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Galactic Cosmic Rays as Probes of the Inner and Outer Heliosphere

József Kóta

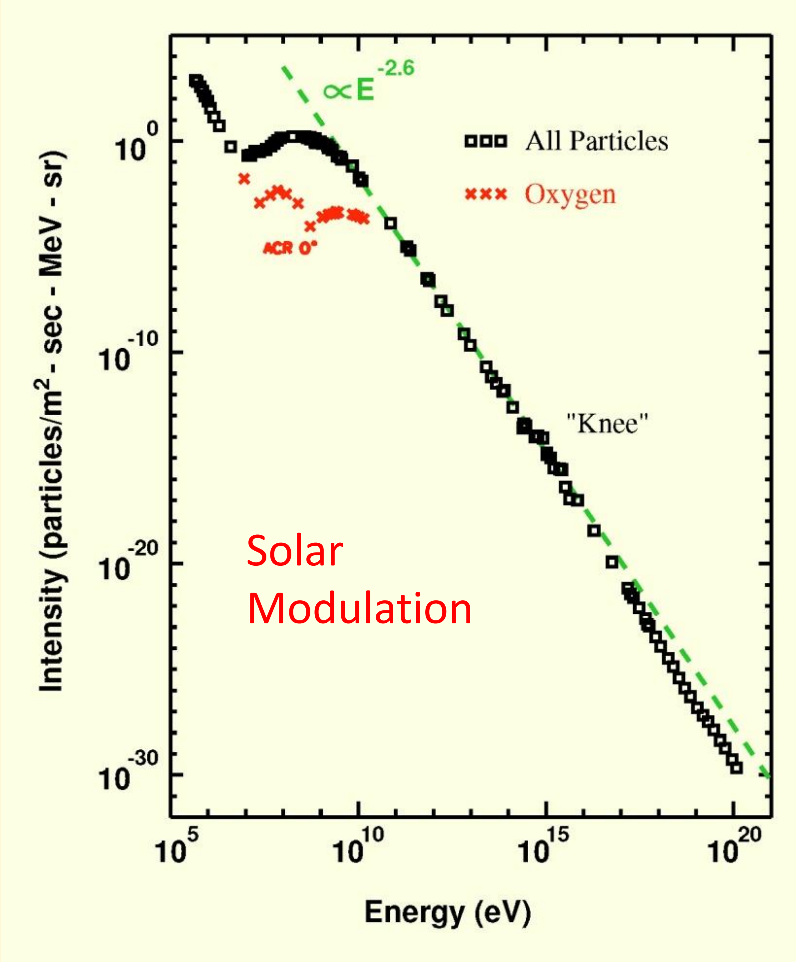
The University of Arizona, Tucson AZ, USA

jkota@arizona.edu

Outline & Motivation

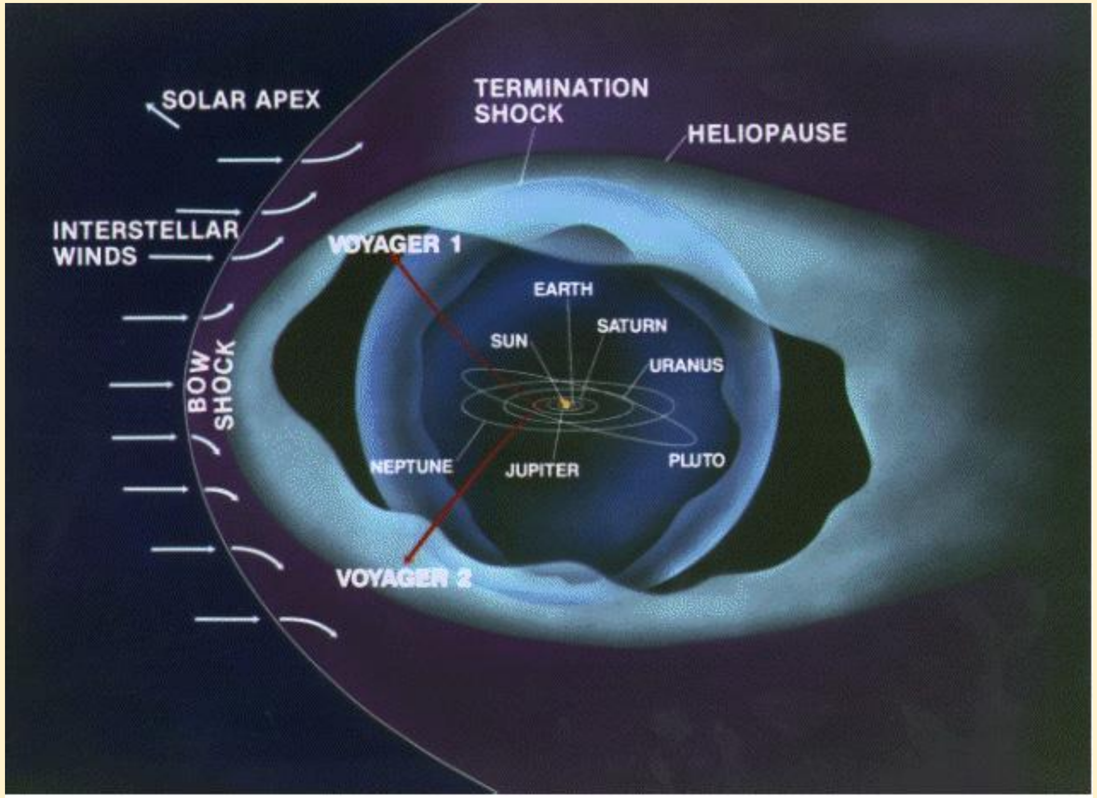
- *Galactic Cosmic rays (GCRs) represent a major threat to long-duration space flight outside the magnetosphere that protect us from large part of the radiation.*
- *The heliosphere provides an additional shield that keeps ~85 % of the radiation away from Earth. This shield depends on the solar magnetic field carried out by the solar wind and its effectiveness changes in response to the solar activity and on our changing interstellar environment (see NASA Shield project)*
- *GCRs can give remote observations on solar activity in the past, and TeV GCRs offer a unique tool to study the magnetic field near the Sun*

Galactic and Anomalous Cosmic Rays (GCRs, ACRs)



- *GCRs: extend over many decades in energy*
- *Most of the radiation at Earth comes from the GeV range*
- *Solar modulation* ***(11-year cycle)*** *is important below few tens of GeV, but solar effect extend to TeV energies.*
- *Proxy of solar activity in the past*

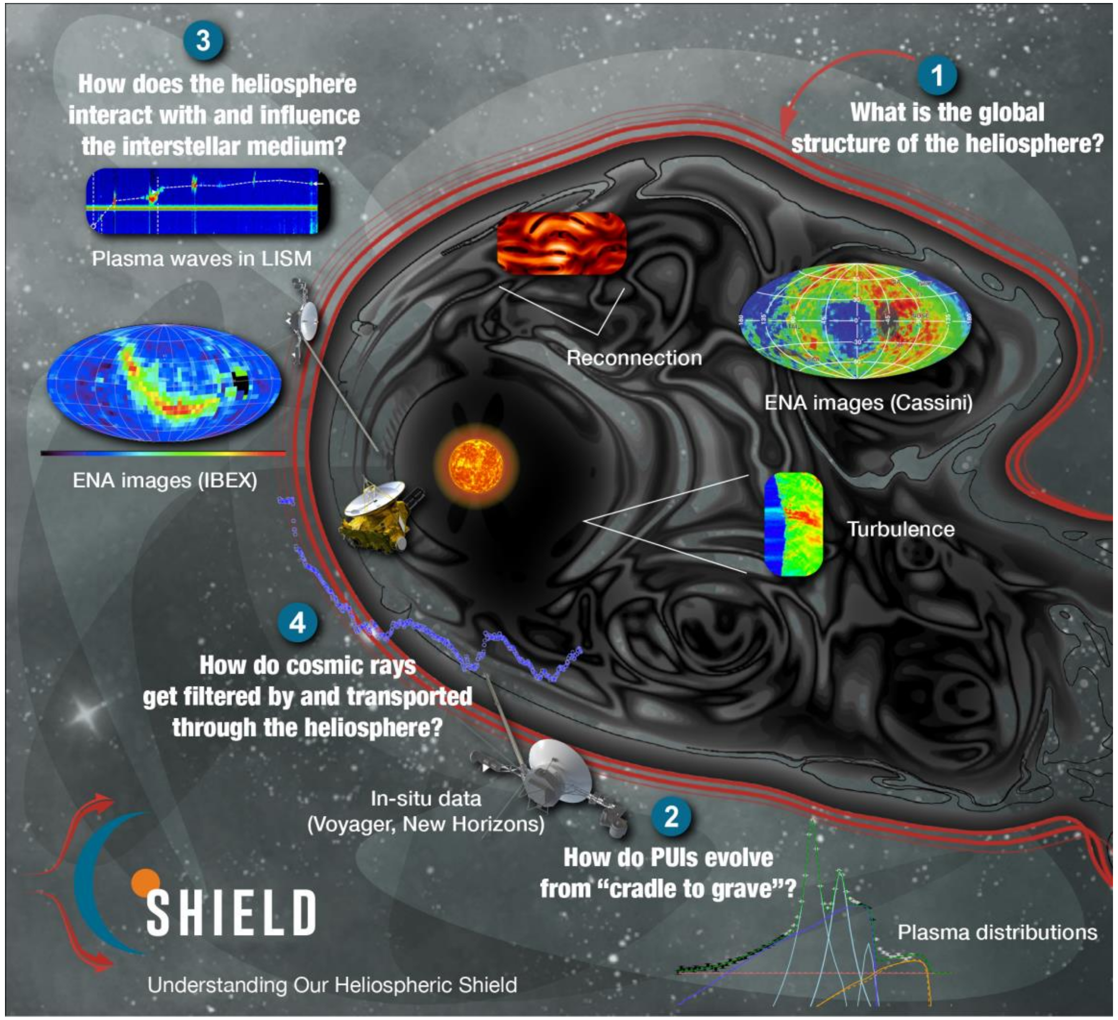
Our Interstellar Environment, Modulation



