# Blue Planets Orbiting Red Dwarfs

**Andreas Quirrenbach**
*and the CARMENES Consortium*

# CARMENES – the Acronym

- **C**alar **A**lto
- High-**R**esolution Search for
- **M** Dwarfs with
- **E**xo-Earths
- With **N**ear-Infrared and Optical
- **E**chelle **S**pectrographs

# The 3.5m Telescope on Calar Alto (Southern Spain)

carmenes

# Why M Dwarfs?

- M dwarfs are very abundant (almost 2/3 of all stars) and thus nearby
  - Excellent targets for follow up
- M dwarfs are small (**<** 0.5 $M_{\odot}$) and faint → "habitable zone" is close to star → relatively large signal → good chance to find Earth-like planets
- Currently no instrument optimized for M stars exists

# Goals and Plan for CARMENES

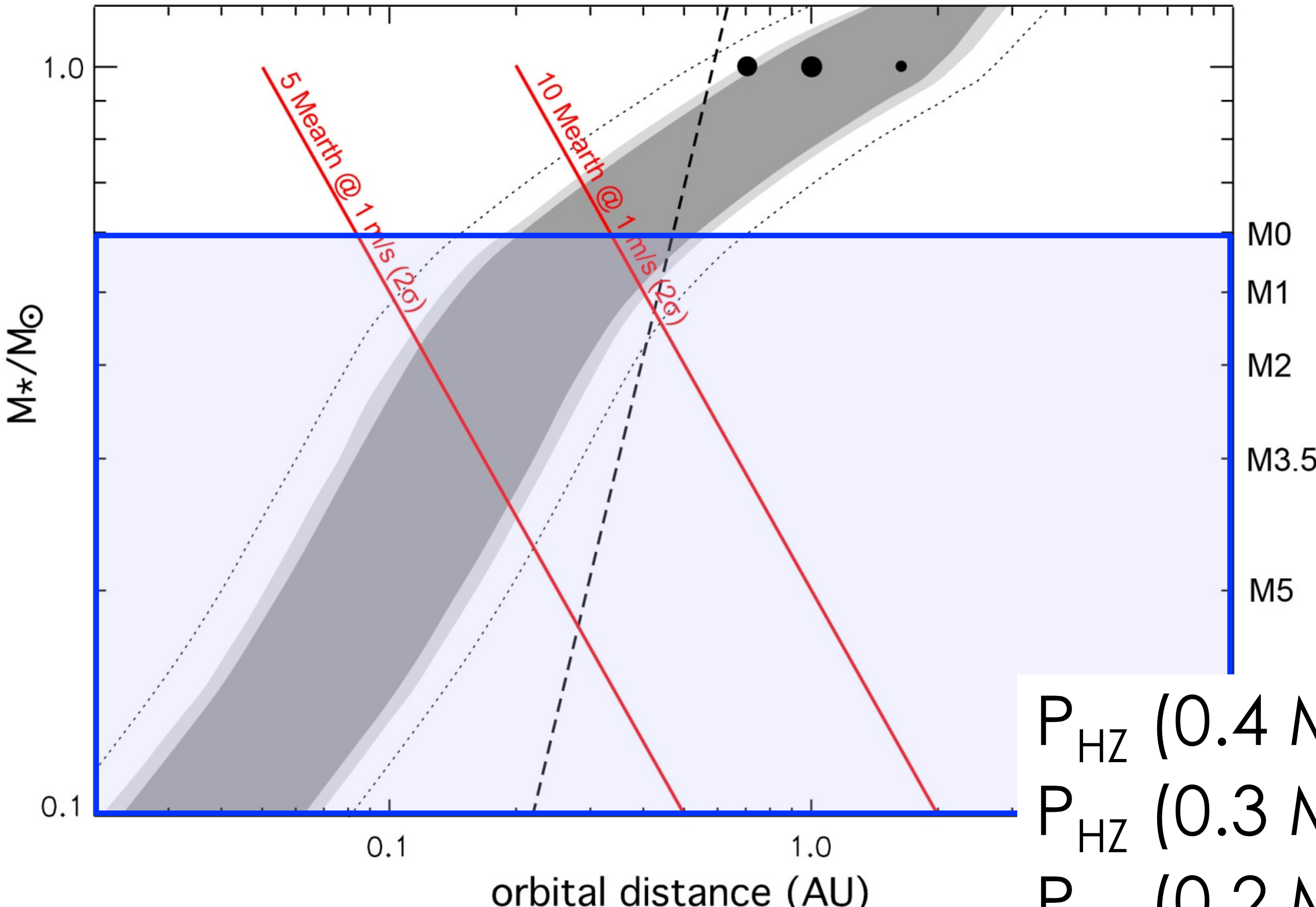
- Search for Earth-like "habitable" planets around low-mass stars (M-stars)
  - Number and formation mechanisms
  - Properties and "habitability"
- Survey of 300 M stars
  - Simultaneously in visible light and near-infrared
- 10 data points per star and year
  - 600 to 750 nights needed
  - Guaranteed in contract with CSIC and MPG

# Key Questions

carmenes

- ~50–100 low-mass planets could be detected; perhaps a few transiting
- Sufficient statistics to assess the overall distribution of planets around M dwarfs
  - Frequency, masses, orbital parameters
- Frequency of ice and terrestrial planets
  - Separations, eccentricities, multiplicities, dynamics
- Very important constraints for models of planet formation and evolution
- “Unique” systems for further characterization

