Predicting solar magnetic activity and its implications for global dynamo models

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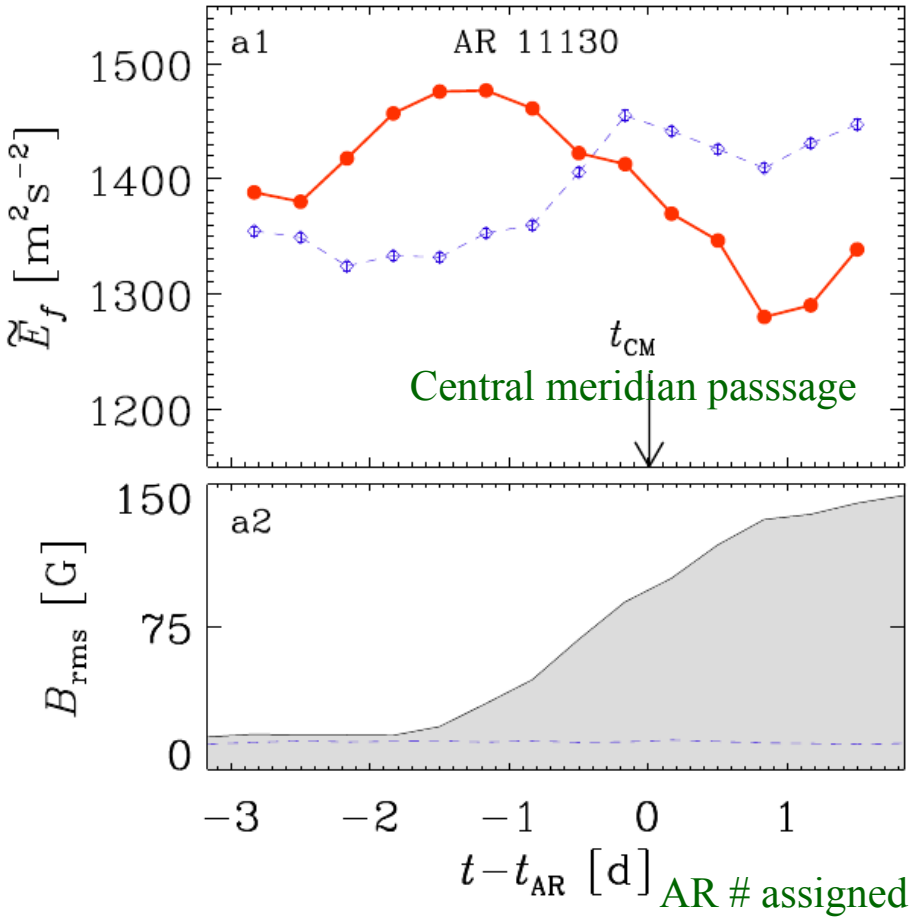
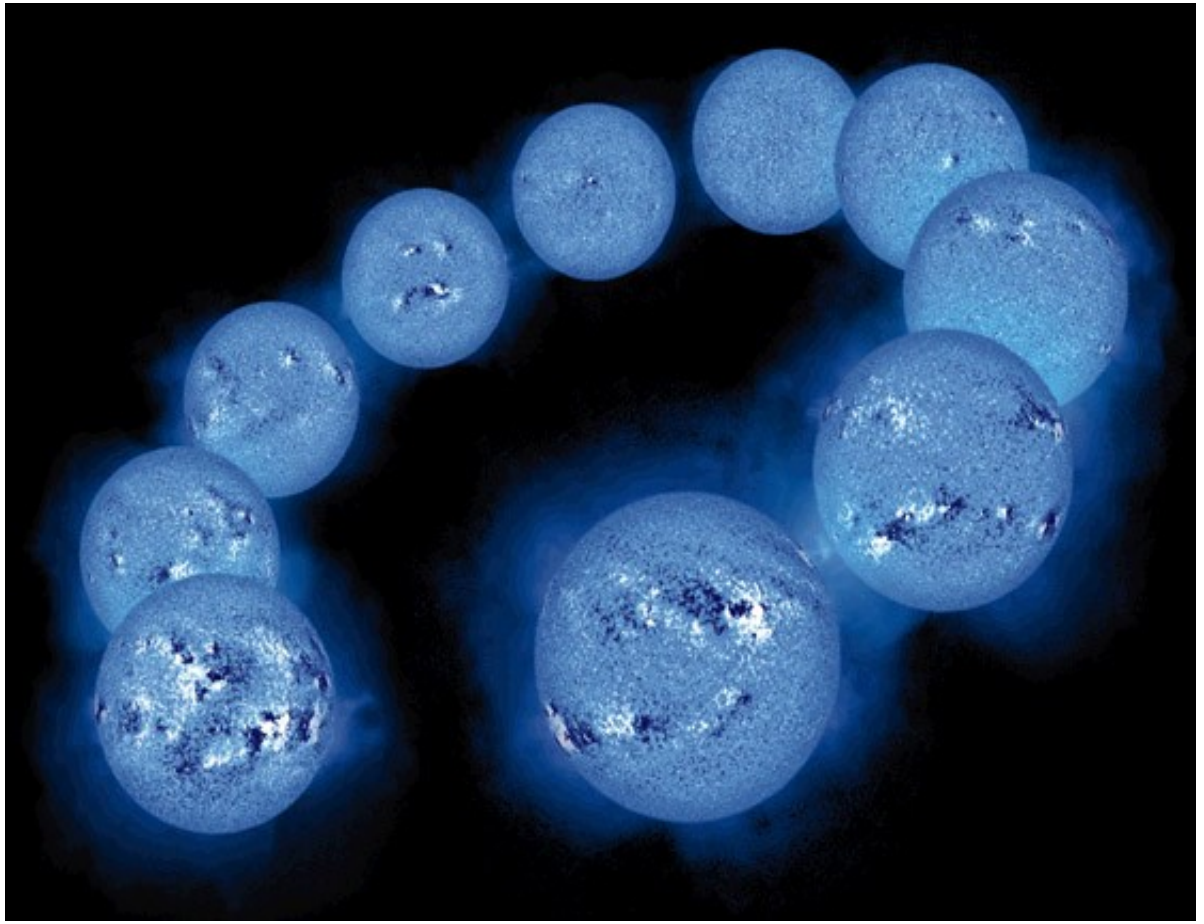
Singh et al, 2016, ArXiv: 1601:00629

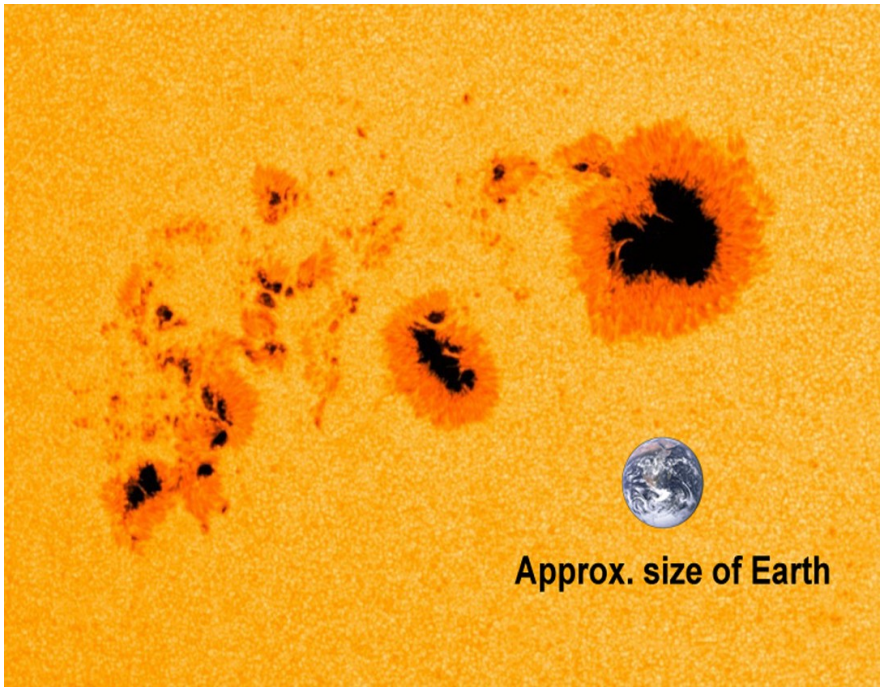


Solar Cycle: Active Regions/Sunspots

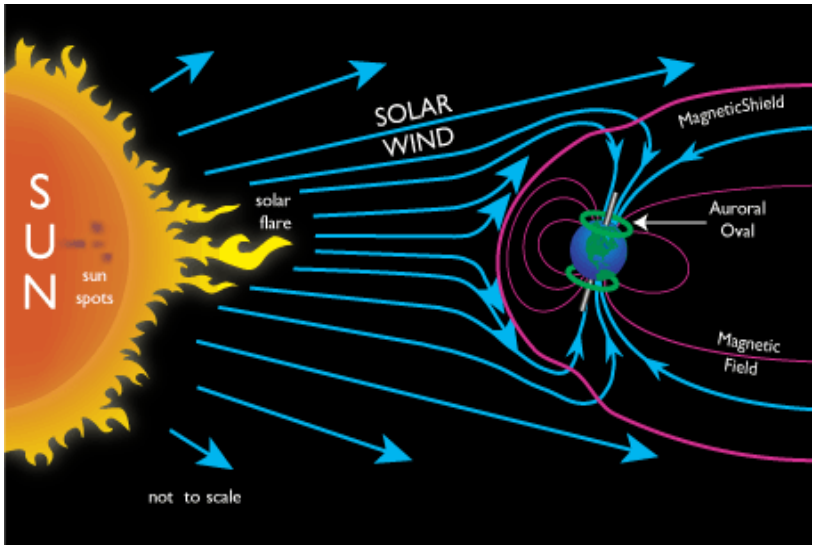


Predicting solar magnetic activity is necessary for *Space Weather Forecasting well in advance!*

- Localized regions of intense B-field
- Strength ~ 1-2 kG
- Size ~ 20-40 Mm
- Foot-points of flare/CME events

