Radial Velocity Technique

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Introduction

- The most successful technique for detecting extrasolar planets
- Measures reflex motion:

$$K_s = 28.4 \frac{M_p \sin i}{(M_s + M_p)^{2/3}} P^{-1/3} \ (\mathrm{m\,s^{-1}})$$

- Largest signal for massive planets in short-period orbits
- Velocity precision has improved from about 10 m/s to ~ 1 m/s or slightly better

- RVs are used for the ***detection*** of extrasolar planets as well as their ***characterization***
- Dopper studies have revealed that:
  - ~10% of FGK stars have at least one planet in the range 0.3–10 M_{Jup} with periods between 2 and 2000 days (Cumming et al. 2008)
  - 17–19% of stars have a gas giant within 20 AU
  - 11% of stars have an Earth-mass planet or larger within 1 AU
  - Gas giant fraction is much more efficient around metal-rich stars

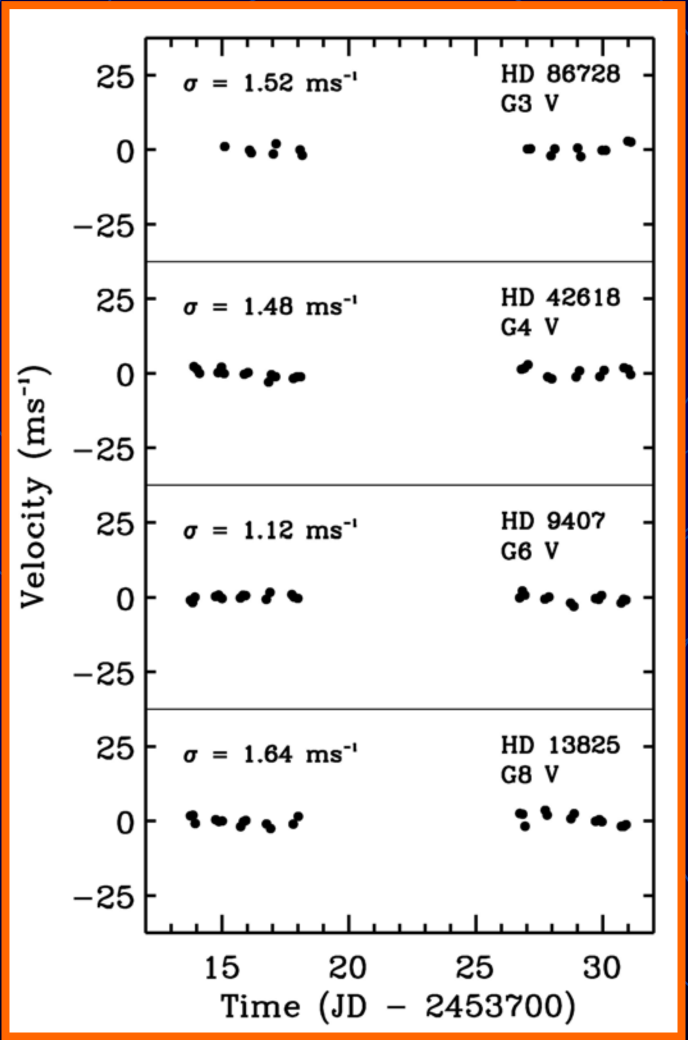
Relevance to Space Missions

- RVs play a key supporting role for astrometric missions (e.g., SIM-Lite, GAIA)
  - Vetting of K giant grid stars
  - Reduce the need for complete astrometric coverage, complement orbital solutions
- RVs play a key role for transit searching missions such as Kepler and CoRoT
  - Rejection of false positives
  - Measurement of planet masses (orbits)
  - Quantitative spectroscopy for characterizing host star

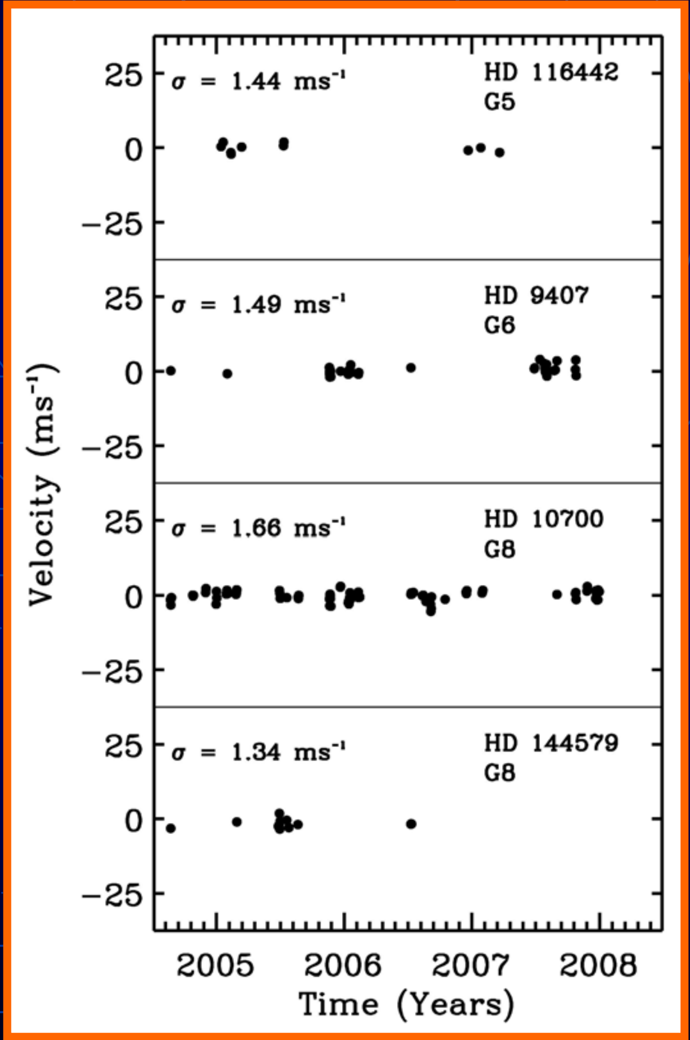
RV Precision History

- 1920-1980: ~500 m/s, CORAVEL ~ 300 m/s
- 1980s
  - Hydrogen fluoride cell gives ~13 m/s
  - Transmission Fabry-Perot Doppler (Univ. of Arizona)
  - Telluric line Doppler (Univ. of Texas)
  - Reflection Fabry-Perot Doppler (Univ. of Texas)
  - Iodine cell at SFSU
- 1995: ~10 m/s with stabilized spectrometer (CORALIE), 3 m/s with iodine cell
- 1997: Fixed-delay interferometry work
- 2004–2005: 1 m/s is achieved with iodine cell (Keck/HIRES) and simultaneous Th-Ar technique and a very stable spectrograph (HARPS)

