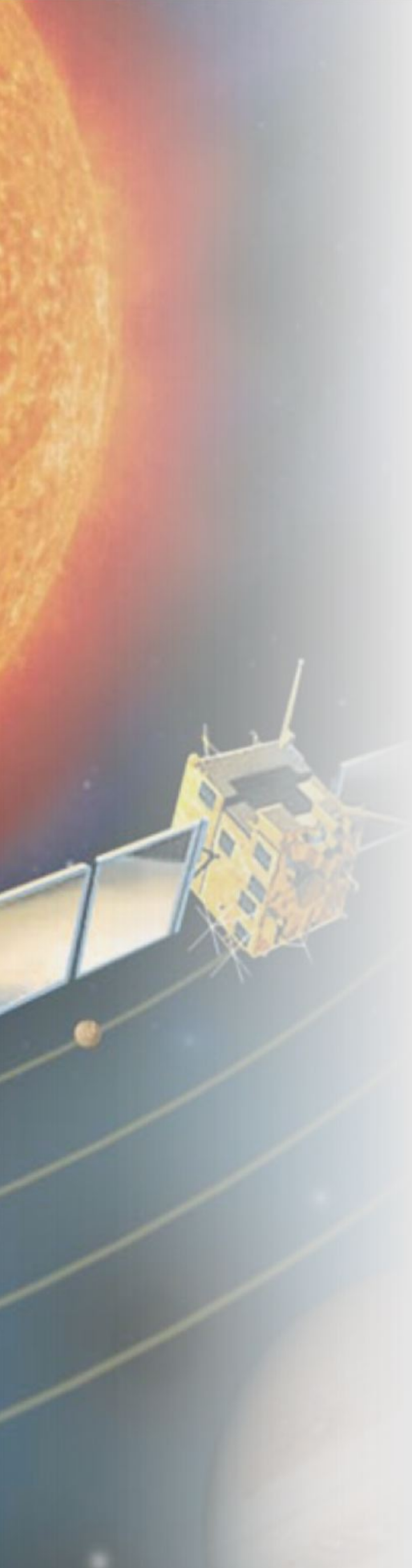

Towards understanding the subsurface structure of sunspots

Hannah Schunker

Max Planck Institute for
Solar System Research

surface structure ✓ ?

radius - Wilson depression - magnetic field

Formation, evolution, lifetime ?
Subsurface structure ?

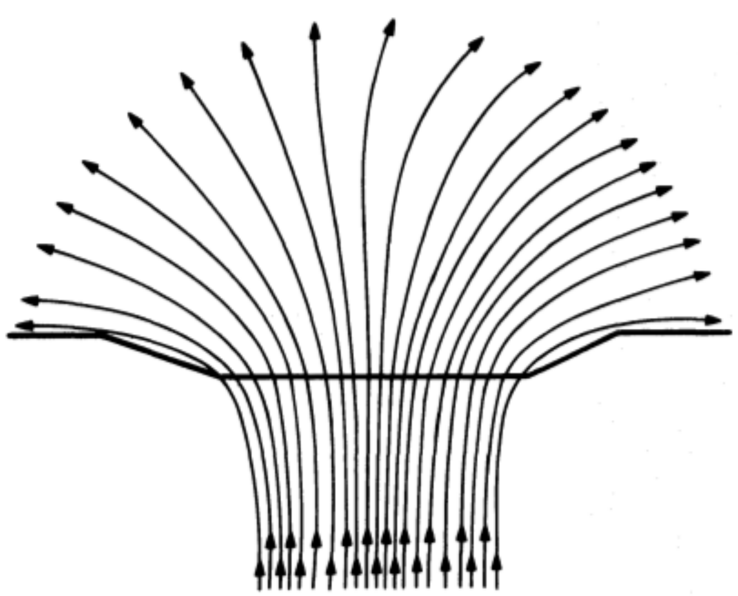

FIG. 1.—A sketch of the conventional idea of the magnetic field configuration of a sunspot. The heavy line represents the visible surface of the Sun.

Parker 1979b

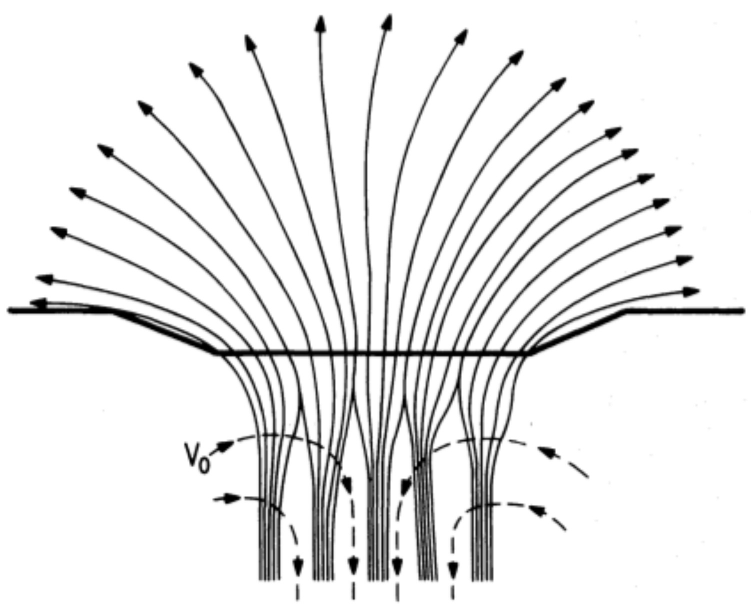

FIG. 2.—A sketch of the proposed magnetic field configuration, in which the field divides into individual flux tubes some distance below the visible surface. The dashed arrows represent the presumed convective downdraft which helps to hold the separate flux tubes together in the tight cluster that constitutes the sunspot.

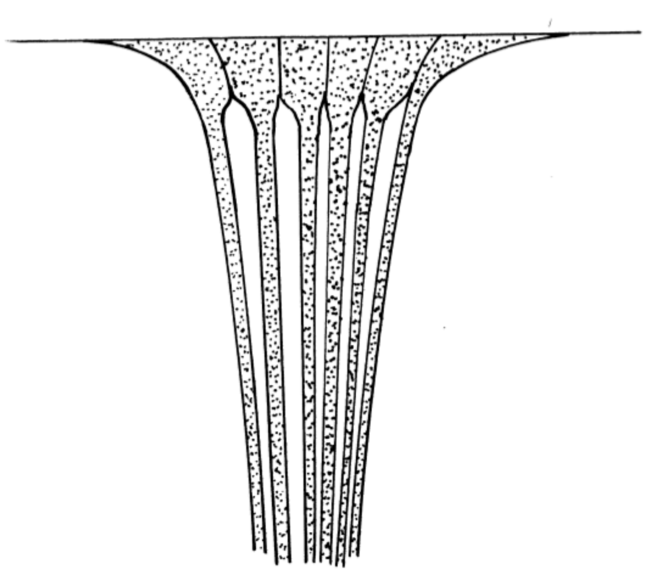

Fig. 1 Model of a sunspot, consisting of individual tubes tied down at a great depth (schematic)

Spruit 1981

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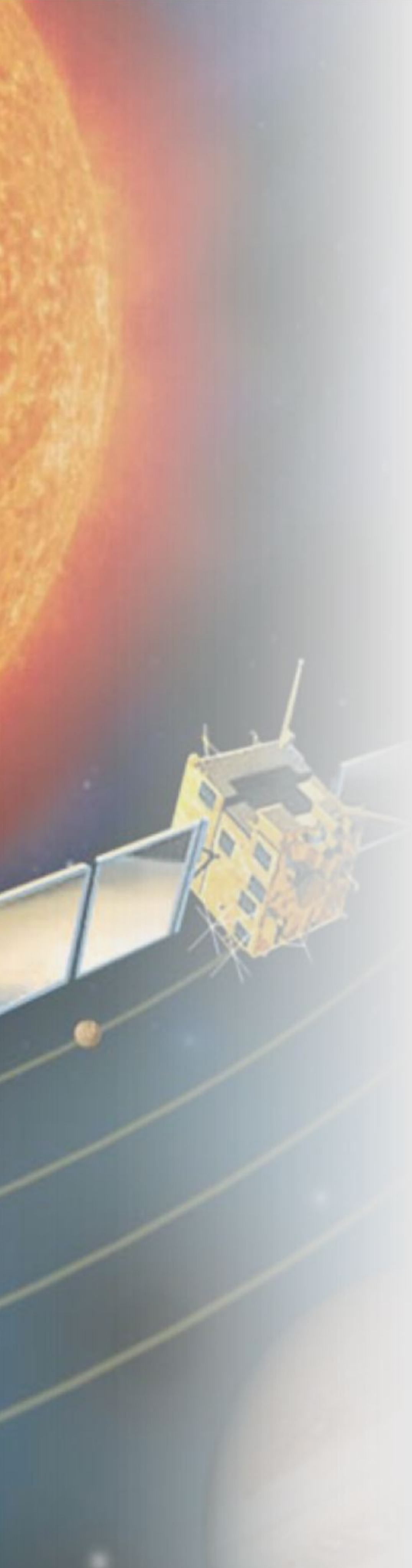

Observational challenges

Computational sunspot seismology

Emerging sunspot regions

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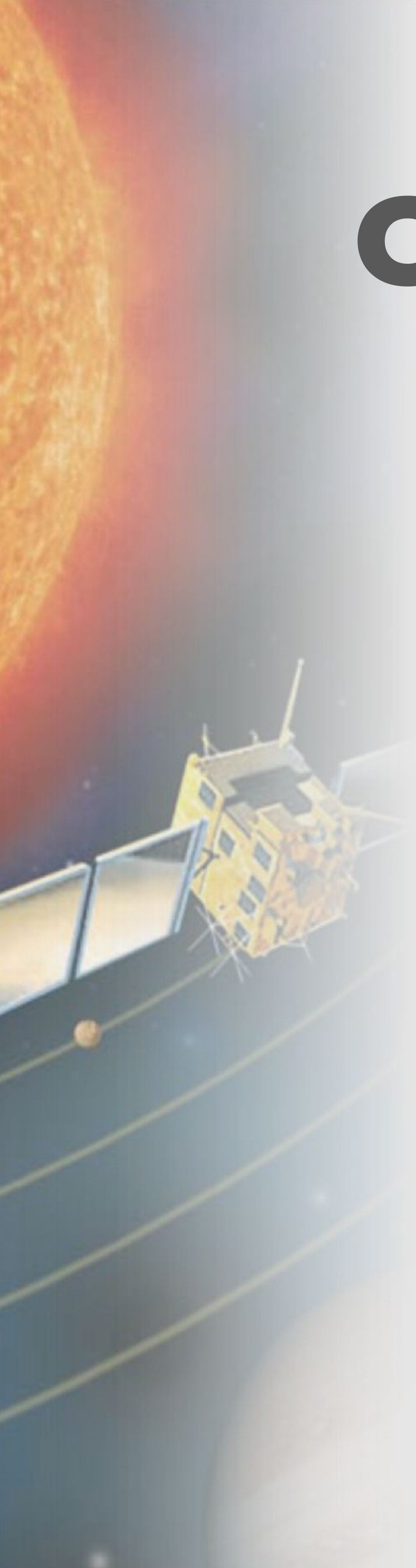

Observational challenges

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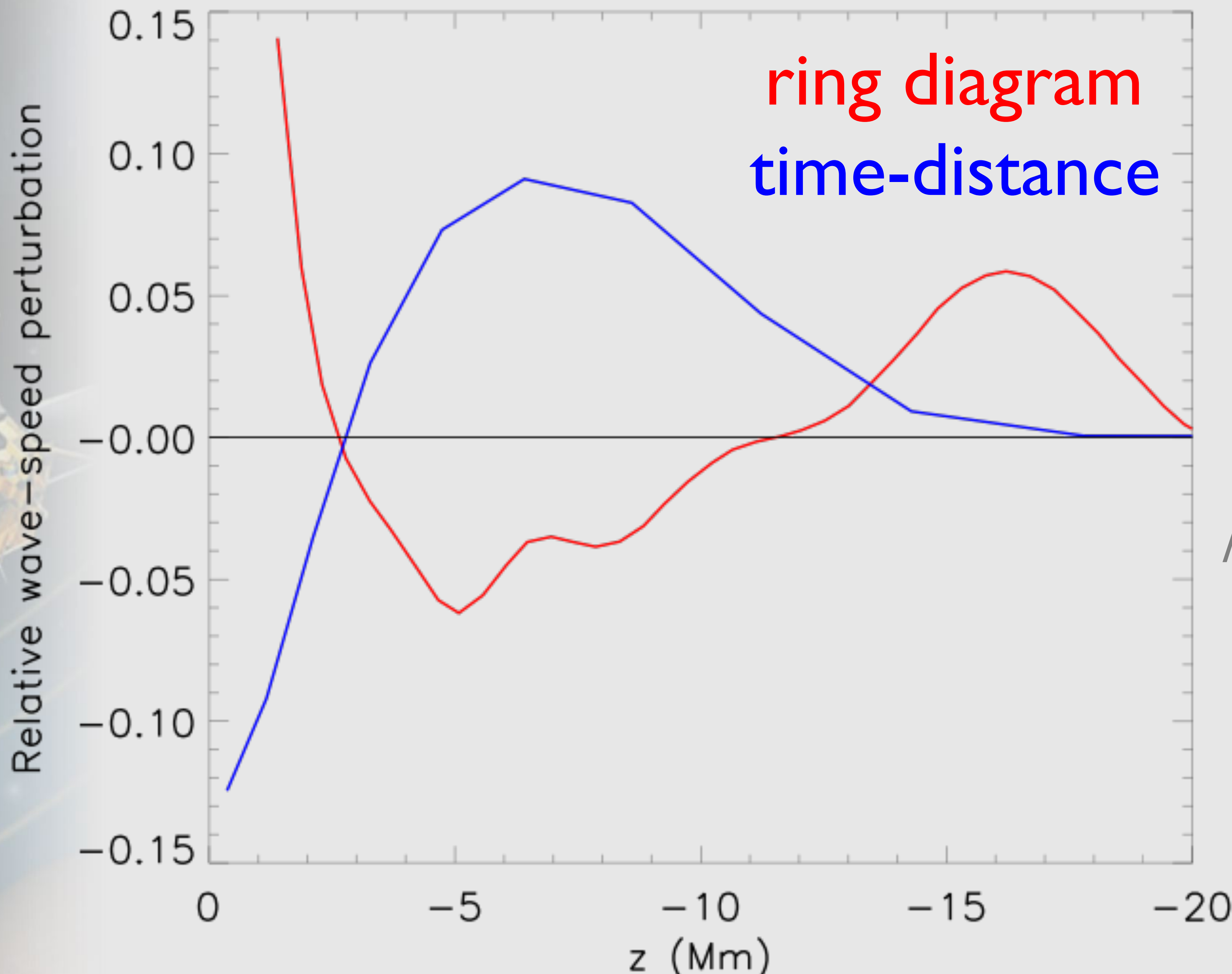
Inconsistencies in helioseismic inversions of subsurface structure



'HELAS sunspot inversion'

AR9787

Gizon et al 2009

Moradi et al 2010

7 days of observation

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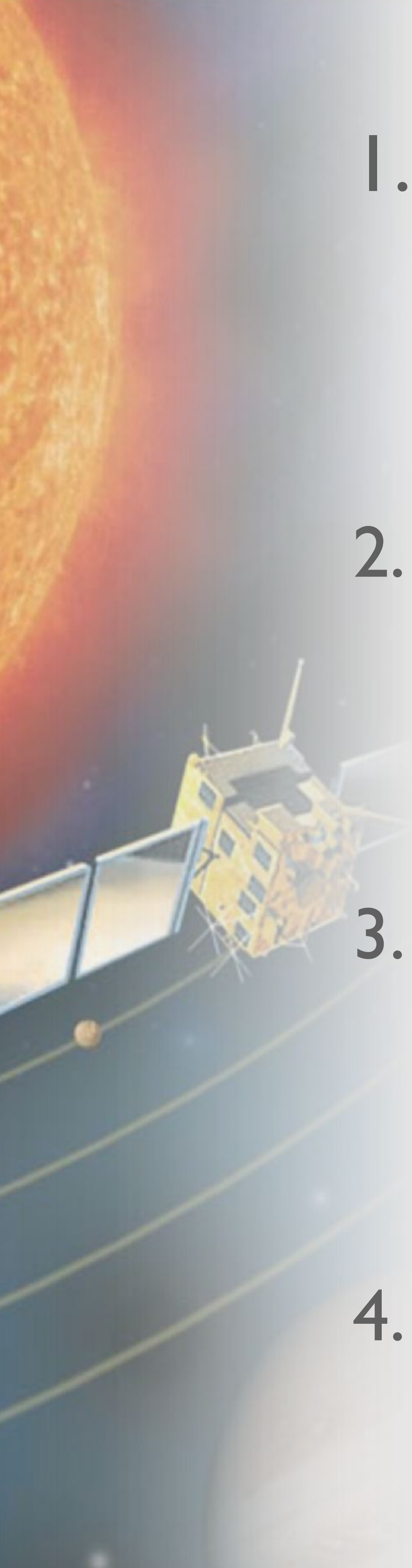

Issues

1. Understanding the physics

   - mode conversion; scattering

   e.g. *Braun et al 1990; Fan et al 1995; Cally & Bogdan 1995; Crouch & Cally 2005; Schunker et al 2005; Lindsey & Braun 2005; Hanasoge et al 2013*

2. Understanding the techniques

   - time distance helioseismology; ring diagrams; holography; hankel analysis

   e.g. *Couvidat & Rajaguru 2007; Braun, Birch & Rempel 2011; Moradi et al 2011*

3. New diagnostics

   - using all available information
   - improving the signal to noise

   e.g. *Gizon et al 2009; Zhao & Chou 2013; Liang et al 2013*

4. New methods of interpretation

   - non-linear inversion

   e.g. *Hanasoge et al 2011; Yang et al in prep*

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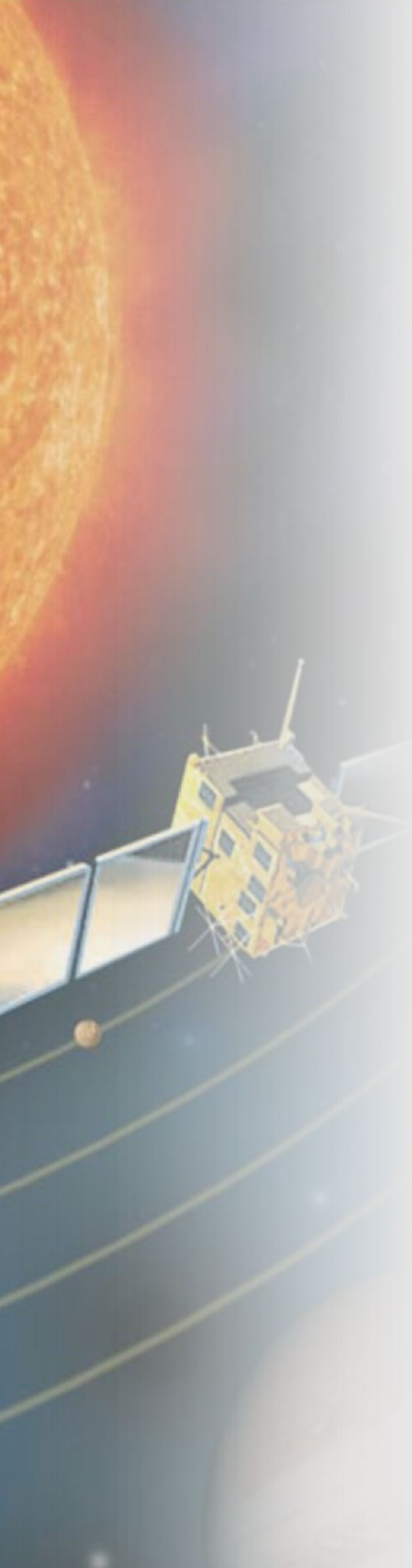

Observational challenges

Computational sunspot seismology

Emerging sunspot regions

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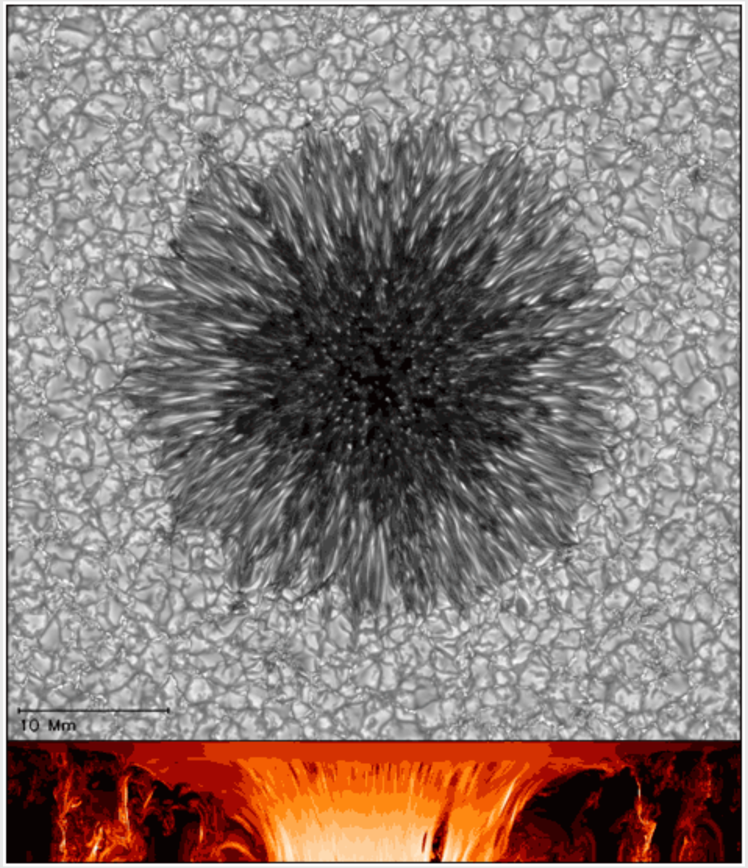
Numerical simulations

