# Galactic Cosmic Ray Intensities during the Space Age and The Holocene

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**Caltech**

**The 2018 Sun-Climate Symposium**

**Lake Arrowhead, CA**

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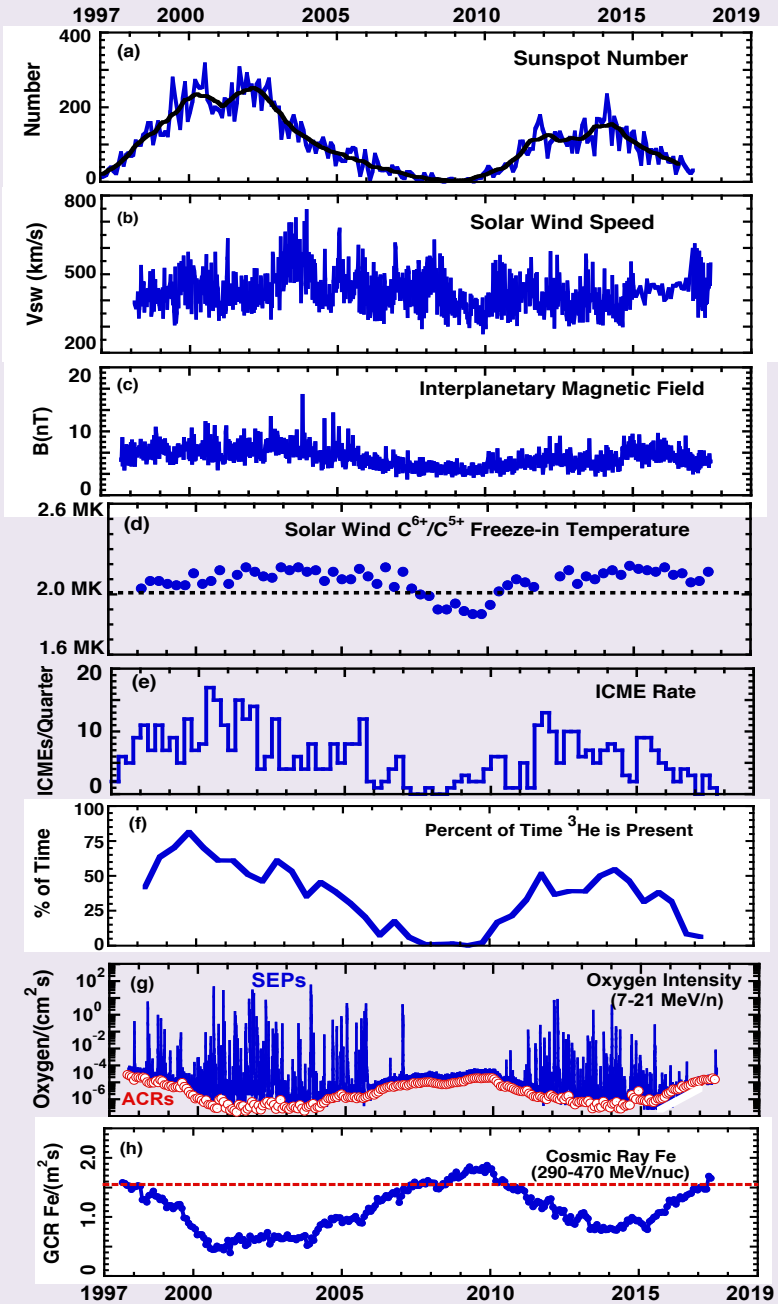



## Twenty Years of ACE Data Reveal Significant Differences between Cycle 23 and Cycle 24. Where is the Sun headed next?

- Solar activity was greatly reduced in Cycle 24.
  - * Weakest solar wind and IMF of the space era in 2009
  - * Highest cosmic-ray intensity of space era
  - * Sunspot number reduced by ~ 30%-40% in cycle 24
  - * ICME rate reduced by 37% in cycle 24
  - * Interplanetary magnetic field weaker by ~35%
- These conditions led to:
  - * ~65% reduction in X-class flares
  - * ~50% reduction in the number of large SEP Events
  - * ~4 times reduction in the >10 MeV proton fluence
  - * ~10 times reduction in severe geostorms
- There are predictions that we may be headed for a period like the Gleissberg, Dalton, or Maunder minima.
- This talk will compare the GCR recovery in cycle 24 to that in cycle 23 and discuss what we might expect.

# Outline

**Relate Cosmic Ray Intensities in Cycle 23 & 24 to those over the space age.**

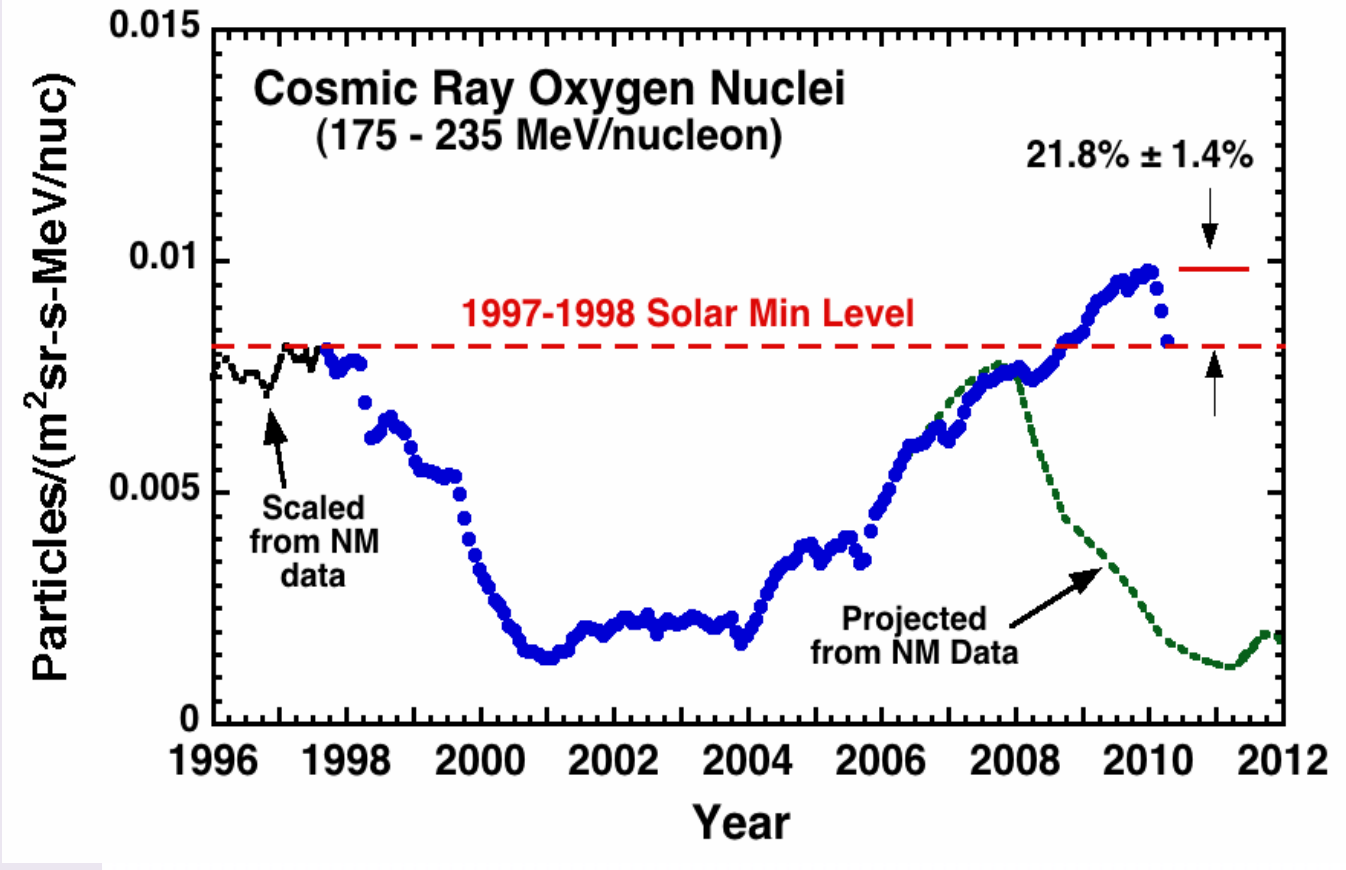
**Summarize what processes cause cosmic ray intensities to vary in time**

**Relate Present-Day GCR Intensities to those in the past**

**Discuss what conditions need to occur to cause present-day GCR intensities to approach those during recent those in the Dalton or Gleisberg Minima?**

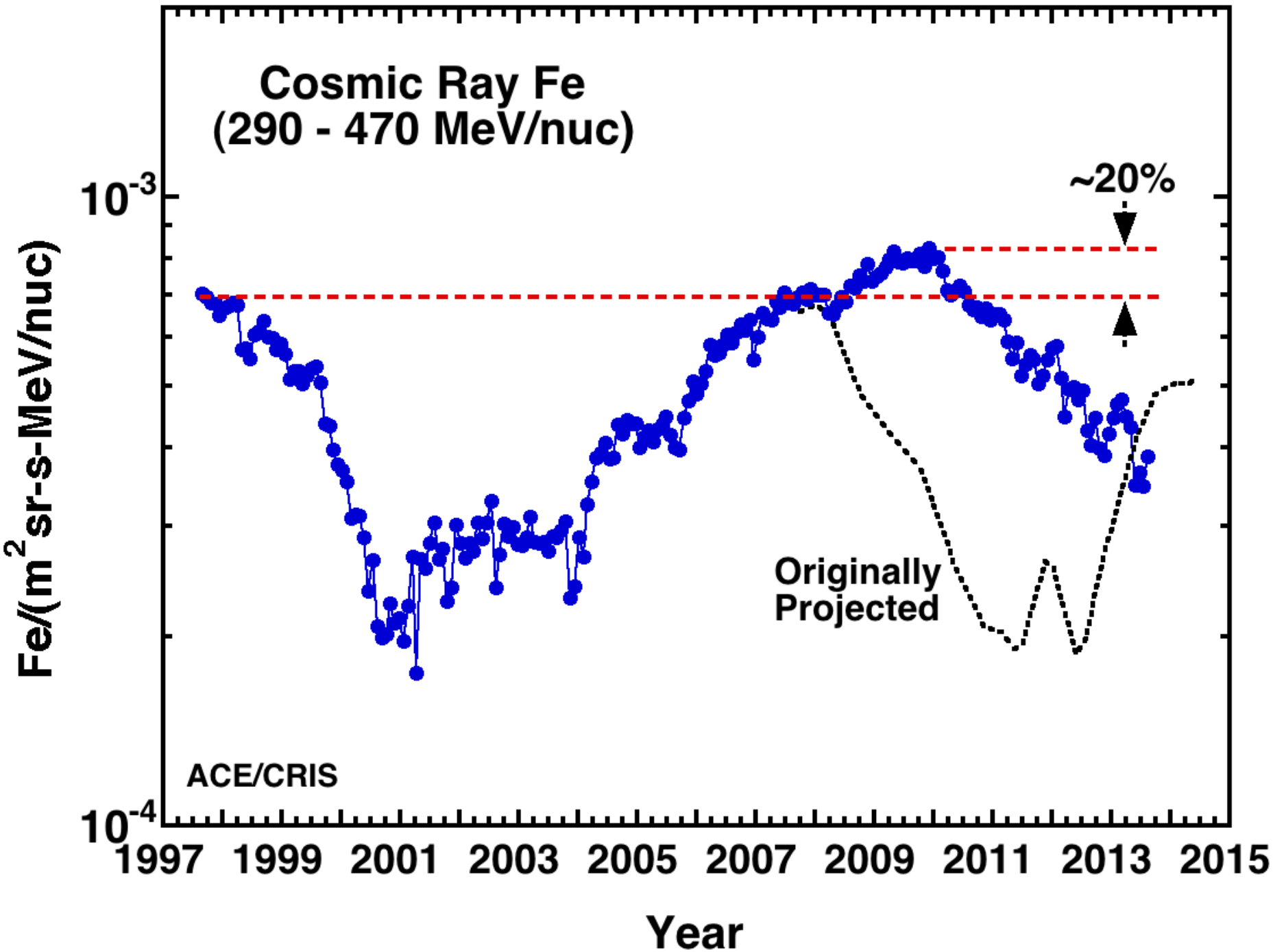
**How would Interplanetary radiation levels change if we enter a new minima?**