As of ~1990

11/22 year modulation cycle

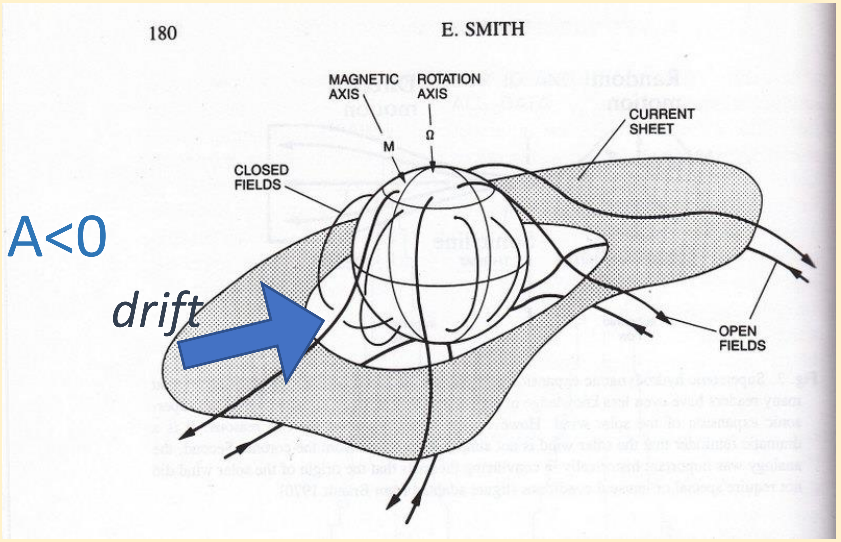
NASA's Shield Project



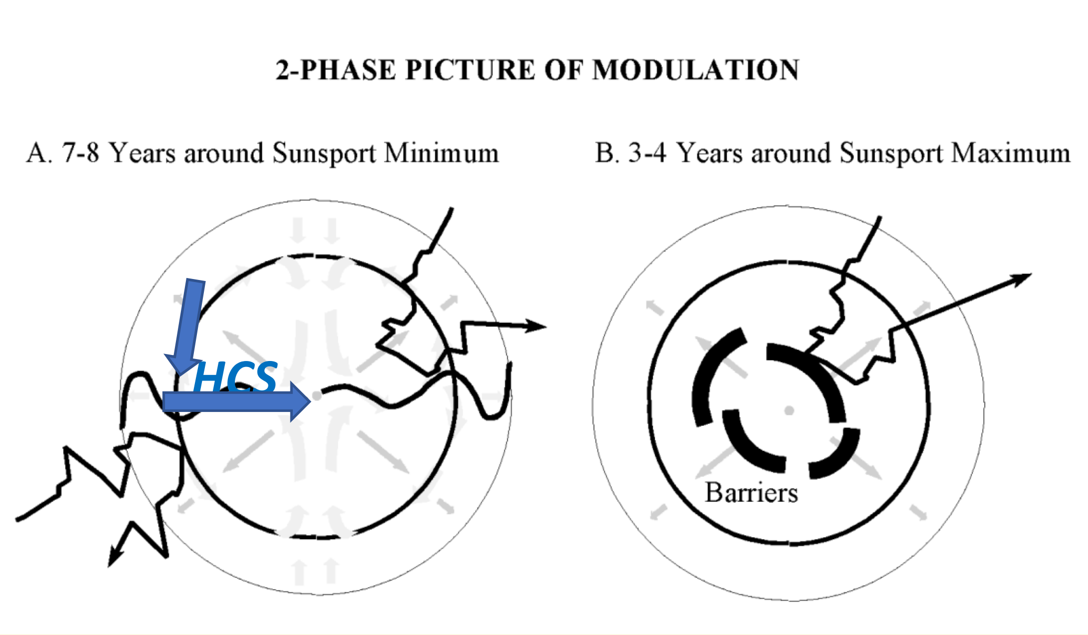
- *Heliospheric magnetic field carried by the solar wind shields Earth from ~85 % of cosmic radiation*
- *Solar effects are still present beyond the Heliopause (HP)*
- *NASA's Shield project is a multi-university program for a complex study of the heliosphere and its interaction with the local interstellar material.*
- *Our interstellar environment (and our heliosphere) changes on long timescales.*

Solar Modulation in a Nutshell: Diffusion, HCS & Drifts

Heliospheric current sheet (HCS)
flattish at Solar Mins.



From Jokipii & Wibberenz



Fast organized GCR drifts along HCS & TS.
changes sign with the polarity state of Sun

Outward moving Barriers (GMIRs) at Solar Max.

Parker (1965) Equation

*Frequent scattering maintains **near isotropy** of GCRs*

Parker (1965): $f = f(x_i, p, t)$ – omnidirectional density

$$\frac{\partial f}{\partial t} - \frac{\partial}{\partial x_i}\left(\kappa_{ij}\frac{\partial f}{\partial x_j}\right) + (V_{dr,i} + V_i)\frac{\partial f}{\partial x_i} - \frac{p}{3}\frac{\partial V_i}{\partial x_i}\frac{\partial f}{\partial p} = Q$$

Diffusion *Drift* + *Convection* *Energy loss*

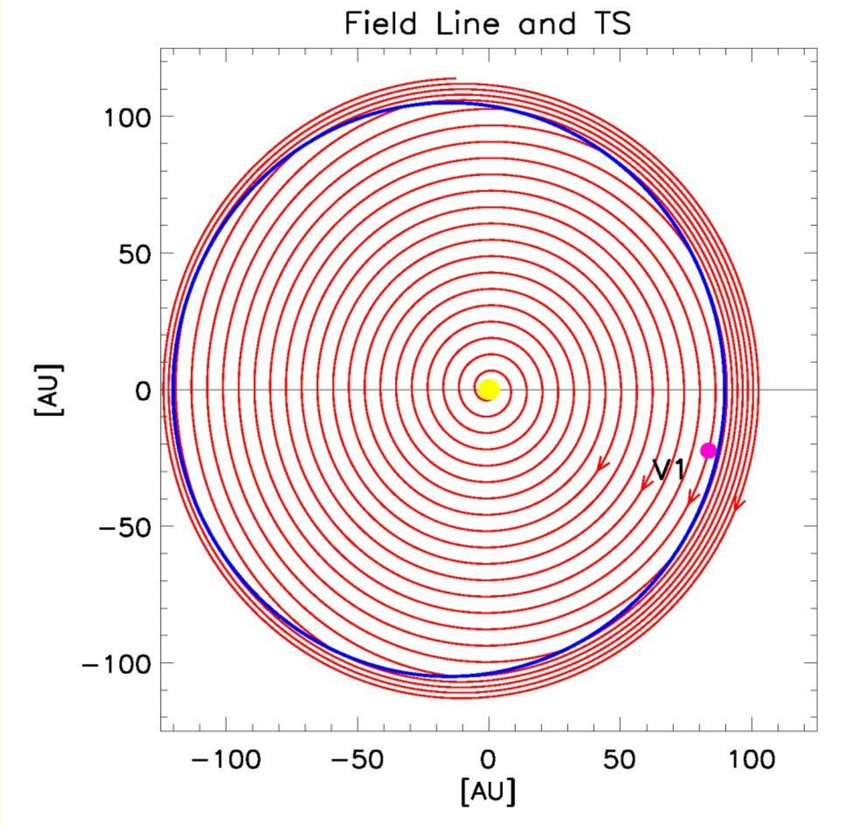
Different parallel and perpendicular diffusion coefficients

