# Cumulative theoretical uncertainties in Lithium Depletion Boundary Age

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- Reconstructing the Milky Way's History: Spectroscopic Surveys, Asteroseismology and Chemodynamical Models -
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# Introduction (1)

## Lithium Depletion Boundary:
## Alternative method to assign an age to young clusters (20-300 Myr)

(9 clusters, see e.g. reviews of Jeffries 2006, Soderblom et al 2013)

## Lithium depletion:

- $^{7}$Li destroyed during the PMS ($T_c > 2.5 \times 10^6$ K) for stellar mass $M > 0.06 M_{sun}$

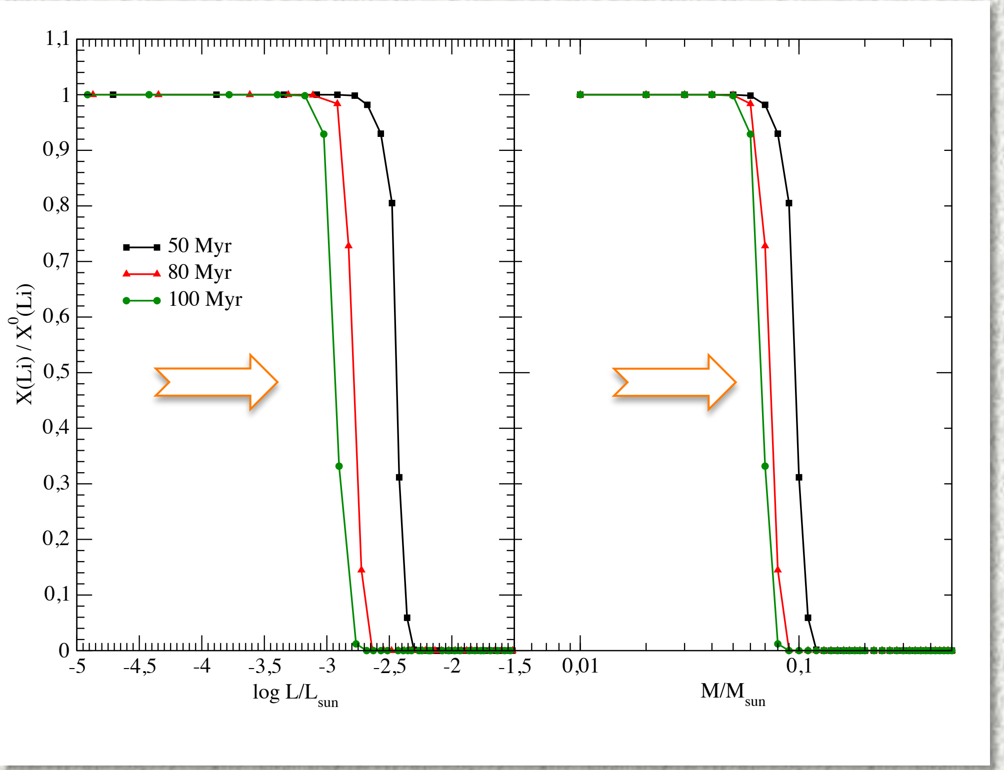
- Completely destroyed in fully convective stars: $0.06 M_{sun} < M < 0.5\ M_{sun}$

- Destruction timescale ($\tau_{ldb}$) depends on $T_c$: $T_c = T_c(M)$

- $\tau_{ldb}$ decreases with the stellar mass: strongly dependent on M

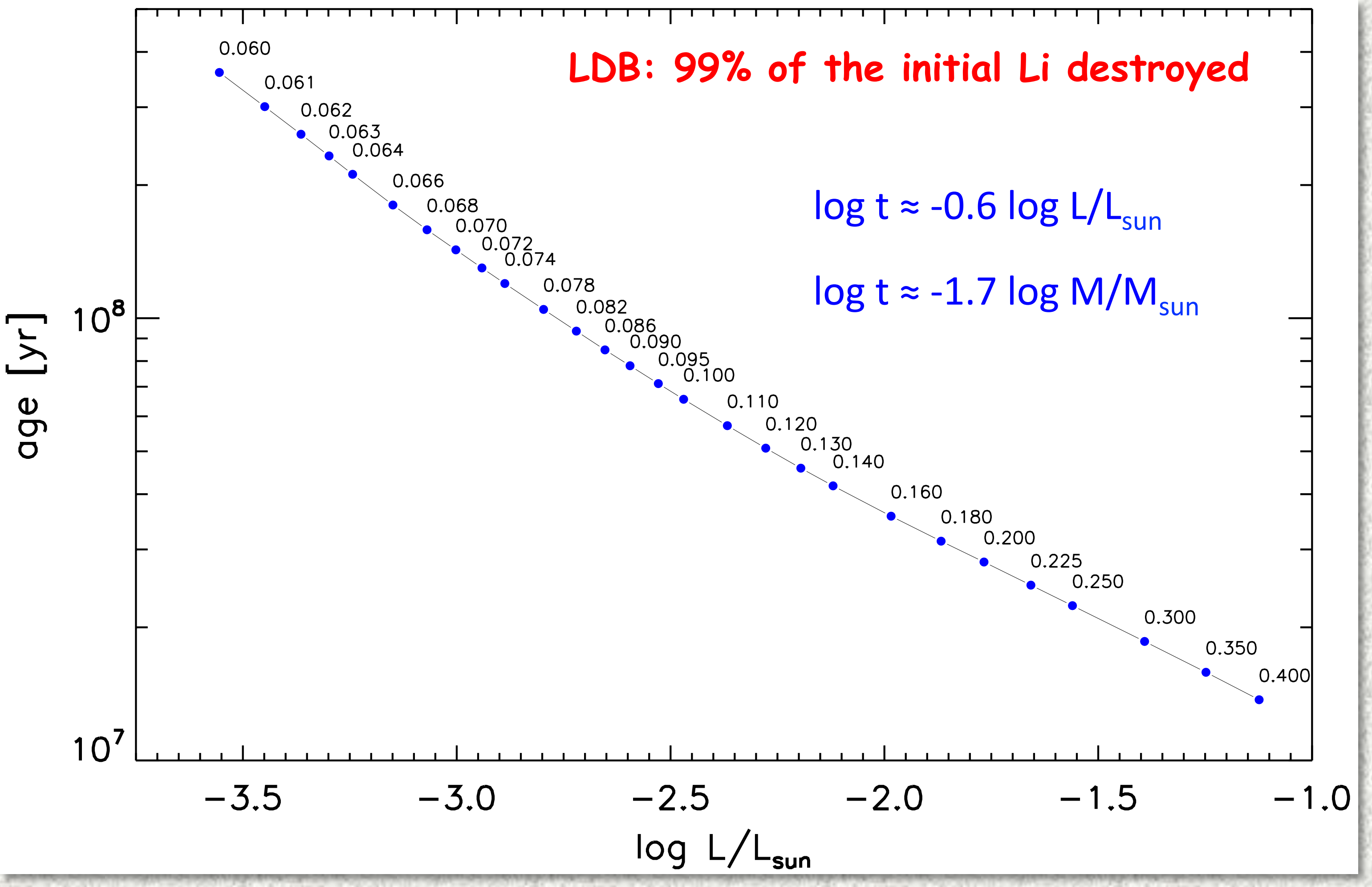
## Lithium depletion boundary (LDB):