## Cosmic Ray Oxygen Intensities during Solar Cycle 23

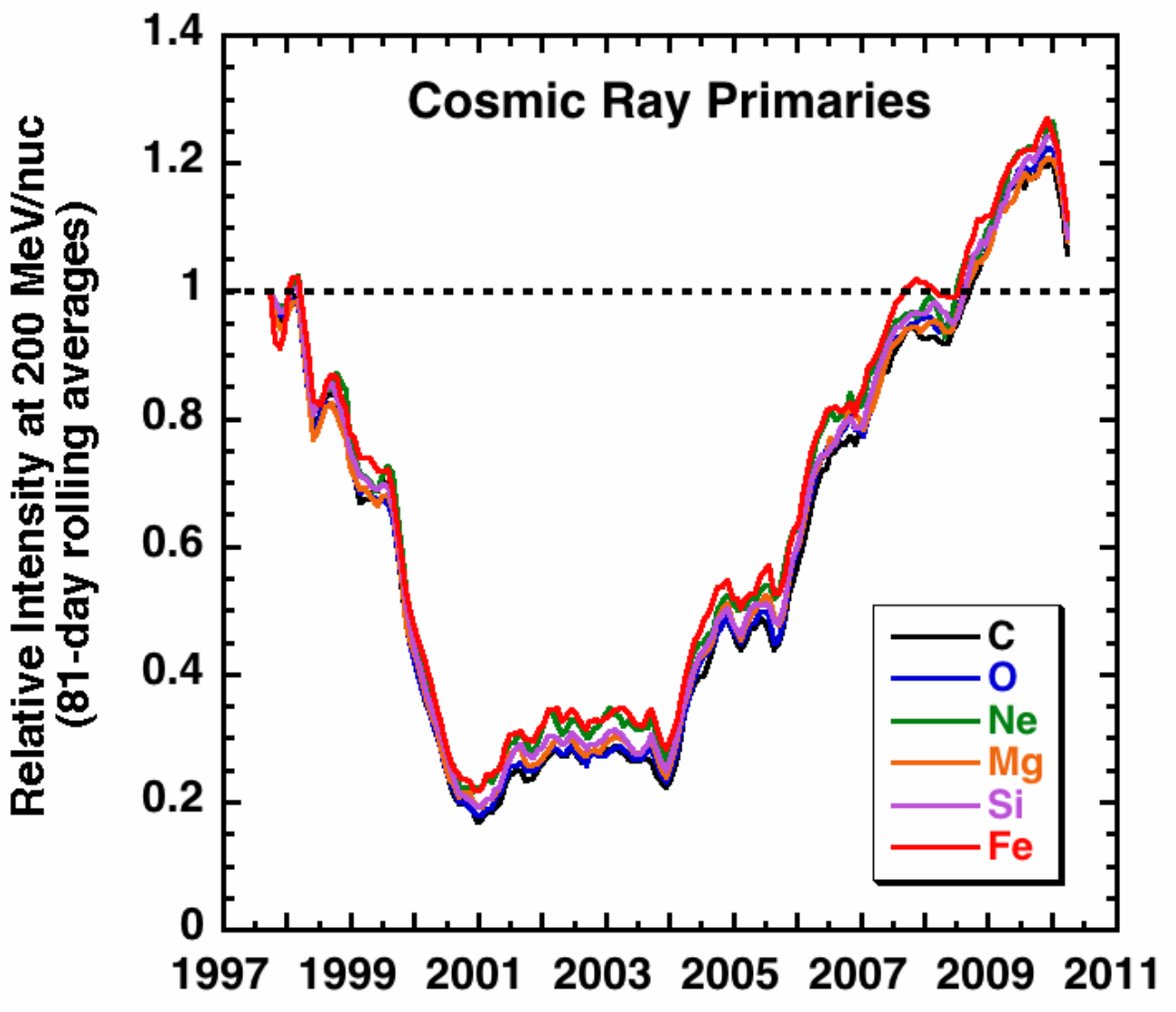



- **Based on solar cycles 19-22 the GCR intensity was expected to decline in 2008.**
- **At the time GCR intensities were approaching those in 1997-98 and also in 1976.**
- **Instead, solar minimum persisted, and GCRs began to increase in early 2008, reaching record levels in 2009**
- **In early 2010 the intensities suddenly returned to 1997 levels**

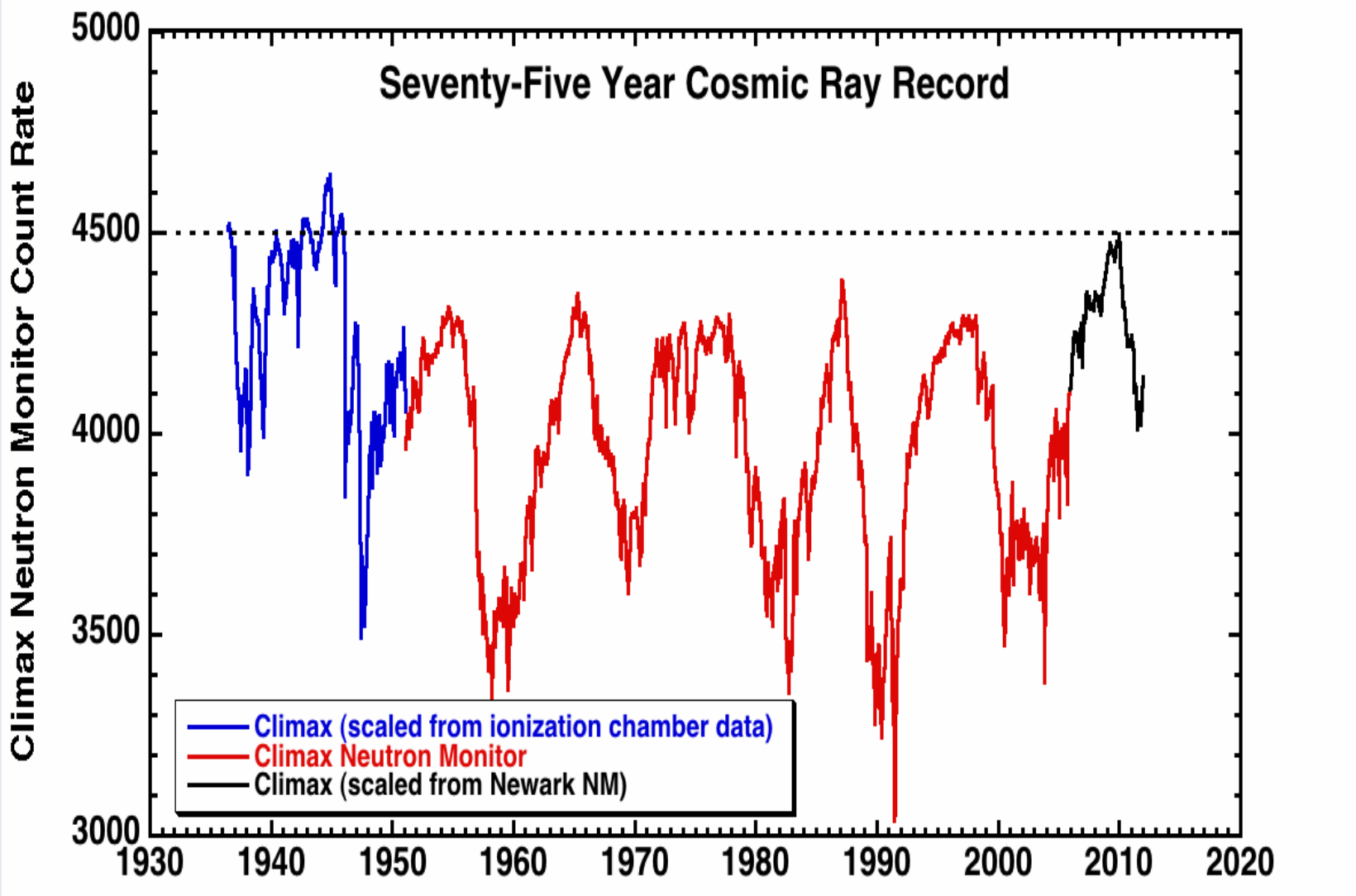
Mewaldt et al. 2010


Cosmic Ray Fe
(290 - 470 MeV/nuc)
~20%
Originally
Projected
ACE/CRIS
$10^{-3}$
$10^{-4}$
Fe/(m$^2$sr-s-MeV/nuc)
1997
1999
2001
2003
2005
2007
2009
2011
2013
2015
Year