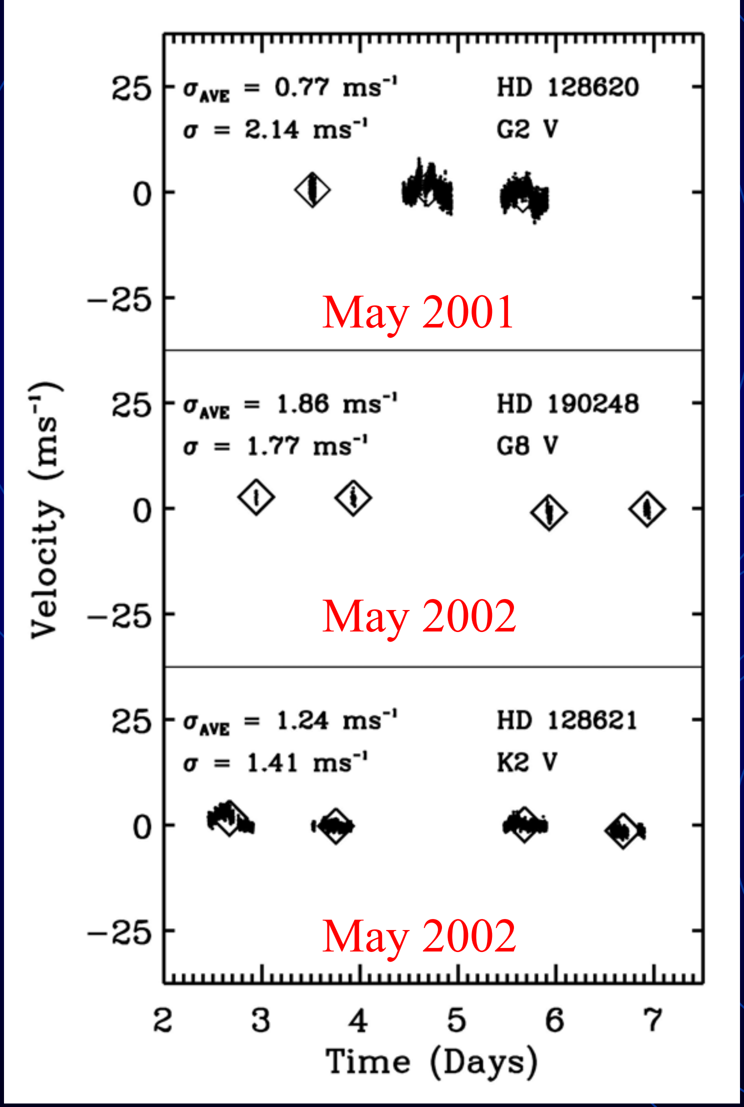
Today



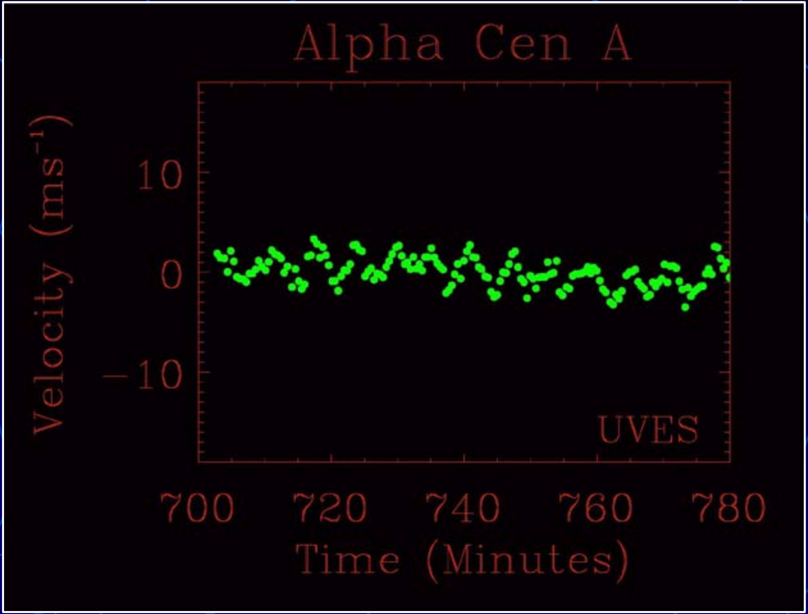
Keck I HIRES



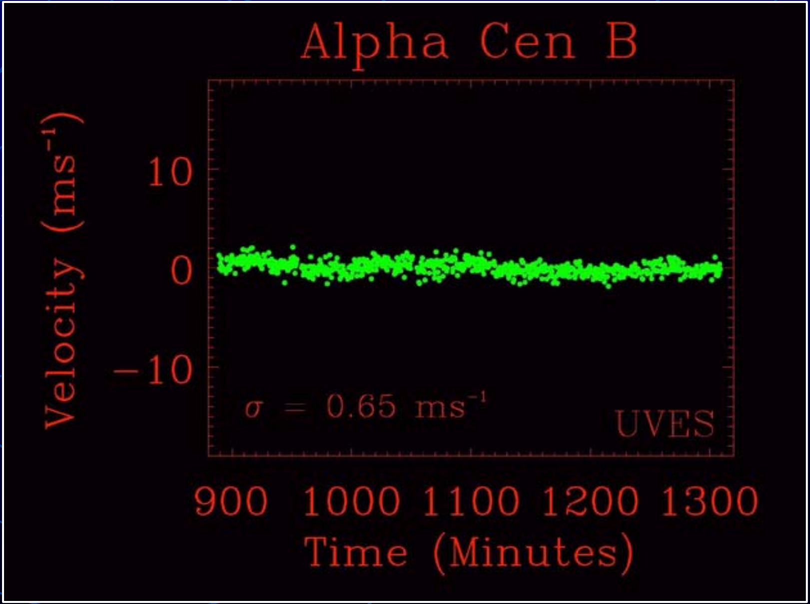
VLT/UVES



σ_{AVE} = 0.77 ms^{-1}
σ = 2.14 ms^{-1}
HD 128620
G2 V
May 2001
σ_{AVE} = 1.86 ms^{-1}
σ = 1.77 ms^{-1}
HD 190248
G8 V
May 2002
σ_{AVE} = 1.24 ms^{-1}
σ = 1.41 ms^{-1}
HD 128621
K2 V
May 2002
Velocity (ms^{-1})
Time (Days)



