Limits of RV precision

valeri.makarov@usno.navy.mil

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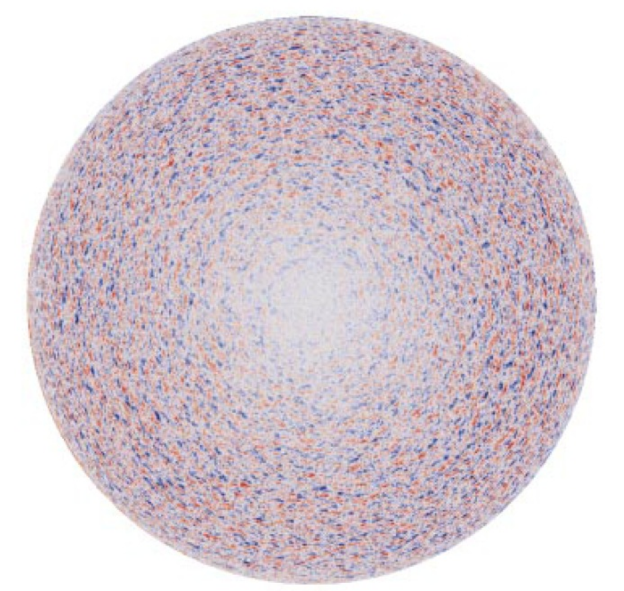
Precision or accuracy ?

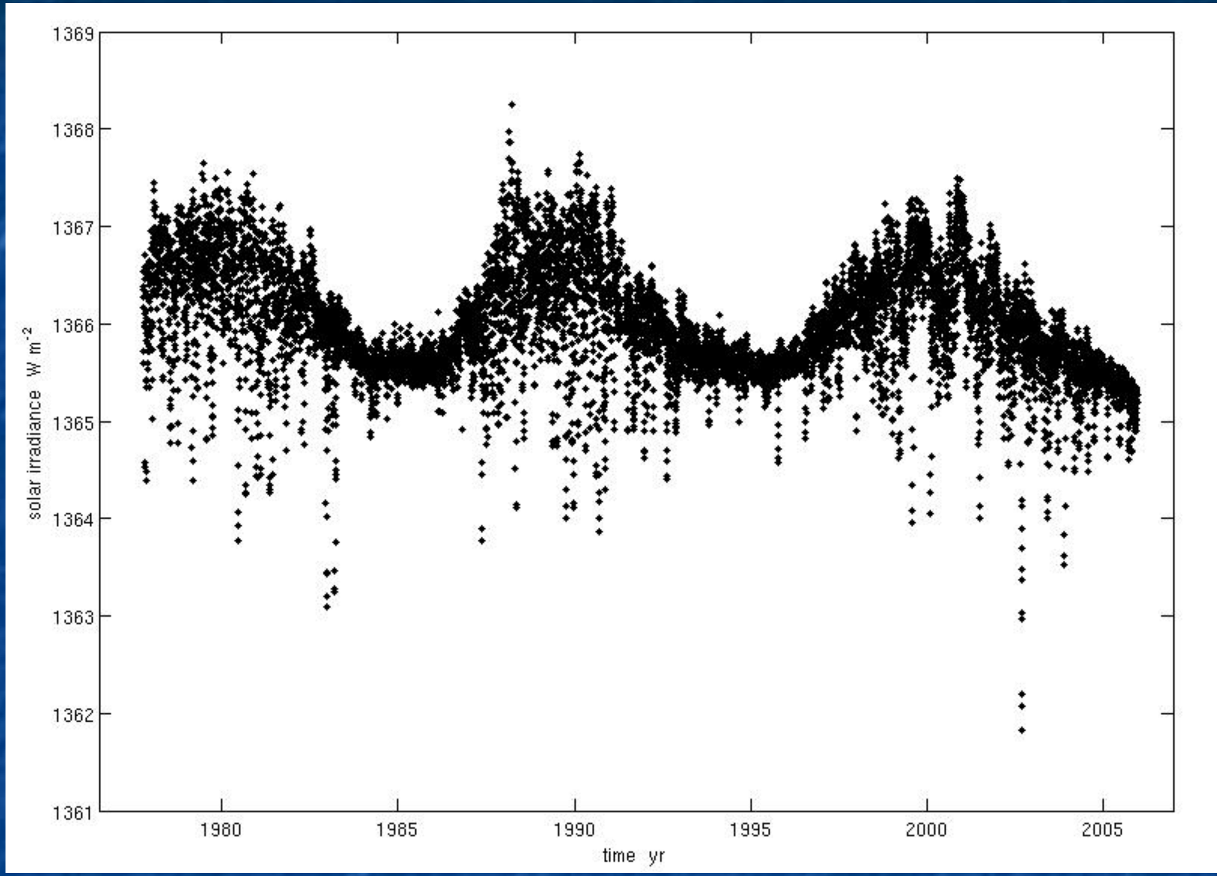
- Precision versus accuracy: we are not interested in the absolute radial velocity of stars (which is the projected space velocity with respect to the solar barycenter along the line of sight) but only in RV variations relative to an arbitrary zero-point
- Things that change RV of a star
  - Convection and limb shift
  - Pulsations
  - Surface motion (flows)
  - Spots and other photometric blemishes
  - Physical acceleration (e.g., orbital motion)



Typical velocities in supergranules 300-400 m/s

Total solar irradiance and its variability

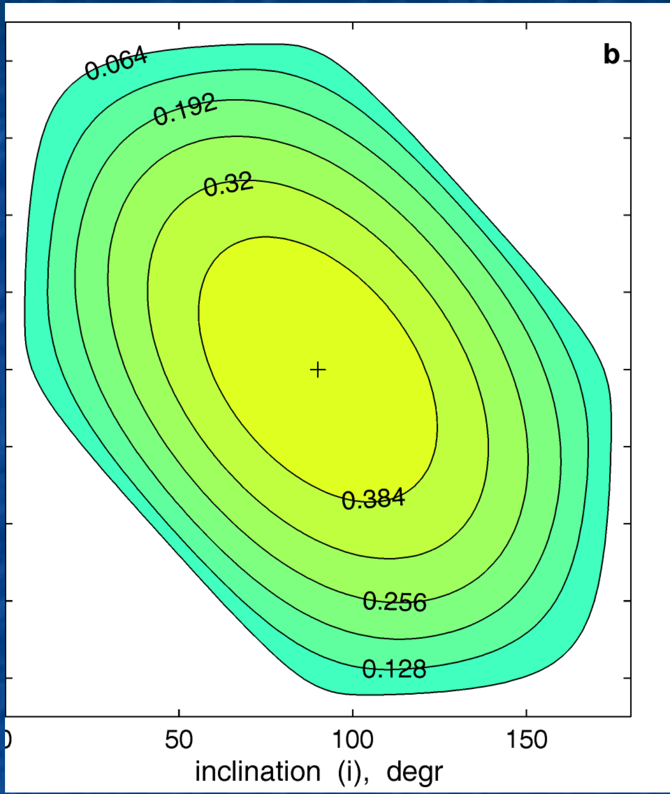
- Assumption: photometric variability caused by spots and plages
- The sun is brighter when it's more active
- The overall standard deviation of daily variations σ_f=0.575 W m^{-2} = 422 ppm