- Realistic numerical simulations:
  Rempel et al. 2009; Braun, Birch & Rempel 2011
  -include full physics
  -waves are naturally excited
  -computationally expensive
  -*Braun, Birch, Rempel & Duvall 2012;*
  De Grave, Jackiewicz & Rempel 2014



- Linearised simulations:
  Cameron et al. 2007; Hanasoge et al. 2008; Khomenko & Collados 2006; Parchevsky & Kosovichev 2007; Shelyag et al. 2008
  -faster to compute
  -free to choose any background model
  -require stable background model
  -model of excitation

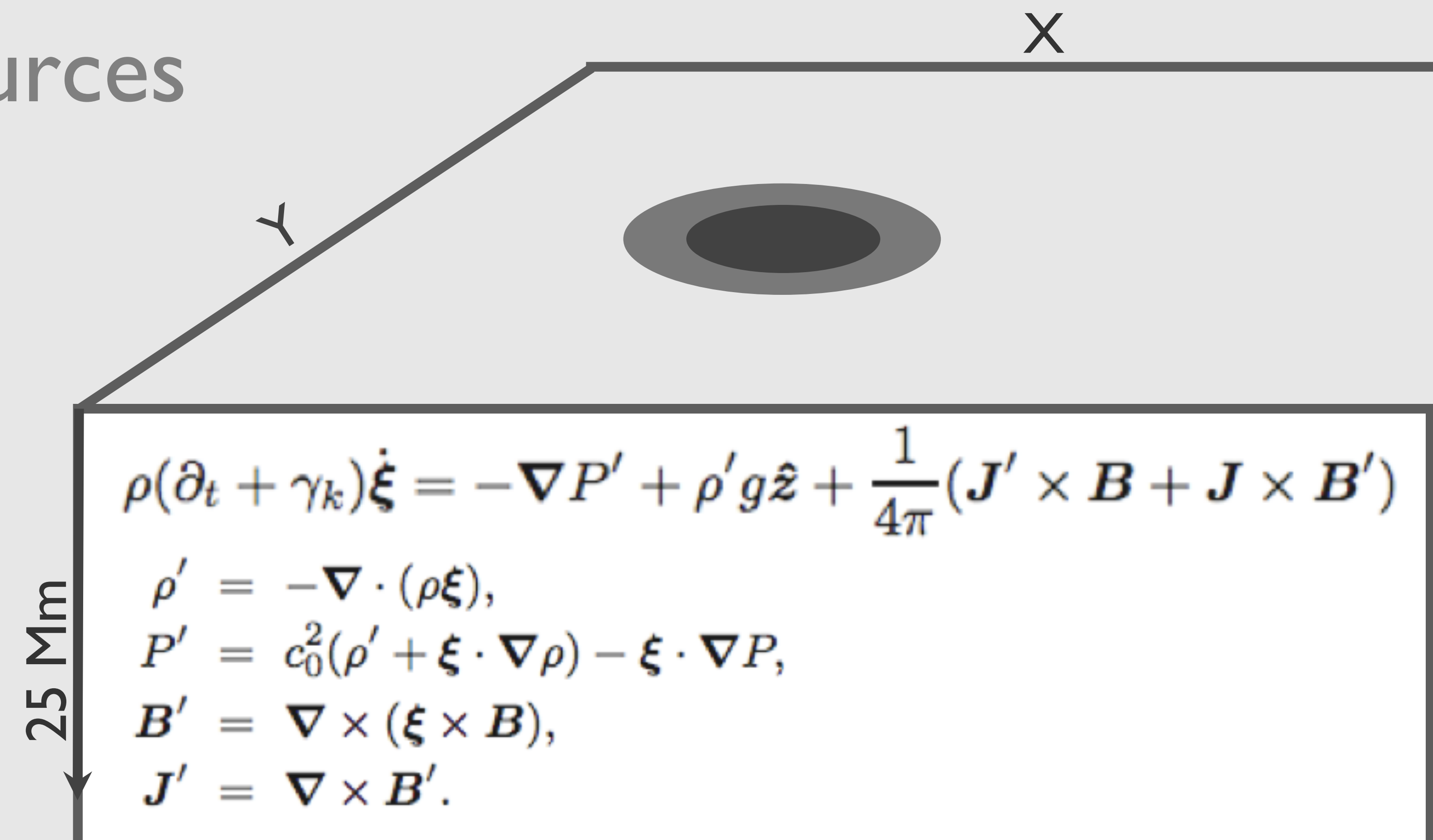
MHD linear numerical simulations

Propagation: SLiM code — *Cameron et al 2008*

Quiet-Sun model: CSM_A — *Schunker et al 2010*

Sunspot model: semi-empirical — *Cameron et al 2011*

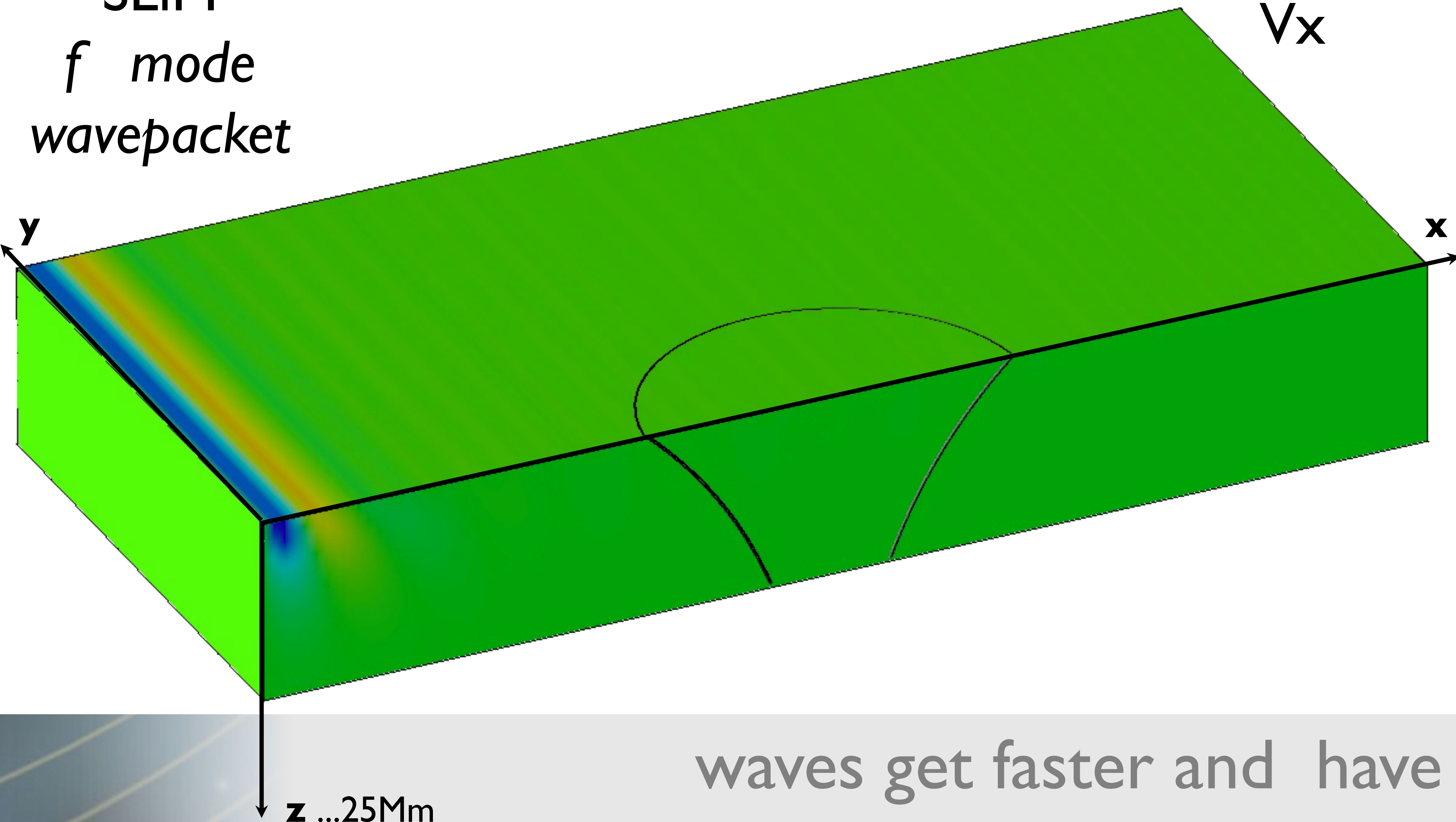
Waves: wave packet initial condition or random sources — *Cameron et al 2008*



$$\rho(\partial_t + \gamma_k)\dot{\boldsymbol{\xi}} = -\boldsymbol{\nabla} P' + \rho' g \hat{\boldsymbol{z}} + \frac{1}{4\pi}(\boldsymbol{J}' \times \boldsymbol{B} + \boldsymbol{J} \times \boldsymbol{B}')$$

$$\begin{aligned} \rho' &= -\boldsymbol{\nabla} \cdot (\rho \boldsymbol{\xi}), \\ P' &= c_0^2(\rho' + \boldsymbol{\xi} \cdot \boldsymbol{\nabla} \rho) - \boldsymbol{\xi} \cdot \boldsymbol{\nabla} P, \\ \boldsymbol{B}' &= \boldsymbol{\nabla} \times (\boldsymbol{\xi} \times \boldsymbol{B}), \\ \boldsymbol{J}' &= \boldsymbol{\nabla} \times \boldsymbol{B}'. \end{aligned}$$

SLiM
f mode
wavepacket



waves get faster and have lower amplitude

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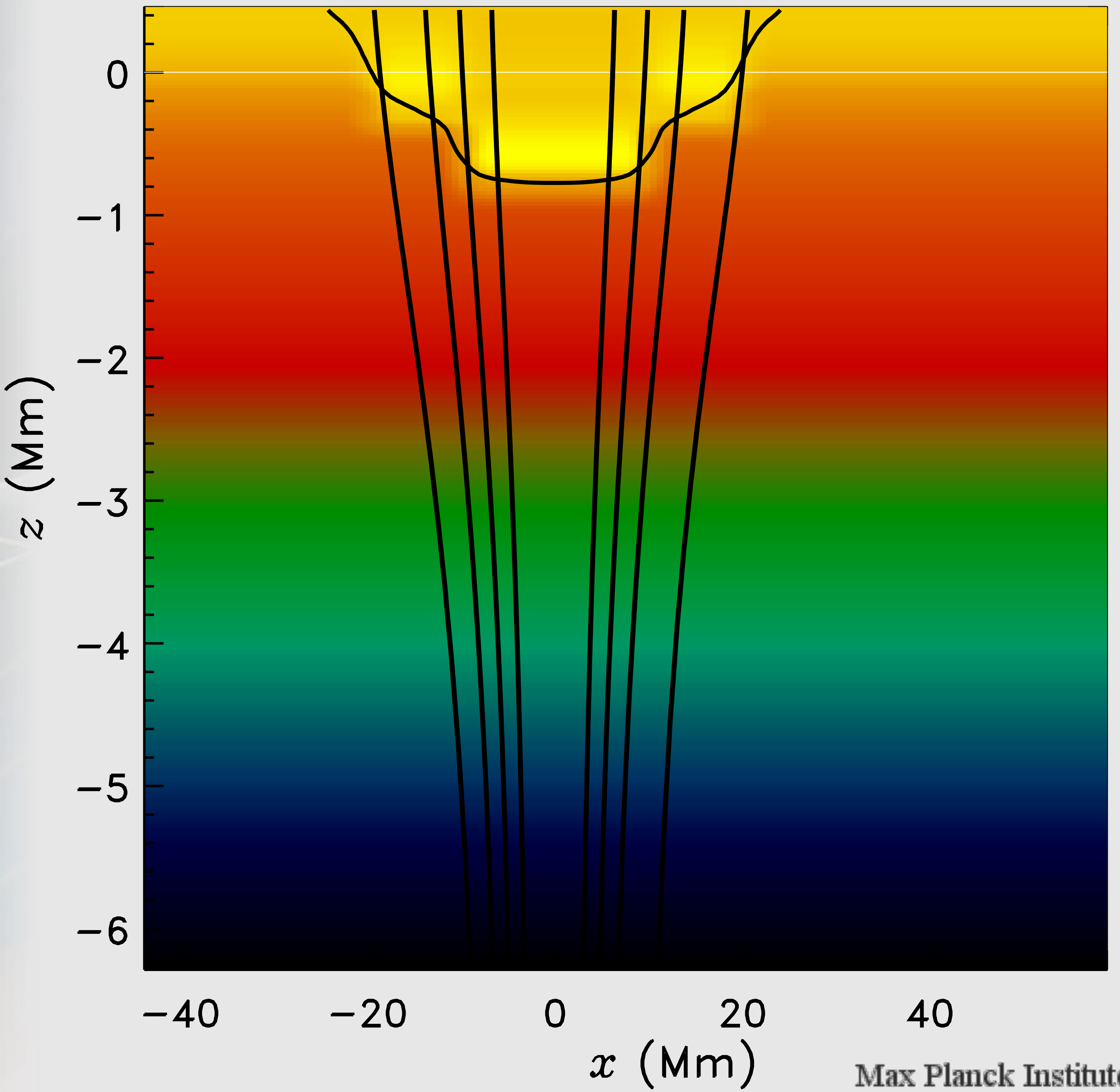
Cameron et al. 2008

Reference sunspot model



Based on observed sunspot AR9787

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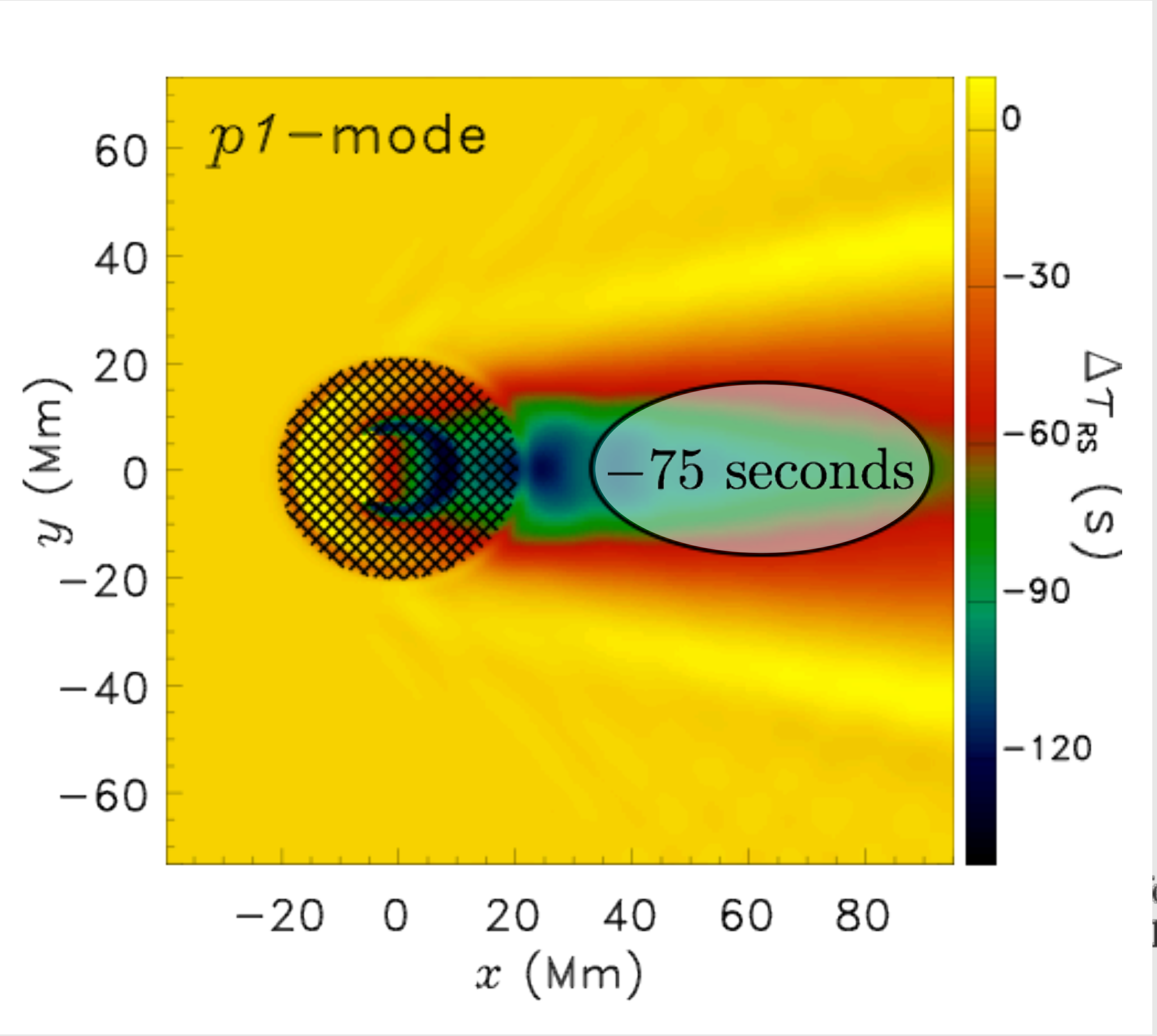
calculating the travel-time shift

$$F(x, y, \tau) = \frac{\int \tilde{v}_z(x, y, t) v_z(x, t - \tau) dt}{\int |v_{z\mathrm{QS}}(x, t)|^2 dt}$$



Schunker et al *2013*

Can perturbations to the sound speed beneath a sunspot be detected?

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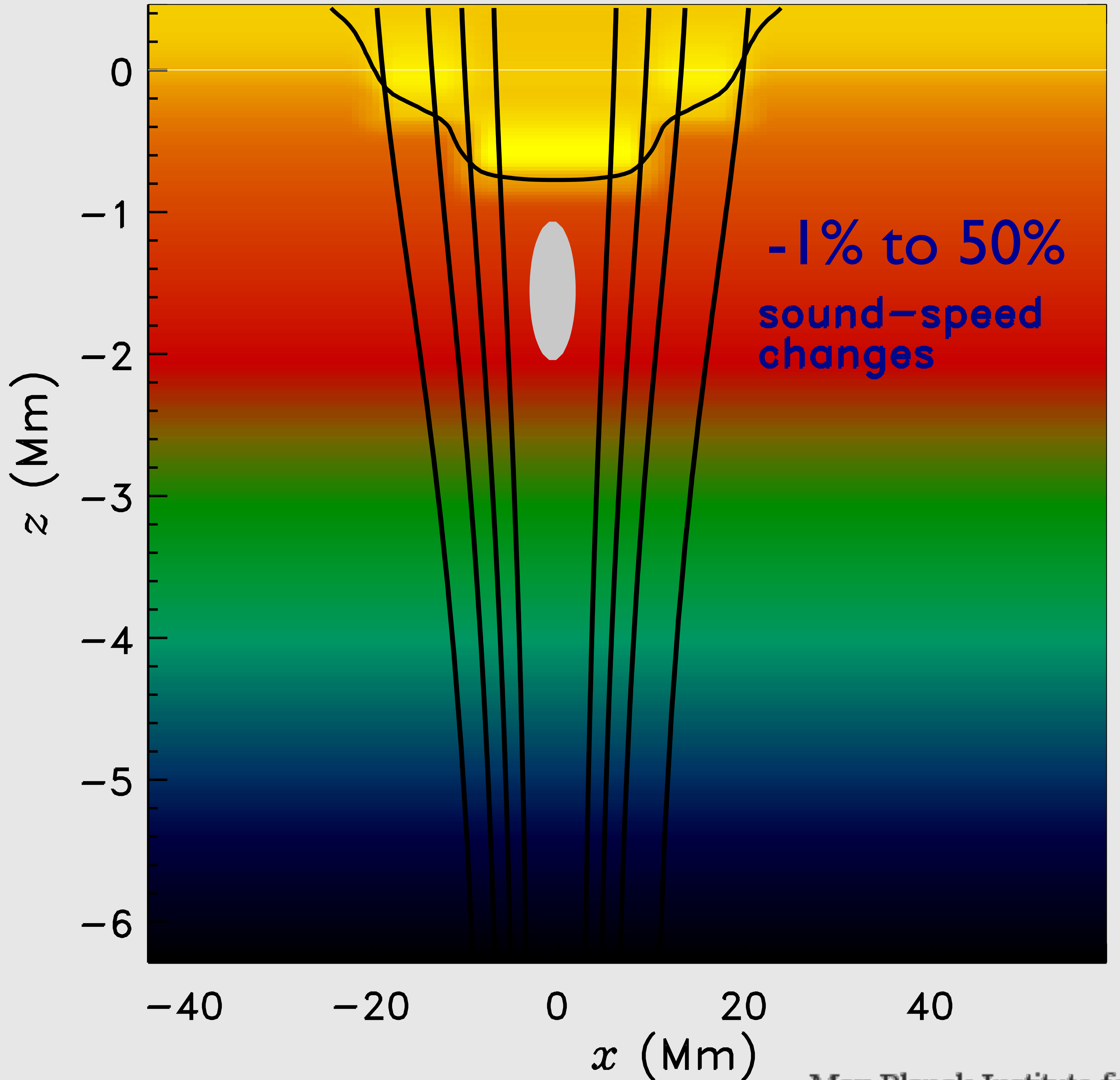
Sound-speed Perturbations



