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A DEEP-SEATED MECHANISM FOR CYCLE-DEPENDENT SUNSPOT GROUP TILT ANGLES

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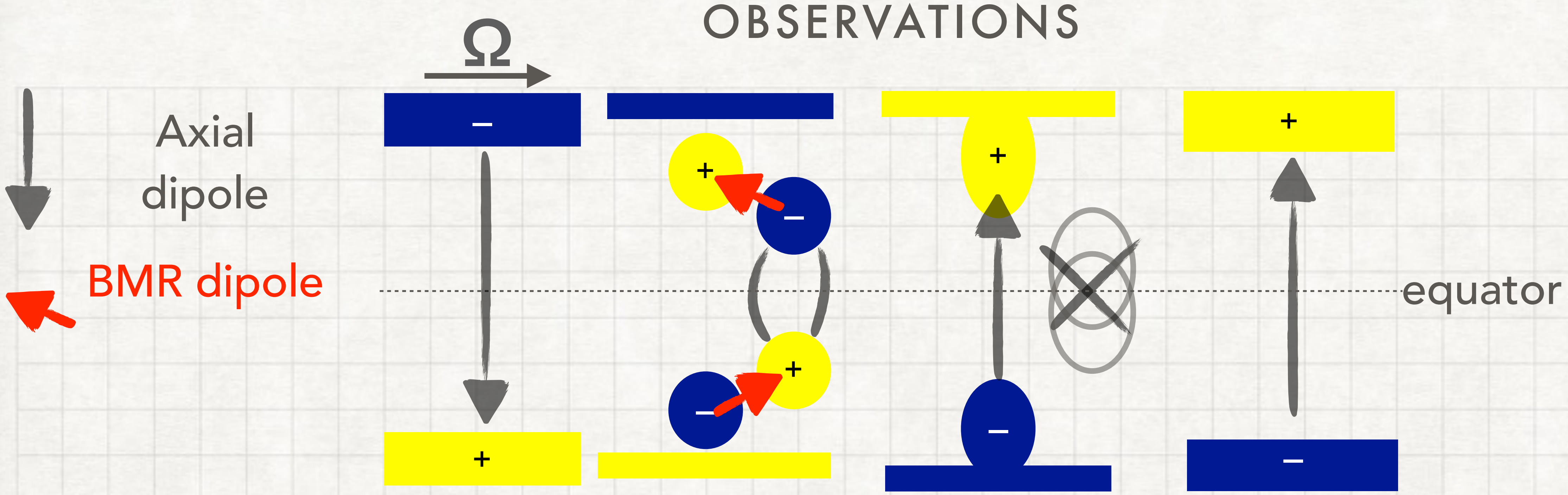
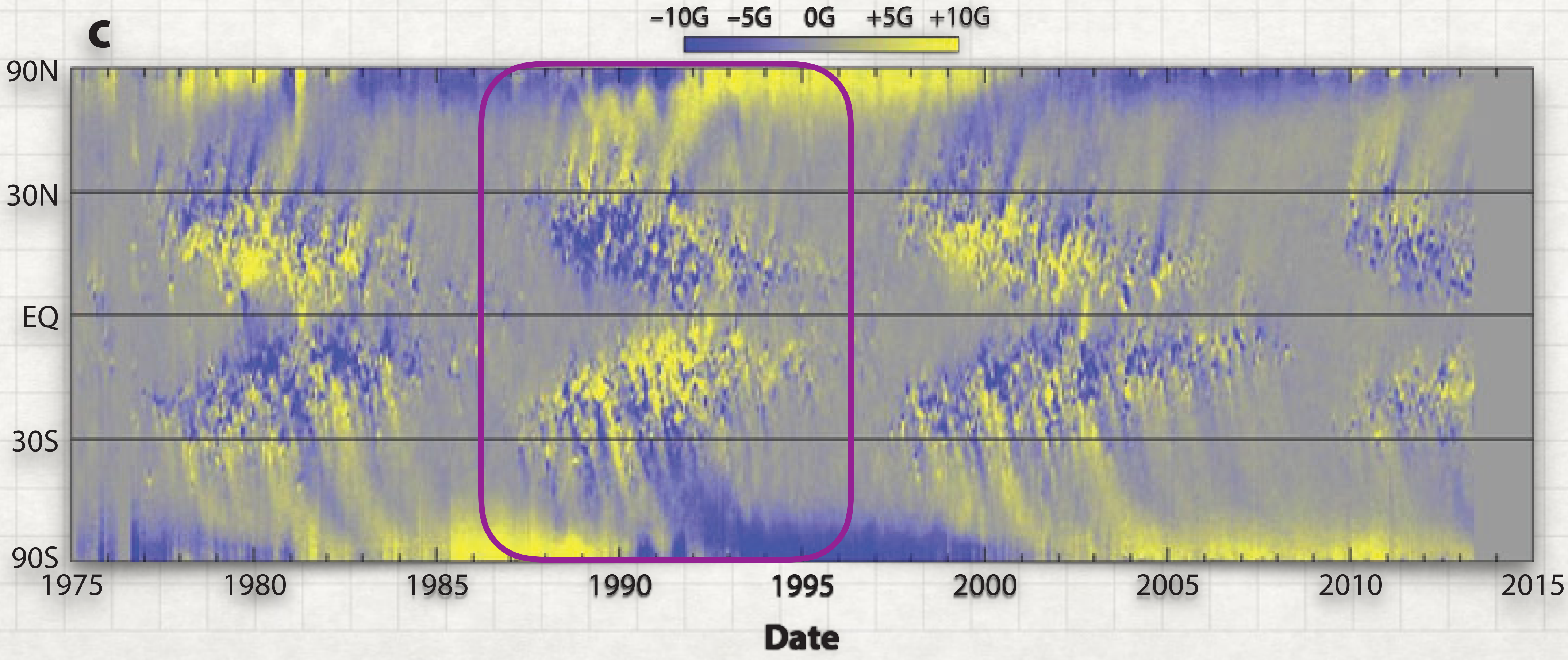
SOLAR MAGNETIC CYCLE

