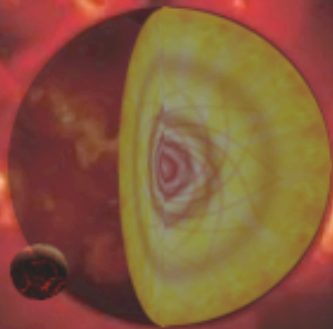


*Twinkle twinkle little star how I wonder
what you are:*

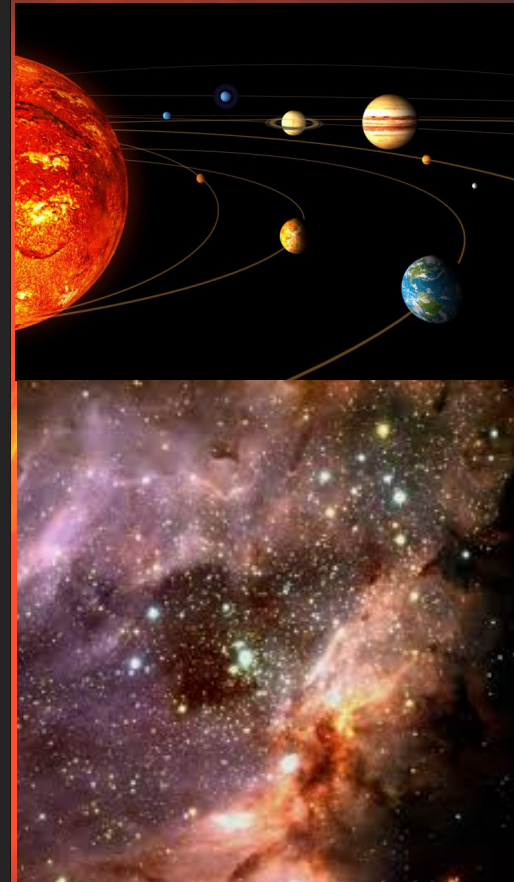
**Towards Age/Rotation/Magnetic
activity relation with seismology**



*Savita Mathur
Space Science Institute
Boulder (USA)*

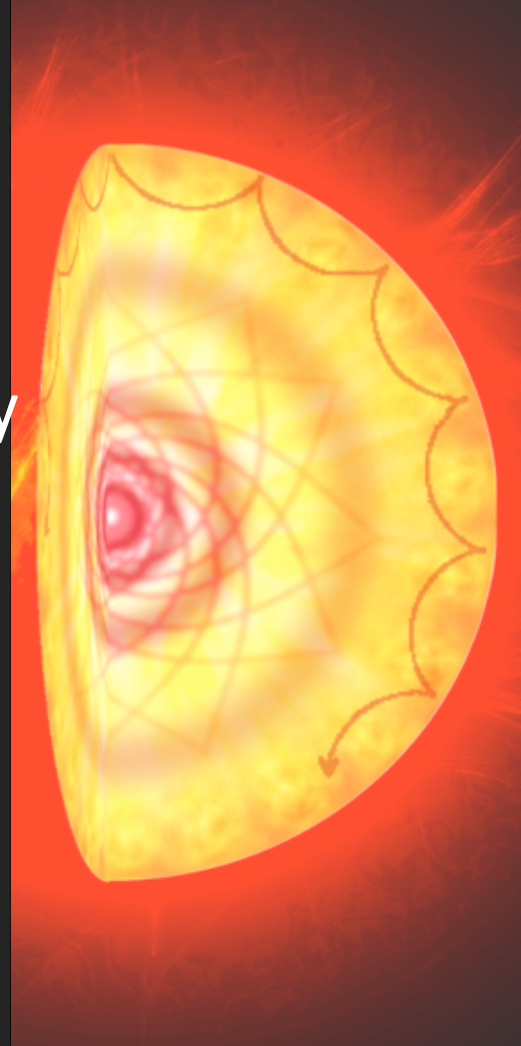
Stellar ages

- Why are they important? [See poster #2]
 - For planetary system evolution studies
 - For star formation history...
- But stellar ages difficult to determine for low-mass field stars:
 - Among a given cluster, coeval stars but more difficult for field stars
 - Some stellar phases evolve more or less rapidly depending on stellar mass



Outline

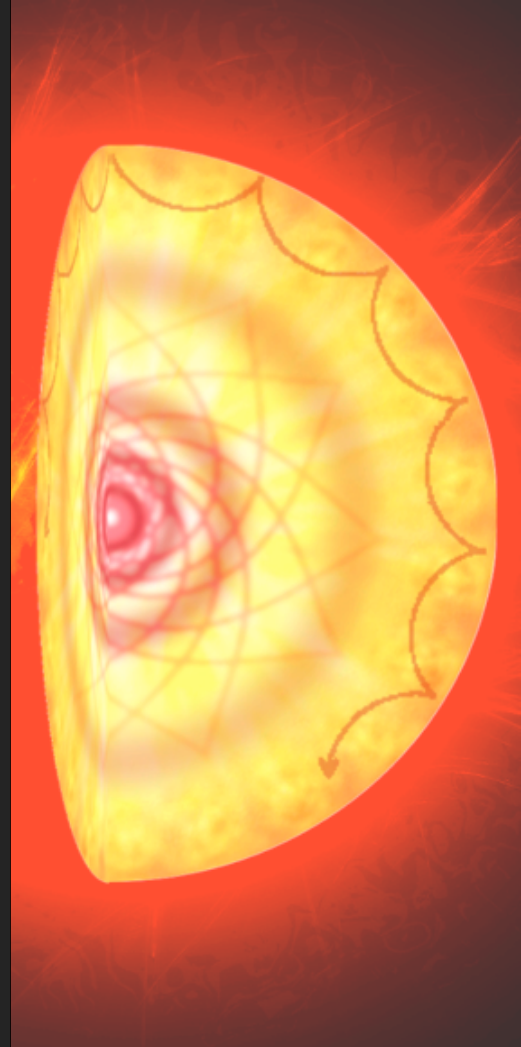
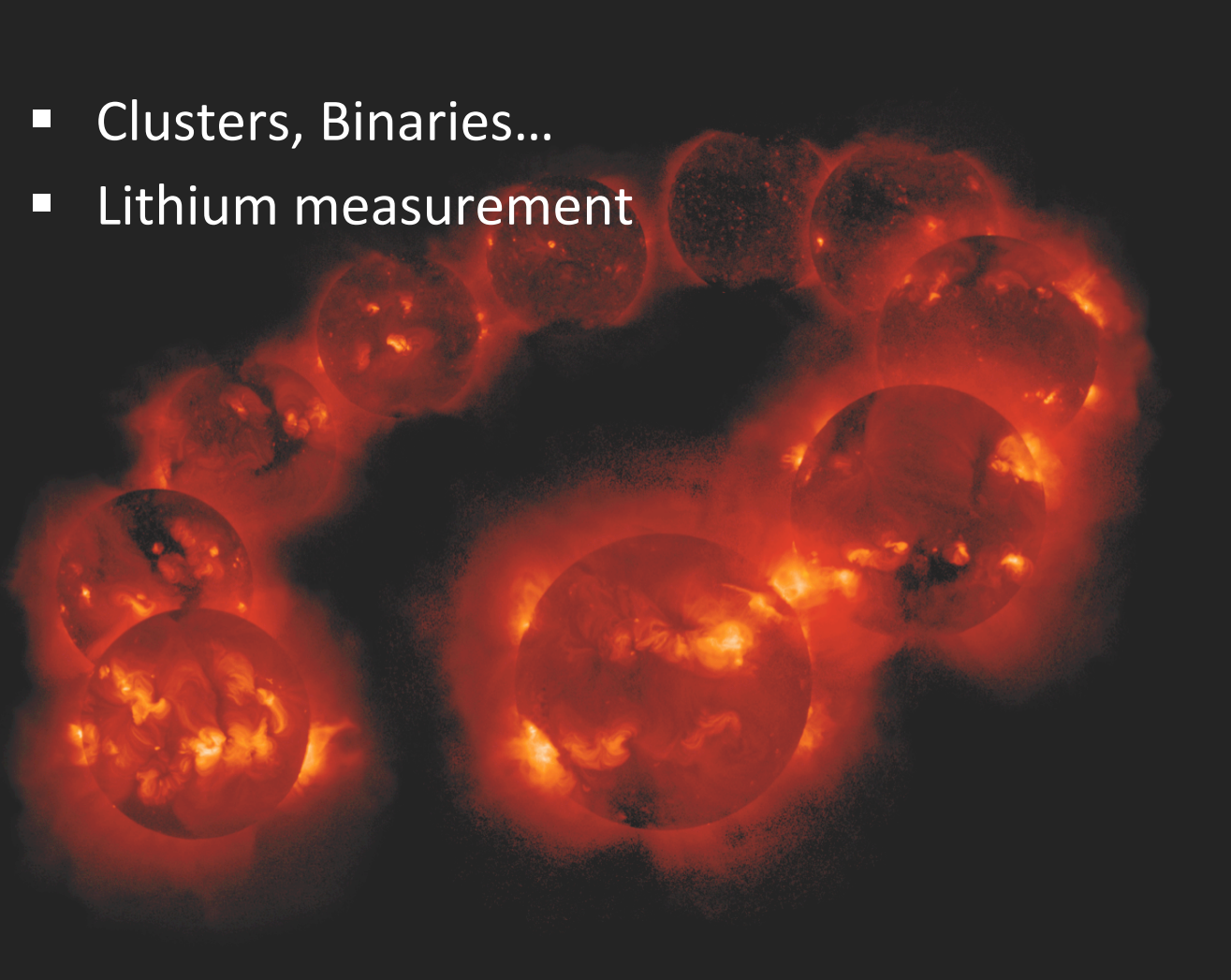
- I. History of age/rotation/activity relations
- II. Measuring rotation and magnetic activity
- III. Seismology inputs
- IV. Results with *Kepler*



History of age/rotation/activity relations

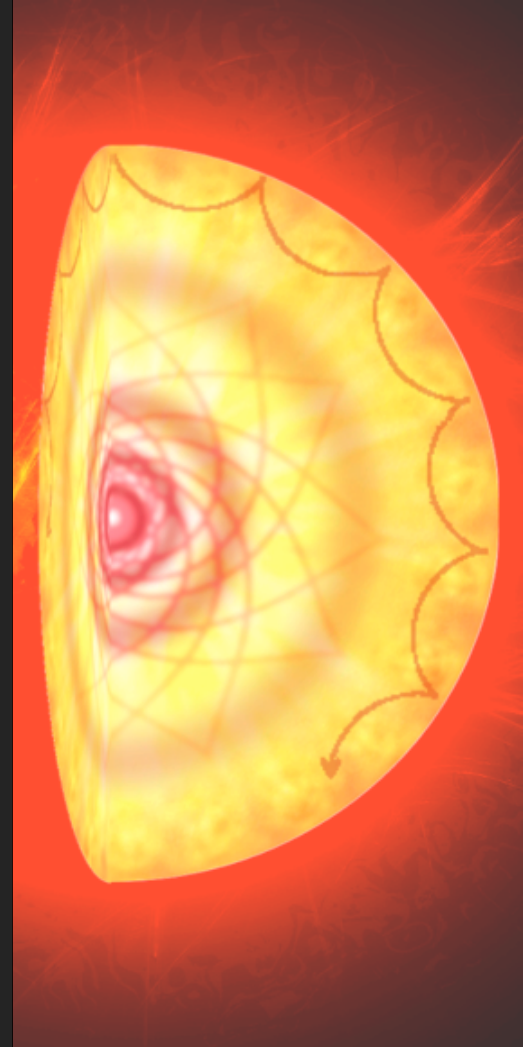
How do we measure ages?

- Clusters, Binaries...
- Lithium measurement



How do we measure ages?

