be dust free

McDonald & Zijlstra (2016)

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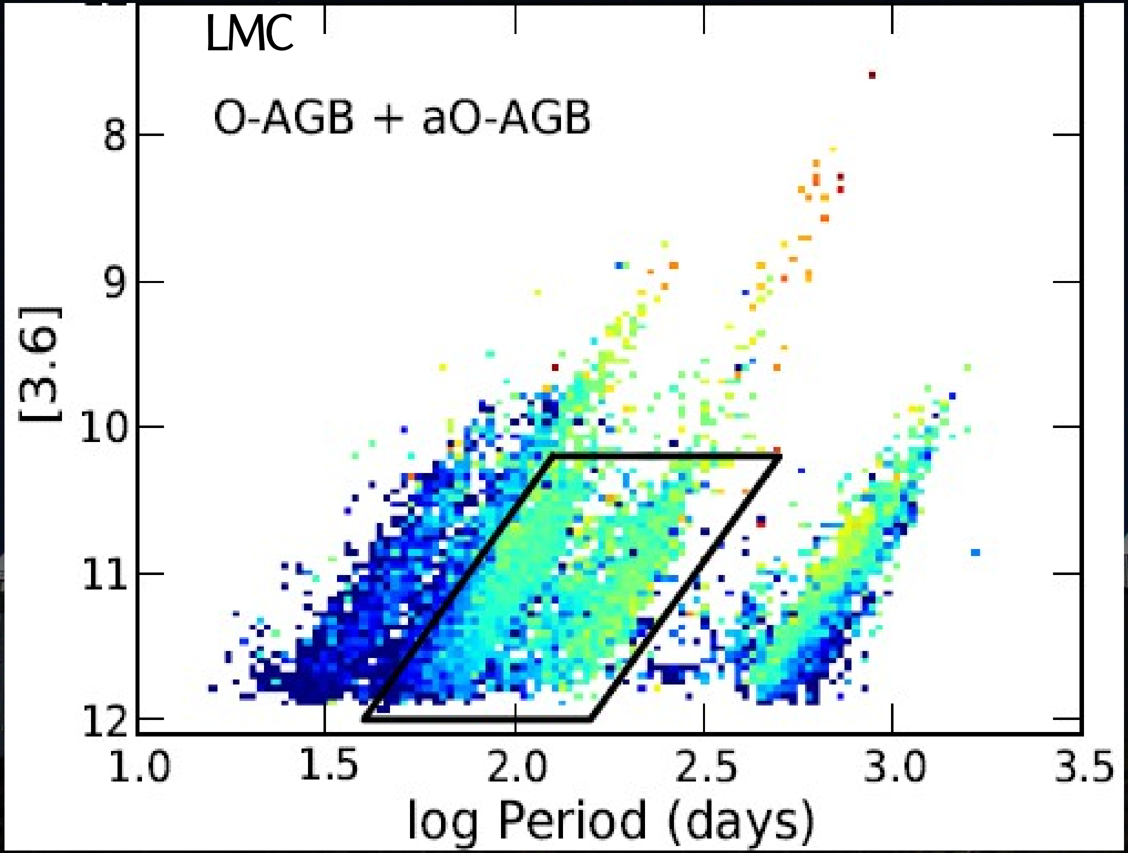


Optically obscured

Lots of dust

More dust

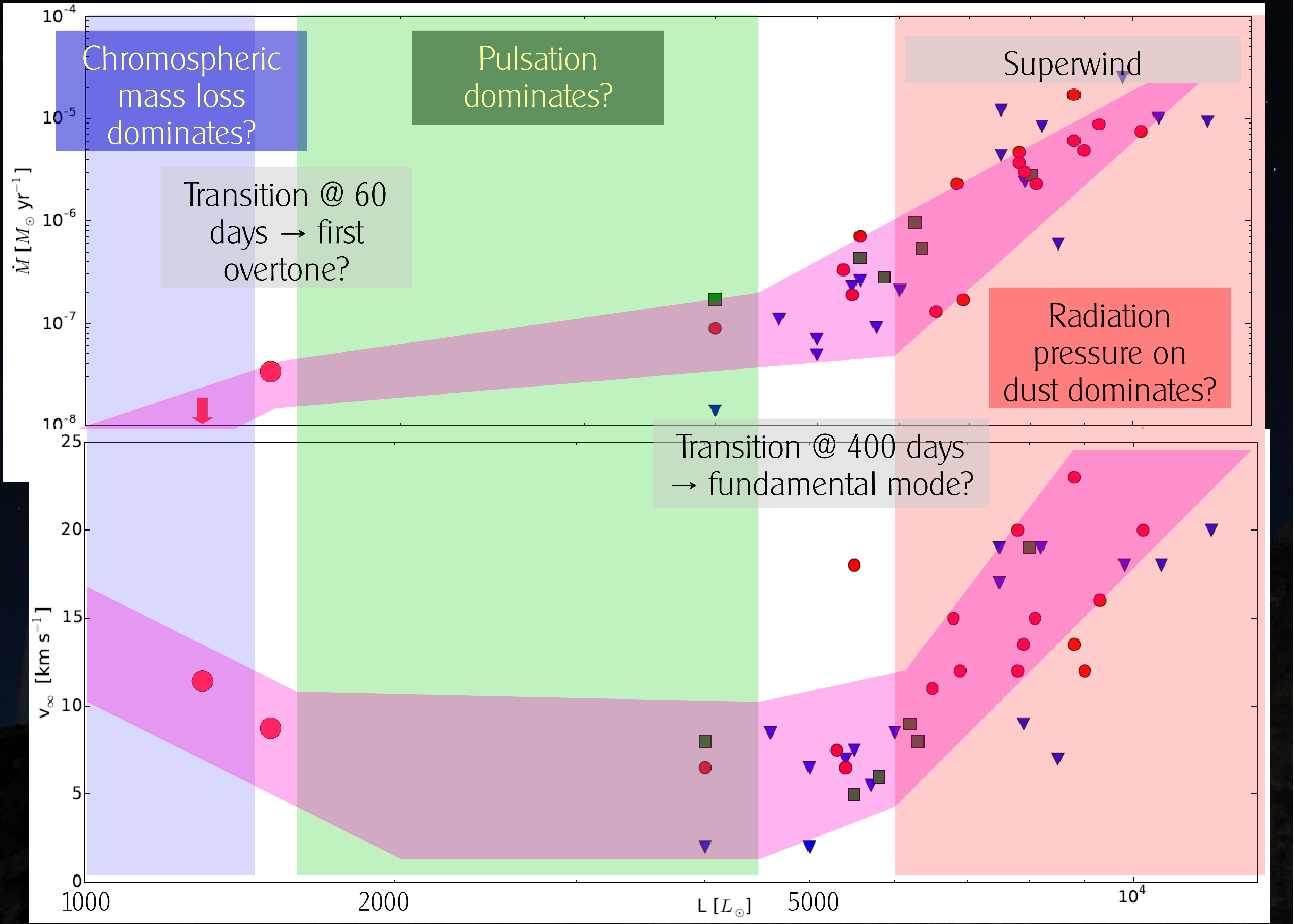
Some dust

No dust production

Boyer et al. (2015)

Higher-overtone RGB & massive stars tend to be dust free

Drivers of mass loss from stars at solar metallicity



Chromospheric mass loss dominates?

Pulsation dominates?

