



# Tracing early stellar evolution with asteroseismology: pre-main sequence stars in NGC 2264



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**T. Ryabchikova**  
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**C. Aerts**

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**Russian Academy of Sciences, Russia**  
**St. Mary's University, Halifax, Canada**  
**KU Leuven, Belgium**

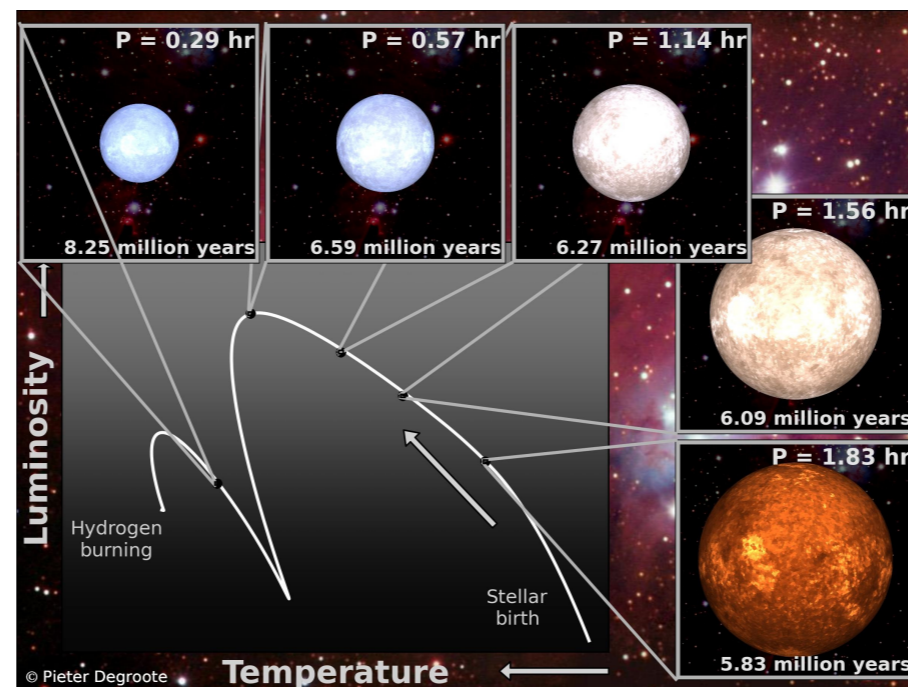
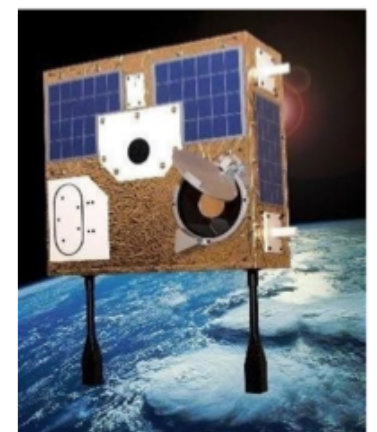




# Echography of young stars reveals their evolution

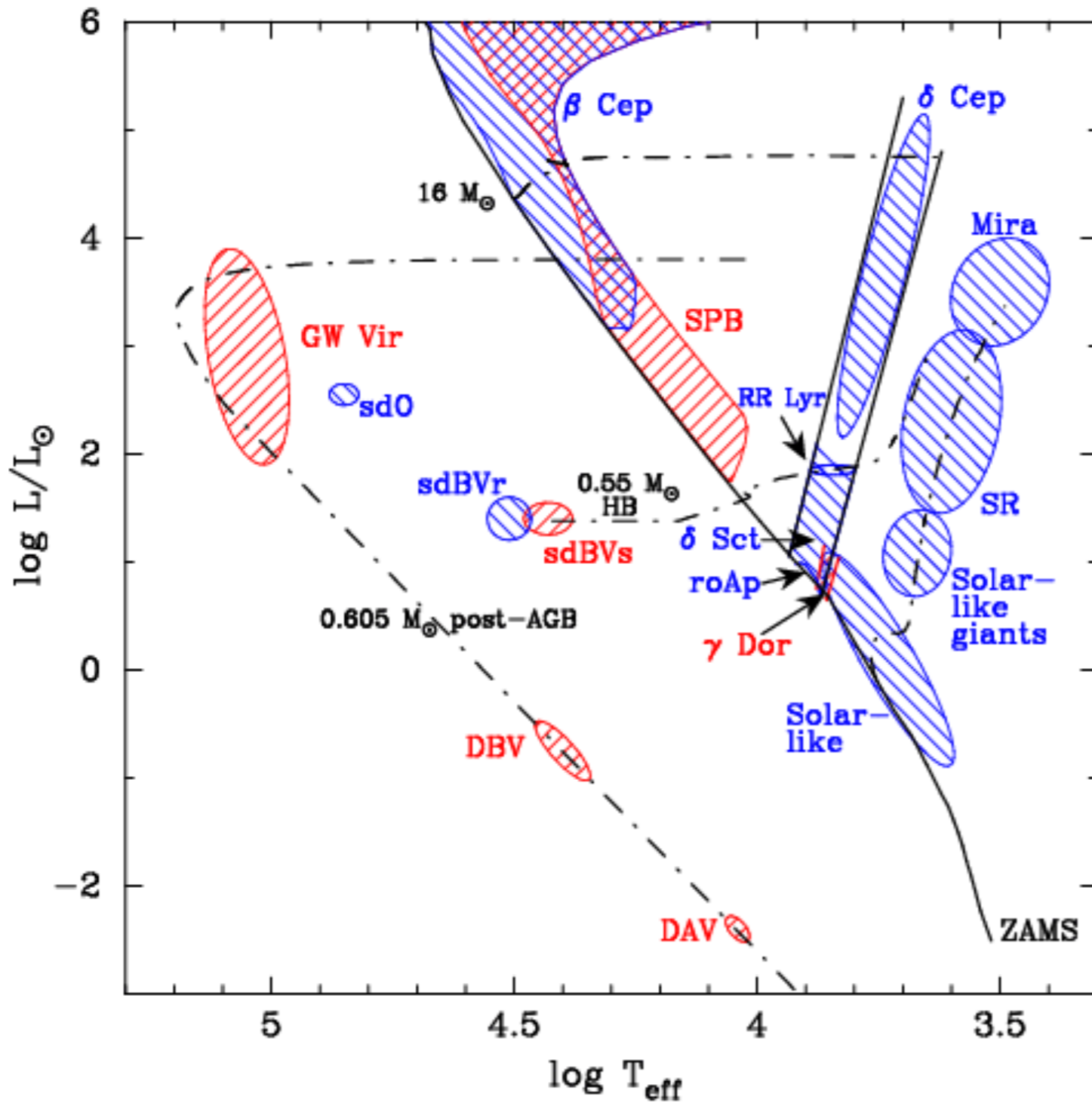
K. Zwintz,<sup>1\*</sup> L. Fossati,<sup>2</sup> T. Ryabchikova,<sup>3</sup> D. Guenther,<sup>4</sup> C. Aerts,<sup>1,5</sup> T. G. Barnes,<sup>6</sup> N. Themeßl,<sup>7</sup> D. Lorenz,<sup>7</sup> C. Cameron,<sup>8</sup> R. Kuschnig,<sup>7</sup> S. Pollack-Drs,<sup>7</sup> E. Moravveji,<sup>1</sup> A. Baglin,<sup>9</sup> J. M. Matthews,<sup>10</sup> A. F. J. Moffat,<sup>11</sup> E. Poretti,<sup>12</sup> M. Rainer,<sup>12</sup> S. M. Rucinski,<sup>13</sup> D. Sasselov,<sup>14</sup> W. W. Weiss<sup>7</sup>

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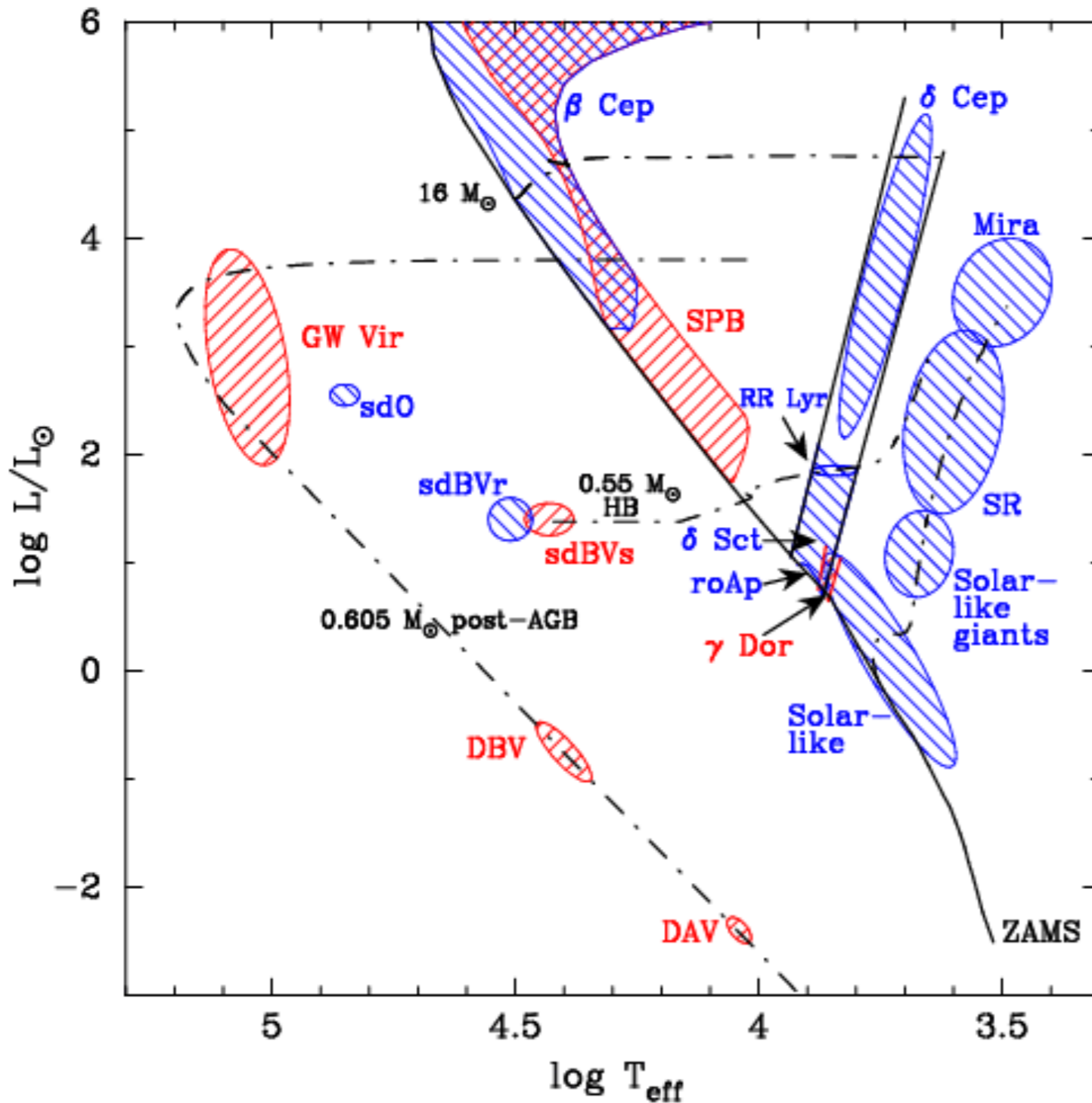


# Stellar Pulsations in the HRD





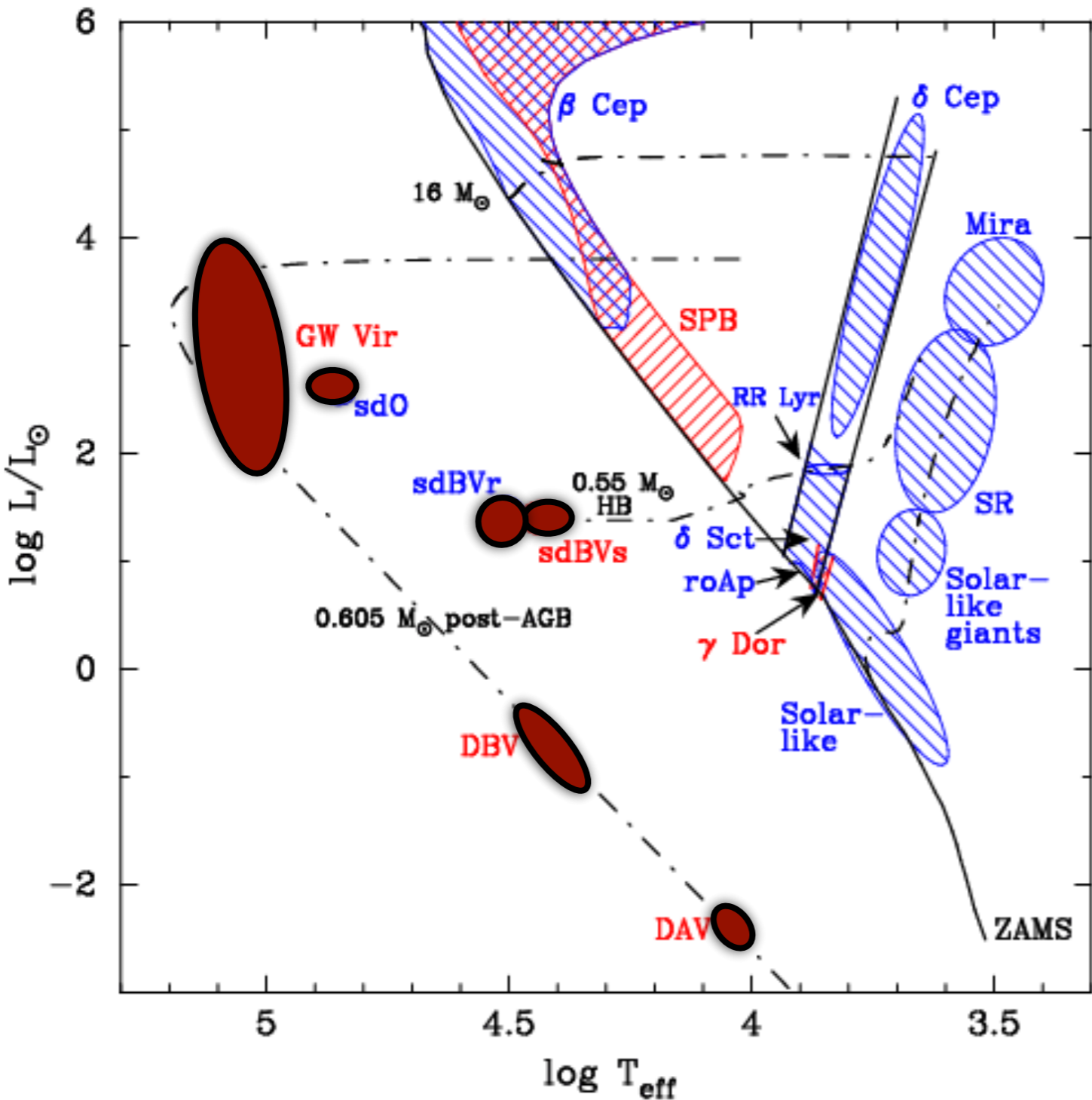
# The 3<sup>rd</sup> dimension: evolutionary stage



mixture of evolutionary stages  
= mixture of ages



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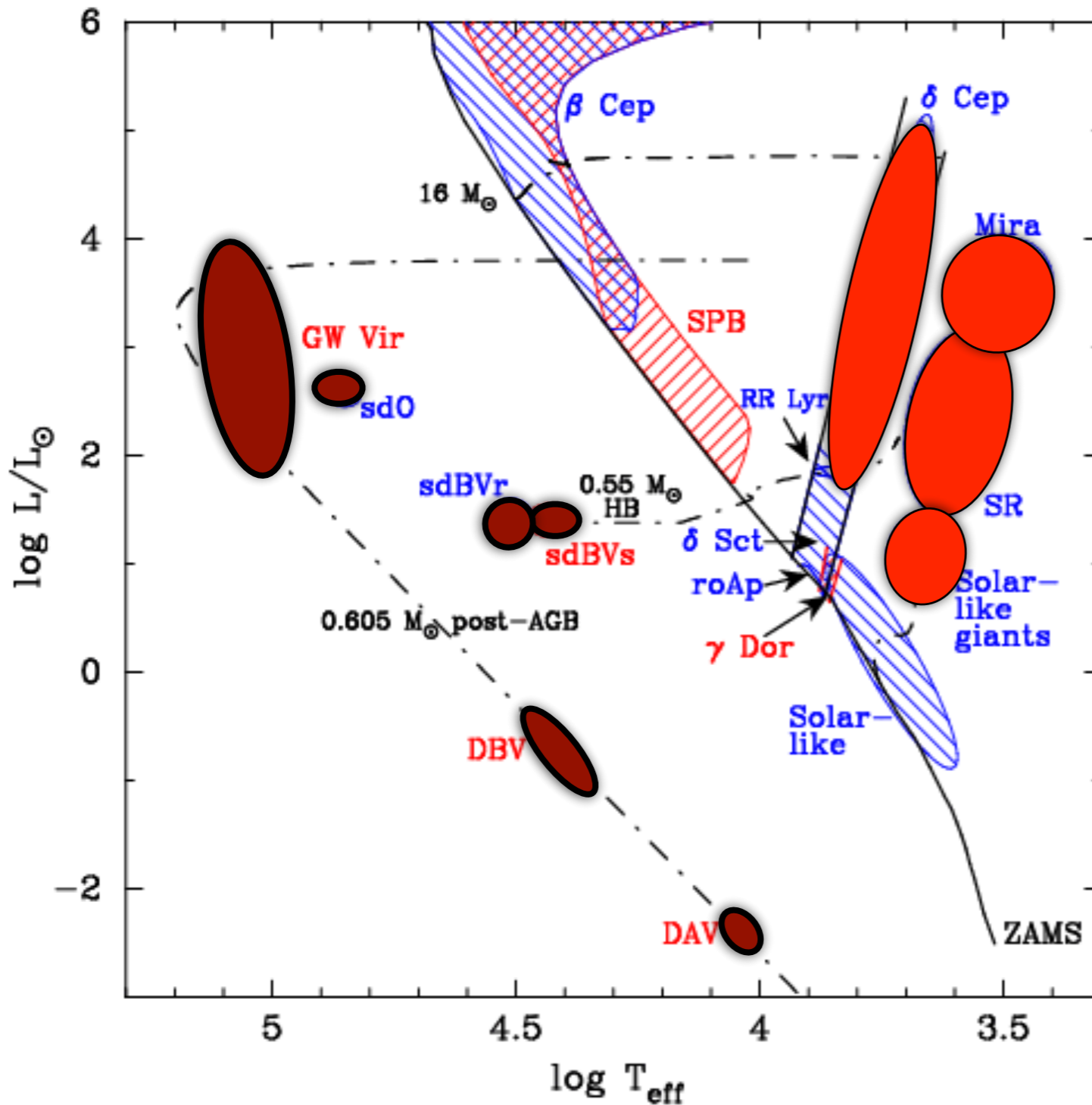


 evolved post-MS

mixture of evolutionary stages  
= mixture of ages



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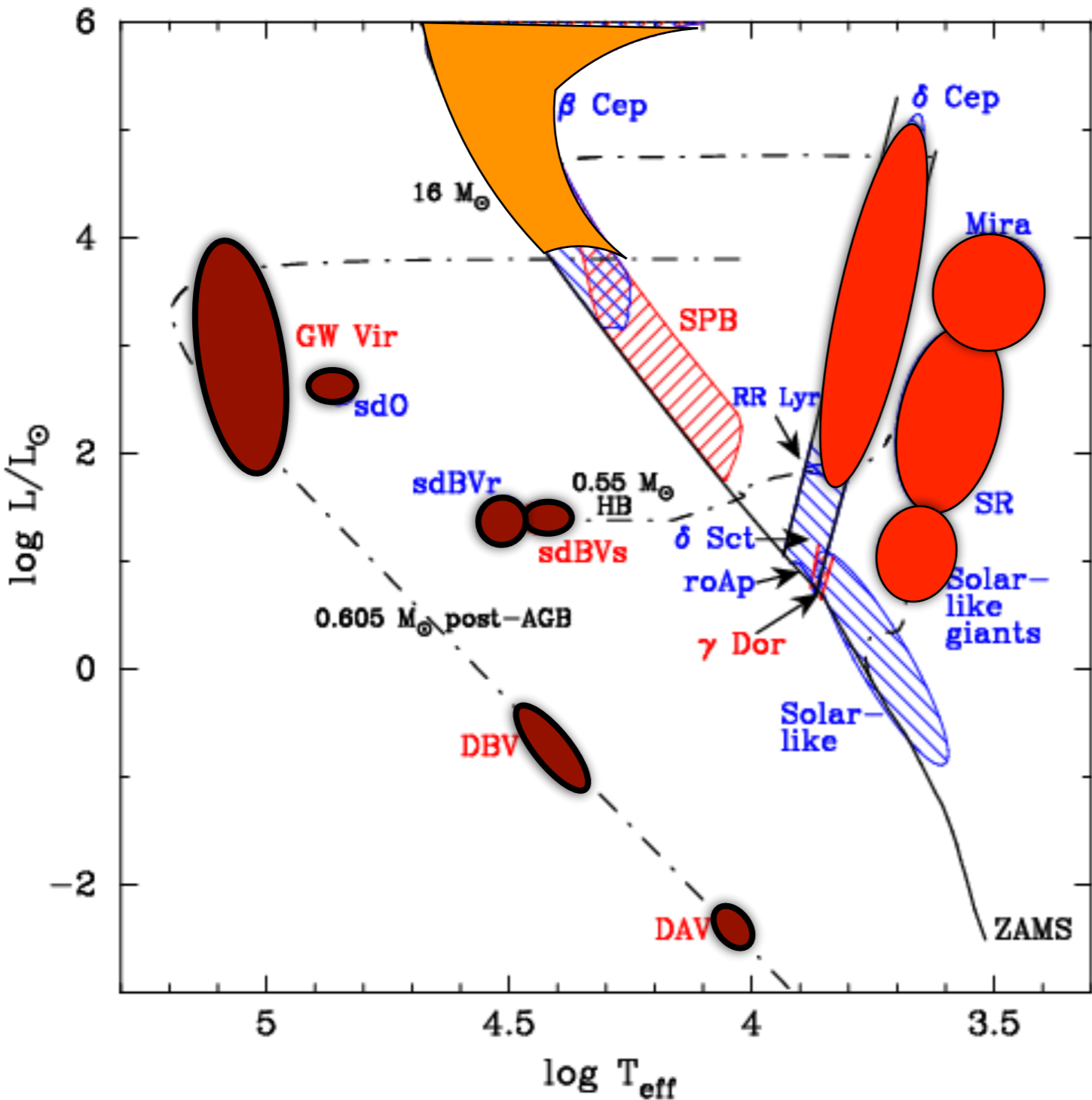


