The Sun's magnetic surface (& convective turbulence)

AR emergence 'nonequilibrium'
add MRI sims (w some movies)

Yukawa 3/11/11

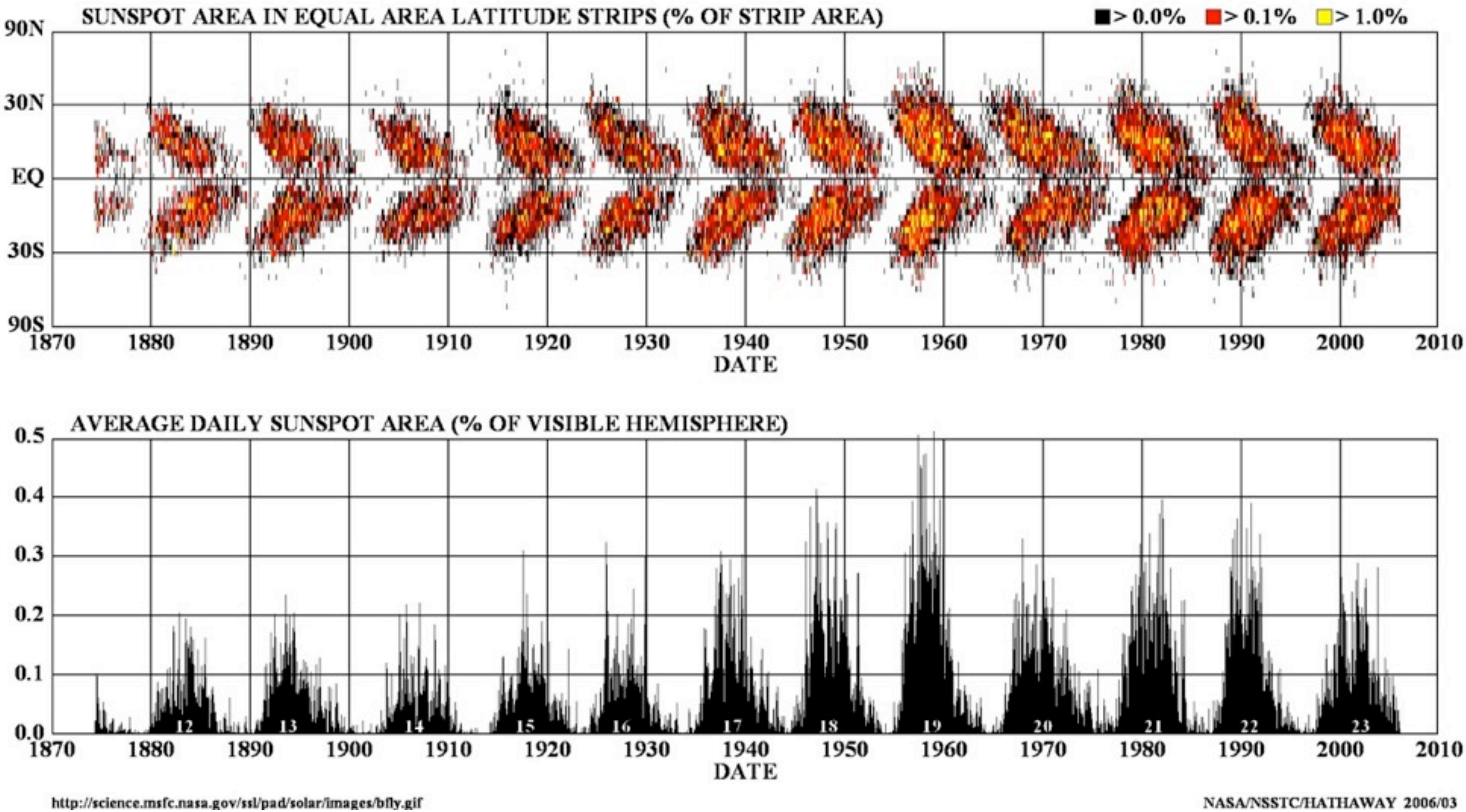
The Sun's magnetic surface

Tells more about what happens below than realized in most models of the cycle.

- Surface clues on how the solar cycle works

- Numerical MHD simulations of surface fields

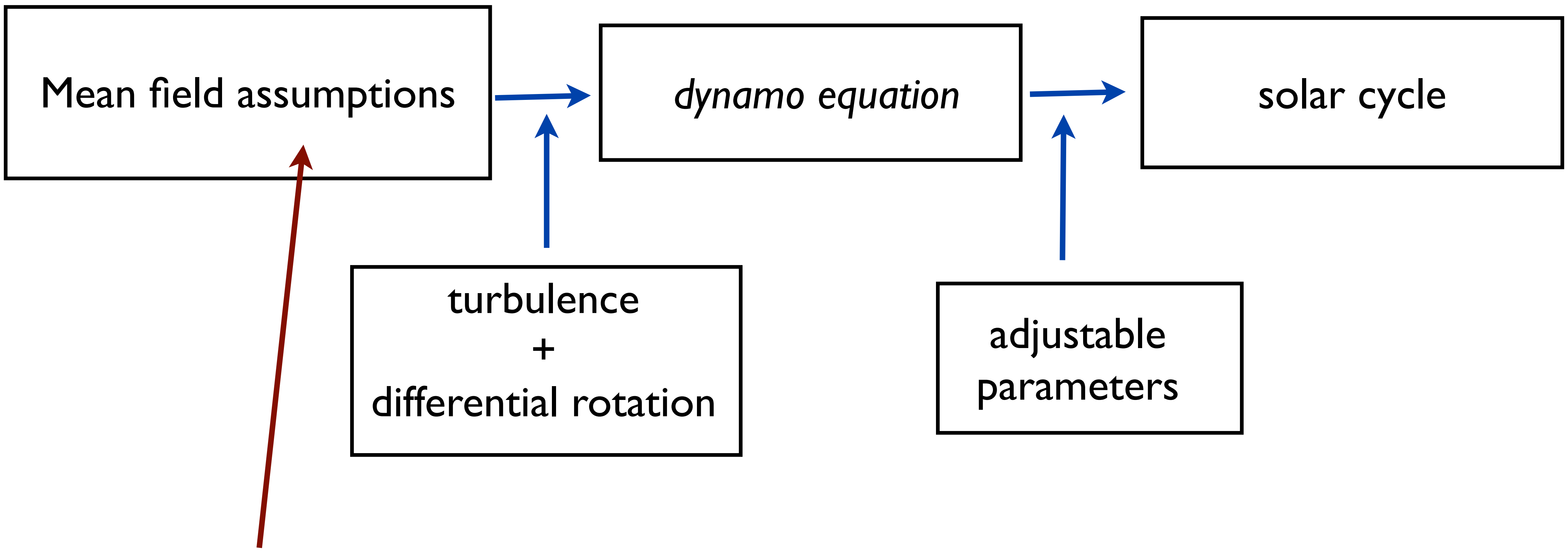
- Magnetic brightening of the Sun



Yukawa 3/11/11

turbulent convective dynamos

convection -> dynamo eqs
(magical box) -> B
- diverge unconditionally
- restricted models,
interpreted as



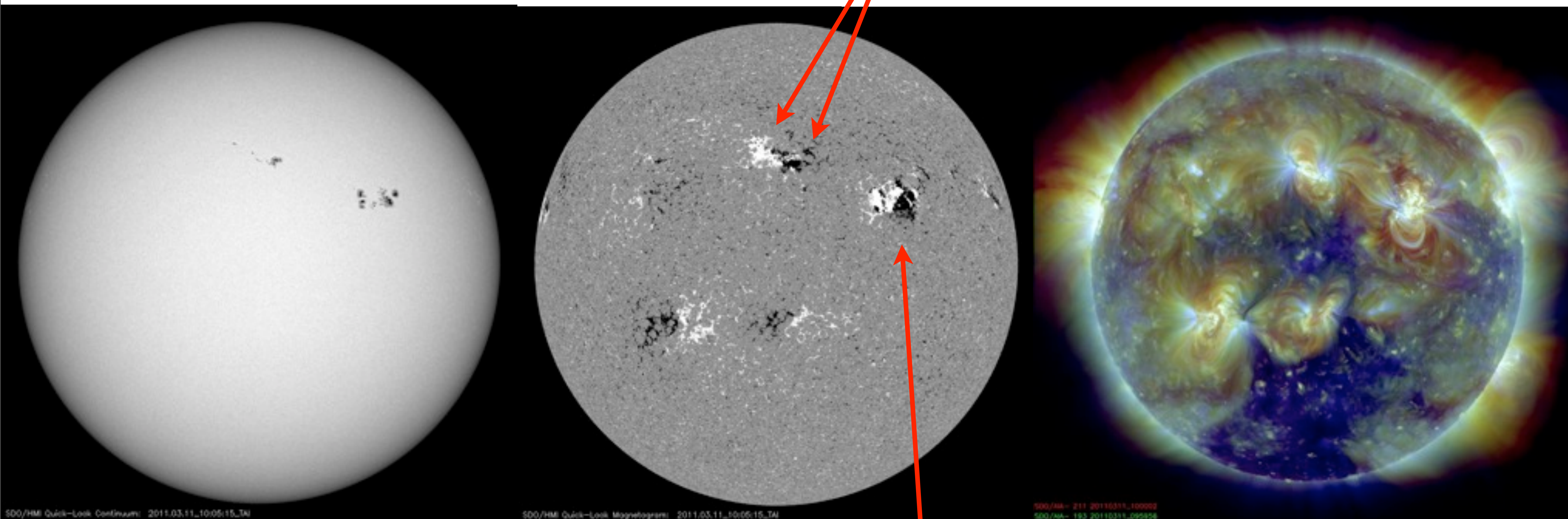
- 1 theoretical problems @ large $\mathrm{Re_m} = \dfrac{LV}{\eta}$

- 2 *mismatch with observations*

Yukawa 3/11/11

white/black: polarity

white light — magnetic — corona (soft X-rays)



Courtesy of NASA/SDO and the AIA, EVE, and HMI science teams

smallscale stuff everywhere. Origin? later in brightness part

Hale's polarity law

Yukawa 3/11/11

what the Sun looked earlier this year (lots of sunspots

18 April -15 May 2011

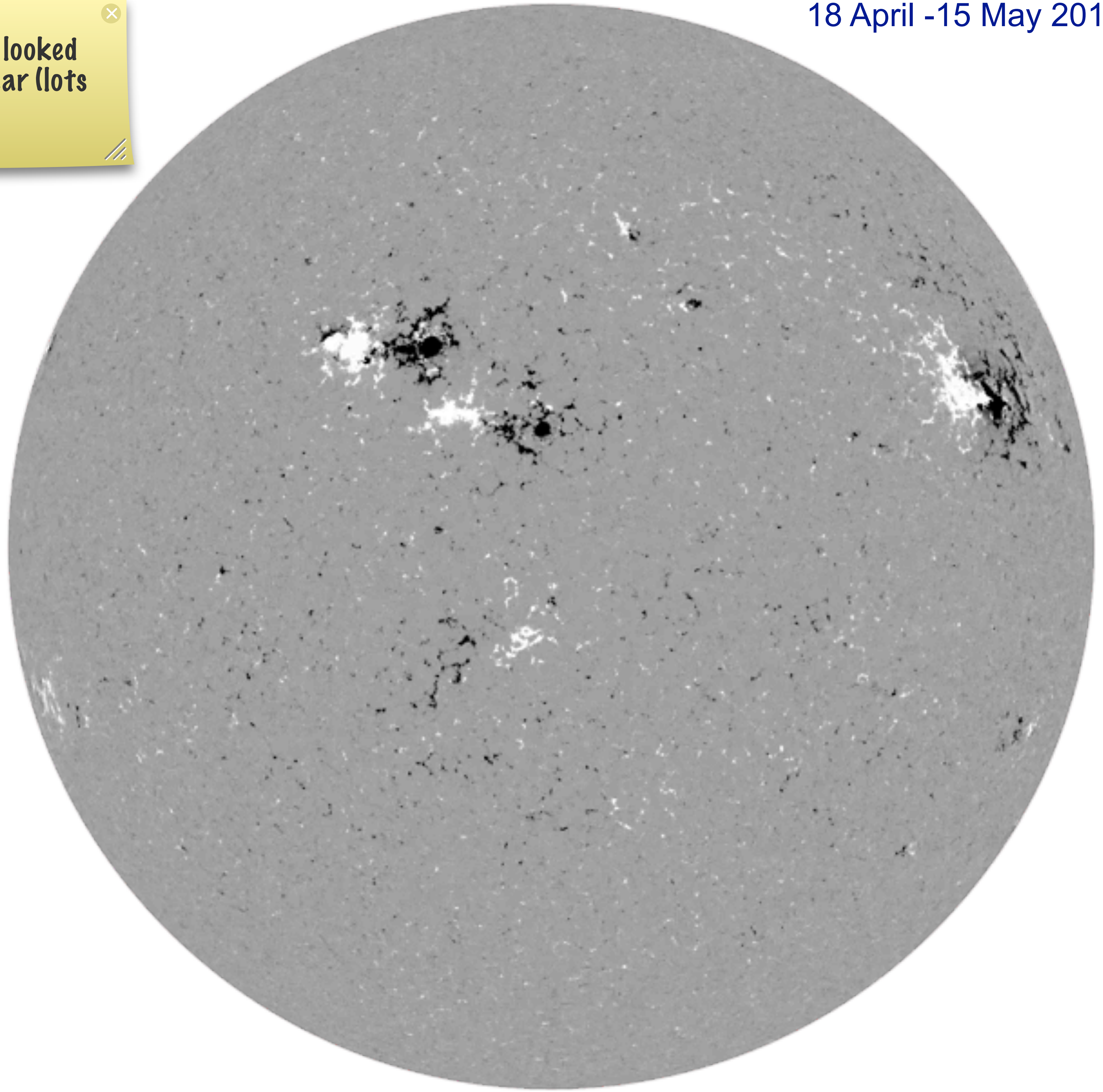
SDO movie

A.M. Title, NASA/SDO and the HMI science teams

Yukawa 3/11/11

what the Sun looked earlier this year (lots of sunspots

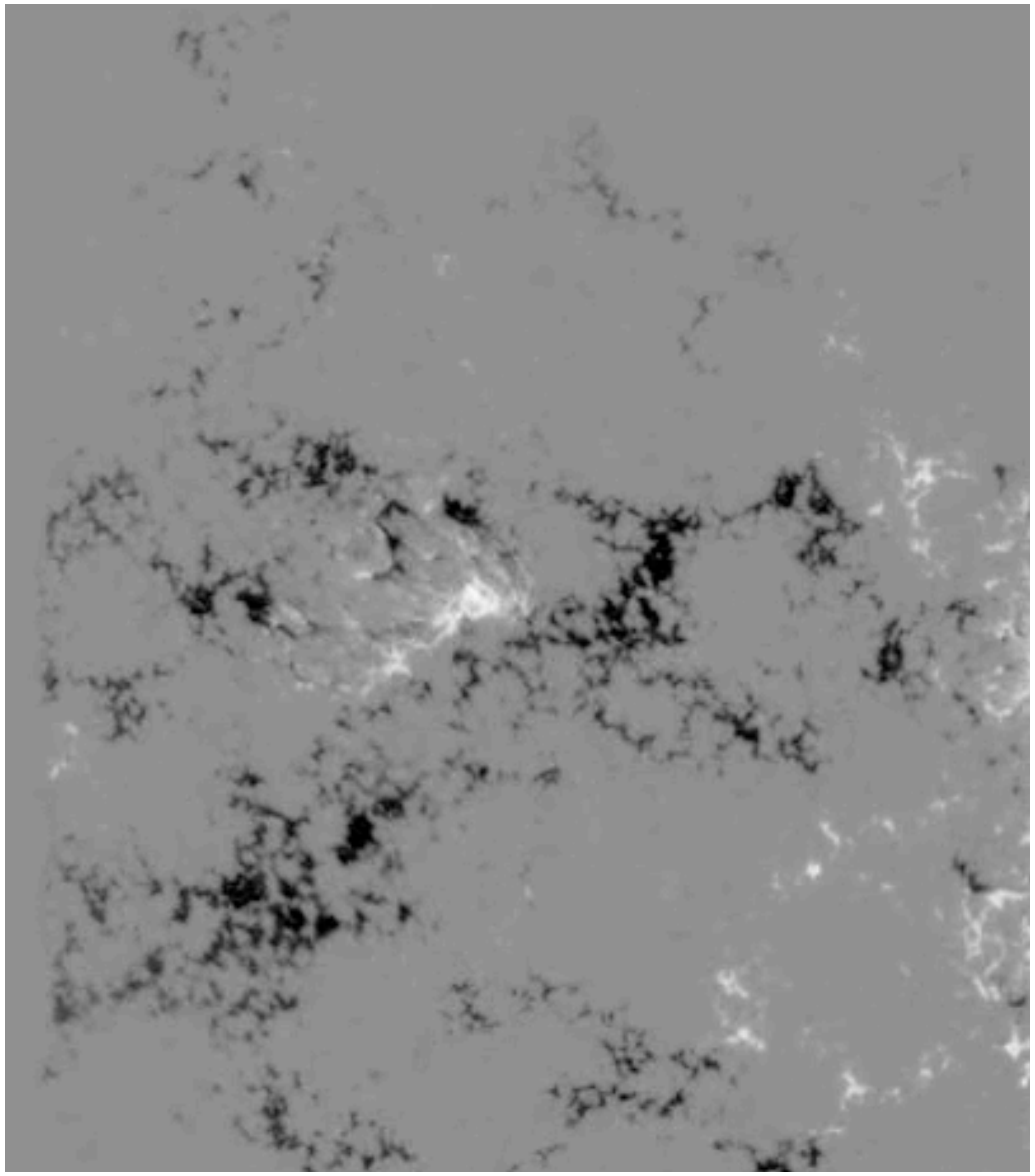
18 April -15 May 2011



A.M. Title, NASA/SDO and the HMI science teams

Yukawa 3/11/11

Active region emergence



Hinode JAXA/NASA   The Hinode 'trilobite'

Fields move independent of surface flow.

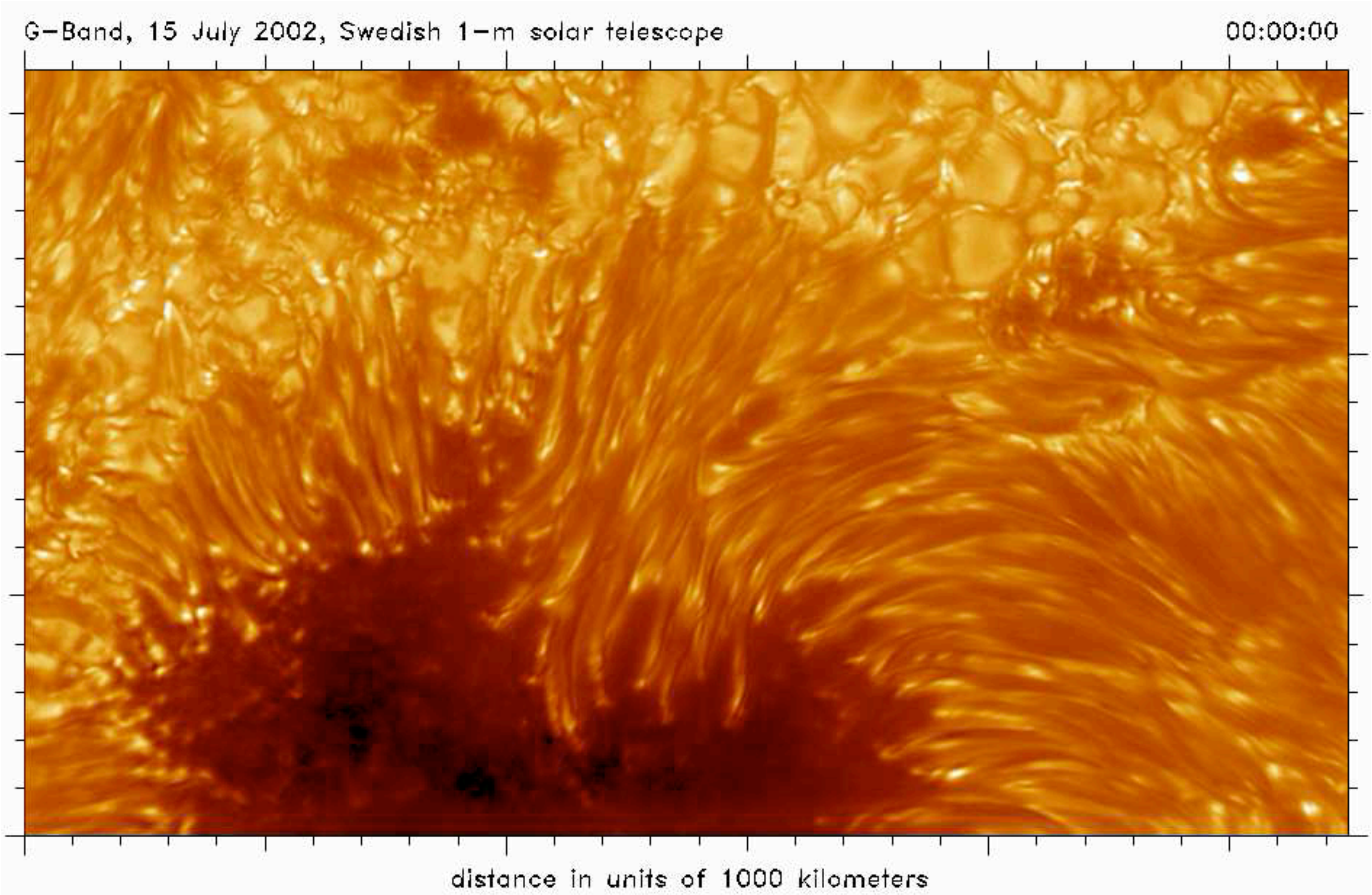
+,- polarities separate from a mix:
`**antidiffusion**'.