Alpha Cen A
Velocity (ms^{-1})
UVES
Time (Minutes)



Alpha Cen B
Velocity (ms^{-1})
σ = 0.65 ms^{-1}
UVES
Time (Minutes)

HARPS

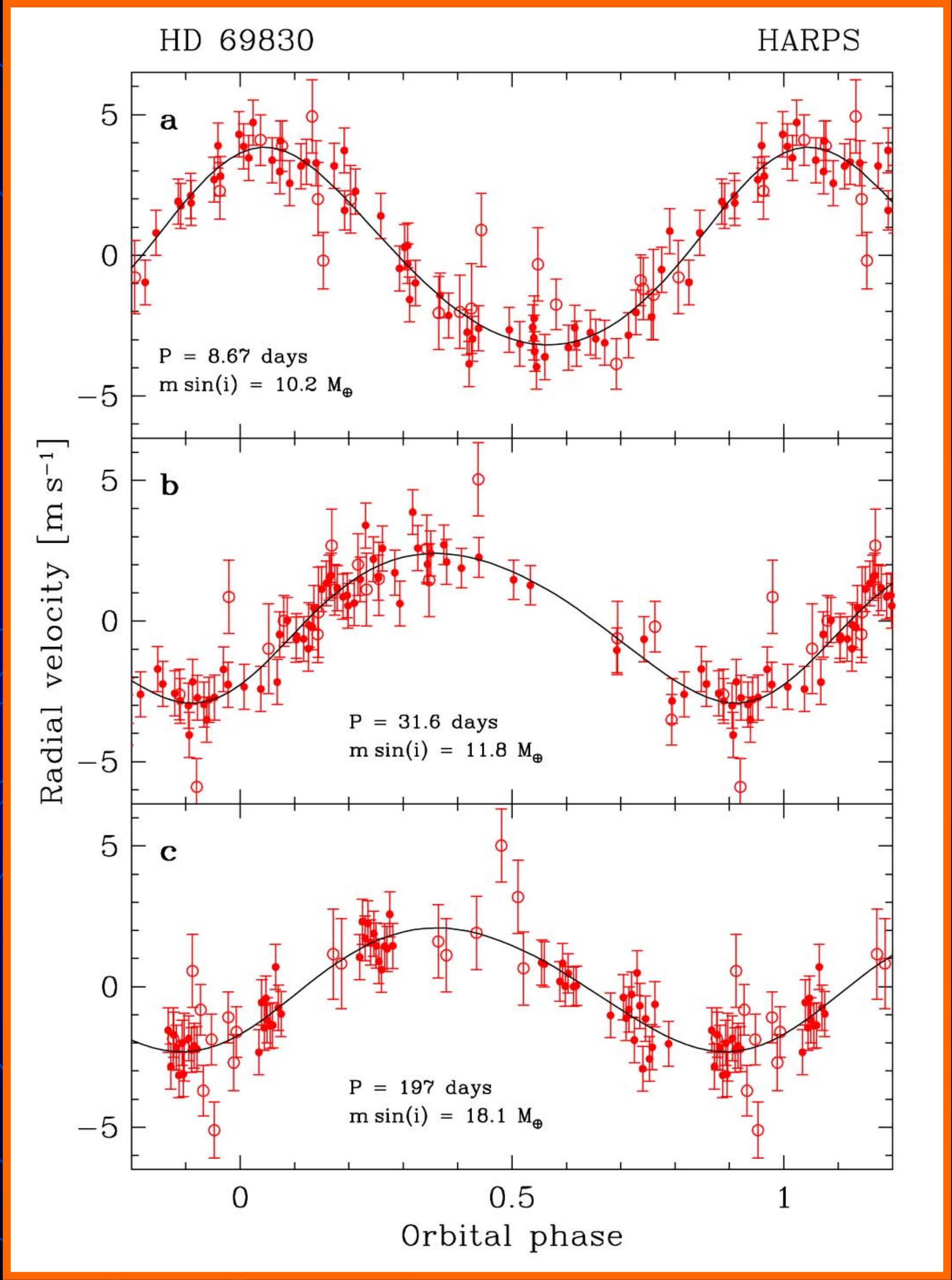
Three-planet system around a K0V star, $V = 5.95$

Overall RMS = 0.81 m/s (after 3-planet orbital fit)

Early exposures (4 min) give RMS of 1.50 m/s

More recent exposures (15 min) give RMS of 0.64 m/s

Lovis et al. (2006)



Main Limitations to RV Precision

- Photon noise
- Wavelength calibration
- Telescope guiding
- Stability in the illumination of spectrograph
- Detector-related effects
- Stellar noise (“jitter”) on different timescales
  - p-mode oscillations
  - Stellar granulation noise (granulation, meso-granulation, super-granulation)
  - Active regions
  - Magnetic cycles