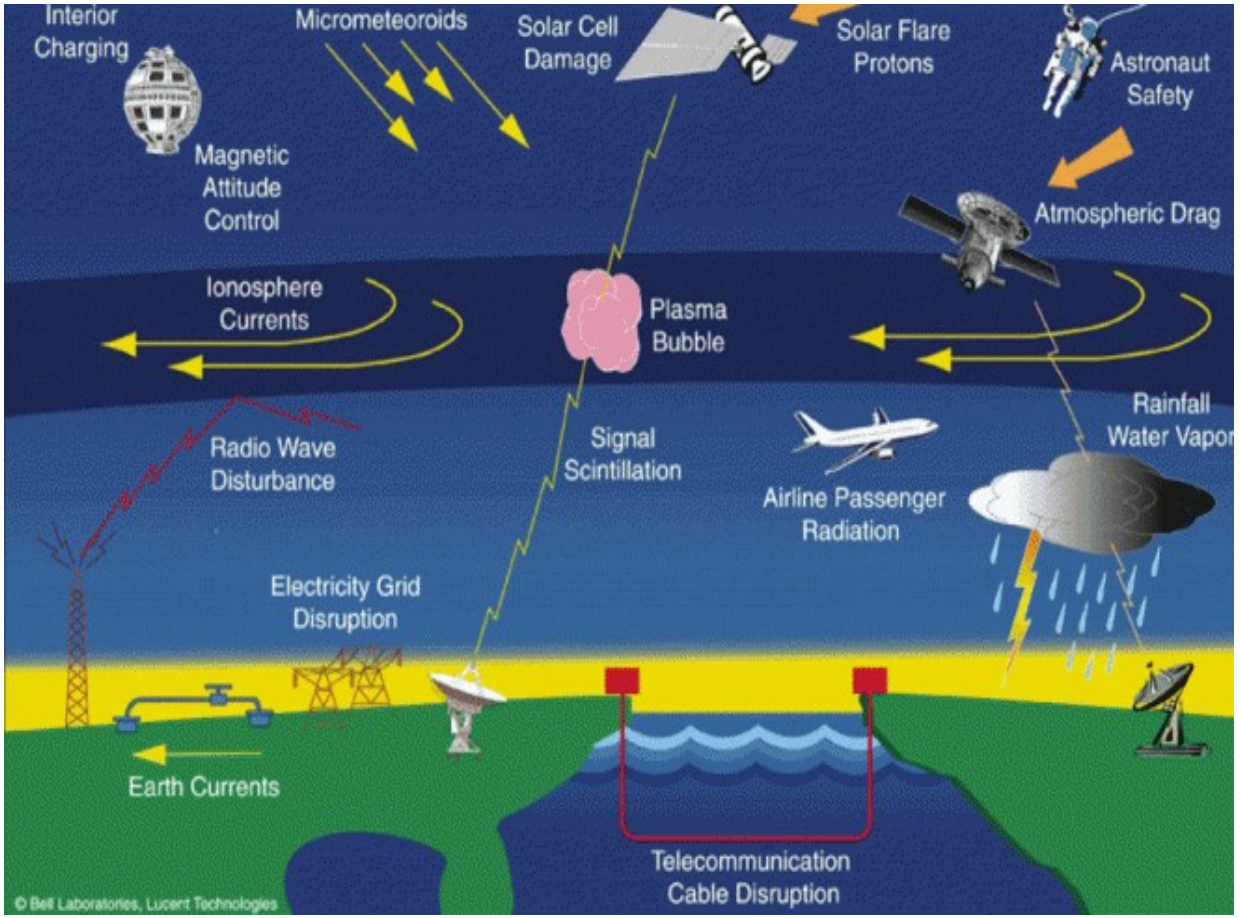


Popular Motivation: Space Weather



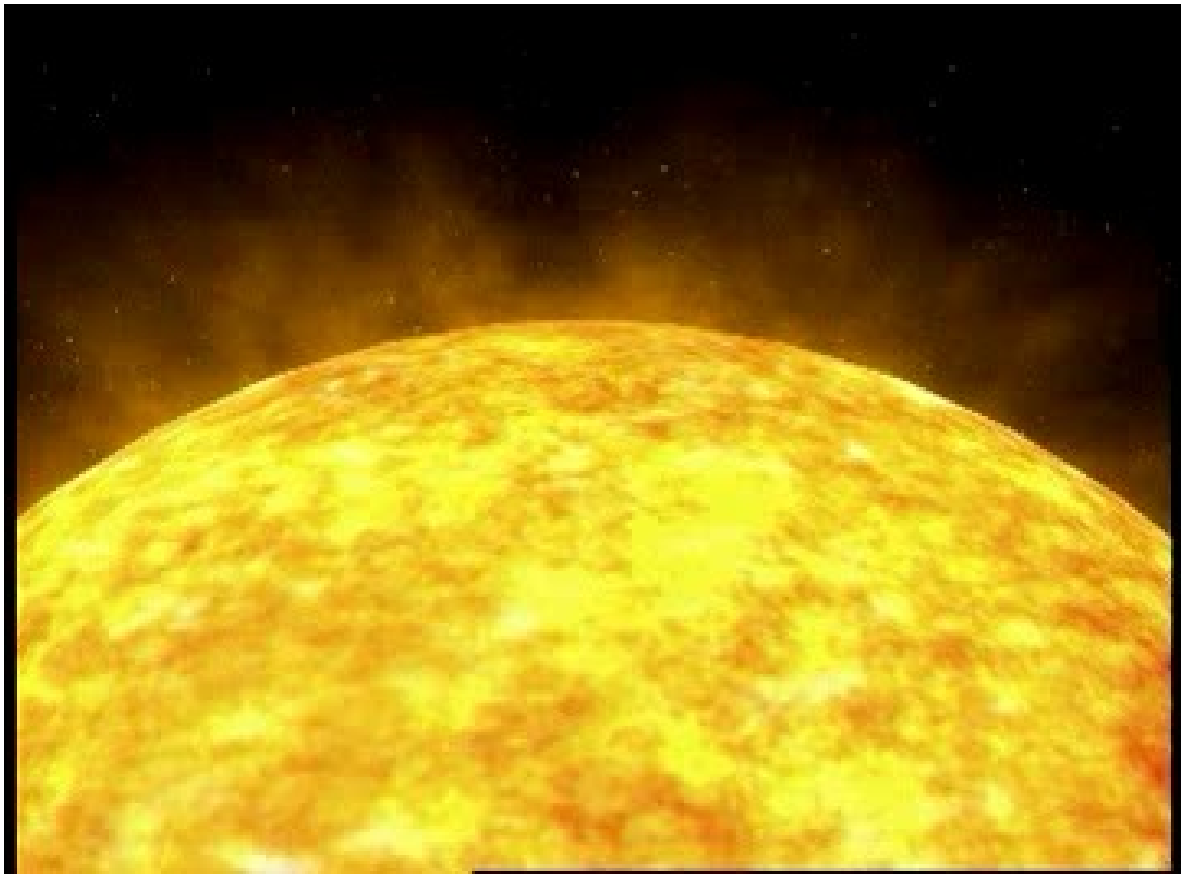
- Affects radio based systems; GPS ...
- Solar radio bursts: disrupt wireless ...
- Location errors: satellite loss …
- Power grid failures …
- Threat for manned space flights ...

- Cuba 1859: $2 Trillion
- New York 1921: Central rail system knocked out; telecommunication disruption worldwide
- Quebec 1989: over $2 Billion loss due to power grid failure
- Nov 2003: major loss of GPS accuracy with error over 50 meters ...