# A "Shortcut": M-Type Dwarfs

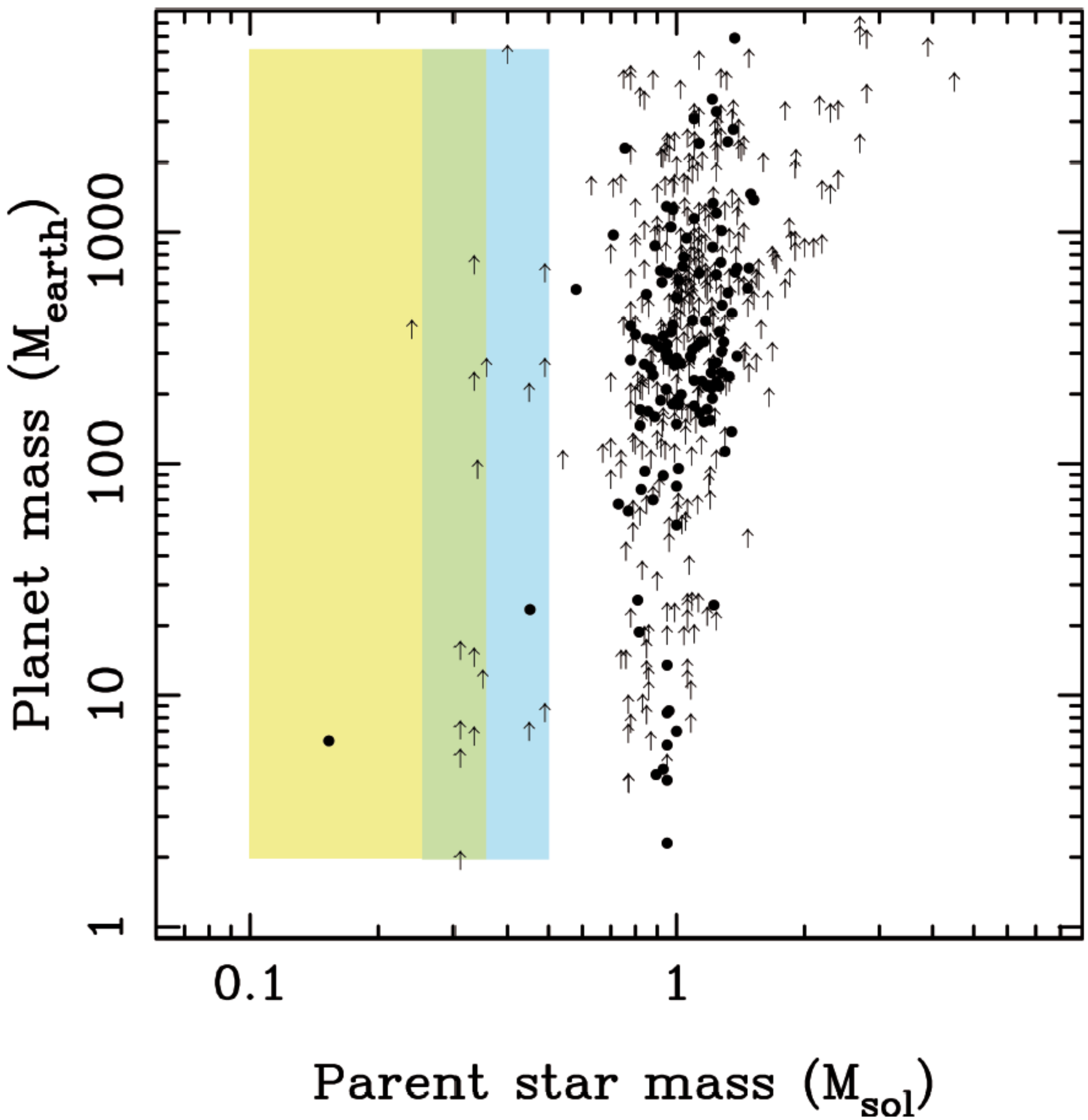



$P_{HZ}$ (0.4 $M_\odot$) = 25 d

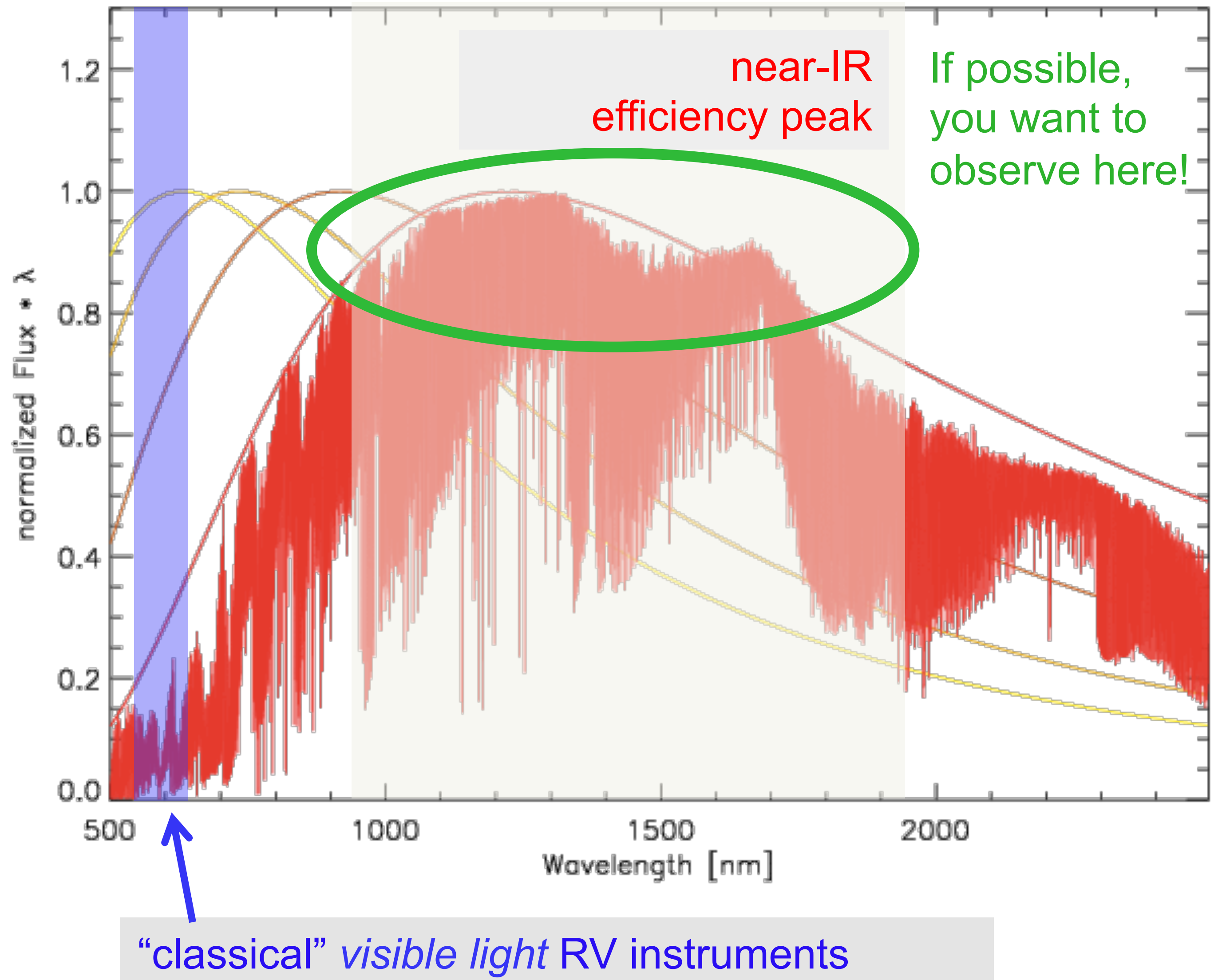
$P_{HZ}$ (0.3 $M_\odot$) = 18 d

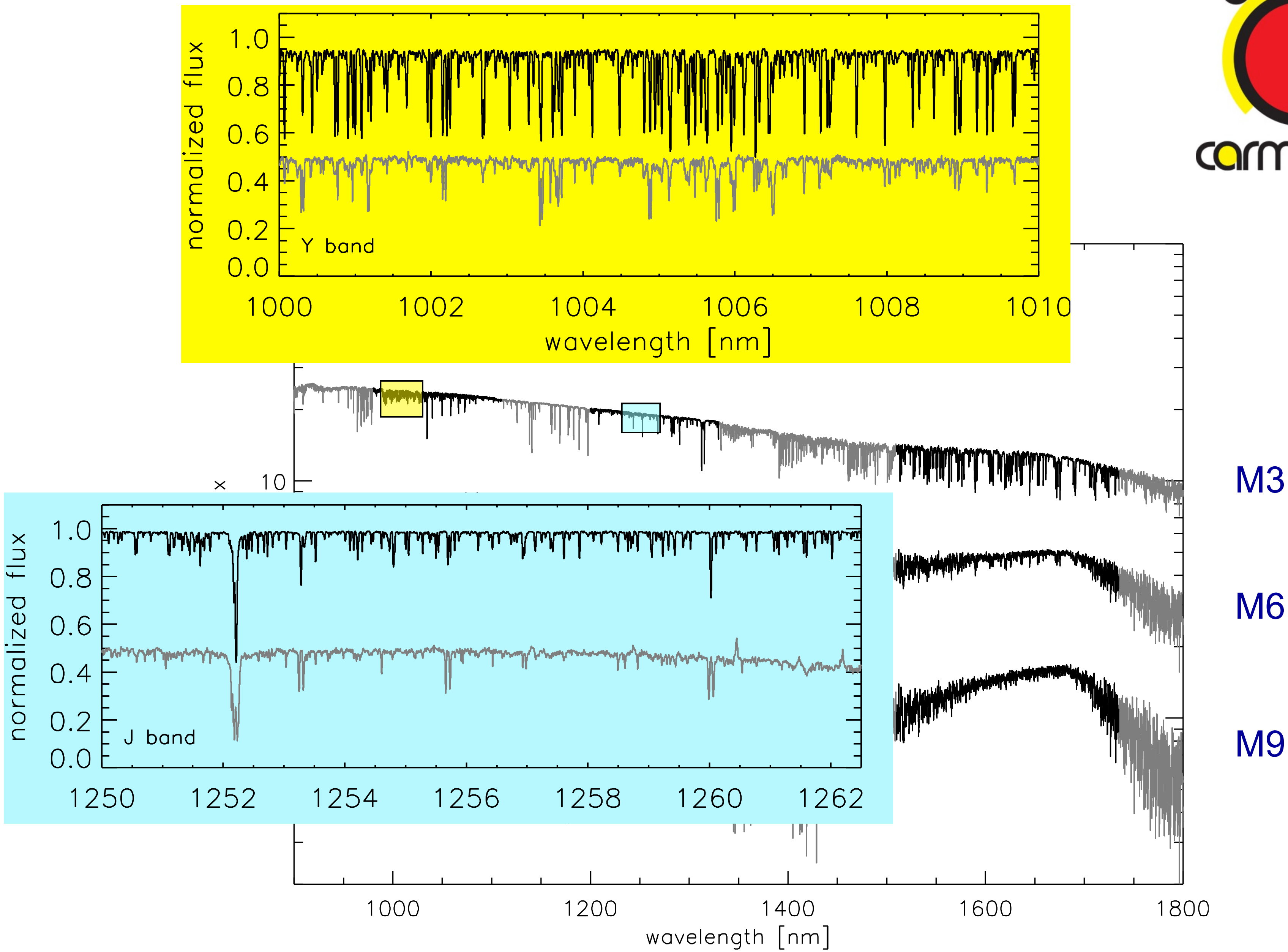
$P_{HZ}$ (0.2 $M_\odot$) = 12 d

# A New Niche



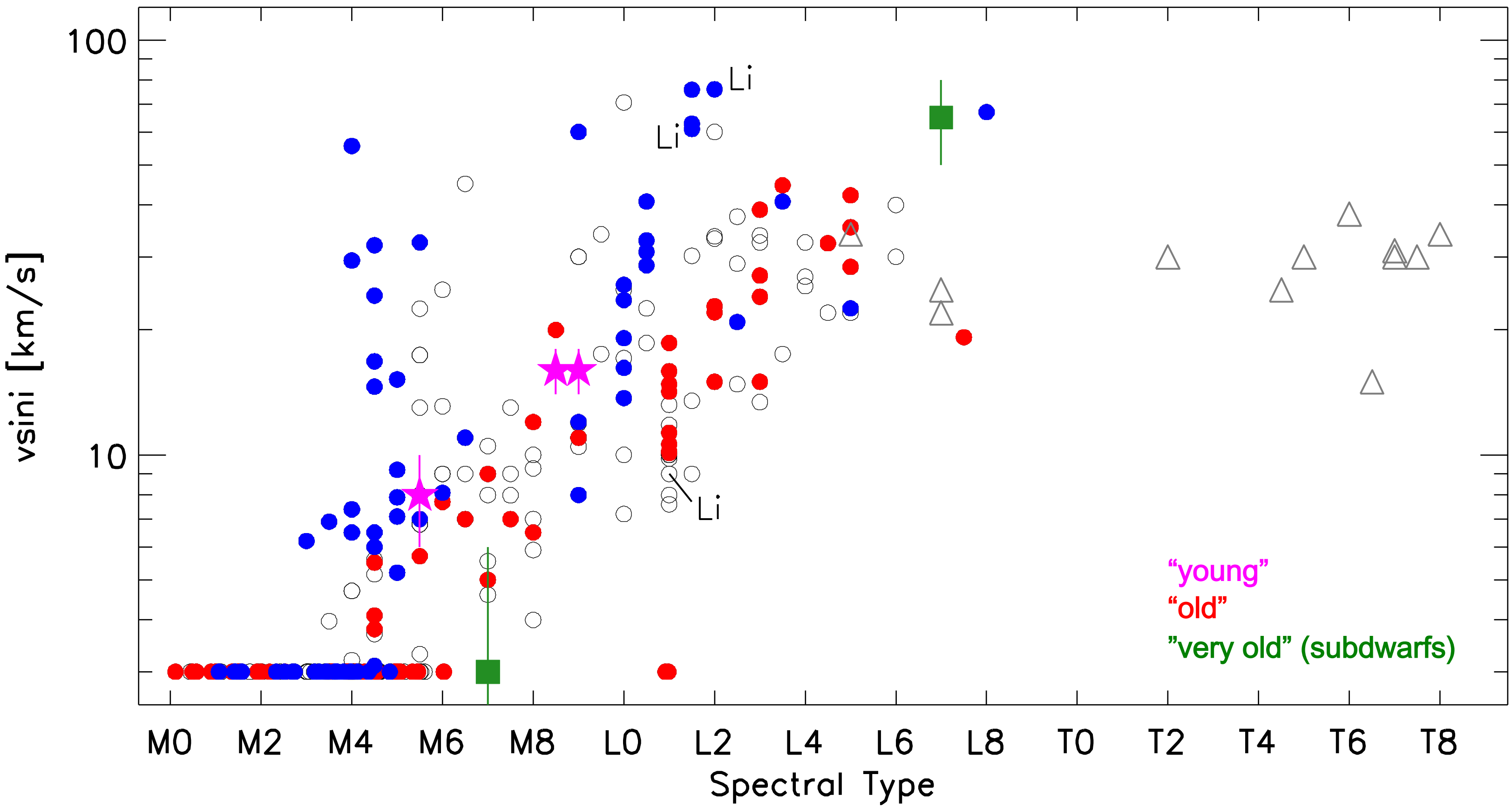
