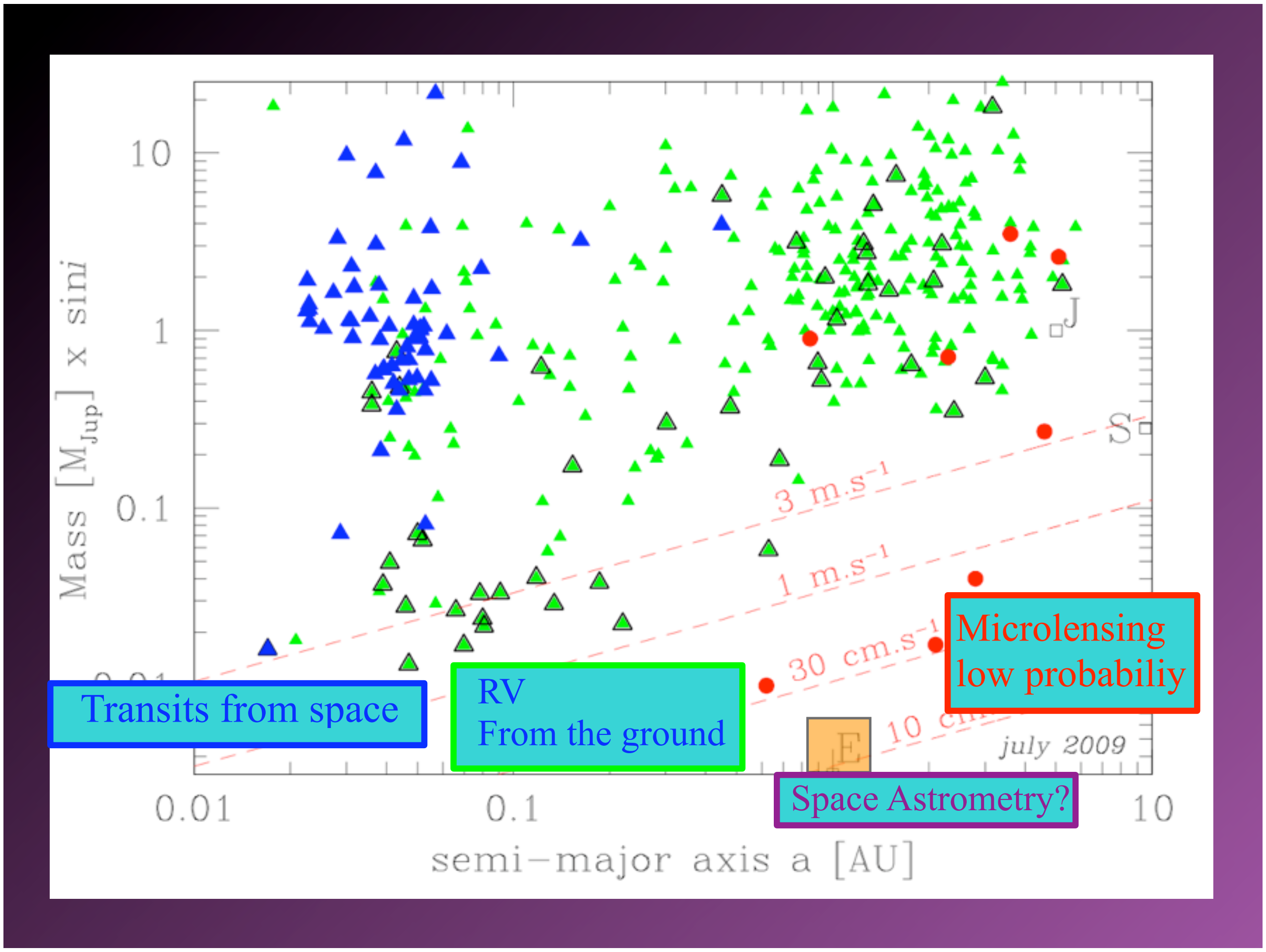
Detection of Earth twins in the HZ of solar-type stars ?

Political efforts

- Best approach to take?
  - different approaches (astrometry, direct detection, etc.)
- USA
  - NASA decadal plane
  - Exoplanet Task Force (Astron. and Astroph. Advisory Committee, Lunine et al.)
  - Exoplanet Forum (NASA Navigator Program, Traub et al. Precursor science for the Terrestrial Planet Finder)
- Europe
  - Astronet infrastructure roadmap
  - Blue Dot Team (lobbying for planet characterisation mission)
  - ESA ExoPlanet Roadmap Advisory Team (EPR-AT)



Present state of RV searches

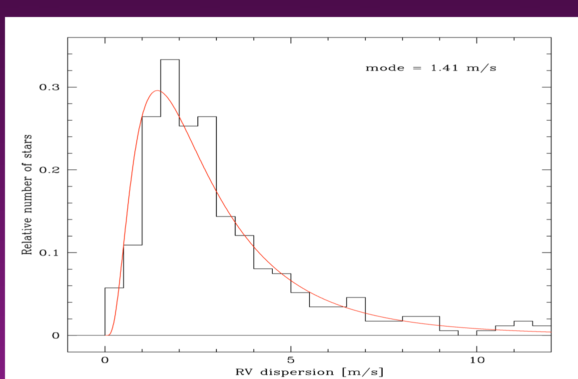
- majority of known planets: ~ 400

  => statistical distributions of planet and star parameters

- HARPS precision:

  ~80 cm/s = best “raw” rms around published solution

  Distribution of rms of high-precision HARPS survey: mode=1.4m/s



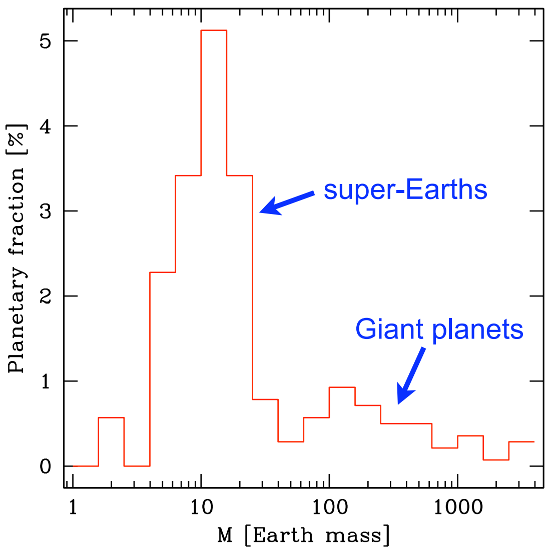
=> includes
- instrumental effects
- stellar effects
- photon-noise
- unknown planets

- Population of Neptune-mass planets and super-Earths

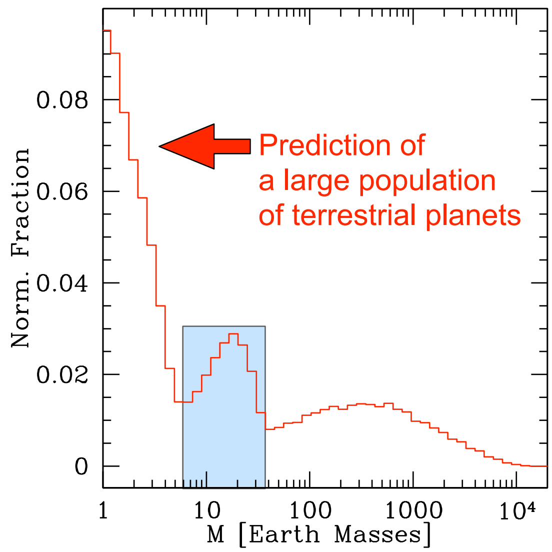
Some properties of close-in low-mass planets

1) Mass distribution

Observations
(normalized distribution)



Models
(Mordasini et al. 2009)



Planet Detectability with radial velocities

$$k_1 = \frac{28.4\ \mathrm{m\,s^{-1}}}{\sqrt{1-e^2}} \frac{m_2 \sin i}{M_{\mathrm{Jup}}} \left(\frac{m_1 + m_2}{M_{\mathrm{Sun}}}\right)^{-2/3} \left(\frac{P}{1\ \mathrm{yr}}\right)^{-1/3}$$

Jupiter	@ 1 AU	: 28.4 m s^{-1}
Jupiter	@ 5 AU	: 12.7 m s^{-1}
Neptune	@ 0.1 AU	: 4.8 m s^{-1}
Neptune	@ 1 AU	: 1.5 m s^{-1}
Super-Earth (5 $M_\oplus$)	@ 0.1 AU	: 1.4 m s^{-1}
Super-Earth (5 $M_\oplus$)	@ 1 AU	: 0.45 m s^{-1}
Earth	@ 1 AU	: 9 cm s^{-1}

A few m/s precision OK
for giant planets
e.g. Jupiters out to > 5 AU

Need to go below 1 m/s
for close super-Earths!

Required an order of
magnitude improvement

Radial velocities in a reference frame

$V_r = V_{spectrum} - V_{instrument} - V_{Earth}$

Barycentric radial velocity = wavelength shift reduced to the barycenter of the Solar System

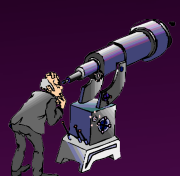
Velocity of the observed spectrum with respect to a reference point (velocity zero point)

Actual velocity of the spectrograph with respect to a reference point (velocity zero point)

Earth rotation and Earth orbital motion around the Solar System's barycenter

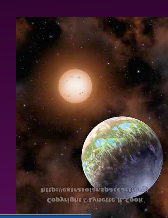
Higher RV precision = …. ????

Earth effect on the Sun = 9 cm/s



Earth atmosphere

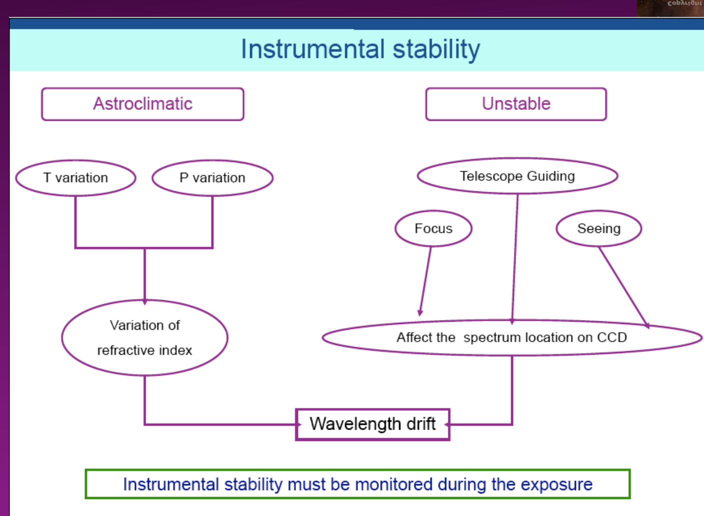
interstellar medium



1) Instrumental error

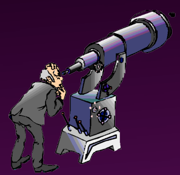
telescope <-> detector

- stability and repeatability



Higher RV precision = ... ????

Earth effect on the Sun = 9 cm/s

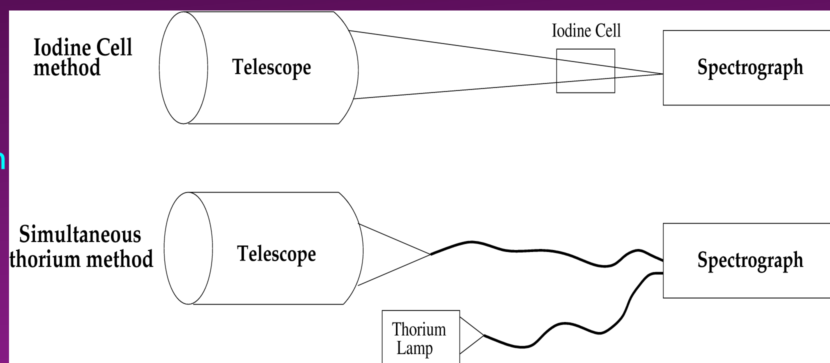


Earth atmosphere interstellar medium

1) Instrumental error

telescope <-> detector

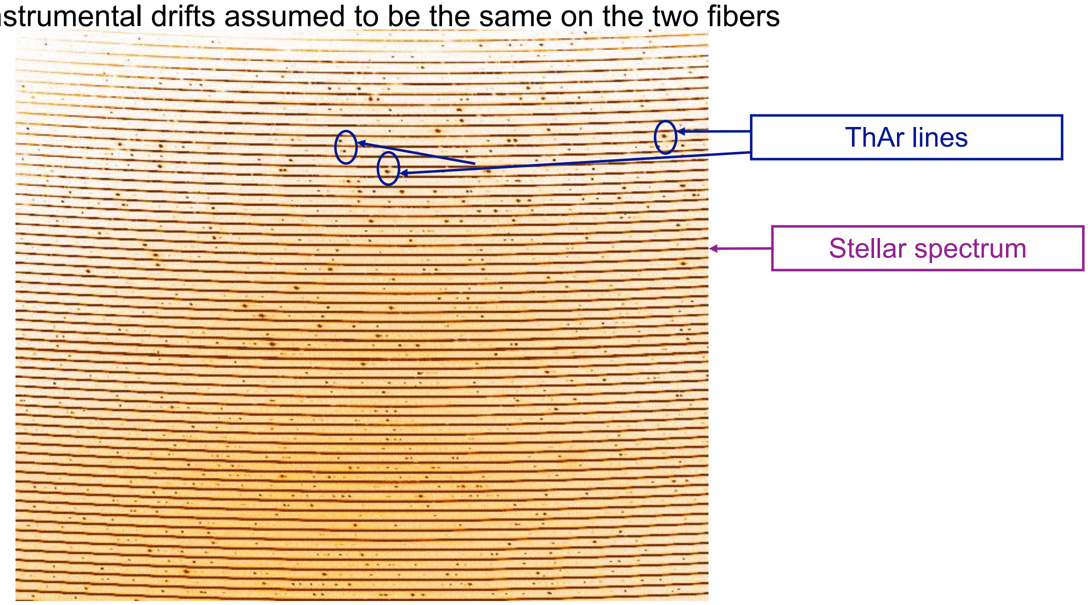
- stability and repetability
- calibration and wavelength solution



The simultaneous thorium technique

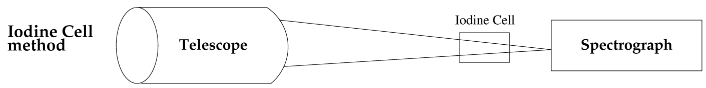
Wavelength calibration and instrumental stability monitoring:

- Reference = emission spectrum from an arc lamp (ThAr)
- Two fibers: A = star light, B = lamp light
- Science exposure contains simultaneous wavelength calibration
- Instrumental drifts assumed to be the same on the two fibers