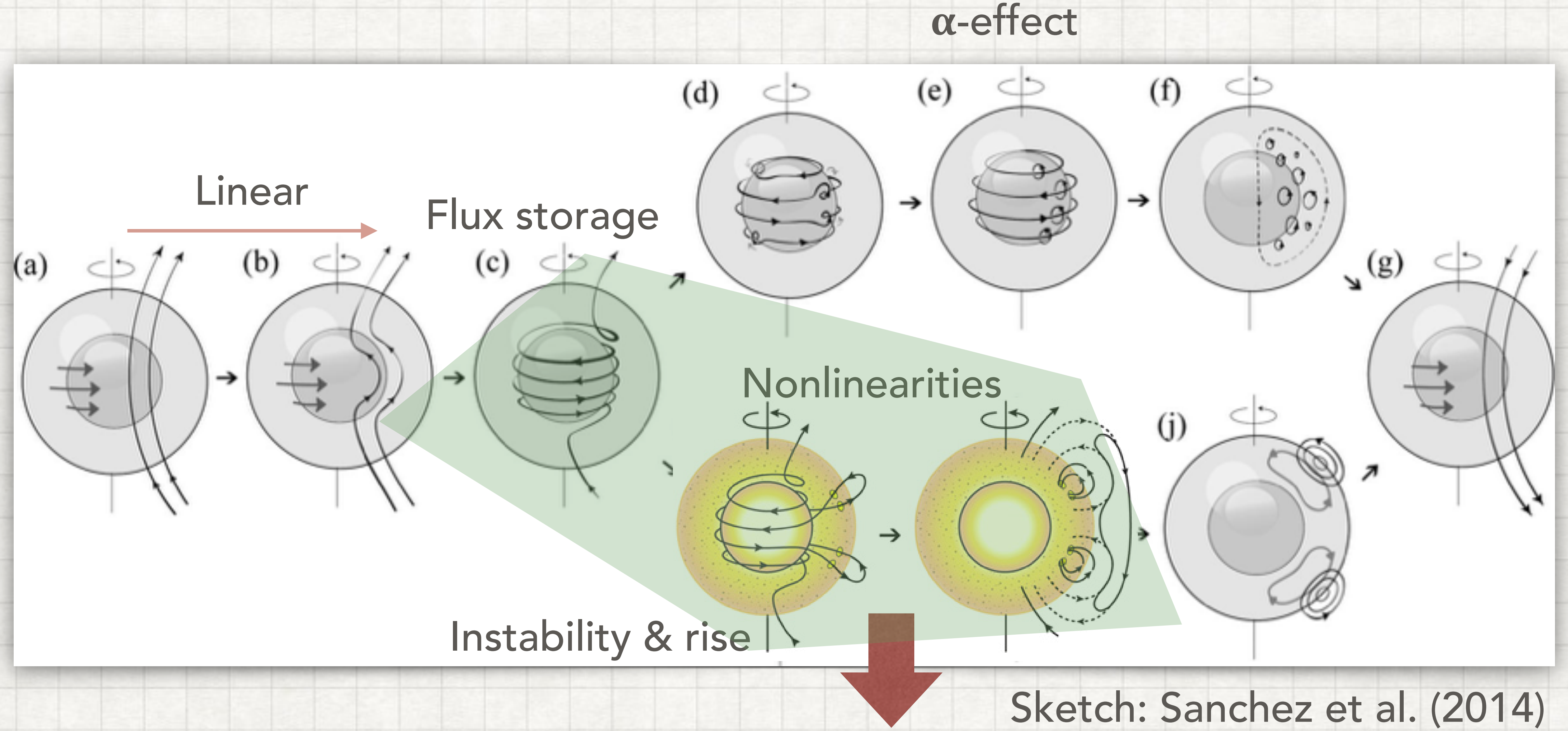
OBSERVATIONS





THE SOLAR DYNAMO

PROPOSED MECHANISMS FOR THE MAGNETIC CYCLE



Sketch: Sanchez et al. (2014)

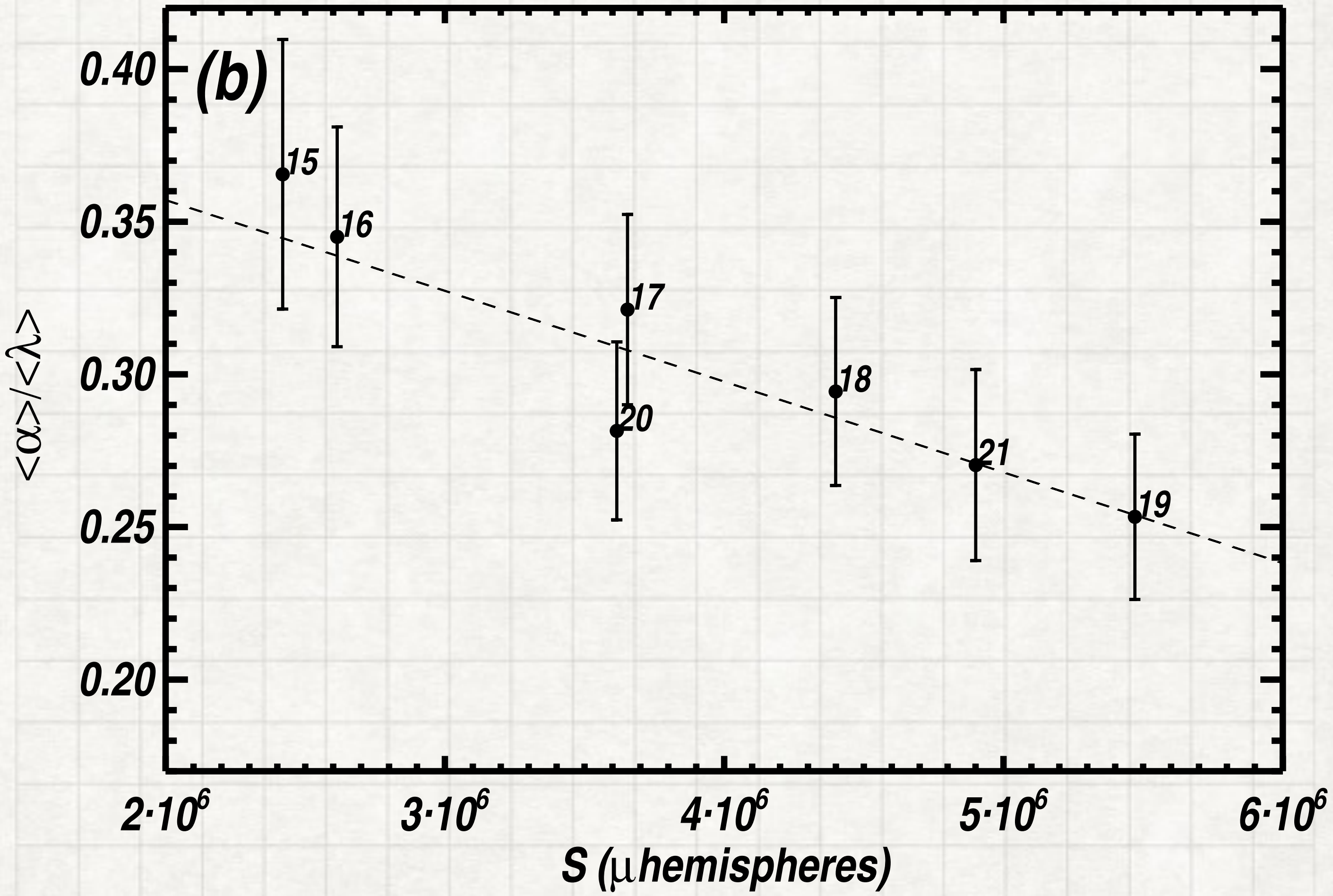
Babcock-Leighton mechanism for poloidal field regeneration

Dasi-Espuig et al. (2010)

HINT #1

VARIATIONS OF AVERAGE TILT ANGLE

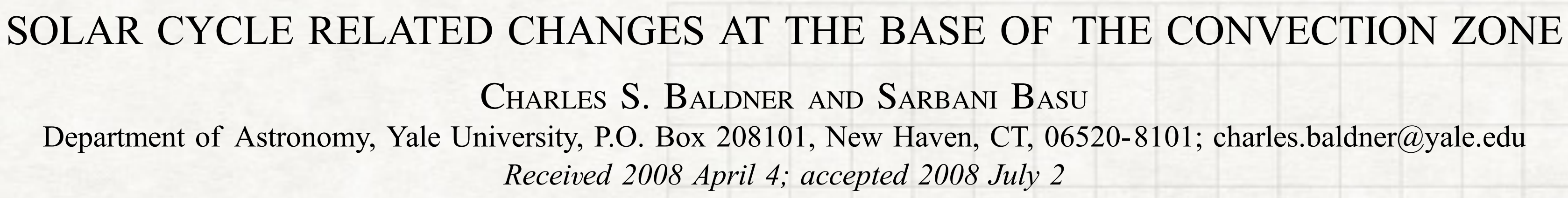
- Cycle-averaged sunspot group tilt angle from Mt. Wilson & Kodaikanal Observatories
- Anti-correlated with cycle strength
- Tilt x S(n) is correlated with S(n+1)
- Essential role in building up the polar field.



