

# Francesco's Legacy

## Star Formation in Space and Time



International Conference  
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Istituto degli Innocenti  
Firenze Italy

**Pulsation in Herbig stars: An idea of Francesco and its realization**

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# *Outline*

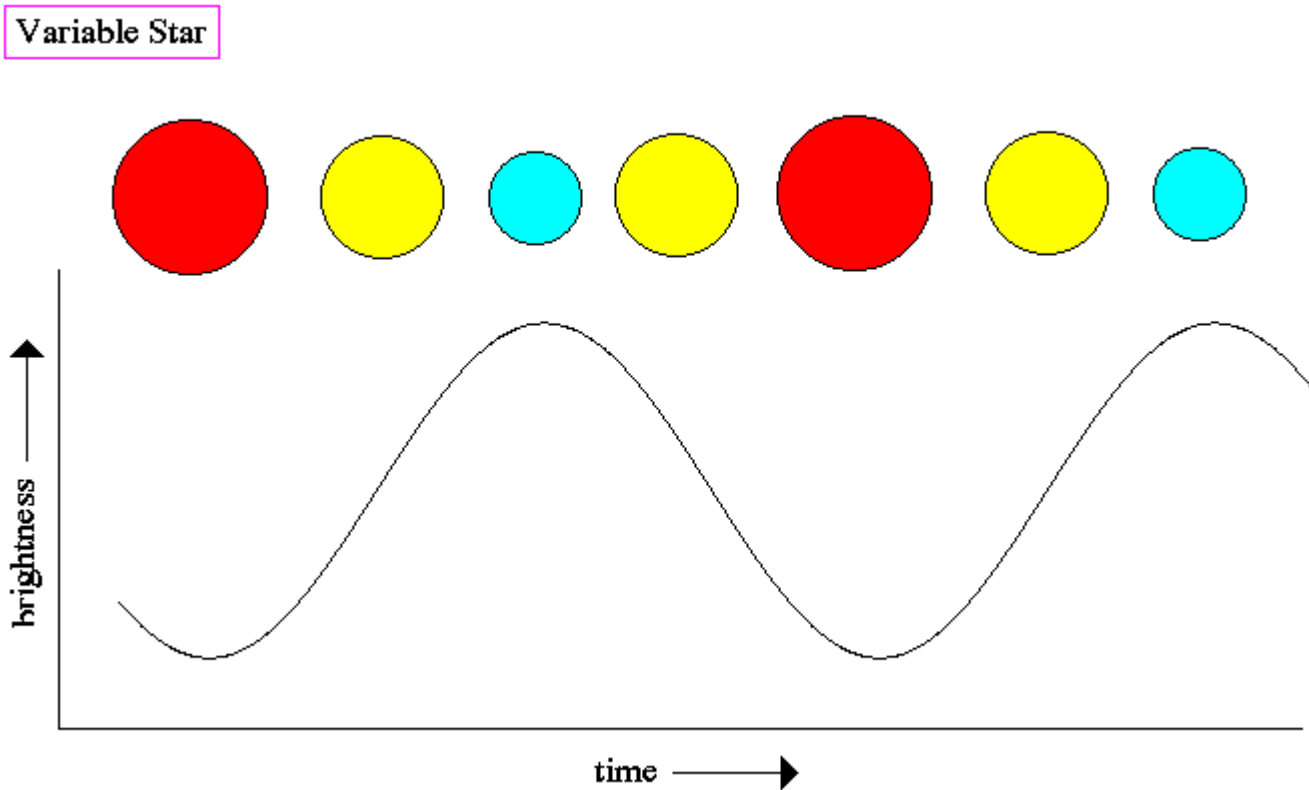
- Properties of pulsating stars
- Why to study Herbig Ae pulsating stars
- First theoretical predictions with Francesco
- Observational and theoretical implications
- Pulsating Herbig Ae stars as age indicators

# Properties of pulsating stars

## *Pulsating Variable stars*

Pulsating stars are intrinsic variables showing cyclic or periodic variations on a time scale of the order of the *free fall* time.

In the simplest case they are radial pulsators.

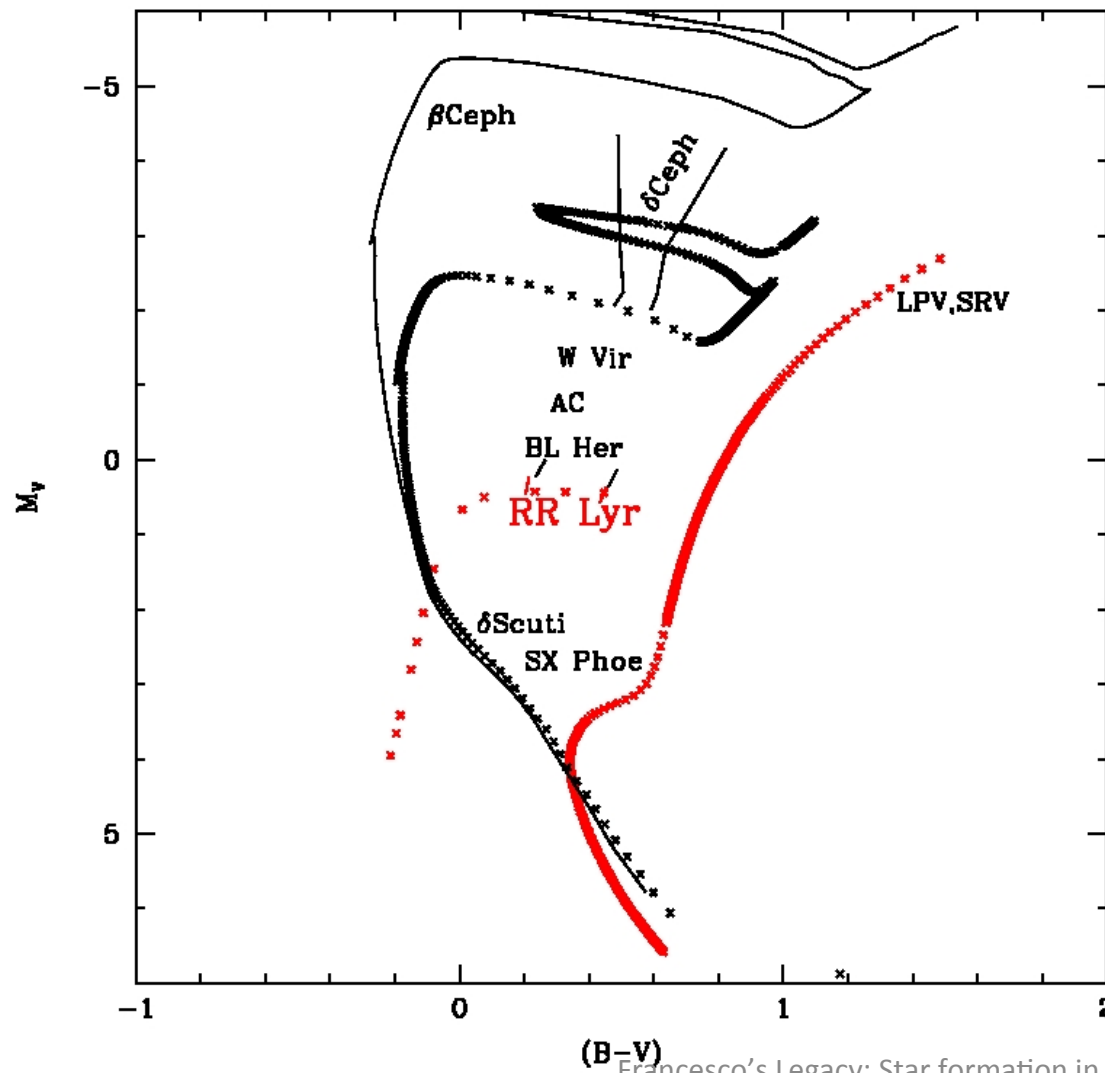


# Properties of pulsating stars

Class	Period (days)	$M_V$	Pop	Evo. Phase
$\delta$ Cephei (CC)	1 - 100(?)	-7(-8) $\div$ -2	I	Blue Loop
$\delta$ Scuti ( $\delta$ Sc)	< 0.5	2 $\div$ 3	I	MS-PMS
$\beta$ Cephei	< 0.3	-4.5 $\div$ -3.5	I	MS
RV Tauri	30 - 100	-2 $\div$ -1	I, II	post-AGB
Miras	> 100	-2 $\div$ 1	I, II	AGB
Semiregulars (SR)	> 50	-3 $\div$ 1	I, II	AGB
RR Lyrae (RRL)	0.2 - 1	$\sim$ 0.5 $\div$ 0.6	II	HB
W Virginis (Type2C)	10 - 50	-3 $\div$ -1	II	post-HB
BL Herculis (Type2C)	< 10	-1 $\div$ 0	II	post-HB
SX Phoenicis (SXPhe)	< 0.1	2 $\div$ 3	II	MS
ACs	0.3 - 2.5	-2 $\div$ 0	?	HB-turnover
SP Cepheids (SPC)	< 2	$\leq$ 0.0	I	Blue Loop
LL Cepheids (LLC)	0.55 - 0.65	$\leq$ 0.4	?	?

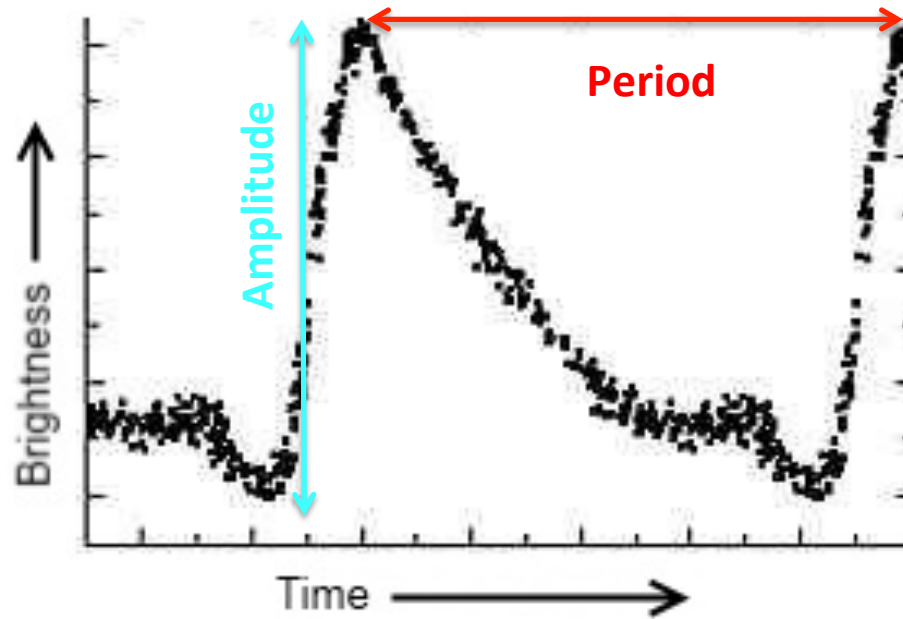
# Properties of pulsating stars

## *Location of pulsating stars in the HR diagram*



# Properties of pulsating stars

- “easily” recognized thanks to the light variations
- Periods and amplitudes are unaffected by distance and reddening