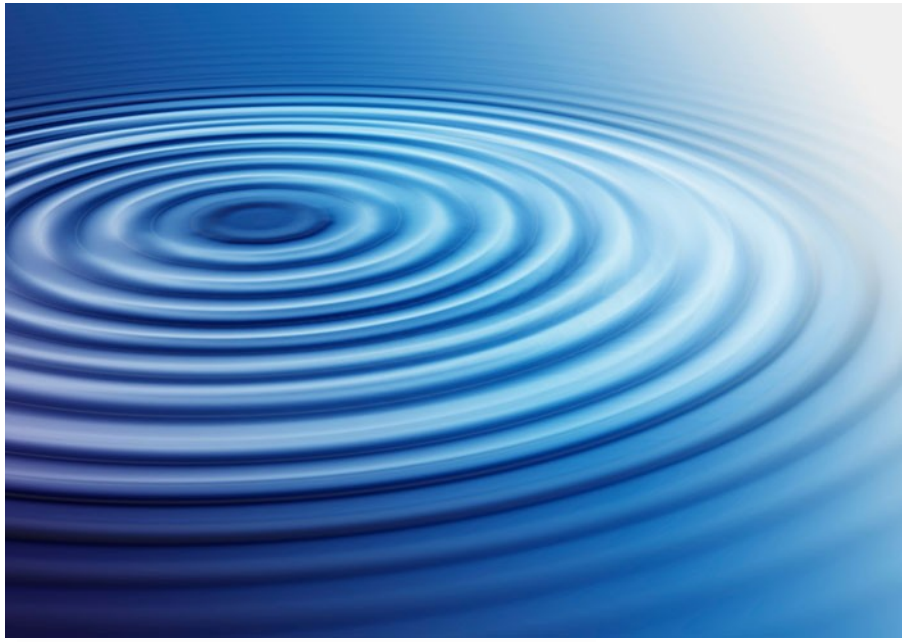


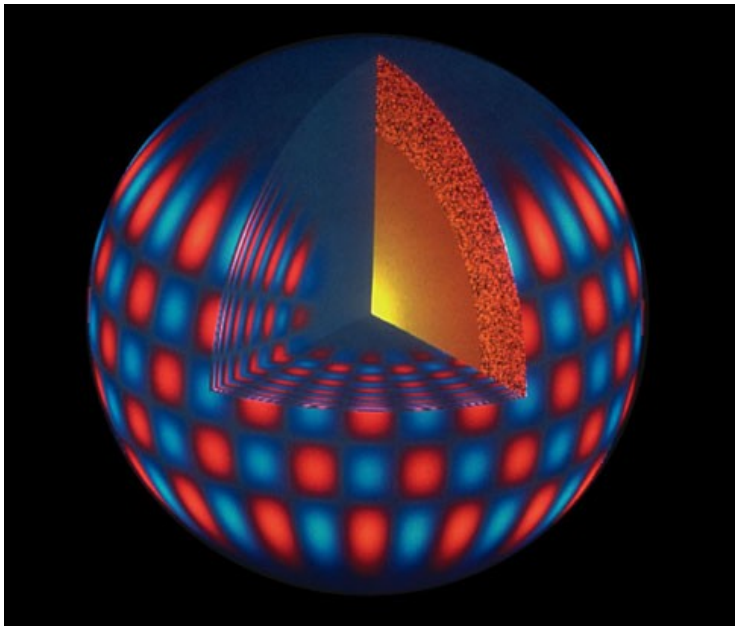
www.thesuntoday.org

Popular motivation: Flares and CMEs

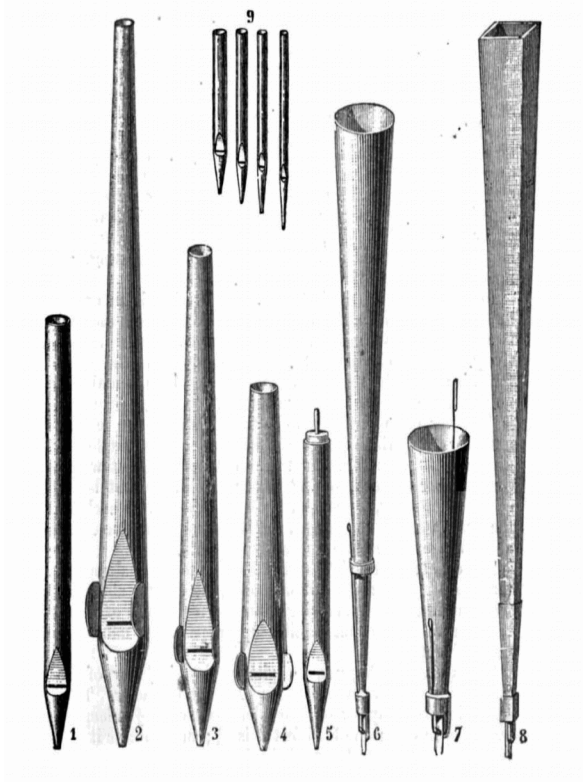


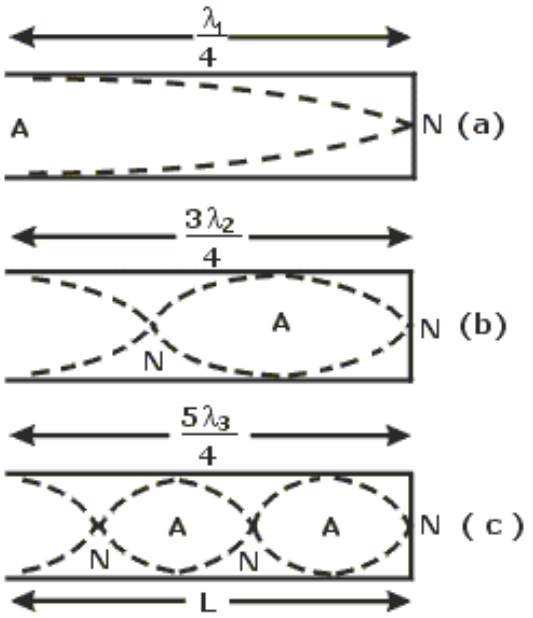
Waves and Modes





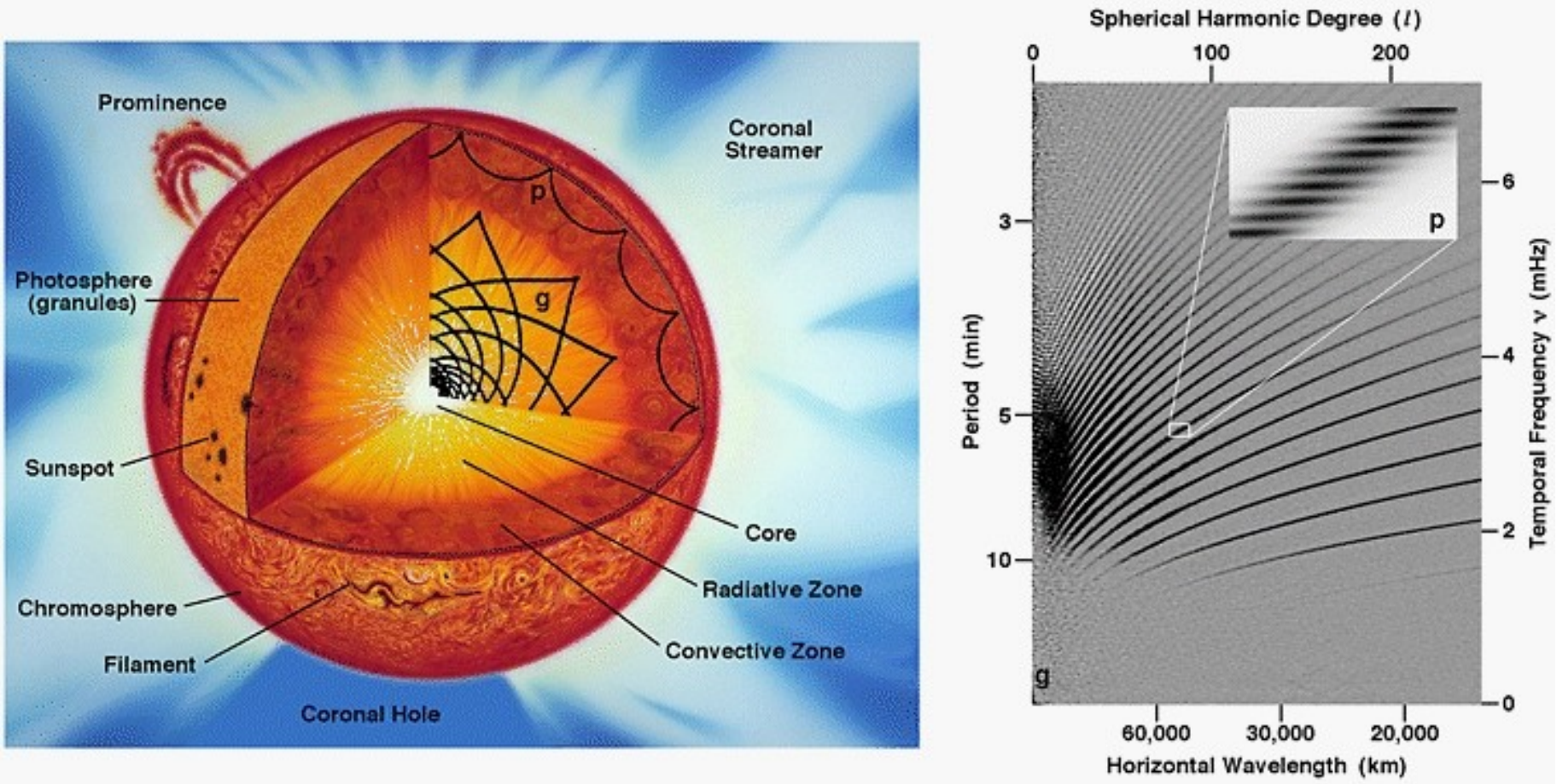
About 250,000 out of 10 million expected modes have been identified





Useful to recall "tuning fork experiment" to measure the speed of the sound

The Sun and Helioseismology



The Sun supports a wide variety of waves

Helioseismology: science studying the wave oscillations in the Sun

Goal is to determine the physical conditions in the Solar interior

Figure Source: SOHO image gallery

Simulations

the pencil-code: https://github.com/pencil-code/

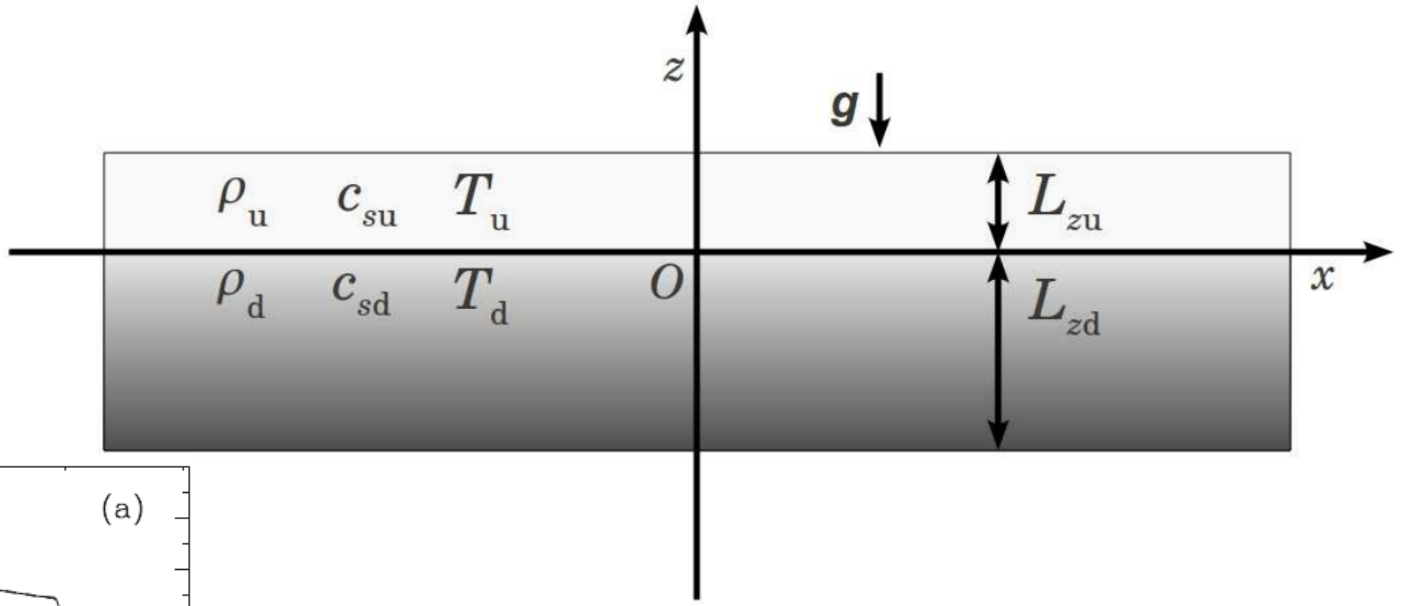
with

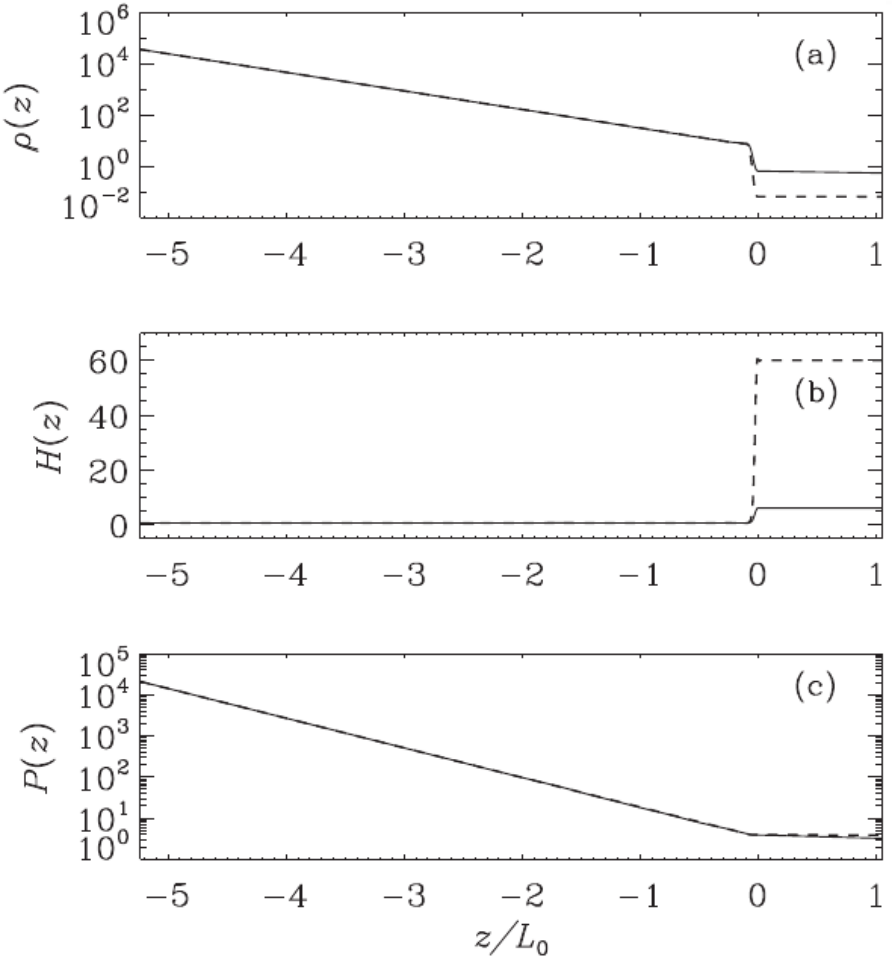
Axel Brandenburg, S. M. Chitre & Matthias Rheinhardt

Singh et al, 2014, ApJL, 795, L8
Singh et al, 2015, MNRAS, 448, 3708

Our model setup and initial conditions

- 2-D Cartesian section
- Stably stratified under ***g***
- Piecewise isothermal
- Interface at $z = 0$
- Bulk ($z < 0$)
- Atmosphere ($z > 0$)





- Sharp jump at the interface:

$$q = \rho_{\rm u}(0)/\rho_{\rm d}(0) = c_{\rm sd}^2/c_{\rm su}^2$$

- Background density:

$$\rho_{\rm d,u}(z) = \rho_{\rm d,u}(0)\exp(-z/H_{\rm d,u})$$

- Scale height:

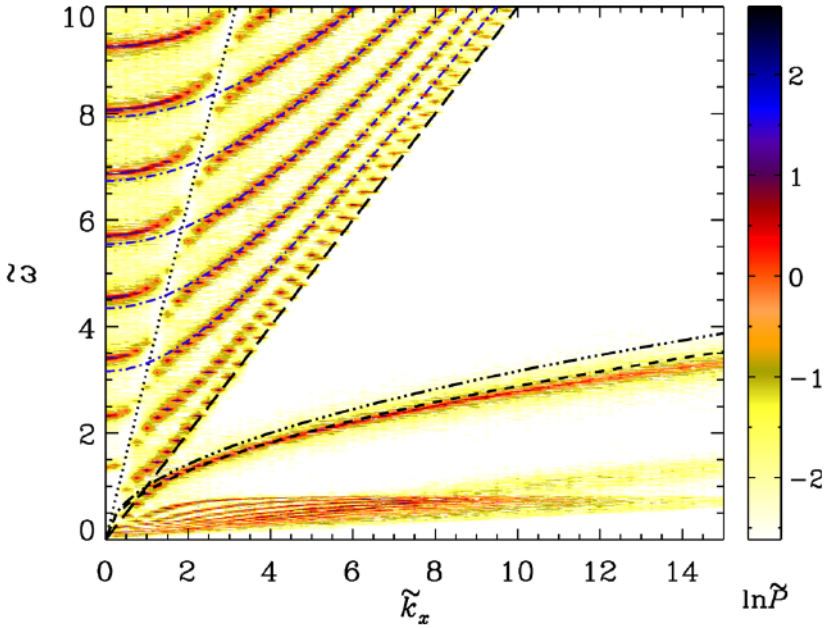
$$H_{\rm d,u} = (c_p - c_v)T_{\rm d,u}/g$$

$$L_0 = \gamma\, H_{\rm d}$$

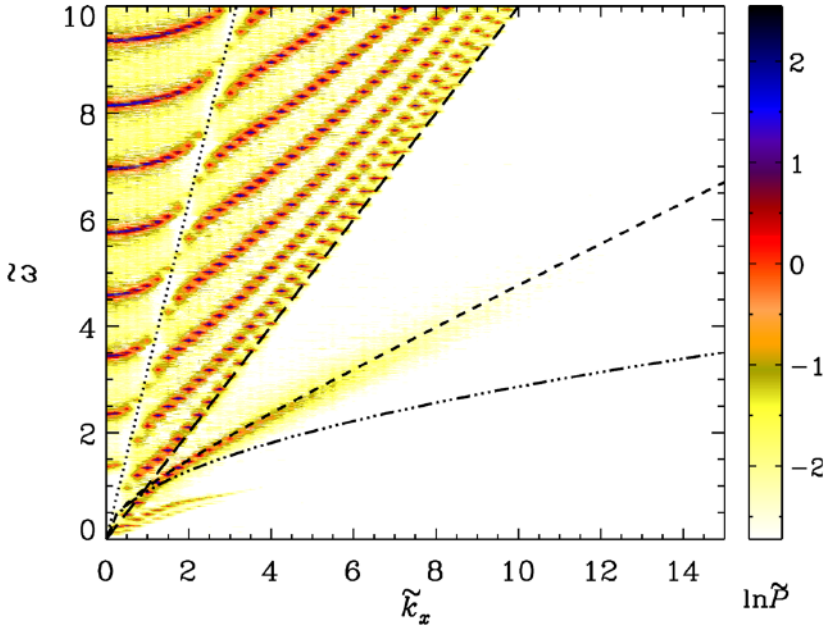
For details: Singh et al, MNRAS (2015)

Fanning out of the *f*-mode: a precursor transient?

