# State of Art: Radial Velocity Spectrograph

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MSc Astrophysics

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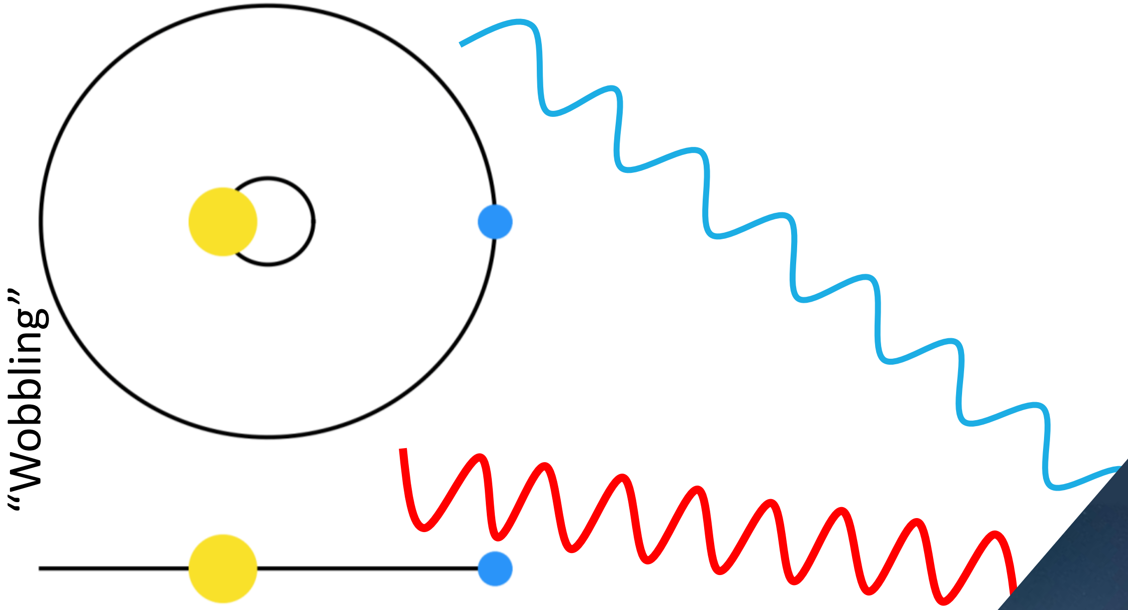
# Agenda

- Radial Velocity Spectrograph
- Historical Development
- Need for high-precision RV Spectrograph
- Timeline: Evolution of Spectrograph
- Problems/Challenges
- Ongoing Studies and Future Developments
- Conclusions
- References

# Radial Velocity Spectrograph



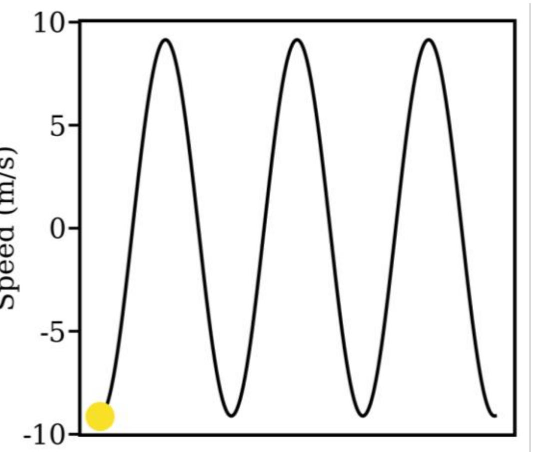




Photo credit: [Alysa Obertas]