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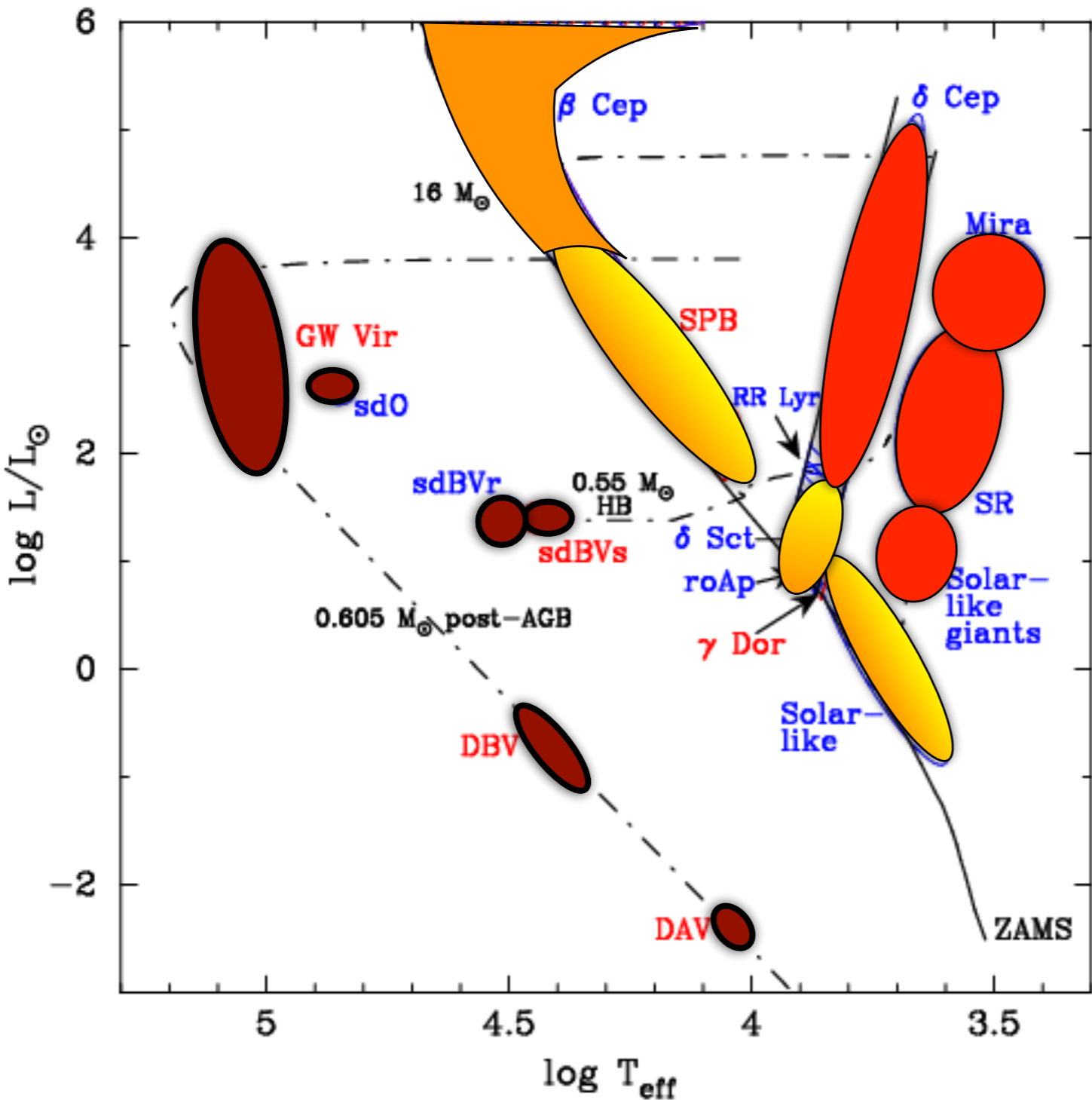


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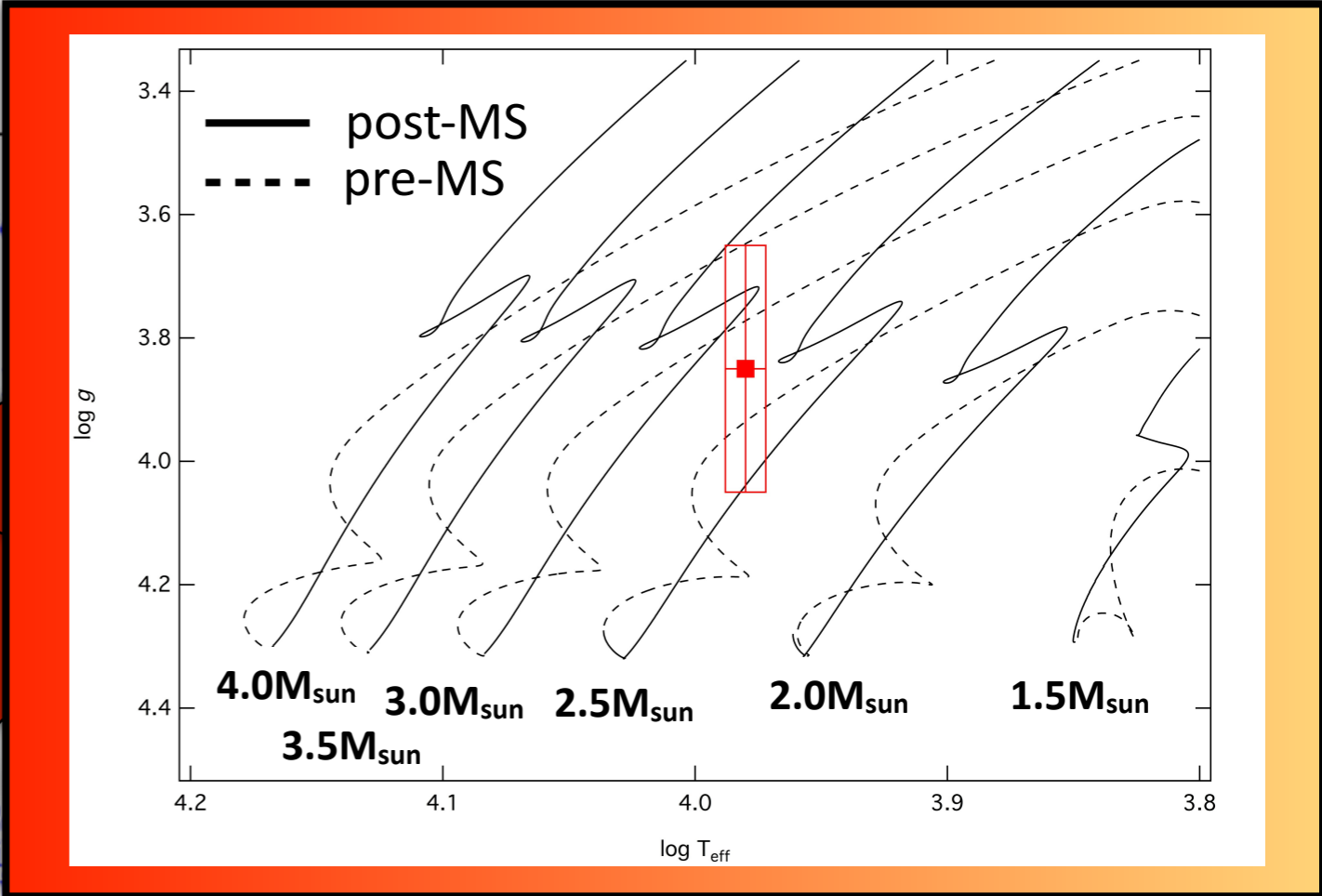
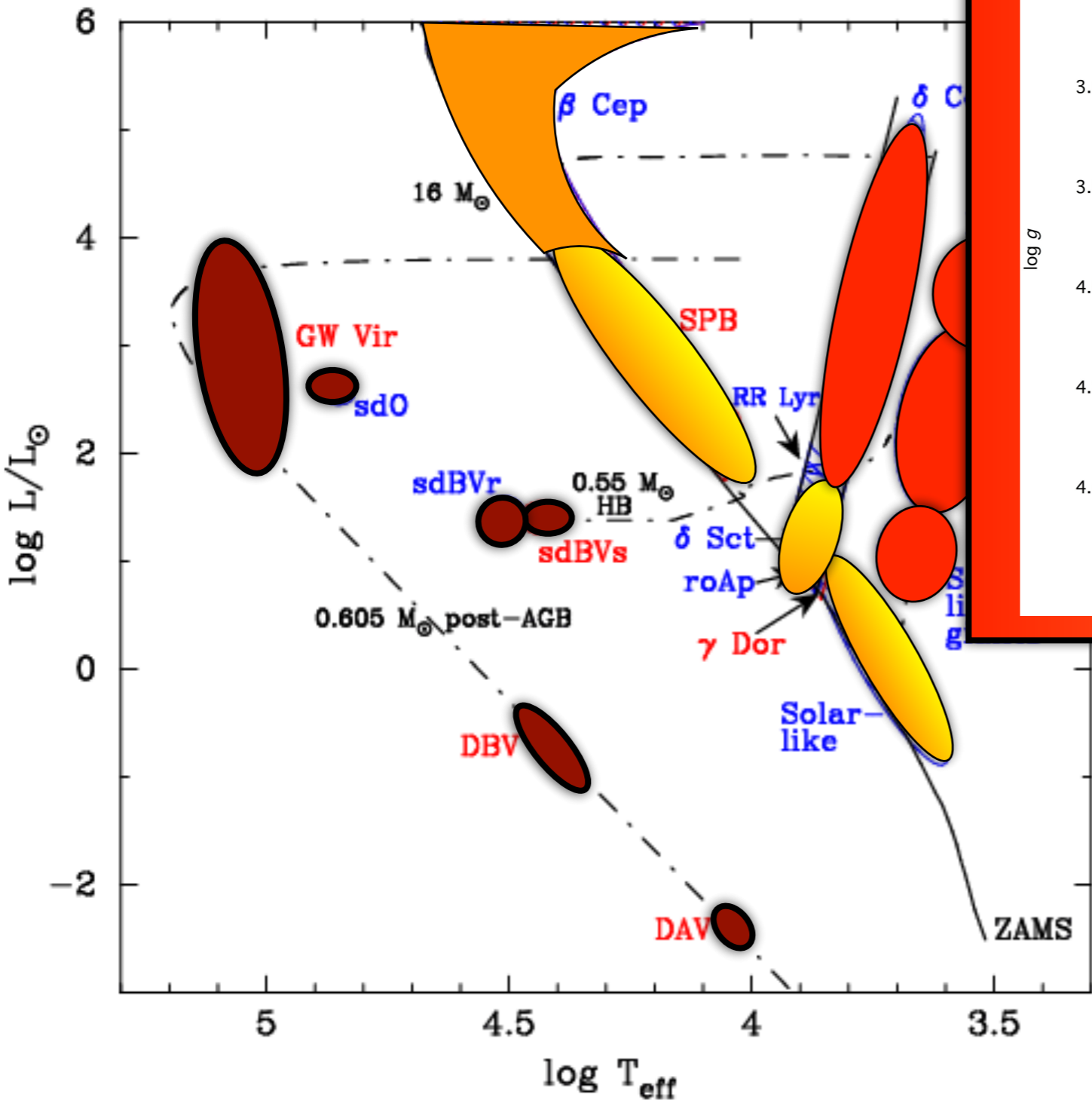
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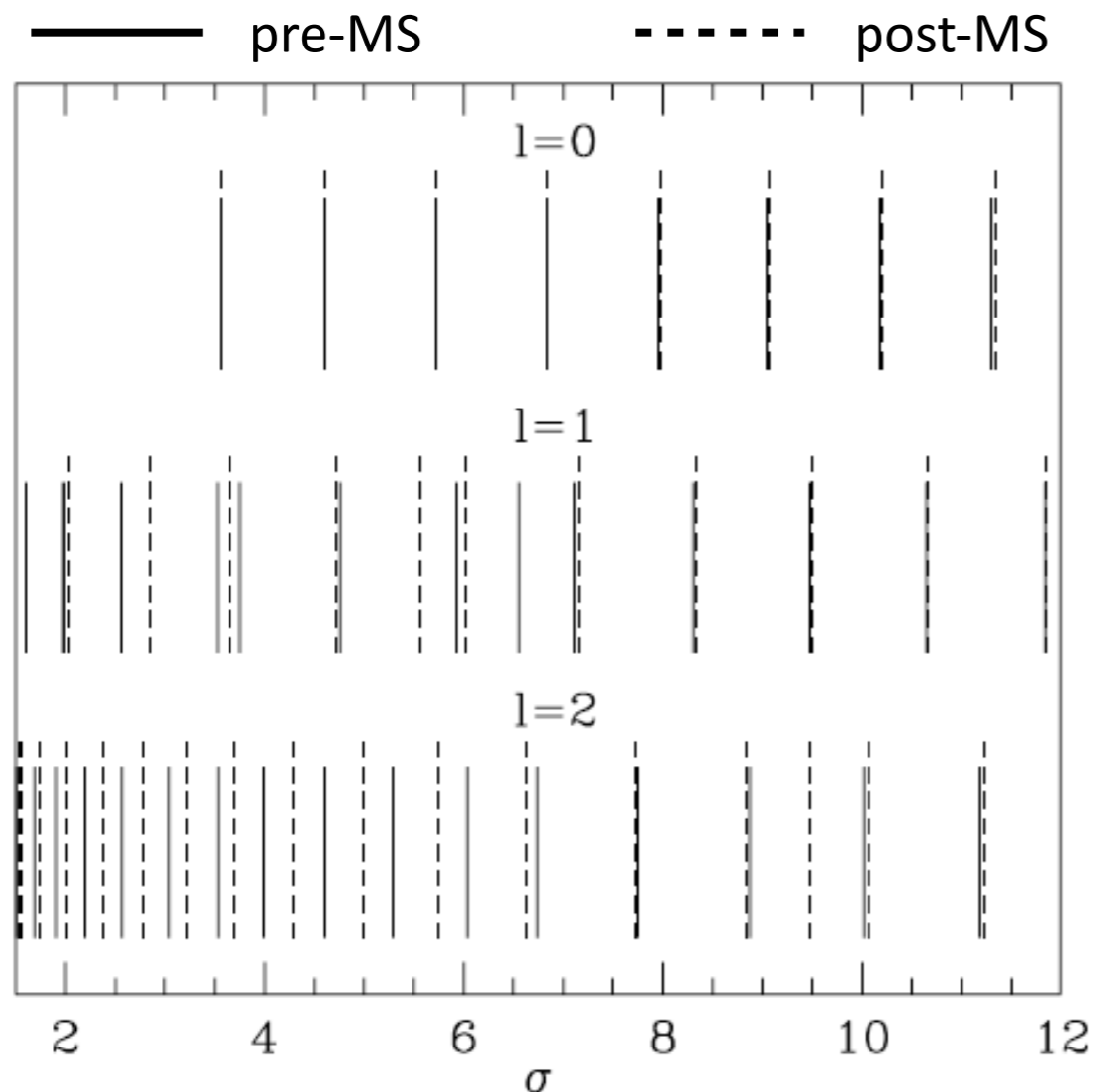


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# Asteroseismology & evolutionary stage

Theoretical frequency patterns for pre- and post-MS  $\delta$  Scuti stars

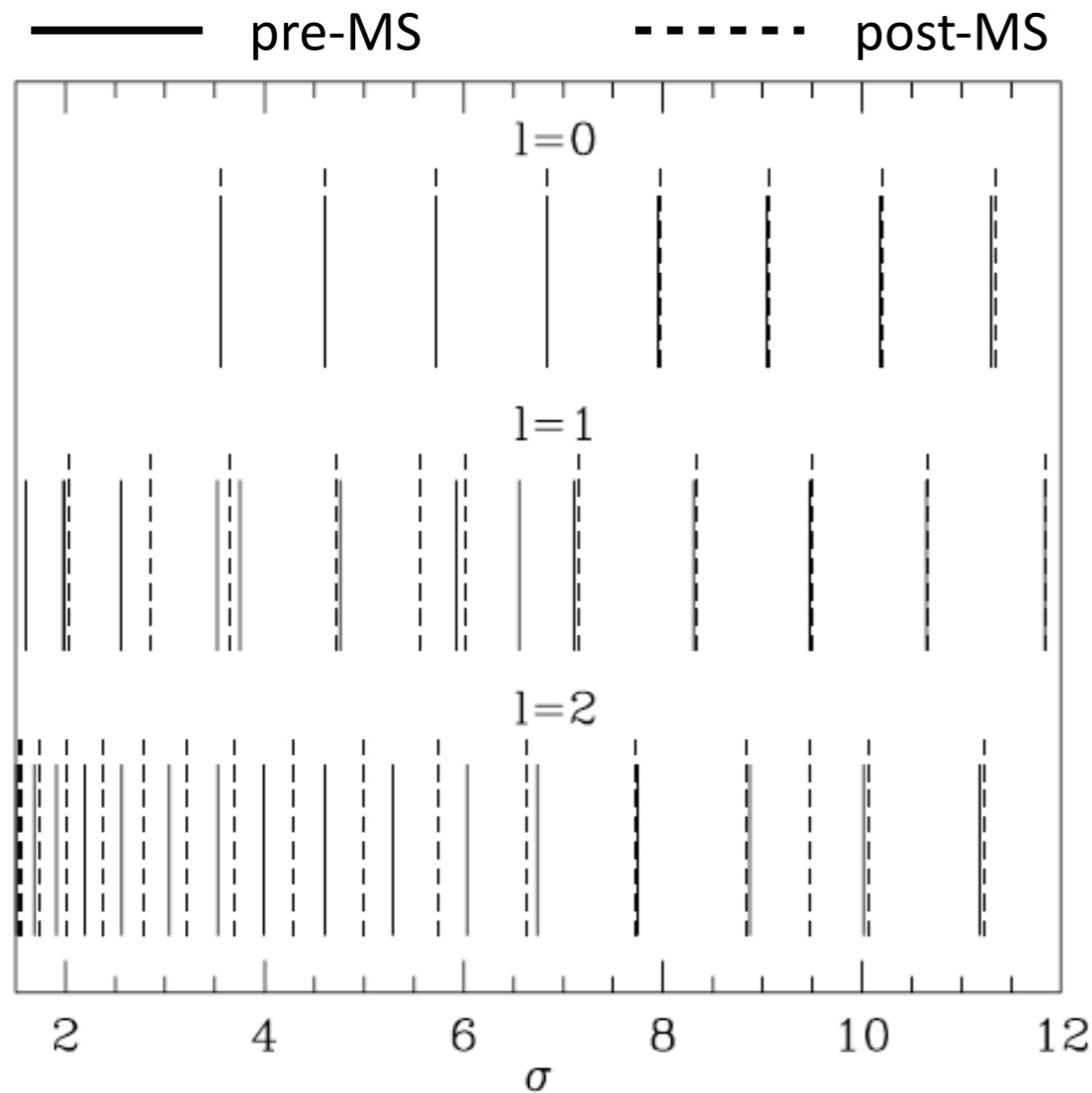


Suran et al. (2001)



