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An *ab initio* approach to solar-cycle dependent cosmic-ray modulation

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Outline

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2. Effective values and time dependence
3. Modulation model
4. Solar minima spectra
5. Long-term modulation
6. Time dependence of diffusion coefficients
7. Summary and conclusions

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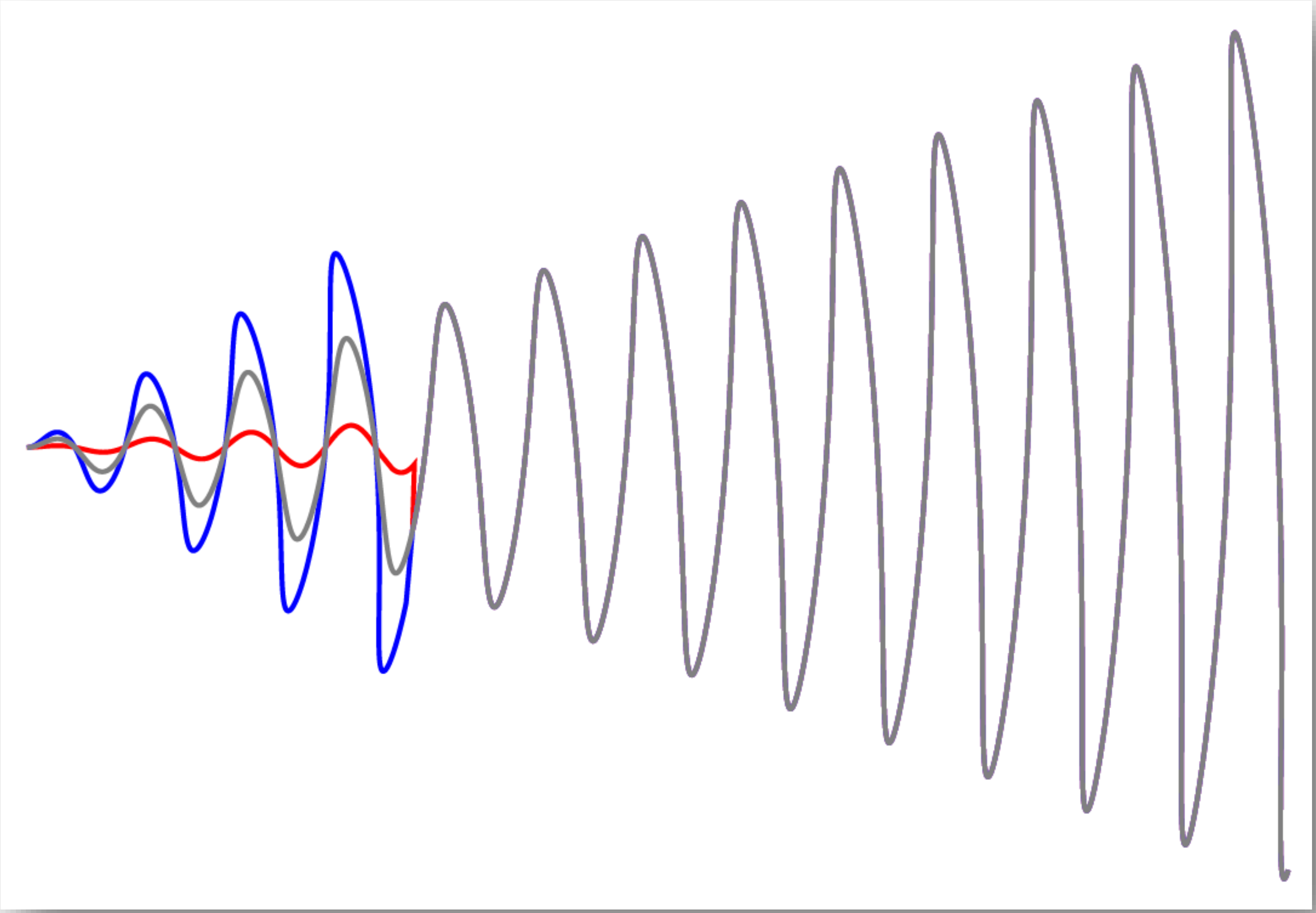
1. Introduction

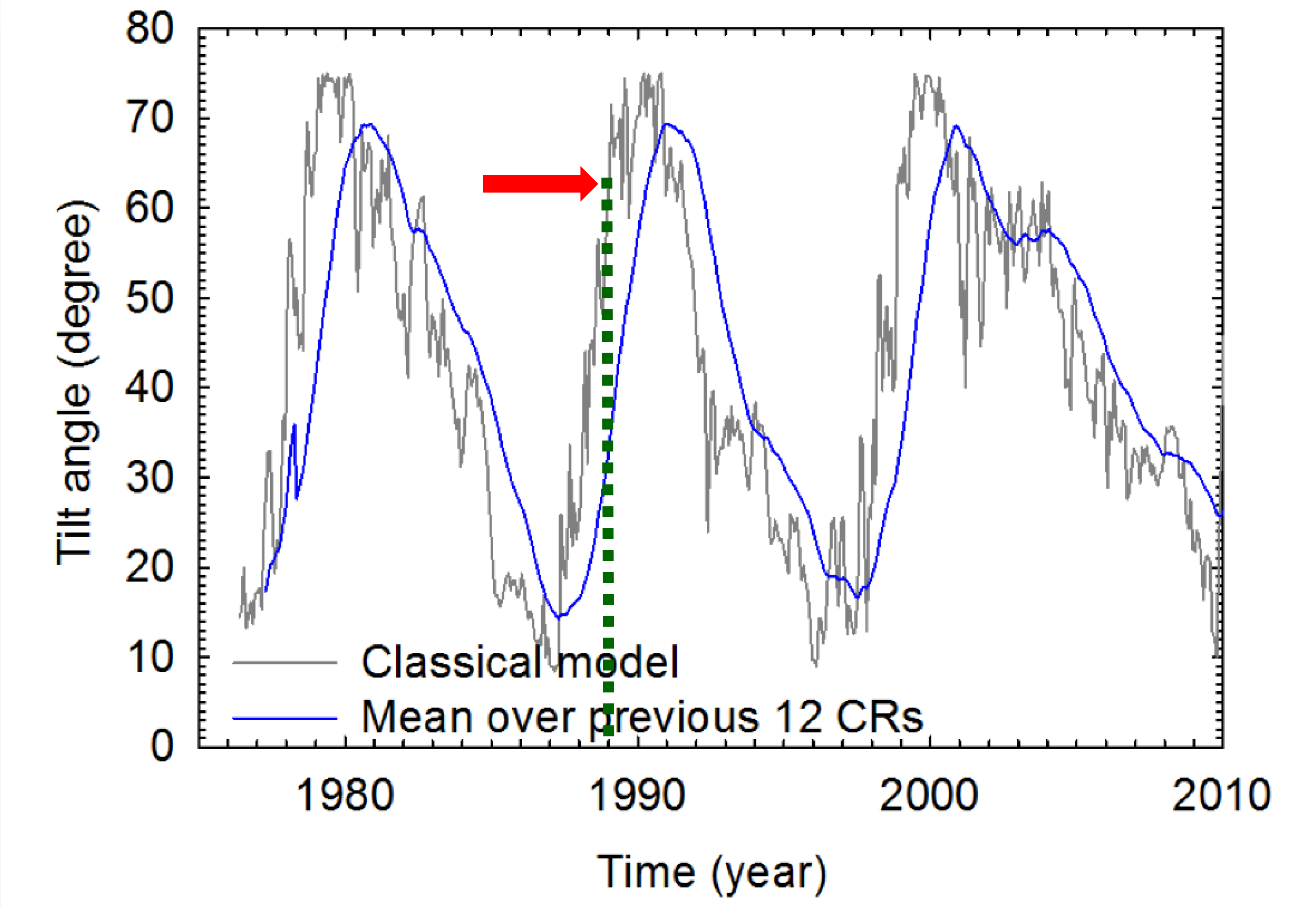
- Starting point of an *ab initio* approach to modulation (e.g. Engelbrecht & Burger 2013a & b, ApJ) is turbulence spectra as input for diffusion tensor
- Simplified version of Engelbrecht's model is used in this study; results are qualitative rather than quantitative
- In his presentation later this afternoon he will illustrate the usefulness of a fully *ab initio* approach
- Emulate time dependence by using time-averaged *effective values* as input to code; very little freedom to "tune" parameters
- Reasonable qualitative agreement with long-term observations as well as 1987 & 2009 energy spectra
- Based on Masters Dissertation of Katlego Moloto

2. Effective values and time dependence

- Steady-state 3D model using “effective” values of 1 AU observations as input, taking into account outward convection by the solar wind



2. Effective values and time dependence



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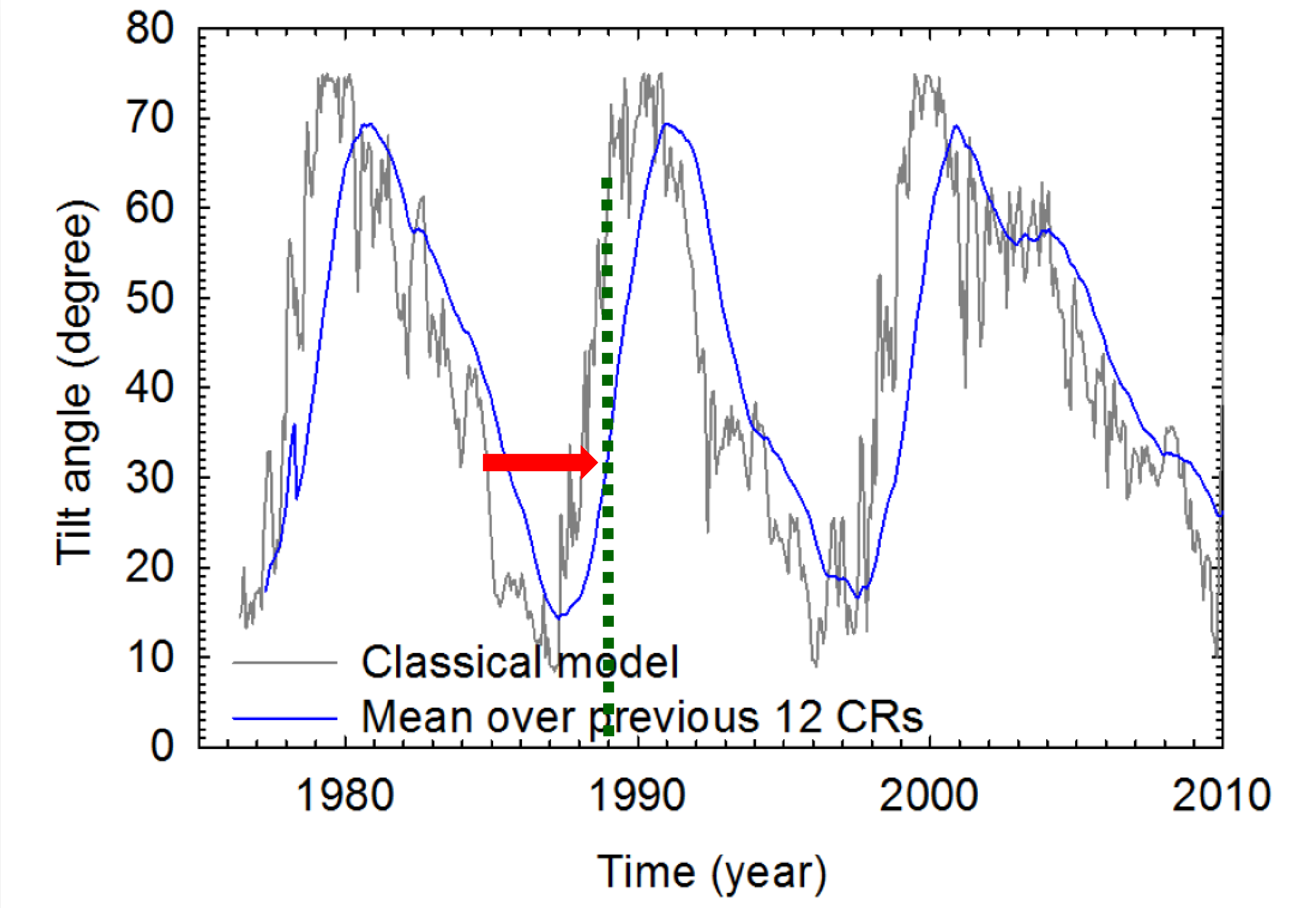