# Properties of pulsating stars

*E.g.*  $P\sqrt{\rho} = \text{const}$

but for Stephan-Boltzman law  $L = 4\pi\sigma R^2 T_e^4$



$$P = P(L, M, T_e)$$

A theoretical and observational study of pulsating stars

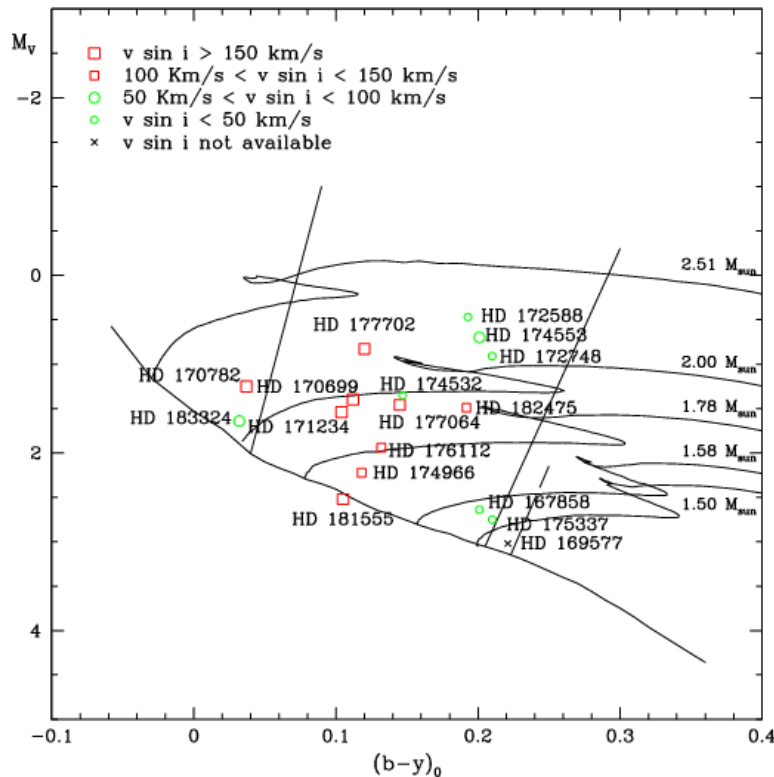
Constraints on stellar intrinsic parameters ( $M, L, \dots$ )

Trace stellar population of different age and chemical composition

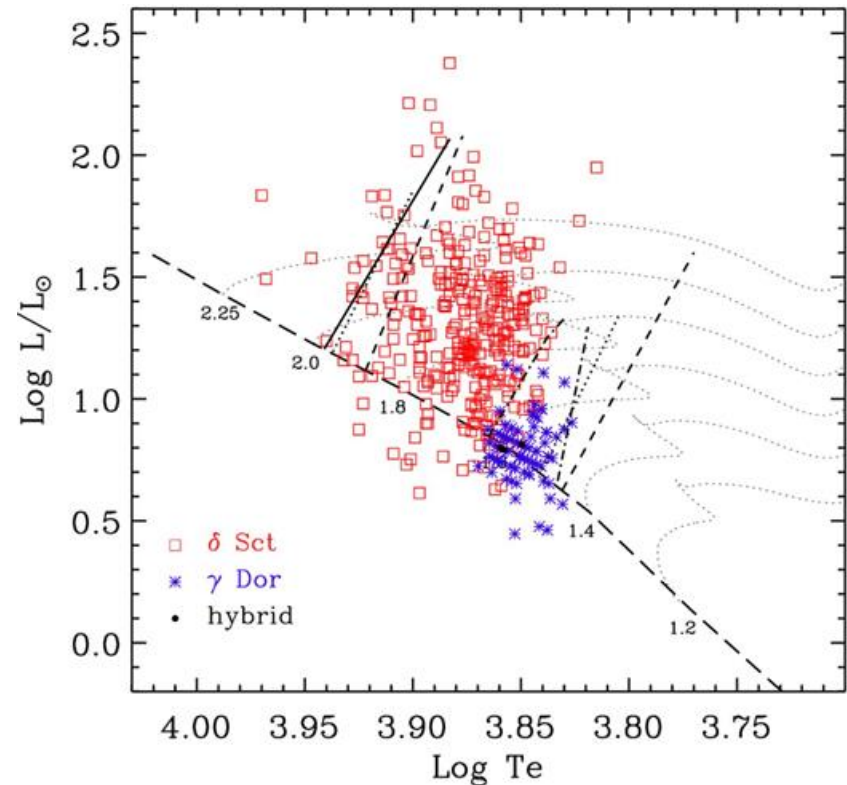
Set the astronomical distance scale

# Among the stars crossing the instability strip...

**Main-Sequence and post-Main-Sequence  $\delta$  Scuti stars: stars crossing the pulsation instability strip during their evolution from the ZAMS**



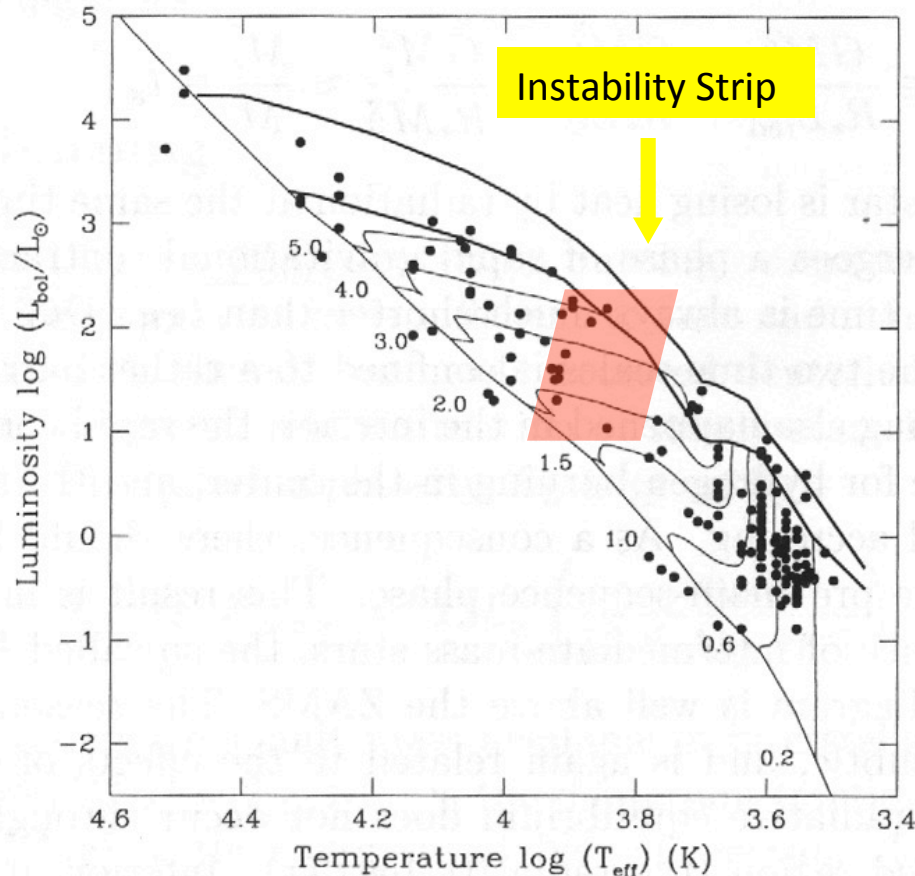
Poretti et al. 2013



Xiong et al. 2016



# The real first crossing of the instability strip



➤ Theory → *birth-line*, i.e. location of stars of different mass when they start their PMS phase.

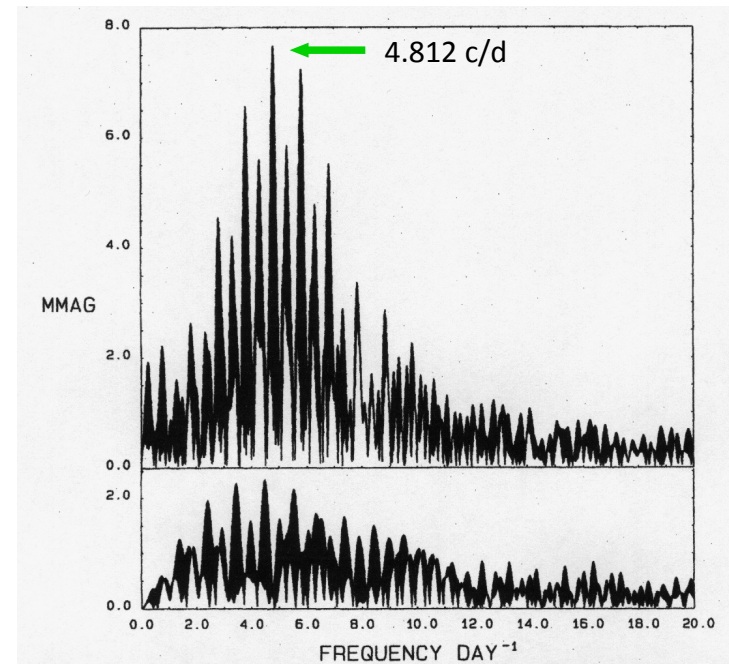
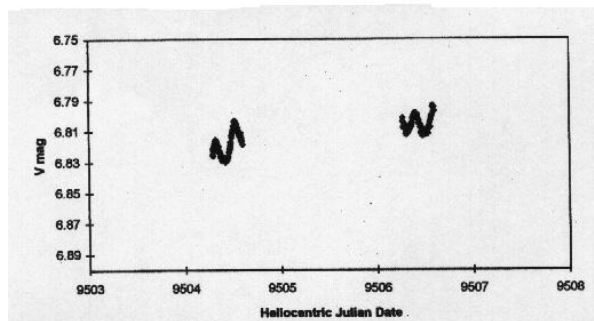
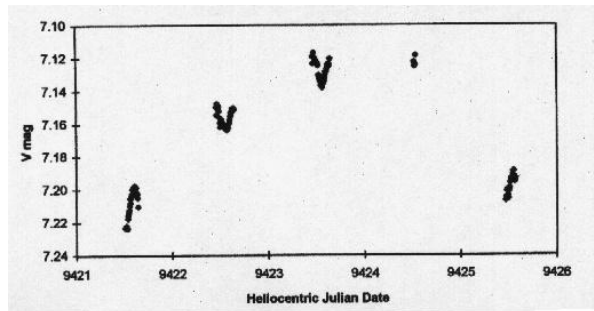
➤ Contraction from the birthline to the Zero Age Main Sequence (ZAMS) on the Kelvin-Helmoltz time scale:  $t=3/7(GM^2)/(RL)$ .