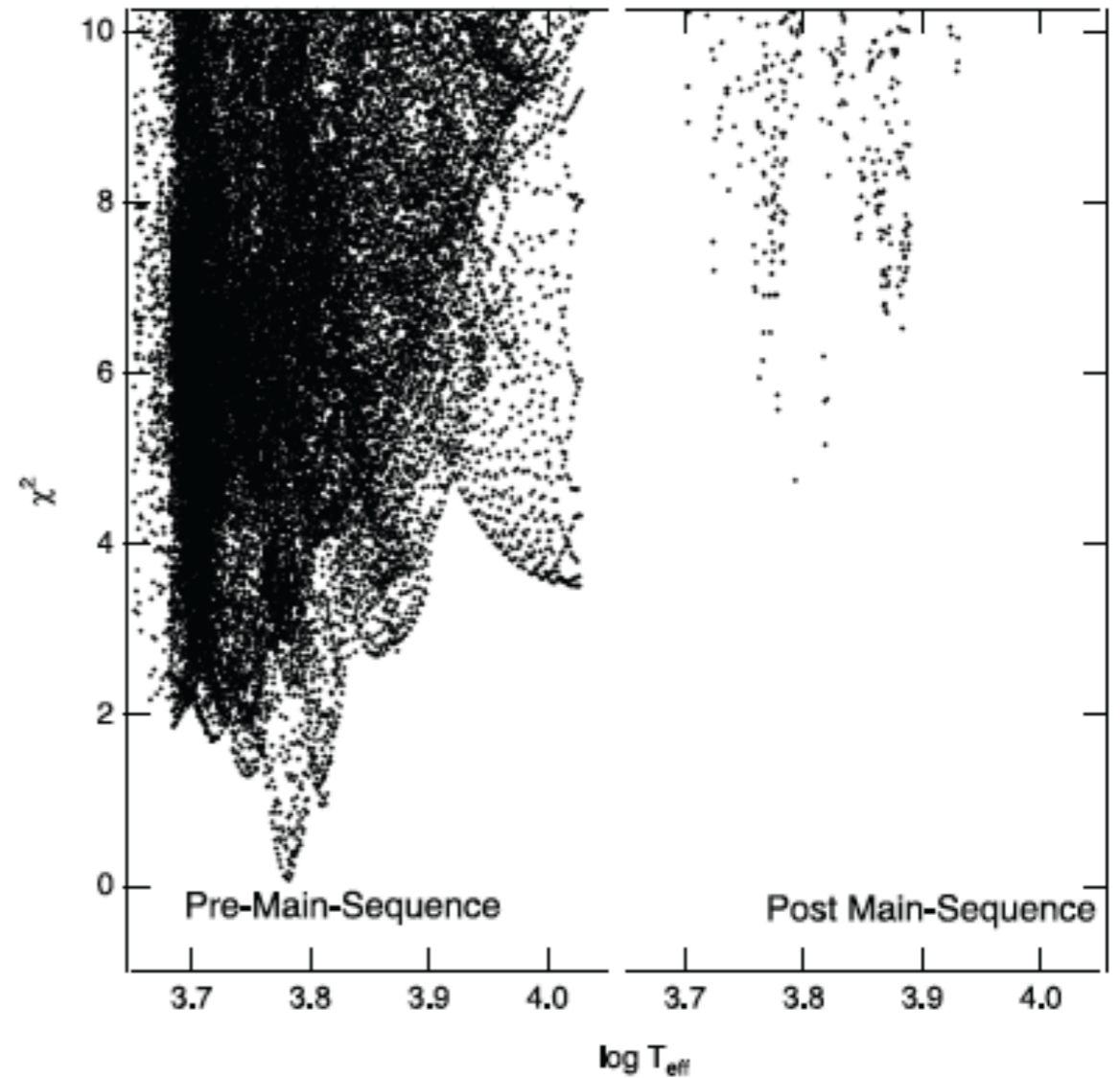
# Asteroseismology & evolutionary stage

Theoretical frequency patterns for pre- and post-MS  $\delta$  Scuti stars



Suran et al. (2001)

Guenther et al. (2007)



Test case: **NGC 6530 ZW278**

First determination of the **evolutionary stage** from 9 pulsation frequencies



# Ingredients

## I. Stars in pre-MS stage



# Features typical for pre-MS stars

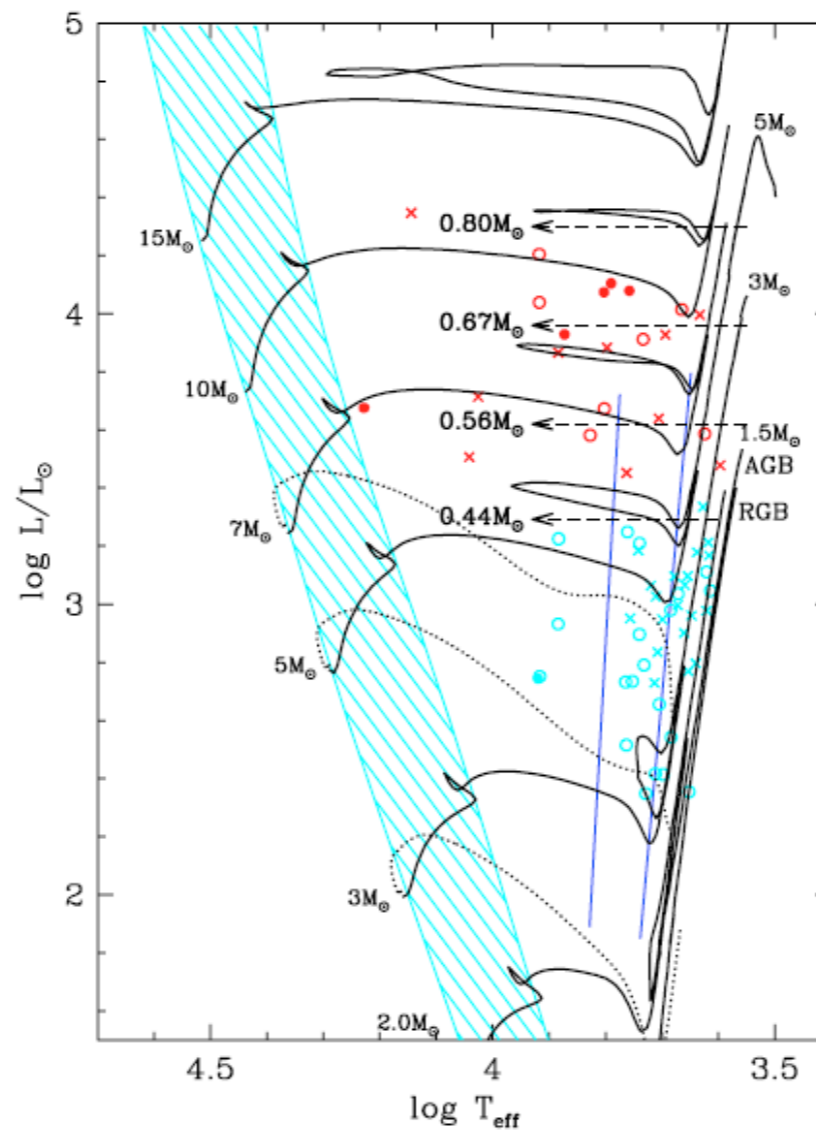
- association to a star forming region
- IR and / or UV excess
- emission lines
- classification as Herbig Ae star



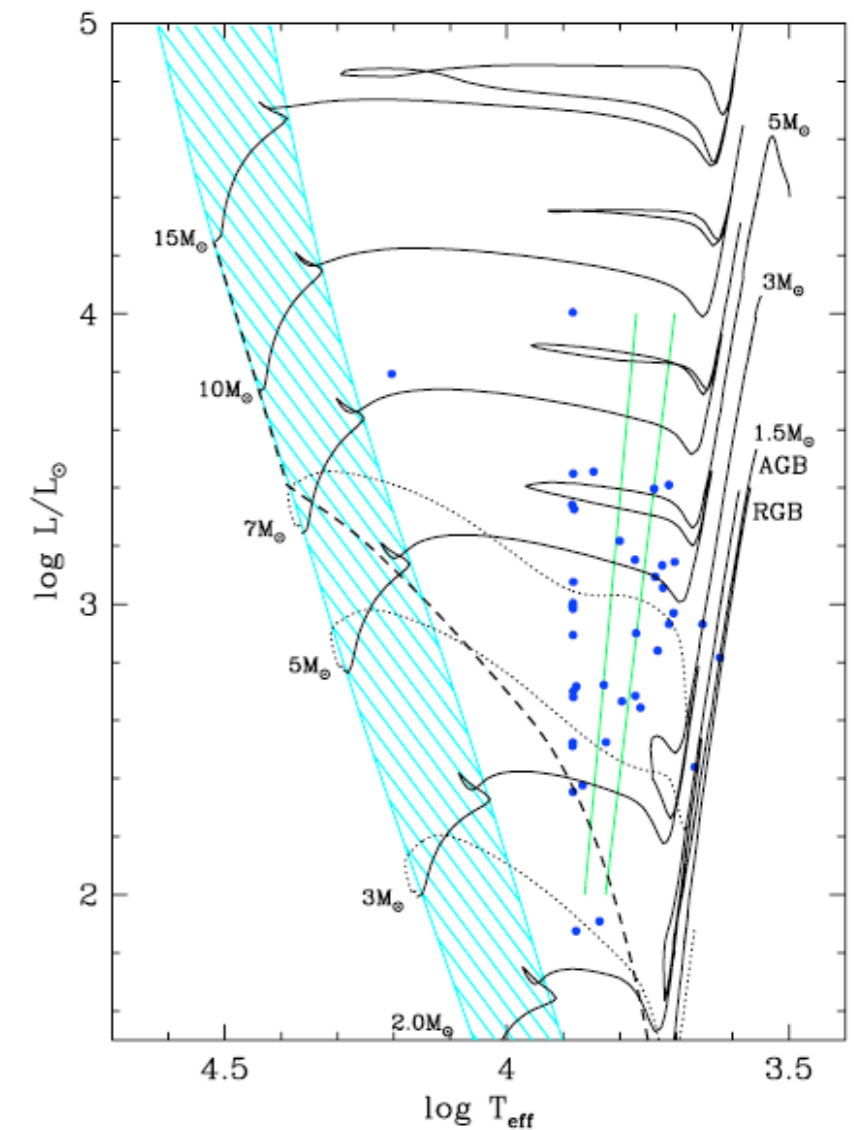
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post-AGB & RGB



young stellar objects



Kamath et al. (2014)

