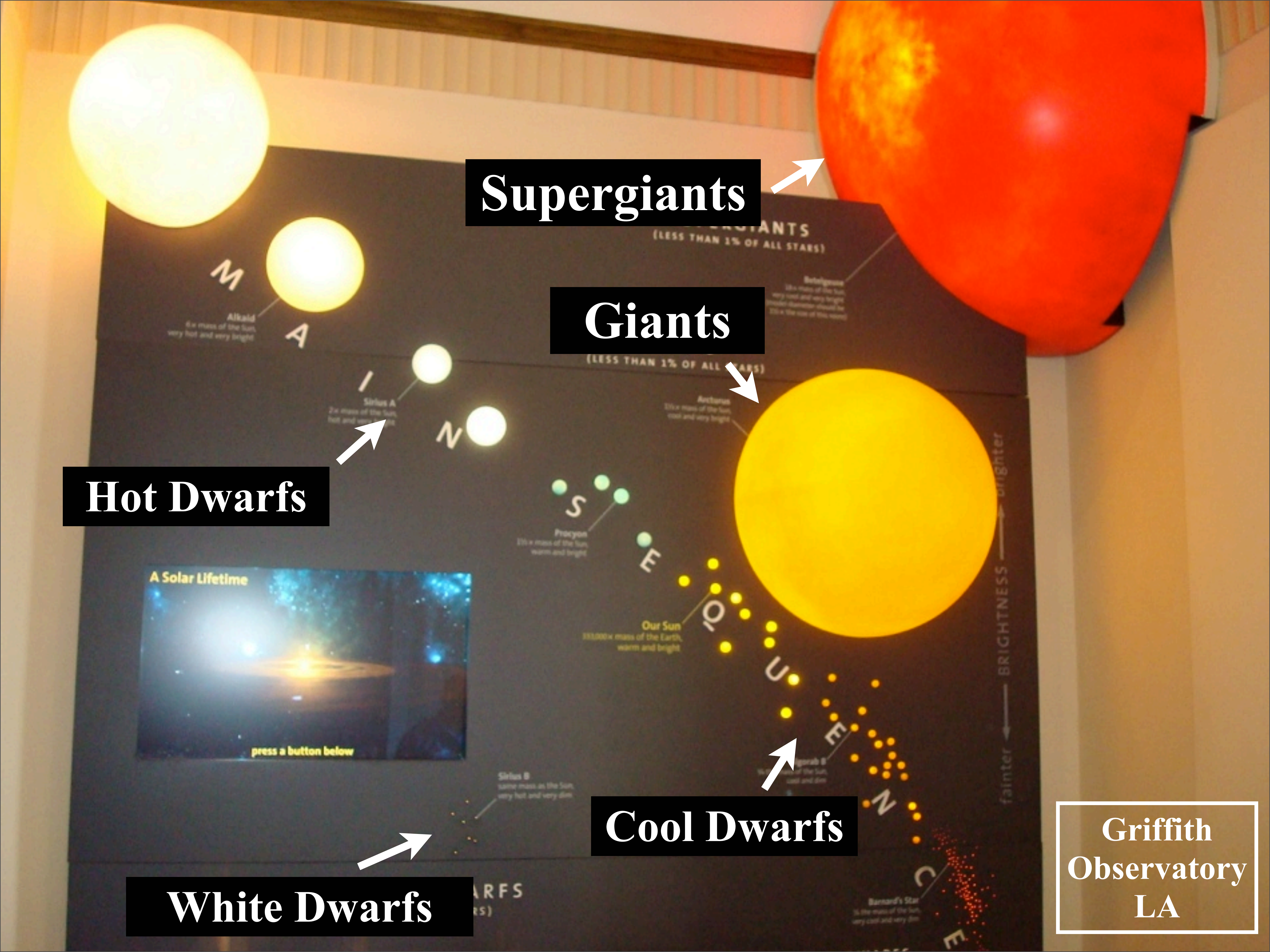
Interferometry & Asteroseismology of Solar-like Stars

(+ their Connection to Exoplanets)

Daniel Huber

NASA Ames Research Center

Feb 11 2014


Supergiants
Giants
Hot Dwarfs
Cool Dwarfs
White Dwarfs
Griffith
Observatory
LA
A Solar Lifetime
press a button below
(LESS THAN 1% OF ALL STARS)
Our Sun
brighter
BRIGHTNESS
fainter

Fundamental Properties of Stars

Temperature (T)

Radius (R)

Chemical Composition

Mass (M)

Surface Gravity (g)

Luminosity (L)

Density (ρ)

Age

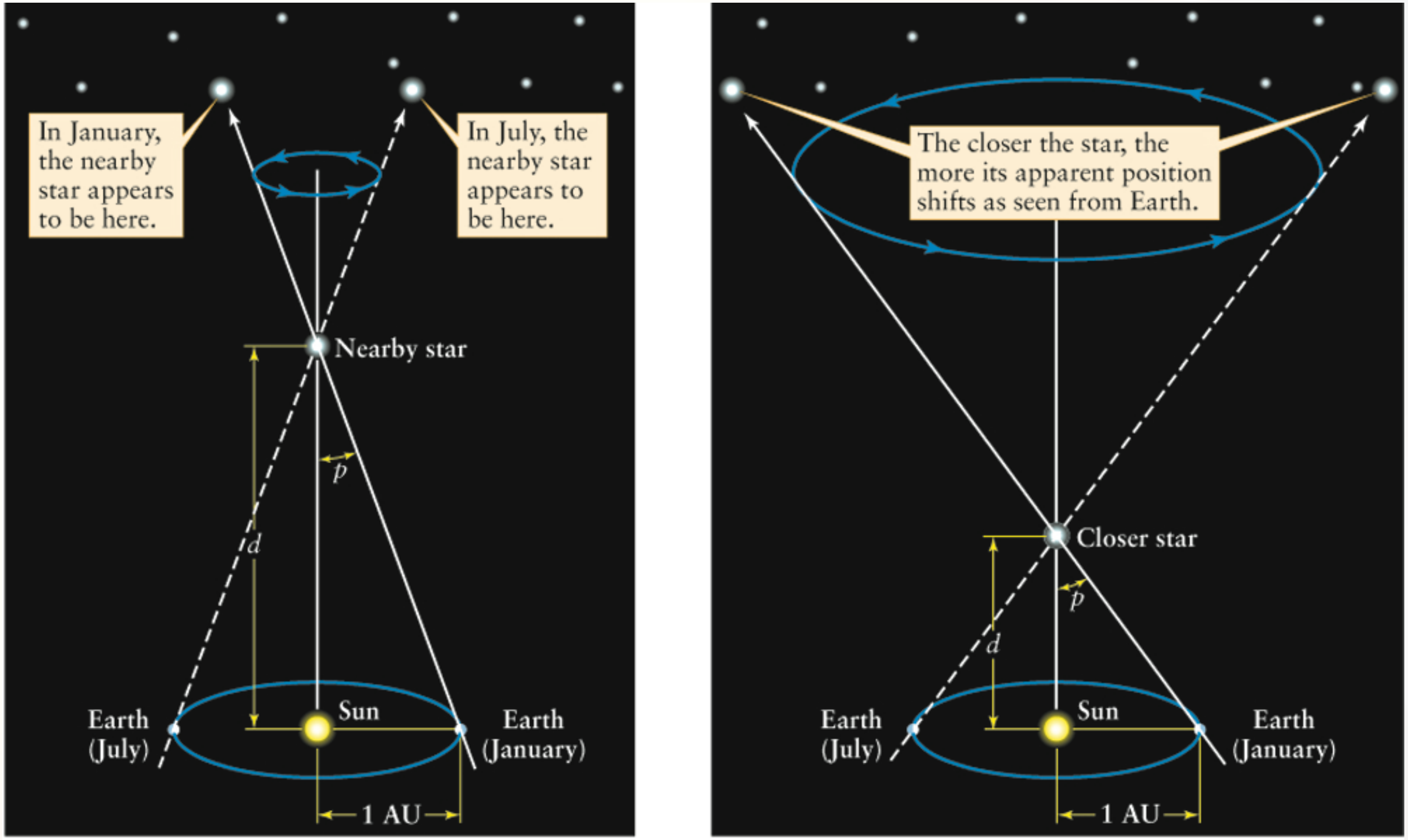
$$g = GM/R^2$$

$$L \propto R^2\, T^4$$

$$\rho \propto M/R^3$$

Goal: use observables to determine measureable stellar properties, in order to test models and infer properties which cannot be directly measured (ages in particular)

Distances to Stars: Parallaxes

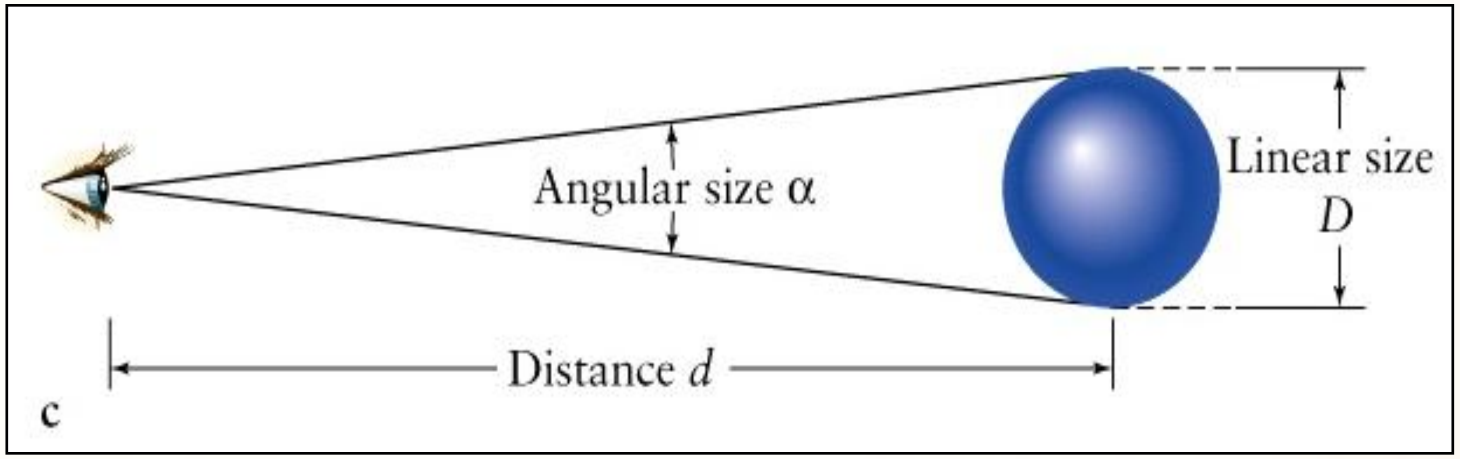


$L \propto f_{bol}\, d^2$

total flux received on Earth

very fundamental; however, distance alone does not give a measurement of stellar properties

Angular Diameters of Stars



$R = d\,\alpha/2$

Angular size + Distance
gives a direct measurement
of the star's Radius

$F = \sigma\, T_{eff}$

↓

$f_{bol} = F\, R^2/d^2$

$R = d\,\alpha/2$

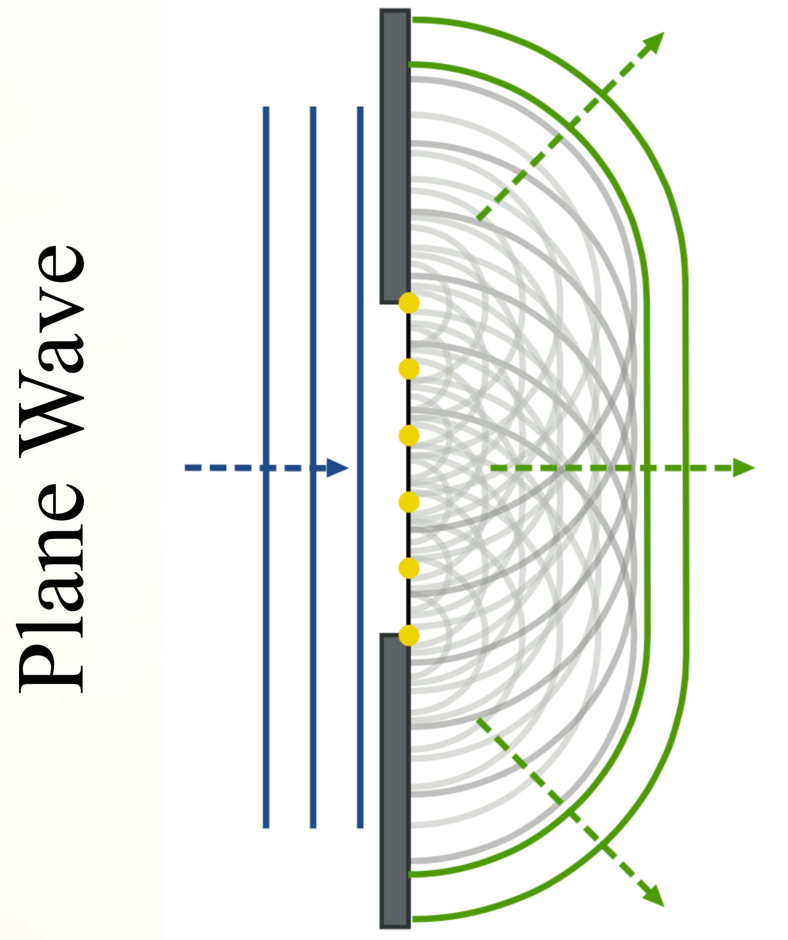
↓

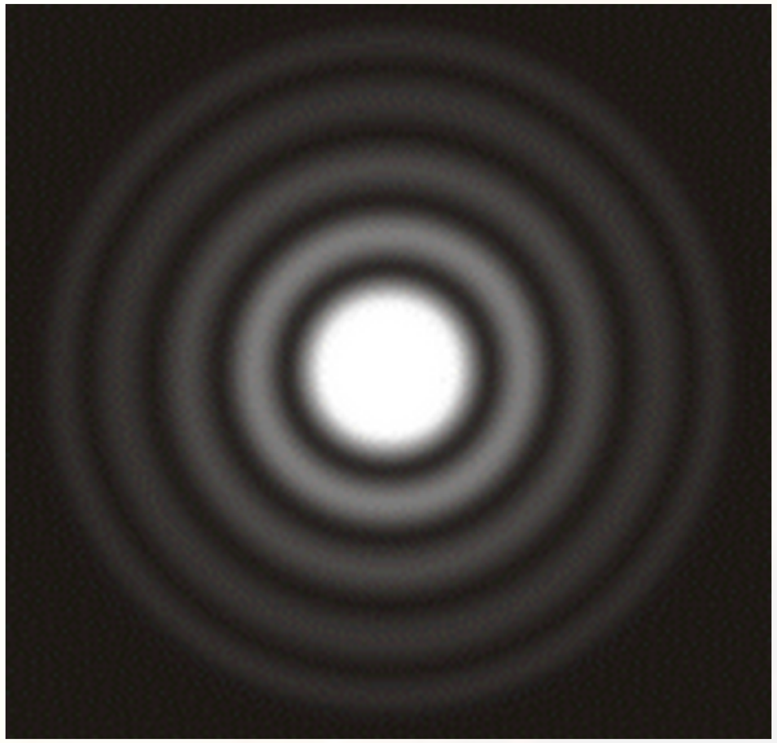
$T_{eff} = (4\, f_{bol} / \sigma\, \alpha^2)$

A stars temperature is defined through it's angular diameter and bolometric flux

Interferometry

Measuring Stellar Angular Diameters





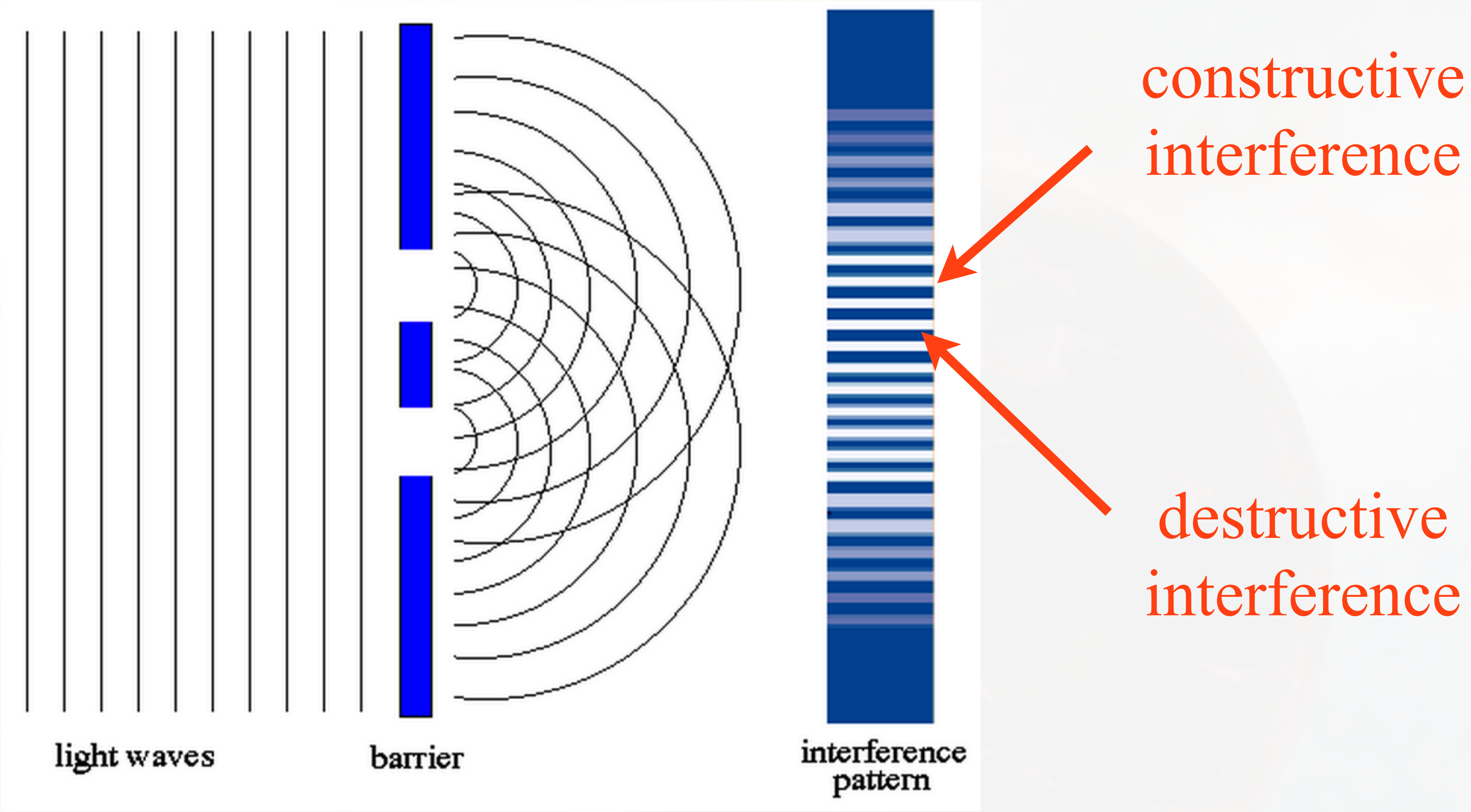
Telescope resolution (Diffraction Limit): $R = 1.22\ \lambda/d$

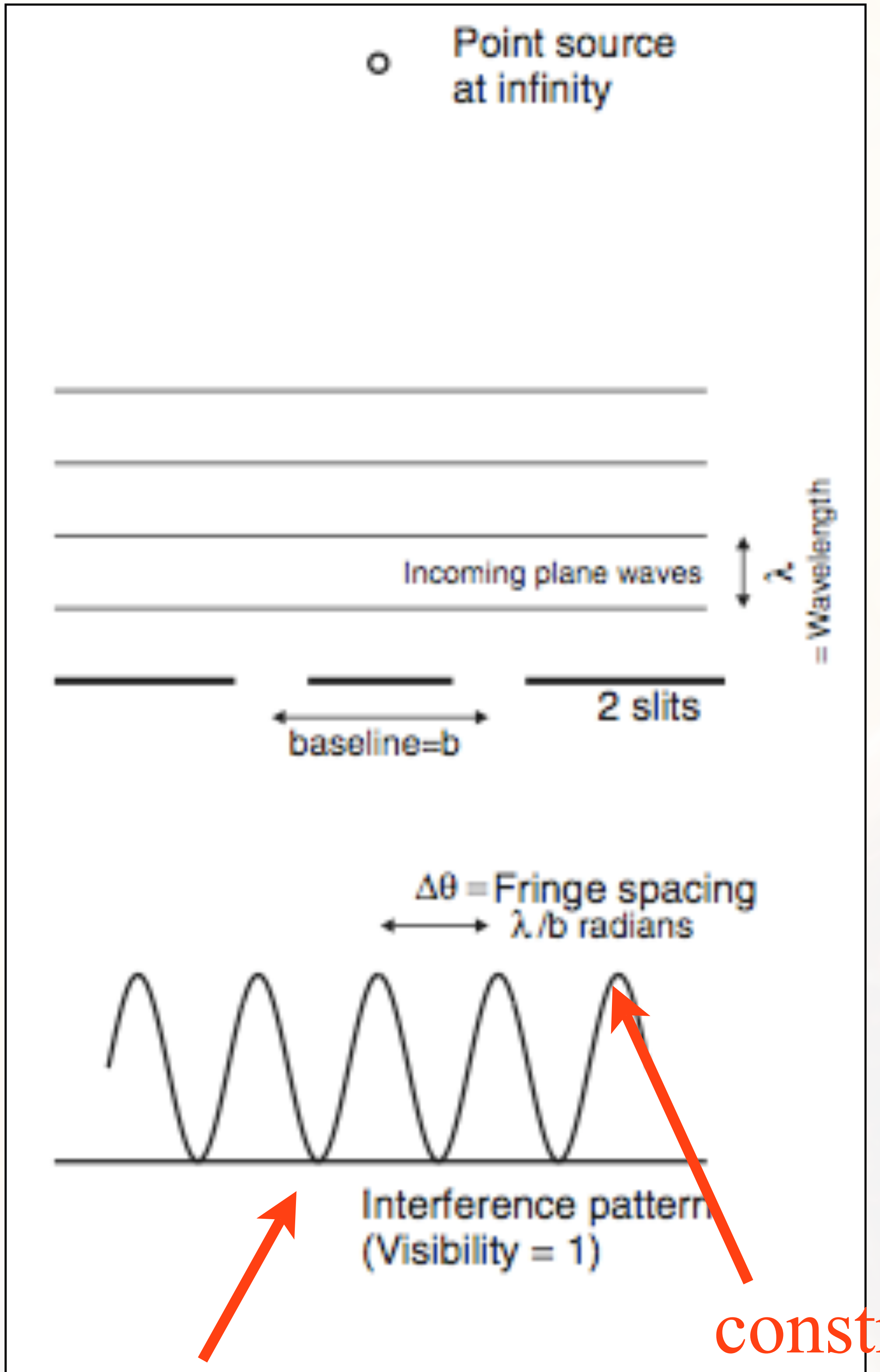
In general, observing at the diffraction limit is not possible because of Earth's atmosphere; observations are "seeing-limited"

(even that wouldn't be enough: the diameter of the Sun at a distance of 5 parsec is ~7 x smaller than the diffraction limit of a 10-m telescope)

Measuring Stellar Angular Diameters

What if we place two telescopes at a large distance apart from each other, and combine the light?