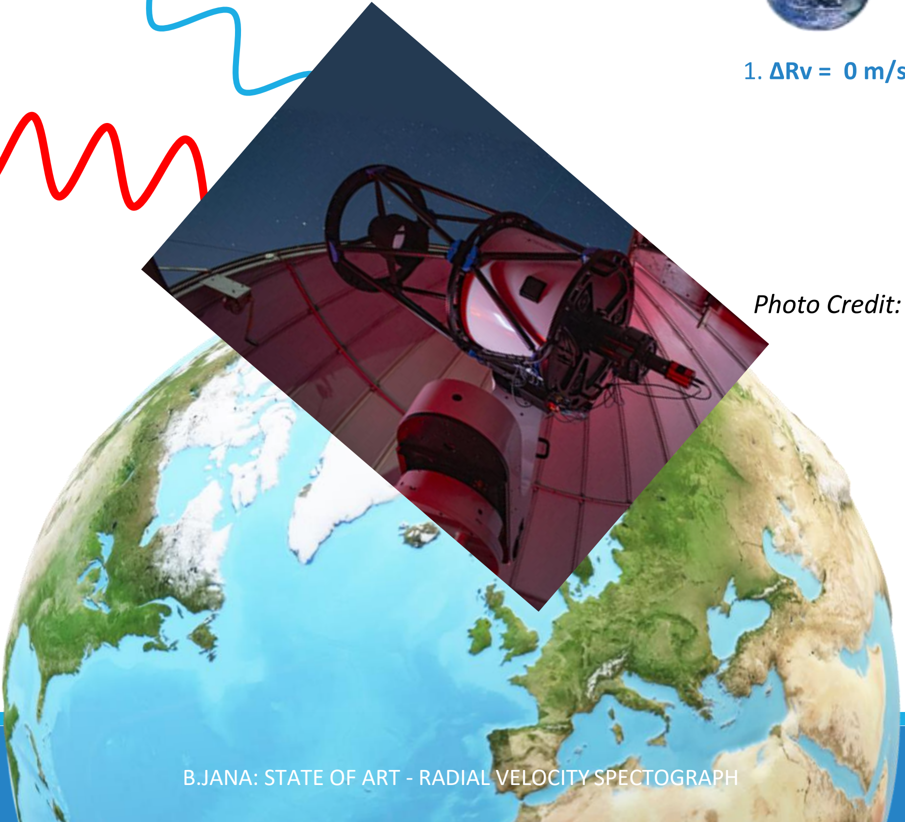
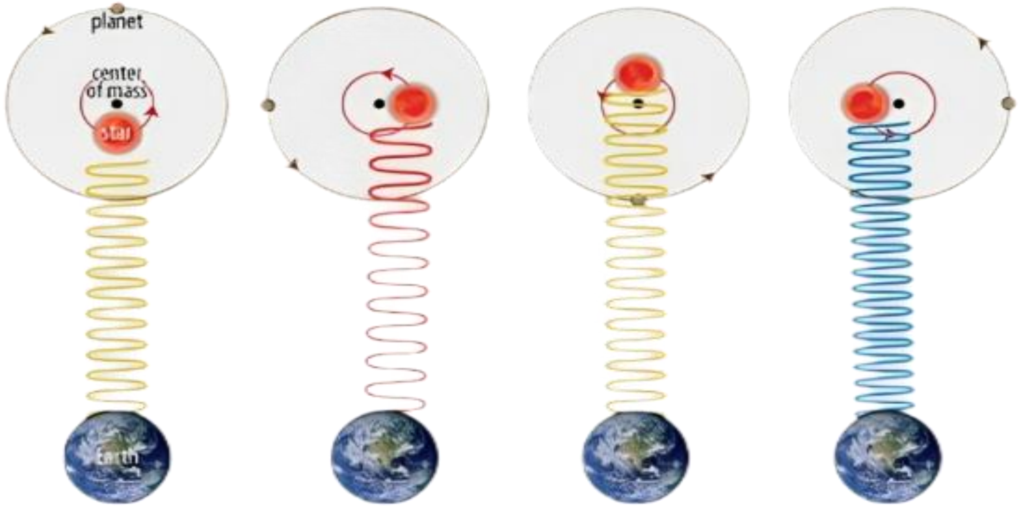


Photo Credit: [CDK24, UH Bayfordbury, UK]




1. ΔRv = 0 m/s    2. ΔRv = 10 cm/s    3. ΔRv = 0 m/s    4. ΔRv = -10 cm/s

Photo Credit: [NEID team]

## RV Spectrograph

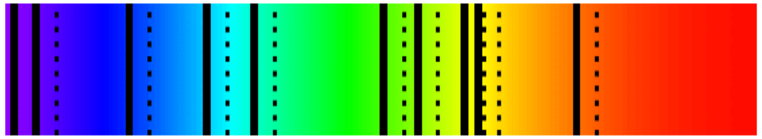


Photo credit: [Alysa Obertas]

# Historical Development

PROPOSAL FOR A PROJECT OF HIGH-PRECISION STELLAR RADIAL VELOCITY WORK

*By Otto Struve*

One of the burning questions of astronomy deals with the frequency of planet-like bodies in the galaxy which belong to stars other than the Sun.

But how should we proceed to detect them?

(Struve, 1952)

***Photo Credit: Struve on a 1949 US Post envelope***

- By 1953, radial velocities were compiled for over 15,000 stars(Wilson,1953)
- Precision: The typical precision was 750 m/s.
- Otto Struve's Proposal: Struve proposed high-precision radial velocity work for planet-hunting.
- Remarkable Assertion: Struve suggested Jupiter-like planets could be as close as 0.02 AU to stars.
- Detectability: He noted that these close-in, massive planets could be detected with 1950s Doppler precision.

