IS CONVECTIVE TURBULENCE THE ONLY EXCITING MECHANISM OF GLOBAL P MODES IN THE SUN?

[Panetier et al., submitted to A&A, under review, 2025]

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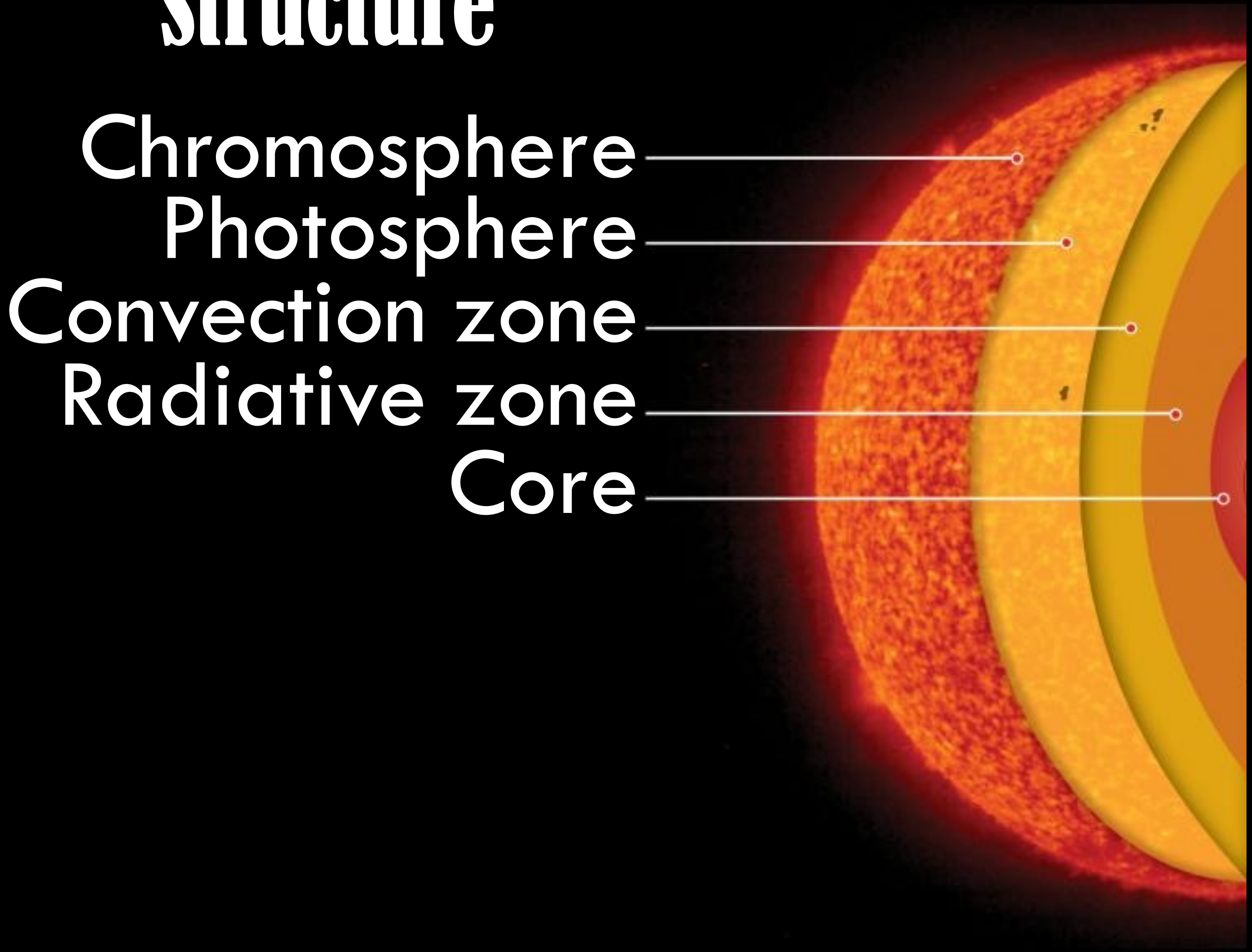
UMR AIM – CEA Saclay DRF/IRFU/DAp

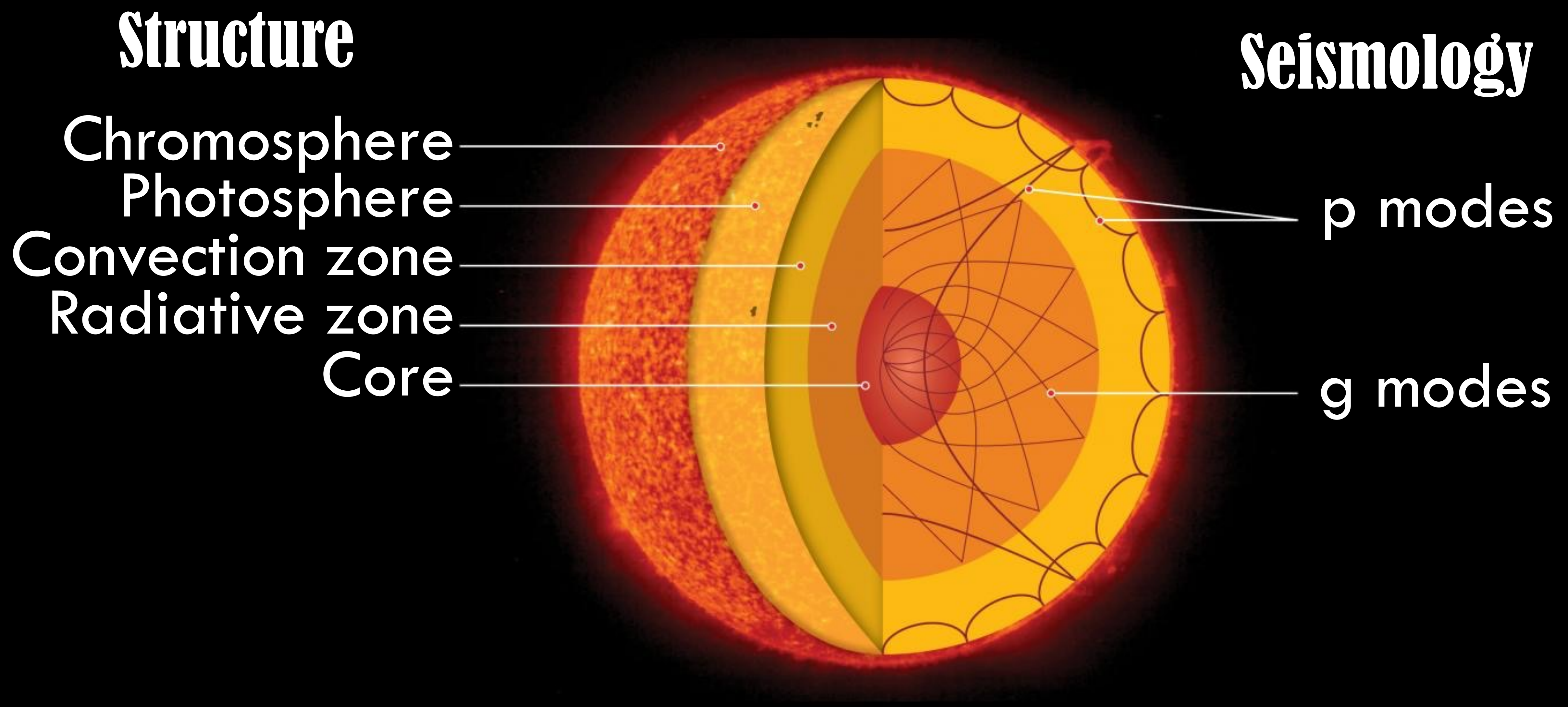
Supervisors: R. A. García, S. N. Breton

Collaborators: A. Jiménez, T. Foglizzo

Structure


Chromosphere
Photosphere
Convection zone
Radiative zone
Core

THE STRUCTURE OF A PULSATING SOLAR-LIKE STAR



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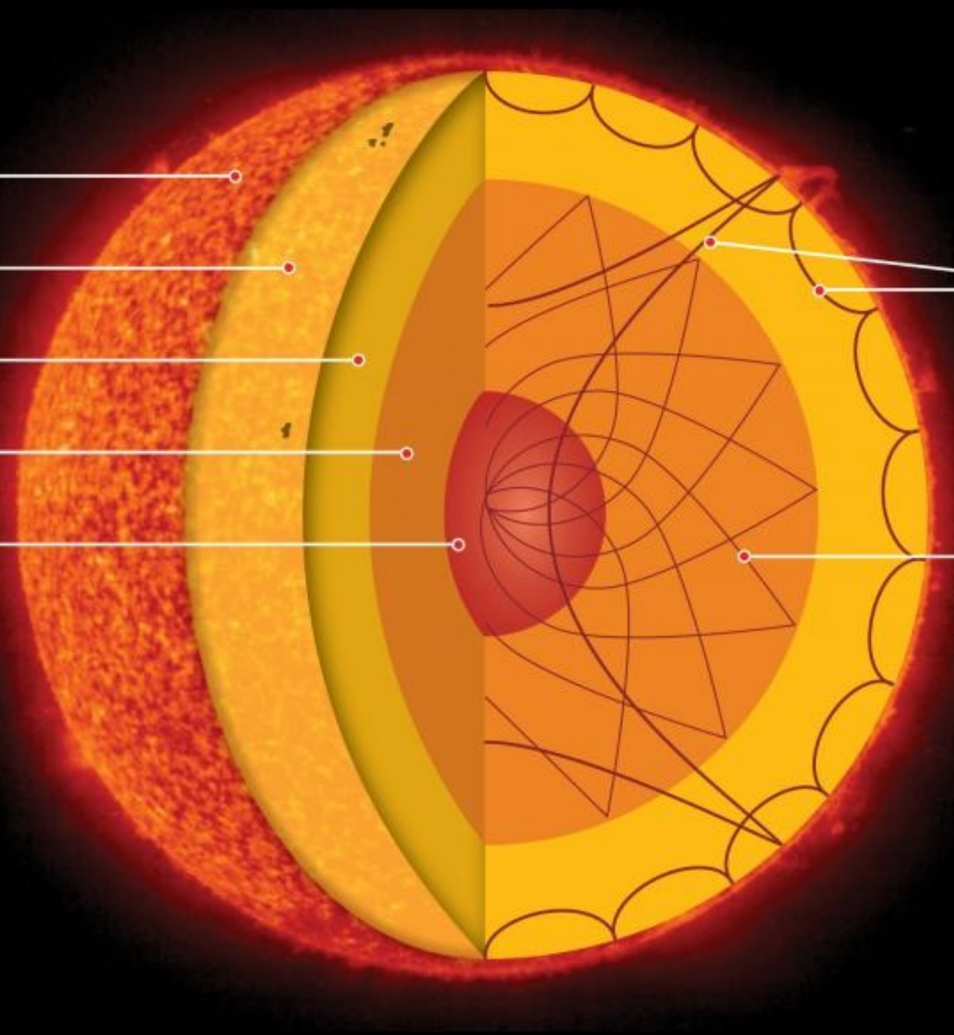

Seismology

p modes
→ Detected in main sequence stars

g modes
→ Not detected in main sequence stars

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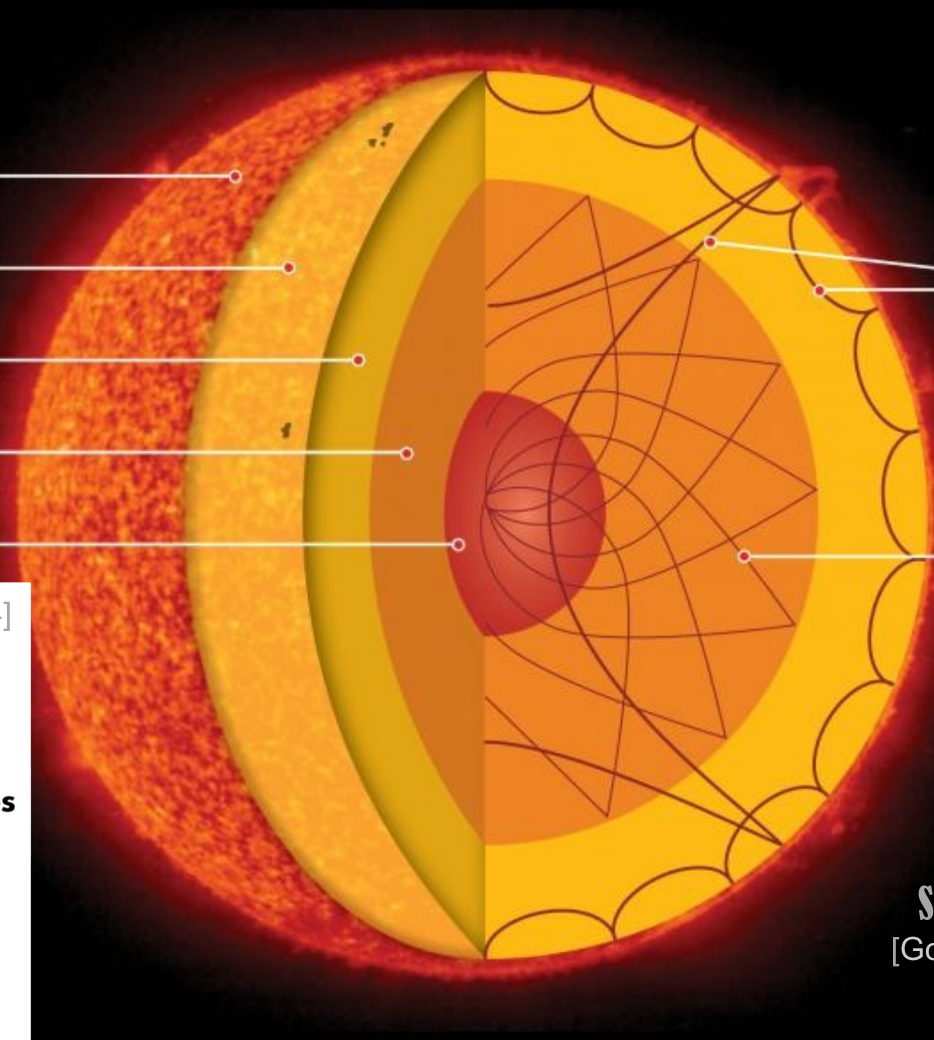