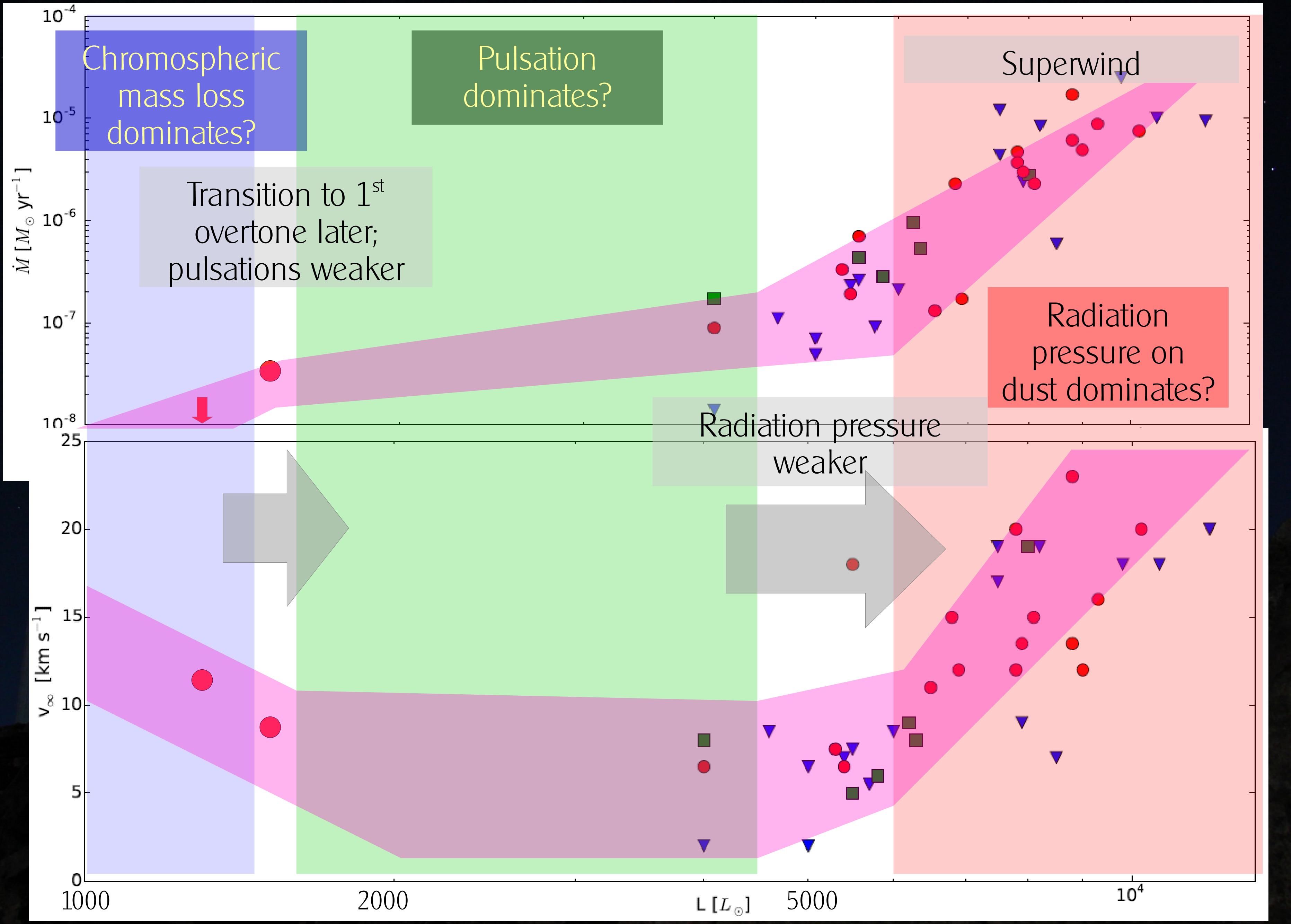
Superwind

Transition @ 60 days → first overtone?

Radiation pressure on dust dominates?

Transition @ 400 days → fundamental mode?

Expectations at [Fe/H] = -0.3 (LMC)



Chromospheric mass loss dominates?

Pulsation dominates?

