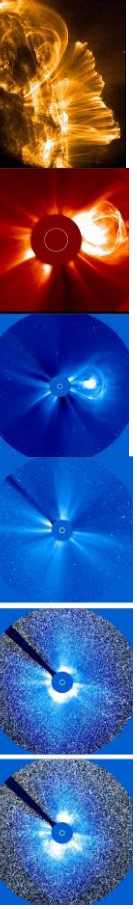
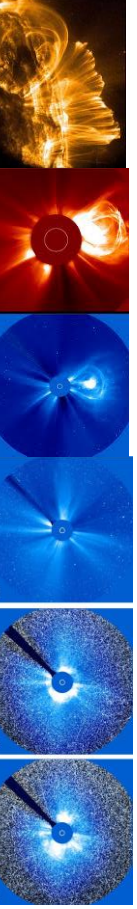


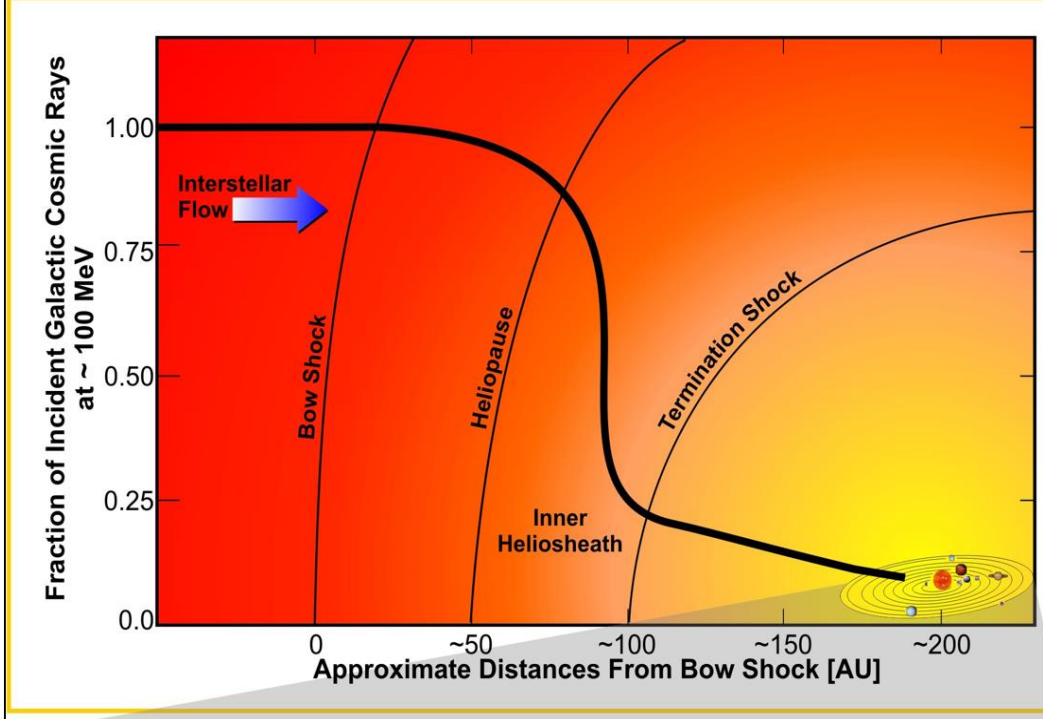
Update on the Worsening Particle Radiation Environment Observed by CRaTER

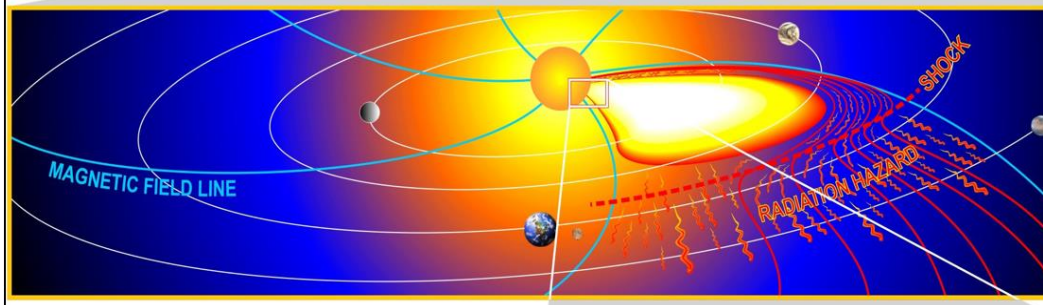
N A Schwadron, F Rahmanifard, J. Wilson, A P Jordan, H E Spence, C J Joyce, J B Blake, A W Case, W d Wet, W M Farrell, J C Kasper, M D Looper, N Lugaz, L Mays, J E Mazur, J Niehof, N Petro, C W Smith, L W Townsend, R Winslow and C Zeitlin

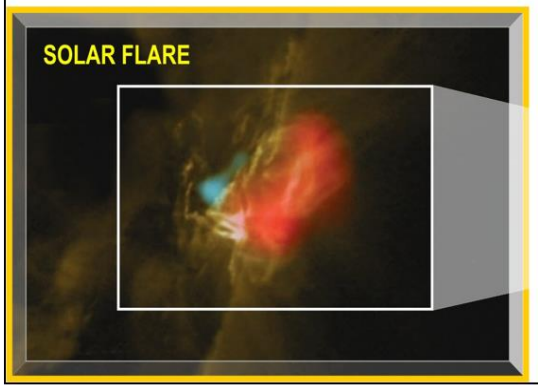


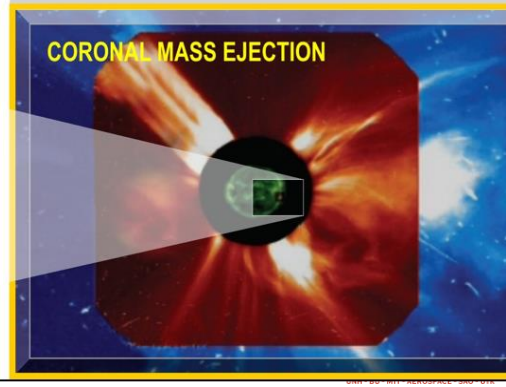
Radiation Hazards, Interactions

- Galactic Cosmic Rays (GCRs)
  - Steady Background
  - Career limit in ~ 1-3 years
- Solar Energetic Particles (SEPs)
  - Acute Sources
  - ESPs versus impulsive component
  - Time-dependent response

