The impact of metal depletion on convective mixing prescriptions in 1D stellar evolution models

Stellar Archaeology as a
Time Machine to the First Stars

Kavli Institute for the Physics and Mathematics of the Universe

5 December 2018

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Australian National University

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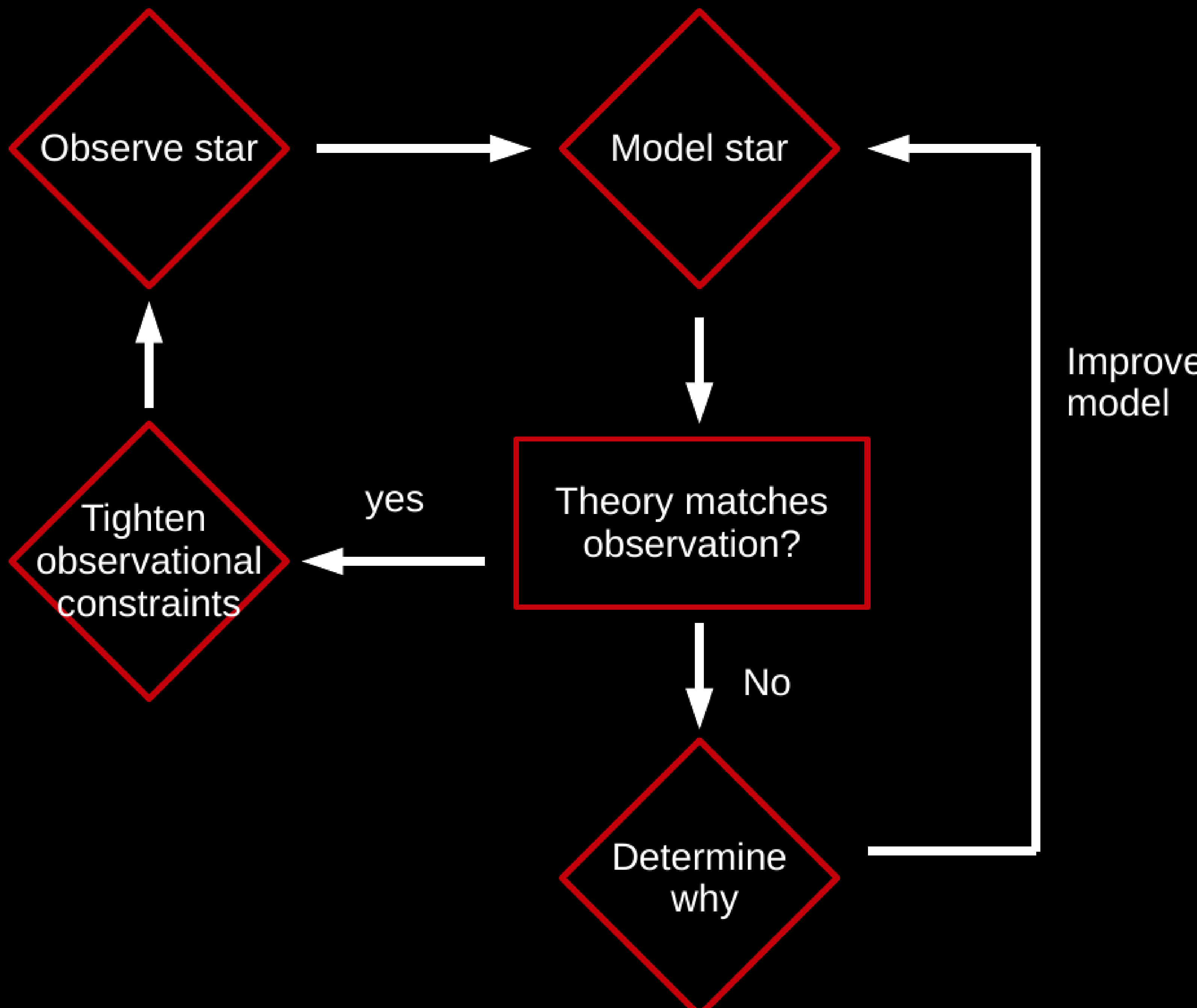
An ancient battle...



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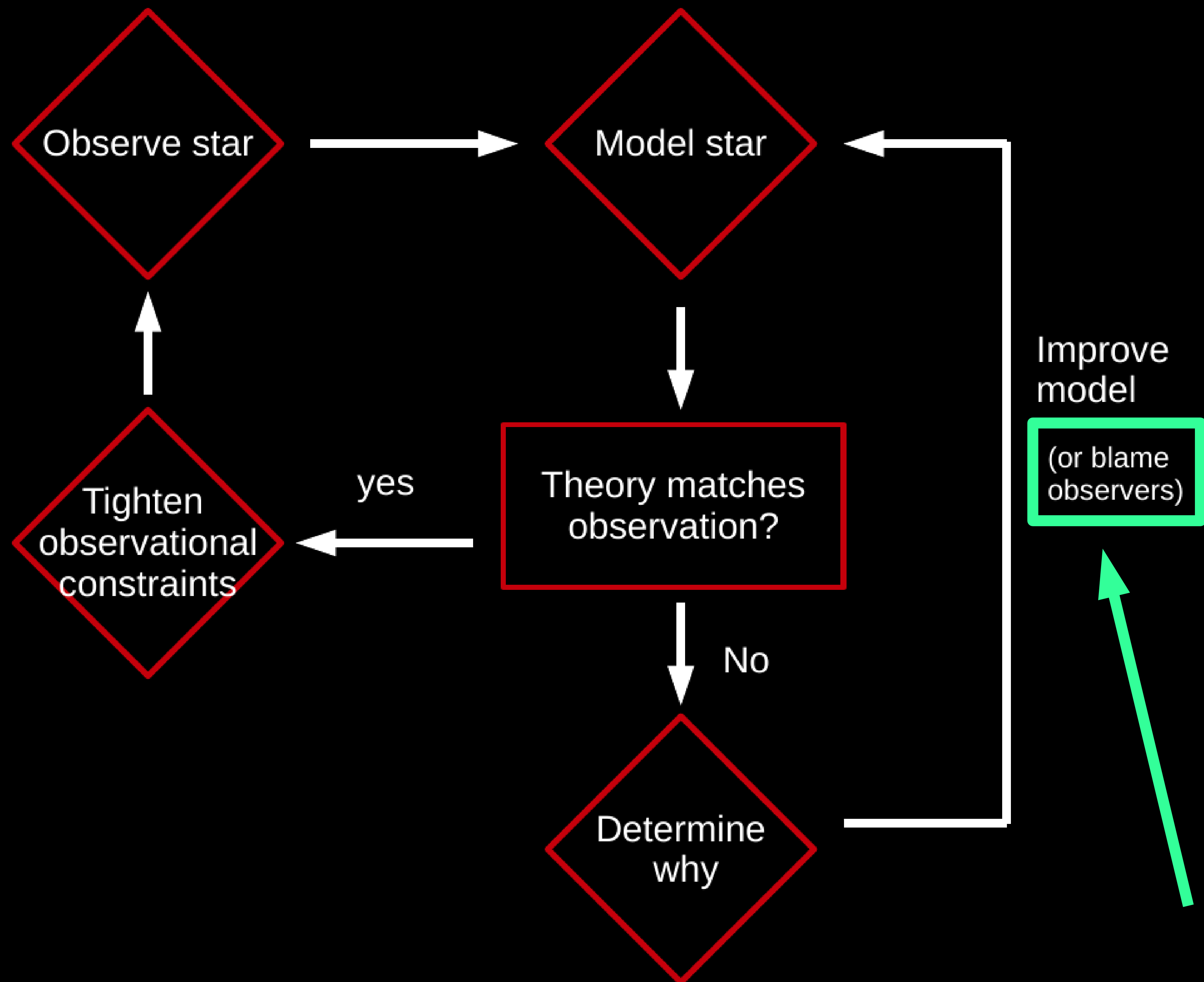
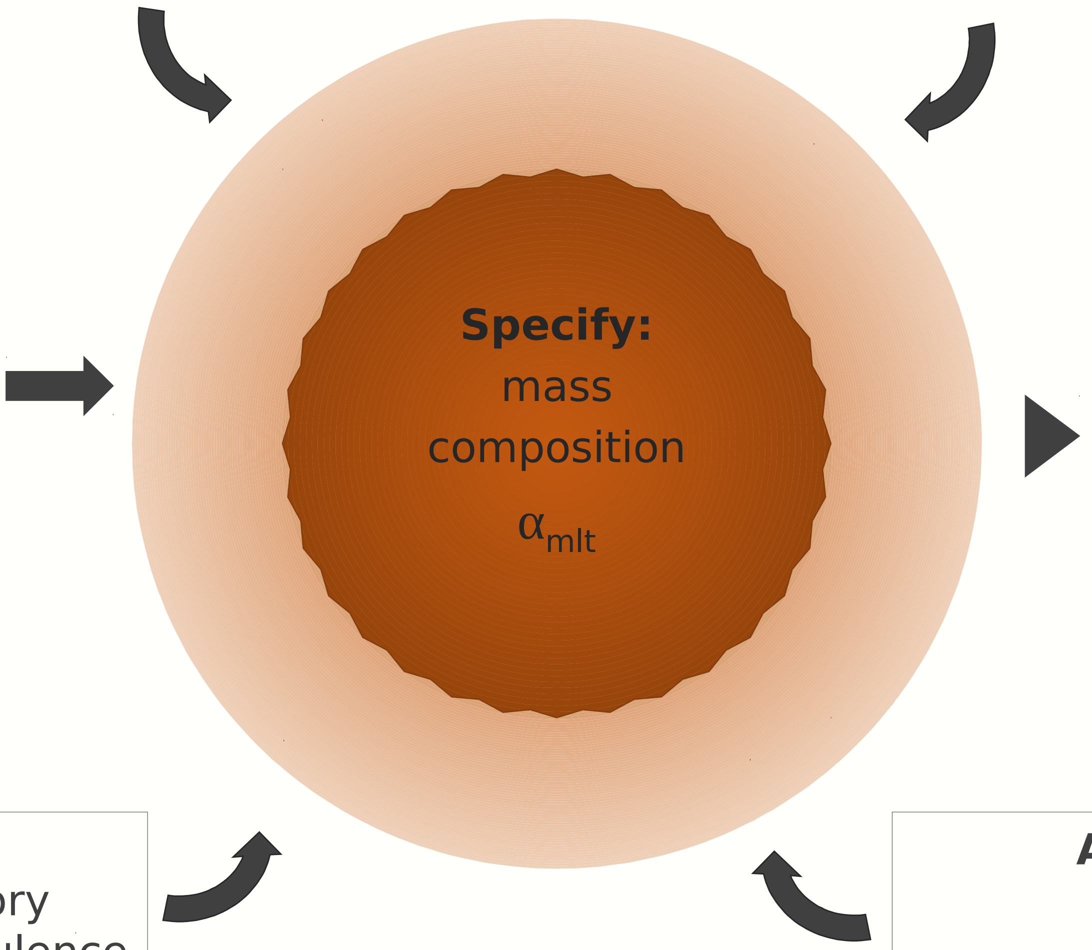


Components of a Stellar Structure and Evolution Code

Standard Equations:
mass & energy conservation
hydrostatic equilibrium
energy transport

Surface Boundary Conditions:
grey – Eddington $T(\tau)$
grey – Krishna Swamy $T(\tau)$
non-grey – stellar atmospheres

Microphysics:
opacities
equation of state
nuclear reactions



Properties:
radius
T_{eff}
luminosity
composition
P, T, ρ

Convection:
mixing length theory
full spectrum turbulence

Additional Physics:
diffusion
variable mass
rotation
magnetic fields / activity

Slide credit: Greg Feiden

1D Stellar Structure and Evolution Codes (SSECs)

DSEP- Dartmouth Stellar Evolution Program

MESA- Modules for Experiments in Stellar Astrophysics

GYRE, Y2, PARSEC, BaSTI, Victoria-Regina, Monash, Geneva, others*

(*don't yell at me if I forgot yours)

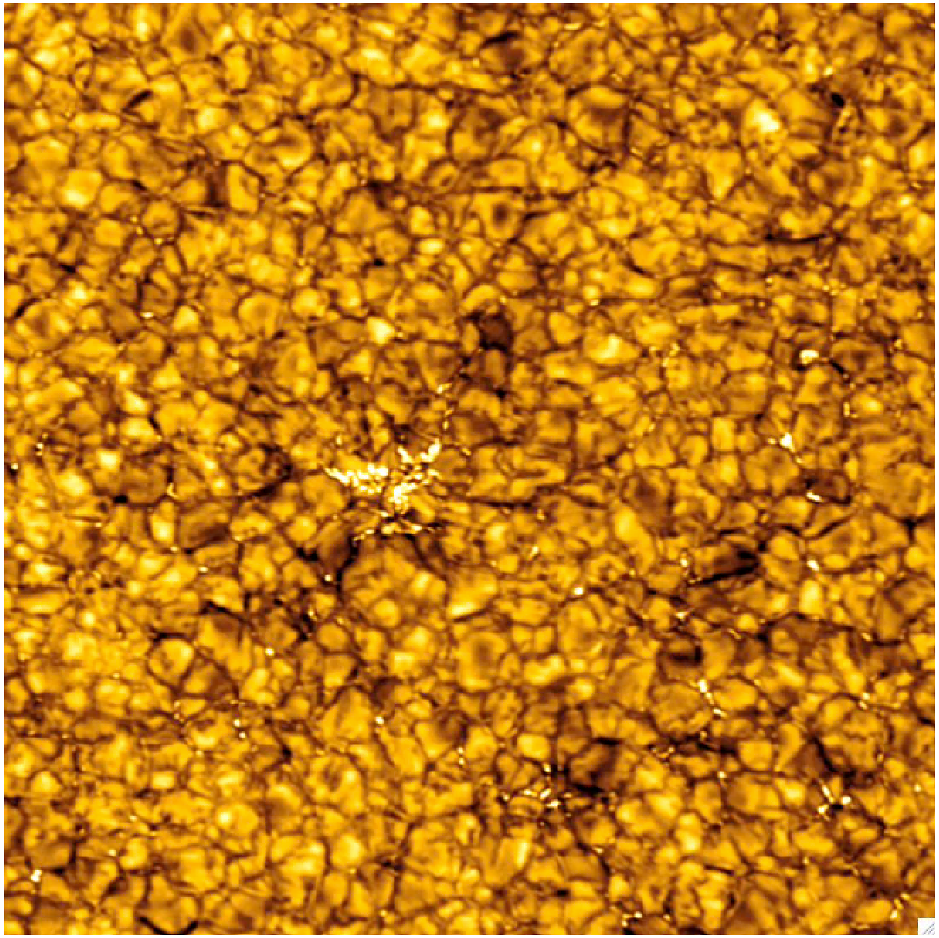
Question:

How do we model
3D stellar physics
with 1D codes?

