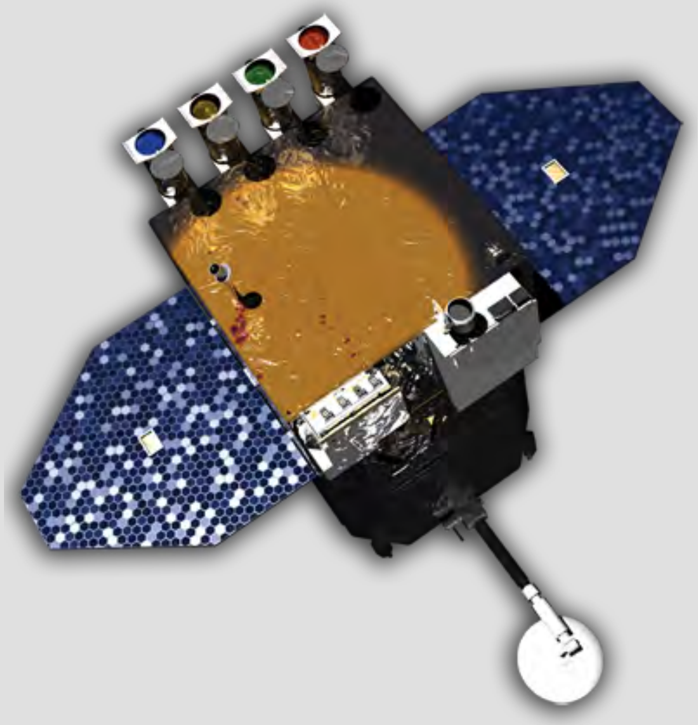
Helioseismology and Asteroseismology: Oscillations from Space



W. Dean Pesnell

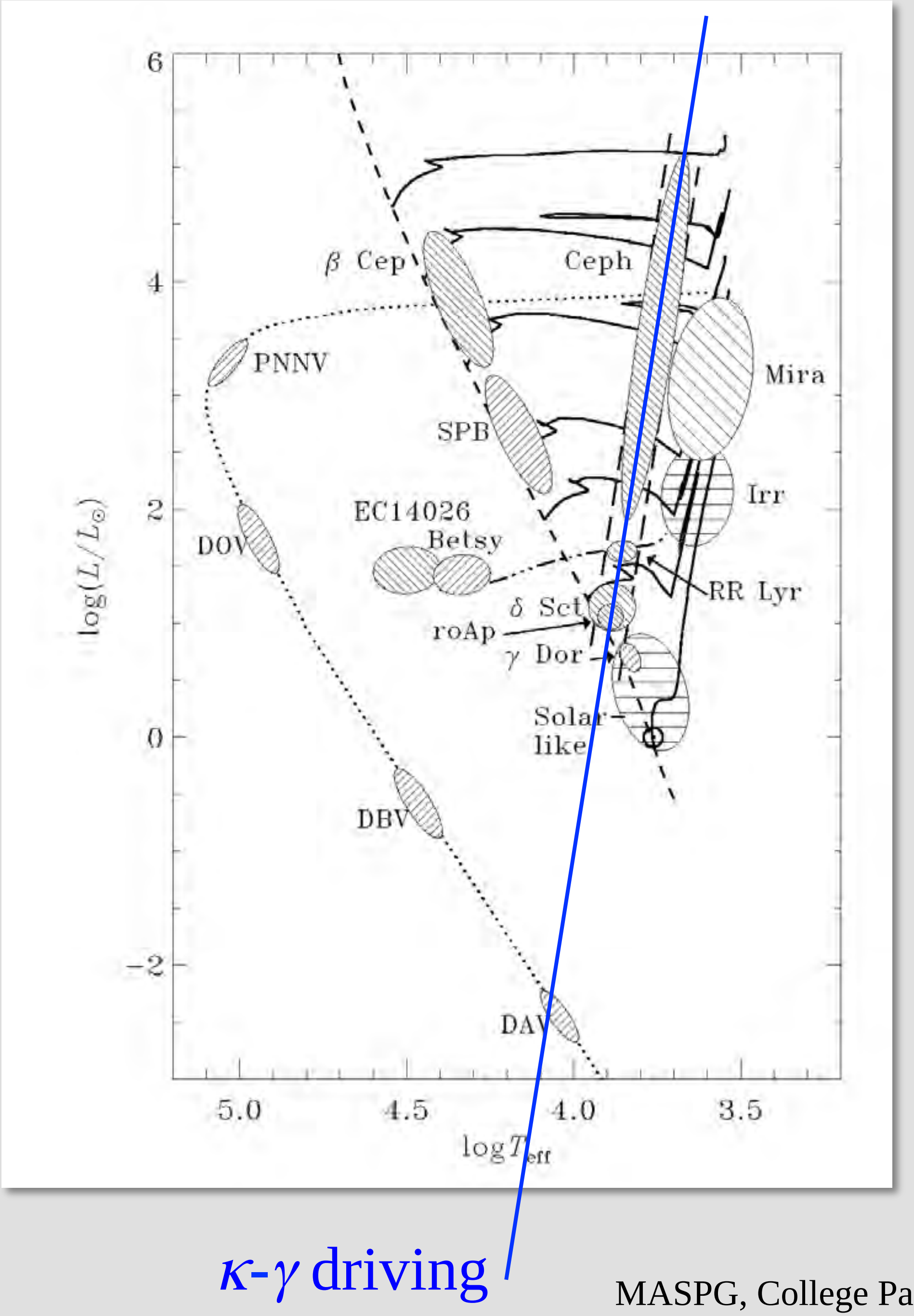
Project Scientist

Solar Dynamics Observatory

- What are variable stars?
- How do we observe variable stars?
- Interpreting the observations
- Results from the Sun by MDI & HMI
- Other stars (Kepler, CoRoT, and MOST)

What are Variable Stars?

Pulsating stars in the H-R diagram



κ-*γ* driving

Variable stars cover the H-R diagram. Their periods tend to be short going to the lower left and long going toward the upper right. Many variable stars lie along a line where a resonant radiative instability called the *κ*-*γ* effect pumps the oscillation.

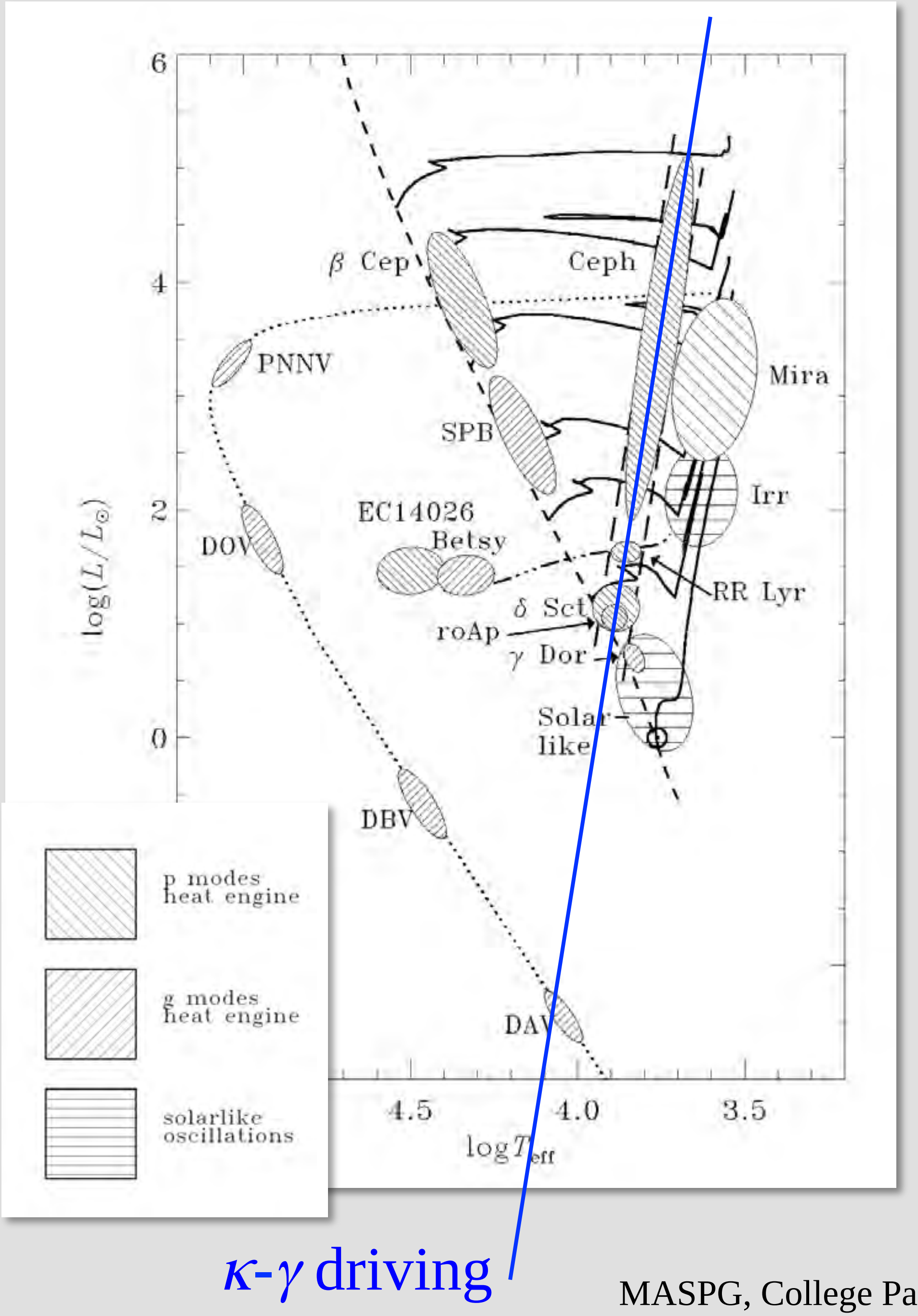
Figures from J. Christensen-Dalsgaard

Pulsating Star Classes

Name	log P (days)	Δm_V	Comments
Cepheids	1.1	0.9	Radial, distance indicator
RR Lyrae	-0.3	0.9	Radial, distance indicator
Type II Cepheids	-1.0	0.6	Radial, confusers
β Cephei	-0.7	0.1	Multi-mode, opacity
δ Scuti	-1.1	<0.9	Nonradial
DAV, ZZ Ceti	-2.5	0.12	g modes, most common
DBV, DOV	-2.5	0.1	g modes
PNNV	-2.5	0.05	g modes, very hot ($T_{\mathrm{eff}} \sim 10^5$ K)
Sun	-2.6	0.01%	p modes

See GCVS Variability Types at http://www.sai.msu.su/groups/cluster/gcvs/gcvs/iii/vartype.txt

What makes them oscillate?

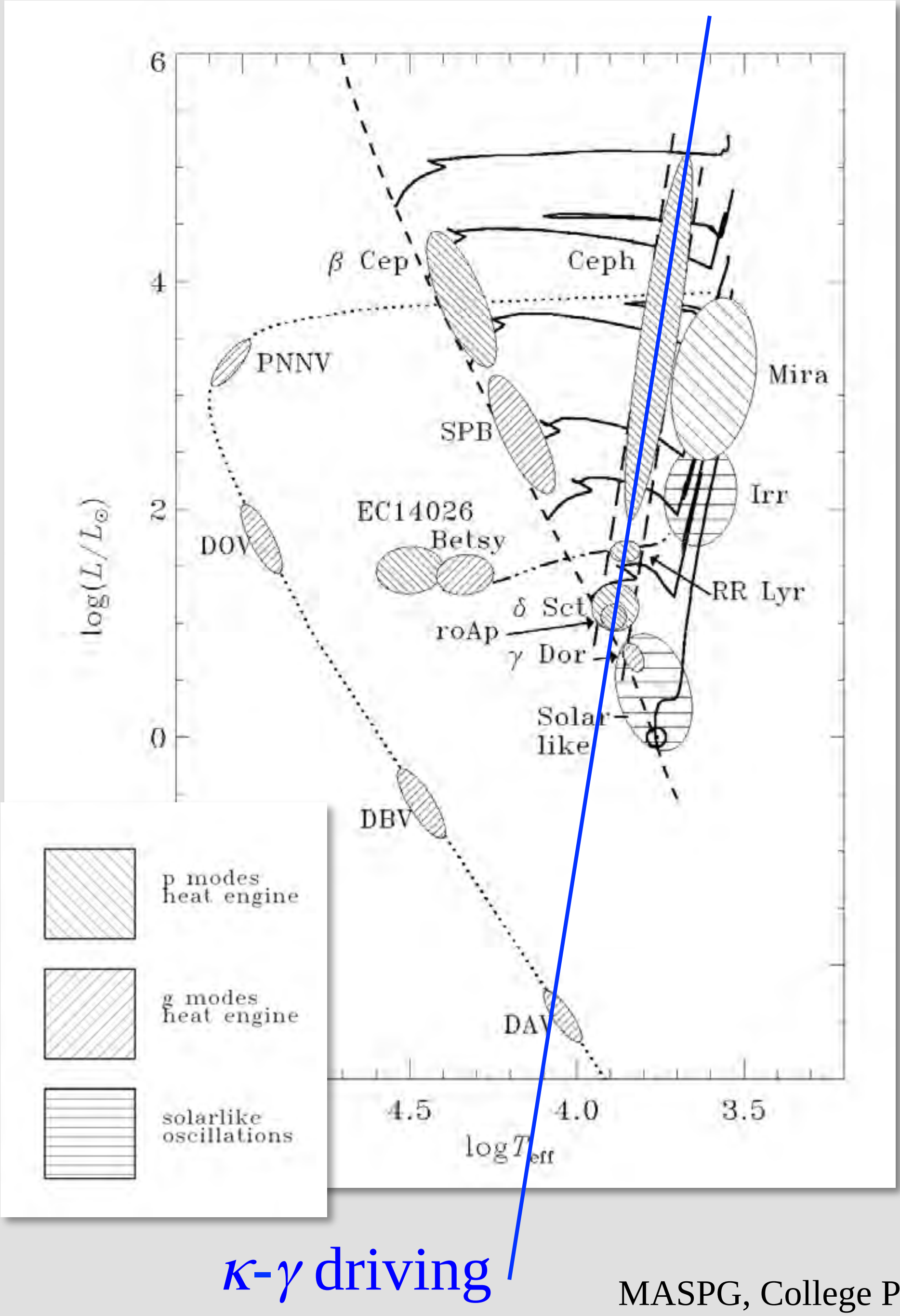


Many variants of the κ-γ effect, a resonant interaction of the oscillation with the luminosity of the star.

The nuclear reactions in the convective core of massive stars may limit the maximum mass of a star.

Solar-like oscillations are driven by stochastic excitation at the top of the convection zone (blobs crashing into the photosphere)

What makes them oscillate?

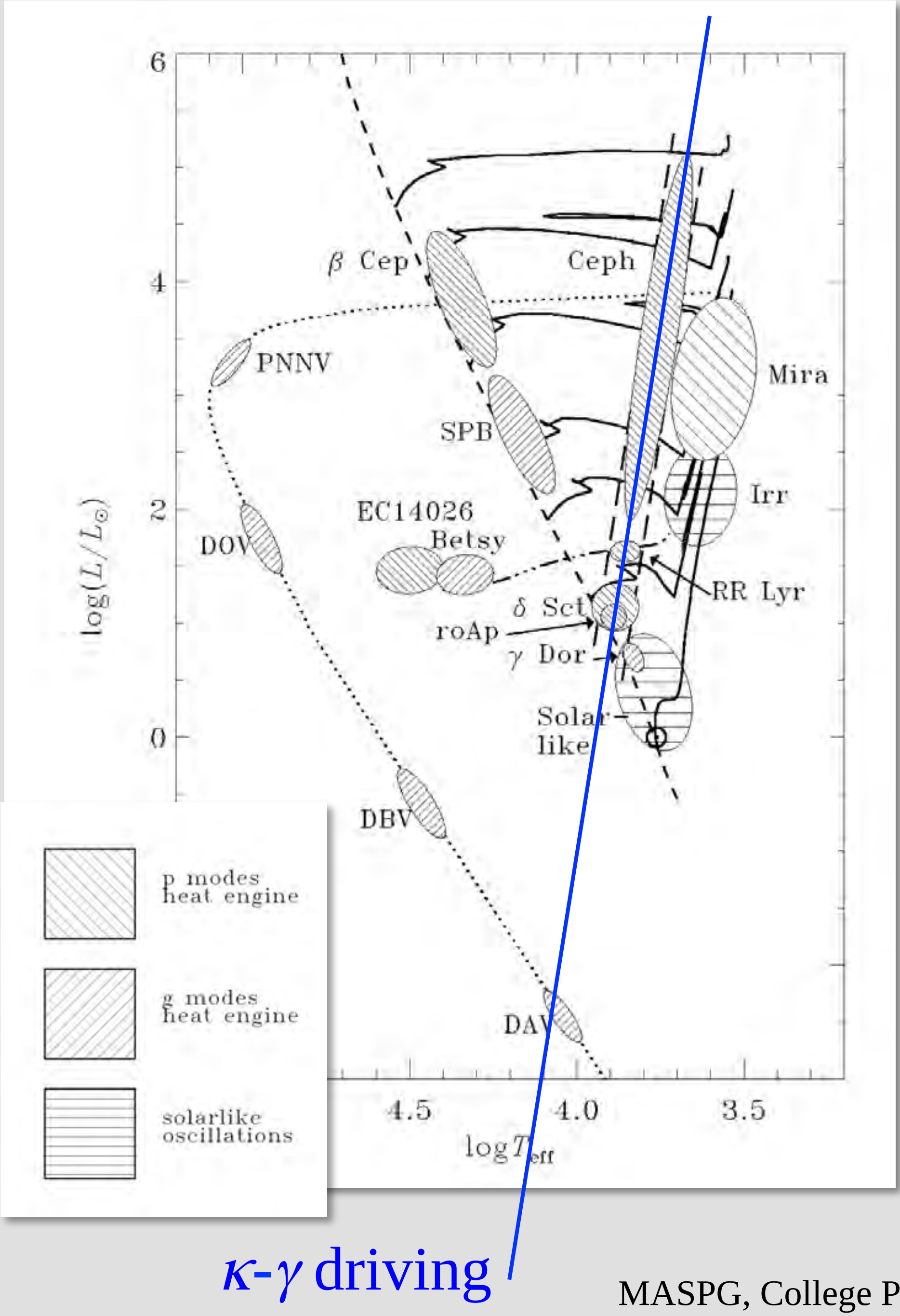



© Peter Gowland

The κ-γ effect is like pumping your legs to swing higher

of the convection zone (blobs crashing into the photosphere)

What makes them oscillate?



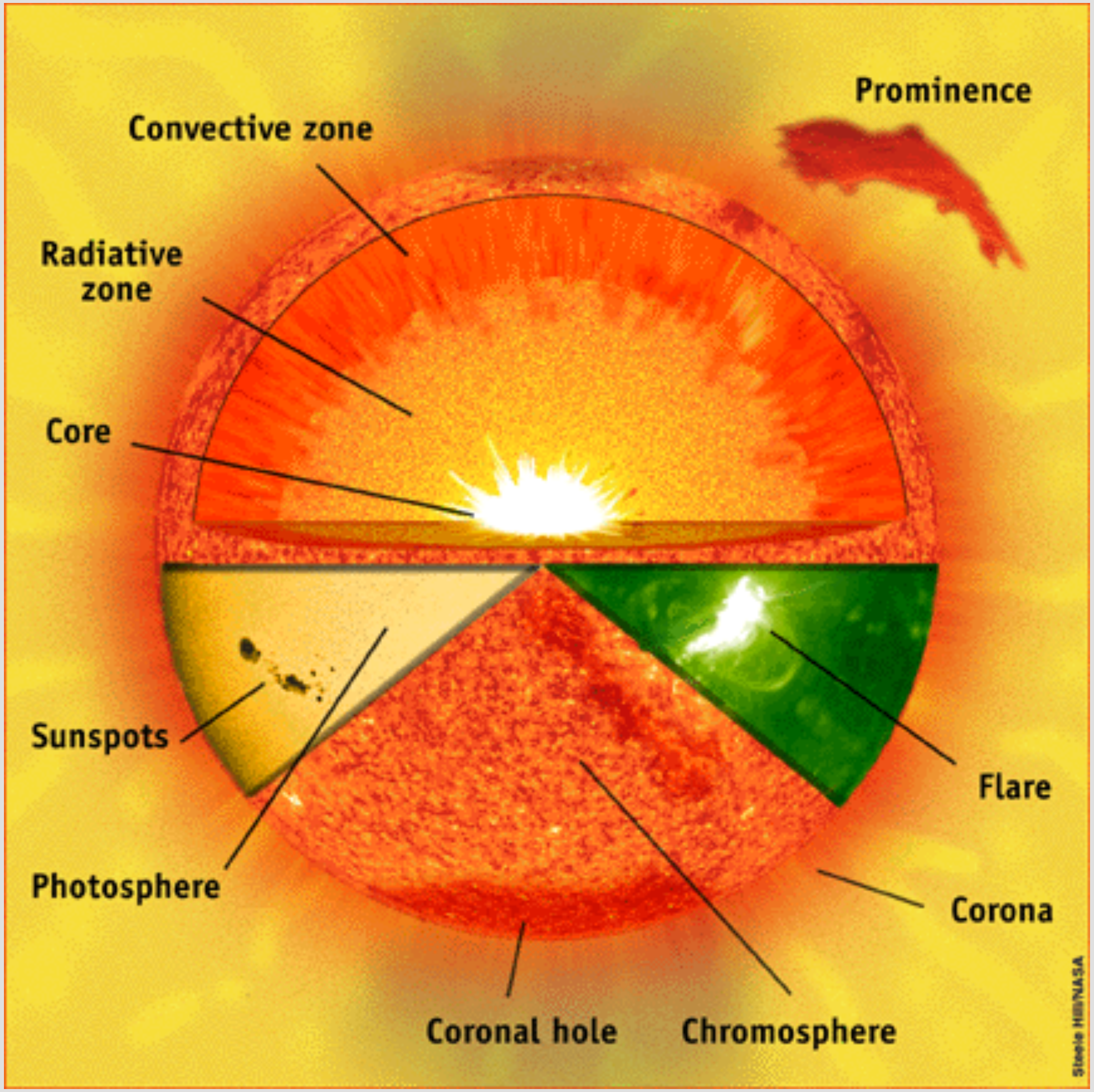
Helioseismology is like thunking a watermelon

iven by stochastic excitation at the top of the convection zone (blobs crashing into the photosphere)

Our Sun

Oscillations are seen in the photosphere, chromosphere, and corona of the Sun. The early results showing 5 min. periods were discussed as coming from all of these places.

p-modes propagating through the interior of the Sun were identified as the cause of the oscillations. Although their nature was known, the excitation and lifetime is still under study.



Steele Hill/NASA

How do we observe variable stars?

What can we measure in stars?