Sunspots

Things happening on the surface

Yukawa 3/11/11

Sunspots



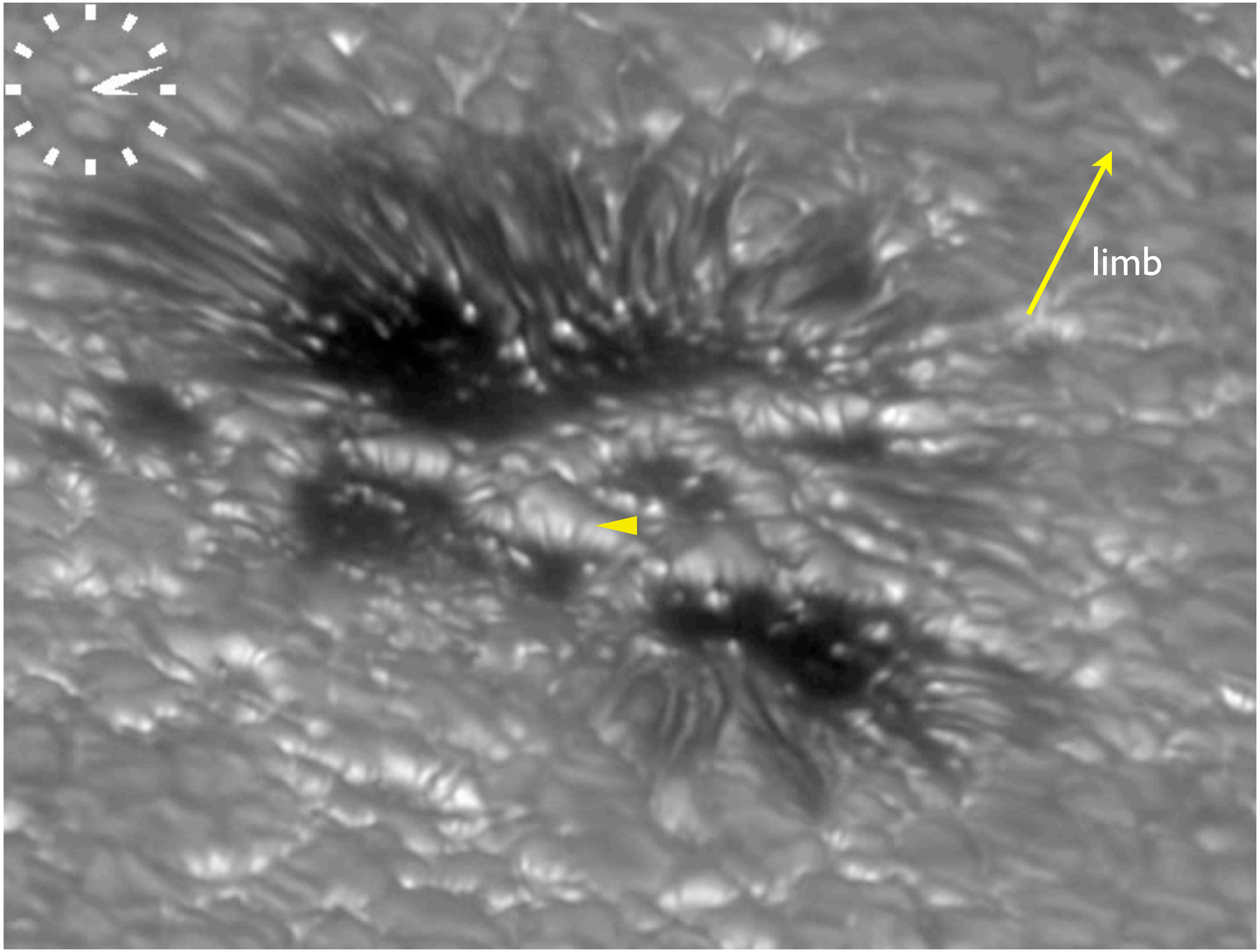
Yukawa 3/11/11

Small scale magnetic field

Swedish 1-m Solar Telescope

Yukawa 3/11/11

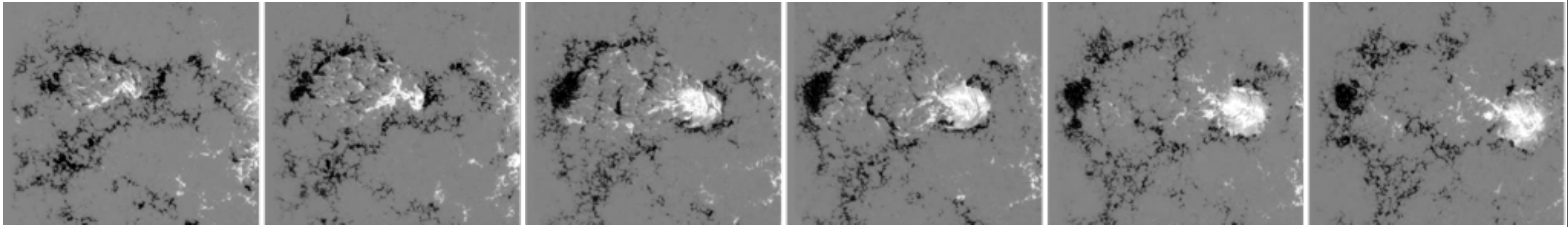
Small scale magnetic field



Swedish 1-m Solar Telescope

Active region emergence

This: single AR, statistics by Howard



the 'trilobite'

Hinode JAXA/NASA

Properties

Hale's l → not 'turbulence'

- regularity of Hale's polarity law
- emerging fields move independent of surface flows, 'antidiffusion'
- sunspot proper motion time scales - a few days
- tilt of AR, continues to settle after emergence

for stationary AR

is understood why (return to this in a min.)

Yukawa 3/11/11

Interpretation

- surface obs: not interior
- why can stil deduce about inner workings? B quite strong, resist v_co
- : not a process of turb convection
- the evidence

active region emergence
(Cowling 1953)

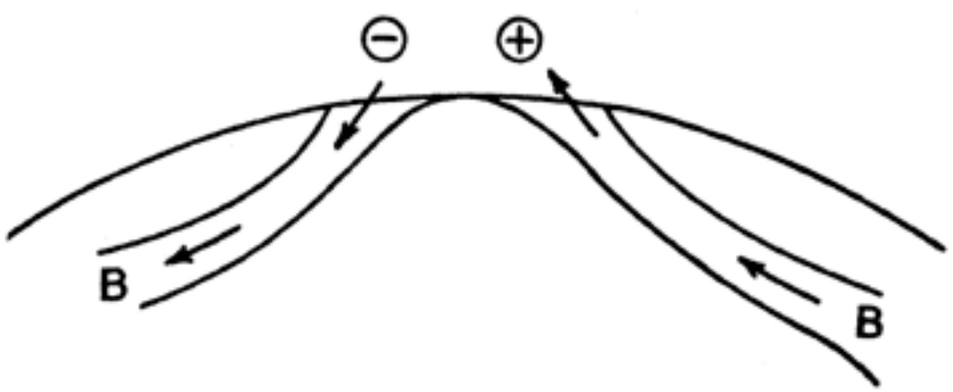
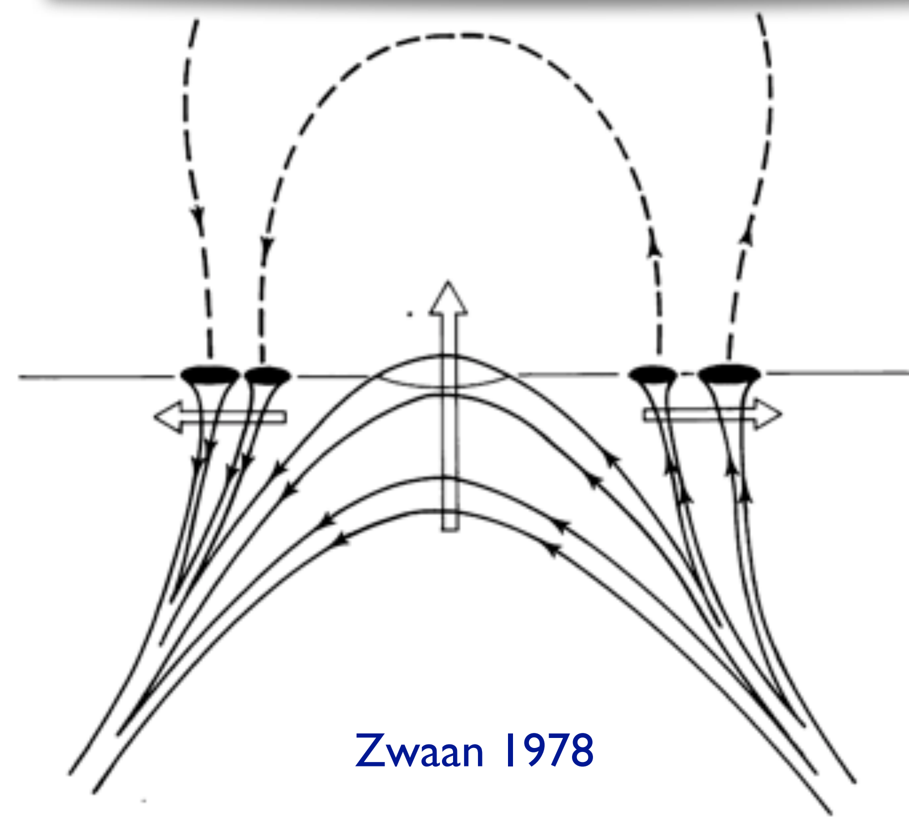


Fig. 5. Showing a strand of the solar toroidal field lifted locally and giving rise to a bipolar sunspot group.

W. Elsaesser 1956



Zwaan 1978

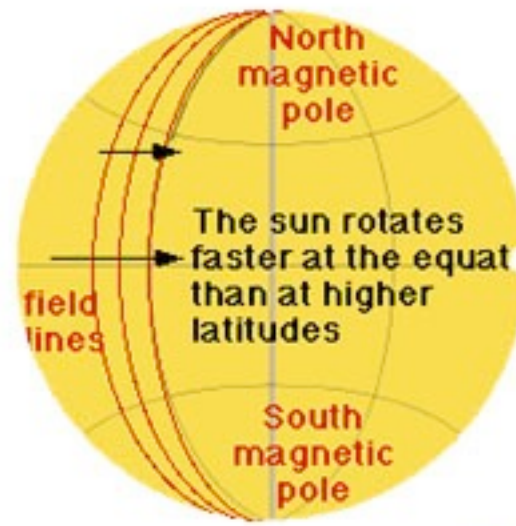
Yukawa 3/11/11

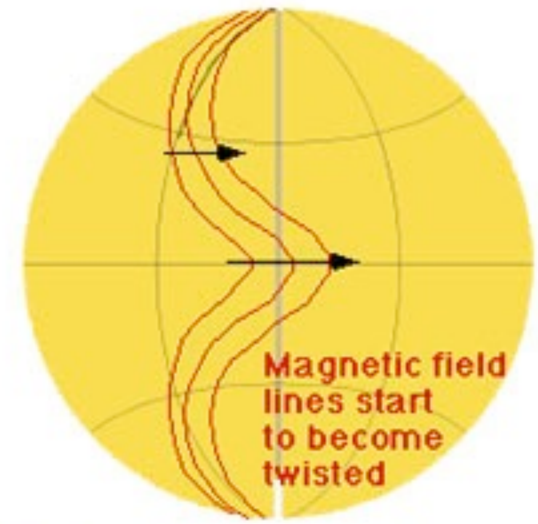
Interpretation (ct.'d)

Q1: why does the field erupt?
A: (Babcock 1953) when it reaches a critical strength

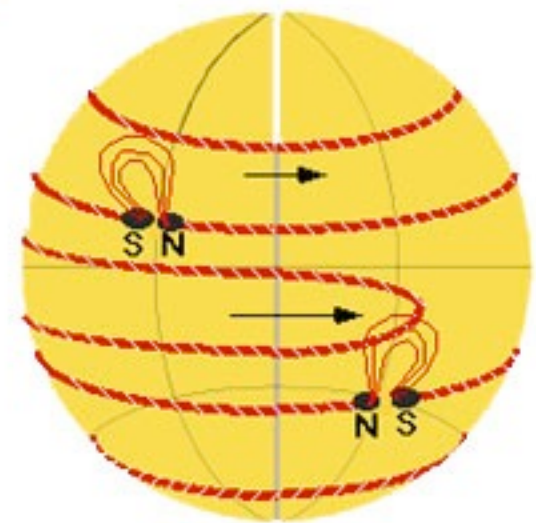
Q2: from which depth?
A: base convection zone.

assume for the now, return to in a moment





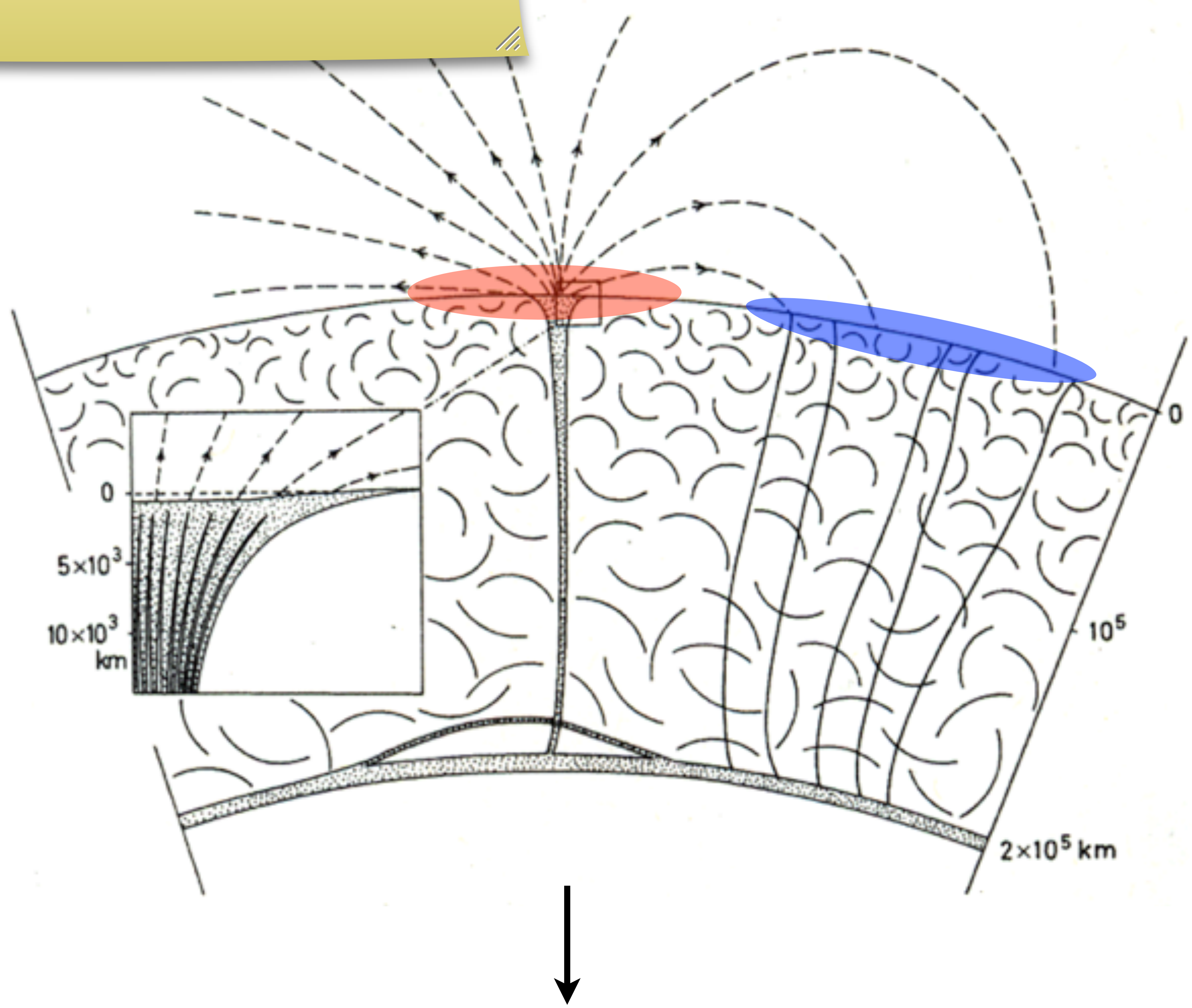
equatorward drift



'Winding-up' by differential rotation with **latitude**

Interpretation (ct.'d)

so this picture based on interp. of obs. Not yet justified why @ base. Later. now summarize how



center of Sun

Yukawa 3/11/11

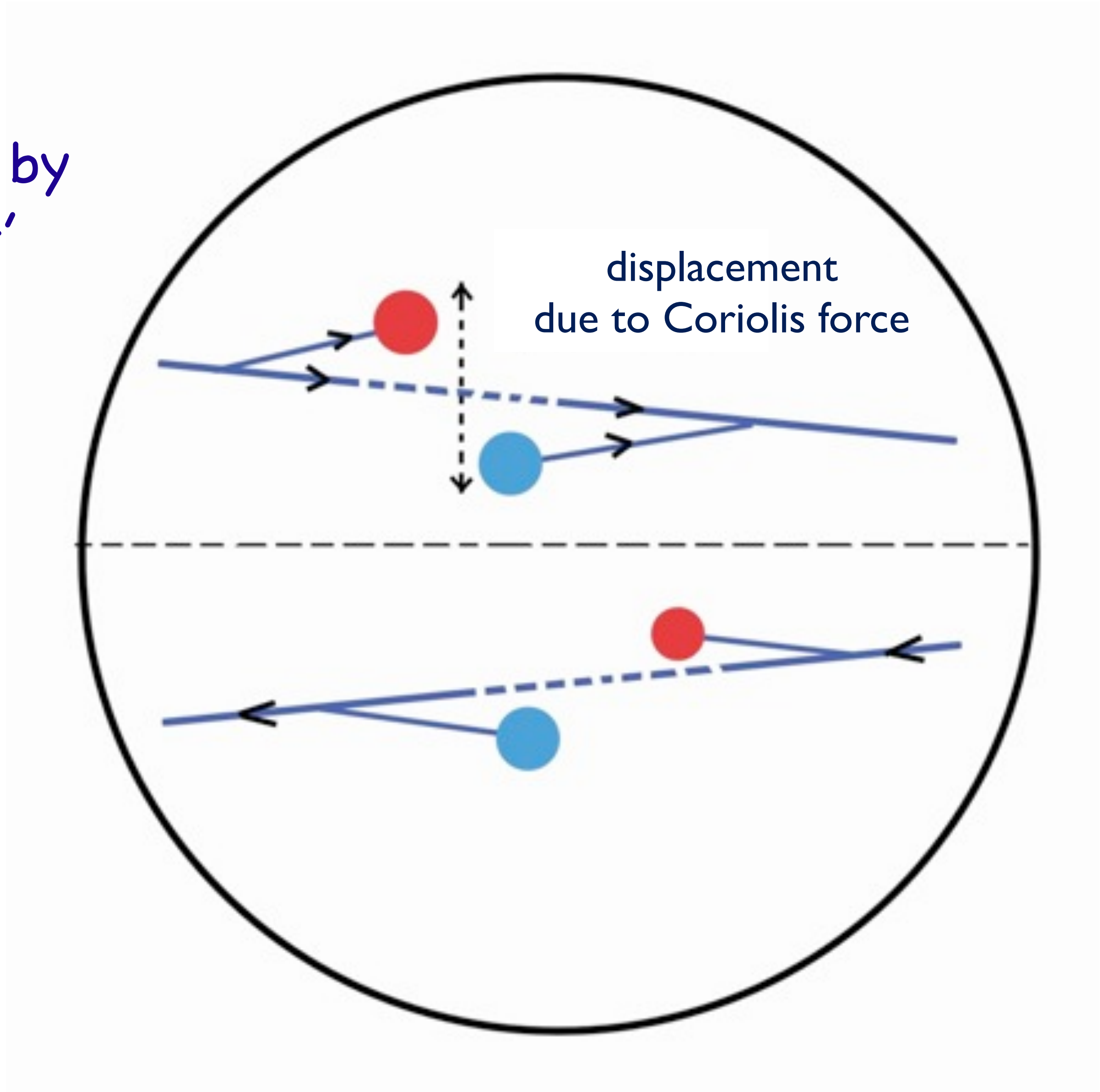
Interpretation (ct.'d)

sketch: field @ base CZ

- active region tilt produced by emergence is the 'α-effect' of the cycle

(R.B. Leighton 1969)

L did not spec where in Sun this takes place, but implication deep inside CZ



Yukawa 3/11/11

no turbulence in this picture ....

steps: - B_phi from diff rot
- rest is done by B itself

other example MRI

Summary observational clues

- field of the solar cycle stronger than convection
- ingredients are: differential rotation + dynamics of the field itself (↔ kinematic picture)

↔ 'magnetorotational turbulence' in accretion disks

Yukawa 3/11/11

Reduce ...