Schunker et al *2013*

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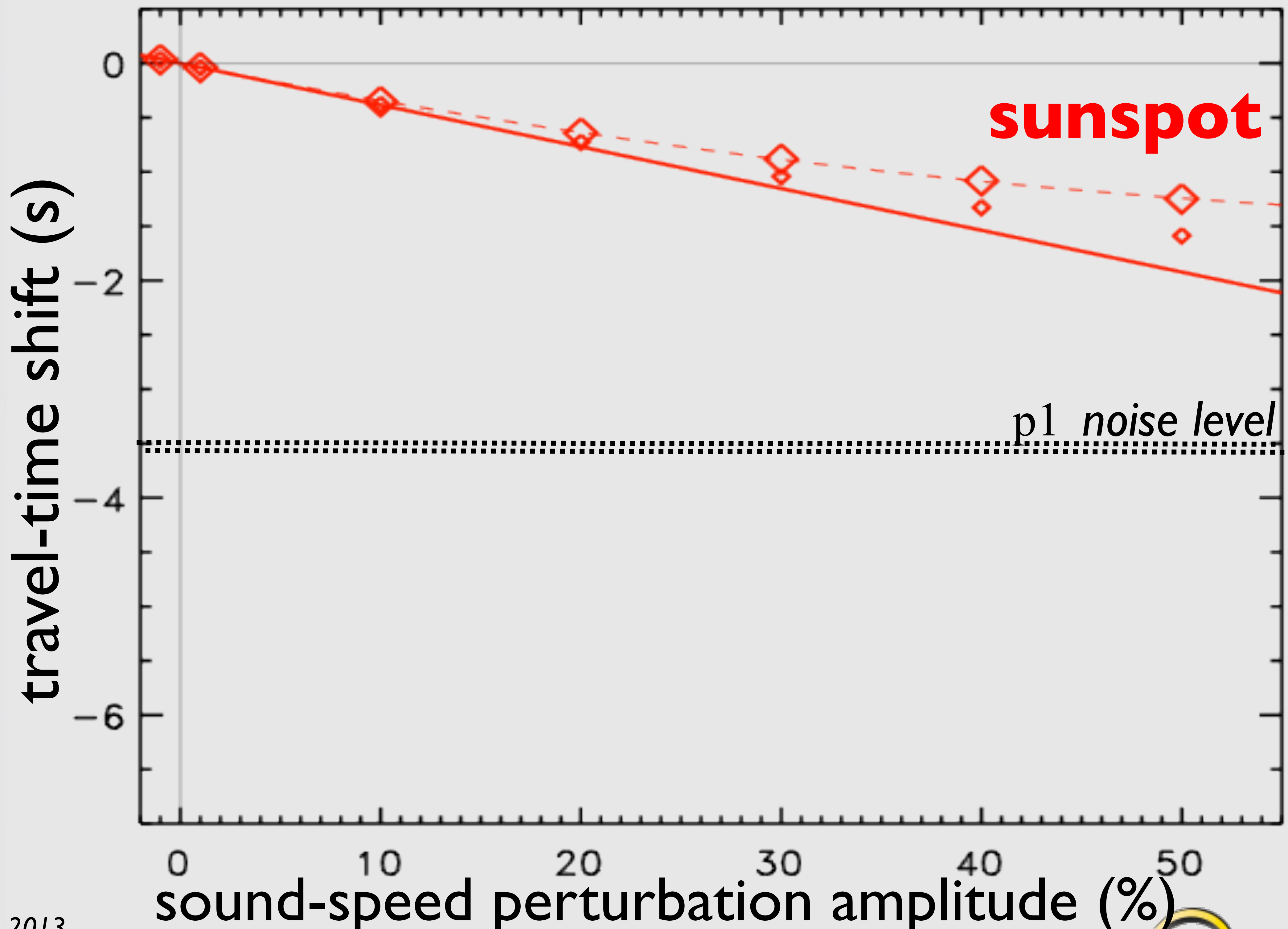
Travel-time shift due to subsurface sound-speed perturbations



Schunker et al *2013*

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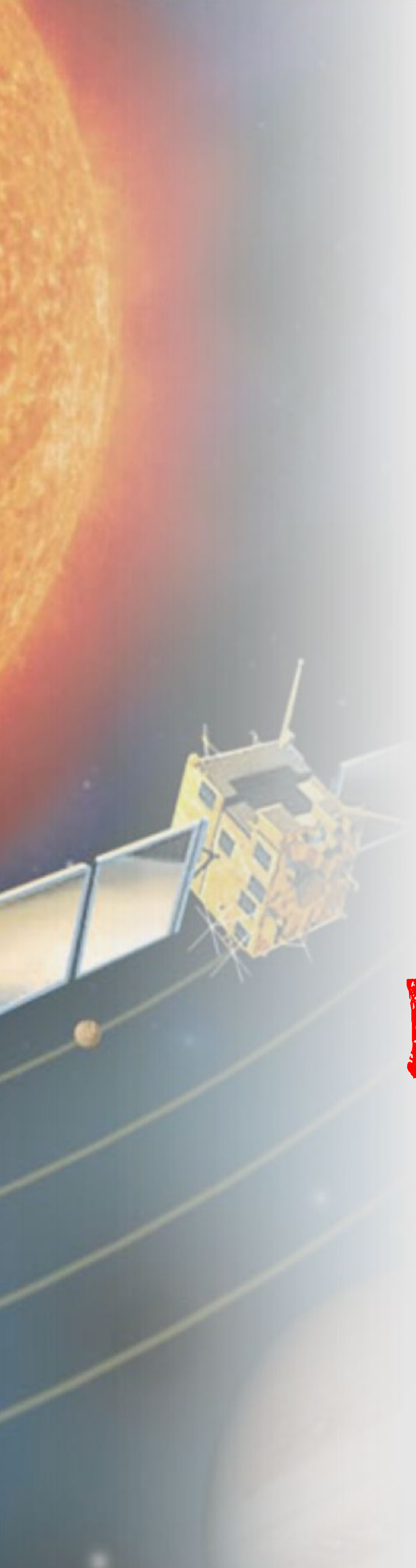

Does the sensitivity of the travel times change?

$$[\ RS + 0.1Cs\ ] - [\ RS\ ] = [\ 0.1Cs\ ]\ ?$$

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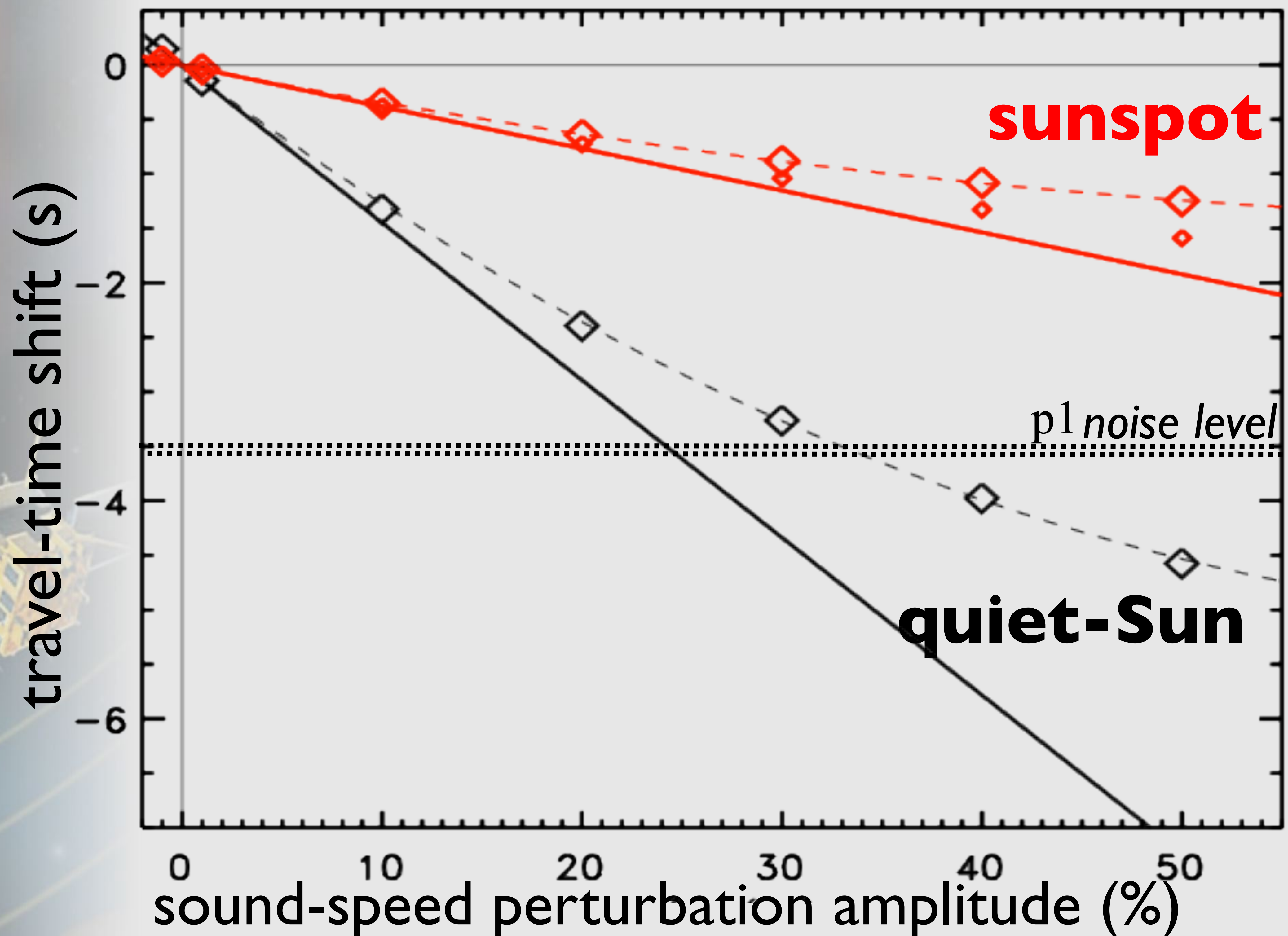
Does the sensitivity of the waves change?



Schunker et al *2013*

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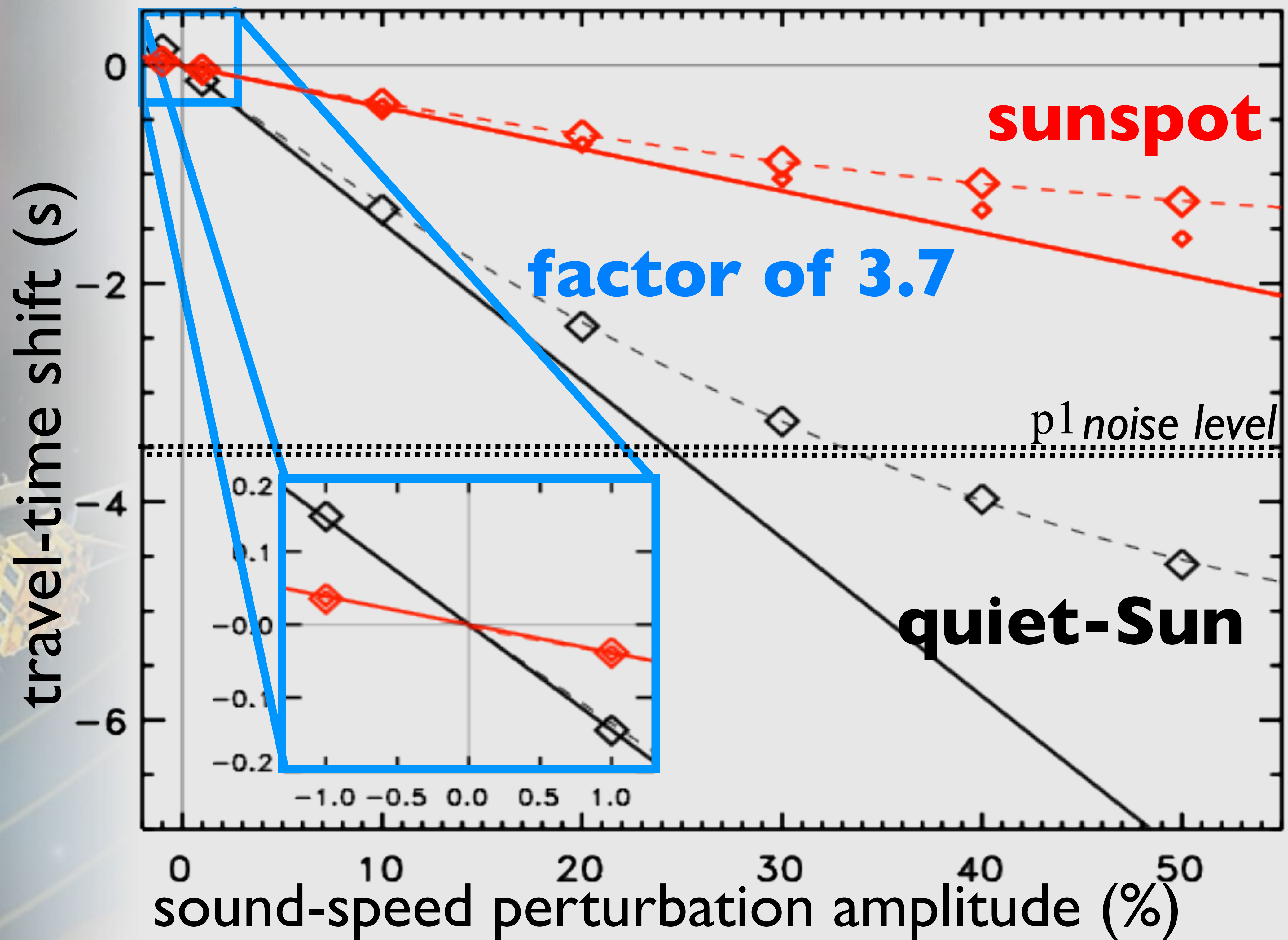
Does the sensitivity of the waves change?



Schunker et al *2013*

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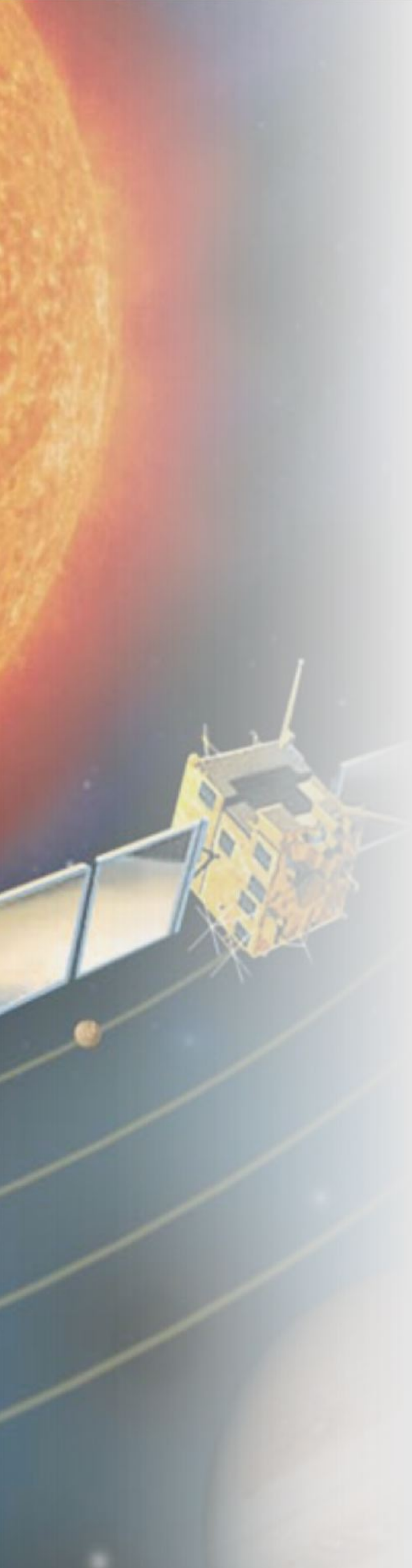
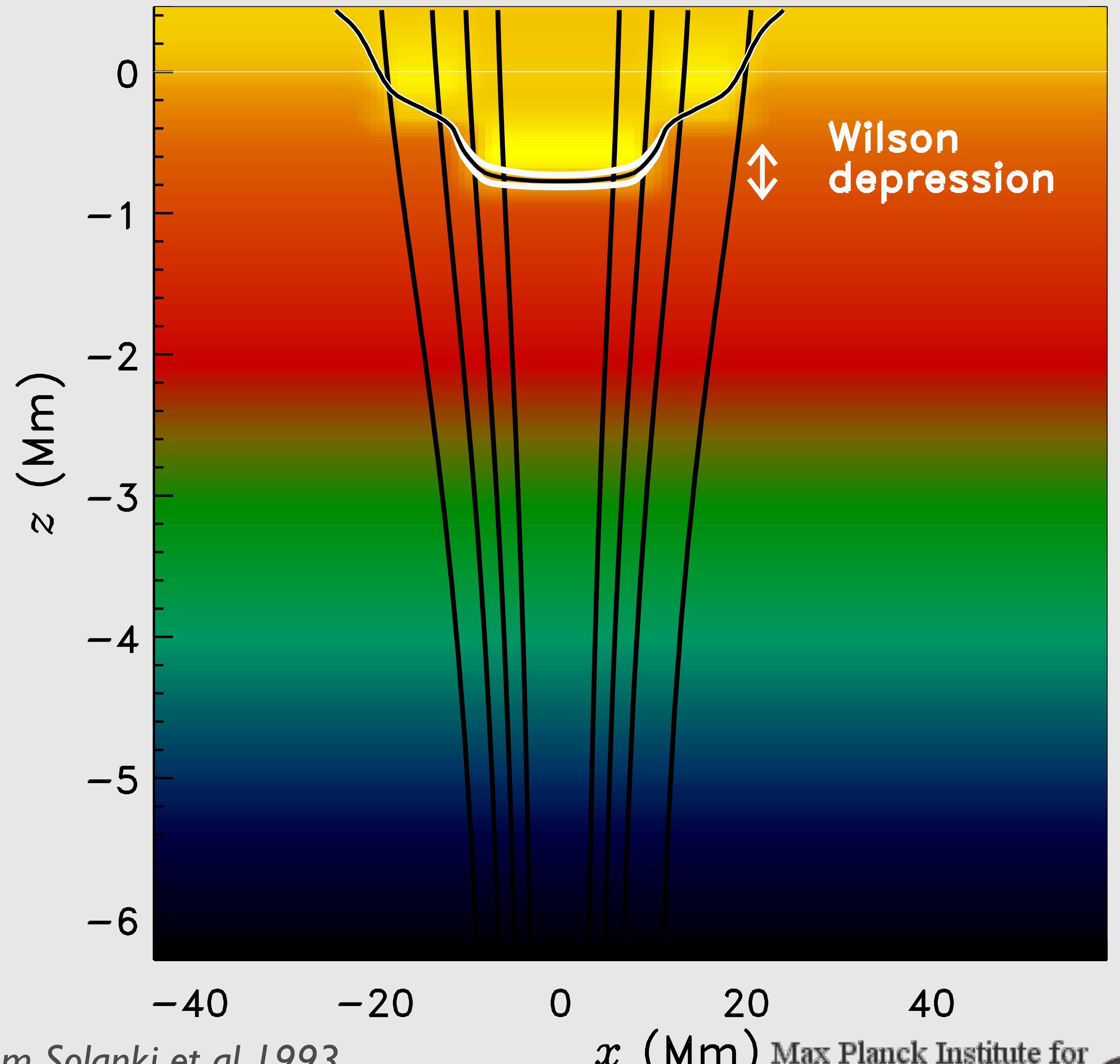


What about other perturbations?