- Clusters, Binaries...
- Lithium measurement

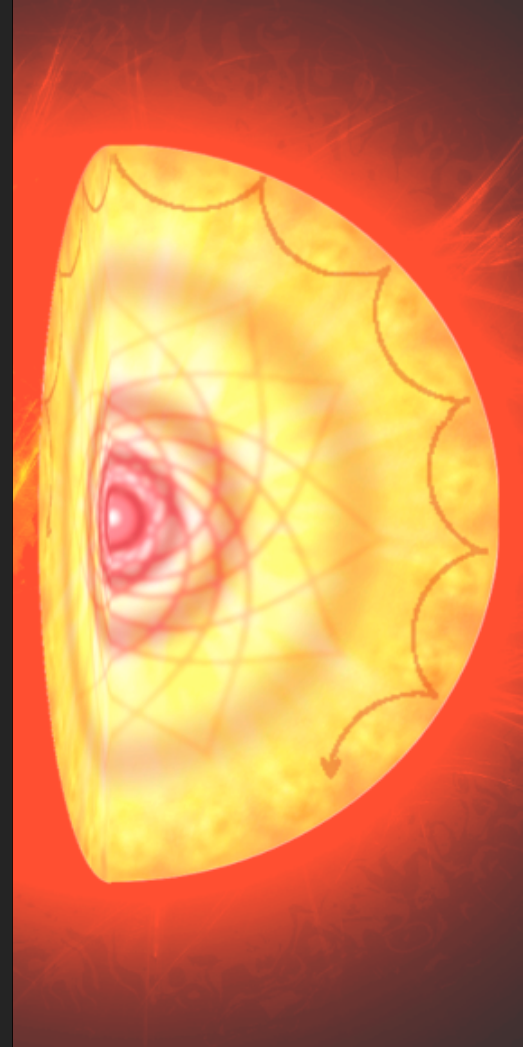


How do we measure ages?

- Clusters, Binaries...
- Lithium measurement

Field stars:

- Isochrones
- Asteroseismology
- Gyrochronology
- Chromochronology (?)



A little bit of history...

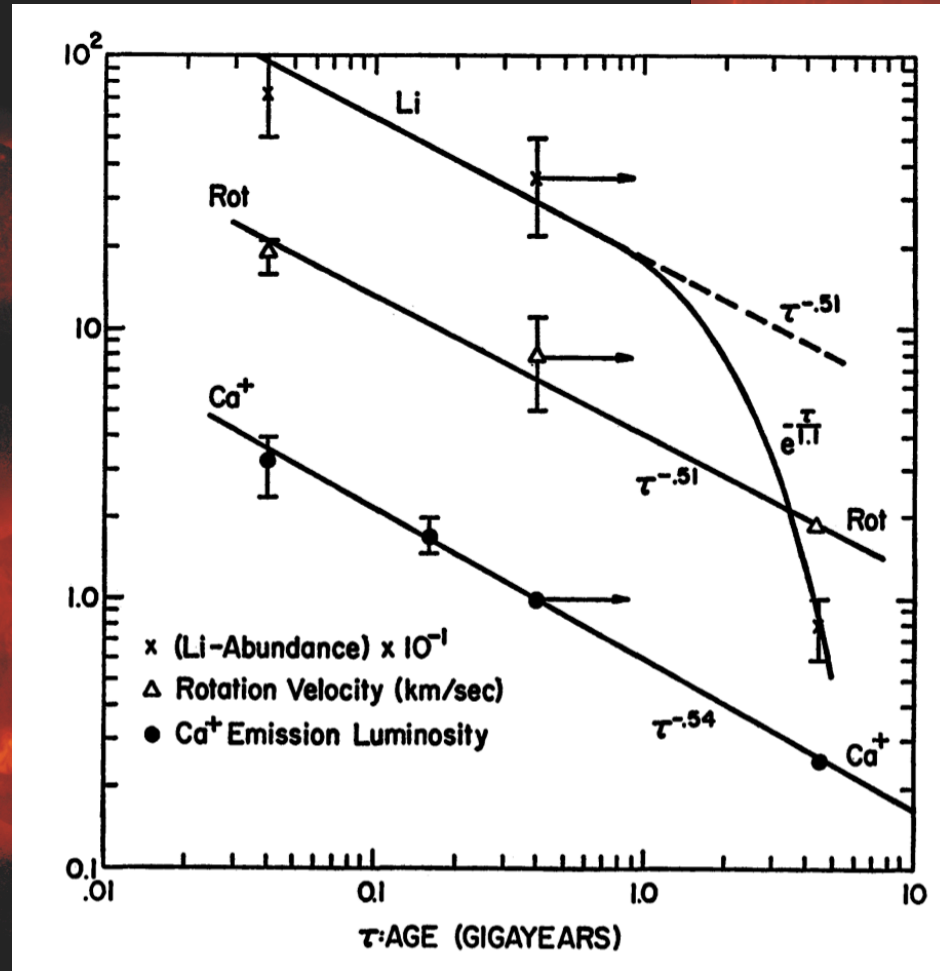
For 3 young clusters and based on

- Rotation
- Magnetic activity
- Lithium

Derived a law with age:

$$P_{\text{rot}} \sim \tau^{-1/2}$$

[e.g. Kawaler (1988);
MacGregor & Brenner (1991)]



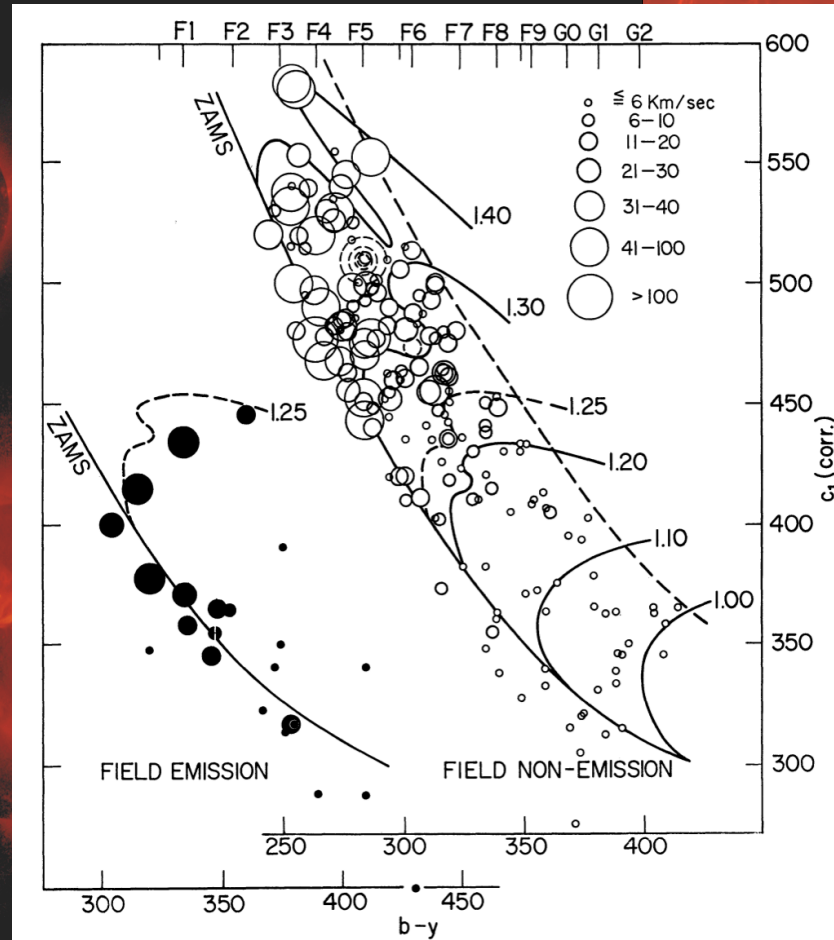
[Skumanich 1972]

A little bit of history...

BUT dependency with the
stellar mass

[e.g. Kraft, 1967; Epstein &
Pinsonneault, 2013]

$M > 1.25 M_{\odot}$: faster rotation



[Kraft, 1967]