# The SED of M-Type Stars





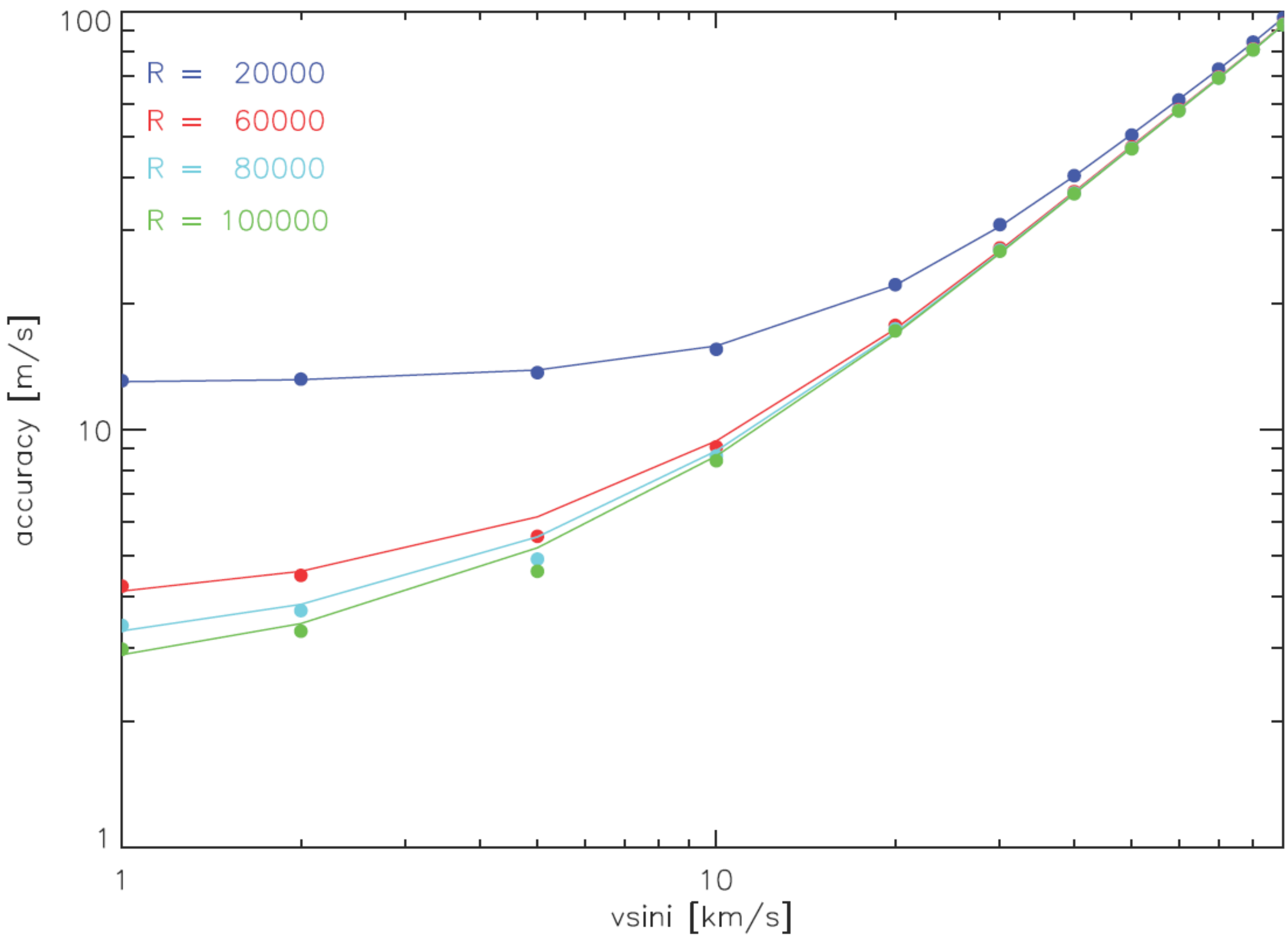

PHOENIX models

# Rotation of M Stars and Brown Dwarfs

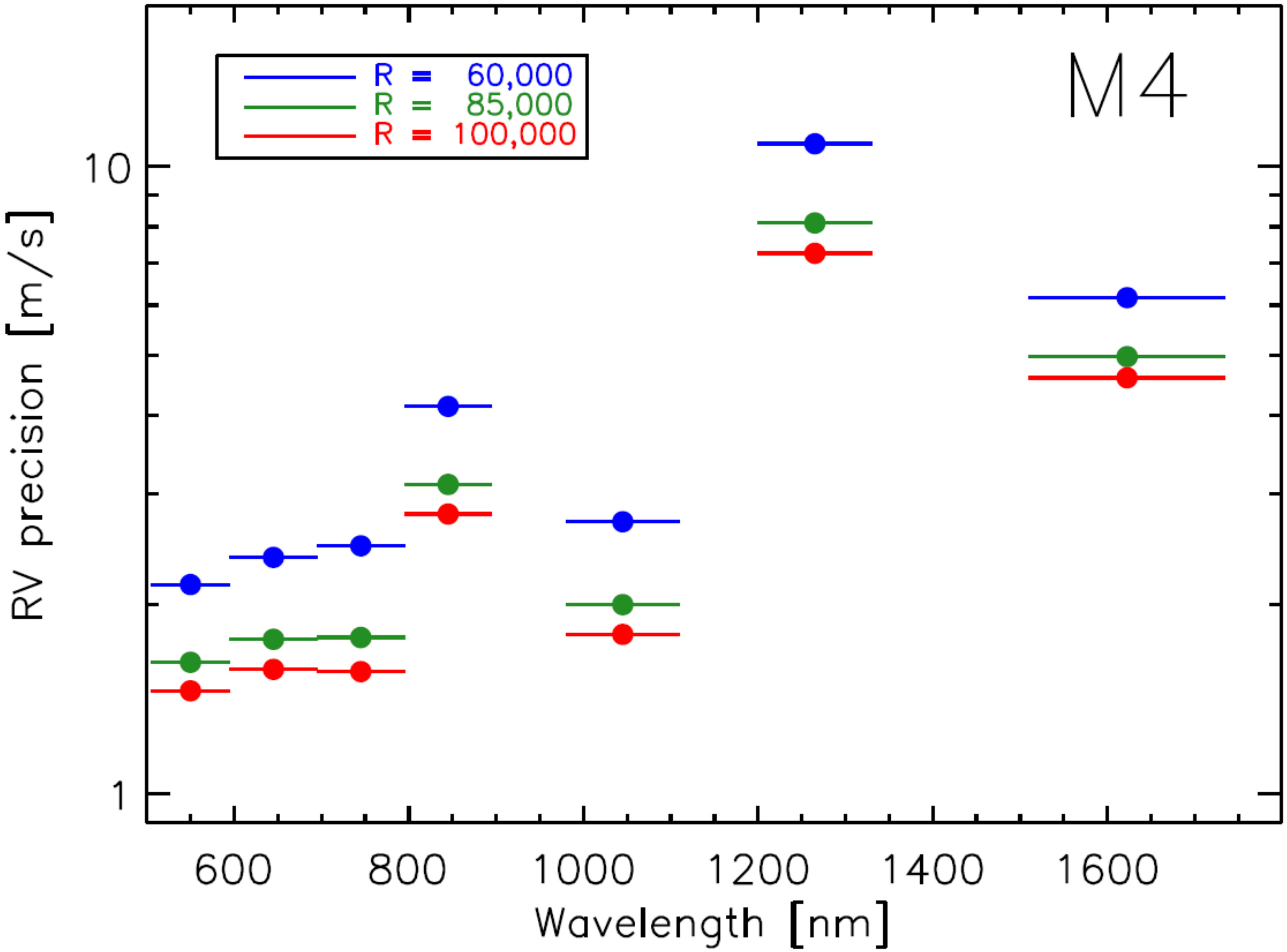



Reiners & Basri, 2008

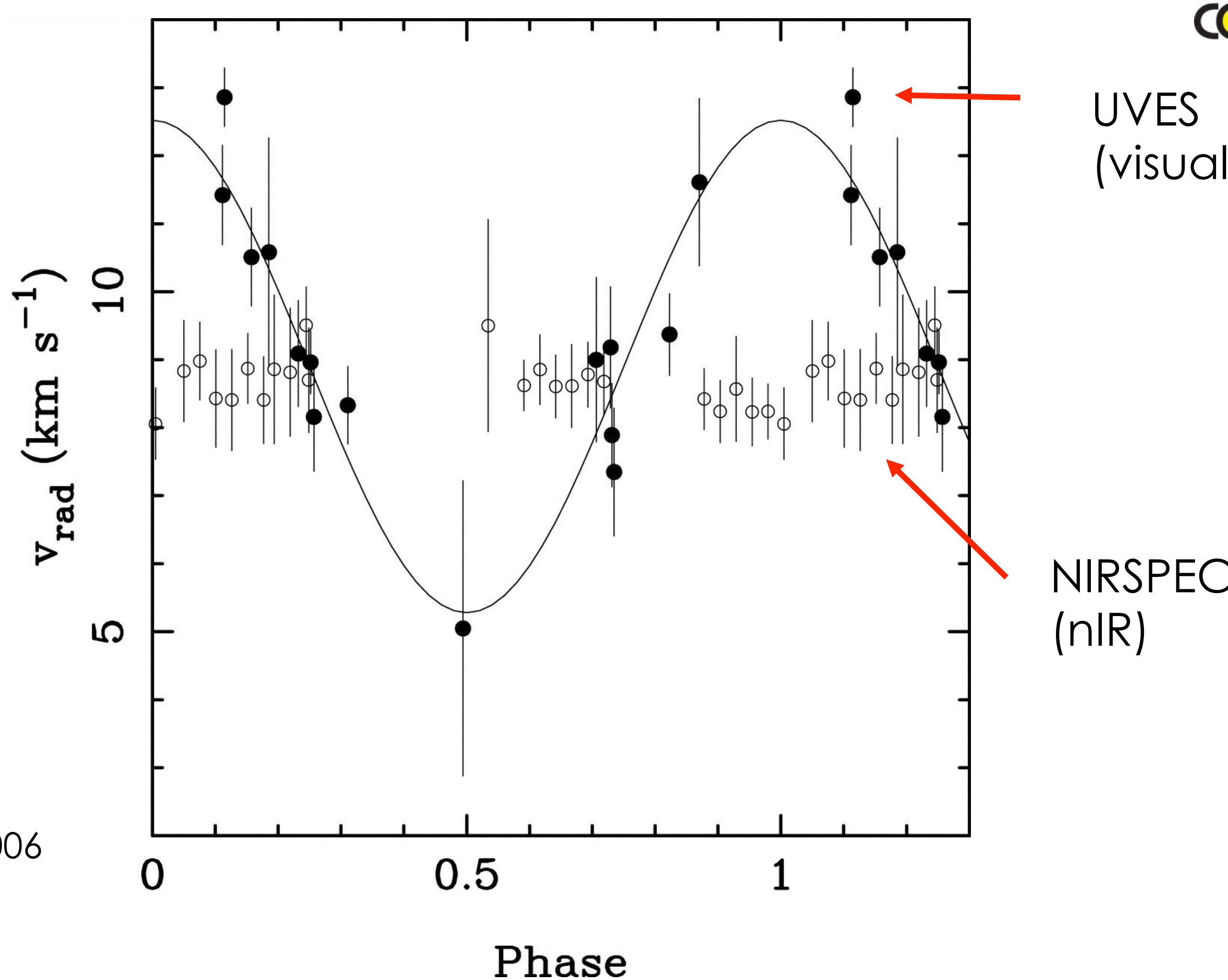
# Precision Achievable for Different Rotational Velocities



