How deep are sunspots ?

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Solar Group Seminar, MPS, Göttingen, 2015-05-12

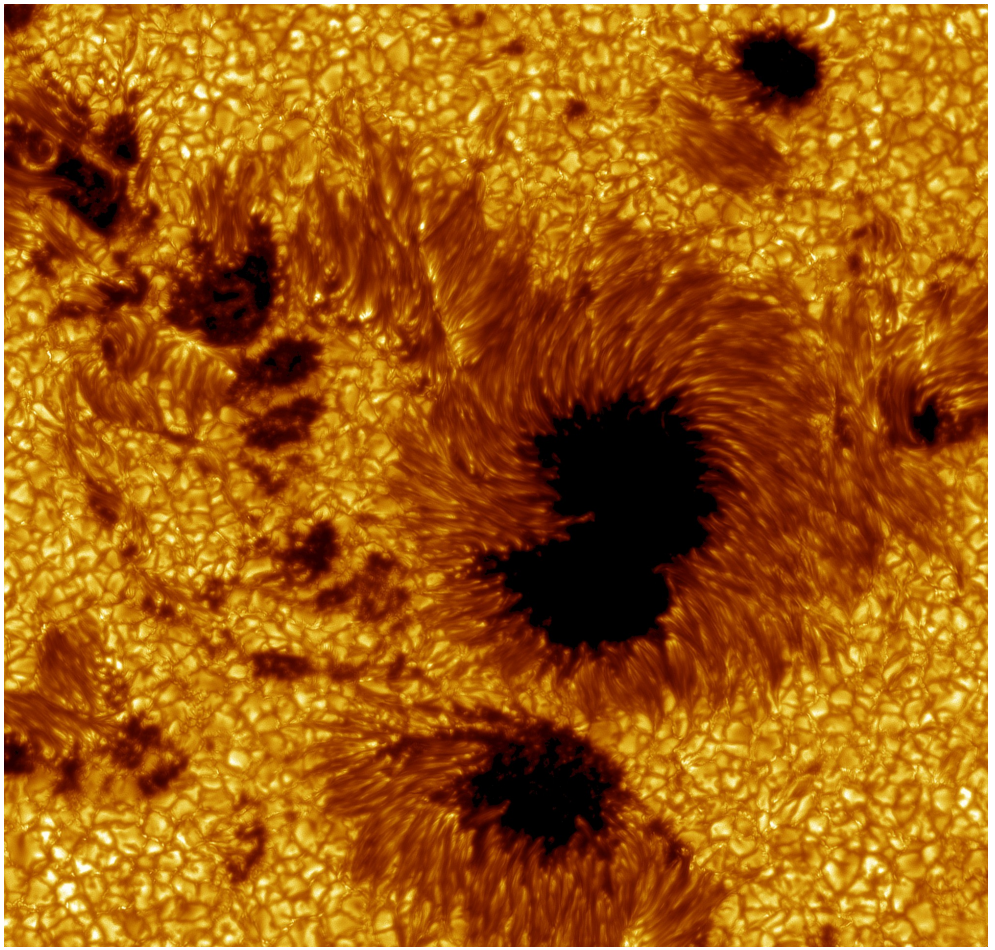
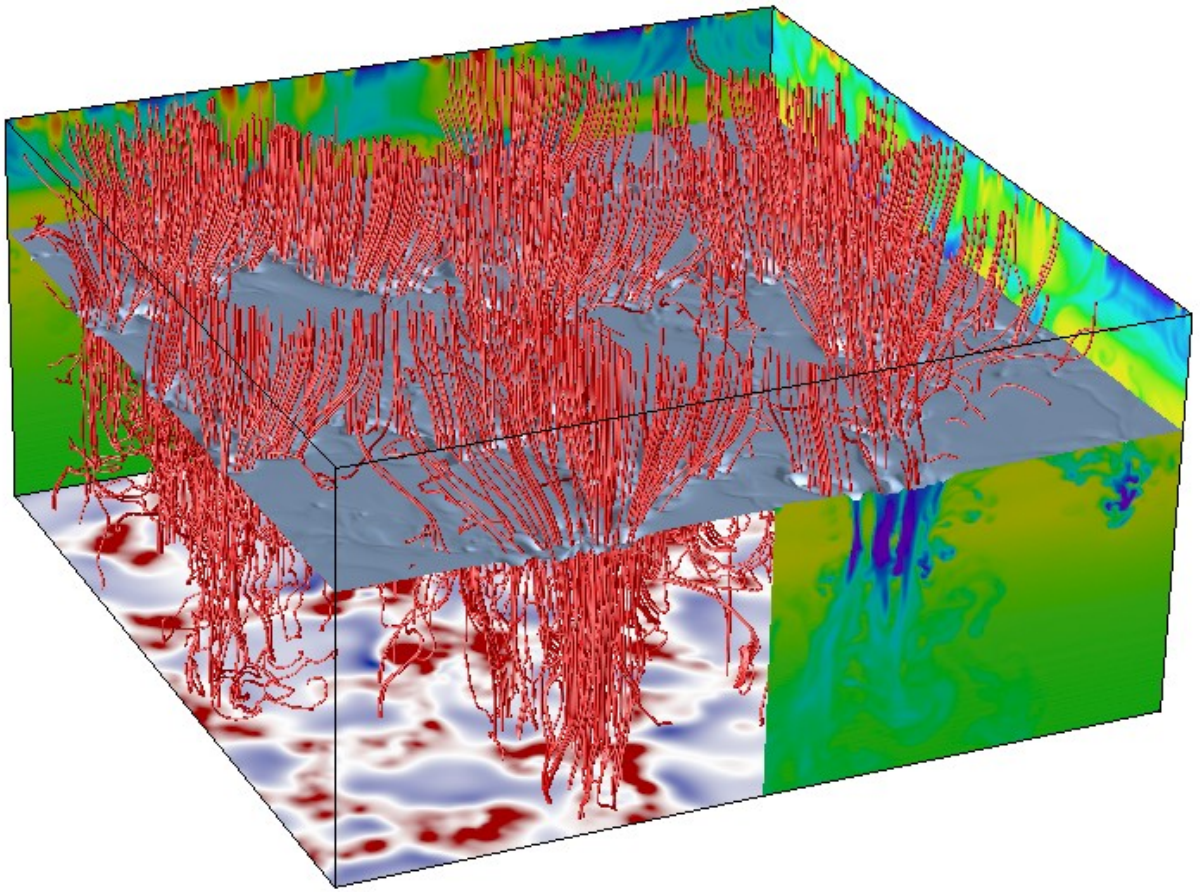


Image credit: G. Scharmer, Institute for Solar Physics, Royal Swedish Academy of Sciences

Simulations of magnetoconvection in cool main-sequence stars

(PhD thesis B. Beeck, 2014)

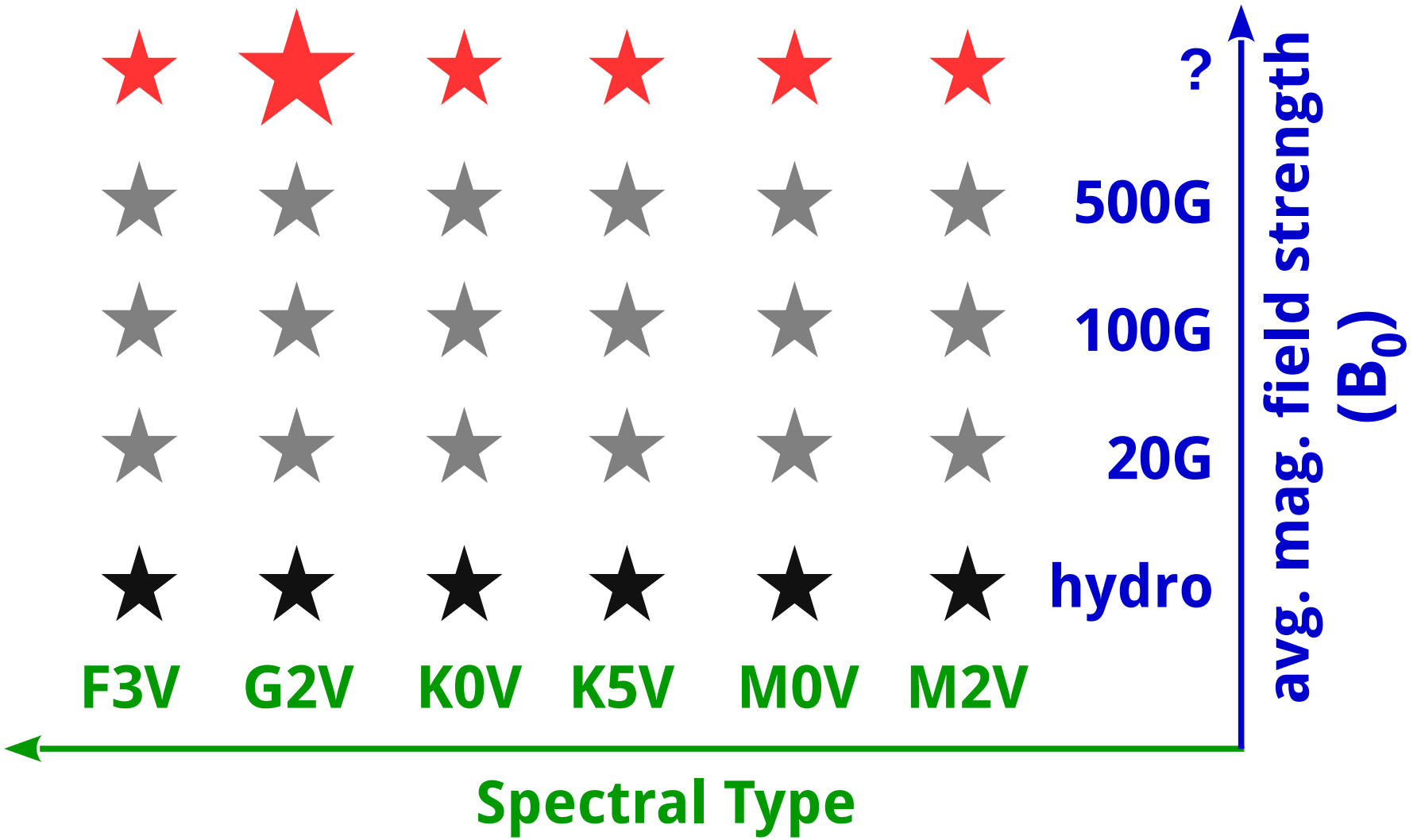


Grid of simulations

log g [cgs]	4.30	4.44	4.61	4.70	4.83	4.83
$T_{\rm eff}$	6900 K	5800 K	4900 K	4400 K	3900 K	3700 K
	F3V	G2V	K0V	K5V	M0V	M2V

Spectral Type

Grid of simulations



- **published:** **Beeck et al. (2013a), Beeck et al. (2013b)**
- **finished:** **Beeck et al. (2015a), Beeck et al. (2015b)**, *both accepted f. pub. in A&A*
- **work in progress**

Starspots

What we **do** know:

- existence (photometry, Doppler imaging)
- caused by magnetic field (activity proxies, theory)
- (distribution on surface)?

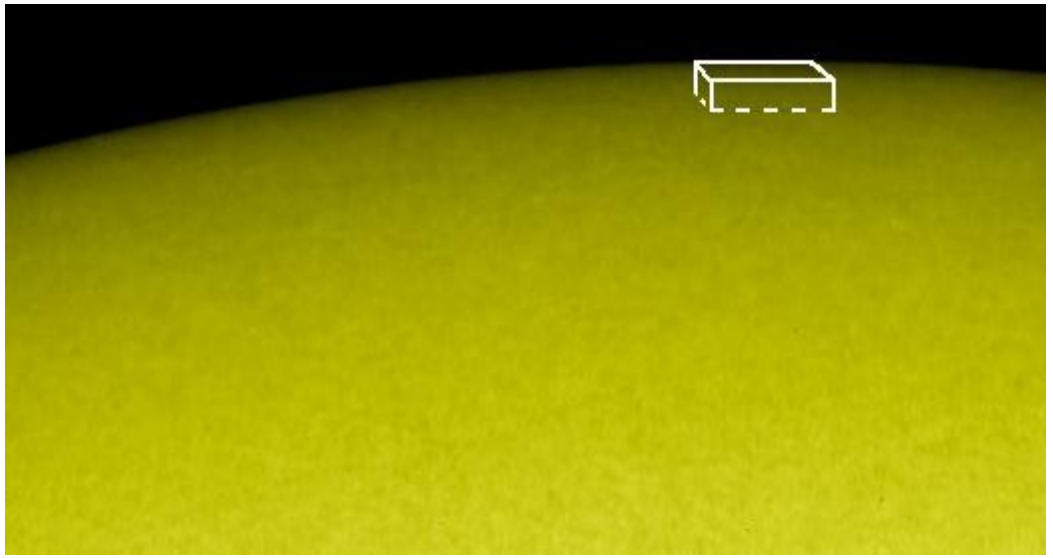
What we **do not** know:

- temperature
- I(μ)
- typical sizes
- magn. field strength
- flux
- structure (penumbra, umbra, UDs, ...)
- (distribution on surface)

MURaM

MURaM = MPS/UofC Radiation MHD code
Developed by the **MPS MHD Group**
in cooperation with the **University of Chicago**

Vögler (2003), **Vögler et al. (2005)**, **Rempel et al. (2009)**, and references therein