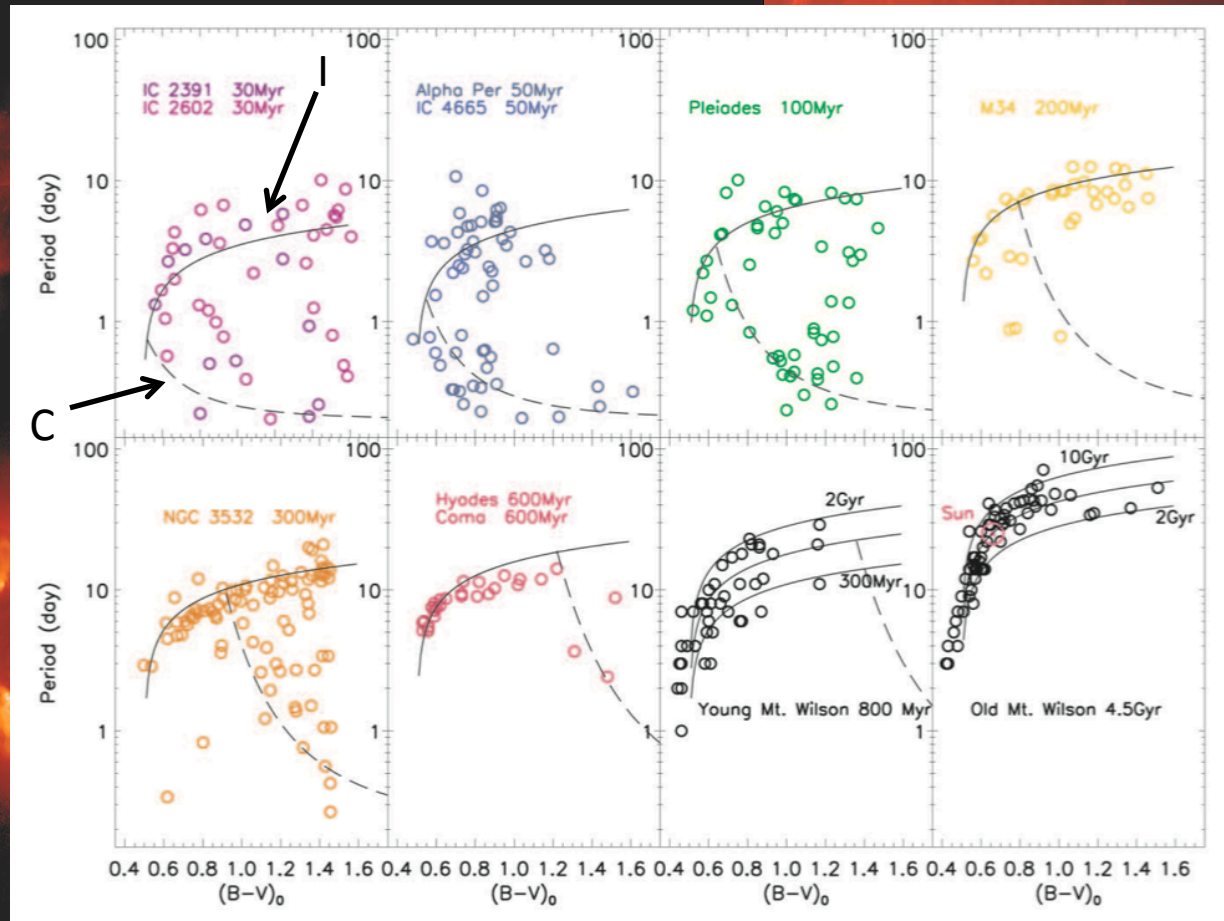
C and I sequences

C (convective):
fast rotators
I (interface):
slow rotators

$$P(B-V, t) = f(B-V)g(t),$$

$$f(B-V) = a[(B-V)_0 - c]^b,$$

$$g(t) = t^n.$$



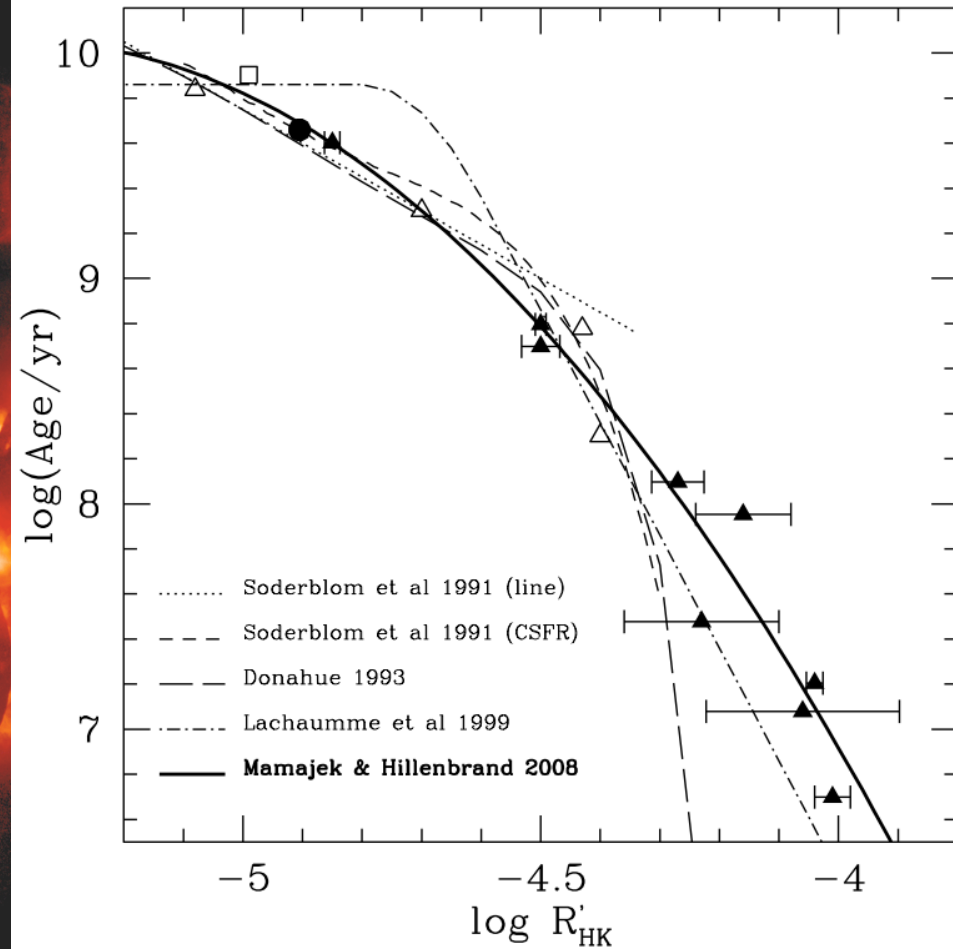
[Barnes et al. 2003, 2007]

Relation with magnetic activity

R'_{HK} index of young clusters with known ages and field stars with isochronal ages

Derive a relation R'_{HK} vs Age

Also adds dependence with B-V.



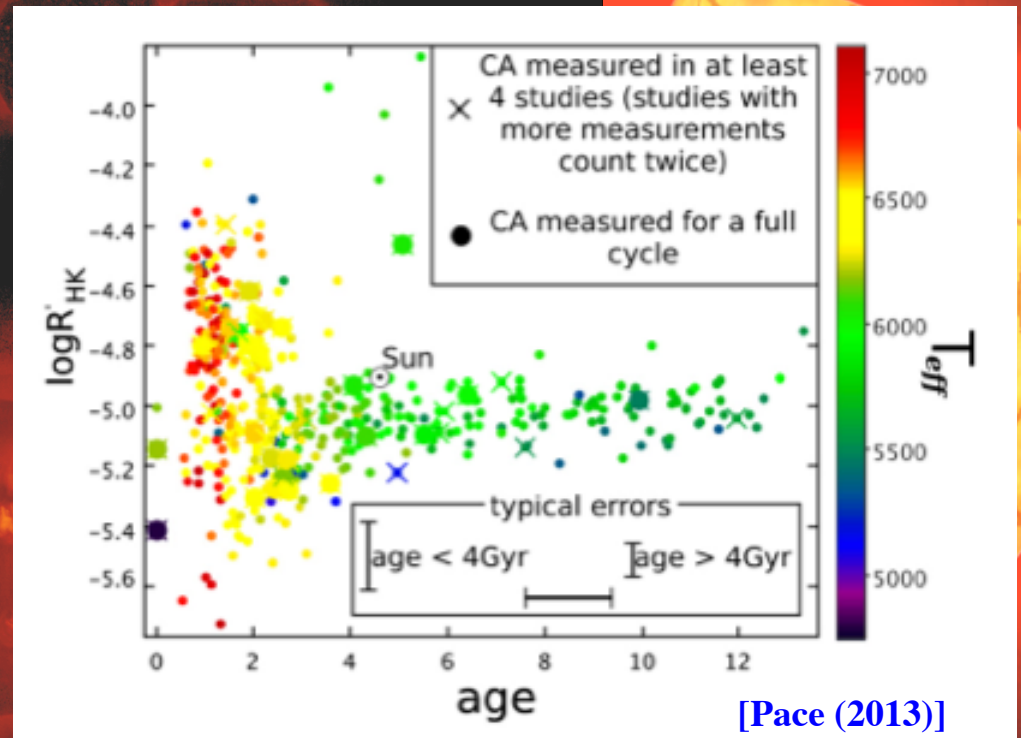
[Mamajek & Hillenbrand, 2008]

Chromospheric activity and age

CA indexes and ages (GCS) of

- Cluster stars
- ~500 field dwarfs

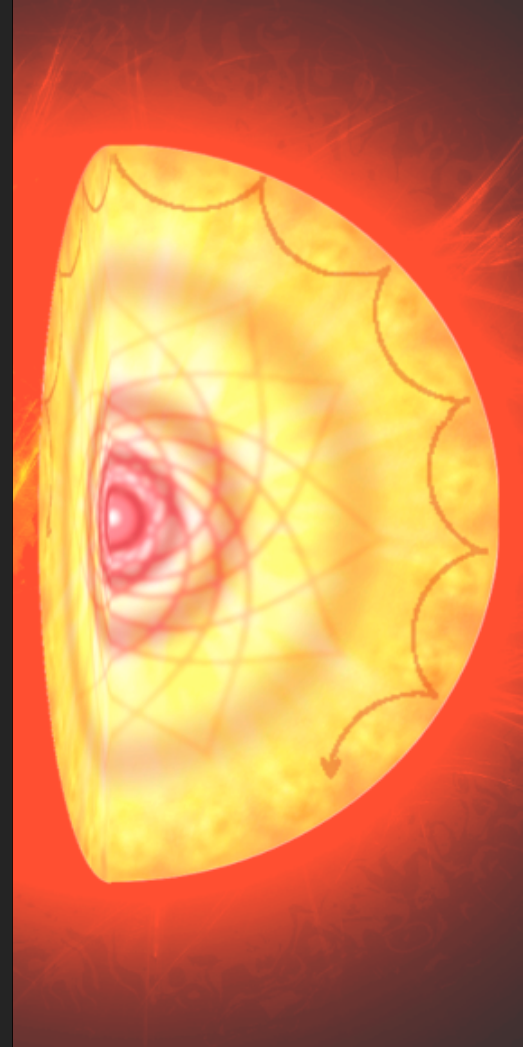
No evolution of R'_{HK} after 1.5 Gyr.



Measuring rotation and magnetic activity

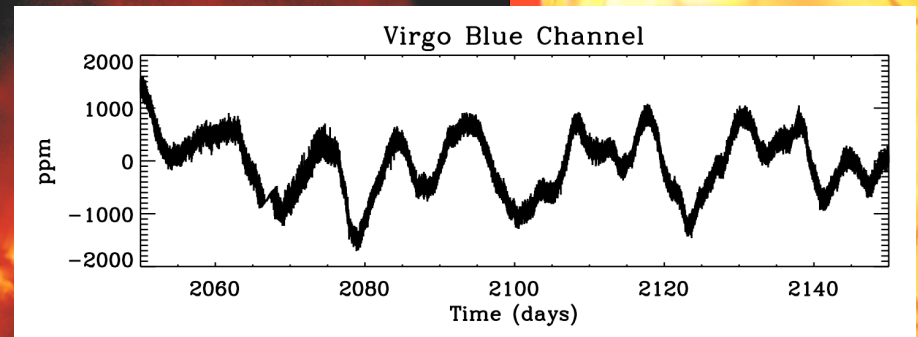
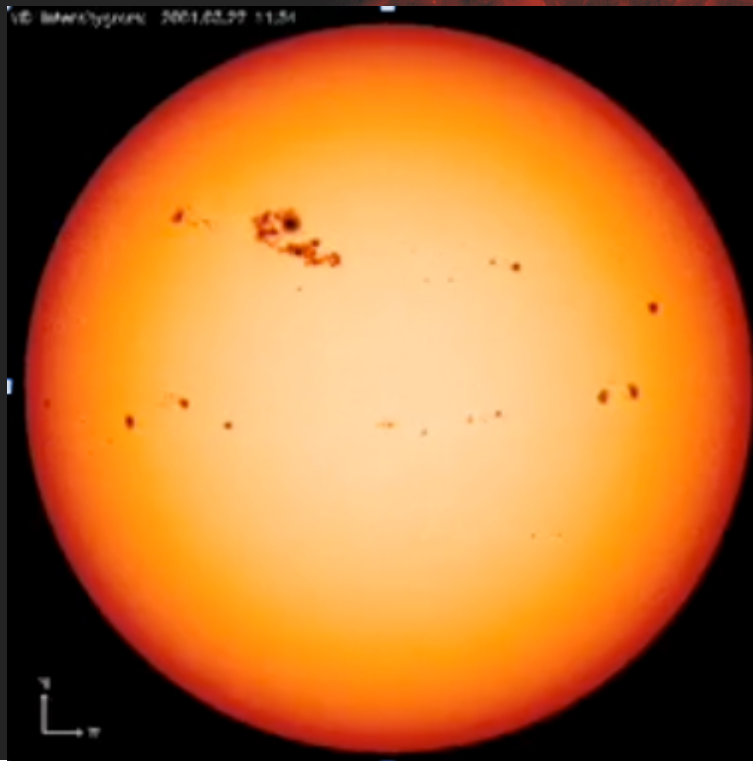
How do we measure rotation and magnetic indexes?