# Relative Precision Achievable for M4 Star in Visible and Near-IR



# Let's Talk About jitter




Martin et al. 2006

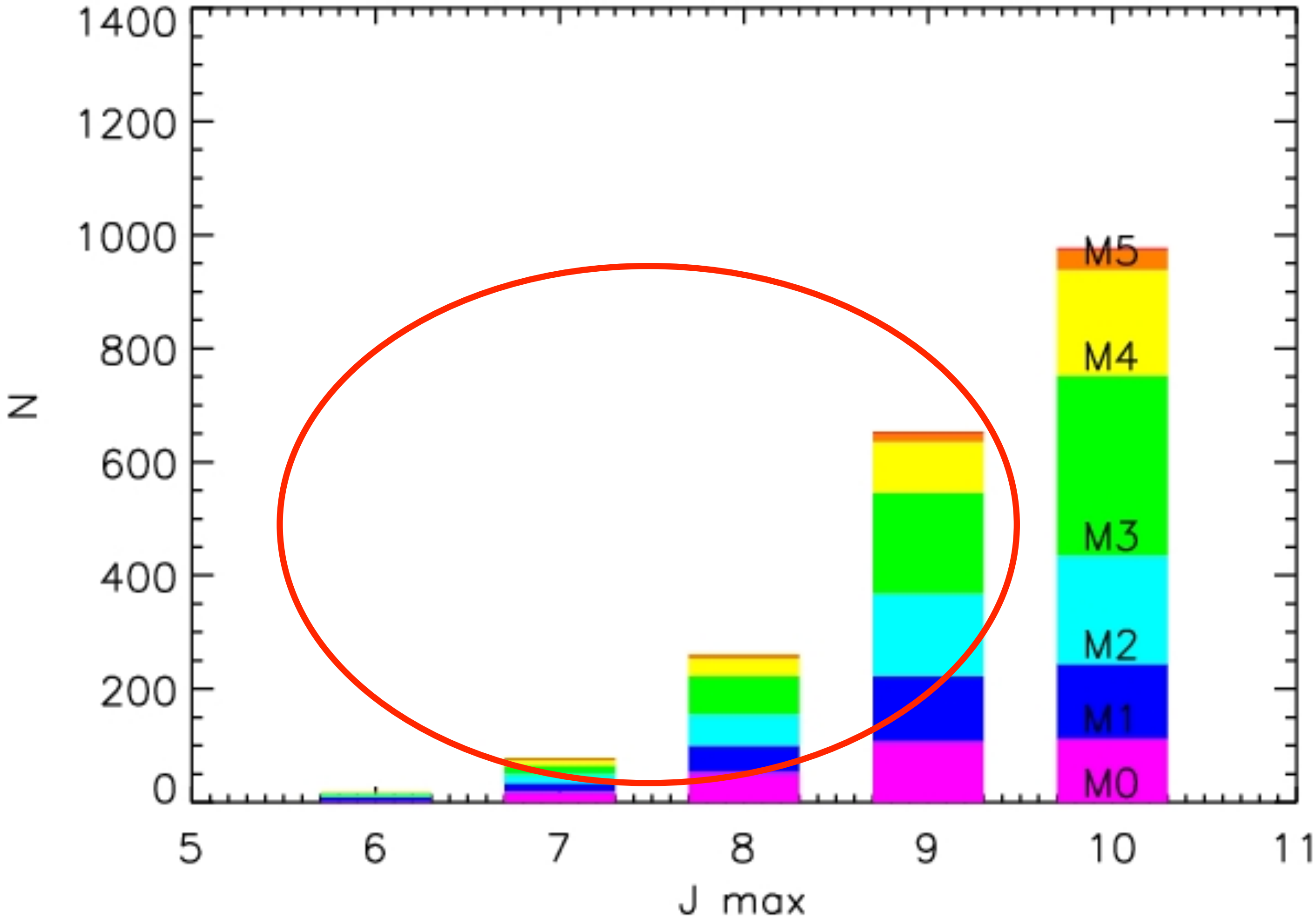
RV curve of the active M9 dwarf LP-944 20

# Observing Strategy

- Start with a larger sample of ~600 stars
- Pre-cleaning (echelle spectra, active stars, fast rotators, binaries) ⇨ 400-450 stars
- Measurements:
    - 3500 for sample clean-up (5-10 per star)
    - 15000 additional for 300 stars (60 each)
    - 4000 additional for 100 stars (100 each)

  ⇨ 22500 measurements
- Time: 15 min + overhead ⇨ 3.5 measurements/hour ⇨ 30 measurements/night ⇨ 750 nights

# Stellar Sample



# Stellar sample

– **S1: 100 stars with M < 0.25 $M_\odot$ (SpType M4 and later)**

– **S2: 100 stars with 0.30 > M > 0.25 $M_\odot$ (SpType M3-M4)**

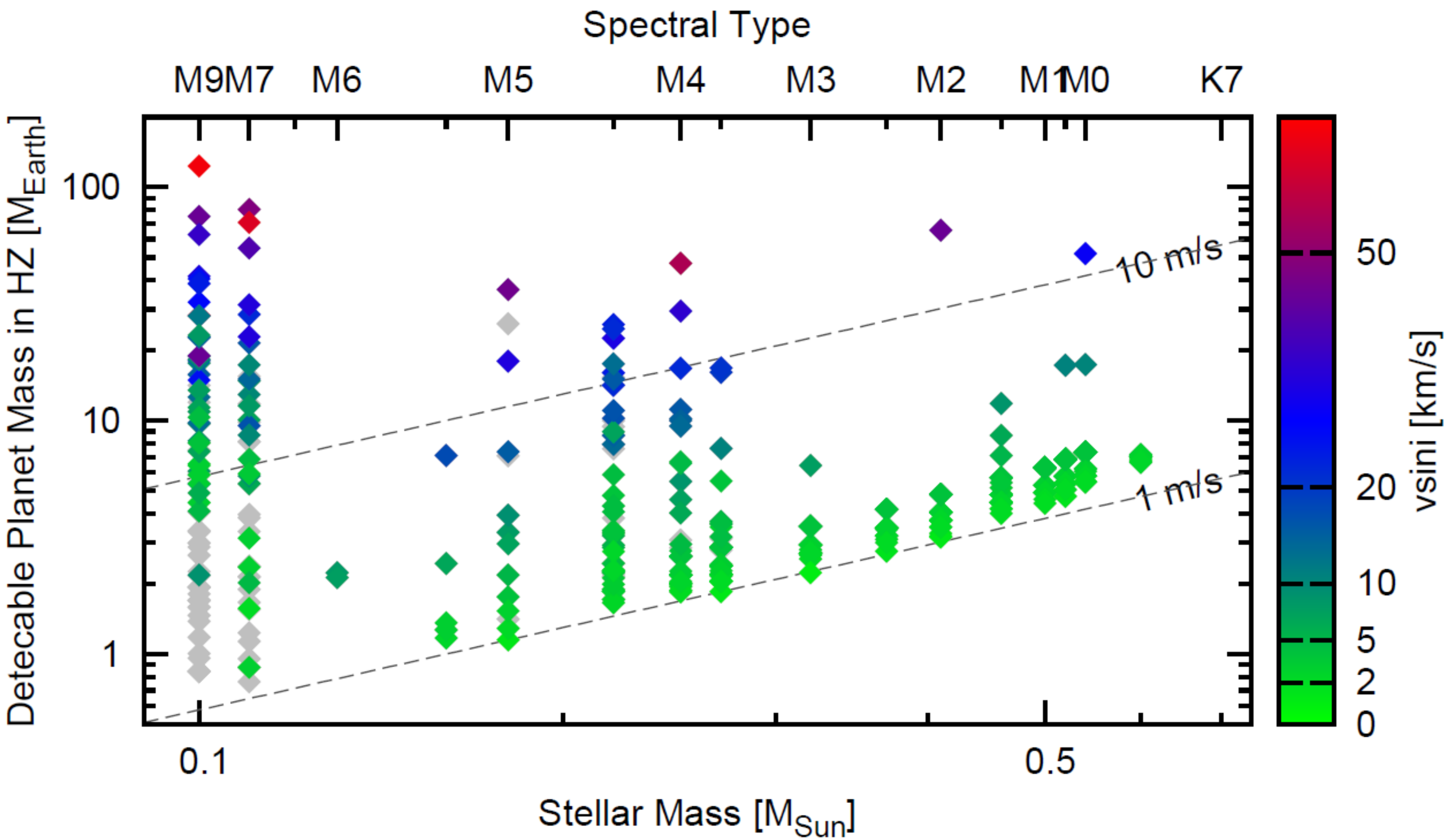
– **S3: 100 stars with 0.60 > M > 0.30 $M_\odot$ (SpType M0-M2; bright)**

carmenes

| Sample | Spectral type | Mass ($M_\odot$) | $J$ | # |
|---|---|---|---|---|
| S1 | ≥M6 | ≤0.15 | ≤10.5 | 12 |
| S1 | M5 & M5.5 | 0.15–0.20 | ≤10 | 35 |
| S1 | M4 & M4.5 | 0.20–0.25 | ≤9.5 | 143 |
| S2 | M3 & M3.5 | 0.25–0.30 | ≤9 | 198 |
| S3 | M2 & M2.5 | 0.30–0.40 | ≤8.5 | 121 |
| S3 | M1 & M1.5 | 0.40–0.50 | ≤8 | 78 |
| S3 | M0 & M0.5 | 0.50–0.60 | ≤7.5 | 55 |

