EXTRASOLAR PLANETS

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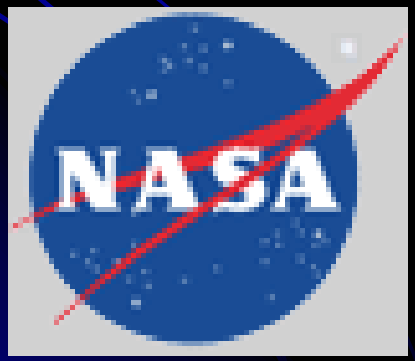
The discovery of extrasolar planets in the past decade was one of the most remarkable achievements of the century, and the culmination of centuries of speculation.

National Academy of Sciences, 2000 Decadal Review of Astrophysics

Extrasolar planets are one of the 3 pillars of modern astrophysics. The foremost goal of explanet research for the next decade is the discovery of nearby habitable planets.

National Academy of Sciences, 2010 Decadal Review of Astrophysics



The year 1584

"There are countless suns and countless earths all rotating around their suns in exactly the same way as the seven planets of our system . . . The countless worlds in the universe are no worse and no less inhabited than our Earth"

Giordano Bruno

in De L'infinito

Universo E Mondi

How are exoplanets found?

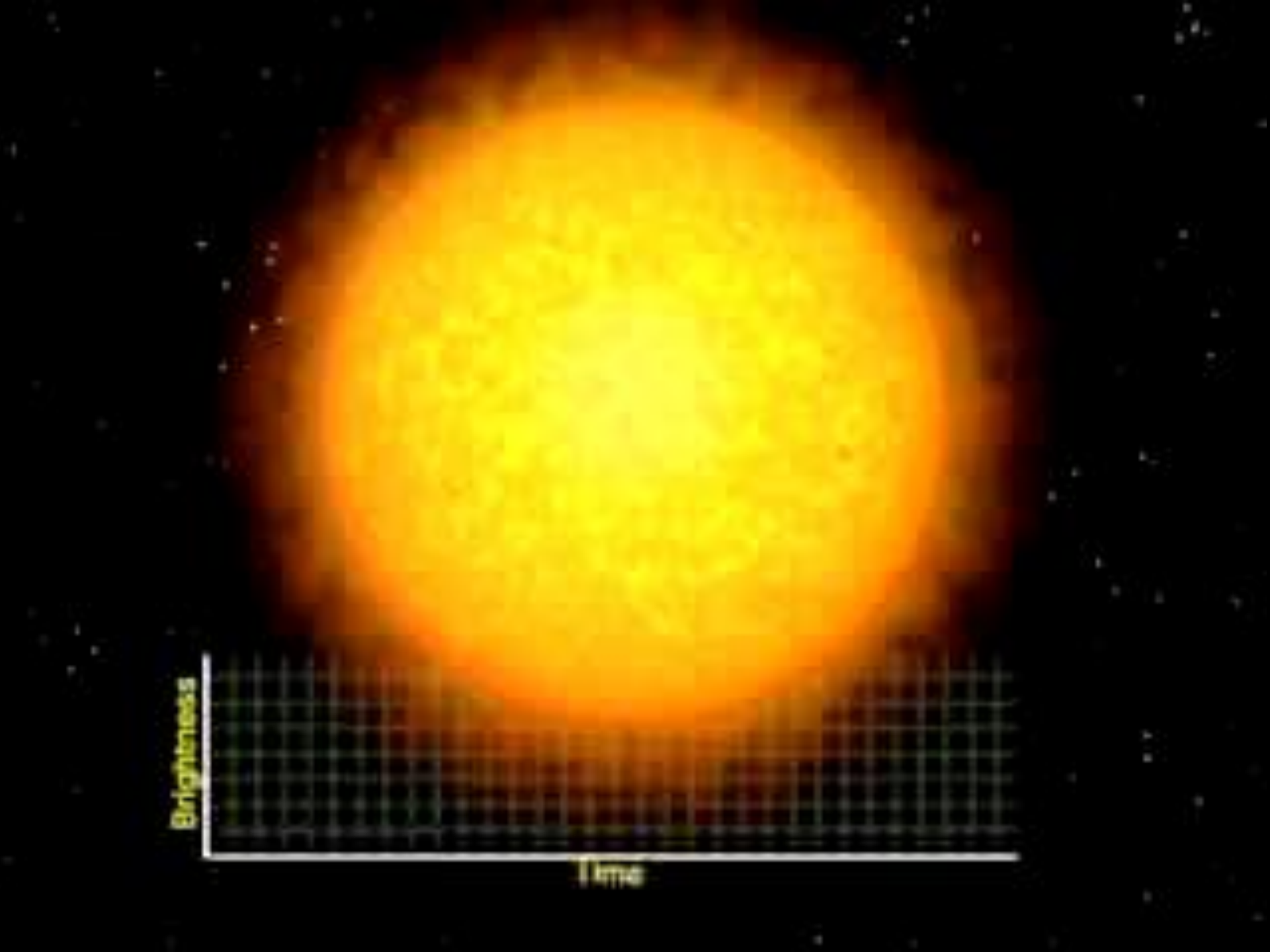
Direct imaging - nearest stars < 30 light years

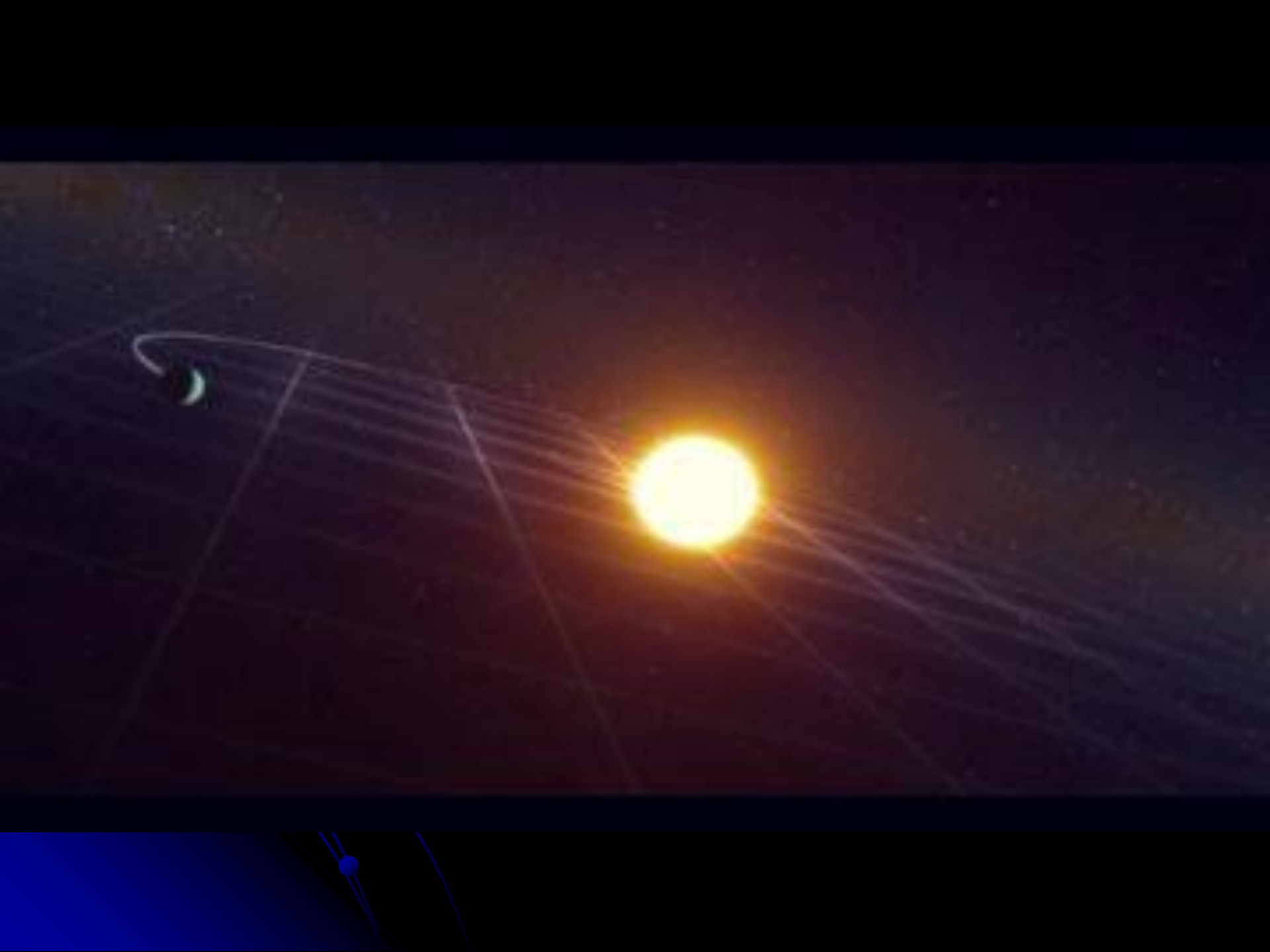
Transits – distant stars > 2000 lights years

Microlensing – distant stars > 30,000 light years

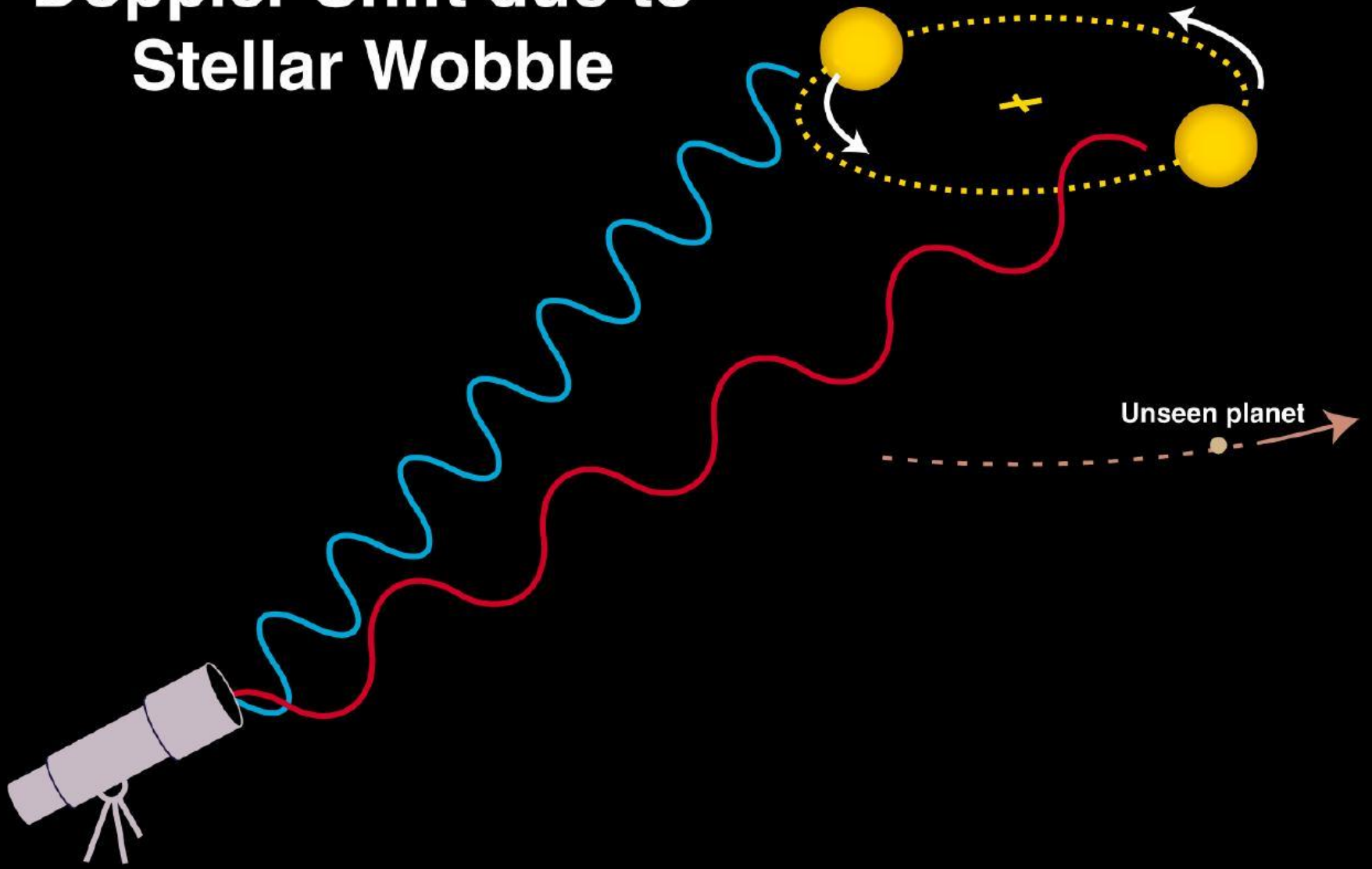
Astrometry – nearest stars < 30 light years

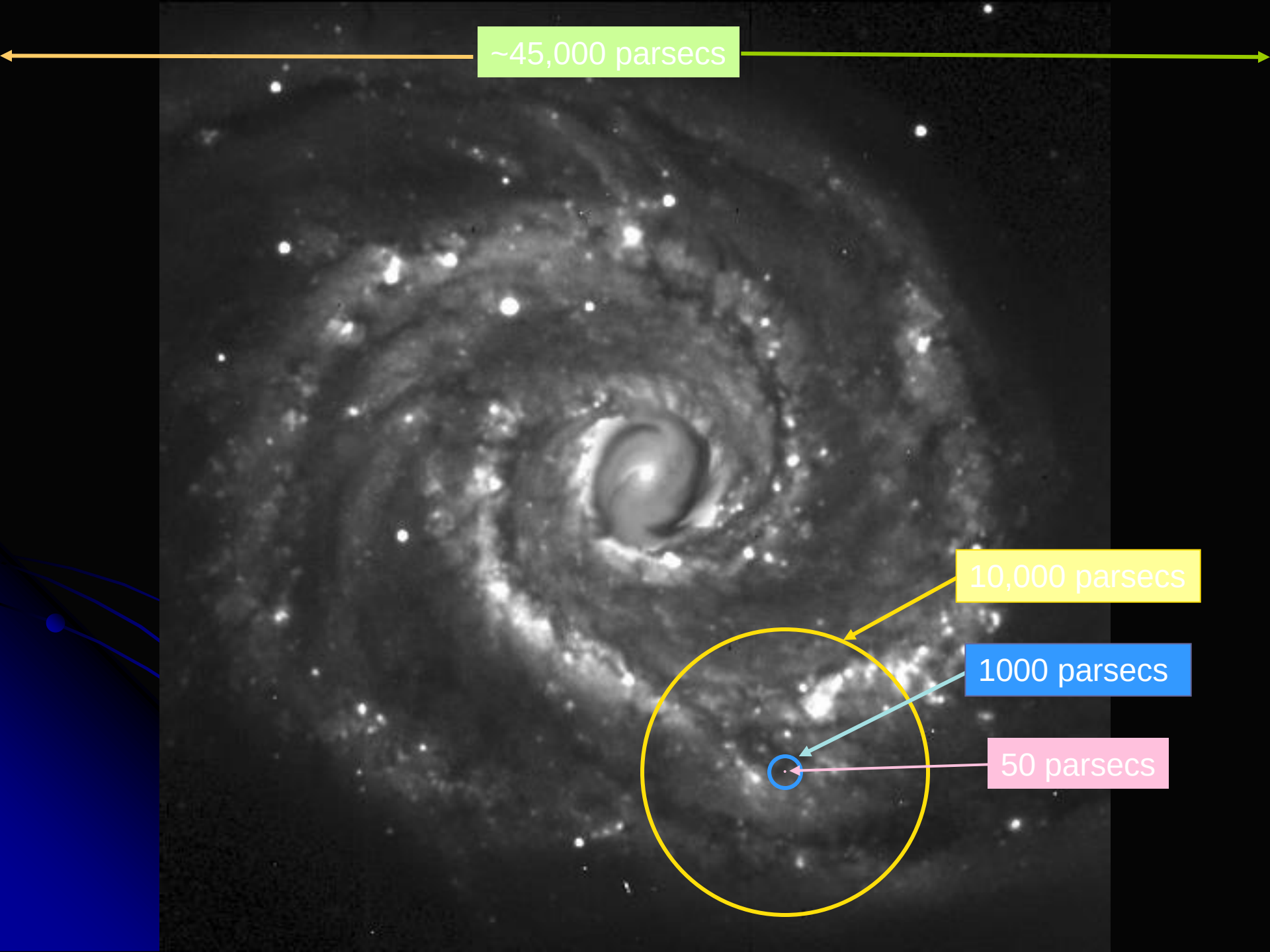
Doppler spectroscopy – nearest stars < 200 light years