Period

Amplitude

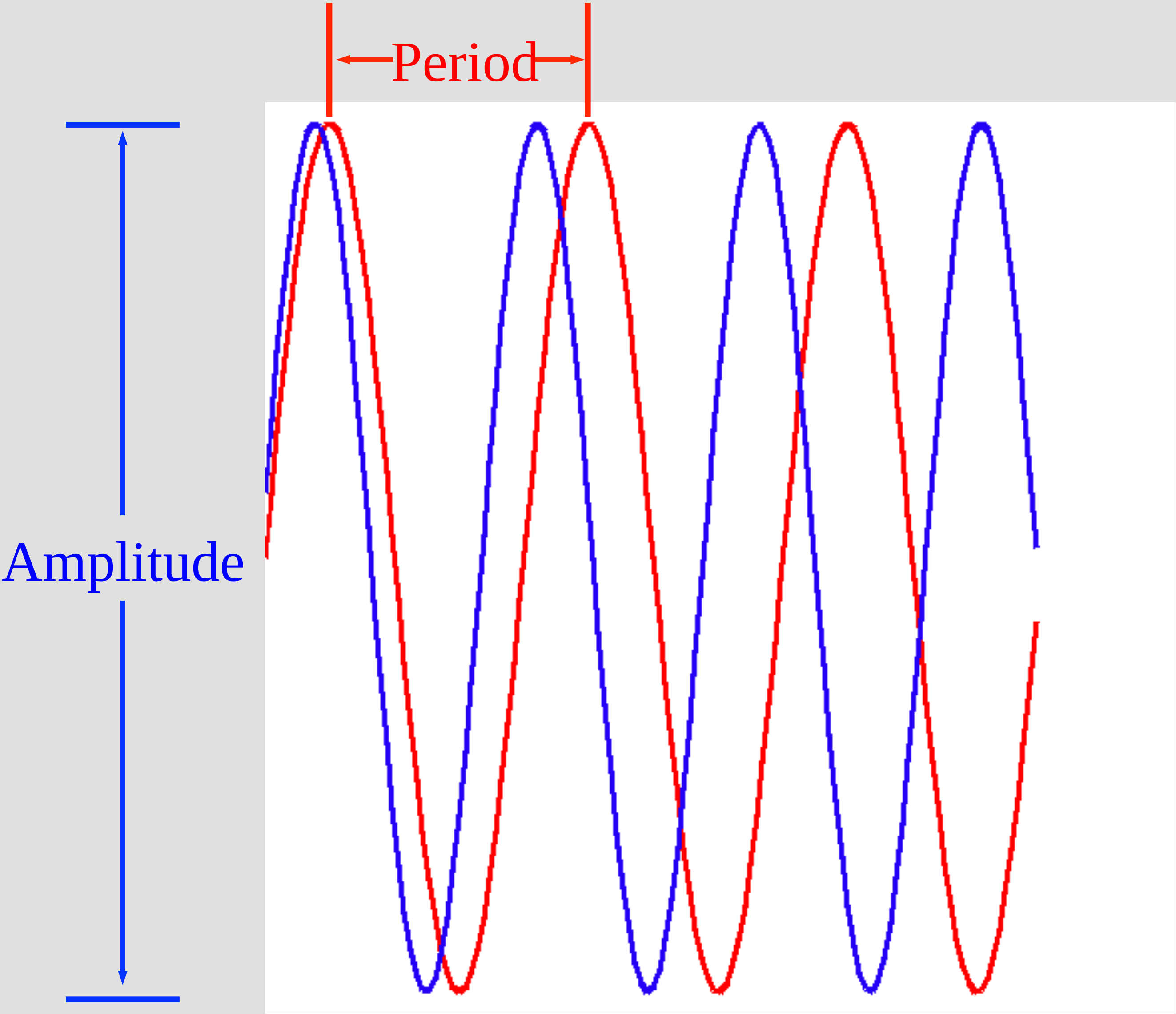
Decay (lifetime)

Infer:

Size and mass

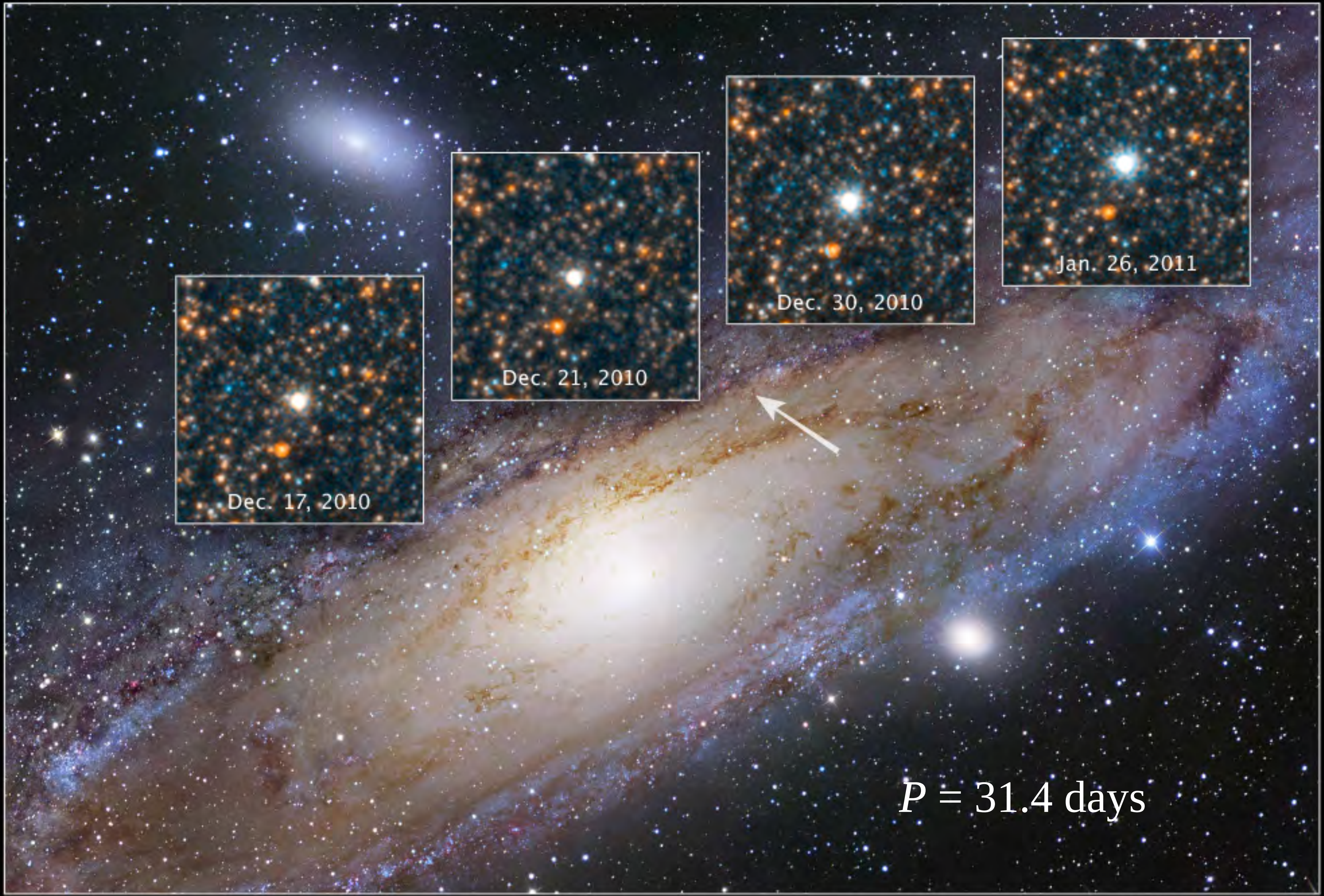
Age

Evolution state



Cepheid Variable Star V1 in M31

Hubble Space Telescope ▪ WFC3/UVIS

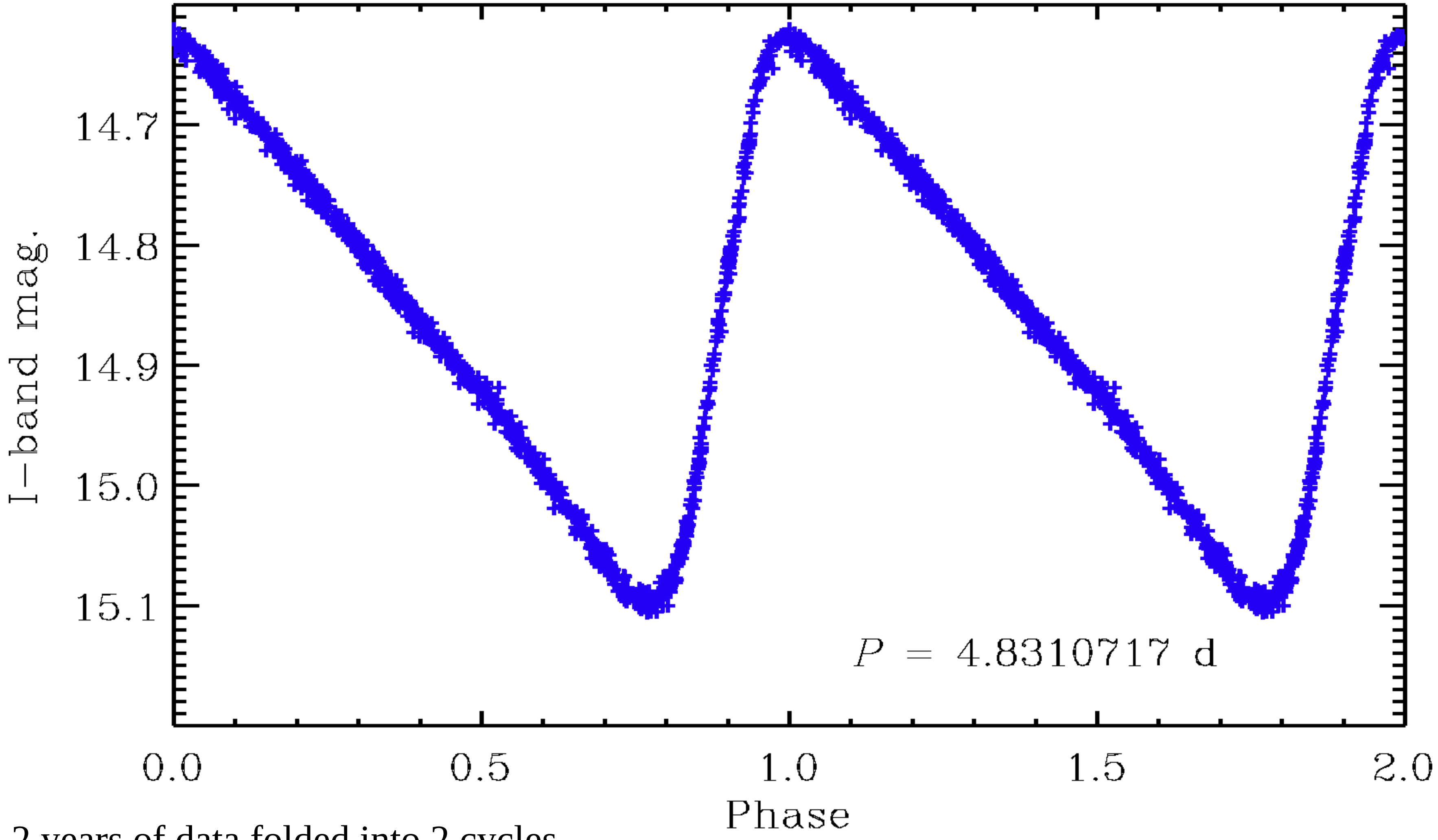


$P = 31.4$ days

NASA, ESA, and the Hubble Heritage Team (STScI/AURA)

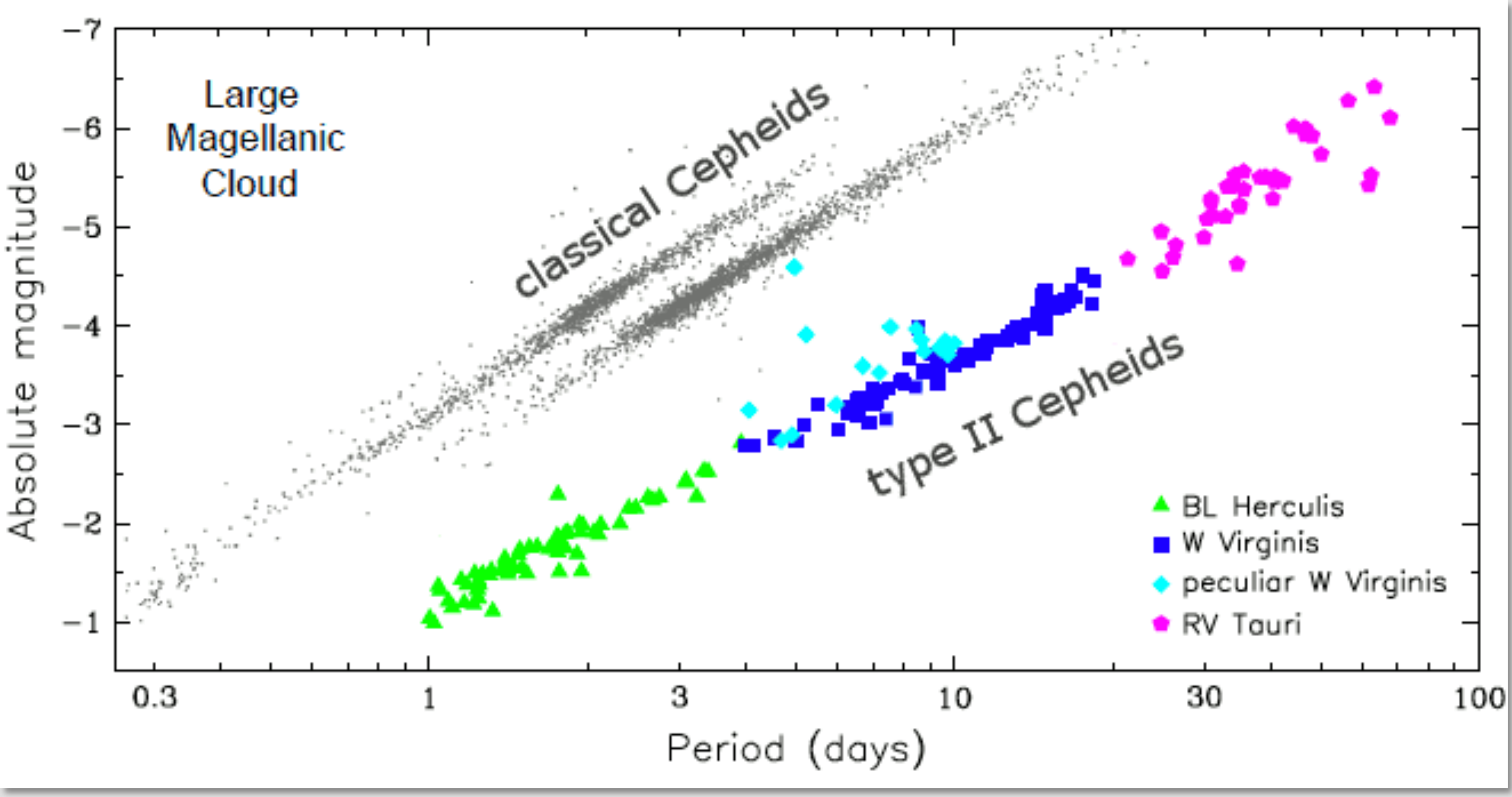
STScI-PRC11-15a

OGLE-LMC-CEP-1778

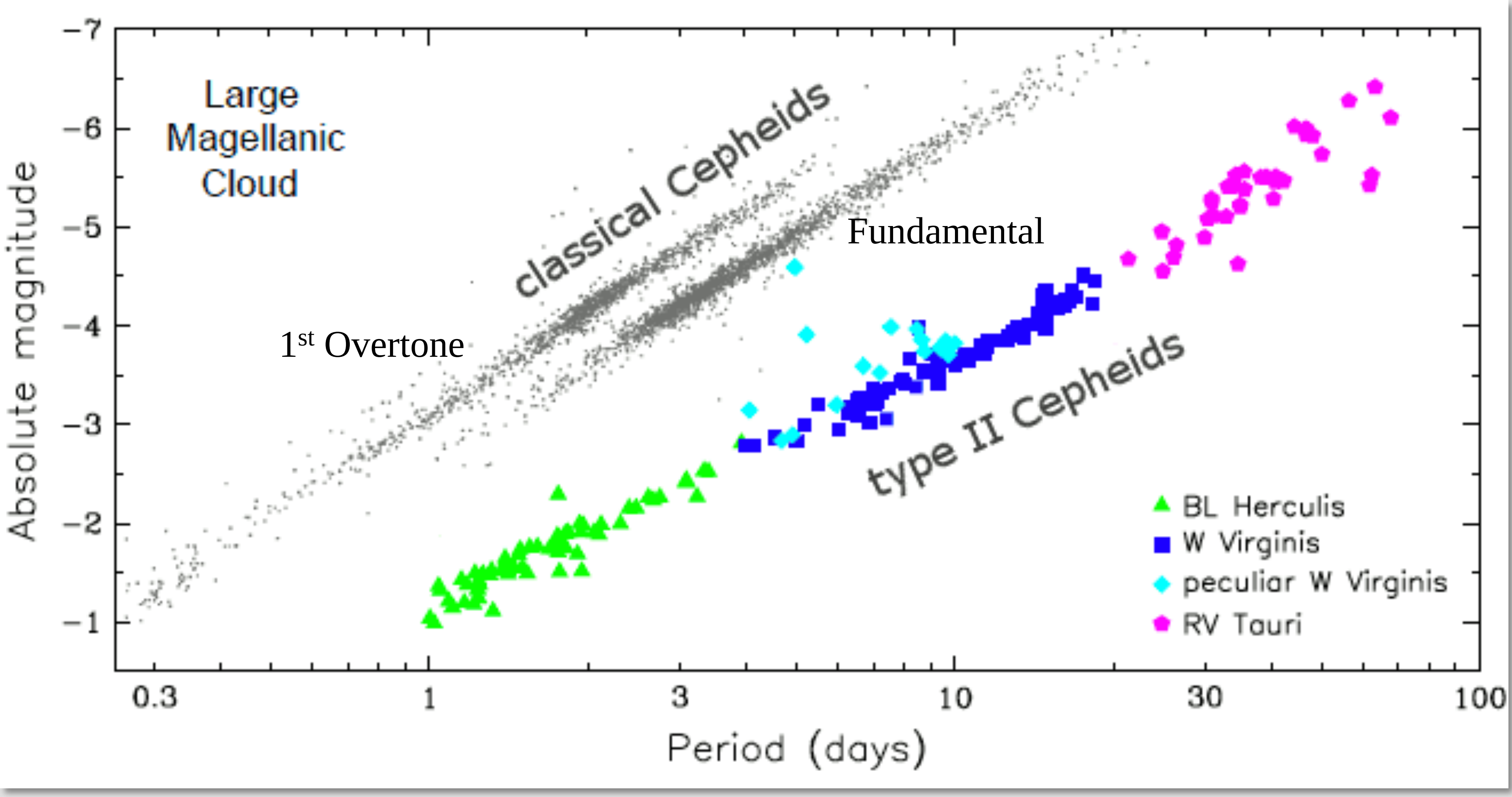


11.2 years of data folded into 2 cycles

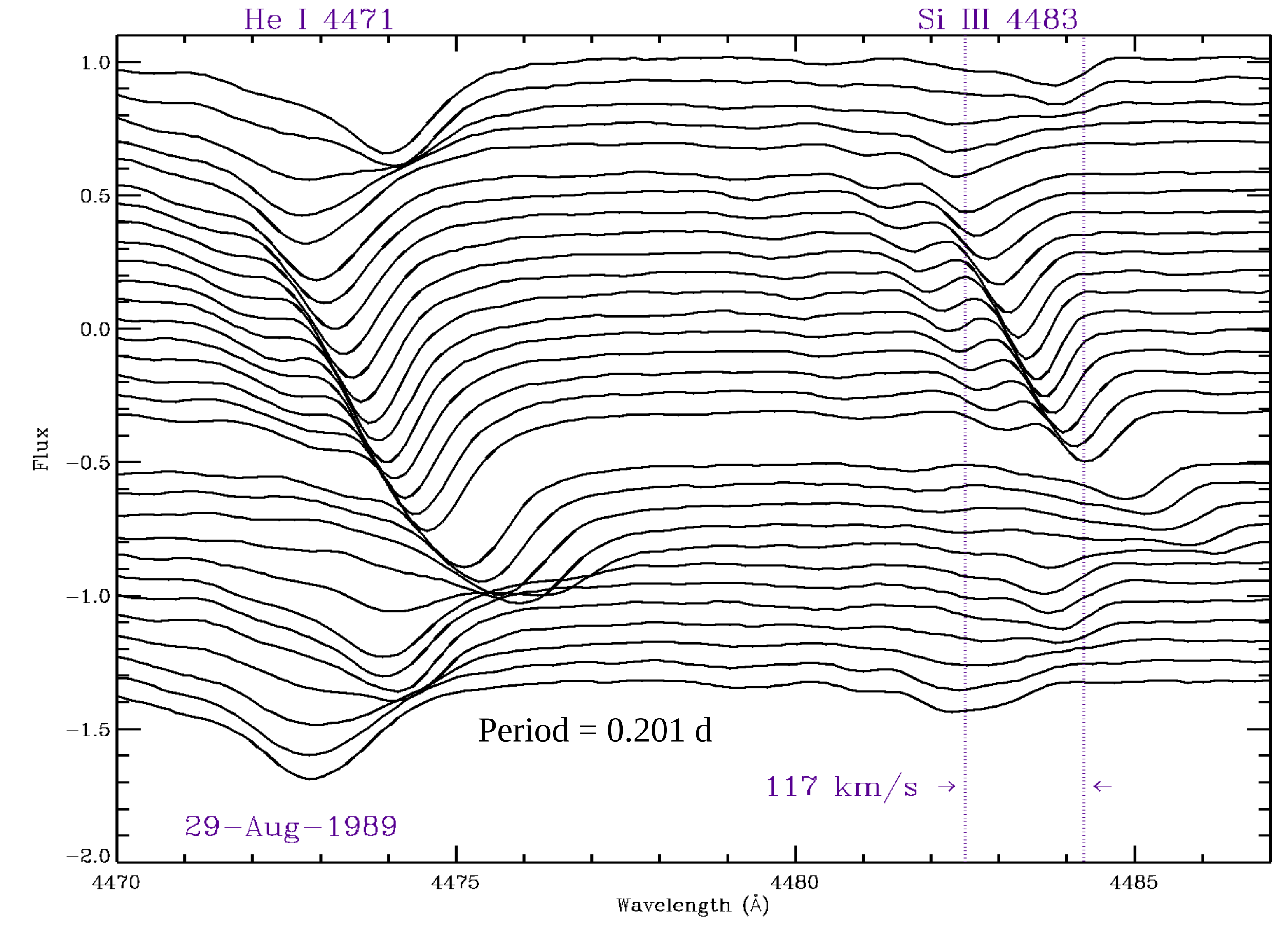
Period-Luminosity Relationship



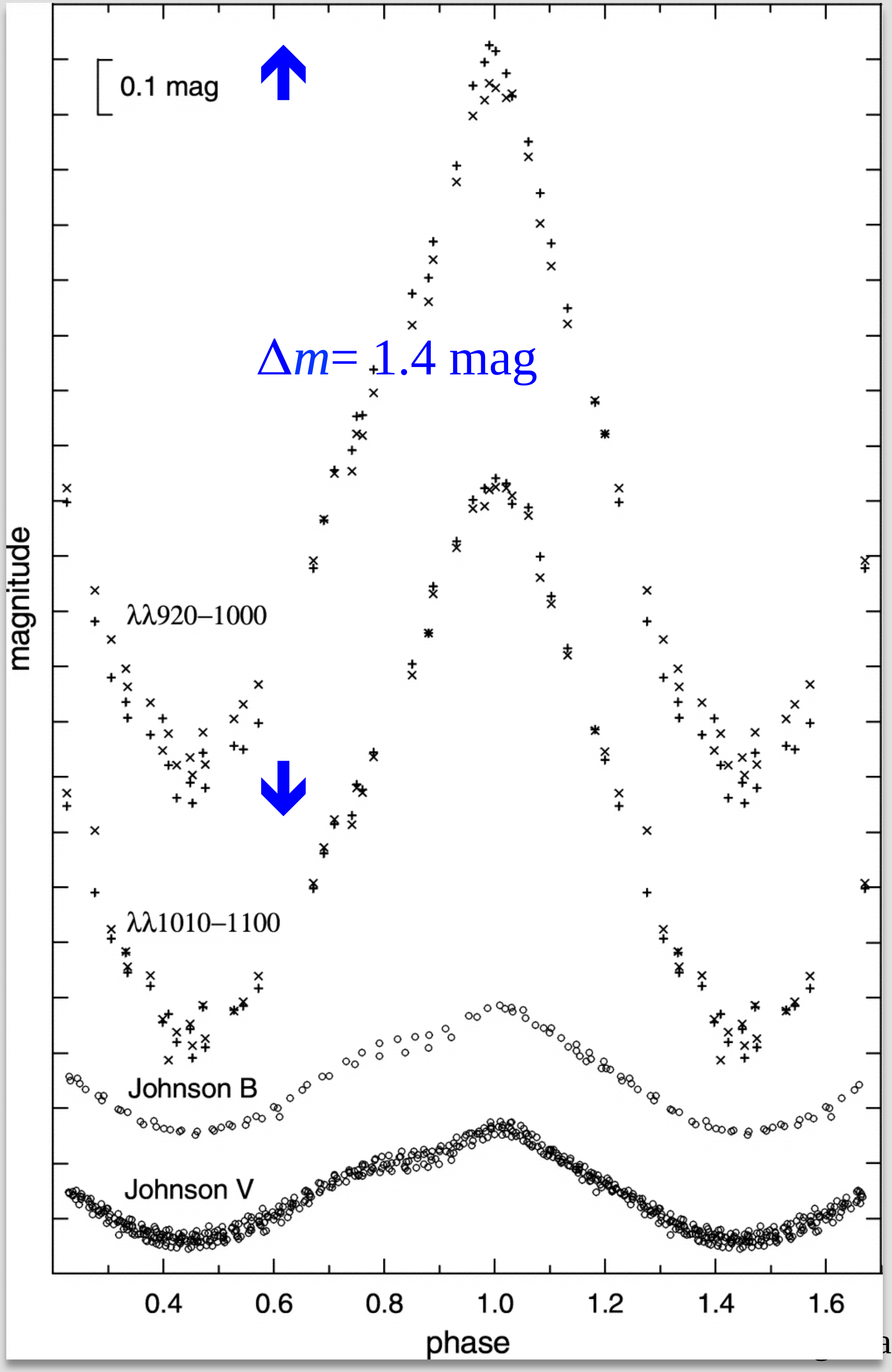
Period-Luminosity Relationship



Spectroscopy of BW Vul, a β Cephei Star



More BW Vul



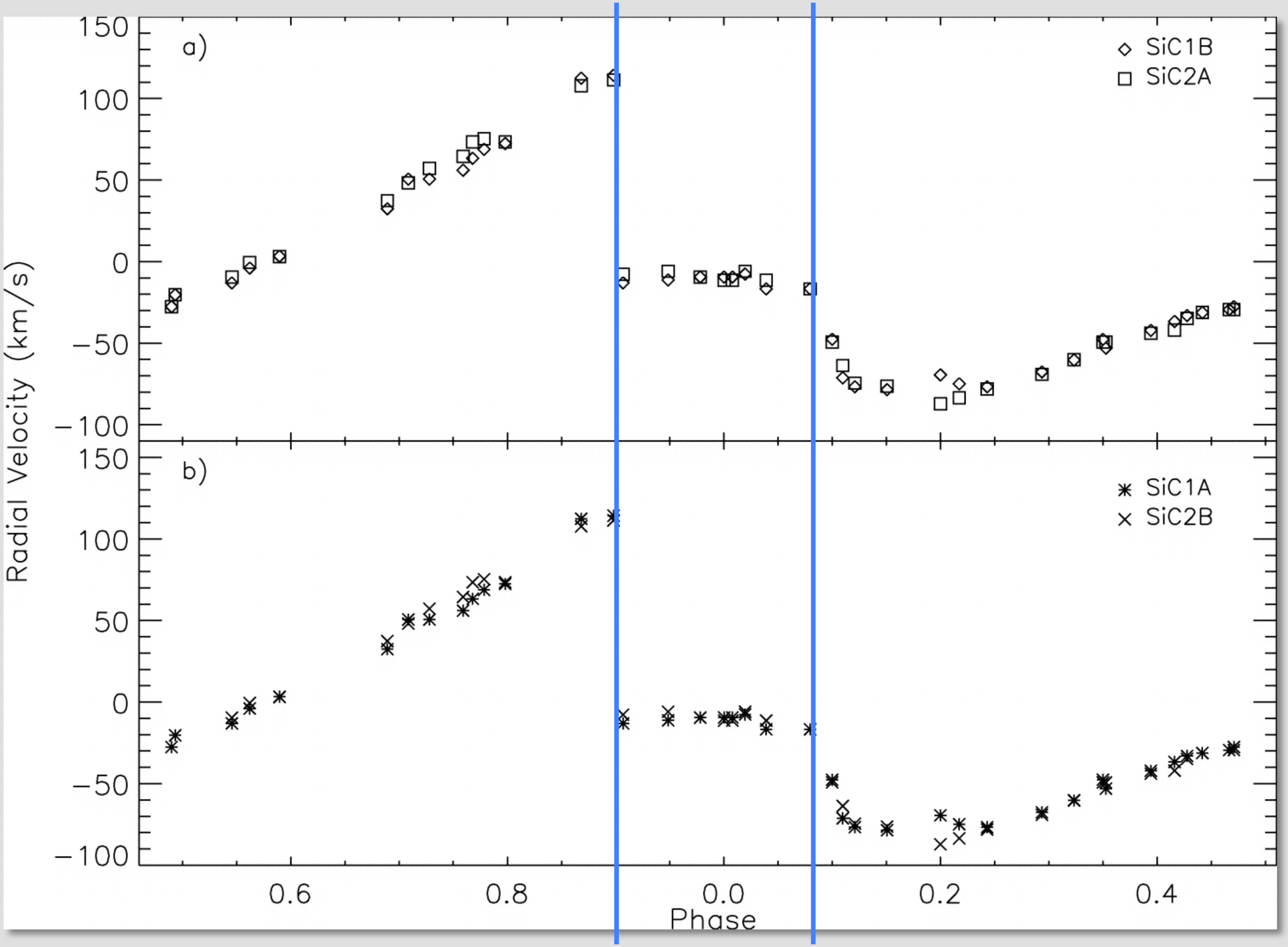
Other people looked at BW Vul in visible and FUSE UV wavelengths. Notice the peak in brightness is at phase 0/1.