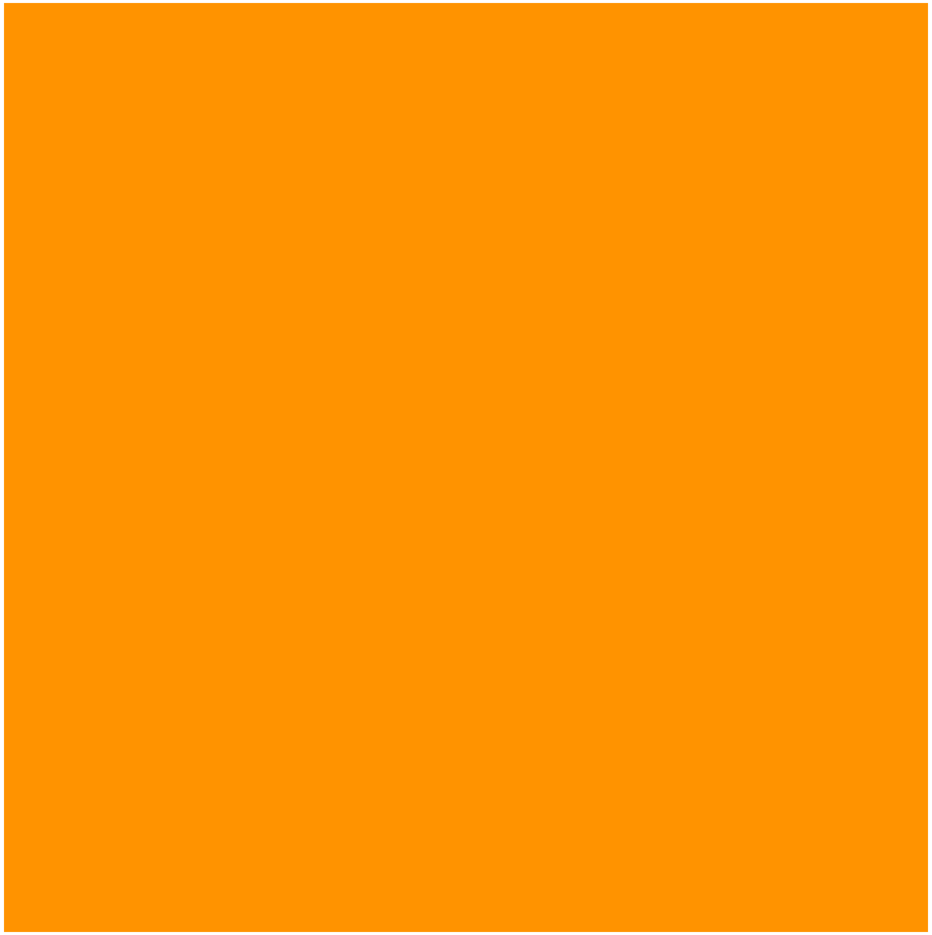
Answer:

Poorly.

1D vs 3D



Observations (SST)



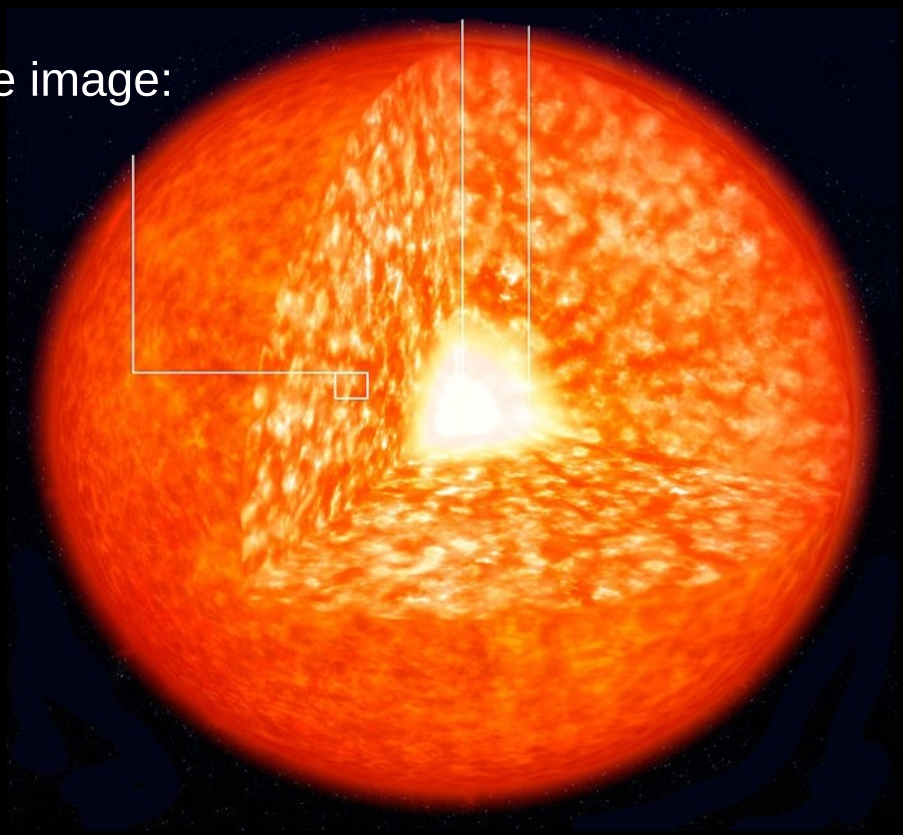
1D simulation

Slide credit: Anish Amarsi

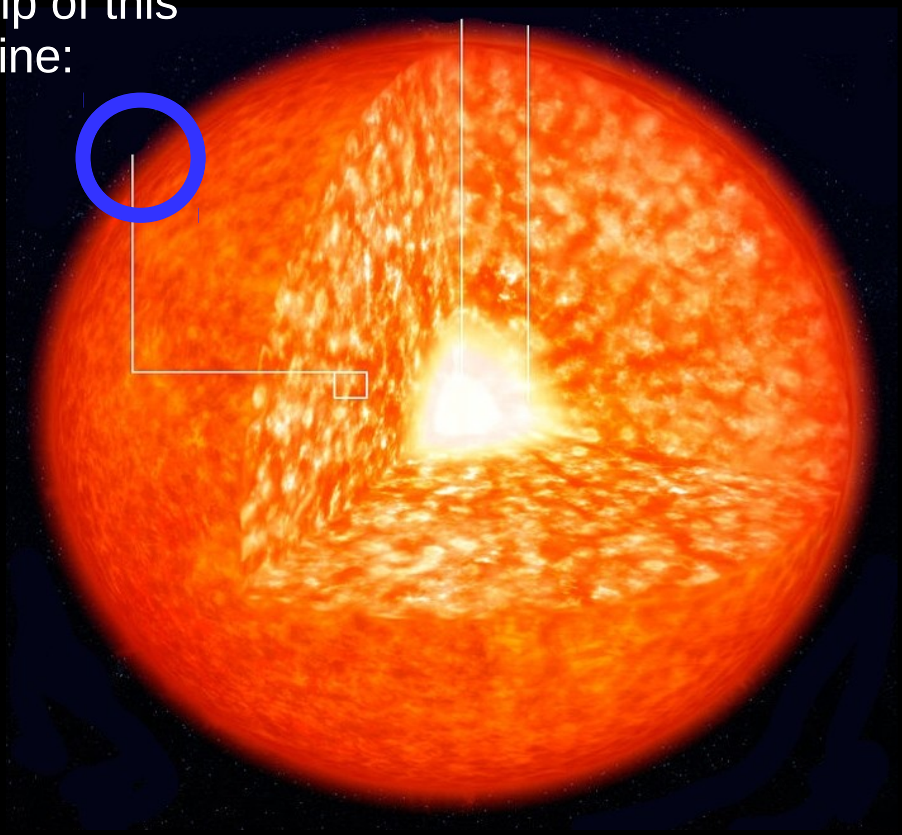
1D vs 3D

Modeling Scale:

whole image:



tip of this line:



1D vs 3D

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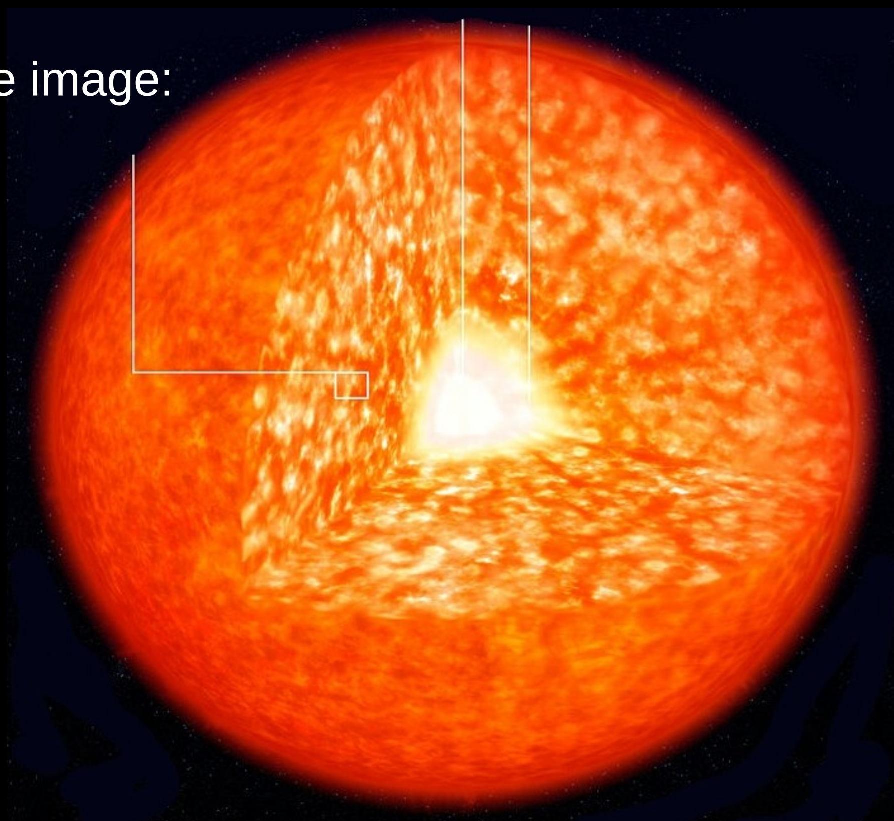
whole image:



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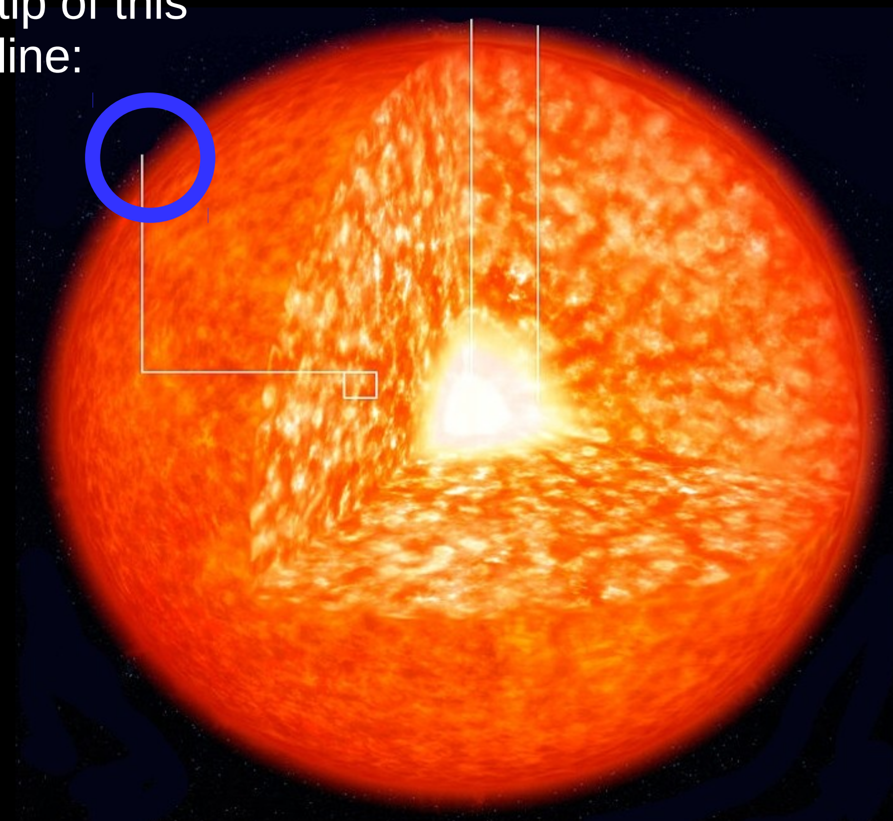
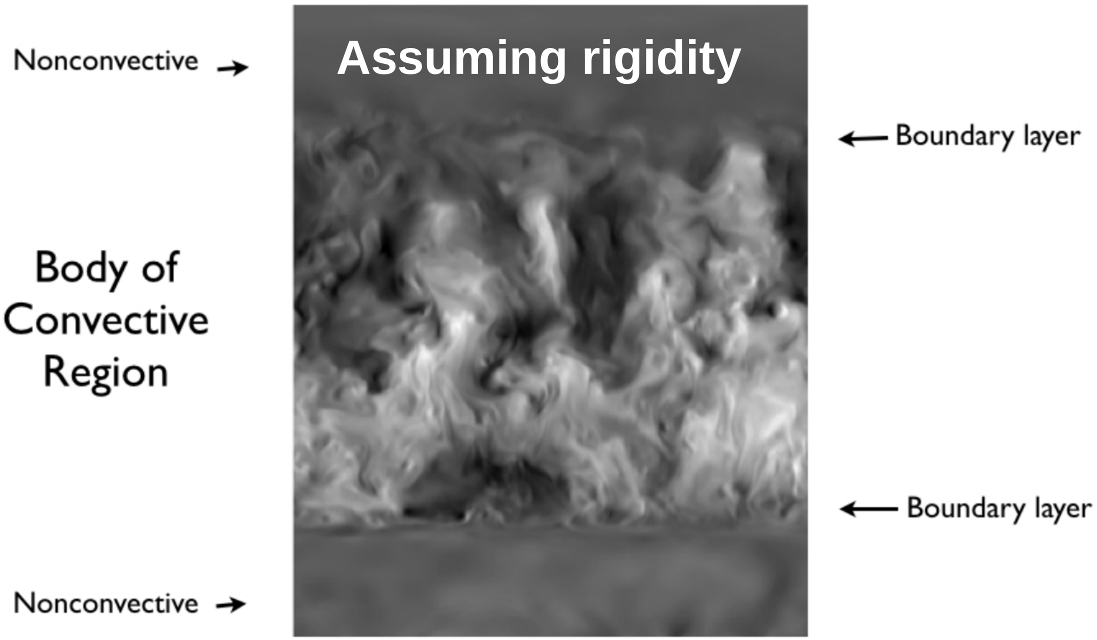


Physical time:

15 Gyr

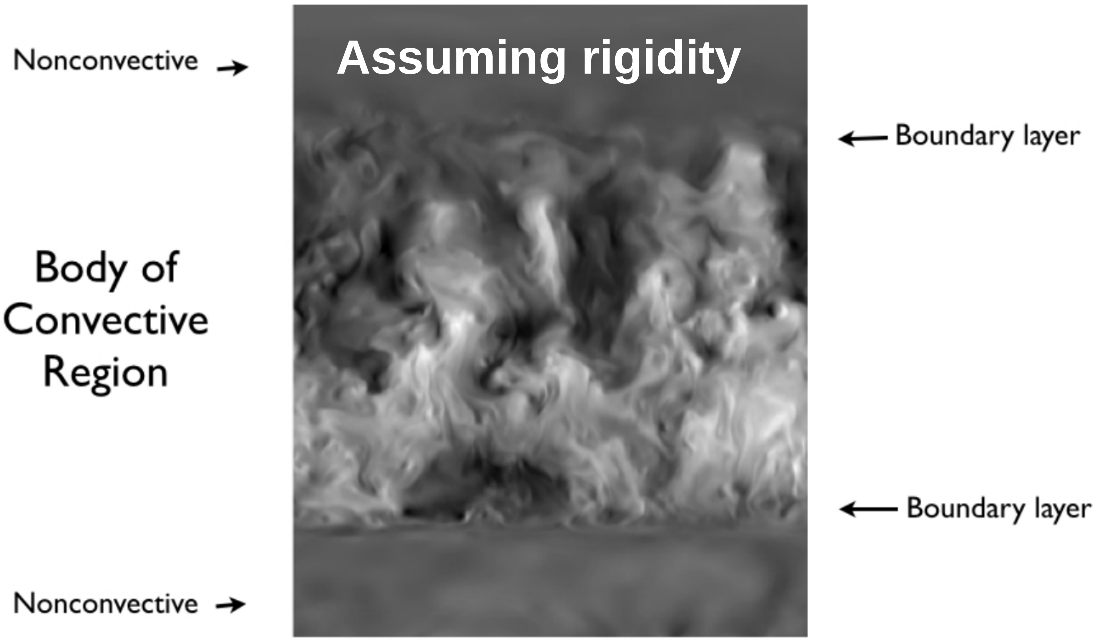
Duration of a conference dinner

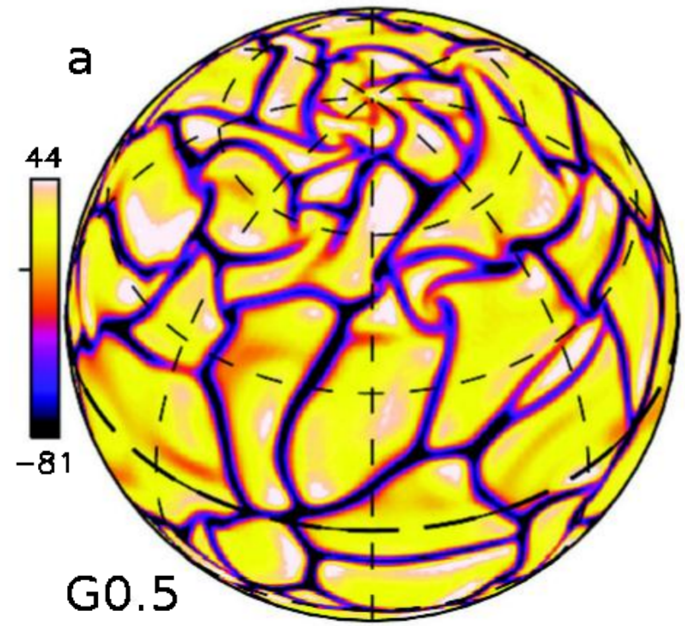
Problems with common assumptions:



Problems with common assumptions:

Negative kinetic flux
& transport asymmetry





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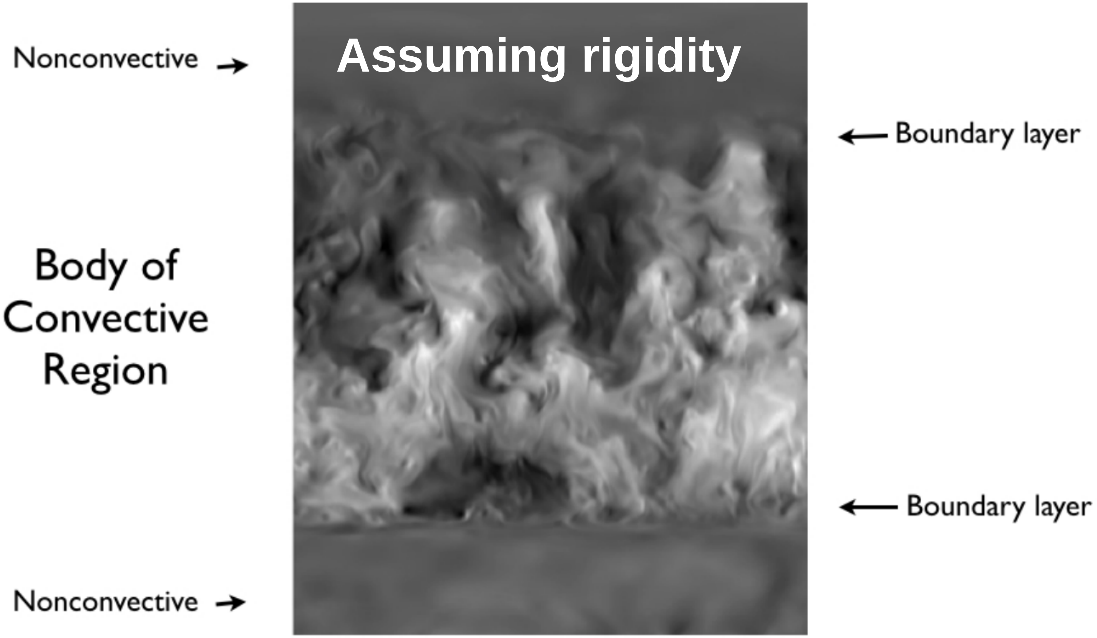
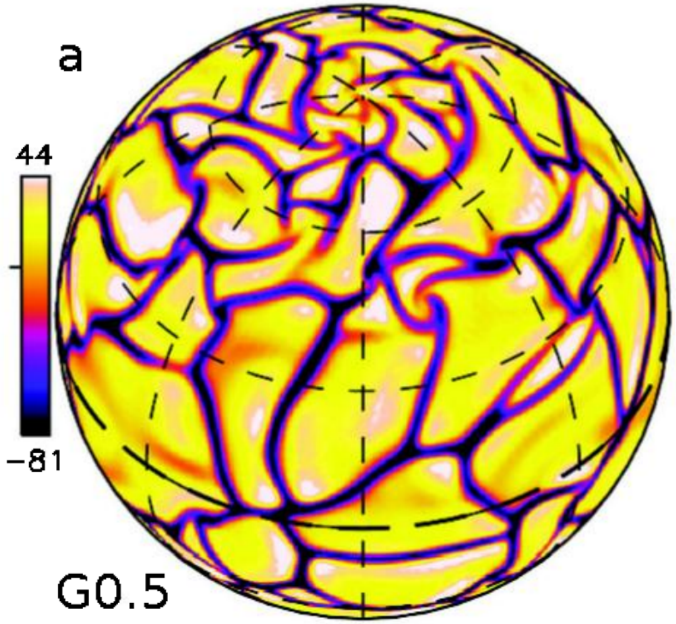
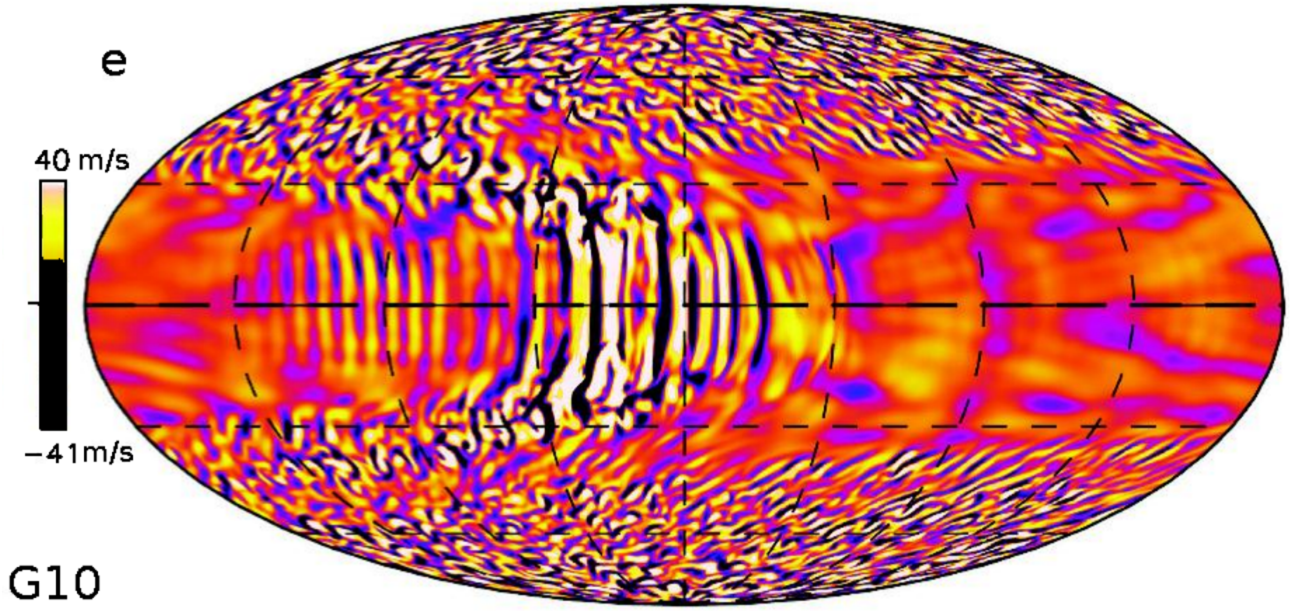


Negative kinetic flux & transport asymmetry





Rotation is a thing!!

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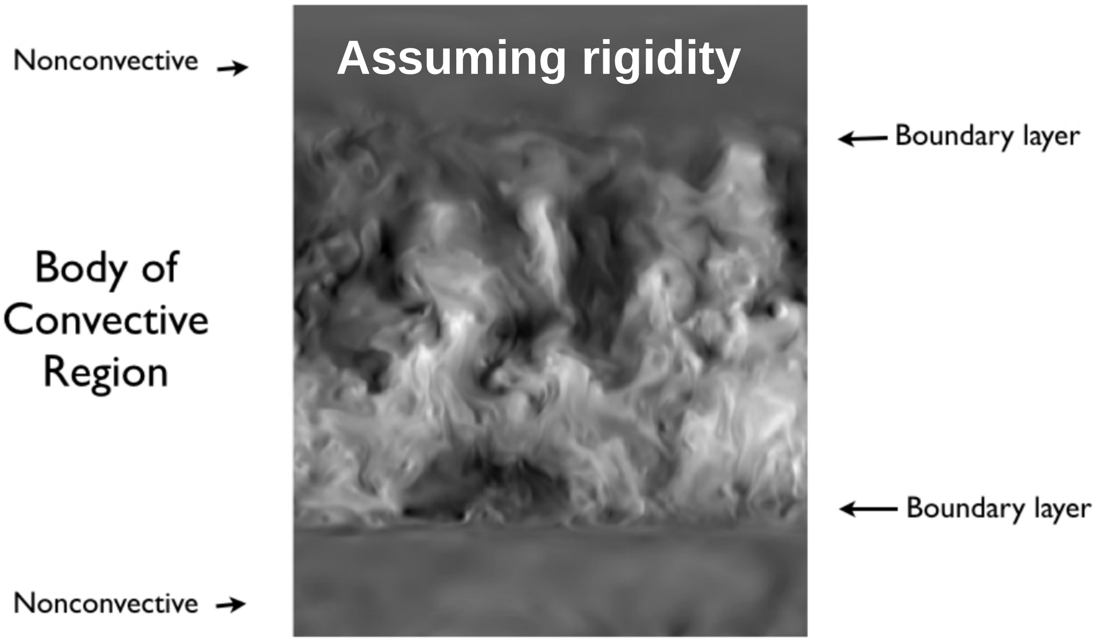

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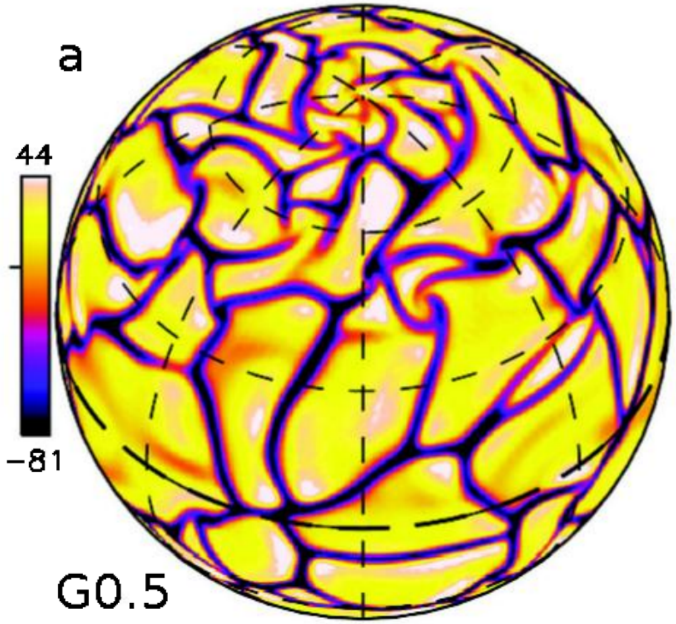
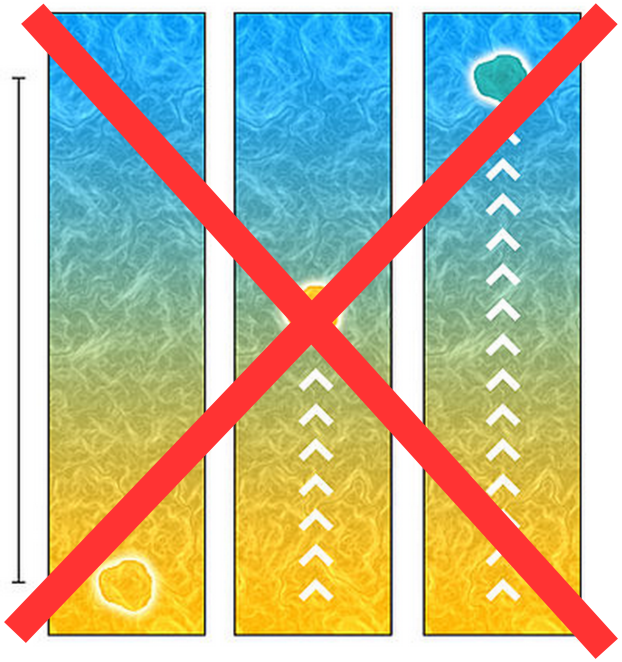
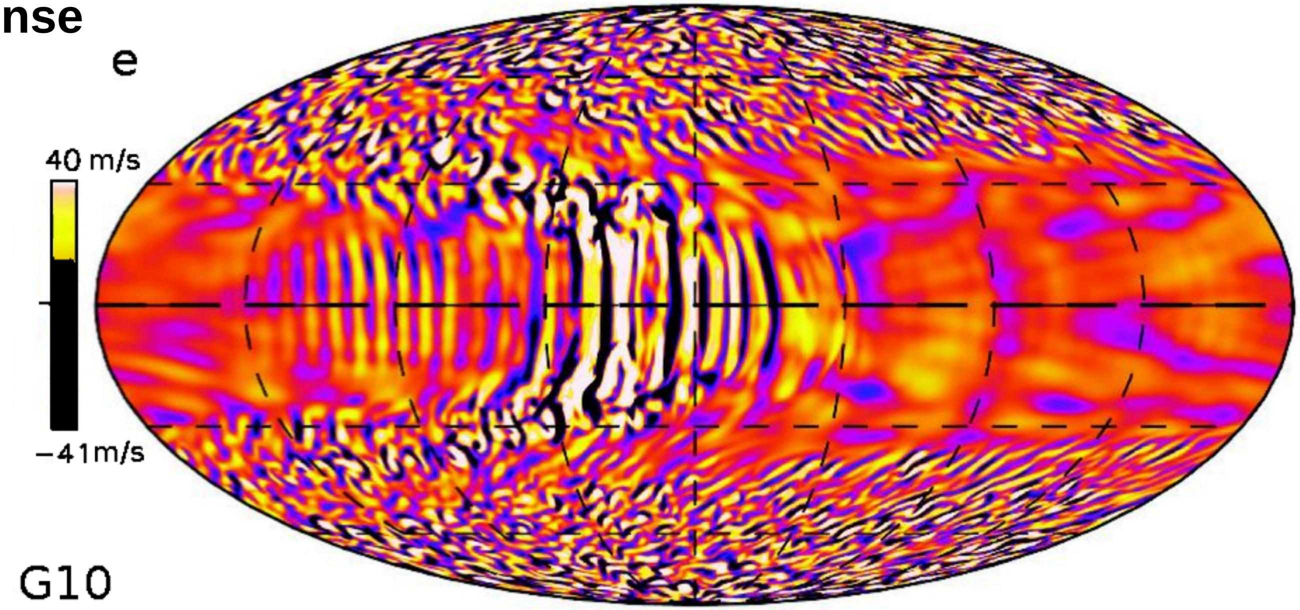


