High precision ground-based photometry

Observing techniques, instrumentation and science for metre-class telescopes II

24.9.2018

Monika Lendl

Austrian Academy of Sciences


Graz, Lustbuehel 50cm


Euler 1.2m, La Silla


TRAPPIST 60cm


Skalnaté Pleso 1.2m, high Tatra

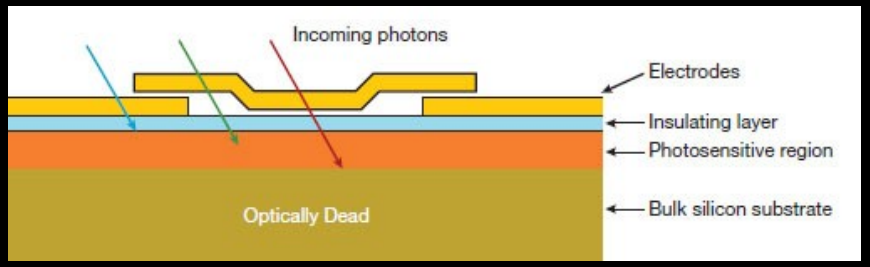

STELLA, Tenerife 2x1.2cm

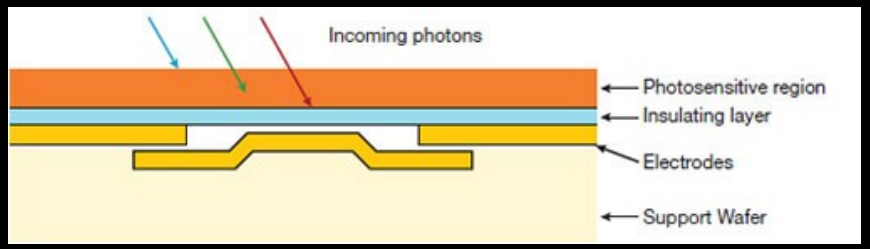

LCOGT 3x1m Cerro Tololo

Instrumentation

Optimized CCDs

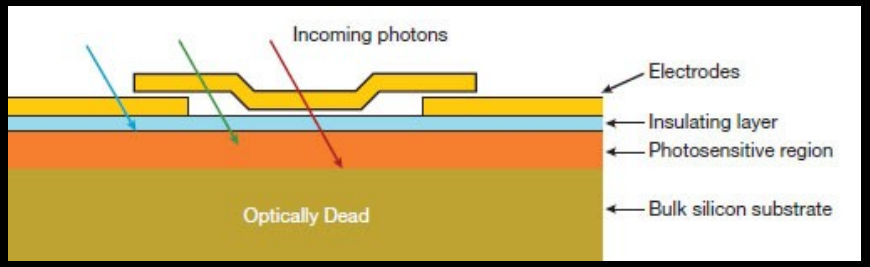
- Improved QE (back illuminated)
- Near-IR sensitivity (deep depleted)
- Multi-stage Peltier cooling (easier to handle than N_2)

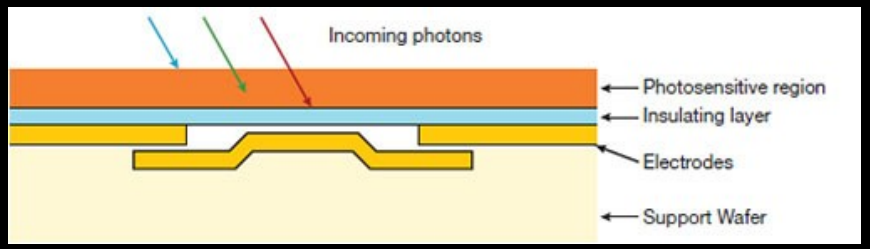


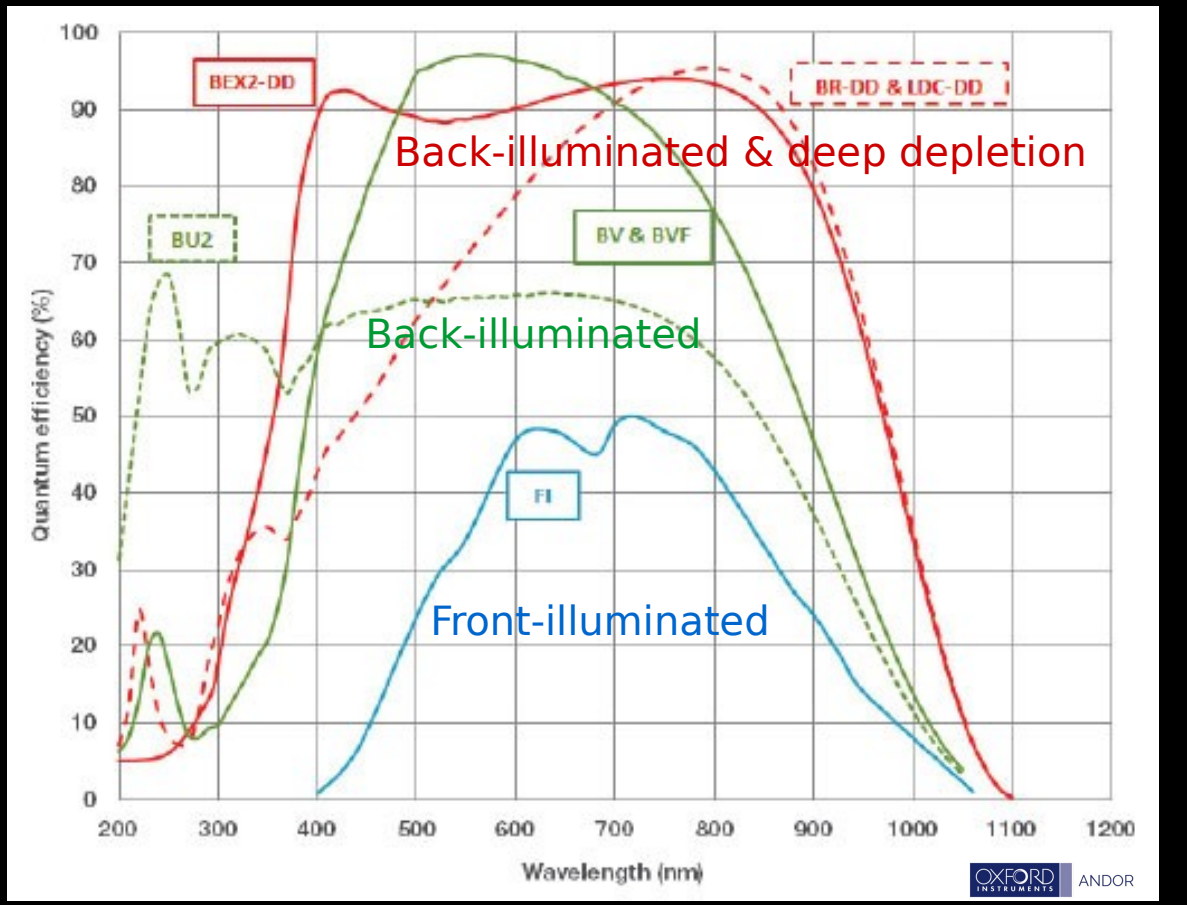


Optimized CCDs

- Improved QE (back illuminated)
- Near-IR sensitivity (deep depleted)
- Multi-stage Peltier cooling (easier to handle than N_2)







Imaging CCDs at small telescopes

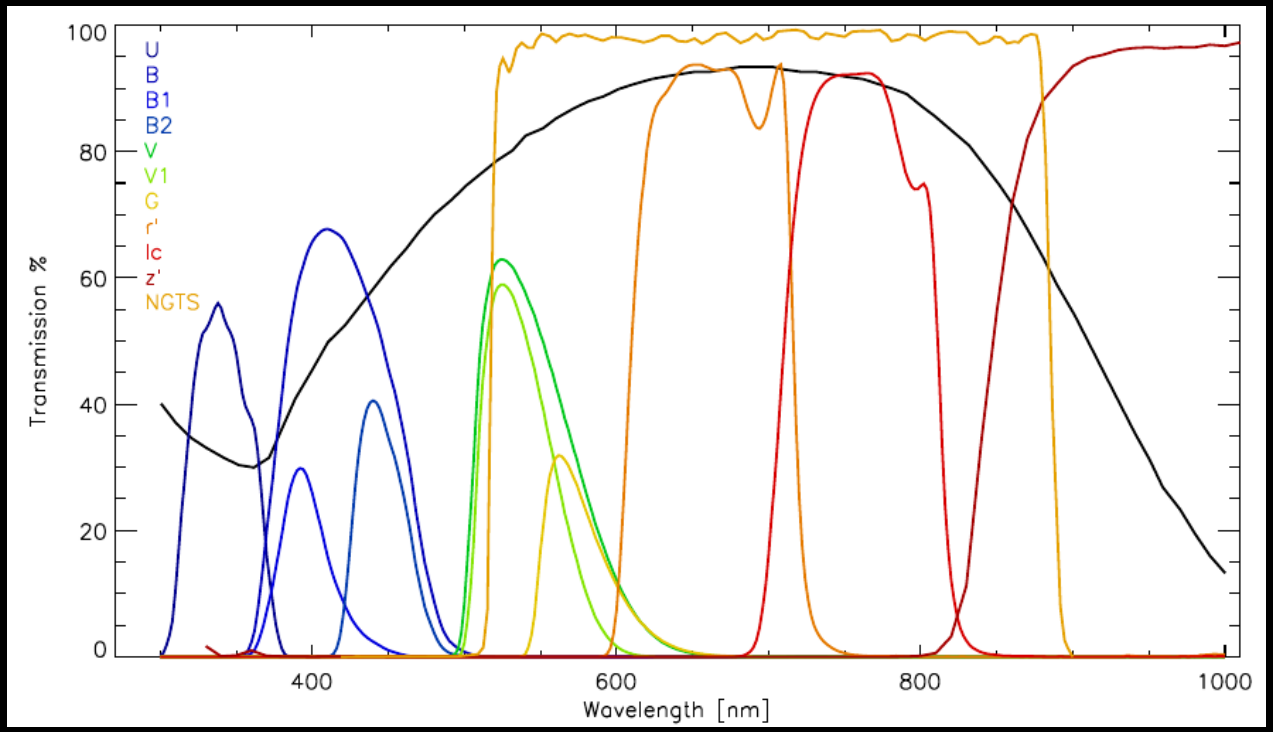
- Technically straight forward

Imaging CCDs at small telescopes

- Technically straight forward
- Easy to automatize, no (little) human interventions necessary

  → roboic/remote operations

- Standard or custom filters

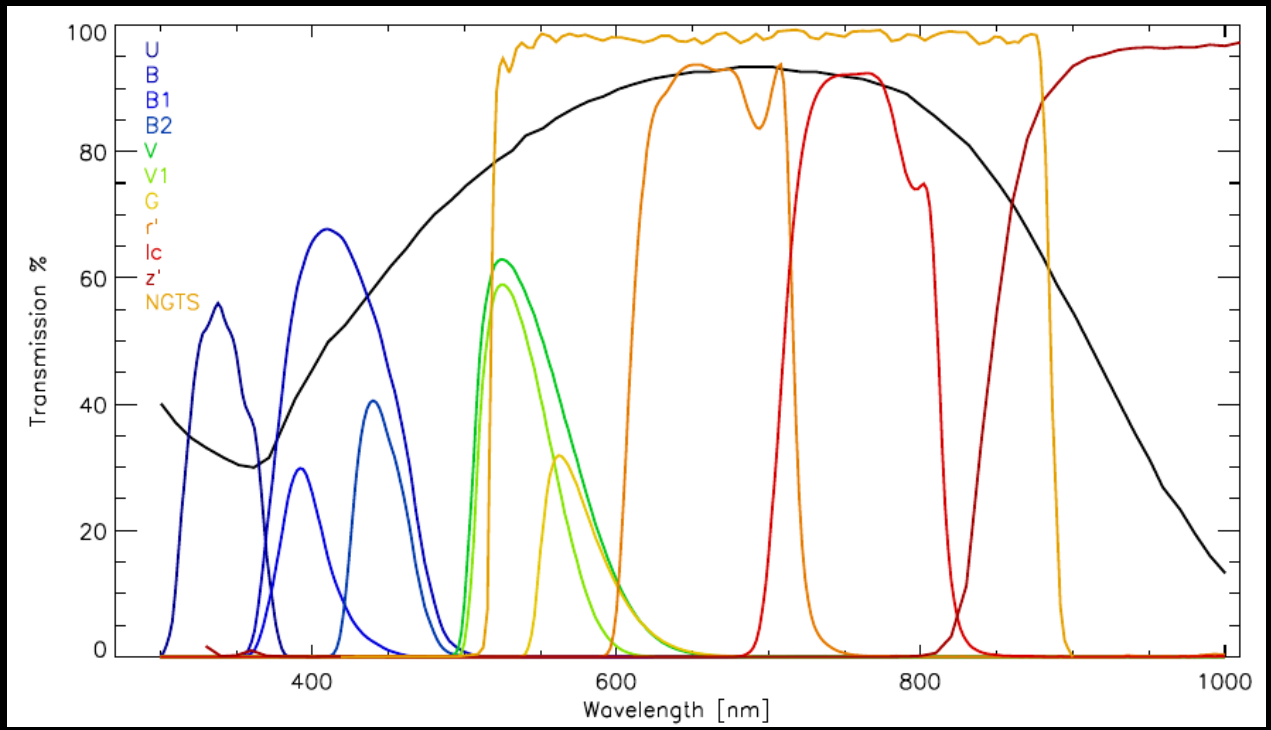


Imaging CCDs at small telescopes

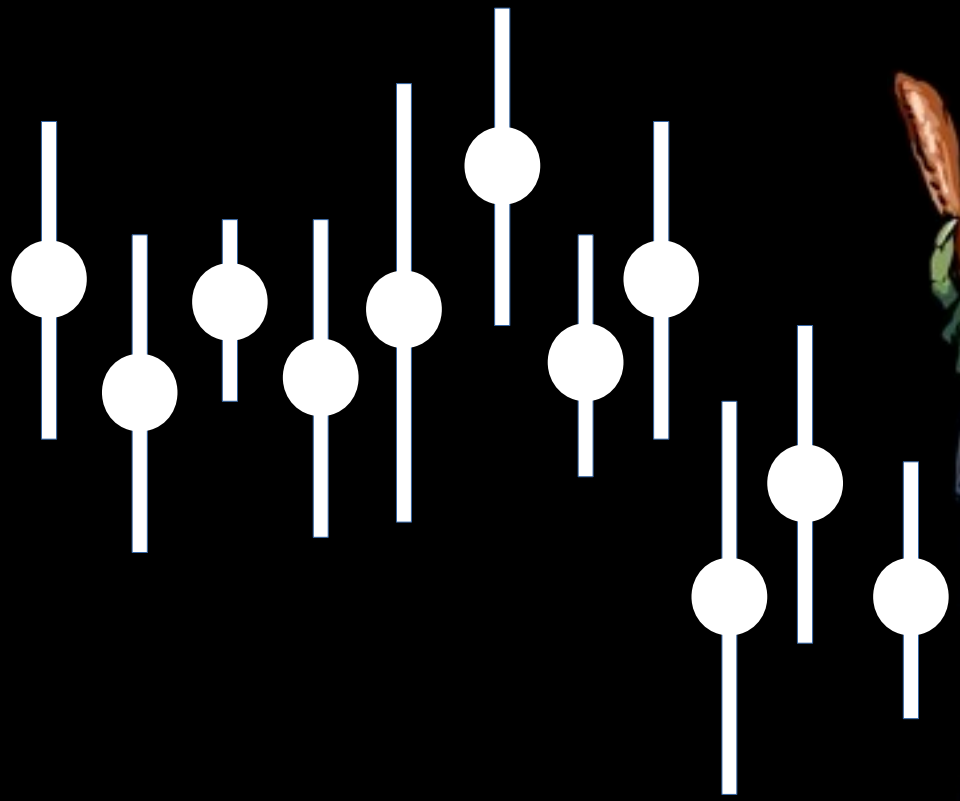
- Technically straight forward
- Easy to automatize, no (little) human interventions necessary

  → roboic/remote operations
- Standard or custom filters
- Large field-of-view easily attainable

  → good for relative photometry of bright stars, or clusters



Data analysis



Aperture photometry

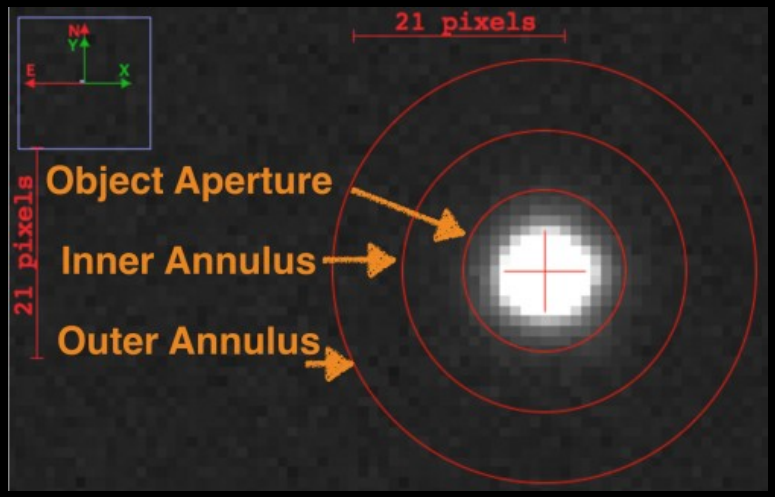


Image: Astrobites / Gudmundur Stefansson

→ Fast and easy

→ Works well for bright, well-resolved objects

Aperture photometry

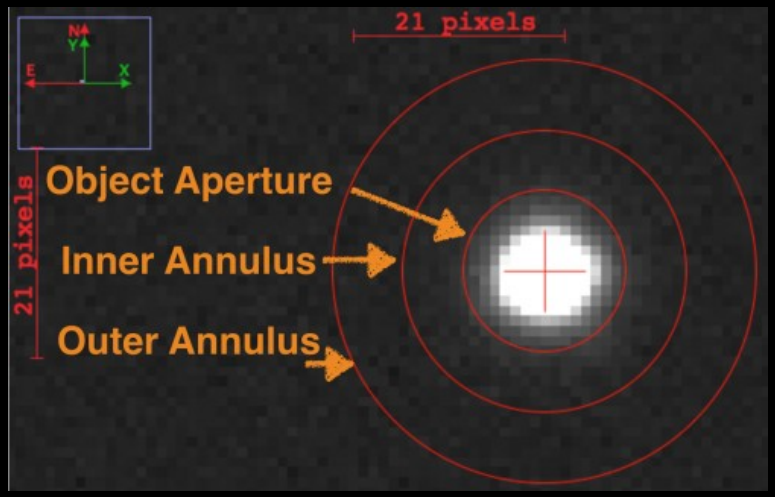


Image: Astrobites / Gudmundur Stefansson

→ Fast and easy

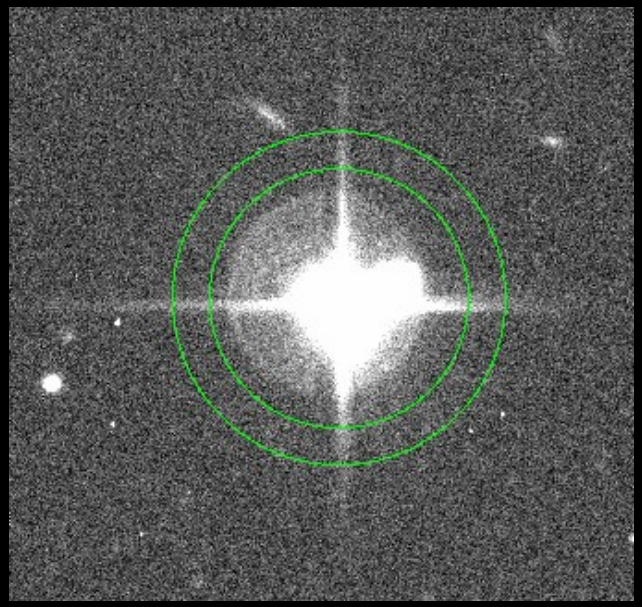
→ Works well for bright, well-resolved objects

Pitfalls:

→ Blending – or stars in sky aperture

→ Centering must be precise

→ Optimization of aperture size and sky annulus can be non-trivial

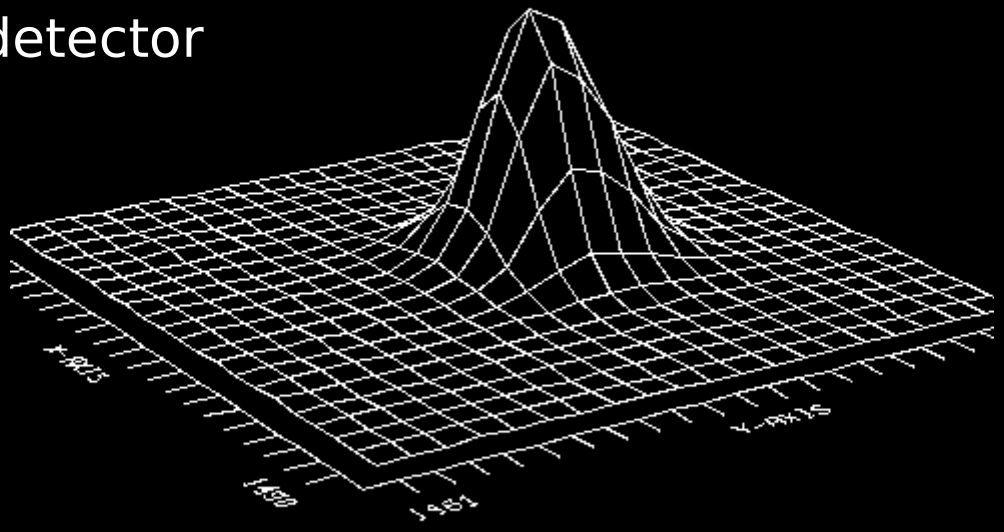


PSF photometry

→ Construct a model PSF for each image

→ Iterative process based on selecting isolated field stars

→ Account for variation across detector

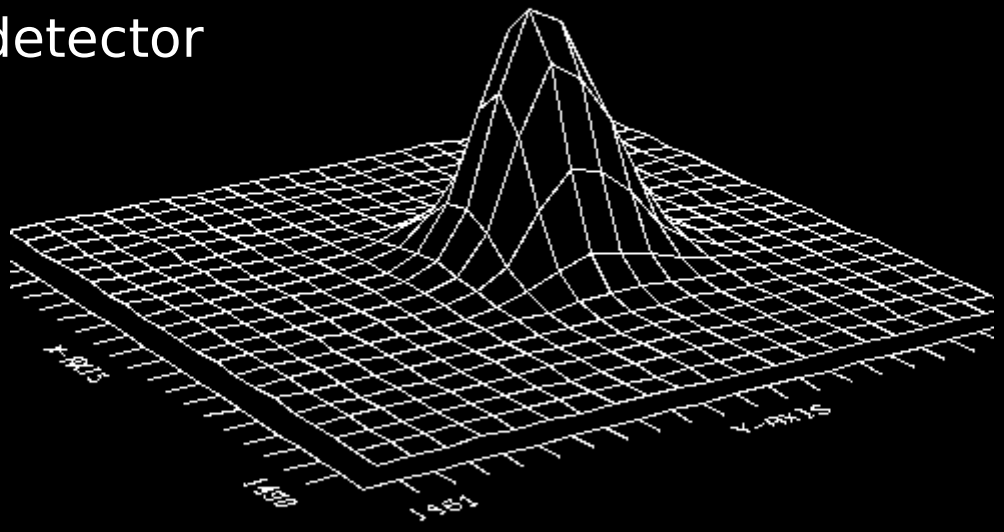


PSF photometry

→ Construct a model PSF for each image

→ Iterative process based on selecting isolated field stars

→ Account for variation across detector



Advantages:

→ Works well for faint sources

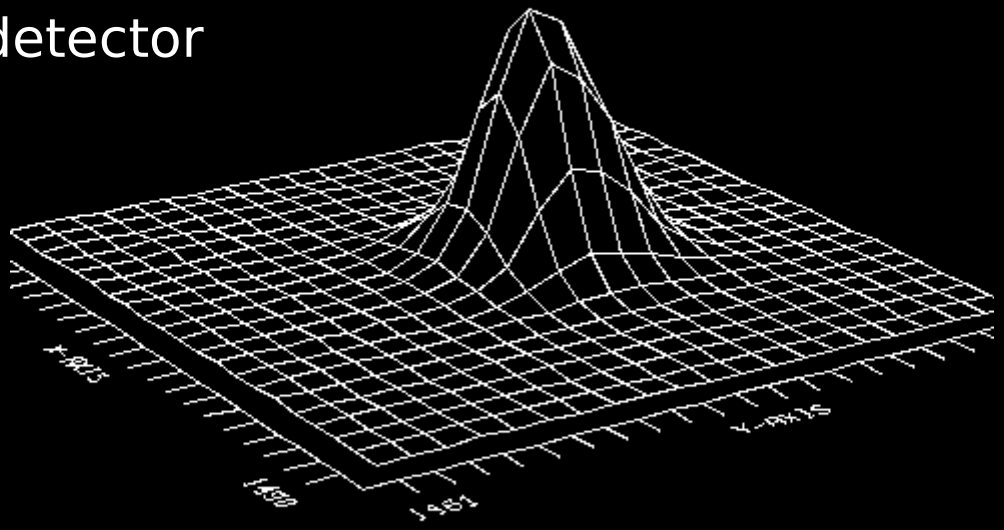
→ Can handle crowded fields

PSF photometry

→ Construct a model PSF for each image

→ Iterative process based on selecting isolated field stars

→ Account for variation across detector



Advantages:

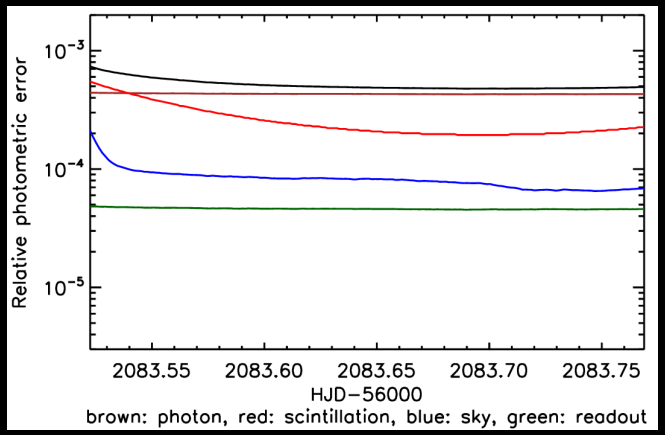
→ Works well for faint sources

→ Can handle crowded fields

Disadvantages:

→ More complex, no added benefit for bright isolated stars

Noise in time-series photometry



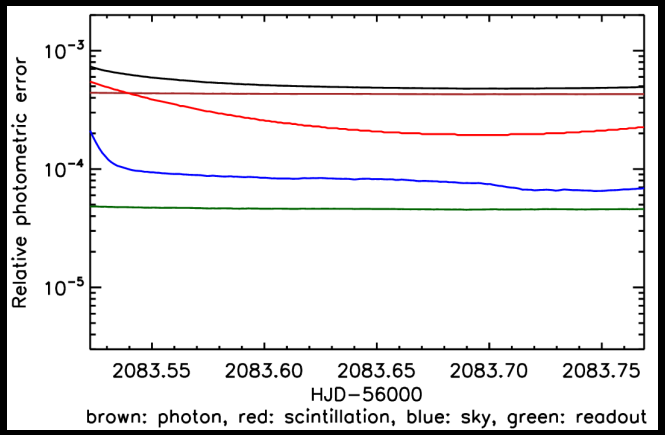
Well-understood noise sources:

→ photon & readout

→ scintillation

→ background (sky)

Noise in time-series photometry



Well-understood noise sources:

→ photon & readout

→ scintillation

→ background (sky)

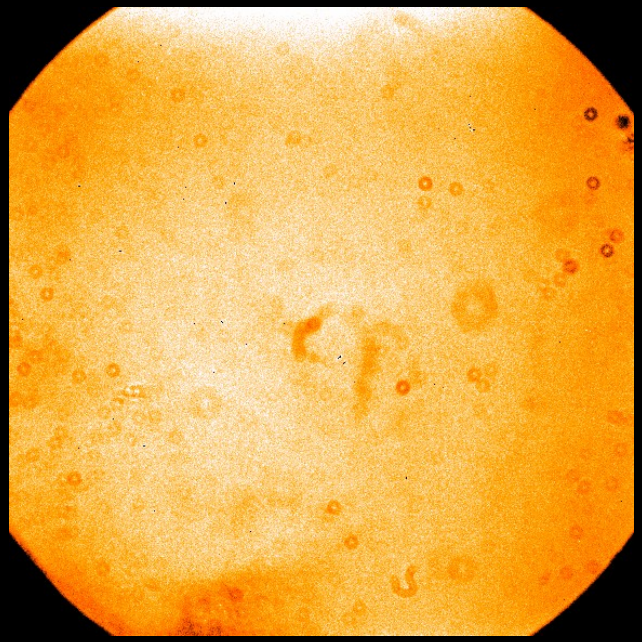
Pesky noise sources:

→ flat field

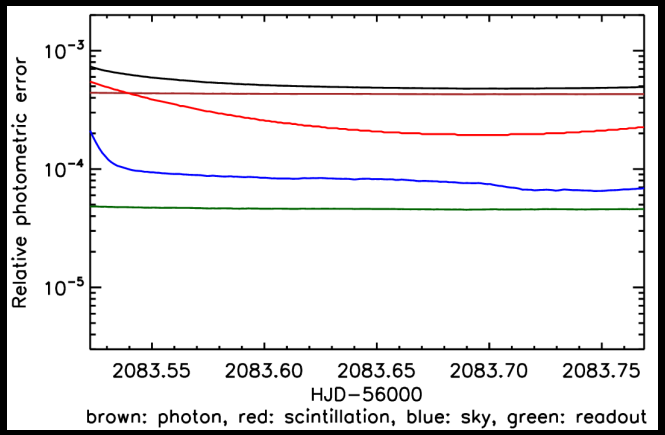
→ PSF variations (time/detector)

→ Cosmics, bad / hot pixels

→ detector non-linearity



Noise in time-series photometry

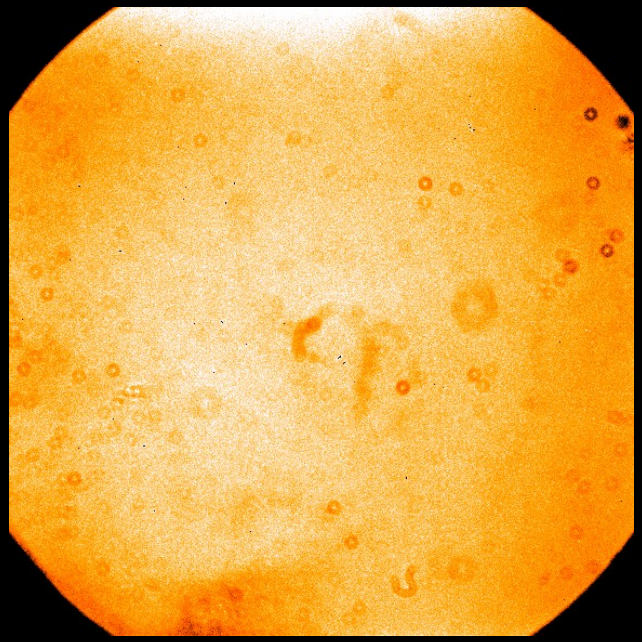


Well-understood noise sources:

→ photon & readout

→ scintillation

→ background (sky)



Pesky noise sources:

→ flat field

→ PSF variations (time/detector)

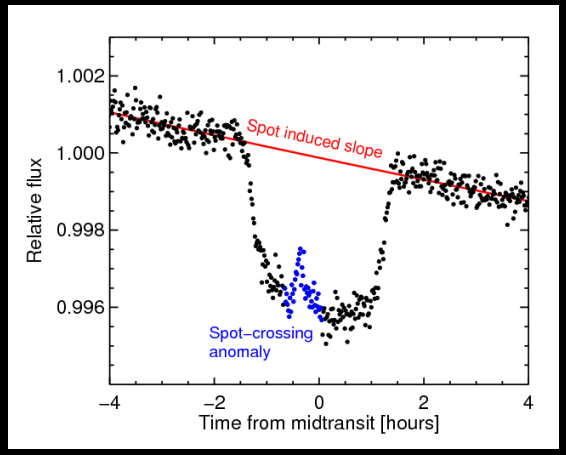
→ Cosmics, bad / hot pixels

→ detector non-linearity

Noise that isn't noise

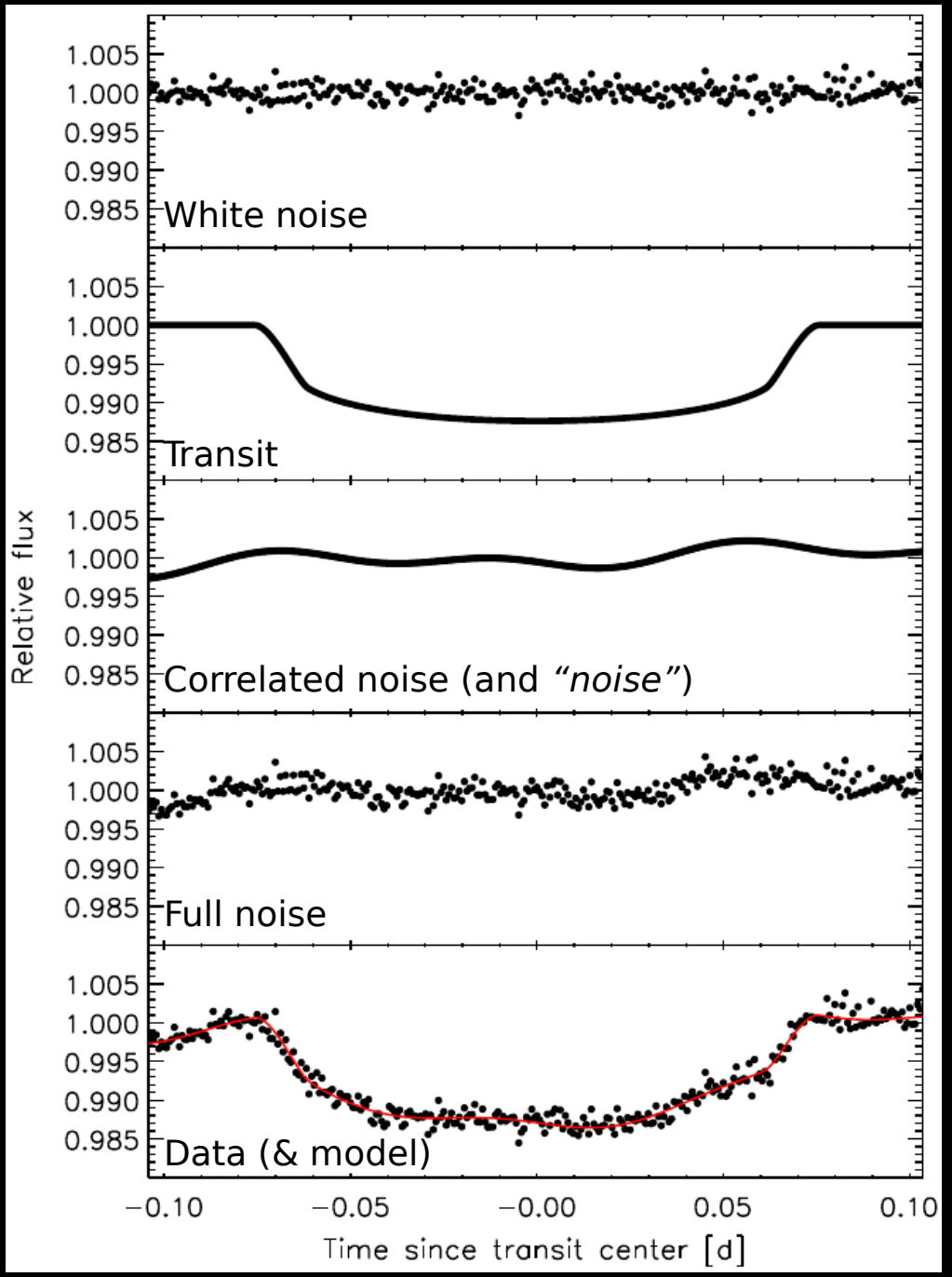
→ various forms of stellar variability

(the one's you are not interested in)



Sanchis-Ojeda+ (2016)