A 1.4 mag change is a 28% increase in brightness.

How does brightness track the surface motion?

Smith, Sterken, and Fullerton, 2005, *Ap. J.*, **634**, 1300-1310.

More BW Vul

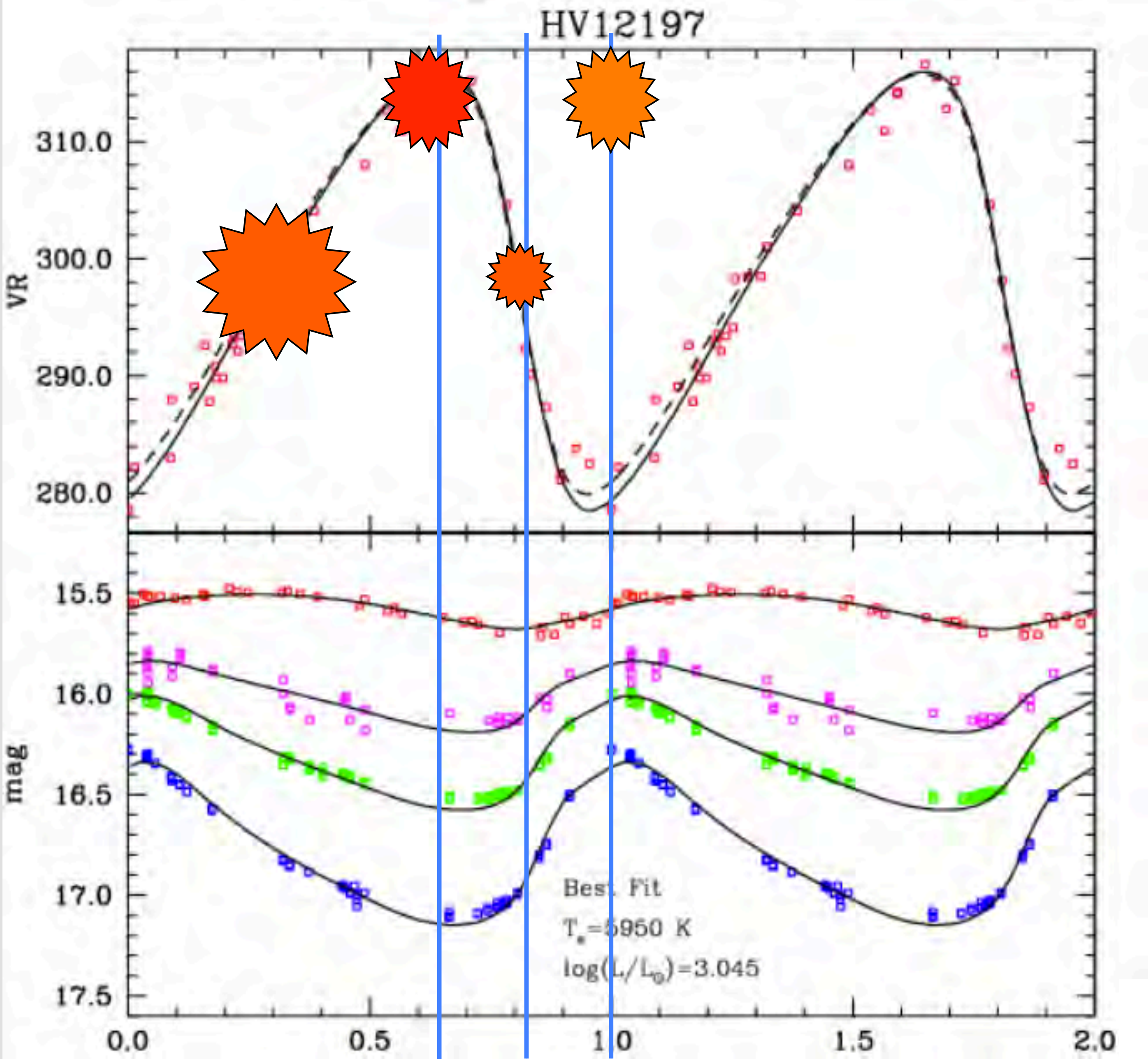


Surface is moving inward and appears to stop at phase 0.9 and moves outward after a period of stillness.

Brightness has a bump at 0.8.

Smith, Sterken, and Fullerton, 2005, *Ap. J.*, **634**, 1300-1310.

Cepheid Velocity



This LMC Cepheid has recent radial velocity curves.

Various peaks are not in phase. Cepheids tend to have there maximum brightness while expanding thru their eq. size.

It is quite red at maximum velocity (minimum brightness), more yellow at the other extreme.

$P = 3.144$ d

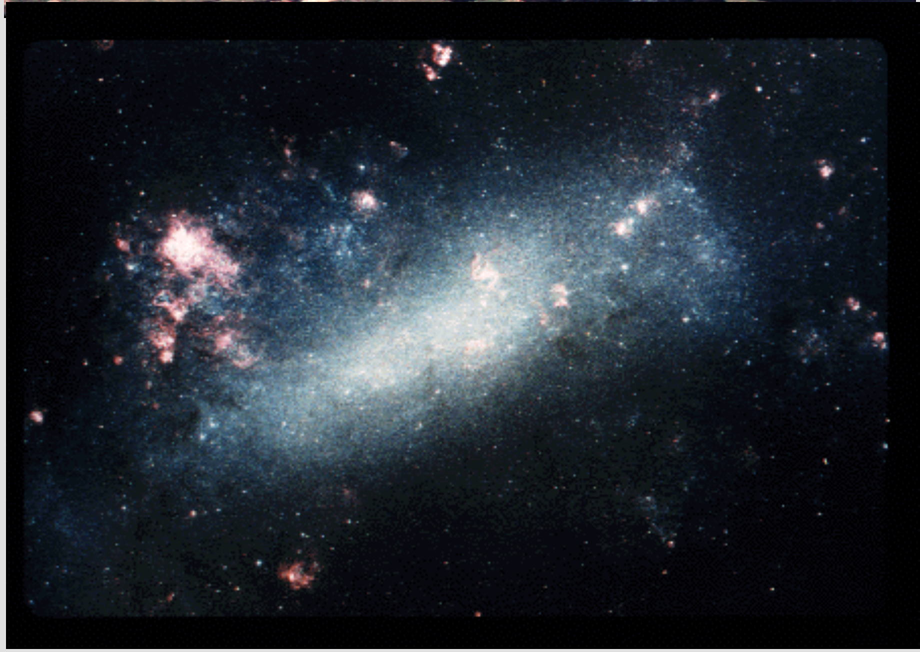
Marconi, *et al*., 2013, *MNRAS*, **428**, 2185-2197.

Observations

We can measure the brightness and radial velocity of stars. Until recently, we looked at individual stars. But in most cases we can only see a small set of modes (more about that in a minute.)

Ground-based micro-lensing surveys such as MACHO also find and measure variable stars in the LMC and SMC. (Here is the Mt. Stromlo Obs. and the LMC.) This survey found more variable stars than MACHOs!

Satellites also record large swaths of the sky and see many variable star candidates.



SOHO and Helioseismology

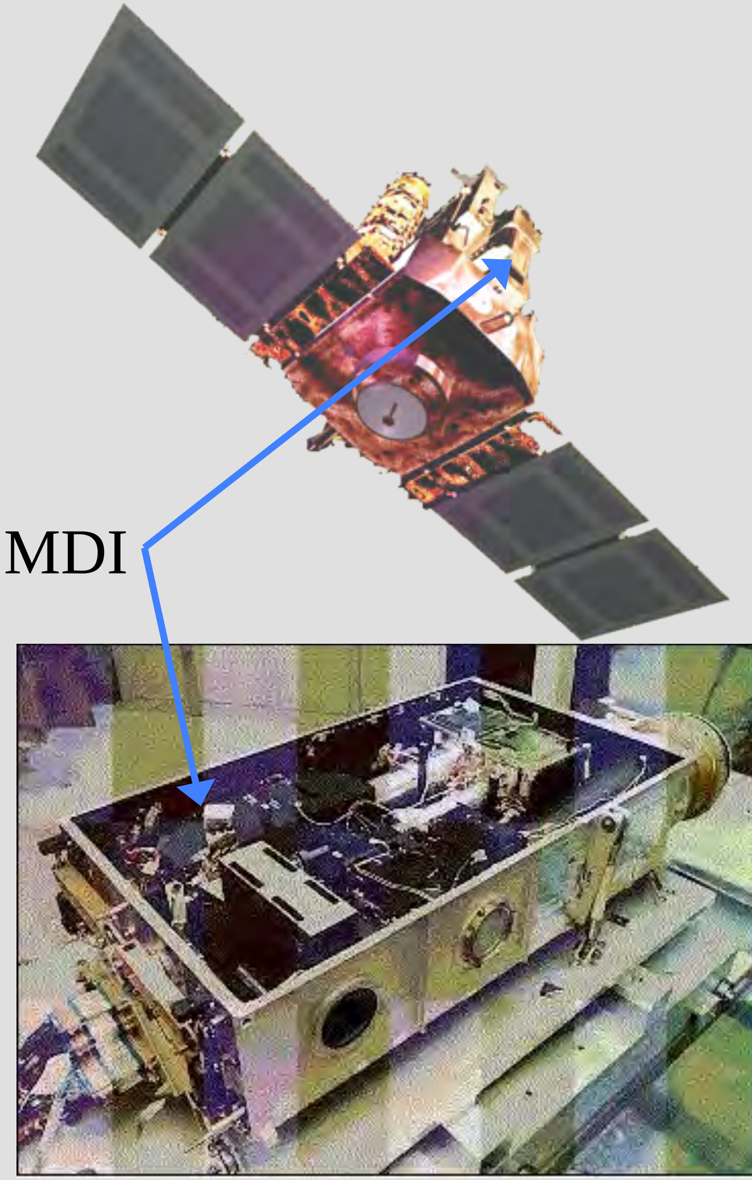
We can see the surface of the Sun. This allows us to watch the waves rippling across the surface, in both intensity and velocity. This allowed a new field, local helioseimology, to be developed.

There have been two notable satellites in this field.

The Solar and Heliospheric Observatory (SOHO) is a cooperative mission between ESA and NASA. It was launched December 2, 1995, into an L1 halo orbit.

SOHO has been an extremely successful mission, and still runs today!

The Magnetic Doppler Imager (MDI) measured the Doppler shift and Zeeman splitting of Ni I 6768 Å across the disk.

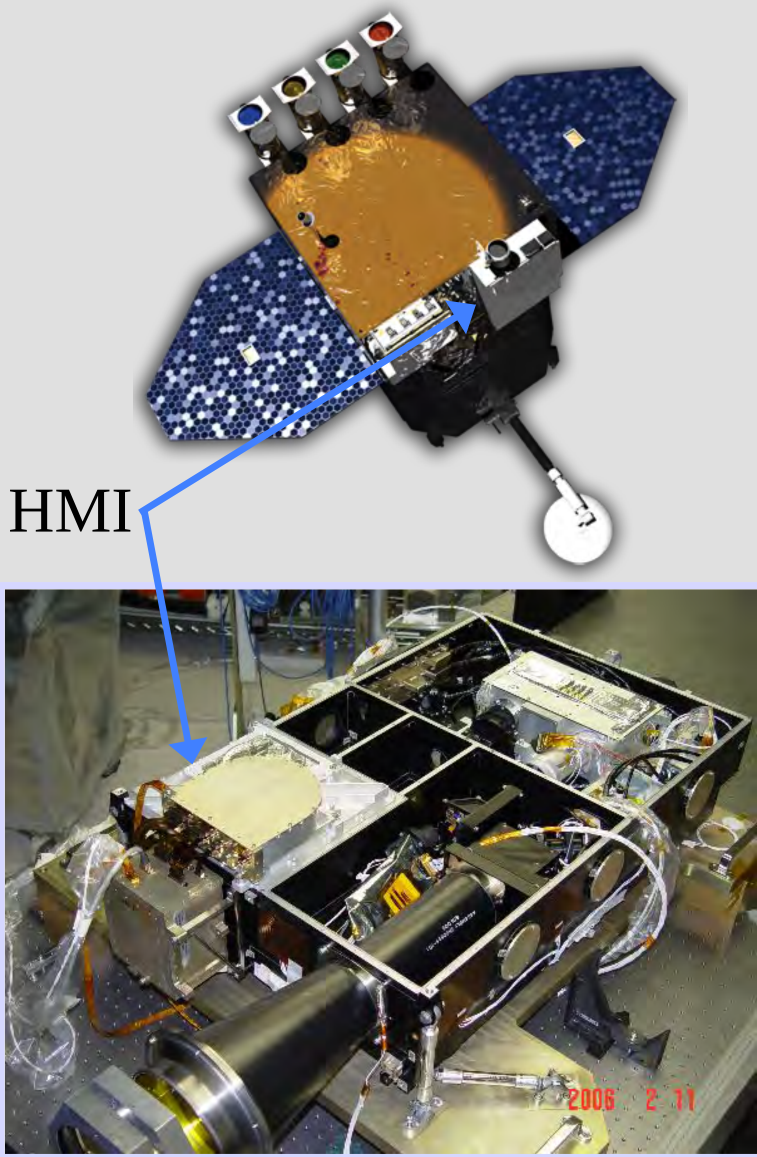


SDO and Helioseismology

NASA's Solar Dynamics Observatory (SDO) is the first Living With a Star mission. It was launched February 11, 2010, into a geosynchronous orbit over White Sands, NM.

Our goals are to understand how solar activity is produced, how it affects our society, and to predict when the most destructive effects will happen.

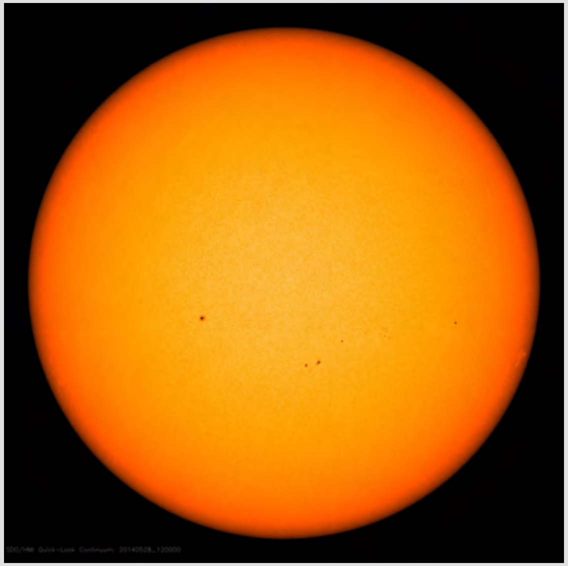
The Helioseismic and Magnetic Imager (HMI) measures the Doppler shift and Zeeman splitting of Fe I 6171 Å across the disk.

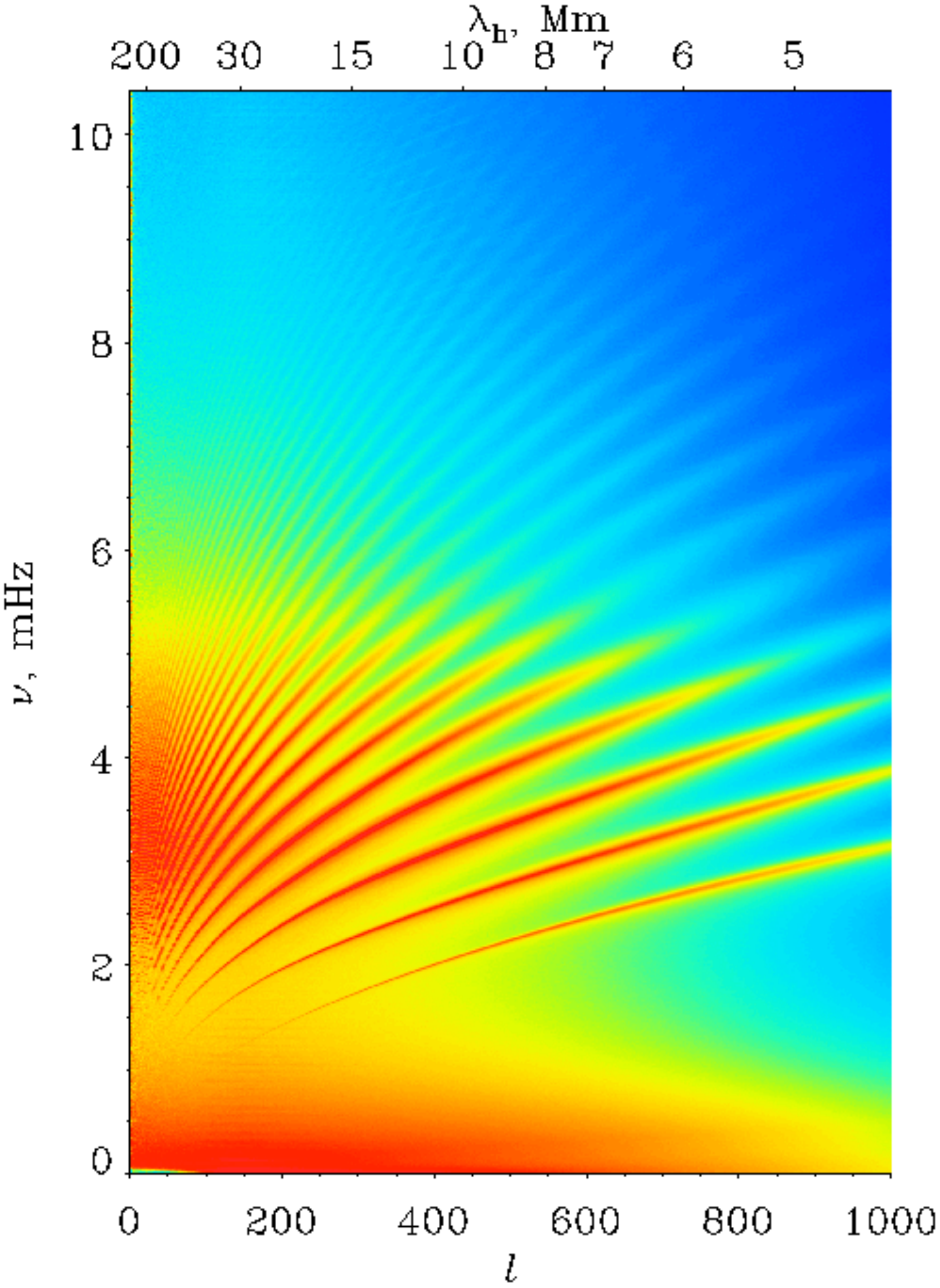


HMI Data Rate

- HMI has 2 4096 x 4096 CCDs
- Observes polarized light to also measure the magnetic field
- Data include
  - Doppler velocities
    - Oscillations
    - Local Analysis
  - Longitudinal magnetograms
  - Vector magnetograms
- Generates 20 images every 45 seconds
- 65 Mbps, 24x7
- Kepler is 42 CCDs, 95 Mpixels, but returns only a small part of each image
- Biggest challenge in space-based work is getting the data to the scientist

HMI and AIA use 4096 x 4096 CCDs built by e2v in England.





Solar p-Modes

When Dopplergrams are analyzed they produce dispersion diagrams like this one from MDI.

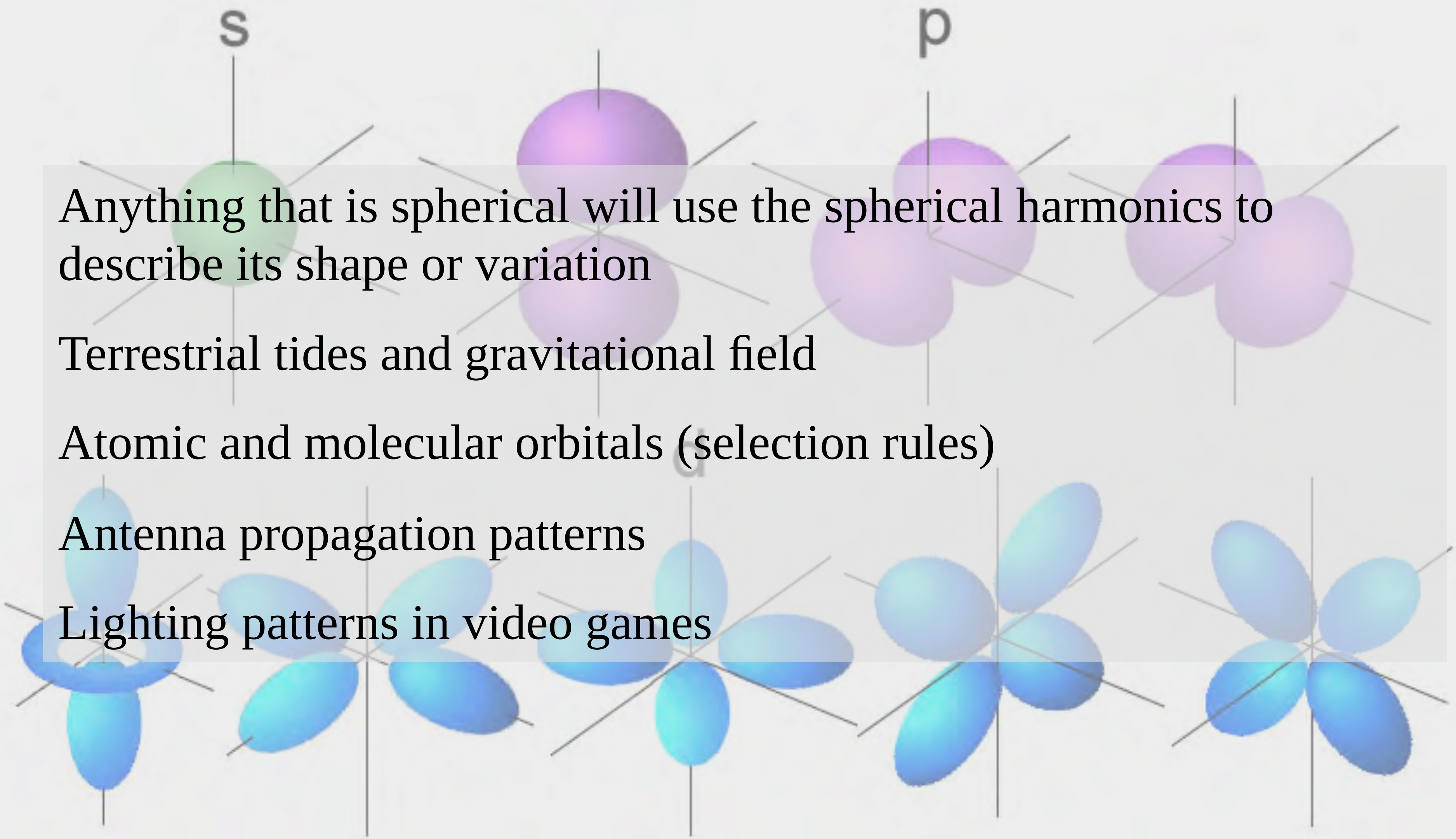
Power is concentrated in ridges, with discrete ridges at low-*l*.