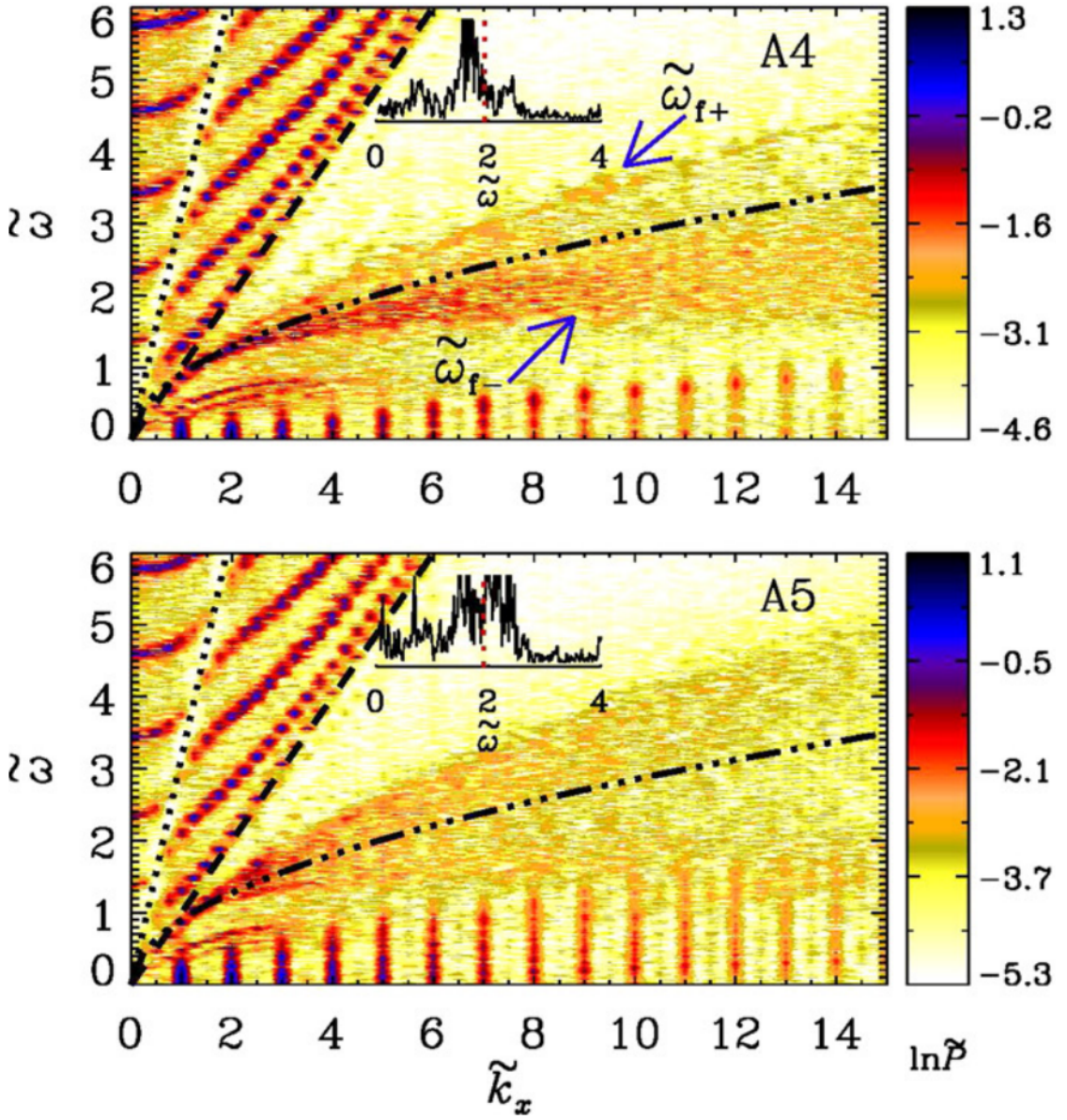
Classical: non-magnetic



Horizontal magnetic

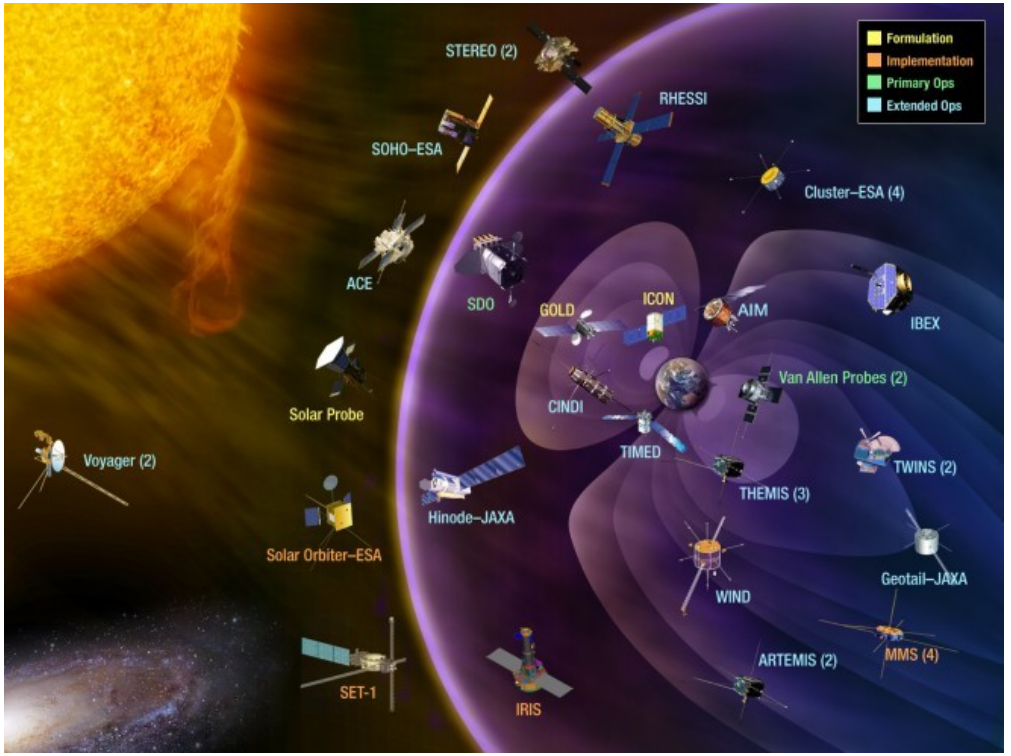


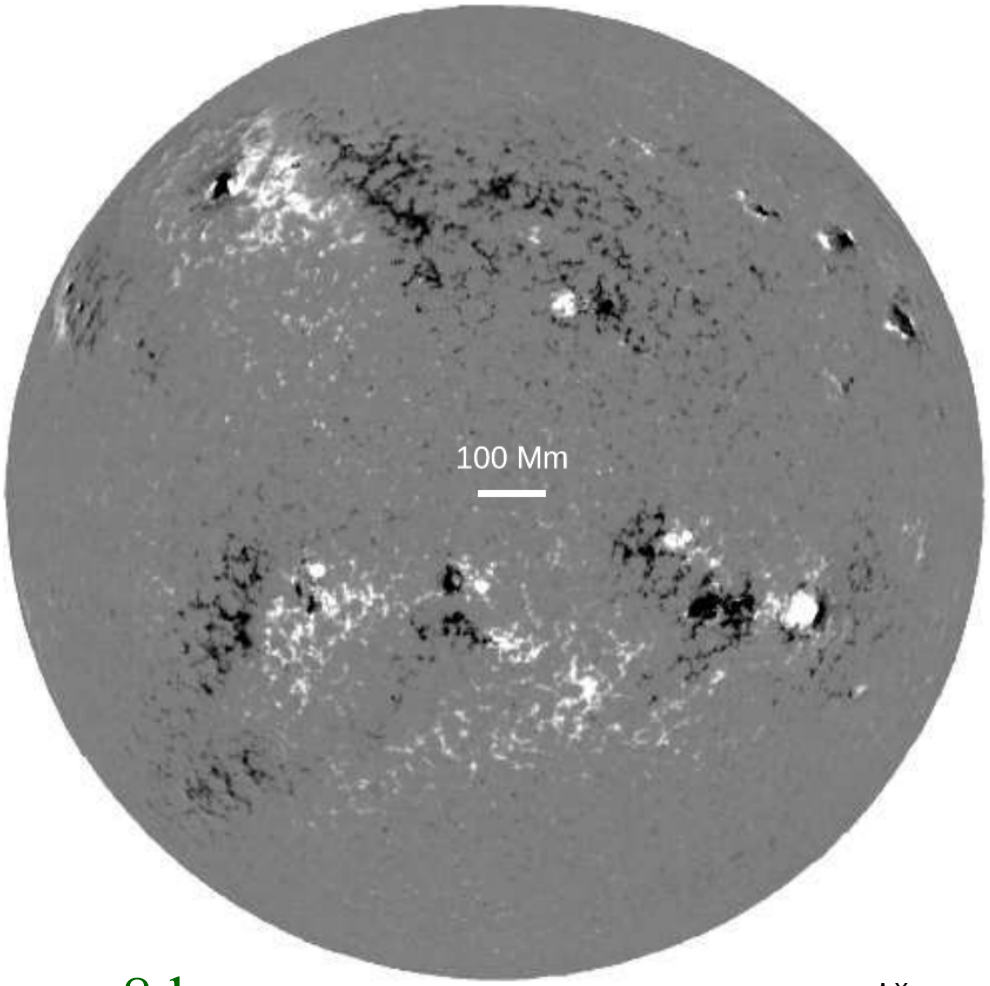
Non-uniform magnetic (Subsurface)



Observations: ARs are transient
HMI/SDO

Tracked (Carrington) & Mapped (Cylindrical Equal Area Projection)





