Extra-solar planets

Earths twins in the HZ of solar type stars with E-ELT/HRS

Design Reference Mission

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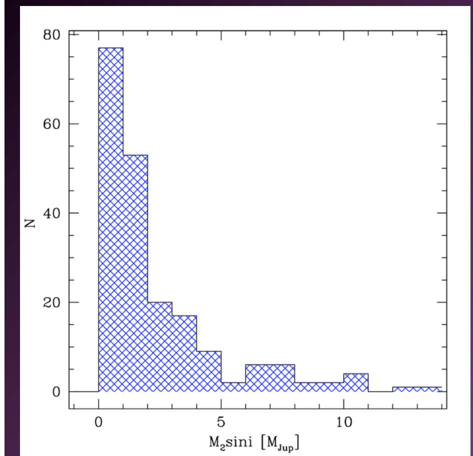
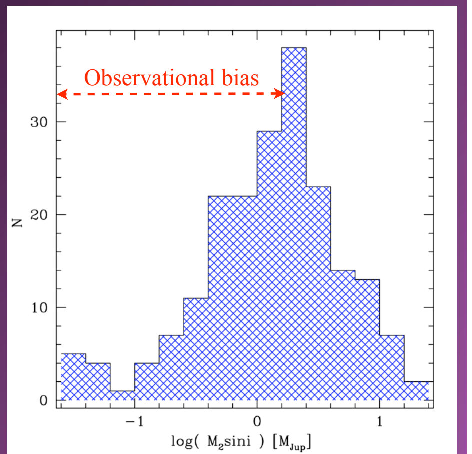
D. Naef, M. Haehnelt, L. Pasquini,
and the CODEX team

Main points to focus on

- Results: Low-mass solid planets are numerous
  - detections (VR, microlensing)
  - formation models
- Limitations of the RV approach
  - Stable instrument
  - Overcome the stellar limitations → Target sample
  - Large telescopes
- E-ELT future RV programmes → CODEX
  - RV search: finding new Earths
  - Telescope time estimate

Planetary mass distribution

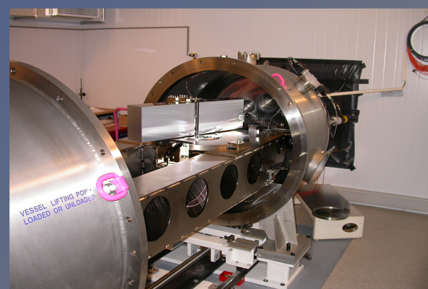




The HARPS search for low-mass planets

- Sample of ~400 slowly-rotating, nearby FGK dwarfs from the CORALIE planet-search survey + known planets
- HARPS log(R'_HK) => ~250 good targets
- Observations ongoing since 2004
- Focus on low-amplitude RV variations

  => about 50% of HARPS GTO time



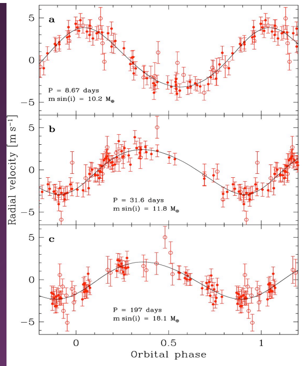
HARPS

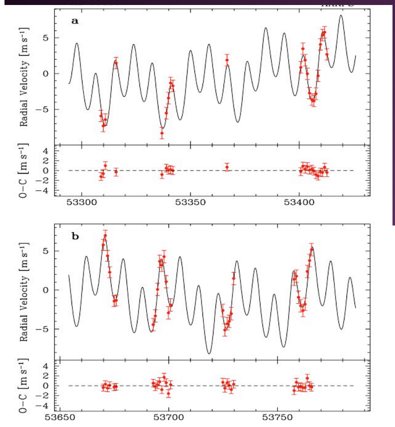
ESO-3.6m @ La Silla

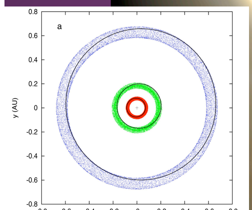
HD 69830: A trio of Neptunes

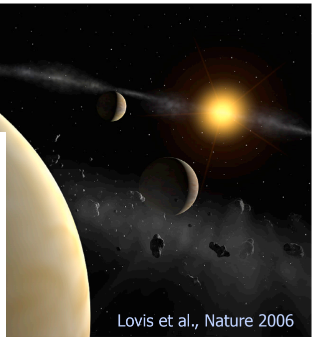
P1 = 8.67 days a = 0.078 AU M sini = 10.2 M_{Earth}
P2 = 31.6 days a = 0.186 AU M sini = 11.8 M_{Earth}
P3 = 197 days a = 0.63 AU M sini = 18.1 M_{Earth}

HARPS@3.6-m telescope, ESO La Silla



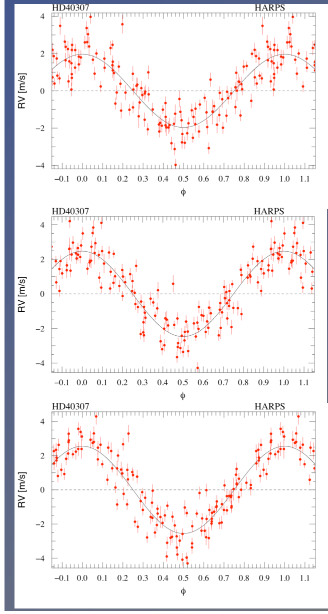






An emerging population of Hot Neptunes and Super-Earths

Mayor et al. A&A 2009



P_1 = 4.31 days
e_1 = 0.02
m_1 sini = 4.3 $M_\oplus$

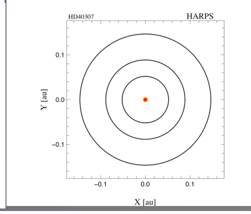
P_2 = 9.62 days
e_2 = 0.03
m_2 sini = 6.9 $M_\oplus$

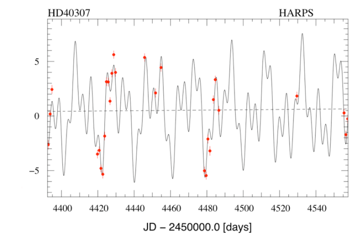
P_3 = 20.5 days
e_3 = 0.04
m_3 sini = 9.7 $M_\oplus$