Why discrete ridges?

How do we interpret those observations?

A brief mathematical interlude.

Spherical Harmonics



Anything that is spherical will use the spherical harmonics to describe its shape or variation

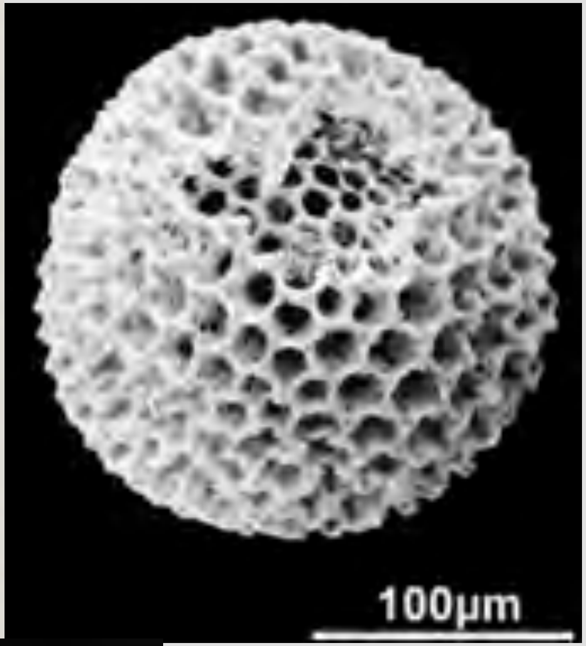
Terrestrial tides and gravitational field

Atomic and molecular orbitals (selection rules)

Antenna propagation patterns

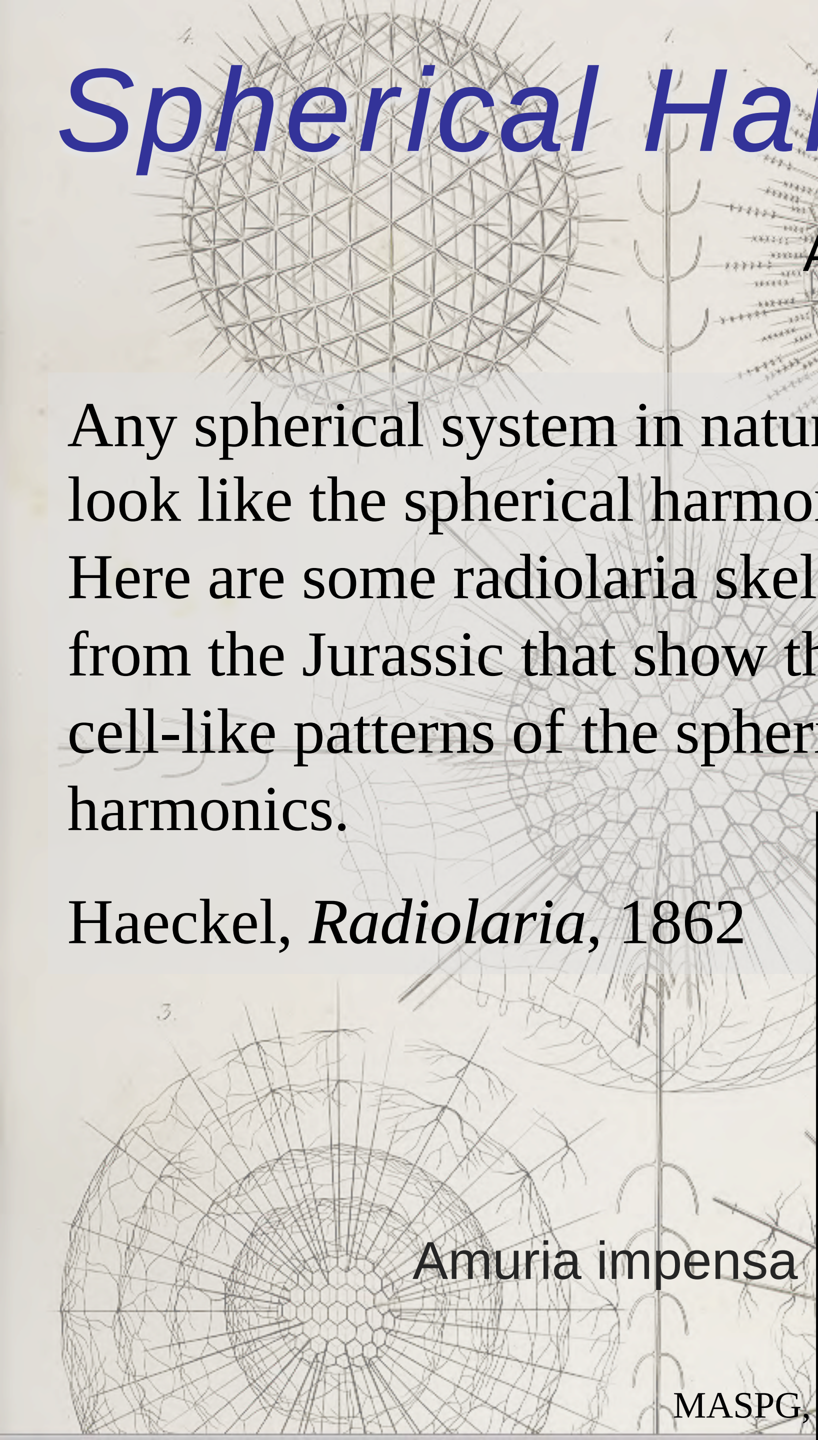
Lighting patterns in video games

Spherical Harmonics in Nature

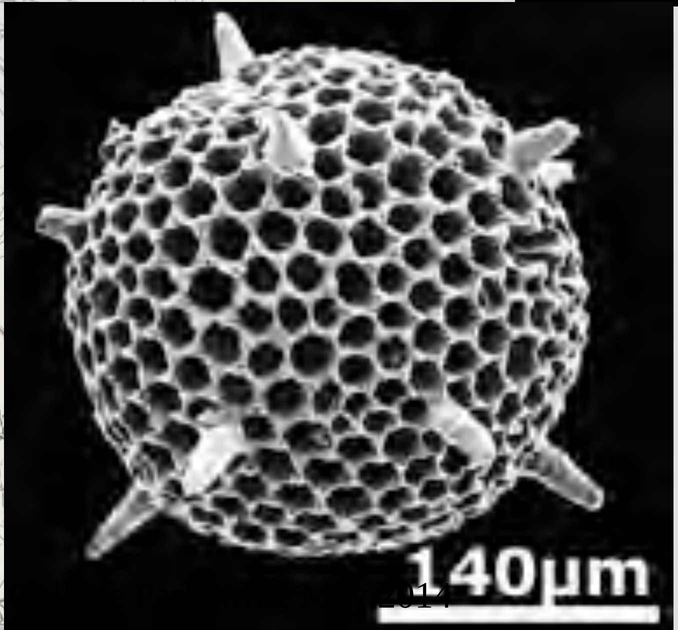


Archaeocenosphaera ruesti

Any spherical system in nature will look like the spherical harmonics. Here are some radiolaria skeletons from the Jurassic that show the cell-like patterns of the spherical harmonics.

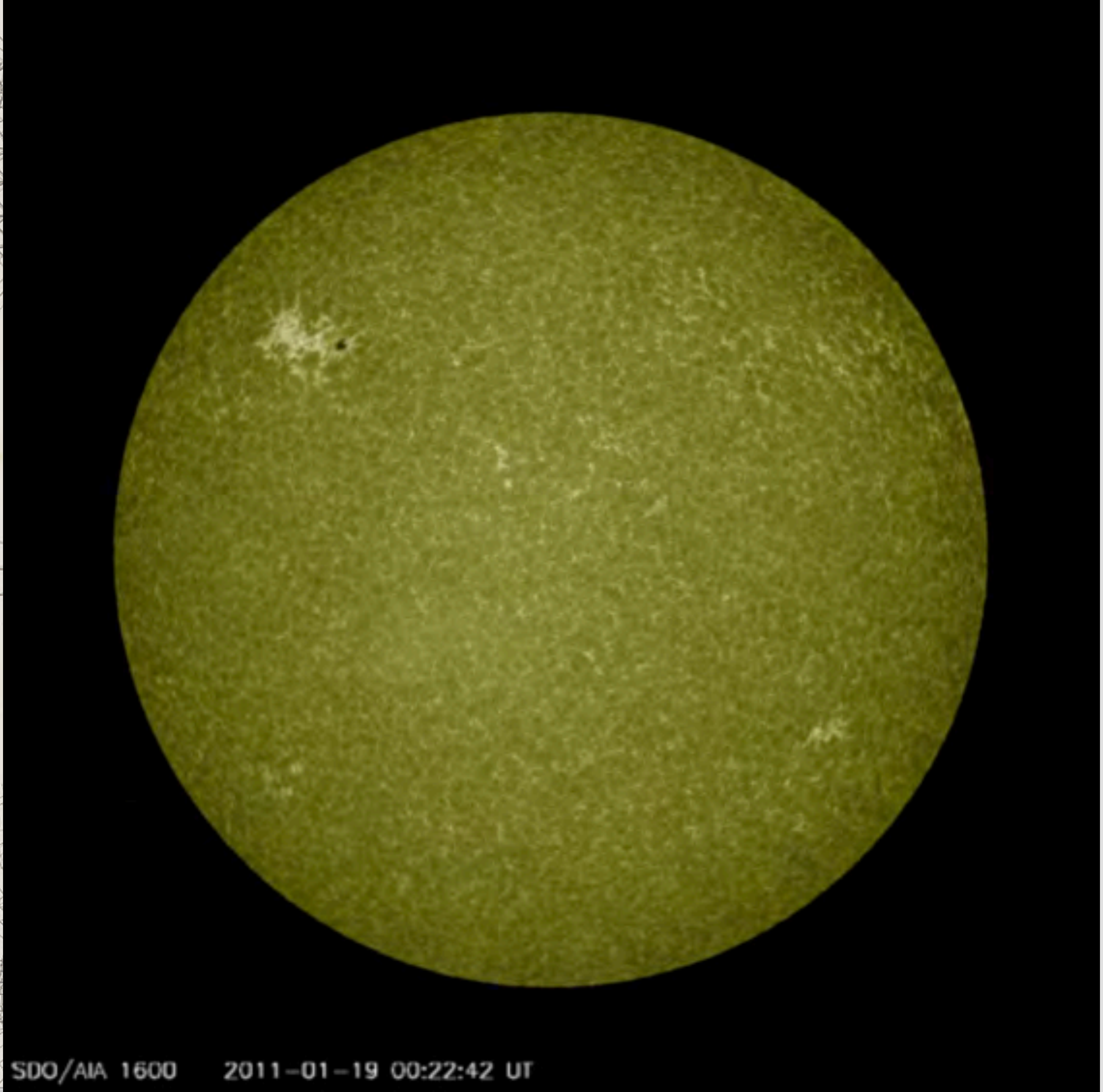


Haeckel, *Radiolaria*, 1862



Amuria impensa

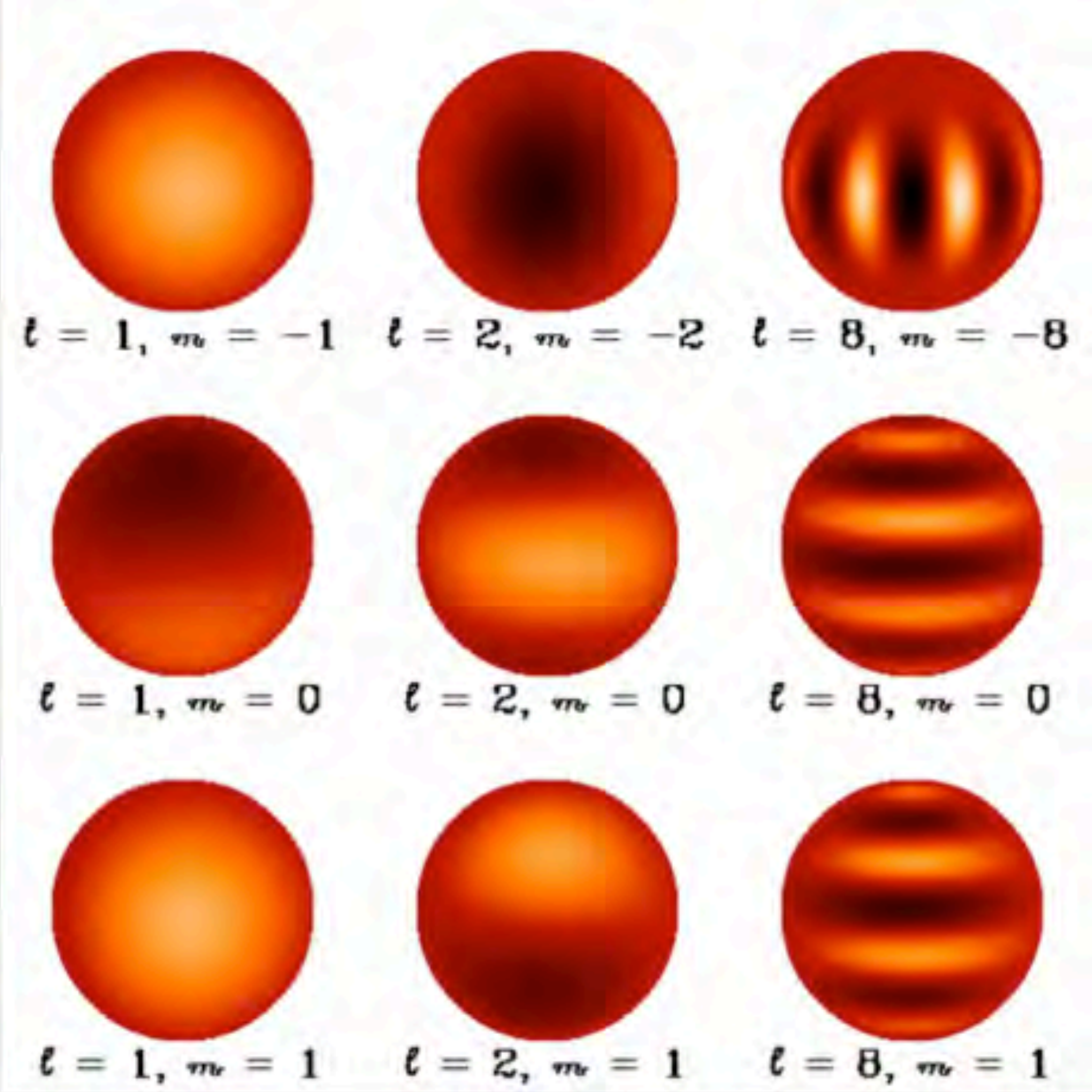
The solar chromospheric network!



Spherical Harmonics

Waves on a sphere are also described by the traveling-wave spherical harmonics.

Here are examples. The projected velocity is plotted for a pulsation velocity of 100 km/s, rotation velocity of 5 km/s, and an inclination of 80º.

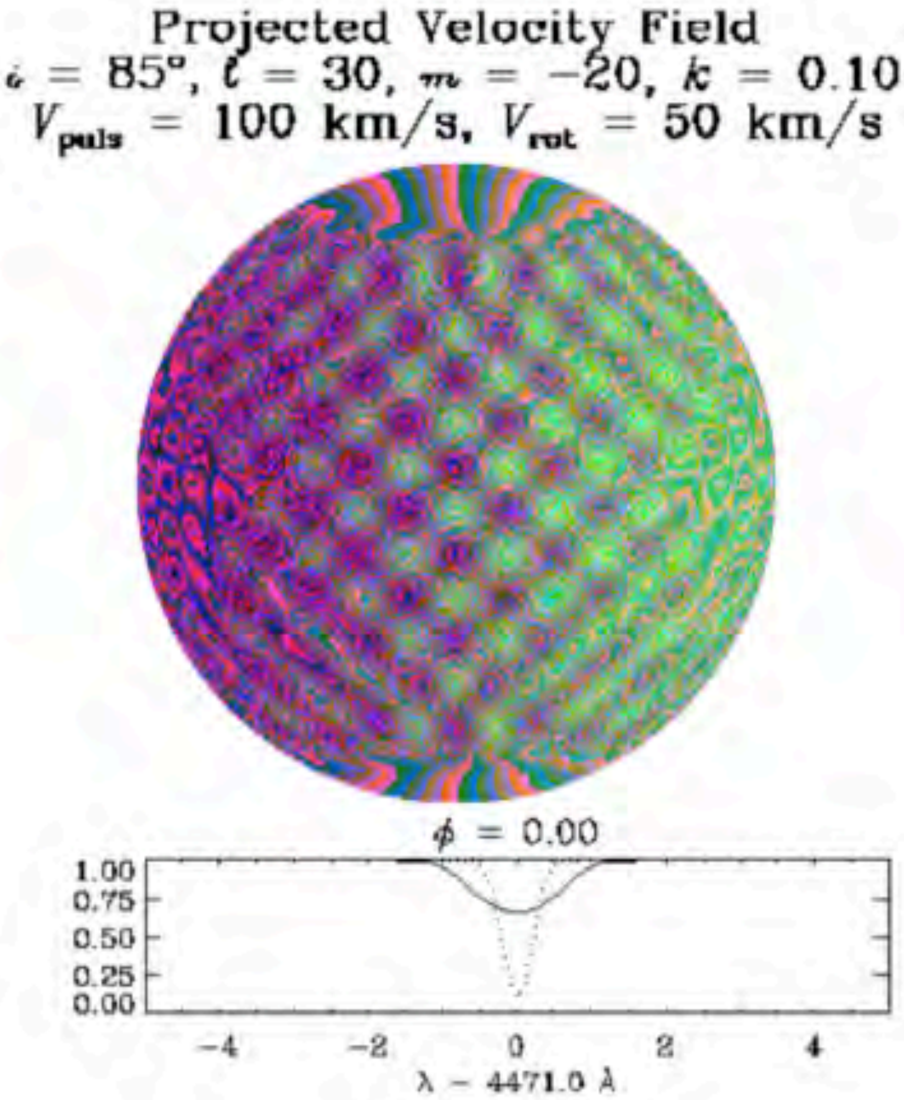


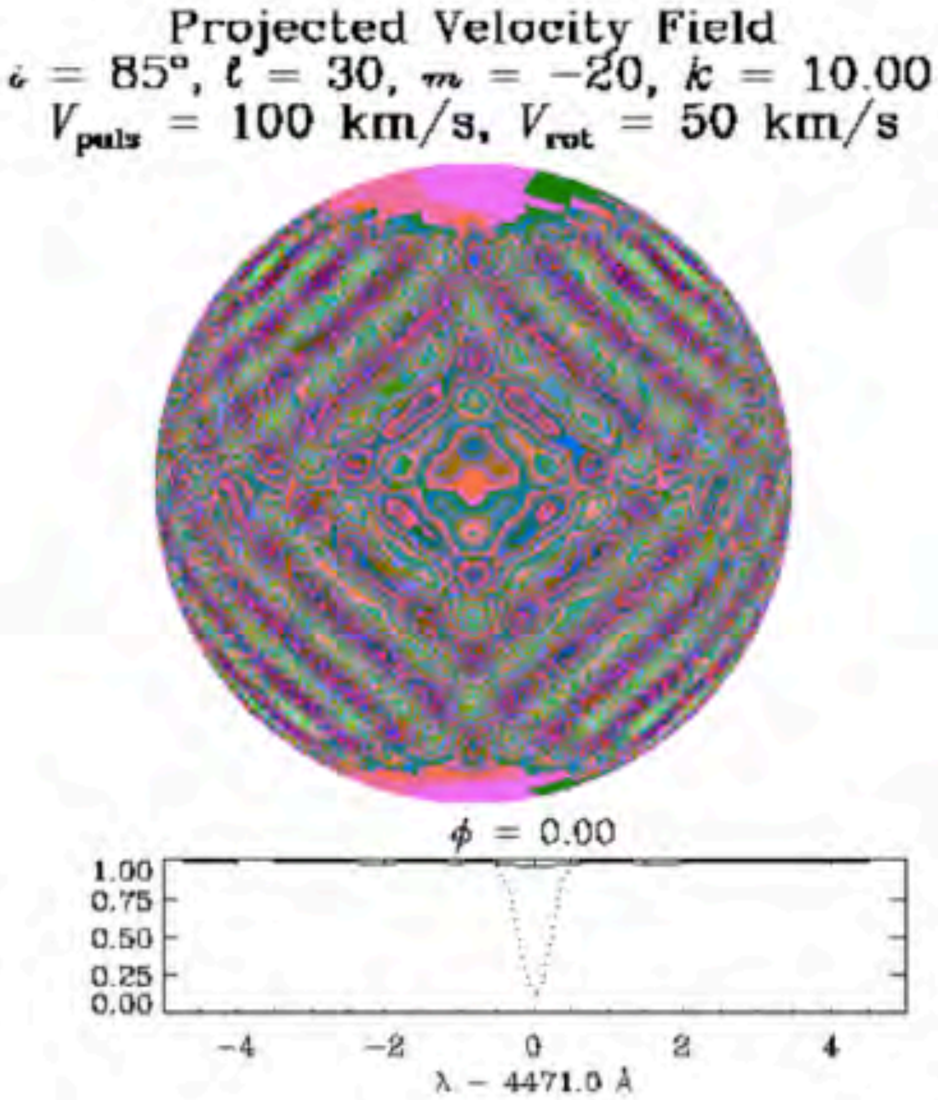
$\ell = 1, m = -1$ $\ell = 2, m = -2$ $\ell = 8, m = -8$

$\ell = 1, m = 0$ $\ell = 2, m = 0$ $\ell = 8, m = 0$

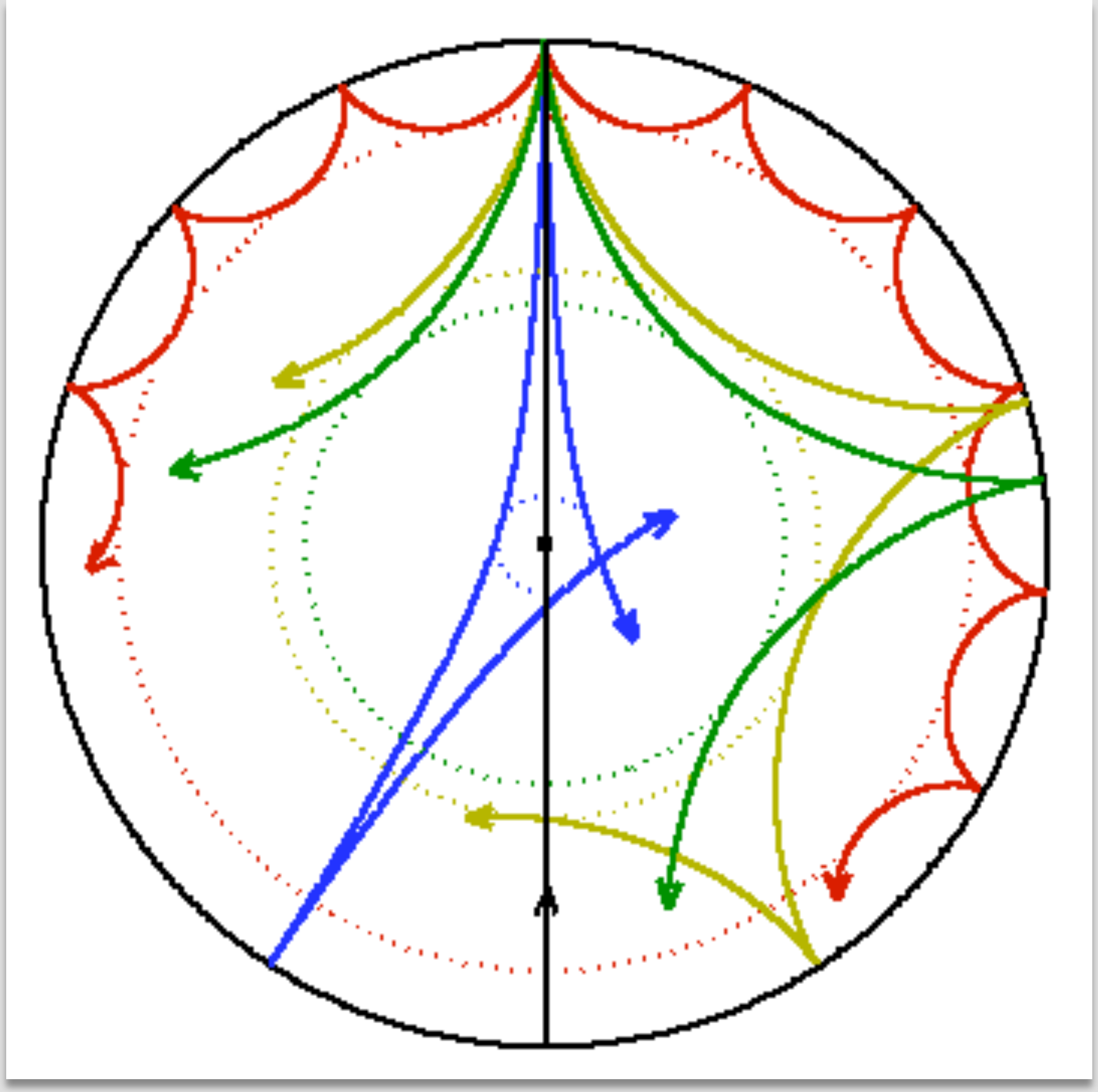
$\ell = 1, m = 1$ $\ell = 2, m = 1$ $\ell = 8, m = 1$

Radial vs. Horizontal Motion





Rays & Turning Points



The modes have internal nodes as well. You can think of this as the place the wave turns around and heads back toward the surface.