Patch: 180x180 Mm^2

Time span: 8 hrs

The observable

- *f*-mode power: $P_f(k_y,\omega) = |\hat{v}_f|^2 = P - P_{\rm cp}$

- *f*-mode dispersion: $\langle v^2\rangle_f = 2AT\int_0^\infty\int_0^\infty kP_f(k,\omega)\,\frac{{\rm d}k}{2\pi}\,\frac{{\rm d}\omega}{2\pi}$

$$= L\sum_k kP_{f,k}$$

- Integrated power: $P_{f,k} = 2\sum_\omega P_f(k,\omega)$

- *f*-mode energy: $E_f(t) \equiv \frac{1}{2}\langle v^2\rangle_f(t) = \frac{1}{2}\left(\frac{L}{R_\odot}\right)\sum_k \psi(k)$

with $\psi(k) = kR_\odot P_{f,k}$

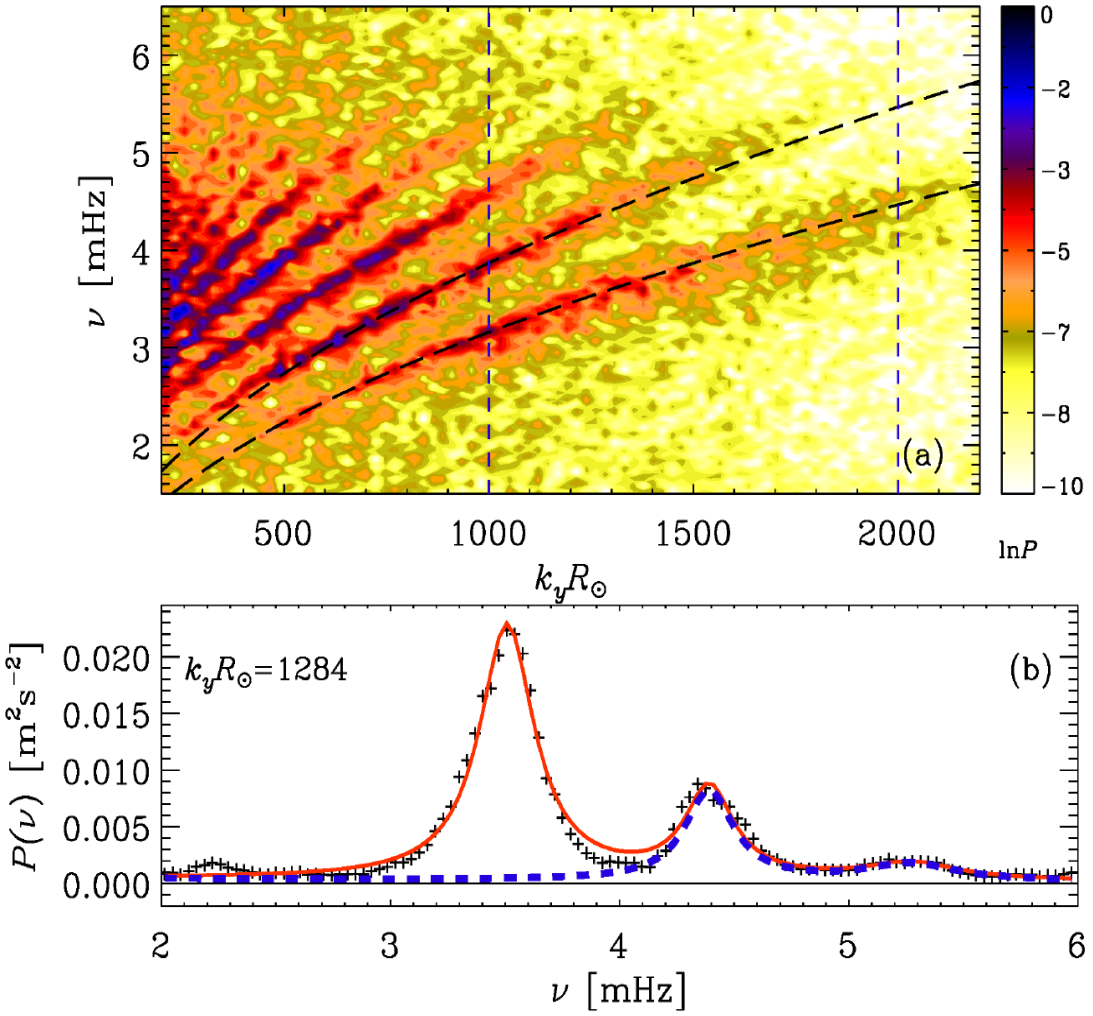
The observables to be monitored

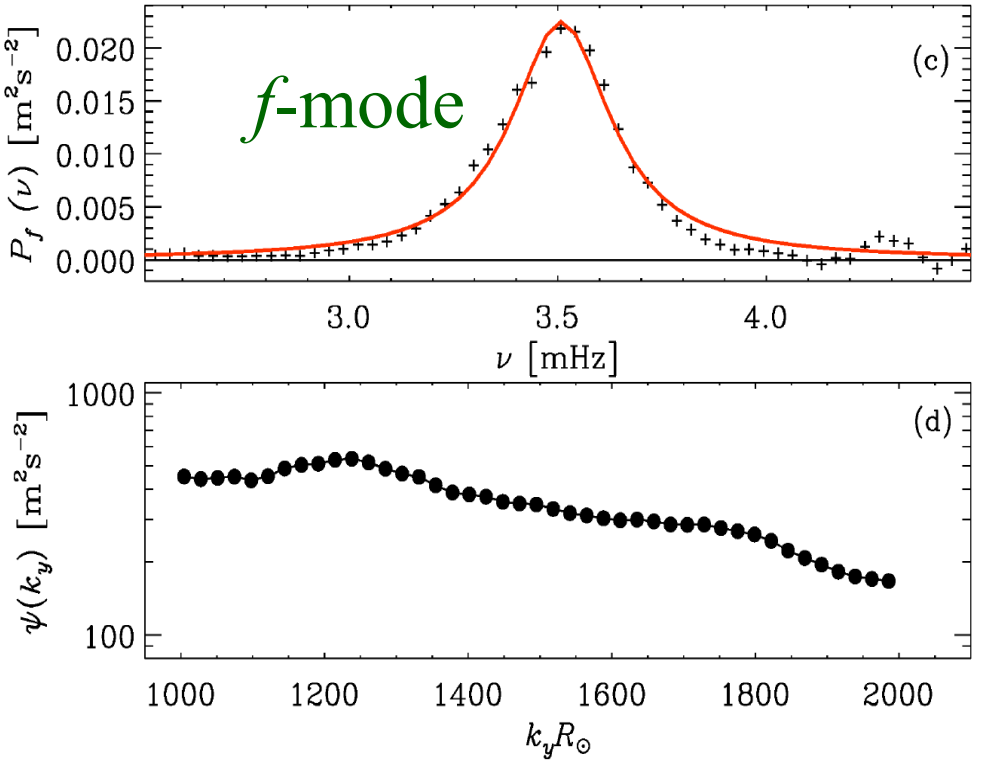
- Dominant modulation due to projection:

$$\cos\alpha = \cos\vartheta\cos\varphi\ ; \quad \varphi = \varphi_* - \varphi_0 + \Omega_{\rm syn} t$$

- Define: $\widetilde{E}_f \equiv E_f/\zeta$ with $\zeta(\cos\alpha) = \cos\alpha(1 + 0.72\cos\alpha)$
- Corresponding quiet sun: $\widetilde{E}_f^{\dagger}$ (from mirror locations in opposite hemisphere)
- Energy difference: $\Delta\widetilde{E}_f = \widetilde{E}_f - \widetilde{E}_f^{\dagger}$
- Monitoring $\widetilde{E}_f$ and $\Delta\widetilde{E}_f$ will be useful for transient signals

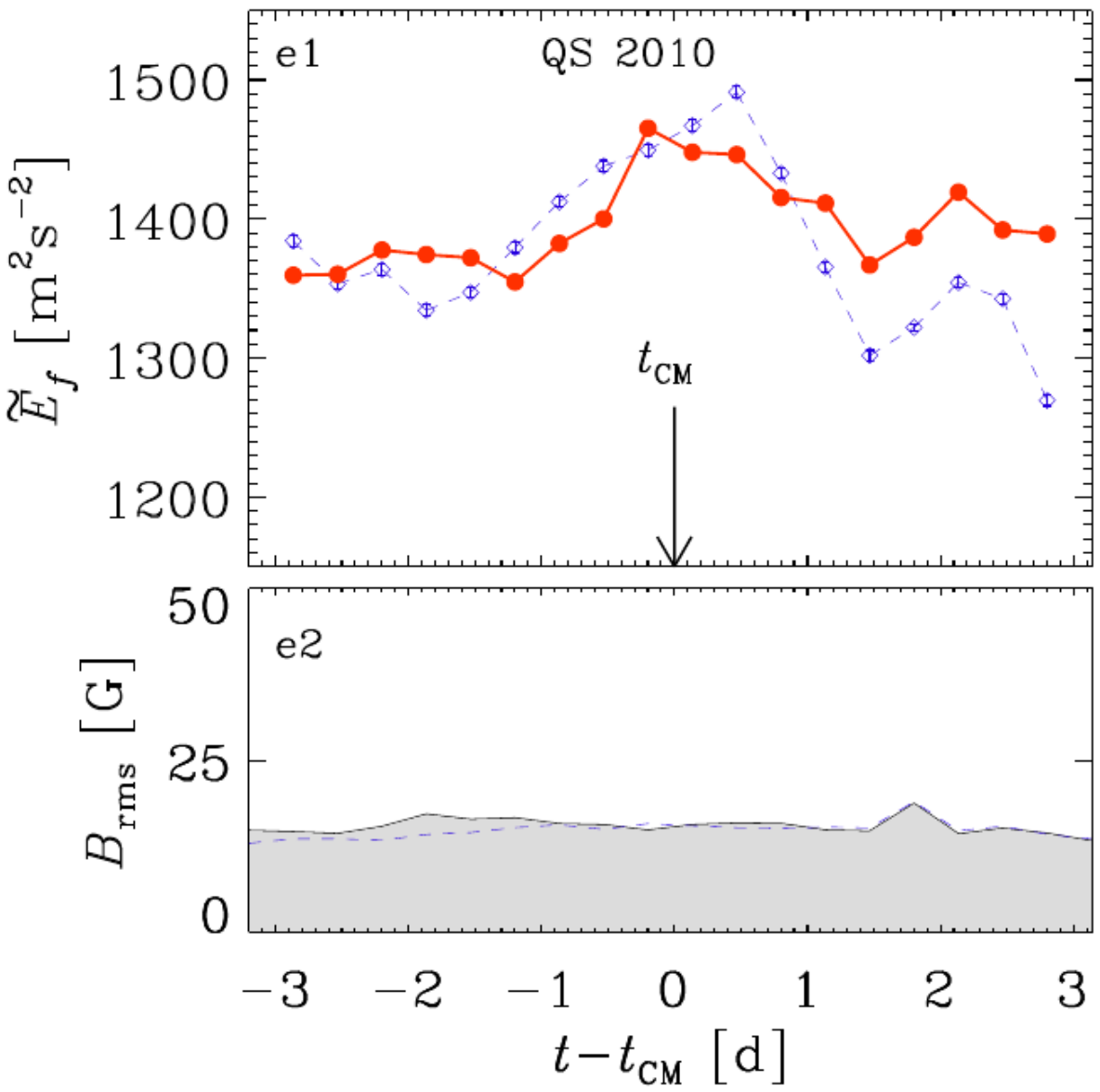
Power Spectrum: diagnostic diagram

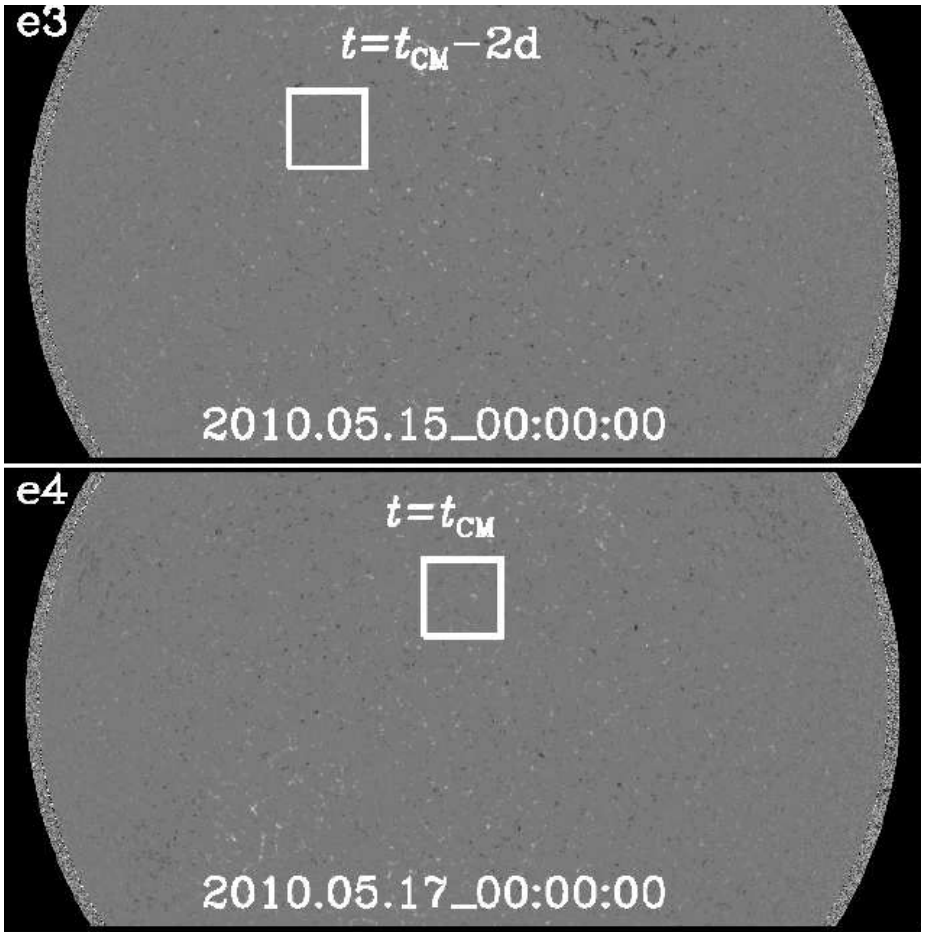




We determine the observable from $k_y\omega$ plane

Quiet Sun (14-20 May, 2010)

