Asteroseismology: star quakes and good vibrations

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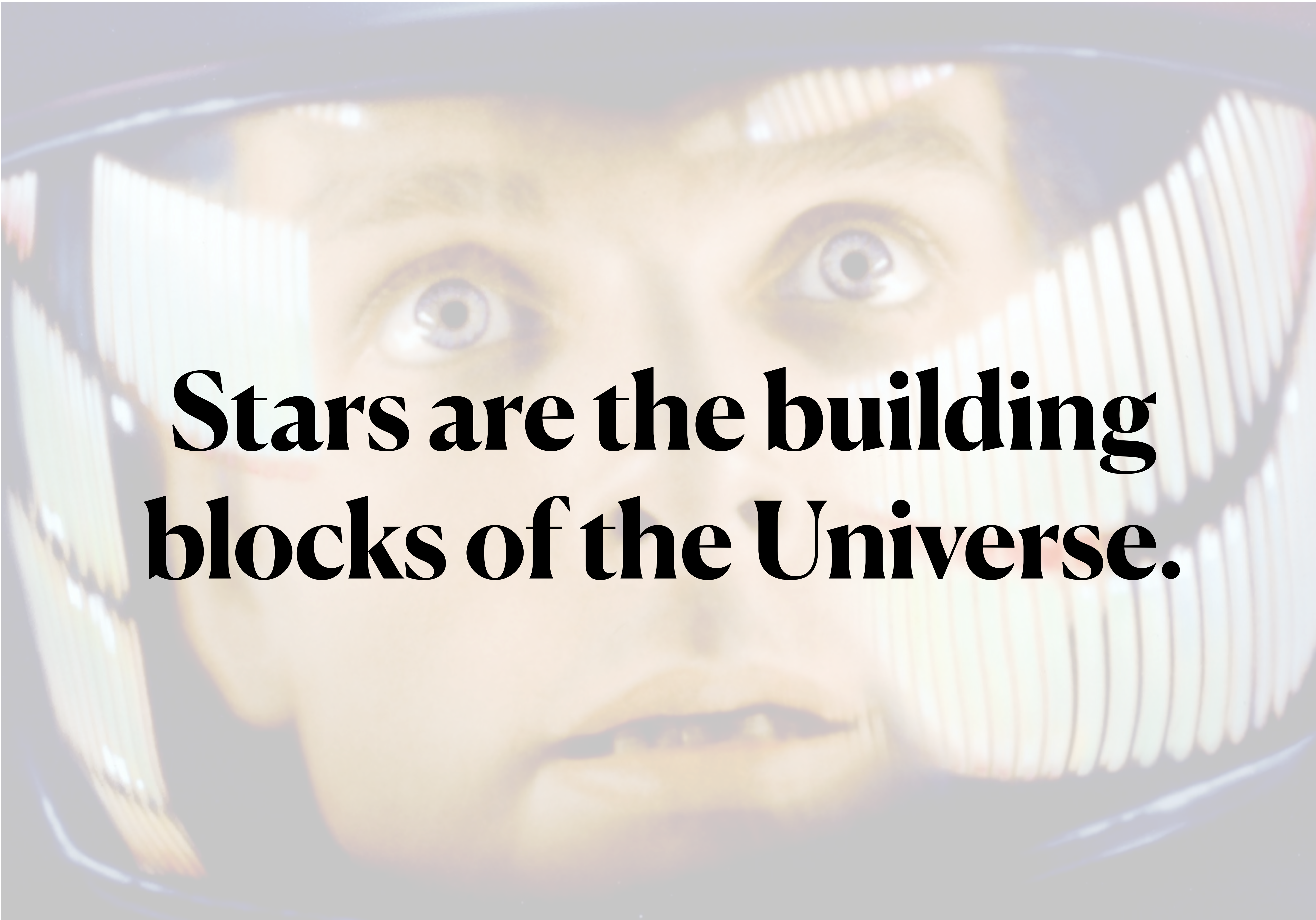
Bolyai College Seminar - 2024.02.28.

KONKOLY

SeismoLab



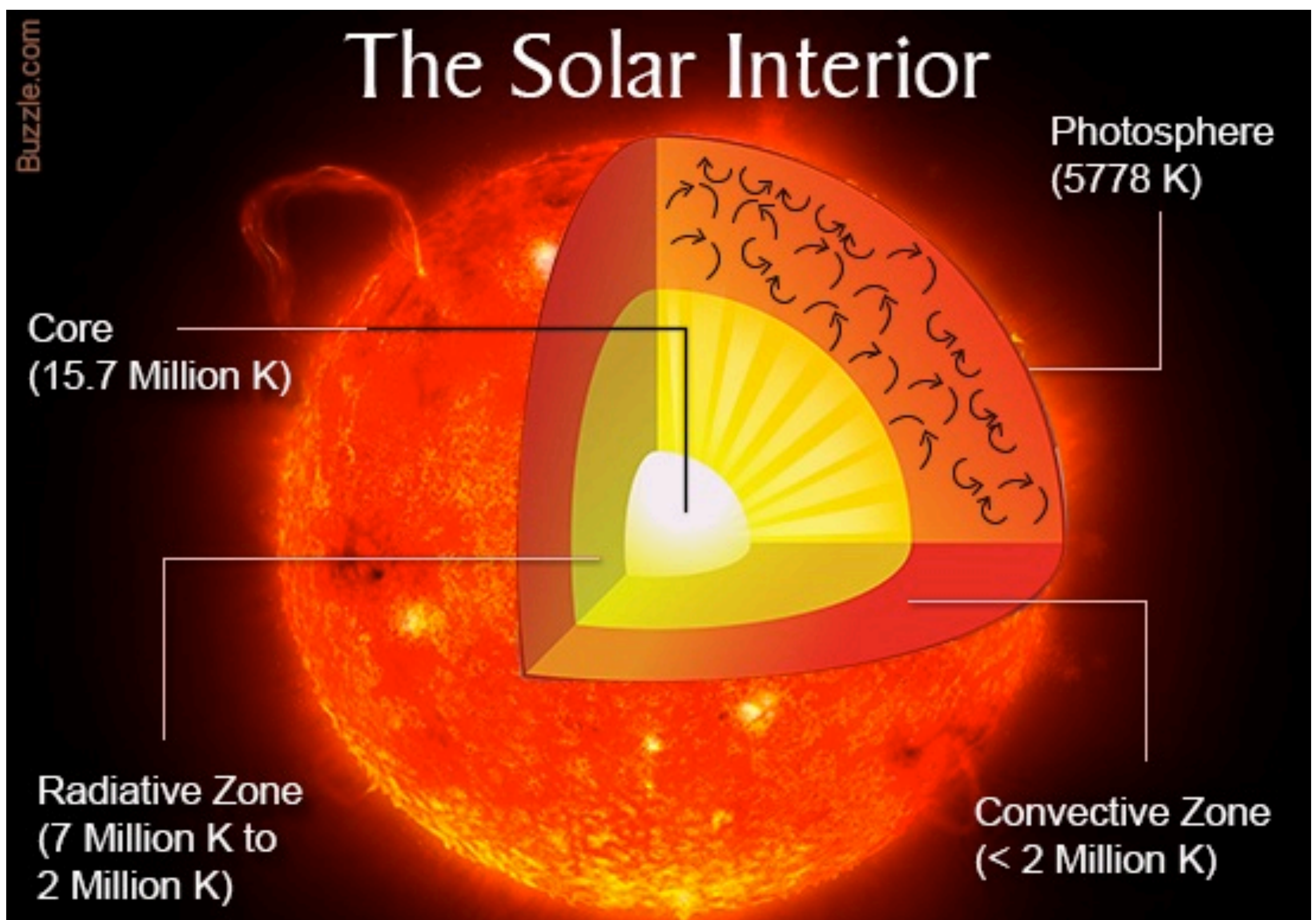
Stars are the building blocks of the Universe.

Stars 101

- Born out of the collapse of massive molecular clouds

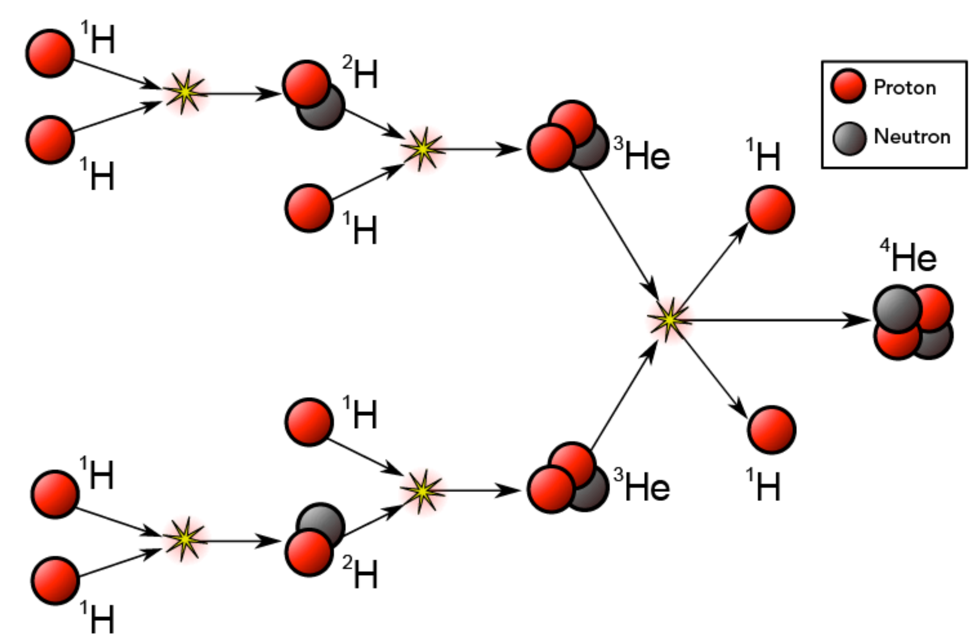
Stars 101

- Born out of the collapse of massive molecular clouds
- Sustained by nuclear fusion in the core: balance between gravity and radiation



Stars 101

- Born out of the collapse of massive molecular clouds
- Sustained by nuclear fusion in the core: balance between gravity and radiation
- Their lives are entirely predetermined by two factors*
  - their initial, or birth mass
  - nuclear physics



*The first rule of binary star evolution is that we don't talk about binary star evolution

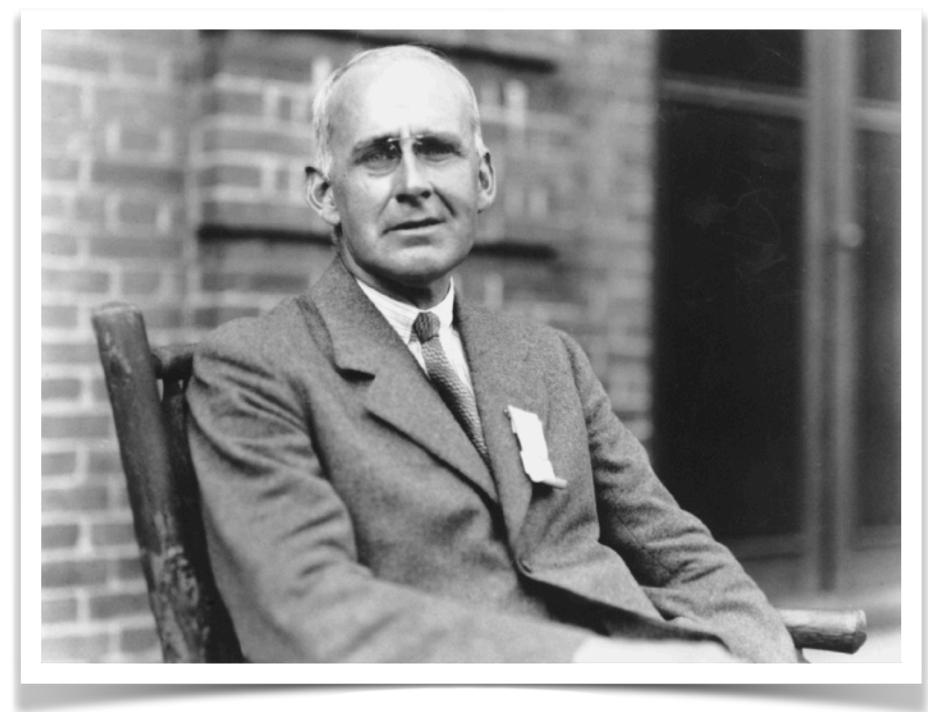
The problem

- What stars are out there? What state follows what? How long do they live? What happens in the inside?
- All* stages of stellar evolution are too slow to observe on human timescales

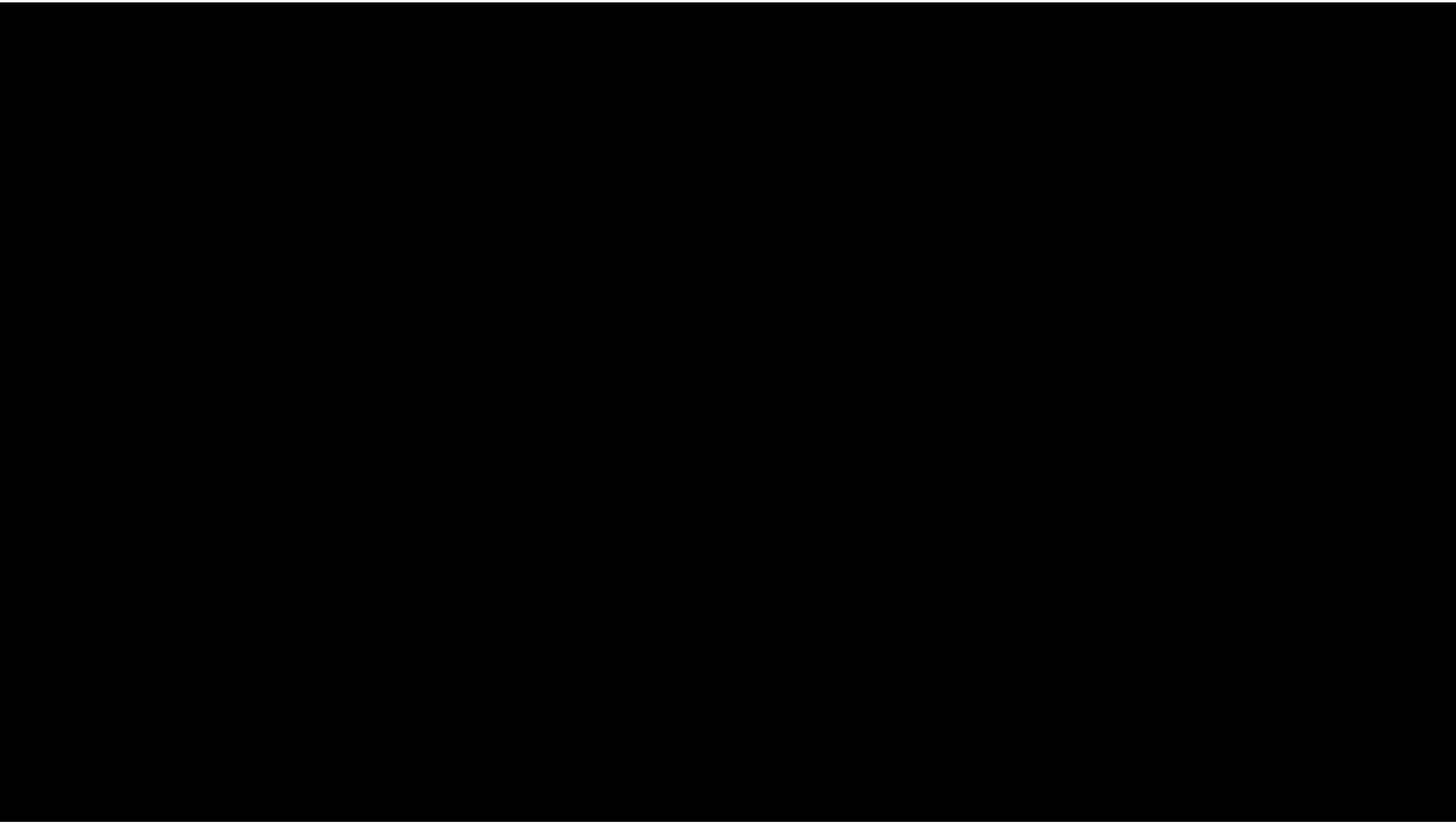
*Not all, guess and/or ask me in the end

The two problems

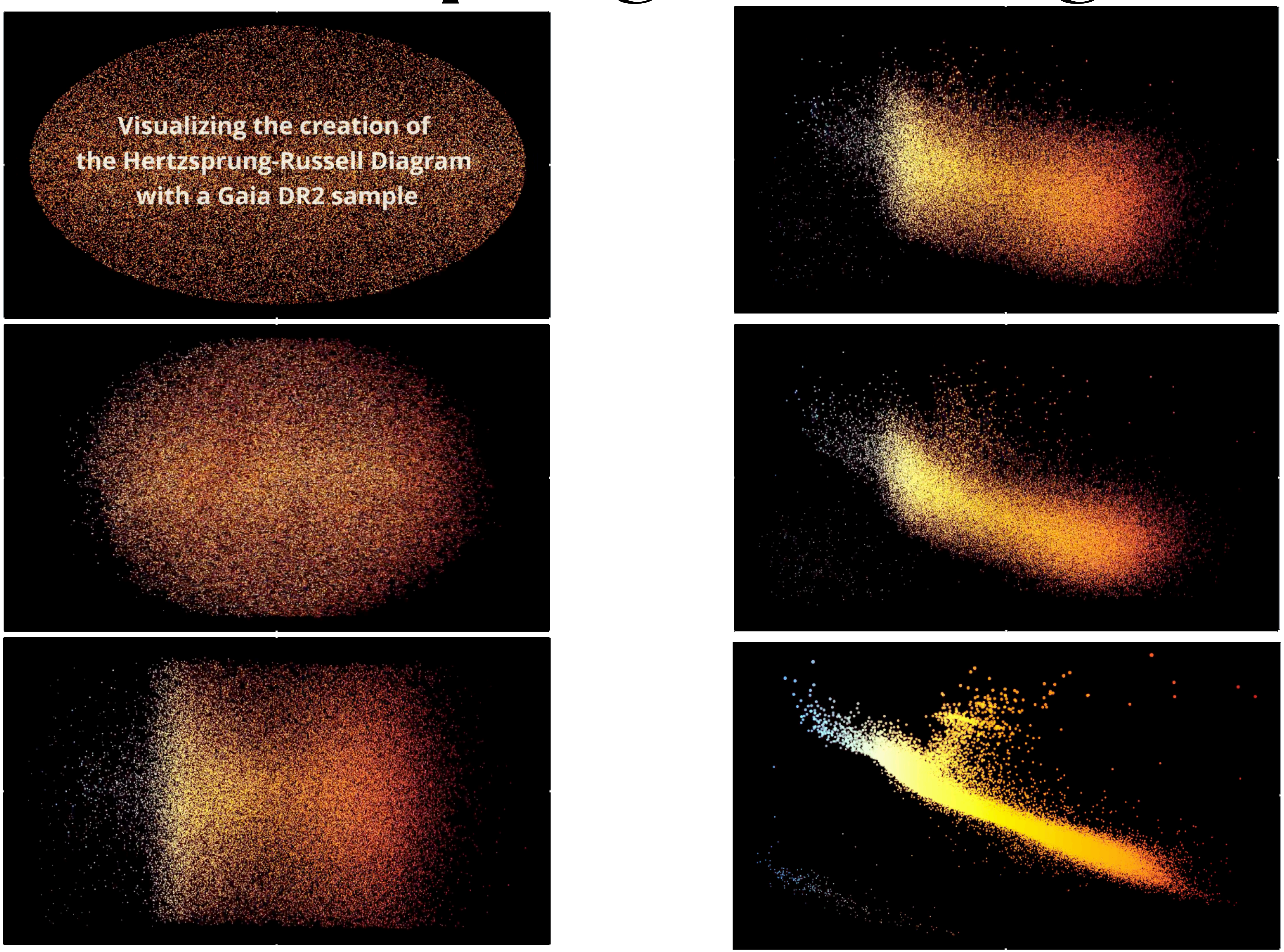
- What stars are out there? What state follows what? How long do they live? What happens in the inside?
- All* stages of stellar evolution are too slow to observe on human timescales
- *"At first sight it would seem that the deep interior of the sun and stars is less accessible to scientific investigation that any other region of the universe. … What appliance can pierce through the outer layers of a star and test the conditions within?"*
  - Arthur Eddington, 1926



The Hertzsprung-Russell diagram



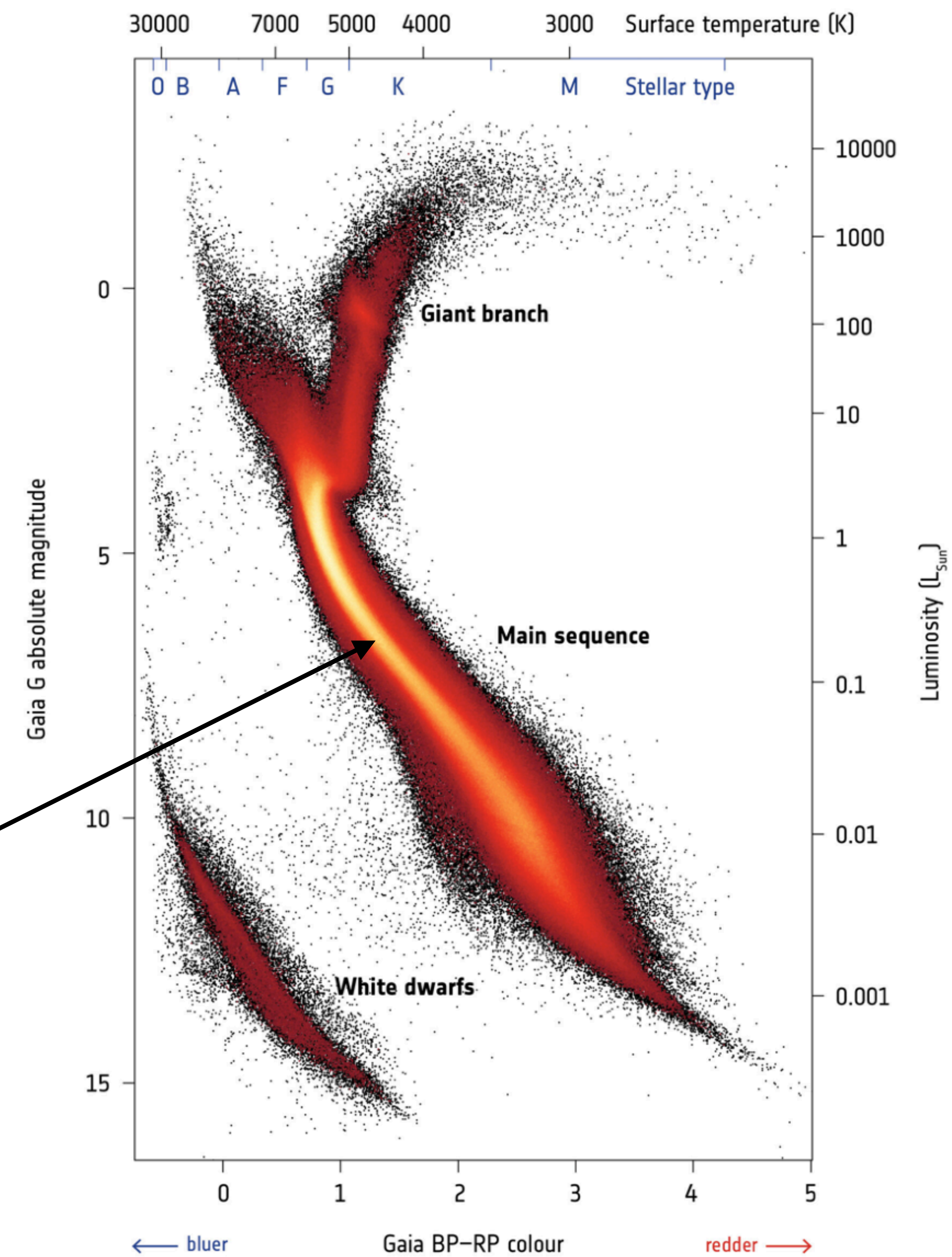
The Hertzsprung-Russell diagram



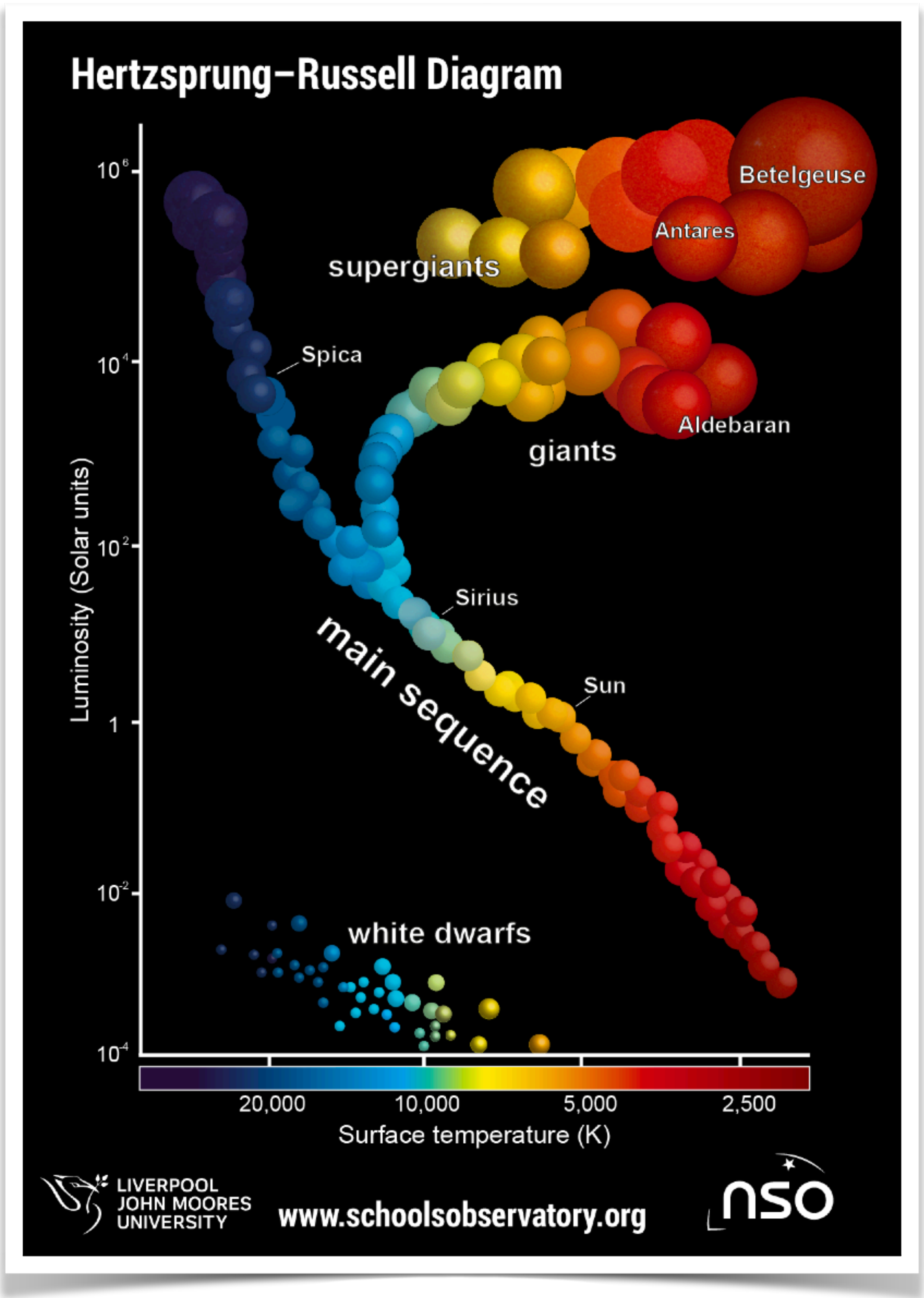
The Hertzsprung-Russell diagram

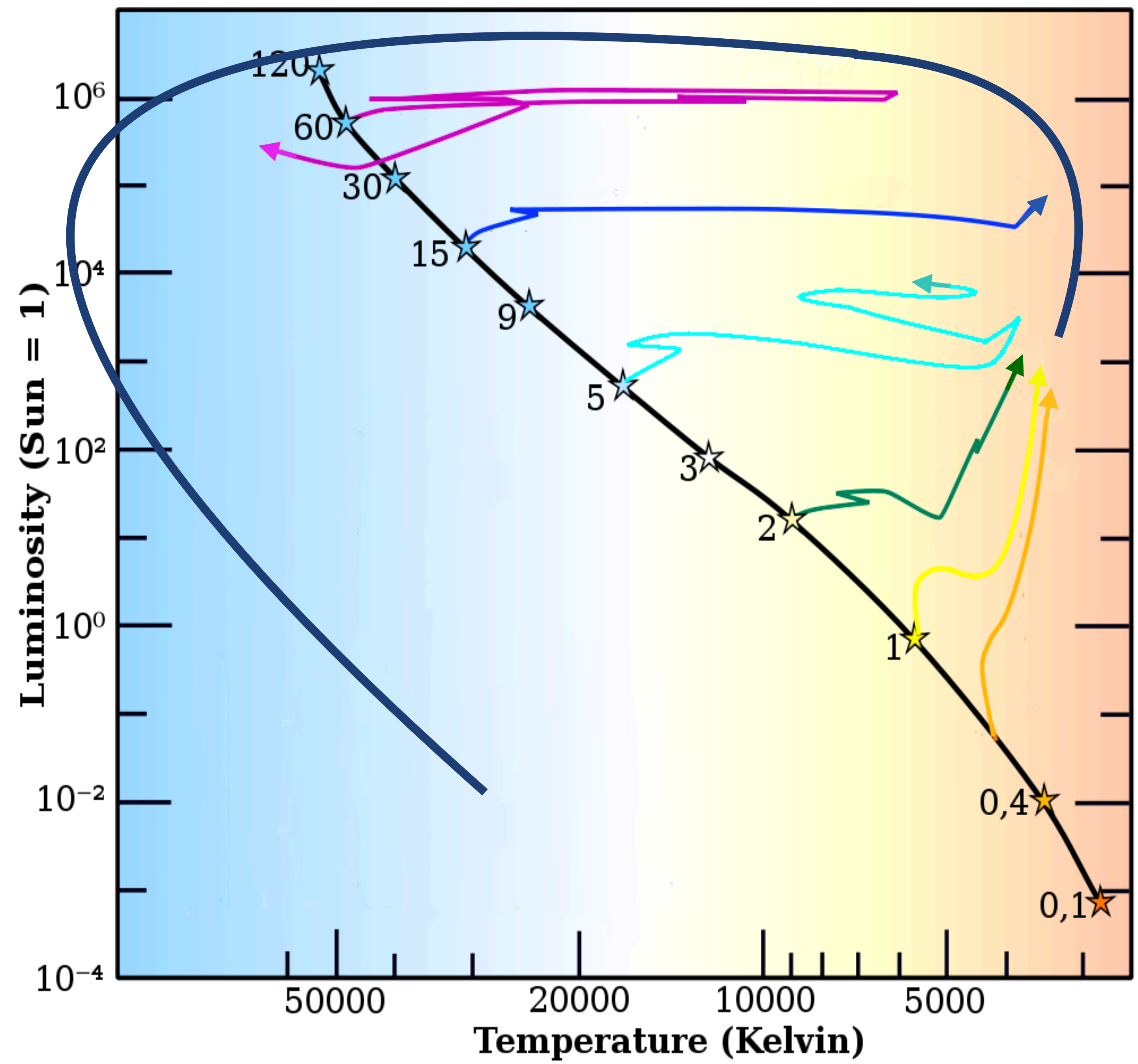
- Stars are not distributed homogeneously in the brightness-temperature plane
- Most of them are in the Main Sequence
- but they wander around as they grow old

