SONG 2018
1st workshop on Science with SONG: 4 more years
Tenerife, Spain, 23-26 October, 2018

Asteroseismology of the slowly rotating active subgiant-giant EK Eridani

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What we know about EK Eri

- HR 1362, HD 27536, V = 6.0 (at maximum), has been monitored photometrically since 1978
- Evolved star of spectral type G8 (T_{eff} ~ 5100 K) and log g = 3.39
- Precise photometric period measured with observing campaigns since 1978 give P_{rot} = 309 d
  Strassmeier & Hall 1988; Derman et al. 1989; Strassmeier et al. 1990b; Strassmeier et al. 1999; Dall et al. 2010
- Has very slow rotation, vsin *i* < 1 km/s, difficult to resolve spectroscopically
- Suggested axis inclination *i* ~ 90° from high-res spectroscopy and radius-vsin *i* diagram
  Strassmeier et al. 1999
- Observed solar Li-abundance, and metallicity
  Strassmeier et al. 1999

What we know about EK Eri

- First model by Aurière et al. (2008) for standard, non-rotating star using solar metallicity

- The star has recently ended the Hertzsprung gap phase and appears to be entering the first dredge up (G8III-IV)

- $M = 2.0\ M_{Sun}$

  $R = 4.68\ R_{Sun}$

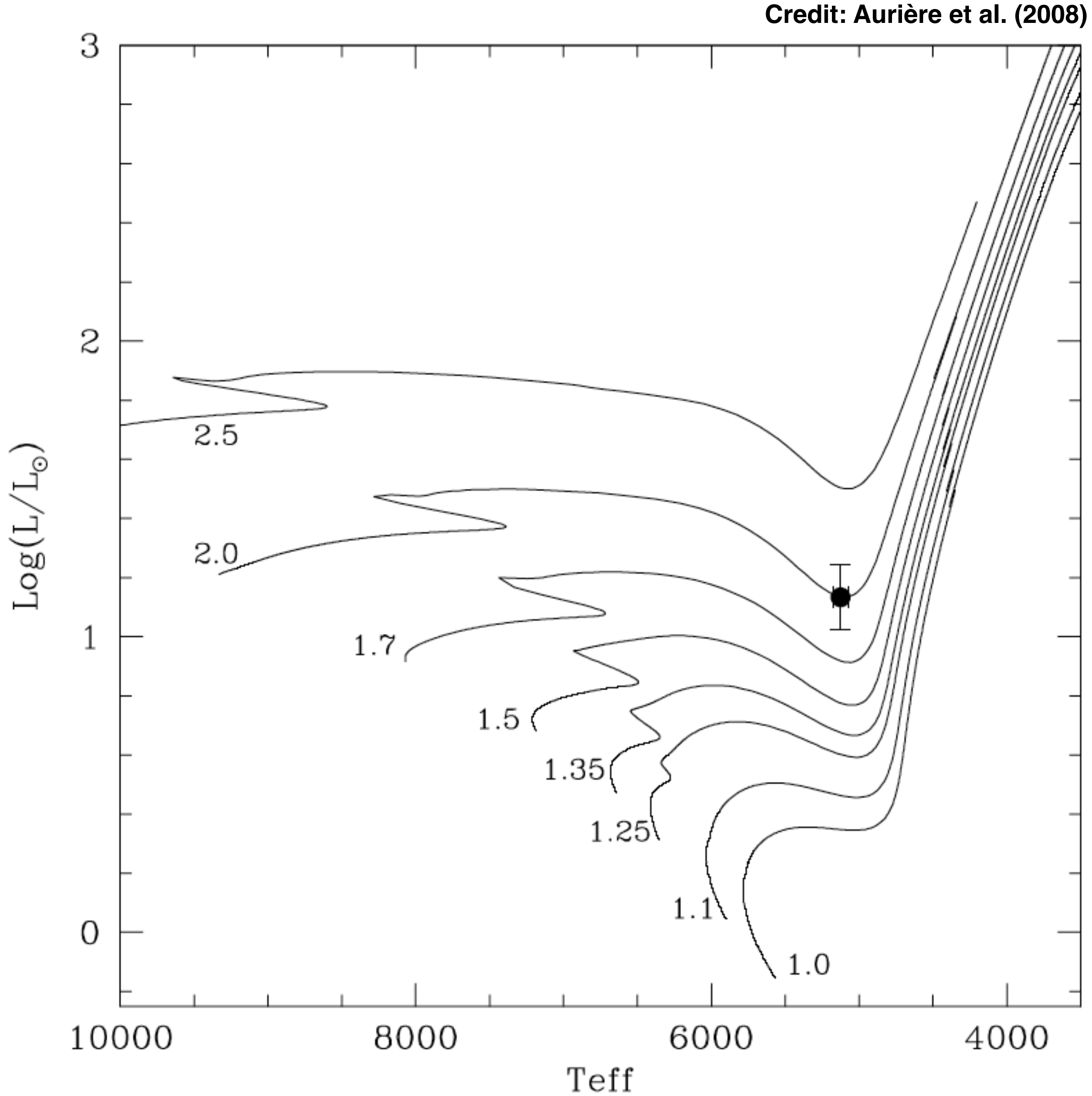
  from evolutionary tracks

- Convective zone has $M_{CZ} = 0.37\ M_{Sun}$

- Radius fully consistent with estimate from Hipparcos parallax $4.7 \pm 0.3\ R_{Sun}$
  Strassmeier et al. 1999

- Li abundance expected to decrease because of first dredge-up

Credit: Aurière et al. (2008)



Which progenitor?

- We have an early giant with 2 M_{Sun} and spectral type G8
- Can the progenitor be a A5V star?
- These stars rotate (in general) rapidly (about 100 km/s) and end up with a rotation period of about ~20 km/s at EK Eri's evolutionary phase
- But EK Eri has v ~ 0.16 km/s from its P_{rot} !
- Then EK Eri more likely descendant of CP A star (Ap), which are slow rotators (10 % of total A-type stars)

Magnetic field

- First direct measurement of magnetic field in EK Eri by Aurière et al. (2008) using spectropolarimeter NARVAL (Zeeman effect)
- EK Eri has large scale magnetic field, dominated by a poloidal, mostly axysimmetric component
- Magnetic field strength **very high**! About **|B| = 270 G** !
  About **100** times more active than other magnetically active G-K giants (Sun has only 1 G)
- Can the progenitor be a strongly magnetized Ap star?
  Stepień 1993; Strassmeier et al. 1999
- Half of Ap stars are also magnetically active
  Abt and Moreell 1995