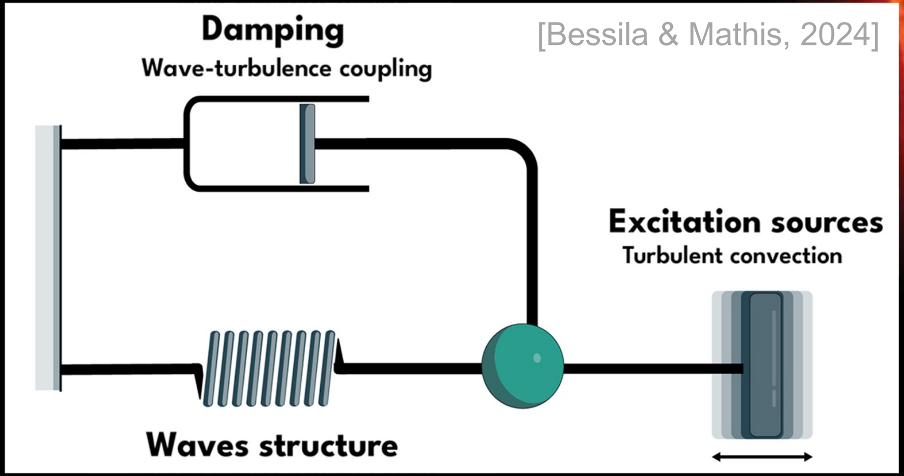

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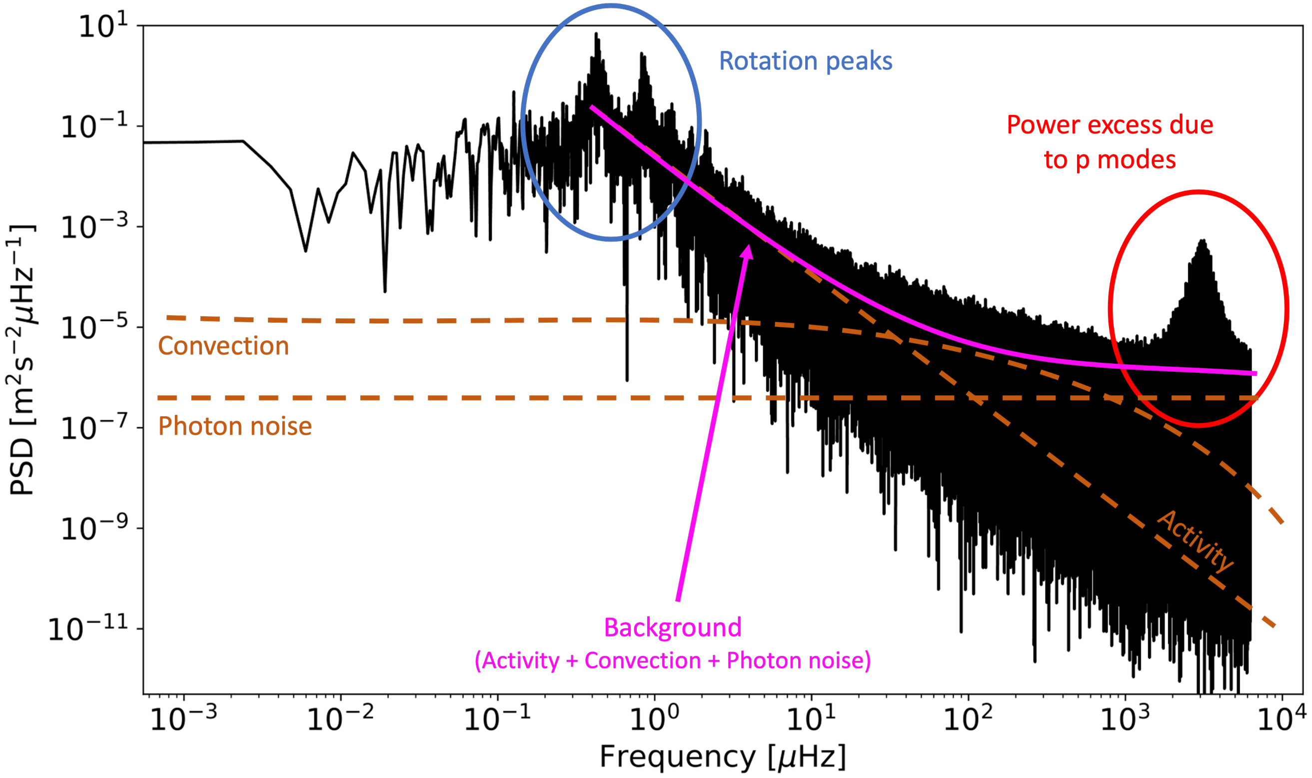
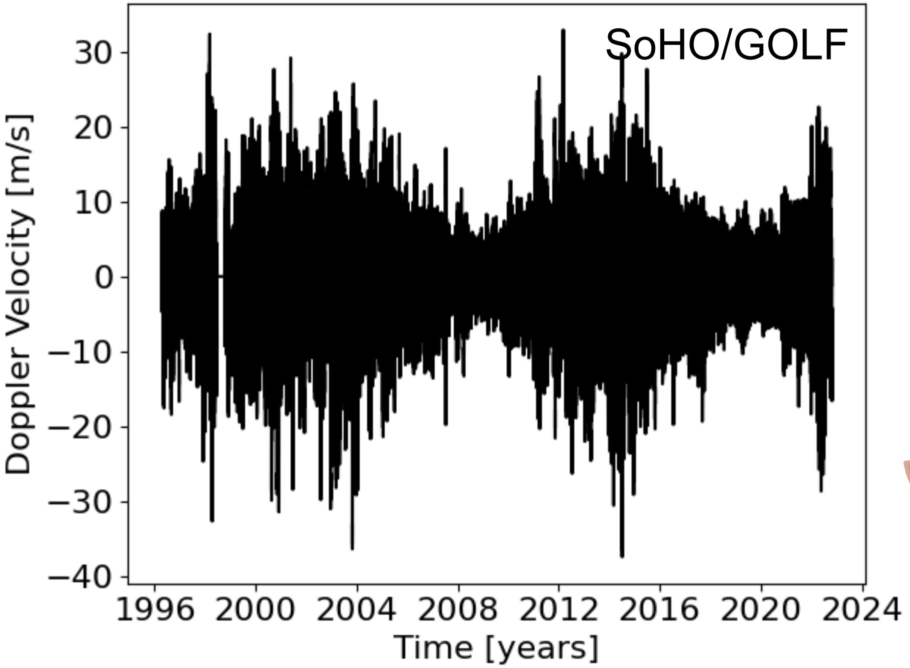
Stochastic excitation by turbulent convection
[Goldreich & Keeley, 1977; Kumar & Goldreich, 1988; Balmforth, 1992; Belkacem et al. 2008]

TIME-SERIES FROM SoHO SPACECRAFT





PSD
(Power Spectrum Density)

[Domingo et al. 1995]

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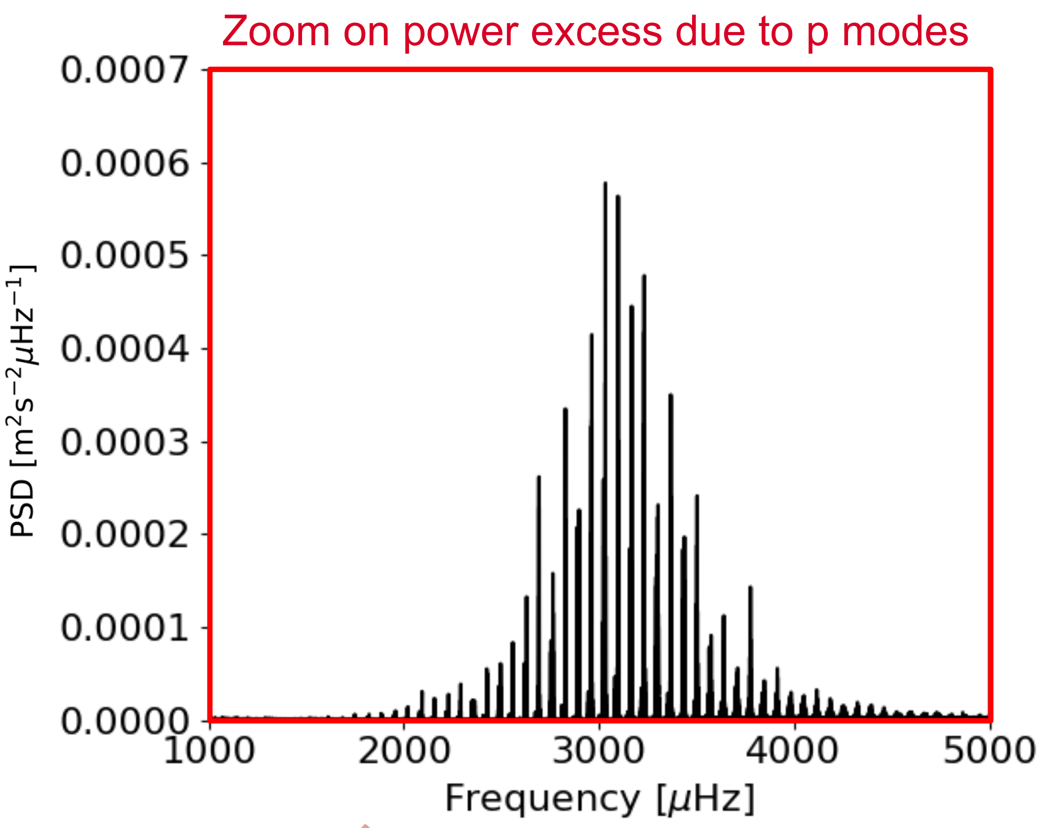

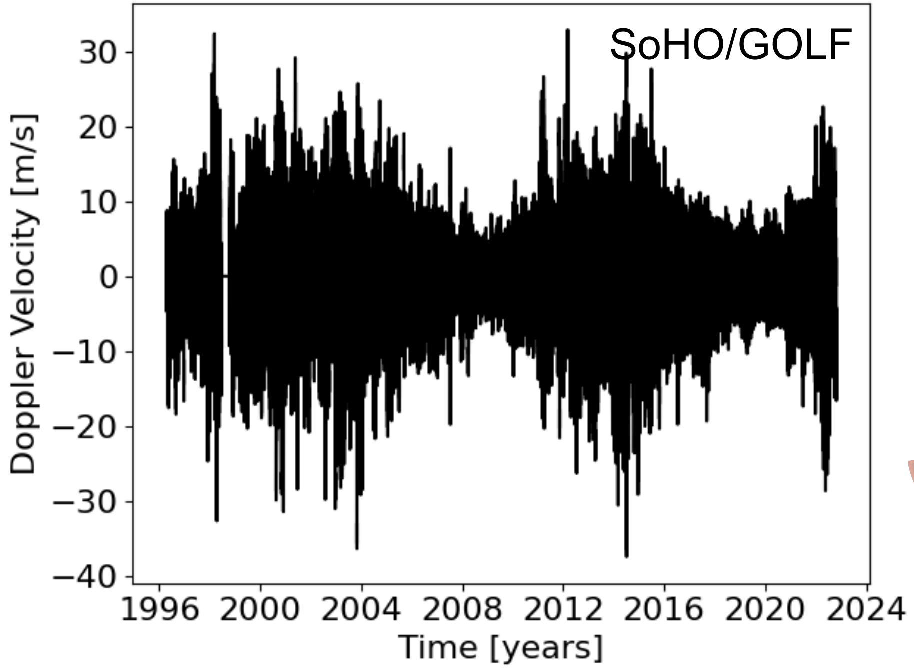

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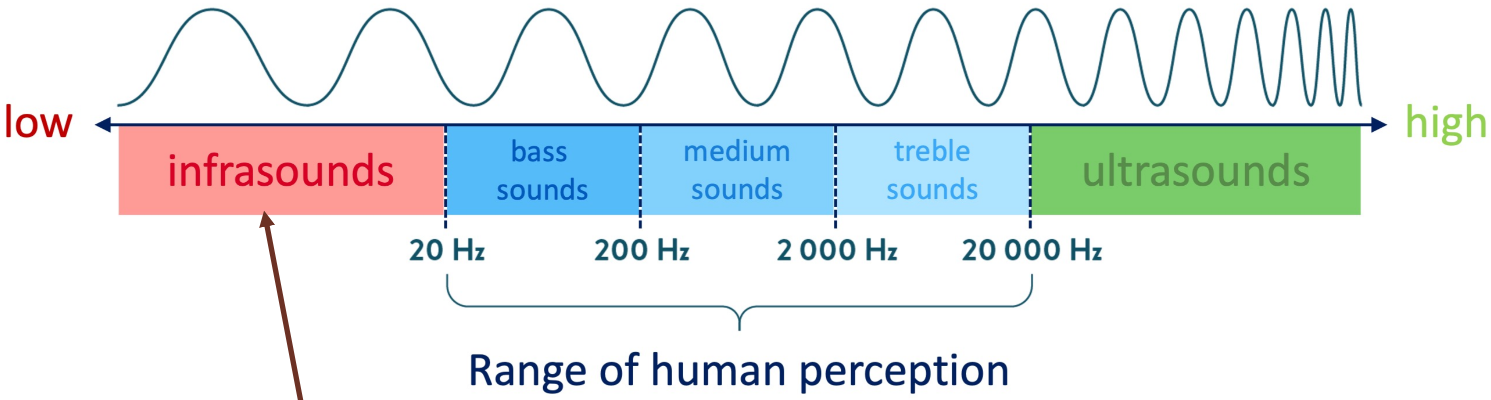
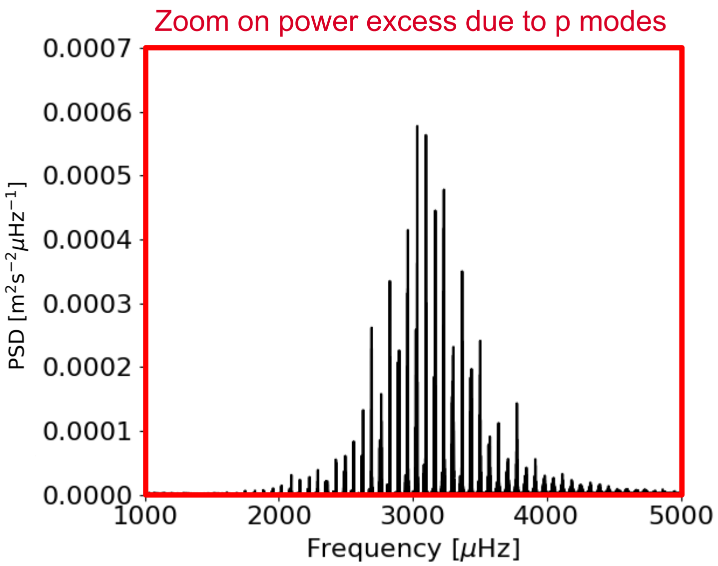
THE MUSIC OF STARS

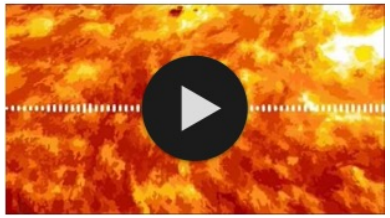

Image generated by DALL·E with input from ChatGPT, OpenAI, 2024.

Sound frequency



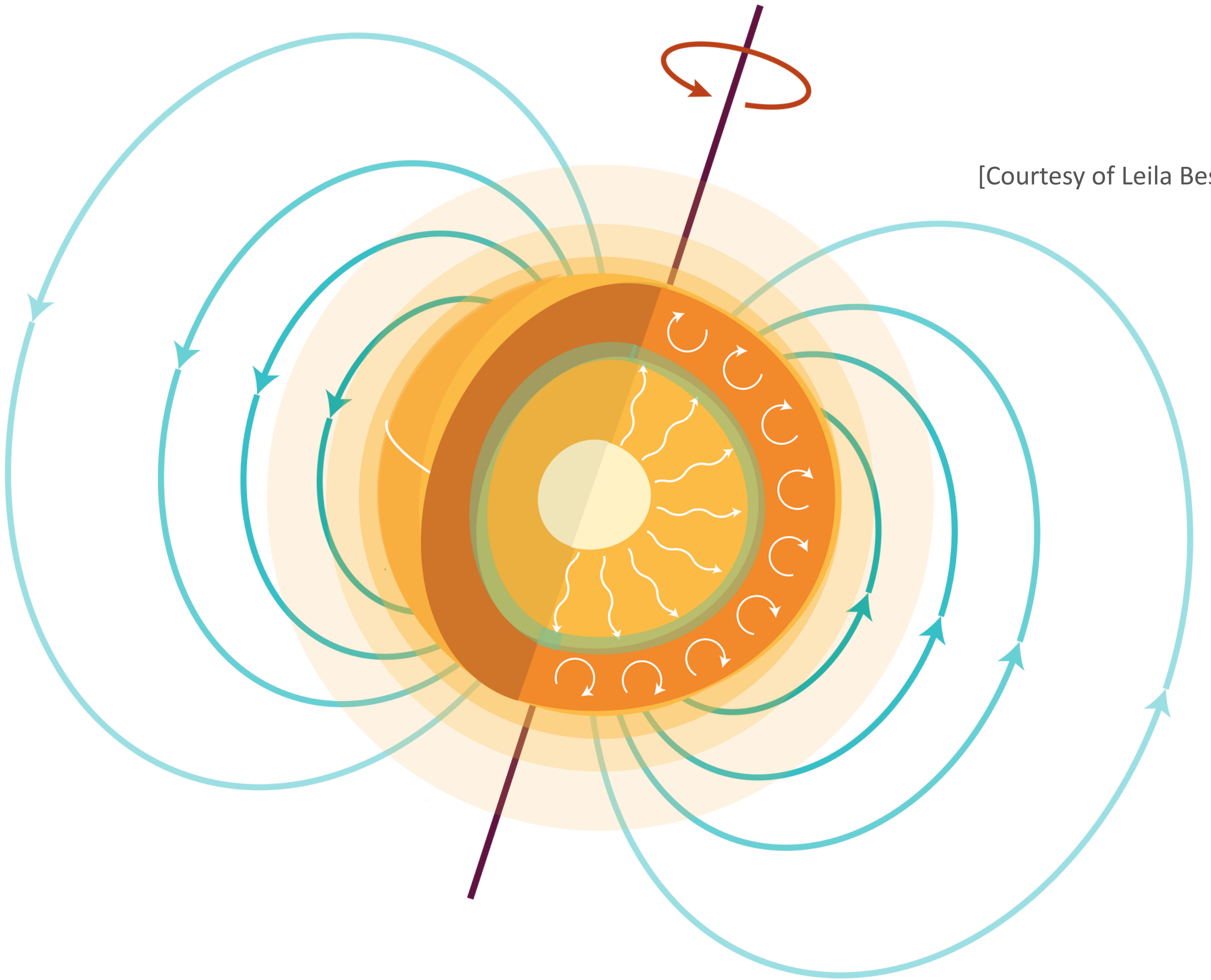


[NASA]



https://www.youtube.com/watch?v=-l-zdmg_Dno

SOLAR MAGNETIC FIELD



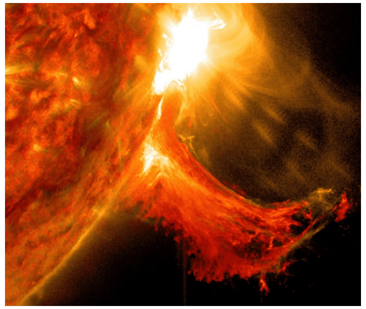
[Courtesy of Leila Bessila]