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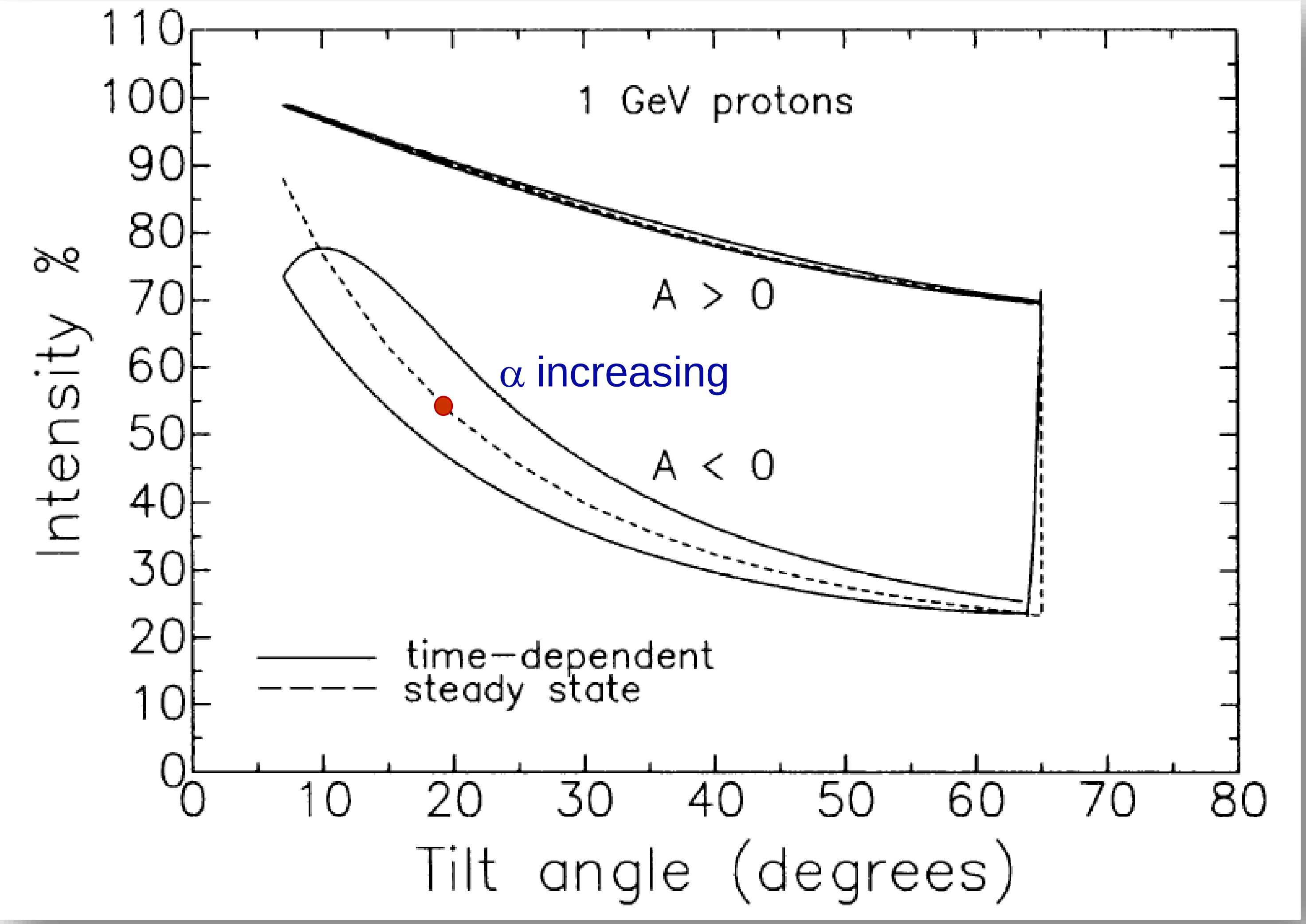

Le Roux & Potgieter (1990, ApJ)

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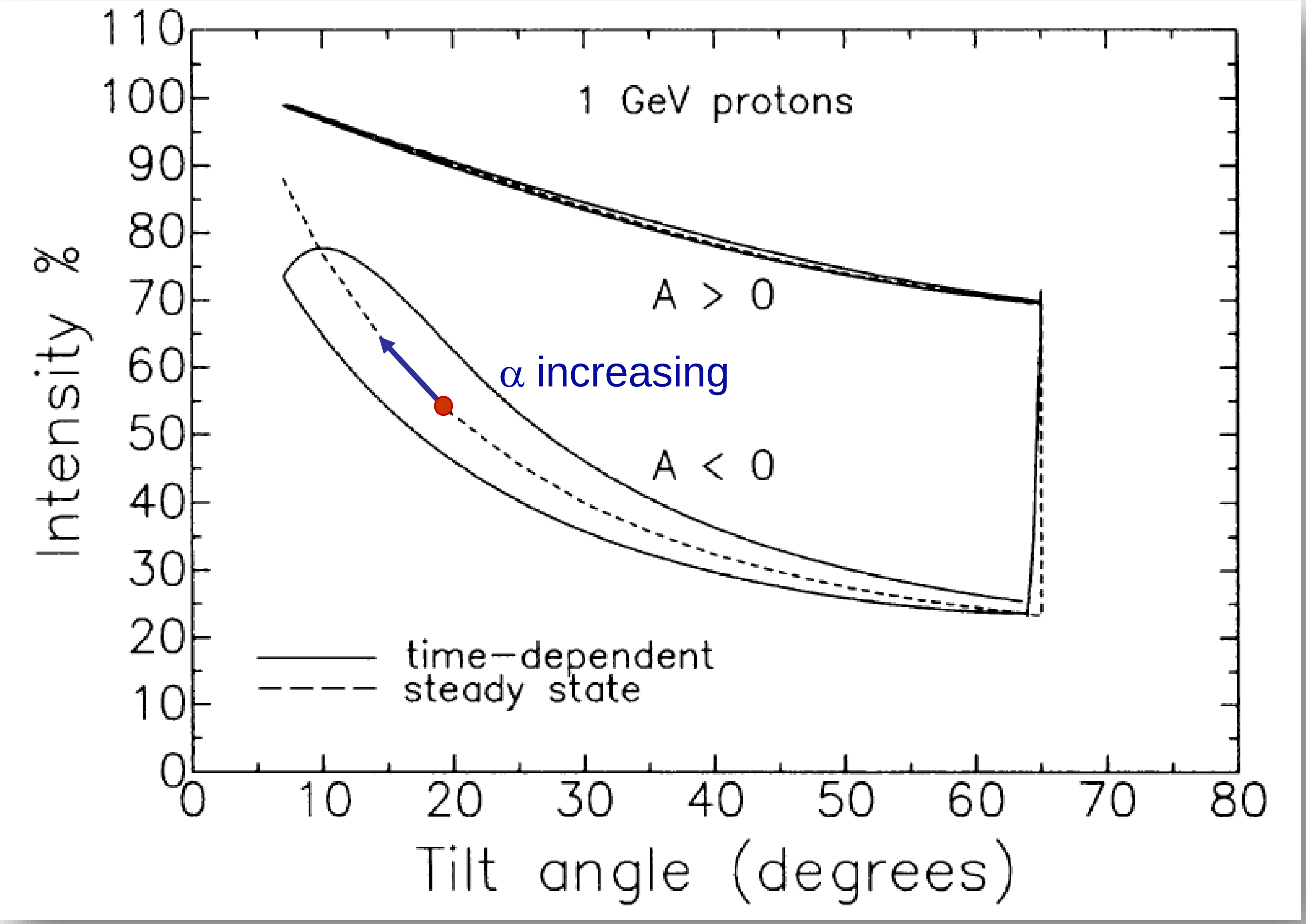

