Recent Cosmic Ray Observations from Voyagers 1 and 2

A. C. Cummings and E. C. Stone, *Caltech*
N. Lal and B. Heikkila, *Goddard Space Flight Center*

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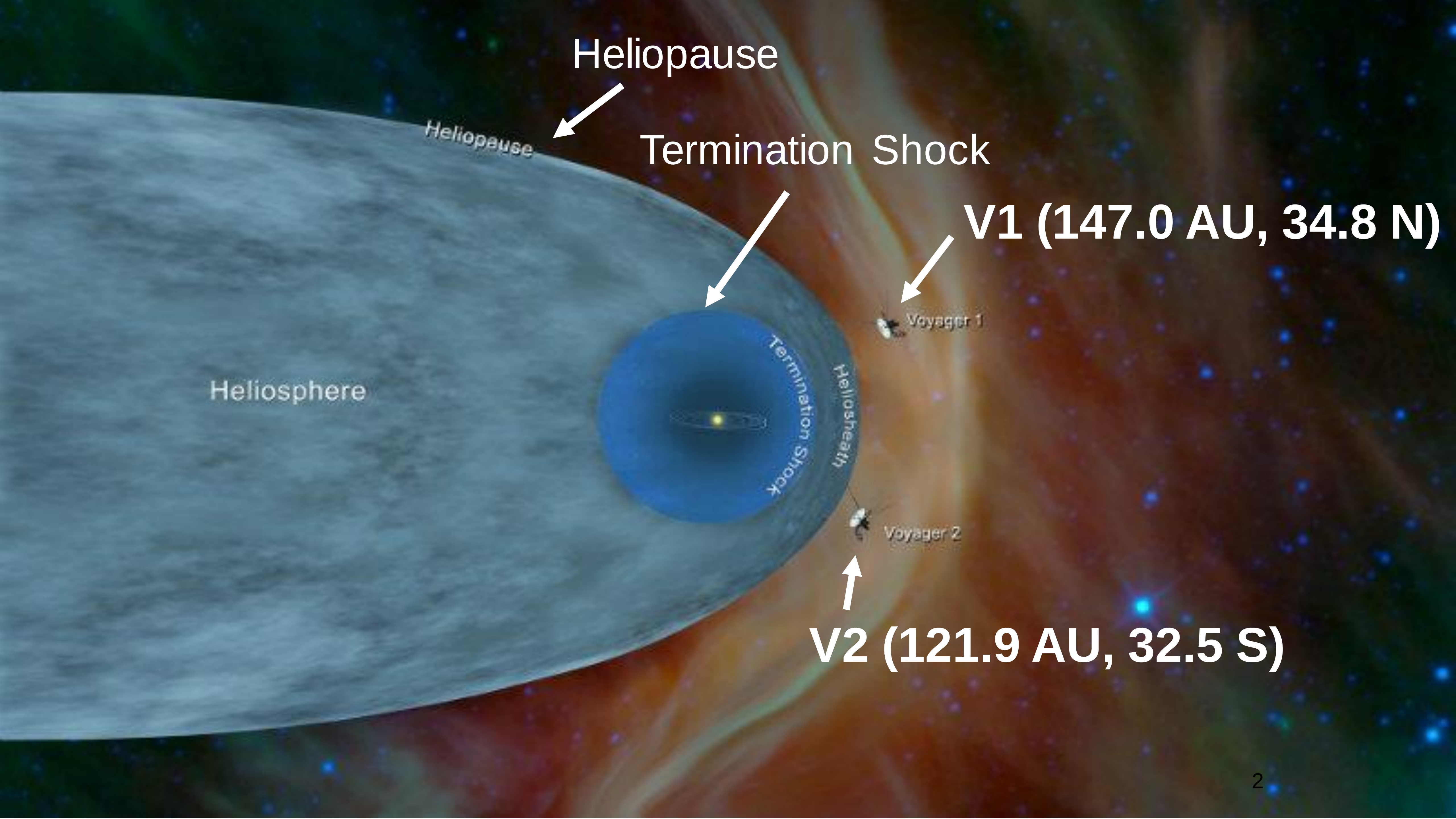
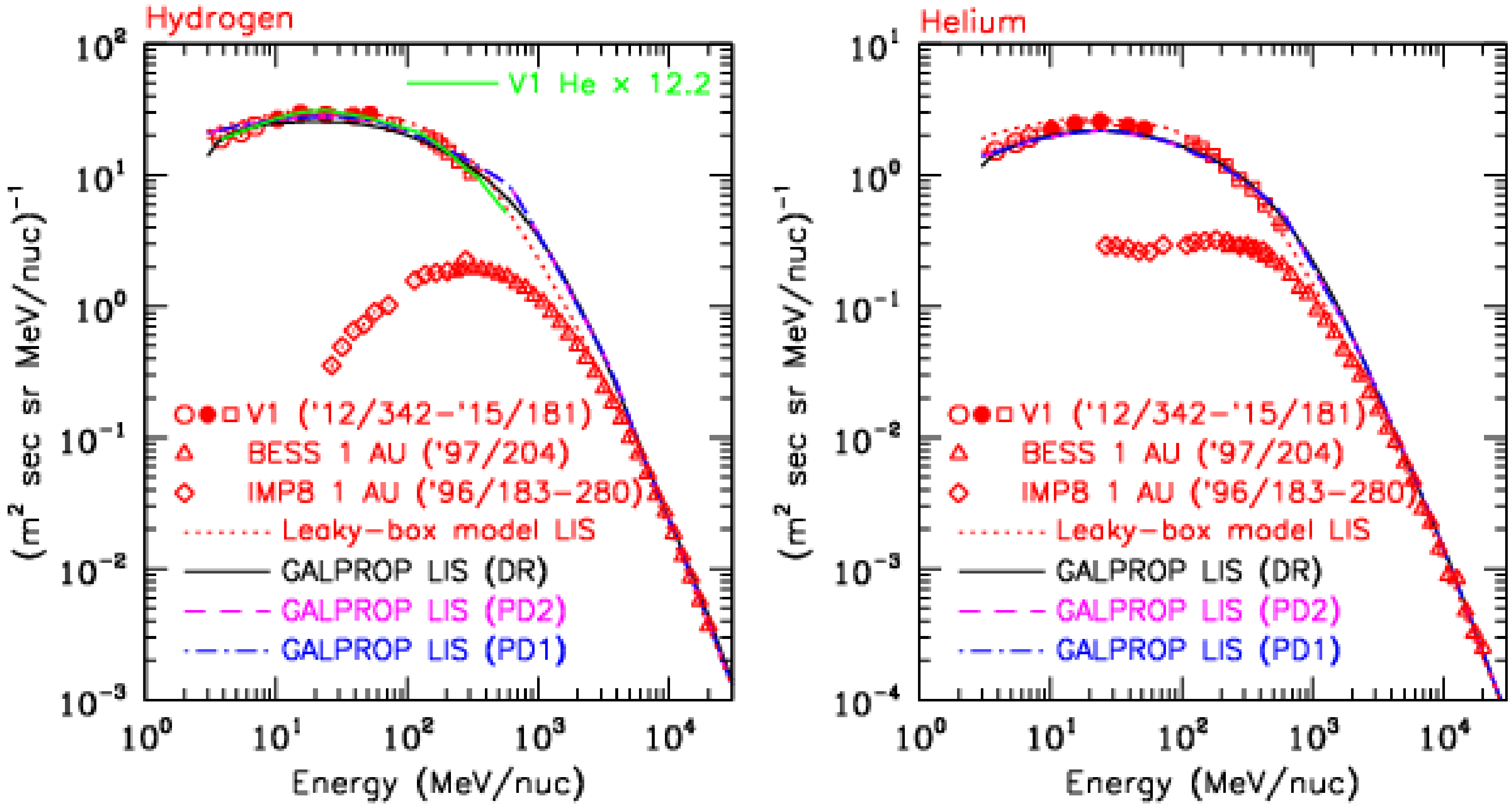

Heliopause
Termination Shock
V1 (147.0 AU, 34.8 N)
Heliopause
Voyager 1
Heliosphere
Termination Shock
Heliosheath
Voyager 2
V2 (121.9 AU, 32.5 S)

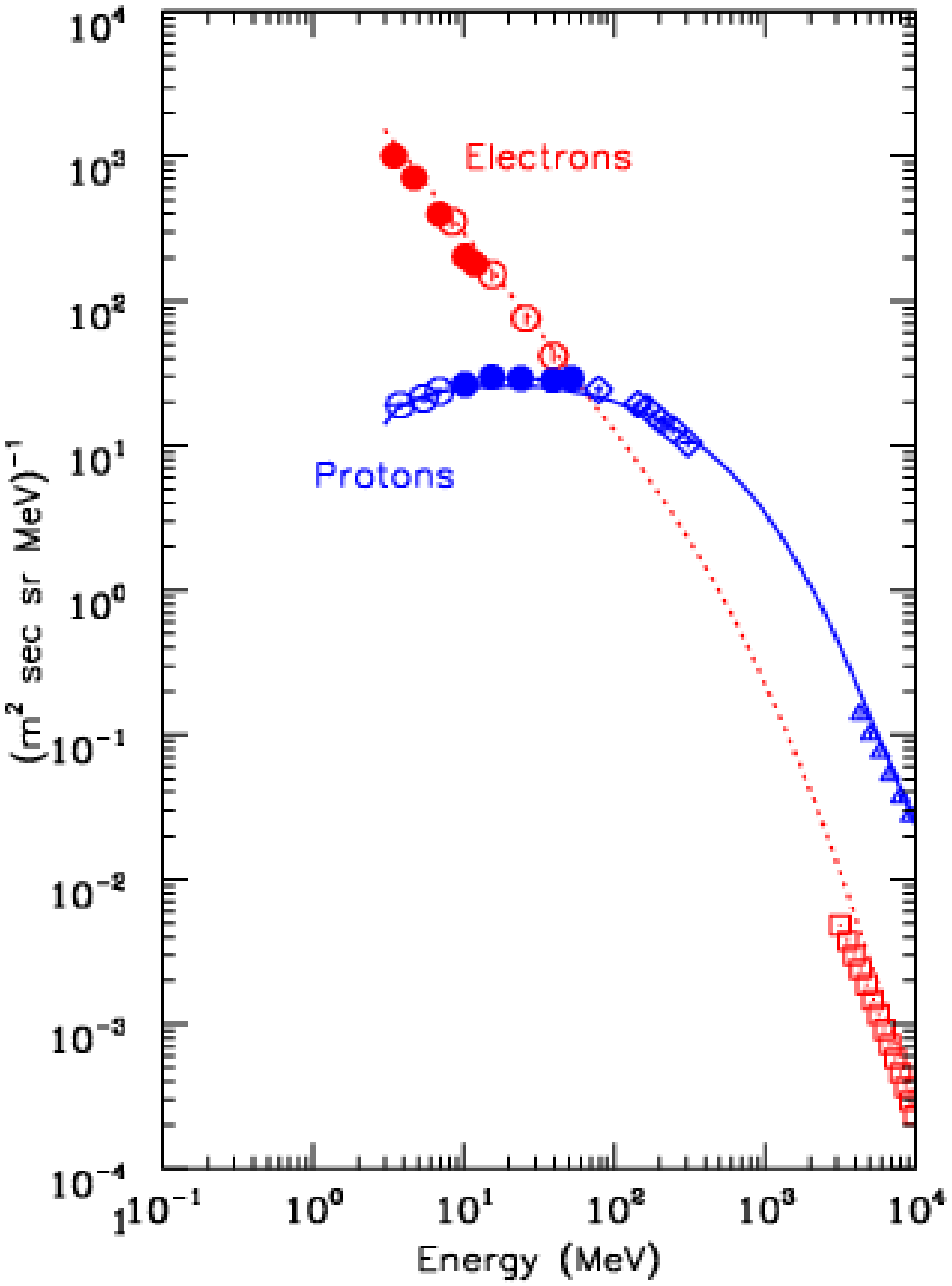


Cummings et al., ApJ, 2016

V1 H, He energy spectra for 2012/342-2015/181 in the VLISM. Also shown are 1 AU modulated spectra and four models of interstellar spectra. The four models are used to get four estimates of the energy density of cosmic rays and of the ionization rate of atomic H.

V1 spectra flatten below few hundred MeV/nuc due to ionization energy losses and peak at ~10-50 MeV/nuc with H/He ratio = 12.2±0.9 at ~3-346 MeV/nuc (see green line).

Same spectral shape for H and He indicates not modulated in solar wind.



