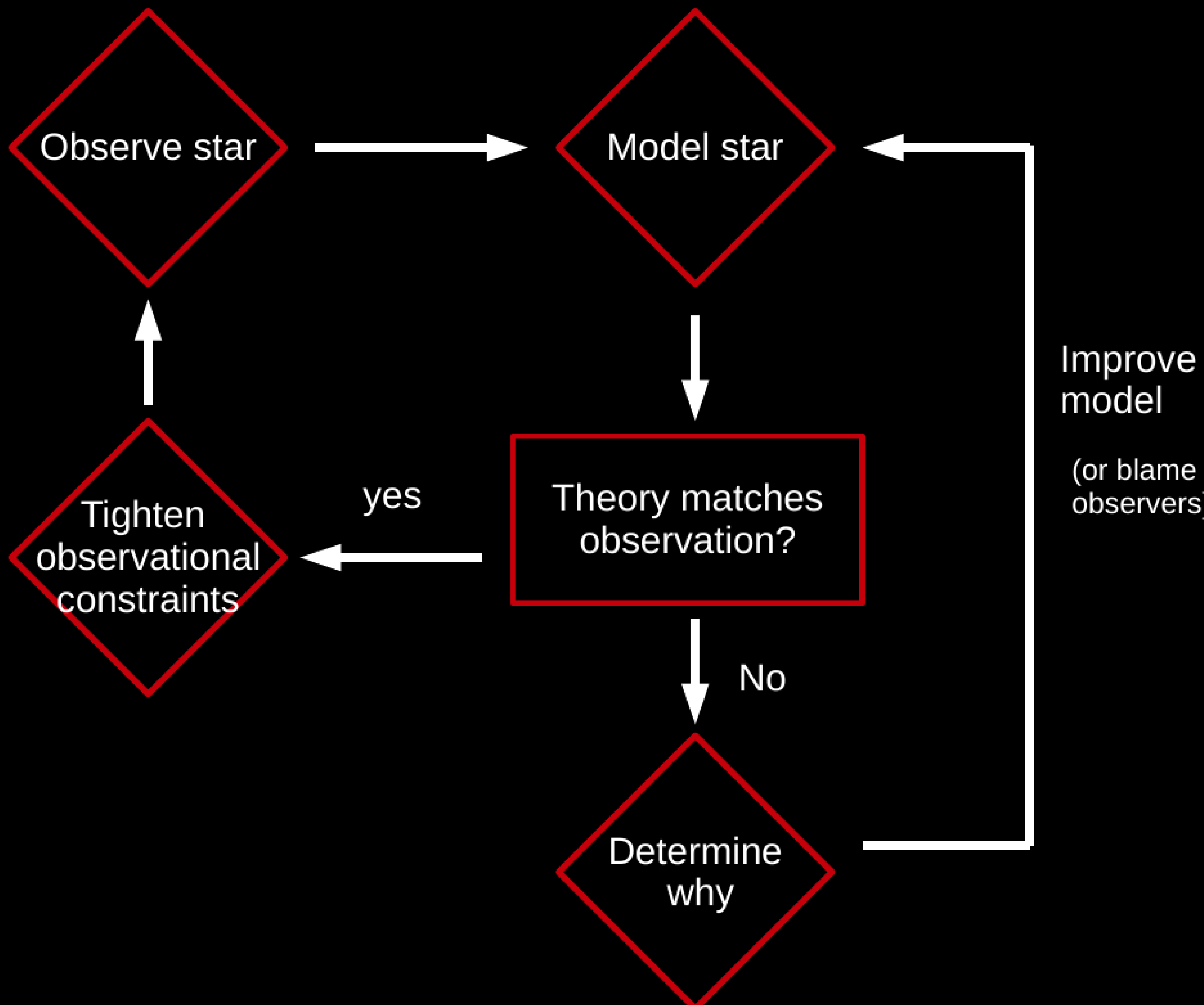
The power of high resolution spectroscopy for mixing length calibrations in theoretical stellar evolution models

Advances with SALT

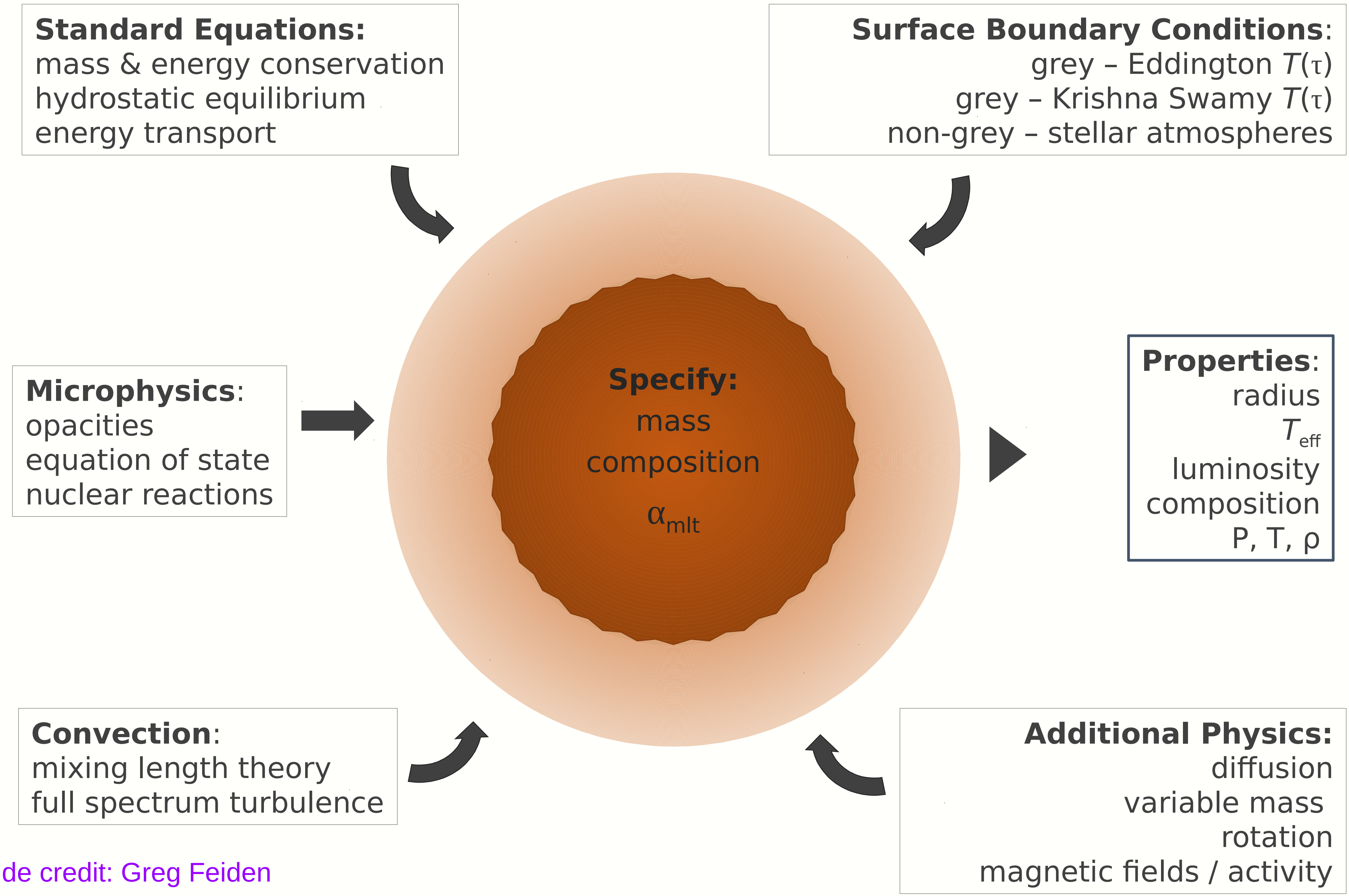
16 November 2018

Dr. Meridith Joyce
RSAA Postdoctoral Fellow
Australian National University

An ancient battle...