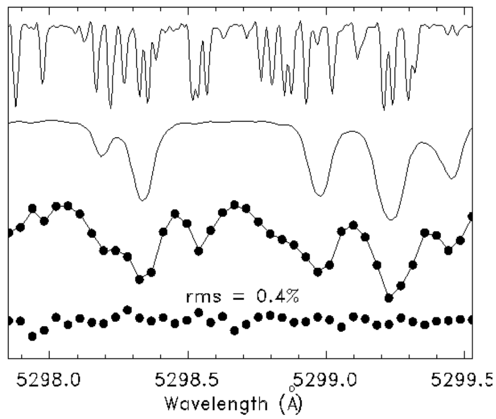


The iodine cell technique

- Wavelength calibration and instrumental stability monitoring:
  - Reference: iodine absorption cell at the spectrograph's entrance



  - Iodine spectrum superimposed on stellar spectrum



Pros and Cons of the Two Techniques

Iodine cell:

+ Easy to implement on any spectrograph
+ Suitable for slit spectrographs

− Spectral range: 500-630 nm
− Requires very high S/N spectra

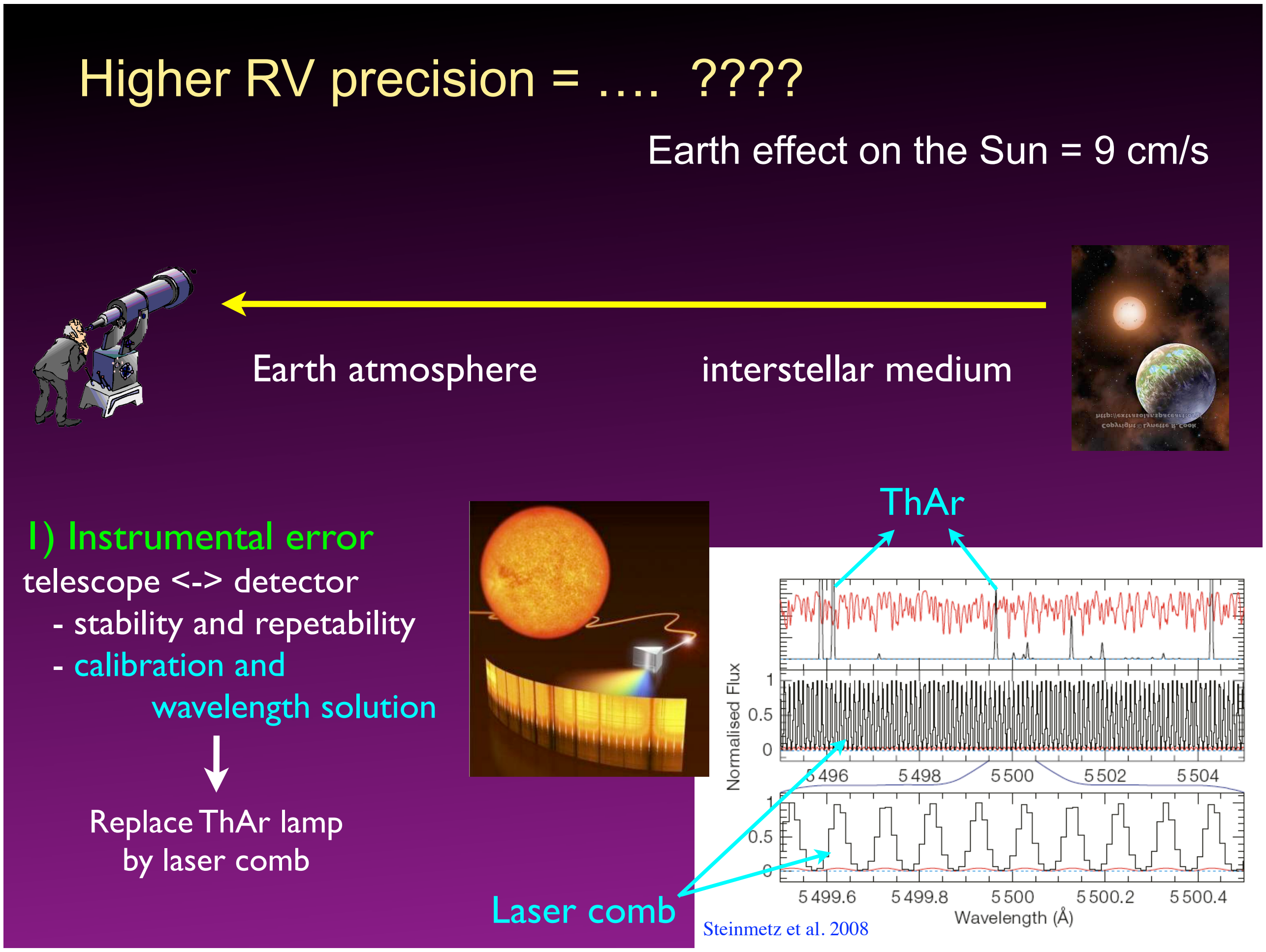
- Precision of 2-3 m/s

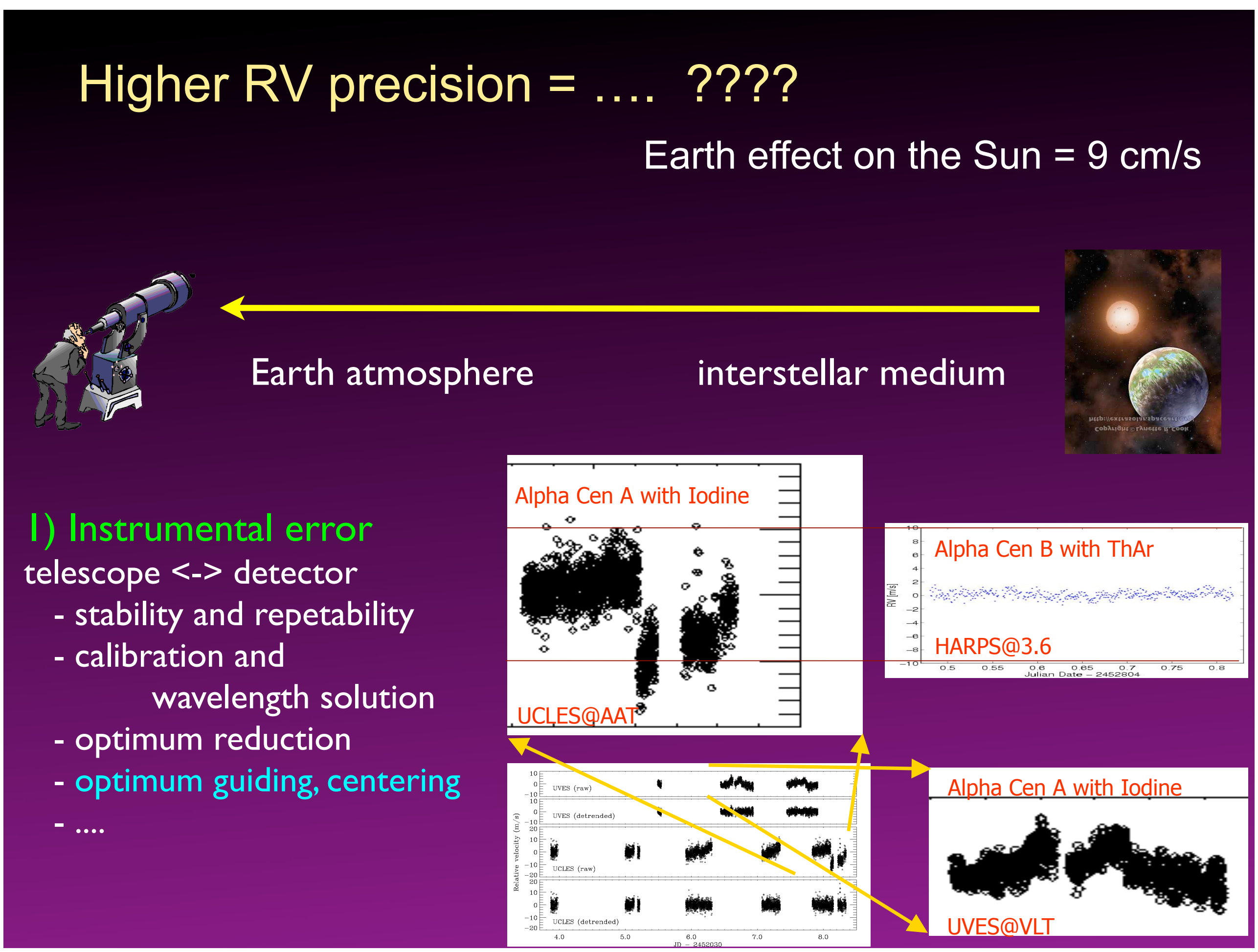
Simultaneous thorium:

− Requires a stabilized spectrograph
− Suitable for fiber spectrographs only
+ Spectral range: 380-680 nm
+ Requires high S/N spectra

- Precision of <1 m/s

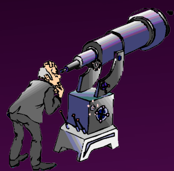
For a similar precision, the iodine cell technique requires > ~10 times much more photons than the simultaneous thorium technique


Higher RV precision = …. ????
Earth effect on the Sun = 9 cm/s
Earth atmosphere
interstellar medium
I) Instrumental error
telescope <-> detector
- stability and repetability
- calibration and
wavelength solution
Replace ThAr lamp
by laser comb
ThAr
Laser comb
Normalised Flux
Wavelength (Å)
5 496
5 498
5 500
5 502
5 504
5 499.6
5 499.8
5 500
5 500.2
5 500.4
Steinmetz et al. 2008


Higher RV precision = …. ????
Earth effect on the Sun = 9 cm/s
Earth atmosphere
interstellar medium
I) Instrumental error
telescope <-> detector
- stability and repetability
- calibration and
wavelength solution
- optimum reduction
- optimum guiding, centering
- ….
Alpha Cen A with Iodine
UCLES@AAT
Alpha Cen B with ThAr
HARPS@3.6
Alpha Cen A with Iodine
UVES@VLT

Higher RV precision = …. ????

Earth effect on the Sun = 9 cm/s



Intermediate medium

Earth atmosphere interstellar medium

1) Instrumental error

telescope <=> detector

- stability and repeatability
- calibration and wavelength solution
- optimum reduction
- optimum guiding, centering
- ….

ESPRESSO @ VLT (1 UT – 4 UT)

Expected precision ~10 cm s^{-1}

Small-mass planets, fundamental constant variability, QSOs, cosmology

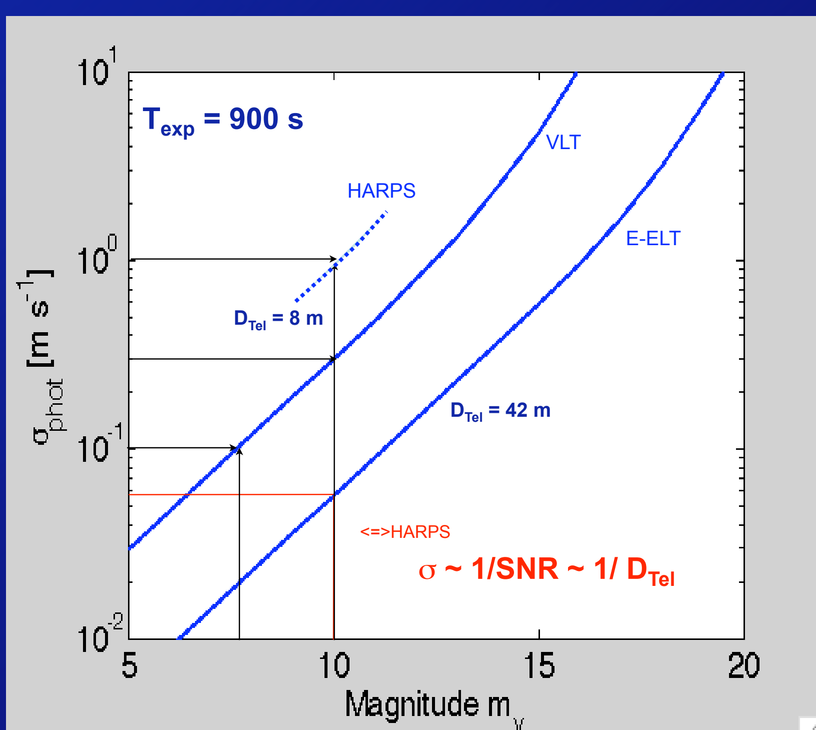
CODEX @ E-ELT

Expected precision ~1 cm s^{-1}

Cosmology (expansion of the Universe), QSOs, planets, etc.