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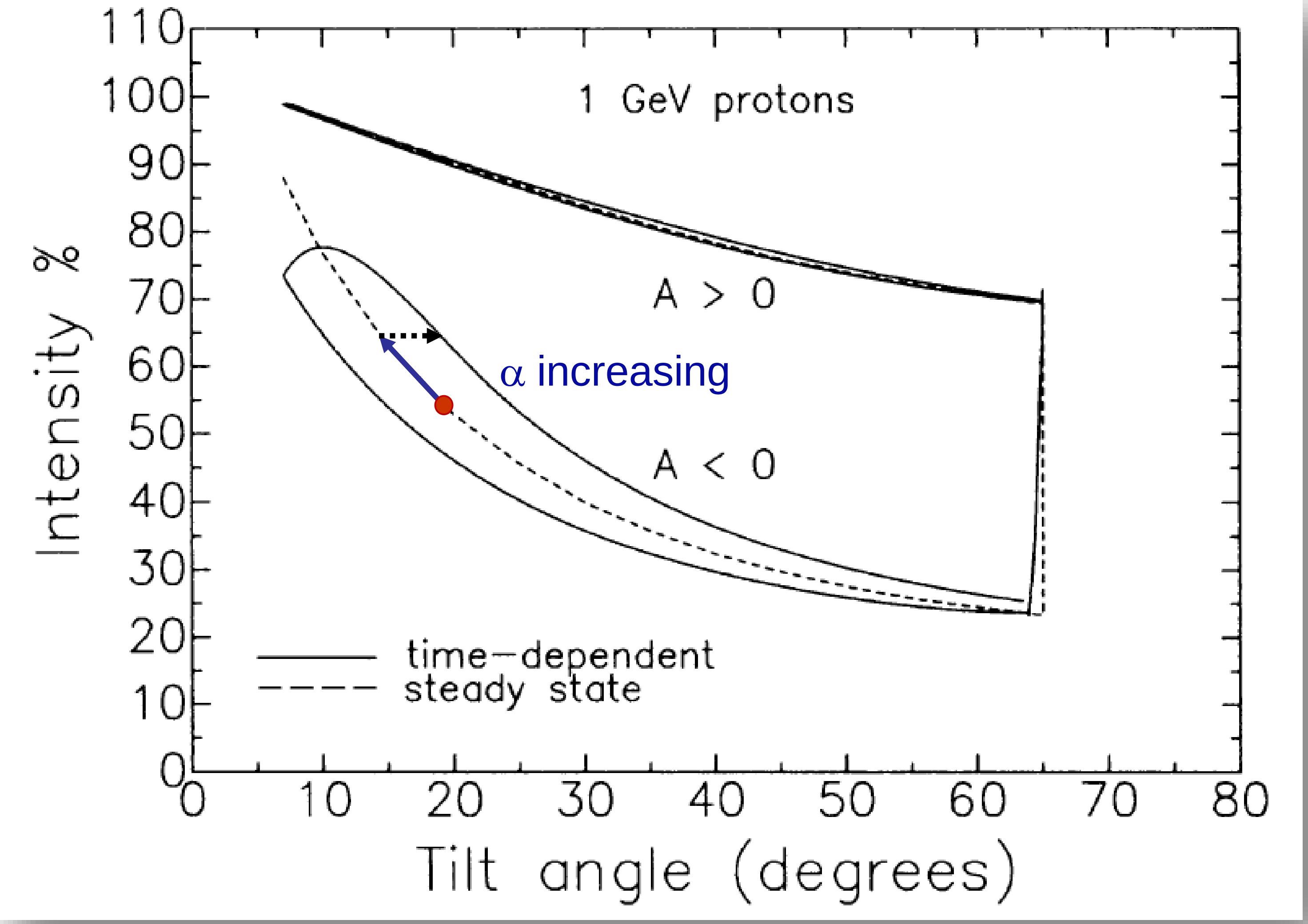

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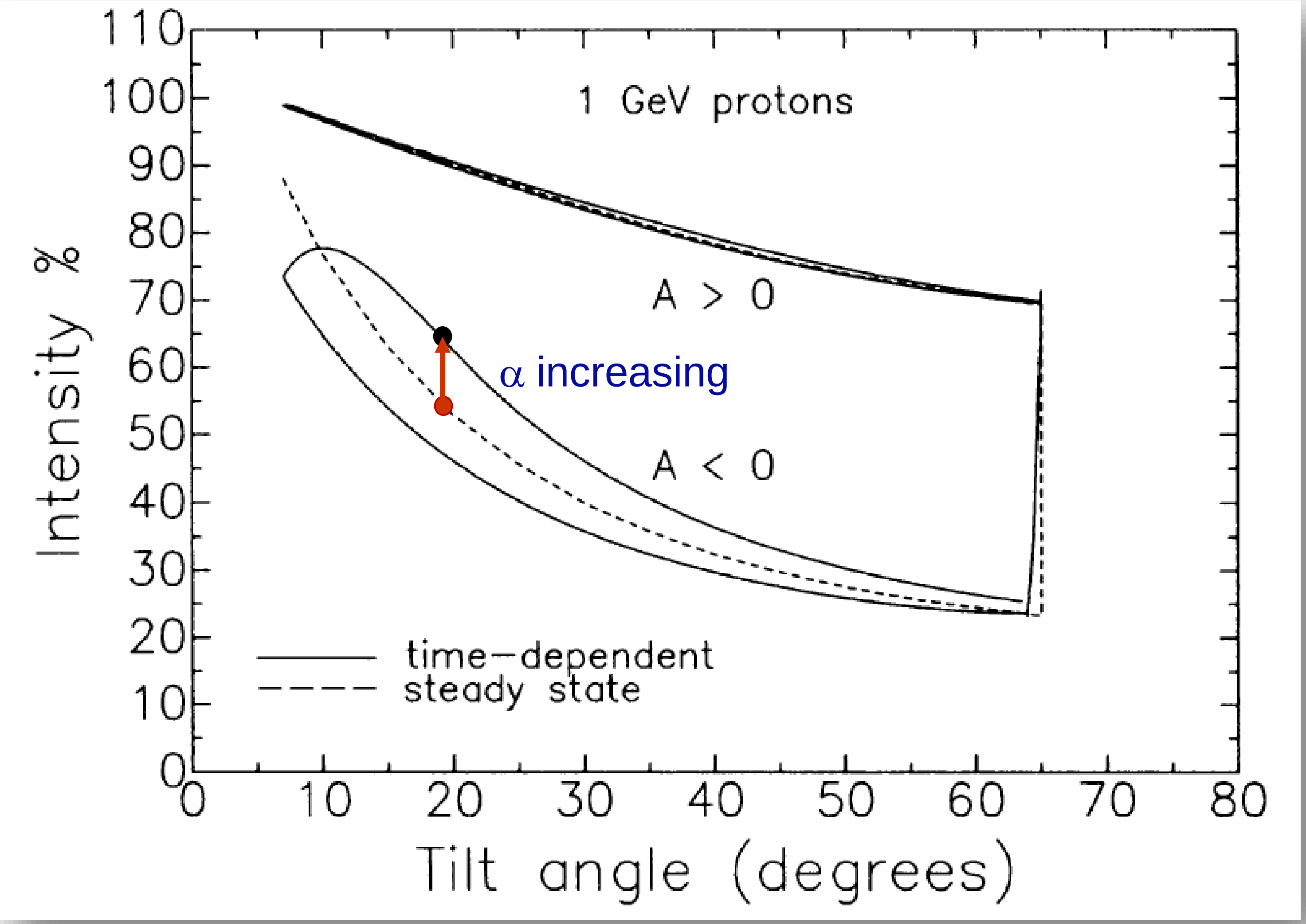

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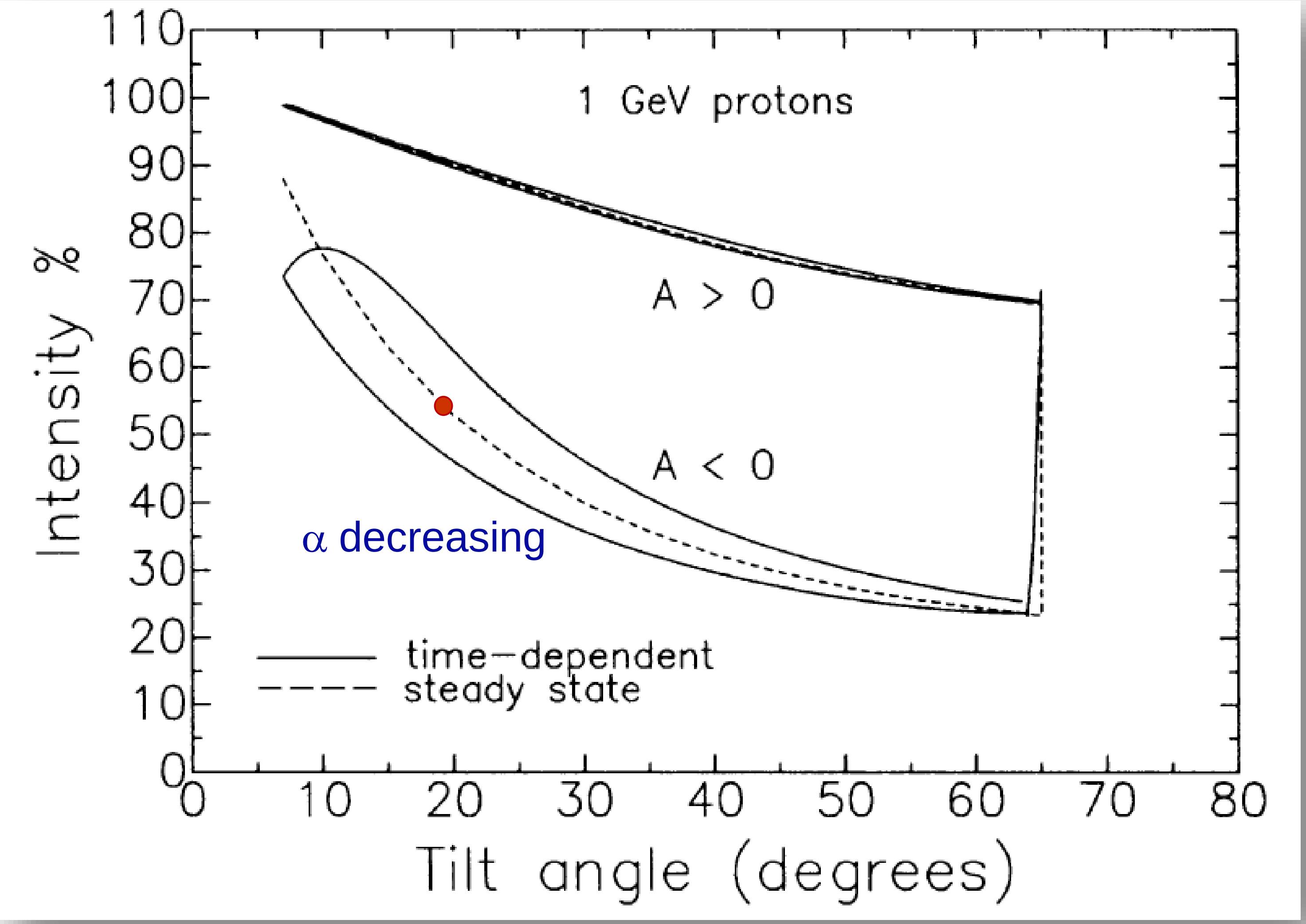