It appears possible to reach 10–20 cm/s in the near future

Science Goals

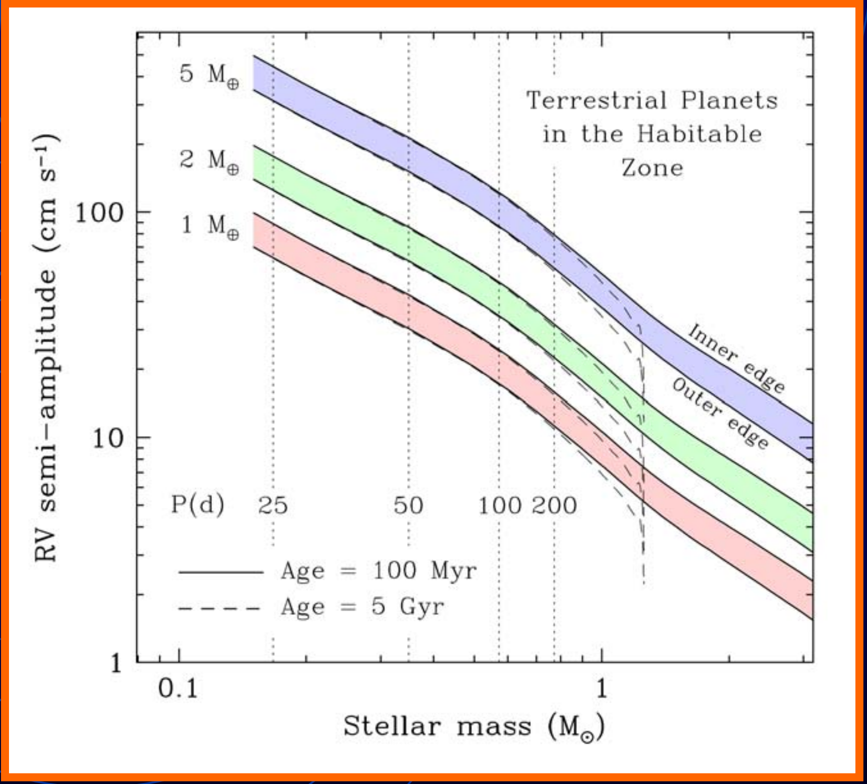
- Find Earth-type planets, particularly in the habitable zone of nearby stars
  - M dwarfs are attractive (GJ 581, Udry et al. 2007; GJ 436, Gillon et al. 2007)
- Solar System analogs: how common are they?
- Identify planetary systems with dynamical room for stable Earth-like planets in the HZ
- Provide targets for JWST (e.g., transiting low-mass planets)

Science Requirements

- Significantly increase access to telescope time
  - Leading RV groups are essentially shot-noise limited and cadence limited
  - Cadence is important to reduce impact of astrophysical noise
  - Longer exposures and more telescope nights would immediately bring
    - Higher precision
    - Fainter M stars into reach: exposing such stars for long enough to avoid being limited by photon noise requires enormous amounts of observing time, not presently available

- In the optical, achieve a RV precision of ~20 cm/s, particularly for nearby M dwarfs
  - Detection of Earth-mass planets (surveys)
  - Characterization (follow-up)

$$K_s = 28.4 \frac{M_p \sin i}{(M_s + M_p)^{2/3}} P^{-1/3} \ (\mathrm{m\,s^{-1}})$$



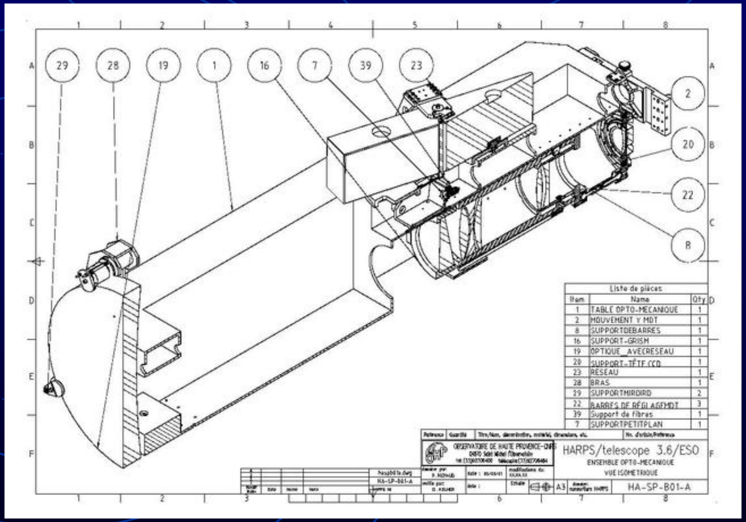
- Achieve a RV precision better than 10 m/s in the NIR, where M stars emit most of their energy. Preferably, push toward 1–3 m/s
  - Majority of stars within 8 pc are M dwarfs (120/150)
  - Faint M dwarfs are beyond reach in the optical, but within reach in the NIR: an M4 dwarf at 20 pc has V ~ 14, but J ~ 9.5
- Characterize stellar "jitter" (p-mode oscillations, granulation, active regions, magnetic cycles, all have different timescales)

"Observatory Concept"

- (0) Mission: Gain more access to telescope time
  - Crucial for the success of Kepler and CoRoT
  - Viewed as a significant cost item for RVs
  - Options:
    - Buy more telescope time on existing telescopes equipped with 1 m/s RV precision capability (e.g., AAT, Keck)
    - Build more instruments with 1 m/s capability and place them on existing telescopes that have available time or are underutilized (e.g., 4-m class telescopes)
    - Build dedicated large ground-based telescopes equipped with 1 m/s capability. Examples: N-S pair of 6–8m class Magellan-style clones, or a global network of 2–4m class telescopes with high-precision RV spectrometers

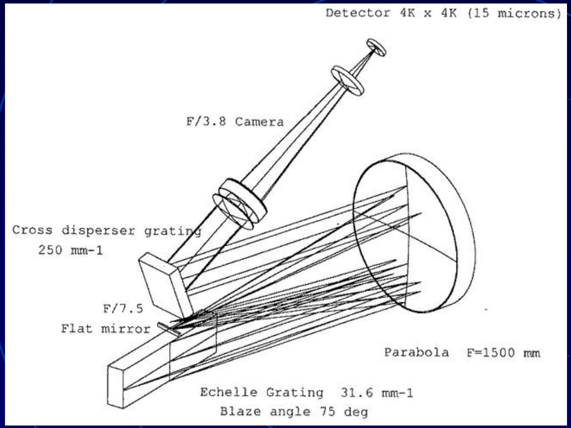
Observatory Concepts

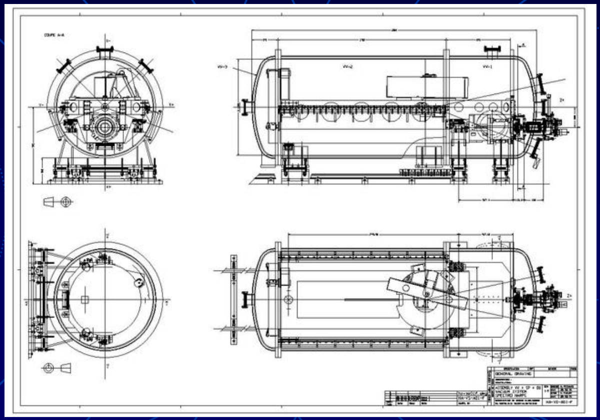
- (1) Ultra high precision RV machine (HARPS-NEF)
  - Cross-dispersed fiber-fed echelle spectrograph with *R* ~ 120,000, λλ378-690 nm, designed after the very successful HARPS, but with updates and improvements: 10–20 cm/s RV precision (simultaneous Th-Ar technique, possibly laser comb)
  - Will be one of the workhorses for Kepler follow-up