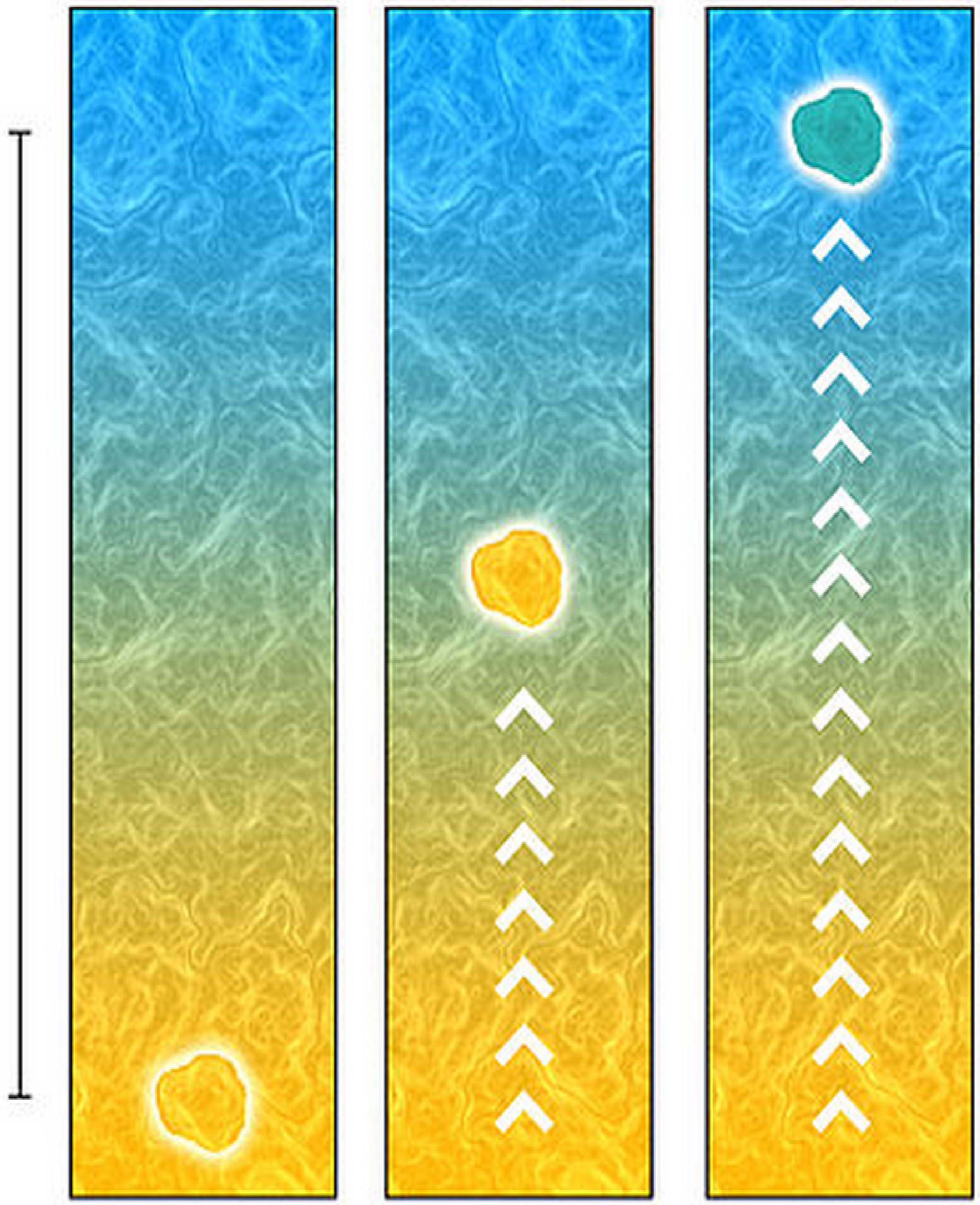


Components of a Stellar Structure and Evolution Code



Slide credit: Greg Feiden

Mixing Length Theory (MLT) Formalism



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

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

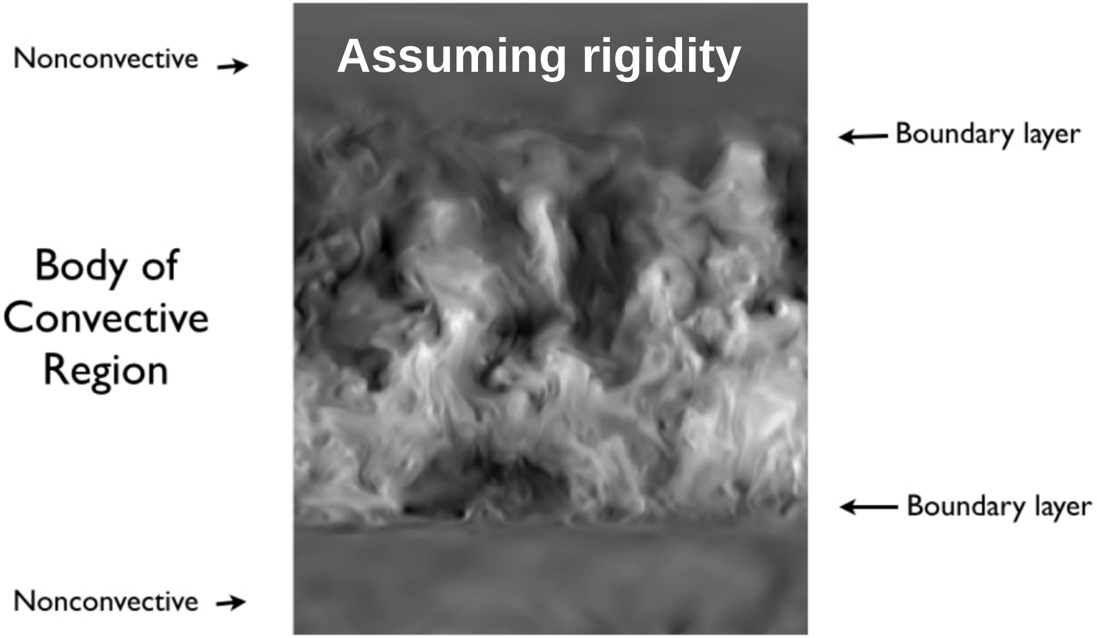
-discrete parcels consist of fluid which is in pressure, but not thermal, equilibrium

-parcels move along vertical trajectories

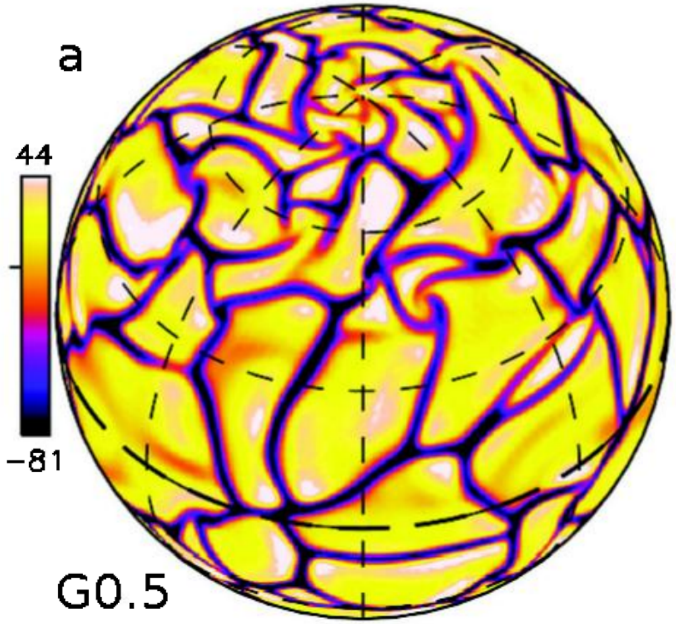
-distance which parcels can travel before denaturing is the "mixing length"