# All Species had Similar Excesses in 2009-2010

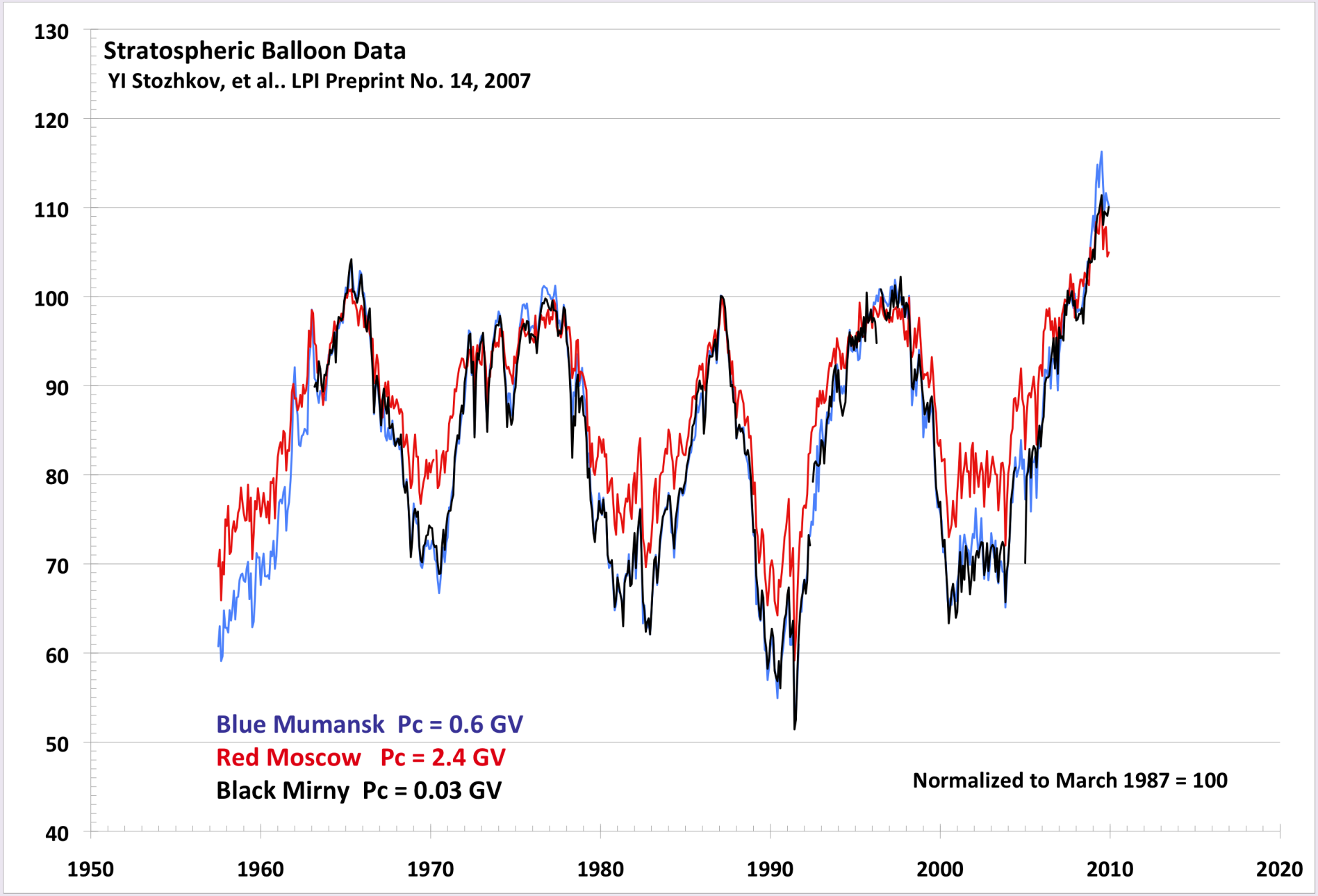



Mewaldt et al. 2010

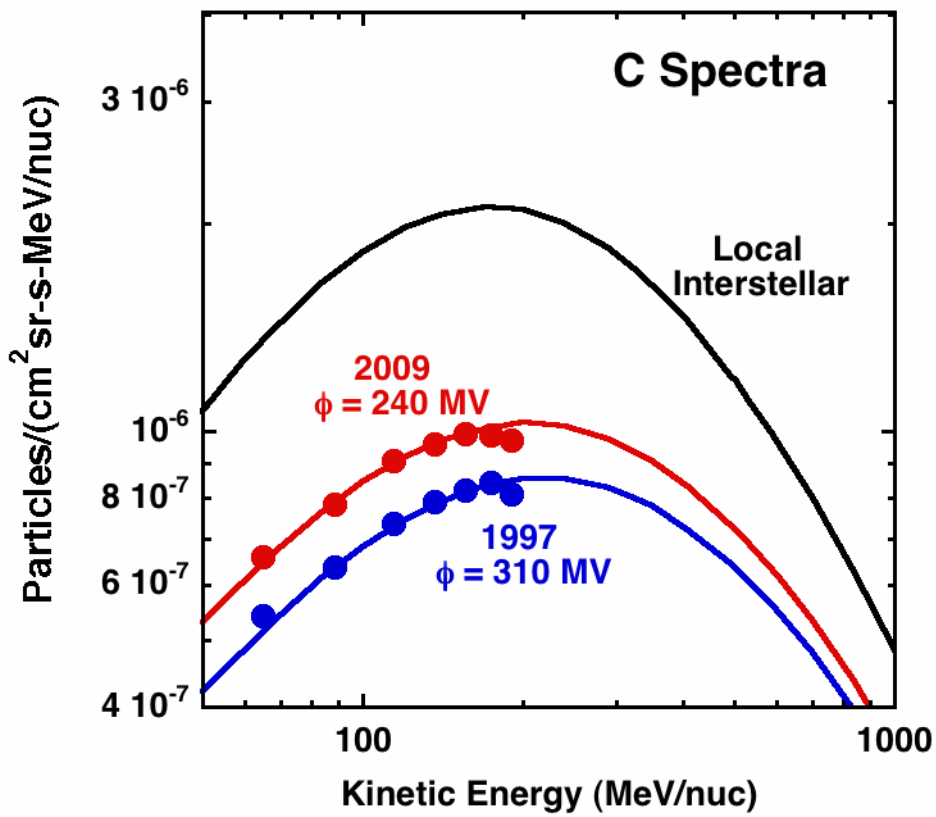


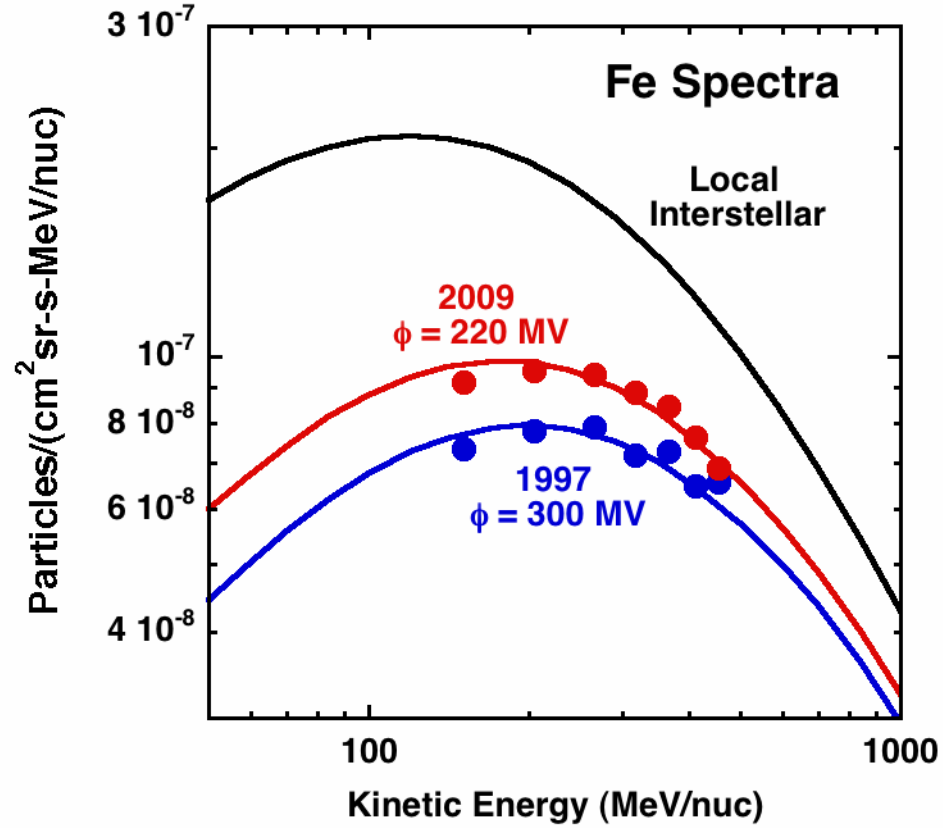

**Ionization chamber based on Forbush 1948, Neher 1971, and McCracken et al. 2004; Climax & Newark Neutron Monitor data (see Mewaldt 2013)**

# 50 Years of Cosmic-ray Intensities in the Stratosphere



# Cosmic Ray Energy Spectra



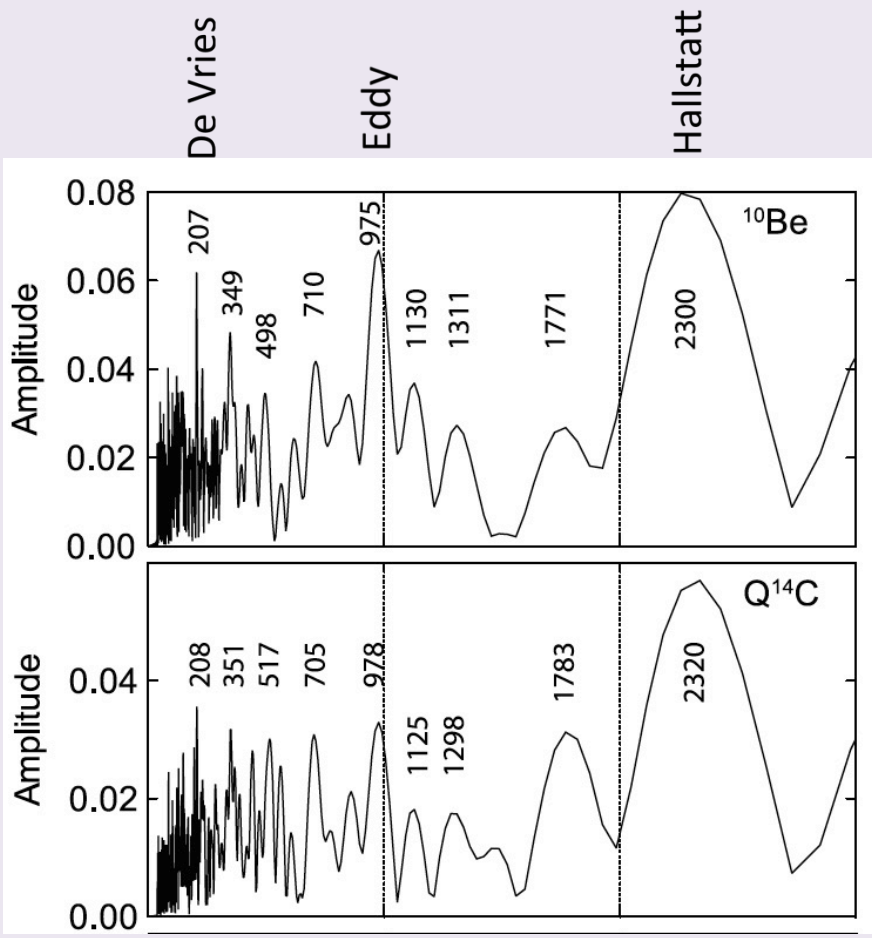

The "modulation parameter":

$$\phi \propto \int_{1\ \mathrm{AU}}^{\mathrm{boundary}} \frac{V_{SW}}{\kappa}\, dr$$

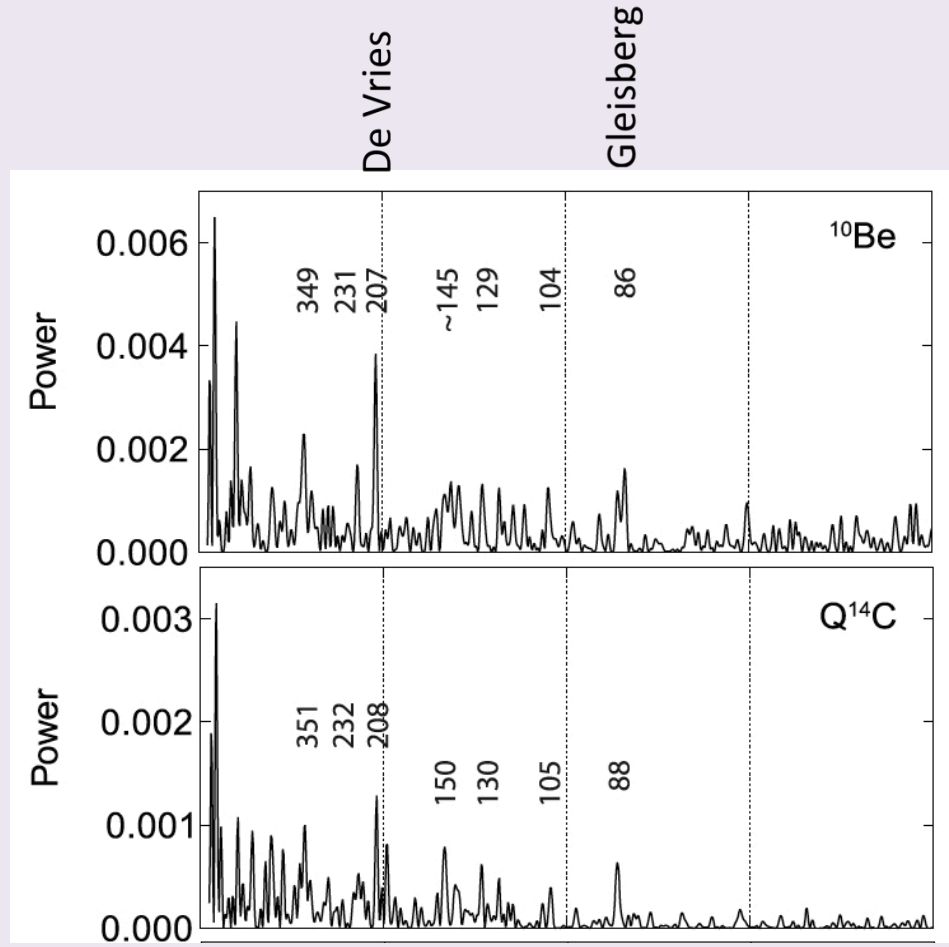
**Gleeson and Axford (1968)**

**ACE/CRIS data; Mewaldt et al. 2010**

# Cosmic Ray Variations over the Past 9400 Years (McCracken et al. 2013)



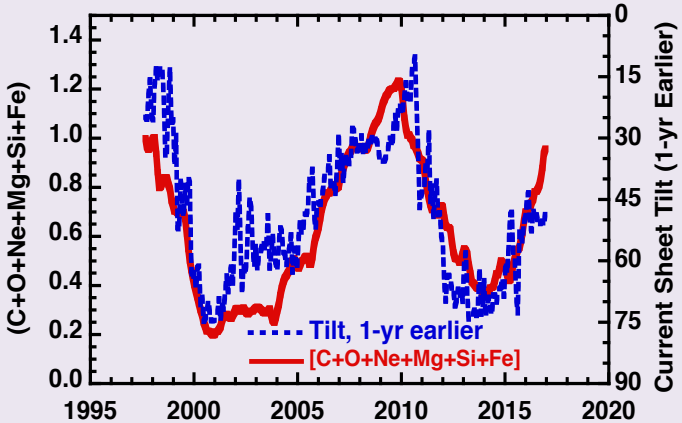

Fourier amplitude Spectra for $^{14}$C & $^{10}$Be periodicities 200<T<3000 years BP (before 1950). The strongest are for the de Vries, Eddy, and the Hallstatt periods.

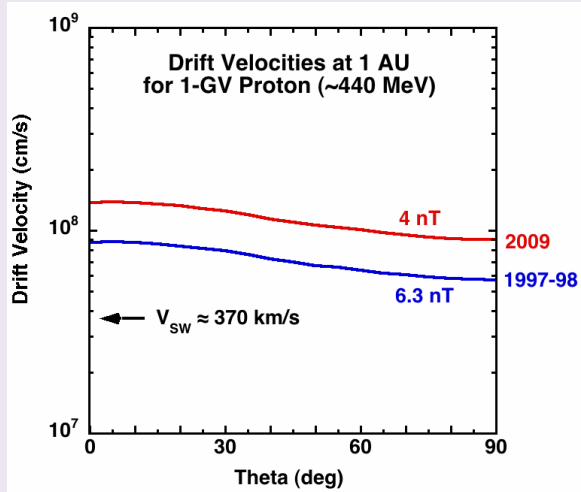


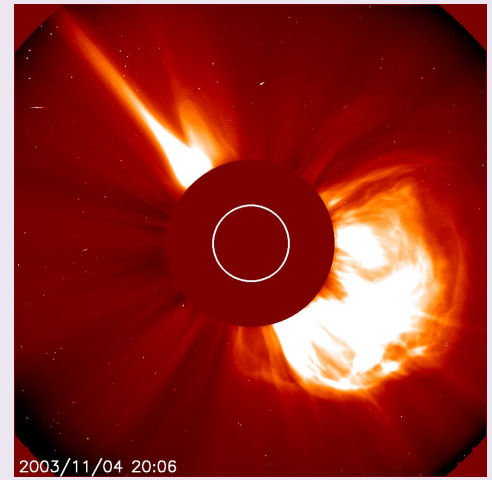

$^{14}$C & $^{10}$Be power spectra for periods of 50<T<400 years based on data from 300 to 9,400 years BP. Periods of 87 yr (Gleisberg), 208 yr (De Vries) & 350 yr are clear.