Magnetic field generated and maintained by **dynamo effect**

→ Interaction between convection and rotation

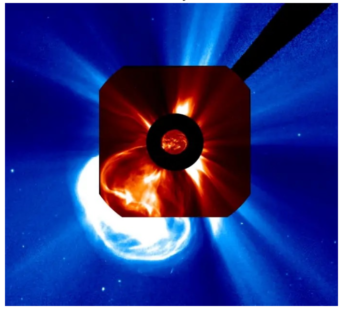
SOLAR MAGNETIC ACTIVITY

Flare



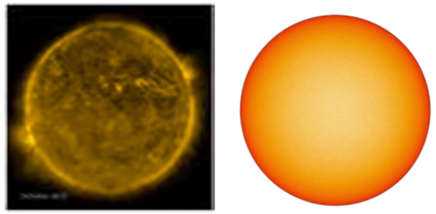
Localized emission of electromagnetic radiation in the Sun's atmosphere

Coronal Mass Ejection (CME)

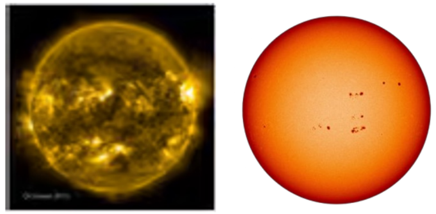


Ejection of plasma mass from the Sun's corona into the heliosphere

Solar minimum



Solar maximum



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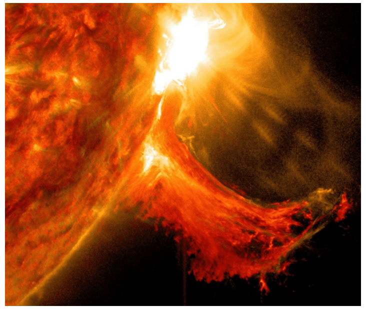

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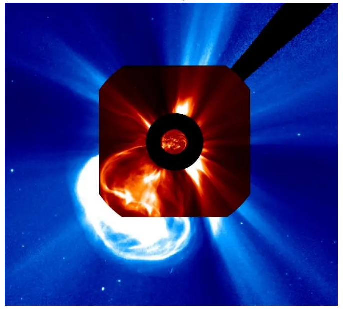

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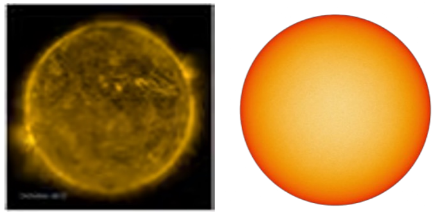

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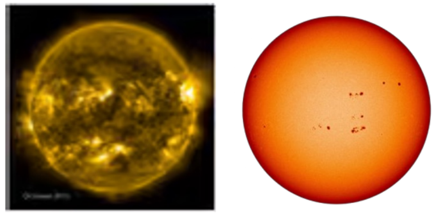
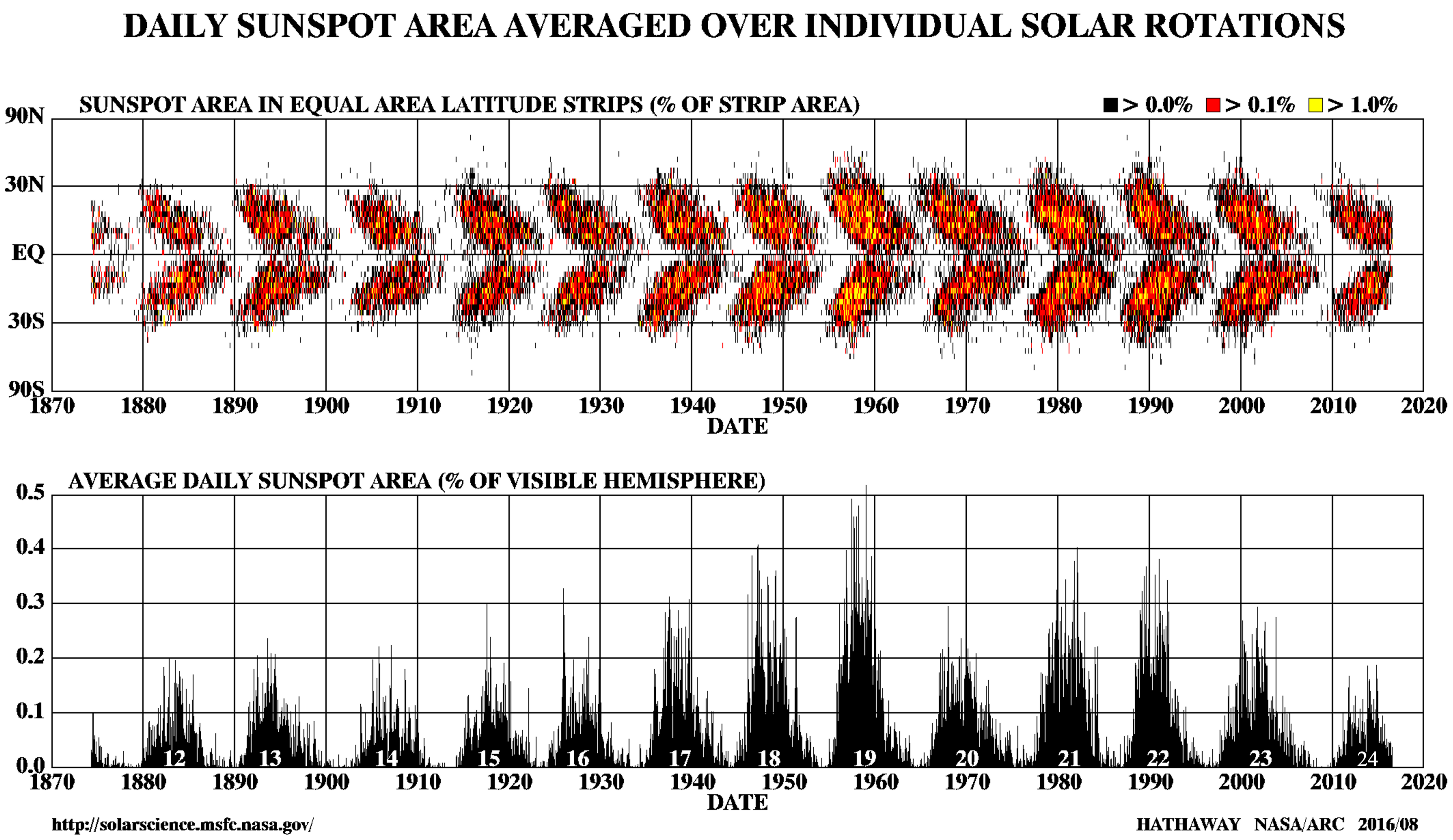


The number of sunspots as a proxy



→ Schwabe cycle: 11 years, with a change in polarity at each cycle end

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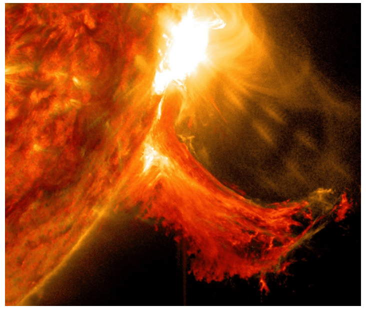

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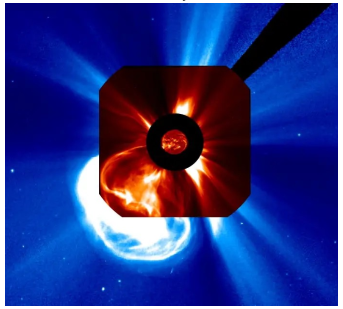
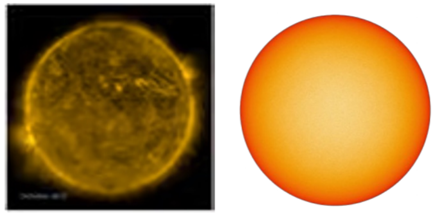


Ejection of plasma mass from the Sun's corona into the heliosphere

At solar maxima:

+ Energetic flares
+ Coronal Mass Ejections (CMEs)
+ Sun spots

Solar minimum



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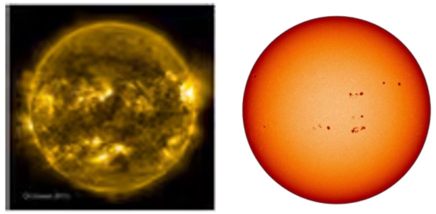

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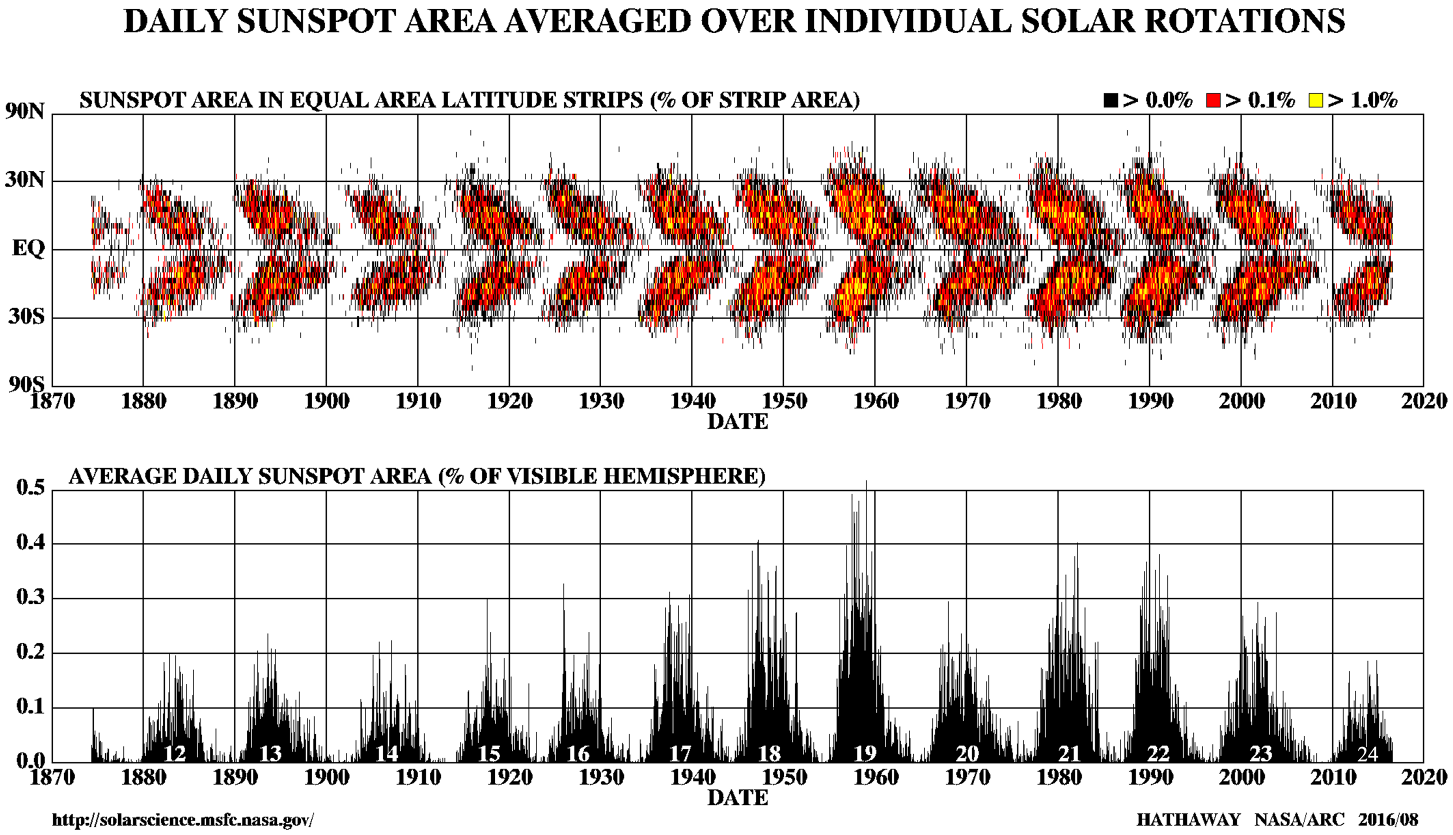

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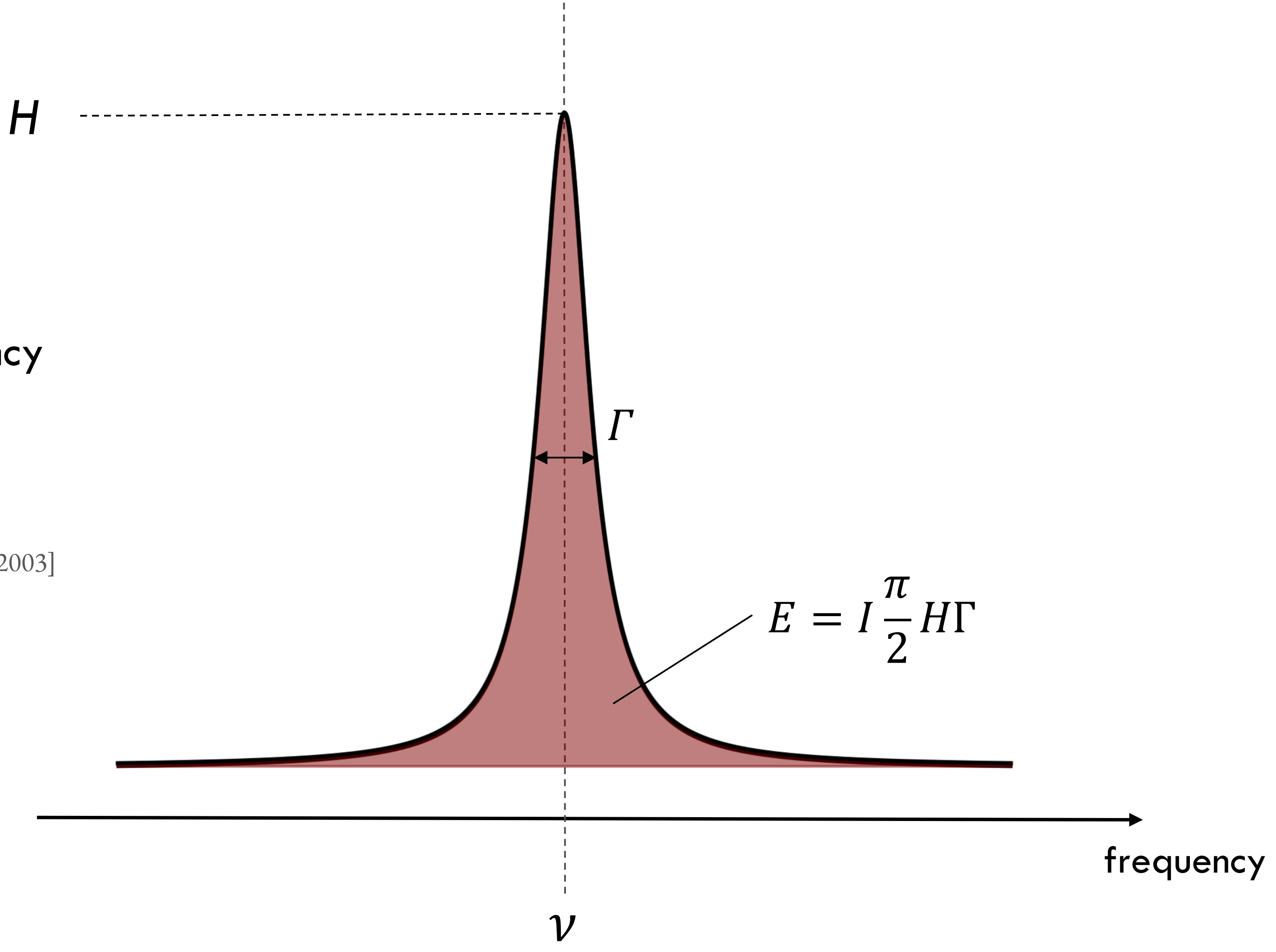
PROBING THE MAGNETIC CHANGE WITH THE MODE PARAMETERS