PMOD (TSI) solar irradiance data, almost 30 years of daily observation

Scaling relations for RMS(RV)/RMS(flux)

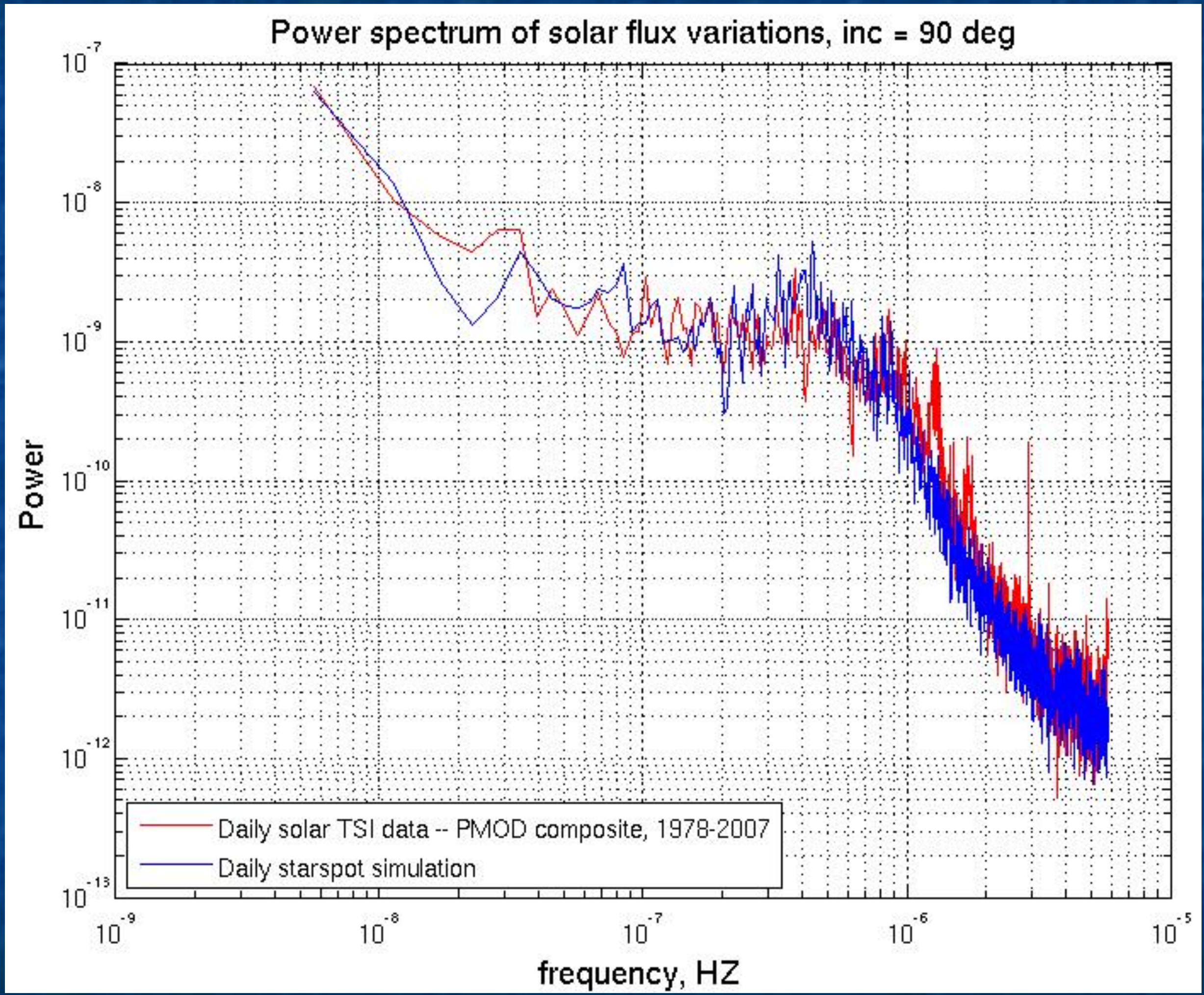
- Simple scaling relations exist between the RMS of RV and RMS of flux for a small spot (or bright area): Makarov et al. 2009 ApJ 707
- Graph to the right show the ratio RMS(RV)/RMS(flux) as function of inclination of rotation angle and latitude of the spot in units of V_{eq} *(0.19-sin² b)*
- Taking the central value 0.448, the expected RMS(RV) for the Sun is



$$0.448 \times 4.22E\text{-}4 \times 2 \text{ km/s} = 0.38 \text{ m/s}$$

Catanzarite's simulations

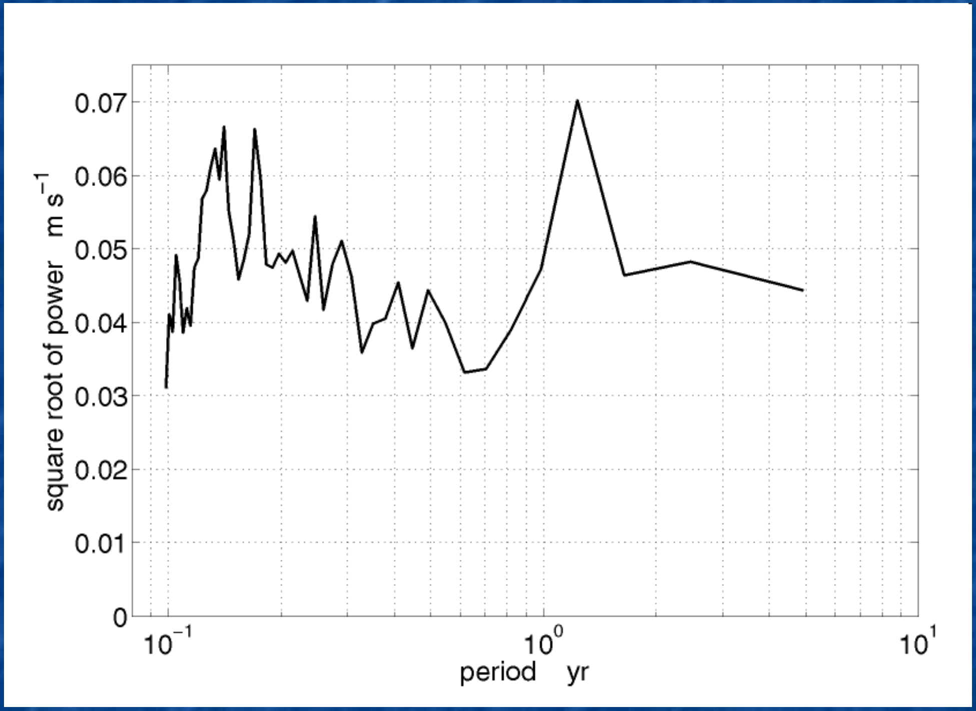
- Adjust sunspot parameters (rate, area, lifetime) until the simulated power spectrum looks like the TSI data
- No Maunder butterfly – all spots on the equator
- No spot decay
- Predicted RMS jitter: photocenter 0.9 µAU; RV 0.4 m/s