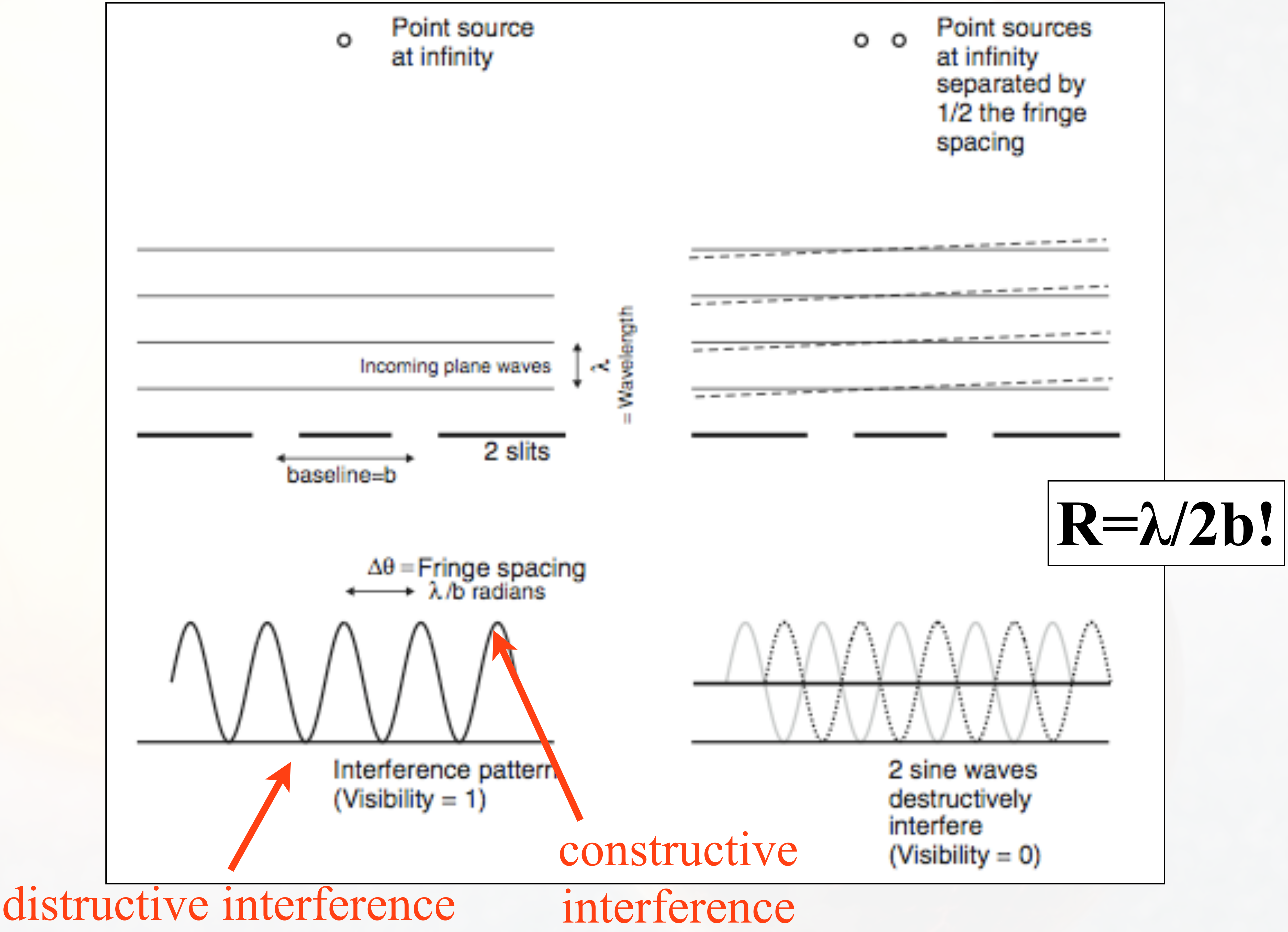
destructive interference

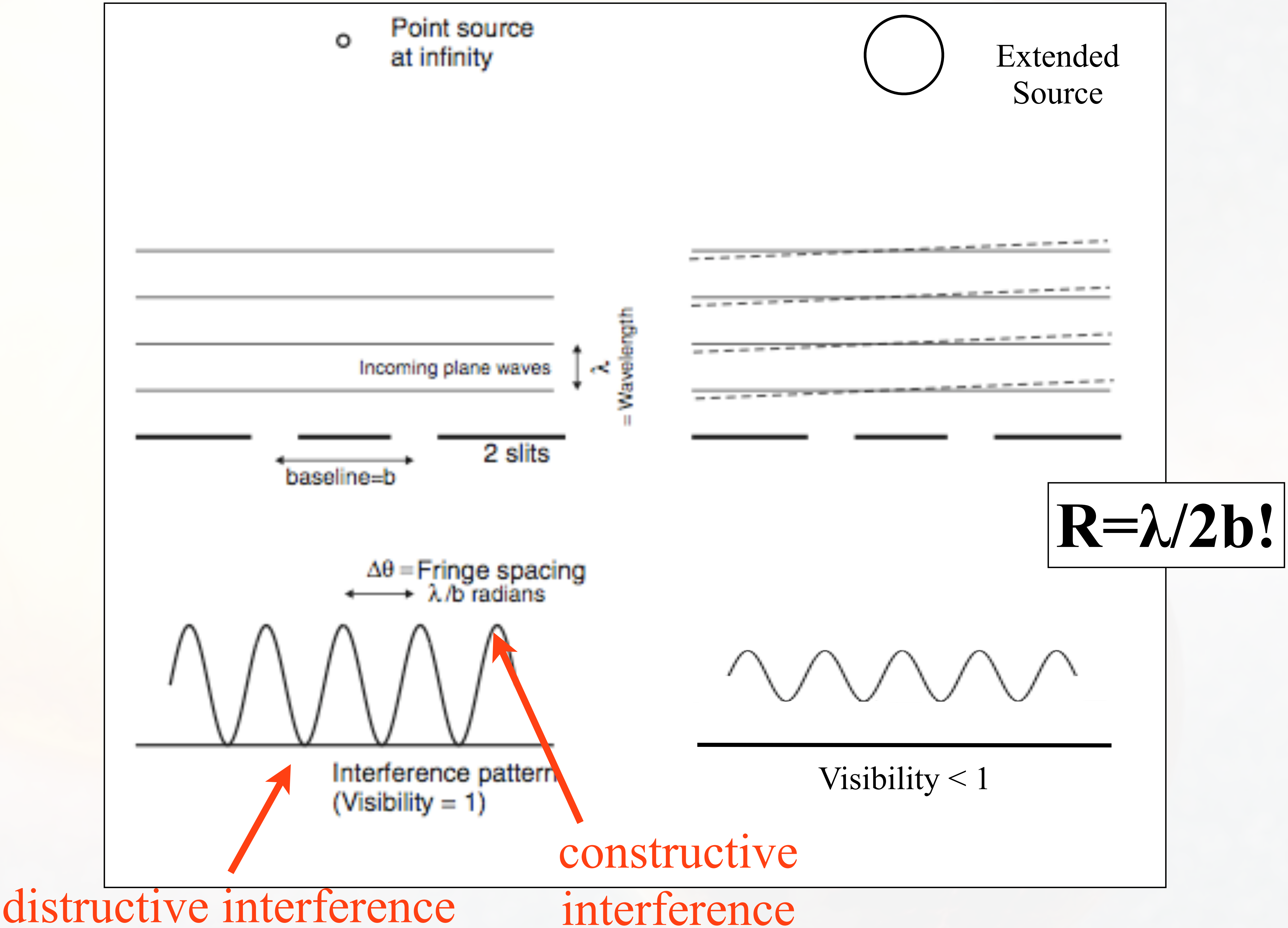
constructive
interference

"Visibility" = Contrast of the observed interference ("Fringe") pattern

$$V = (I_{max}+I_{min})/(I_{max}-I_{min})$$

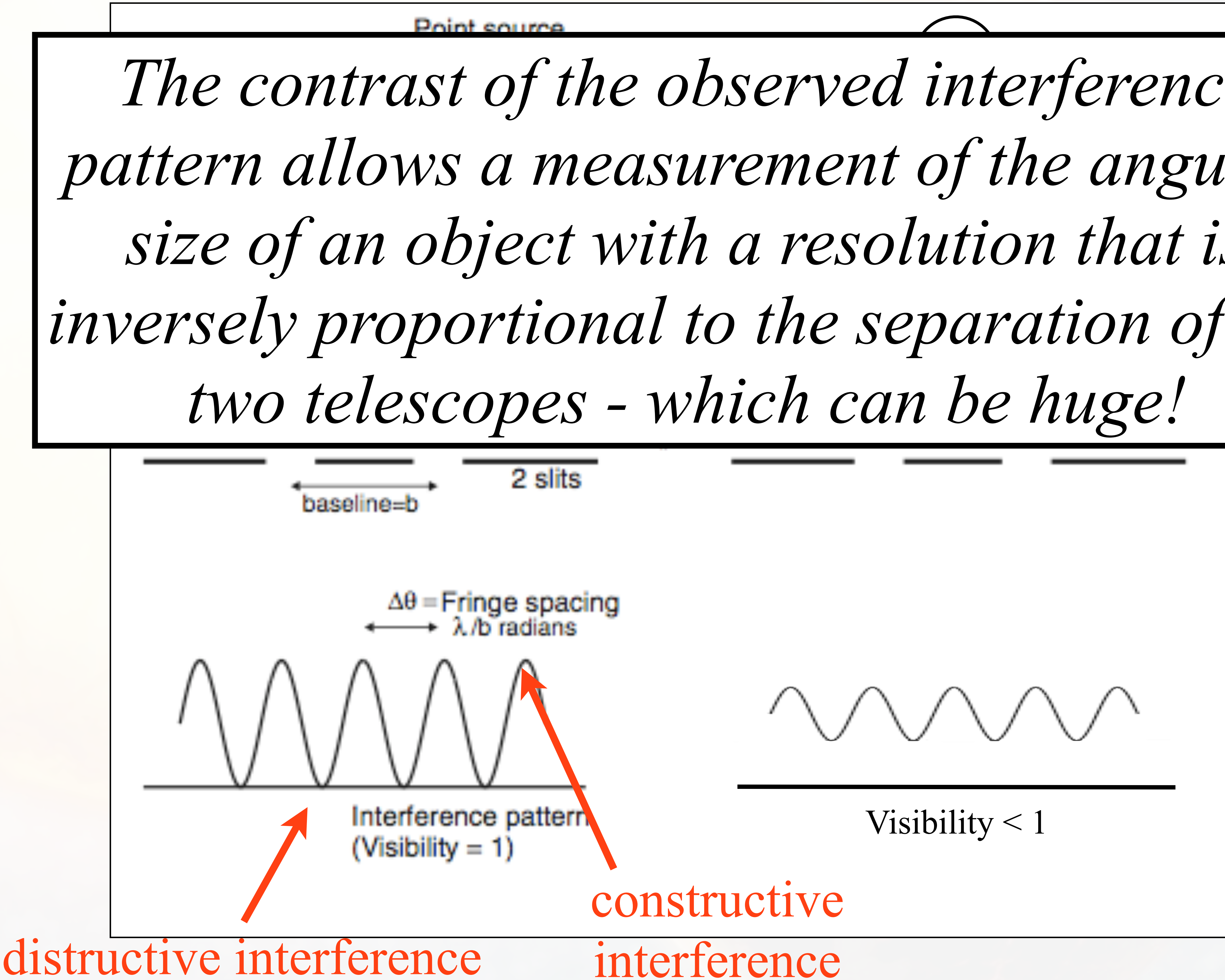
For a point source at infinity, V=1 (perfect interference)


Point source
at infinity
Point sources
at infinity
separated by
1/2 the fringe
spacing
Incoming plane waves
λ = Wavelength
2 slits
baseline=b
R=λ/2b!
Δθ = Fringe spacing
λ/b radians
Interference pattern
(Visibility = 1)
2 sine waves
destructively
interfere
(Visibility = 0)
constructive
interference
distructive interference

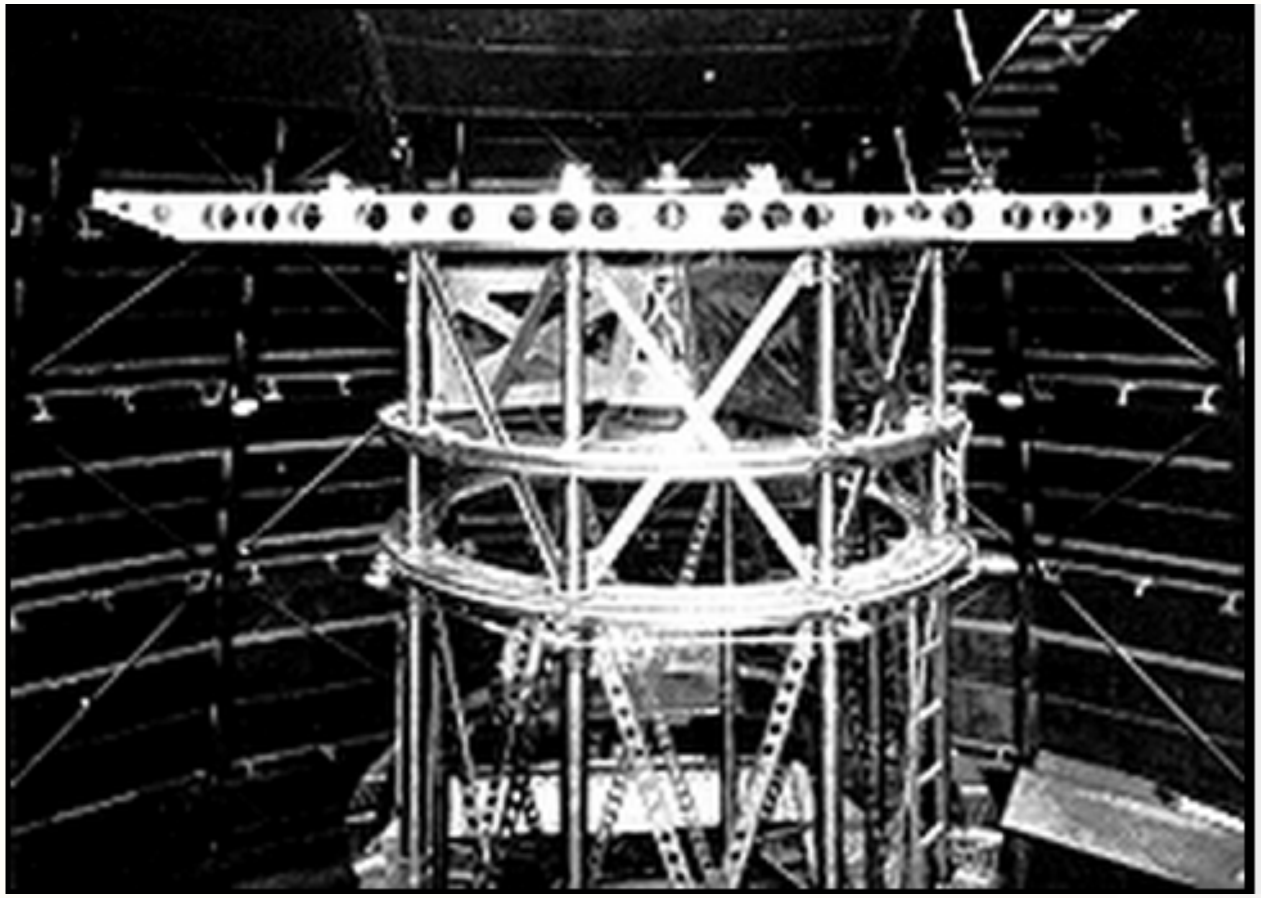


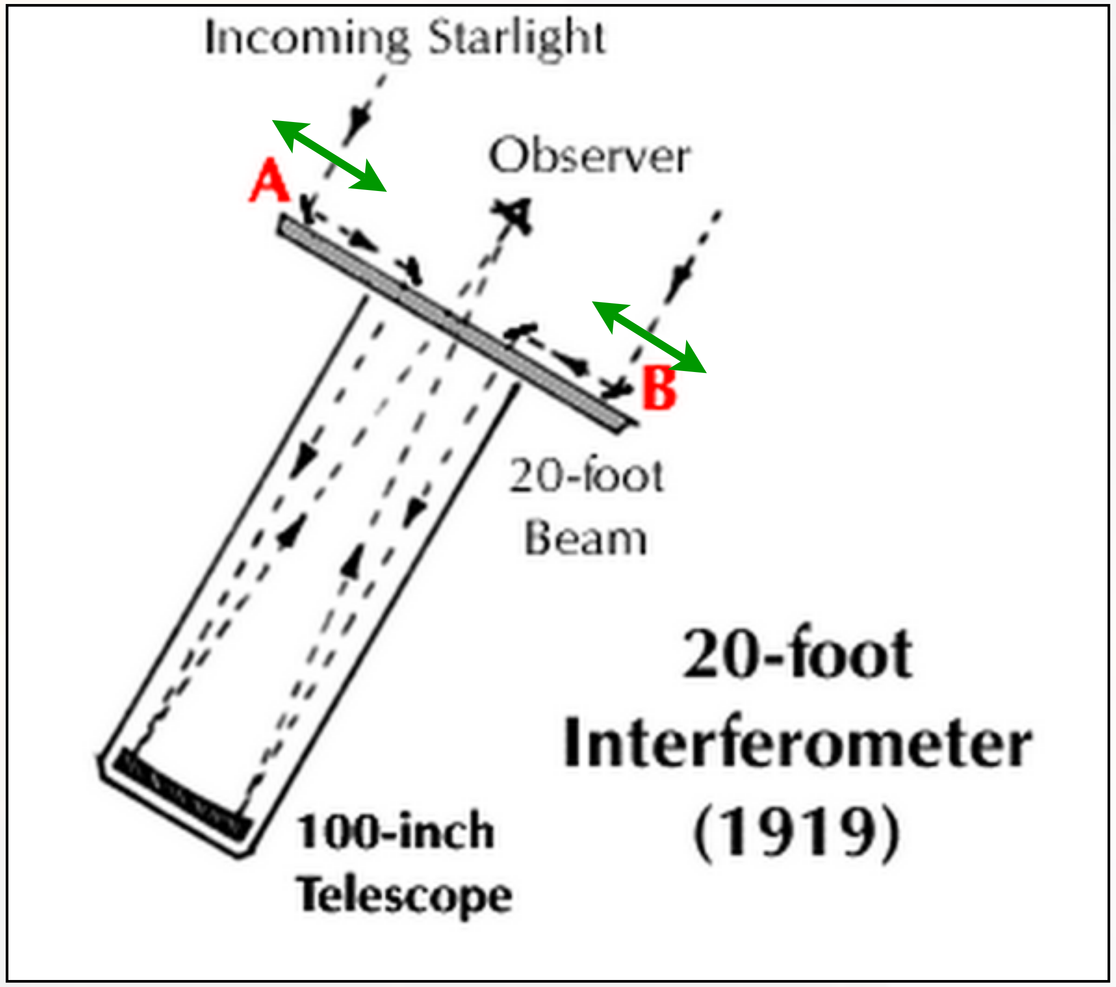
Point source
at infinity
Extended
Source
Incoming plane waves
λ = Wavelength
2 slits
baseline=b
R=λ/2b!
Δθ = Fringe spacing
λ /b radians
Interference pattern
(Visibility = 1)
Visibility < 1
constructive
interference
distructive interference

The contrast of the observed interference pattern allows a measurement of the angular size of an object with a resolution that is inversely proportional to the separation of the two telescopes - which can be huge!



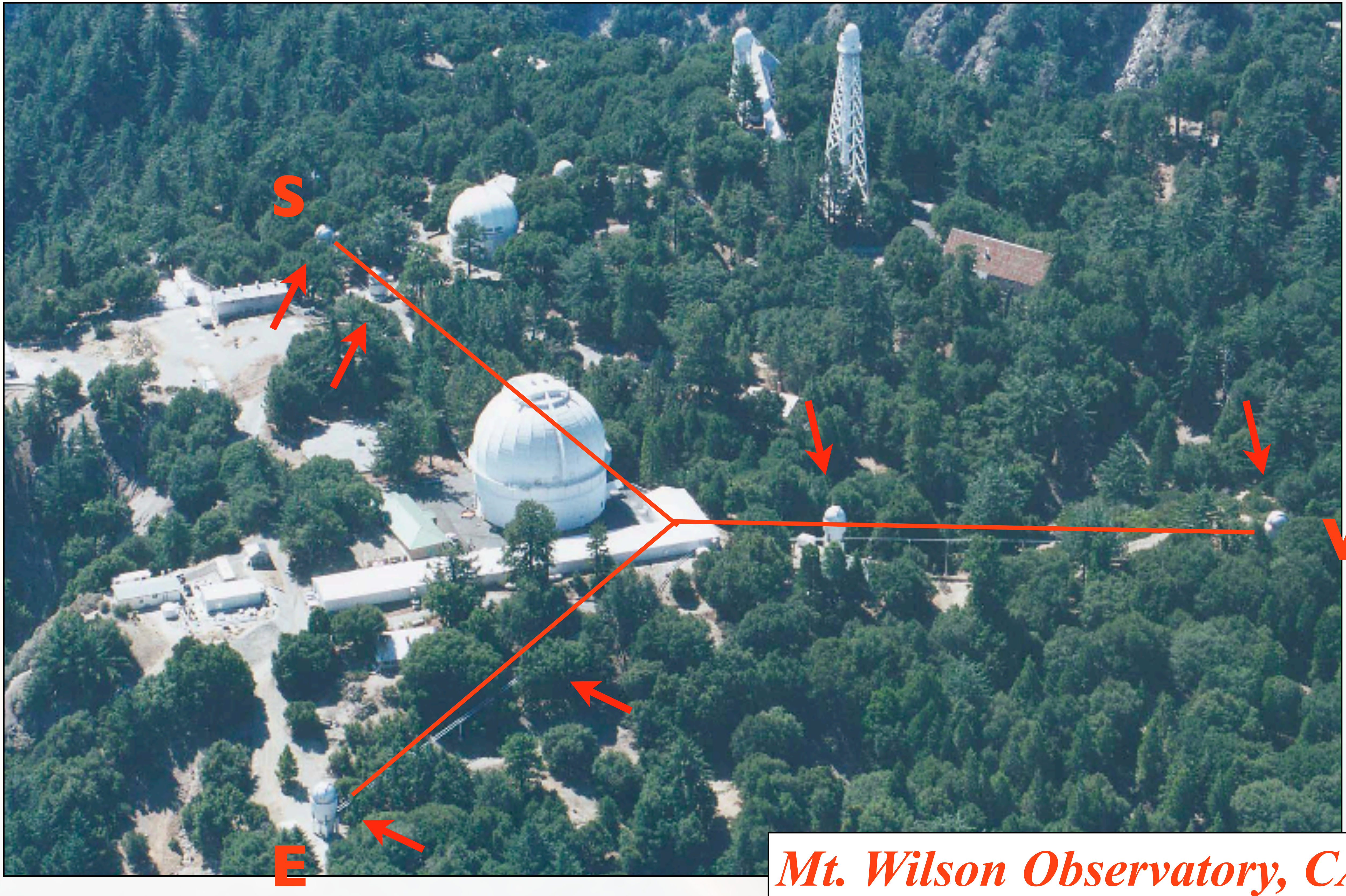
Early Days: the Michelson interferometer





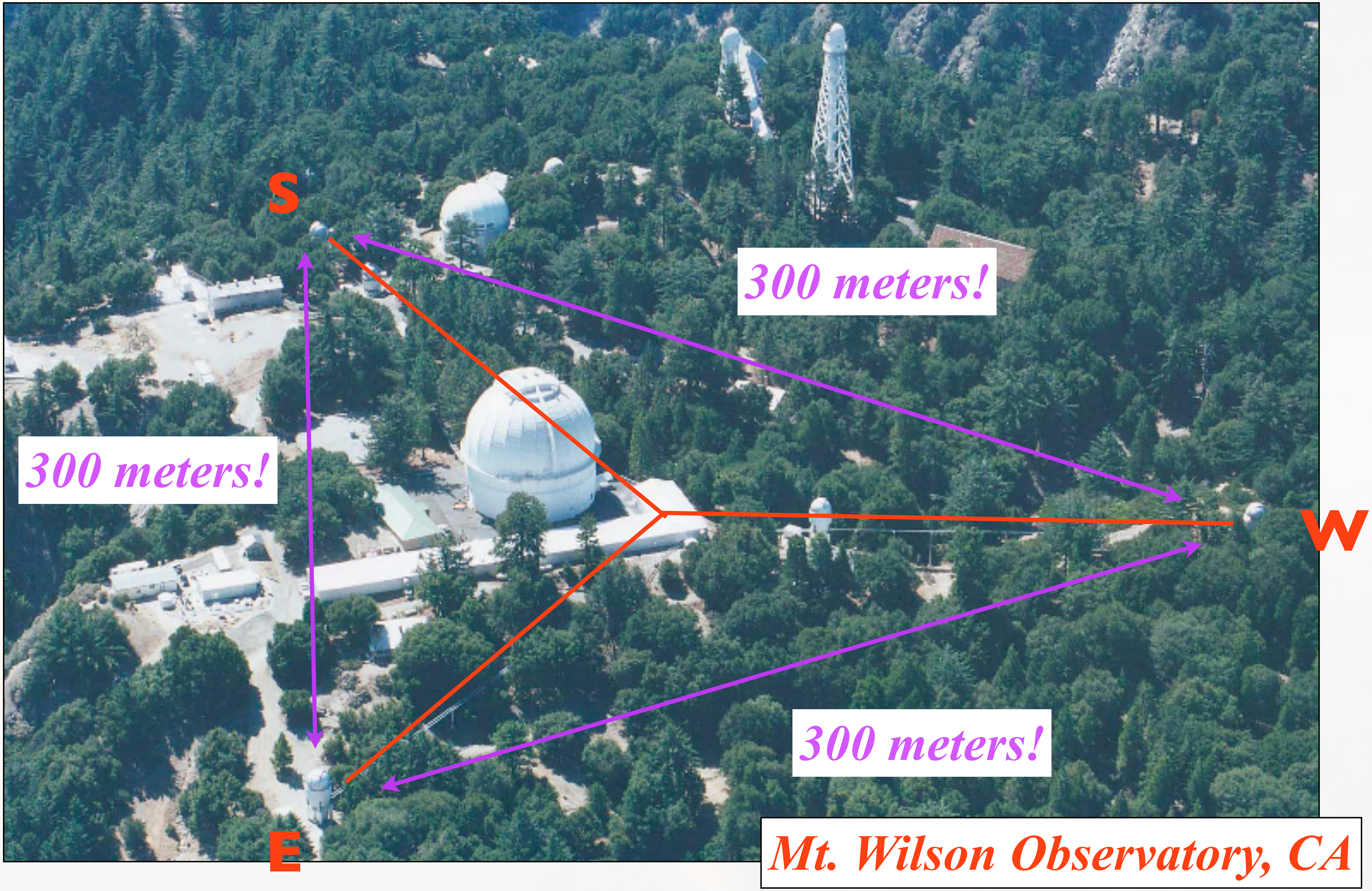
Albert Michelson measured the angular size of Betelgeuse to be ~0.05 arcseconds ~ 1×10^{-5} degrees; combined with it's parallax, the radius was determined to be 150×10^6 km (roughly the perihelion distance of Mars) - the first stellar diameter measurement!