Baldner & Basu (2008)

HINT #2

HELIOSEISMIC INDICATIONS



SOLAR CYCLE RELATED CHANGES AT THE BASE OF THE CONVECTION ZONE

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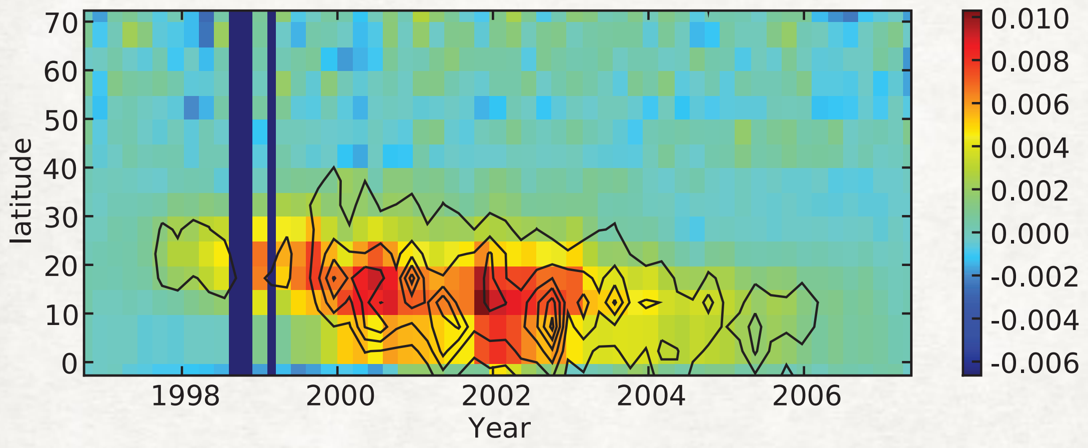
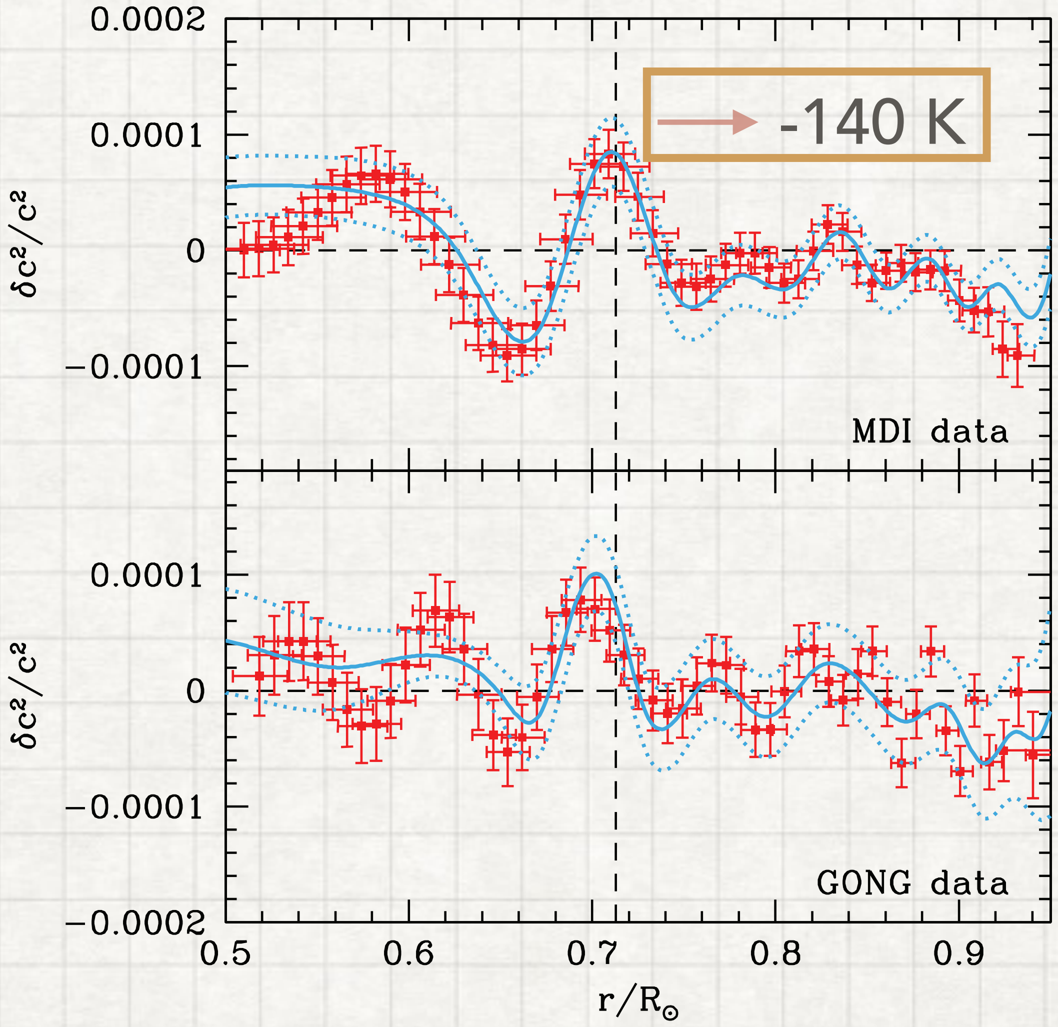


$$\delta c^2/c^2 = (7.23 \pm 2.08) \times 10^{-5}$$

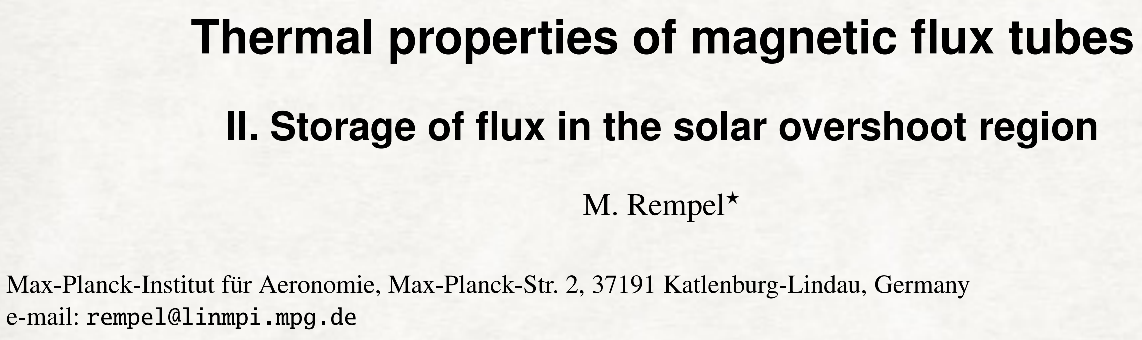

→ -140 K

- Sound speed reduced near base (Cyc 23 min-to-max)
- Reduction pattern correlated with surface magnetograms

Rempel (2003)