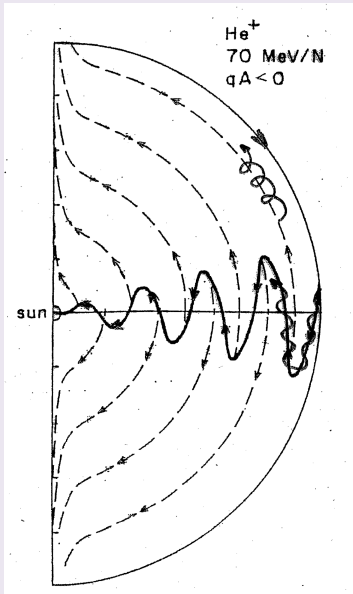
# Solar/Interplanetary Parameters affecting the GCR Intensity

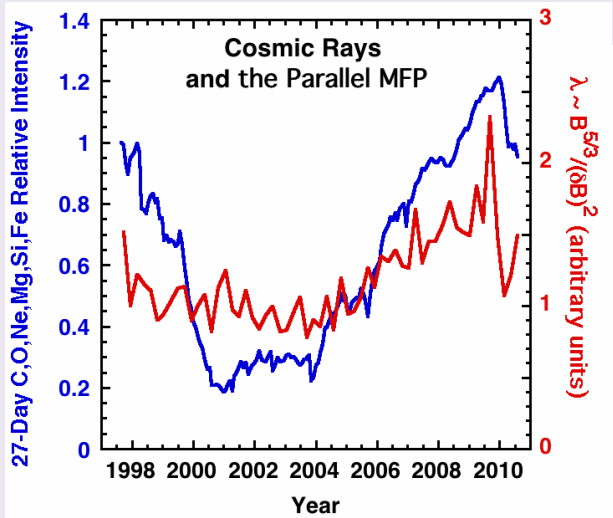
1. Tilt of the heliospheric current sheet
2. Gradient and curvature drifts
3. Interplanetary turbulence
4. CMEs and other transients
5. Solar wind speed
6. SW dynamic pressure

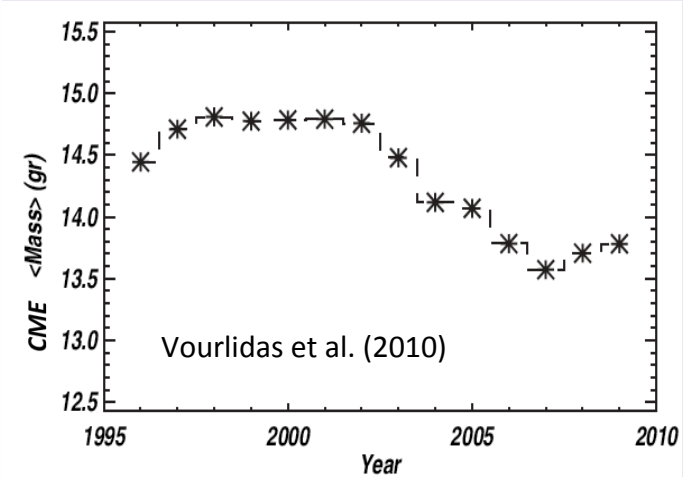


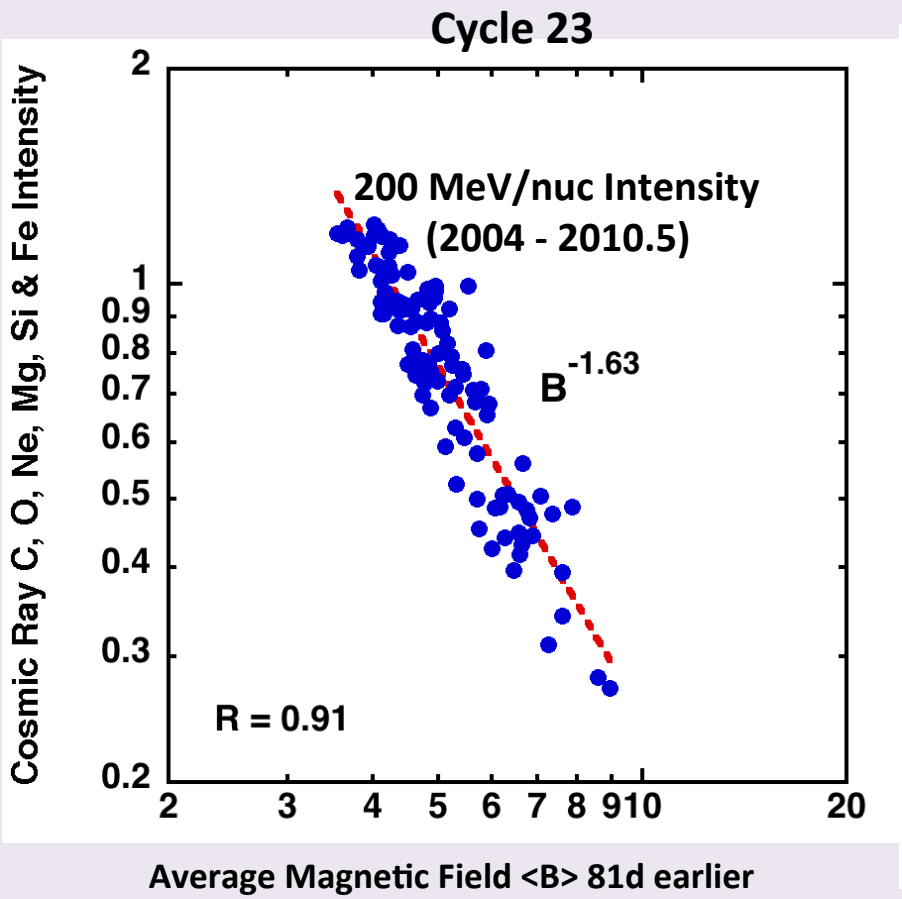



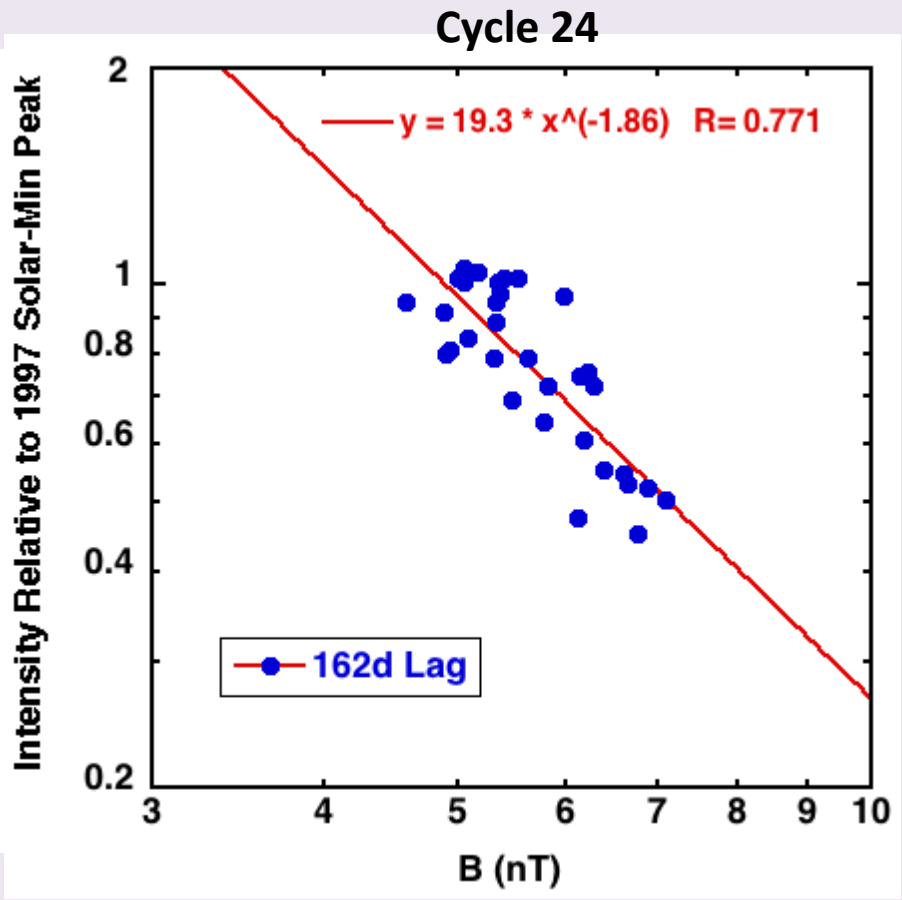



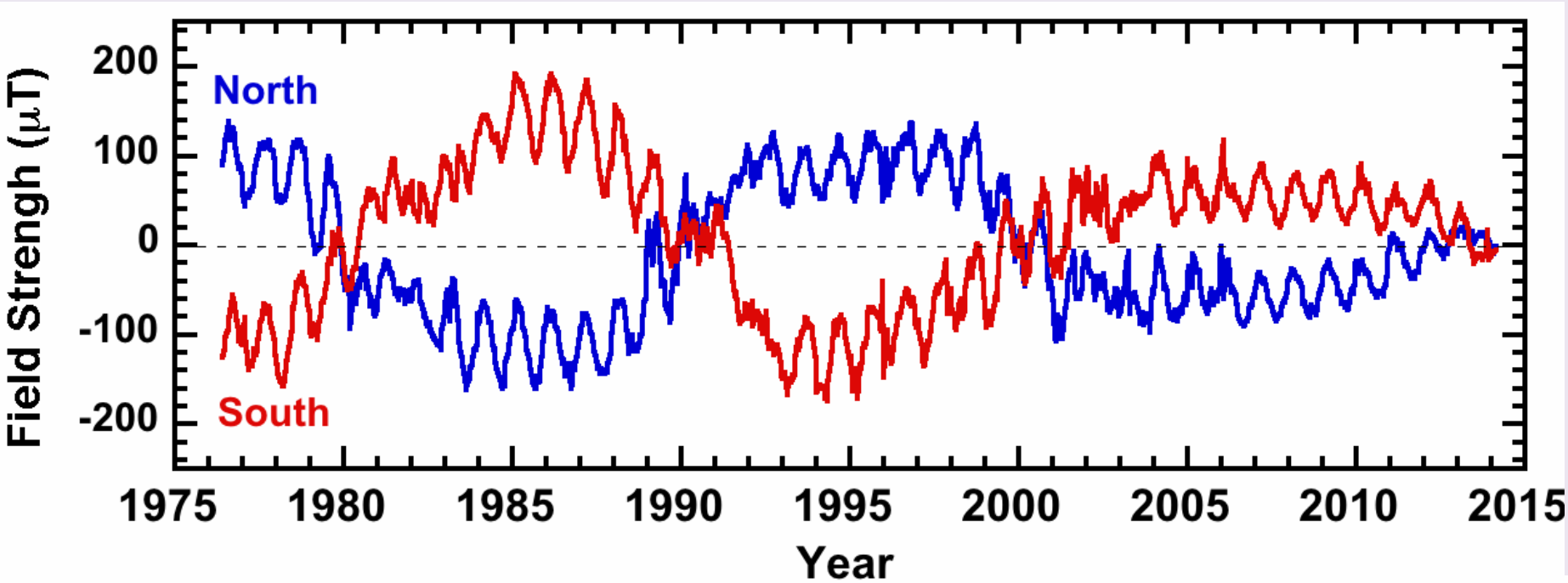



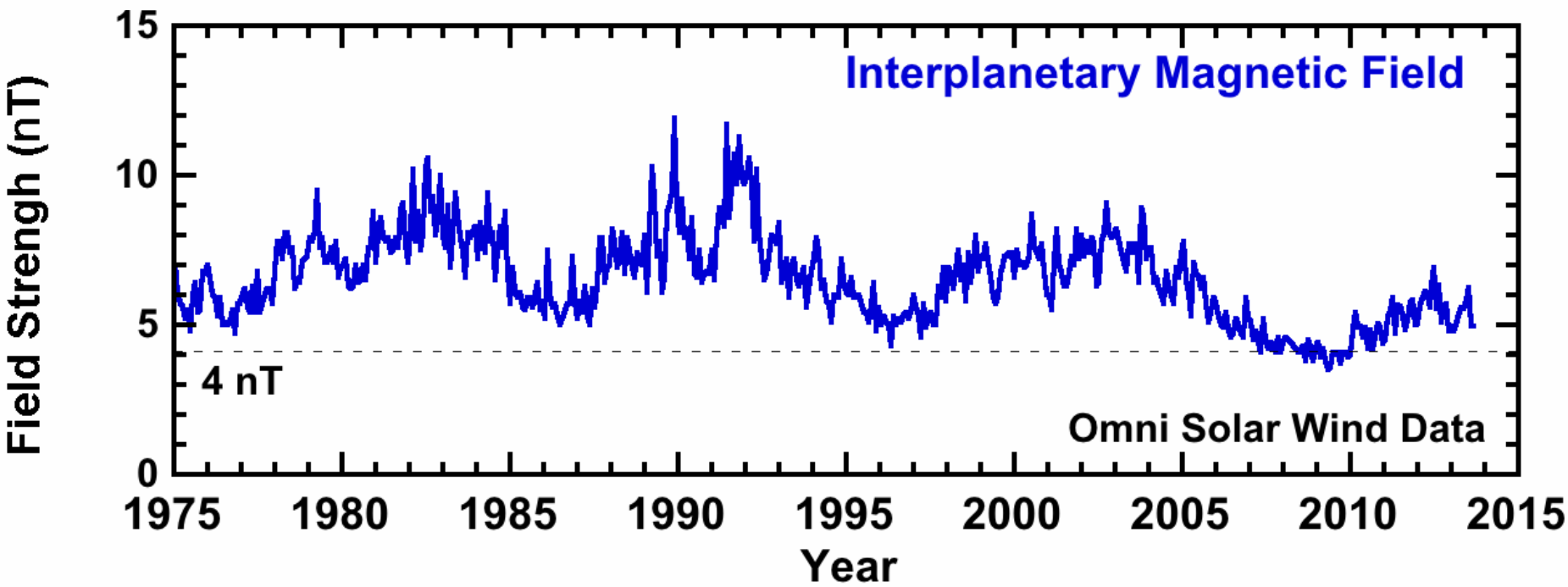
## The Single Most Important Parameter in the Regulating Cosmic Ray Intensity at 1 AU is the Interplanetary Magnetic Field Strength