Brightness
Time

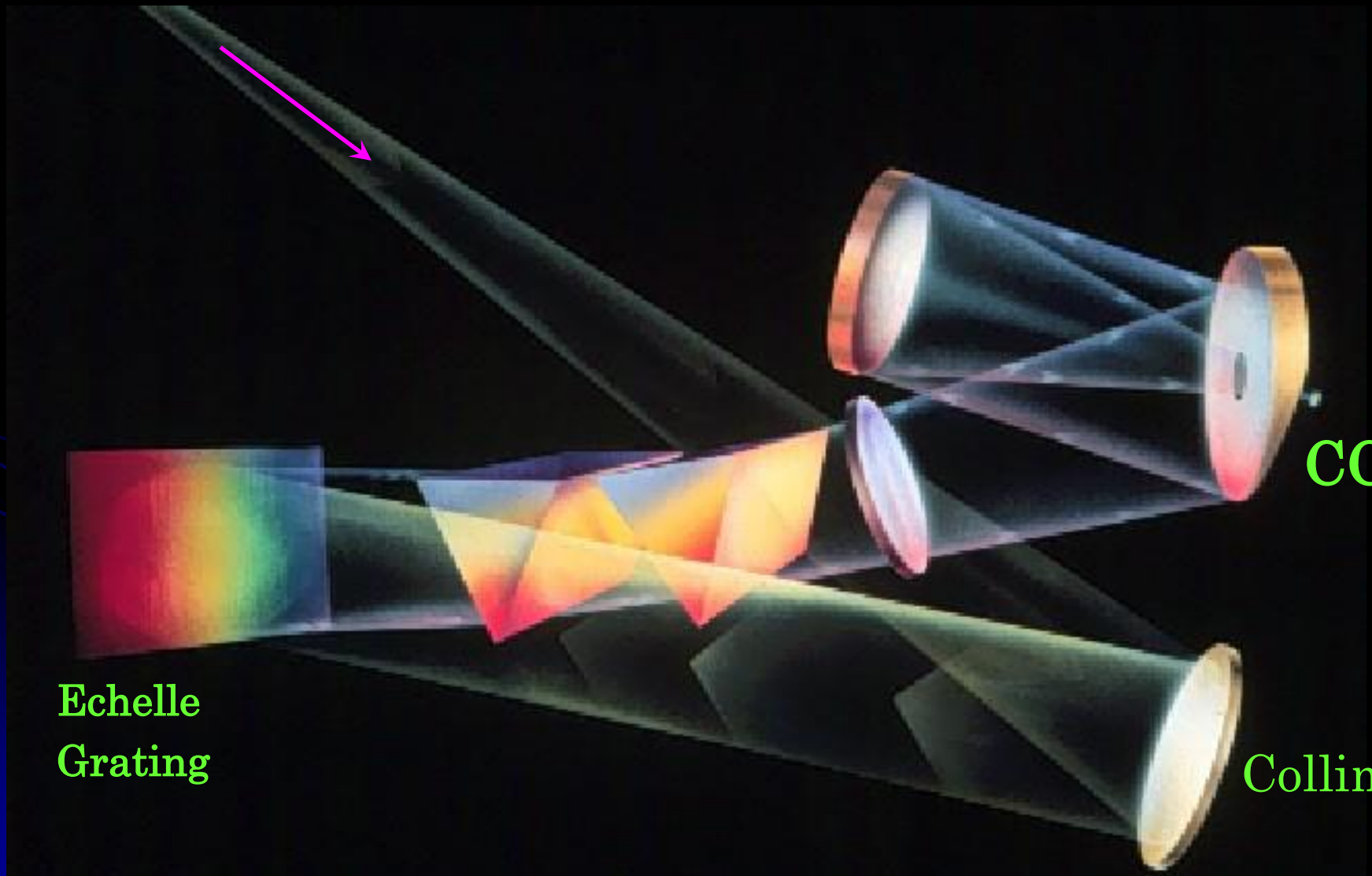


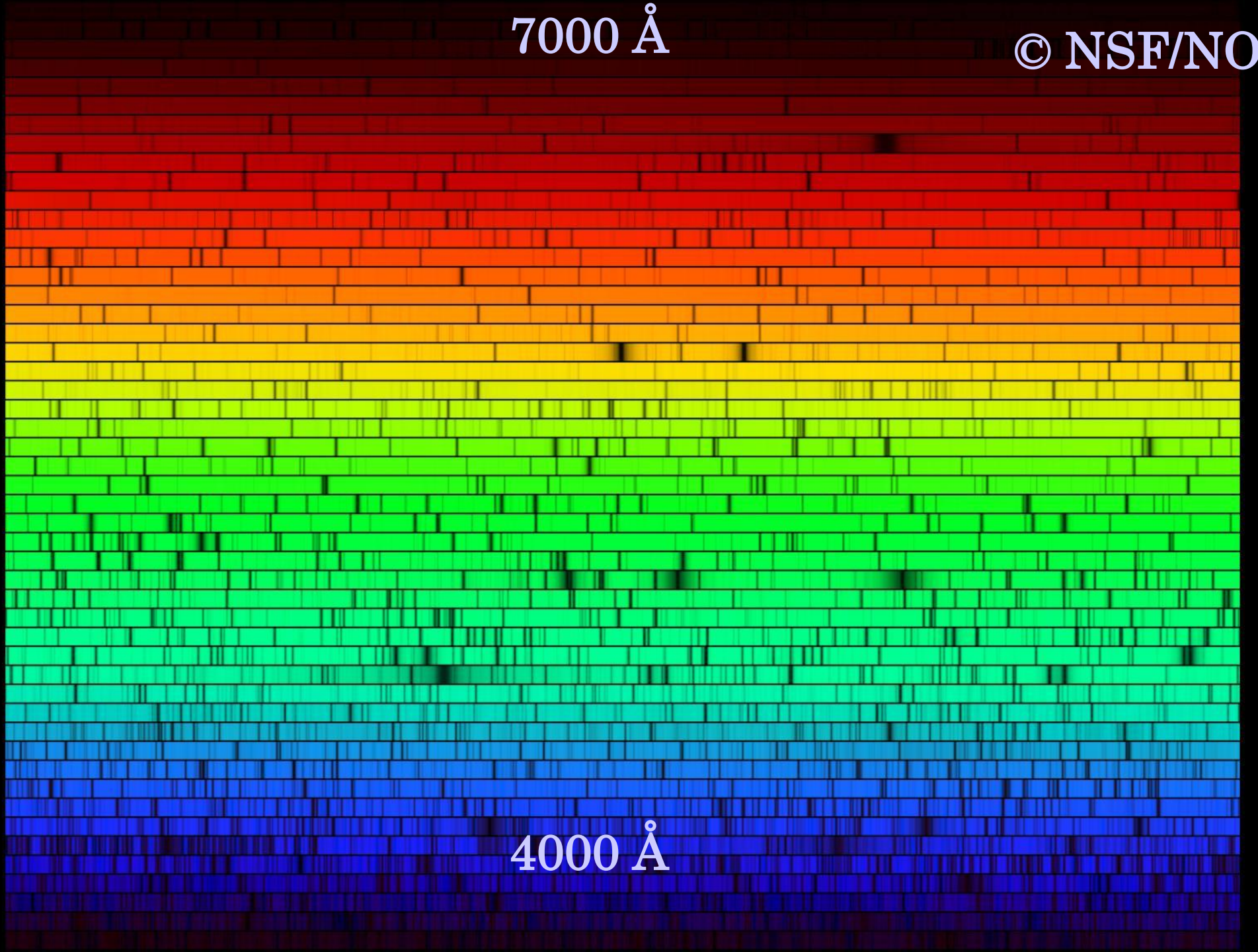
Doppler Shift due to Stellar Wobble

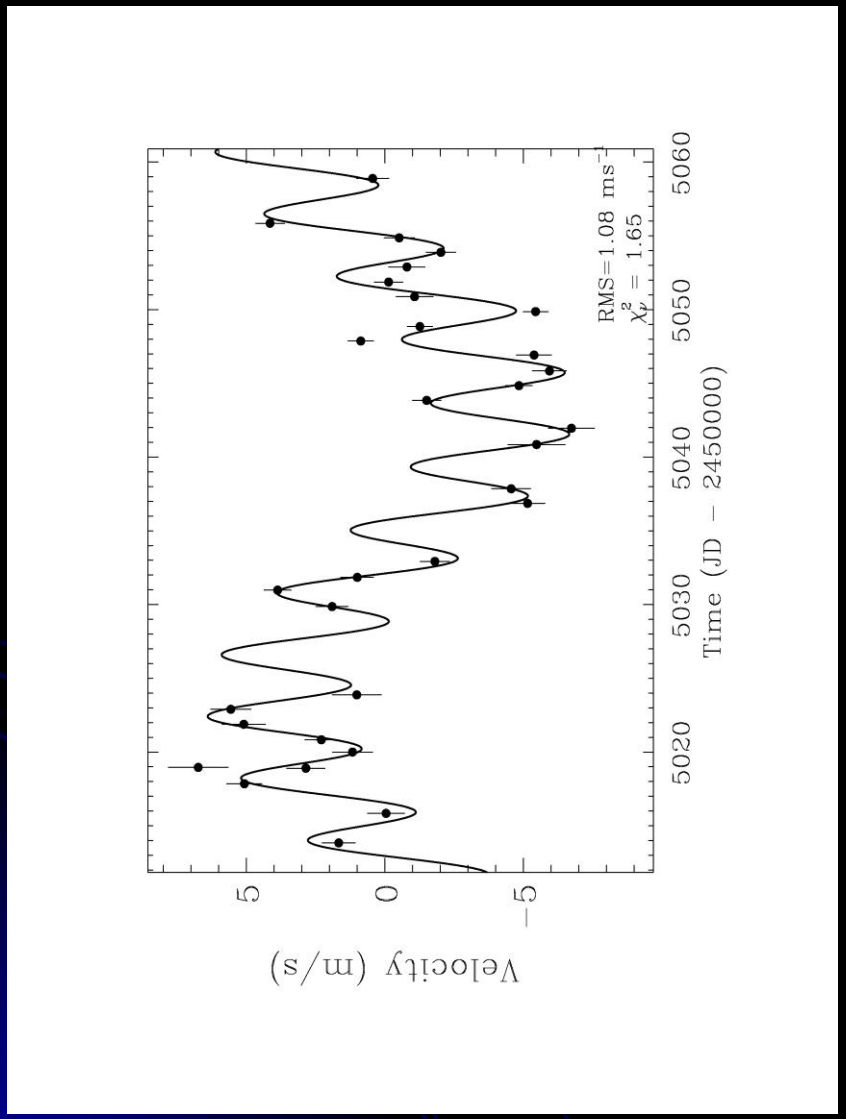



~45,000 parsecs
10,000 parsecs
1000 parsecs
50 parsecs

Echelle Spectrometer



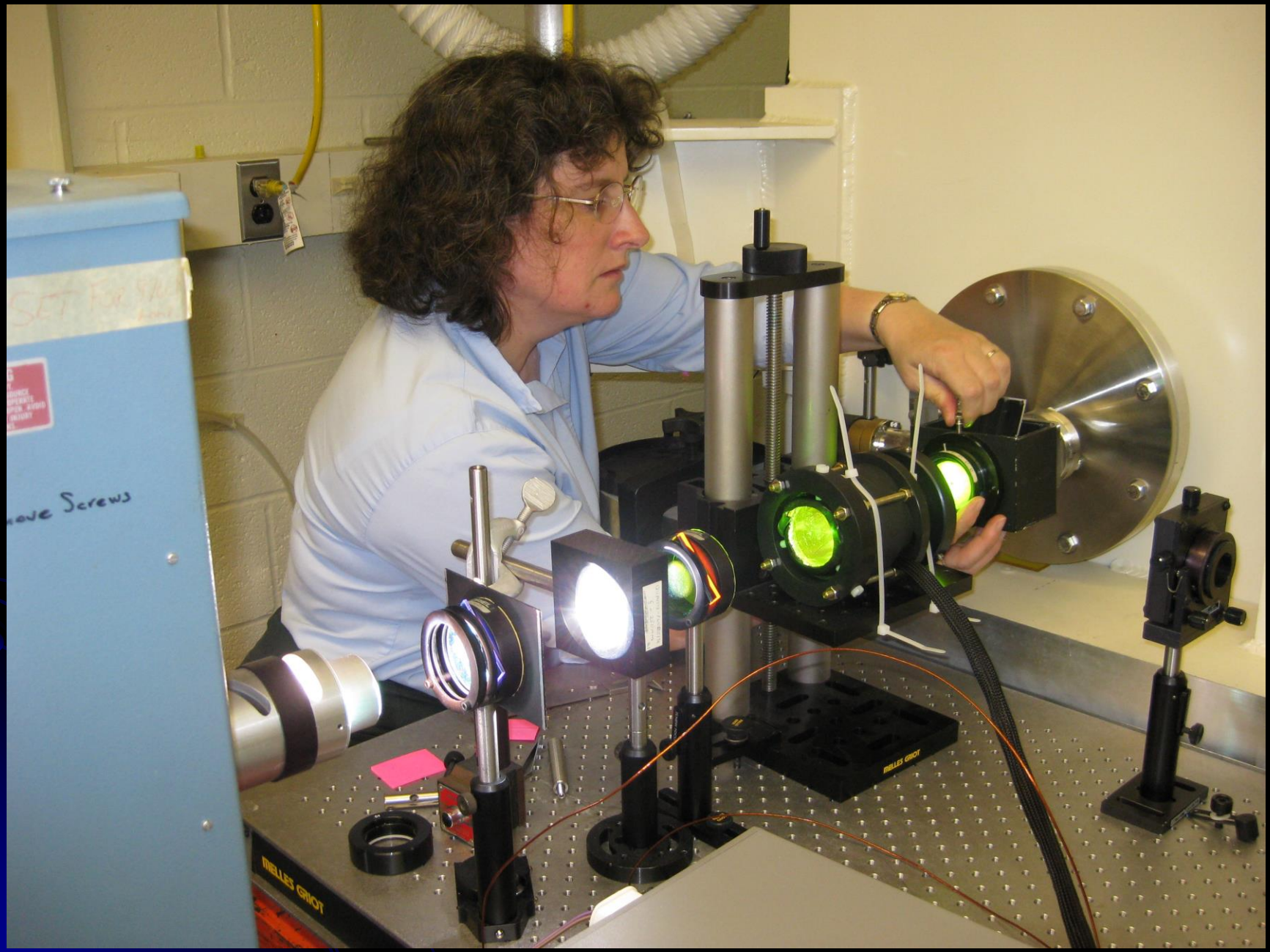

7000 Å
© NSF/NO
4000 Å



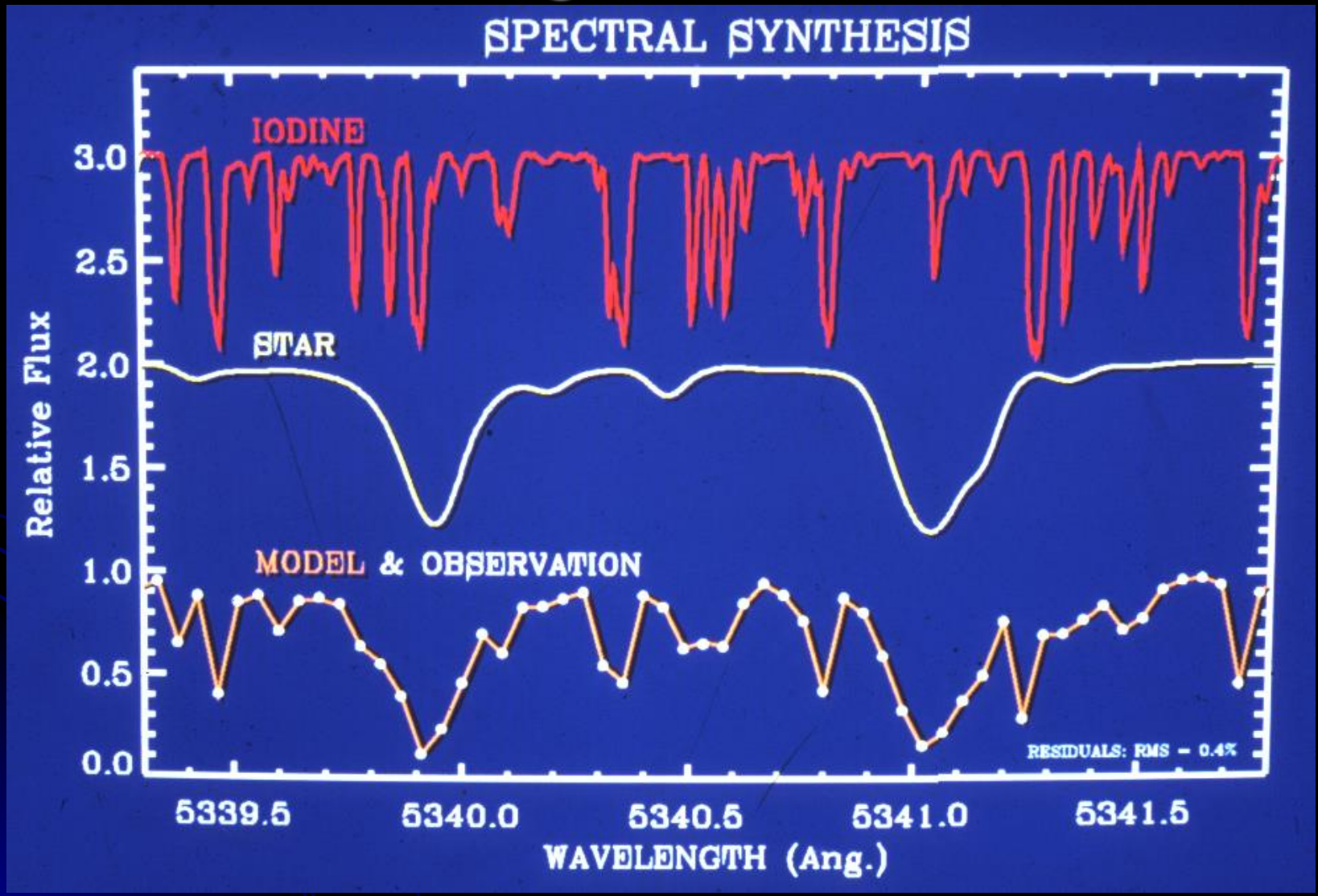
Spectrometer Wizard:

Steve Vogt

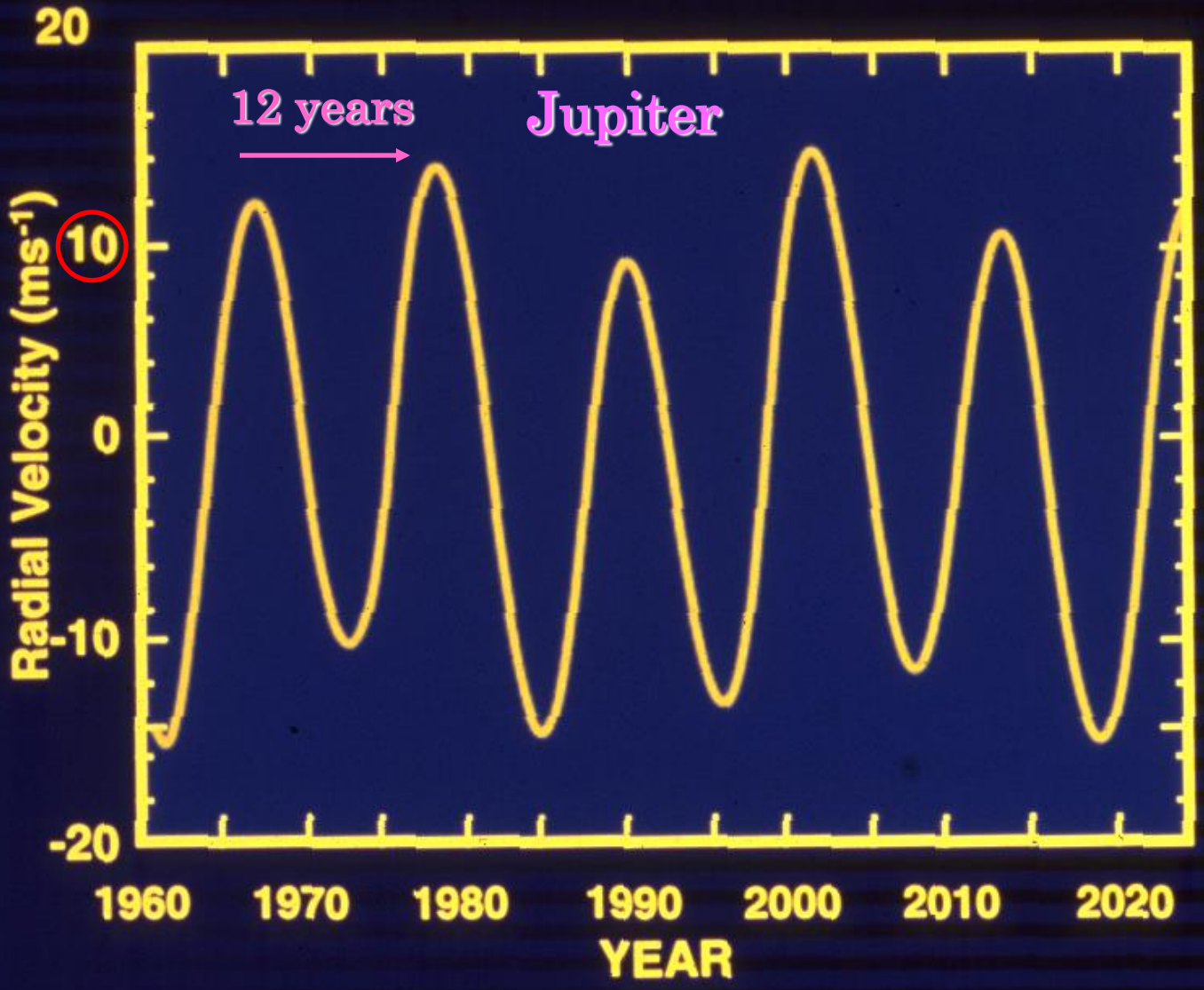
UC Santa Cruz


MELLES GRIOT
MELLES GRIOT

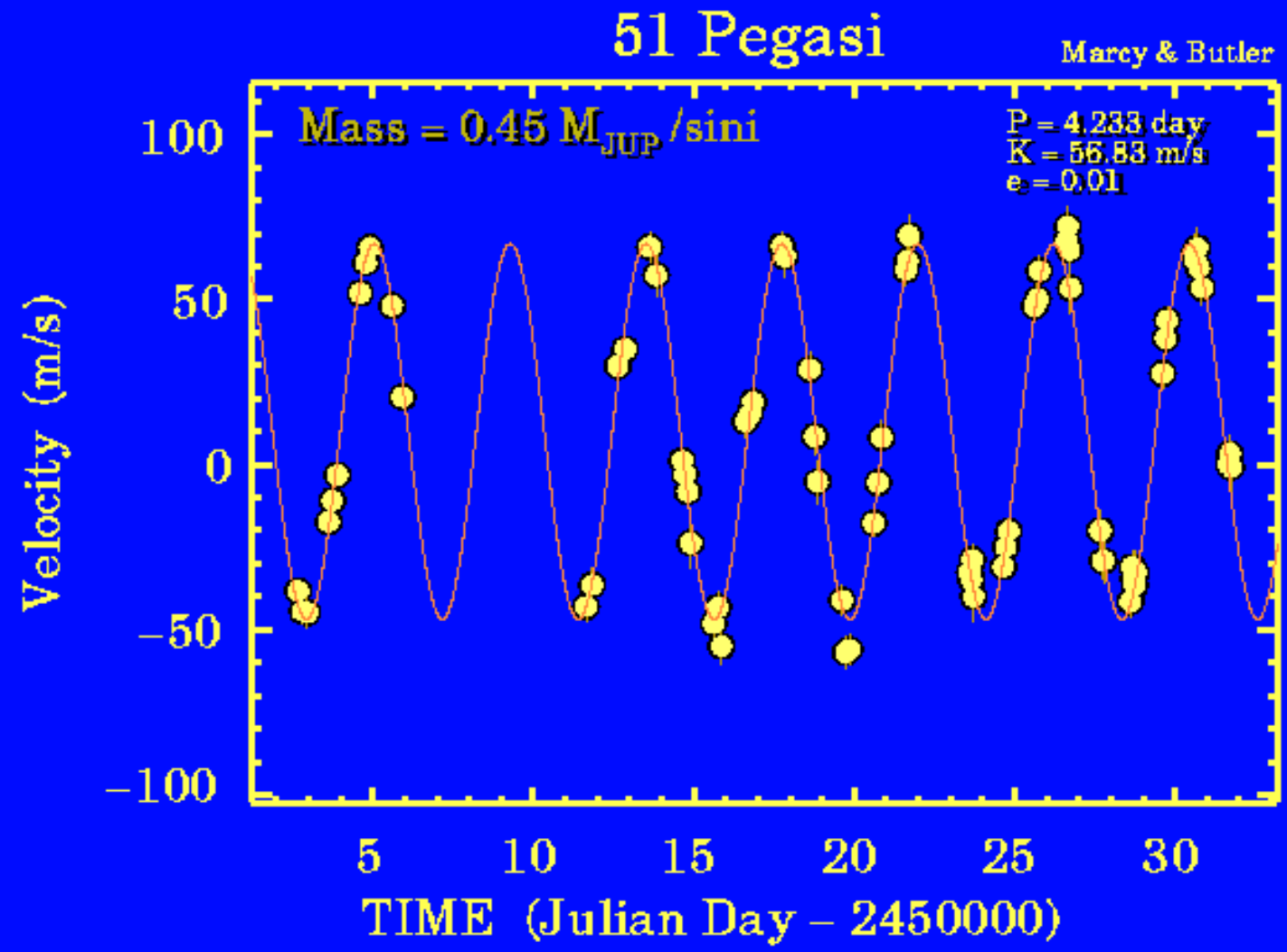
Key to Doppler Measurements:
Wavelength Calibration



Doppler Shift of the Sun



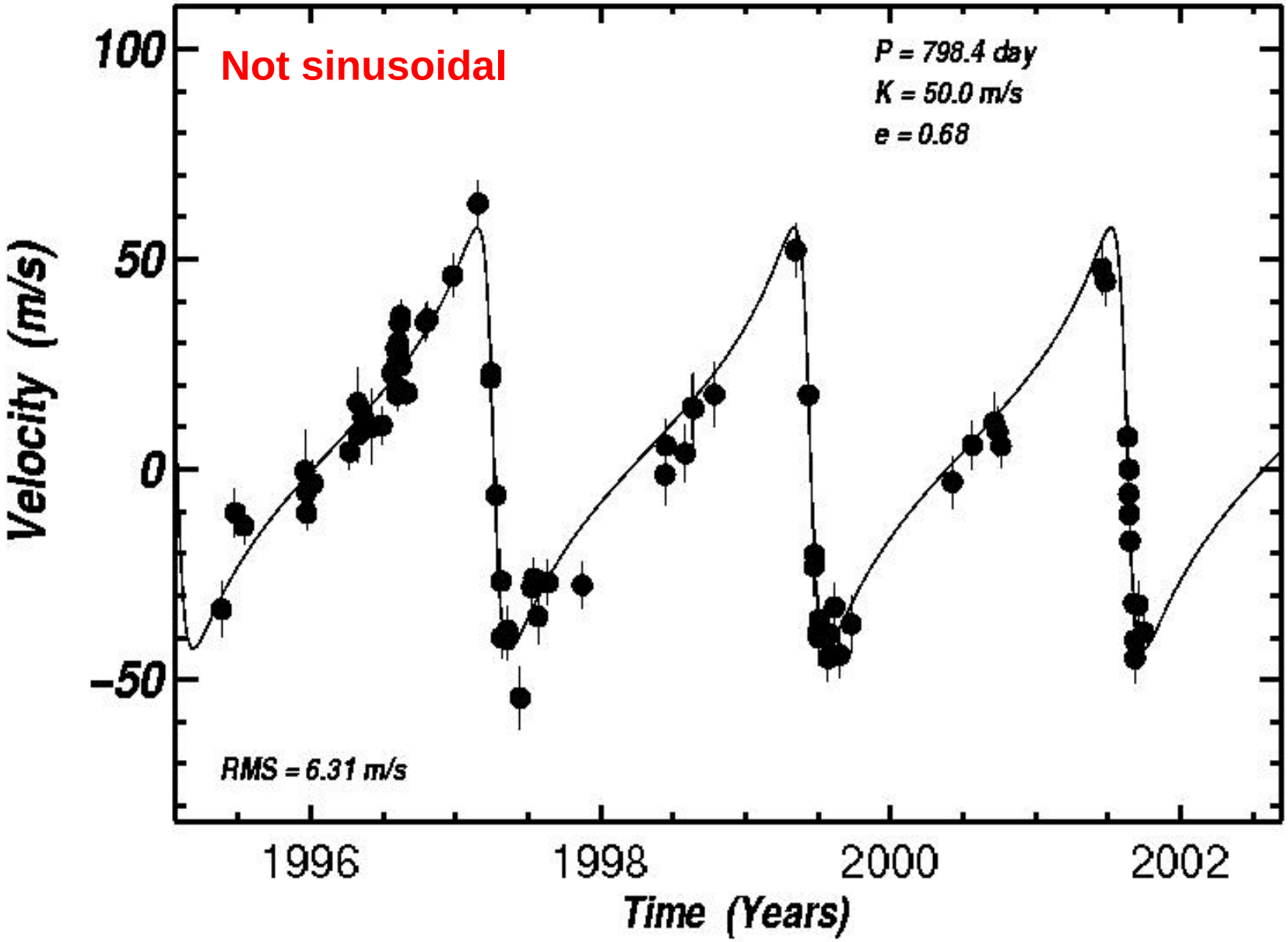
- The radial velocity of the Sun as it orbits the center of mass of the Solar System.


51 Pegasi
Marcy & Butler
Mass = 0.45 M_JUP /sini
P = 4.233 day
K = 56.83 m/s
e = 0.01
100
50
0
−50
−100
Velocity (m/s)
5
10
15
20
25
30
TIME (Julian Day – 2450000)

51 PEG SYSTEM

All Dimensions To Scale

16 Cygni B


Not sinusoidal
P = 798.4 day
K = 50.0 m/s
e = 0.68
RMS = 6.31 m/s
100
50
0
−50
Velocity (m/s)
1996
1998
2000
2002
Time (Years)


FEBRUARY 5 1996 $2.95
Dole Drops, Clinton Rises
TIME
IS ANYBODY OUT THERE?
How the discovery of two planets brings us closer to solving the most profound mystery in the cosmos

The First Decade:

3 m/s Discovery of (Giant) Exoplanets
Hot Jupiters
Eccentric Planets

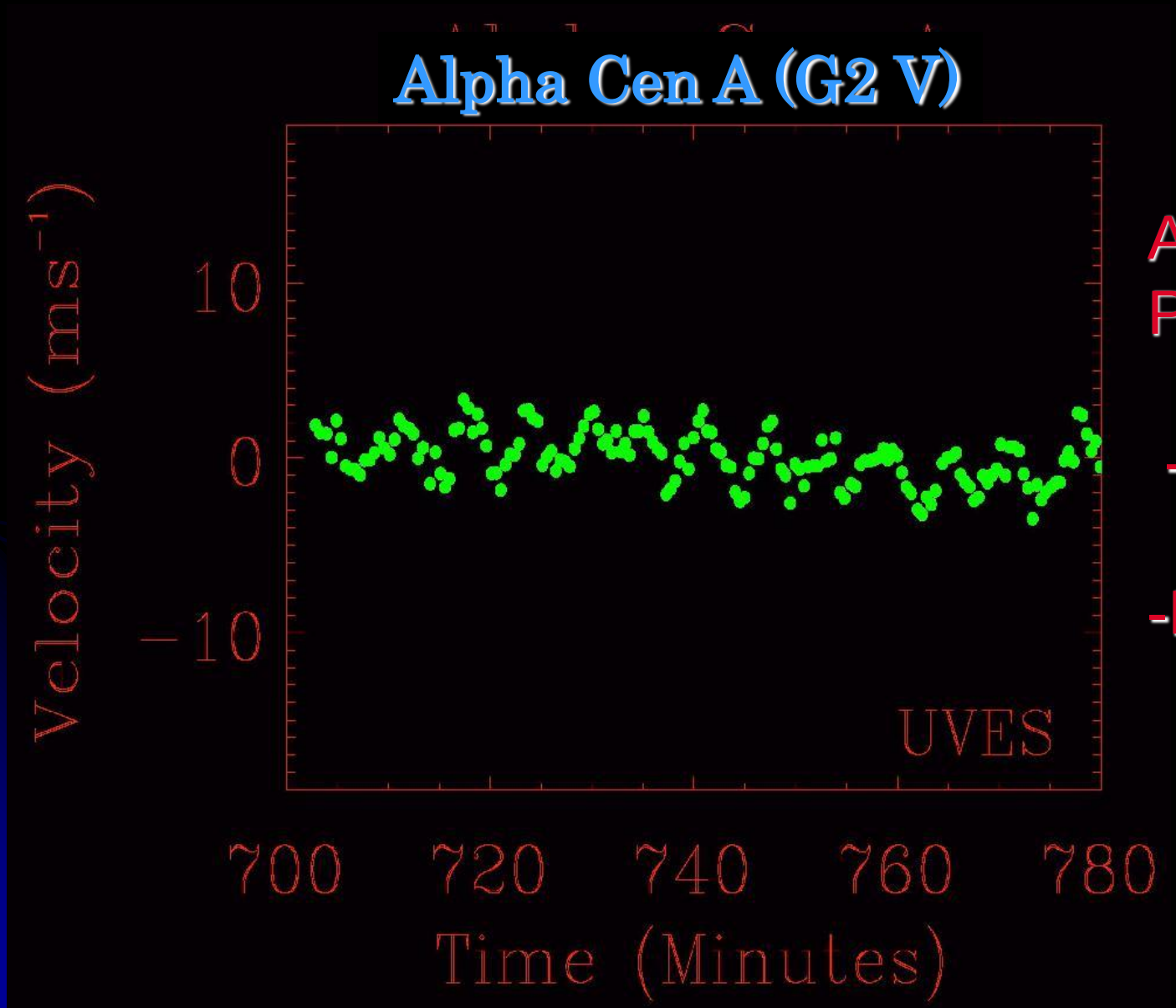
The Next Decade:

1 m/s Discovery of Super-Earths
Discovery of Potentially Habitable Planets

The Decade After:

Giant Telescopes & Adaptive Optics
Space-based telescopes?
Direct Imaging & spectroscopy