HINT #3

THEORETICAL EXPECTATIONS



Thermal properties of magnetic flux tubes

II. Storage of flux in the solar overshoot region

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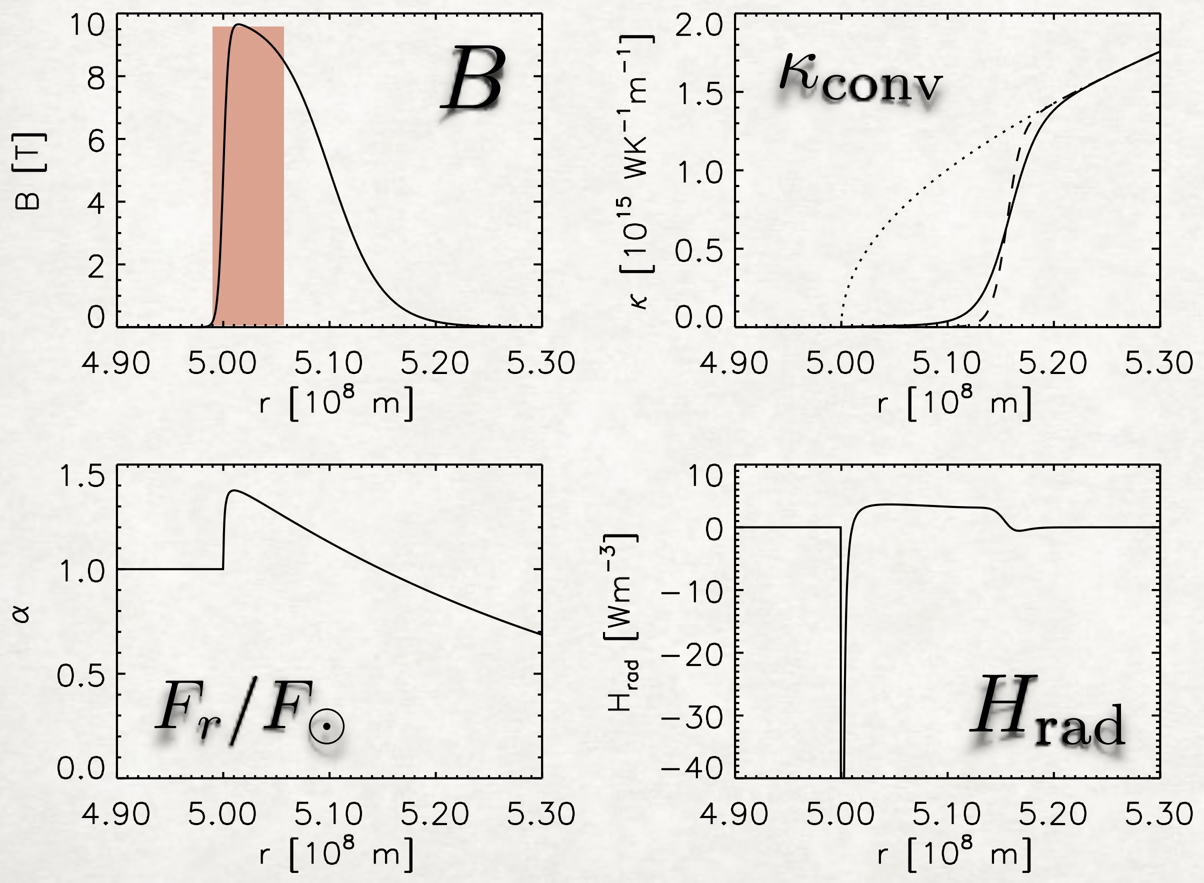
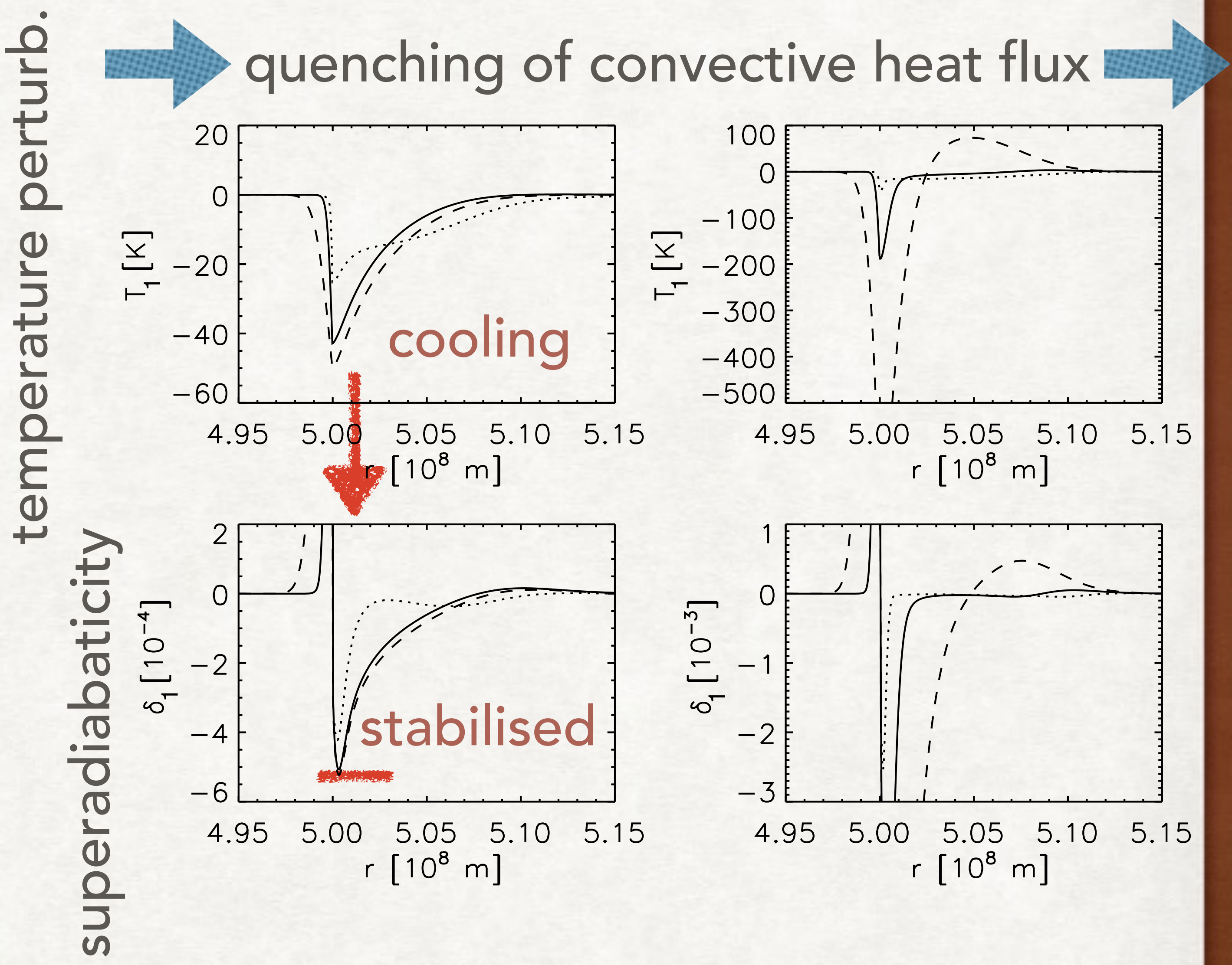


quenching of convective heat flux



**B@OVERSHOOT "STABILISES"
THE OVERSHOOT STRATIFICATION**

Işık 2015 *ApJ Lett.* 813, L13

MODIFIED STRATIFICATION

[BASED ON 1D NON-LOCAL MIXING LENGTH MODEL]