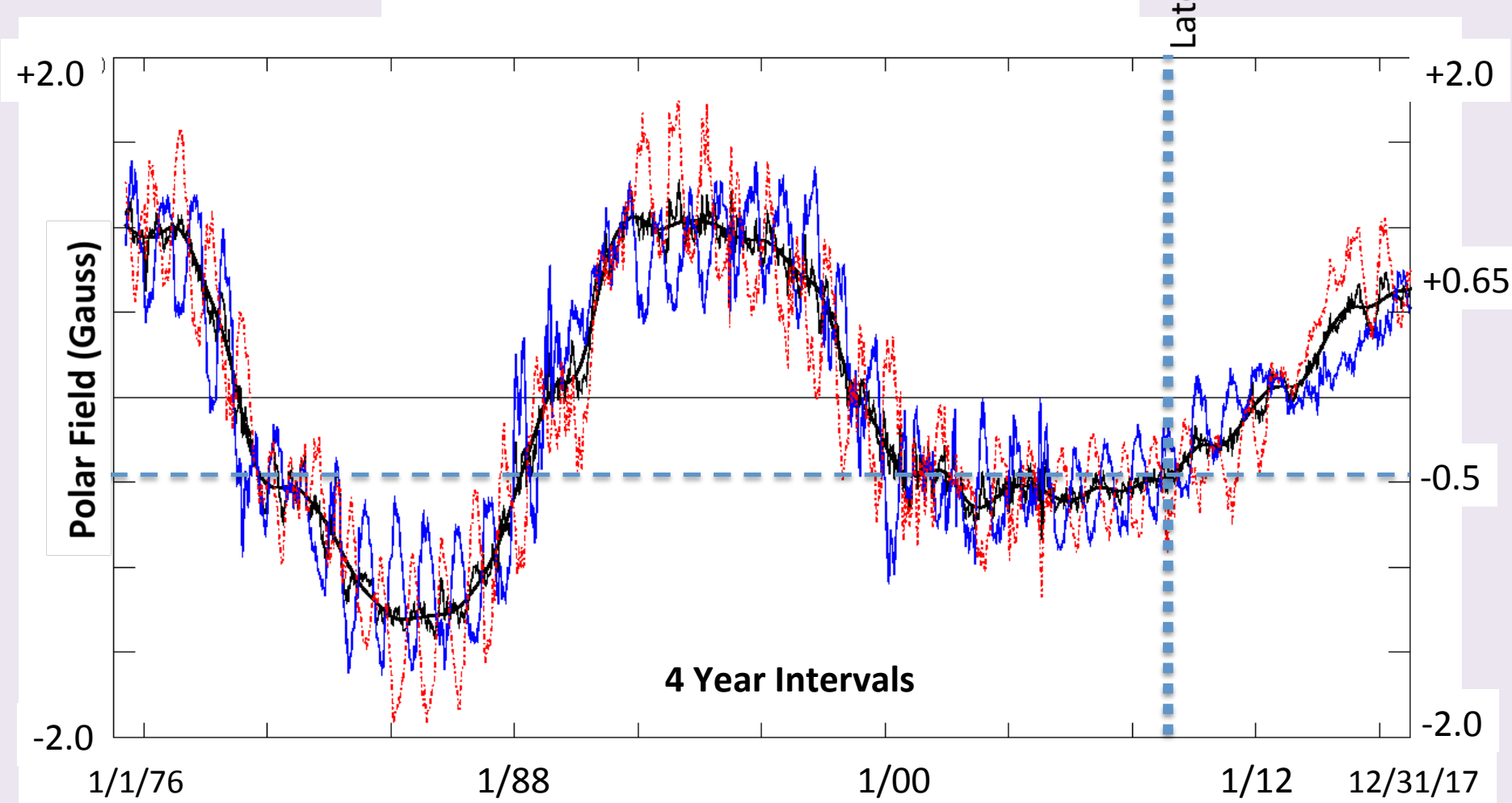




Mewaldt et al. (2010)


North
South
Field Strengh (μT)
200
100
0
-100
-200
1975
1980
1985
1990
1995
2000
2005
2010
2015
Year

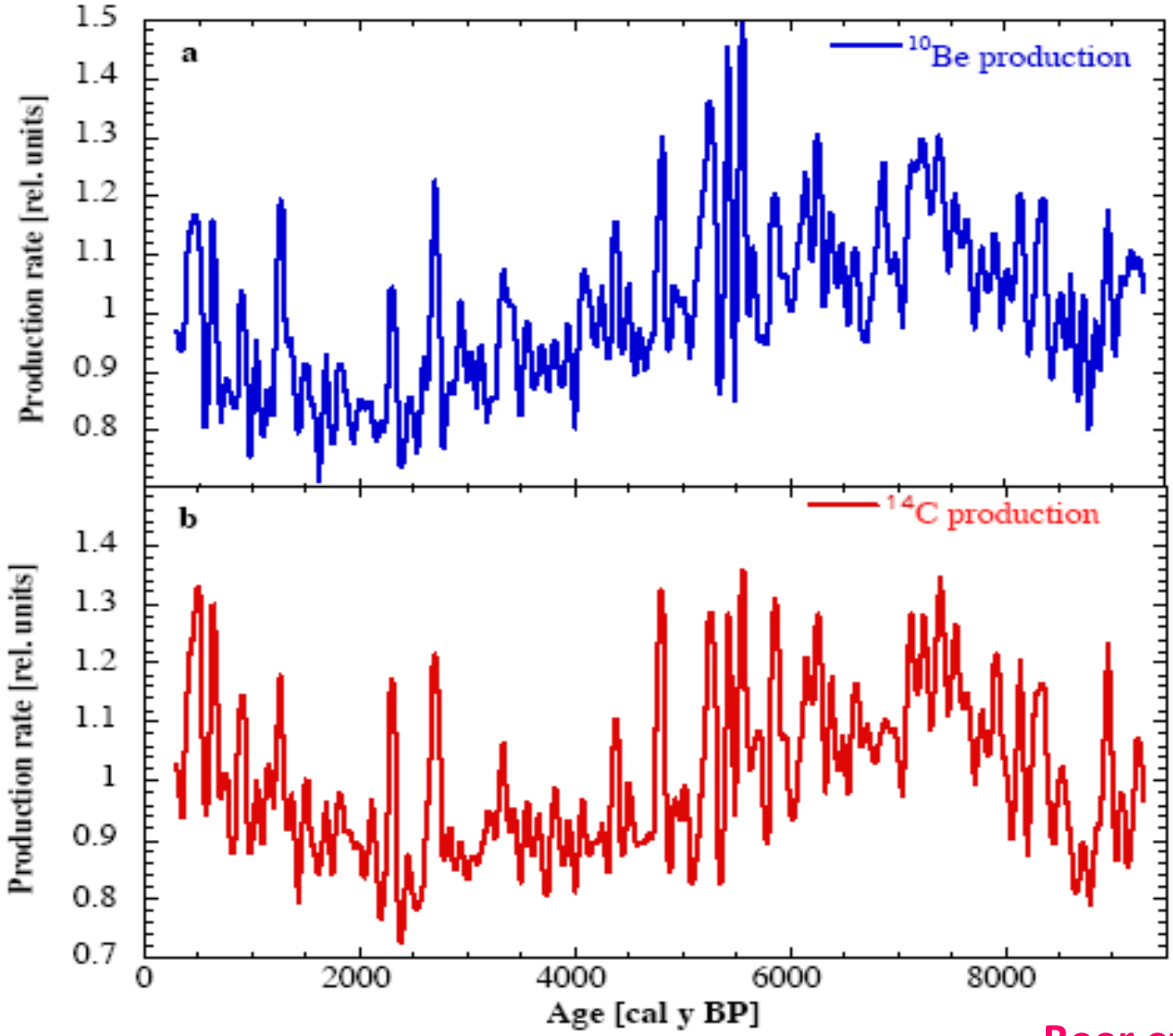

Interplanetary Magnetic Field
4 nT
Omni Solar Wind Data
Field Strengh (nT)
15
10
5
0
1975
1980
1985
1990
1995
2000
2005
2010
2015
Year