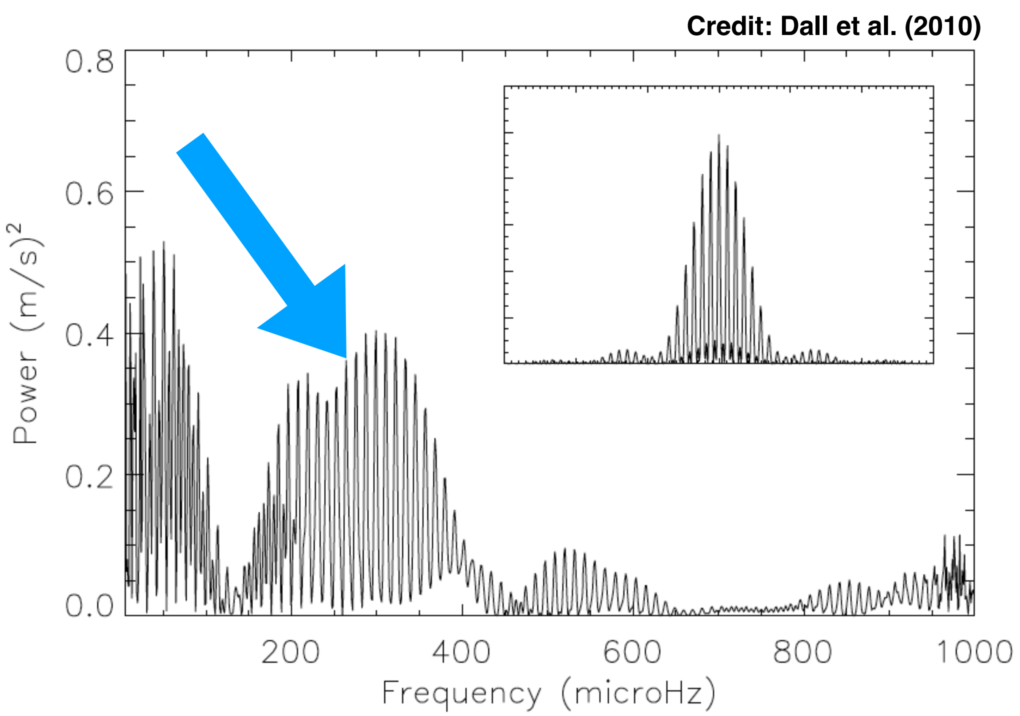
Puzzling case

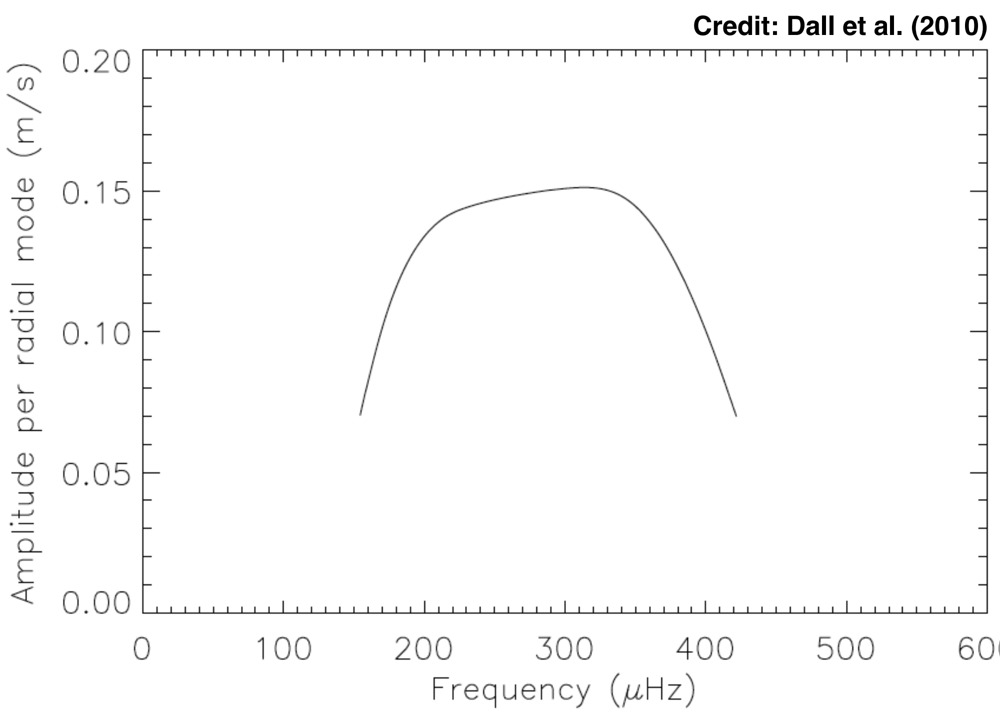
- EK Eri is a very slow rotator (P_{rot} = 309 d)
- In general, standard α-ω dynamo mechanism is not activated if critical angular velocity not reached.
- Also, α-ω dynamo stops operating once the star has slowed down sufficiently from the MS phase (after core-H-burning exhaustion)

Puzzling case

- EK Eri has very high level of chromospheric activity and high coverage of cool star spots.
- Indication that strong surface magnetic fields are at play, and these are believed to be originated from a dynamo mechanism
- But magnetic field strength expected to decrease as $1/R^2$ as star evolves (if flux is conserved!). Not the case for EK Eri
- Maybe α^2 dynamo operating in EK Eri ?

Solar-like oscillations





- First detection of solar-like oscillations by Dall et al. (2010) using HARPS high-precision RV observations (3 nights)

- Characteristic frequency of maximum oscillation power

$$\nu_{\max} = 320 \pm 32\,\mu\mathrm{Hz}$$

- Oscillation amplitude lower than expected (about factor 3)

$$A_{\max,\ell=0} = 0.15\,\mathrm{m/s}$$

Solar-like oscillations

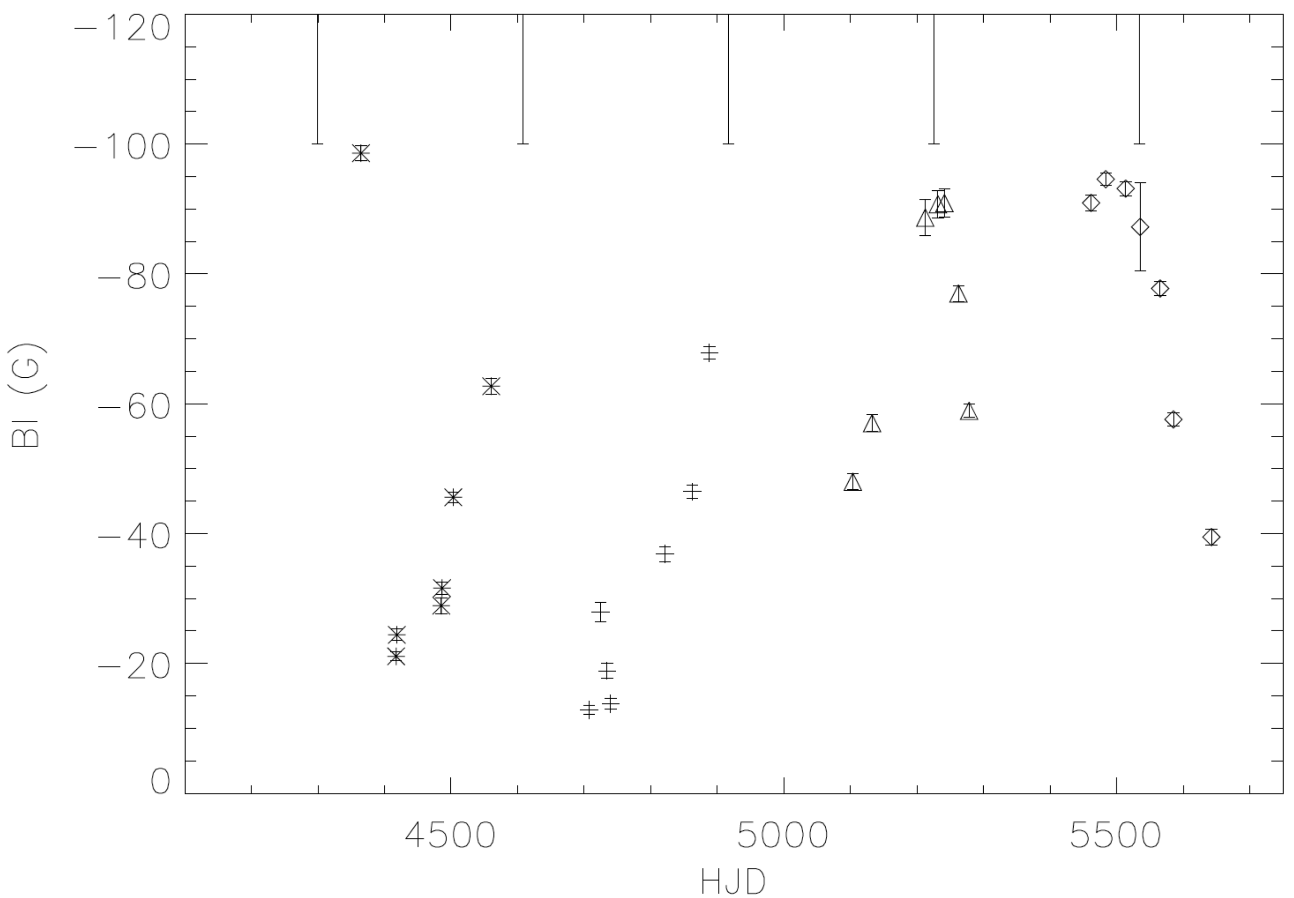
- Using the high S/N HARPS spectra, **Dall et al. (2010)** derived the following fundamental properties
  - T_{eff} = 5135 ± 60 K
  - log g = 3.39 ± 0.06
  - [M/H] = +0.02 ± 0.04

- And from isochrone (BaSTI) fitting
  - M = 1.92 ± 0.13 M_{Sun}
  - R = 4.87 ± 0.29 R_{Sun}
  - Age: 1.1 ± 0.2 Gyr
  - log g = 3.35 ± 0.06

- They propose that $P_{rot} = 2P_{phot}$ = 618 d
  EK Eri is a dipole-dominated rotator viewed close to equator-on and having two big spots separated by 180° on the surface

More insights on magnetic field

Credit: Tsvetkova PhDT (2014)



- Tsvetkova PhDT (2014) obtained new measurements of magnetic field with spectropolarimeter NARVAL - from 2007 to 2011
- Magnetic field B only shows negative polarity, and has seasonal variation
- Similar trends found in Ca II IR, S-index, Hα

- Isolated enhancements of both B and activity indicators - **flares** as possible cause (present in other active Giants)
  Konstantinova-Antova et al. 2000, 2005a

More insights on magnetic field

- Conclusion is that EK Eri only shows one pole of the dipole
  Therefore **$P_{rot} = P_{phot} = 309$ d**

- From ZDI (Zeeman Doppler Imaging) models suggest
  vsin i ~ 0.7 km/s and *i* ~ 60°

- Magnetic field topology:
  - dipolar component should contain 90% of magnetic energy
  - magnetic/photometric star spot possibly corresponds to remnant of magnetic pole of Ap progenitor

Why is EK Eri important?