Diffusion tensor

$$K_{ij} = \begin{pmatrix} \kappa_\parallel & 0 & 0 \\ 0 & \kappa_\perp & \kappa_A \\ 0 & -\kappa_A & \kappa_\perp \end{pmatrix}$$

Drift is hidden in the anti-symmetric component: $vr_g/3$ in weak scattering limit, reduced otherwise

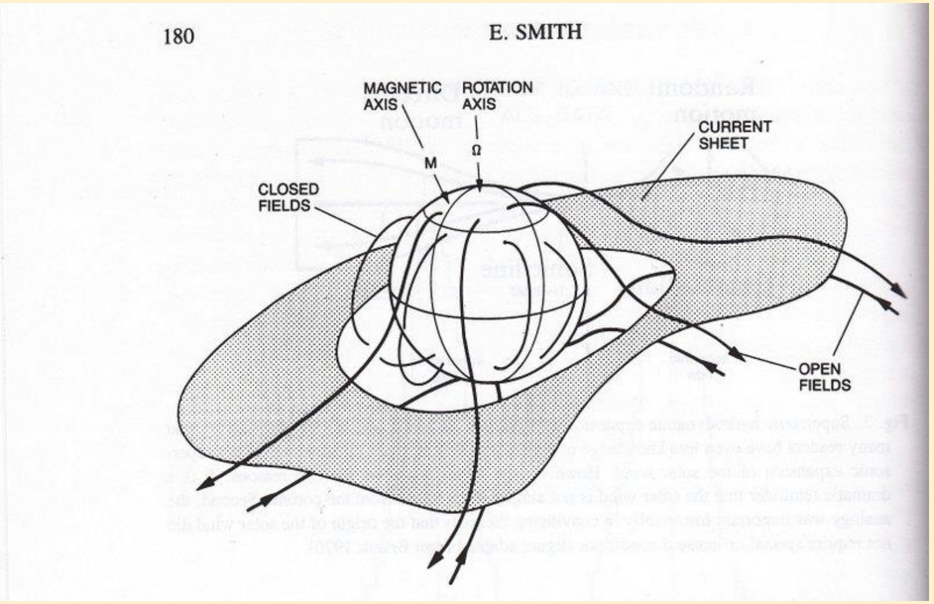
Parker Spiral of Field Lines: Parallel vs. Perpendicular diffusion



Parker spiral B is tightly wound
Cross-field diffusion is important

Perpendicular diffusion wins
in the outer heliosphere

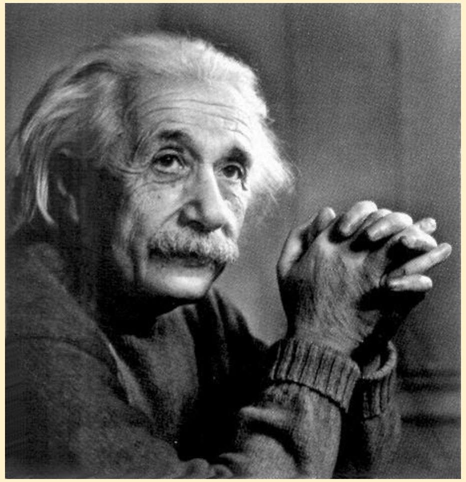
Particle Drifts in the Large-scale Magnetic Field



- ***Jokipii** et al (1977) pointed out that drift motion is an important part of GCR transport.*
- *Drift is charge/polarity dependent, that appears in asymmetries of even and odd cycles (anisotropies-peak-plateau cycles – latitudinal gradients)*
- *Fast, polarity dependent drifts along the HCS and TS allows fast transport along the HCS. May appear as large perpendicular diffusion*

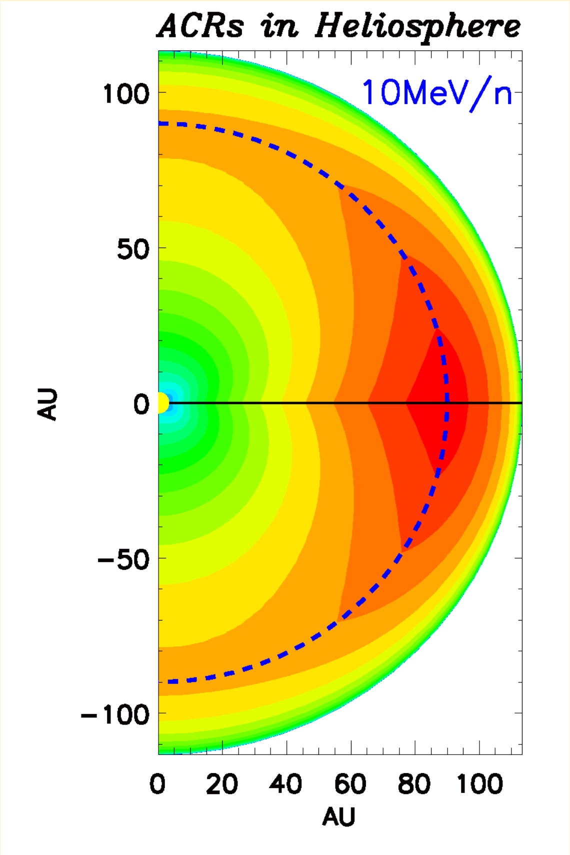
Drift Effects – why are they important

- *GCRs can "freely" drift along the HCS and the termination shock (TS)*
- *This might appear as a fast perpendicular diffusion of unknown origin.*
- *This would be a simplification that loses the essential physics of even-odd asymmetries*
- *Drift is an indispensable part of GCR transport.*

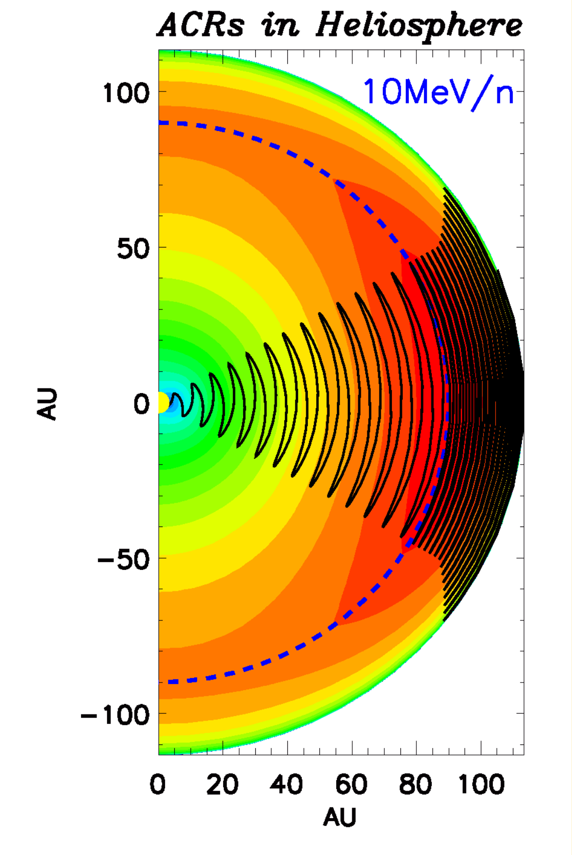


"Make everything as simple as possible, but not simpler "

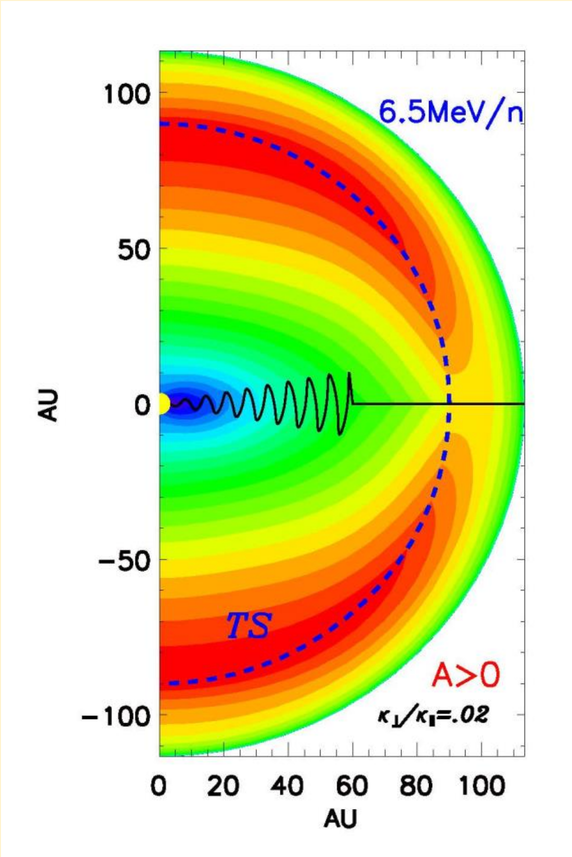
Numerical simulation: of a 22-year Solar Cycle



