SLOWLY ROTATING B STARS AS A TEST OF SEMI-CONVECTIVE MIXING

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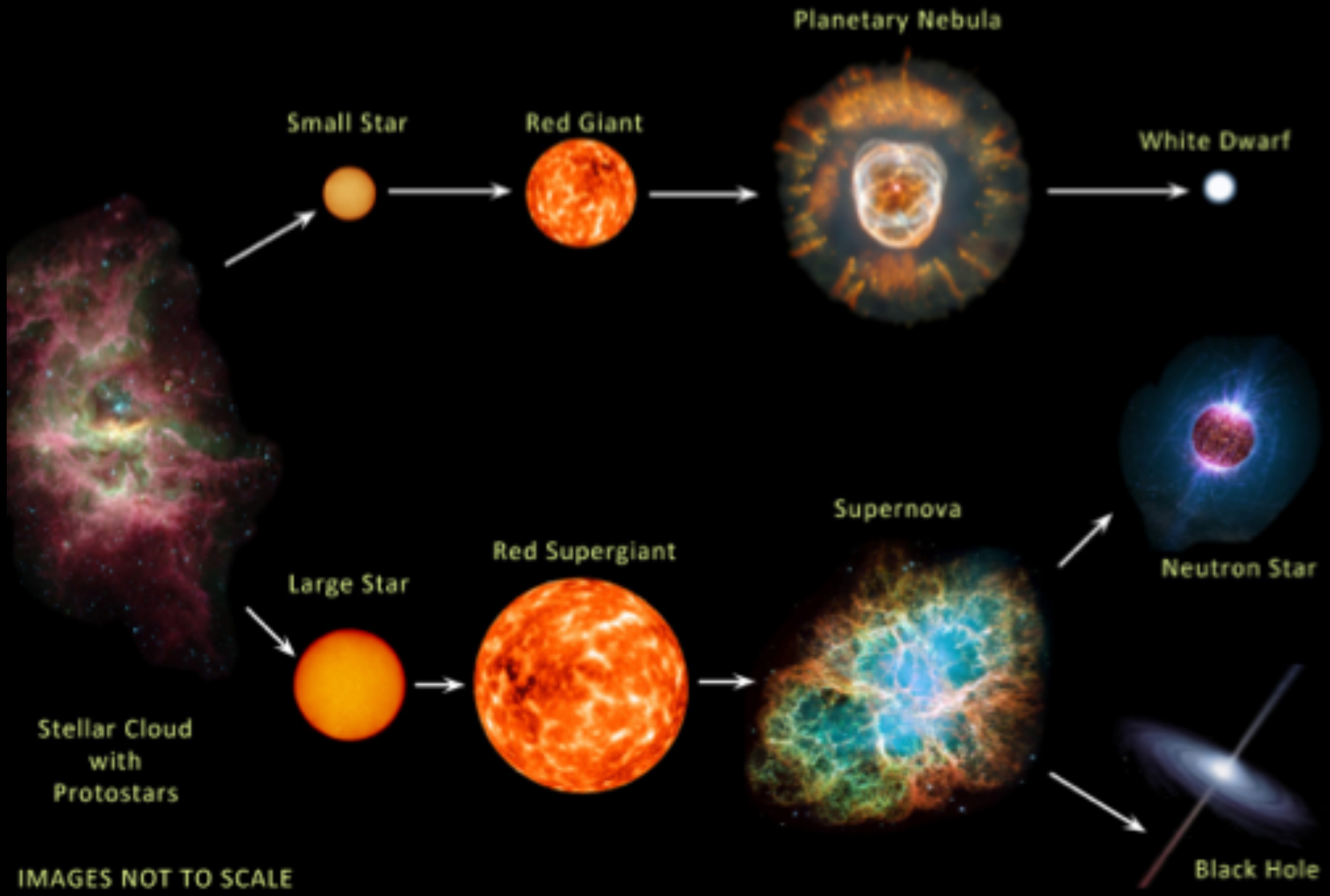
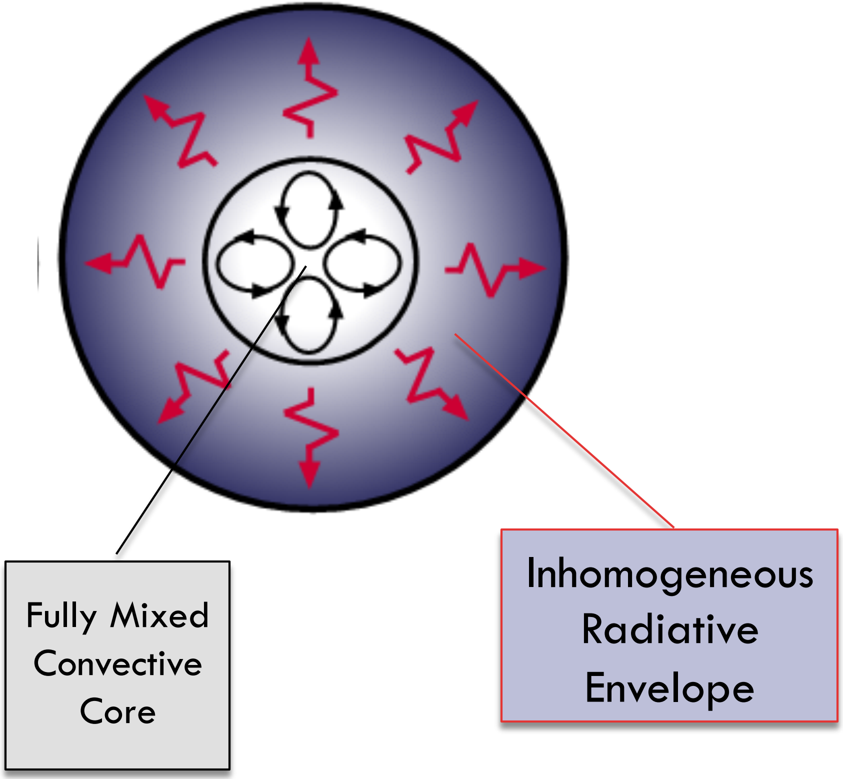