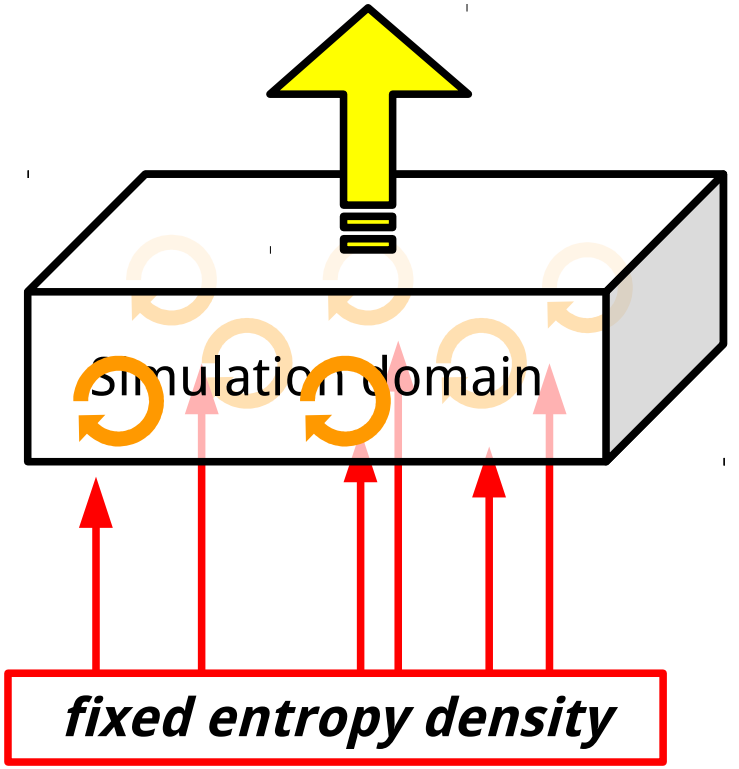


- Local-box code
- Solves compressible MHD on a three-dimensional cartesian grid
  - 4th order centred spatial difference scheme
  - explicit time stepping: 4th order Runge-Kutta
- radiative transport
  - short characteristics
  - ~~non-grey: opacity binning (τ-sorting)~~ here: grey
  - LTE
- realistic OPAL EoS (including partial ionisation of the most relevant species)

Bottom boundary

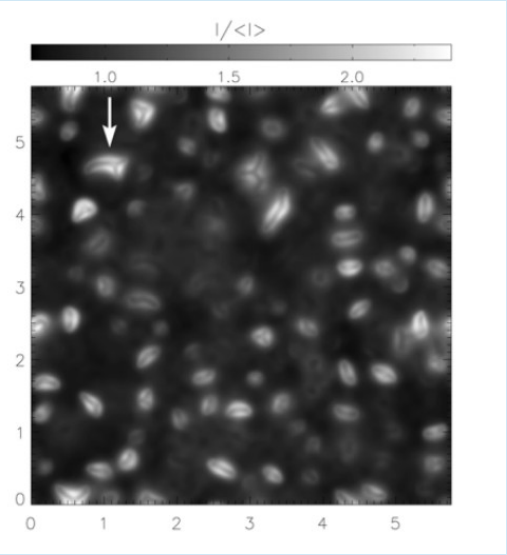
The bottom boundary can be

- **open**
  - inflows with ***constant entropy density*** and pressure
  - entropy density determines adiabat → T_{eff}
- **partly closed**
  - v=0 at bottom for B> B_{crit}
- **closed**
  - v=0 at bottom

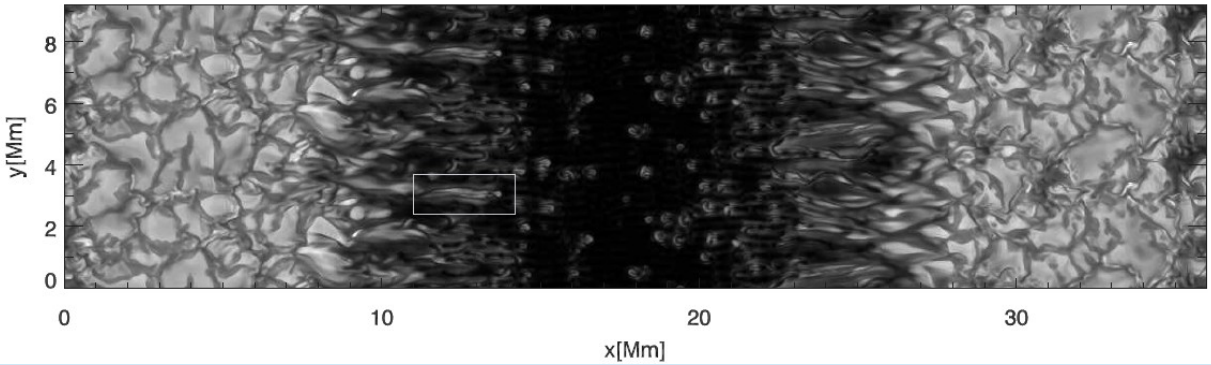


MURaM sunspot simulations

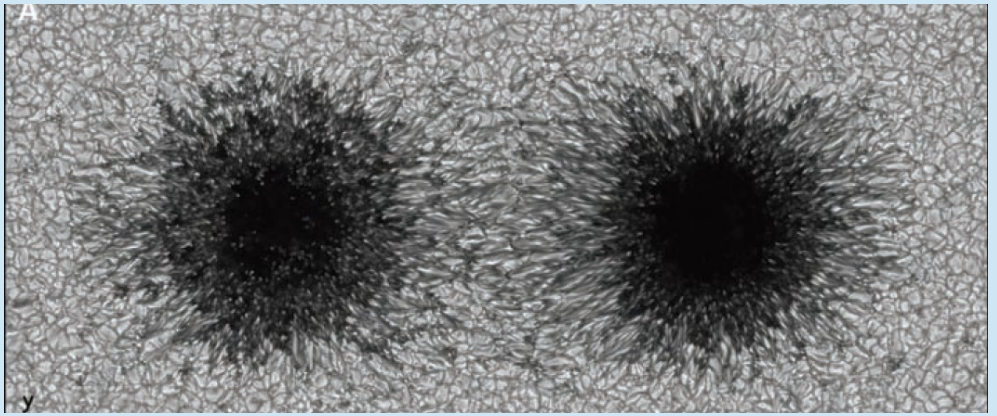
sunspot umbra simulations
Schüssler & Vögler (2006)



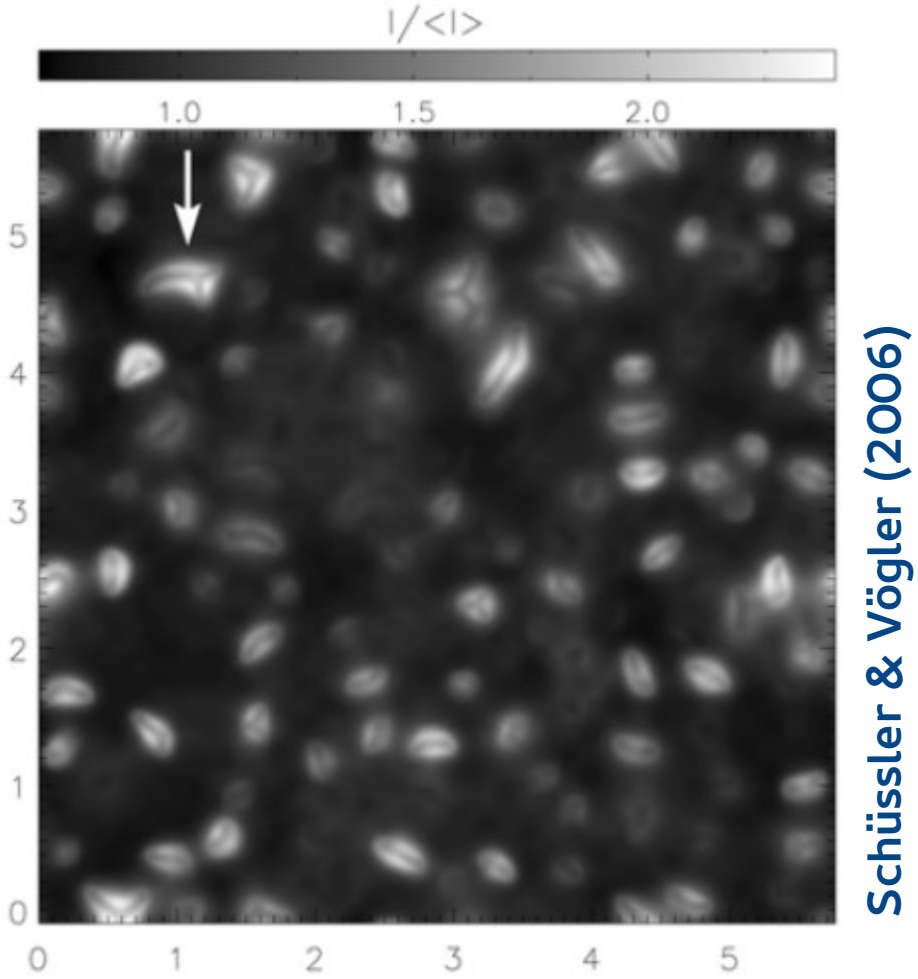
sunspot slab Rempel et al. (2009a)



sunspot pair Rempel et al. (2009b)



Umbra simulations

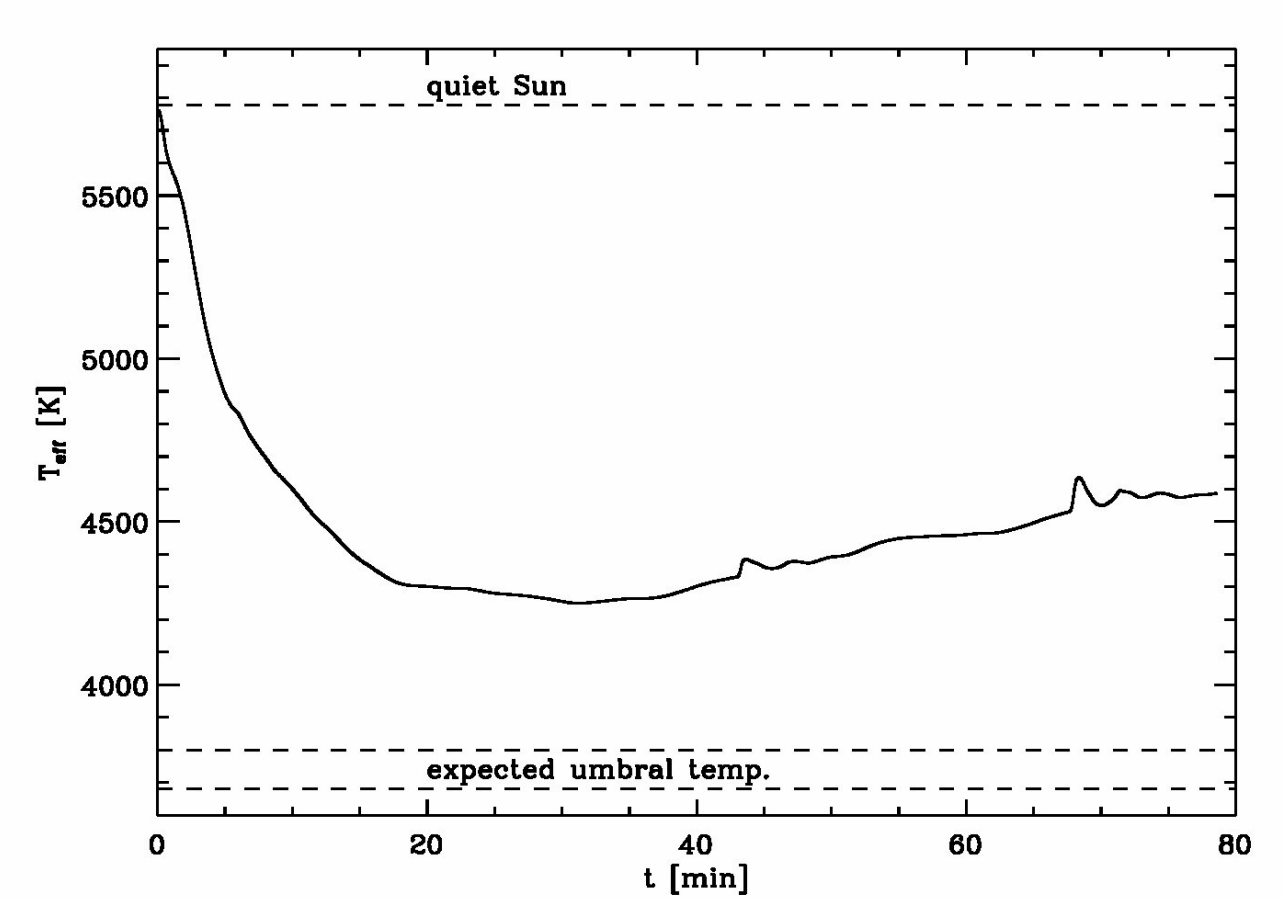


Schüssler & Vögler (2006)

- Box dimensions:
  5.76 Mm × 5.76 Mm × 1.6 Mm
  (1.2 Mm below τ_R=1)
- Initial condition:
  - 2D hydro snapshot
  - 2.5 kG uniform vertical magn. field
- Relaxed in 2D, then evolved in 3D.
- *Entropy density of inflows at the bottom boundary adapted to match observed F_{rad}!*