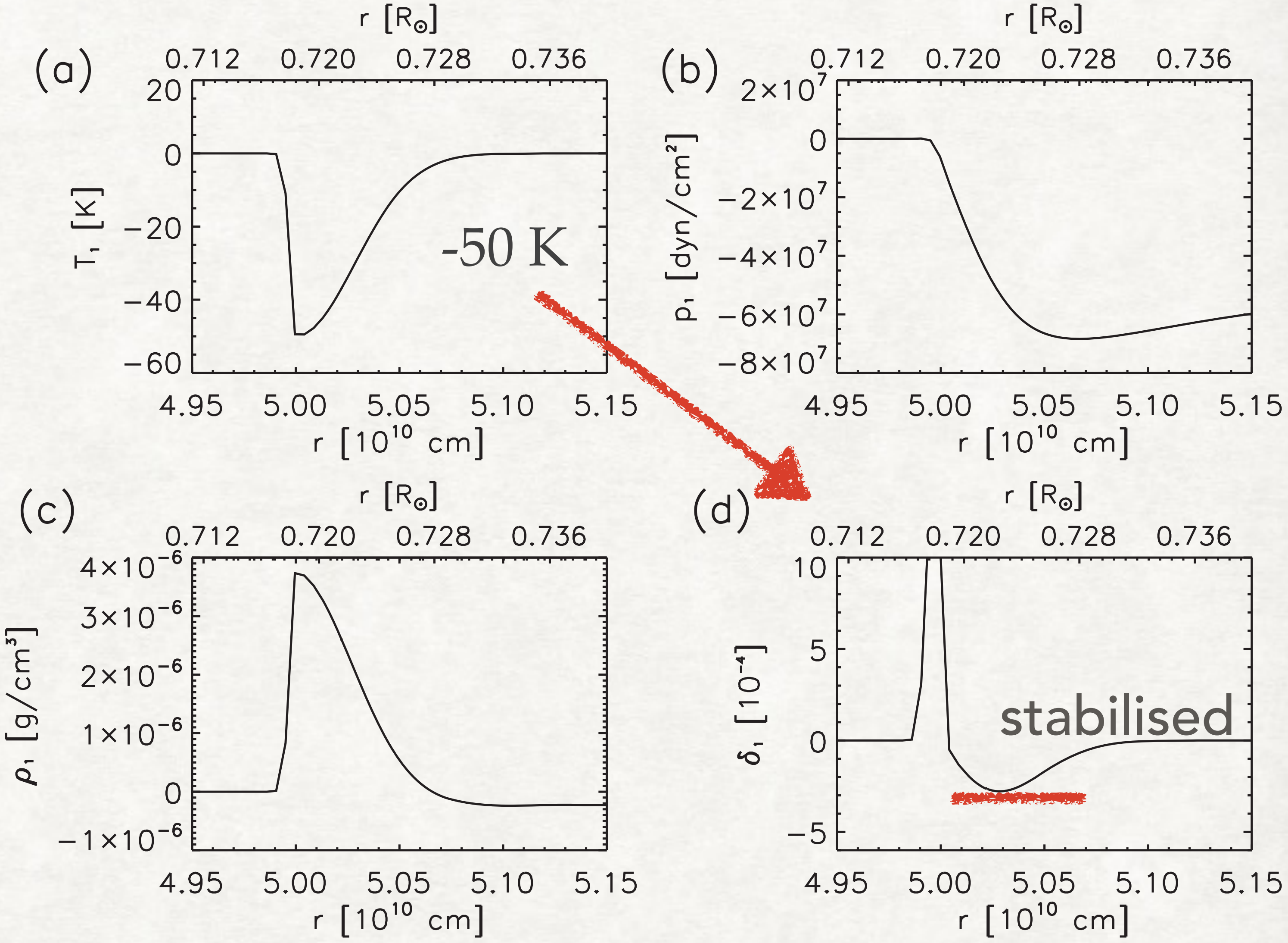
$$T_1 = T_\mathrm{m} \exp\left[\frac{-(r - r_p)^2}{\sigma_\pm^2}\right],$$

$$\rho_1 = \rho_0\left(\frac{p_1}{p_0} - \frac{T_1}{T_0}\right).$$

$$\frac{dp_1}{dr} = -\frac{p_1}{H_{p0}} + \rho_0 g \frac{T_1}{T_0},$$

$$s_1 = c_p\left(\frac{T_1}{T_0} - \nabla_\mathrm{ad}\frac{p_1}{p_0}\right),$$

$$\delta_1 = -\frac{H_{p0}}{c_p}\frac{ds_1}{dr}.$$



Non-local mixing length model (Skaley & Stix 1991)

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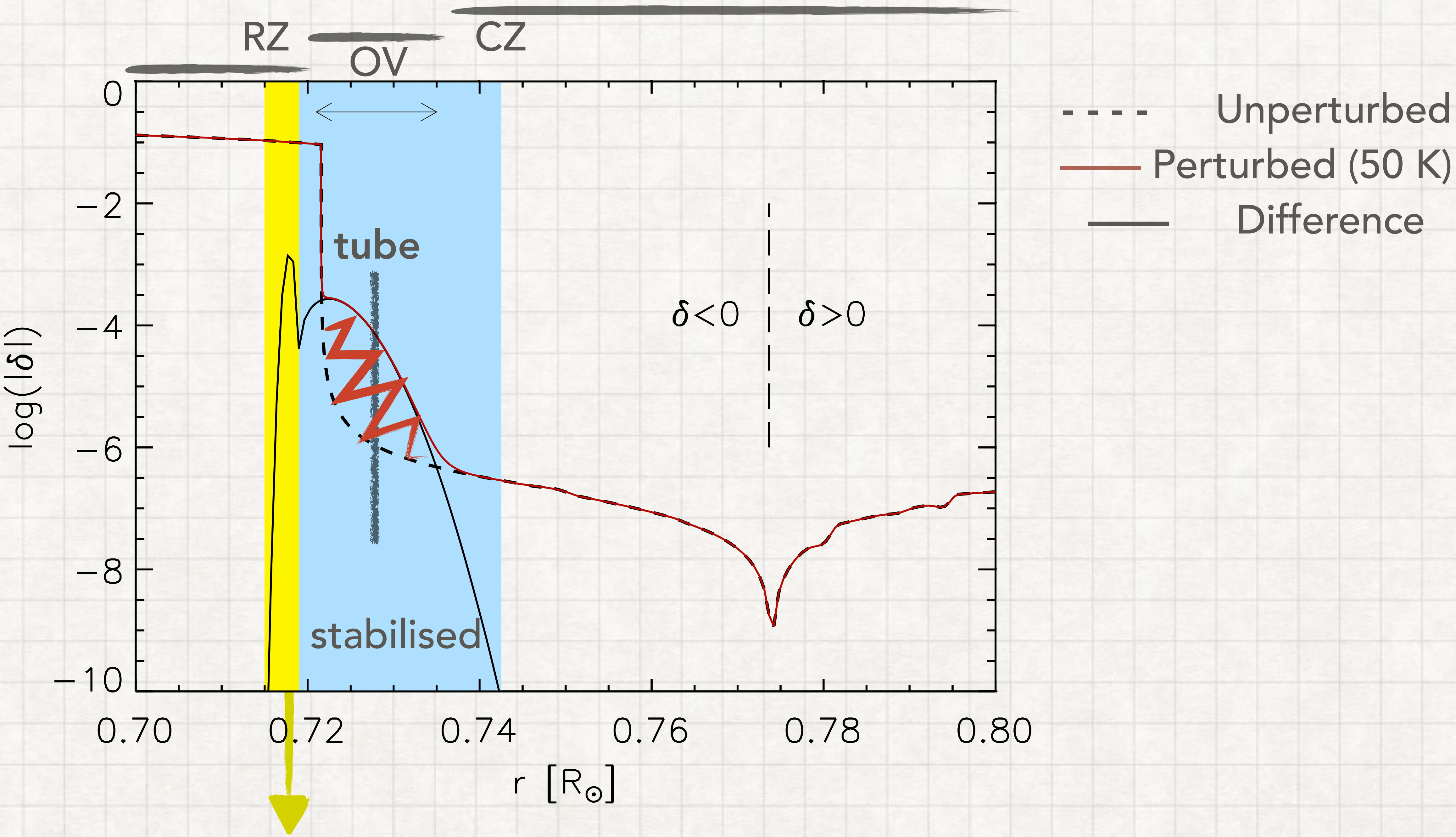
A STABILISED OVERSHOOT REGION