In a cluster: the faintest object with ≈ 0 surface $^7$Li abundance




Age inferred by comparing the **observed** and **theoretically** computed **LDB luminosity**. Uncertainty on the models propagates into a final age uncertainty (Bildsten et al. 1997, Burke et al. 2004)

# LDB age-luminosity



# Stellar Models (1)

**PROSECCO: Pisa stellar evolutionary code**
(Degl'Innocenti et al. 2008)

Updated input physics
(Tognelli et al. 2012, Dell'Omodarme et al. 2012, Tognelli et al. 2014)

Detailed atmospheric models: PHOENIX atmospheric code
(Brott & Haushildt 2005)

Equation of state: extension to the brown dwarf regime
(Saumon, Chabrier & VanHorn 1995)

Updated nuclear cross sections for light elements (deuterium, lithium, beryllium, and boron)

Recently updated solar metals abundances (Asplund et al. 2009)

# Stellar Models (2)

## Uncertainty analysis

(Tognelli et al. 2015, MNRAS)

## Input physics and initial chemical composition

$$LDB = LDB(\{p_l\}, \{x_k\})$$

**$\{p_l\}$ = input physics quantity** (i.e. opacity, cross section, mixing lenght…)

**$\{x_k\}$ = element abundance**

- **Independent variation** of each quantity.
  Individual uncertainty source.

  input physics: $LDB = LDB(p_j \pm \Delta p_j, \{p_{l\neq j}\}, \{x_k\})$

  chemical composition: $LDB = LDB(\{p_l\}, x_j \pm \Delta x_j, \{x_{k\neq i}\})$

- **Cumulative error stripe.**
  **Simultaneous** variation of all the analysed quantities at the same time.

# Individual Uncertainty source (1)

## Input Physics

**Table 3.** Input physics varied in the computation of perturbed stellar models and their assumed uncertainty or range of variation. The flag "yes" specifies the quantities taken into account in the cumulative uncertainty calculation (see Sect. 5).

| quantity | Individual Error Analysis |
|---|---|
| $^2H(p,\gamma)^3He$ reaction rate | ±3% |
| $^2H(^2H,n)^3He$ reaction rate | ±5% |
| $^2H(^2H,p)^3H$ reaction rate | ±5% |
| $^7Li(p,\alpha)\alpha$ reaction rate | ±10% |
| electron screening($p+^7Li$) $^{(a)}$ | +50%, +100% |
| BCs $^{(b)}$ | BH05, AHF11, KS66 |
| $\tau_{ph}$ $^{(a)}$ | 2/3, 100 |
| EOS $^{(b)}$ | OPAL06, FreeEOS08, SCVH95 |
| $\overline{\kappa}_{rad}$ | ±5% |

Uncertainty estimation not available...(future?!)