➤ During their evolution toward the ZAMS intermediate mass ( $1.5 \leq M/M_{\odot} \leq 4.0$ ) PMS stars can **cross the instability strip** of more evolved  $\delta$  Scuti

# A past century question was: Do Herbig Ae/Be stars pulsate?

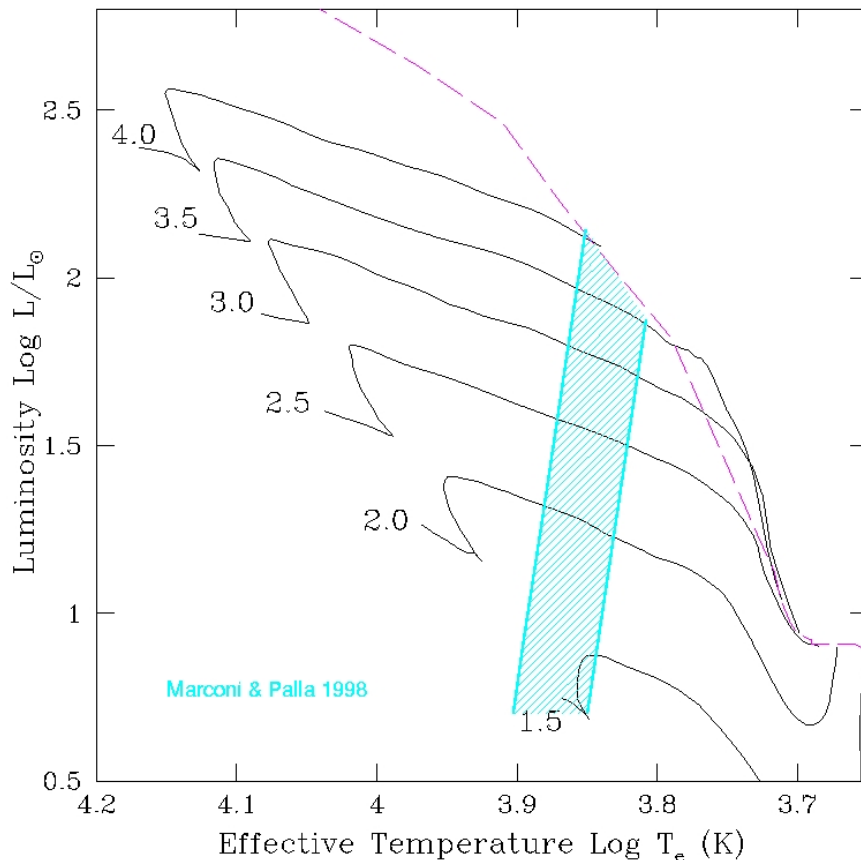
$\delta$  Scuti-like pulsation among Herbig Ae stars was originally suggested by Breger (1972)  $\rightarrow$  two candidates (V588 Mon and V589 Mon) but few hours of observation on 3 nights separated by several months

Subsequent observations by Kurtz & Marang (1995) for HR5999 and Donati et al. (1997) for HD104237 seemed to confirm the existence of  $\delta$  Scuti like pulsation among Herbig Ae/Be stars.



# Francesco had the idea of producing the first theoretical prediction for this class of stars

- **Marconi & Palla 1998 ApJL** → the first theoretical instability strip for the first three radial modes based on nonlinear convective radial pulsation models and the PMS tracks by Palla & Stahler



Along each PMS evolutionary track, models were selected by varying  $T_e$ .

→ modal stability investigated for the first three radial modes: Fundamental, First Overtone and Second Overtone.

→ Pulsation instability region: between the second overtone blue edge and the fundamental red edge.

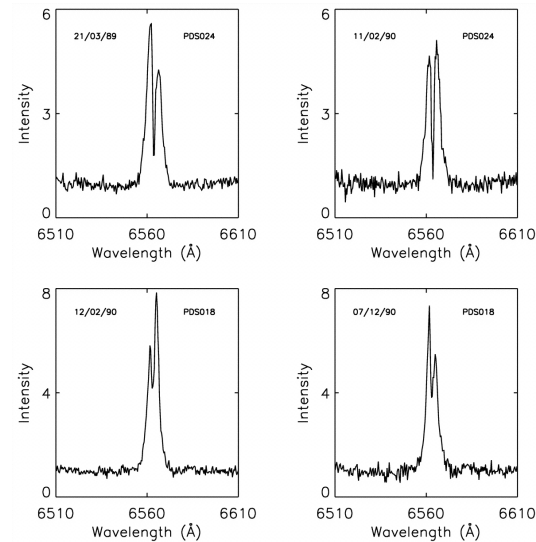
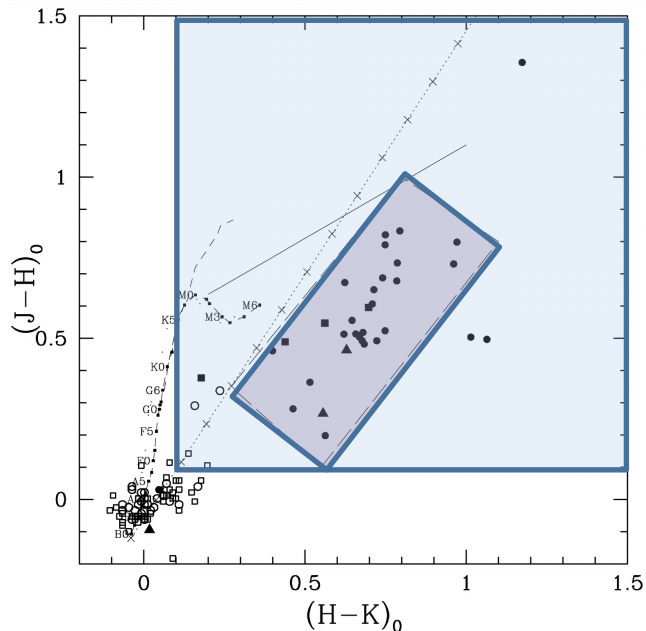
→ evaluated crossing time  $\sim 5\text{-}10\%$  of the total contraction time towards the MS ( $10^5 \div 10^6$  years).

This theoretical paper triggered a burst of activity:

- ◆ from the observational point of view → search for pulsating Herbig Ae stars both from the ground and from the space;
- ◆ from the theoretical point of view → prediction of higher radial mode and nonradial pulsation in PMS intermediate mass stars.

# Selection of Herbig Ae stars (infrared excess, H $\alpha$ emission) that are expected to lie between the predicted boundaries of the instability strip.

- Young intermediate mass stars ( $1.5 < M < 8.0$ ) are often referred to as Herbig Ae/Be. By definition:
  - spectral type B-A/F(early)
  - strong IR (and/or UV) excess
  - emission (Balmer lines)

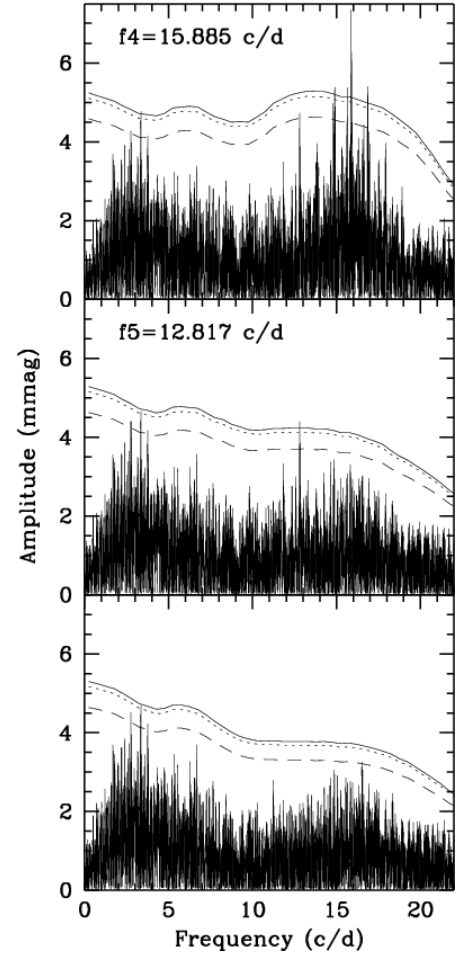
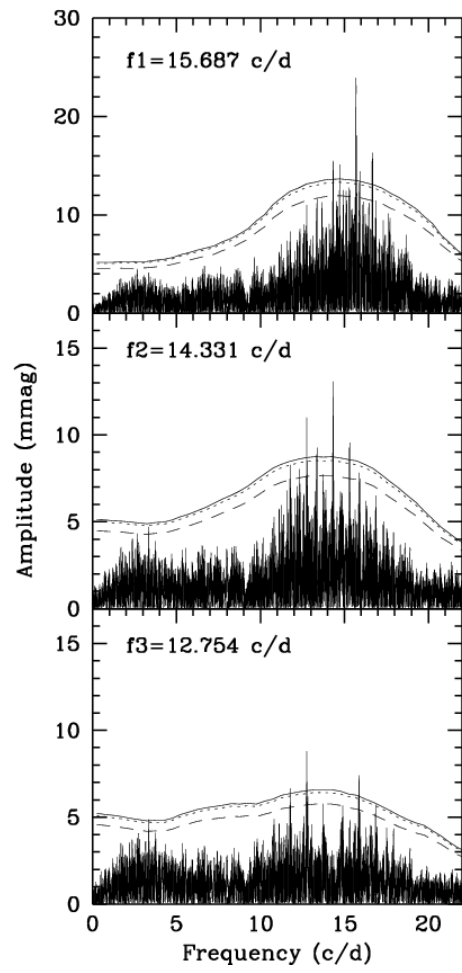
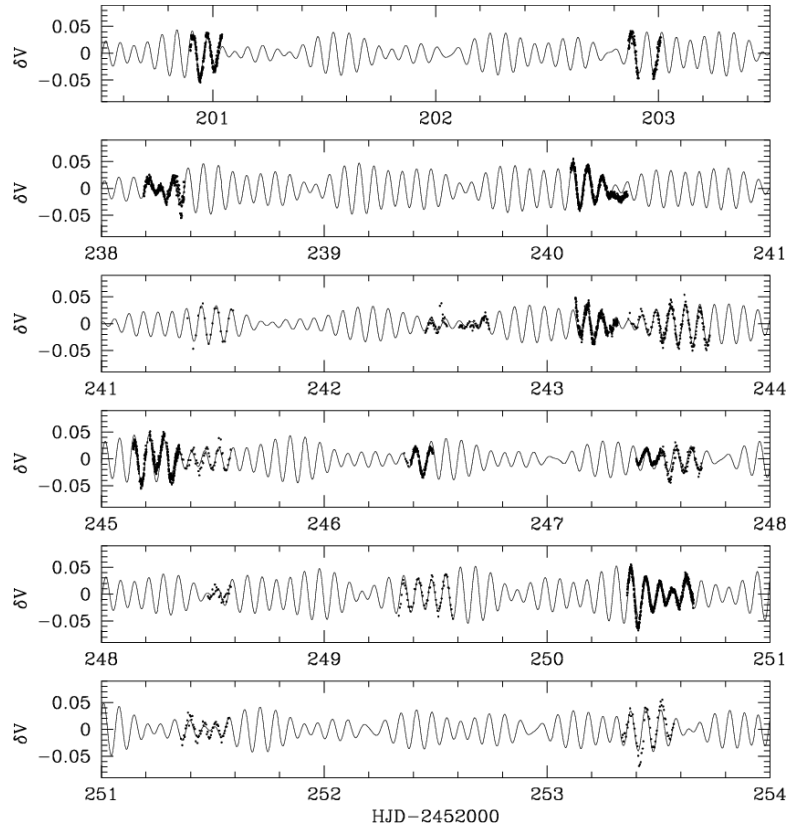


Selection of Herbig Ae stars (infrared excess, H $\alpha$  emission) that are expected to lie between the predicted boundaries of the instability strip.