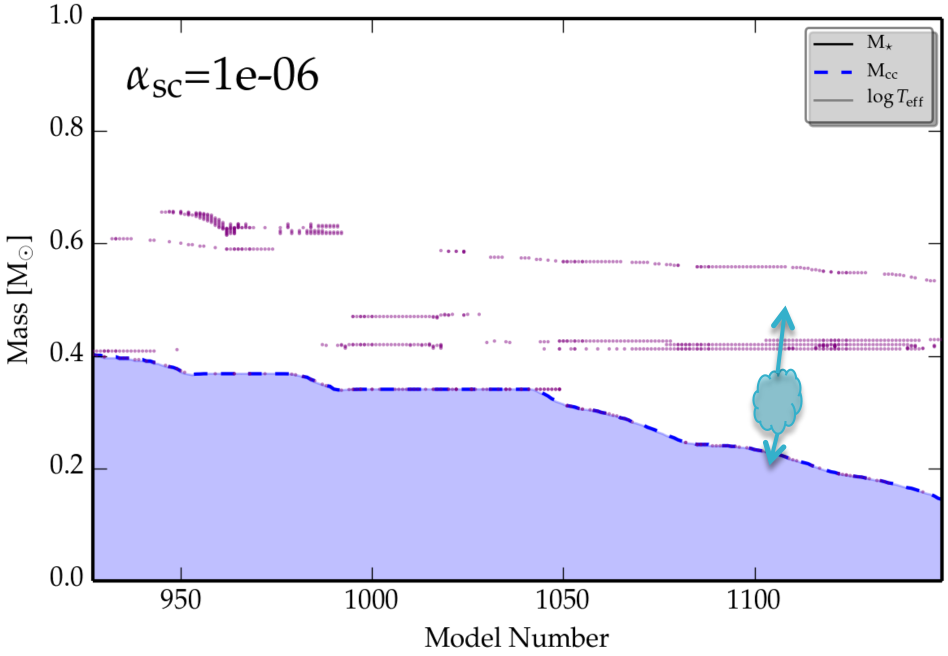
Planetary Nebula
Small Star
Red Giant
White Dwarf
Supernova
Neutron Star
Red Supergiant
Large Star
Stellar Cloud
with
Protostars
Black Hole
IMAGES NOT TO SCALE

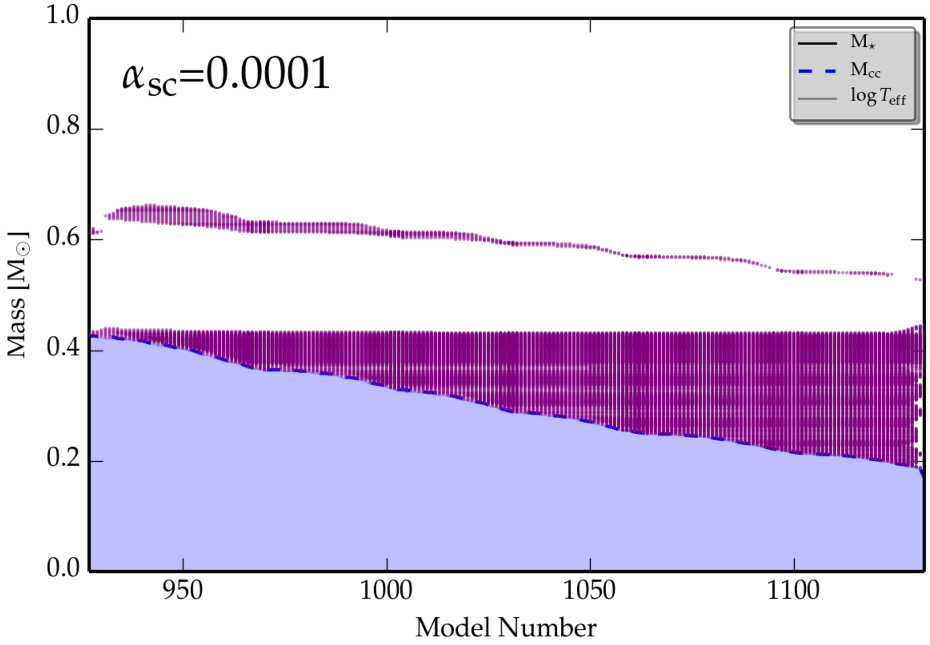
Sources of Composition Mixing in Stars

- Convection
- Magnetic Field
- Rotation-induced Mixing
- Overshooting
- Semi-Convection



Occurrence of Semi-Convection (Langer+1983)





We use MESA (Paxton et al. 2011, 2013) to calculate structure and evolution of stars.