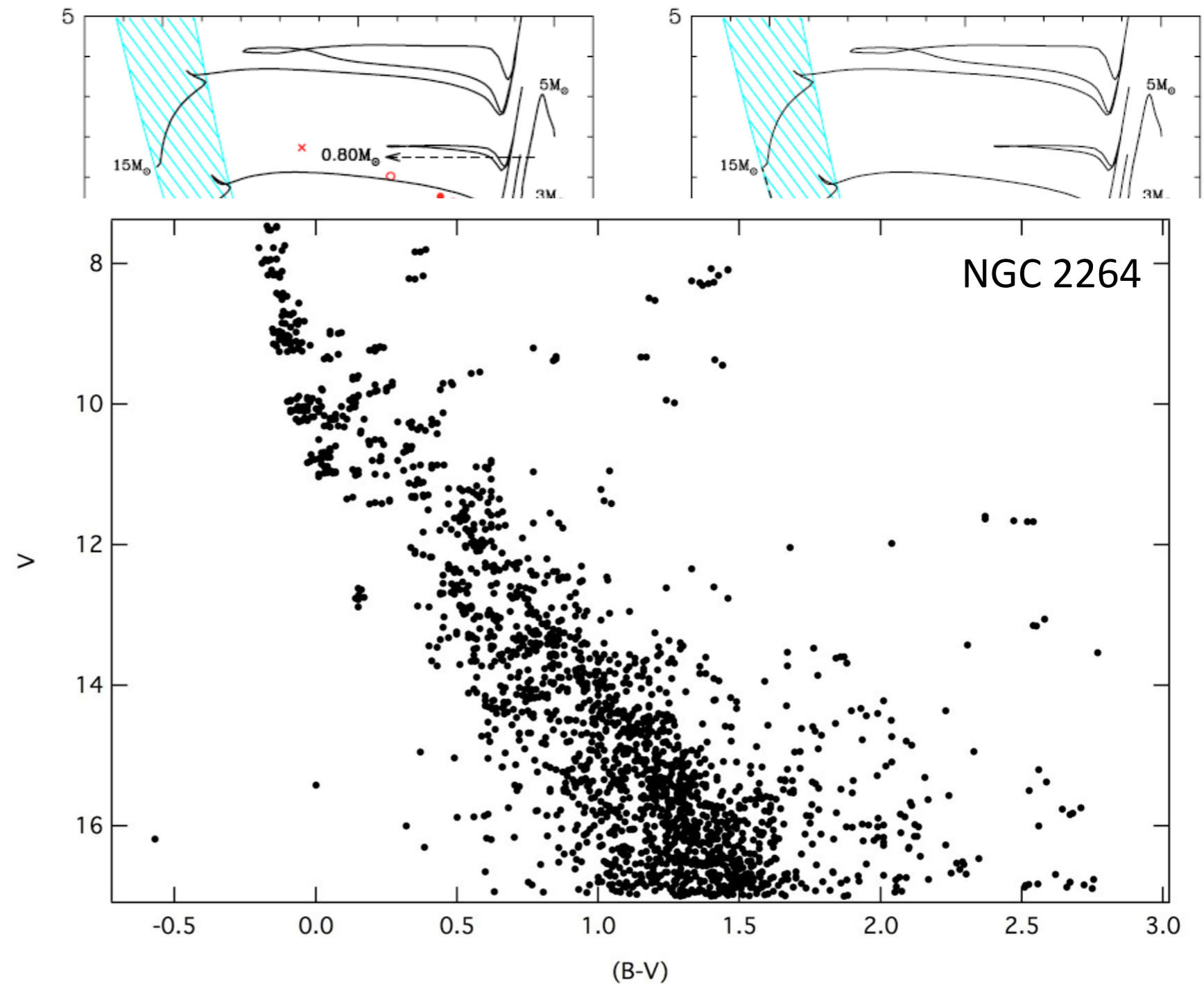


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post-AGB & RGB

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source: the WEBDA database

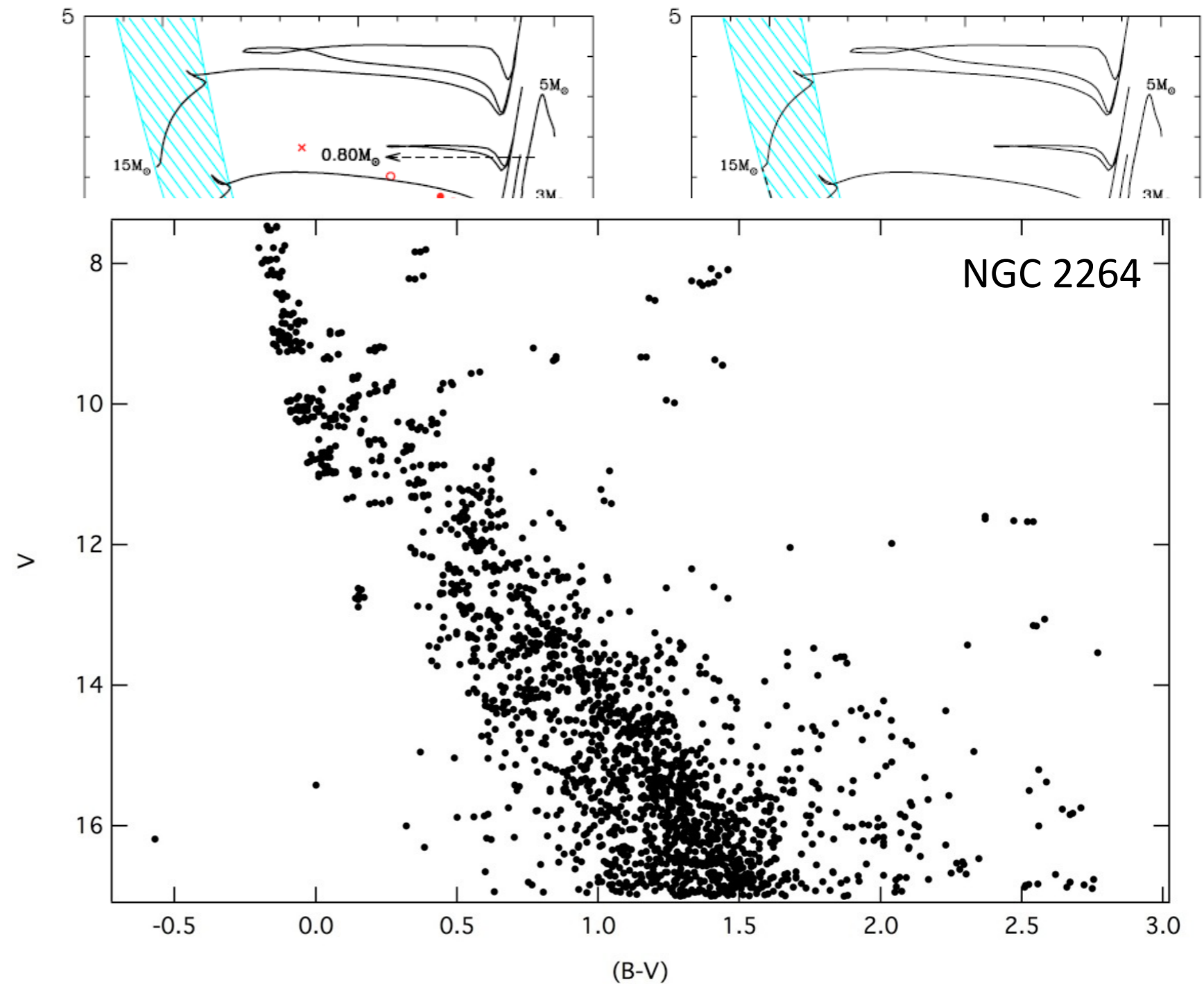


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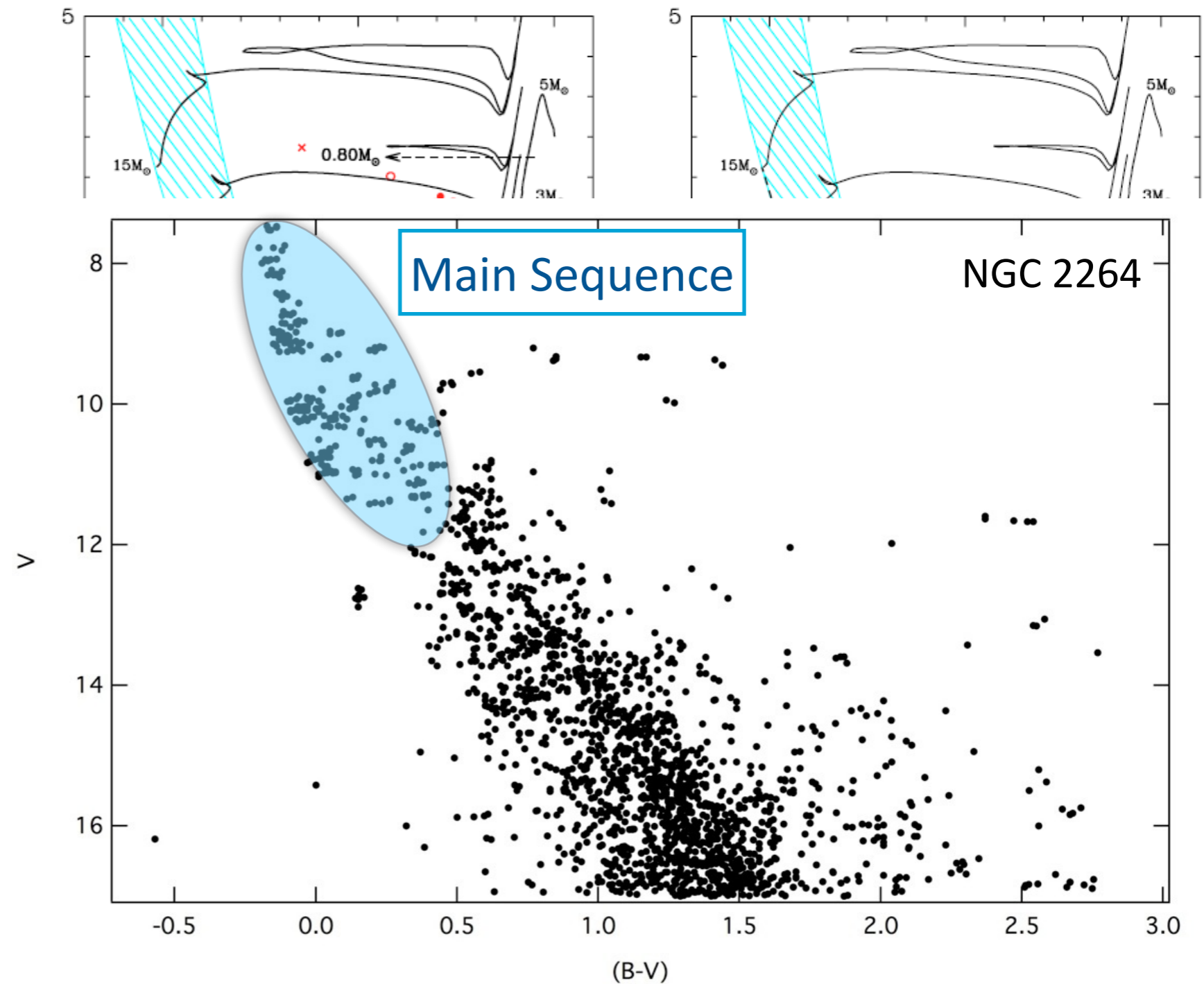


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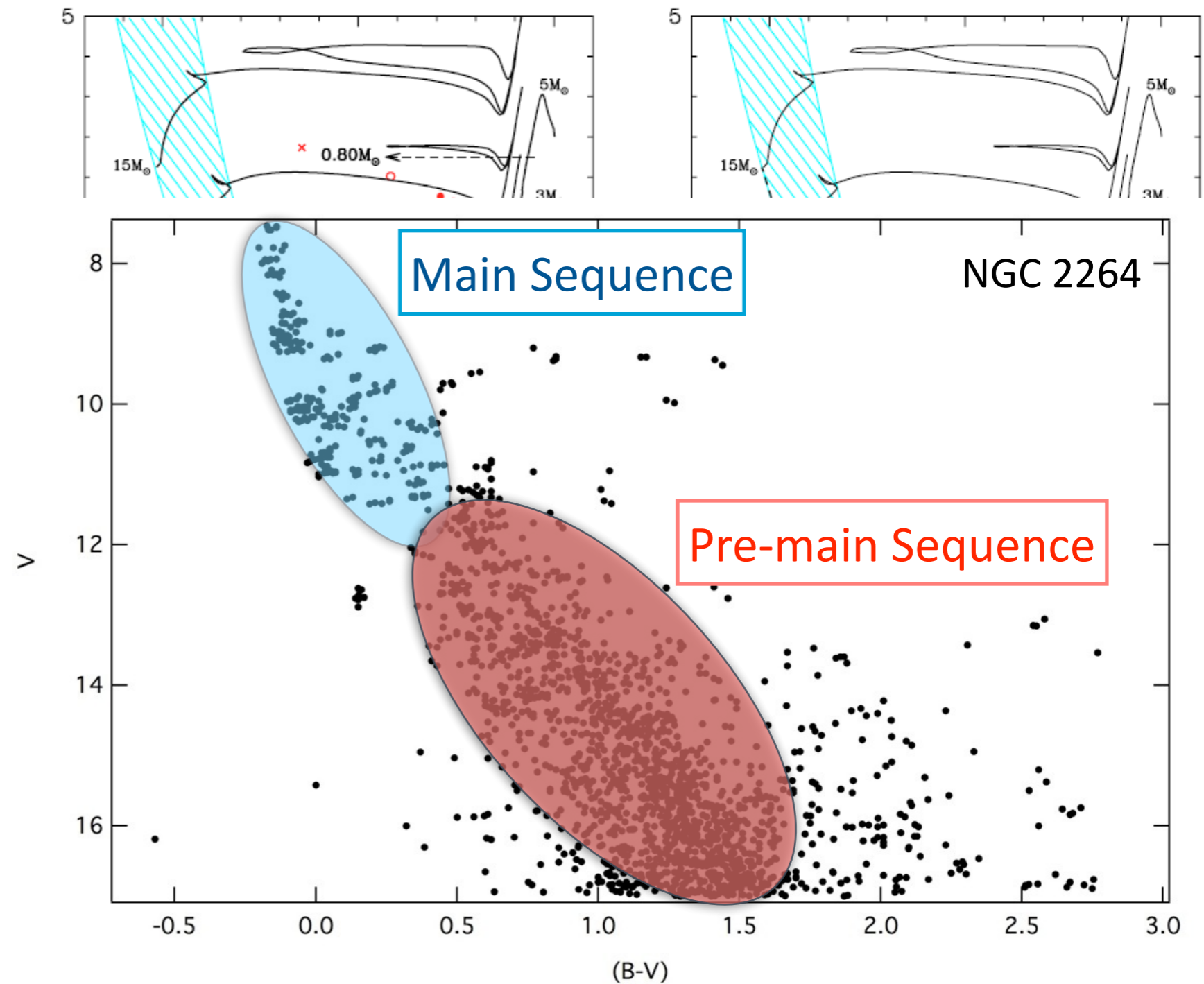


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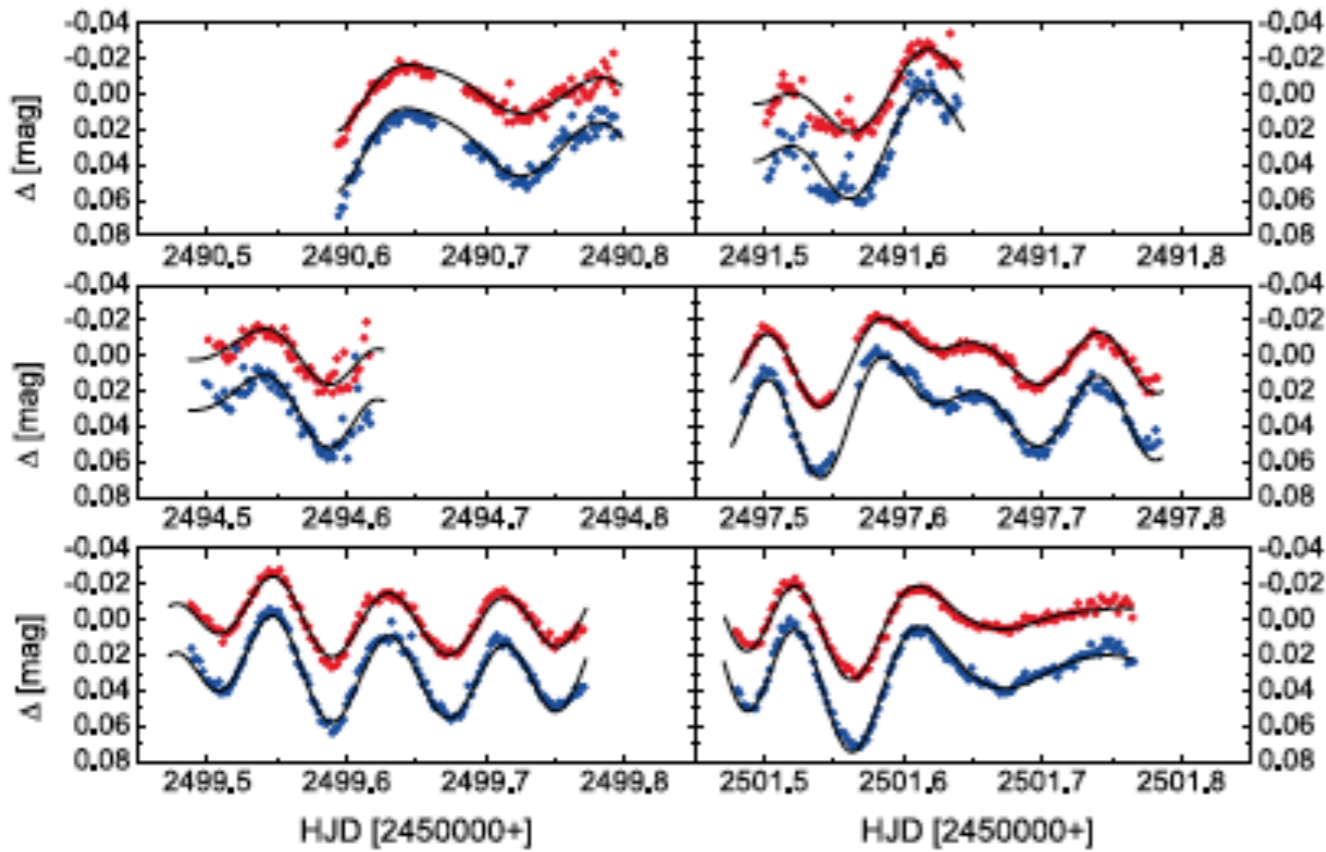




# Ingredients

- I. Stars in pre-MS stage
- II. Time-series to discover and analyze variability

# Photometric time-series



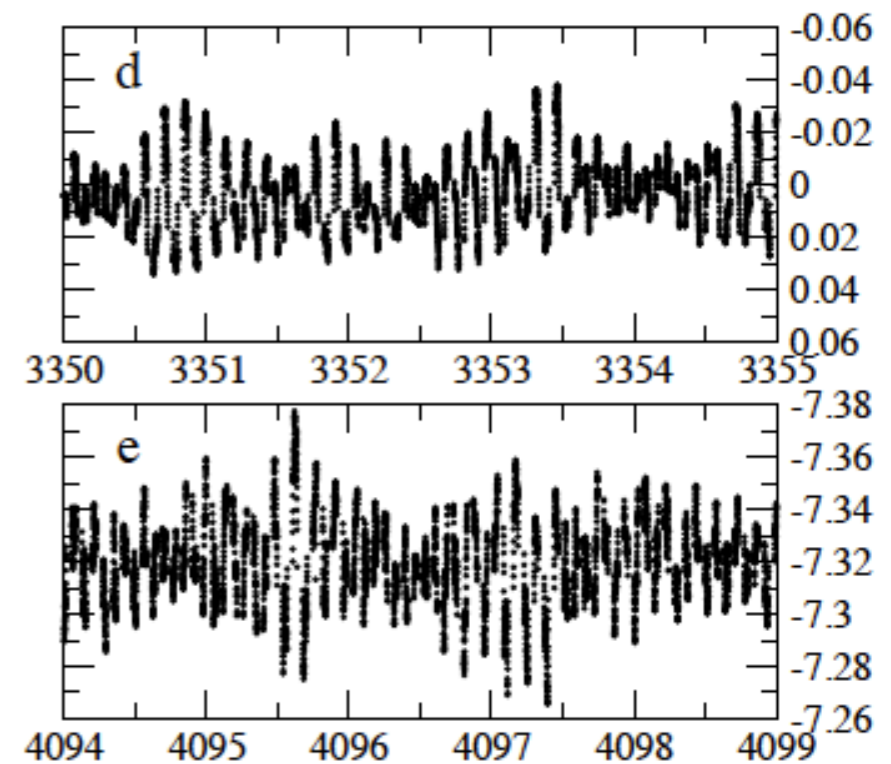
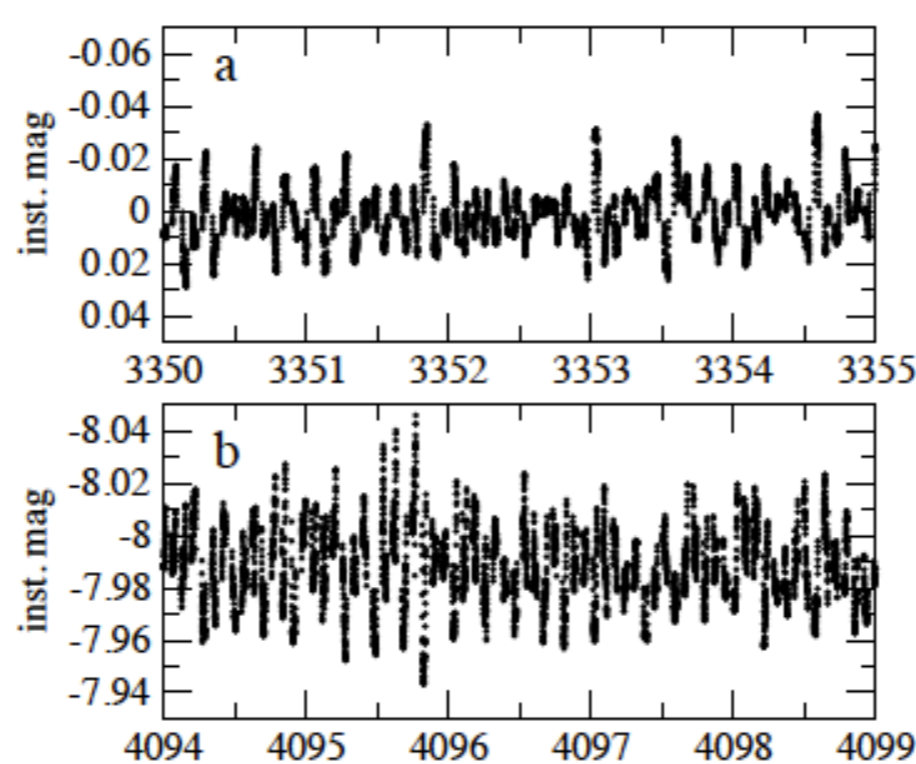
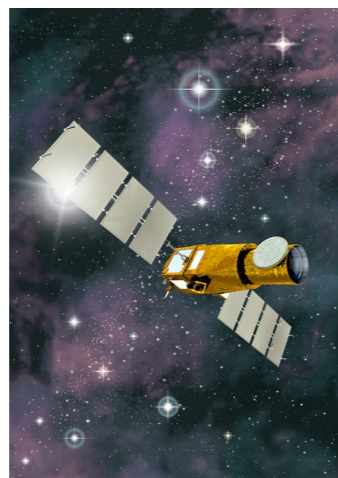
Ground-based

NGC 6530 ZW278  
Zwintz & Weiss (2006)