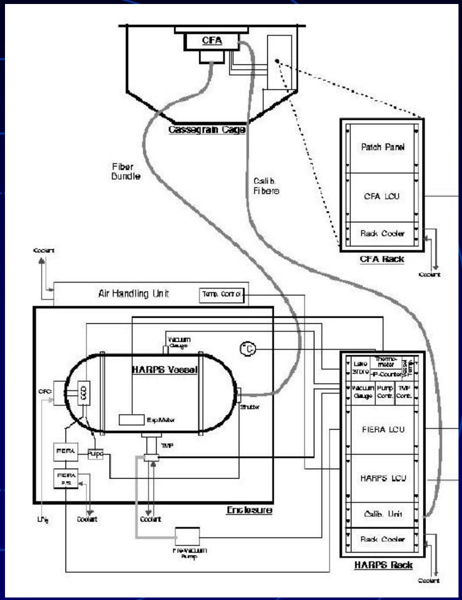


Harvard Origins of Life Initiative / Geneva Observatory

(1) Cont.

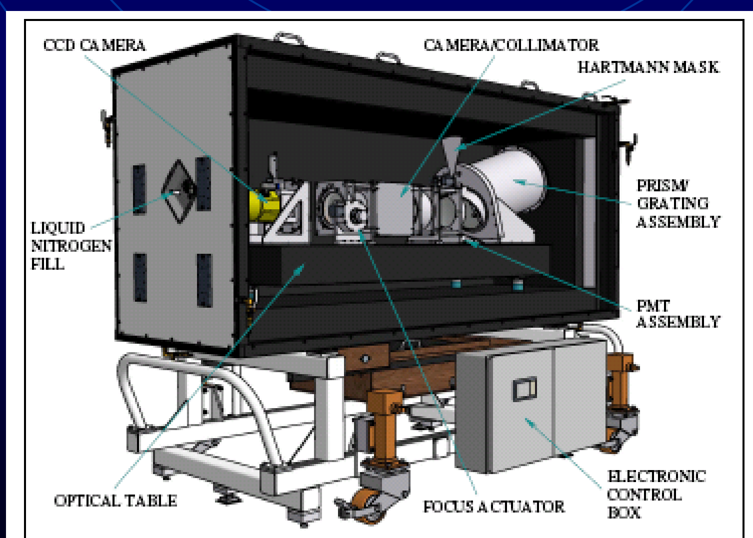


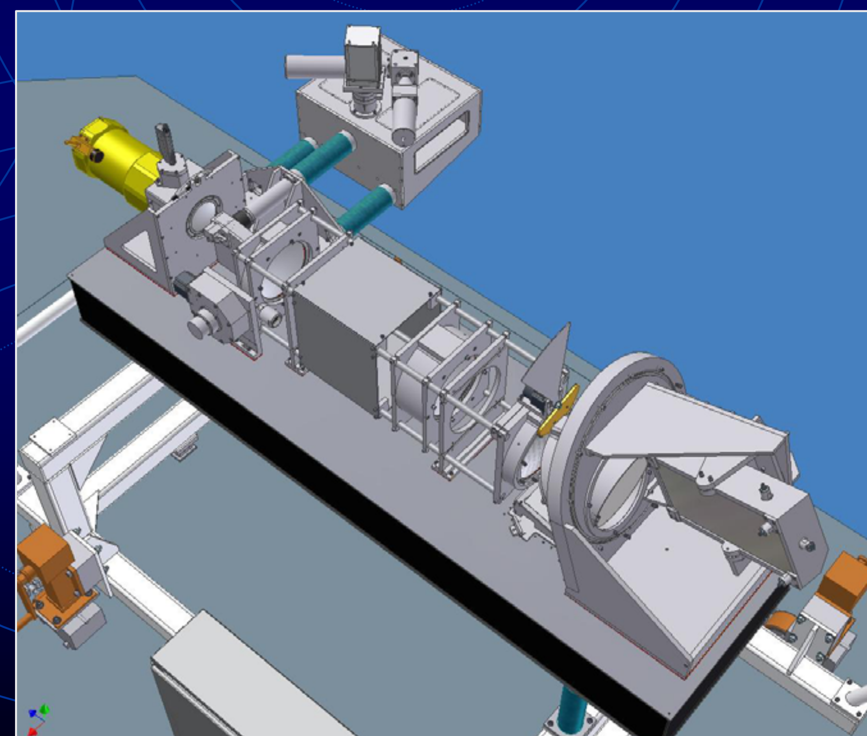




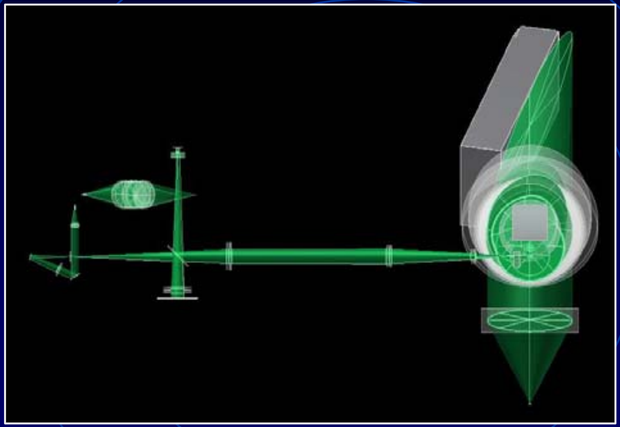
- Designed for long-term stability (in vacuum, temperature controlled), to enable discovery and characterization of terrestrial planets around $V < 12$ mag stars
- Placed on 4-m class telescope in the North