“Convective parcels” are nonsense



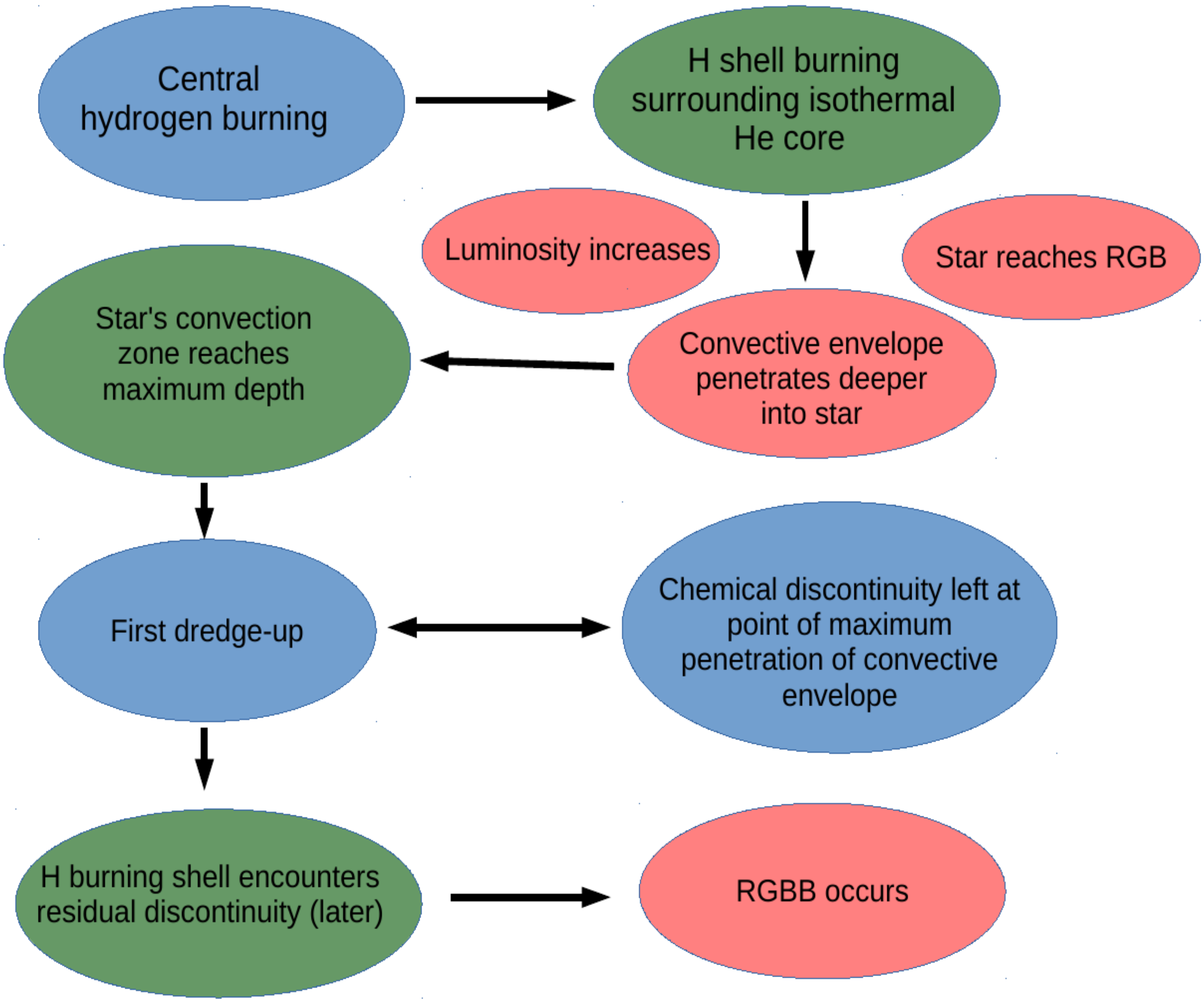


Rotation is a thing!!

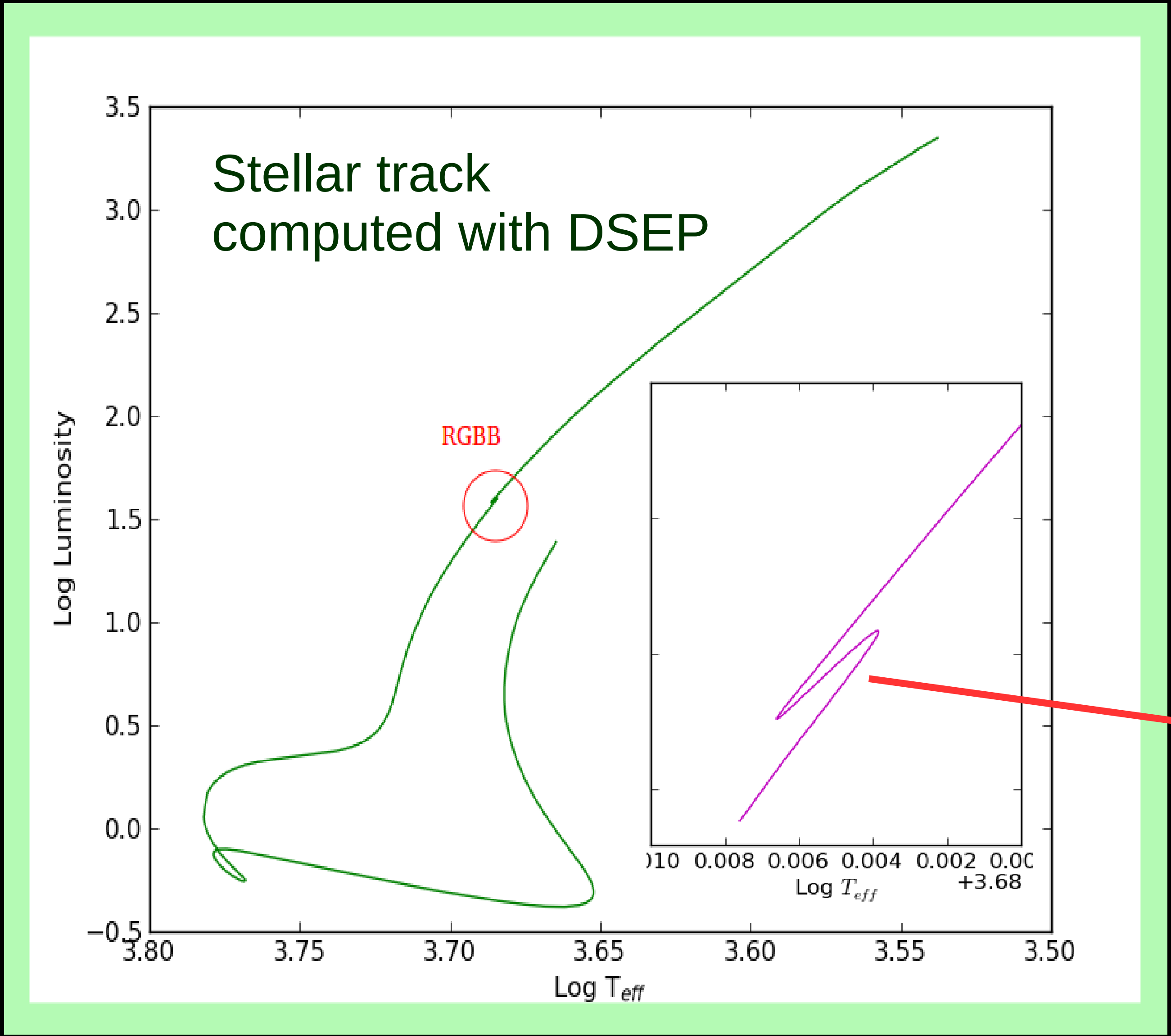
Study 1:

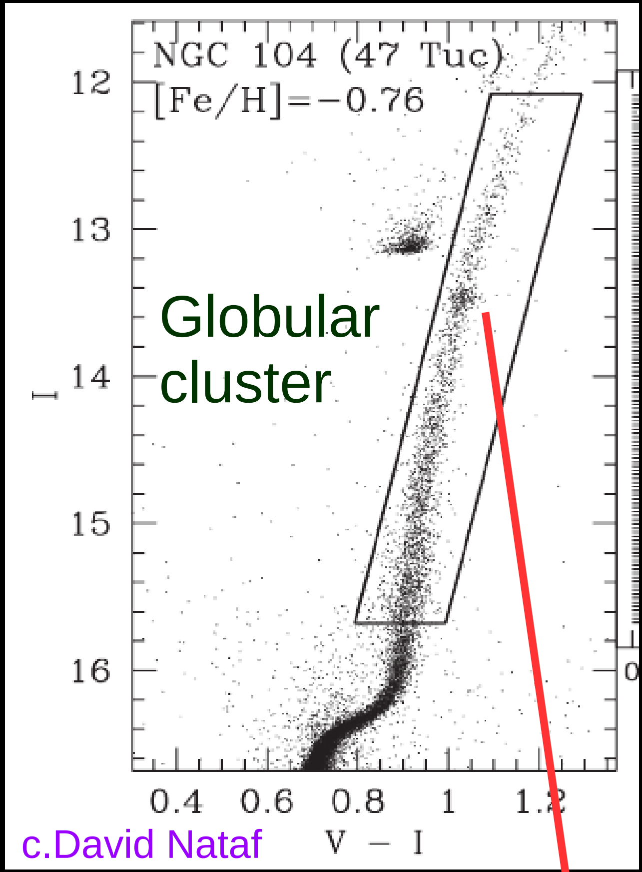
Using convective overshoot to address low-metallicity modeling discrepancies