Noise in time-series photometry



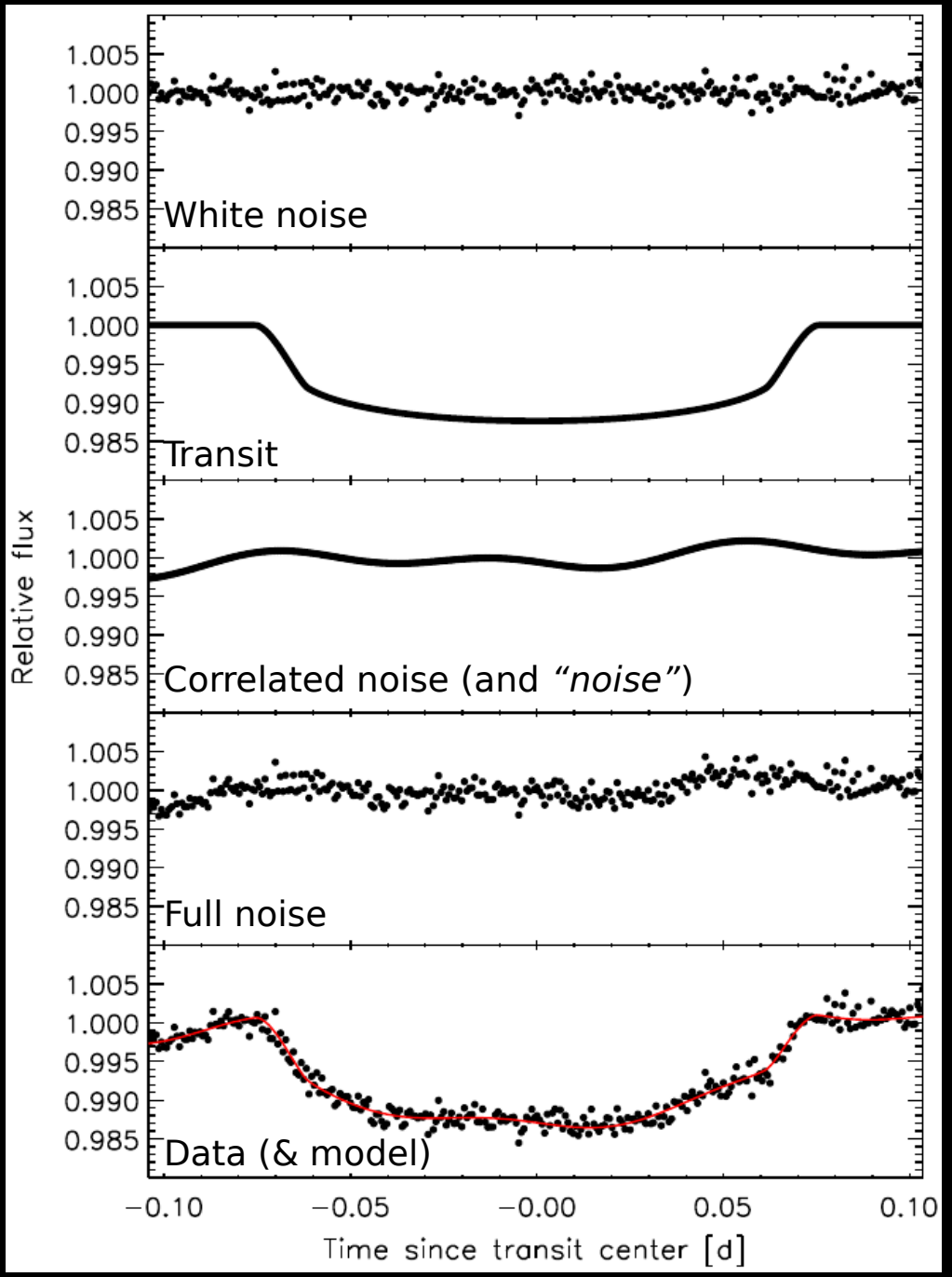
Noise in time-series photometry

This is an ideal case

non-Gaussian random noise ←

noisy correlations ←

Variable noise properties ←



Noise in time-series photometry

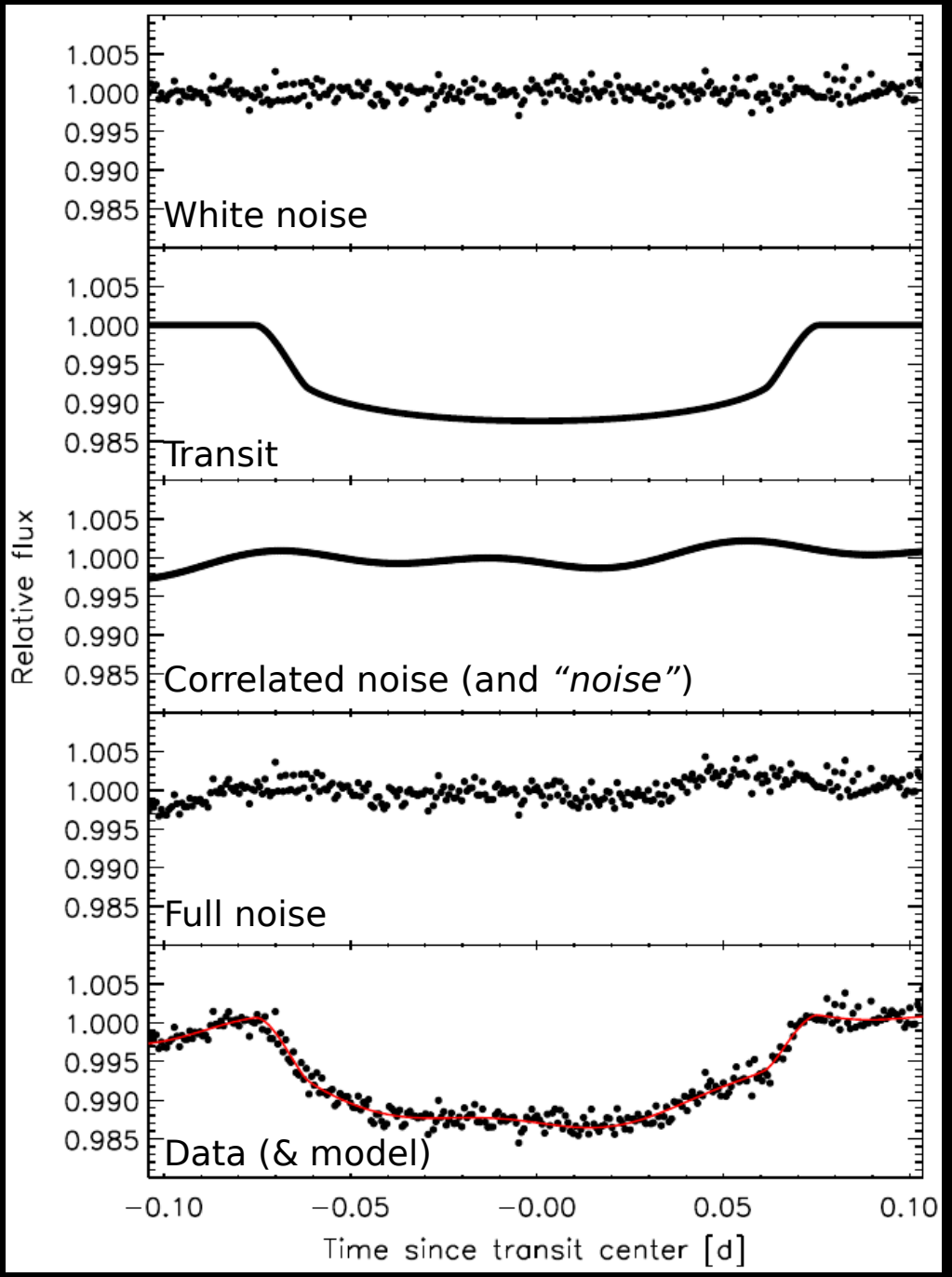
This is an ideal case

non-Gaussian random noise ←

noisy correlations ←

Variable noise properties ←

Different ways of treating correlated noise in time-series photometry



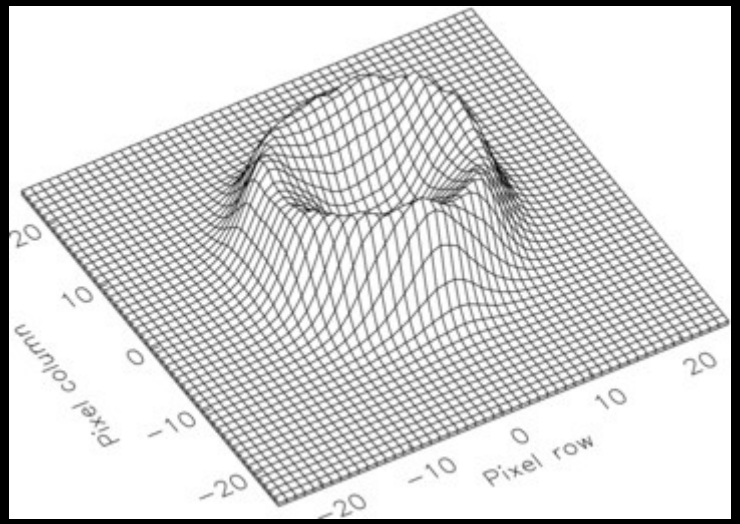
Step 0: Minimize it!

High PSF sampling

→ pixel-to-pixel differences smoothed out

→ optimize detector resolution

→ defocus if target well-resolved



Southworth+ (2009)

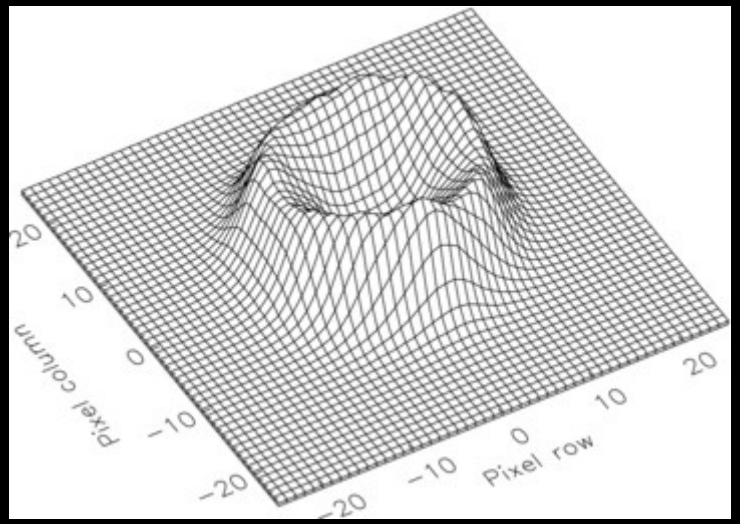
Step 0: Minimize it!

High PSF sampling

→ pixel-to-pixel differences smoothed out

→ optimize detector resolution

→ defocus if target well-resolved



Southworth+ (2009)

Optimize tracking

→ pixel-to-pixel effects as constant as possible

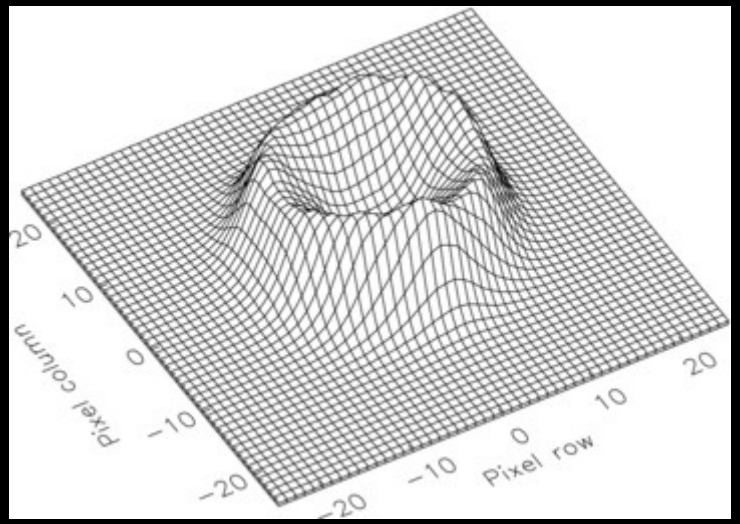
Step 0: Minimize it!

High PSF sampling

→ pixel-to-pixel differences smoothed out

→ optimize detector resolution

→ defocus if target well-resolved



Southworth+ (2009)

Optimize tracking

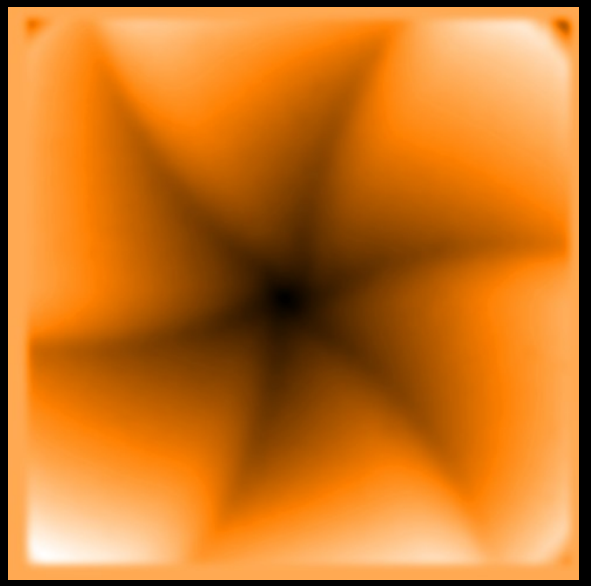
→ pixel-to-pixel effects as constant as possible

Optimize exposure times

→ avoid tiny expusure times to reduce shutter effects

Know your detector linearity range

→ it may be smaller than you think!



Option 1: parametric models

Model your noise as a function of external parameters

→ Model = astrophysics * baseline

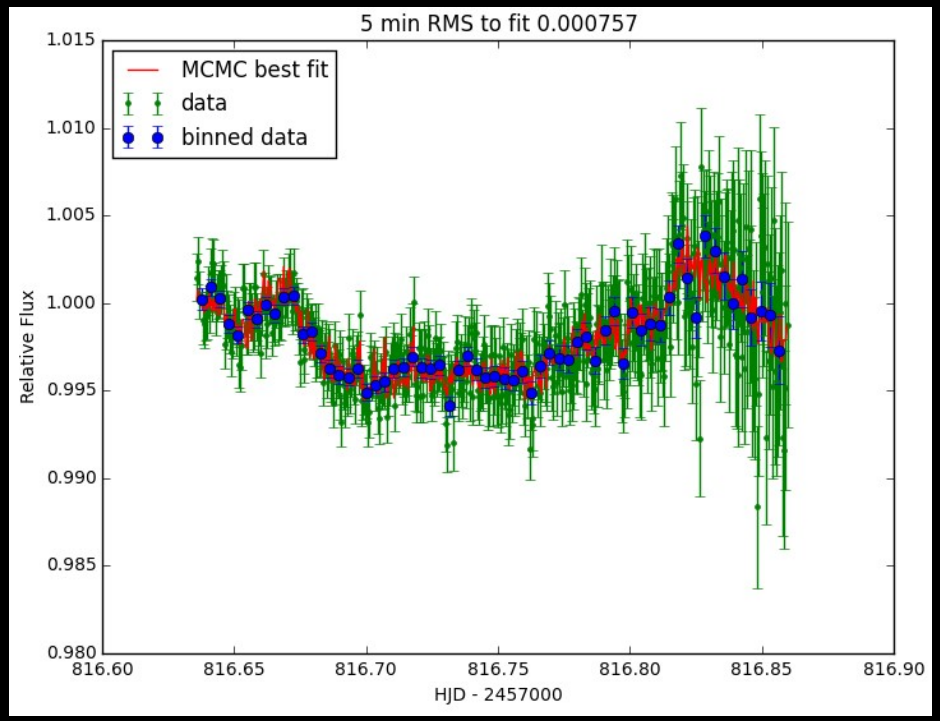
→ works well if the relationship is cleanly described by the function you are using, e.g. a polynomial

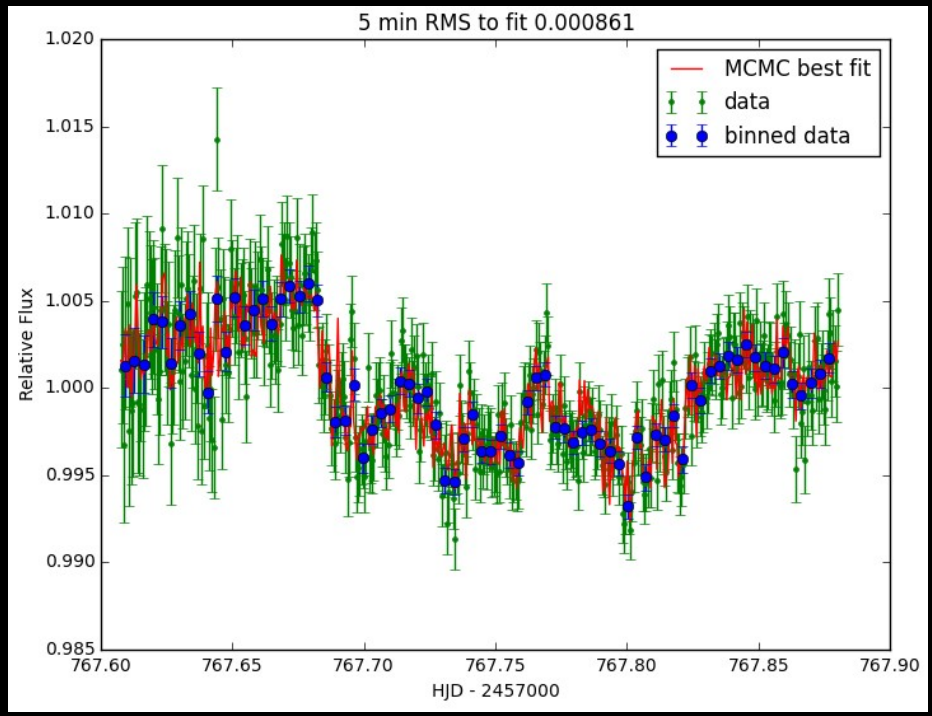
Option 1: parametric models

Model your noise as a function of external parameters

→ Model = astrophysics * baseline

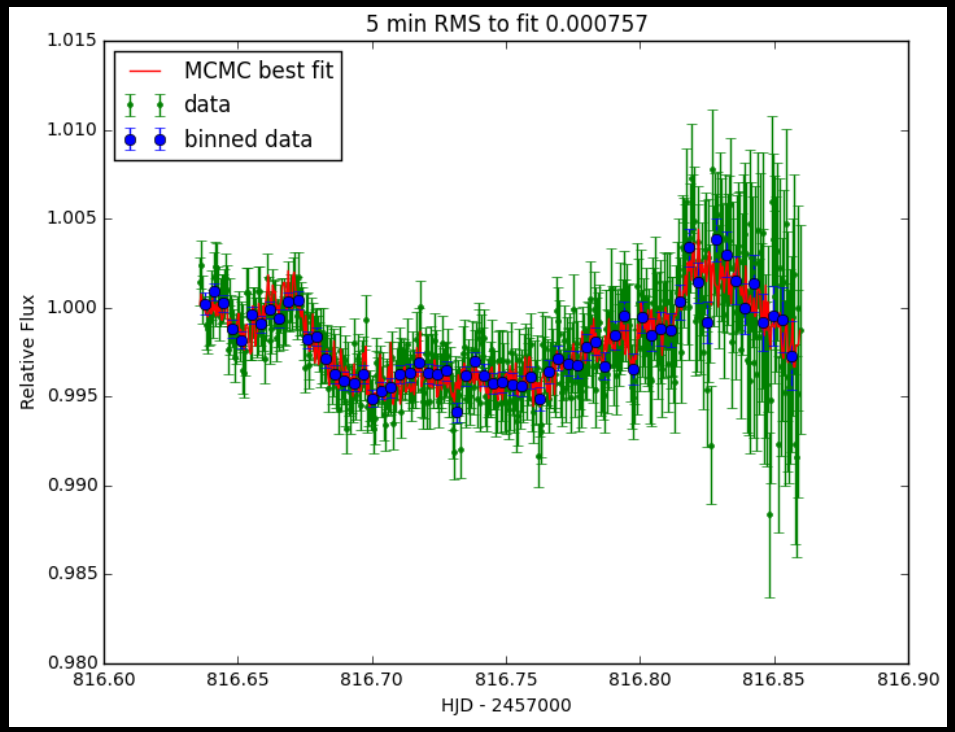
→ works well if the relationship is cleanly described by the function you are using, e.g. a polynomial

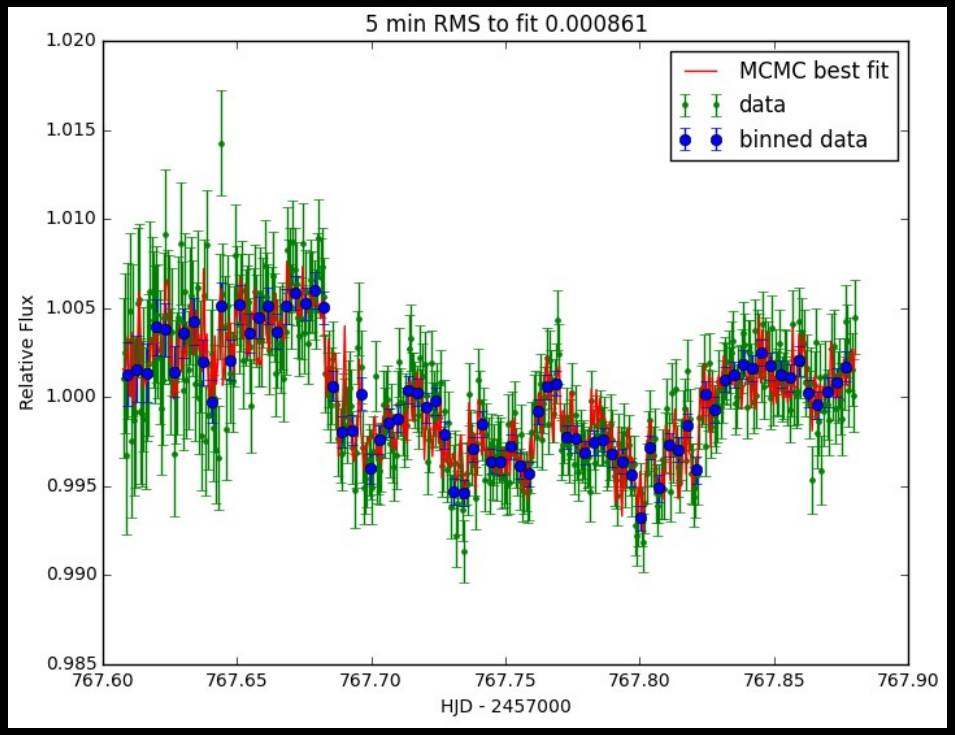




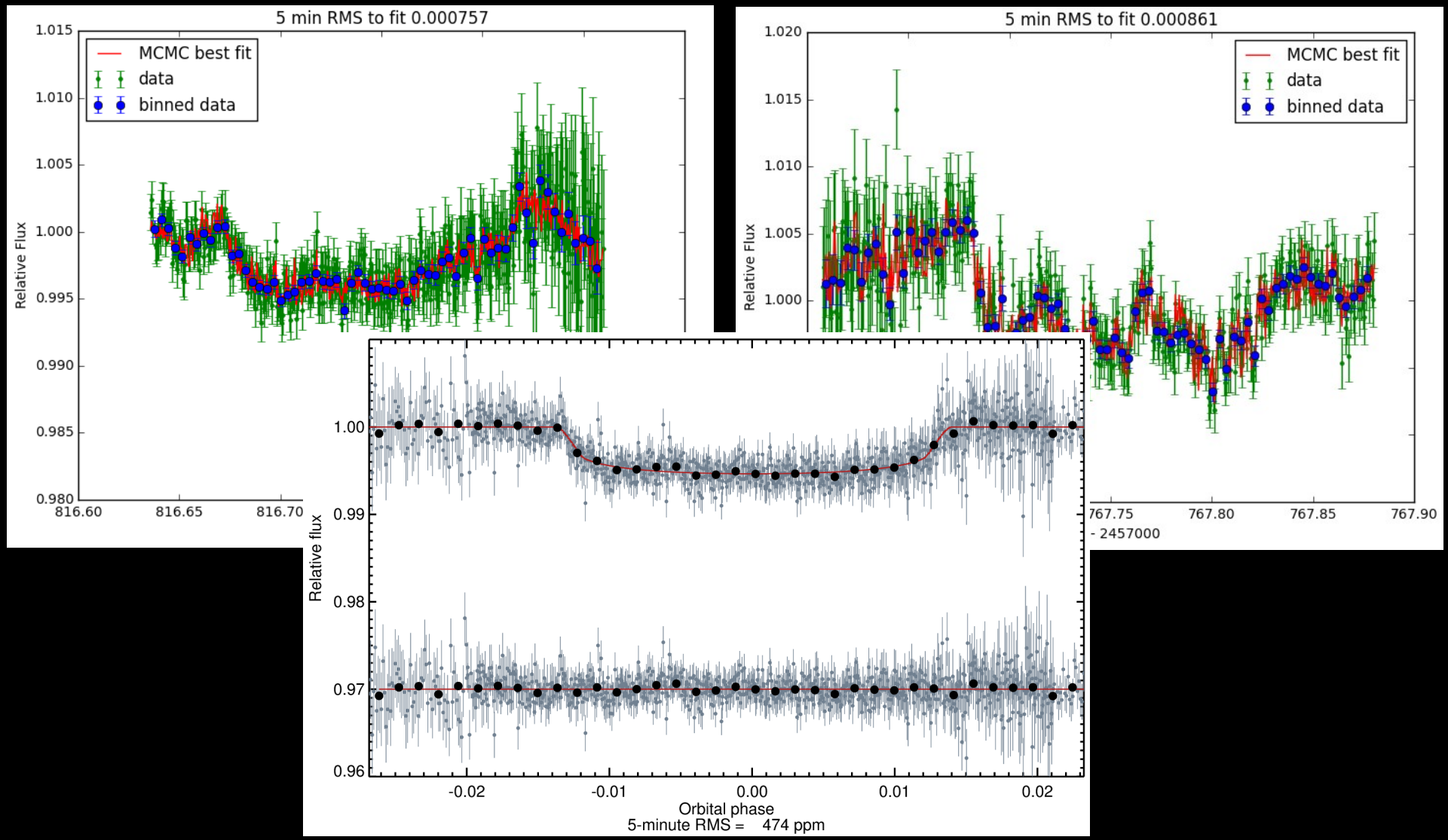
Transit LCs with nonlinearity problem: baseline = $A_0 + A_1$*FWHM + A_2*FWHM^2