Interpretation (ct.'d)

magnetic energy density bubbling up

Why at base CZ?

- observations: field is not passively carried by flow,
  → stronger than equipartion w. convection
- stratification of convection zone has no restoring forces
- fields can not 'float midway' for as long as years
- floats to top or sinks to bottom (if heavy enough ...)

--> winding-up during cycle must happening @ base

leaving out a detail in the argument

- **If** at base CZ:

- field becomes unstable (Parker instab.) at $\approx 10^5$ G (Schüssler et al. 1994)

'rising tube' simulations:

- rise time $\approx$ days
- in the observed latitude range
- with right AR tilt

} (Choudhuri & D'Silva, Caligari etal, Fan & Fischer 1993-1996)

Yukawa 3/11/11

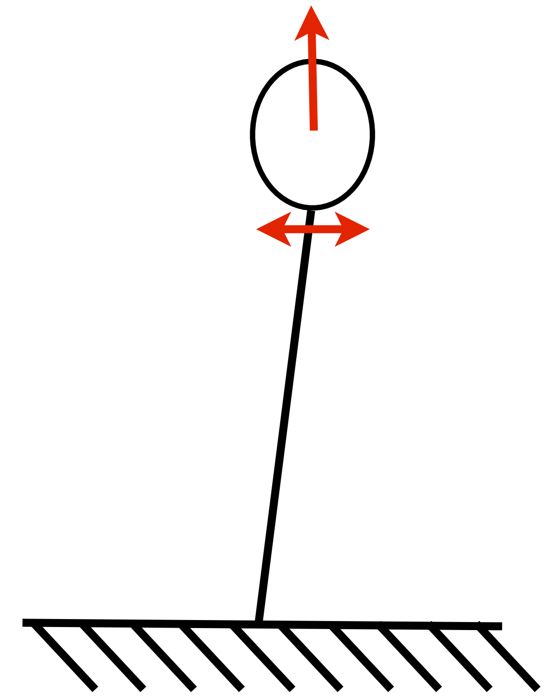
- this insight is not a theory of the cycle
- but is enough to eliminate some theories

Interpretation

-> contact made between MHD of interior and observations @ surface.

Explains:

- Hale's & Joy's laws
- time scale of spot proper motions (Alfvén travel time)



'Tethered balloon'

consequences:

- Field is stronger than convection
- → direct connection between surface and interior
- B not generated by `interaction with turbulent convection':
  cycle operates on differential rotation and instability of B.
  (compare: field generation in accretion disks)
- Differential rotation with latitude (not radius)

Theories

- turbulent mean field models
- superficial sunspots
- flux transport models

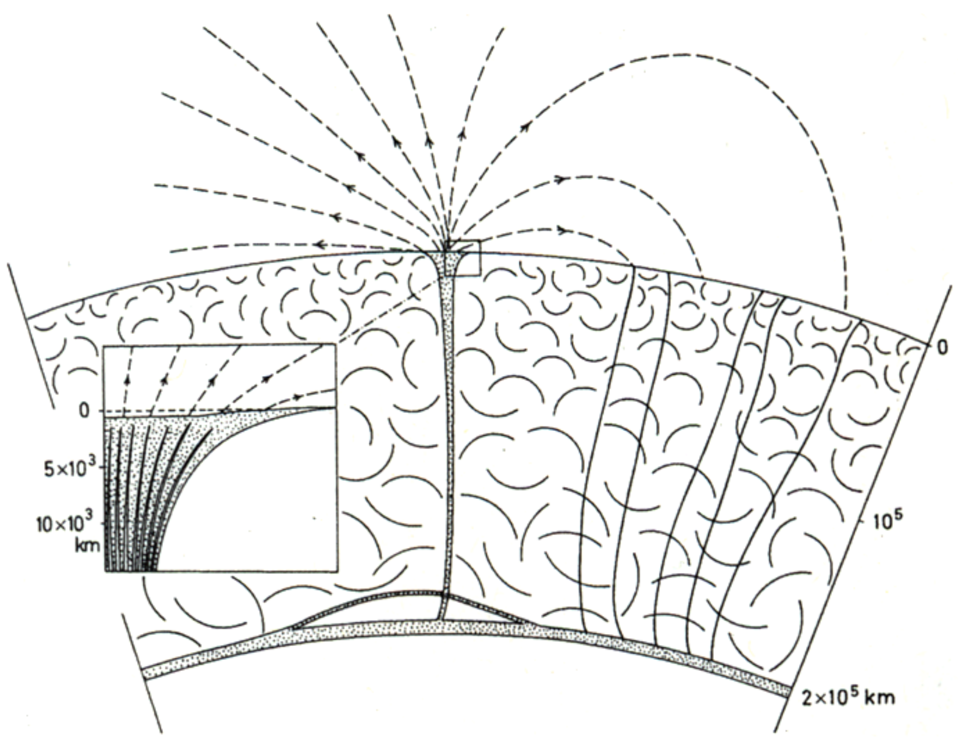
Flux transport dynamos: leave out

Solar cycle: open issues

1 'Thermodynamic problem':
strength of the field @base requires low temperatures

$$B = 10^5 \hat{=} \delta T/T \sim 10^{-4}$$

2 Flux disappearance rate (Labonte & Howard 81: AR flux lives 10d)



- turbulent diffusion: not an explanation.
- reconnection: where?

Yukawa 3/11/11

Realistic MHD

Def realistic:
- qualitatively and qu. correct.
- correct: includes all required physics quantitatively
- reproduces the observations qualit and quantit.

needed for realism

- 3-D
- accurate radiative transport
- depth range

When possible, and why?

convection zone

- time scales: seconds - years
- length scales: km to solar radius
- density range 10^6

→ not possible from scratch

Tall order. Not often possible.
- what done instead (gen purp MHD code, no rad because that's not MHD), results: unquantifiable significance.
- can often do better by exploiting limiting case nature. Example hydrodynamics. (<-> particle sims)

Simplifications in limiting cases

(Nordlund, 1979-1989)

- limiting case: large density range
- with right BCs: need only compute surface layers

Yukawa 3/11/11

Numerical simulations of the magnetic surface

Why surface?
- beta ~ 1. corona harder,
- interior: length/time scales problem
num: general case
easiest (l's,t's similar)
anal.: small parameter
case easier

- realistically possible: upper ~ 10 Mm
- nonmagnetic (since 1979): make use of large density ratio, taken into acct with lower boundary condition
- B: have to specify B @ lower boundary

→ cannot answer how/why a spot is formed.

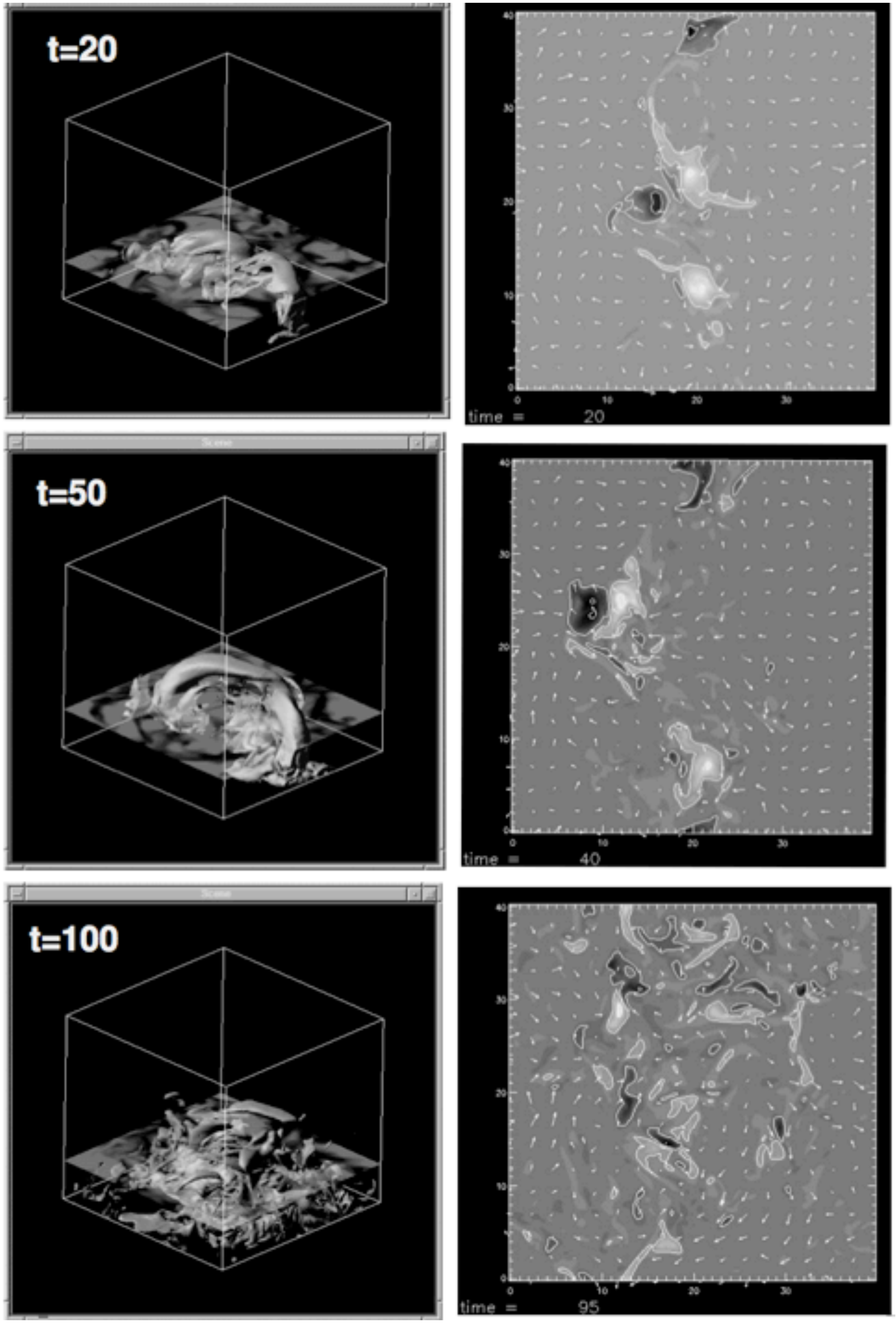
- **can** address surface phenomena in a spot
- **can** make quantitatively realistic small scale fields ('flux tubes')

general about sims:
- actual par range not accsble
- many sims don't make ctct
- need phys judgement in choice of sim
- small/large par simpfc

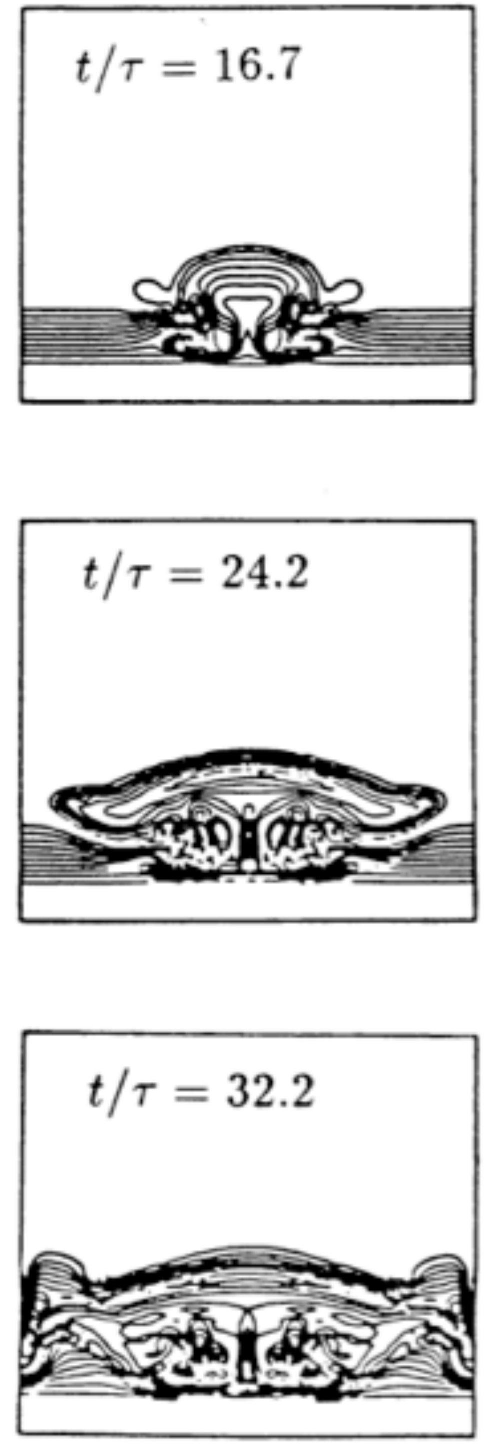
MHD sims: not as well def.
- more put in by hand:
- field @base (unlike field-free upflow case)

Yukawa 3/11/11

flux emergence in 3D MHD simulations



Isobe & Shibata 2004



Matsumoto et al 1993

Yukawa 3/11/11

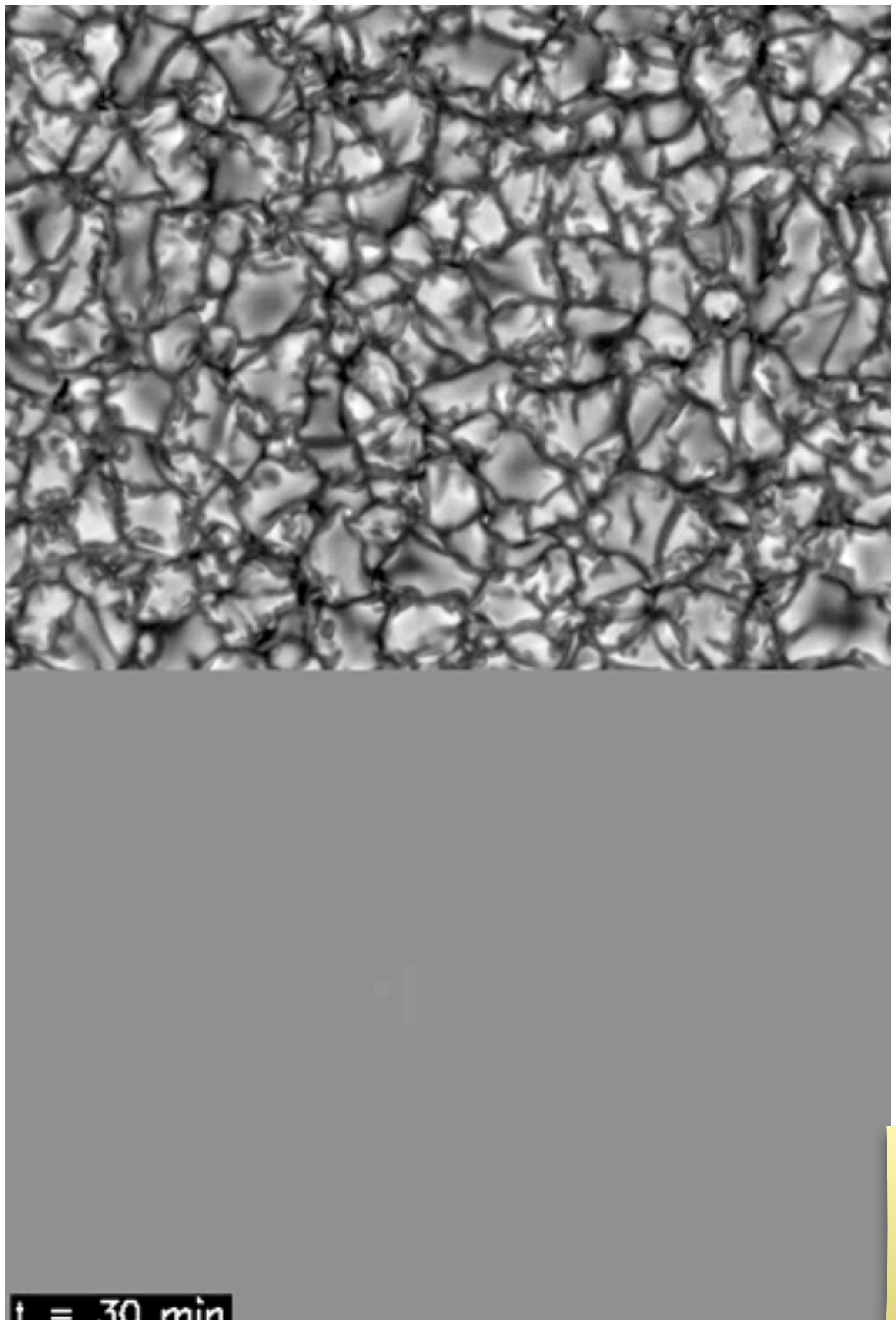
flux emergence in MHD simulations ...

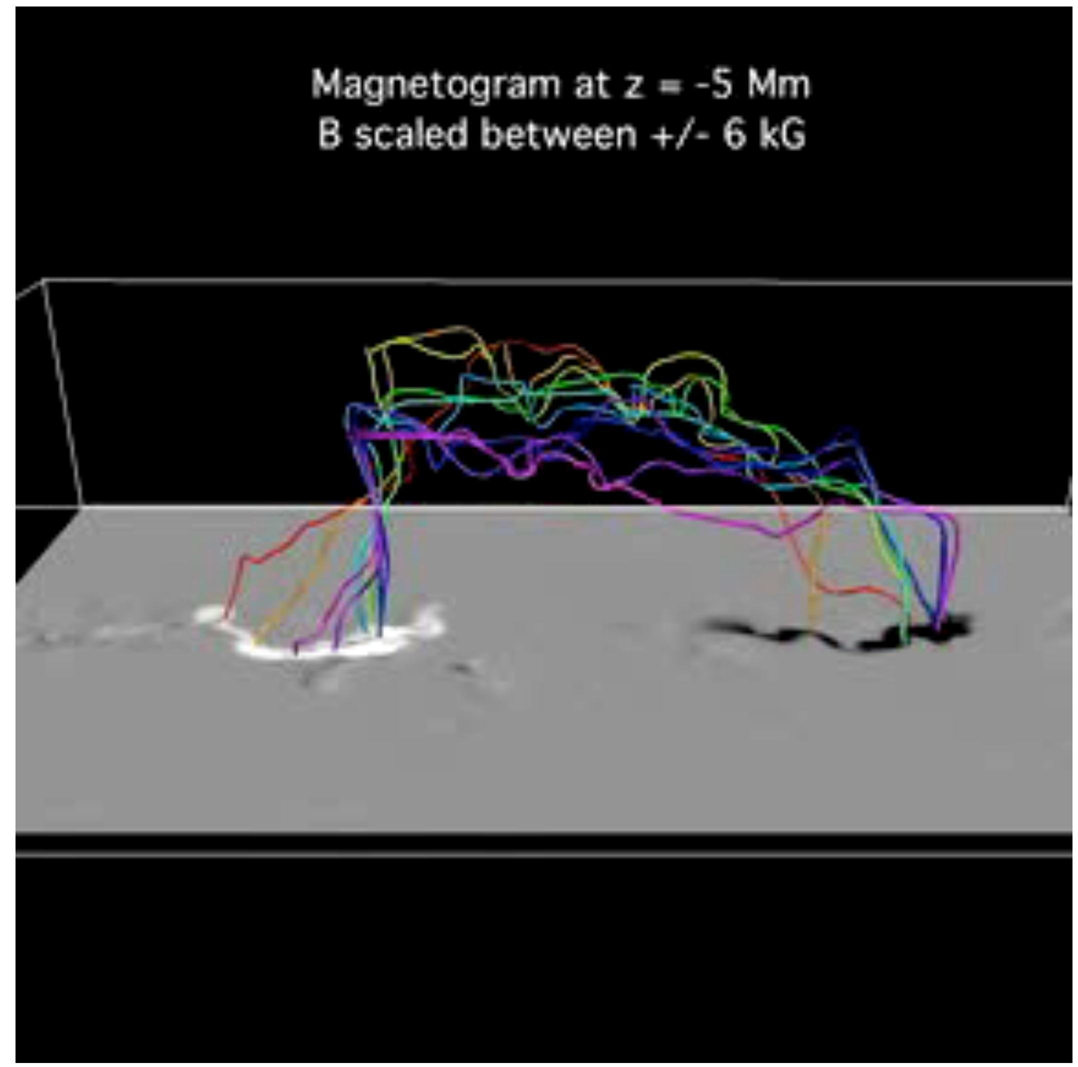
Cheung, Schüssler, Rempel, Title, 2009

Q: why no spots?
A: conditions @ lower b

Yukawa 3/11/11

flux emergence in MHD simulations ...