- Spectroscopy
 - Broadening of the lines ($v \sin i$)
 - Changes in absorption lines (CaHK, H α ...)
- Spectropolarimetry
 - Gives a measurement of B and its topology
[e.g. Fares et al. 2009; Petit et al. 2011; Auriere et al. 2012; Madsen et al. subm.]
- Light curves



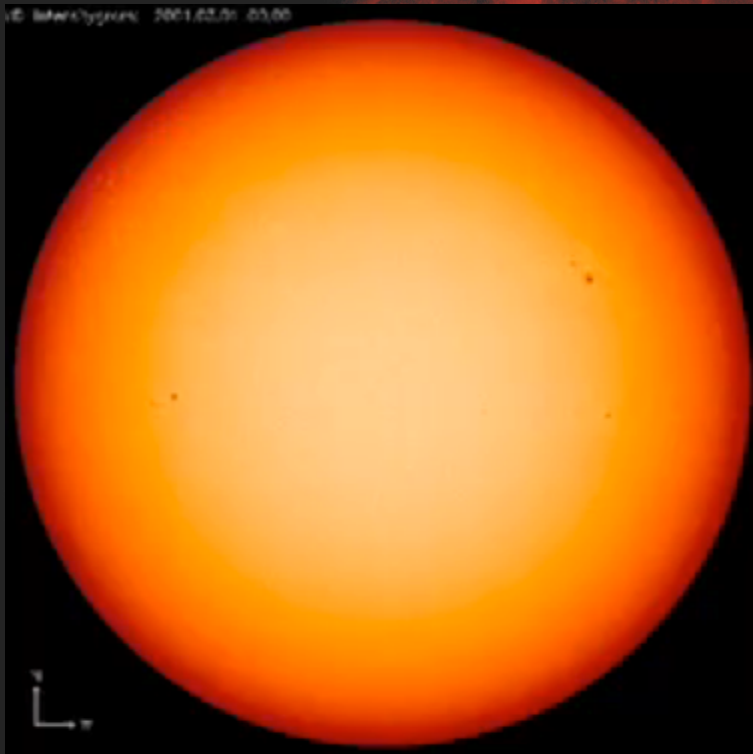
Surface rotation

- Stellar spots crossing the visible disk of stars
 - Modulation in light curves

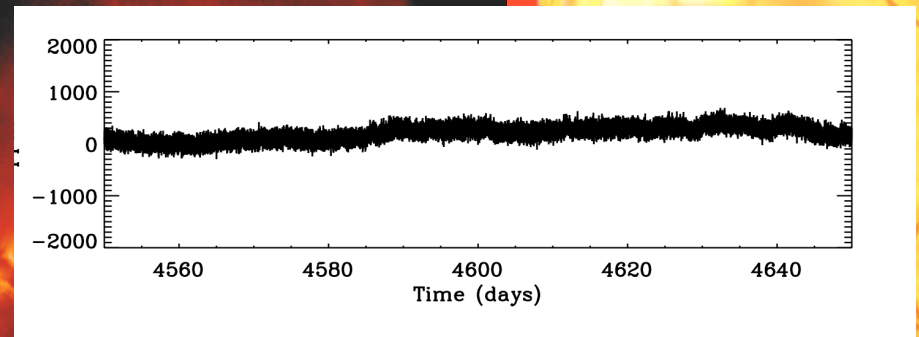


Surface rotation

- Stellar spots crossing the visible disk of stars
 - Modulation in light curves
 - *Need active star*

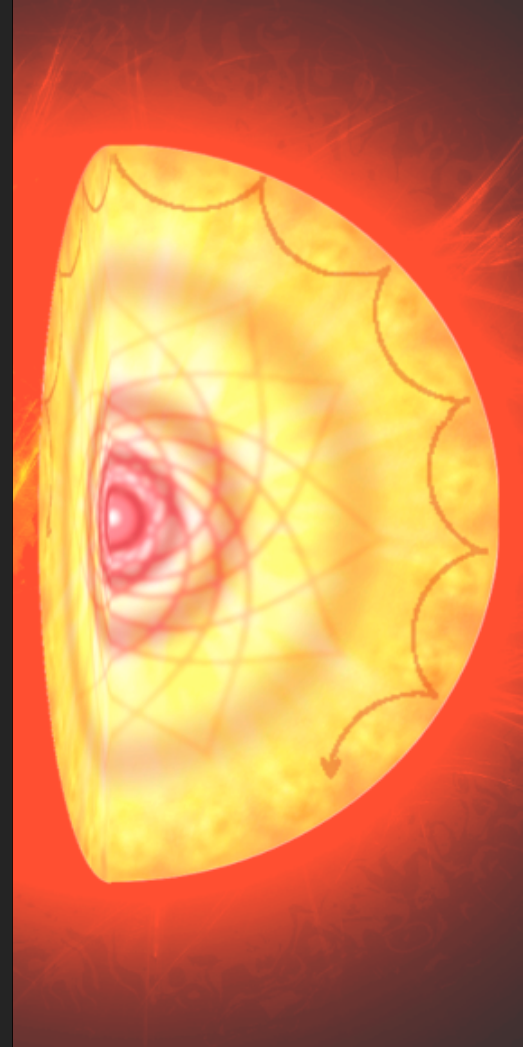


Solar Activity Minimum

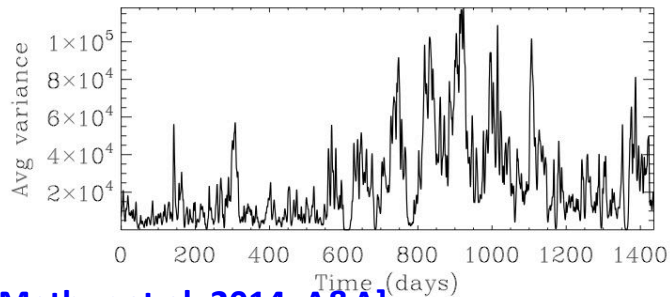
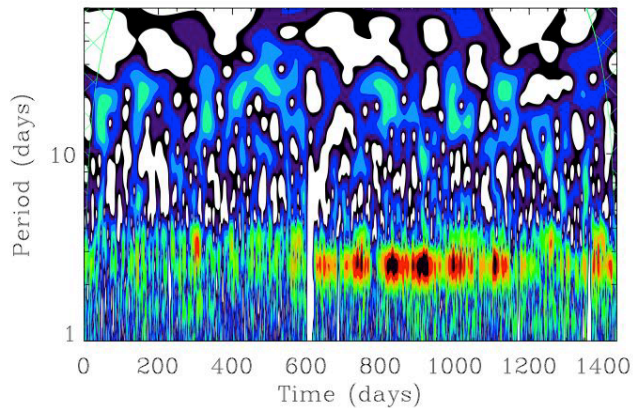
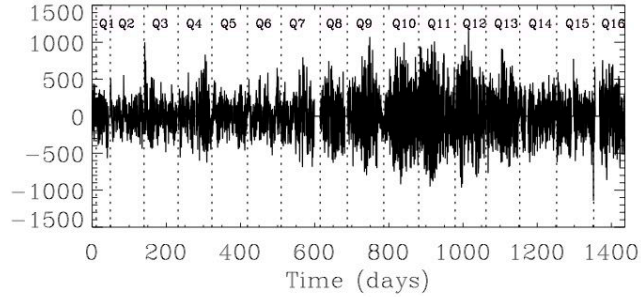


How do we measure rotation periods?

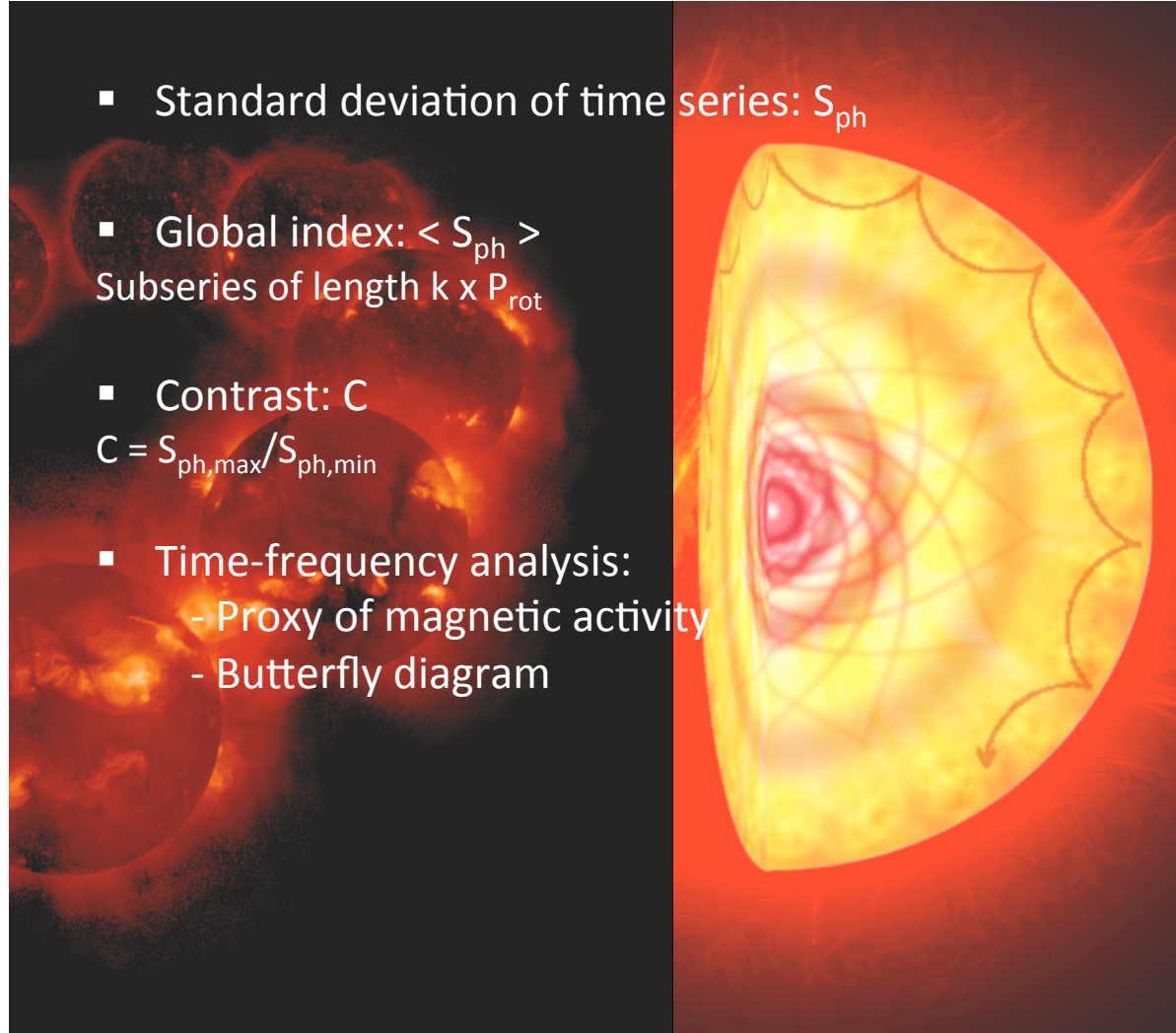
- Spectroscopy
 - Broadening of the lines ($v \sin i$)
 - Changes in absorption lines (CaHK, H α ...)
- Spectropolarimetry
 - Gives a measurement of B and its topology
[e.g. Fares et al. 2009; Petit et al. 2011; Auriere et al. 2012; Madsen et al. subm.]
- Light curves
 - Periodogram [Nielsen et al. 2013, Reinhold et al. 2013]
 - Time-frequency [Mathur et al. 2010; Vida et al. 2014; Mathur et al. 2014; Garcia et al. subm.]
 - Auto-correlation [McQuillan et al. 2013a, b; Mathur et al. 2014]



How do we measure magnetic activity?



- Standard deviation of time series: S_{ph}
- Global index: $\langle S_{ph} \rangle$
Subseries of length $k \times P_{rot}$
- Contrast: C
 $C = S_{ph,max}/S_{ph,min}$
- Time-frequency analysis:
 - Proxy of magnetic activity
 - Butterfly diagram



[Mathur et al. 2014, A&A]

Seismology inputs

Stellar Modeling

■ Stellar models:

- Diffusion
- Composition
- Equation of state
- Opacities
- Mixing length theory
- Overshoot?
- ...