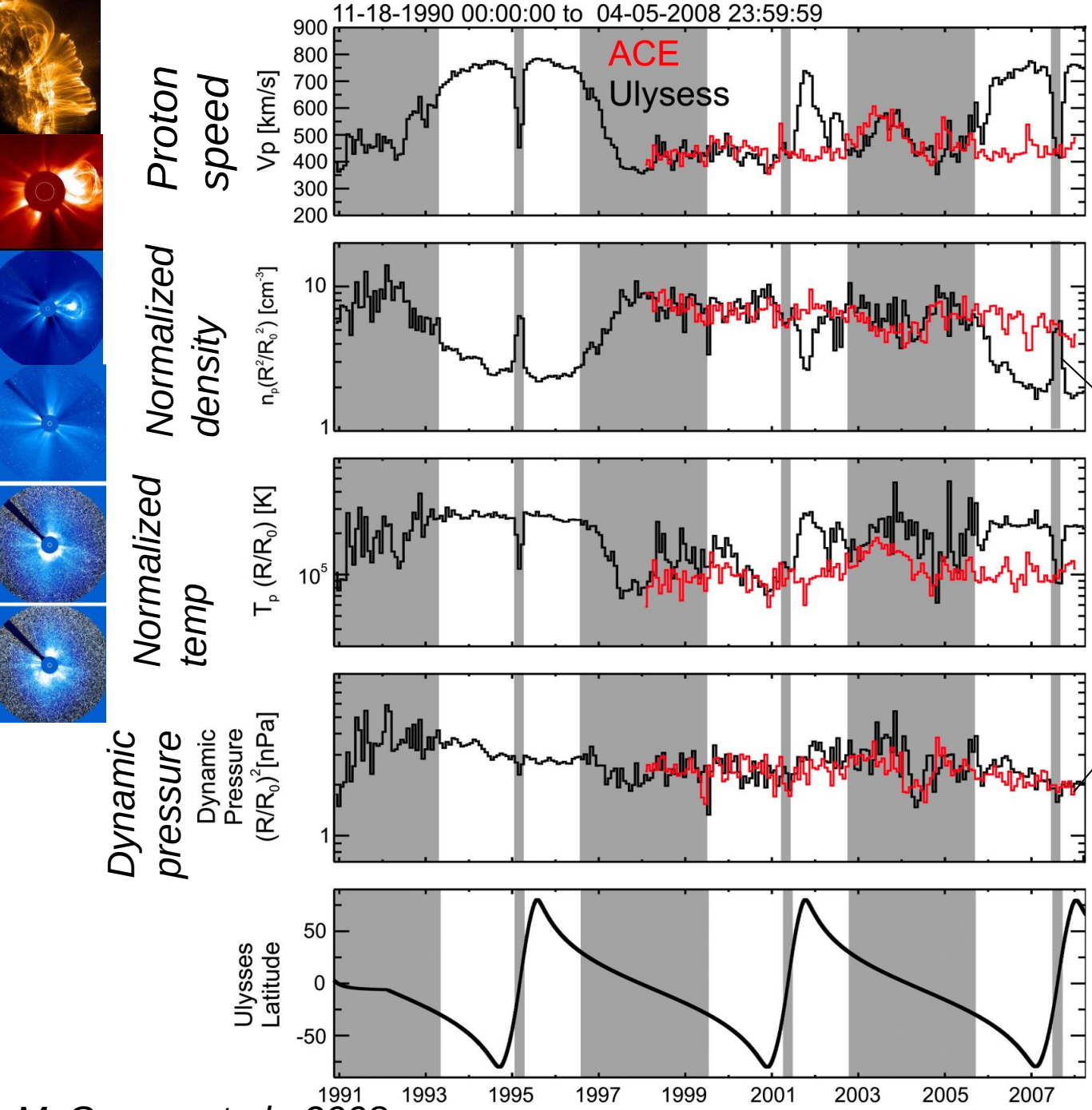






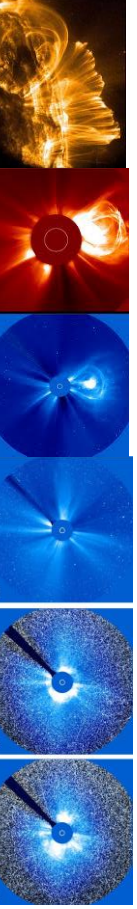


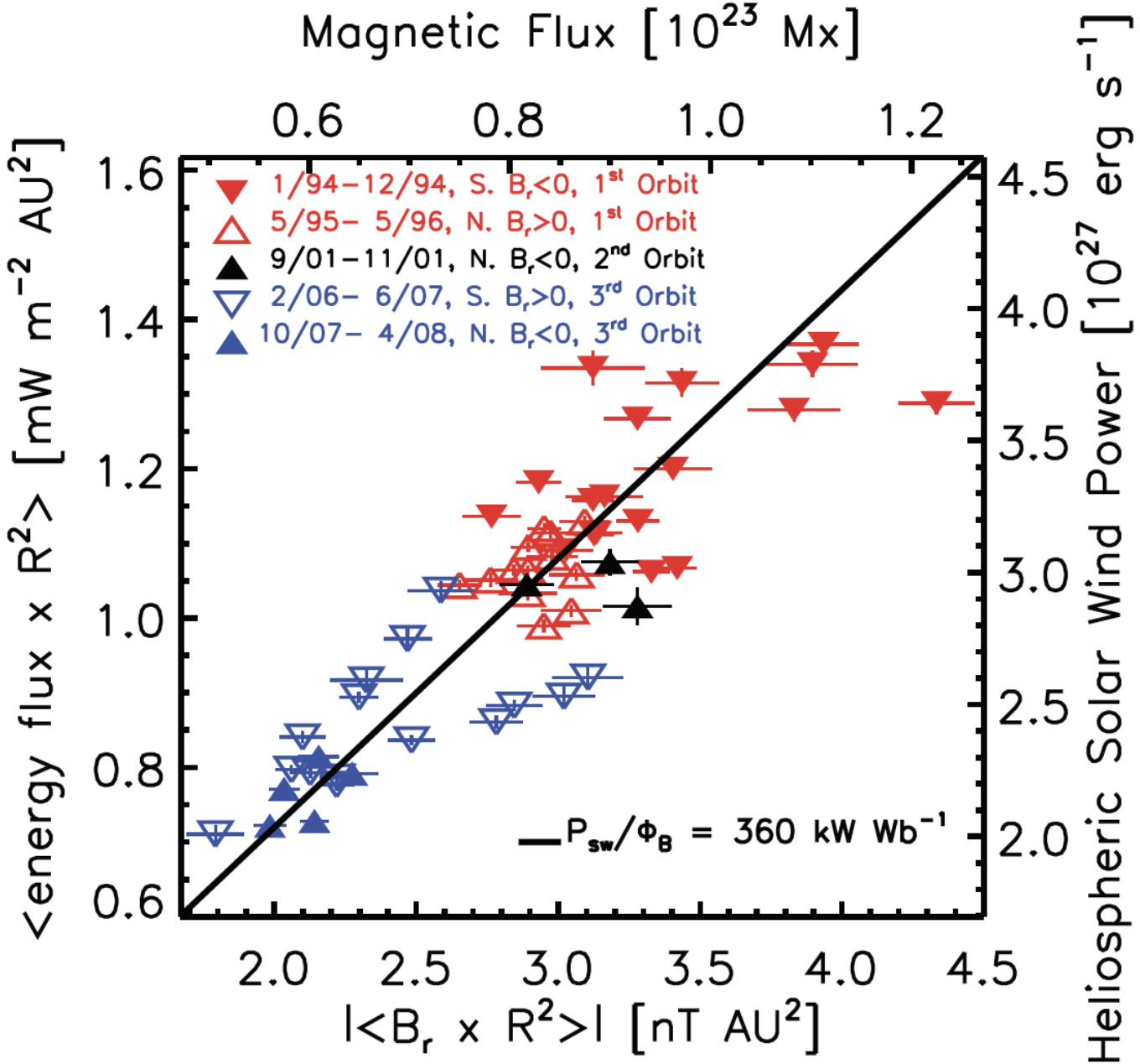
ACE & Ulysses Comp.