Spectrum of RV jitter

- The RV signature of Earth is 0.089 m s^{-1}
- In the habitable zone of sun, the detection threshold (3.5σ) due to sunspot jitter is:

  0.25 m s^{-1}



Quiet Sun

- Most of the long-term photometric variability of the Sun (442 ppm) comes from the solar cycle
- Divide PMOD data into 962-day segments and re-determine TSI variance
- The largest sigma is about 260 ppm, the smallest ~70 ppm
- At quietest times, the expected spot jitter is

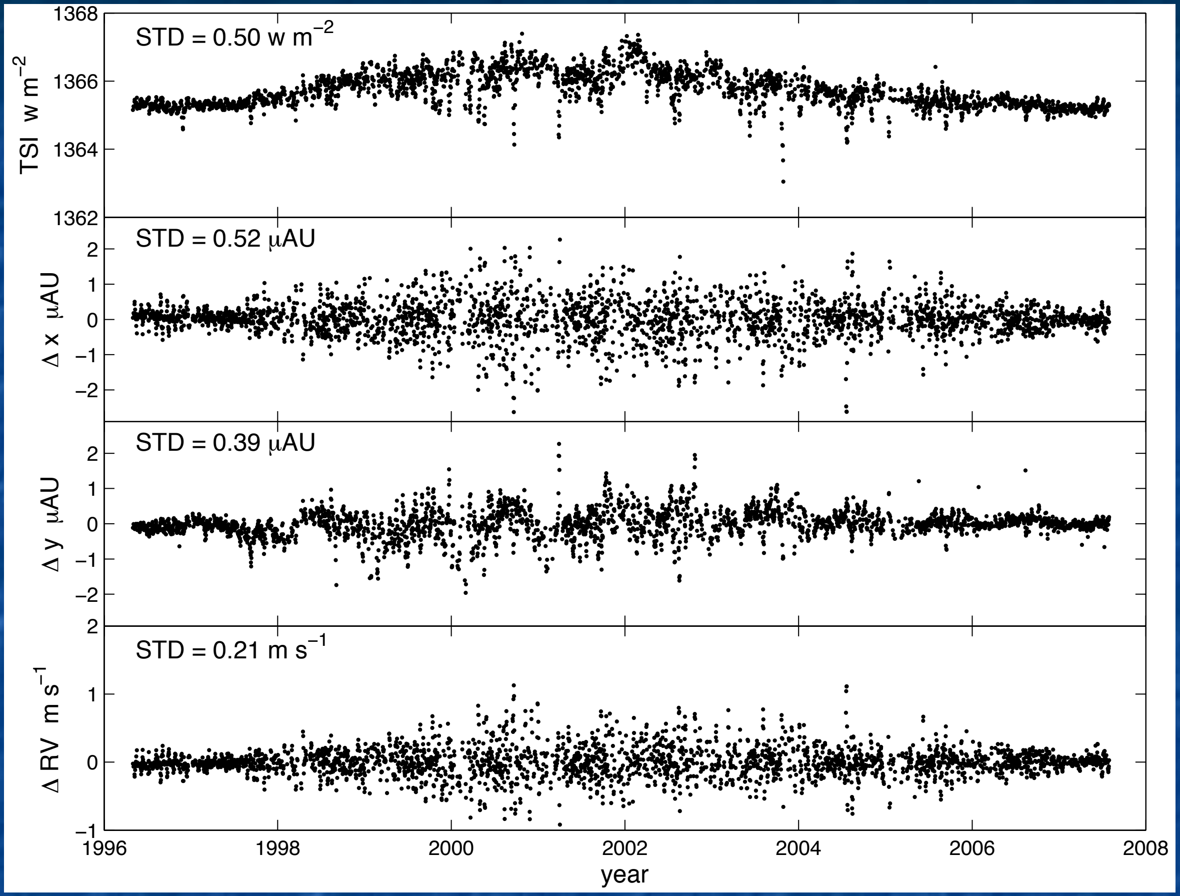
$$0.448 \times 7E\text{-}5 \times 2 \text{ km/s} = 0.062 \text{ m s}^{-1}$$

Catch the low-activity spans!