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

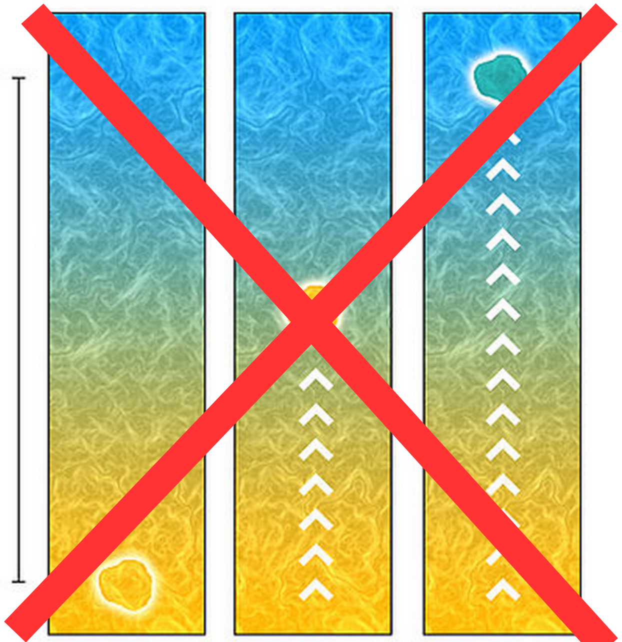
Problems with mixing length theory

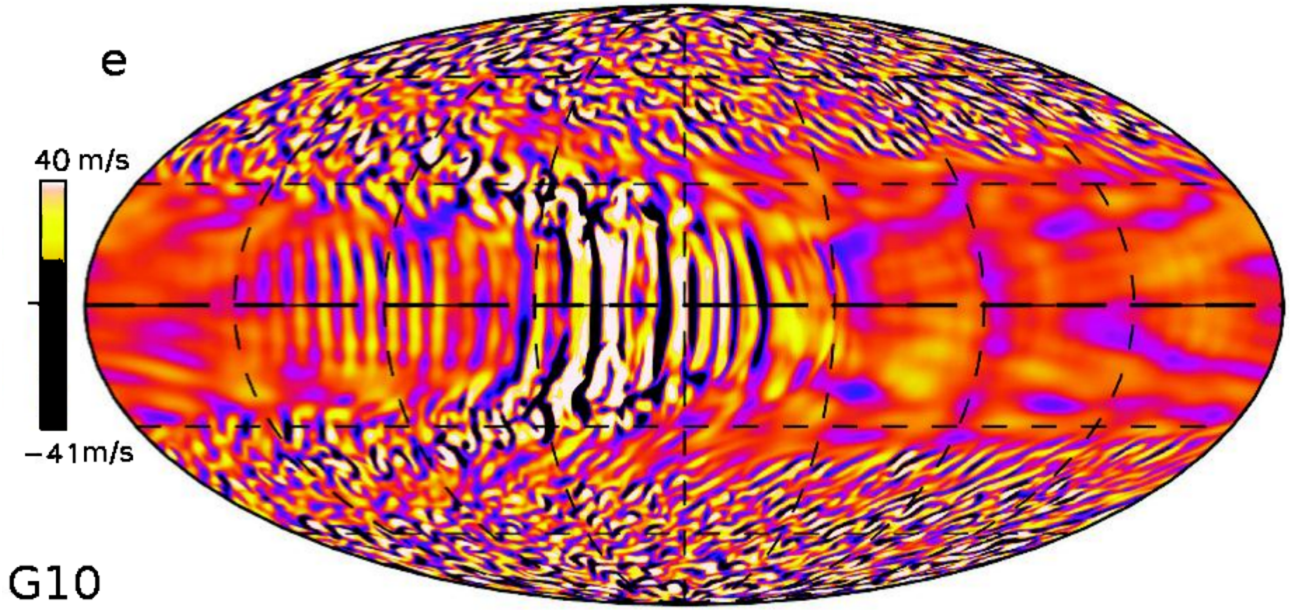


Negative kinetic flux & transport asymmetry



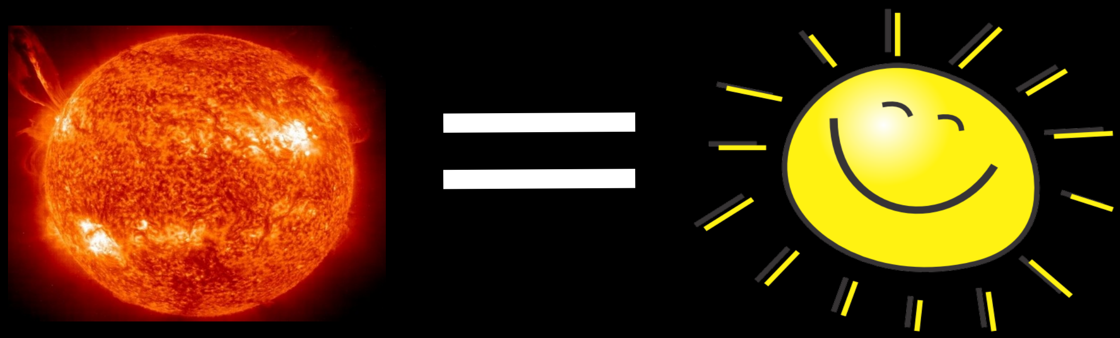
Parcels are nonsense





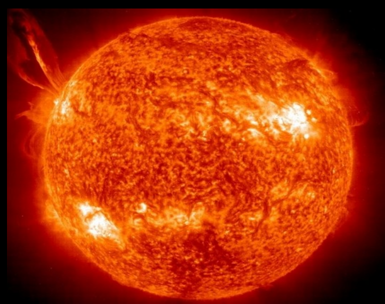
Rotation is a thing!!

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…

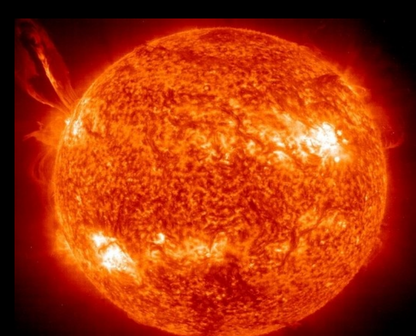
Not All Stars are the Sun



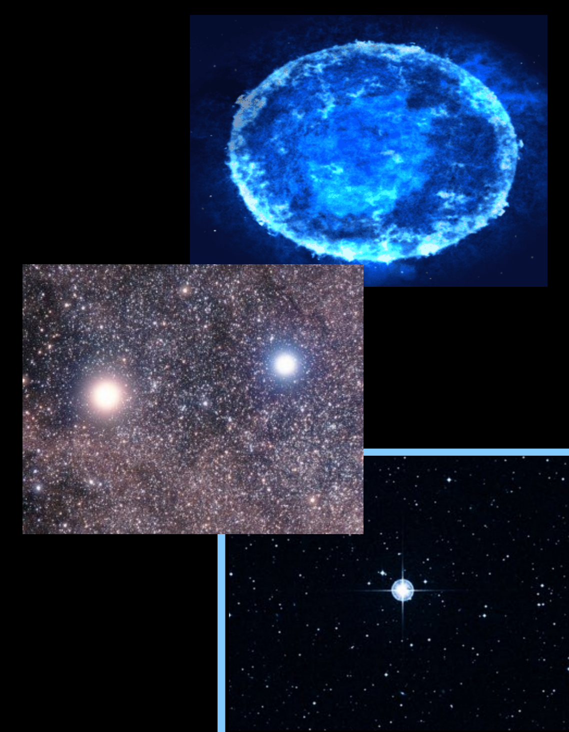
=

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!**

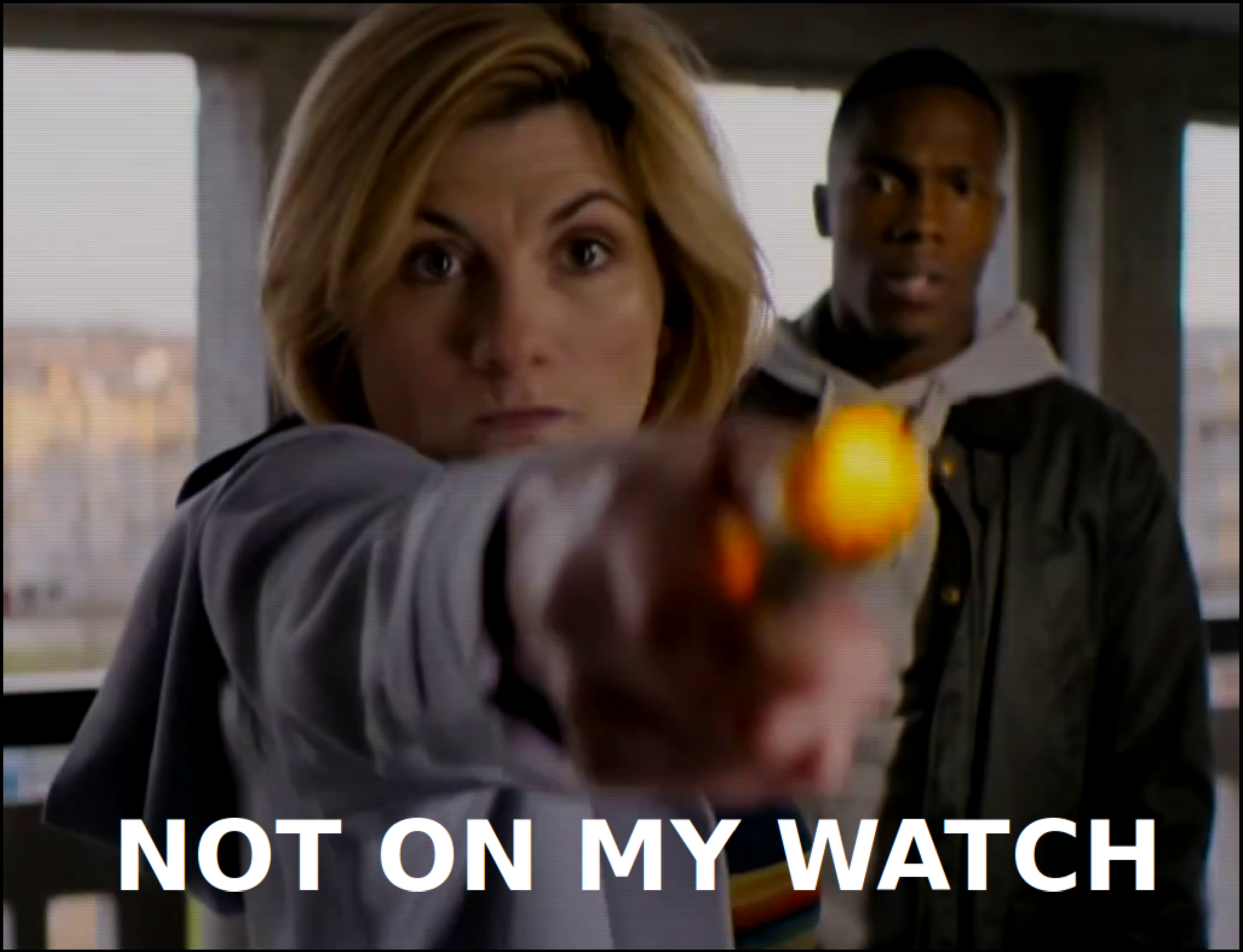


≠



A necessary evil?