$\langle d_{S1+S2+S3} \rangle = 13$ pc

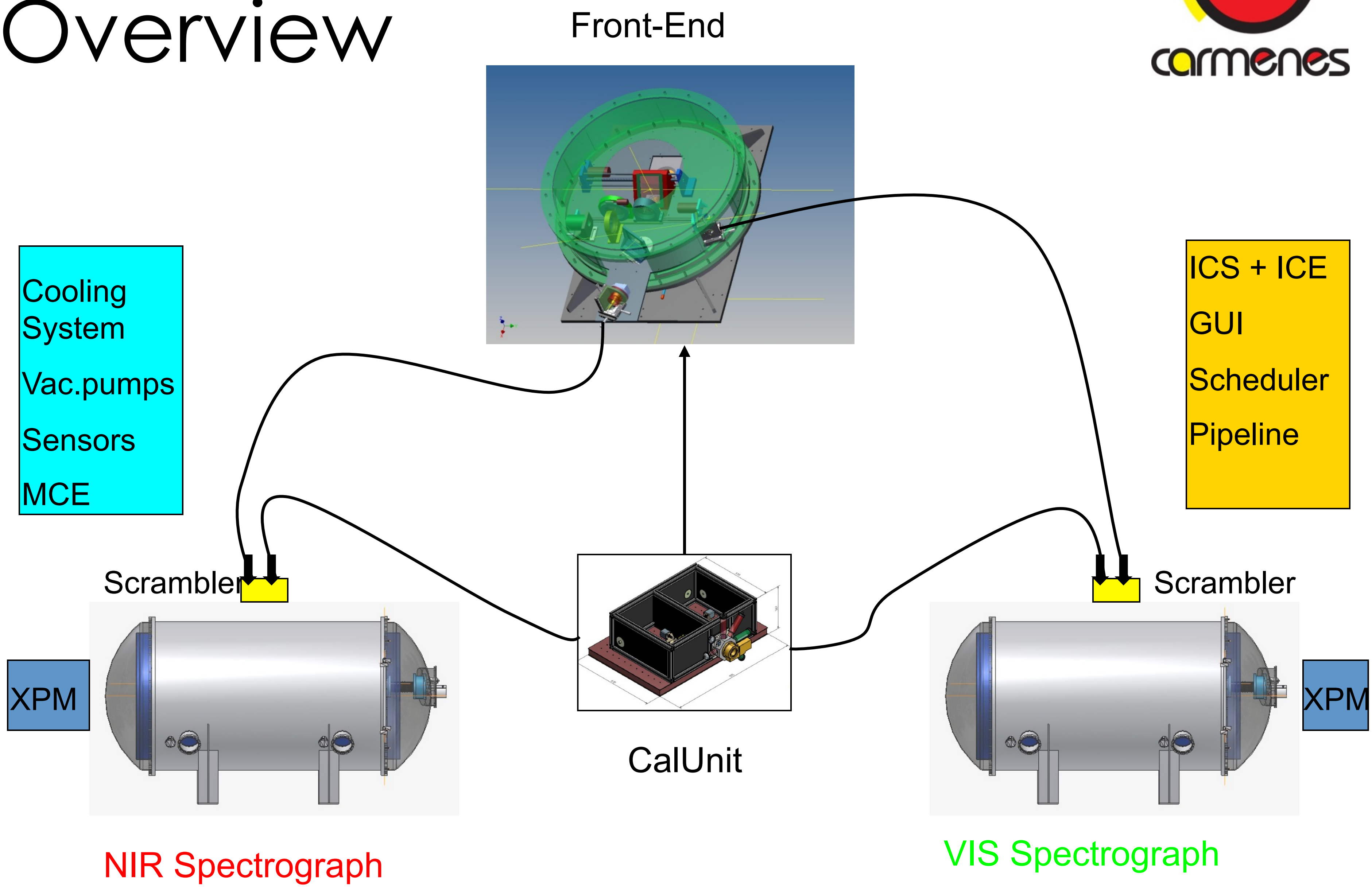
# Detectability Simulations



# Guiding Principles for Instrument

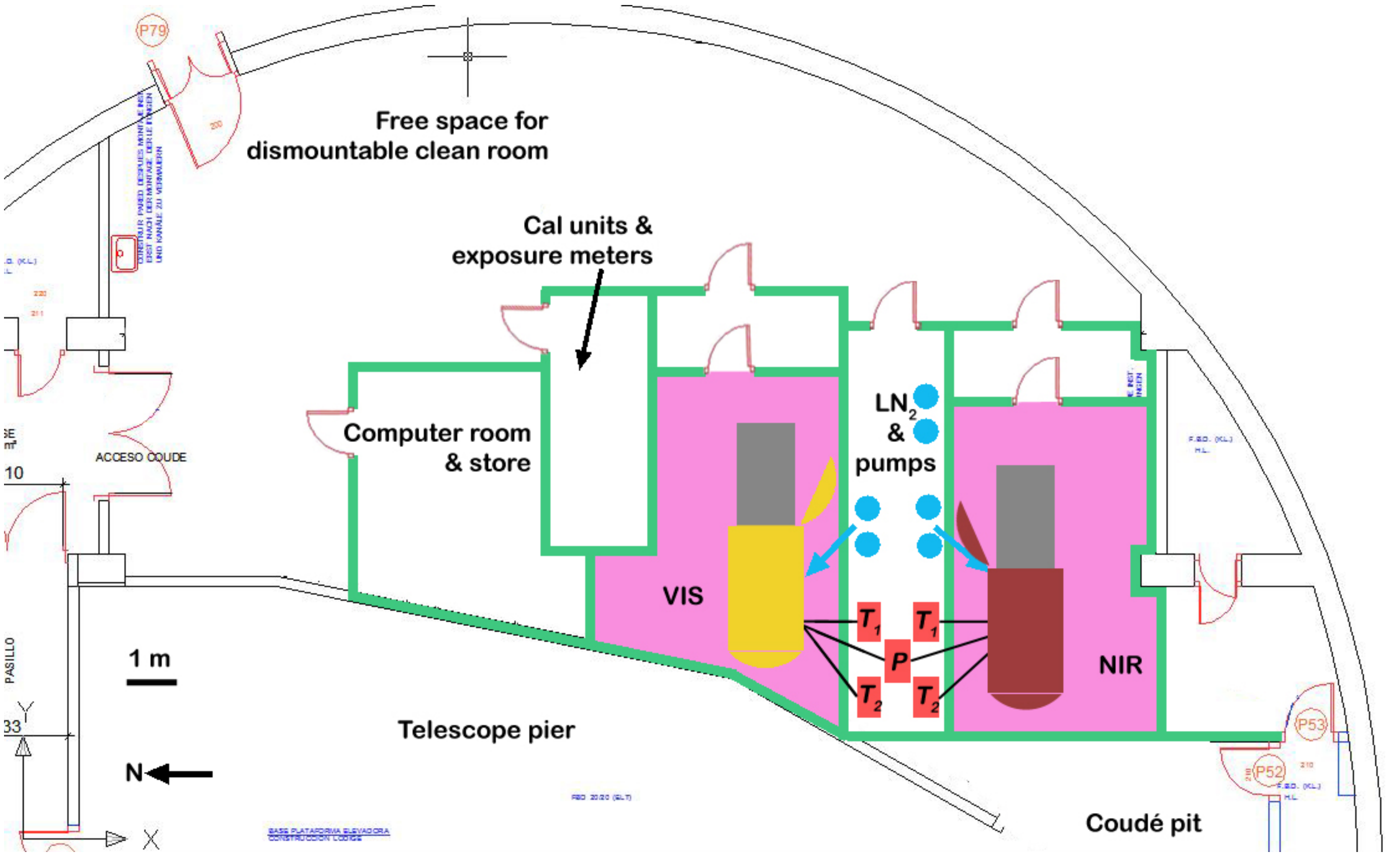
- Single-purpose instrument
  - Design driven by survey requirements
- High stability for terrestrial planet detection
  - Thermal and mechanical stability
  - Stable input
  - No moving parts in spectrographs
- High resolution for slow rotators
- Large wavelength coverage for discrimination against intrinsic variability
- High efficiency for faint stars

# Instrument Overview



# Instrument Location

- 1 Climatic room for each channel.
- Environmental conditions: 285-288 ±1 K.



# Properties of Spectrographs

- Optical spectrograph
  - 0.53 … 1.05 $\mu$m, R = 82,000
  - Precision ~1 m/s
  - Vacuum tank, temperature stabilized
  - 4k x 4k deep depletion CCD detector
- Near-Infrared spectrograph
  - 0.95 … 1.7 $\mu$m, R = 82,000
  - Vacuum tank, cooled to 140K, stabilized
  - Precision goal 1 m/s
  - Two 2k x 2k Hawaii 2.5 µm detectors

# The NIR Requirements Dilemma

- We want:
  - High resolution
  - Good sampling (Nyquist)
  - Large wavelength coverage (0.95…1.7 $\mu$m)
  - No gaps between orders
  - Large inter-order spacing (cross-talk!)
  - High SNR
- We have:
  - 2 x 2048 x 2048 pixels
  - Non-uniform sampling
  - Non-uniform order spacing
  - Non-uniform efficiency (blaze function!)
- We need to compromise!

# Spectrograph Layout

**White pupil fiber-fed echelle spectrograph**

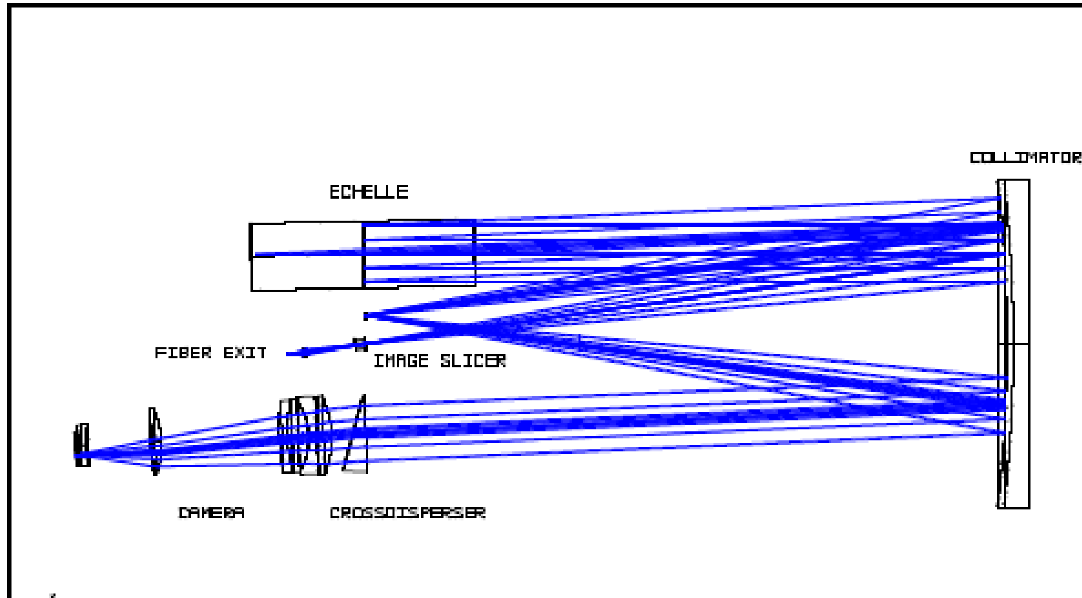
FiberExit-FNoptics-Slicer

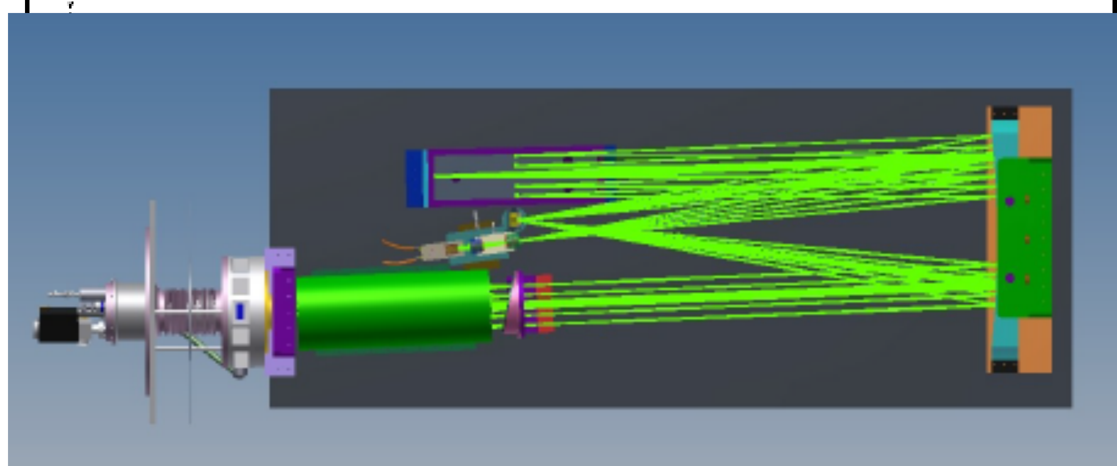
Single-piece Collimator (3passes)