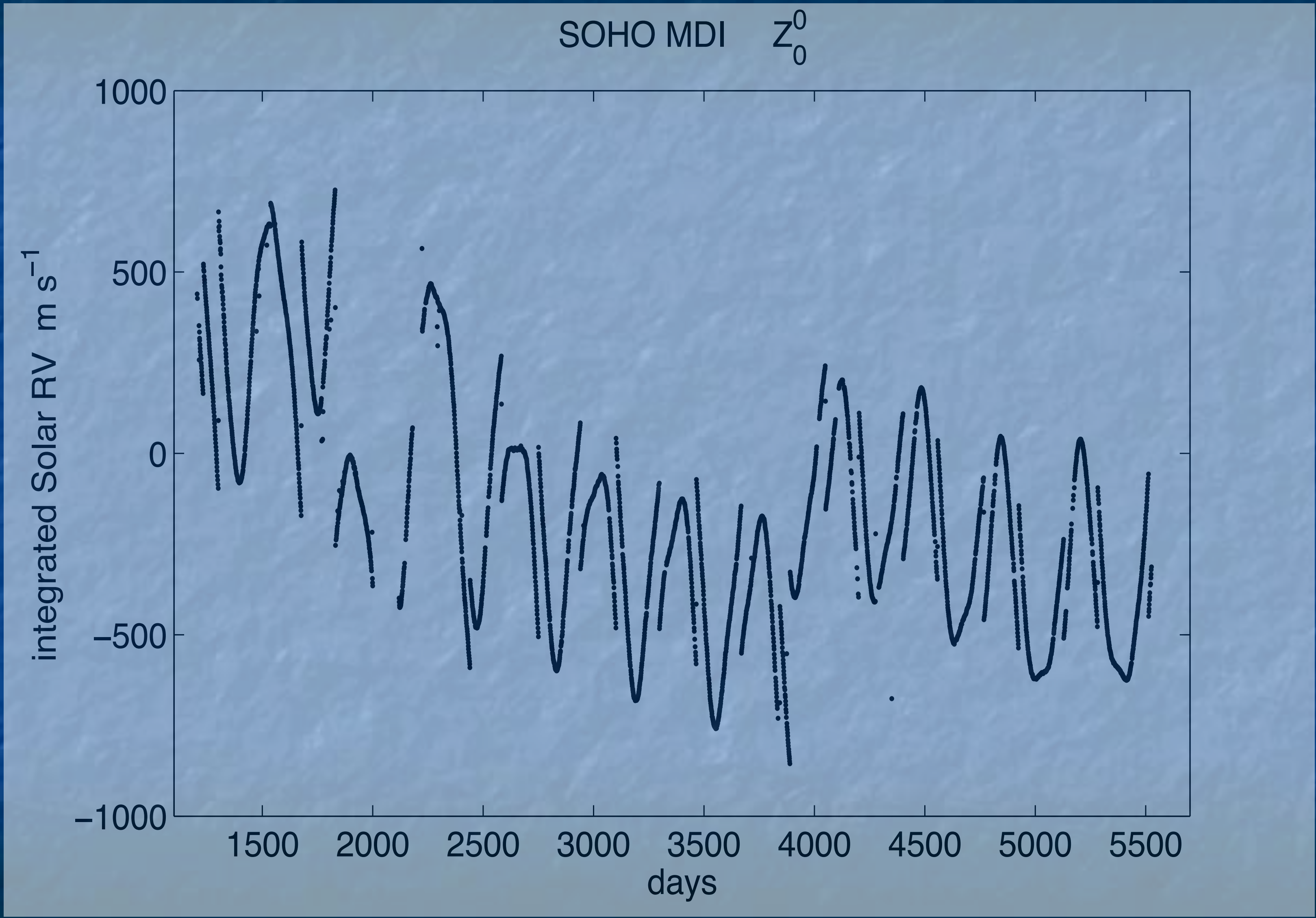
Surface brightness maps

Makarov, Parker & Ulrich 2010, ApJ 717 integrated high-resolution solar surface brightness maps derived from Mount Wilson observations

The RV std varies between 0.02 m s^{-1} on the quietest months and 0.5 m s^{-1} at the maximum of activity in 2000



SOHO MDI measurements



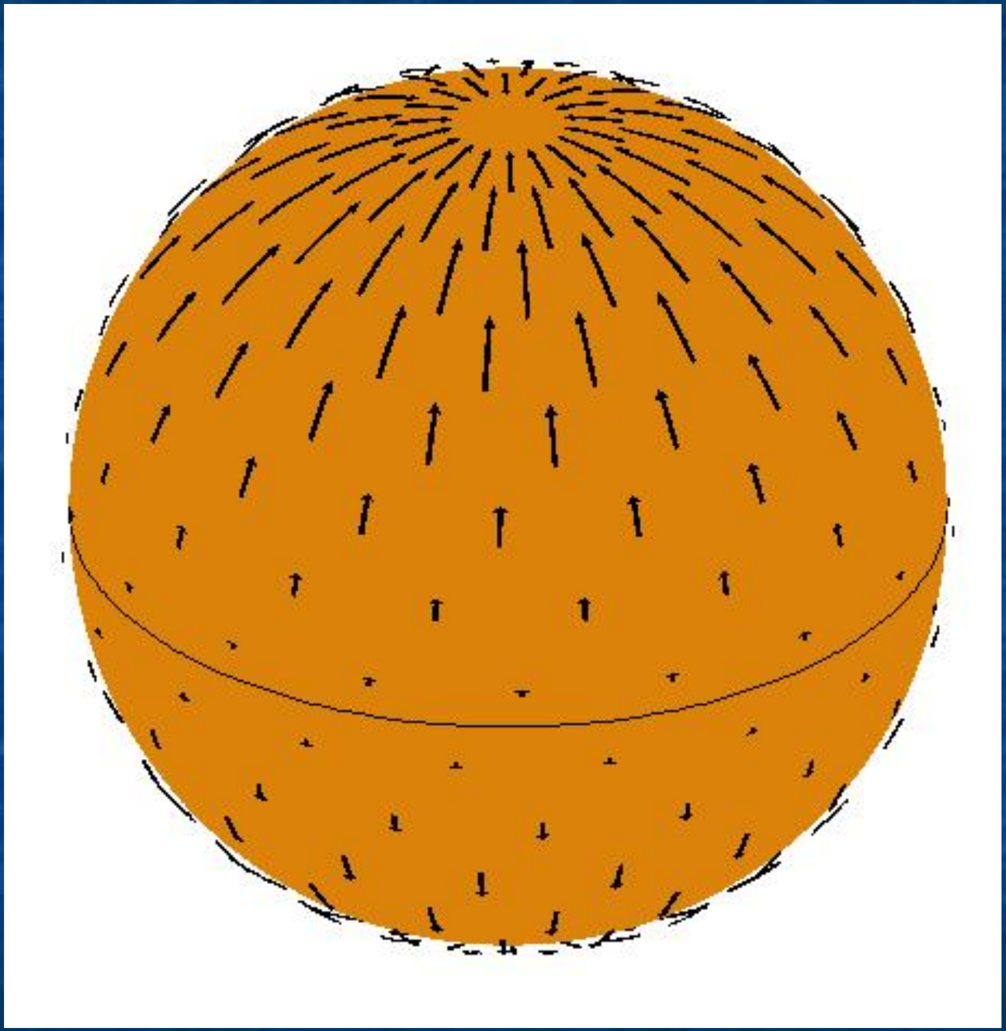
Spot jitter of solar-type stars

GO for smaller stars!

Solar type	**Sun**	**F5V**	**K5V**
Rotation period, days	25.4	18	30
RV signal from Earth, m s^{-1}	0.089	0.078	0.109
RV jitter long-term, m s^{-1}	0.38	0.69	0.23
RV SNR long-term	0.23	0.11	0.47
RV jitter quiet spells, m s^{-1}	0.062	0.11 ?	0.038 ?
RV SNR quiet spells	1.4	0.71 ?	2.9 ?