# Solar Polar Field Strength vs. Time (Wilcox Solar Observatory)




**Key: Lt. Solid = North; Dashed = -South; Med. Solid = (N-S)/2; Heavy Solid = smoothed Ave.**

# Consistent $^{10}$Be and $^{14}$C records over the last 9300 years



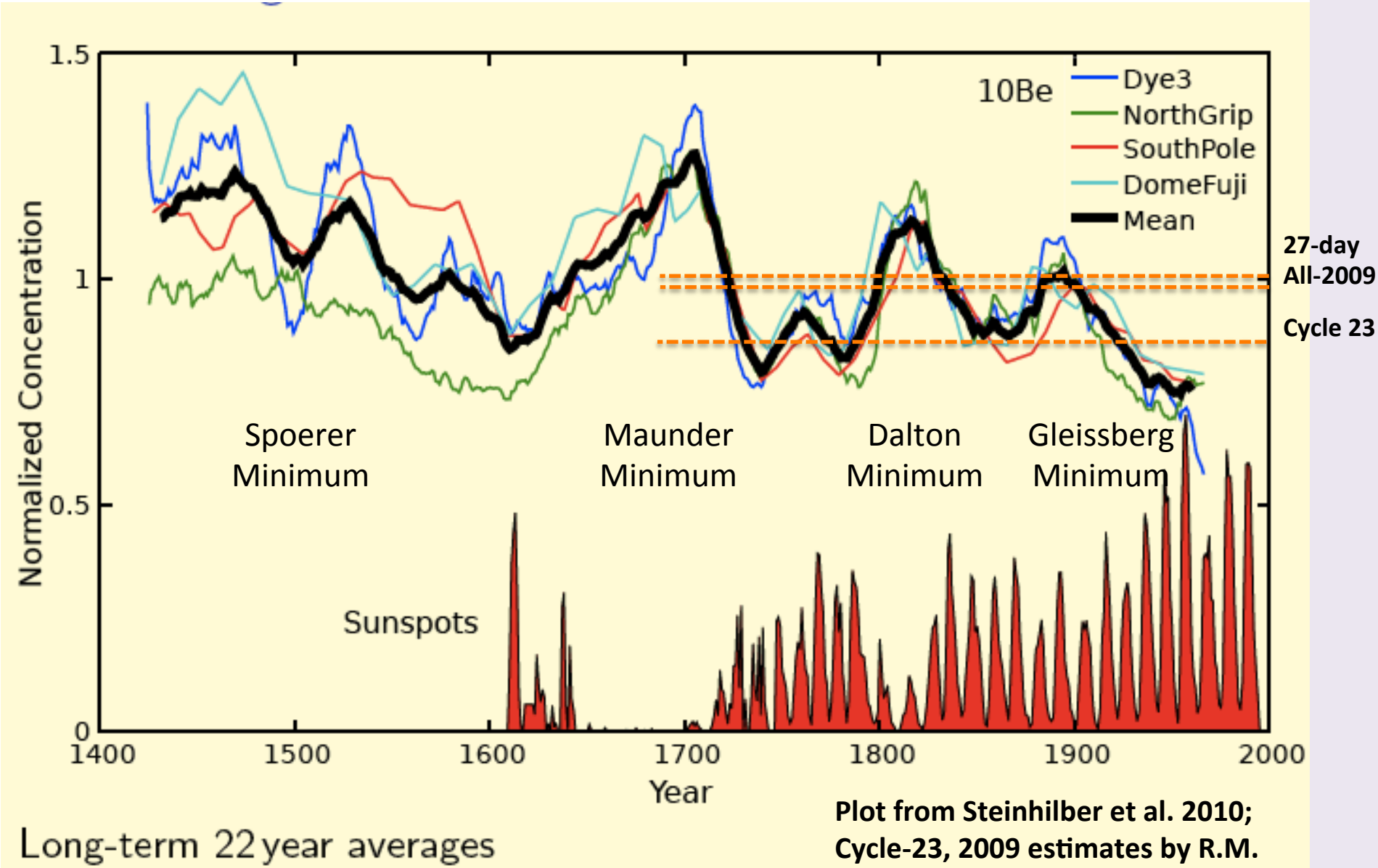

40-year running means

Beer et al, 2007

# The space era has occurred during a period of low cosmic ray activity

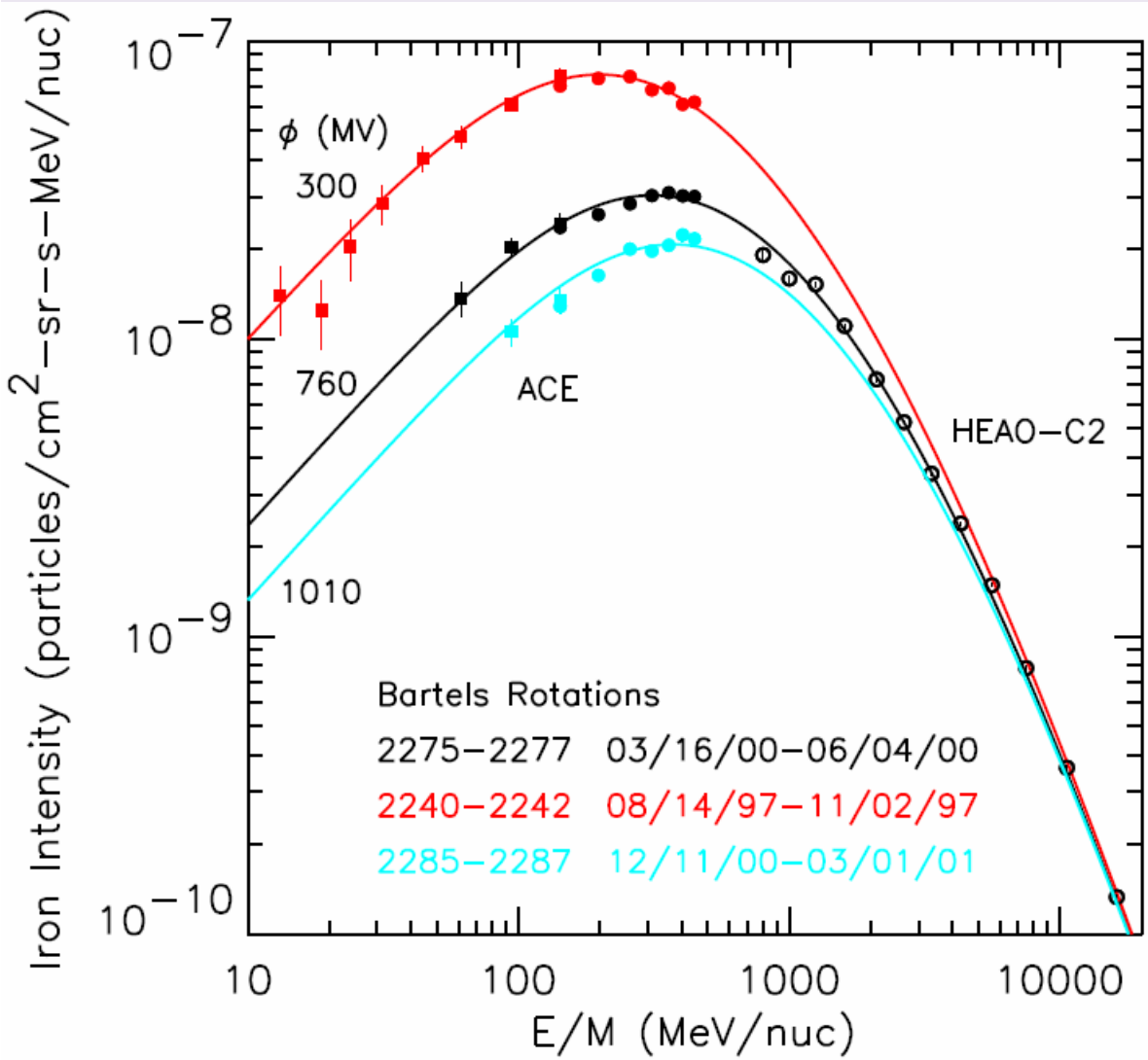
**Relation of 2009 to the last 600 years**

**Plot from Steinhilber et al. 2010**




**Plot from Steinhilber et al. 2010; Cycle-23, 2009 estimates by R.M.**

# Cosmic-ray spectral variations over the solar cycle




Spectral shape changes are reasonably-well accounted for by the "modulation parameter" ($\phi$):

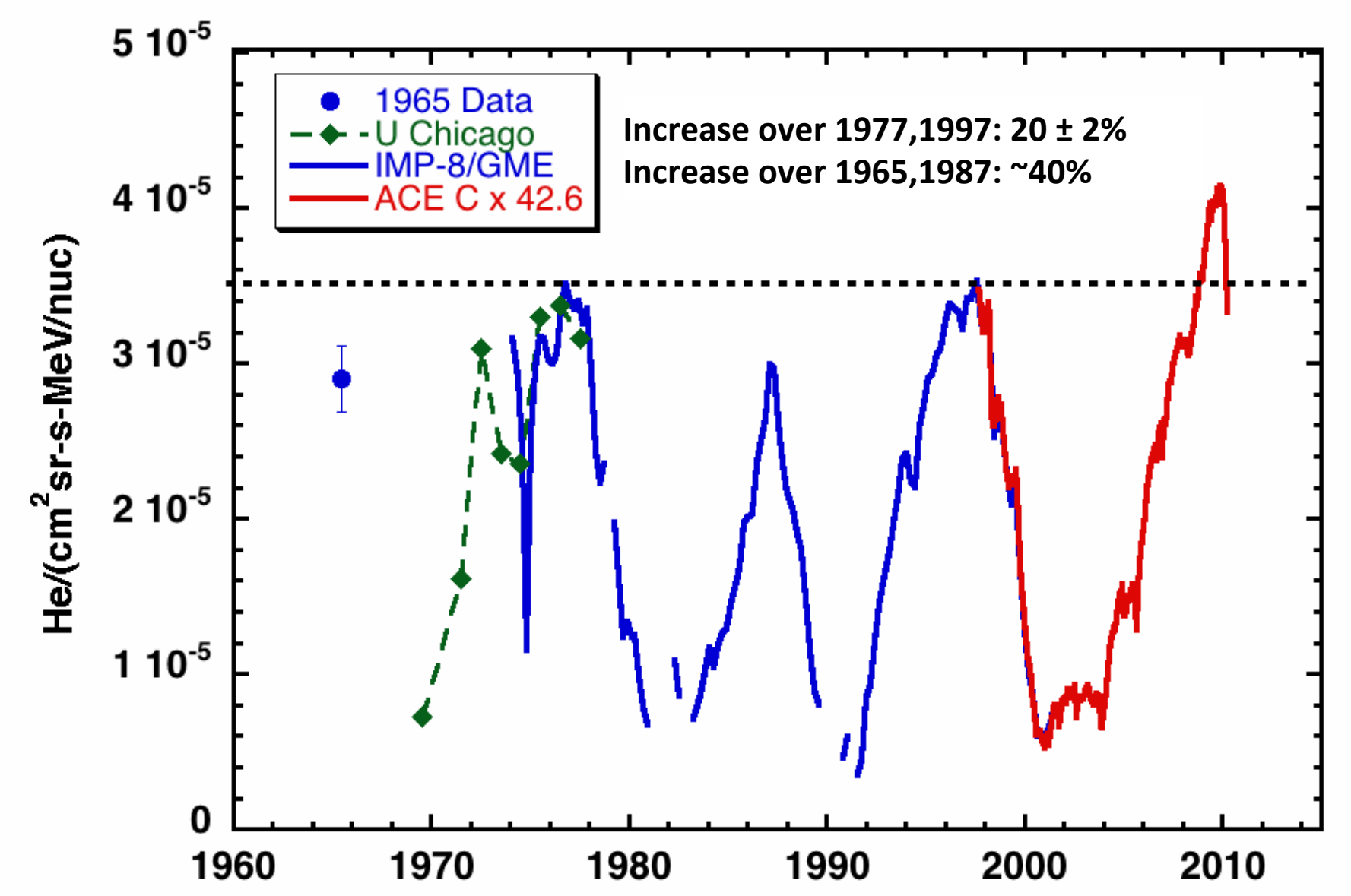
$$\phi \propto \int_{1\ \mathrm{AU}}^{\mathrm{boundary}} \frac{V_{SW}}{\kappa}\, dr$$

Here Vsw is the solar wind speed, and $K$ is the diffusion coefficient, which depends on the magnetic field strength and turbulence level (e.g., Gleeson & Axford, 1968).

Note: Most of the changes are at low energy

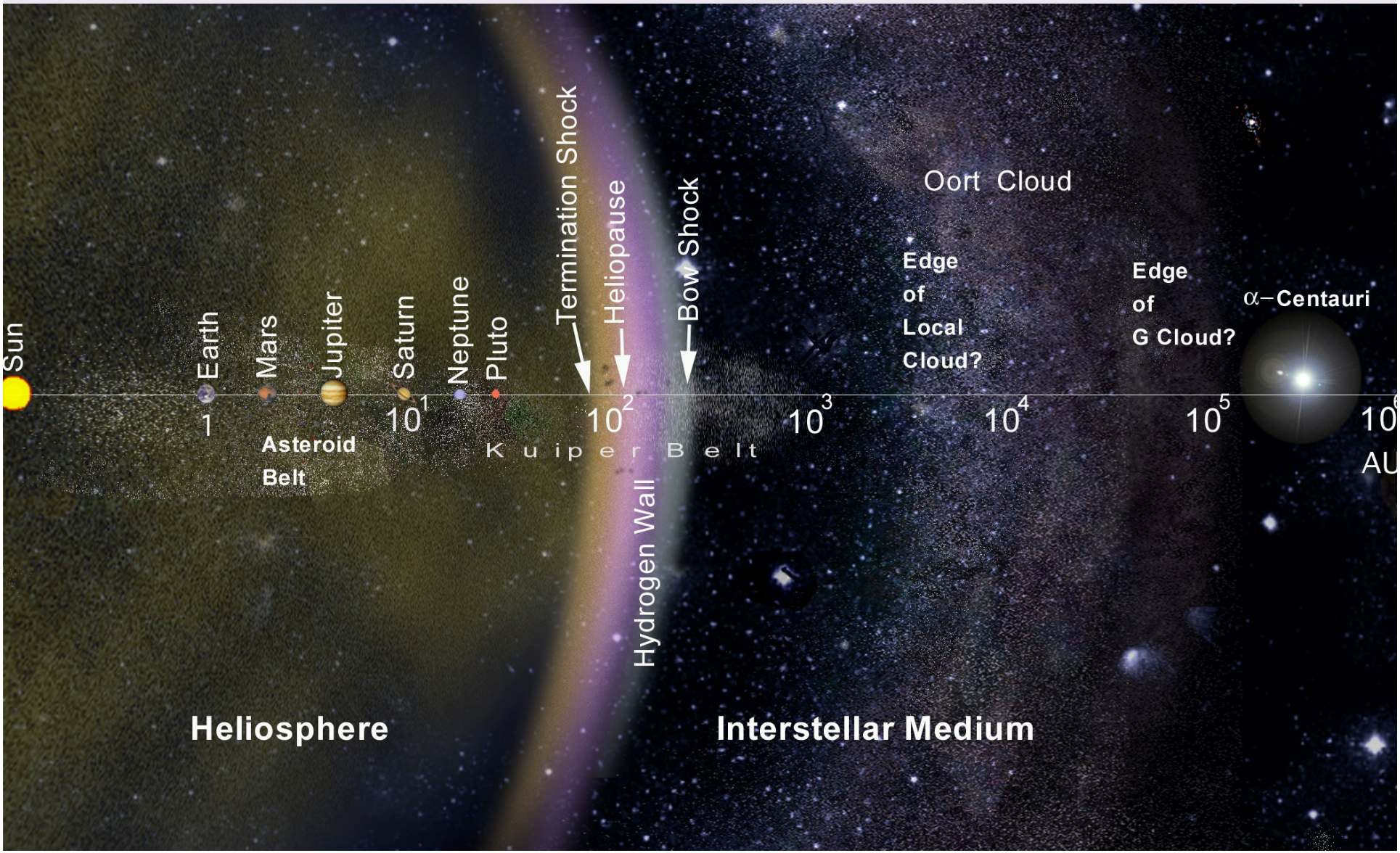
from Wiedenbeck (2007)