Wilson depression & magnetic field perturbations



WD +/-50km Solanki et al 1993

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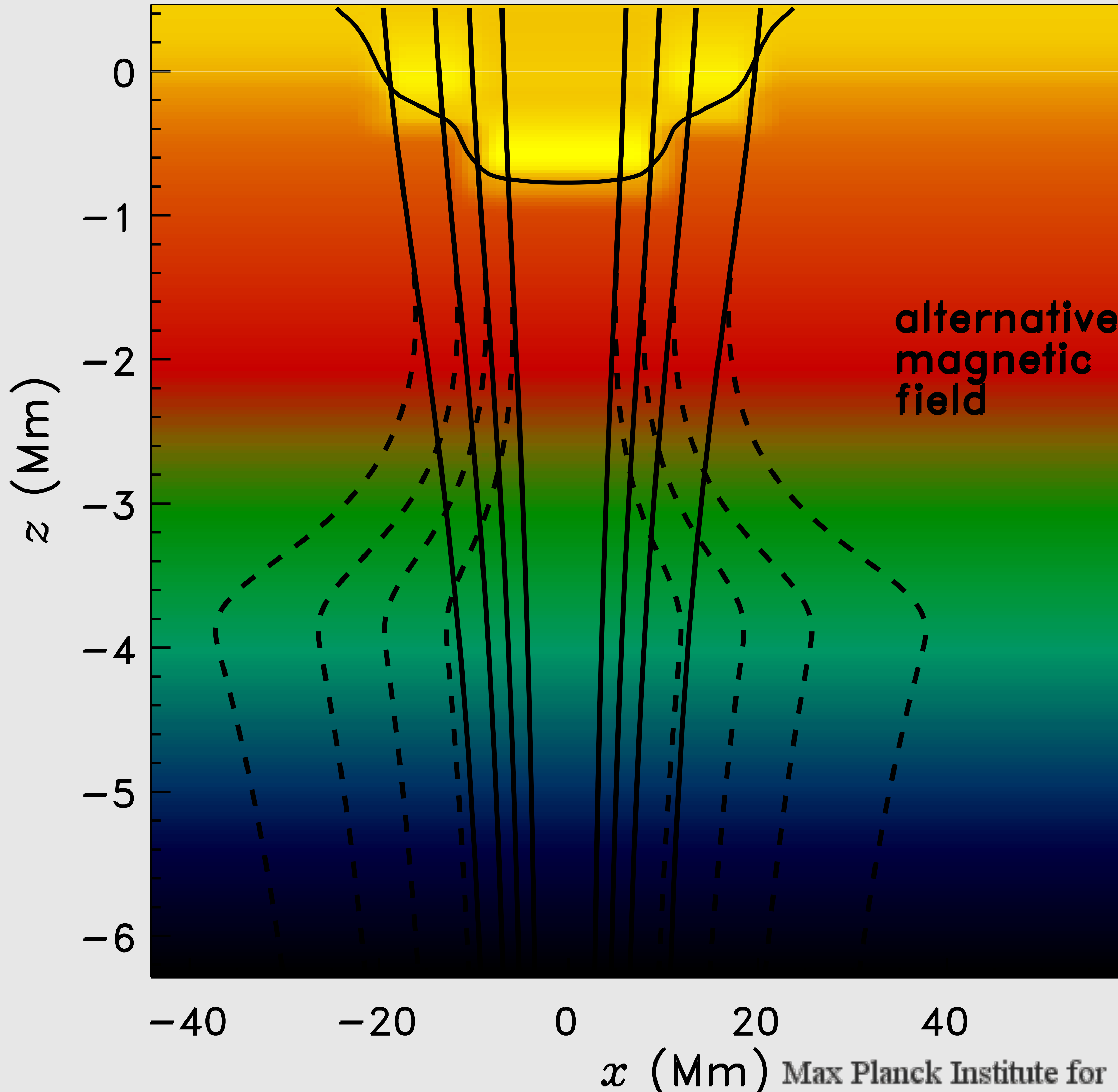
Wilson depression & magnetic field perturbations



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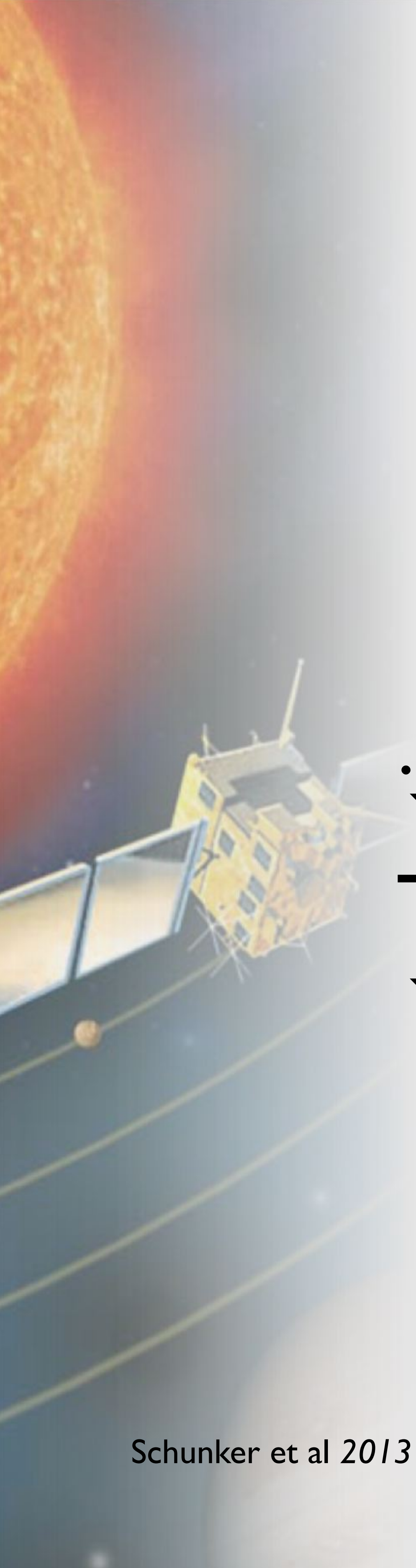


Travel-time shifts

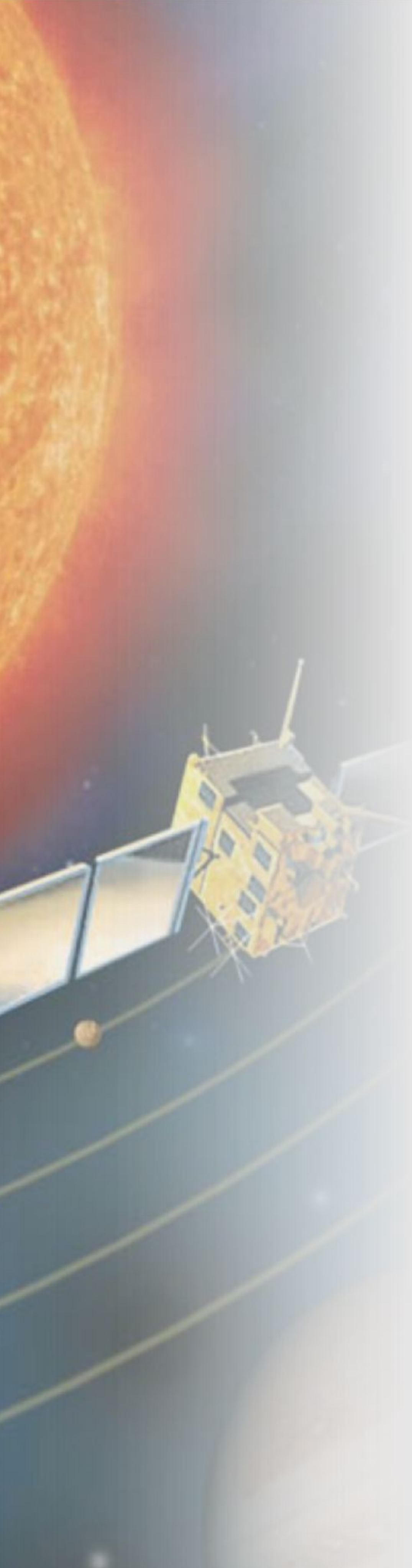
with respect to travel-time shifts due to the reference sunspot model

wave packet radial order

perturbation

	f	p1	p2
Deep Wilson depression -50 km	+0.5 s	-2.2 s	-3.4 s
Shallow Wilson depression +50 km	-0.3 s	+1.9 s	+2.8 s
Magnetic field fanning out below 1Mm	-2.5 s	-2.8 s	-3.4 s
Obs. Noise level	3.7s	3.5s	1.6s

Schunker et al *2013*



Validation of SLiM

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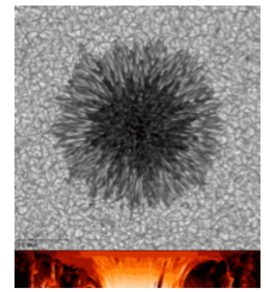
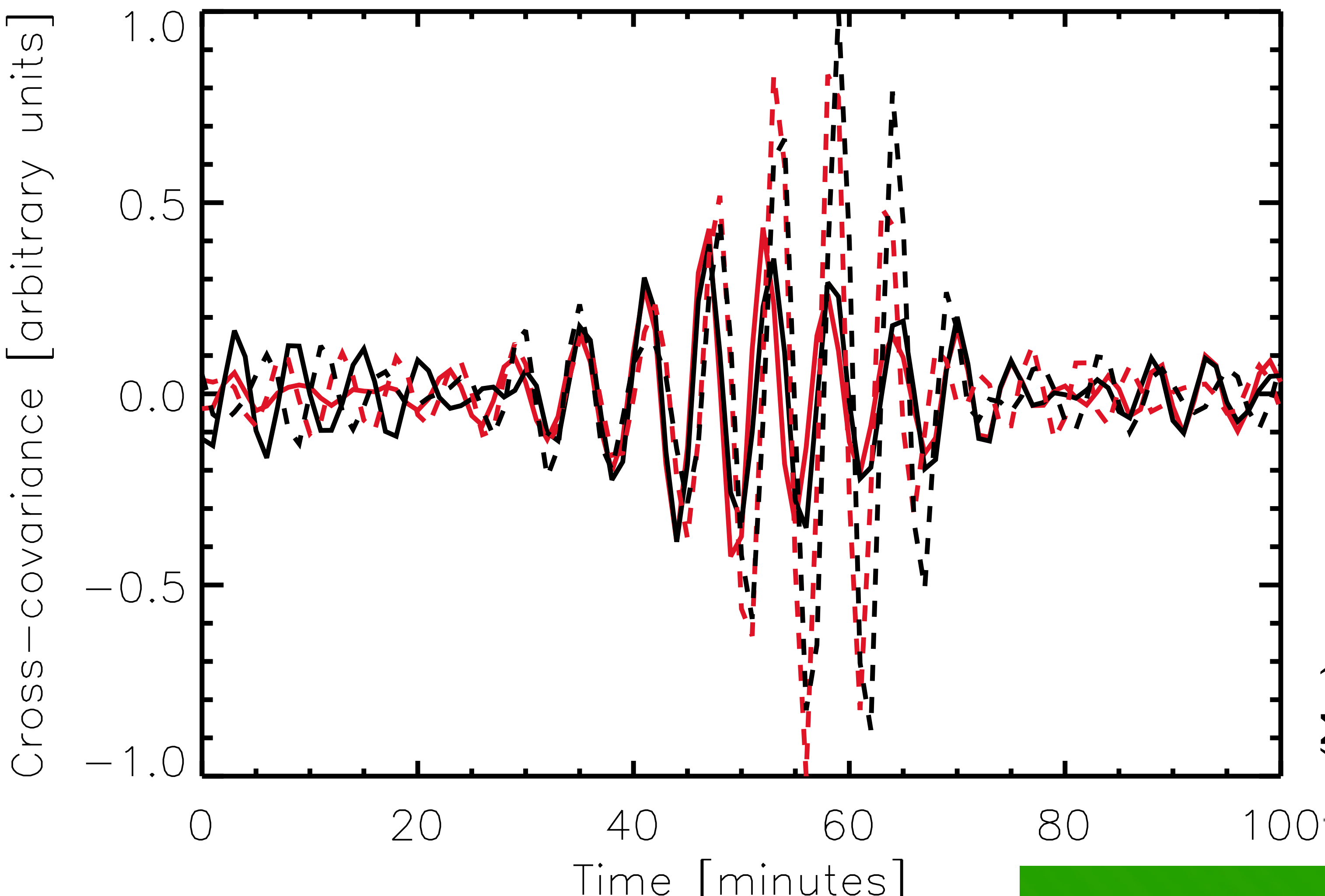
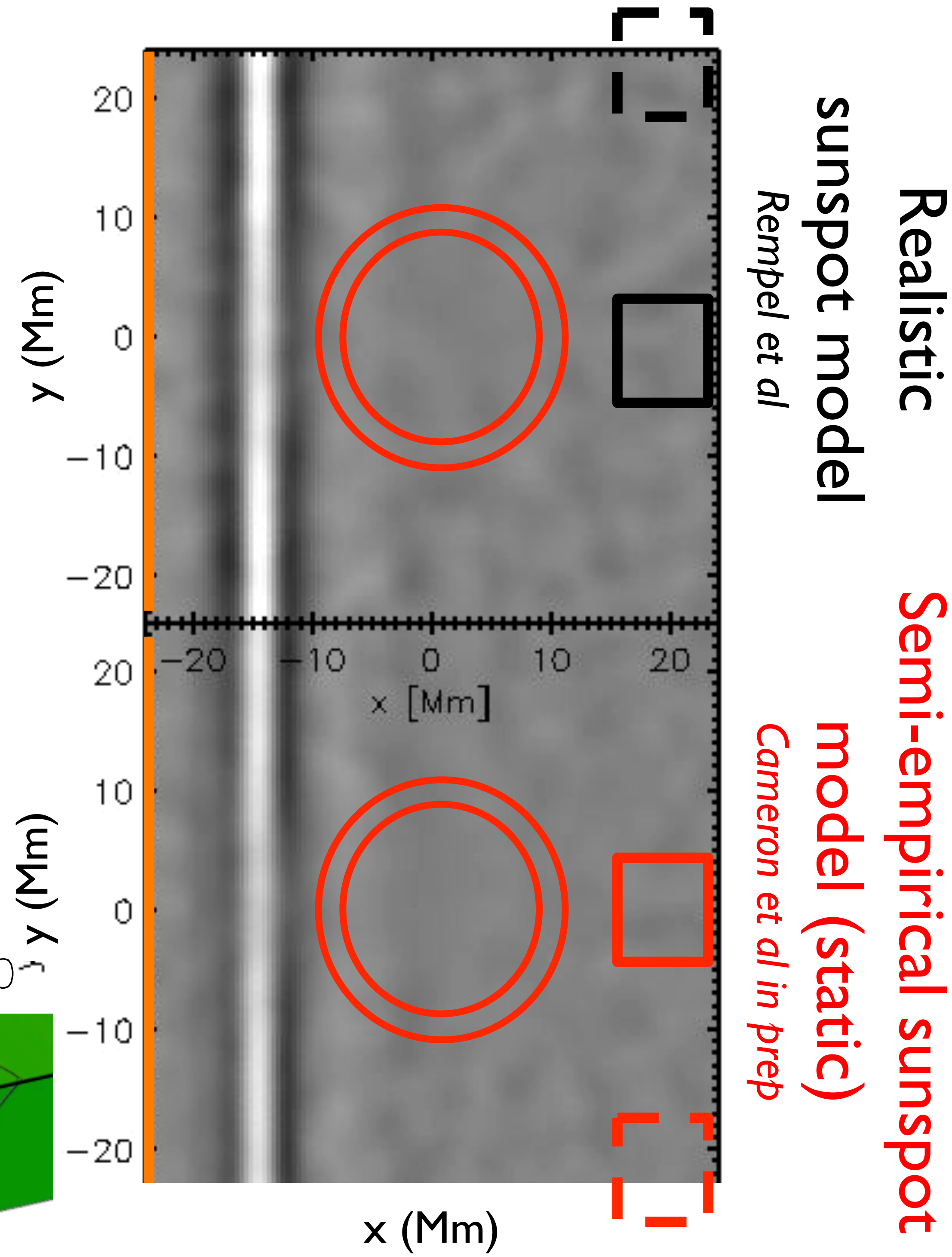
Validation of linearised simulations

24 hours
p1 modes

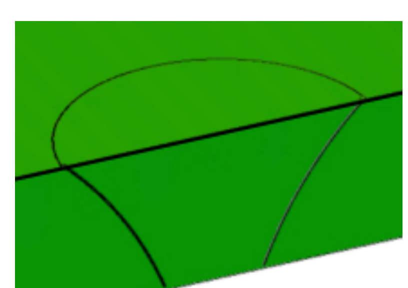




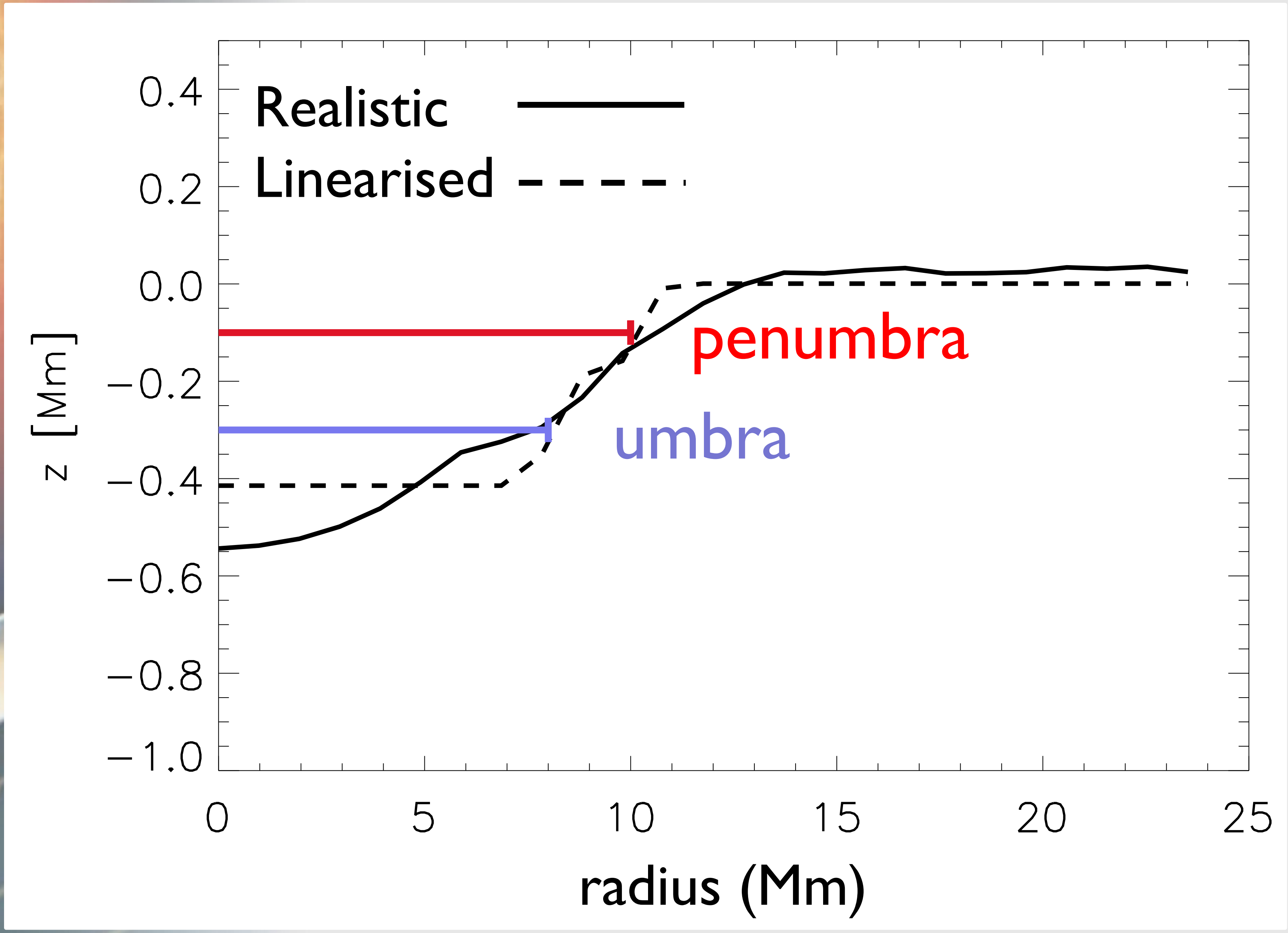
cross-covariance of a line



Cameron, Schunker, Birch & Yang in prep



Parameter space study



Cameron, Schunker, Birch & Yang in prep

Radii
- penumbra
  8 to 14 Mm
- umbra
  2 Mm smaller

Wilson depression
450km to 600km

Constrain surface properties – large perturbations

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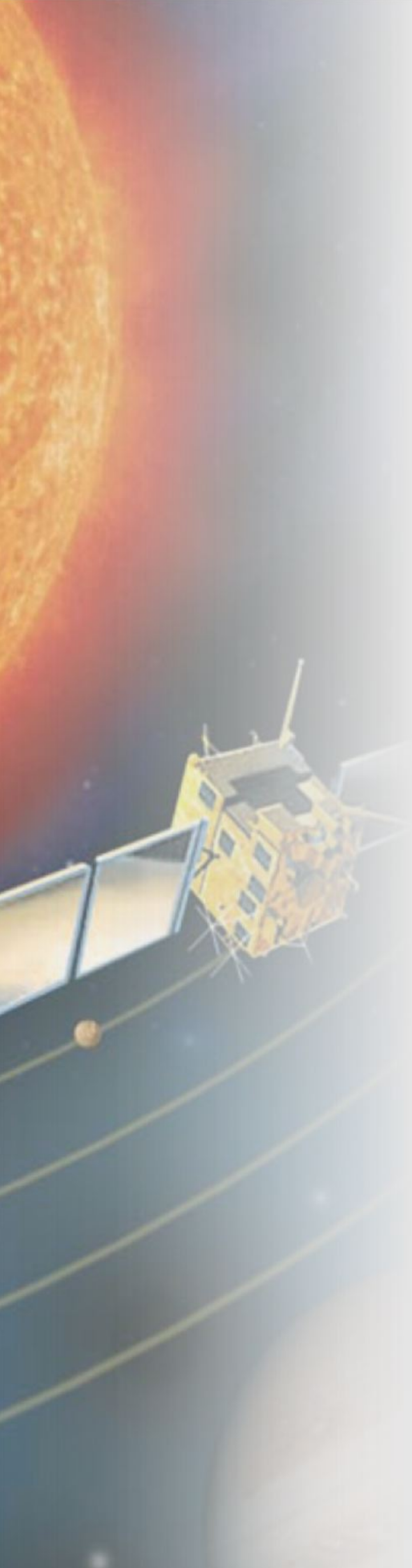