- Because coexistence of:
  + very slow rotation period
  + very high dipolar magnetic field strength

  Aurière et al. 2008; Tsvetkova PhDT 2014

  + typical dynamo-like surface features (star spots, chromospheric activity, and possibly flares)

  Strassmeier et al. 1999; Tsvetkova PhDT 2014

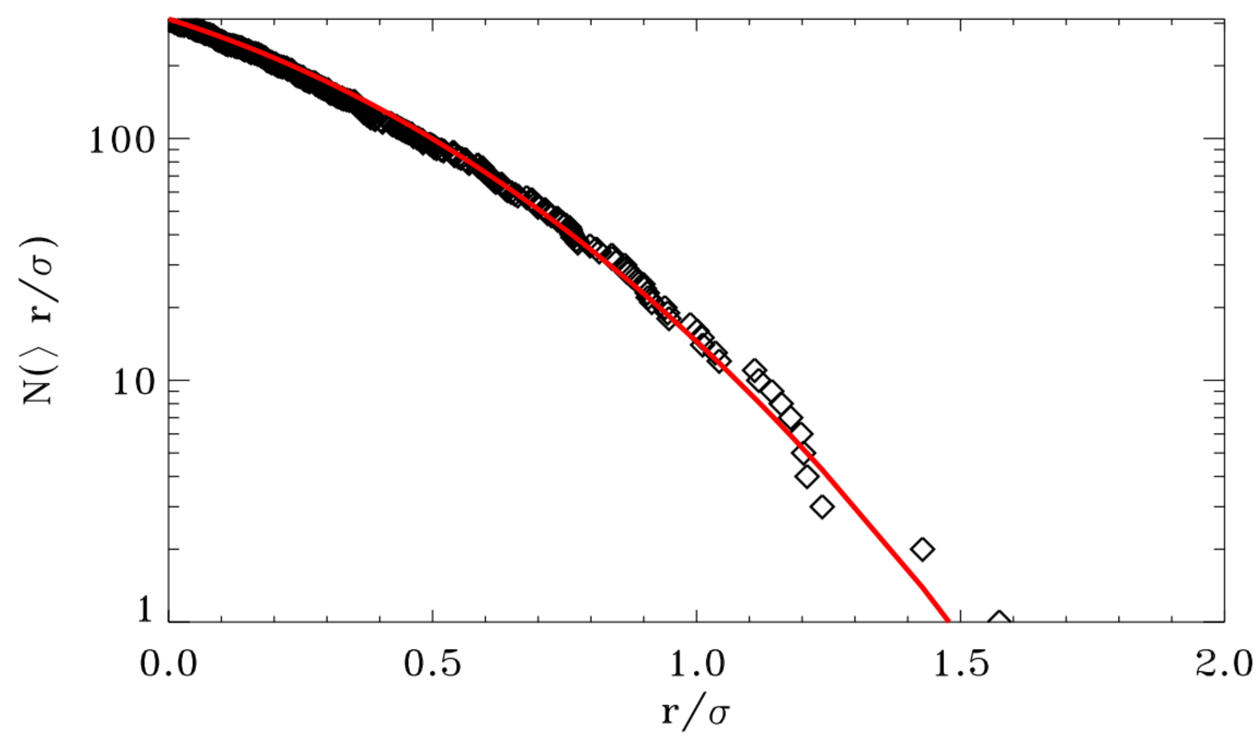
  + solar-like oscillations

  Dall et al. 2010

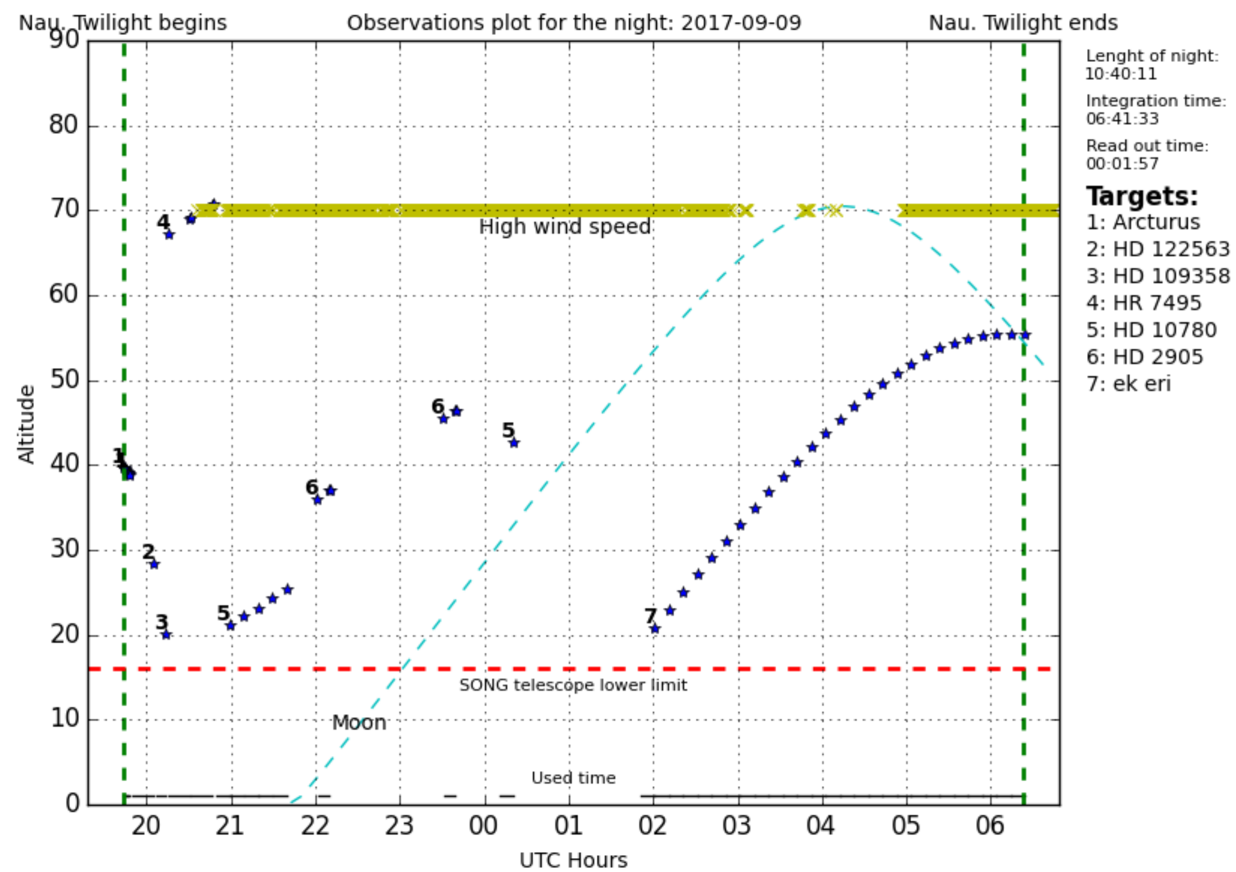
- EK Eri is a test case for stellar dynamo theories and to study the impact of magnetic fields on stellar oscillations