# Comparing 100-200 MeV/n He over 5 Solar Minima

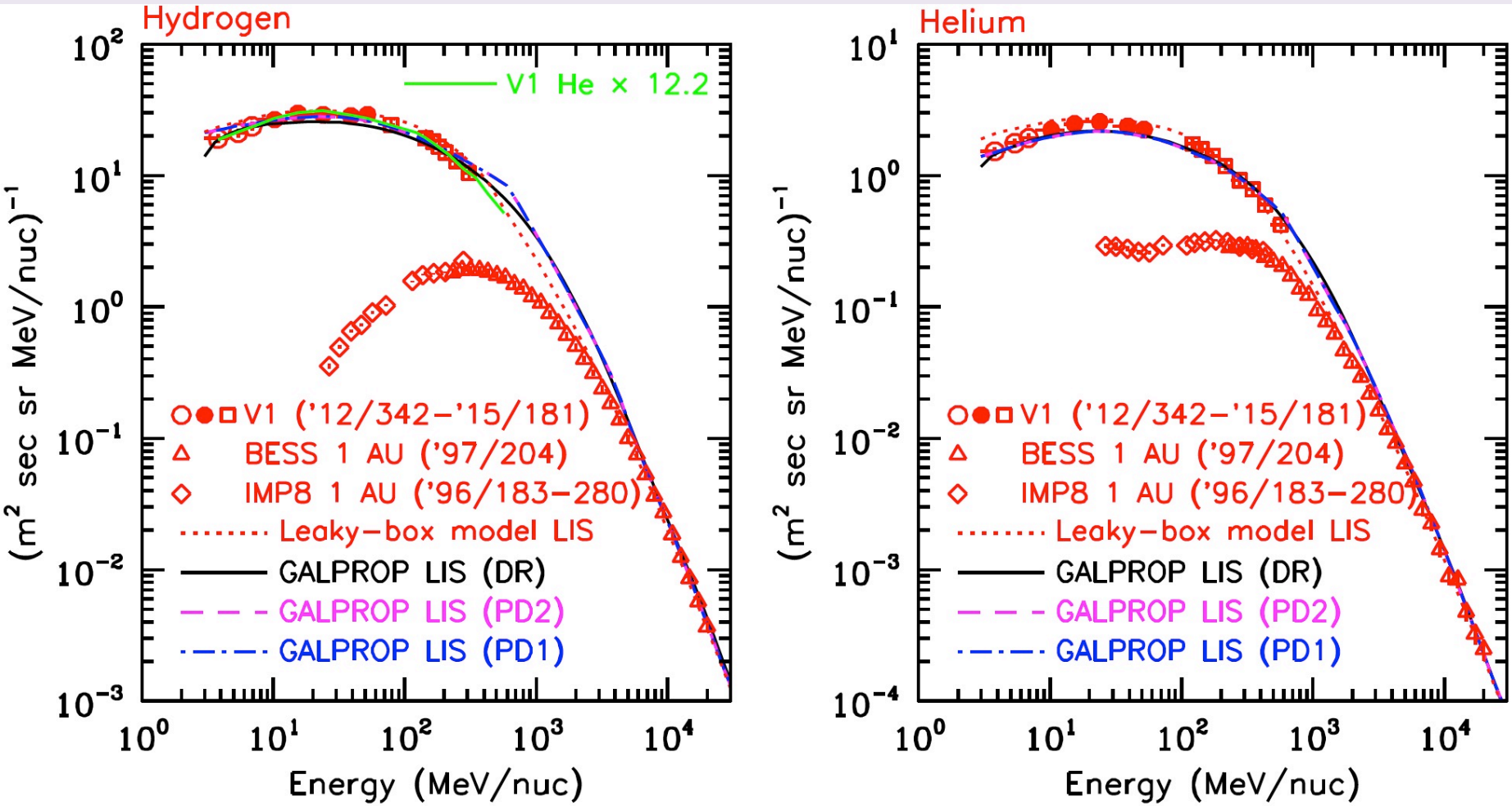



Mewaldt et al. 2010

**In 2012 Voyager-1 entered our nearby galactic neighborhood. Since that time it has been measuring the local-interstellar energy spectra – a worst-case cosmic-ray environment.**

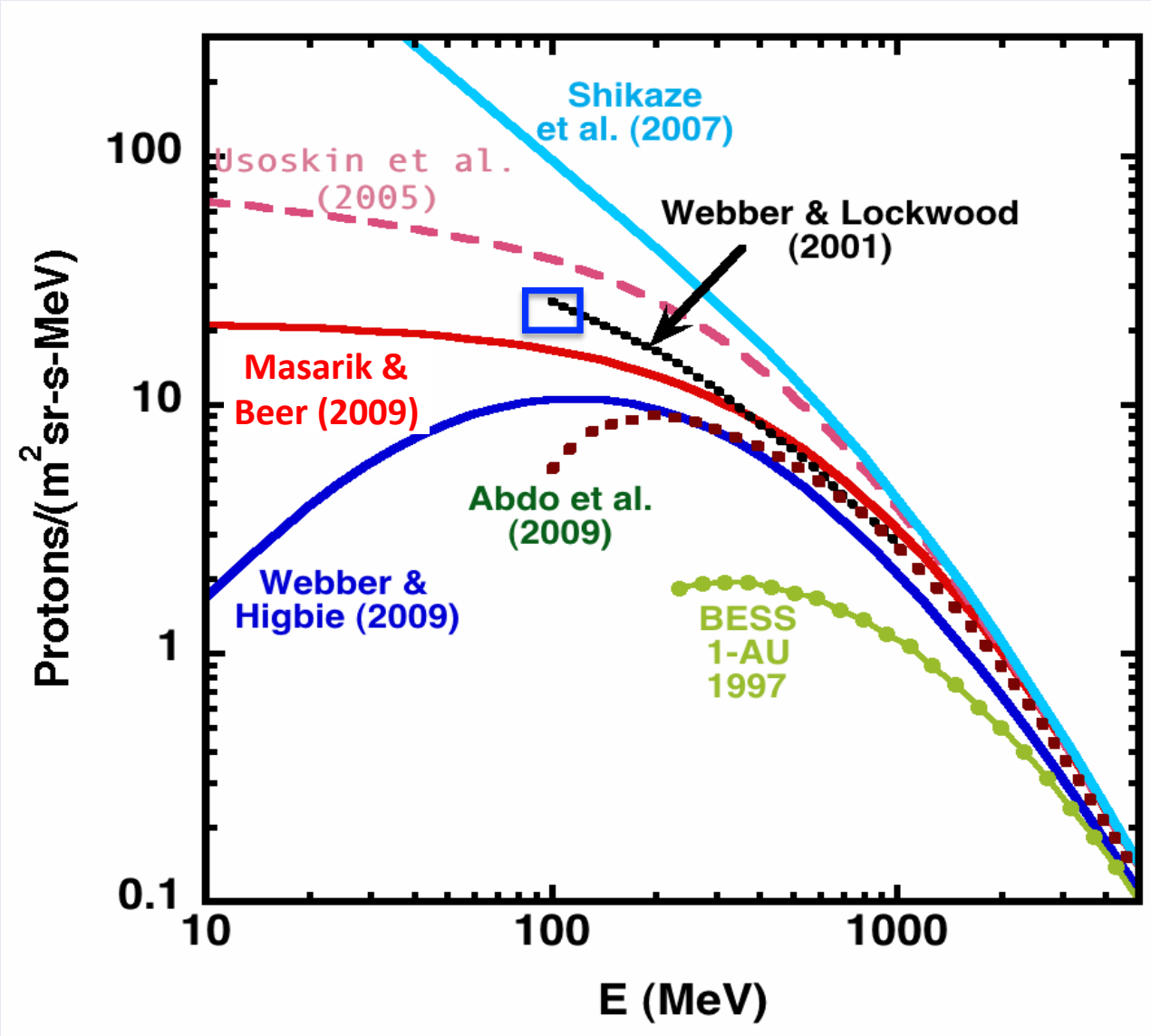


**Voyager 1 has provided the first measurements of the interstellar spectra of of galactic cosmic rays. They extend from 3 to 308 MeV for H and from 3 to 661 MeV/nuc for He. They can be extended by fitting models. These data provide possible upper limits to the GCR intensity that Earth experienced in the past.**



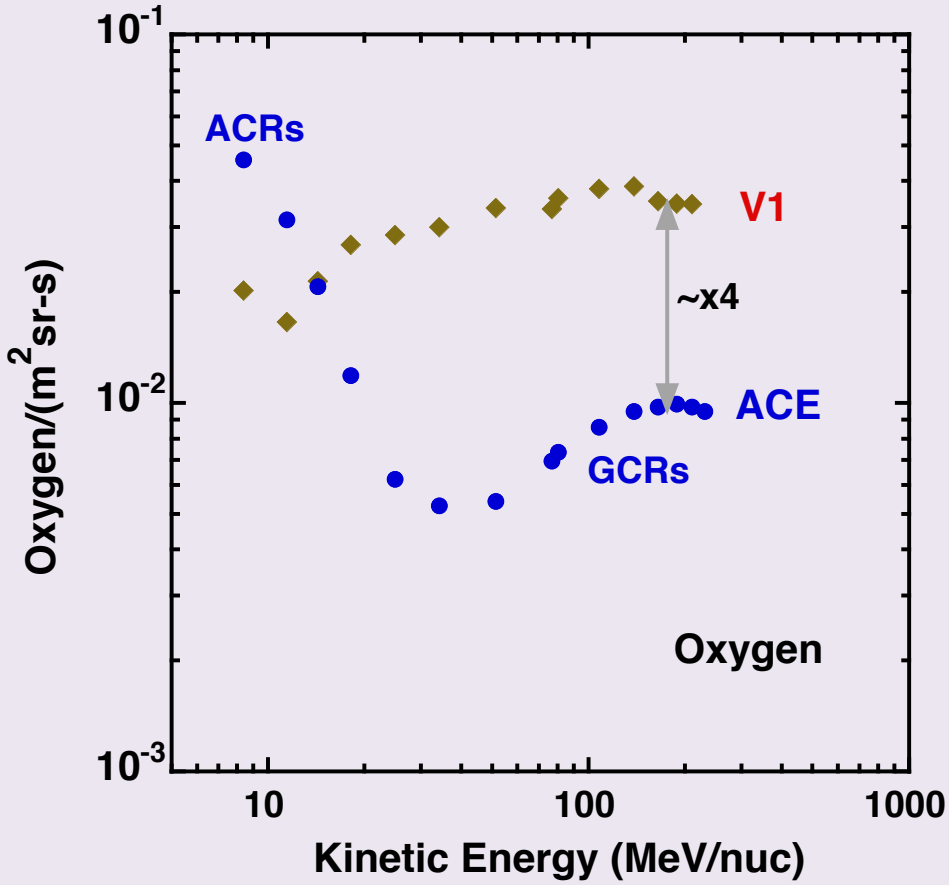

**Cummings et al. (2016)**

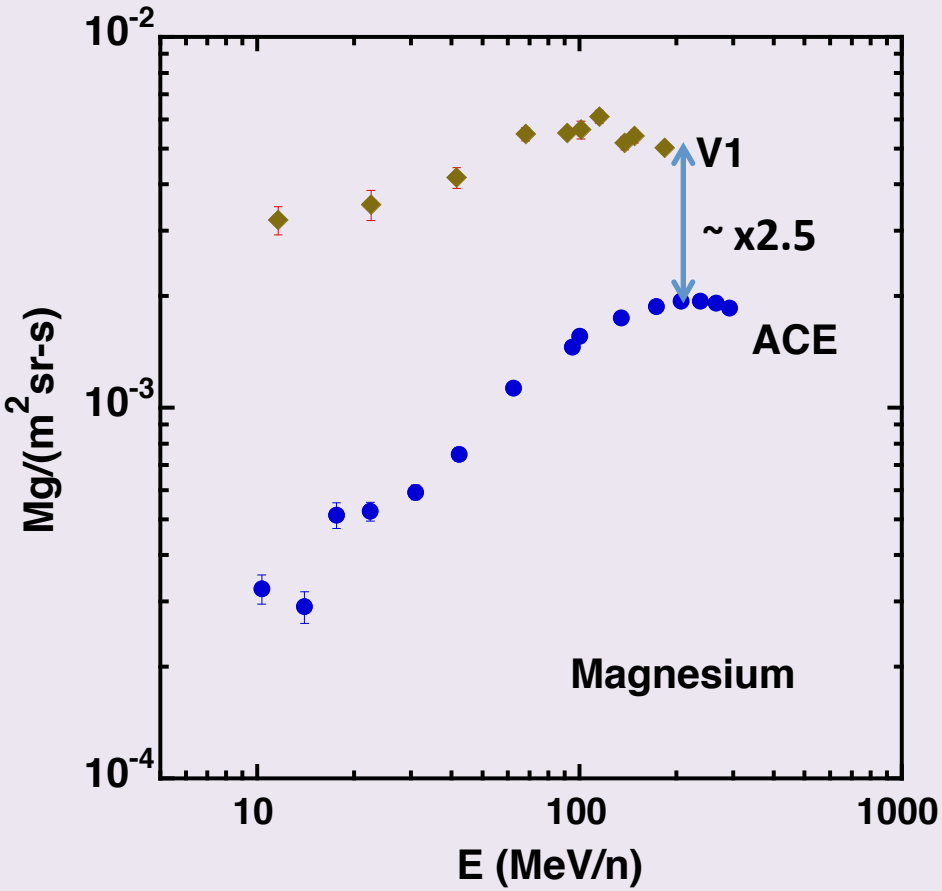
**Voyager measurements of the cosmic-ray interstellar proton spectrum quickly ruled out several proposed IS spectra; some of which are based on cosmic-ray acceleration and transport models, and some of which are based on convenient mathematical expressions that fit the high-energy spectra.**