Meridional flow

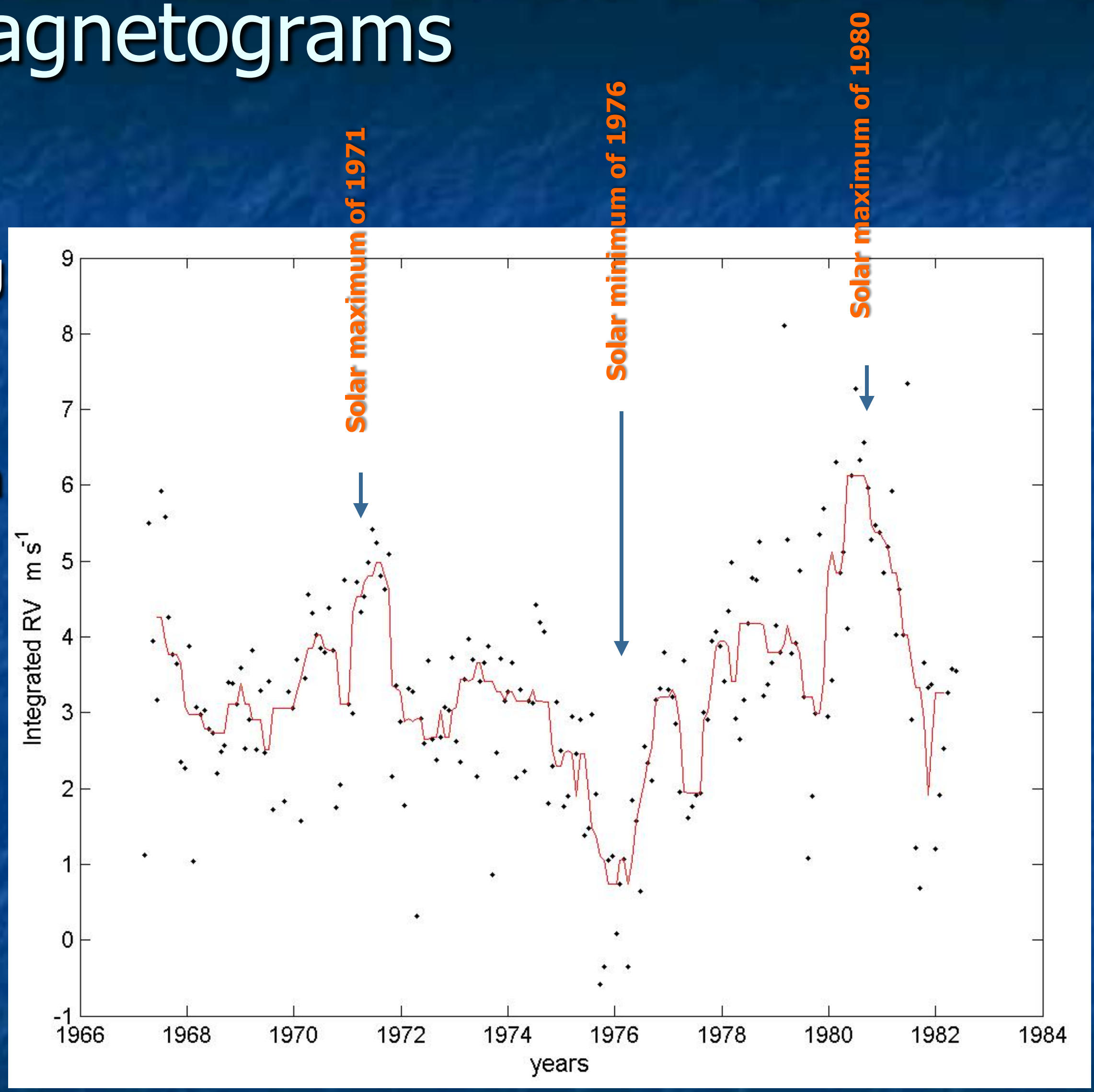
- Stars rotate differentially, therefore, there is meridional angular momentum transfer
- Is symmetric around equator ⏩ net nonzero contribution to observed RV
- Directed from the equator toward the poles – most of the time!
- Of order 20 m/s in amplitude



Mount Wilson magnetograms

- Daily Doppler velocity measurements covering 1967--1982
- Fe I line 5250.2 Å
- Discovered variations in the solar velocity field of tens of m/s
- The original (inadequate) model by Howard et al. 1982 can be refitted using meridional flow and limb shift terms:

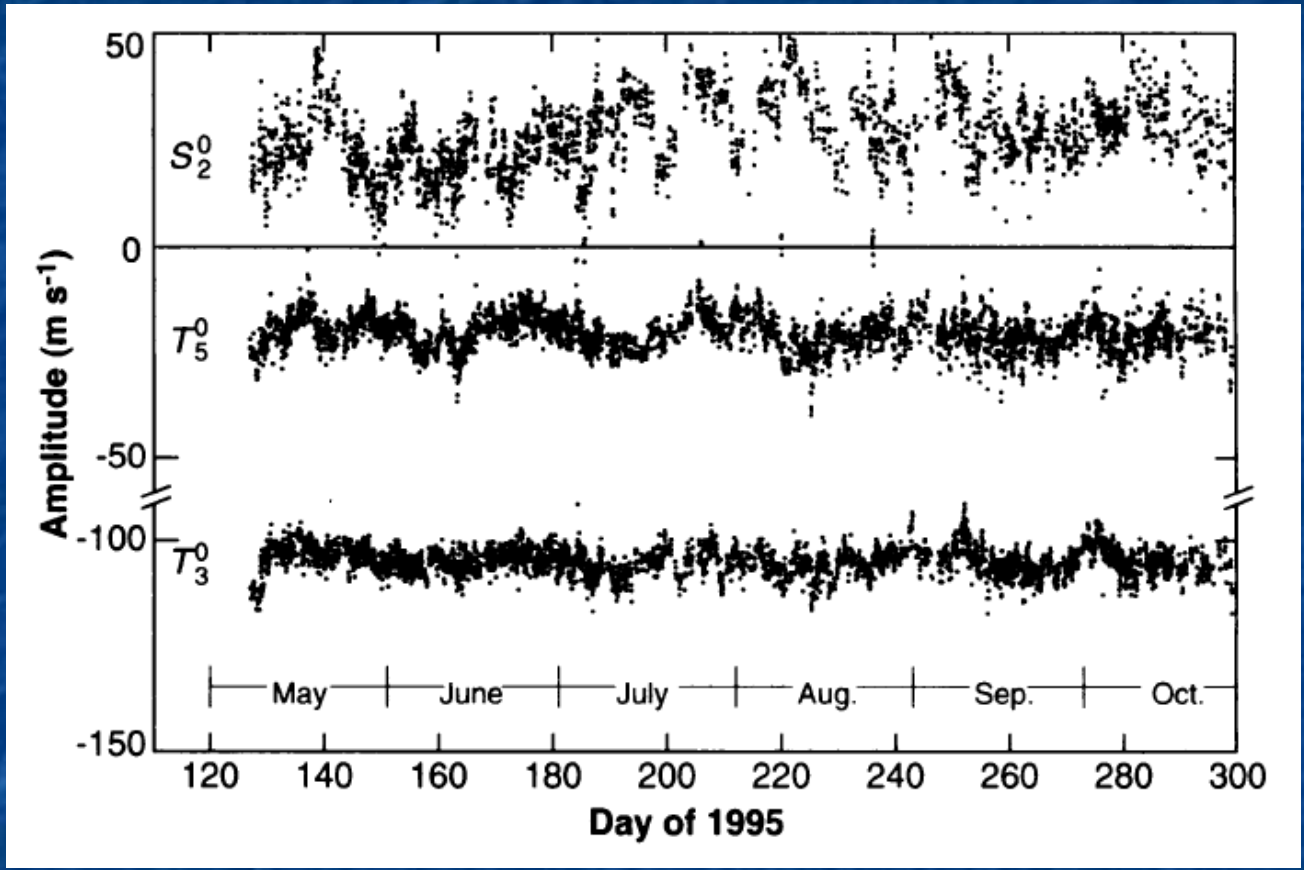
Makarov 2010 ApJ 715



σ = 1.4 m/s

GONG observations of surface flows

- From Hathaway et al. 1996 Science 272, 1306
- Note: S^0_2 is the main term of meridional flow



χ^2 periodogram of solar RV

A generic planet detection algorithm detects two bogus planets at >99% confidence with