Comparison of V1 electron and proton spectra

At 10 GeV, e/p ~0.01
At 50 MeV, e/p ~1
At 3 MeV, e/p ~50

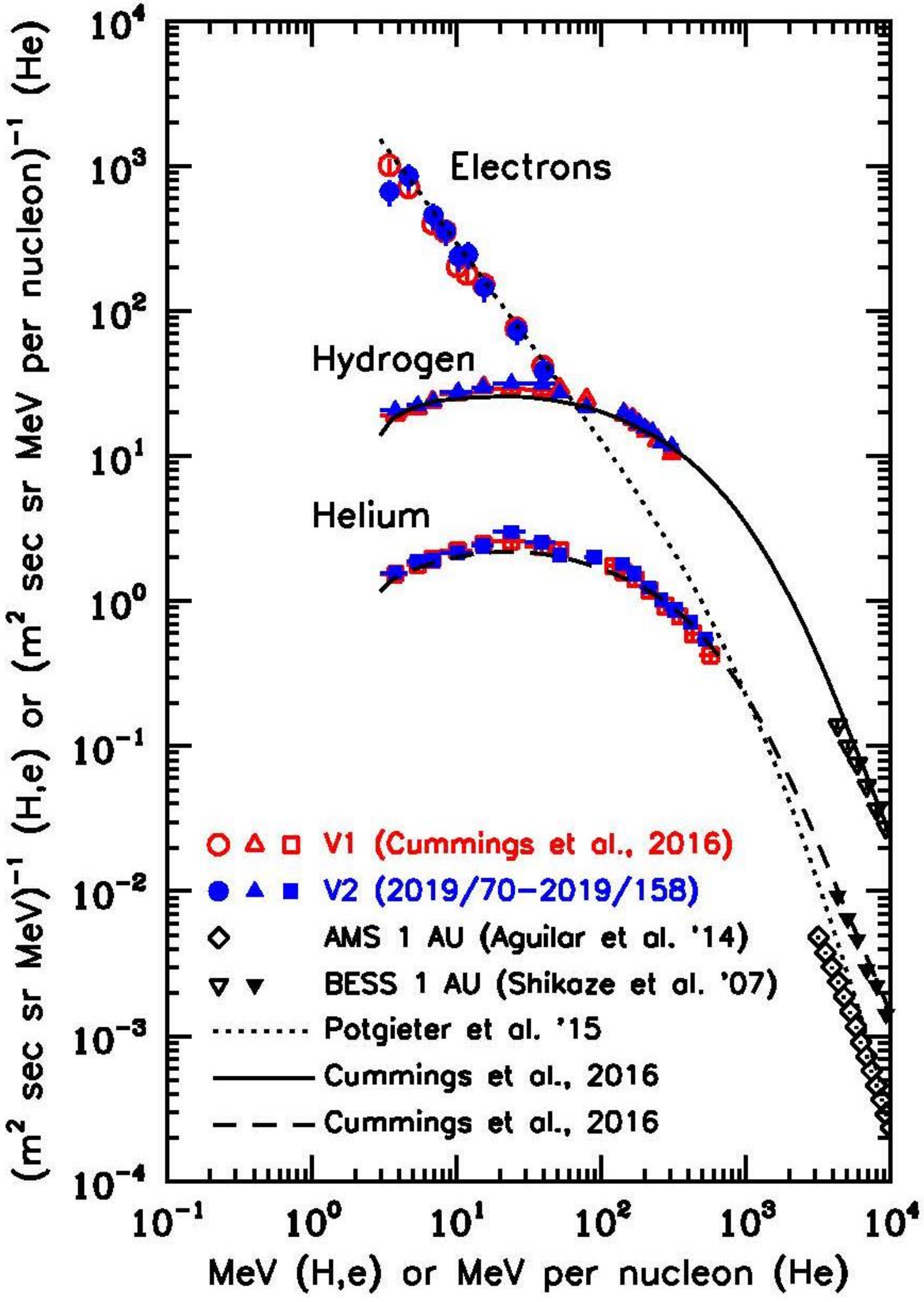
So, the typical notion that GCR electrons are ~1% of protons is only true at high energies. At a few MeV, it's just the opposite.

Voyager 1 electron (e- + e+) spectrum (circles) and AMS (e- + e+) at 1 AU (squares). High energy protons (triangles) are BESS data.

Dotted line is from Potgieter et al., 2015, and is used for energy density and ionization rate calculations.

Solid line is GALPROP DR model.

Cummings et al., ApJ, 2016

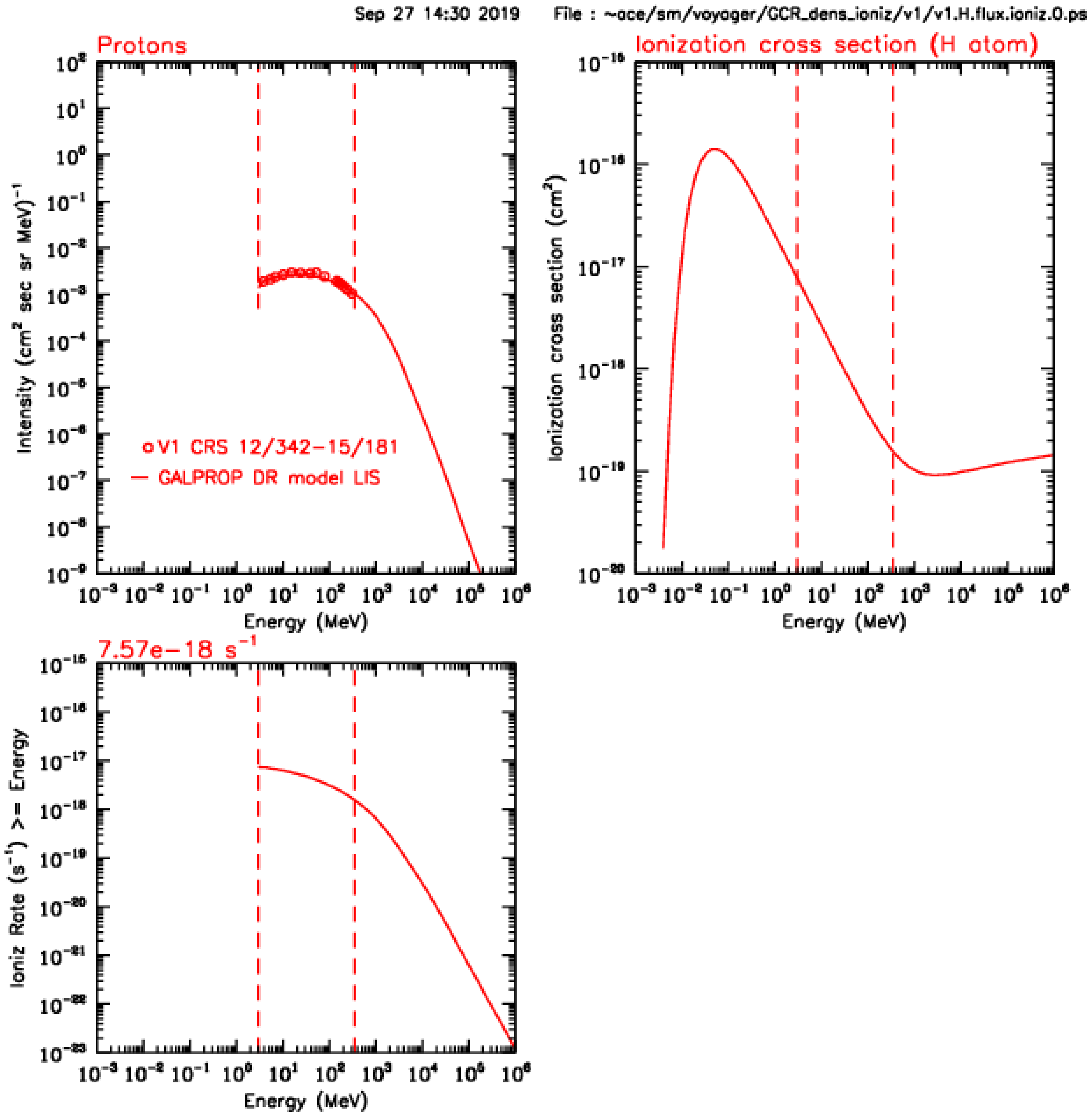


V2 just crossed the heliopause into interstellar space on 5 November 2018.

Comparison of V1 and V2 electron, H, and He spectra in the VLISM.

No significant gradient over ~167 AU separation in VLISM.

Stone et al., Nature Astronomy, 2019 (submitted)



Ionization of interstellar H atoms by GCR **protons:**

$$\zeta_{\rm H} = 4\pi\xi_{\rm H}\int_{E_{\rm low}}^{E_{\rm high}} J(E)\sigma(E)dE \qquad (1)$$

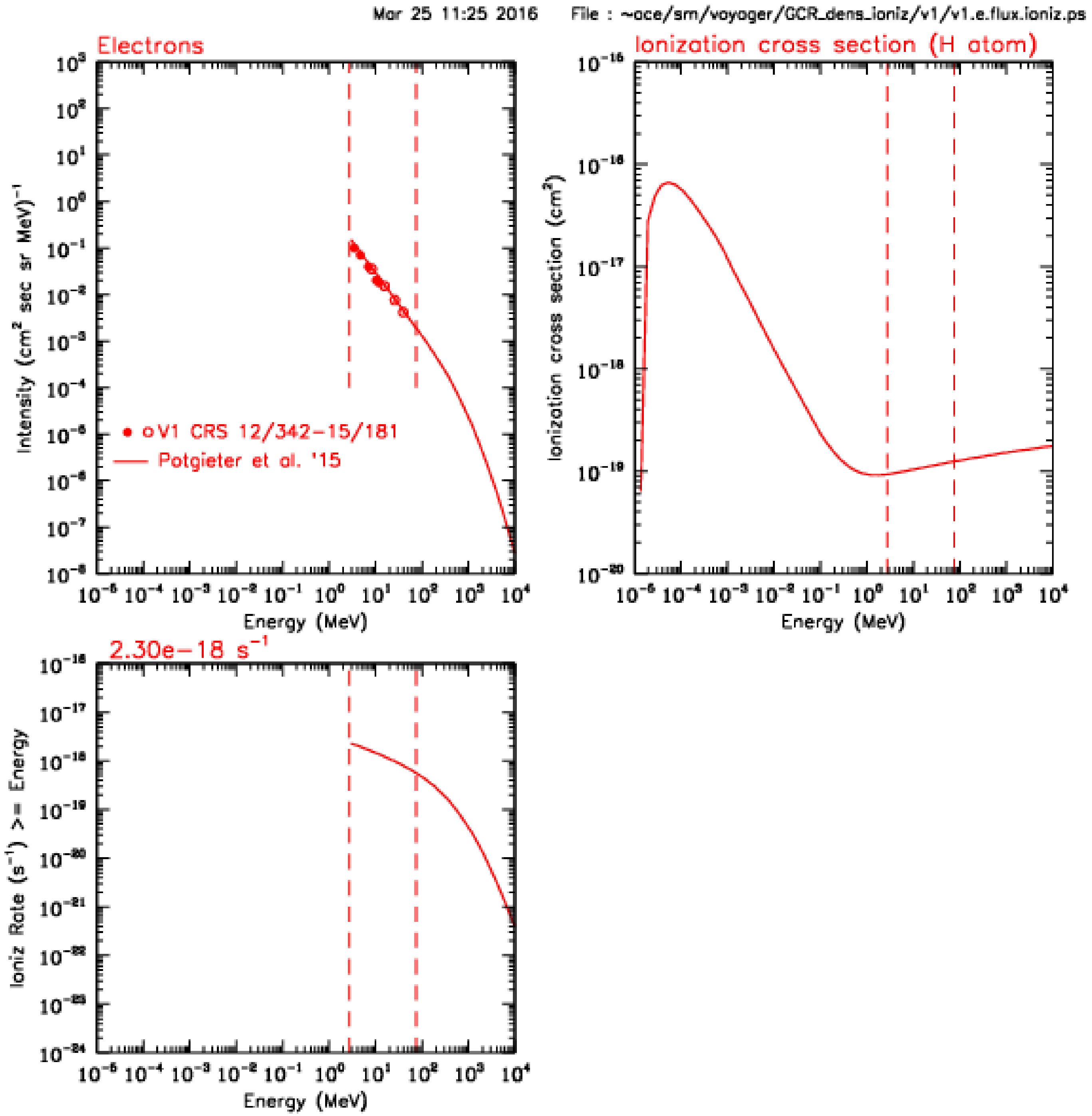
where $\xi_{\rm H} = 1.5$ to account for ionization due to secondary electrons produced in the initial ionizing event (Glassgold & Langer 1974) and $E_{\rm low}$ is 3 MeV for GCR protons and electrons and 3 MeV nuc^{-1} for GCR nuclei with $Z > 1$.

Vertical dashed lines mark extent of new Voyager observations in LISM.

Top right: cross section, which peaks at very low energies, ~50 keV.

Bottom left: Integral ionization rate.

Ionization rate from ≥ 3 MeV protons is 7.6 x 10^{-18} s^{-1} from GALPROP DR model.