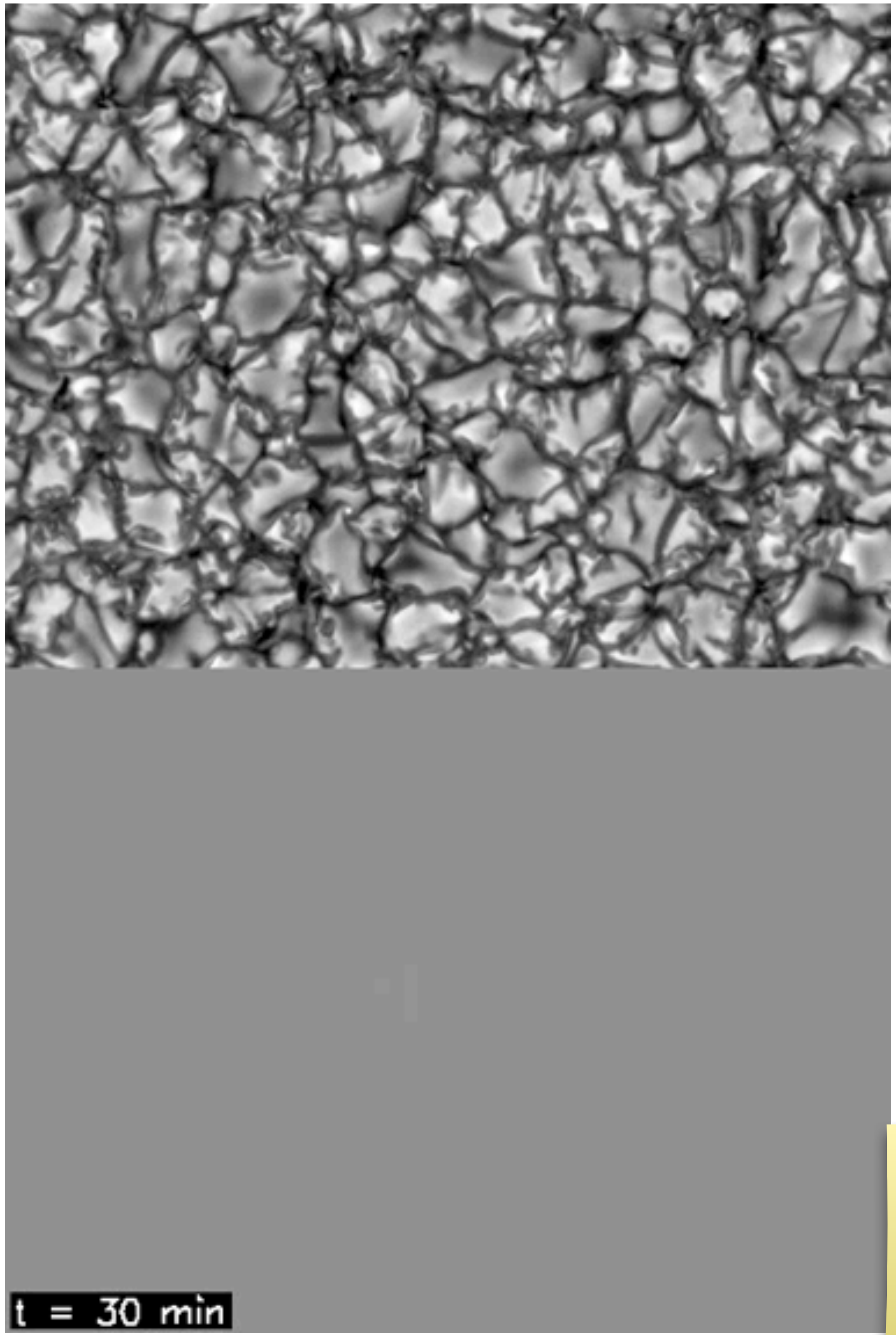


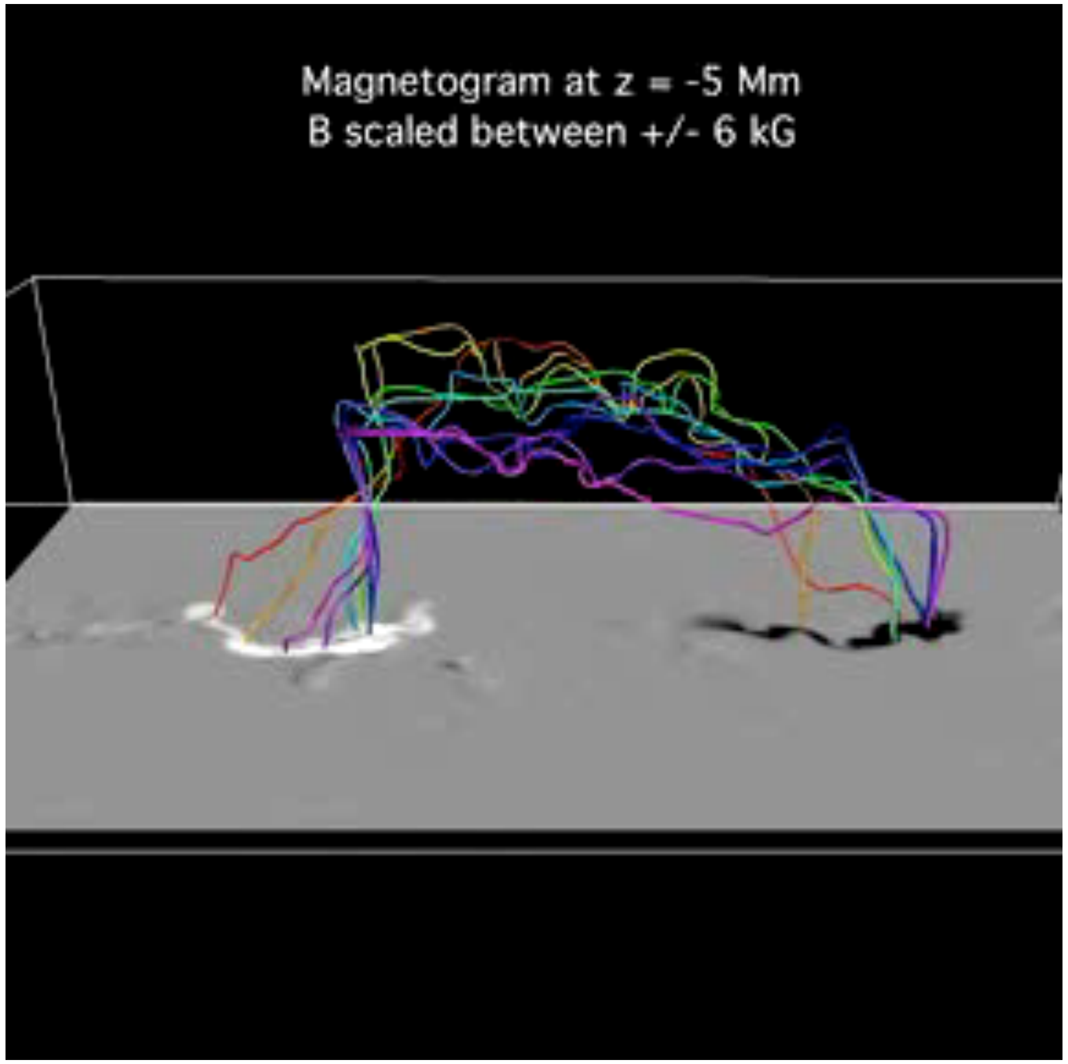
Cheung, Schüssler, Rempel, Title, 2009

Q: why no spots?
A: conditions @ lower b

Yukawa 3/11/11

flux emergence in MHD simulations ...