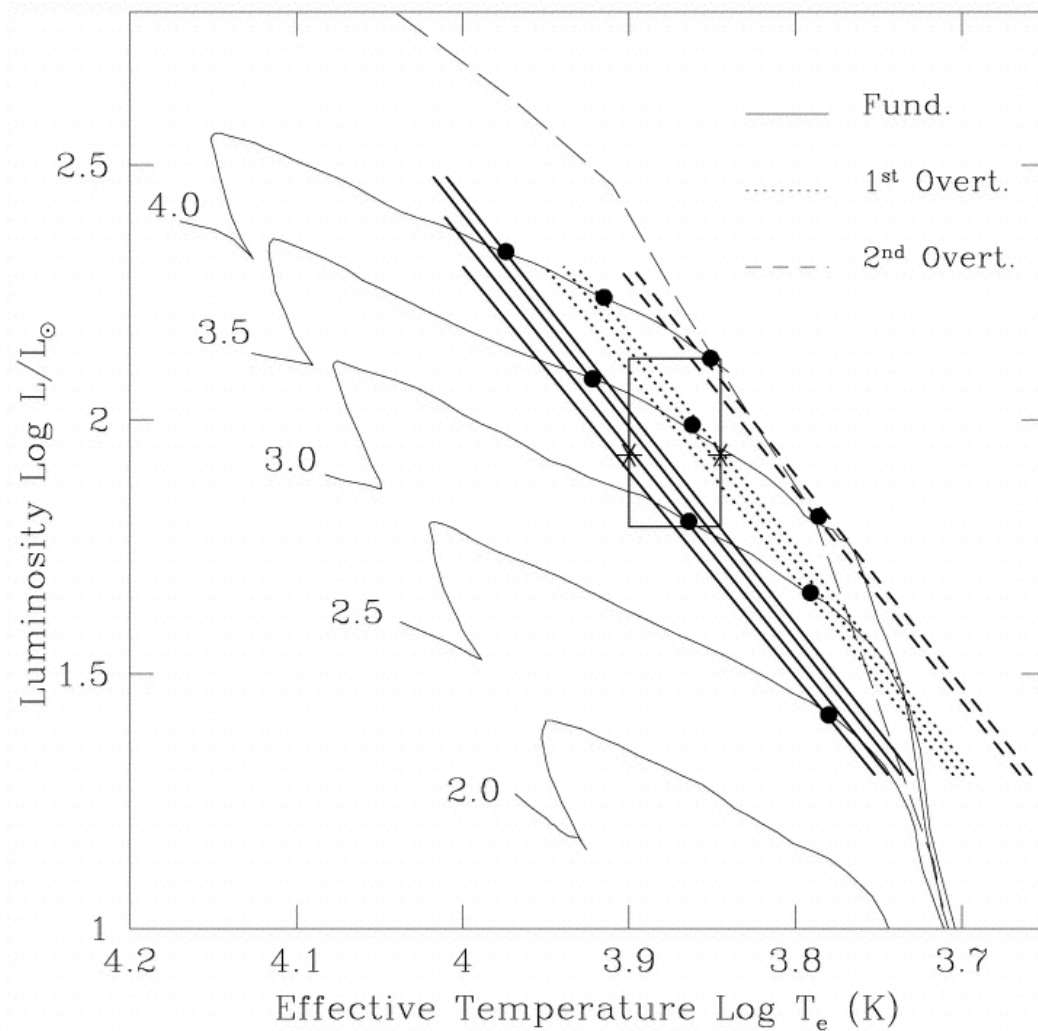
- Herbig Ae/Be stars show a high degree of activity:
  - photometric & spectroscopic variabilities (time scale from hours to years)
  - interaction with stellar environment

Time-series multi-site observations → frequency/frequencies in the  $\delta$  Scuti range

The case of V351 Ori  
(Ripepi et al. 2003)



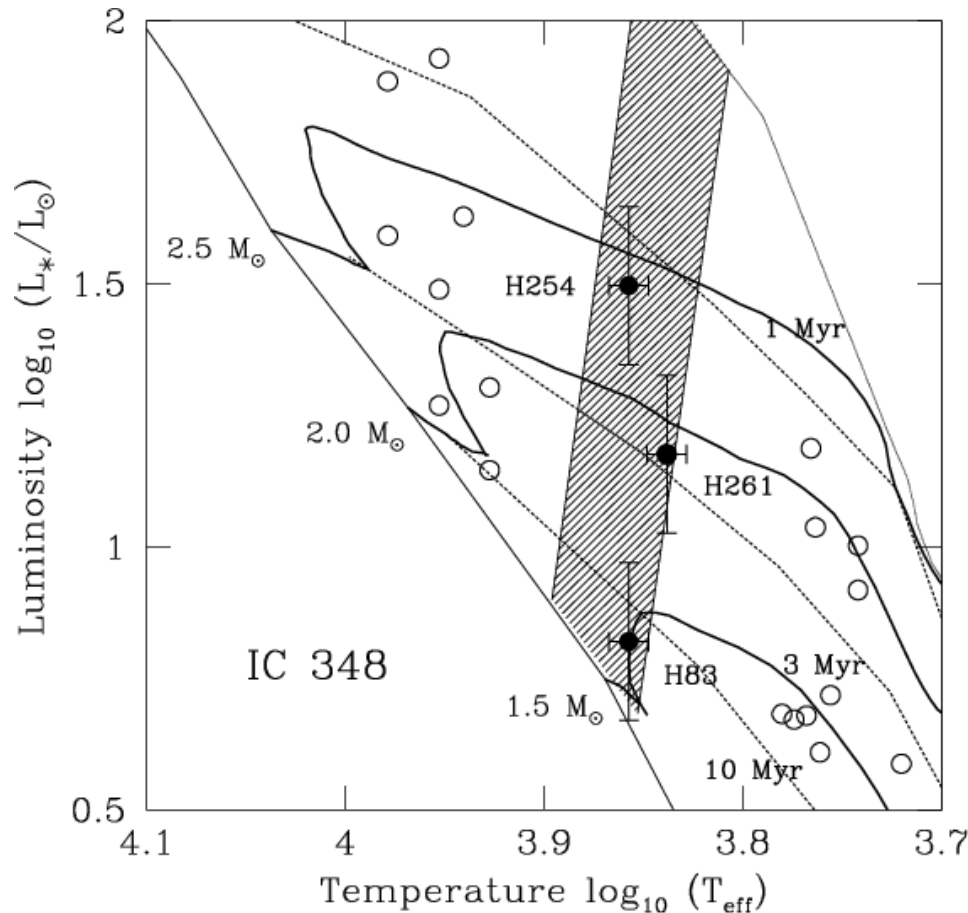
Isoperiodic sequences (corresponding to the observed periods) of models are computed  $\rightarrow$  lines in the HR diagram



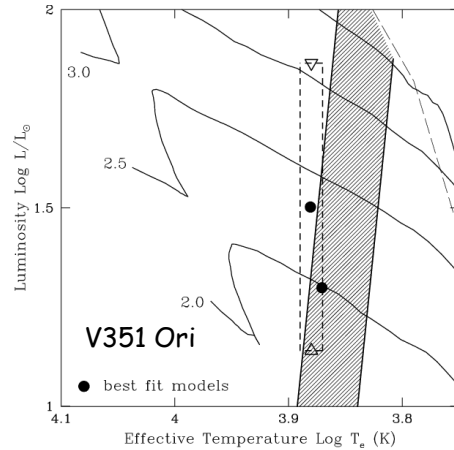
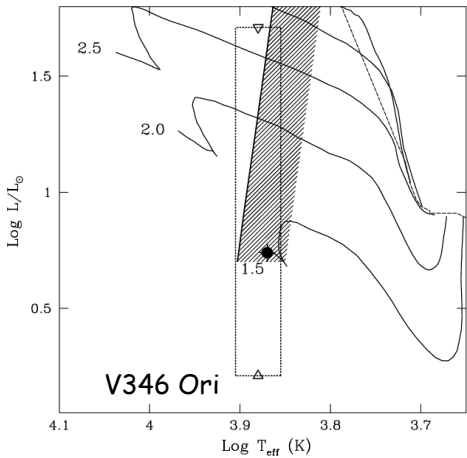
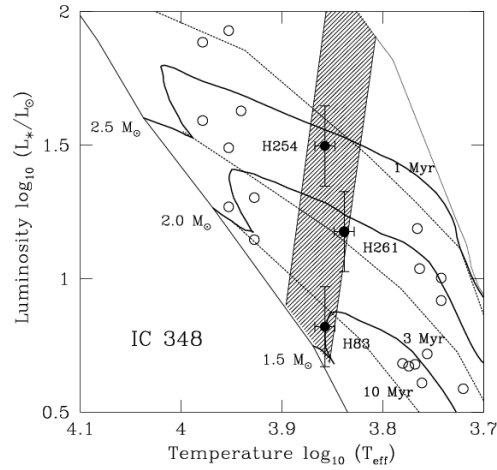
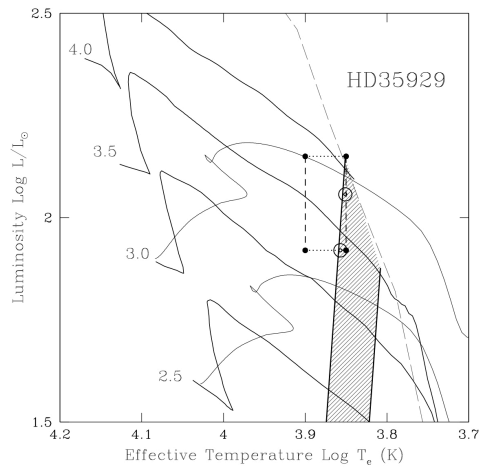
**Marconi & Palla 1998**



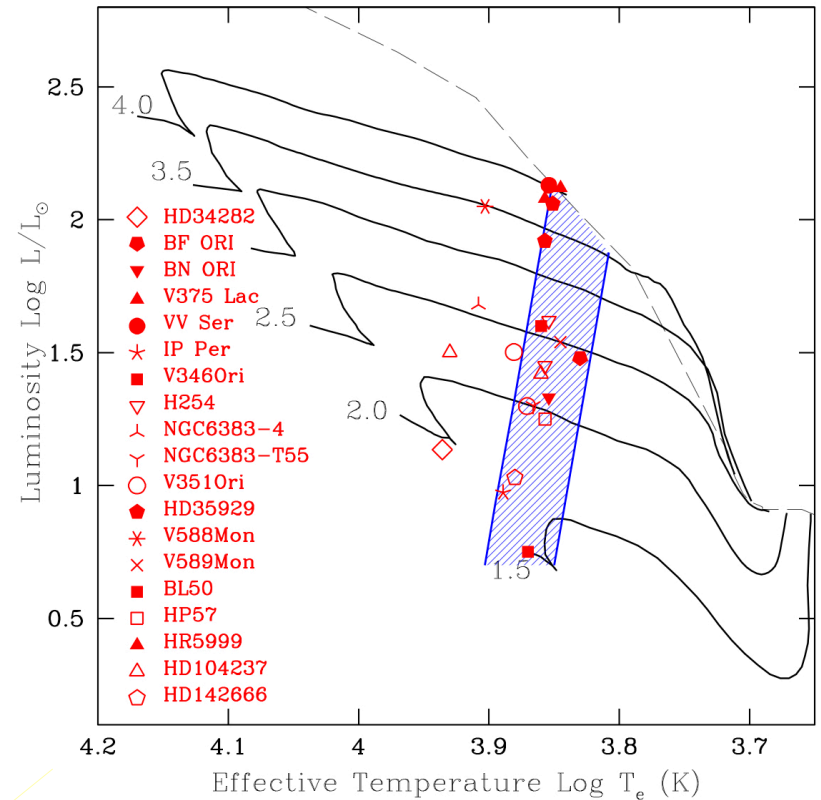
Combined constraints from PMS evolutionary tracks, pulsation model results, independent spectroscopic measurements → **intrinsic stellar parameters (stellar mass, effective temperature, luminosity) and individual distances**