Reduced Density and Dynamic Pressure

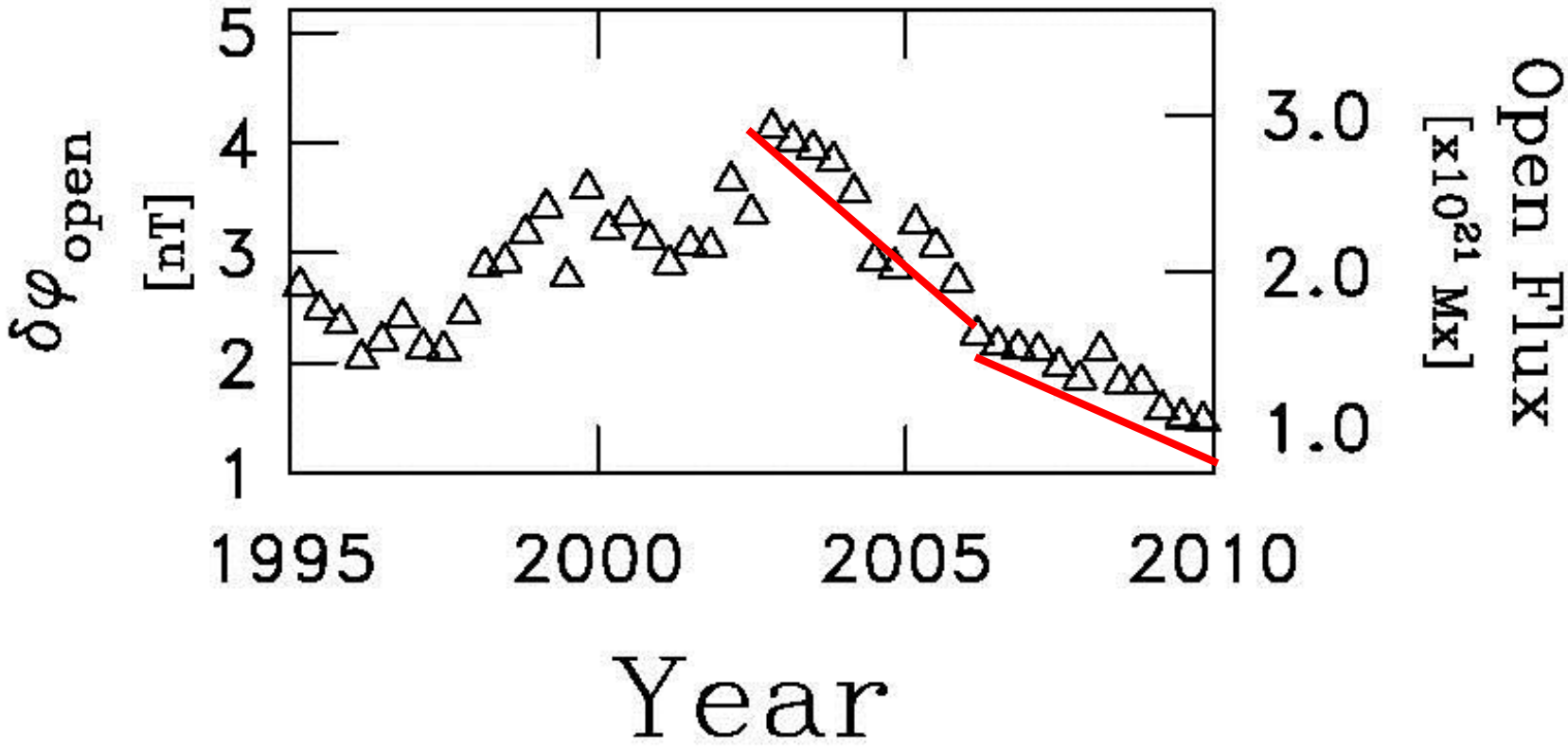
McComas et al., 2008





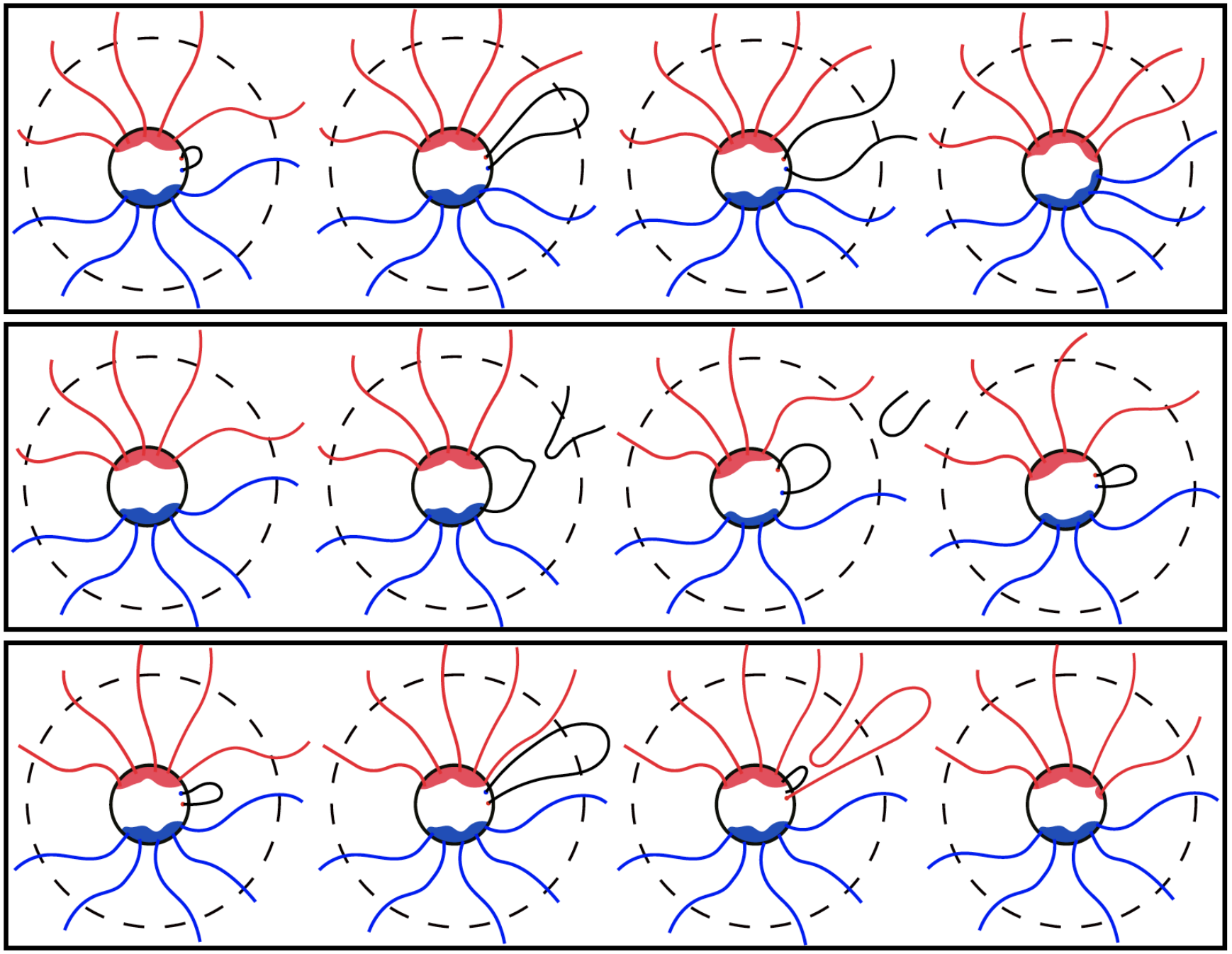
Schwadron and McComas, 2008

Open Flux Depletion



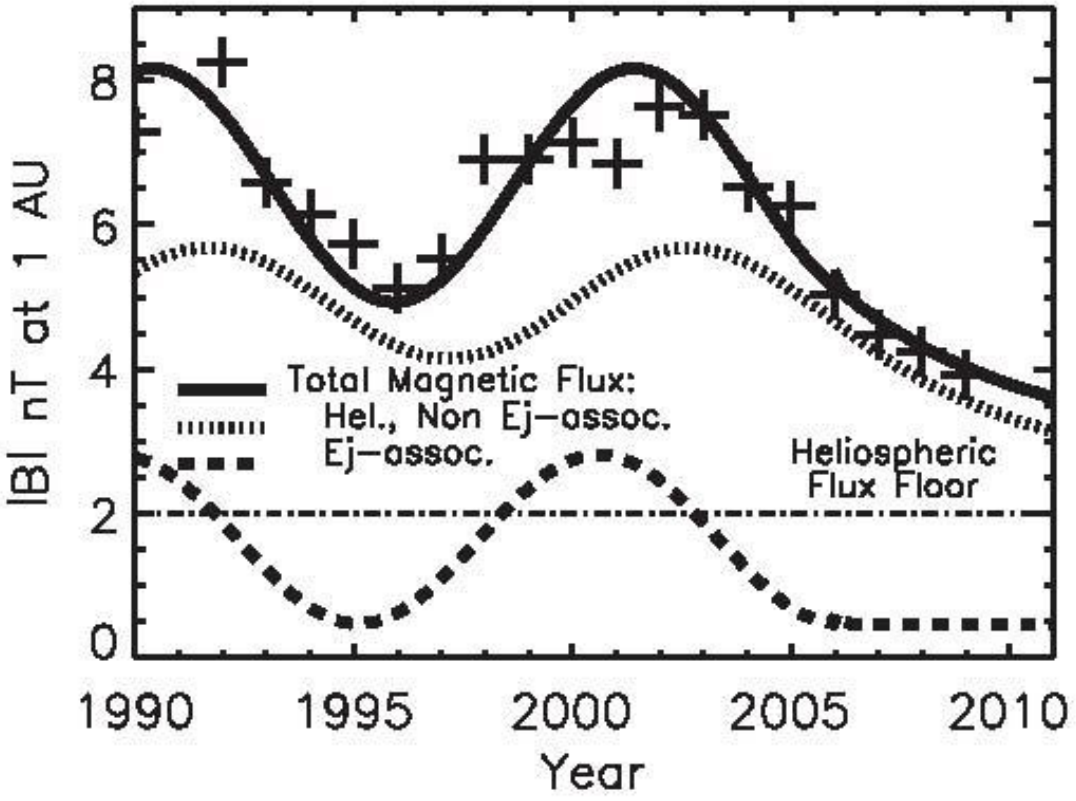
There is a 2-phase depletion of open field lines: first during the "normal phase" of solar min when ICME activity is small, and then later when ICME activity is virtually zero.

Connick et al., Astrophys. J., 2011.



Rahmanifard et al., 2016

Integration into Heliospheric Models



$|B| = \sqrt{2}\Phi/4\pi R_1^2$ where

$R_1 = 1$ AU;

$\phi_{ICME} = 1 \times 10^{13}$ Wb;

$D = 1/2$;

$\tau_{ic} = 40$ days;

$\tau_0 = 2.5$ years;

$\tau_d = 4.4$ years;

$F_{lo} = 0.5$ day^{-1};

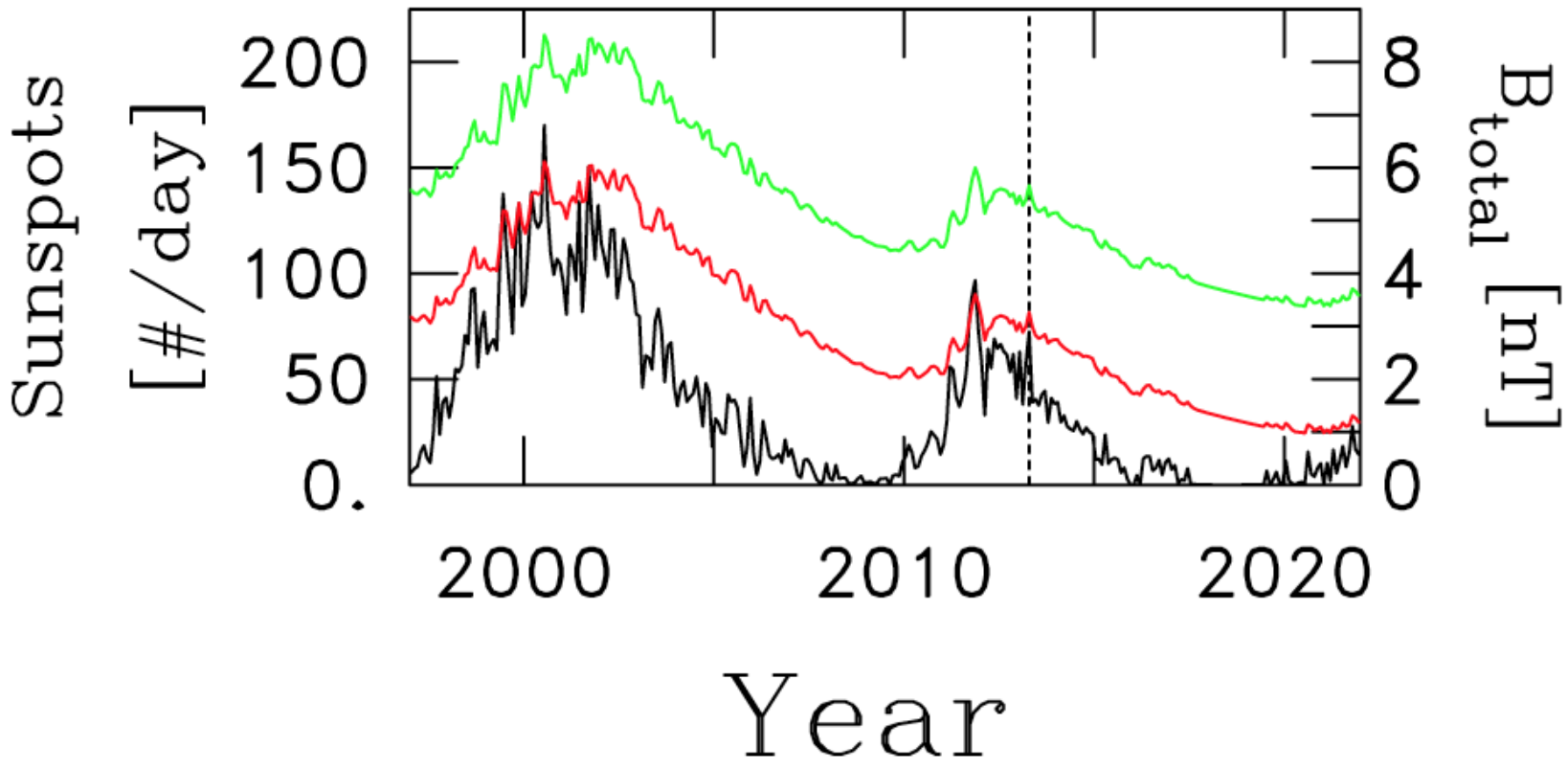
$f_{hi} = 3$ day^{-1};

$\Phi_{flr} = 4 \times 10^{14}$ Wb ($|B| = 2$ nT).

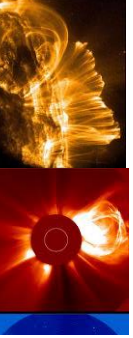
More recent theoretical coniderations are predicting a lower flux floor.