ν : frequency
H : height
Γ : width
E : energy

[Jiménez-Reyes et al., 2003]



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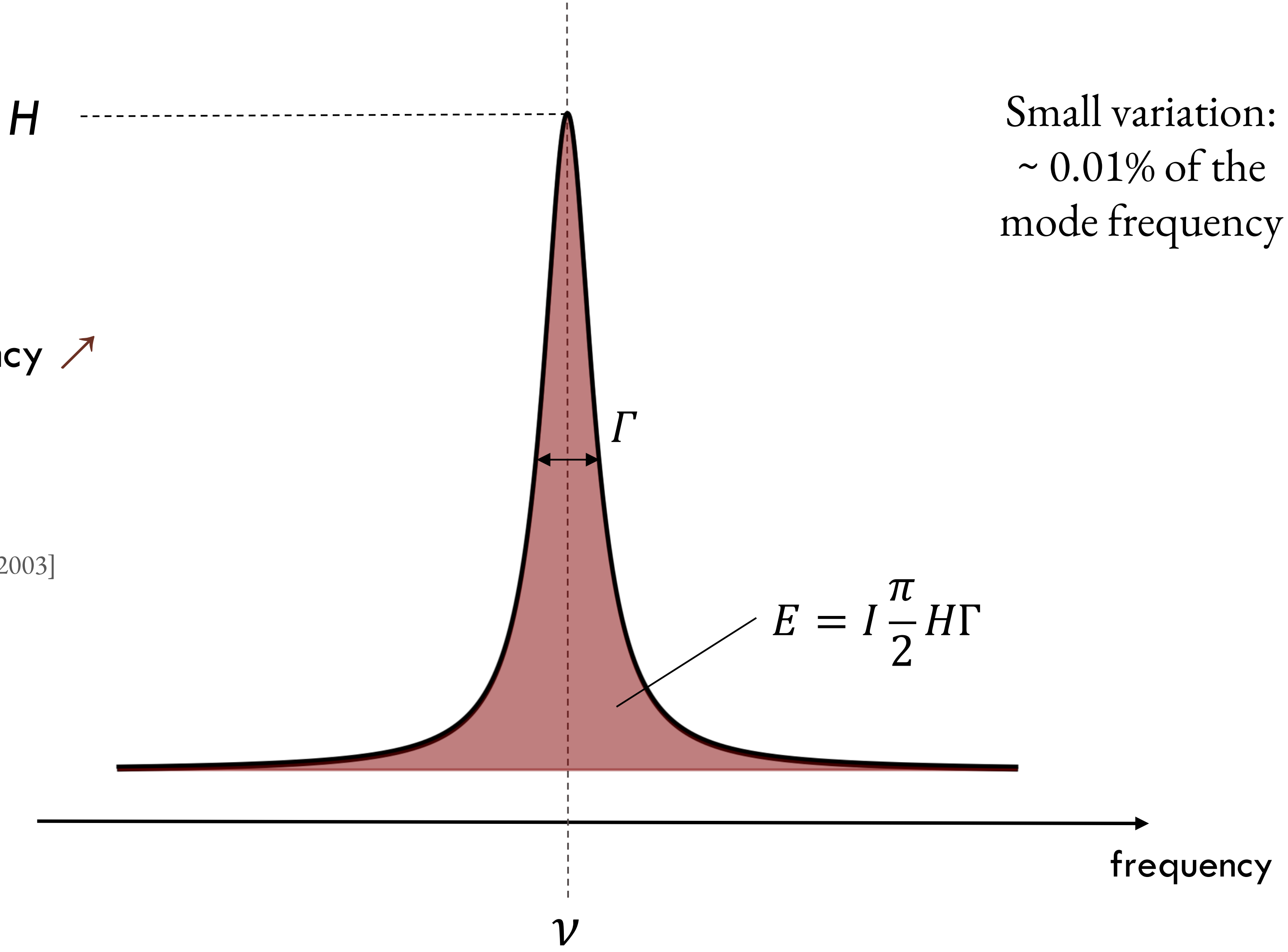
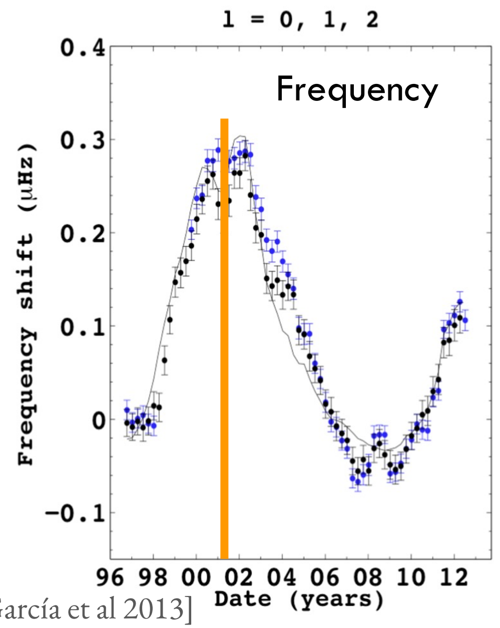


Small variation:
~ 0.01% of the
mode frequency



[García et al 2013]

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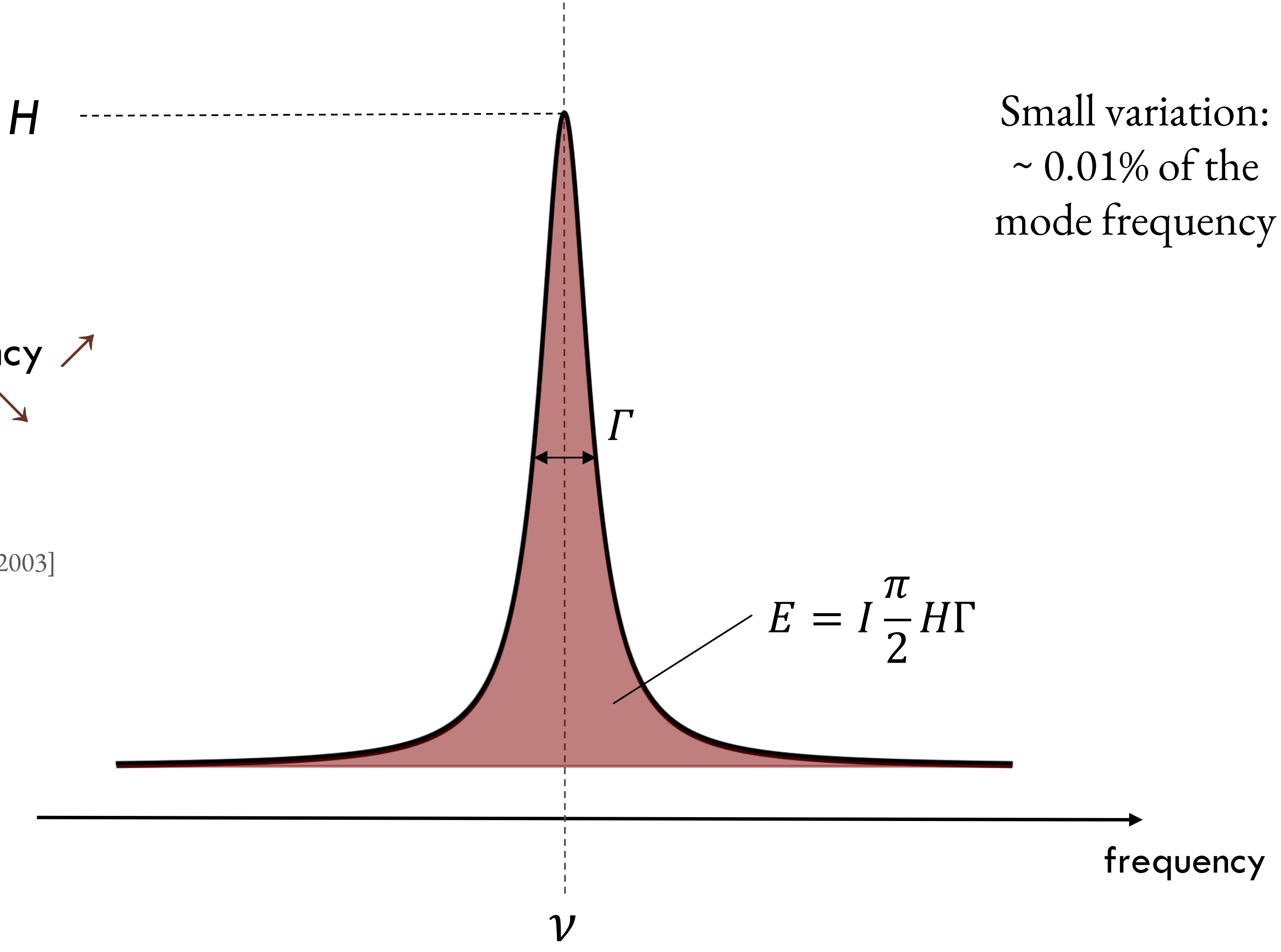

$$E = I\frac{\pi}{2}H\Gamma$$

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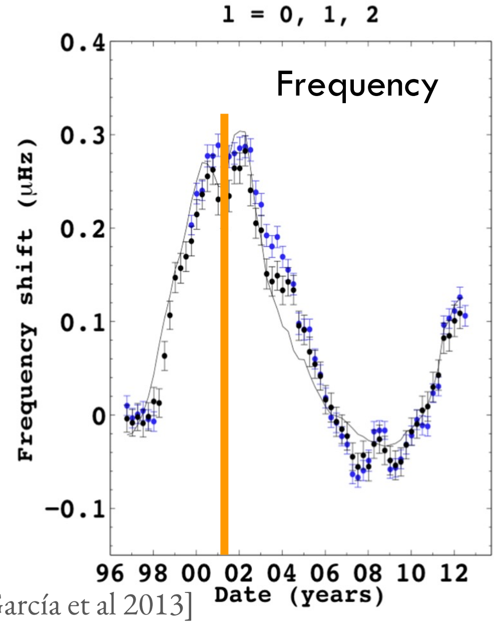

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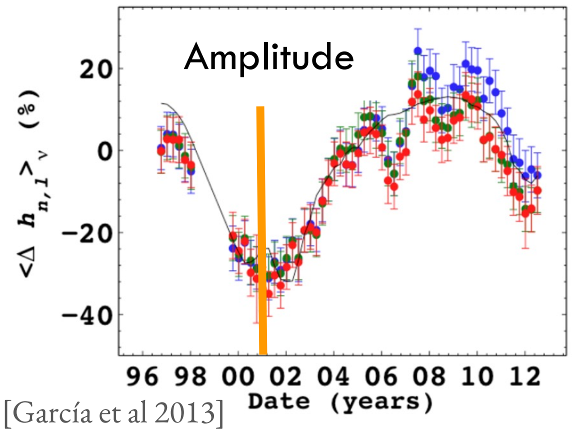

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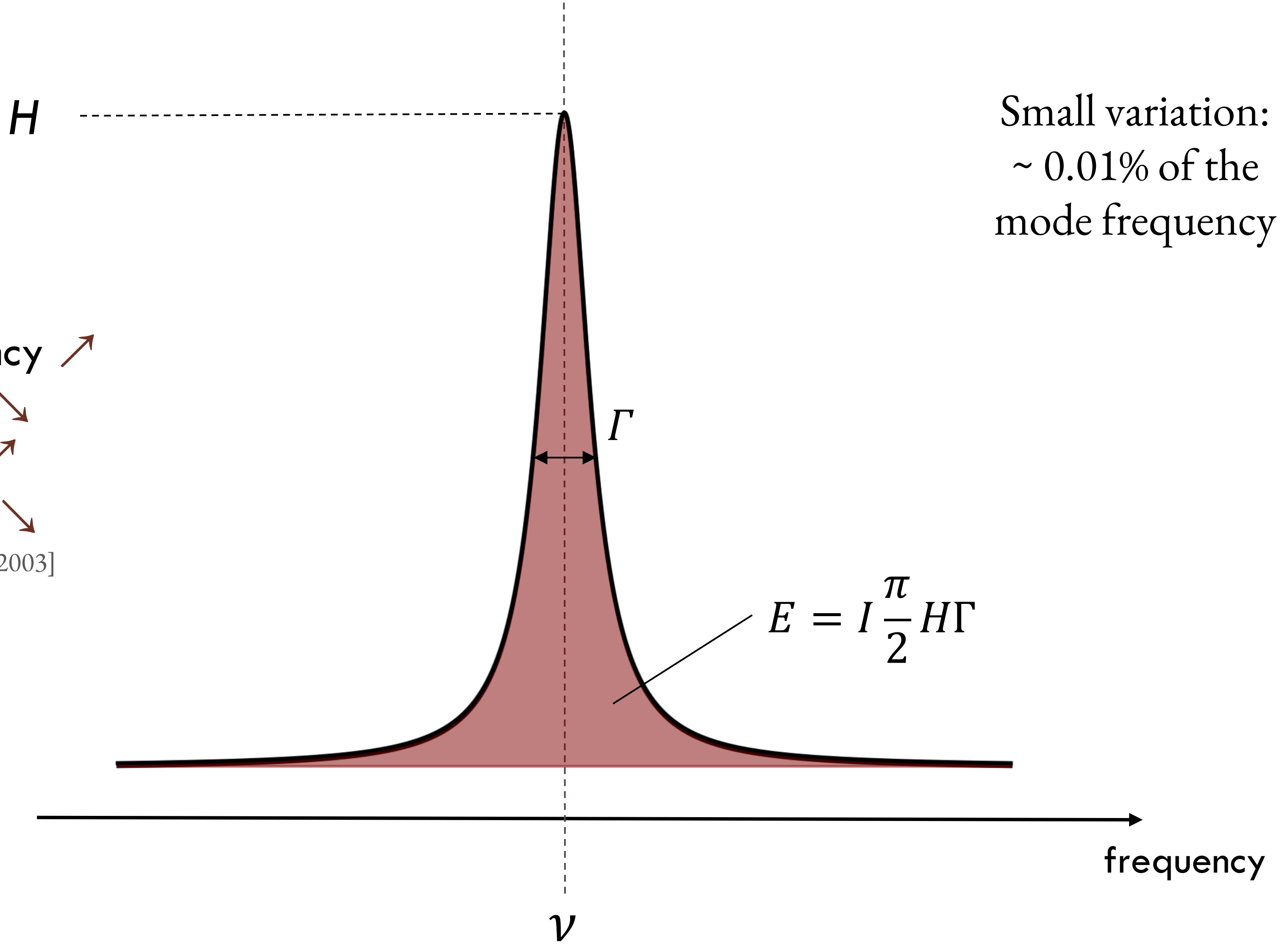

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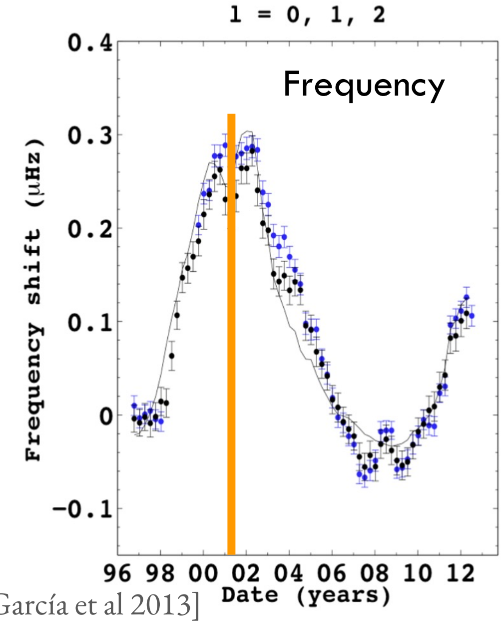

