Observing Variable Objects

Lecture 8

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November 13

Outline

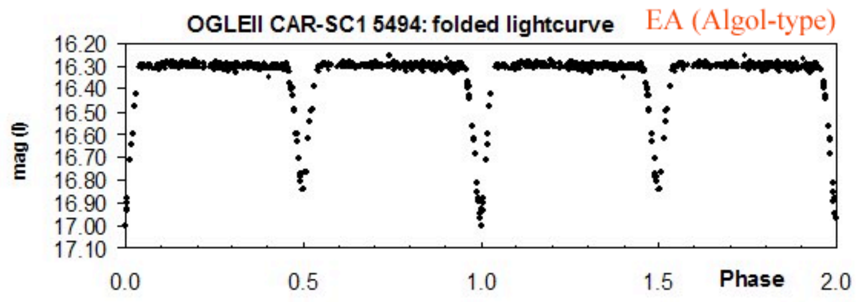
- Examples of astrophysical variability
- Key observational requirements

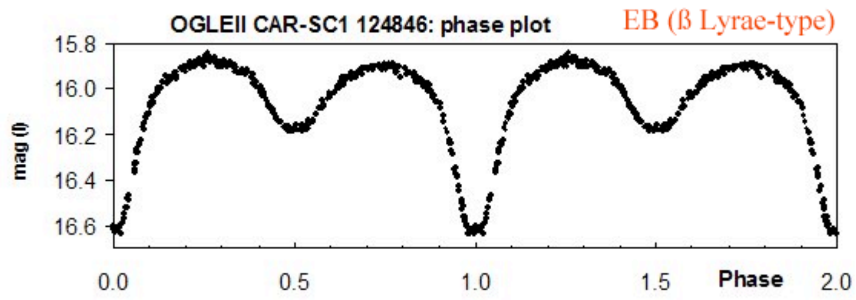
Astrophysical variability

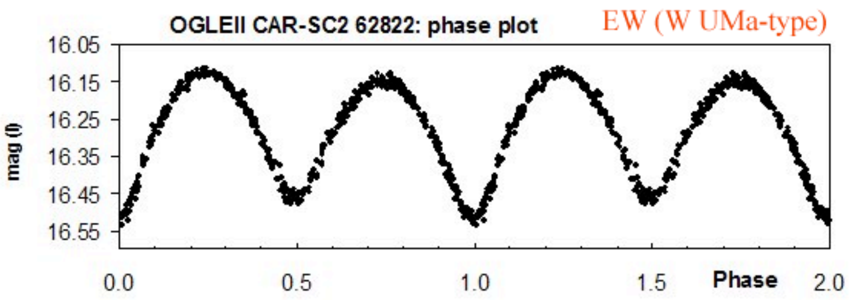
- Binary stars and exoplanets
- Star spots
- Stellar pulsations
- Transients
- Cosmology