Develop new diagnostics

Cross-correlation of a line (wave-packet) *Gizon et al 2009*

Other quantities

Amplitude, phase shifts, geometry

Combine all diagnostics

Average over many sunspots

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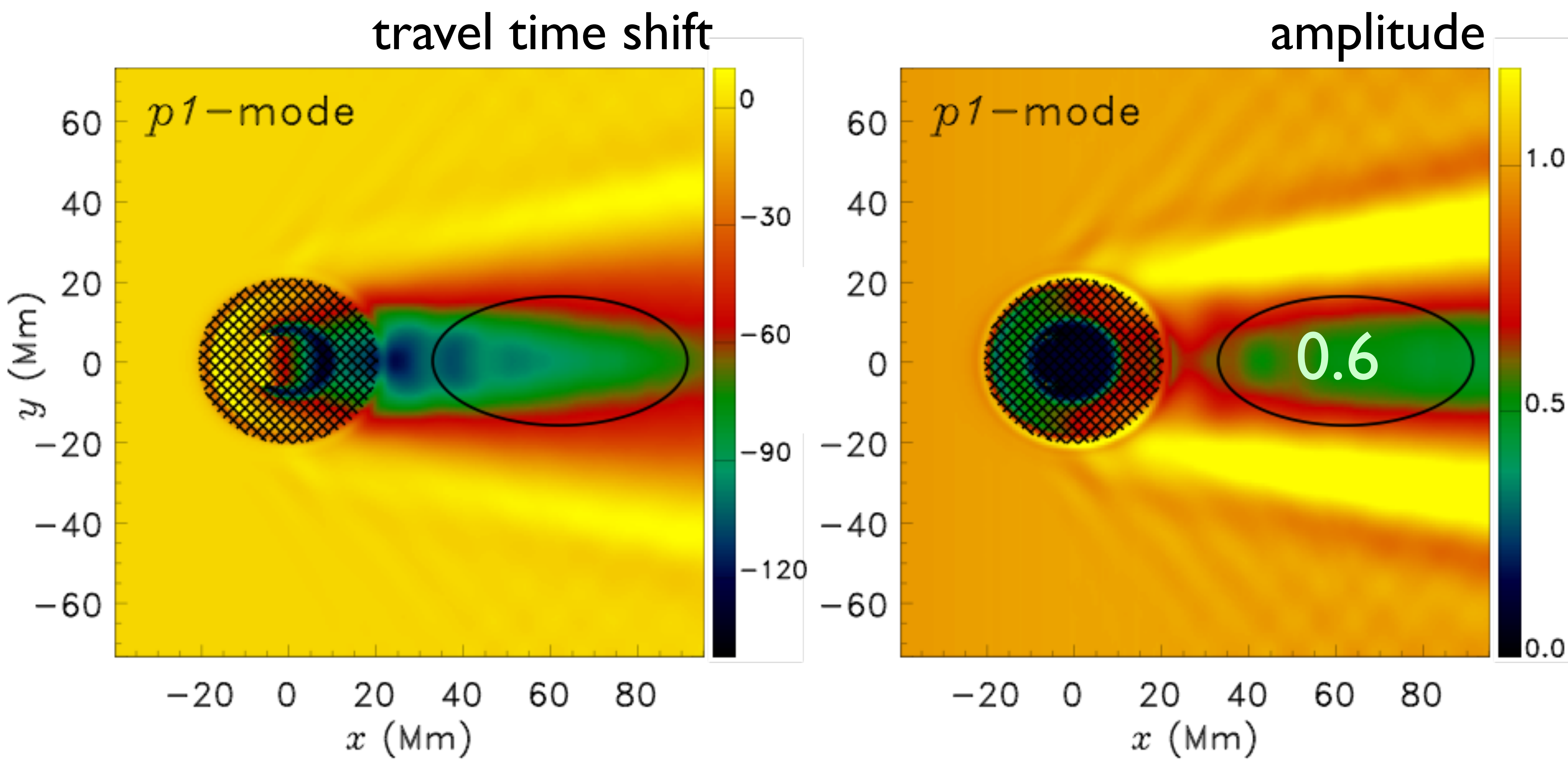
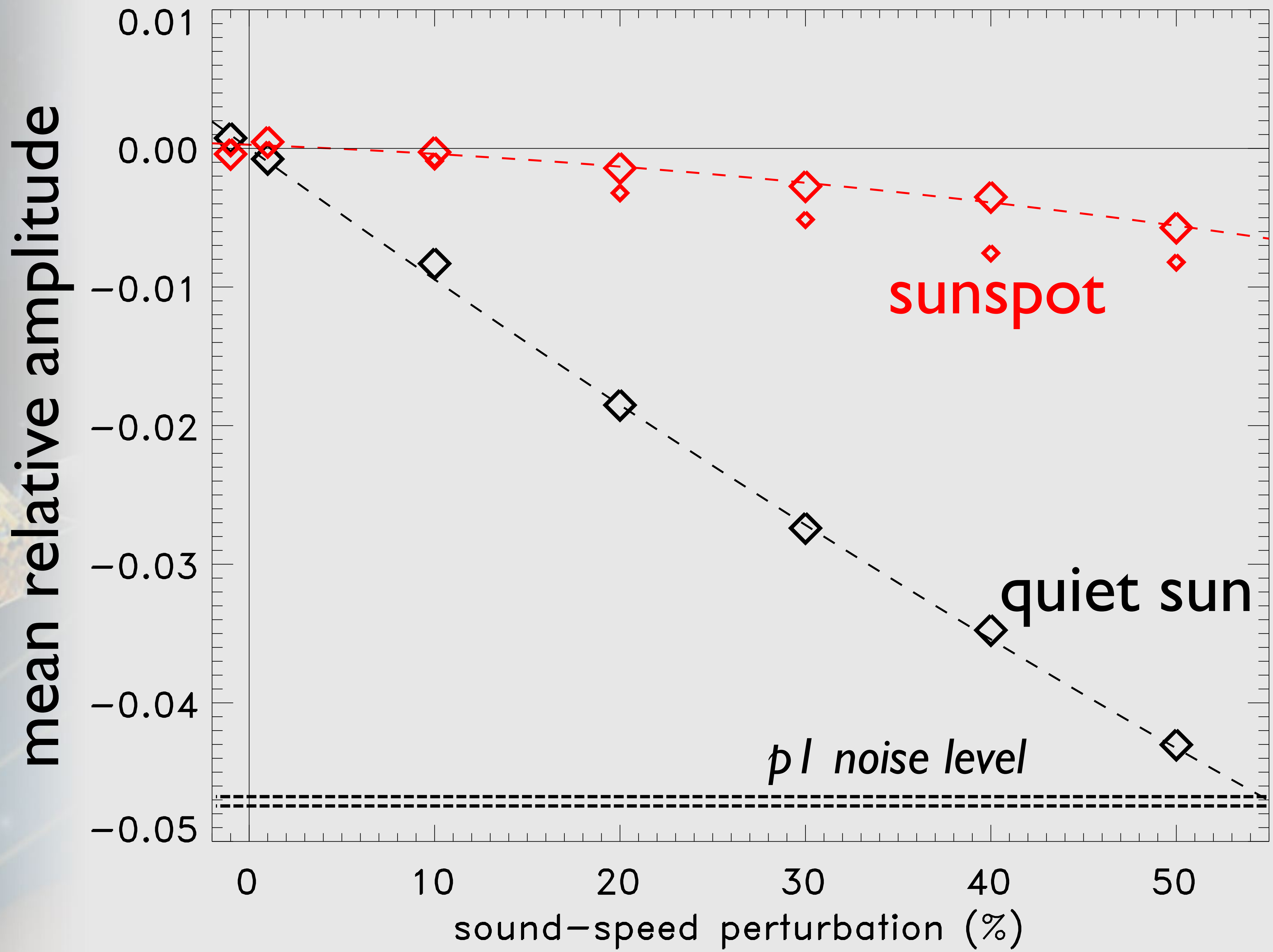
Amplitude

$$F(x,y,\tau) = \frac{\int \tilde{v}_z(x,y,t)v_z(x,t-\tau)dt}{\int |v_{z\mathrm{QS}}(x,t)|^2 dt}$$

Liang, Gizon & Schunker 2013



What about the amplitude sensitivity?



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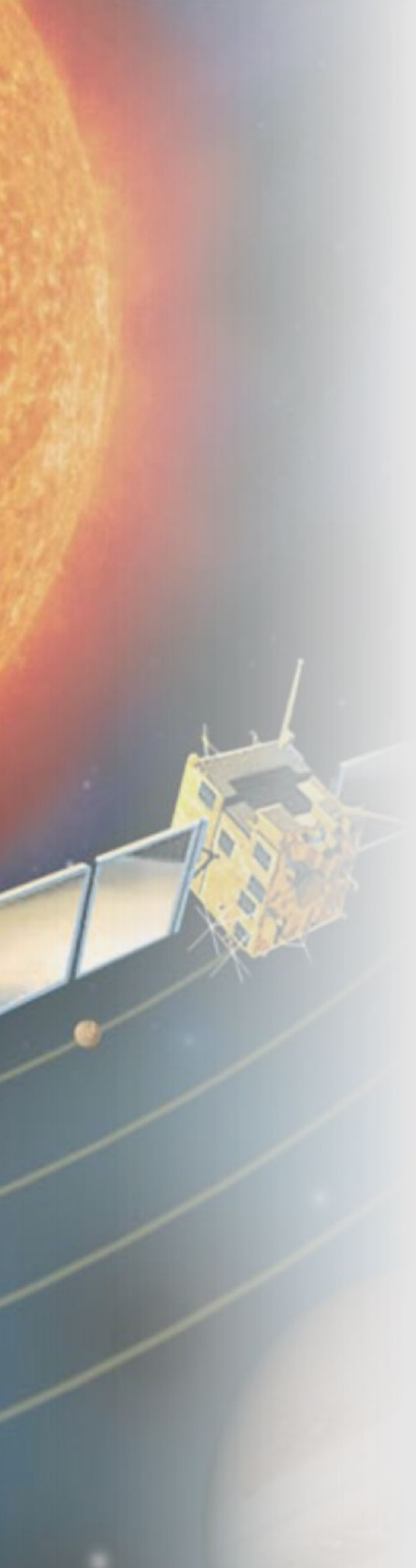

New methods of interpretation

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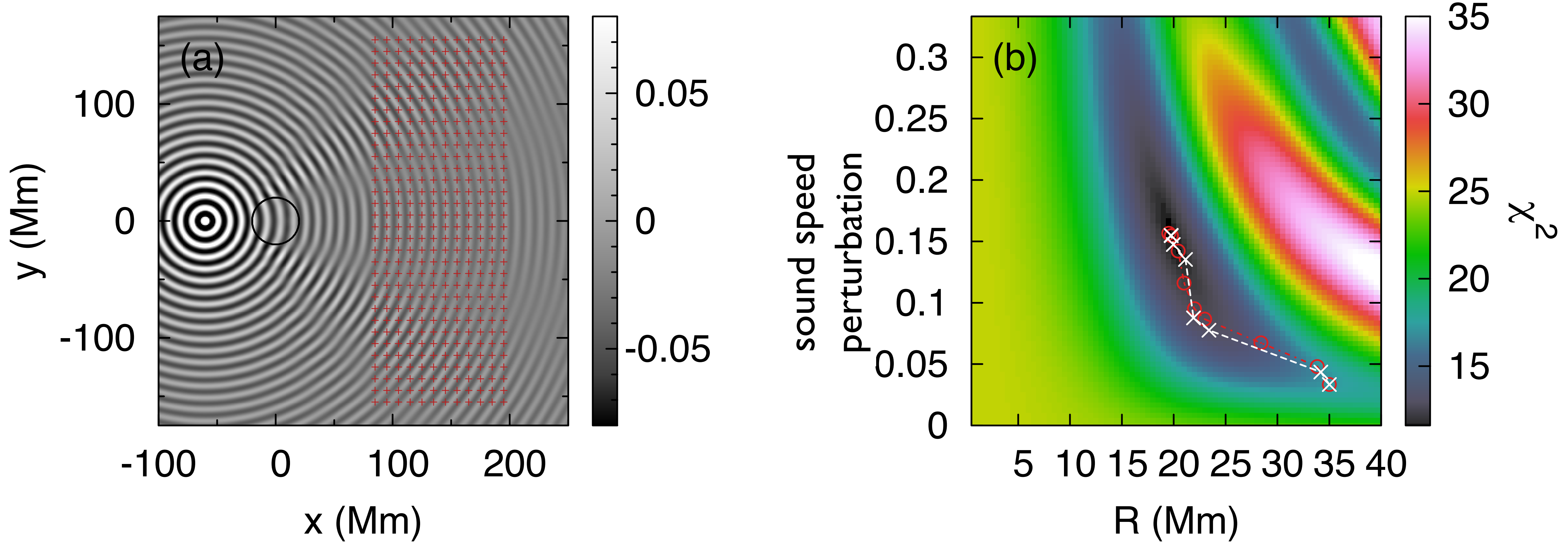
Assessing the adjoint method

Hanasoge et al 2011; M.H.Yang et al. in prep

$$\chi = \int \mathrm{d}t \left[\psi(\mathbf{x_r}, t; R, \delta c) - \psi(\mathbf{x_r}, t; R_0, \delta c_0)\right]^2$$



With 7 days observations p2-modes

radius to within 1Mm

sound speed to within 1%

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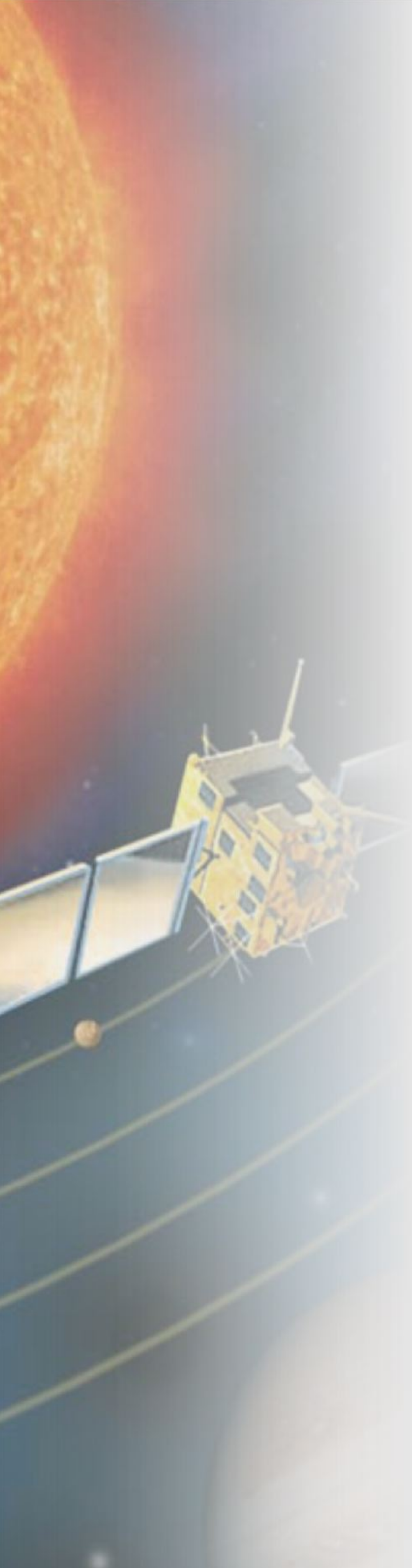

Computational sunspot seismology summary

Understand the physics

Develop new diagnostics

New methods of interpretation

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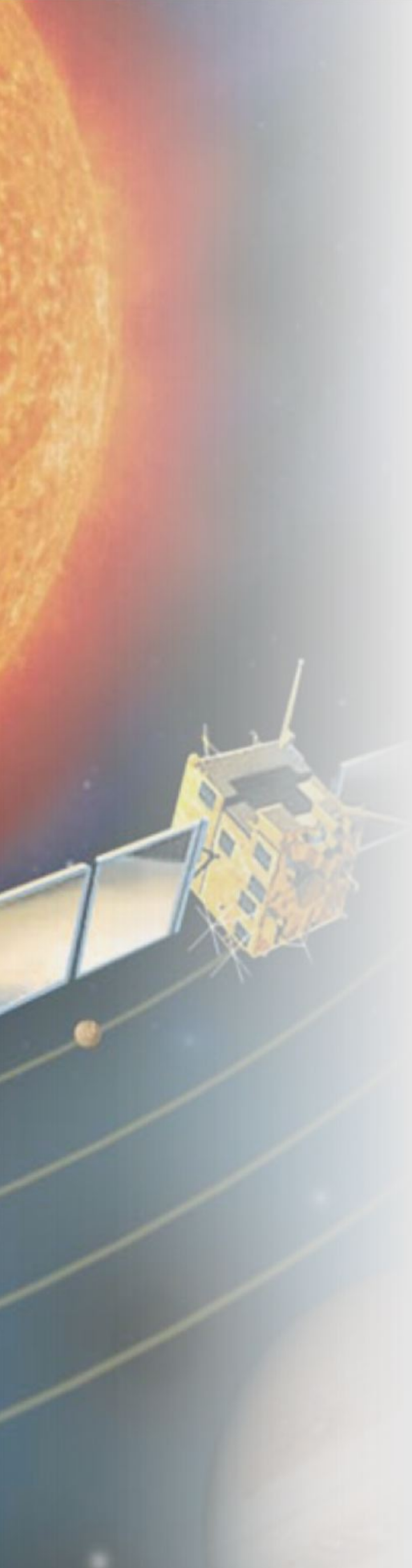

Observational challenges

Computational sunspot seismology

Emerging sunspot regions

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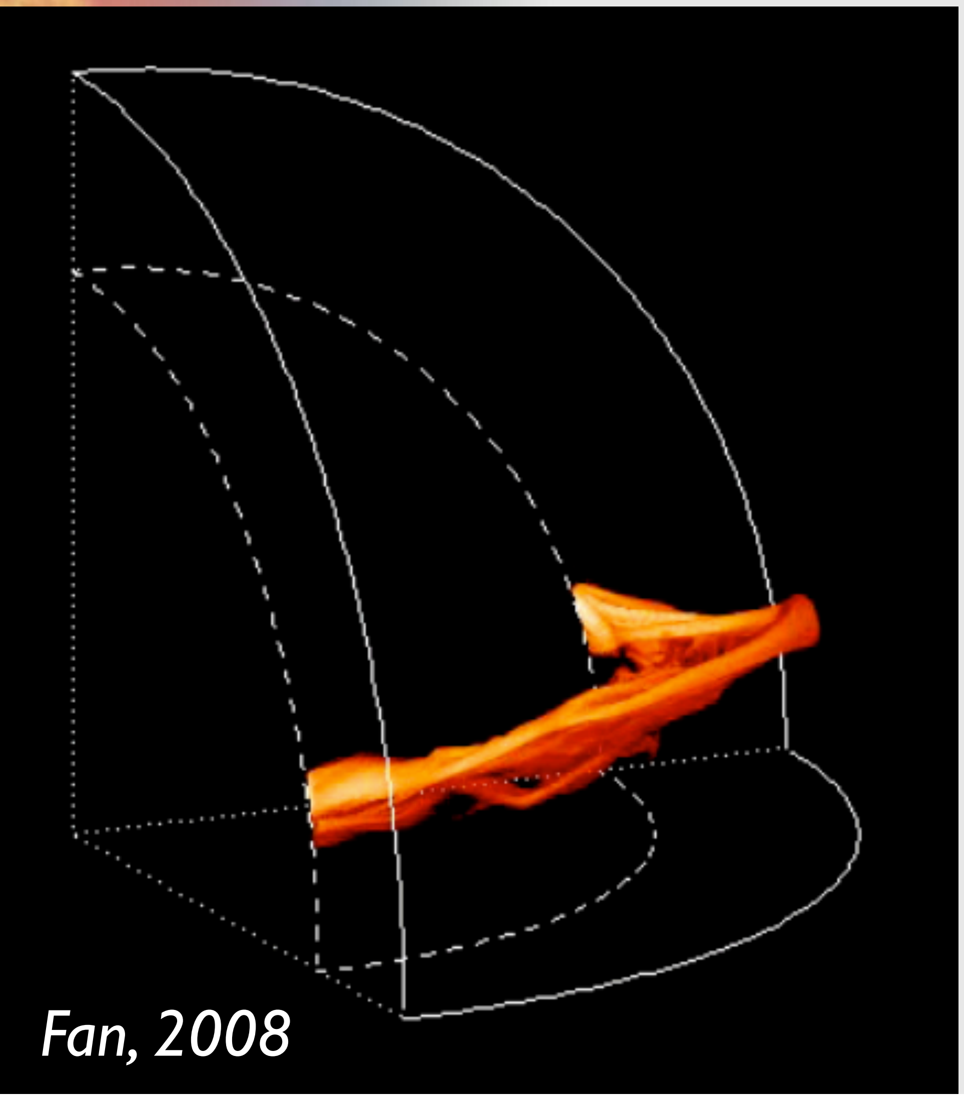
How do sunspots emerge?

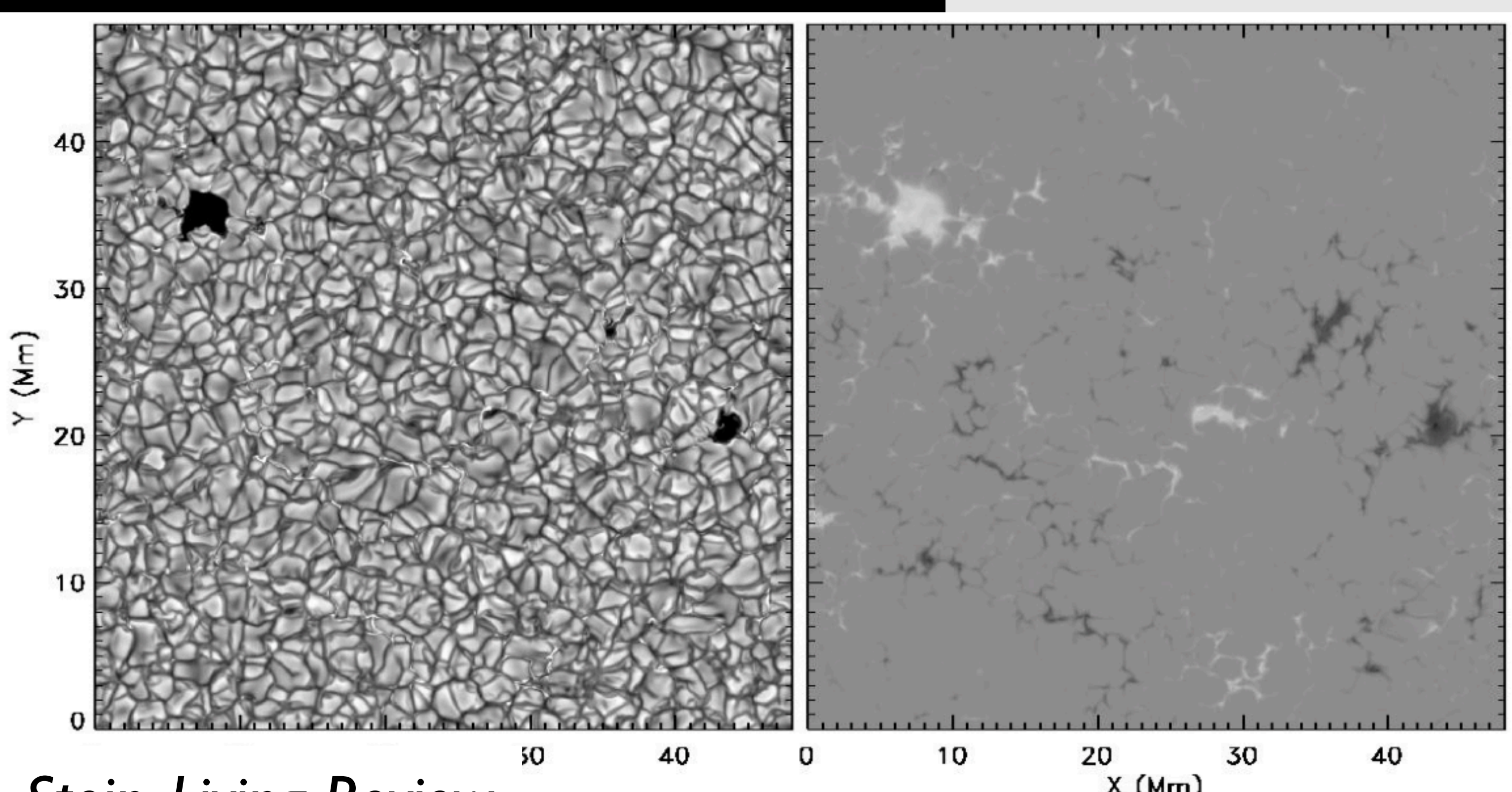


Fan, 2008

1. Rising flux tube

2. Conglomeration of near surface magnetic field

Near-surface shear layer? Magneto-convection?