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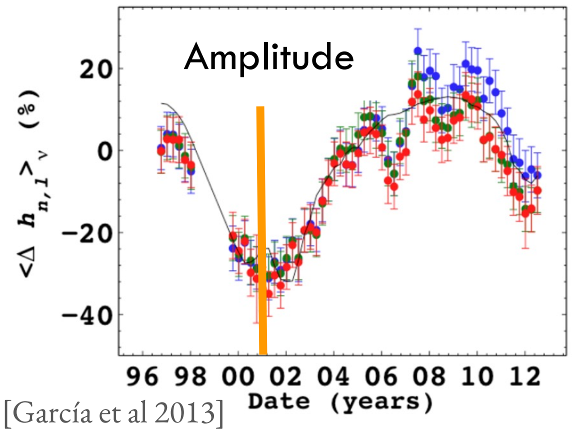

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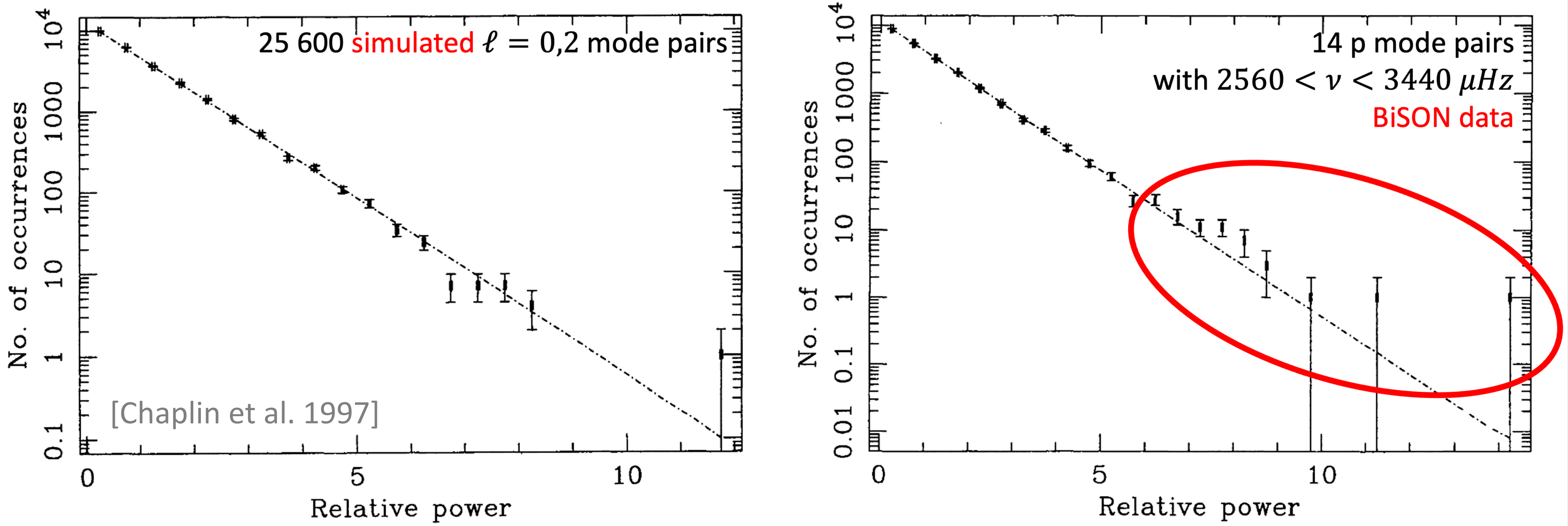
A POWER EXCESS IN THE MODES?

→ Simulations of p-modes assuming a stochastic excitation **do not reproduce p mode power excess**

[Chaplin et al. 1997, Chang & Gough, 1998]

→ No dependence on mode frequency appearing



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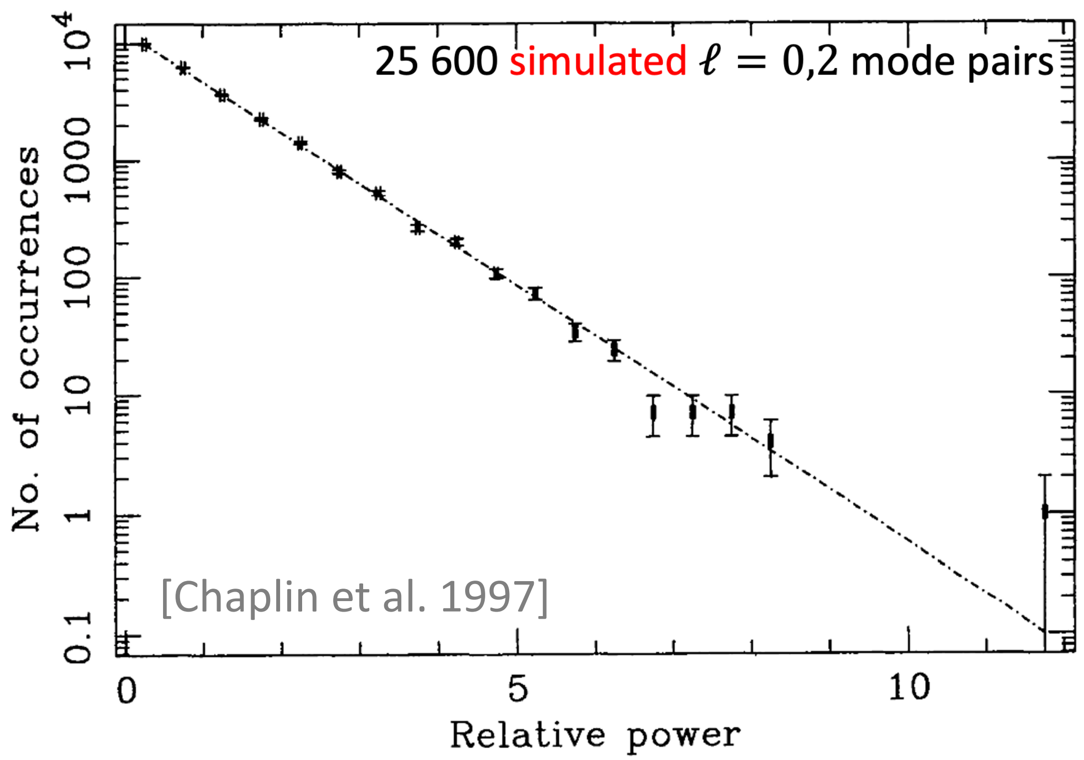
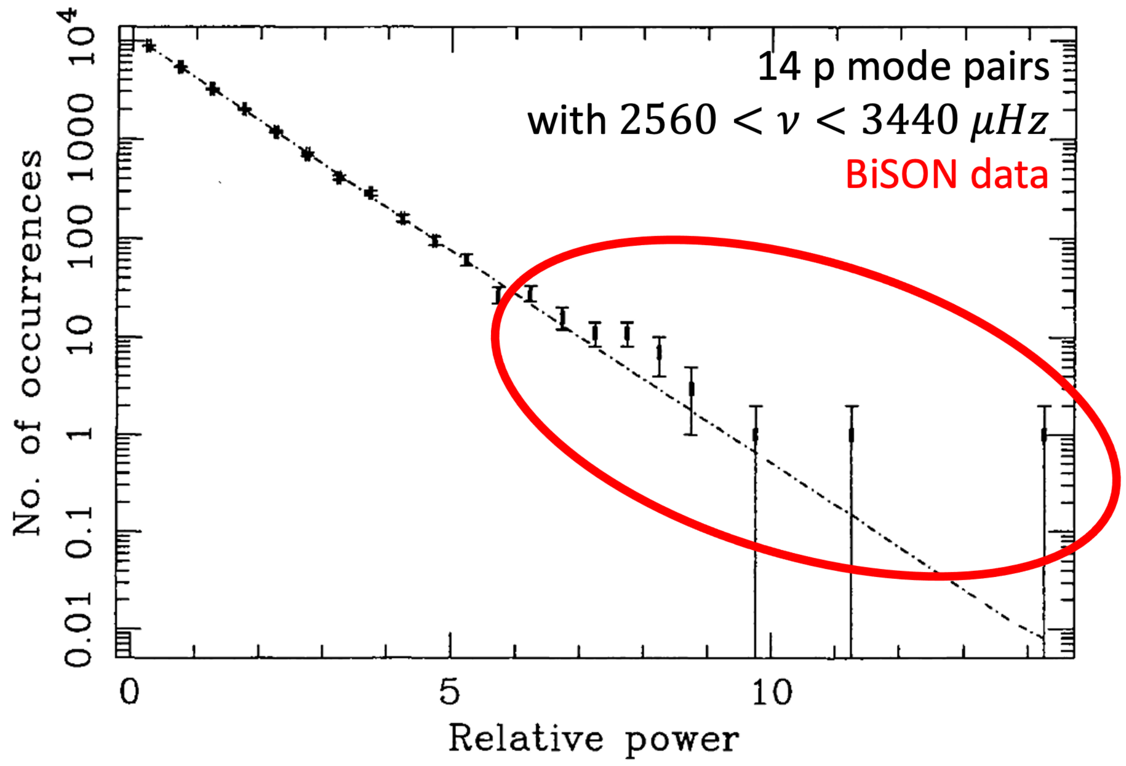
[Chaplin et al. 1997, Chang & Gough, 1998]

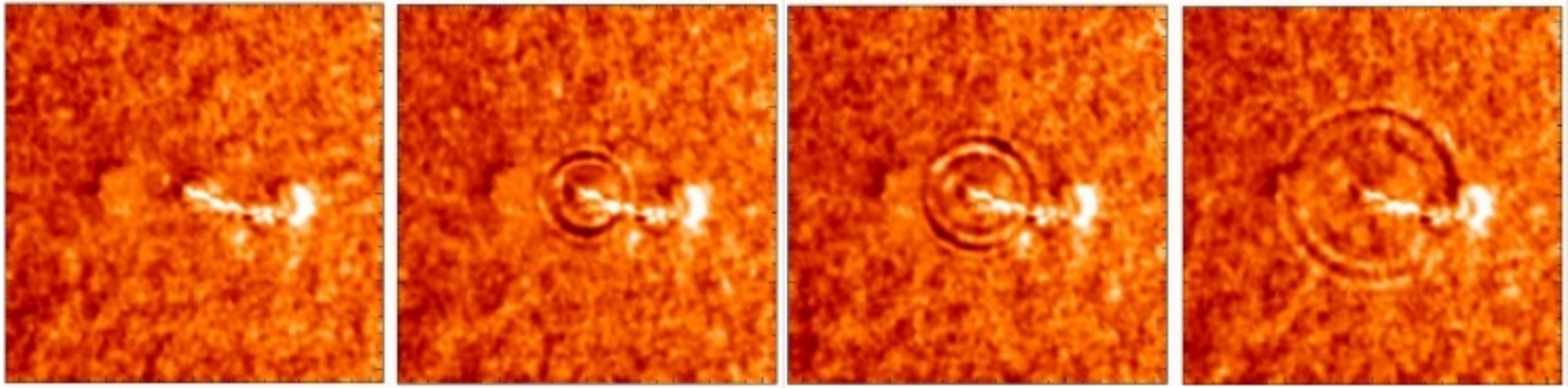
⟶ No dependence on mode frequency appearing

▷ Origin from other excitation mechanisms ?





A SUN-QUAKE FROM A FLARE



[MDI SoHO, Kosovichev & Zharkova 1998]

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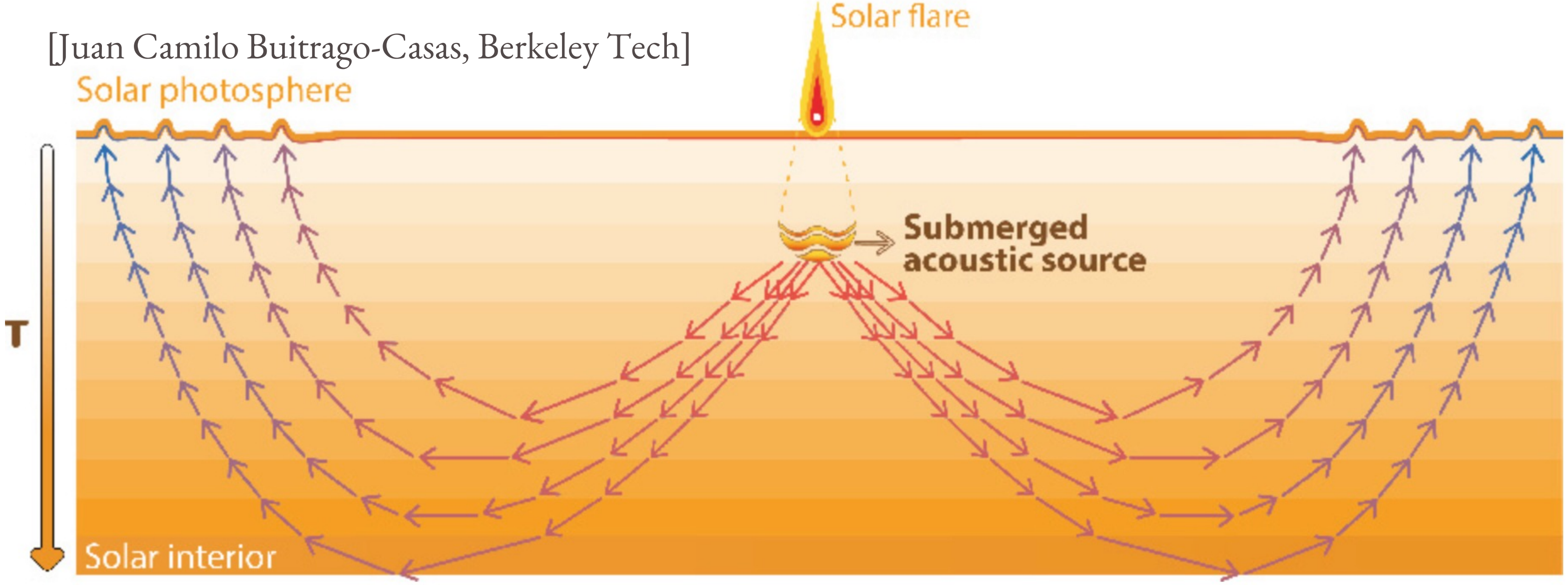

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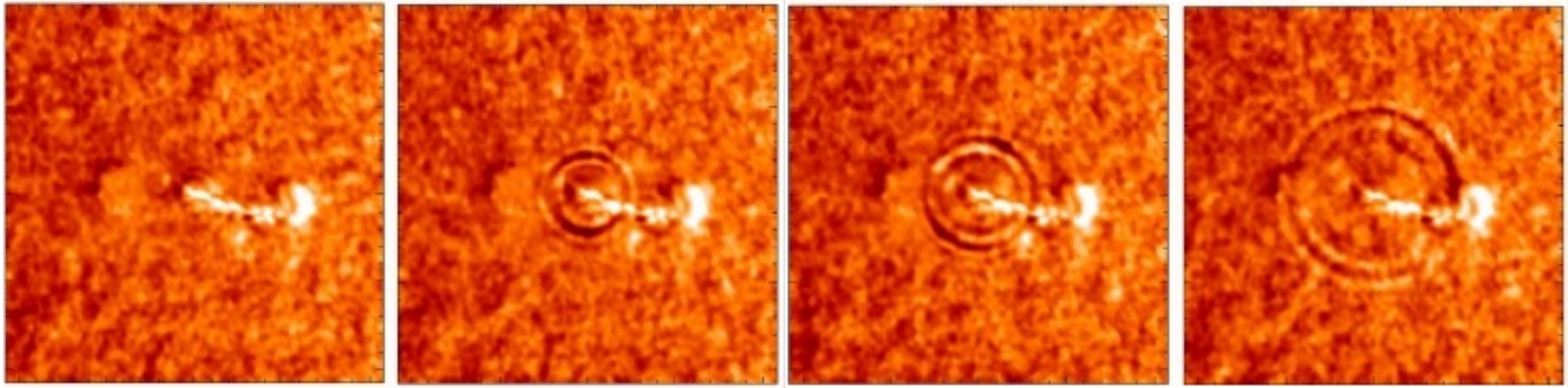