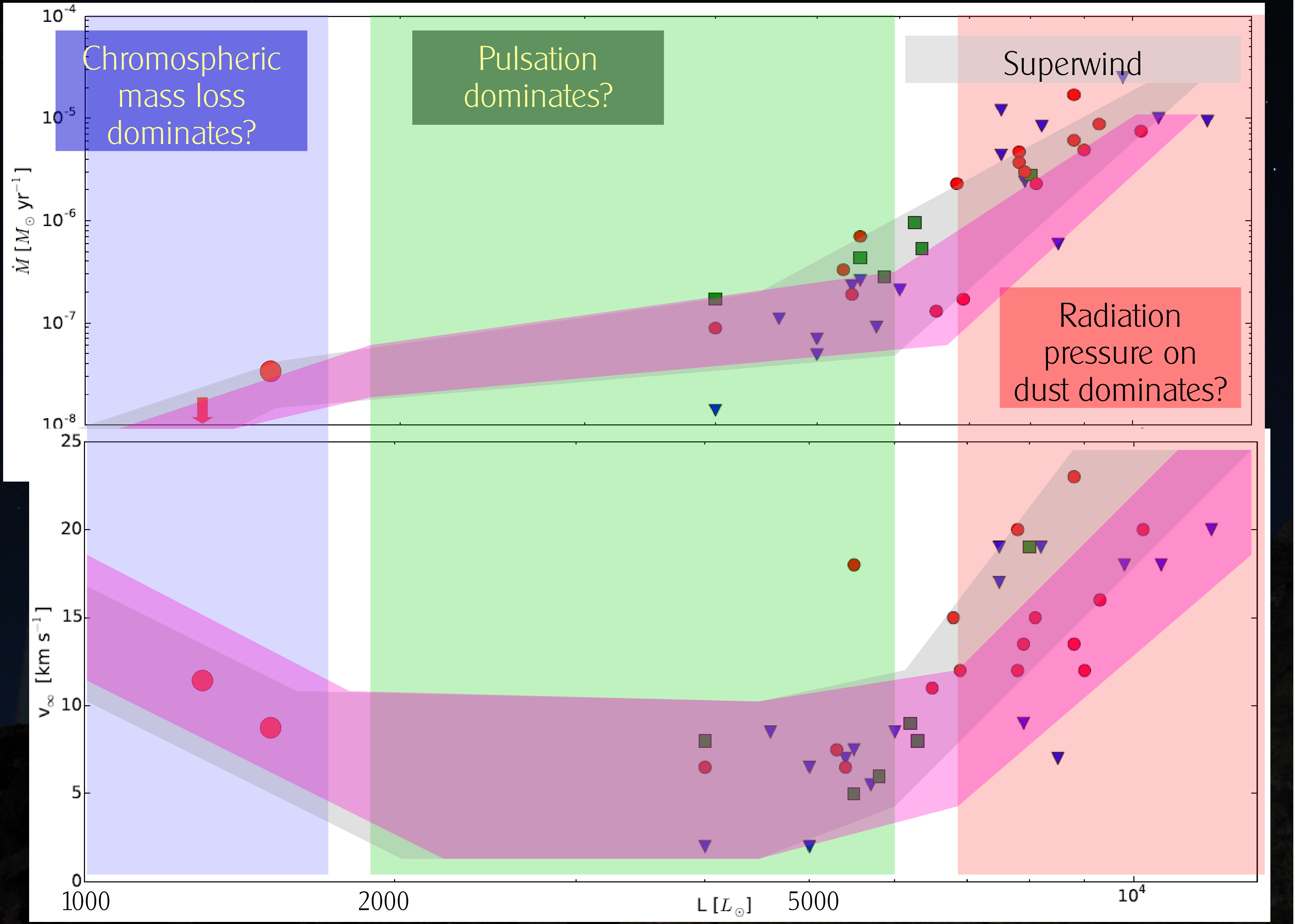
Superwind

Transition to 1st overtone later; pulsations weaker

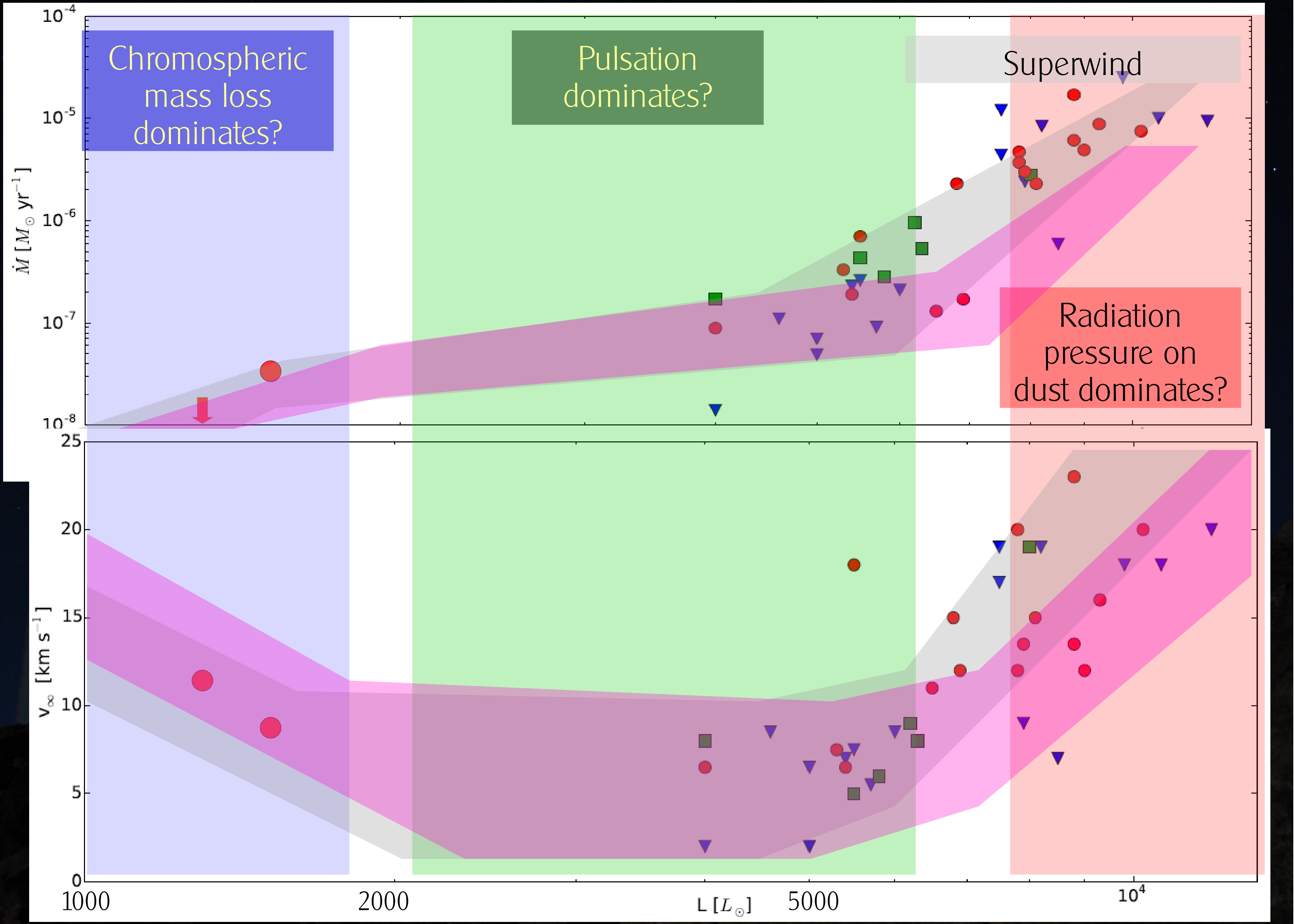
Radiation pressure on dust dominates?

Radiation pressure weaker

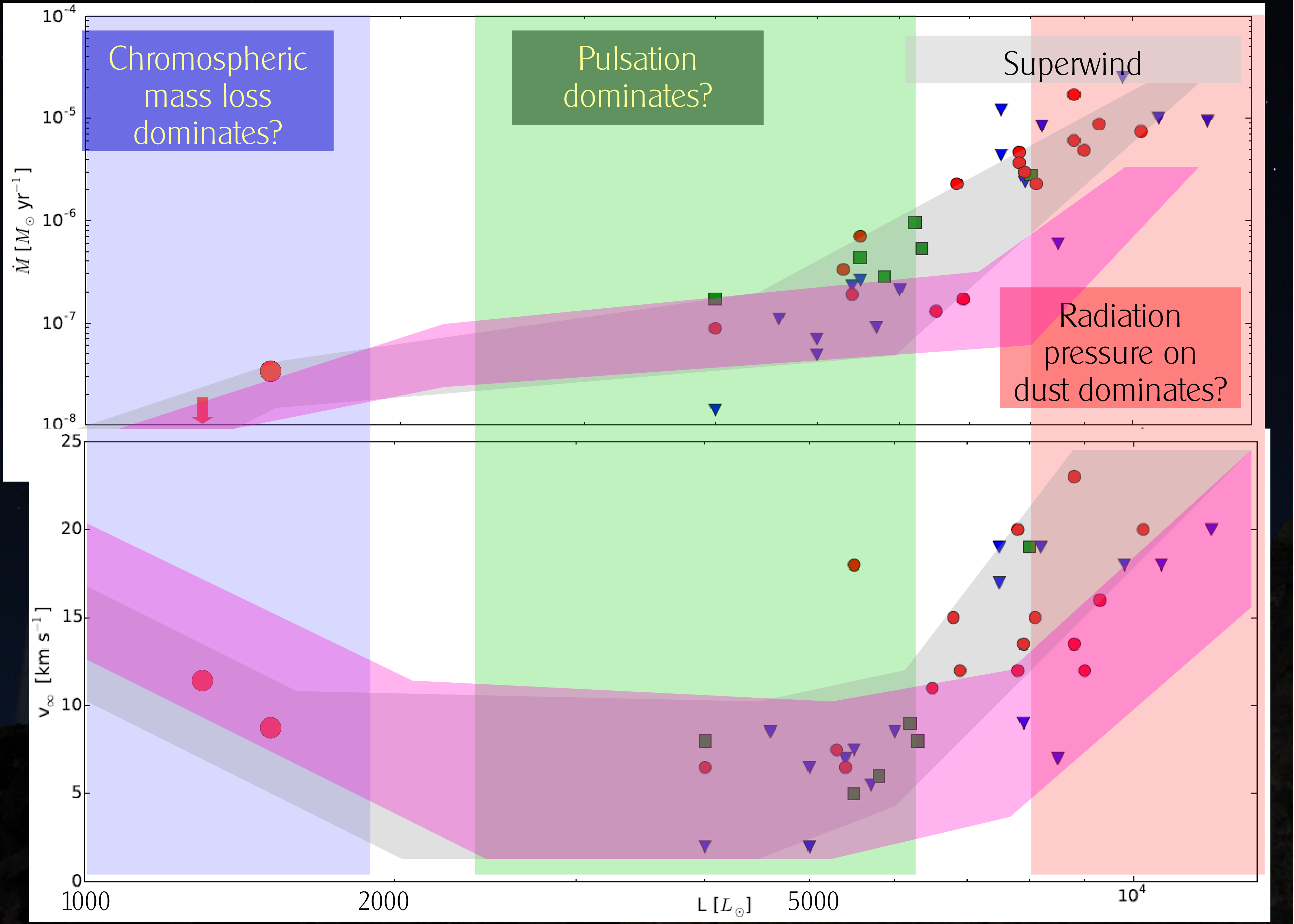
Expectations at [Fe/H] = -0.3 (LMC)