Here be hydrogen-burning

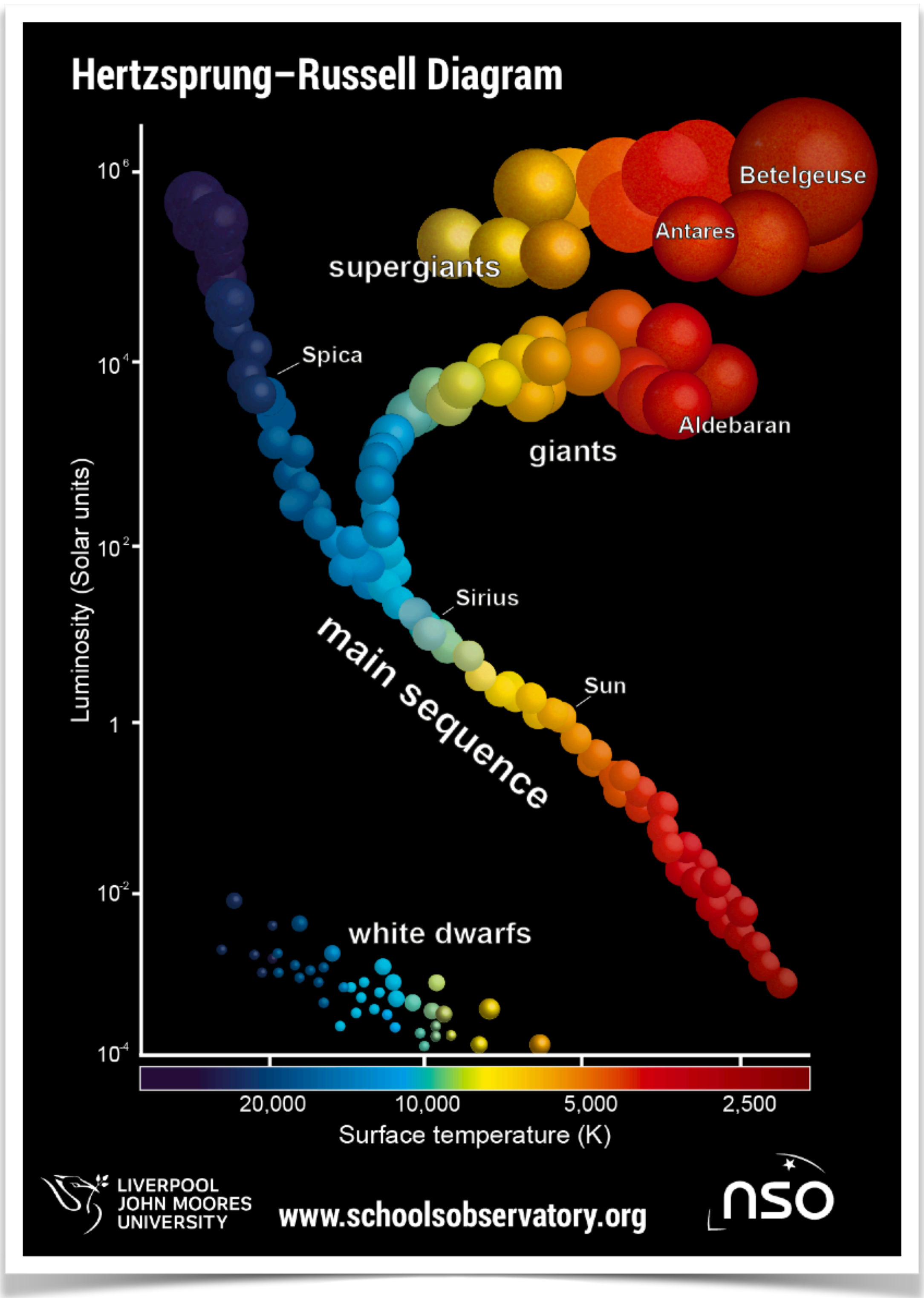


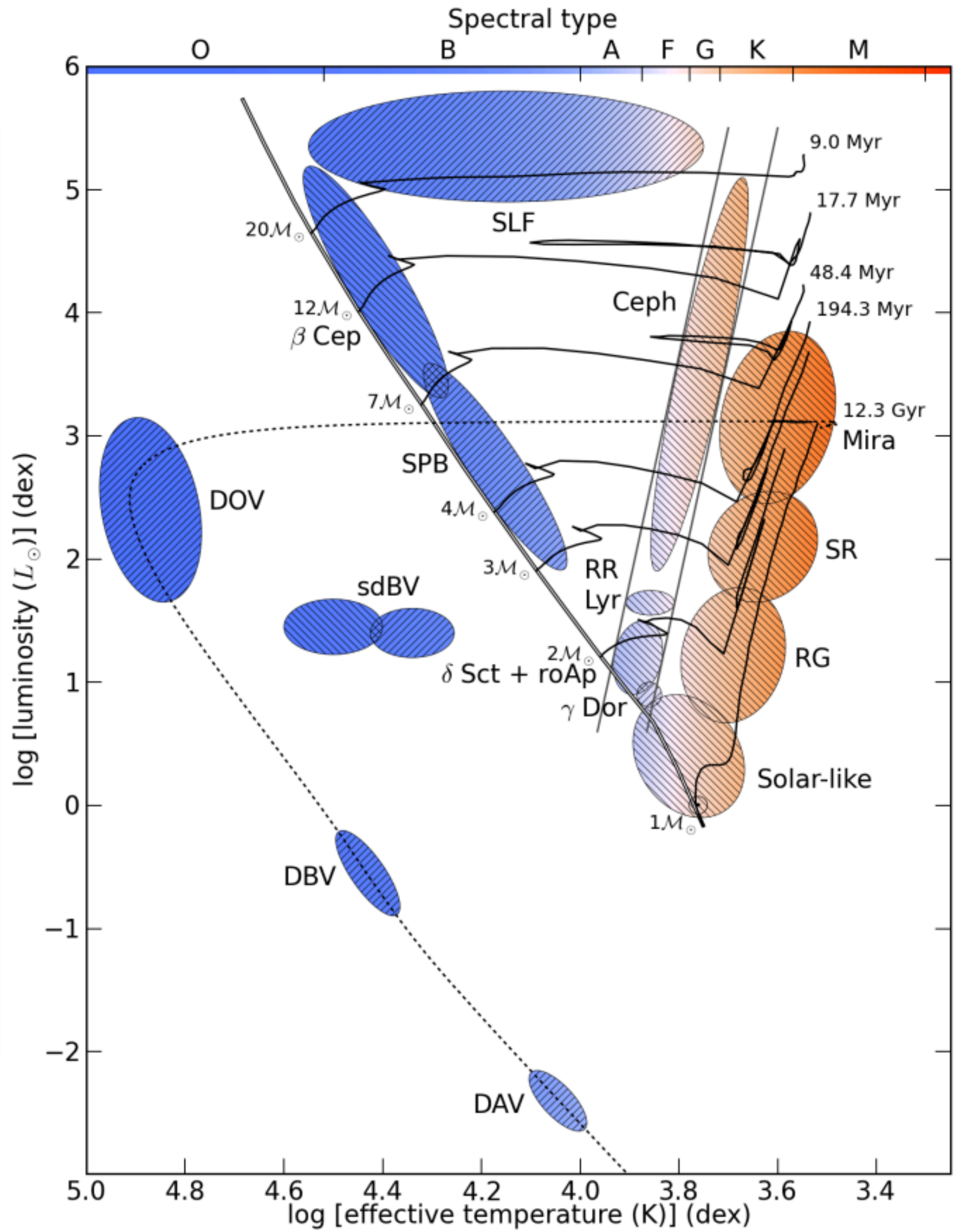
The Hertzsprung-Russell diagram

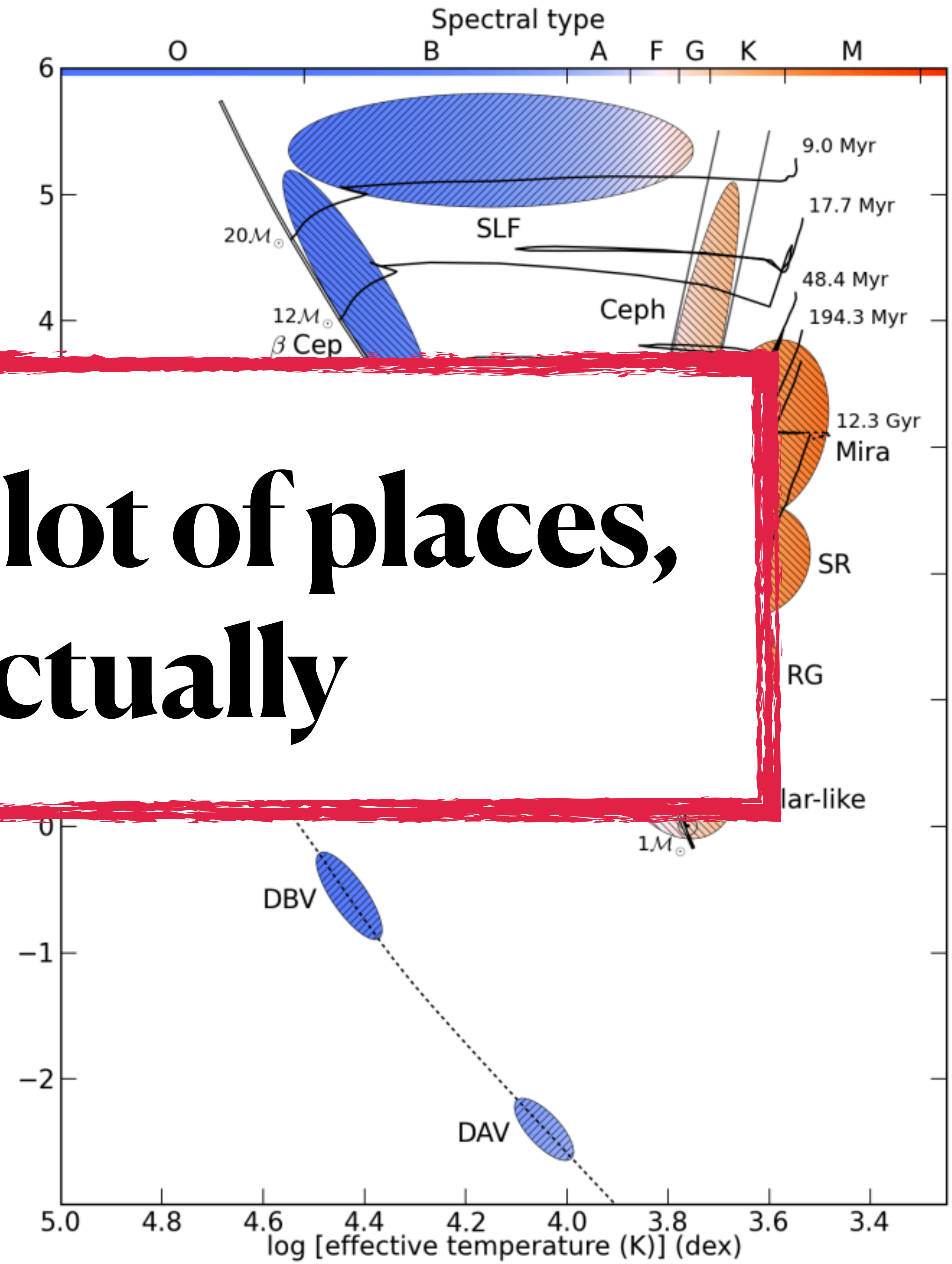




In some places stars are not in complete (hydrostatic) equilibrium

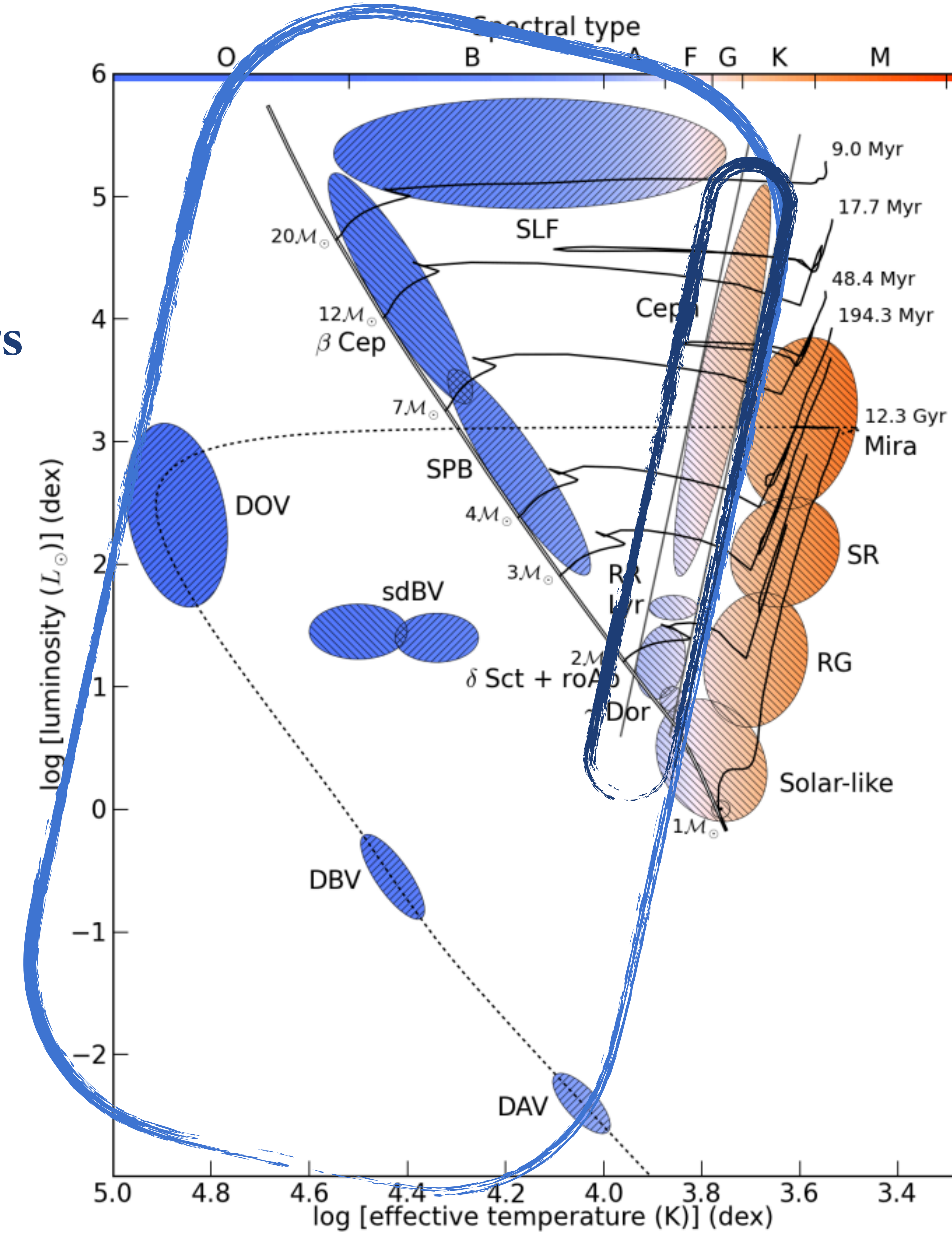

Hertzsprung–Russell Diagram
Betelgeuse
Antares
supergiants
Spica
Aldebaran
giants
Sirius
main sequence
Sun
white dwarfs
Luminosity (Solar units)
10^6
10^4
10^2
1
10^{-2}
10^{-4}
20,000
10,000
5,000
2,500
Surface temperature (K)
LIVERPOOL JOHN MOORES UNIVERSITY
www.schoolsobservatory.org
nso


Spectral type
O
B
A
F
G
K
M
9.0 Myr
17.7 Myr
48.4 Myr
194.3 Myr
12.3 Gyr
SLF
Ceph
Mira
SR
RG
Solar-like
$20\mathcal{M}_\odot$
$12\mathcal{M}_\odot$
β Cep
$7\mathcal{M}_\odot$
SPB
$4\mathcal{M}_\odot$
$3\mathcal{M}_\odot$
RR Lyr
$2\mathcal{M}_\odot$
δ Sct + roAp
γ Dor
$1\mathcal{M}_\odot$
DOV
sdBV
DBV
DAV
log [luminosity ($L_\odot$)] (dex)
log [effective temperature (K)] (dex)
6
5
4
3
2
1
0
−1
−2
5.0
4.8
4.6
4.4
4.2
4.0
3.8
3.6
3.4

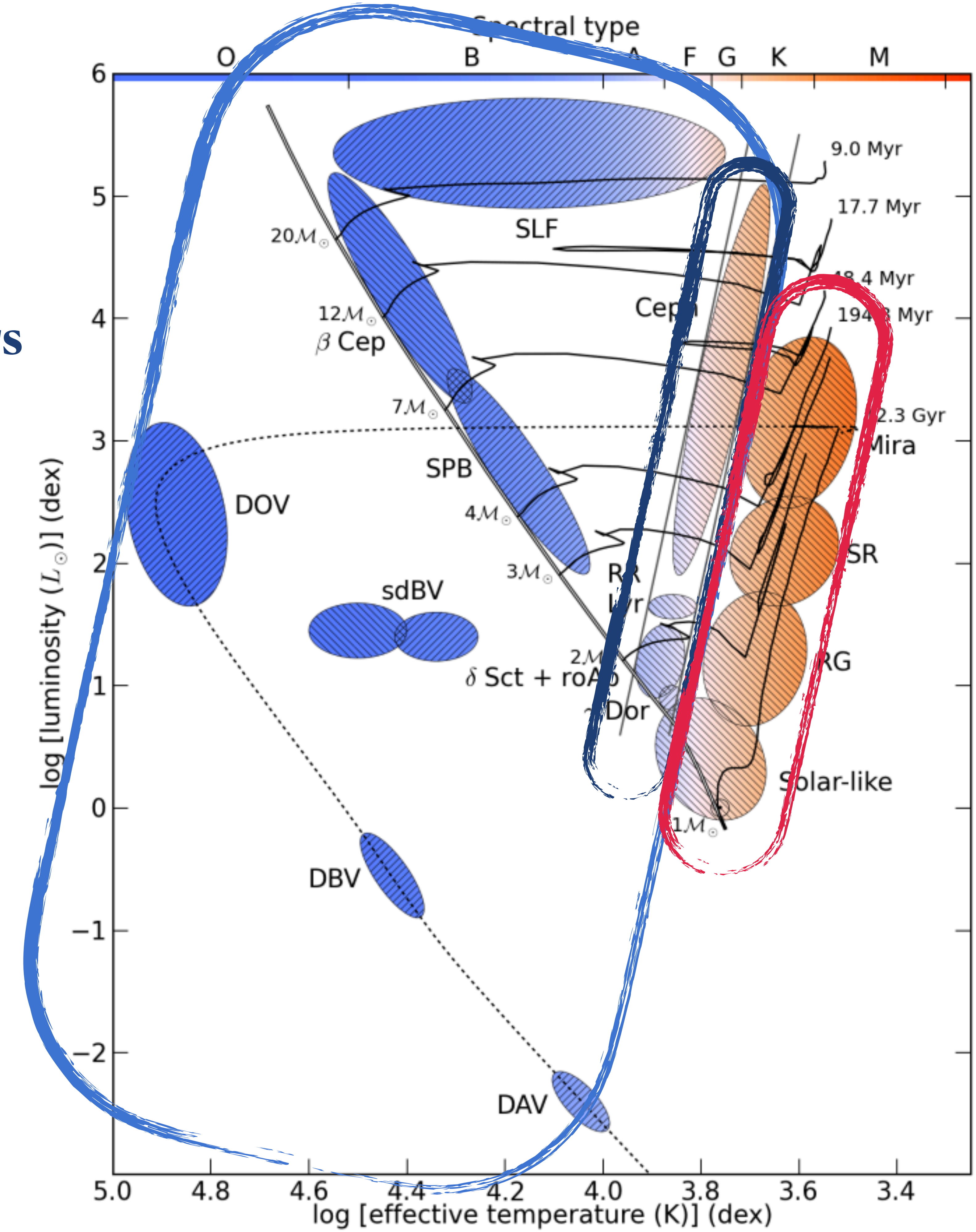


Quite a lot of places, actually

pulsating stars



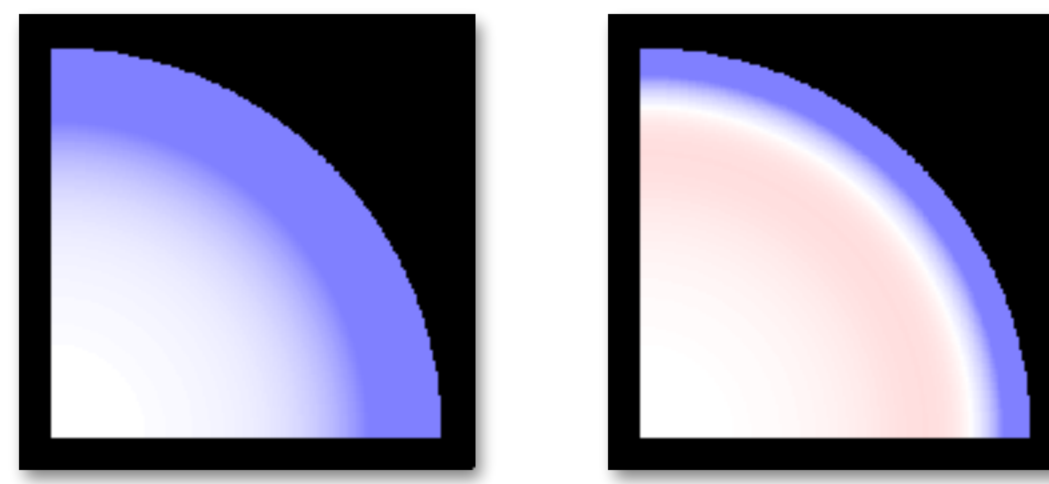
pulsating stars



solar-like oscillations

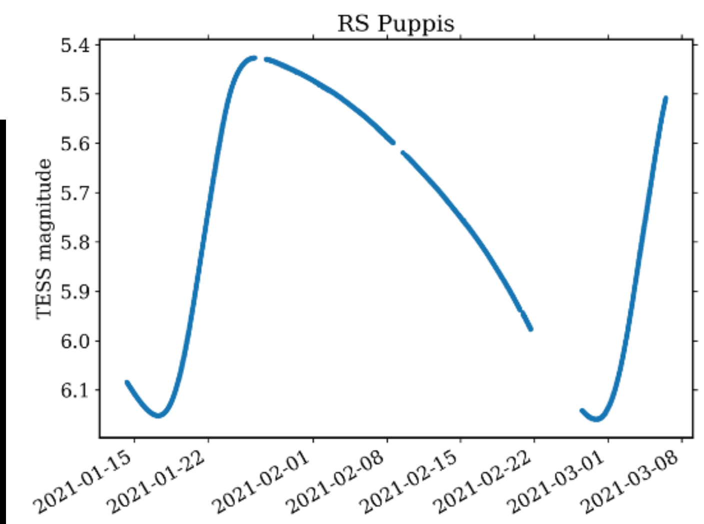
Pulsating stars

- One or more global, self-sustaining, coherent oscillations
- Either sound waves (ringing) or gravity waves (rippling)
- Periodic changes in the:
  - brightness
  - surface temperature
  - surface velocity
  - radius



- Period proportional to the average density —> physics!

The light echoes of RS Puppis



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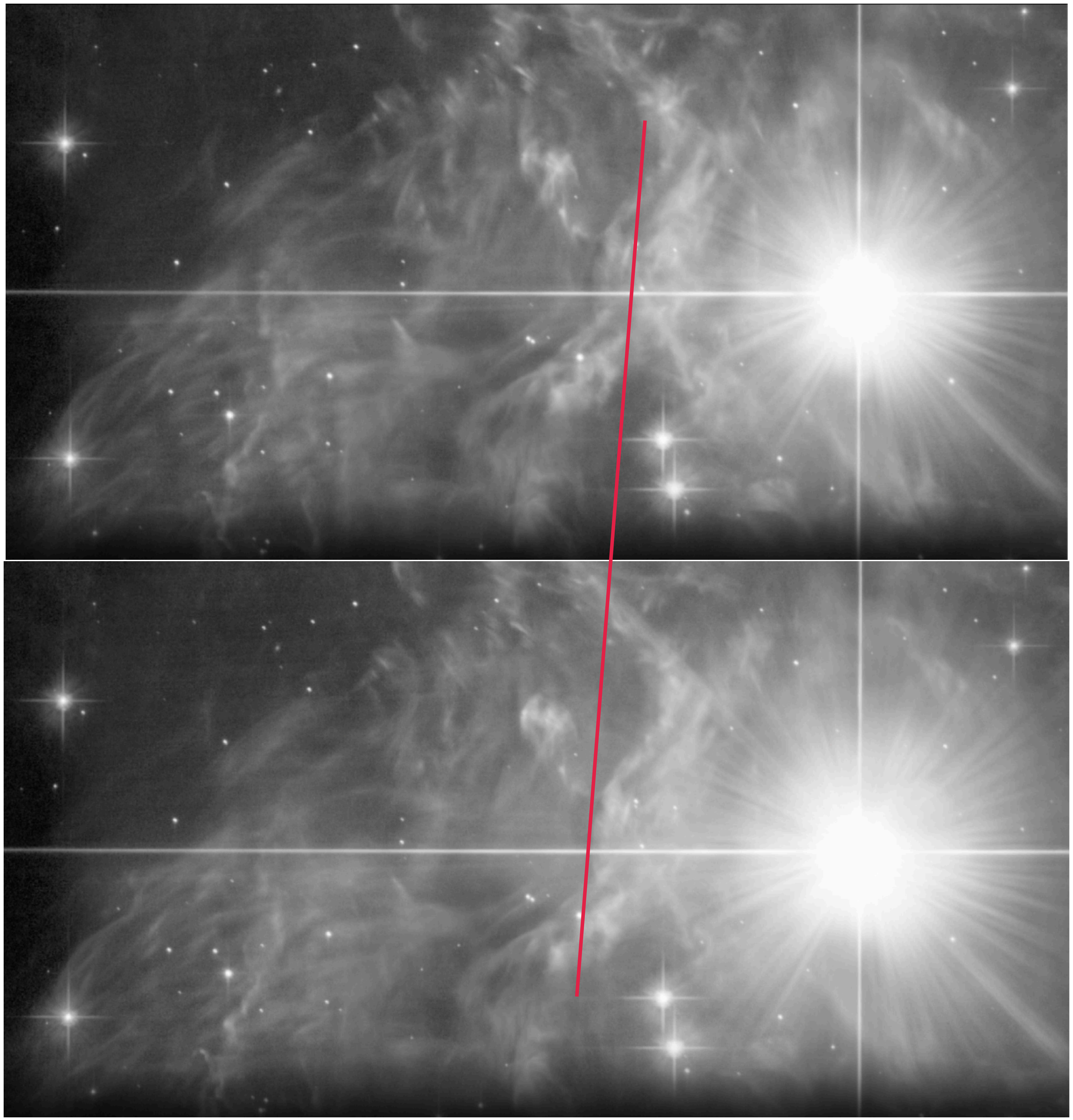
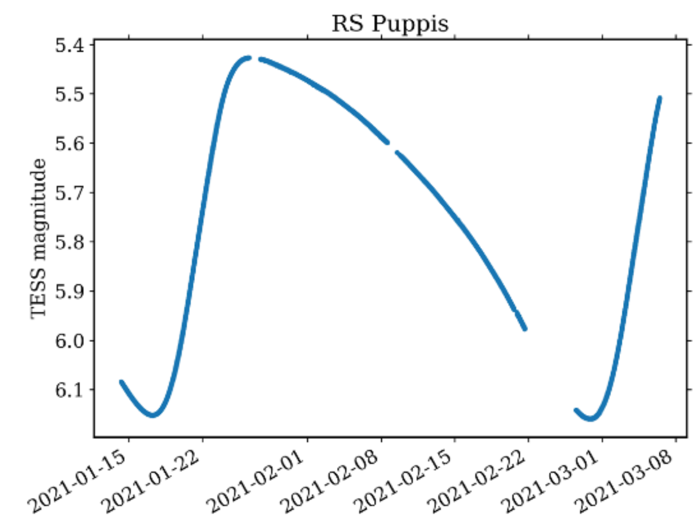
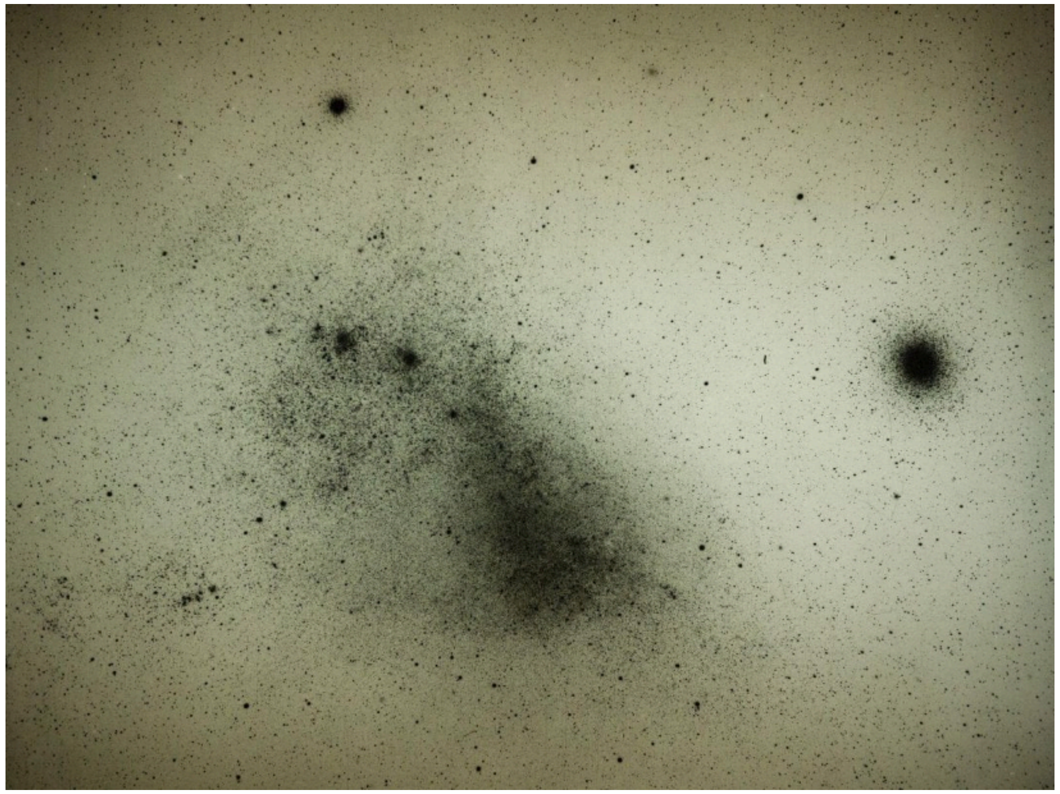
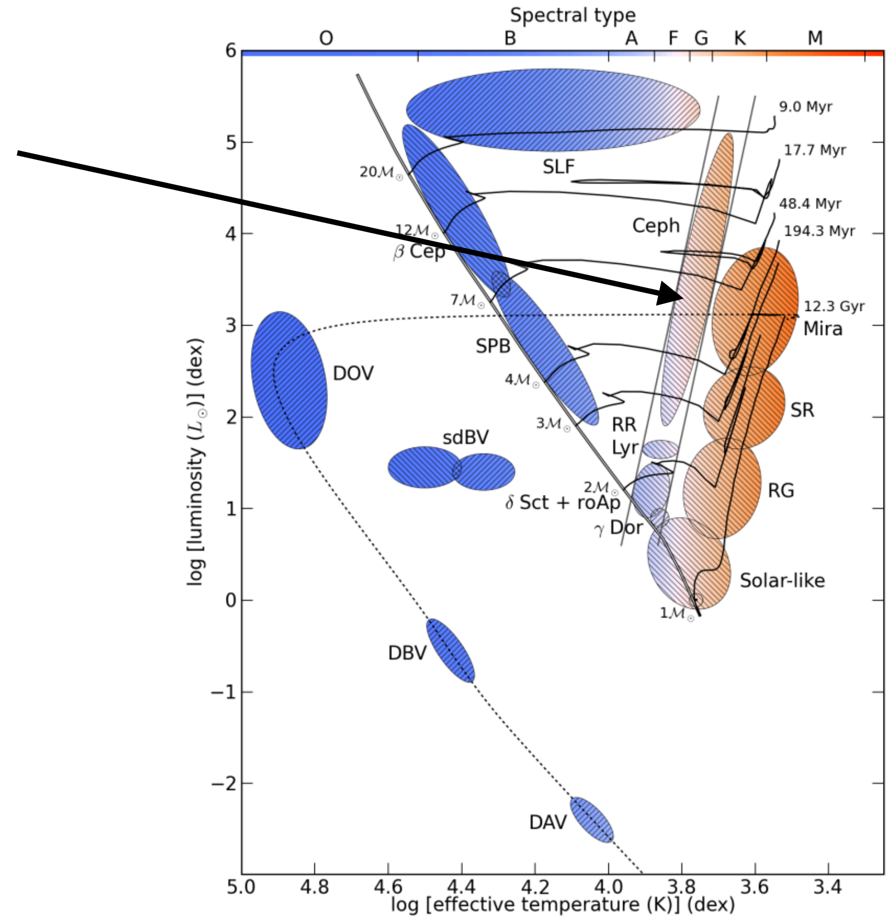




A crucial discovery

- Henrietta Swan Leavitt, 1912:
- Cepheid stars in the Magellanic Clouds: ~same distance
  - stars with longer periods are also brighter





A crucial discovery

- Henrietta Swan Leavitt, 1912:
- Cepheid stars in the Magellanic Clouds: ~same distance
    - stars with longer periods are also brighter
- **Period-luminosity relation, a.k.a., Leavitt's law:**
    - if we know how bright Cepheids should be at a given period, we can measure their distances

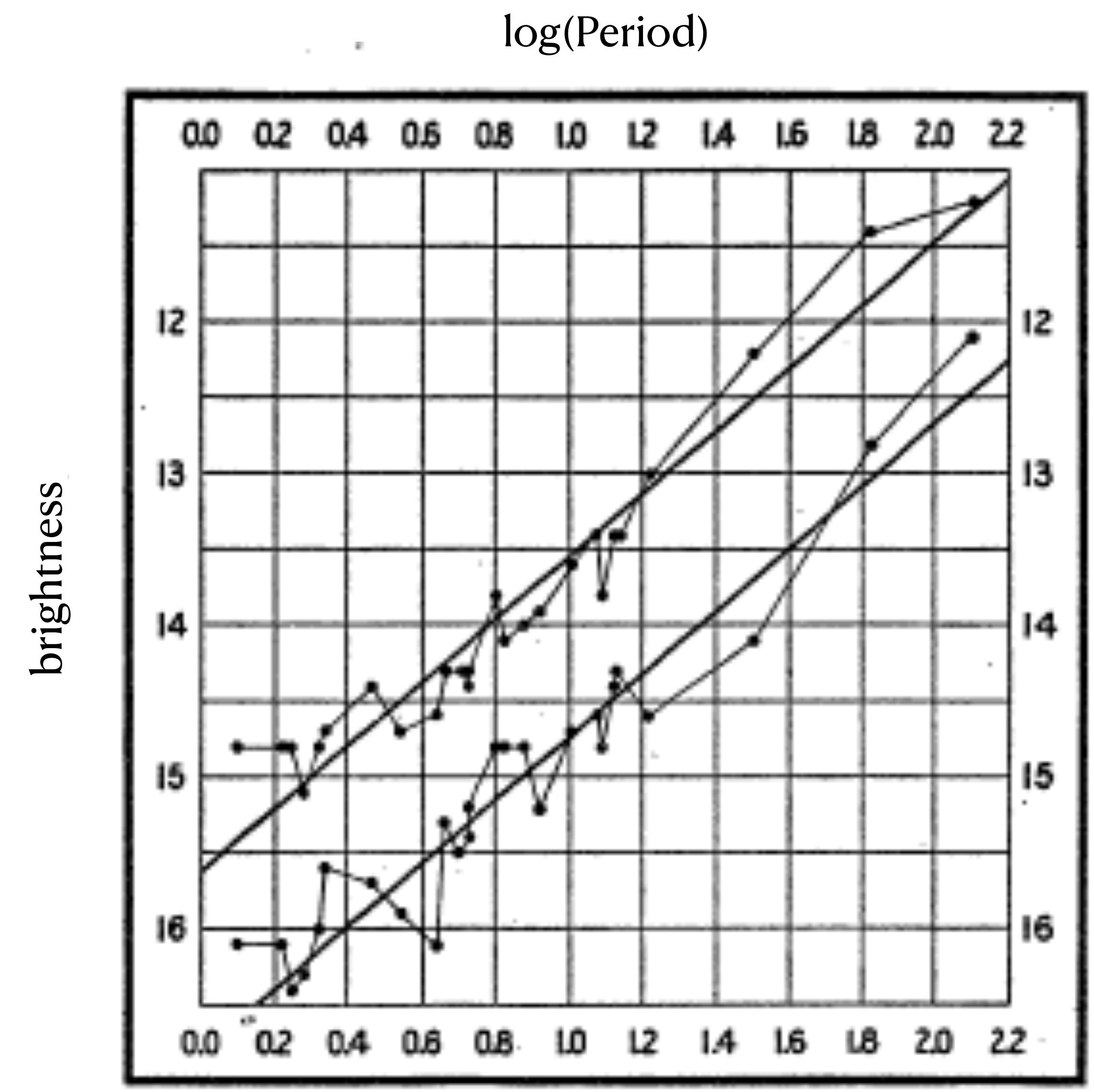


FIG. 2.