First attempt

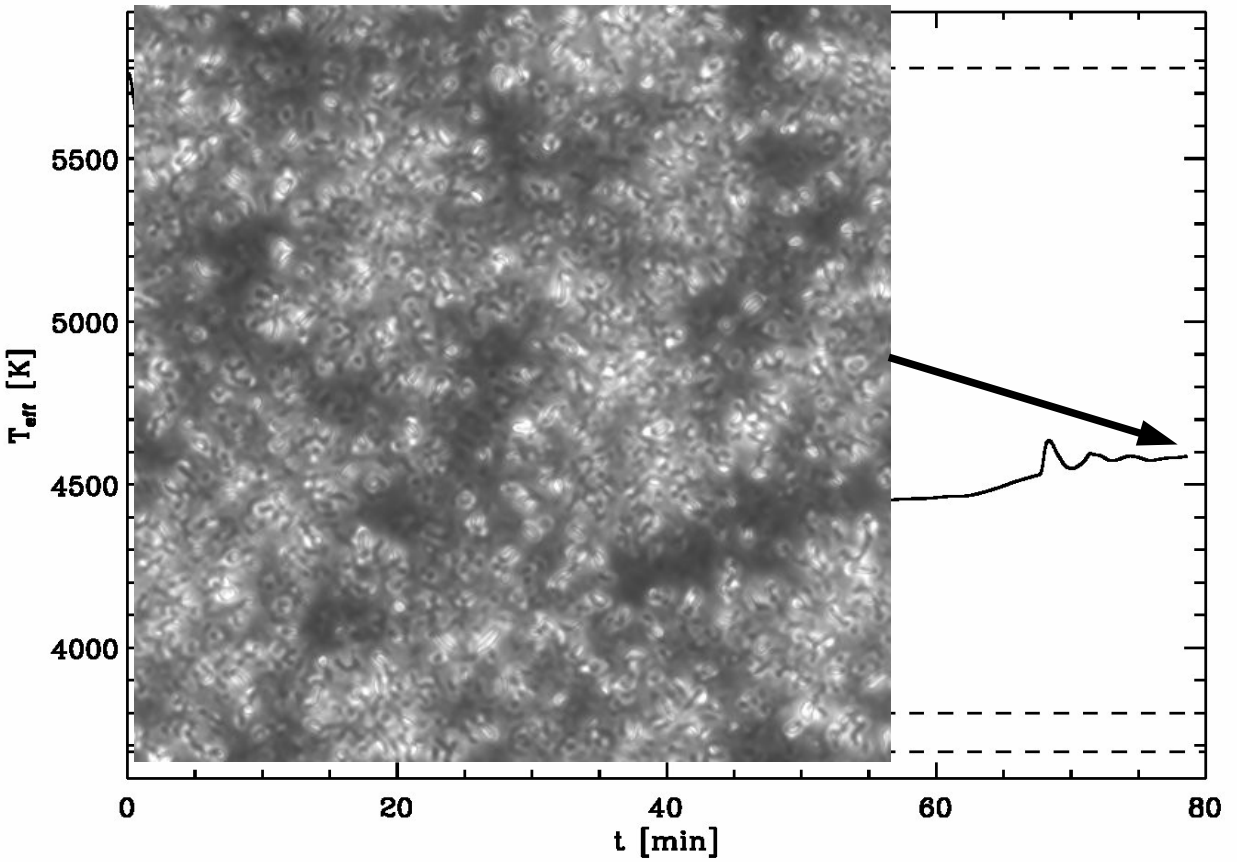
- 3D
- depth below τ_R=1: 2.3 Mm
- initial condition
  - hydro run
  - + vertical homogeneous field with B=2kG
- open bottom boundary
  - entropy density set to hydro-case value



First attempt

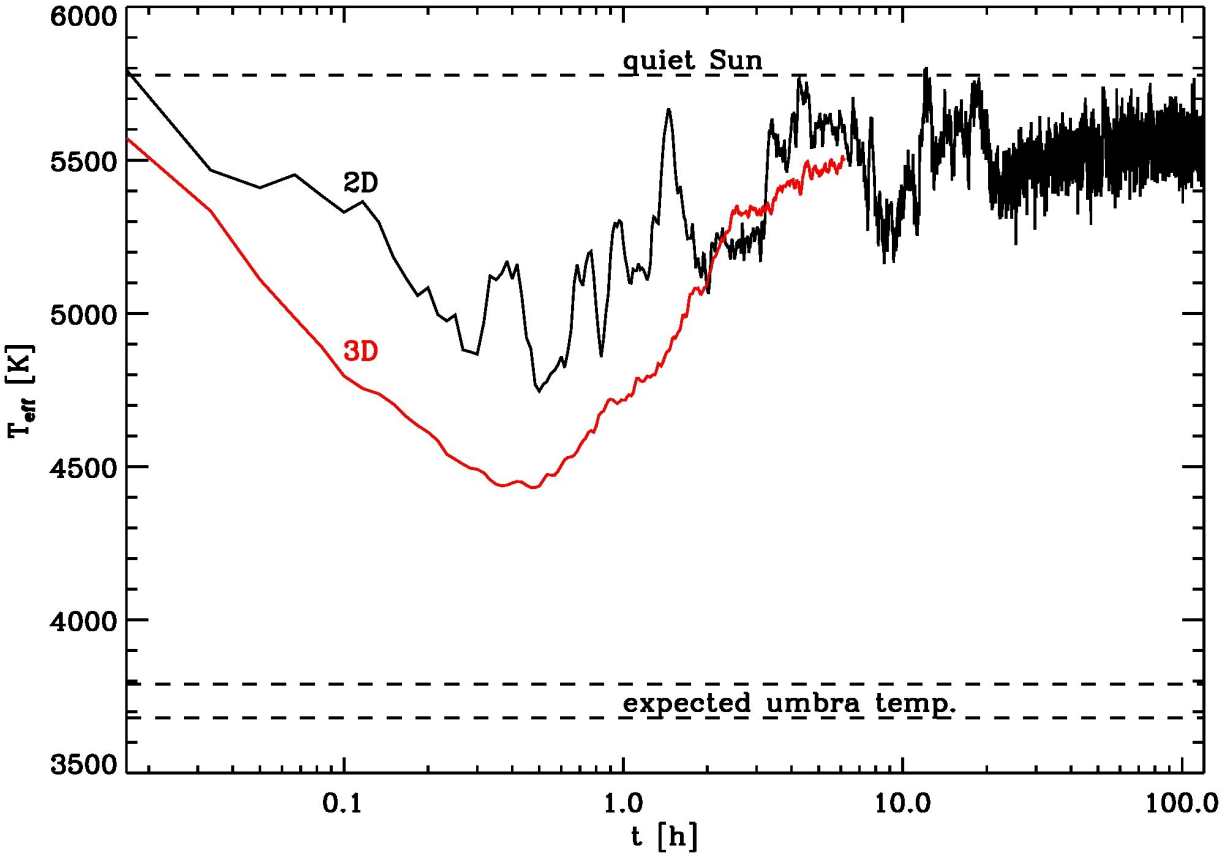
- 3D
- depth below τ_R=1: 2.2 Mm
- initial condition
  - hydro run
  - + vertical homogeneous field with B=2kG
- open bottom boundary
  - entropy density set to hydro-case value

FAILED



Deeper Box

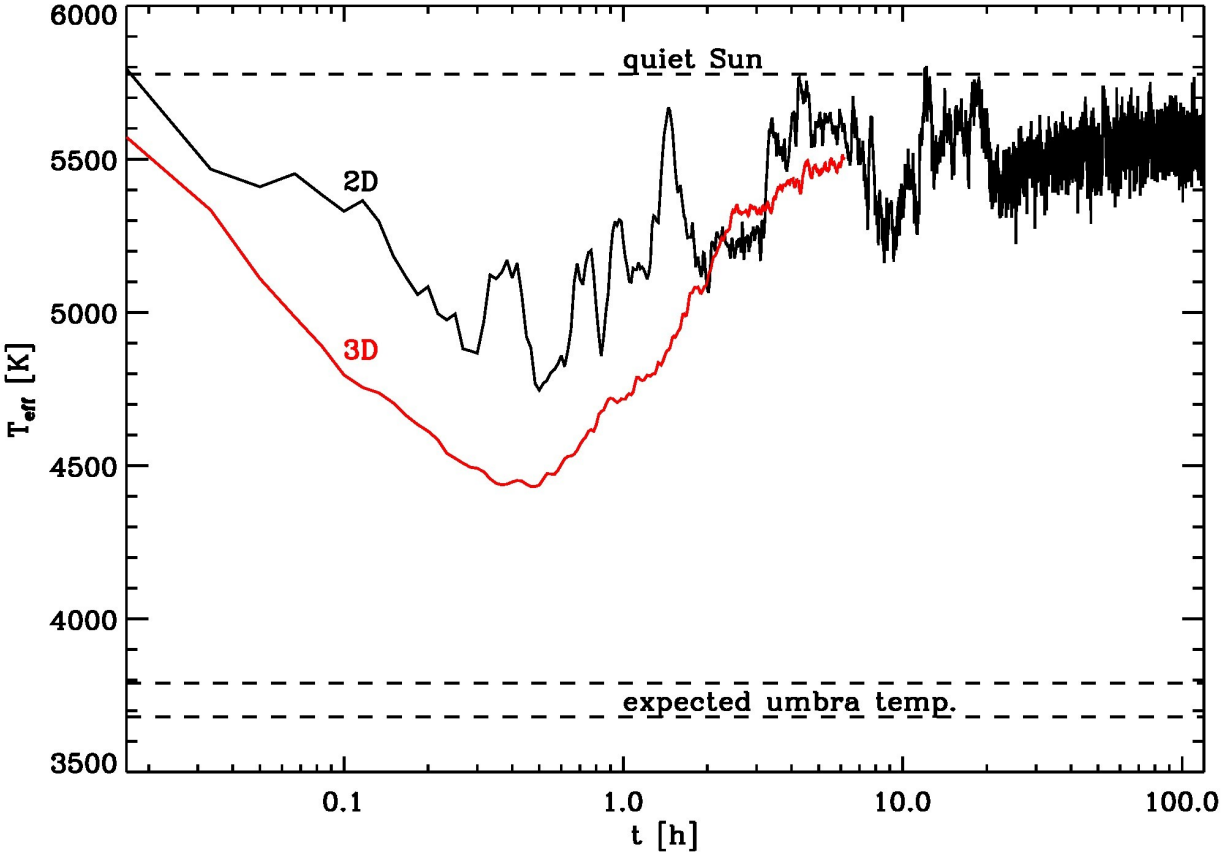
- 3D **and 2D**
- depth below τ_R=1: **6.5 Mm**
- initial condition
  - hydro run
  - + vertical homogeneous field with B=2kG
- open bottom boundary
  - entropy density set to hydro-case value



Deeper Box

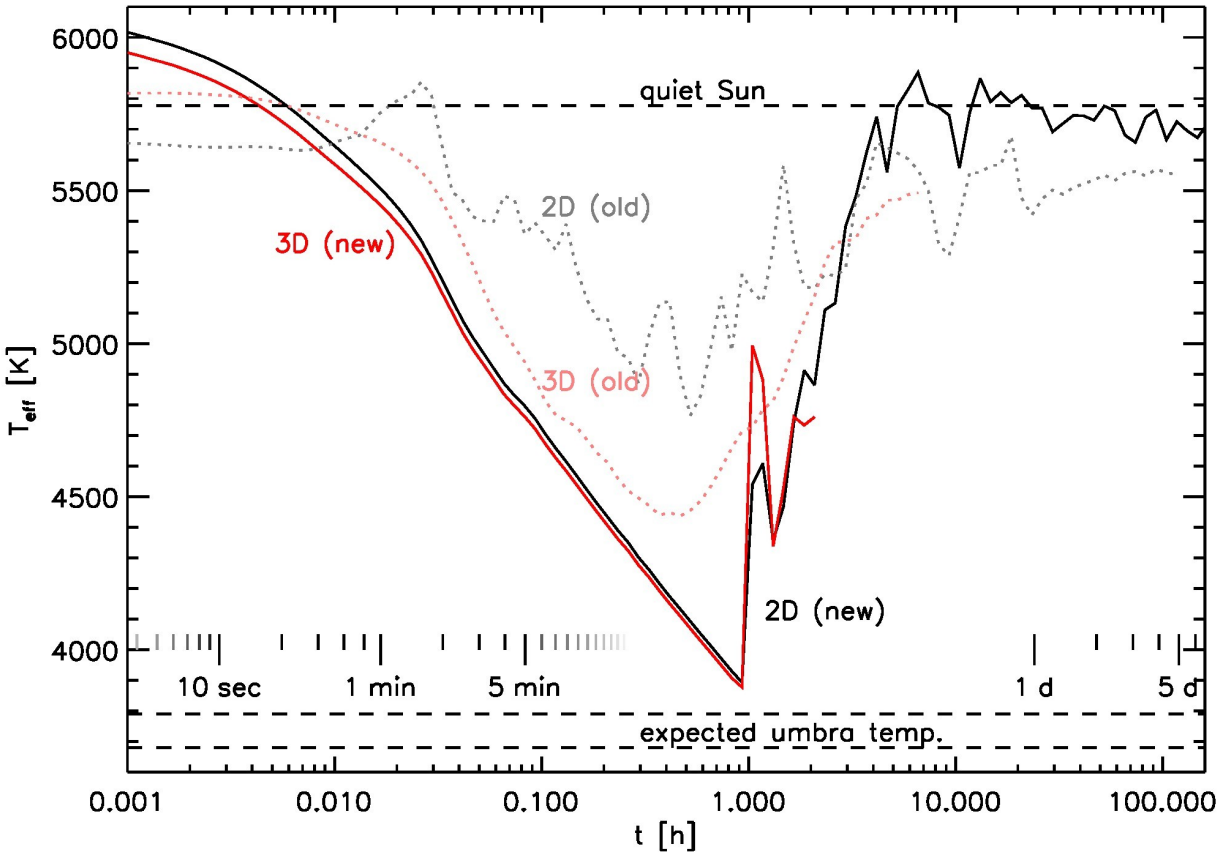
- 3D **and 2D**
- depth below τ_R=1 : 6.4 Mm
- initial condition
  - hydrostatic
  - + vertical homogeneous field with B=2kG
- open bottom boundary
  - entropy density set to hydro-case value

FAILED



Closed bottom (+ static IC)