Option 1: parametric models





Option 1: parametric models



Danger: of over-fitting, incorrect error propagition

Option 2: Gaussian processes

→ Treat the time series as a stochastic process defined by its covariance function

→ The covariance function is assumed to have an analytic form, e.g. exponential decay or periodic function

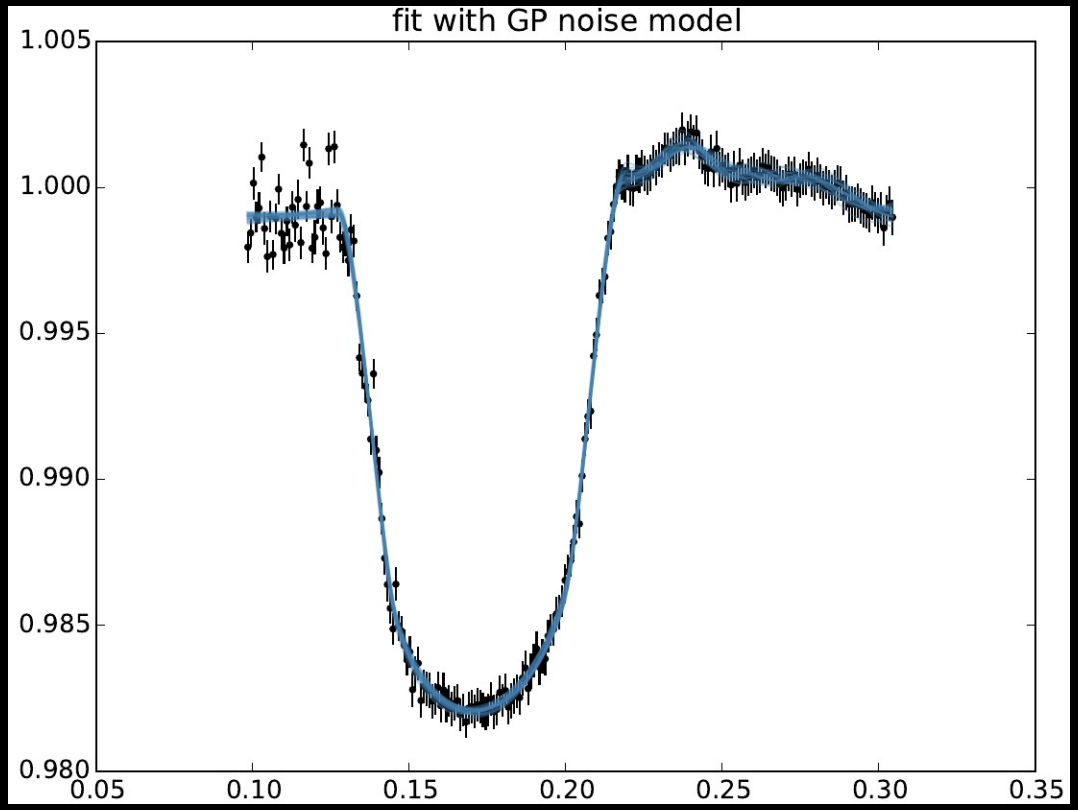
→ The coefficients are fit with the data

Option 2: Gaussian processes

→ Treat the time series as a stochastic process defined by its covariance function

→ The covariance function is assumed to have an analytic form, e.g. exponential decay or periodic function

→ The coefficients are fit with the data



→ Gibson+ 2013,
Foreman-Mackey 2015

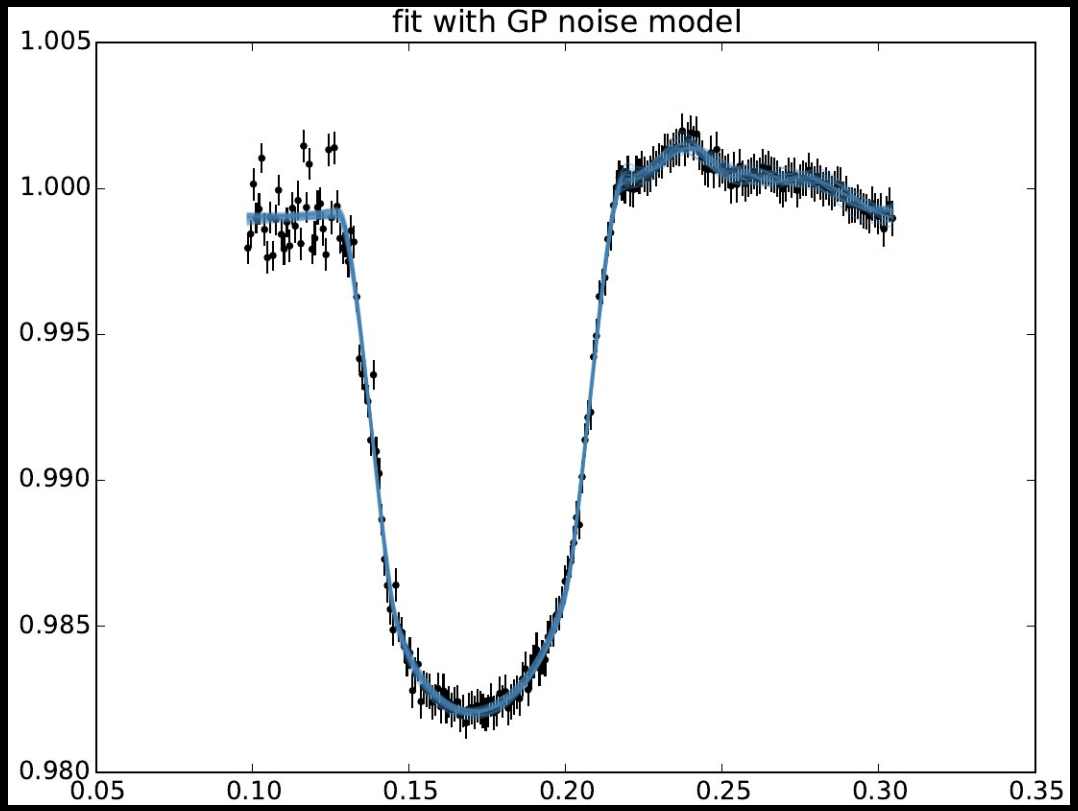
Option 2: Gaussian processes

With great power comes great responsibility

→ GPs are good at modeling the data, based on the data

→ Kernel parameters can be ill-constrained but fit looks good

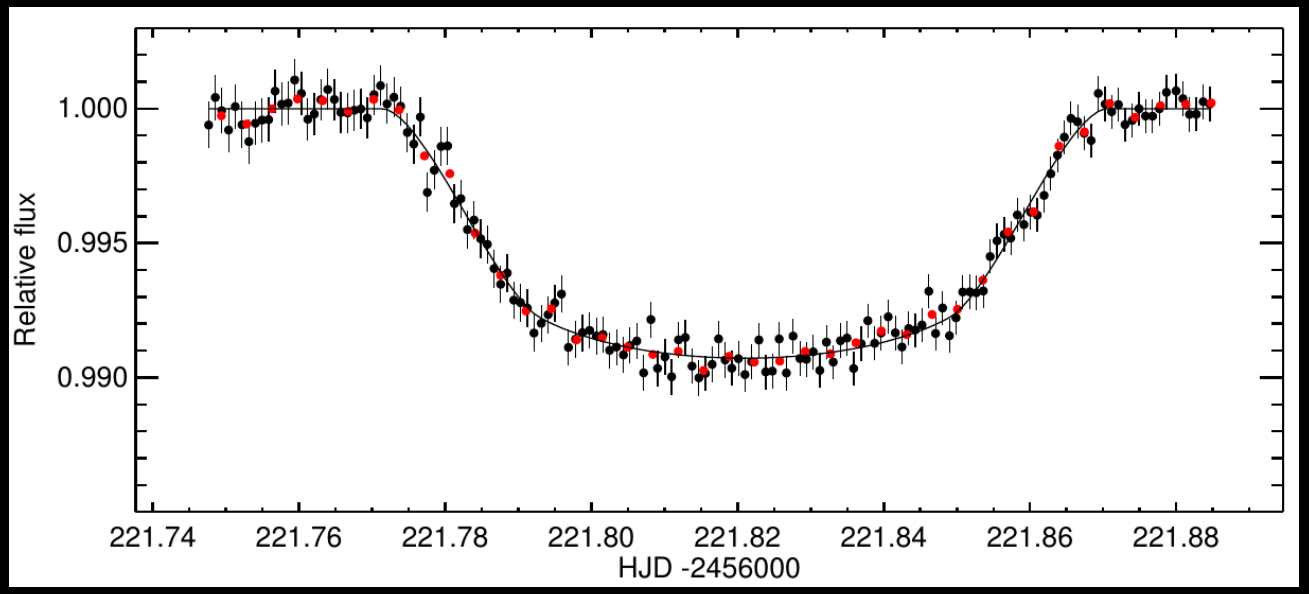
→ Size of errors are key (but you can fit for white noise)



In a nutshell

→ Decrease noise sources by optimizing observation strategy (defocus, optimize exposure times, guiding)

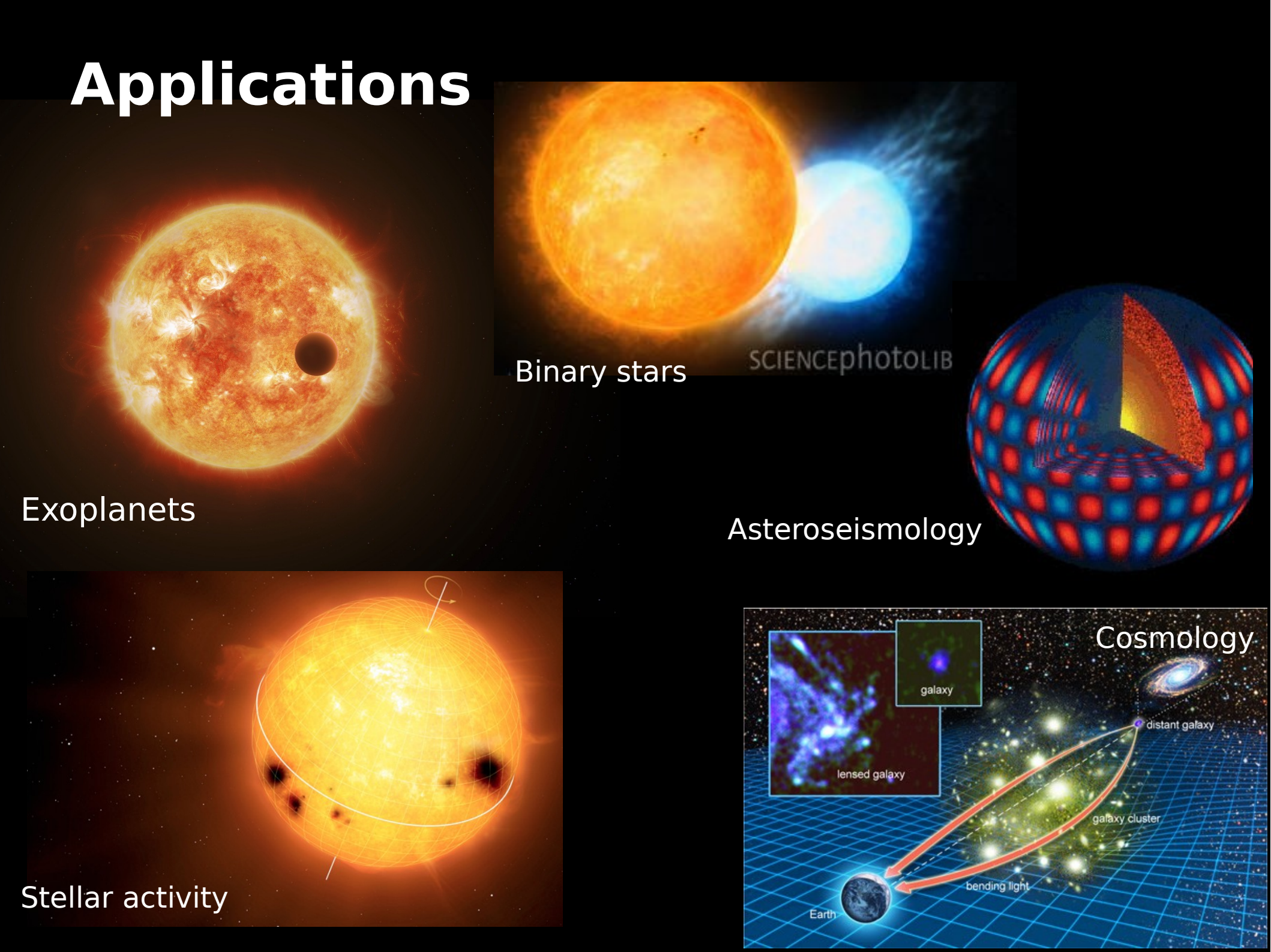
→ Model red noise *together* with your favourite astrophysics