# Individual Uncertainty source: INPUT PHYSICS (2)

**Reaction Rate:**

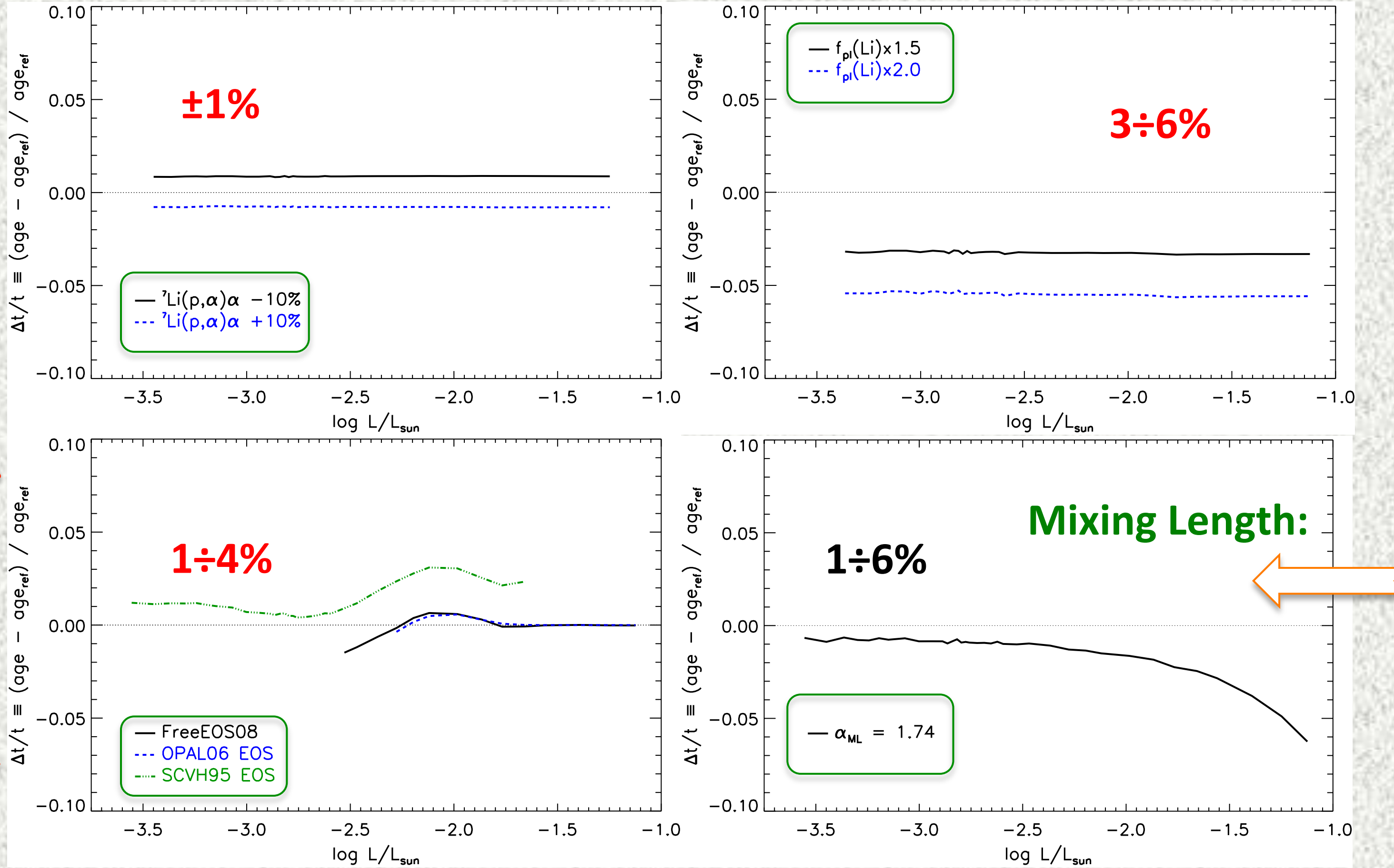
older

younger

**EOS:**

older

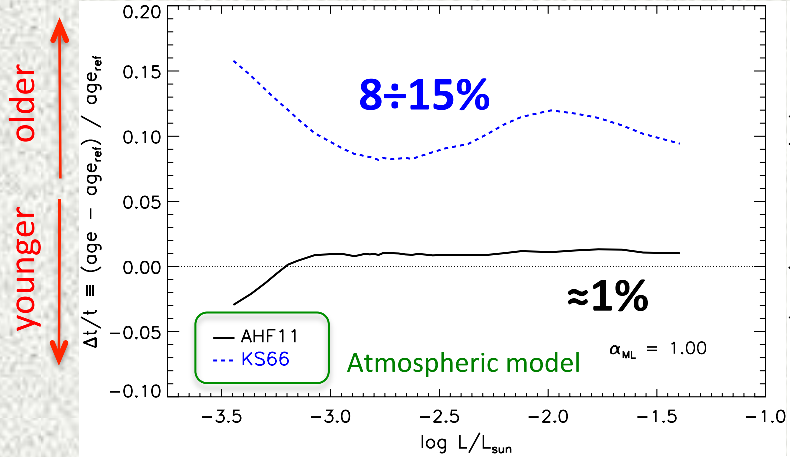
younger

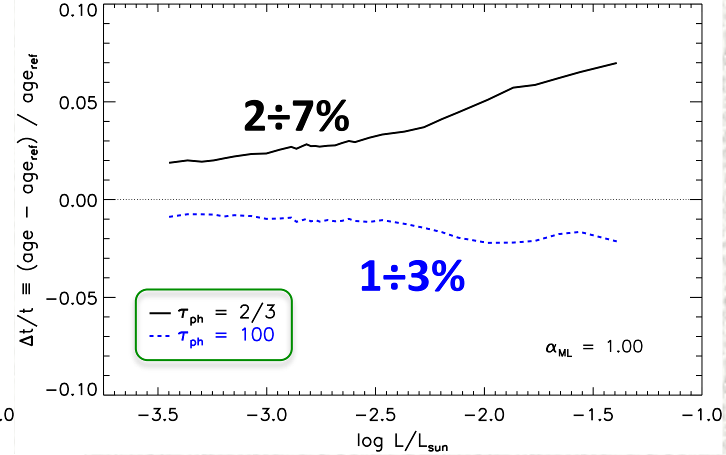


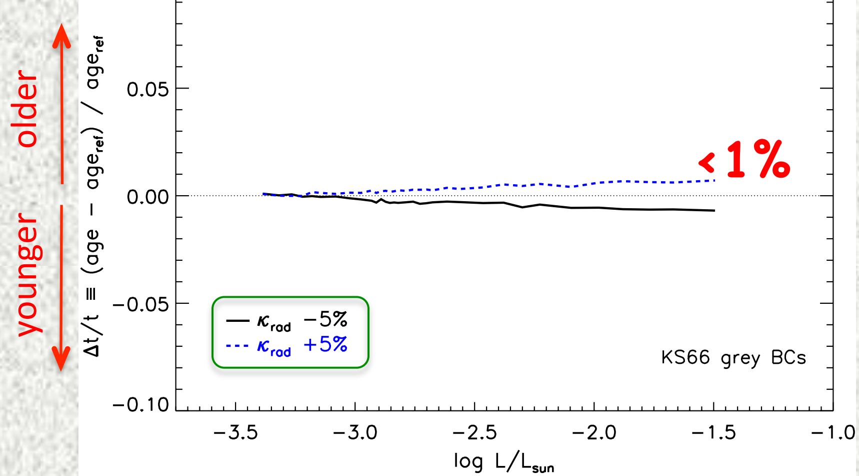

$T_c \propto M/R$,
$R = R(t)$

# Individual Uncertainty source: INPUT PHYSICS (3)

**Surface Boundary Conditions:**




**Opacity variation in the atmosphere (outer boundary conditions)**

# Individual Uncertainty source (4)

## Chemical Composition

**(analysed for the first time)**

**Table 4.** Chemical composition parameters varied in the computation of perturbed stellar models and their assumed uncertainty. The flag "yes" in the last column specifies the quantities taken into account in the cumulative uncertainty calculation (see Sect. 5).

| quantity | Individual Error Analysis |
|---|---|
| [Fe/H] | $\pm 0.1$dex |
| $\Delta Y/\Delta Z$ | $\pm 1$ |
| $(Z/X)_\odot$ | $\pm 15\%$ |
| $X_\mathrm{d}$ | $\pm 1 \times 10^{-5}$ |

$$Y = Y_\mathrm{P} + \frac{\Delta Y}{\Delta Z} Z$$

$$Z = \frac{(1 - Y_\mathrm{P})(Z/X)_\odot}{10^{-[\mathrm{Fe/H}]} + (1 + \Delta Y/\Delta Z)(Z/X)_\odot}$$