P-modes in Solar-type stars



Amp ~ 1.5 m/s
Per = 5 min

- Seismology

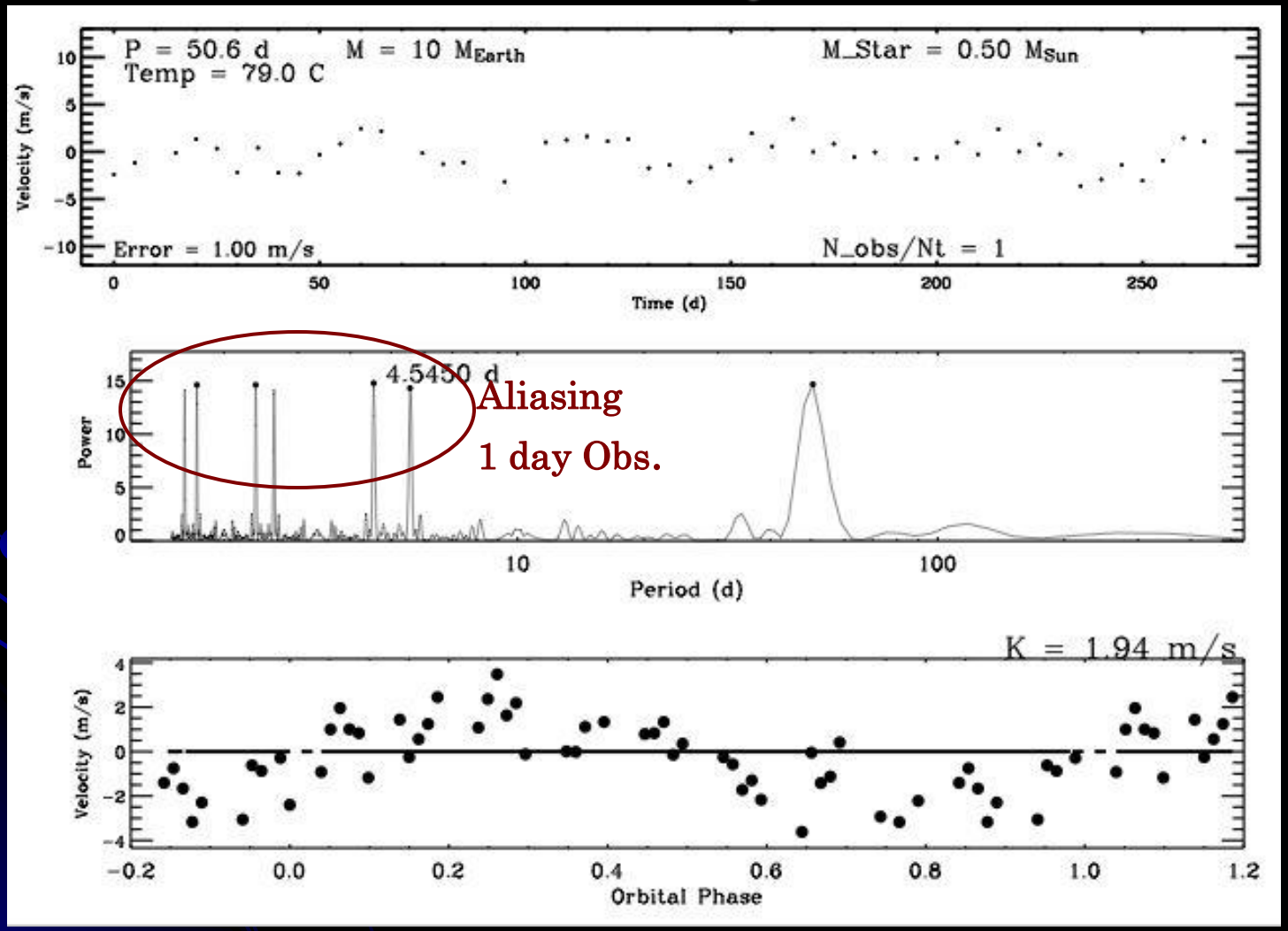
-Noise:

Avg over
P-modes !