Center for High-Angular Resolution Astronomy

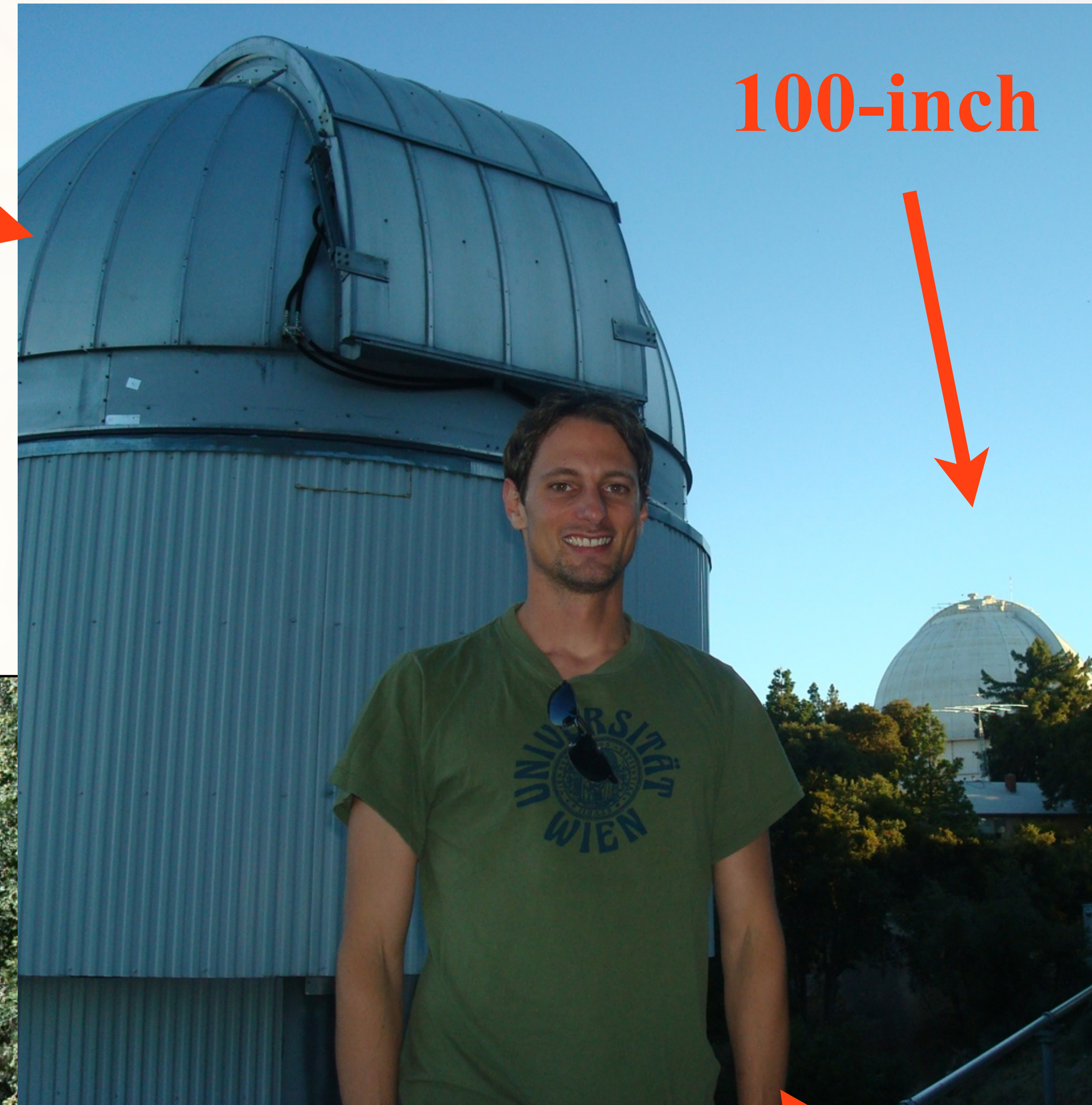


Mt. Wilson Observatory, CA

Center for High-Angular Resolution Astronomy



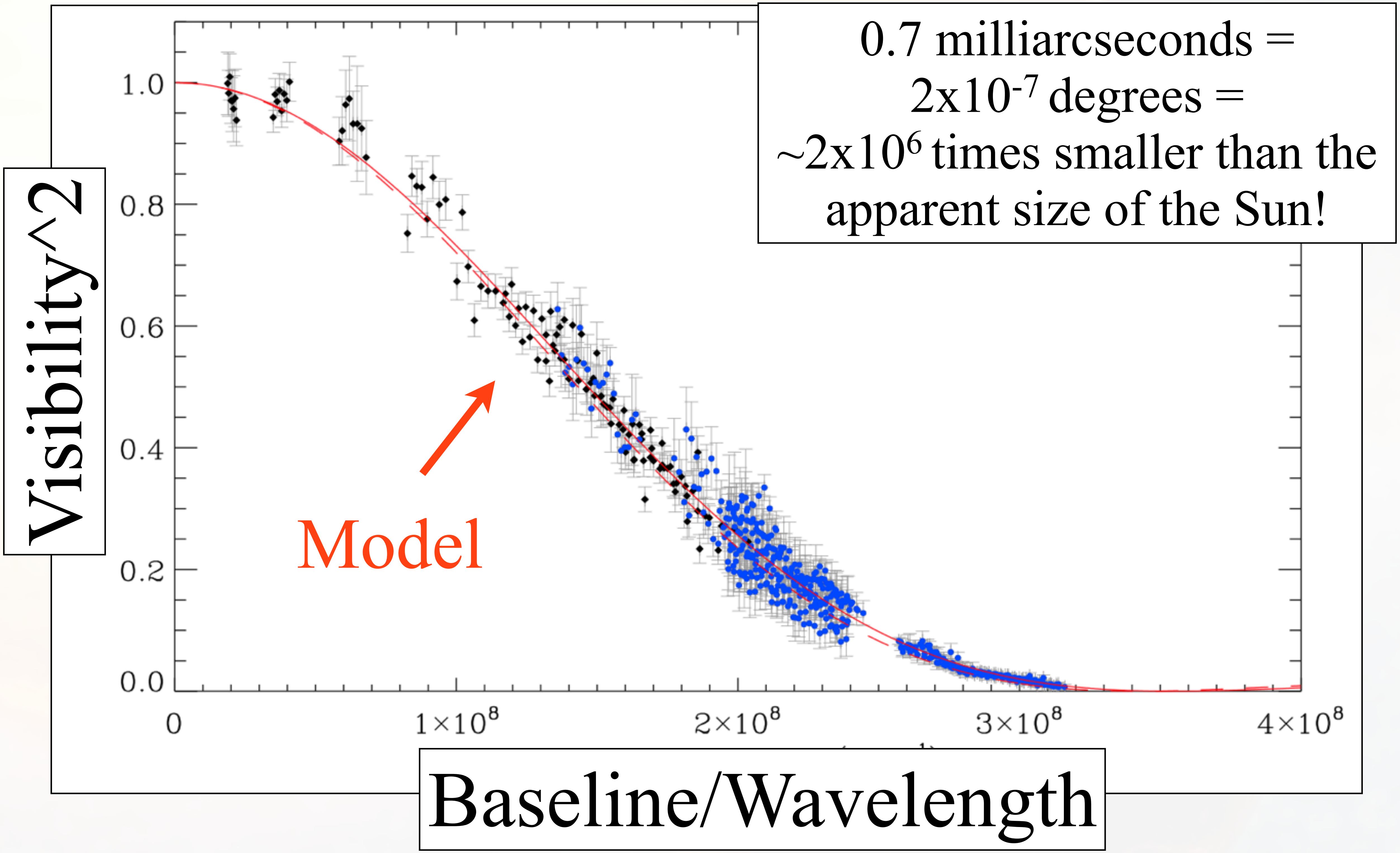
1-m telescope



Vacuum tubes

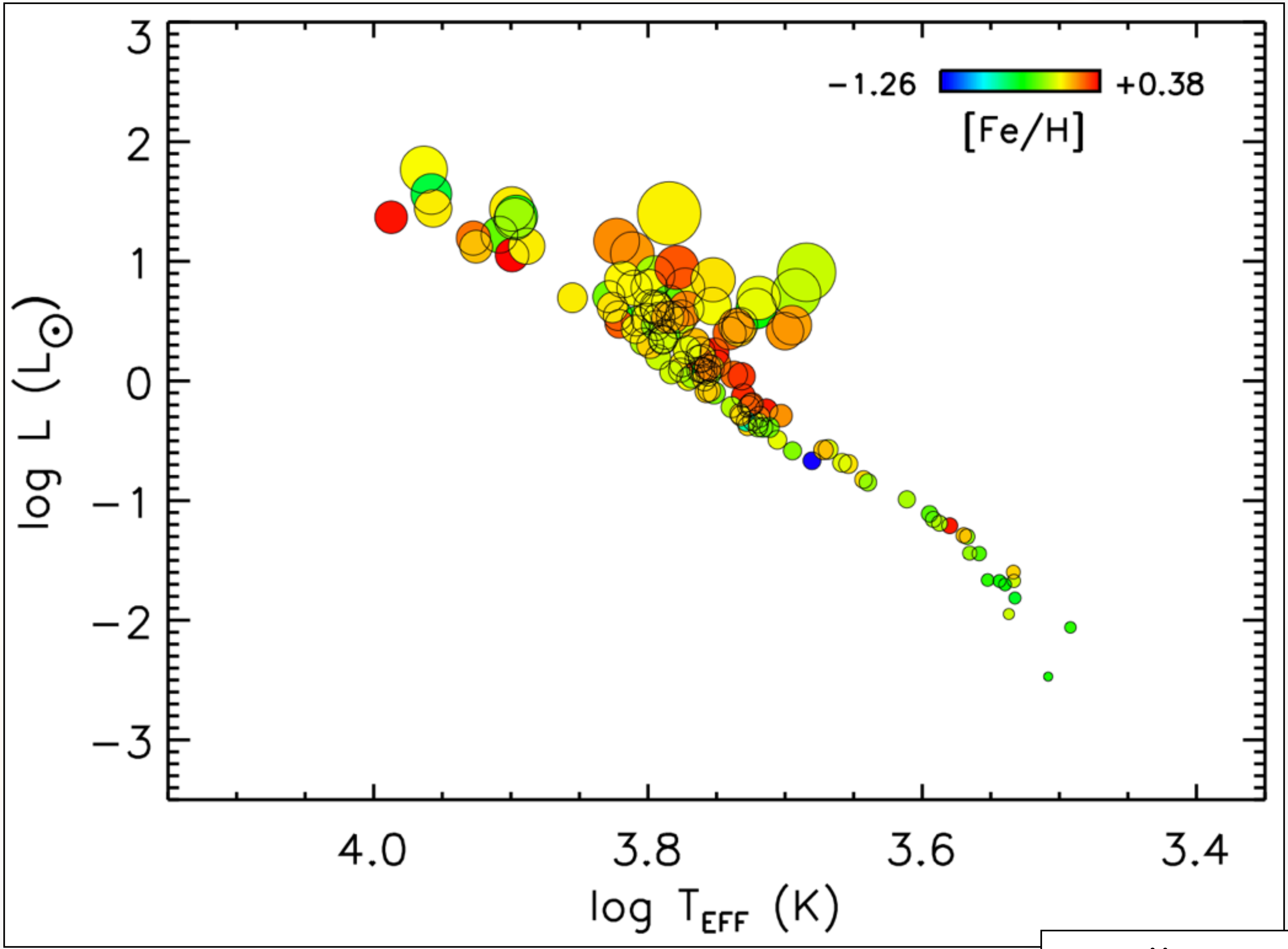
me

CHARA Data of a Solar-like Star



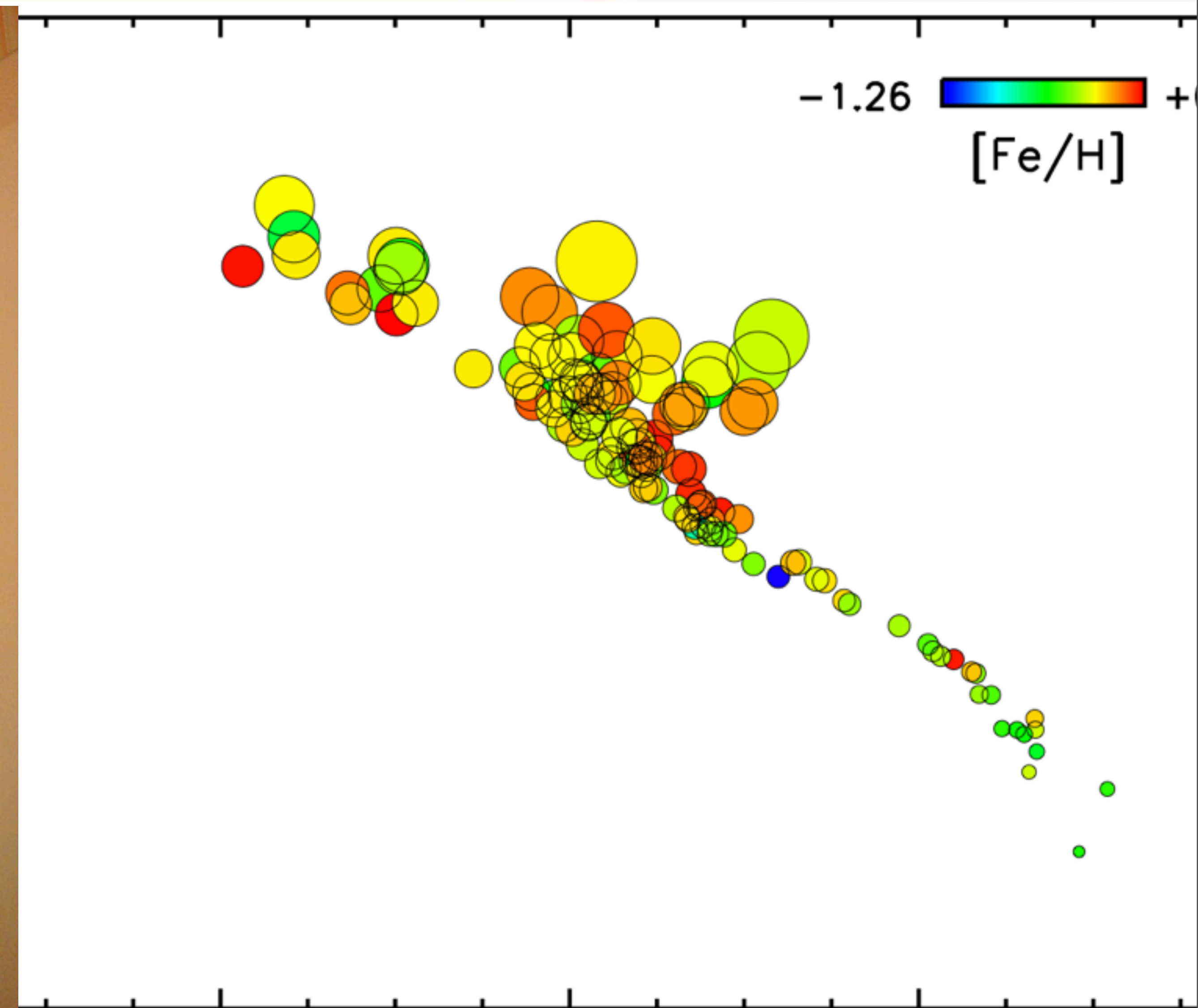
White et al. 2013

A Measured HR Diagram!



Boyajian et al. 2012

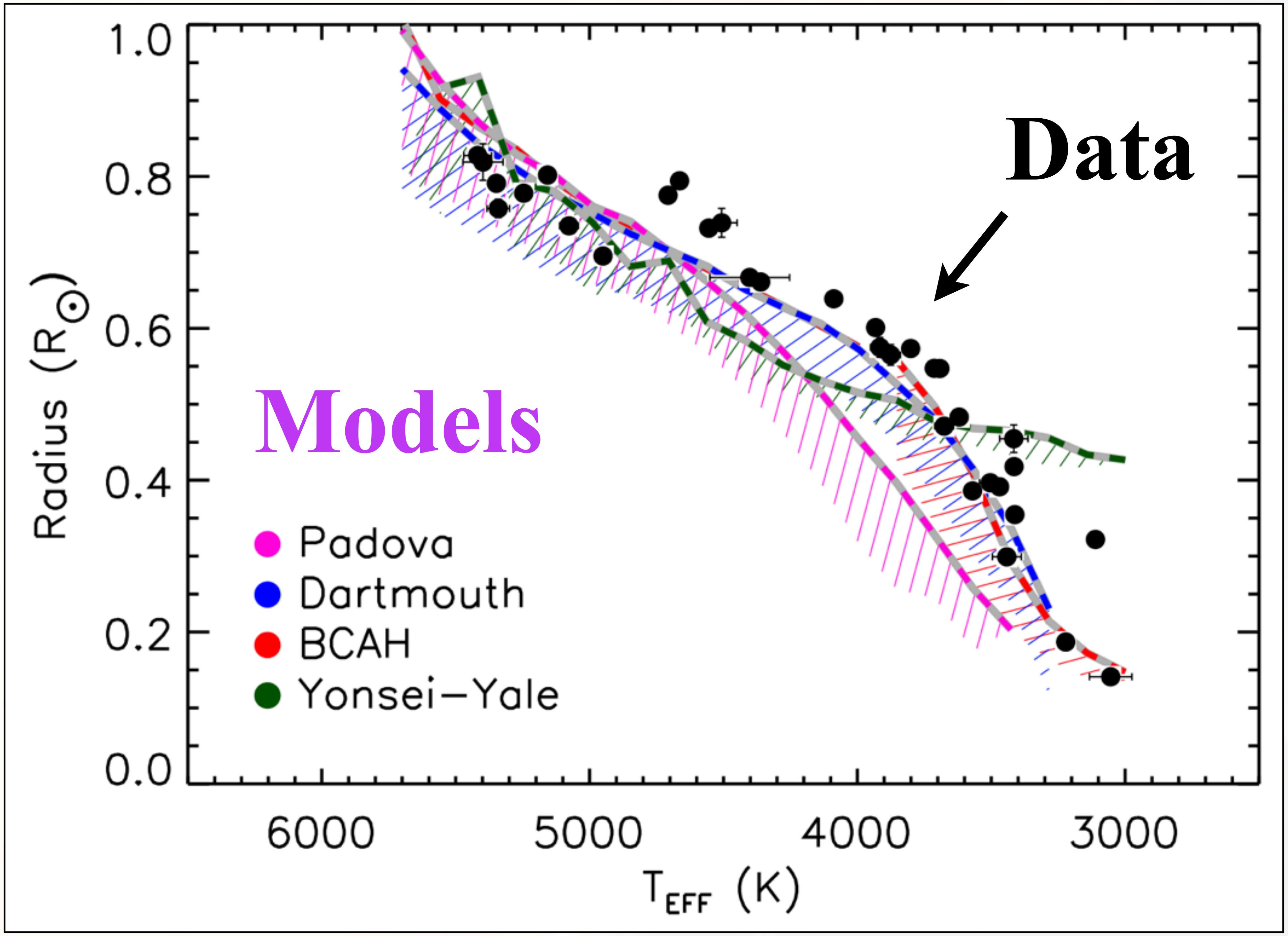
SUPERGIANTS
(LESS THAN 1% OF ALL STARS)
GIANTS
(LESS THAN 1% OF ALL STARS)
M A I N S E Q U E N C E
A Solar Lifetime
press a button below
Our Sun
WHITE DWARFS
(3% OF ALL STARS)
RED DWARFS
fainter
BRIGHTNESS



−1.26
[Fe/H]

“Model”

Data



observed radii of cool dwarfs (spectral type M) are systematically higher than predicted by models by up to 20%; a major unsolved problem in stellar astrophysics!

Fundamental Properties of Stars

Temperature (T) ✓

Radius (R) ✓

Chemical Composition

Mass (M)

Surface Gravity (g)

Luminosity (L) ✓

Density (ρ)

Age

$$g = GM/R^2$$

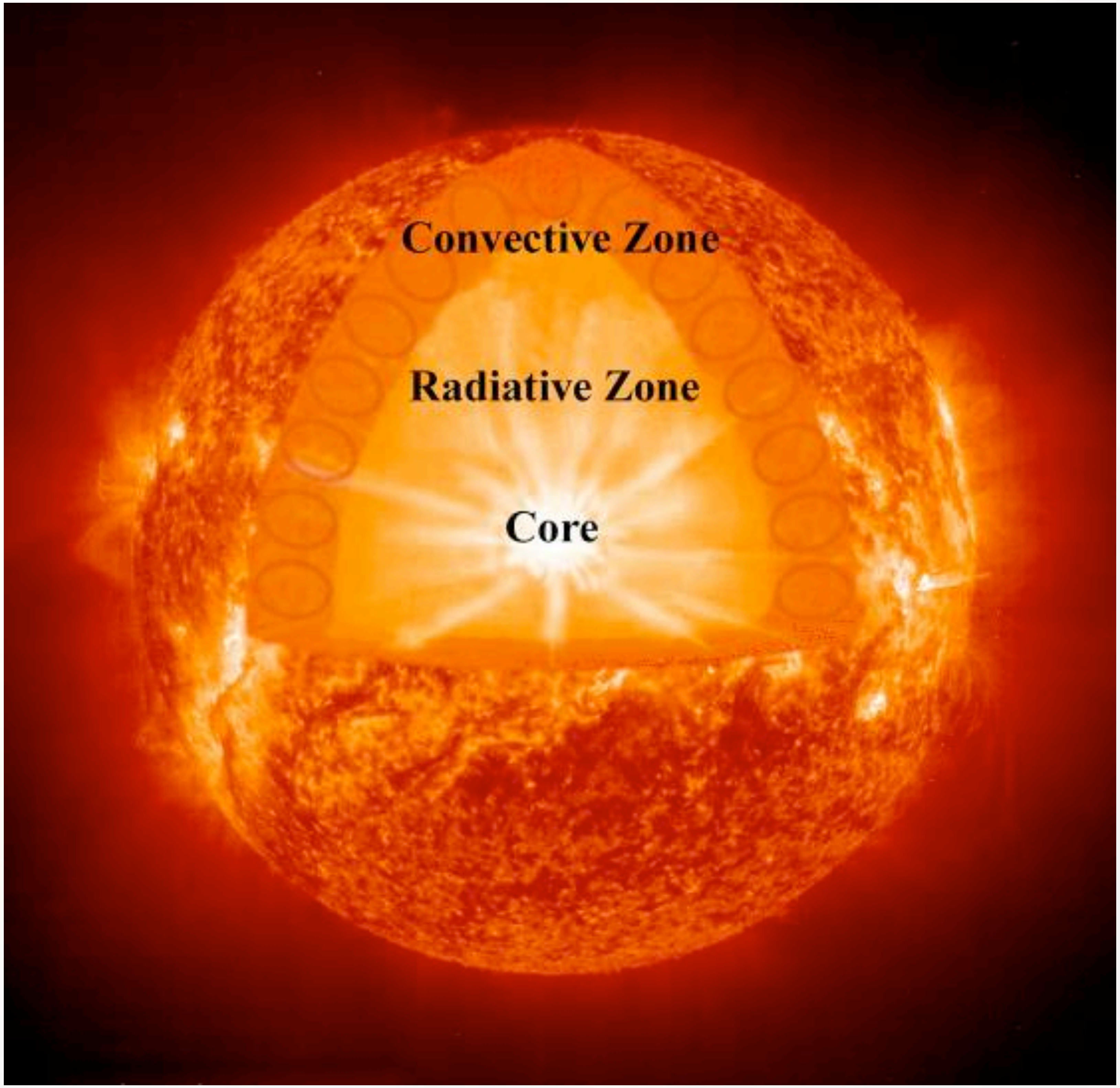
$$L \propto R^2 T^4$$

$$\rho \propto M/R^3$$

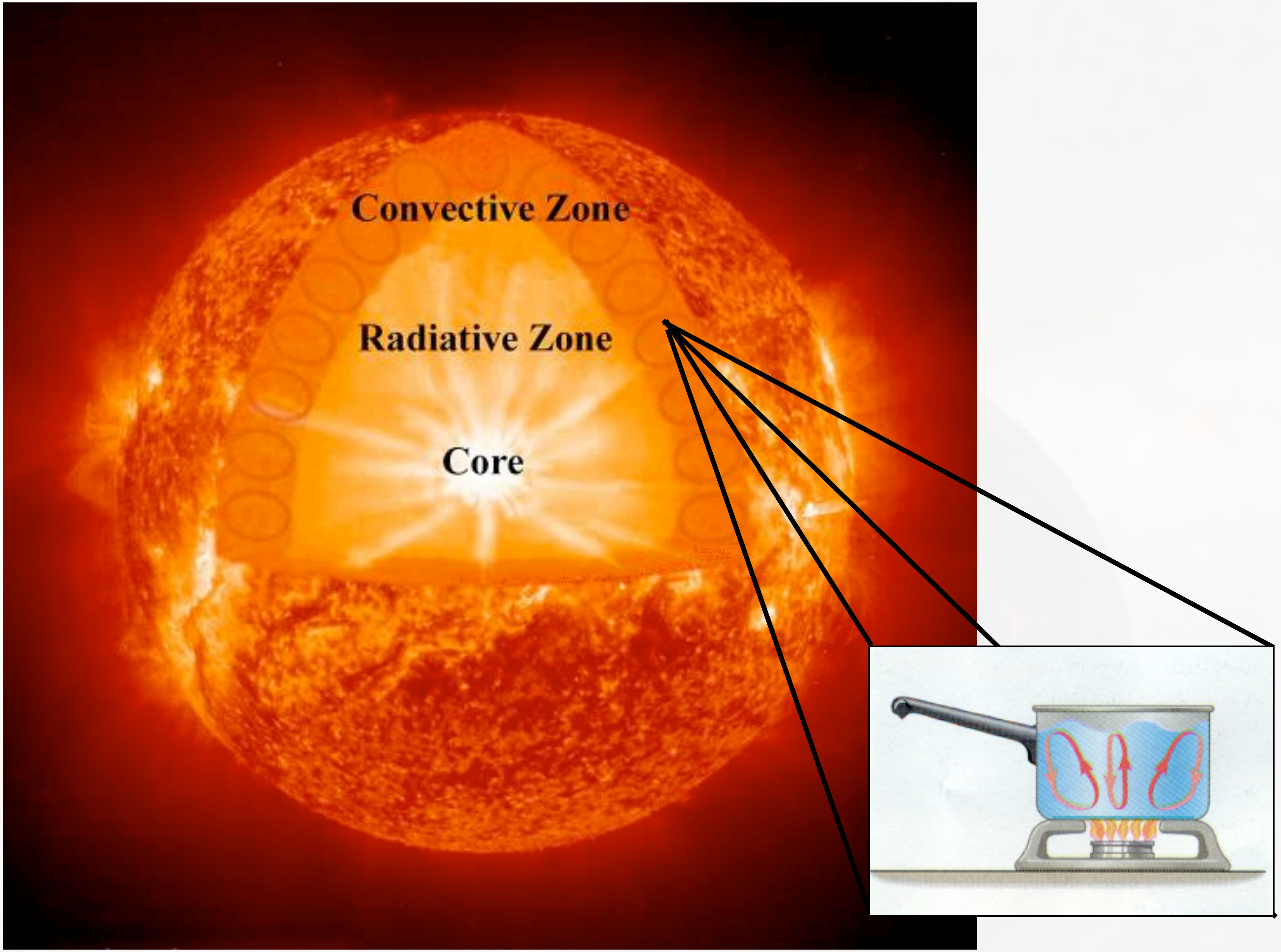
to really test stellar models, we still need a way to measure a star's density, gravity, or mass

Asteroseismology

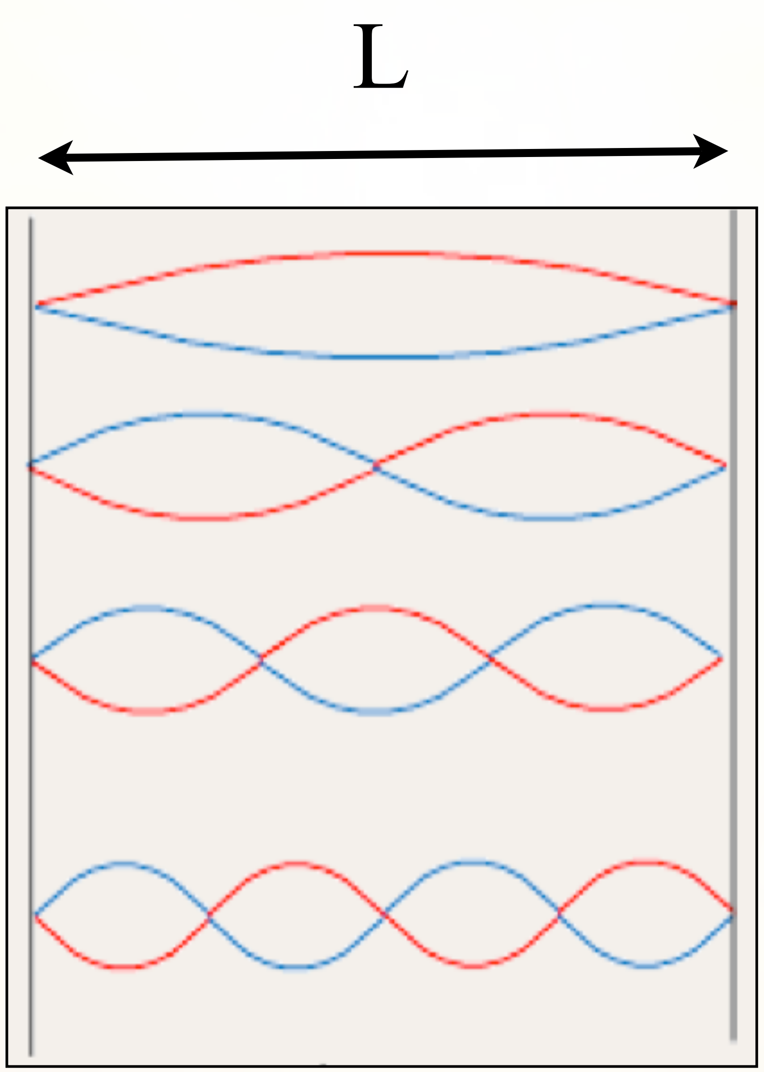
What causes Stellar Oscillations?

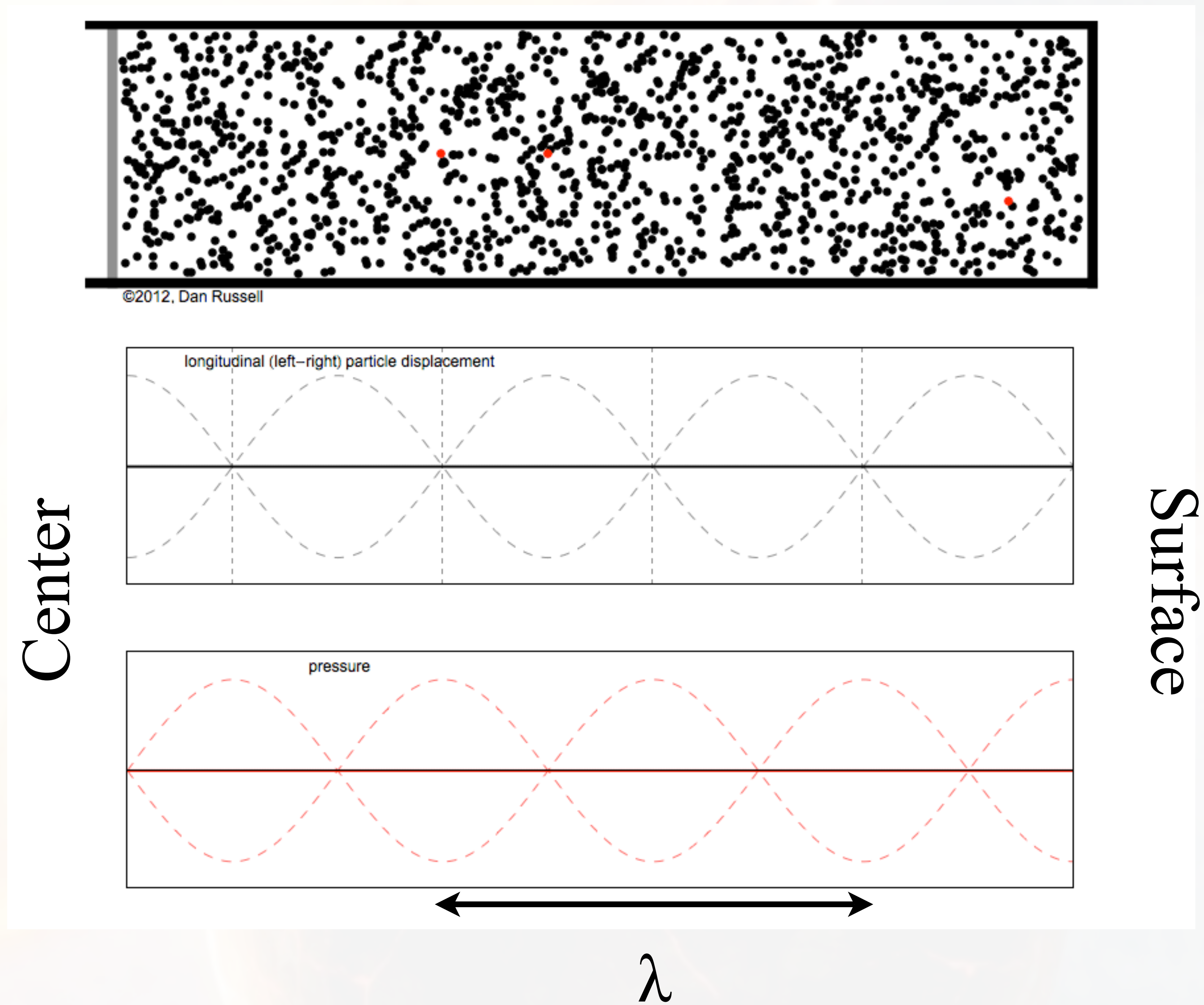


What causes Stellar Oscillations?