EFFECTS ON FLUX TUBE STABILITY?



destabilised,
but ineffective

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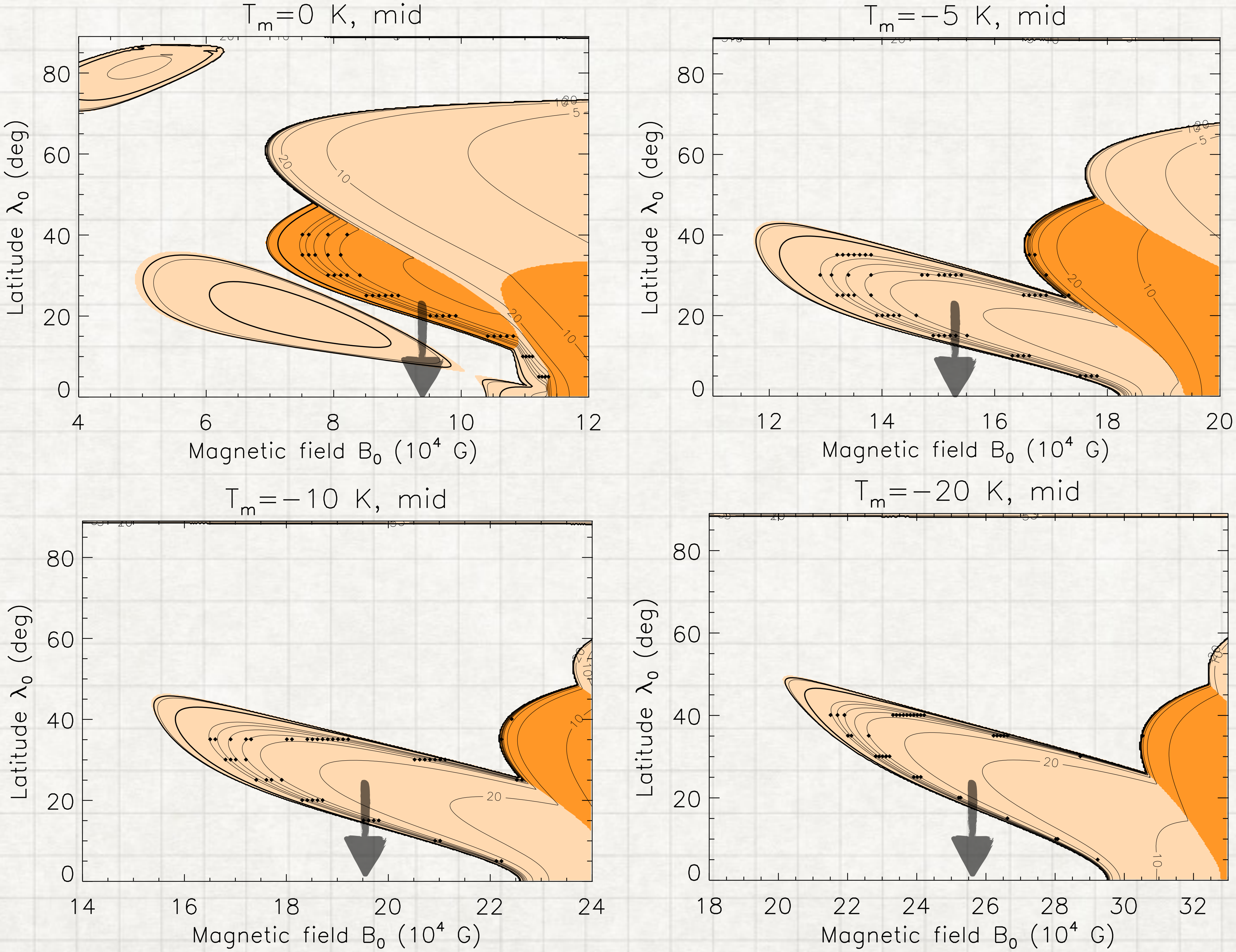
LINEAR STABILITY ANALYSIS

HOW MAGNETIC FLUX TUBES (WITH SIMILAR GROWTH RATES) ARE STABILISED



Latitude [deg]

Field strength of the tube

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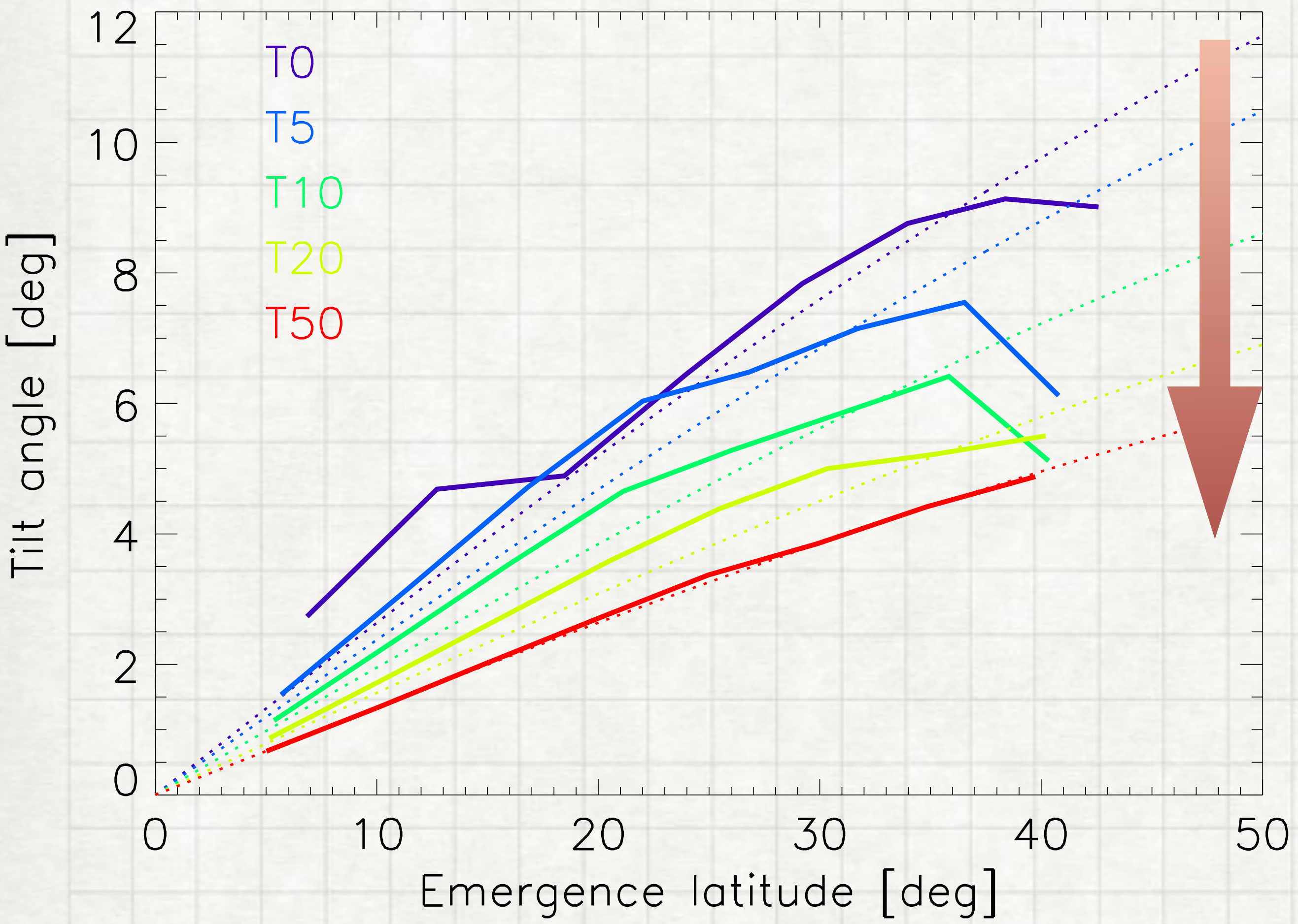
JOY'S LAW & ANTI-CORRELATION