A crucial discovery

- Standard candles: we can measure the Universe

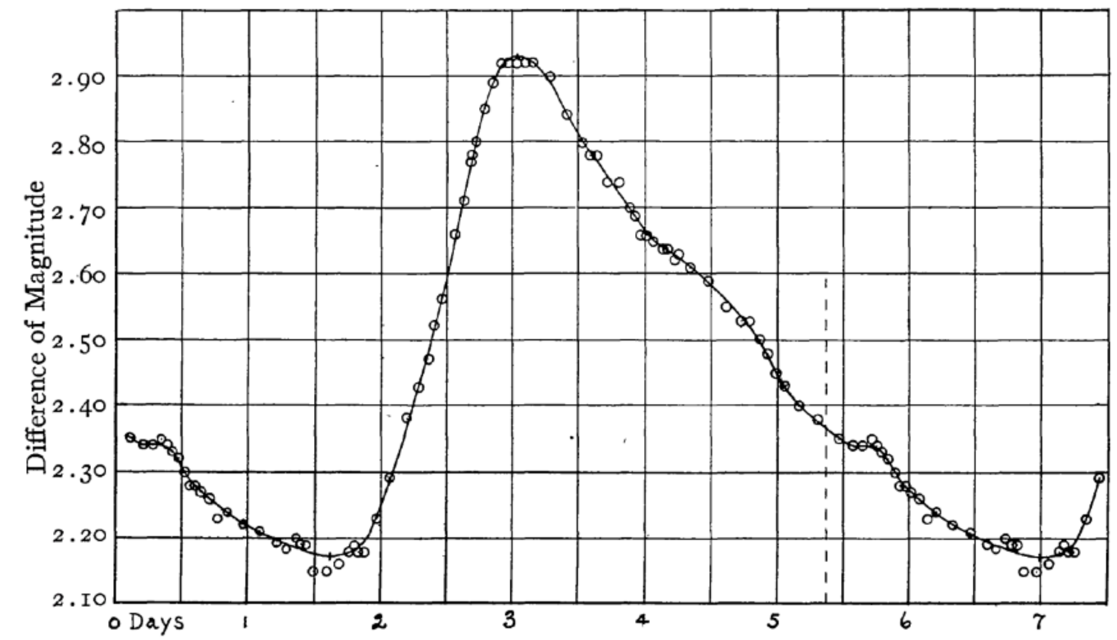


FIG. 1.—Light-Curve of δ *Cephei*.

1908

A crucial discovery

- Standard candles: we can measure the Universe

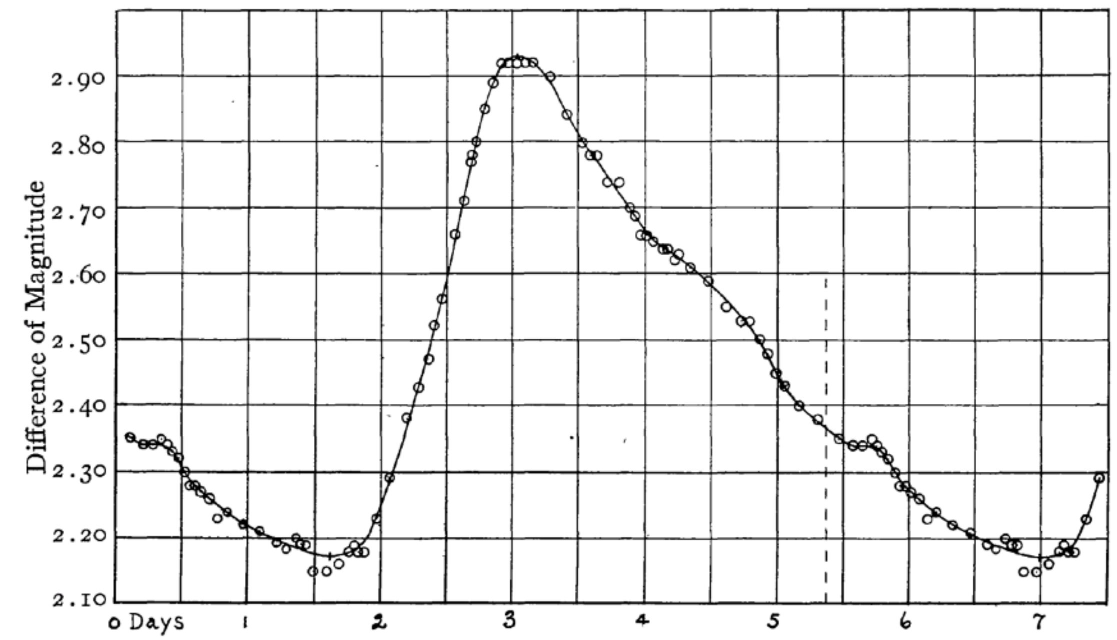
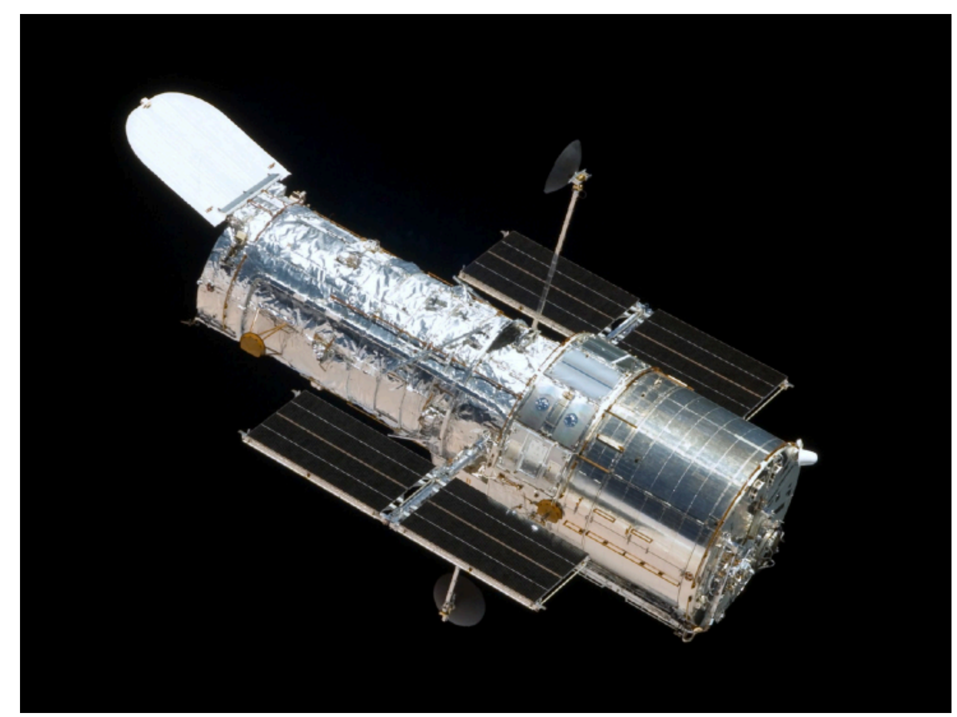


FIG. 1.—Light-Curve of δ *Cephei.*

1908

- Fast forward 70 years:
- One reason behind the Hubble Space Telescope was…
  to measure Cepheids



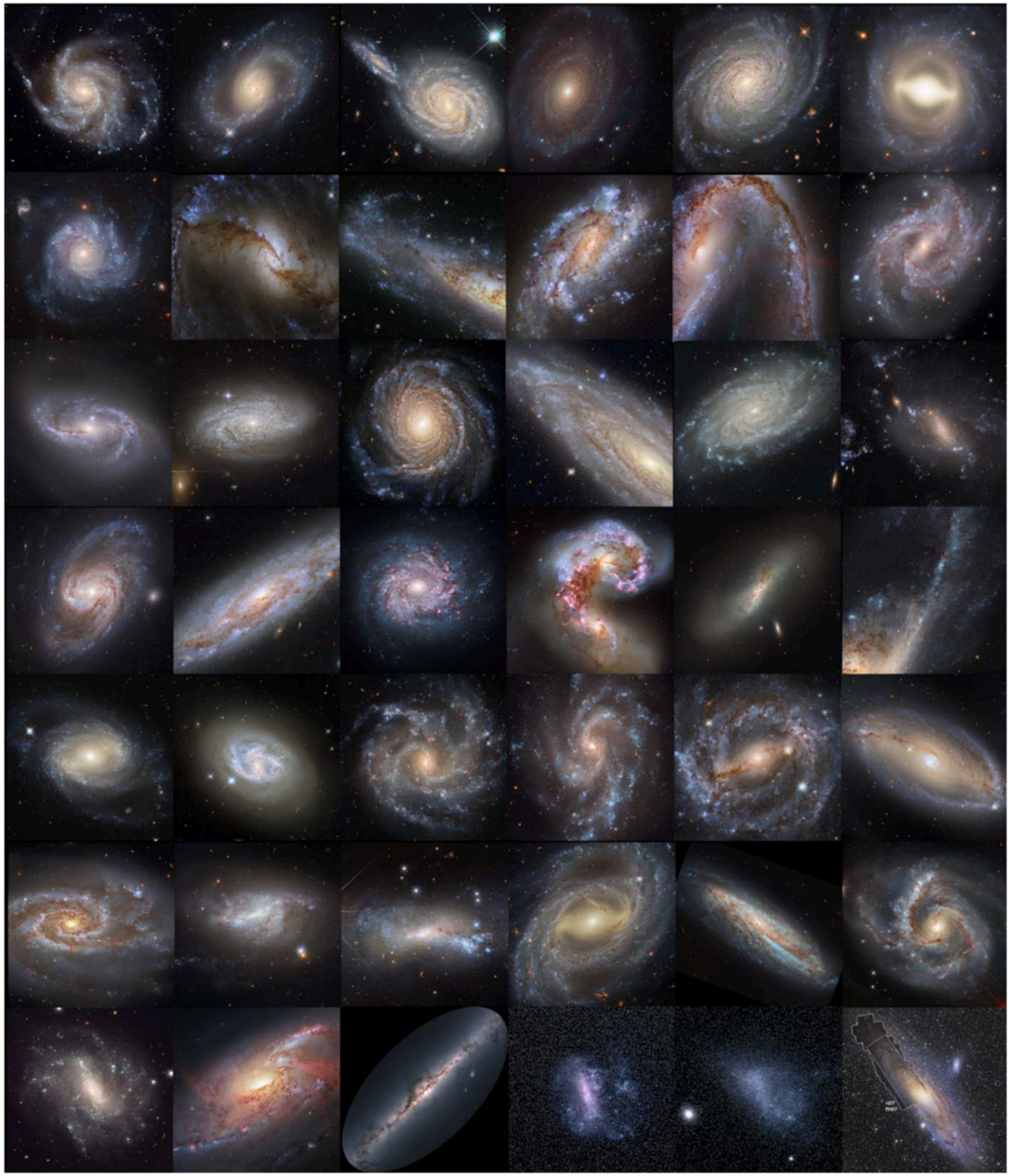
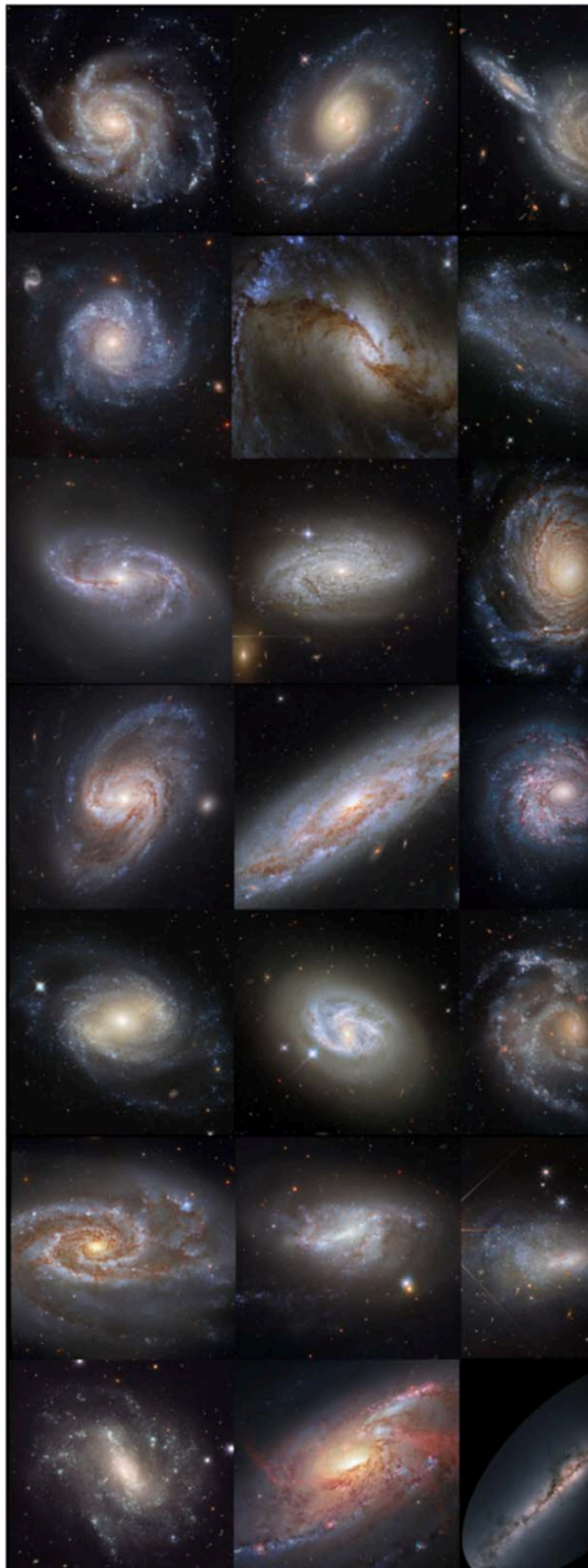


Figure 4. Pseudocolor images of all Cepheid-bearing galaxies analyzed in this work. From top left, 37 hosts of 42 SNe Ia presented in the same order as Table 1. The last row includes our three anchors (NGC 4258, MW, and LMC) and two supporting galaxies (SMC and M31). Galaxies are presented at arbitrary plate scales, though in most cases the panels encompass the entire ACS or WFC3/UVIS field of view. Credits: SN hosts and NGC 4258—ESA Hubble site; MW, LMC, and SMC—ESA Gaia site; M31—STScI.



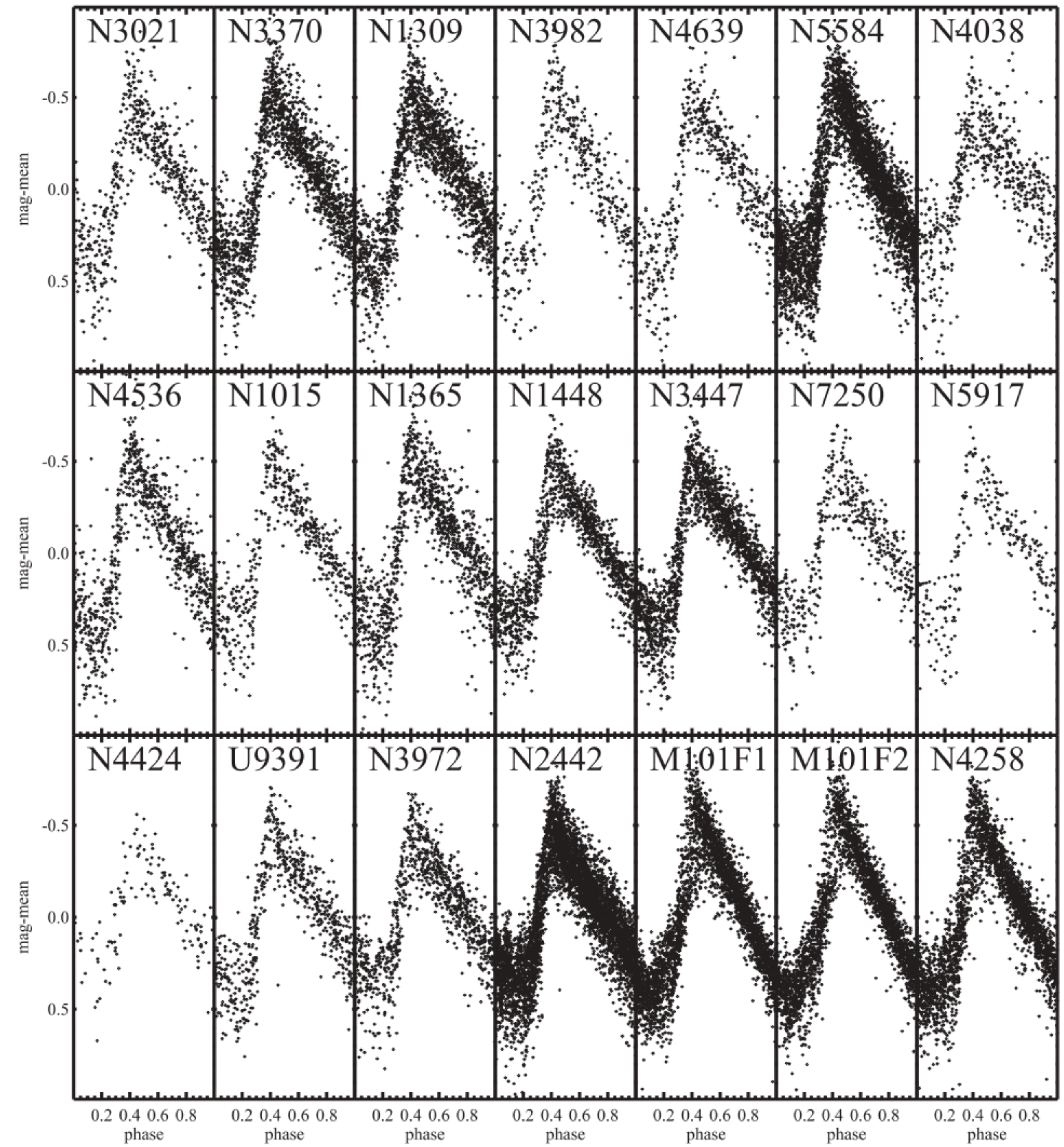
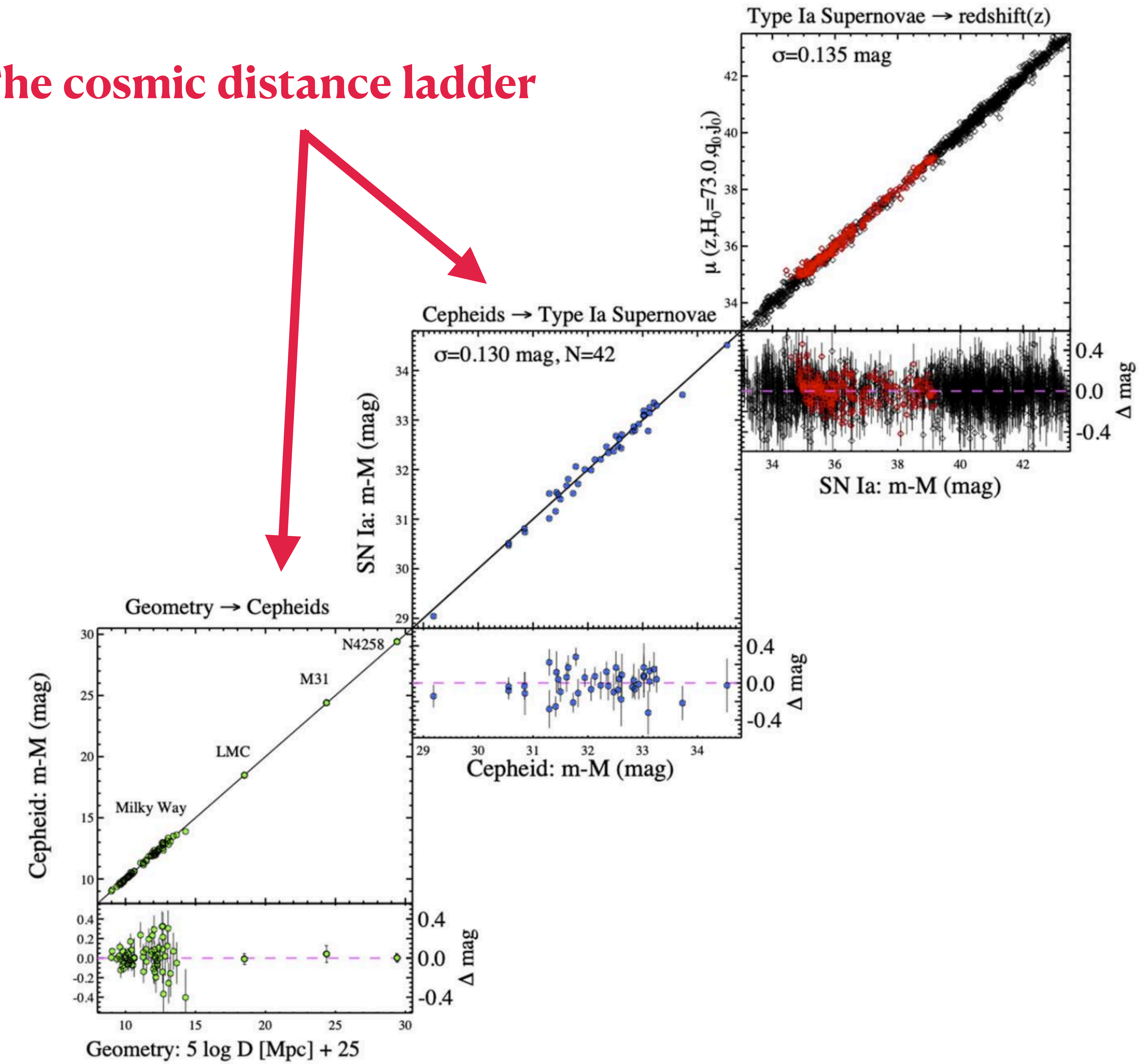
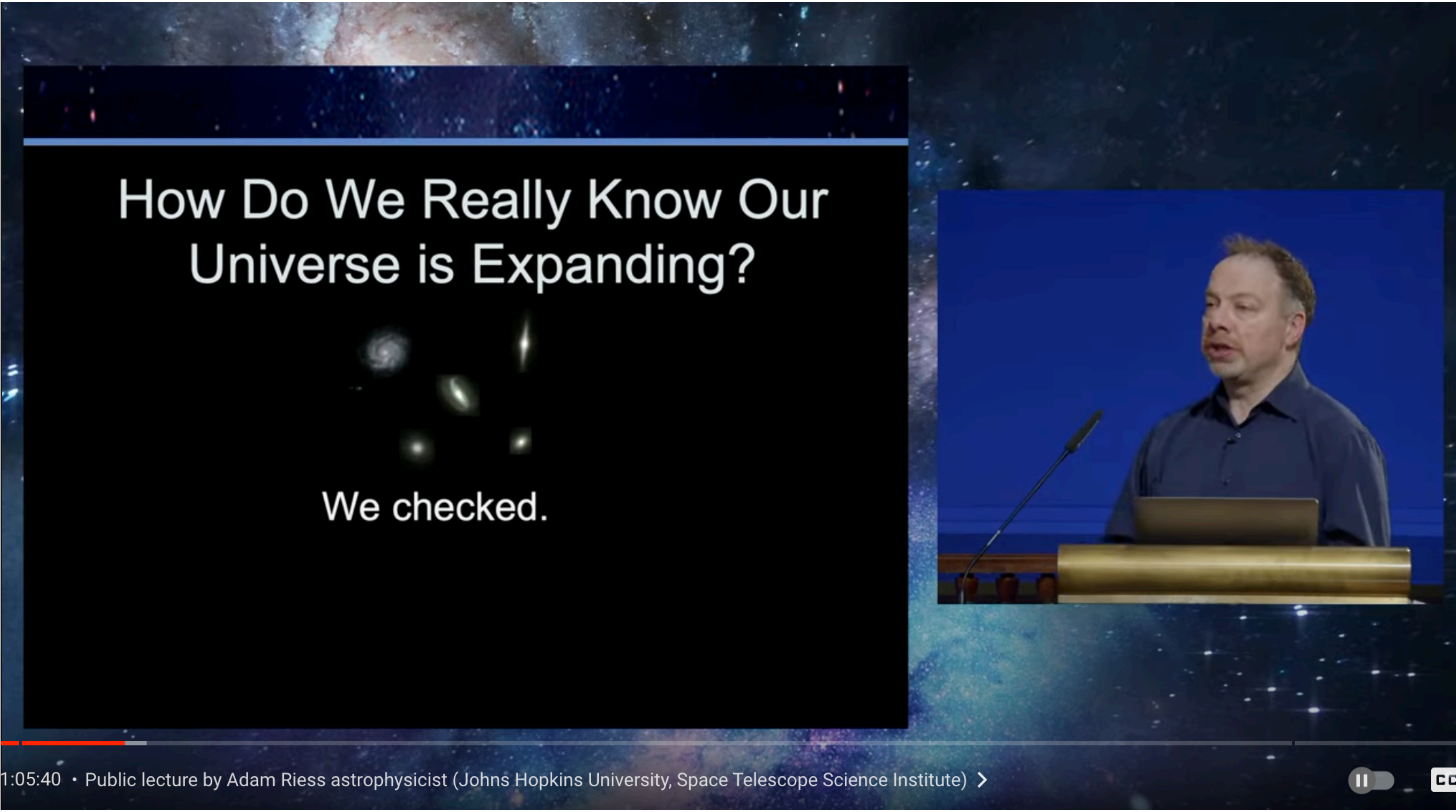


Figure 4. Composite visual (*F555W*) or white-light (*F350LP*) Cepheid light curves. Each *HST* Cepheid light curve with $10 < P < 80$ days is plotted after subtracting the mean magnitude and determining the phase of the observation. Two fields (F1 and F2) are shown for M101.

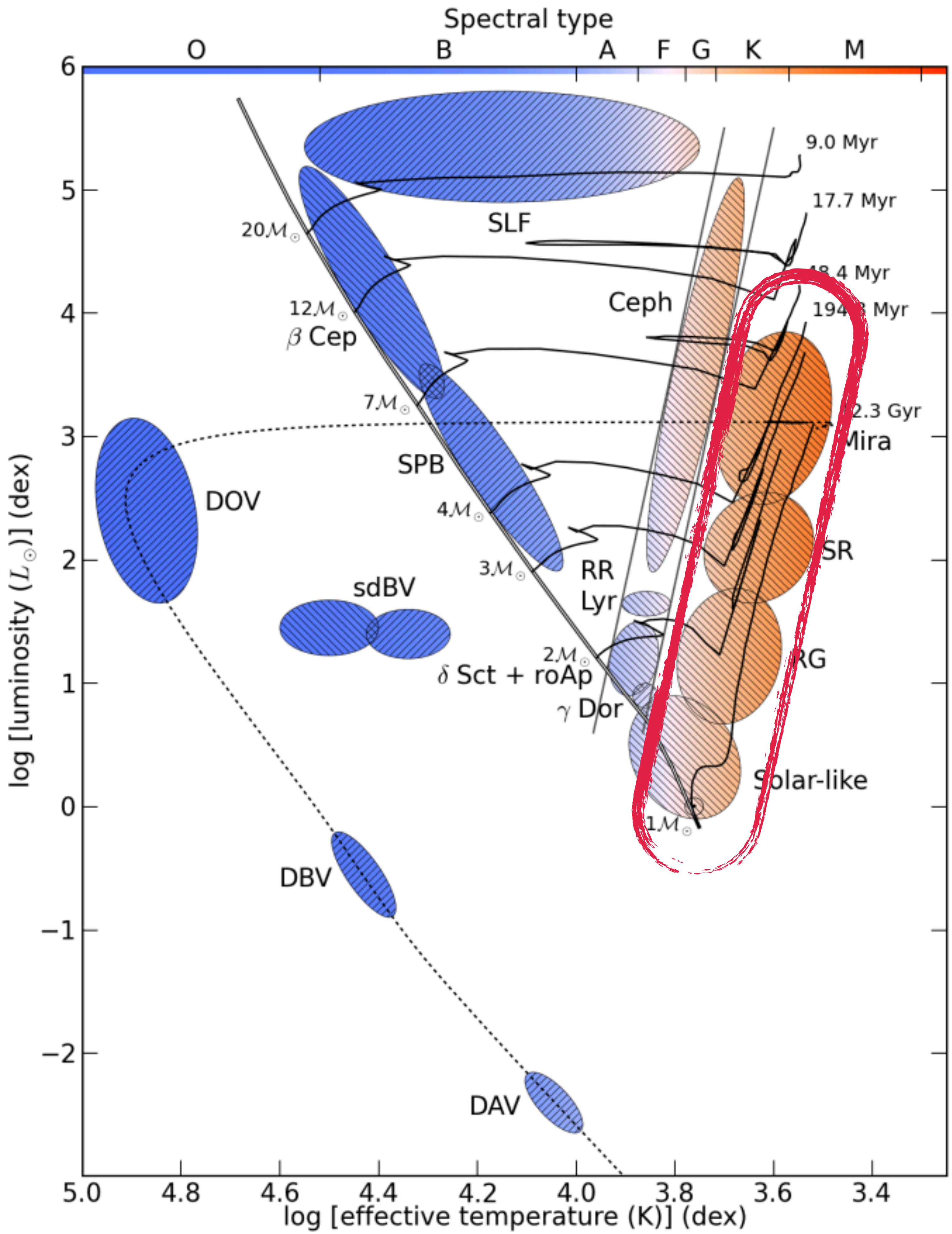
Figure 4. Pseudocolor images of all Cepheid-bearing galaxies analyzed in this work. From top left, 37 hosts of 42 SNe Ia presented in the same order as Table 1. The last row includes our three anchors (NGC 4258, MW, and LMC) and two supporting galaxies (SMC and M31). Galaxies are presented at arbitrary plate scales, though in most cases the panels encompass the entire ACS or WFC3/UVIS field of view. Credits: SN hosts and NGC 4258—ESA Hubble site; MW, LMC, and SMC—ESA Gaia site; M31—STScI.

