Cosmic Ray Pitch Angle Anisotropies in the Very Local Interstellar Medium

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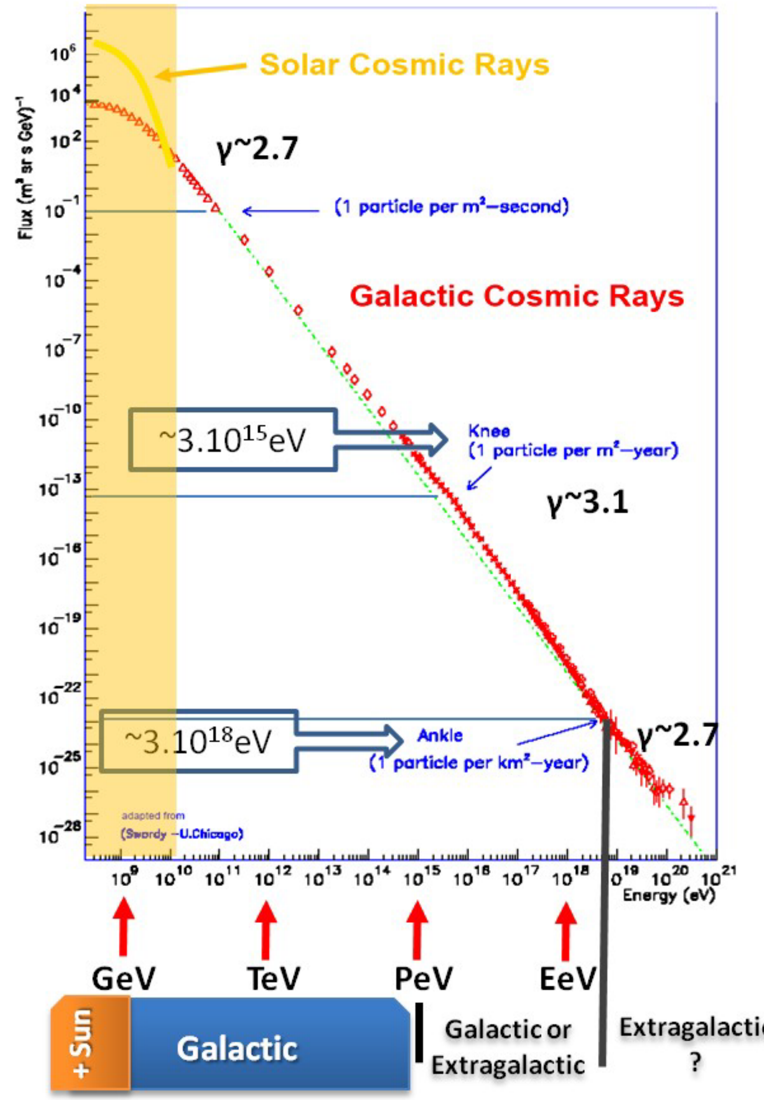
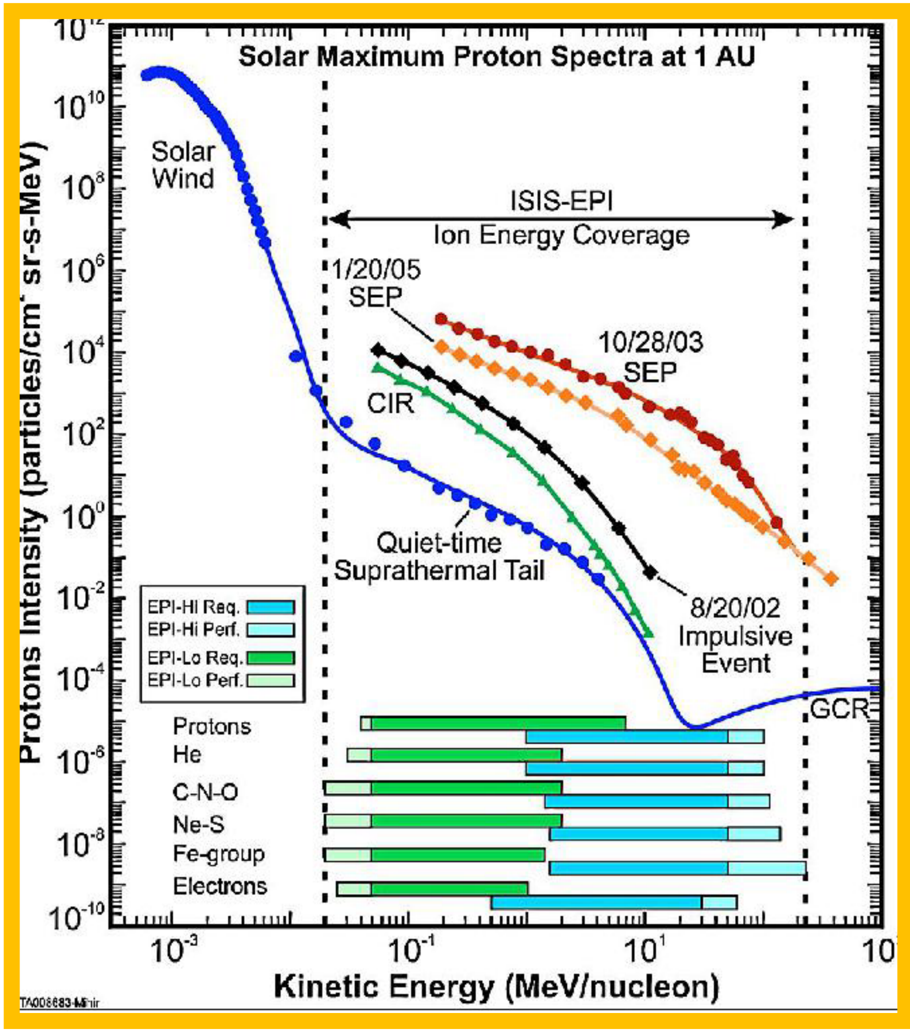
Cosmic Ray Anisotropy Workshop: Layola University, Chicago – May 16-19, 2023

Cosmic Rays at which Energy?

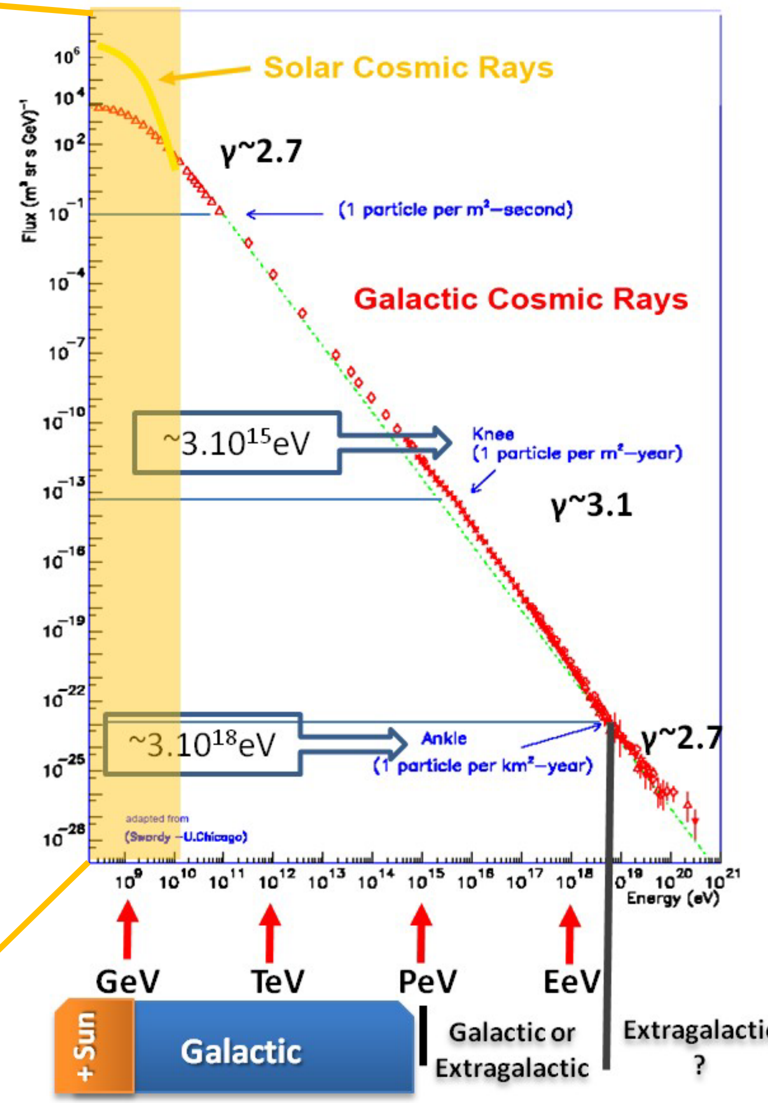


https://blogs.egu.eu/divisions/st/2018/03/19/cosmic-rays-messengers-from-space/

Cosmic Rays at which Energy?

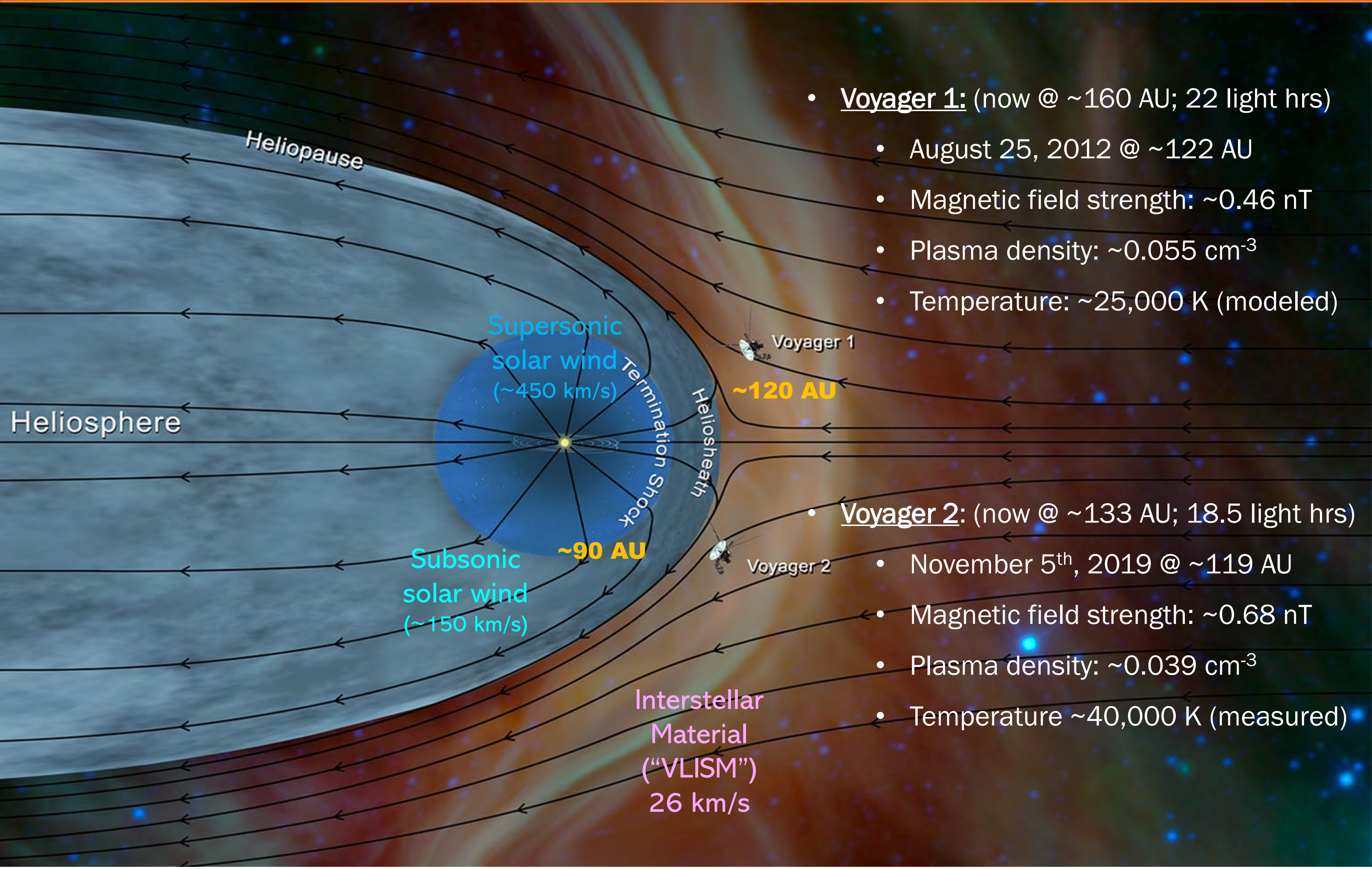


McComas et al. 2014, SSRv, 204:187



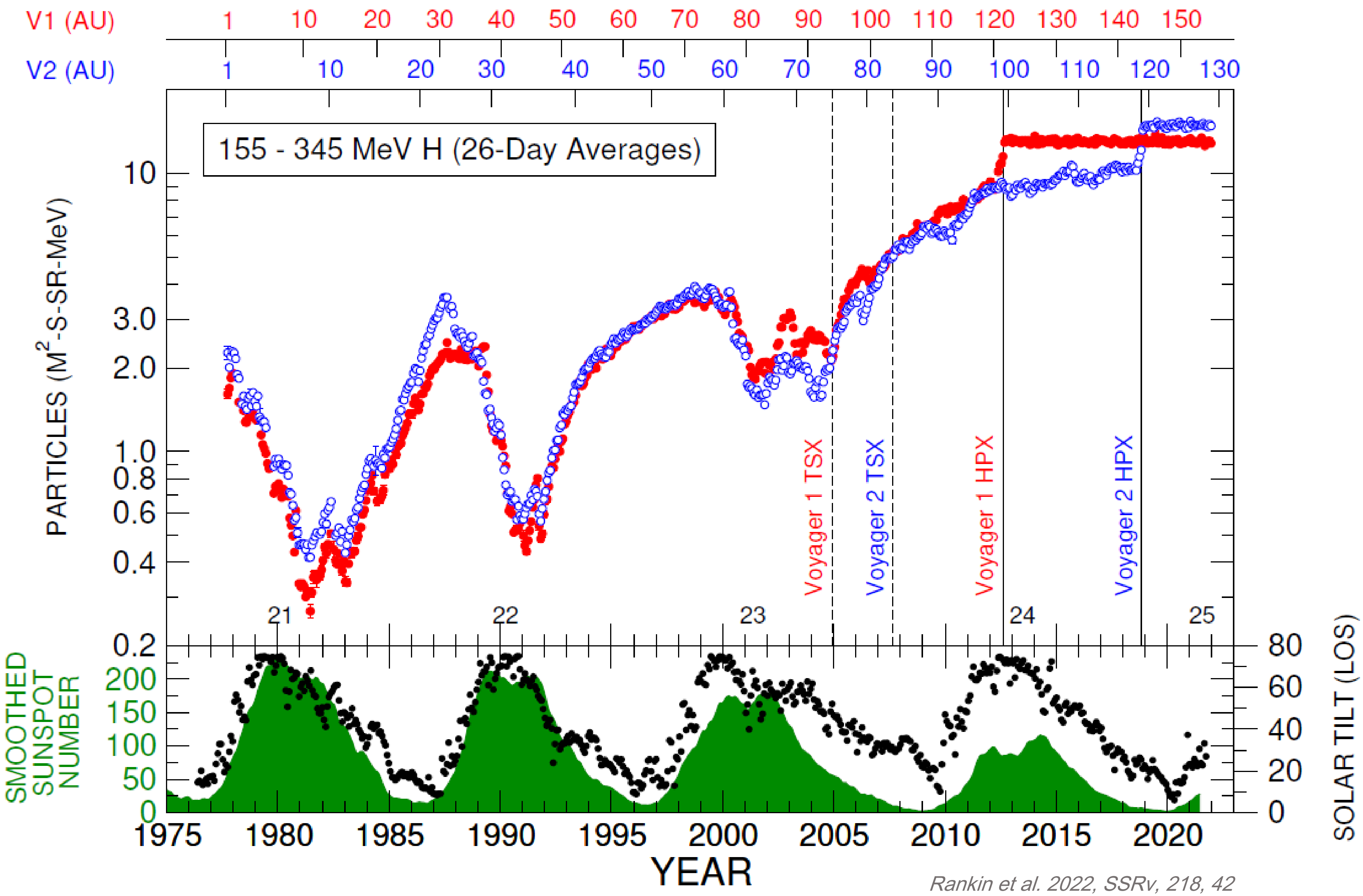
https://blogs.egu.eu/divisions/st/2018/03/19/cosmic-rays-messengers-from-space/