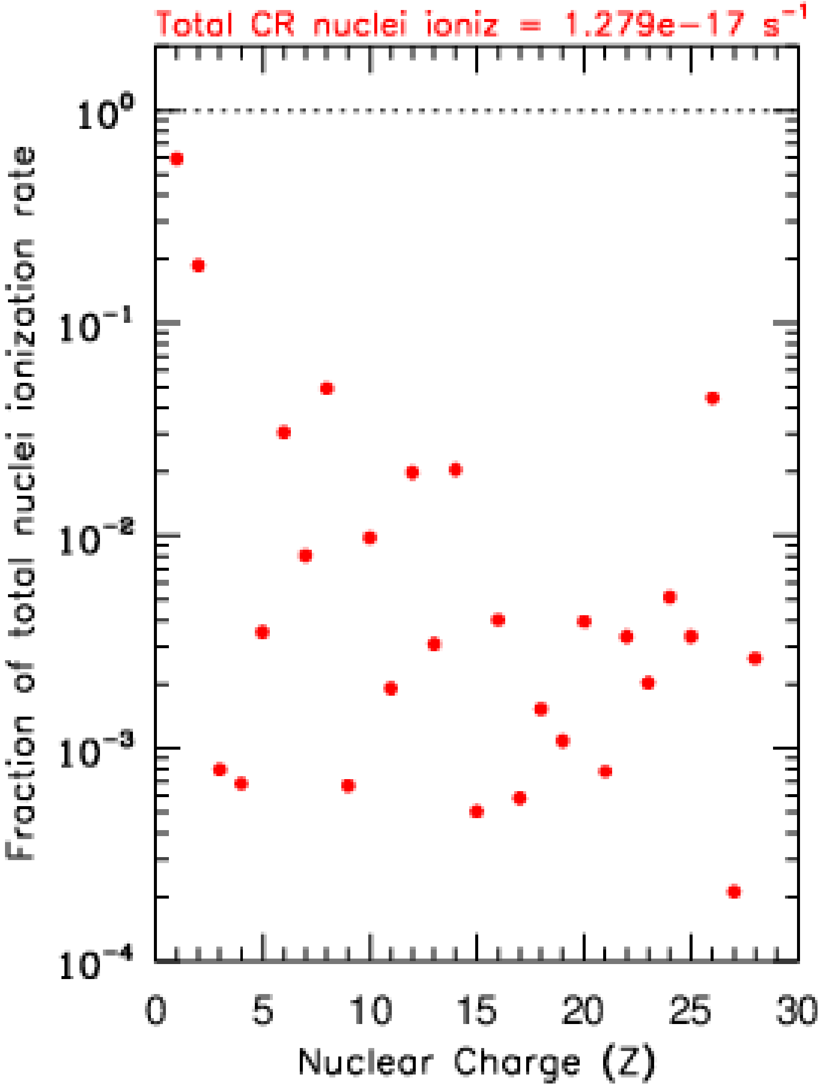
Ionization of interstellar H atoms by GCR electrons:

Vertical dashed lines mark extent of new Voyager observations.

Top right: cross section, which peaks at very, very low energies, ~60 eV.

Bottom left: Integral ionization rate.

Ionization rate of H atoms from ≥ 3 MeV electrons is
2.3×10^{-18} s^{-1} from Potgieter et al. 2015 LISM energy spectrum.



Calculated ionization rate from all nuclei ≥3 MeV/nuc from GALPROP DR model. Not shown are estimates from Cu through U, which add negligible amount (2.1 x 10^{-21} s^{-1}) .

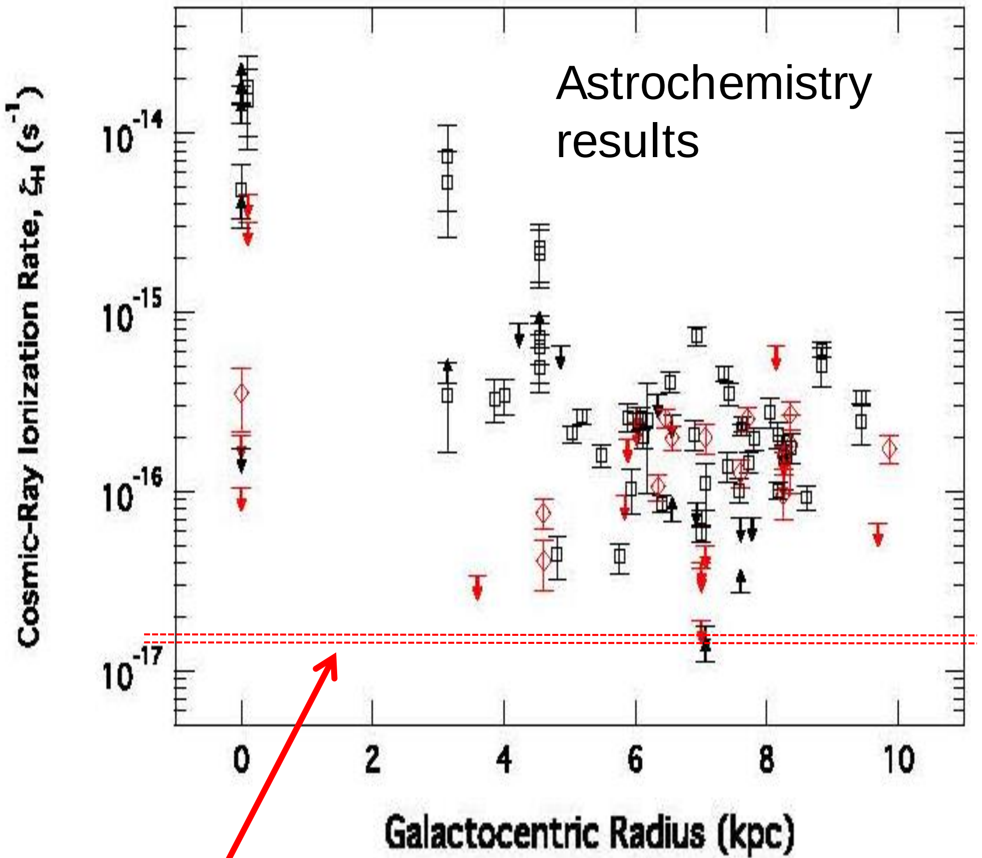
Total nuclei + electrons ionization rate of atomic H at ≥ 3 MeV/nuc is 1.5 x 10^{-17} s^{-1} from GALPROP DR model.

Propagation Model for Nuclei	Ionization Rate, 10^{-17} s^{-1}				
	H	He	Li–Ni	*e*	Total
LBM	0.85	0.27	0.28	0.23	1.64
DR	0.76	0.24	0.28	0.23	1.51
PD1	0.83	0.24	0.28	0.23	1.56
PD2	0.83	0.24	0.27	0.23	1.56

1.51-1.64 x 10^{-17} s^{-1}

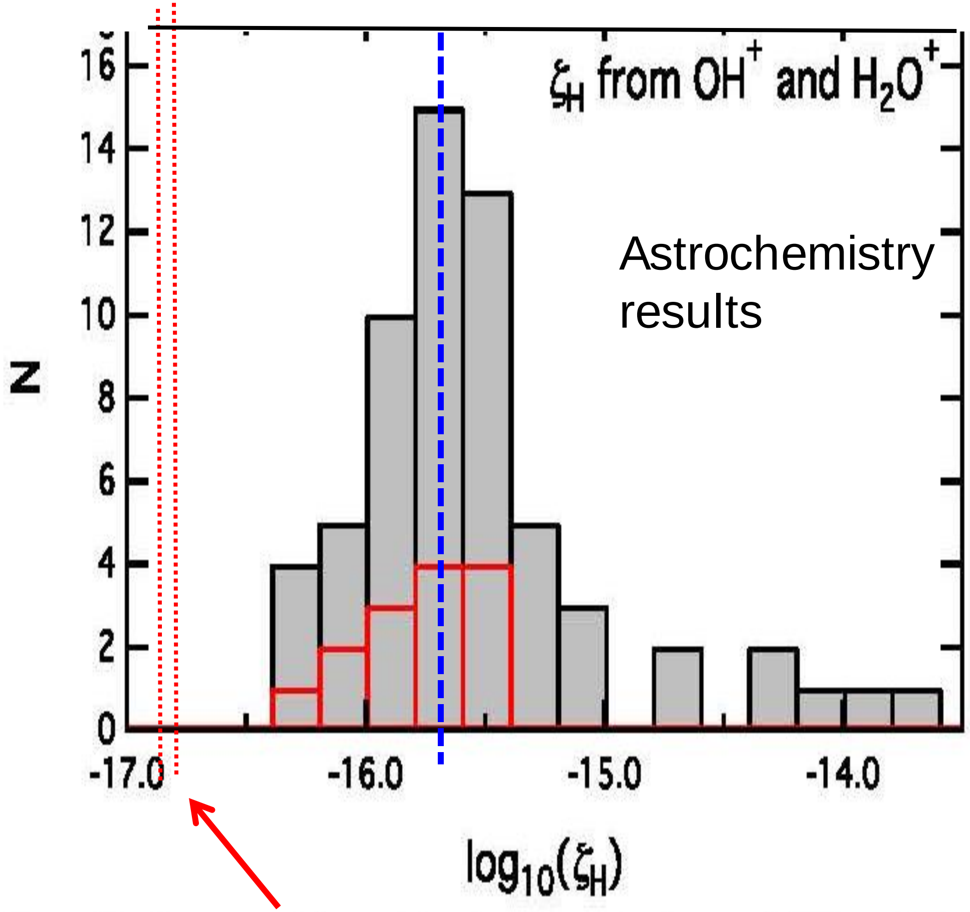
Range from models is 1.51-1.64 x 10^{-17} s^{-1} which is about a factor of 11-12 below estimates in diffuse interstellar clouds using astrochemistry methods (~1.78 x 10^{-16} s^{-1})

INDRIOLO ET AL. THE ASTROPHYSICAL JOURNAL, 800:40 (26pp), 2015 February 10

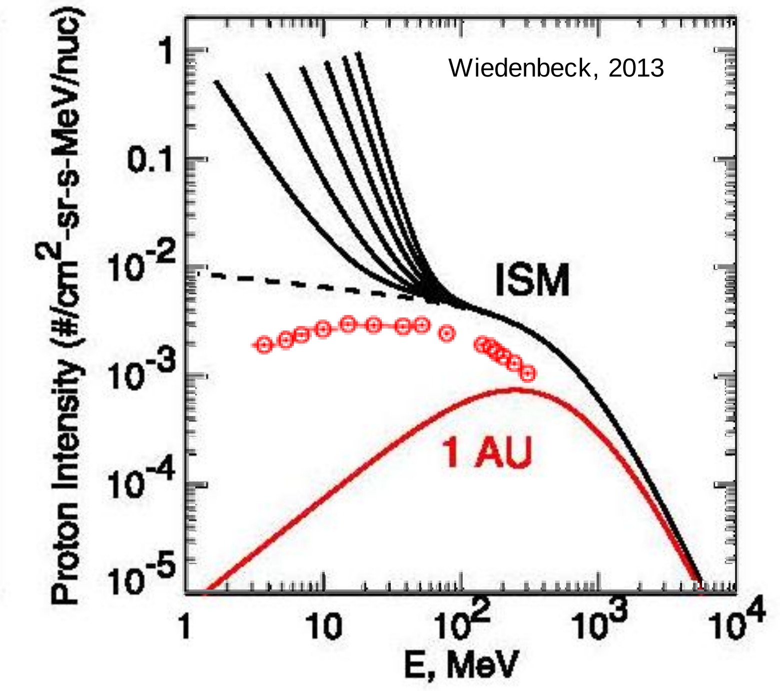


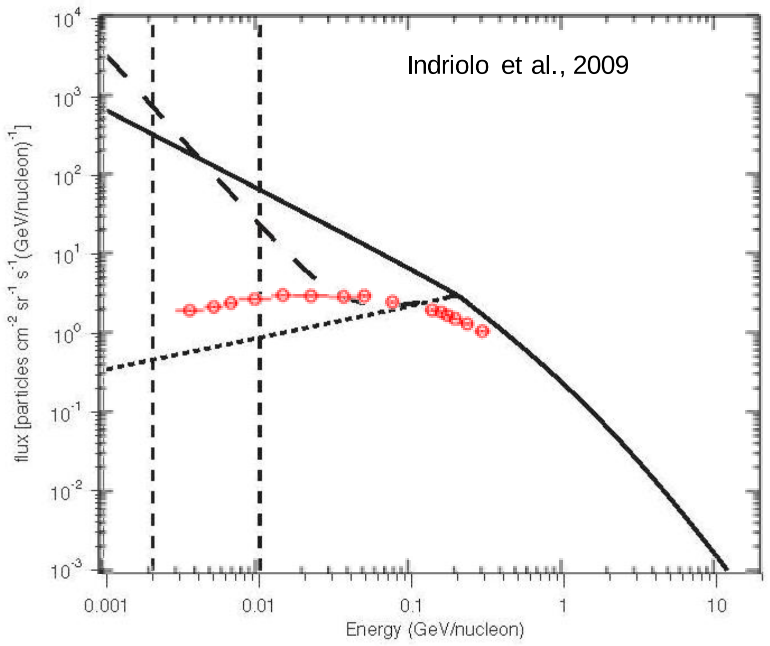
Voyager
$1.51\text{-}1.64 \times 10^{-17}$ s^{-1}

1.78×10^{-16} s^{-1}



Voyager
$1.51\text{-}1.64 \times 10^{-17}$ s^{-1}





This is not a new issue.