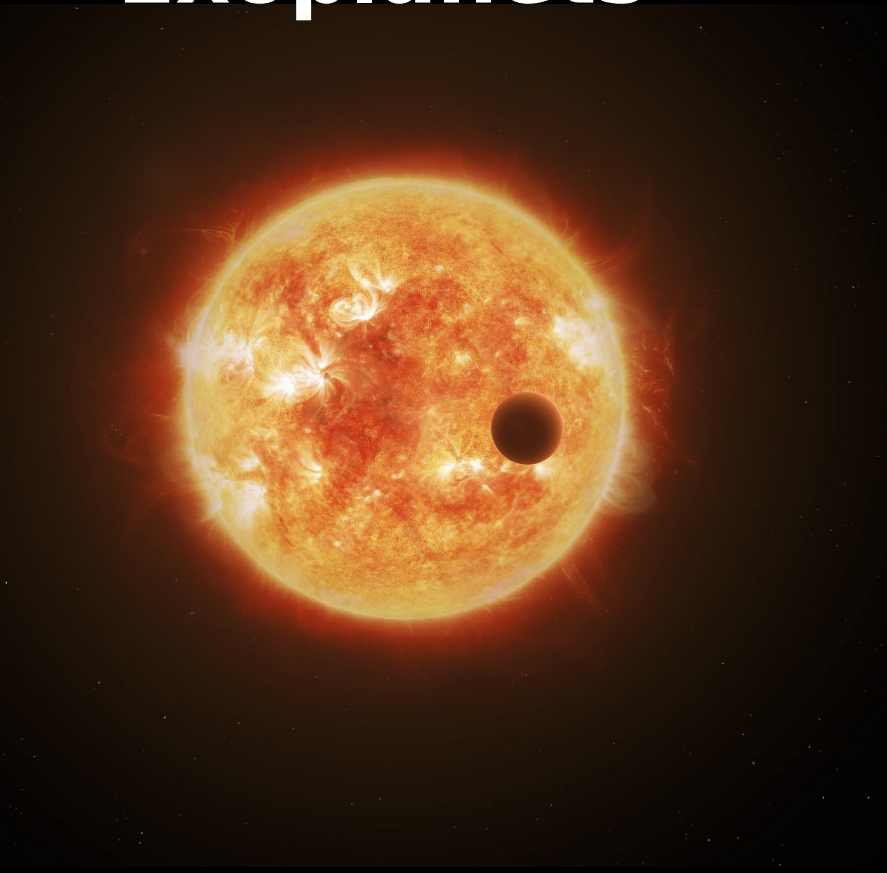
WASP-146 with EulerCam

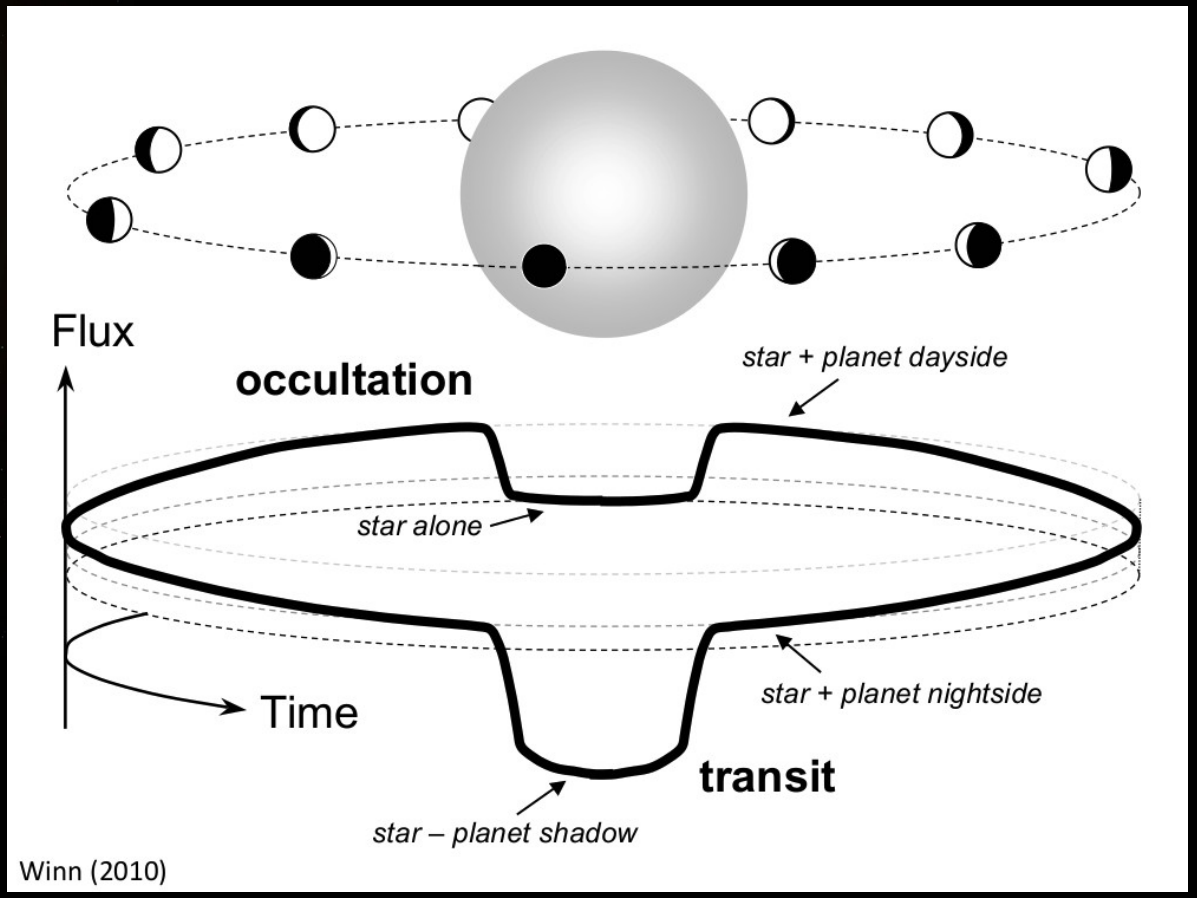
RMS/5min = 245ppm

Applications

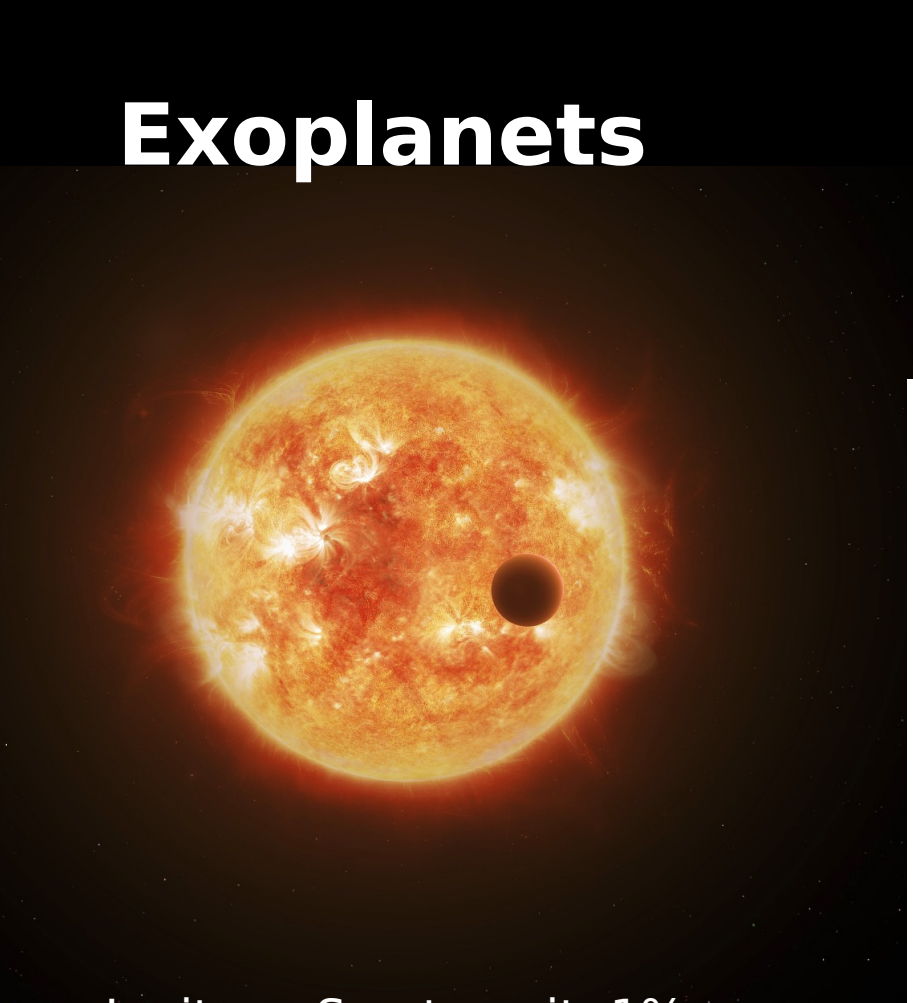


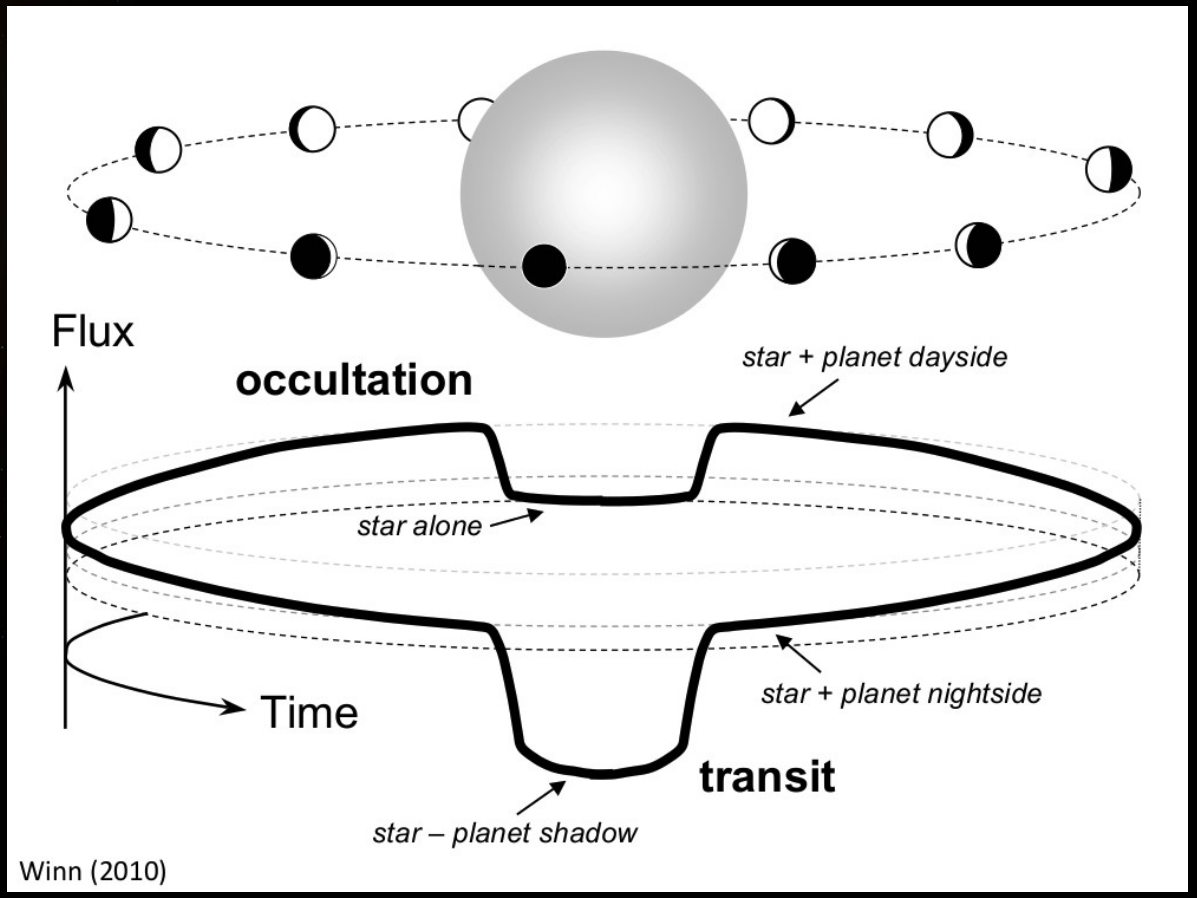
Exoplanets




Flux
occultation
star + planet dayside
star alone
Time
star + planet nightside
transit
star – planet shadow
Winn (2010)

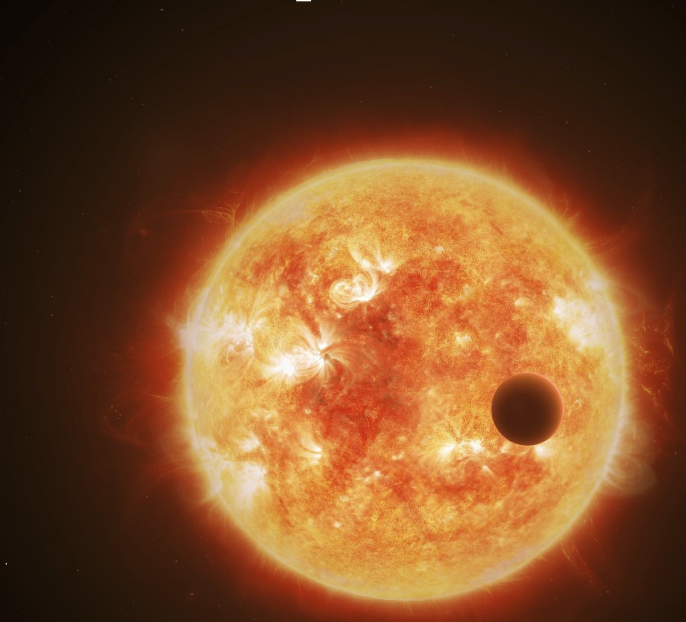
Exoplanets

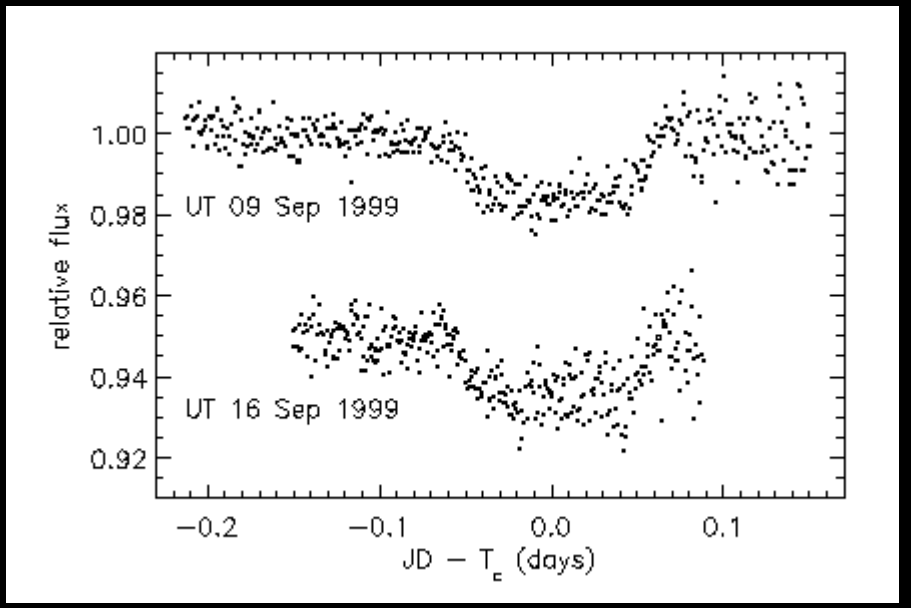




- Jupiter – Sun transit: 1%
- Earth – Sun transit: 80 ppm
- Earth – late M star transit: 1%
- 2000K hot Jupiter occultation (z): ~500 ppm

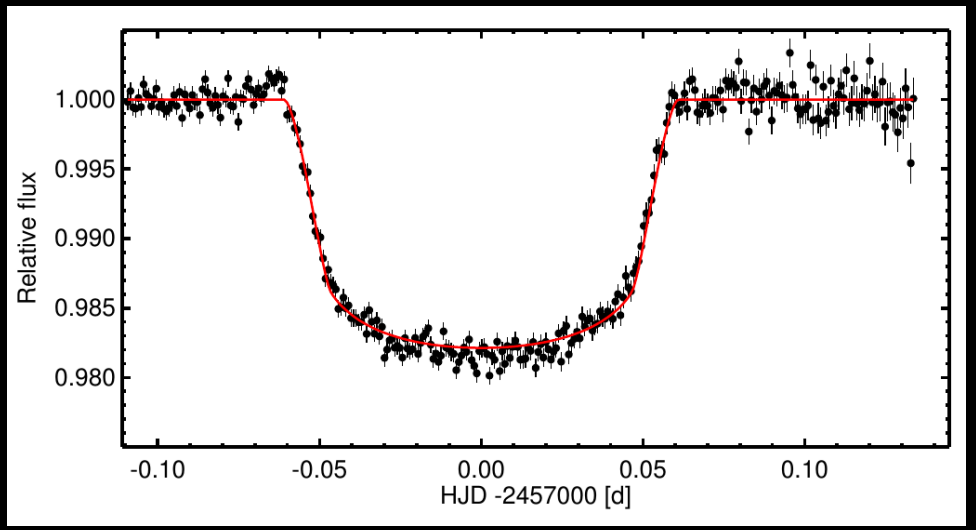
Exoplanets





HD 209458 Charbonneau+ 2000

- Jupiter – Sun transit: 1%
- Earth – Sun transit: 80 ppm
- Earth – late M star transit: 1%
- 2000K hot Jupiter occultation (z): ~500 ppm



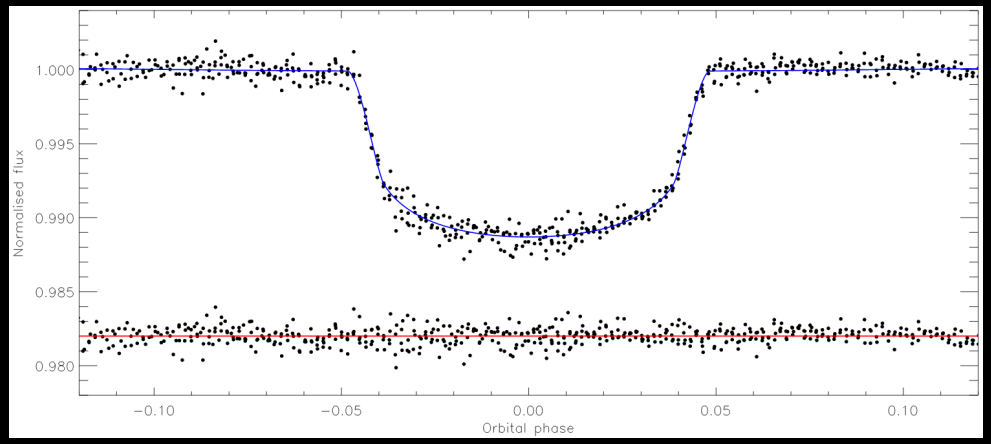
WASP-121, EulerCam, January 2018

Sizing planets

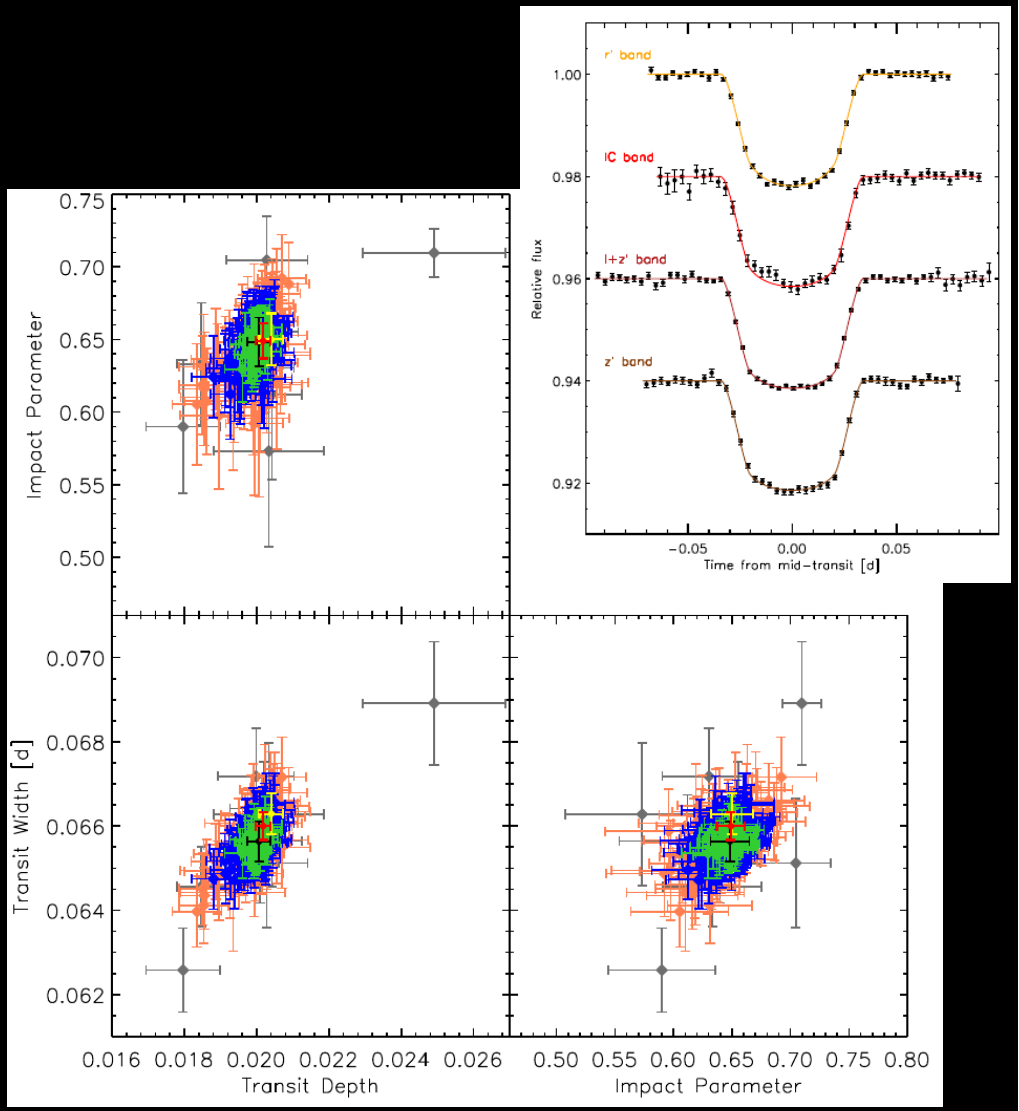
Measure precise transit shapes to better determine

→ planetary radius
→ orbital parameters a_{sm}, incl.