A necessary evil?





Interferometry

Asteroseismology

High resolution spectroscopy

High precision photometry

...Oh my!

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**?

Study 1:

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

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 prescriptions in DSEP:

not taking physics for granted ✓

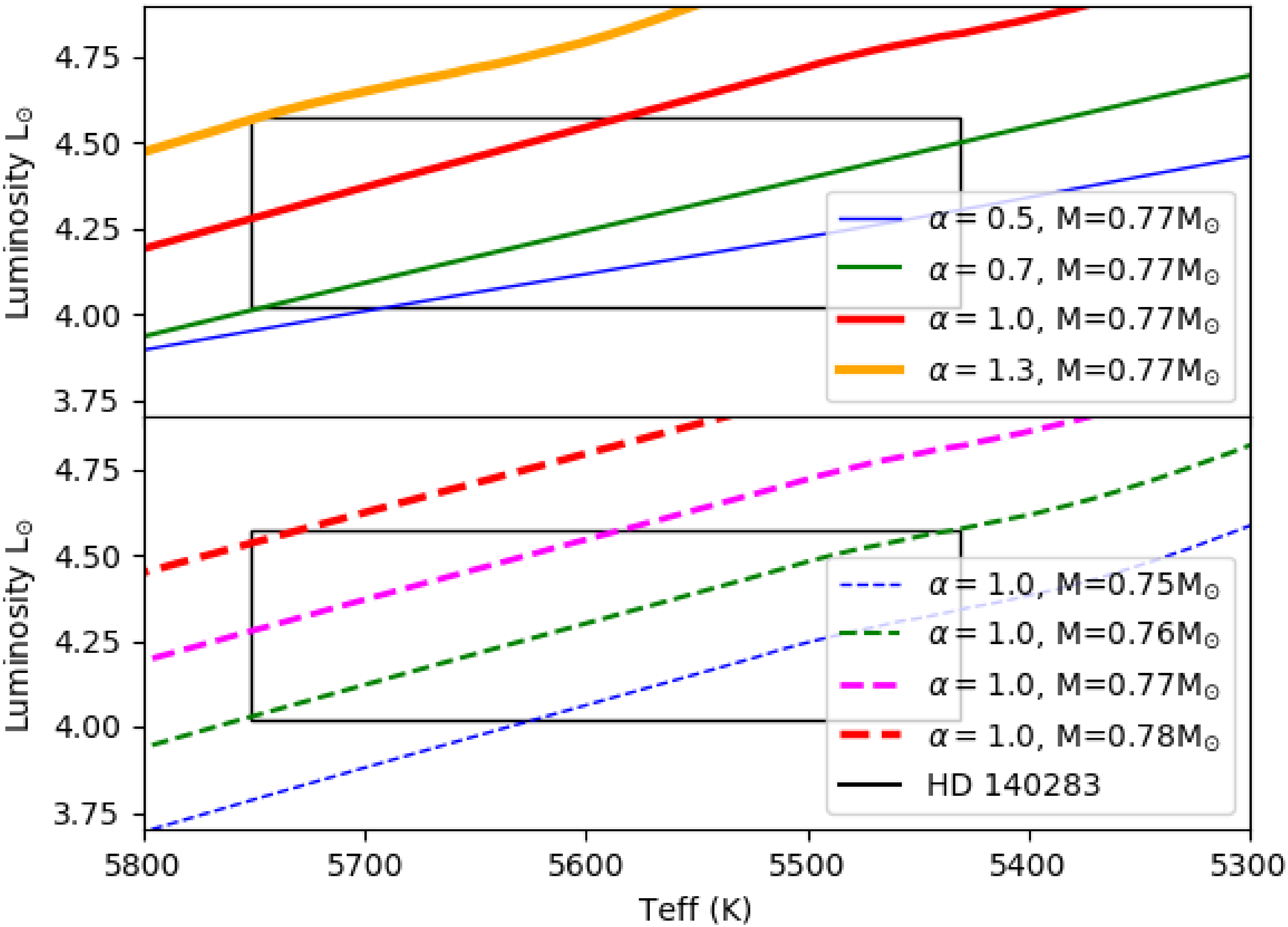
SOLAR-CALIBRATED MIXING LENGTH VALUES FOR VARIOUS PHYSICAL CONFIGURATIONS

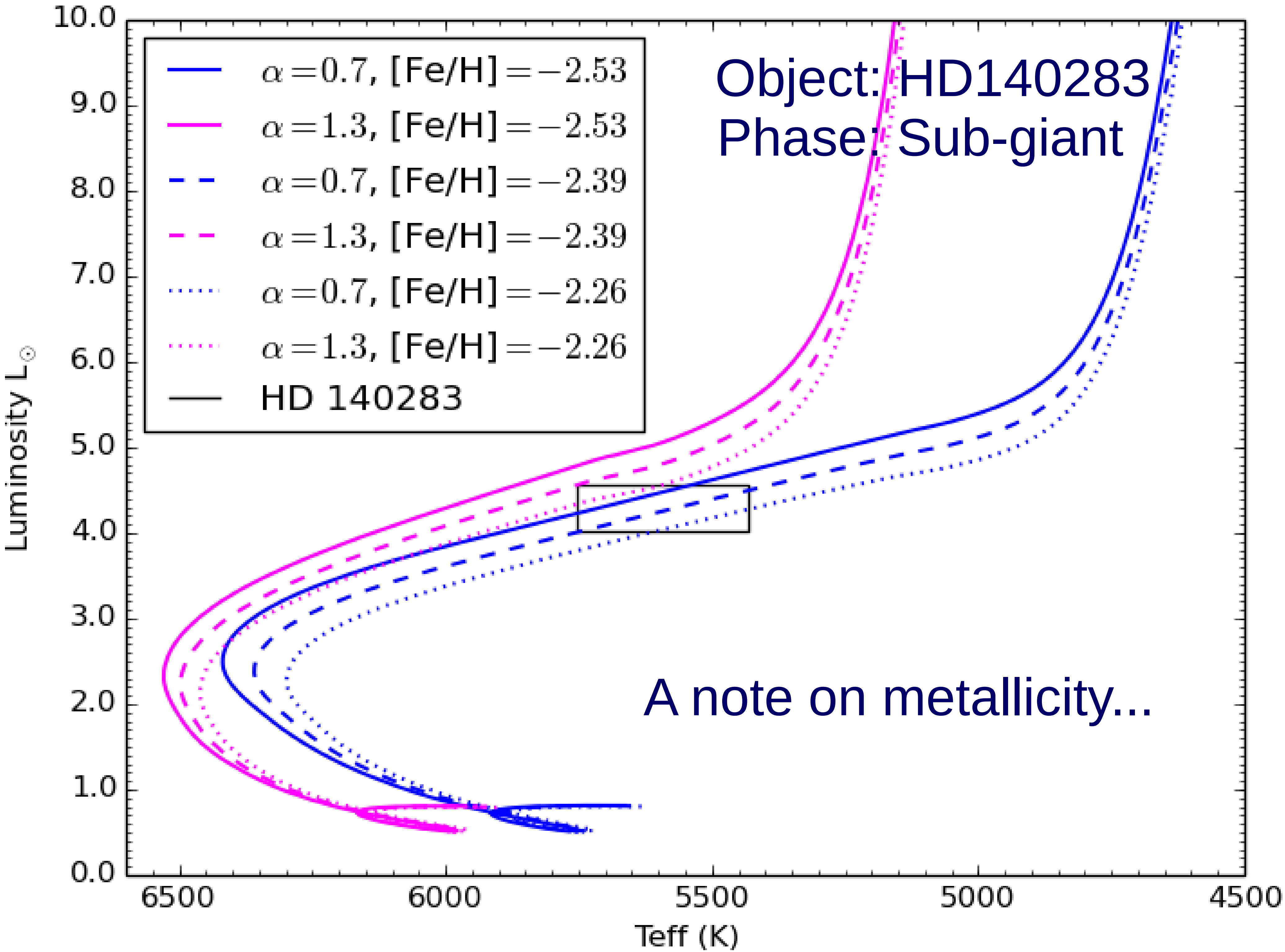
Atmosphere	η_D	$\alpha_\odot$	Y_{in}	Z_0
PHOENIX	1.0	1.9258	0.275	0.019
Grey	1.0	1.8205	0.282	0.019
PHOENIX	0.5	1.8292	0.277	0.0176
PHOENIX	1.5	1.9780	0.282	0.0192

Also!