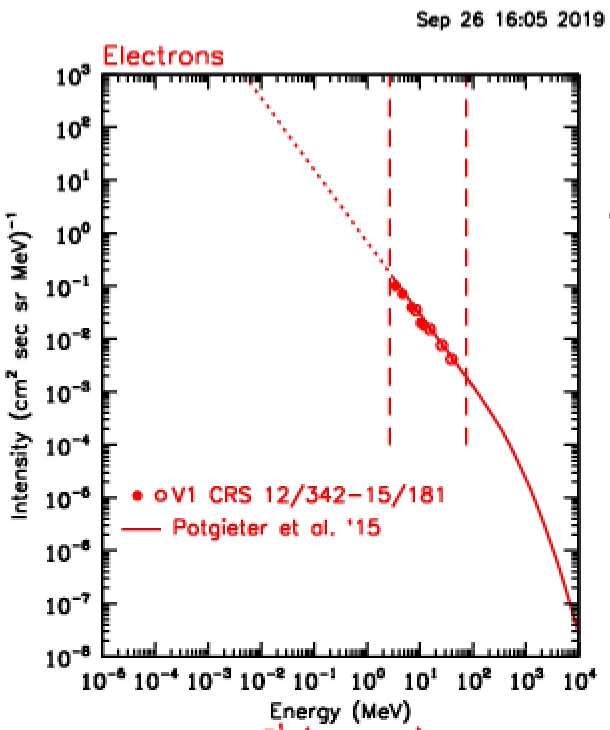
Since the ionization cross section is higher at lower energies, the typical approach has been to add an upturn to the spectrum at low energies to get the higher ionization rate.

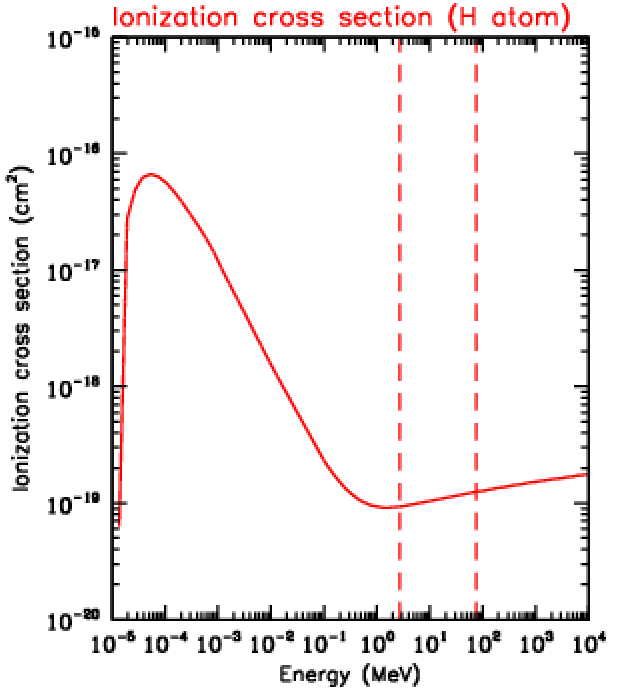
The new Voyager data are showing there is no upturn in the energy spectra in the VLISM down to ~3 MeV/nuc.

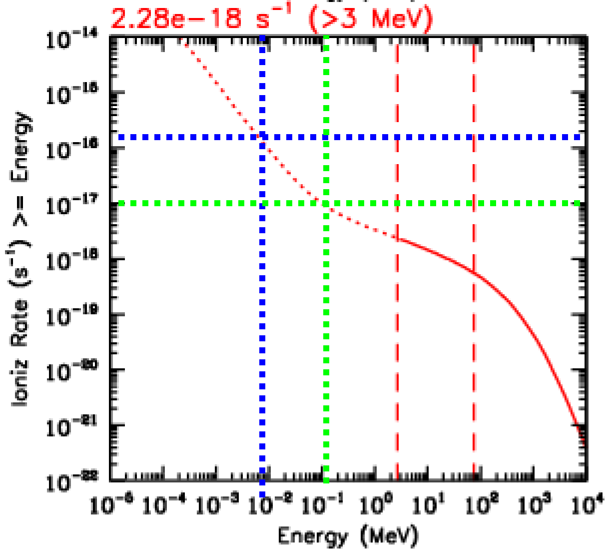
Possibilities to explain the ionization rate discrepancy:

Electrons below 3 MeV could be contributing significantly since electron spectrum is continuing to increase towards lower energies and the ionization cross-section is doing that as well.

GCR intensity could vary spatially in galaxy, since a larger ionization rate is expected in the major spiral arms, which host most GCR sources, and the Sun is in a minor arm.







1.6×10^{-16} s^{-1}

at 6 keV

Ionization of interstellar H atoms by GCR electrons:

Extend Potgieter et al. 2015 electron spectrum to low energies.

To get enough ionization rate to make up for the discrepancy with astrochemistry results, the spectrum would have to extend to ~6 keV as a power law.

Not likely – spectrum should bend over at higher energies (see next slide).

Even if extended to 100 keV as a power law, it would only contribute ~1×10^{-17} s^{-1}, and the discrepancy would still be a factor of ~7.

I am skeptical that low-energy electrons can solve the problem.

Range vs energy from Padovani et al., 2018.
GCR protons intensity peaks near 30 MeV.

Would expect GCR electrons to peak near 2.5 MeV. No indication of that down to 3 MeV.

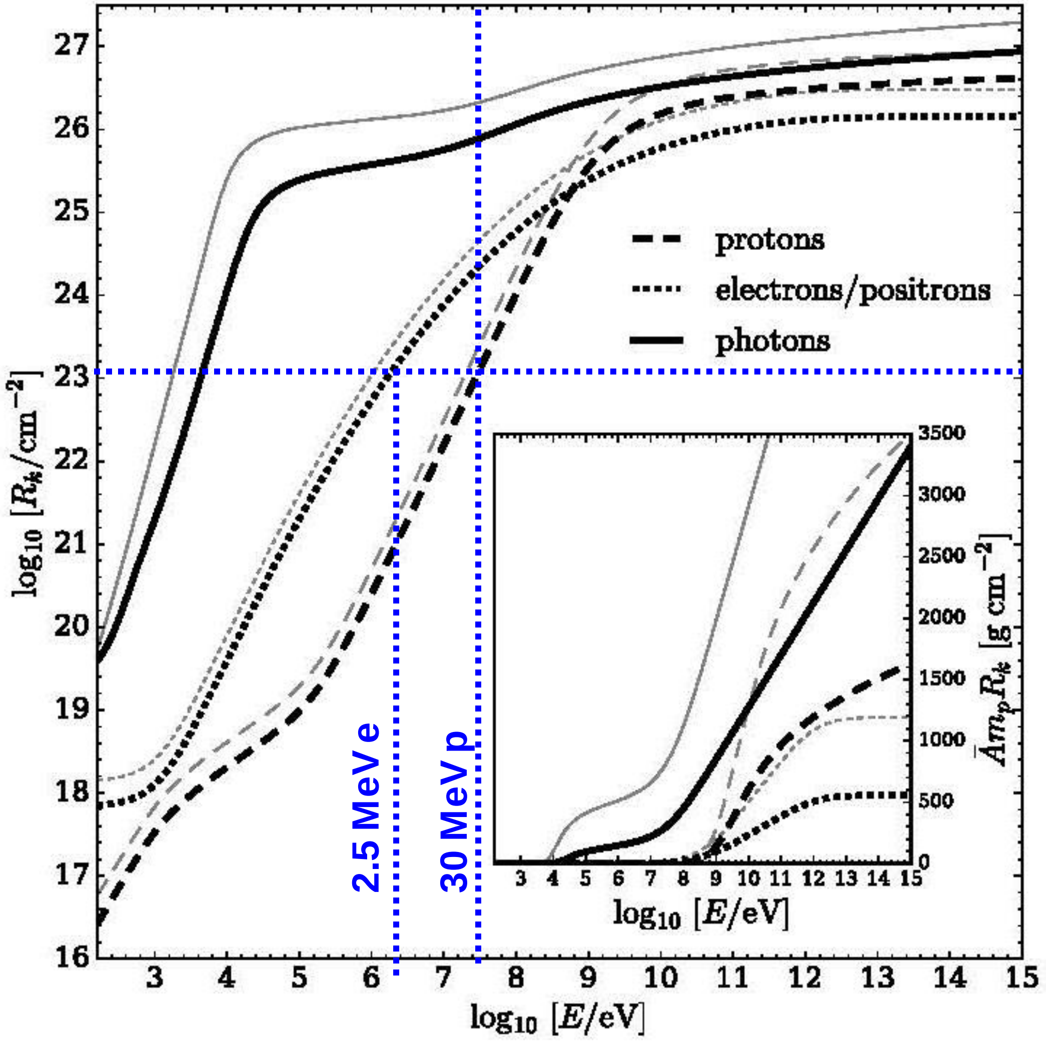


Fig. 2. Total range functions, $R_k(E)$, of primary and secondary CR particles (thick black lines), Eq. (9). The inset shows the total range functions multiplied by $\bar{A}m_p$, to highlight the behaviour at large surface densities. For comparison, the range functions for atomic hydrogen are also plotted (thin grey lines).

Padovani et al., A&A, 2018

Boschini et al. 2018

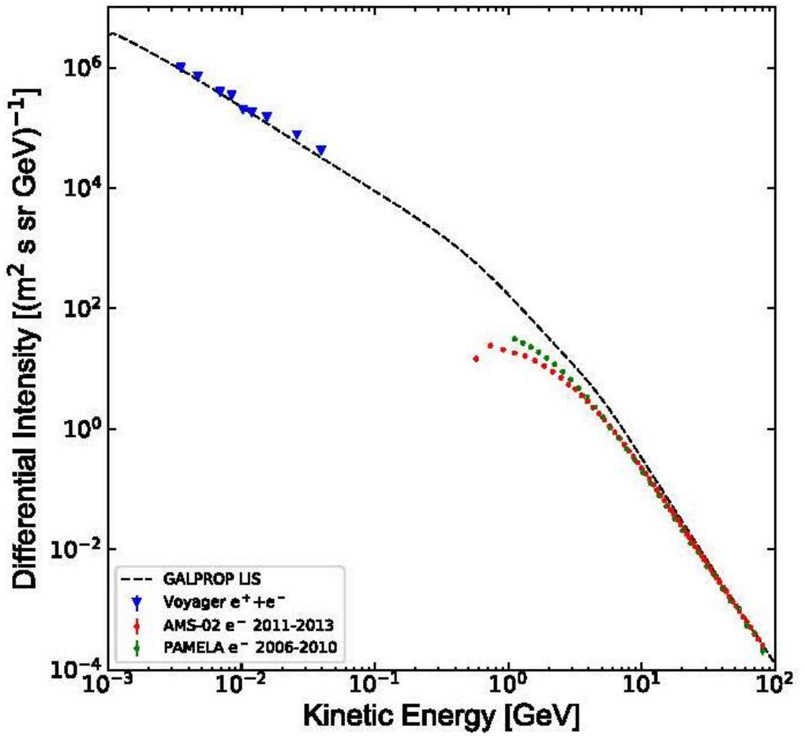
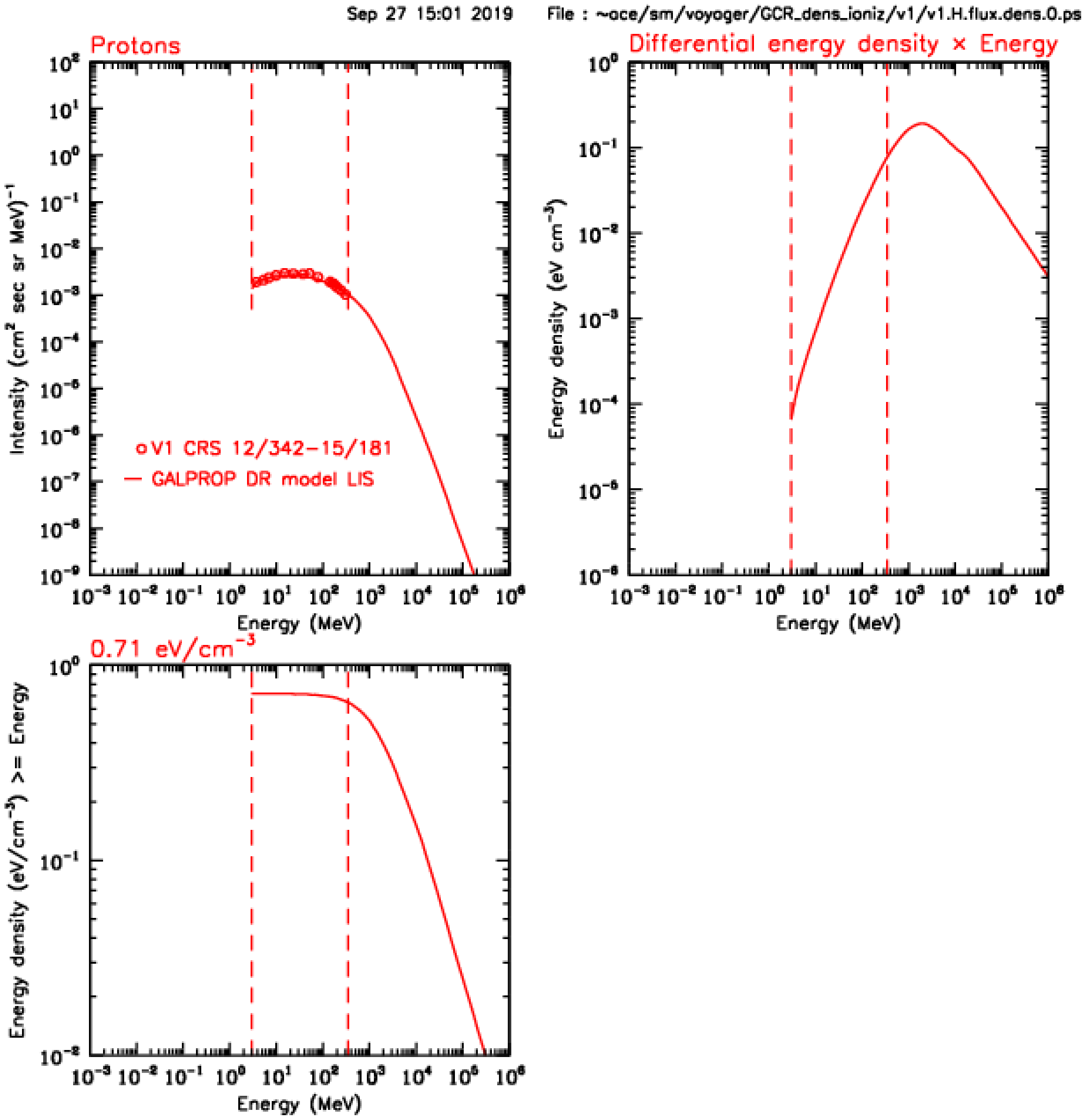


Figure 1. Electron LIS (dashed) as derived from the MCMC procedure compared with AMS-02, PAMELA, and *Voyager 1* measurements (see the text).