Voyager Interstellar Mission



- <u>Voyager 1:</u> (now @ ~160 AU; 22 light hrs)
  - August 25, 2012 @ ~122 AU
  - Magnetic field strength: ~0.46 nT
  - Plasma density: ~0.055 cm^{-3}
  - Temperature: ~25,000 K (modeled)
- <u>Voyager 2</u>: (now @ ~133 AU; 18.5 light hrs)
  - November 5th, 2019 @ ~119 AU
  - Magnetic field strength: ~0.68 nT
  - Plasma density: ~0.039 cm^{-3}
  - Temperature ~40,000 K (measured)

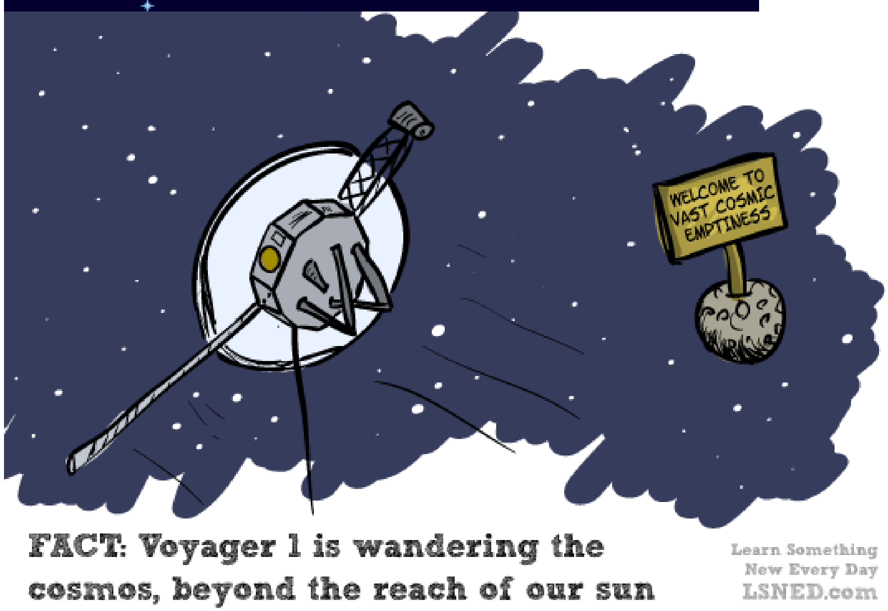
Cosmic Rays Through the Heliosphere



Rankin et al. 2022, SSRv, 218, 42

Very Local Interstellar Medium (VLISM)

https://spaceplace.nasa.gov/interstellar/en/



- Original Definition: [Holzer 1989]
  - Local Interstellar Medium:
    within 100 pc of the sun
  - Very Local Interstellar Medium:
    within 0.01 pc of the Sun
    (~2000 au)

Very Local Interstellar Medium (VLISM)

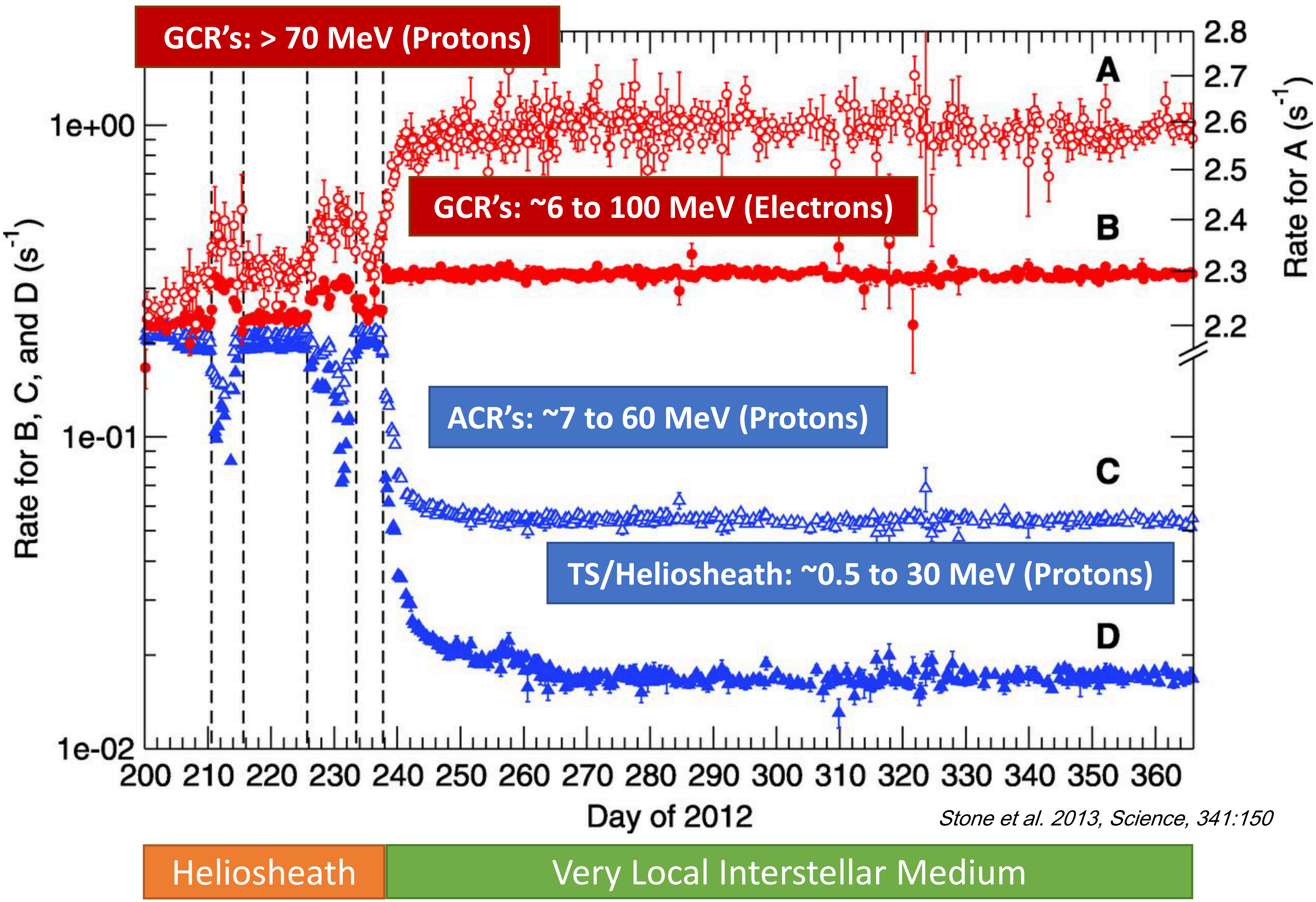
https://spaceplace.nasa.gov/interstellar/en/

- Original Definition: [Holzer 1989]
  - Local Interstellar Medium: within 100 pc of the sun
  - Very Local Interstellar Medium: within 0.01 pc of the Sun (~2000 au)
- New Definition: [Zank 2017]

"[The] region of the interstellar medium surrounding the Sun that is modified or mediated by heliospheric processes or material."

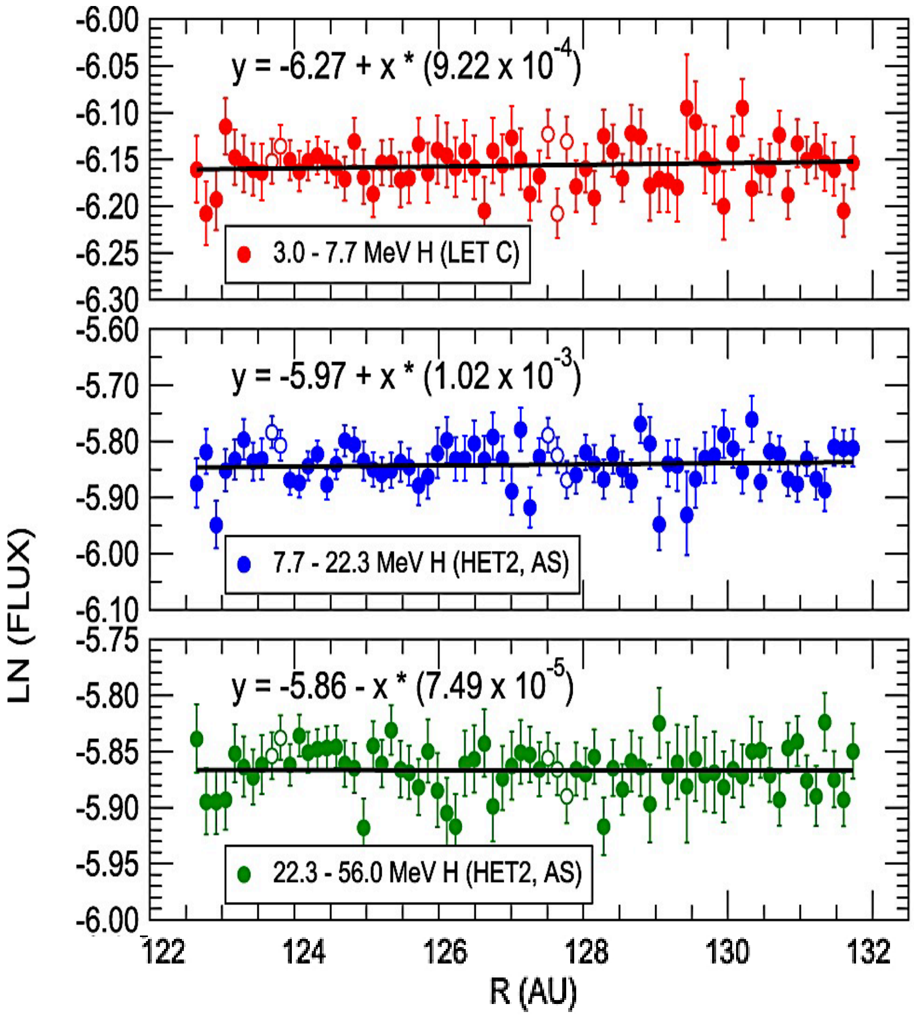
Interstellar Arrival: An Abrupt GCR Transition