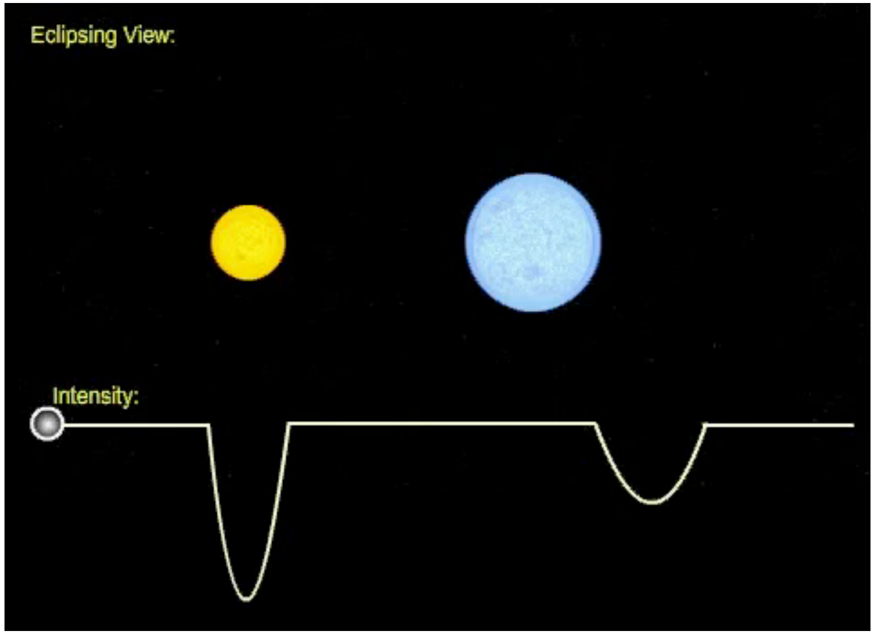
Eclipsing binaries

The only source of model-free stellar parameters





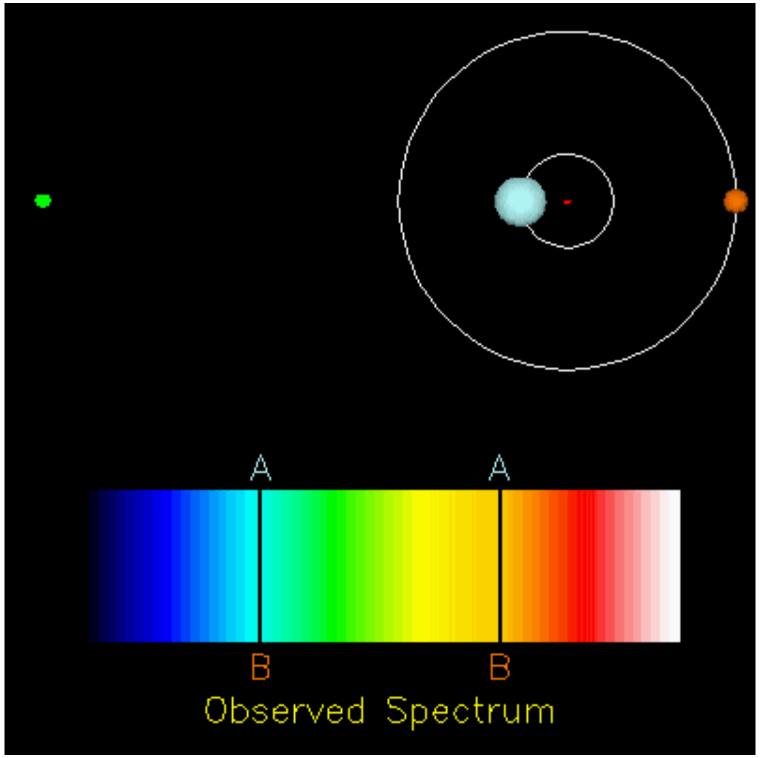


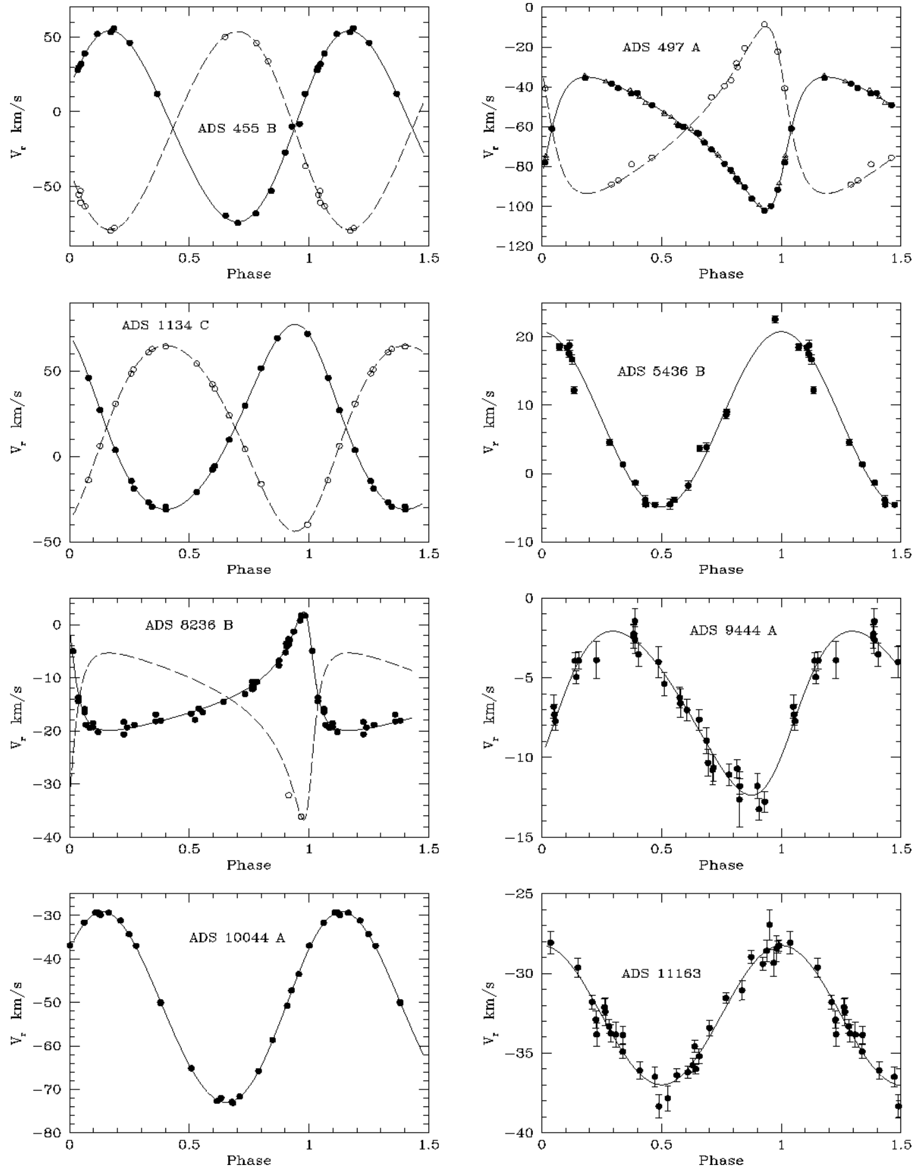


Periods <u>0.5-100 d</u>

Photometric amplitudes ~<u>0.1-1.0 mag</u>

Spectroscopic binaries

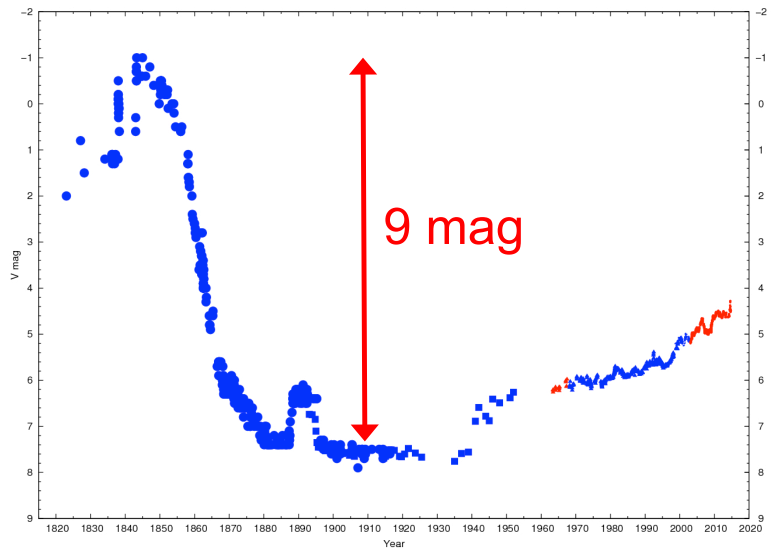


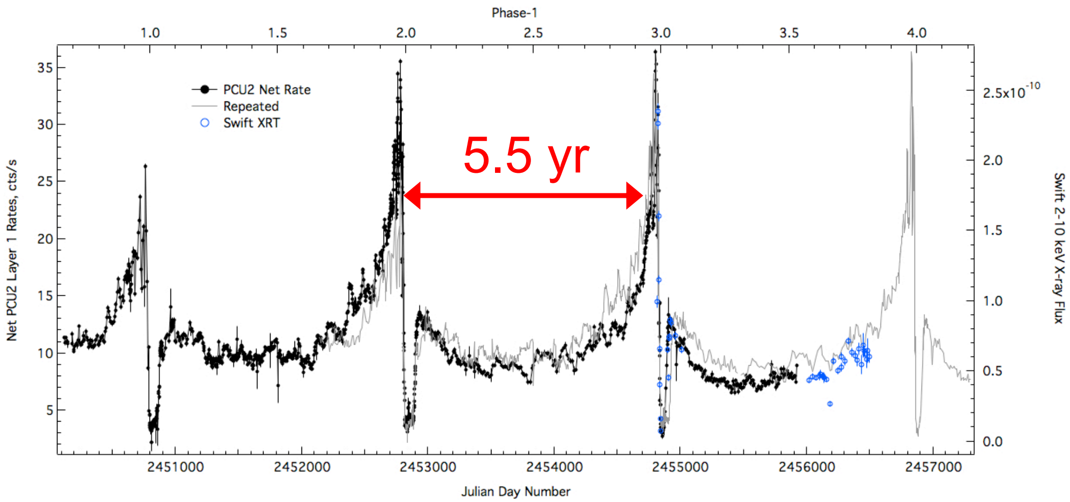


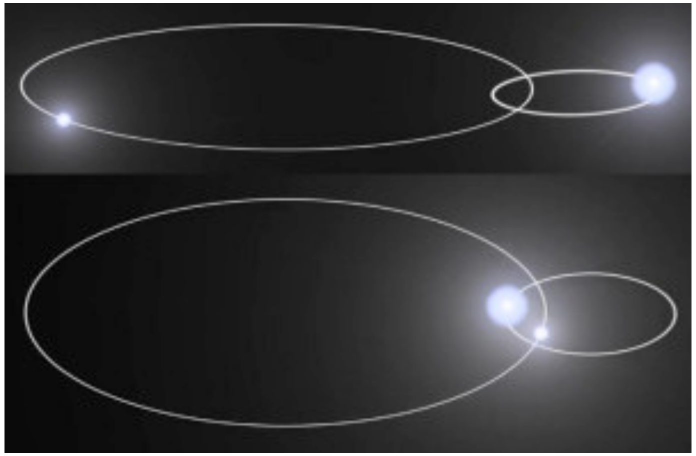
RV amplitudes ~1-100 km/s

Long-period binaries

Eta Car: erupting massive binary, P_{orb}=5.5 yr

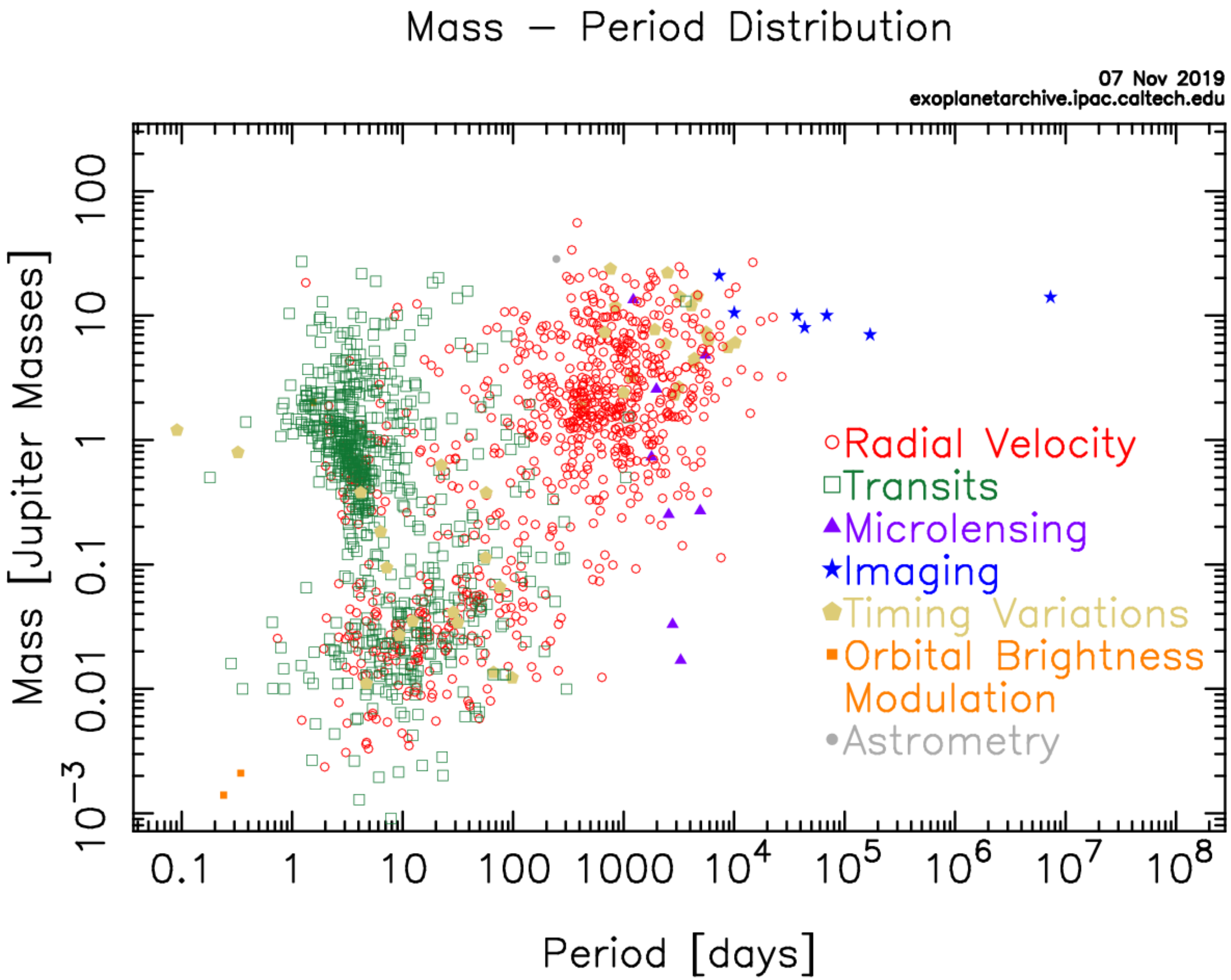






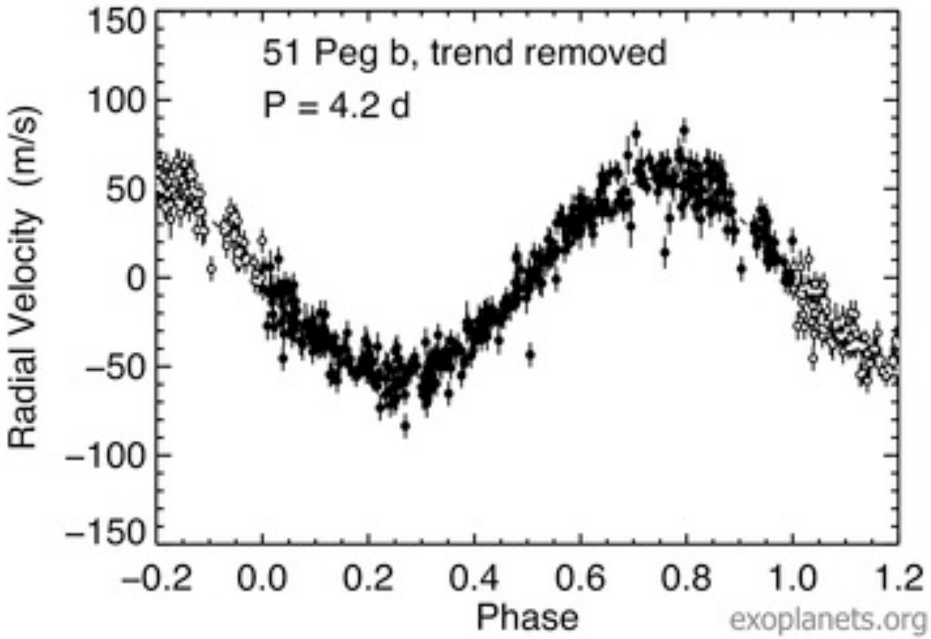
Exoplanets

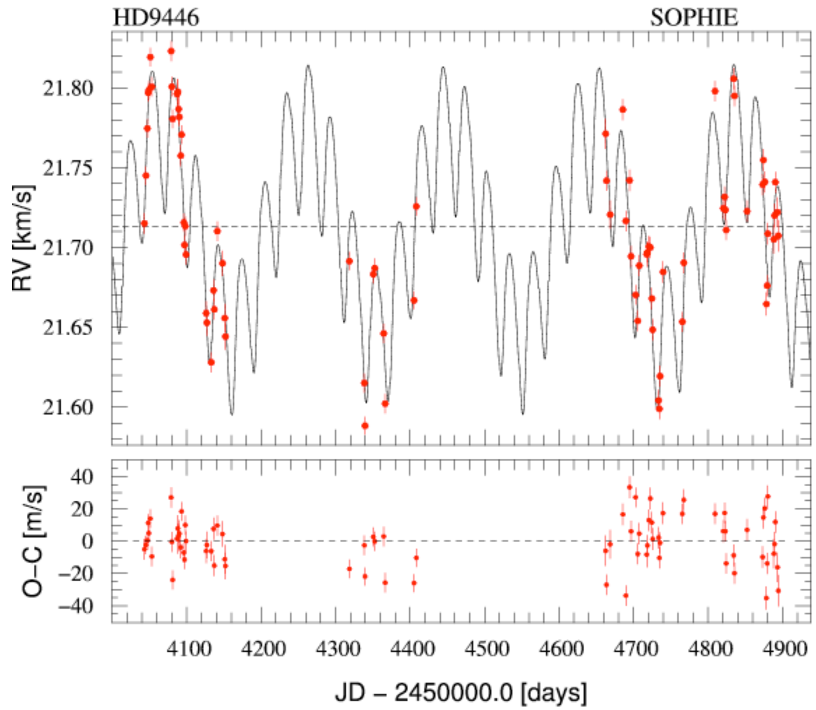
Main discovery methods: precise RVs and transit photometry



Exoplanet RVs

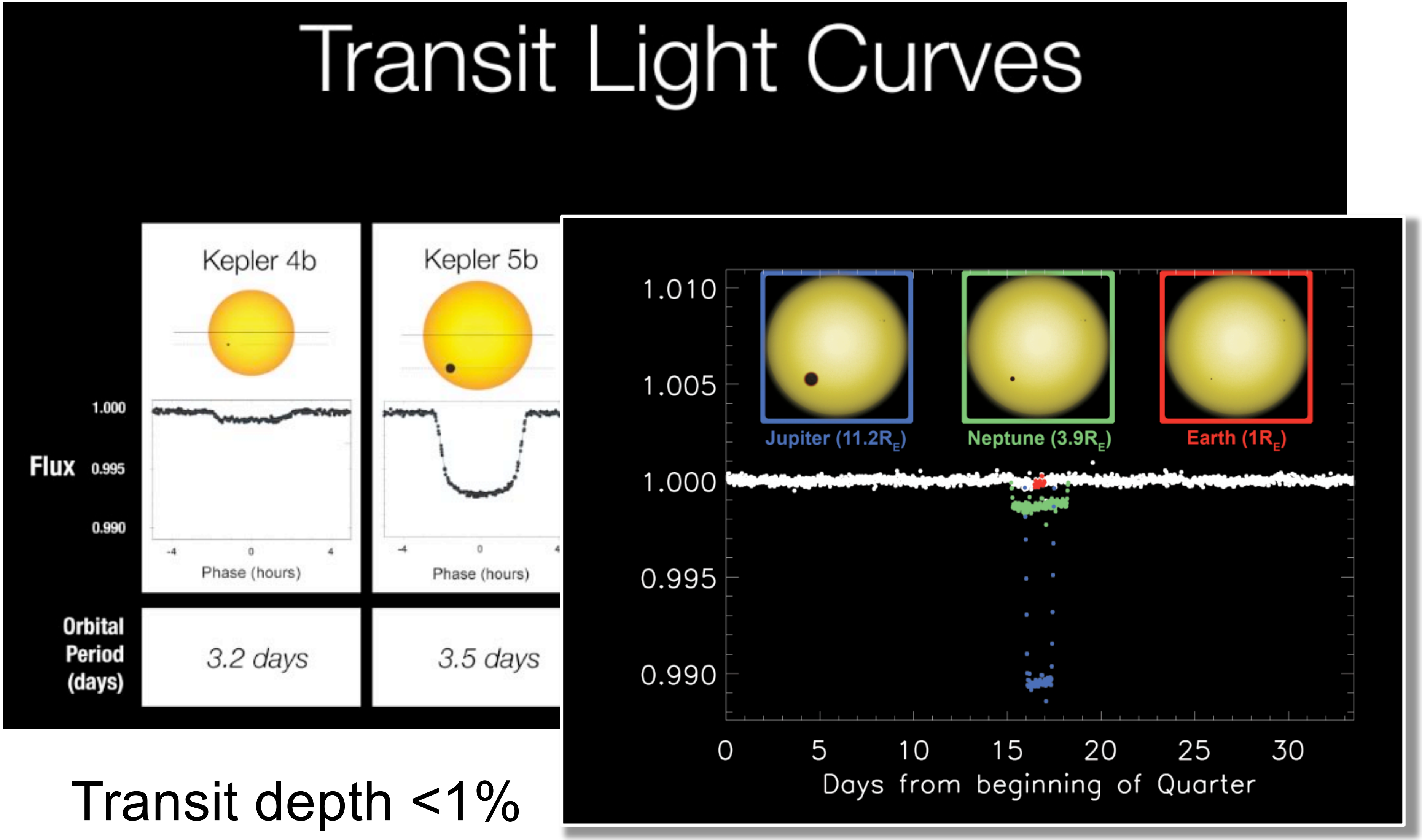
RV amplitudes 1-100 m/s; periods 1-1000 d