*Schwadron et al., Astrophys. J. Lett., **722**, L132, 2010.*

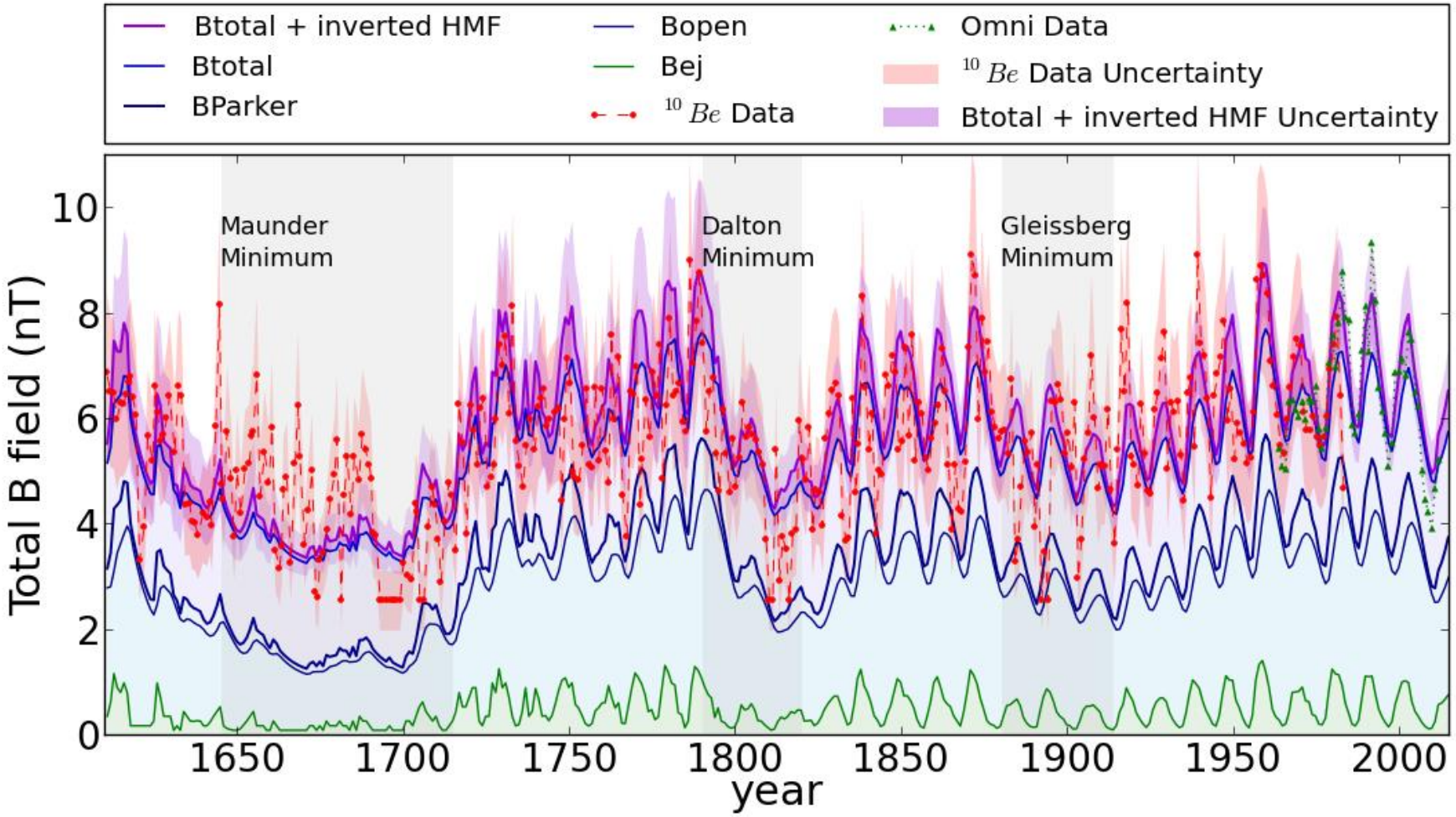
Continued Decay of Magnetic Flux in the Dalton-like Minimum



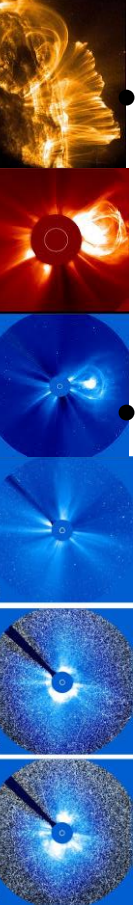
Goelzer et al., ApJ, 2013



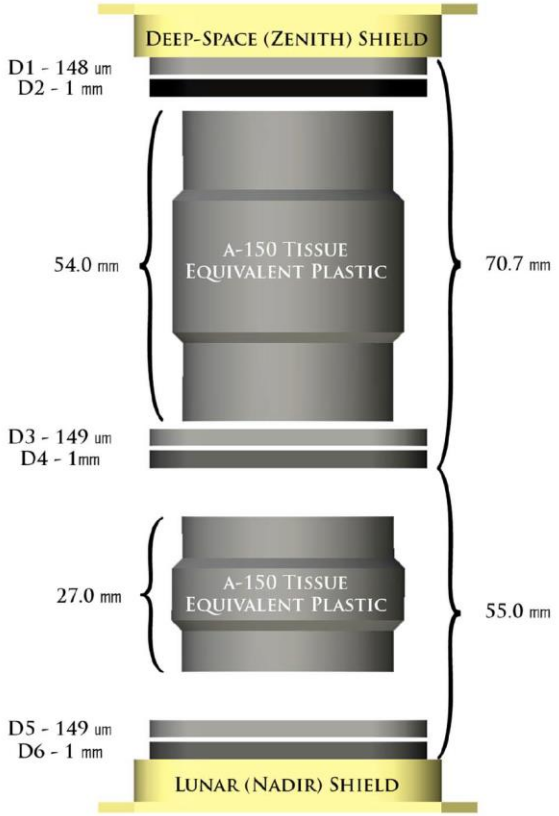
Strong Reduction in Field Possible – Much Higher GCR Flux

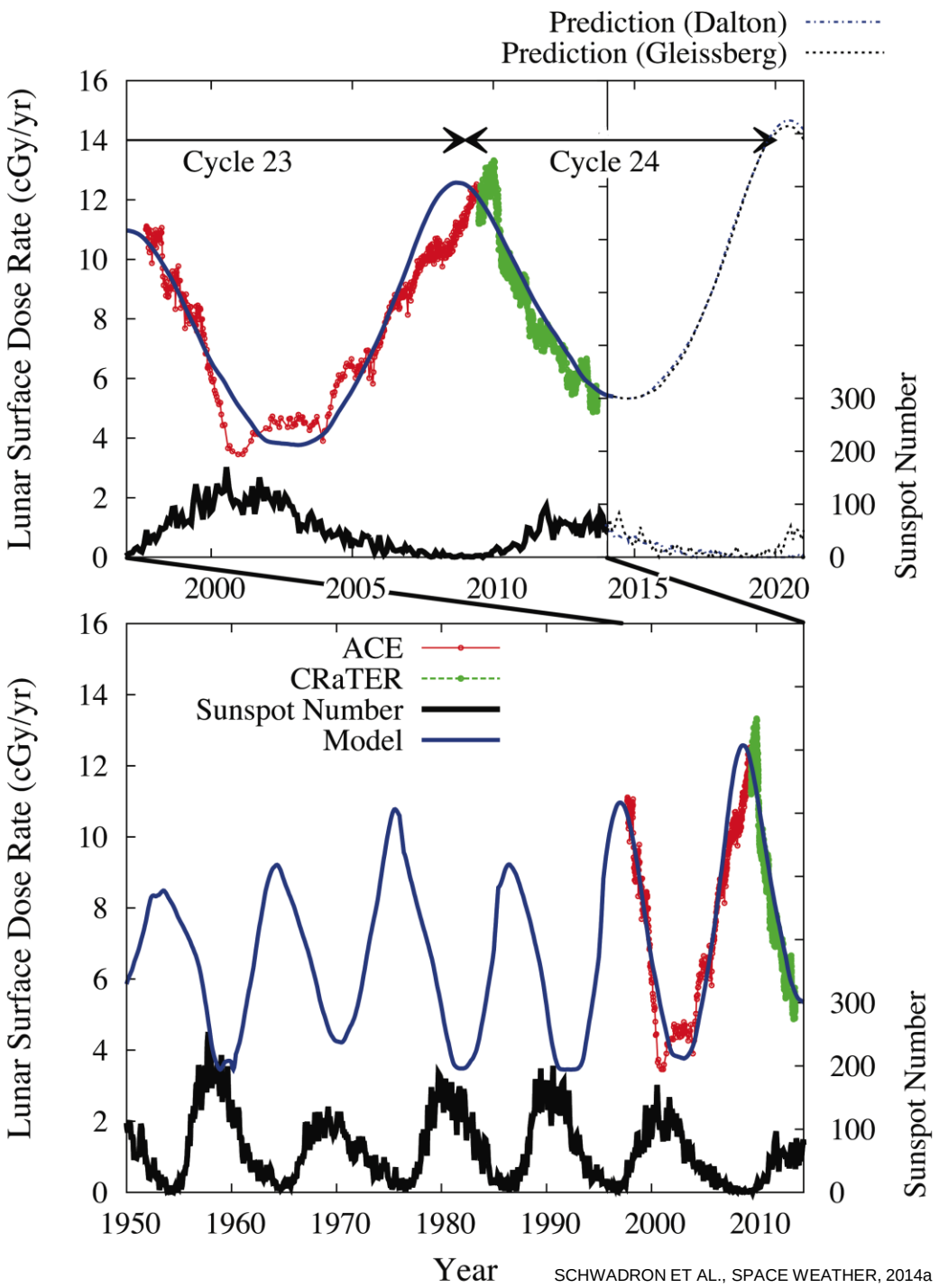


Rahmanifard et al., 2016

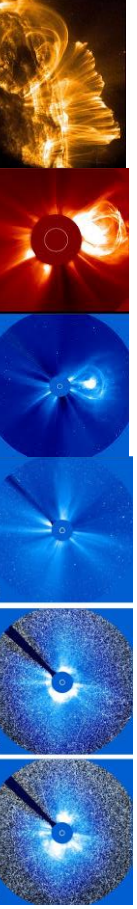


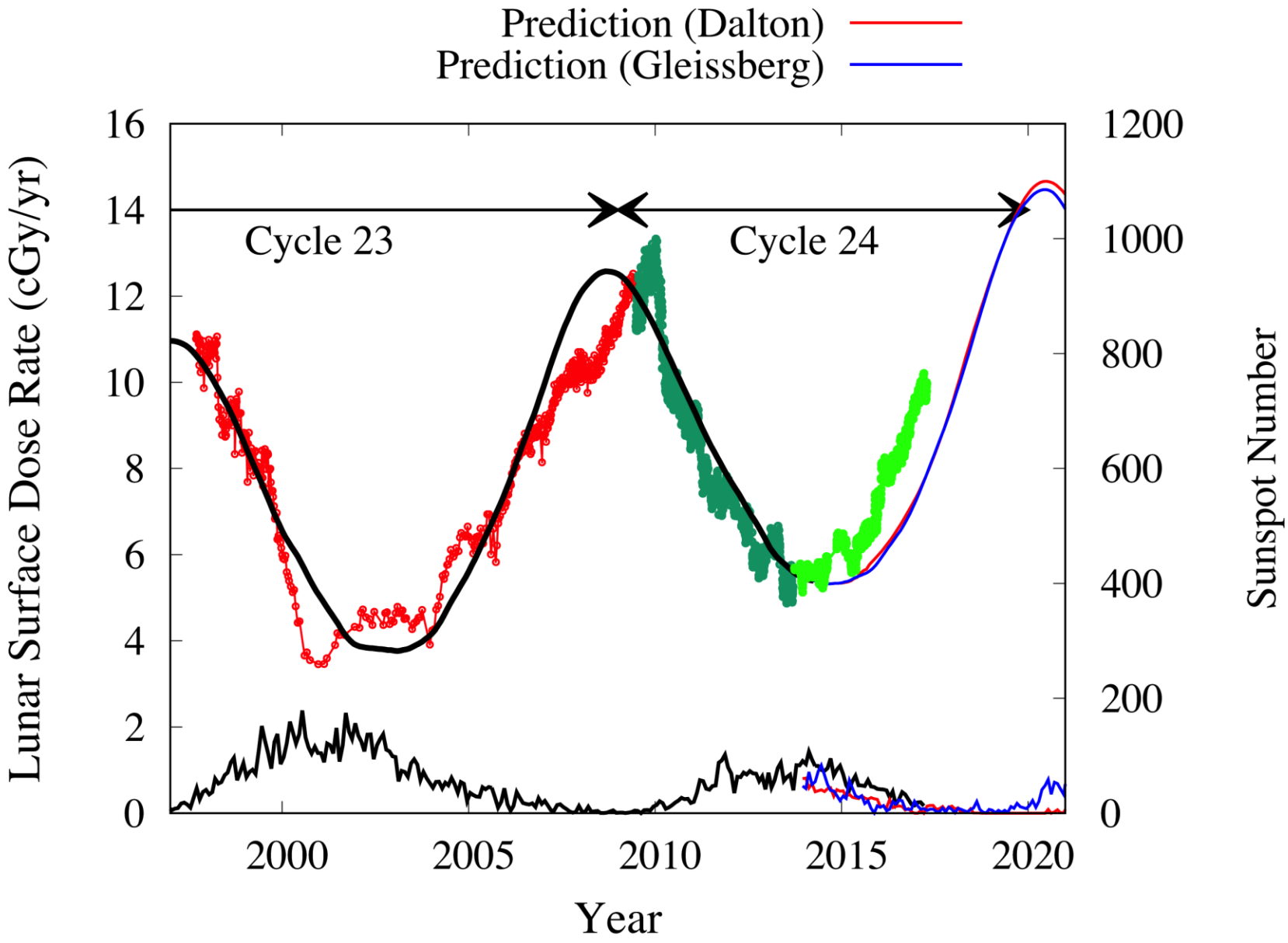
- Highest GCR doses in space age in recent cycle 23 solar minima
- Continues trend observed by Ulysses, ACE