Single telescope

10 Earth-Masses

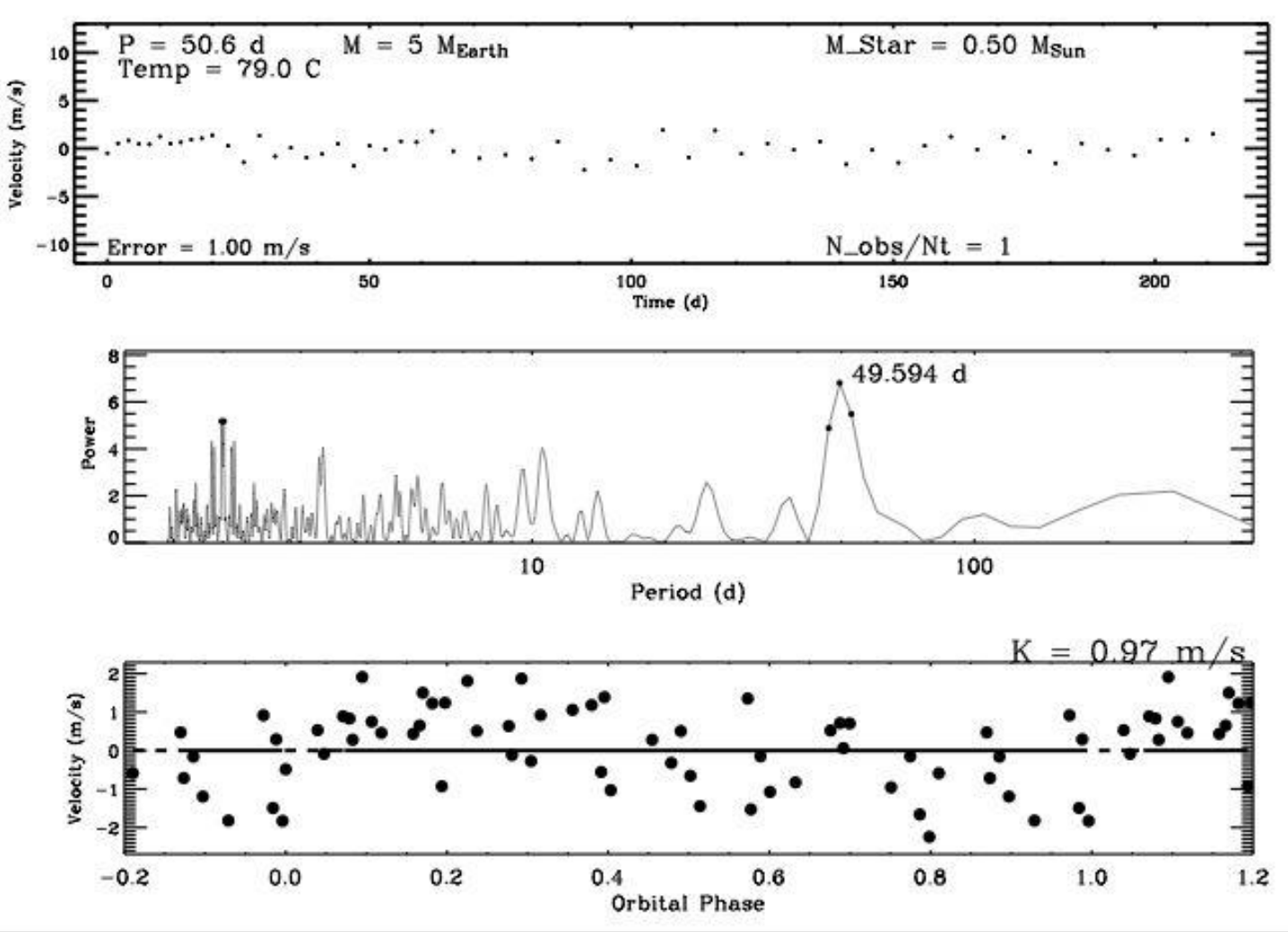
P = 50 day



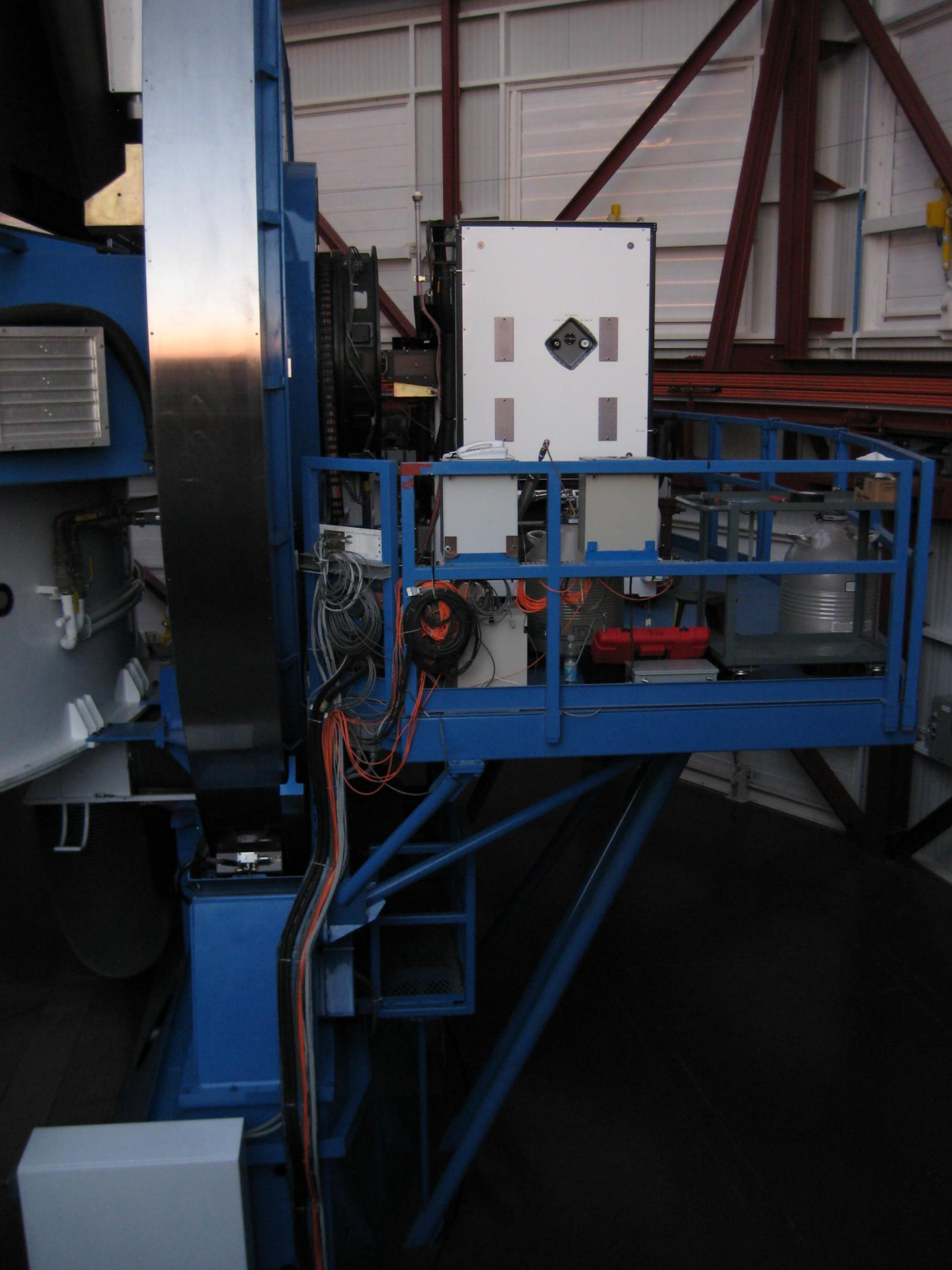
Single telescope

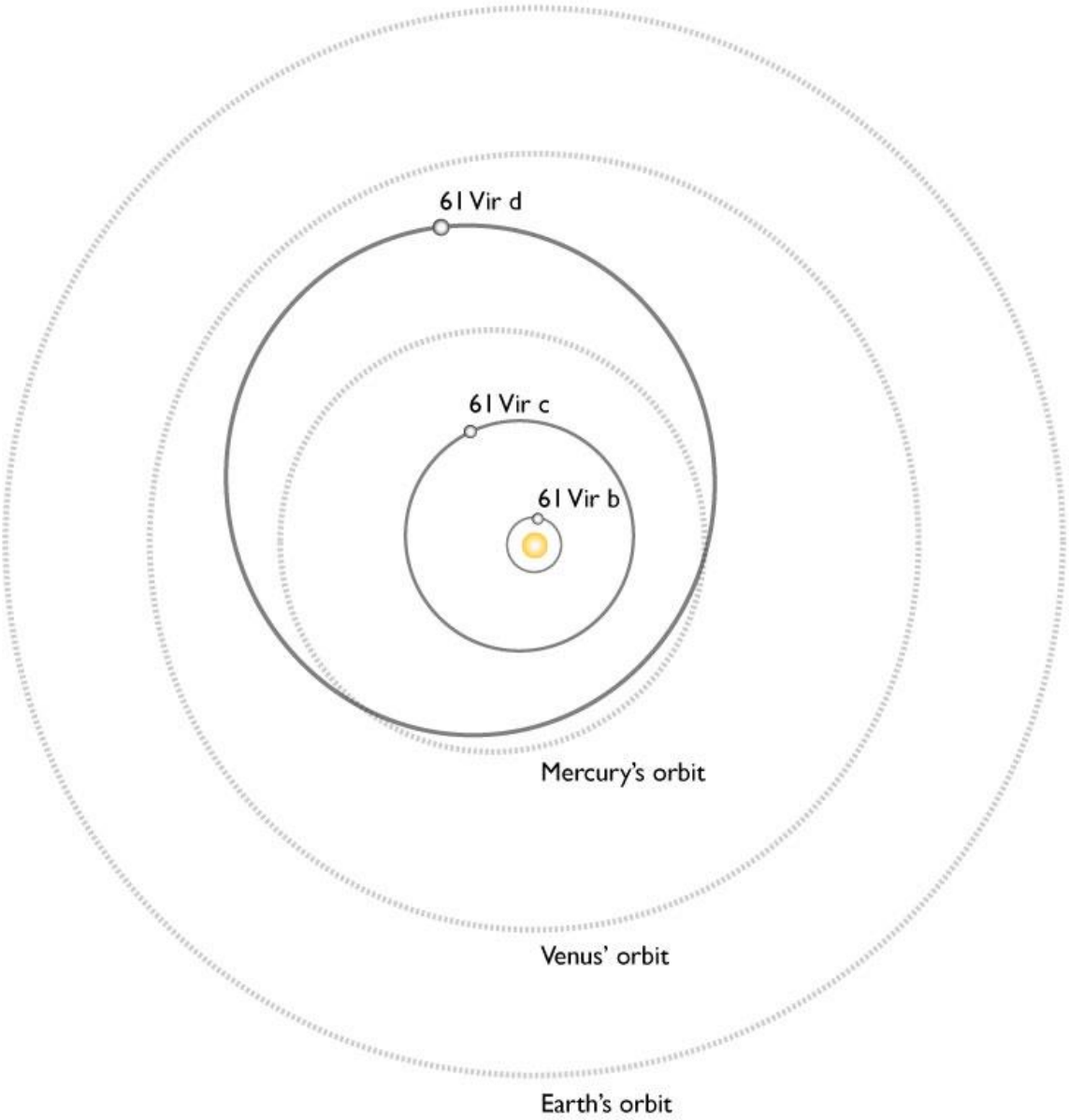
5 Earth-Masses

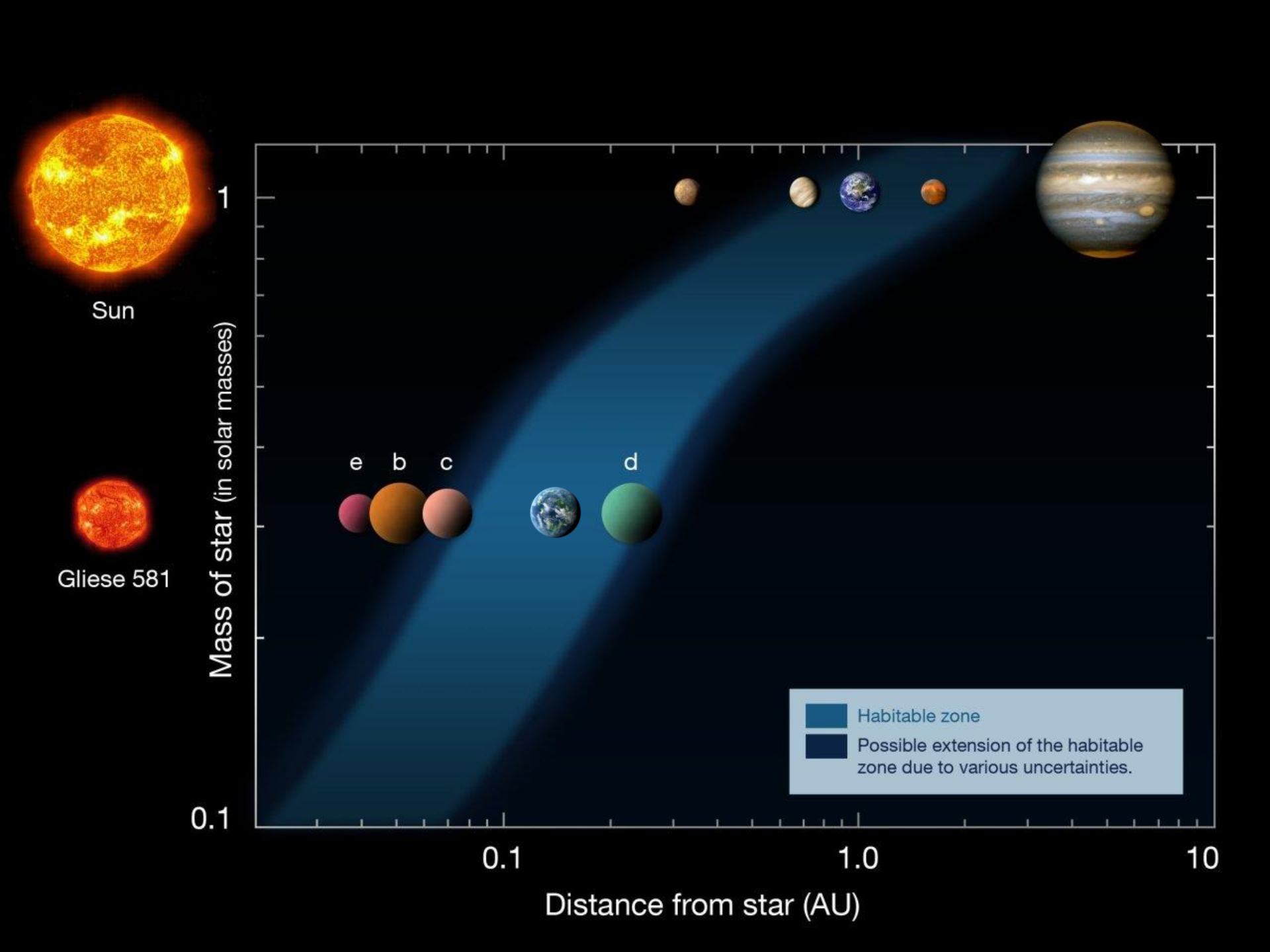
P = 50 day

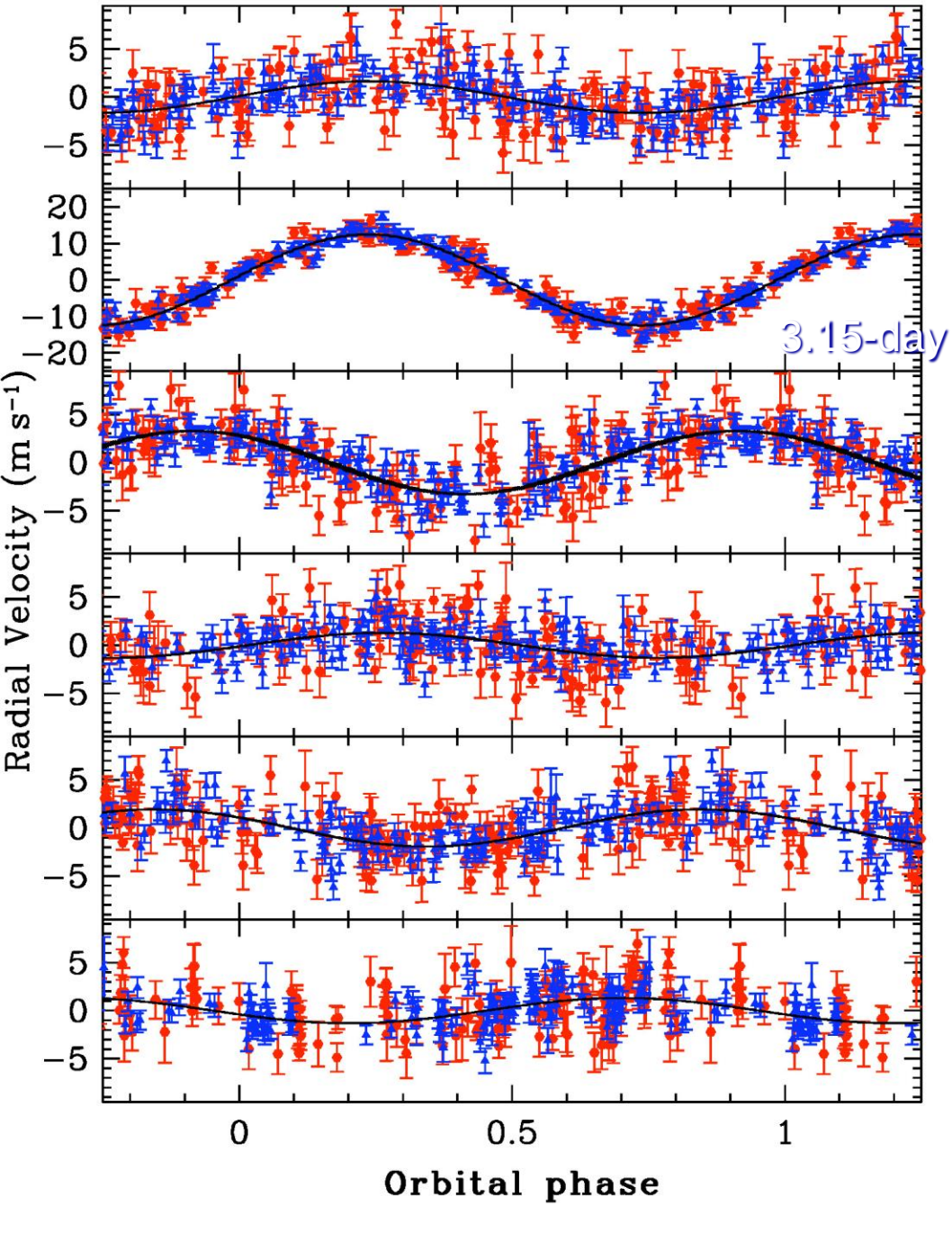


- Nature is cruel and vicious, doesn't give up secrets easily
- The most interesting planets come in packed systems
- Lots of planetary signals require lots of data to disentangle




61 Vir d
61 Vir c
61 Vir b
Mercury's orbit
Venus' orbit
Earth's orbit


Sun
Gliese 581
Mass of star (in solar masses)
1
0.1
e
b
c
d
Habitable zone
Possible extension of the habitable zone due to various uncertainties.
0.1
1.0
10
Distance from star (AU)



3.15-day

5.7-day

12.9-day

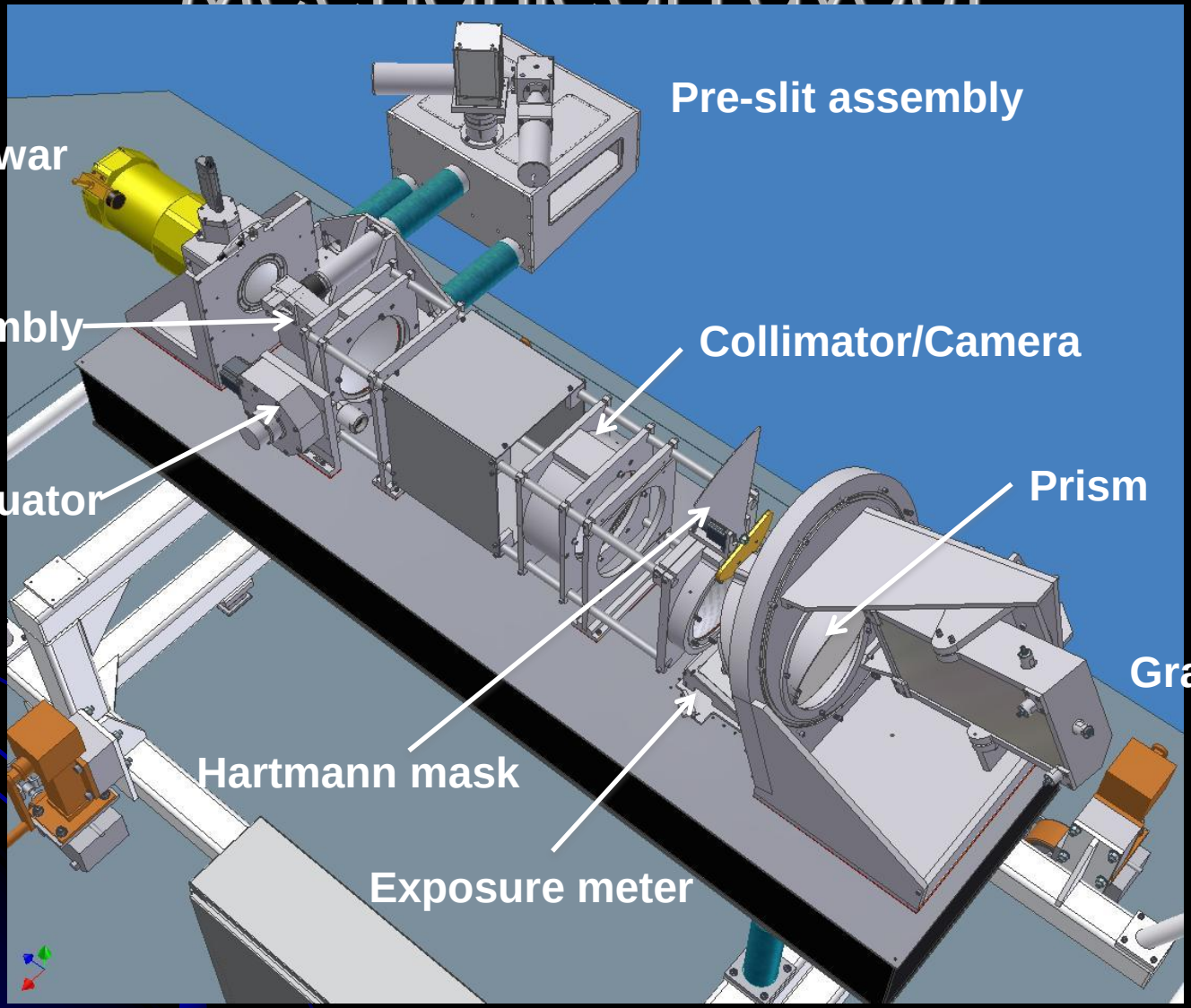
37-day

67-day

433-day

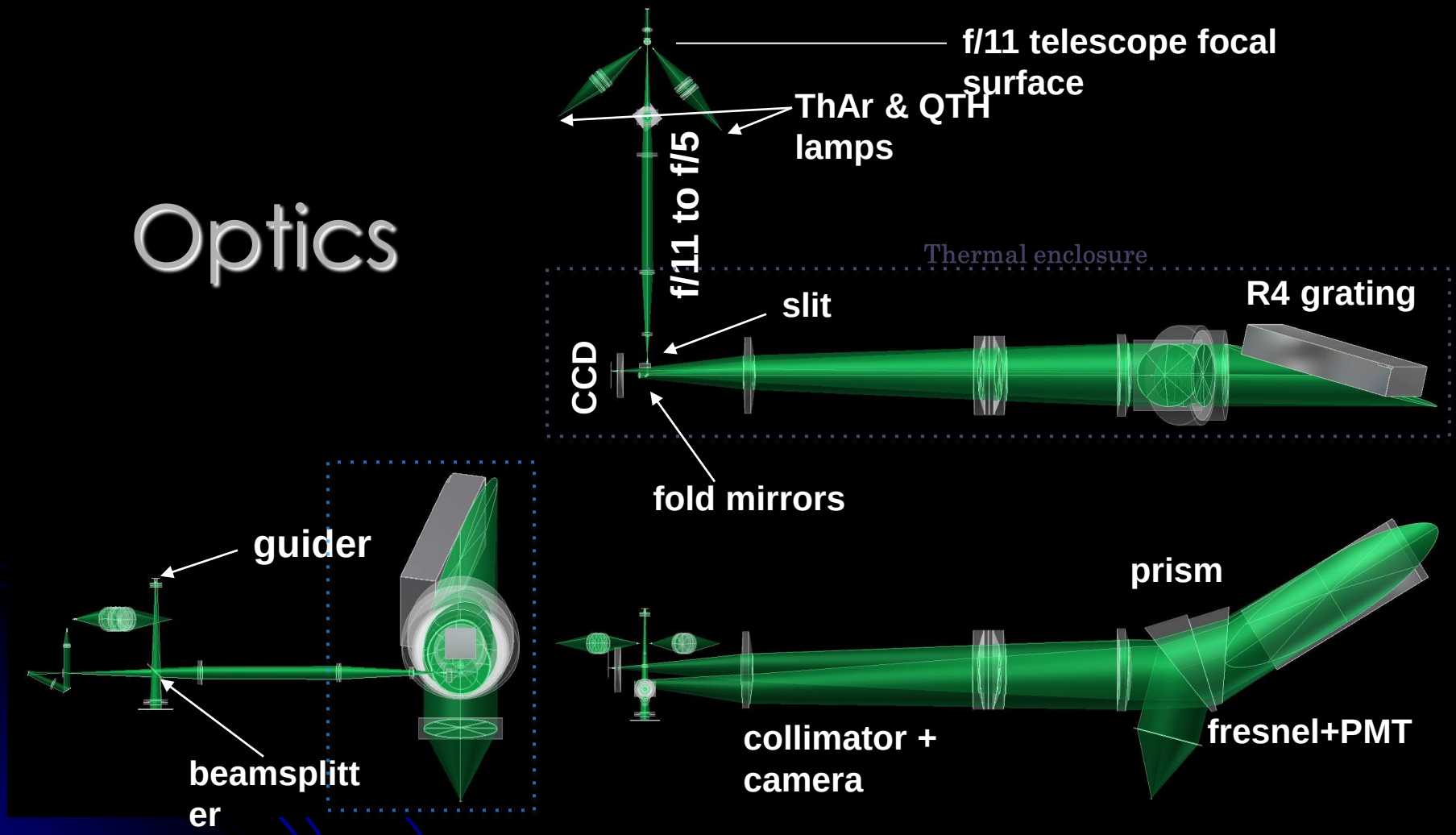
Magellan Planet Finding Spectrometer

Mechanical Layout



Thermal enclosure removed

Optics

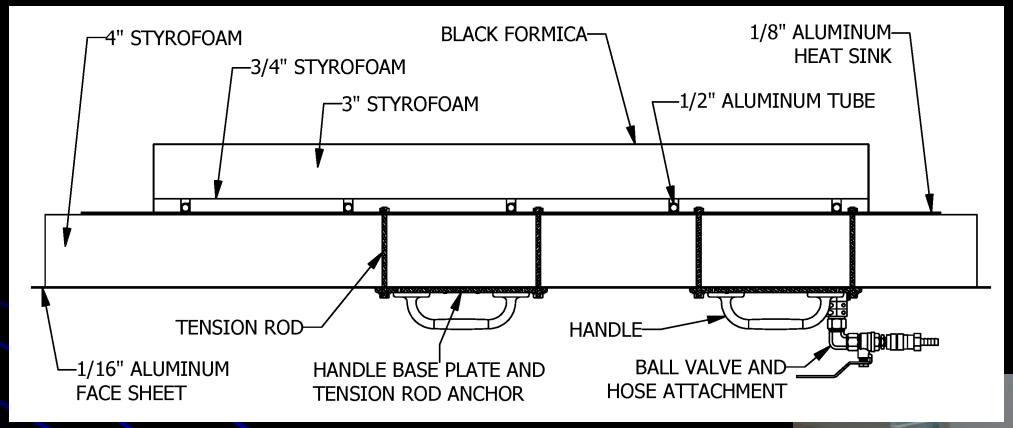


Calibration lamp system enabled in configuration shown

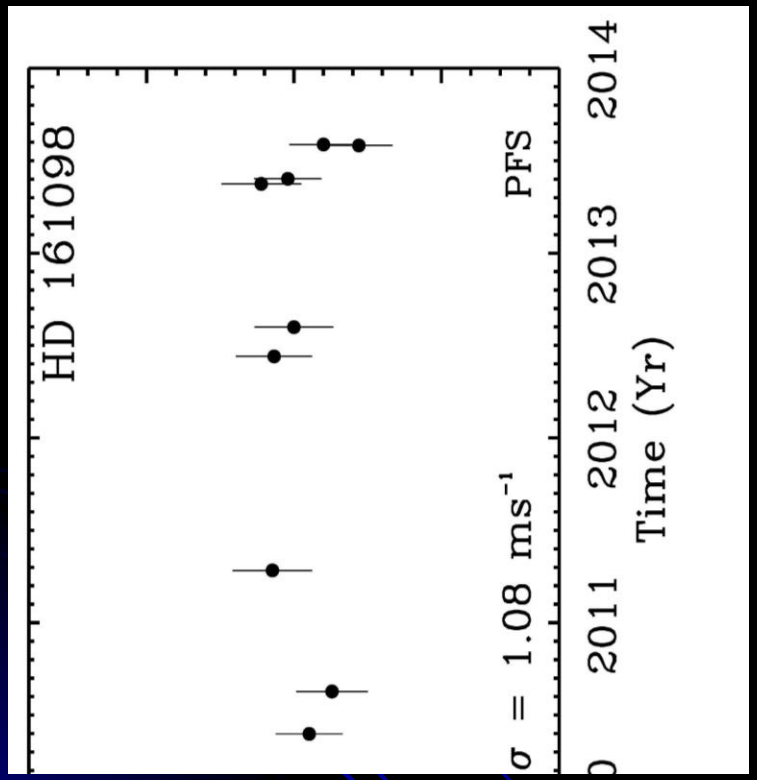
Thermal control

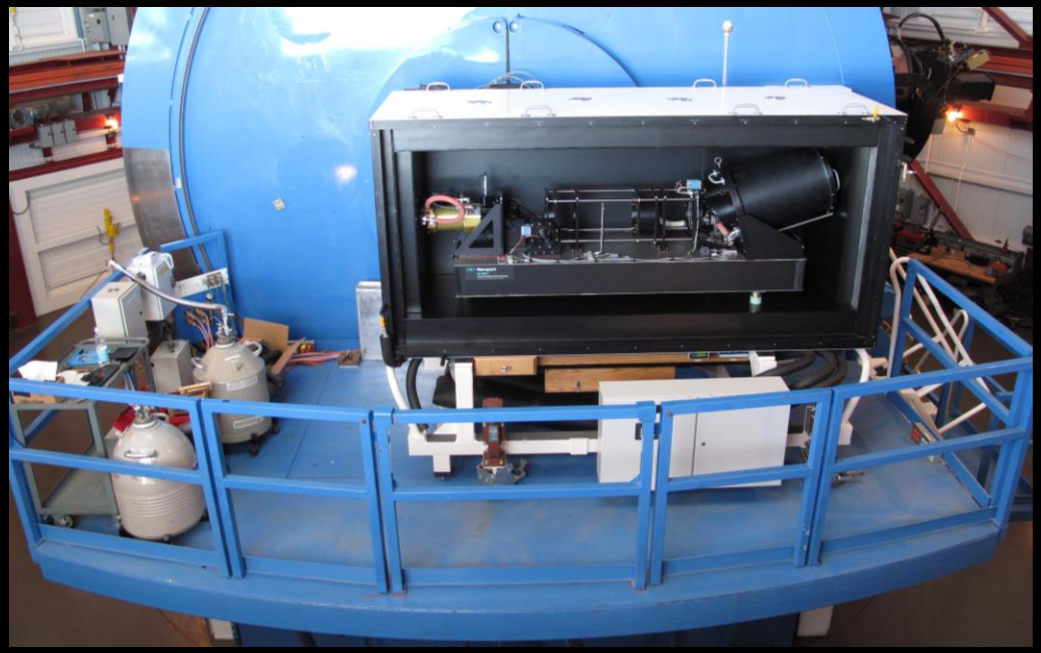
Instrument sees a 25° C isothermal box around it.