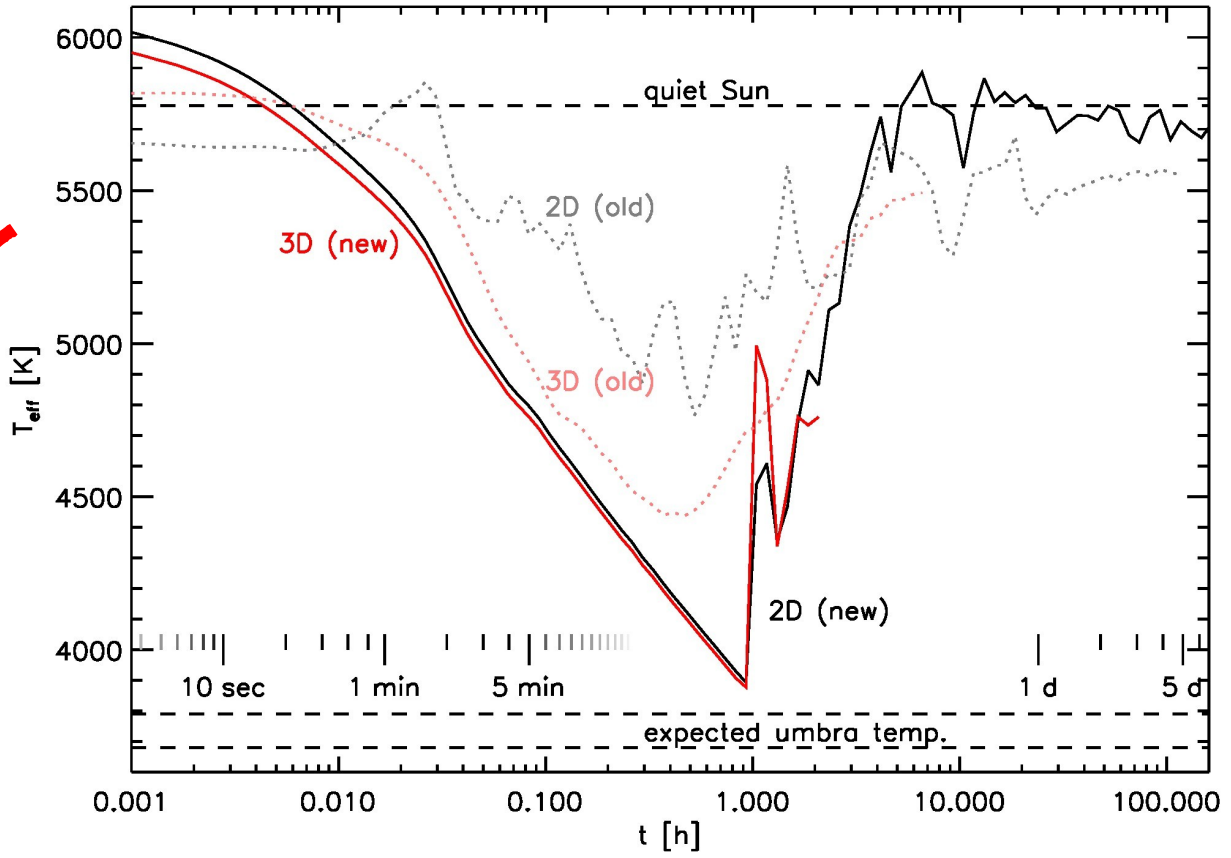
- 3D and 2D
- depth below τ_R=1: 6.5 Mm
- initial condition
  - **hydrostatic**
  - + vertical homogeneous field with B=2kG
- **closed** bottom boundary



Closed bottom (+ static IC)

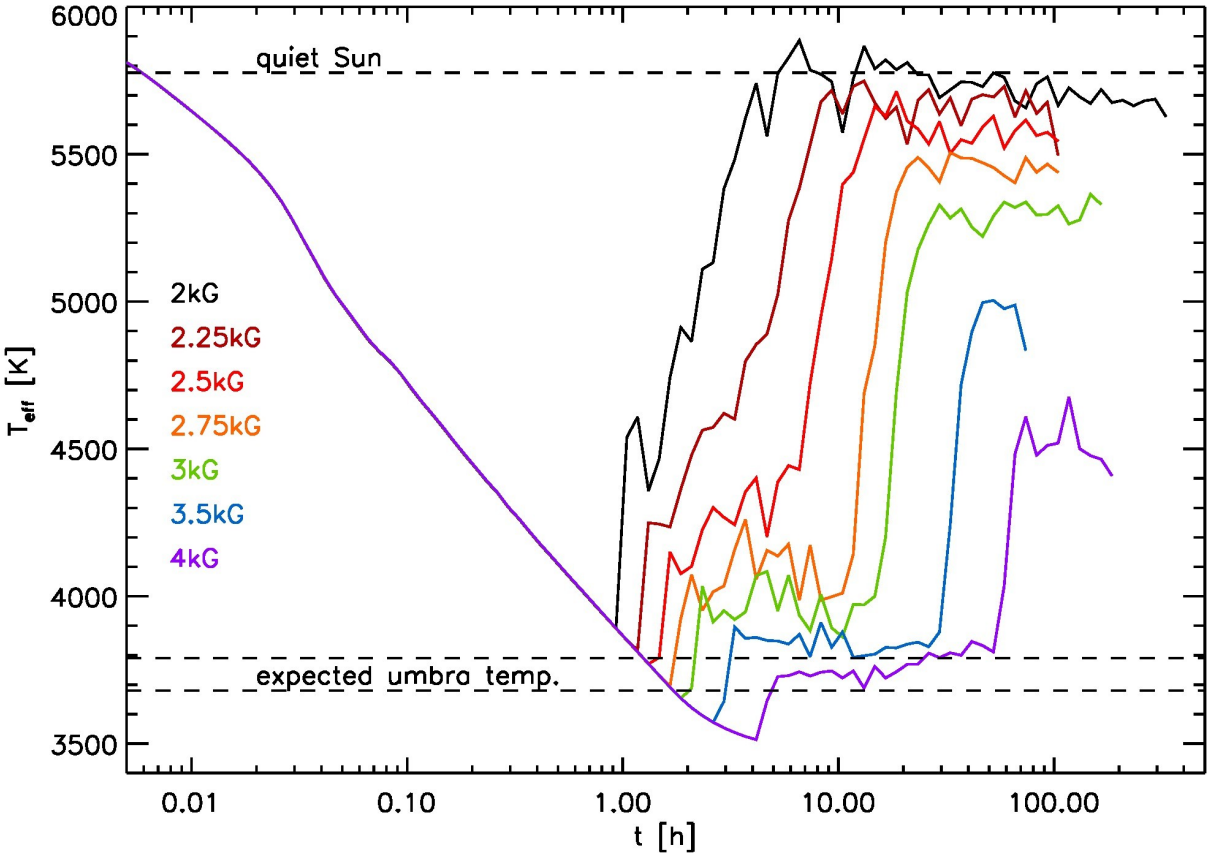
- 3D and 2D
- depth below τ_R=1 : 6.. M
- initial condition
  - hydrostatic
  - + vertical homogeneous field with B=2kG
- closed bottom boundary

FAILED



Higher magnetic field strength

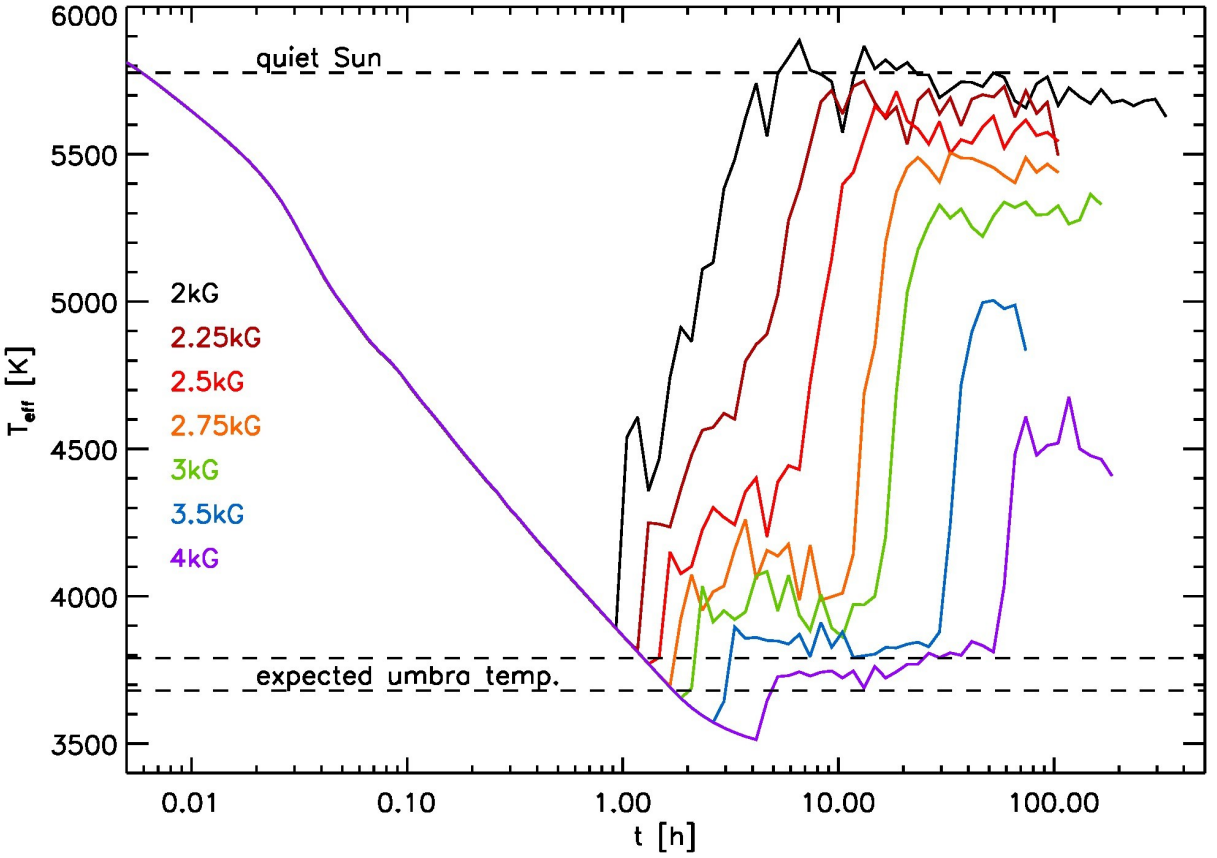
- 2D
- depth below τ_R=1: 6.5 Mm
- initial condition
  - hydrostatic
  - + vertical homogeneous field with **B≥2kG**
- closed bottom boundary
  - entropy density set to hydro-case value



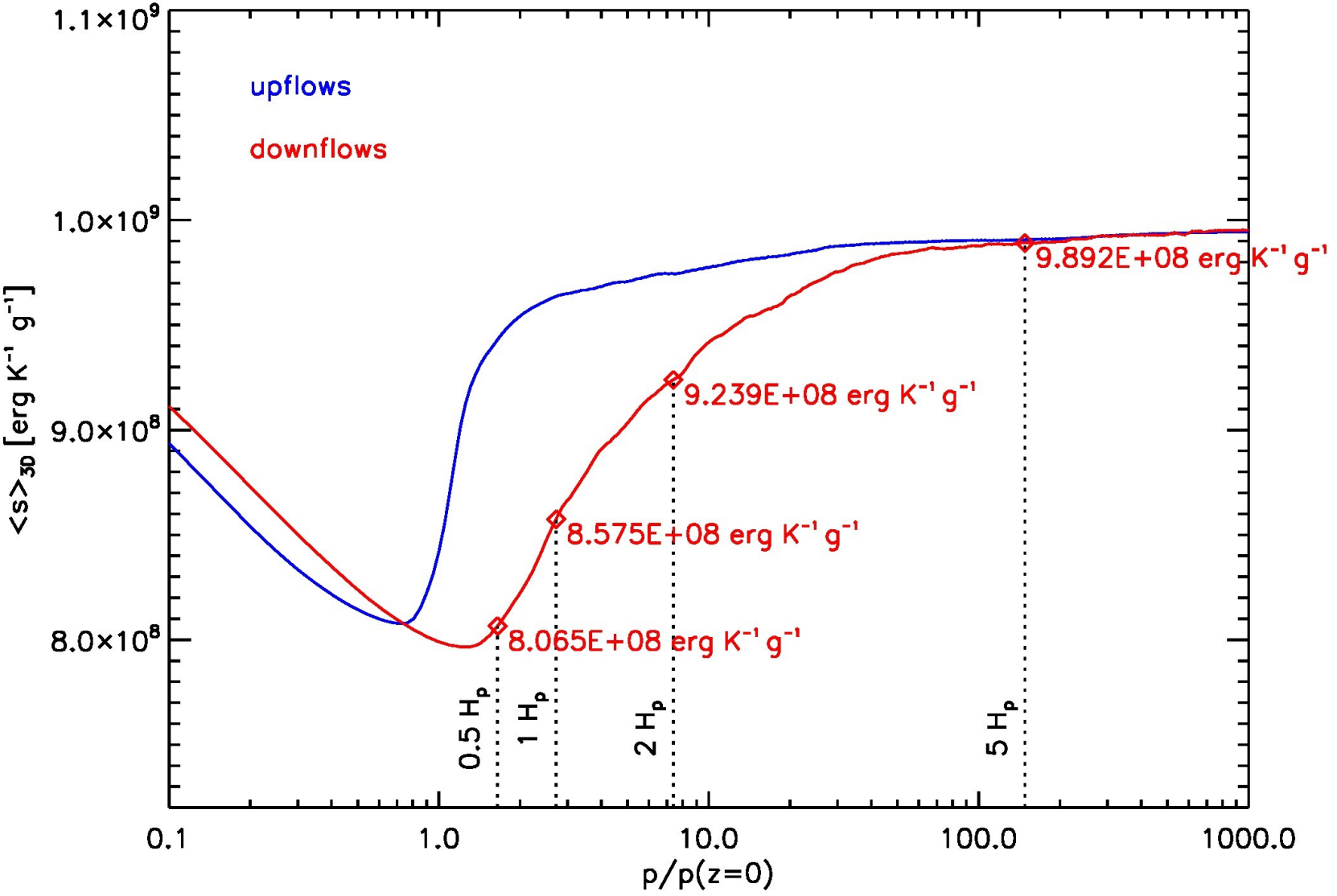
Higher magnetic field strength

- 2D
- depth below τ_R=1, 6.. Mm
- initial condition
  - hydrostatic
  - + vertical homogeneous field with B>2kG
- closed bottom boundary entropy density set to hydro-case value