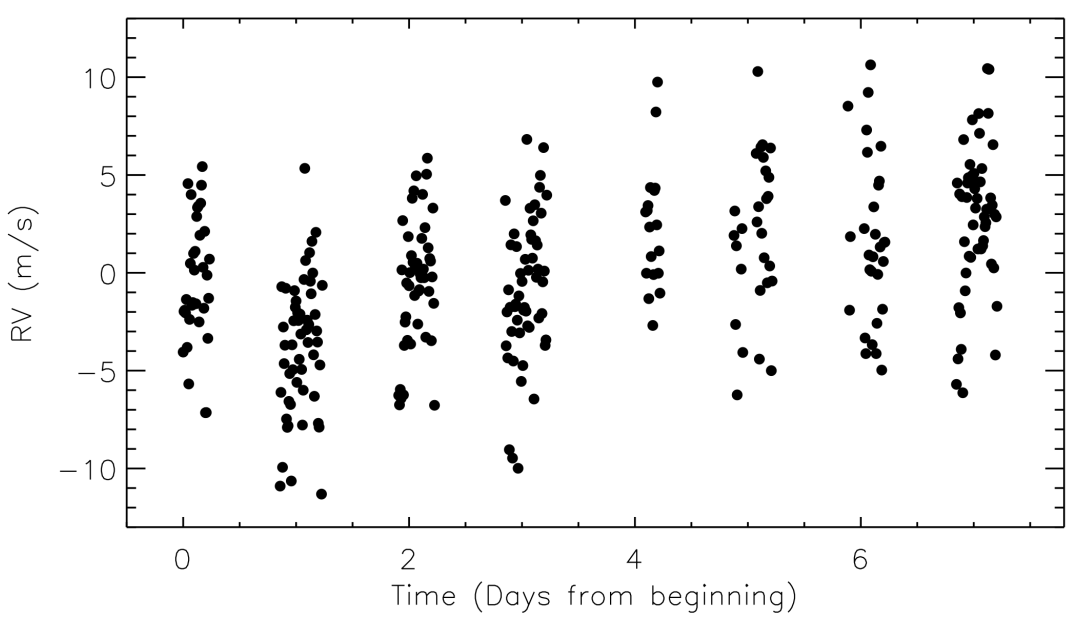
New SONG observations

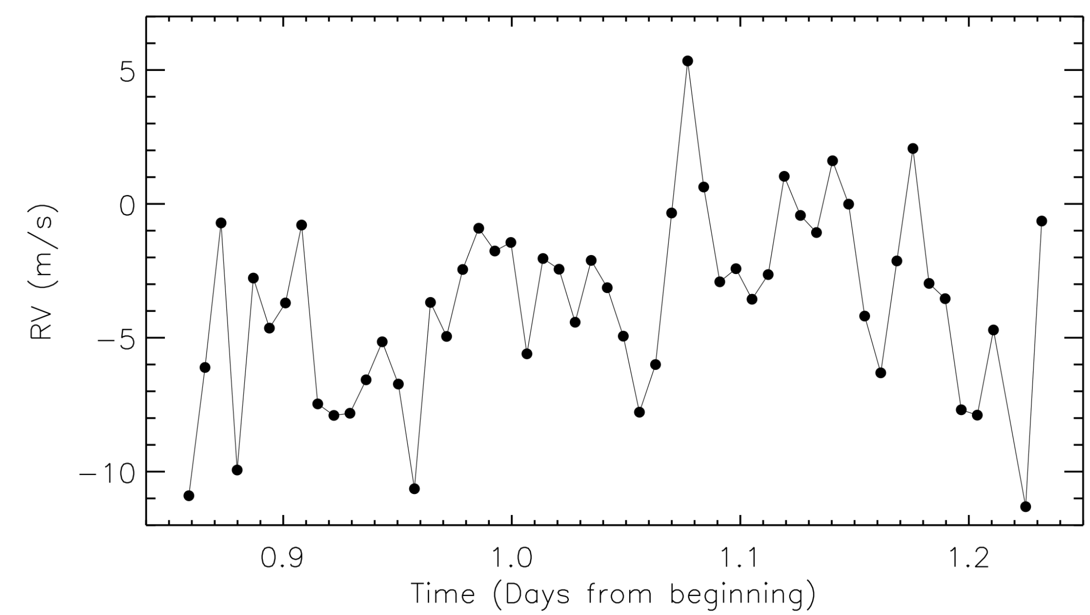
- EK Eri observed in Period 06 - December 2017
  for a total of ~8 nights
- ~370 RV measurements, with rms precision of ~3.3 m/s
- Time-series processed with outliers analysis
  Corsaro et al. 2012a



New SONG observations



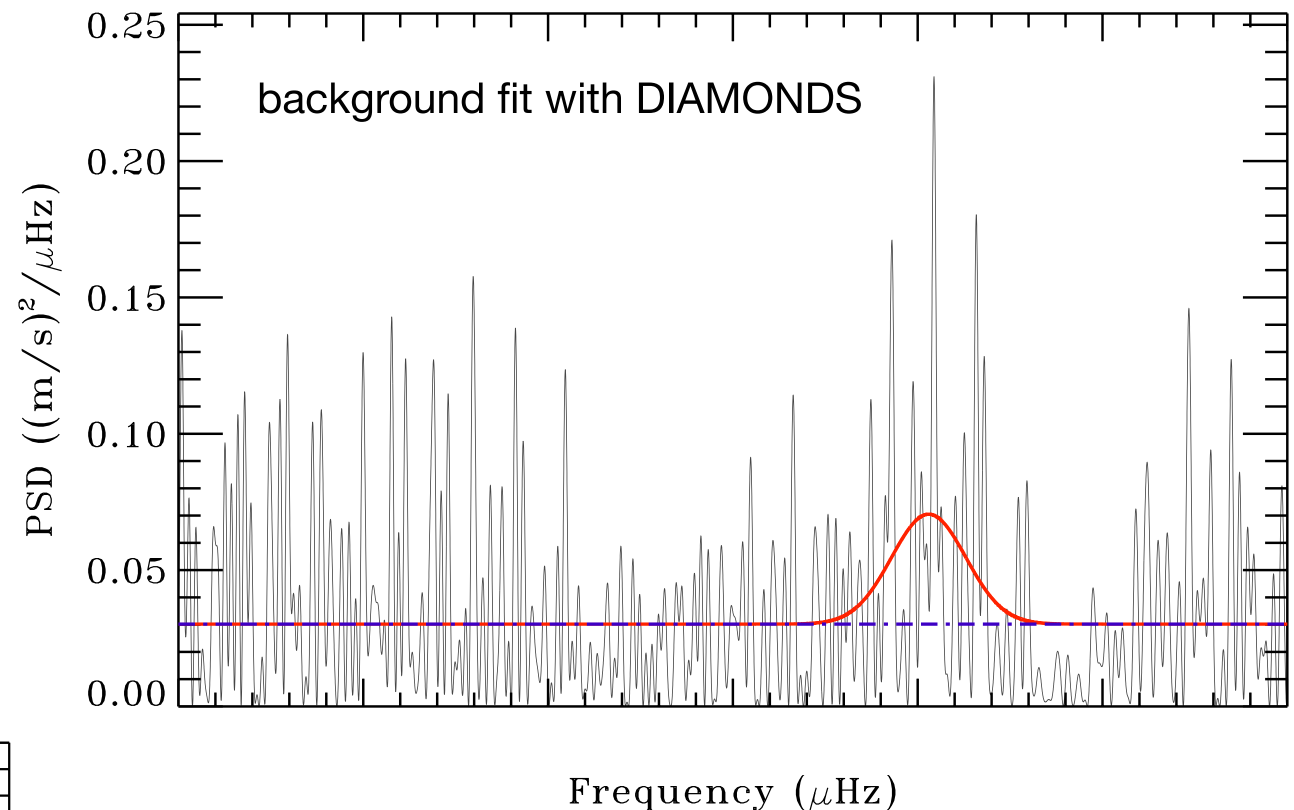


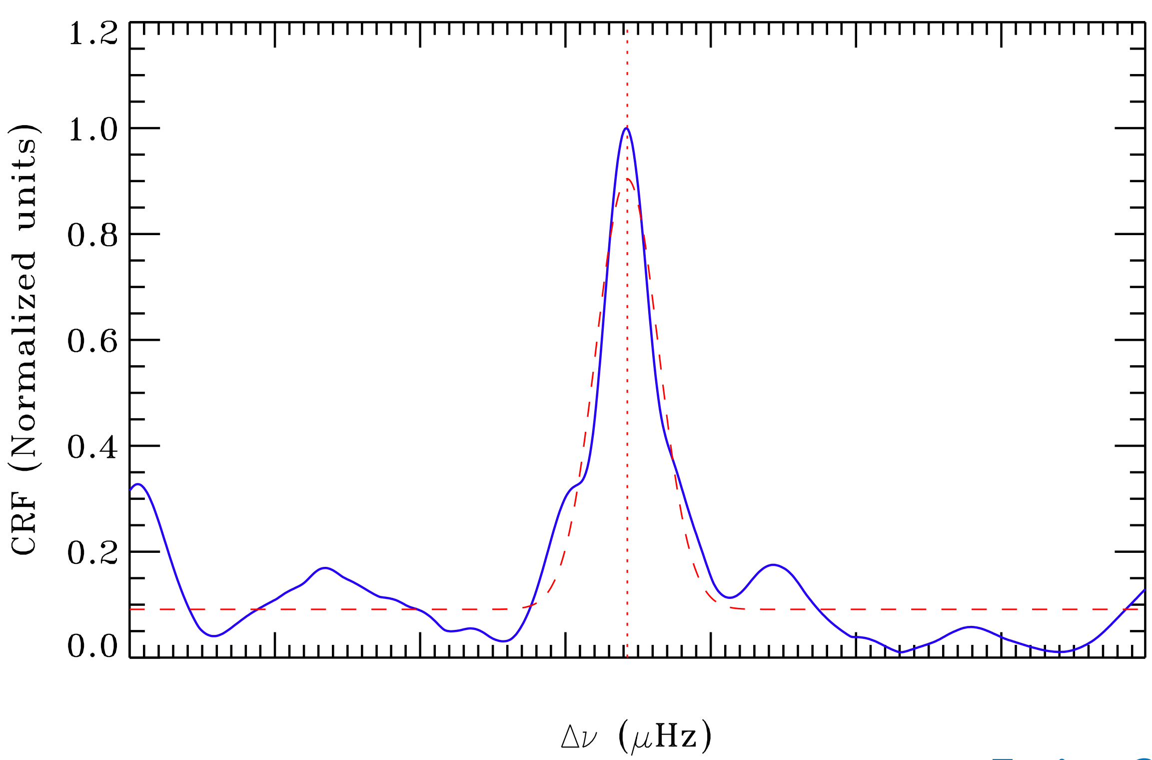


Asteroseismology

- Detected oscillation bump, but lower frequency than in Dall et al. (2010)

$$\nu_{\mathrm{max}} < 300\,\mu\mathrm{Hz}$$





- Detected clear signal of large freq. sep. from 10 highest peaks in oscillation region through CRF (Corsaro et al. 2012a, Bonanno et al. 2008)

$$10\,\mu\mathrm{Hz} < \Delta\nu < 20\,\mu\mathrm{Hz}$$

New results

- Use spectroscopic T_{eff} from Dall et al. (2010)