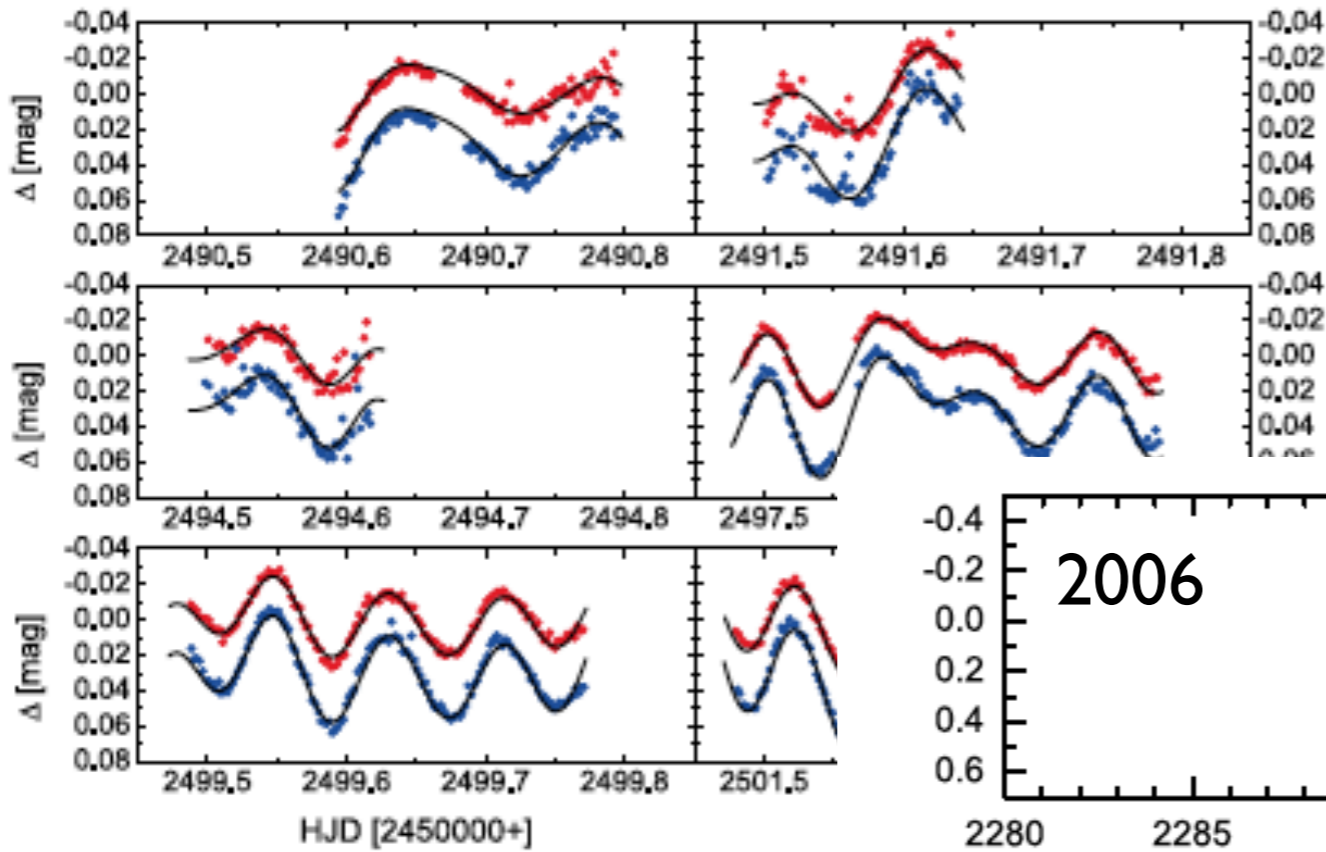
V 588 Mon

V 589 Mon

Space-based



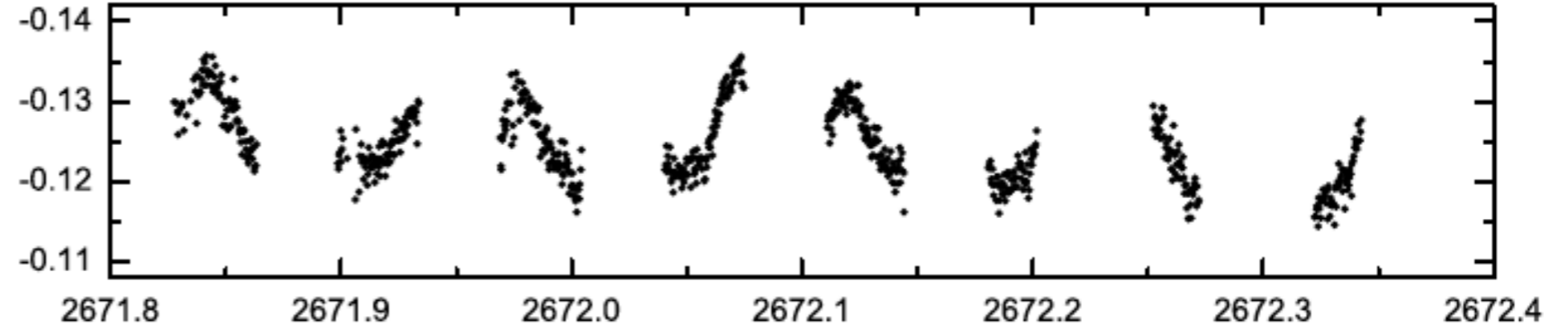
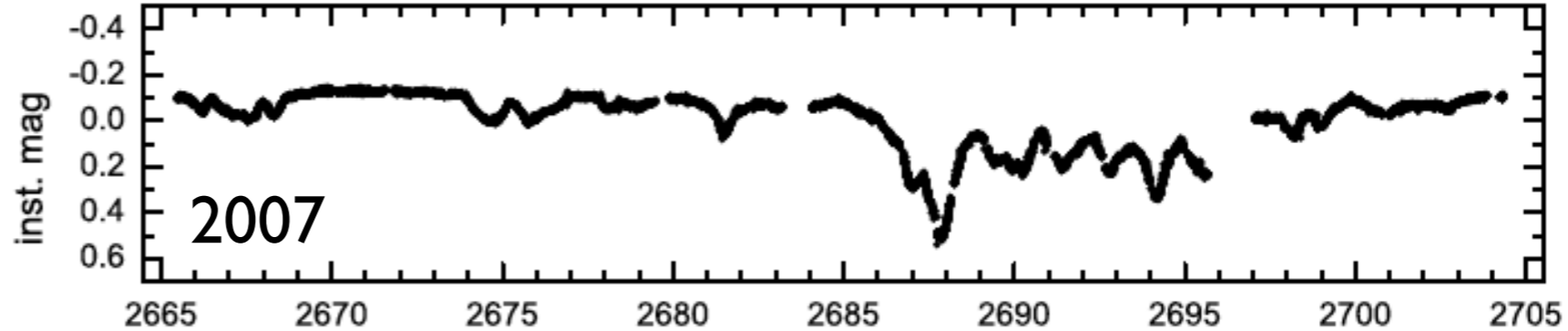
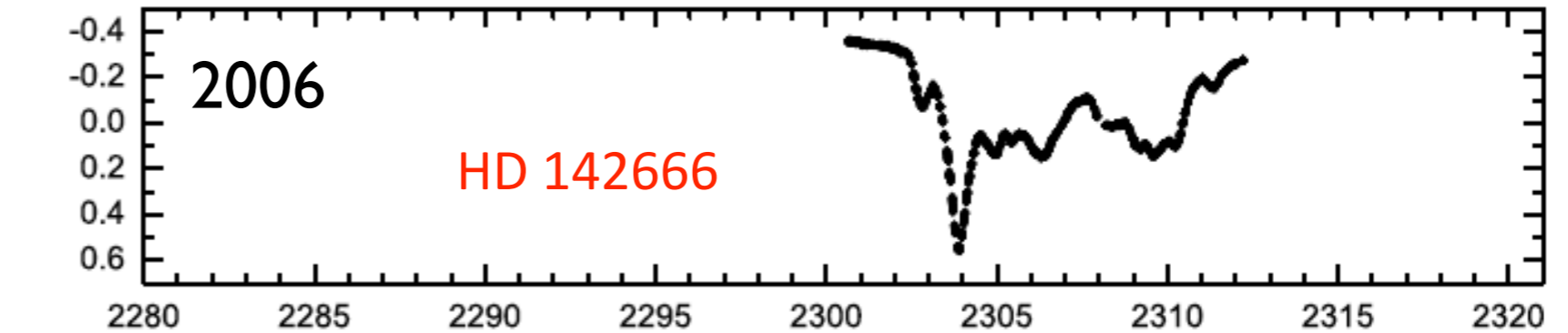
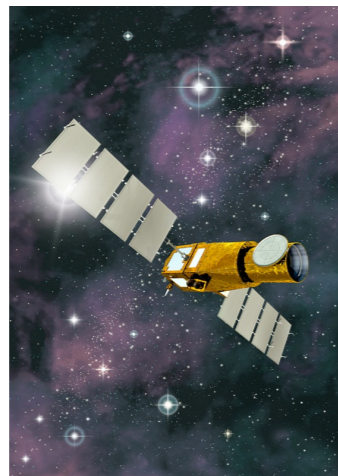
# Photometric time-series



Ground-based

NGC 6530 ZW278  
Zwintz & Weiss (2006)

Space-based



HJD - 2451545.0 [d]  
Zwintz et al. (2009)



# Ingredients

- I. Stars in pre-MS stage
- II. Time-series to discover and analyze variability
- III. Position in the HRD



# Determination of Fundamental Parameters

- **High-resolution, high S/N spectroscopy**

- Mc Donald Observatory 2.7m telescope
- ESO VLT UVES & ESO HARPS
- CFHT with ESPaDOnS
- 1.2m Mercator telescope with HERMES



- **Low resolution spectra**

- CTIO 1.5m telescope

- **Literature & Archive data**



**$T_{\text{eff}}, \log g, v \sin i, v_{\text{rad}}, [\text{Fe}/\text{H}]$**



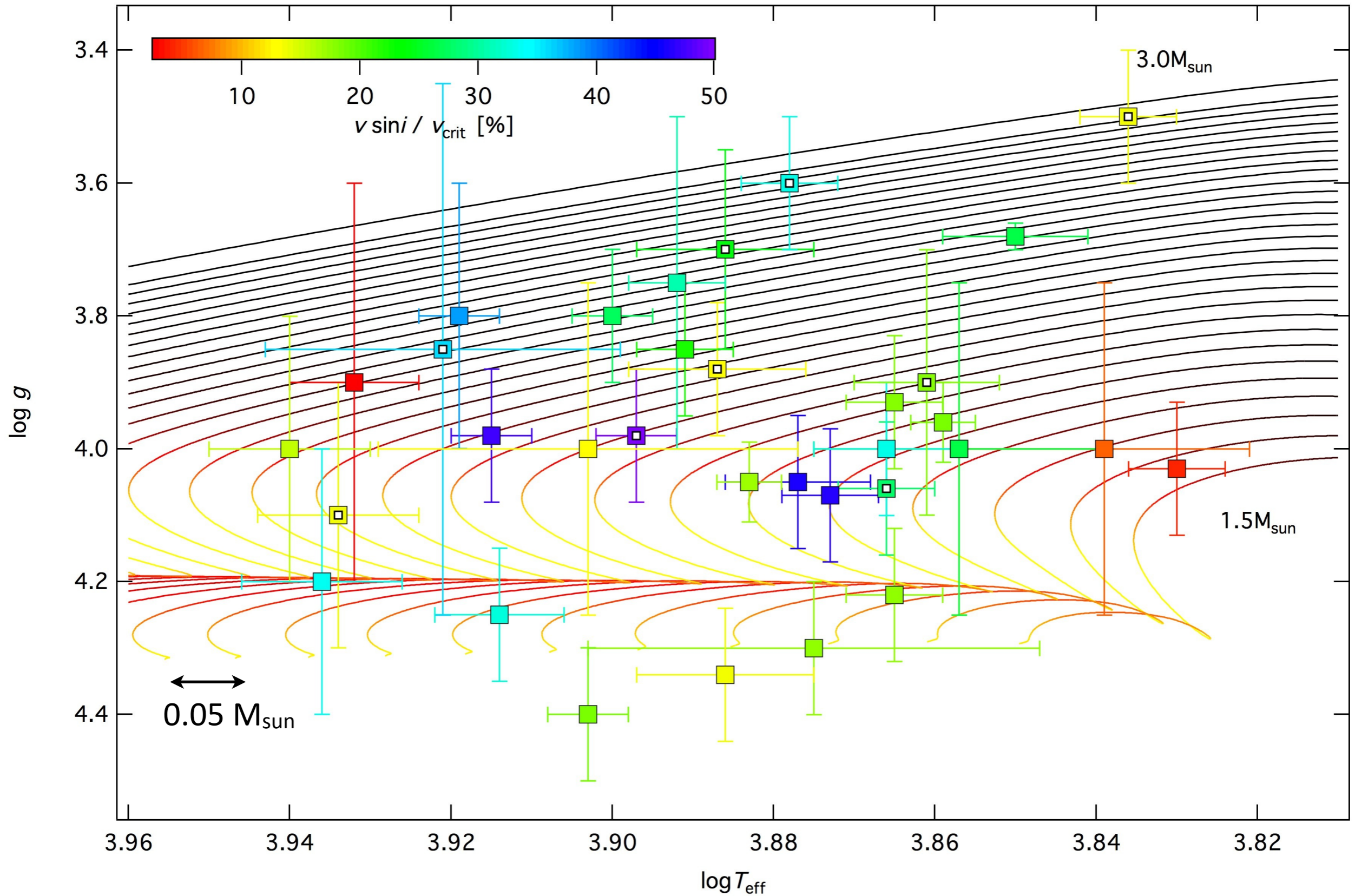
# Ingredients

- I. Stars in pre-MS stage
- II. Time-series to discover and analyze variability
- III. Position in the HRD
- IV. Pre-MS evolutionary tracks





# 34 pre-MS $\delta$ Scuti stars: angular momentum



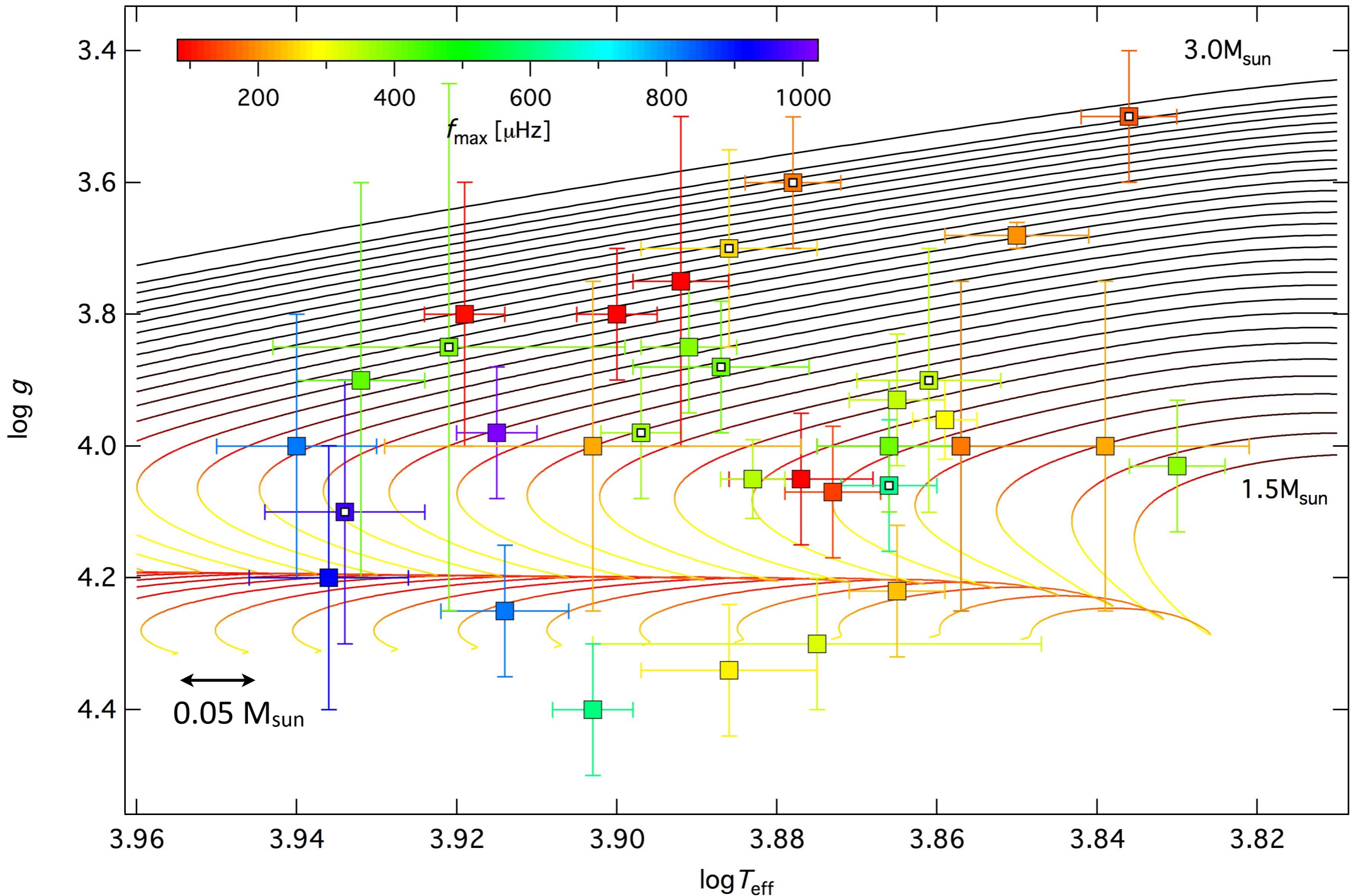


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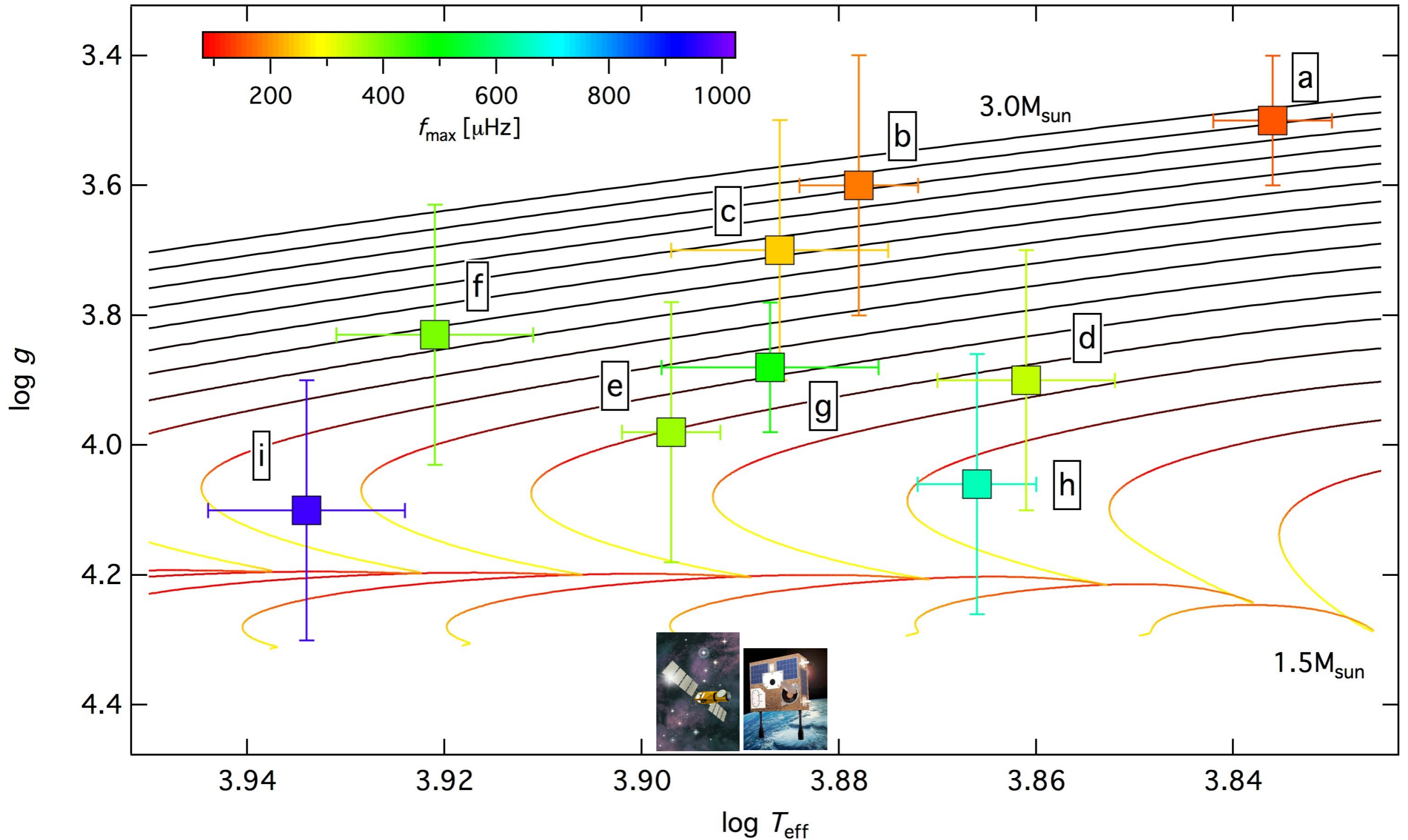
- I. Stars in pre-MS stage
  - II. Time-series to discover and analyze variability
  - III. Position in the HRD
  - IV. Pre-MS evolutionary tracks
- ➔ **Interpretation**