The pulsation analysis allowed us also to derive an independent estimate of the distance to IC 348 of about 320 pc



Predicted position in the HR diagram



Marconi et al. 2000, 2001 A&A  
 Ripepi et al. 2002, 2003 A&A  
 Pinheiro et al. 2003 A&A  
 Zwintz et al. 2005 MNRAS

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Marconi & Palla 2003, 2004, 2005:  
 15 more candidates PMS Scuti  
 in 6 years

# Pre-main-sequence stars in the star-forming complex Sh 2-284

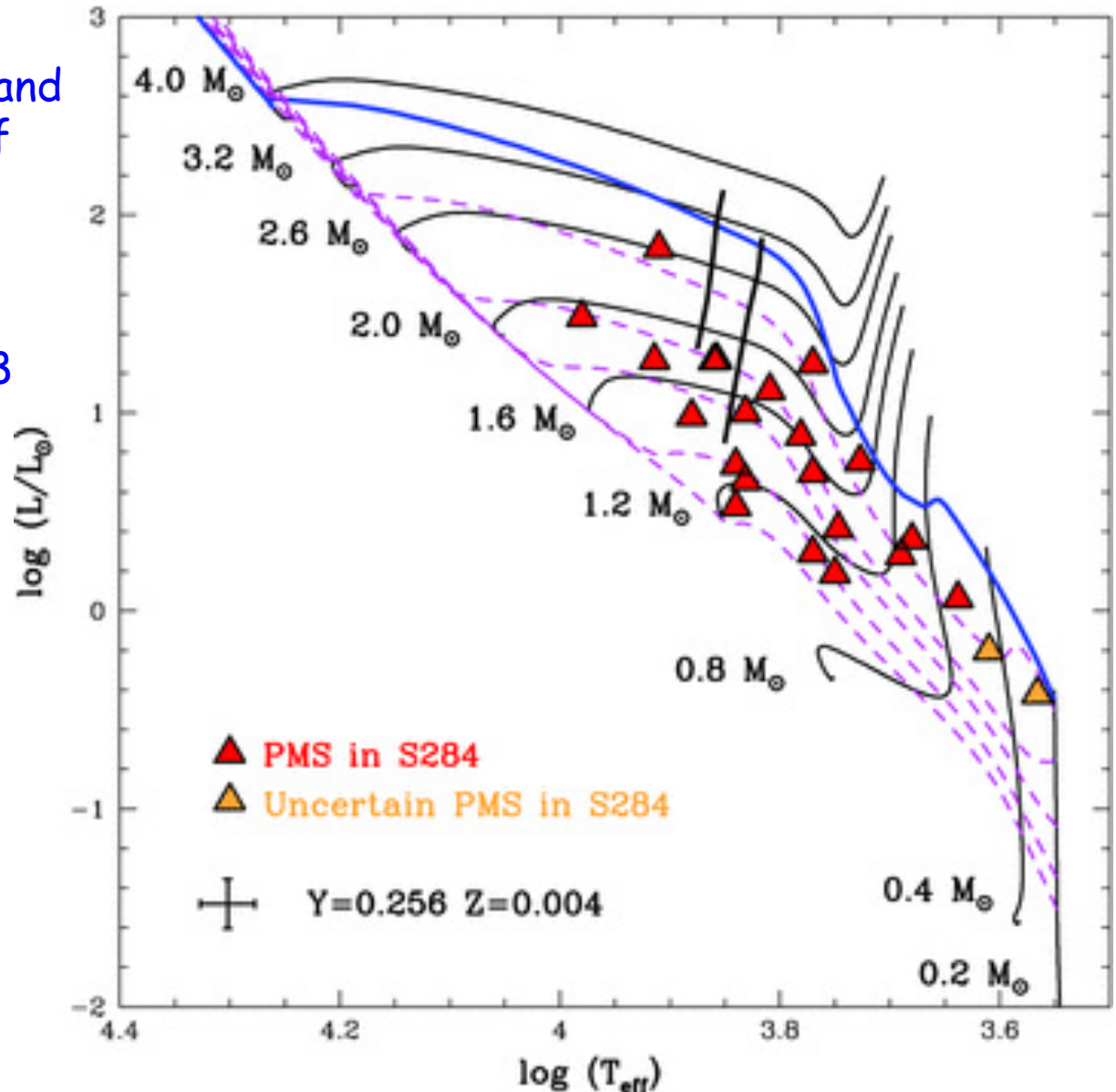
Results of a photometric and spectroscopic follow-up of Sh 2-284 using VIMOS

Among the 23 discovered young stars, we selected 8 with intermediate mass.

8 very good candidates for PMS  $\delta$  Scuti-type pulsation.



1 observed by CoRoT



Cusano et al. 2011 MNRAS

# CoRoT 102699796, the first metal-poor Herbig Ae pulsator: a hybrid $\delta$ Sct- $\gamma$ Dor variable?

CoRoT candidate  $\rightarrow$  5 independent oscillation frequencies

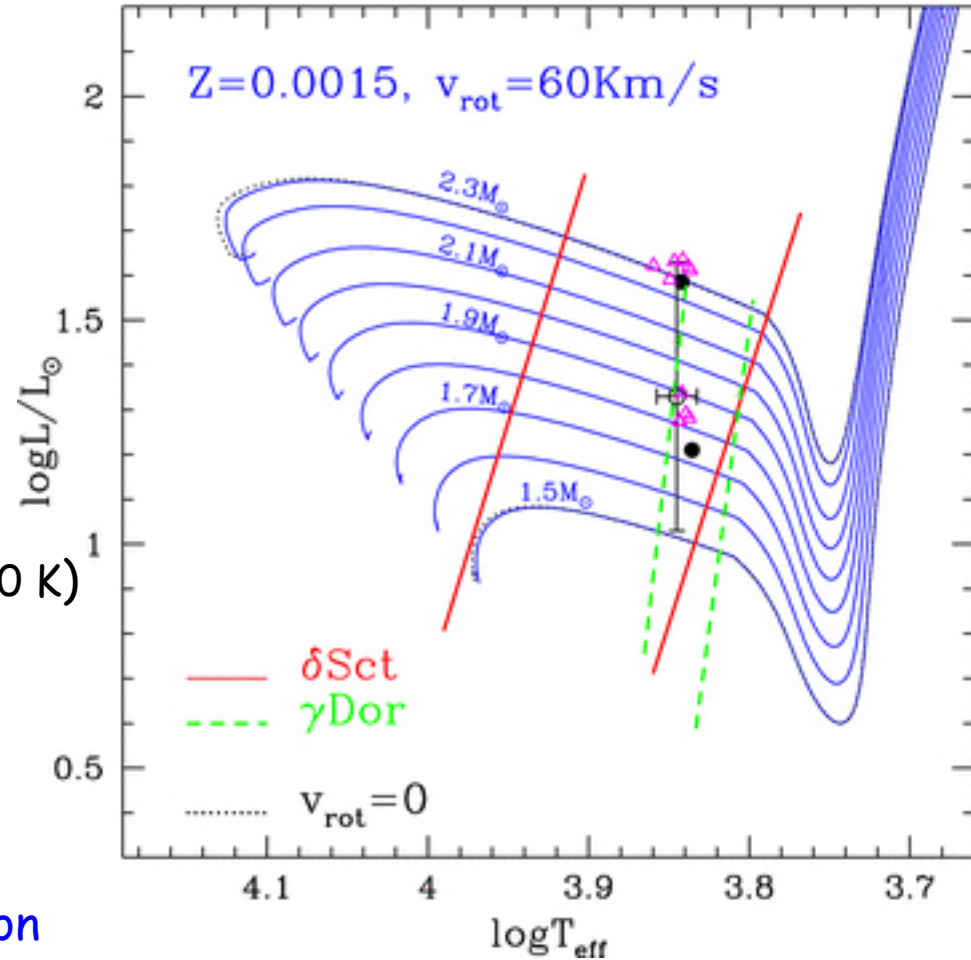
Flames@VLT data  $\rightarrow$   $T_{\text{eff}}$ ,  $\log(g)$ ,  $v \sin i$ ,  $\log L/L_{\odot}$ .

Frequencies interpreted with non-radial pulsation theory (Di Criscienzo et al. 2008 MNRAS).

Best-fitting model ( $M = 1.84 M_{\odot}$ ,  $T_{\text{eff}} = 6900$  K)  
 $\rightarrow$  isochronal age of  $t \sim 2.5$  Myr.

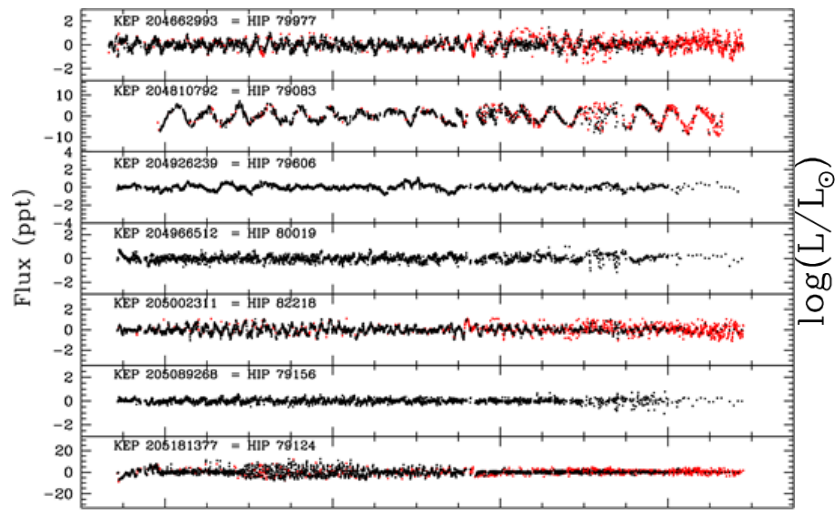
Interpretation as **p and g modes** of low-moderate  $n$ -value  $\rightarrow$  first time in a intermediate-mass PMS pulsating star.

CoRoT 102699796 lies at the intersection between  $\delta$  Sct and  $\gamma$  Dor stars  $\rightarrow$  it is likely the first PMS hybrid  $\gamma$  Dor- $\delta$  Sct pulsator.