R4 Echelle grating

Grism cross-disperser

Dioptric camera



# Spectrograph and Vacuum Tank Layout

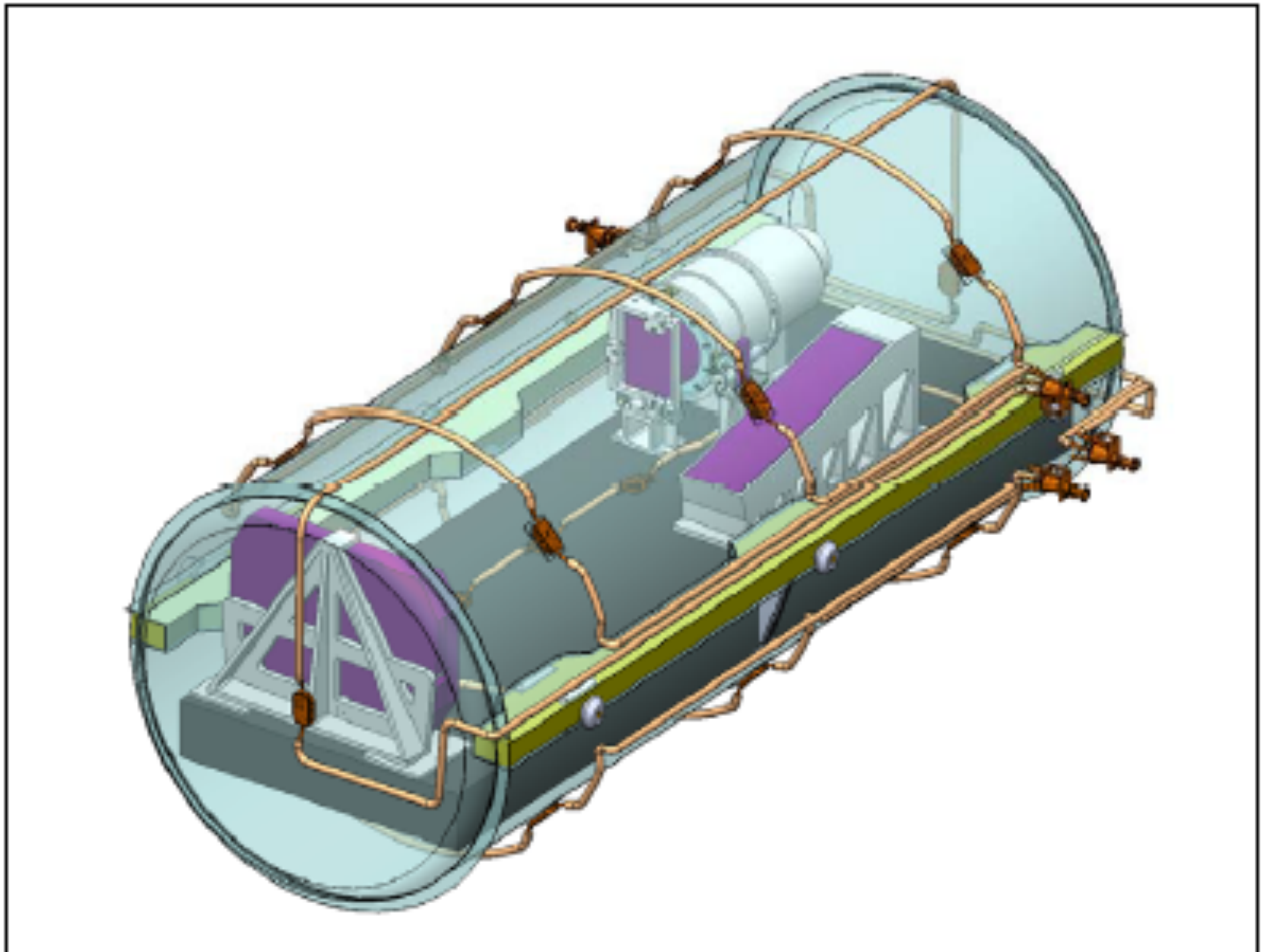
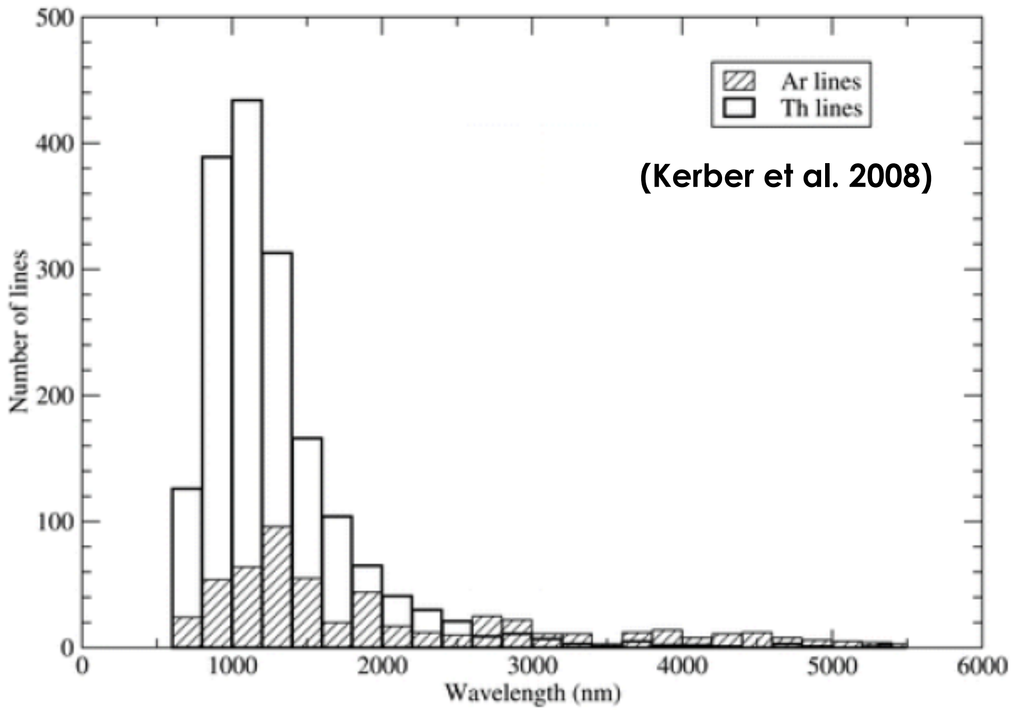
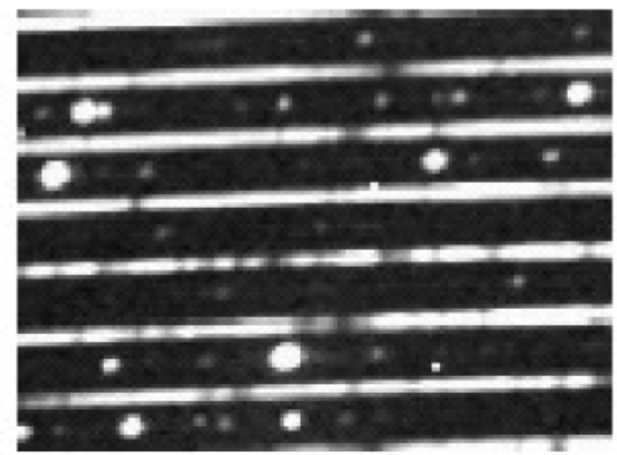


Figure 2. General view of the CARMENES NIR Optical Bench fully assembled.

# Calibration: Wavelength Reference

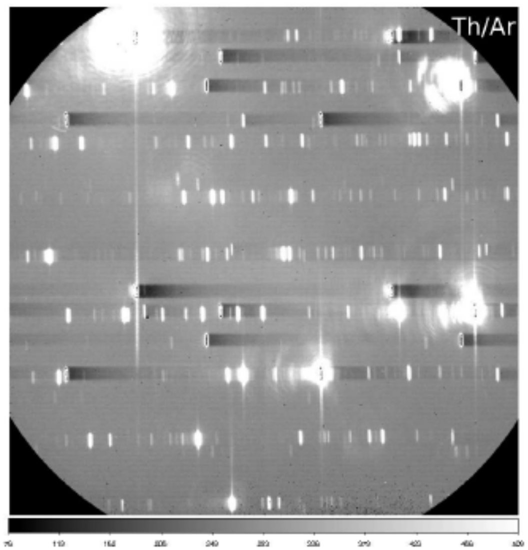
- Hollow cathode lamps: Thorium-Argon-Neon for daily and master calibrations.