Photon noise

HARPS-type spectrograph: R > 100'000, ε_{Tot} = 6%

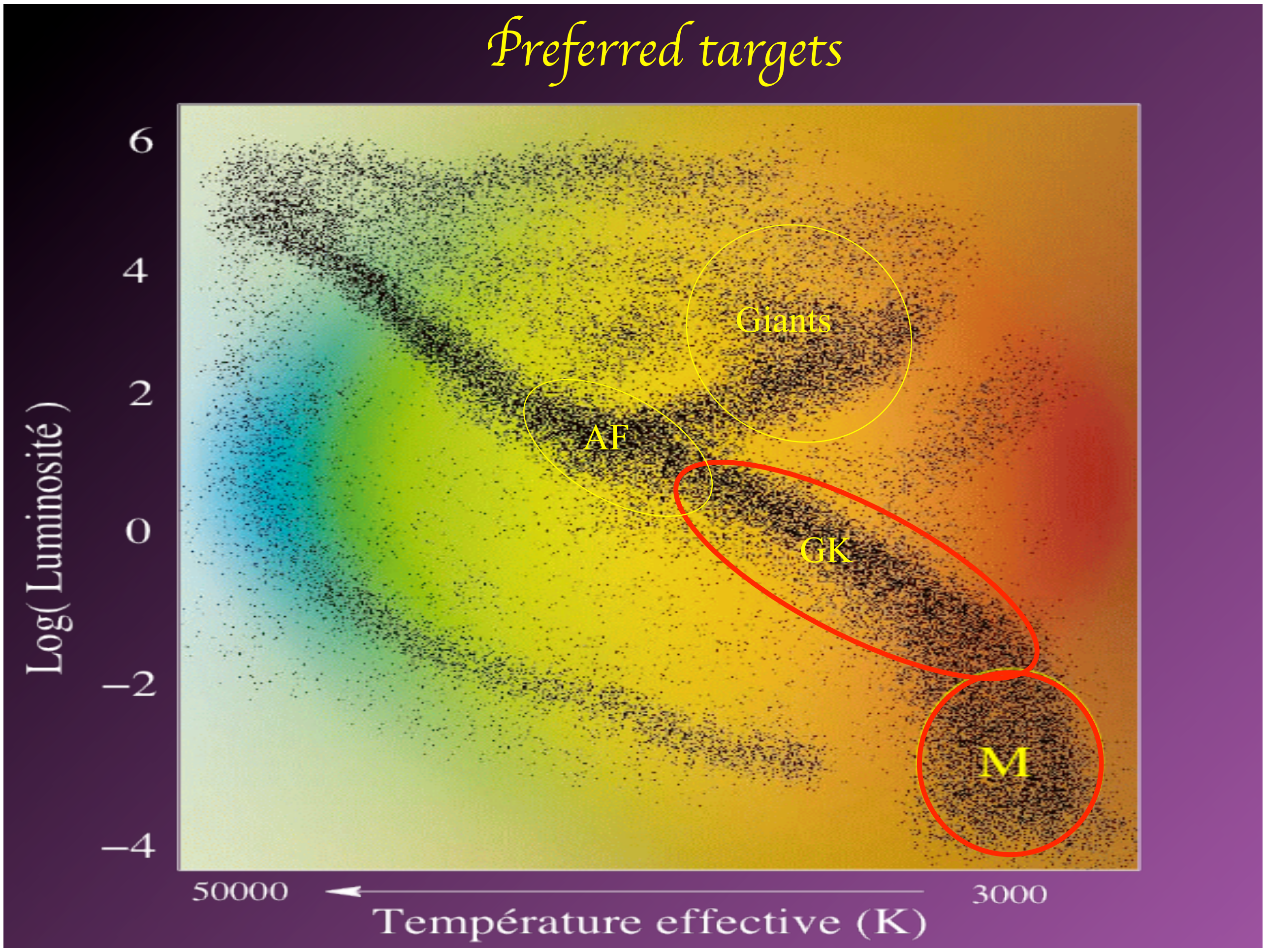


1) HARPS/ 3.6m
   1 m/s in 15' on V=10 star
   -> 25-30 cm/s on VLT
   -> ~5 cm/s on E-ELT

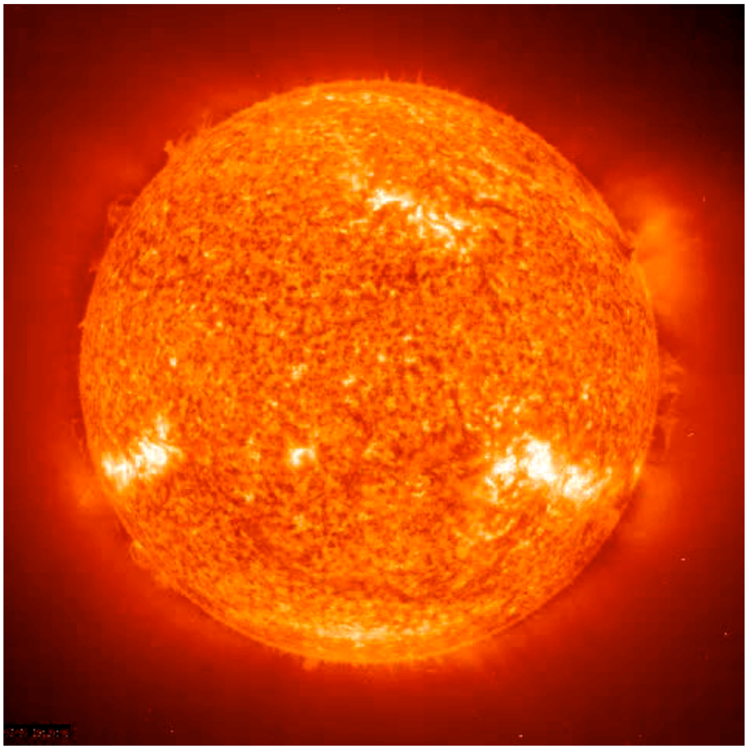
2) ESPRESSO/VLT
   Vlim = ~8 for 10 cm/s in 15'
   => Many solar-type stars
   ~700 non-active stars
   => Earth twin search

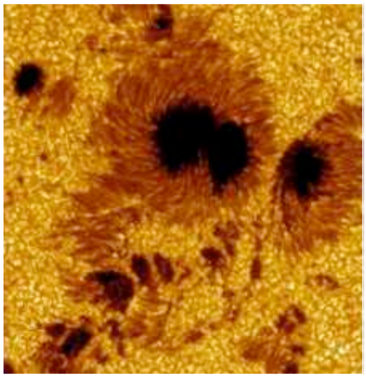
For 1-3 cm/s, 3-5 mag brighter
=> TEST for CODEX on
a few very bright stars

3) CODEX/E-ELT
   1 cm/s on star with V<6
   10 cm/s on V=11 stars
   TRANSITS (PLATO)



Stellar intrinsic limitations



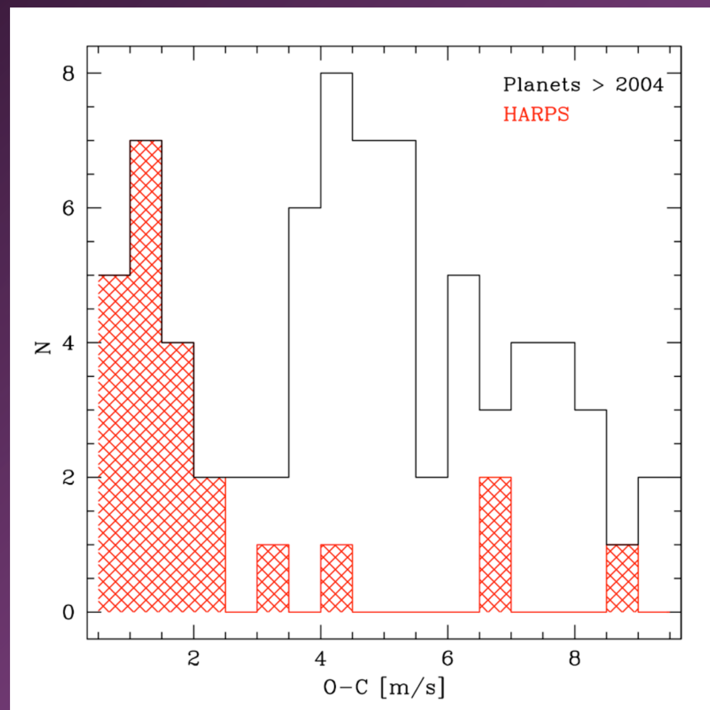


Harps: exploration of small-mass domain

All published orbits with residuals < 2.5 m/s between 2004 and 2008 are from HARPS

Before HARPS, limit in precision was not set by the star but by the instrument

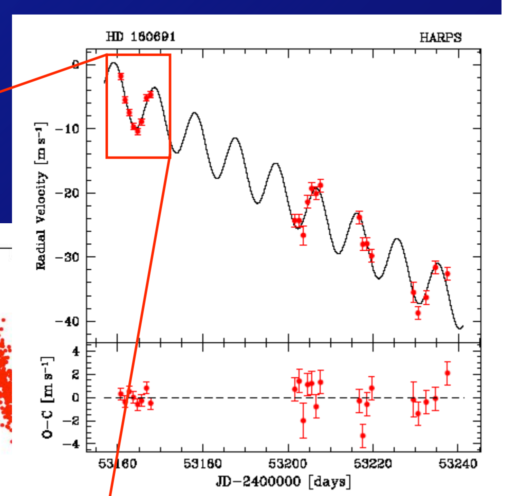
Still true with HARPS?

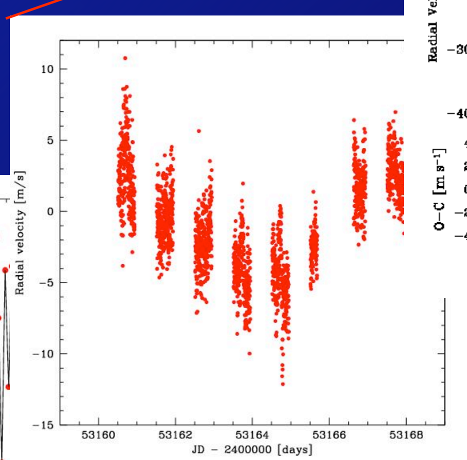


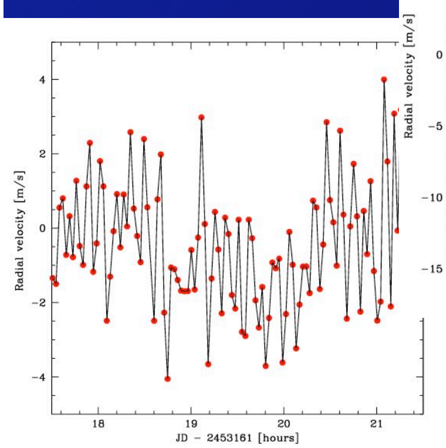
Stellar oscillation
The μ Ara example

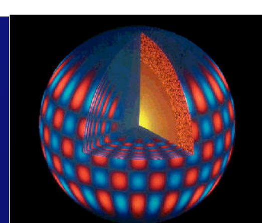
8 nights
250 measures/night
Photon noise < 20 cm/s