The cosmic distance ladder




How Do We Really Know Our Universe is Expanding?
We checked.
1:05:40 • Public lecture by Adam Riess astrophysicist (Johns Hopkins University, Space Telescope Science Institute)

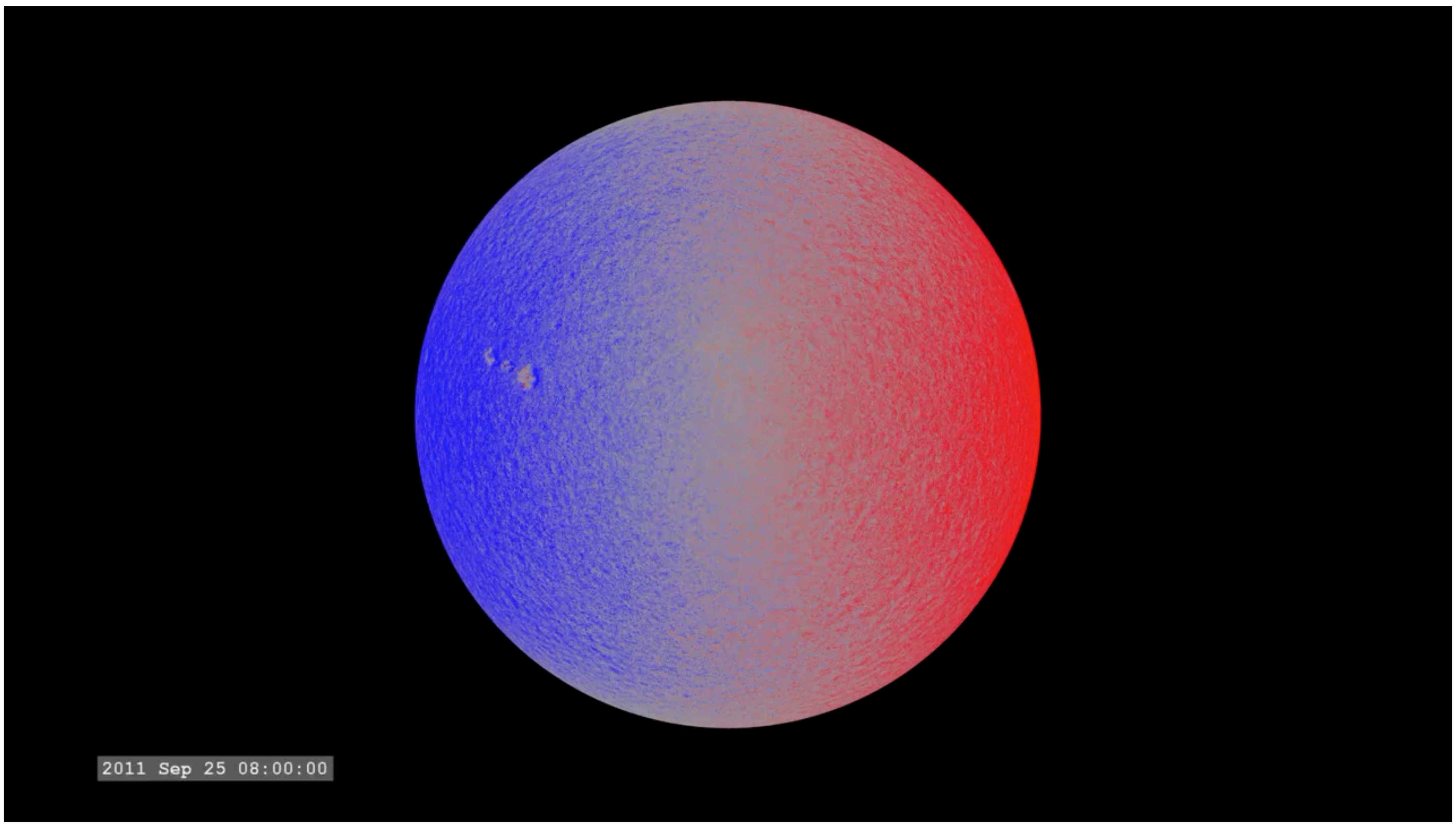
Good vibrations



solar-like oscillations

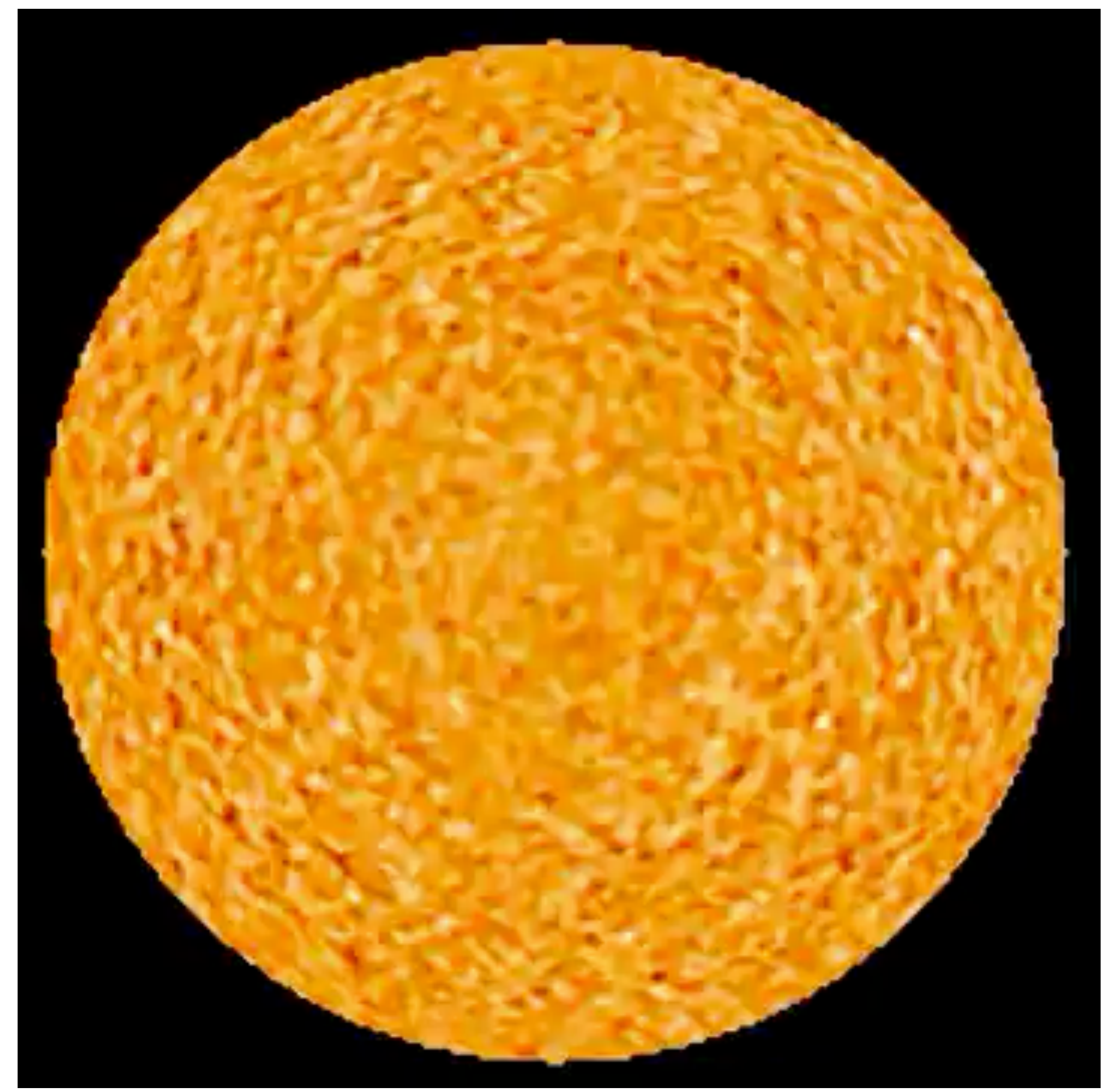
Helio- and asteroseismology

- The Sun doesn't seem to… do much



Helio- and asteroseismology

- Unless we look close enough

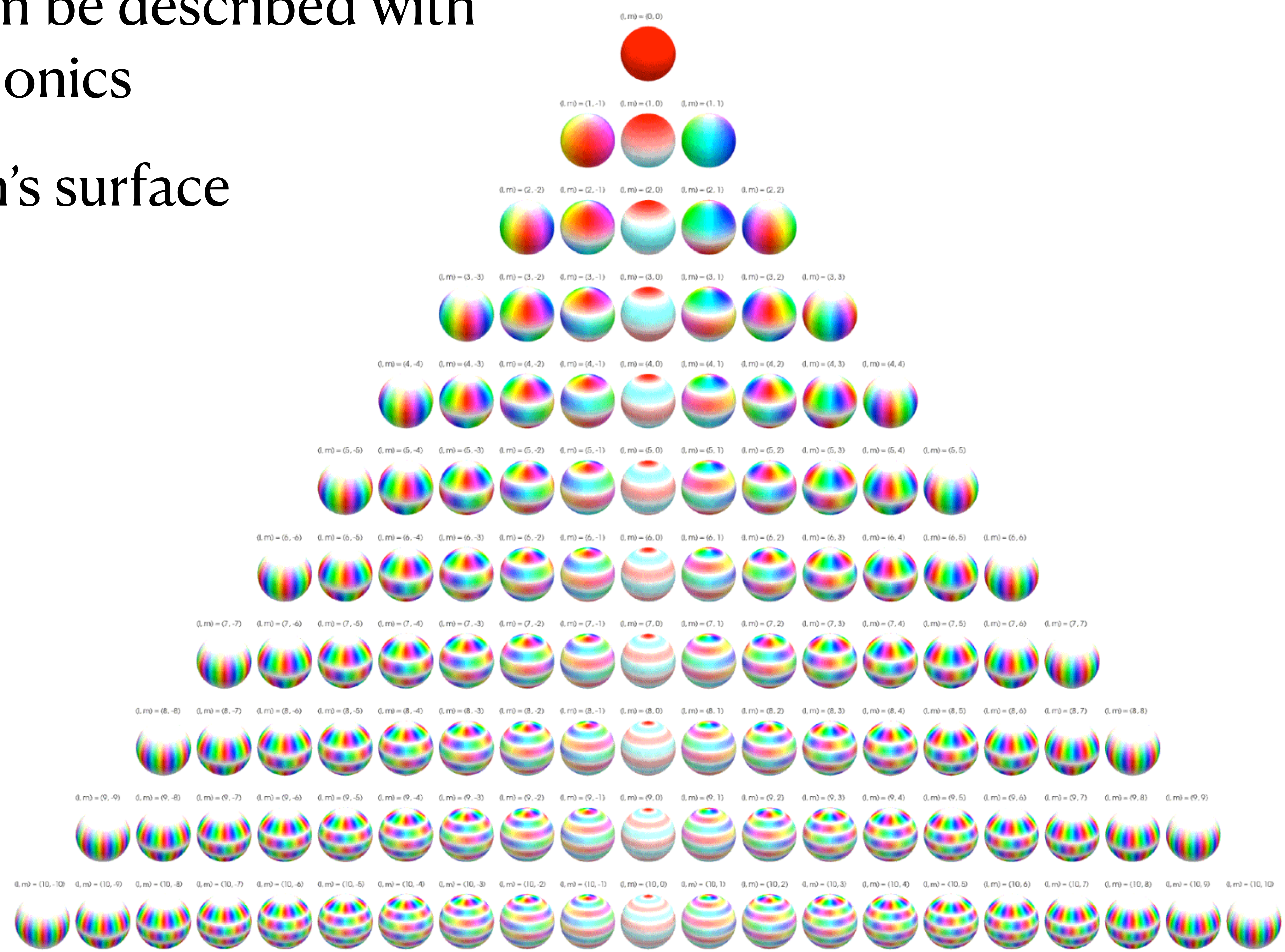


- Five-minute oscillations
- Strongest oscillations among a variety of modes

- Convective motions continually re-excite damped oscillations —> solar-like oscillations

Helio- and asteroseismology

- Oscillations can be described with spherical harmonics
- We see the Sun's surface resolved



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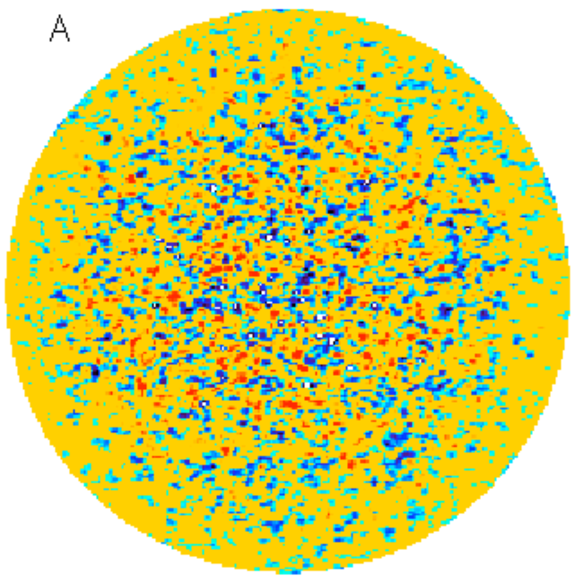
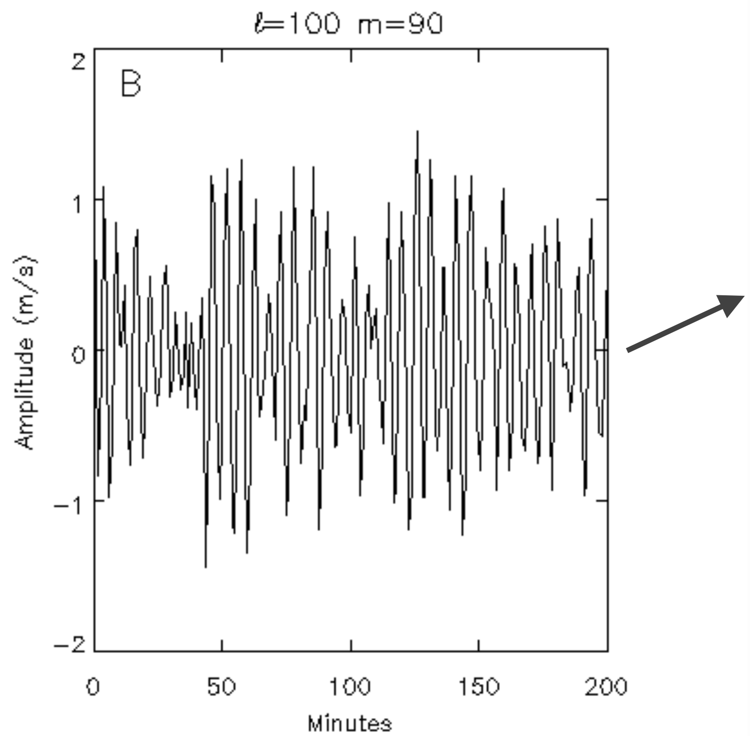
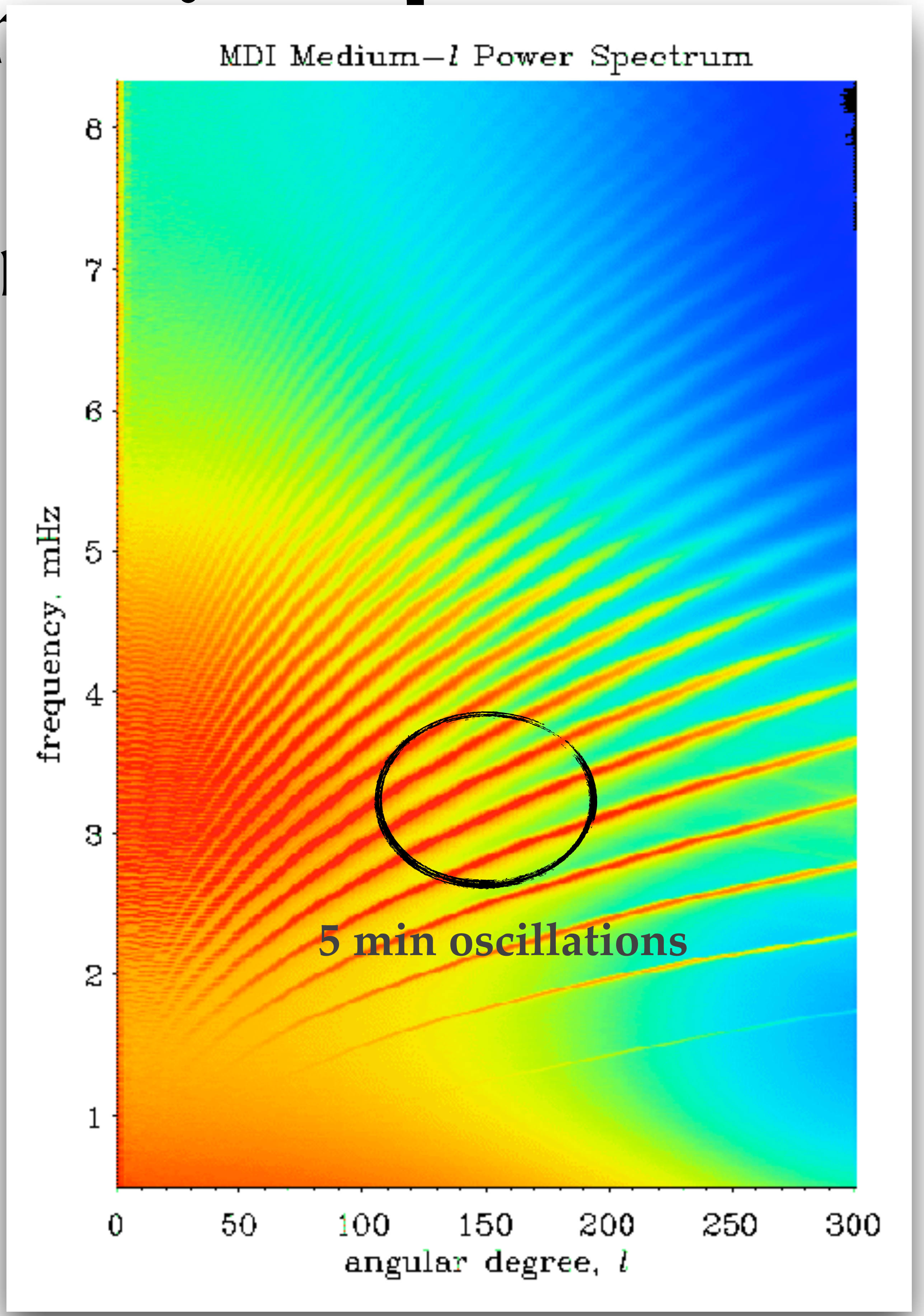
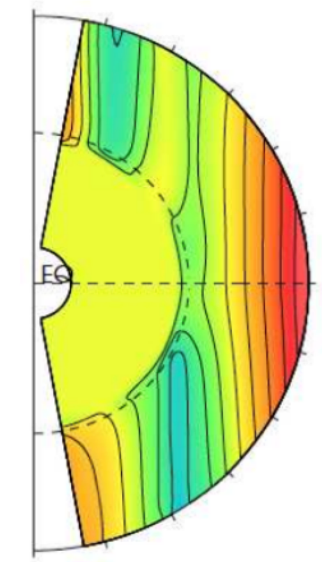






Helioseismology wins

- How does the Sun rotate, below the surface?
- Different oscillation modes probe different depths
- Assumption: differential rotation is a set of cylinders:



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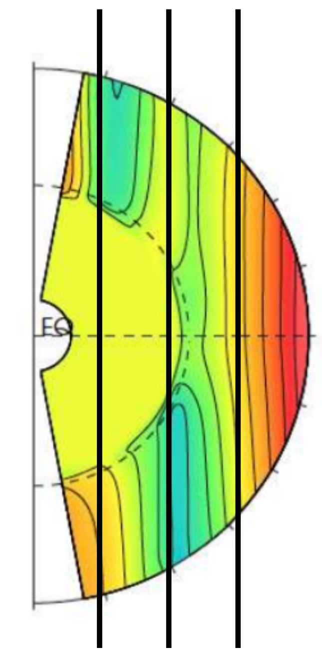
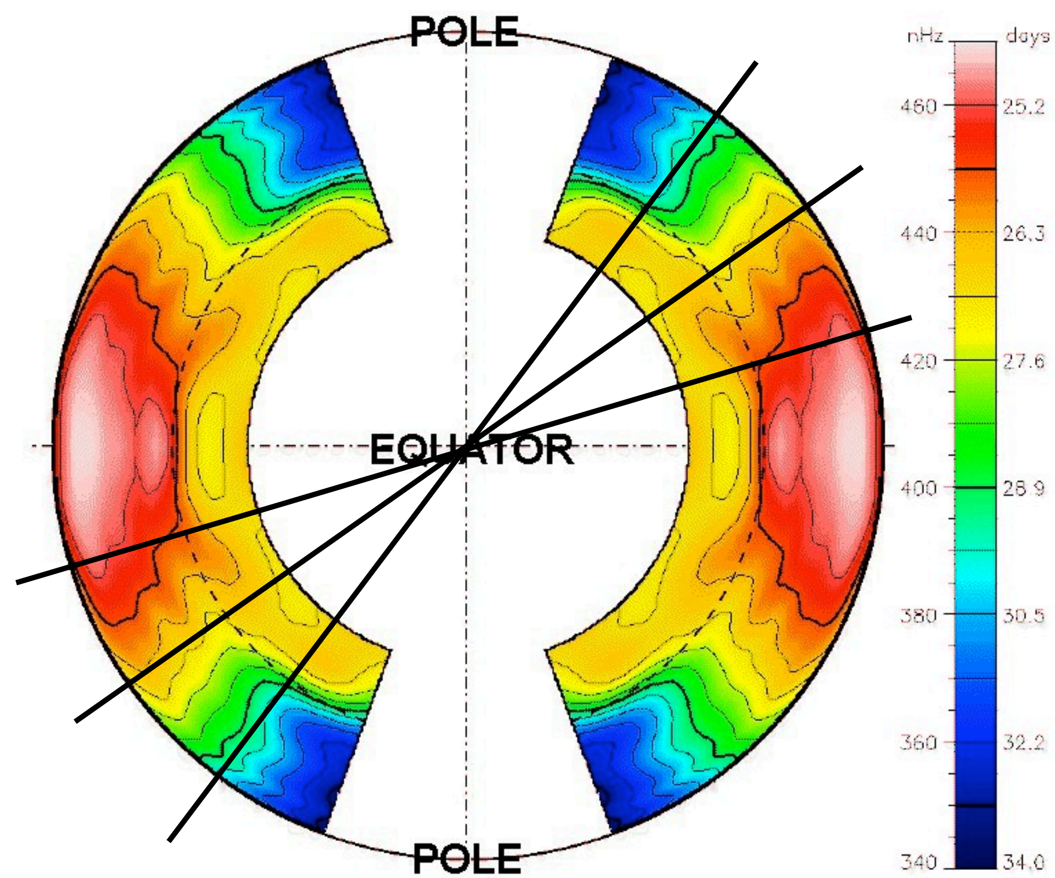


- Inversion of seismic data:
- it actually scales
  with latitude, and
  rotates rigidly below



Helioseismology wins

- The solar neutrino problem
- Neutrino observatories detect less electron neutrinos than predicted by solar nucleosynthesis models

- Is something wrong with the Sun?
  - Fast-rotating core?
  - different chemical composition/opacities in the core?

Helioseismology wins

- The solar neutrino problem
- Neutrino observatories detect les
  predicted by solar nucleosynthesi
- Is something wrong with the Sun?
- Seismic models of the Sun:
  the Sun is fine
- the neutrinos have
  a problem: they have mass

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Evidence from solar seismology against non-standard solar-core models

Y. Elsworth, R. Howe, G. R. Isaak, C. P. McLeod & R. New

Nature **347**, 536–539 (1990) | Cite this article

Abstract

GLOBAL oscillations of the Sun[1] have been used to test solar models[2], but modelling the oscillation frequencies to their measured accuracies of a few microhertz has proved difficult, mostly owing to ignorance of the structure of the Sun's outer layers[3]. The frequency separation between closely spaced modes in the acoustic spectrum is expected to depend more on core properties[4], however, and thus to provide constraints on models of the solar core. Our observations combine data from a global network of observing stations, which reduces the masking effect of daily sidebands in the spectral analysis. Here we present precision measurements of fine structure and its variation with frequency. Our results agree with standard solar models[5–7], and seem to remove the need for significant mixing[8,9] or weakly interacting massive particles (WIMPS)[10,11] in the core, both of which have been advanced to explain the low measured flux of solar neutrinos[12,13]. This suggests that the solar neutrino problem must be resolved within neutrino physics, not solar physics; neutrino oscillations and a finite neutrino mass form a possible explanation.

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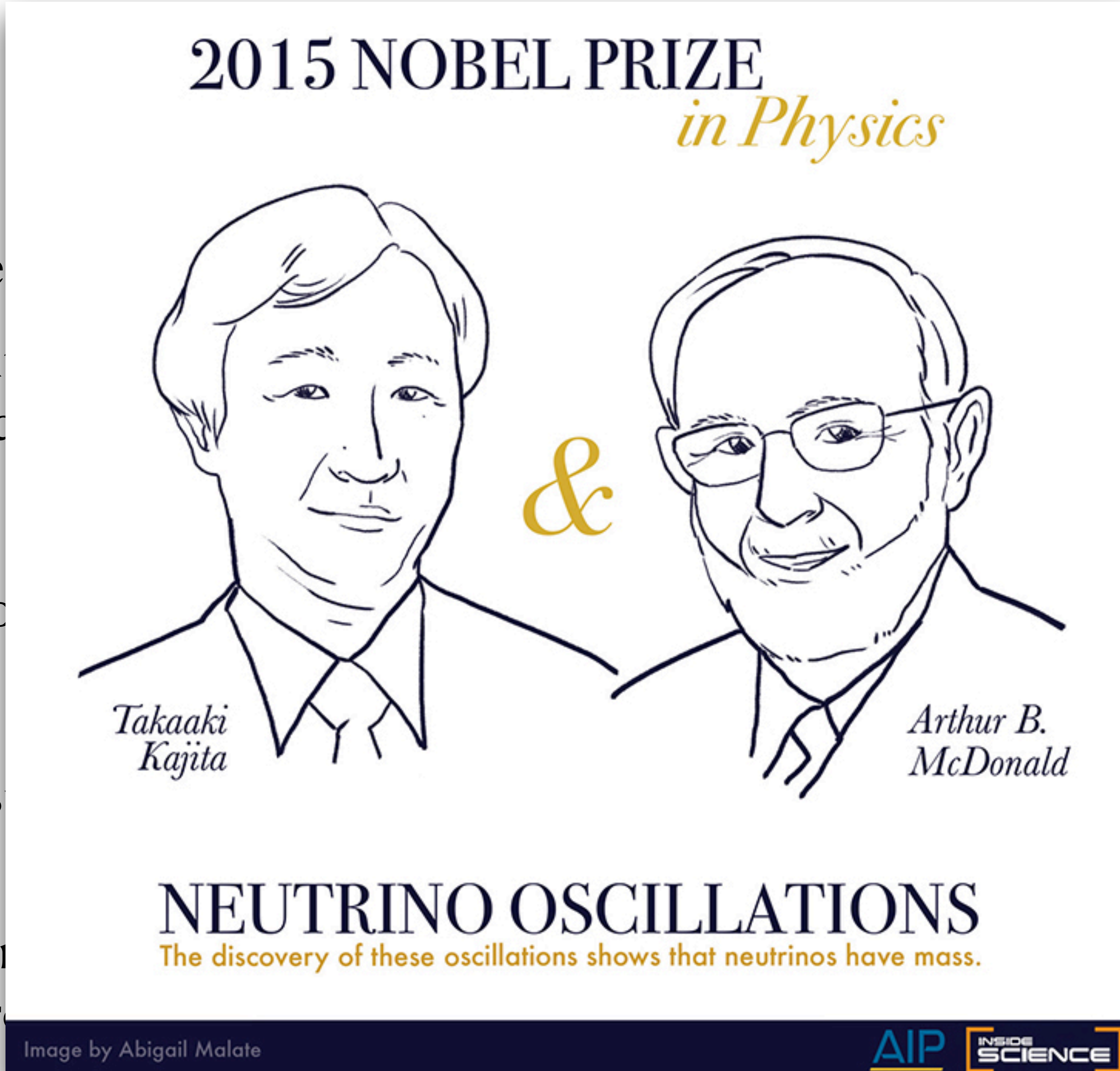

be

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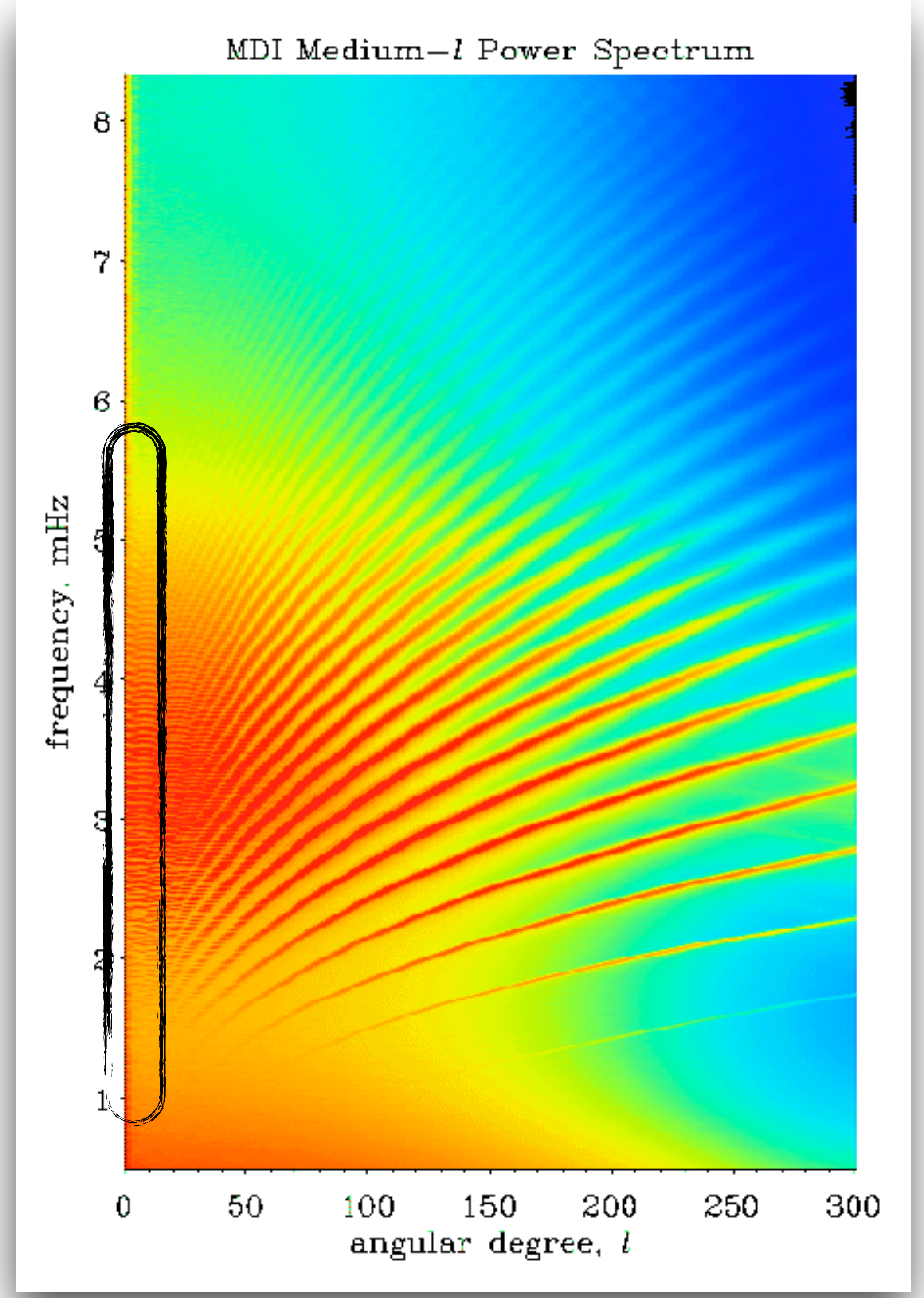
xpected to depend
models of the solar
ng stations, which
ere we present
cy. Our results agree
ant mixing[8,9] or
hich have been
uggests that the solar
hysics; neutrino

Can we do the same for other stars?

The Sun as a star

- Can't resolve the surface of stars
  - We're limited to the lowest degrees
- We have A LOT less incoming flux
  - SNR ~ $\sqrt{N}$
- How would the Sun look from afar?