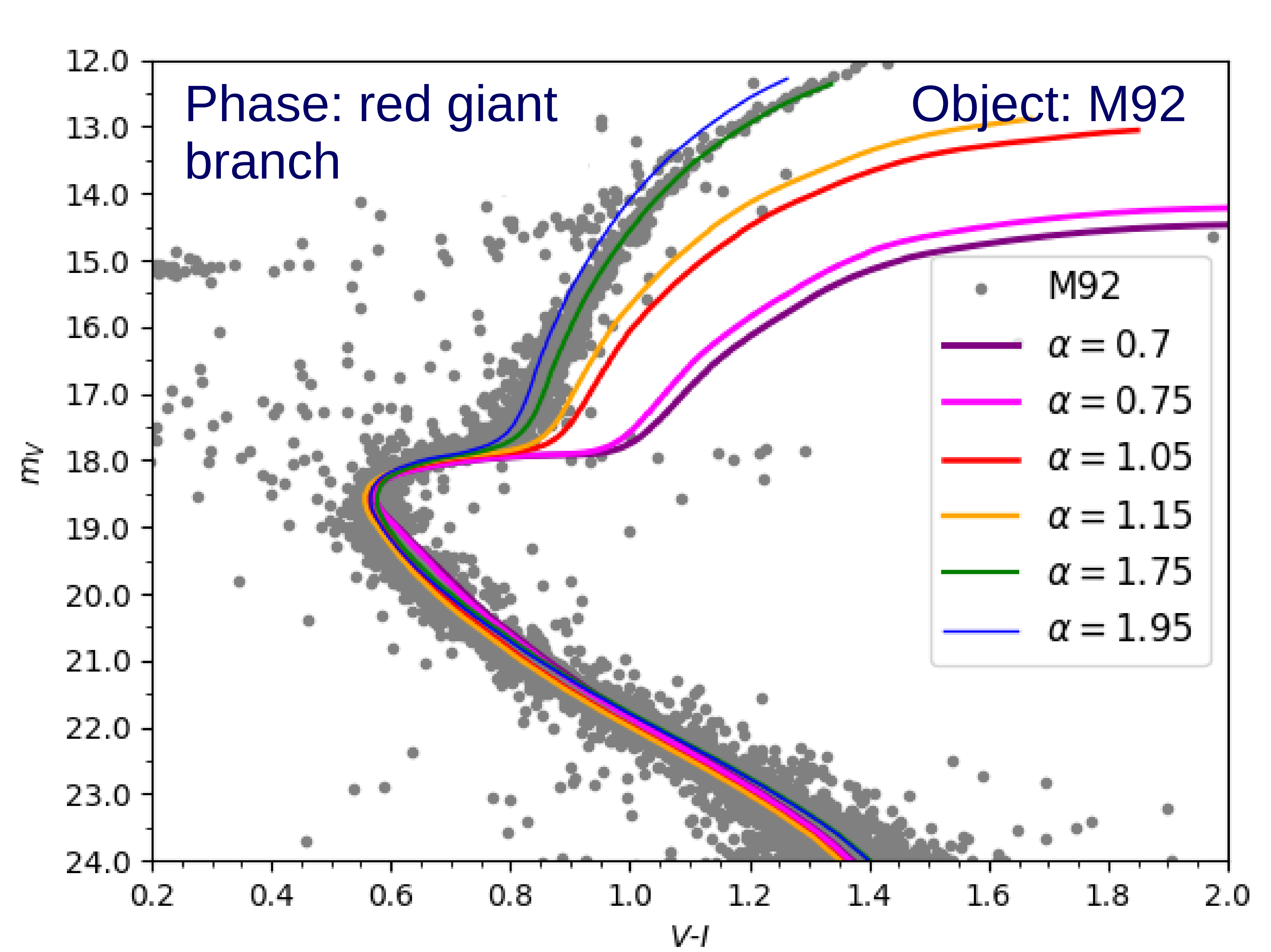
These six objects span a decent portion of the HR diagram, allowing us to test the hypothesis that the mixing length should vary with stellar phase