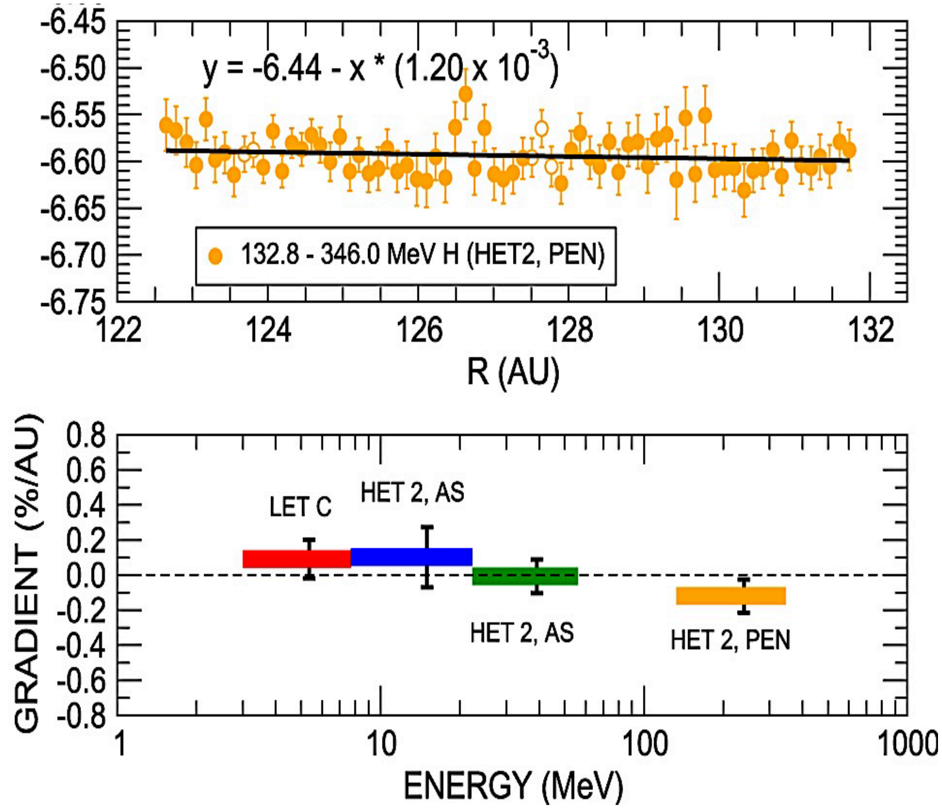
Voyager 1: Cosmic Ray Subsystem



Stone et al. 2013, Science, 341:150

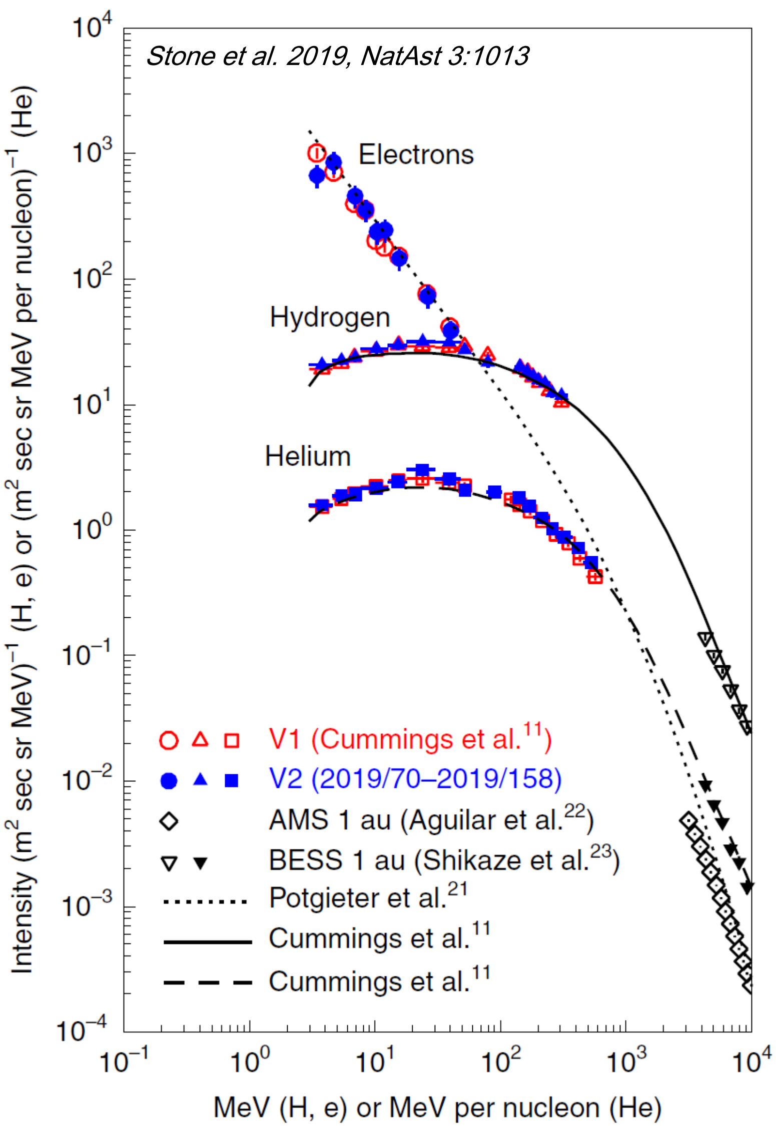
Cosmic Rays: No Radial Gradient





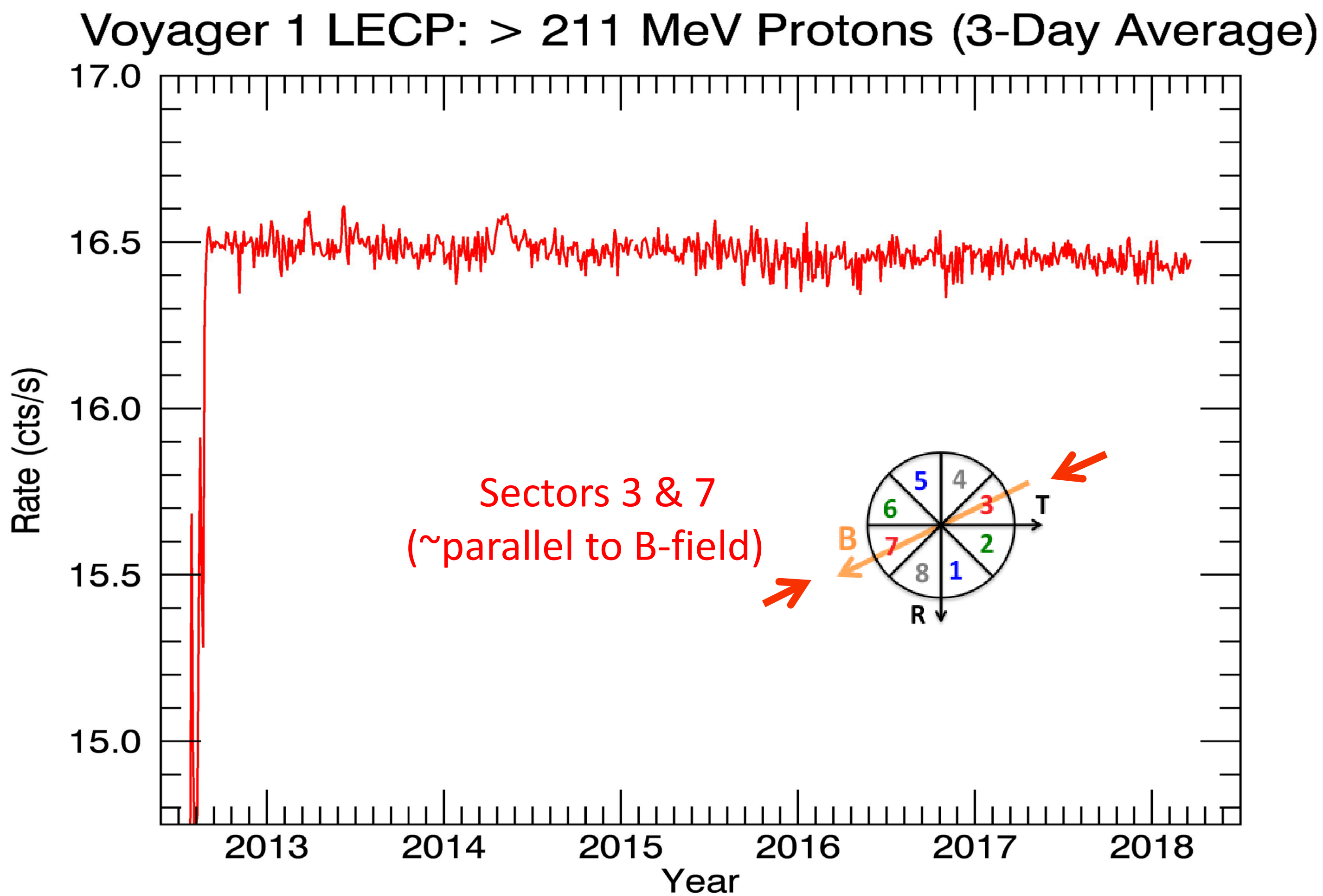
Cummings et al. 2016, ApJ 831:18

Low-Energy Interstellar Spectra!

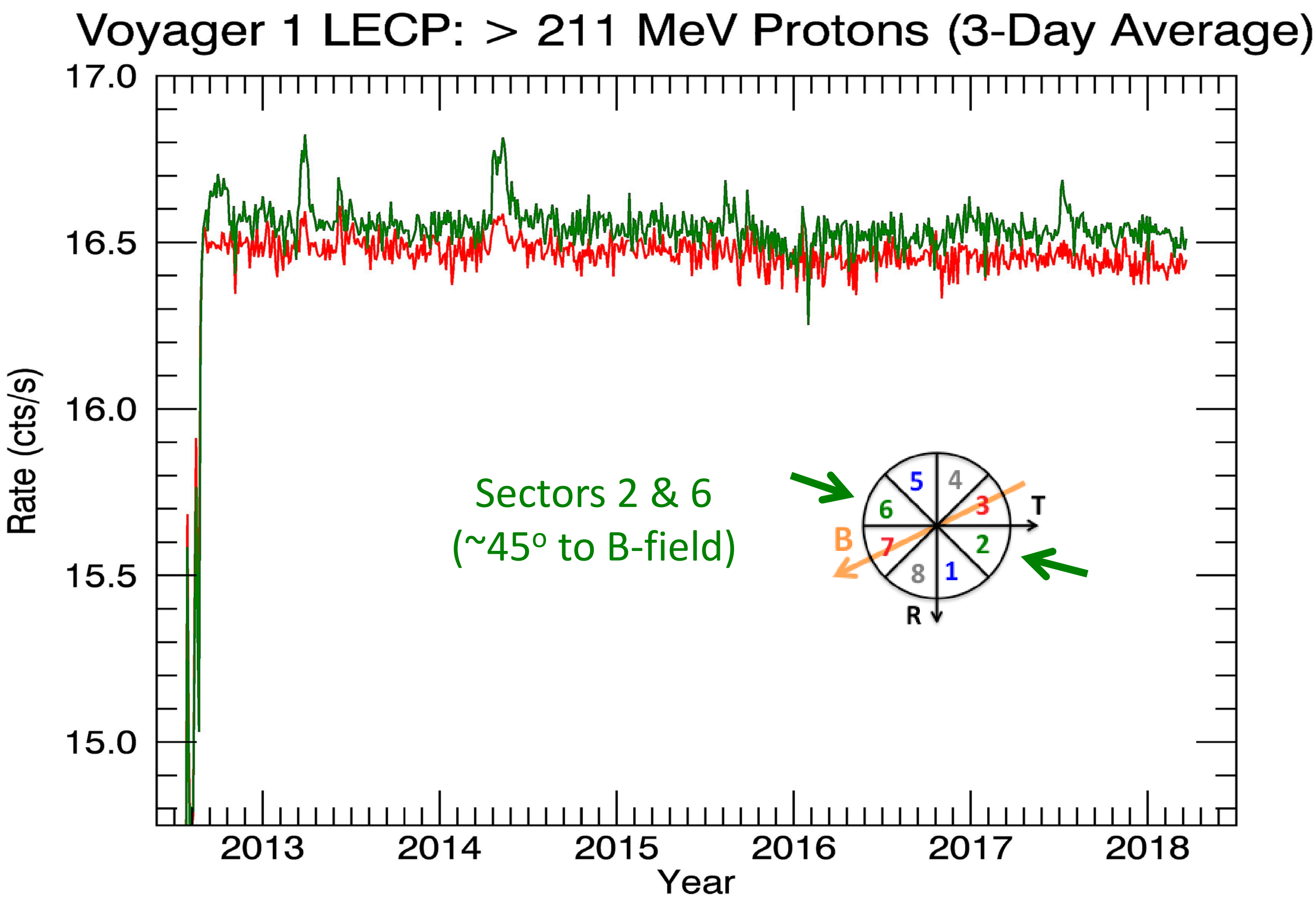


- Lowest-energy GCRs ever observed!
  - 14 decades in energy (NOT 11)
- Voyager GCRs:
  - H to Ni ~3 to ~350 MeV
  - "electrons" ~3 to ~75 MeV
    - Consistent with spectra derived from solar wind observations [Potgeiter et al. 2015]
- Unmodulated spectra?
  - Remarkably uniform flux; no clear indications of a radial gradient (so far, at 155 AU and counting)
  - Remarkable consistency between the two spacecraft at very different longitudes and latitudes!

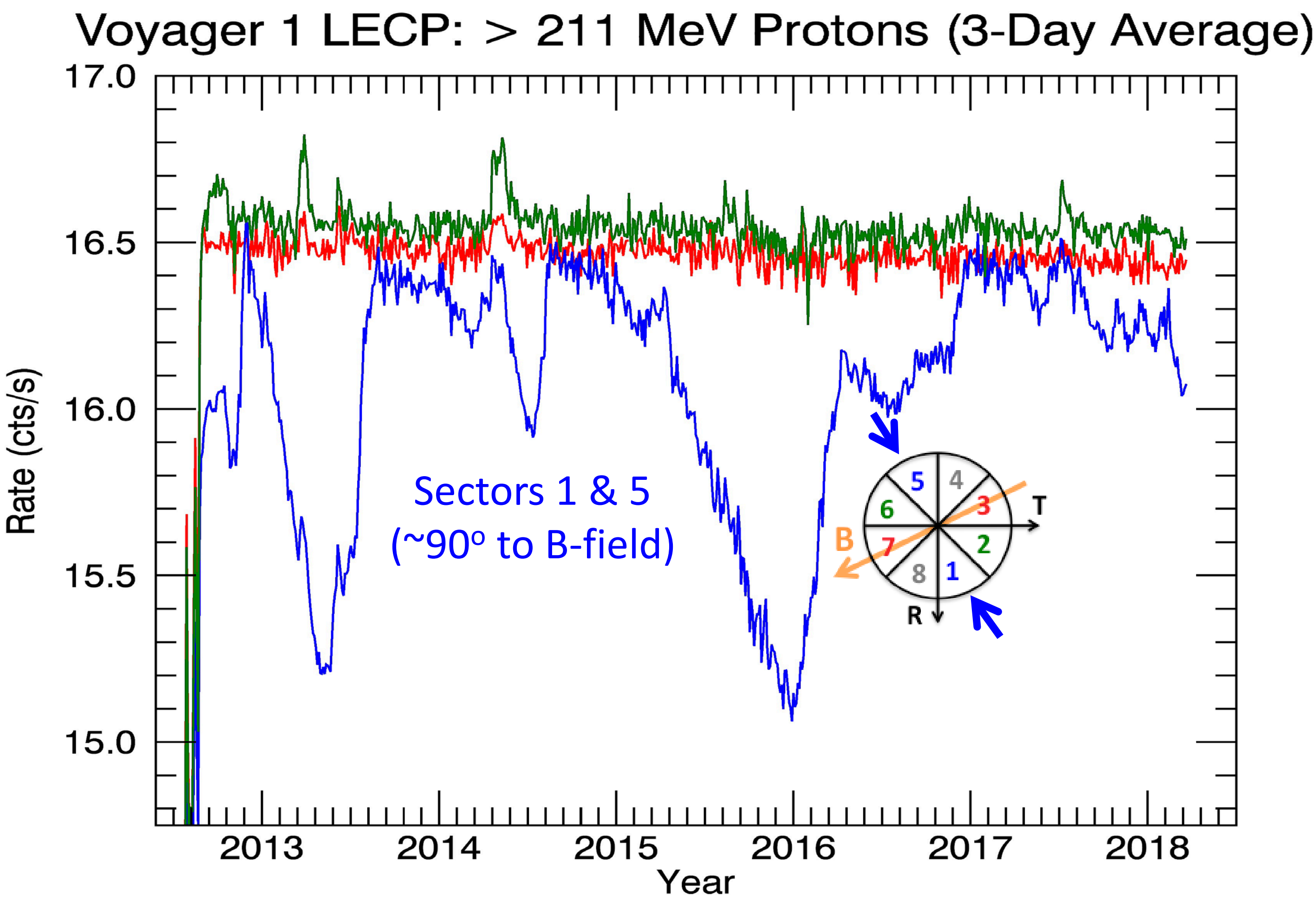
Uniform GCR Intensities Beyond the Heliopause



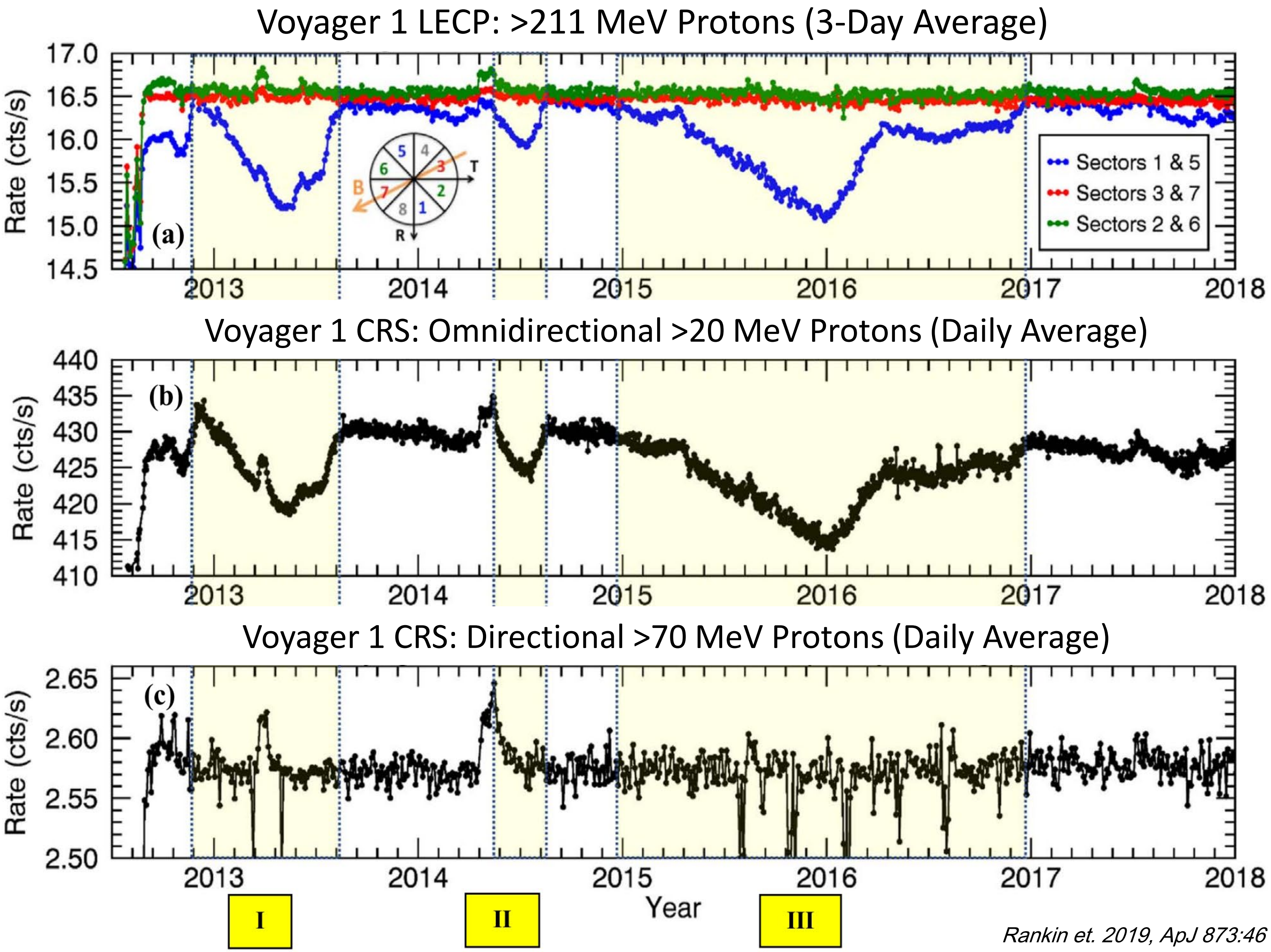
Uniform GCR Intensities Beyond the Heliopause



Uniform GCR Intensities Beyond the Heliopause!?