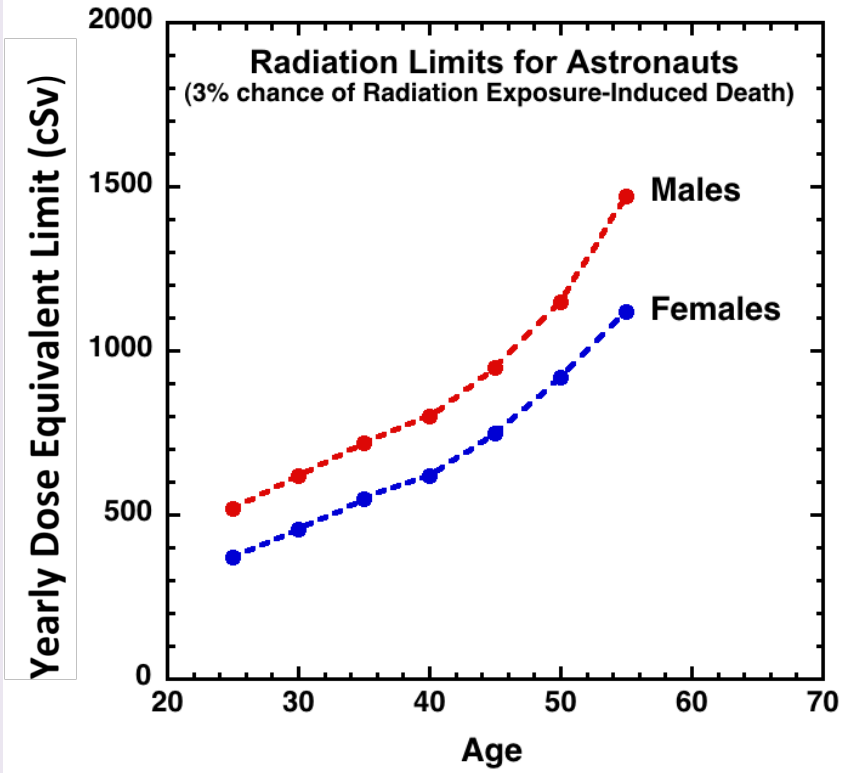

Mewaldt et al. (2013)

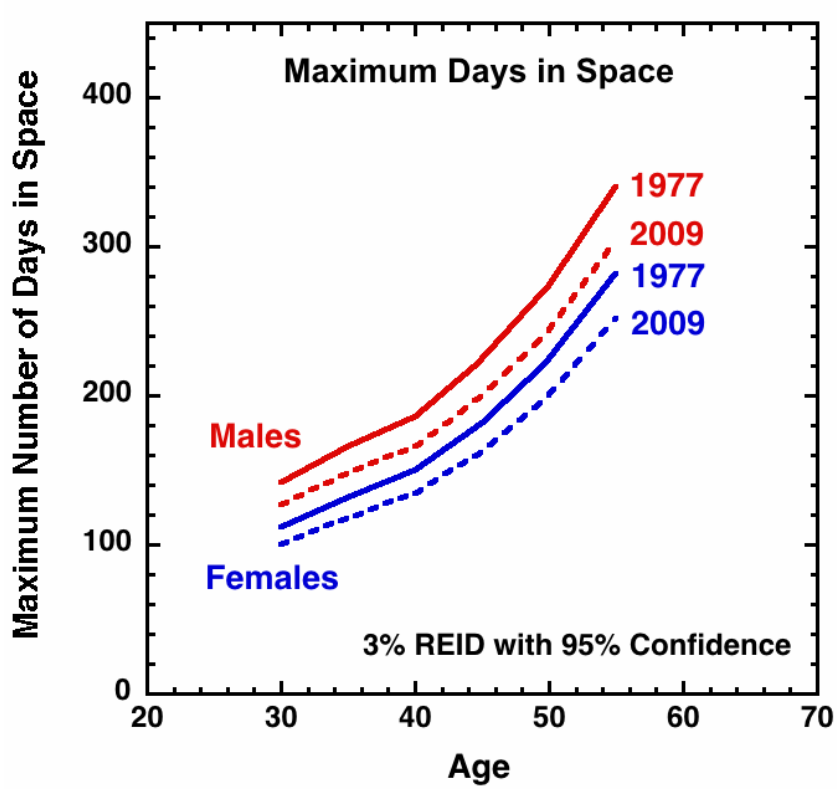
**Comparisons of Voyager-1 Interstellar Spectra with ACE spectra during the highest intensity period of the Space era (late 2009; see Mewaldt et al. 2010). Note that Oxygen inside the heliosphere has contributions from anomalous cosmic rays below ~40 MeV/nuc.**



**The 2009 intensities reduced the maximum time in space by ~10%**
**(Based on the increased fluence >100 MeV/nuc)**



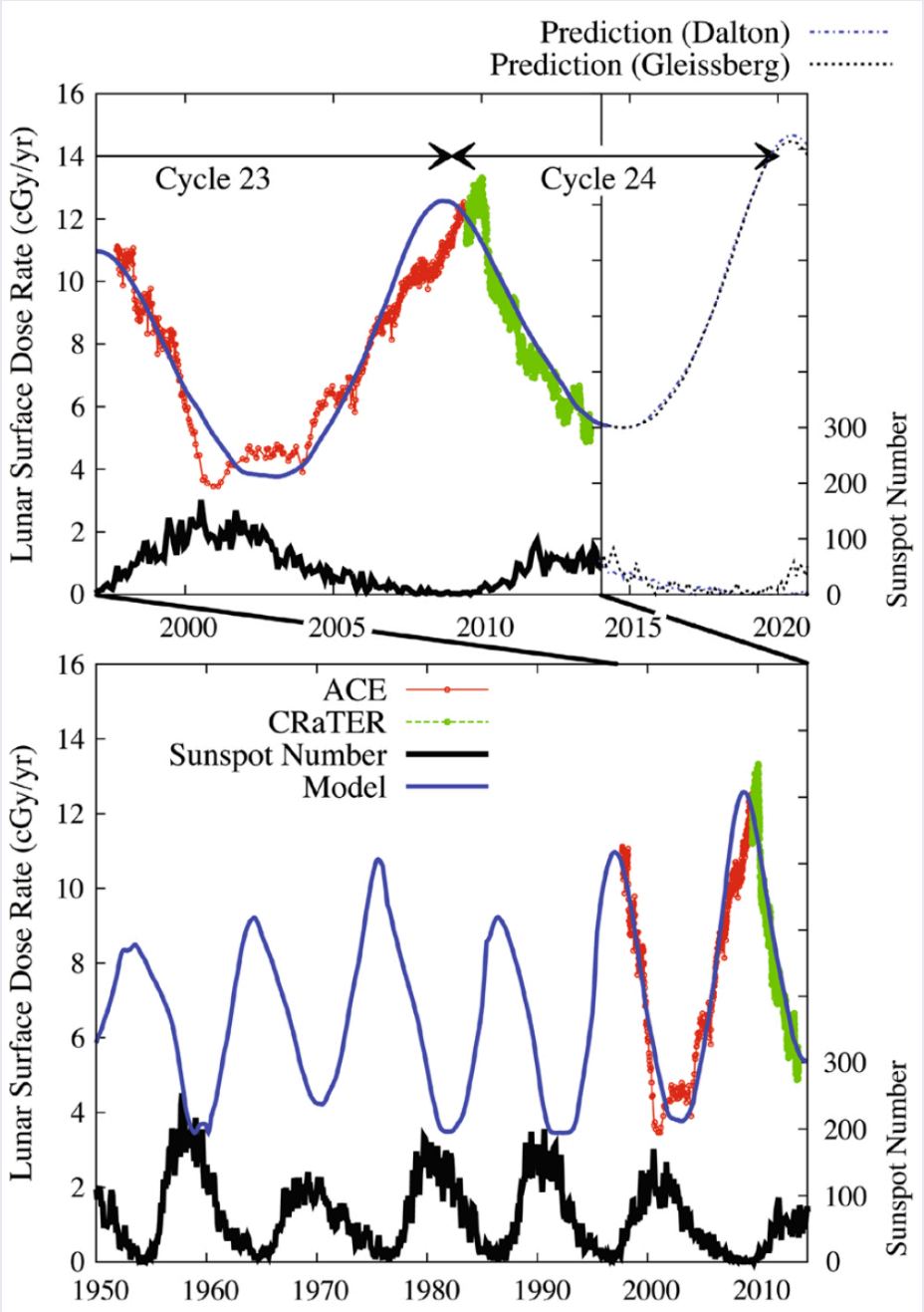

**Based on "Managing Space Radiation Exposure in the New Era of Space Exploration"**
**NAS/NRC 2008**

**Mewaldt et al. 2010**

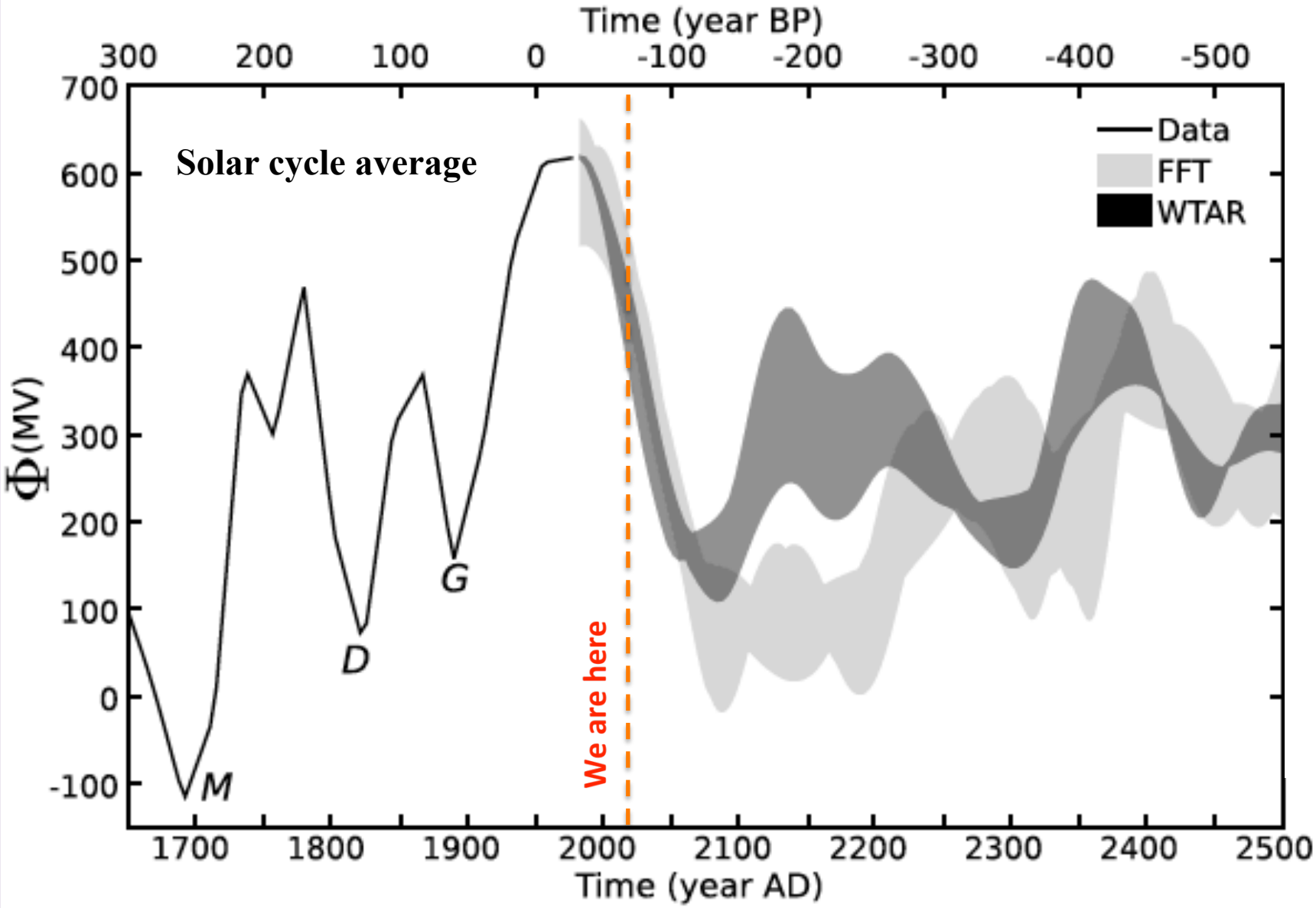
## Possible Radiation Dose Increases in Gleisberg or Dalton-like Solar Minima

**Schwadron et al. (2017) estimate that the lunar surface dose rate increased by ~12% in going from 1997 to 2009 conditions.**

**If we enter Gleisberg or Dalton-like minima conditions the increased Dose rate from 1997 would be ~32%.**



STEINHILBER AND BEER: PREDICTION OF SOLAR ACTIVITY (2013)



# Summary

**The C-14 and Be-10 records show that cosmic ray intensities were often considerably higher than during the space era.**

**Although the space age is only ~60+ years old, we are finding that cosmic-ray intensities are trending to higher levels in the cycle 23 and 24 minima.**

**The most important influence on cosmic ray intensities is the interplanetary magnetic field strength, which is depends on the Sun's polar fields.**

**Other key properties include the tilt of the current sheet, the CME rate, and solar wind turbulence.**

**If we enter Gleisberg or Dalton minima conditions, the radiation dose in local interplanetary space will increase by ~30% or more.**