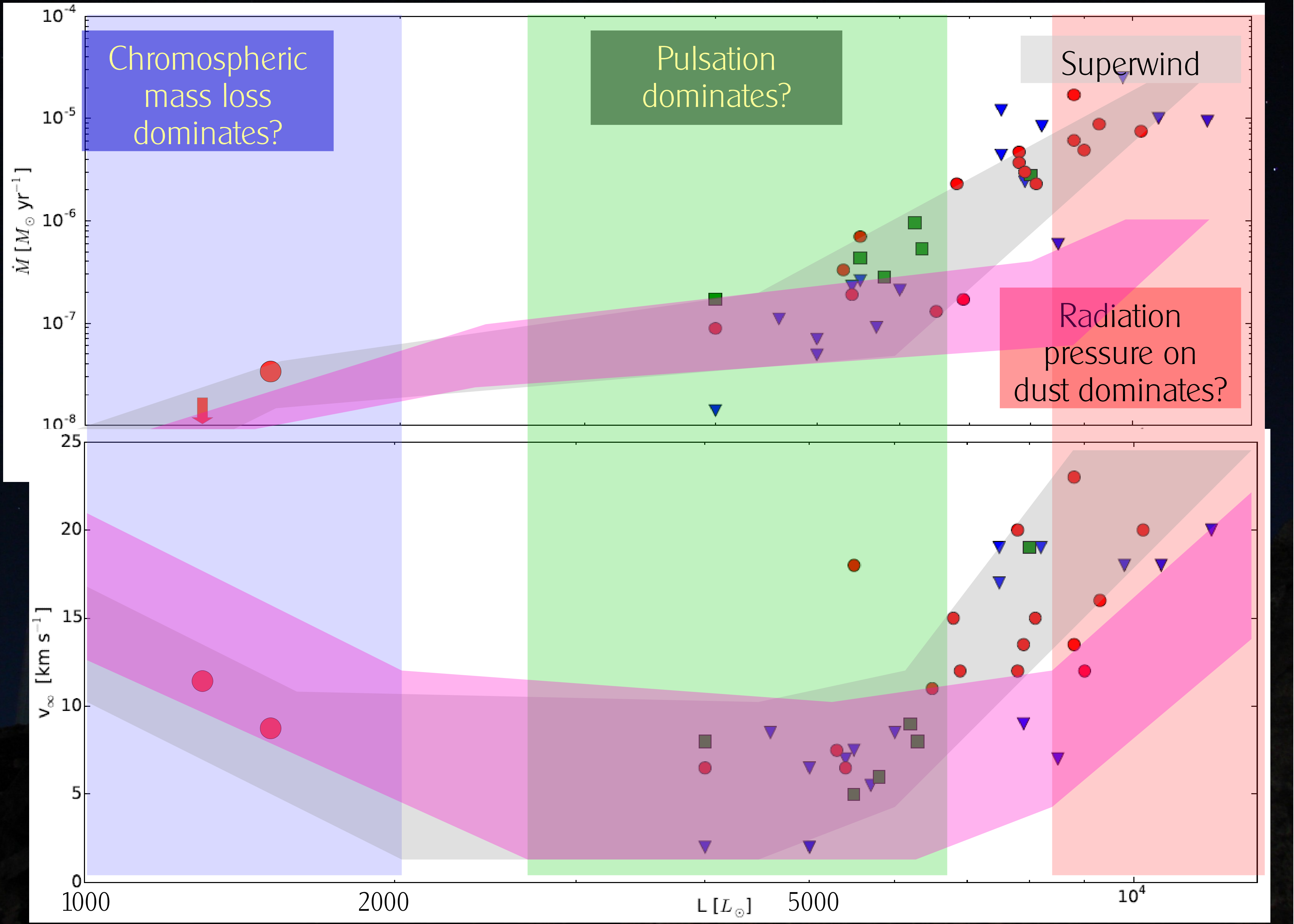
Expectations at [Fe/H] = -0.5 (SMC; Sgr dSph)



Expectations at [Fe/H] = -0.7 (47 Tuc)



Expectations at [Fe/H] = -1.3 (Sextans B)



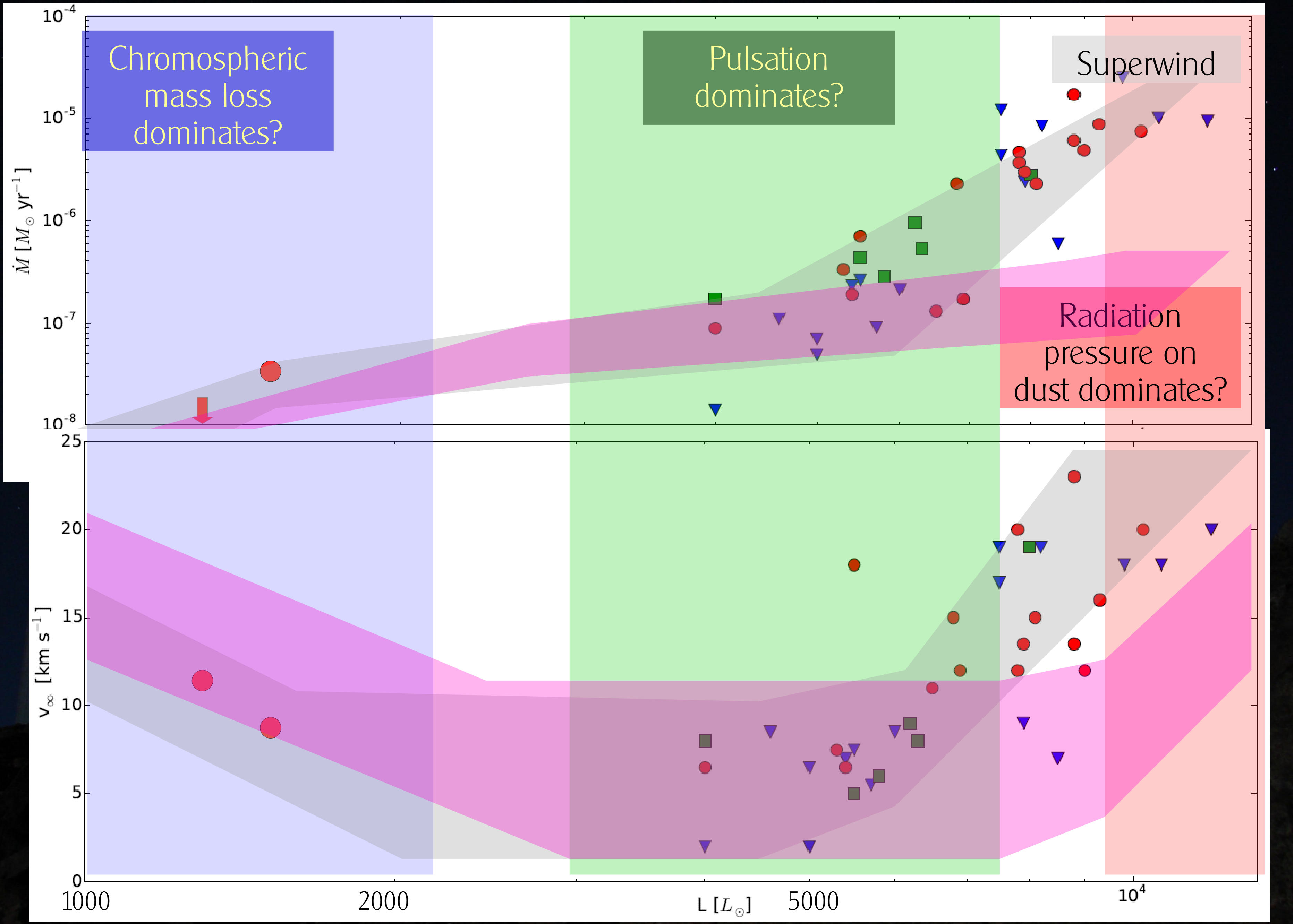
Chromospheric mass loss dominates?

Pulsation dominates?

Superwind

Radiation pressure on dust dominates?

Expectations at [Fe/H] = -1.7 (omega Cen; dSphs)