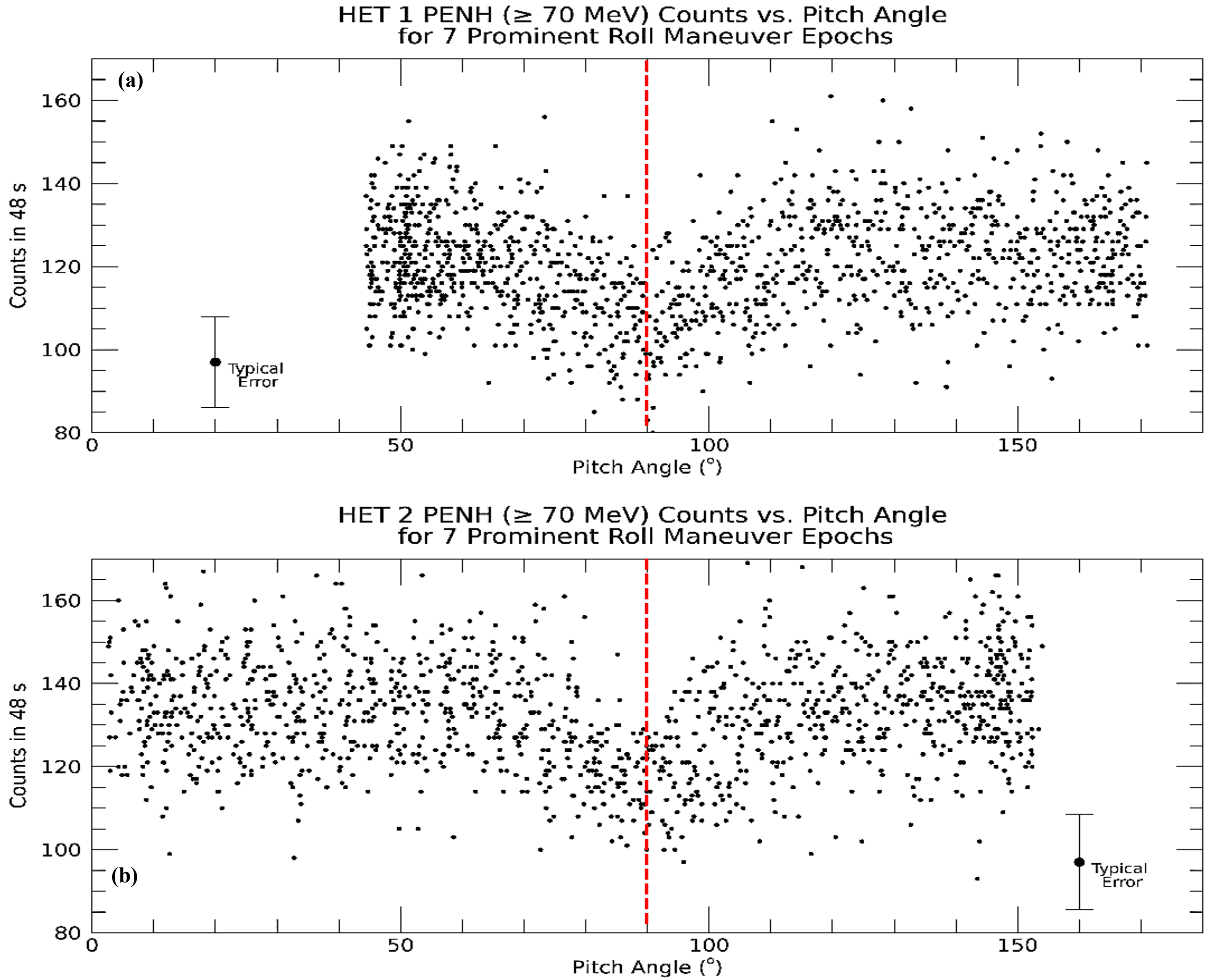


Unexpected GCR Anisotropy @ Voyager 1



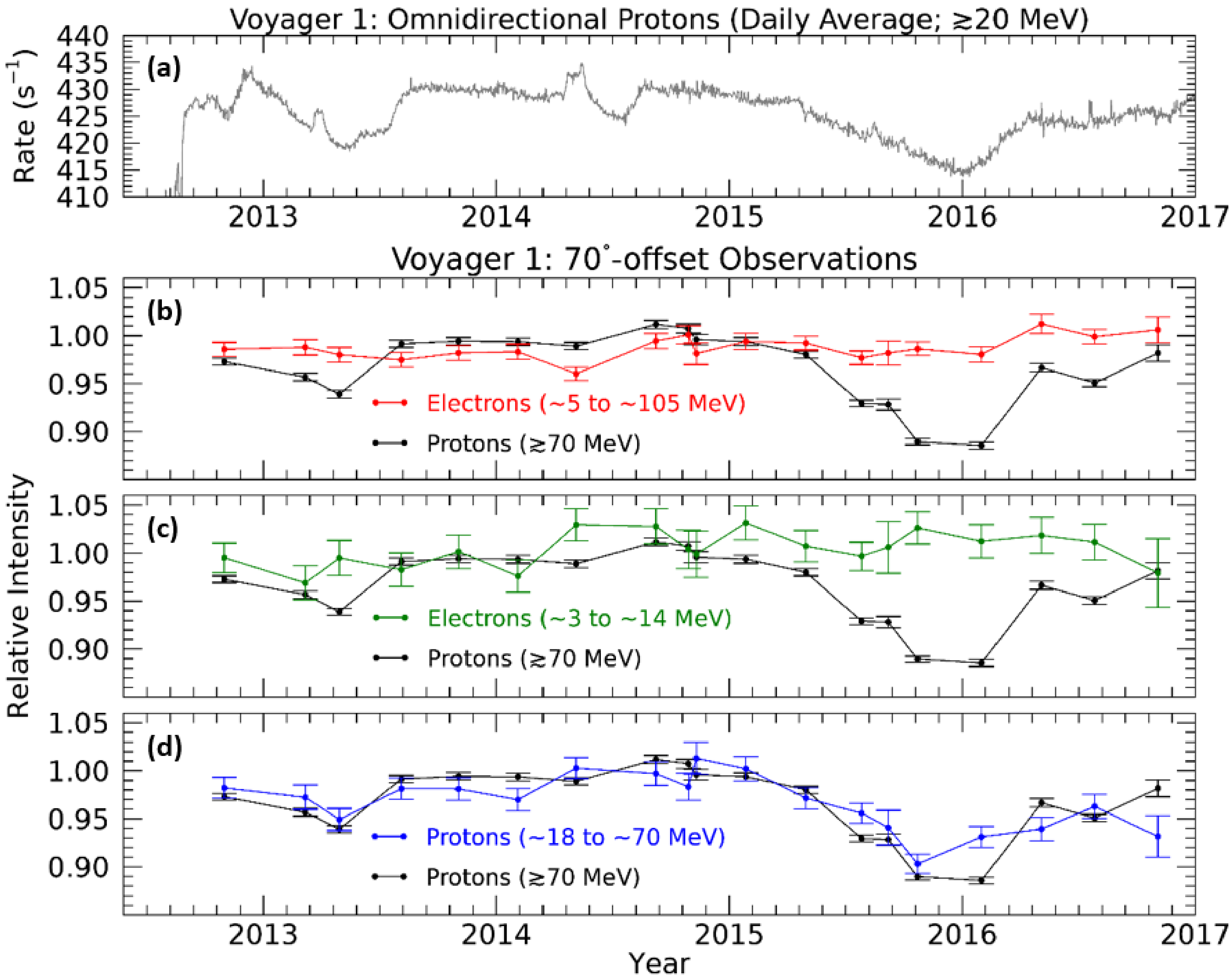
Rankin et. 2019, ApJ 873:46

GCR Anisotropy: Centered on 90° Pitch Angle



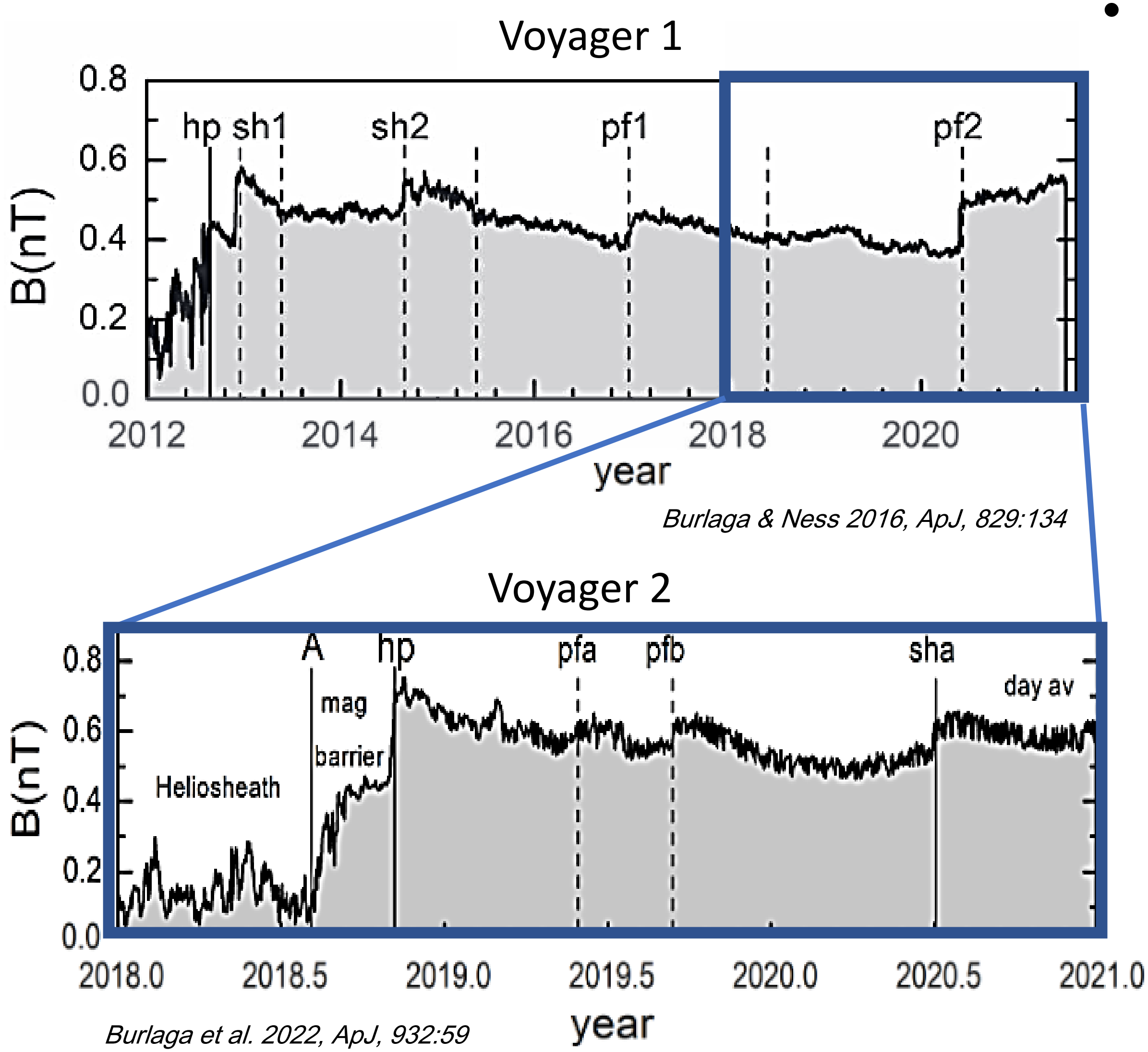
Rankin et al. 2019, ApJ 873:46

GCR Pitch Angle Anisotropy: Species Dependent



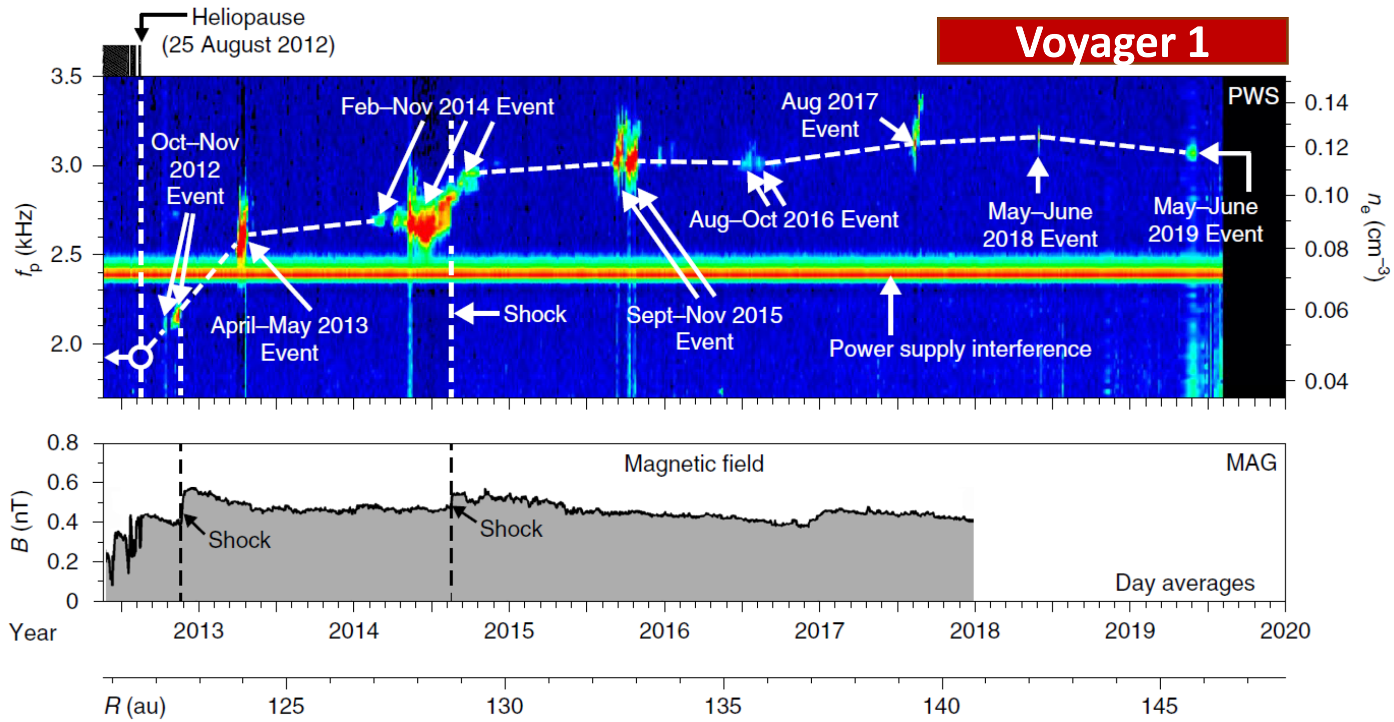
Rankin et al. 2020, ApJ, 895:103

Transient Disturbances in the Magnetic Field



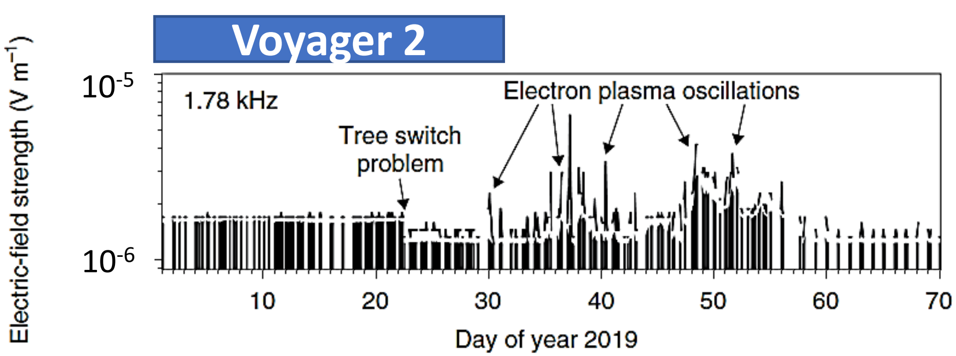
- Voyager 1 & 2 "Shocks"
  - weak, subcritical, laminar, resistive, and quasi-perpendicular
  - 10^7 km thick
    - 1000 x's thicker than 1-AU counterparts
  - small jump ratios
    - ~1.4 in 2012
    - ~1.1 in 2014
  - Likely collisional
    - Mostafavi & Zank 2018, ApJ 854:L15

Transient Electron Plasma Oscillations



Voyager 1: Plasma Wave Subsystem

- Wideband Receiver
- Emission frequency: 2.65 kHz to 3.11 kHz
- First event's plasma density: 0.055 cm^{-3}
- Radial distance: 122.6 AU
- Peak plasma density: 0.12 cm^{-3}