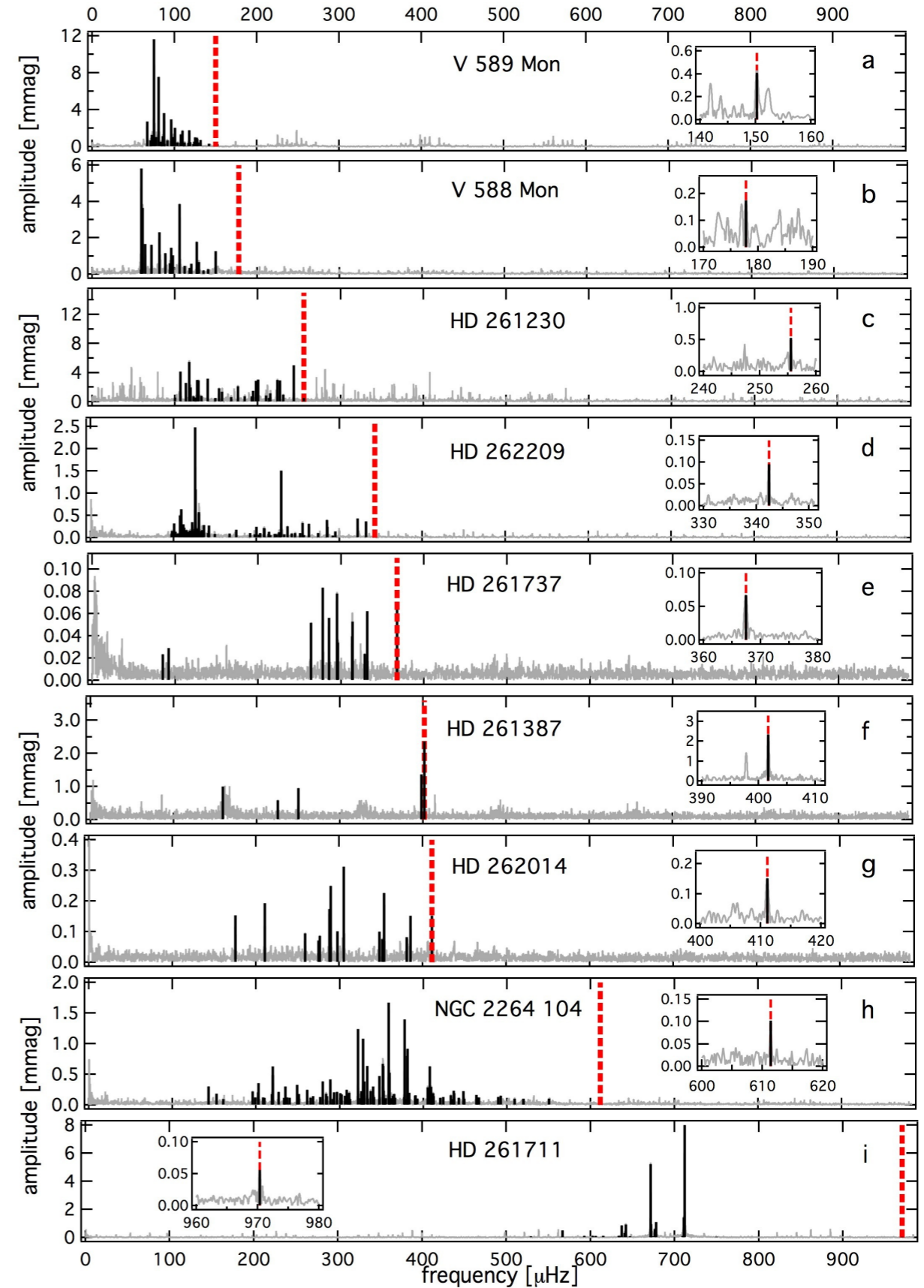
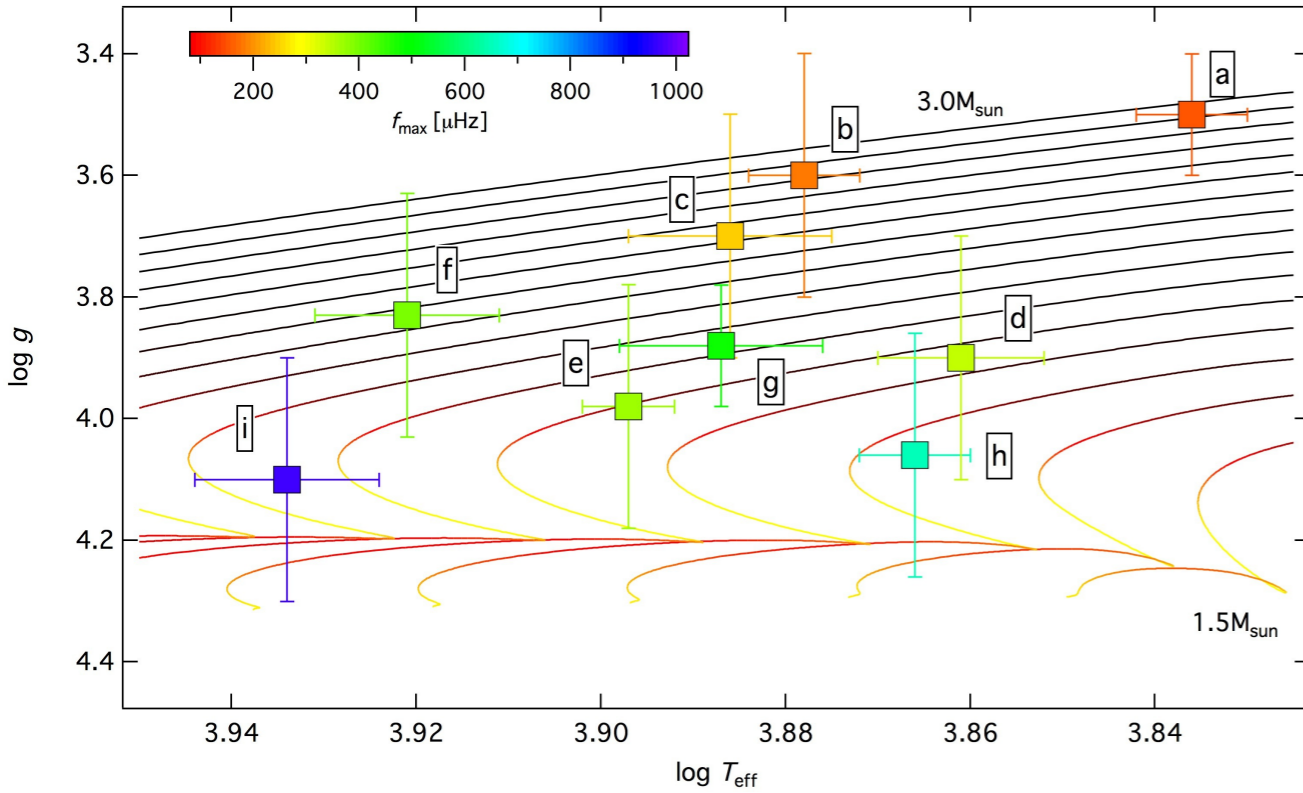
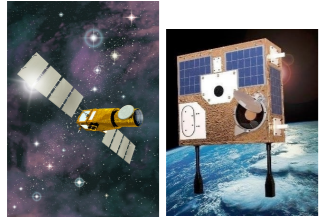
# Pre-MS $\delta$ Scuti stars: highest p-mode frequency



# 9 pre-MS $\delta$ Scuti stars in NGC 2264

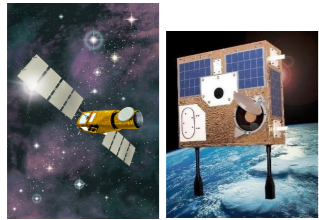


# Oscillations & phase in pre-MS evolution

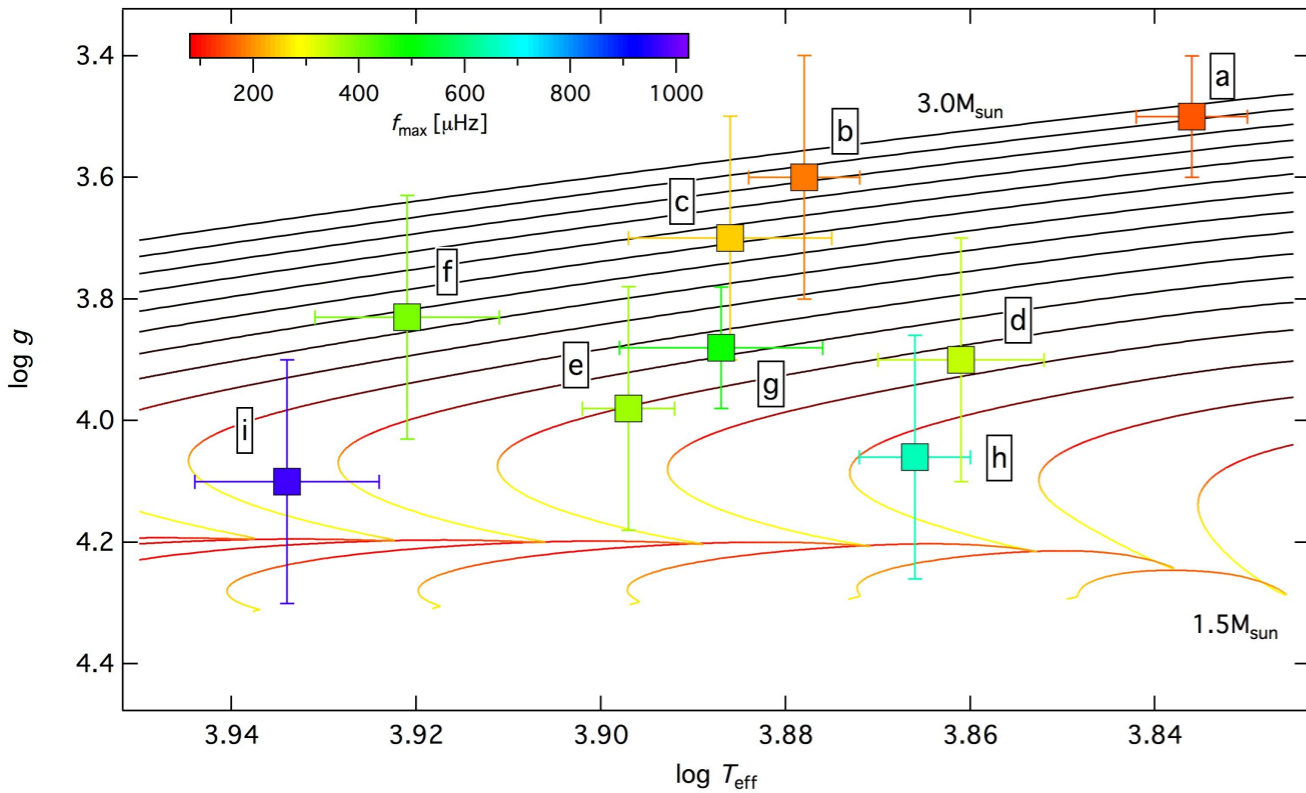




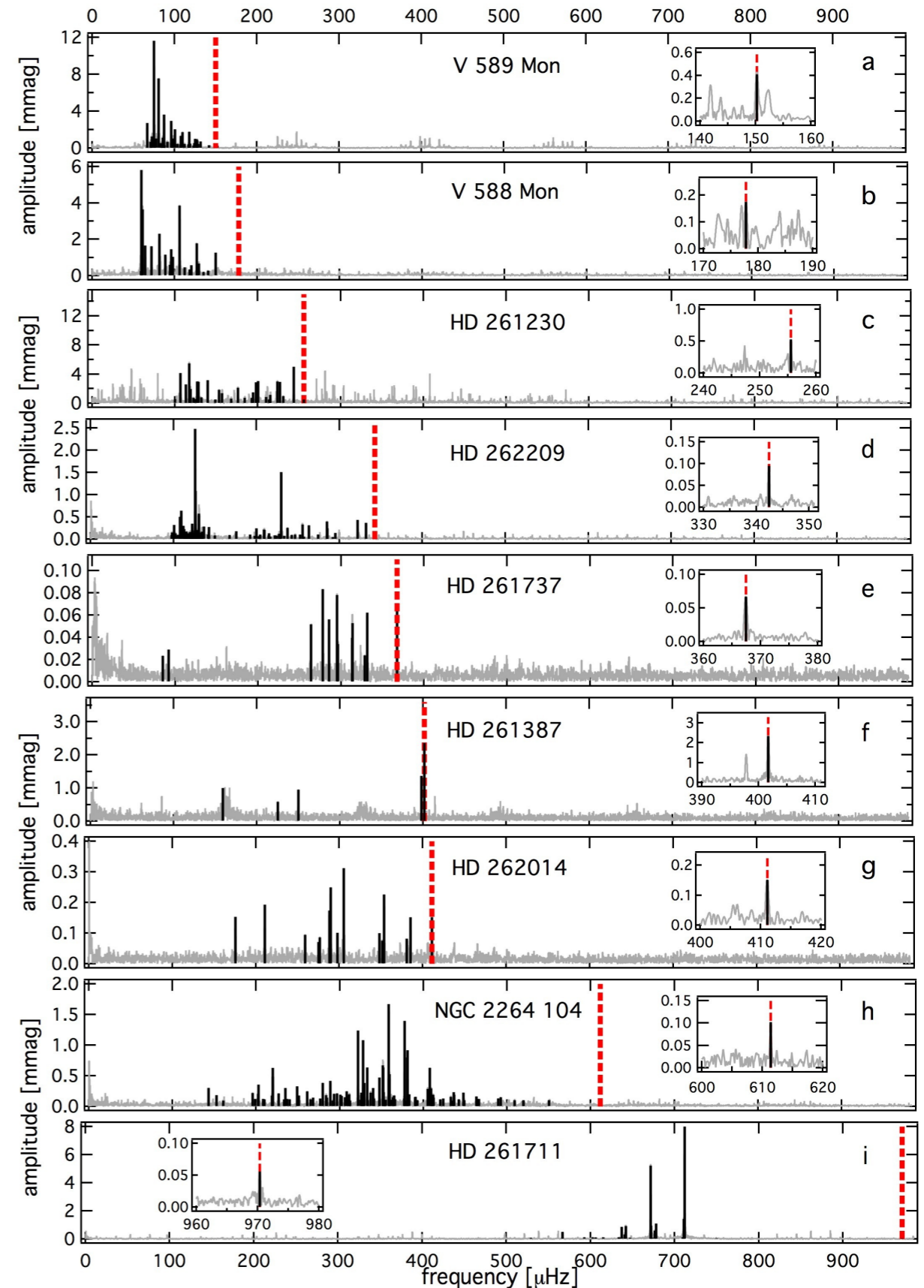
# Oscillations & phase in pre-MS evolution



slowest pulsator & least evolved star

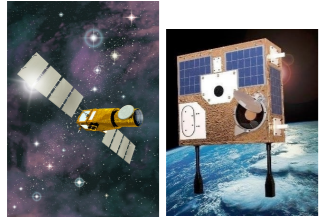


fastest pulsator & most evolved star

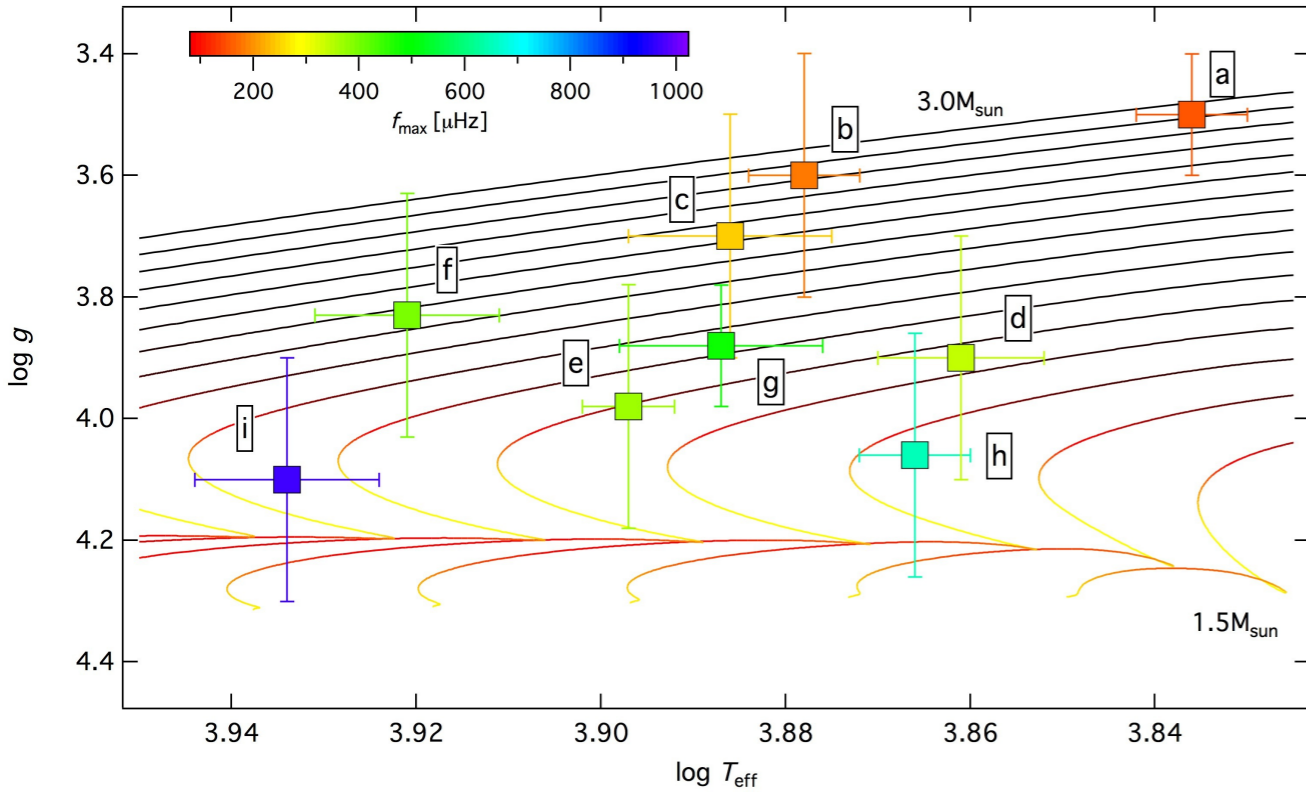




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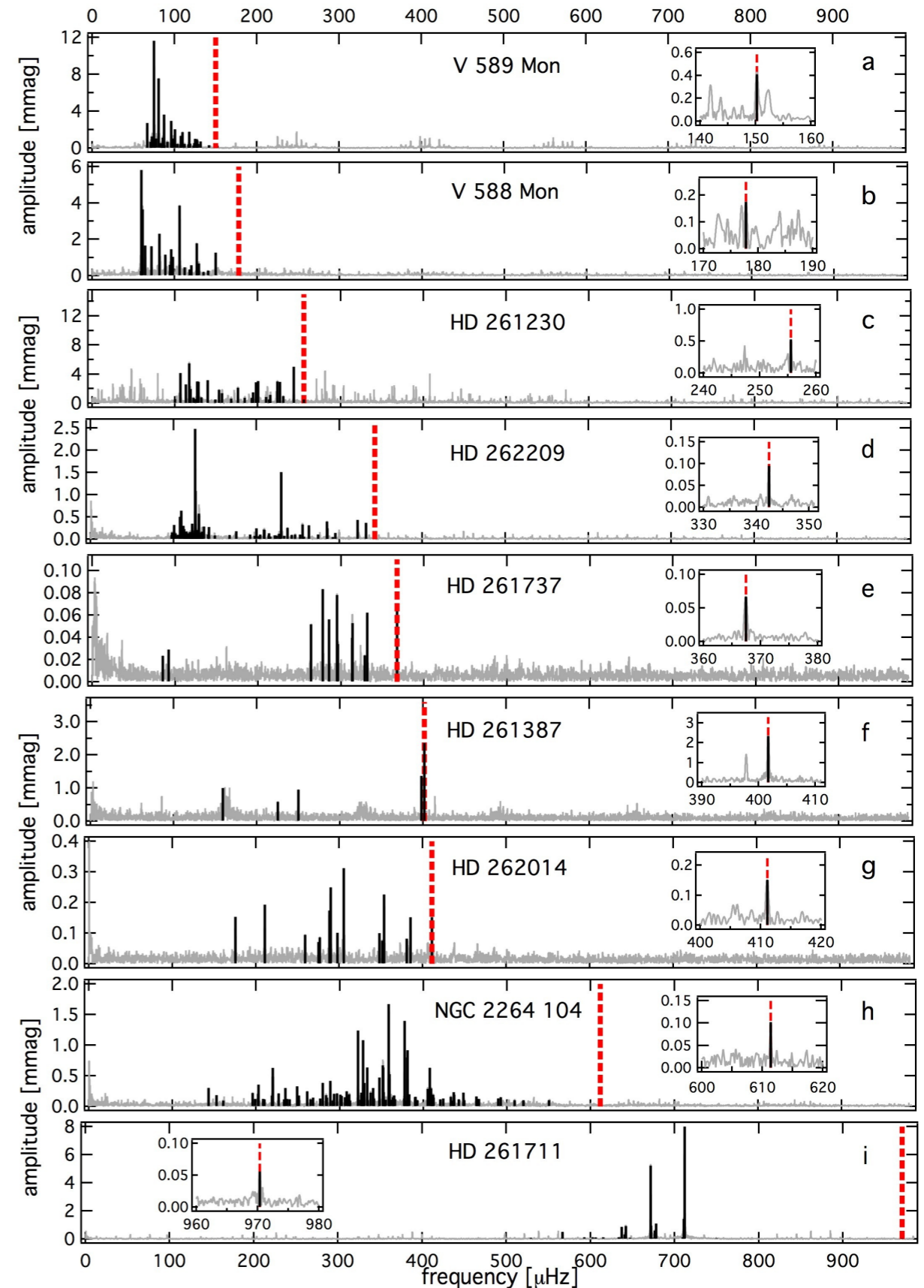