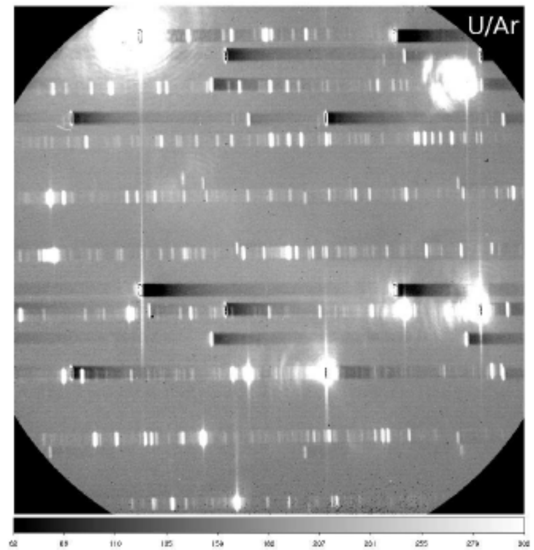


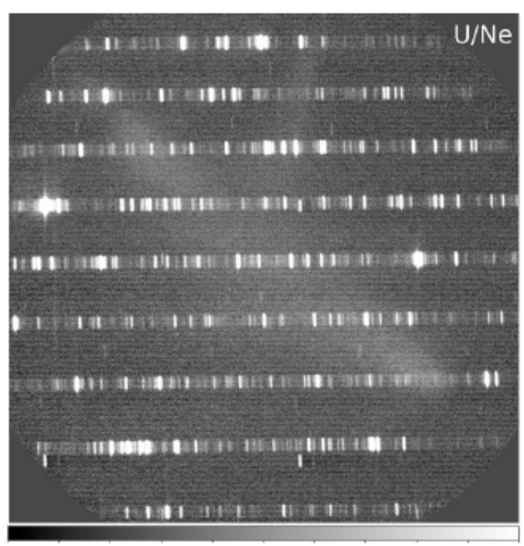



Enough suitable Th-Ar lines in the NIR range

# Comparison of Th/Ar, U/Ar and U/Ne Lamps

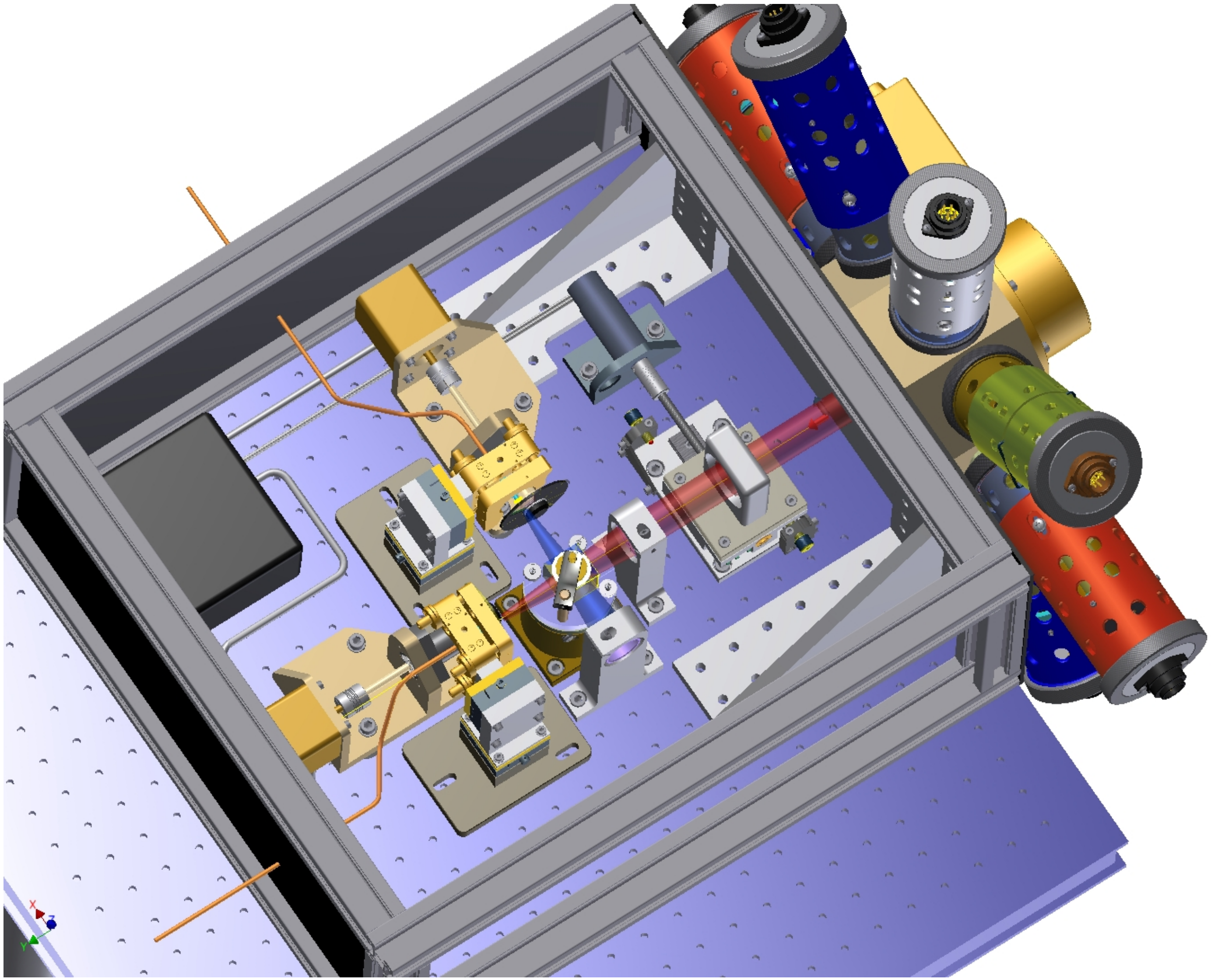



Redman et al. 2011

# Calibration Unit

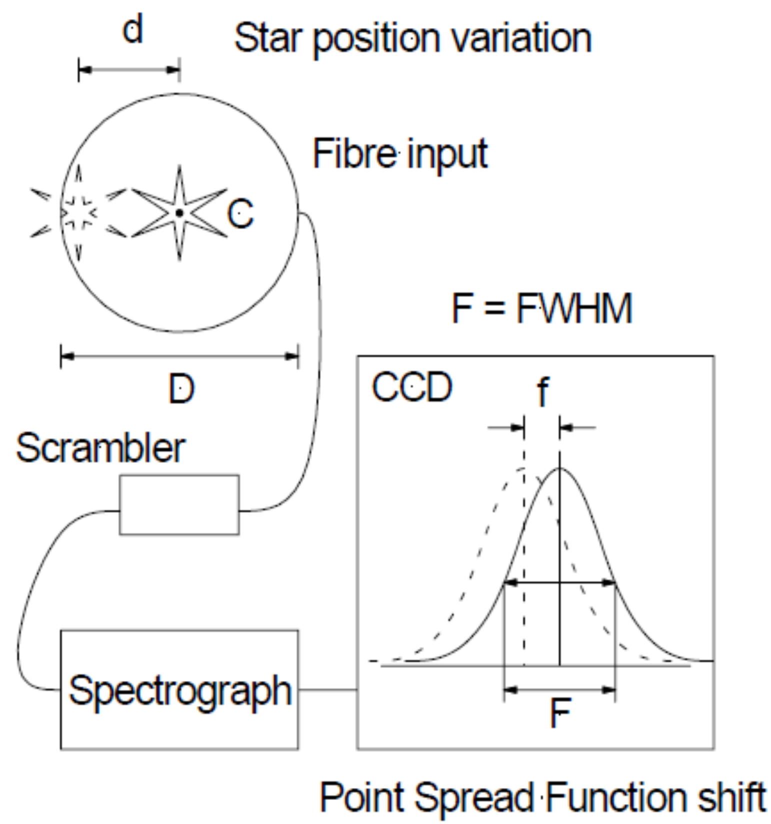


# Requirements for RV Precision

Stable slit illumination and instrument are required for high RV precision.

–Highly stable injection of light in the fibre (guiding ~0.1")

–Image scrambler or octagonal fiber




Avila & Singh (2008)

# Near Field and Far Field Scrambling

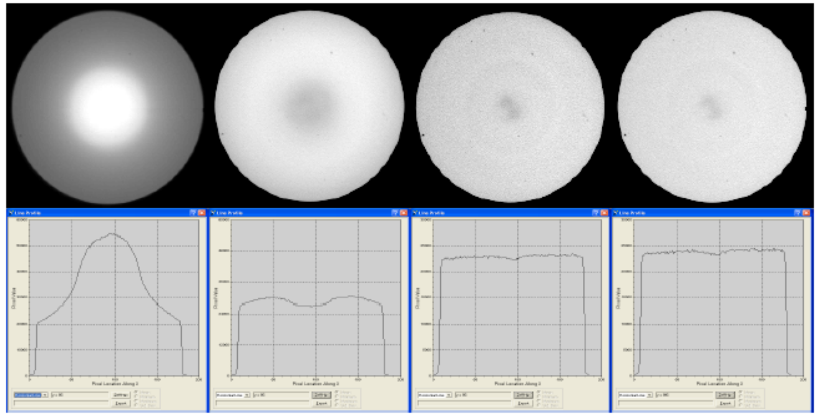


Figure 3. Near field scrambling patterns in a 600 µm, 3 m FVP fibre. From left: a 250 µm spot is centred on the fibre. The spot is shifted by 175 µm. The spot is in the centre but the fibre is squeezed with ΔFRD = 20%. The spot is shifted by 175 µm and fibre squeezed.