(see e.g. Gennaro et al. 2010)

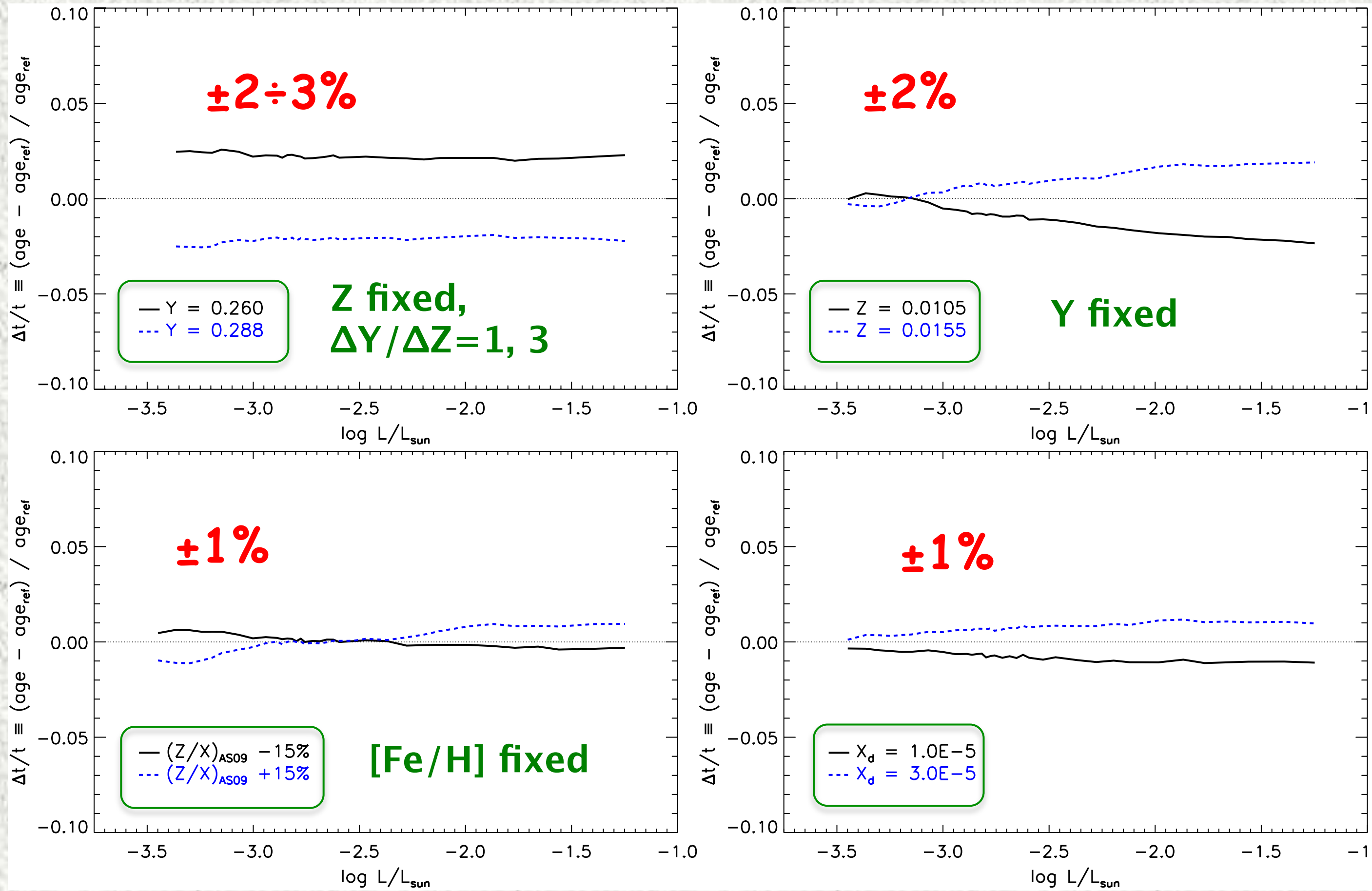
# Individual Uncertainty source: CHEMICAL COMPOSITION (5)

**Helium:**

**Metallicity:**

**Deuterium:**

older / younger




$$Y = Y_{\rm P} + \frac{\Delta Y}{\Delta Z} Z$$

$$Z = \frac{(1 - Y_{\rm P})(Z/X)_\odot}{10^{-[{\rm Fe/H}]} + (1 + \Delta Y/\Delta Z)(Z/X)_\odot}$$

Reference values:
Y=0.274, Z=0.013

# Cumulative Error Stripe (1)

**Input physics and chemical composition quantities/parameters can vary at the same time**

$$LDB = LDB(\{p_l\}, \{x_k\})$$

**Input physics**

$$p_j \Rightarrow \begin{cases} p_j + \Delta p_j \\ p_j \\ p_j - \Delta p_j \end{cases}$$