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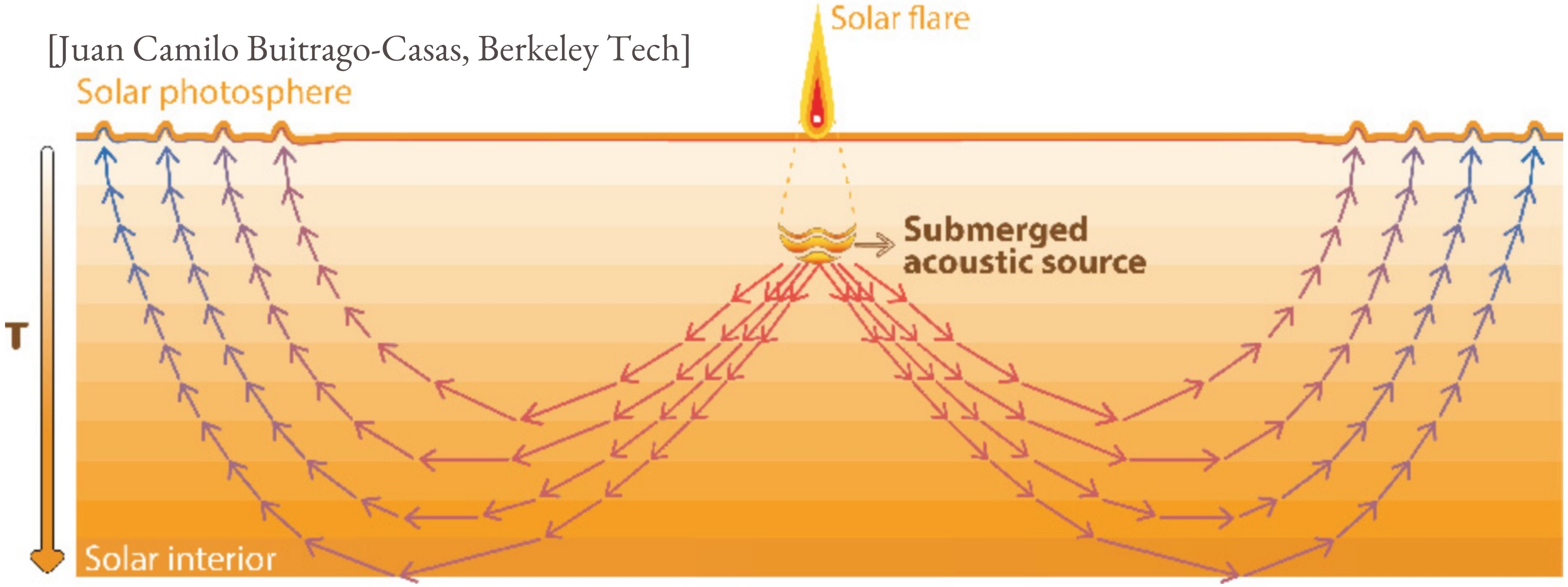

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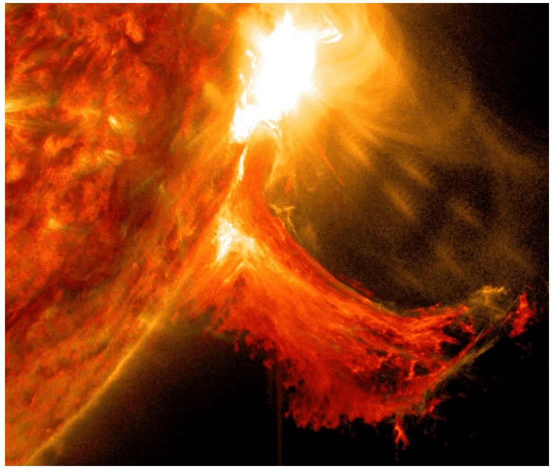
Is this also exciting global p modes?

POSSIBLE EXCITATION BY FLARES OR CMES

[Foglizzo et al. 1998; Foglizzo, 1998]

Flare



✓ **small characteristic size**

→ is able to excite 10^4 modes

✕ **strength**

(Mean energy $\sim 10^{30}$ ergs)

→ too few energy per mode

→ Equi-distribution of the input energy between all the modes

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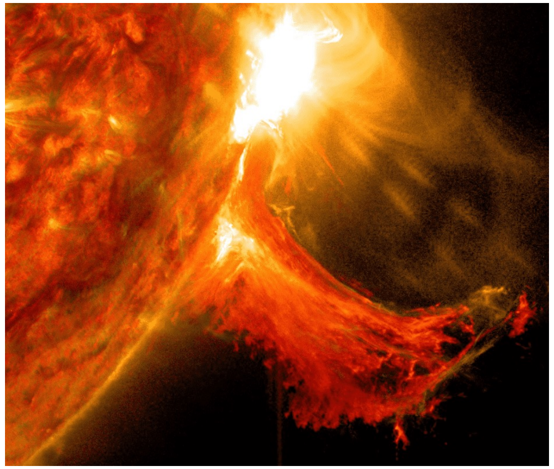

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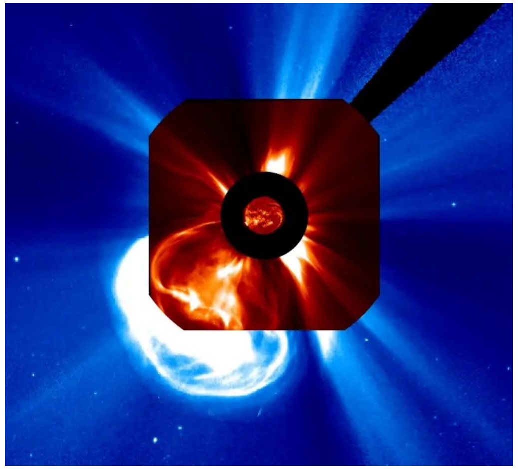

? **larger characteristic size**

→ should be able to excite

≤100 low-degree modes

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(Mean energy $\sim 8.5\ 10^{30}$ ergs)

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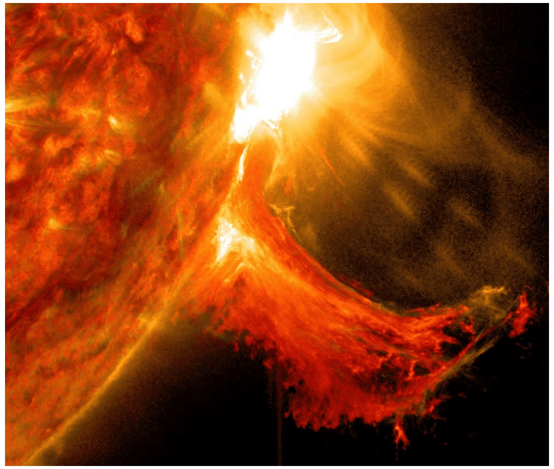

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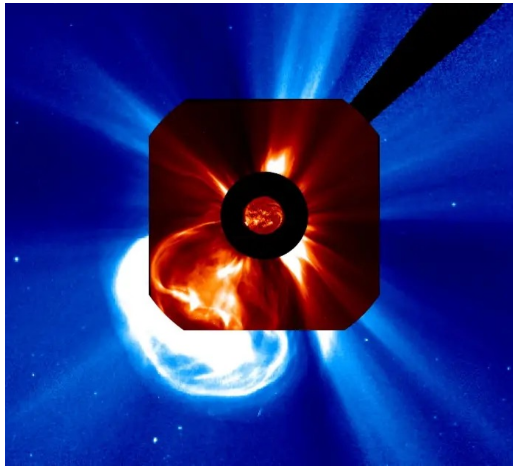

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→ 310 days of GOLF data

→ **Correlation between several low-degree modes**

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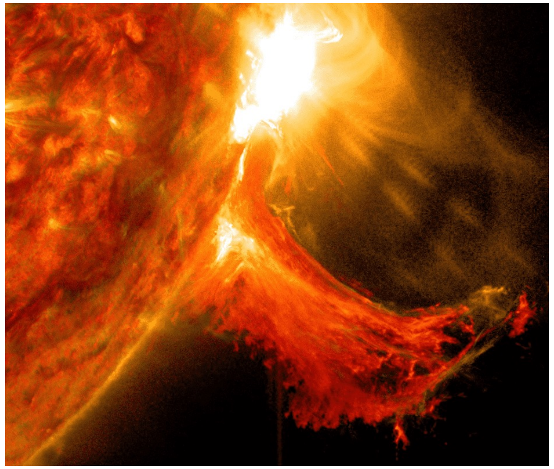

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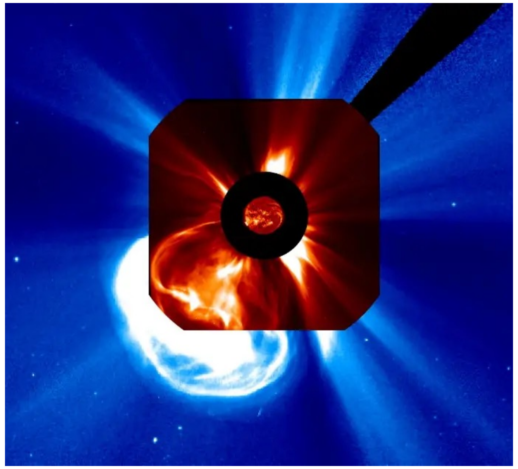

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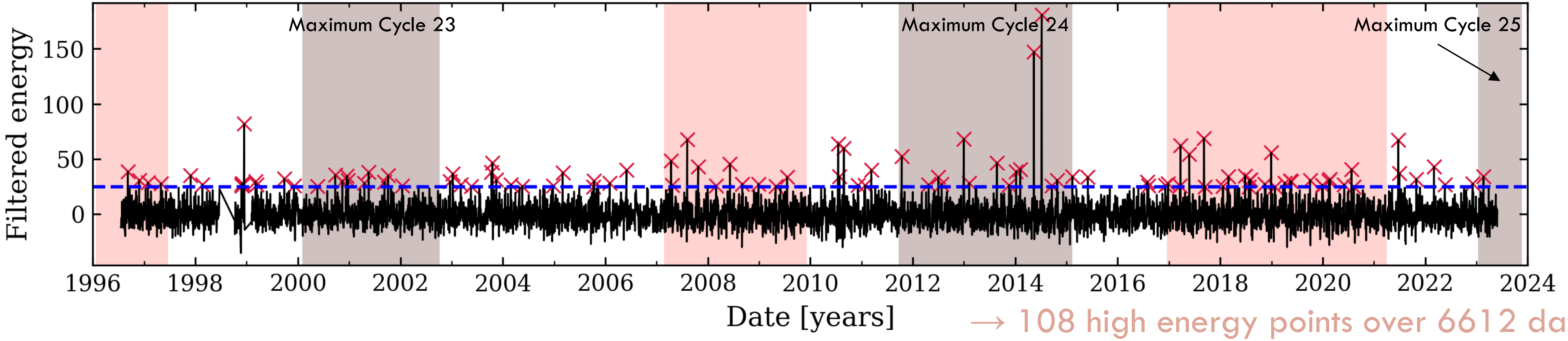
→ **Correlation between several low-degree modes**

→ **Now, more than 27 years of data available**

THE COMBINED ENERGY TIME SERIES OF THE MODES



→ 108 high energy points over 6612 data points

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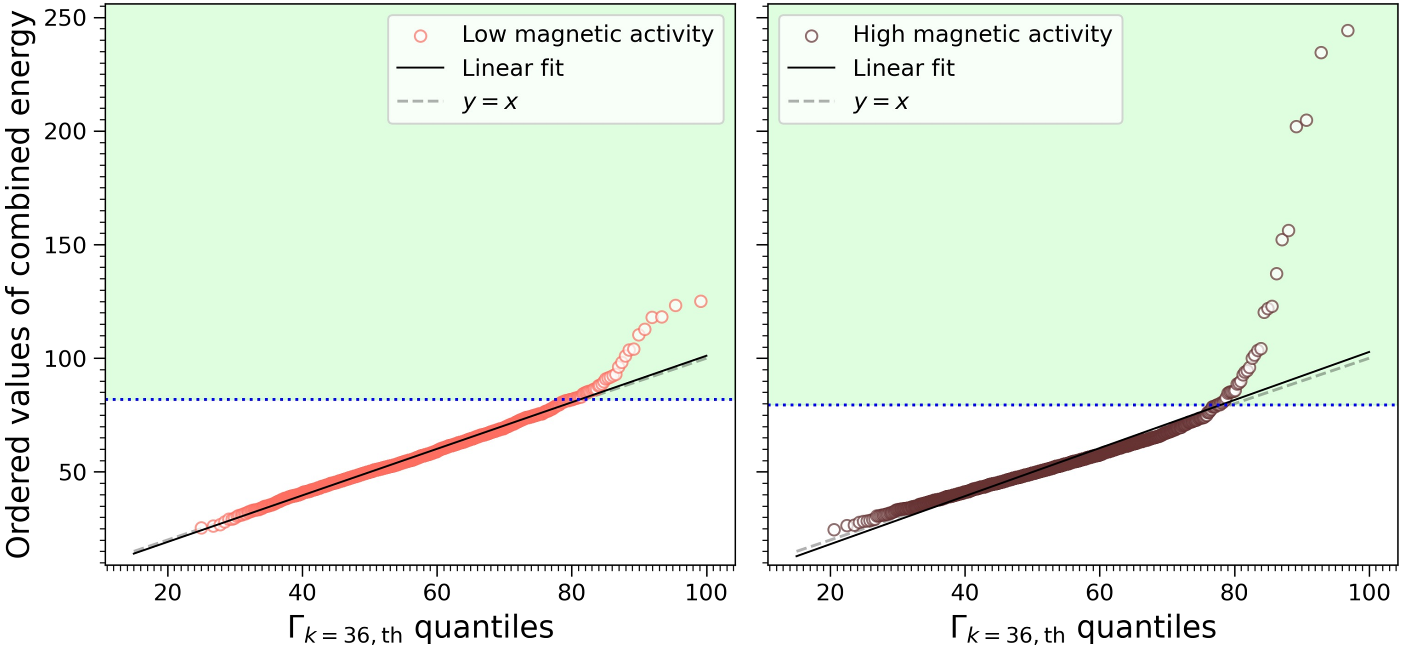