Santos et al. 2004
Bouchy et al. 2005
Bazot et al. 2005

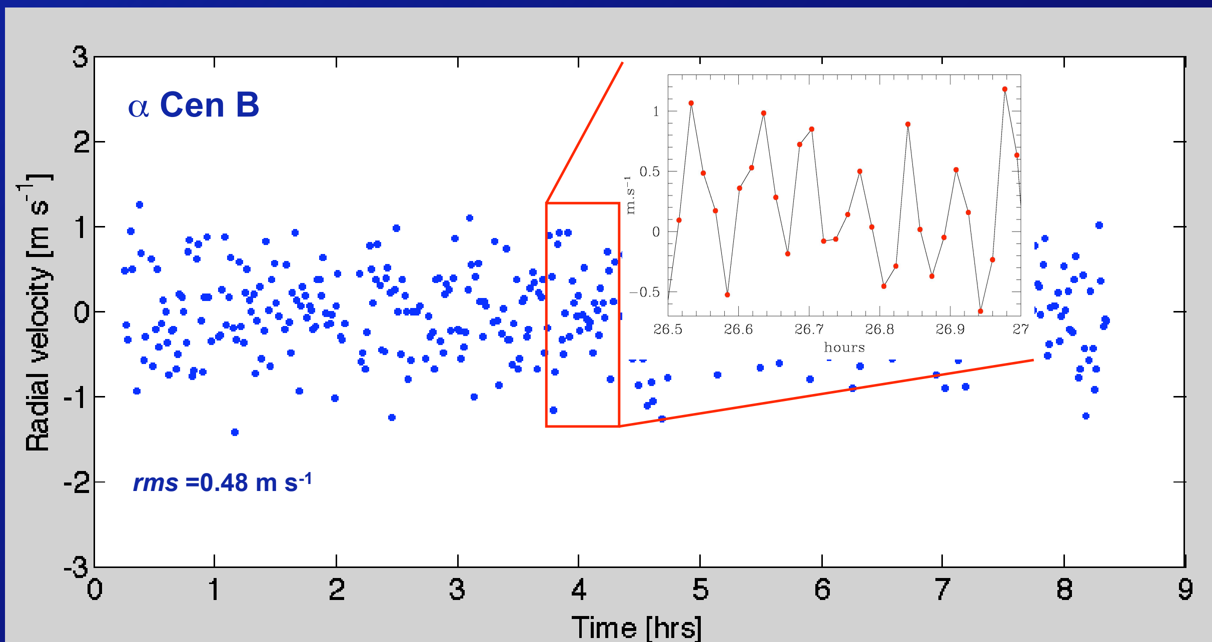




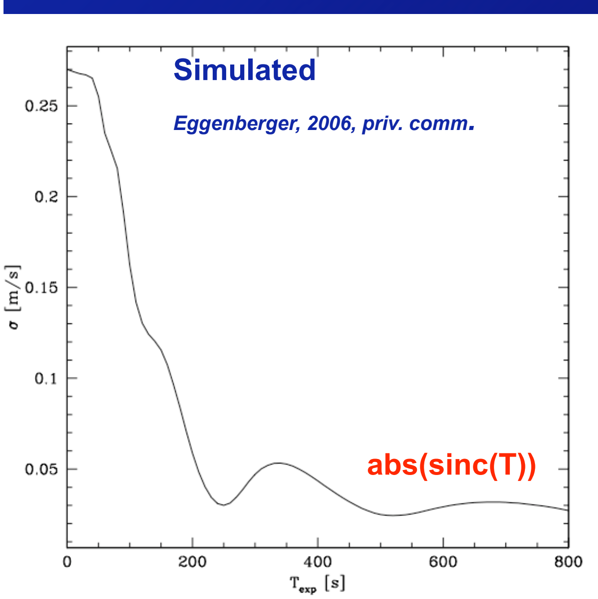


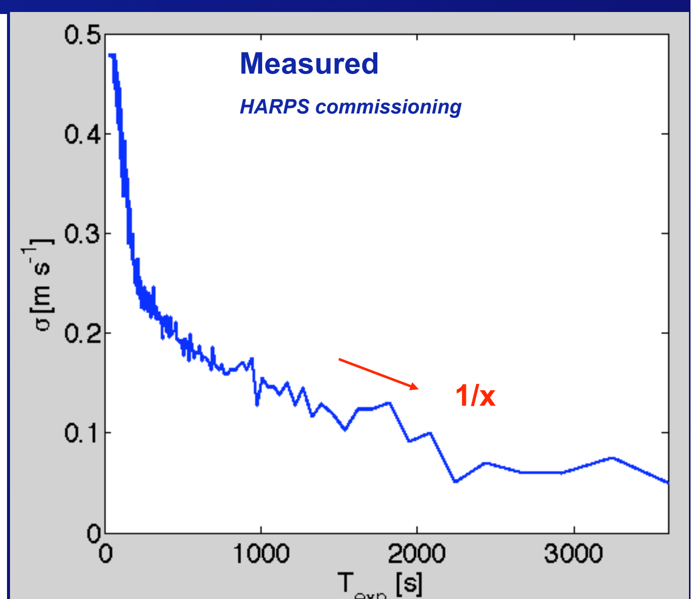


Stellar oscillations

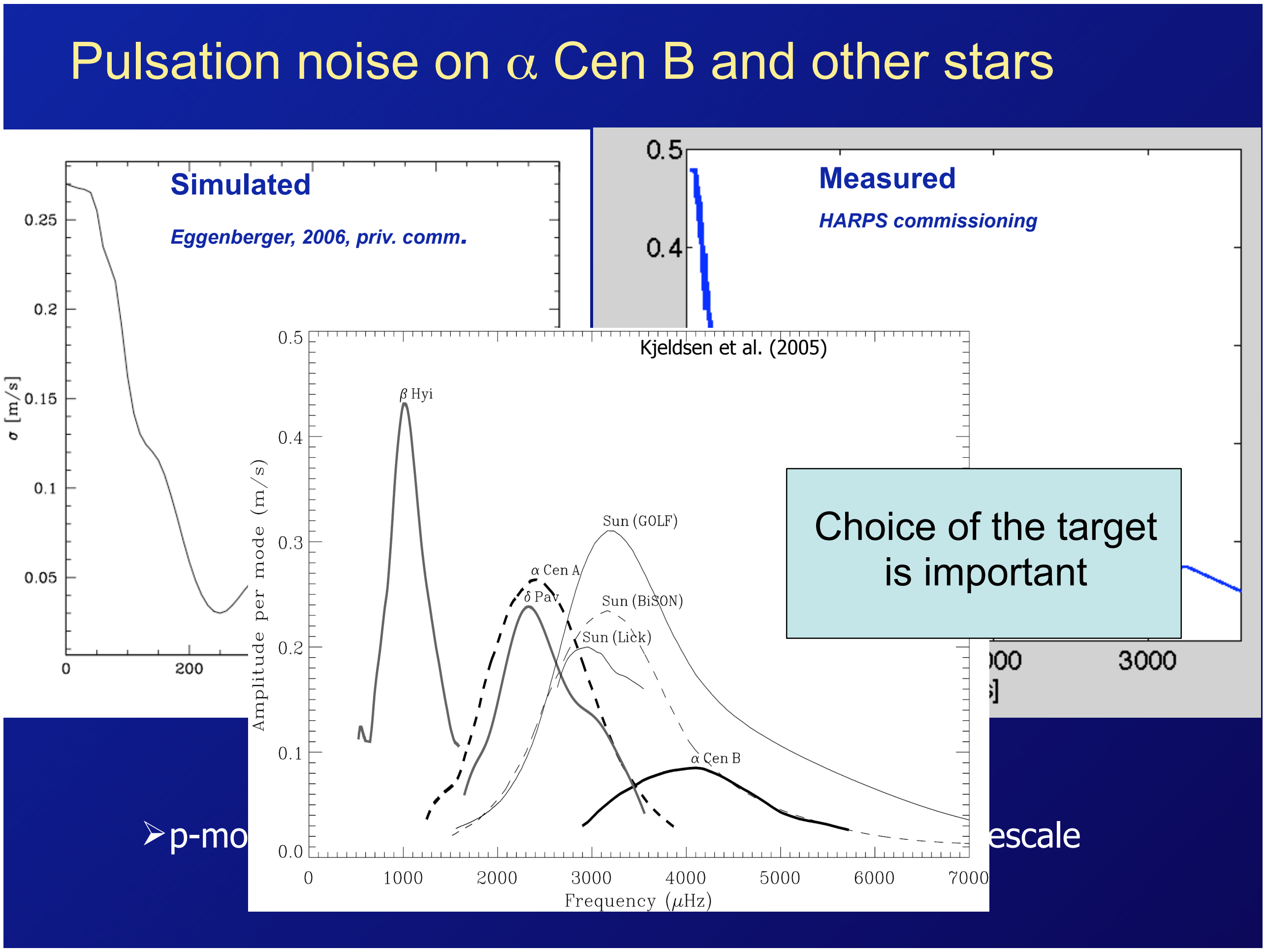


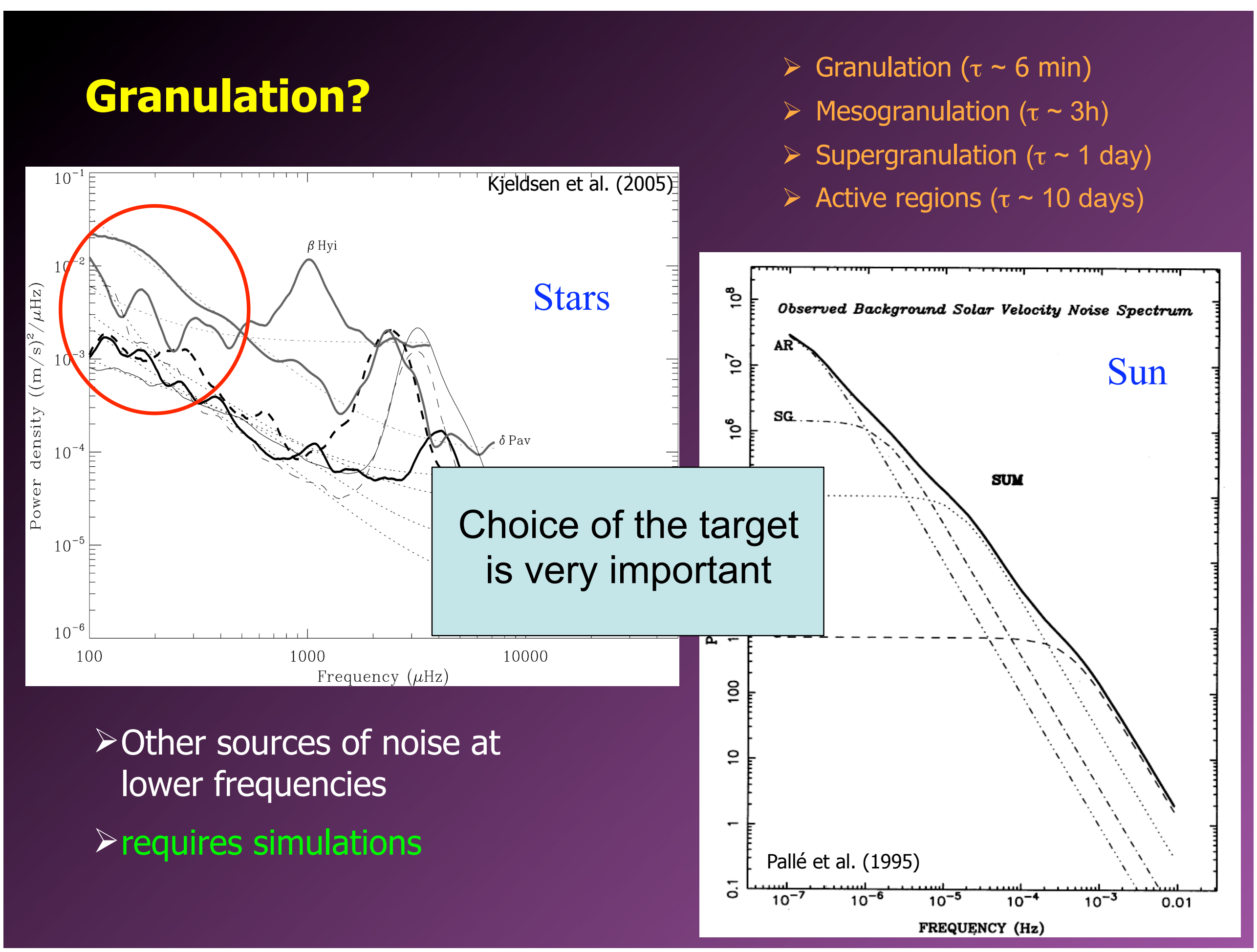
Pulsation noise on α Cen B and other stars





- p-modes average well on time > ~1 characteristic timescale

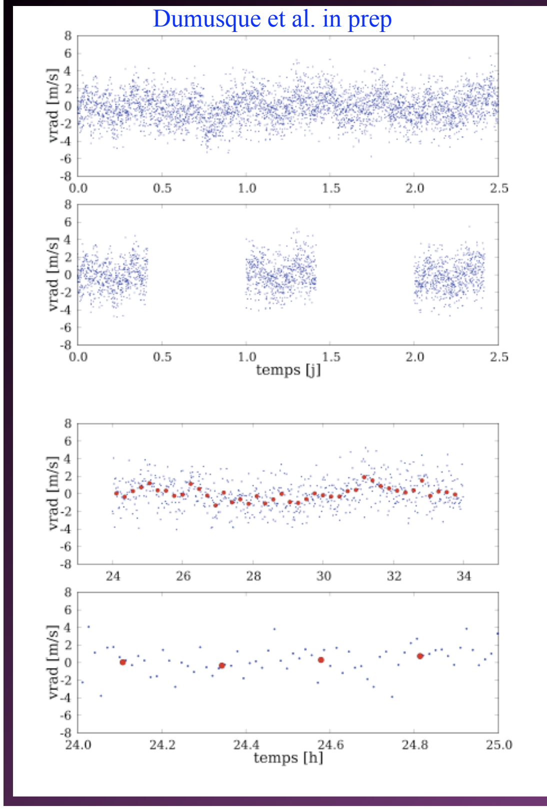

Pulsation noise on α Cen B and other stars
Simulated
Eggenberger, 2006, priv. comm.
σ [m/s]
Measured
HARPS commissioning
Kjeldsen et al. (2005)
β Hyi
α Cen A
δ Pav
Sun (GOLF)
Sun (BiSON)
Sun (Lick)
α Cen B
Amplitude per mode (m/s)
Frequency (μHz)
Choice of the target is important


Granulation?
Granulation (τ ~ 6 min)
Mesogranulation (τ ~ 3h)
Supergranulation (τ ~ 1 day)
Active regions (τ ~ 10 days)
Kjeldsen et al. (2005)
β Hyi
δ Pav
Stars
Power density ((m/s)²/μHz)
Frequency (μHz)
Choice of the target is very important
Observed Background Solar Velocity Noise Spectrum
AR
SG
SUM
Sun
Pallé et al. (1995)
FREQUENCY (Hz)
Other sources of noise at lower frequencies
requires simulations

Simulations

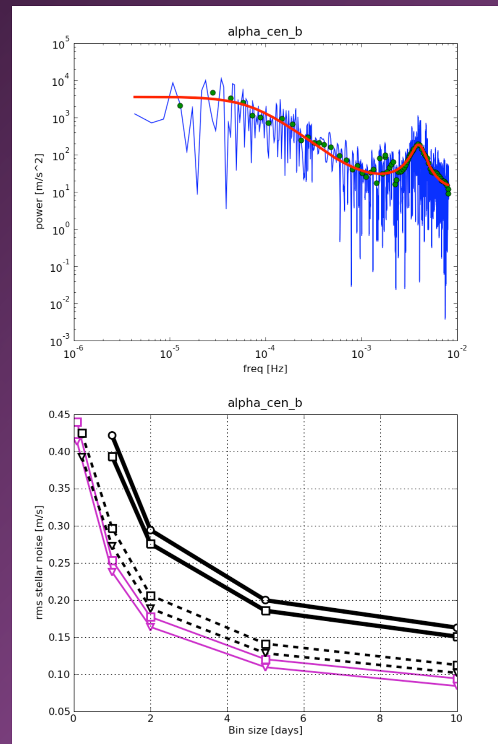
- real asteroseismology observations

-> noise model => synthetic observations



Beat the stellar limitations with

- good target selection
- clever observational strategy

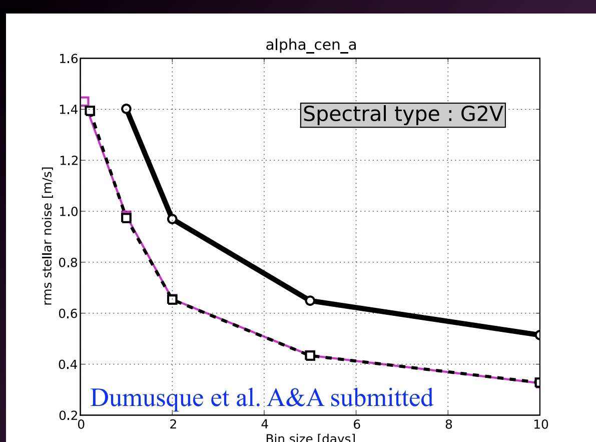


strategy
-> RV rms

-> detection limits in the mass-period diagram

Detection limits from calculated rms -> detection criterium: K > 2 x rms

(conservative)

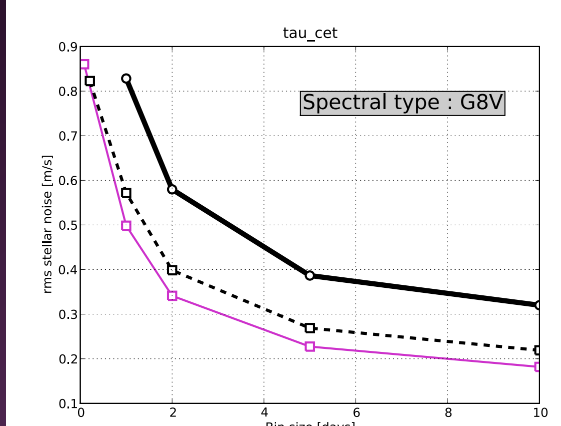


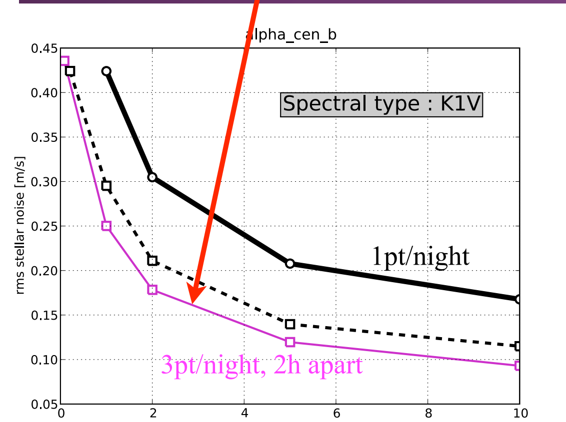
From p-modes+granulation point of view

Detection capability depends on

- spectral type
- luminosity class (evolution)

Observing strategy only applicable on bright stars!!!
=> requires very low photon-noise





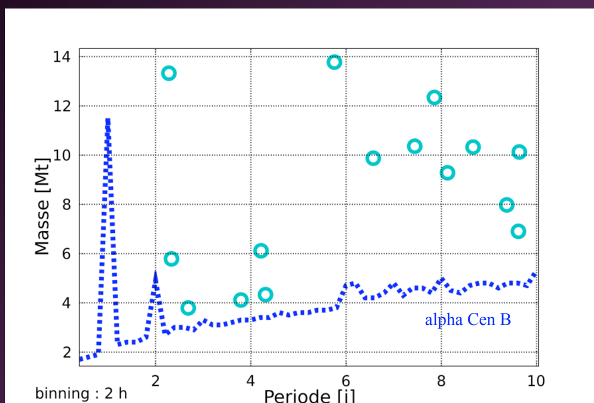
Detection limits (simultions)