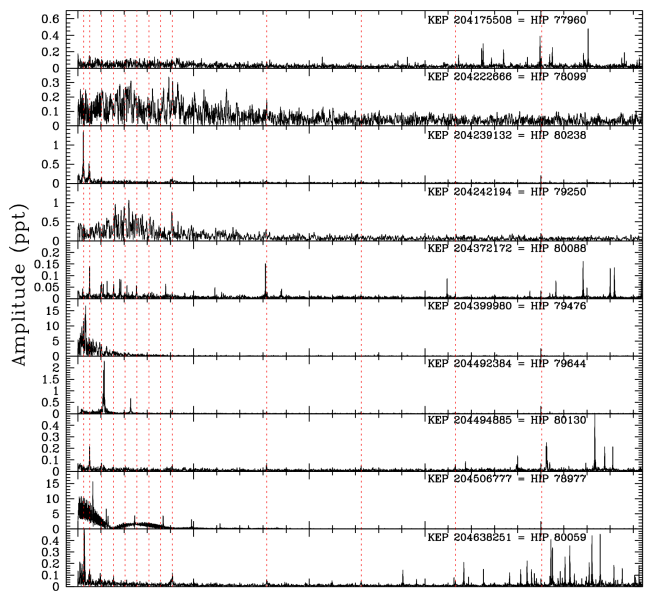


Ripepi et al. 2011 MNRAS

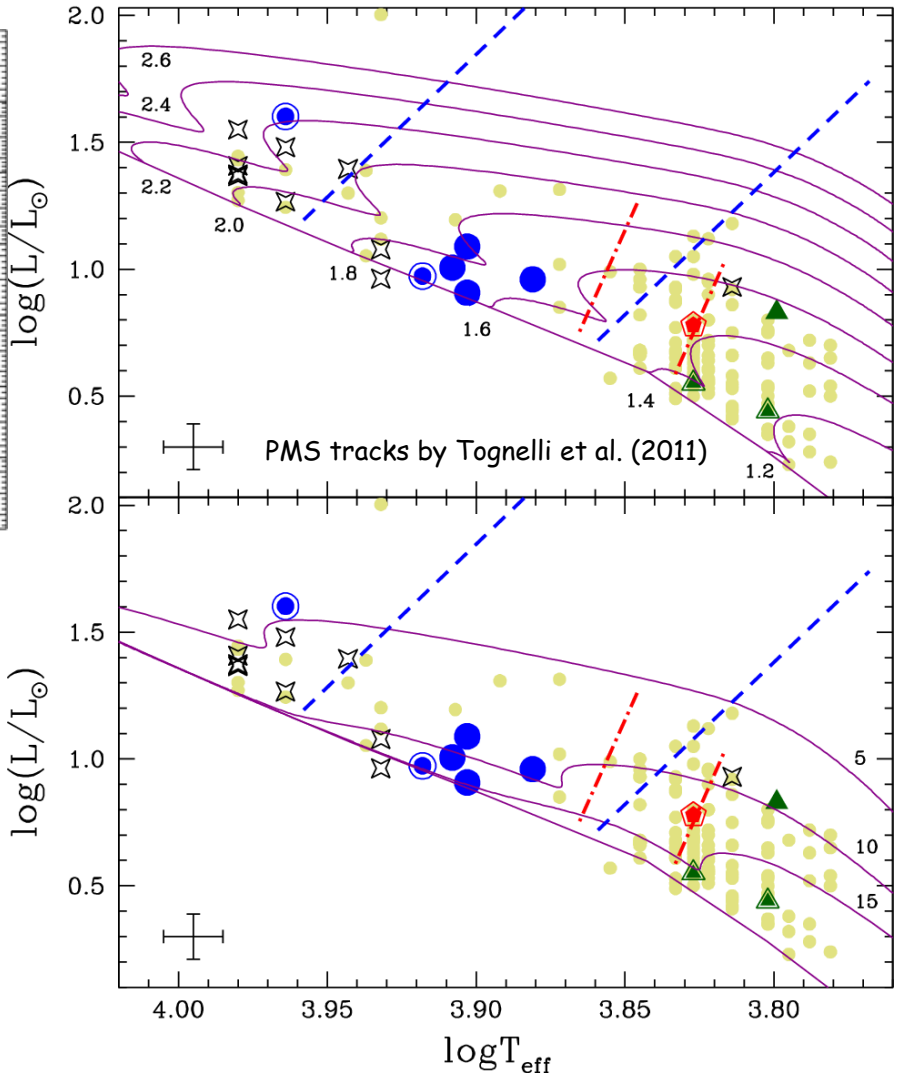
# Kepler observations of A-F pre-main-sequence stars in Upper Scorpius (one of earliest Francesco's targets) → 6 new PMS $\delta$ Scuti + 1 PMS Gamma Dor



BJD-2456000



BJD-2456000



Ripepi et al. 2015 MNRAS

Using photometric time series from ground and space (MOST, CoRoT, Spitzer & Kepler) the number of confirmed pulsating pre-main sequence stars has increased significantly.

*Bernabei et al. 2007 CoAst, 2009 A&A*

*Cusano et al. 2011 MNRAS*

*Marconi et al. 2000, 2001 A&A, 2002 CoAST, 2003 Ap&SS, 2004 CoAst, 2010Ap&SS*

*Pinheiro et al. 2003 A&A*

*Ripepi et al. 2002, 2003, 2006, 2007 A&A, 2010 Ap&SS, 2011, 2014, 2015 MNRAS*

*Zwintz et al. 2005 MNRAS, 2006, 2009 A&A, 2011 ApJ, 2013 A&A, 2014 IAUS*

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**About 50 known PMS intermediate-mass pulsating stars**

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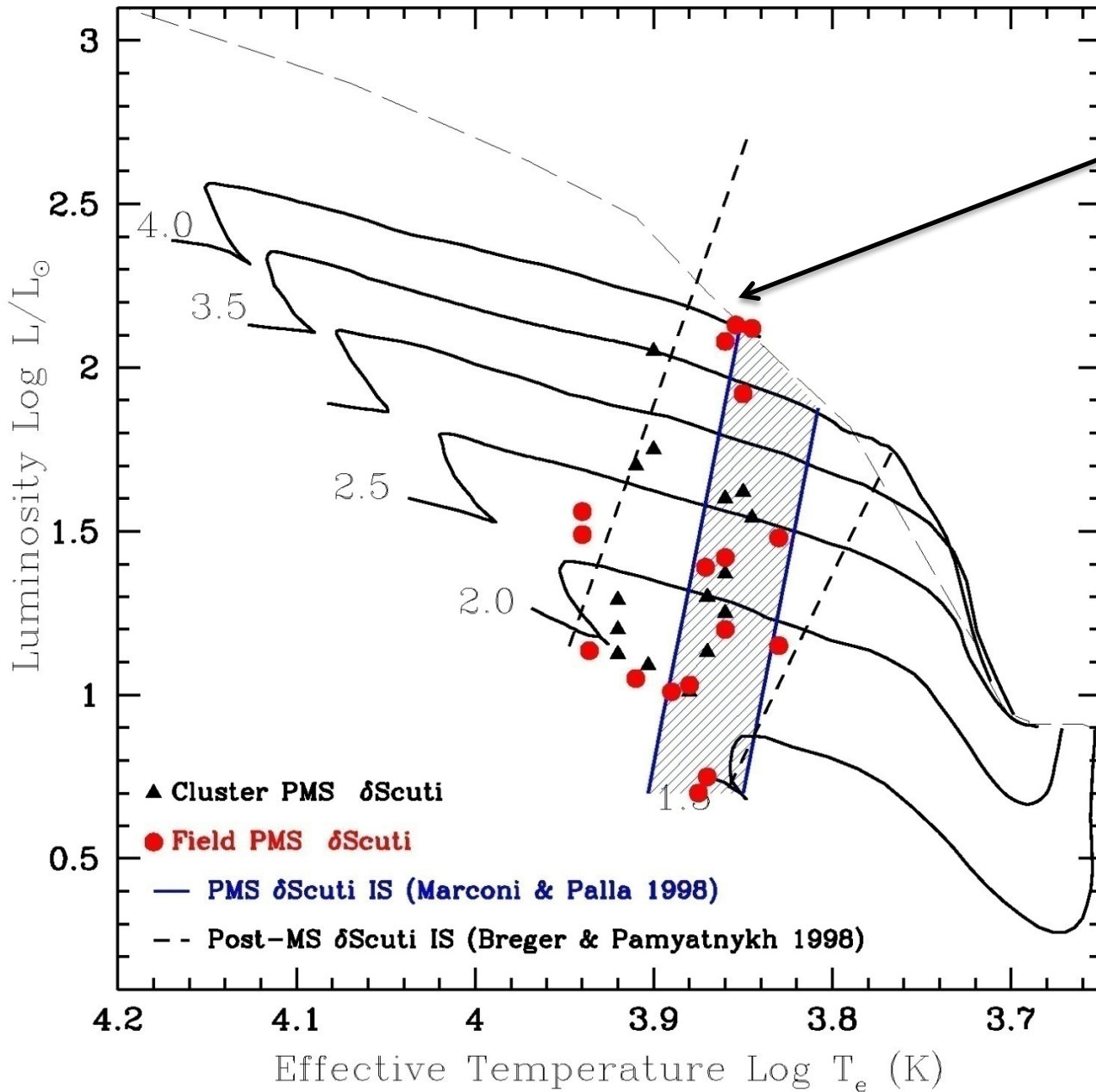
*Ripepi et al. 2002, 2003, 2006, 2007 A&A, 2010 Ap&SS, 2011, 2014, 2015 MNRAS*

*Zwintz et al. 2005 MNRAS, 2006, 2009 A&A, 2011 ApJ, 2013 A&A, 2014 IAUS*

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**About 50 known PMS intermediate-mass pulsating stars**

**But there were also significant theoretical developments**



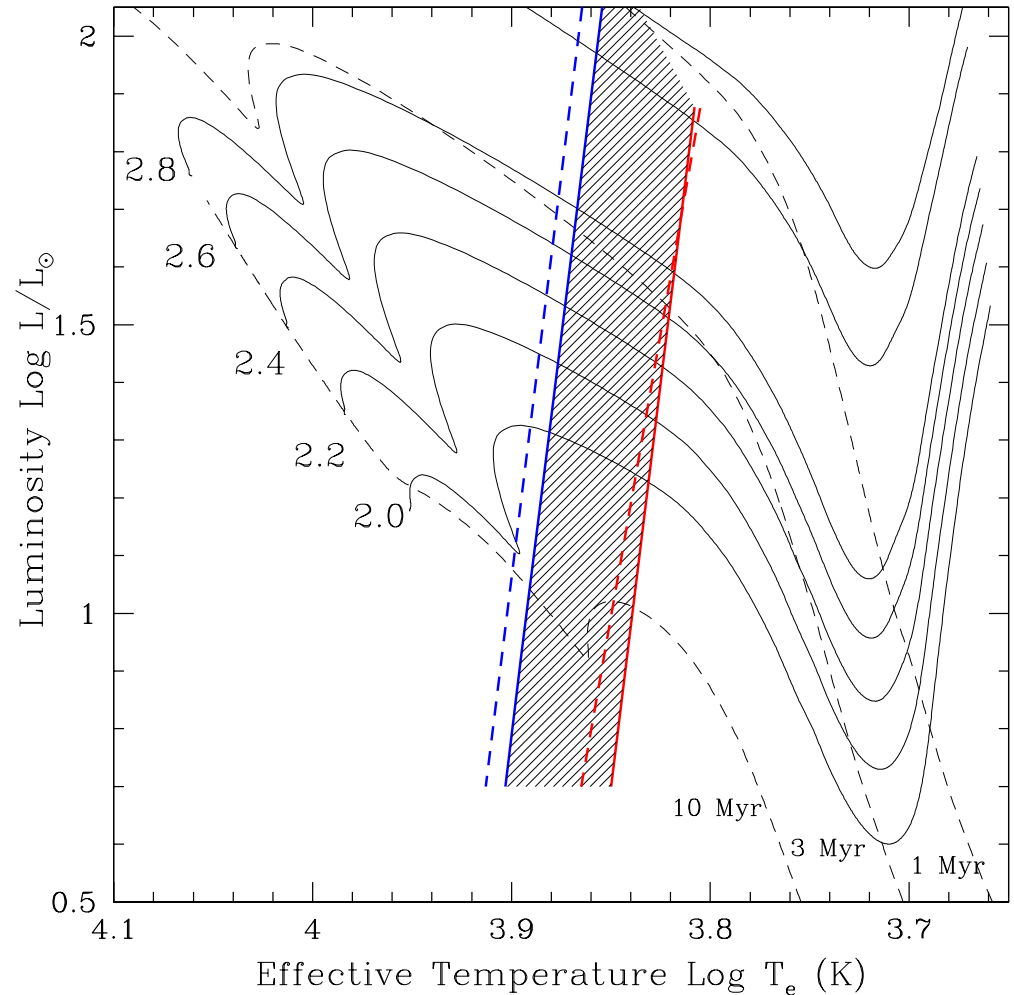
Empirical evidence of pulsating stars bluer than the second overtone blue edge  
→ wider strip than predicted