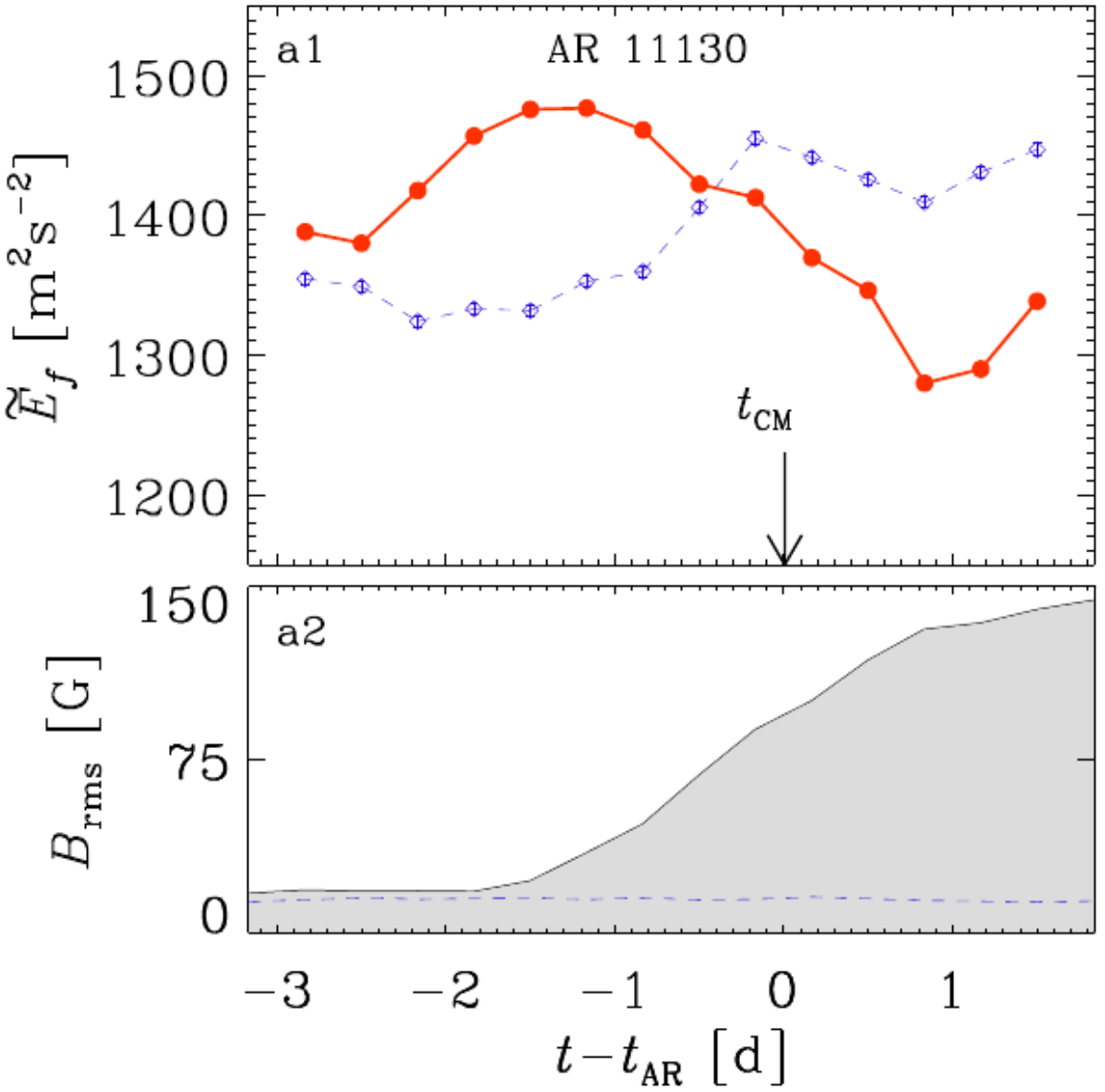


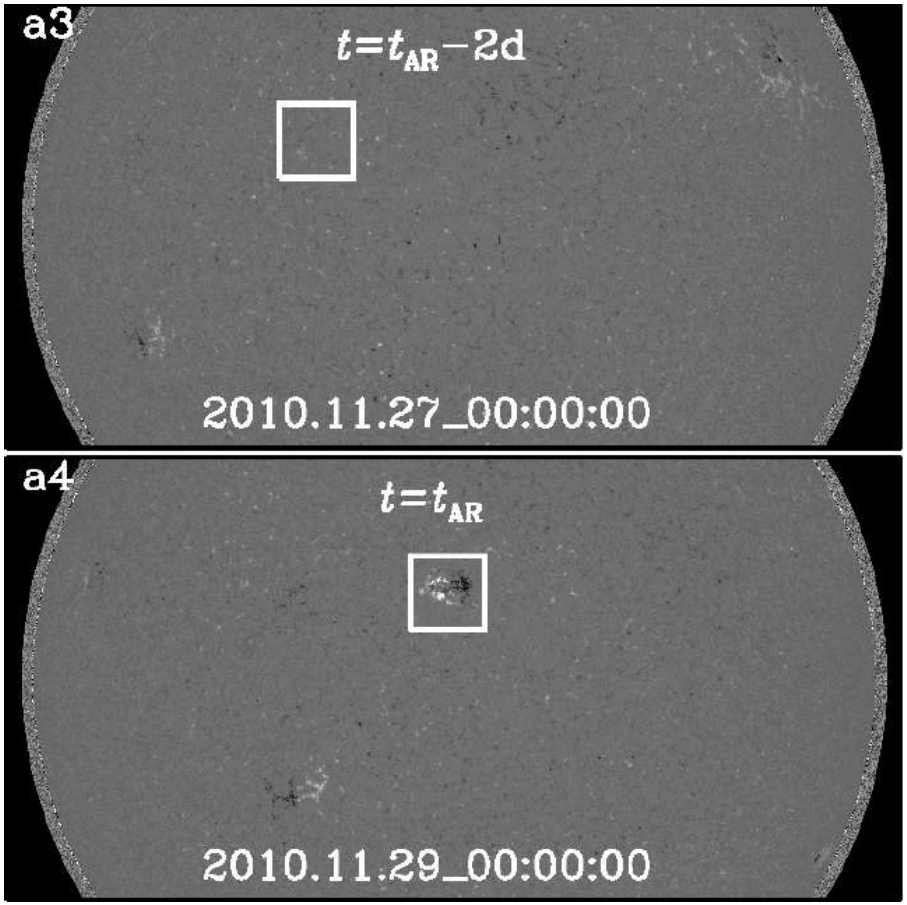


f-mode is symmetrically distributed in the quiet phase !

AR 11130 (26-30 November, 2010)