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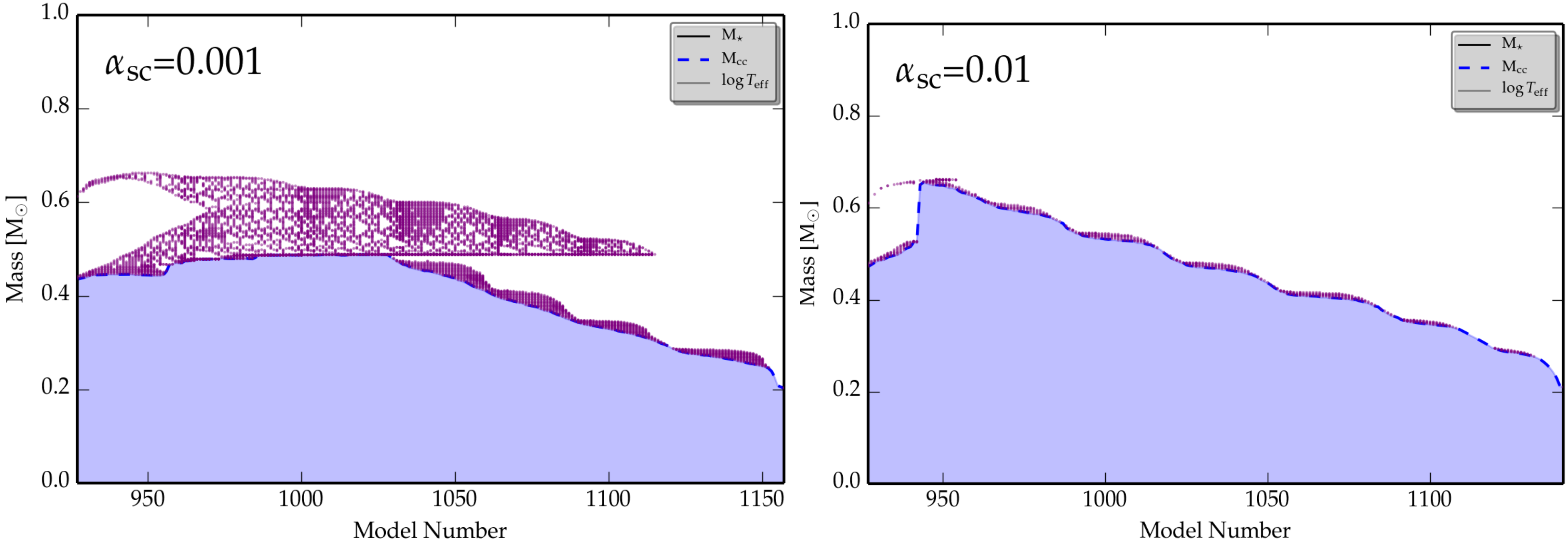
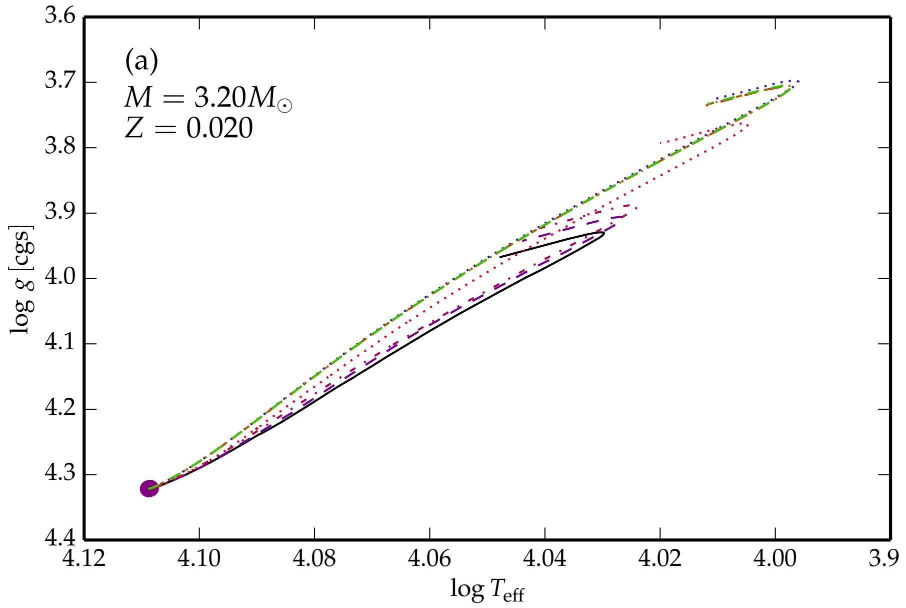
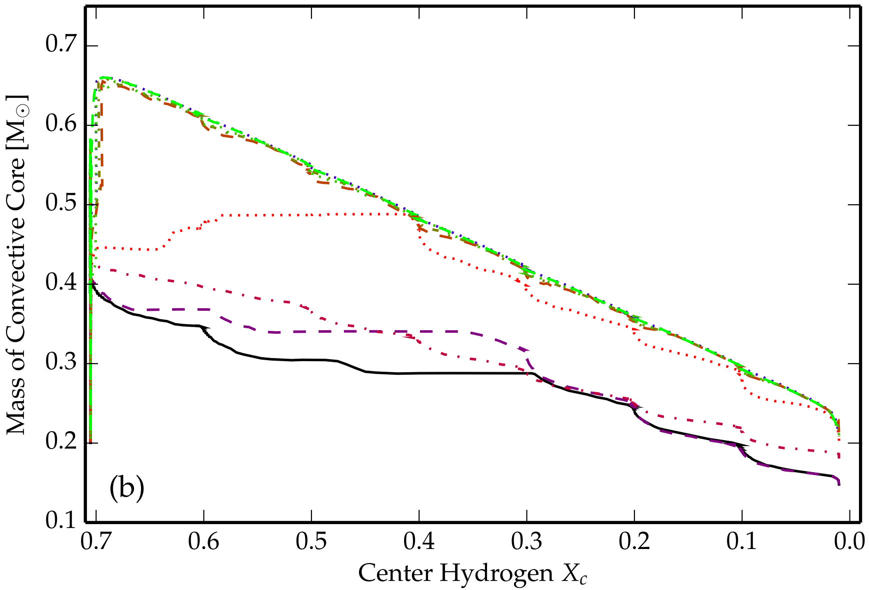
Occurrence of Semi-Convection



Evolutionary Effects of Semi-Convection



α_{sc} impacts the width of main-sequence.