The Sun as

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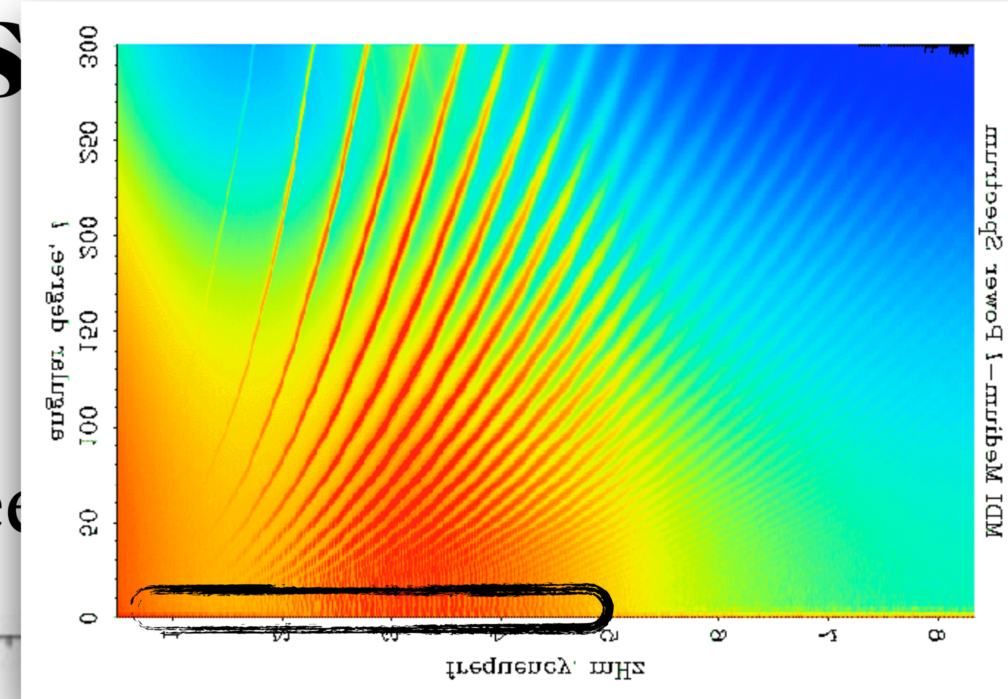

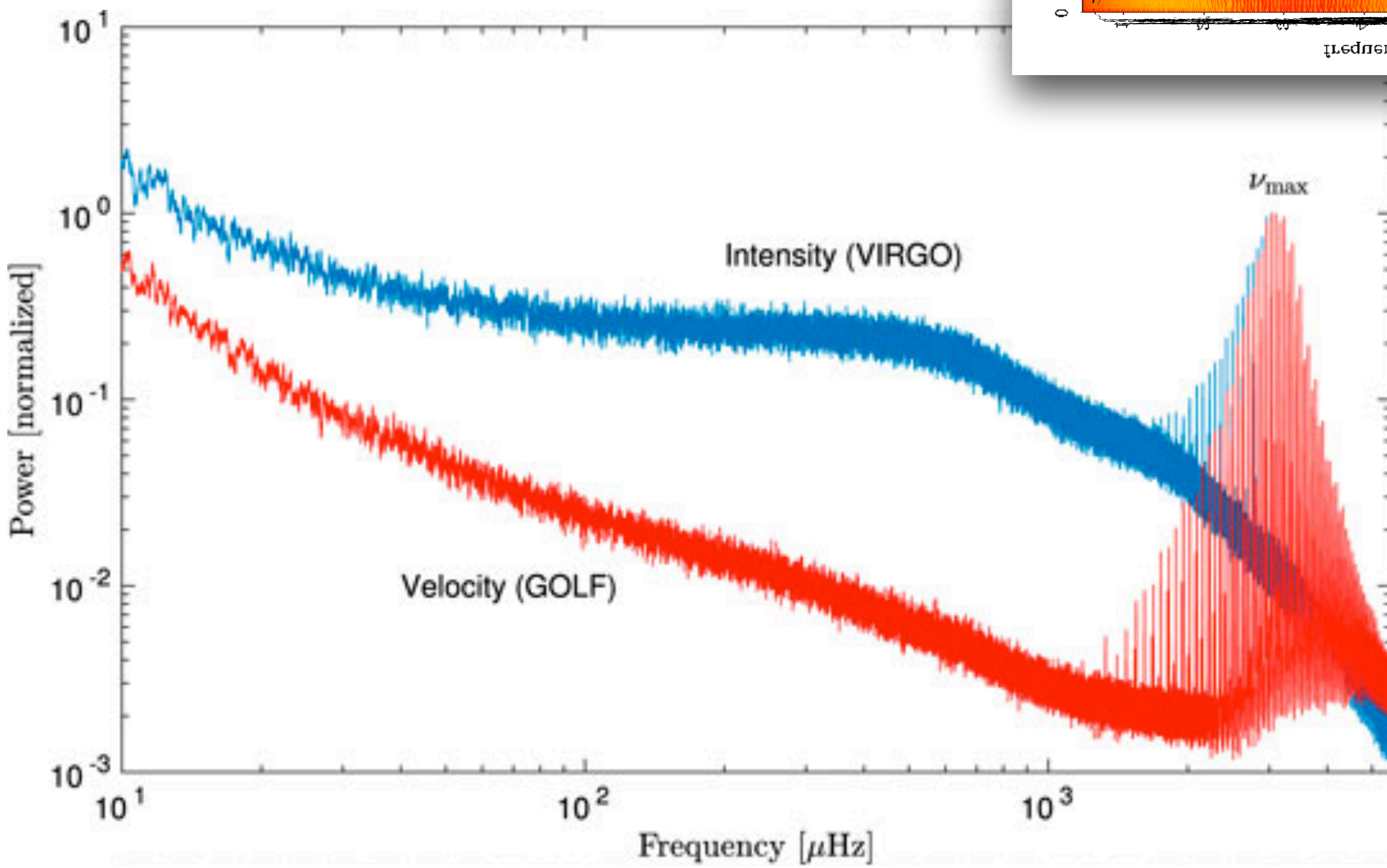

The big (space) guns

- Asteroseismology requires:
    - very high photometric precision (10-100 ppm)
    - fast observing cadence (Sun goes brrr in 5 minutes!)
    - long, continuous data (no night-day cycles, no weather)
- Go to: space

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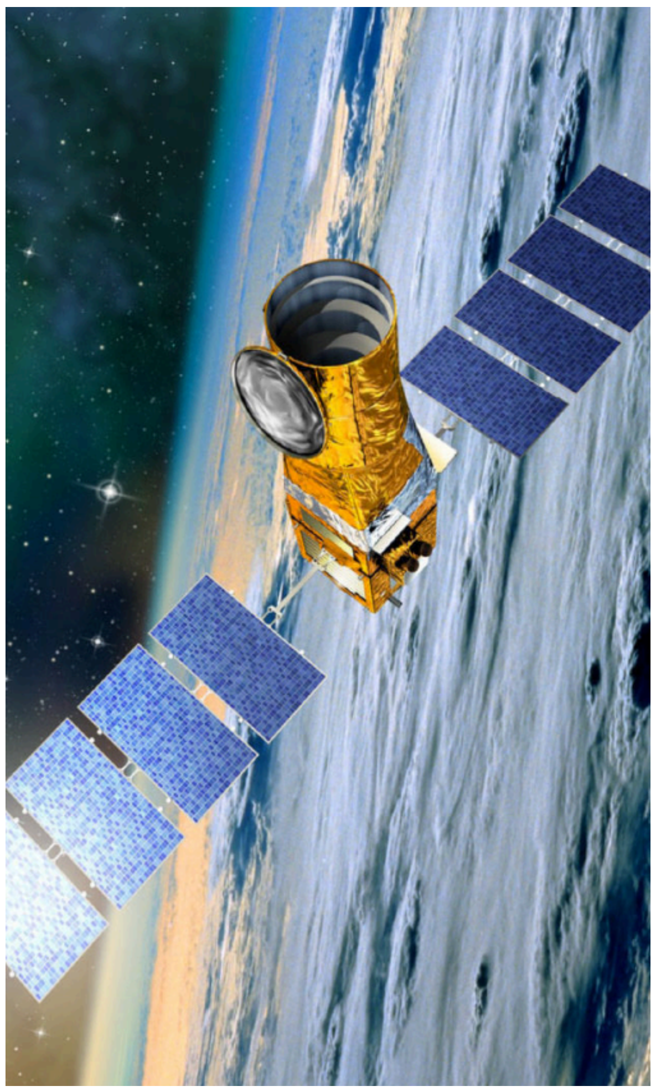
  - long, continuous data (no night-day cycles, no weather)
- Go to: space
- Happy coincidence:
  requirements for transiting exoplanet search are the same!

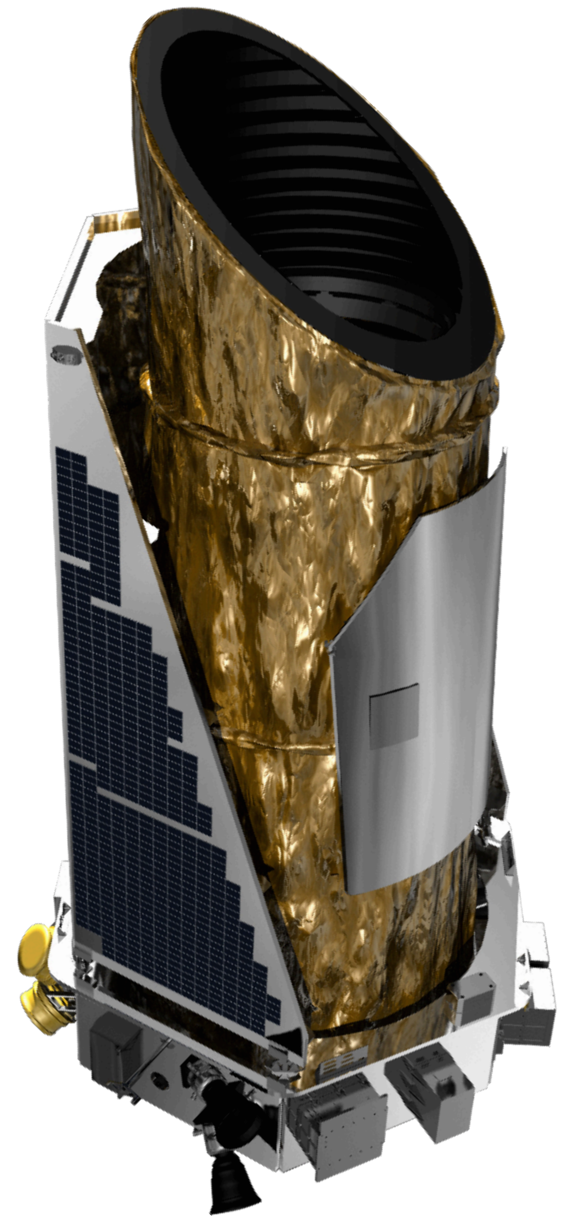
The big (space) guns

2006-2012



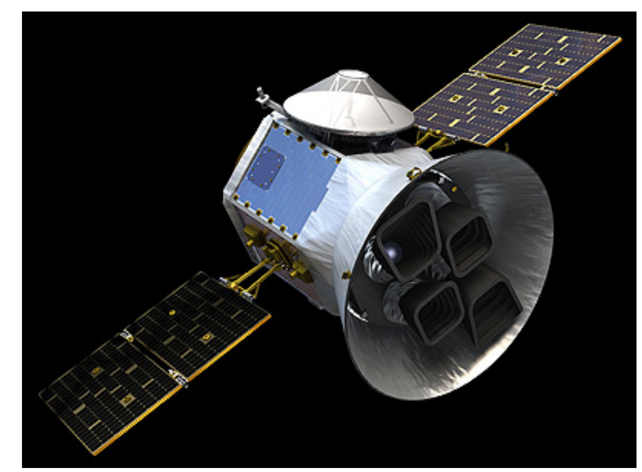
CoRoT

2009-2018



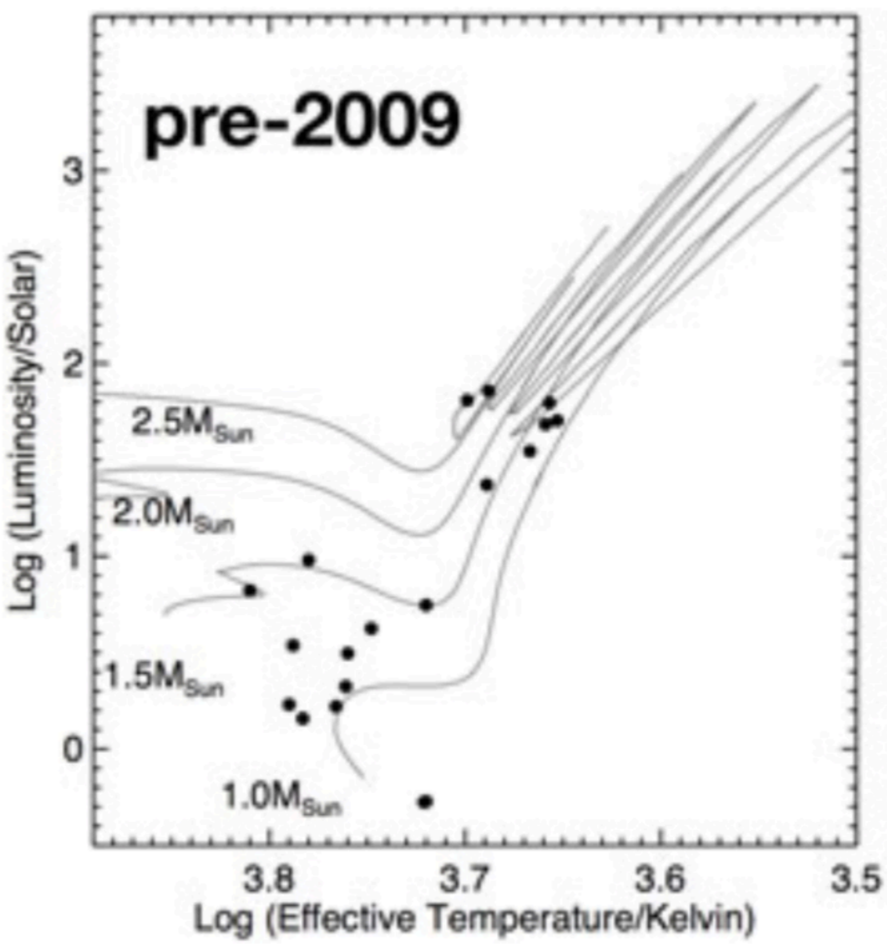
Kepler

2018-



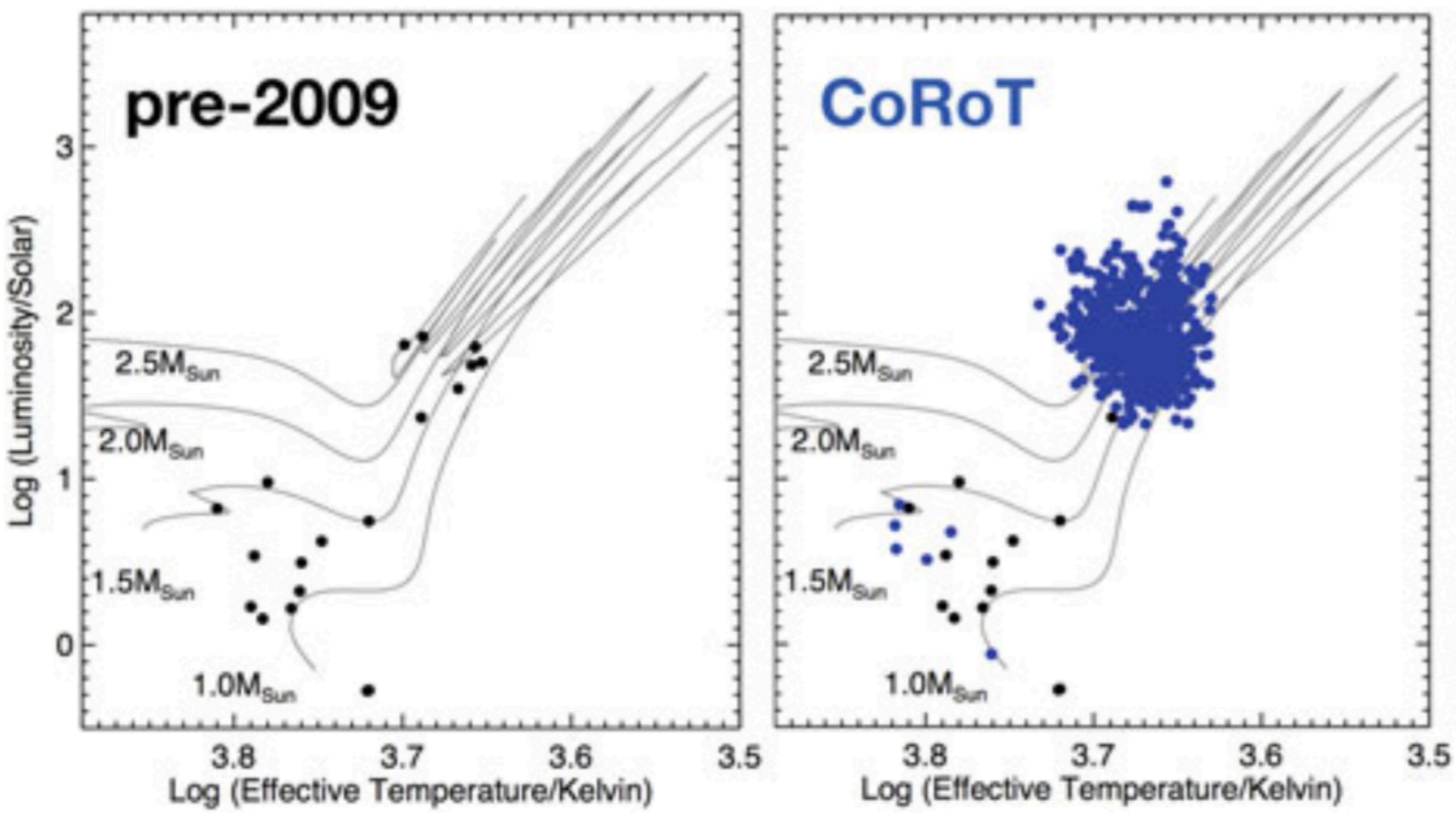
TESS

The asteroseismic revolution



few of the brightest
stars in the sky

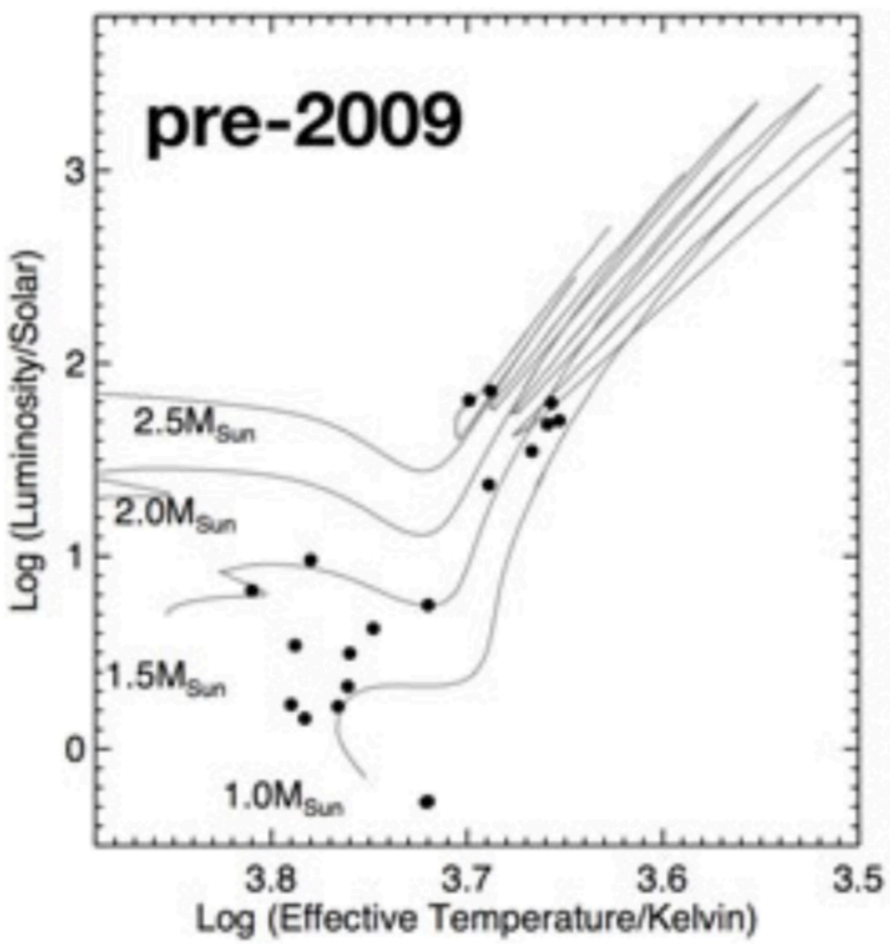
The asteroseismic revolution



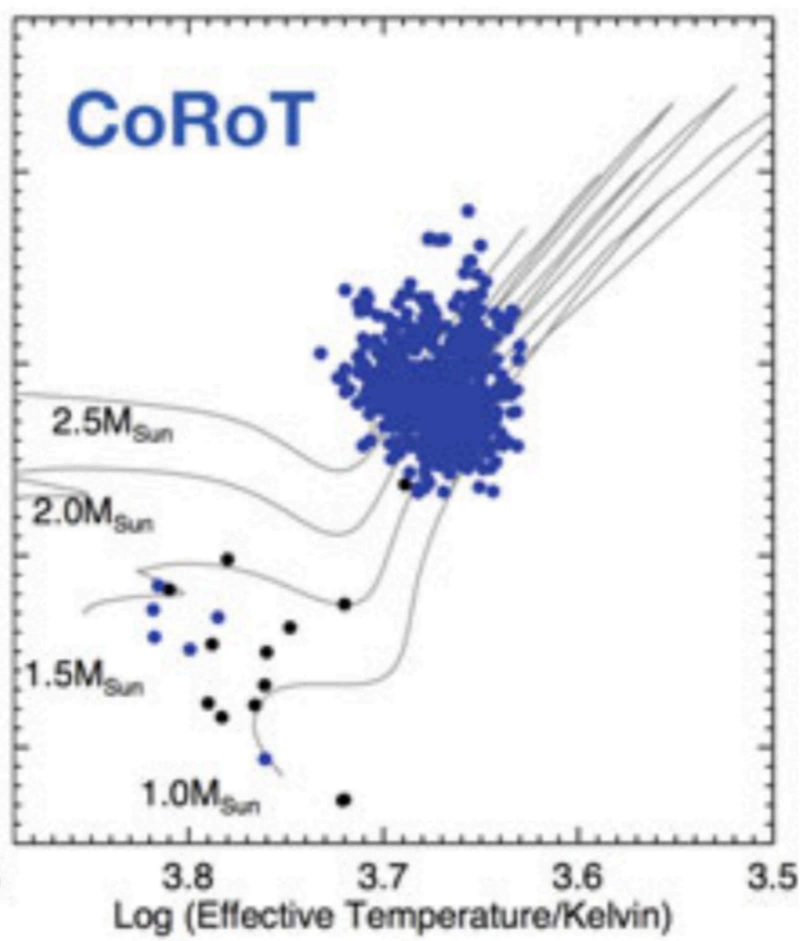
few of the brightest
stars in the sky

hundreds of
(smaller) red giants

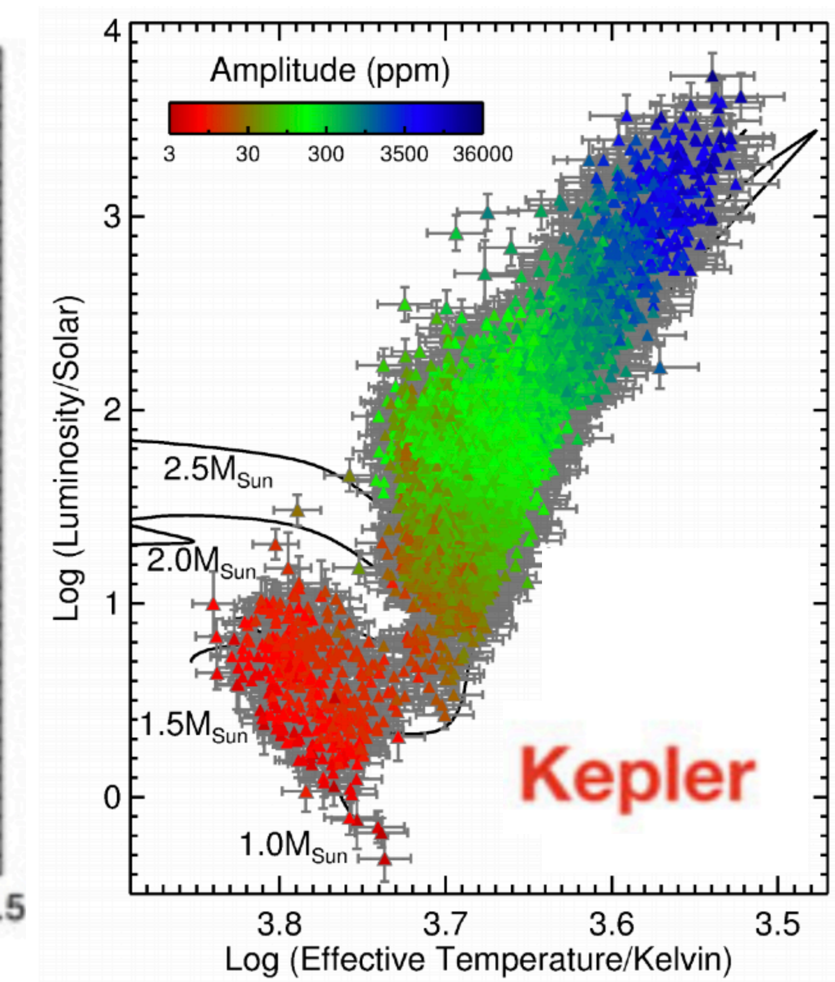
The asteroseismic revolution



few of the brightest
stars in the sky



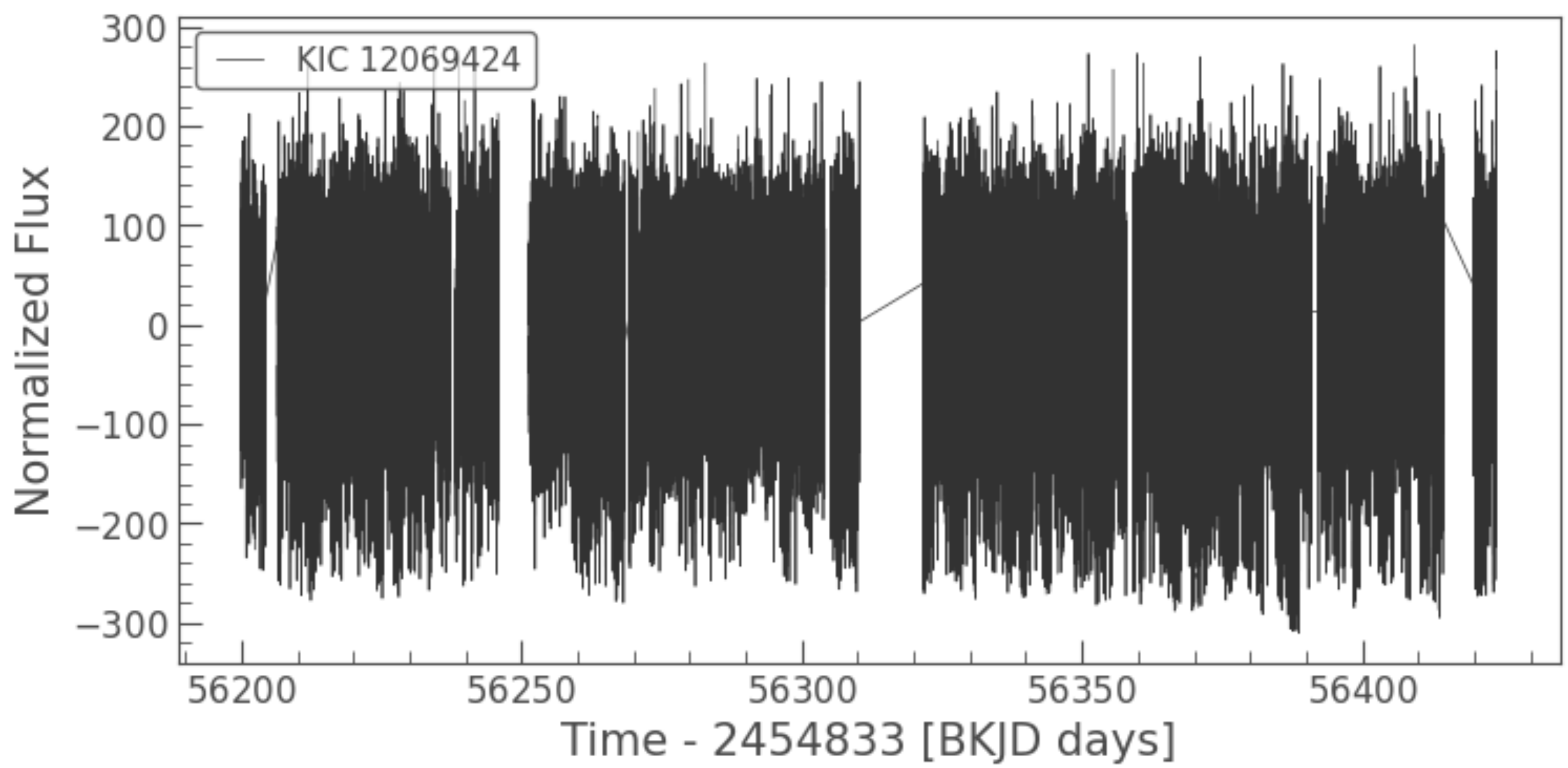
hundreds of
(smaller) red giants



tens of thousands of red giants,
hundreds of solar-like stars

The asteroseismic revolution

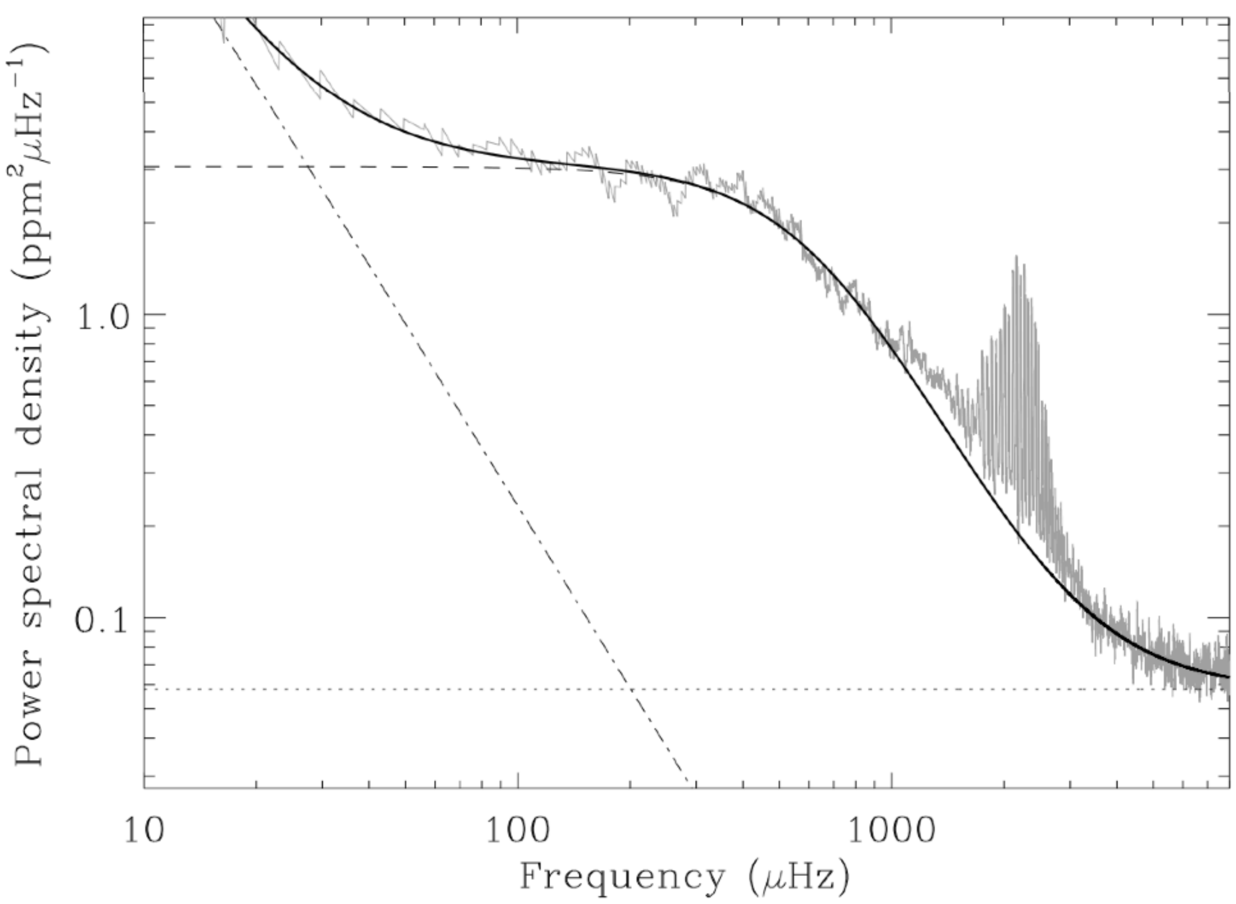
- A plethora of continuously re-excited modes is not… aesthetic in the time domain (it's basically structured noise)