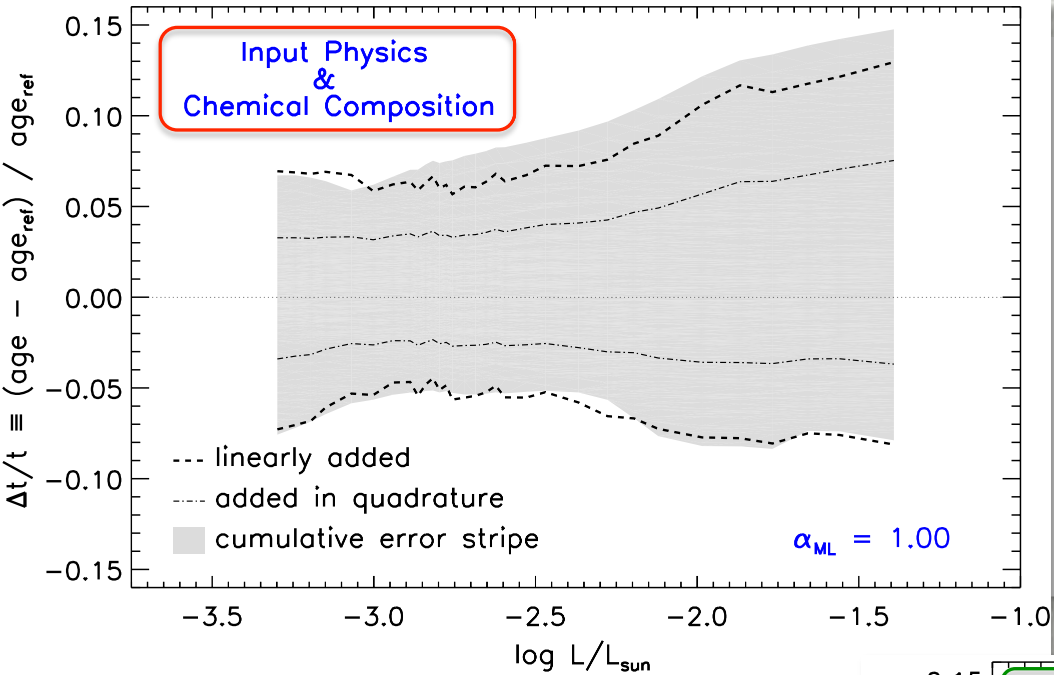
**Chemical composition**

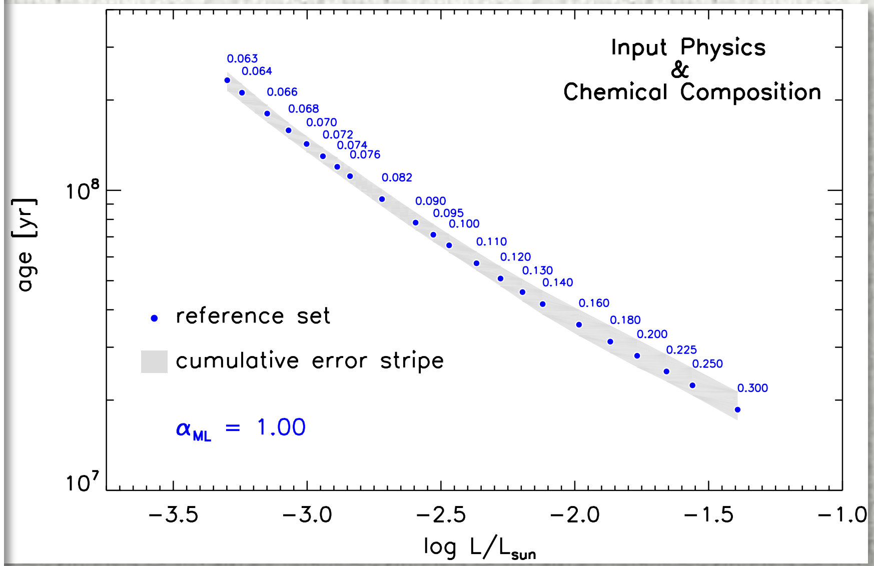
$$x_k \Rightarrow \begin{cases} x_k + \Delta x_k \\ x_k \\ x_k - \Delta x_k \end{cases}$$

**To obtain the error stripe we computed all the possible permutations of the perturbed $\{p_j\}$ and $\{x_k\}$**

**For a total of ≈ 400 sets of models!**

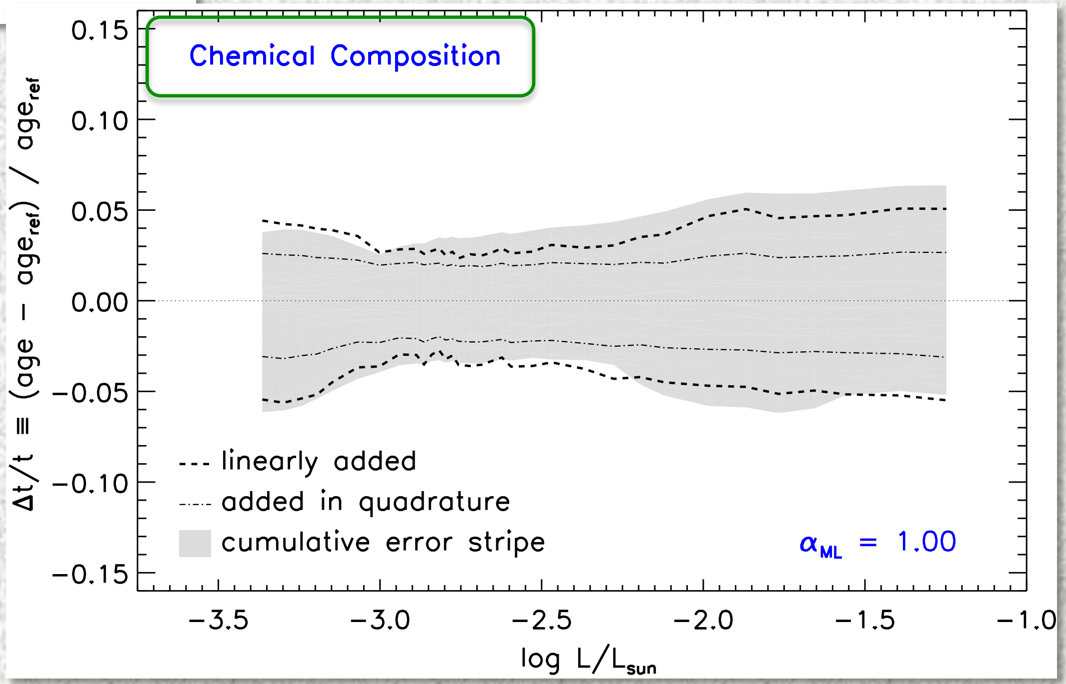
# Cumulative Error Stripe (2)