# A Jupiter-mass companion to a solar-type star

**Michel Mayor & Didier Queloz**

Geneva Observatory, 51 Chemin des Maillettes, CH-1290 Sauverny, Switzerland

**The presence of a Jupiter-mass companion to the star 51 Pegasi is inferred from observations of periodic variations in the star's radial velocity. The companion lies only about eight million kilometres from the star, which would be well inside the orbit of Mercury in our Solar System. This object might be a gas-giant planet that has migrated to this location through orbital evolution, or from the radiative stripping of a brown dwarf.**

FOR more than ten years, several groups have been examining the radial velocities of dozens of stars, in an attempt to identify orbital motions induced by the presence of heavy planetary companions[1-5]. The precision of spectrographs optimized for Doppler studies and currently in use is limited to about 15 m $s^{-1}$. As the reflex motion of the Sun due to Jupiter is 13 m $s^{-1}$, all current searches are limited to the detection of objects with at least the mass of Jupiter ($M_J$). So far, all precise Doppler surveys have failed to detect any jovian planets or brown dwarfs.

Since April 1994 we have monitored the radial velocity of 142 G and K dwarf stars with a precision of 13 m $s^{-1}$. The stars in our survey are selected for their apparent constant radial velocity (at lower precision) from a larger sample of stars monitored for 15 years[6,7]. After 18 months of measurements, a small number of stars show significant velocity variations. Although most candidates require additional measurements, we report here the discovery of a companion with a minimum mass of 0.5 $M_J$, orbiting at 0.05 AU around the solar-type star 51 Peg. Constraints originating from the observed rotational velocity of 51 Peg and from its low chromospheric emission give an upper limit of 2 $M_J$ for the mass of the companion. Alternative explanations to the observed radial velocity variation (pulsation or spot rotation) are unlikely.

The very small distance between the companion and 51 Peg is certainly not predicted by current models of giant planet formation[8]. As the temperature of the companion is above 1,300 K, this object seems to be dangerously close to the Jeans thermal evaporation limit. Moreover, non-thermal evaporation effects are known to be dominant[9] over thermal ones. This jovian-mass companion may therefore be the result of the stripping of a very-low-mass brown dwarf.

The short-period orbital motion of 51 Peg also displays a long-period perturbation, which may be the signature of a second low-mass companion orbiting at larger distance.

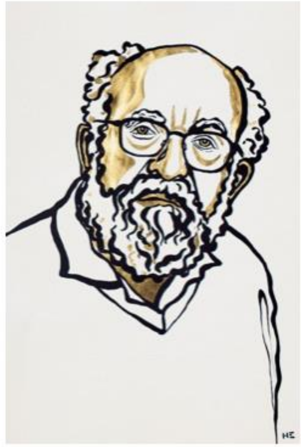
## Discovery of Jupiter-mass companion(s)

Our measurements are made with the new fibre-fed echelle spectrograph ELODIE of the Haute-Provence Observatory, France[10]. This instrument permits measurements of radial velocity with an accuracy of about 13 m $s^{-1}$ of stars up to 9 mag in an exposure time of <30 min. The radial velocity is computed



*Ref: Mayor and Queloz, 1995*





Ill. Niklas Elmehed. © Nobel Media.

Michel Mayor

Ill. Niklas Elmehed. © Nobel Media.