Cheung, Schüssler, Rempel, Title, 2009

Q: why no spots?
A: conditions @ lower b

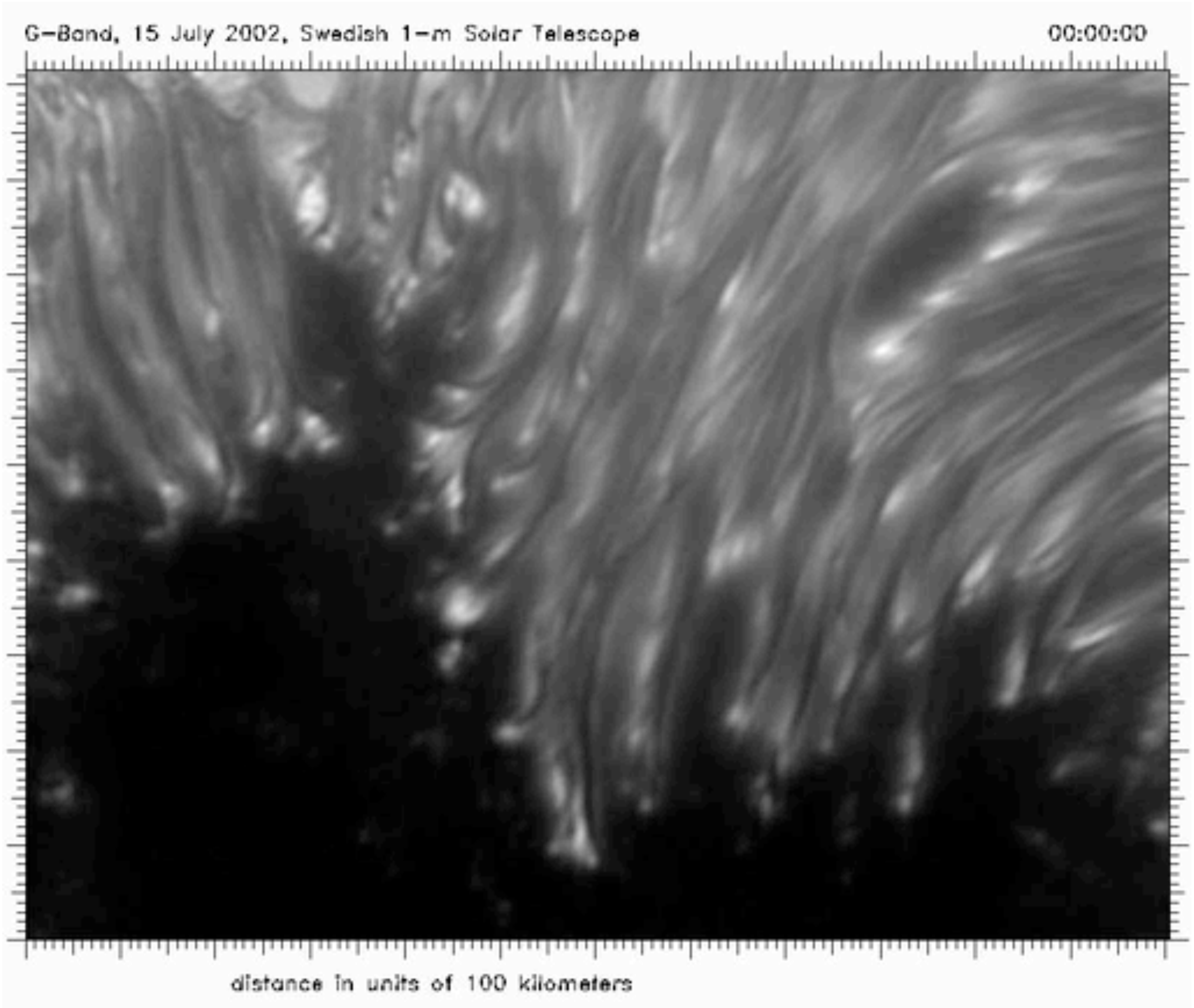
Yukawa 3/11/11

Dark cores over penumbral filaments

SST

Yukawa 3/11/11

Dark cores over penumbral filaments



SST

Yukawa 3/11/11

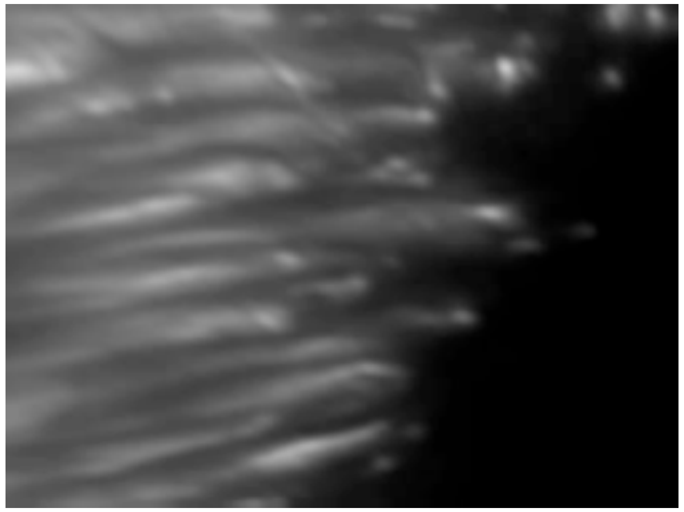
Striation of penumbral filaments

Ichimoto et al. 2007

Scharmer et al. 2010

1-m Swedish telescope

Yukawa 3/11/11



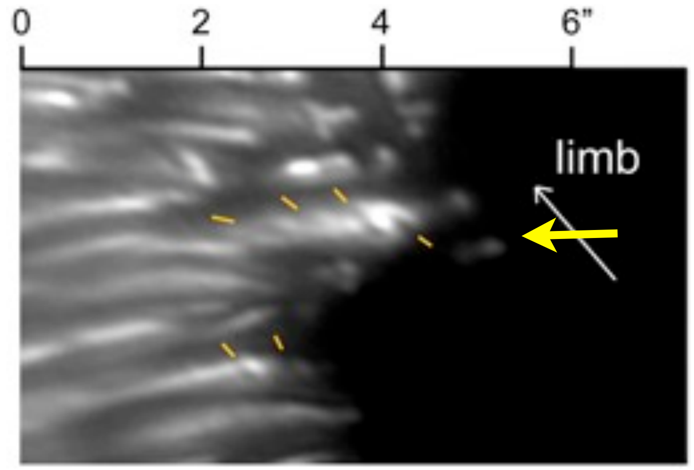
1-m Swedish telescope

Striation of penumbral filaments

Ichimoto et al. 2007

Scharmer et al. 2010

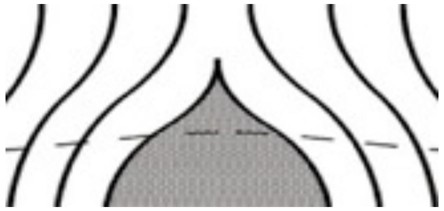
Yukawa 3/11/11

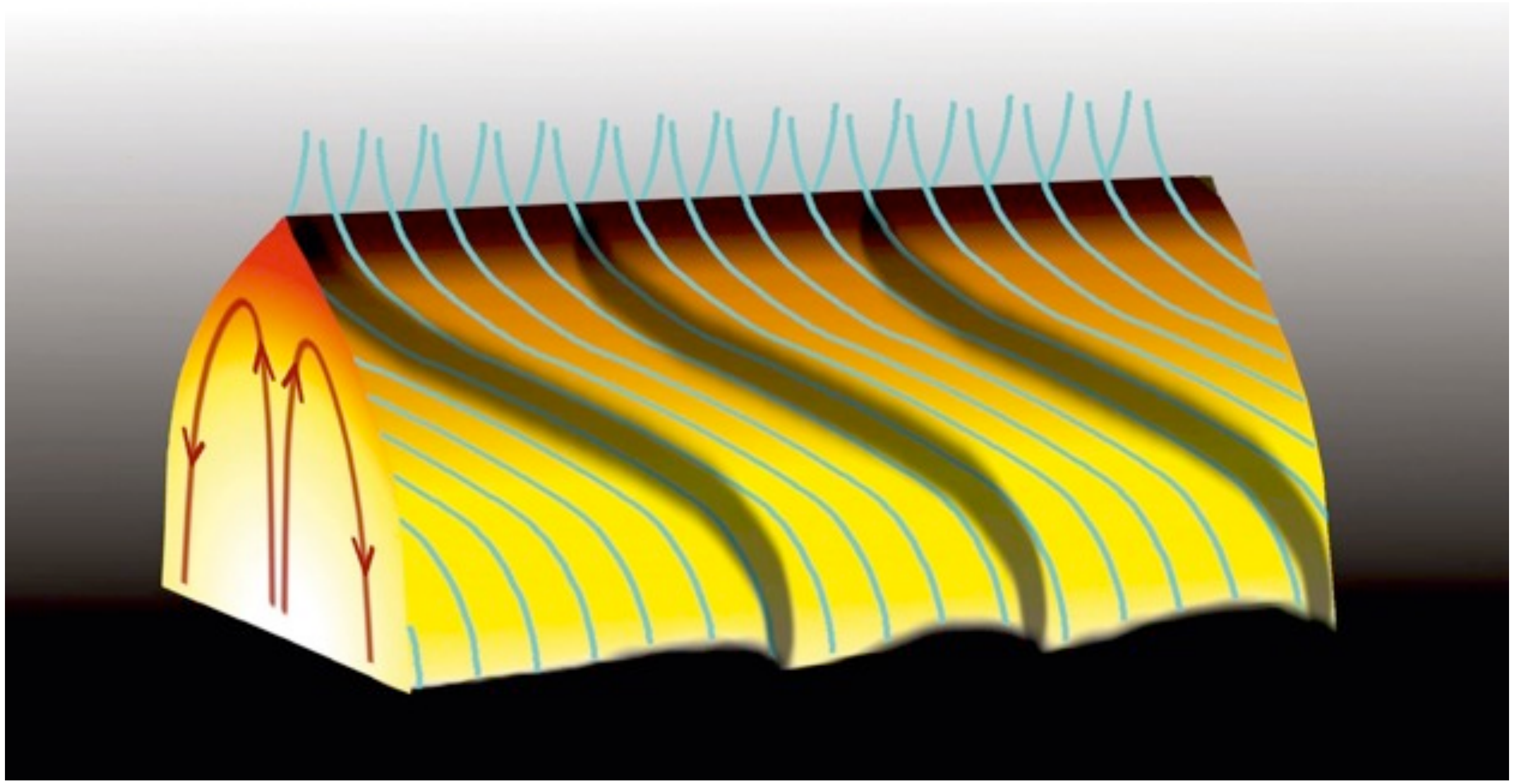


The gappy penumbra

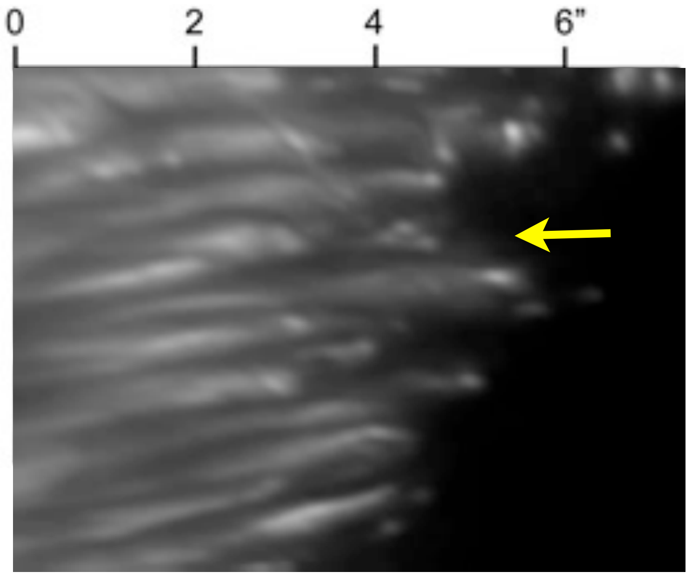
HCS & Scharmer A&A 2006

cf.: umbral dots E.N. Parker, 1979





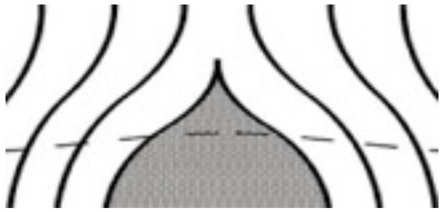
Yukawa 3/11/11

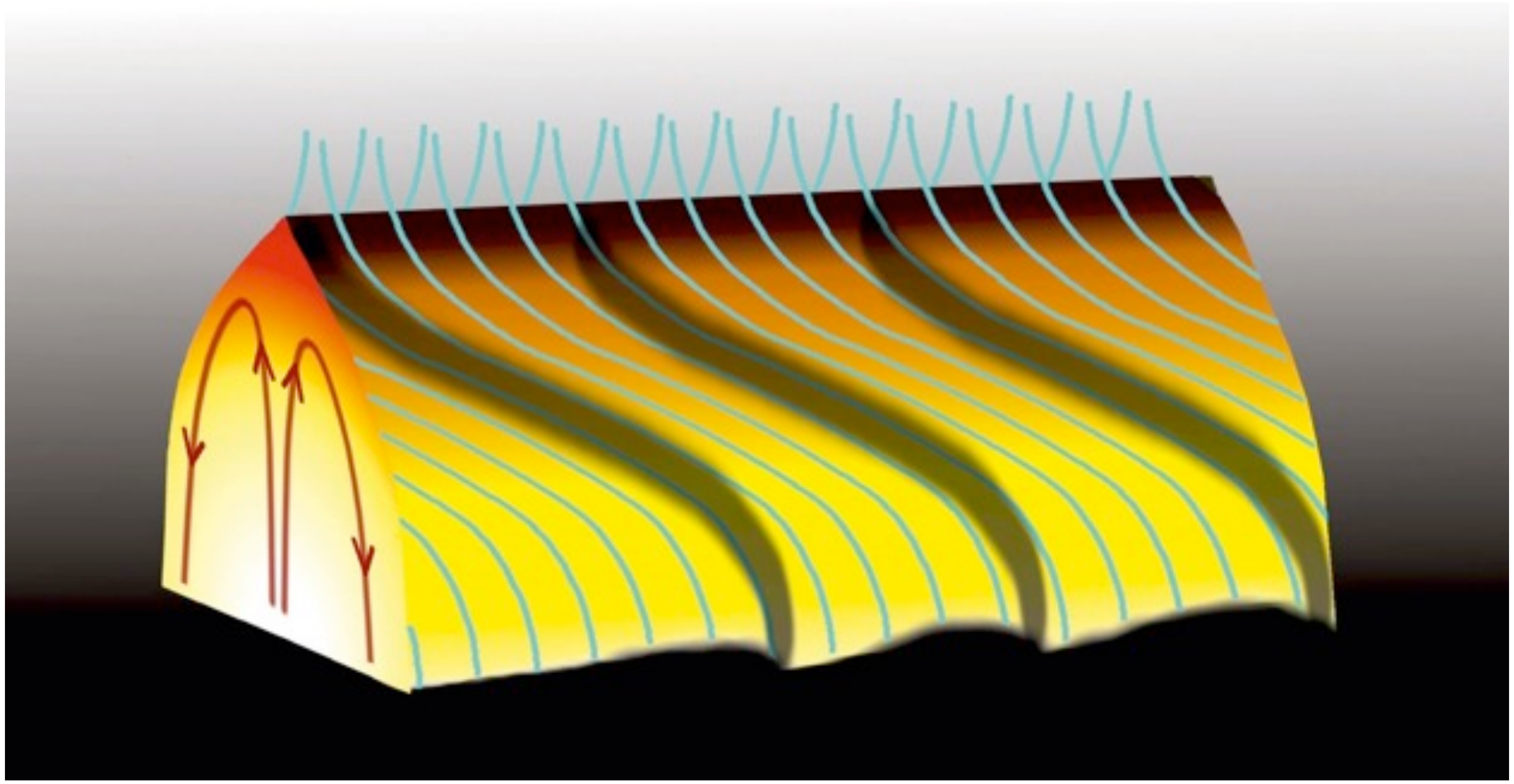


The gappy penumbra

HCS & Scharmer A&A 2006

cf.: umbral dots E.N. Parker, 1979





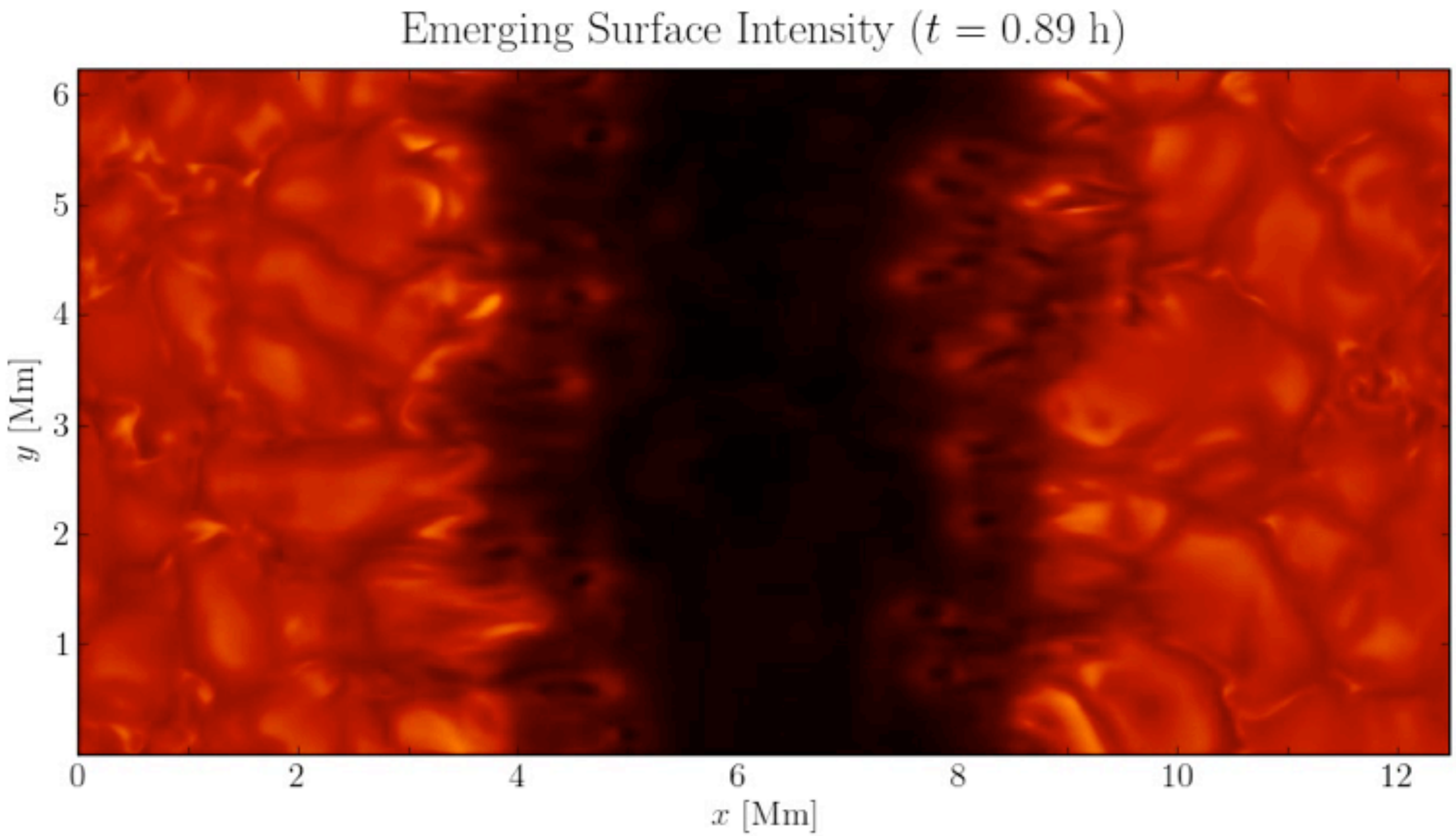
Yukawa 3/11/11

Synthetic 'spot'

Heinemann, Nordlund, Scharmer & Spruit A&A 2007

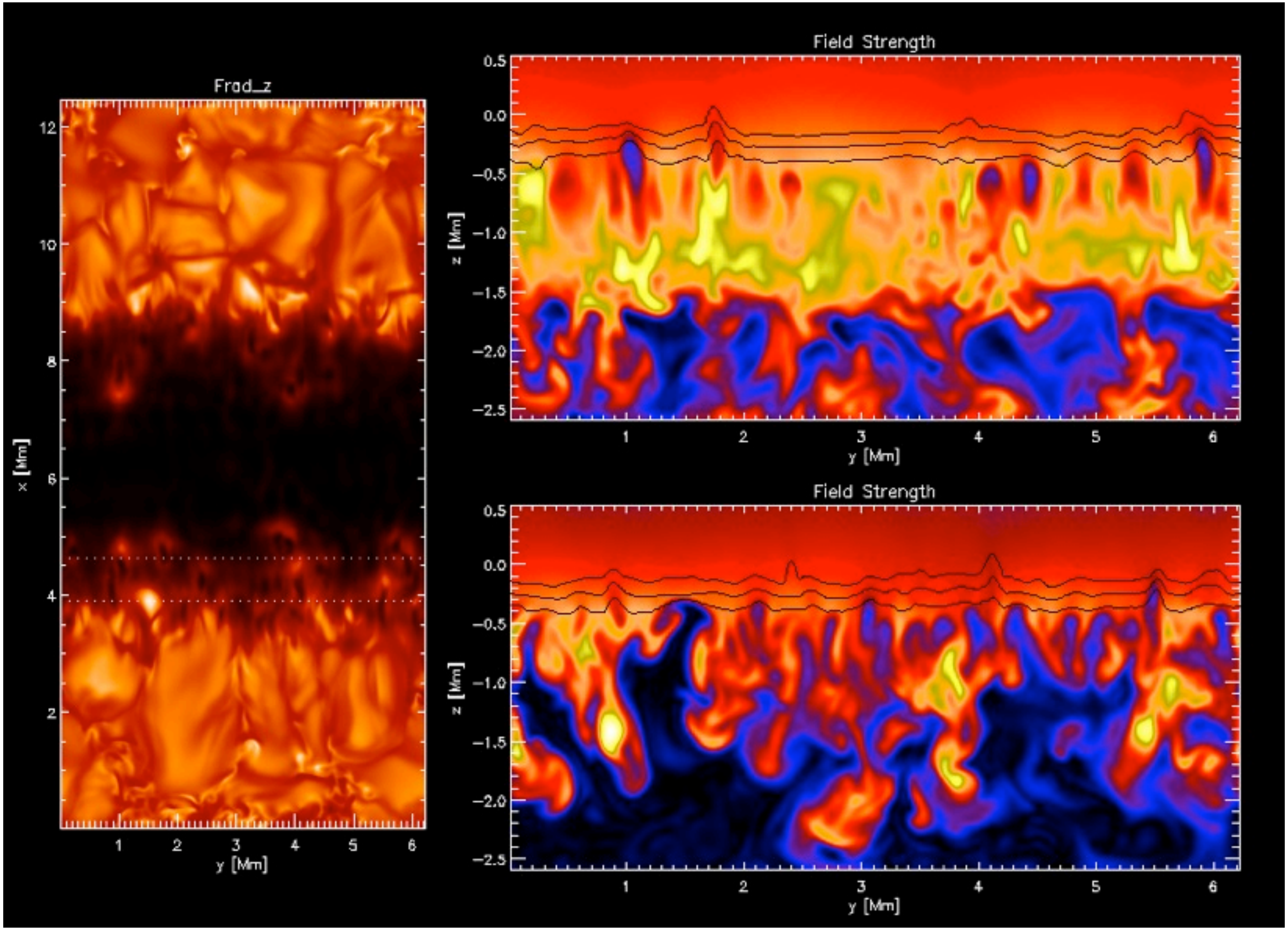
Yukawa 3/11/11

Synthetic 'spot'



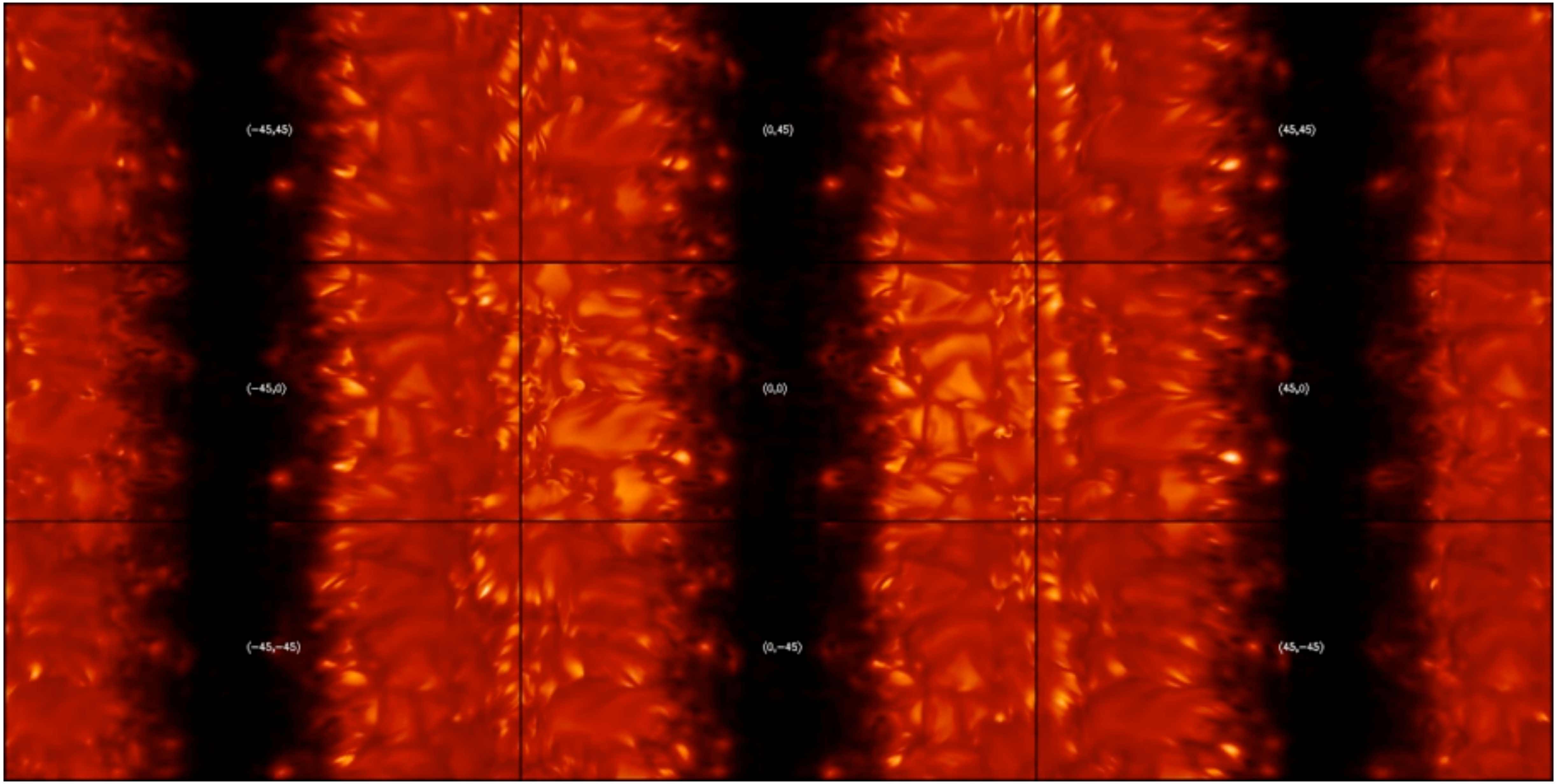
Heinemann, Nordlund, Scharmer & Spruit A&A 2007