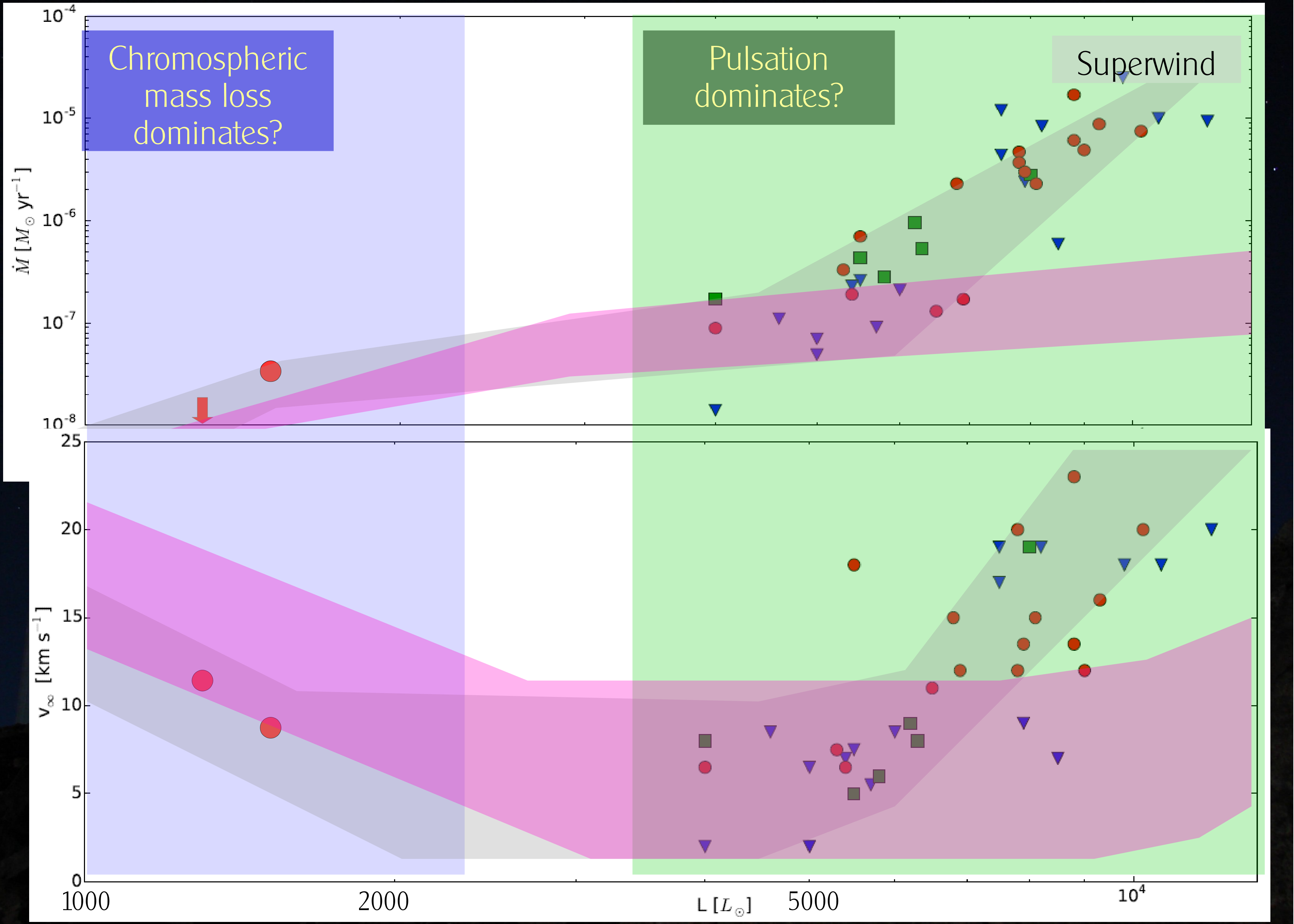
Chromospheric mass loss dominates?

Pulsation dominates?

Superwind

Radiation pressure on dust dominates?

Expectations at [Fe/H] = -2.3 (M15)

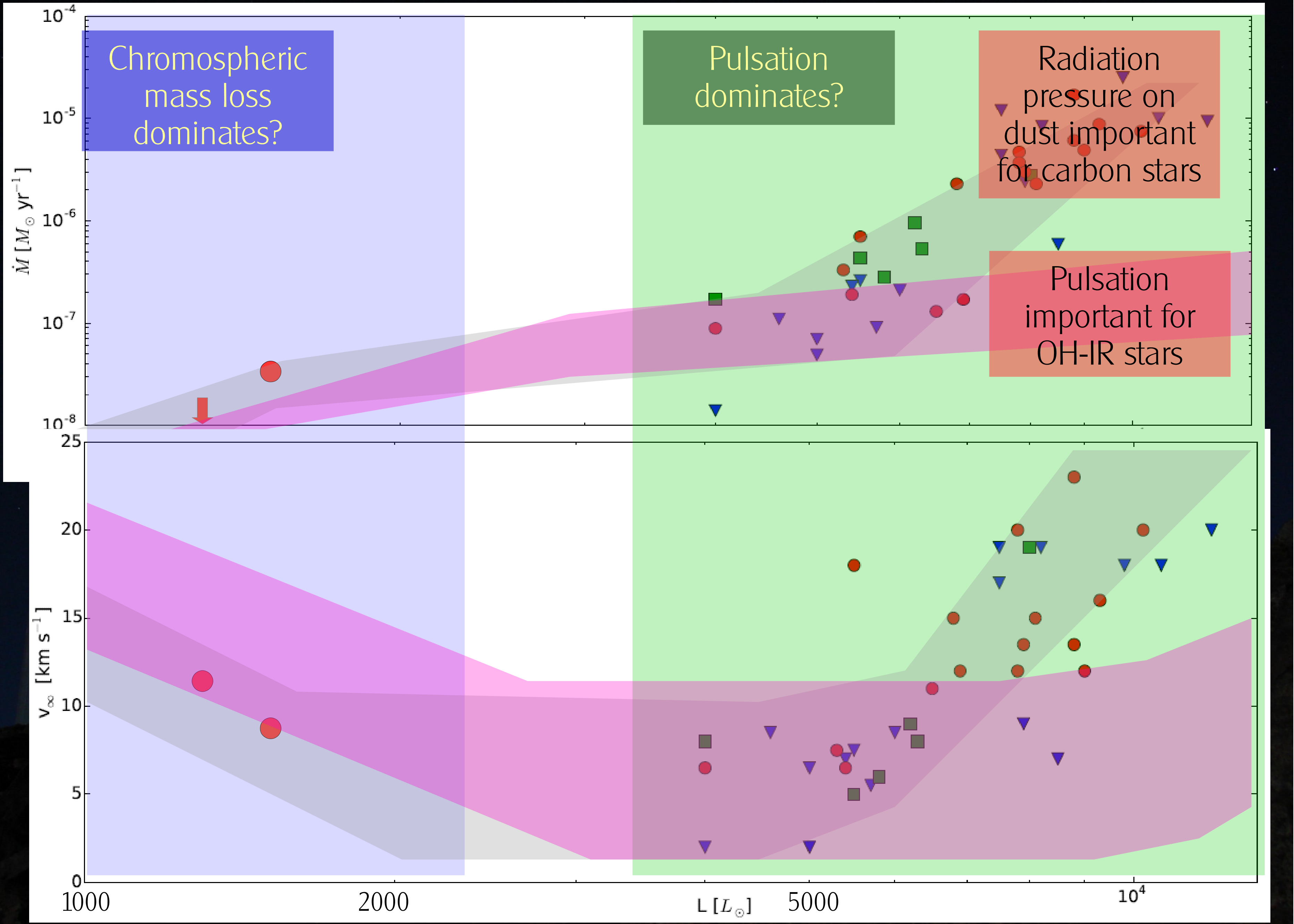


Chromospheric mass loss dominates?

Pulsation dominates?

Superwind

Expectations at [Fe/H] = -2.3 (M15)



Chromospheric mass loss dominates?

Pulsation dominates?

Radiation pressure on dust important for carbon stars

Pulsation important for OH-IR stars

Expectations: summary

1. Minimum in wind velocity of ~few – 10 km/s at a few 1000 $L_{\odot}$.
2. Winds of most stars adequately described by Reimers' (1975) law or similar.
3. Little change in MLR or v_{exp} with metallicity until radiation pressure becomes important.

Following this:

4. C & O star winds have similar MLRs and v_{exp} at solar metallicity (same radiation pressure on dust).
5. C & O star MLRs and v_{exp}'s will separate for luminous metal-poor stars.
6. O-rich MLRs and v_{exp} will decline at low metallicity as radiation pressure becomes ineffective.
7. C-rich winds will still be radiation driven.

Causing:

8. Gradual extension of lifetimes / peak luminosities for OH-IR stars at low metallicity.
9. Gradual vertical separation of C stars and OH-IR stars in infrared CMDs.

Tests:

10. Use CO lines to determine MLR & v_{exp} for a variety of stars at different *M* and [Fe/H].
11. Search for unexpected gaps in metal-poor luminosity functions just above upper C star limit.