Didier Queloz

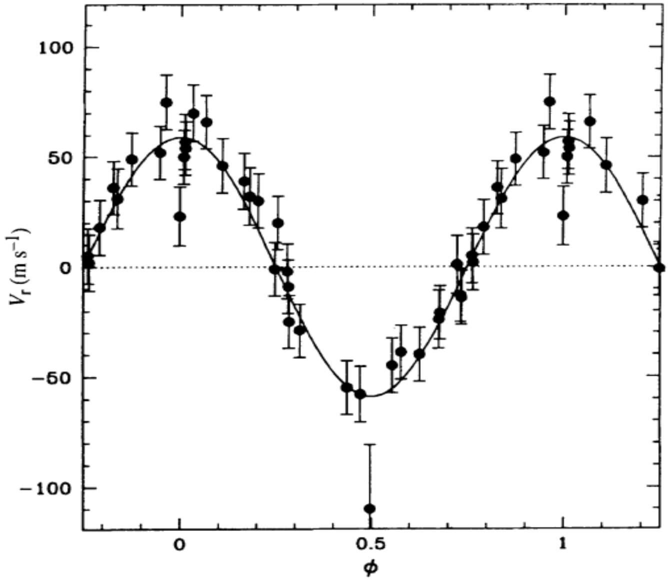
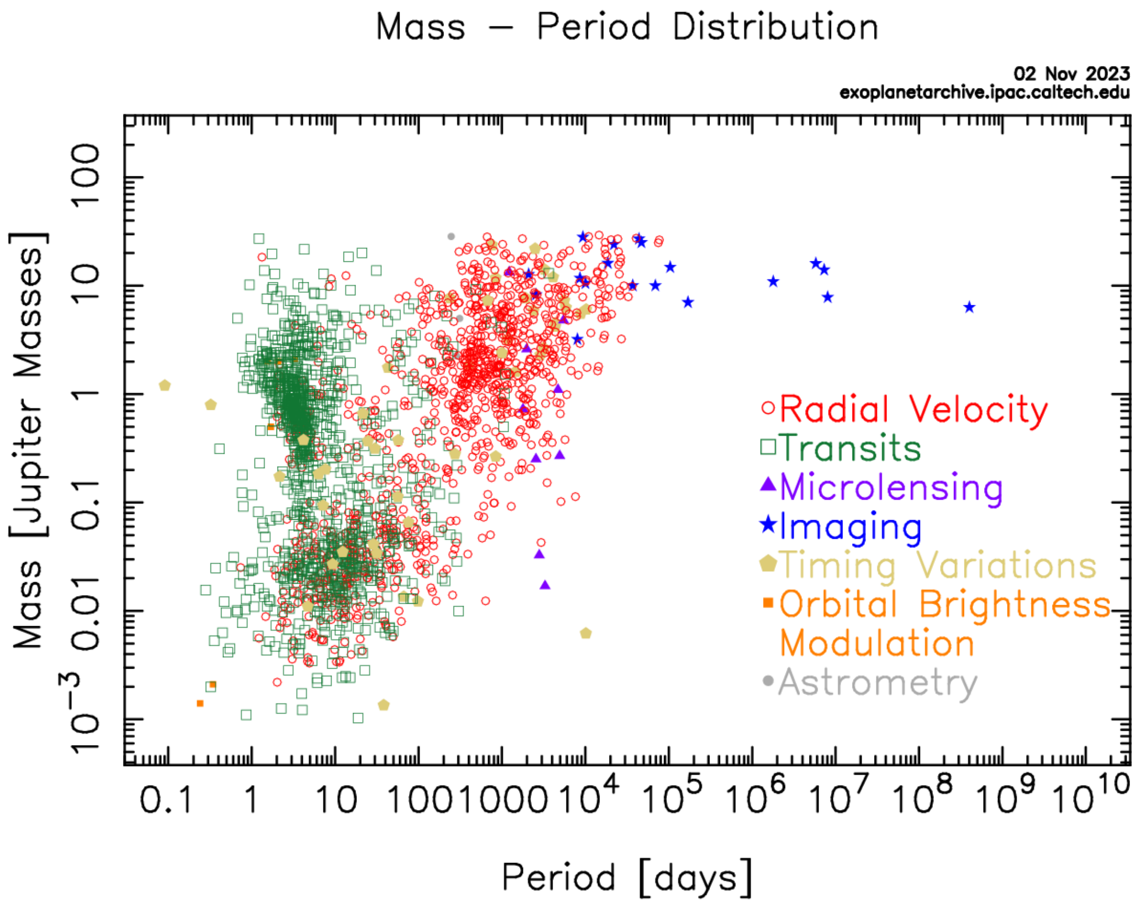
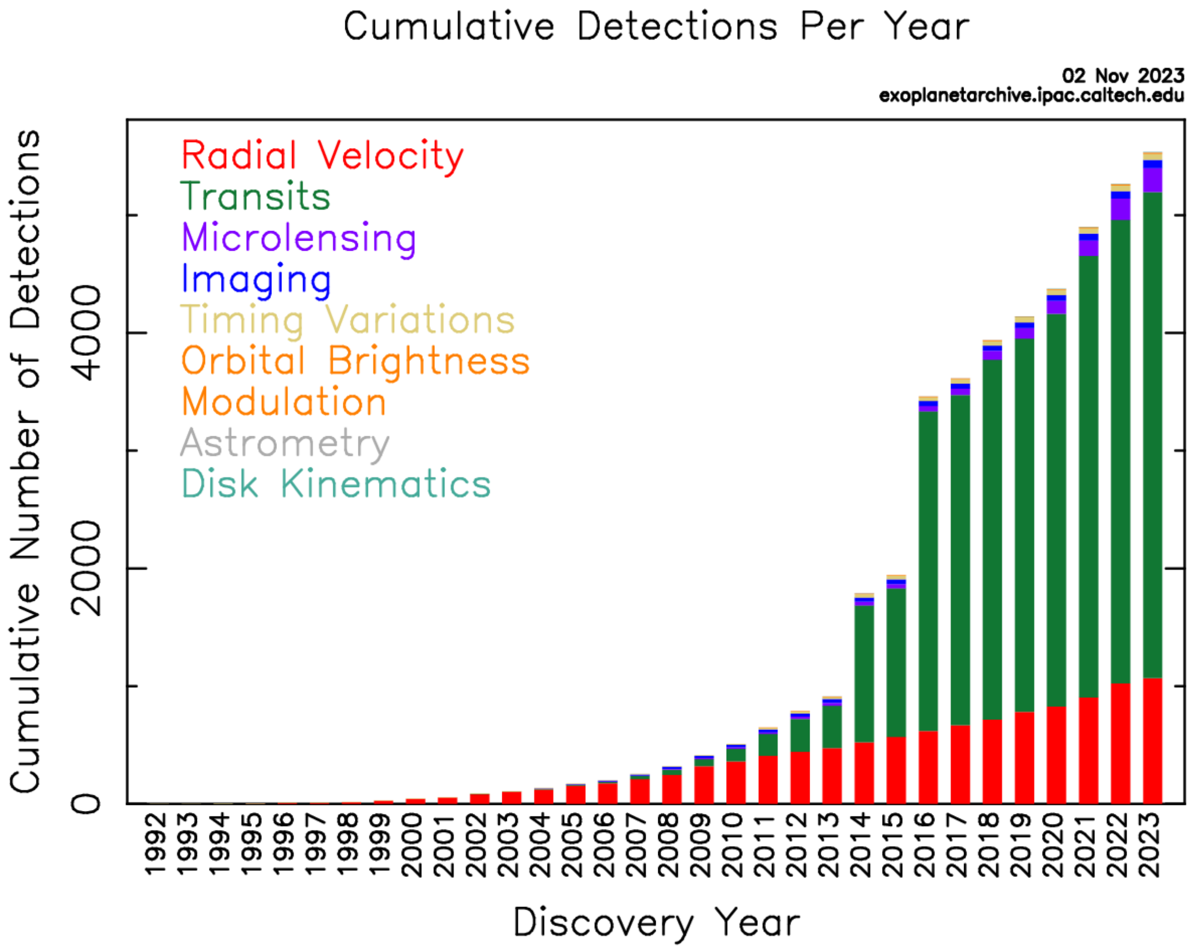