vertical structure of filaments



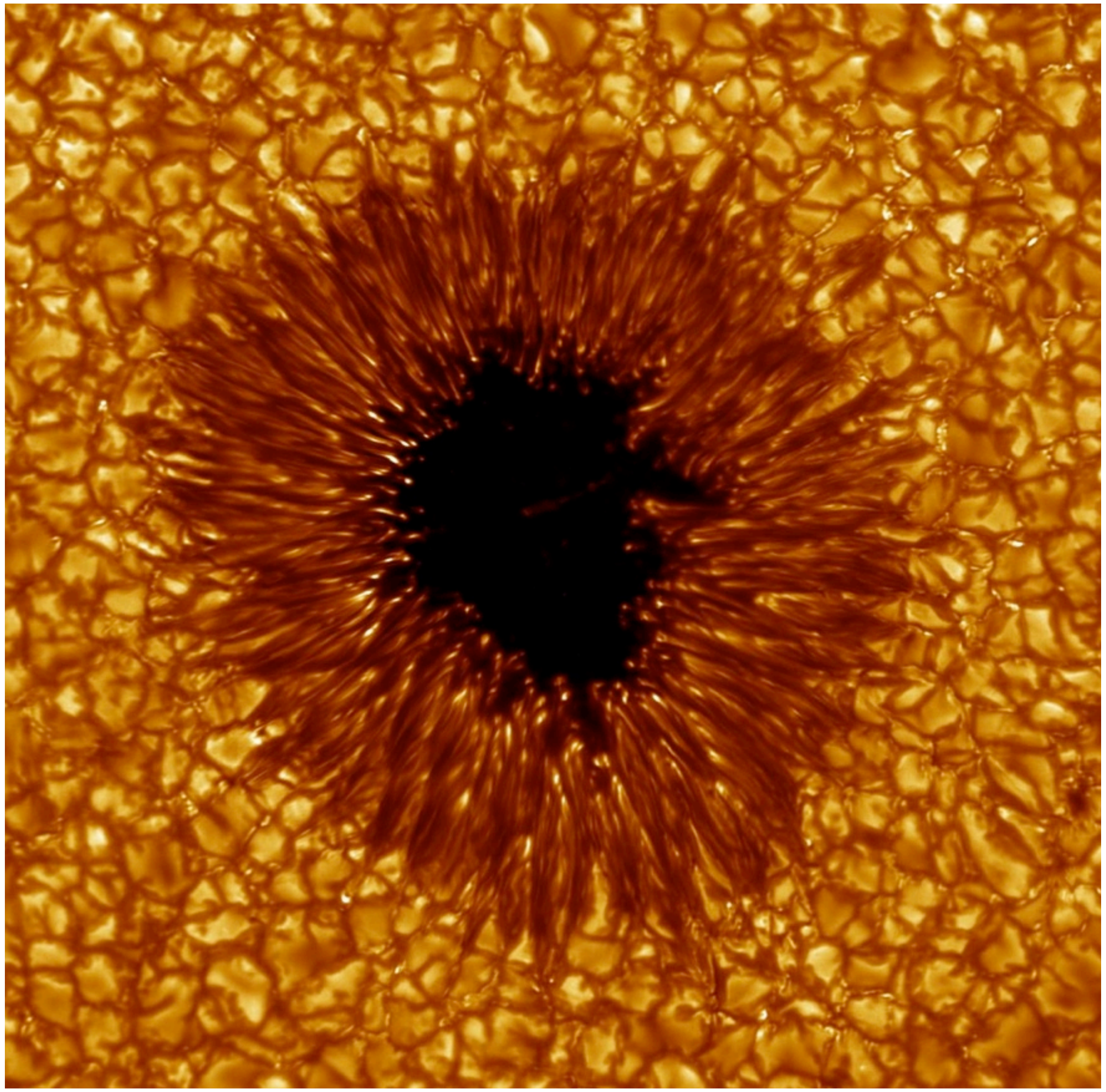
Yukawa 3/11/11

dependence on viewing angle

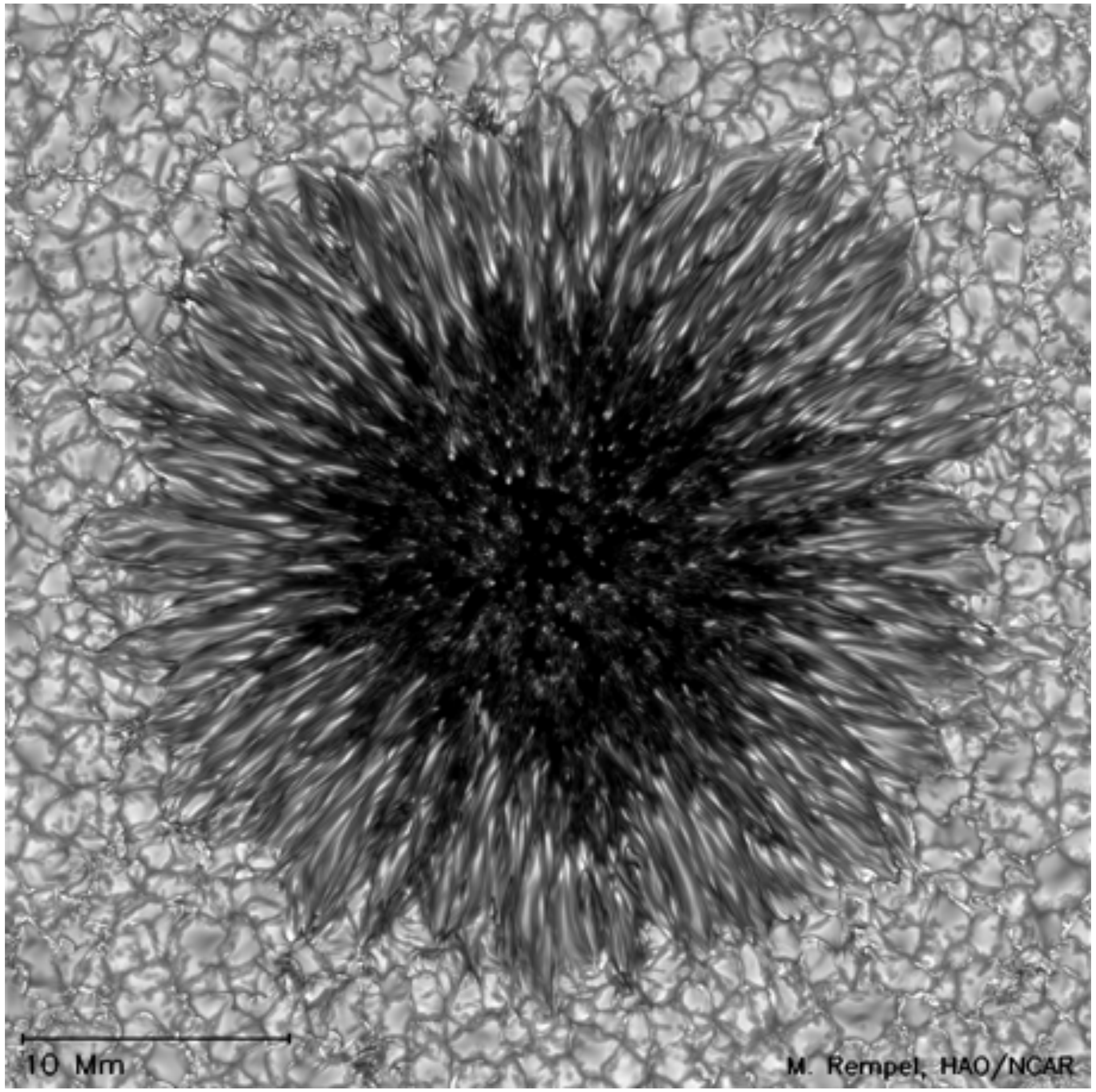


Yukawa 3/11/11

Real and synthetic spots



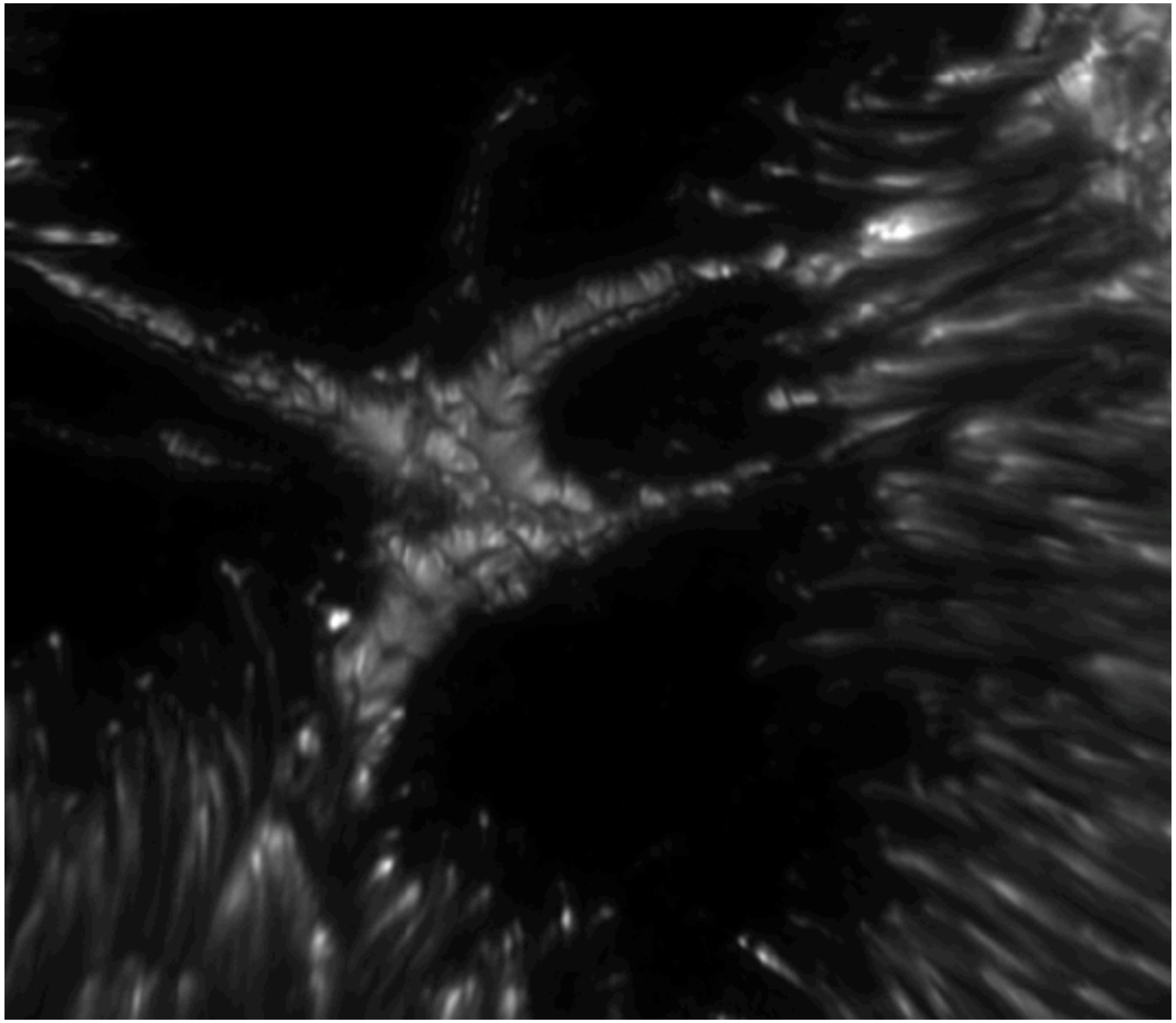
Swedish 1-m Solar Telescope



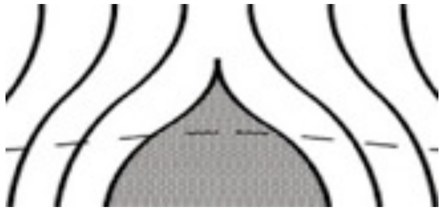
Simulation (M. Rempel)

Yukawa 3/11/11

Dark cores over light bridges



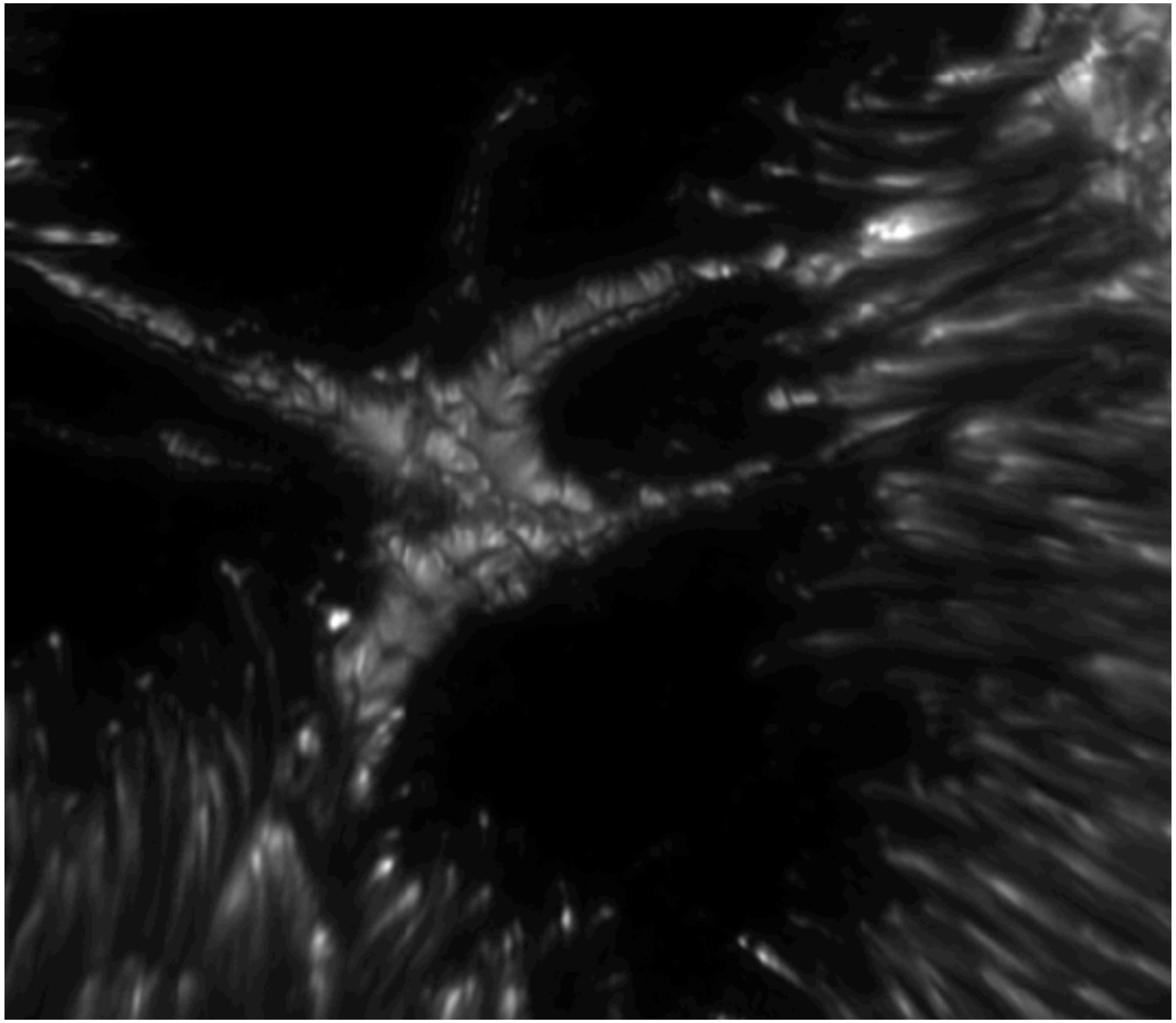
SST



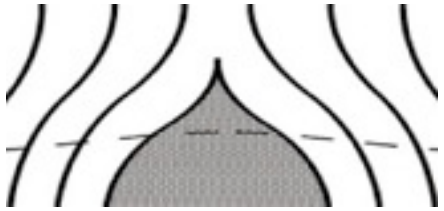
(Nordlund and Stein 2007)

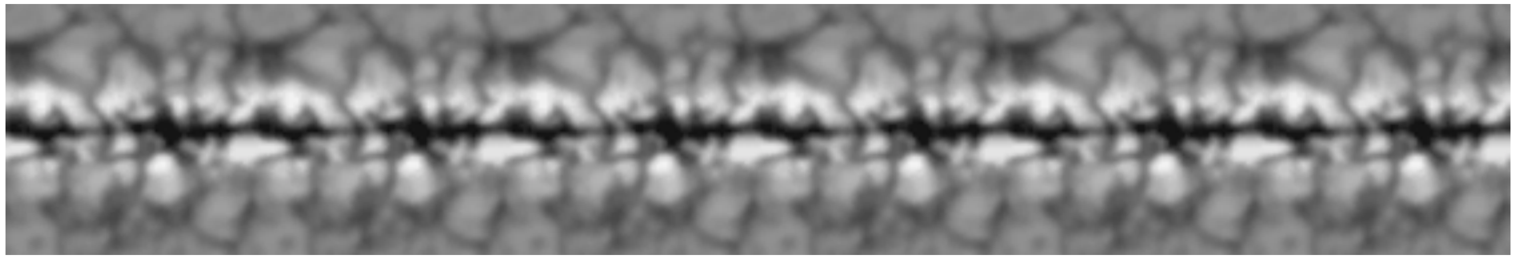
Yukawa 3/11/11

Dark cores over light bridges



SST





(Nordlund and Stein 2007)

Yukawa 3/11/11

simulations: conclusions

small scale field: last part

numerically possible:
- surface phenomenology of magnetic structures

reproduces:
- moat flow, inward propagation of filaments, dark cores, Evershed flow.

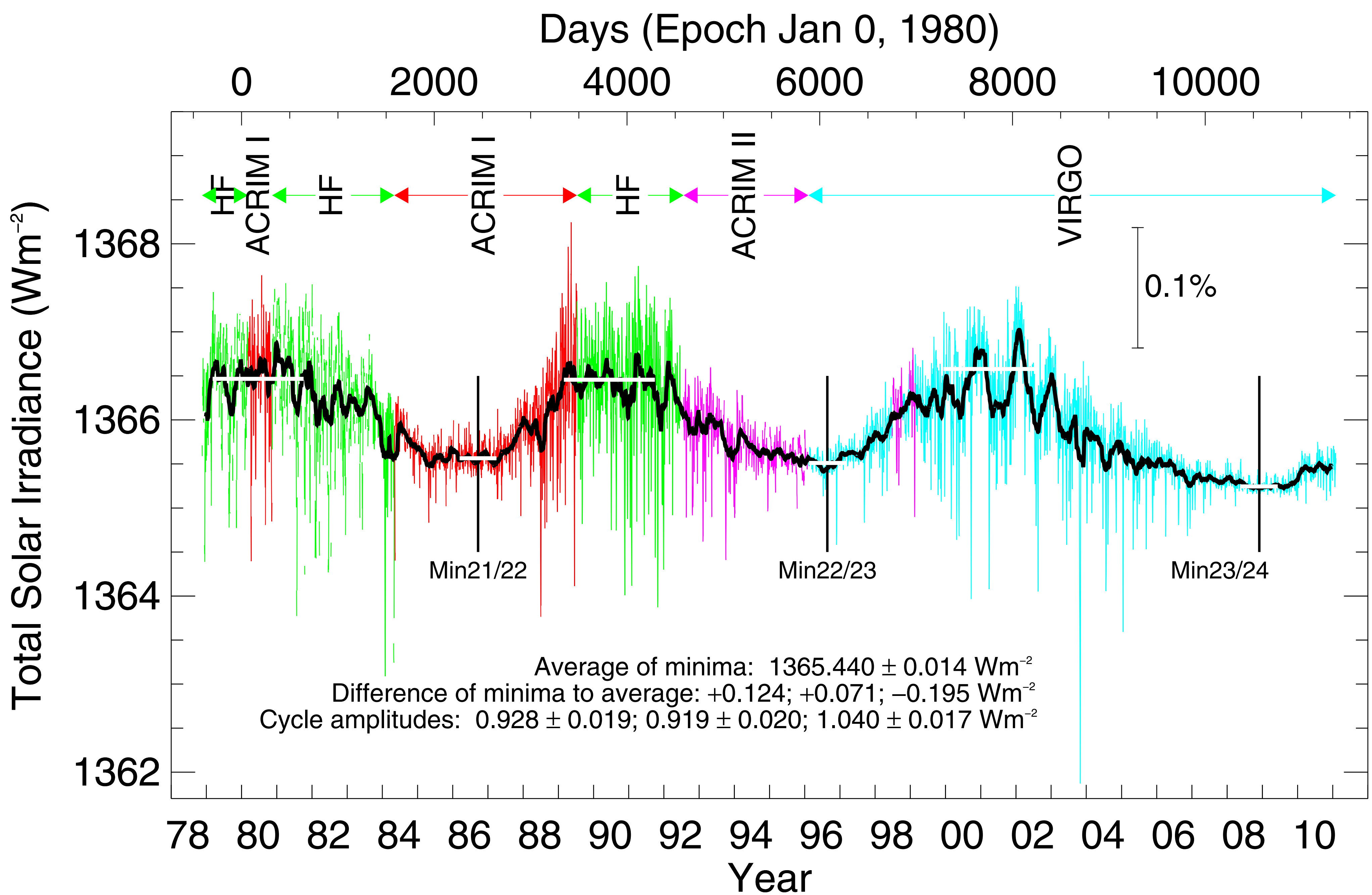
physical explanation: still t.b.d ...

convergence with observations at $\leq 0\farcs1$

not possible:
- AR/spot size, surface distribution, depth of origin
- the solar cycle

$\therefore$: confidence in the numerics + physics included in realistic MHD

Magnetic brightening of the Sun



C. Fröhlich et al. 2011

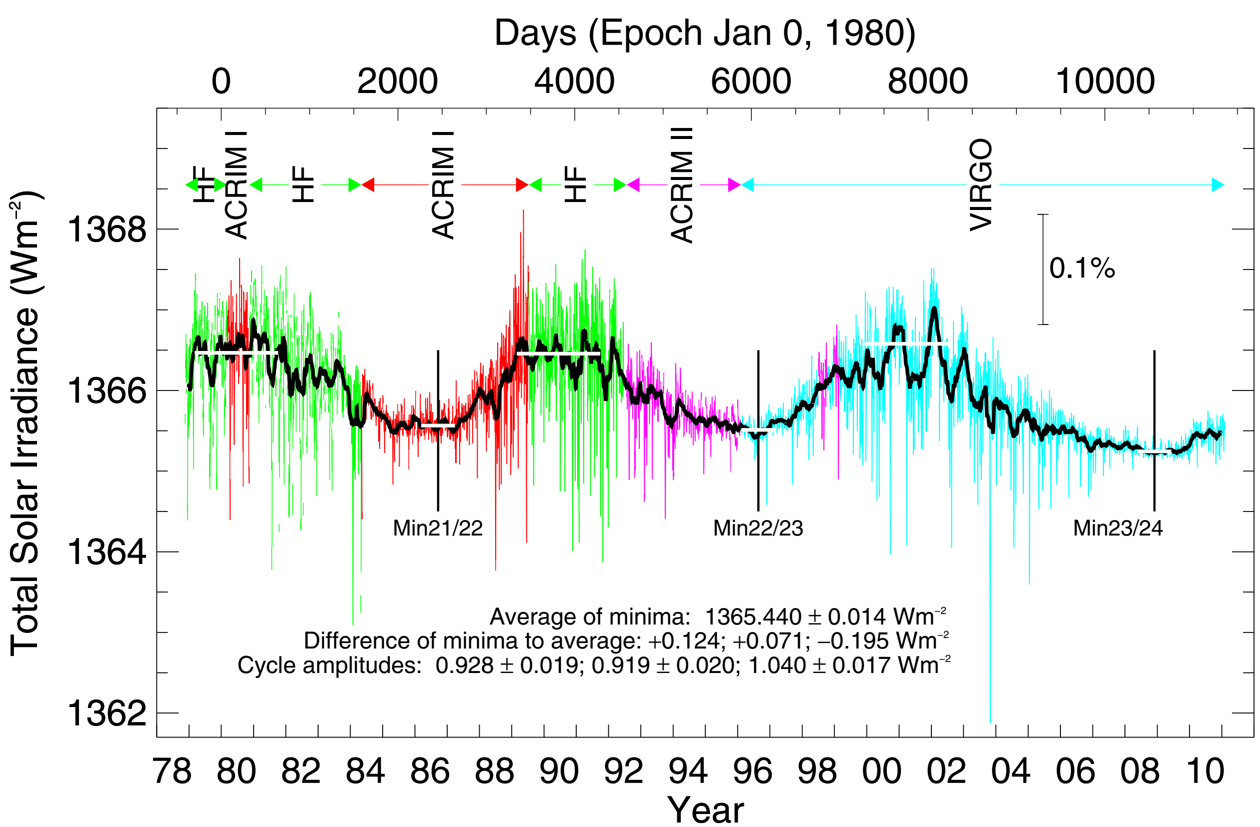
Yukawa 3/11/11

<-- more subtle effects
- `amplification' : unlikely

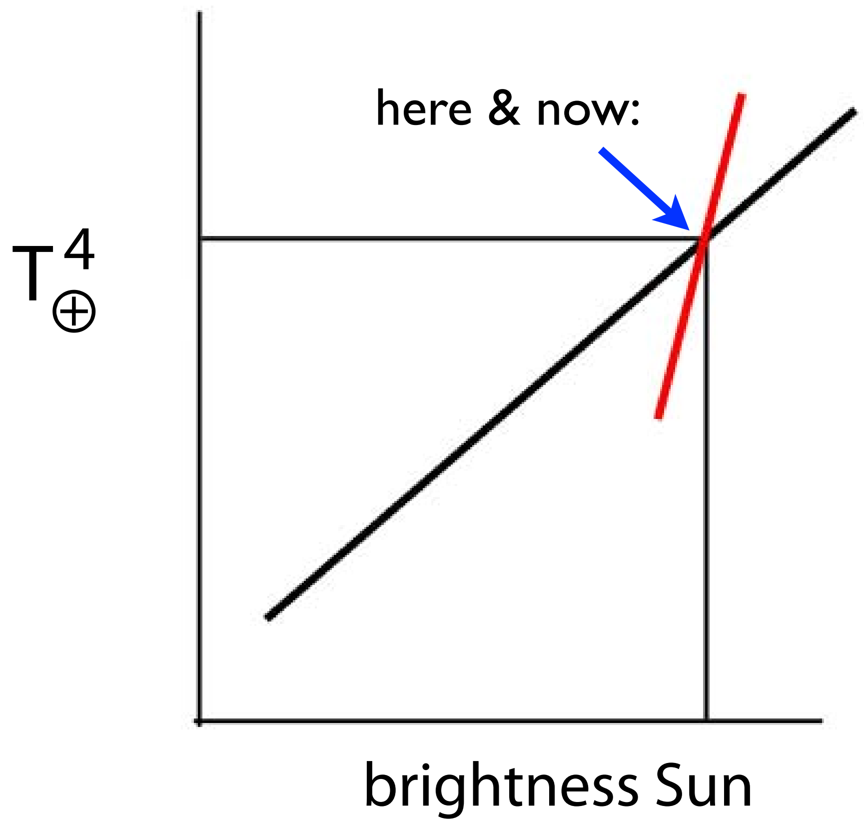
Magnetic brightening of the Sun

- brightness of small scale field dominates over spot darkening
- 0.08% cycle variation of TSI has no climate effect

- possibly larger longer term variations?
  * magnetic fields
  * as yet unknown mechanisms