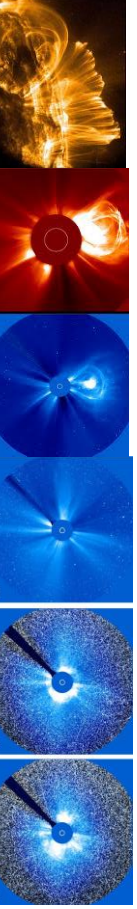


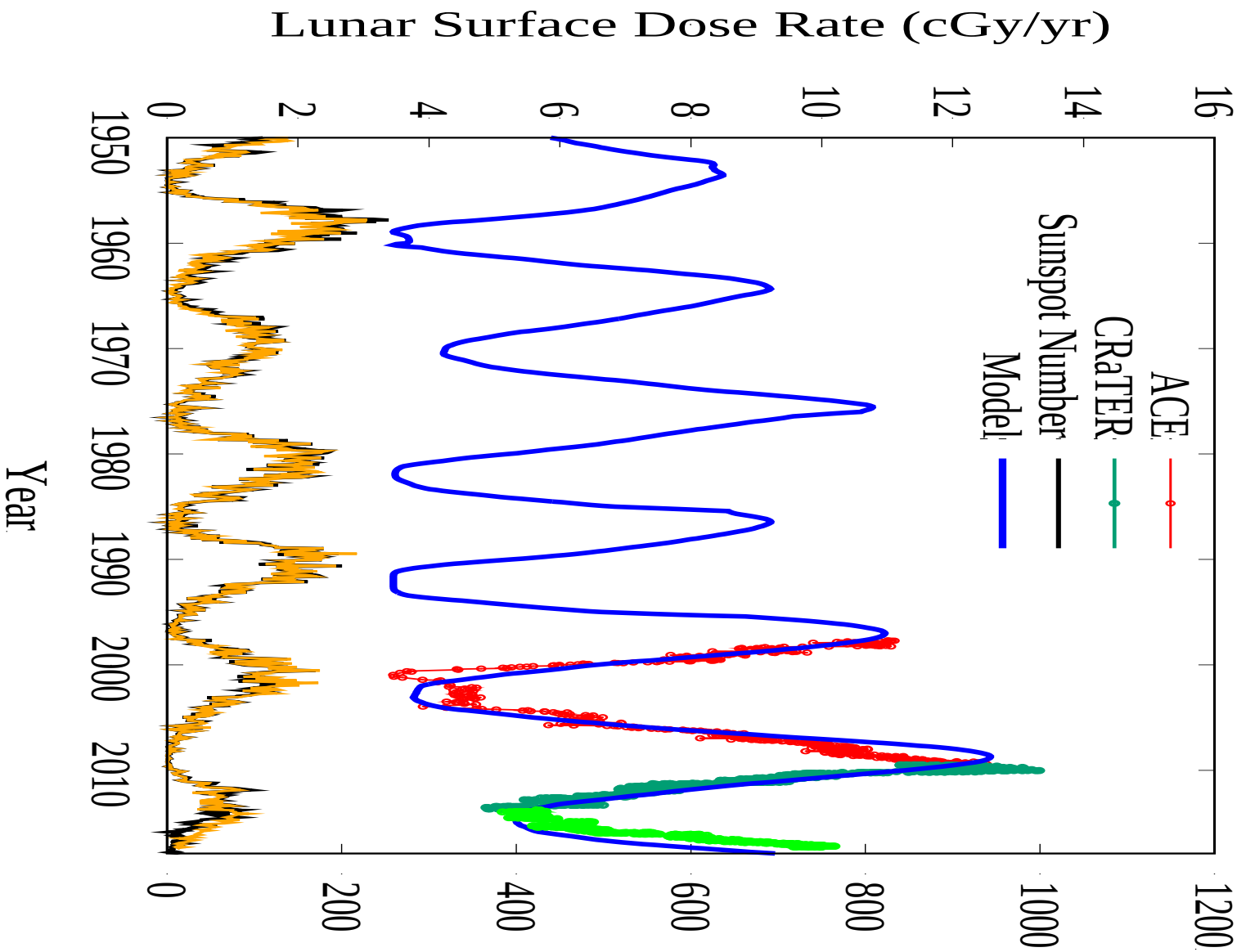


SCHWADRON ET AL., SPACE WEATHER, 2014a




Prediction (Dalton)
Prediction (Gleissberg)
Cycle 23
Cycle 24
Lunar Surface Dose Rate (cGy/yr)
Sunspot Number
Year
0
2
4
6
8
10
12
14
16
0
200
400
600
800
1000
1200
2000
2005
2010
2015
2020





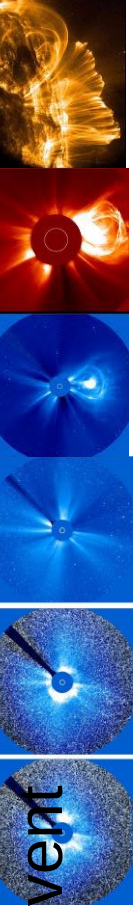
Schwadron et al., Space Weather, 2017

Solar Proton Model Prediction/Validation

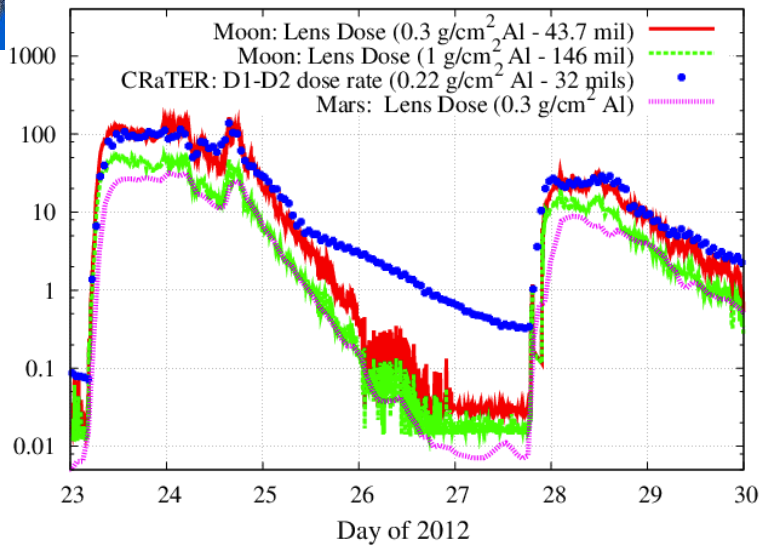
After Schwadron et al., 2012

SEP Events During 2012: Indicators of Larger SEP Events in the New Cycle (24)

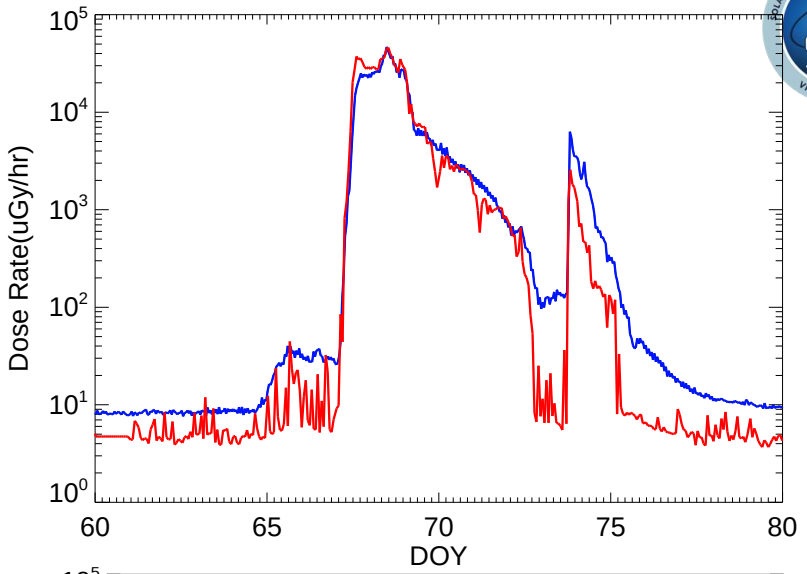
- Shown here are the major SEP events of 2012 and the comparisons between CRaTER observations (blue) and prediccs predictions (red and green).
- Agreement reveals overall accuracy of models, while deviations likely reveal heavy ion contributions to dose observed by CRaTER