*Photo Credit: Mayor and Queloz, 1995*

- Jupiter Mass Companion
- Noble Winning Discovery, 2019



Mass — Period Distribution
02 Nov 2023
exoplanetarchive.ipac.caltech.edu
Mass [Jupiter Masses]
Period [days]
Radial Velocity
Transits
Microlensing
Imaging
Timing Variations
Orbital Brightness Modulation
Astrometry

Cumulative Detections Per Year
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Cumulative Number of Detections
Discovery Year
Radial Velocity
Transits
Microlensing
Imaging
Timing Variations
Orbital Brightness Modulation
Astrometry
Disk Kinematics

# Need for High-Precision RV Spectrograph

- Earlier spectrometers (1990s-2000s) achieved 1- few m/s precision

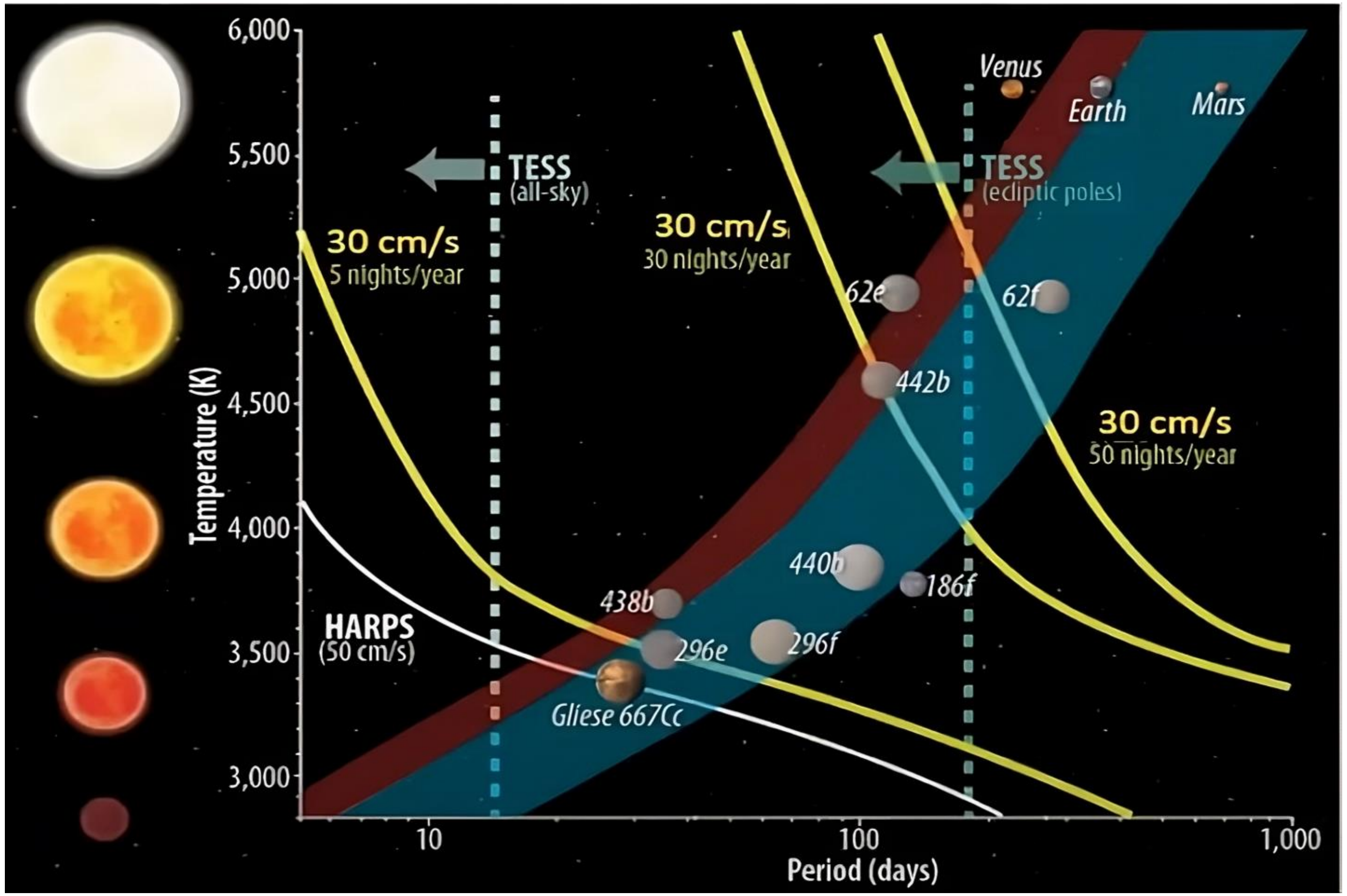
  *Examples: **HARPS**, the most precise, reaching 50-70 cm/s*