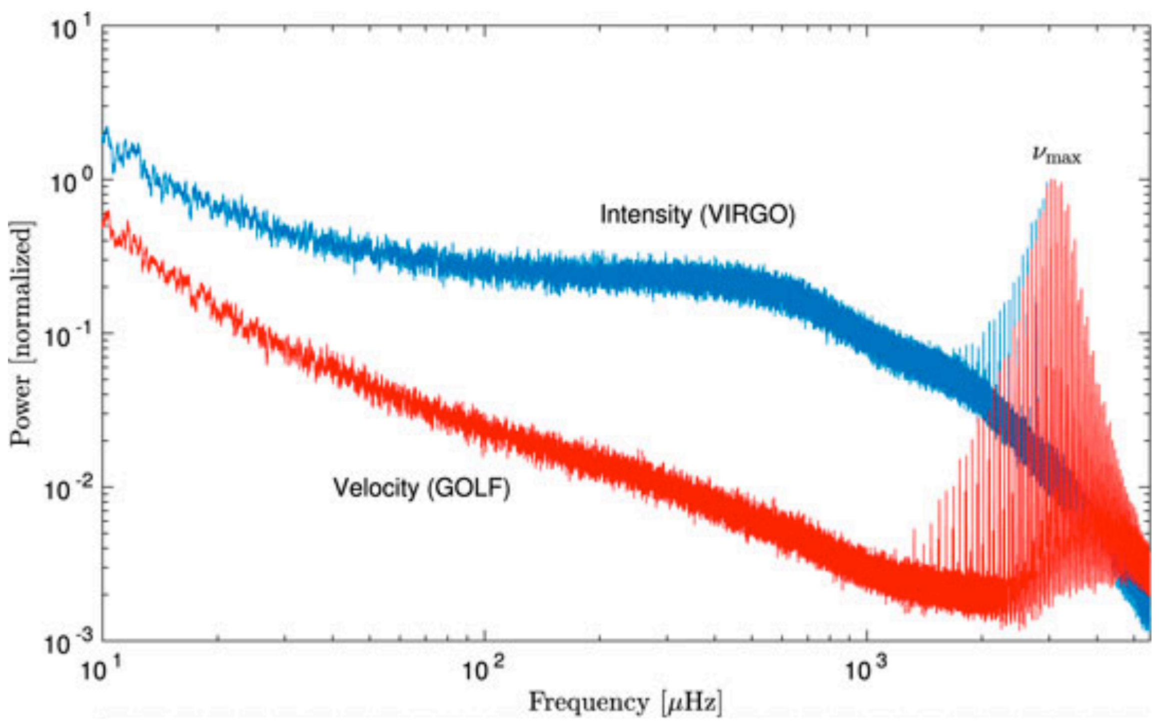
The asteroseismic revolution

- But it is in the Fourier domain

16 Cyg A



Sun



The asteroseismic revolution

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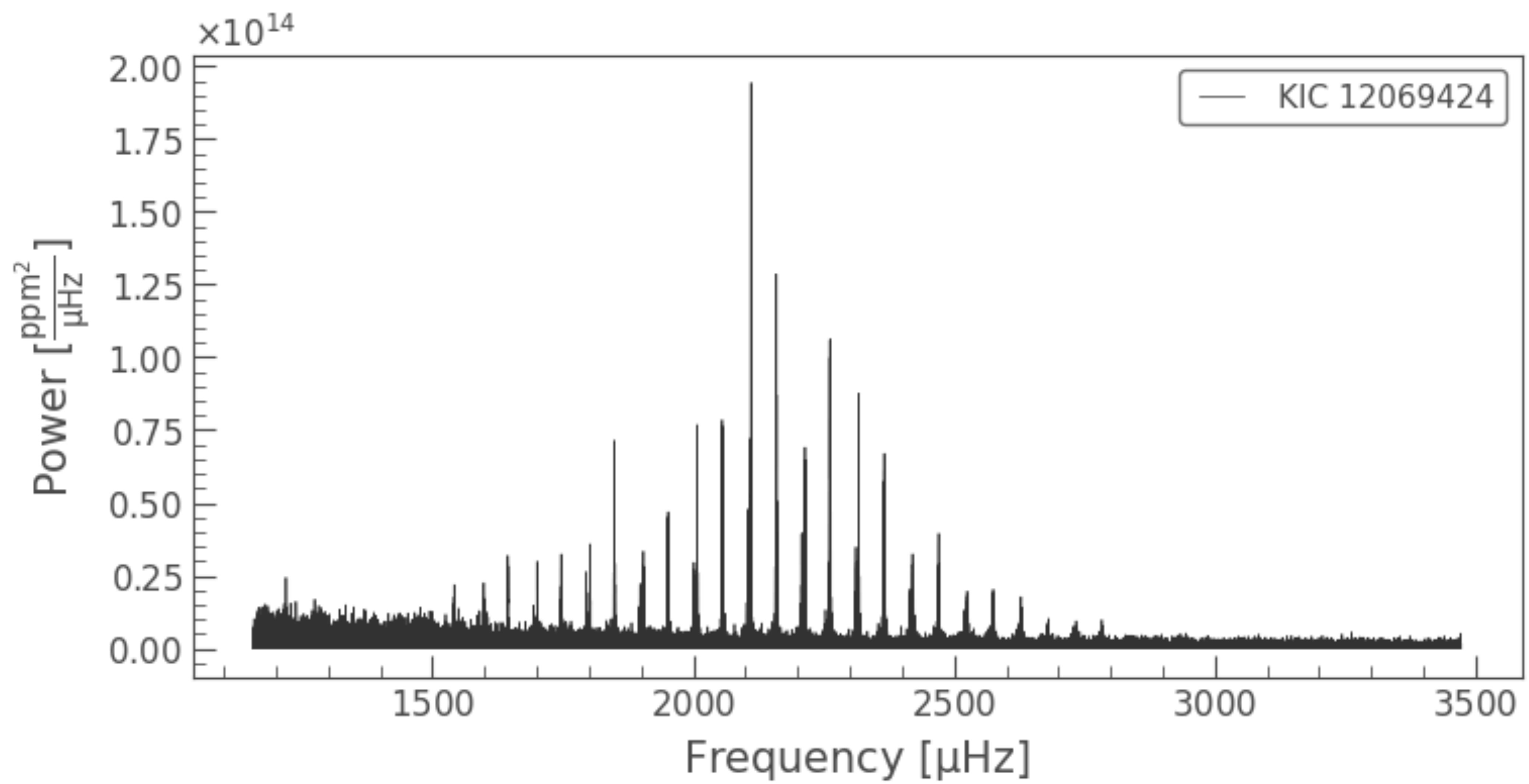
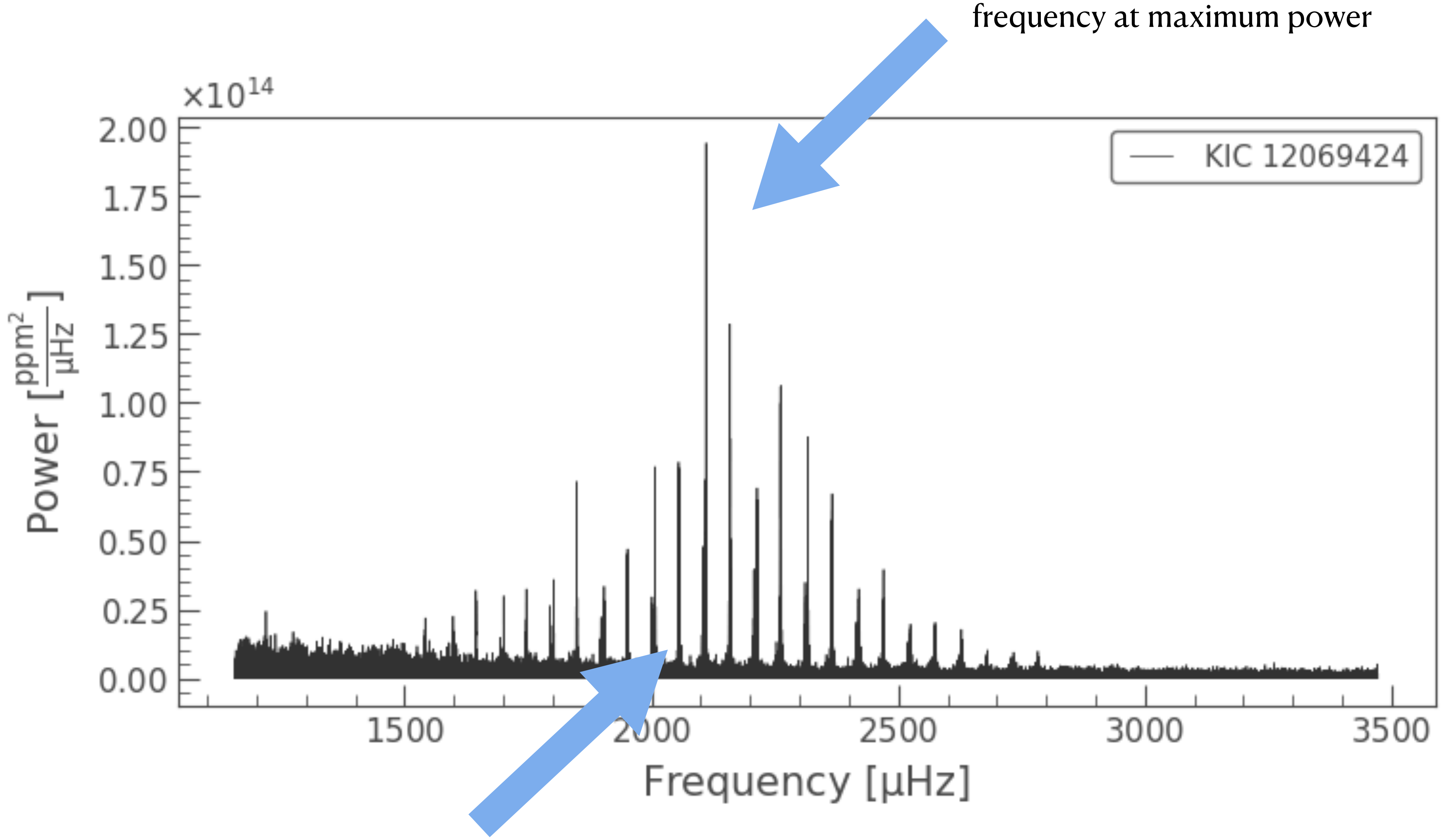


The asteroseismic revolution

- But it is in the Fourier domain

frequency at maximum power



frequency separation of successive modes

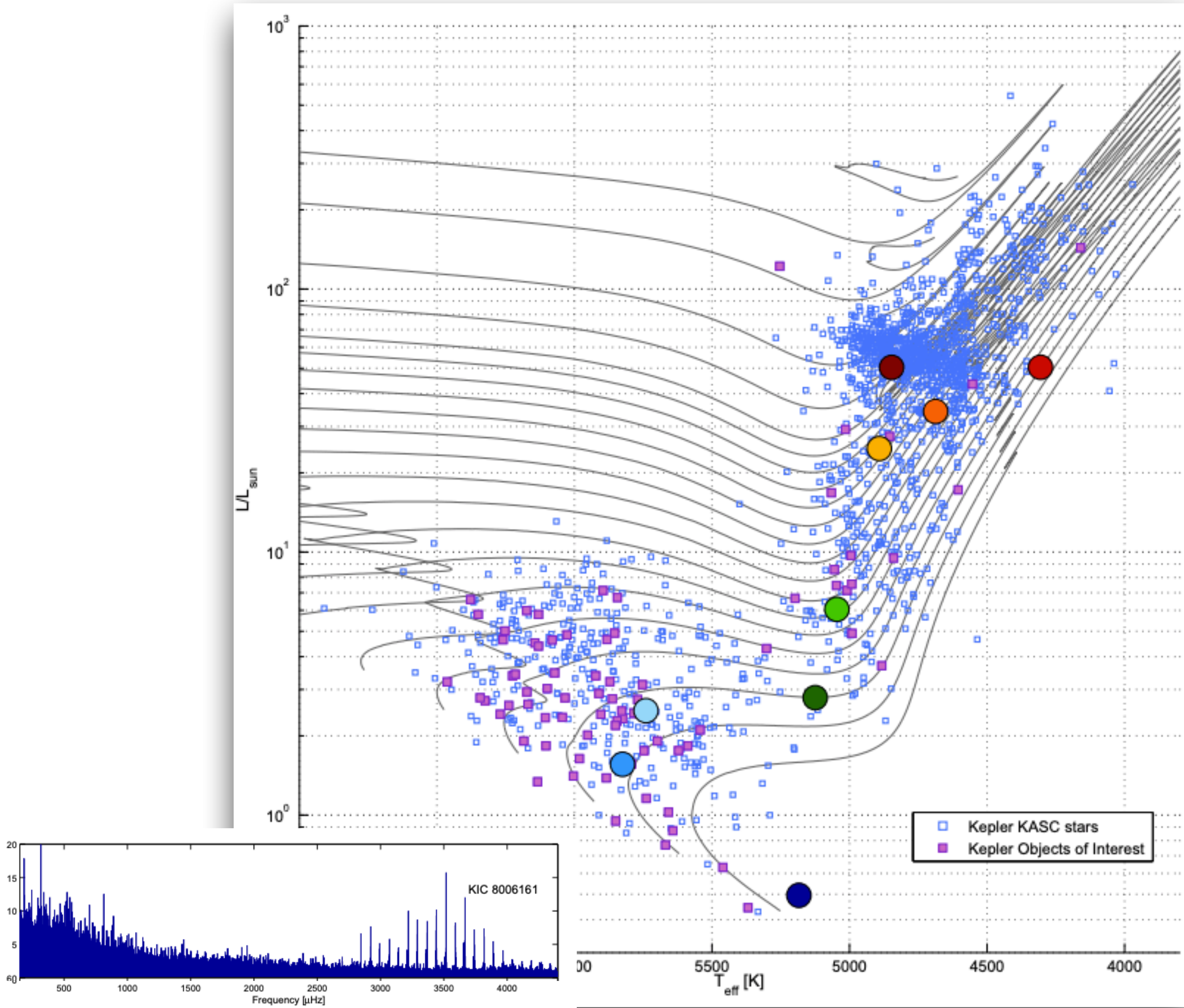
The asteroseismic revolution

- observed mode frequencies scale with physical parameters
- we can build stellar models to predict them
- We can:
    - Determine physical parameters from model fits
    - Test the fidelity of our models with benchmark stars

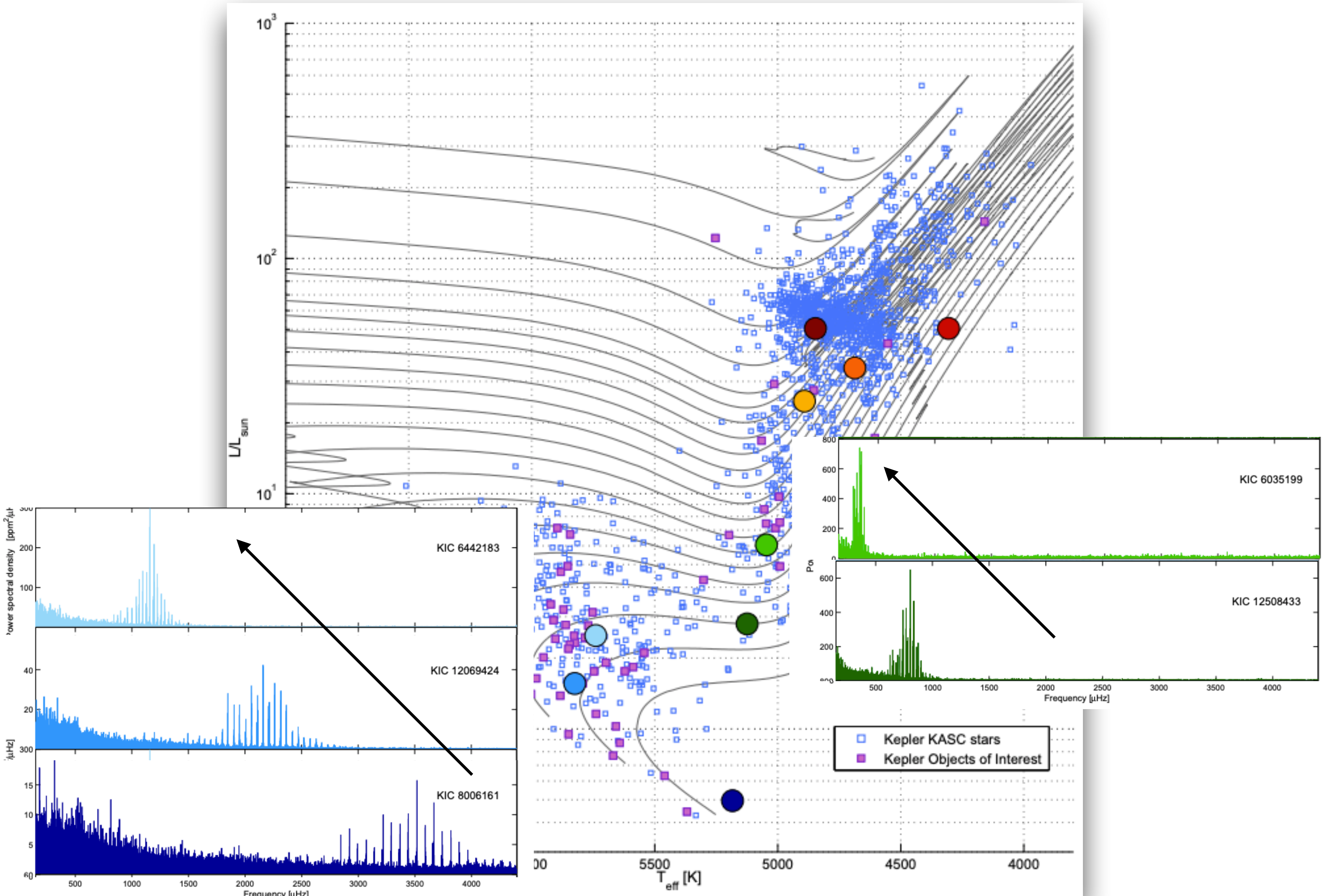
The asteroseismic revolution

- observed mode frequencies scale with physical parameters
- we can build stellar models to predict them
- We can:
    - Determine physical parameters from model fits
    - Test the fidelity of our models with benchmark stars
- We can:
    - be extremely precise! ~5% in mass, ~2% in radius
    - **10-20% in age!**
    - (also: stellar rotation and inclination, internal structure)

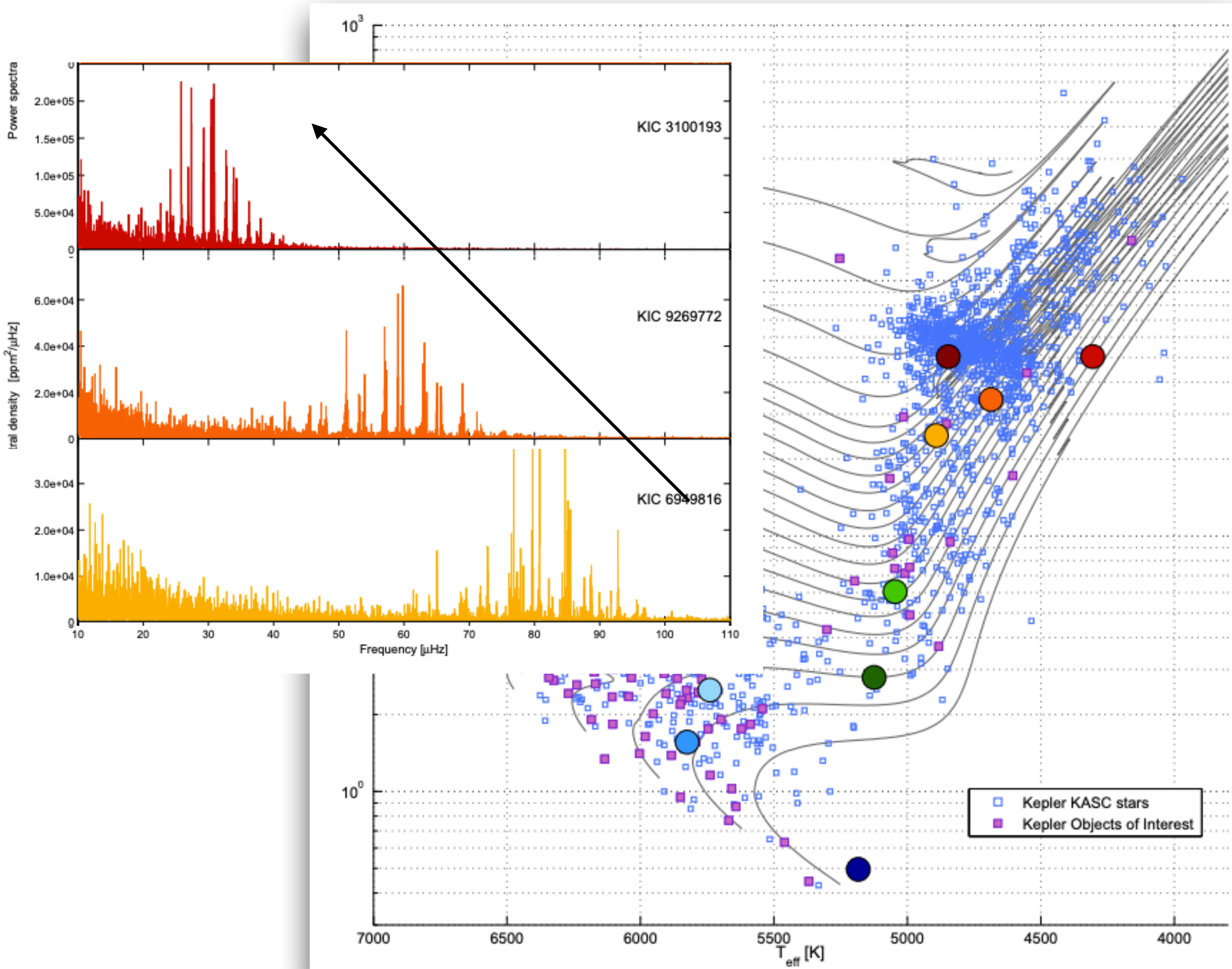
The asteroseismic revolution



The asteroseismic revolution



The asteroseismic revolution

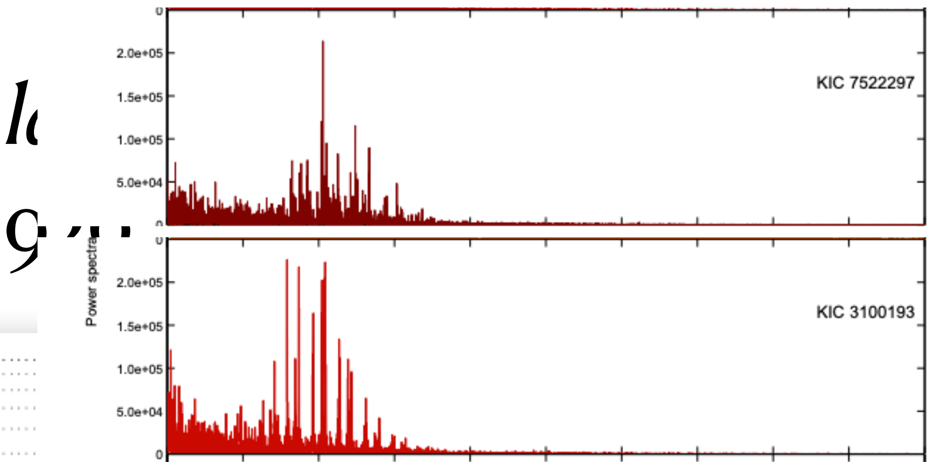


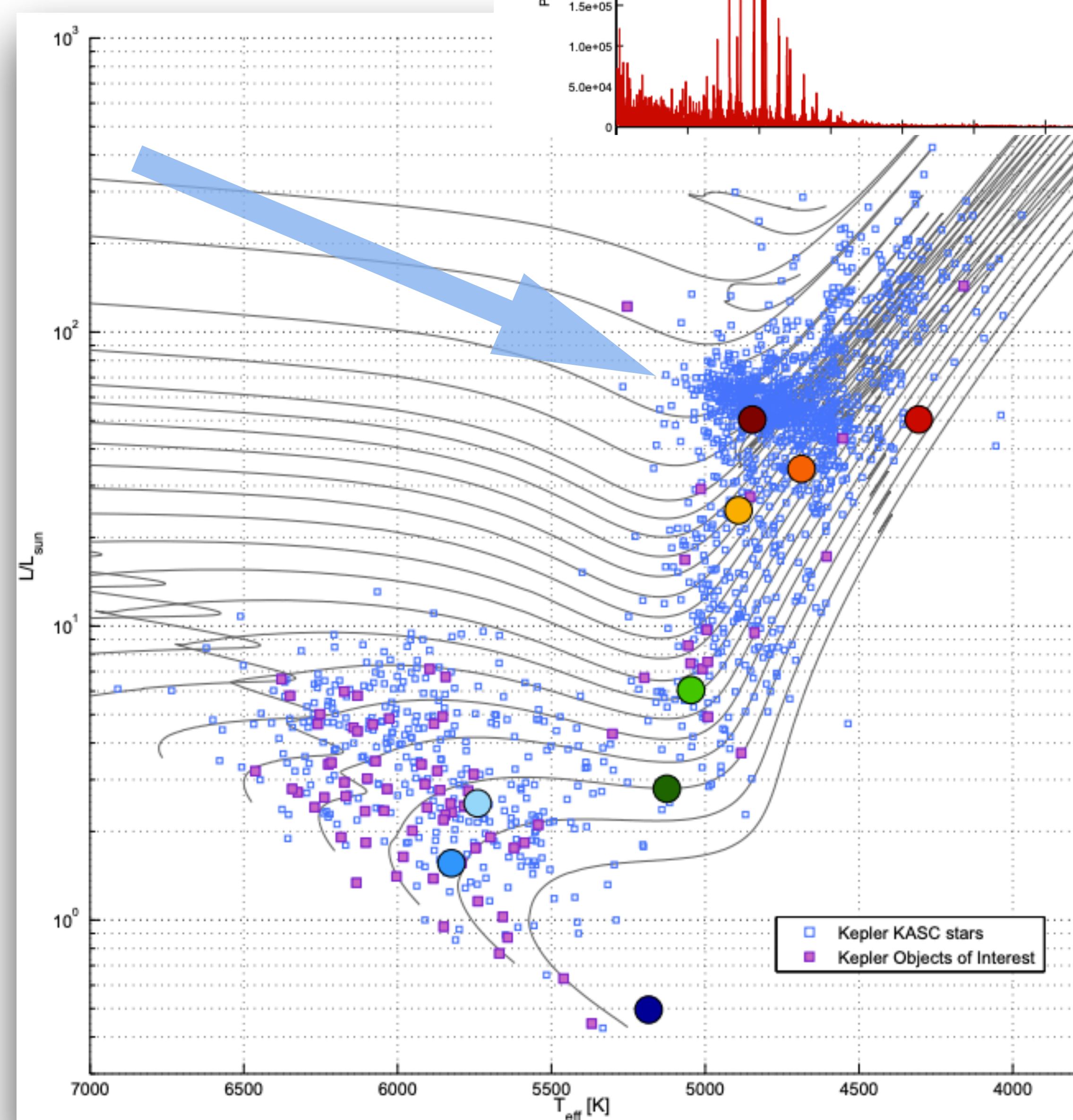
The asteroseismic revolution

- *“What appliance can pierce through the outer layers of a star and test the conditions within?”* - Arthur Eddington, 1926
- Solar-like oscillations!

The asteroseismic revolution

- *“What appliance can pierce through the outer l the conditions within?”* - Arthur Eddington, 19
- Solar-like oscillations!
- This spot: two different types of stars
- Red giant branch: shell H-burning, inert core
- Red clump: core He-burning





The asteroseismic revolution

- RGB and RC stars can look the same, but cores are different
- Sound waves sample the envelope, gravity waves sample the core
- Hard to detect both, but if we can…

The asteroseismic revolution

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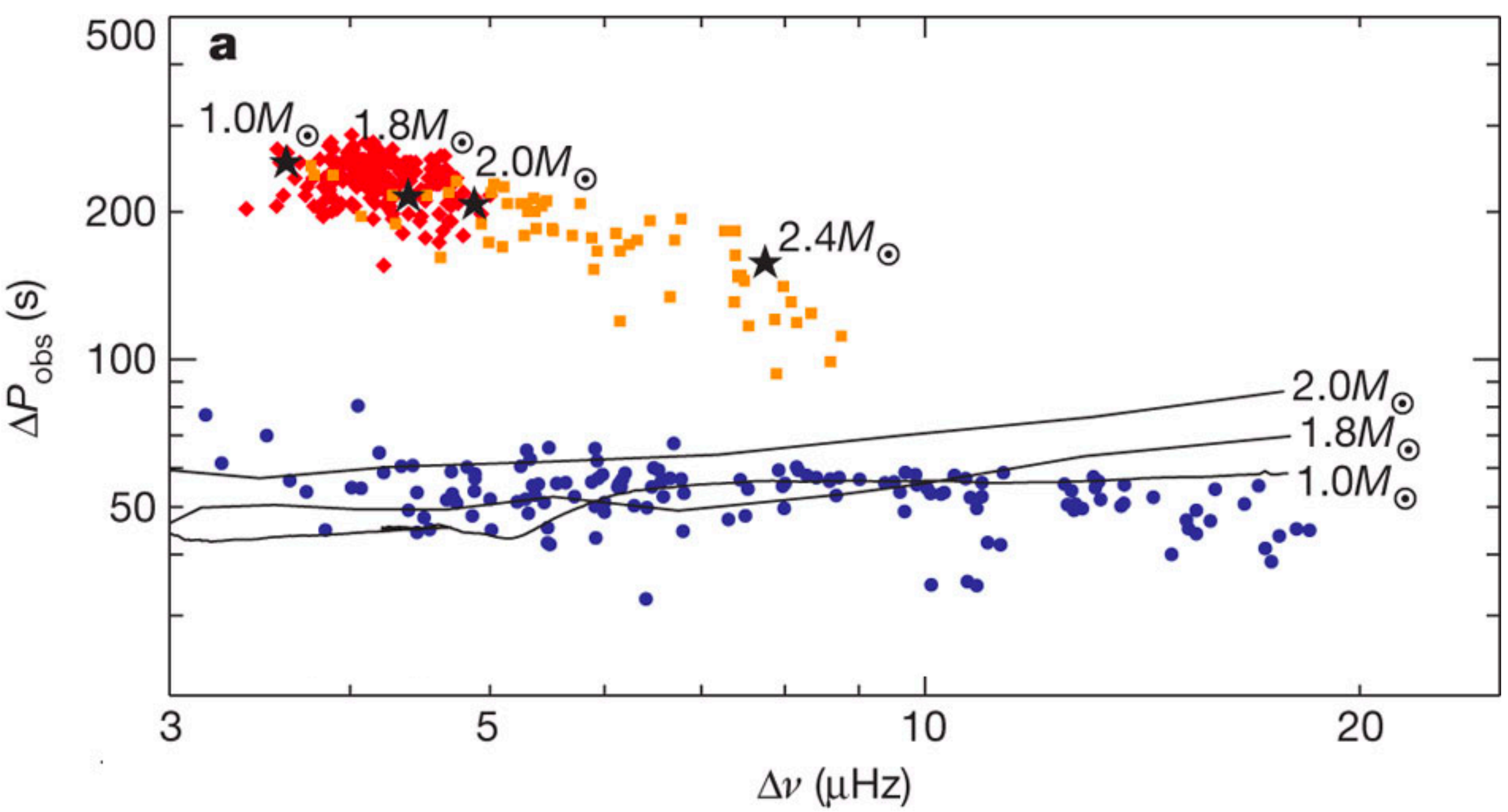
- Sound waves sample the envelope, gravity waves sample the core
- Hard to detect both, but if we can... with Kepler:

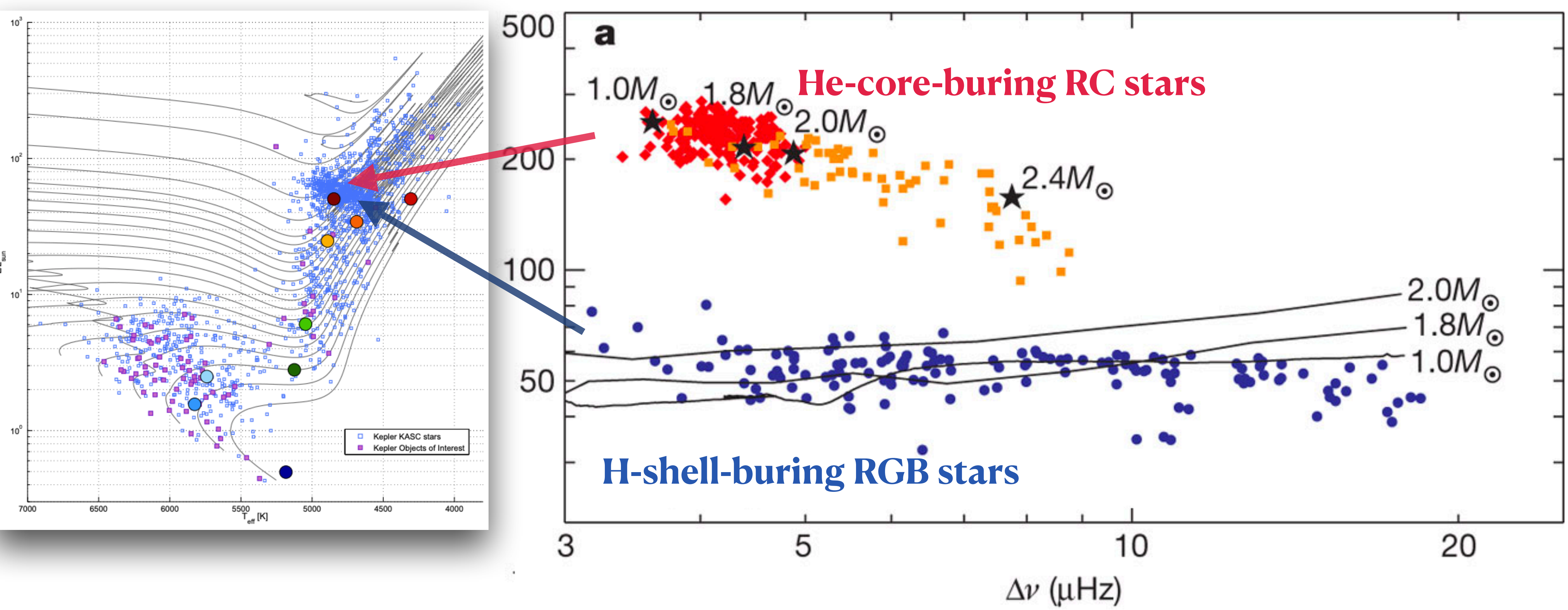
G mode (gravity wave) period separations