HD 40307
K2 V
Dist 12.8 pc
[Fe/H] = -0.31

O-C = 0.85 m/s
135 observations

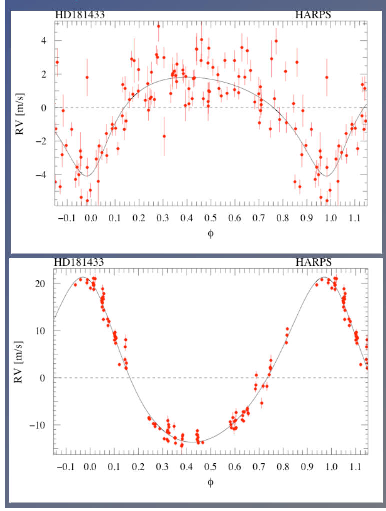
+ drift = 0.5 m/s/y





An emerging population of Hot Neptunes and Super-Earths

Bouchy et al. A&A 2009

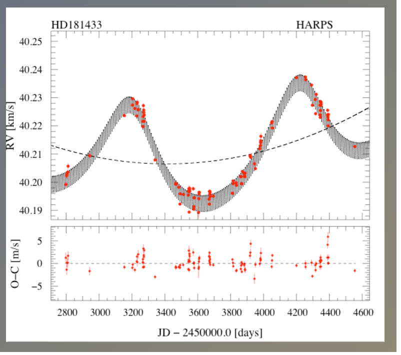


P_1 = 1024 days
e_1 = 0.23
m_1 sini = 0.72 M_{Jup}

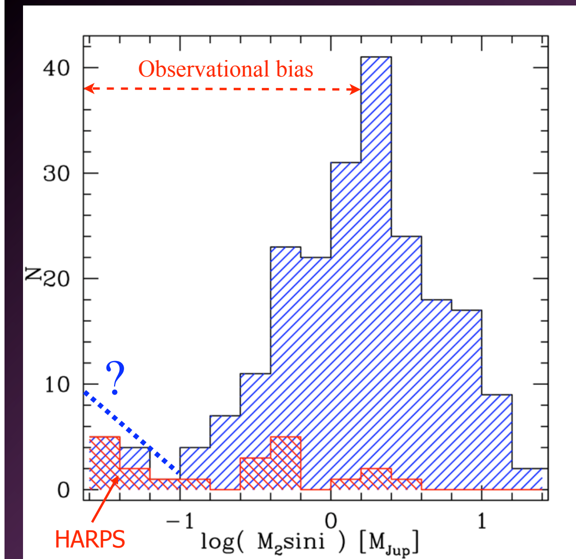
P_2 = 9.37 days
e_2 = 0.40
m_2 sini = 7.5 $M_\oplus$

HD 181433
K3 IV
d = 26 pc
m = 8.4
[Fe/H] = +0.33

Another triple system



Harps: exploration of small-mass domain



1. New mass domain

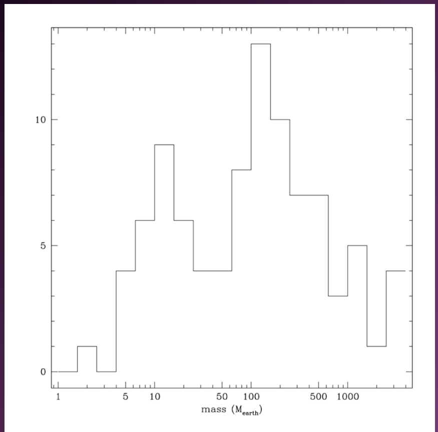
2. "Rise" towards the the very small masses?

New "category" of planets

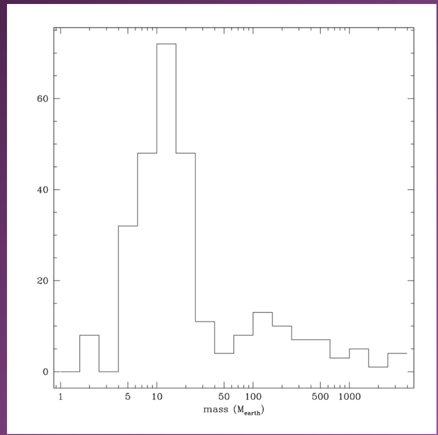
3. Incompleteness (det. bias) Normalisation

Harps: exploration of small-mass domain

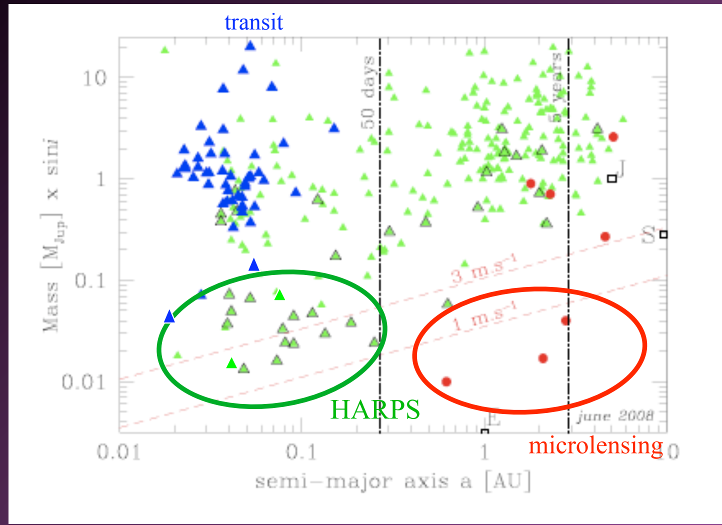
"Completeness" (P<100 d)



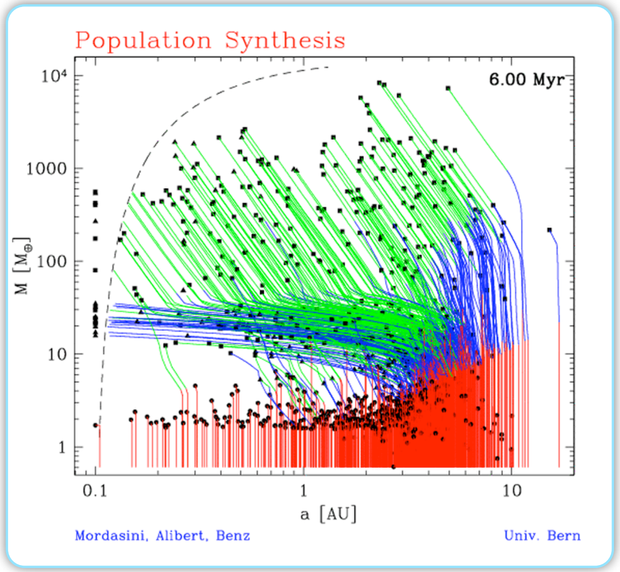
Renormalization (factor 8)



Observations: small mass planets everywhere?