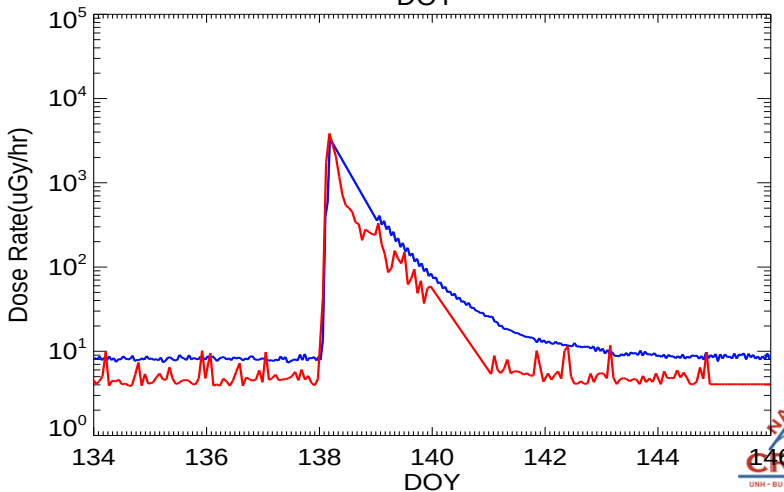
Jan. 23rd, 2012 Event



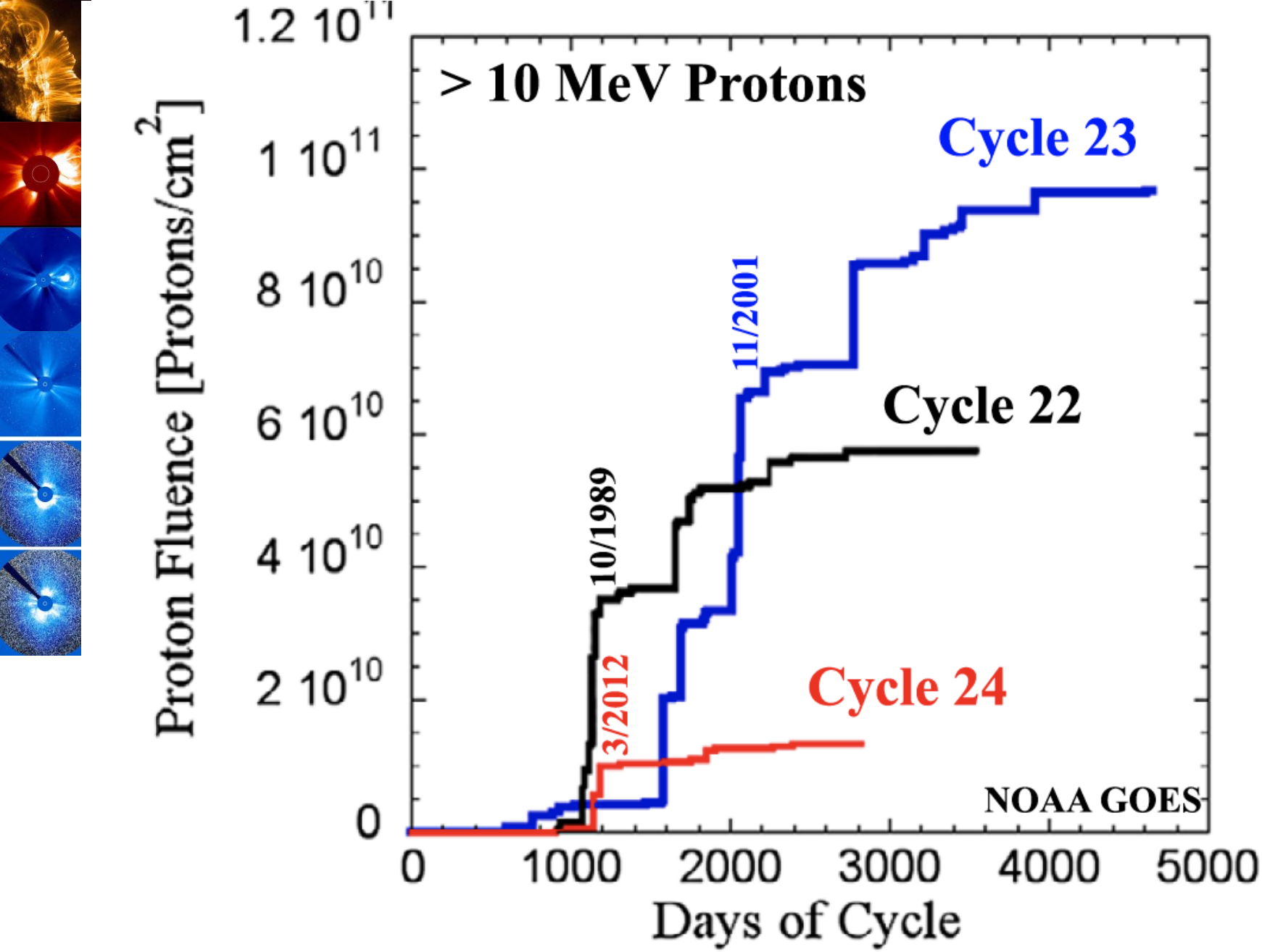
CRaTER (blue) EMMREM (red)