- 2010s: 3rd gen instruments aimed for 30 cm/s precision

  *Examples: NEID, EXPRES, **ESPRESSO**, KPF*

- Near-infrared spectrographs target M-dwarfs, aiming for 1 m/s precision

  *Examples: Carmenes, HPF, **MaroonX**, etc.*

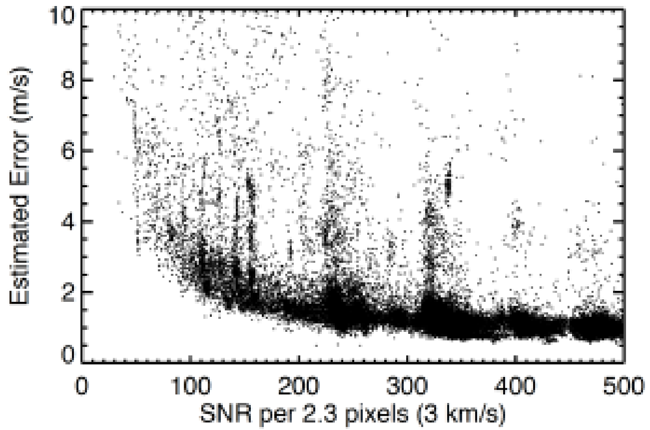


# Key Doppler Surveys for Extreme Precision Radial Velocities by Fischer et al. (2016)

- Summary of Challenges in achieving 10 cm/s precision
- Need for improved environmental control
- Stable illumination and better detectors
- Precise wavelength calibration and broad spectra
- Future instruments with higher spectral resolution
- Key parameters for Doppler surveys
- Pushing radial velocity precision beyond 1 m/s
- Challenge of achieving long-term velocity rms

**Table 1**
Current Doppler Planet Search Programs

| Spectrograph | slit or fiber | Temp Control | Spectral Resolution | Wavelength range [nm] | Wavelength calibrator | SMP [m $s^{-1}$] SNR = 200 | Number of stars | Duration of program |
|---|---|---|---|---|---|---|---|---|
| HARPS | f | Y | 115,000 | 380 – 690 | ThAr | 0.8 | 2000 | 2003 – |
| HARPS-N | f | Y | 115,000 | 380 – 690 | ThAr | 0.8 | 500 | 2012 – |
| PARAS | f | Y | 67,000 | 380 – 690 | ThAr | 1.0 | 27 | 2012 – |
| CHIRON | f | Y | 90,000 | 440 – 650 | Iodine | 1.0 | 35 | 2011 – |
| SOPHIE | f | Y | 75,000 | 387 – 694 | ThAr | 1.1 | 190 | 2011 – |
| PFS | s | Y | 76,000 | 390 – 670 | Iodine | 1.2 | 530 | 2010 – |
| HIRES | s | Y | 55,000 | 364 – 800 | Iodine | 1.5 | 4000 | 1996 – |
| Levy (LCPS) | s | Y | 110,000 | 376 – 970 | Iodine | 1.5 | 100 | 2013 – |
| Levy (CPS) | s | Y | 100,000 | 376 – 940 | Iodine | 2.0 | 300 | 2013 – |
| SONG | s | N | 90,000 | 440 – 690 | Iodine | 2.0 | 12 | 2014 – |
| HRS | s | Y | 60,000 | 408 – 784 | Iodine | 3.0 | 100 | 2001 – 2013 |
| Hamilton | s | N | 50,000 | 390 – 800 | Iodine | 3.0 | 350 | 1987 - 2011 |
| UCLES | s | N | 45,000 | 478 – 871 | Iodine | 3.0 | 240 | 1998 – |
| Tull | s | N | 60,000 | 345 – 980 | Iodine | 5.0 | 200 | 1998 – |