Tracks saturate to fully mixed for $\alpha_{sc} \geq 10^{-2}$

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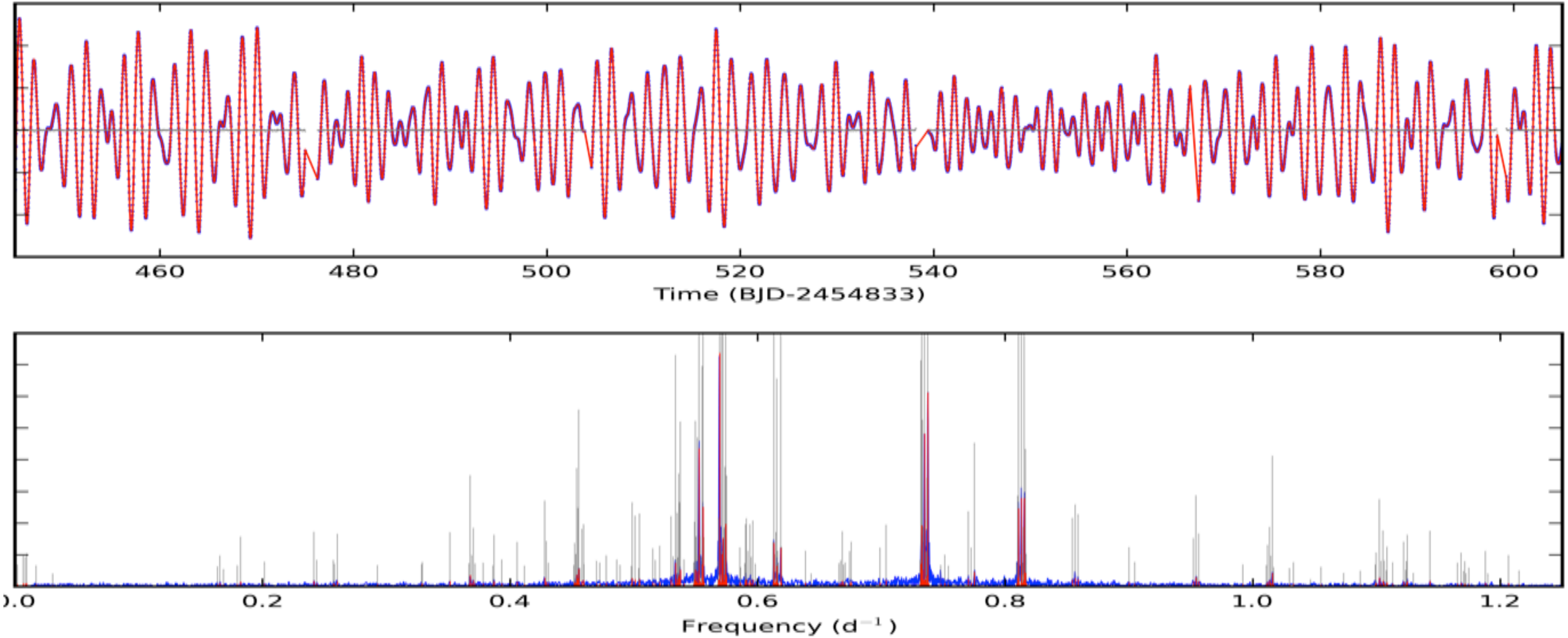
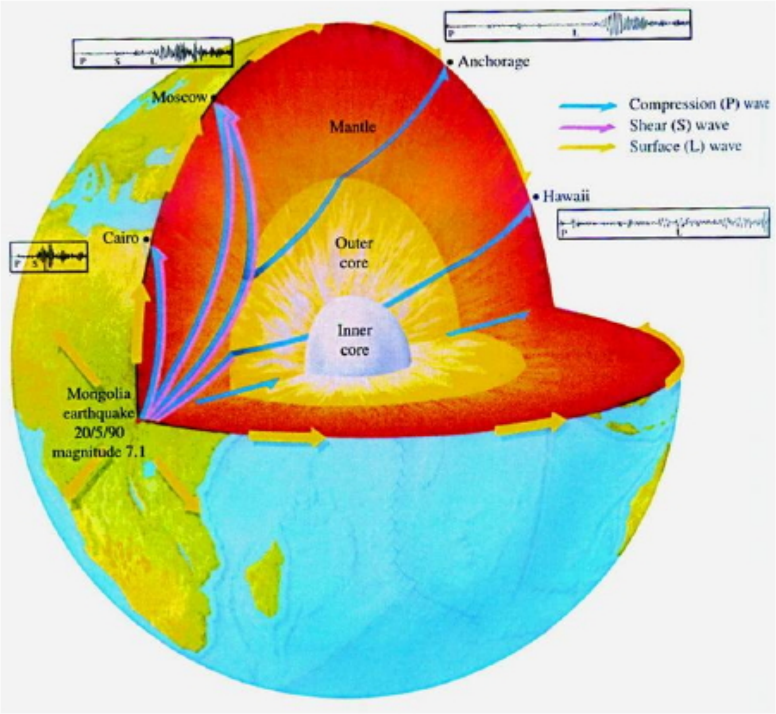
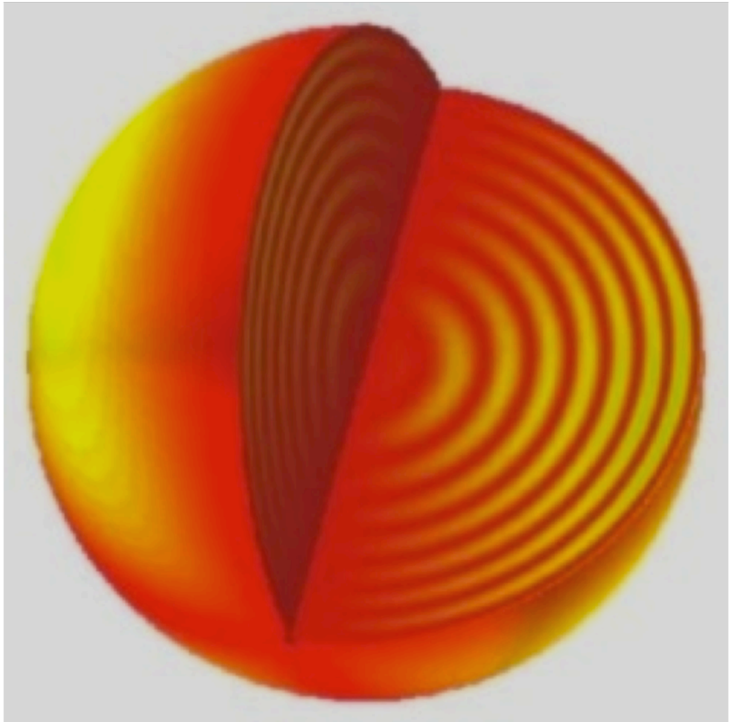
A Young, Non-Rotating Kepler SPB Star