Solar min. Flat HCS A<0

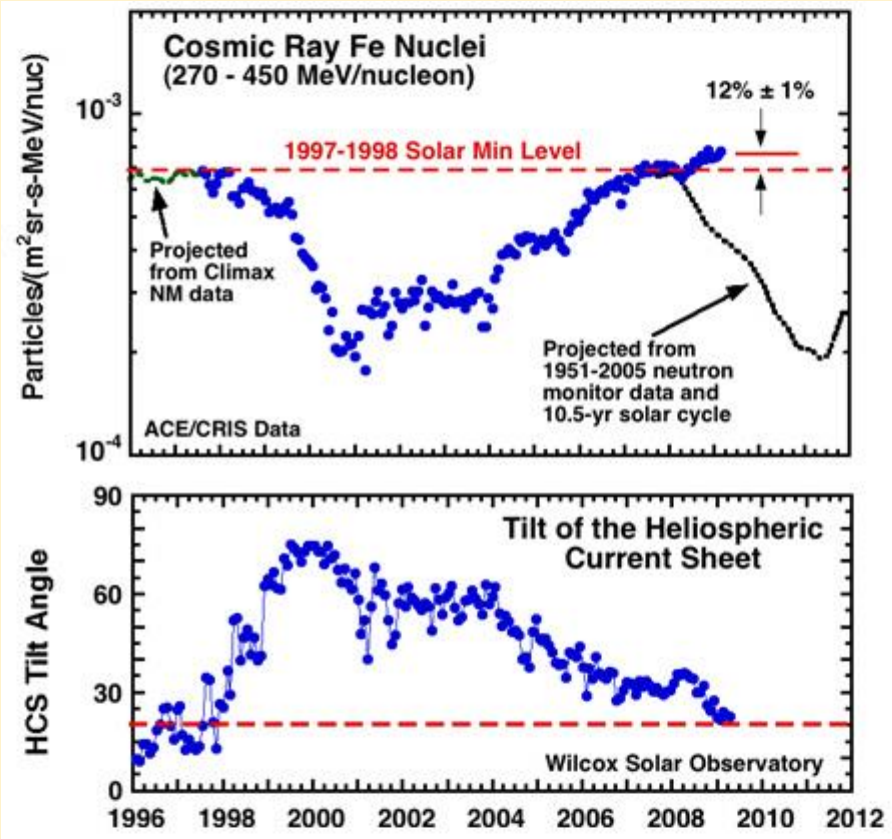


Toward Solar max, Wavy HCS



Solar Min. Flat HCS A>0

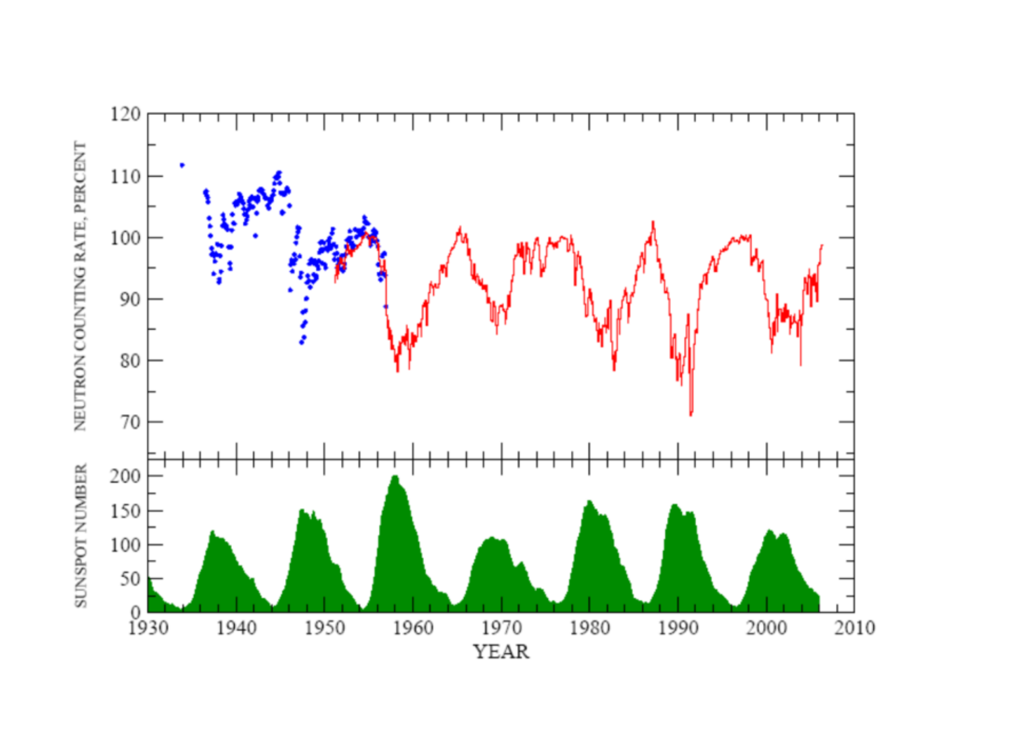
Recent Weak Solar Cycles: Record high GCR fluxes at Earth

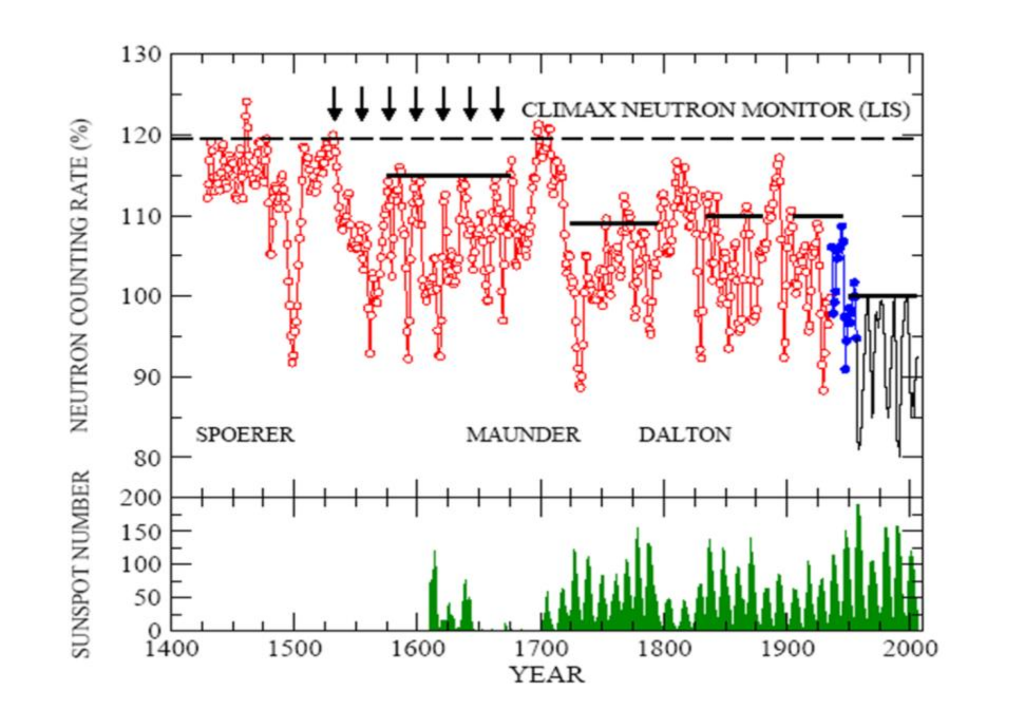


- *Unusually long and weak Solar Cycle*
- *Magnetic field weakest ever recorded*
- *Solar wind ram pressure small*
- *HCS flattens only in 2009*
- *Record high GCR intensities measured by direct observations*

GCRs as Proxies of Solar Activity in the Past
Cosmogenic isotope C14 (from Ken McCracken)

Cosmic-ray flux as inferred from cosmogenic measurement were ~20% higher than their current solar minimum values