Some nodes dive deep into the star, others stay close to the surface.

Provides depth information!

Tools

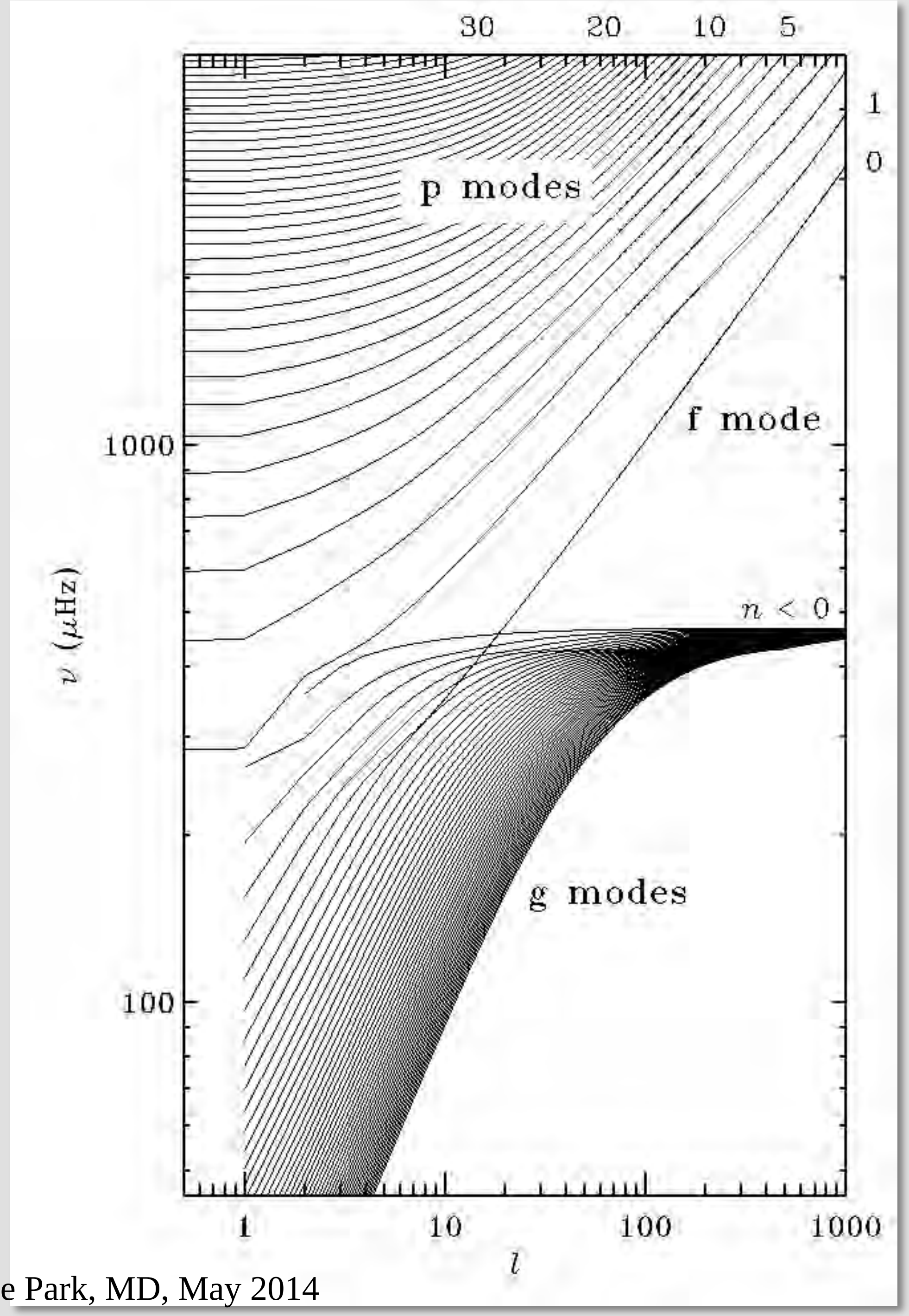
Adiabatic theory, $\delta P = c^2\,\delta\rho$

real frequency, no decay, no intrinsic driving

p-modes: restoring force is pressure, short periods

g-modes: restoring force is buoyancy, long periods

f-mode: restoring force is gravity



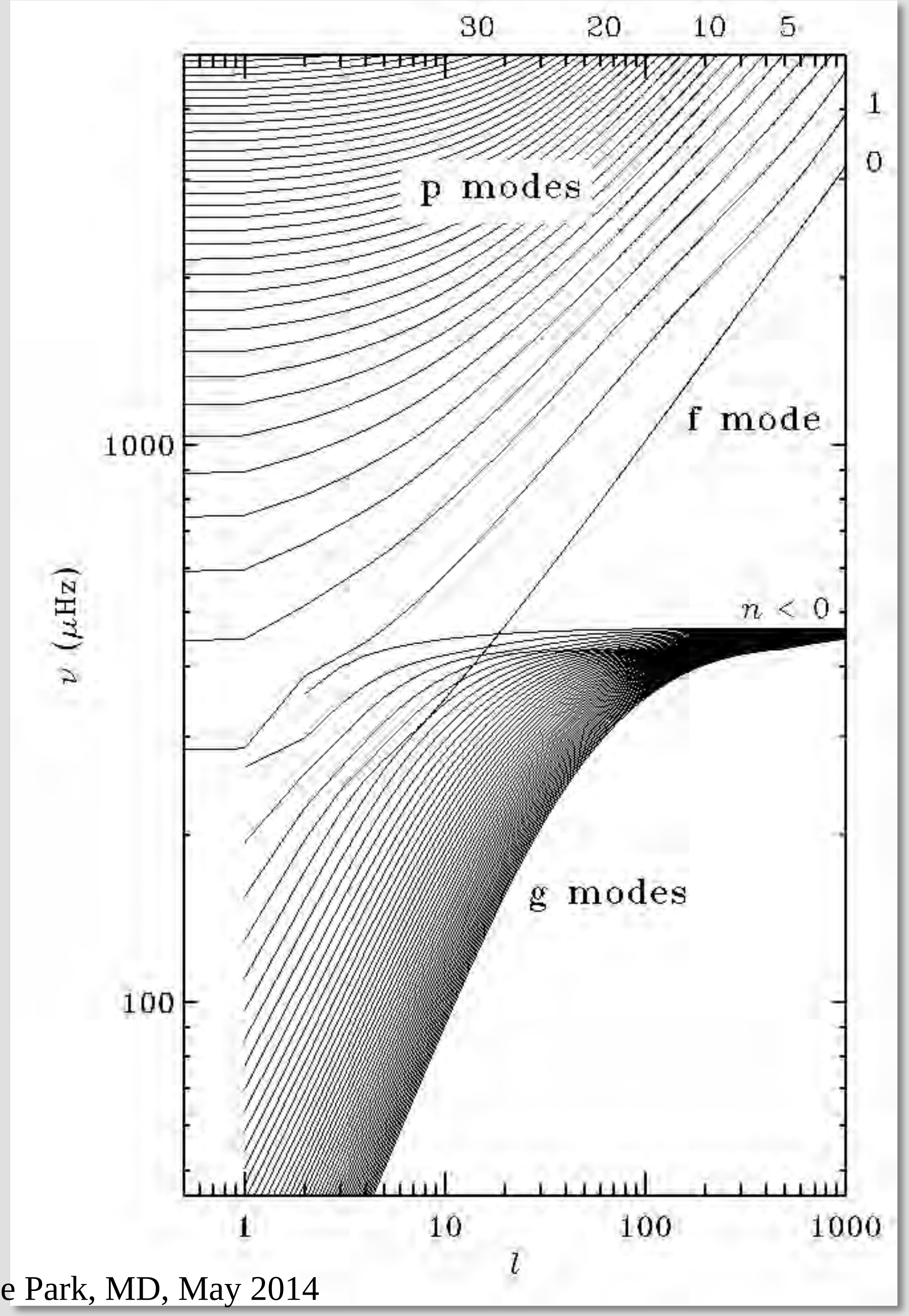
Tools

Adiabatic theory, $\delta P = c^2\, \delta\rho$

- real frequency, no decay, no intrinsic driving
- *p*-modes: restoring force is pressure, short periods
- *g*-modes: restoring force is buoyancy, long periods
- *f*-mode: restoring force is gravity

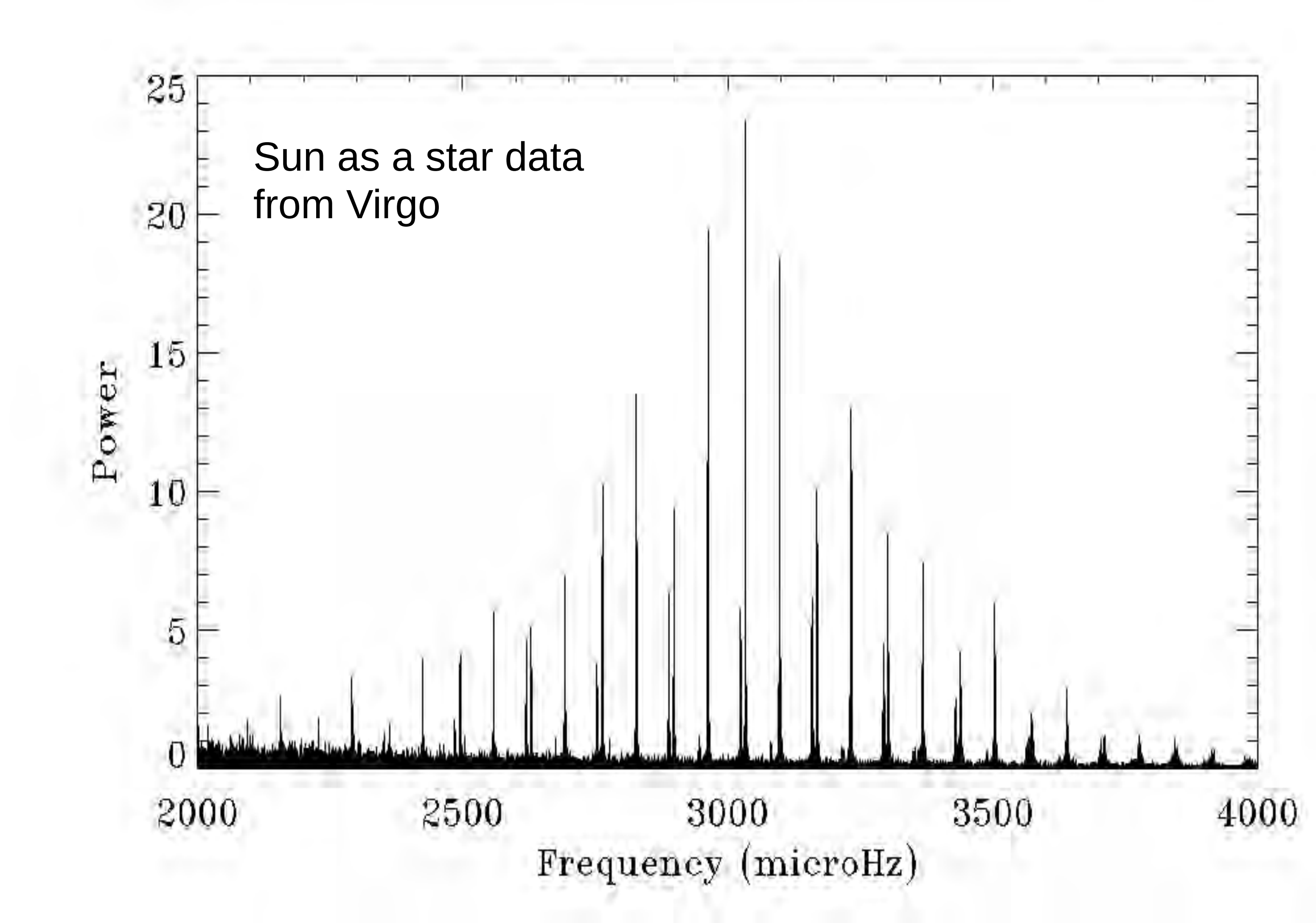
Nonadiabatic theory

- uses energy equation
- decay and intrinsic driving are possible

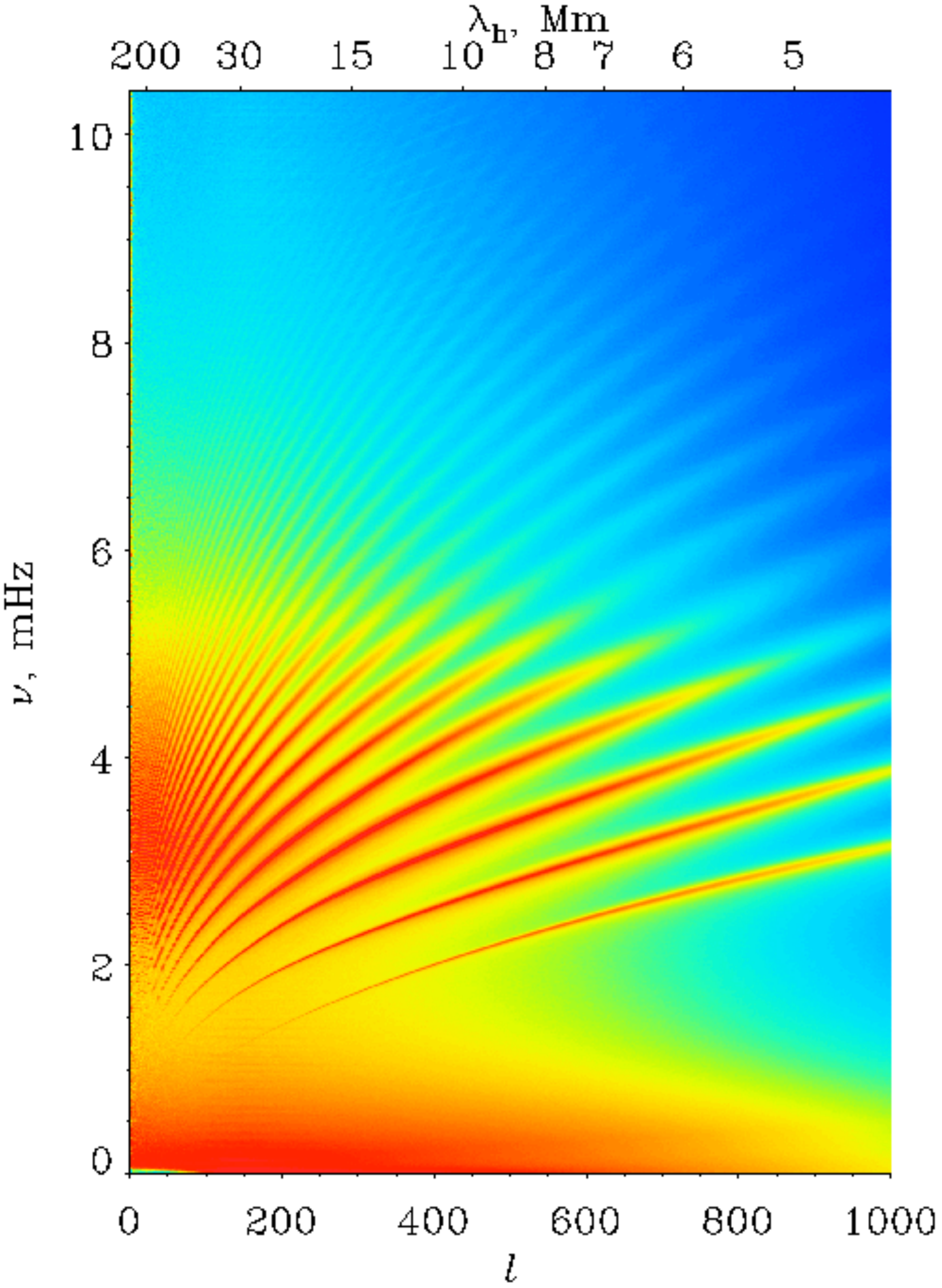


Solar p-modes

Period — sound speed — temperature —hydrostatic eq. — density



Solar p-Modes



When Dopplergrams are analyzed they produce dispersion diagrams like this one from MDI.

Power is concentrated in ridges, with discrete ridges at low-*l*.

Why discrete ridges?

Organizing the modes with critical frequencies

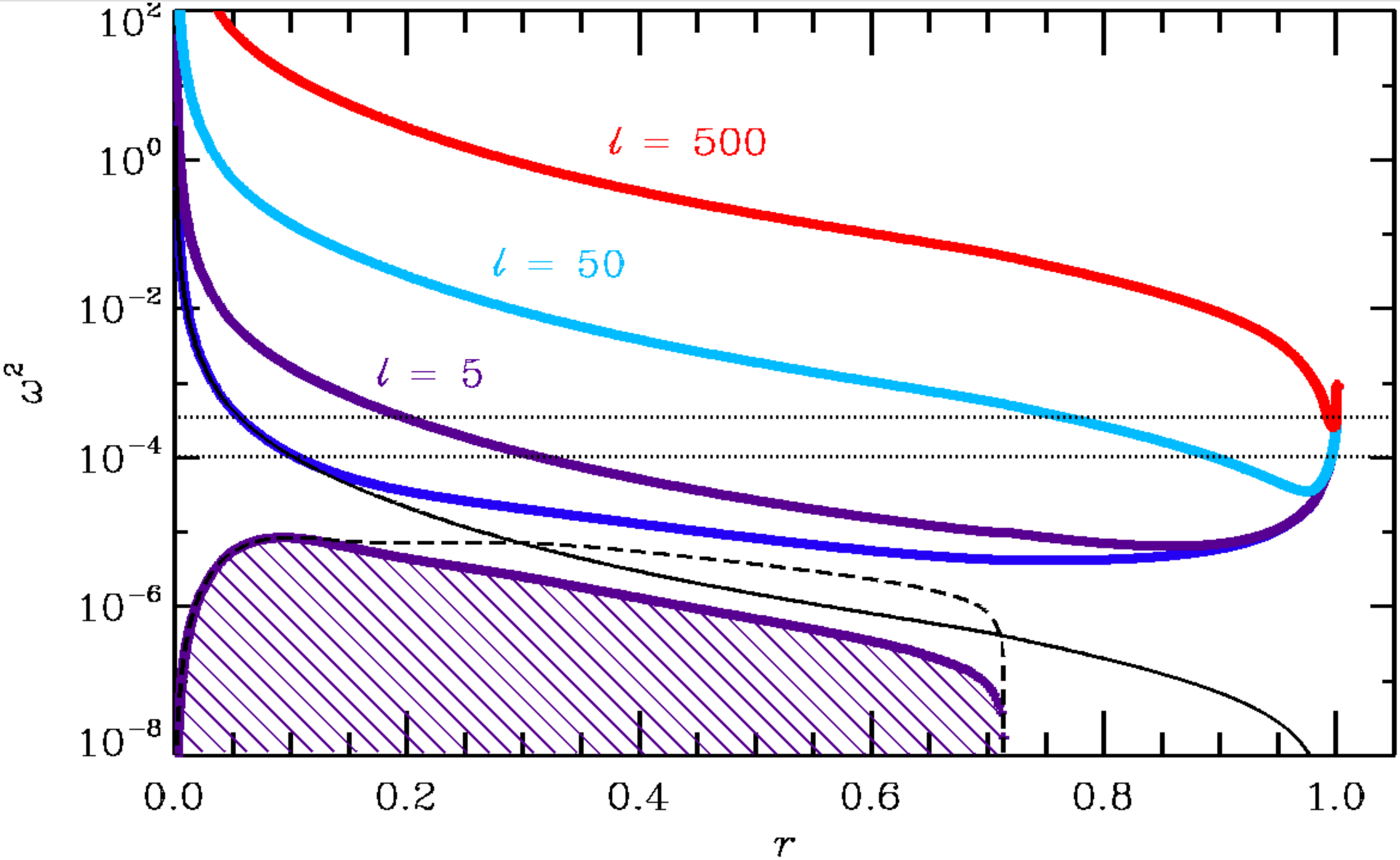
Lamb: $S_\ell^2 = \frac{\ell(\ell+1)c_s^2}{r^2}$

Brunt-Väsäilä: $N^2 = -gA \sim -\frac{\nabla - \nabla_{ad}}{H_p}$

Acoustic Cutoff: $\omega_{ac}^2 = \frac{c_s^2}{4H_p^2}\left(1 - 2\frac{dH}{dr}\right)$

$$\omega_\pm^2 = \frac{1}{2}\left(S_\ell^2 + \omega_{ac}^2\right) \pm \sqrt{\frac{1}{4}\left(S_\ell^2 + \omega_{ac}^2\right)^2 - N^2 S_\ell^2}$$

Organizing the modes with critical frequencies



Organizing the p-modes

$$\nu_{n,\ell} = \Delta\nu\left(n + \frac{\ell}{2} + \alpha + \frac{1}{4}\right) + \varepsilon_{n,\ell}$$

$$\Delta\nu = \left(2\int_0^{R_*}\frac{dr}{c}\right)^{-1} \approx \nu_{n+1,\ell} - \nu_{n,\ell} = \Delta\nu_\ell$$

$$\delta\nu_\ell = -\frac{(4\ell+6)\Delta\nu}{4\pi^2\nu_{n,\ell}}\left[\int_0^{R_*}\frac{dc}{dr}\frac{dr}{r}\right] \approx \nu_{n,\ell} - \nu_{n-1,\ell+2}$$

Organizing the p-modes

Surface boundary conditions

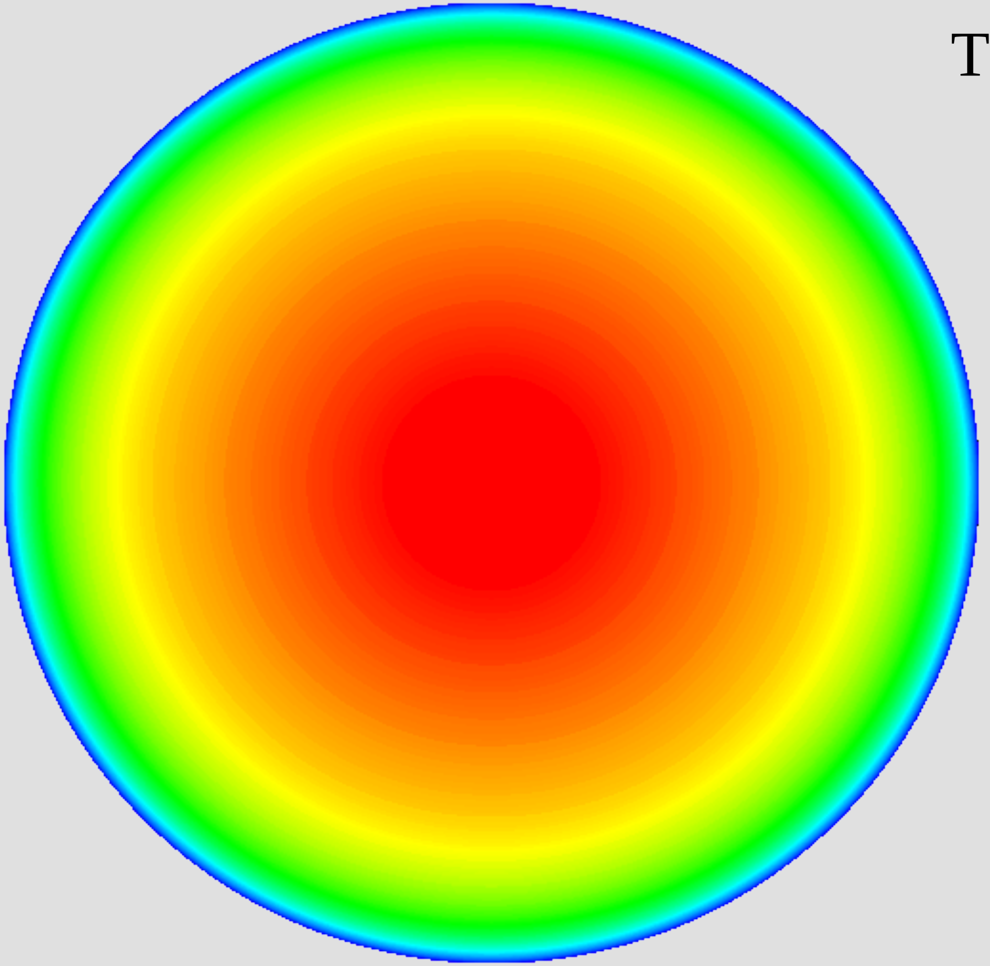
$$\nu_{n,\ell} = \Delta\nu\left(n + \frac{\ell}{2} + \alpha + \frac{1}{4}\right) + \varepsilon_{n,\ell}$$

Core conditions

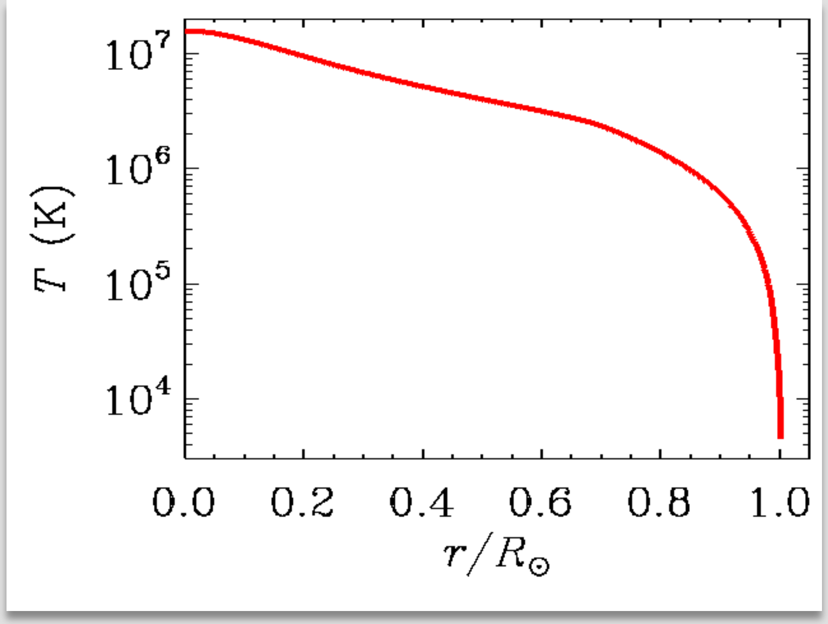
$$\delta\nu_{\ell} = -\frac{(4\ell + 6)\Delta\nu}{4\pi^2\nu_{n,\ell}}\left[\int_0^{R_*}\frac{dc}{dr}\frac{dr}{r}\right] \approx \nu_{n,\ell} - \nu_{n-1,\ell+2}$$

What can we learn?