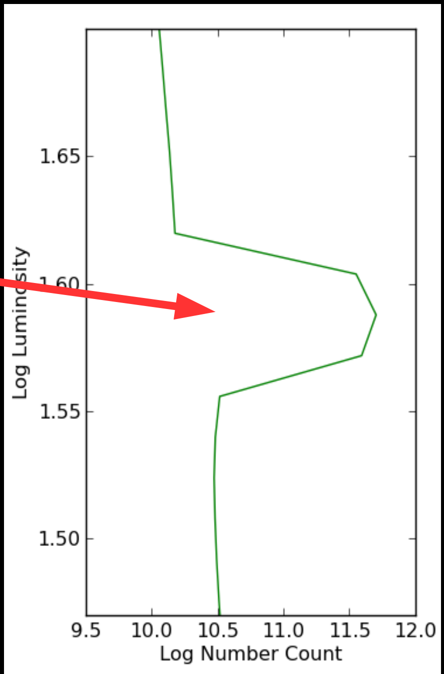
Physics of the Red Giant Branch Bump

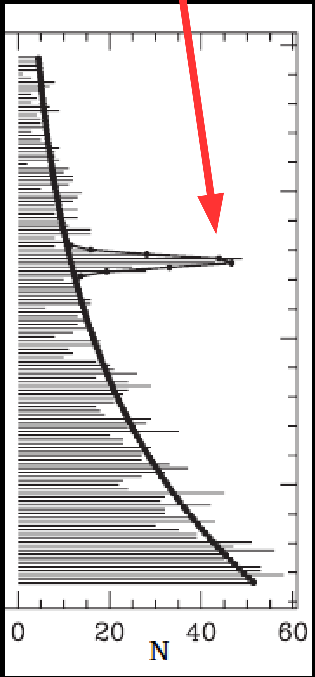


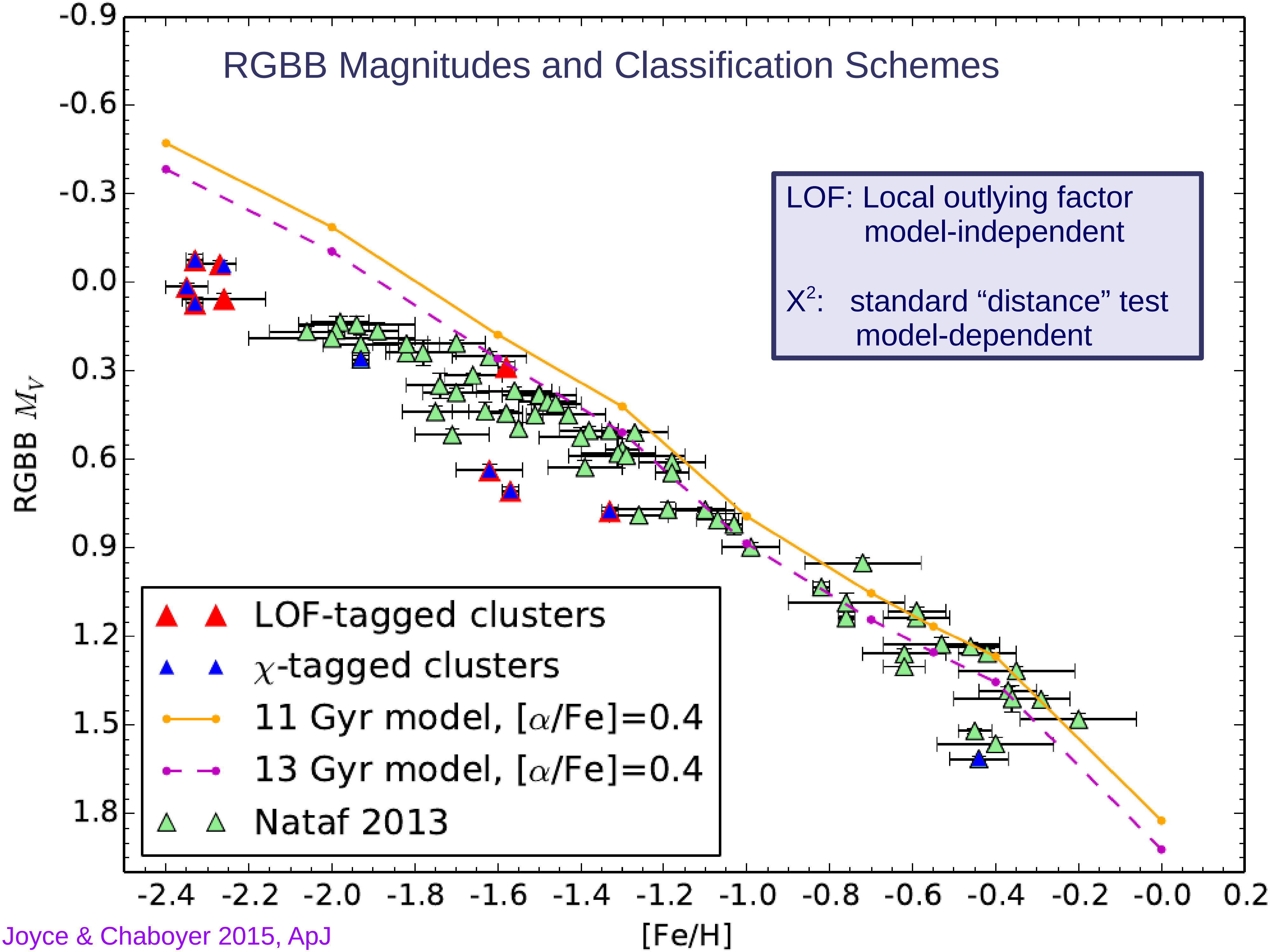
Comparing between theory and observation



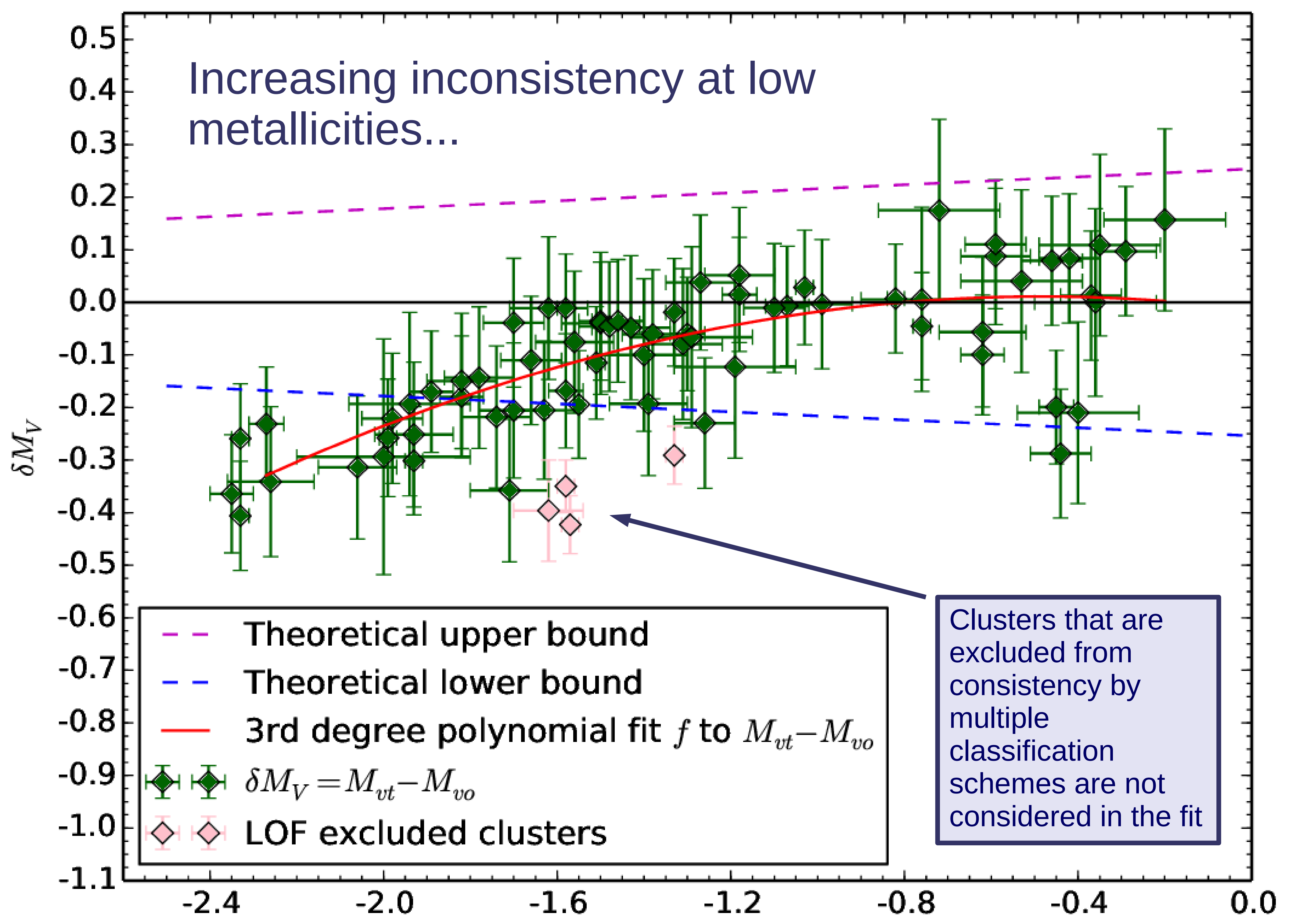








Joyce & Chaboyer 2015, ApJ



Joyce & Chaboyer 2015, ApJ

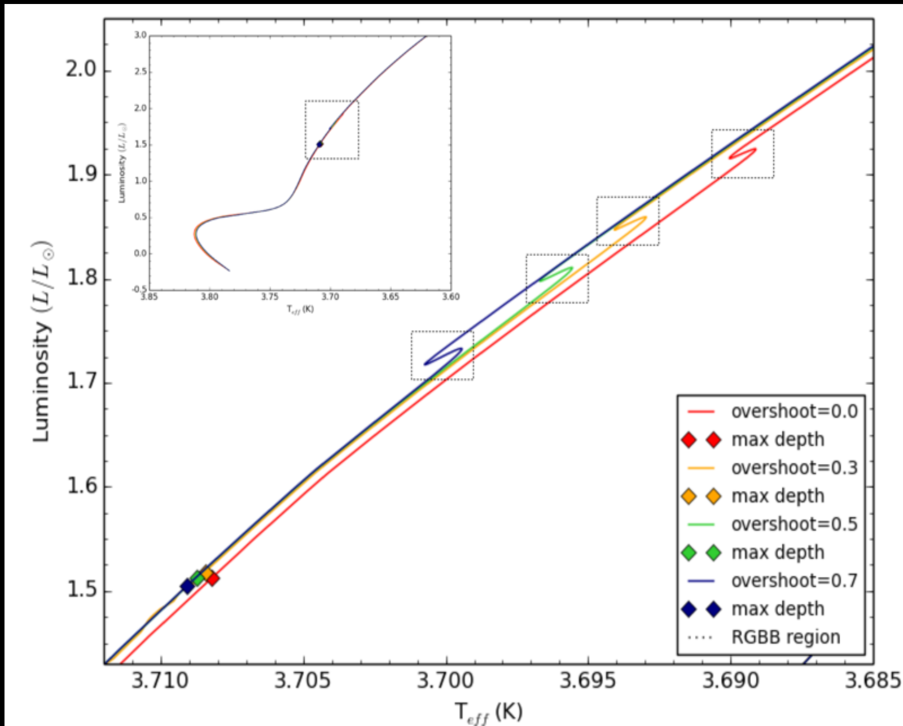
Resolving discrepancy with convective overshoot

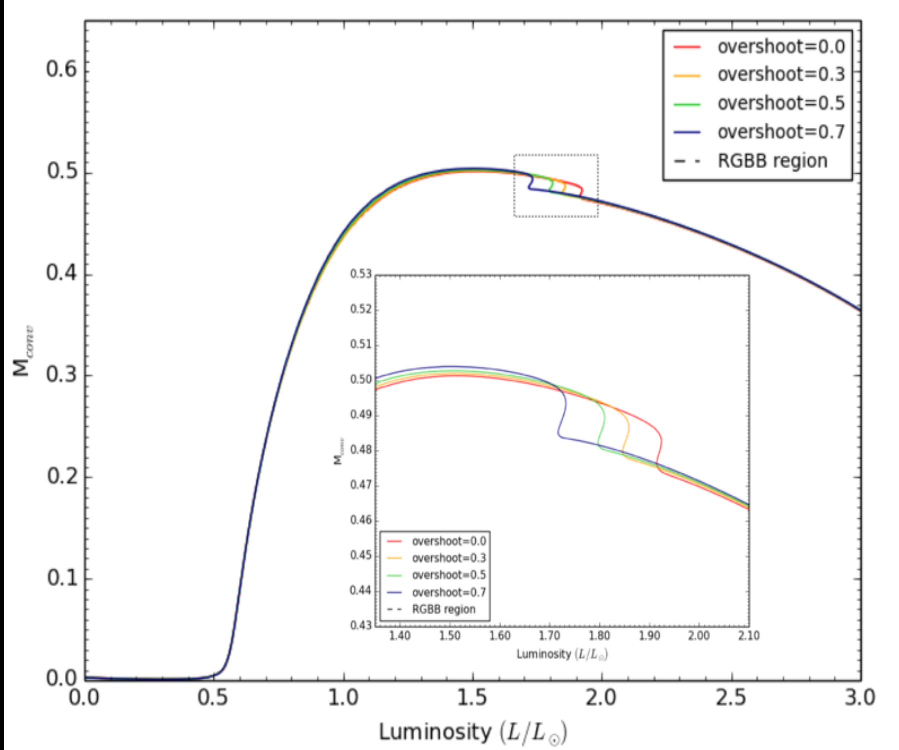
increasing overshoot...

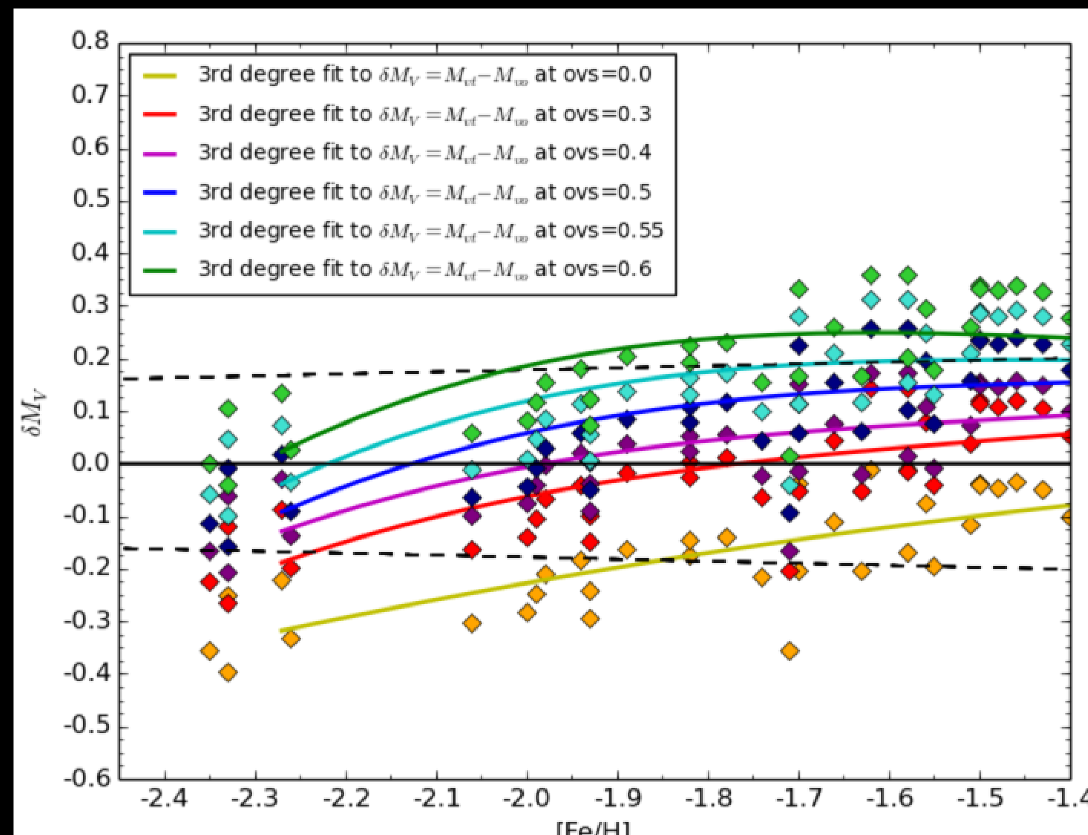
- allows for more “transmission” of material between convective and radiative zones