# New theoretical results

→ Decreasing the metallicity from solar to half solar the instability strip gets bluer

→ The effect is not enough



# New theoretical results

- Radial modes higher than the Second Overtone are commonly observed in these stars and predicted by pulsation theory (see also Grigahcène et al. 2006)
- PMS  $\delta$  Scuti pulsate both in radial and nonradial modes (Suran et al. 2001, Ruoppo et al. 2007, Di Criscienzo et al. 2009, Guenther et al. 2009)

Frequency of pulsation mode:  $\nu(l,m,n)$

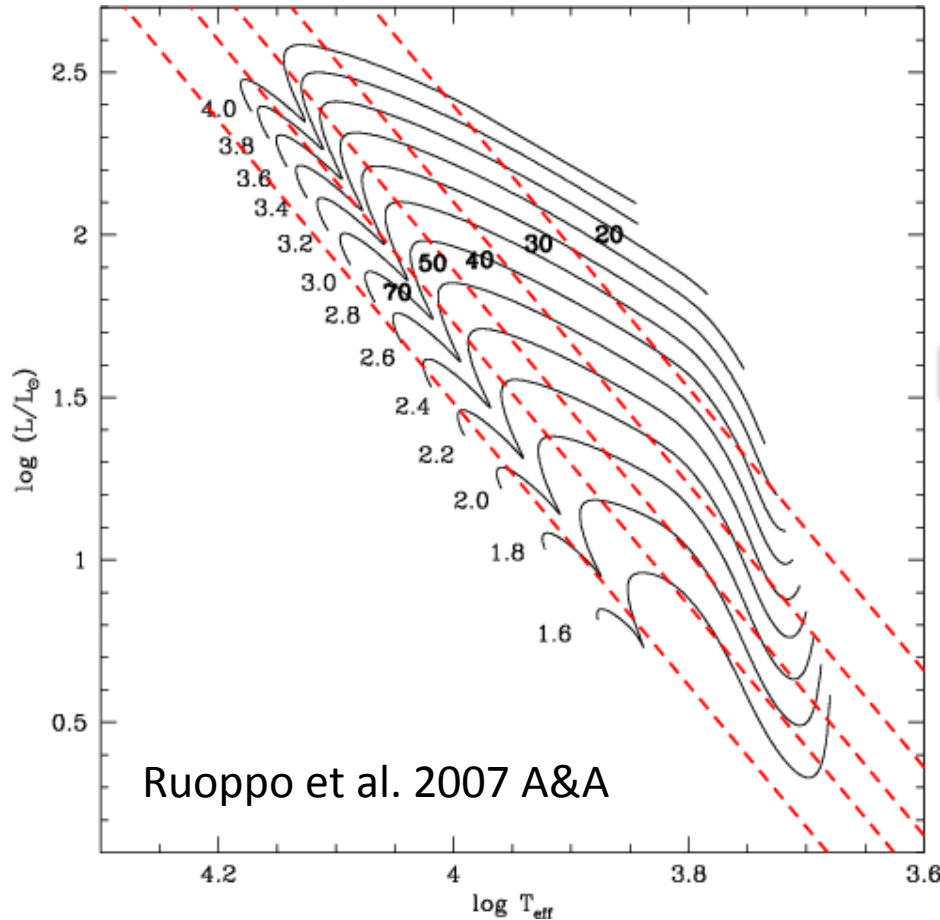
Nonradial modes described by  $Y_l^m(\theta, \varphi)$

$n$ : radial order;  $l$ : angular degree,  $m$ : azimuthal order

Large frequency separation

$$\Delta\nu_{n,l} \equiv \nu_{n,l} - \nu_{n-1,l} \cong \Delta\nu$$

$\log \Delta\nu$  is related to  $\log L/L_{\odot}$  and  $\log T_{\text{eff}}$



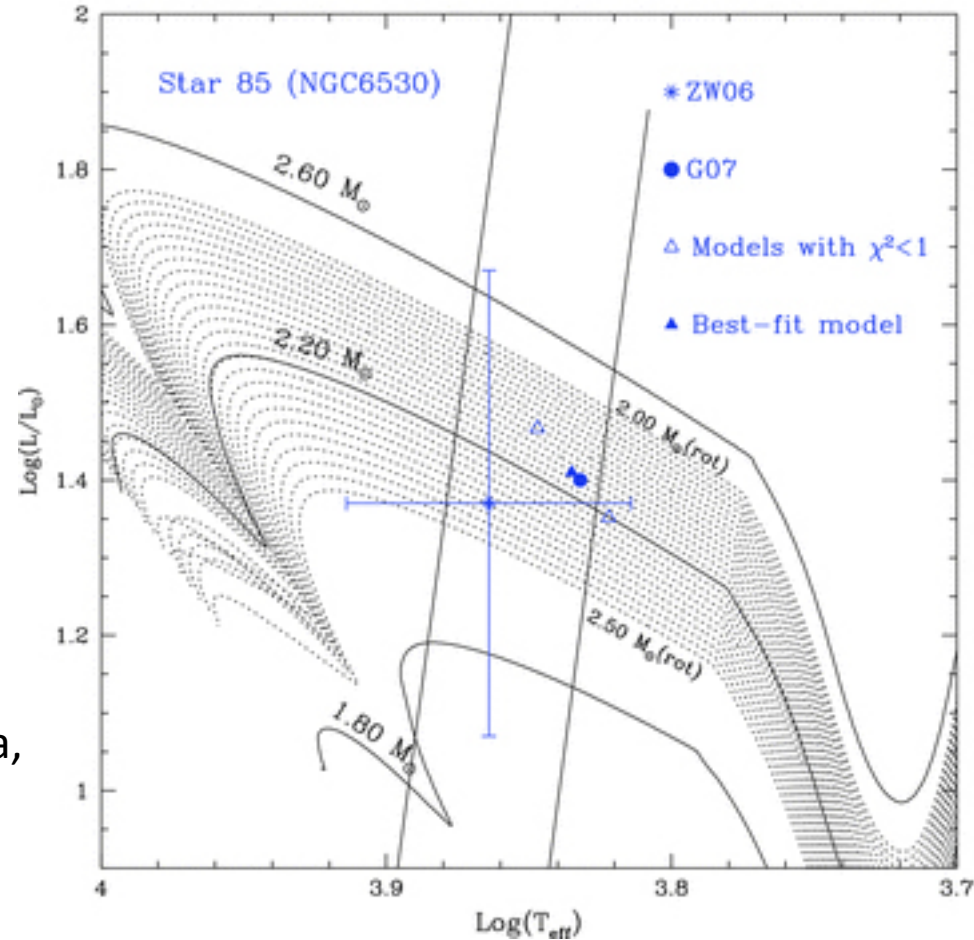
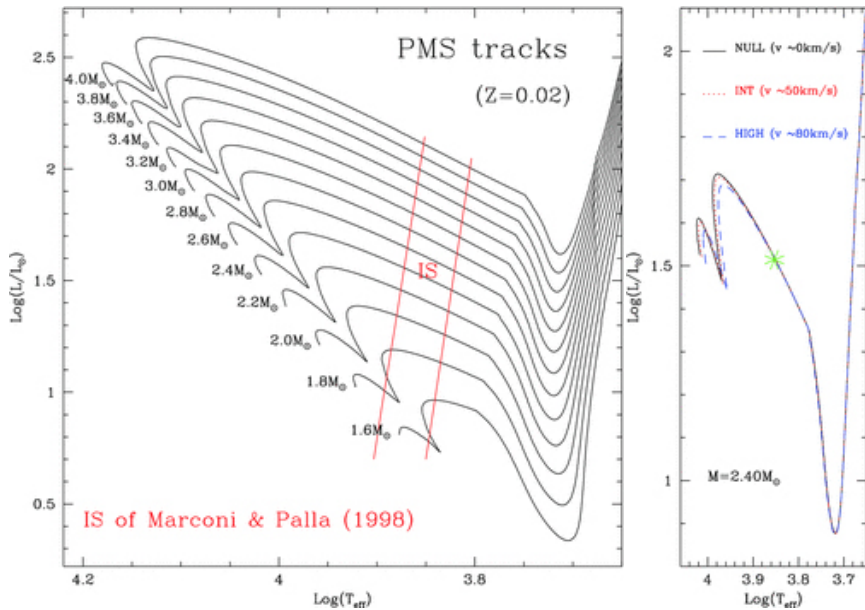
Constraints on the position in the HR diagram

Optimization of the FRANEC code for asteroseismological purposes  
(*Degl'Innocenti et al. 2008; Marconi et al. 2008*)

Developments of specific tools to interpret PMS delta Scuti frequencies  
(*Guenther & Brown 2004; Di Criscienzo et al. 2008; Guenther et al. 2009; Casey et al. 2013*)

# New theoretical results

Using ATON evolutionary tracks, also including the effect of rotation  
(*Di Criscienzo et al. 2008 MNRAS*)



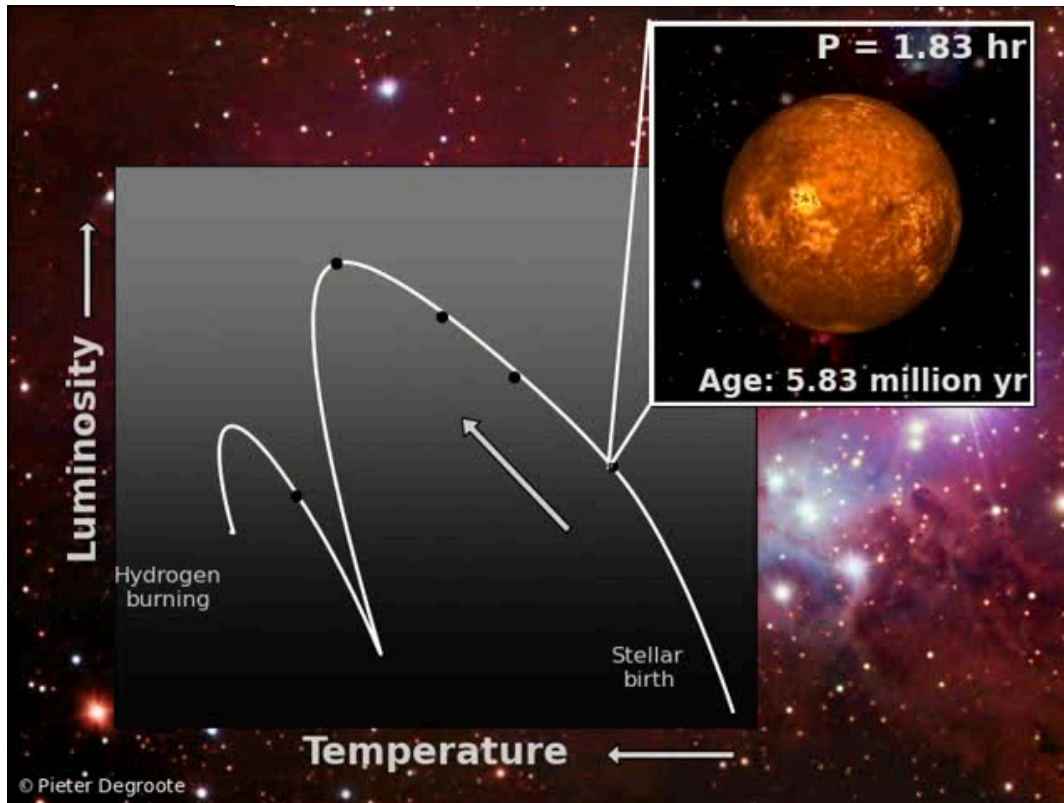
→ confirm with self-consistent rotating models, previous interpretation of the data, attributing three close frequencies to the mode  $n=4$ ,  $l=1$  and  $m=0, +1$  and  $-1$ .