- Scaling relations parameters:
  $M_{Astero} \approx 1.99$
  $R_{Astero} \approx 5.12$

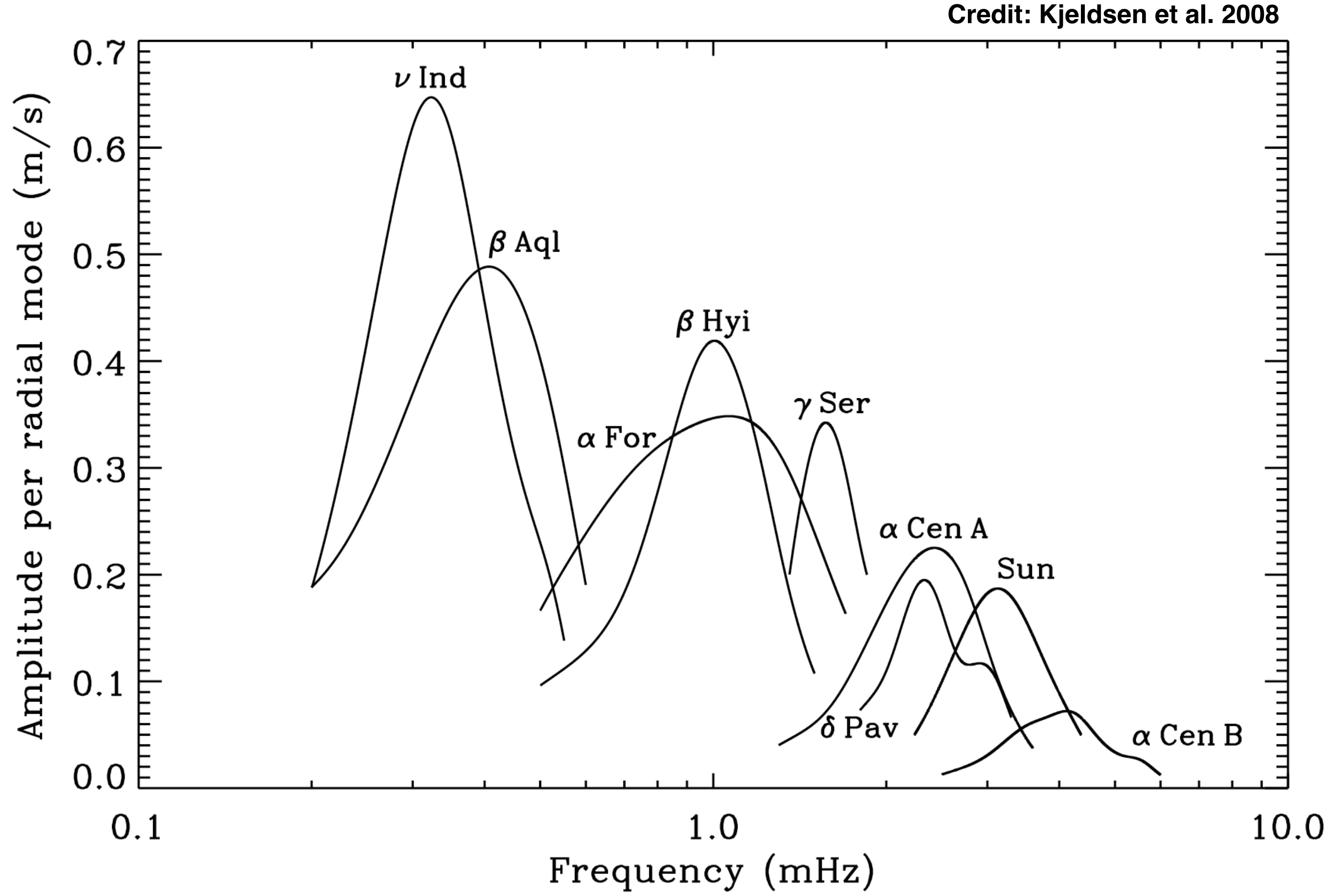
- Gaia DR2 parallax
  - d = 64.1692 ± 0.0002 pc
  - Bol. Corr. (Flower 1996)
  - A_V from 3D dust map PanSTARRS-1 (Green et al. 2015)

  - **$R_{Gaia}/R_{Sun} = 4.91 \pm 0.13$**
    $L/L_{Sun} = 15.07 \pm 0.35$

- Very good agreement with previous estimates
  Dall et al. 2010, Auriére et al. 2008