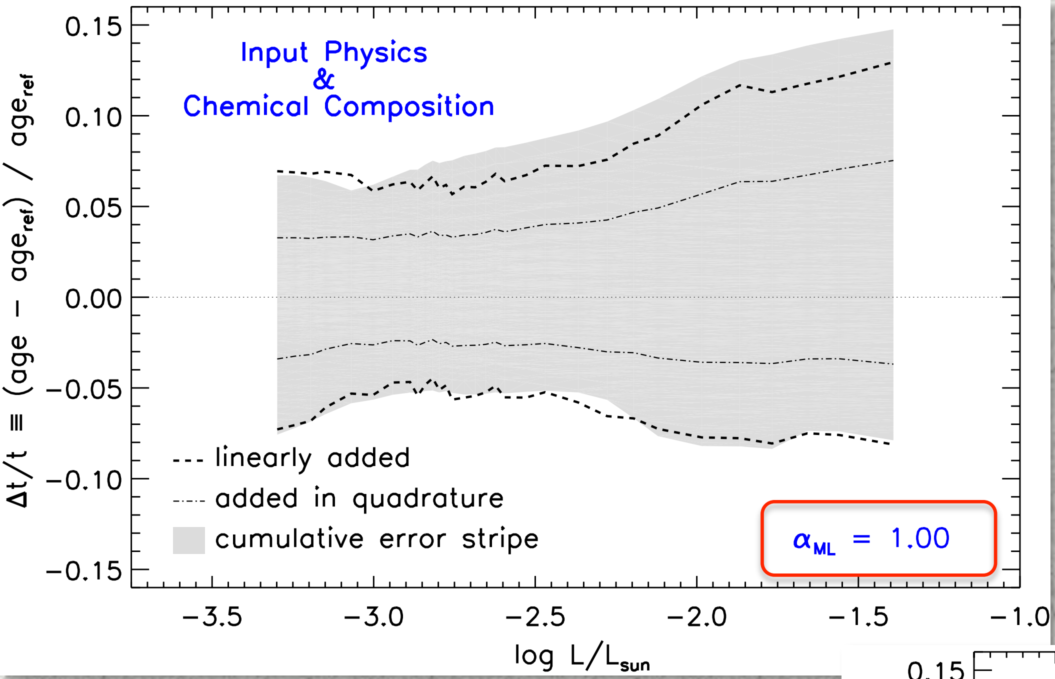




**Error stripe: from 5% up to 15%**

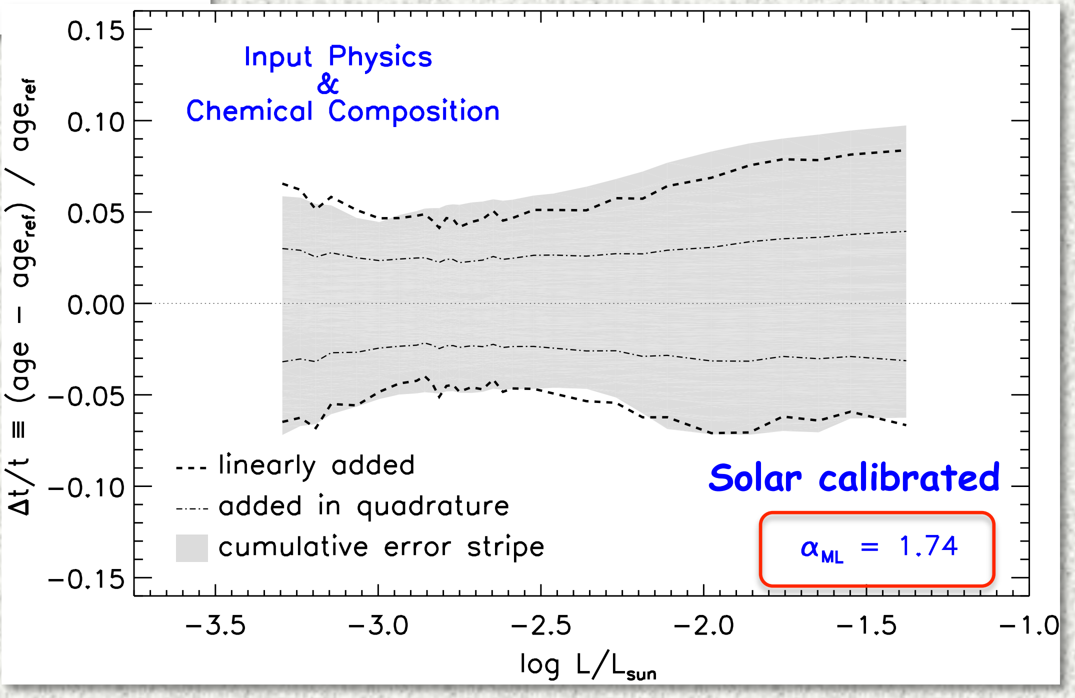
**Chemical composition:**
**40% of the total error budget**



# Cumulative Error Stripe (3)




## Effect of the Mixing Length parameter



# Summary

- Analysis of the main uncertainty sources affecting theoretical LDB age determination

- Individual uncertainty sources: input physics and chemical composition

- For the first time cumulative error stripe: simultaneous variation of the input physics and chemical composition quantities/parameter

- Error stripe: 40% of the total error budget due to the uncertainty on the initial chemical composition

- Cumulative Error Stripe well reproduced by linealy adding the uncertainty due to individual variation