→ stellar mean density (Seager & Mallen-Ornelas 2003)



WASP-18, Southworth+ 2009



14 transits of WASP-19, Lendl+ 2012

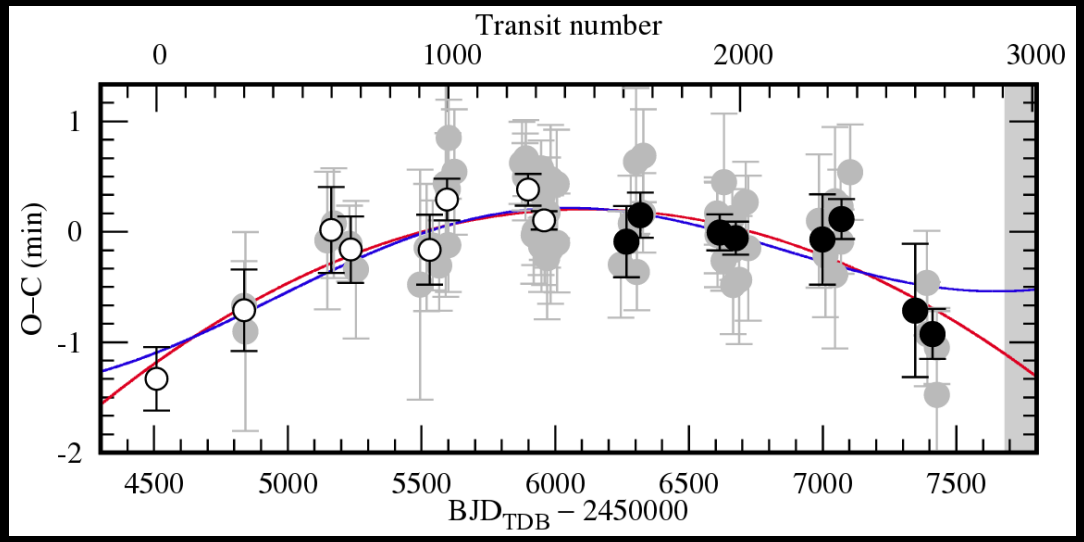
Transit Timing Variations

Measure precise mid-transit times over a long time baseline searching for period variations

→ additional bodies

→ orbital decay

→ orbital precession



29+ transits of WASP-12, Maciejewski+ 2016

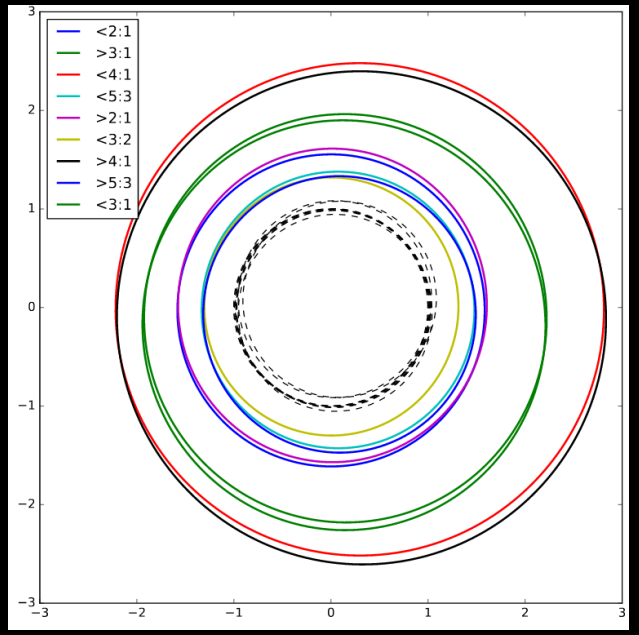
Transit Timing Variations

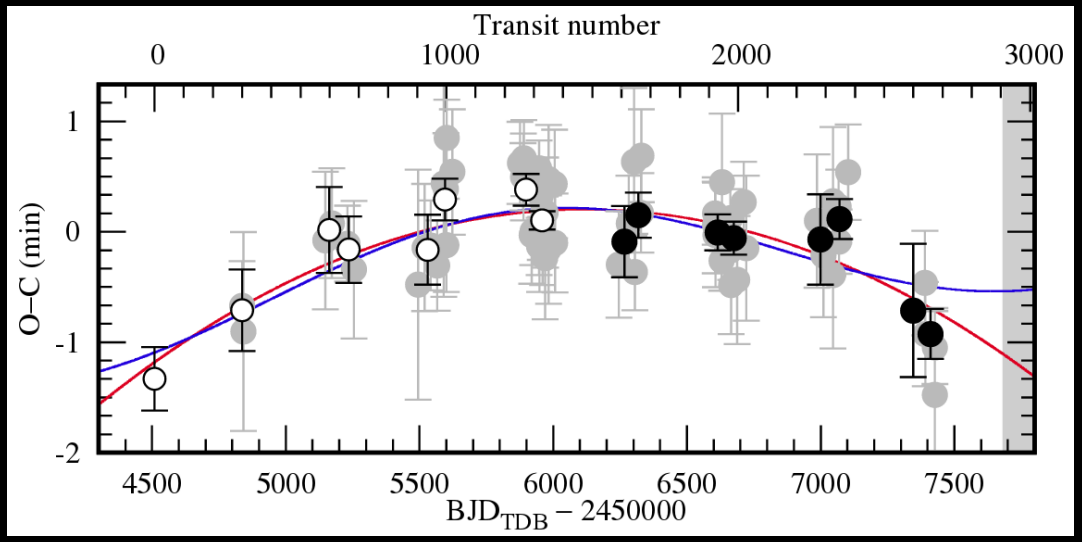
Measure precise mid-transit times over a long time baseline searching for period variations

→ additional bodies

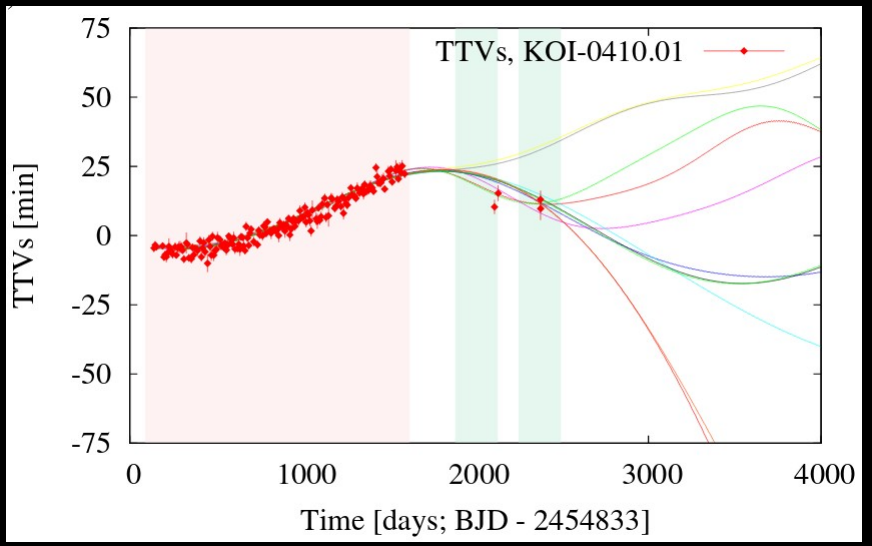
→ orbital decay

→ orbital precession



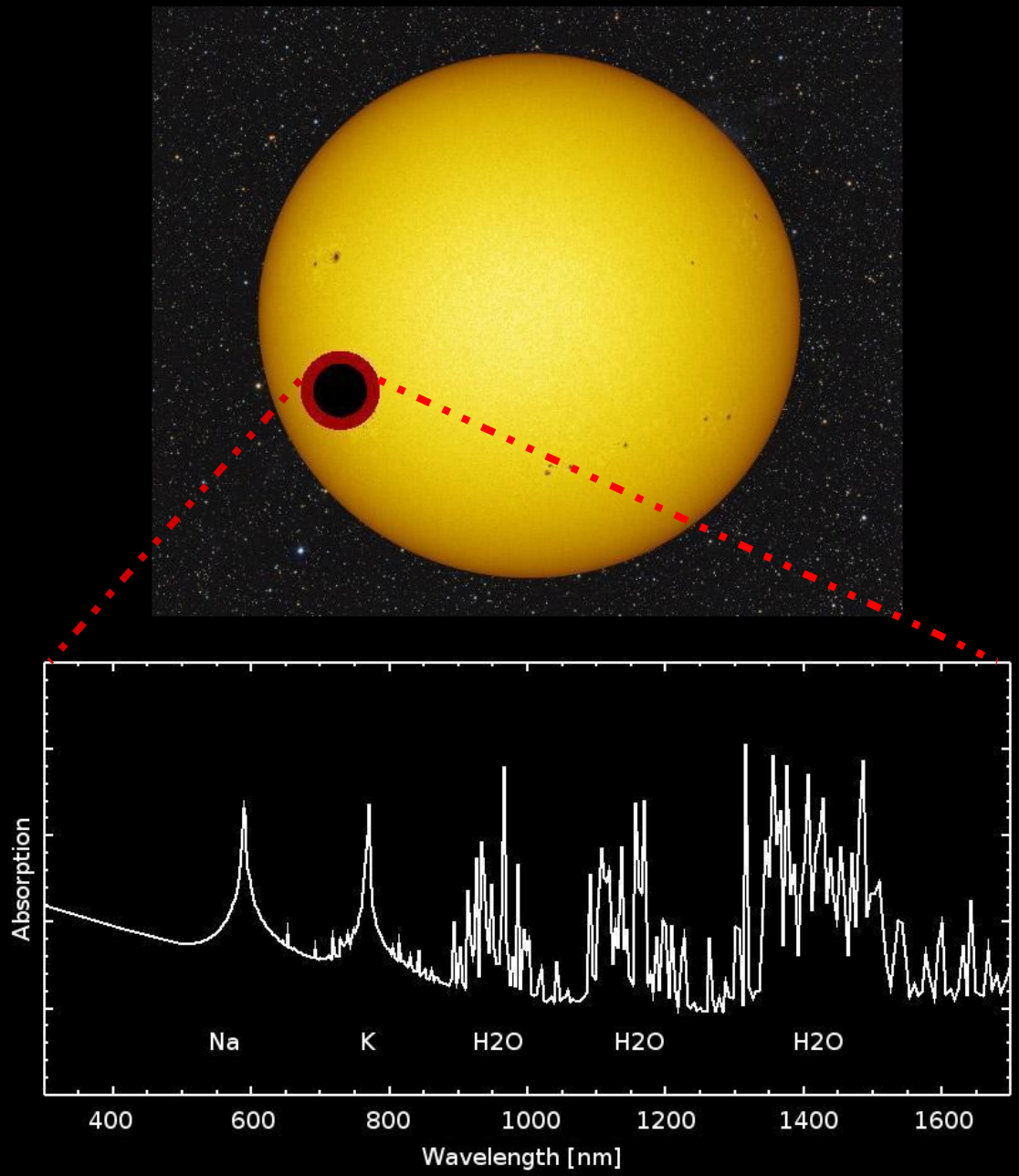


29+ transits of WASP-12, Maciejewski+ 2016



KOI-04191.01, von Essen+ 2018

Transmission spectra

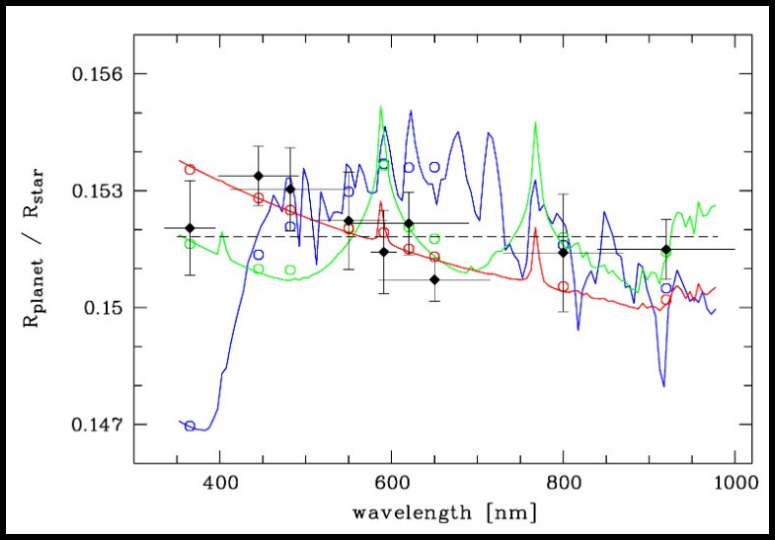


Transmission spectra

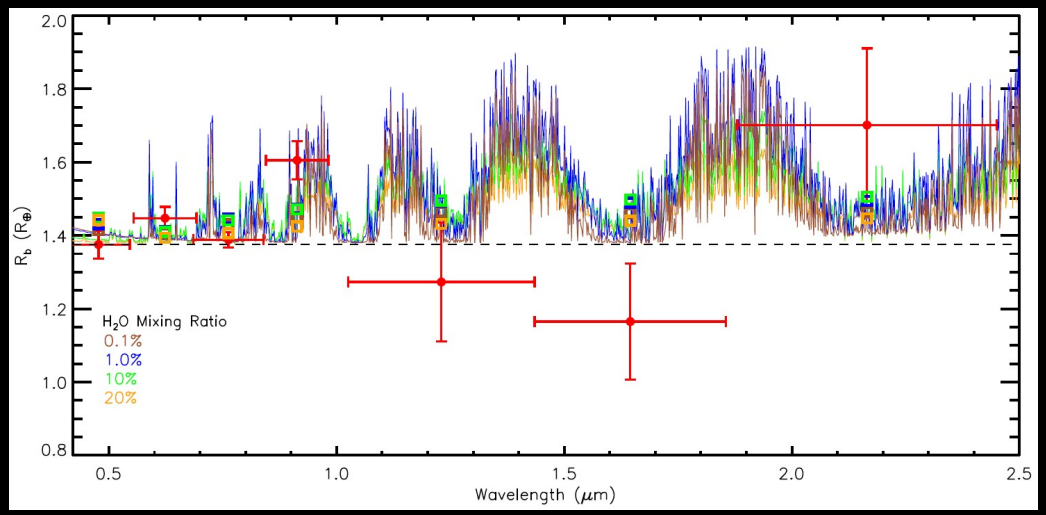
Wavelength-dependent variations in transit depth

→ absorption features in planetary atmosphere

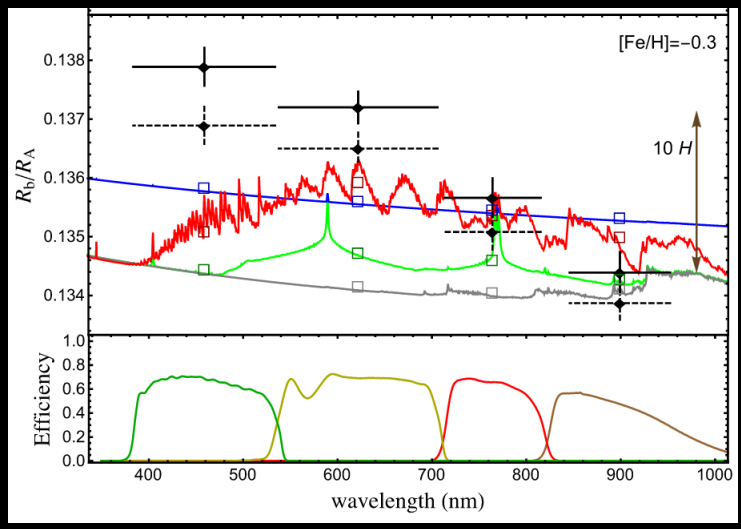
→ Na, K, H_2O, TiO, VO, Aerosols



HAT-P-32, Mallonn+ 2016



GJ1132, Southworth+ 2017



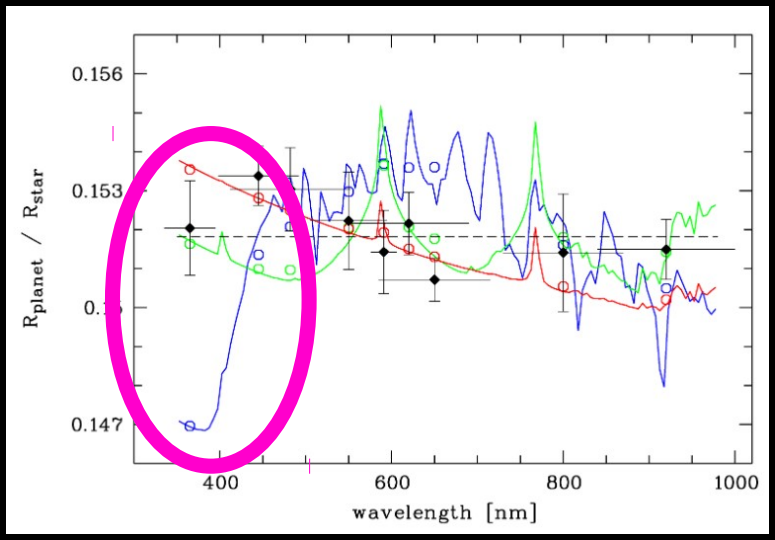
WASP-36, Mancini+ 2016

Transmission spectra

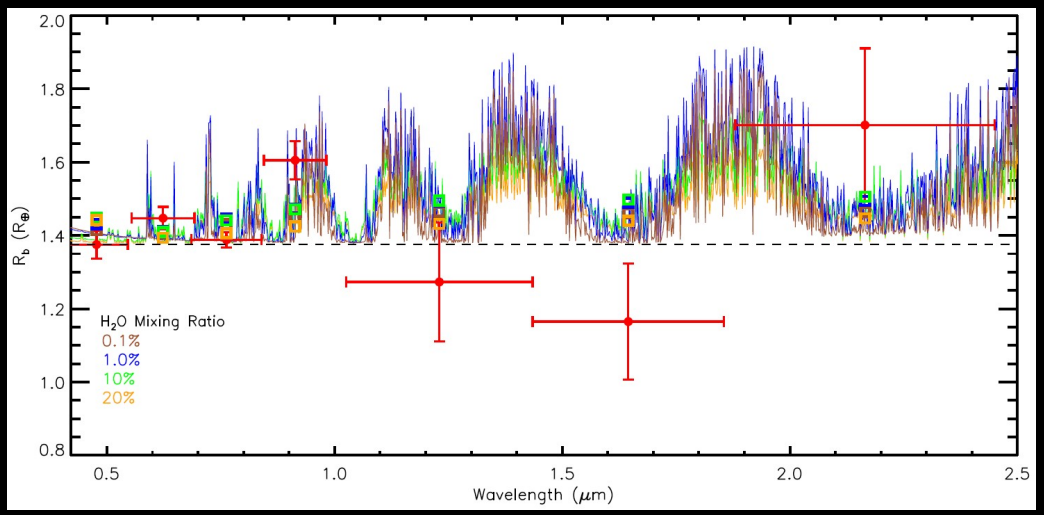
Wavelength-dependent variations in transit depth