Formation tracks



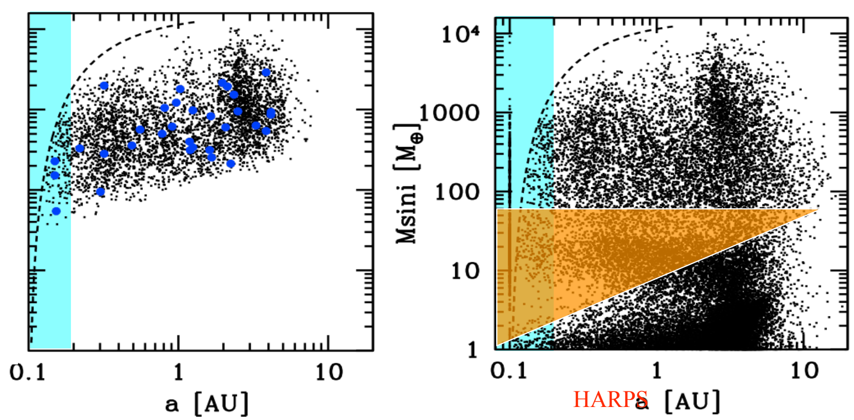
M_{star}=1 $M_\odot$
Nominal model

Type I migration
(Analytical rate reduced by f_I)

Type II migration
(Disk dominated: M_p<$M_{disk,loc}$)

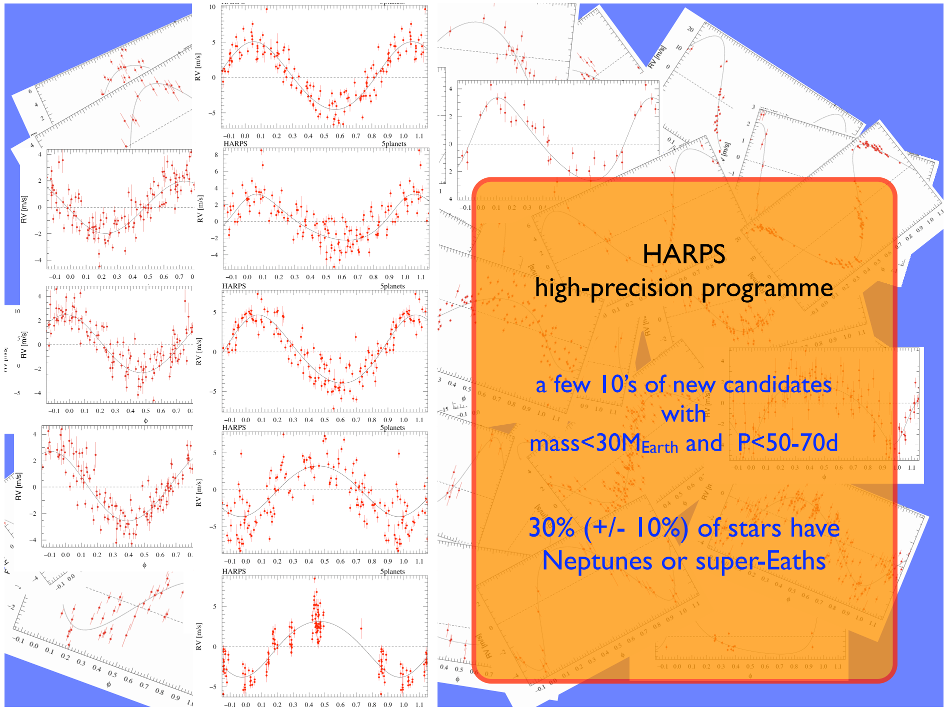
Type II migration
(Planet dominated: M_p>$M_{disk,loc}$ & disk limited gas accretion)

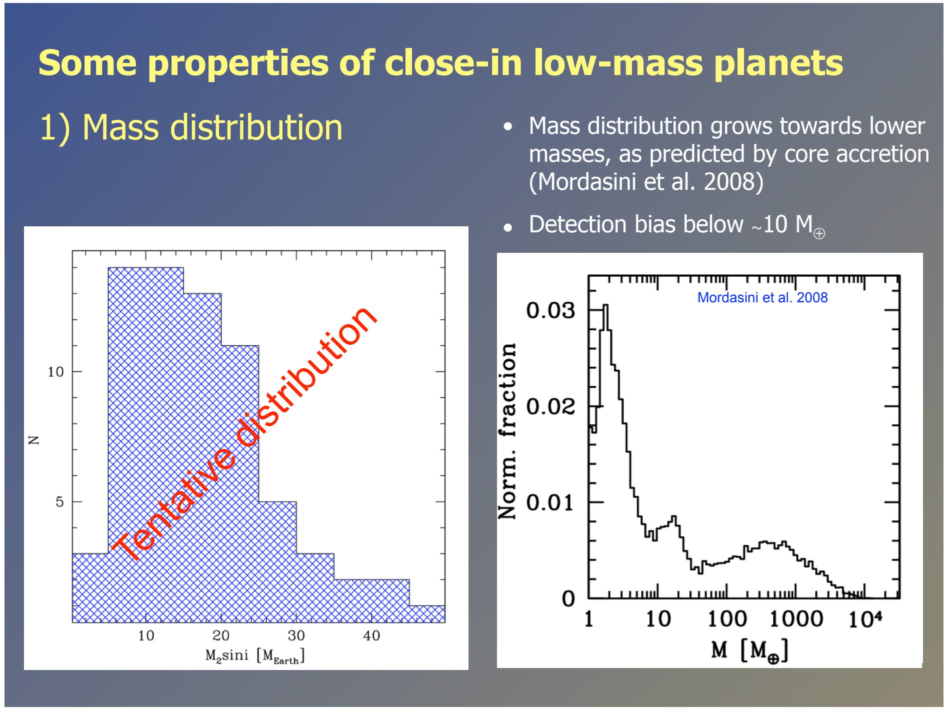
Monte-Carlo Simulations of planet formation via core accretion