(Papics et al. 2014)

Earth Seismology vs. Asteroseismology





Dense Grid of MESA+GYRE Models

Parameter	From	To	Stepsize	N
Mass	3.00	3.30	0.05	7
α_{sc}	10^{-6}	1		7
Metallicity	0.010	0.025	0.001	16
X_c	0.70	0.60	0.001	101
Total Num.				**~74 000**

- **MESA**: grid parameter range,
- Using ~ 74 000 input models,
- **GYRE**: theoretical oscillation frequencies.

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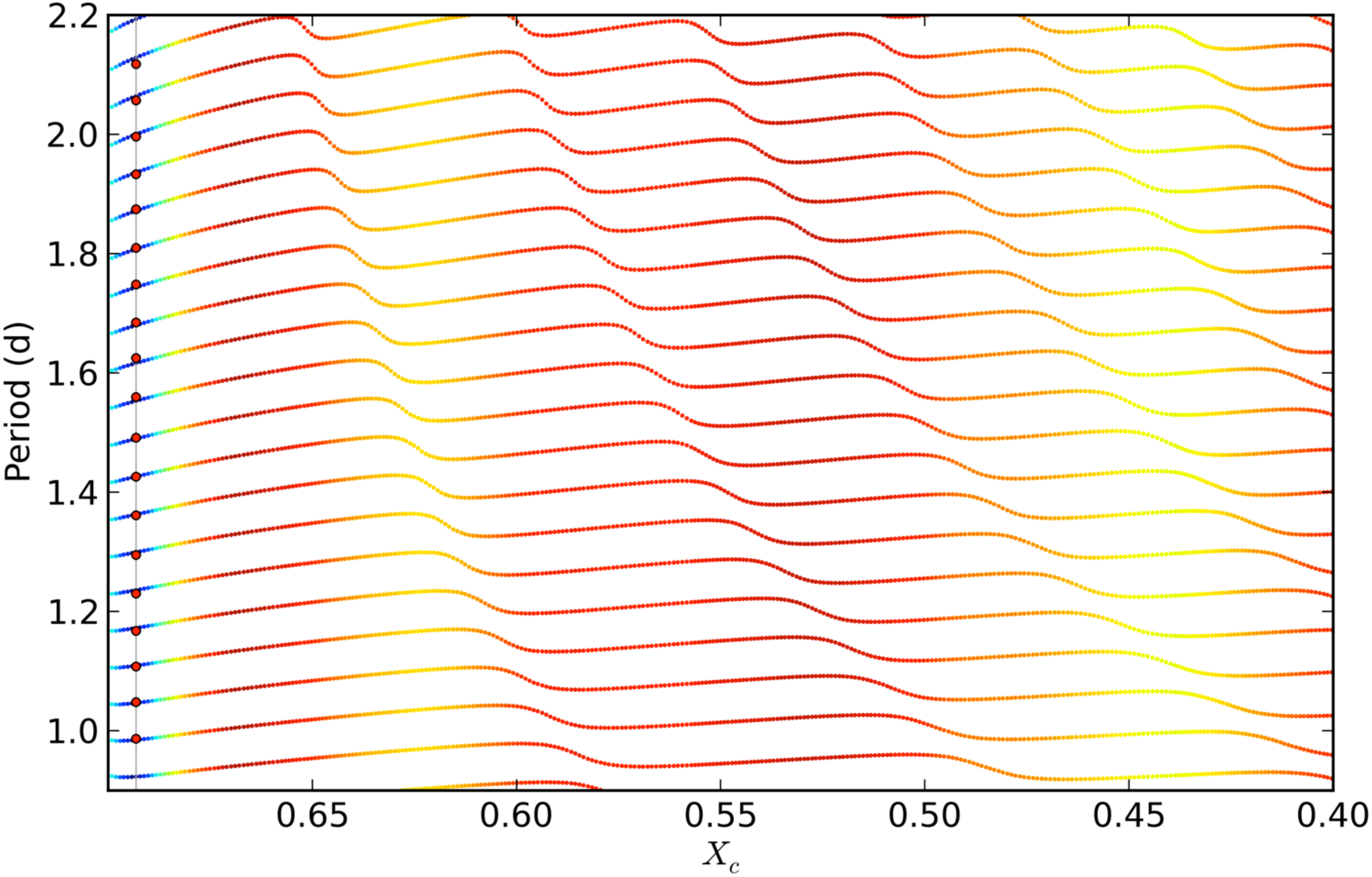
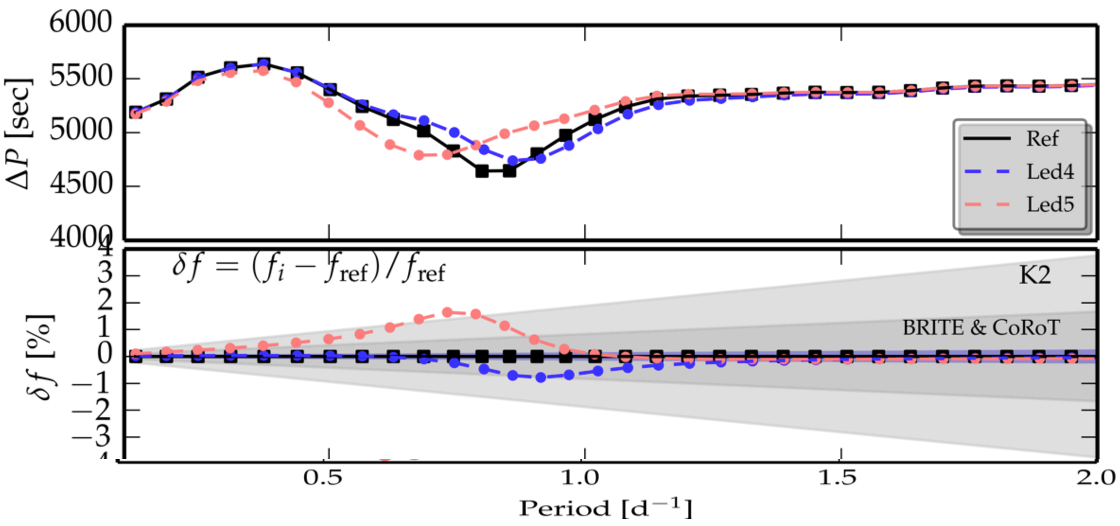