Recent GALPROP LISM electron spectrum shows no turn over down to 1 MeV.

It would be interesting to know at what energy it does turn over.



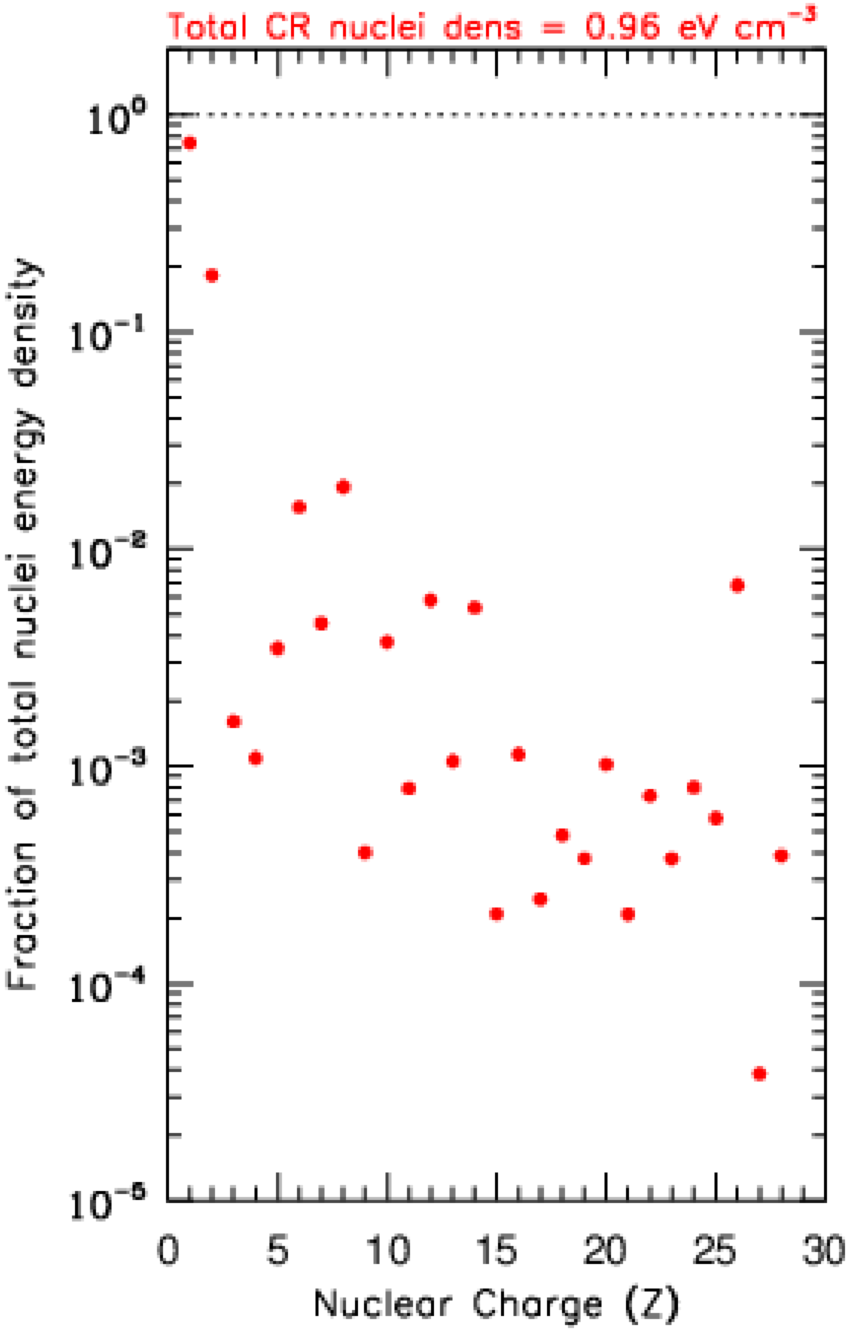
Energy density:

$$\epsilon_{\mathrm{GCR}} = 4\pi N \int_{E_{\mathrm{low}}}^{E_{\mathrm{high}}} E\,(J\,(E)/v)\,dE \qquad (6)$$

where v is the particle velocity in cm s^{-1} and the intensity $J(E)$ is in (cm^2 s sr eV)$^{-1}$ for protons and electrons, where $N = 1$, and in (cm^2 s sr eV nuc^{-1})$^{-1}$ for heavier ions with N being the number of nucleons.

Energy density is a higher-energy phenomenon. Most of the contribution is above the Voyager energy range.

Energy density from protons with E ≥ 3 MeV is 0.71 eV/cm^3 using GALPROP DR model.



Calculated energy densities from all nuclei at ≥ 3 MeV/nuc from GALPROP DR model. Not shown are estimates from Cu through U, which add negligible amount (2.1 x 10^{-5} eV/cm^3)

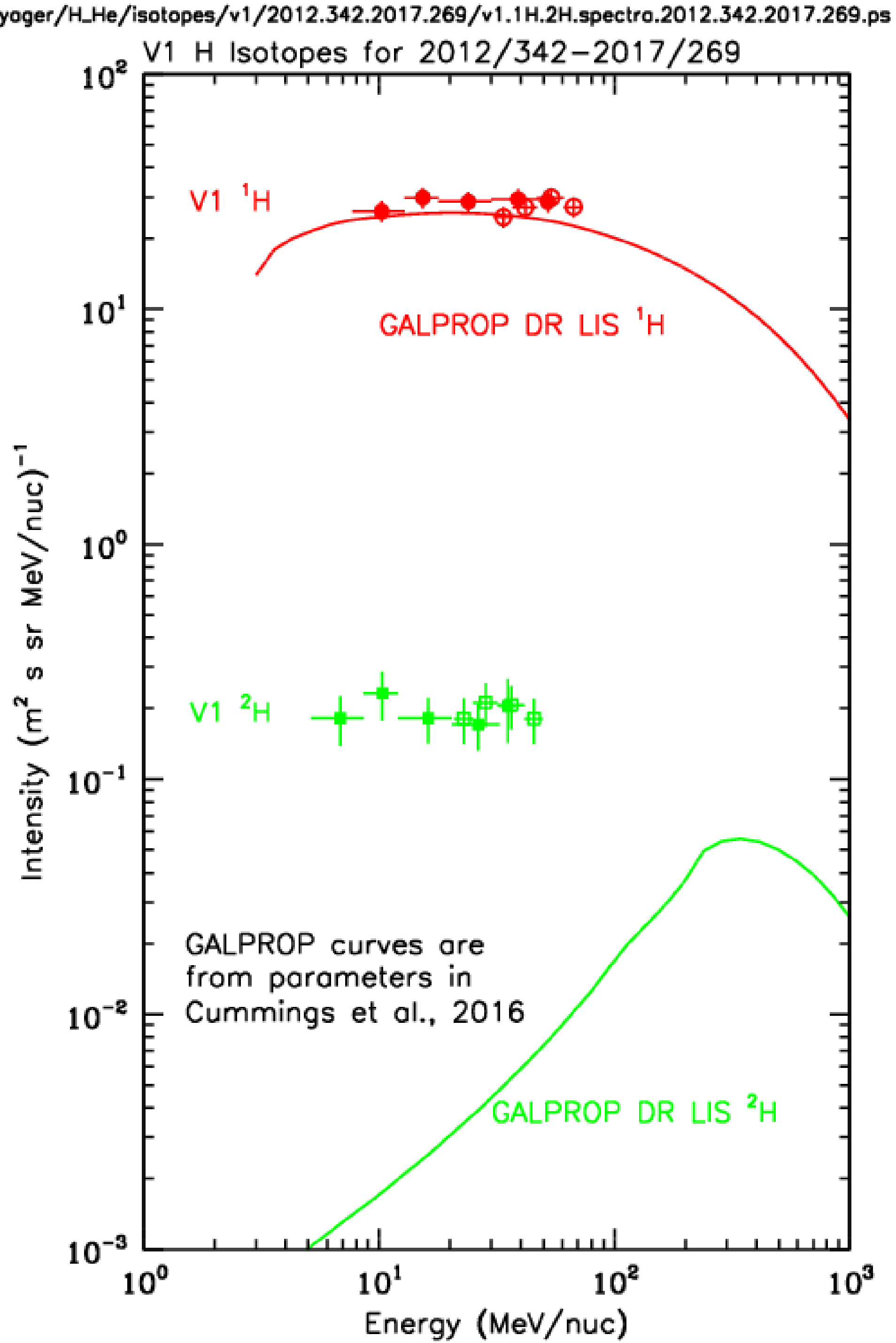
Total nuclei + electrons energy density at ≥ 3 MeV/nuc is 1.0 eV/cm^3 from the DR model.

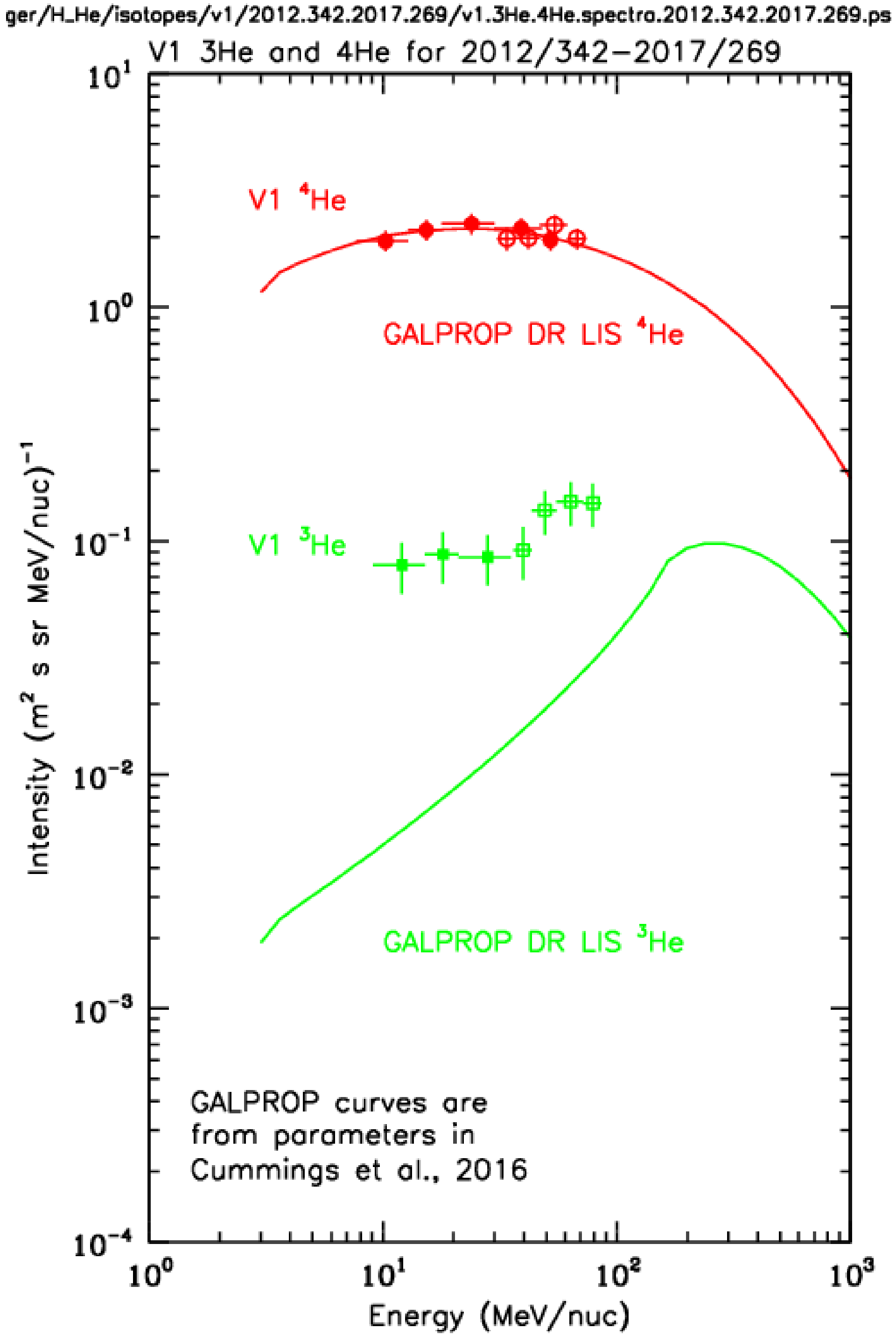
Propagation Model for Nuclei	Energy density, eV cm^{-3} H	He	Li-Ni	e	Total
LBM	0.58	0.15	0.07	0.04	0.83
DR	0.71	0.18	0.07	0.04	1.00
PD1	0.73	0.17	0.07	0.04	1.02
PD2	0.73	0.17	0.07	0.04	1.01

~1 eV/cm^3

Range from models is 0.83-1.02 eV/cm^3 .