Oscillations are Standing Sound Waves





$$L = n\,\lambda/2$$

$$L\,k = n\,\pi$$

n = number of node lines

$$L\,k = n\,\pi$$

dispersion relation: $\omega = c\,k \longrightarrow \omega = n\,\pi\,c\,/\,L$

The sound speed depends on the properties of the gas:

for an ideal gas: $c \propto \sqrt{T/\mu}\,.$

The measurement of frequencies of oscillations in stars allow us to probe the sound speed (and hence temperature and composition) in the stellar interior

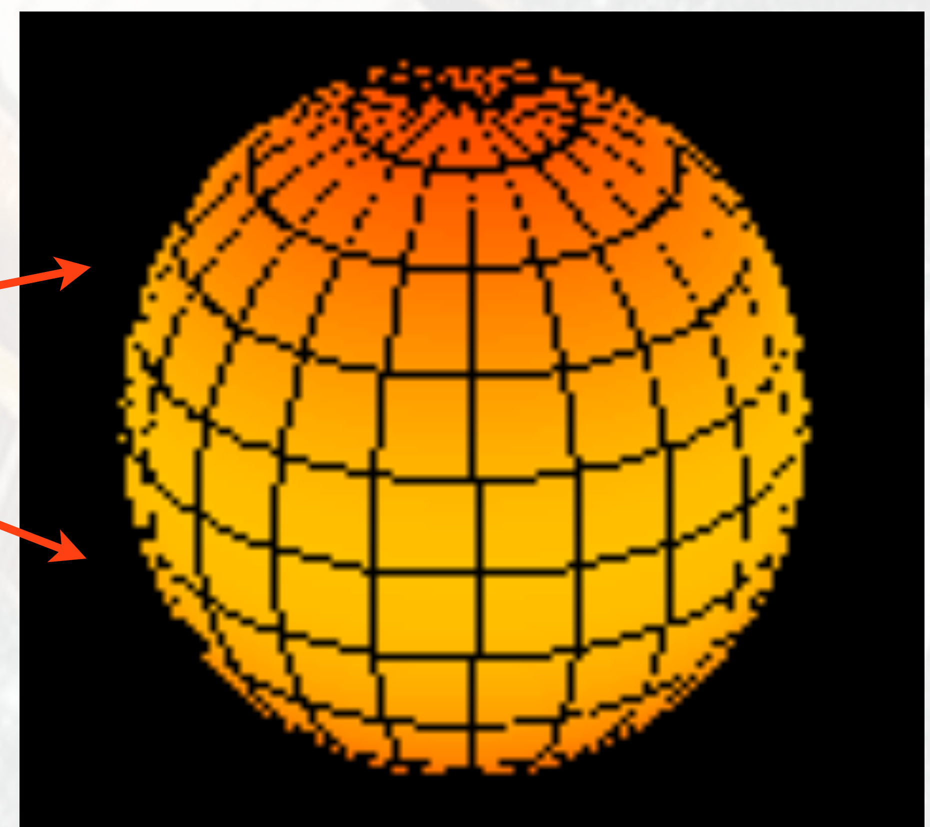
Surface Node Lines

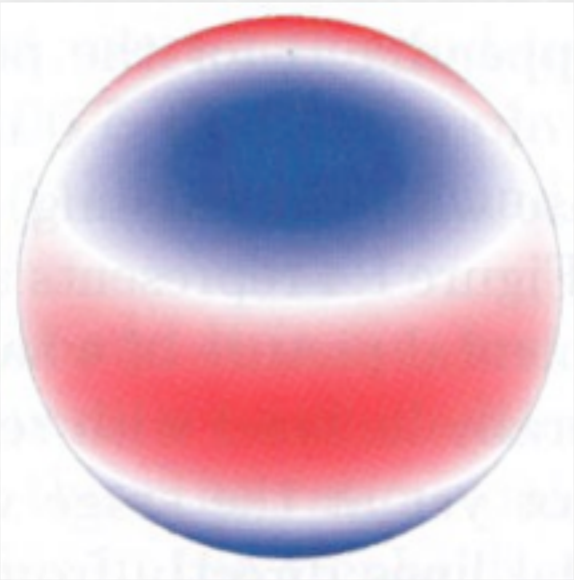
l = spherical degree (total number of surface node lines)

m = azimuthal order (number of azimuthal node lines, i.e. going through the rotation axis)

m <= l

l = 2
m = 0





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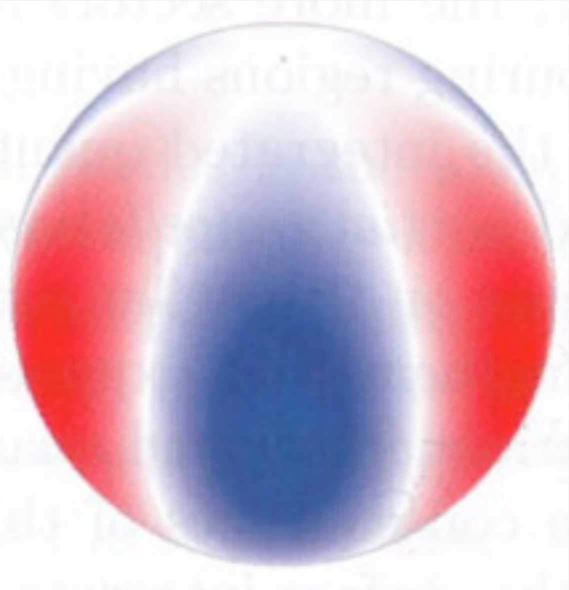

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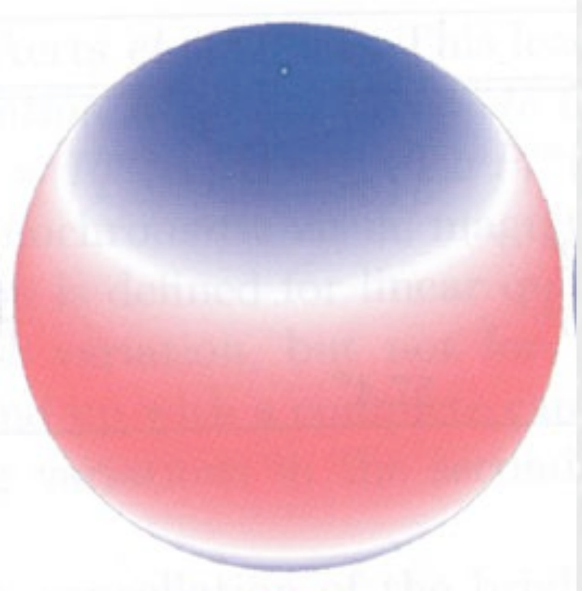

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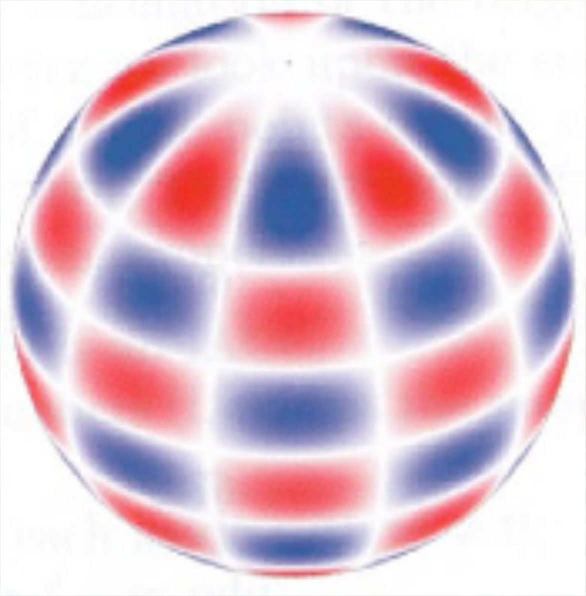

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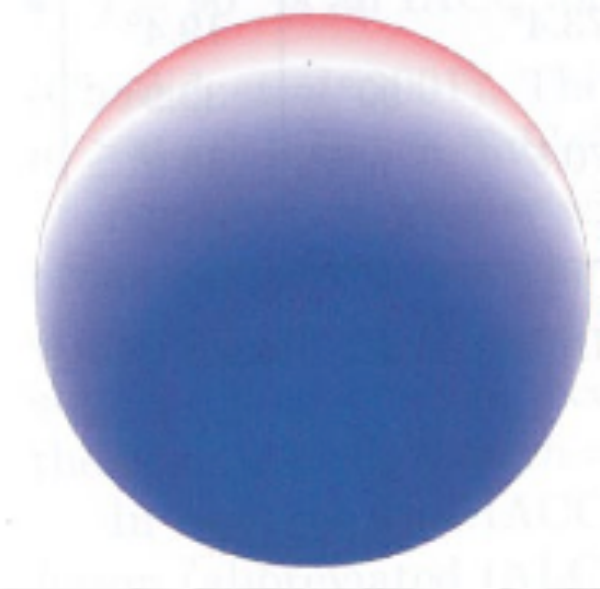

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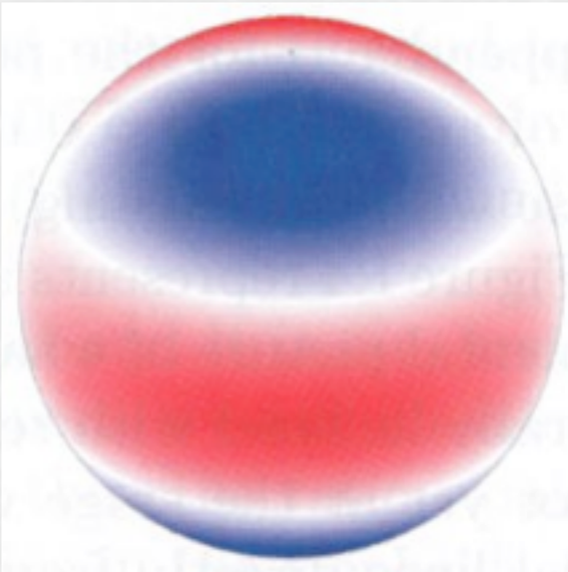
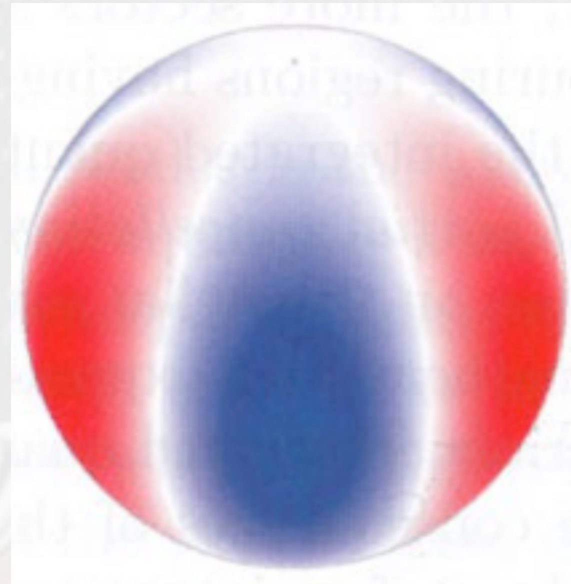
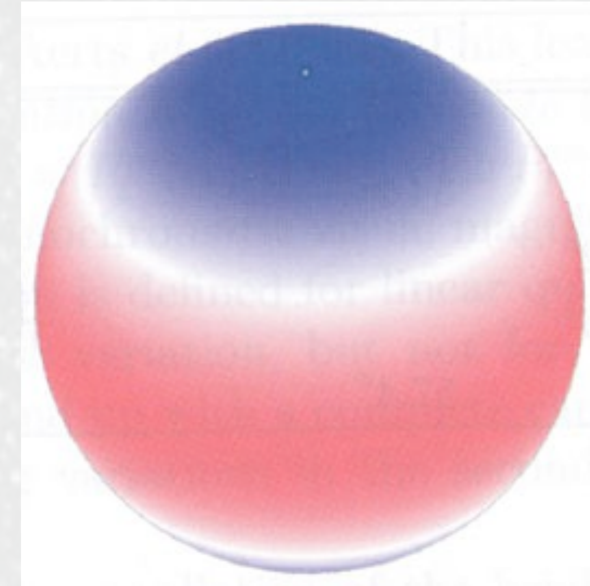


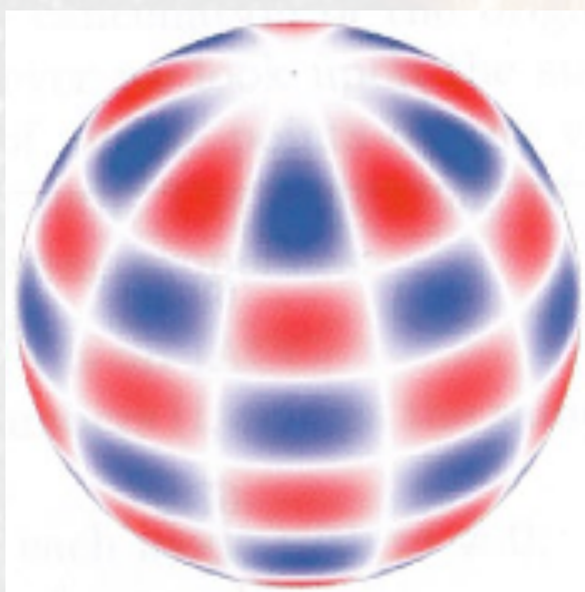
l=3, m=1



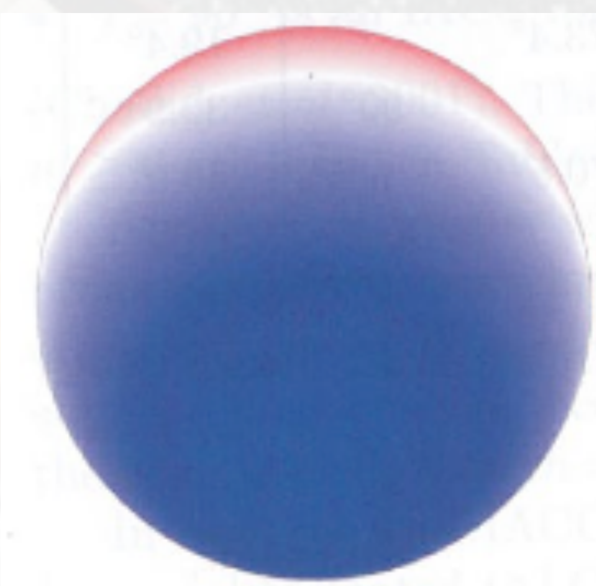
l=3, m=3



l=2, m=0

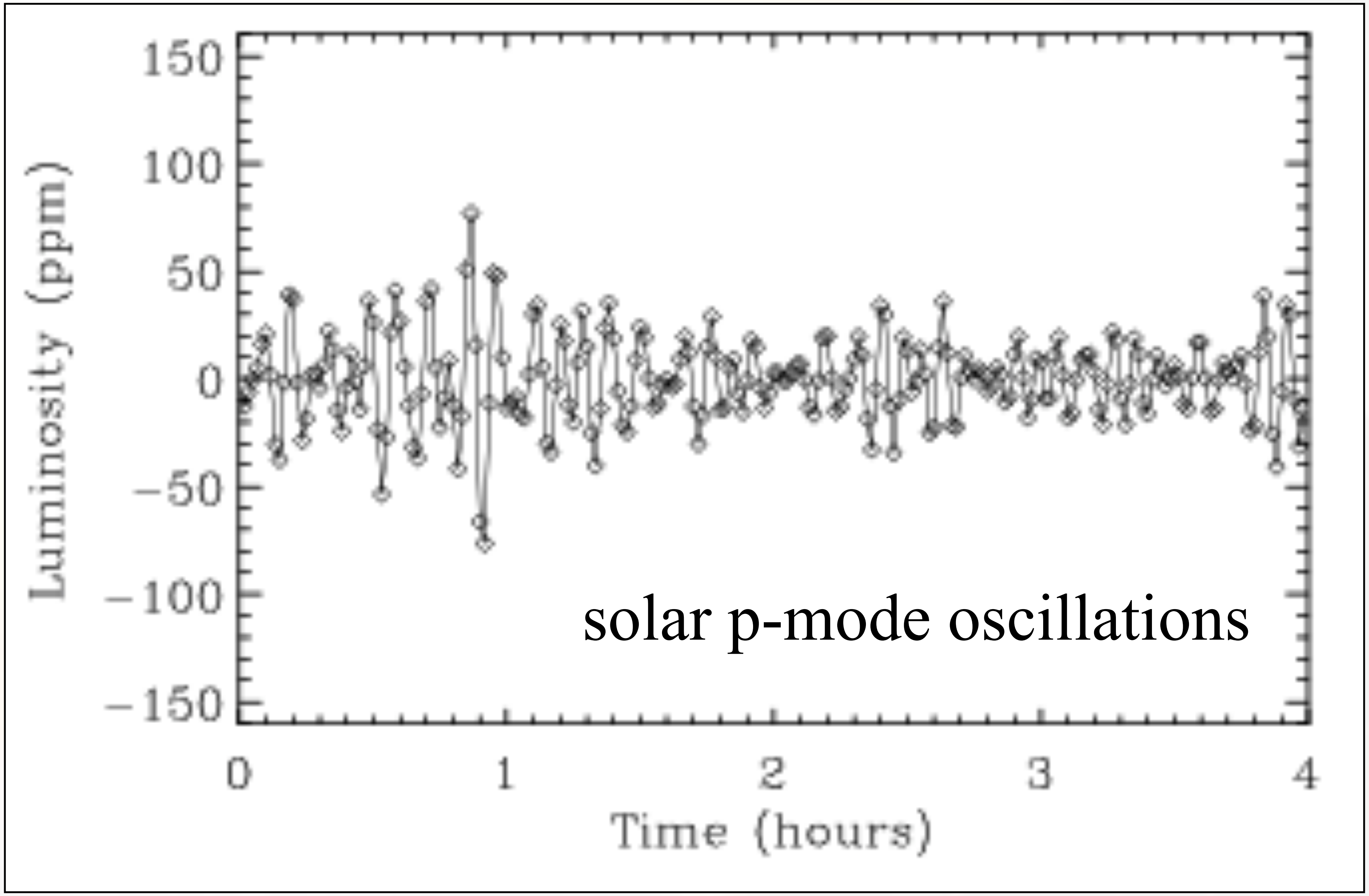


l=10, m=5

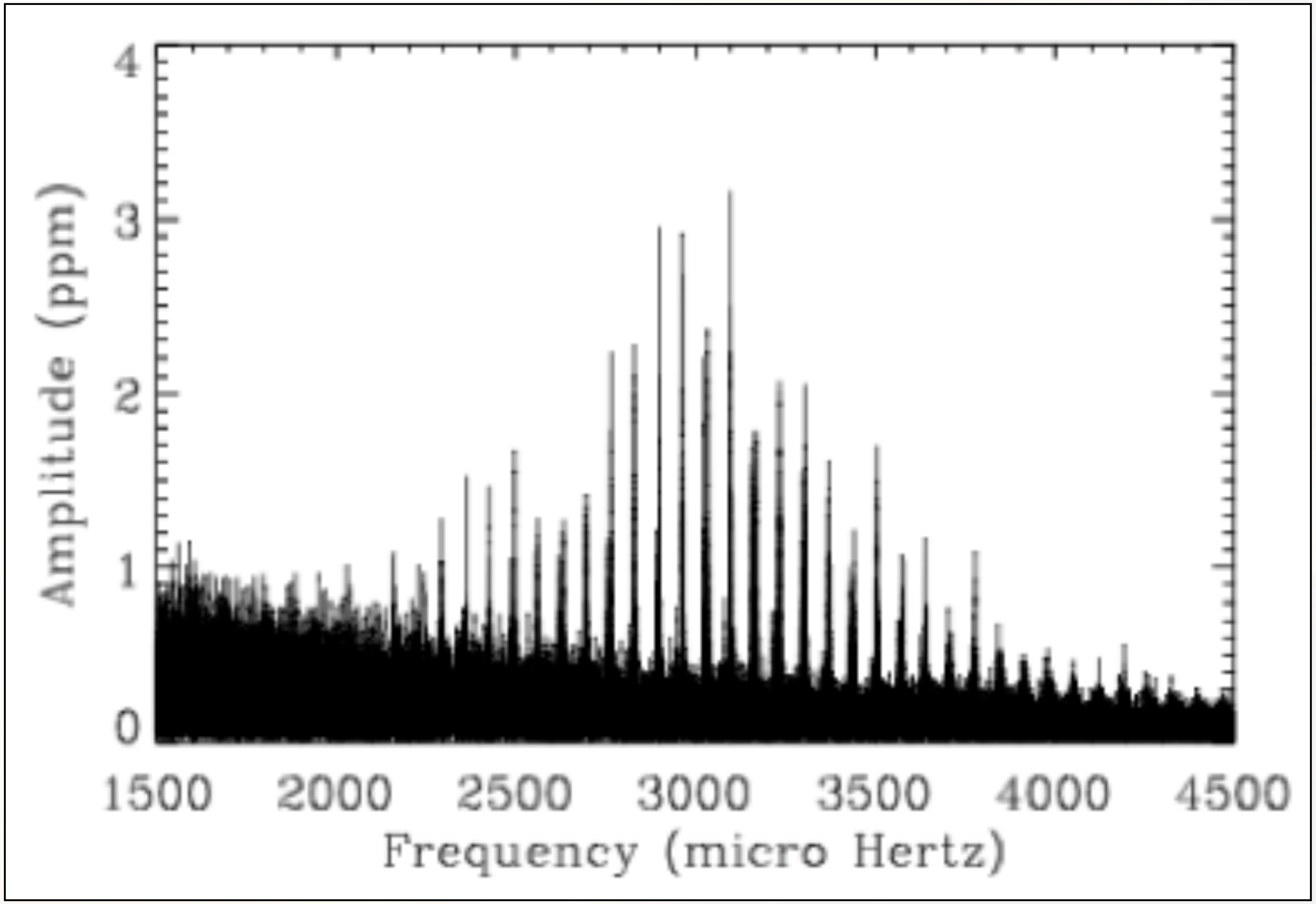


l=1, m=1

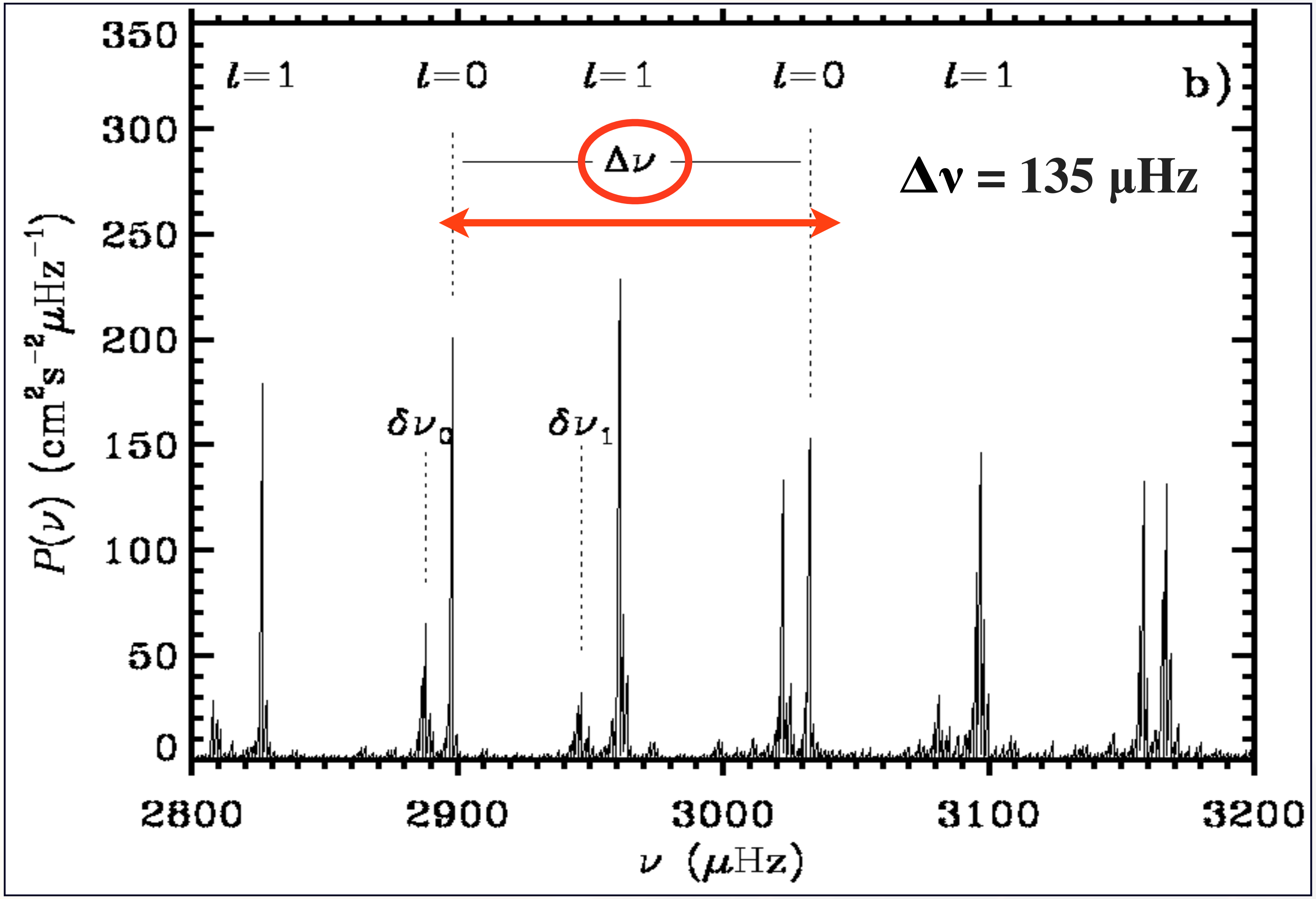
Stellar Oscillations cause Variations in Brightness



Fourier transform -> Frequency Spectrum

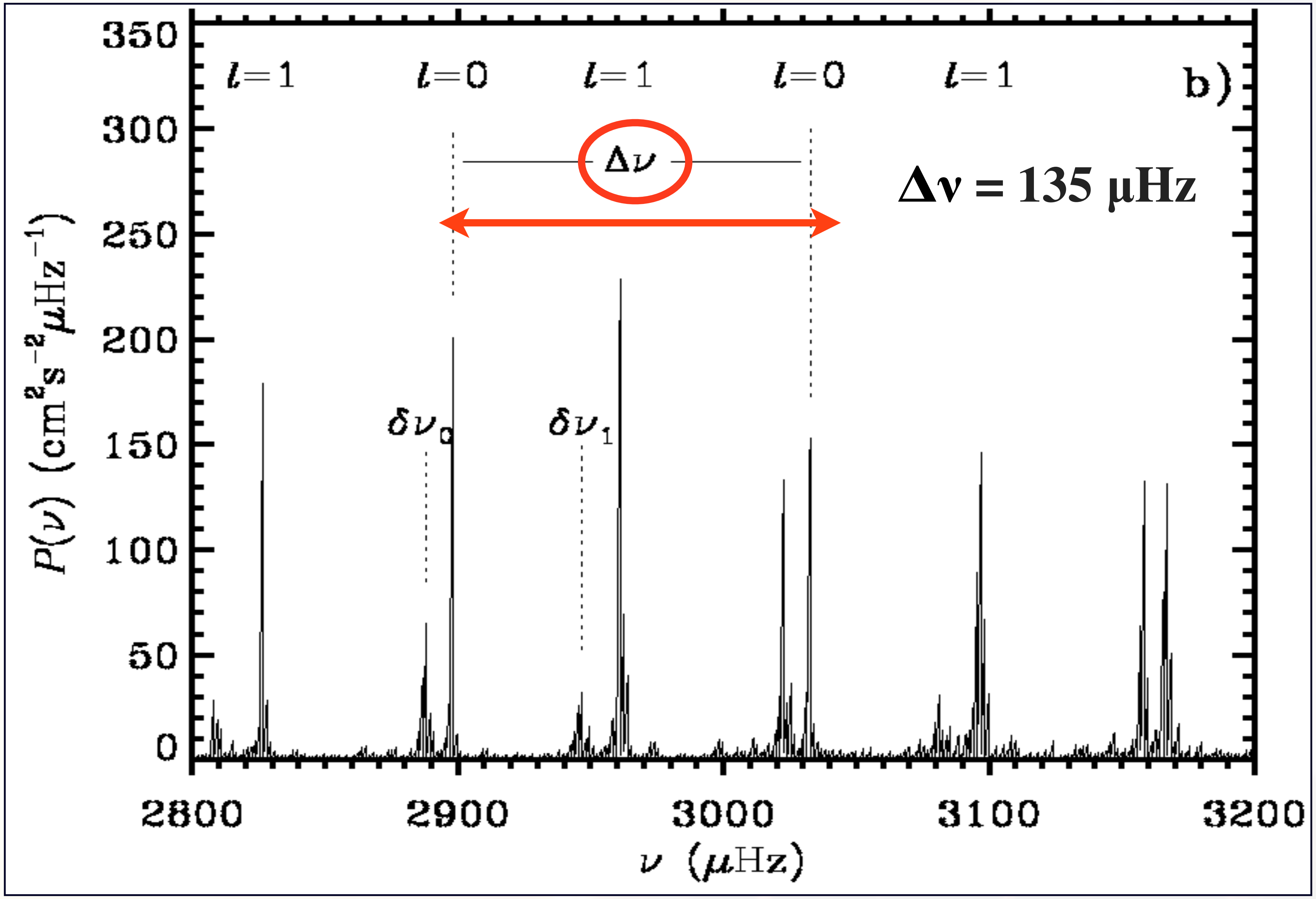


Oscillations driven by convection ("solar-like" oscillations) typically show a very rich spectrum of frequencies



$$\Delta\nu = (2 \int dr/c_s)^{-1}$$

$(\omega = n \pi c / L!)$



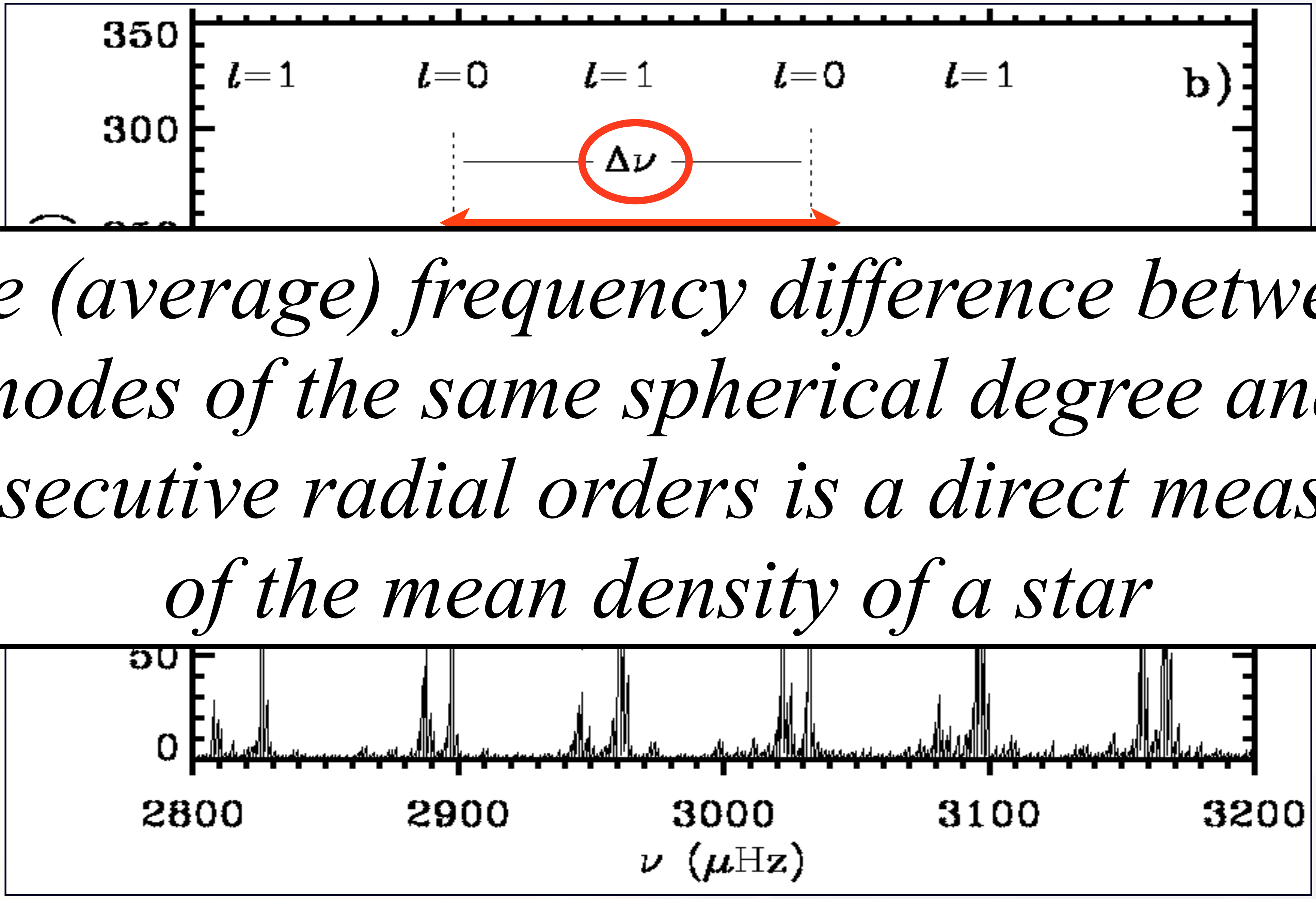
sound speed c

$c \propto \sqrt{T/\mu}\,.$

$T \propto \mu M/R$

$\Delta\nu = (2 \int dr/c_s)^{-1} \propto (M/R^3)^{1/2}$

($\omega = n\,\pi\,c\,/\,L!$)