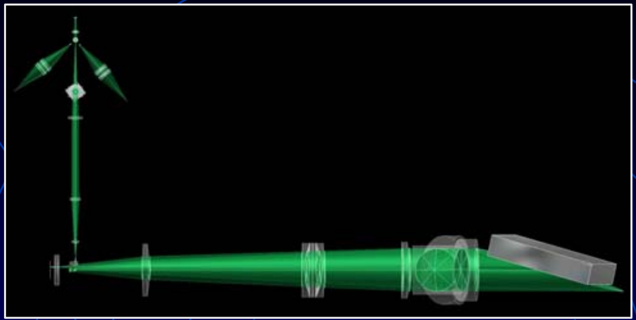
- (2) Planet Finder Spectrograph (Carnegie), designed specifically for 1 m/s precision, to gain more "air time" to detect and characterize planets
  - Double-pass slit echelle spectrograph with passive and active temperature control. High resolution (R4 grating, *R*~38,000/"), high-efficiency

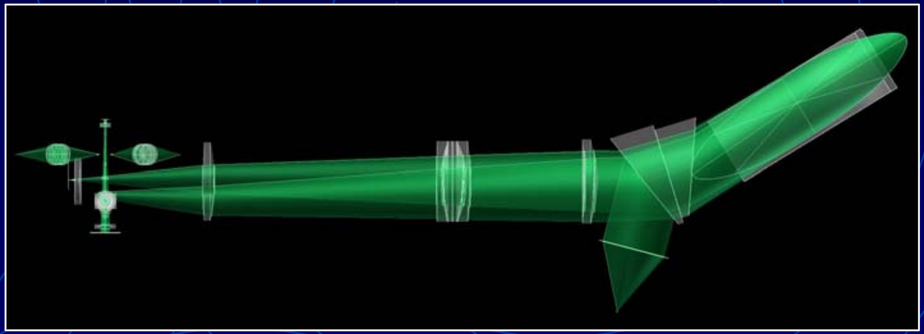




(2) Cont.

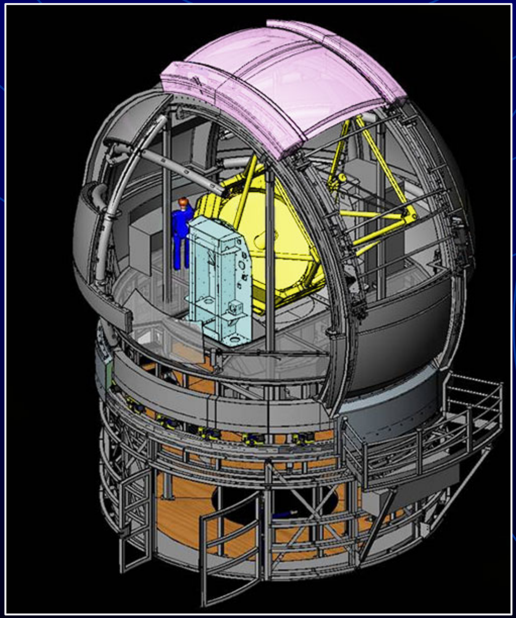


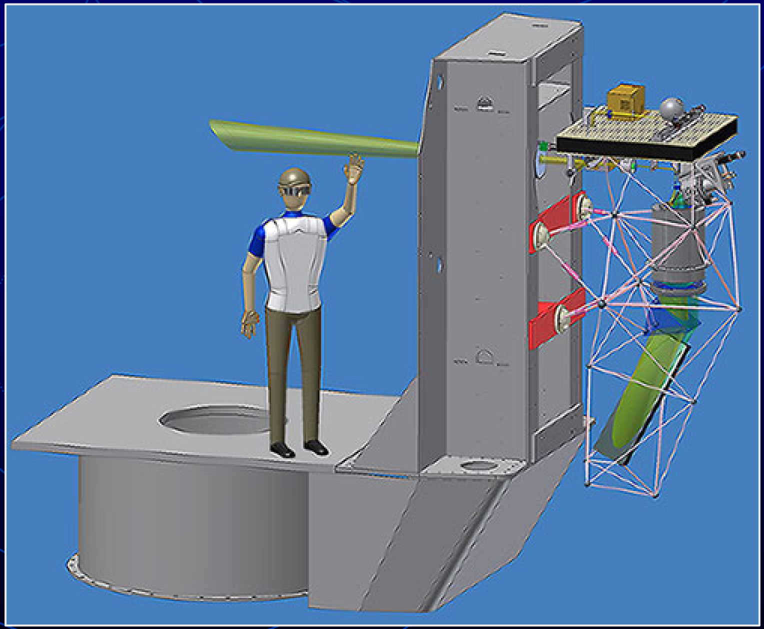




- Careful slit and pupil illumination to minimize RV errors, and very high-quality flat-fielding
- Mounted on 6-m class telescope in the South
- Achieve 2 m/s for a single exposure, and 1 m/s by binning 4 exposures over suitable timescales to average out p-mode stellar oscillations

- (3) Automated Planet Finder (Lick Obs.)
  - Completely robotic 2.4-m telescope equipped with a high-resolution spectrograph designed for RV precision of 1 m/s
  - Optimized specifically for the Doppler detection of planets having masses 5–20 $M_{\oplus}$