FAILED

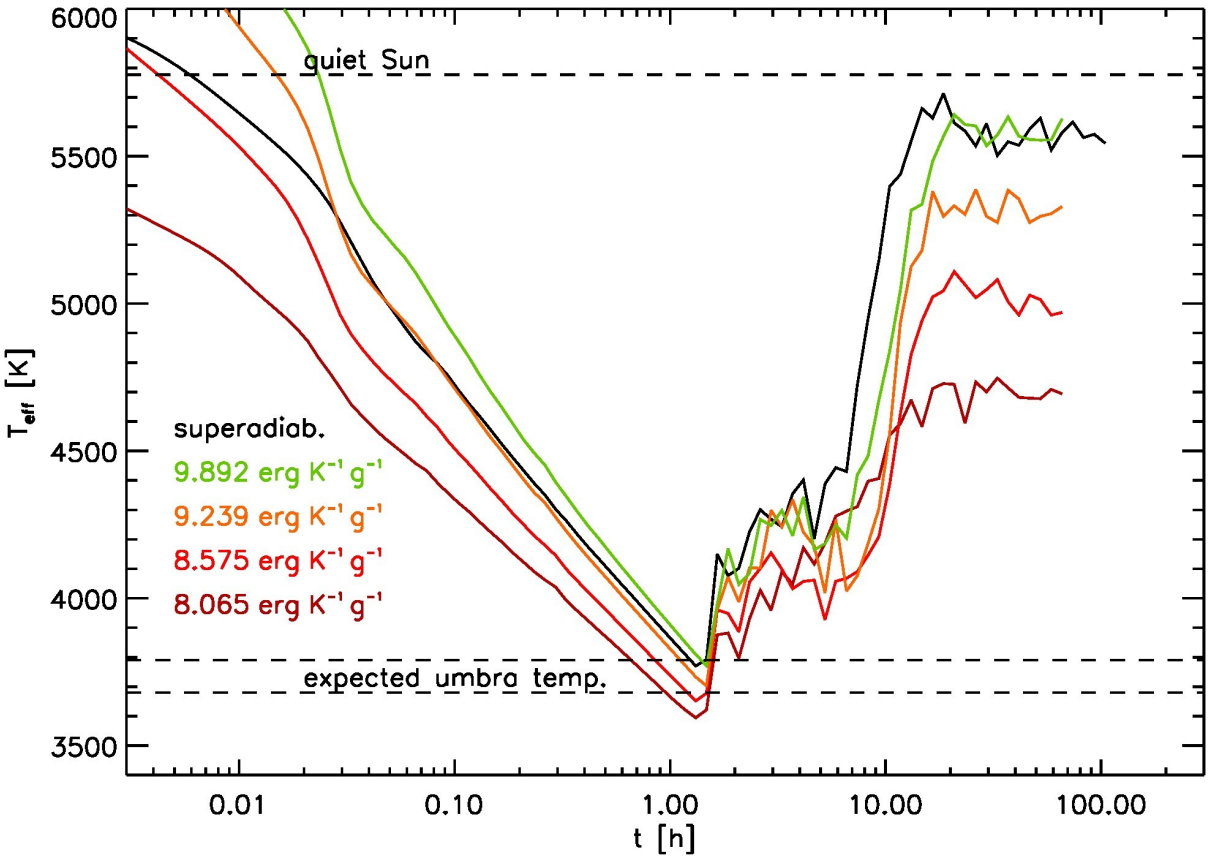


Entropy density of the 3D hydro run



Isentropic IC

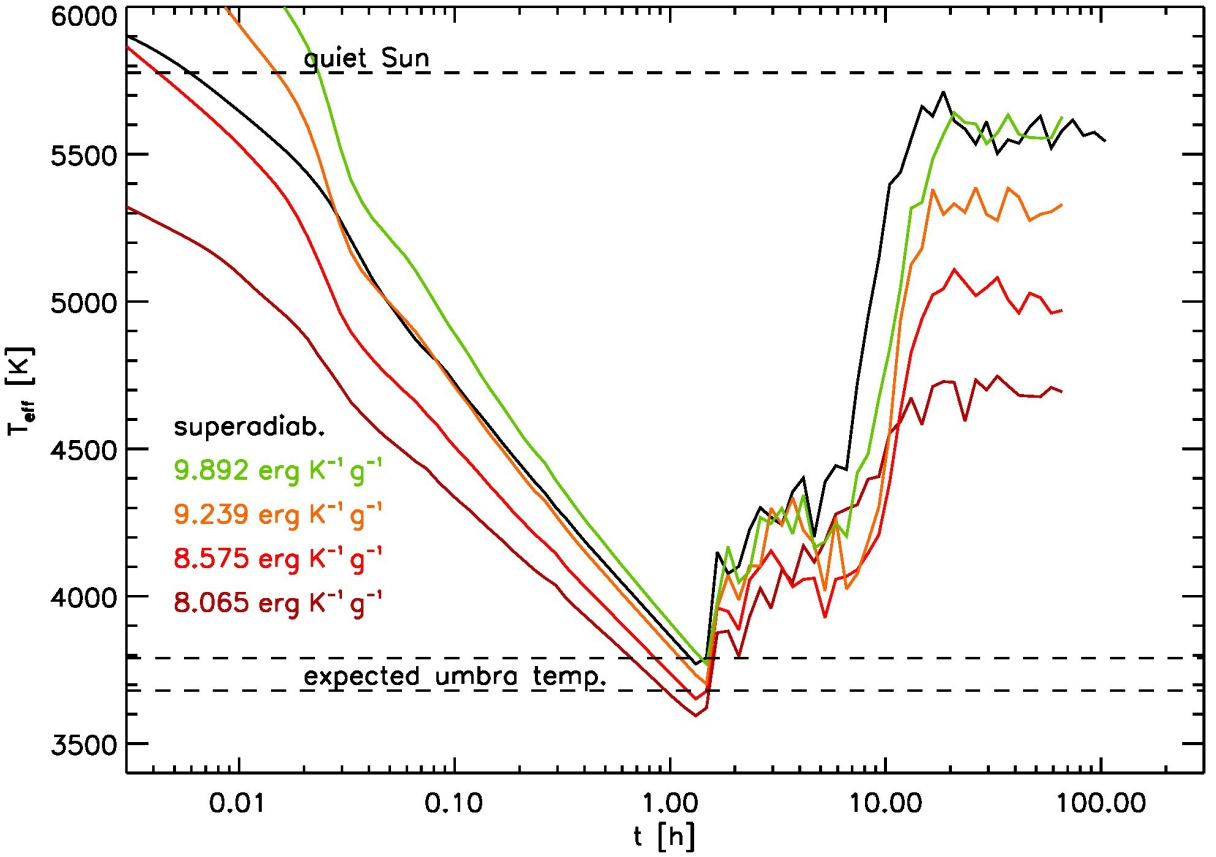
- 2D
- depth below τ_R=1: 6.5 Mm
- initial condition
  - hydrostatic, **isentropic**
  - + vertical homogeneous field with **B=2.5kG**
- closed bottom boundary
  - **entropy density set to value of hydro downflows**



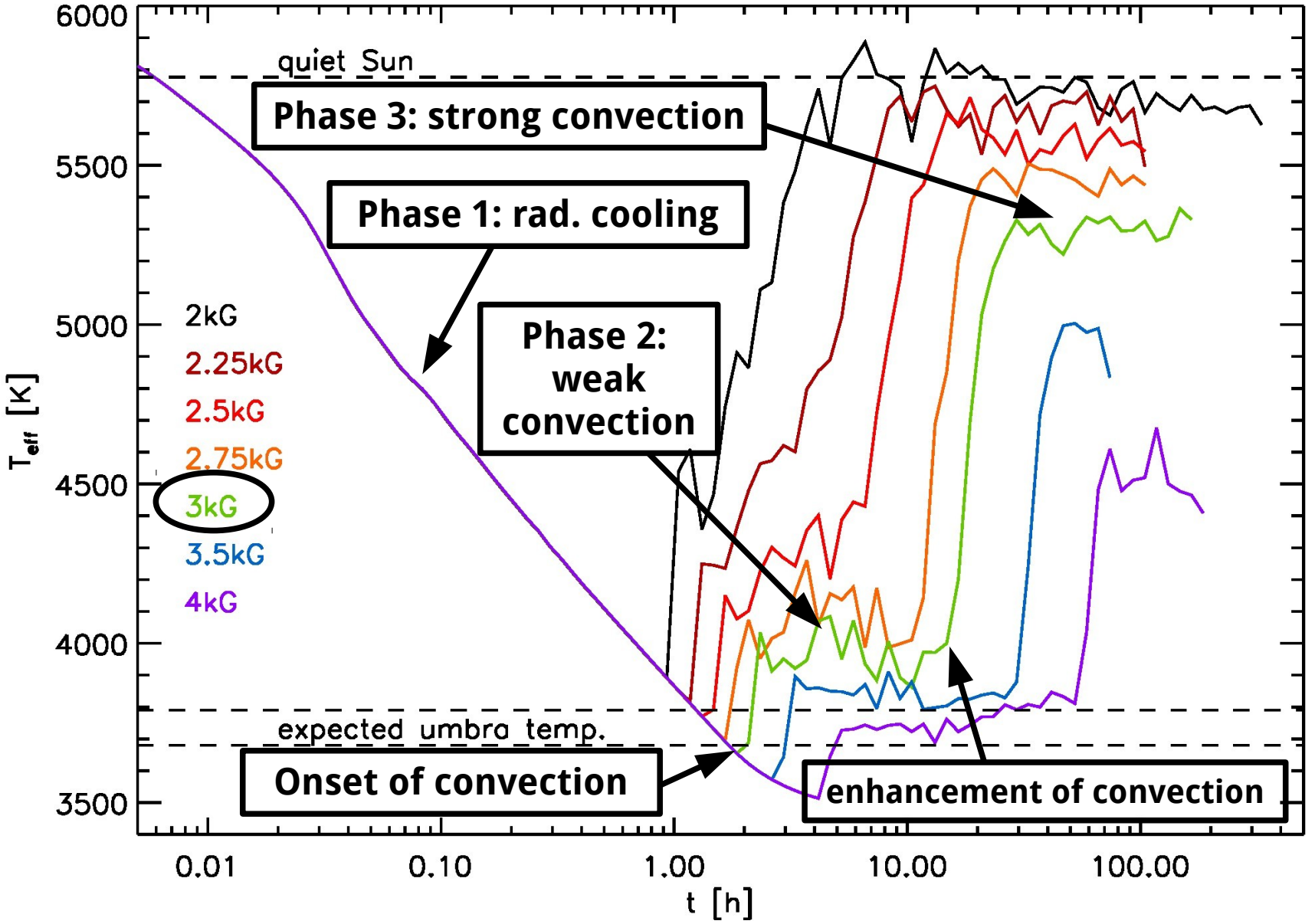
Isentropic IC

- 2D
- depth below τ_R=1: 6.. Mm
- initial condition
  - hydrostatic **isentropic**
  - + vertical homogeneous field with **B=2.5kG**
- closed bottom boundary **entropy density set to value of hydro downflows**

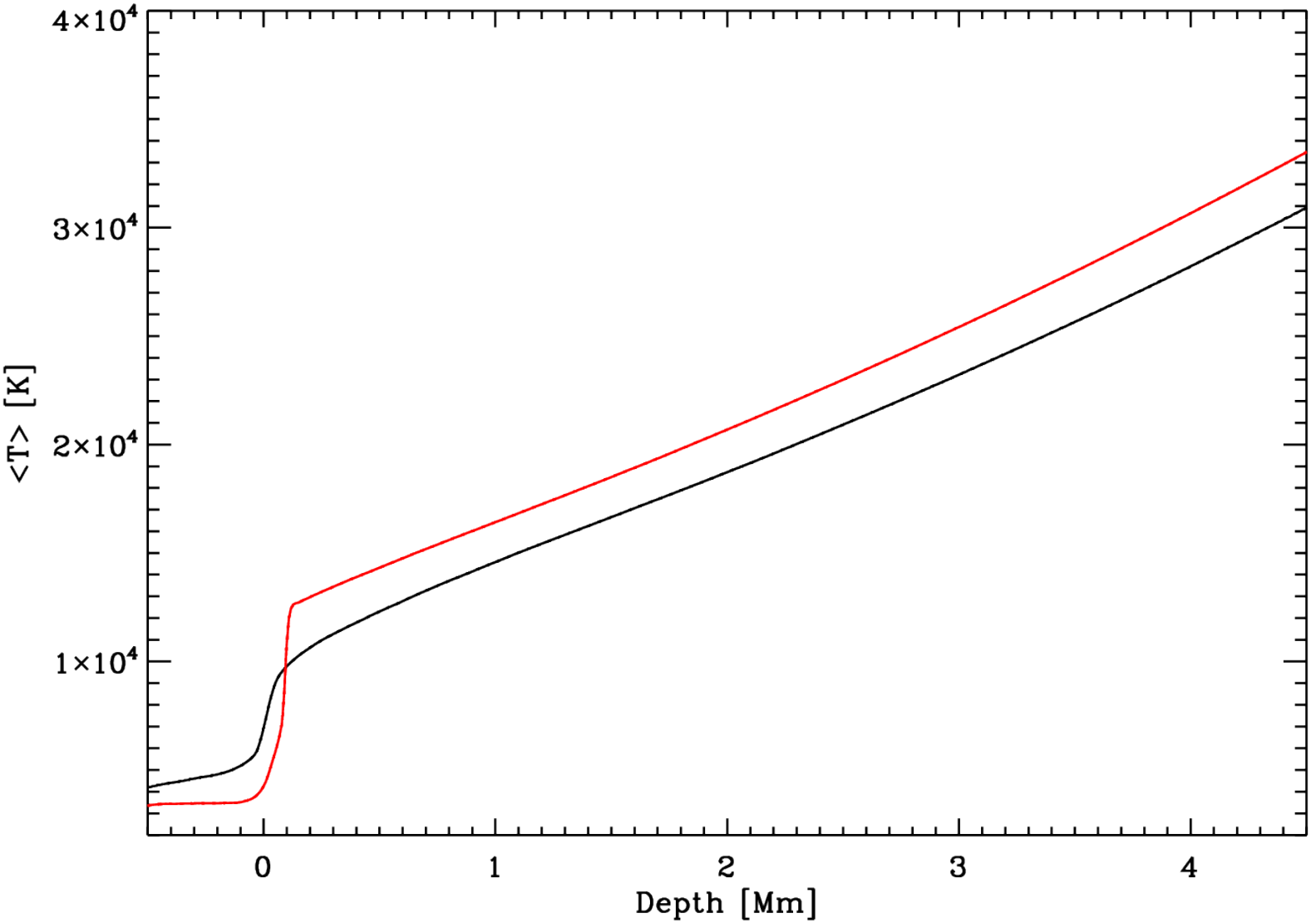
FAILED



What happens?