→ absorption features in planetary atmosphere

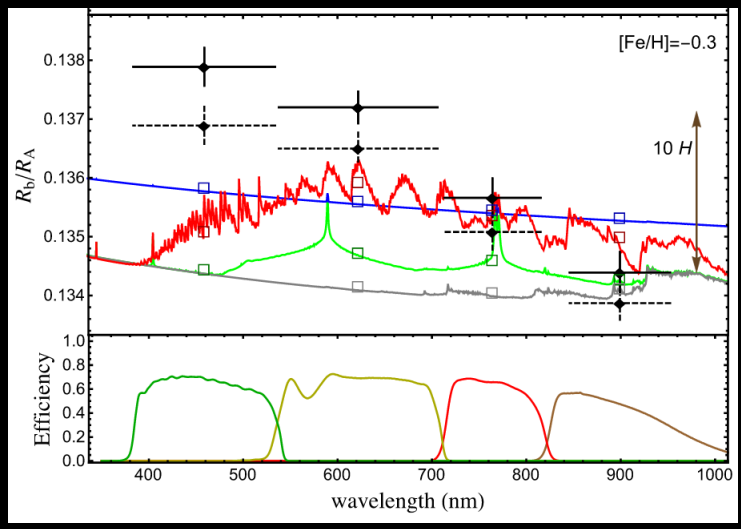
→ Na, K, H_2O, TiO, VO, Aerosols



HAT-P-32, Mallonn+ 2016

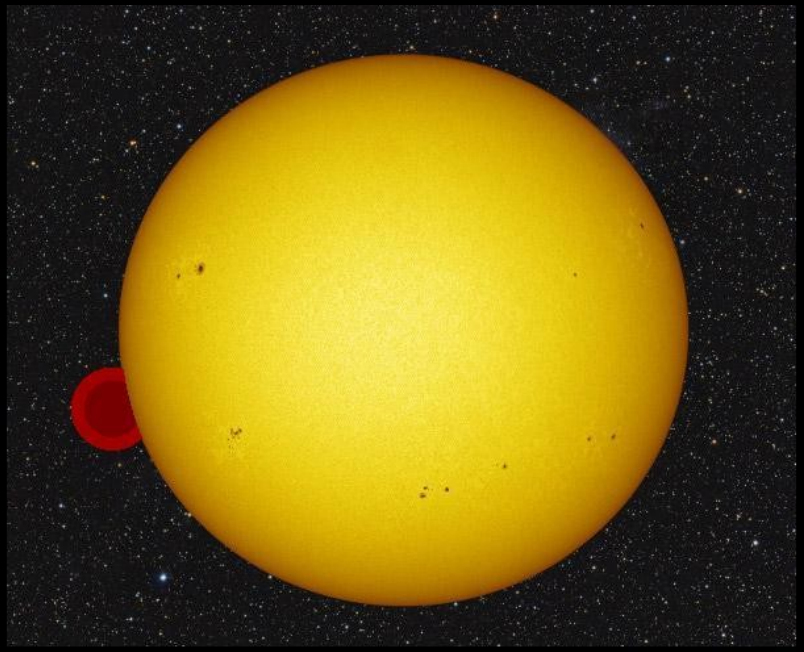


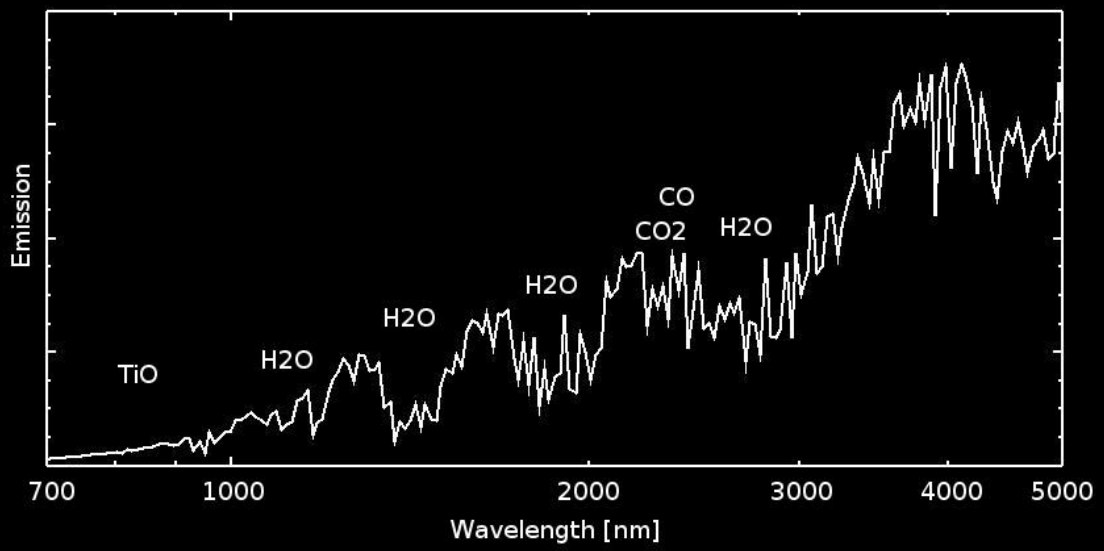
GJ1132, Southworth+ 2017



WASP-36, Mancini+ 2016

Emission spectra





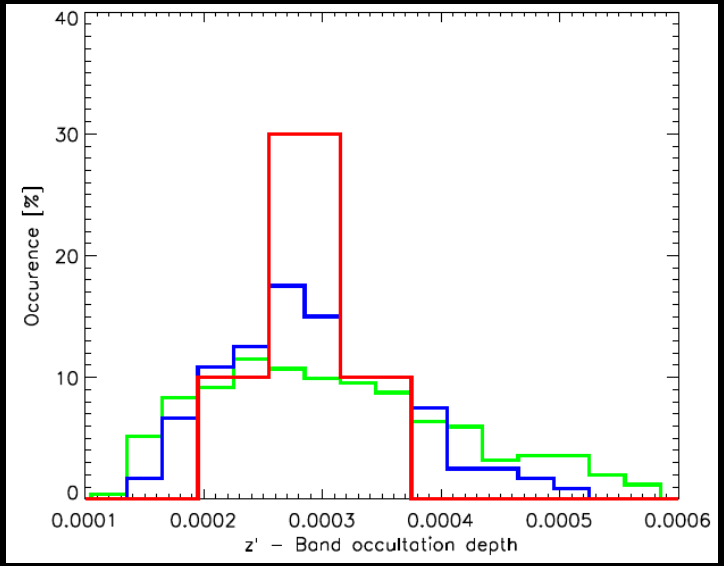
Emission spectra

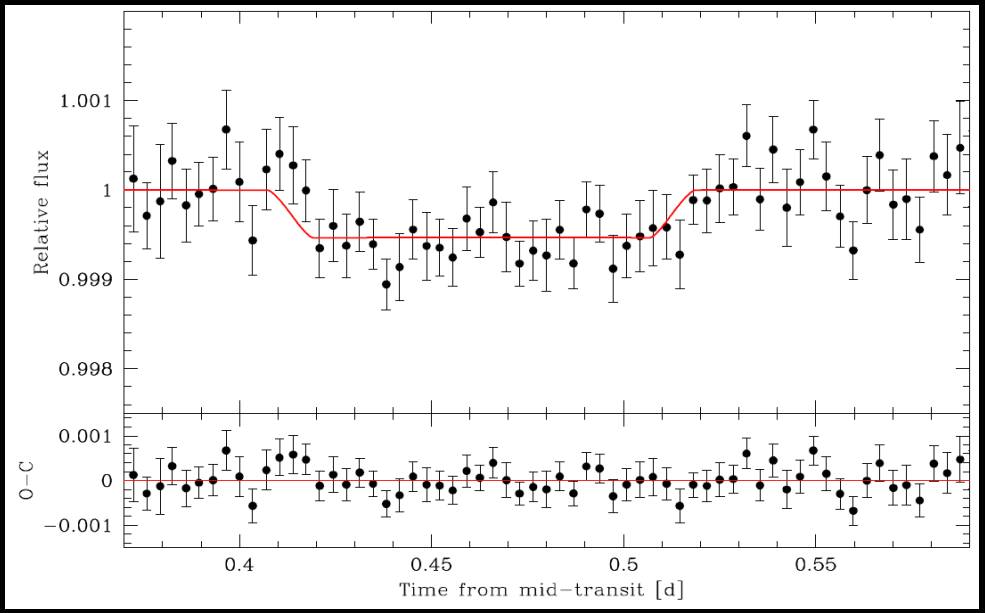
Occultations reveal planetary emission

→ planetary temperatures

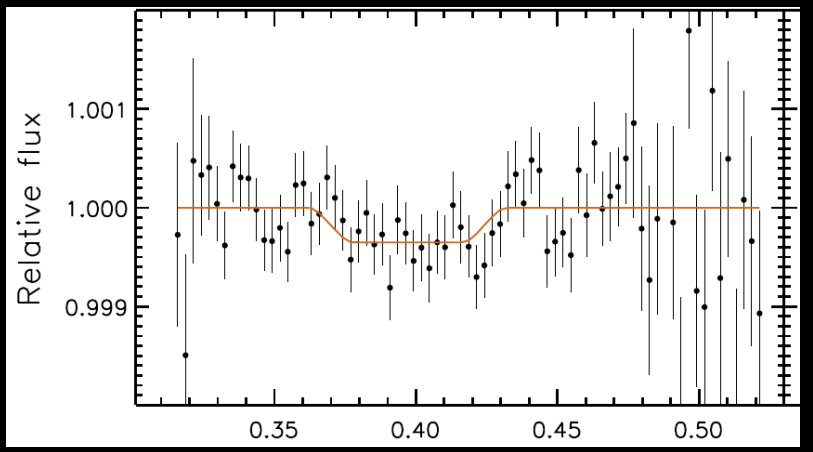
→ planetary composition/thermal profile

→ feasible with small facilities in z' band





WASP-103, 16 occultations combined,
Delrez+ 2018



WASP-19, 10 occultations combined,
Lendl+ 2013

Surveys

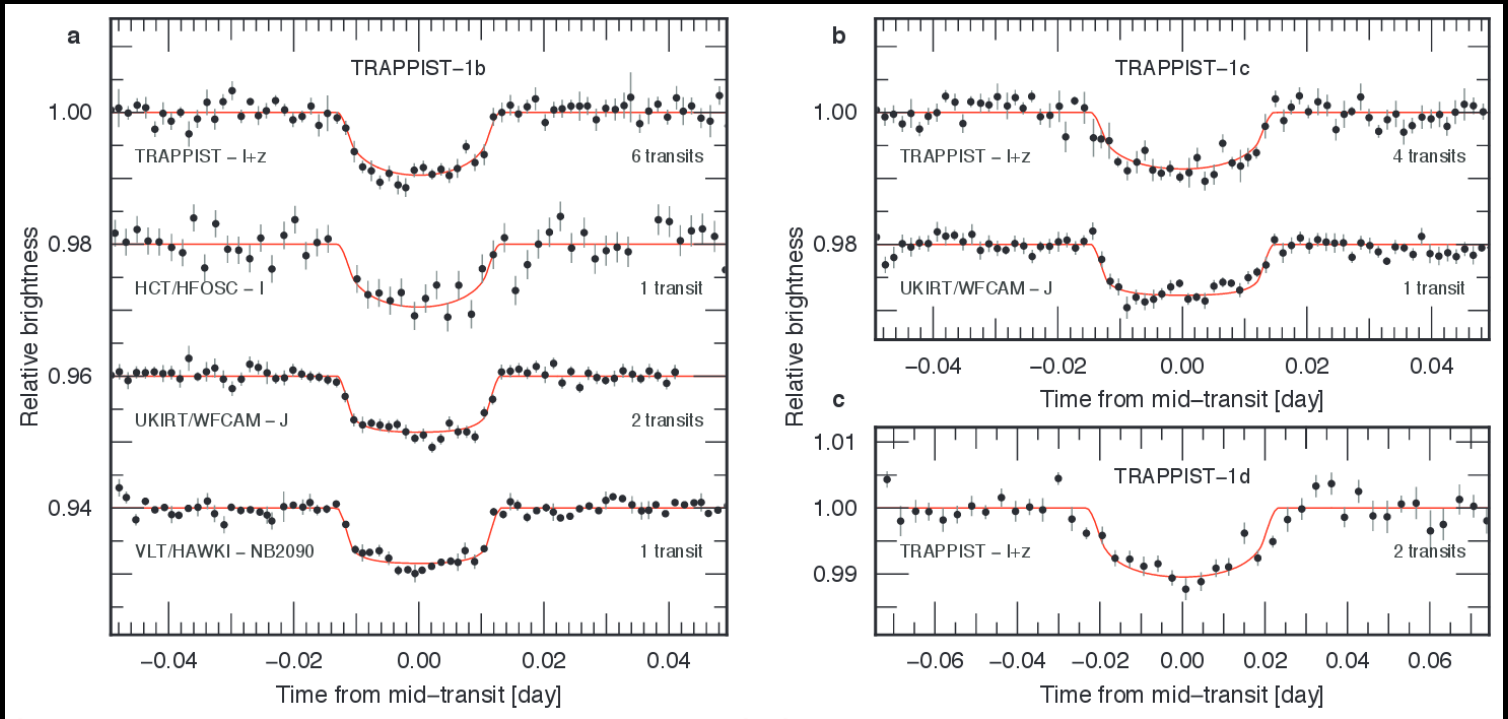
Point-and-stare surveys

→ high risk – high gain

Surveys

Point-and-stare surveys

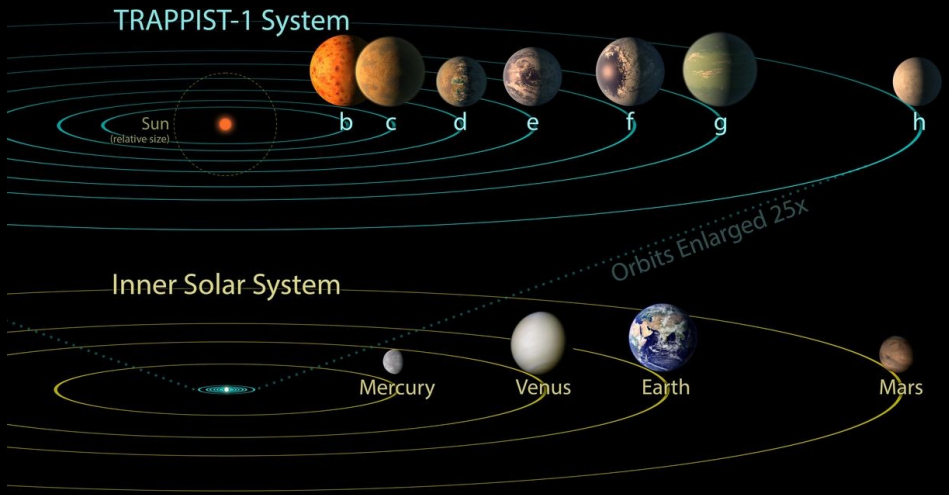
→ high risk – high gain

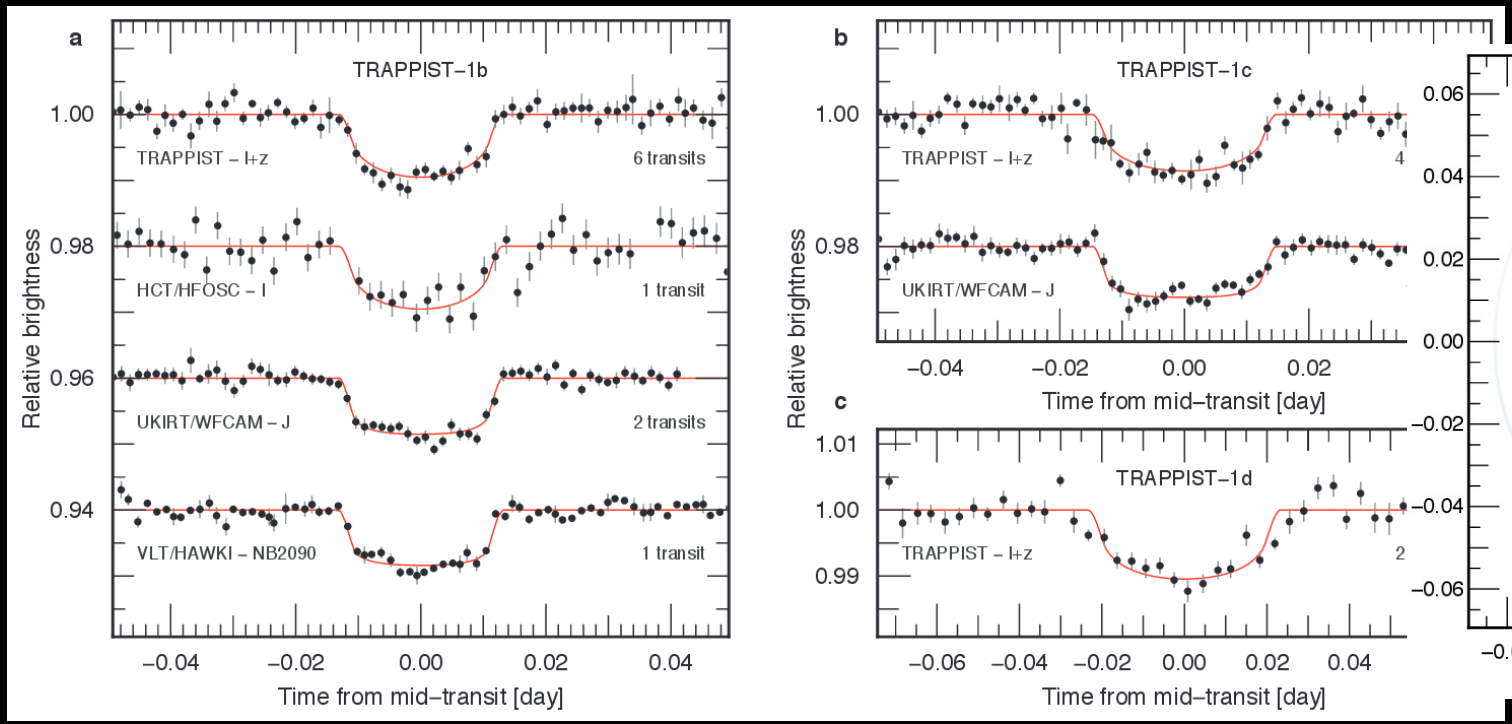


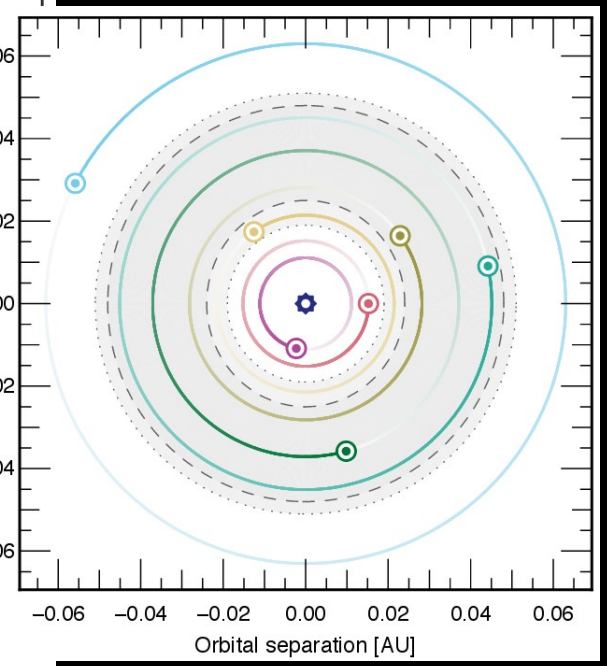
Surveys

Point-and-stare surveys

→ high risk – high gain

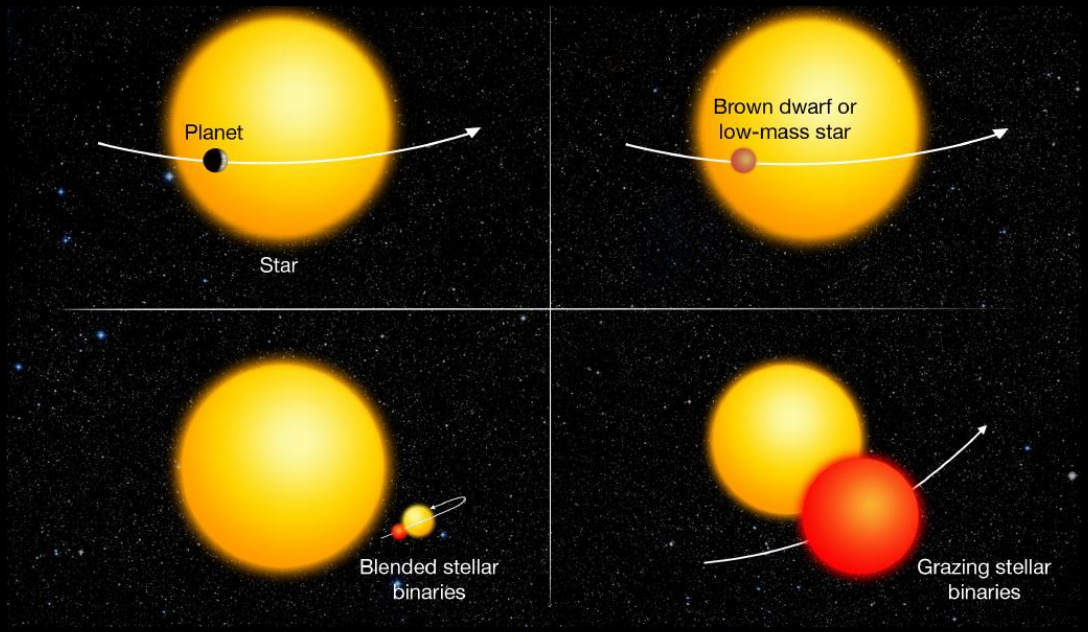






Binary Stars

High number of eclipsing binaries
found in transit surveys



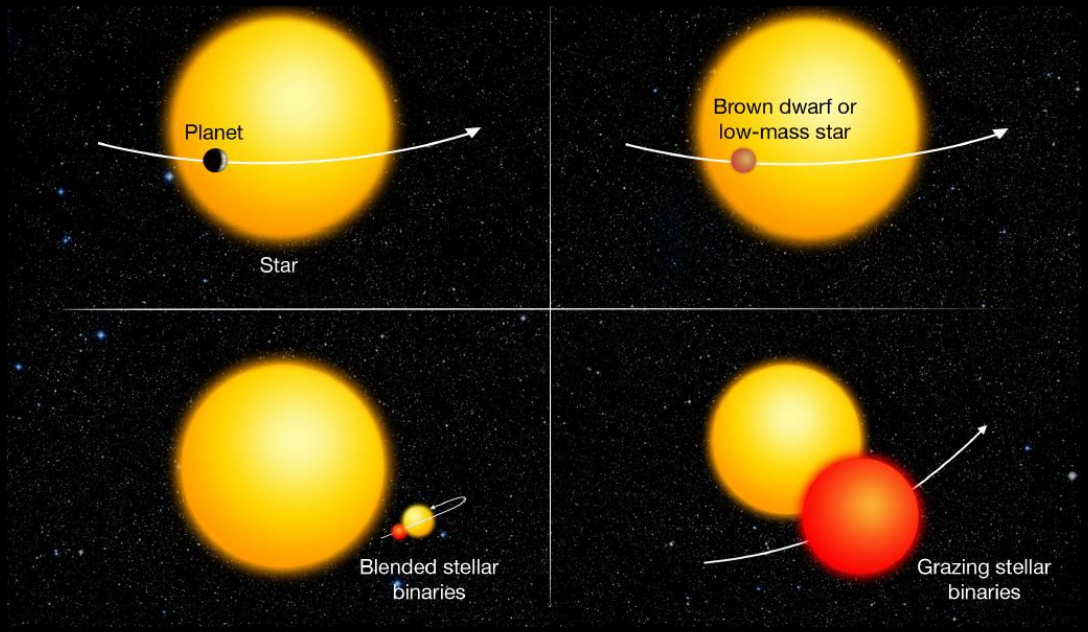
→ Tightly constrain stellar mass/radius

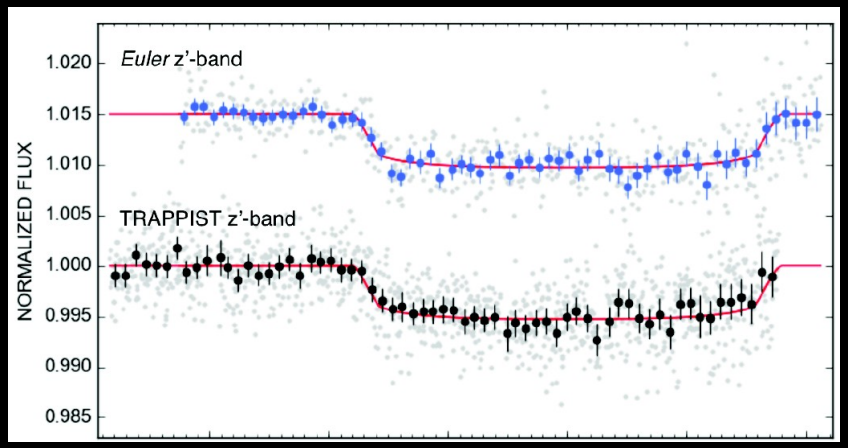
→ Constrain stellar evolutionary models

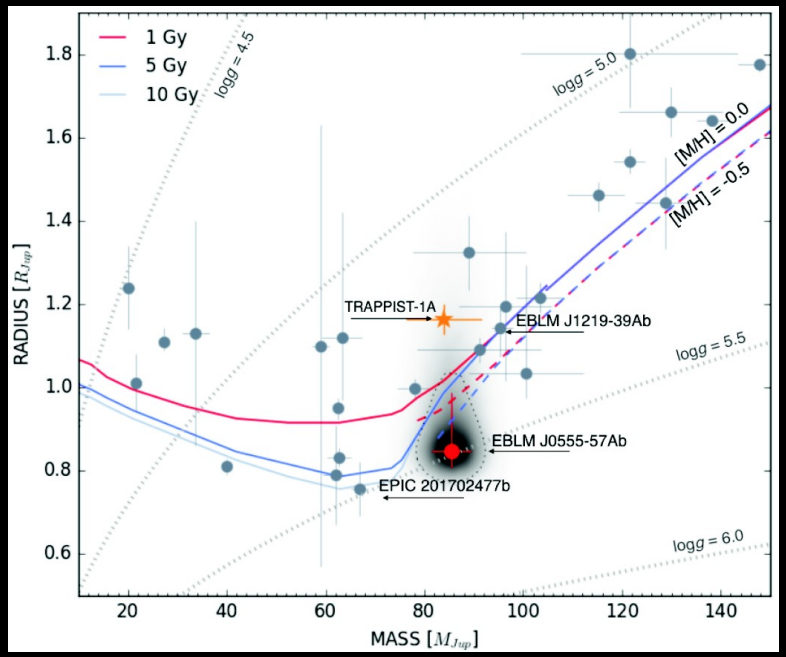
→ Many low-mass systems

Binary Stars

High number of eclipsing binaries found in transit surveys