Mar 7, 2012 Event

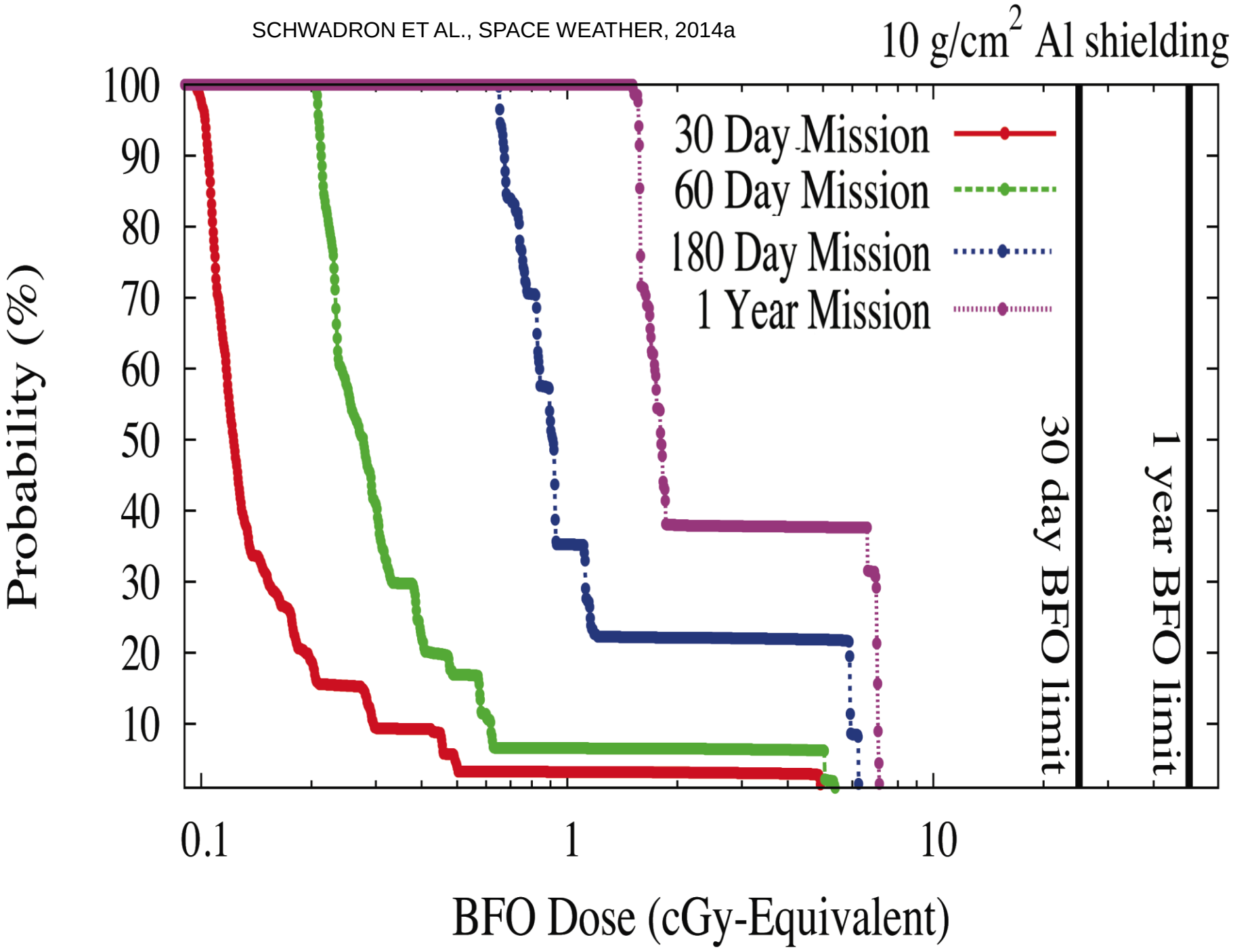


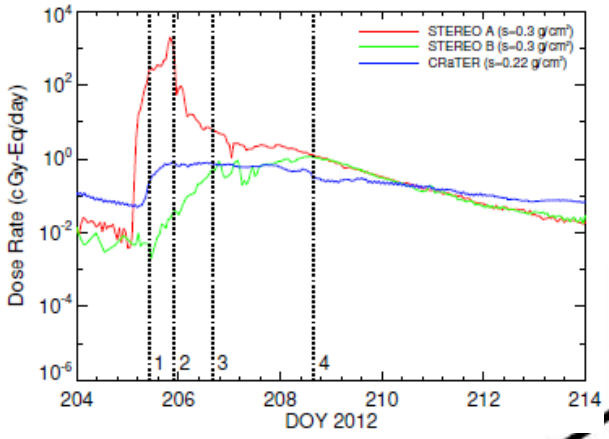
May 16, 2012 Event

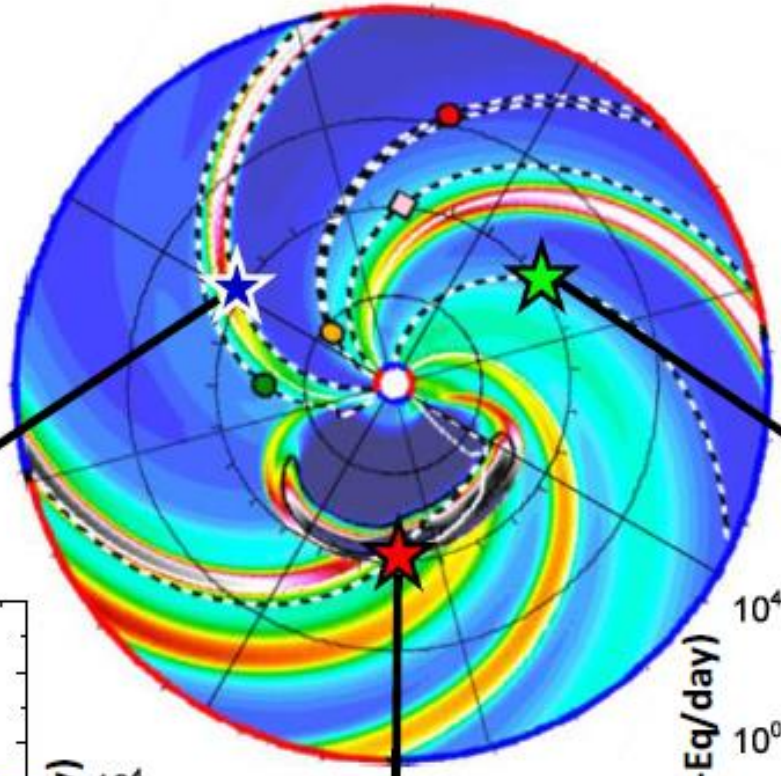


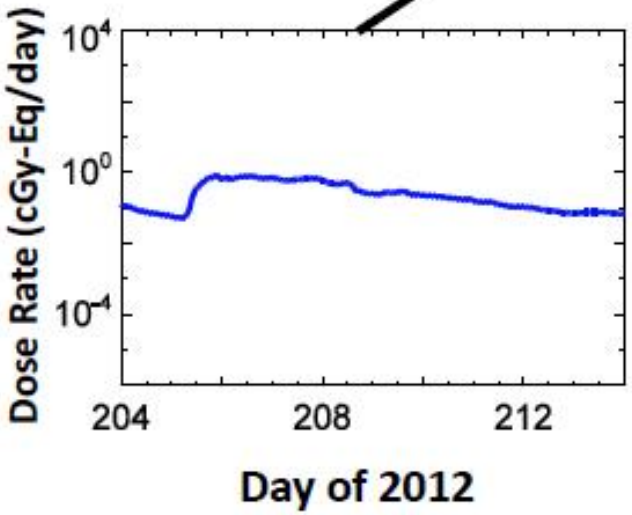
MeWaldt et al., 2015 *Schwadron et al., 2017*