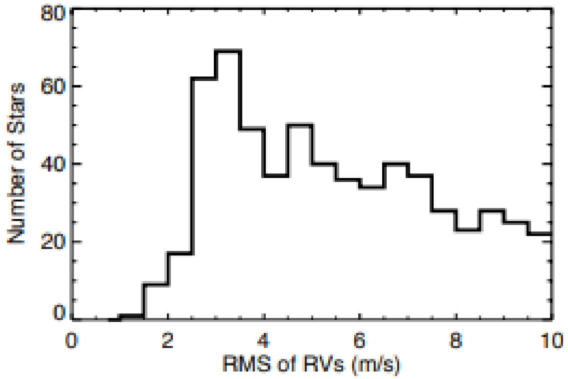




*Photo and Table Credit: Fischer et al., 2016*

# HARPS(High Accuracy Radial velocity planet searcher)

*Photo Credit: [European Southern Observatory]*

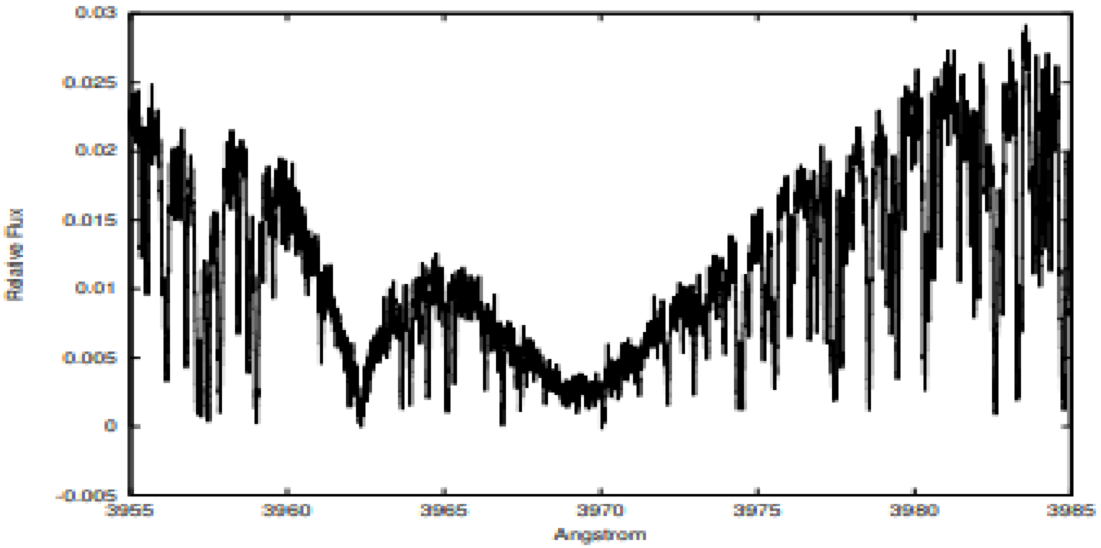



*Photo Credit: [Pepe et al., 2004]*

- **Exoplanet Detection:** HARPS specializes in precise radial velocity measurements for exoplanet detection.
- **Unprecedented Precision:** Achieves remarkable 1 m/s accuracy, enabling detection of "giant" planets.
- **Scientific Impact:** Instrument vital for super-Earth discoveries and low-mass planet research.
- **Limits of Detection:** Still can't find Earth-like planets due to 10 cm/s sensitivity.
- **Consortium Development**: Developed by Geneva Observatory and partners.
- **Observatory Installation**: Located at La Silla Observatory since 2003.
- **Exceptional Performance**: Continuously delivering high-precision measurements.