Oscillation amplitude

Credit: Kjeldsen et al. 2008

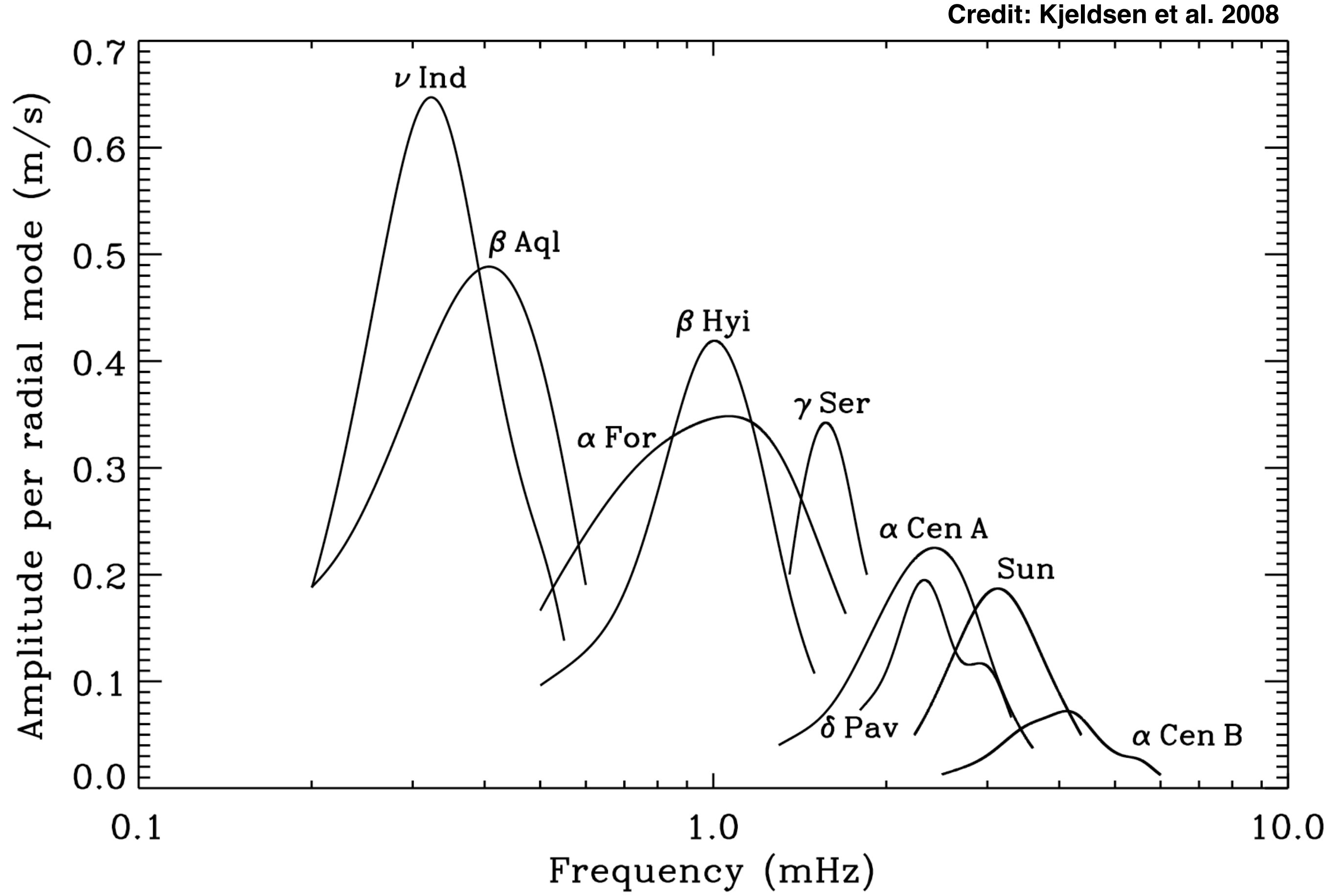


Kjeldsen & Bedding 1995

Oscillation amplitude

$$A_{\max} \propto \left(\frac{L/L_{\odot}}{M/M_{\odot}} \right)$$

Credit: Kjeldsen et al. 2008



Kjeldsen & Bedding 1995

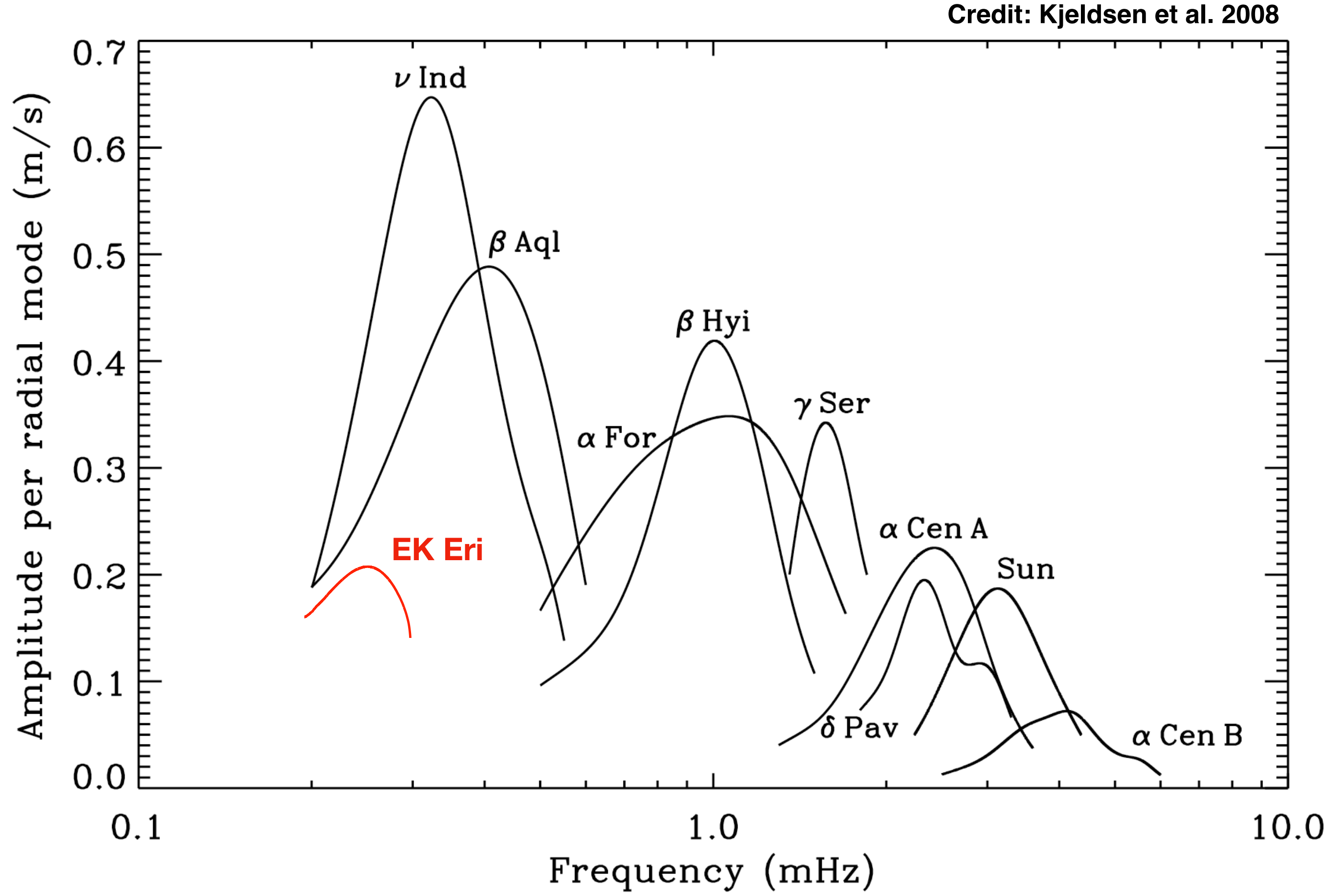
Oscillation amplitude

Strong suppression by magnetic field (almost factor 10) !

$$A_{\max,\ell=0} = 0.22\,\mathrm{m/s}$$

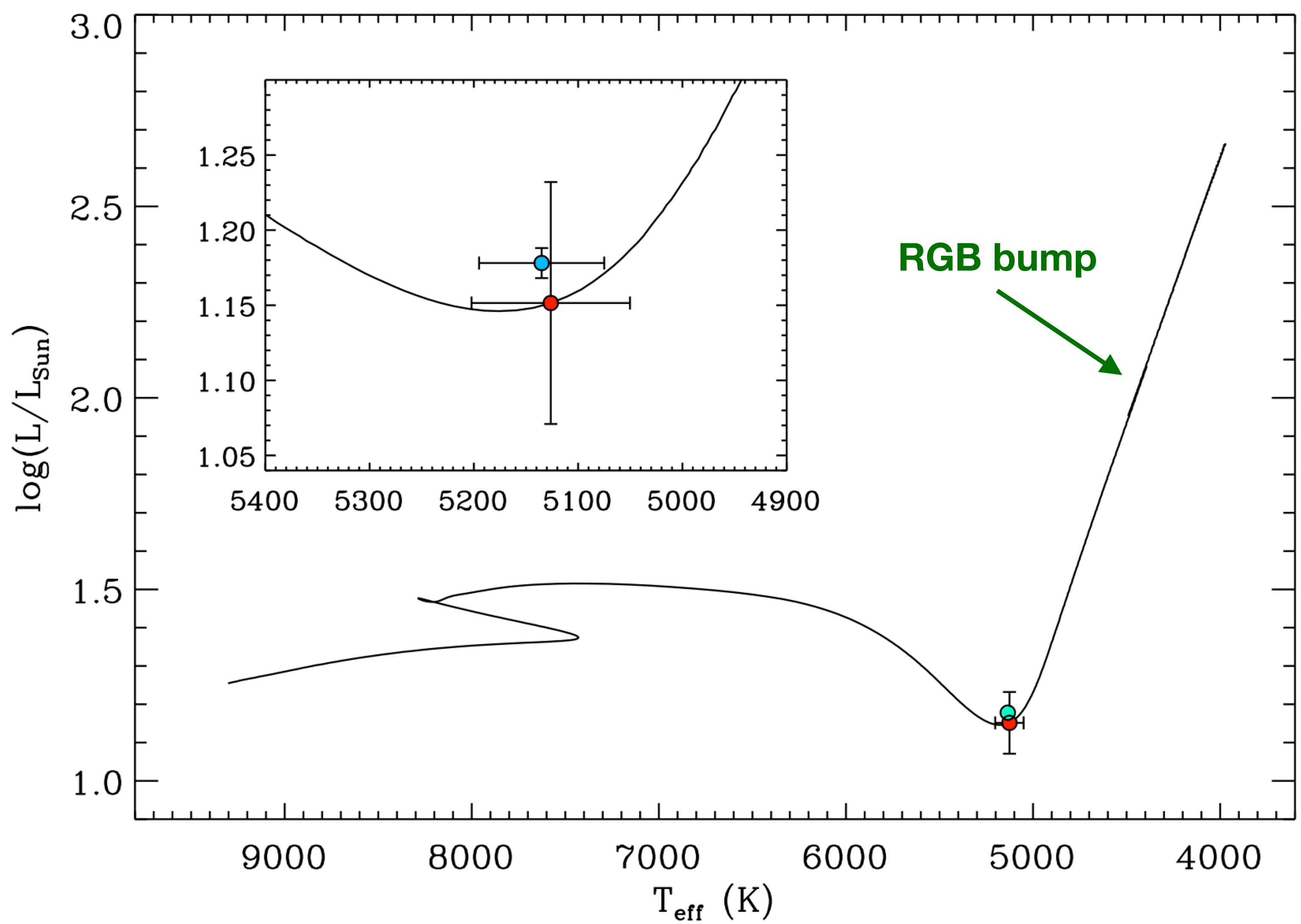
$$A_{\max} \propto \left(\frac{L/L_\odot}{M/M_\odot}\right)$$