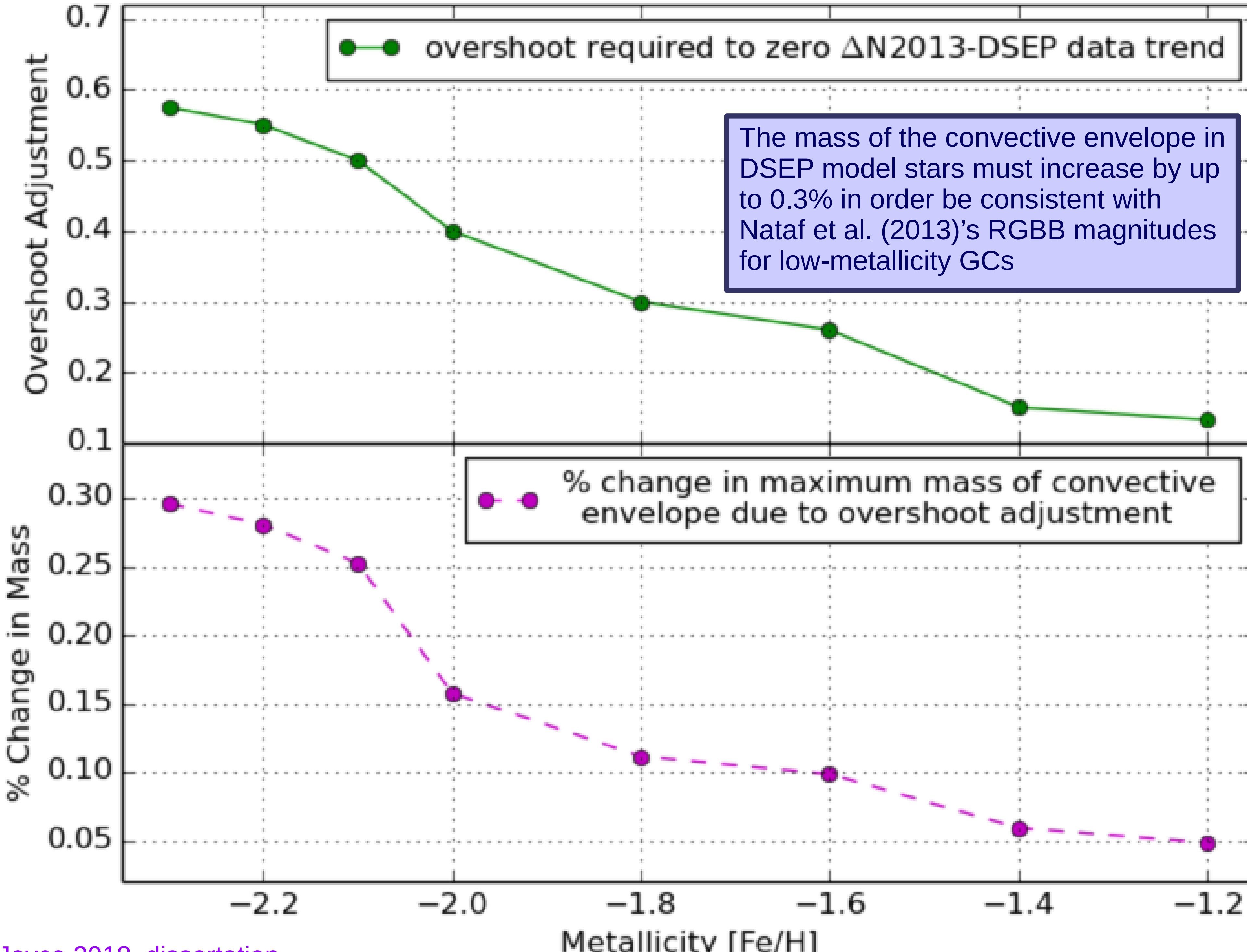
- moves the boundary of the convective envelope deeper into the interior

- RGBB occurs earlier, at higher temperatures and lower luminosities







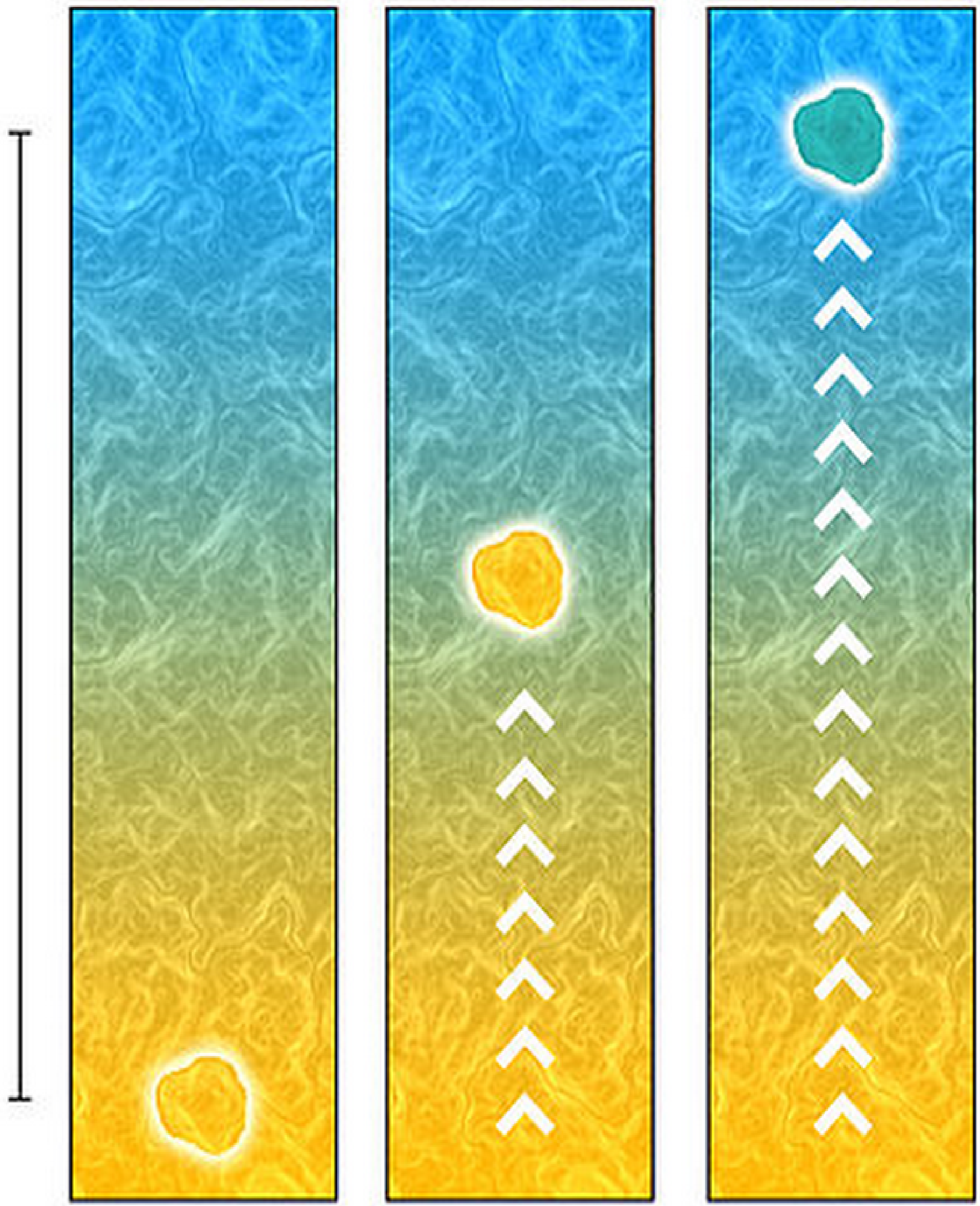


Joyce 2018, dissertation

Study 2:

Empirically calibrating the mixing length for 6 stars with [Fe/H] < -2.3

Mixing Length Theory (MLT) Formalism



$$F_{\mathrm{conv}} = \frac{1}{2}\rho v c_p T \frac{\lambda}{\mathrm{H_P}} (\nabla_T - \nabla_{\mathrm{ad}}).$$

$$\alpha_{\mathrm{MLT}} = \frac{\lambda}{\mathrm{H_P}} \qquad \nabla_T = \left(\frac{d\ln T}{d\ln P}\right)$$

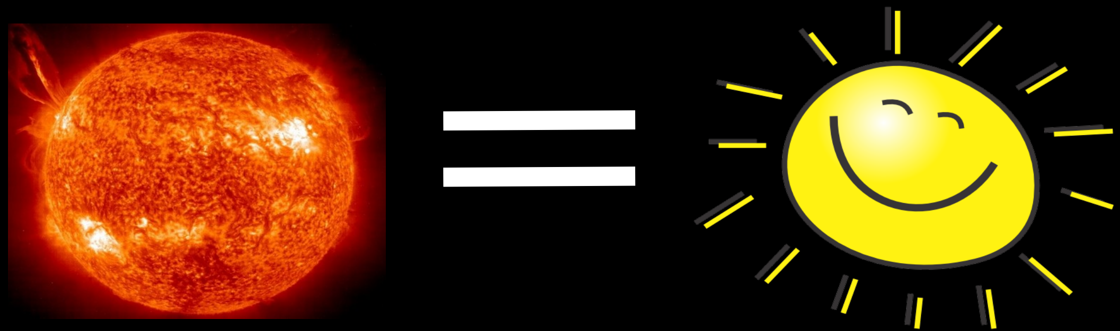
-discrete parcels consist of fluid which is in pressure, but not thermal, equilibrium

-parcels move along vertical trajectories

-distance which parcels can travel before denaturing is the “mixing length”

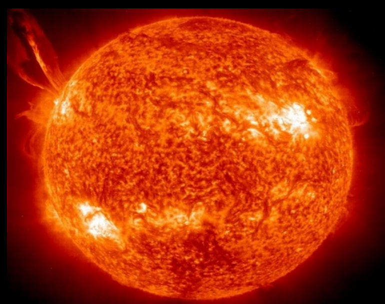
-α_{MLT} represents mean free path measured in pressure scale heights, $H_P = d\ln(P) / d\ln(T)$

Not All Stars are the Sun



Mixing length is calibrated by minimizing differences between modeled and measured values of the solar radius, luminosity, and surface abundance…

Not All Stars are the Sun



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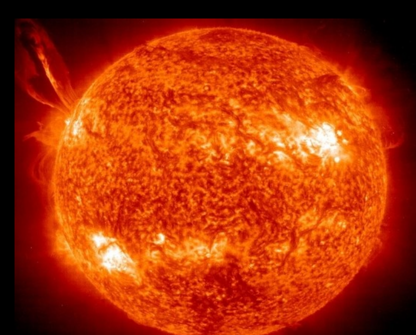
Mixing length is calibrated by minimizing differences between modeled and measured values of the solar radius, luminosity, and surface abundance…

but these features are specific **to a particular star!**



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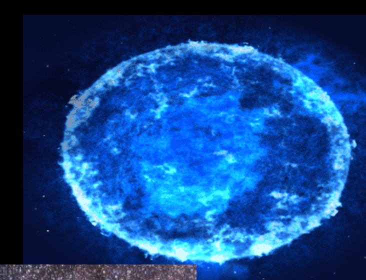
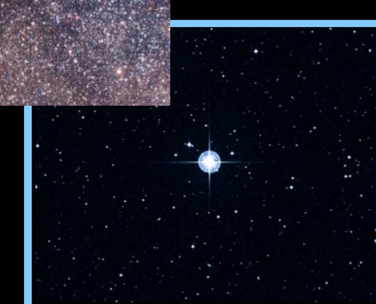




Common Approach	Better Approach?
• Assume a solar mixing length in other stellar models, ad hoc. Choose not to worry about it	• Remove the Sun entirely. Can we **directly calibrate** the mixing length in conditions that are as non-solar as possible?
• Adopt a “standard” choice for input physics in models. Choose not to worry about it	• What happens when we **change** our assumptions about **the modeling physics**?
• Maybe explore how mixing length varies with some input (e.g. metallicity) for solar analogs	• Can we extrapolate the behavior of the mixing length as a function of **stellar phase** and **mass**?

Six metal-poor calibrators:

not the Sun

Properties of Fitted Objects

Name	V	$V-I$	[Fe/H]	Reference
HD 140283	7.21	0.0	−2.46	Creevey et al. (2015)
HIP 46120	10.12	0.752	−2.22	Chaboyer et al. (2017)
HIP 54639	11.38	0.914	−2.50	Chaboyer et al. (2017)
HIP 106924	10.36	0.803	−2.23	Chaboyer et al. (2017)
WOLF 1137	12.01	0.85	−2.53	O'Malley et al. (2017)
M92	-	-	−2.24	Sarajedini et al. (2007)

Four physical configurations in DSEP:

not taking physics for granted

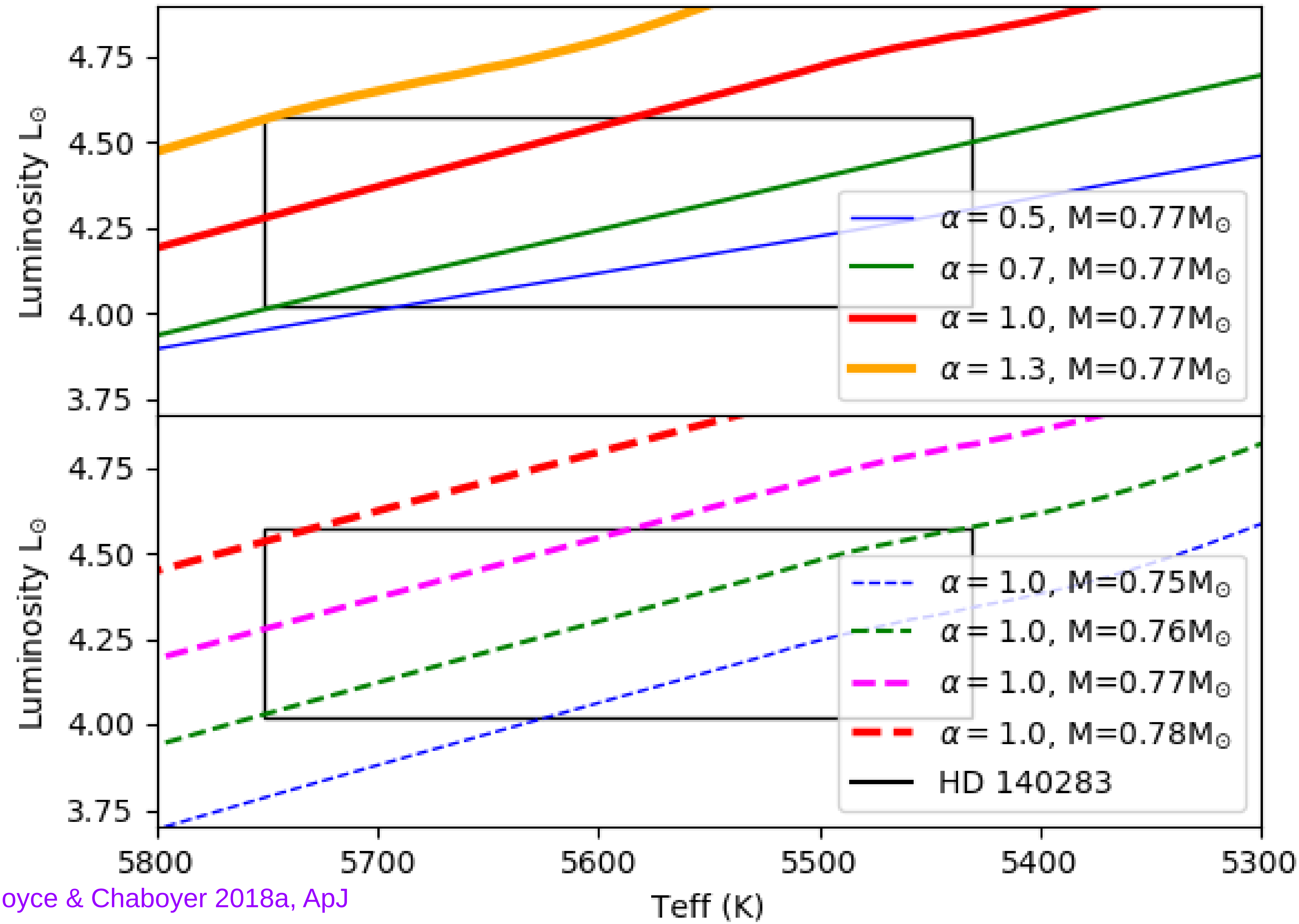
Solar-Calibrated Mixing Length Values for Various Physical Configurations

Atmosphere	η_D	$\alpha_\odot$	Y_{in}	Z_0
PHOENIX	1.0	1.9258	0.275	0.019
Grey	1.0	1.8205	0.282	0.019
PHOENIX	0.5	1.8292	0.277	0.0176
PHOENIX	1.5	1.9780	0.282	0.0192

Key point!