Period — sound speed — temperature —hydrostatic eq. — density



This yields a spherical model.



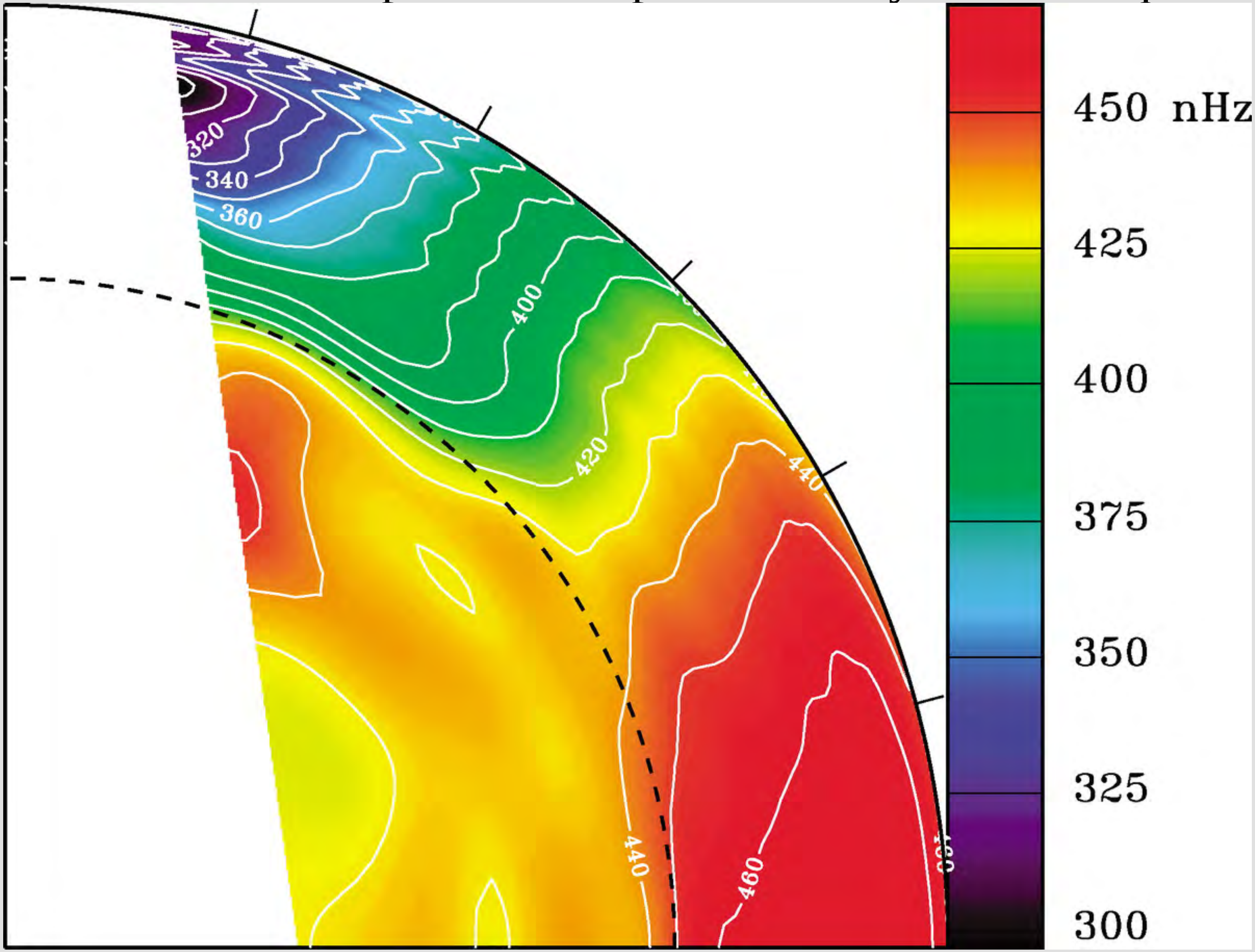
What can we learn?

Period — sound speed — temperature —hydrostatic eq. — density

- But what a spherical model!
- Major revisions in solar & stellar physics
  - Microscopic diffusion (Michaud & Proffitt 1993)
  - Internal rotation profile (MDI, Couvidat et al. 2003)
- Major revisions in physics
  - Neutrino physics (MDI, Turck-Chièze et al. 2001)

What can we learn?

Period — sound speed — temperature —hydrostatic eq. — density



25.7 d

28.9

33.1

38.6

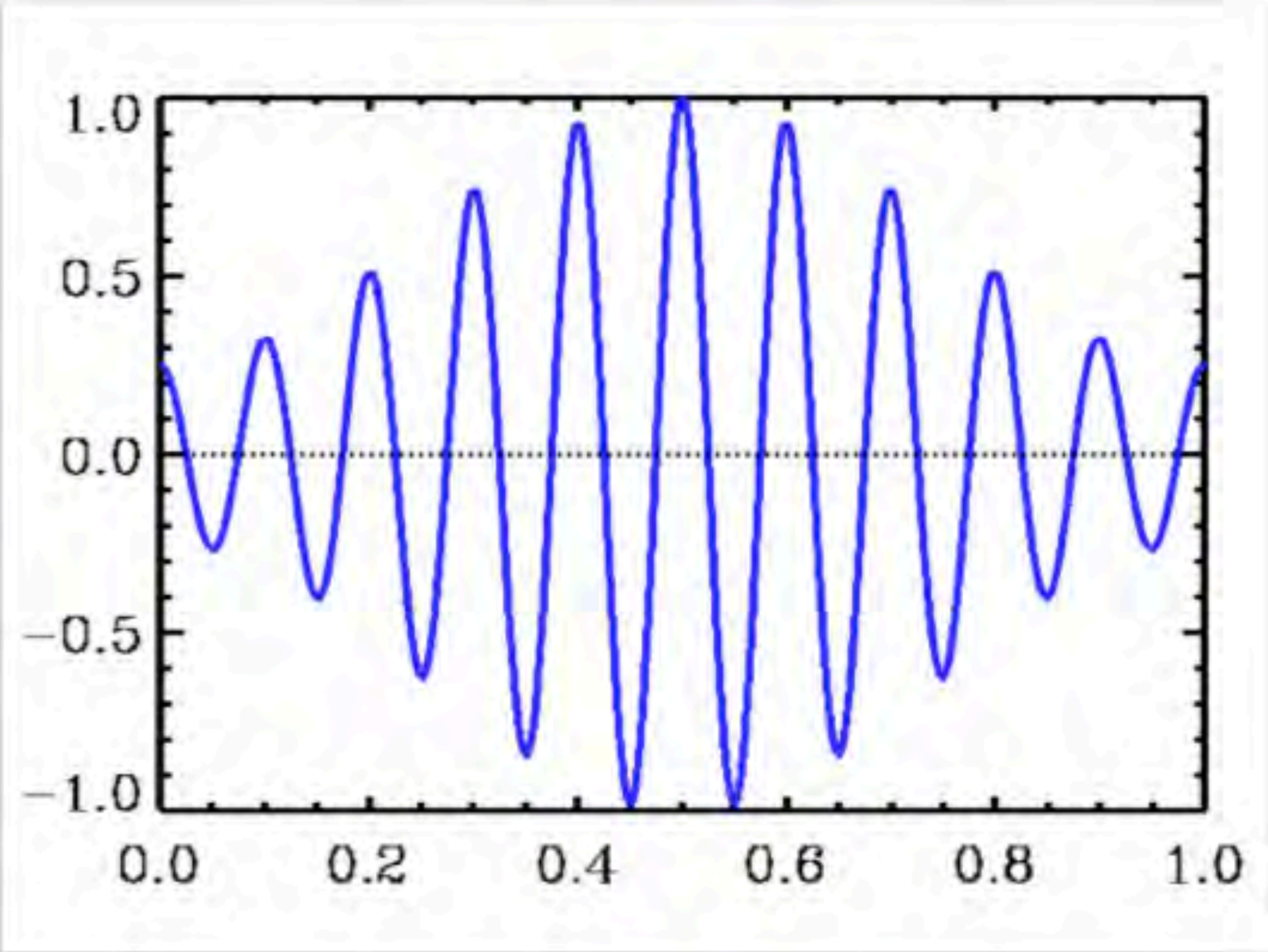
Organizing the g-modes

$$P_{n,\ell} = \frac{P_0}{\sqrt{\ell(\ell+1)}}(n + \alpha_{\ell,g})$$

$$P_0 = 2\pi^2 \left(\int_{r_1}^{r_2} N \frac{dr}{r} \right)^{-1}$$

Organizing the g-modes

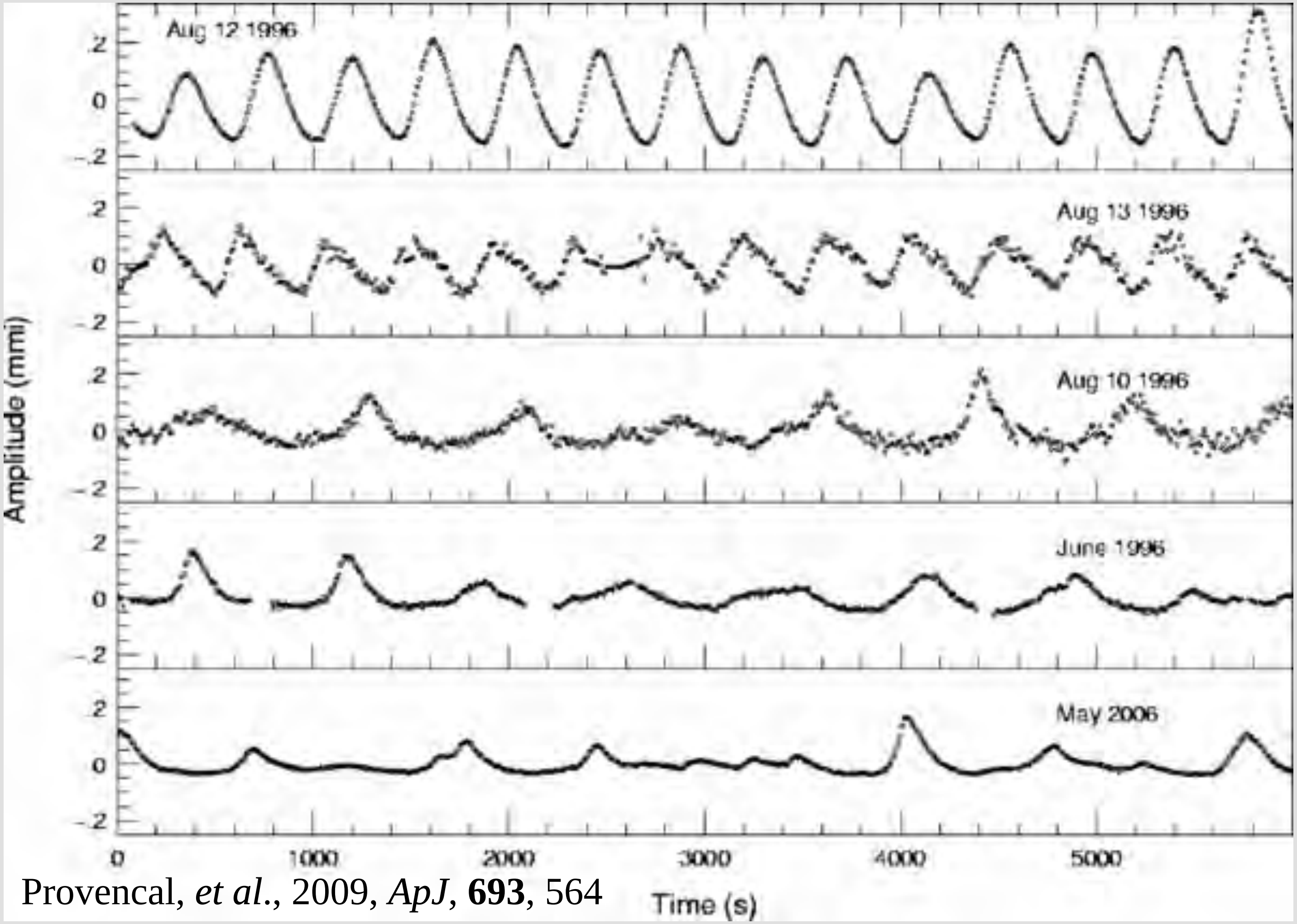
g-modes are interesting because the energy flows in the opposite direction of the wave. In Earth's atmosphere seen as the quasi-biennial oscillation.



Seen in variable white dwarf stars.

Despite many years of effort, g-modes have not been seen in the Sun, except possibly indirectly.

GD 358 or V777 Her
The first DBV star!



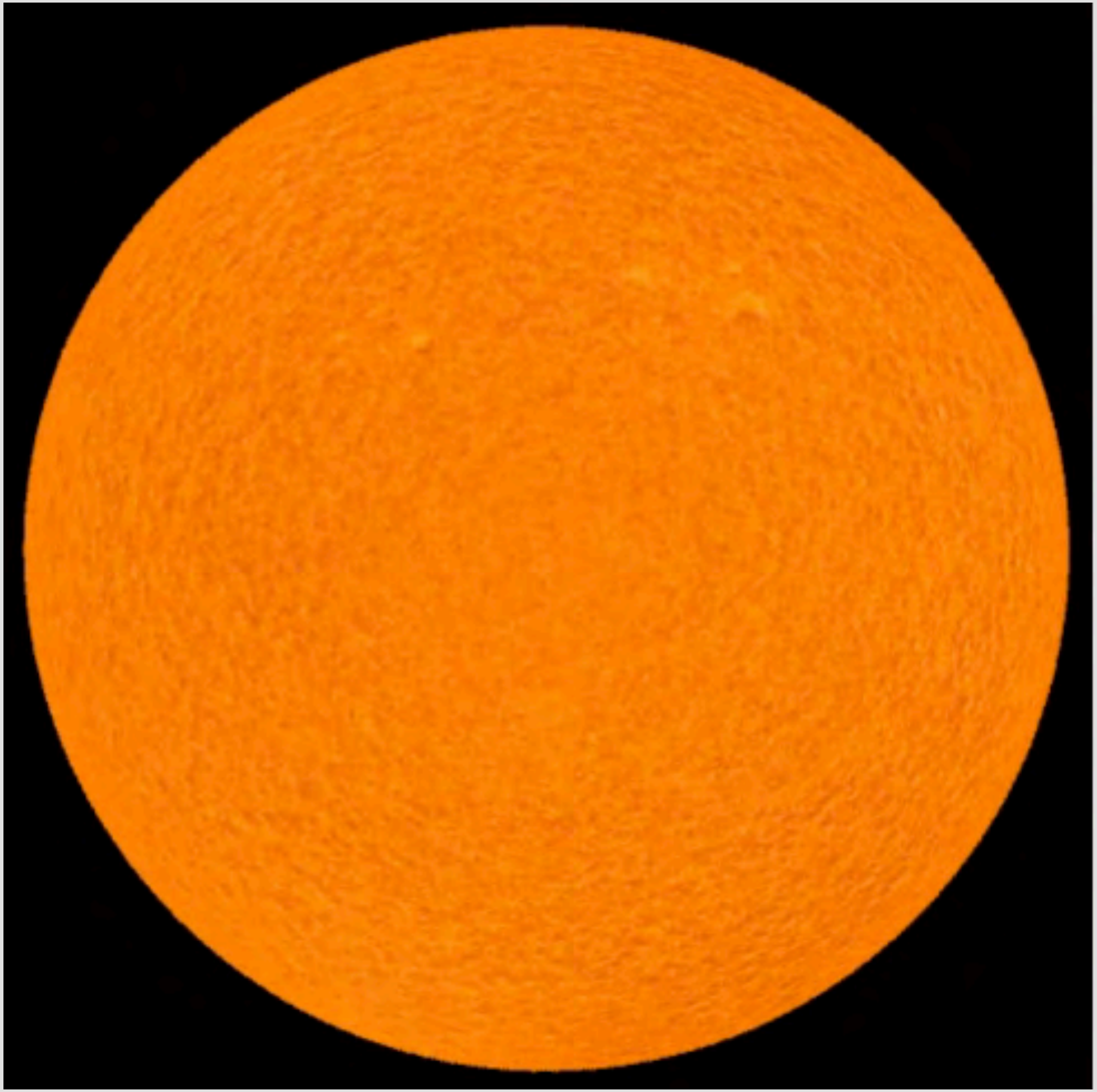
Provencal, *et al.*, 2009, *ApJ*, **693**, 564

GD 358 was the first member of a class of variables predicted by modeling. It’s the κ-γ effect again.

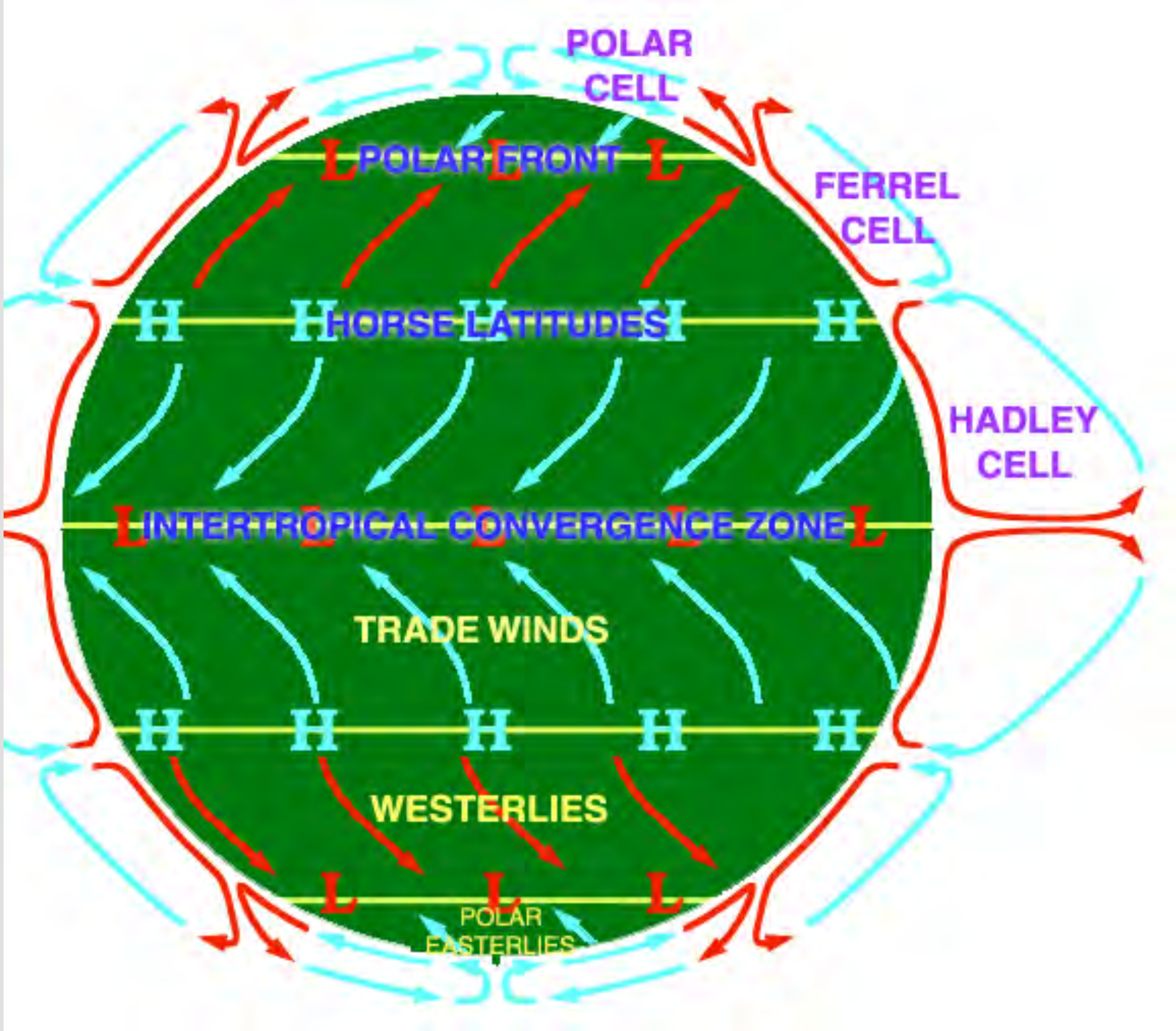
Here we can see mode switching over a decade. This might be a nonlinear mode coupling!