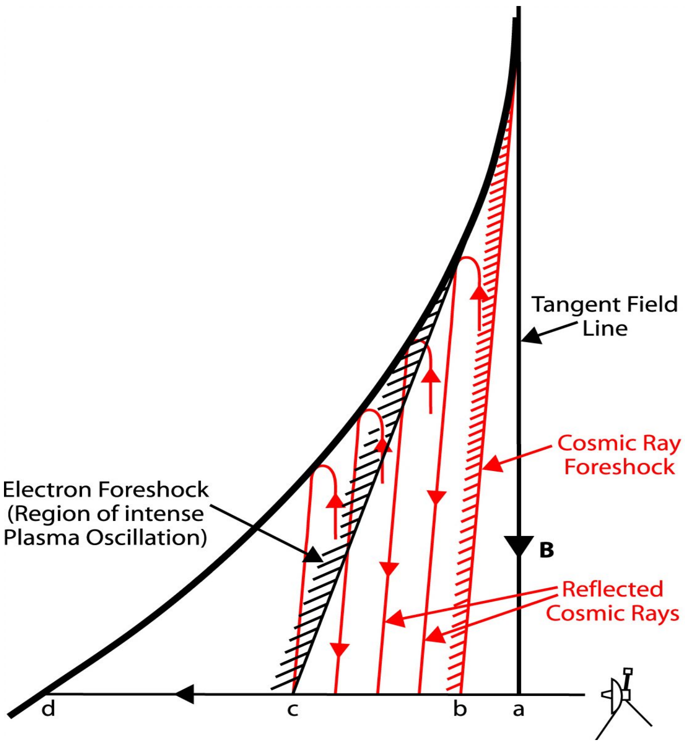


Gurnett & Kurth 2019, NatAst 3:1024

Voyager 2: Plasma Wave Subsystem

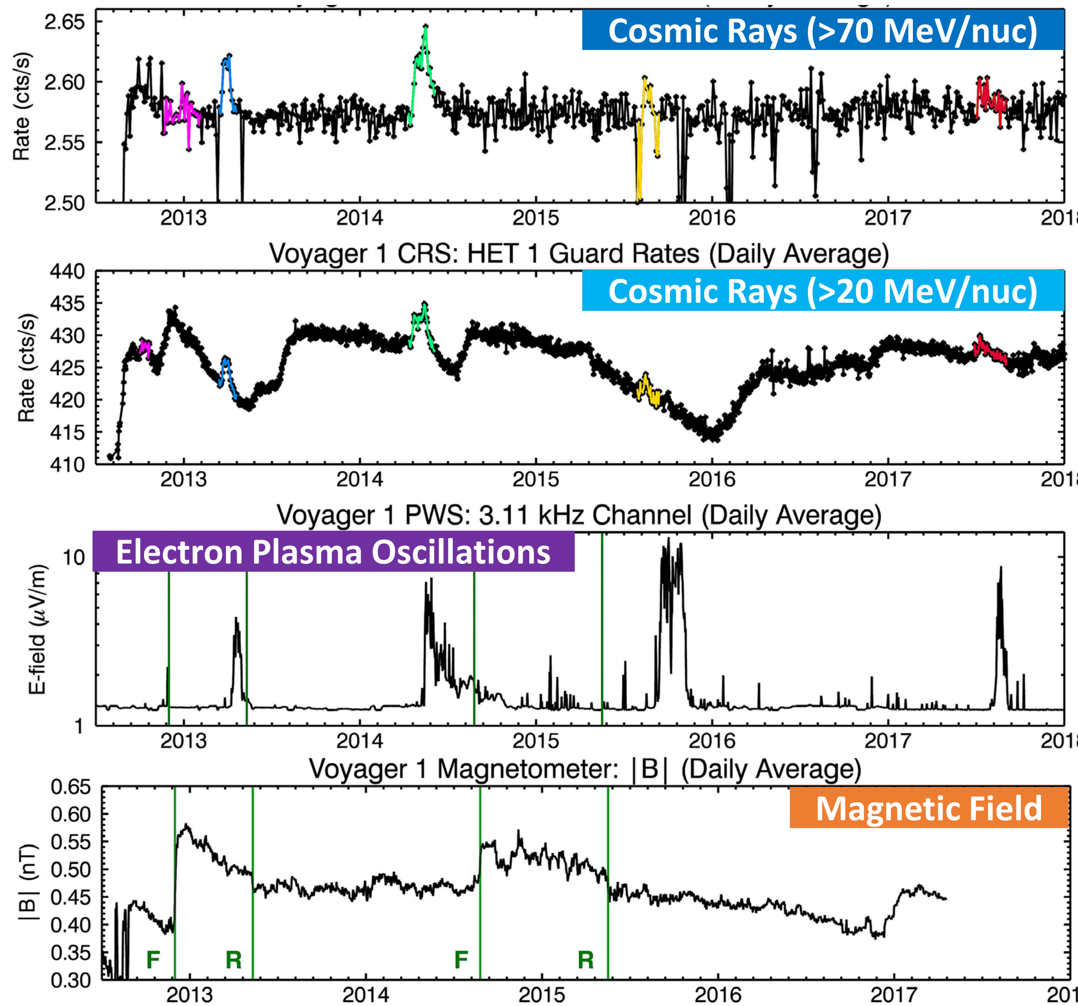
- 16-channel Spectrum analyzer
- Emission frequency: 1.78 kHz
- Plasma density: 0.039 cm^{-3}
- Radial distance: 119.7 AU

Shock-Energized Plasma & Cosmic Rays



Gurnett et al. 2015, ApJ, 809:121

Voyager 1

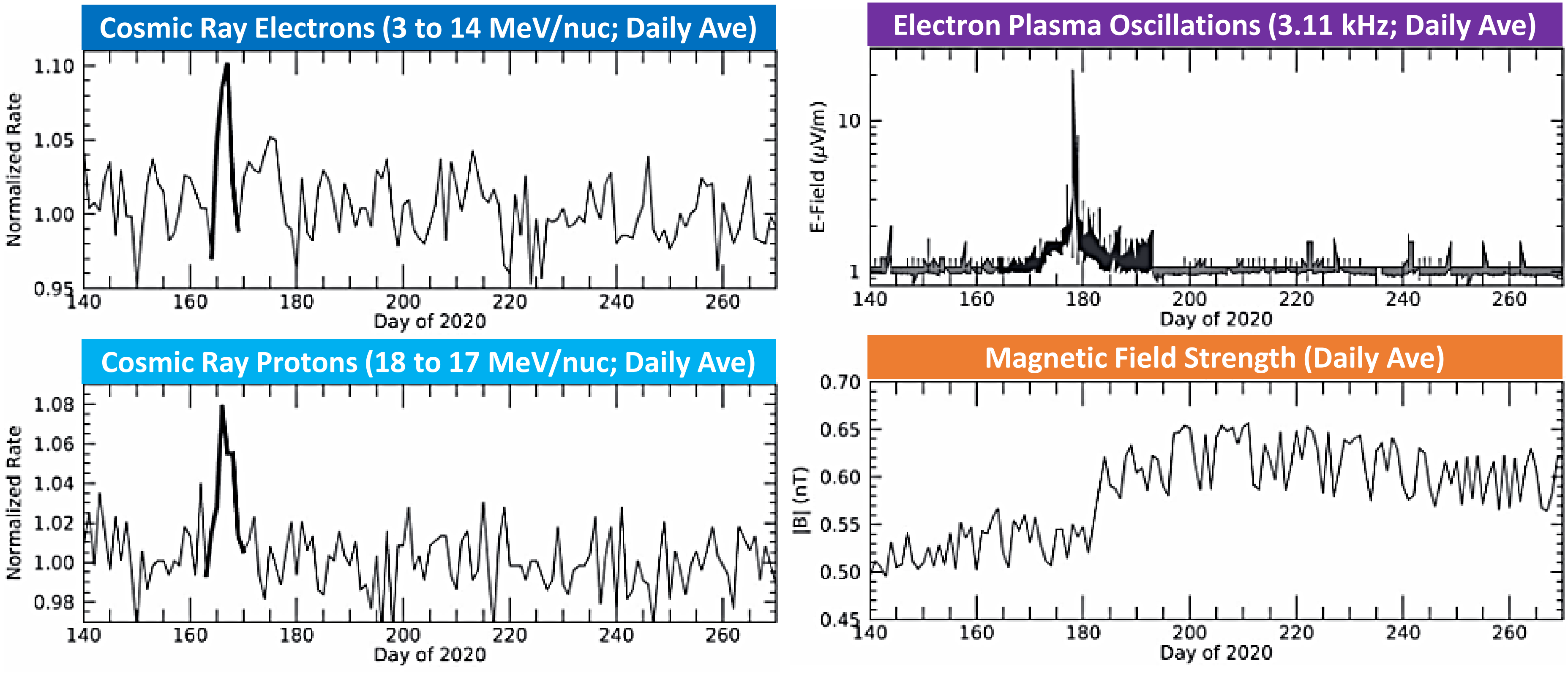


Rankin 2018, Caltech PhD Thesis (adapted)

- Estimated energy of the electron beams: ~20-100 eV
  - *Gurnett et al. 2021, ApJ 161:11*
  - Derived from relative timing of cosmic rays and plasma oscillations

Shock-Energized Plasma & Cosmic Rays

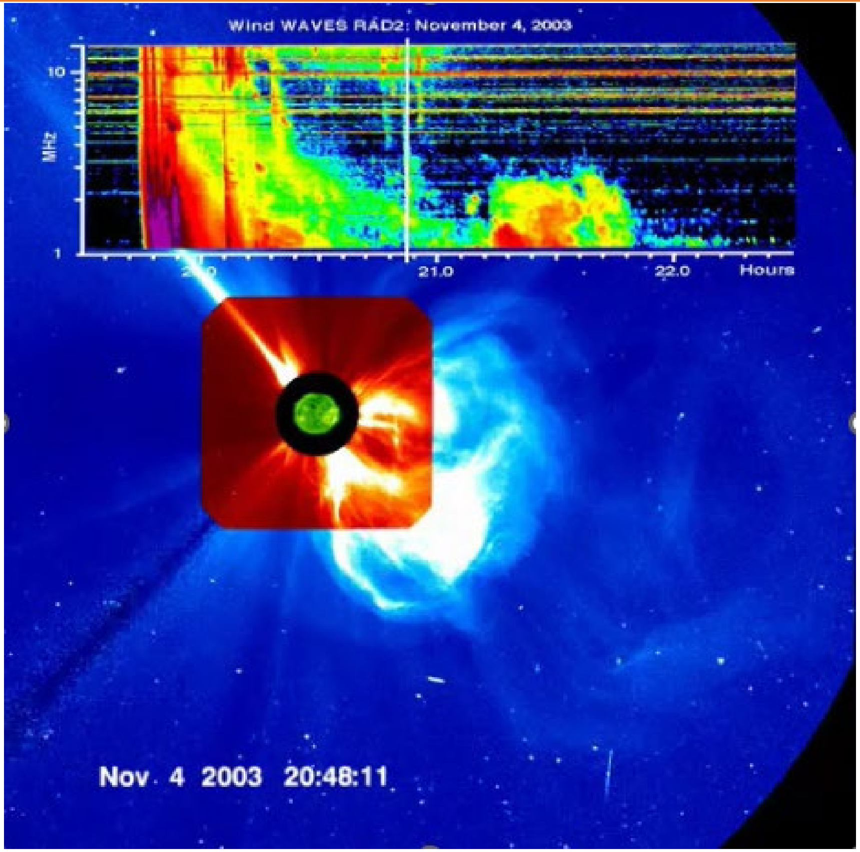
Voyager 2

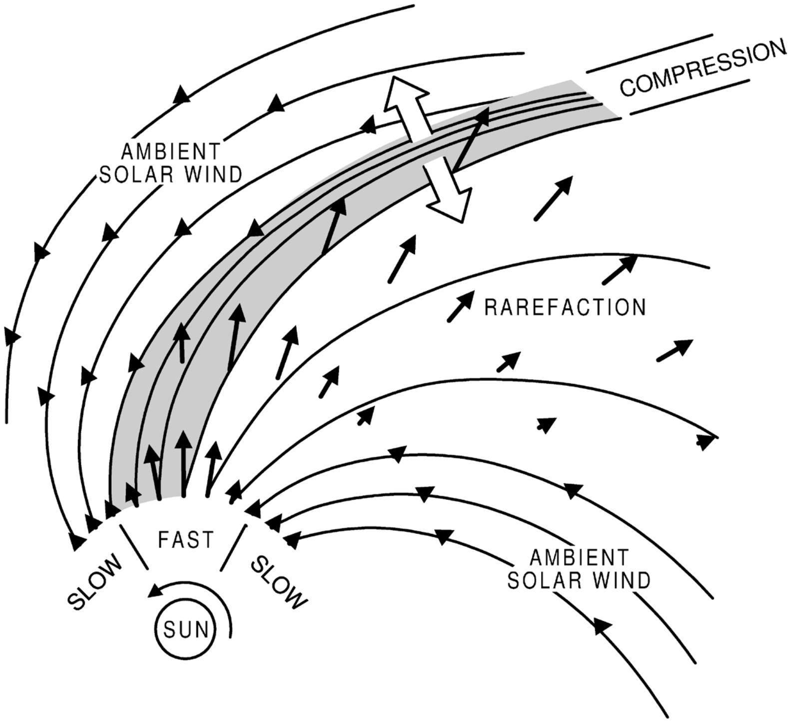


Burlaga et al. 2022, ApJ, 932:59

Transient Events from Solar Activity

https://svs.gsfc.nasa.gov/2936





Coronal Mass Ejection

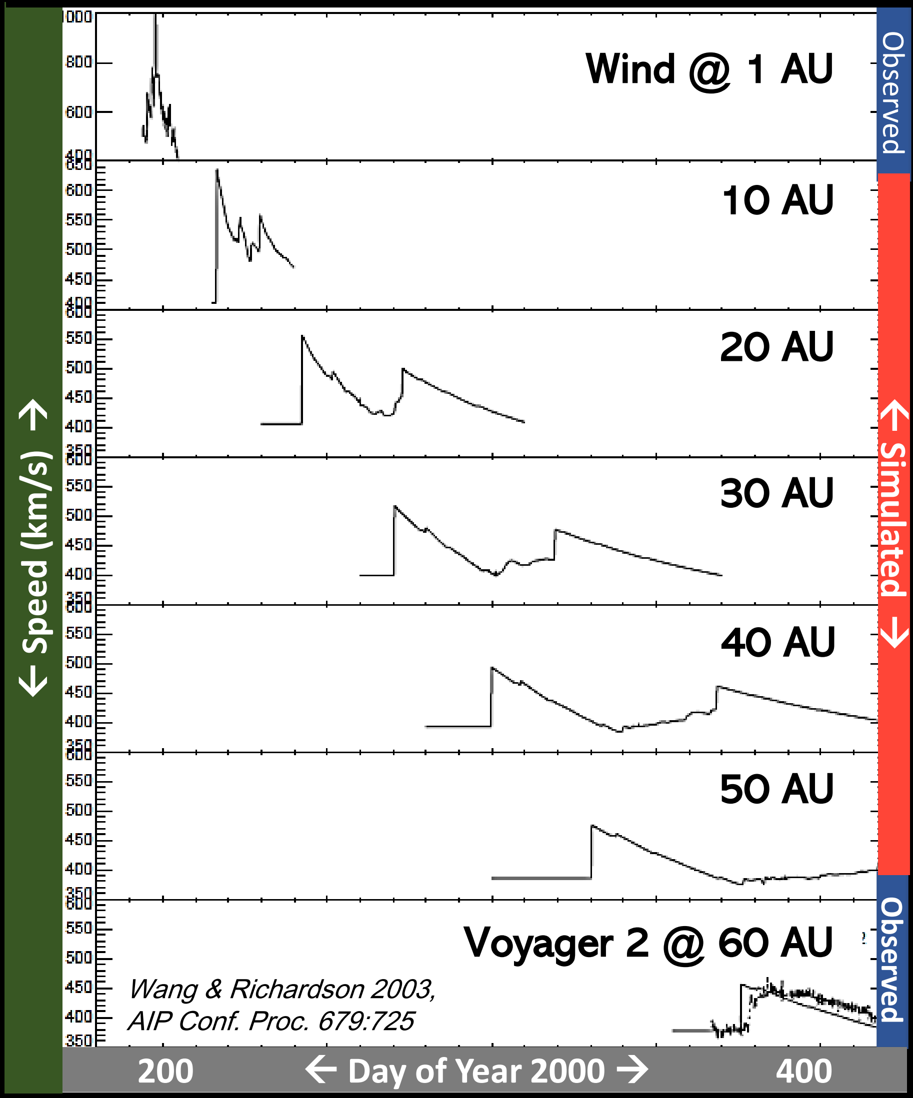
- Large flares often associated with huge ejections of mass from the sun (up to 100 billion kg of material loss)
- Speeds can reach up to 1000 km/s
- Resulting shocks accelerate particles ahead of the loop

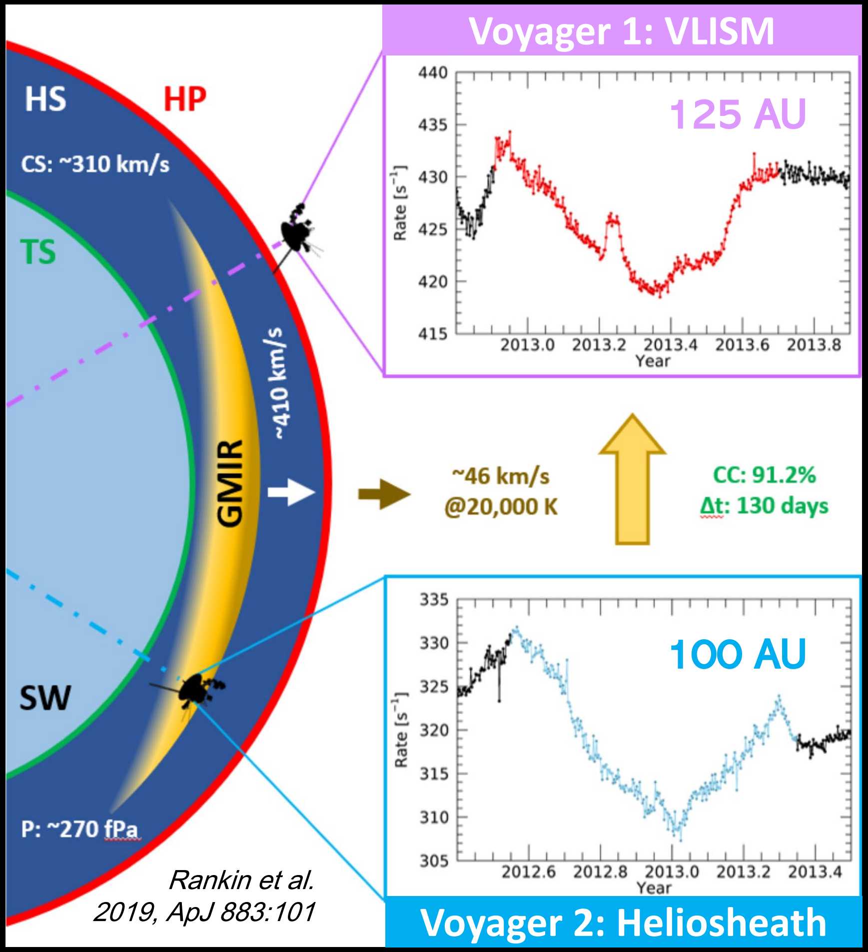
Corotating Interaction Region

- A fast stream runs into the slow wind, forming a compression region between the two, which results eventually in the formation of a forward-reverse shock pair
- Pattern rotates with the sun (long-lived coronal holes source)

Transients through the Heliosphere… …and into the Very Local Interstellar Medium!