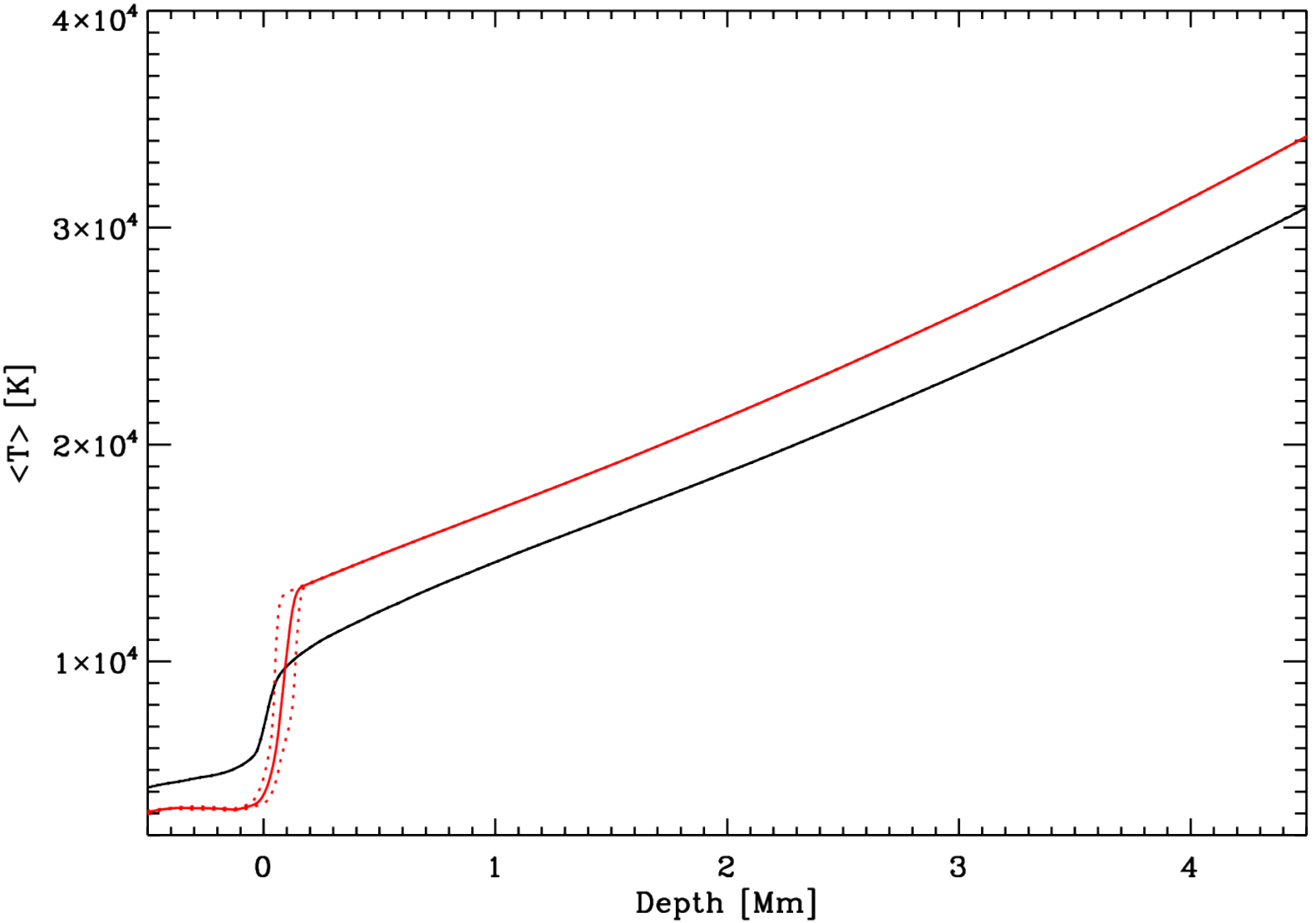
What happens?



t=0 (IC)

t= 0.7 h (radiative cooling phase)

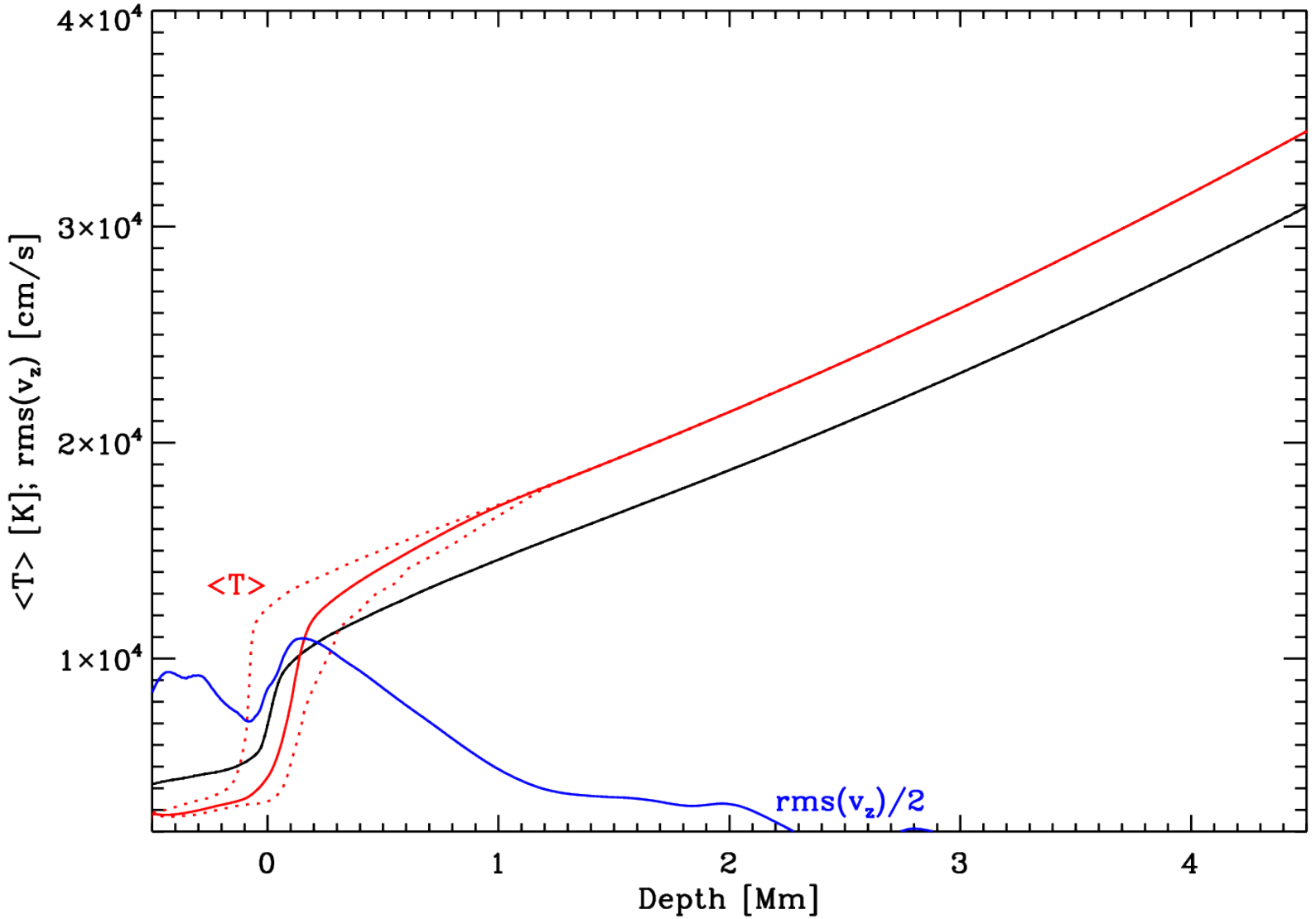
What happens?



t=0 (IC)

t= 2.1 h (onset of weak convection)

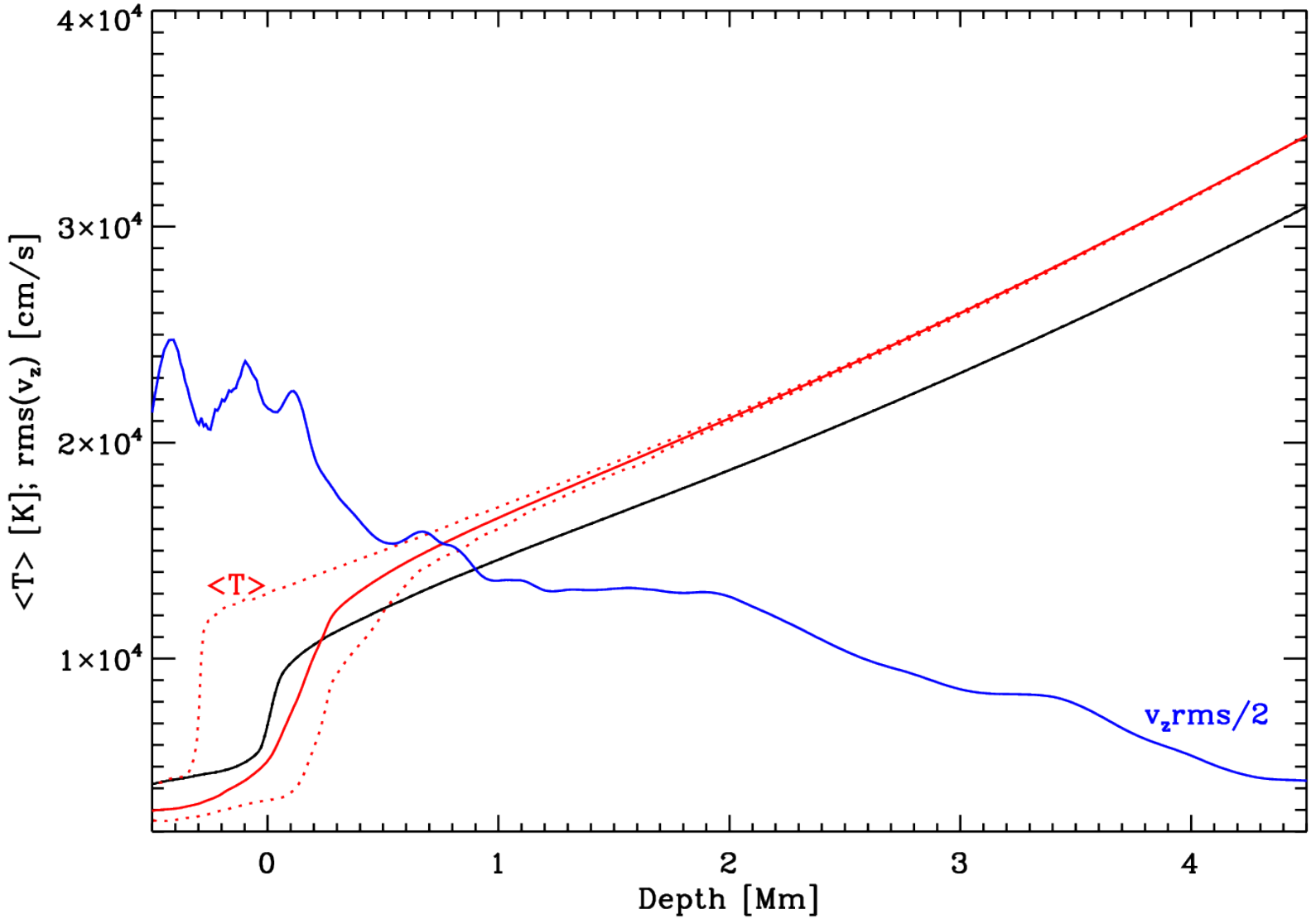
What happens?



t=0 (IC)

t= 5.3 h (weak convective phase)