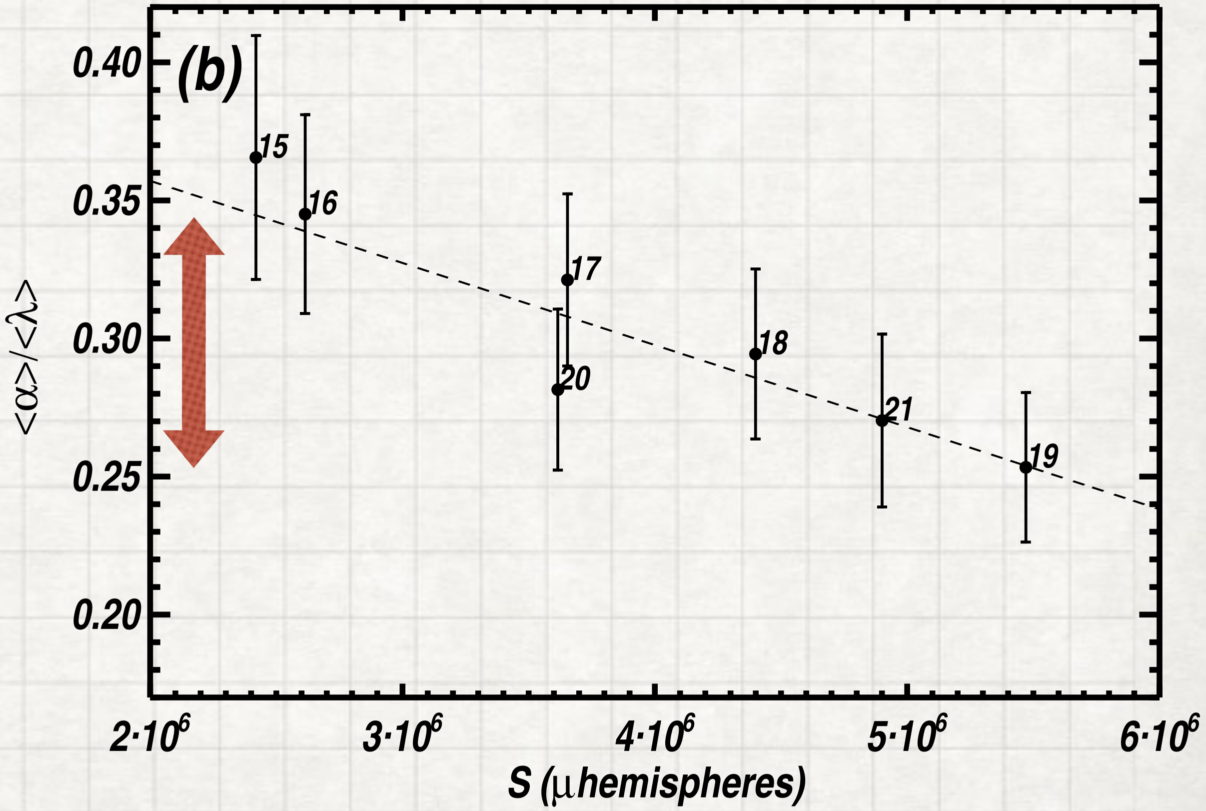
NON-LINEAR SATURATION OF THE BL MECHANISM?



Mean Tilt Angles and Joy's Law Parameters

T_m (K)	δ ($\times 10^{-5}$)	$\langle\alpha\rangle$	$\langle\alpha\rangle/\langle\lambda\rangle$	a	γ_0	T
0	−0.098	6.69	0.23	0.25	15.2	1.39
−5	−0.636	5.34	0.21	0.23	13.7	1.22
−10	−1.16	4.29	0.17	0.19	11.2	1.03
−20	−2.24	3.63	0.14	0.15	9.0	0.86
−50	−54.9	2.91	0.11	0.13	7.7	0.72