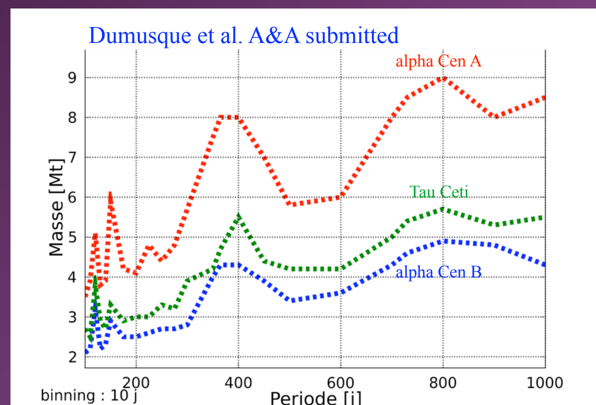
alpha Cen B with actual calender of HD69830 (3-Neptune system)

- Averaging => weak period effect!
- This case = “no spot” phase (~3 years for the sun)

short P

at 1 AU



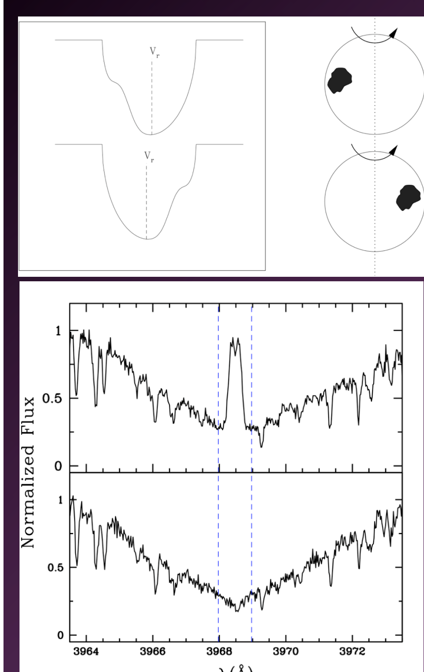


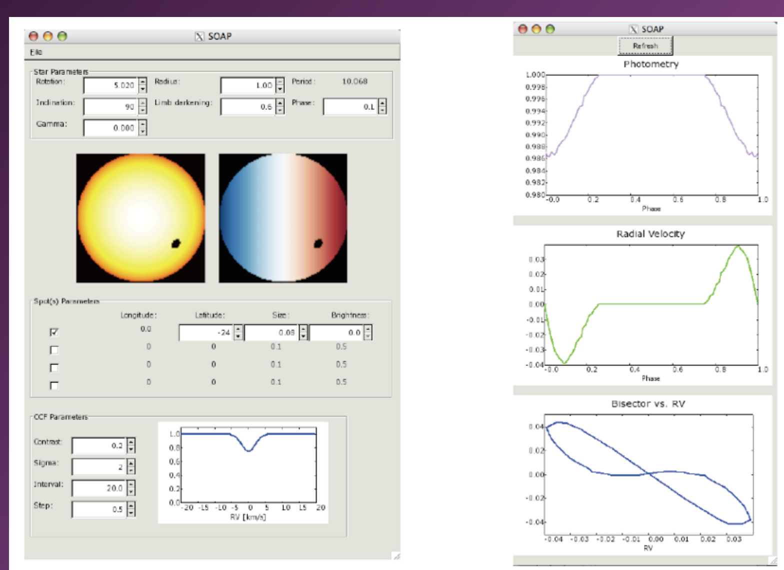
- Spot simulations to introduce activity effect in a better way
  still missing the longer timescales

Simulations of spot effects on radial velocities

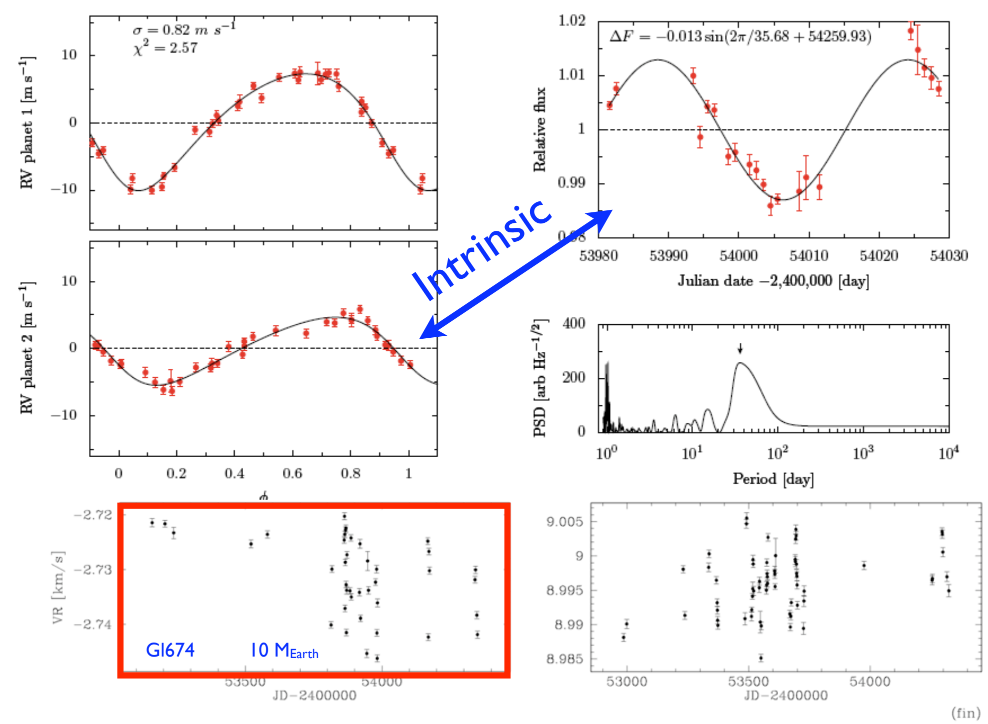
Activity index: log(R’$_{HK}$)

1) SOAP: effect of 1 spot (Bonfils et al. in prep)

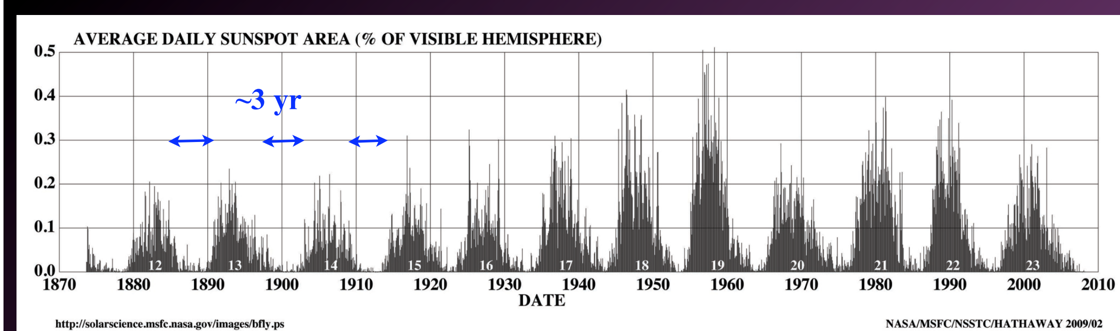




Harps: M-dwarf sample



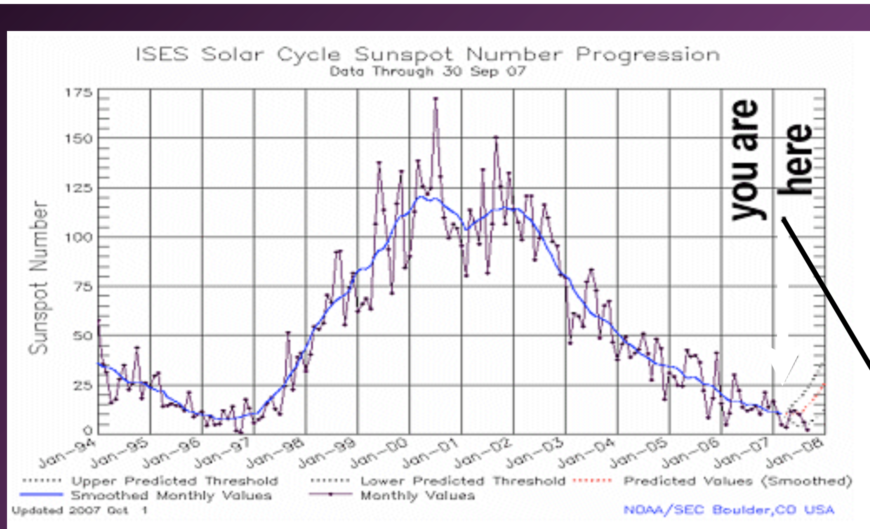
Bonfils et al. A&A 2006



Log(R'$_{HK}$)

← -4.9

← -5.0



Feb-10

Simulations of spot effects on radial velocities

2) Realistic families of spots

1 family = ~ 25 spots

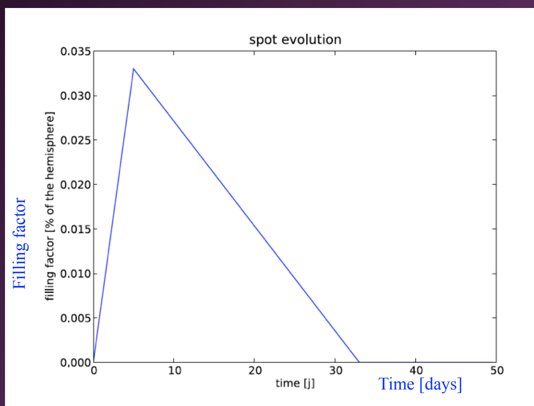
Takes into account: from observation of the Sun

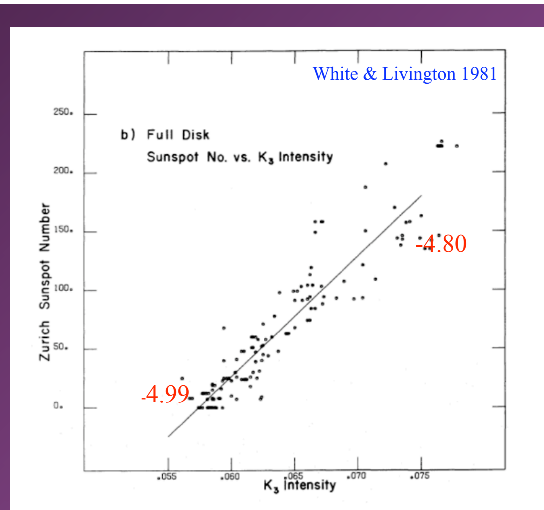
- Evolution of spots: growth, filling factor
- # of spots = f(log[R‘$_{HK}$])

Law of appearance of spots:

$$P[(N(t+\tau)-N(t))=k]=\frac{e^{-\lambda\tau}(\lambda\tau)^k}{k!}\qquad k=0,1,\ldots$$

Spot life

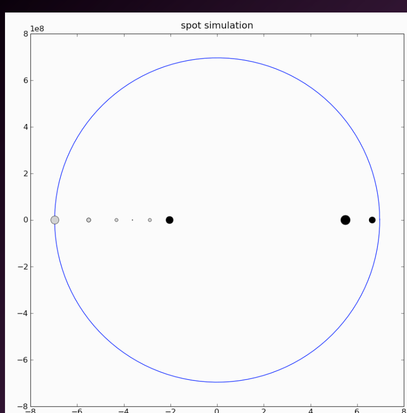


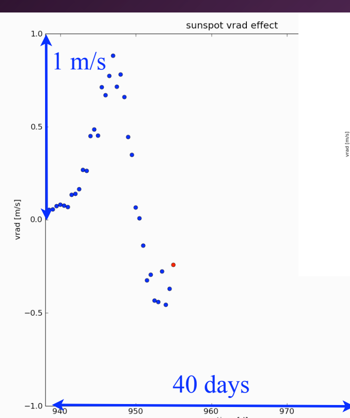


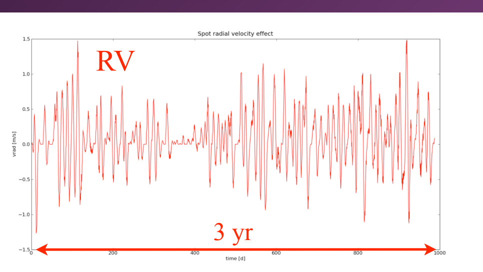
Number of spots depends on activity level

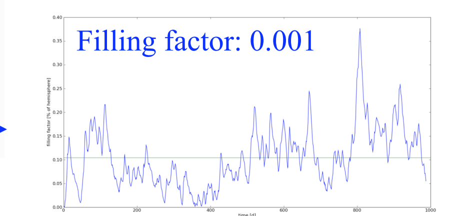
Simulations of spot effects on radial velocities

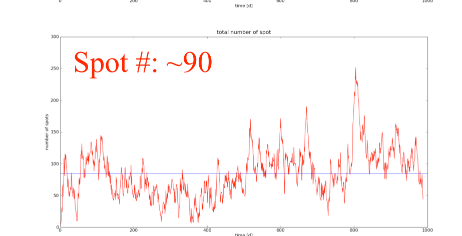
3) effect of realistic spot models: case for log(R‘_HK)=-4.9