These six calibrators span the HR diagram at “fixed” metallicity ([Fe/H]=~-2.3), allowing us to isolate possible variations with stellar phase while focusing on depleted stars

Object: HD140283 Phase: Sub-giant



Joyce & Chaboyer 2018a, ApJ

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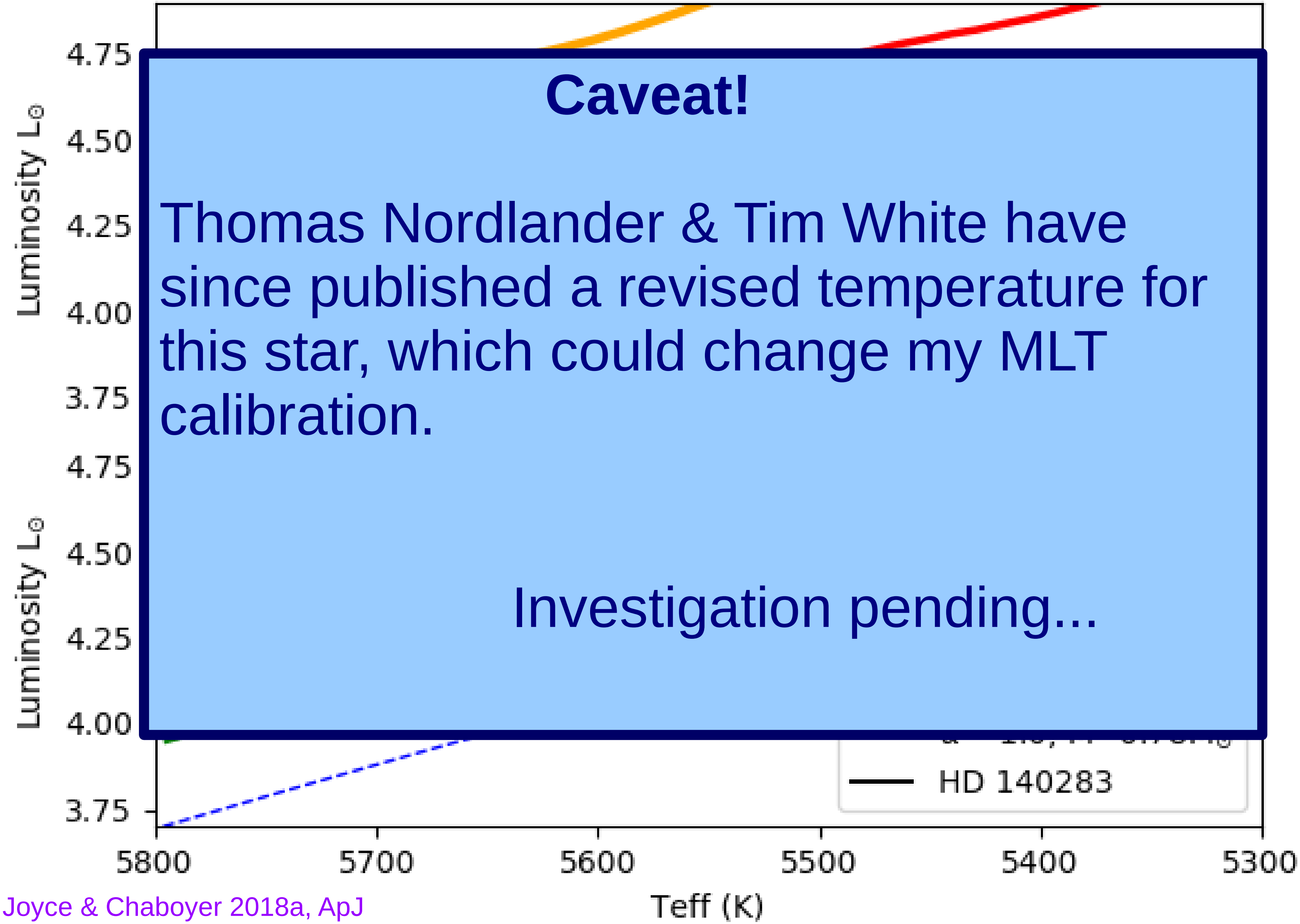
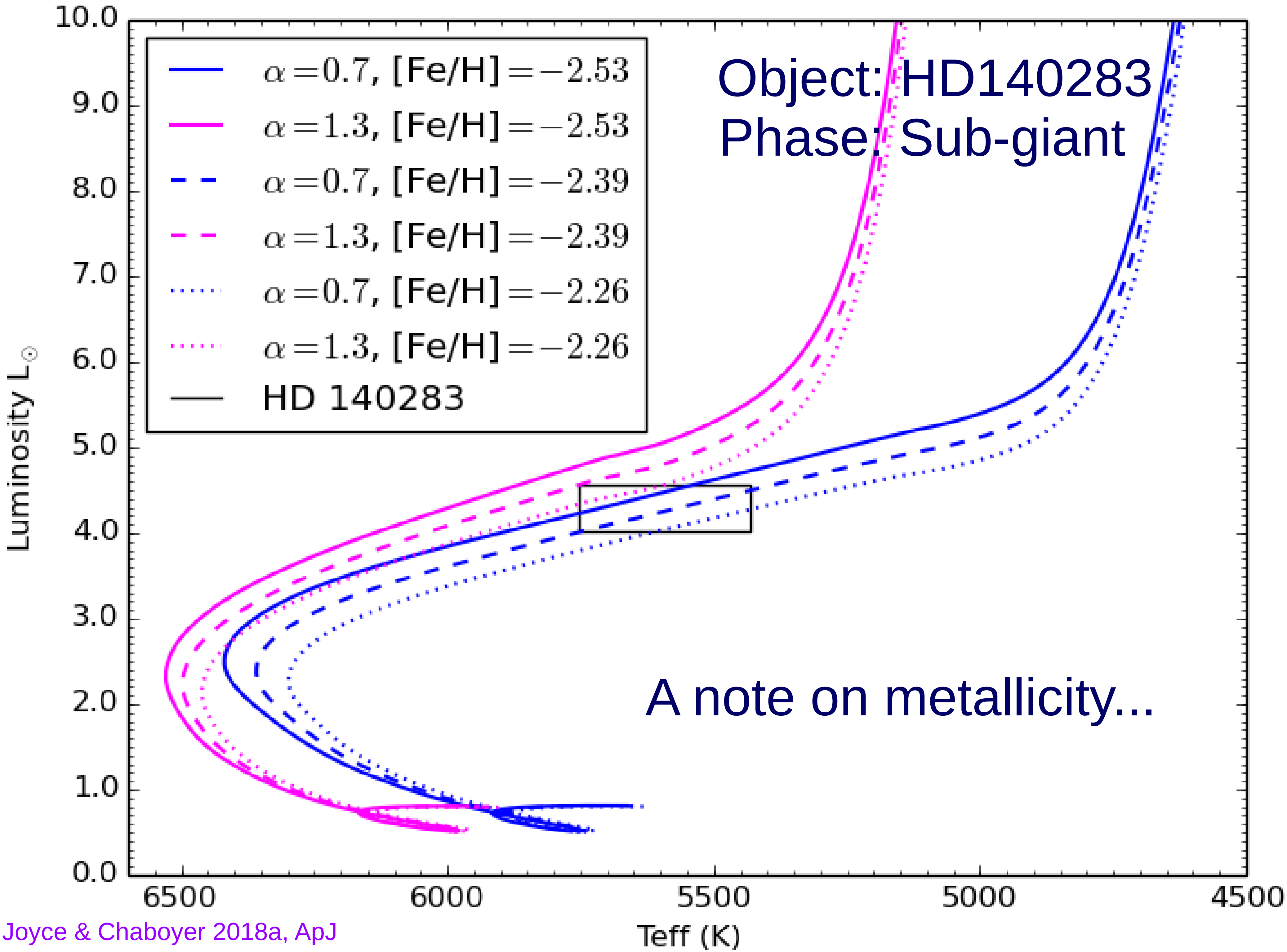


Caveat!

Thomas Nordlander & Tim White have since published a revised temperature for this star, which could change my MLT calibration.

Investigation pending...

Joyce & Chaboyer 2018a, ApJ



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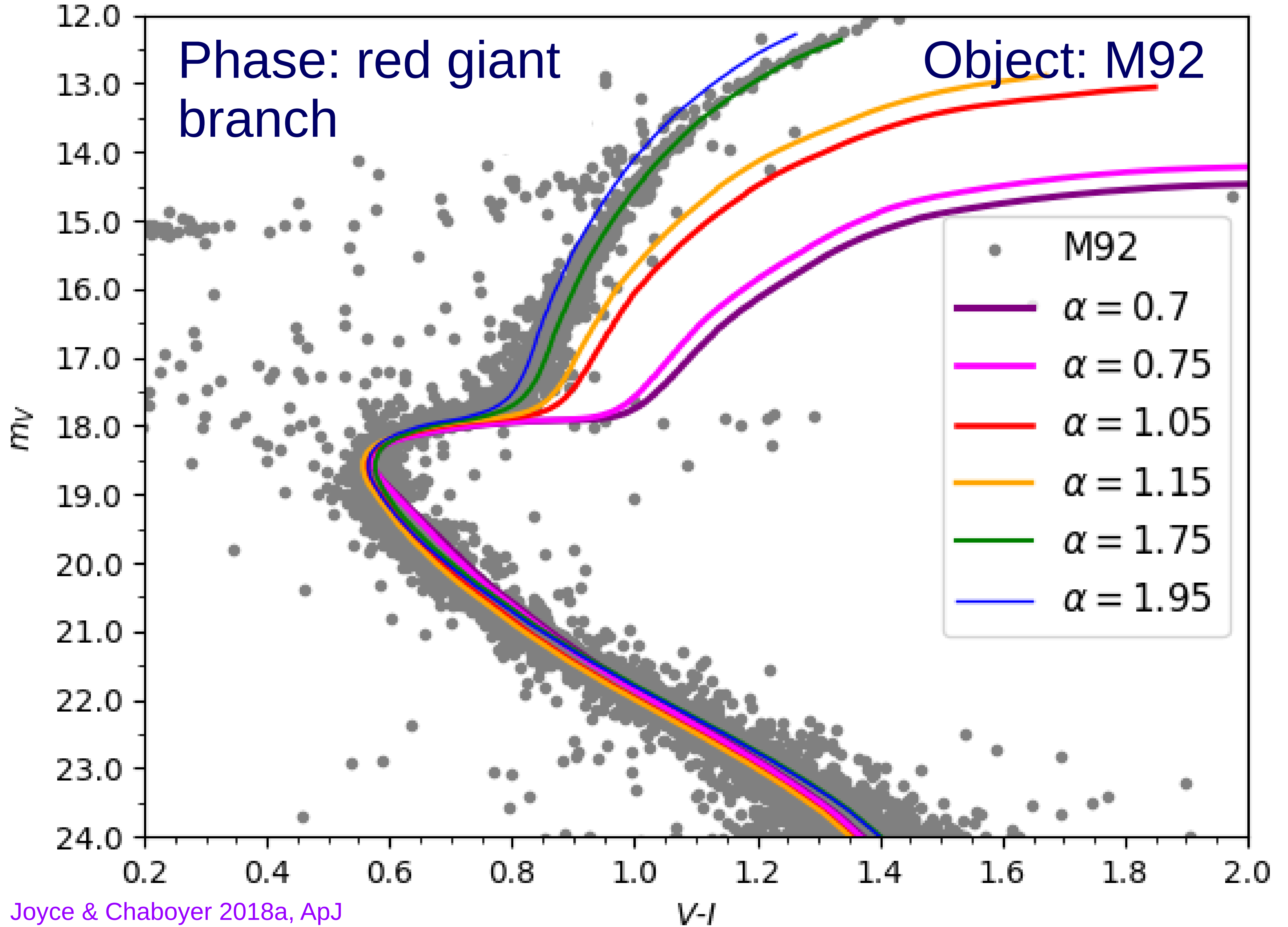

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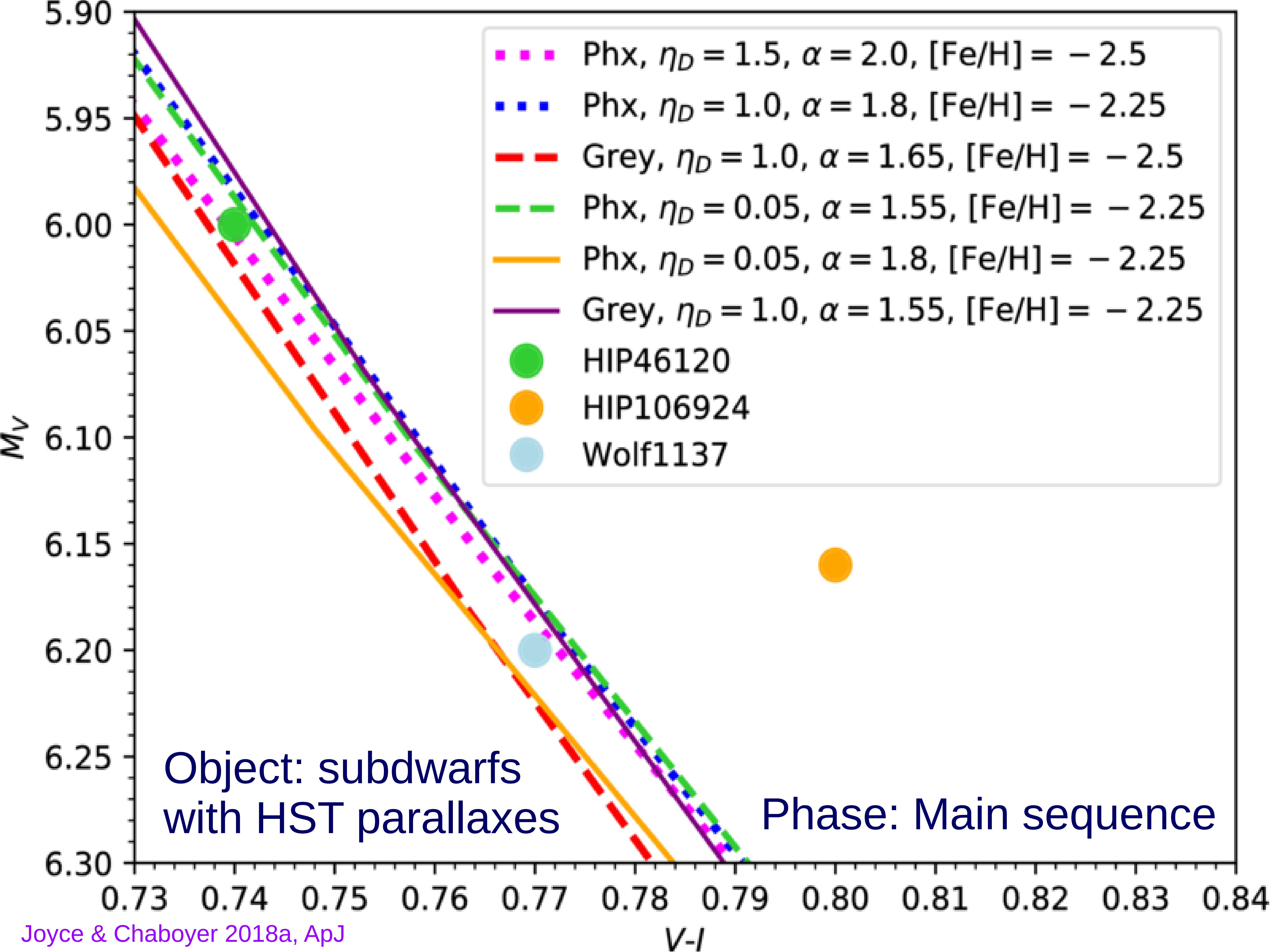