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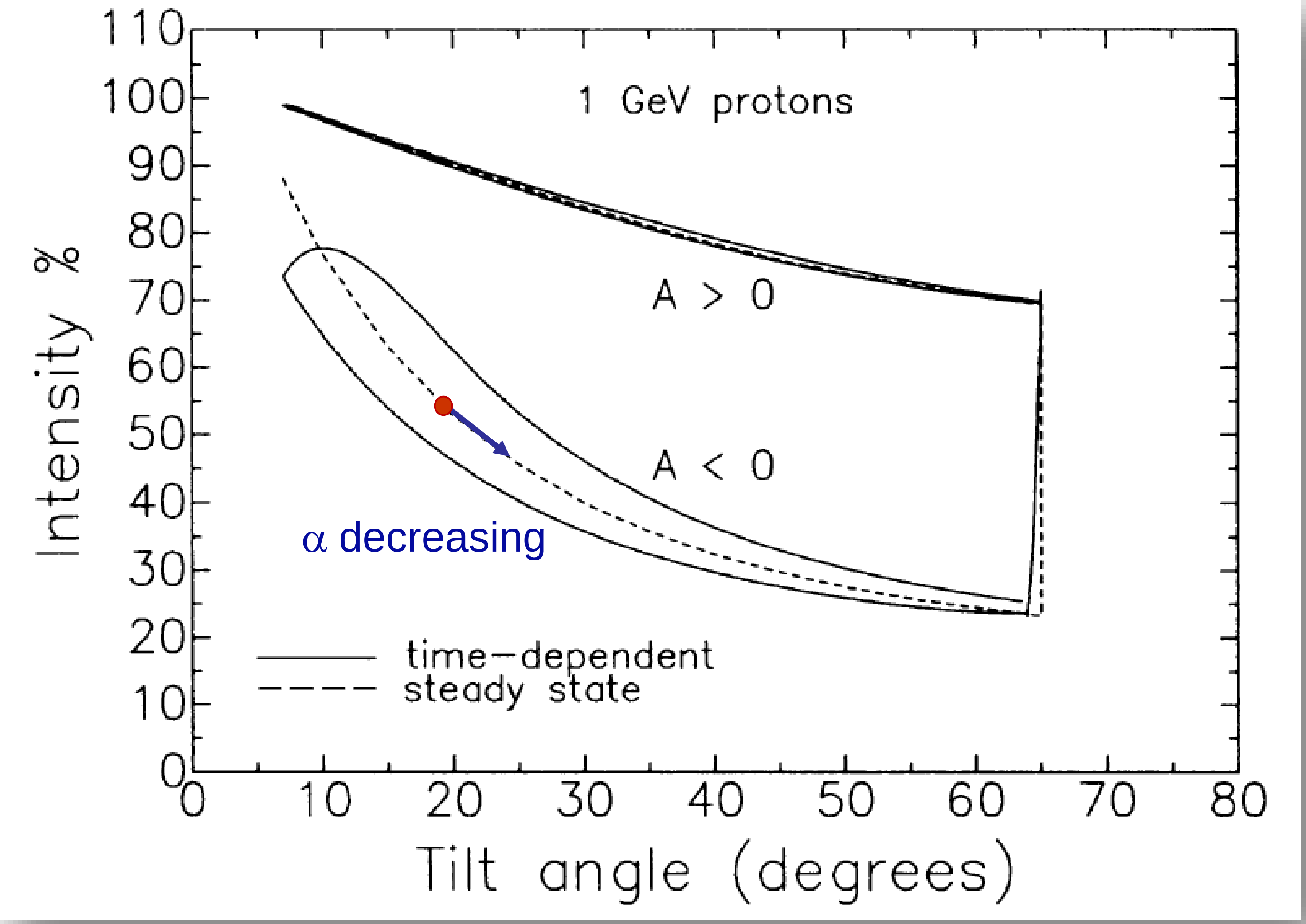

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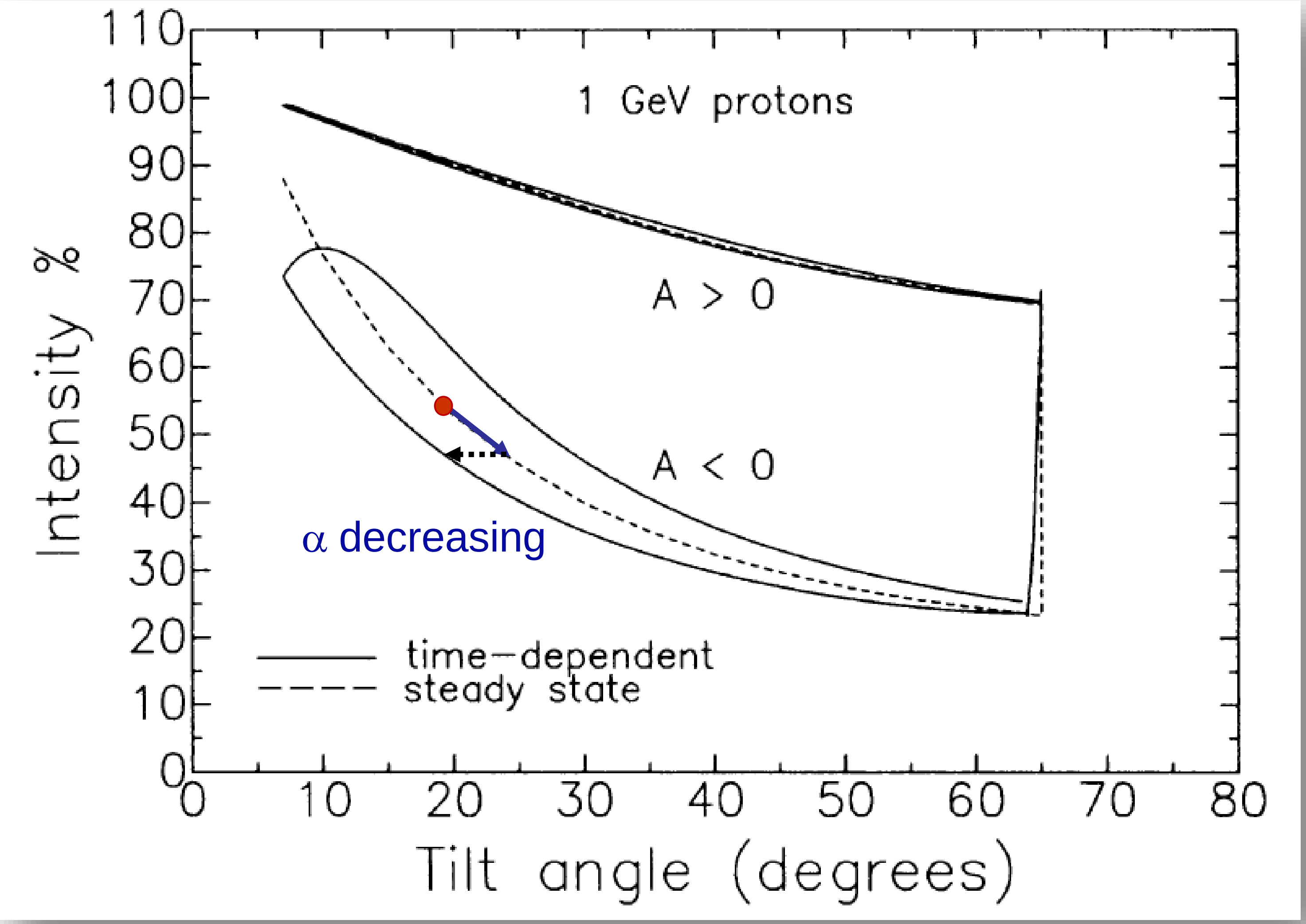

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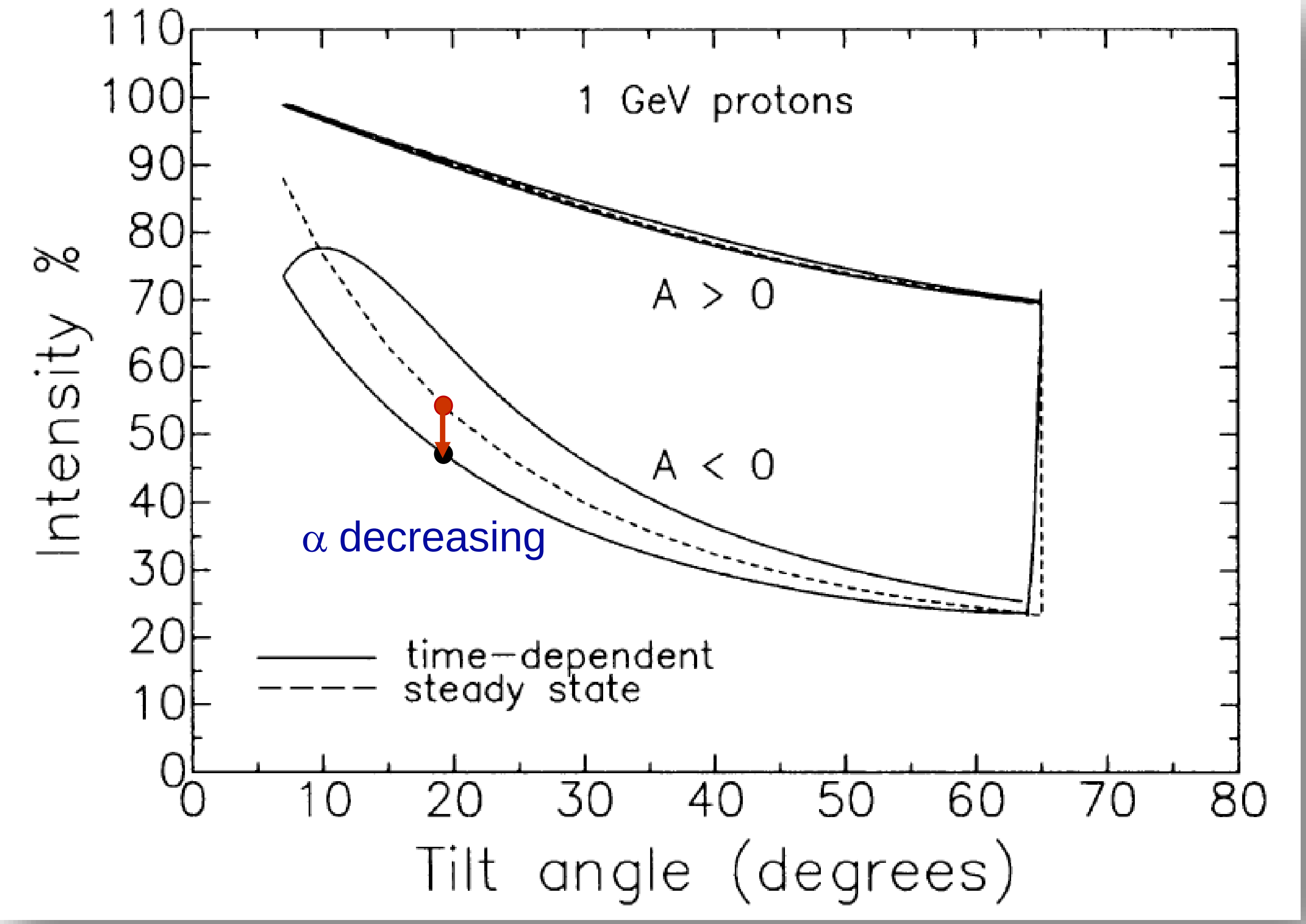


Le Roux & Potgieter (1990, ApJ)