- **Metal plates embedded in foam enclosure**
- **Closed-loop, re-circulating glycol solution**



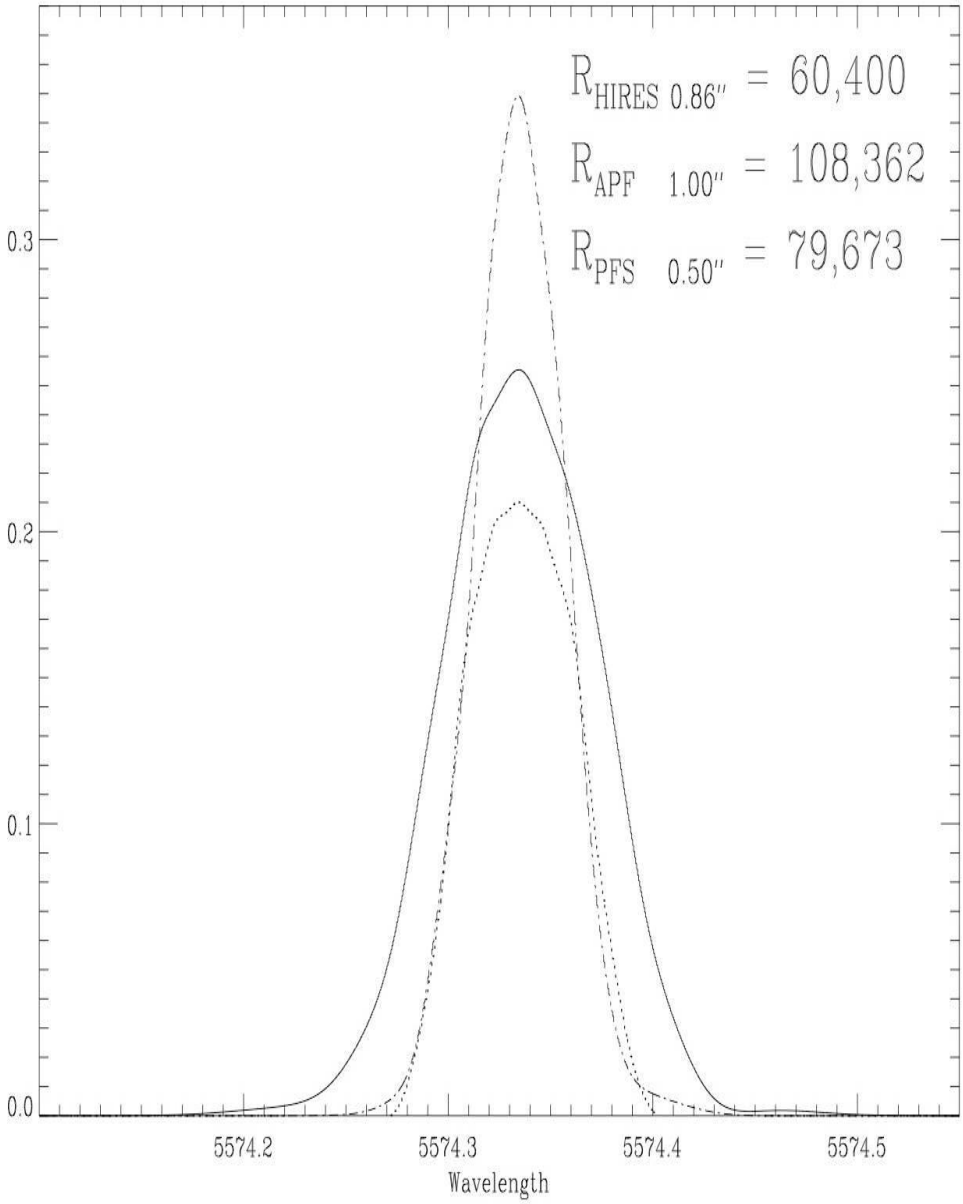
On the Nasmyth Platform

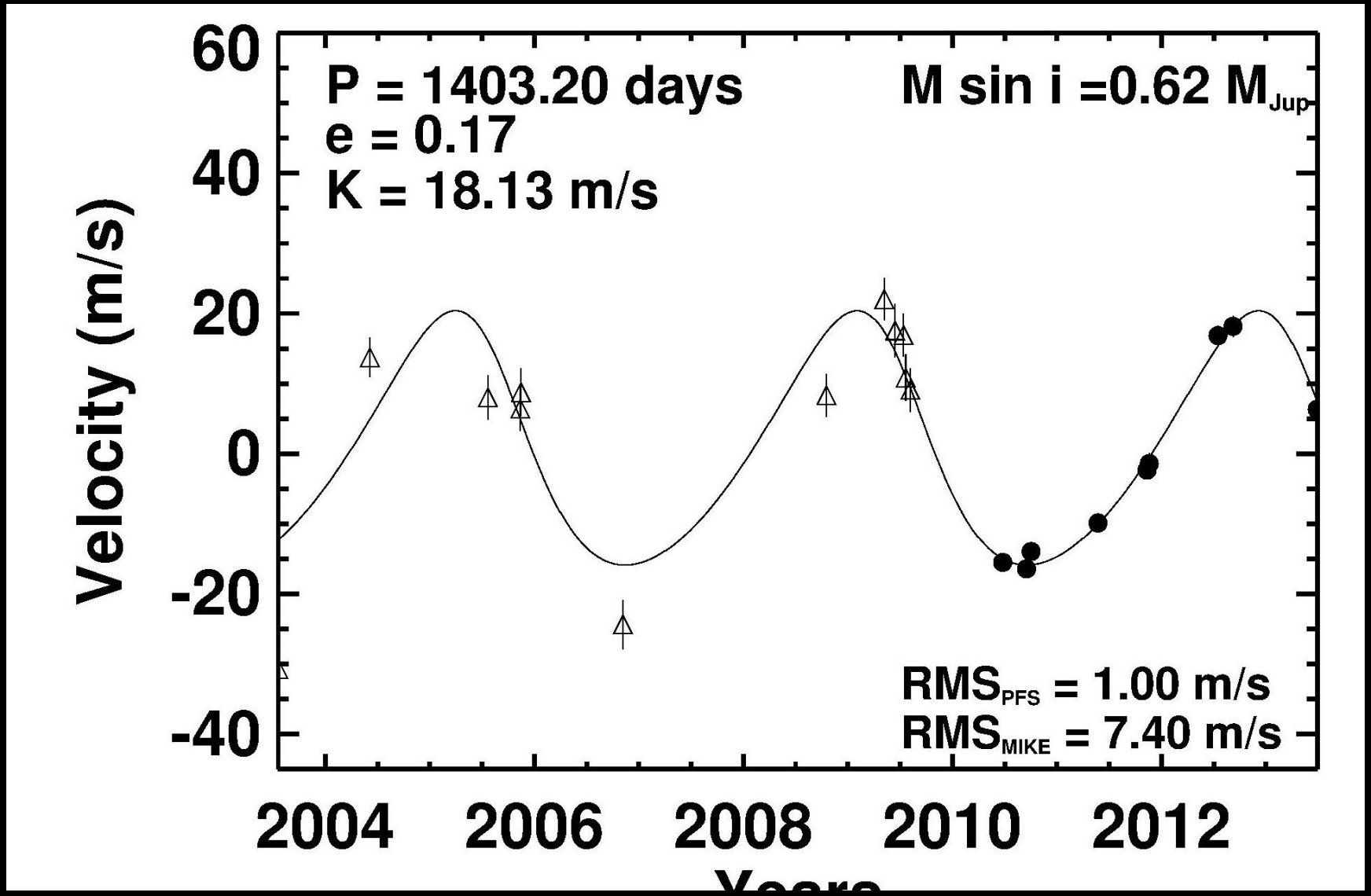


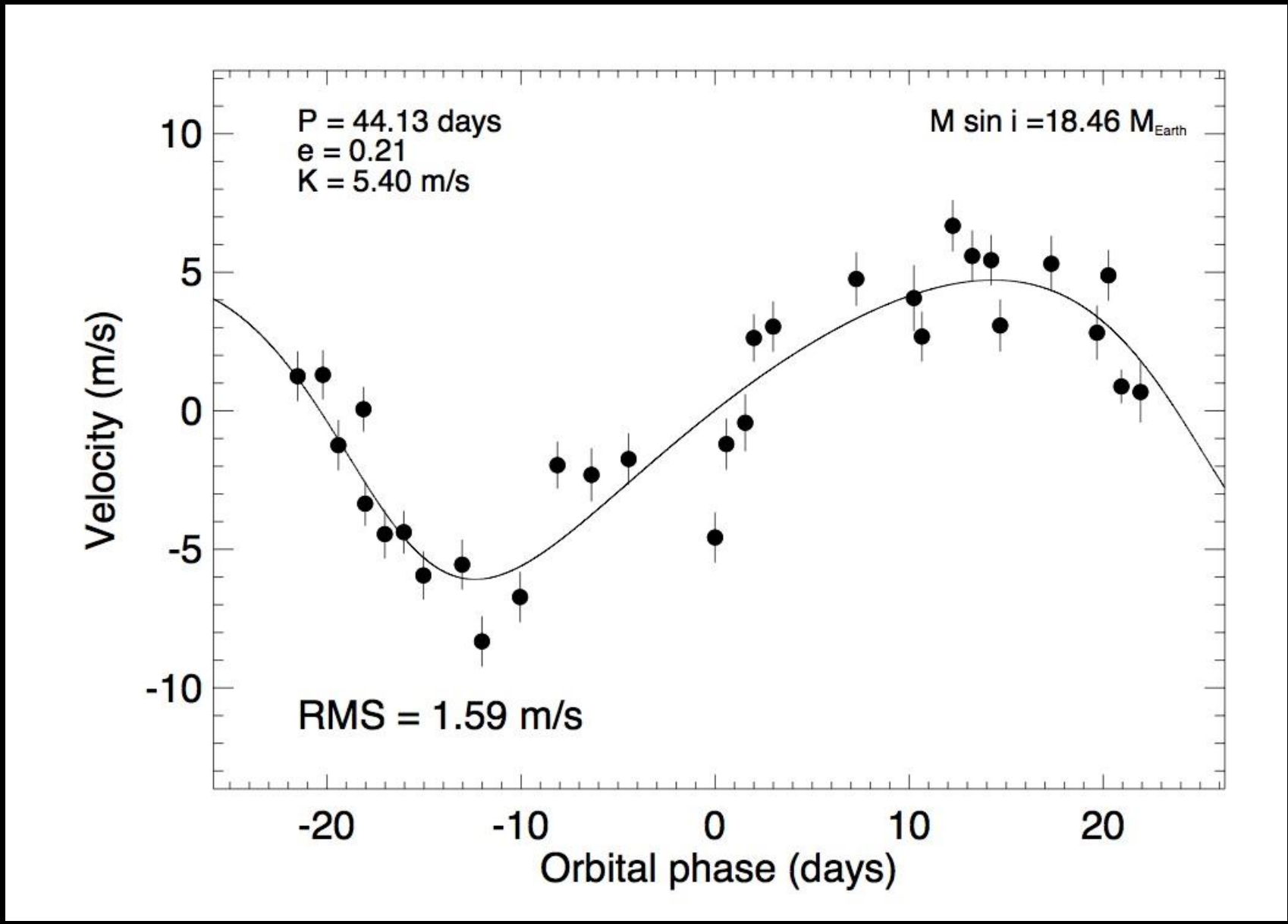


Side insulation panel is removed to show instrument interior

- Mobility required since the nasmyth focus is shared with other instruments

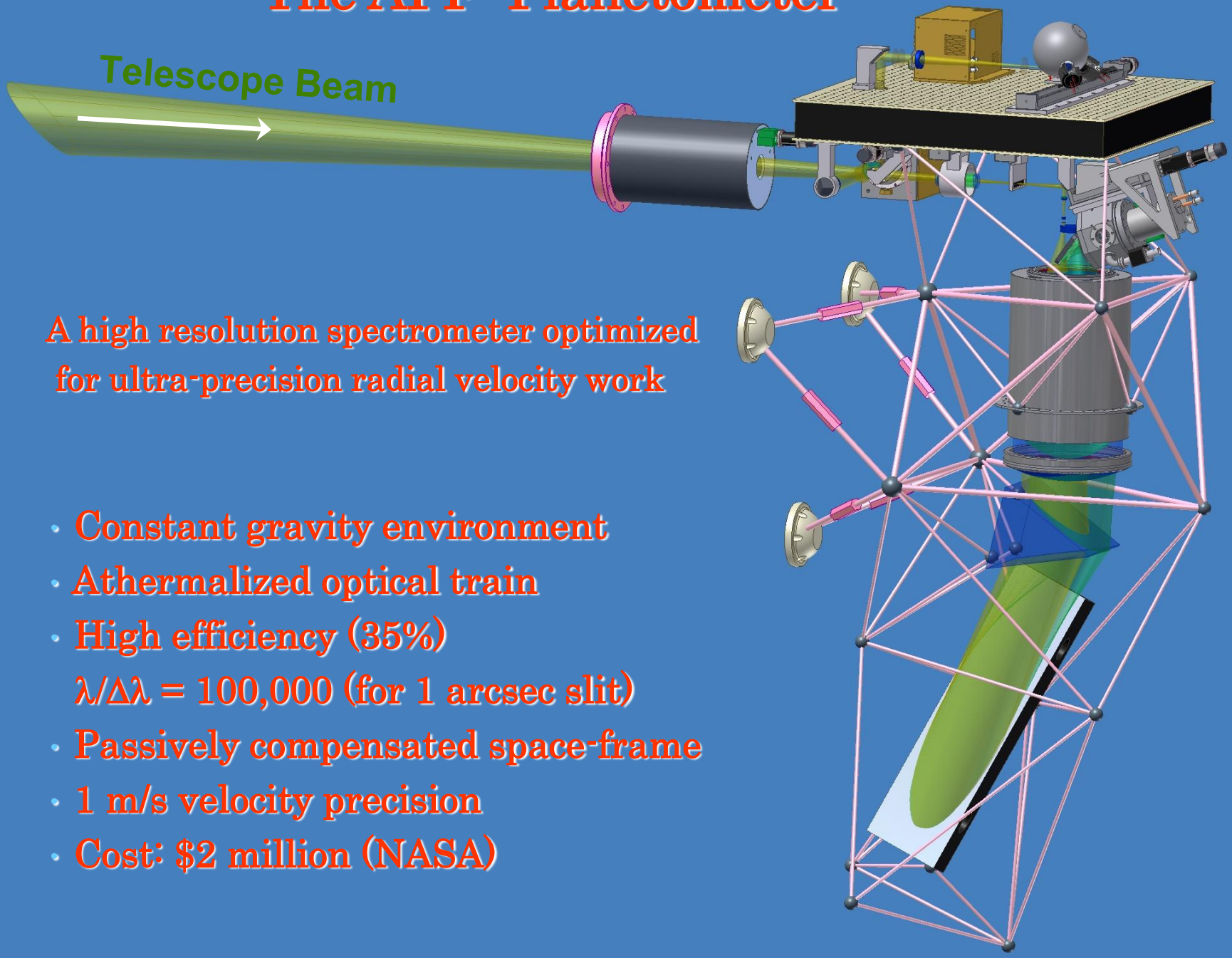

$R_{HIRES\ 0.86''}$ = 60,400
$R_{APF\ 1.00''}$ = 108,362
$R_{PFS\ 0.50''}$ = 79,673
0.3
0.2
0.1
0.0
5574.2
5574.3
5574.4
5574.5
Wavelength