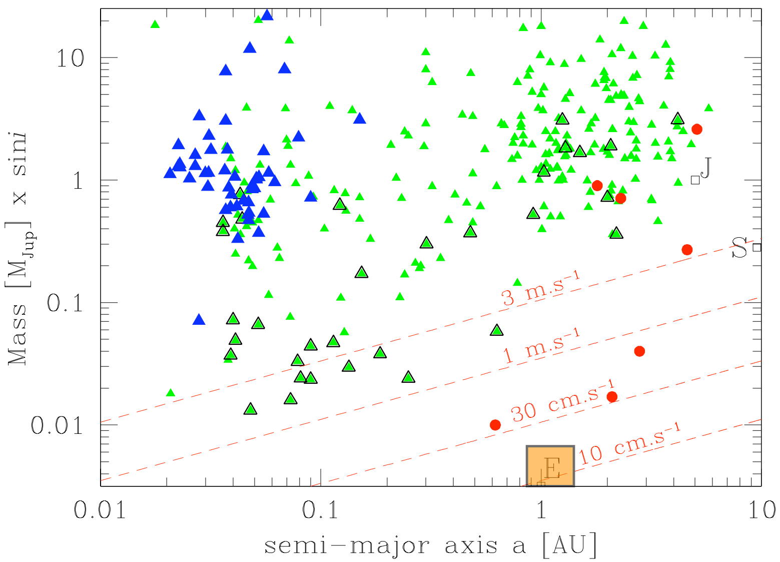


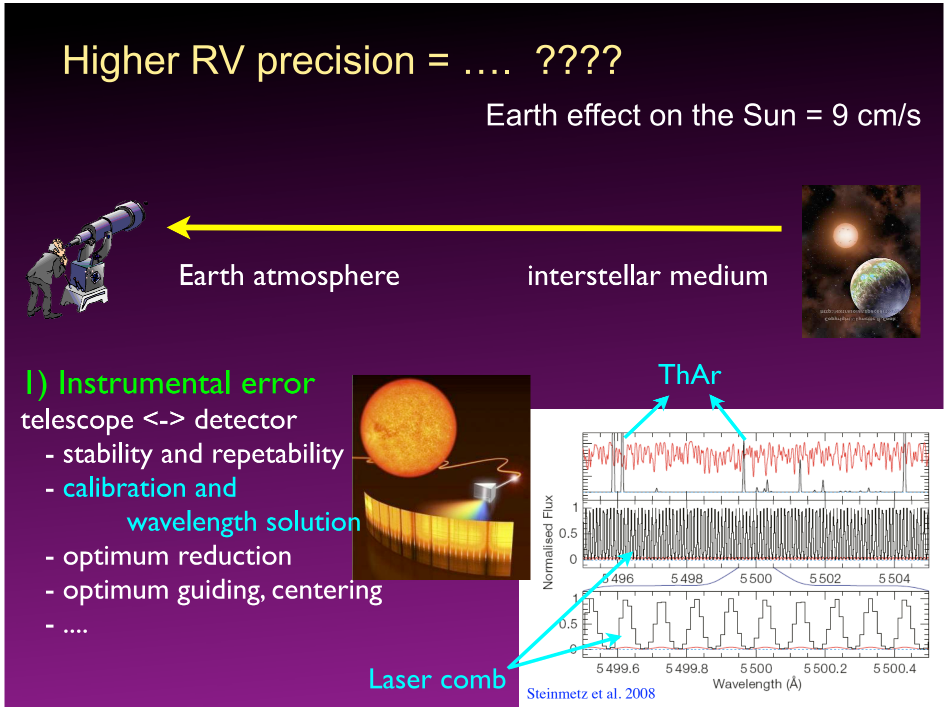
Prediction: Many very small mass, solid planets

- Mordasini, Benz, Alibert (2004-2009)
- Ida & Lin (2004-2009)


HARPS
high-precision programme
a few 10's of new candidates
with
mass<30MEarth and P<50-70d
30% (+/- 10%) of stars have
Neptunes or super-Eaths

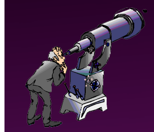

Some properties of close-in low-mass planets
1) Mass distribution
• Mass distribution grows towards lower masses, as predicted by core accretion (Mordasini et al. 2008)
• Detection bias below ~10 M⊕
Tentative distribution
N
10
5
10
20
30
40
M2sini [MEarth]
Mordasini et al. 2008
Norm. fraction
0.03
0.02
0.01
0
1
10
100
1000
10⁴
M [M⊕]


Mass [MJup] x sini
10
1
0.1
0.01
semi−major axis a [AU]
0.01
0.1
1
10
3 m.s-1
1 m.s-1
30 cm.s-1
10 cm.s-1
J
S
E

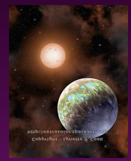

Higher RV precision = …. ????
Earth effect on the Sun = 9 cm/s
Earth atmosphere
interstellar medium
1) Instrumental error
telescope <-> detector
- stability and repetability
- calibration and
wavelength solution
- optimum reduction
- optimum guiding, centering
- ....
ThAr
Laser comb
Normalised Flux
Wavelength (Å)
Steinmetz et al. 2008

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
- 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