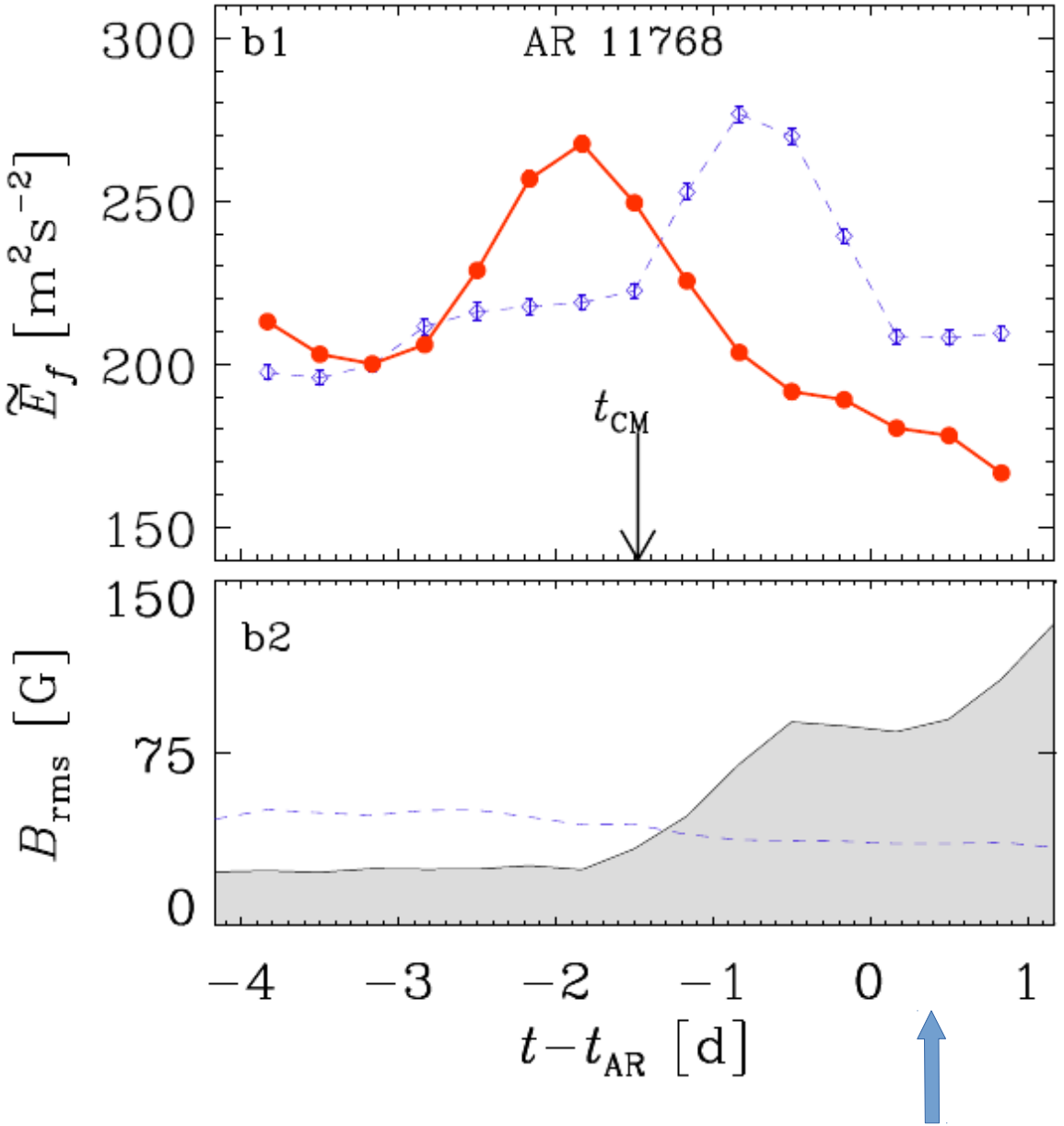
An ideal example

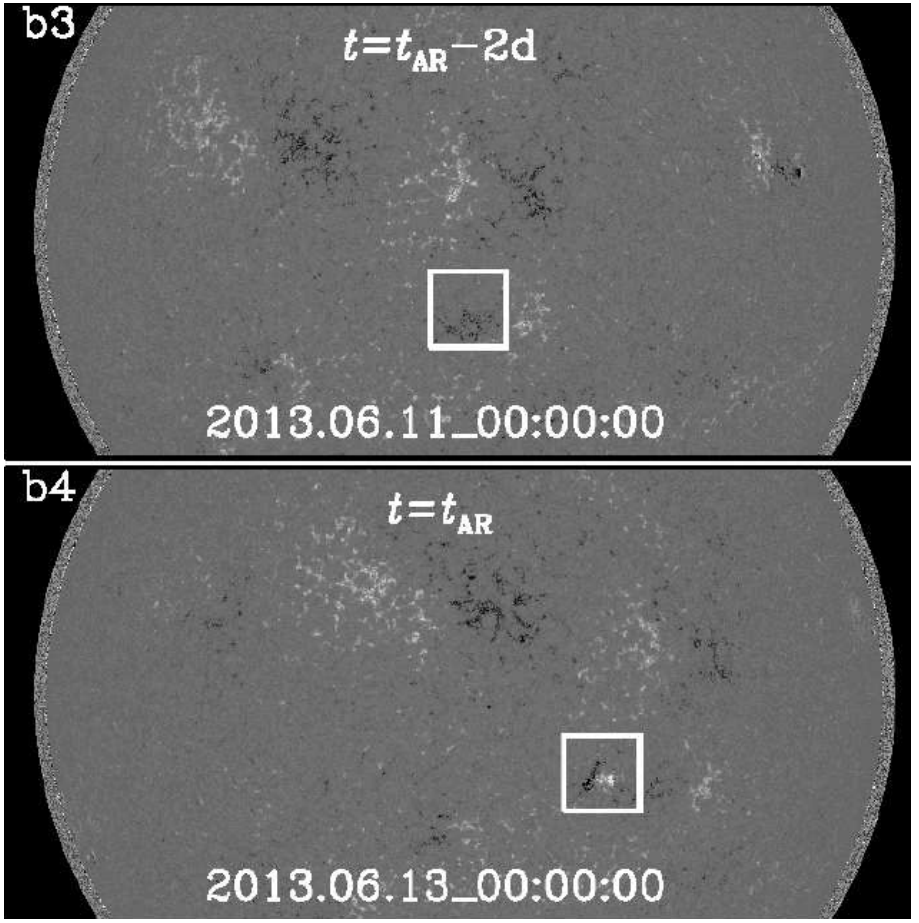




An AR breaks the symmetry of the *f*-mode !

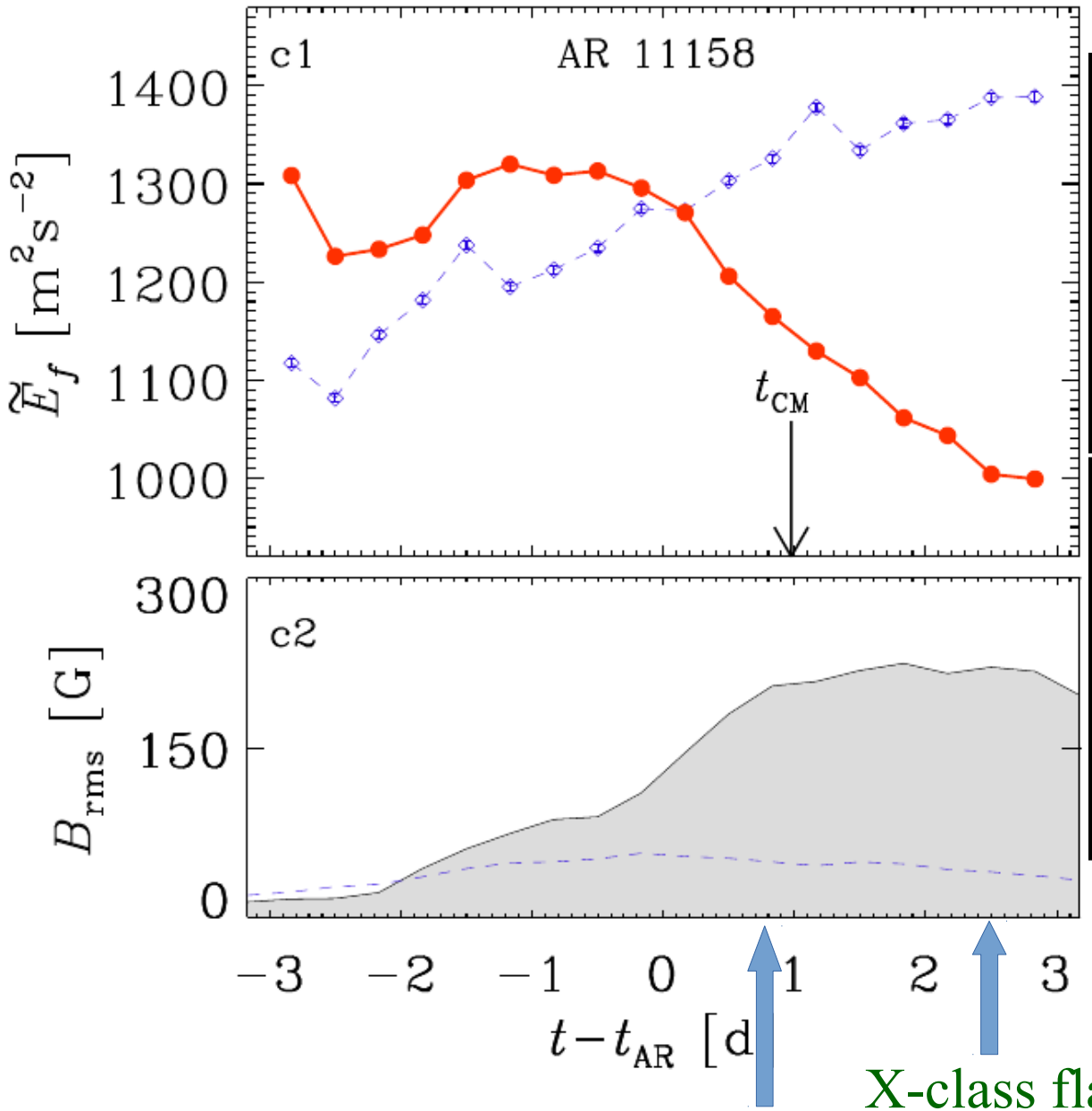
AR 11768 (10-13 June, 2013)

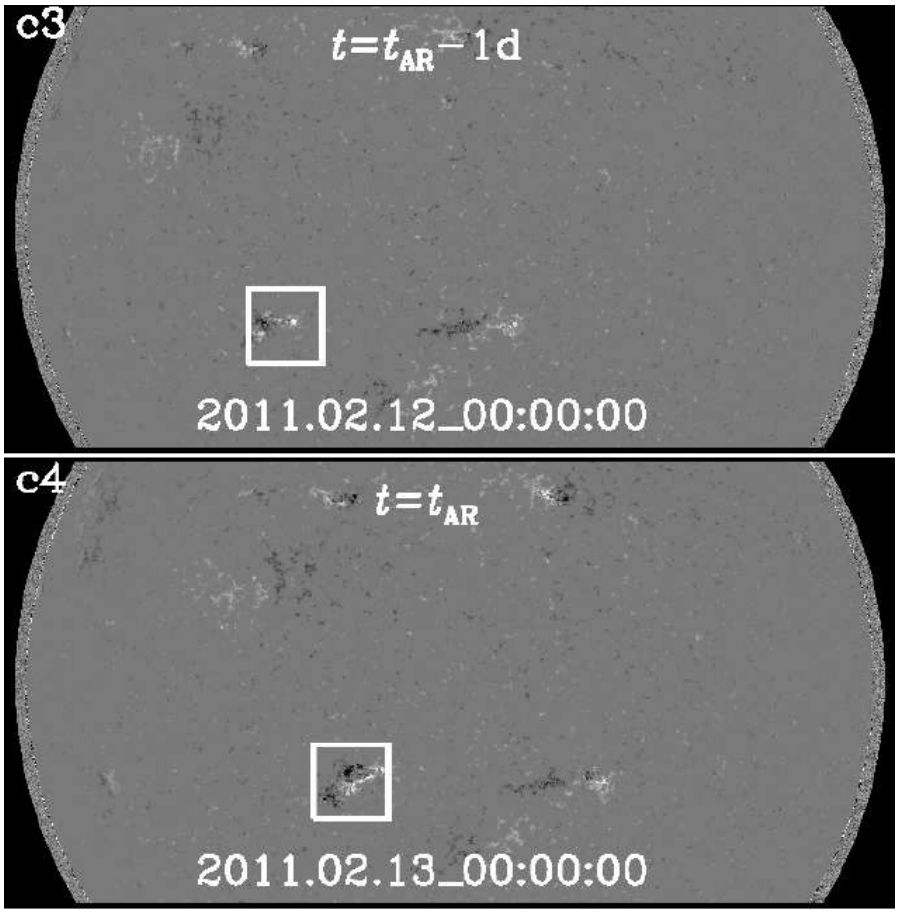




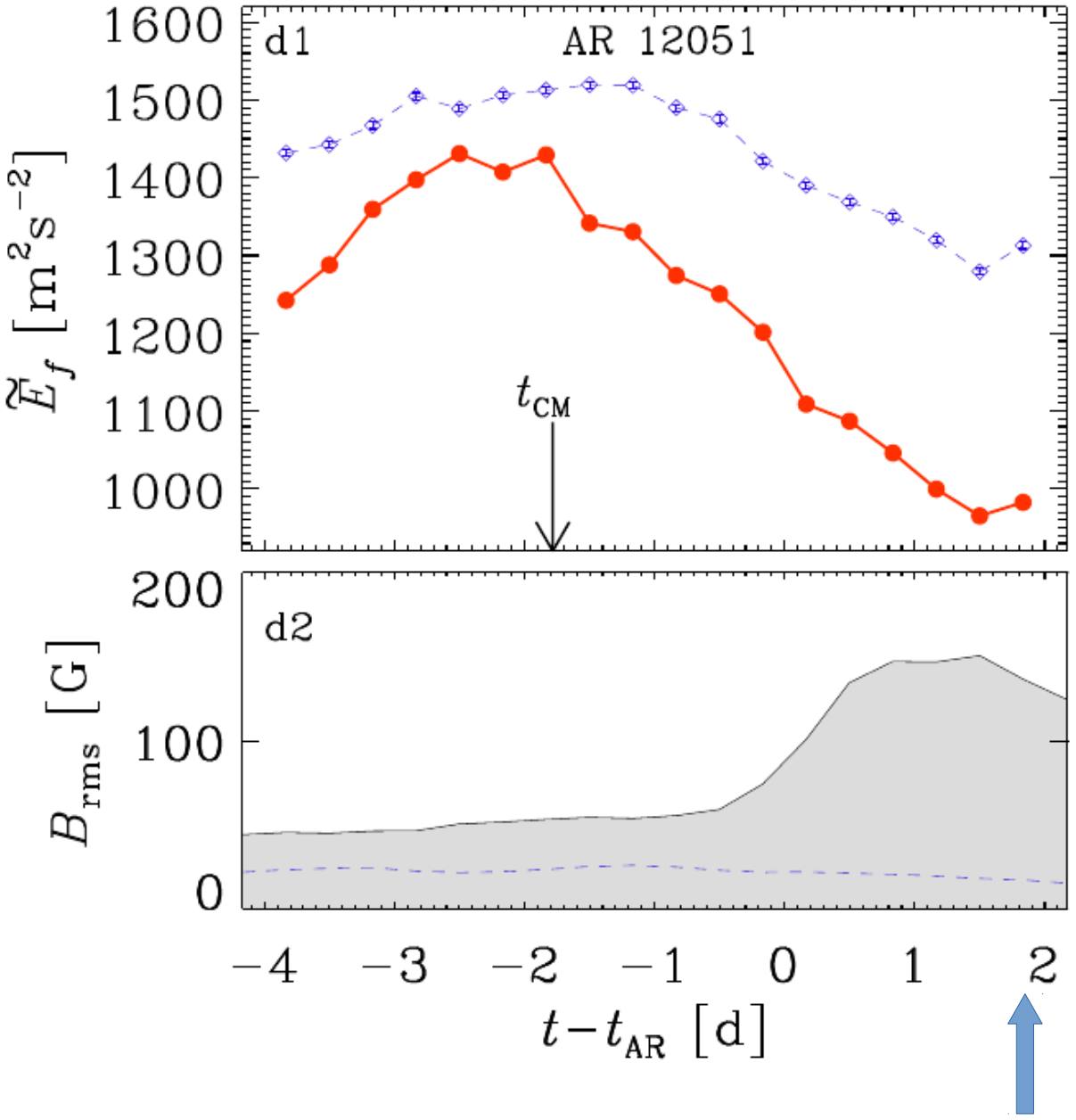
B-class flare

AR 11158 (10-15 February, 2011)