Stein, Living Review

Helioseismology needs ~100 Active Regions

Birch et al. 2010

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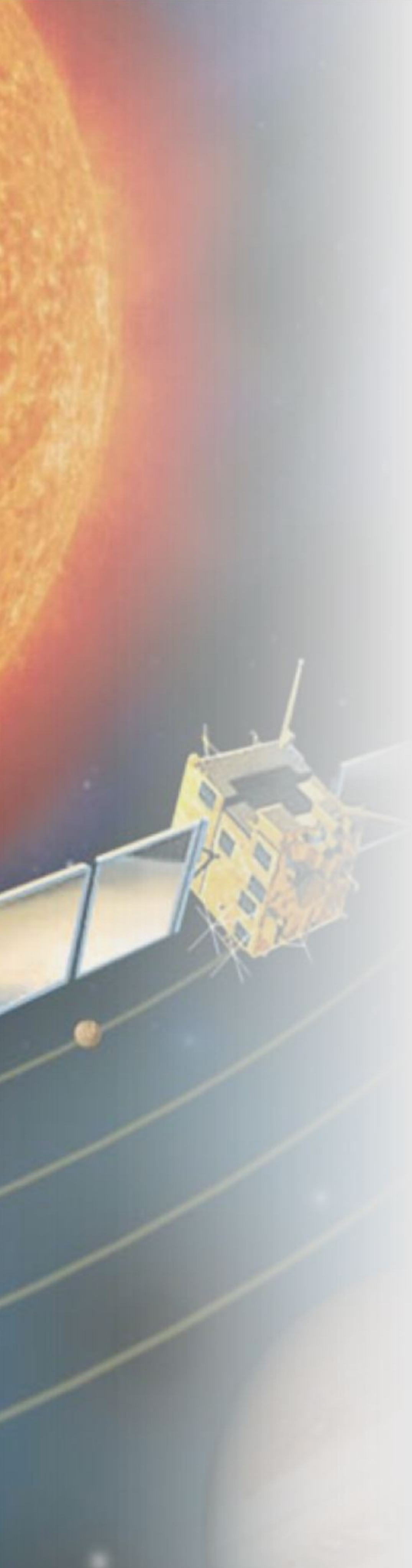
MPS



Previous GONG survey

Paper I, Data and Target Selection, Leka et al 2013
Paper II, Average Emergence Properties, Birch et al 2013
Paper III, Statistical Analysis, Barnes et al 2013

- GONG Dopplergrams, MDI magnetograms
- 100 Emerging Active Regions (EARs) &
  100 control regions (CRs) (2001-2007)
- Emerge within 30 degrees of central meridian
- ~30 hours before emergence
- Up to 20 Mm below the surface
  (no significant flows)

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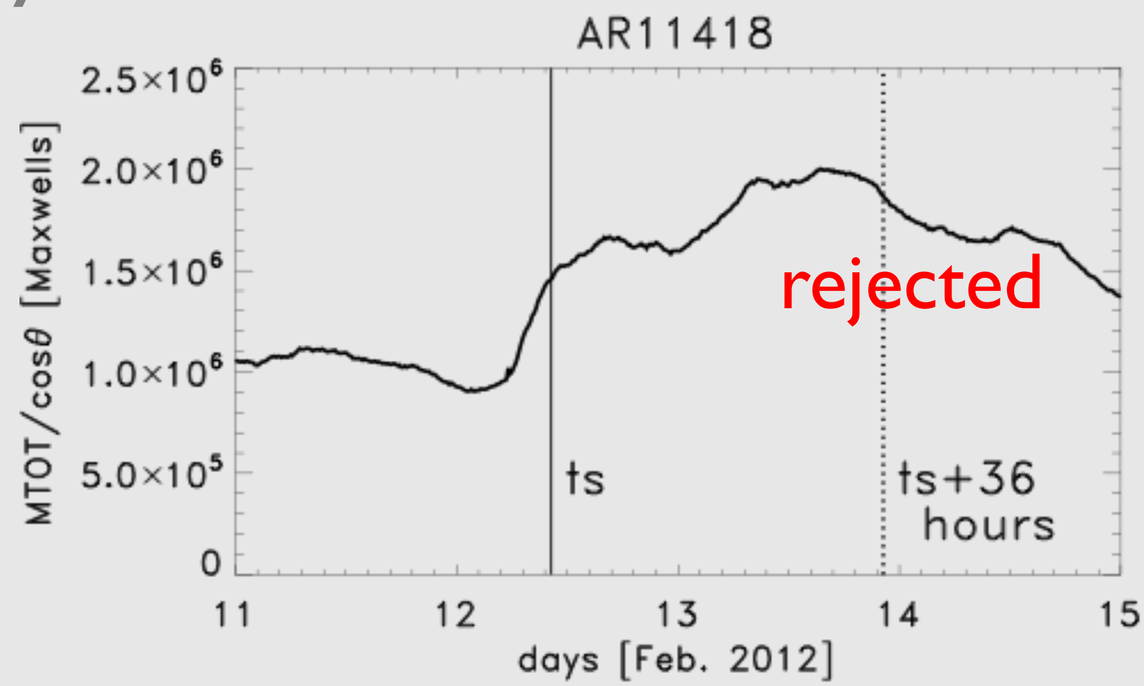
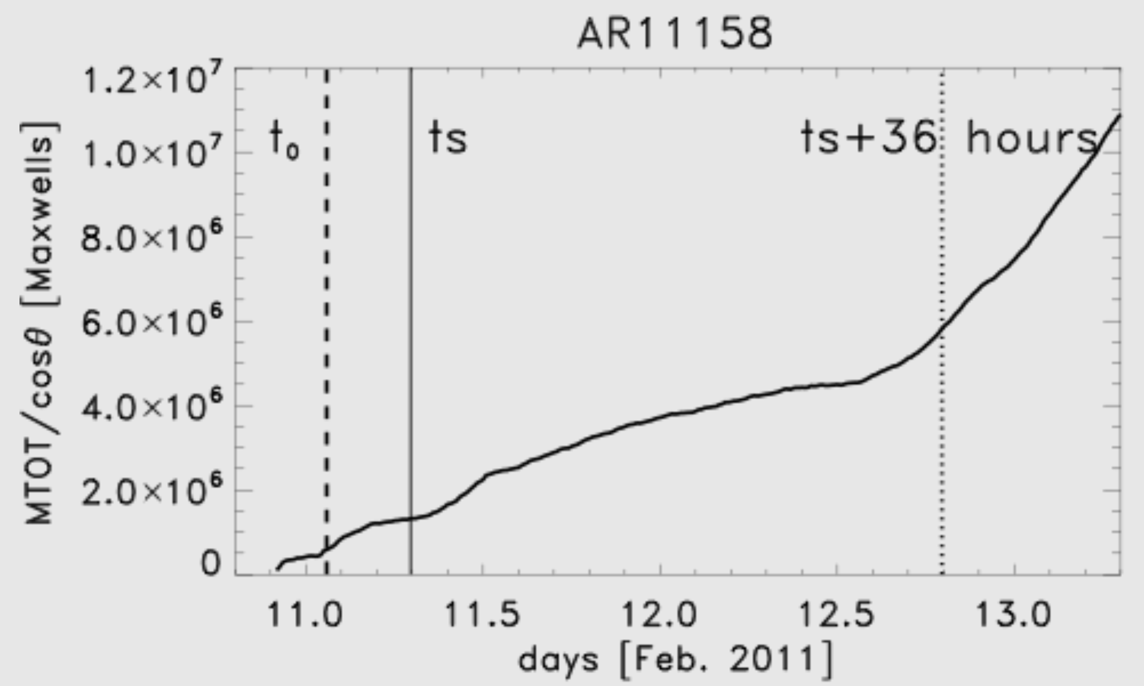
Emerging Sunspot Regions with HMI

- 105 'clean' ESRs identified by NOAA (May 2010 – November 2012, AR11066 - AR11624)
- Emergence time identified as when the flux reaches 10% of the maximum flux after forming a sunspot. (using 'corrected' MTOT keyword in HARPS; cadence of HARP 720 seconds)
- Tracked region up to 7 days pre- and post-emergence 65 degrees from central meridian





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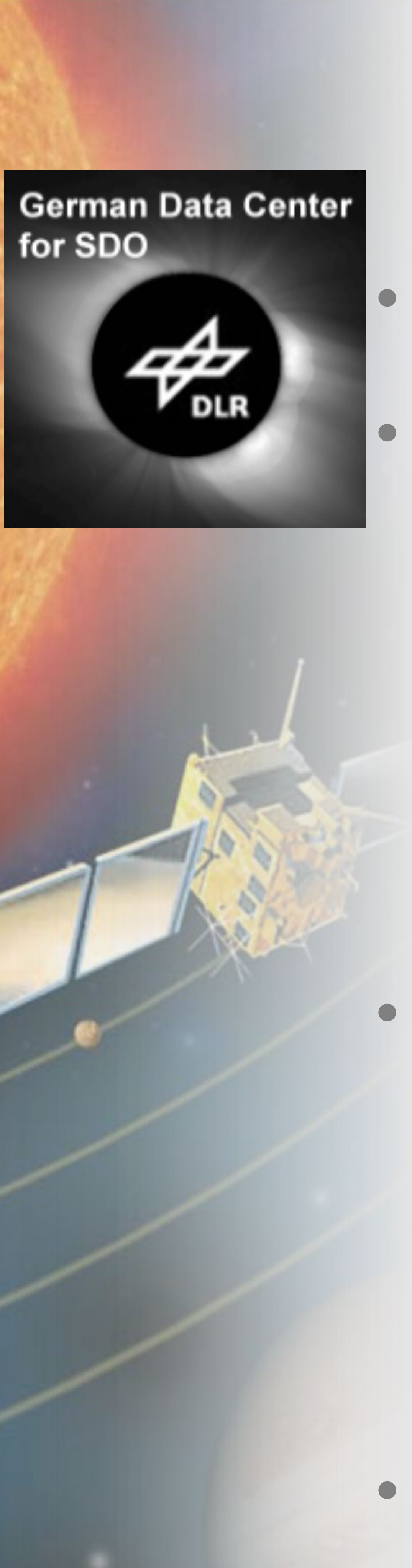
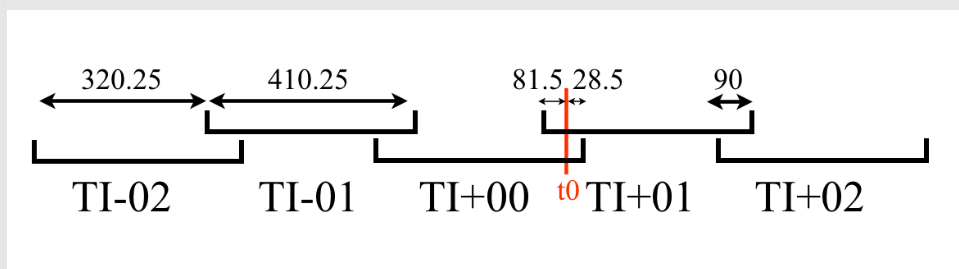
The SDO/HESR catalogue

Schunker, Braun, Birch & Burston in prep



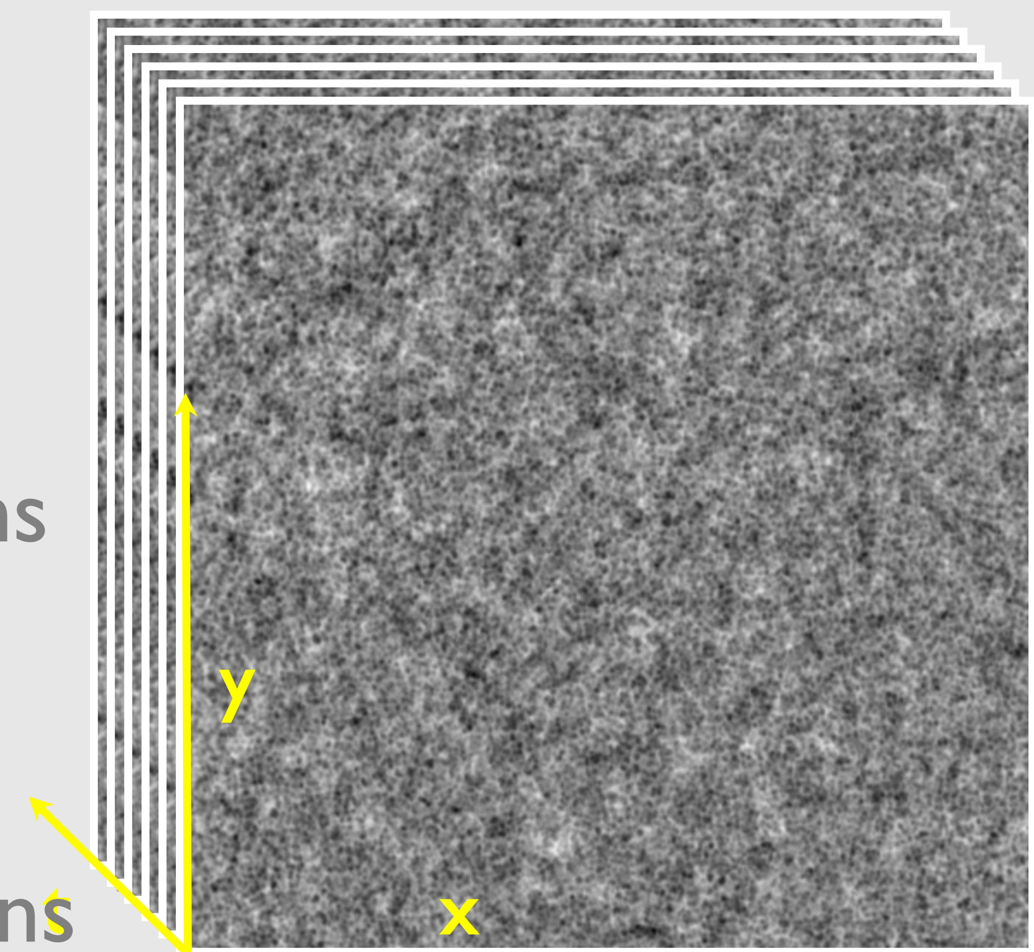
- Computed using The German Data Centre for SDO

- Datacubes tracked at Carrington rotation and mapped
  512x512 pixel, 1.4 Mm/pixel,
  410 min datacubes, overlap 90 mins
  45 second cadence



- Doppler velocity
  Magnetic field (line of sight)
  Averaged magnetograms
  Intensity continuum
  (~14 TB)

- Exactly paired control regions



The SDO/HESR catalogue
– control regions

- Exactly paired latitude, CMD for each ESR separated in time by at least 2 days

- Make sure there are no ARs within 30 degrees at the time of ‘emergence’ and six days before (using HARPS data series)

- No restriction on the absolute magnetic field strength
  -- must not show evidence of emergence
  -- ideally ‘quieter’ than the paired EAR

- No check to see if an AR eventually emerges in the location of the CR!

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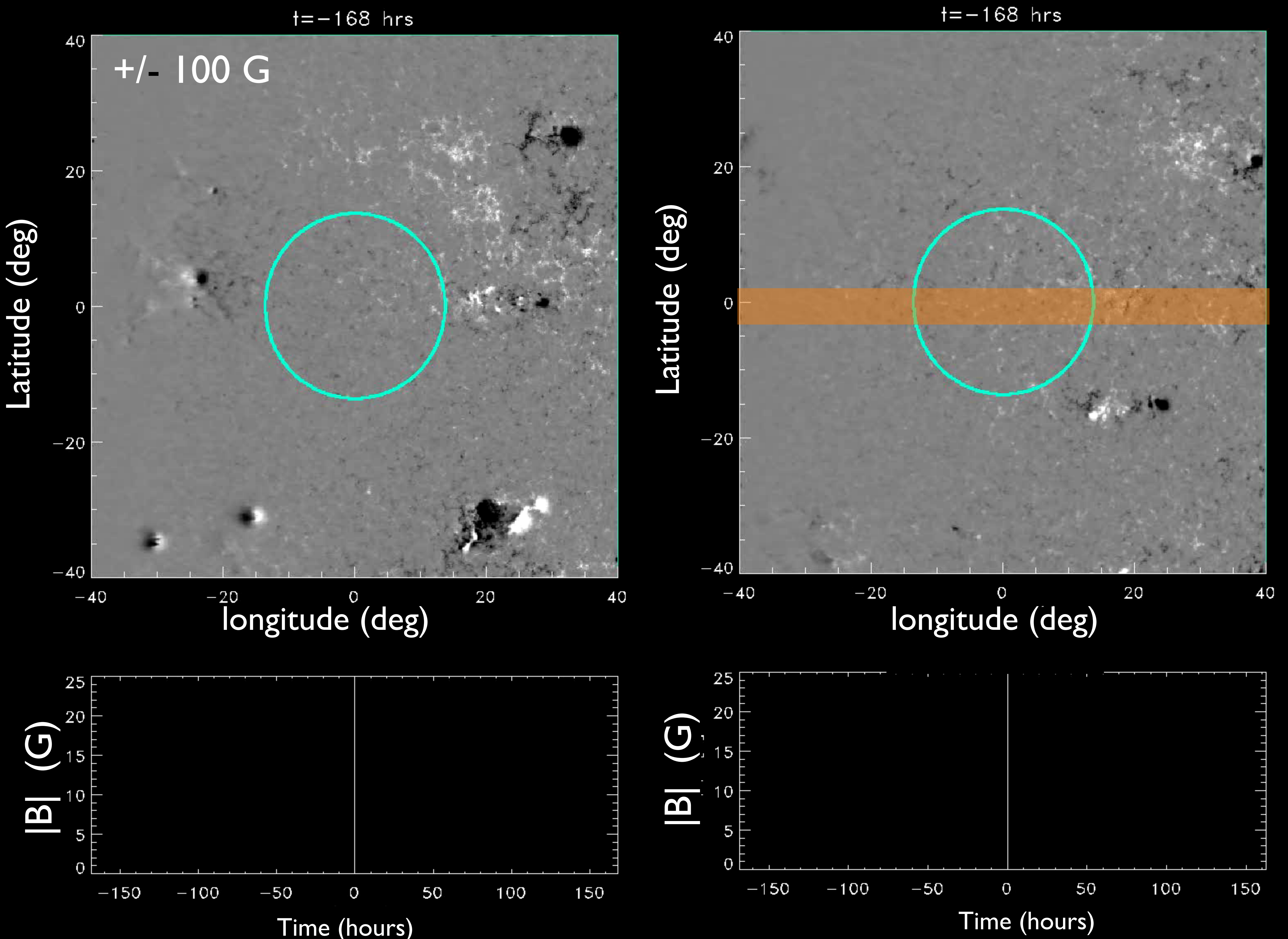
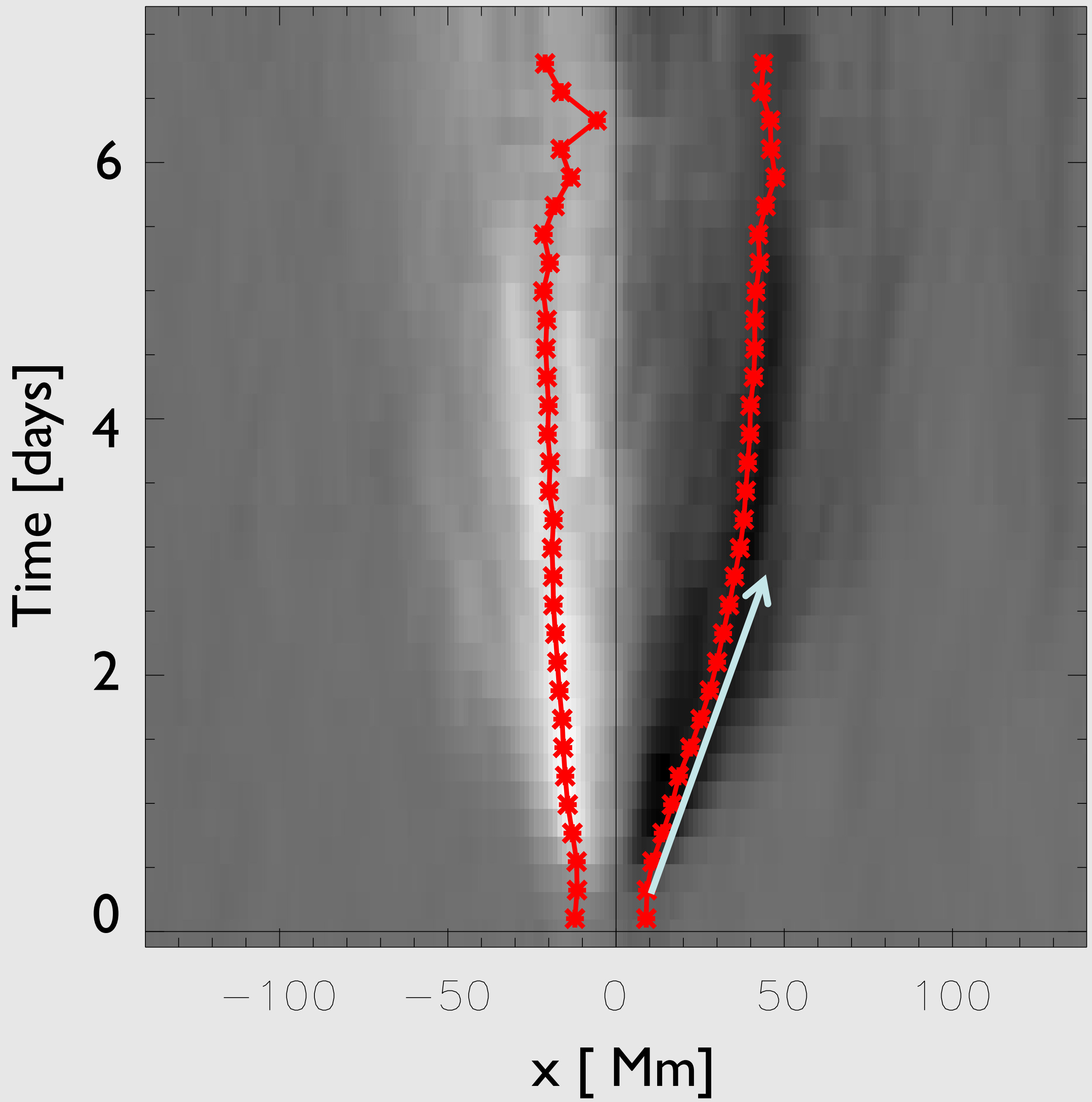


t=−168 hrs
+/- 100 G
Latitude (deg)
longitude (deg)
t=−168 hrs
Latitude (deg)
longitude (deg)
|B| (G)
Time (hours)
|B| (G)
Time (hours)