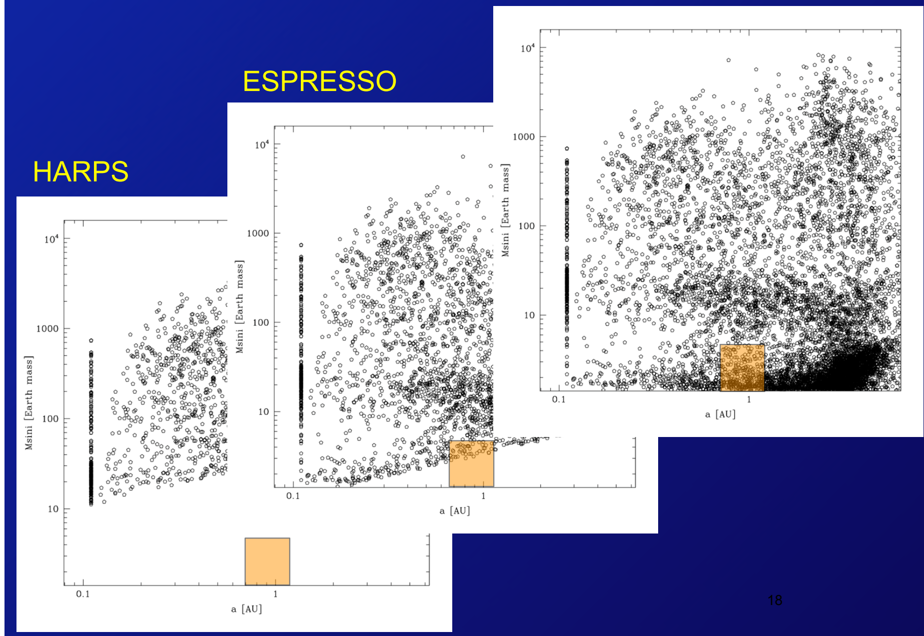
Expected precision ~1 cm s^{-1}

Cosmology (expansion of the Universe), QSOs, Earth twins, fondamental constants, etc.

CODEX

ESPRESSO

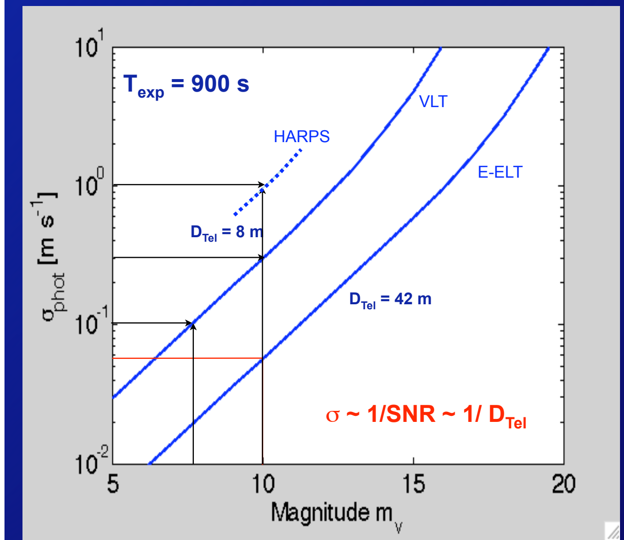
HARPS



18

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
-> ~10 cm/s on E-ELT

2) ESPRESSO/VLT
Vlim = ~8 for 10 cm/s in 15'

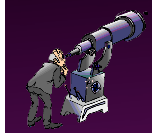
3) CODEX/E-ELT
1 cm/s in 15' on star with V<6
5 cm/s in 15' on star with V<9.5
10 cm/s in 15' on star with V=11

=> Many solar-type targets >1000 non-active stars with V<9-9.5

=> Earth twin search

Higher RV precision = …. ????

Earth effect on the Sun = 9 cm/s



Earth atmosphere ← interstellar medium

1) Instrumental error

telescope <-> detector

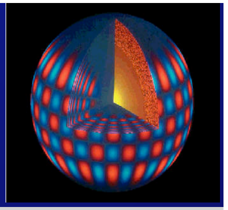
- stability and repetability
- calibration and wavelength solution
- optimum reduction
- optimum guiding

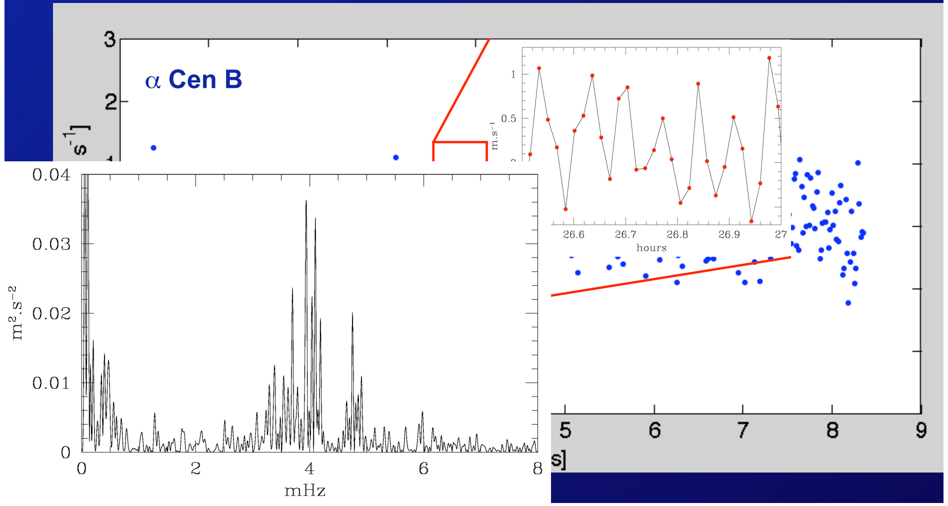
3) Stellar intrinsic "noise"