3. **Modulation model:** Diffusion tensor

- Based on QLT for parallel- (Teufel & Schlickeiser 2003, A&A) and NLGC for perpendicular diffusion (Matthaeus et al. 2003, ApJL)

$$\kappa_{||} \sim v \frac{B_0^2}{\delta B_{slab}^2} k_{\min} R_L^2 \left[1 + \frac{10}{k_{\min}^{5/3} R_L^{5/3}} \right]$$

$k_{\min} R_L \gg 1$ energy range of spectrum dominates

$k_{\min} R_L \ll 1$ inertial range of spectrum dominates

$\kappa_{||} \sim B_0^0$ (high energy) and $B_0^{5/3}$ (low energy)

3. Modulation model: Diffusion tensor

$$\kappa_{\perp} \sim v\left(l_{2D}\frac{\delta B_{2D}^2}{B_0^2}\right)^{2/3}\kappa_{||}^{1/3}$$

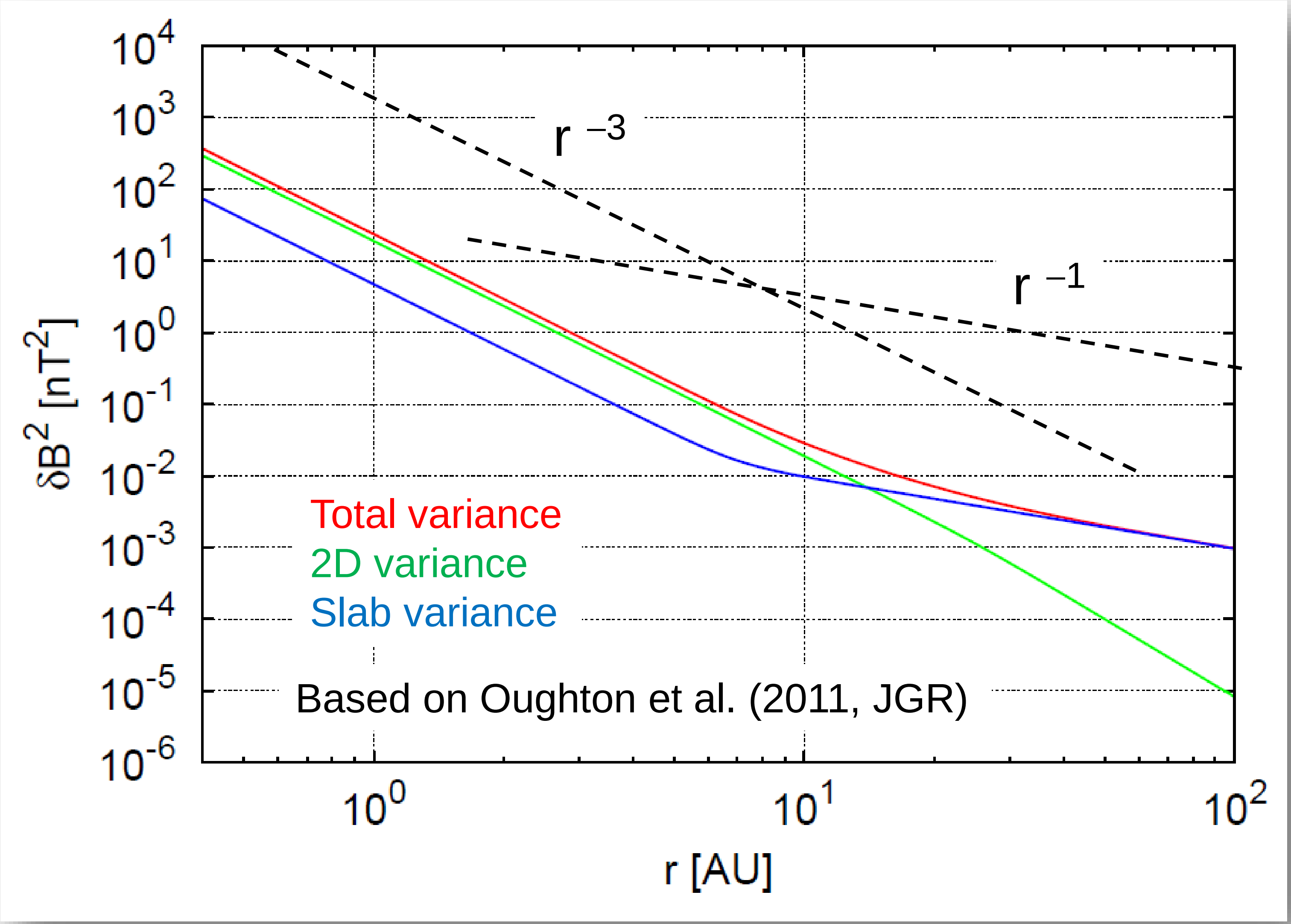
$\kappa_{\perp} \sim B_0^{-4/3}$ (high energy) and $B_0^{-7/9}$ (low energy)

- Drift coefficient parametric fit of Burger and Visser (2010, ApJ)

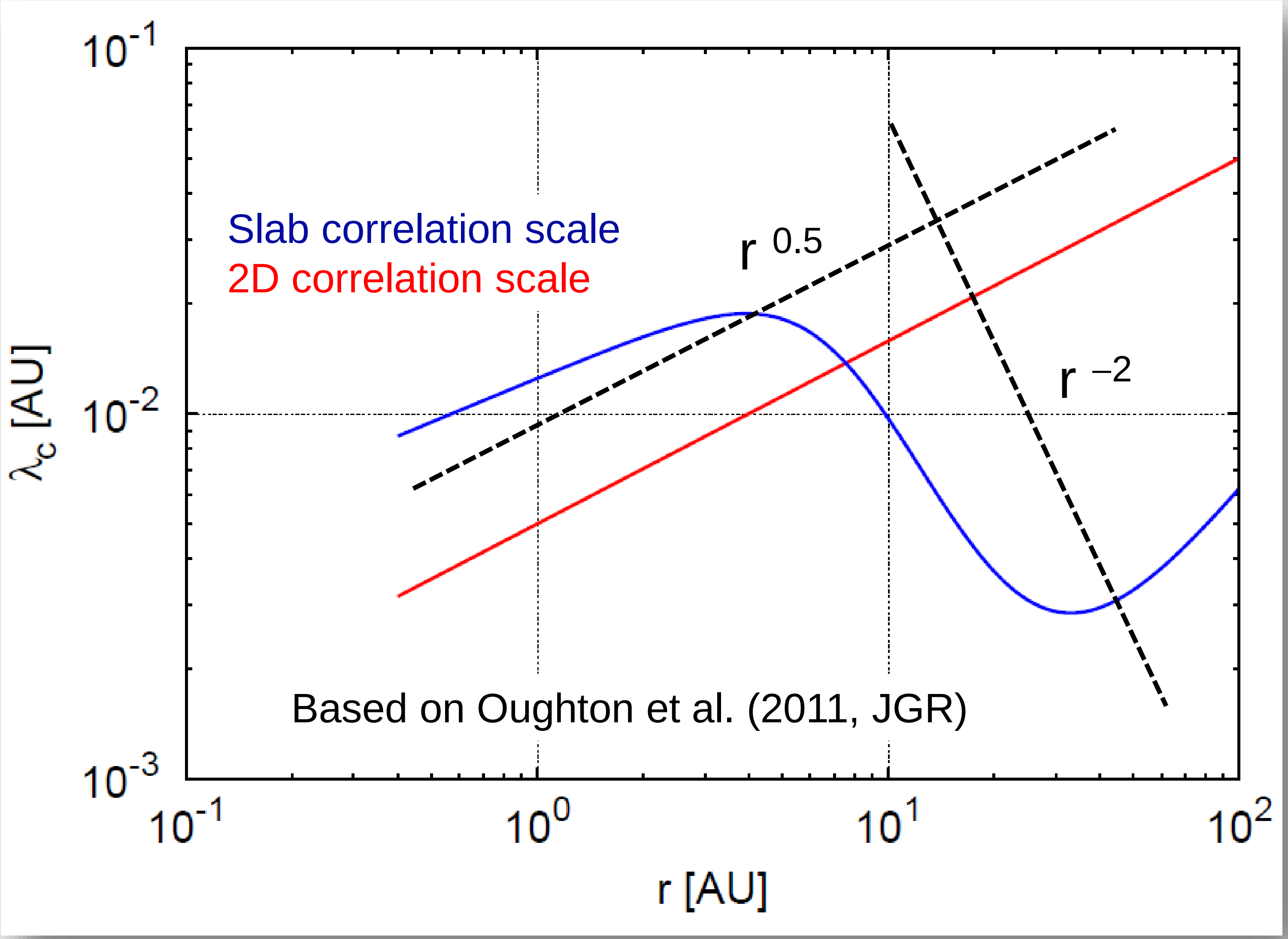
3. Modulation model: HMF & turbulence parameters

15 month averages	1987	1996	2009
B (nT)	5.8	5.7	4.4
Variance of N-component (nT^2)	8.3	9.4	5.7
Tilt angle (degree)	4.1	4.5	11.2
Inertial range spectral index	–1.67	–1.67	–1.67