If equipartition holds, B would be 5.7-6.2 μG, compared to ~4 to 5.5 μG currently measured by V1. Disparity is even greater, since V1 observation likely enhanced by draping.

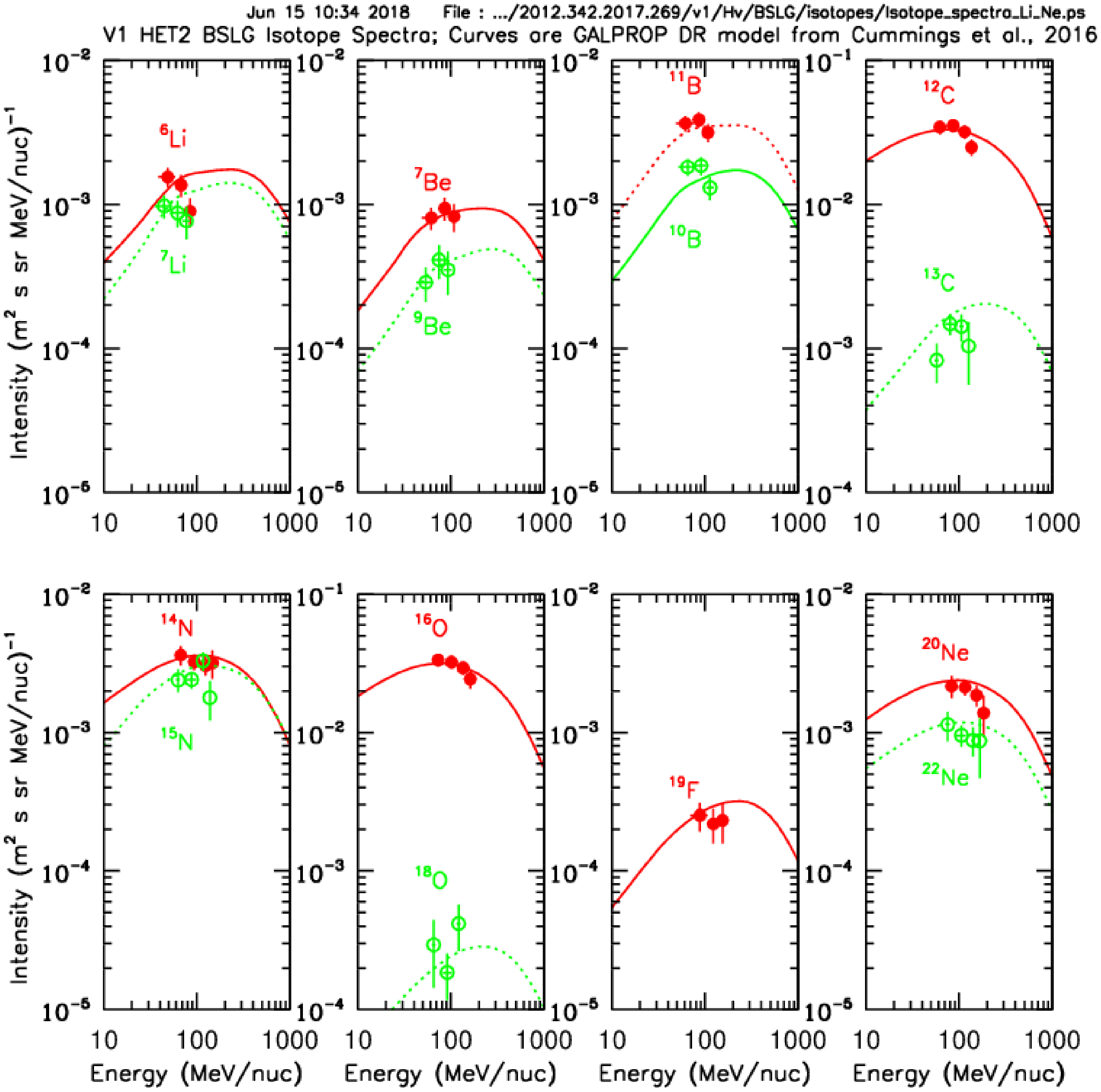




Isotopes of GCR H and He in the LISM (Preliminary)

We see a lot more 2H and 3He than the GALPROP model would predict.

We suspect that the cross-sections in GALPROP need investigation.



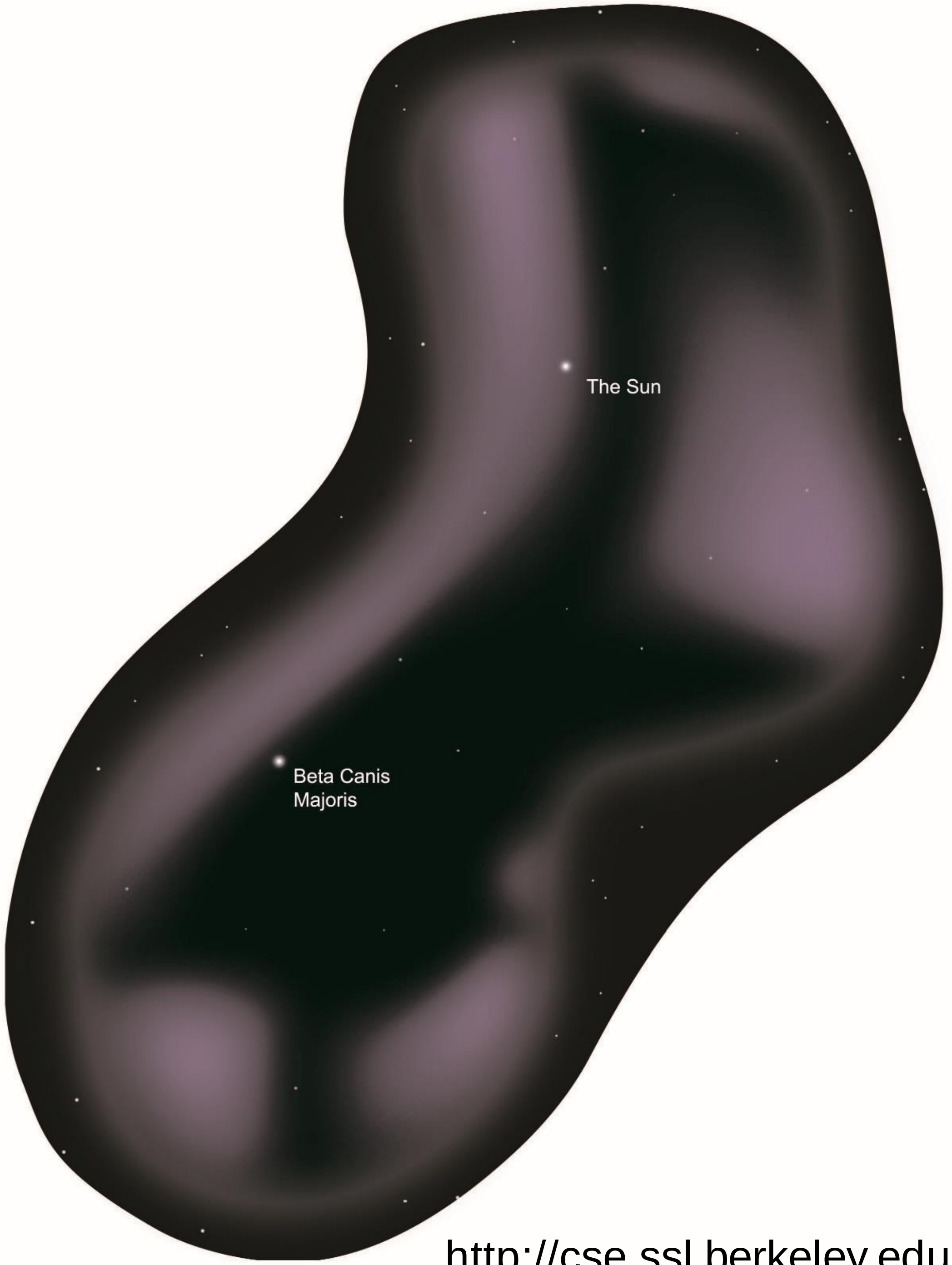
On the other hand, spectra of the heavier isotopes seem to be better aligned with predictions.

These are preliminary spectra of some of the heavier isotopes from Voyager 1 in the LISM. The curves are from parameters in the GALPROP DR model in Cummings et al., 2016.

Possible ways to resolve the 2H, 3He problem in the LISM:

1) Review production cross sections for 2H and 3He used in the models (see Coste et al., 2012, for a compilation of these).

2) Adjust rigidity dependence of diffusion coefficient or escape mean free pathlength at low rigidities, but need to preserve agreement with heavier secondaries data.



http://cse.ssl.berkeley.edu/chips_epo/bubble.pdf

Local Bubble and the Shape of the Cosmic Ray Spectra in the Local Interstellar Medium

Silsbee & Ivlev 2019 suggest an interesting possibility for why the Voyager spectra roll over and peak near 30 MeV (for protons).

Suppose the spectrum outside the Local Bubble is dJ/dE ~E^{-1} , as expected from diffusive shock acceleration for a strong shock.

Suppose the edge of the Bubble is a thin, dense region of compressed magnetic fields that are parallel to the edge (Alves et al., 2018).

Impress that E^{-1} spectrum on the Bubble and the particles will be guided to propagate along that field in the edge region and scatter back and forth as well. They can lose a lot of energy in doing so.

Local Bubble and the Shape of the Cosmic Ray Spectra in the Local Interstellar Medium