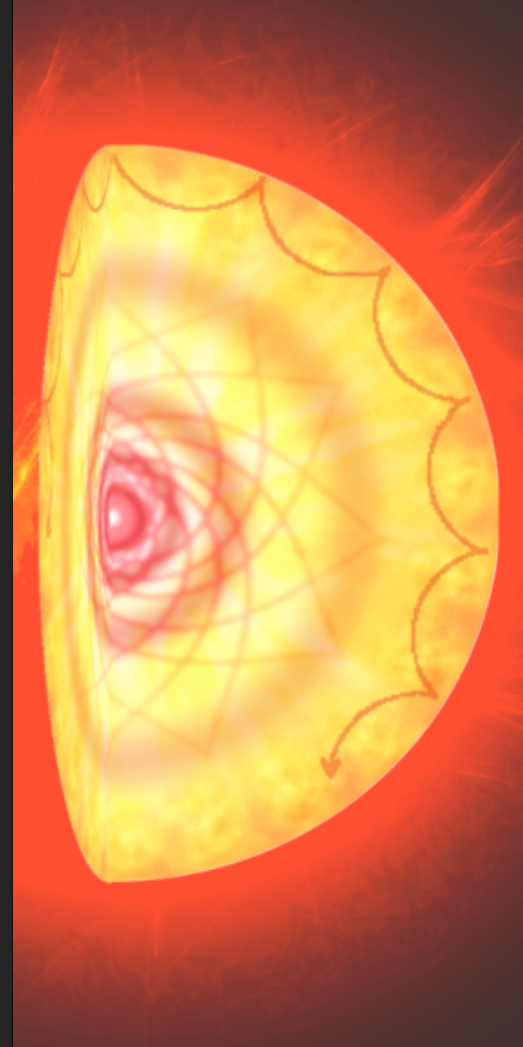
■ Observables:

- Spectroscopic:
 T_{eff} , Fe/H, $\log g$, L
- Seismic: $\Delta\nu$,
 ν_{max} , $\nu_{n,l}$

Find the best model that fits all the observables available

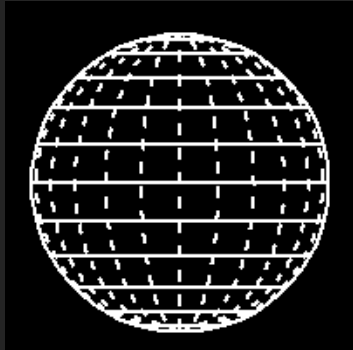
Stellar modeling

- Best-fit model
 - Grid modeling [Chaplin et al. 2014]
 - E.g. Asteroseismic Modeling Portal [Metcalf et al. 2009]
- Large sample of stars [Mathur et al., 2012; Metcalfe et al. subm.]
 - Improve precision on M, R, age
 - Structure



Effect of rotation on modes

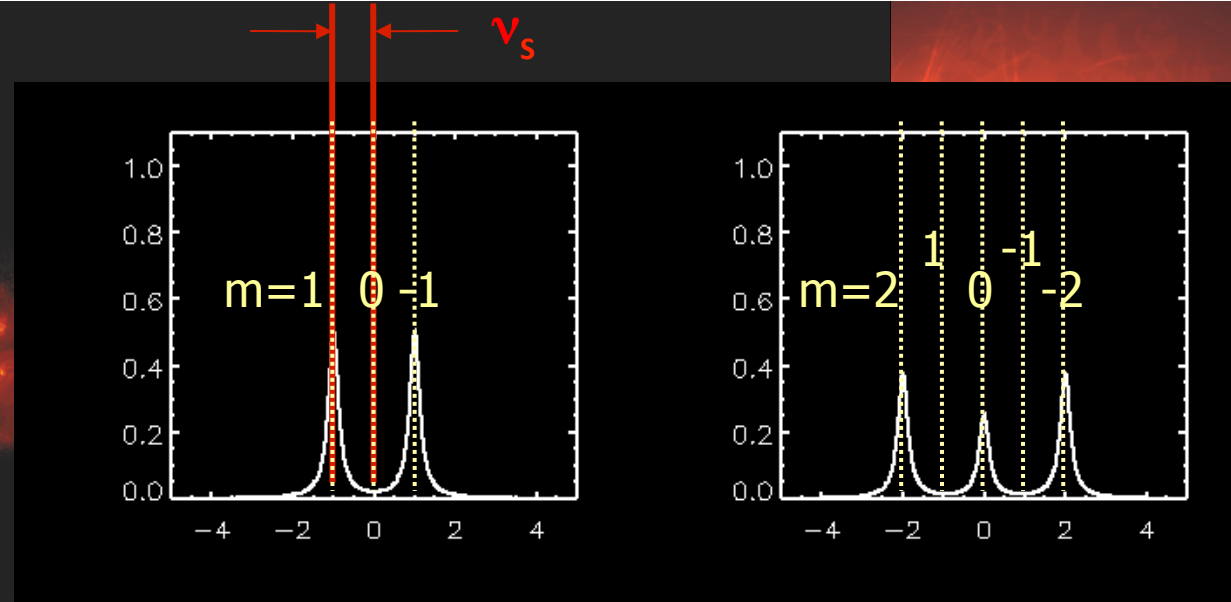
$$\Omega = 1,0$$



$$i = 90^\circ$$

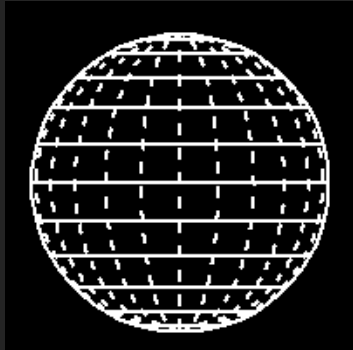
Internal rotation:

- Rotational splittings
- Depends on inclination angle



Effect of rotation on modes

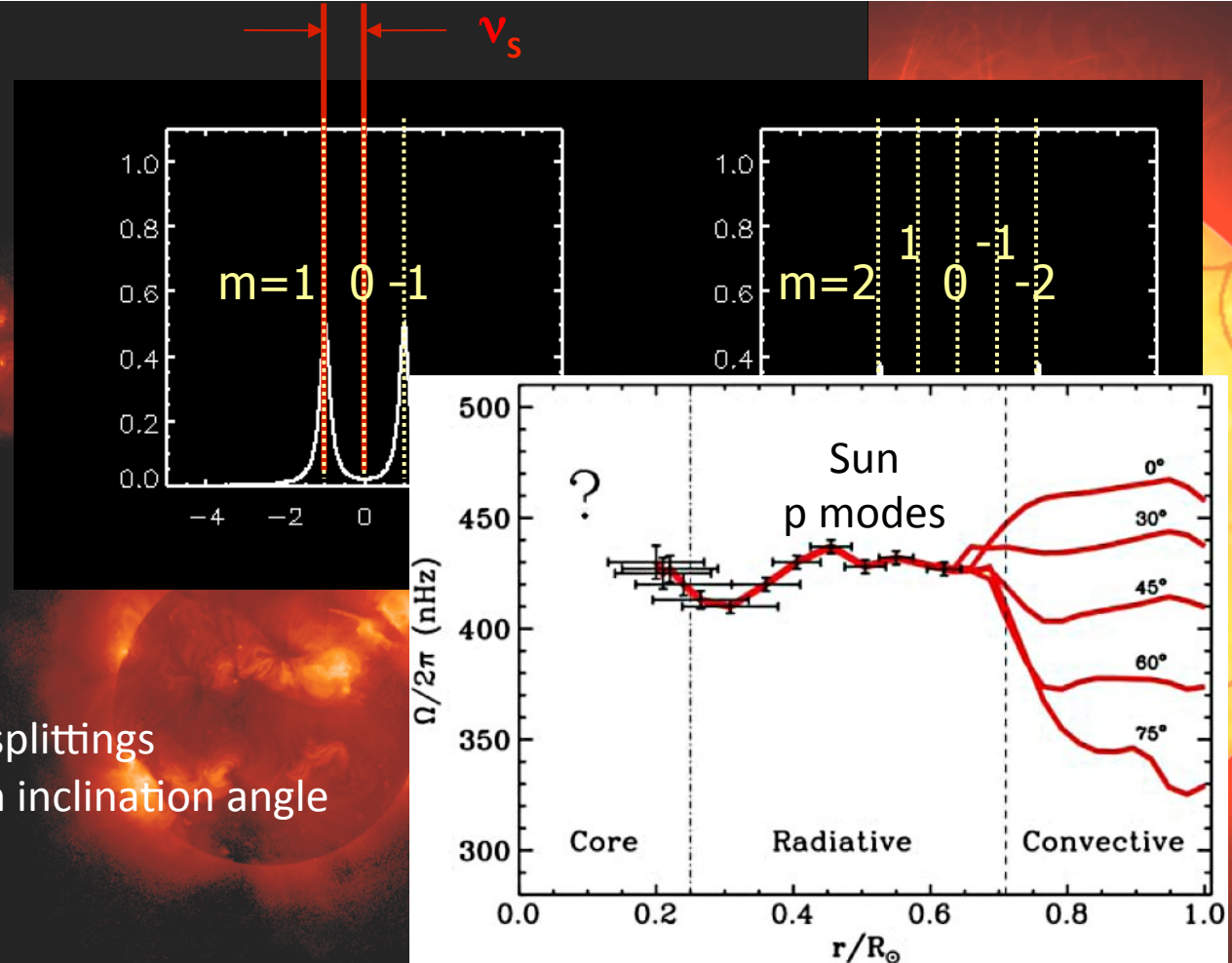
$$\Omega = 1,0$$



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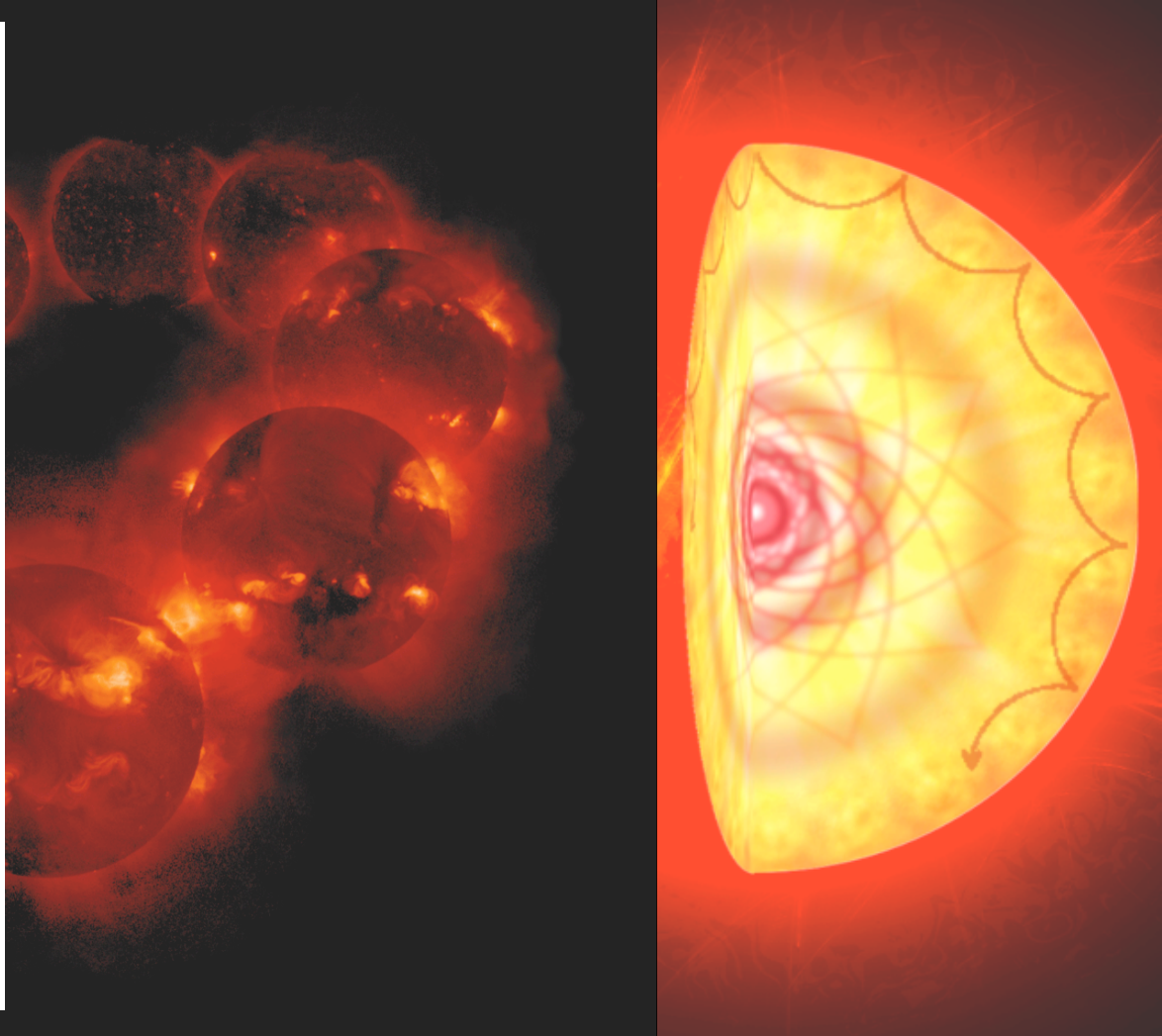
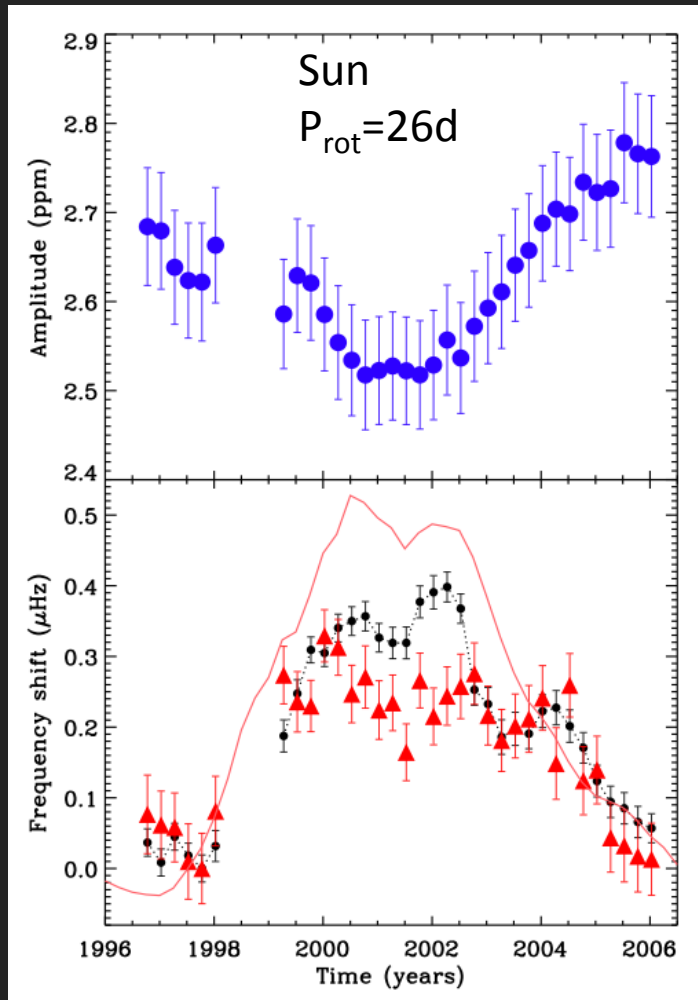
Internal rotation:

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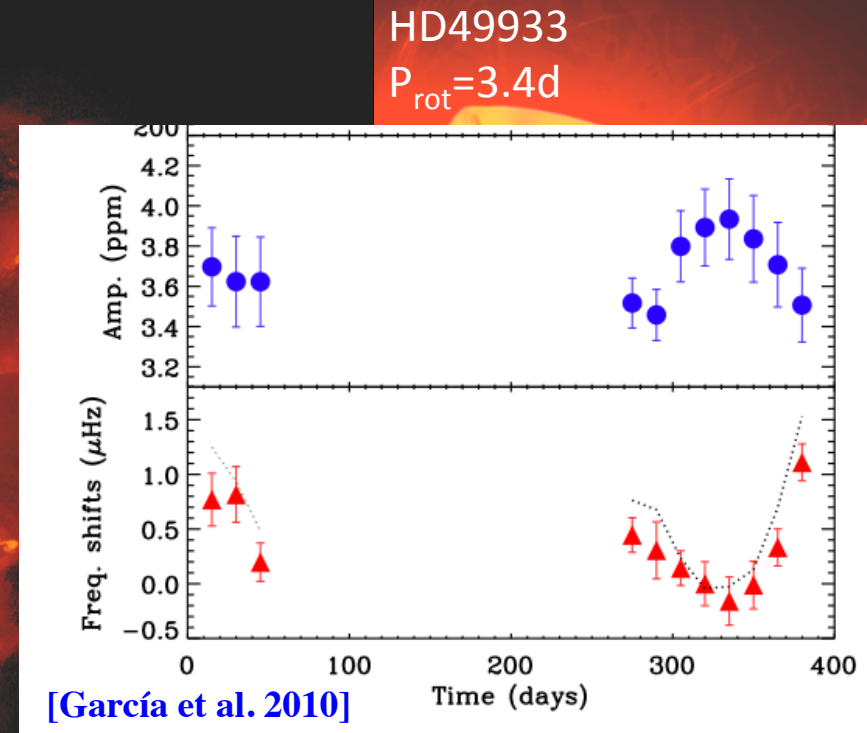
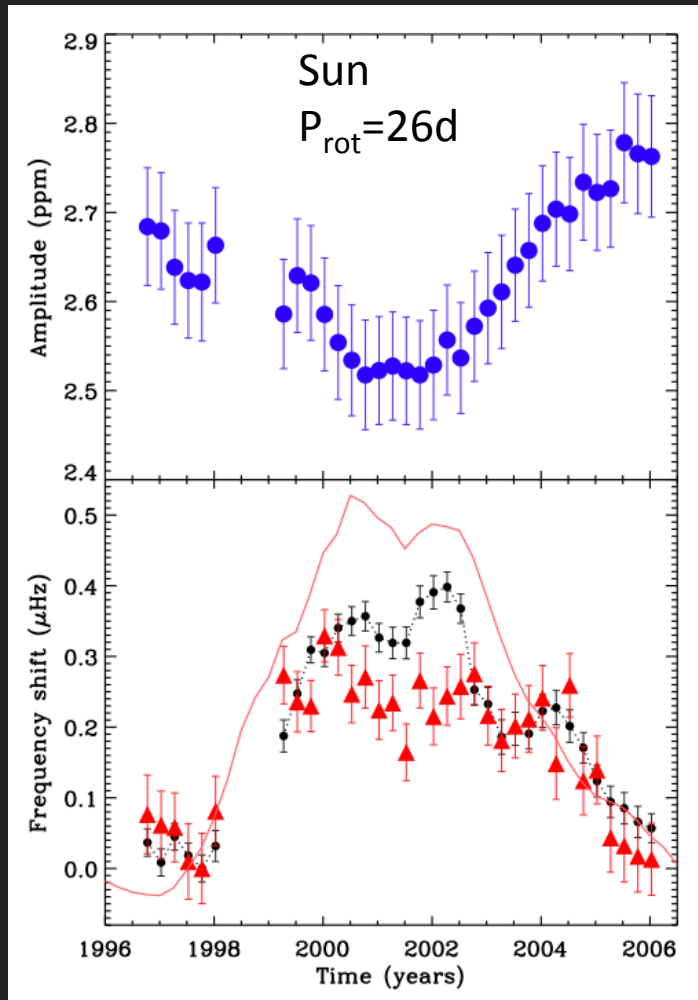


[García et al., 2007 Science]

Hints of a magnetic-activity cycle



Hints of a magnetic-activity cycle



Anticorrelation between amplitude variation and frequency shifts

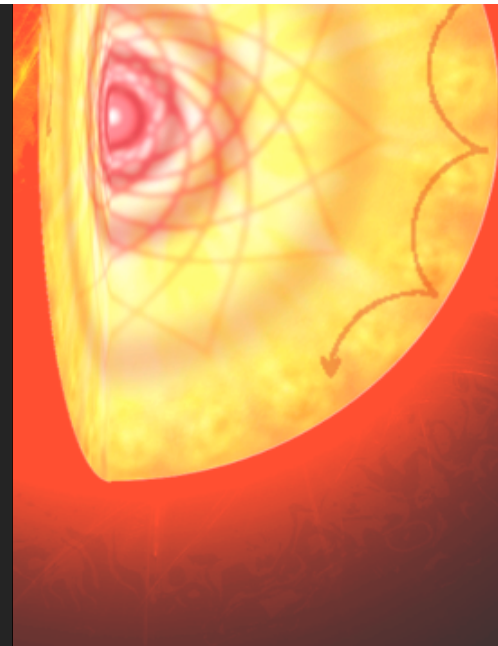
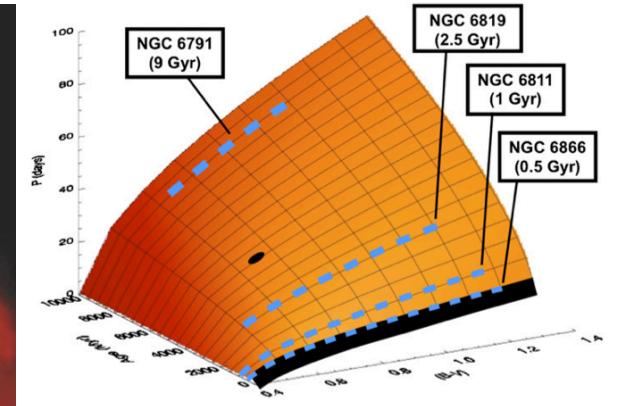
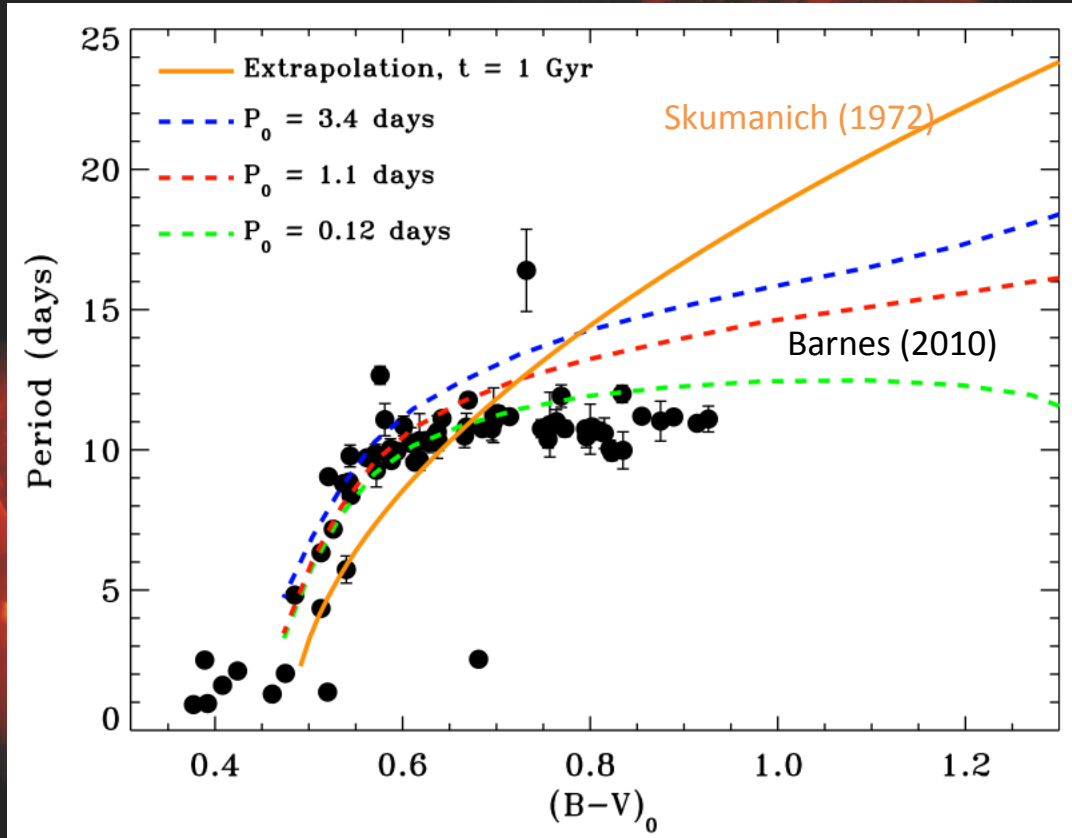
$P_{\text{cyc}} > 120\text{days}$