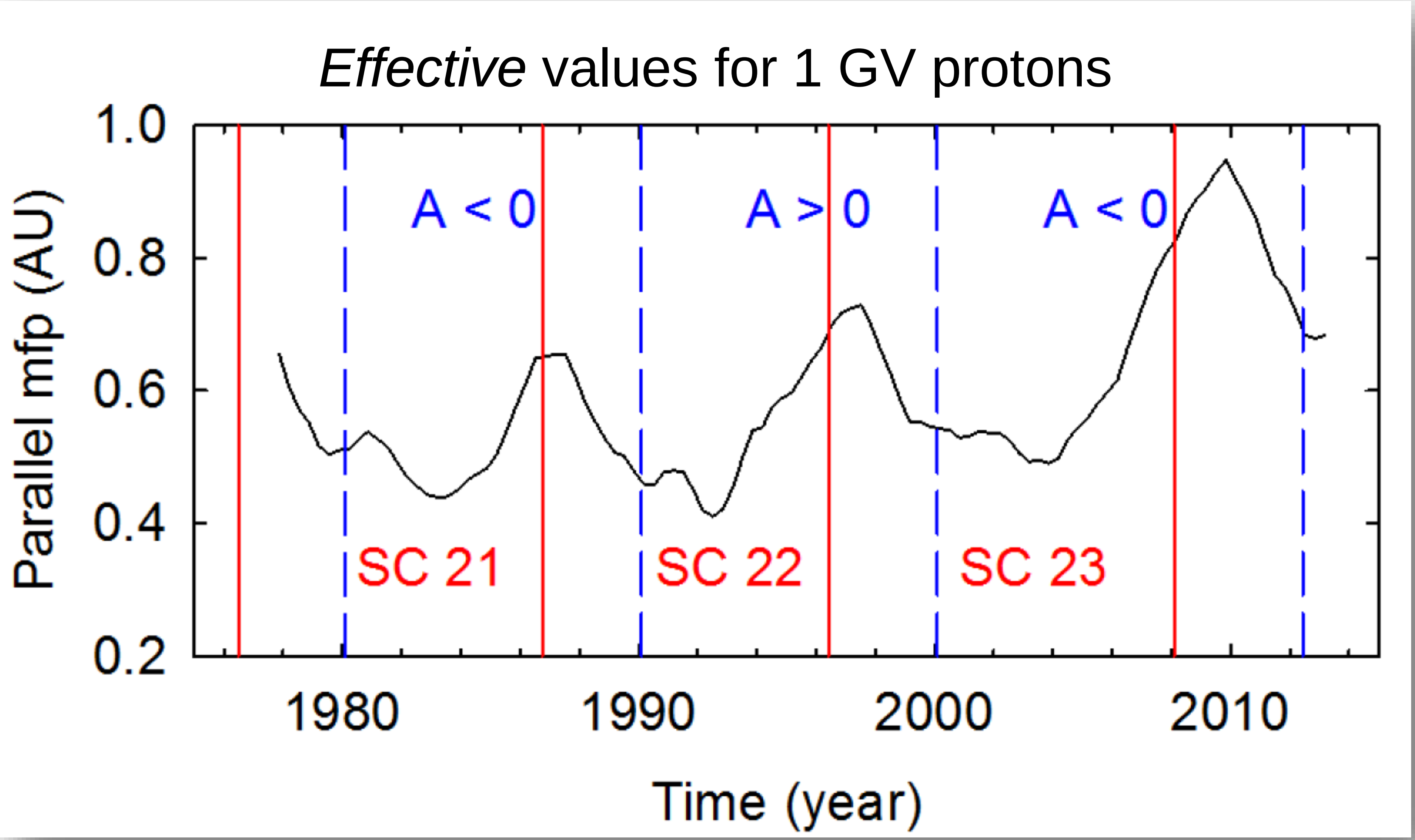
3. Modulation model: Variance



3. Modulation model: Correlation scales



3. Modulation model: S-C dependence of parallel mfp



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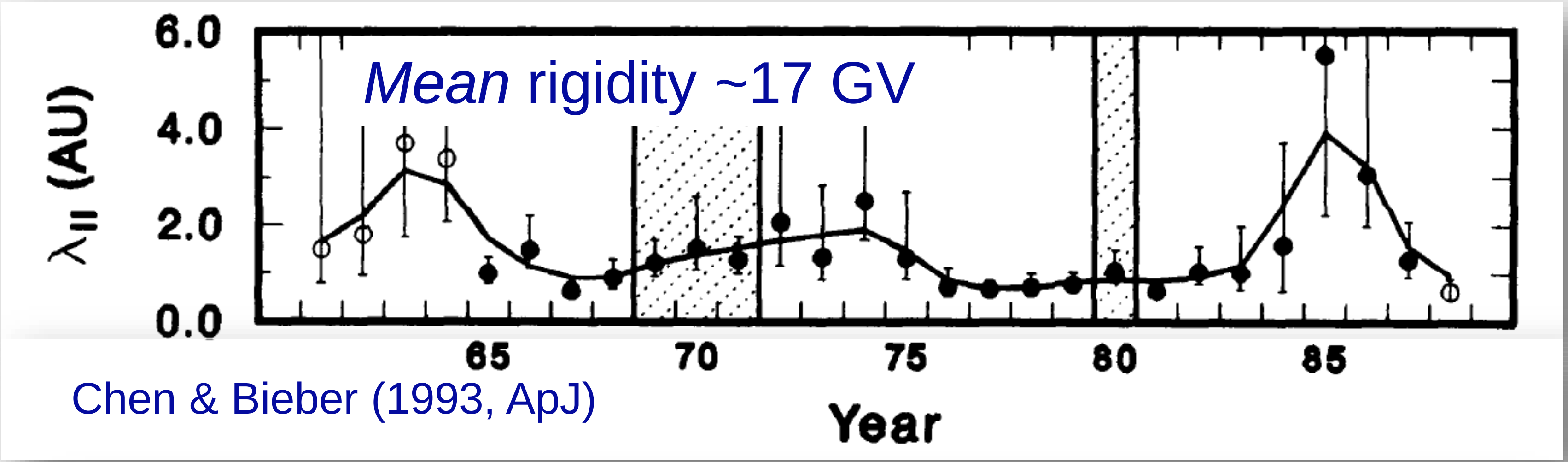
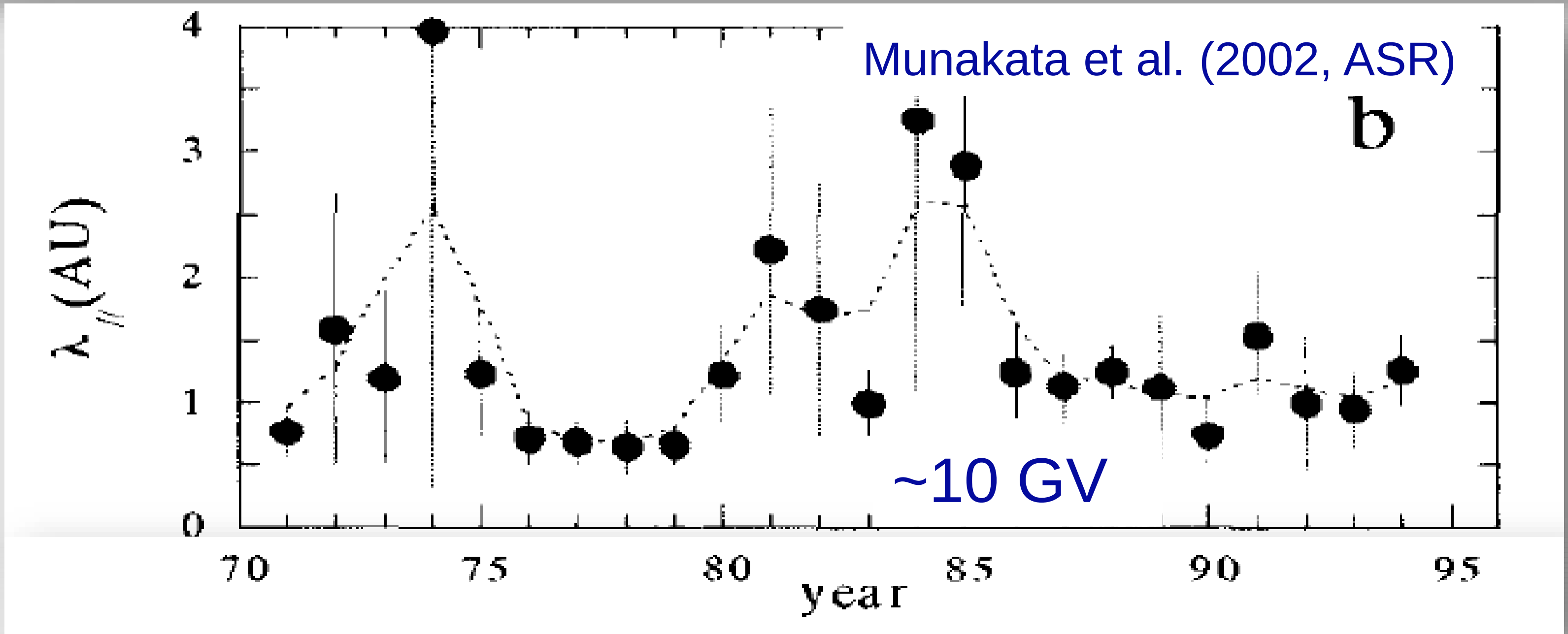
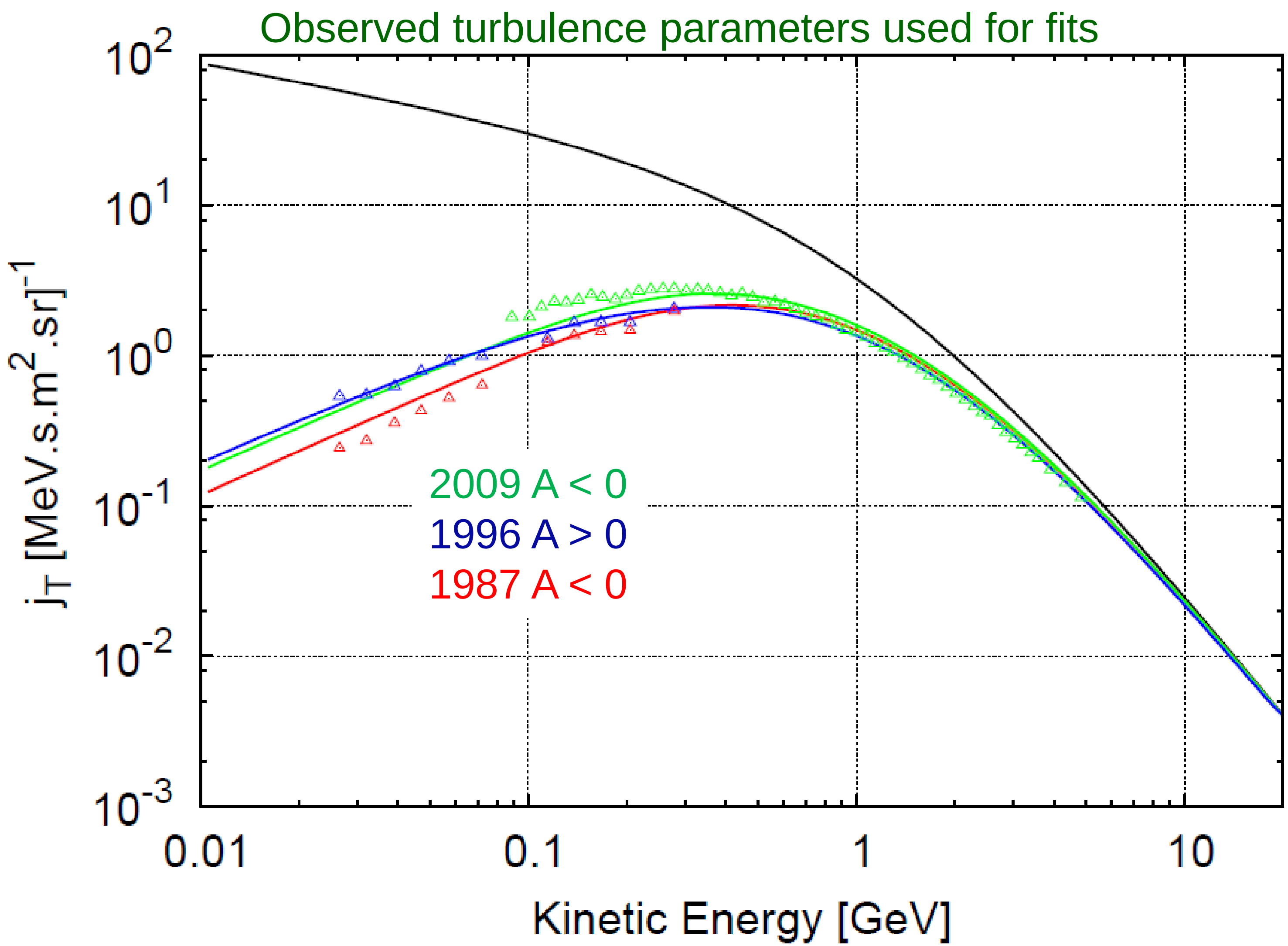
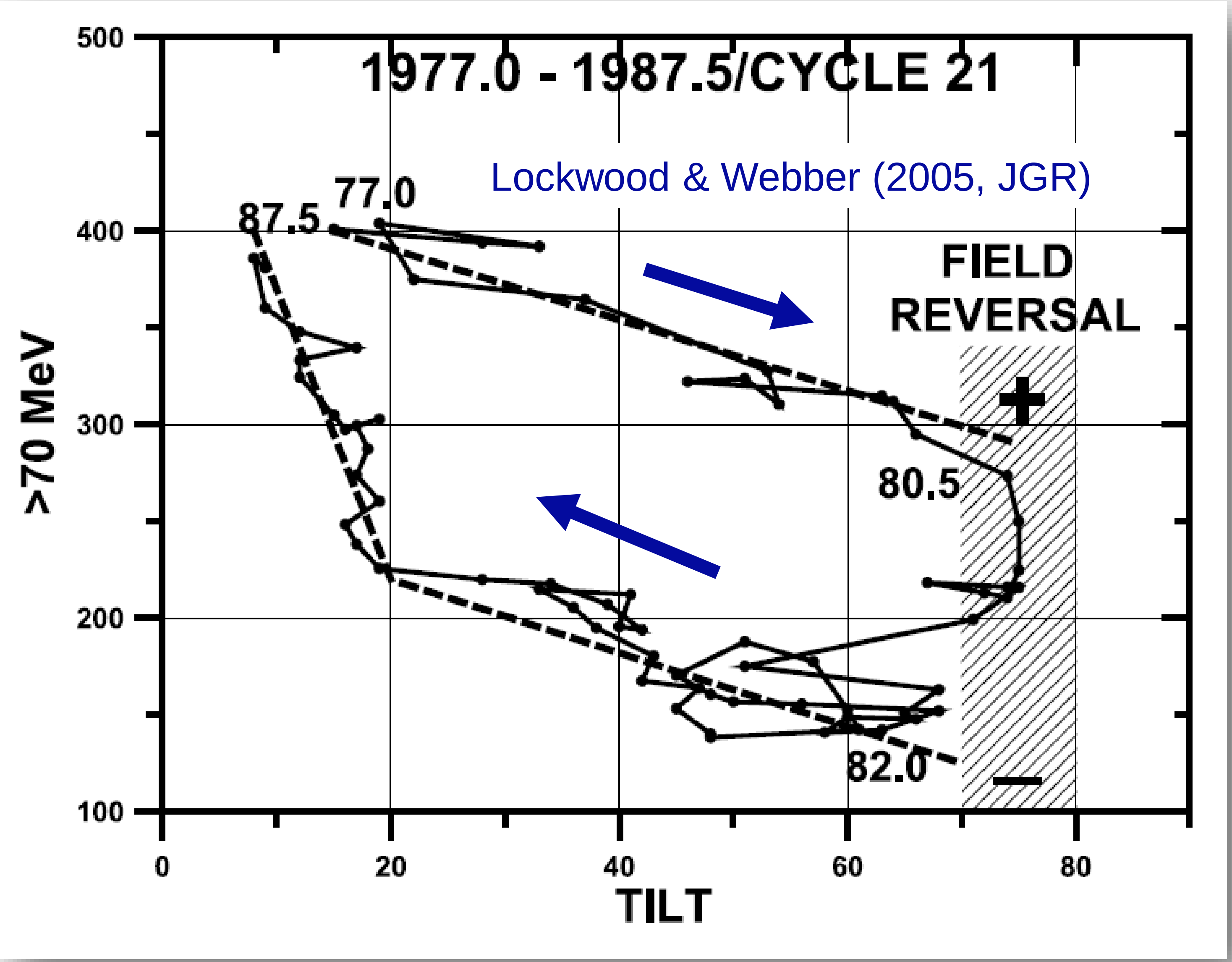