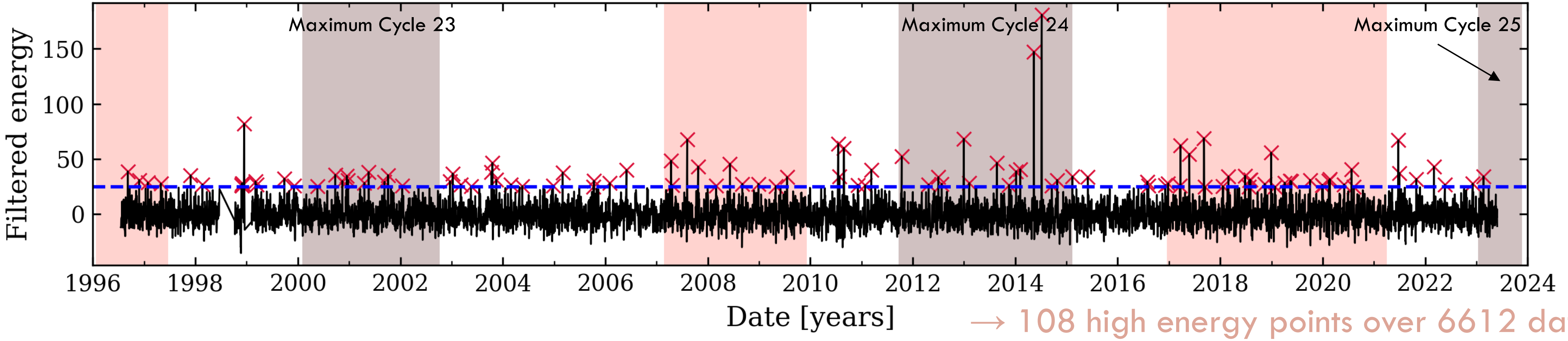

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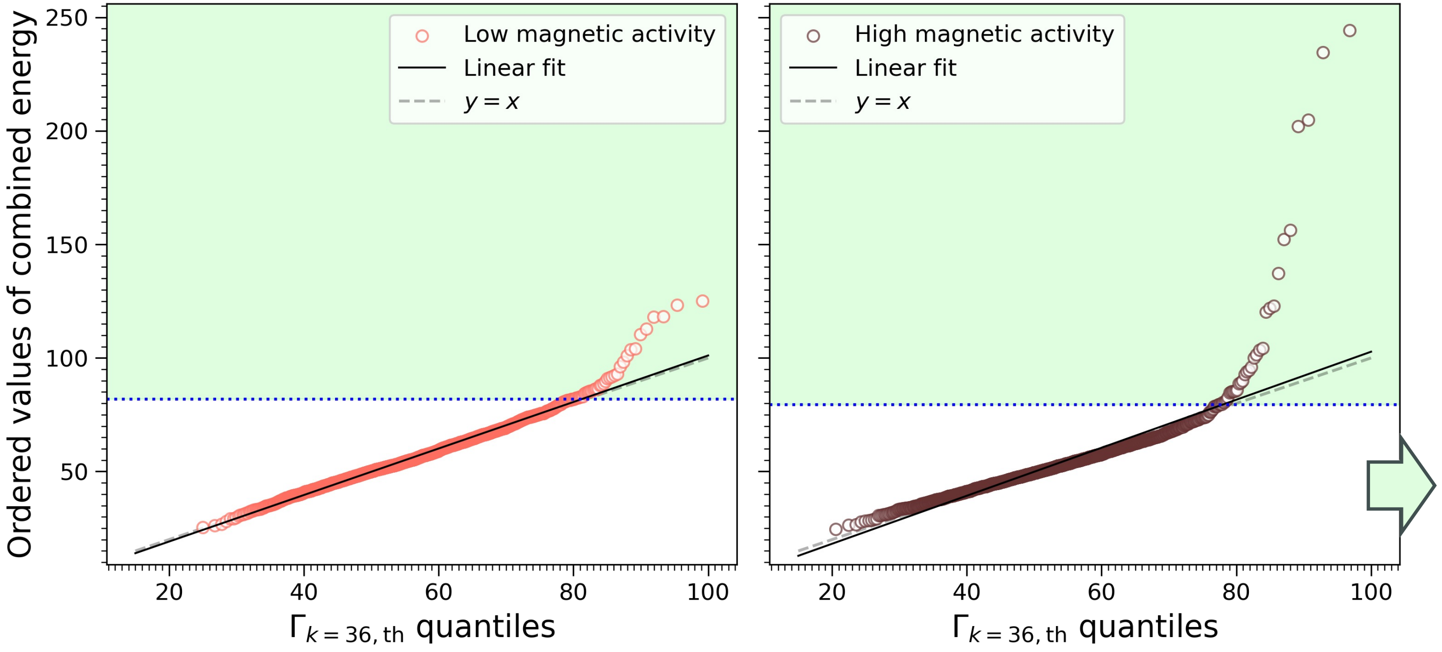

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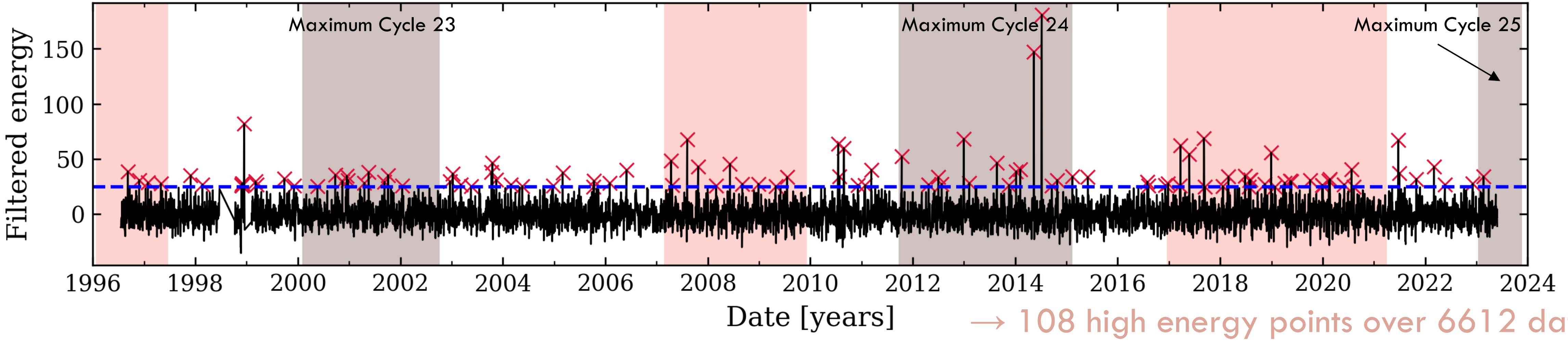

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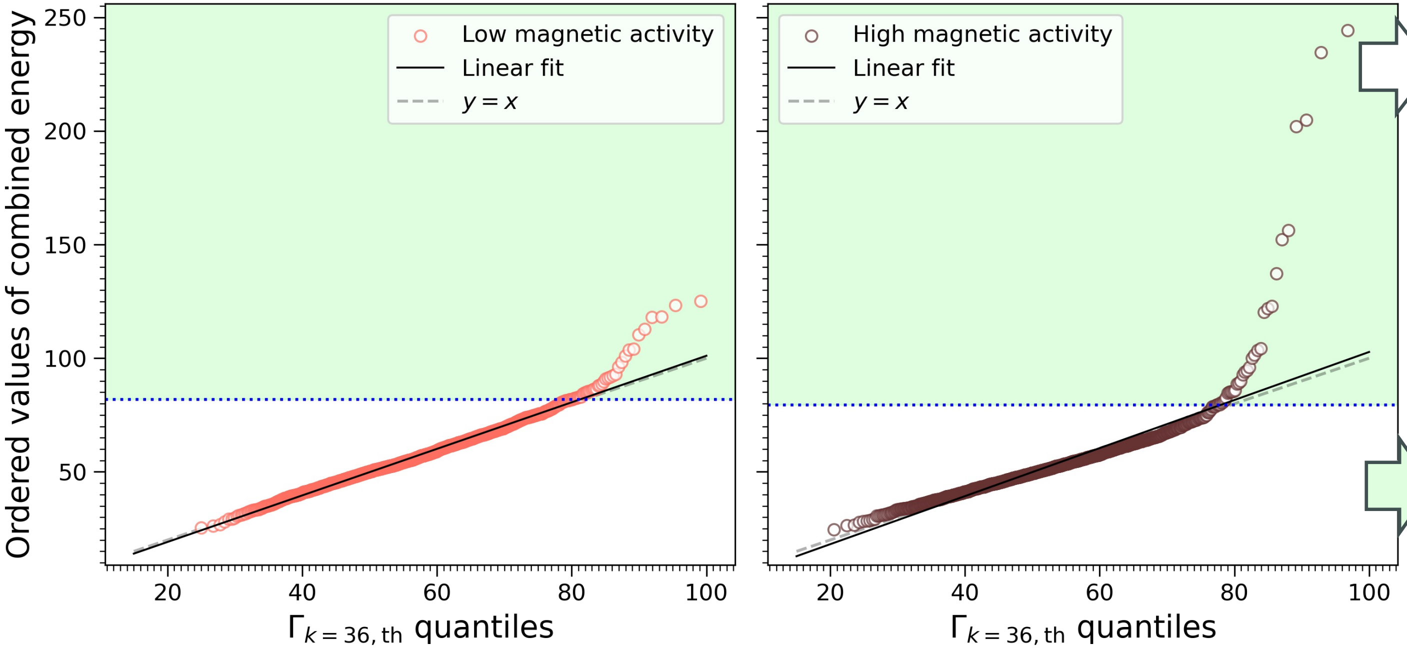
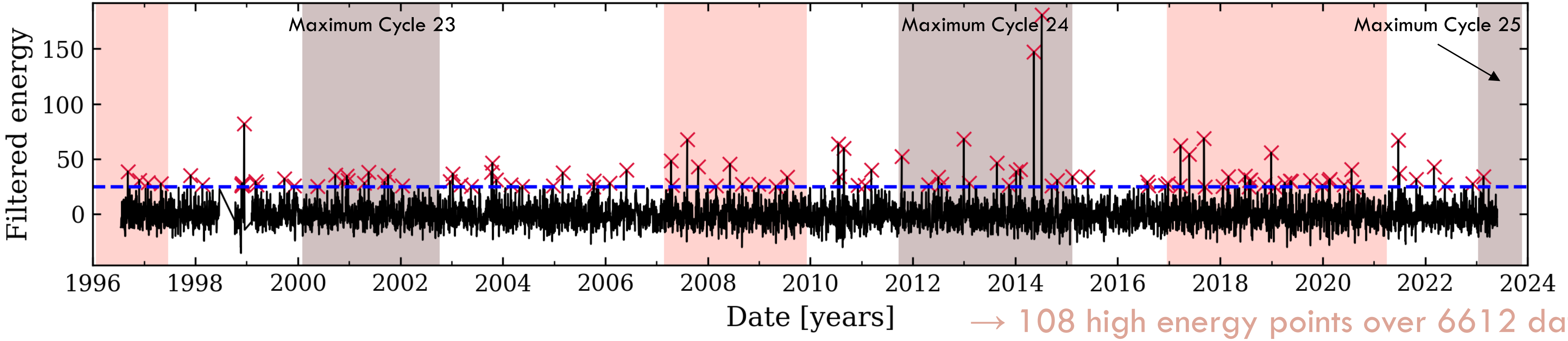


Not compatible with a stochastic excitation by turbulent convection

Theoretical probability of observing these events:

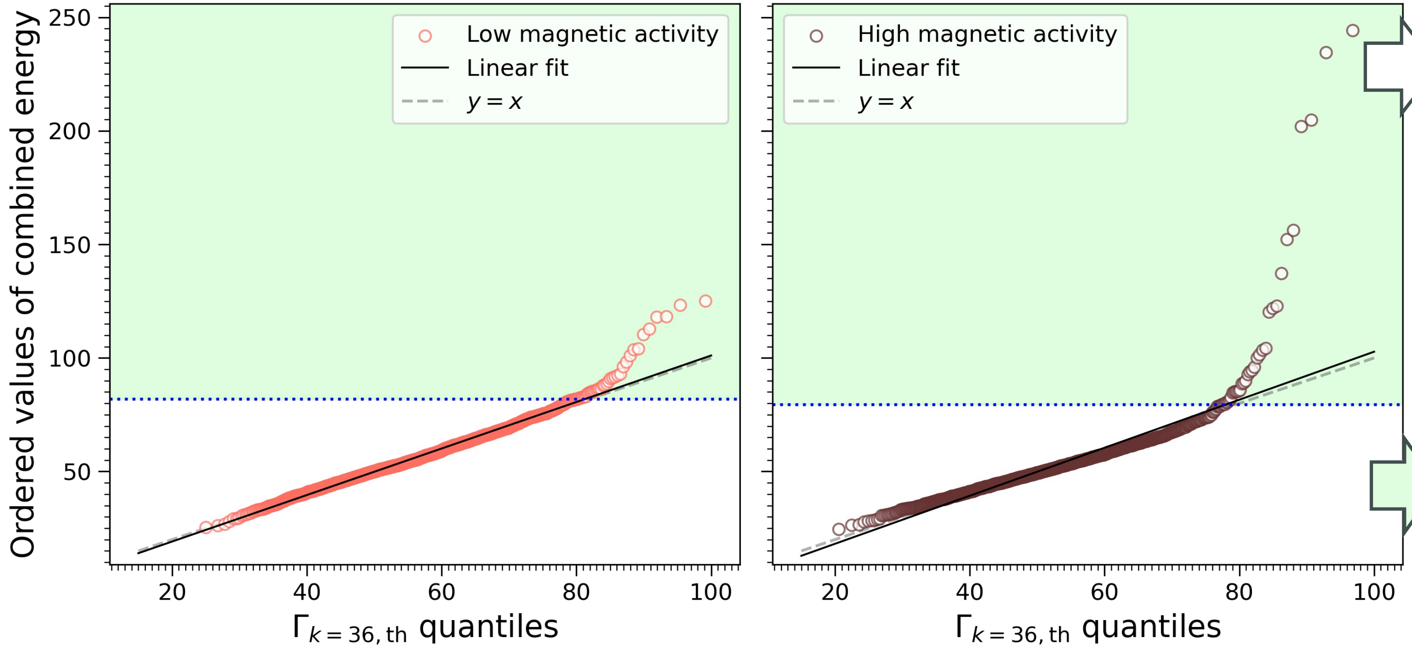
$P < 10^{-3}$ $\neq$ 1.6% observed

Compatible with a stochastic excitation by turbulent convection



→ 108 high energy points over 6612 data points

THE COMBINED ENERGY TIME SERIES OF THE MODES



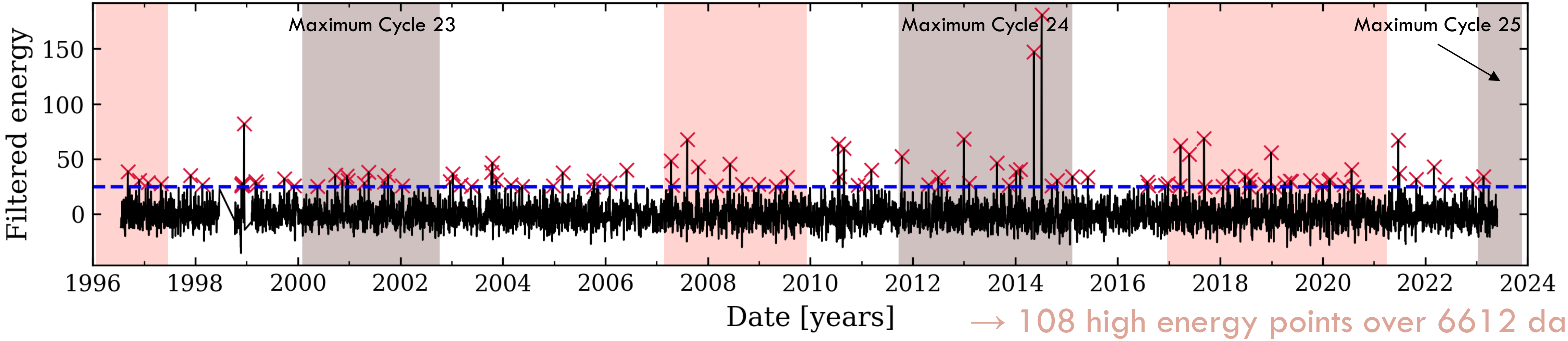
Not compatible with a stochastic excitation by turbulent convection

Theoretical probability of observing these events:

$P < 10^{-3}$ $\neq$ 1.6% observed

→ Very significant

Compatible with a stochastic excitation by turbulent convection



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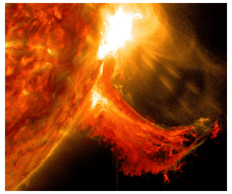

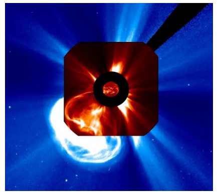

CONCLUSION

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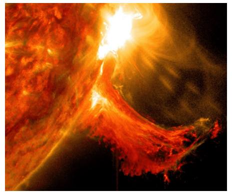
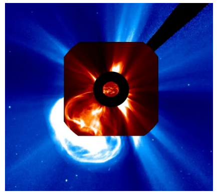