Requires:

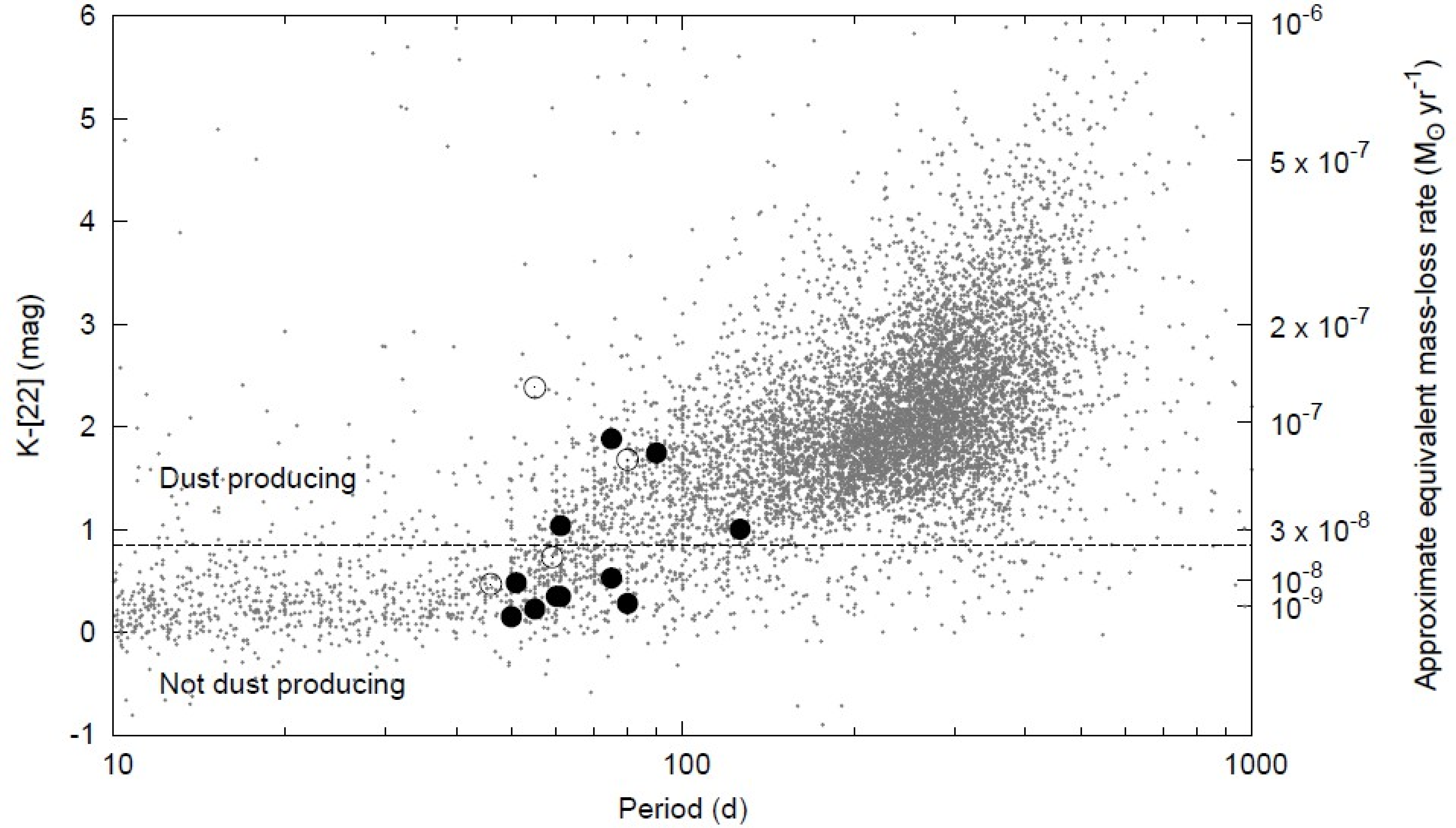
12. A large observational sample of stars with well-characterised *M* and [Fe/H].
13. Correct prediction of periods (including growth rates!) from stellar evolution models.

THE END?

Encore

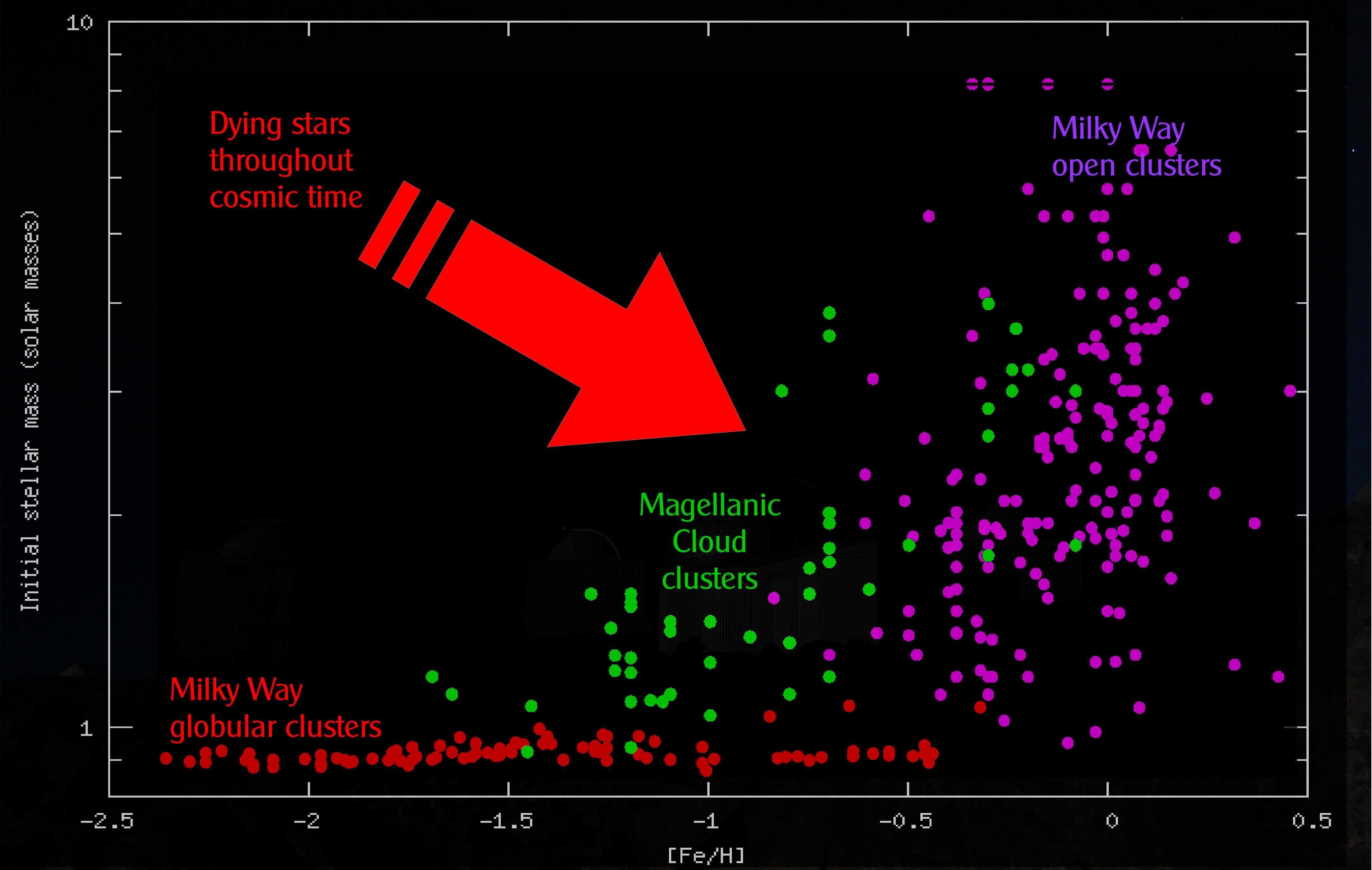
Futures: nearby stars

APEX observations this semester to observe CO(2-1) around 11 nearby stars in transitional regime