4. Solar minima spectra



5. Long-term modulation



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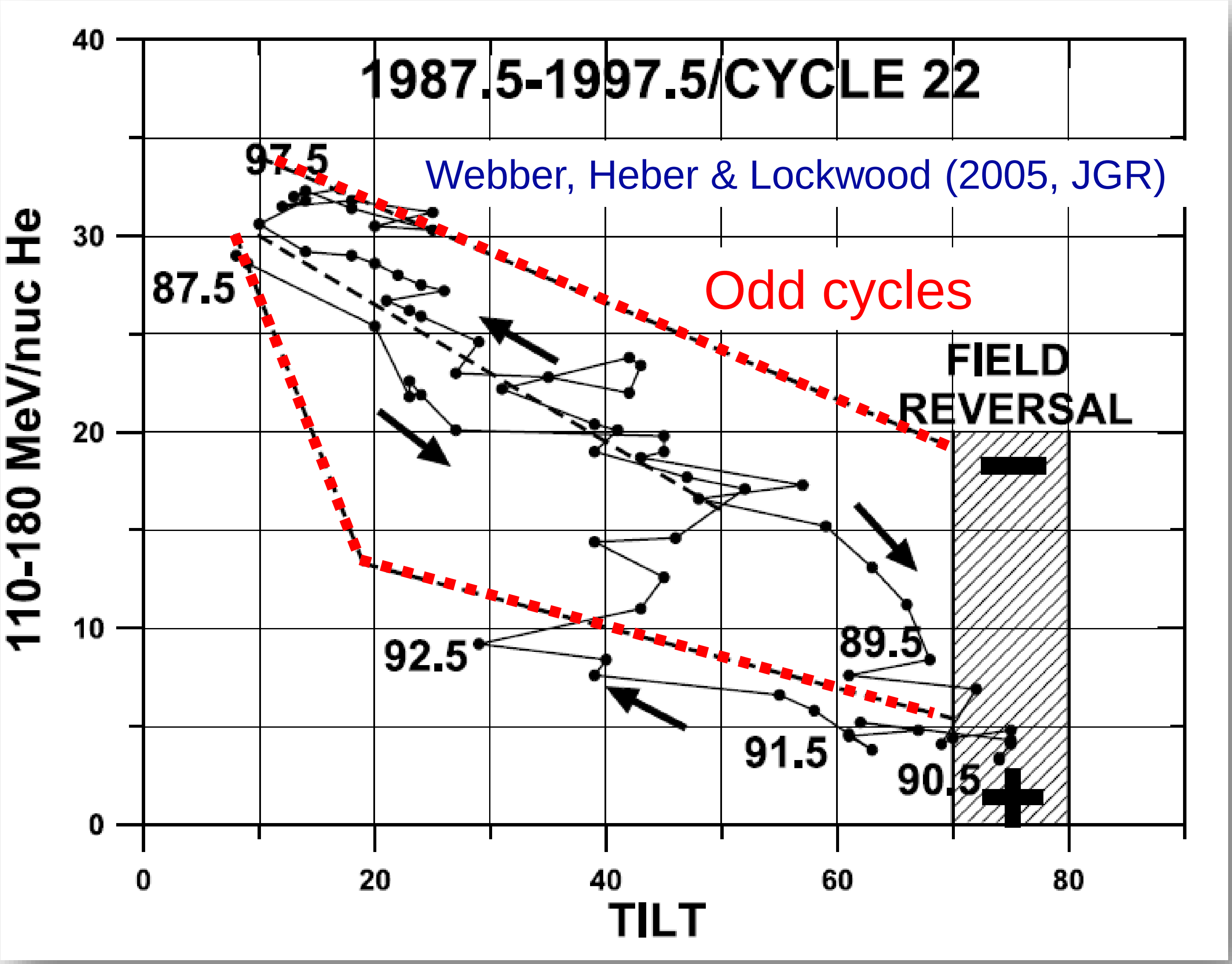