The (average) frequency difference between modes of the same spherical degree and consecutive radial orders is a direct measure of the mean density of a star

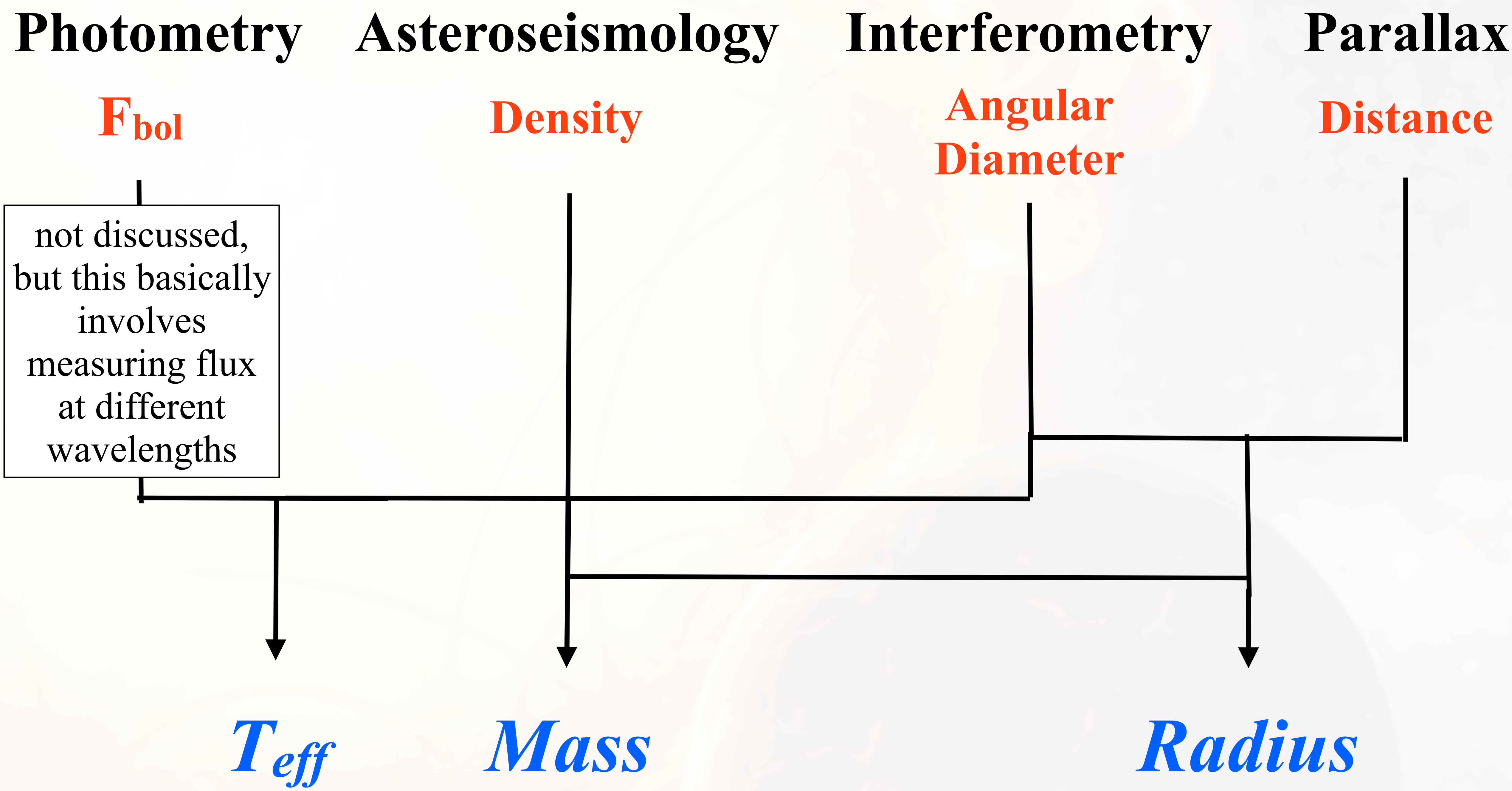
sound speed c

$c \propto \sqrt{T/\mu}\,.$

$T \propto \mu M/R$

$\Delta \nu = (2 \int dr/c_s)^{-1} \propto (M/R^3)^{1/2}$

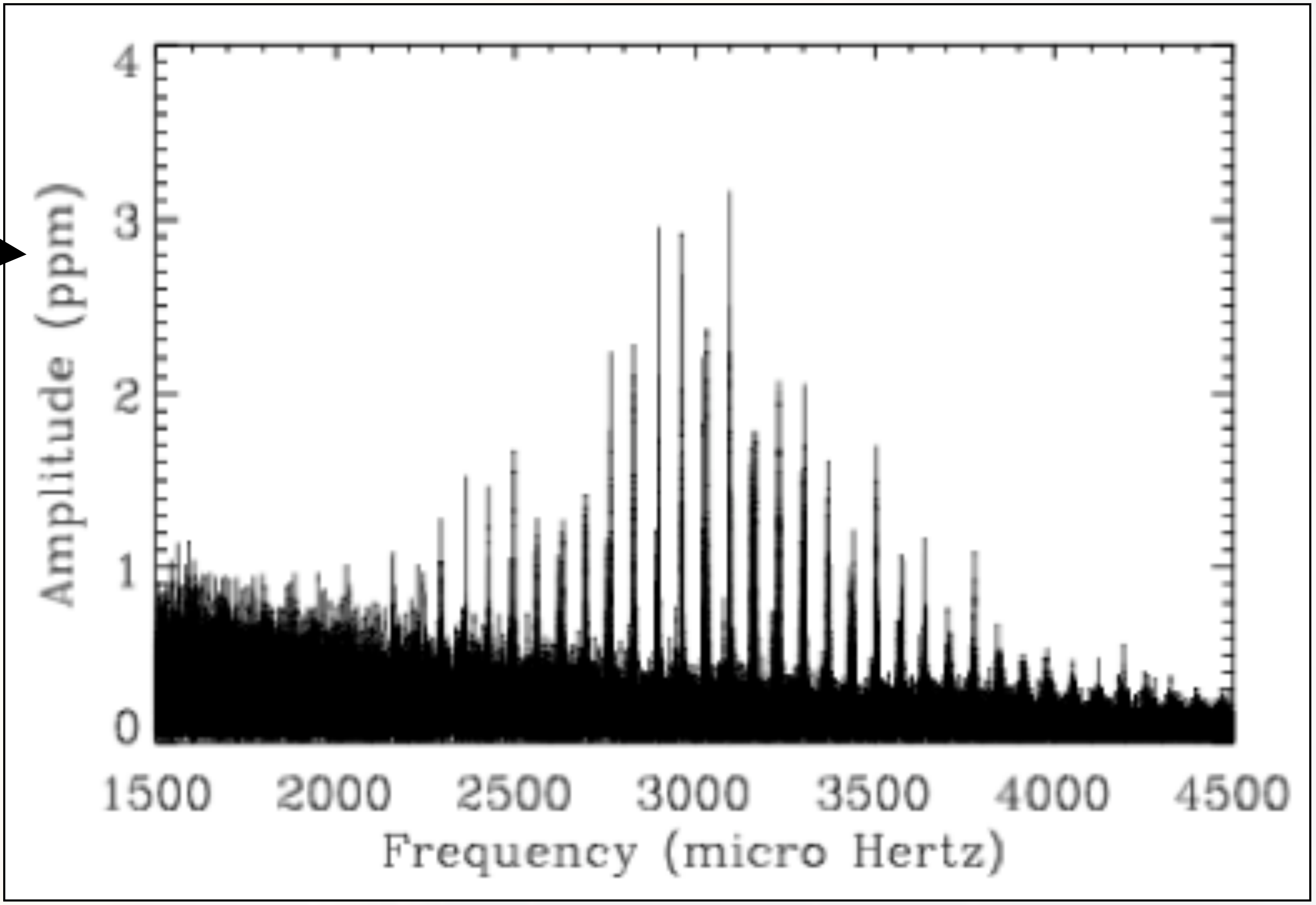
($\omega = n\, \pi\, c$ / L!)



(nearly) model-independent!

Caveat: oscillations are very hard to detect

parts per million!



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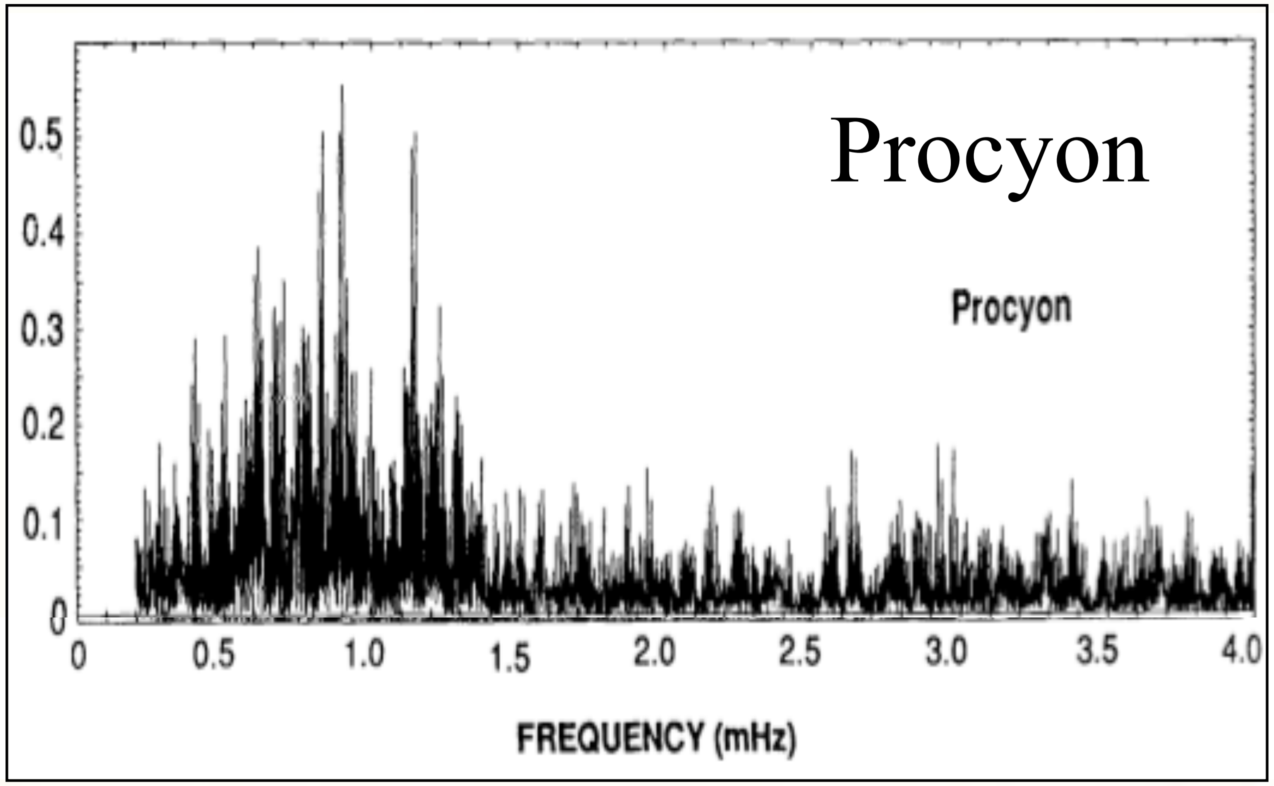
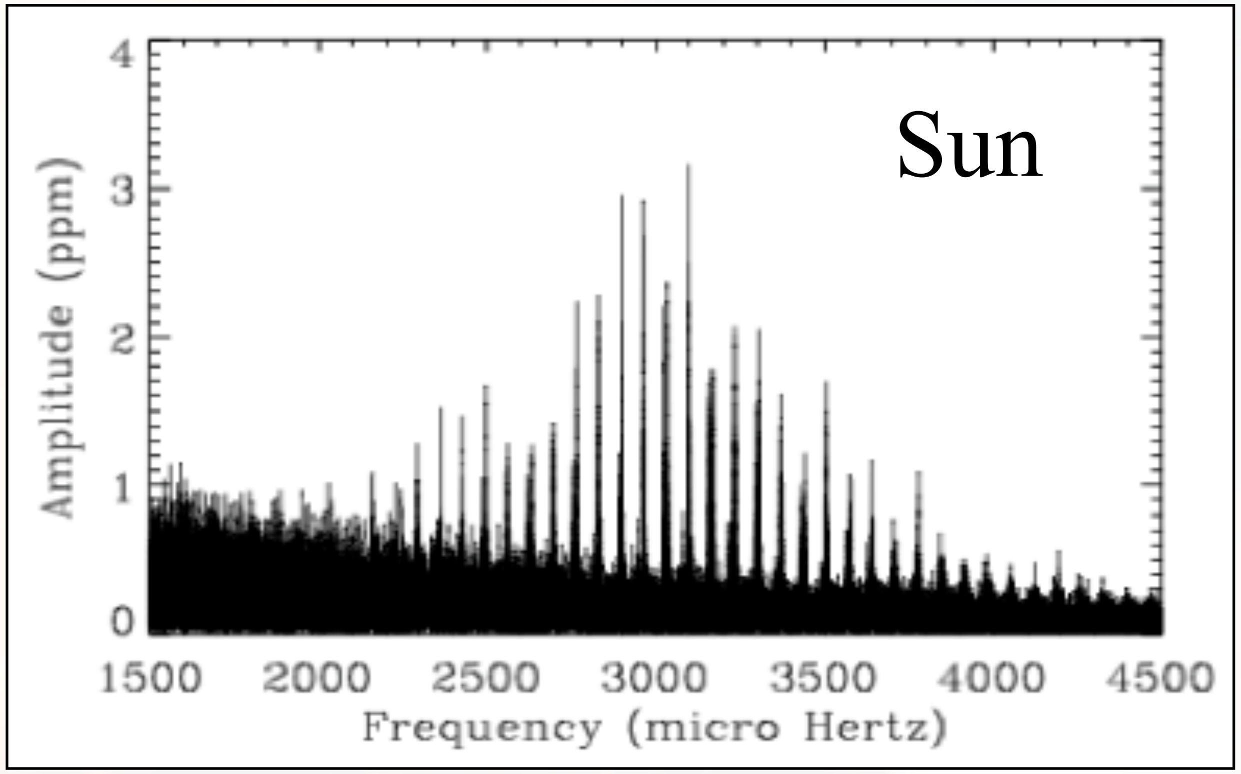


Brown et al. 1991

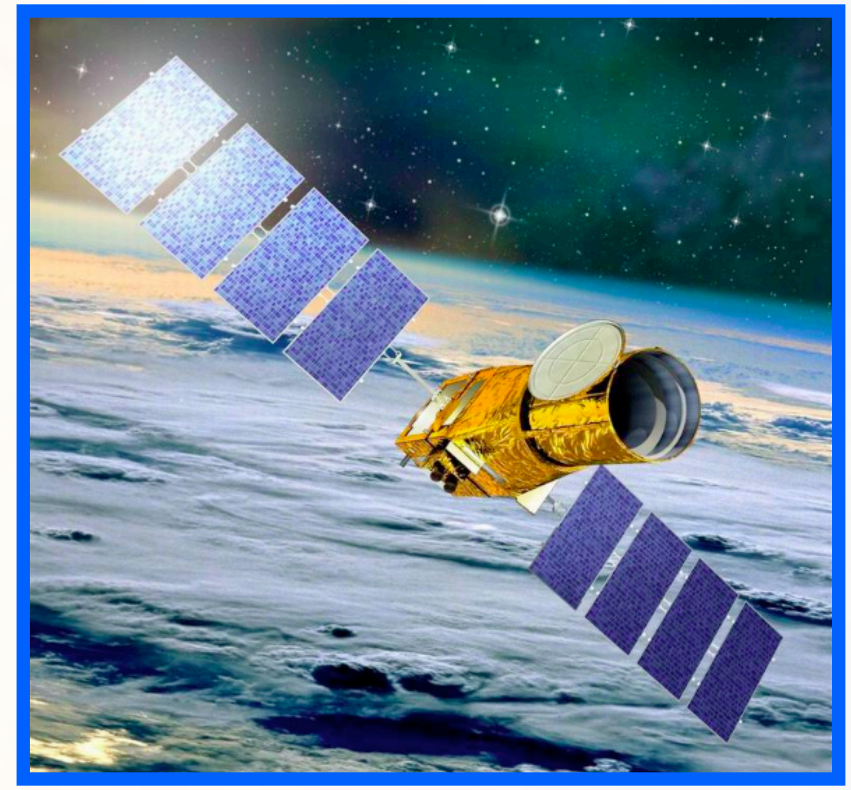


VIRGO/SOHO

ground-based observations of oscillations in solar-like stars are very difficult due to Earth's atmosphere; however, space-based observations have revolutionized asteroseimology in the past few years!

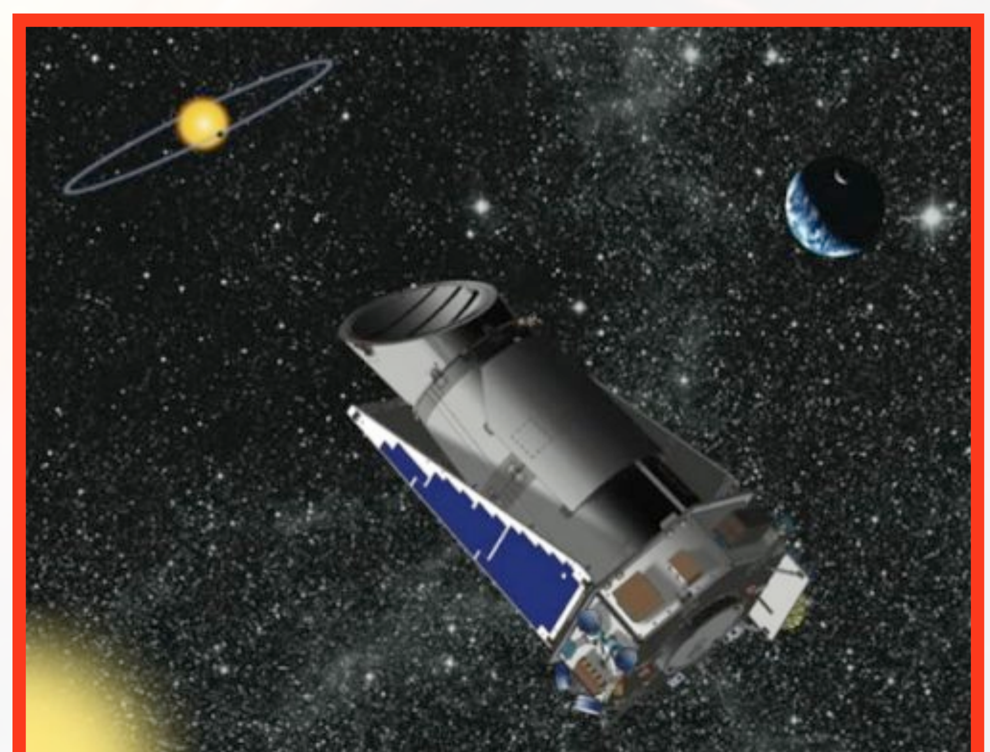
MOST

(launched 2003)



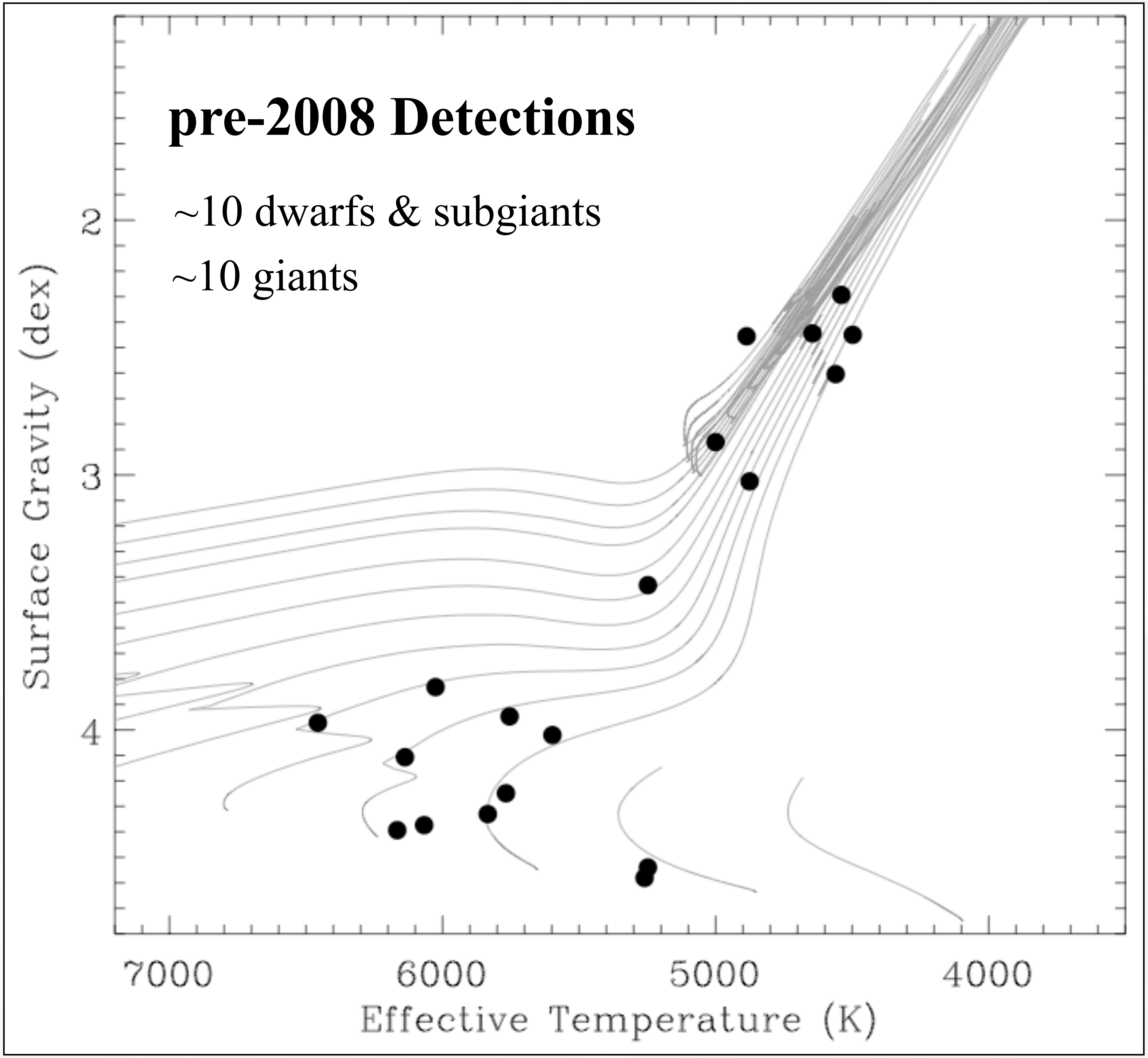
CoRoT

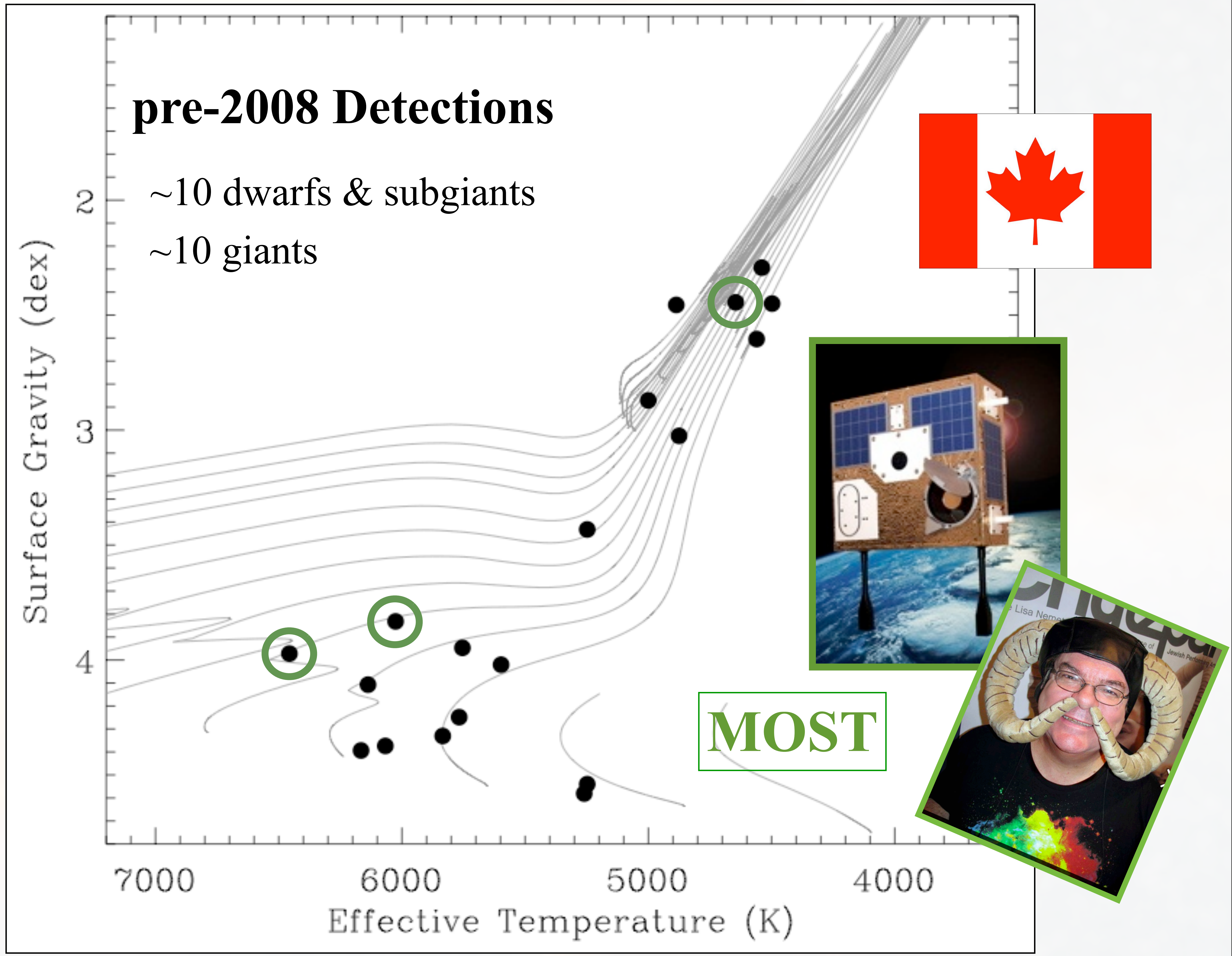
(launched 2007)