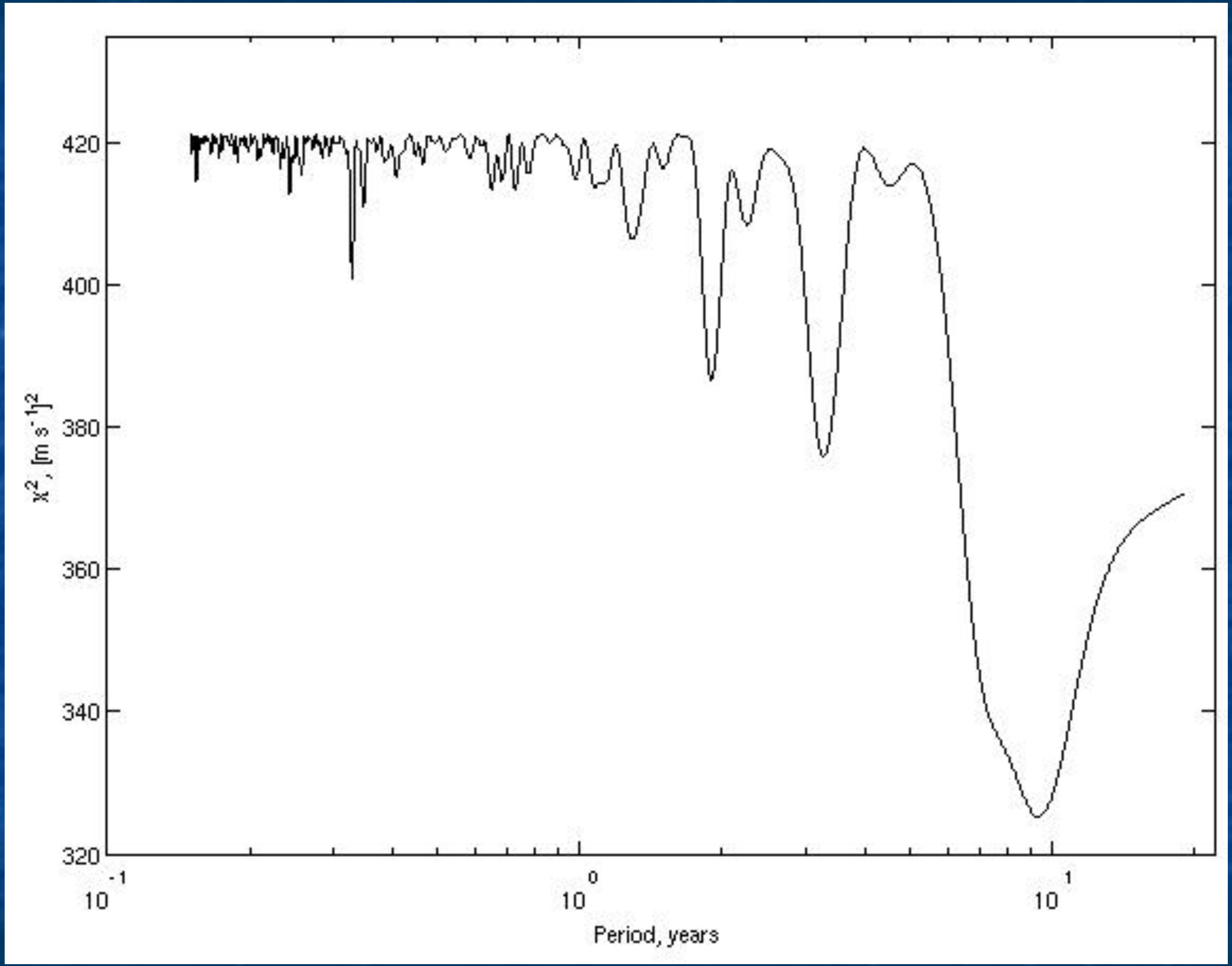
P_1=9.35 yr,

M_1=26 M_E

and

P_1=6.35 yr,

M_2=15 M_E

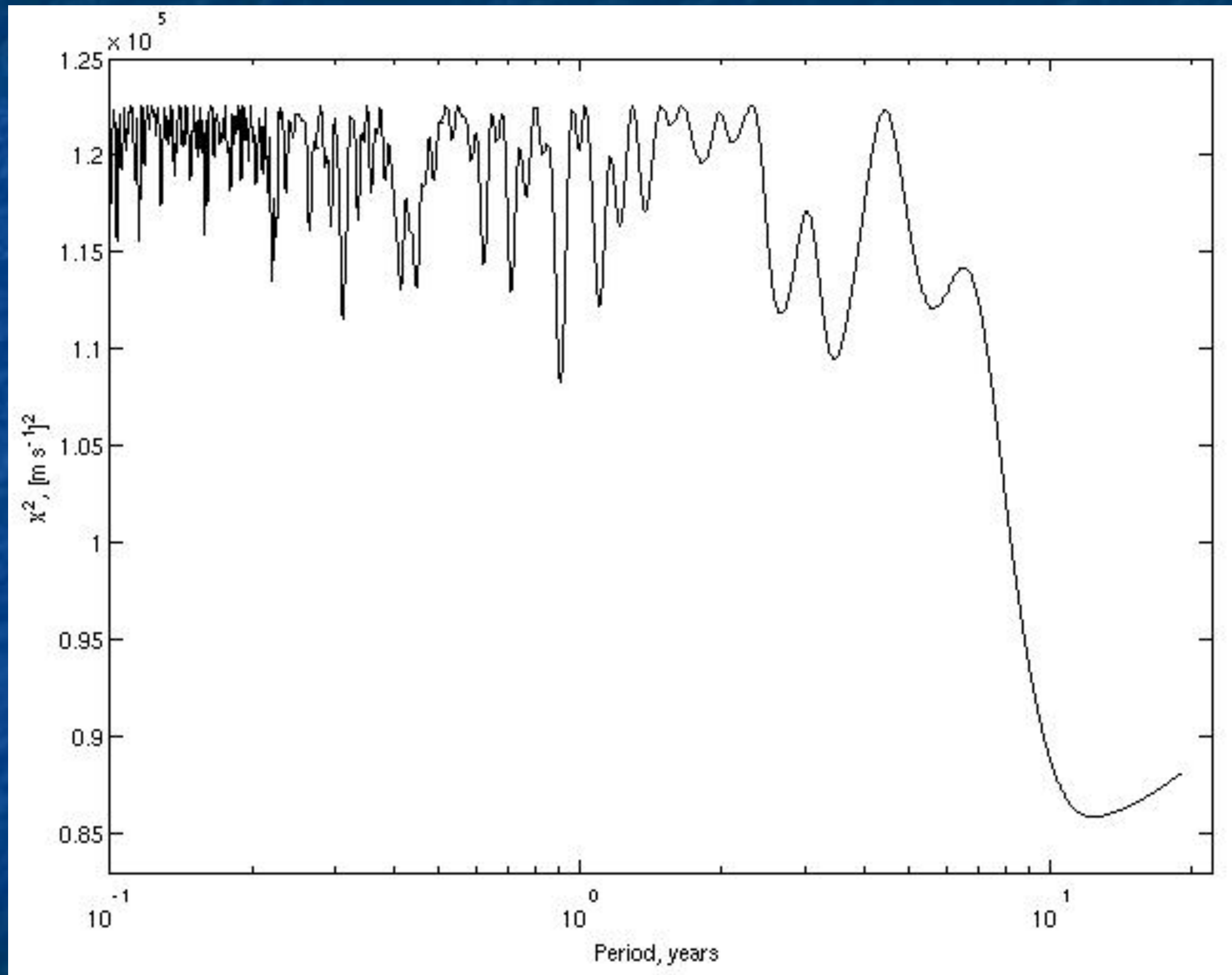


Planets and RV jitter of 55 Cnc

K0/G8 V star
T_{eff} = 5234 K
Fe/H = +0.31
Log R'_{HK}=-4.84
Age > 2 Gyr
v sin i = 2.4±0.5 km/s
M = 0.94 M_{sun}
P_{rot} = 43 d

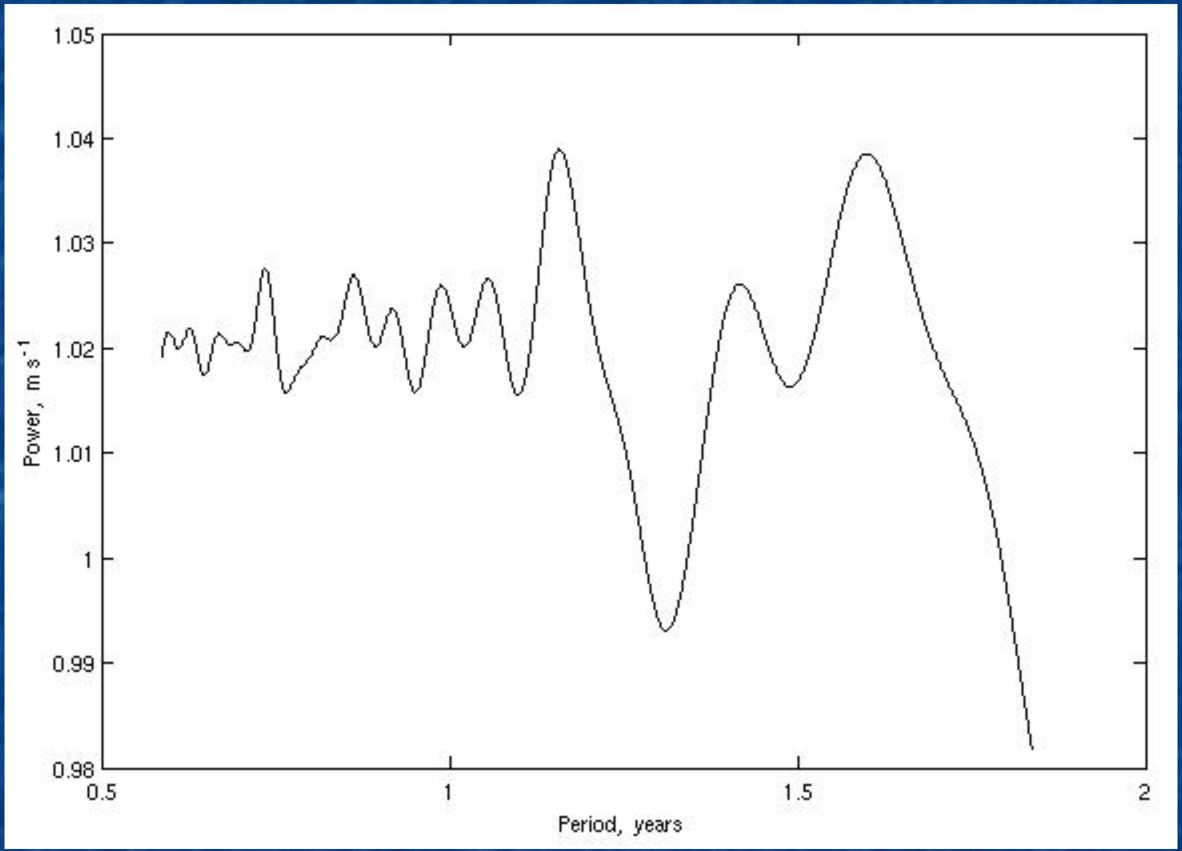
Close solar analog except for higher metallicity

Fischer et al 2008:
5 planets with periods between 2.8 d and 5220 d
After subtracting all detectable planets, STD(residual RV)=7.5 m/s
⏩ intrinsic scatter 5 m/s