- stellar pulsations
- granulation
- activity

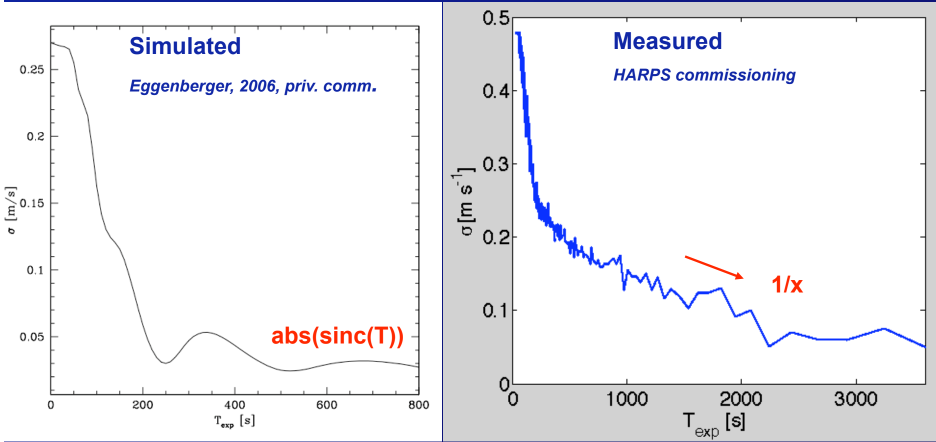
2) Photon noise

Stellar oscillations: p-modes



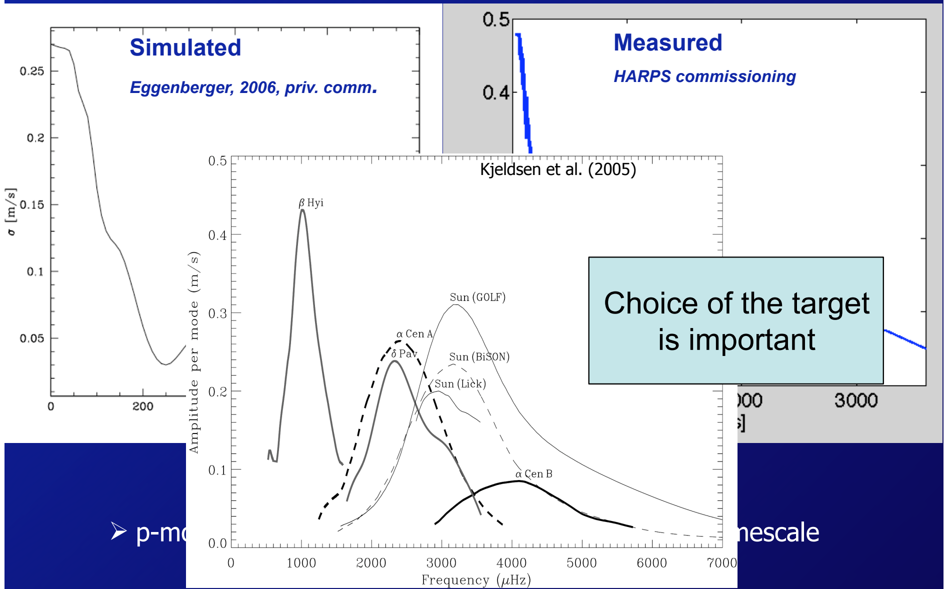


Pulsation noise on α Cen B and other stars

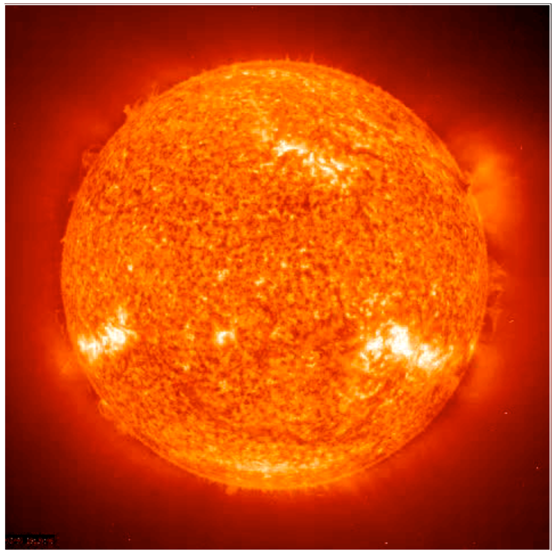


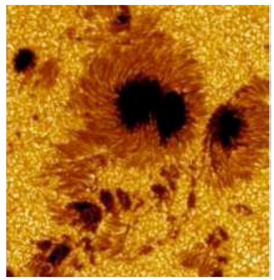
➢ p-modes average well on time > ~1 characteristic timescale

Pulsation noise on α Cen B and other stars



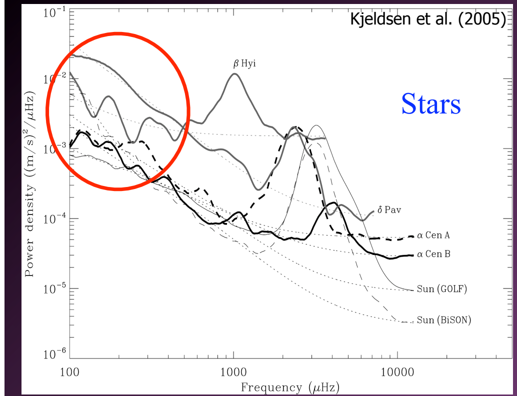
Stellar intrinsic limitations

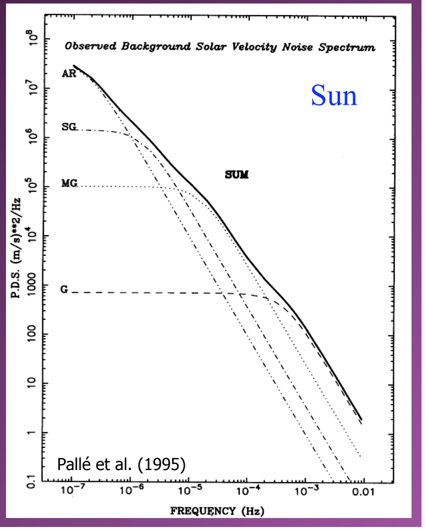




Granulation?