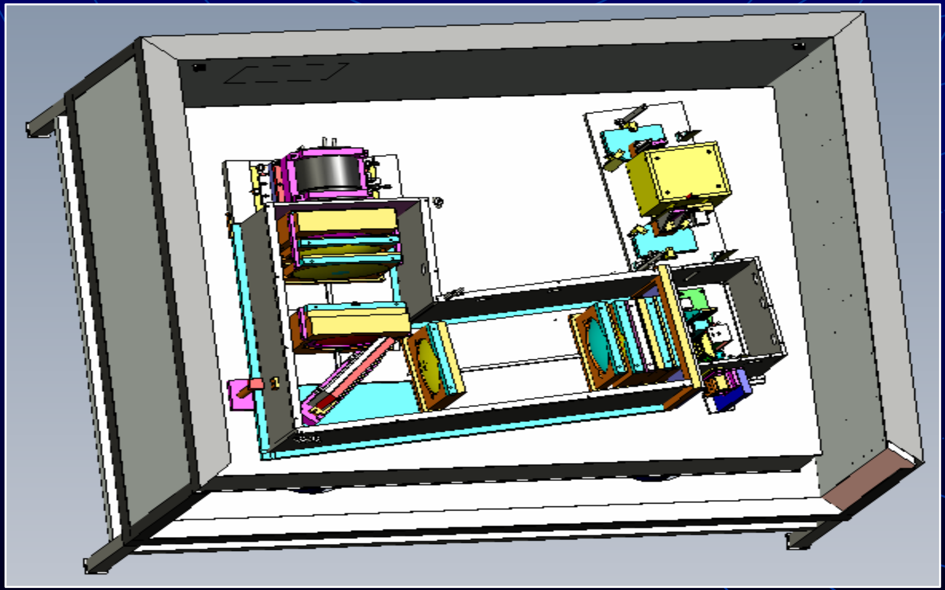


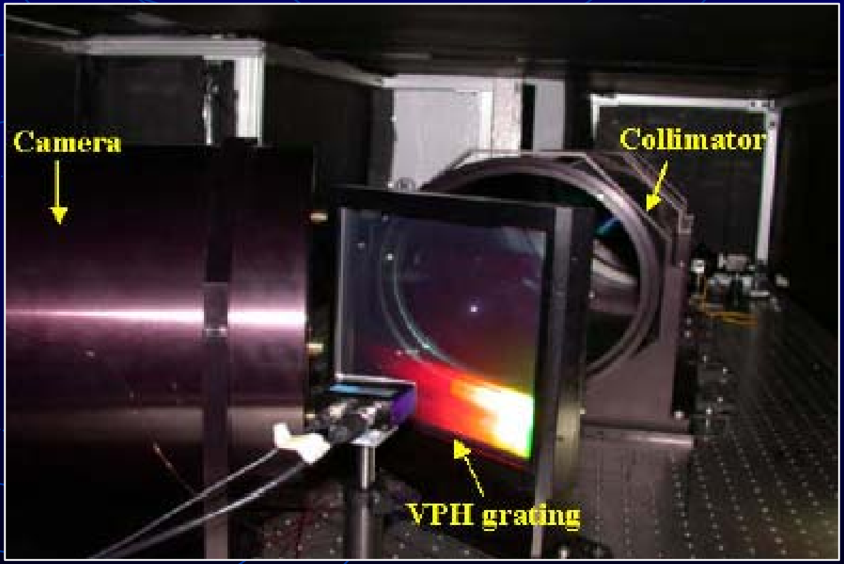


- *Dedicated telescope*. Makes intelligent decisions each night about which stars to observe, what data quality is optimal, and whether a planet is nearly detected
- Optimized for high efficiency
  - Secondary obscuration kept small
  - Uses protective silver coatings on the secondary and tertiary mirrors.
- The optical train includes an atmospheric dispersion compensator (to stabilize the image centroid against variable dispersion caused by changing zenith distance) and an Iodine cell precision radial velocity reference
- One example of what could be a network

- (4) Multi-object (60 fibers) RV machine based on a dispersed fixed-delay interferometer
  - Wide-angle Michelson interferometer coupled with a medium-resolution spectrograph
  - Iodine gas absorption cell for the wavelength reference

MARVELS, University of Florida

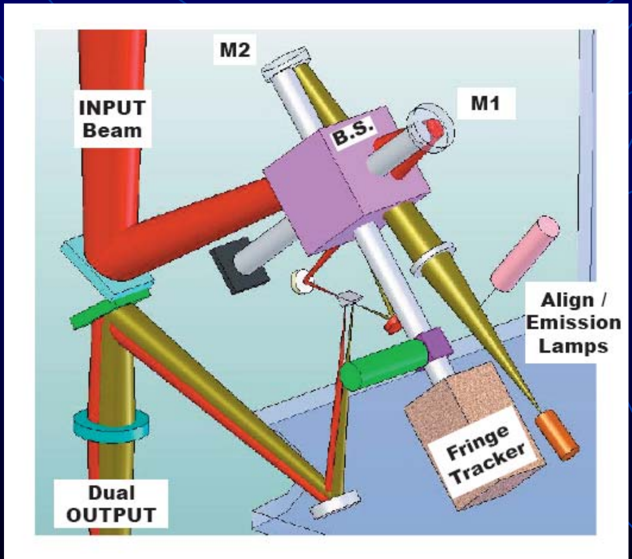


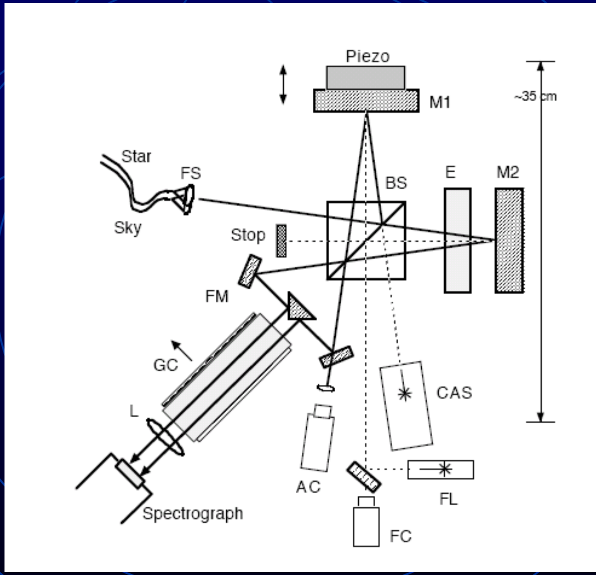


(4) Cont.