slowest pulsator & least evolved star



→ Tracing stellar evolution with oscillations

fastest pulsator & most evolved star



# What pre-MS stars and red giants have in common...



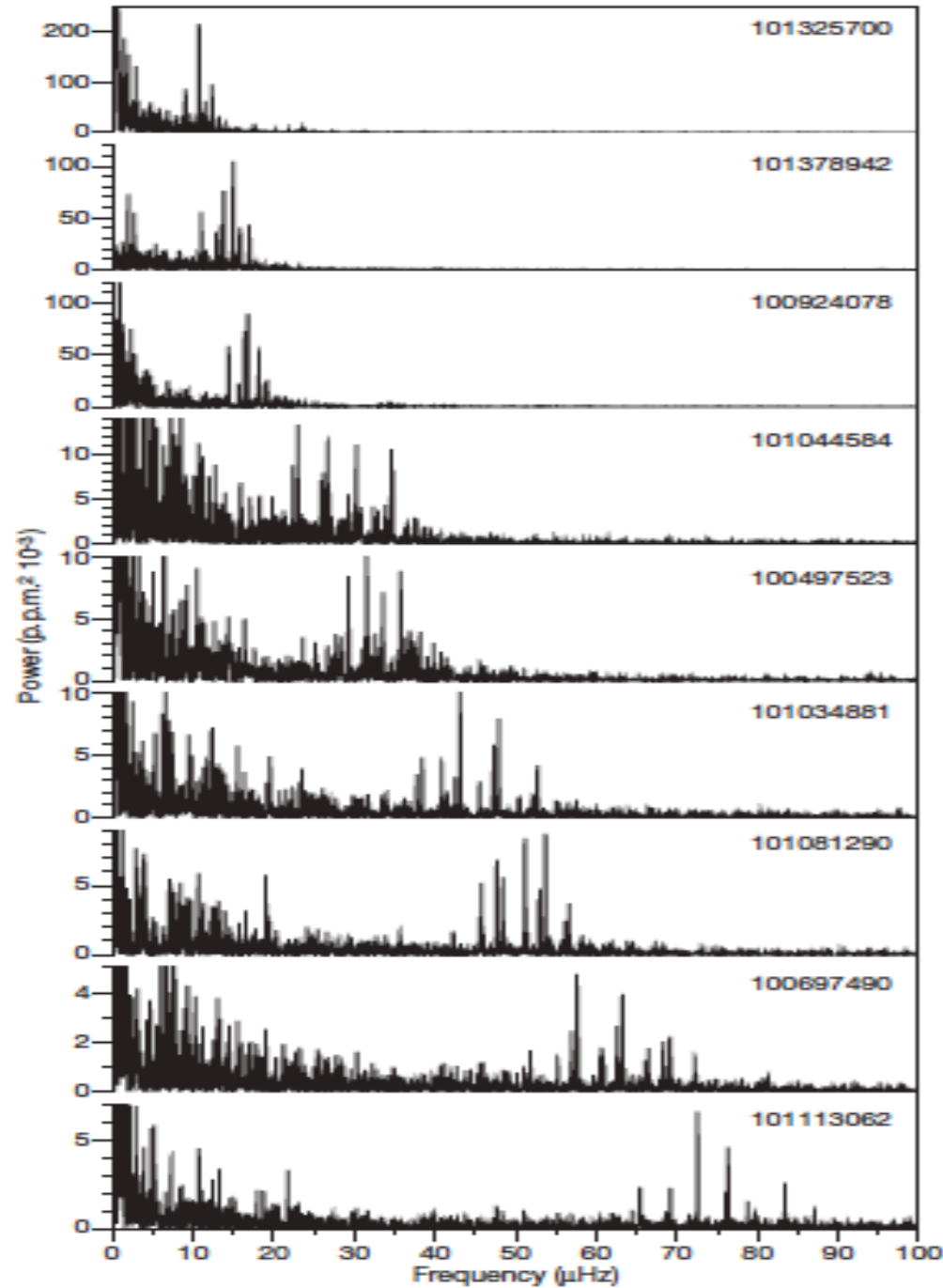


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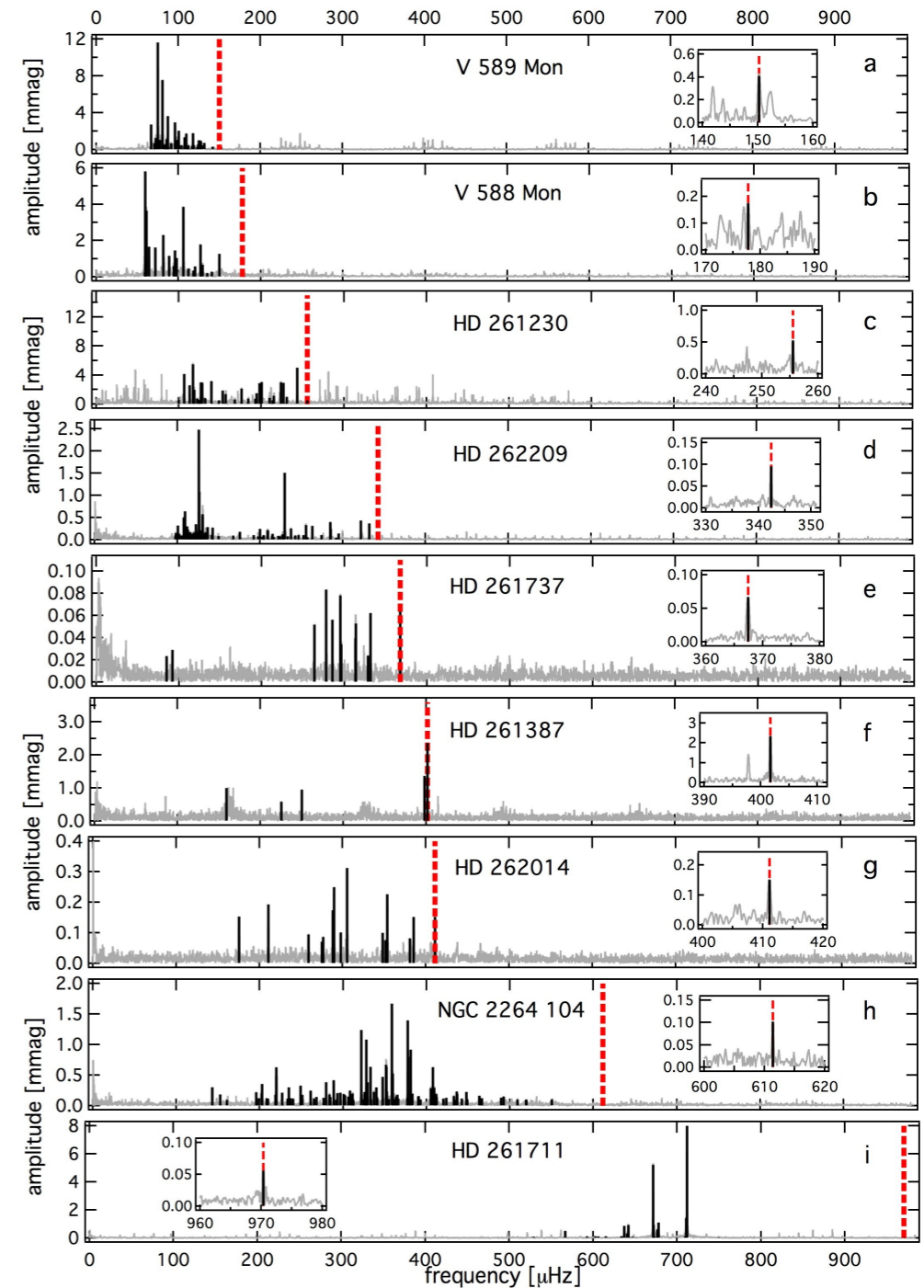
## 9 Red Giants

De Ridder et al. 2009 (Nature)



## 9 Pre-MS δ Scuti stars in NGC 2264

Zwintz et al. 2014 (Science)

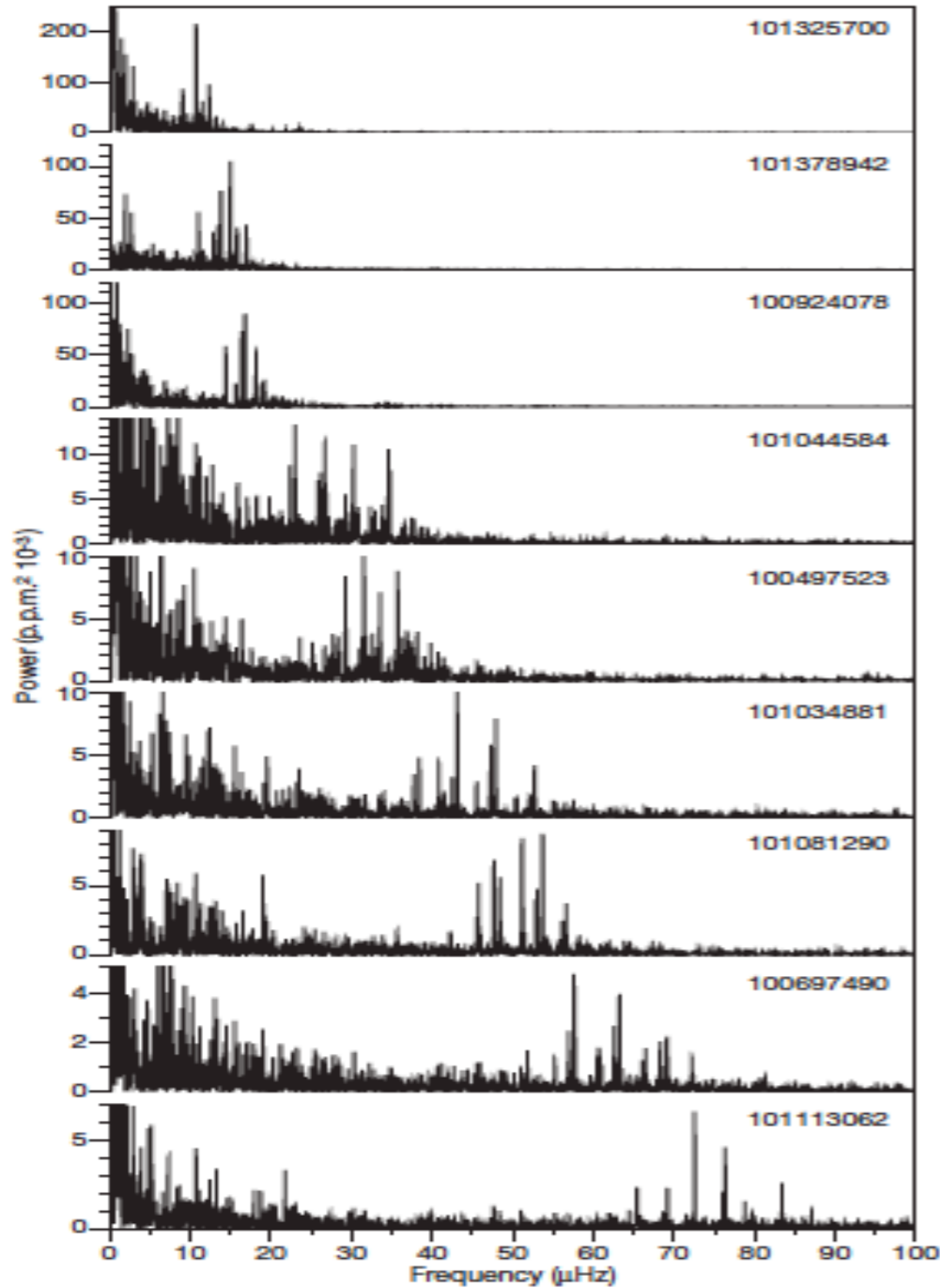


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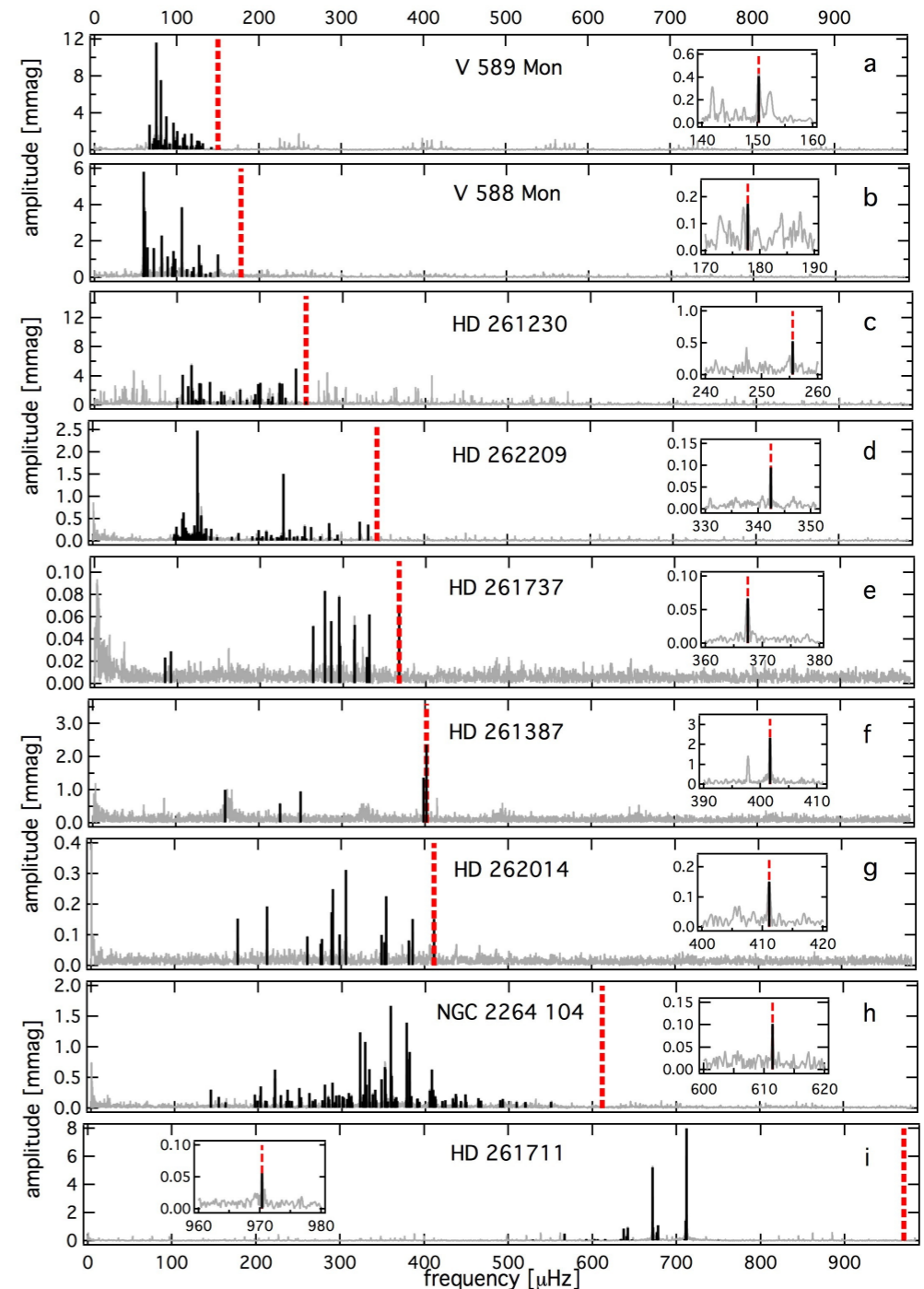
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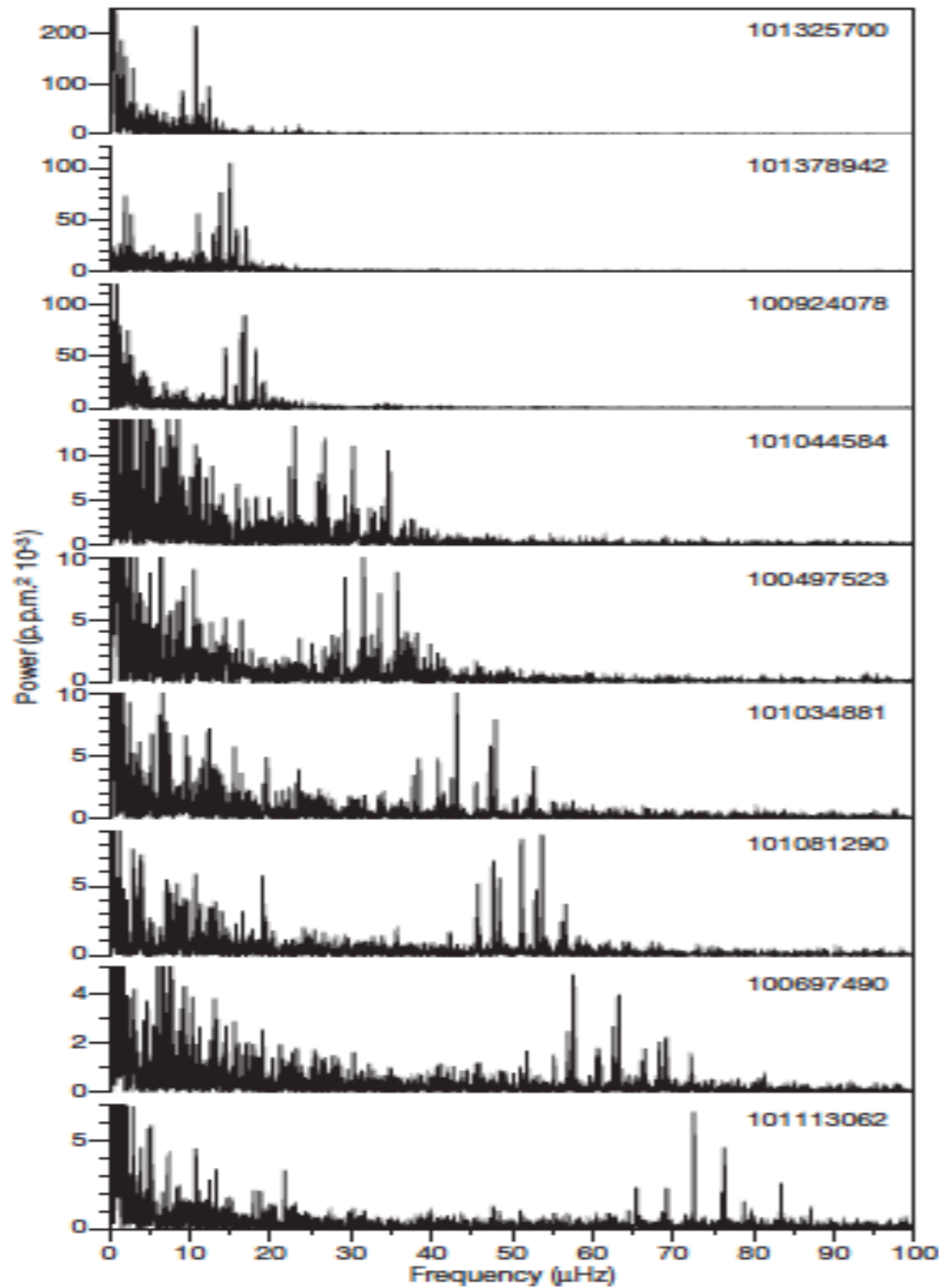
Common start:  
**MOST &**  
**CoRoT data**