Average separation speed



Leading polarity = 200-300 m/s

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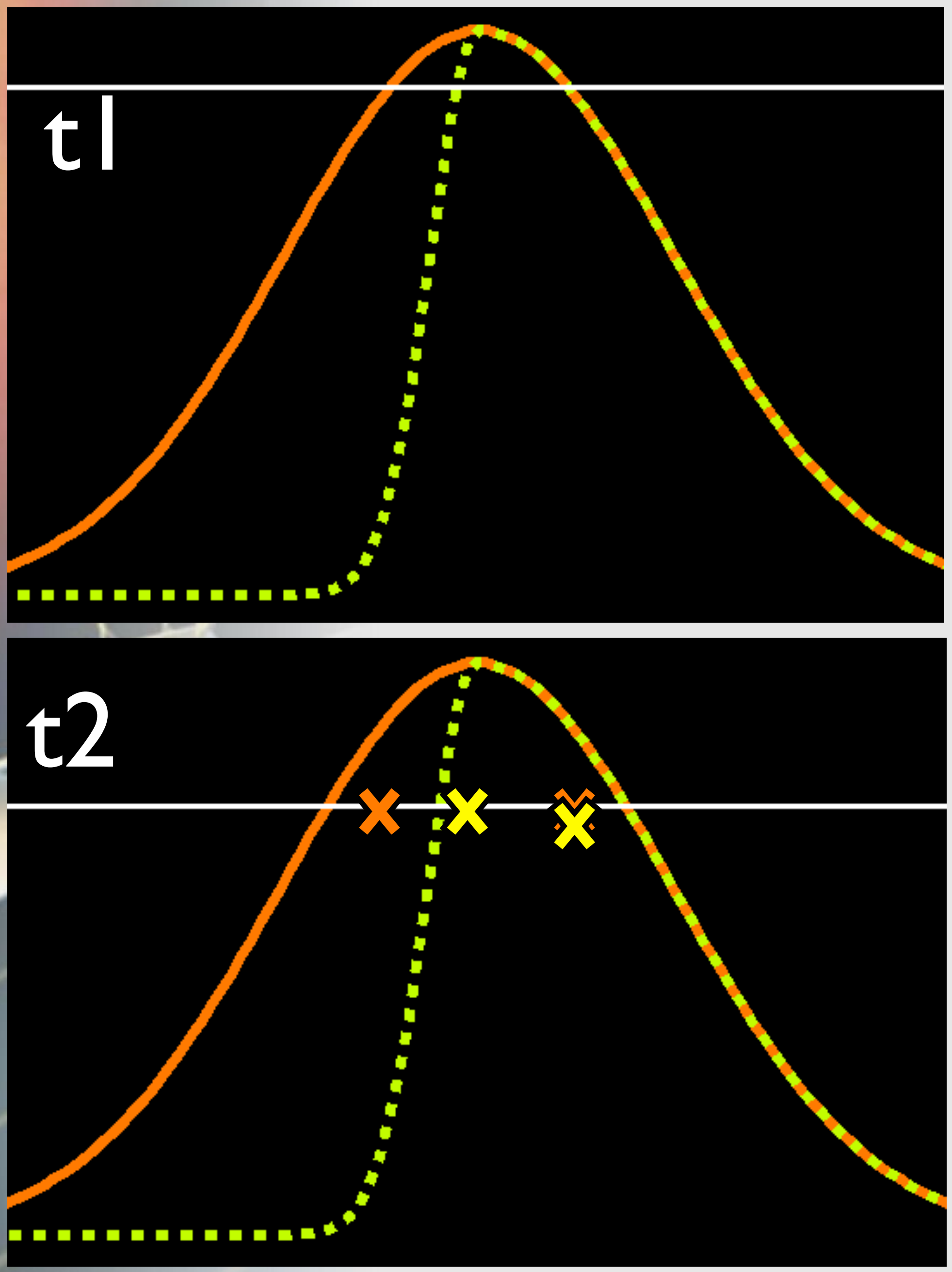
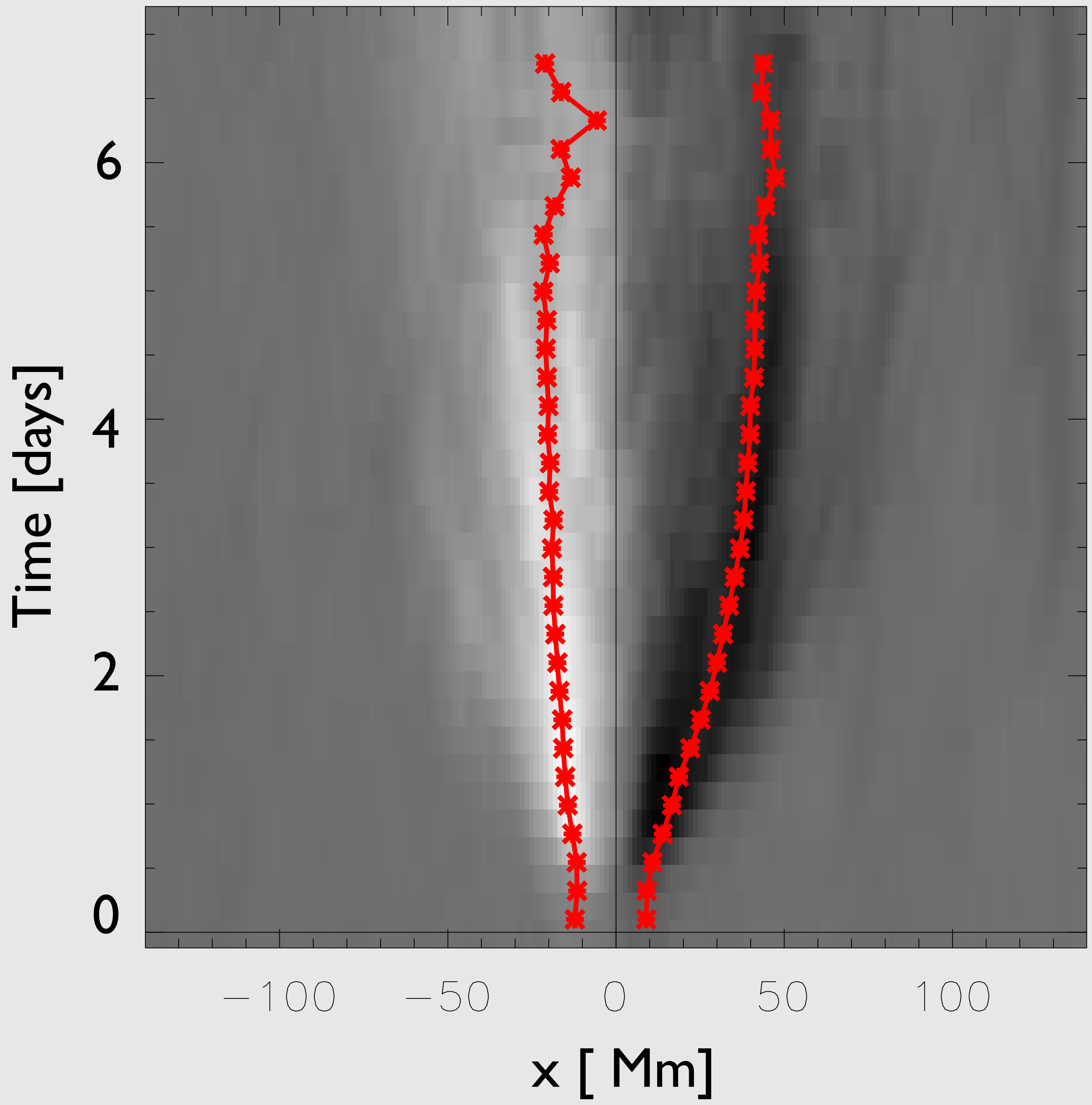
Average separation speed





Gilman & Howard 1984;
D'Silva & Howard 1994;
Caligari et al 1995;Weber et al 2011

Leading polarity = 200-300 m/s

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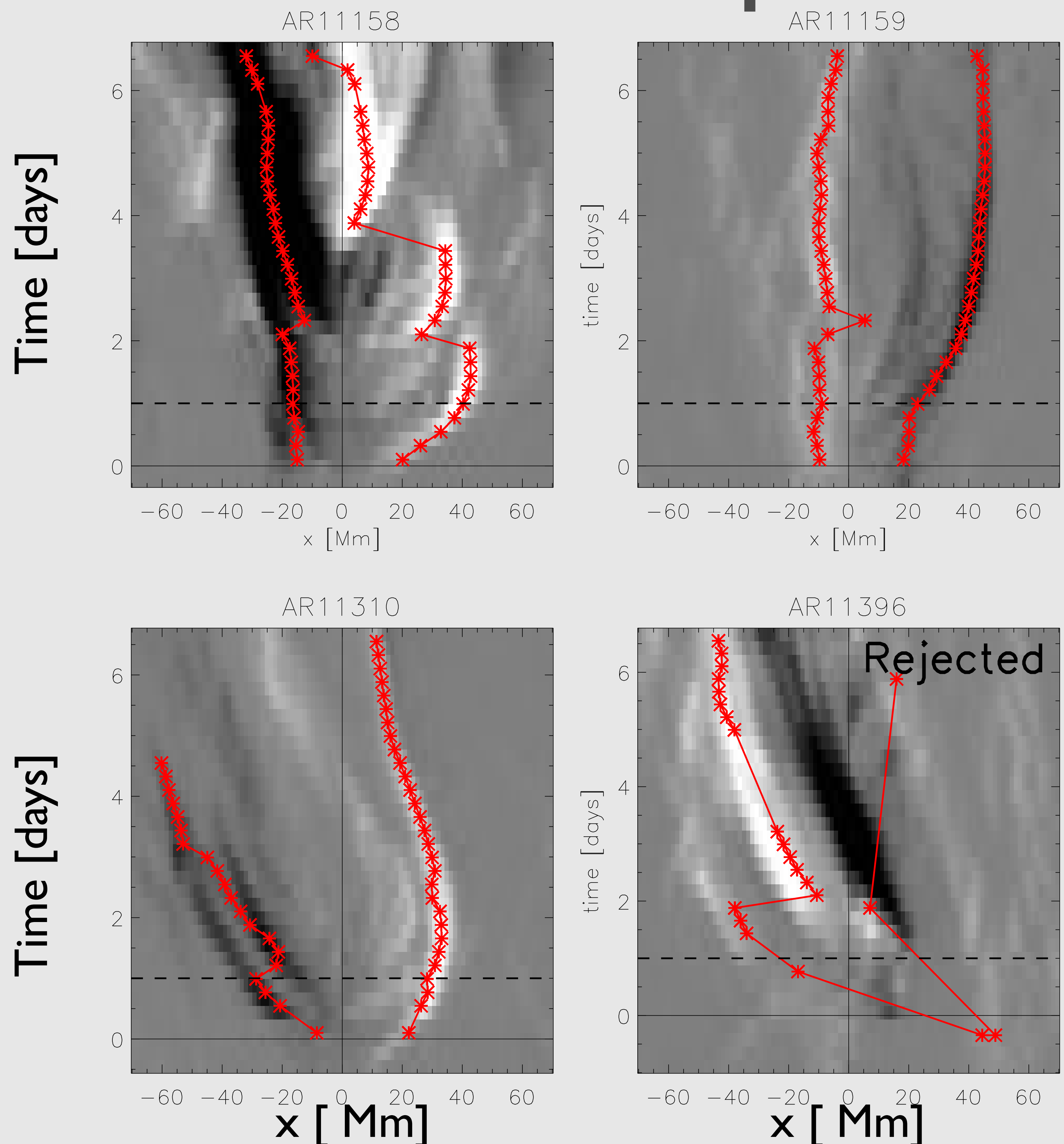
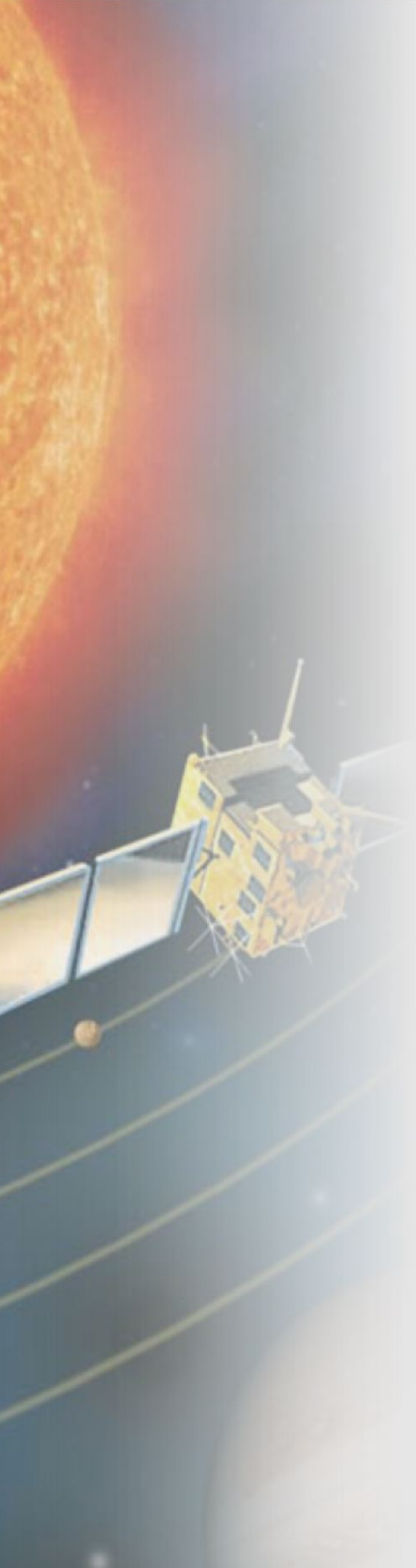
Individual separation speed





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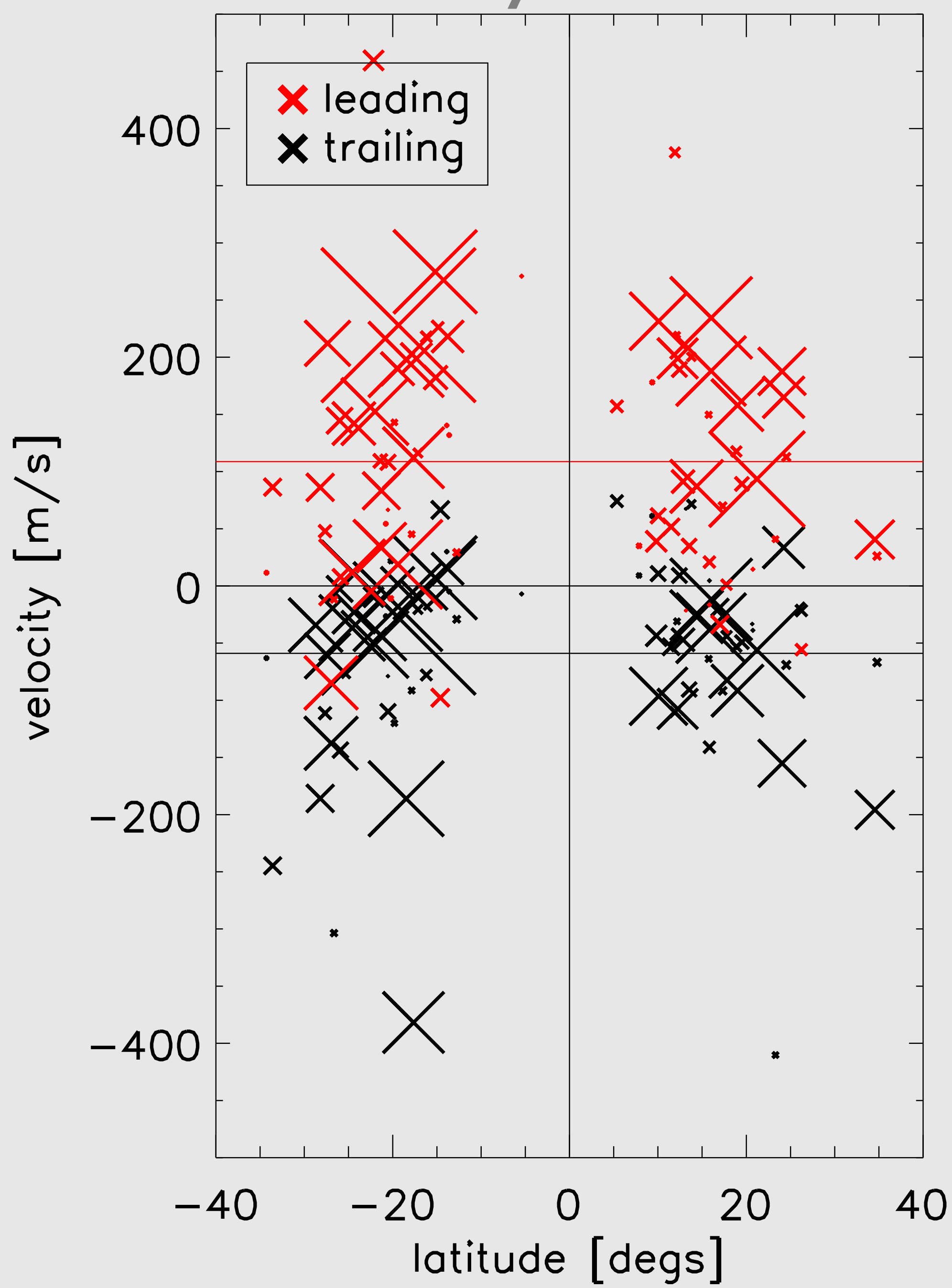
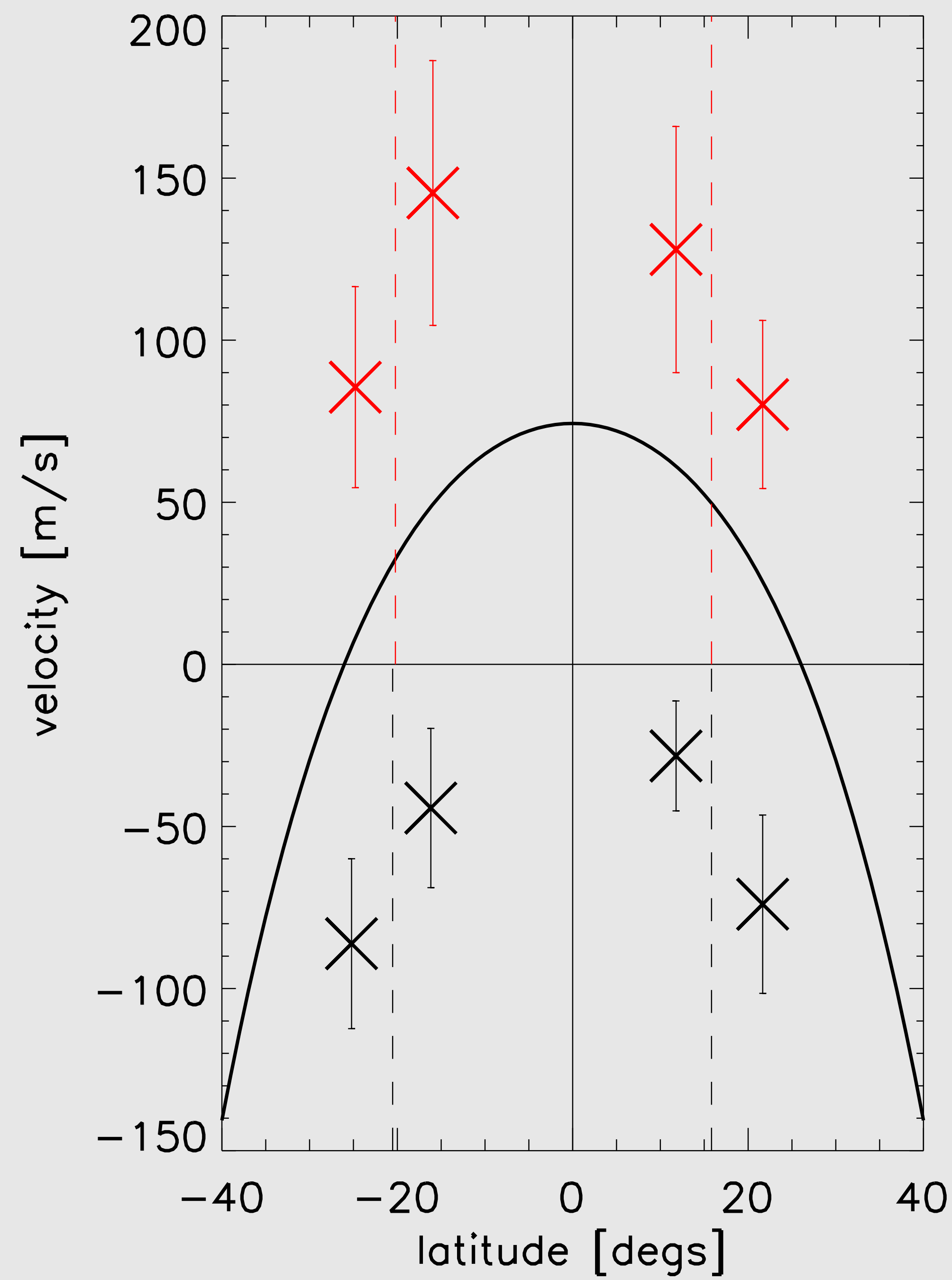
Individual separation speed