P mode (sound wave) frequency separations

The asteroseismic revolution

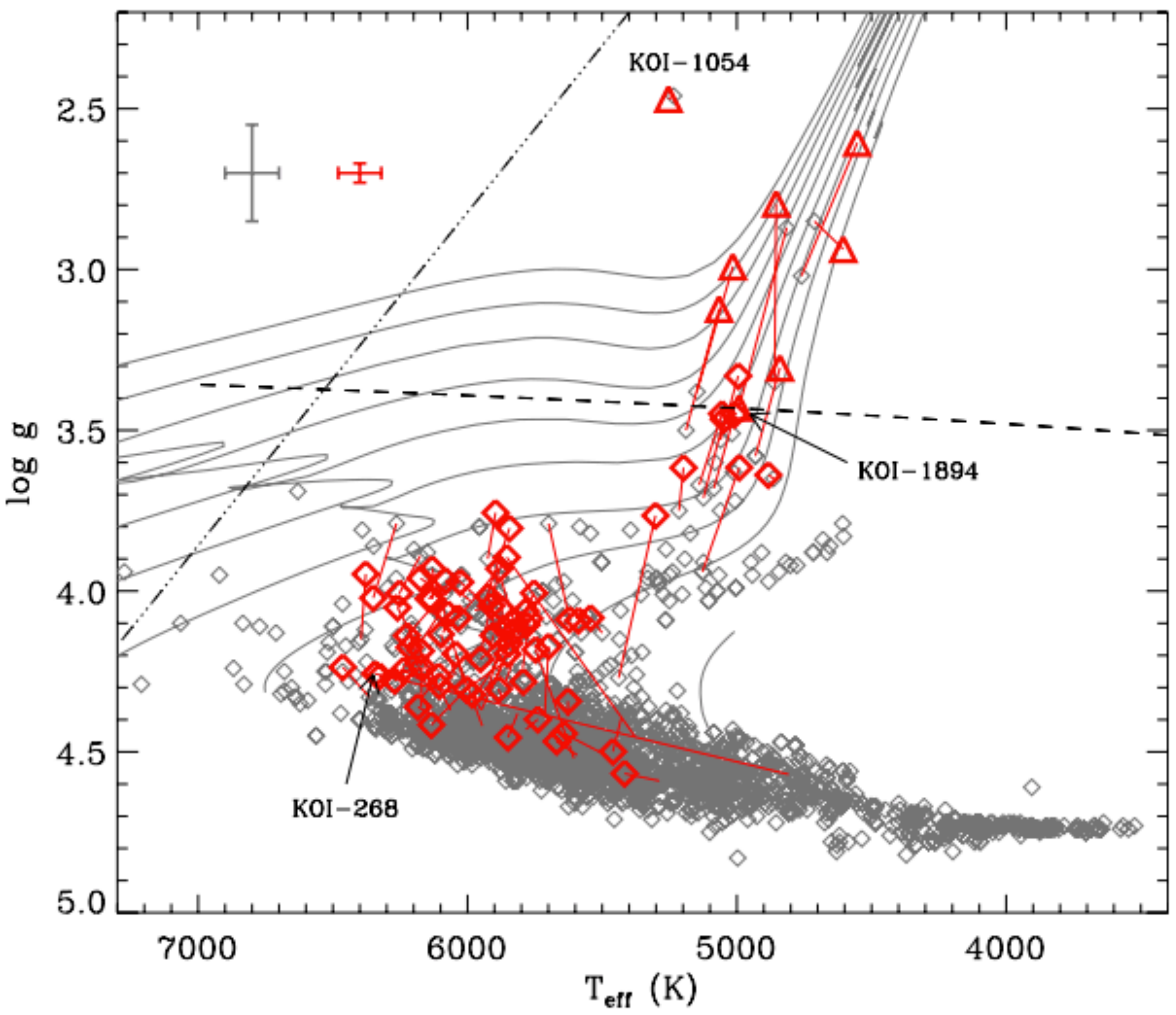
- RGB and RC stars can look the same, but cores are different
- Sound waves sample the envelope, gravity waves sample the core
- Hard to detect both, but if we can… with Kepler:

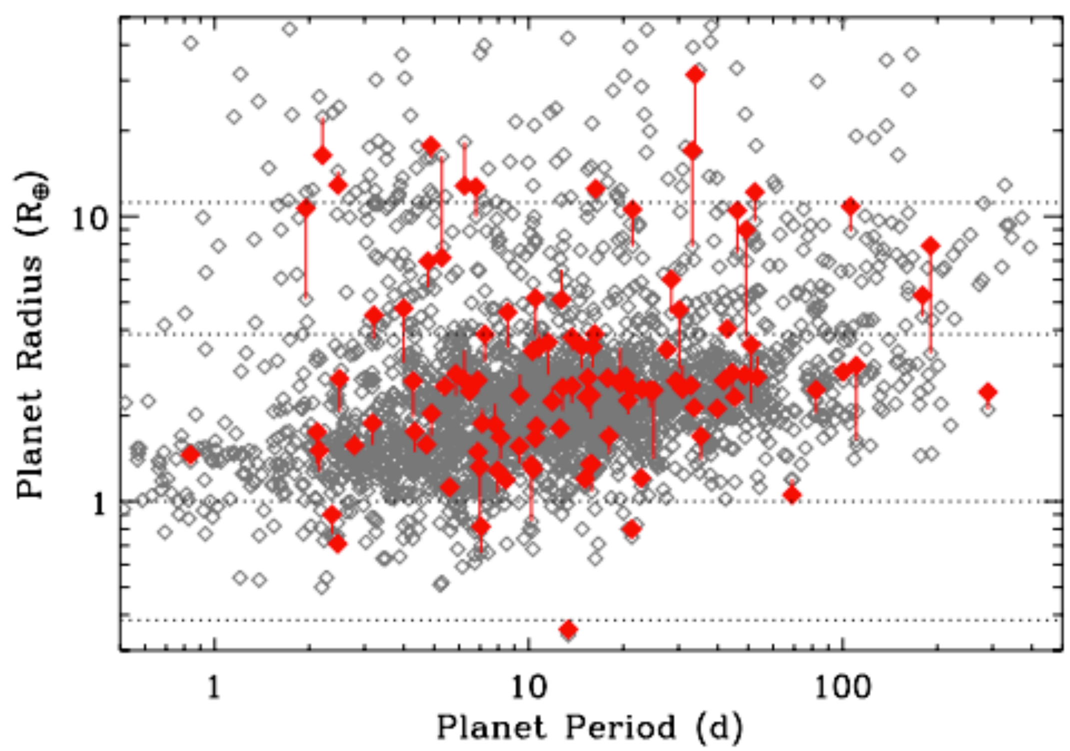


P mode (sound wave) frequency separations

The asteroseismic revolution

- Characterize exoplanet hosts —> better planet parameters



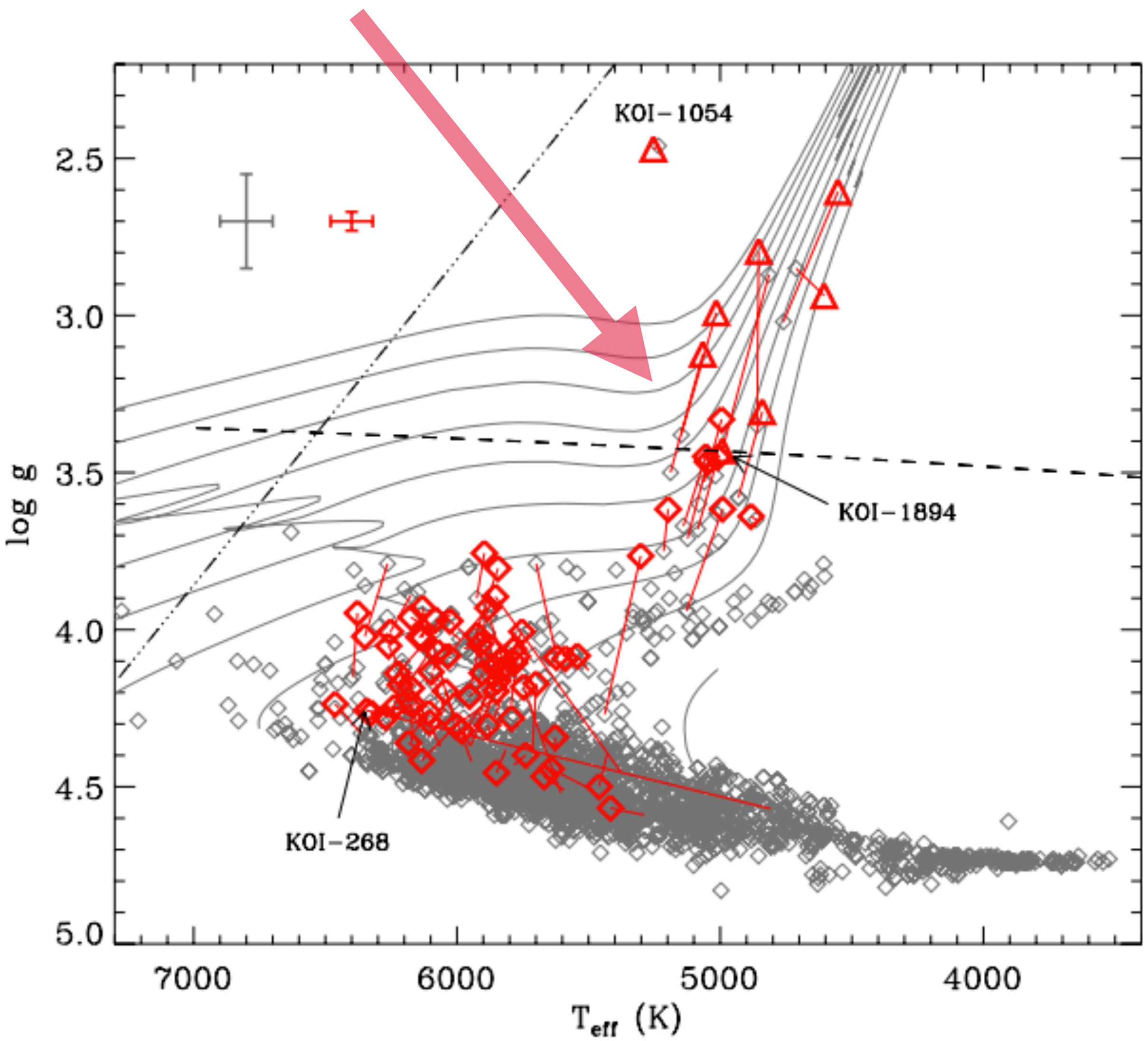


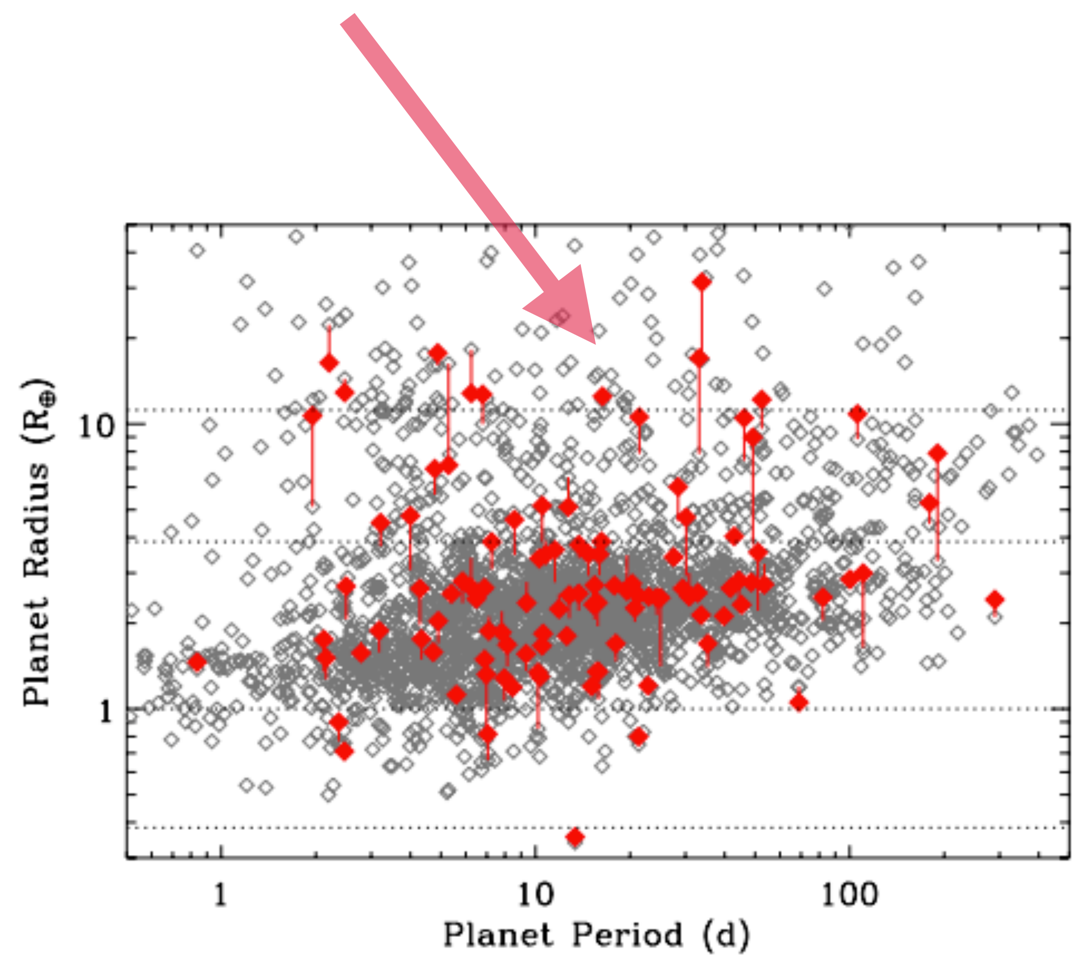
The asteroseismic revolution

- Characterize exoplanet hosts —> better planet parameters

Kepler red giant sample:
positions got revised by seismology

Kepler planet sample:
positions got revised by seismology



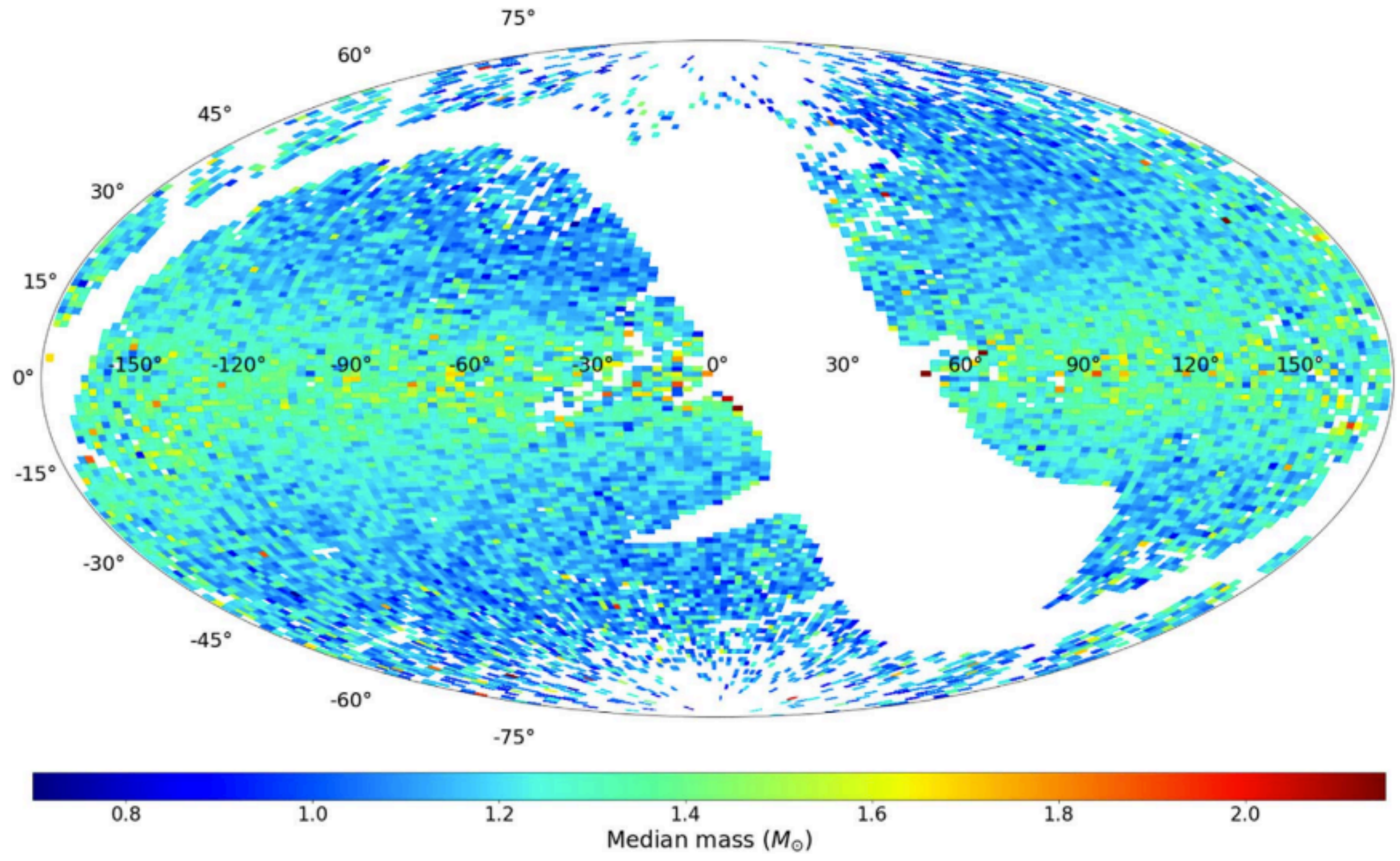


The asteroseismic revolution

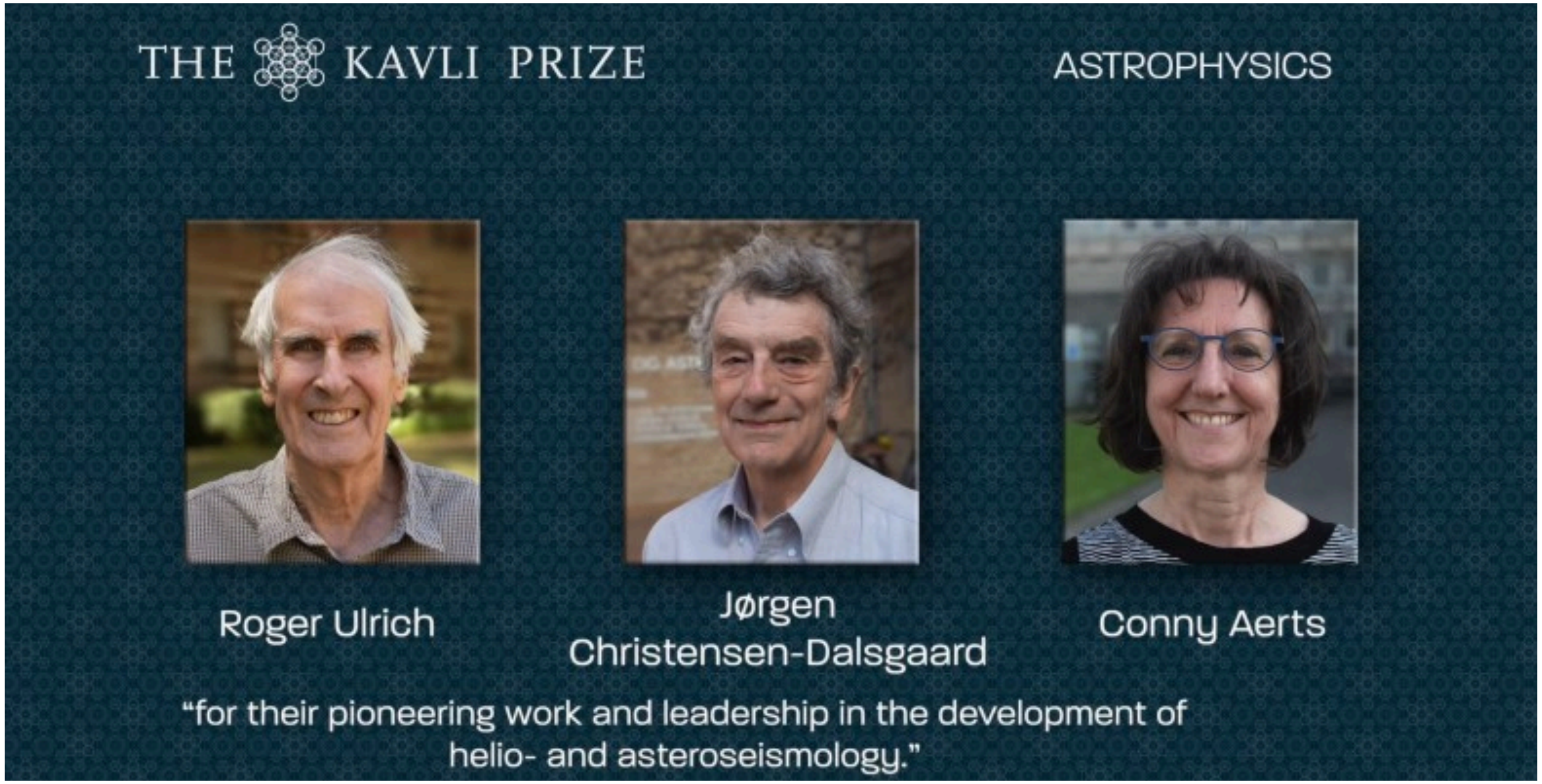
- Characterize exoplanet hosts —> better planet parameters

- Galactic archaeology —> map the structure and evolution of the Milky Way

more massive stars
live in the Galactic disk:



Is a Nobel for helio/asteroseismology close?



What we do

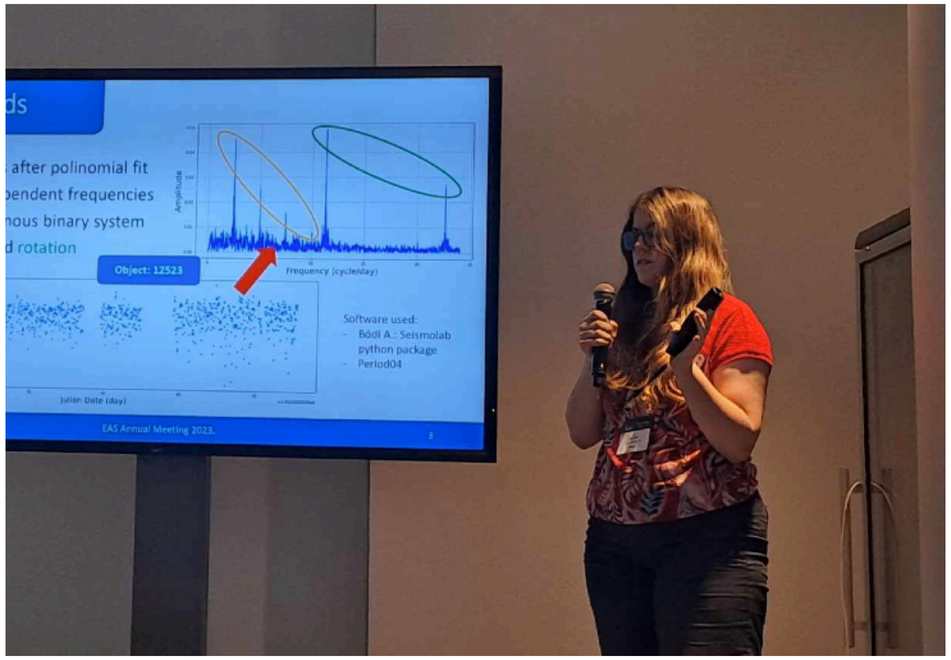
The SeismoLab group

SeismoLab

An Élvonal research excellence project

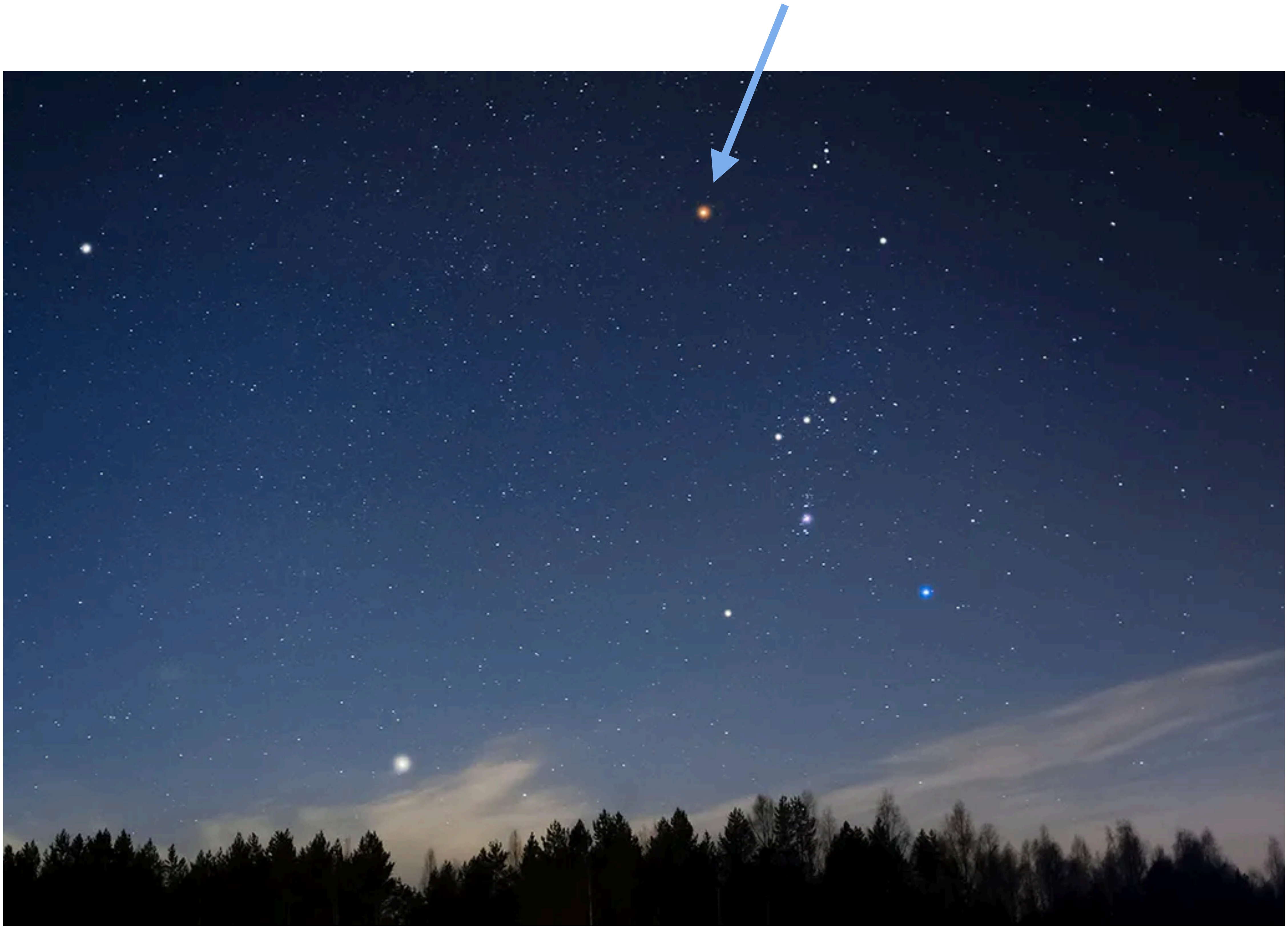
nkfih

Plus all the juniors



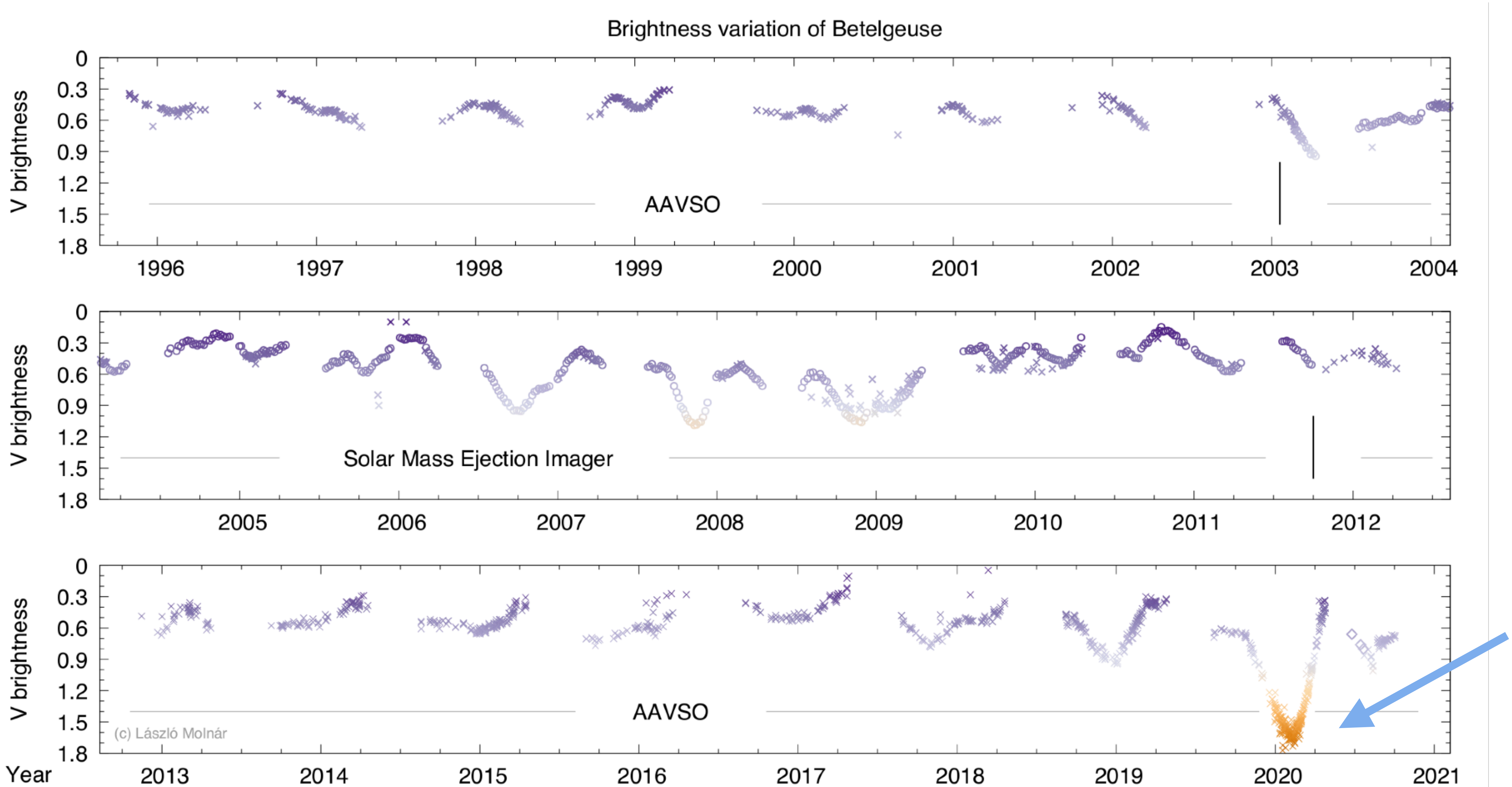
Csilla Kalup, Rozália Ádám,
Vázsony Varga, Dóra Takács,
Anett Simon-Zsók,
Viktória Fröhlich,
Alexandra Grósz,
Balázs Kertész...

Measuring Betelgeuse



Measuring Betelgeuse

- The Great Dimming of 2020 - will it blow up? (...please?)