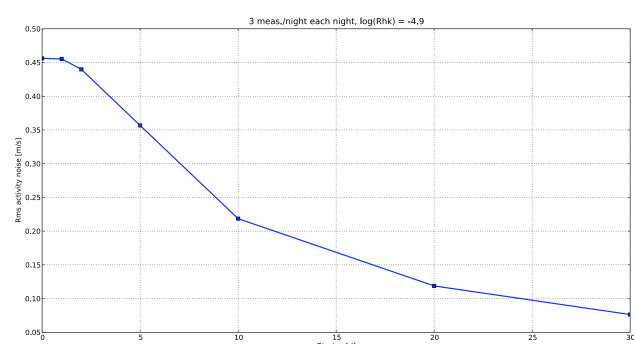






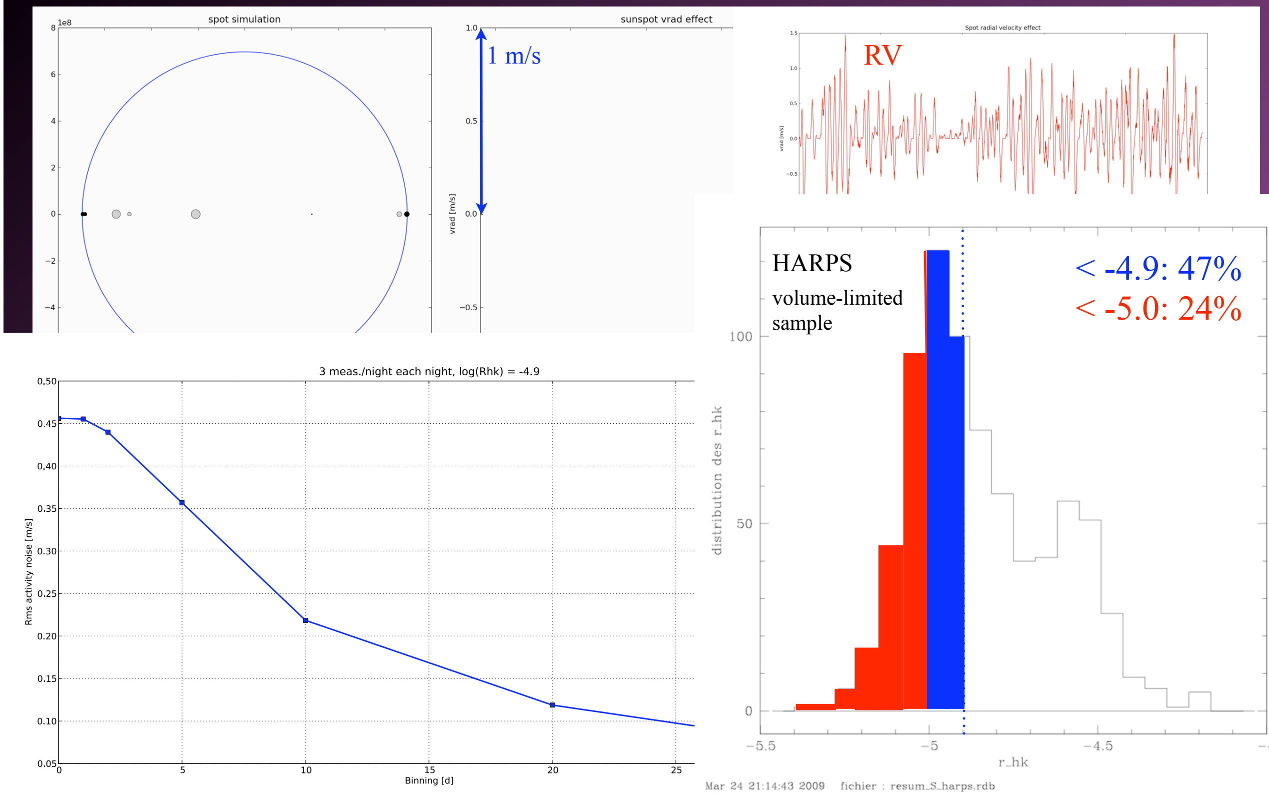






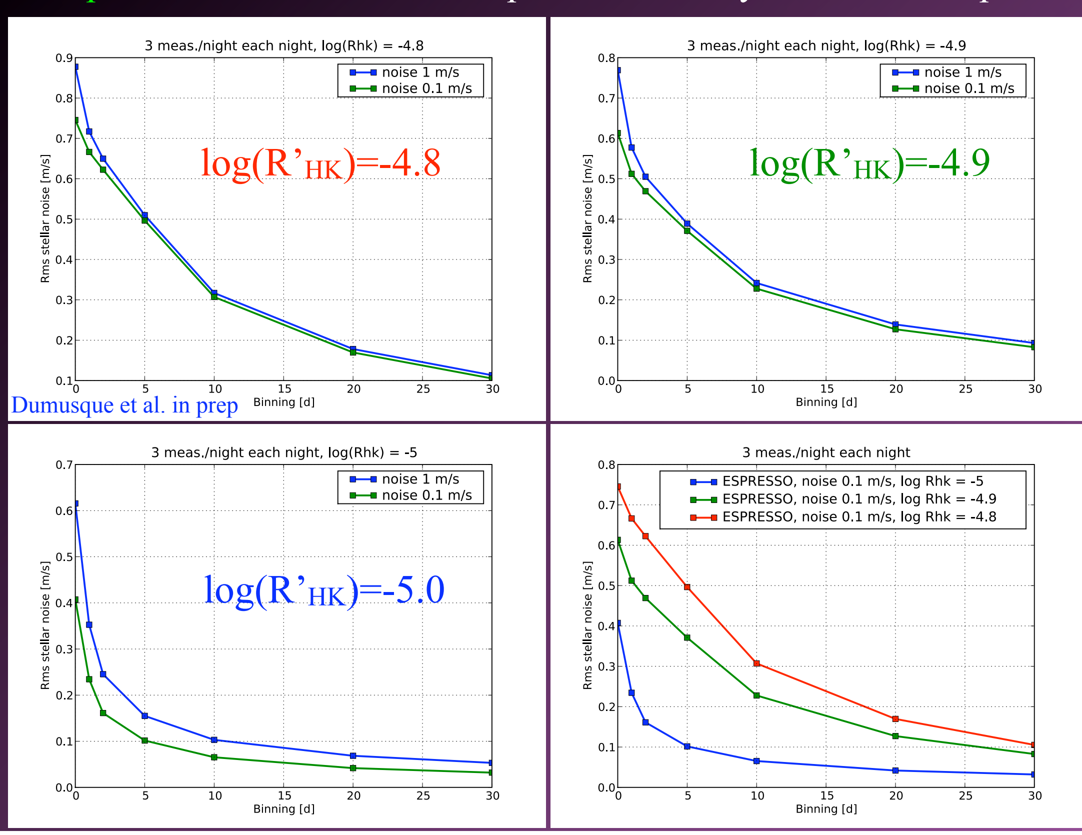
Simulations of spot effects on radial velocities

3) effect of realistic spot models: case for log(R'_HK)=-4.9



Simulations of spot + granulation + p-mode effects on radial velocities

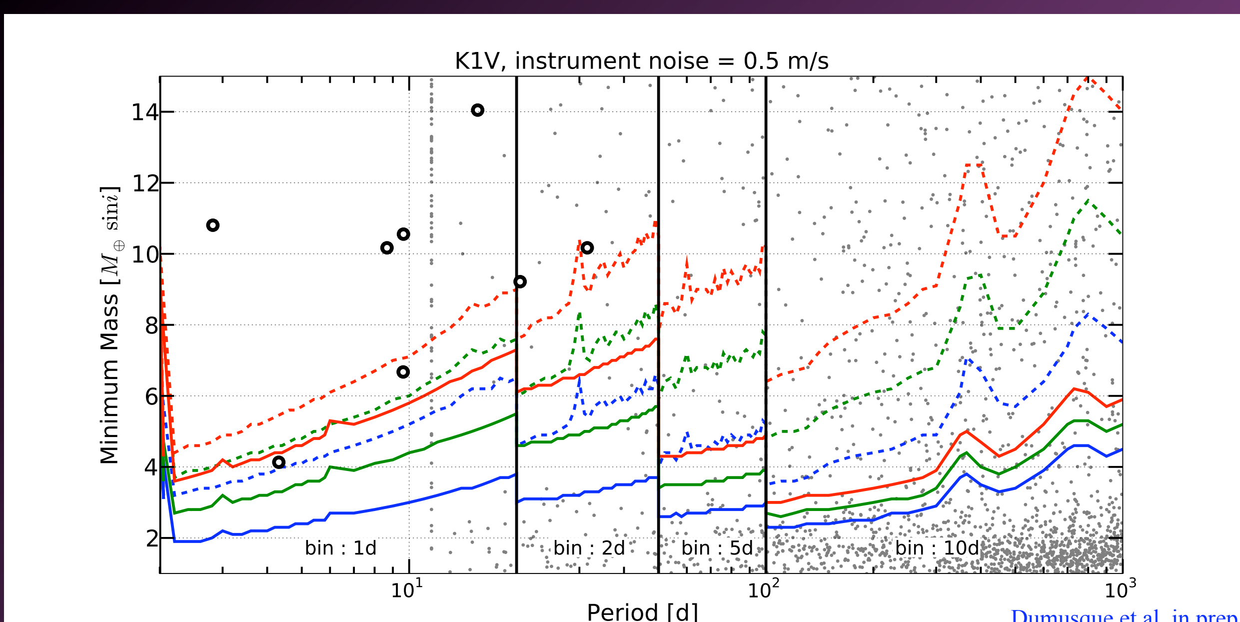
Diff. precisions and activities => precision mainly drives total exposure time



Optimum "affordable" observing strategy

- 10-15 min on target per measurement
  => to average stellar oscillations => <~5 cm/s of photon noise
- 3 measures per night (over 3-4 hours) to average granulation
- observe the star over several +/- consecutive nights to average activity effects
- follow the star as much as possible along the year: 8 months
- derive simultaneous diagnostics to characterize the activity level
  => correct the effect if possible

From RV rms to detection limits through Monte Carlo simulations

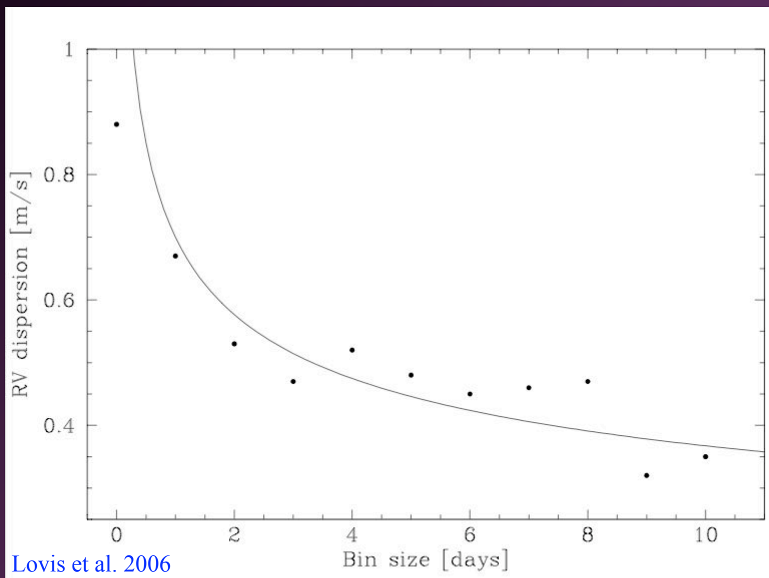


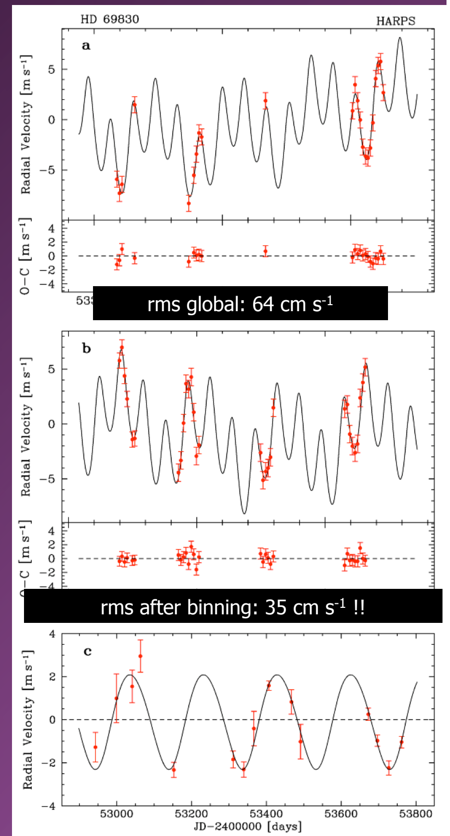
Dumusque et al. in prep

Longer periods => larger possible bins for average
=> small effect of the period on detection capability

HD 69830 >>>>> 0.35 m/s

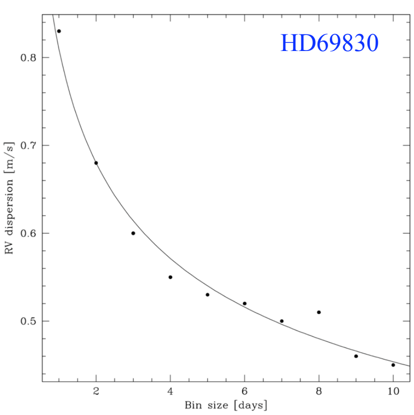
- On 5 seasons ...
  residuals to the orbital fit
  - Residuals as function of the binning on .... days

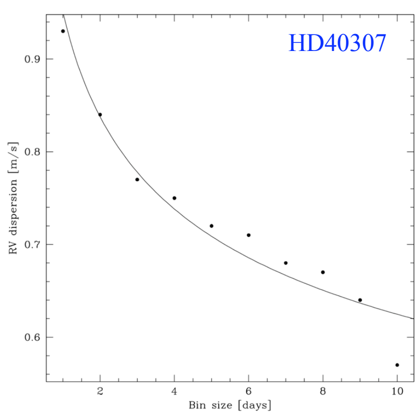


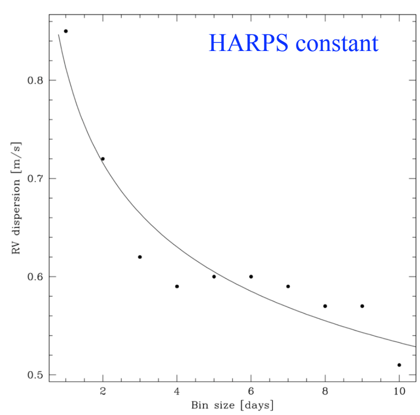


Encouraging results....

Binning effect calculated on several HARPS stars





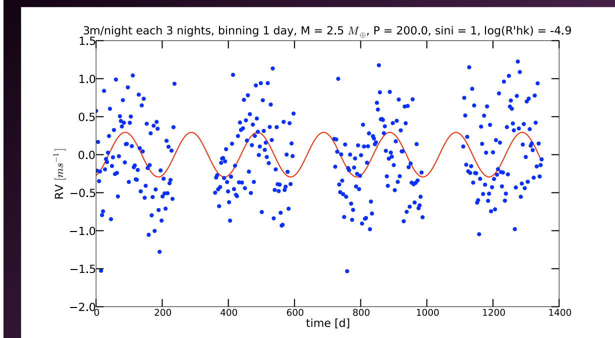


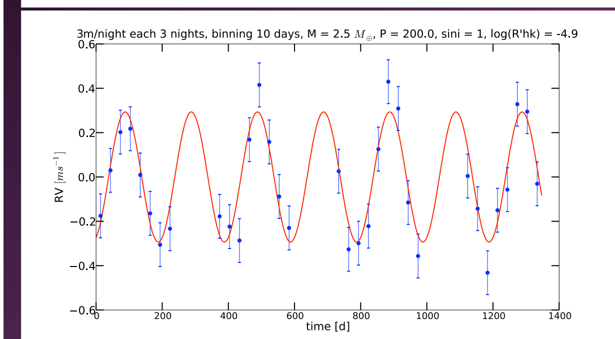
Warning: observation strategy not optimum + instrumental effect + photon noise
- only 1 observation per night
- sparse sampling (not every night)

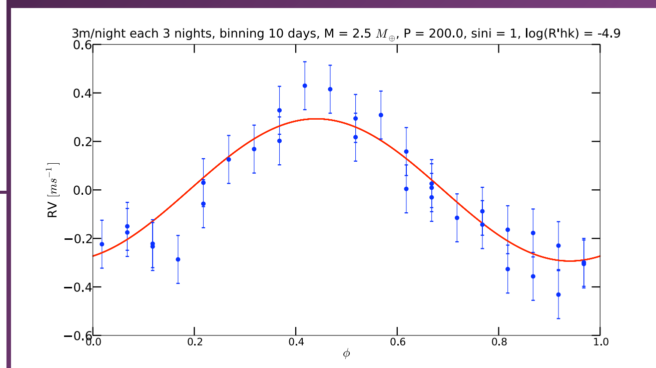
Simulations of stellar noise applied to ...