→ Tightly constrain stellar mass/radius

→ Constrain stellar evolutionary models

→ Many low-mass systems

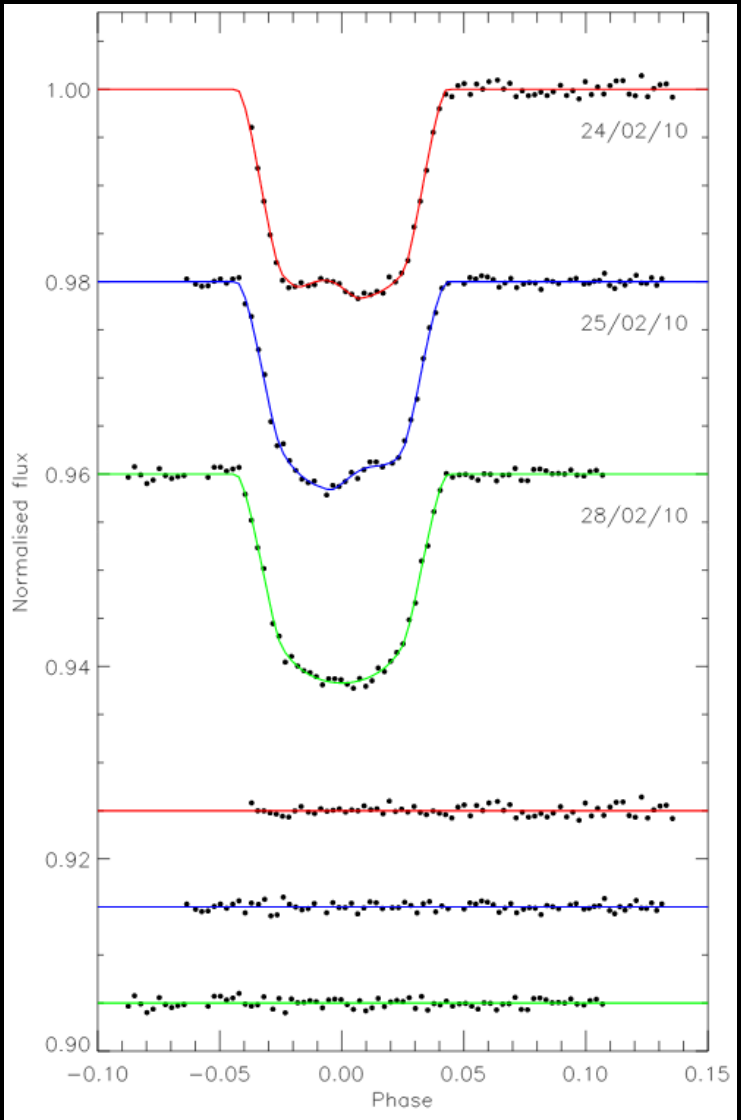
EBLM0555-57, von Boetticher+ 2017

Stellar activity and rotation

Light curve shape anormalities, long-term monitoring

→ Irrecularities on stellar surface: spots (or faculae)

→ Rotational modulation



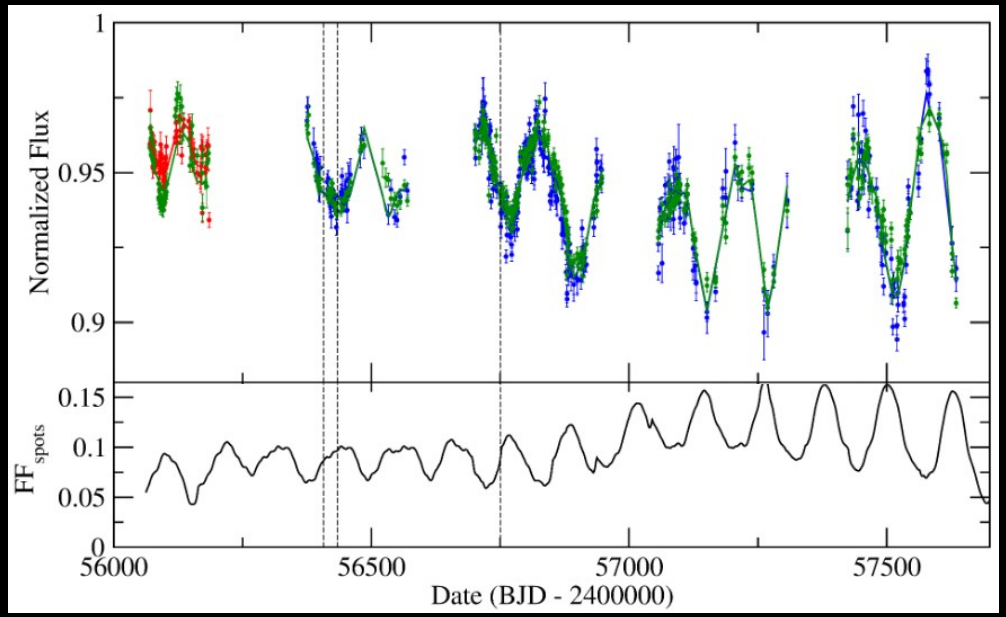
WASP-19, Tregloan-Reed+ 2013

Stellar activity and rotation

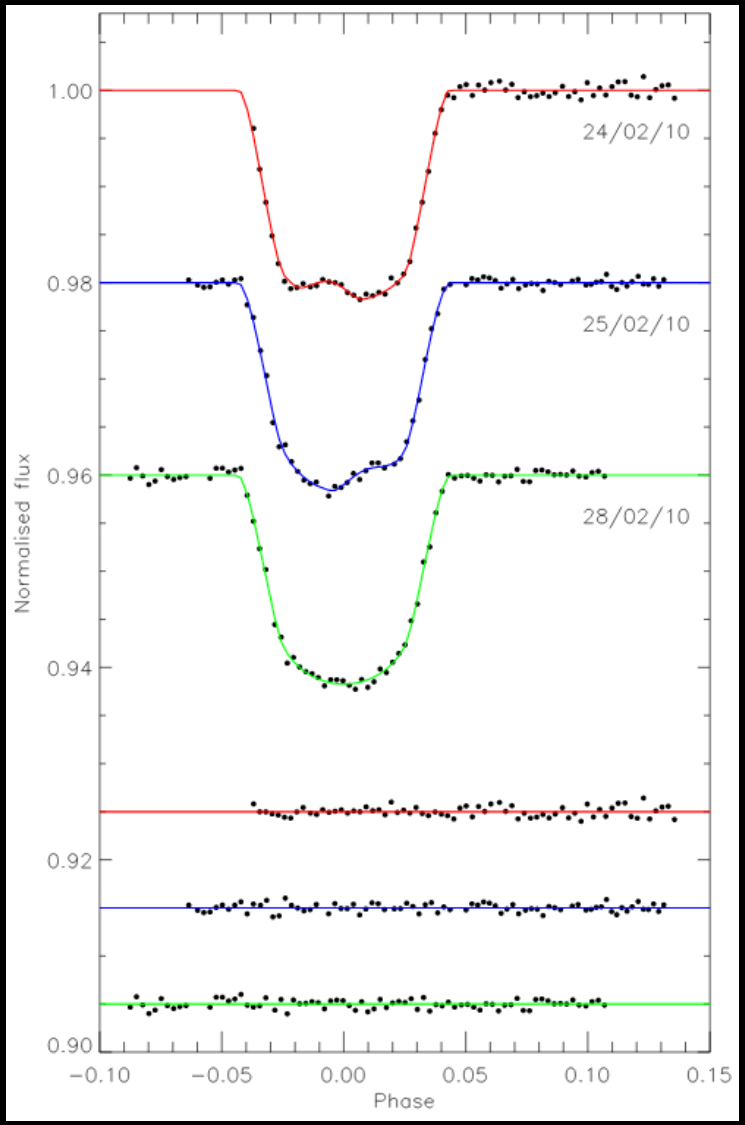
Light curve shape anormalities, long-term monitoring

→ Irrecularities on stellar surface: spots (or faculae)

→ Rotational modulation



GJ1214, Mallonn+ 2018



WASP-19, Tregloan-Reed+ 2013

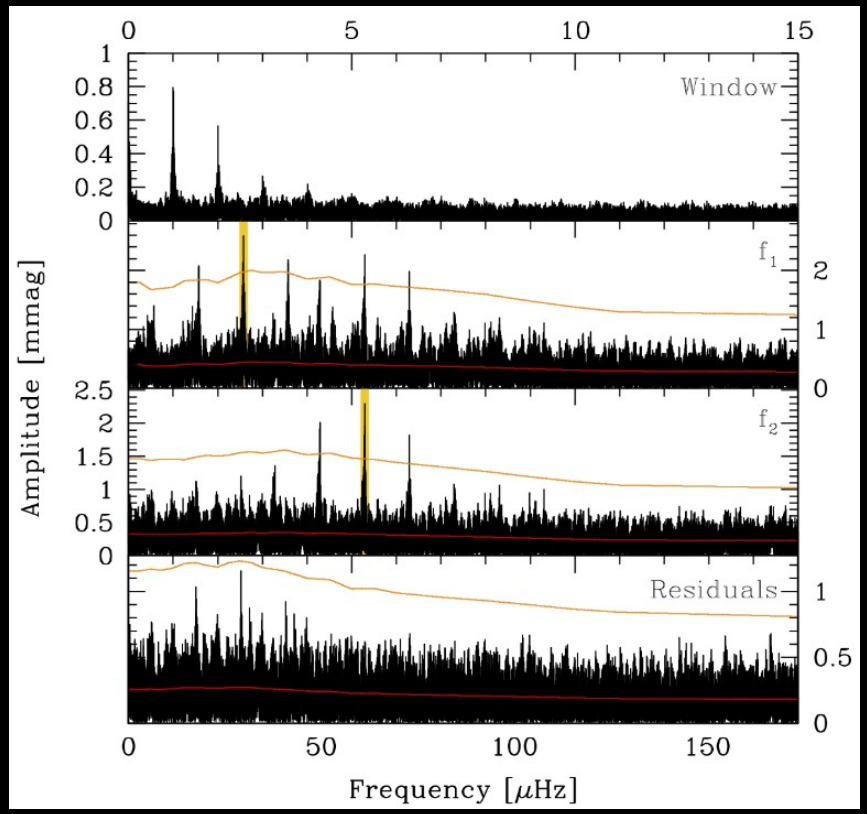
Asteroseismology

→ Stellar oscillations directly probe stellar structure

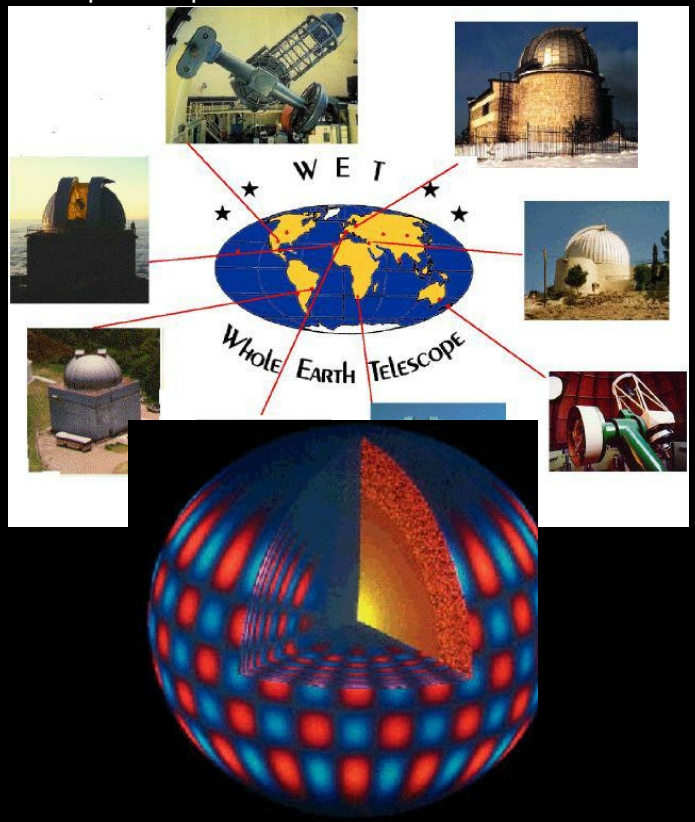
→ Similar strategy but duration and cadence of observations is critical

→ Coordinated observations between facilities (e.g. “Whole Earth Telescope”)

→ Long-term monitoring of specific fields



http://www.public.iastate.edu/~sdk/AstroIowaSt/wet.html



Mowlawi+ 2013

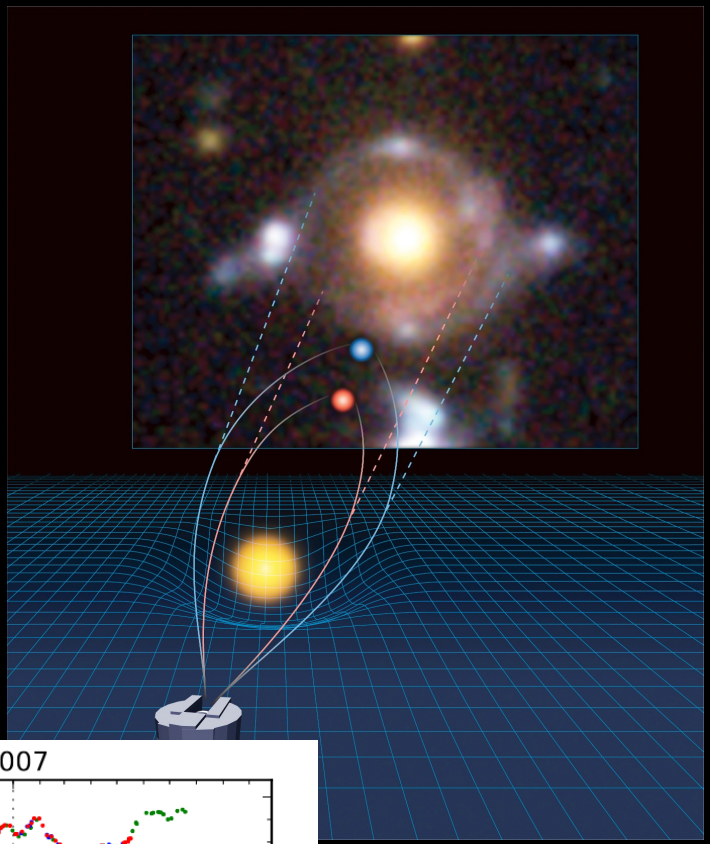
A new class of variables in NGC 3766 from 7 years of monitoring

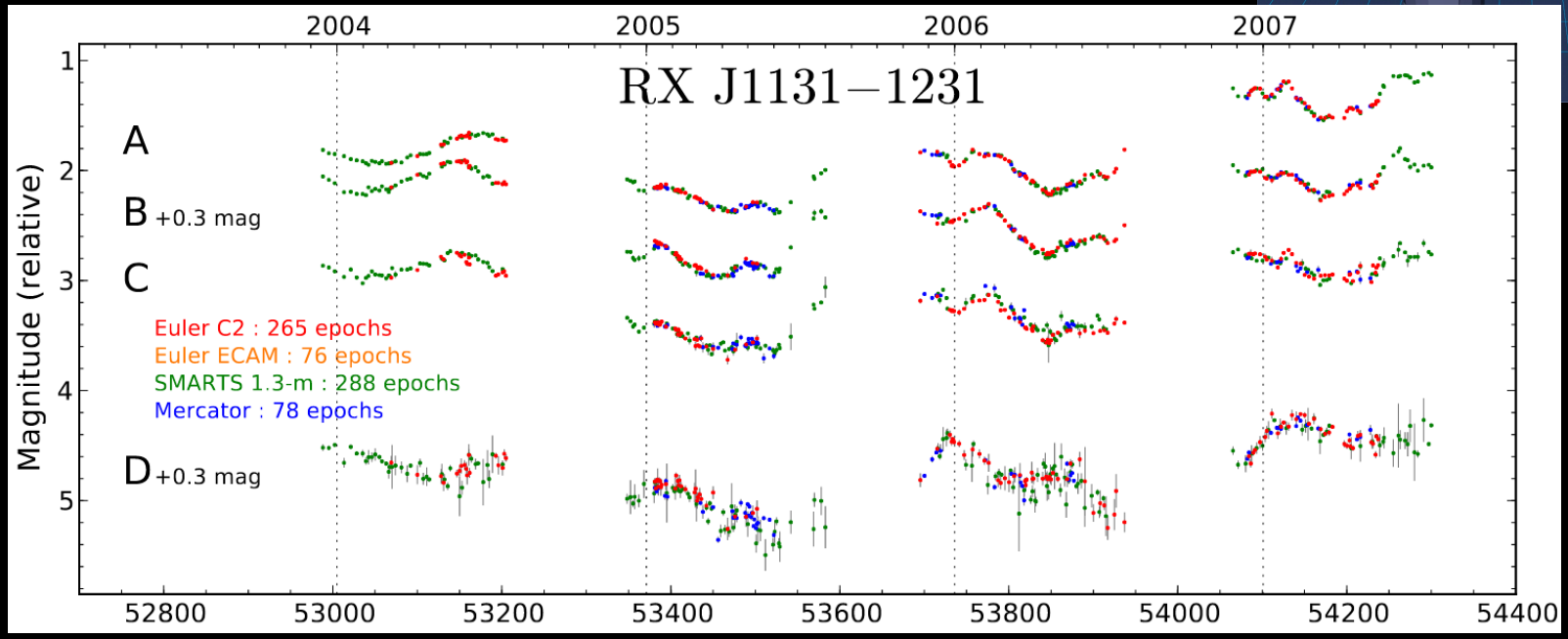
Gravitational lenses

→ Obtain light curves for different elements of a lensed object

→ Time delays between the components

→ Constrain H_0





Quasar RX J1131

Tewes+ 2013

… and a lot more!