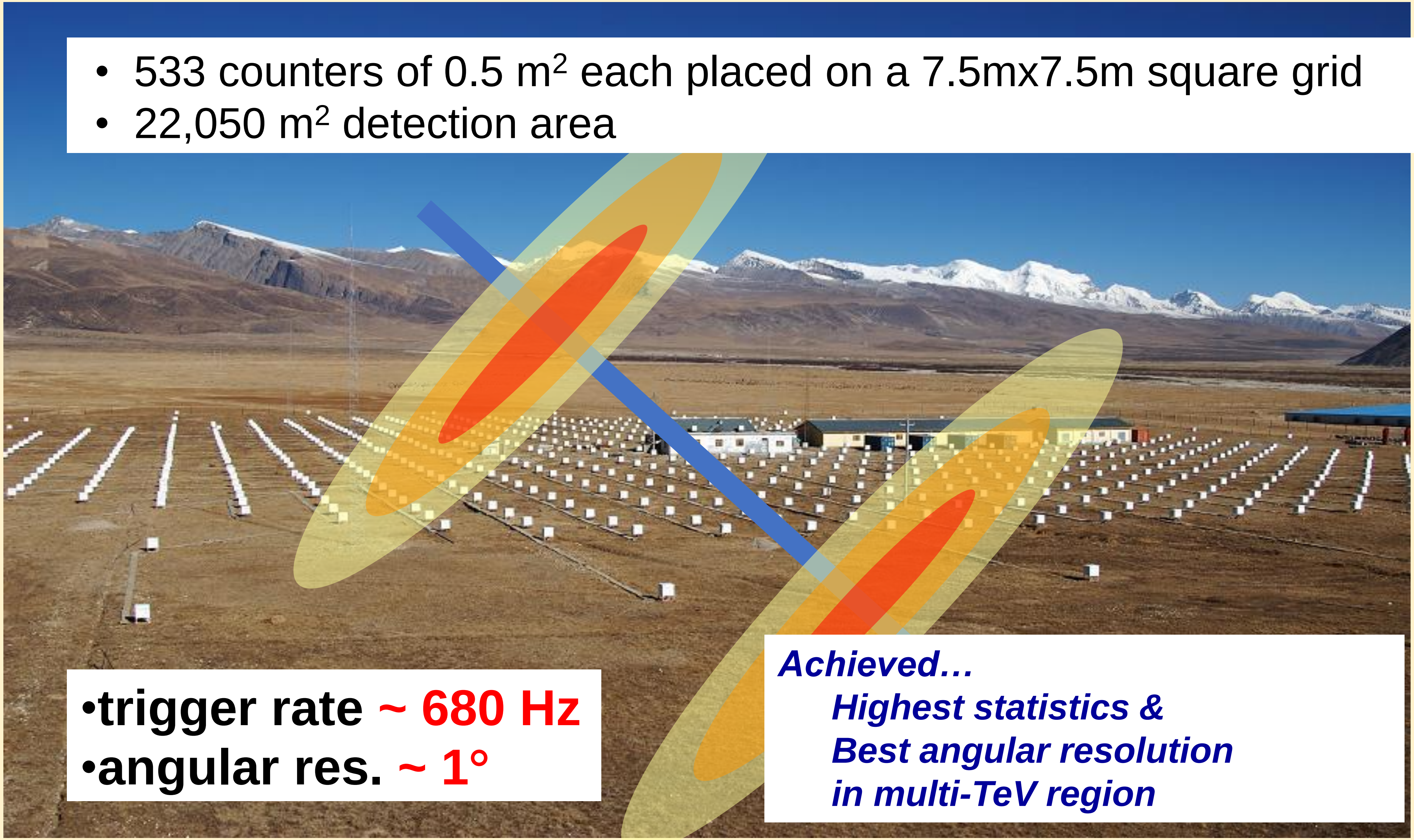
GCR flux during Grand Minima appears to show 11 and 22-year variations. *Drift effects at work* ?

Application 1-10 TeV GCRs ; Tibet Air-shower (EAS) Array (Amenomori et al, Science 2013):
*What do they tell on the **Magnetic Field near the Sun?***

- *The Sun (like the Moon) blocks GCRs and creates a cosmic-ray shadow*
- *that changes its size, and*
- *is displaced relative to the optical size/center*
- *TeV trajectories are traced back in a synthetized field using magnetogram data.*
- *PFS & CSSS compared*
- *Relevant to Solar gammas*

Resolving the incident direction

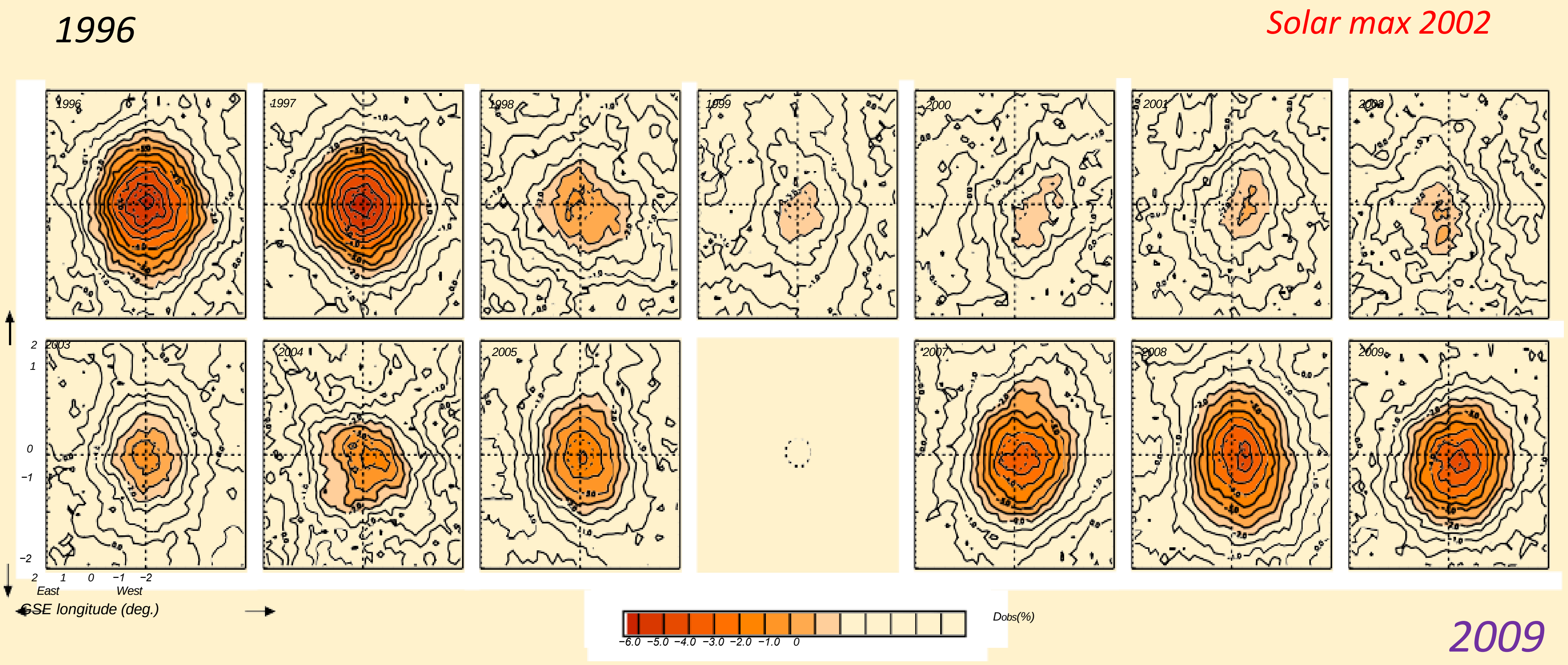
- 533 counters of 0.5 m^2 each placed on a 7.5mx7.5m square grid
- 22,050 m^2 detection area



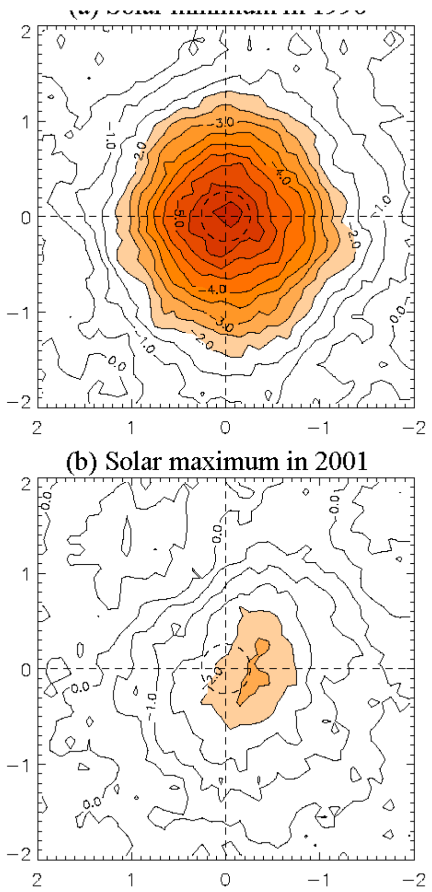
•trigger rate ~ 680 Hz
•angular res. ~ 1°

Achieved…
Highest statistics &
Best angular resolution
in multi-TeV region

Sun's Shadow in GCRs: 11-year cycle (1996-2009)