Object: HD140283 Phase: Sub-giant

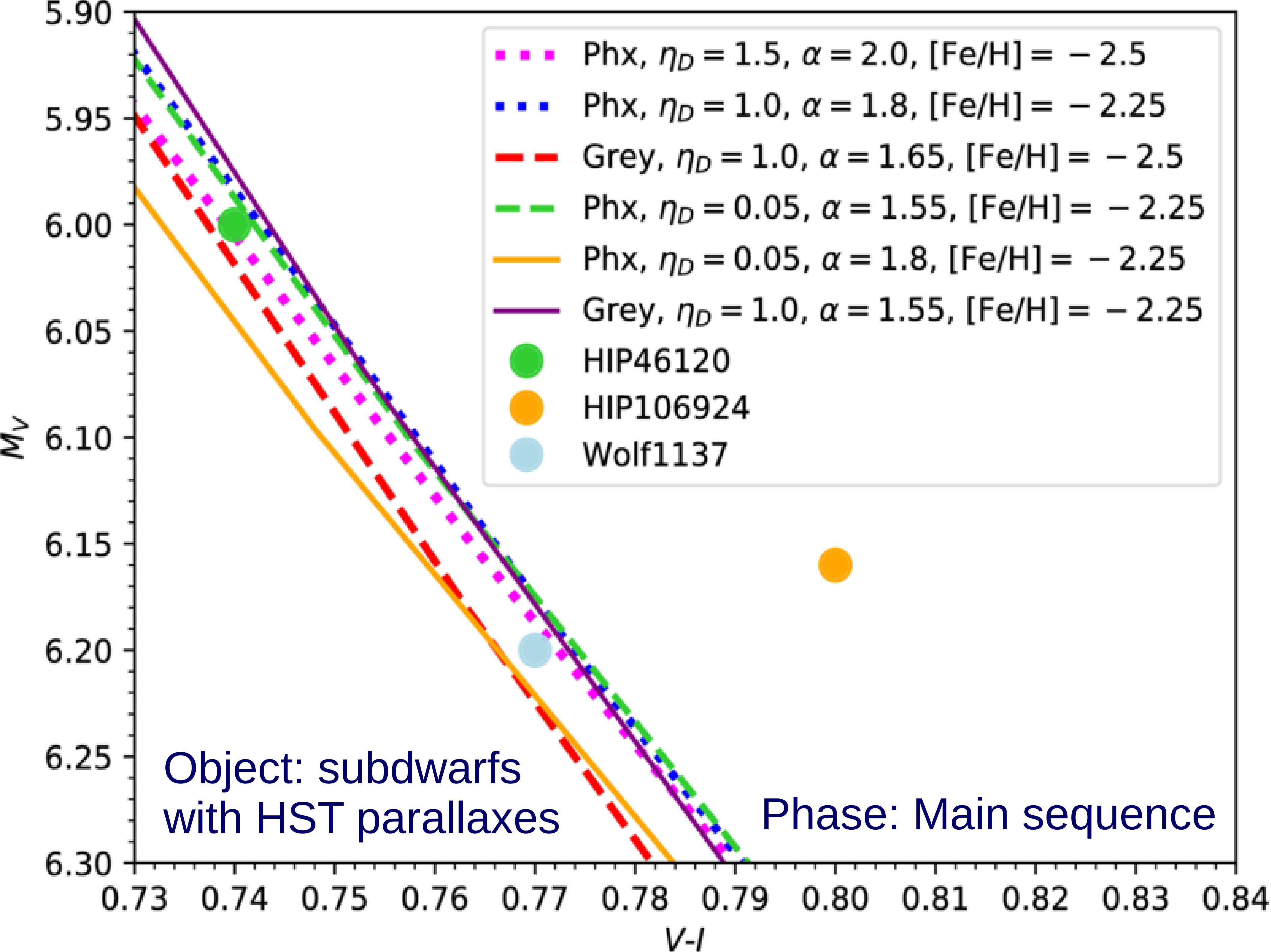




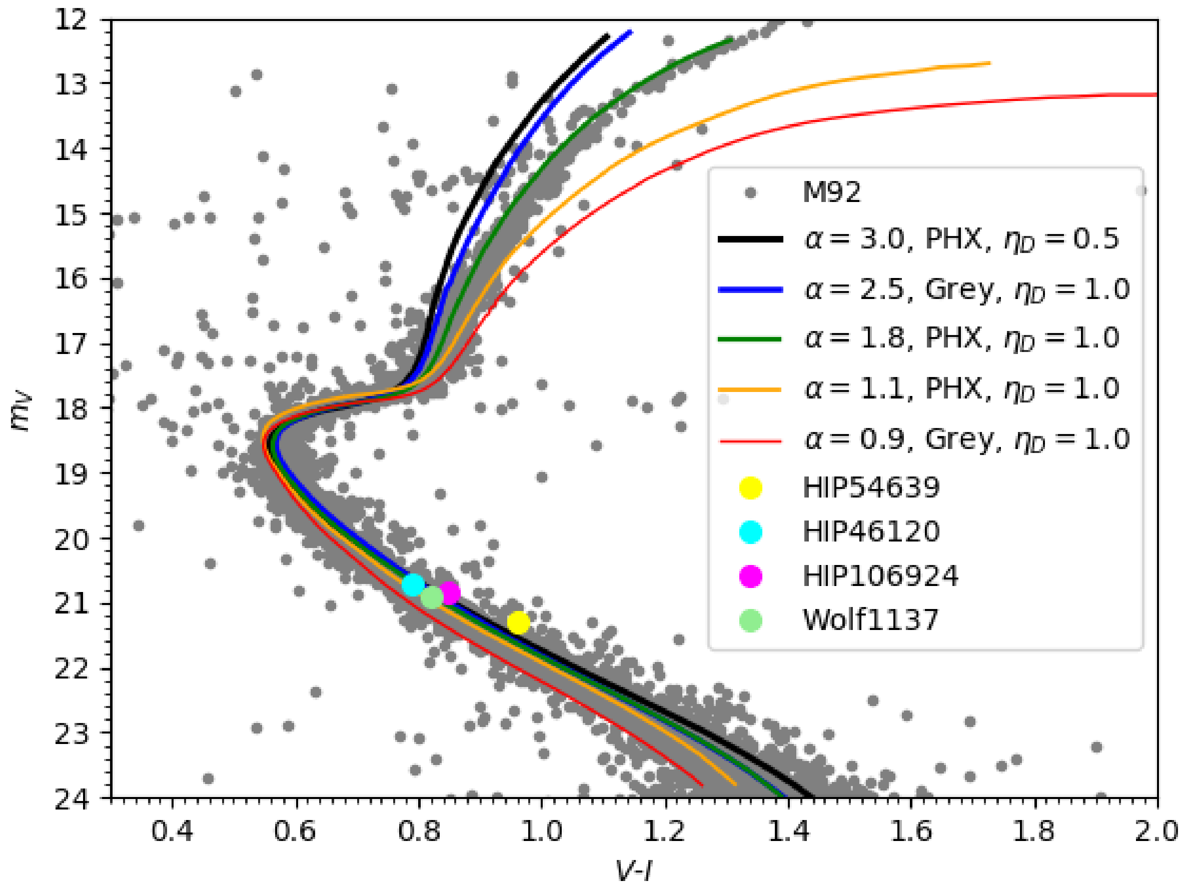
Object: HD140283
Phase: Sub-giant
A note on metallicity...
$\alpha = 0.7$, [Fe/H] $= -2.53$
$\alpha = 1.3$, [Fe/H] $= -2.53$
$\alpha = 0.7$, [Fe/H] $= -2.39$
$\alpha = 1.3$, [Fe/H] $= -2.39$
$\alpha = 0.7$, [Fe/H] $= -2.26$
$\alpha = 1.3$, [Fe/H] $= -2.26$
HD 140283
Luminosity $L_\odot$
Teff (K)
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
6500
6000
5500
5000
4500



Phase: red giant branch
Object: M92
M92
α = 0.7
α = 0.75
α = 1.05
α = 1.15
α = 1.75
α = 1.95
m_V
V-I
12.0
13.0
14.0
15.0
16.0
17.0
18.0
19.0
20.0
21.0
22.0
23.0
24.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0



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
Phx, $\eta_D = 0.05$, $\alpha = 1.8$, [Fe/H] = −2.25
Grey, $\eta_D = 1.0$, $\alpha = 1.55$, [Fe/H] = −2.25
HIP46120
HIP106924
Wolf1137
Object: subdwarfs with HST parallaxes
Phase: Main sequence
M_V
V-I
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



We've attempted to **take metallicity out of the equation** and begun compiling α_{MLT} values as a function of location in the HR diagram

Main Sequence results are inconclusive! Need **more of these candidates**

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

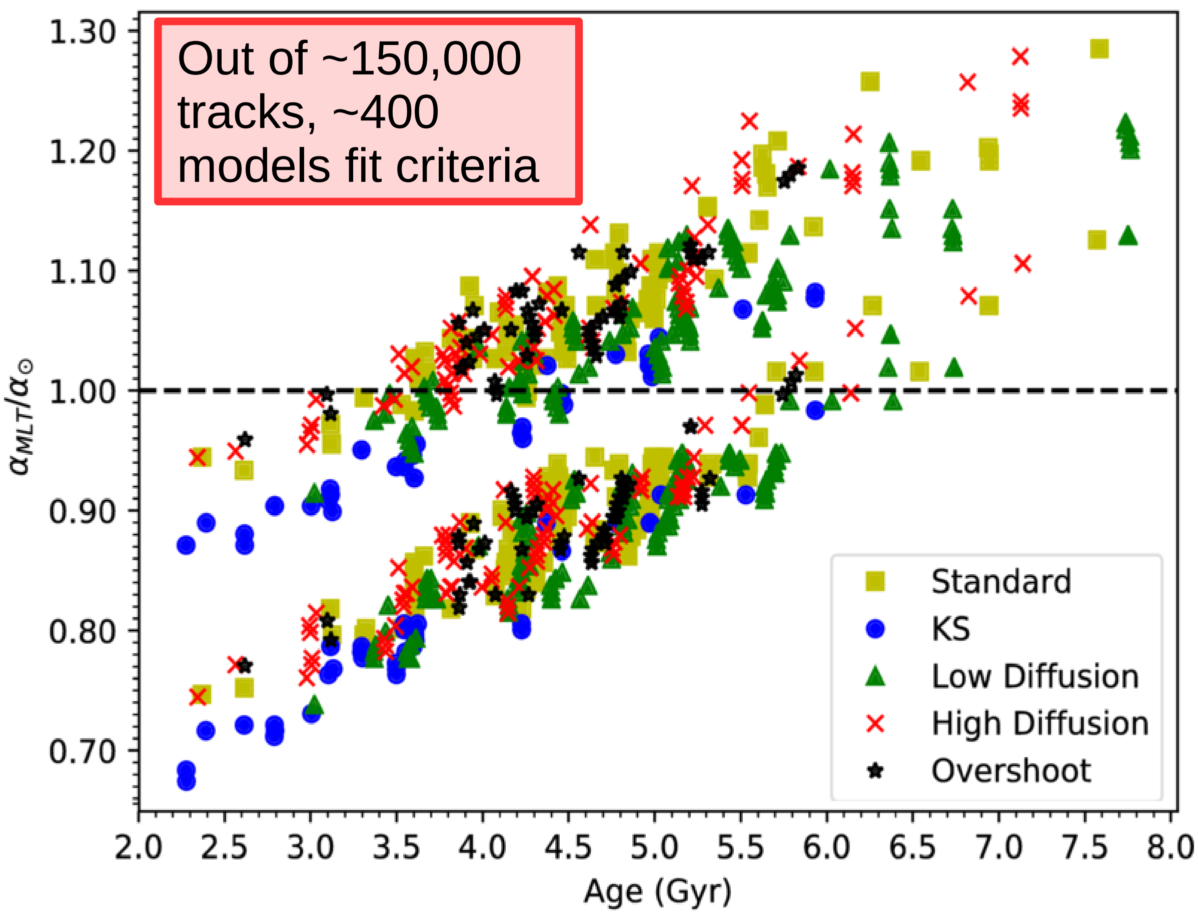
Study 2:

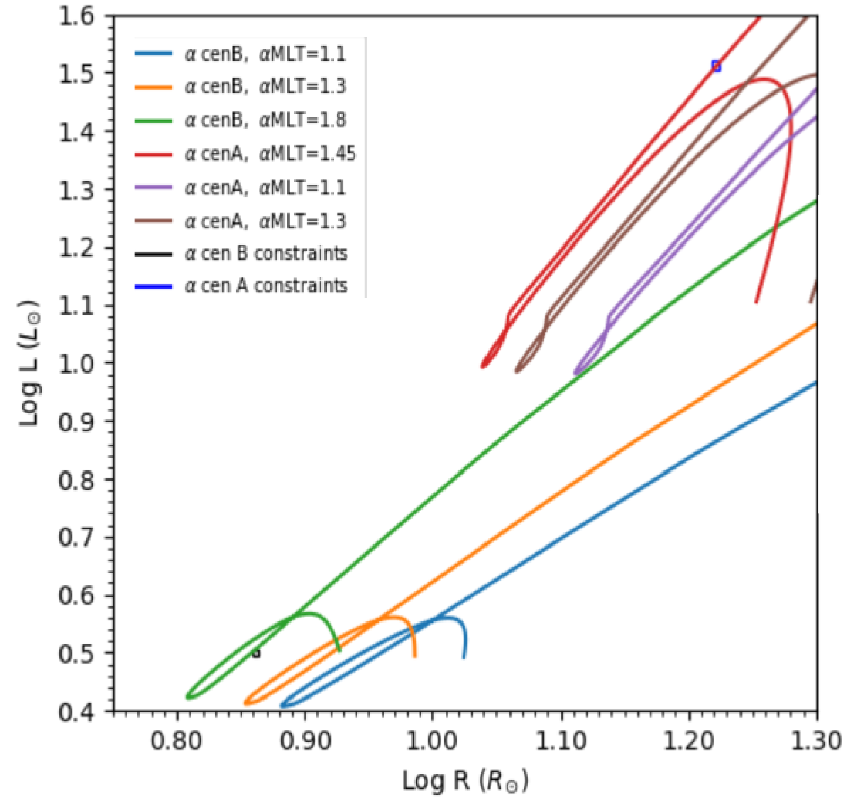
The mixing lengths in
α Centauri A & B:
calibrated
classically and
asteroseismically