2.2
2.0
1.8
1.6
1.4
1.2
1.0
Period (d)
0.65
0.60
0.55
0.50
0.45
0.40
X_c

Is Asteroseismology Sensitive to α_{sc}?

Yes!

- **MESA:** 3.2 $M_{\odot}$, Z=0.02, X_c=0.70
- Ref: α_{sc}=0.0
  Led4: $\alpha_{sc}=10^{-4}$
  Led5: $\alpha_{sc}=10^{-3}$
- K2~75 days, BRITE~180 days, Kepler~1400 days
- **GYRE:** compute oscillation frequencies



Short-period modes are sensitive to α_{sc}, but challenging to observe

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The Physical Parameters of the Best Model

Best Model:

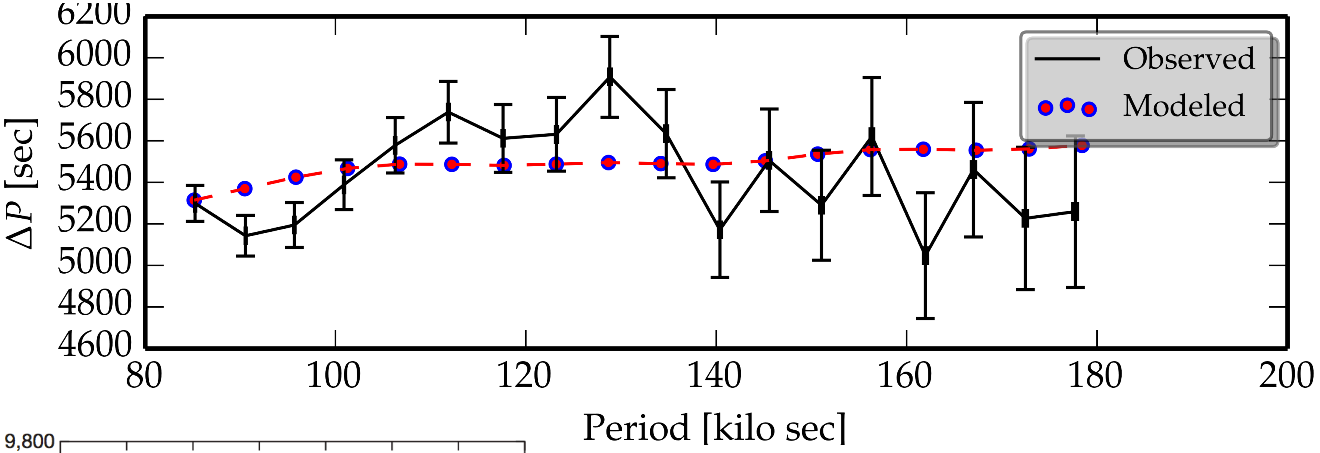
$M = 3.20\ M_{\odot}$

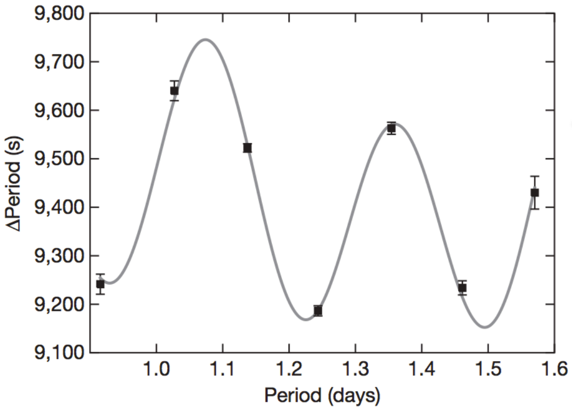
$Z = 0.024$

$\alpha_{ov} = 0.00$

$Xc = 0.694$

$\alpha_{sc} = 10^{-3}$