Spectral power of solar RV in the range of habitable zone

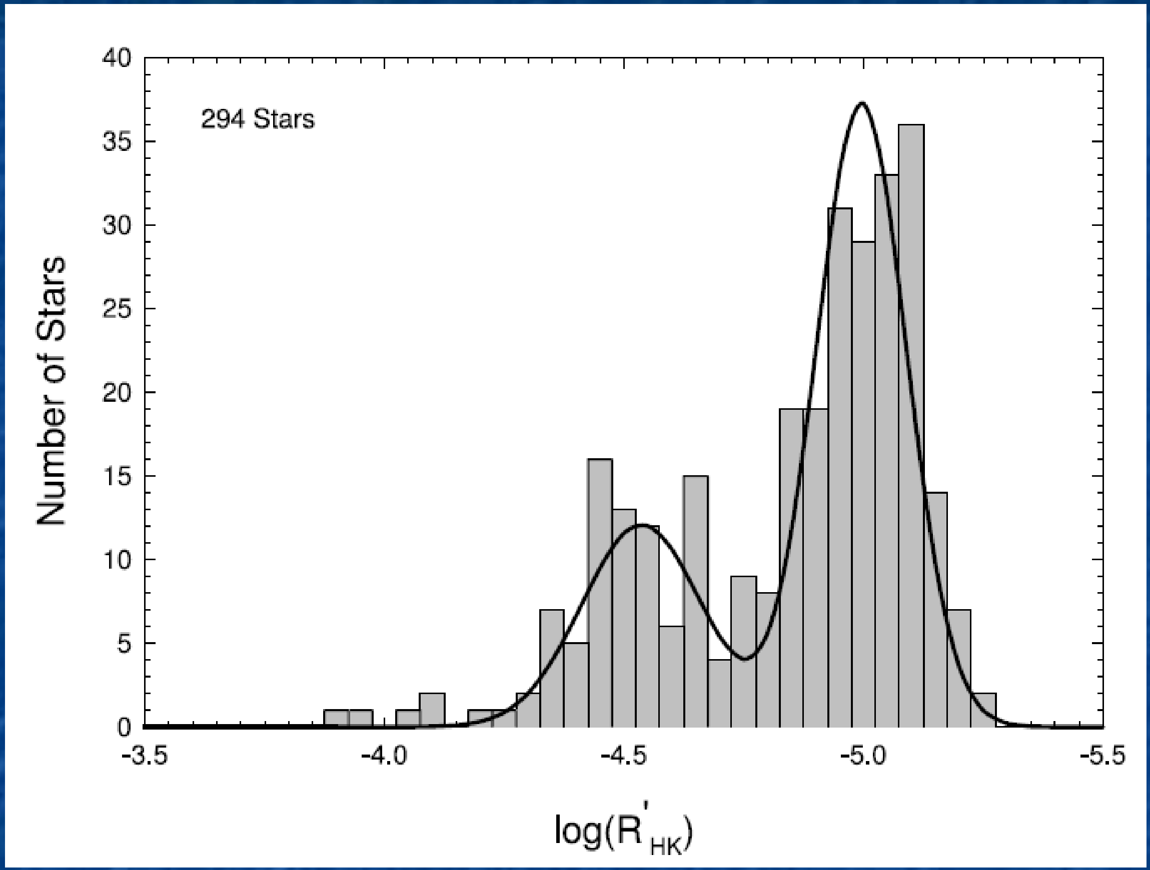
- The impact on detection of habitable planets around the Sun is defined by the spectral power of RV perturbations in the corresponding range of periods, which is about 1 m/s
- The signature of Earth is 0.089 m/s



What about other stars?

- Most of nearby solar-type stars have chromospheric activity of the Sun

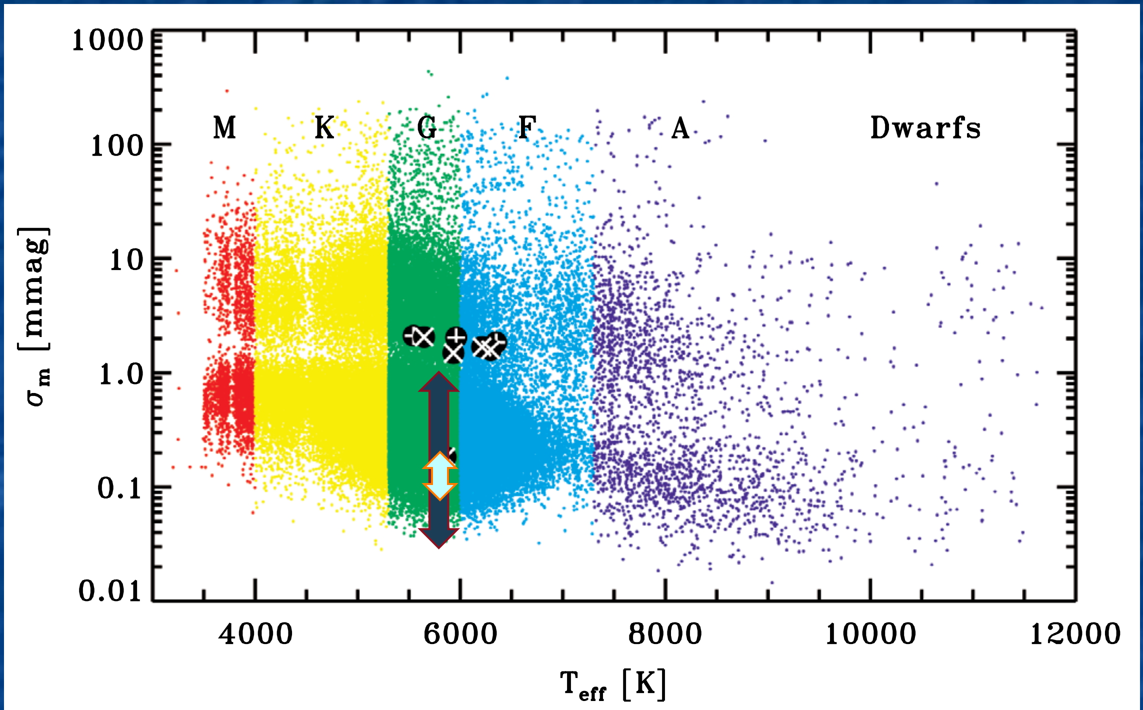
  log R'HK = -4.96
- Periods of rotation correlate with this parameter, statistically depend on age
- Star spot area is correlated with this parameter as well
- Decay rate of sun spot groups is correlated with area



From Gray et al. 2003

Variability of dwarfs

- On the timescale of 1 month, the lowest σ(TSI) is 23 ppm, the largest ~1300 ppm
- The range of solar cycle variation is overplotted on the graph showing the Kepler data for dwarfs
- The Sun is exceptionally inactive – but only when it's quiet



From Ciardi et al. 2011

Detection of Earths may be possible if

… the host star is small
… the host star is exceptionally inactive
… the host star is caught asleep
… no signs of differential rotation
… stars seen pole-on?