...ESPRESSO/VLT

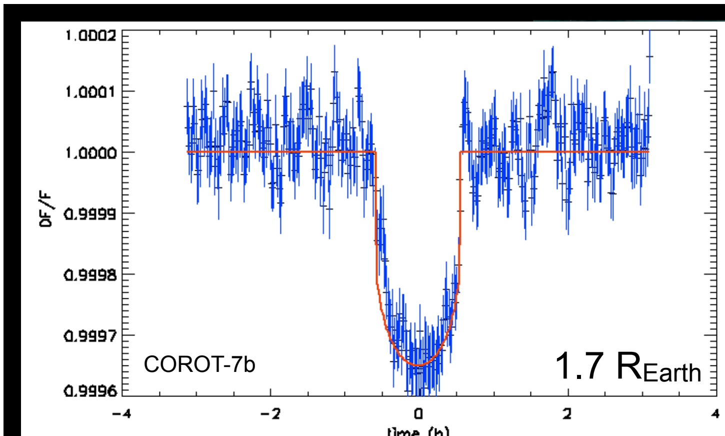
A 2.5 Earth-mass planet in the habitable zone of a quiet K star (P=200 days)

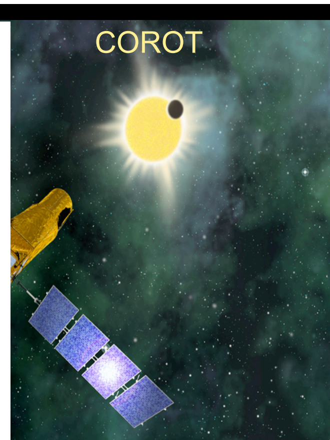






(Santos et al. 2009, Porto conf;
Dumusque et al., in prep)

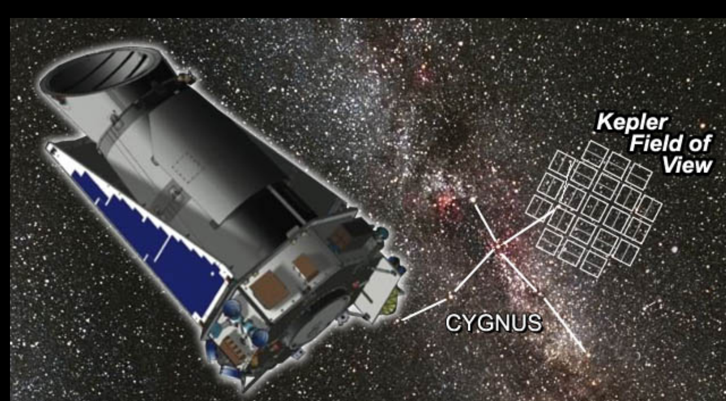


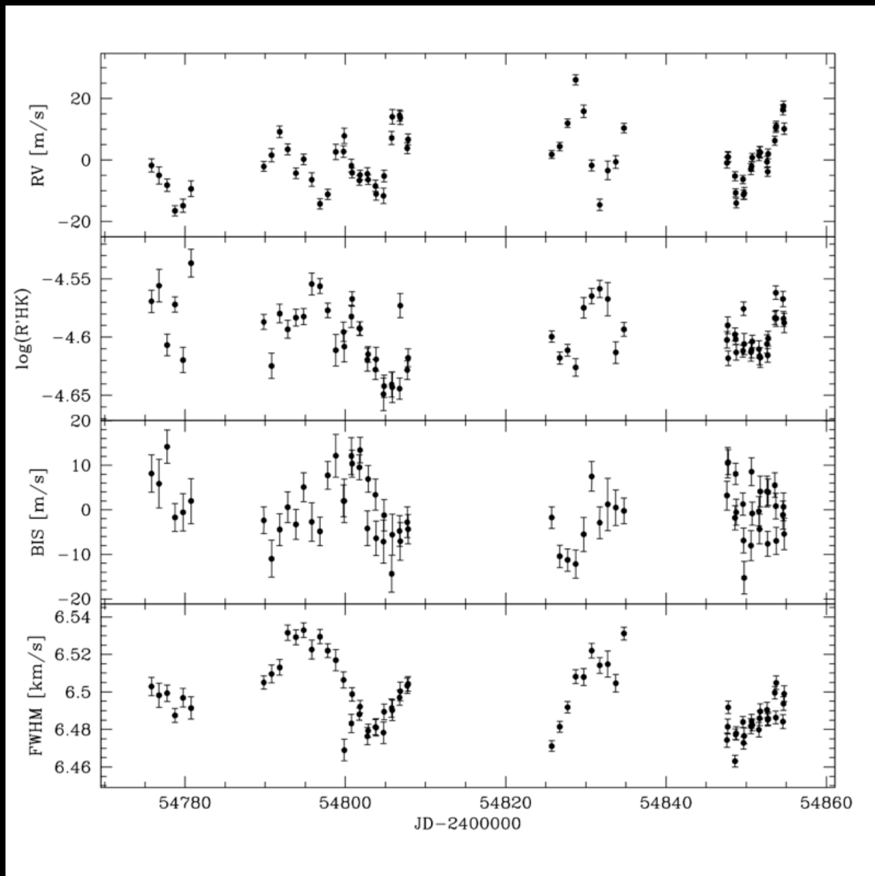


Transits of terrestrial planets

- Giant planets : 0.01 mag
- Terrestrial planets: 0.0001 mag

Transits from space
Kepler: waiting for results
CoRoT: CoRoT-7b





Active star
=> Effect of the planet much smaller than the observed RV variation!!!

Activity indicators

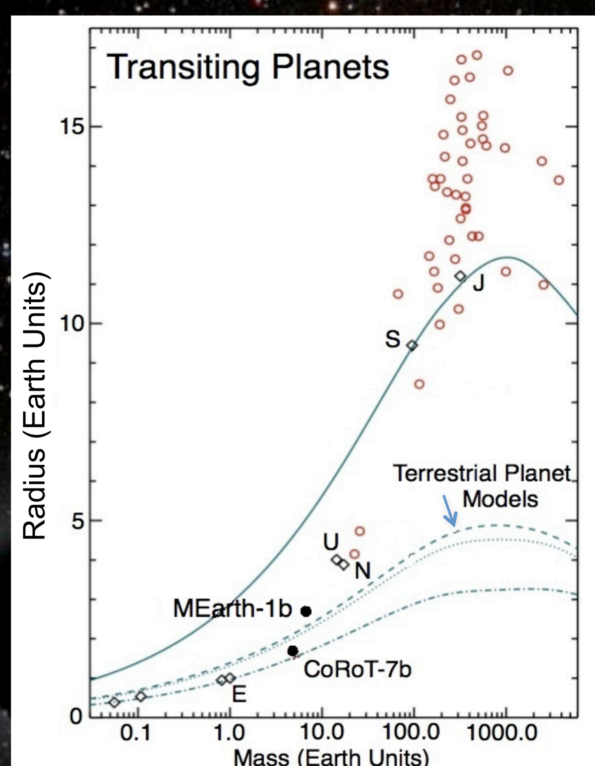
CoRoT-7b
(Queloz et al. 2009)

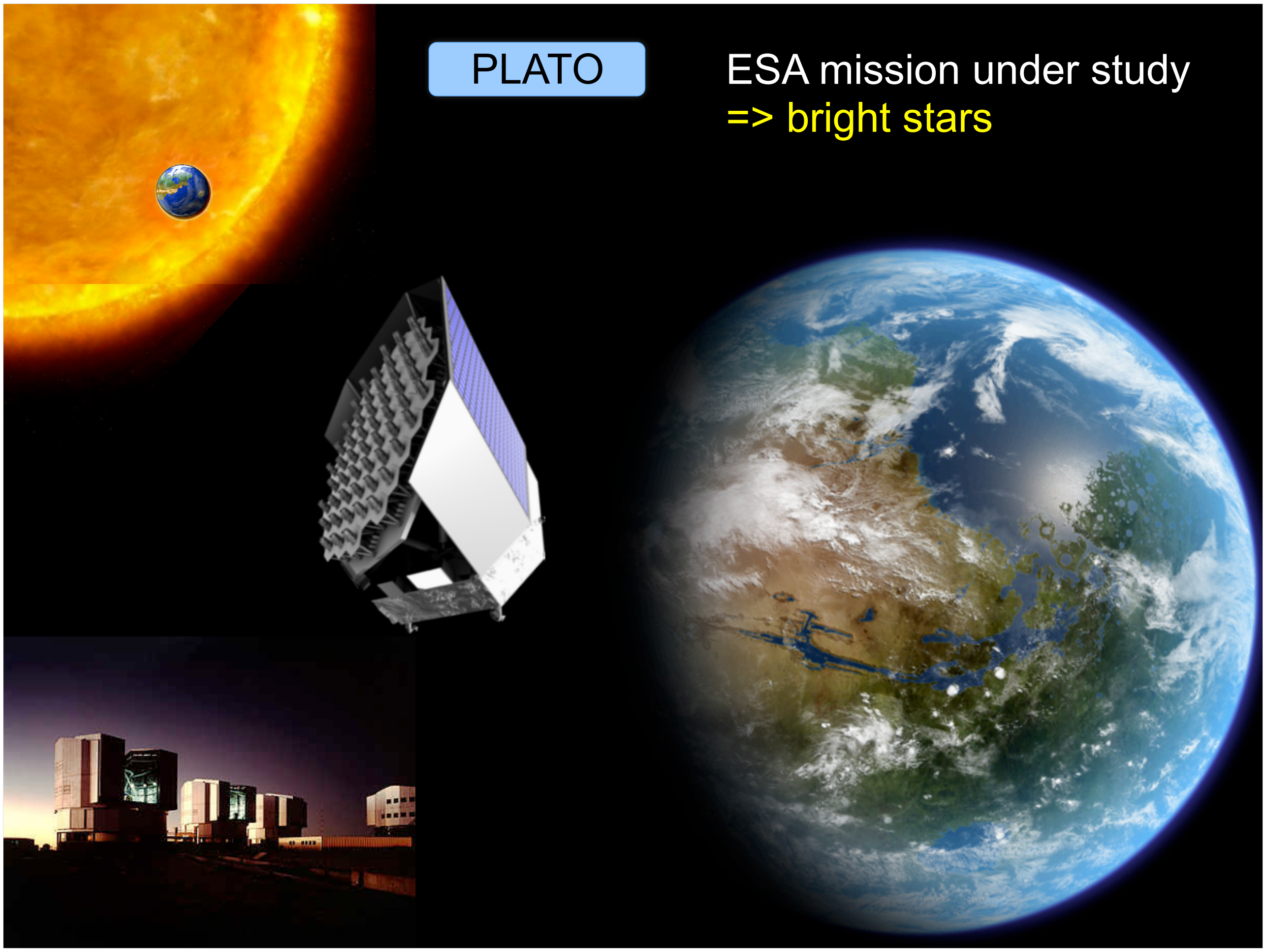
Planet diversity

CoRoT, M-Dwarf surveys

- Transit → fractional radius
  (relative to host star)
  → inclination.
- RV → planetary mass
- 2 solid planets:
  - CoRoT-7b : Period ~ 0.85 d
  - MEarth-1b: Period ~ 1.50 d

=> Diversity

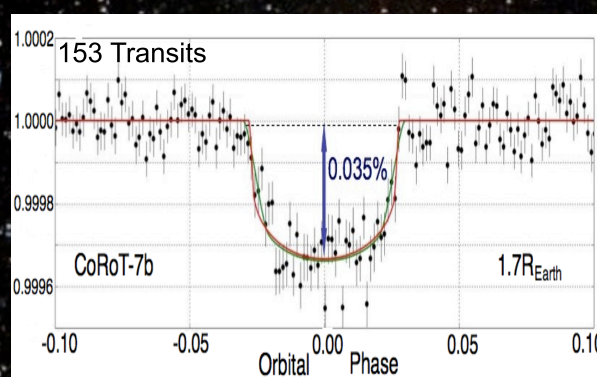




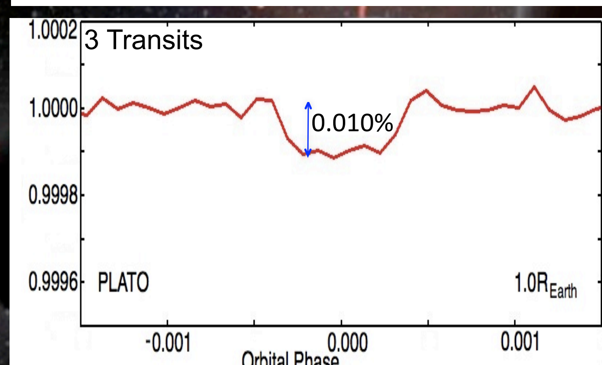
Planetary radius - Tools

Light curves from space:

CoRoT-7b
the first confirmed rocky extrasolar planet.



Simulation
1 M_{earth} planet around a solar type star.