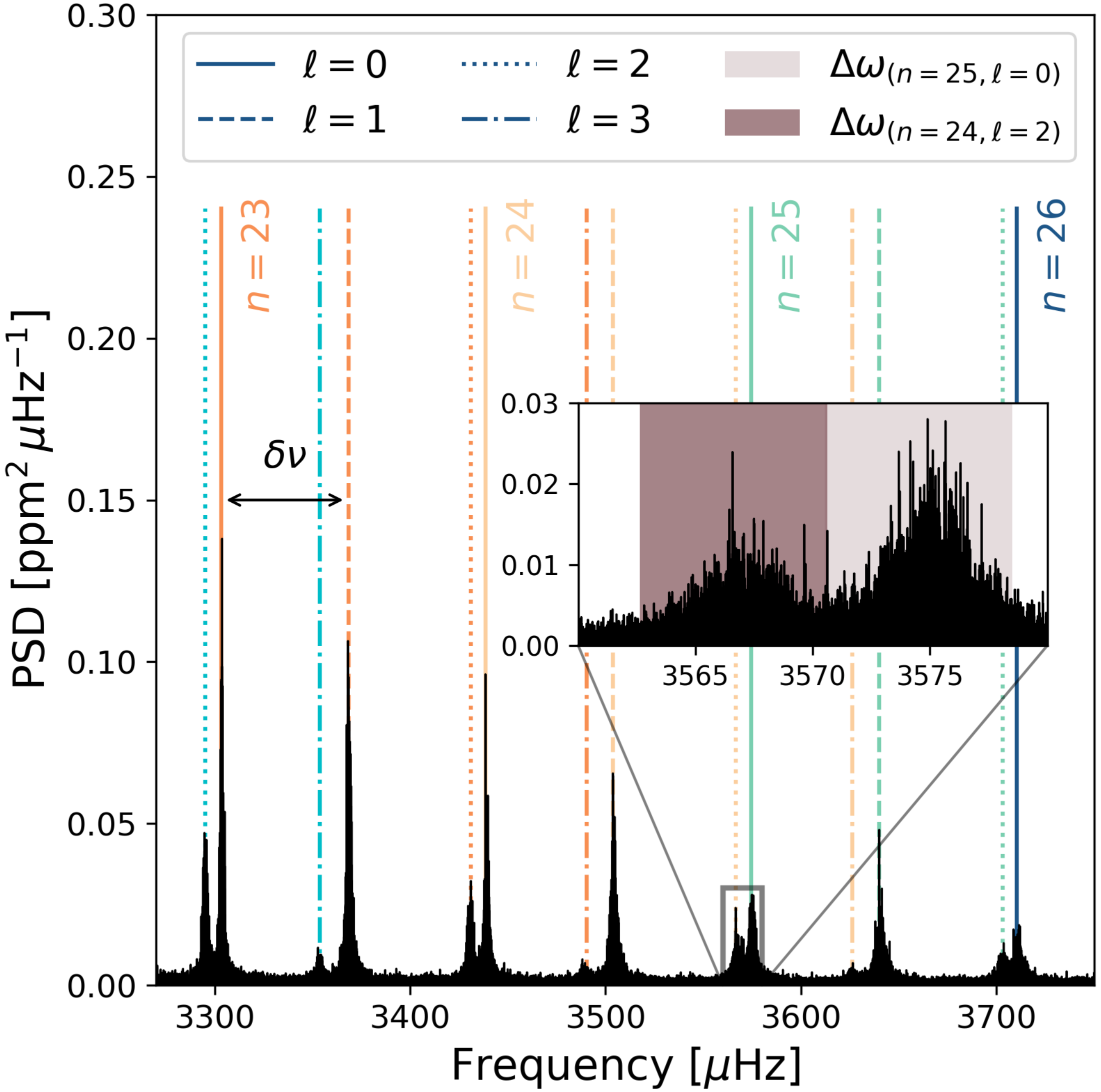


3 comes slightly more often **from the most external layer** of the convective zone

Thank you for your attention

RETRIEVING ENERGY TIME-SERIES OF THE MODES

[Panetier et al., in prep]



→ Inverse Fourier Transform

$$f_v(t) = \int_{-\frac{\Delta\omega}{2}}^{+\frac{\Delta\omega}{2}} \hat{v}\,(\omega_0 + \omega)\, e^{i\omega t}\, d\omega$$

→ Selected window of $\Delta\omega = 8\ \mu Hz$

→ Energy time-series for each mode n, ℓ retrieved with:

$$E_{n,\ell} = 2|f_v(t)|^2$$

[Foglizzo et al. 1998]

Time resolution:

$$\delta t = \frac{1}{\Delta\omega} = 1.45 \text{ days}$$

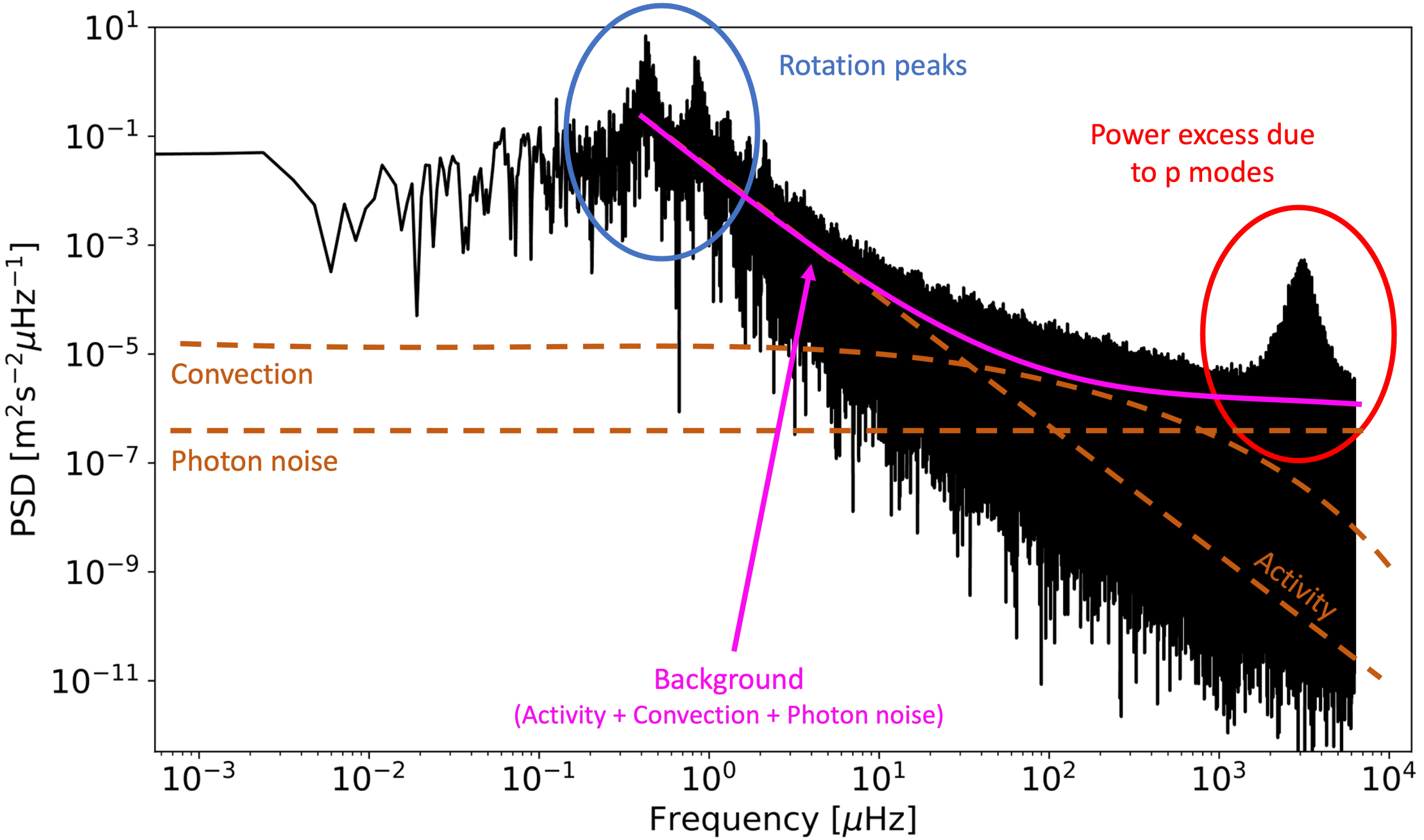
For all $\ell = 0,1,2$ and $14 \leq n \leq 25$ modes

→ Results in **36 energy time-series**

POSSIBLE EXPLANATIONS TO THE EXCESS OF ENERGY

Related to the instrumental noise or signal not related to modes (particles hitting the detector, cosmic rays, etc) → should be visible at other frequencies

- **26 high peaks** correlated with noise



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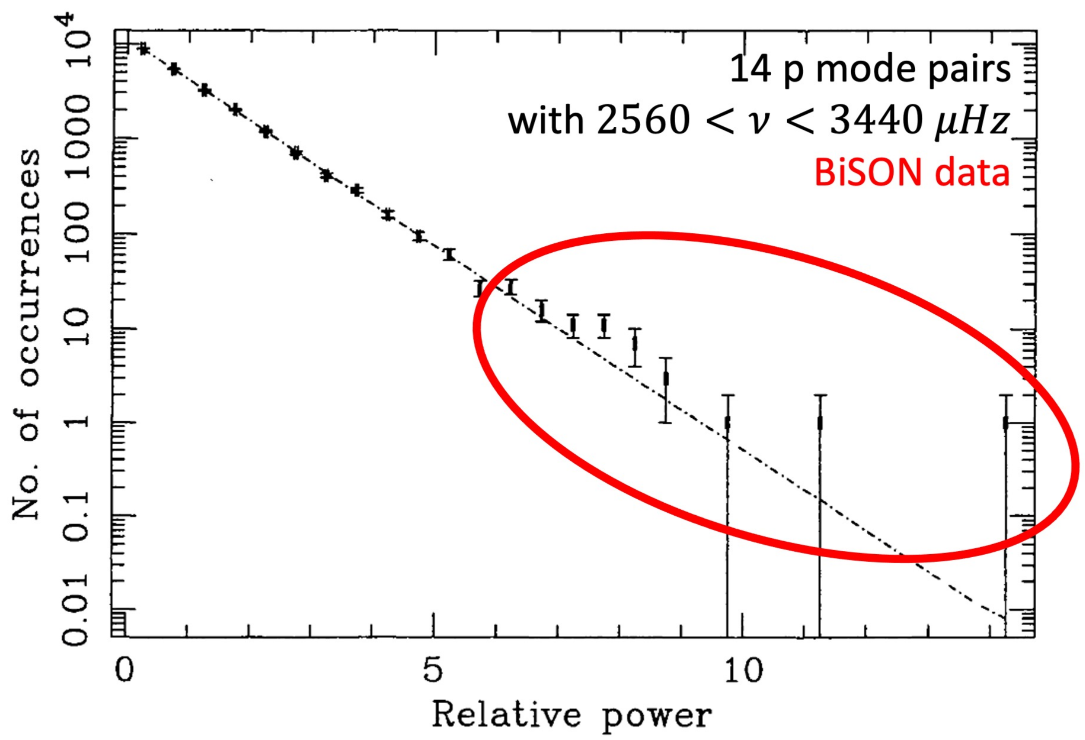

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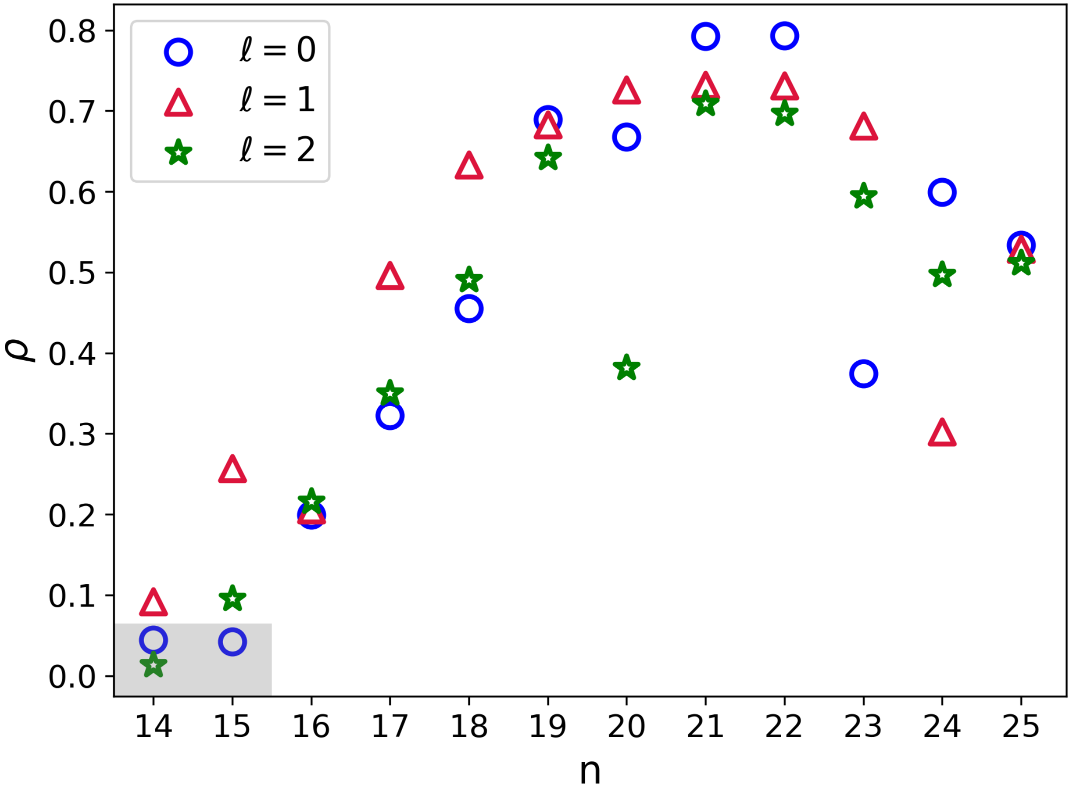

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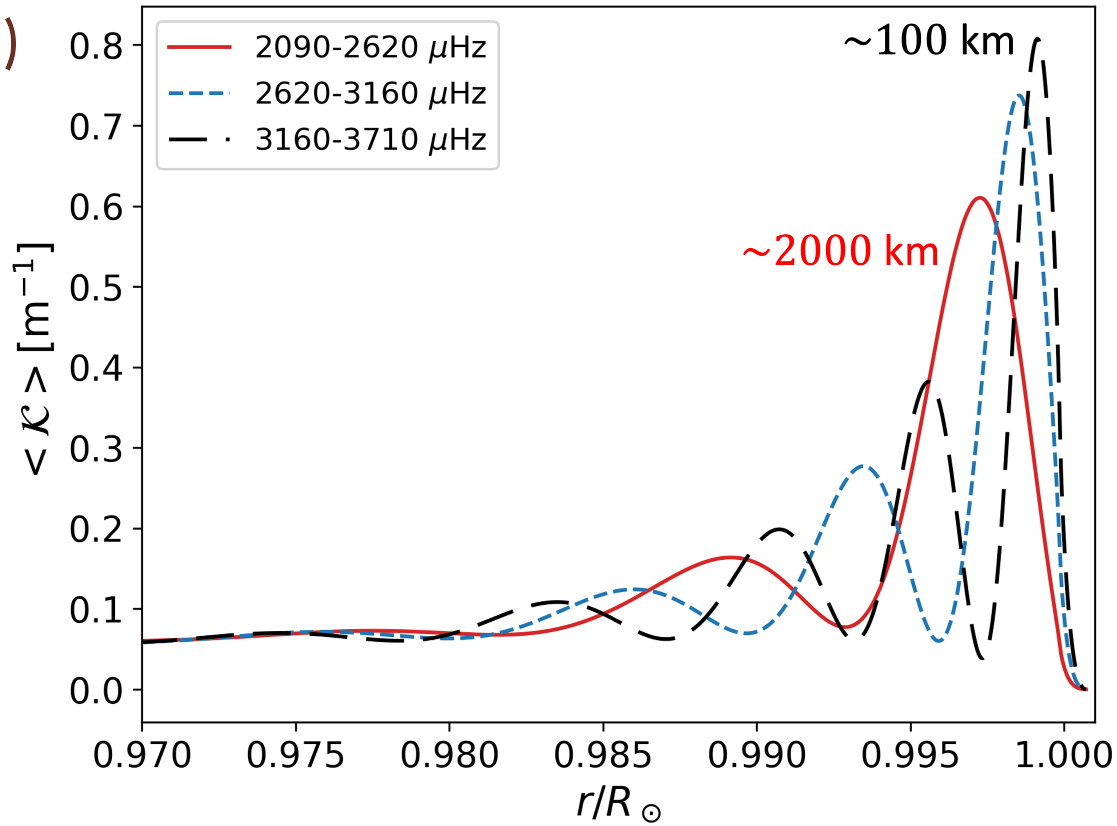

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→ location of the source of excitation

- **20 high peaks** from the lower frequencies
- **23 high peaks** from the medium frequencies
- **28 high peaks** from the higher frequencies

depth