With *Kepler*

Clusters of *Kepler*

NGC6811 Age~1Gyr

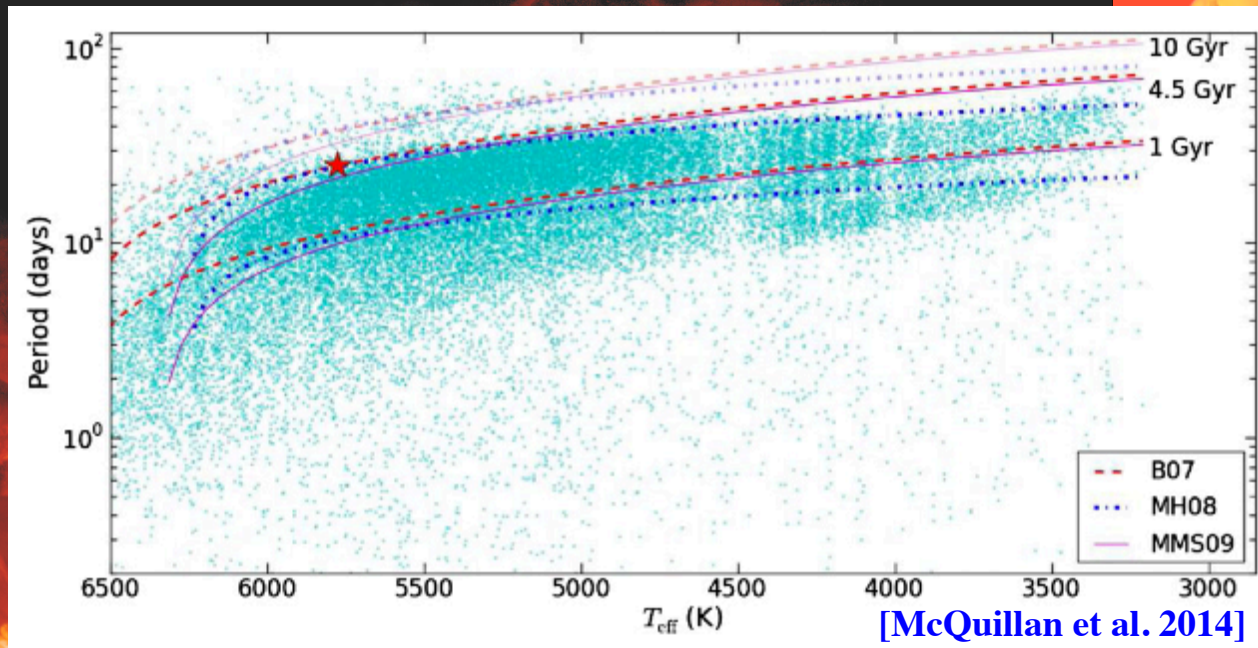
Analysis of surface rotation of 71 stars



[Meibom et al. 2011]

Gyrochronology with field stars

Surface rotation periods measured for 34,000 stars with ACF



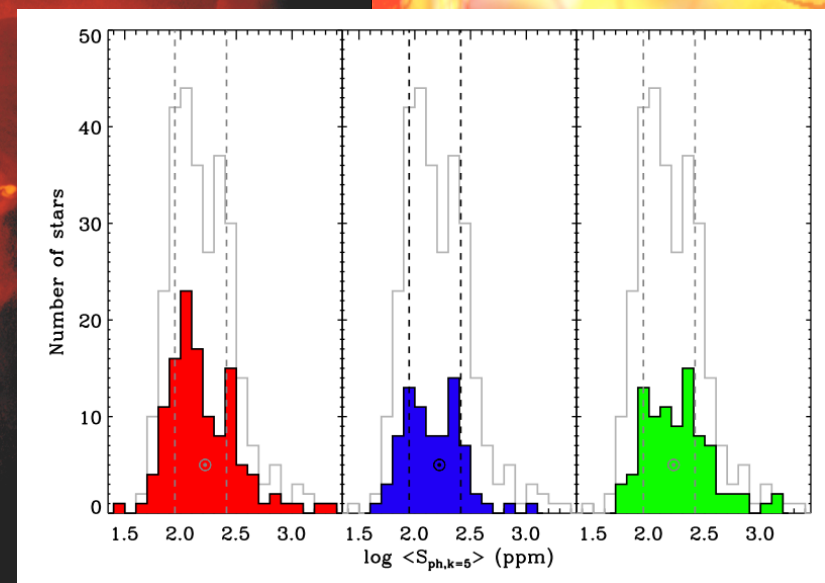
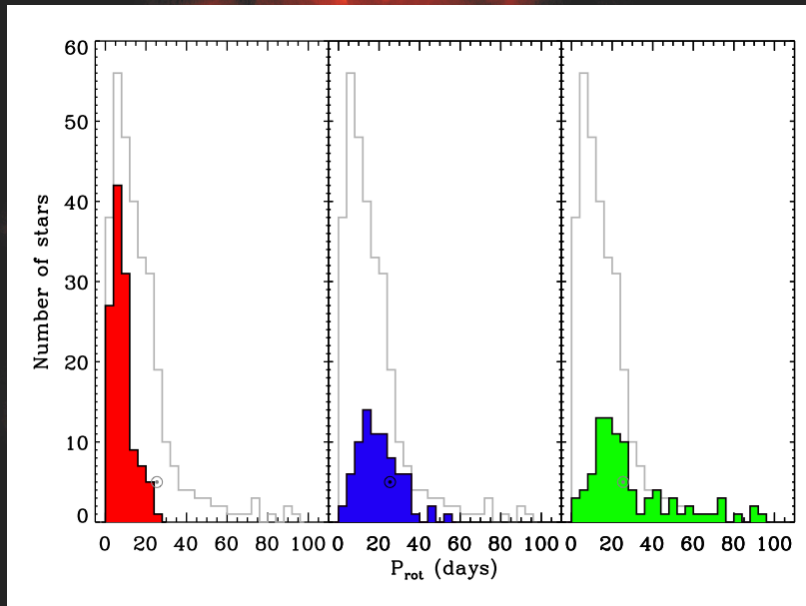
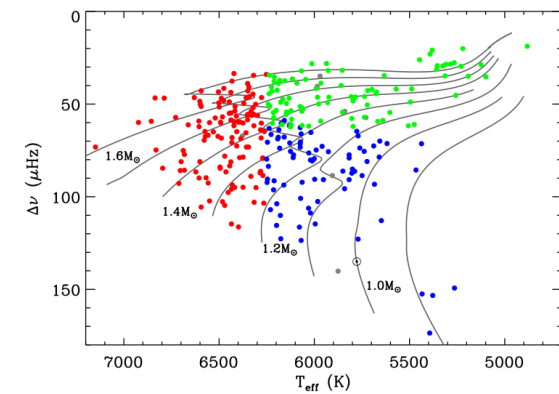
Few stars older than 4.5 Gyr
Many stars are younger than 1 Gyr

[See T. Mazeh's talk]

Solar-like stars

Analysis of 540 solar-like stars with asteroseismic constraints on mass, radius, and age

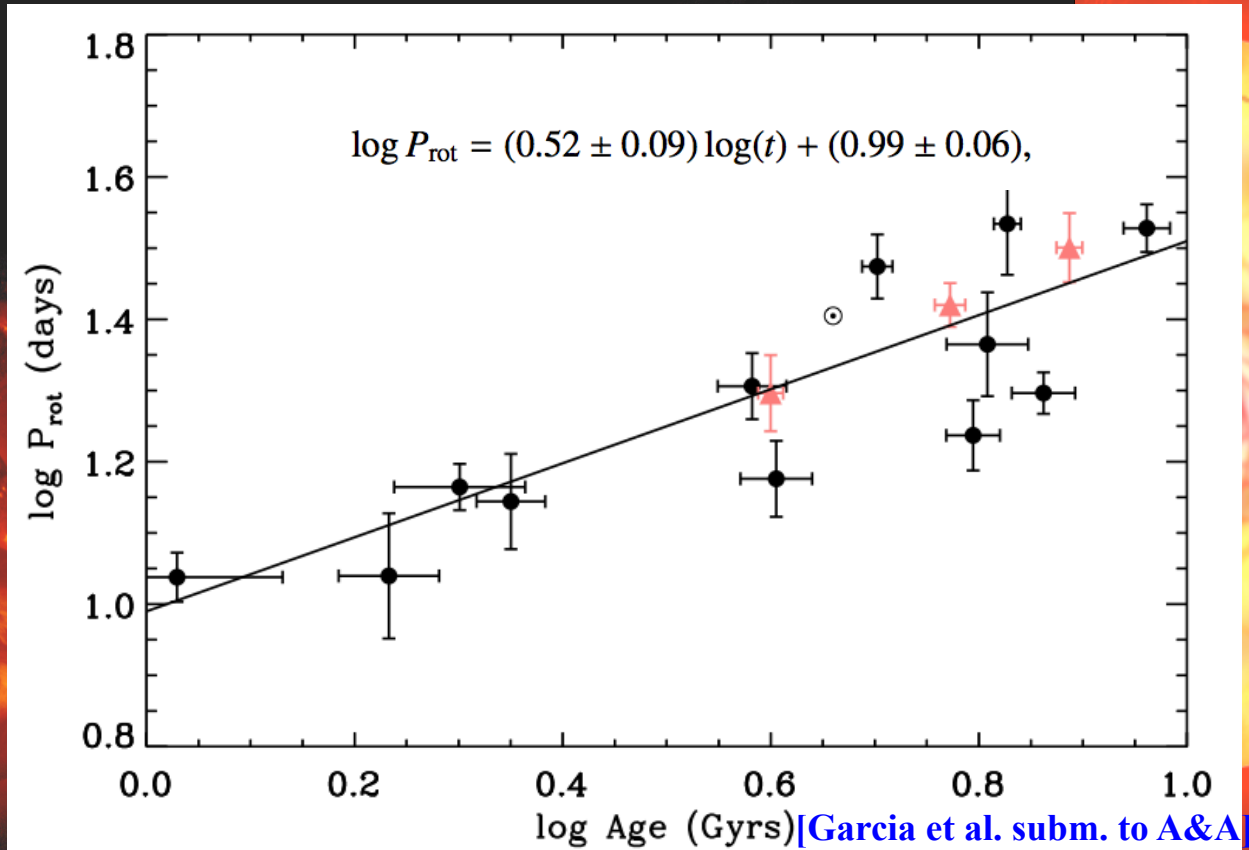
[Chaplin et al. 2014]



[Garcia et al. subm. to A&A]