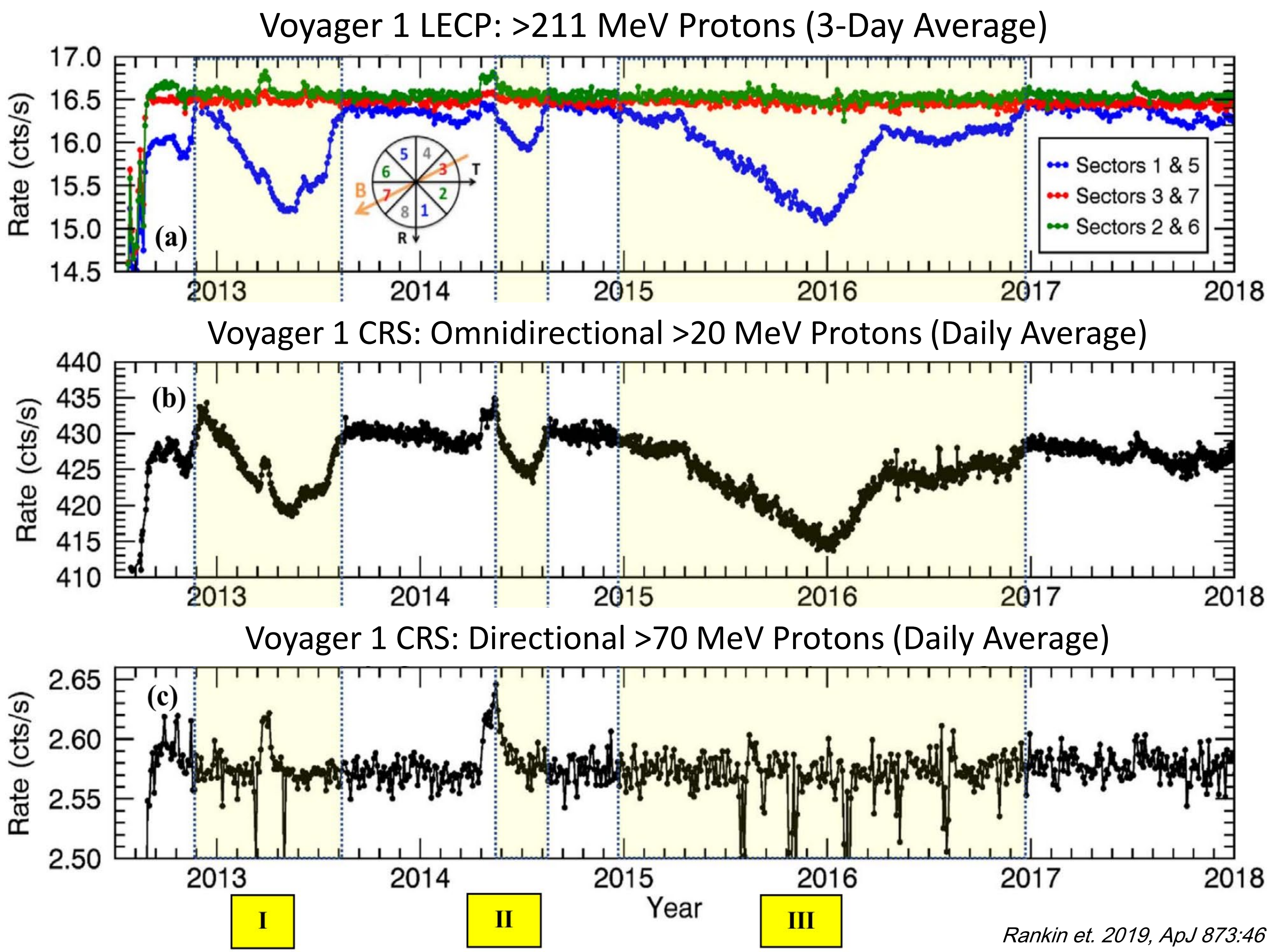
Plasma Disturbance from 1 to 60 AU





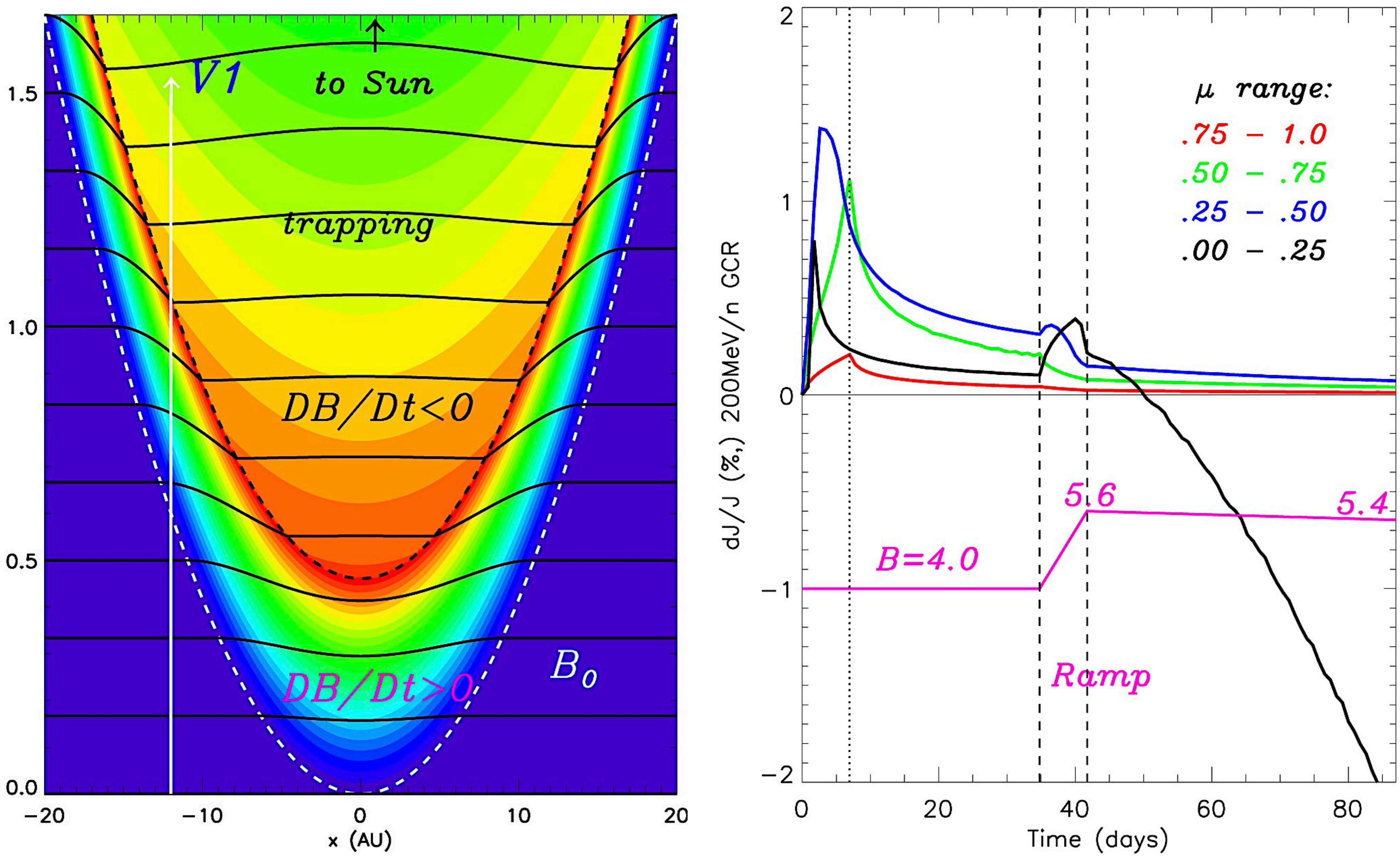
GCR Disturbances from 100 to 125 AU

Unexpected GCR Anisotropy @ Voyager 1



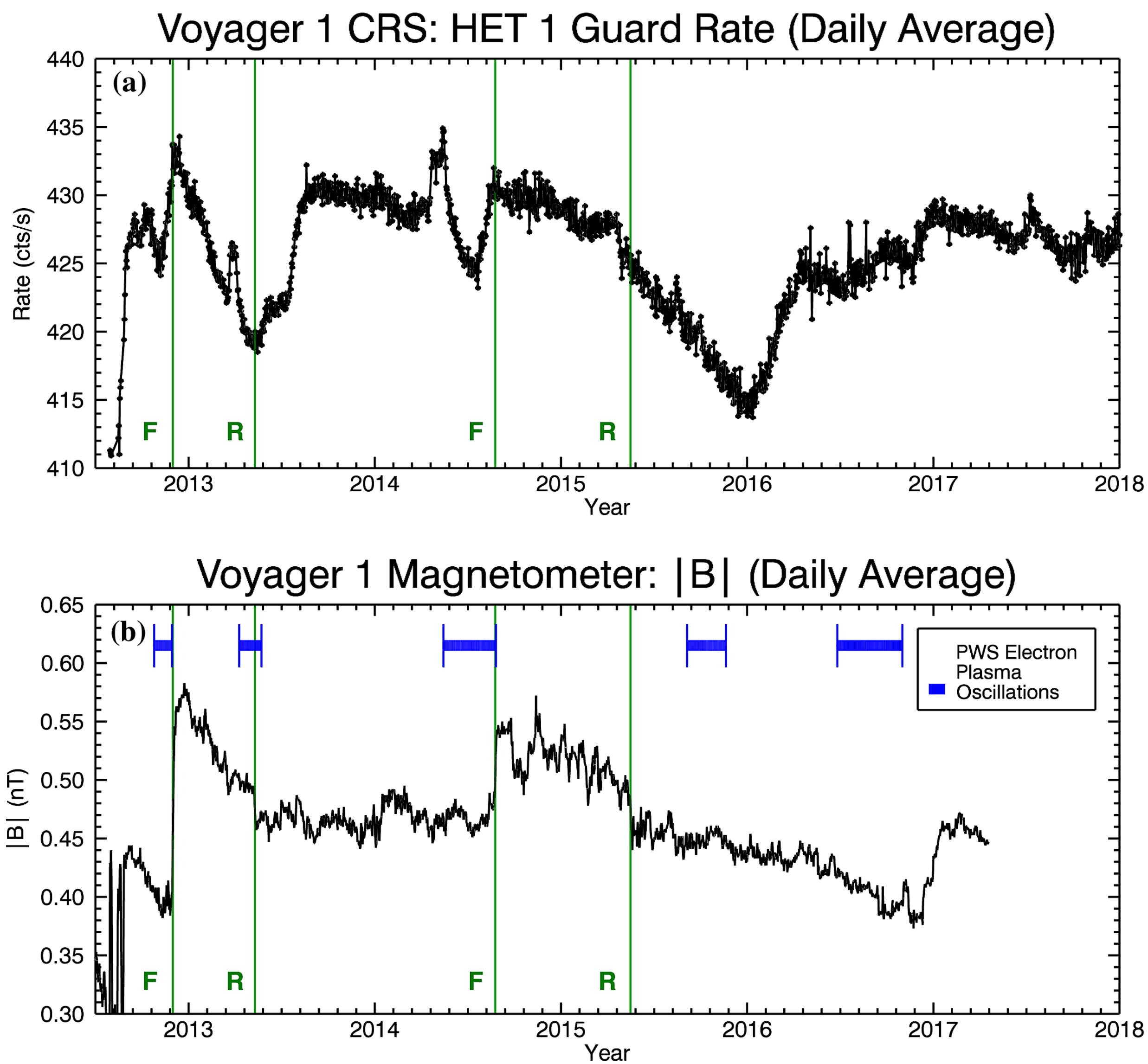
Rankin et. 2019, ApJ 873:46

Leading Theory for the Pitch-Angle Anisotropy: Trapping and Cooling Downstream of Shocks



Kóta & Jokipii, 2017, ApJ 839:126

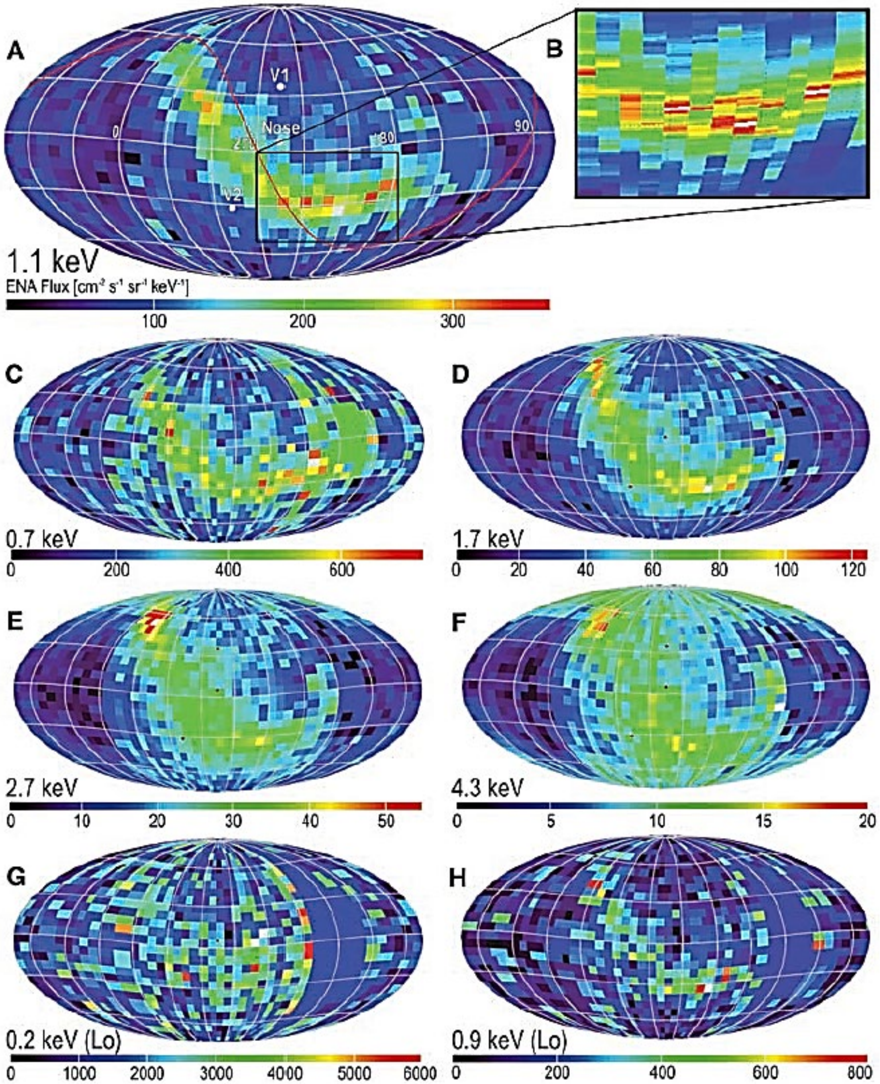
Correlation with the Local Magnetic Field?