Measuring Betelgeuse

- Can we explain it with our models?
- No, but we could say a lot of other things!
- Cooperation between me and Meridith Joyce (currently a Marie Curie Widening Fellow at Konkoly)

↑ He works with observational data

↑ She develops stellar models

Measuring Betelgeuse

- We determined the pulsation periods (with added new data)
- We modeled those pulsation periods
- We determined updated values for
  - its birth mass (18-21 M_{Sun}), it's current mass (16-19 M_{Sun})
  - its current radius (764 +- 80 R_{Sun})

Measuring Betelgeuse

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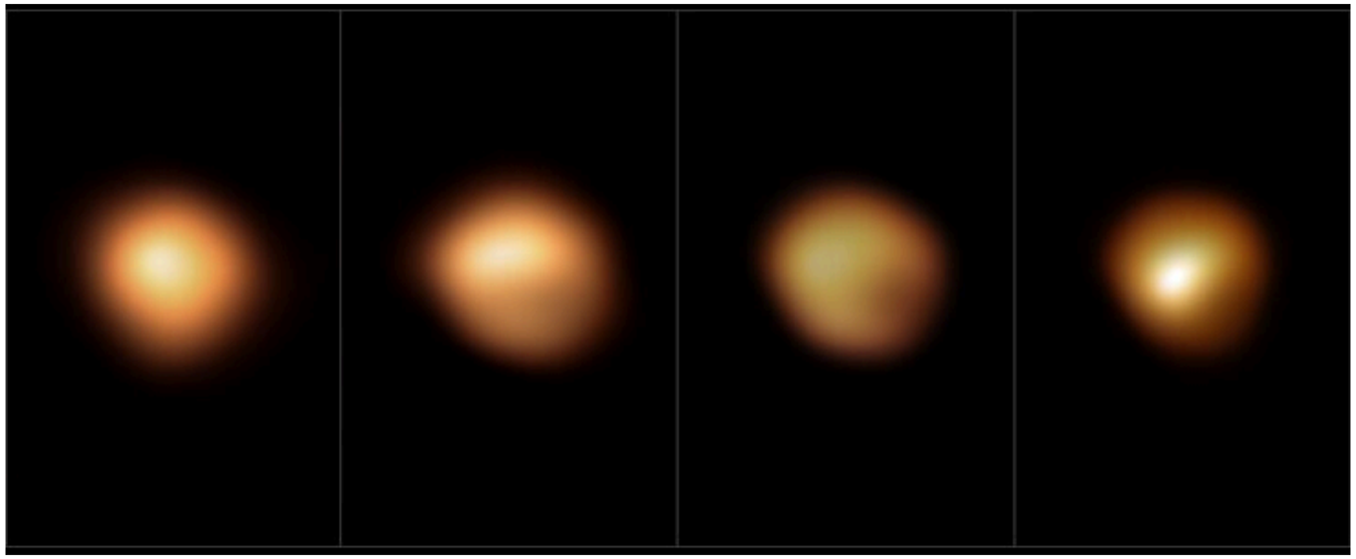
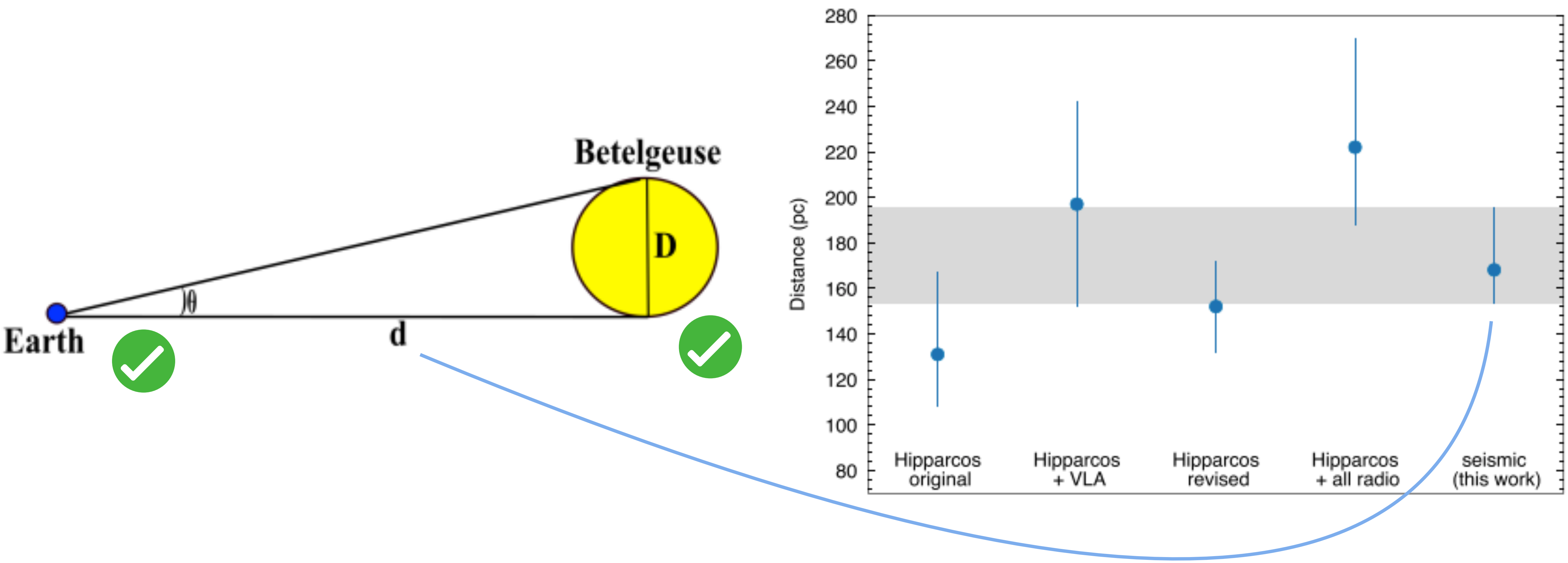
  - its current radius (764 +- 80 R_{Sun})

- But Betelgeuse is big enough to be resolved:



Measuring Betelgeuse

- We calculated its physical radius (764 +- 80 R_{Sun})
- Others have measured its apparent diameter on the sky (43 mas)
- —> we have a new way to measure its distance!



...ing Betelgeuse

...adius (764 +- 80 R_{Sun})

...parent diameter on the sky (43 mas)

...asure its distance!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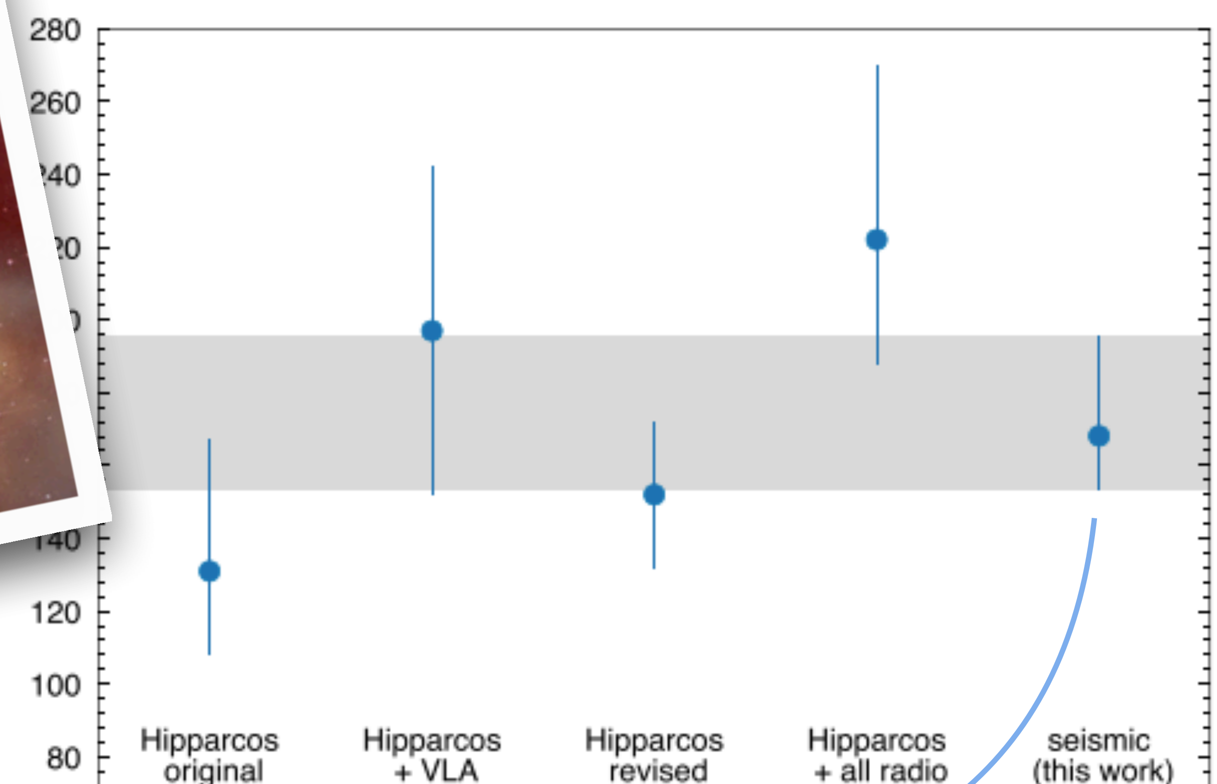
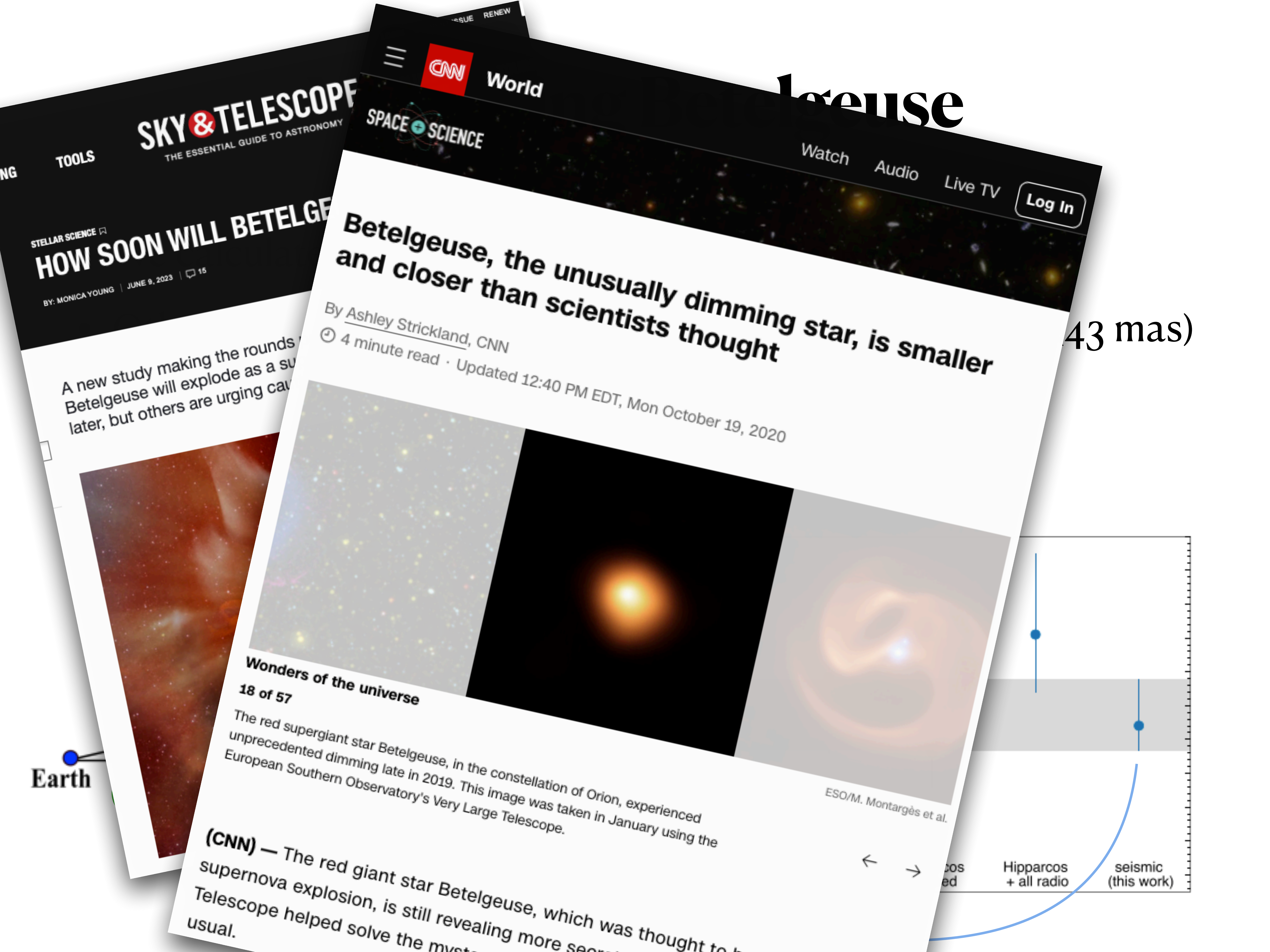
HOW SOON WILL BETELGEUSE BLOW?

BY: MONICA YOUNG | JUNE 9, 2023 | 15

A new study making the rounds predicts that supergiant Betelgeuse will explode as a supernova sooner rather than later, but others are urging caution.

Earth

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Betelgeuse, the unusually dimming star, is smaller and closer than scientists thought
By Ashley Strickland, CNN
4 minute read · Updated 12:40 PM EDT, Mon October 19, 2020
Wonders of the universe
18 of 57
The red supergiant star Betelgeuse, in the constellation of Orion, experienced unprecedented dimming late in 2019. This image was taken in January using the European Southern Observatory's Very Large Telescope.
ESO/M. Montargès et al.
(CNN) — The red giant star Betelgeuse, which was thought to
supernova explosion, is still revealing more
Telescope helped solve the myst
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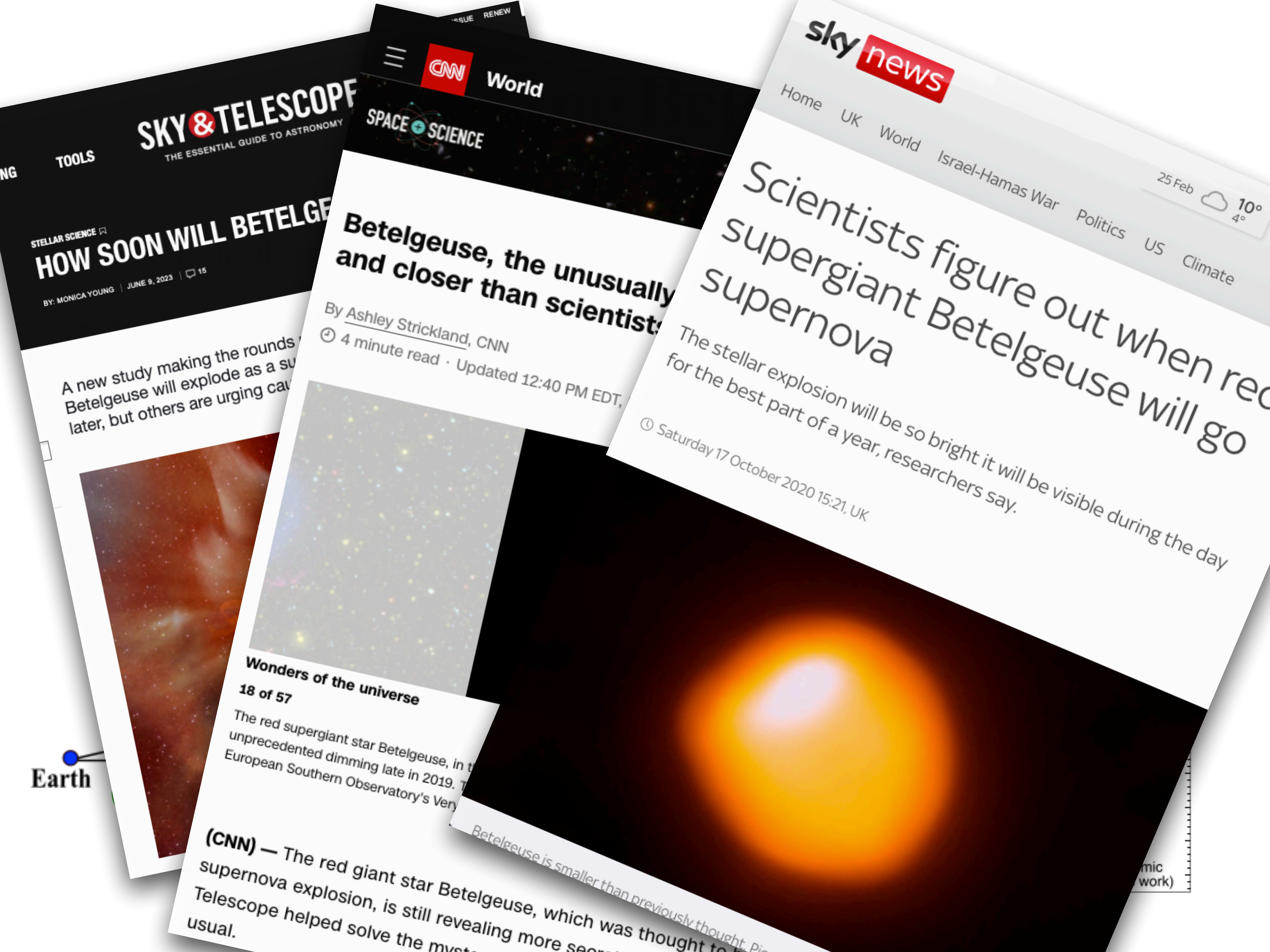
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Telescope helped solve the
usual.
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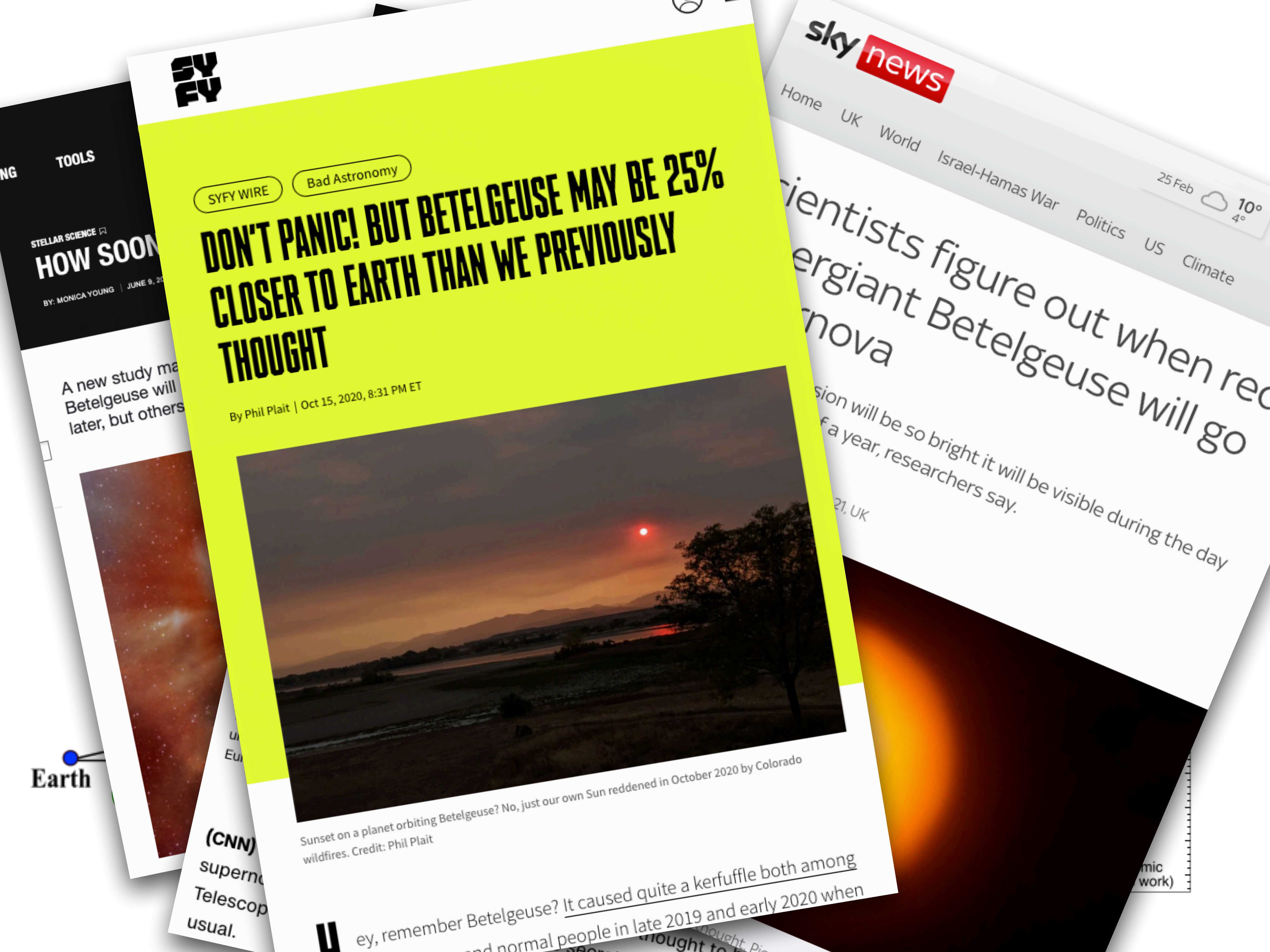
25 Feb 10° 4°
Scientists figure out when red supergiant Betelgeuse will go supernova
The stellar explosion will be so bright it will be visible during the day for the best part of a year, researchers say.
Saturday 17 October 2020 15:21, UK
Betelgeuse is smaller than previously thought.



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DON'T PANIC! BUT BETELGEUSE MAY BE 25% CLOSER TO EARTH THAN WE PREVIOUSLY THOUGHT
By Phil Plait | Oct 15, 2020, 8:31 PM ET
Sunset on a planet orbiting Betelgeuse? No, just our own Sun reddened in October 2020 by Colorado wildfires. Credit: Phil Plait
Hey, remember Betelgeuse? It caused quite a kerfuffle both among
and normal people in late 2019 and early 2020 when
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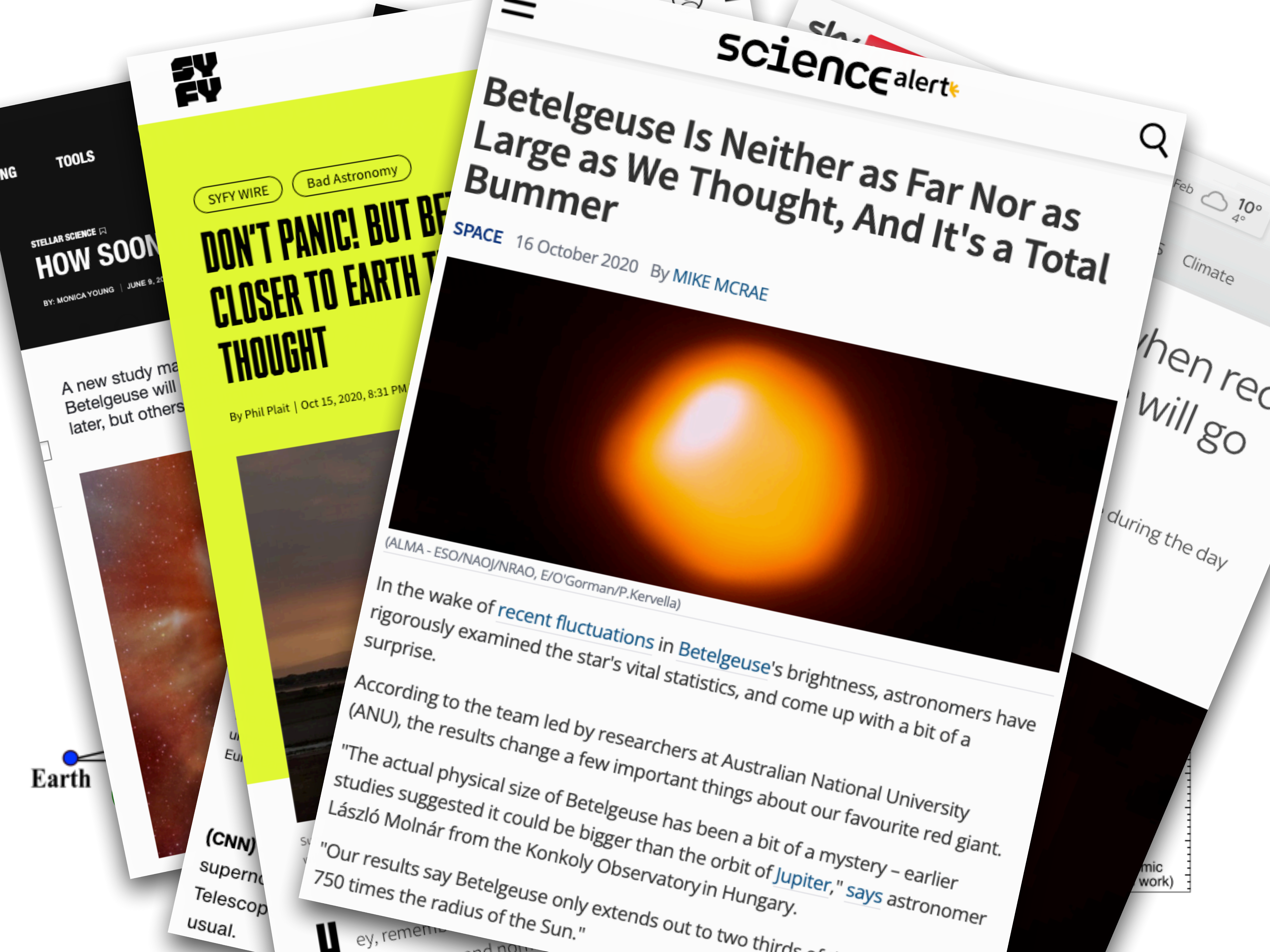

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science alert
Betelgeuse Is Neither as Far Nor as Large as We Thought, And It's a Total Bummer
SPACE 16 October 2020 By MIKE MCRAE
(ALMA - ESO/NAOJ/NRAO, E/O'Gorman/P.Kervella)
In the wake of recent fluctuations in Betelgeuse's brightness, astronomers have rigorously examined the star's vital statistics, and come up with a bit of a surprise.
According to the team led by researchers at Australian National University (ANU), the results change a few important things about our favourite red giant.
"The actual physical size of Betelgeuse has been a bit of a mystery – earlier studies suggested it could be bigger than the orbit of Jupiter," says astronomer László Molnár from the Konkoly Observatory in Hungary.
"Our results say Betelgeuse only extends out to two thirds of
750 times the radius of the Sun."
Feb 10° 4°
Climate
hen re
will go
during the day

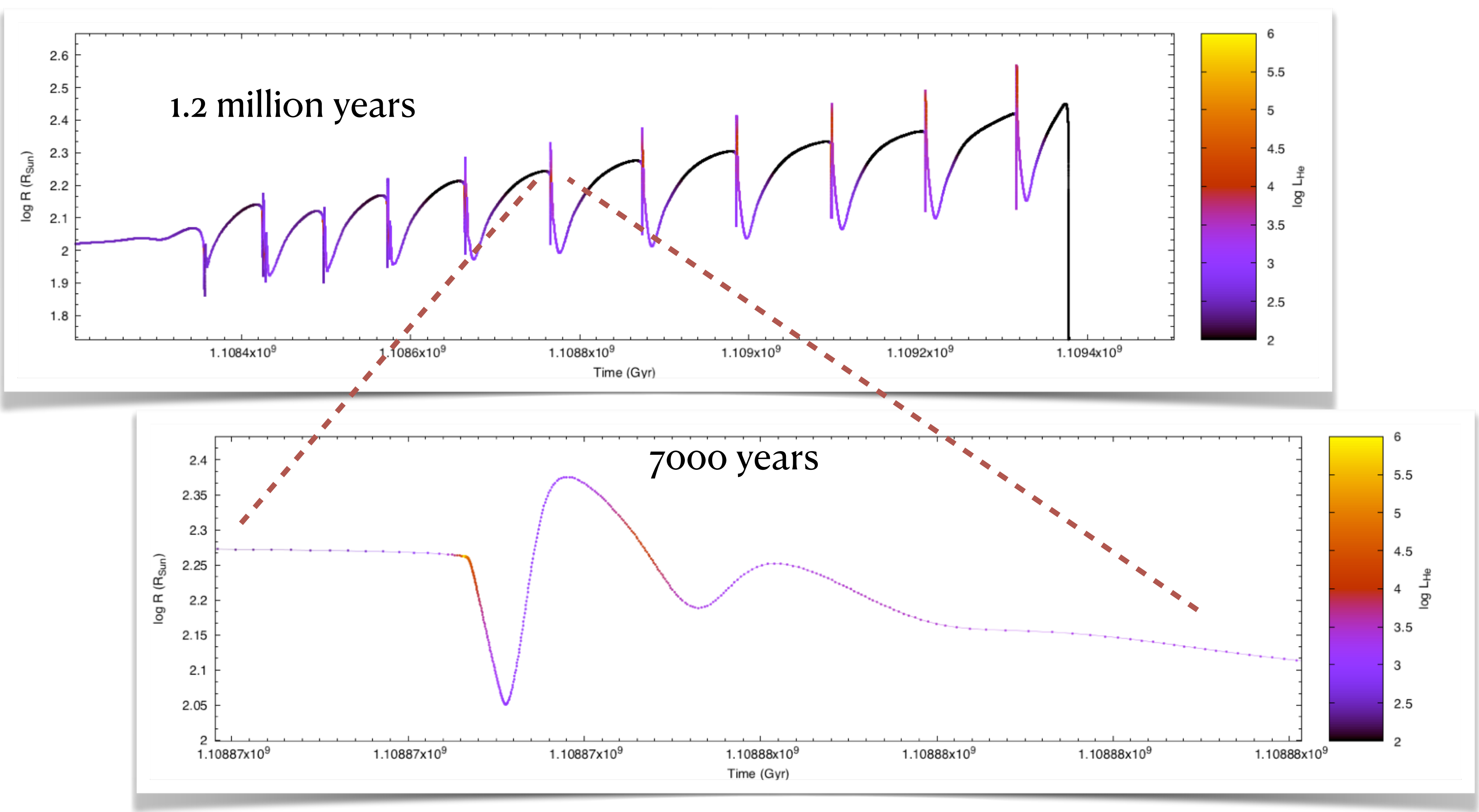
Hope to be in the news again with more discoveries!

Thank you for your attention!

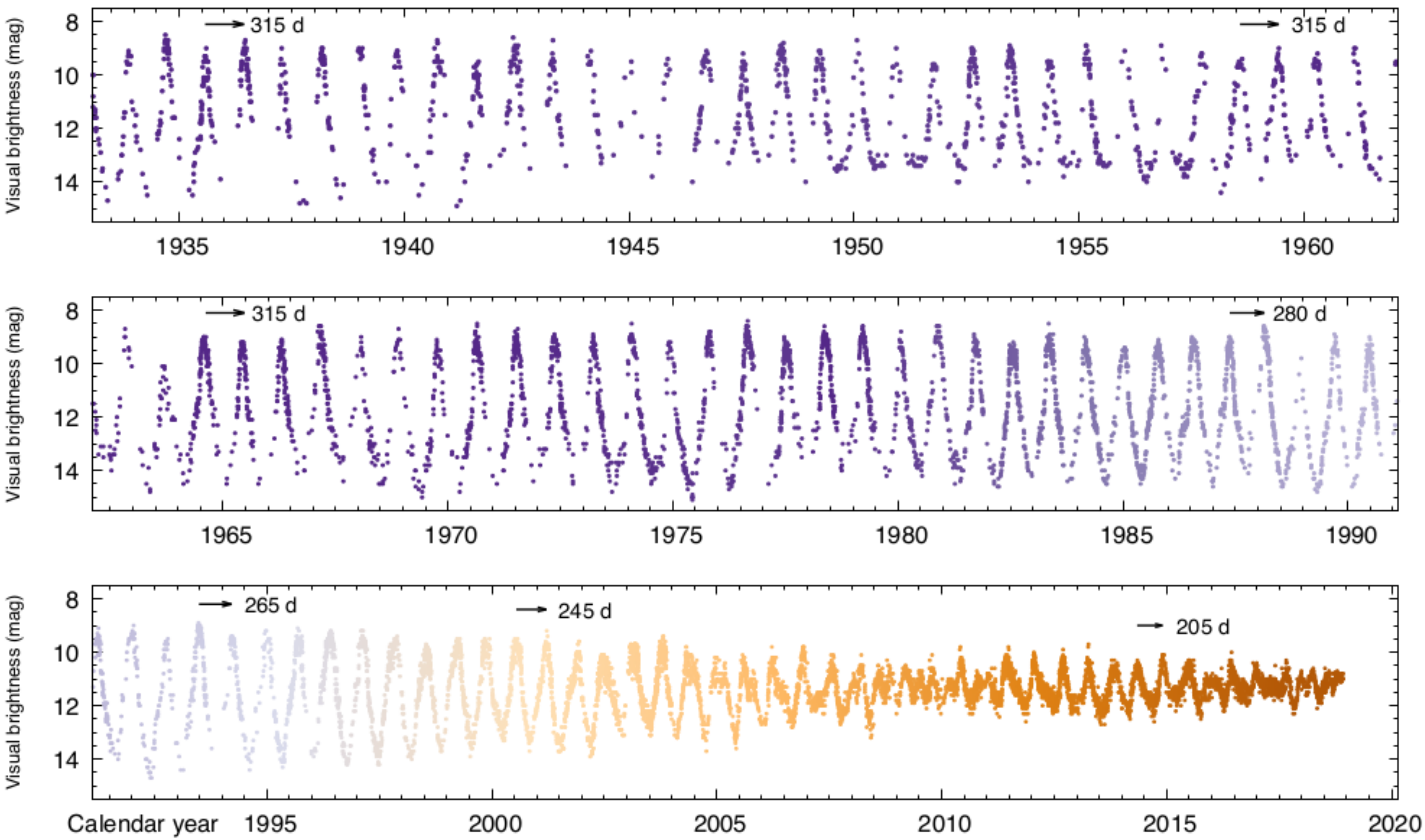
SeismoLab KONKOLY HUN REN CSFK

Stellar evolution in real time

- End of the red giant life: H-shell burning around the inert core
  - quite unstable: He shell periodically ignites violently



- T Ursae Minoris:
  a Mira variable whose period suddenly started to drop



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