Phx, $\eta_D = 1.5$, $\alpha = 2.0$, [Fe/H] $= -2.5$
Phx, $\eta_D = 1.0$, $\alpha = 1.8$, [Fe/H] $= -2.25$
Grey, $\eta_D = 1.0$, $\alpha = 1.65$, [Fe/H] $= -2.5$
Phx, $\eta_D = 0.05$, $\alpha = 1.55$, [Fe/H] $= -2.25$
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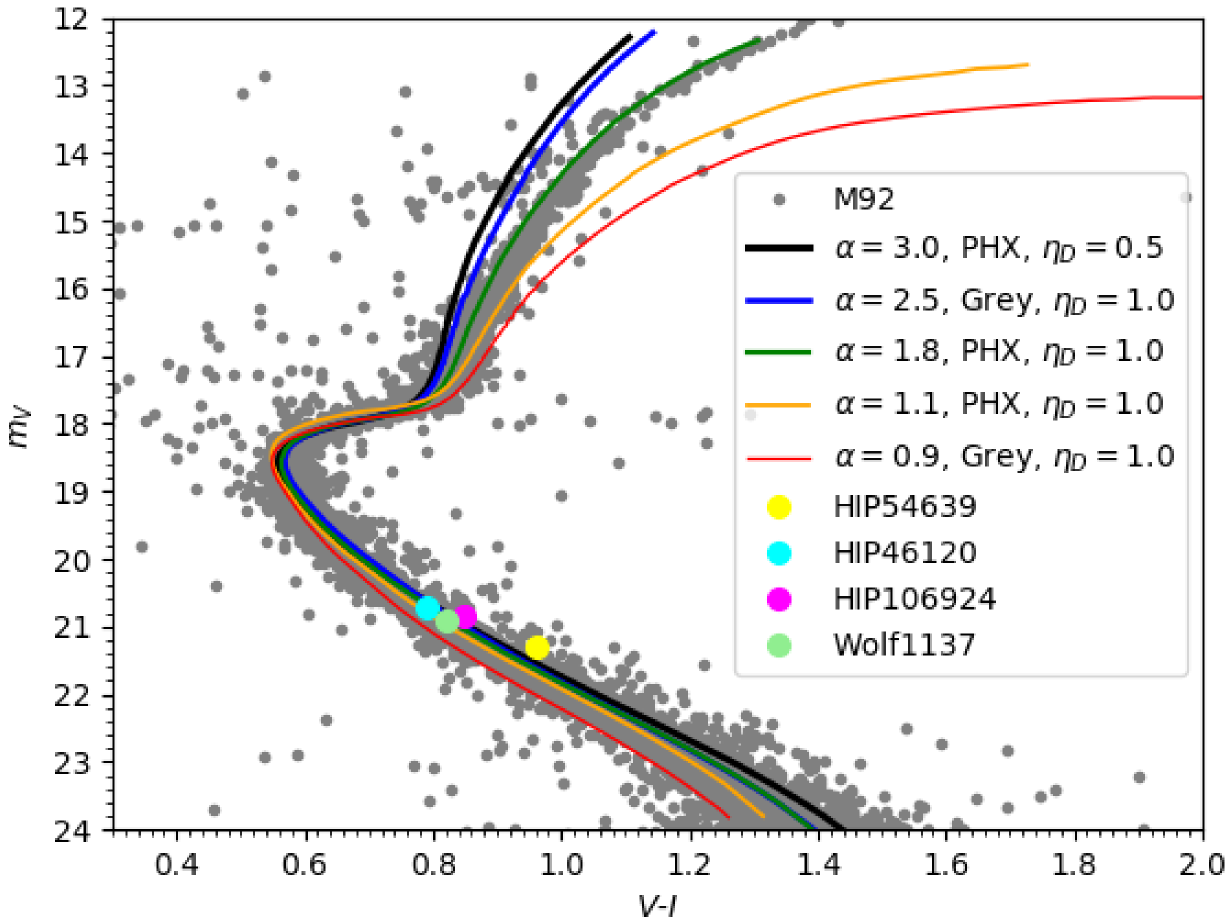
Grey, $\eta_D = 1.0$, $\alpha = 1.55$, [Fe/H] $= -2.25$
HIP46120
HIP106924
Wolf1137
M_V
5.90
5.95
6.00
6.05
6.10
6.15
6.20
6.25
6.30
0.73
0.74
0.75
0.76
0.77
0.78
0.79
0.80
0.81
0.82
0.83
0.84
V-I
Object: subdwarfs with HST parallaxes
Phase: Main sequence
Joyce & Chaboyer 2018a, ApJ



We've tried to **isolate metallicity as a variable** and compute α_{MLT} as a function of location in the HR diagram

Red giant: ~10% below solar

Sub-giant: SUPER LOW! Half the solar value!

Main Sequence: inconclusive! Need **more of these candidates**

Big picture: solar value isn't right**;** α_{MLT} should probably **adapt over the course of a single evolutionary calculation**

Summary: Best-Fitting Mixing Lengths to All Objects

Object	Evolutionary Phase	Default α_{MLT}	Average $\alpha_{MLT}/\alpha_{\odot}$	$\alpha_{MLT}/\alpha_{\odot}$	Age (Gyr)	Fit Method
HD140283	subgiant	1.3	0.52	0.36-0.68	12.5	stellar track
M92	Red Giant	1.75	0.91	0.91	13	isochrone
HIP46120	main sequence	1.85	0.96	0.92	12	isochrone
HIP54639	main sequence	0.7	0.36	0.33	13	isochrone
HIP106924	main sequence	1.1	0.57	0.56	13	isochrone
Wolf1137	main sequence	1.95	1.01	0.96	12	isochrone

Bonus Problem!

Are there issues with adopting solar MLT in other non-solar environments?

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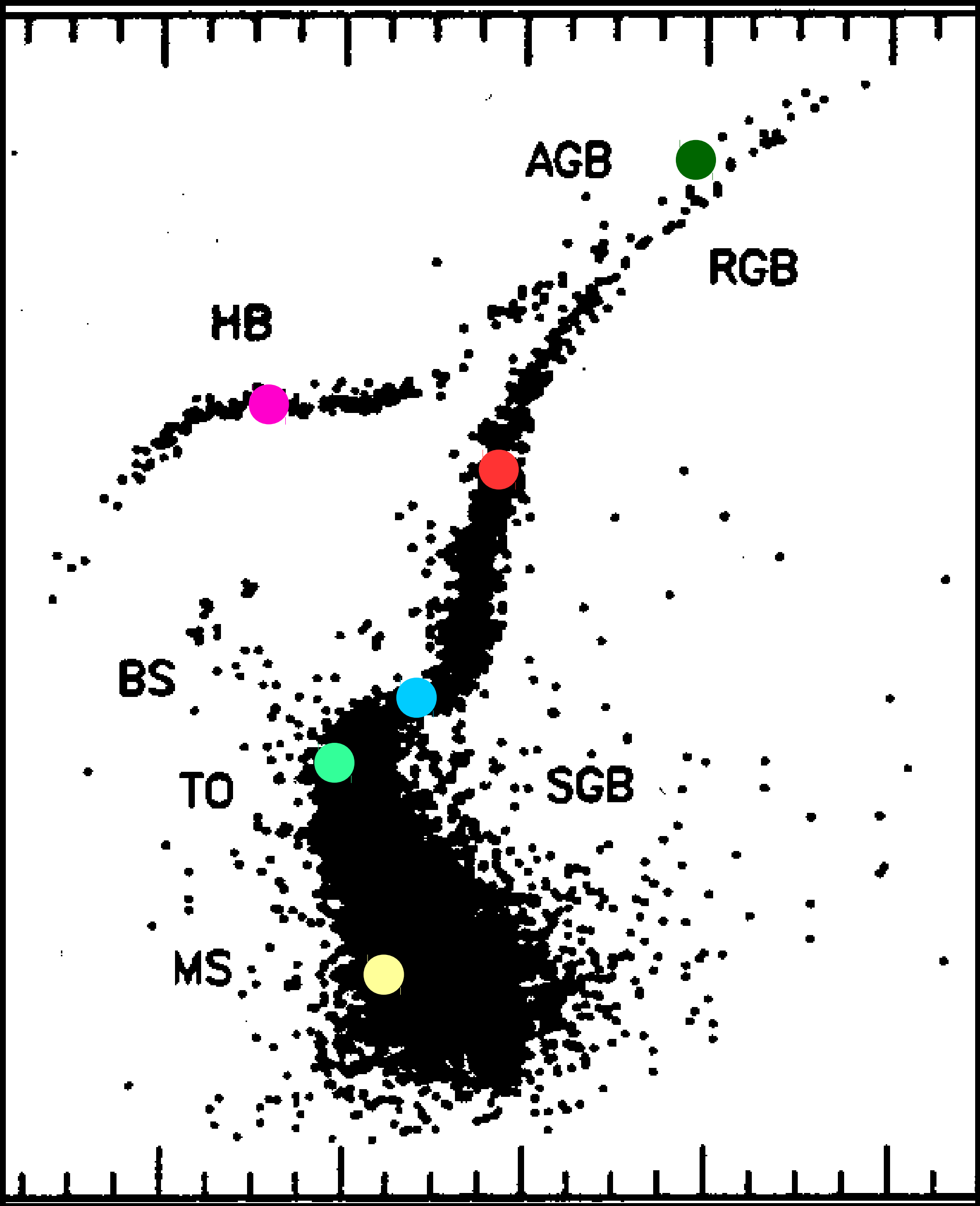
Yes!

See Joyce & Chaboyer 2018b for MLT calibrations to α Cen A & B!

(a talk for another conference...)

To hone MLT properly in stellar models….



- Have four, need more- Brian & Christina on the job!
- aCen A&B are near here, but not low [Fe/H]
- HD 140283
- M92
- Need one of these!
- One of these too!
  But is structure too convoluted?

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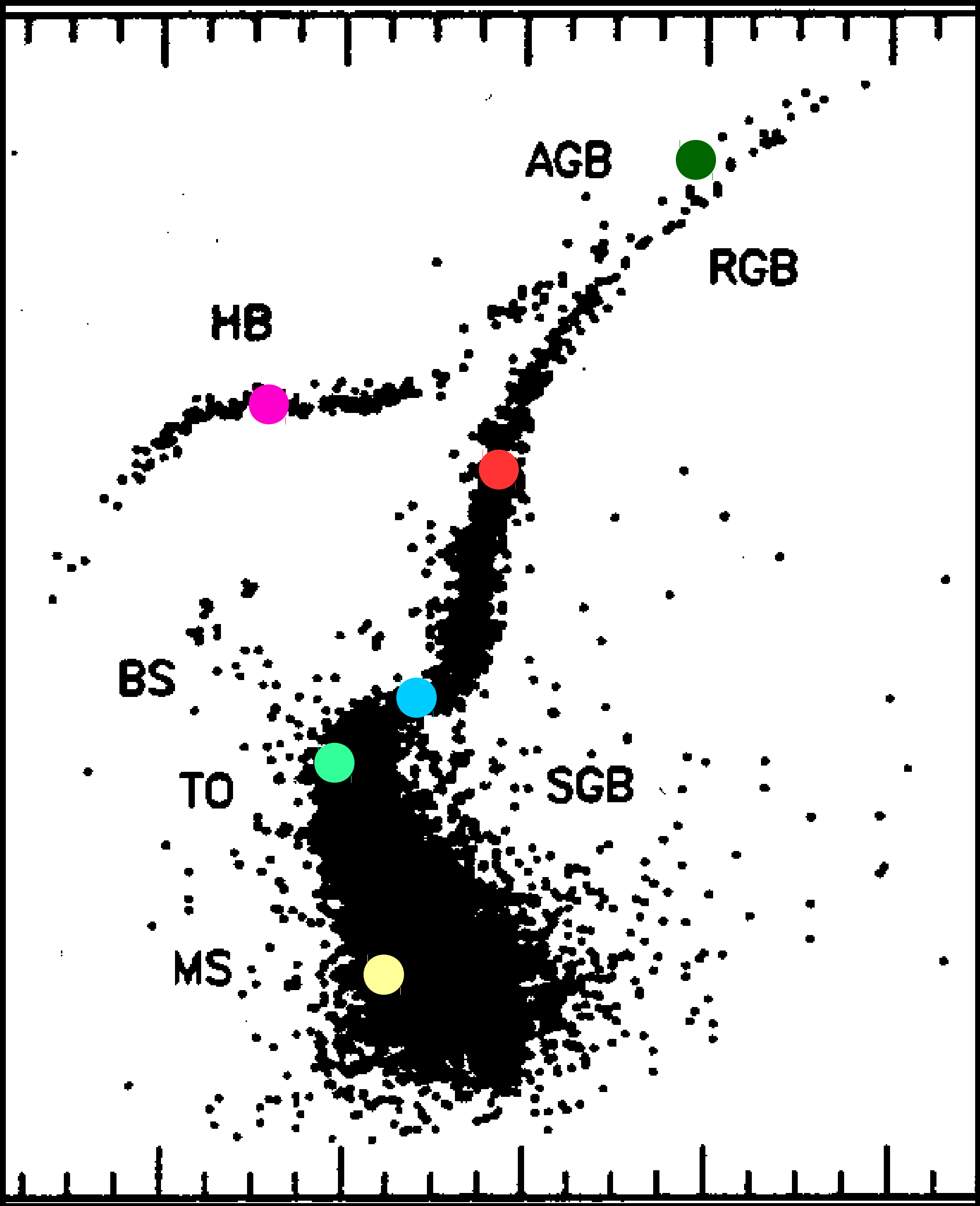

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aCen A&B are near here, but not low [Fe/H]

HD 140283

M92

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Thoughts to take with you...

(1) There is strong potential for using metal-poor RGBB measurements to constrain the size and mass of surface convection zones in low-mass stars

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(4) Empirically-removed treatment of convection in 1D evolutionary models is **unacceptable and unnecessary** in the modern observational climate