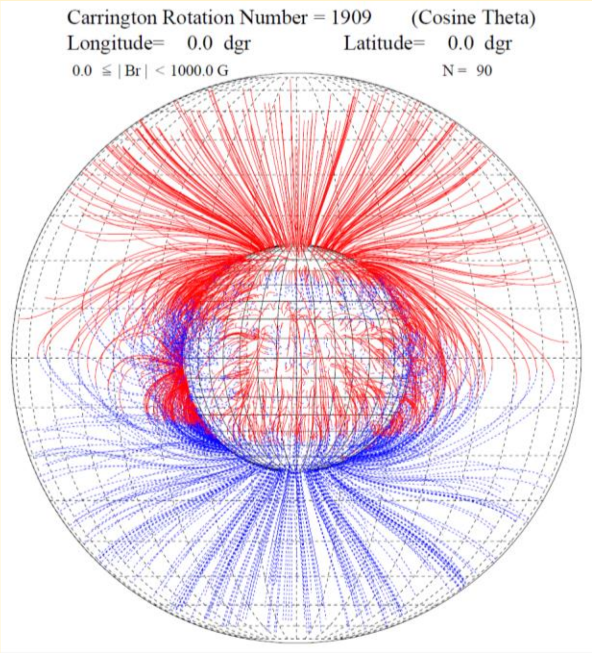


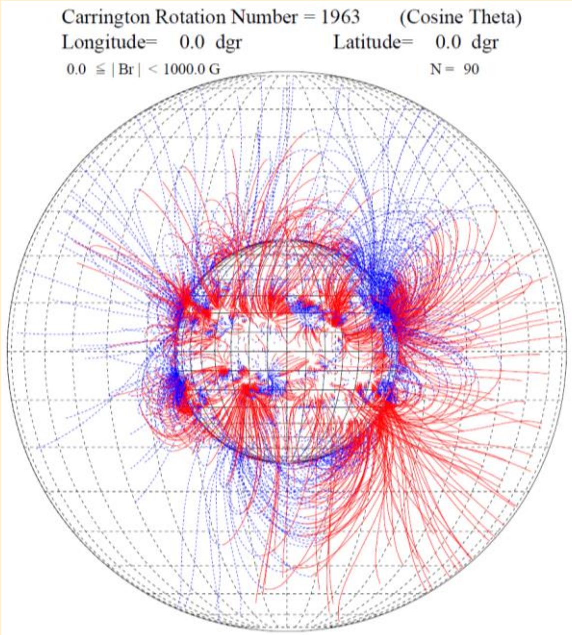
Sun’s Shadow in TeV cosmic ray observations



- Sun’s cosmic-ray shadow changes in 11 & 22 year cycle
- Solar minima: strong shadow
- Solar maxima: shadow essentially disappears
- Shadow is displaced in longitude and latitude as the Sun’s polarity reverses
- PFSS and CSSS models are compared (CSSS gave better fit)

TeV GCRs as probes Magnetic Field near the Sun





Related topic: TeV GSRs hitting the Sun produce high-energy gammas that are detected by satellite Fermi. Results are still puzzling

Summary: progress is being made ☺

Basic principles well understood
Still lot of things to think about

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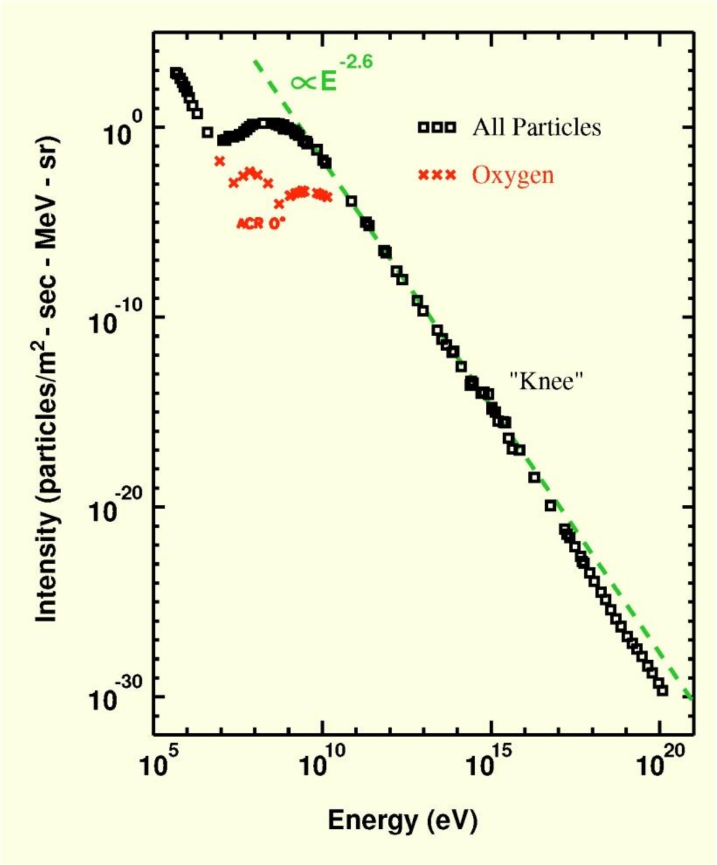
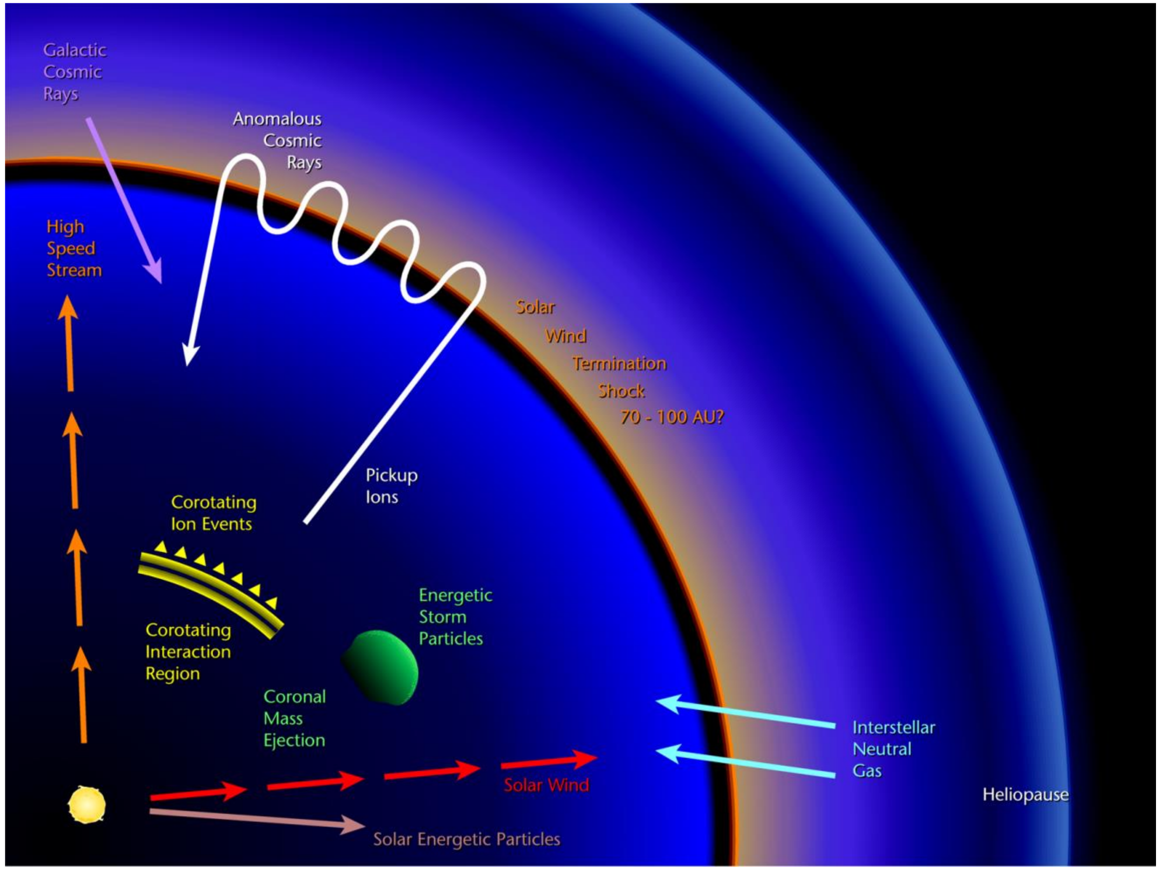
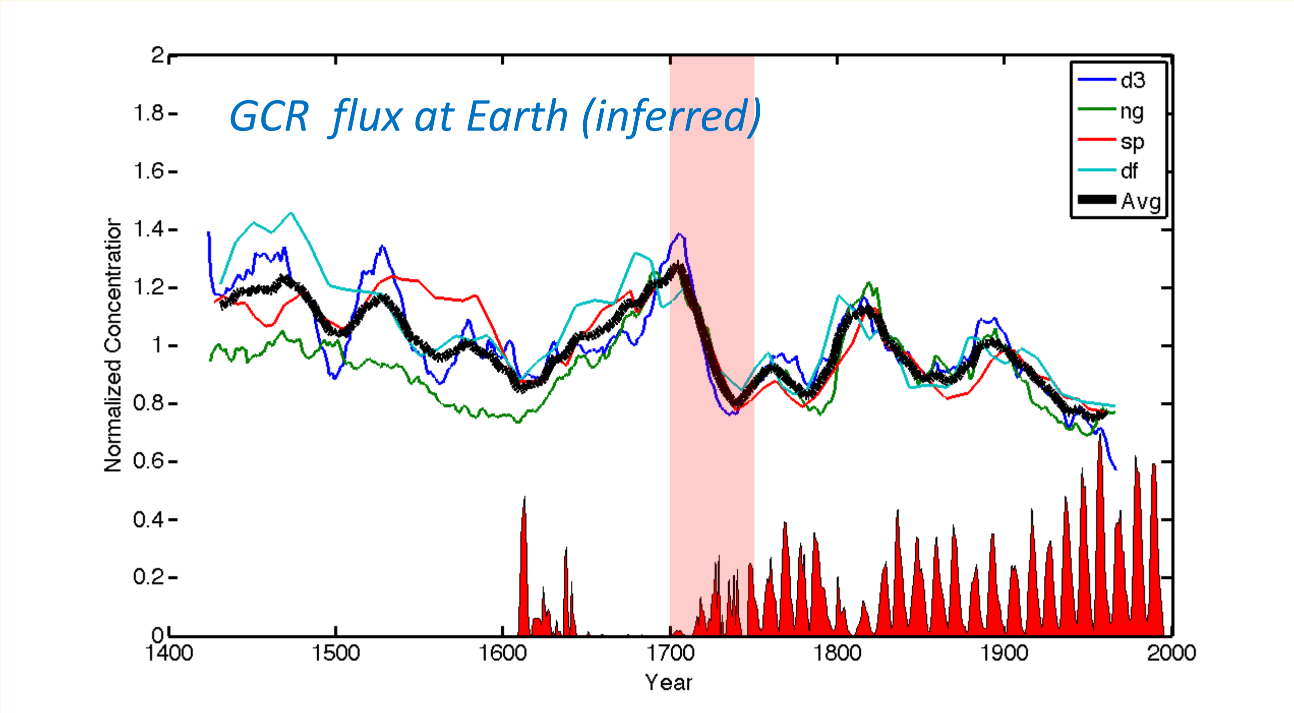
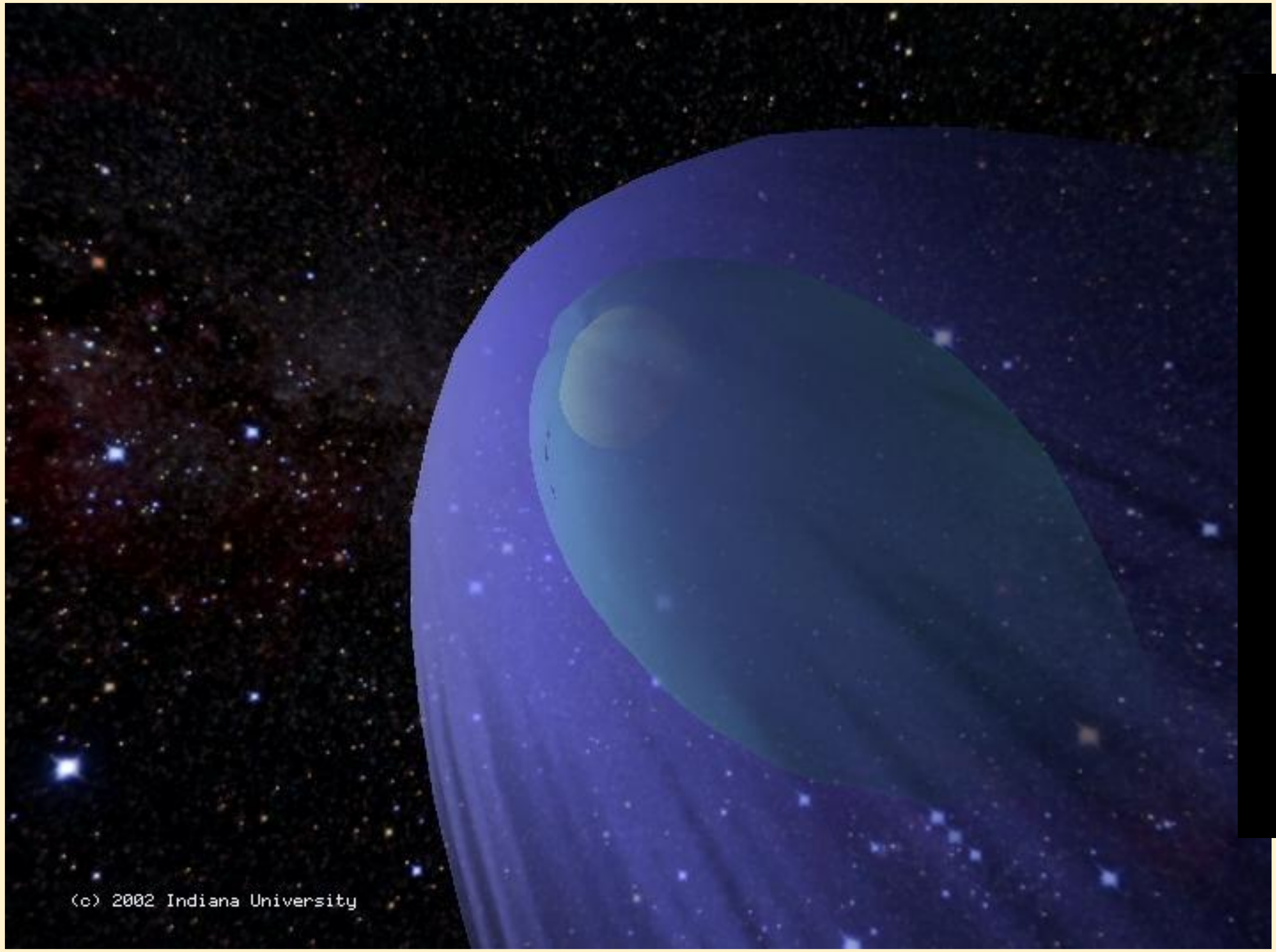