Rankin et al. 2019, ApJ 873:46

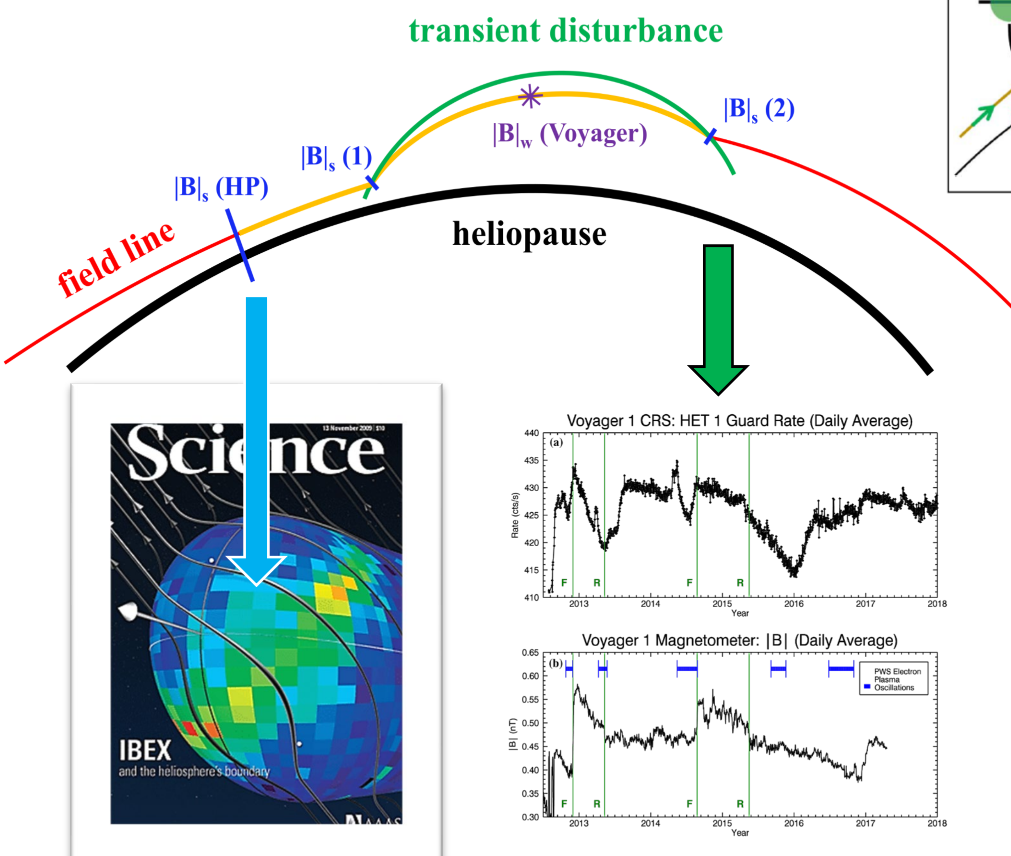
Space Physics at Princeton

Connecting to Global Observations



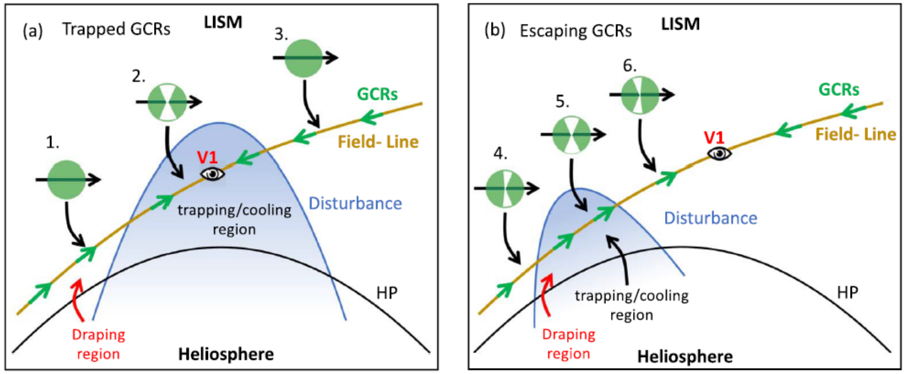
McComas et al. 2009, Science 326:13

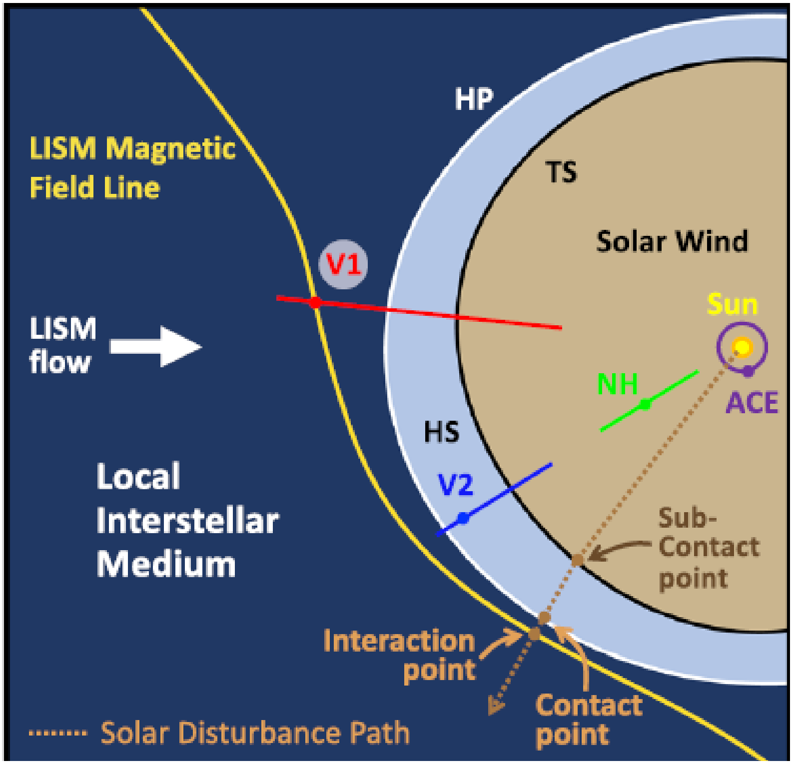
Connecting to Global Observations



McComas et al. 2009, Science 326:13

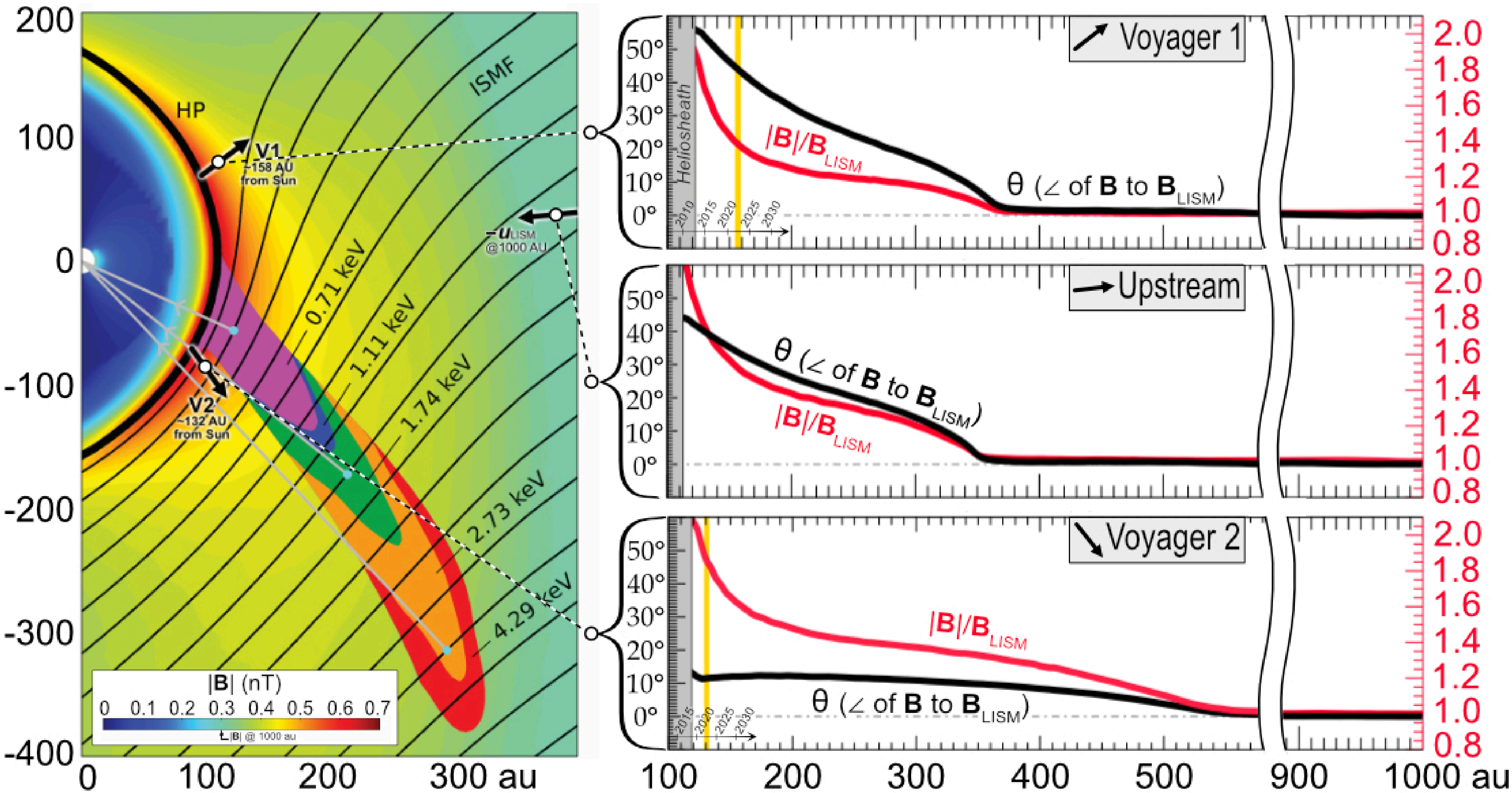
Rankin et al. 2019, ApJ 873:46





Hill et al. 2020, ApJ 905:69

IBEX-Predicted Trends in the Large-Scale Magnetic Field



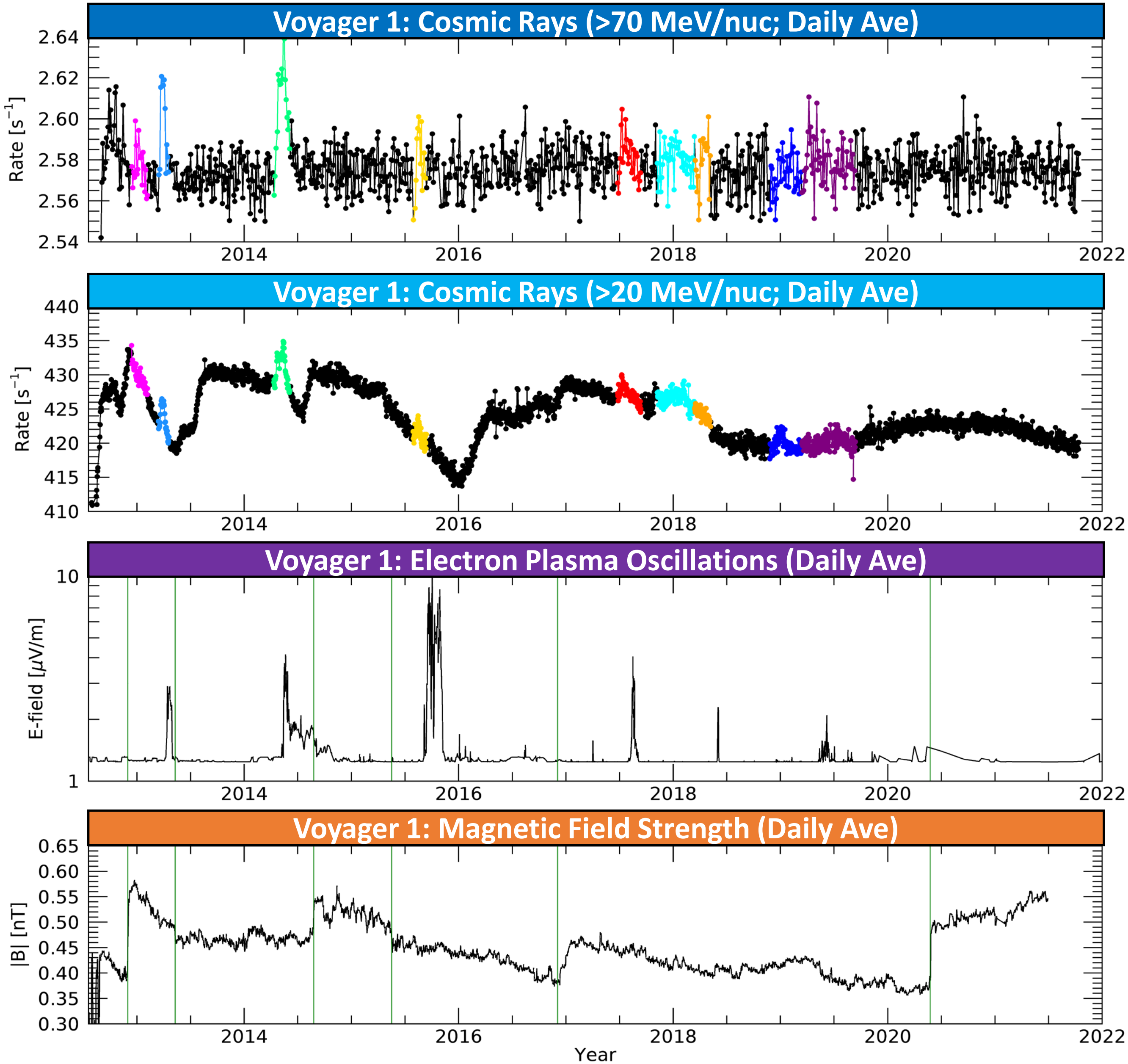
Rankin et al. (2023) ApJL 945:L31

Pristine ISMF determined by IBEX:

- 2.93 ± 0.08 μG
- 227.3° ± 0.7° ecliptic longitude
- 34.6° ± 0.5° ecliptic latitude

Zirnstein et al. (2016) ApJL 818:L18

A New, Exciting GCR Regime



Space Physics at Princeton

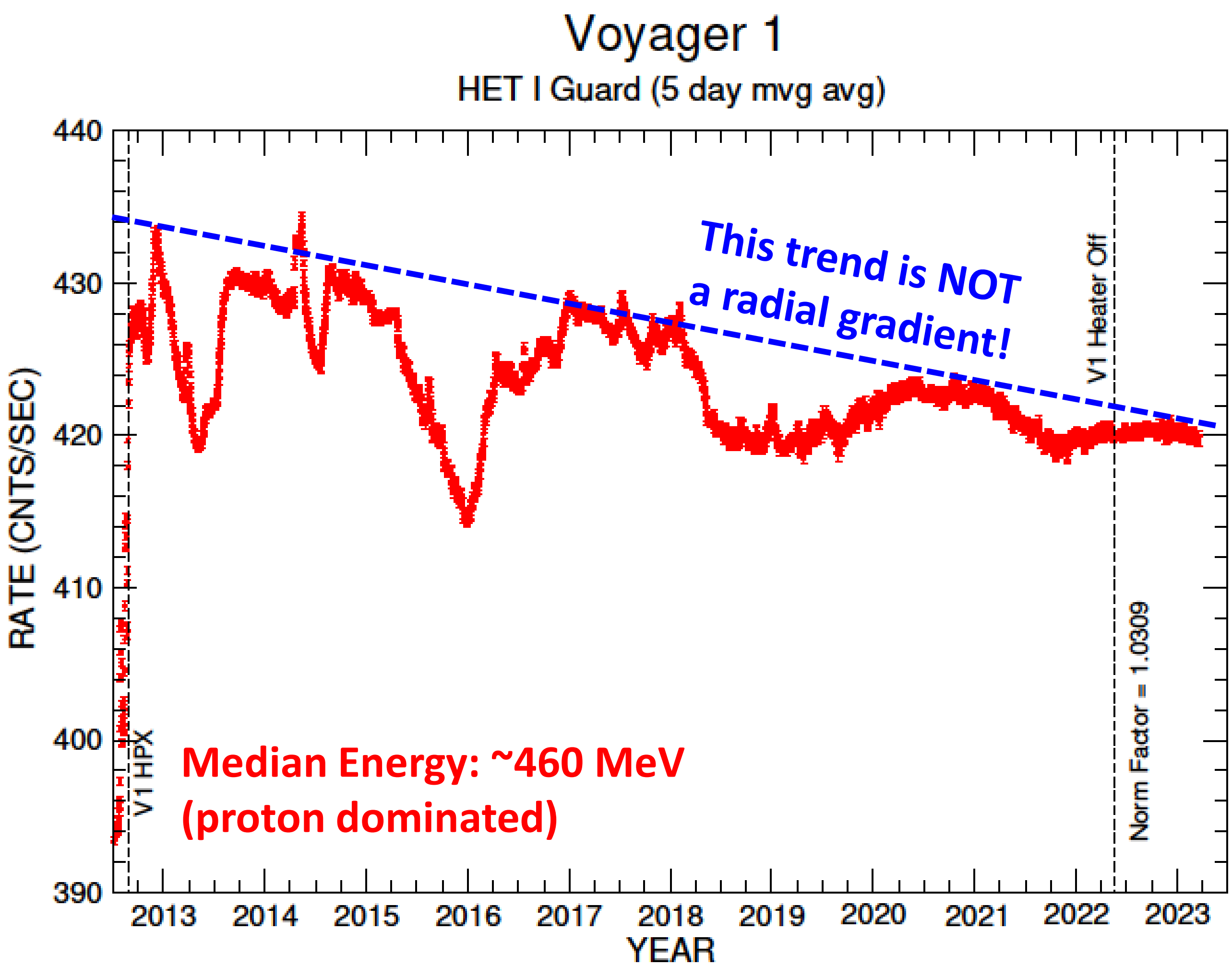
Summary & Takeaways

- Nearly a decade of remarkable measurements of GCRs made by both Voyager space probes in the Very Local Interstellar Medium
  - heliopause boundary
  - low-energy interstellar spectra
  - pitch-angle anisotropy
  - interstellar transients
- Significant progress made on larger heliophysics questions:
  - What determines the interaction of the Sun with the Solar System and the interstellar medium? → the relationship is a lot more dynamic than we think!
  - What can we discover about our own star by looking at it from outside-in rather than inside-out?
  - How do our interstellar surroundings influence the Sun and our Solar System?
- Open questions
  - What is the underlying physics that governs the GCR pitch angle anisotropy?
  - Why is the pitch angle anisotropy observed in protons but NOT electrons?
  - What mechanisms accelerate GCRs prior to the passage of the weak shocks beyond the heliopause?
  - What role does the magnetic field play in trapping (accelerating) & cooling (heating) the GCR's?
  - What are fundamental processes do we see here that are relevant to GCRs throughout the universe?