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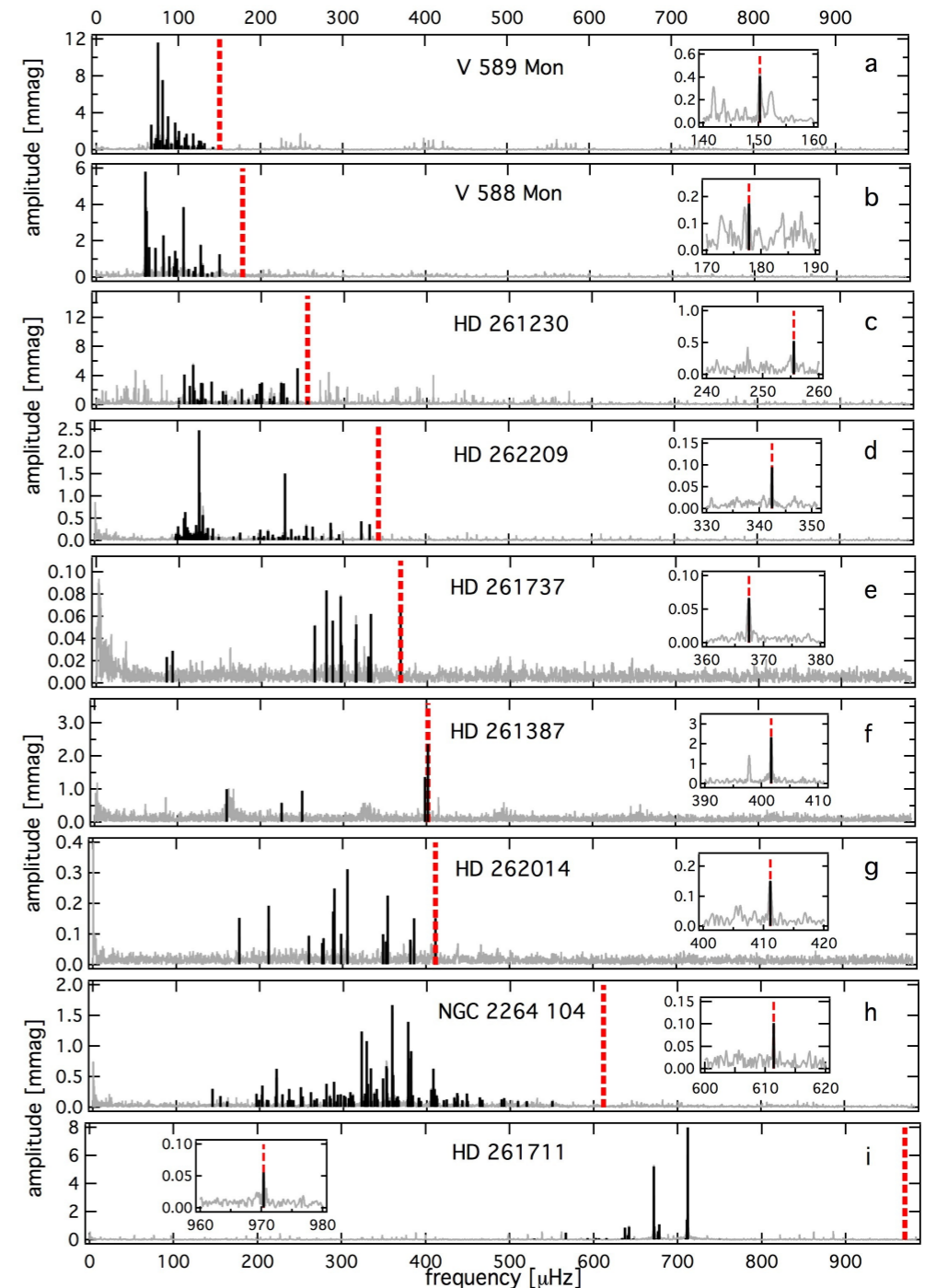
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Giant leap for

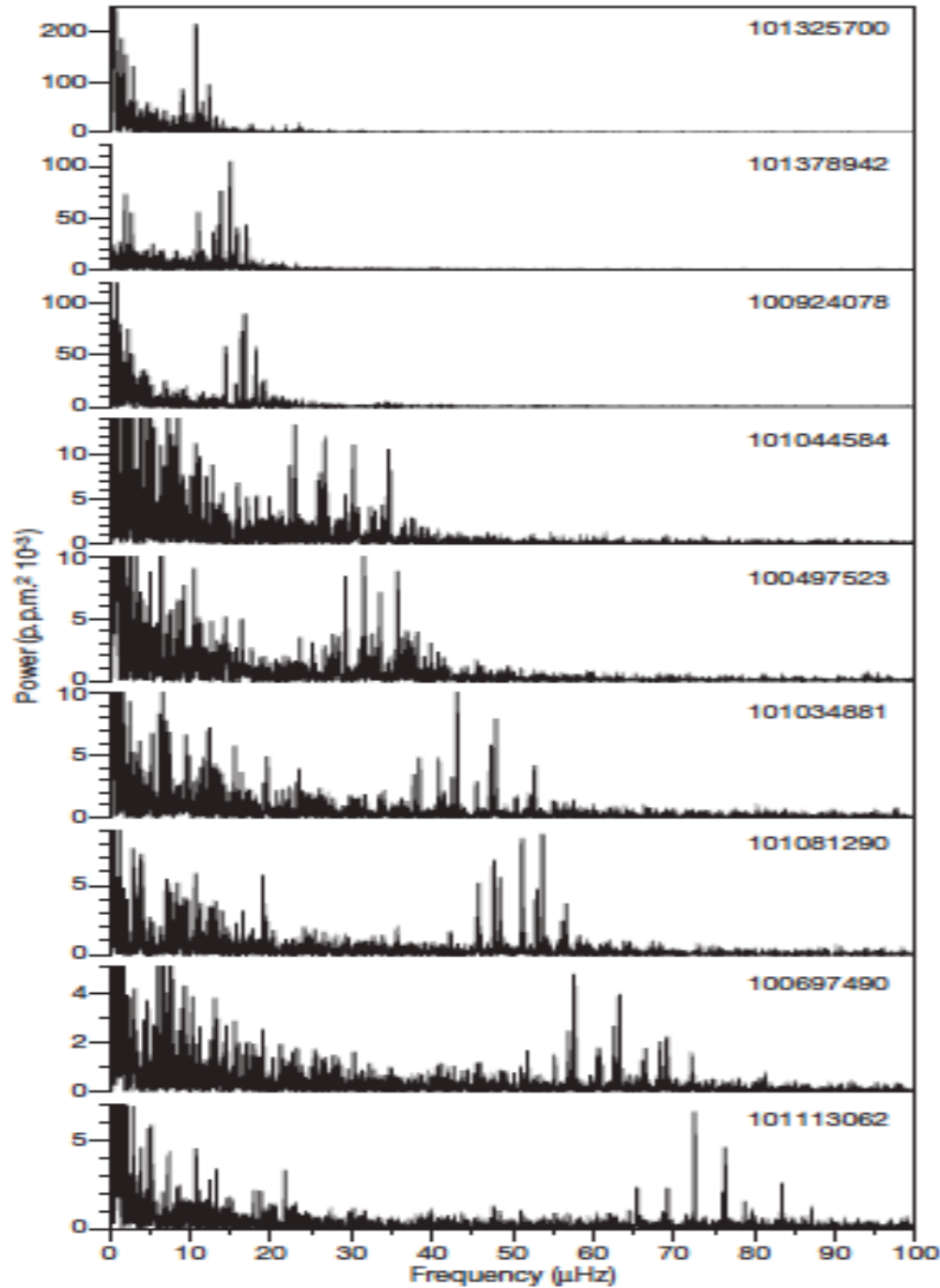
**Red Giants:  
Kepler data**

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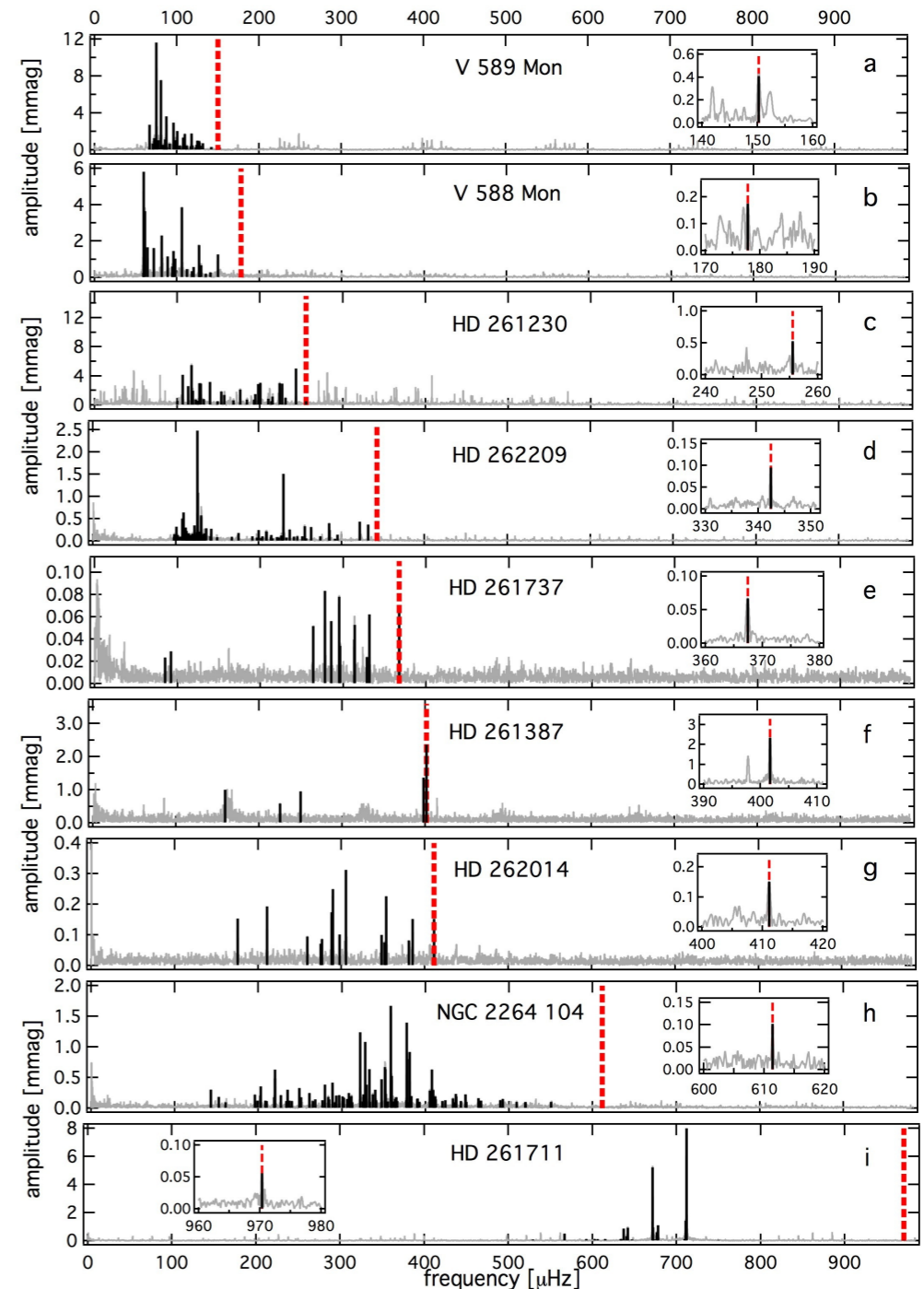
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Common start:  
**MOST & CoRoT data**

Giant leap for Red Giants:  
**Kepler data**

But for pre-MS stars ?



# Future space data

- **MOST**: as long as possible...



## Future space data

- **MOST**: as long as possible...
- **K2**: no pre-MS stars (yet)...
- White Paper „**Ensemble Asteroseismology of the Young Open Cluster NGC 2244**“ by C. Aerts, K. Zwintz et al. (arXiv 1309.3042A)



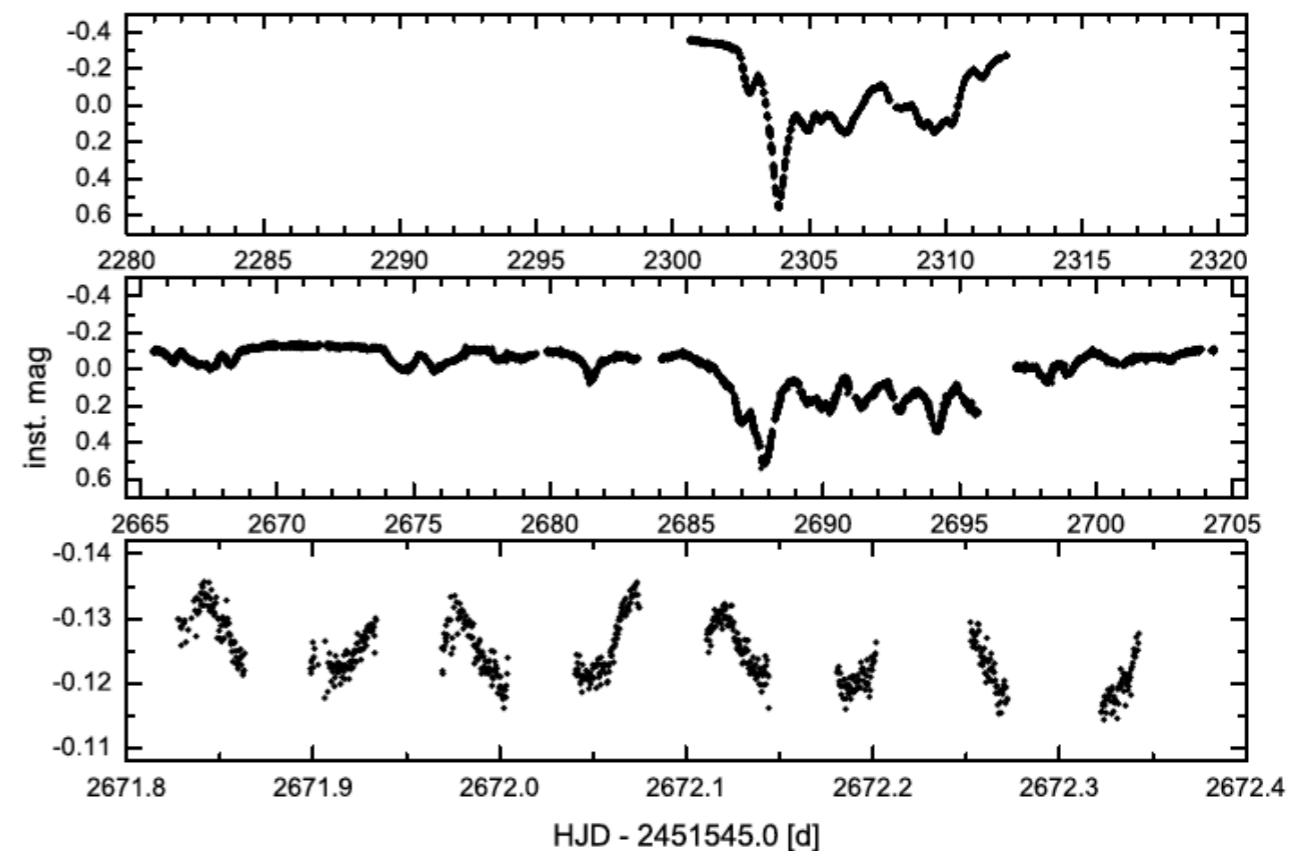
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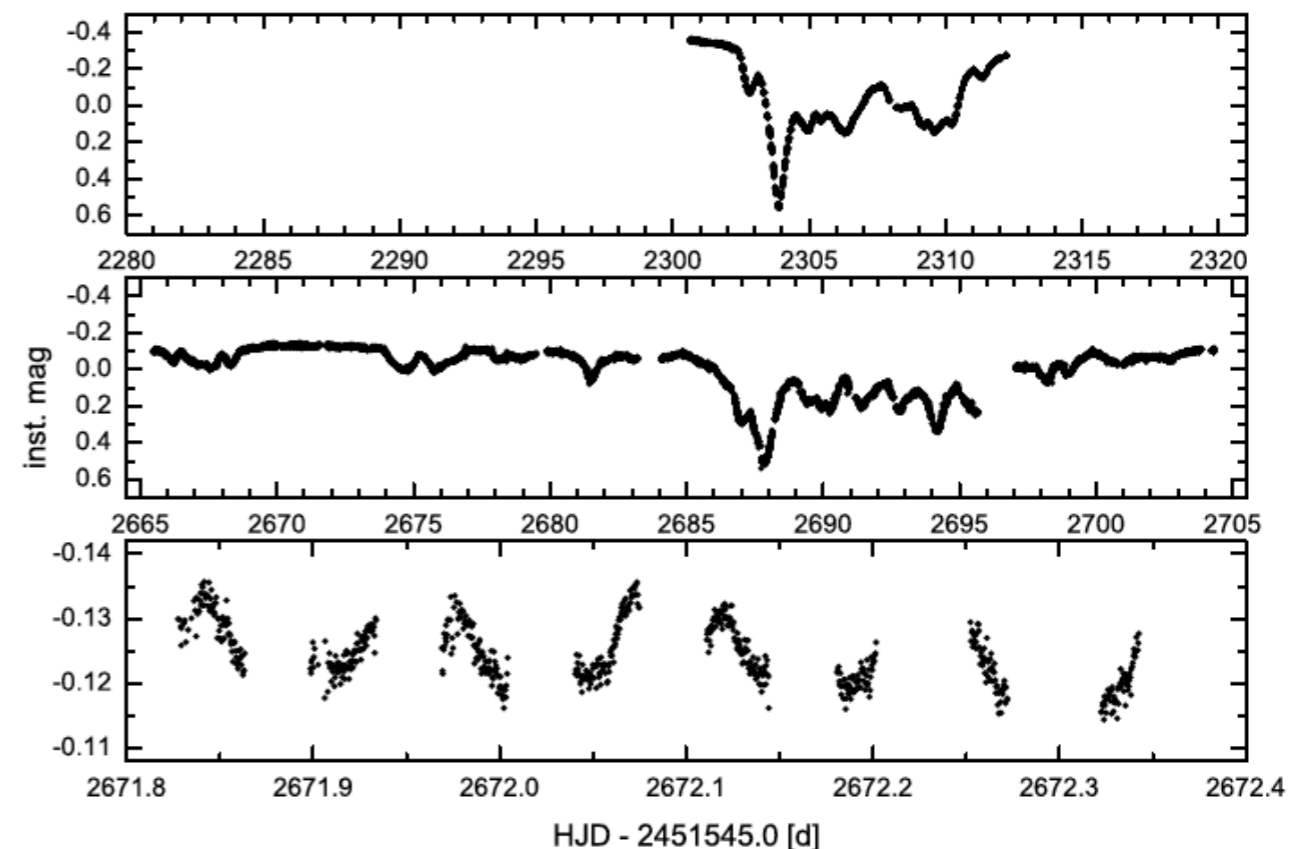
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**WHY OBSERVE THEM?**

**Star- and planet formation connected**

Zwintz et al. (2009)

# The Space Photometry Revolution for young stellar objects has started ...

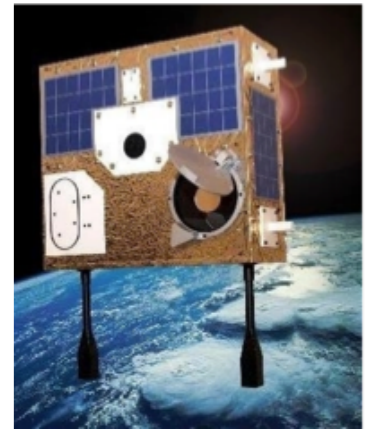


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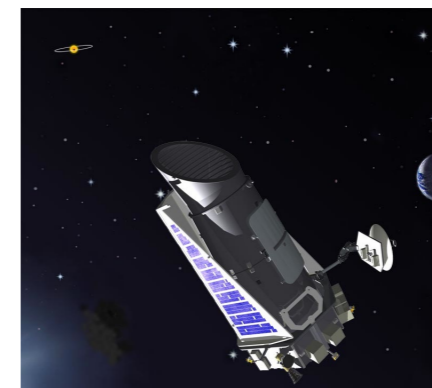


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Maybe continue with **K2 data** in the near future?



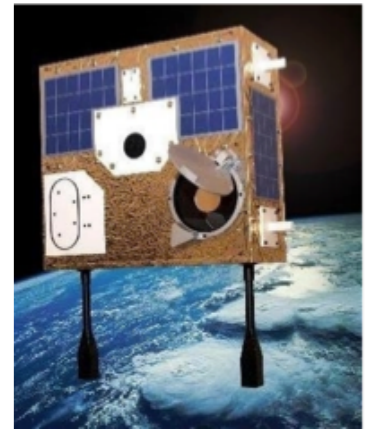


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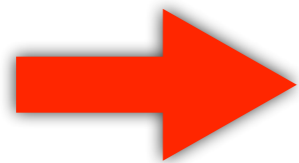
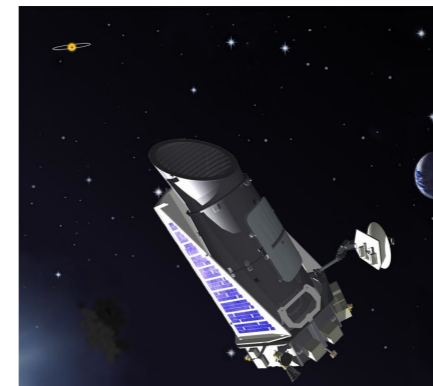


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Pre-MS stars for **PLATO**