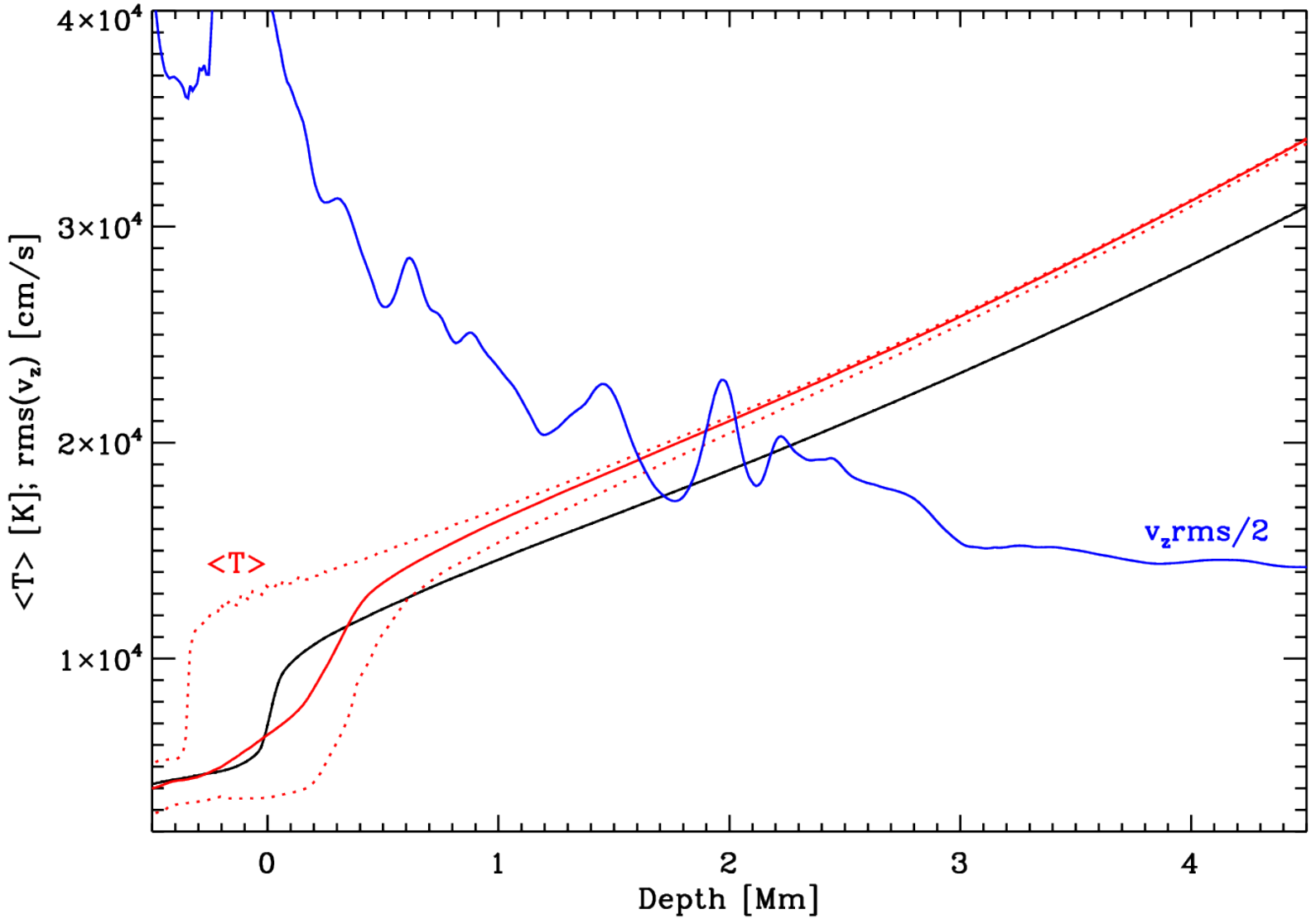
What happens?



t=0 (IC)

t= 18 h (onset of strong convection)

What happens?

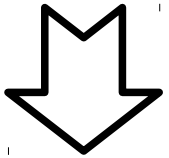


t=0 (IC)

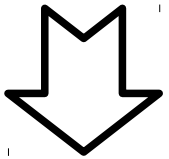
t= 35 h (strong convection phase)

Result I

All simulations with a **homogeneous vertical magnetic field** in the range of observed surface field strengths **failed**!



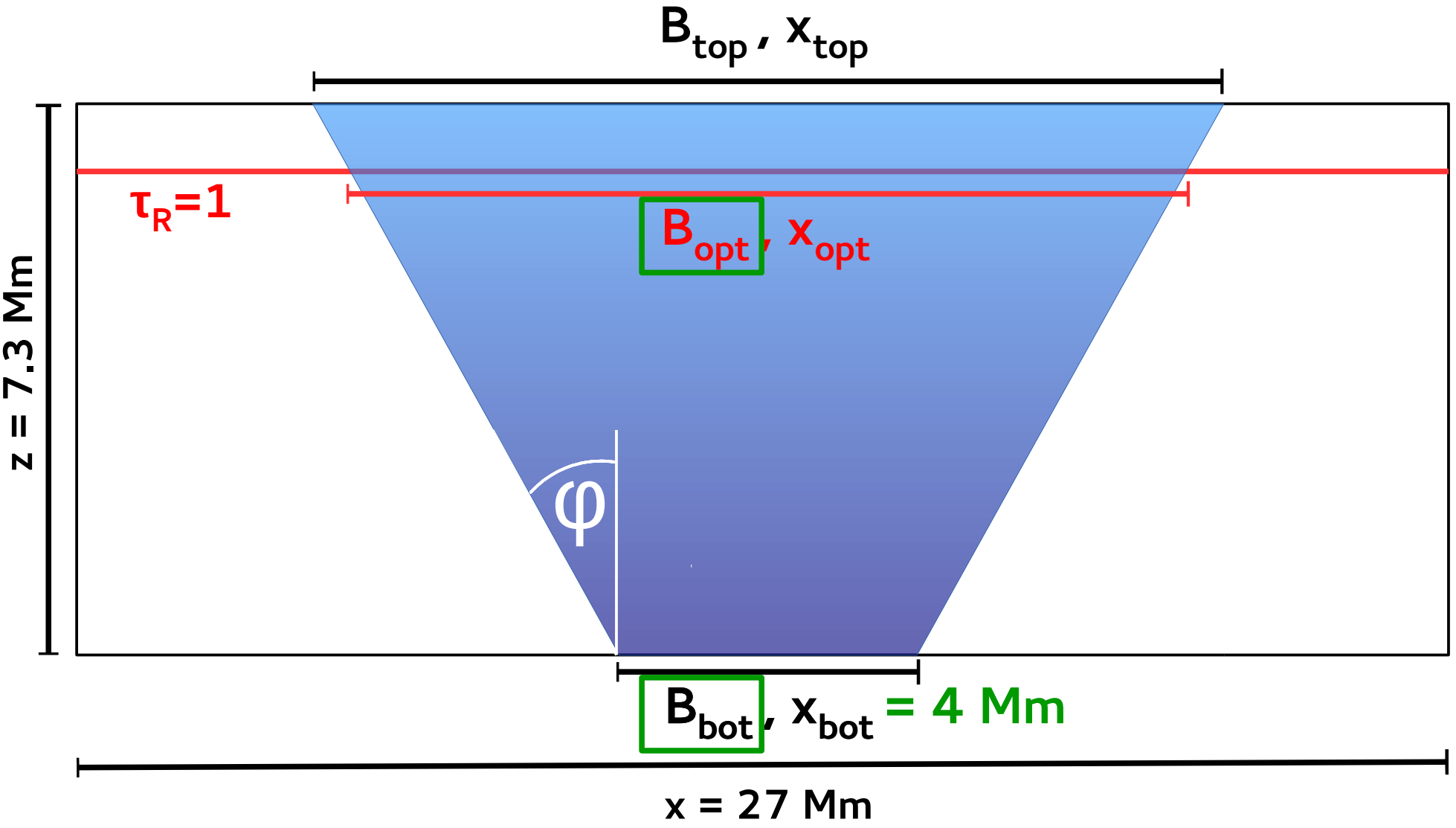
Stable sunspots require a magnetic field of **> 4kG** in the subsurface layers. The structure (e.g. T gradient) **below z~2-3 Mm** seems to be important for the stability of sunspots.



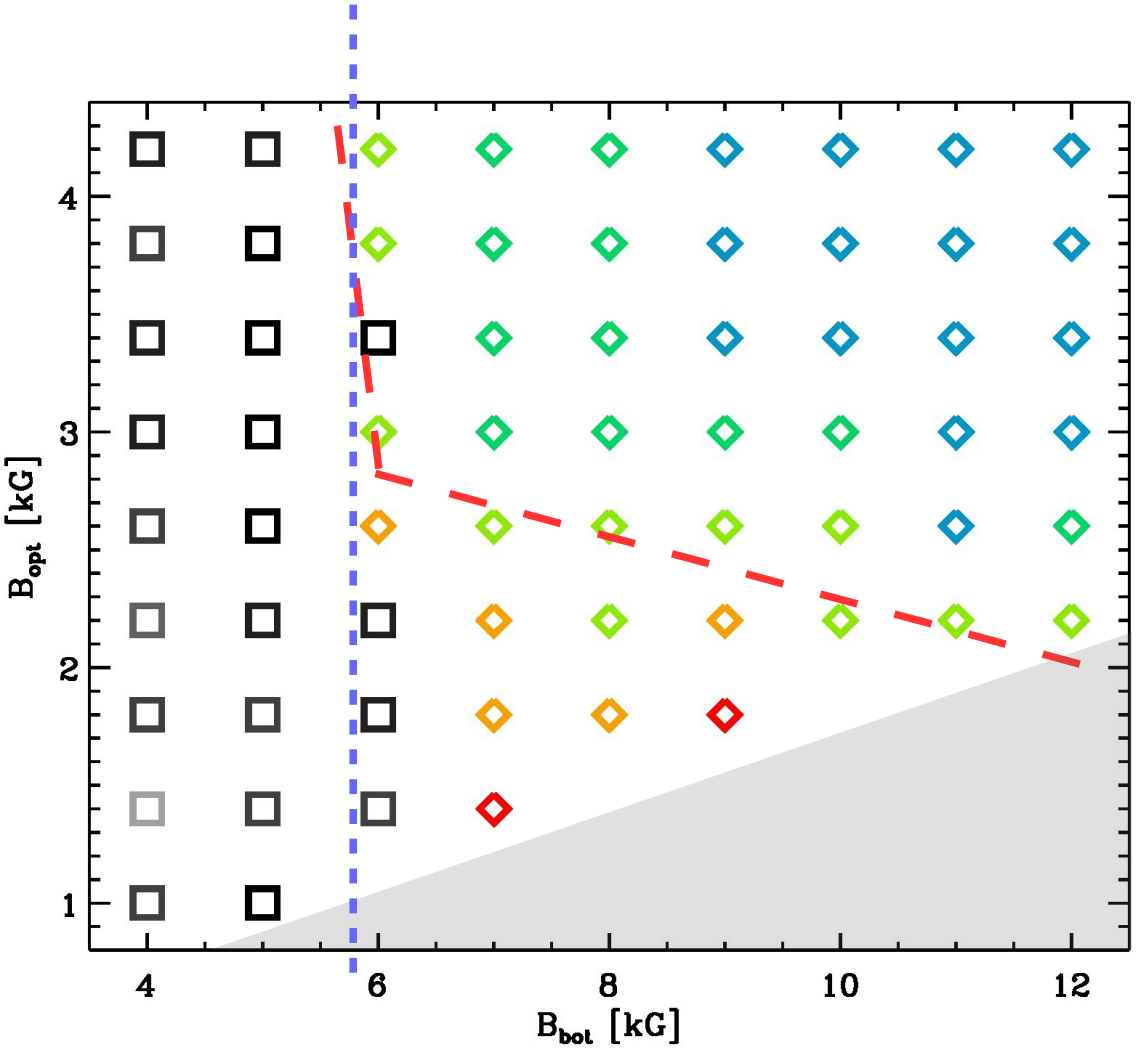
This also indicates that sunspots **cannot be very shallow phenomena**.

Slab sunspots

(wedge geometry of magnetic field)



2D parameter study

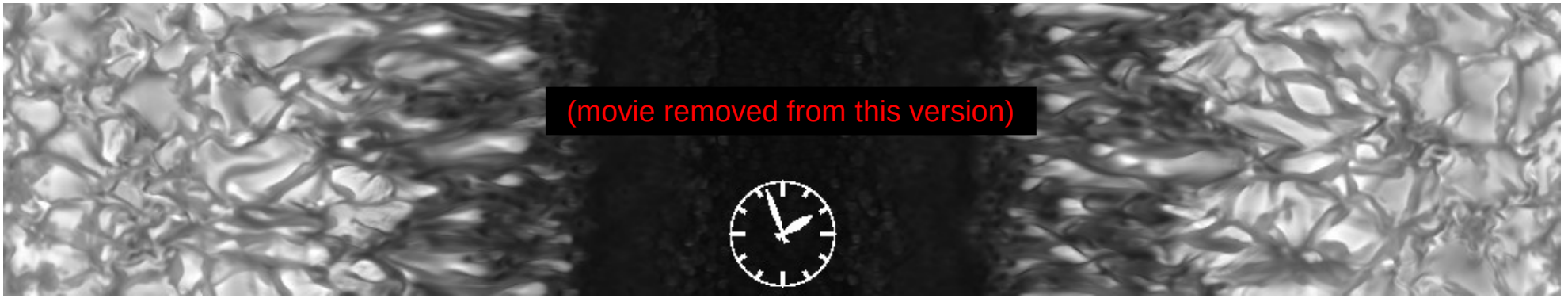


- instability after 0–2h
- instability after 2–4h
- instability after 4–6h
- instability after 6–8h
- instability after 8–10h
- instability after 10–12h
- instability after 12–14 h
- instability after >14 h

- stable, I > 0.3 I_{QS}
- stable, 0.3 I_{QS} > I > 0.25 I_{QS}
- stable, 0.25 I_{QS} > I > 0.22 I_{QS}
- stable, 0.22 I_{QS} > I > 0.2 I_{QS}
- stable, 0.2 I_{QS} > I > 0.18 I_{QS}
- stable, 0.18 I_{QS} > I > 0.15 I_{QS}
- stable, 0.15 I_{QS} > I > 0.1 I_{QS}
- stable, I < 0.1 I_{QS}