Sun's RV variation due to Jupiter: 12.4 m/s, 12 yr

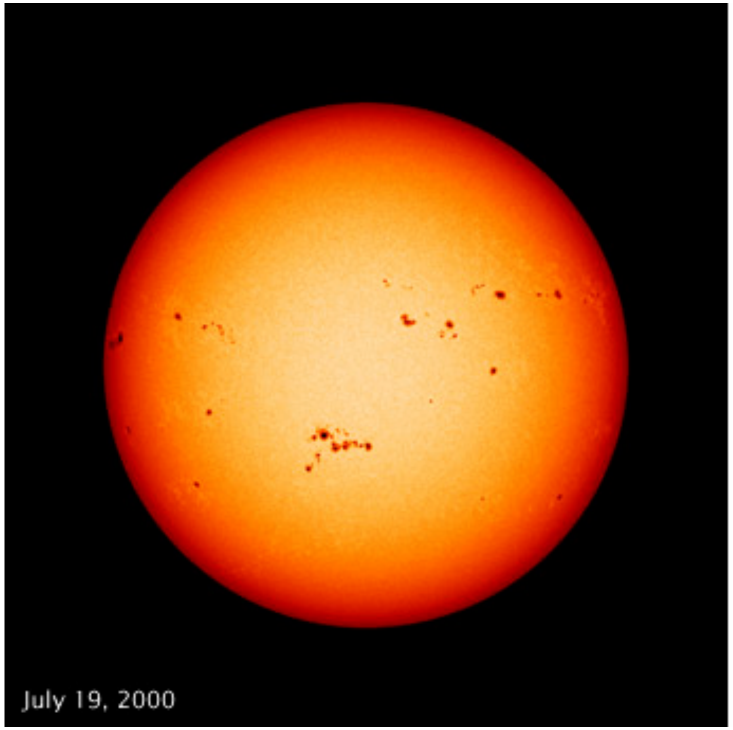
Exoplanet transits

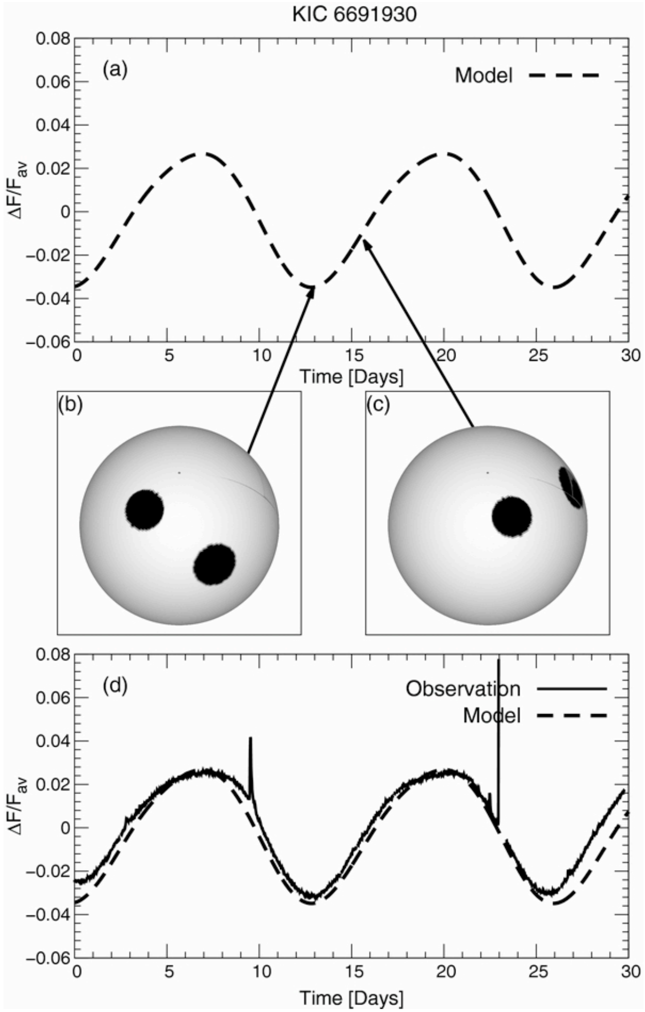


Transit depth <1%

Star spots

Inhomogeneities => photometric variation

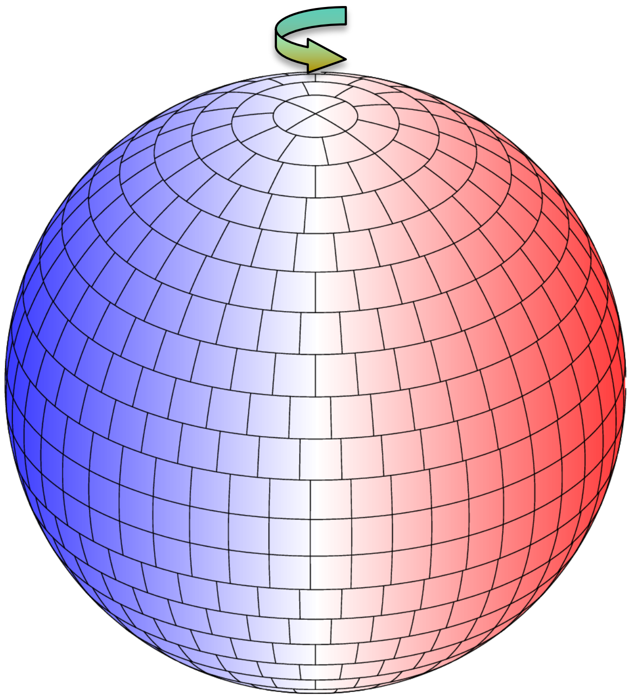


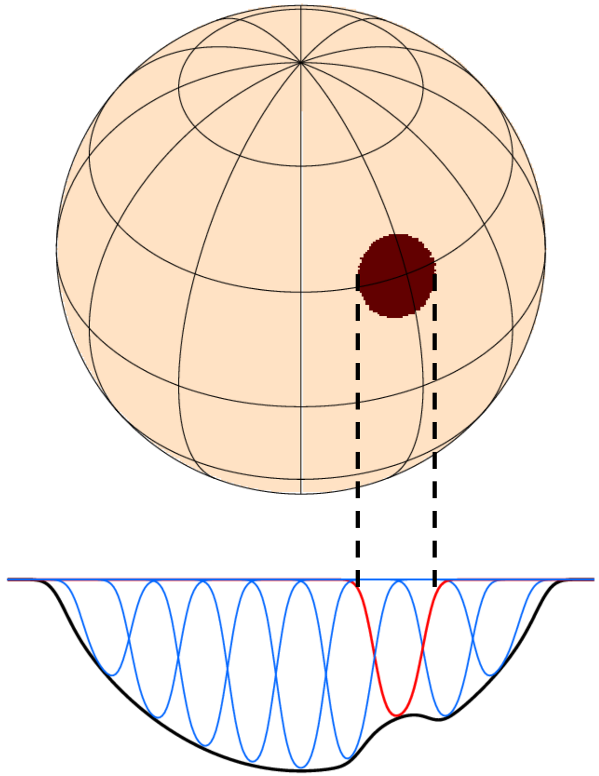


Photometric amplitudes
≤0.1-0.2 mag, periods 0.5-50d,
activity cycles ~10 yr

Star spots

Inhomogeneities => RV and line profile variation

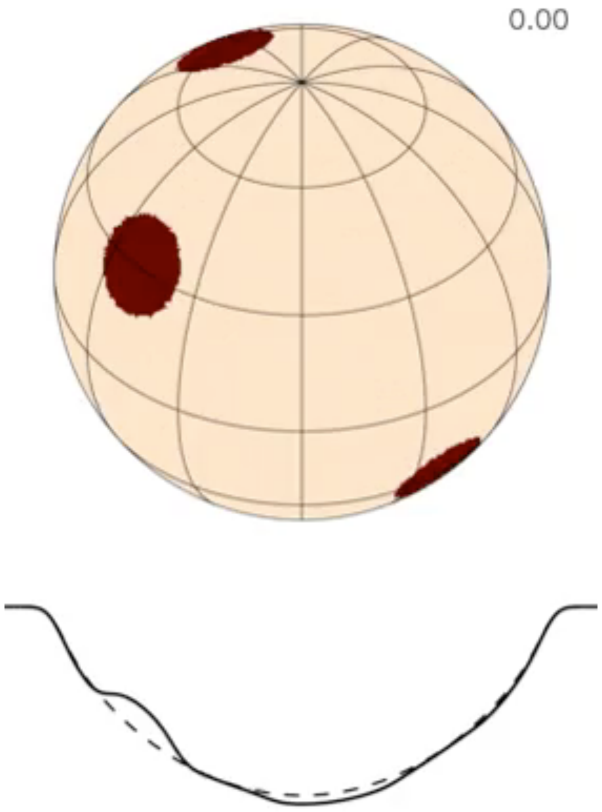


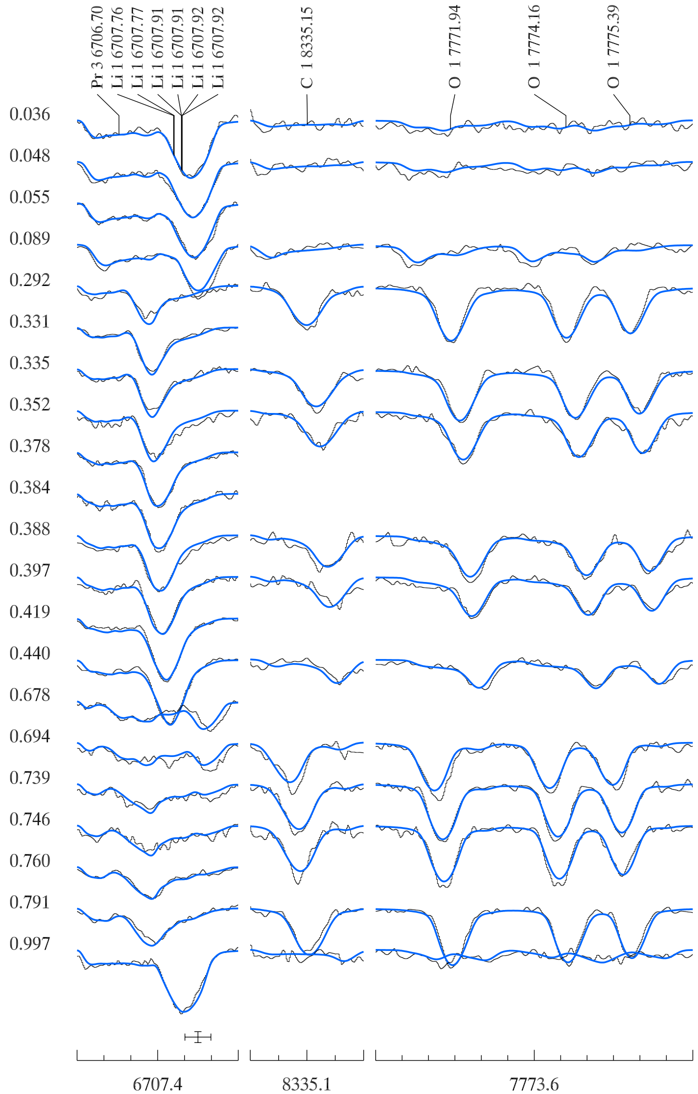


High-resolution spectroscopy
$\lambda/\Delta\lambda \geq 50{,}000$, S/N≥100

Star spots

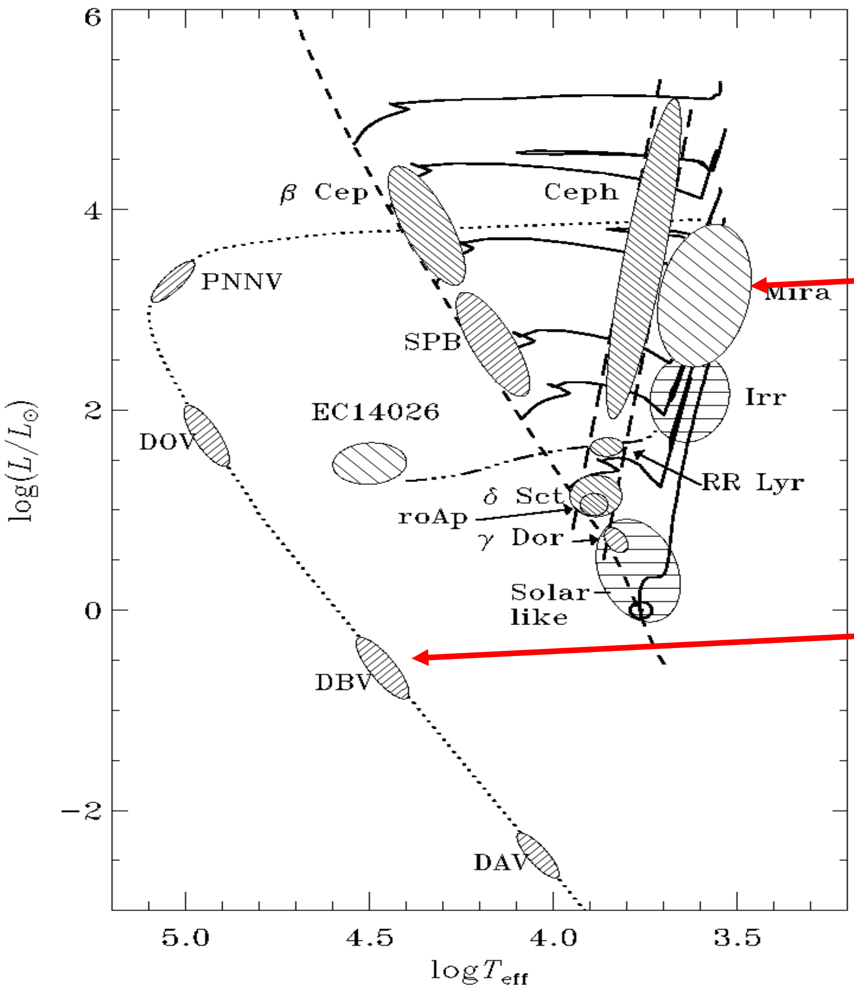
Inhomogeneities => RV and line profile variation





Stellar pulsations

Most stars oscillate due to interior effects



Pulsation periods

from years in

evolved giants

to ~1 min in

white dwarfs

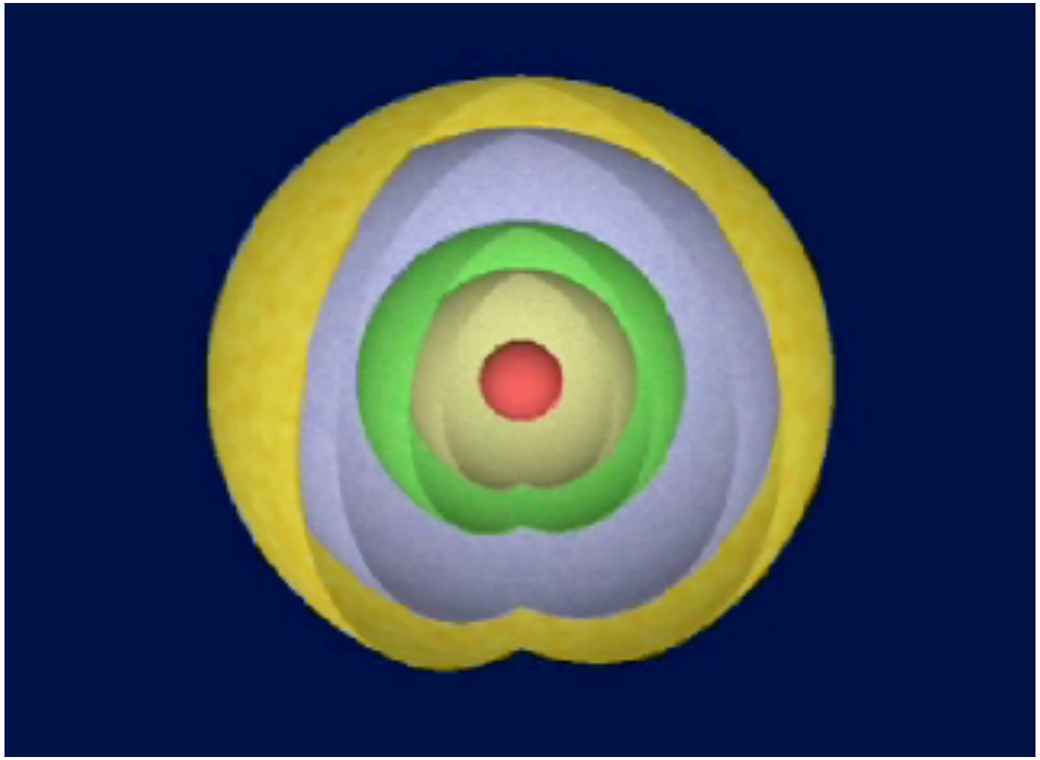
Asteroseismology

- Shape of pulsational perturbation
  - radial dependence: overtone number *n*
  - angular dependence: spherical harmonics; angular degree *l* and azimuthal number *m*
- Frequencies of pulsational variation
- Oscillations observed at the stellar surface are directly determined by interior properties

Frequencies + mode identification =>
helioseismology and asteroseismology

Radial and non-radial pulsations

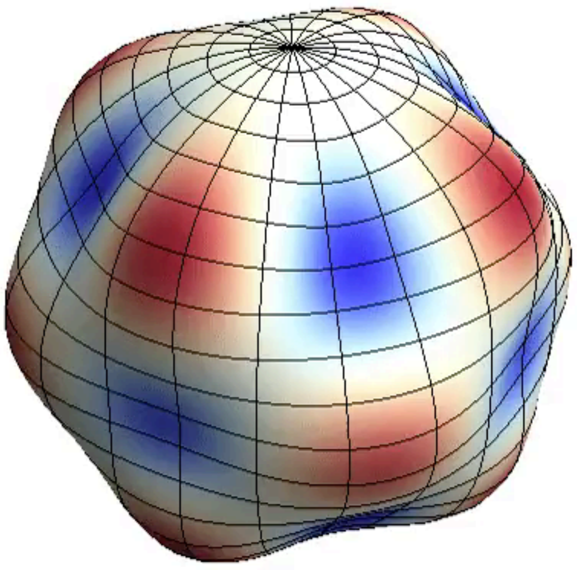
- Radial modes: $l = m = 0$, the star maintains spherical symmetry; all points at a given radius move with the same phase



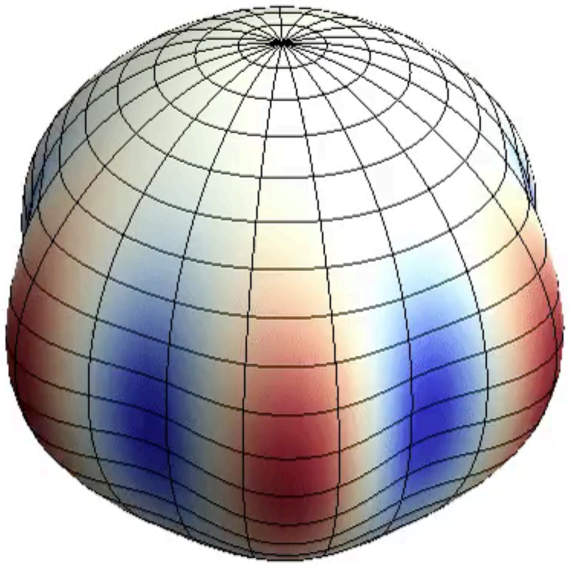
Radial and non-radial pulsations

- Non-radial modes: $l \geq 1$, pulsation phase varies across the stellar surface