# Challenges

**Instrument Stability** - Environmental factors (temperature, pressure, wavelength calibration, detectors

**Information Content** - SNR, Spectral resolution and sampling

**Analysis error** - Modelling(e.g. impact of PSF), Telluric Contamination, Extracting signals from noisy data

**Astrophysical Noise** - Spots, Pulsation, Granulation

*Photo Credit:* *[European Southern Observatory]*

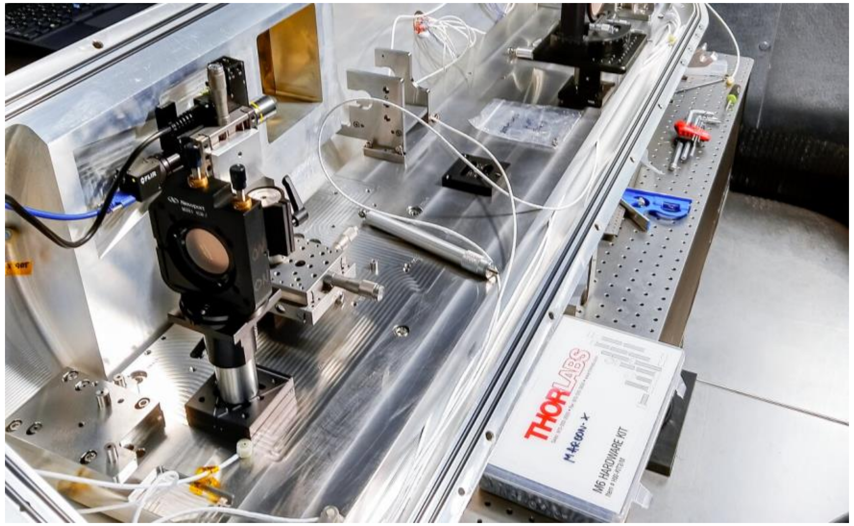



*Photo Credit:* *[International Gemini Observatory/NOIRLab/NSF/AURA/A. Peck]*

# Ongoing Studies and Future Developments

- **ESPRESSO (Echelle Spectrograph for Rocky Exoplanets and Stable Spectroscopic Observations)**
  - Earth Twin Detection: Designed to detect and characterize Earth twins in the habitable zones of solar-like stars.
  - Four-Telescope Feeding: Can simultaneously receive light from up to four Unit Telescopes (UTs).
  - Ultra-stabilized design: Maintains stability with a thermally stabilized vacuum vessel at mK levels and low pressure.

- **Maroon X**
  - Designed for M Dwarfs: Aiming to detect Earth-size planets in the habitable zones of mid- to late-M dwarfs.
  - Unprecedented Precision: Capable of achieving 1 m/s radial velocity precision, far beyond any existing instrument.
  - Wavelength Range: Operating in the 700-900 nm region for maximum radial velocity information.

These advanced spectrographs push the boundaries of radial velocity precision and have diverse applications in exoplanet hunting.



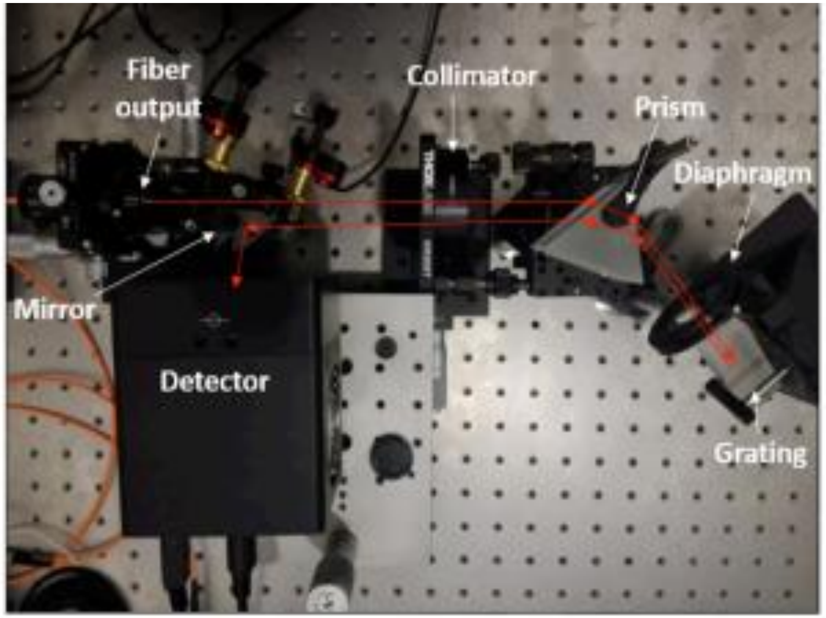




*Photo Credit: Lhospice et al., 2019*

# Ongoing Studies and Future Developments

**EXOhSPEC (Jones et al., 2021)**

- Design: Inexpensive, High-res spectrograph with optical innovations.
- Prototype: In-plane echelle spectrograph with active control.
- Compact: Minimal optical components, 20x30 cm dimensions.
- Resolution: >70,000, works in the optical regime.
- Fiber-fed: Bifurcated fiber for telescope and calibration.
- Real-time control: Piezo-electric actuators for guiding.
- Precision: 4 m/s in a standard laboratory environment.

# Conclusions

- High-precision radial velocity spectrographs are vital tools in the search for exoplanets.
- Over the years, technological advancements have pushed the boundaries of precision.
- Instruments like HARPS, MAROON-X, and ESPRESSO showcase our quest for perfection.
- EXOhSPEC represents an innovative approach to achieving high resolution at lower costs.
- The future holds exciting possibilities for radial velocity spectrometry.
- As we conclude, let's remember that our journey to explore distant worlds continues, one spectrograph at a time.

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