- Capable of surveying ~11,000 stars in the brightness range V = 8–12 (current samples collectively include ~3,000 stars)
- Placed on 2–3-m class telescope with wide FOV
- Science motivation
  - Provide the largest homogeneous giant planet sample for revealing the diversity in giant exoplanet populations and testing models of formation, migration, and dynamical evolution
  - Find rare planets
  - Find transiting planets

- (5) High-precision infrared RV instrument
  - Based on externally dispersed interferometry technique (similar to previous design)
  - Simultaneous *JHK*-band coverage
  - Placed on 4–5-m class telescope in the North
  - Designed to survey M dwarfs

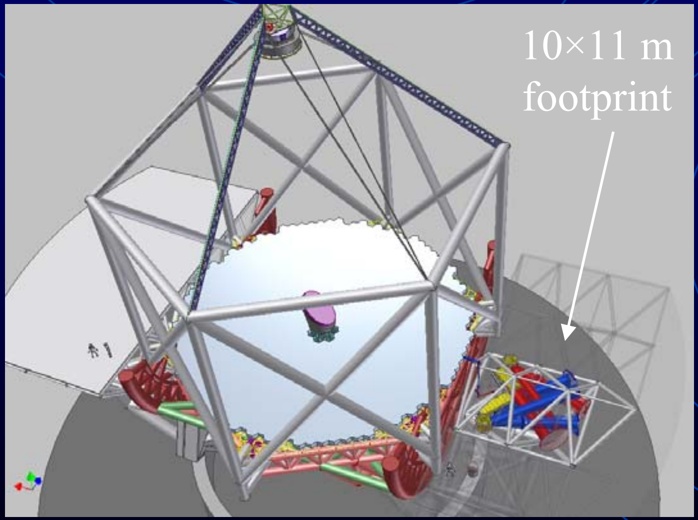


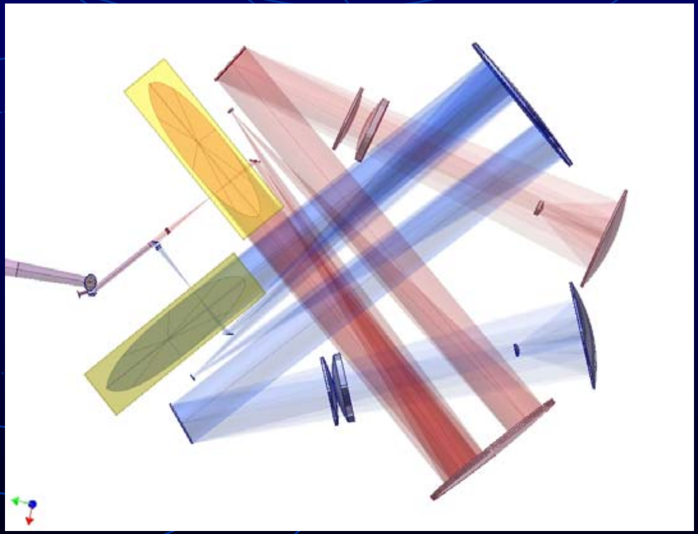


T-EDI

UC Berkeley
Cornell
LLNL

- (6) Moderate to High Resolution spectrometer (MTHR) for 30-m telescope (UCO/Lick)
  - Combines the best advantages of VLT's UVES and Keck's HIRES; large optics (1.0×3.5m echelle)
  - Dual-white-pupil/dual-arm configuration, high throughput cross-dispersed echelle, optimized for RVs





(6) Cont.

- Queue-scheduled instrument
- Would be fast enough to deliver 1 m/s on M dwarfs
  - Achieving 1 m/s RV precision on a reasonable sample (many hundreds) of M dwarfs (*V* ~ 12–13) is currently not practical with an 8–10m-class telescope, requiring 1-hr to 2.8-hr exposures. However, with a 30-m GSMT, exposures for 1 m/s precision are:

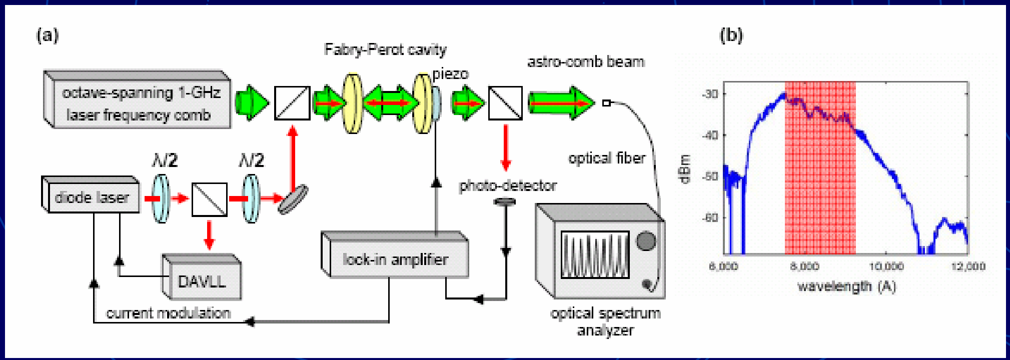
3.3 minutes at *V*=12.0: reaching ~540 nearby M0 stars

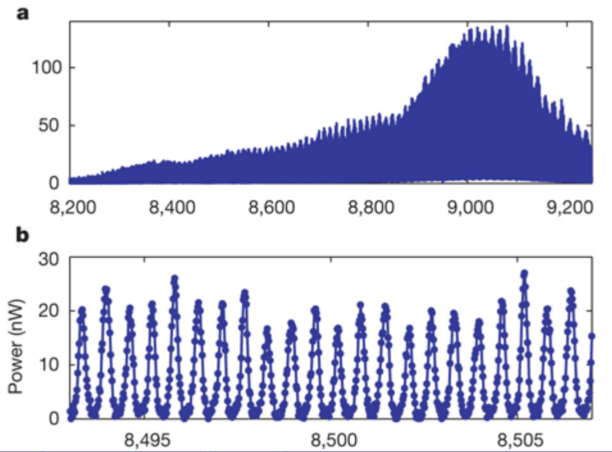
10 minutes at *V*=13.2: reaching ~2260 of the nearest M0-M4 stars

25 minutes at *V*=14.2: reaching ~9000 of the nearest M0-M4 stars

Technology Milestones

- Wavelength calibration
  - Femto-second laser frequency combs





  - Gas absorption cells in NIR
    - Wind currents limit usefulness of telluric lines to 10-30 m/s
    - Possible species: CH_3I, C_2H_2, NH_3, HCN, etc.
- Other hardware issues in NIR to address lack of high resolution and small wavelength coverage

Research and Analysis Goals

- Support research to significantly improve stability of wavelength reference in the optical and NIR (laser comb, gas cells)
- Support design efforts for high-precision Doppler instruments for 20–30-m class telescopes
- Support development of multi-object high-precision instruments
- Support efforts to improve precision of NIR RVs
- Support efforts to understand stellar jitter