$l = 6$, $m = 4$

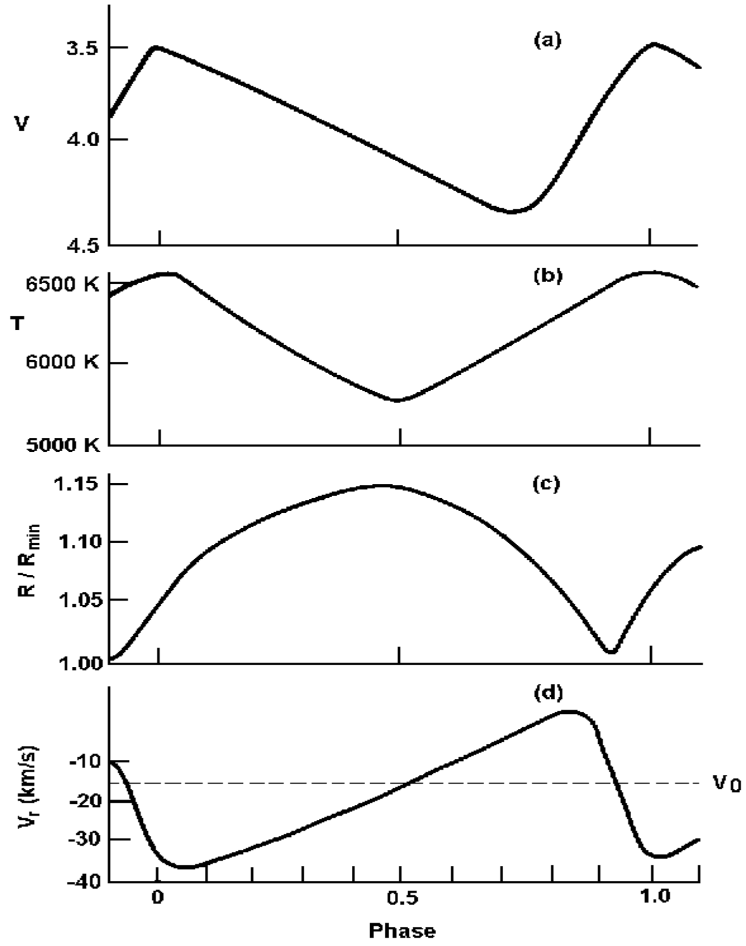


$l = 6$, $m = 6$



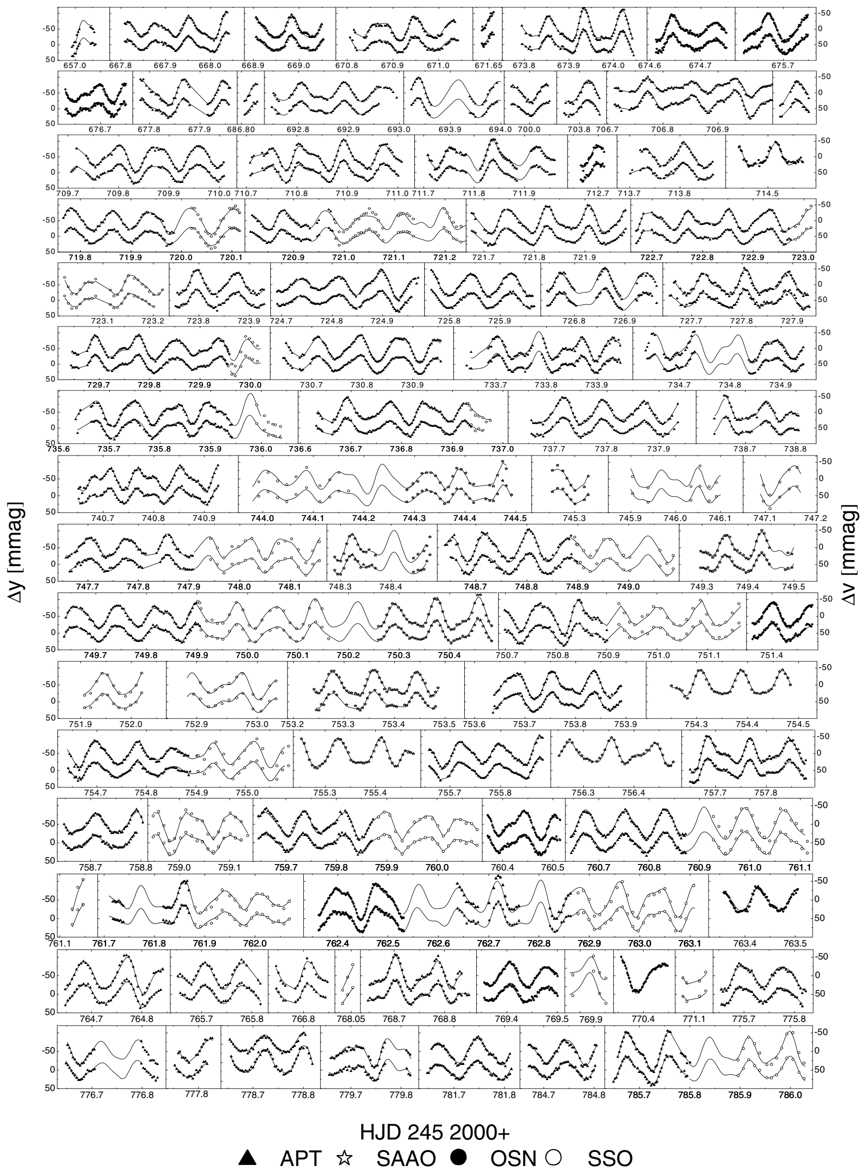
Pulsational observables

- Photometry $\rightarrow$ stellar brightness $\rightarrow$ L, T
- Interferometry $\rightarrow$ angular diameter $\rightarrow$ R
- Spectroscopy $\rightarrow$ radial velocity, equivalent width, line profiles $\rightarrow$ V, T, *mode identification*



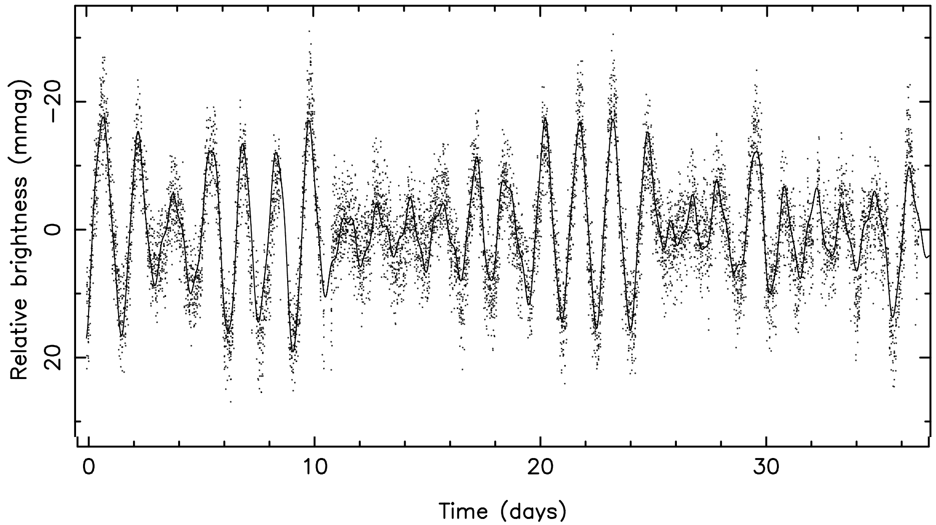
Pulsational amplitudes: 0.5-10^{-6} mag, 10-10^{-5} km/s

Photometric observations of stellar pulsations

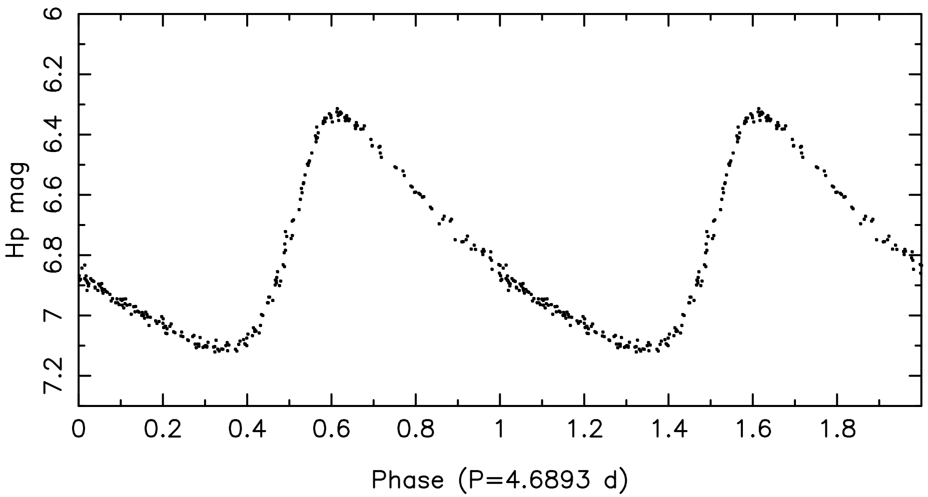


delta Scuti-type star variation from a multi-cite campaign

Photometric observations of stellar pulsations

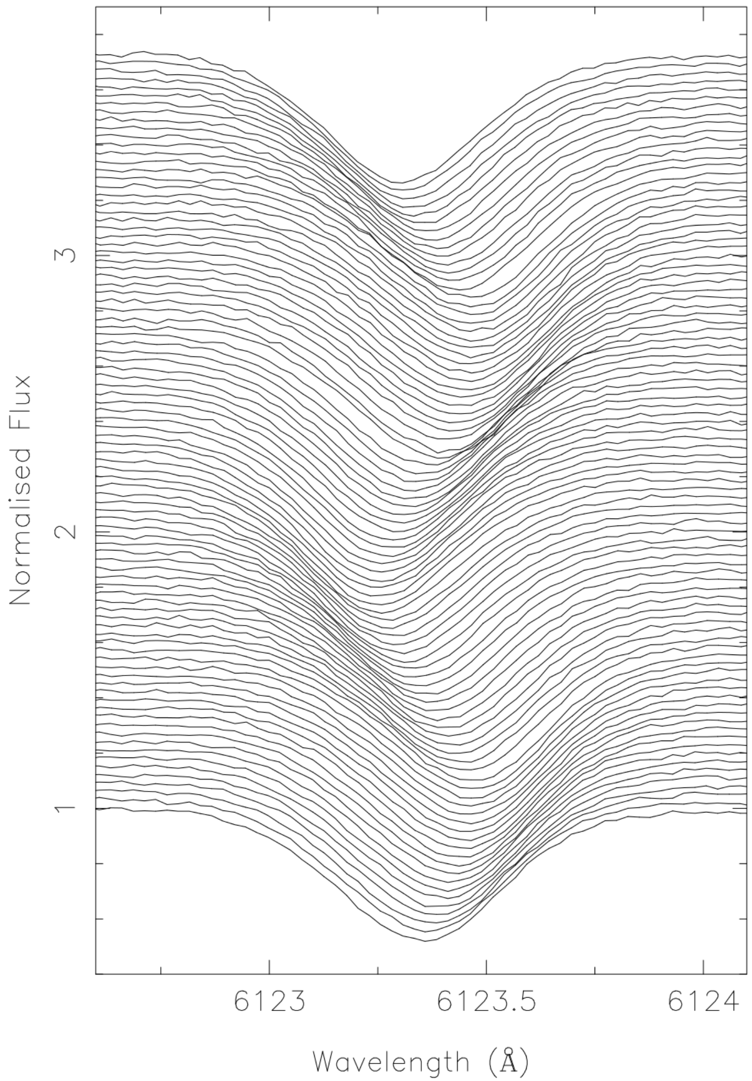


SPB-type star variation from space photometry (MOST)

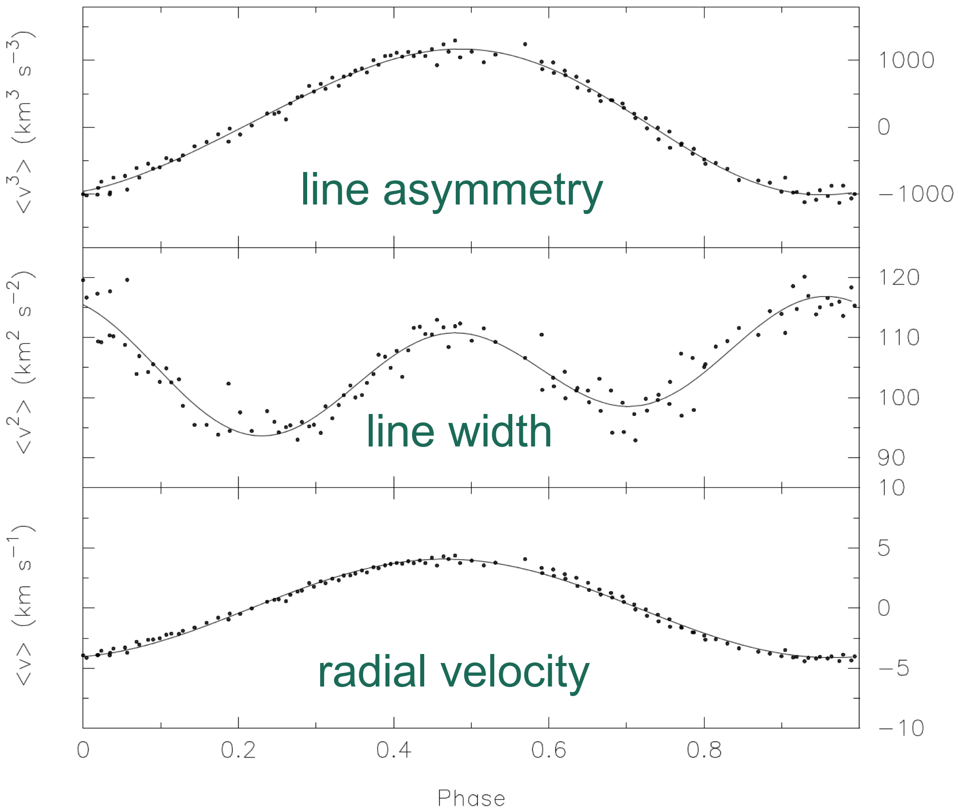


Cepheid-type star variation from space photometry (Hipparcos)