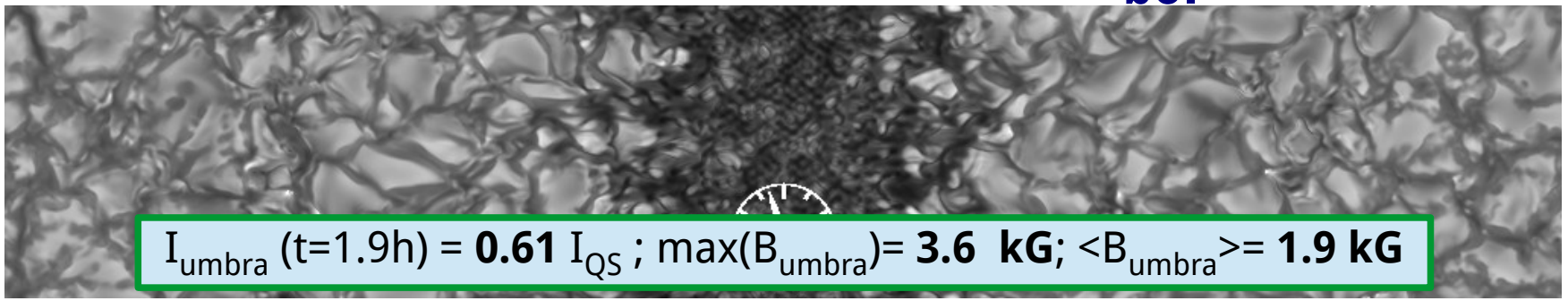
preliminary 3D results (here: I_{bol})

B_{bot}= 5 kG

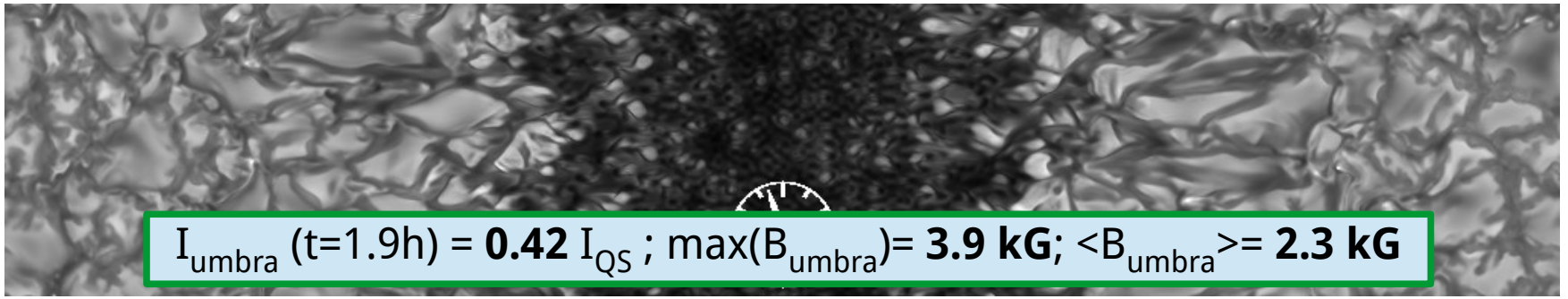


B_{bot}= 11 kG

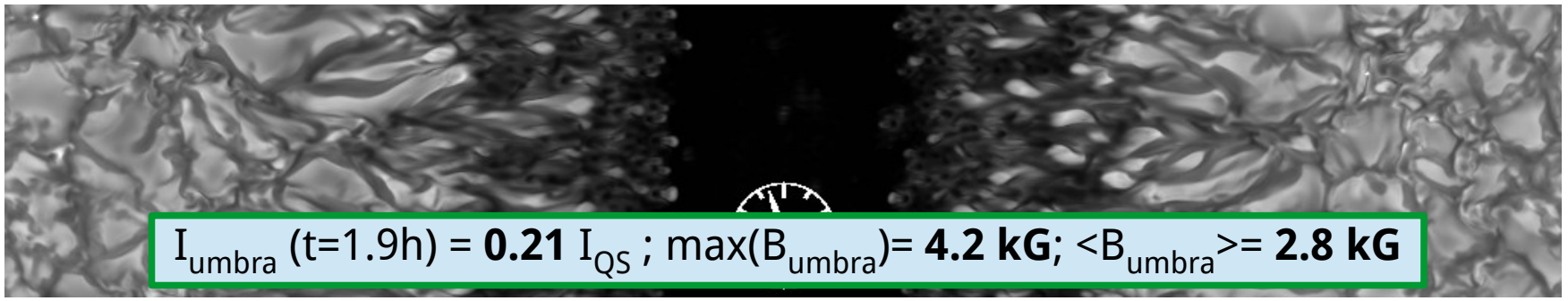
3D results (here: I_{bol})



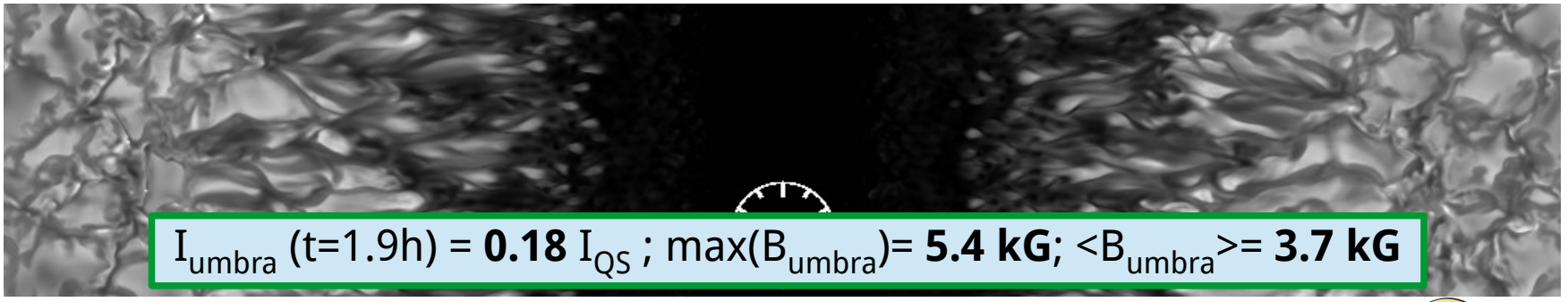
B_{bot}= **5 kG**



B_{bot}= **7 kG**

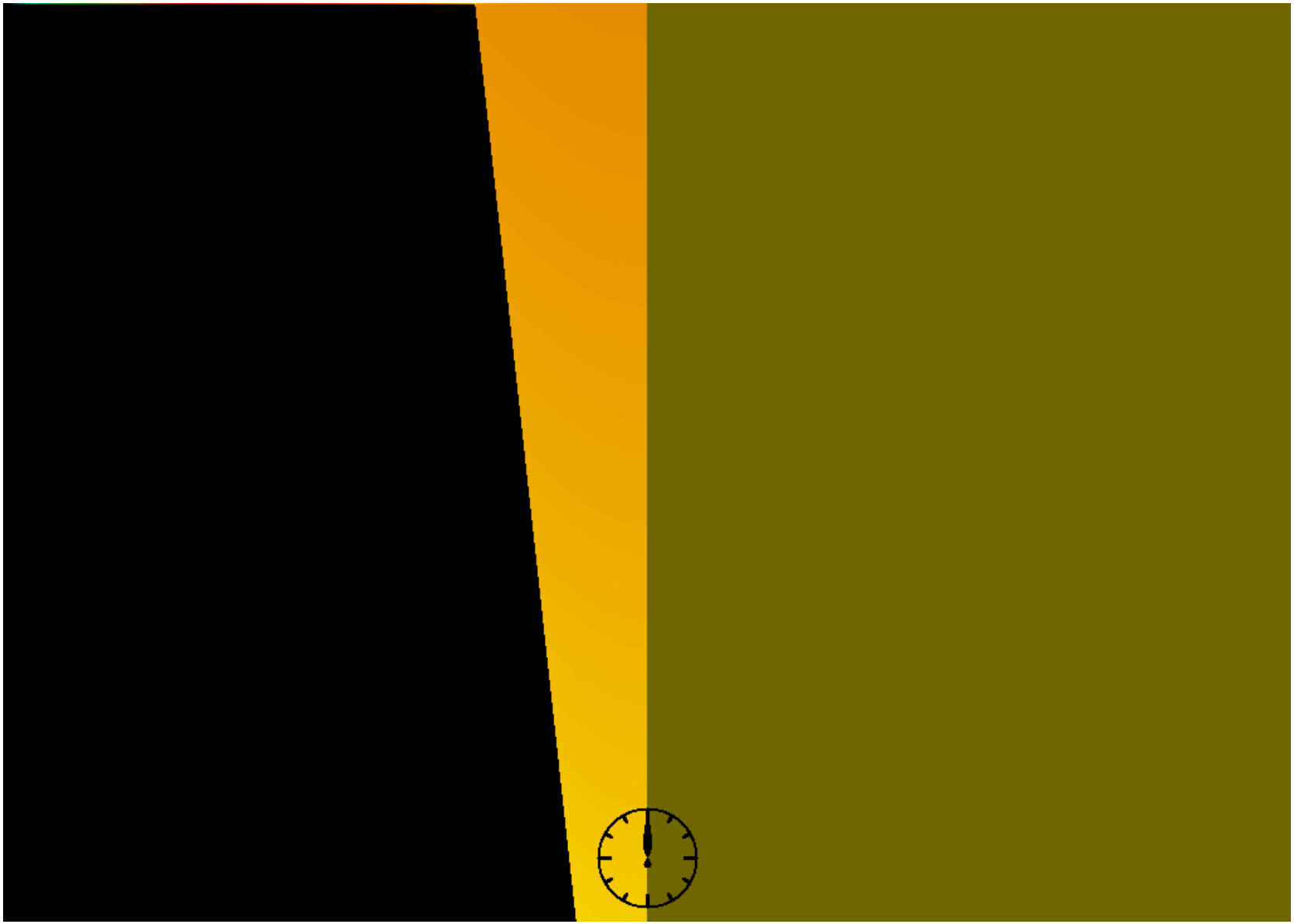


B_{bot}= **9 kG**

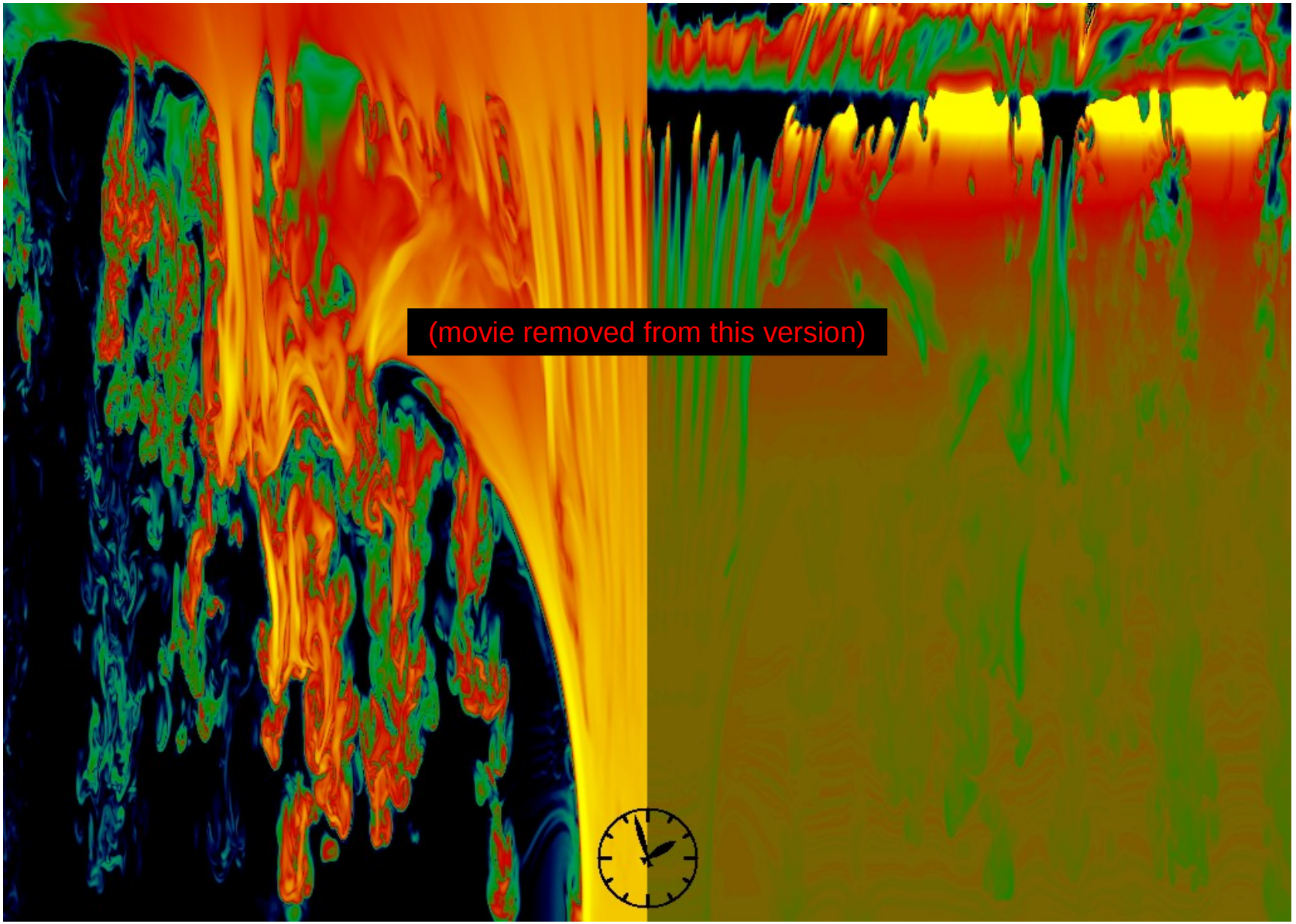


B_{bot}= **11 kG**

$|B|$ / $T-\langle T \rangle_{hor}$



$|B|$ / $T-\langle T \rangle_{hor}$



Conclusion

Some results…

- A stable, dark starspots need a magnetic field of **B ≥ 6 kG** at depths of **5-6 Mm**.
- This probably **rules out very flat sunspot geometries**.
- In wedge/slab geometry, higher bottom field strength leads to **lower umbral intensity** and a **more pronounced penumbra**.

… and some open questions

- Why **dependence on B_{opt}** in 2D? Also in 3D?
- Is the different penumbra structure and umbral intensity really related to B_{bot} or rather to the **total magn. flux**?
- How can we exploit our findings for the simulation of **starspots**?

A 2D snapshot of a K0V starspot with umbral dots