First day





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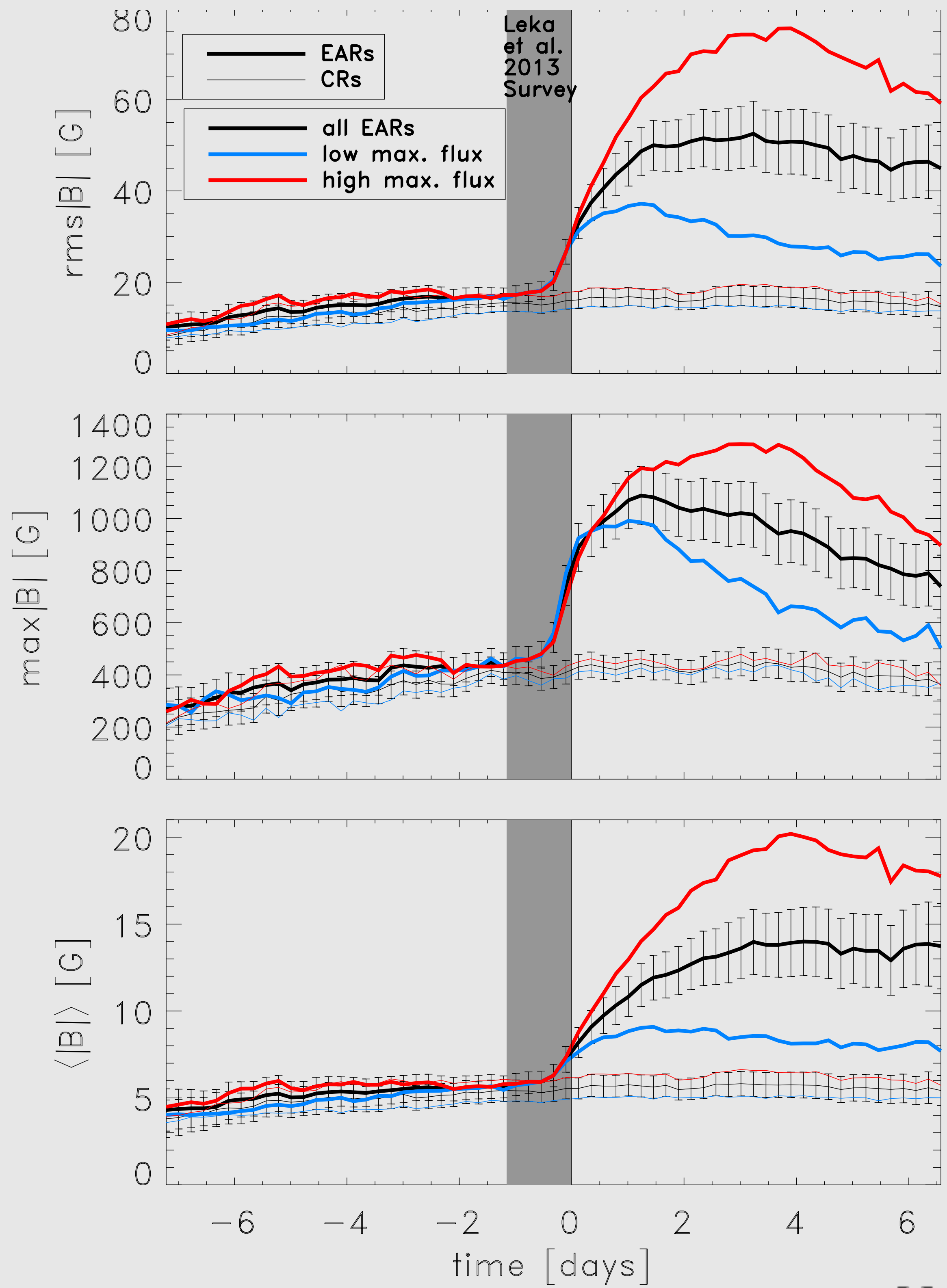
Magnetic Field Evolution



10 degree average

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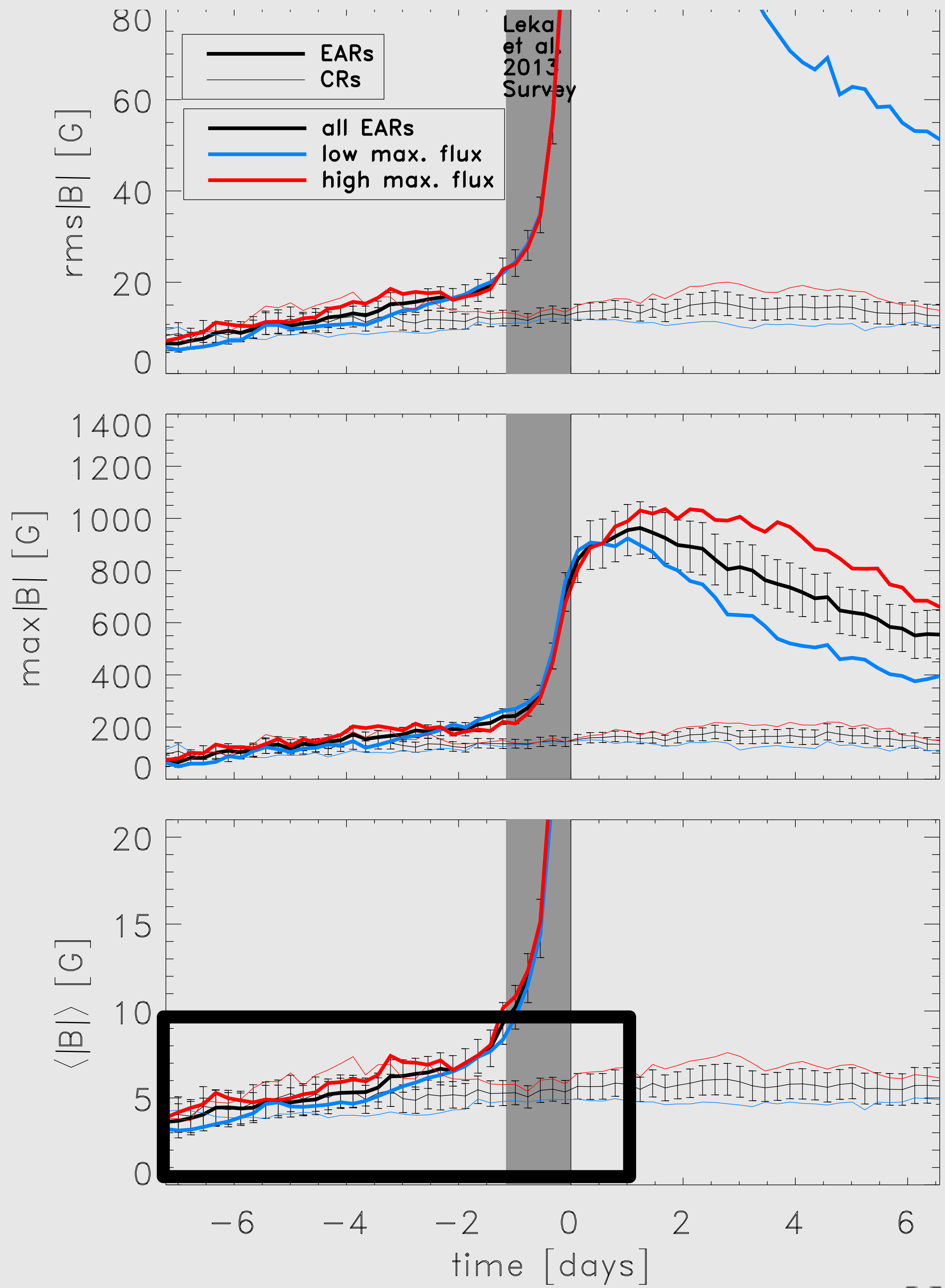
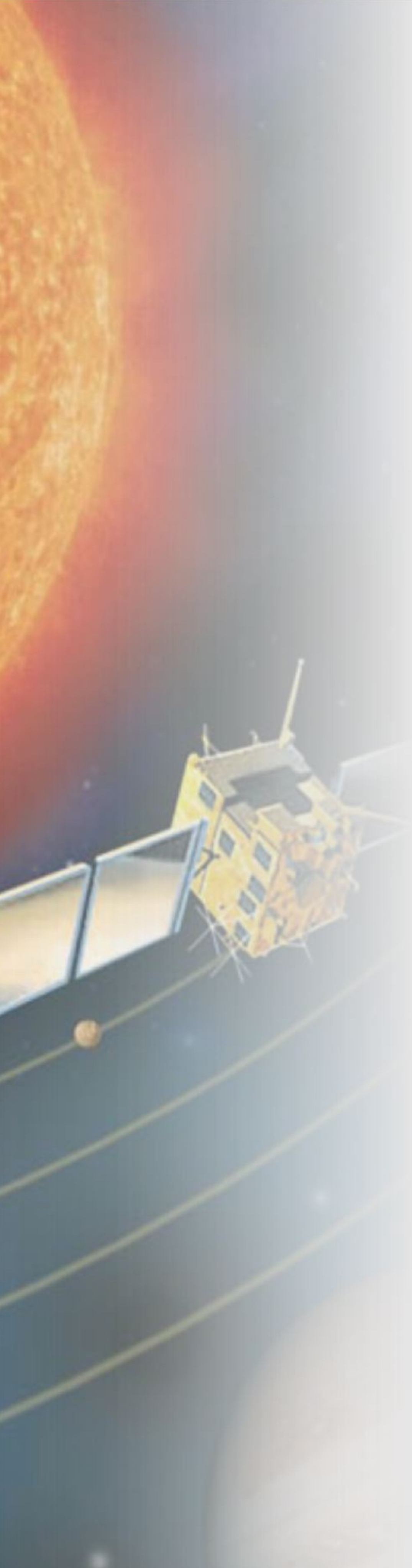
Magnetic Field Evolution

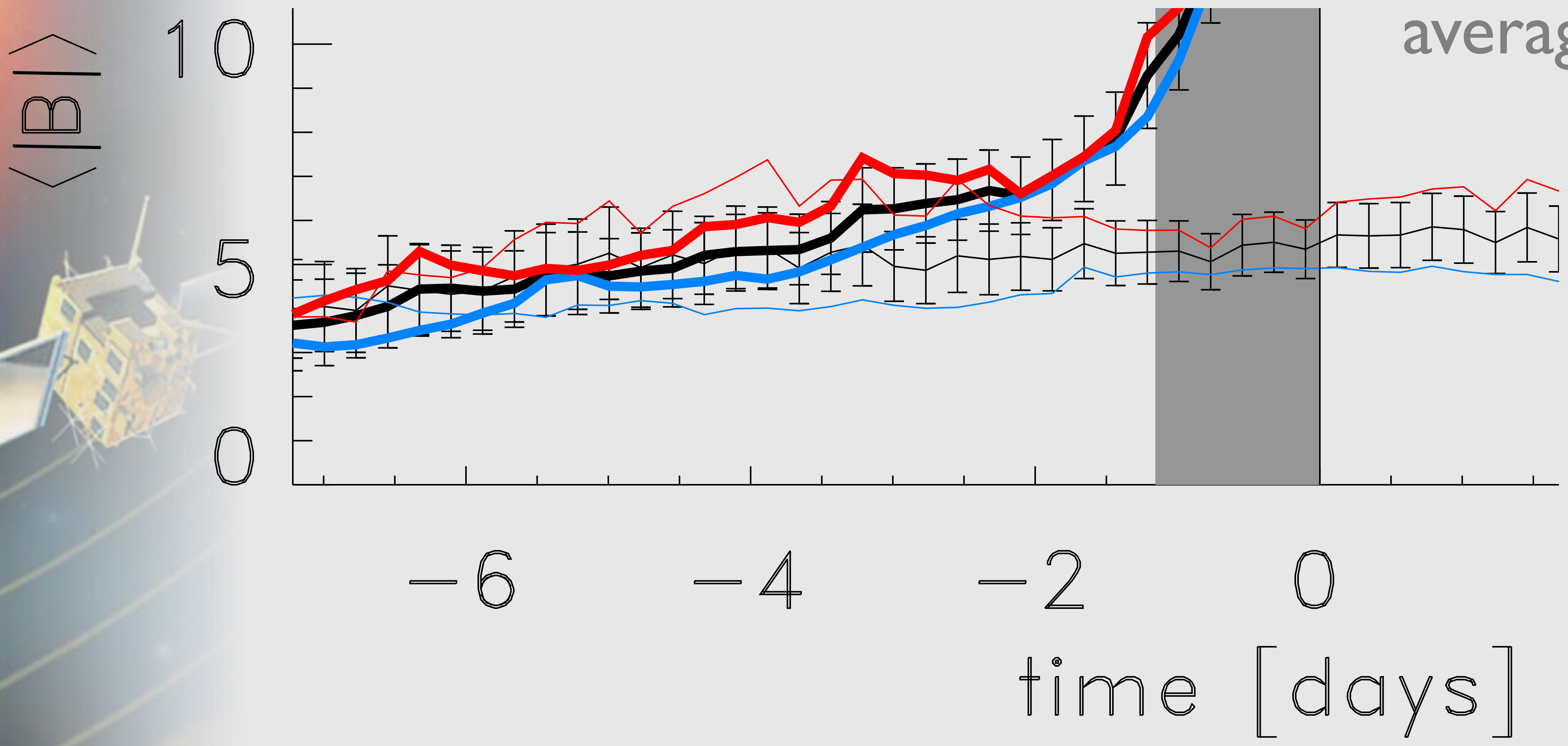


2 degree average



Magnetic Field Evolution

2 degree average



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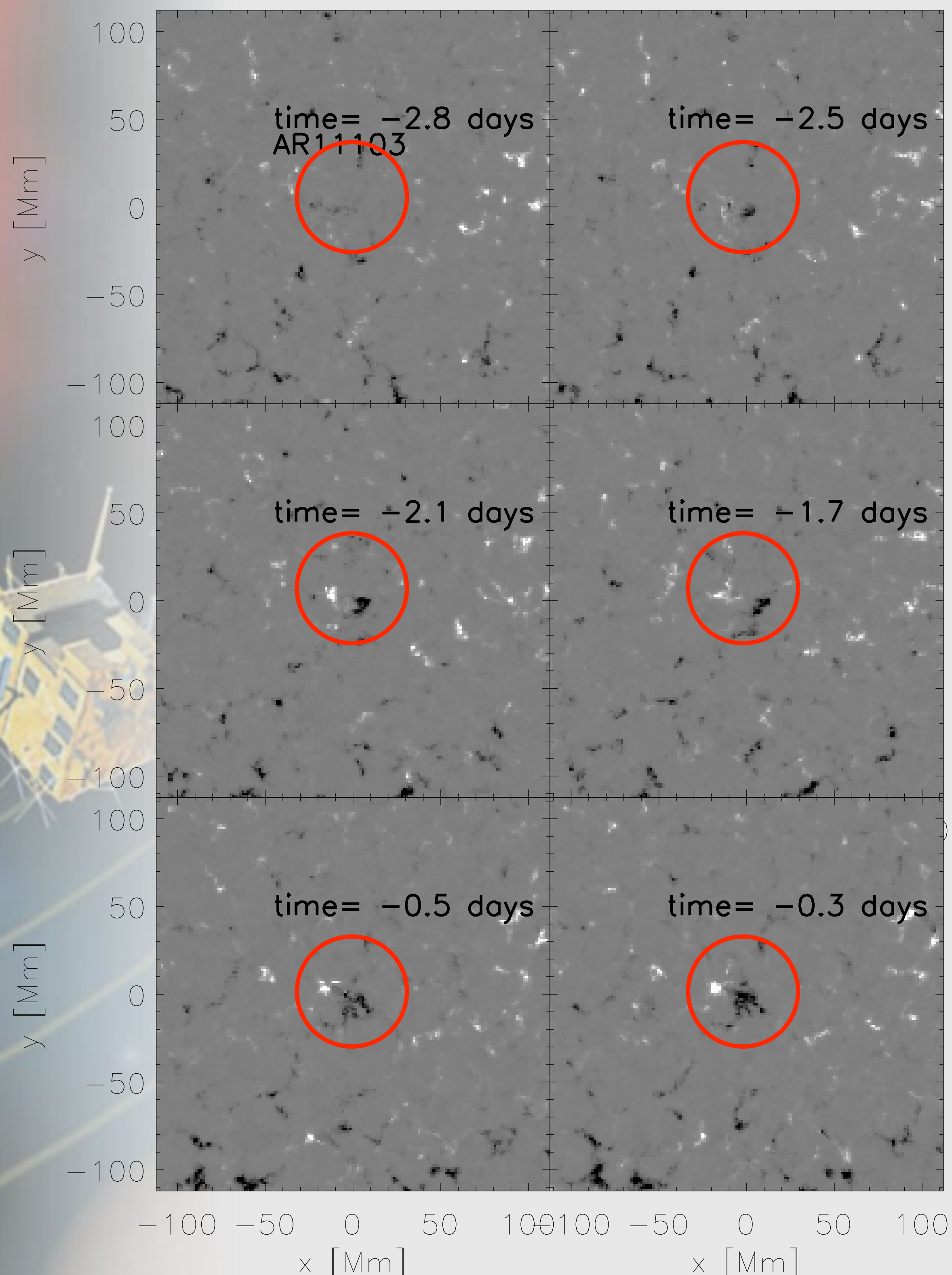
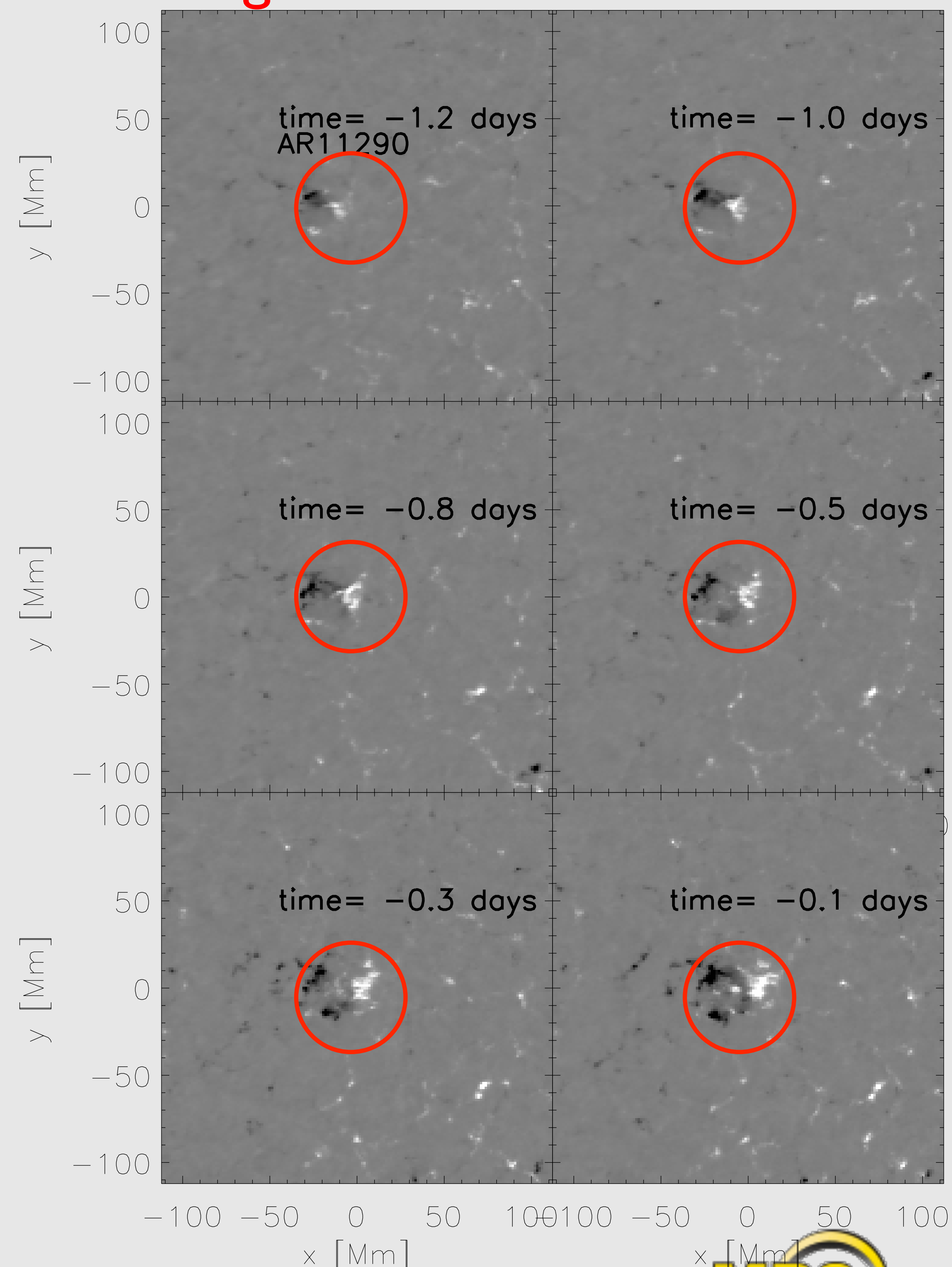
Evolution of Sunspot Regions

Low Maximum Flux



High Maximum Flux



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Emerging sunspot regions summary

High resolution, standardised database

magnetic field, intensity, doppler velocity

Follow the emergence and evolution with high cadence

separation velocity, tilt angles, flux evolution

Local helioseismology

see talk by Aaron Birch tomorrow

Summary

Sunspots are a large perturbation to the waves

Need computational sunspot seismology

- To understand the physics
- Understand new diagnostics
- Develop new methods of interpretation

Study emerging active regions

see talk by Aaron Birch tomorrow

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