(*Di Criscienzo et al. 2008 MNRAS*)

In the latest years Francesco was particularly fascinated by the idea of using seismic analysis to identify young stars and their evolutionary status



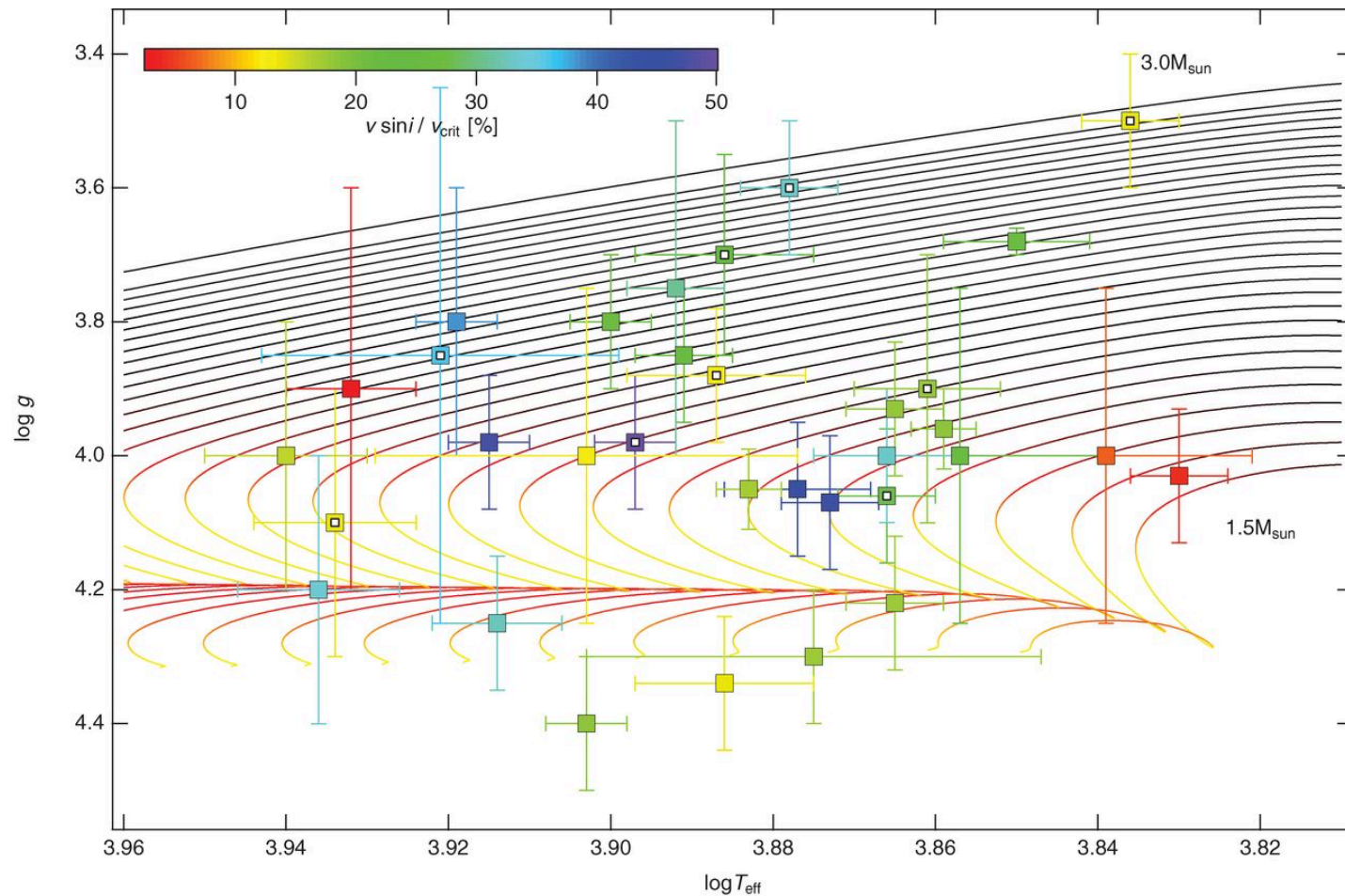
**The beat of young stars**  
Steven Stahler and Francesco Palla  
*Science* **345**, 514 (2014);  
DOI: 10.1126/science.1257301



**Francesco** and **Steven** nicely introduced a work by Zwintz et al. (2014, *Science*) on the variation of the oscillation frequencies with ages.

This is a consequence of the well known Period-Density relation but with challenging implications

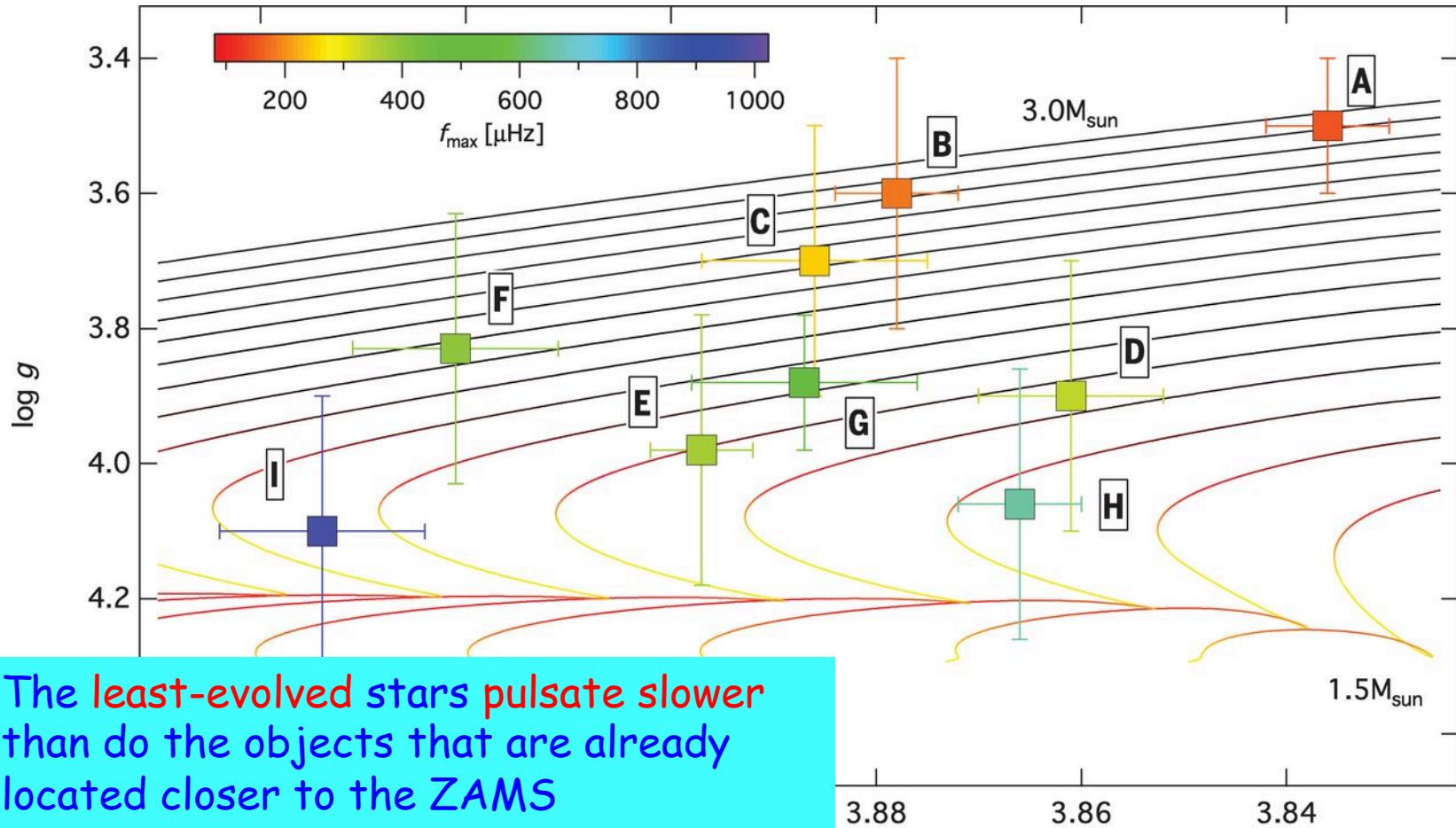
# Evolutionary diagram of surface gravity versus effective temperature for 34 pulsating pre-MS stars



Zwintz et al. 2014 Science

The hottest and most evolved stars have the highest  $f_{\text{max}}$  values and pulsate with the shortest periods.

Evolutionary diagram of surface gravity against effective temperature showing a subset of nine pulsating pre-MS stars in the young cluster NGC 2264 (MOST and CoRoT data)



The **least-evolved** stars pulsate slower than do the objects that are already located closer to the ZAMS

- Sequential star formation
- Dispersion in age of  $\approx 5\text{Myr}$

See also Poster #94 (Laura Venuti)

Zwintz et al. 2014 Science

# This approach has also been applied to the Upper Scorpius association (Ripepi et al. 2015)

Very interesting due to:

- the large number of known A-F members
- The availability of accurate individual distances based on Hipparcos (and Gaia)
- stellar parameters independently estimated for most of the member stars.



Differently from the case of NGC2264, the **maximum oscillation frequency is similar** for all the investigated members.

In the case of Upper Scorpius the **age difference of its members seems to be very small**, or the correlation is not always present in young clusters/associations (Stahler & Palla 2014)



# Conclusions

PMS Scuti stars are Herbig Ae stars crossing the instability strip while evolving towards the ZAMS

They are important to constrain PMS structure and evolution

Francesco had the idea of theoretically predicting the Instability Strip for the first three radial modes

This theoretical result had a significant impact on the study of young pulsating stars → many new observational and theoretical works

→ We published more than 30 papers with Francesco on this subject

# Conclusions

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Francesco was particularly fascinated by the possibility of individually dating PMS stars belonging to clusters or associations through pulsation

- Giving one age for all cluster members is not sufficient and could be affected by large errors in particular for the youngest stars
- With new ultra-precise observations from the space (Gaia, PLATO, TESS) we will be able to seismically calibrate pre-MS stellar structure models and to better understand early stellar evolution.

Thanks Francesco !!!