P = 1403.20 days
e = 0.17
K = 18.13 m/s
M sin i =0.62 M_Jup
RMS_PFS = 1.00 m/s
RMS_MIKE = 7.40 m/s
Velocity (m/s)
60
40
20
0
-20
-40
2004
2006
2008
2010
2012
Years


P = 44.13 days
e = 0.21
K = 5.40 m/s
M sin i =18.46 M_Earth
RMS = 1.59 m/s
Velocity (m/s)
Orbital phase (days)
10
5
0
-5
-10
-20
-10
0
10
20

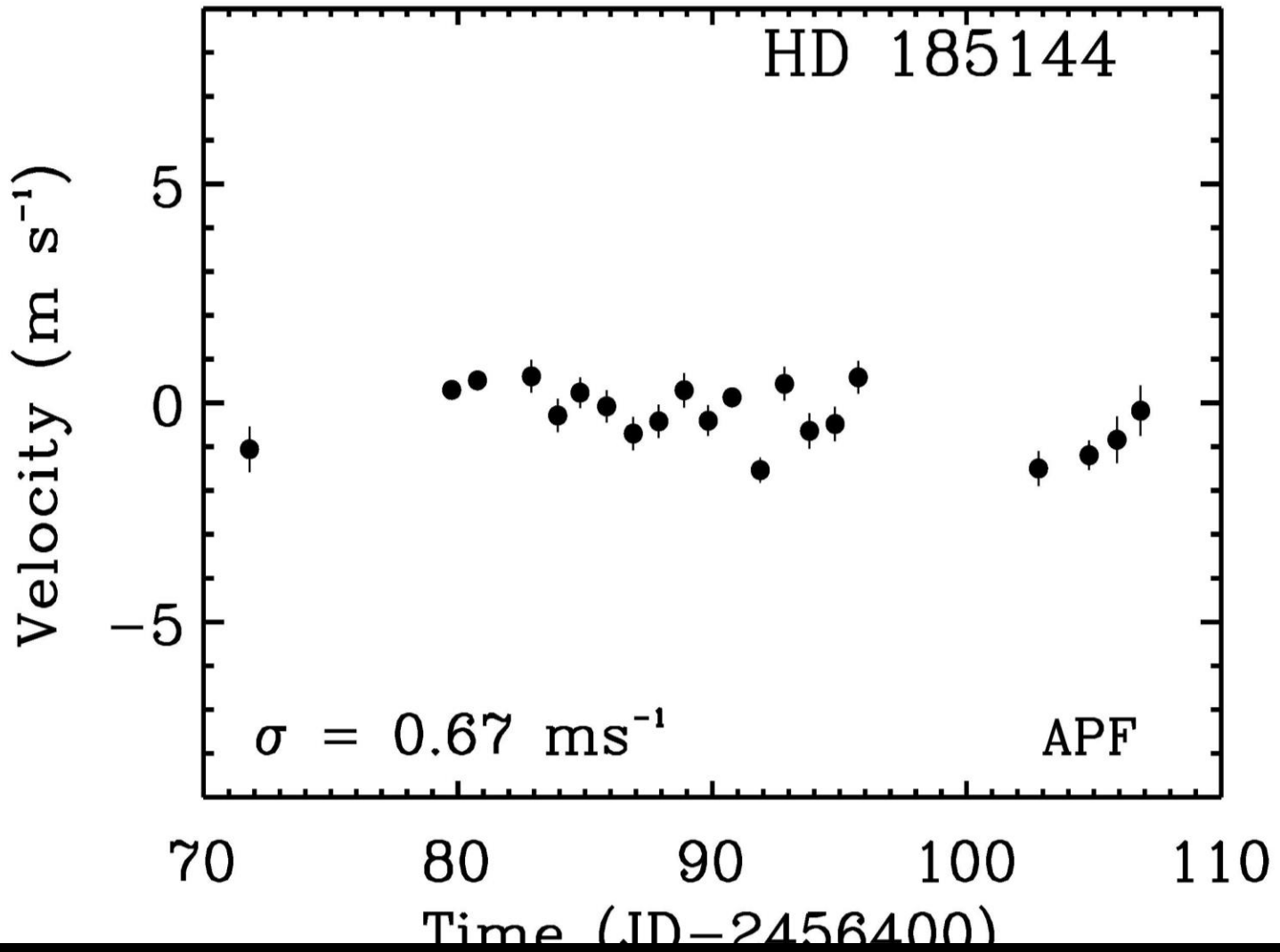
2.4m Automated Planet Finder

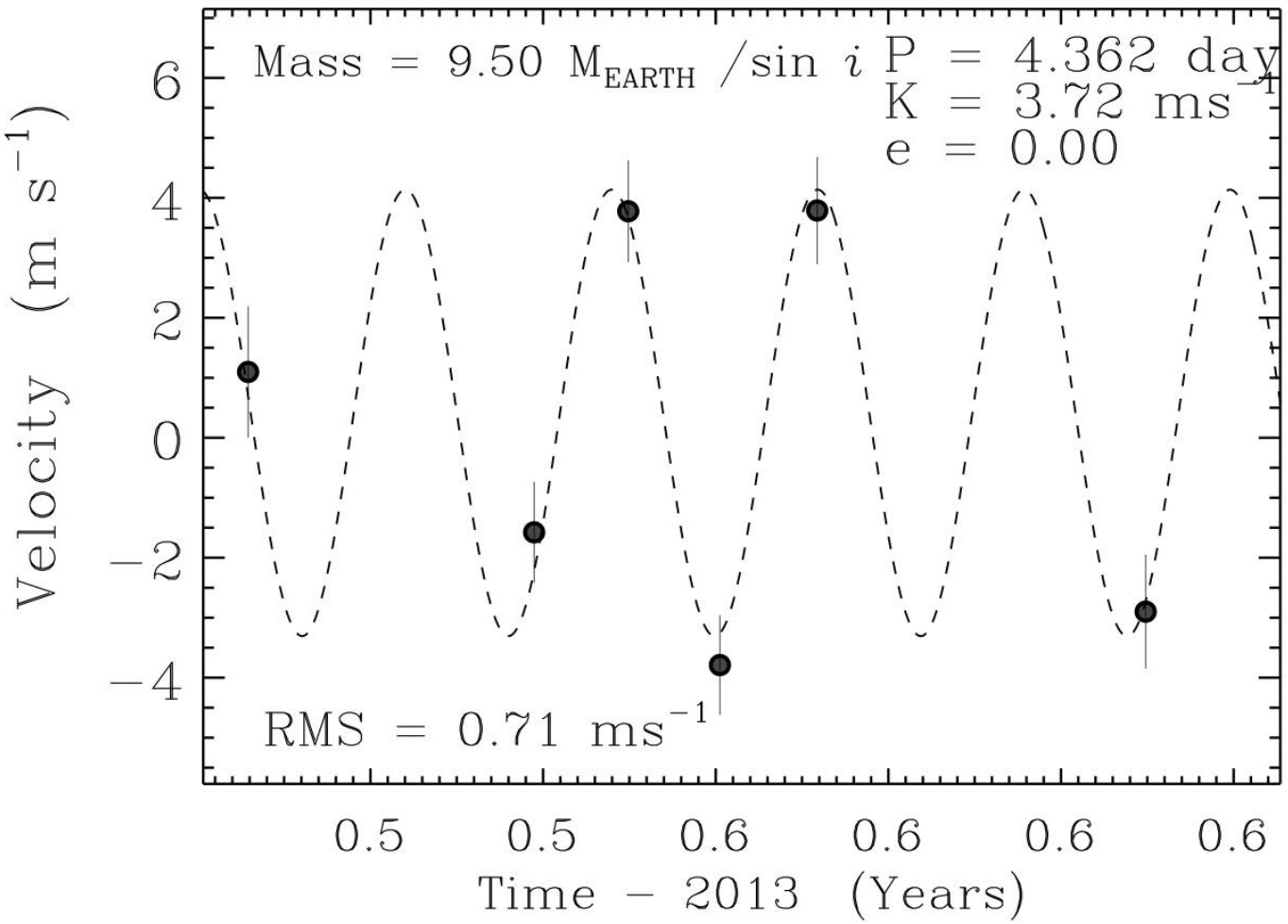
The APF Planetometer



A high resolution spectrometer optimized for ultra-precision radial velocity work

- Constant gravity environment
- Athermalized optical train
- High efficiency (35%)
  $\lambda/\Delta\lambda = 100{,}000$ (for 1 arcsec slit)
- Passively compensated space-frame
- 1 m/s velocity precision
- Cost: $2 million (NASA)

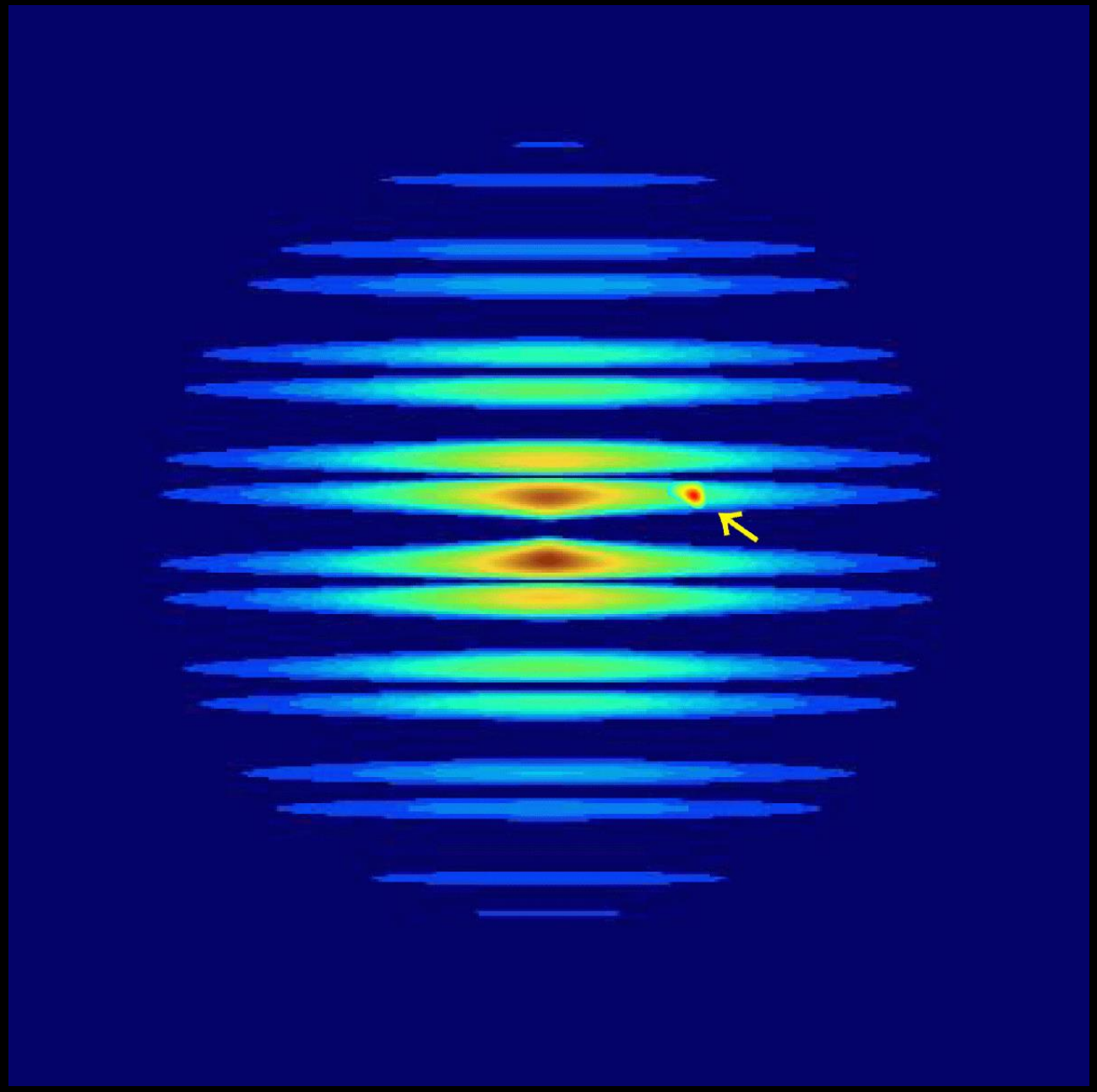

HD 185144
Velocity (m s^{-1})
5
0
−5
σ = 0.67 ms^{-1}
APF
70
80
90
100
110
Time (JD−2456400)


Mass = 9.50 M_EARTH /sin i
P = 4.362 day
K = 3.72 ms^-1
e = 0.00
RMS = 0.71 ms^-1
Velocity (m s^-1)
6
4
2
0
−2
−4
0.5
0.5
0.6
0.6
0.6
0.6
Time − 2013 (Years)

Beyond 2030

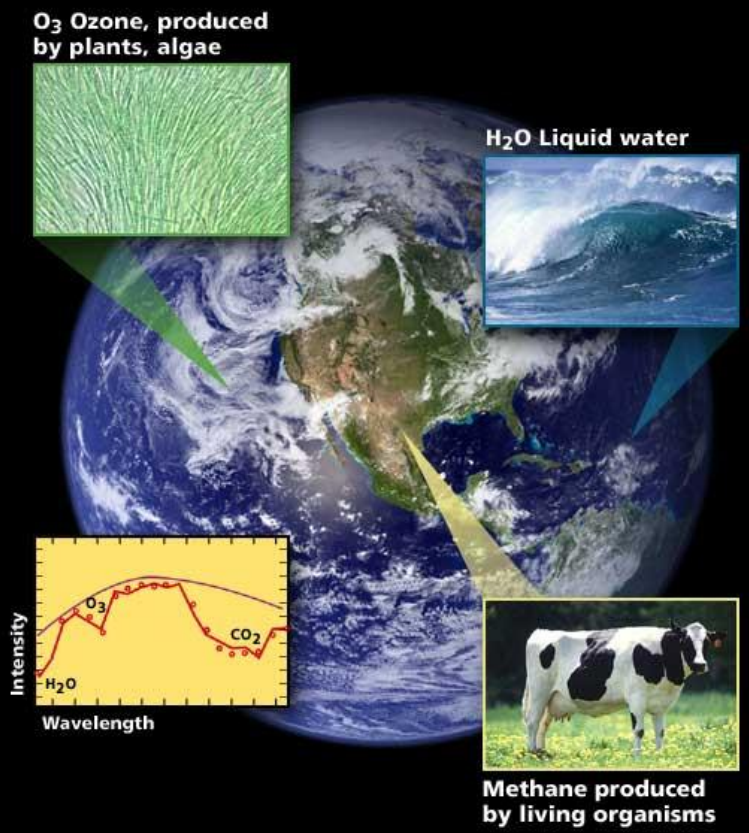
Terrestrial Planet Finder

DARWIN



And how will we know a planet supports life?