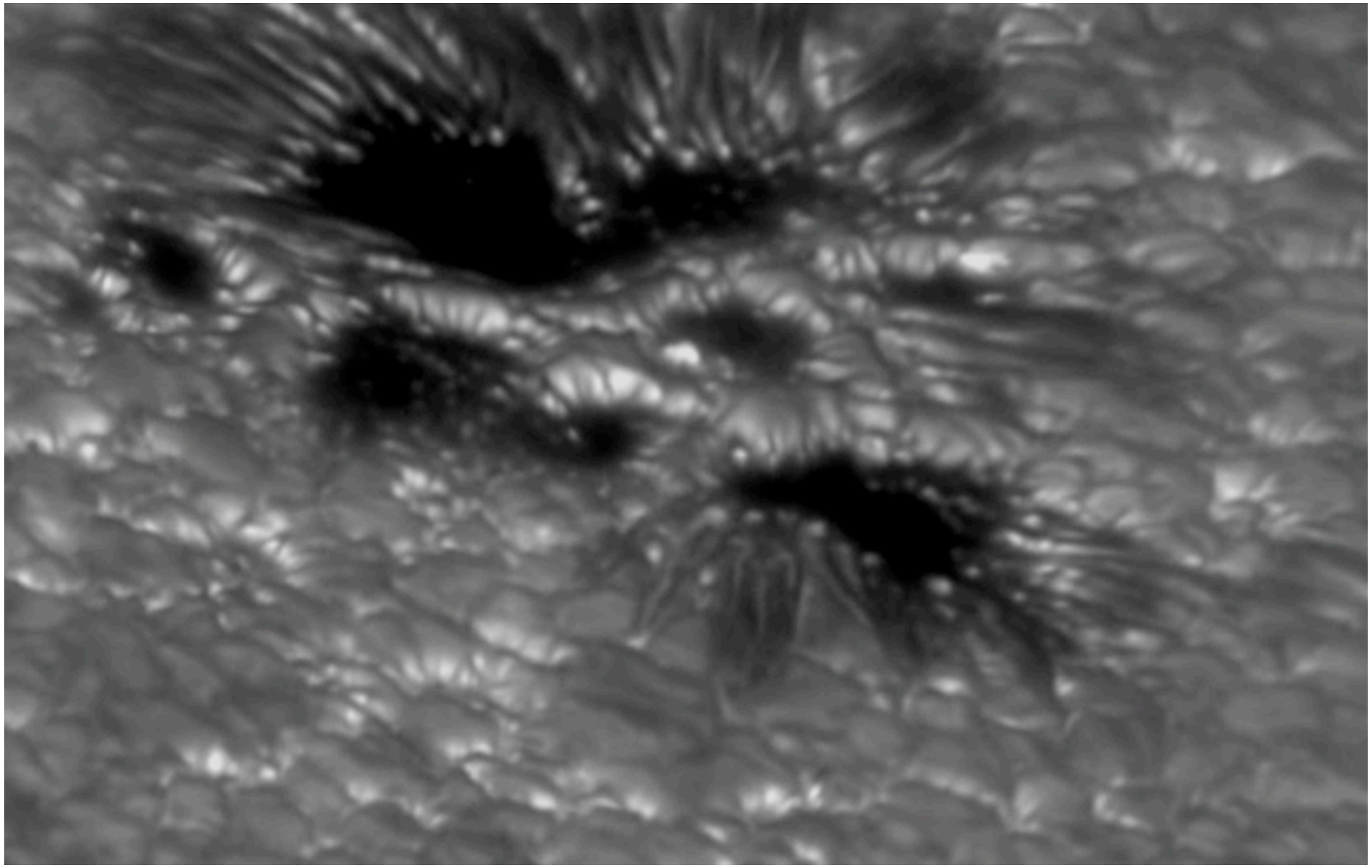
amplification:



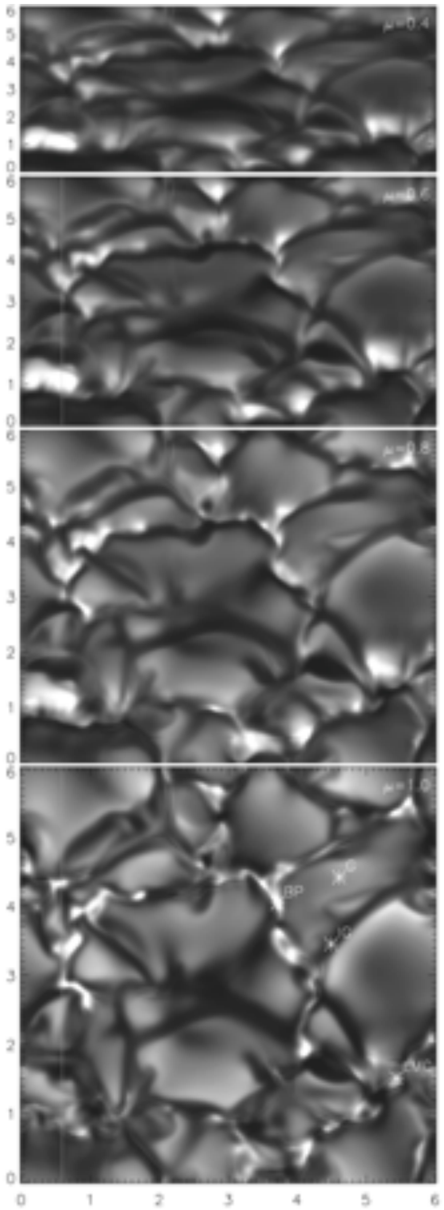
Yukawa 3/11/11

Magnetic brightening of the Sun

'bright wall effect' :



SST

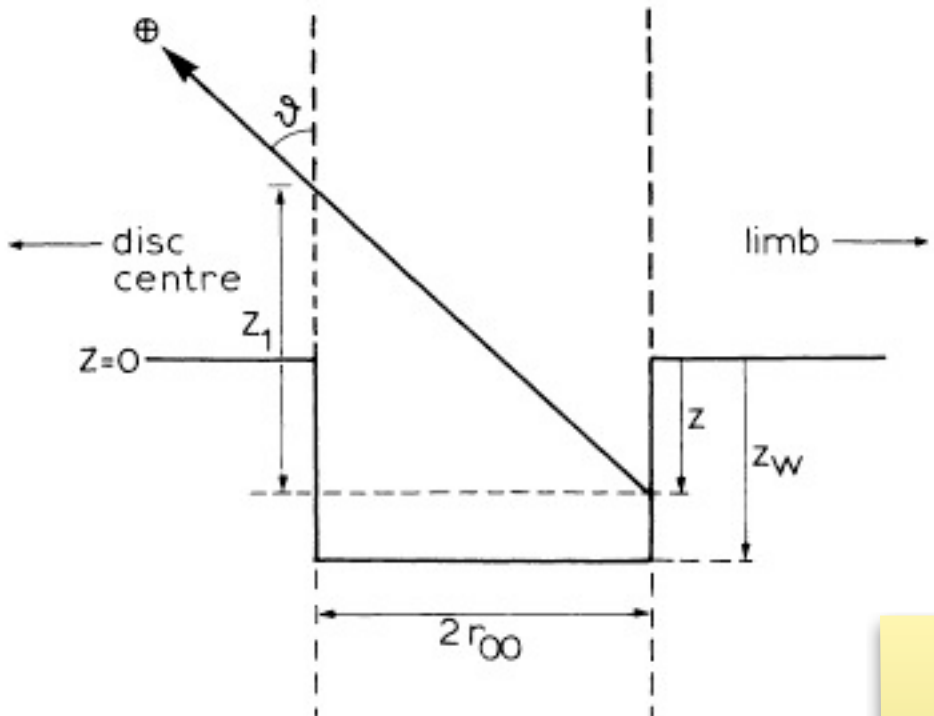


simulation

Yukawa 3/11/11

Magnetic brightening of the Sun

'bright wall effect' :



- small scale field causes heat leaks in surface HCS 1977

→ enhanced cooling

→ geostrophic flows around AR → 'torsional oscillation' HCS 2003

important epicycle skipped here ...

Yukawa 3/11/11

Magnetic brightening of the Sun

'quiet Sun' : $\langle |B_z| \rangle \approx 10\,\mathrm{G}$

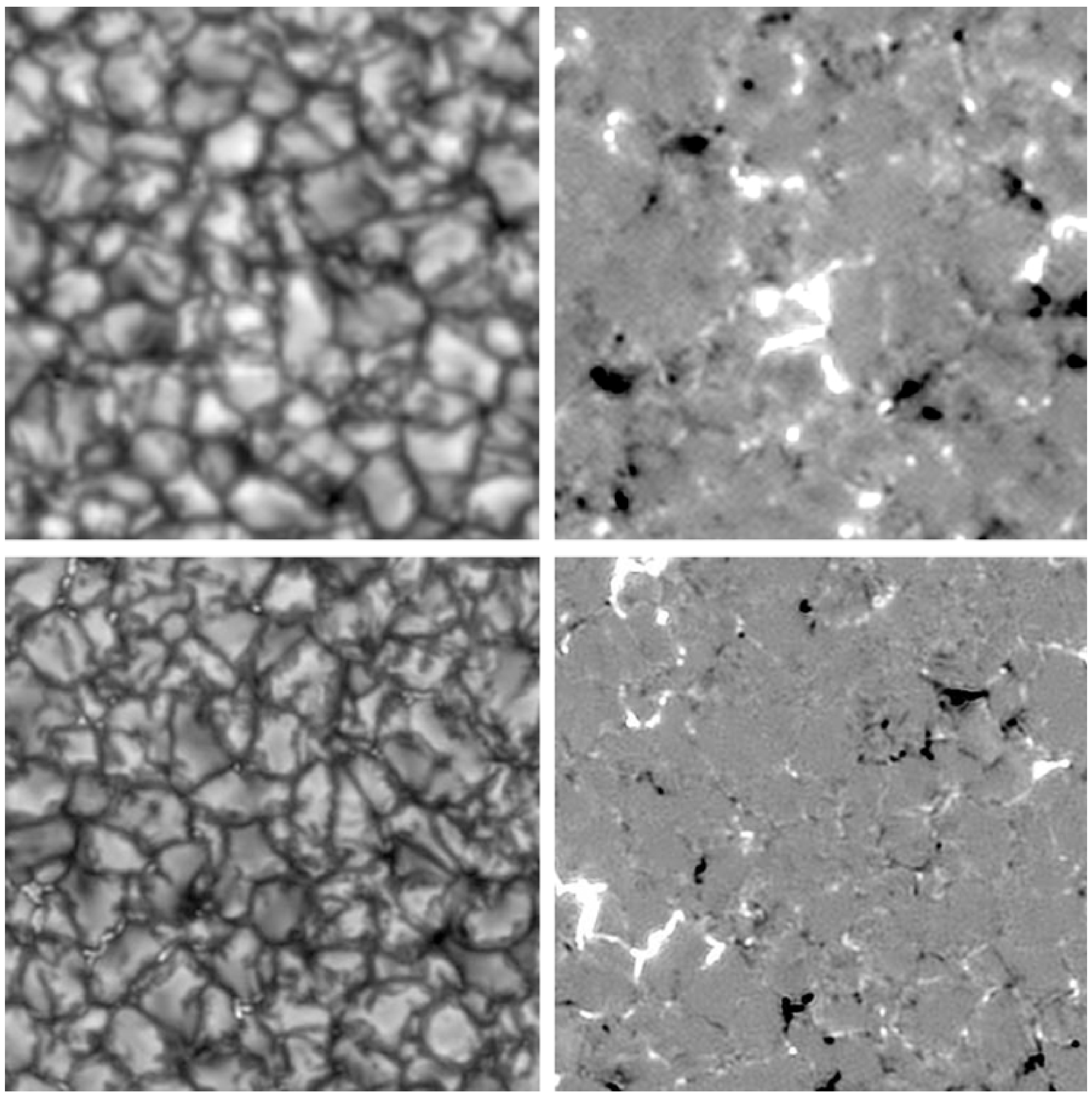
Q: - dependence on cycle phase?
- effect on brightness?
- long term variation?

Yukawa 3/11/11

Measuring magnetic brightening of the Sun

R. Schnerr & HCS, 2011

I_630　　　　B_z



disk center

Hinode

<|B_z|>=11 G

$$\delta I_{\rm mag}/I = 1.2\,10^{-3}$$

SST

<|B_z|>=10 G

$$\delta I_{\rm mag}/I = 1.5\,10^{-3}$$

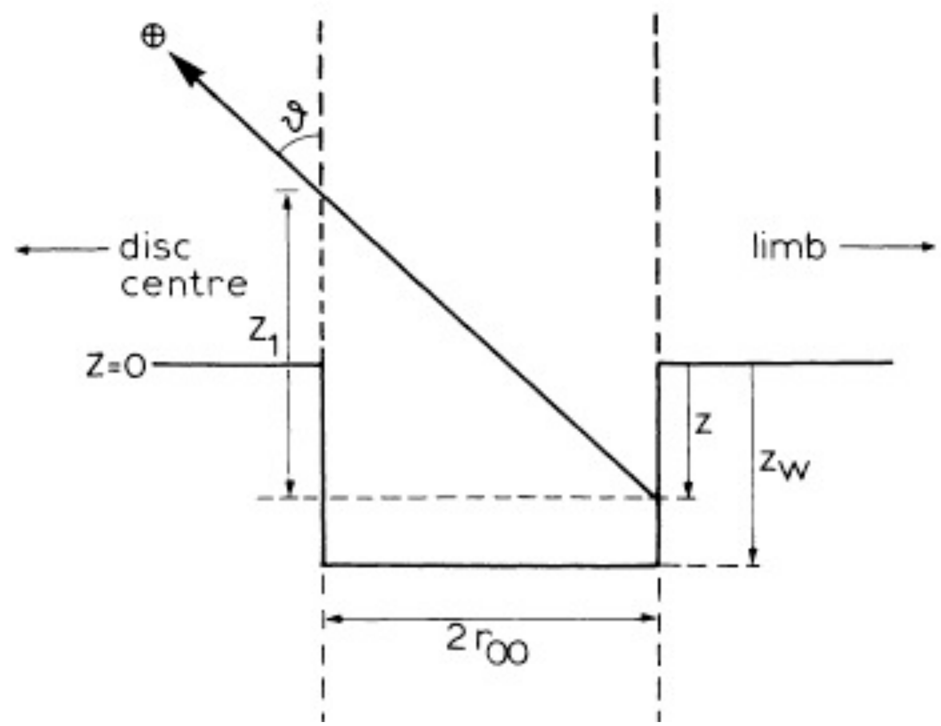
relation with `inner network' fields
(Livingston & Harvey 1975)

Yukawa 3/11/11

measured (disk center): $\delta I_{\rm mag} \approx 1.5\,10^{-3}$ $(\langle B_z \rangle = 10\,{\rm G})$

does not include:

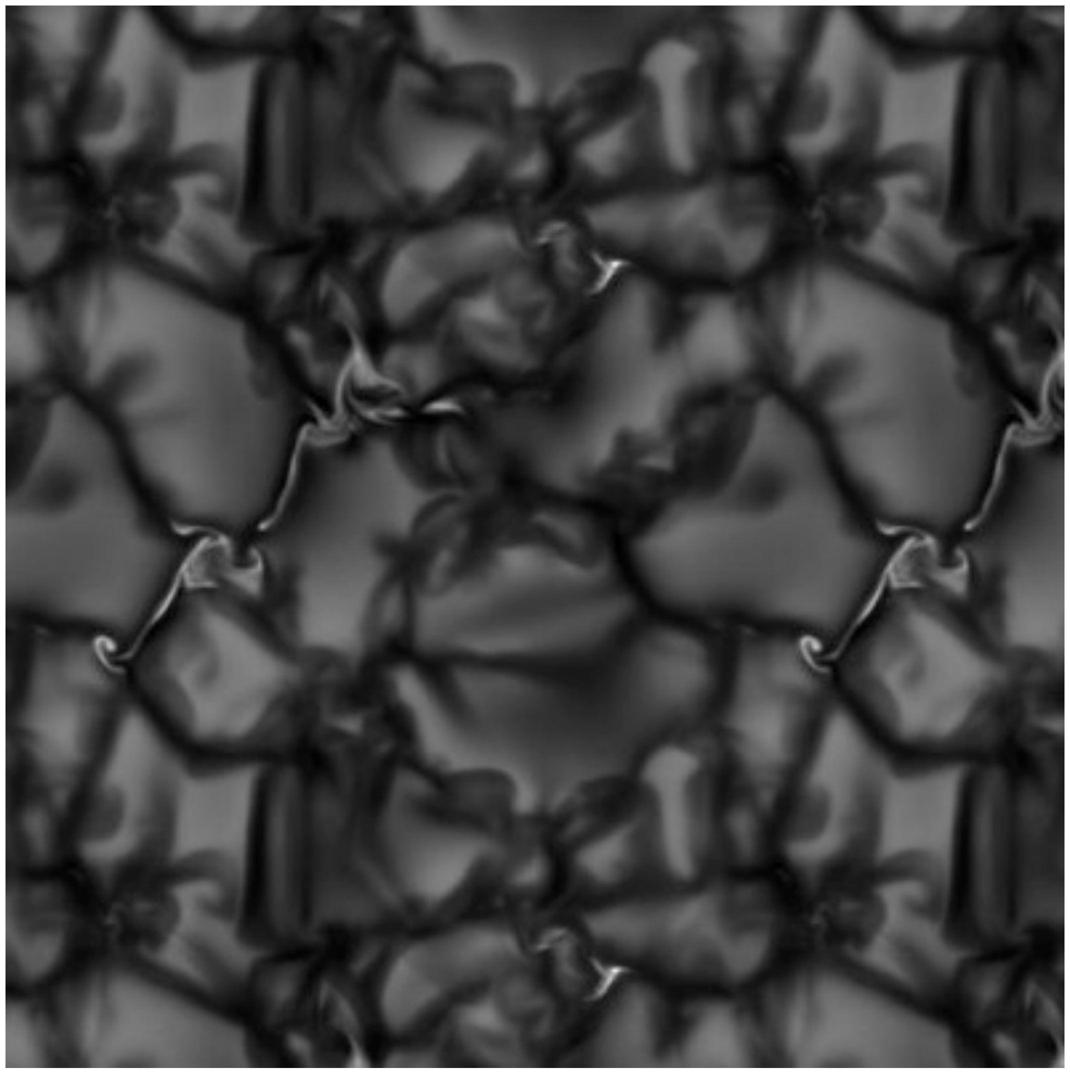
- dark rims (compensation)
- effect on surrounding granulation ??