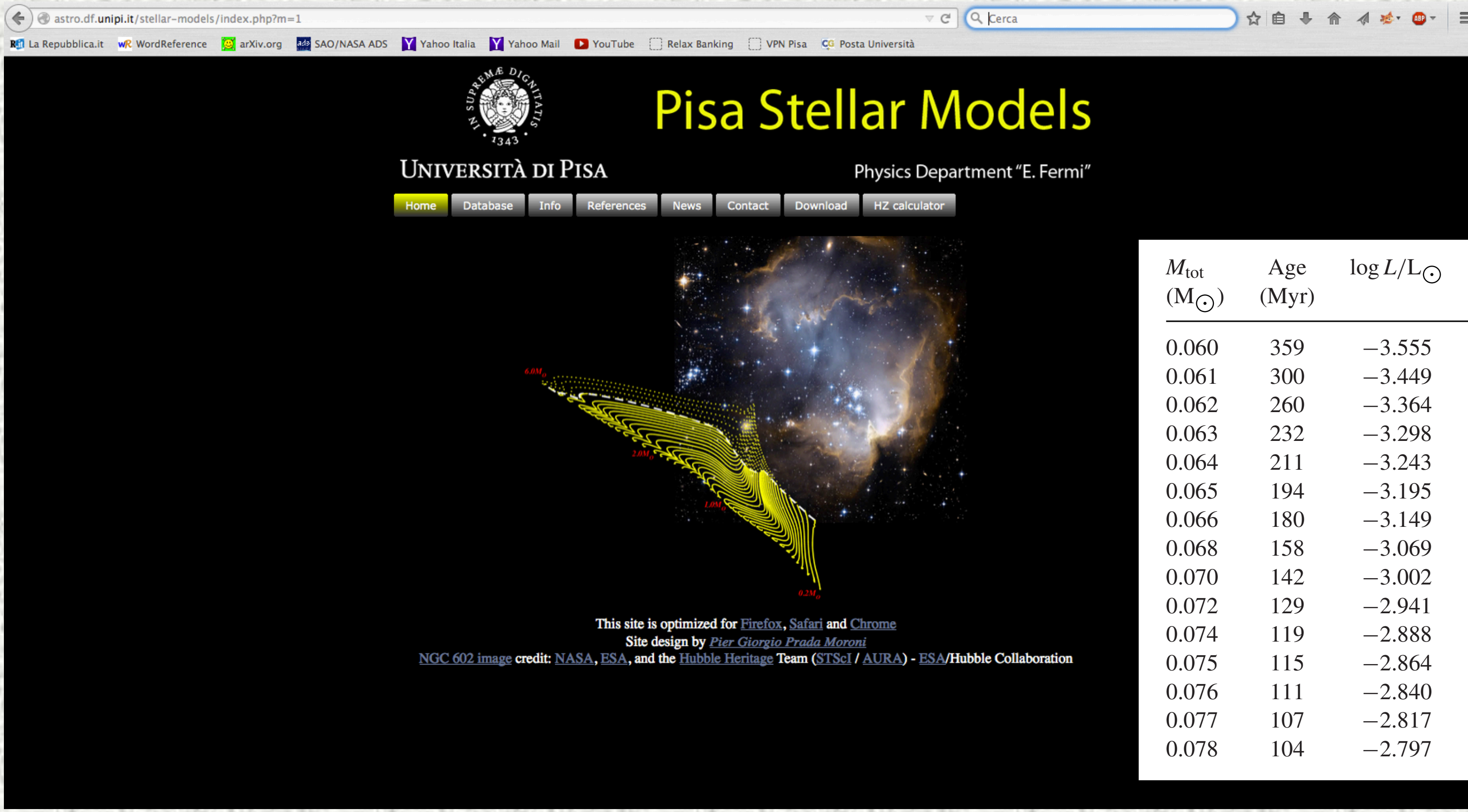
- Age uncertainty: from 5-8% (100 Myr) to 8-15% (20 Myr)

- Future: additional uncertainty sources (rotation, magnetic fields, accretion…)

# Pisa Pre-Main Sequence and Low Mass Stars Database

http://astro.df.unipi.it/stellar-models/ → **stellar models:** tracks/isochrones

http://astro.df.unipi.it/stellar-models/ldb/ → **LDB:** for [Fe/H] = +0.1, 0.0, -0.1




| $M_{tot}$ ($M_\odot$) | Age (Myr) | $\log L/L_\odot$ | $\log R/R_\odot$ | $\log g$ (cm $s^{-2}$) | $\log T_{eff}$ (K) |
|---|---|---|---|---|---|
| 0.060 | 359 | −3.555 | −0.972 | 5.160 | 3.359 |
| 0.061 | 300 | −3.449 | −0.954 | 5.132 | 3.377 |
| 0.062 | 260 | −3.364 | −0.939 | 5.108 | 3.390 |
| 0.063 | 232 | −3.298 | −0.925 | 5.088 | 3.400 |
| 0.064 | 211 | −3.243 | −0.913 | 5.070 | 3.407 |
| 0.065 | 194 | −3.195 | −0.902 | 5.055 | 3.414 |
| 0.066 | 180 | −3.149 | −0.891 | 5.040 | 3.420 |
| 0.068 | 158 | −3.069 | −0.872 | 5.015 | 3.430 |
| 0.070 | 142 | −3.002 | −0.855 | 4.993 | 3.439 |
| 0.072 | 129 | −2.941 | −0.839 | 4.972 | 3.446 |
| 0.074 | 119 | −2.888 | −0.824 | 4.954 | 3.452 |
| 0.075 | 115 | −2.864 | −0.817 | 4.946 | 3.454 |
| 0.076 | 111 | −2.840 | −0.809 | 4.937 | 3.456 |
| 0.077 | 107 | −2.817 | −0.803 | 4.929 | 3.459 |
| 0.078 | 104 | −2.797 | −0.796 | 4.922 | 3.461 |

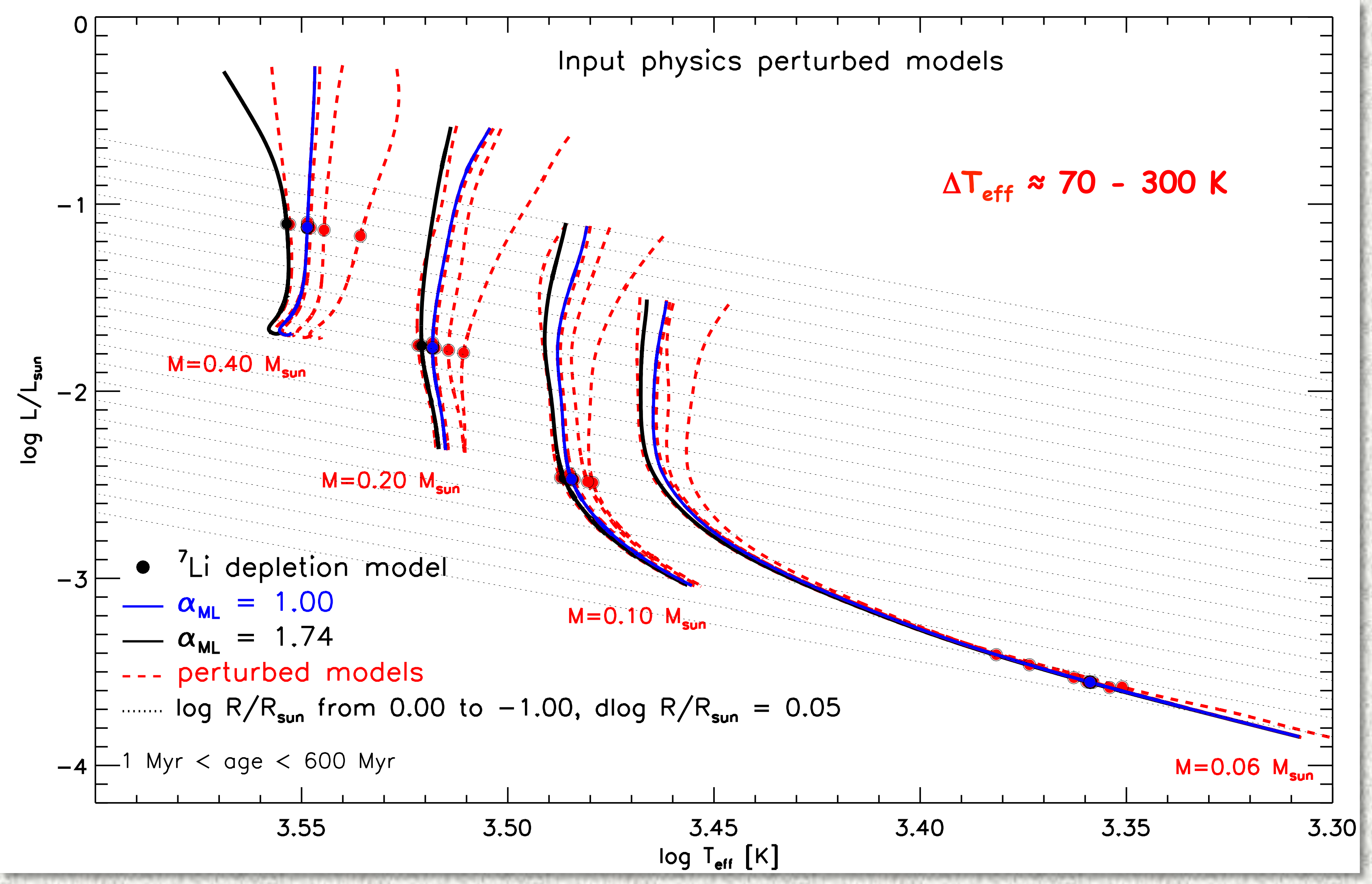
**Pre-Main Sequence: isochrones (1-100 Myr) and tracks (0.2 - 6.0 $M_{sun}$)**