The Astrophysical Journal, 879:14 (7pp), 2019 July 1

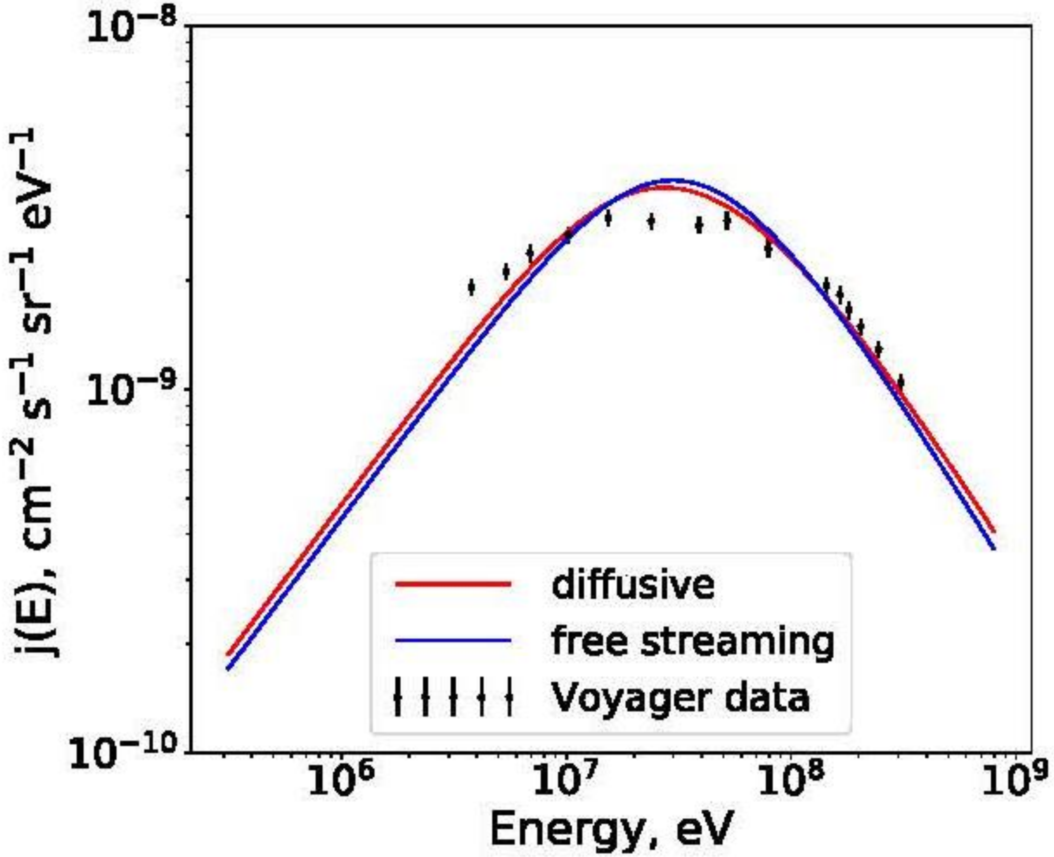


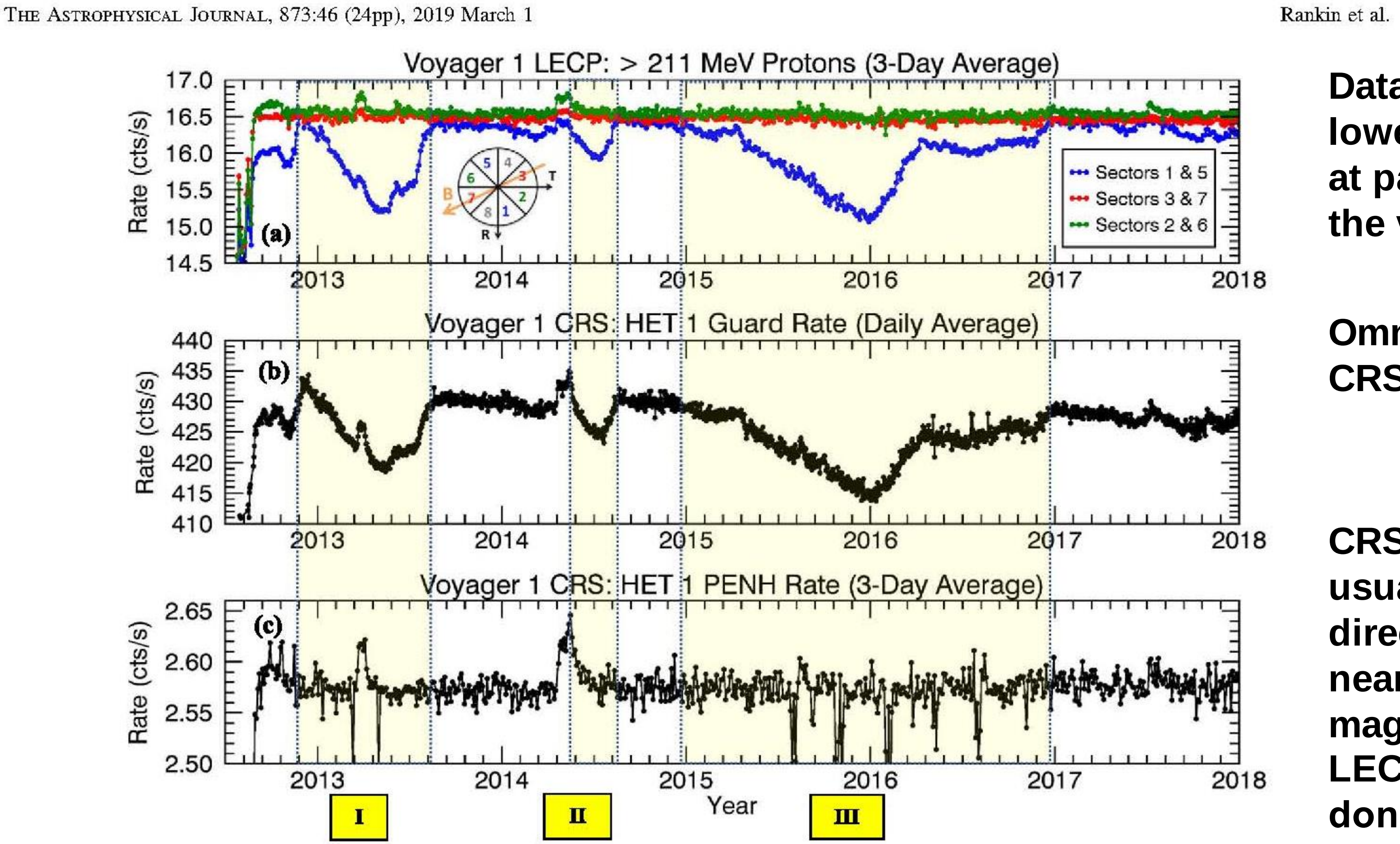
Figure 2. Red and blue curves show the best-fit attenuated spectra from Equations (21) and (30) respectively. The black points with error bars represent the *Voyager* data (Cummings et al. 2016).

Silsbee & Ivlev 2019 find that they can get an approximate representation of the Voyager spectrum with such a model.

The column density for the diffusive case is a reasonable number, 5 x 10^{21} cm^{-2} .

(Column density is unreasonably high for the free-streaming case, 1.4 x 10^{23} cm^{-2})

GCR Anisotropy at V1 in VLISM



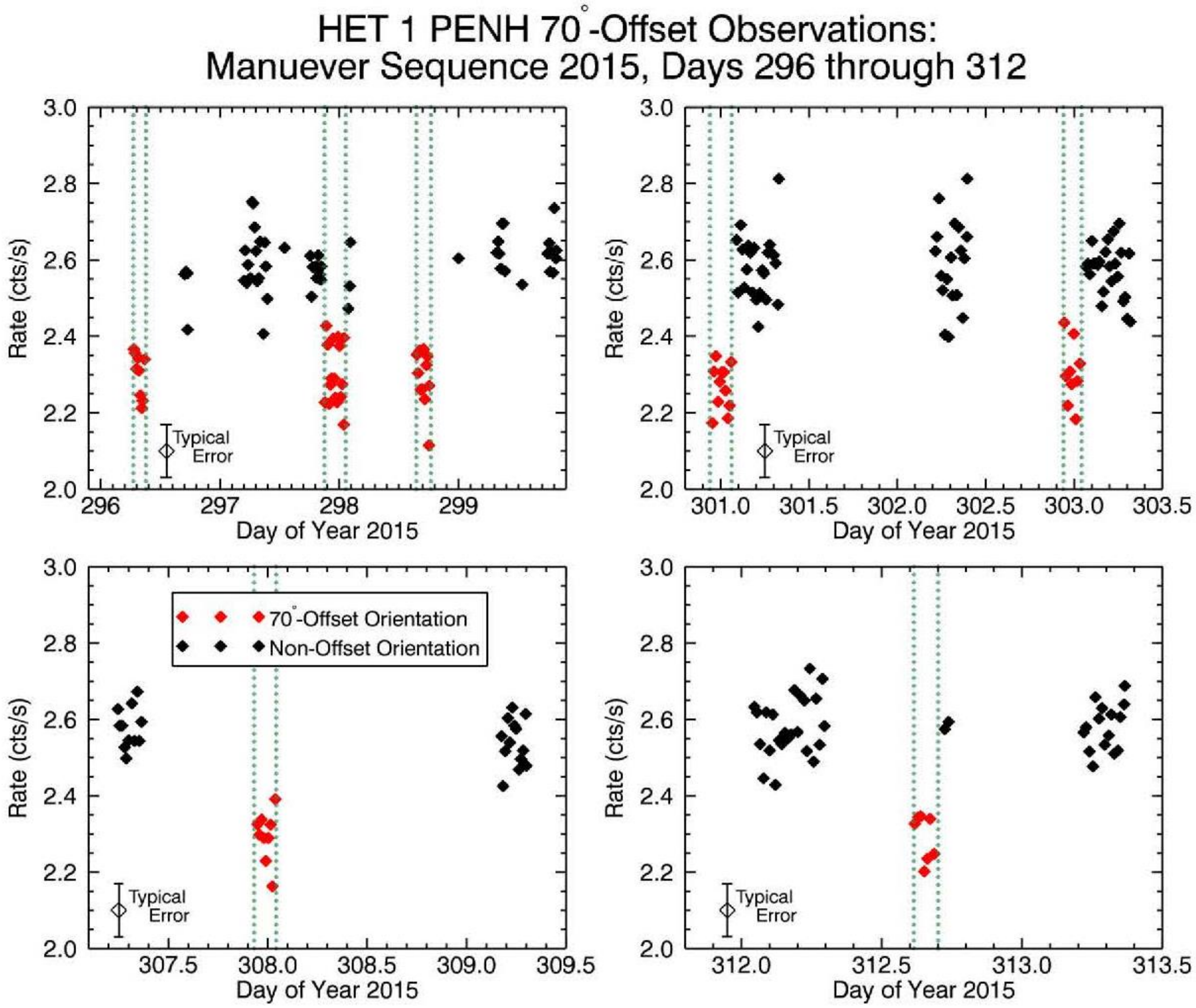
Data from V1 LECP showing lower rates for sectors looking at particles with pitch-angles in the vicinity of 90º (blue curve).

Omni-directional rate from V2 CRS showing similar profile.

CRS rate from telescope usually pointed in a fixed direction, not usually pointed near 90º with respect to the magnetic field. Looks similar to LECP data from sectors that don't include the perpendicular direction to the magnetic field.

GCR Anisotropy at V1 in VLISM

THE ASTROPHYSICAL JOURNAL, 873:46 (24pp), 2019 March 1 Rankin et al.



But sometimes HET 1 points in a different direction; during periods designed to change the angle of the LECP rotation plane.

These are data from some of those occasional off-nominal-pointing data collection periods.

The HET 1 field of view is 40º and in the off-nominal position, the perpendicular to the field direction is within the telescope field of view and the rate is lower (red points).

GCR Anisotropy at V1 in VLISM

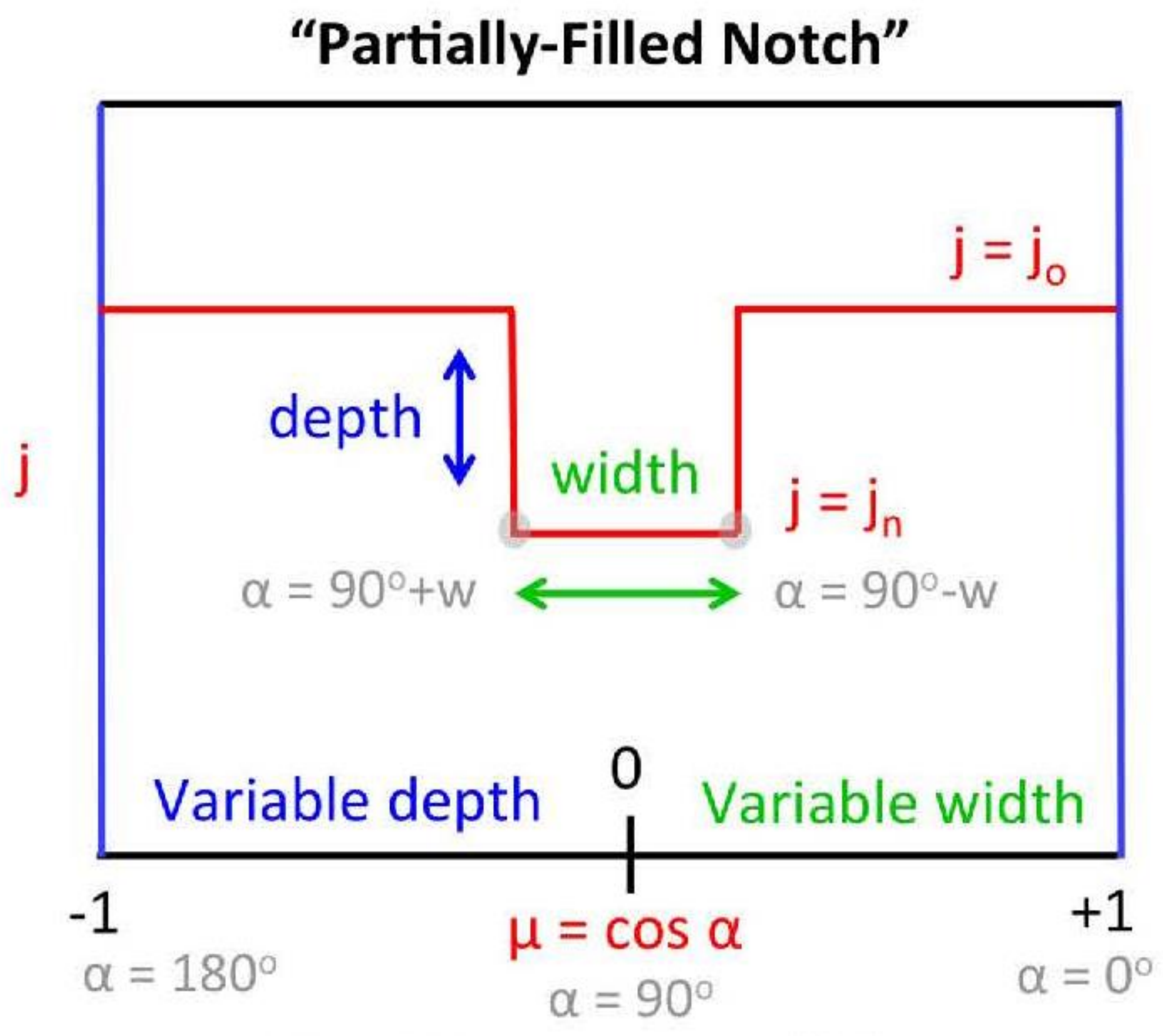


Figure 19. Diagram of notch model #2.

Rankin et al. modeled the pitch-angle distribution as a rectangle, with a width and a depth centered on the perpendicular to the magnetic field.

Using response functions of the HET 1 and HET 2 telescopes and of the omni-directional "telescope", Rankin et al. found curves of depth vs width in the pitch-angle distribution that would fit the observations for the off-nominal maneuvers and in the omni-directional case.