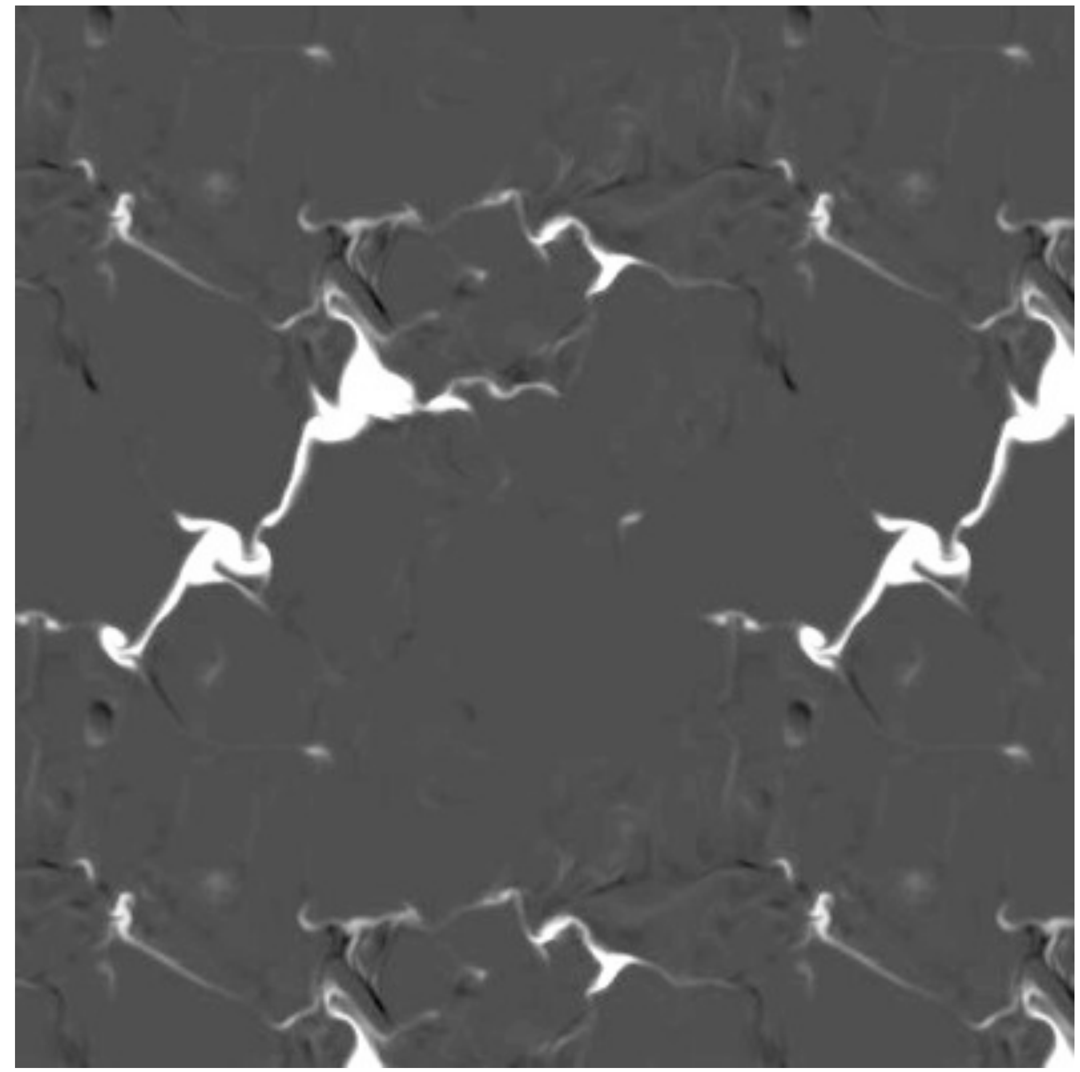


Yukawa 3/11/11

Measuring magnetic brightening with numerical simulations

Bolometric flux $< B_z >= 50\,\mathrm{G}$ B_z

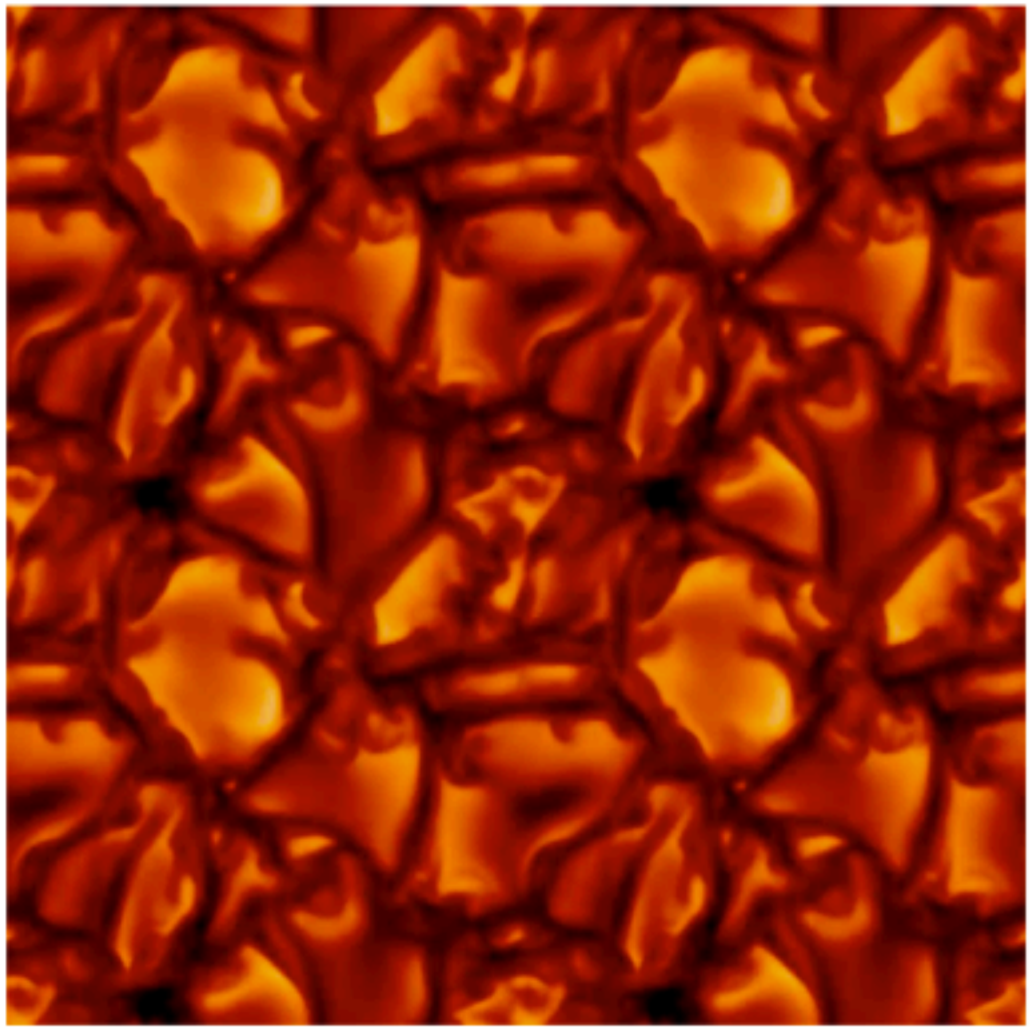




Thaler et al. in prep. 6x6 Mm, Stagger code 320x320x200

Measuring magnetic brightening with numerical simulations

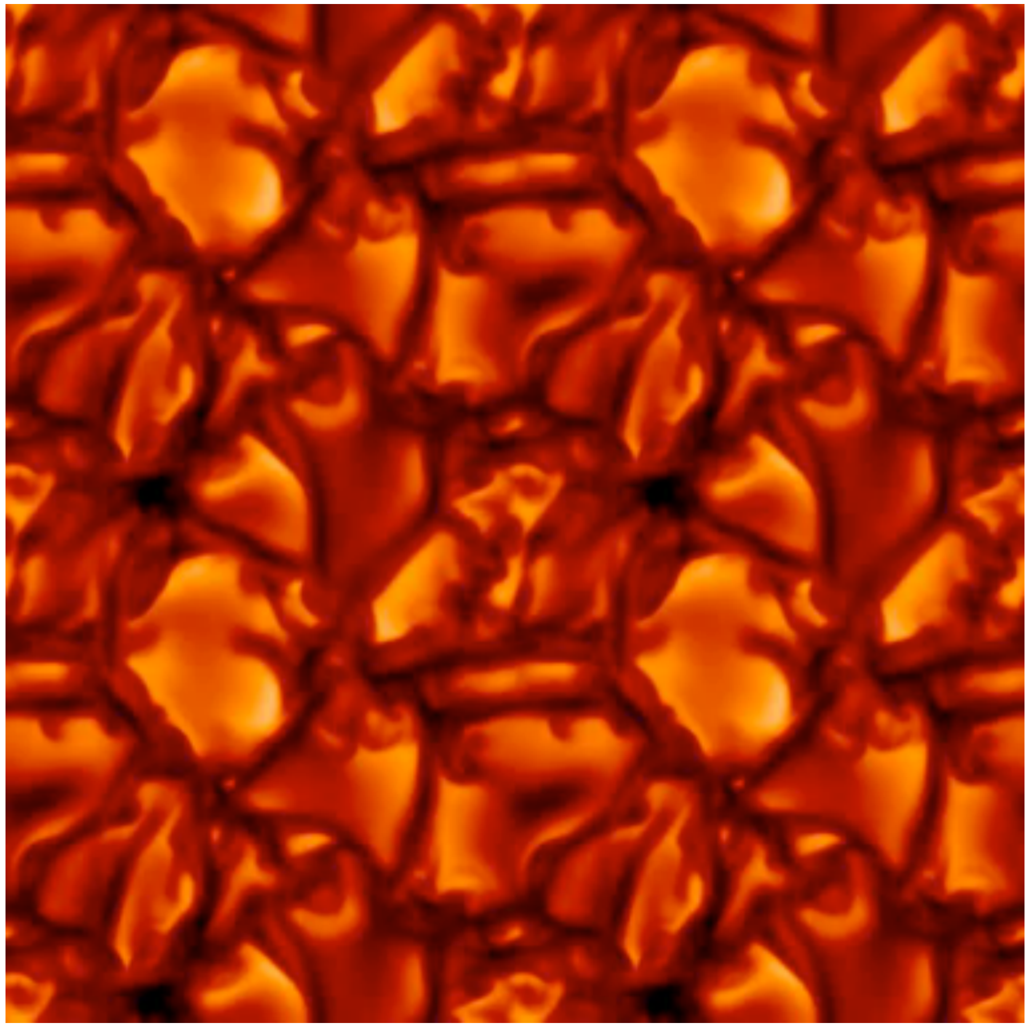
Bolometric flux $< B_z >= 50\,\mathrm{G}$ B_z



Irina Thaler & Remo Collet @ MPA

Measuring magnetic brightening with numerical simulations

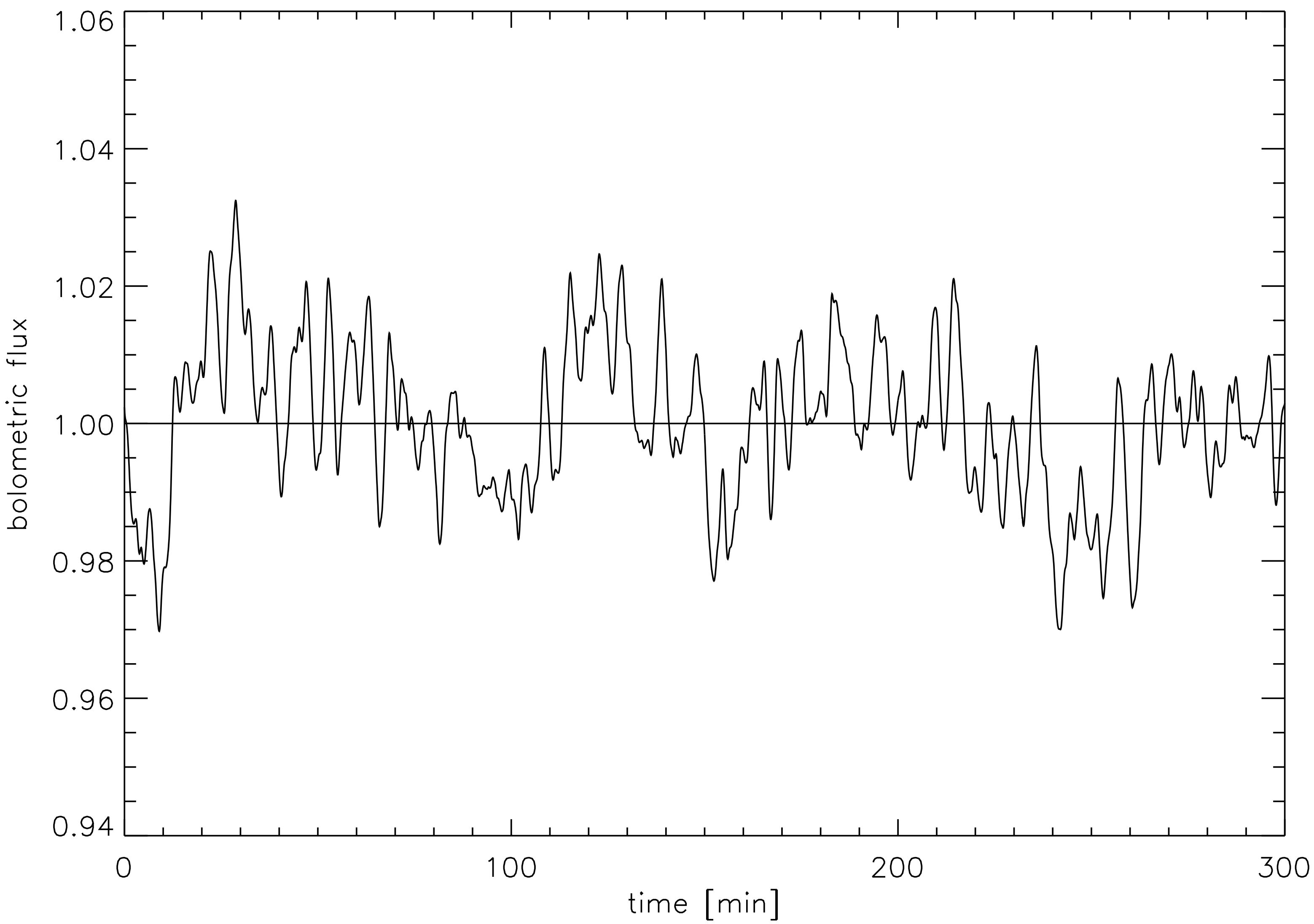
Bolometric flux $< B_z >= 50\,\mathrm{G}$ B_z

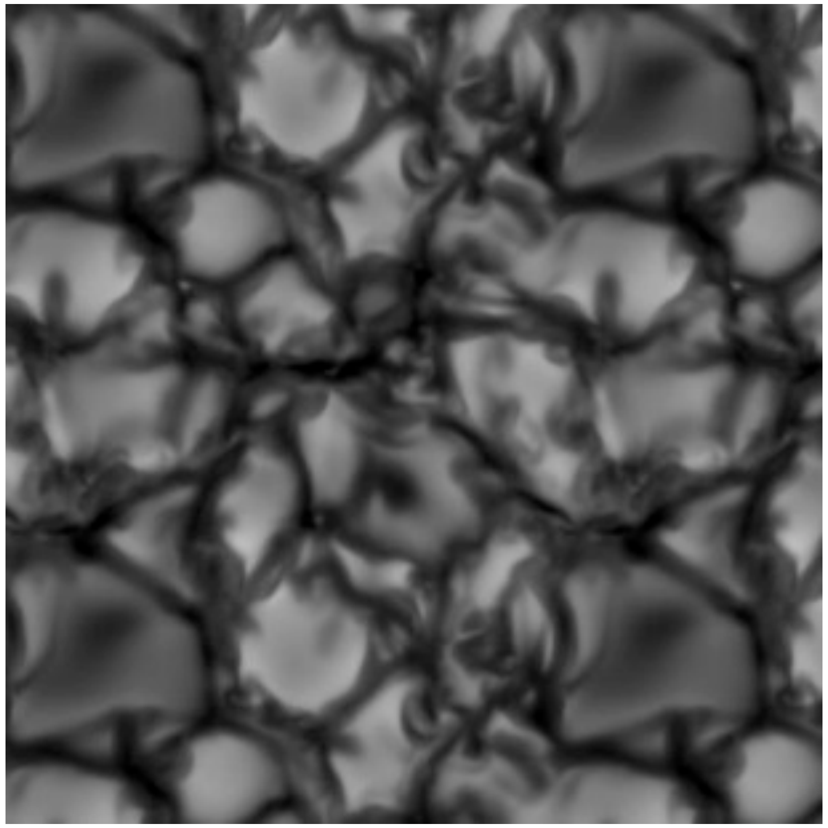


Irina Thaler & Remo Collet @ MPA

Opposite polarities develop. Inner network field? (Livingston & Harvey 1975)
'surface dynamo'? (Schüssler et al. 2007)

Granulation (B=0, 6x6 Mm)





Yukawa 3/11/11

result (preliminary):

$$\langle B_z \rangle = 50\,\mathrm{G} \rightarrow \delta F/F_{\mathrm{bolometric}} < 0.5\%$$

(effect possibly **negative**)

under investigation ...

Q: - cycle dependence?
- is the background field a 'local dynamo'?

Conclusions

- observations contain more clues about the cycle than used in models.
- observations rule out the 'turbulent interaction' type of model.

- num sim of the whole solar cycle **cannot** be done from scratch
- other things **can** be done:
  * granulation
  * surface structure of small scale fields and sunspots
    (done by hand: magnetic field imposed at bottom boundary)

- results from sims:
  * quantitative understanding of small surface B structures:
  * penumbral filament structure understood
  * inward propagation & Evershed flow reproduced
  * → confidence in completeness of physics and numerical methods

- magnetic brightening:
  * possible effect on climate very controversial
  * contribution of the weak 'background' field ? sign?

Yukawa 3/11/11

Howl’s moving castle (Miyazaki)

Backside view with helioseismic reconstruction

Also can send a satellite to look @ back: cheating

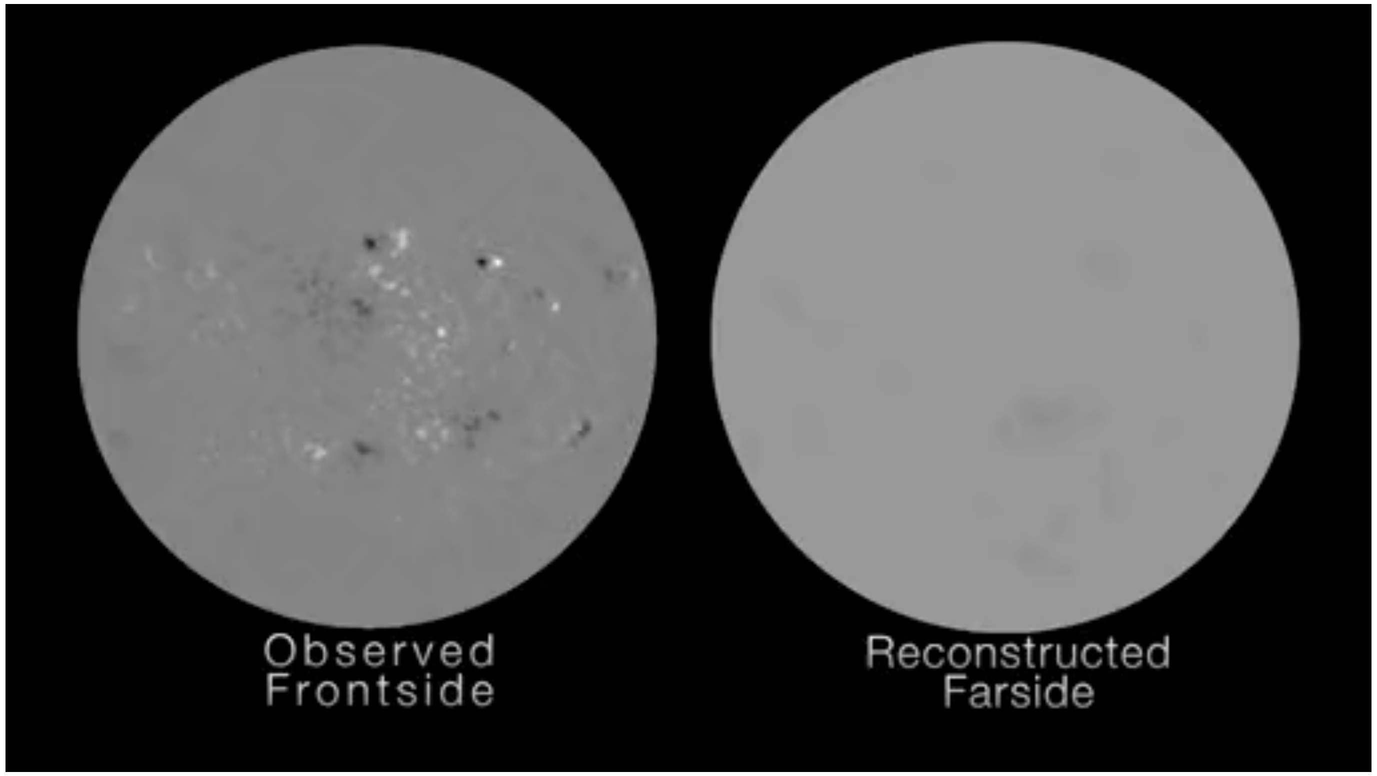
SOHO/MDI, Stanford Solar Oscillations group

... still think it's cheating

Yukawa 3/11/11

Backside view with helioseismic reconstruction

Also can send a satellite to look @ back: cheating



SOHO/MDI, Stanford Solar Oscillations group

... still think it's cheating

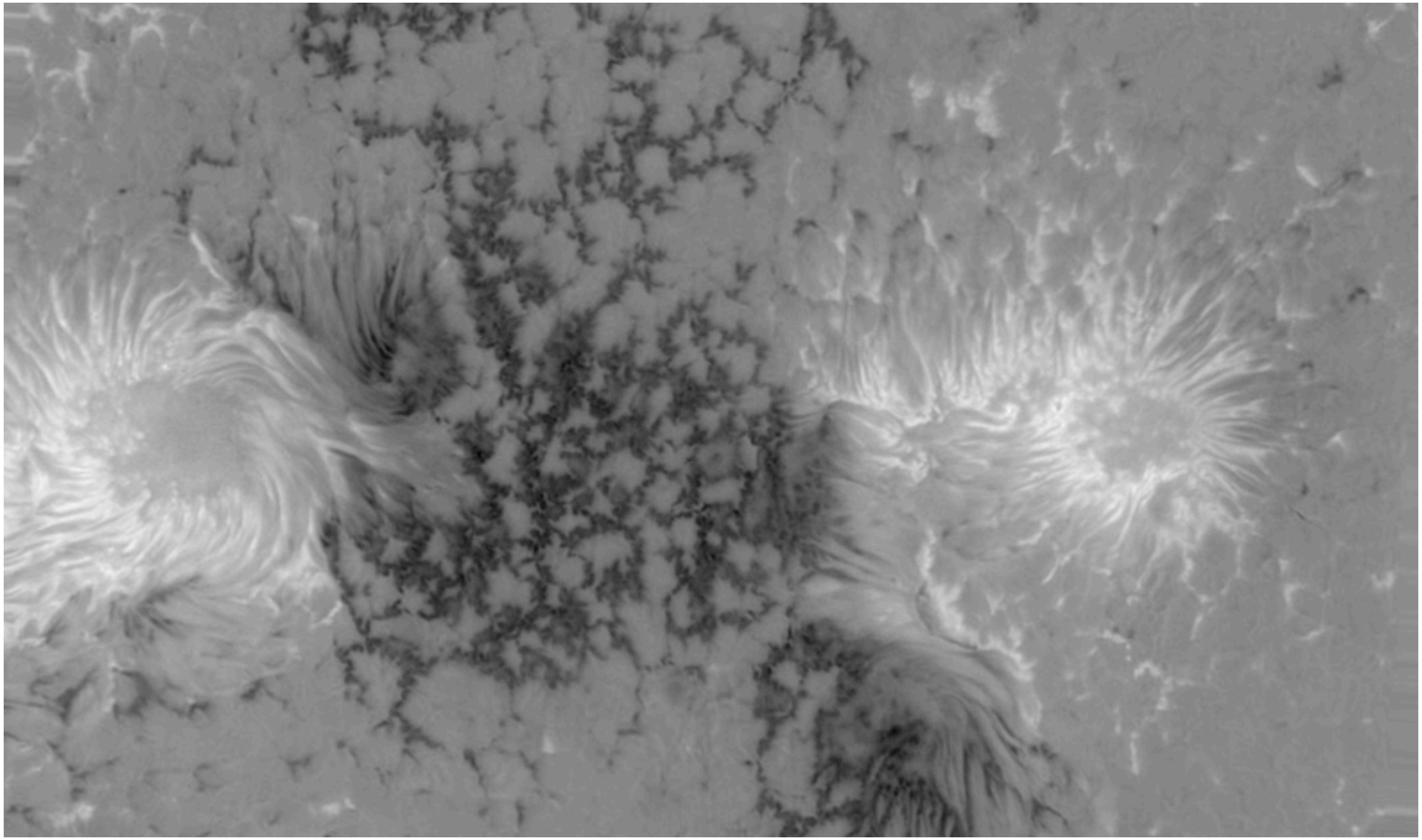
Yukawa 3/11/11

Magnetic field in an active region

Swedish 1-m Solar Telescope

Yukawa 3/11/11

Magnetic field in an active region



Swedish 1-m Solar Telescope

Yukawa 3/11/11

Things happening on the surface

- Emergence of active regions: clues to the cycle's workings
- Sunspot structure (success in realistic radiative MHD simulations)
- Small scale fields: brightness effect

Yukawa 3/11/11

Yukawa 3/11/11