Classical optimization of α Centauri

$$s^2_{\text{classic}} = \left[\frac{R_{\text{A,obs}} - R_{\text{A,mod}}}{\sigma_{R_{\text{A,obs}}}}\right]^2 + \left[\frac{R_{\text{B,obs}} - R_{\text{B,mod}}}{\sigma_{R_{\text{B,obs}}}}\right]^2 + \left[\frac{L_{\text{A,obs}} - L_{\text{A,mod}}}{\sigma_{L_{\text{A,obs}}}}\right]^2 + \left[\frac{L_{\text{B,obs}} - L_{\text{B,mod}}}{\sigma_{L_{\text{B,obs}}}}\right]^2 + \left[\frac{Z/X_{\text{obs}} - Z/X_{\text{mod}}}{\sigma_{Z/X_{\text{obs}}}}\right]^2$$

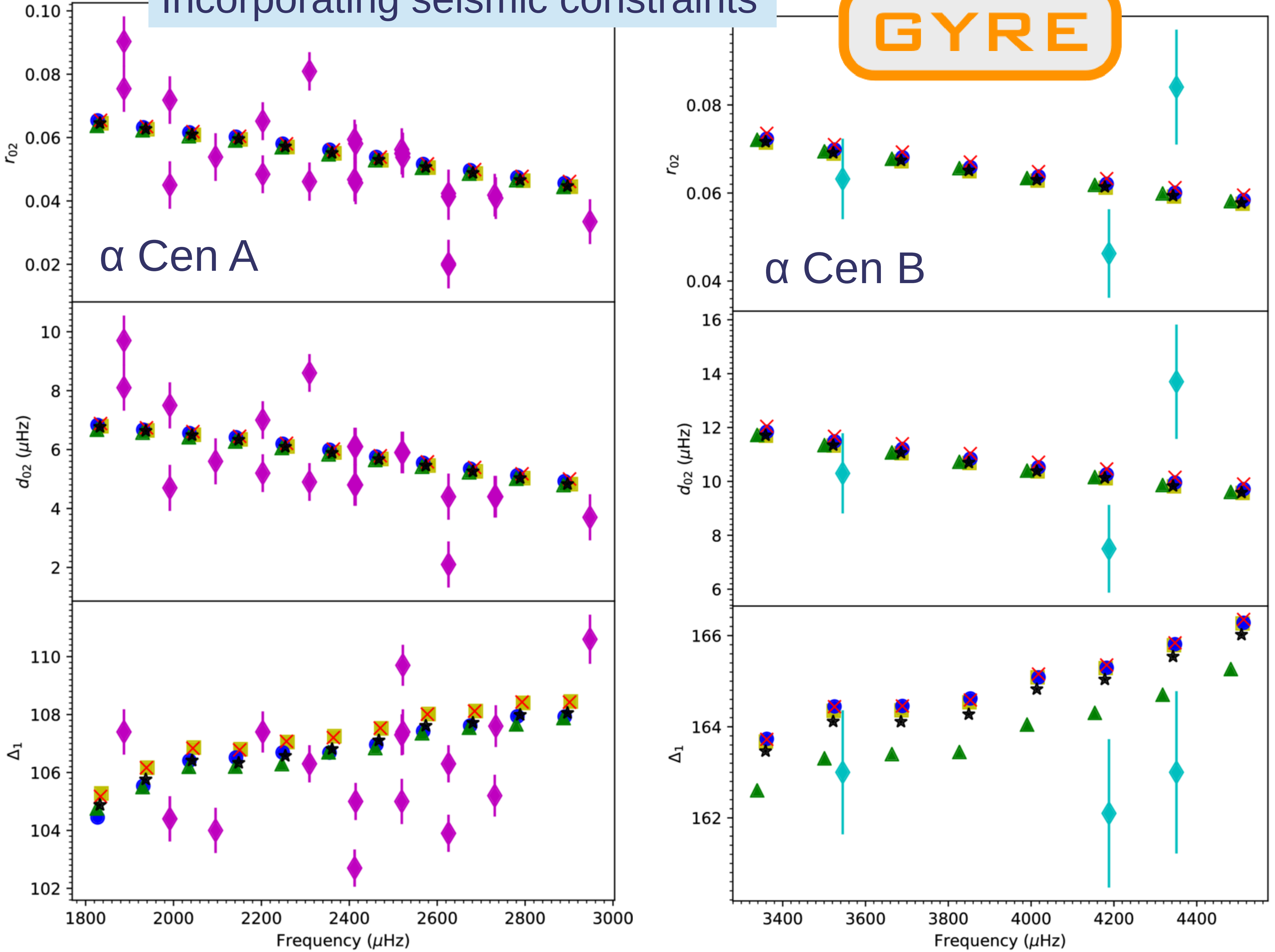
$$s^2_{\text{binary}} = \left[\frac{\tau_A - \tau_B}{5\,\text{Myr}}\right]^2 + \left[\frac{Y_A - Y_B}{0.005}\right]^2 + \left[\frac{Z_A - Z_B}{0.0005}\right]^2$$





Models must satisfy 9 independent observational constraints and a “common age” criterion