Credit: Kjeldsen et al. 2008

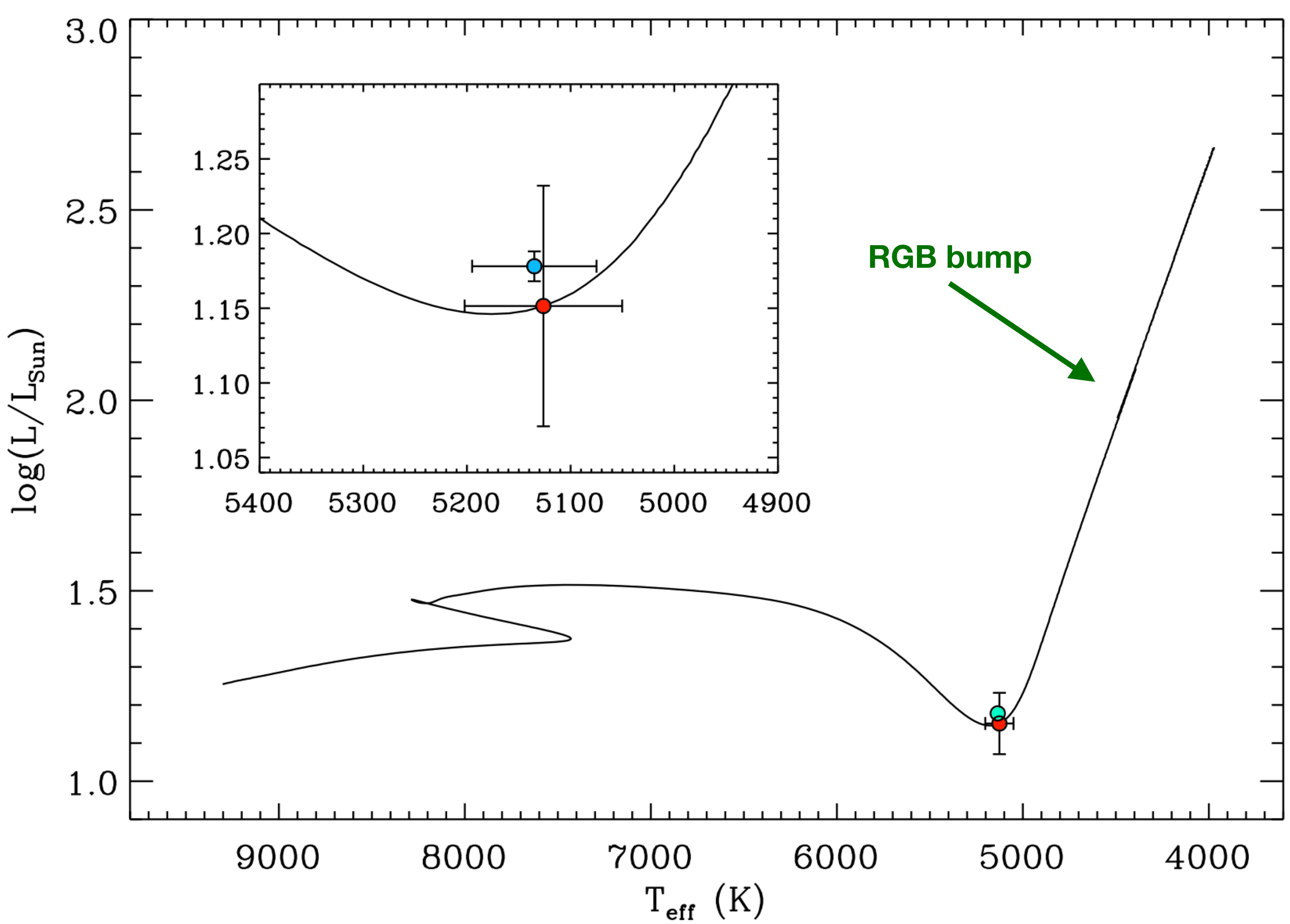


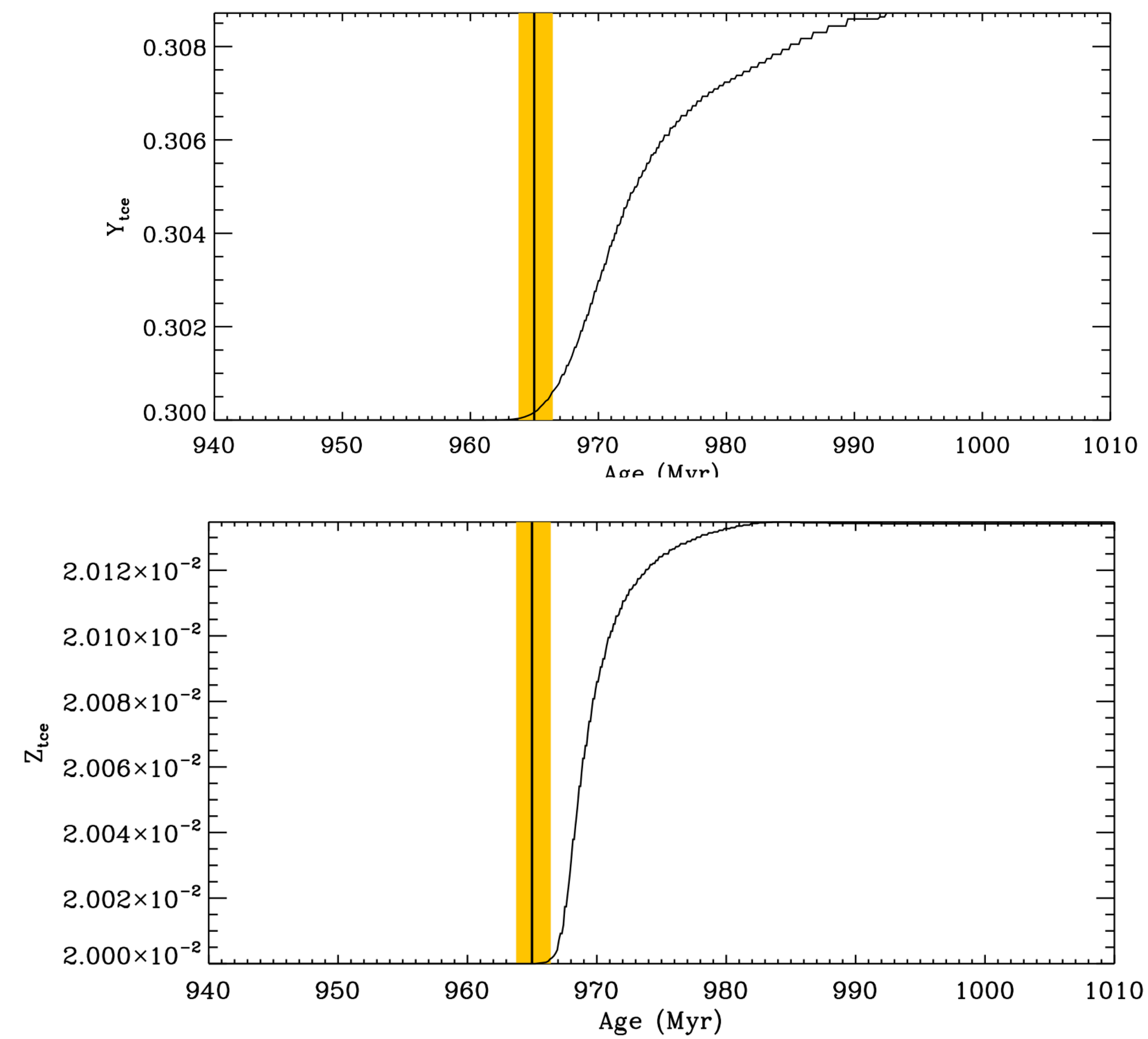
Evolutionary track

- Investigated different Y_i for solar Z, α
- Stellar evolutionary tracks for M = 2 M_{Sun} computed with GARSTEC
- Fit to the observed value of Δν, Teff and L/L_{Sun}
- Best solution for:
  Y_i = 0.300
  L/L_{Sun} = 14.17 ± 1.20
  R/R_{Sun} = 4.78 ± 0.35
  Age ≃ 965 Myr
- In agreement with literature and observations from SONG
  Progenitor: A3V
  Murphy PhDT