Spectroscopic observations of stellar pulsations

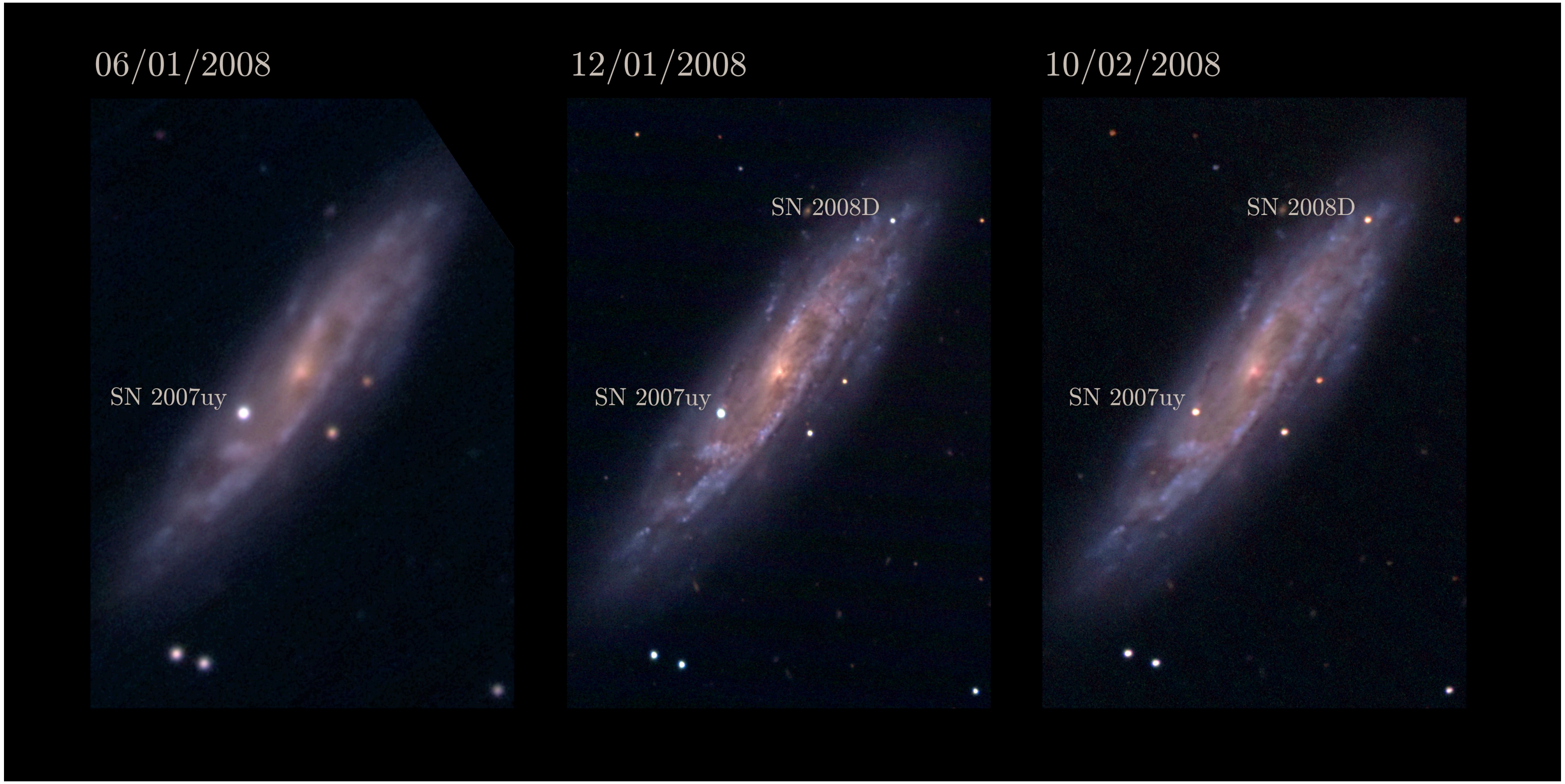


delta Scuti-type star



Transients

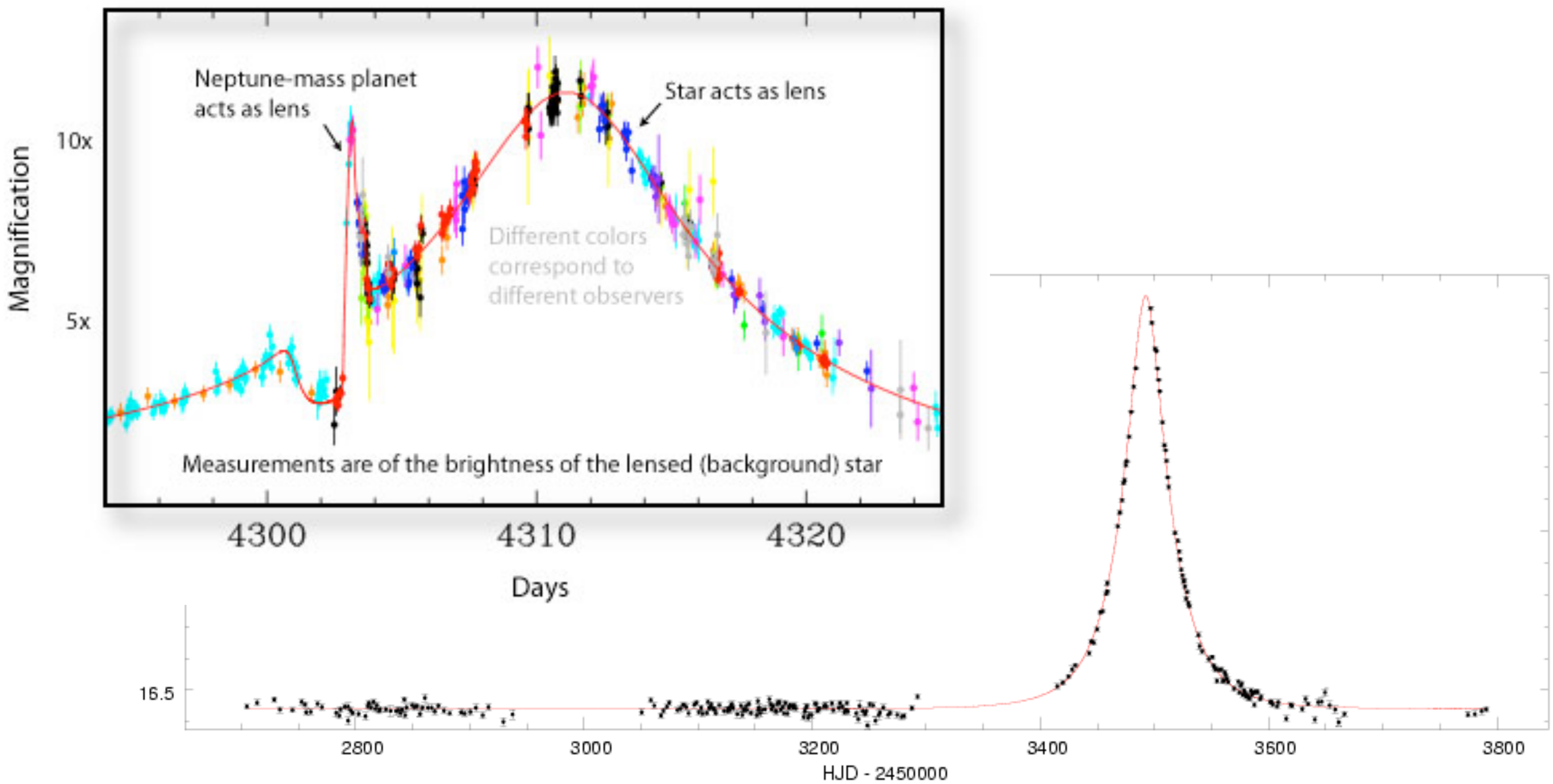
- GRBs, SNe, Novae



Transients

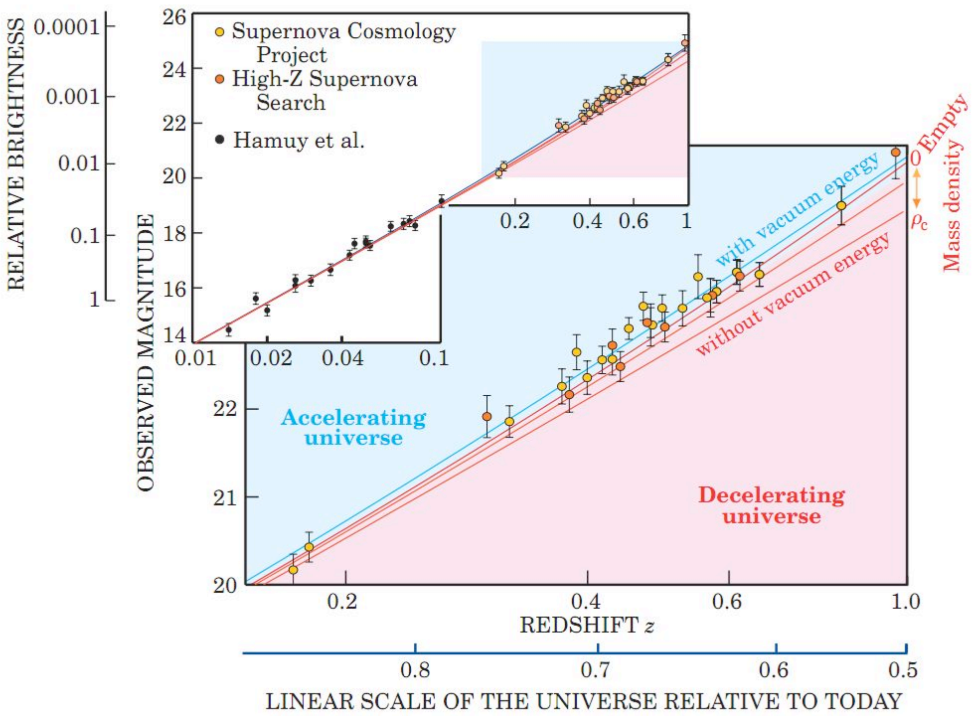
- GRBs, SNe, Novae
- Gravitational microlensing

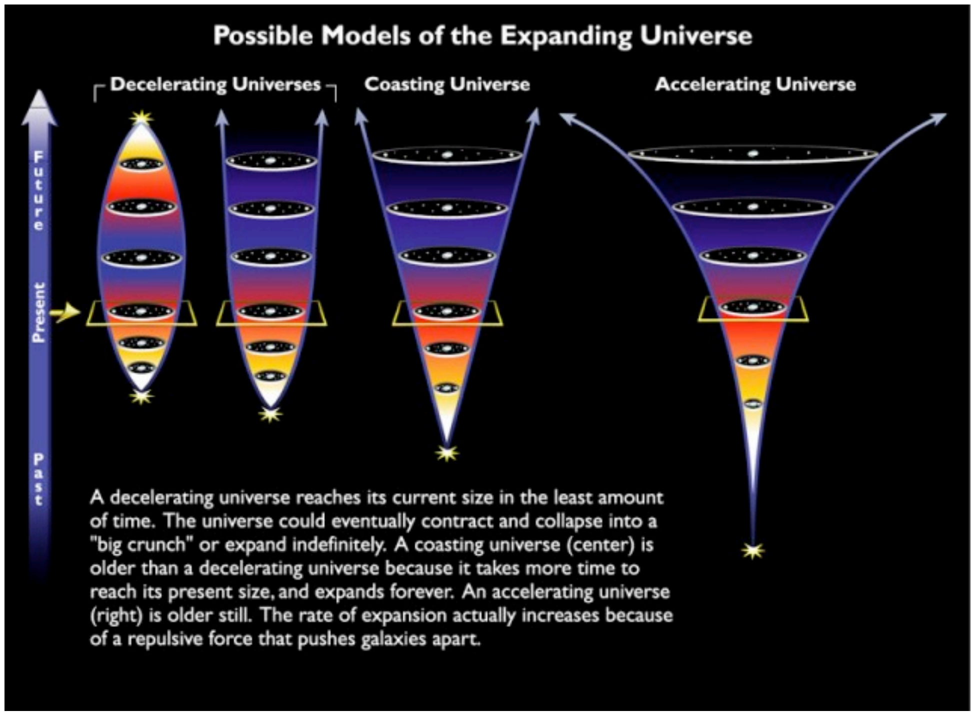
The signature of a Neptune-mass planet orbiting a ~0.65 Solar Mass star



Expansion of the Universe

Evidence from SNe points to accelerating expansion

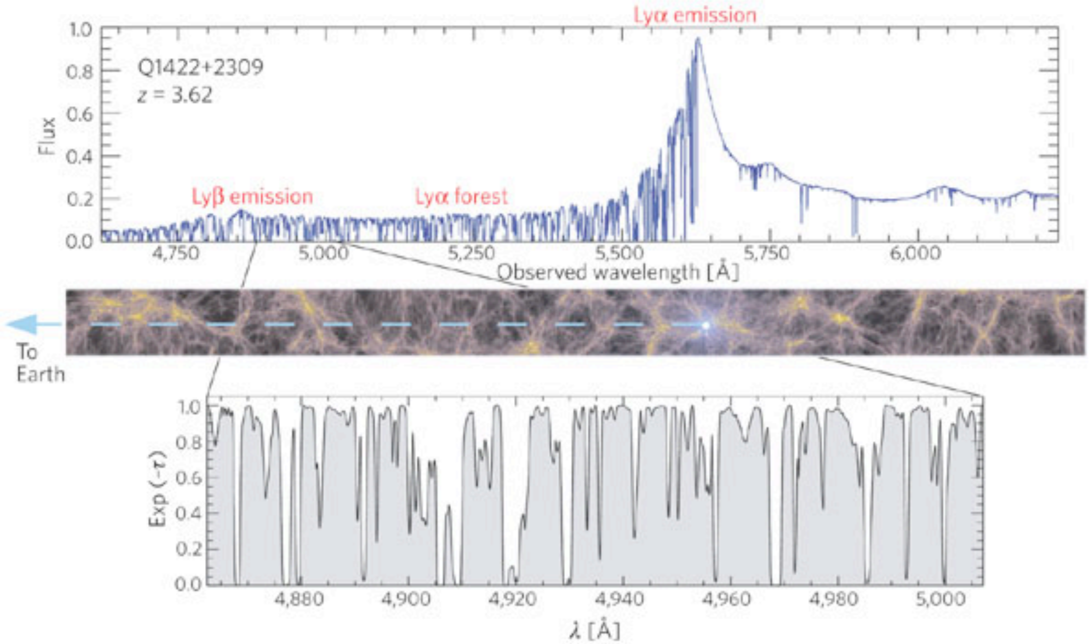


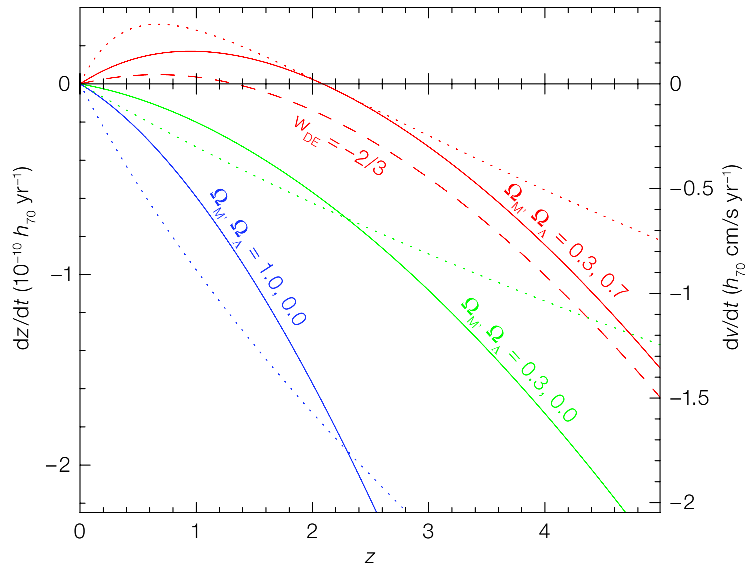


Sandage test

Direct observations of expansion history of the Universe via redshift drift measurement

Measurements of *z* variation on the time scale of decades for individual for *z*~3 *L*α forests





Expected signal of d*z*/d*t* is <u>~20 cm/s in 20 years</u>

Observations of variability

- General considerations
- Frequency analysis
- Photometry
- Spectroscopy

General considerations

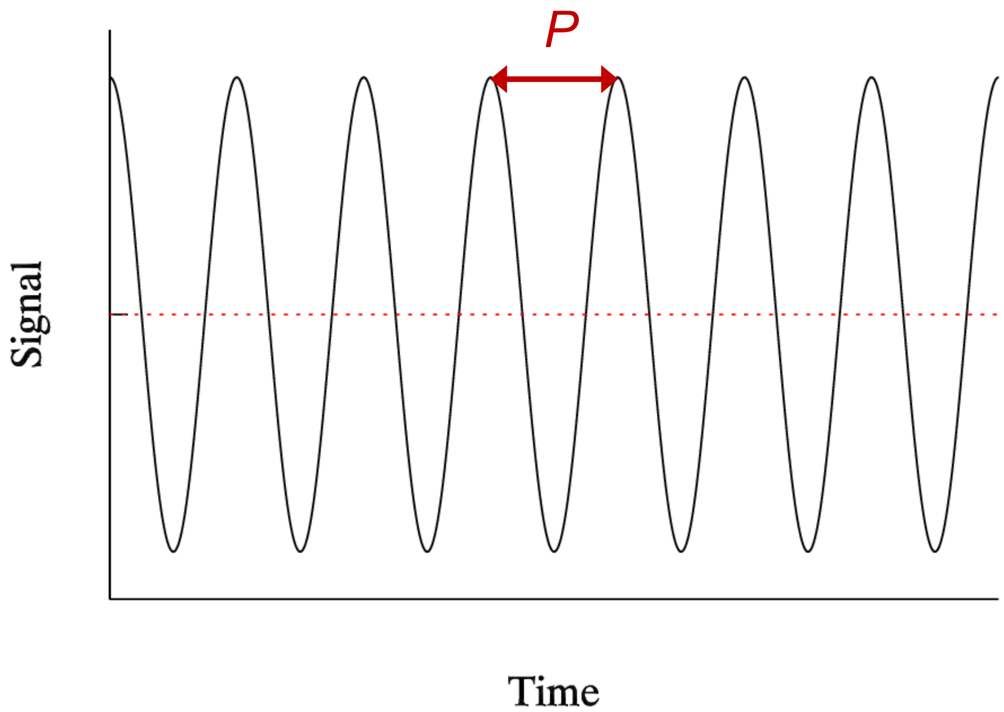
- Observational errors: accuracy and precision
- Duty cycle: single site, multi-site, space
- Signal sampling: Nyquist limit, readout time
- Time keeping: UTC, JD, HJD, BJD
- Instrumental errors: periodic and random
- Rapid follow-up of transients