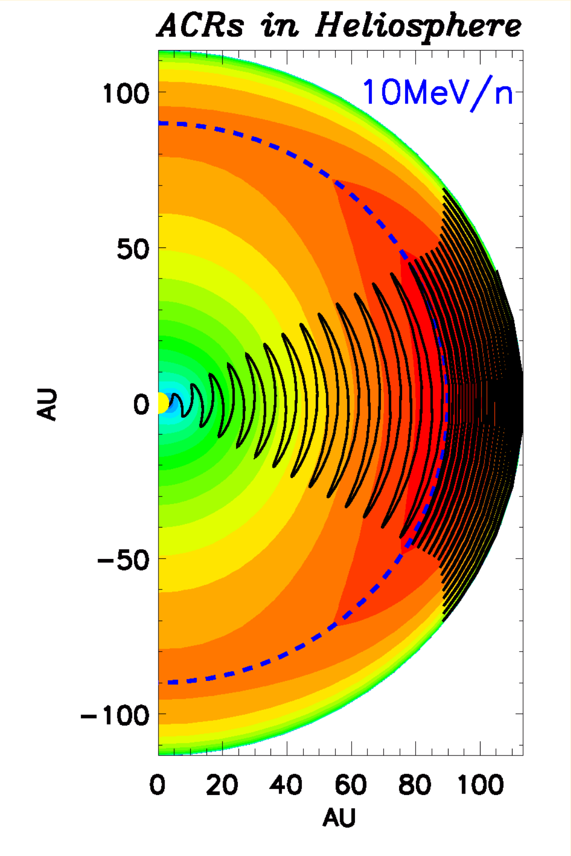
GCRs on longer Time-scales (from K. McCracken)