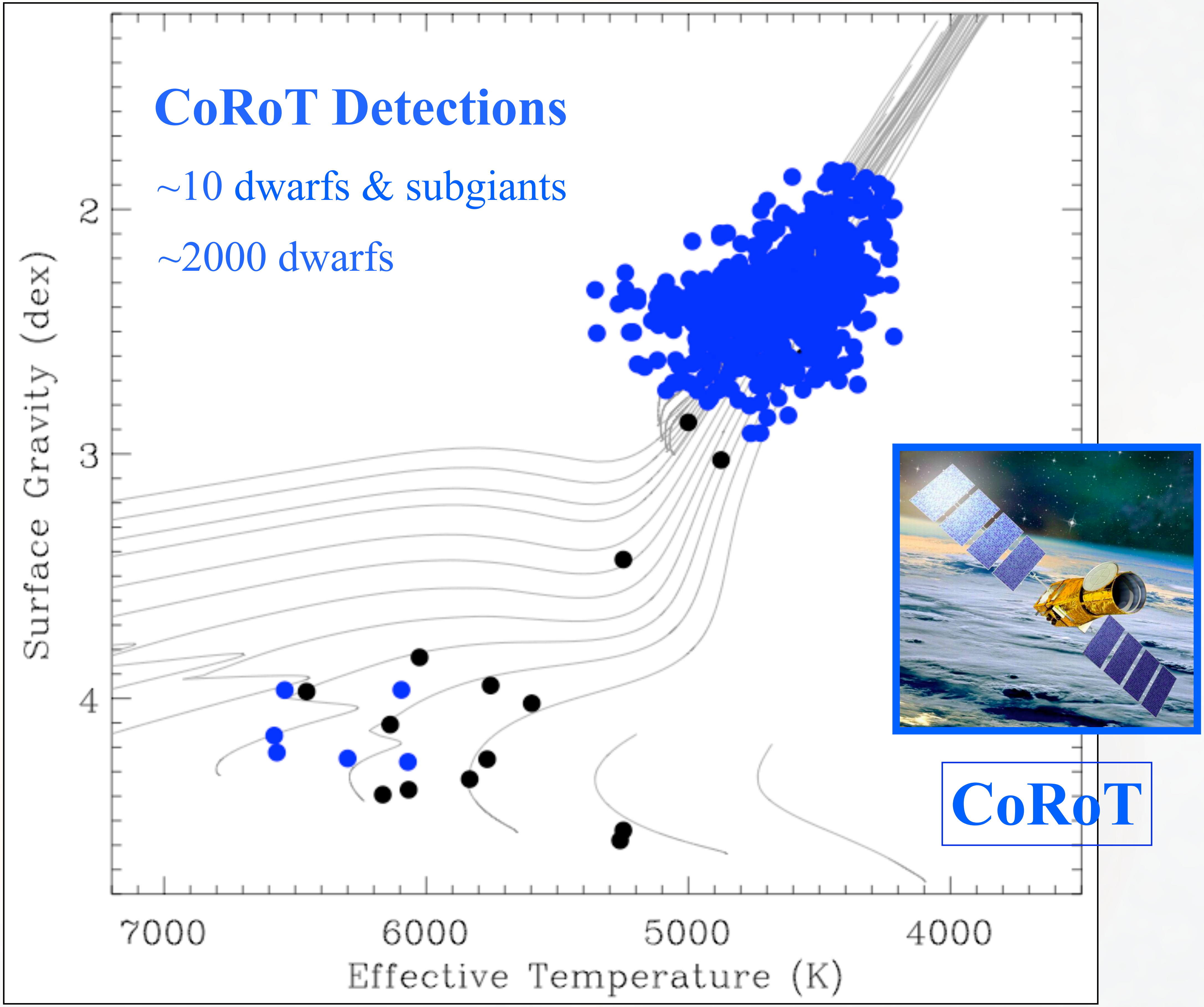


Kepler

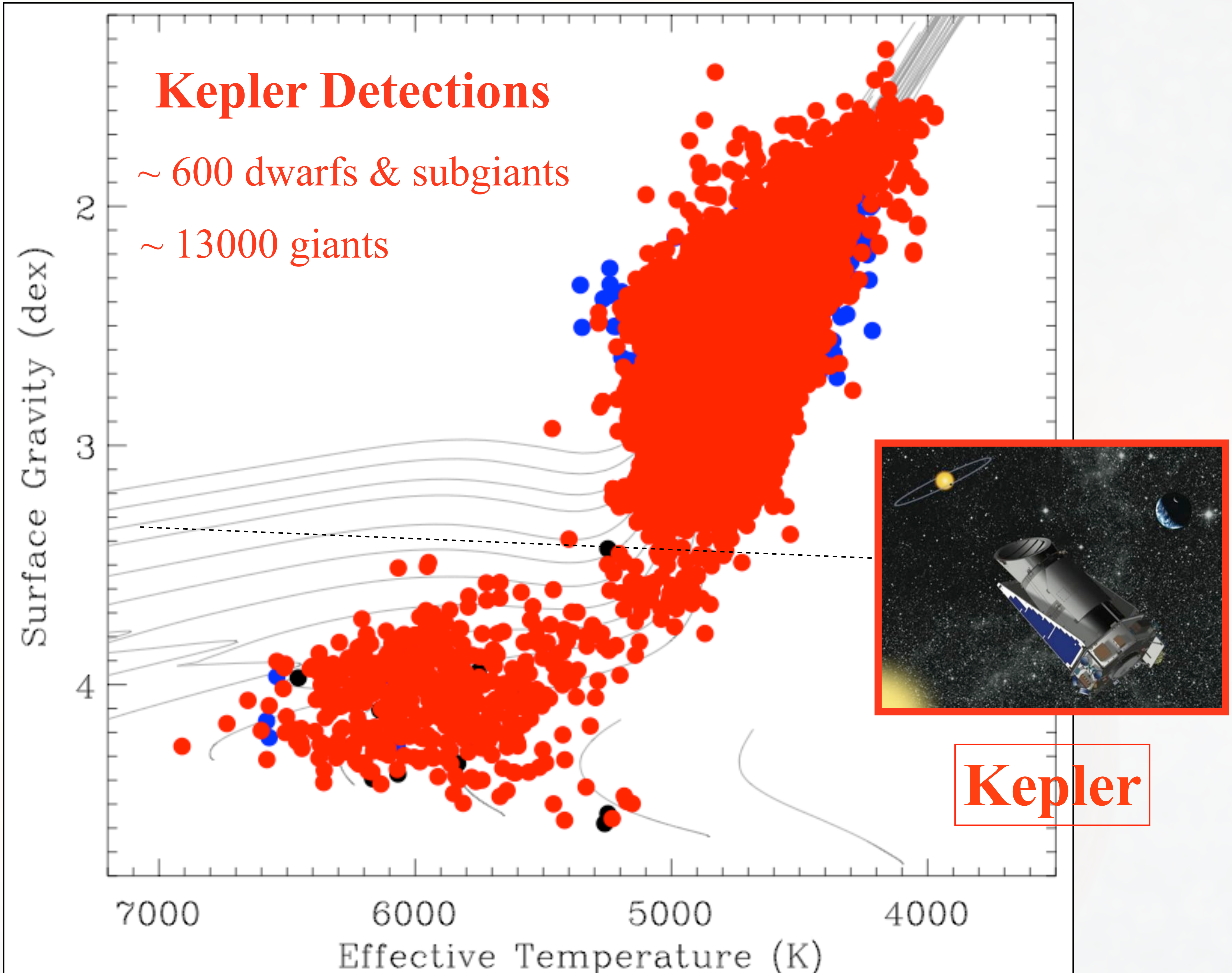
(launched 2009)


pre-2008 Detections
~10 dwarfs & subgiants
~10 giants
2
3
4
Surface Gravity (dex)
7000
6000
5000
4000
Effective Temperature (K)


pre-2008 Detections
~10 dwarfs & subgiants
~10 giants
Surface Gravity (dex)
2
3
4
7000
6000
5000
4000
Effective Temperature (K)
MOST

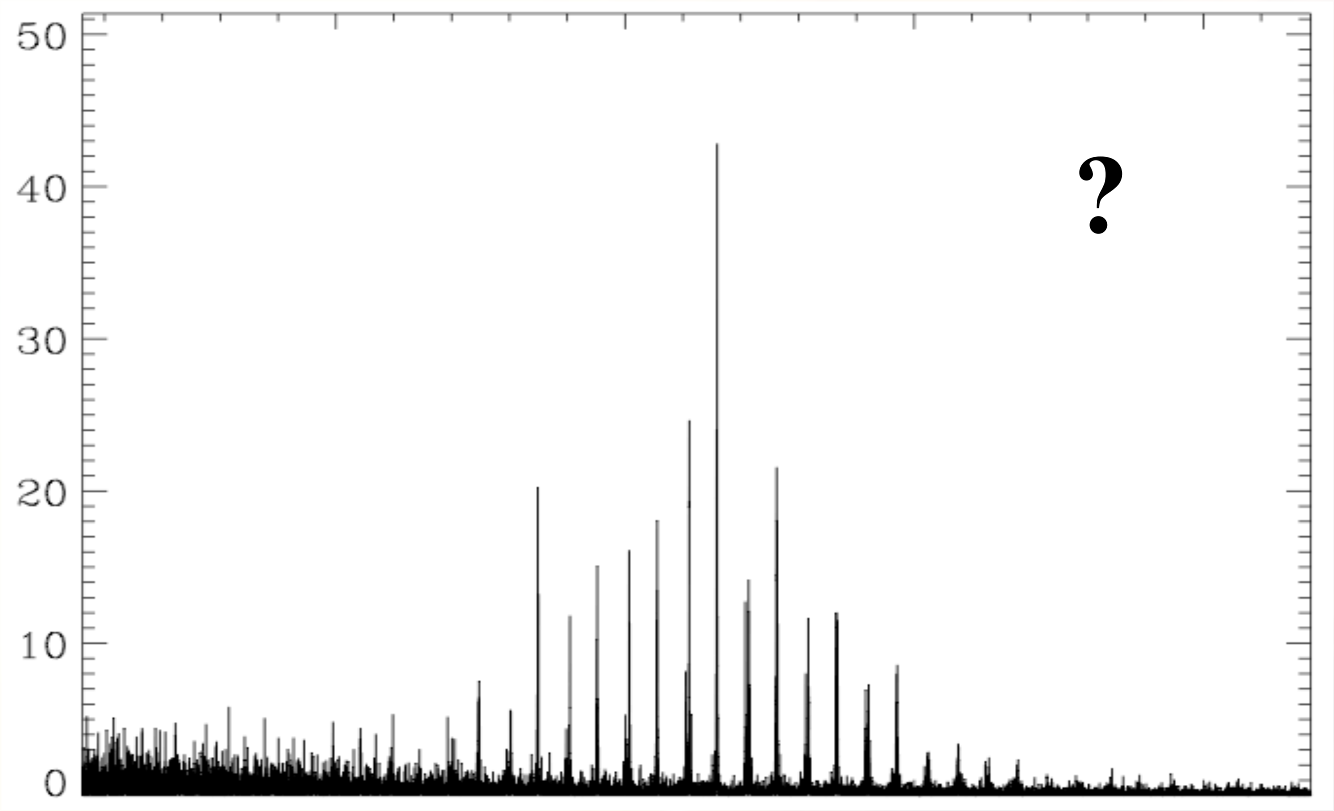

CoRoT Detections
~10 dwarfs & subgiants
~2000 dwarfs
Surface Gravity (dex)
2
3
4
7000
6000
5000
4000
Effective Temperature (K)

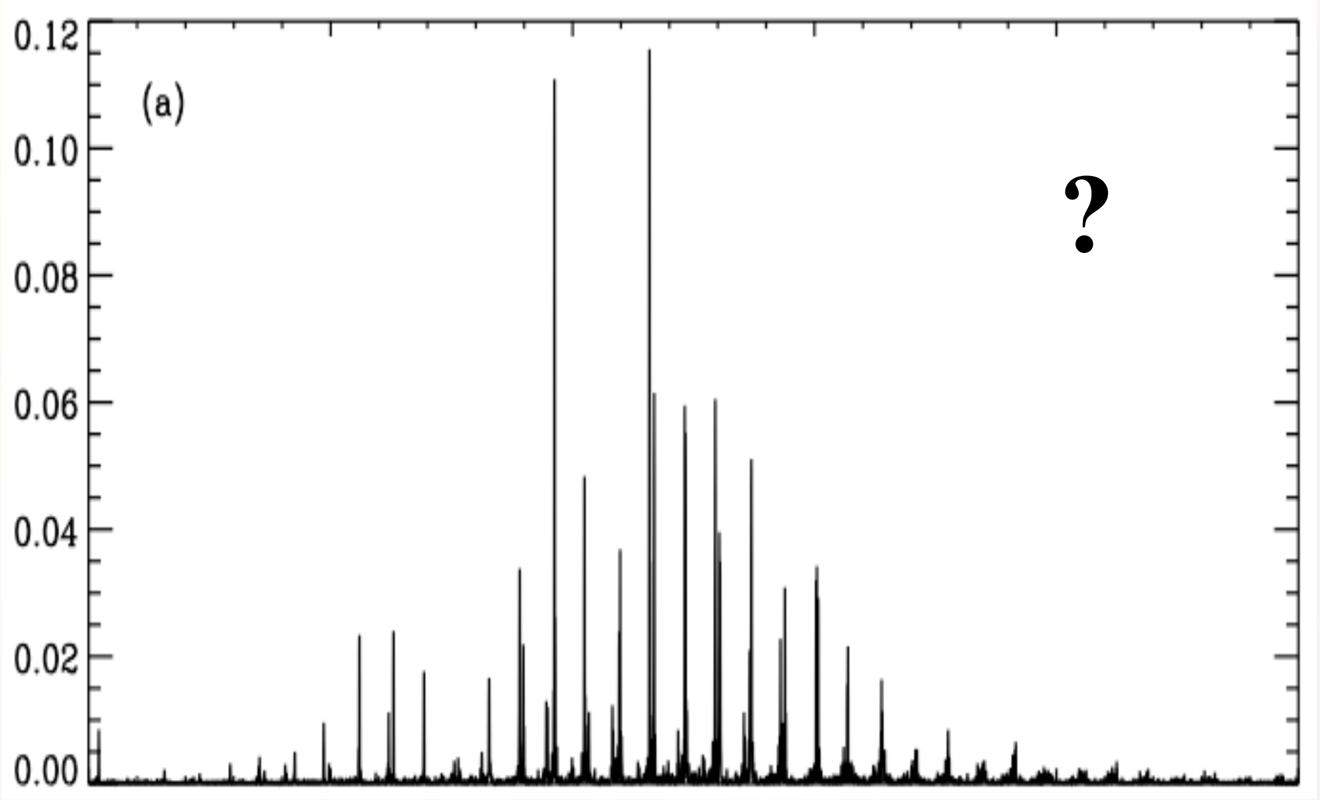
CoRoT



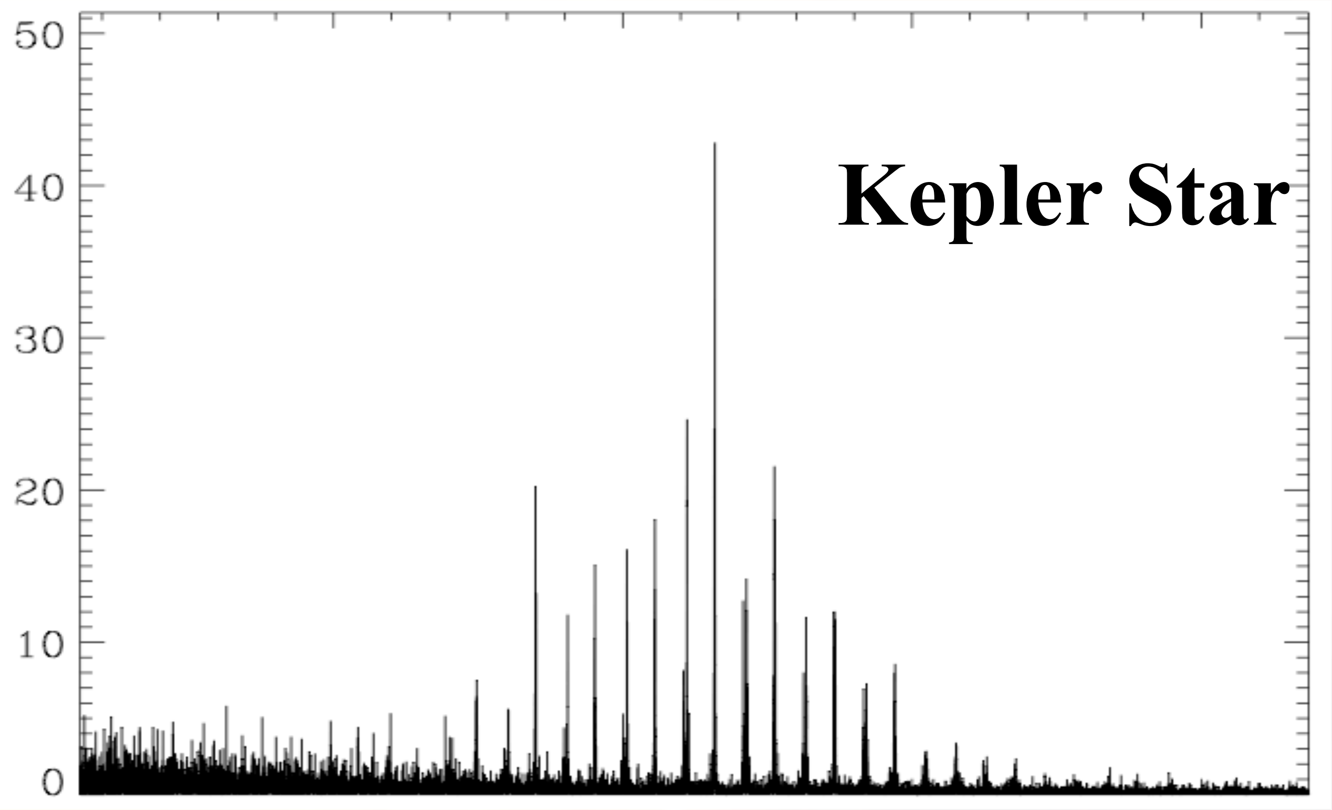
Kepler Detections
~ 600 dwarfs & subgiants
~ 13000 giants
Surface Gravity (dex)
2
3
4
7000
6000
5000
4000
Effective Temperature (K)
Kepler

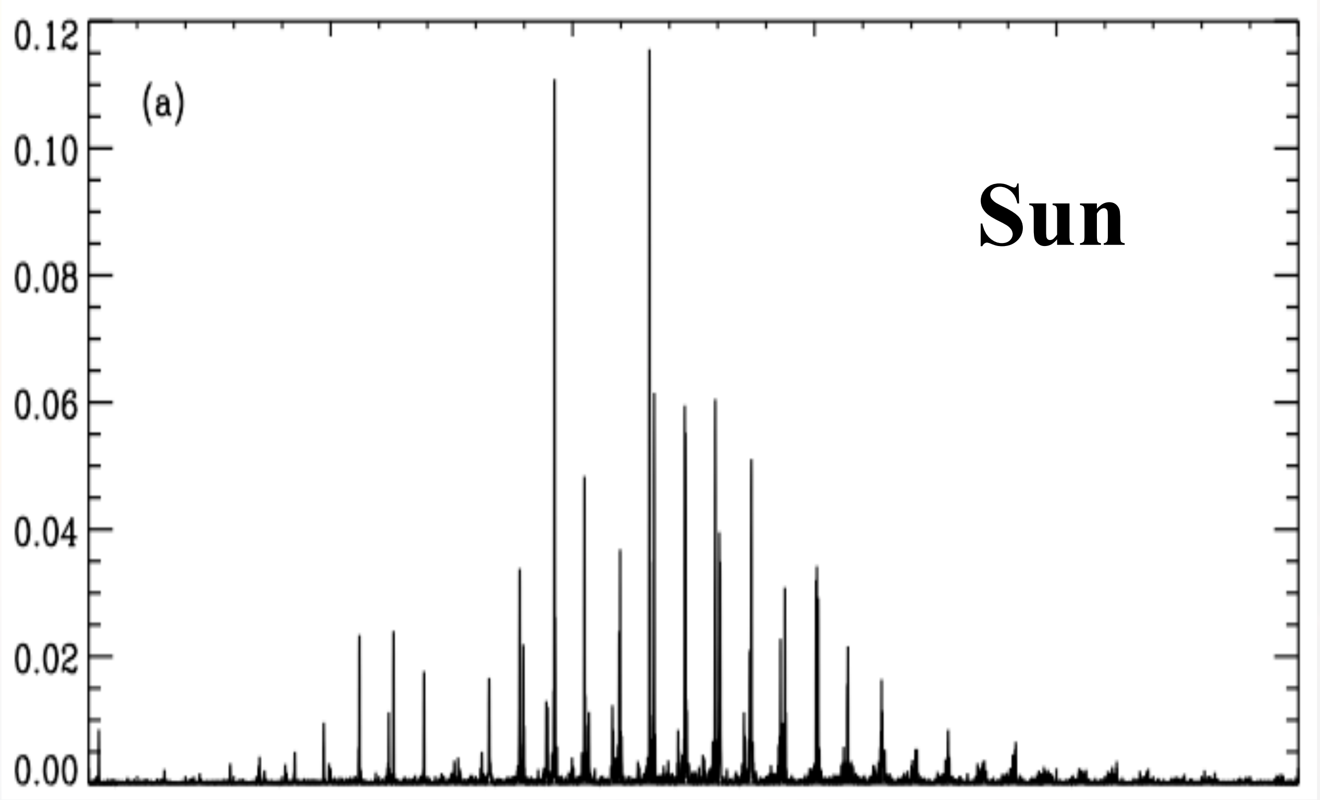
Which one is the Sun?





Which one is the Sun?





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Temperature (T) ✓

Radius (R) ✓

Chemical Composition

Mass (M) ✓

Surface Gravity (g) ✓

Luminosity (L) ✓

Density (ρ) ✓

Age

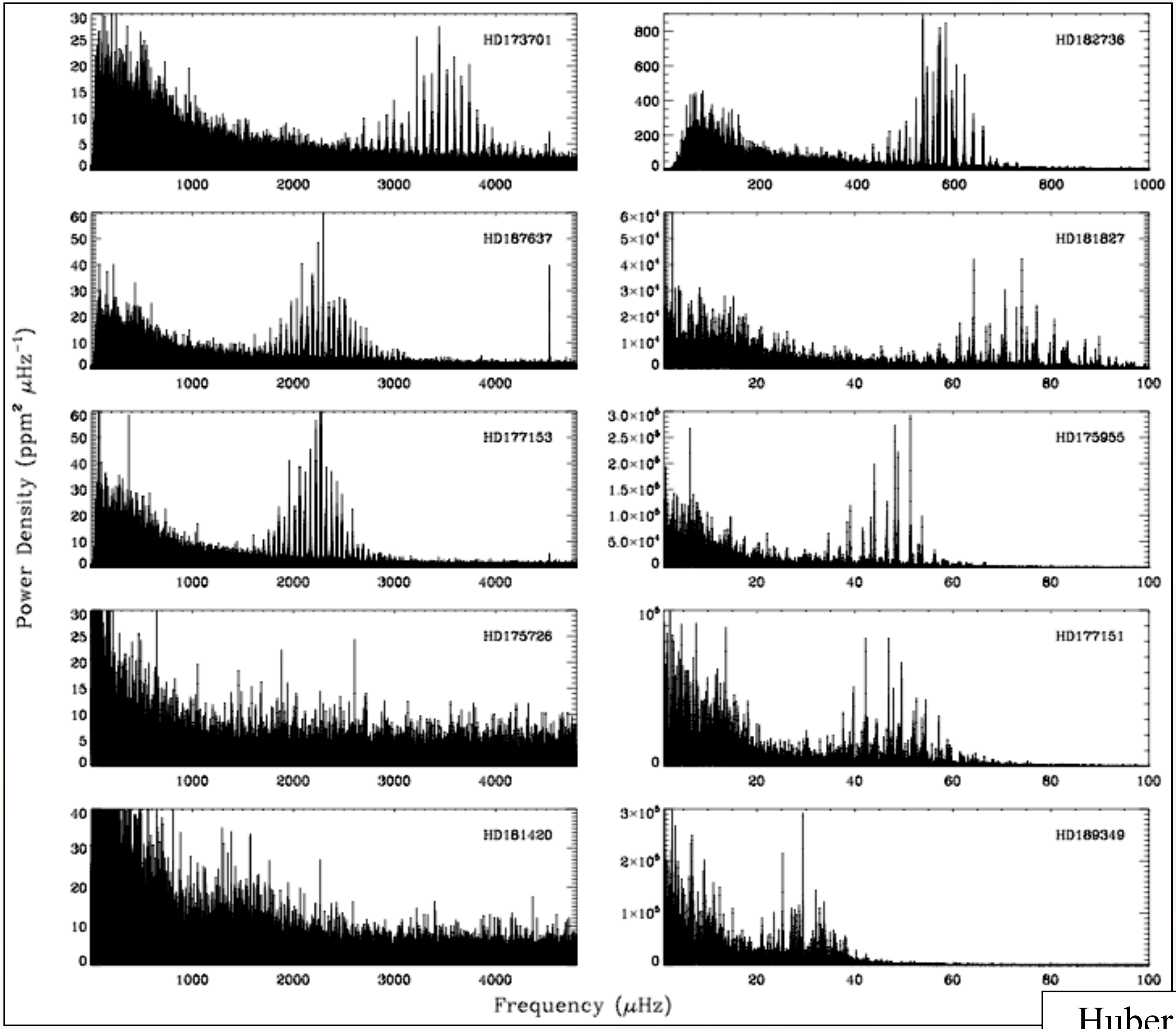
$$g = GM/R^2$$

$$L \propto R^2 T^4$$

$$\rho \propto M/R^3$$

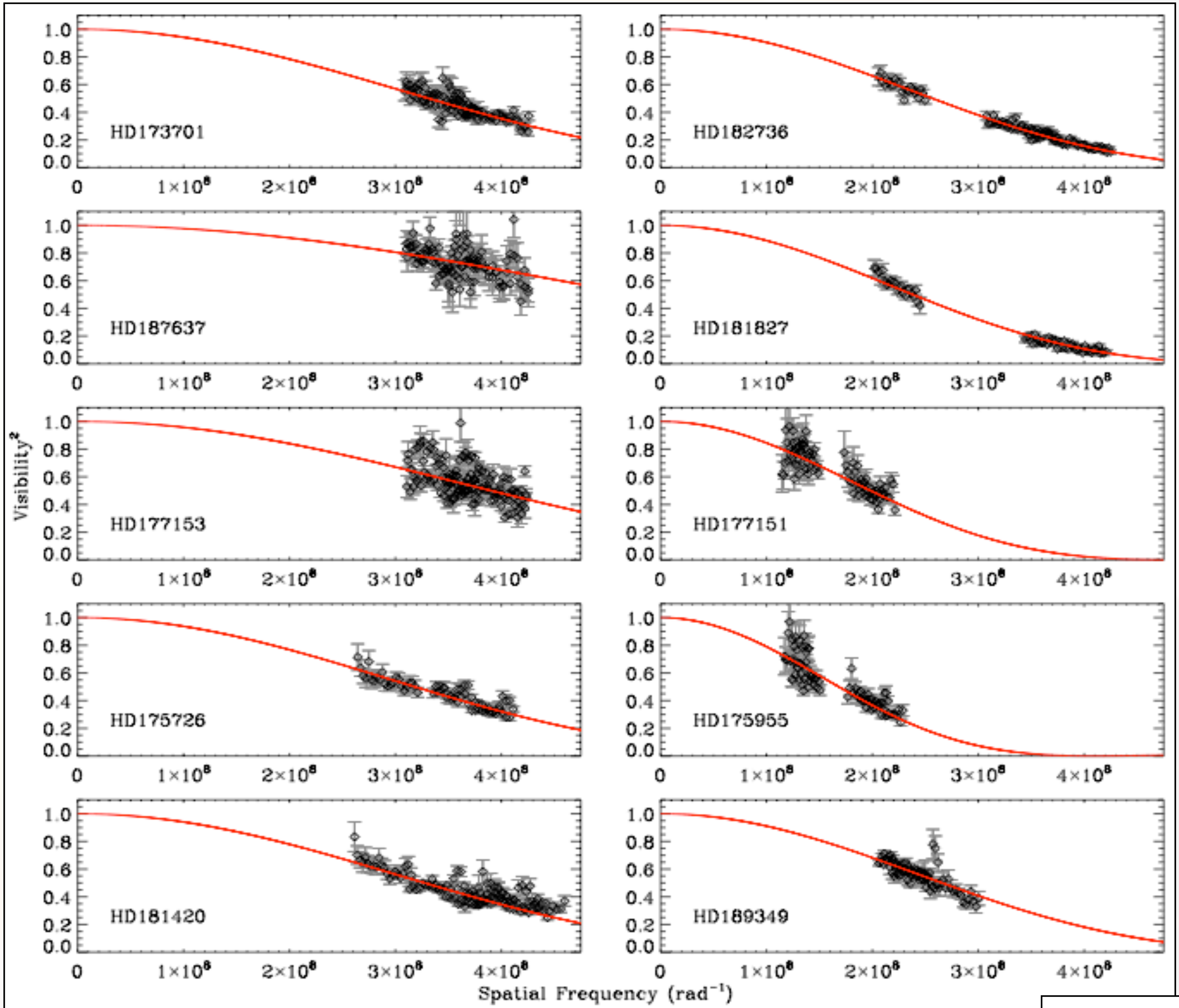
Goal: find a sample for which we can measure oscillations *and* angular diameters!