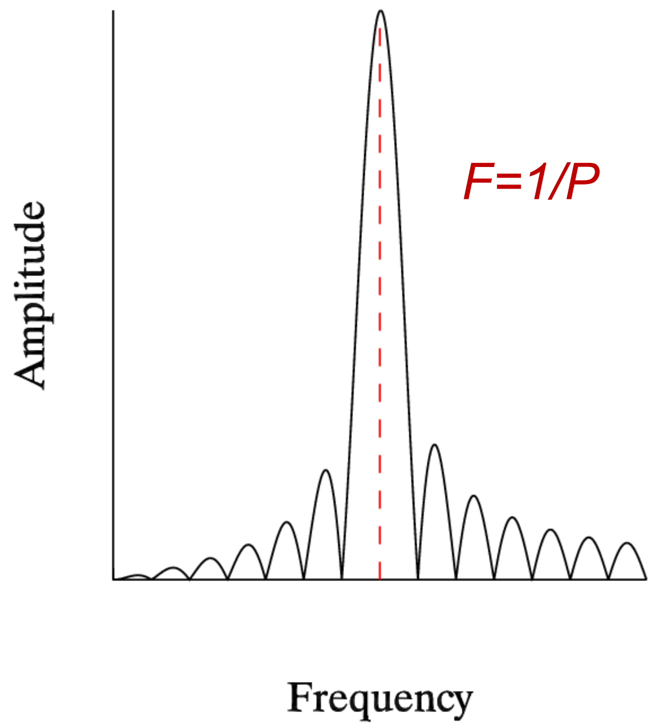
Frequency analysis

Fourier transform

$$F(\nu) \equiv \int_{-\infty}^{+\infty} x(t)\exp(2\pi \mathrm{i}\,\nu\,t)dt.$$ continuous

$$F_N(\nu) \equiv \sum_{i=1}^{N} x(t_i)\exp(2\pi \mathrm{i}\,\nu t_i).$$ discrete

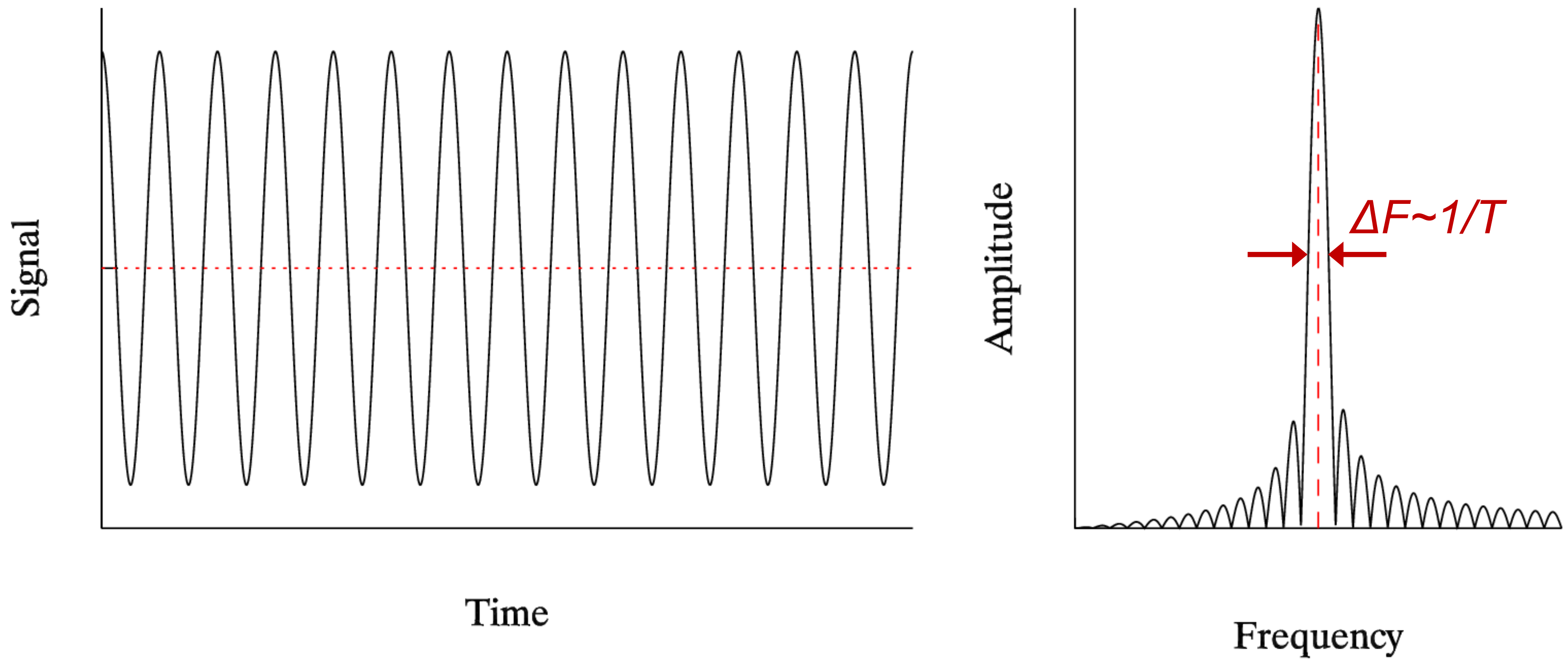




Frequency analysis

Frequency precision increases with the length of time series

=> frequencies are the most precise astronomical observables



Frequency analysis

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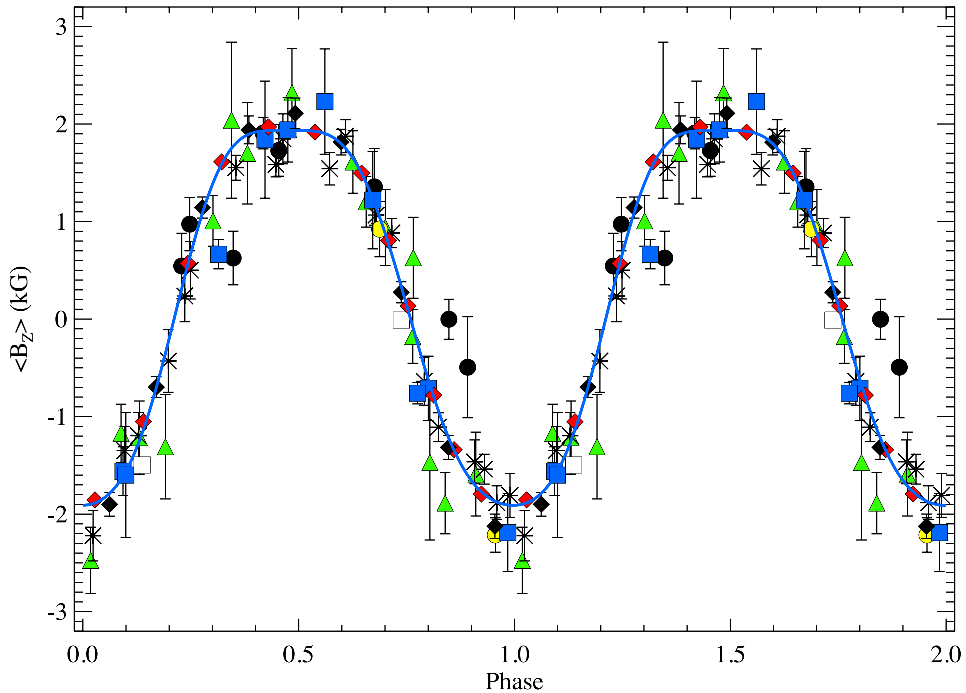


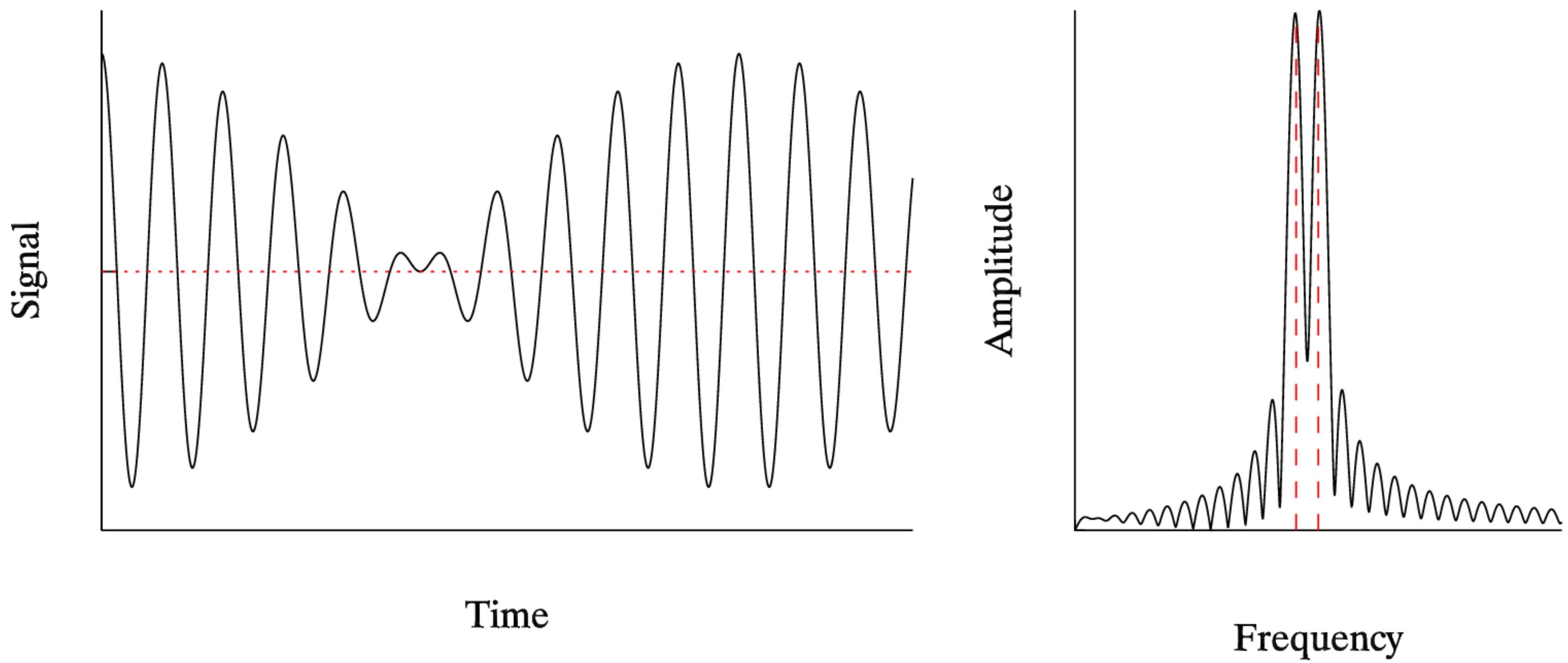
Rusomarov et al. (2015)
longitudinal field variation
of a magnetic Ap star based
on ~50 years of observations

$$\mathrm{HJD}(\langle B_z \rangle_{\min}) = 2\,433\,103.95 + 9.29558(6) \cdot E.$$

period of ~9 days is known to
5 second precision (error 6 ppm)