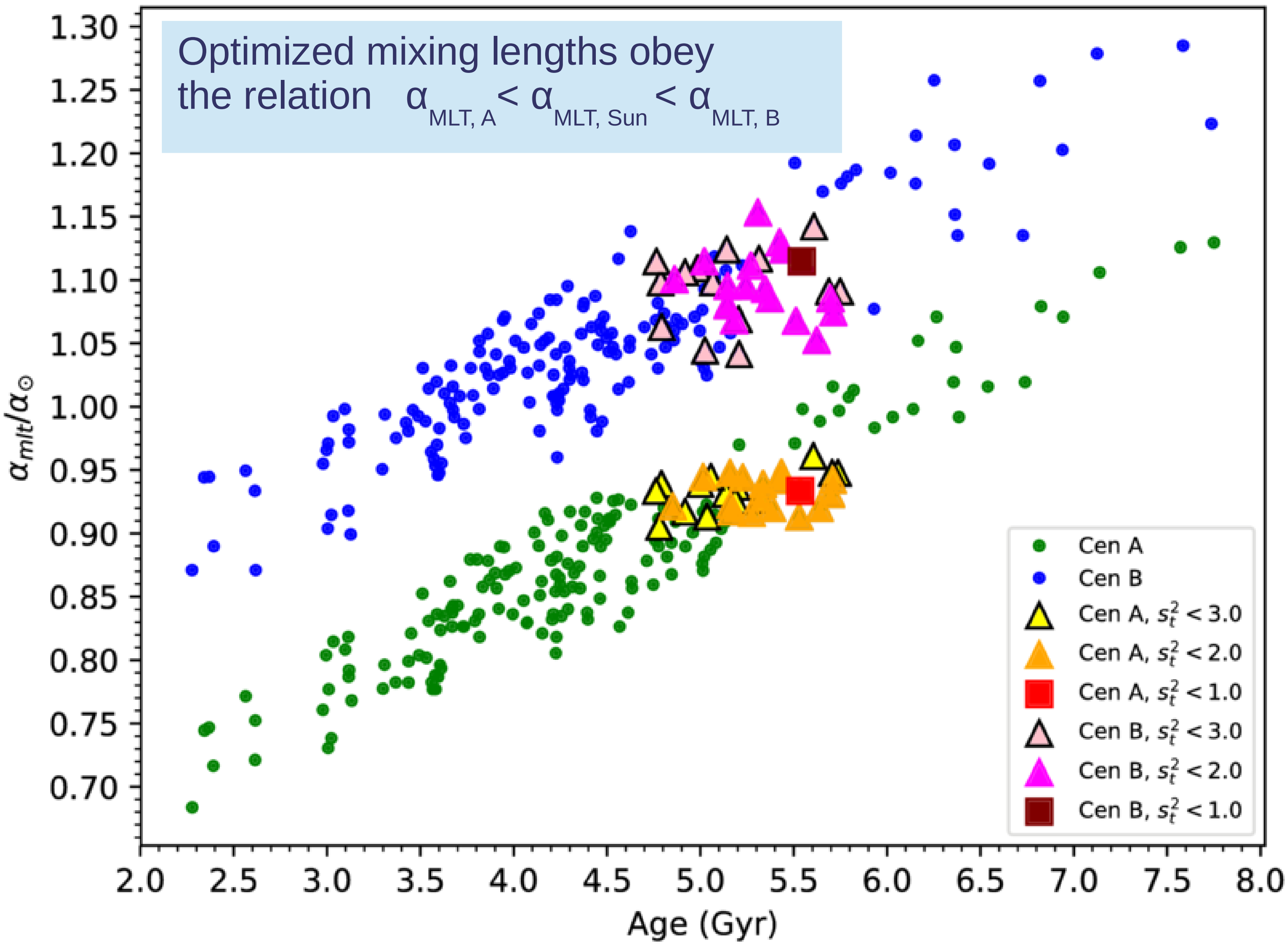
Incorporating seismic constraints



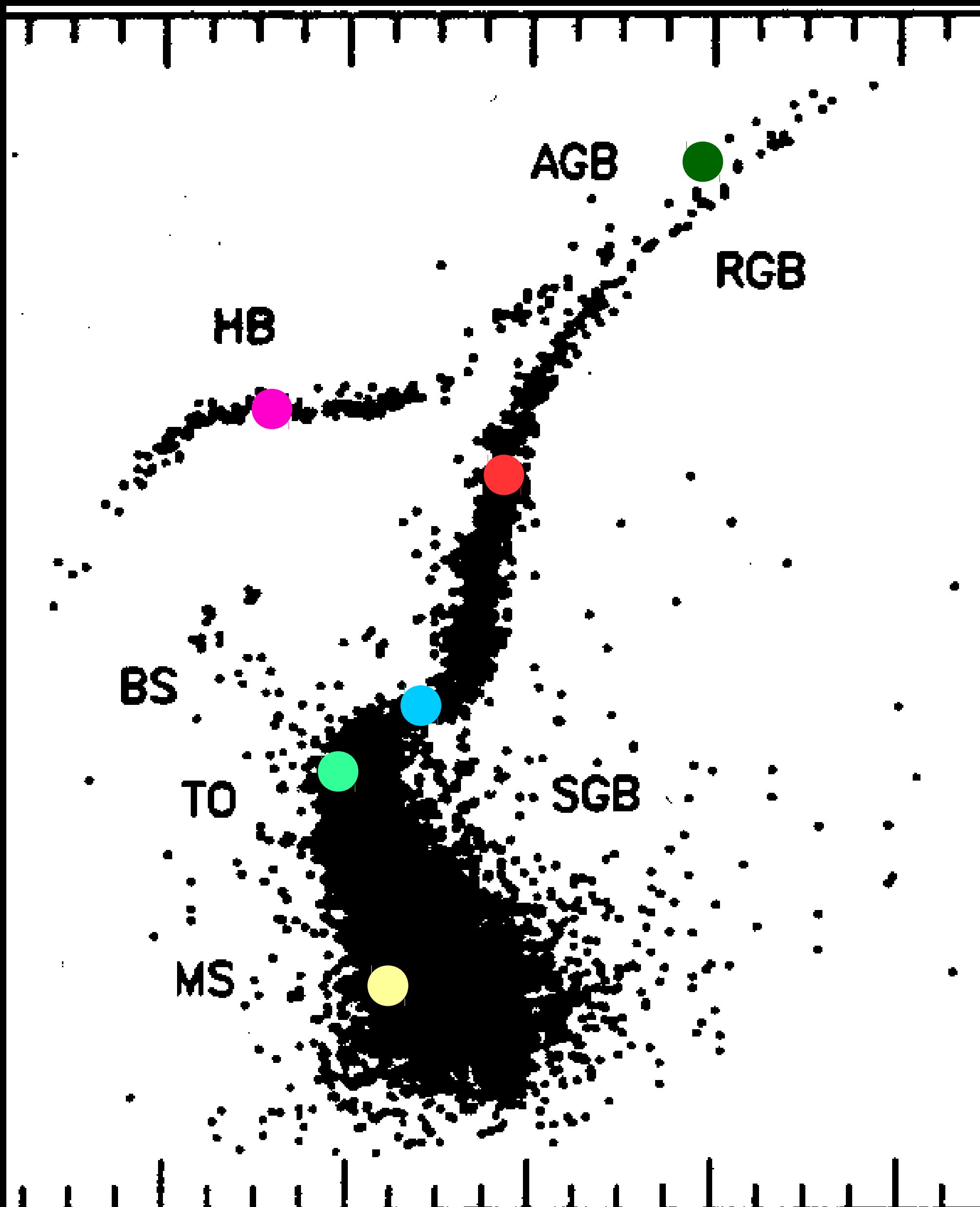
Incorporating seismic constraints

$$s^2_{\mathrm{seismic,w}} = \frac{1}{2}\left[\frac{r_{\mathrm{A,obs}} - r_{\mathrm{A,mod}}}{\sigma_{r_{02,\mathrm{A}}}}\right]^2 + \left[\frac{r_{\mathrm{B,obs}} - r_{\mathrm{B,mod}}}{\sigma_{r_{02,\mathrm{B}}}}\right]^2$$

Including seismic criterion reduces number of viable models from ~400 to just 31 (within 3σ)

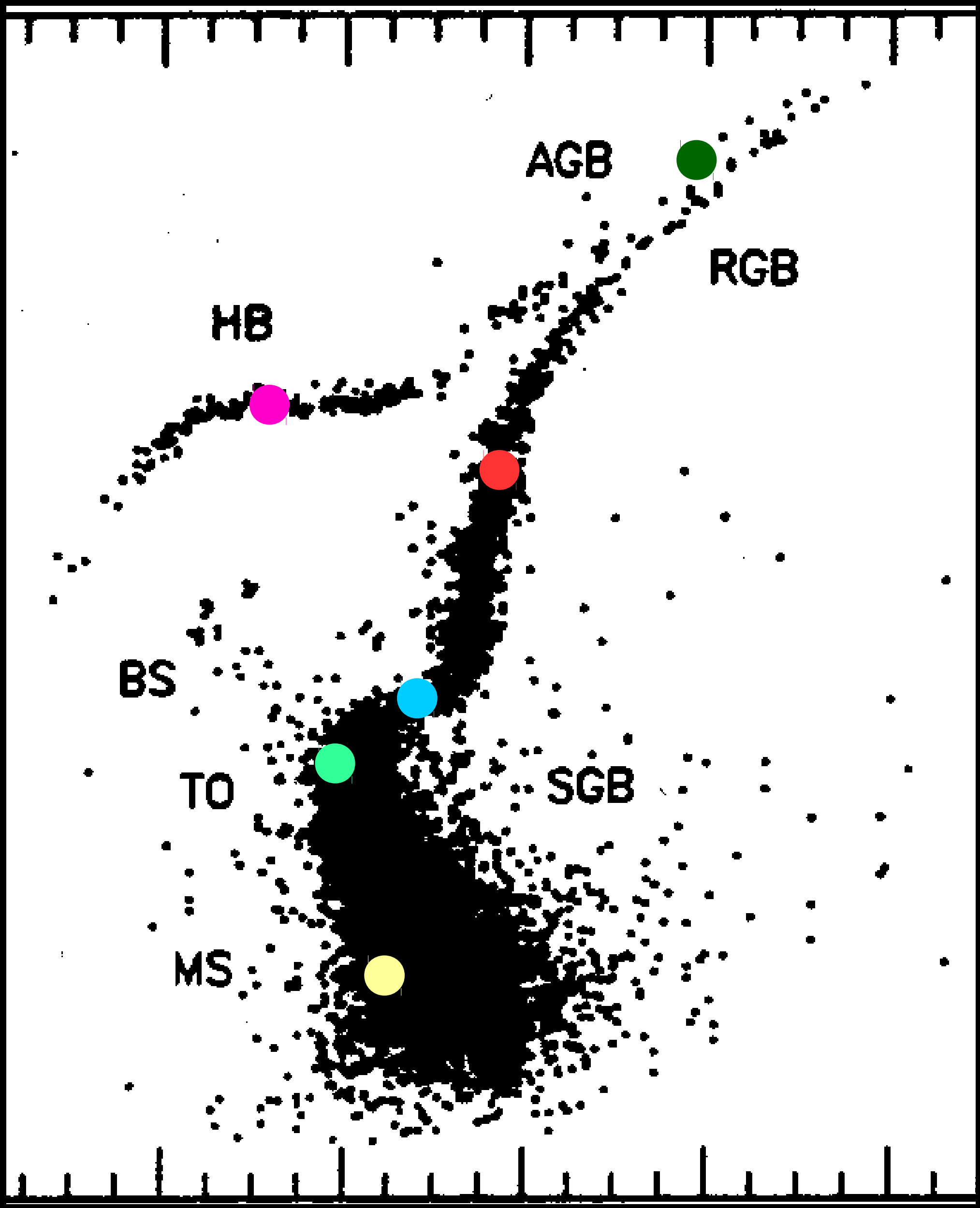


To hone MLT properly in stellar models….



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

To hone MLT properly in stellar models….



Have four, need more- Brian & Christina on the job!

aCen A is near here (but not low [Fe/H])

HD 140283

M92

Need one of these!

One of these too!
But is structure too convoluted?

To do:

(1) fill in the α_{MLT} HR diagram!

To do:

(1) fill in the α_{MLT} HR diagram!

(2) build statistical populations of stars w/ empirically calibrated α_{MLT} values!

To do:

(1) fill in the α_{MLT} HR diagram!

(2) build statistical populations of stars w/ empirically calibrated α_{MLT} values!

(3) apply HRS and other high-precision observations to new calibrators!

To do:

(1) fill in the α_{MLT} HR diagram!

(2) build statistical populations of stars w/ empirically calibrated α_{MLT} values!

(3) apply HRS and other high-precision observations to new calibrators!

(4) save the world!