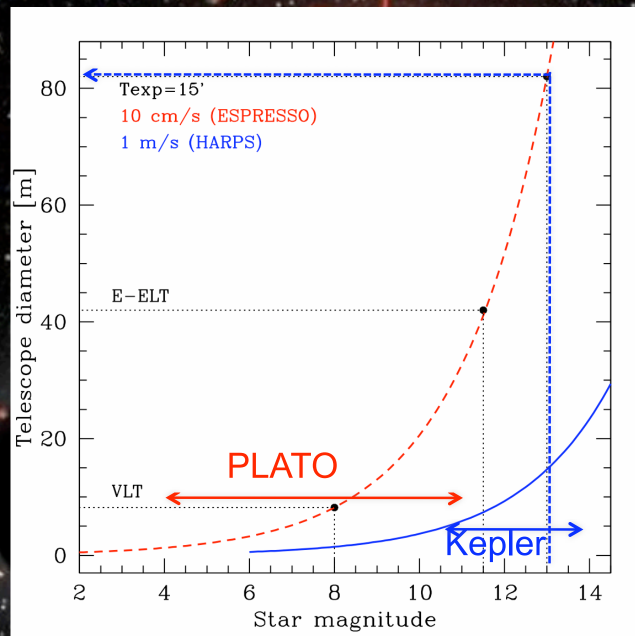


Planetary mass

RV Amplitude 10cm/s for Earth analog

Planet	Separation (AU)	RV Amp. (m/s)
Jupiter	1	28.4
Neptune	0.1	4.8
Neptune	1	1.5
SuperEarth	0.1	1.4
SuperEarth	1	0.5
Earth	1	0.1

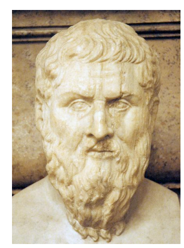
Radial velocity: photon starving



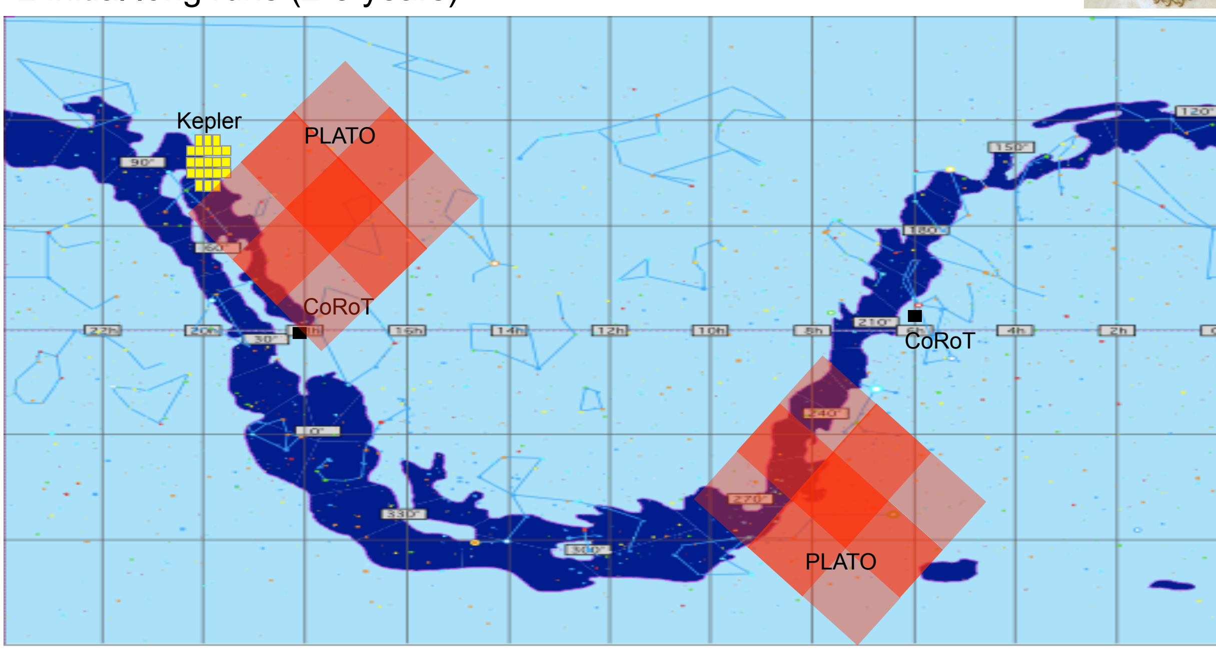
Observation strategy:

→ minimize stellar "noise"

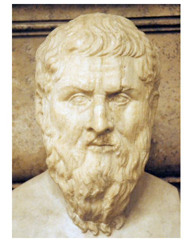
PLATO field-of-view



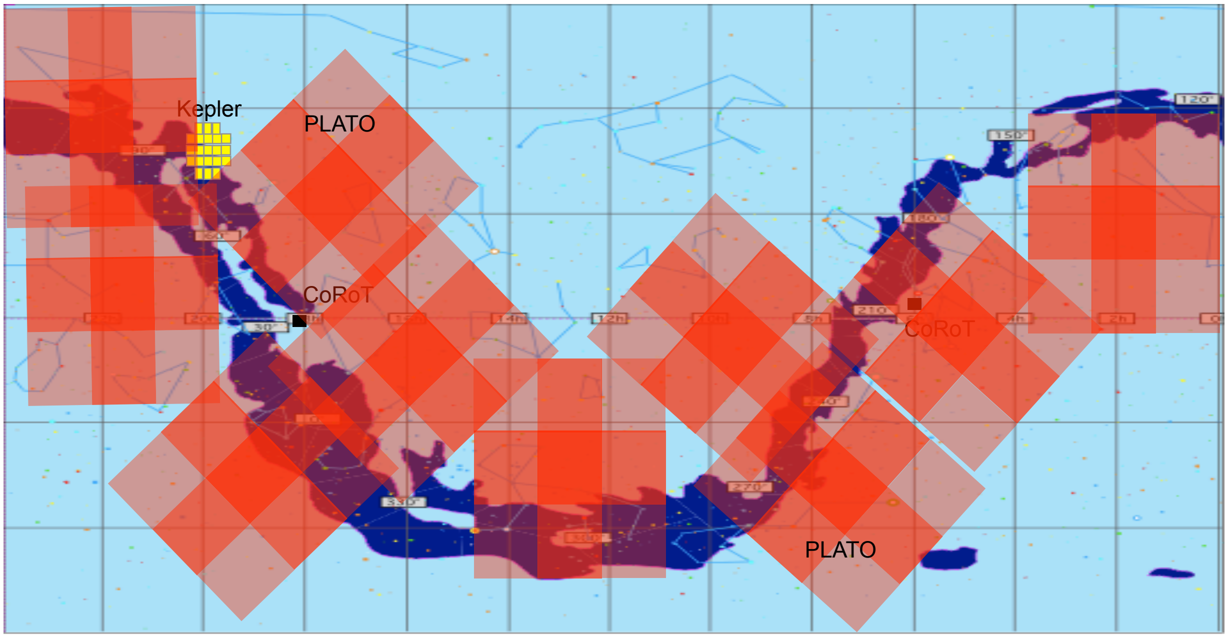
2 initial long runs (2-3 years)



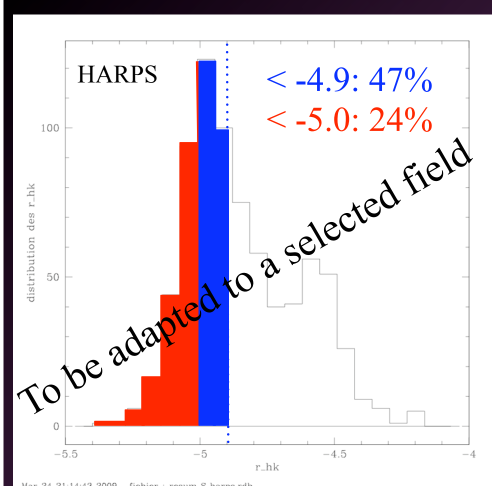
PLATO field-of-view

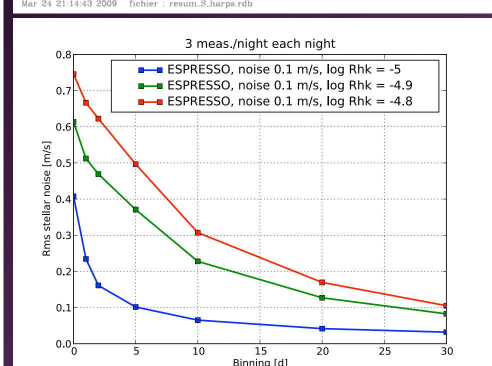


With a 2nd year step and stare



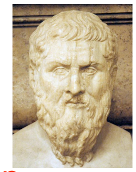
Simulations of *confirmed planets* yield





1. Select star in the field (list)
   - spectral type, vsini, magV
2. Select the activity level (random)
   - log(R'_HK)=f[N(B-V)]
3. Select a planet (e.g. from set of Bern models) (determined orrandom)
   - mass, period (separation)
   - ➡ P => possible binning
   - ➡ corresponding RV precision
4. Detection criteria = f(M_{pl}, RV precision)
   - ➡ planet is characterized or not

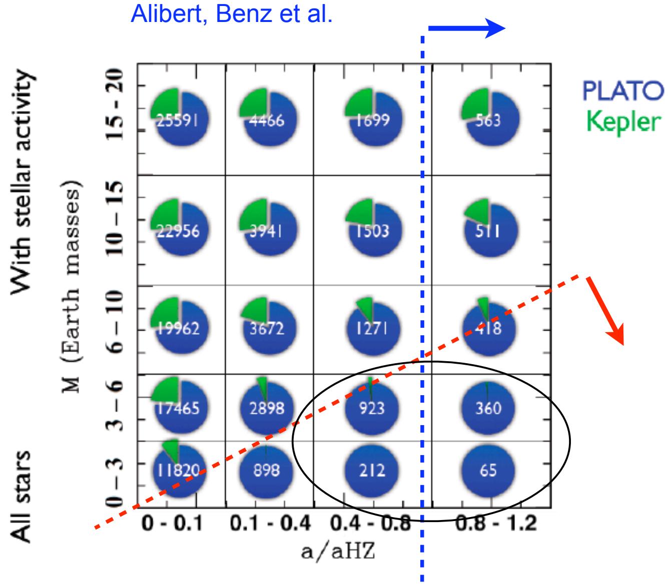
Kepler/Harps-N vs PLATO/ESPRESSO



RV precision 1 m/s 10 cm/s

Probability of confirmed planets: photometric detection + RV follow-up
geometric probability star magnitude

Alibert, Benz et al.



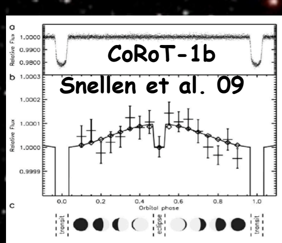
Only the long runs

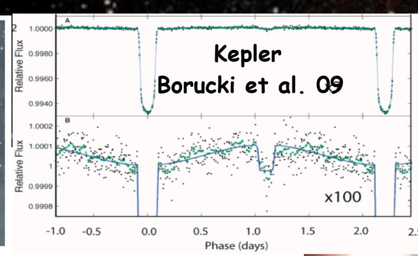
Hypotheses

- Sample (Kepler+PLATO)
  450'000 stars
- Every planet type
  around every star

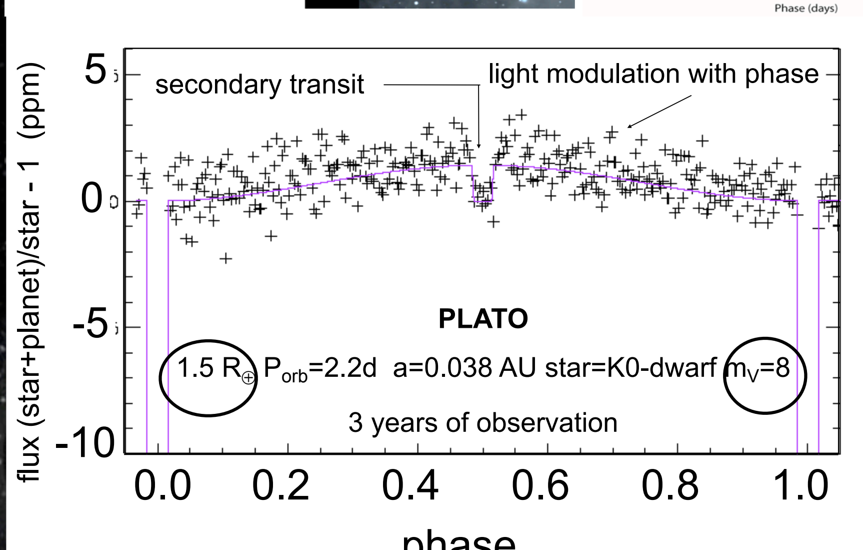
Stellar reflected light and secondary transits

measurement of albedo and T = characterisation of planet surface/atmosphere



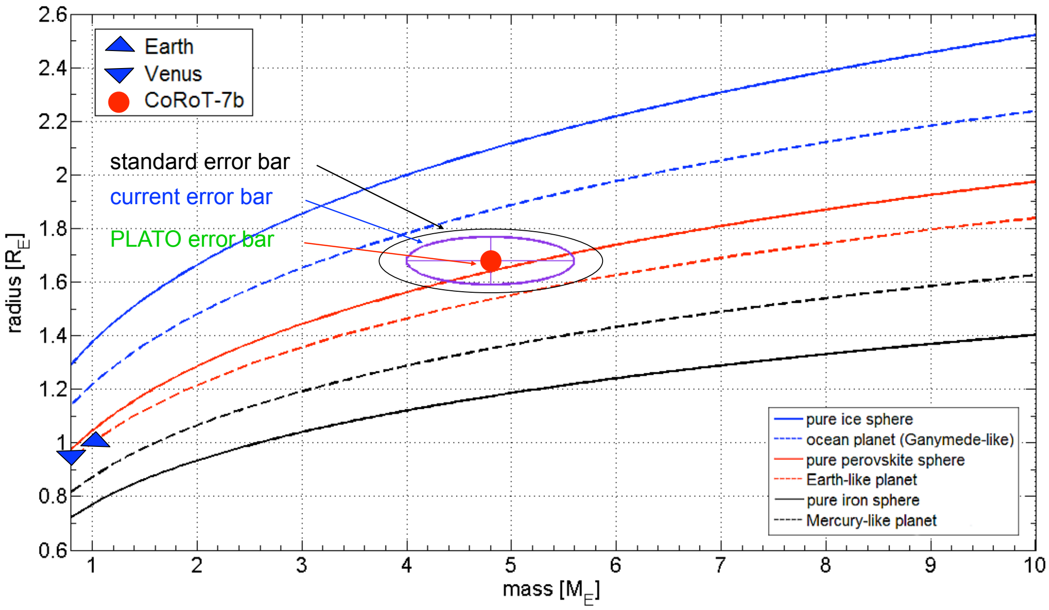


HAT-P-7b
130 ± 11 ppm
m_V = 10.5
15.3 $R_\oplus$
0.038 AU
P = 2.2 days
duration: 10 days



PLATO:
>1,000 such stars
many transiting
planets expected

Impact of mass and radius measurements



For terrestrial planets accurate radii from transit photometry provide strong constraints on planet interior!

Wagner et al. 2009, also: Valencia et al. 2007