- Granulation (τ ~ 6 min)
- Mesogranulation (τ ~ 3h)
- Supergranulation (τ ~ 1 day)
- Active regions (τ ~ 10 days)



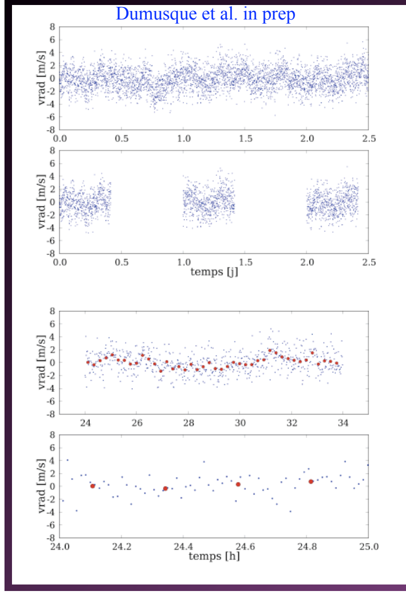


- Other sources of noise at lower frequencies
- requires simulations

Simulations

- real asteroseismology observations

-> noise model => synthetic observations

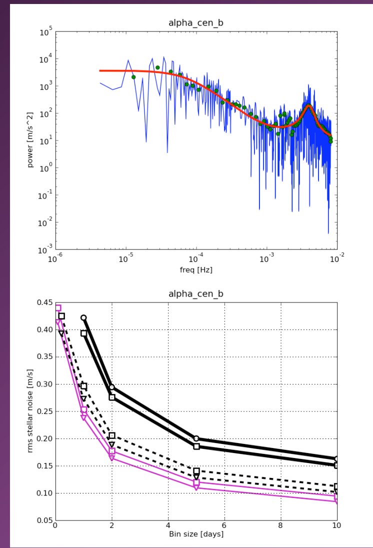


Beat the stellar limitations with

- good targe selection
- clever observational strategy

strategy

-> RV rms



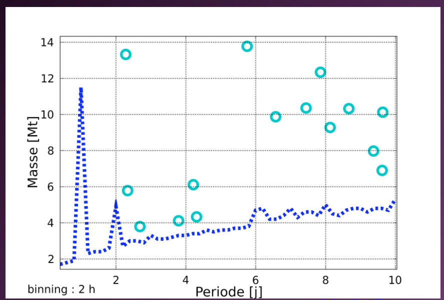
-> detection limits in the mass-period diagram

Detection limits

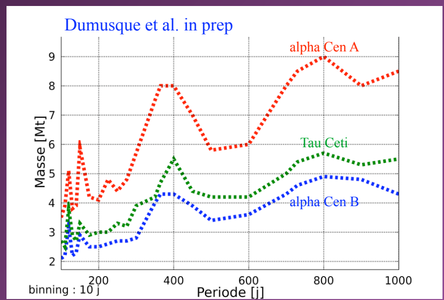
Simulations with actual calender of HD69830 (3-Neptune system)

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

short P



at 1 AU => feasible

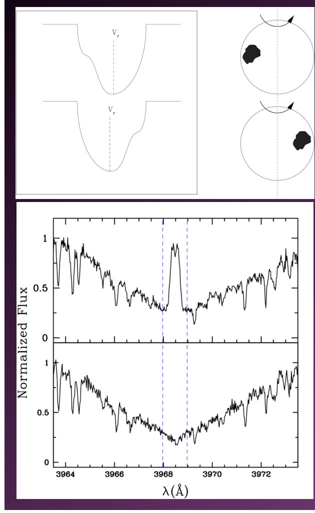


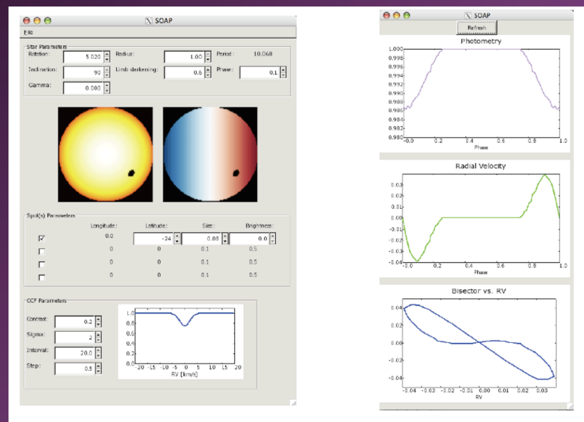
- Spot simulations to introduce activity effect in a better way still missing the longer timescales

Simulations of spot effects on radial velocities

Activity index: $\log(R'_{HK})$

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





Simulations of spot effects on radial velocities

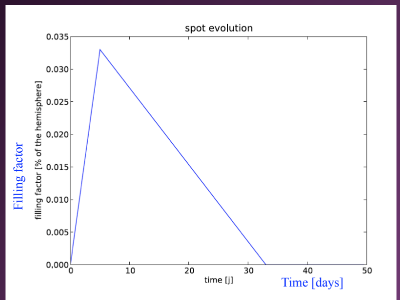
2) Realistic families of spots
1 family = ~ 25 spots

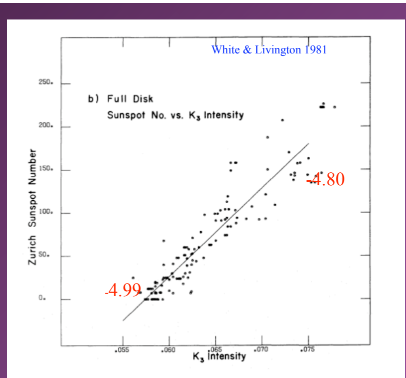
Takes into account: from observation of the Sun
- Evolution of spots: growth, filling factor
- # of spots = f(log[R'$_{HK}$])