Look for evidence



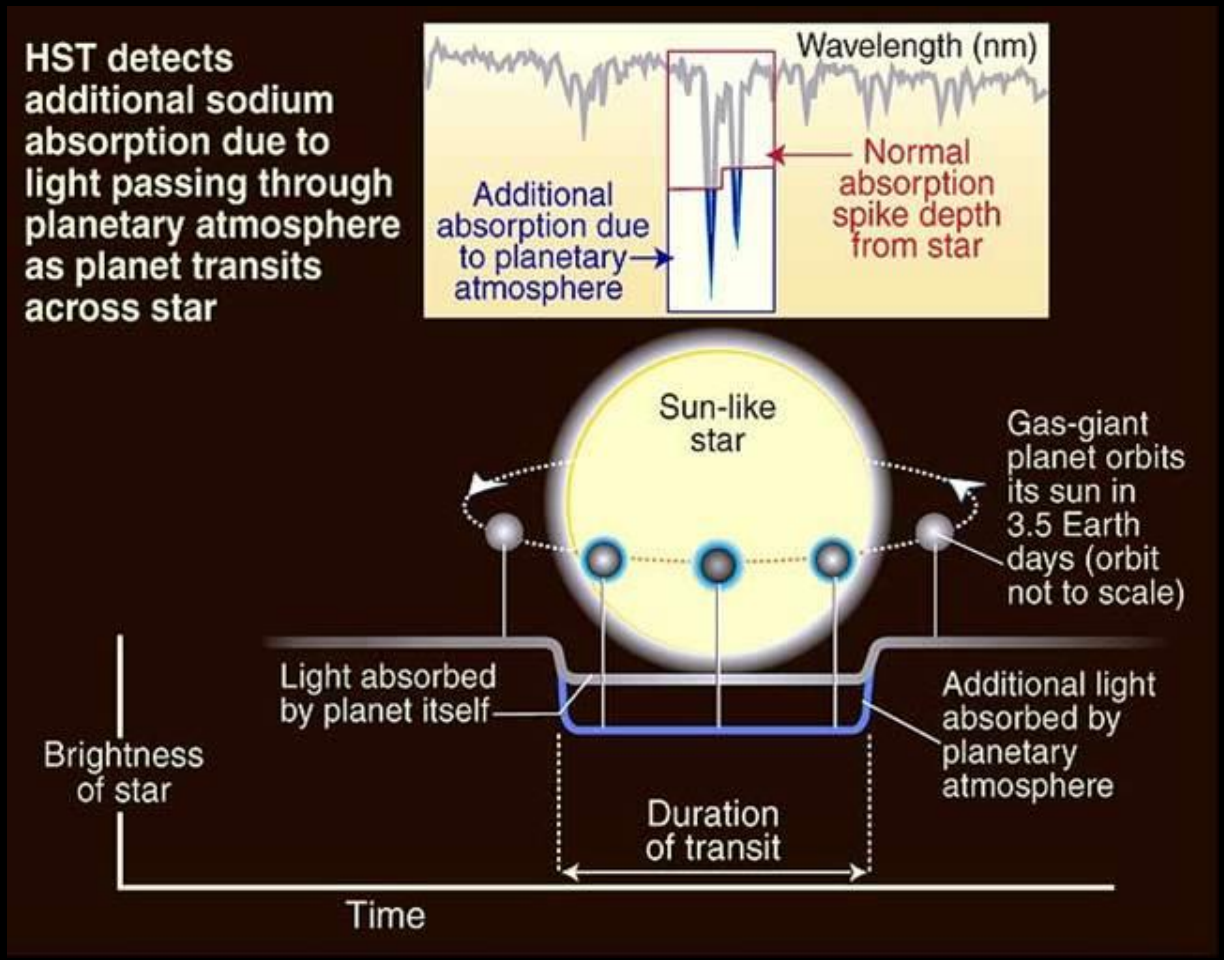
Look for liquid

Analyze the reflected light from

Look for signs of biological

and rule out other explanations.

HD209458: Transiting Planet



M=0.63 MJUP

R = 1.4 RJUP

➔ Gas Giant

Grav. Contract. Suppressed.

(Burrows et al.)

T.Brown & D.Charbonneau

Known Planets, March 2013

Exoplanet Missions

JWST

AFTA

TESS

Kepler

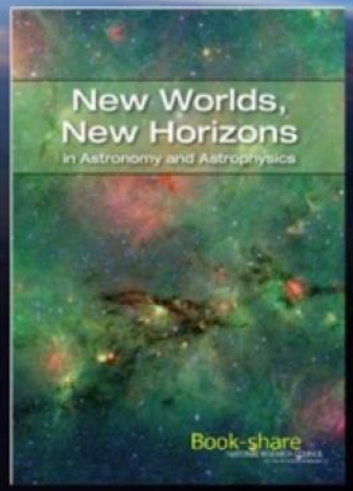
New Worlds Telescope

Spitzer

Hubble

Ground-based Observatories

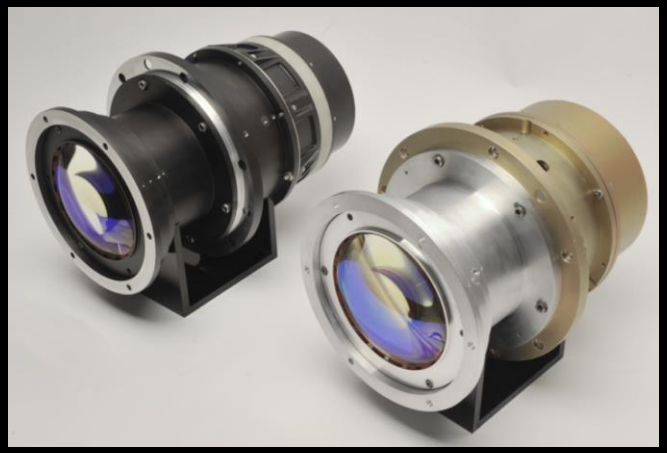
2001 Decadal Survey



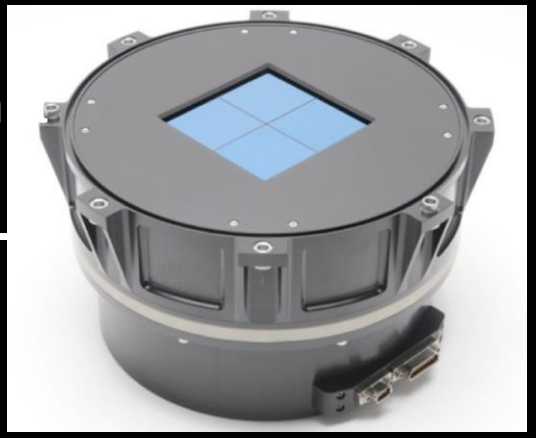
2010 Decadal Survey


siting
lanet Survey
lite
S S
ed Explorer
(launch 2017)
he brightest
an all-sky
Am
es
CfA
MIT
GS
FC
Orbi
tal
STS
cl

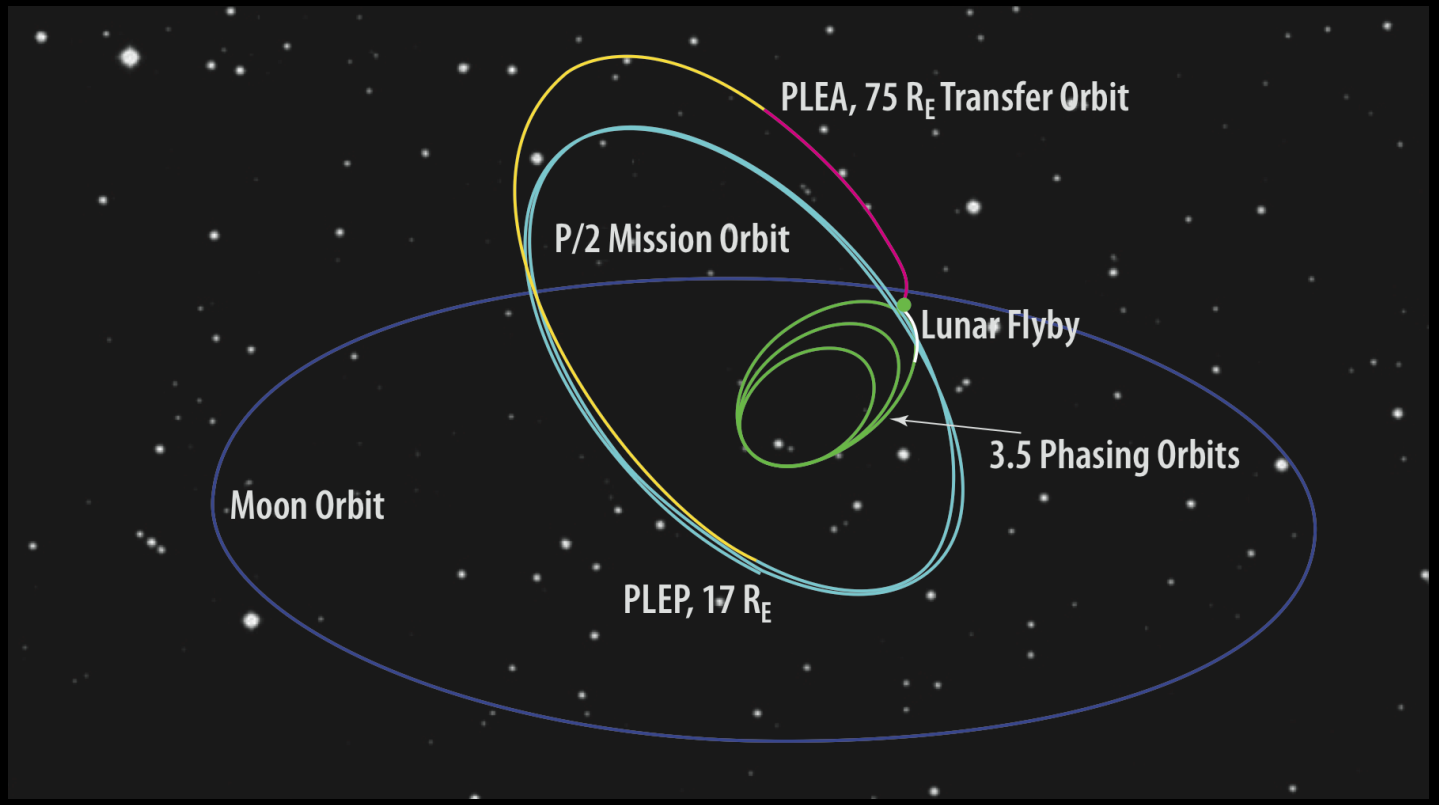
4 wide-field cameras (10 cm, *f*/1.6, 23° FOV)

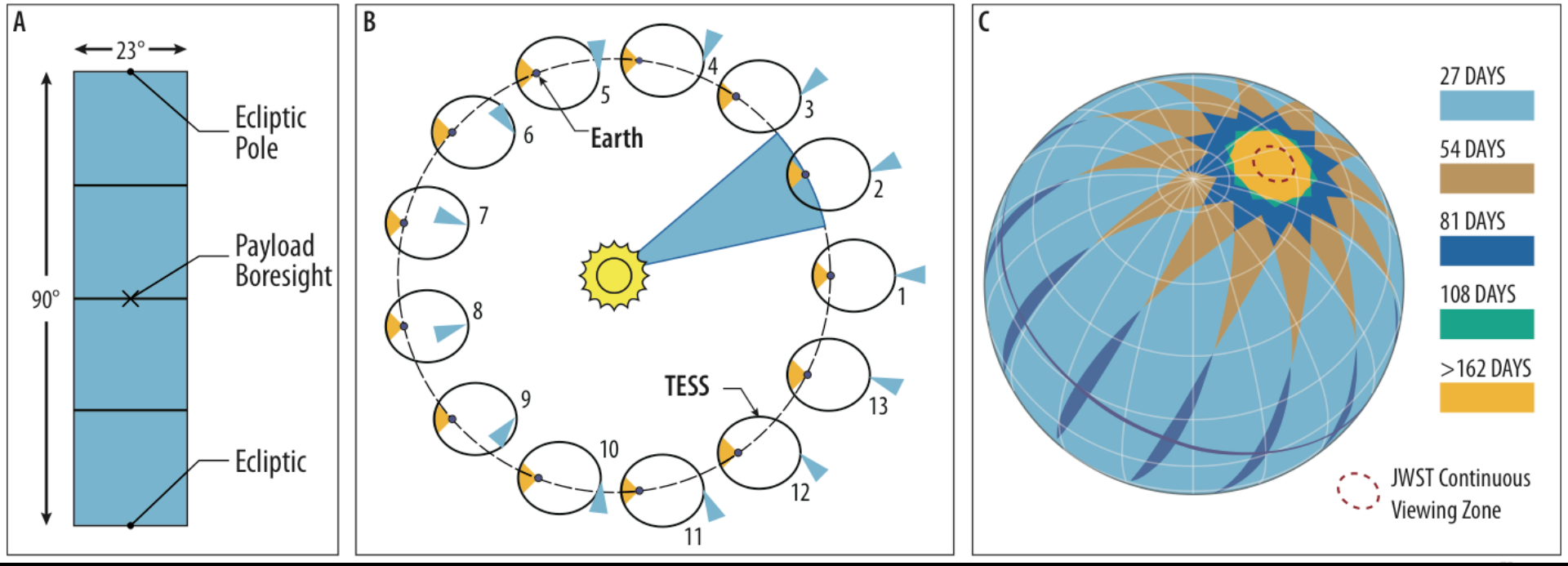


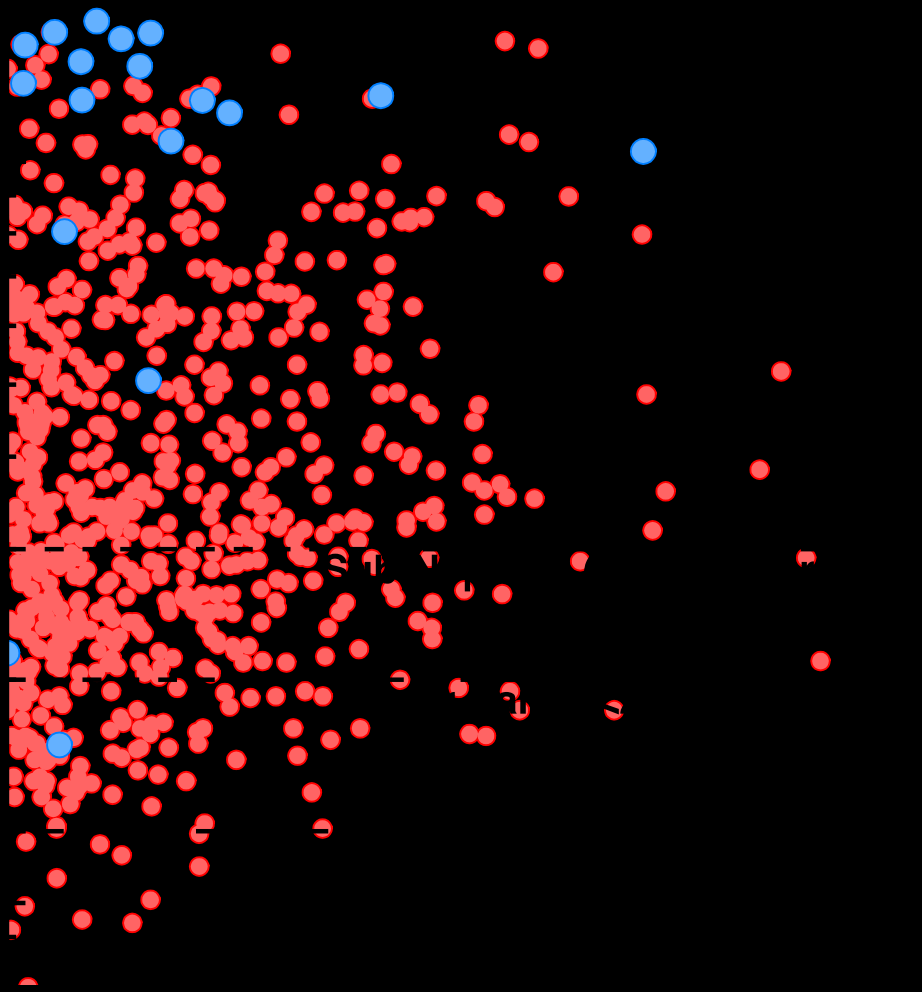
Each with 4k CCD (4 x CCID-80)



High Earth orbit, in 2:1 resonance with the Moon



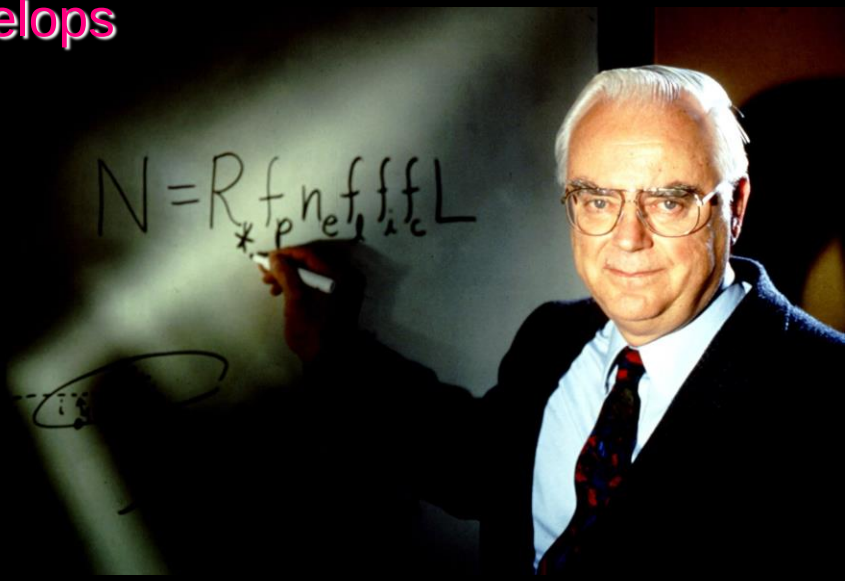

A
23°
90°
Ecliptic Pole
Payload Boresight
Ecliptic
B
Earth
TESS
1
2
3
4
5
6
7
8
9
10
11
12
13
C
27 DAYS
54 DAYS
81 DAYS
108 DAYS
>162 DAYS
JWST Continuous Viewing Zone


Known Planets, March 2013
Predicted TESS Yield

The Drake Equation

Number of communicative civilizations

Rate of formation of suitable stars
Fraction of those stars with planets
Number of “earths” per planetary system
Fraction of those planets where life develops
Fraction of life sites where intelligent life develops
Fraction of planets with technology
Lifetime of communicating civilizations



Crucial People:

Steve Vogt, UCSC

Steve Shectman, Carnegie Observatories

Jeff Crane, Carnegie Observatories

Dante Minniti, Catolica Santiago

Pamela Arriagada, DTM

Greg Laughlin, UCSC

Matias Diaz, U de Chile

Chris Tinney, UNSW

Hugh Jones, U of Hertfordshire

Brad Carter, U of Southern Queensland