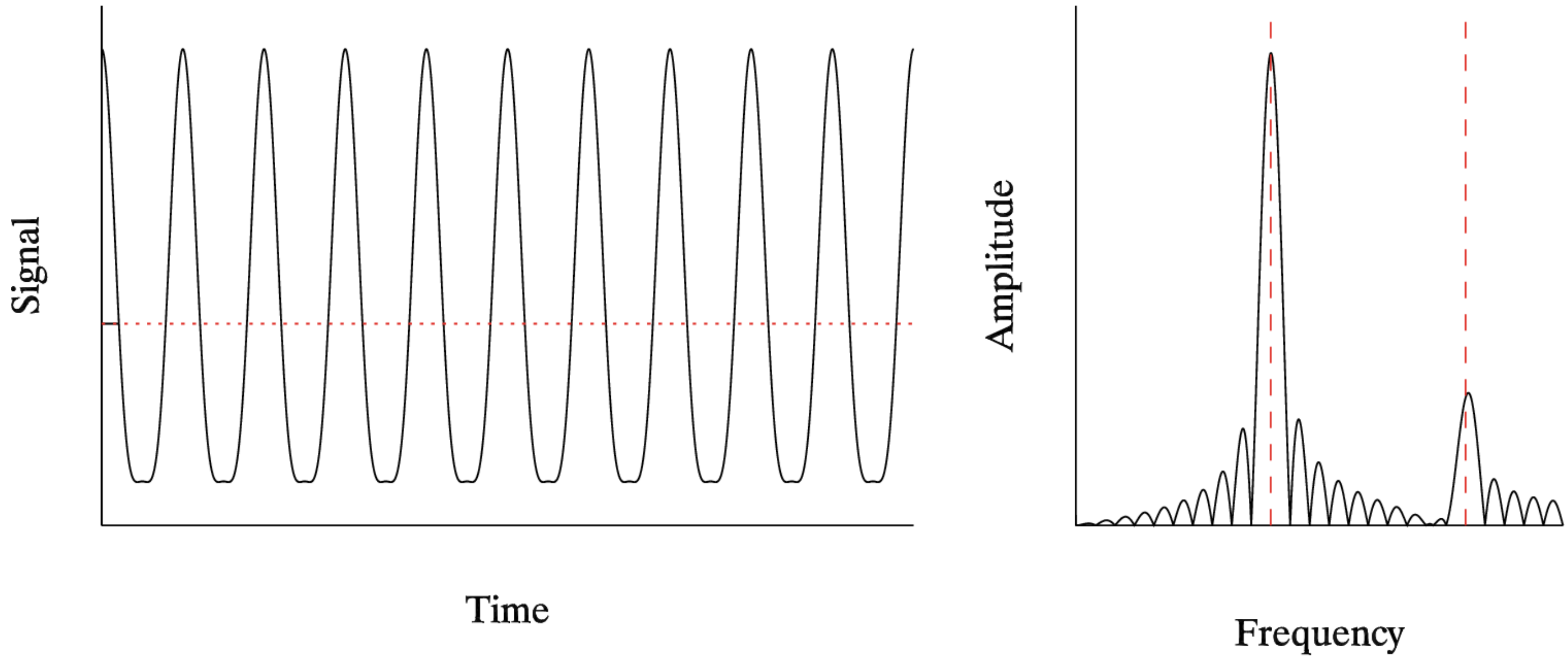
Frequency analysis

Frequency precision <=> frequency resolution



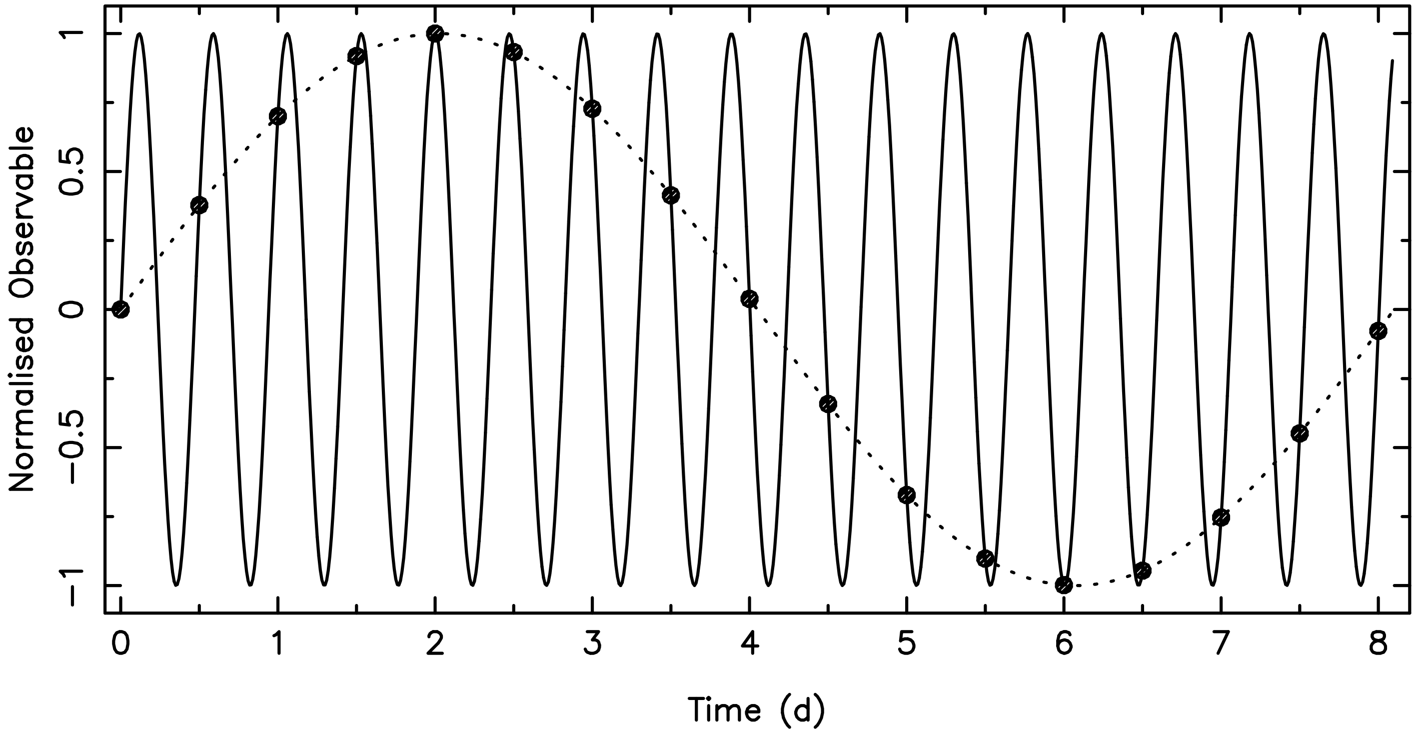
Frequency analysis

Non-sinusoidal variation => harmonic frequencies (F, $2 \times F$, …)



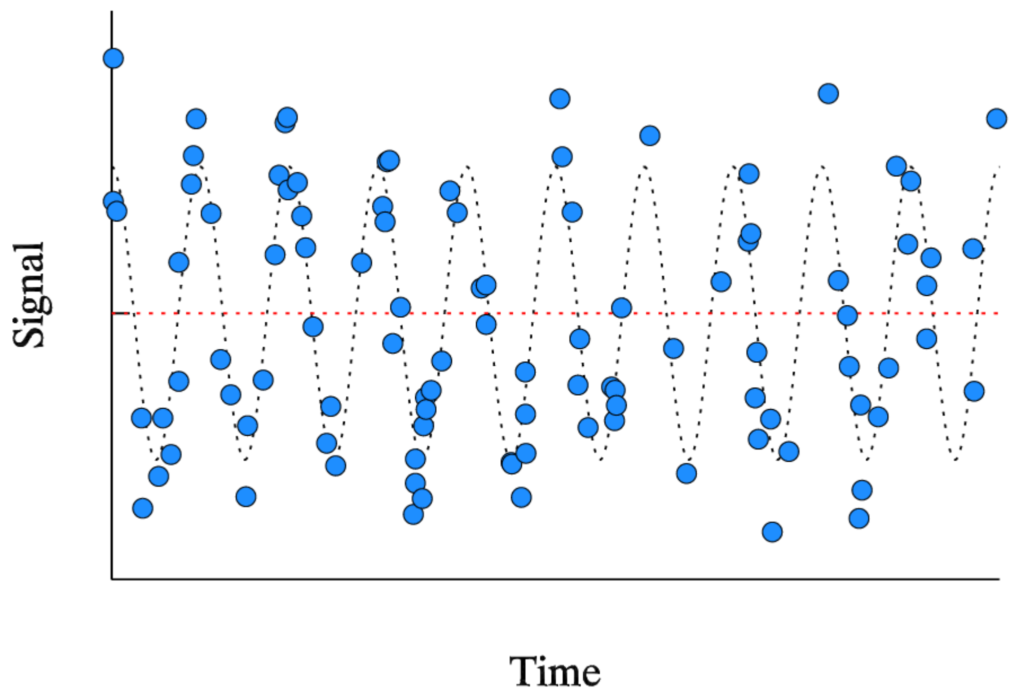
Frequency analysis

Minimum sampling: 2 points per oscillation (Nyquist limit)

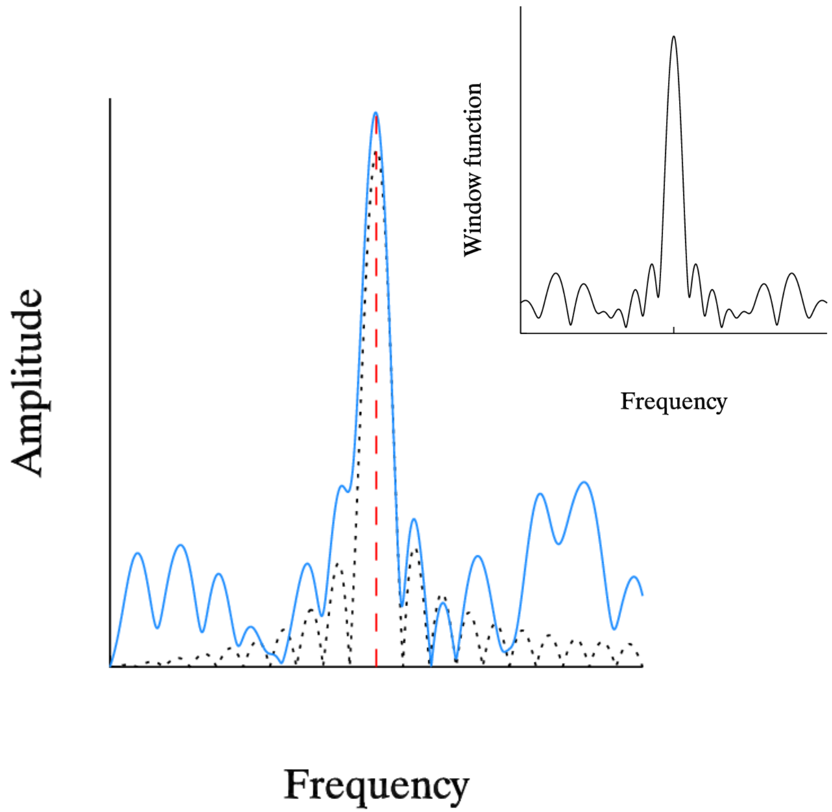


Frequency analysis

Real life: oscillating signal is sampled at <u>discrete times</u> and contains <u>noise contribution</u>

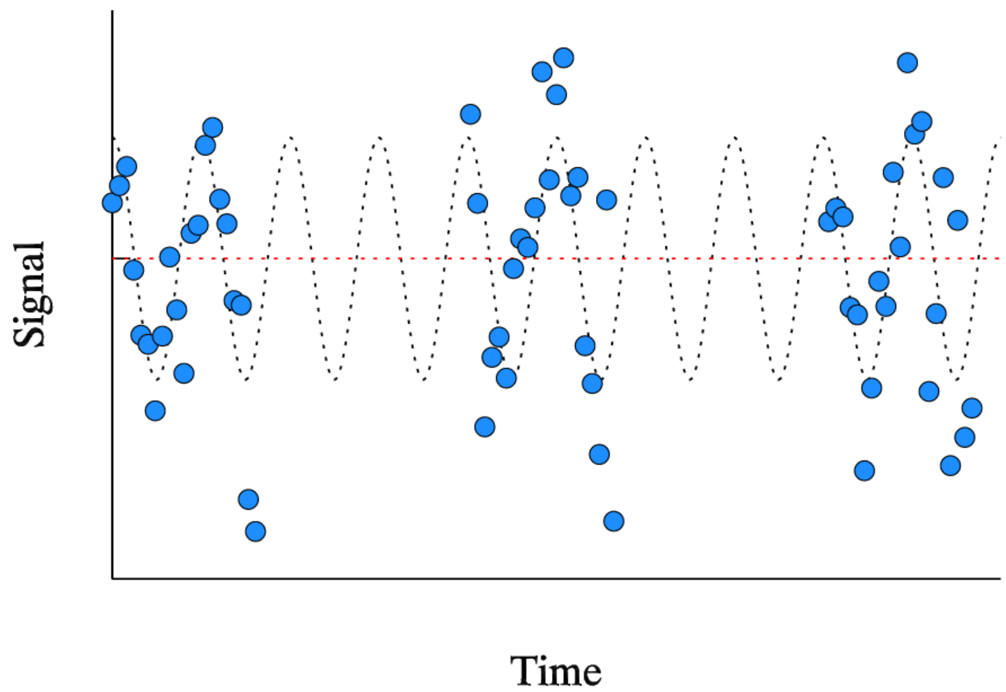


window function



Frequency analysis

Real life: oscillating signal is sampled at discrete times with gaps and contains noise contribution



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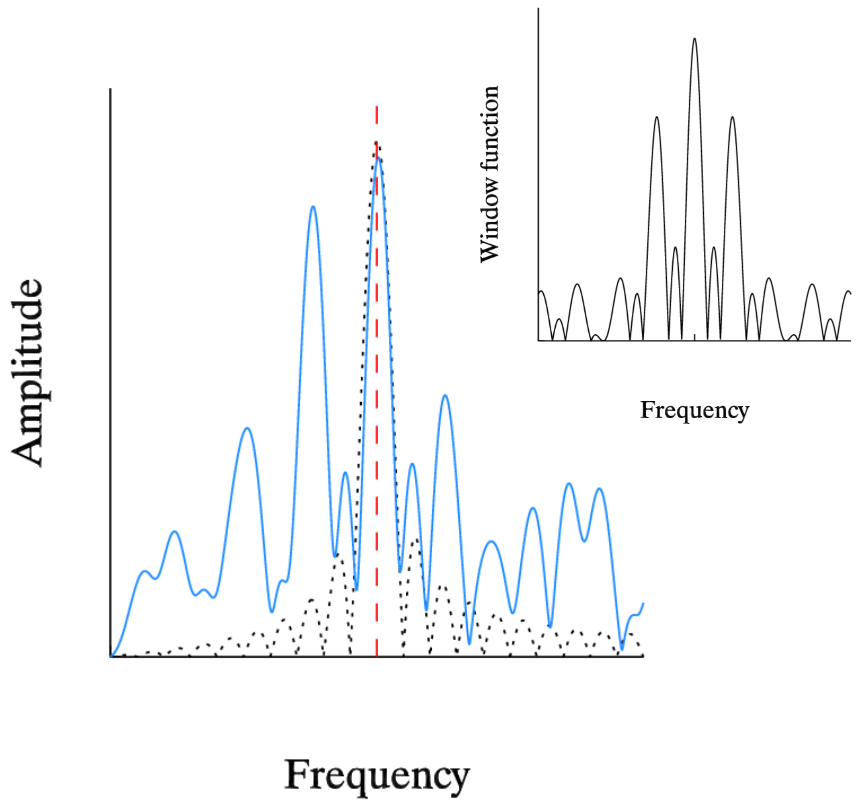
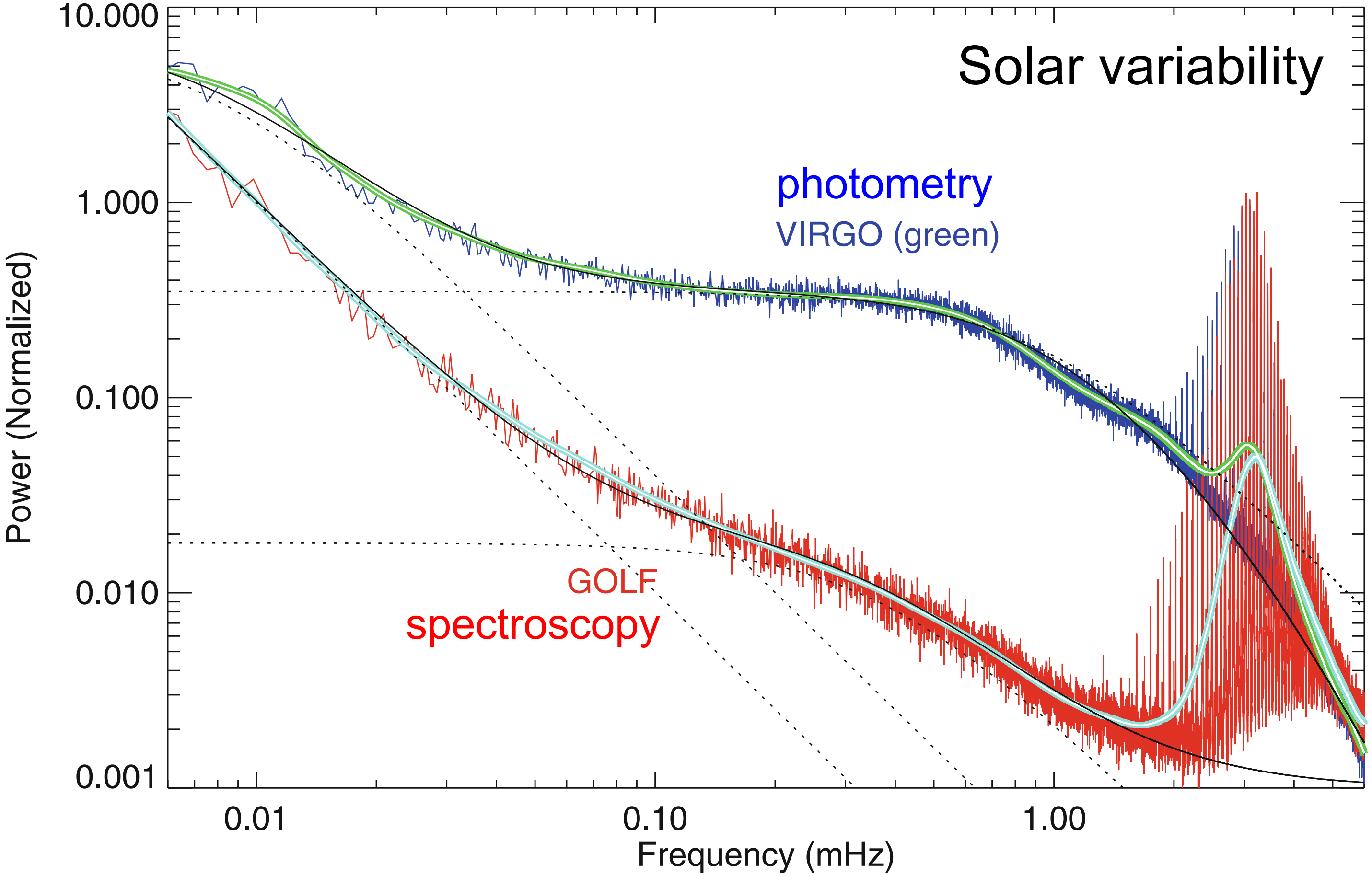