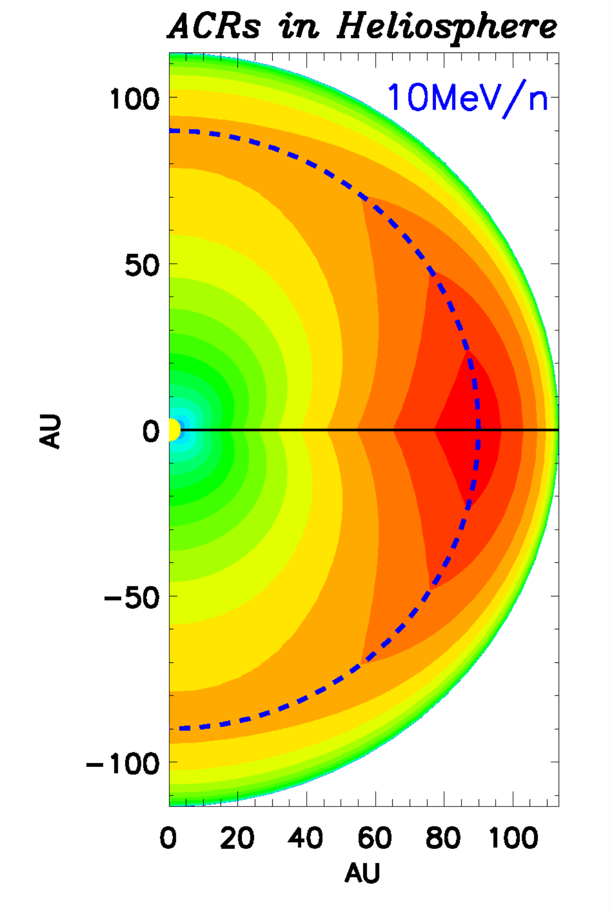


Cosmic Rays & our interstellar environment

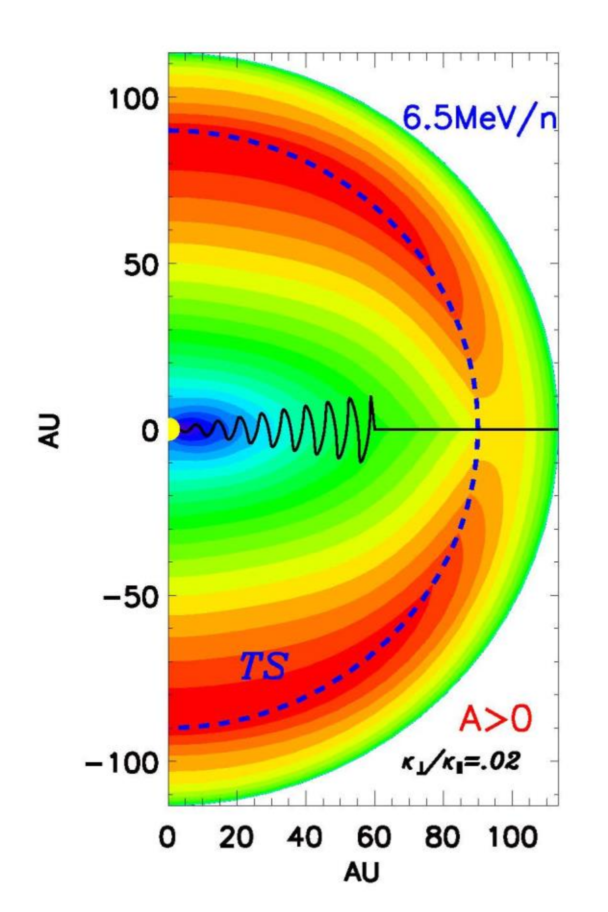


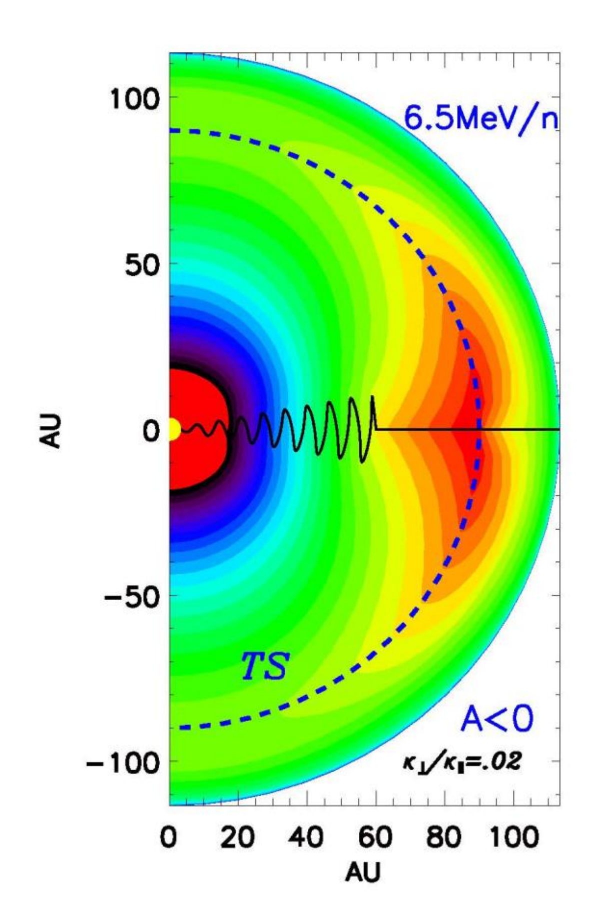
Numerical simulation: of a 22-year Solar Cycle



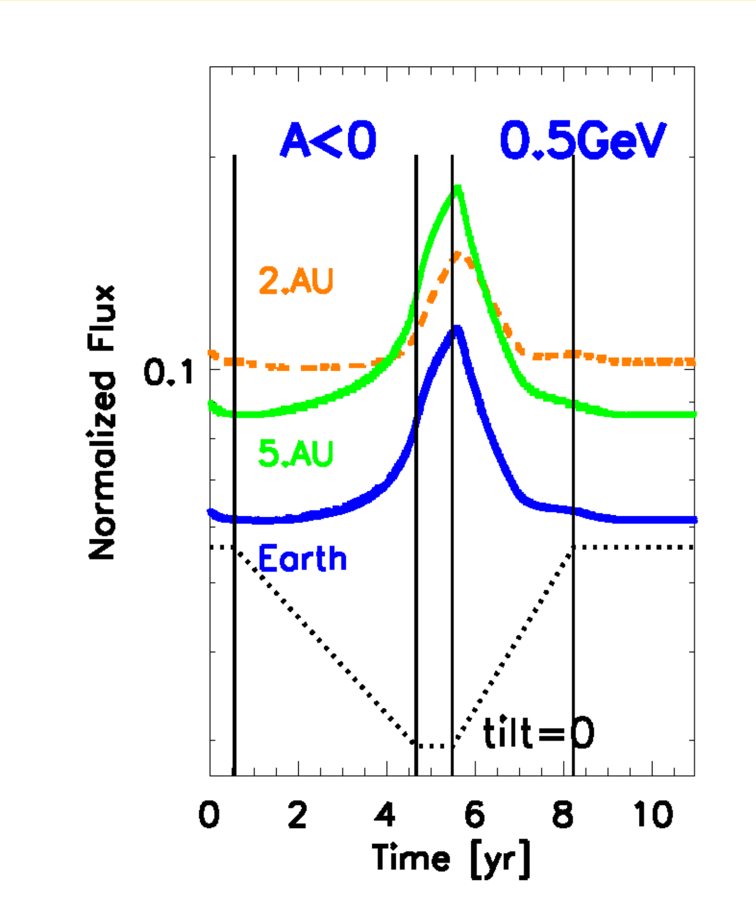


Numerical simulation: 2 cases of Solar Min.

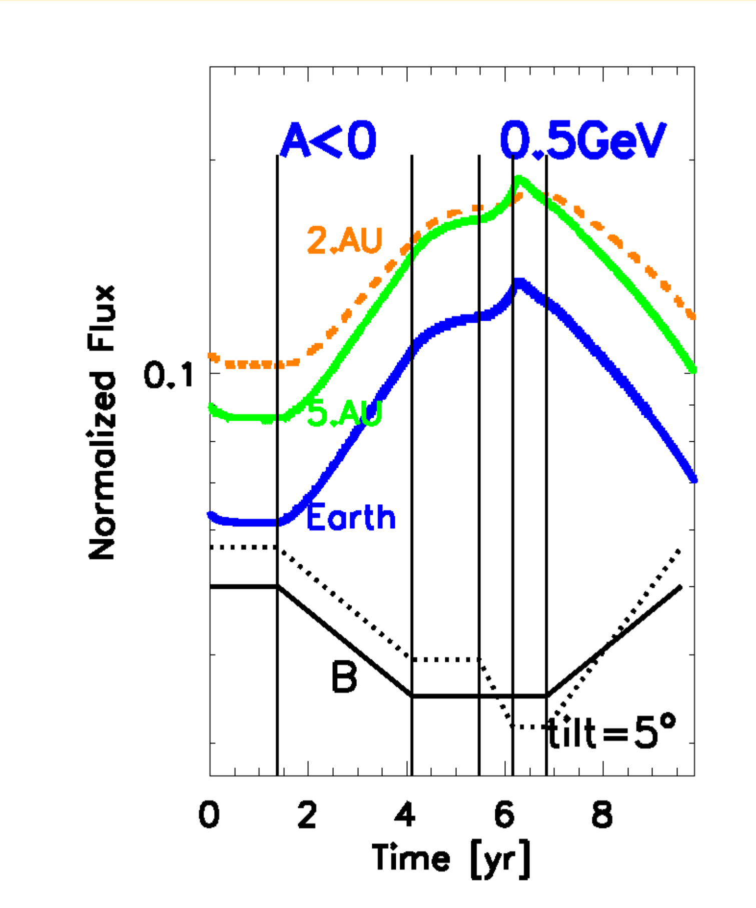




Numerical simulation of GCR flux in an 11-year Cycle



Changing HCS only



HCS & B

Summary: progress is being made ☺

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