Results from the Sun via HMI and MDI

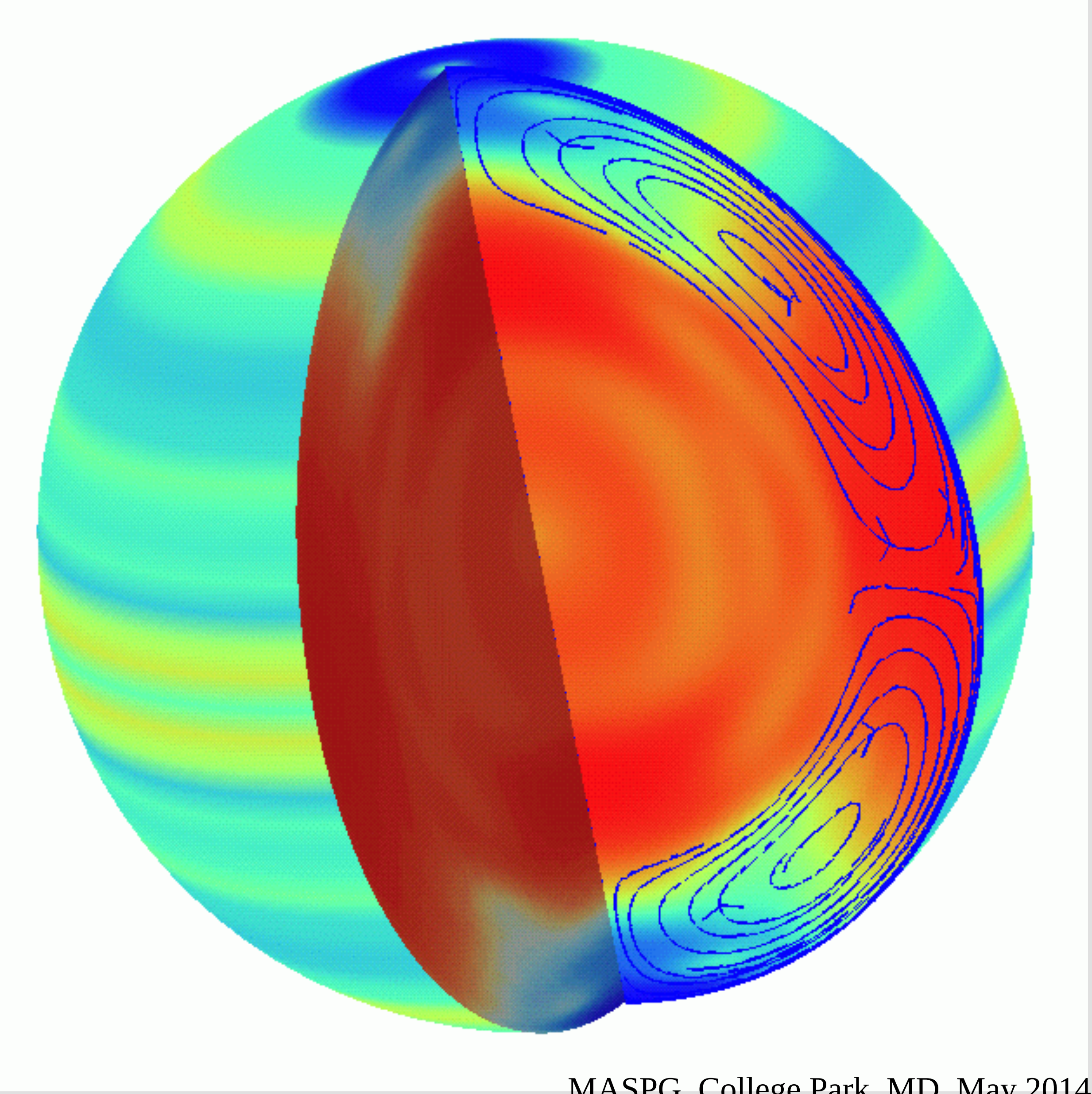
Does a Watched Sun Boil?



Winds of the Earth



Zeeman-splitting: Rotation

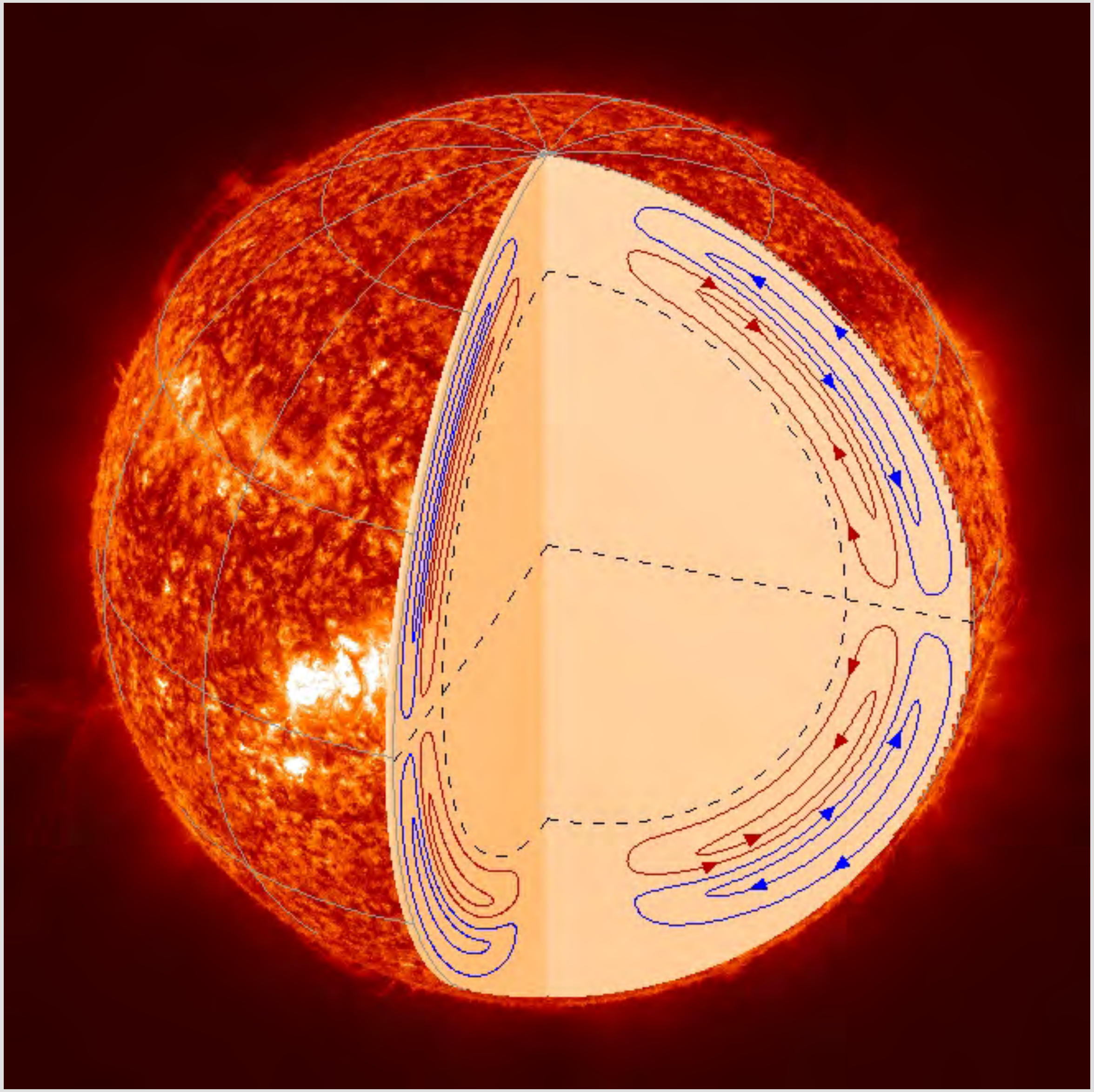


The rotational velocities inside the Sun. These velocities are inferred from helioseismic measurements and represent the differential rotation of the Sun.

The equator rotates a little faster and the poles a little slower than average. We knew this from surface measurements, but the helioseismology tells us the rest of the story.

The radiative core rotates like a solid body while the convection zone does not.

More Doppler Shifts:Winds

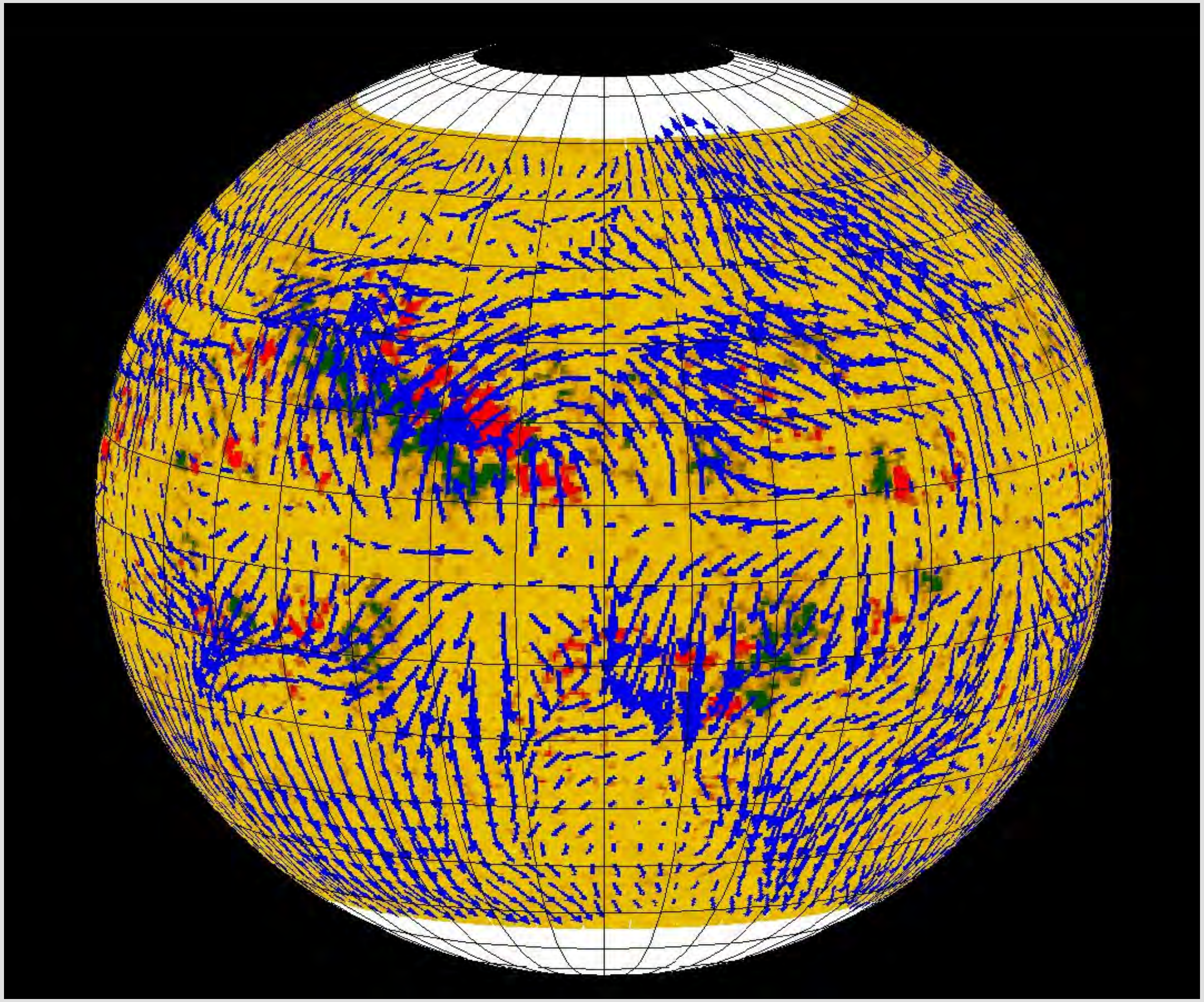


The meridional velocities inside the Sun. These velocities are inferred from helioseismic measurements and represent the slow evolution of the solar convection zone.

The circulation cell is an estimate of the flows necessary to create a solar dynamo.

This pattern is probably too simple as other measurements and models of the convection zone show the meridional flows can have a multi-cellular pattern (like the Hadley cell on Earth.) Part of the problem is how long you integrate the signal. This result required several years of data; shorter spans give more complicated patterns.

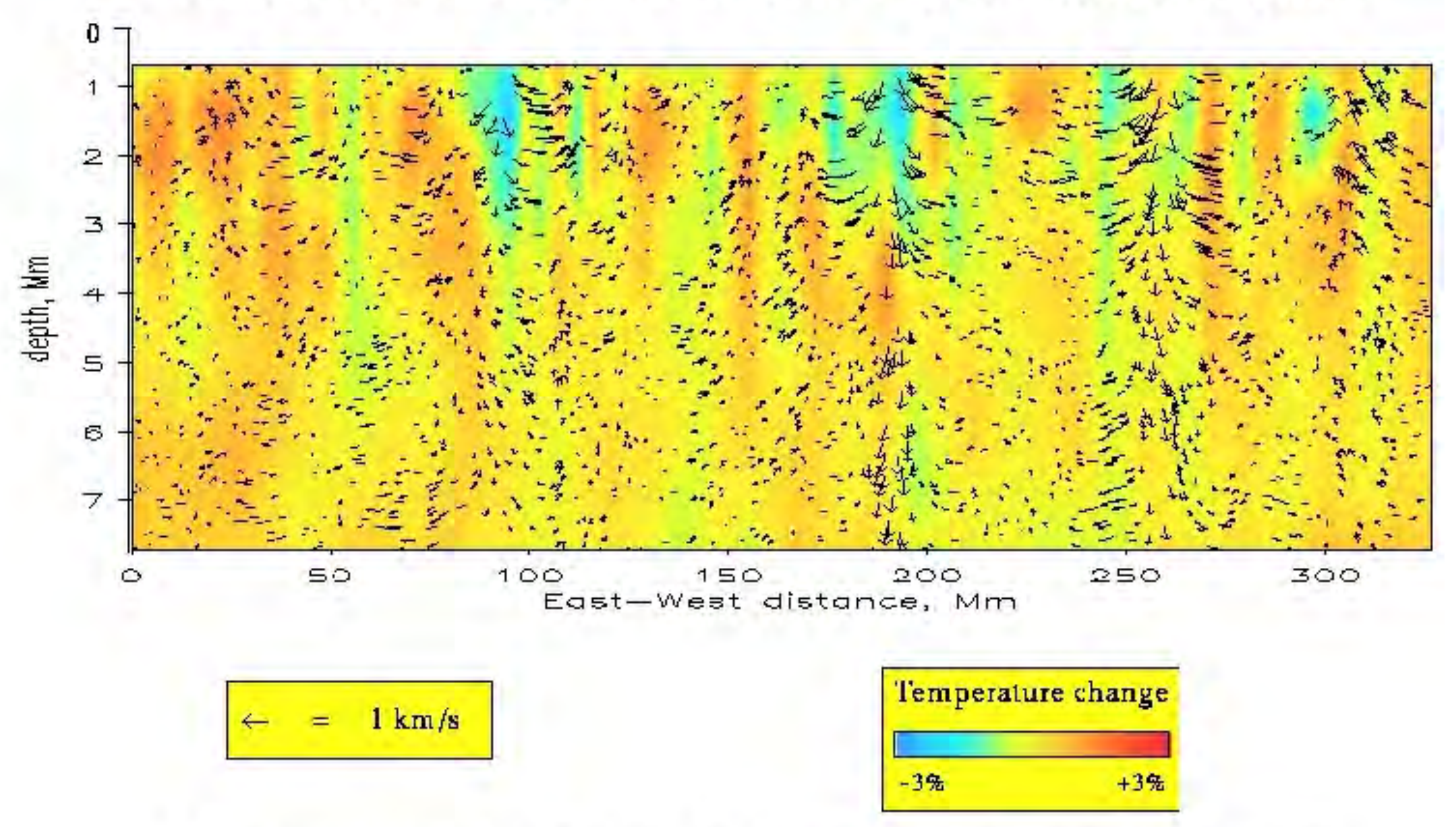
Solar Weather Map



A global weather map of the Sun showing magnetic patterns and wind flow at a depth of 2,000 km below the solar surface in April 2001. Large inflows that stream into the large active region are visible.

Figure courtesy of Deborah A. Haber, JILA, University of Colorado.

Convective Flows Below the Sun's Surface

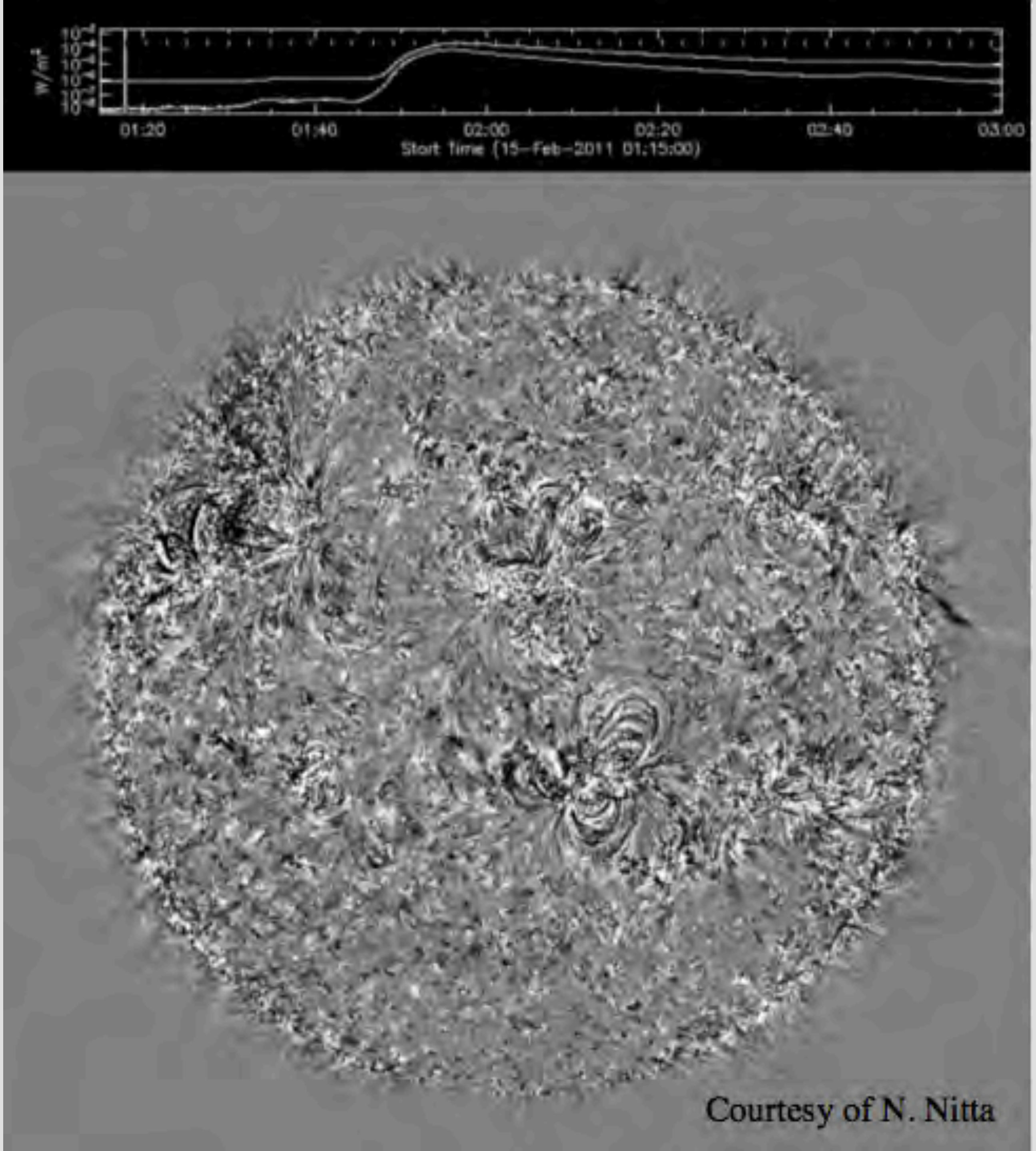


A vertical cut through the outer 1% of the Sun showing flows and temperature variations inferred by helioseismic tomography. These measurements show the short-term behavior of a small part of the Sun-truly Solar weather!

Coronal Dimmings?

A dimming related to an X1-class flare on 29-Mar-2014

Coronal Waves?

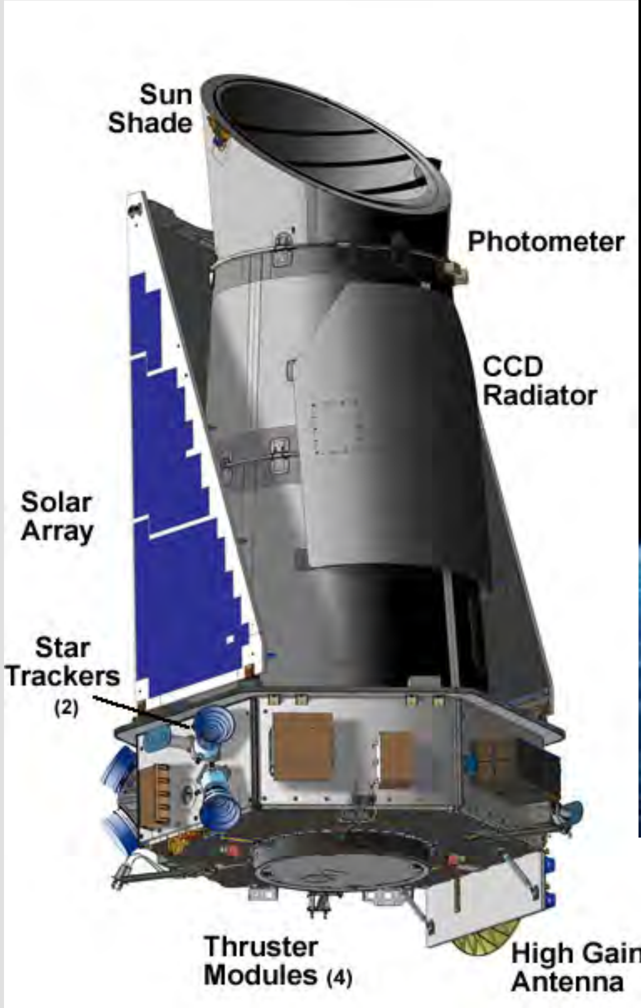


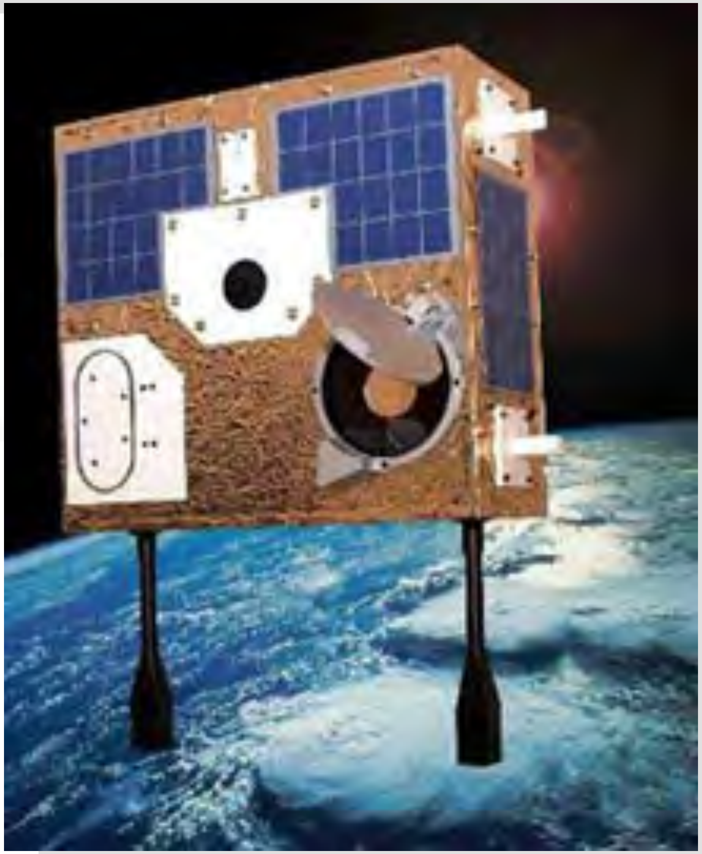
Courtesy of N. Nitta

A nice blast on
15-Feb-2011

Results from other stars (Kepler, CoRoT, MOST)