Age-rotation relationship

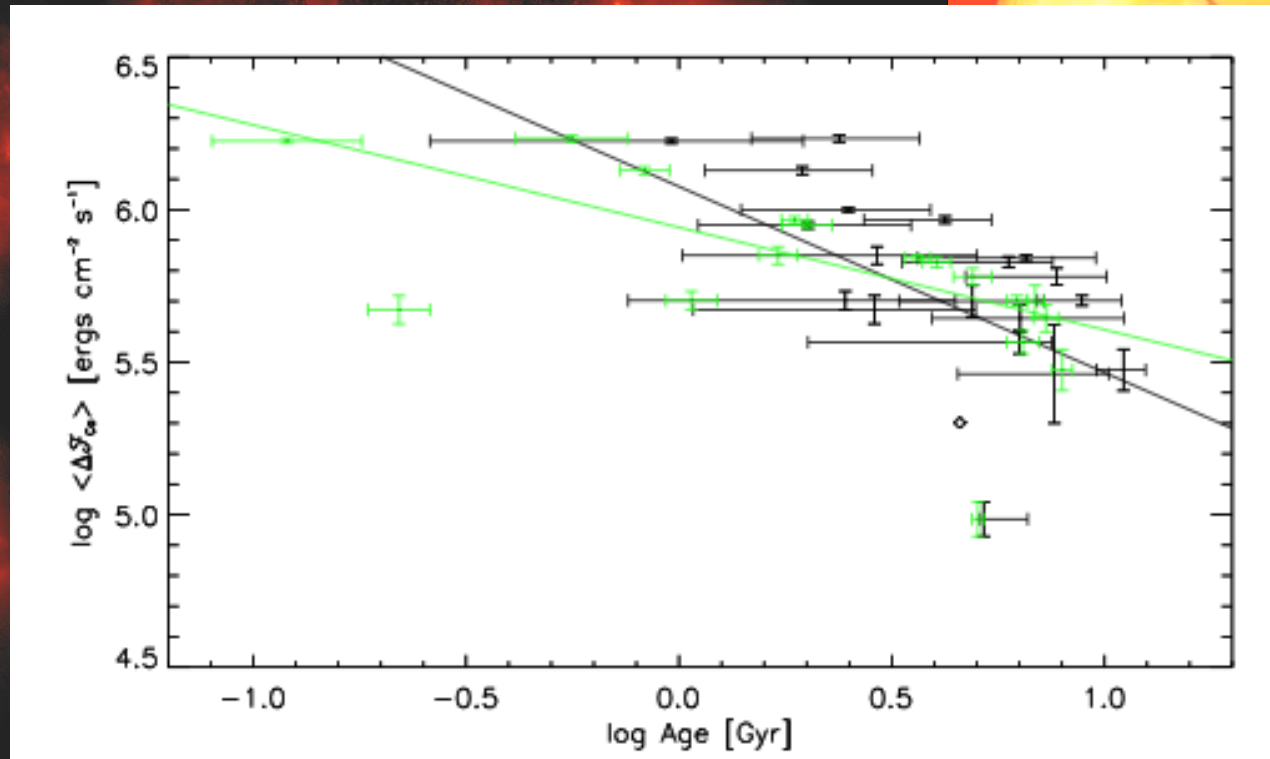
15 stars also modelled by the Asteroseismic Modelling Portal



In agreement with Skumanich (1972), Barnes (2007) and Mamajek & Hillebrand (2008)

Activity-Age relationship

22 solar-like stars observed with Nordic Optical Telescope
Modelled by the Asteroseismic Modelling Portal



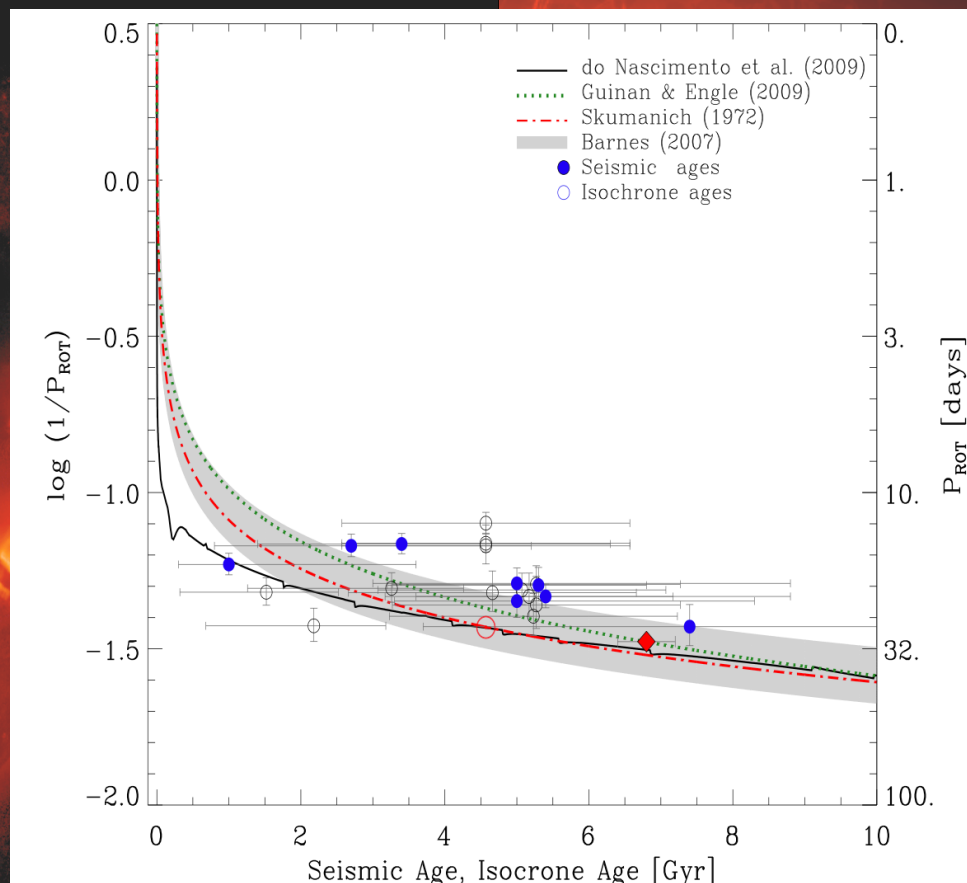
[Karoﬀ et al. 2013; Metcalfe et al. Subm. to ApJ]

Solar analog rotation with *Kepler*

Subsample of 8 solar analogs/twins candidates

Sample of solar analogs based on KIC+
[Huber et al. 2014, ApJS]

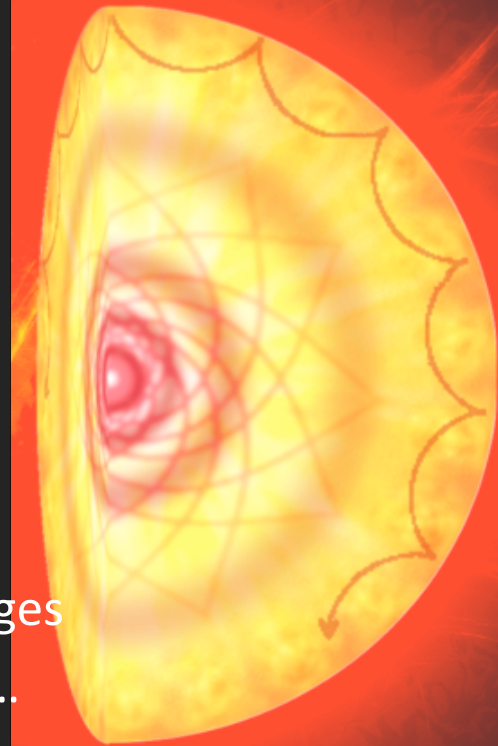
Within error bars, P_{rot} vs Age of seismic sample agree with previous relationships

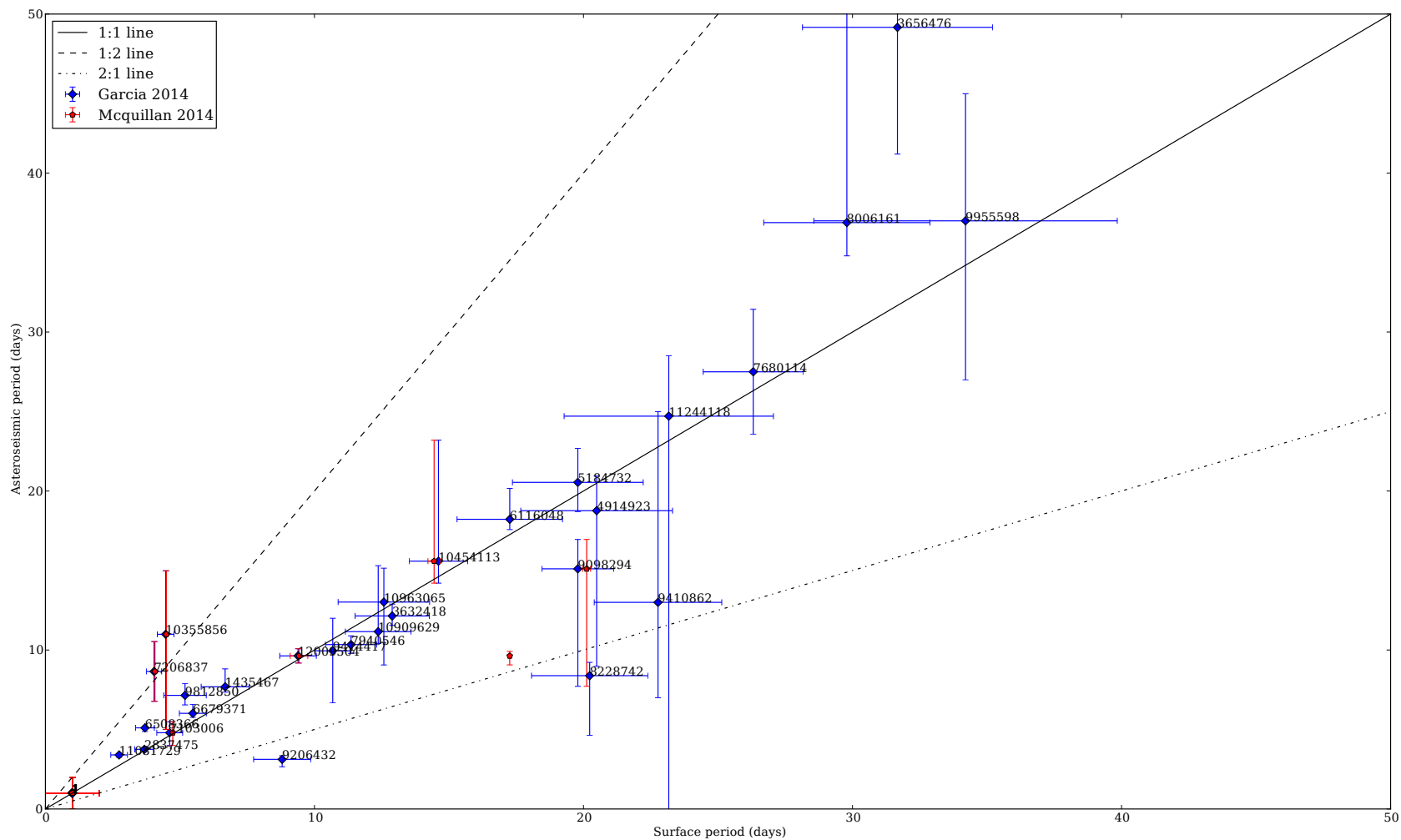


[Do Nascimento et al. 2014, ApJL in press]

Summary

- Spectroscopy + spectropolarimetry + light curves
- Asteroseismology:
 - Ages
 - Rotation periods
 - Magnetic activity
- Gyrochronology based on young clusters
 - Opportunity to study field stars with more precise ages
 - Need to take into account evolutionary stage, mass...





[Davies et al. In prep.]