SCHWADRON ET AL., SPACE WEATHER, 2014a

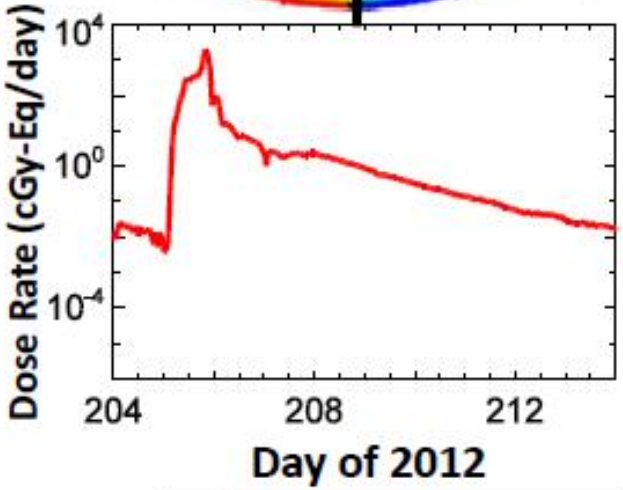




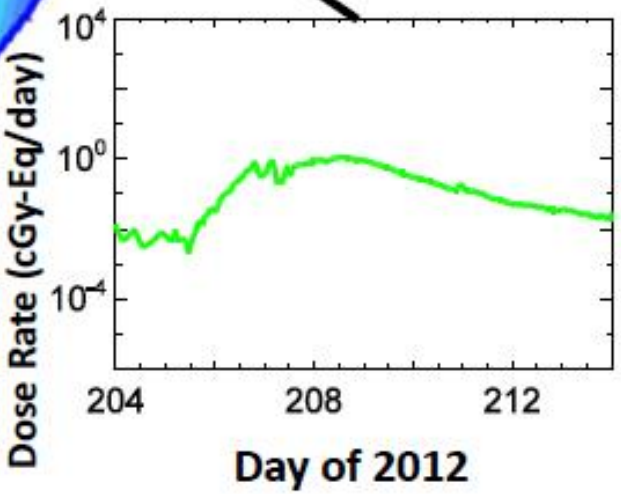




CRaTER

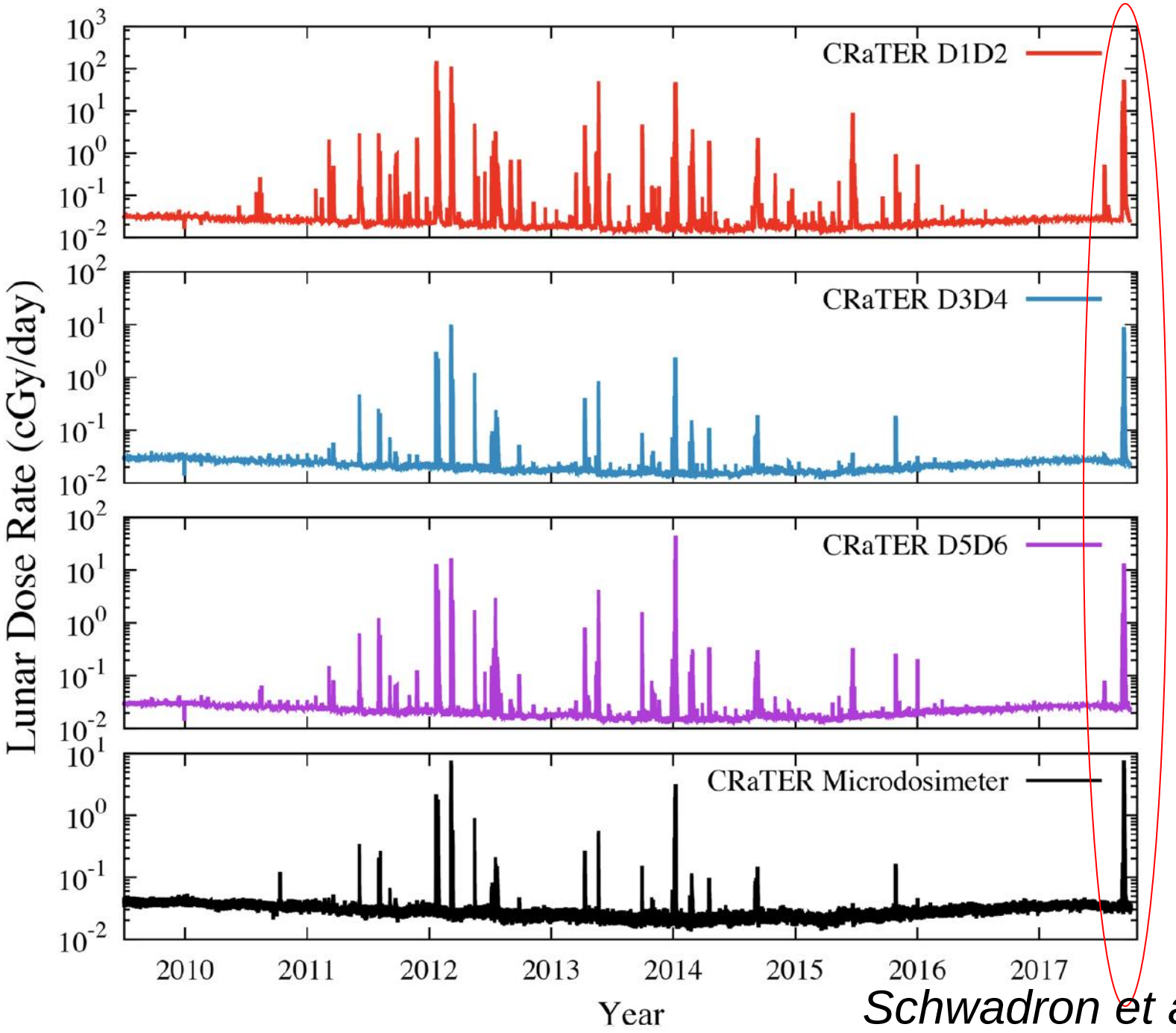


STEREO A

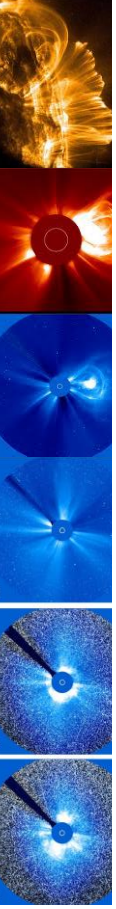


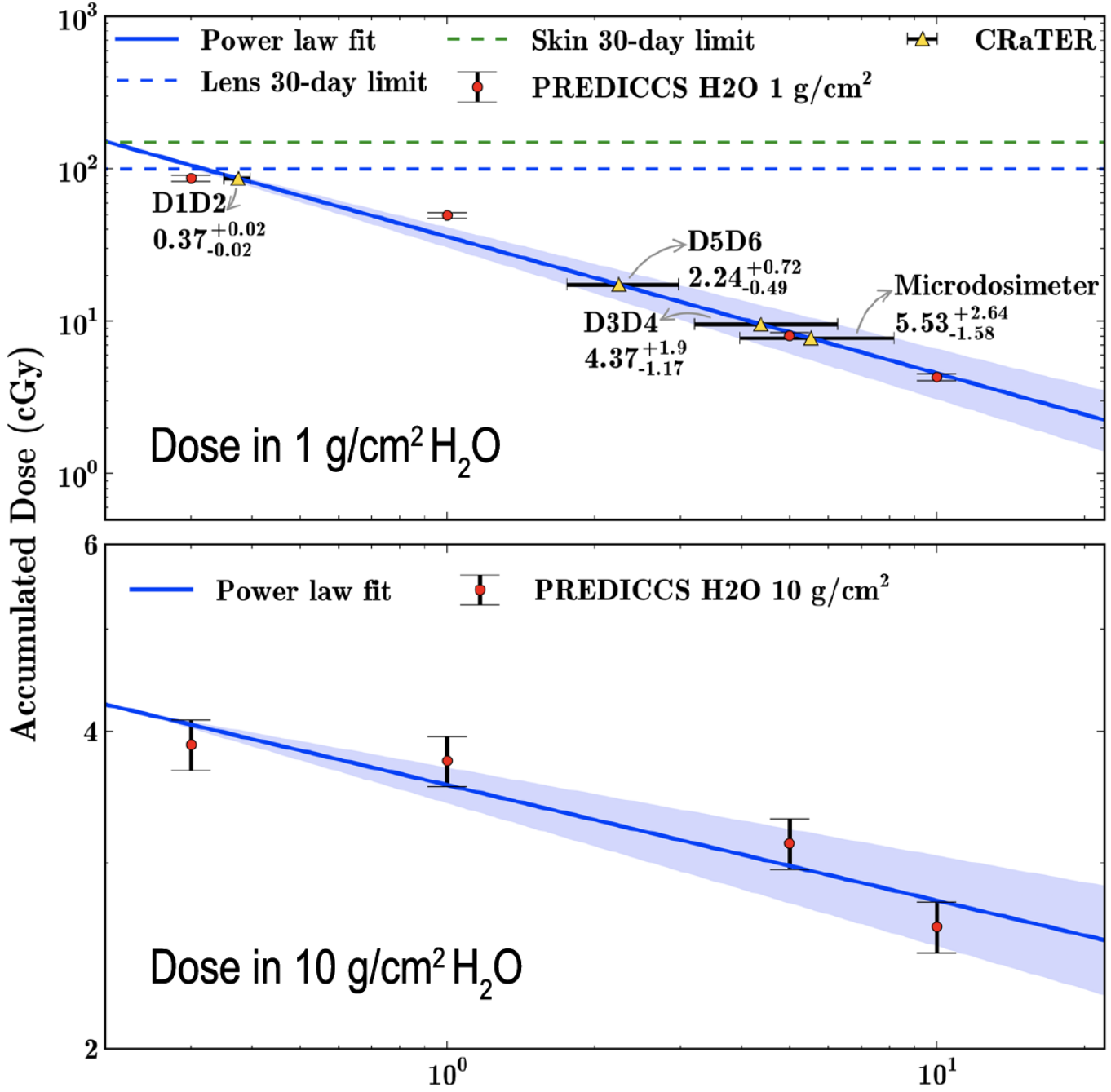
STEREO B

Joyce et al., 2015

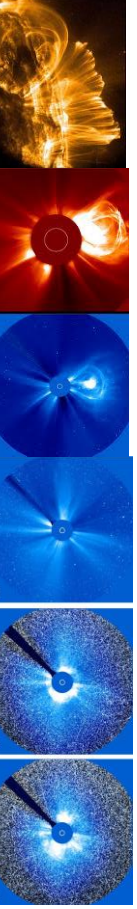


Schwadron et al., 2017

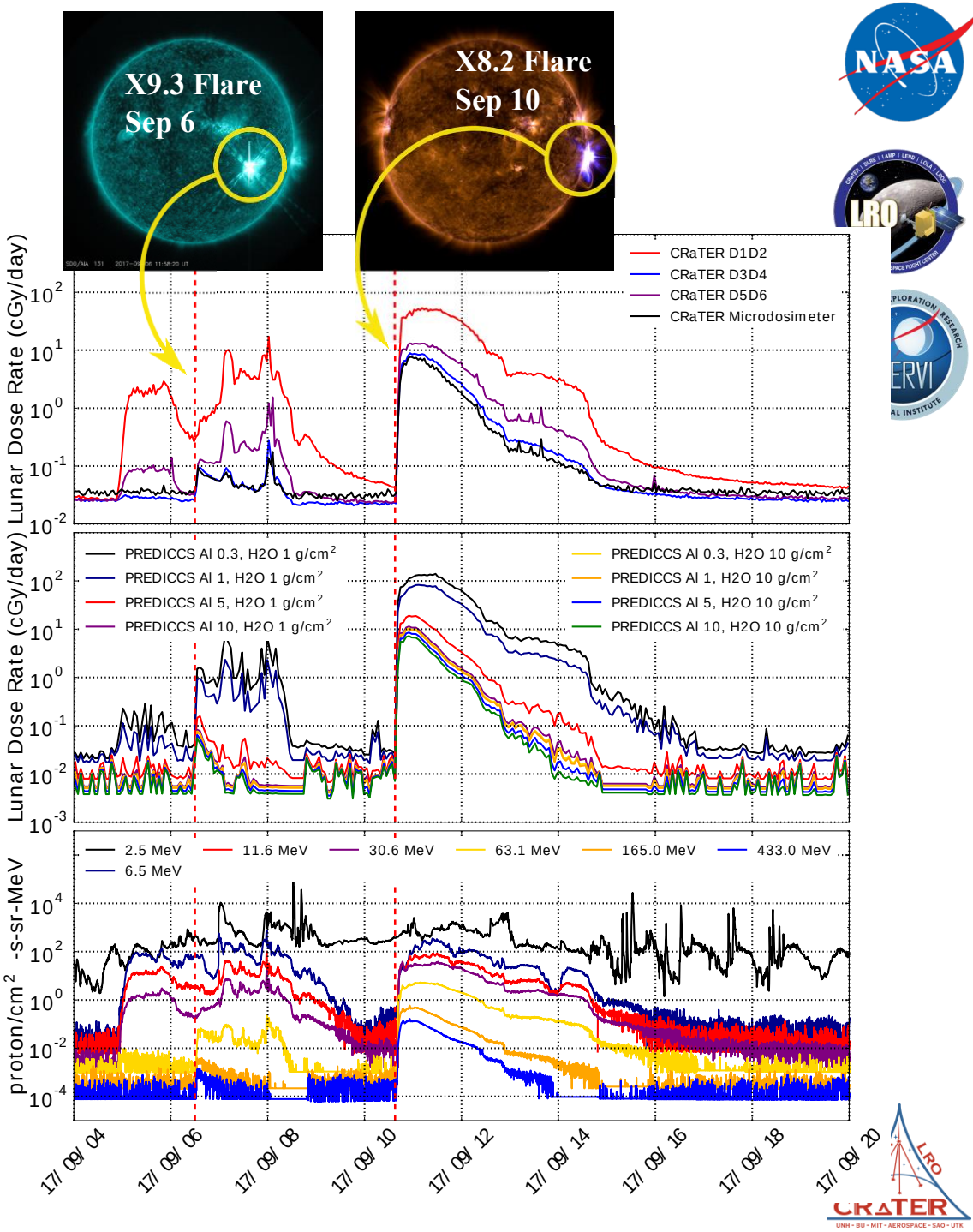




Schwadron et al., 2017



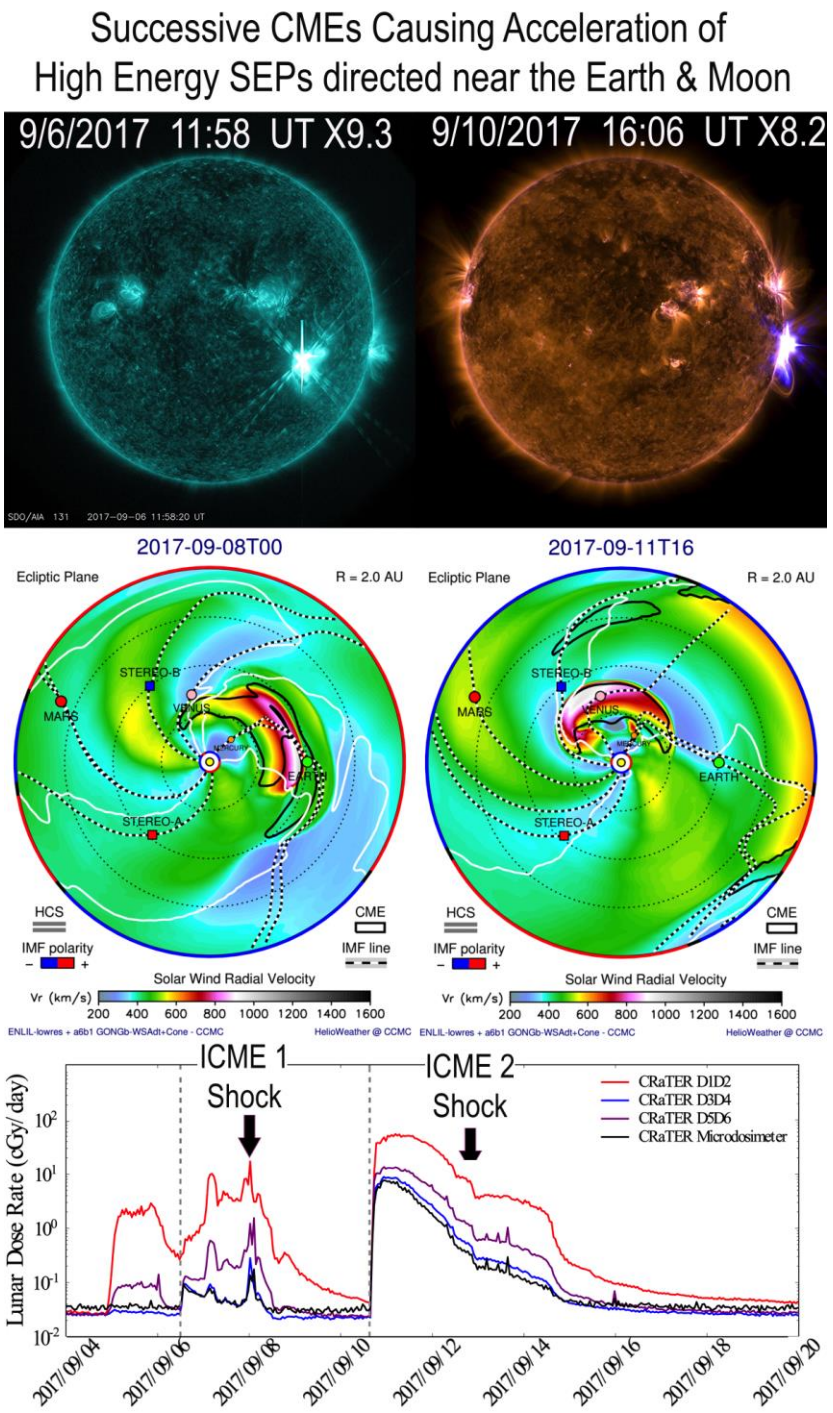
- Example of a large event during decline of cycle 24
- Note importance of seed population

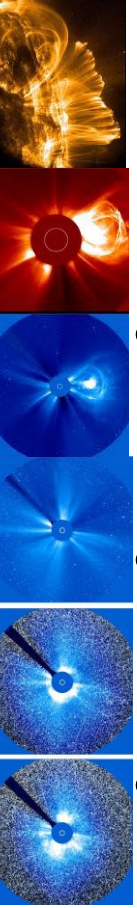


Schwadron et al., 2017

- First event had clear shock, and ESP
- Second event shows prompt acceleration

Schwadron et al., 2017





Conclusions

- Radiation levels continue to increase due to weakening solar activity
- Dose rates even higher than predicted in 2014
- Large events (Sep 2017) in decline of cycle 24 indicate that weak activity does not exclude large SEP events
- Overall, SEP event probabilities still quite low during cycle 24