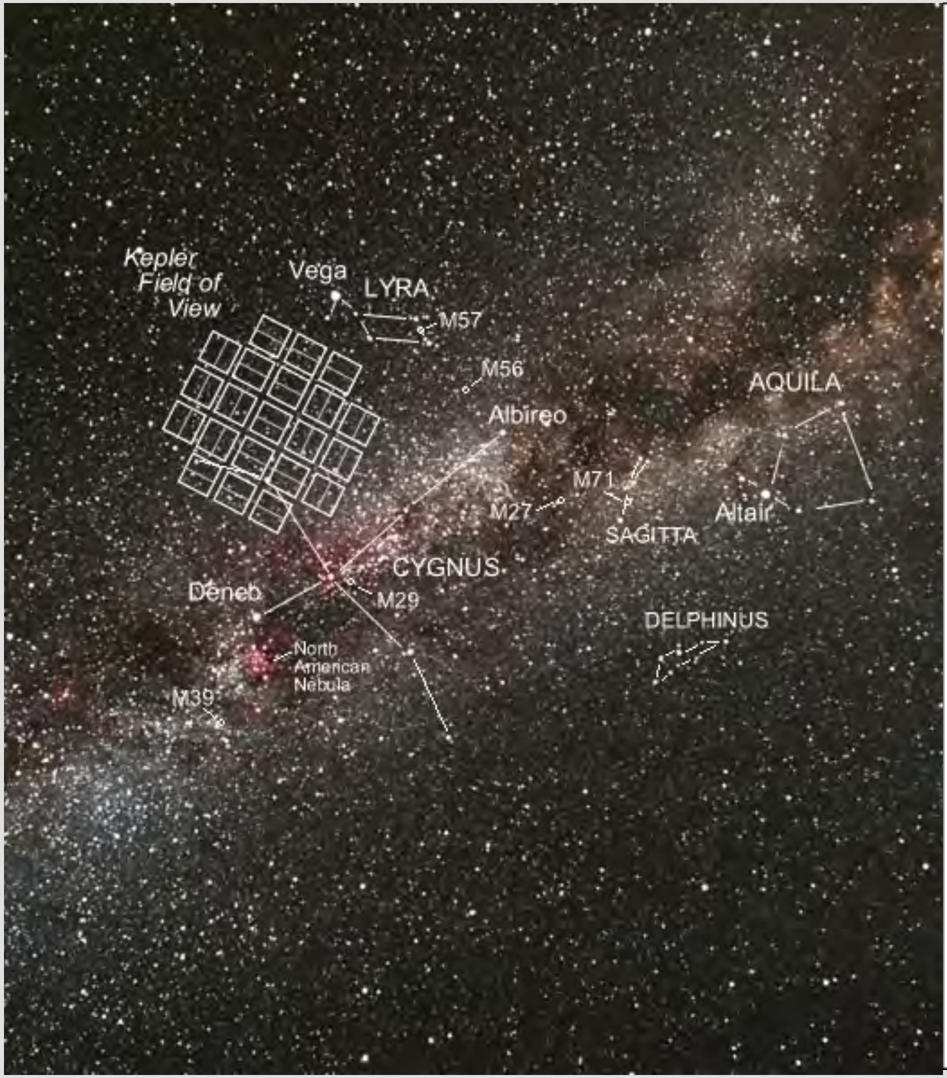
Kepler, MOST, and CoRoT

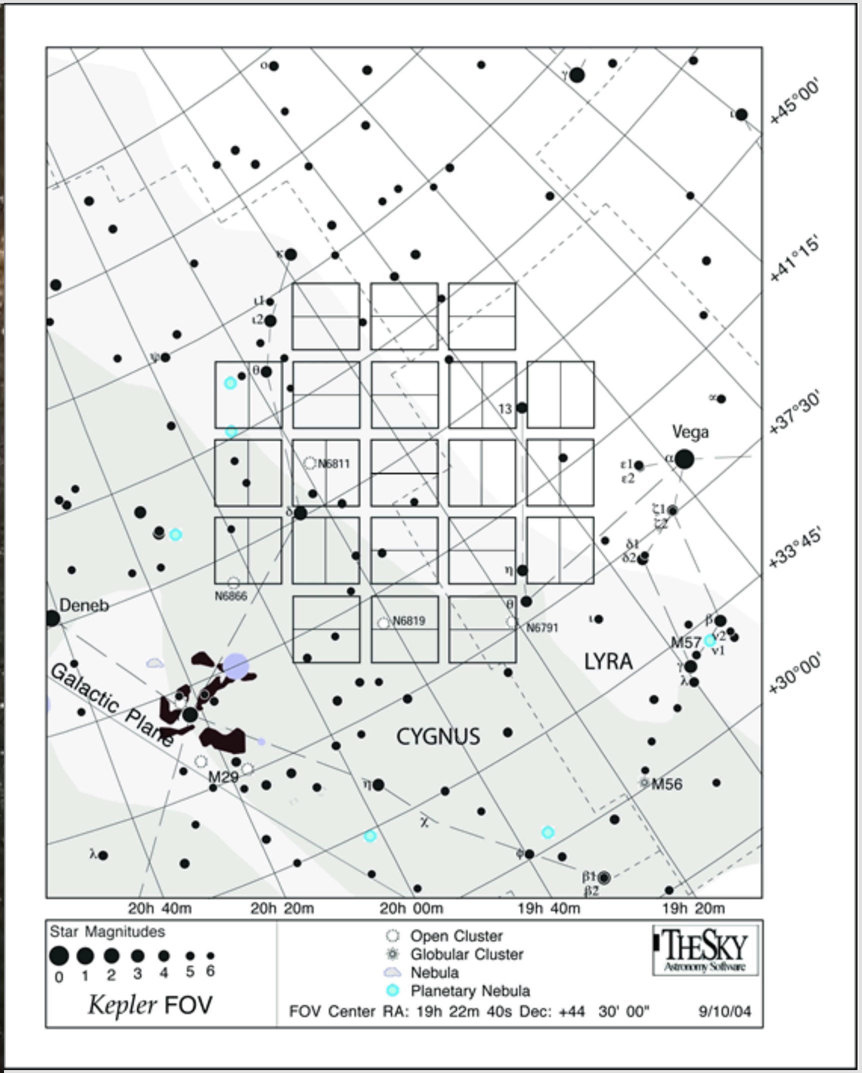




Microvariability & Oscillations of Stars
Microvariabilité et Oscillations STellaire

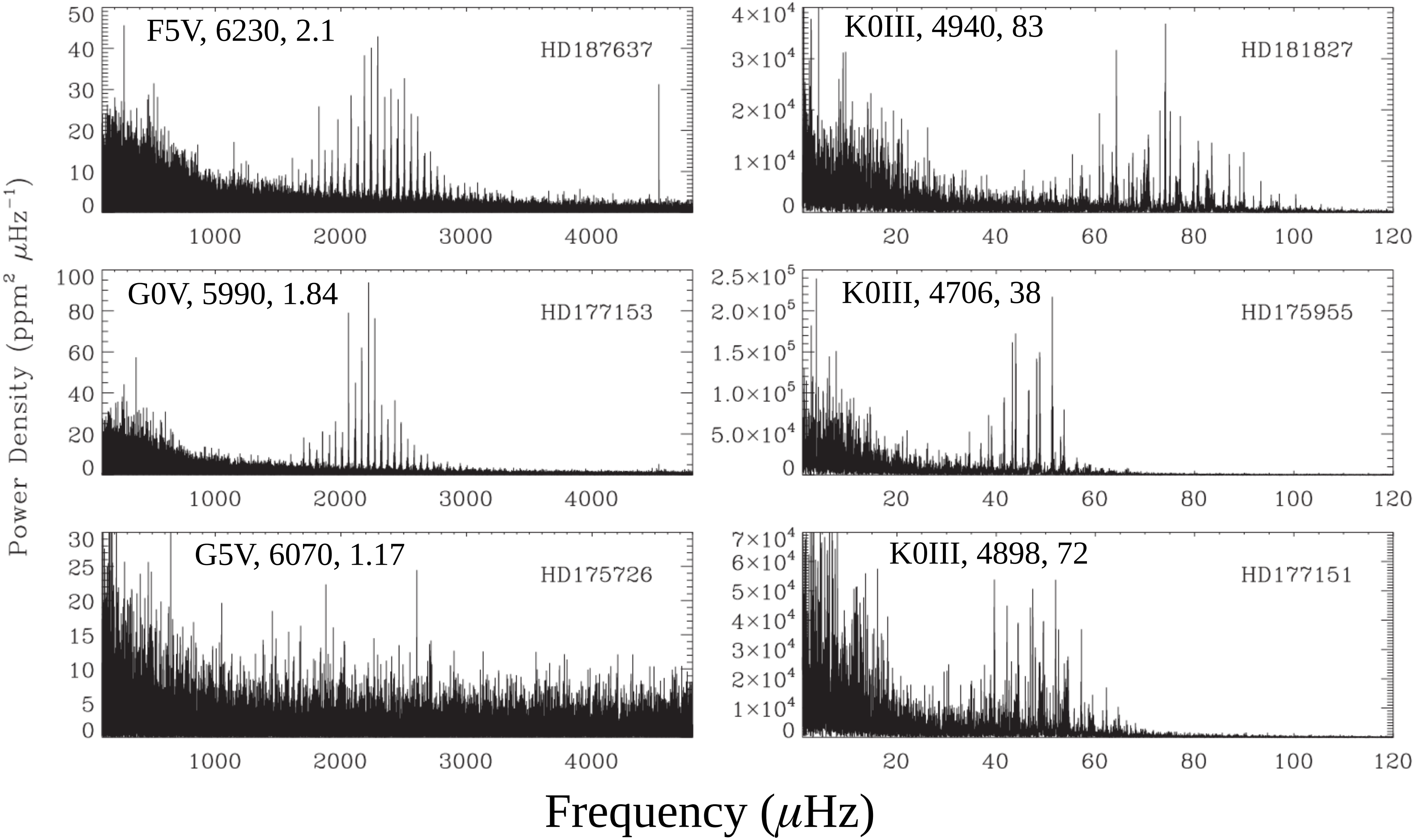
Kepler Field of View





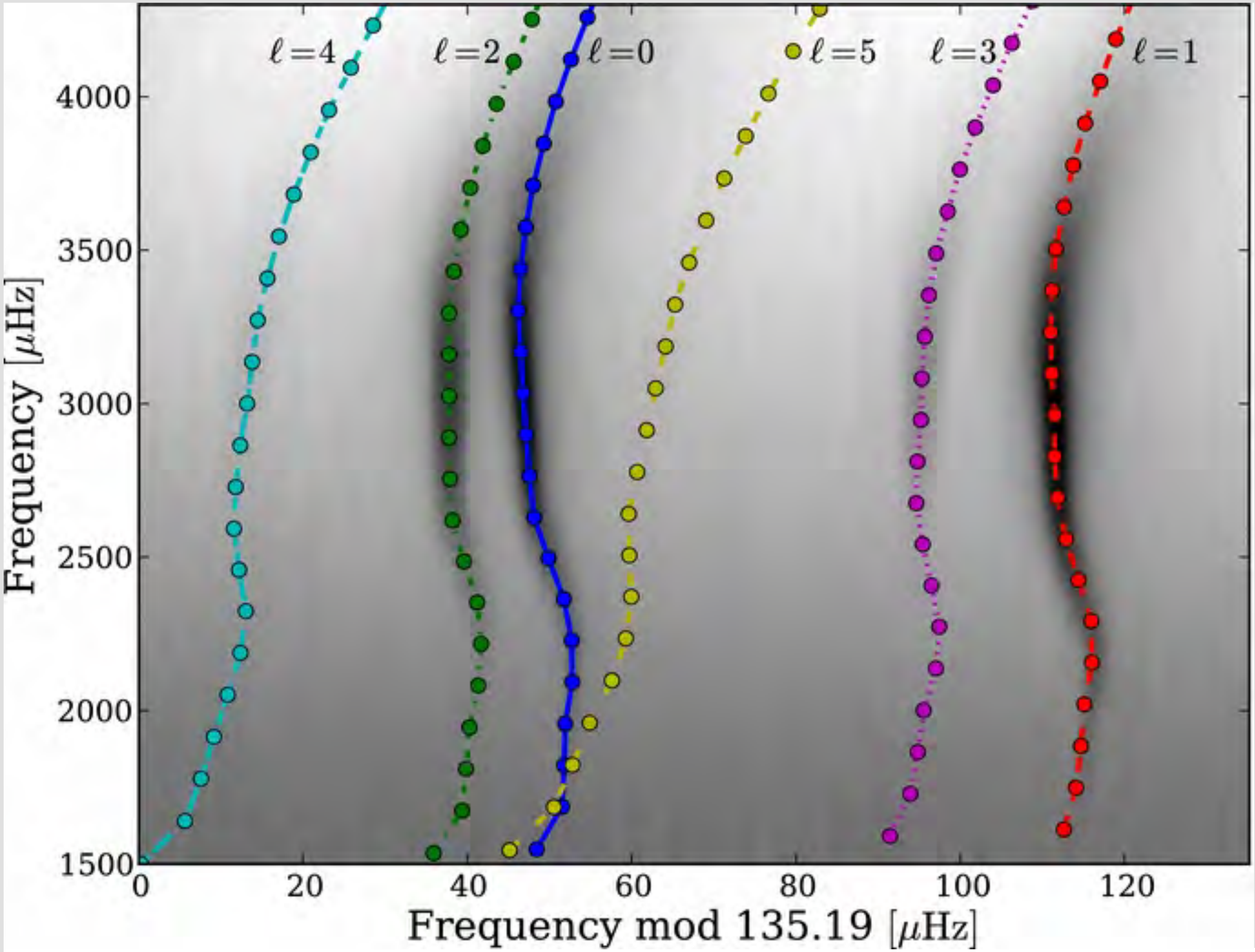
Kepler's FOV was selected to allow watching it all year.

Kepler Fourier Power Plots



From Huber, *et al.*, 2014, *Ap. J.*, **760**, 32.

Échelle Diagrams



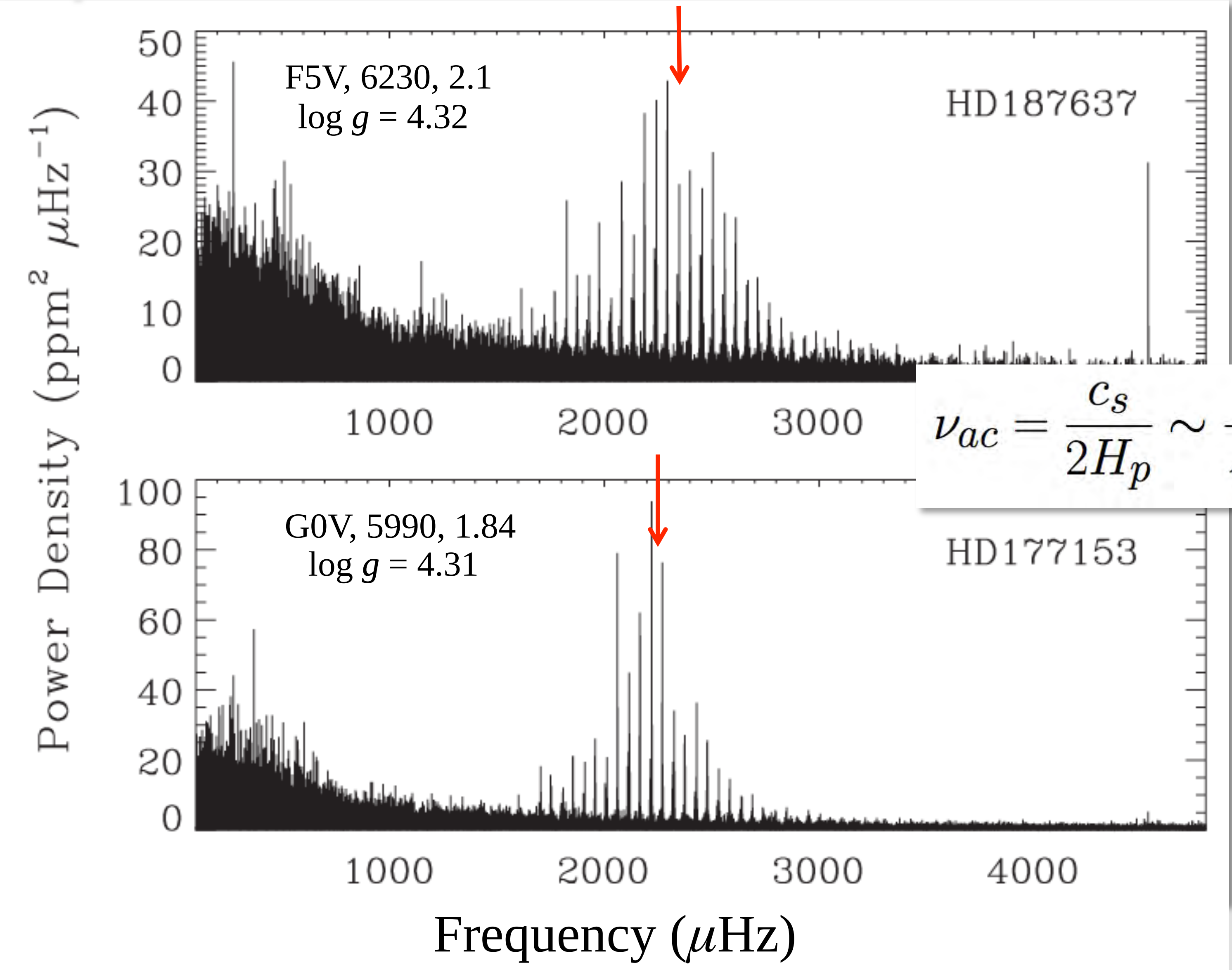
Échelle diagram of Virgo red SPM band solar observations. The Model S frequencies for ℓ = 0-5 are shown as colored disks 5 (yellow). The gray scale goes from white (low power) to black (high power) on a log scale.

Échelle diagrams provide a way to determine ν_0 (here 135 μHz or 124 min.) and assign the degree.

This required 12 years of data to see the l = 4 and a hint of the l = 5 degree modes.

Mikkel Nørup Lund *et al.*, 2014, *ApJ*, **782,** 2

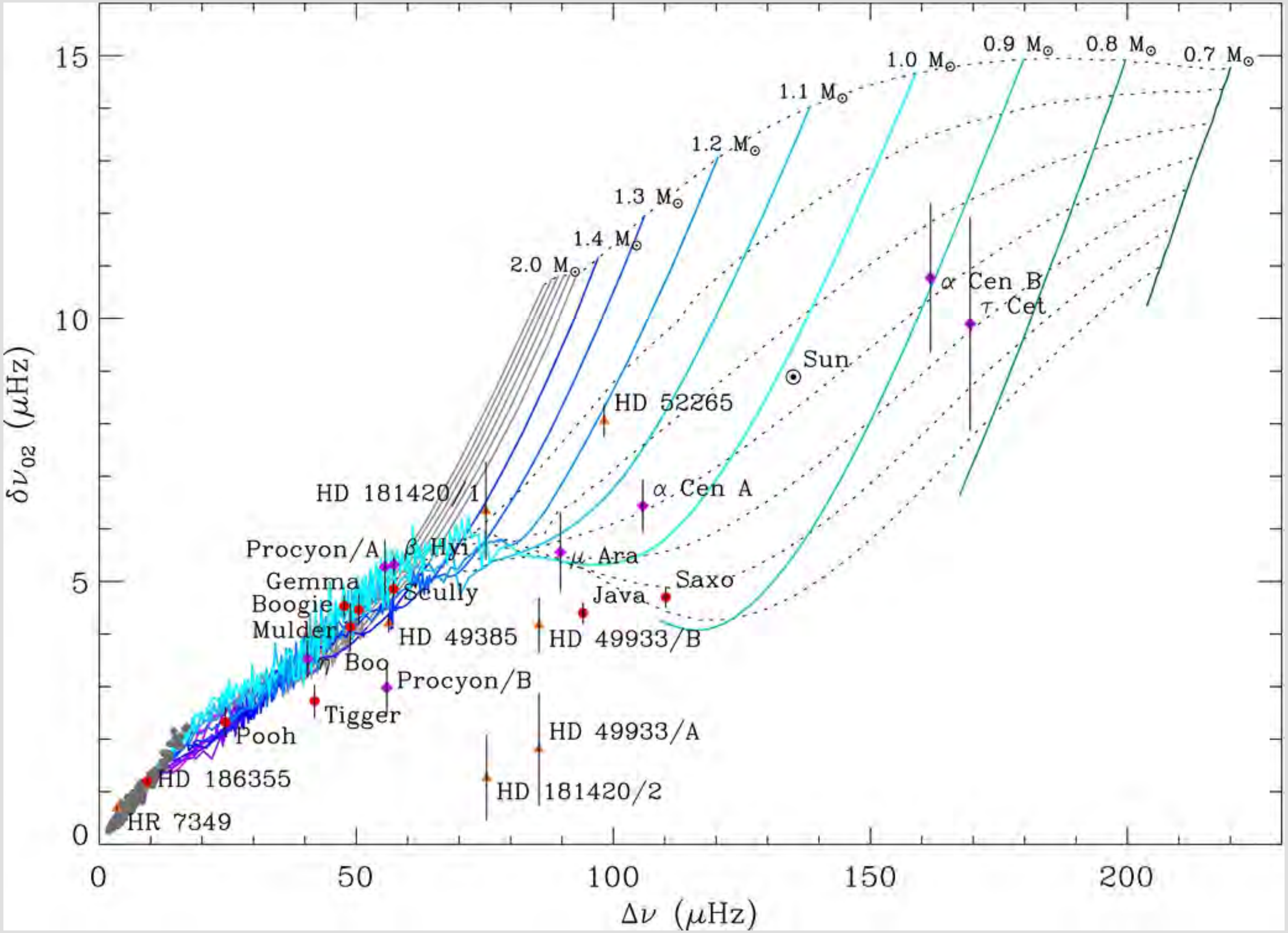
Kepler Fourier Power Peaks



$$\nu_{ac} = \frac{c_s}{2H_p} \sim \frac{g}{\sqrt{T_{\text{eff}}}}$$

From Huber, *et al.*, 2014, *Ap. J.*, **760**, 32.

Solar-like Oscillations



◆ Ground

▲ CoRoT

● Kepler

● Kepler (giants)

Figure 7 from White *et al.*, 2011, *Ap. J.*, **743**, 161

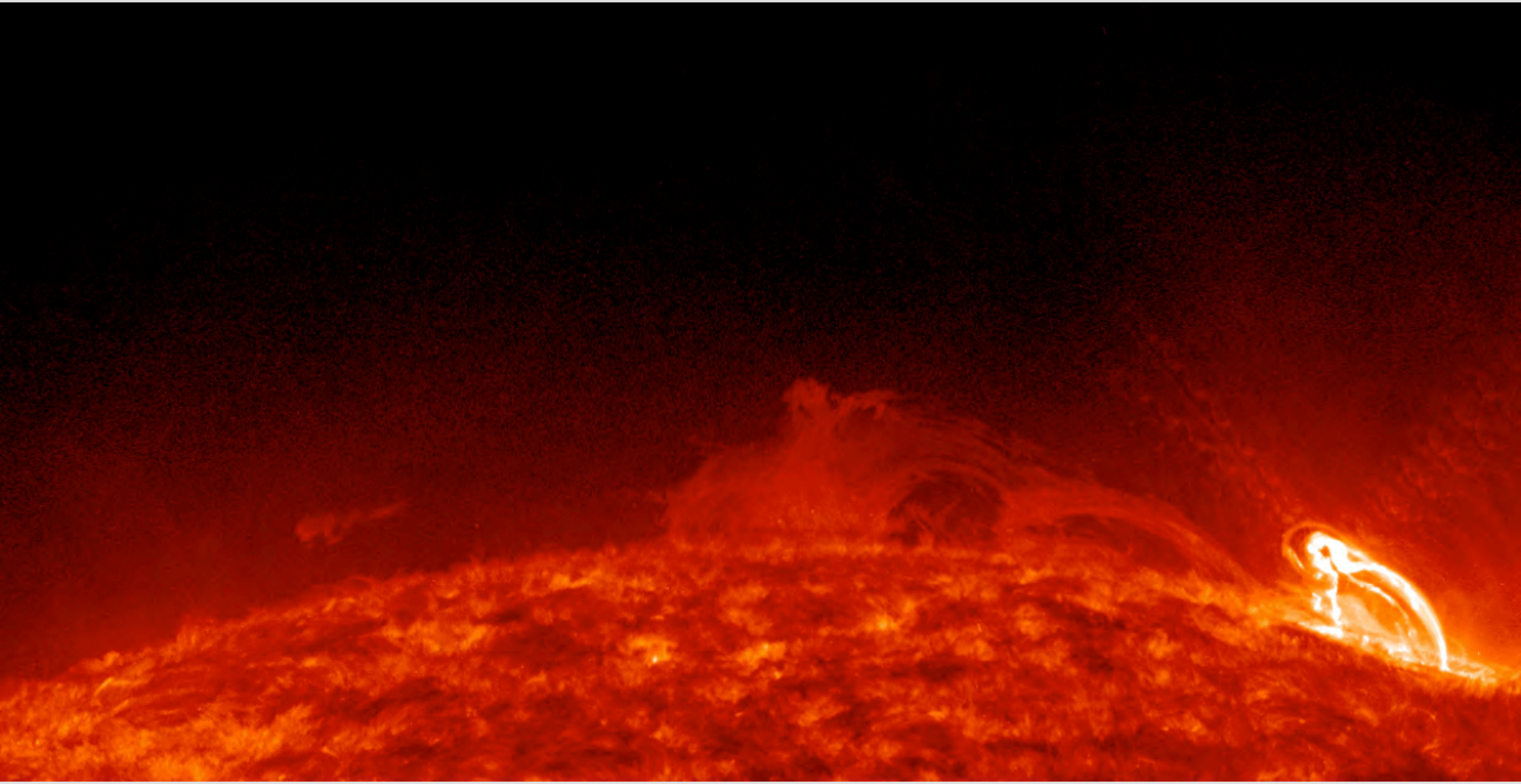
Future

1. Nonlinear mode coupling is only beginning to be studied.
2. Polar Dopplergrams of the Sun would help break some of the degeneracy issues of our ecliptic-dominated data
3. Inverting oscillation data will tell us more and more about stellar evolution, the equation of state, and opacity
4. I hope the first interstellar probe has a wave-imaging instrument. It would double the count of resolved stars but be even more of a challenge to downlink the data

Summary

1. Asteroseismology has come a long way since Mira was first described by Fabricius in 1596.
2. Helioseismology has come a long way since p-modes were discovered in the Sun in 1966.
3. Helioseismology tells us about time-dependent convection, the far-side of the Sun, and how active regions are formed.
4. Only the Sun can receive the full treatment of imaging Dopplergrams, all other stars are global analysis.
5. We are moving to explain other stars in similar ways.
6. Planet finding satellites are *great* for variable star research!

Questions?



AIA He II 304
(roughly 50,000 K)

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