Rich data set, new plasma regime; cosmic ray experts welcome! *jsrankin@princeton.edu*

Backups

Instrumental Caveat: RTG Background

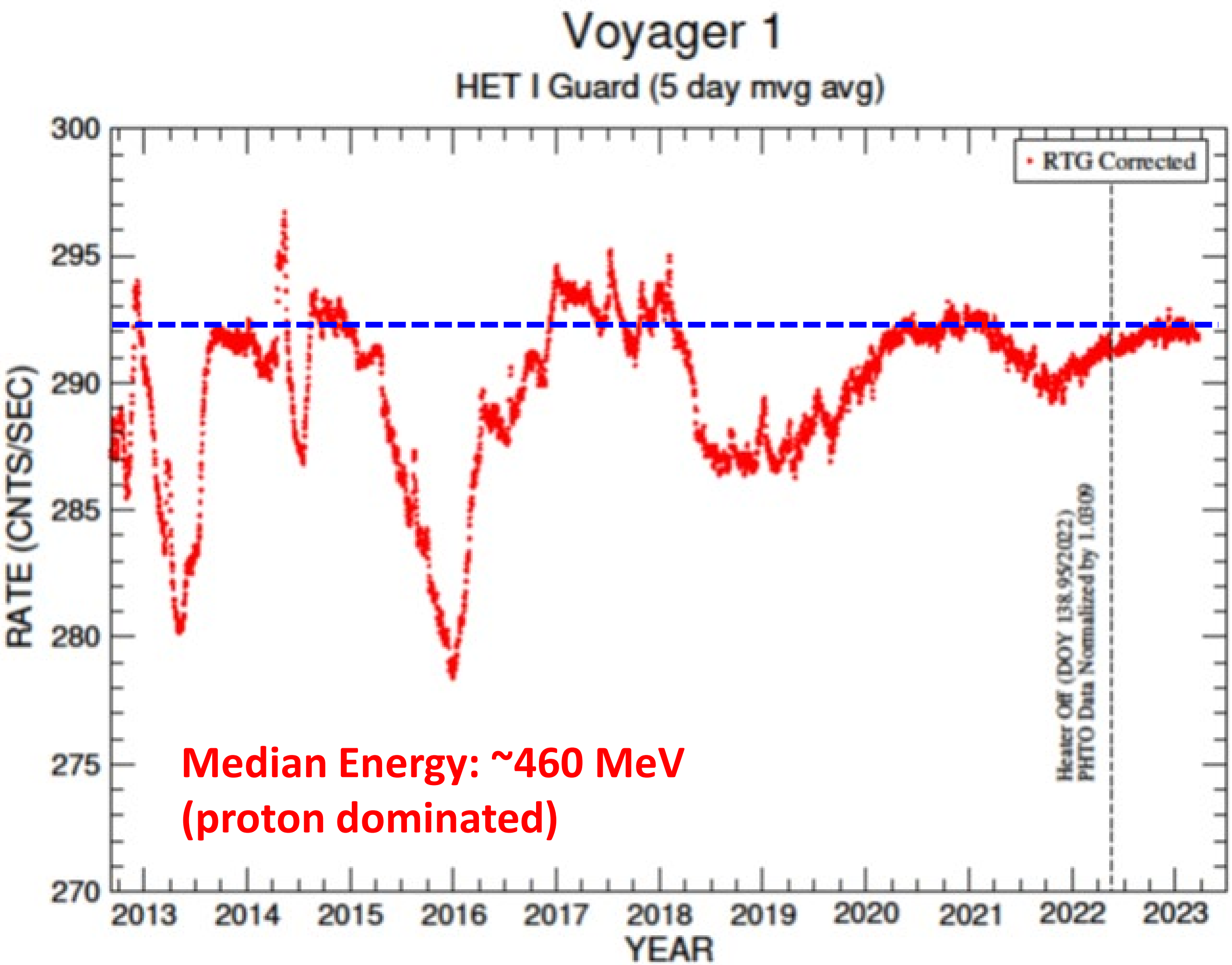


[Voyager Cosmic Ray Subsystem (CRS)]

"Guard Rate" is omnidirectional BUT is NOT background corrected

Significant background caused by the RTG

Instrumental Caveat: Background Corrected!



[Voyager Cosmic Ray Subsystem (CRS)]

Corrections made by subtracting out trend from known decay rate parameters

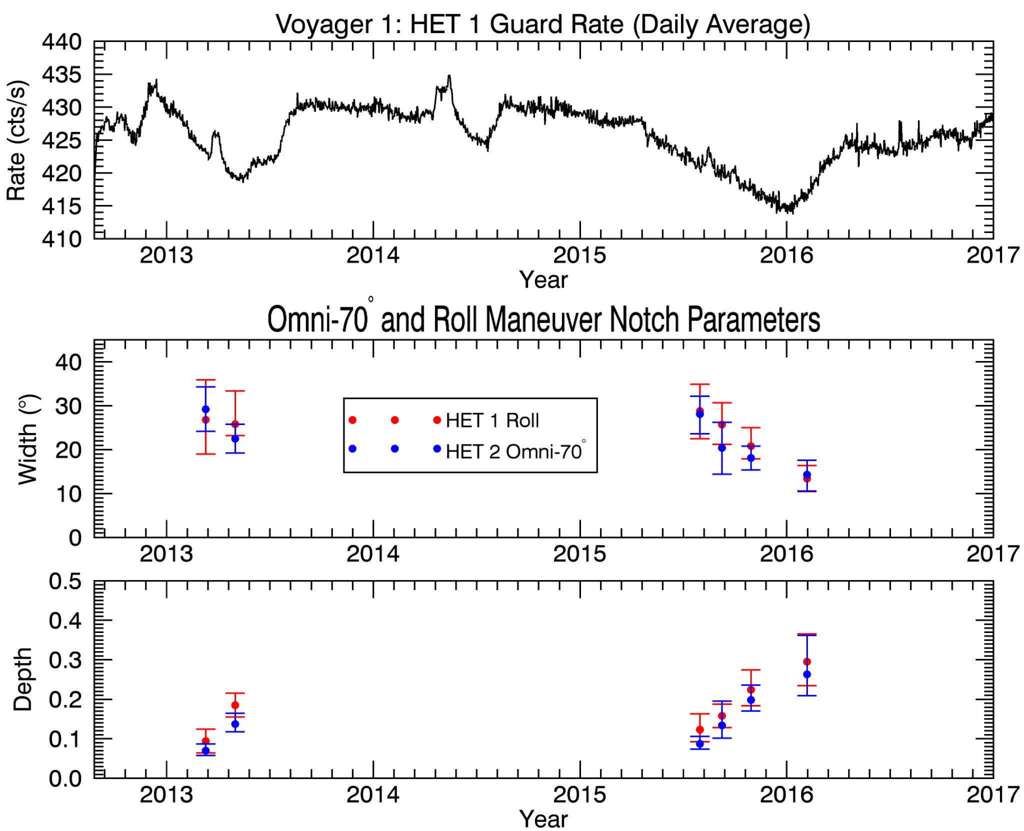
Soon to be published (Cummings+2023)

Voyager GCR Protons & Electrons

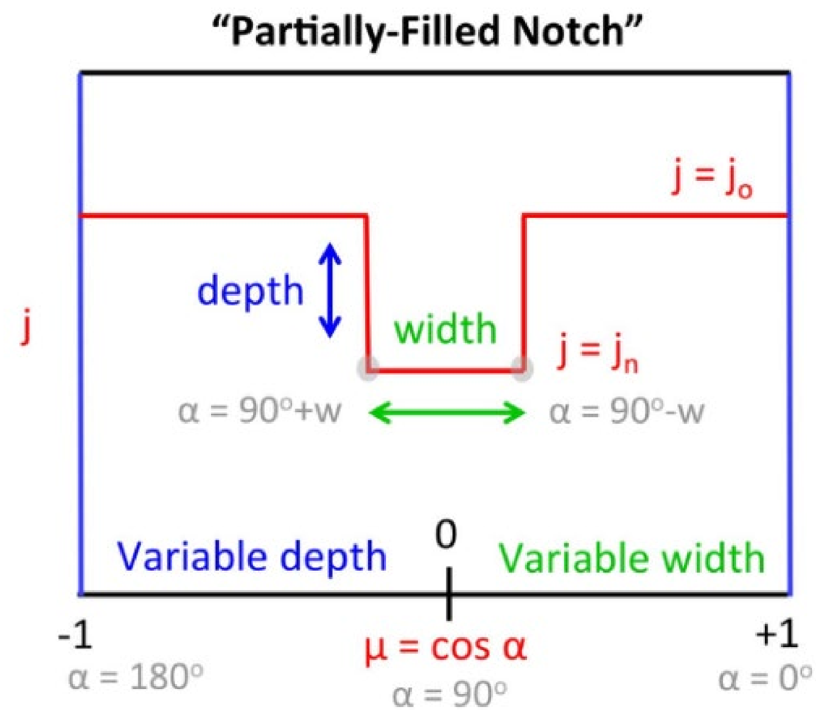
Median Energy & Dominant Species	540 MeV protons	460 MeV protons	43 MeV protons	13 MeV electrons	6.0 MeV electrons	Proton-Electron Ratio
Charge	+	+	+	–	–	NA
Rest Mass [MeV/c^2]	938	938	938	0.511	0.511	1836
Gyroperiod [s]	222	210	148	2.03	0.979	72.9
Rigidity [MV]	1142	1037	287	13.5	6.49	21.3
Gyroradius [km]	8.2×10^6	7.4×10^6	2.1×10^6	9.7×10^4	4.7×10^4	22
Gyroradius [AU]	0.055	0.050	0.014	0.00065	0.00031	22
Lorentz Factor	1.58	1.49	1.05	26.4	12.7	0.12*
Velocity [km/s]	2.32×10^5	2.22×10^5	8.78×10^4	2.998×10^5	2.991×10^5	0.77*
Velocity [β]	0.773	0.741	0.293	0.999	0.997	0.77*
Parallel Mean Free Path [au] (Bieber et al. 1994)	~0.06	~0.06	~0.04	~0.06	~0.09	~0.7
Parallel Mean Free Path [au] (Tautz & Shalchi 2013)	~0.5	~0.5	~0.3	~0.1	~0.1	~3

GCR Pitch Angle Anisotropy: Characteristics

Interval	Width	Depth	δ_{omni}
2013-67	29° ± 5°	7% ± 1%	1.8% ± 0.05%
2013-120	23° ± 3°	14% ± 2%	2.7% ± 0.05%
2015-208	28° ± 4°	9% ± 2%	2.1% ± 0.05%
2015-250	20° ± 6°	13% ± 5%	2.4% ± 0.07%
2015-296	18° ± 3°	20% ± 3%	3.1% ± 0.05%
2016-31	14° ± 4°	26% ± 8%	3.3% ± 0.06%



Rankin et al. 2019, ApJ 873:46



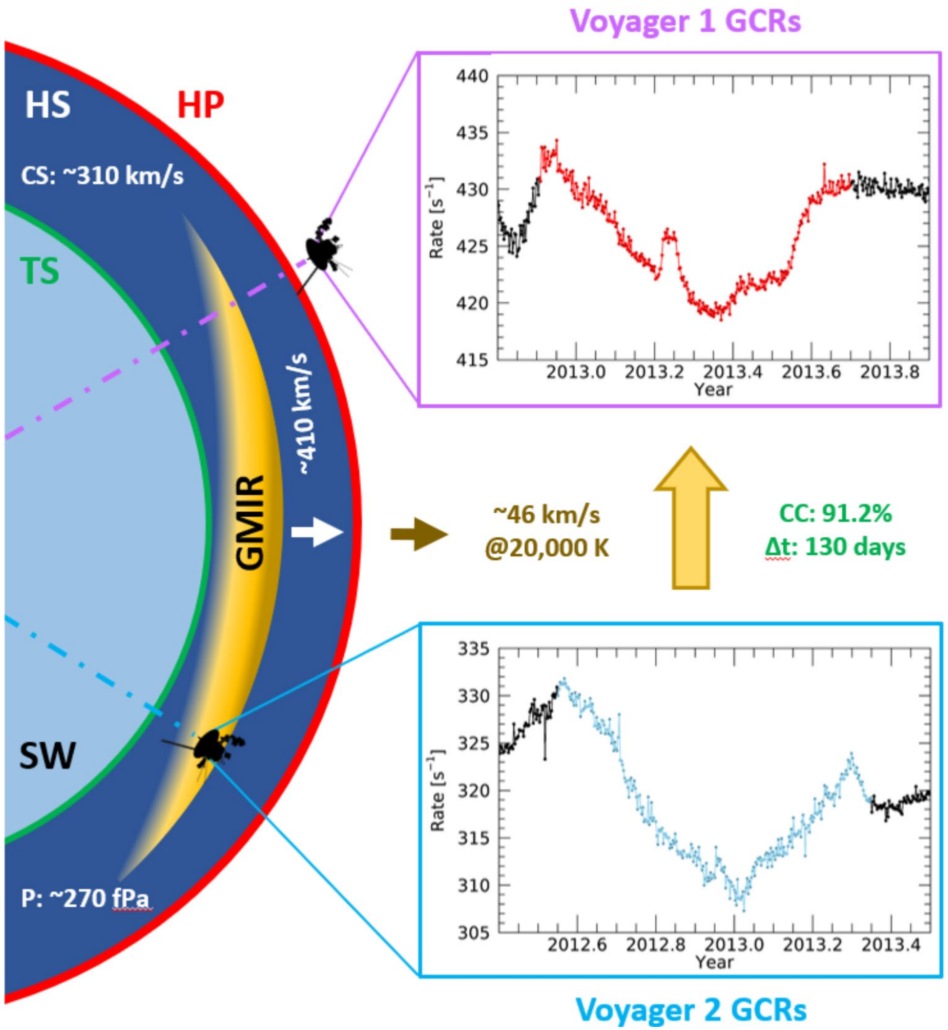
Voyager 2 → Voyager 1 “GMIR”

Heliosphere-VLISM Pressure Balance:

- key unknowns
  - interstellar temperature & heliosheath pressure
- $P_{Total} \sim 270$ fpa (T = 20,000 K)
  - Magnetic, thermal, dynamic: ~15%
  - IBEX PUI: ~45%
  - ACR/GCR: ~22%
  - Remaining: ~18%
- $P_{Total} \sim 242$ fpa (T = 40,000 K)
  - Voyager 2 VLISM Temperature

Heliosheath sound speed:

- $C_{HS} = 314 \pm 32$ km s^{-1}
  - T = 20,000 K
- $C_{HS} = 299 \pm 31$ km s^{-1}
  - T = 40,000 K



Rankin et al. 2019, ApJ 883:101