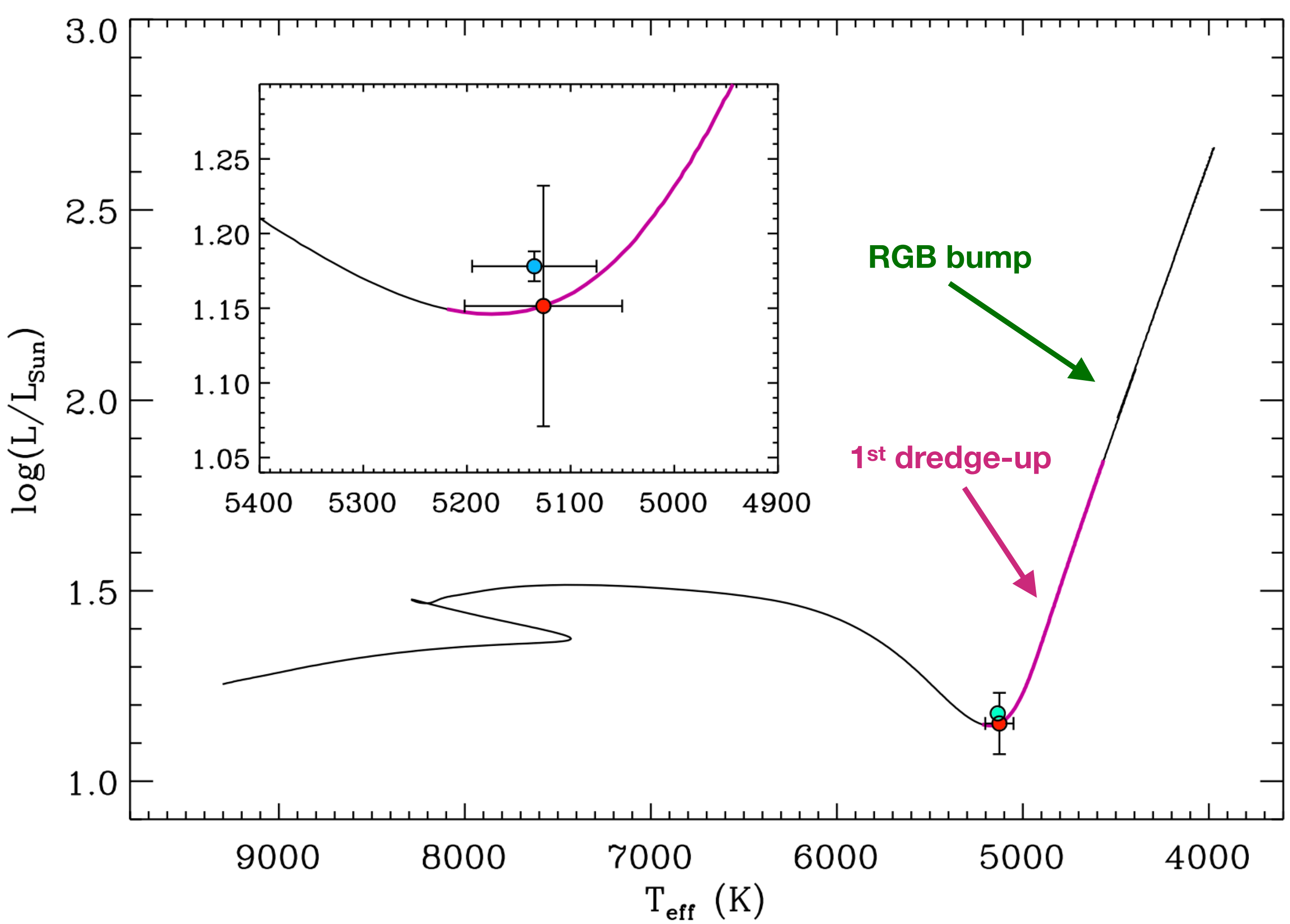


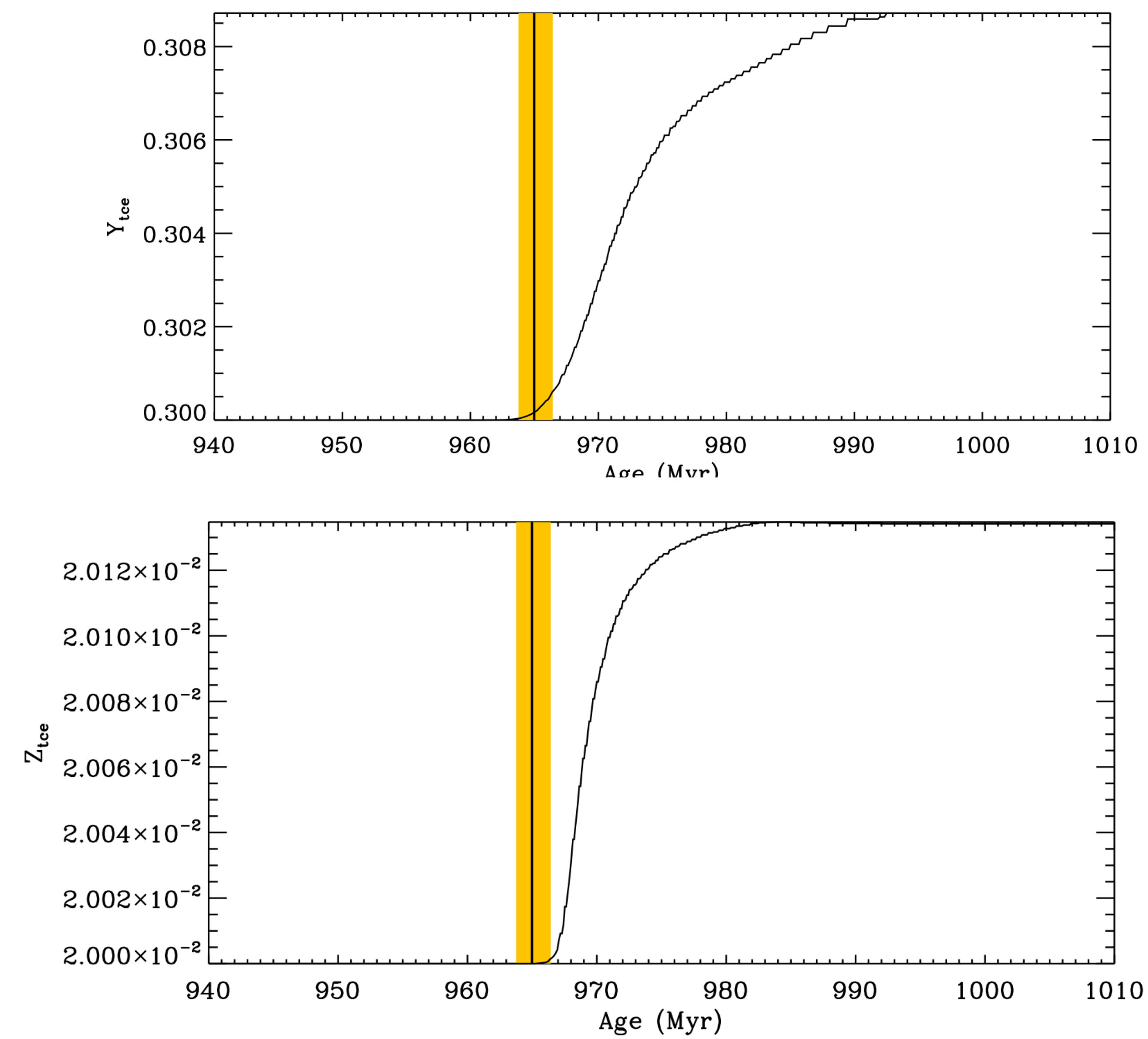
1^{st} dredge-up?





1st dredge-up?





Conclusions

- **R_{Astero}** and **R_{Gaia}** are well compatible
- Star possibly at beginning of 1st dredge-up
- Chemical abundances cannot be changed much from MS
- Hence progenitor A3V is not chemically peculiar (star has solar-type abundances, e.g. **Cr**, cf. Dall et al. 2010, **Li** cf. Strassmeier et al. 1999)
- CE quite deep (**R_{bce} ~ 0.4R**). Cannot explain survival of fossil dipole MF at surface
- Possible explanation of observed MF: dynamo α^2 (fully convective) developed after MS (significant energy contribution from dipole)
- Progenitor is a A3V star: BUT NOT chemically peculiar
  Magnetically active? Slow rotation or strong magnetic braking? **To verify!**

Future work

- Confirm presence of oscillation bump and obtain more accurate asteroseismic parameters from new SONG observations (~1 month, accepted proposal P08) (**to start soon**)

- Explore a more exhaustive grid of stellar evolutionary tracks (varying Y, Z, ML) (**ongoing**)

- Constrain evolutionary stage more accurately: 1st dredge-up at the beginning? (**to be done**)

- Combine TESS observations: new insights on mixed modes lifetimes and amplitudes to test presence of fossil MF inside core **?** (**to start**)

- Compute stellar dynamo model to explain proposed evolution scenario (**ongoing**)

Thank you!

Enrico Corsaro

Puzzling case

- Three possible scenarios proposed by Strassmeier et al. 1999:
  - Photometric period is NOT the rotation period but a spot-cycle period, and star is seen nearly pole on (i ~ 0°)
  - EK Eri is an evolved Ap star, with a magnetic field of intergalactic (primordial) origin and not generated by dynamo process
    Stepień 1993
  - An efficient small-scale turbulent dynamo is in action (e.g. because of exceptionally strong differential rotation), even if $\Omega \rightarrow 0$

Puzzling case

- Three possible scenarios proposed by Strassmeier et al. 1999:
  - Photometric period is NOT the rotation period but a spot-cycle period, and star is seen nearly pole on ($i \sim 0°$)
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    Stepień 1993
  - An efficient small-scale turbulent dynamo is in action (e.g. because of exceptionally strong differential rotation), even if $\Omega \rightarrow 0$
- Most likely scenario is that progenitor Ap star had a strong dipolar magnetic field (~3 kG, found in about 1 star every 10^2-10^3). **True?**
  Stepień 1993; Strassmeier et al. 1999