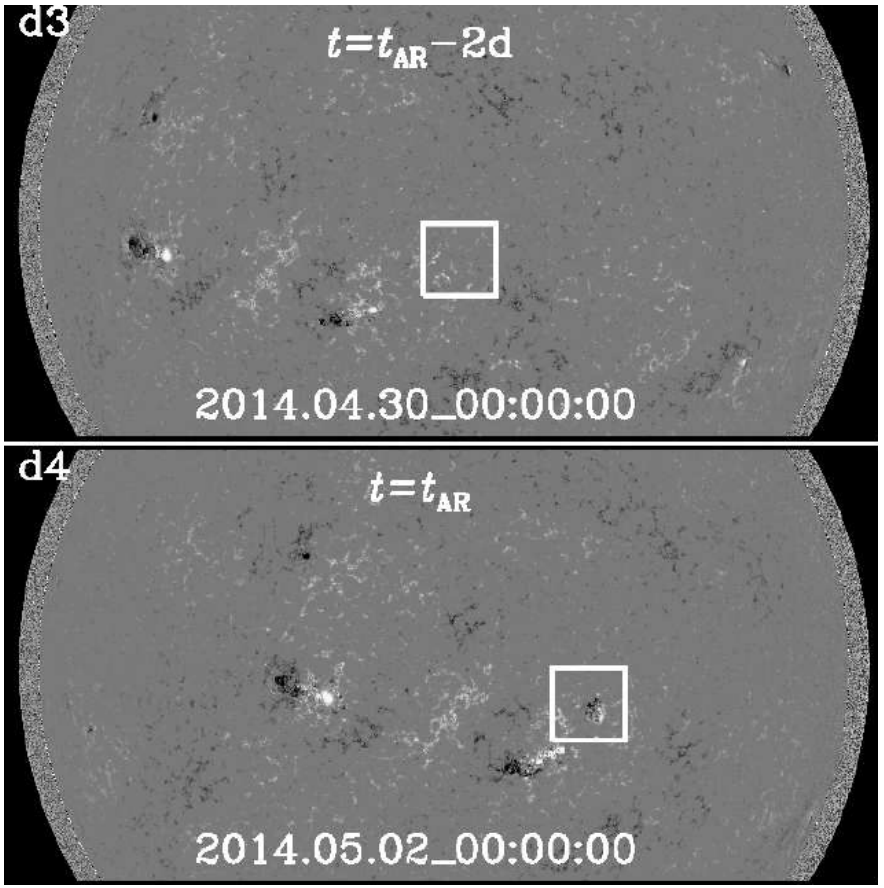




AR 12051 (28 April-03 May, 2014)

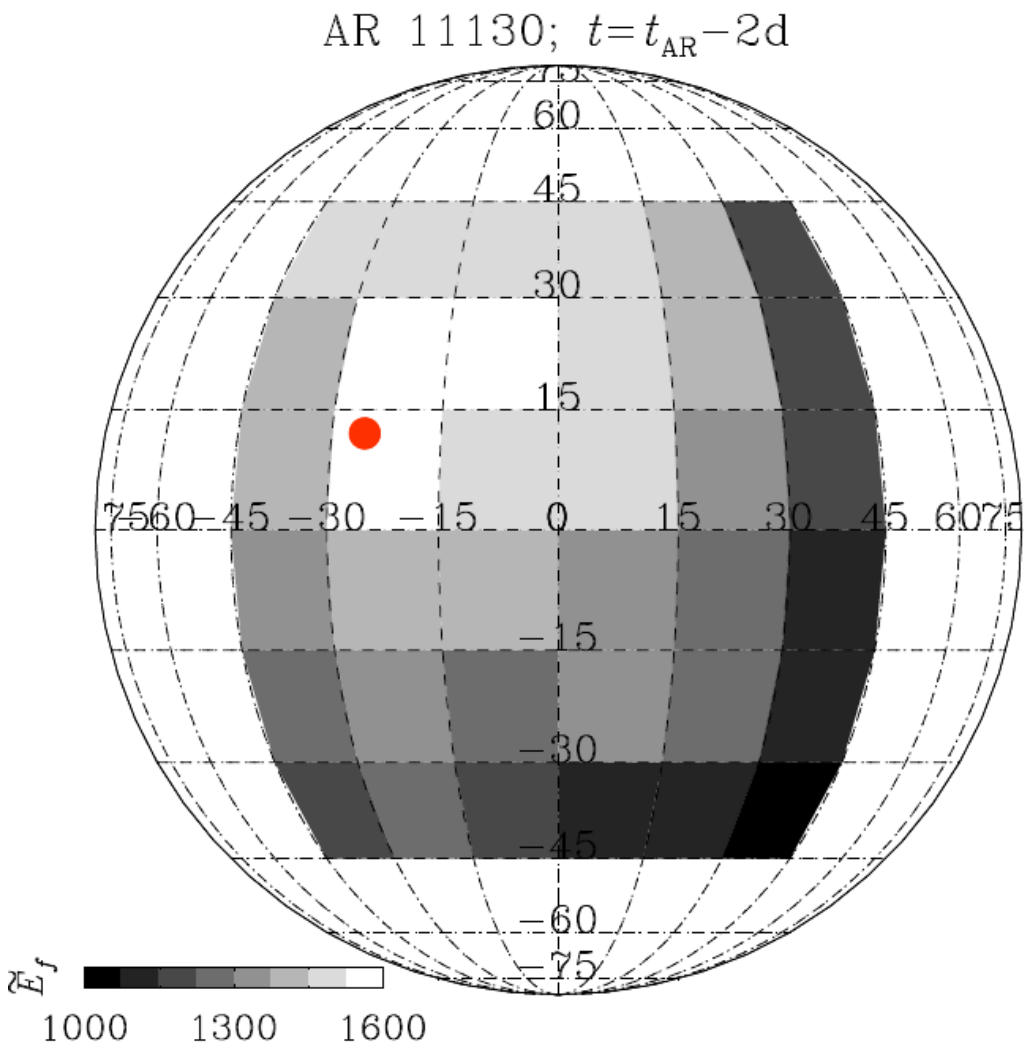


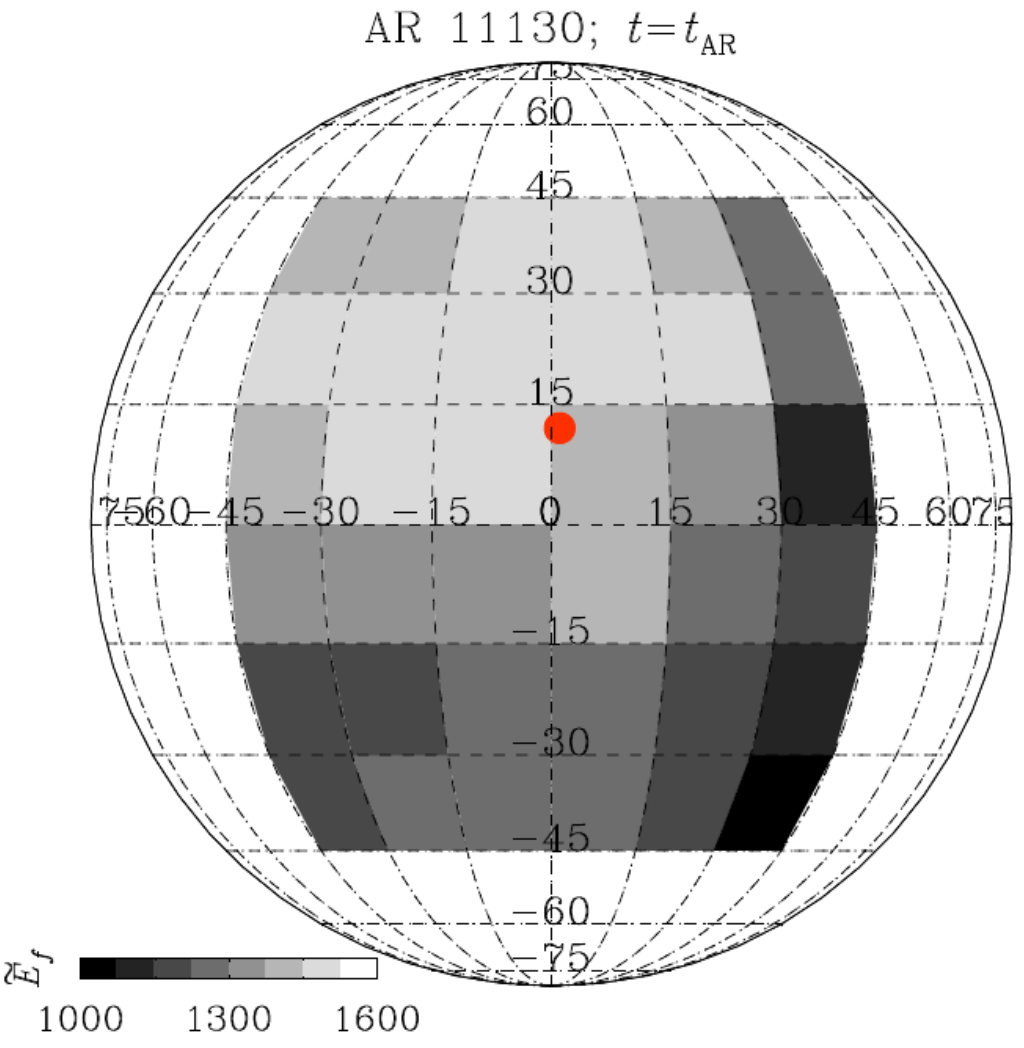
A crowded case



M-class flare

Proposed method to isolate potential sites ...





Solar Images of *f*-mode energy → A Weather Map !

… an ongoing investigation !

Conclusions

- (Uniform) Horizontal and vertical imposed magnetic fields have distinguishing effects
- Goal: To identify diagnostic signatures of nonuniform ***B***-field
- Fanning out of the *f*-mode and pattern of vertical stripes seen
- Fanning and its asymmetry depend on the strength and the location of field concentration beneath the interface

- Analysis: ARs 11130, 11768, 11158, 12051 and QS patches

- Prediction: The *f*-mode energy reaches a maximum about 1.5-2 d before any visible magnetic activity from the same region

- Might play crucial role in predicting solar flares

- Evolutions for each AR differ in detail, but qualitatively similar

Speculations & Challenges

- Global solar magnetic field: As the *f*-mode appears to be perturbed days before any visible magnetic activity on the surface, it must be able to constrain global dynamo models → *near surface formation of ARs ?*

- Solar convection:
  - *f*-mode is intrinsically broadened
  - if it is linked to the convection, as was previously proposed (Murawski+93,00; Duvall+99), then the observed linewidths (QS) might be explained if convective motions are large at high wavenumbers
  - Broadening seem to be enhanced by B-fields (also, QS regions are never field free); making it less dependent on the strength of the convection

- Imaging: might offer a novel method for future space weather predictions

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