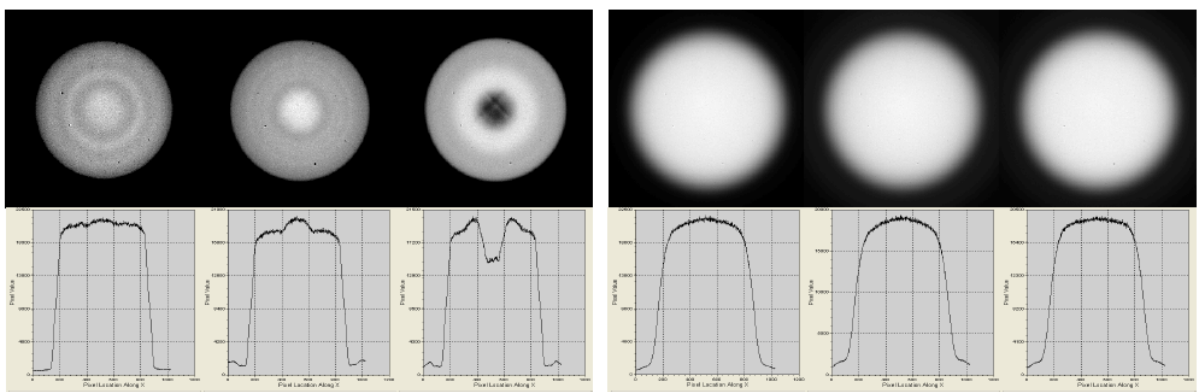
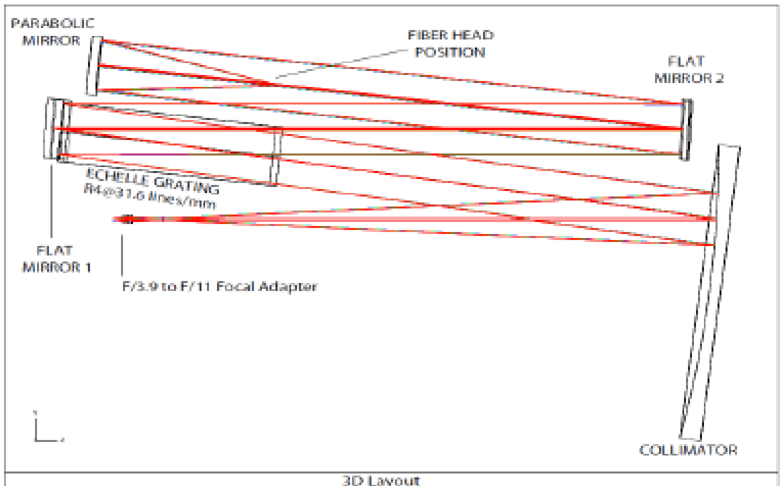
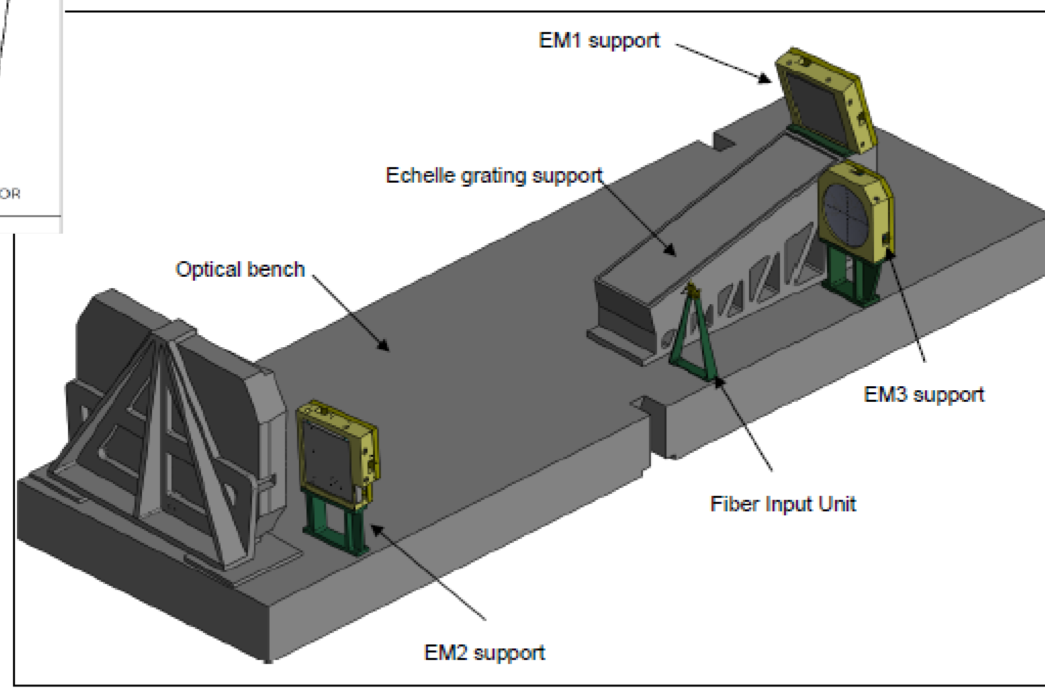


Figure 13. Far field patterns from a WF 200x200/420 N CeramOptec 3 m fibre. Spot size: 150 µm, input aperture beam: F/2.3. Three pictures left: the fibre is free and the spot is at the centre, +50µm and -50µm. The three on the right, the fibre is squeezed (ΔFRD=5%) and the spot is at the centre, +50µm and -50µm

# Exposure Meters

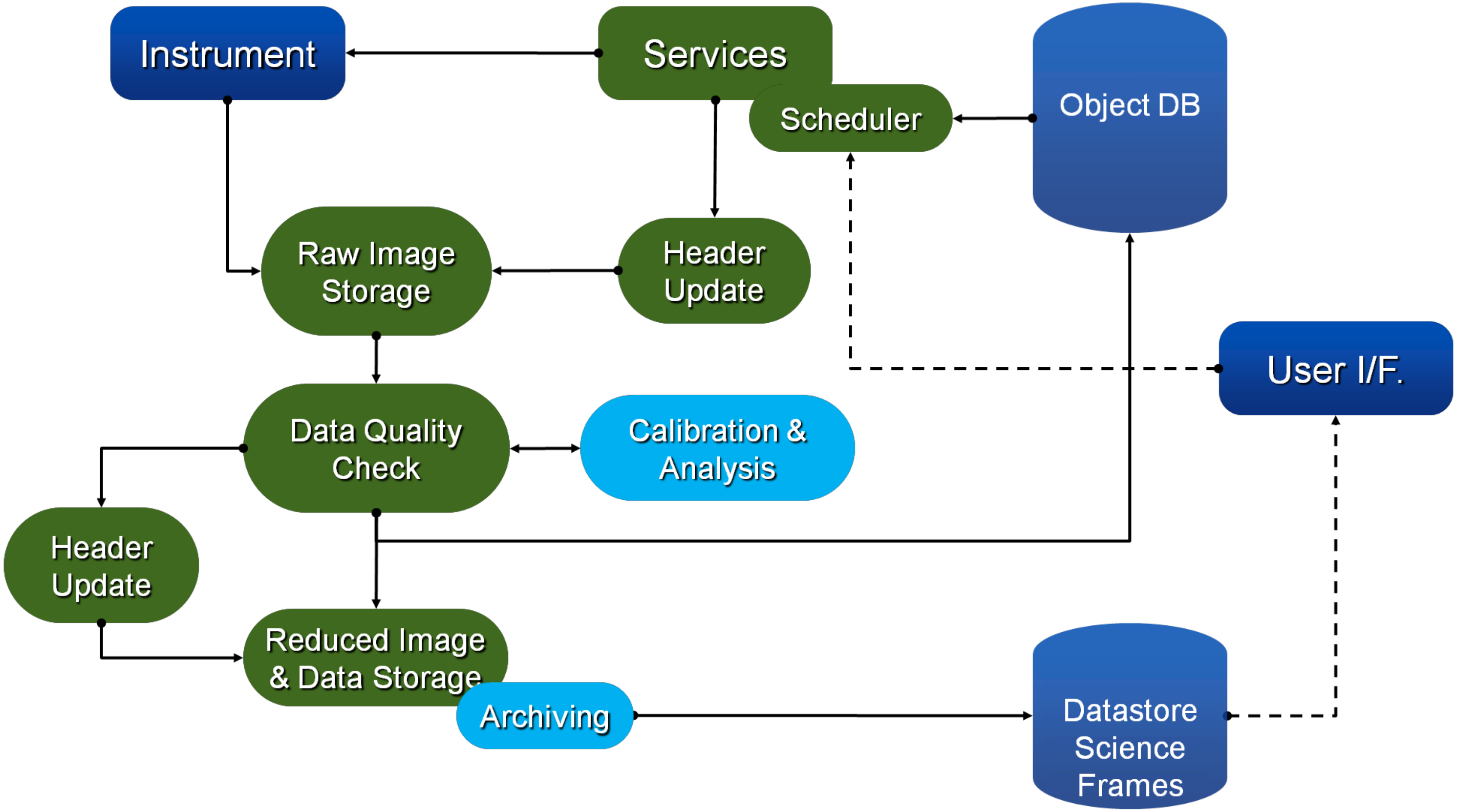



Off-axis system to pick-up 0th order from échelle

Fiber link to Hamamatsu PMTs located outside the instrument vessel

# Data Processing



# Data Pipeline

- Deliverables:
  - Fully reduced, wavelength-calibrated 1D spectra
  - High precision (differential) radial velocities
  - Activity indicators
- Objectives:
  - Automatic pipeline installed:
    - On site (on-the-fly reduction for quality control)
    - Off site (daily reduction for science quality; re-processing of archive data with new pipeline versions)
  - Two separate pipelines for the VIS and NIR arm with similar structure and shared software packages
  - Minimal interaction with the user

# RV Error Sources

| Error source | Contribution | Comment |
|---|---|---|
| Drift measurement with sim. arcs | < 0.2 m/s | ~ 300 arc lines typically > 60 s |
| Wavelength calibration | < 0.1 m/s | > 1000 arc lines during daytime calibration |
| Instrument SRF measurement | < 0.3 m/s | > 1000 arc lines during daytime calibration |
| Photon-weighted centre of integration time | < 0.1 m/s | Median sky conditions (1m/s corresponds to 30s) |
| Opto-mechanical stability | < 0.3 m/s | < 0.1 pixel drift during an observation |
| Centring and guiding | < 0.3 m/s | Spatial scrambling of fibre and CCD guiding |
| Background subtraction | < 0.1 m/s | Stability of background, dark current, bias etc. |
| **Total non-source noise** | **< 0.6 m/s** | RMS |
| | | |
| Source photon noise | 0.8 m/s | $m_Y$=10.5 M6 V ($v\sin i$=5 km/s) at 10 pc S/N=150 in 14 min |
| Source radial velocity jitter | (0-20 m/s) | Sources will be selected for minimum radial velocity jitter |
| Atmospheric noise | ~0.5 m/s | |
| Total noise (1 σ) | **1.1 m/s** | For typical M6 V star at 10 pc (no radial velocity jitter) |

Wavelength calibration

Exposure meter

Current approach: do the best

Scrambling

Reduction strategy

Scrambling

*RV error sources from Barnes & Jones, UKIRT planet finder.*

# Agreement with MPG and CSIC

- MPG and CSIC will operate the 3.5m telescope from 2014 through 2018
- CARMENES will receive at least 600 useable nights
- An additional 150 nights will be allocated if all goes well

# The CARMENES Consortium

- Landessternwarte Königstuhl, U Heidelberg, Germany
- Insitut für Astrophysik, U Göttingen, Germany
- MPI für Astronomie, Heidelberg, Germany
- Thüringer Landessternwarte, Tautenburg, Germany
- Hamburger Sternwarte, U Hamburg, Germany

- Instituto de Astrofísica de Andalucía, Granada, Spain
- Universidad Complutense de Madrid, Madrid, Spain
- Institut de Ciències de l'Espai, Barcelona, Spain
- Instituto de Astrofísica de Canarias, Tenerife, Spain
- Centro de Astrobiología, Madrid, Spain

- Centro Astronómico Hispano-Alemán

# Time Line

| | |
|---|---|
| Official Start | 11/2010 |
| Preliminary Design | to 07/2011 |
| Final Design | 07/2011 – 12/2012 |
| Construction | 01/2012 – 06/2014 |
| Commissioning | 07/2014 – 12/2014 |
| Data Taking | 01/2015 – 12/2018 |