HD 50230 is a ~7$M_{\odot}$ CoRoT star with precise period spacing (Degroote et. al. 2010, Nature)

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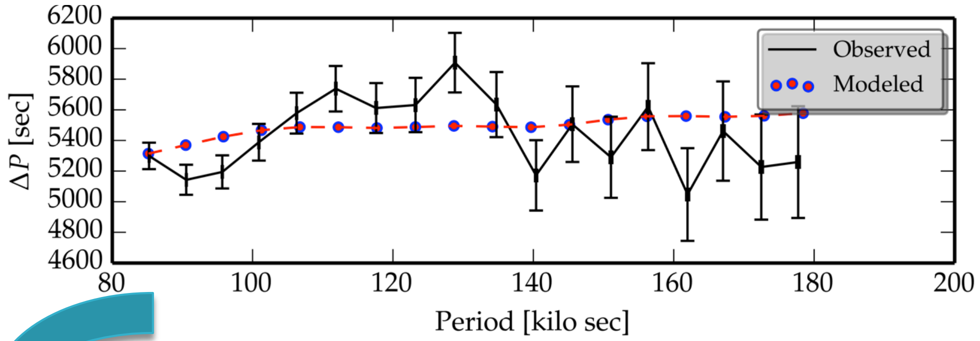
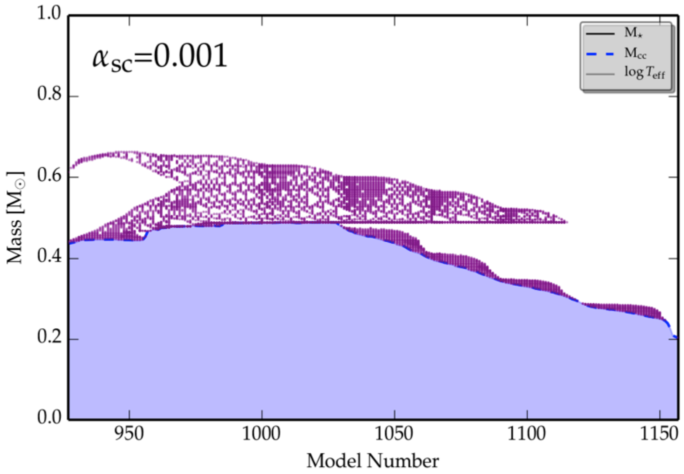
Conclusions

- For a non-rotating massive stars, semi-convection influences the evolution,
- Space photometry from (Kepler & CoRoT) can help constraining the semi-convection
- From asteroseismic modeling, slow mixing (Ledoux criteria) is preferred over rapid (Schwarzscild) mixing, i.e. $\alpha_{sc} \approx 10^{-3}$.





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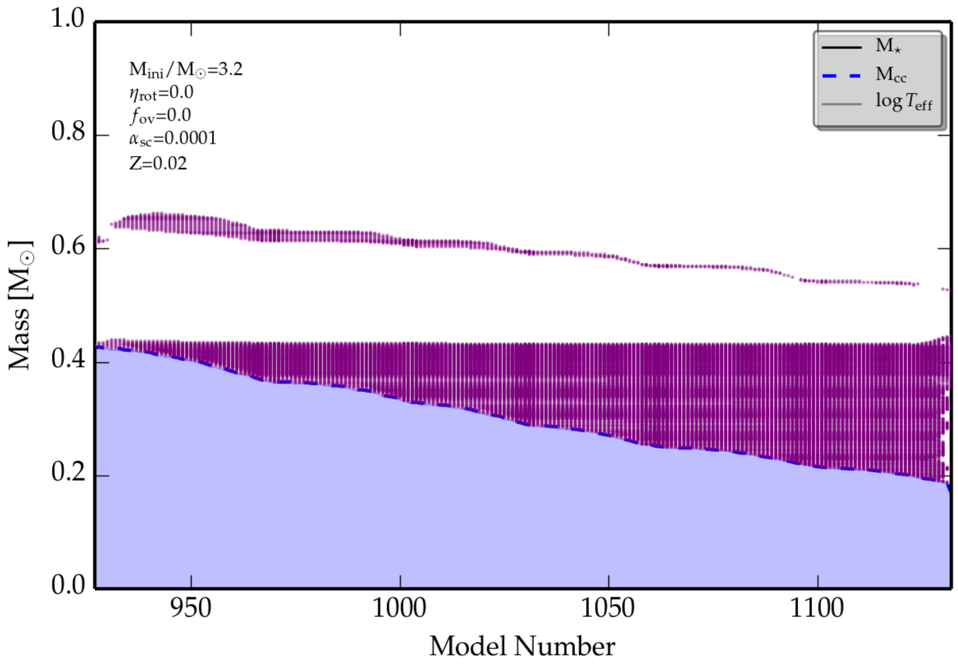
Occurrence of Semi-Convection