**Low Mass Stars: isochrones (8-15 Gyr) and tracks (0.3-1.1 Msun)**

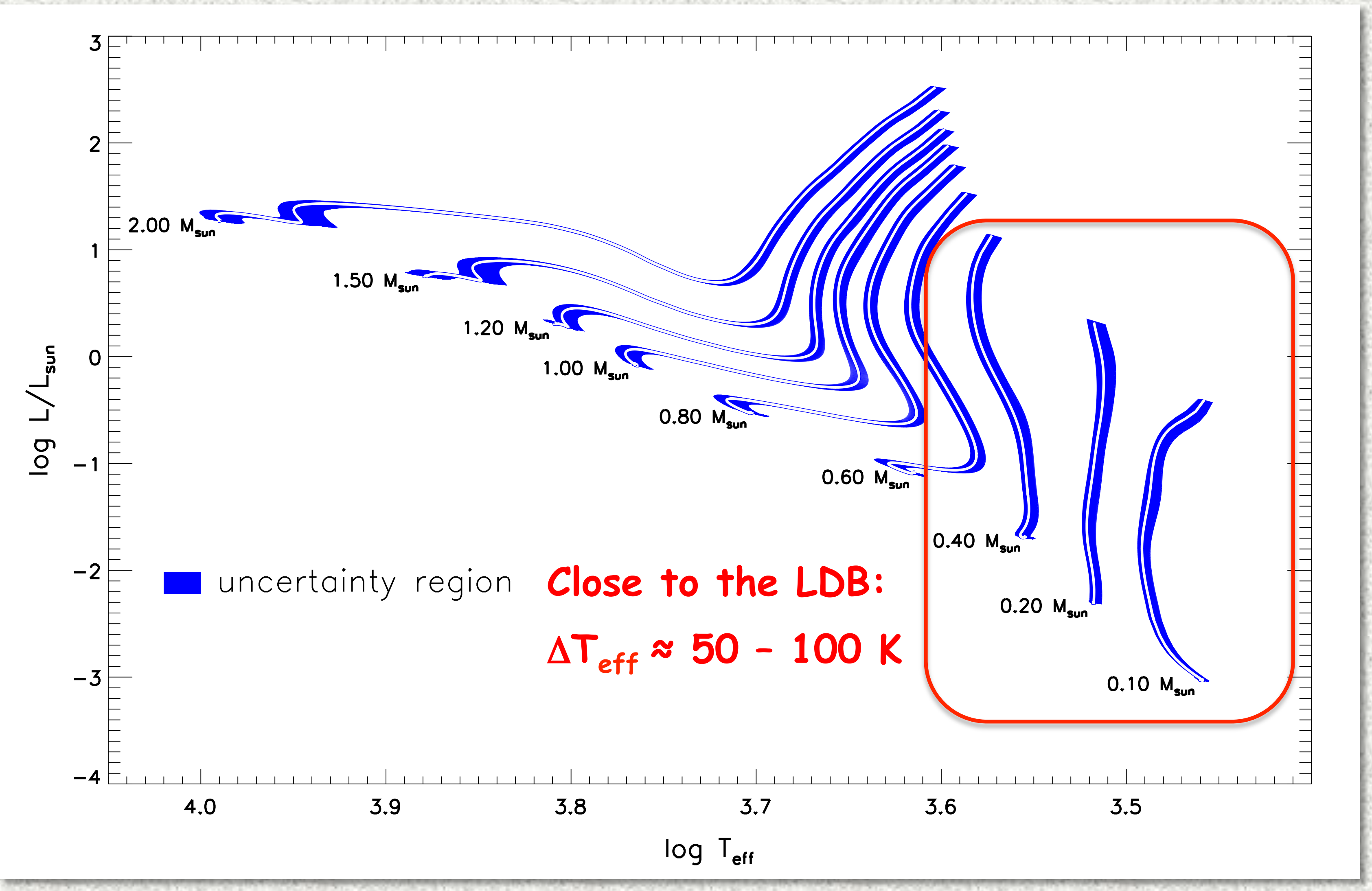

"[…] after all it's been written in the stars […]"
John Lennon, Woman, Double Fantasy, 1980
…The End!!!!

# Individual Uncertainty source (bck1)

## Input Physics



# Individual Uncertainty source (bck2)




**Close to the LDB:**

**$\Delta T_{eff} \approx$ 50 - 100 K**