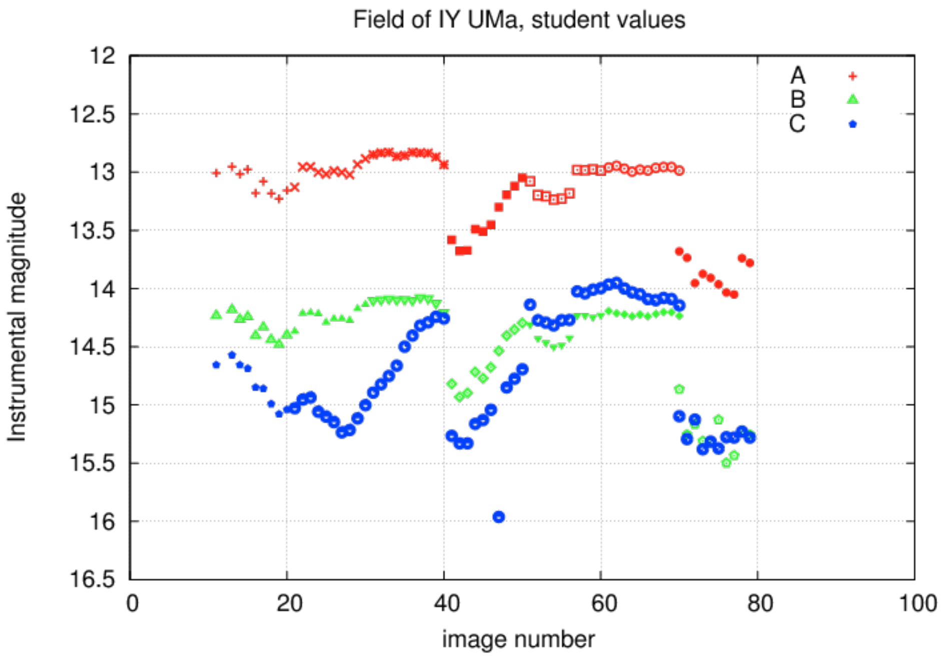
Frequency analysis

Real life: combined effect of different astrophysical signals



Photometric time series

- Photon statistics: S/N=N/sqrt(N)
- Broad-band vs. filter observations
- Sky transparency, extinction, scintillation, seeing
- Aperture vs. PSF CCD photometry
- Differential and high-speed photometry



non-differential
different apertures

Photometric time series

- Photon statistics: S/N=N/sqrt(N)
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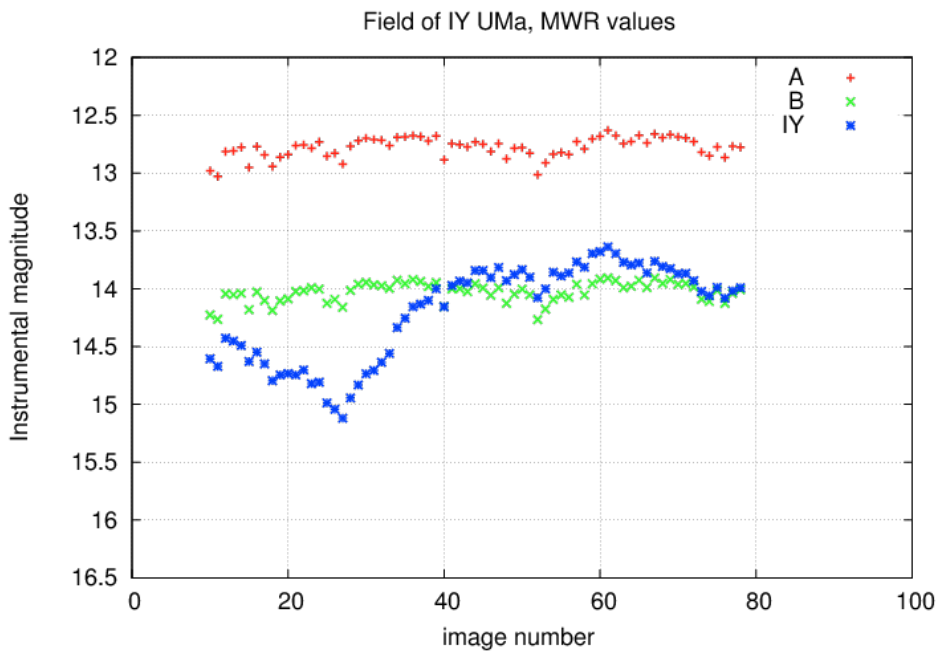

non-differential
same apertures

Photometric time series

- Photon statistics: S/N=N/sqrt(N)
- Broad-band vs. filter observations
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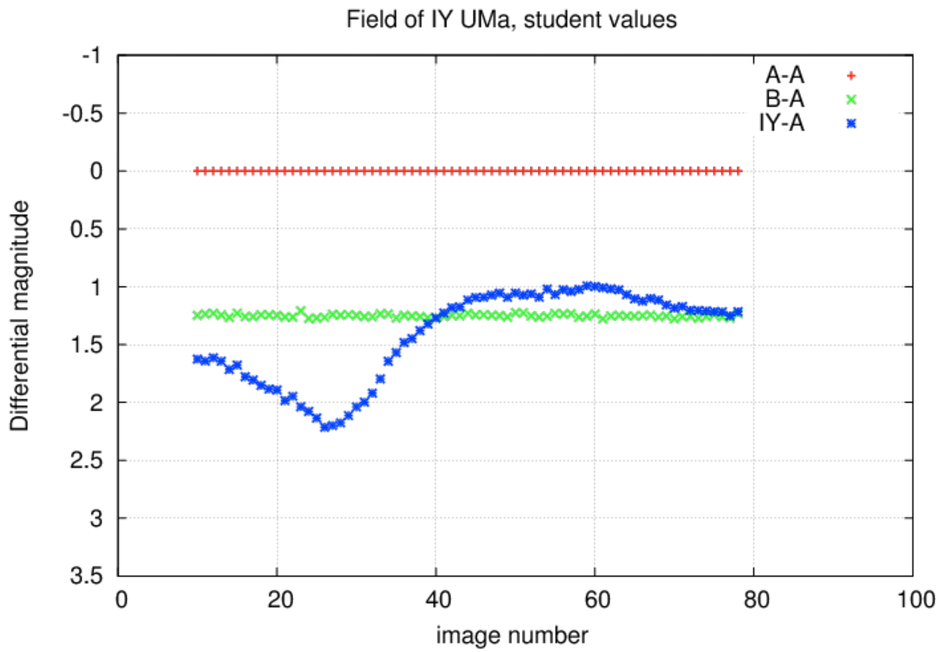
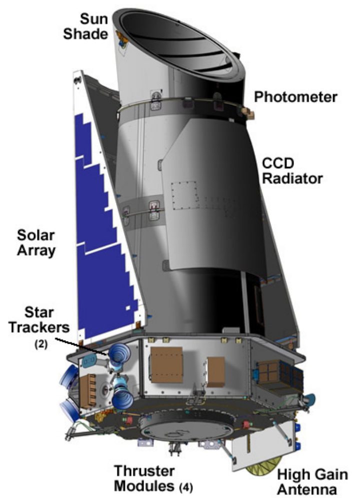
- Differential and high-speed photometry

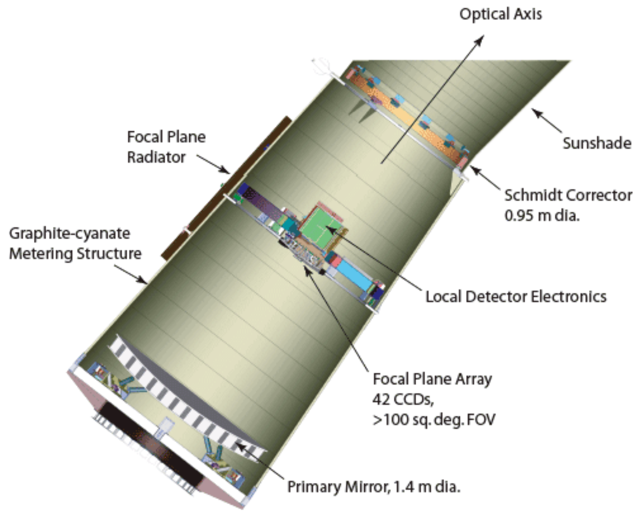


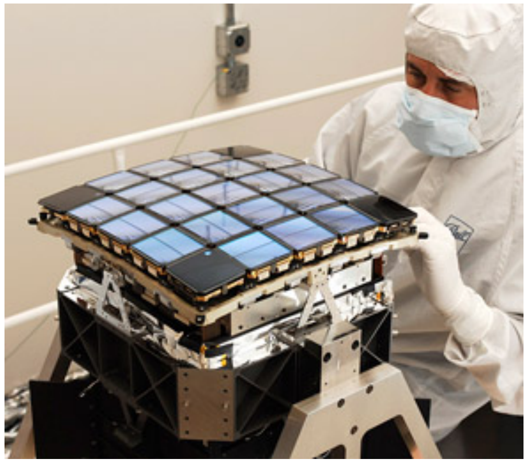
differential
same apertures

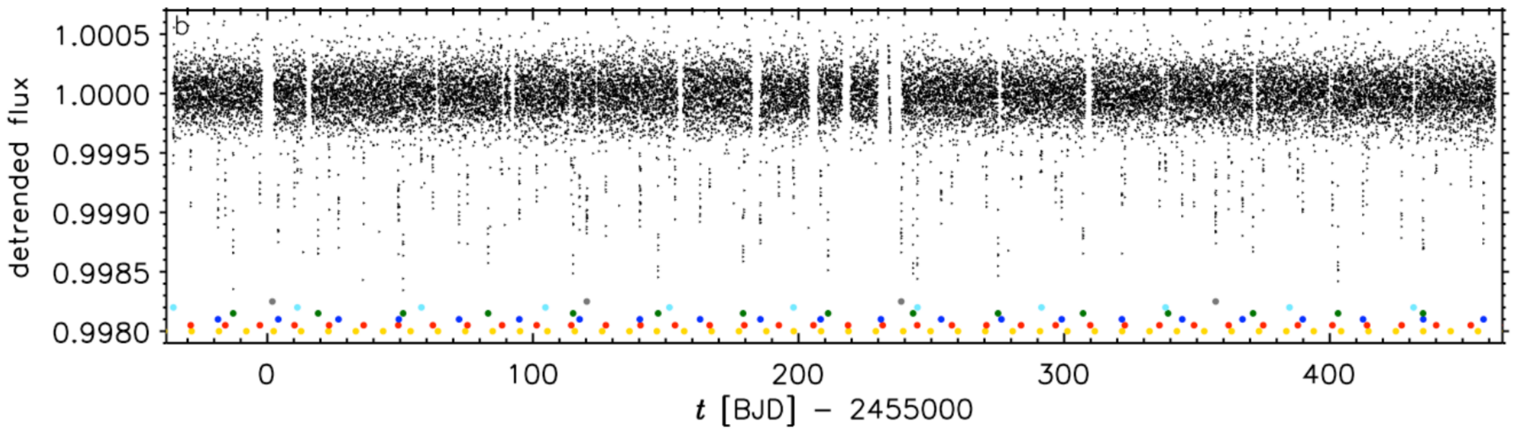
Current state-of-the-art: space photometry

Continuous observations from space at ~ppm precision (MOST, CoRoT, Kepler, BRITE, TESS)









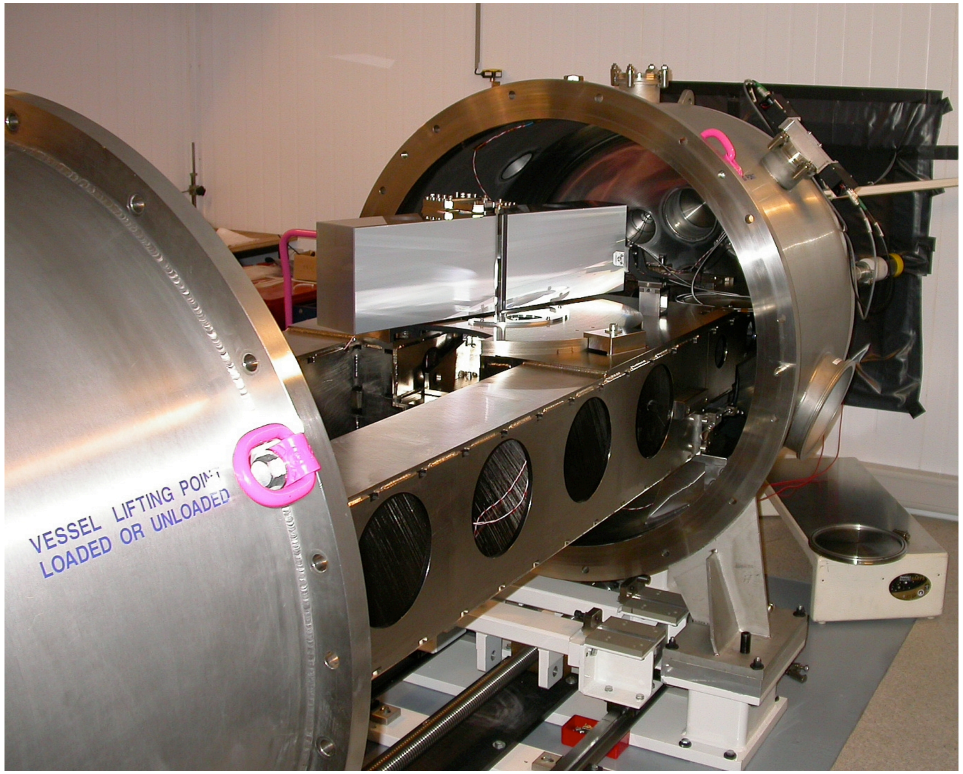
Kepler 11
6 transiting
super-Earths

Spectroscopic time series

- High spectral resolution, high S/N
- Observations at large telescopes
- Stabilized instruments, wavelength stability
- No photometric stability
- Complex data reduction
- Wavelength calibration: non- or simultaneous
  ThAr, iodine cell, laser frequency comb
- Multi-line analysis

Current state-of-the-art: high-precision spectroscopy

Ultra-stable, high-resolution instruments with simultaneous wavelength calibration (HARPS, ESPRESSO)



Frequency comb for wavelength calibration