Oscillation Spectra of 10 Kepler Stars



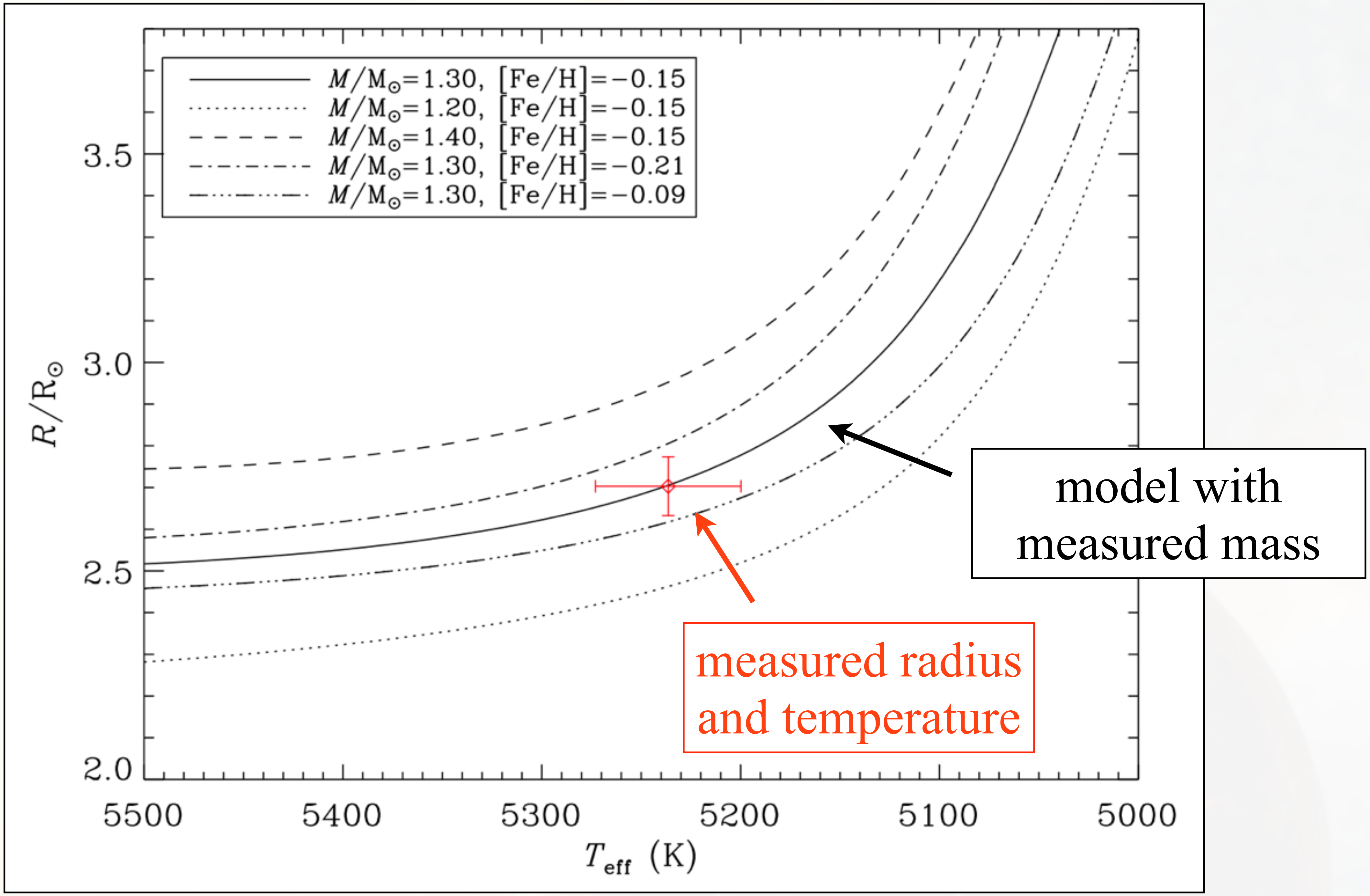
Huber et al. 2012

CHARA Interferometry of 10 Kepler Stars



Huber et al. 2012

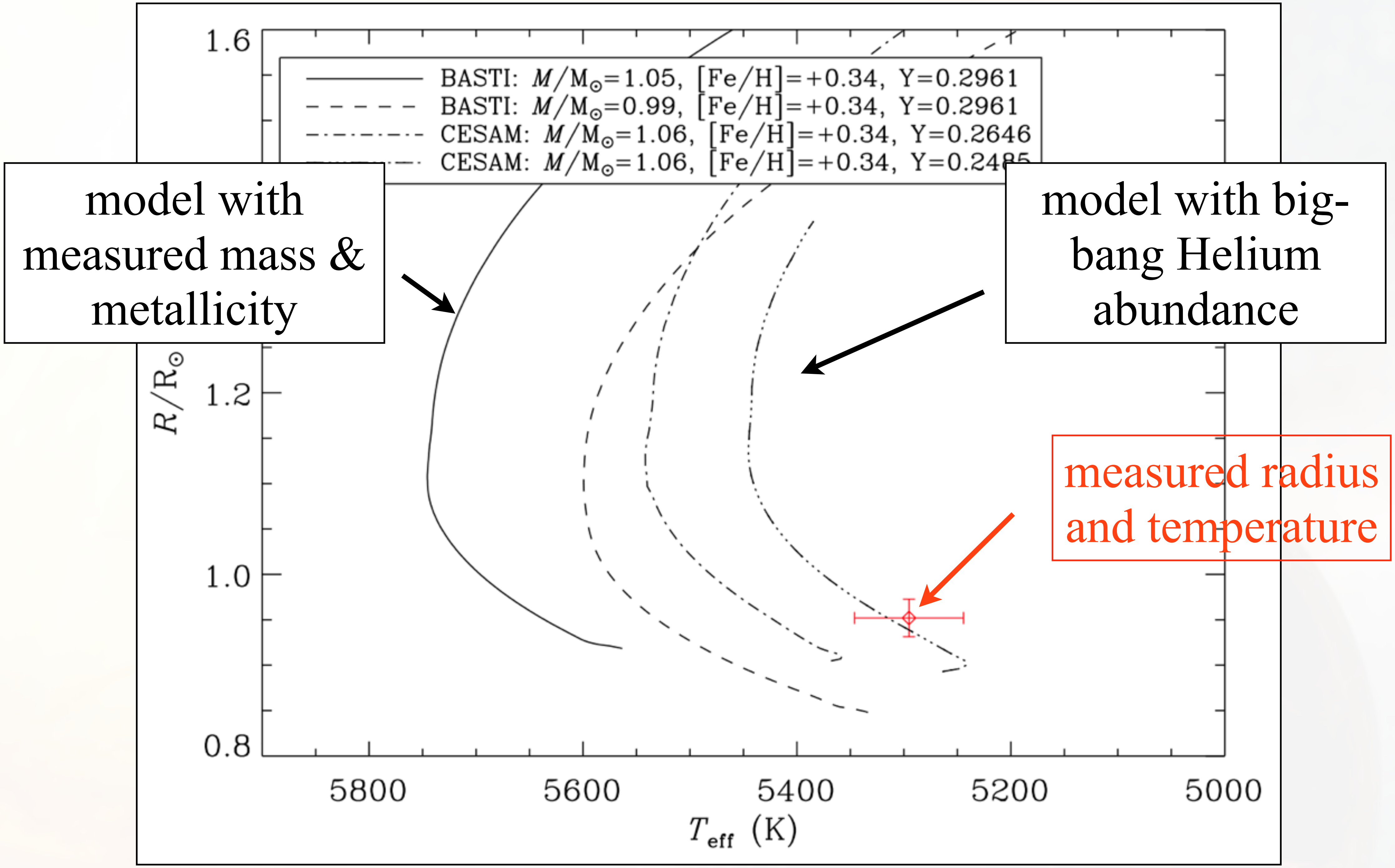
Test Models!



Subgiant with "normal" chemical composition: spot-on agreement

Huber et al. 2012

Test Models!

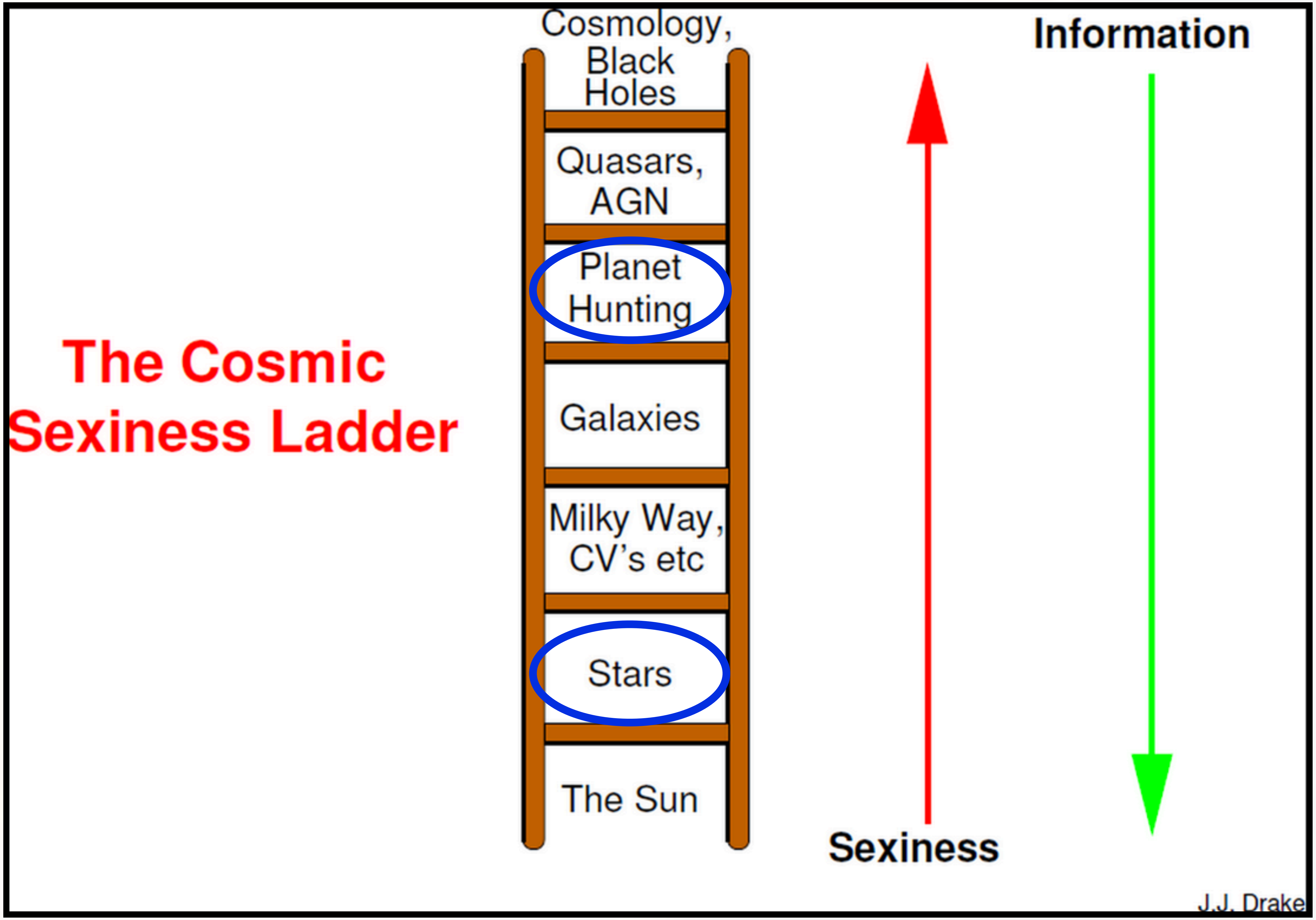


Metal-rich dwarf: slightly impossible; best explanation: model atmospheres (used for bolometric flux) have errors

Huber et al. 2012

The Connection to Planets

(and binary stars)

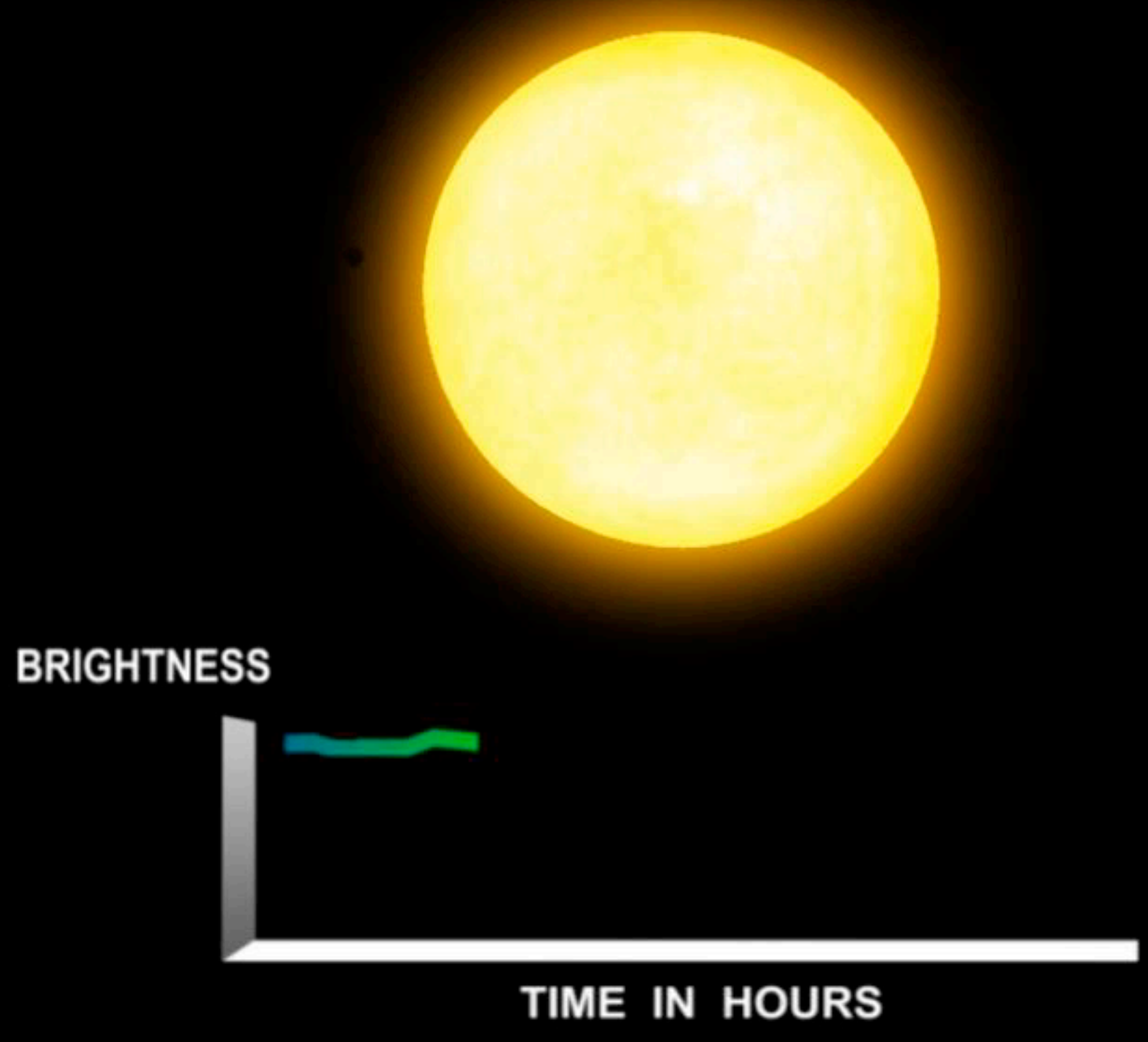


The Cosmic Sexiness Ladder
Cosmology, Black Holes
Quasars, AGN
Planet Hunting
Galaxies
Milky Way, CV's etc
Stars
The Sun
Sexiness
Information
J.J. Drake

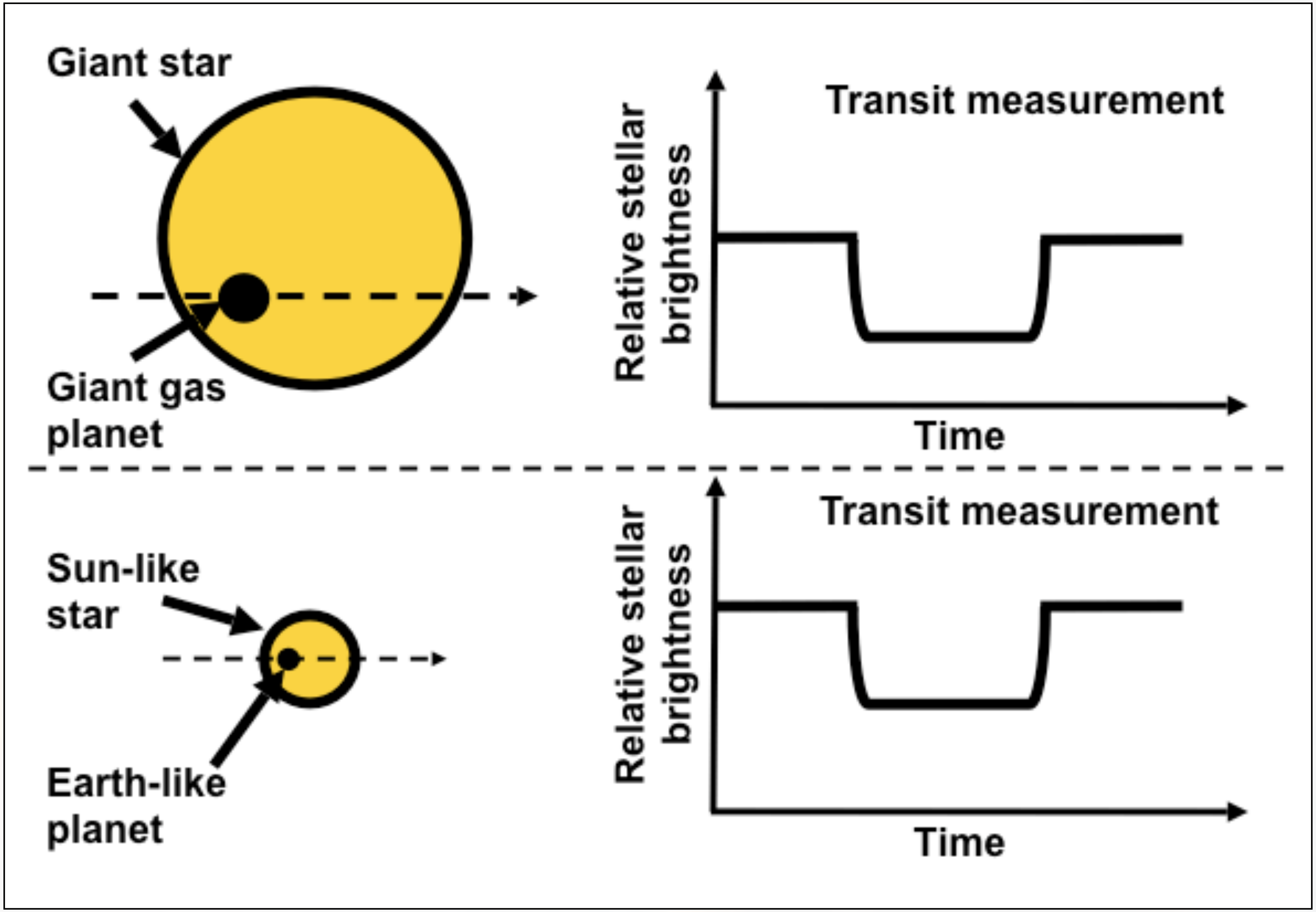
The Kepler Space Telescope

Main mission goal: determine the frequency of Earth-sized planets in the habitable zones of Sun-like stars

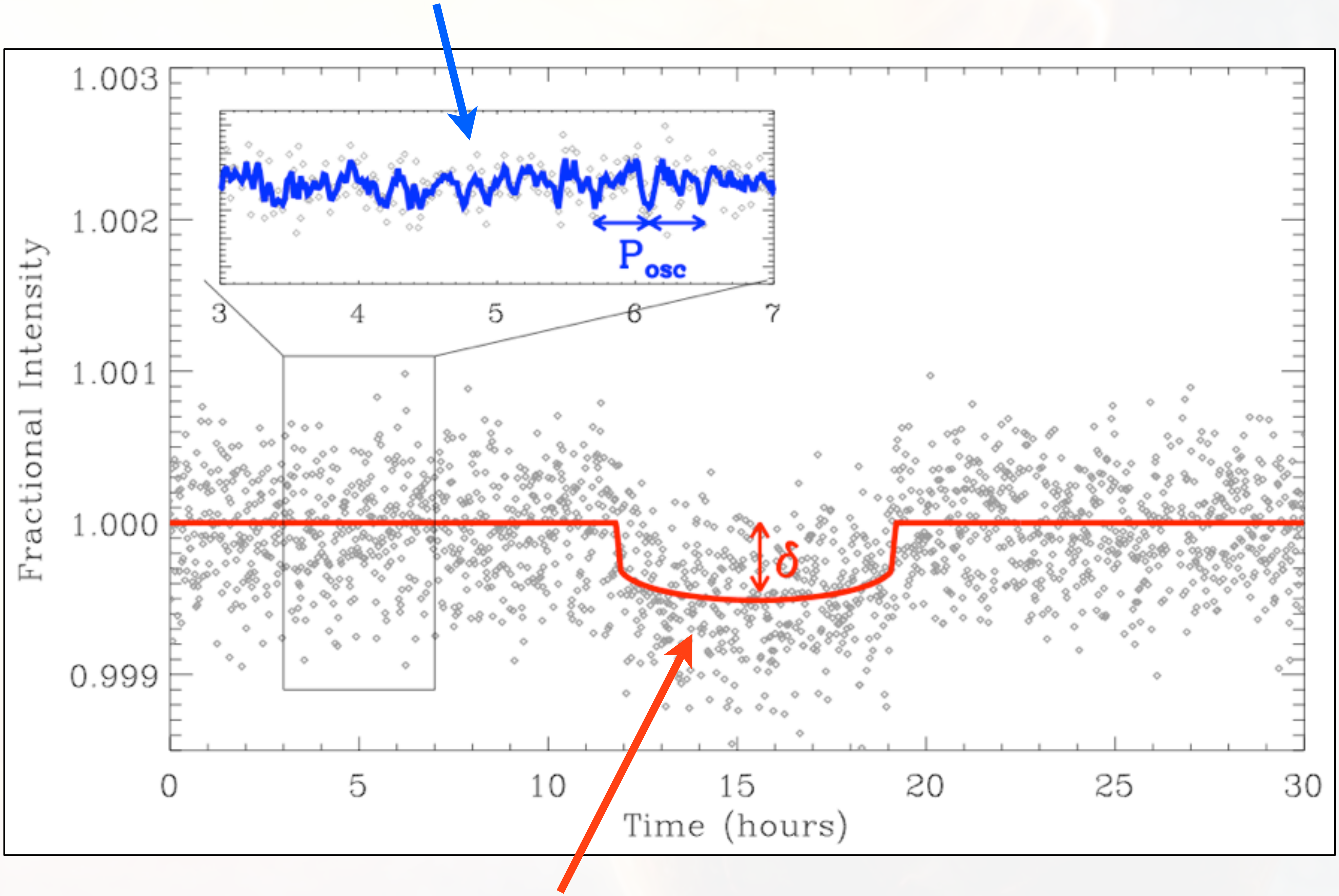
The Transit Method



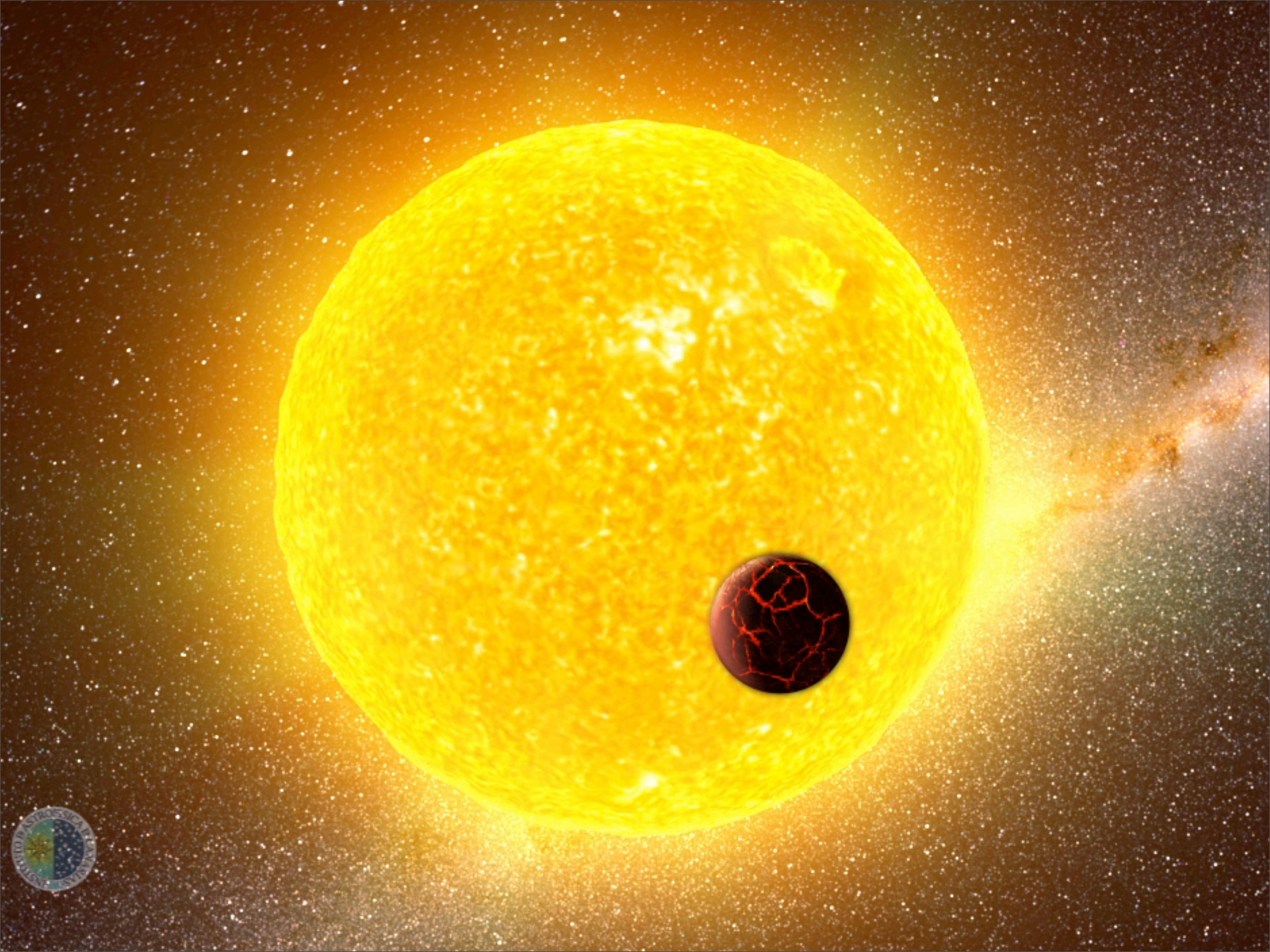
Knowing Star Sizes is important!



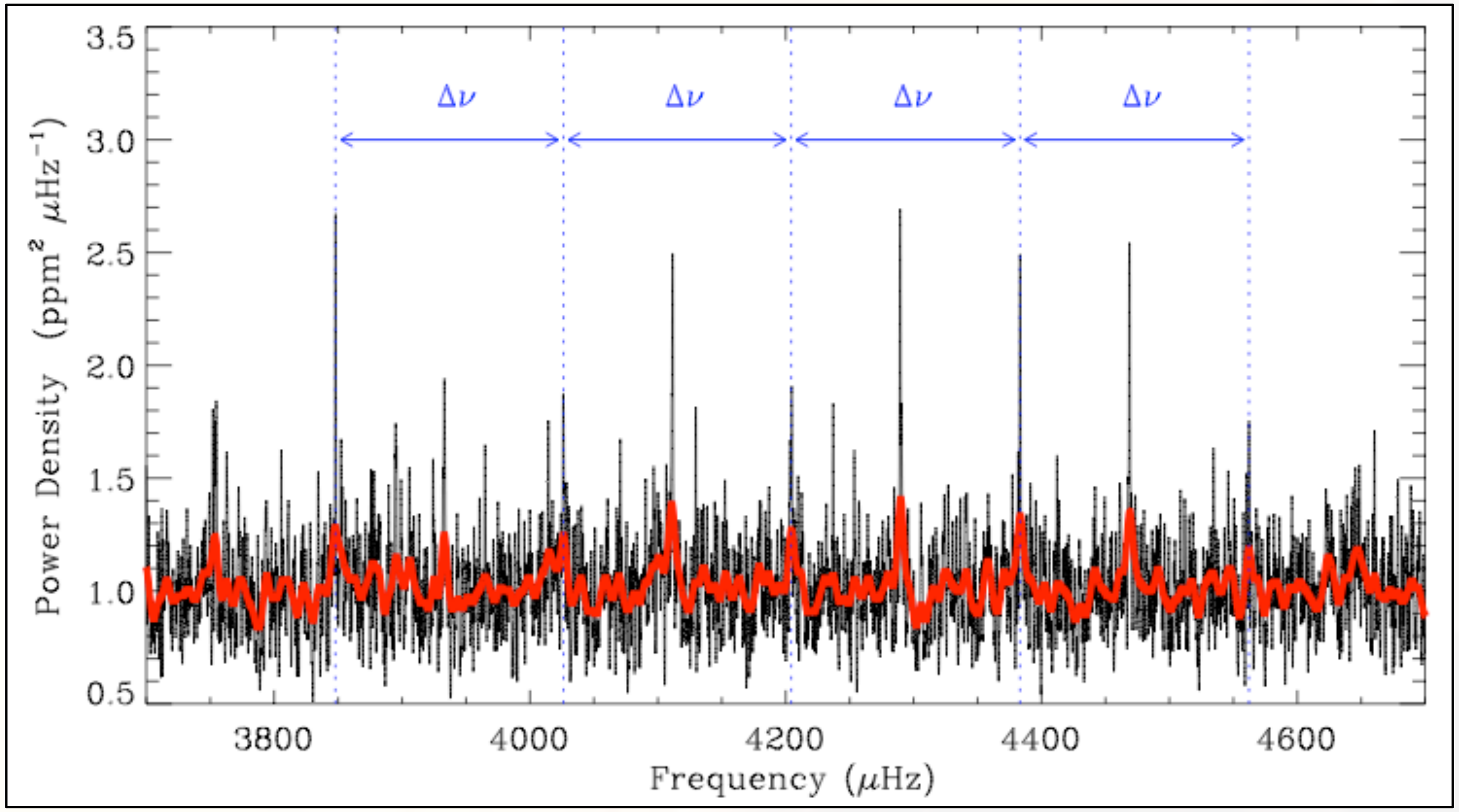
Stellar Oscillations = Size of the Star



Transit = Planet Size relative to Star Size



Kepler-37: Asteroseismology



$\Delta\nu$ = 178.7 μHz

R = 0.772+/- 0.026 R_s

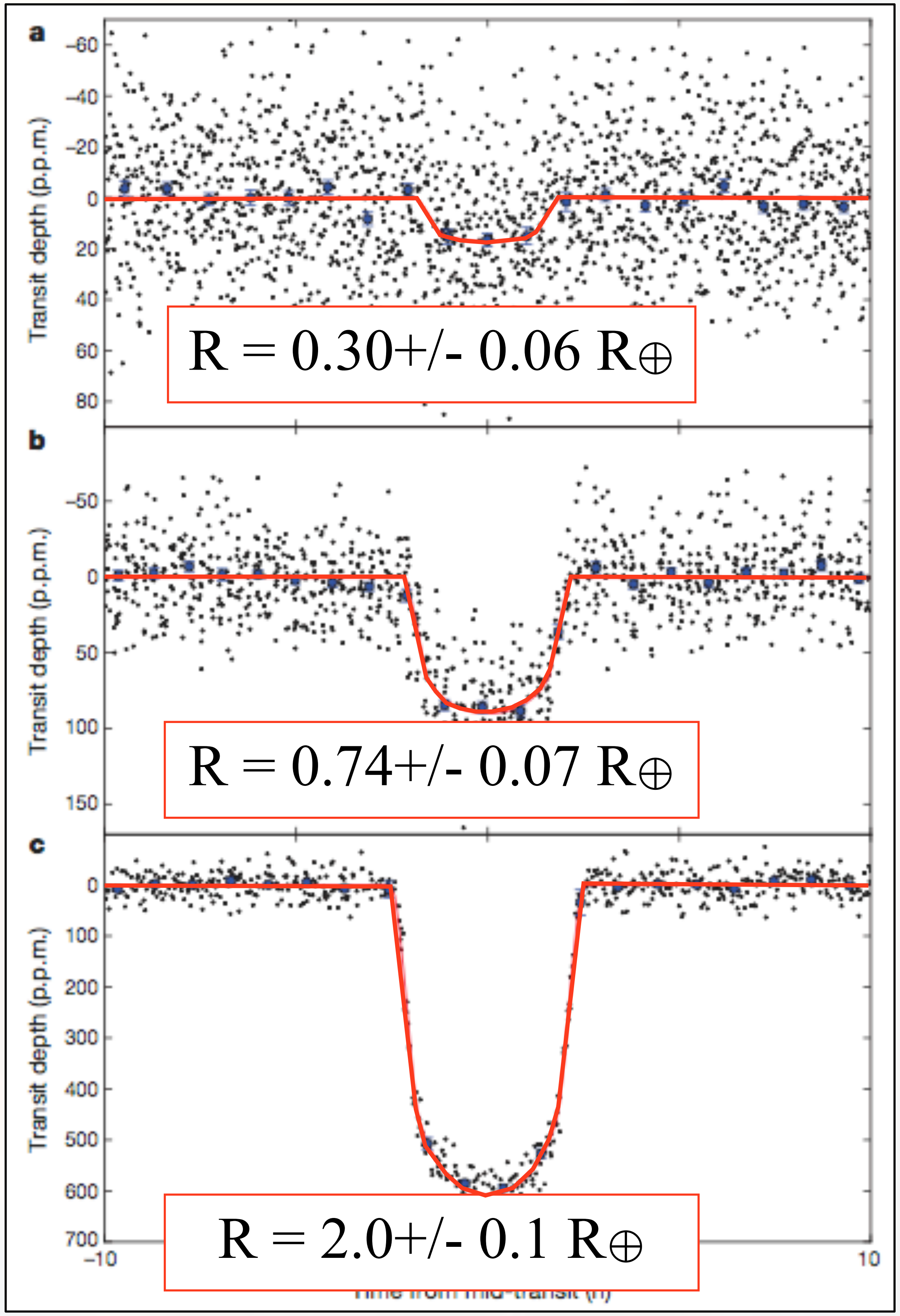
Densest solar-like star with detected oscillations yet!