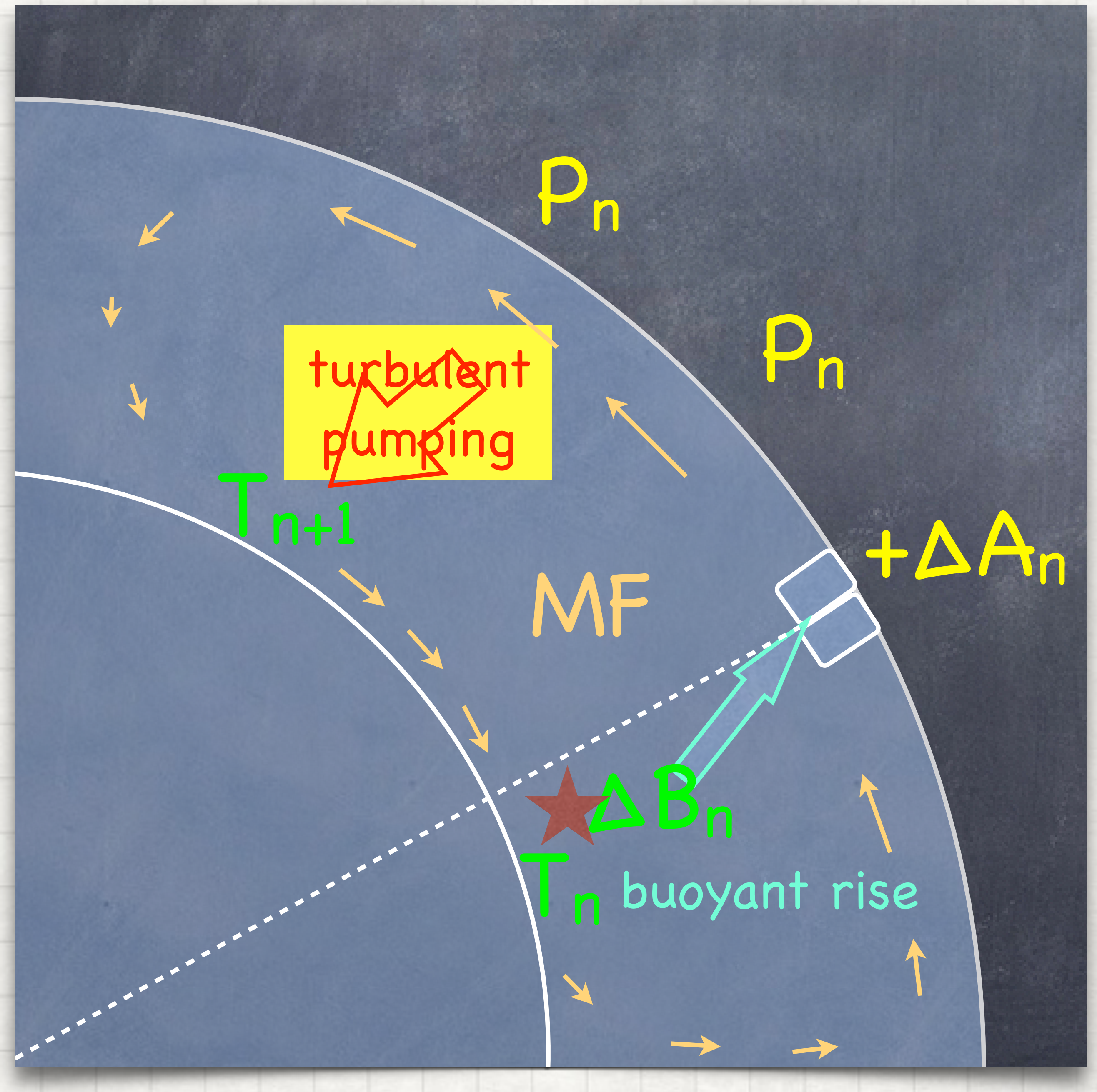
- Stronger cycles — lower tilt angles
- 5-20 K cooling sufficient
- Observed min-max range: 140 K
- Confirmation / more cycles needed!



2D FLUX TRANSPORT DYNAMO WITH RANDOM EMERGENCE

A testbed for stellar dynamos (Işık et al., in prep.)

- Double-ring sources, probabilistically by Φ_{tor} (base)
- Stability and rise of flux tubes as a physical link (latitudes & tilt angles)
- Empirical surface flux distribution
- Nearly critical dynamo solutions
- Next step: introduce saturation



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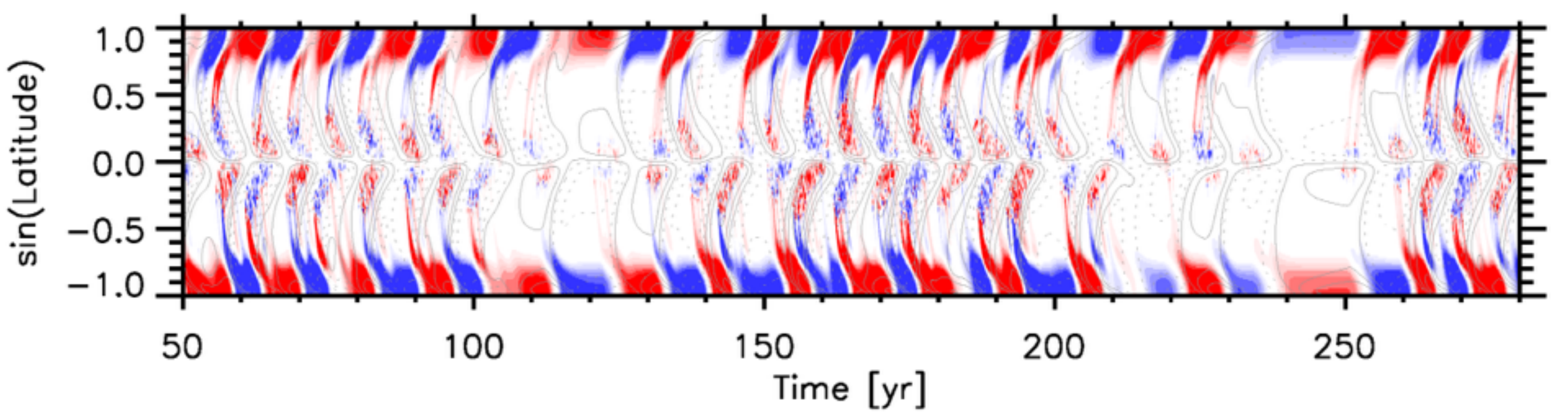

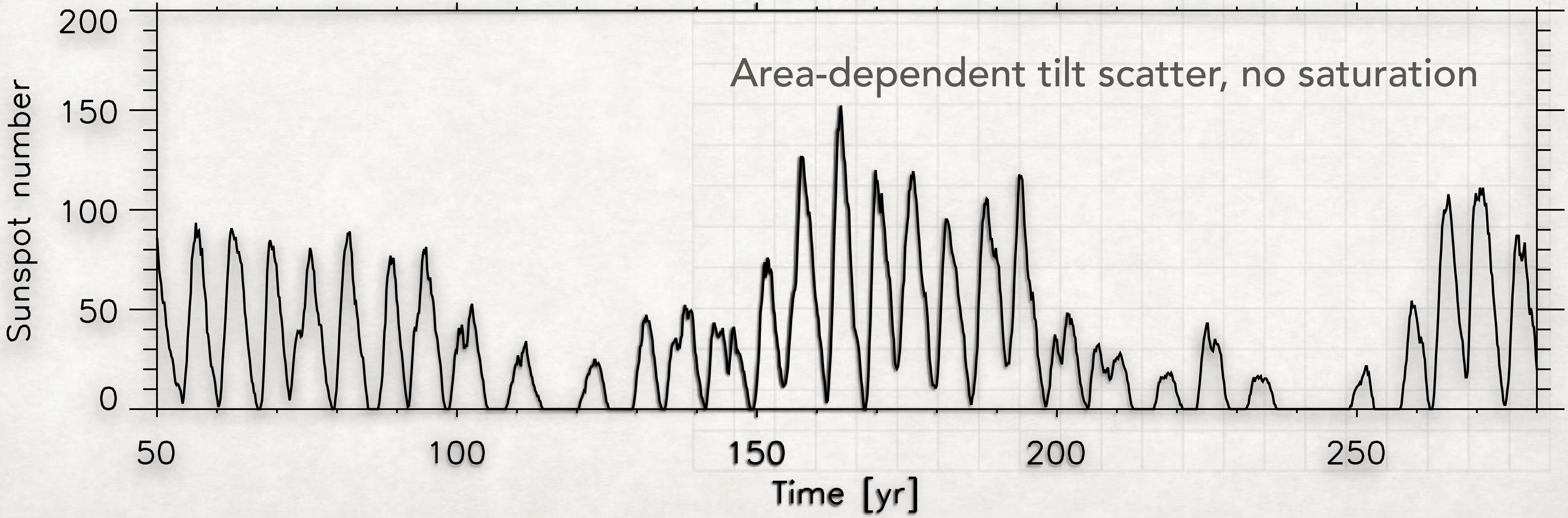

Area-dependent tilt scatter, no saturation

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