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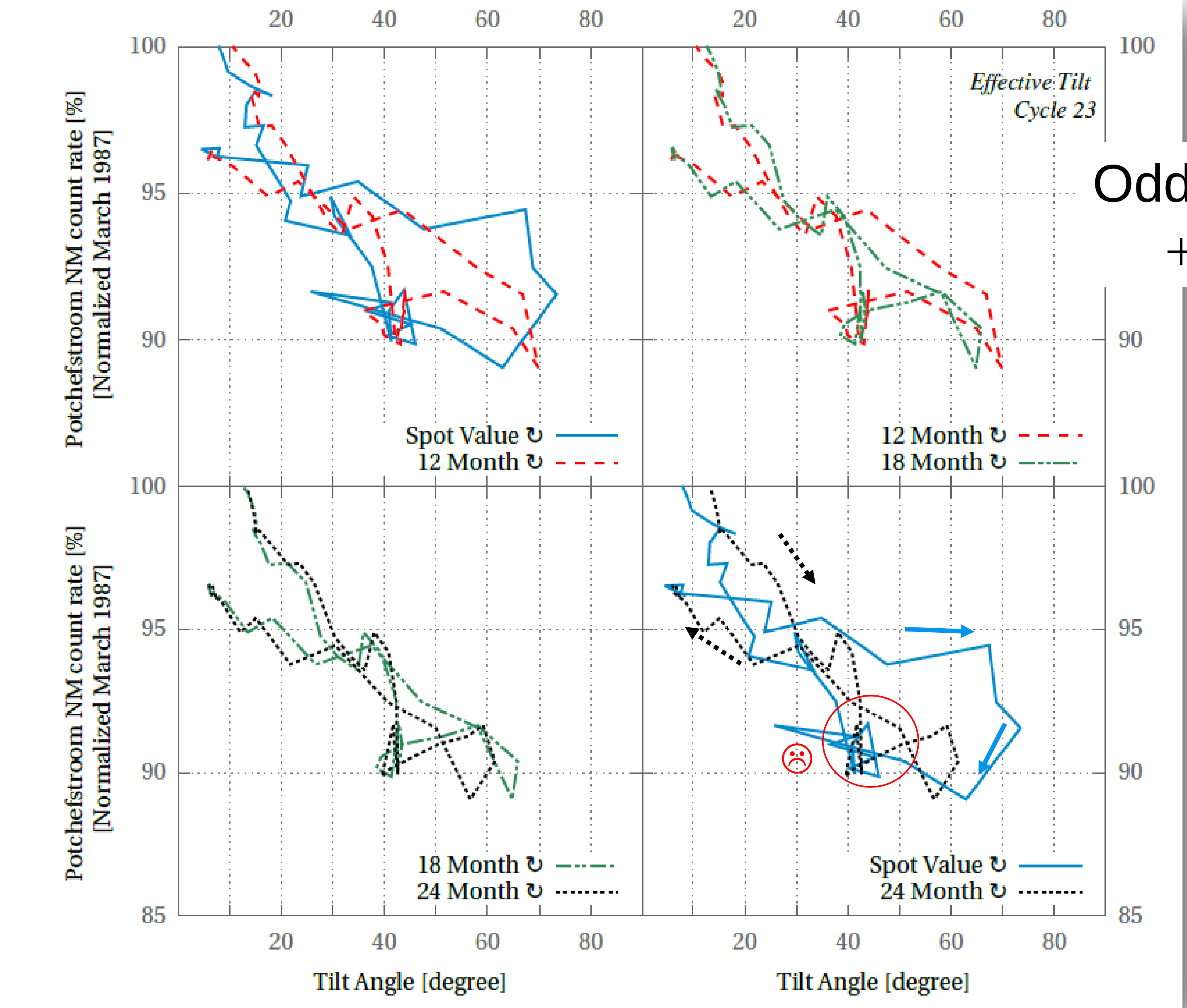
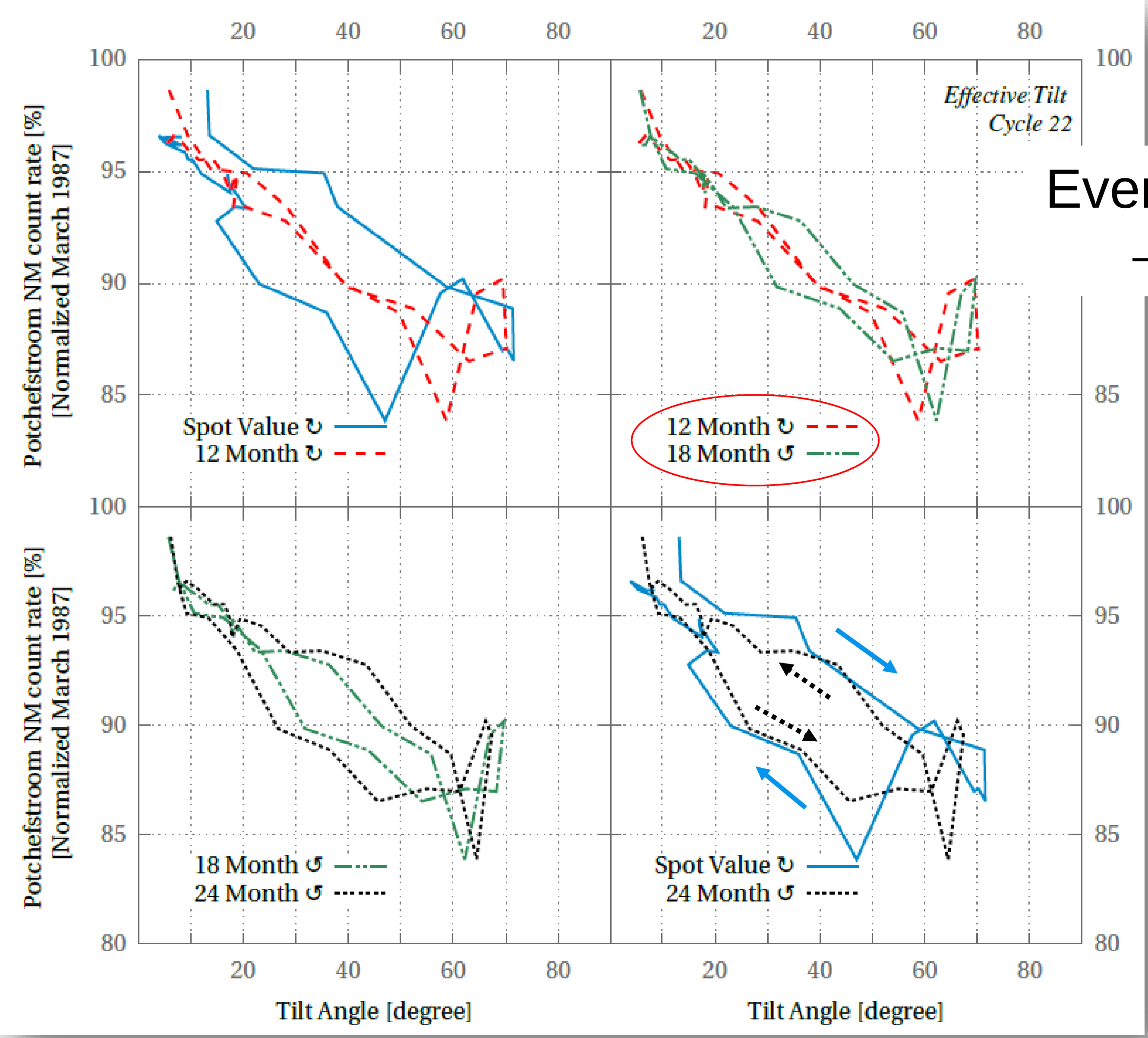


Odd cycles:
+ to –

5. Long-term modulation

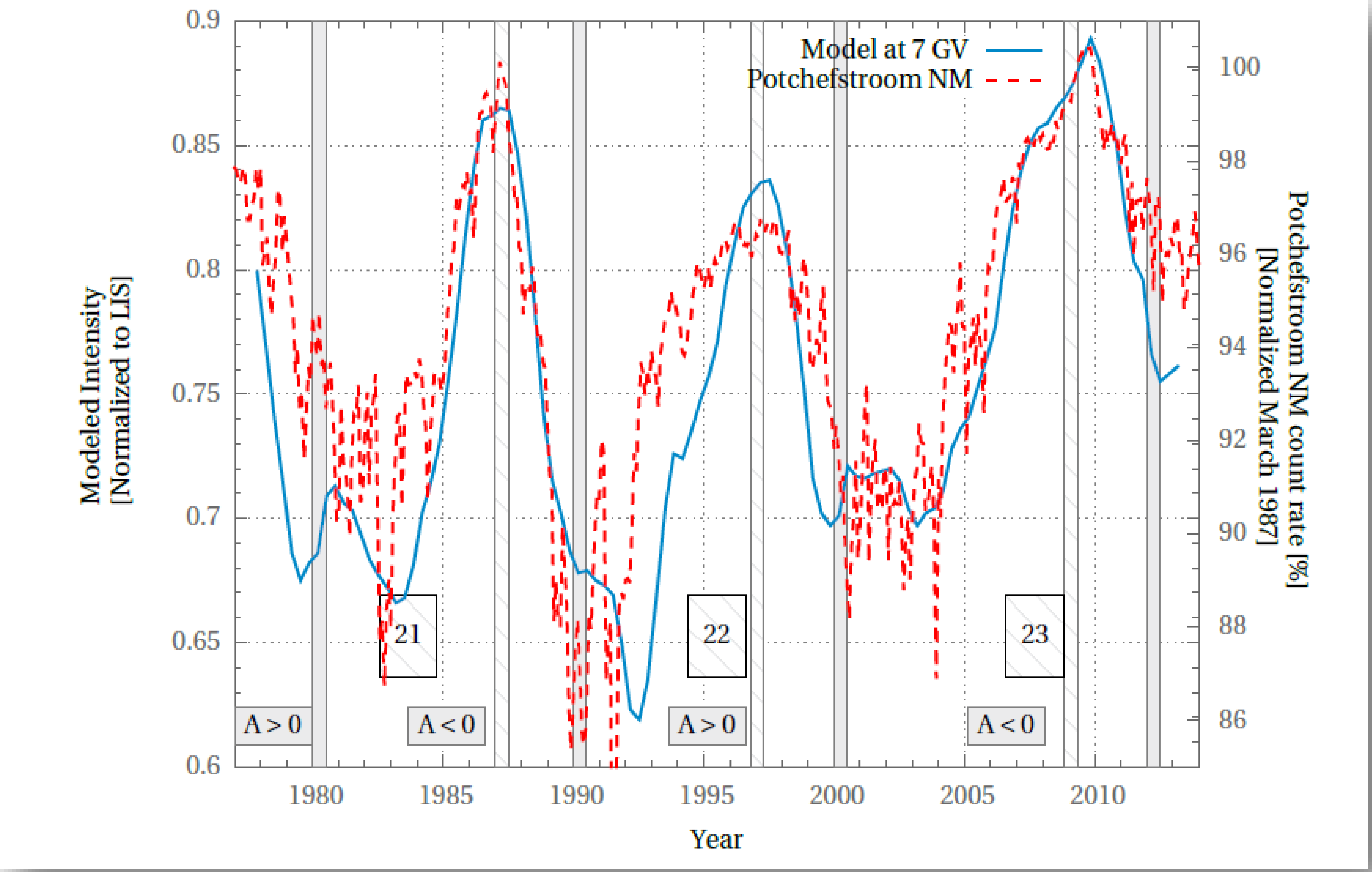


Even cycles:
– to +

5. Long-term modulation

- Using effective tilt rather than tilt at time of intensity observation:
  - ✓ Loop shapes become similar
  - ✓ Sense of rotation becomes the same as for steady state case
- Conversely, if intensities from a steady-state model that uses effective values is plotted as function of tilt at time of intensity observation, it *should* resemble observations…but some work still to be done

5. Long-term modulation



6. Time dependence of diffusion tensor

- Actual scaling of diffusion tensor with magnetic field is know; guestimates for long-term behaviour of turbulence parameters in terms of B can enlighten or mislead:

$$\text{Assume } \delta B_{slab}^2(1\text{AU}, t) \sim \delta B_{2D}^2(1\text{AU}, t) \sim B_0^2(1\text{AU}, t)$$

$$k_{\min}(1\text{AU}, t) \sim B_0(1\text{AU}, t)$$

$$\text{and } l_{2D}(1\text{AU}, t) \sim B_0^{-1}(1\text{AU}, t)$$

6. Time dependence of diffusion tensor

$$\kappa_{||} \sim v k_{\min} R_L^2 \left[1 + \frac{10}{k_{\min}^{5/3} R_L^{5/3}} \right]$$

$\kappa_{||} \sim B_0^{-1}$ at all energies

$$\kappa_{\perp} \sim v \left(l_{2D} \right)^{2/3} \kappa_{||}^{1/3}$$

$\kappa_{\perp} \sim B_0^{-1}$ at all energies

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7. Summary and conclusions

- Difference between being able to fit cosmic-ray data with say a force field approximation and understanding cosmic-ray modulation at the most basic level
- While the solar minimum of 2009 may have been unusual, it seems that the modulation of galactic cosmic rays was not
- Model relies on history of particles, and has the potential to predict intensities – yet to be tested
- Drift coefficient requires much more attention...
- ...as do long-term trends of turbulence quantities

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