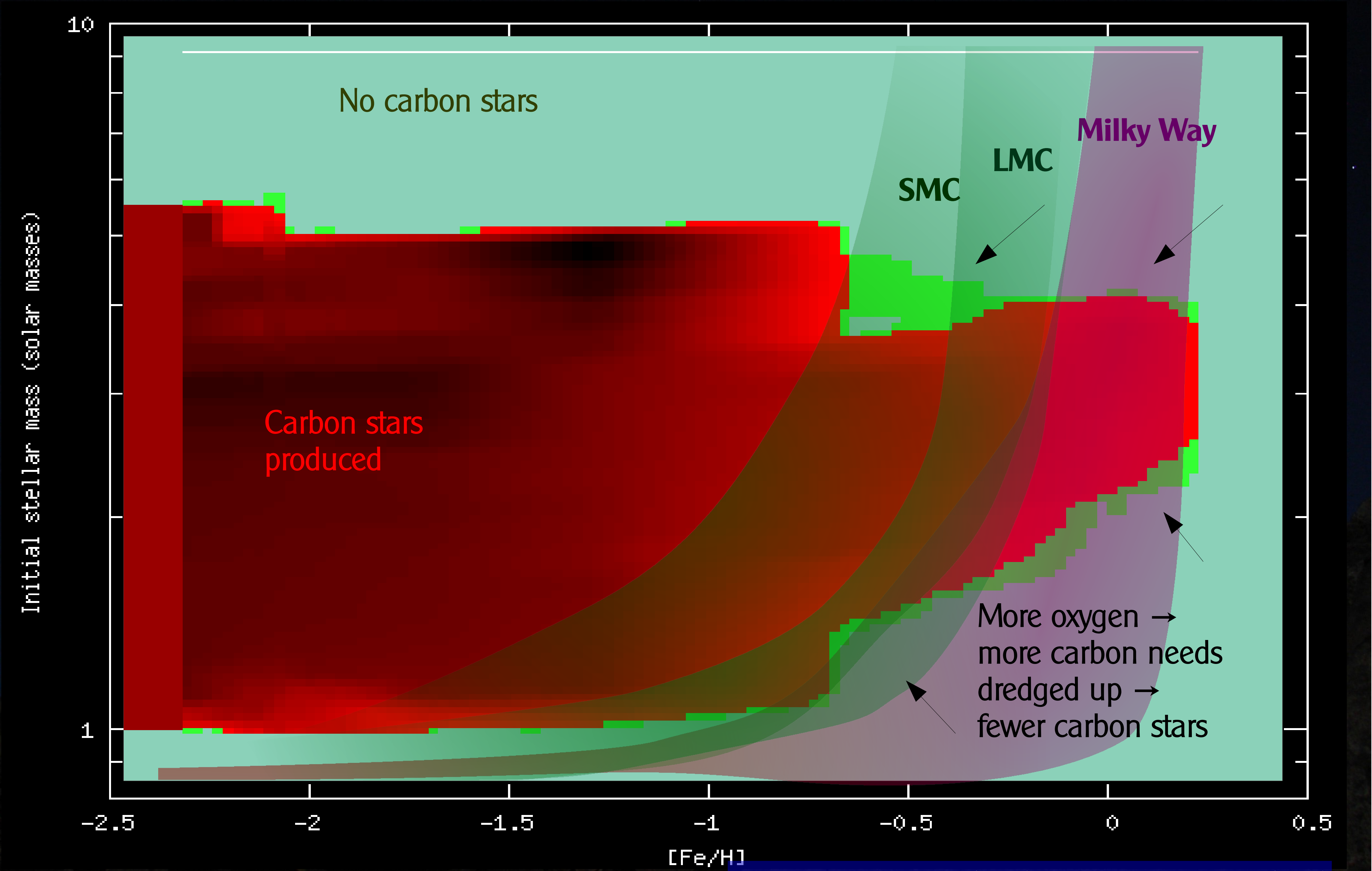


SPHERE programme to look at the effects of binarity and asymmetry in outflows

Futures: JWST studies of nearby populations



Futures: JWST studies of nearby populations



Data: Solid: Marigo et al. (2008); figure: McDonald et al. (2012)