Radiative zones that are Ledoux stable but Schwarzschild unstable undergo a slow mixing with unconstrained time scale

$$\nabla_{ad} < \nabla_{rad} \leq \nabla_L; \quad \nabla_L = \nabla - \nabla_{ad} + \frac{\varphi}{\delta}\nabla_\mu$$

$$D_{sc} = \alpha_{sc}\frac{\kappa_{rad}}{6c_p\rho}\frac{\nabla - \nabla_{ad}}{\nabla_L - \nabla} \quad for \quad 0 \leq \alpha_{sc} \leq 1$$

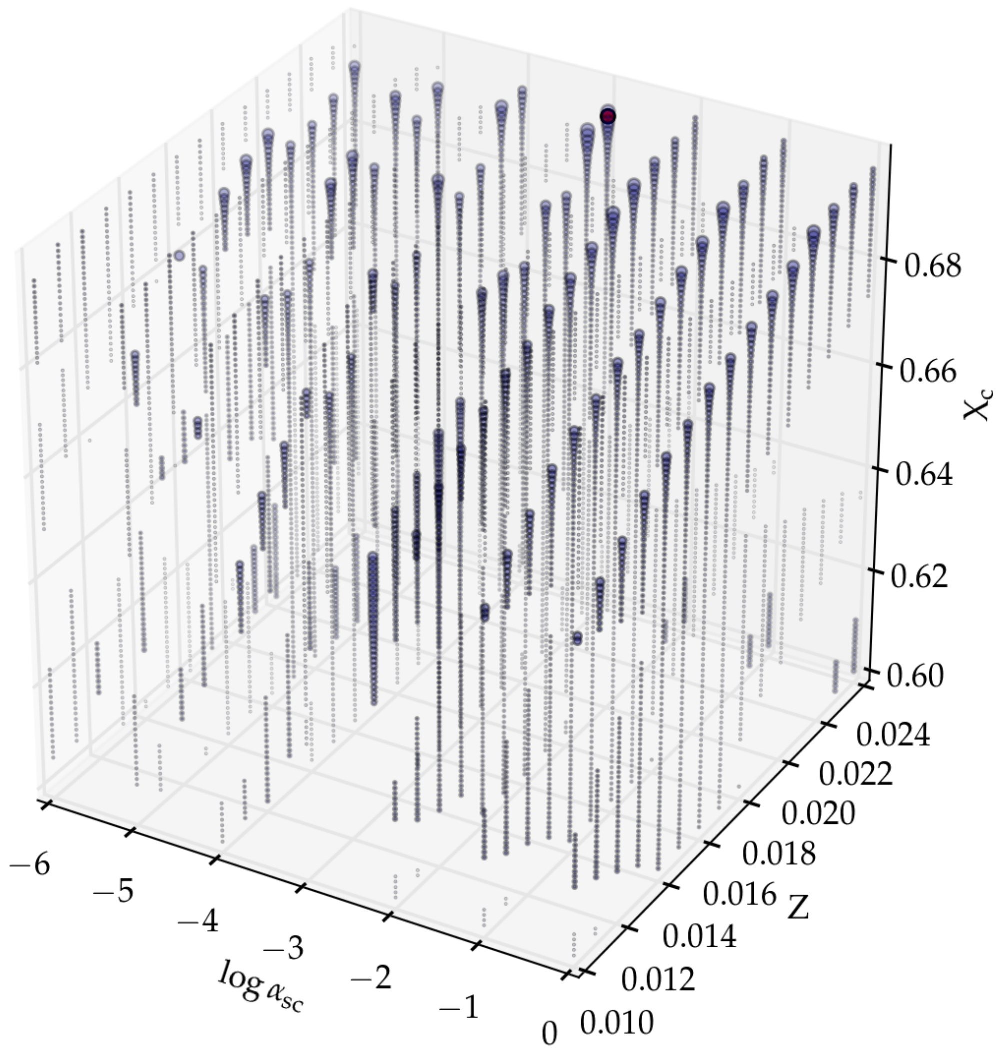
For $\alpha_{sc} \rightarrow 1$: Ledoux $\rightarrow$ Schwarzchild



Evolutionary Effects of Semi-Convection

- MESA (Paxton+2011, 2013) models with OPAL opacity tables and Nieva & Przybilla (2012) composition of B stars (X,Z)=(0.710, 0.014).
- All models are 3.2 $M_\odot$, and Z=0.02
- Schwarzschild track: α_{ov}=0.002
- For Ledoux tracks: $10^{-6} \leq \alpha_{sc} \leq 1$
- Semi-convection impacts the lifetime and width of main-sequence phase.

Name	Led or Sch?	α_{ov}	α_{sc}	M_{He}	Age
Ref	Led	0.0	0.0	0.972	183
Led1	Led	0.01	10^{-6}	0.967	263
Led2	Led	0.0	10^{-6}	0.971	193
Led3	Led	0.0	10^{-5}	0.971	169
Led4	Led	0.0	10^{-4}	0.970	200
Led5	Led	0.0	10^{-3}	0.969	243
Led6	Led	0.0	10^{-2}	0.970	261
Led7	Led	0.0	10^{-1}	0.972	261
Led8	Led	0.0	1.0	0.971	261
Sch1	Sch	0.002	0.0	0.972	262


0.68
0.66
0.64
0.62
0.60
X_c
0.024
0.022
0.020
0.018
0.016
0.014
0.012
0.010
Z
−6
−5
−4
−3
−2
−1
0
$\log \alpha_{sc}$