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

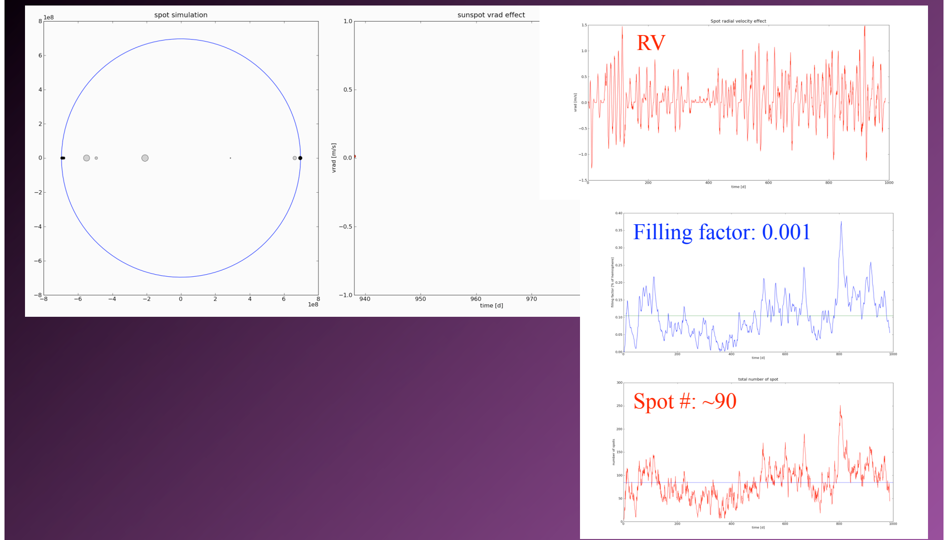




Number of spots depends on activity level

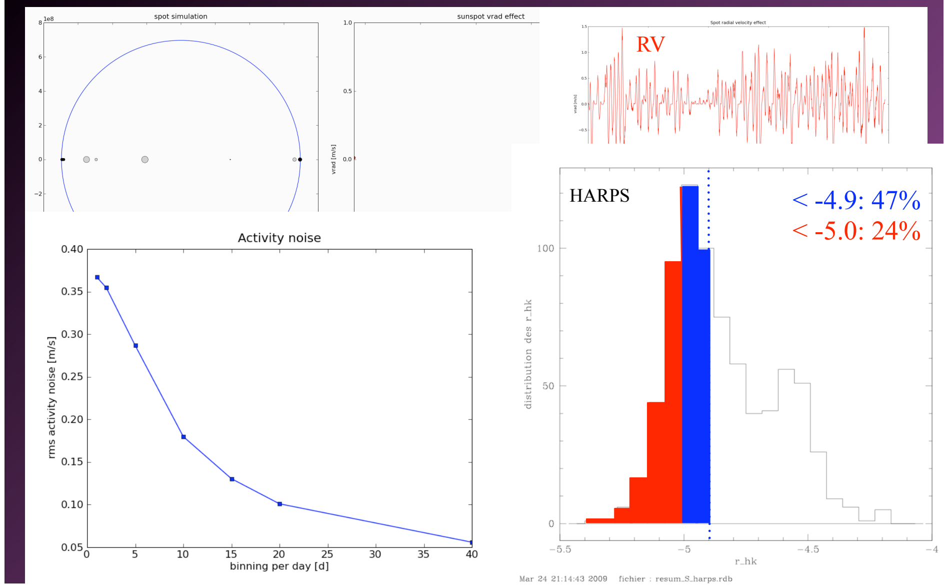
Simulations of spot effects on radial velocities

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



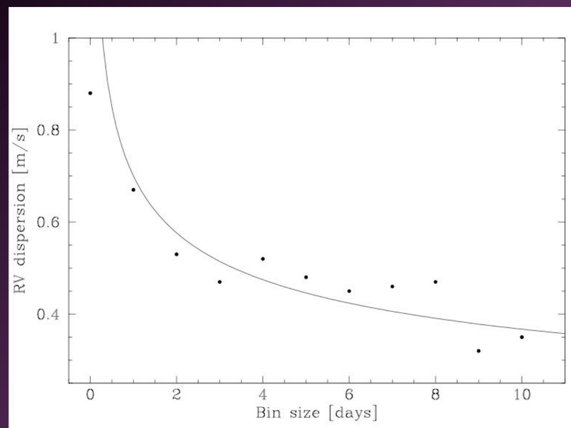
Simulations of spot effects on radial velocities

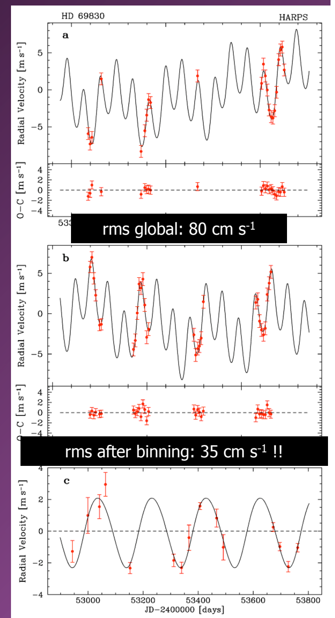
3) effect of realistic spot models: cas log(R'_HK)=-4.9



HD 69830 >>>>> 0.35 m/s

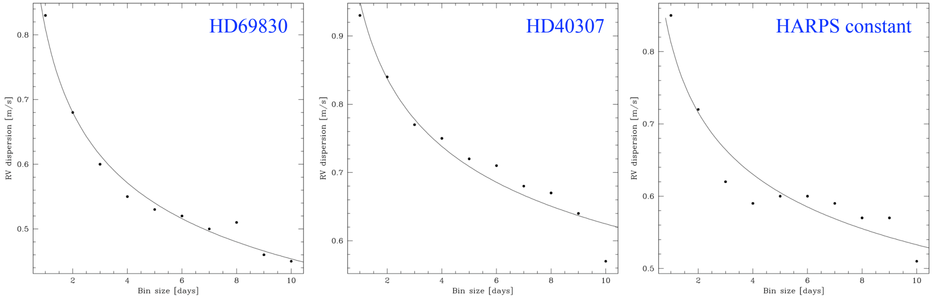
- On 4 seasons …
  residuals to the orbital fit
  - Residuals as function of the binning on …. days





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)

Summary of the DRM case for the detection of terrestrial planets in the habitable zone of solar-type stars

1. Target sample
   - non binary, non active stars from existing planet-search surveys (e.g. HARPS)
   - ~ 25% of solar-type single stars (from log(R'_HK) measurements)

     => probably only the most quiet part of them

     => at least several 100's in each hemisphere with V<9.5 (<5 cm/s in 15 min)

2. Observing strategy (from simulation results)
   - 15 min on target per measurement

     => to average stellar oscillations and to be at the few cm/s of photon noise
   - 3 measures per night (over ~4 hours) to average granulation
   - observe the star over several +/- consecutive nights to average activity effects

     Possible strategy: 5 nights over 10 days per month
   - follow the star as much as possible along the year: 8 months

3. Required telescope time estimate (from HRS/E-ELT ETC)
   - per target, per year: 40 "epochs" of 3 x (15 min + 5 min overheads) = 40 h/yr
   - follow the star over 2 years (for confirmation)
   - complete sample: 20 stars (statistics OK from HARPS results+ models) => 1600 h
   - programme spread over 4 years => 200h = 20 nights per period

4. => Large programme: expensive but high scientific return

RV detections (HARPS)