Kepler-37: Transits

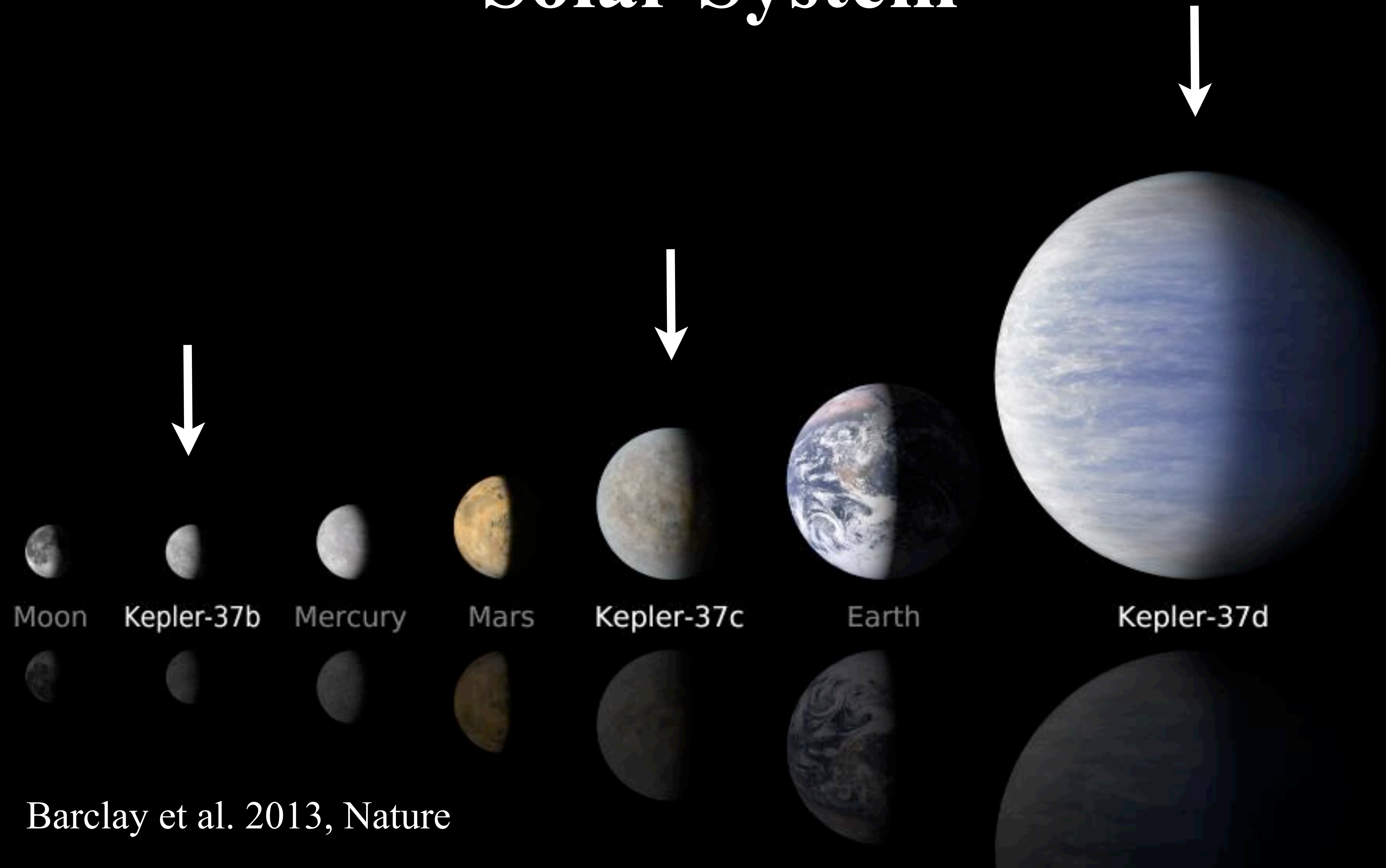
3 transiting planets

orbital periods: 13, 21 and 40 days

precise knowledge of the planet radii thanks to the asteroseismic detection in the host star!

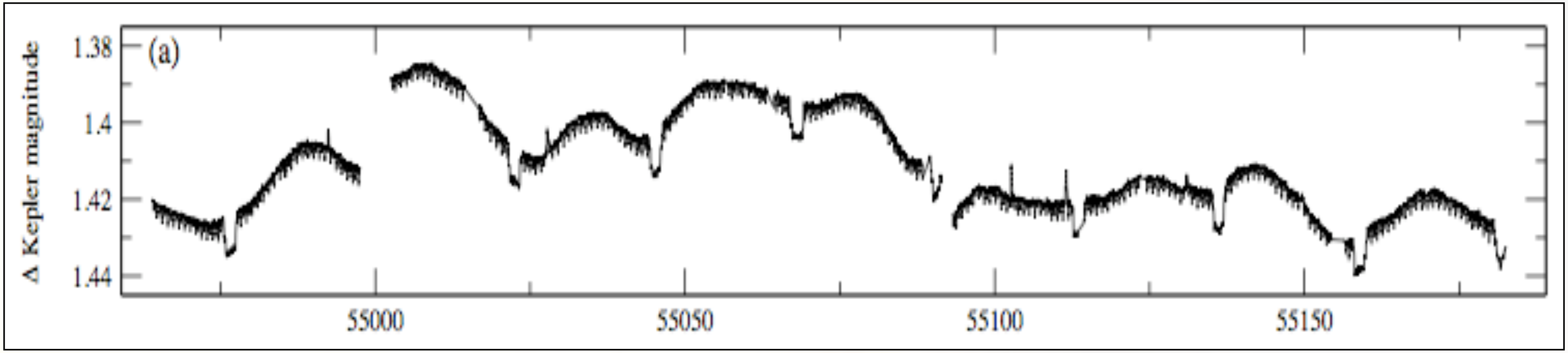


Kepler-37 Planets compared to the Solar System

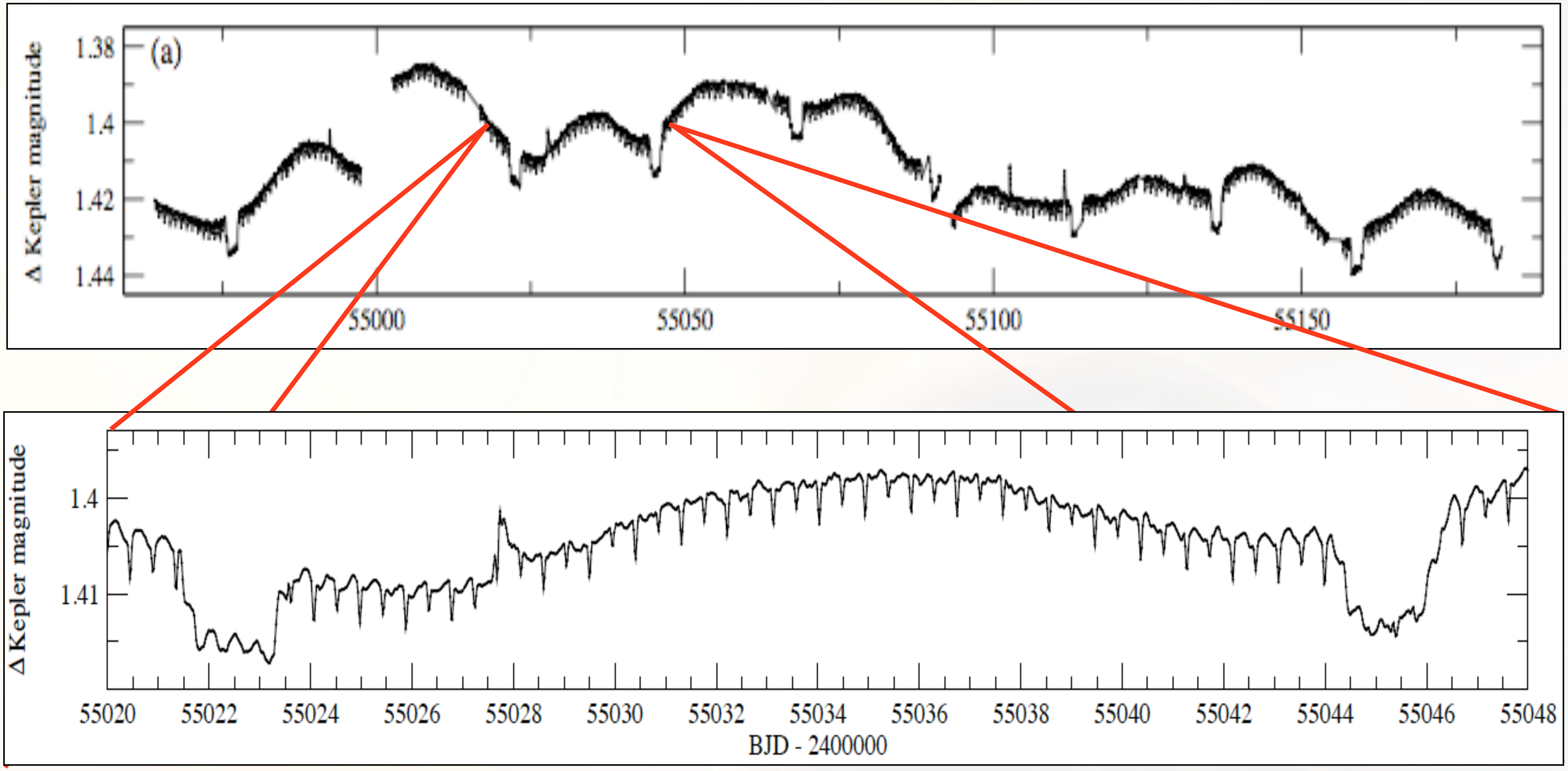


Barclay et al. 2013, Nature

A Kepler Weirdo

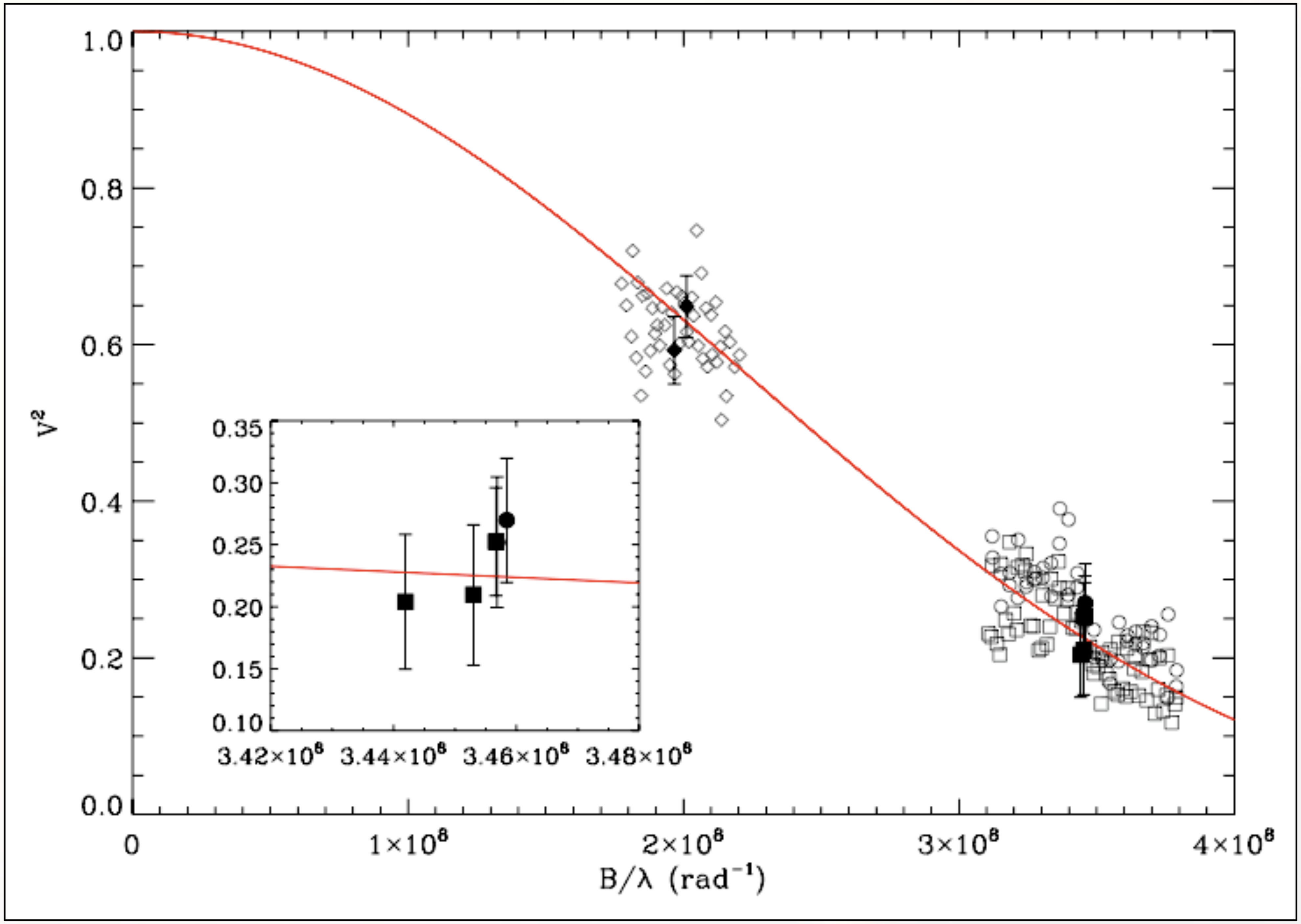


A Kepler Weirdo



Kepler light curve shows deep dips with ~20 day period, and shallow dips with ~1 day period. What's going on?

CHARA Interferometry

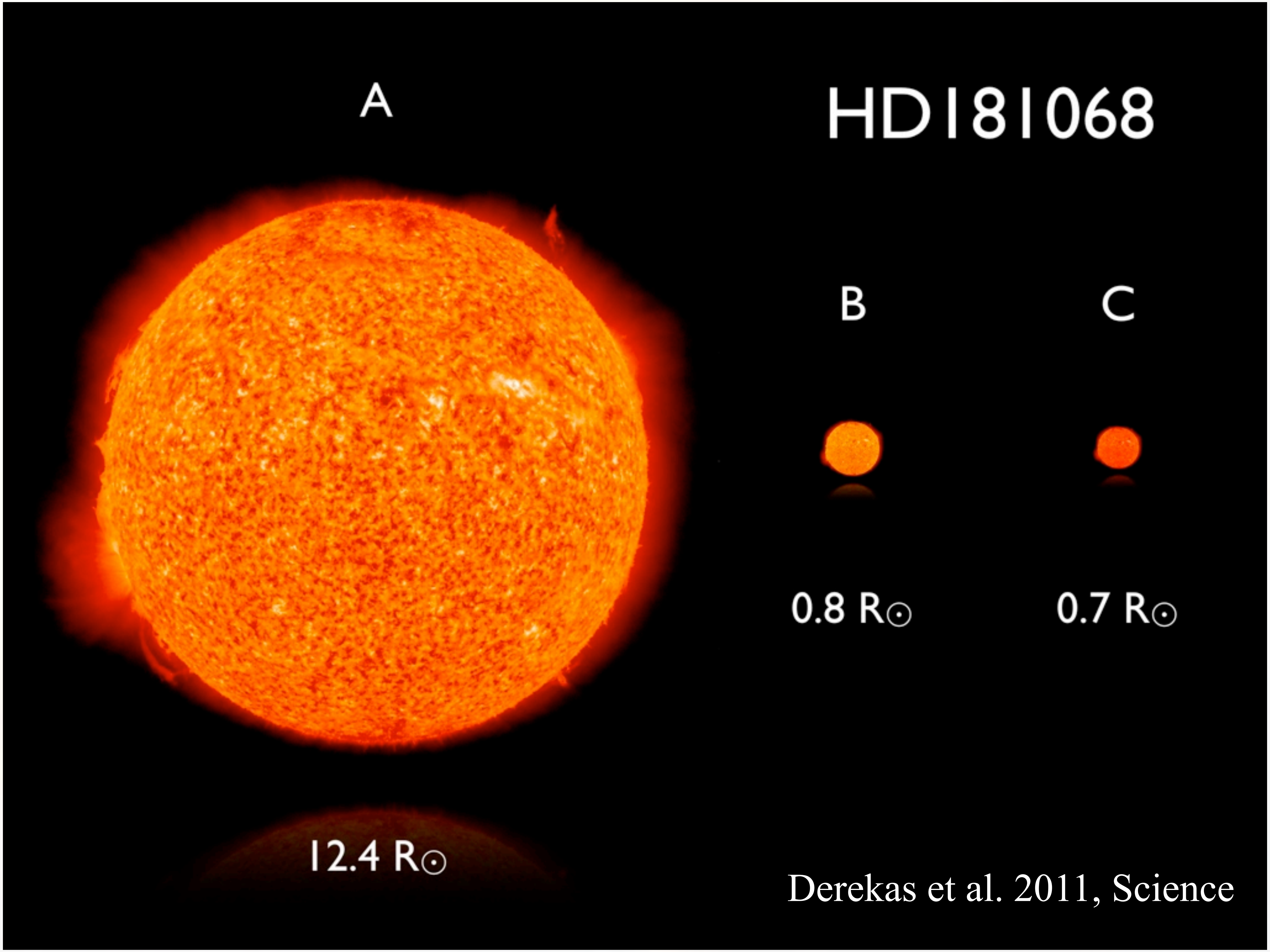


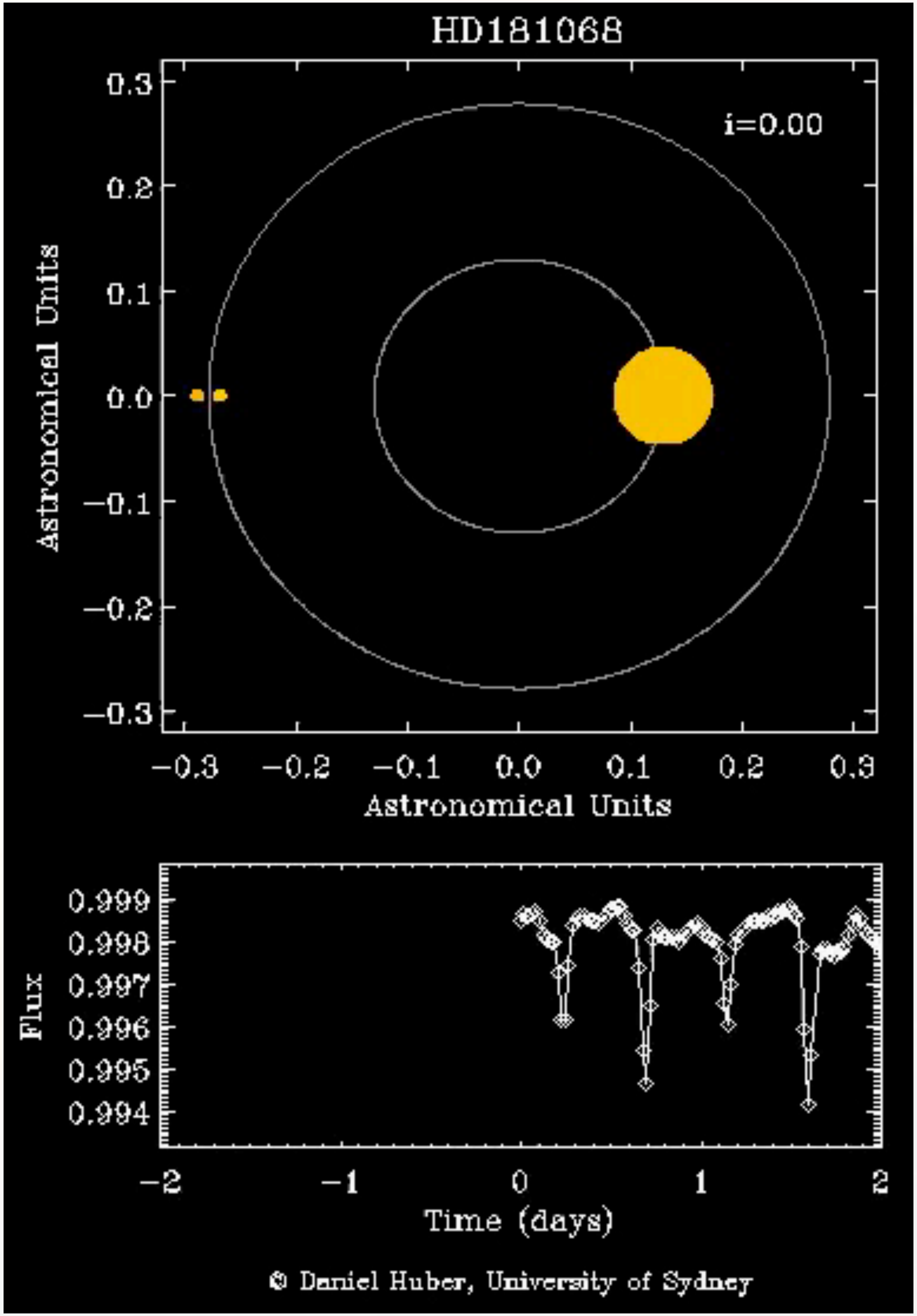
Diameter (mas)
0.461 +/ 0.011
($5x10^6$ times smaller than apparent Sun)

Radius (solar)
12.4 +/- 1.3

Primary Star must be Giant!

Derekas et al. 2011, Science


HD181068
A
B
C
0.8 R⊙
0.7 R⊙
12.4 R⊙
Derekas et al. 2011, Science

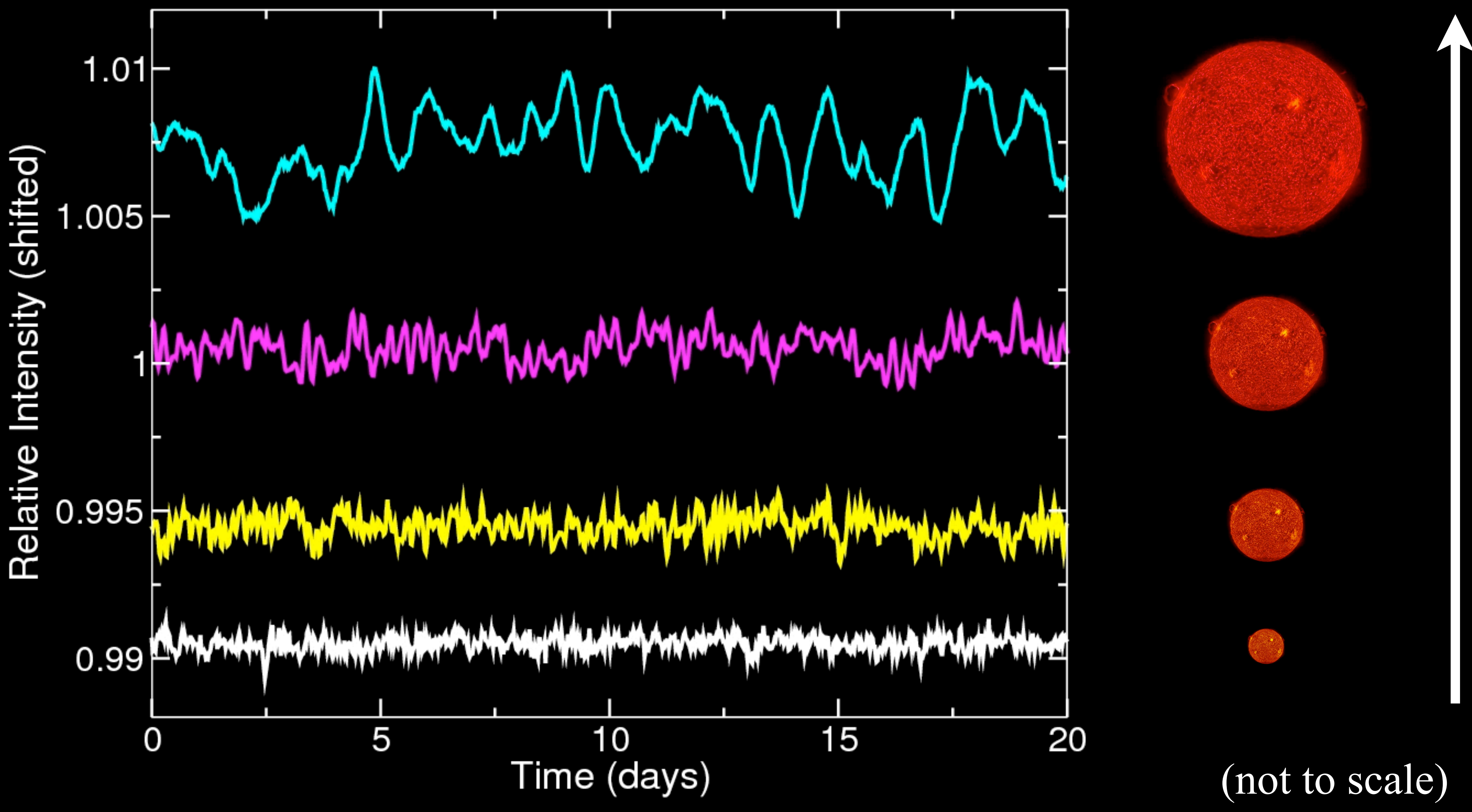


Derekas et al.
2011, Science

A story on Asteroseismology and Public Outreach

(if there is time)

A Kepler "concert" of Red Giant Stars



Astronomers study the sound of stars

Australian Geographic

ENVIRONMENT & SCIENCE | OCTOBER 28, 2010

A 'Red Giant Concert' in the Sky

The Wall Street Journal

Kepler

Телескоп "Кеплер" "пощупал" пульс у тысячи далеких звезд

??? (Russia)

MUSIC

The Future of Rock Stars

By Carmel Lobello Friday, October 29, 2010

"The Wall Street Journal" reported on Friday that astronauts recorded sound waves that resemble humming emanating from a cluster of giant red stars.

But why wait until the earth is uninhabitable to look beyond humans and human-made machines for musical innovation? If Jason Pierce got his hands on Huber's recording, I'm sure he could produce a an emotionally wrenching Spiritualized album that could pave the way for some pretty inspiring, intergalactic collaborations.

Death and Taxes Magazine (USA)

Asteroseismology meets Contemporary Art

JEFF TALMAN

Sound, Video, Sculpture, Graphics, Photography

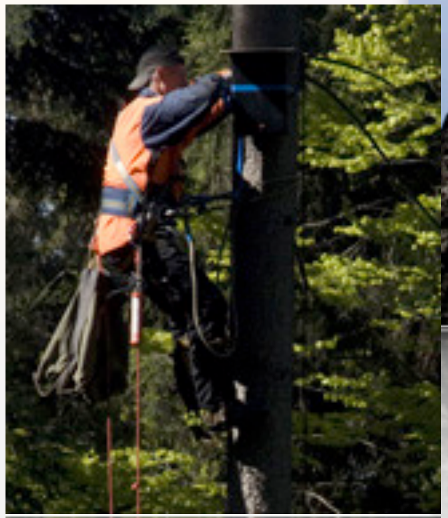
The Bayerische WaldVerein Sektion Furth im Wald presents
BAVARIAN FOREST INSTALLATION IV

NATURE OF THE NIGHT SKY (2011)

in collaboration with Daniel Huber, astrophysicist
Sydney Institute of Astronomy, Australia

May 7 – September 18, Berghof Gibacht
Waldmünchen – Furth im Wald, Germany

Every evening in the forest just after sunset a 50-minute program features the harmonic resonant sound of stars



www.jefftalman.com