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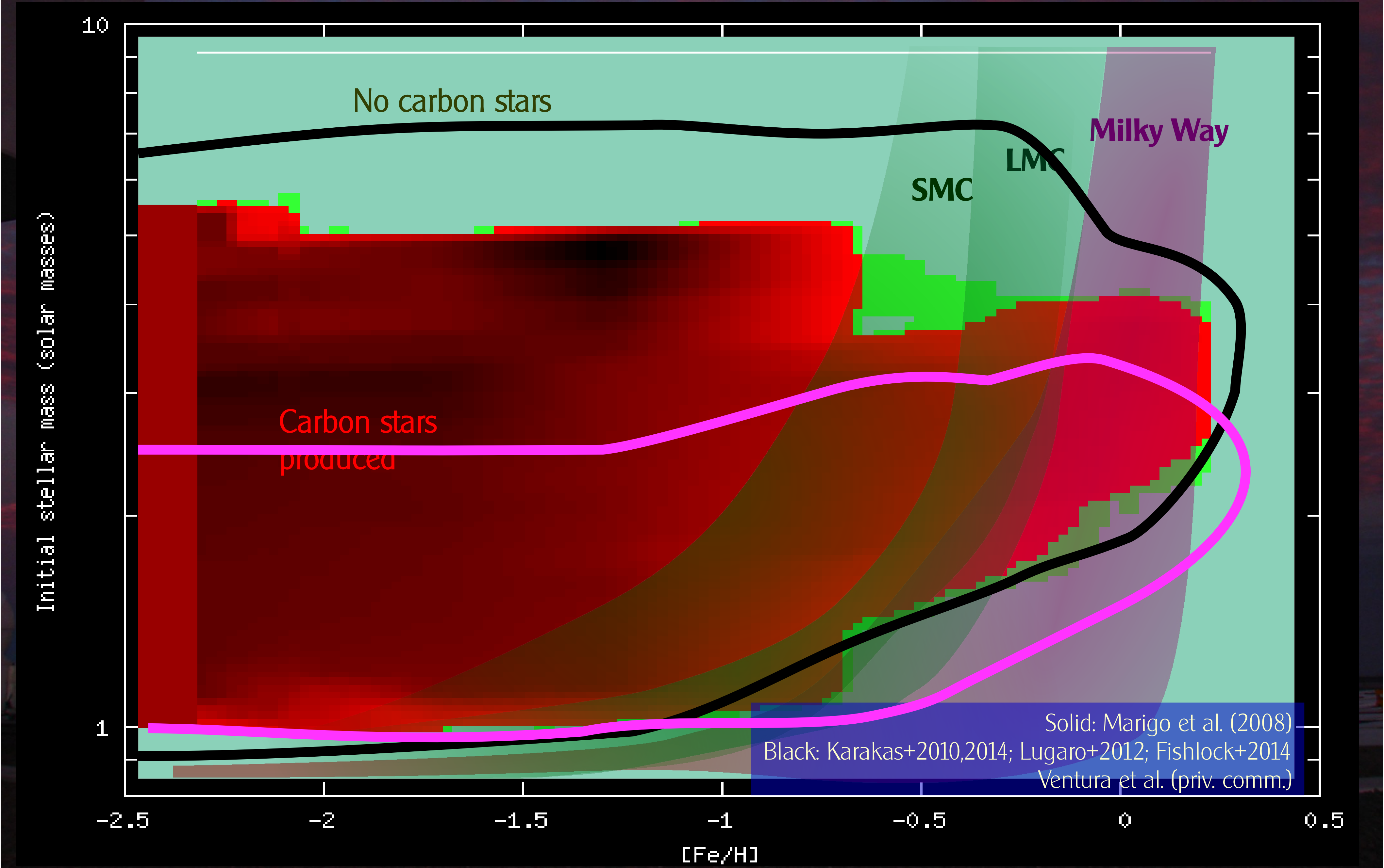
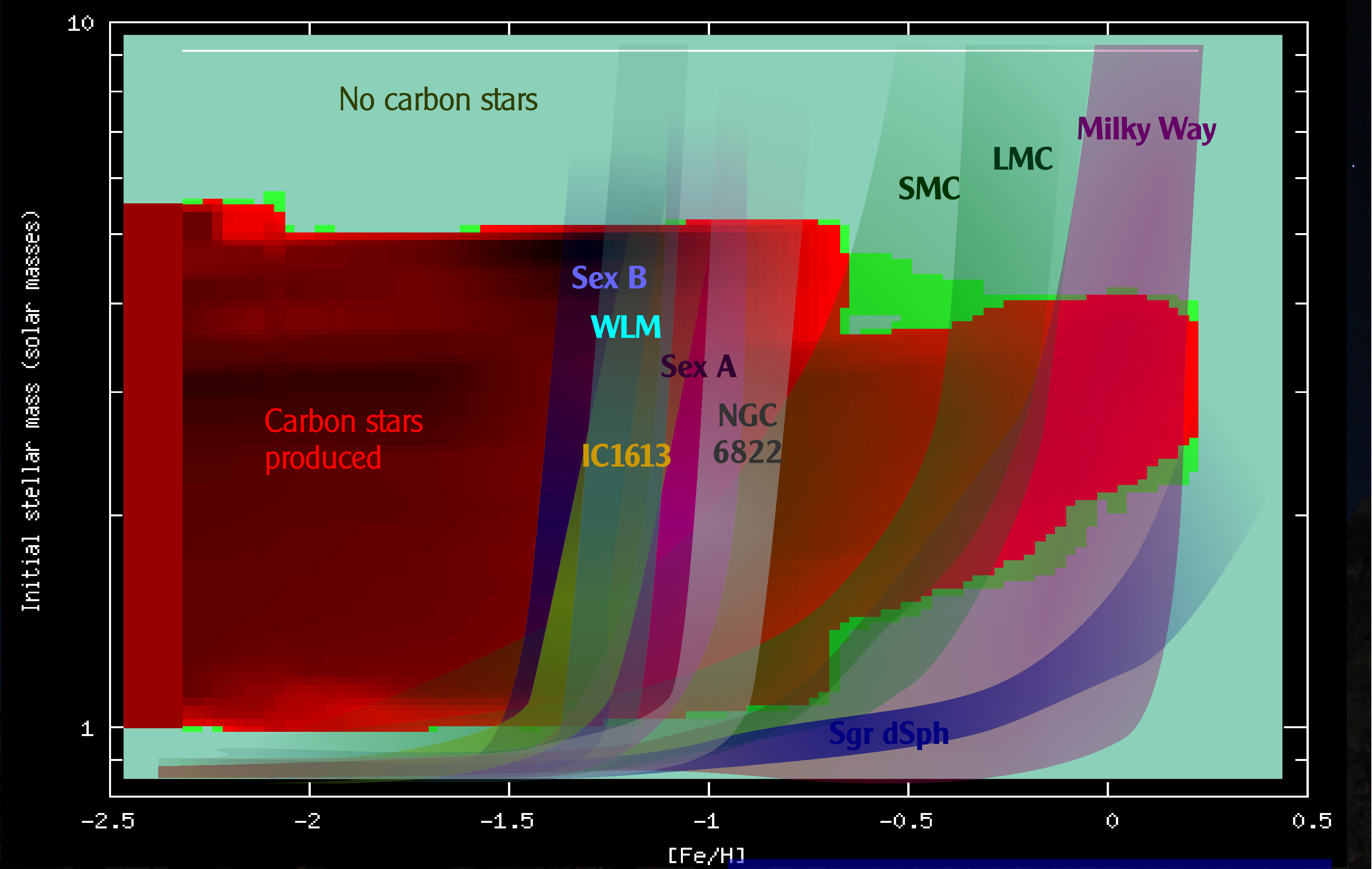
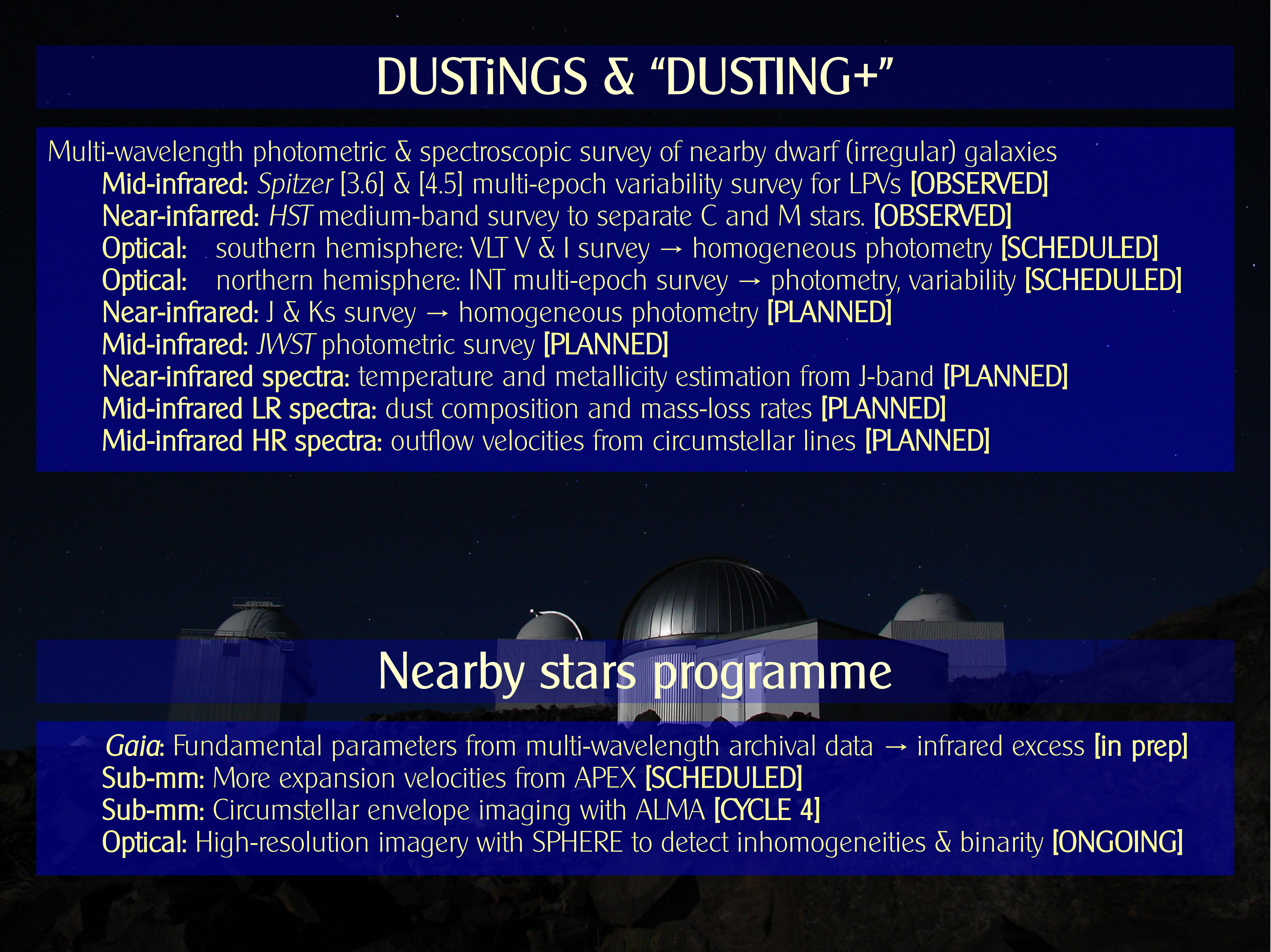


Solid: Marigo et al. (2008)
Black: Karakas+2010,2014; Lugaro+2012; Fishlock+2014
Ventura et al. (priv. comm.)

Futures: JWST studies of nearby populations



Data: Marigo & Girardi (1997); figure: McDonald et al. (2012)



DUSTiNGS & “DUSTING+”

Multi-wavelength photometric & spectroscopic survey of nearby dwarf (irregular) galaxies

Mid-infrared: *Spitzer* [3.6] & [4.5] multi-epoch variability survey for LPVs **[OBSERVED]**
Near-infarred: *HST* medium-band survey to separate C and M stars. **[OBSERVED]**
Optical: southern hemisphere: VLT V & I survey → homogeneous photometry **[SCHEDULED]**
Optical: northern hemisphere: INT multi-epoch survey → photometry, variability **[SCHEDULED]**
Near-infrared: J & Ks survey → homogeneous photometry **[PLANNED]**
Mid-infrared: *JWST* photometric survey **[PLANNED]**
Near-infrared spectra: temperature and metallicity estimation from J-band **[PLANNED]**
Mid-infrared LR spectra: dust composition and mass-loss rates **[PLANNED]**
Mid-infrared HR spectra: outflow velocities from circumstellar lines **[PLANNED]**

Nearby stars programme

***Gaia*:** Fundamental parameters from multi-wavelength archival data → infrared excess **[in prep]**
Sub-mm: More expansion velocities from APEX **[SCHEDULED]**
Sub-mm: Circumstellar envelope imaging with ALMA **[CYCLE 4]**
Optical: High-resolution imagery with SPHERE to detect inhomogeneities & binarity **[ONGOING]**

THE END

(really)