Rankin et al., ApJ, 2019

GCR Anisotropy at V1 in VLISM

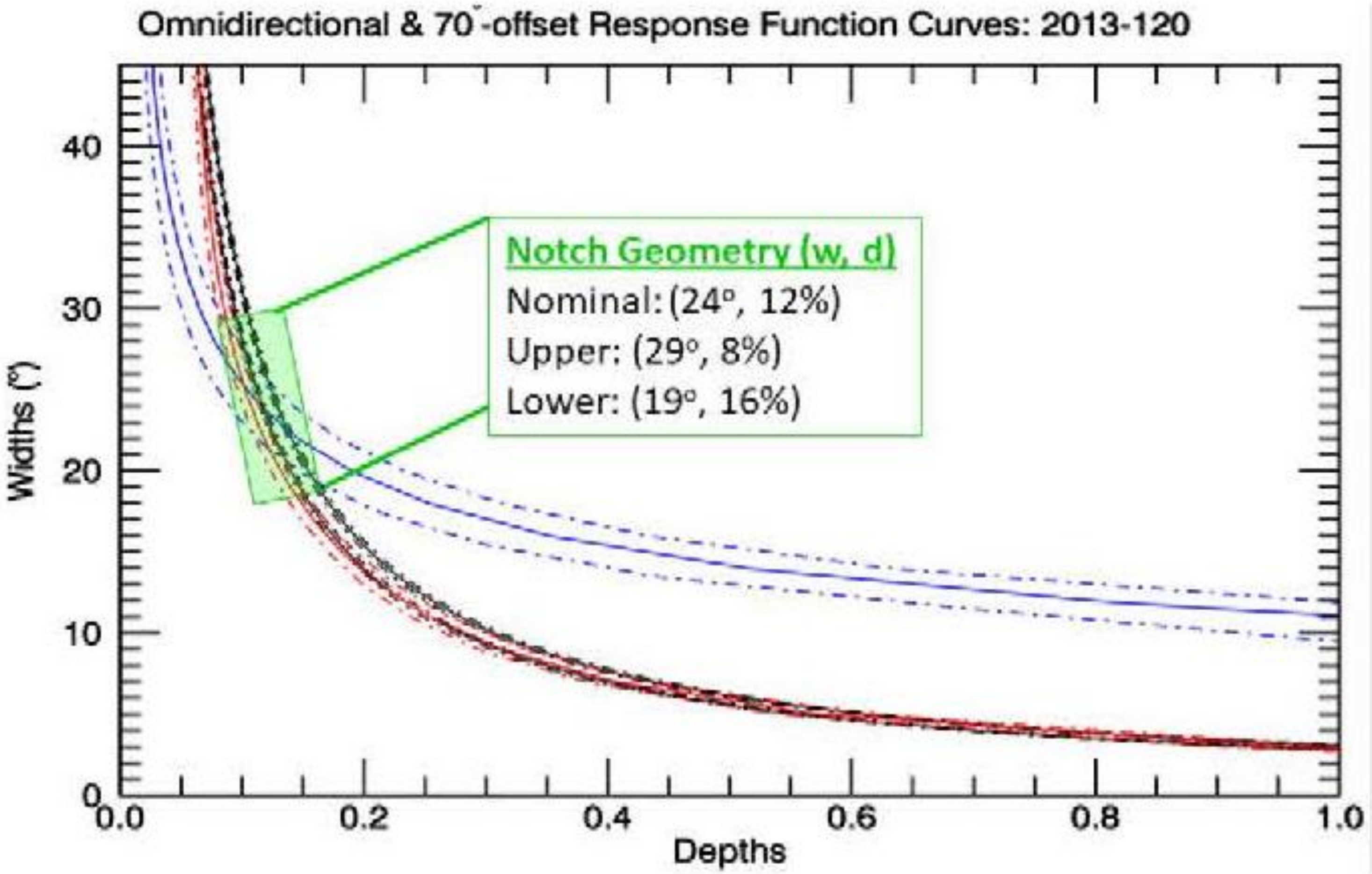


Figure 7. Superposition of HET 1 and HET 2 omnidirectional (black dashed) and 70°-offset response function curves (HET 1 in red, HET 2 in blue) for the 2013-120 offset interval. Note that agreement is achieved by a broad, shallow notch as opposed to a narrow, deep notch (e.g., at the limit of Model #1).

Here is an example for one off-nominal maneuver. Range of intersections of the curves yields a notch in the pitch-angle distribution that is 24° ± 5° wide and 12 ± 4 % deep for this maneuver.

Rankin et al., ApJ, 2019

GCR Anisotropy at V1 in VLISM

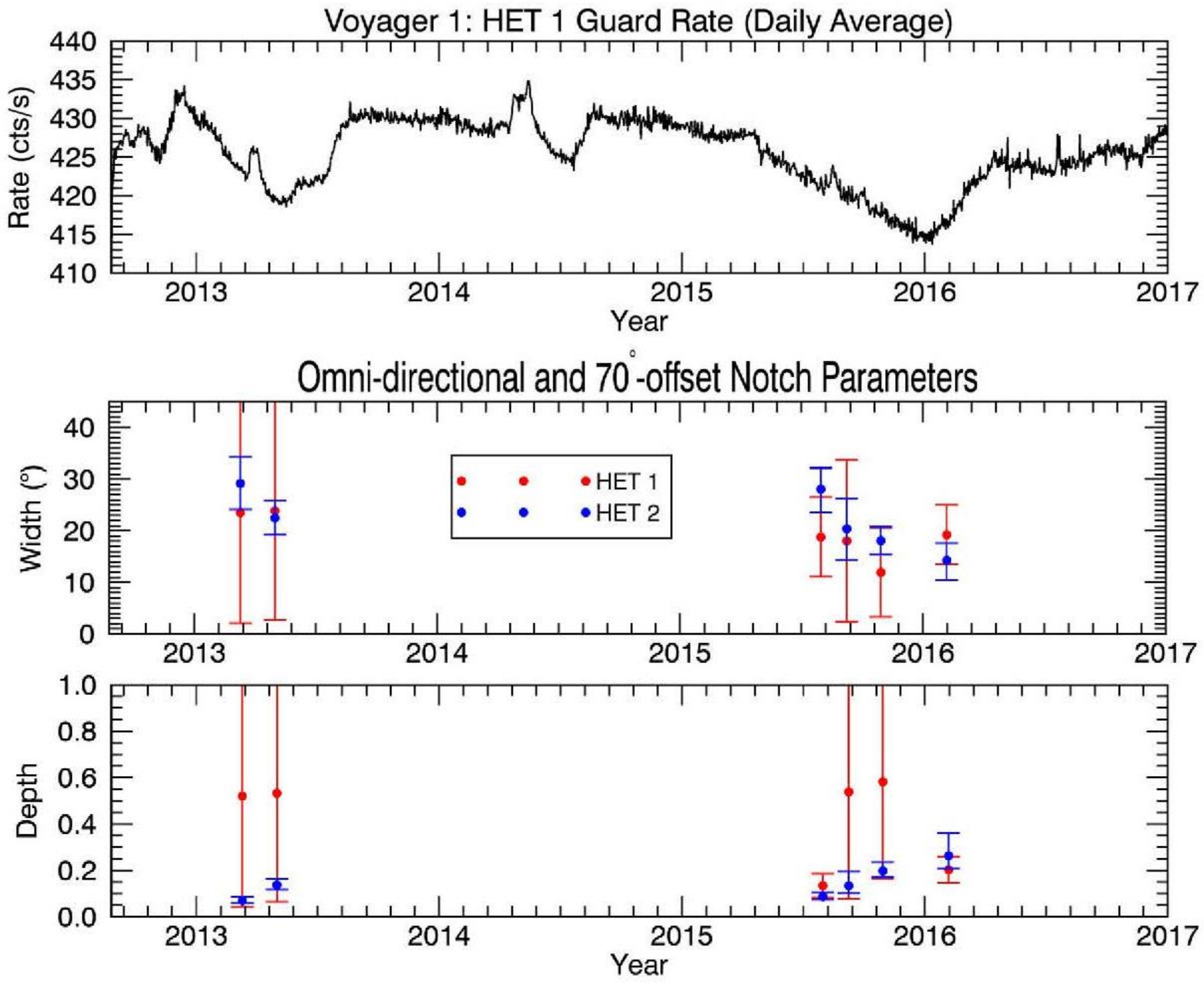


Figure 8. Widths and depths predicted from the intersection of omnidirectional and 70°-offset simulations for HET 1 (red) and HET 2 (blue) incorporating the alternative fields listed in Table 6 of Appendix B.

Here are results for 6 maneuvers. Average is 22° wide and 15% deep.

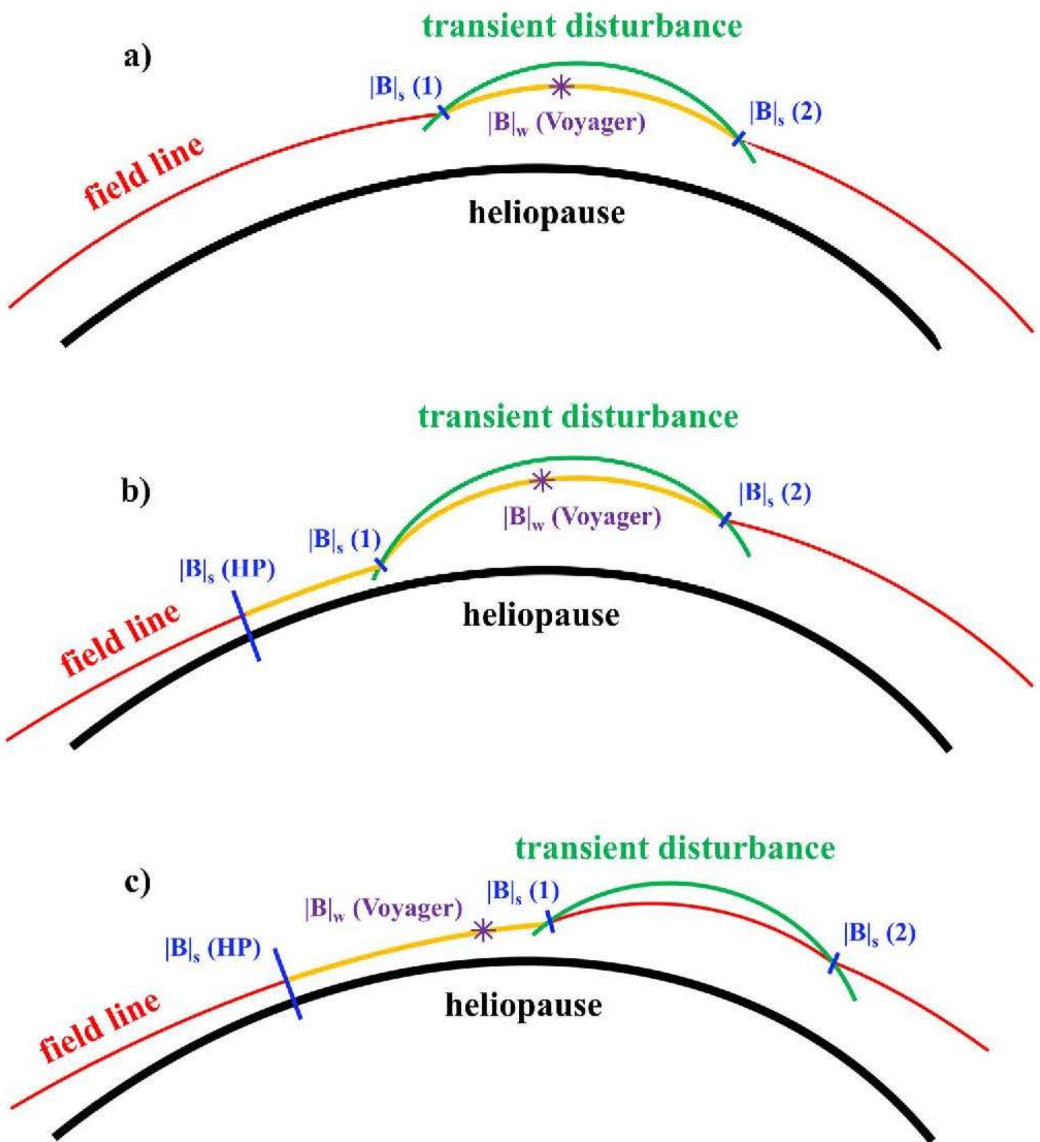
HET 1 proved to not be very constraining.

Rankin et al., ApJ, 2019

GCR Anisotropy at V1 in VLISM

THE ASTROPHYSICAL JOURNAL, 873:46 (24pp), 2019 March 1

Rankin et al., 2019



Rankin et al., 2019, interpretation involves magnetic trapping with higher field strengths on either side of Voyager 1 and energy loss via adiabatic cooling downstream of transient shocks.

Trapping is via conservation of 1st adiabatic invariant:

$$\frac{\sin^2 \alpha(x)}{|B|_x} = \frac{\sin^2 \alpha_o}{|B|_o} = \text{const.}$$

90° pitch-angles only occur at the mirror points, where the strong fields are. V1, in the weak-field region, would see a notch in the pitch angle distribution around 90°.

Except, there is a pre-existing isotropic population. To realize the notch, one needs an energy loss mechanism that affects particles with near 90° pitch angles more than others.

GCR Anisotropy at V1 in VLISM

THE ASTROPHYSICAL JOURNAL, 839:126 (7pp), 2017 April 20

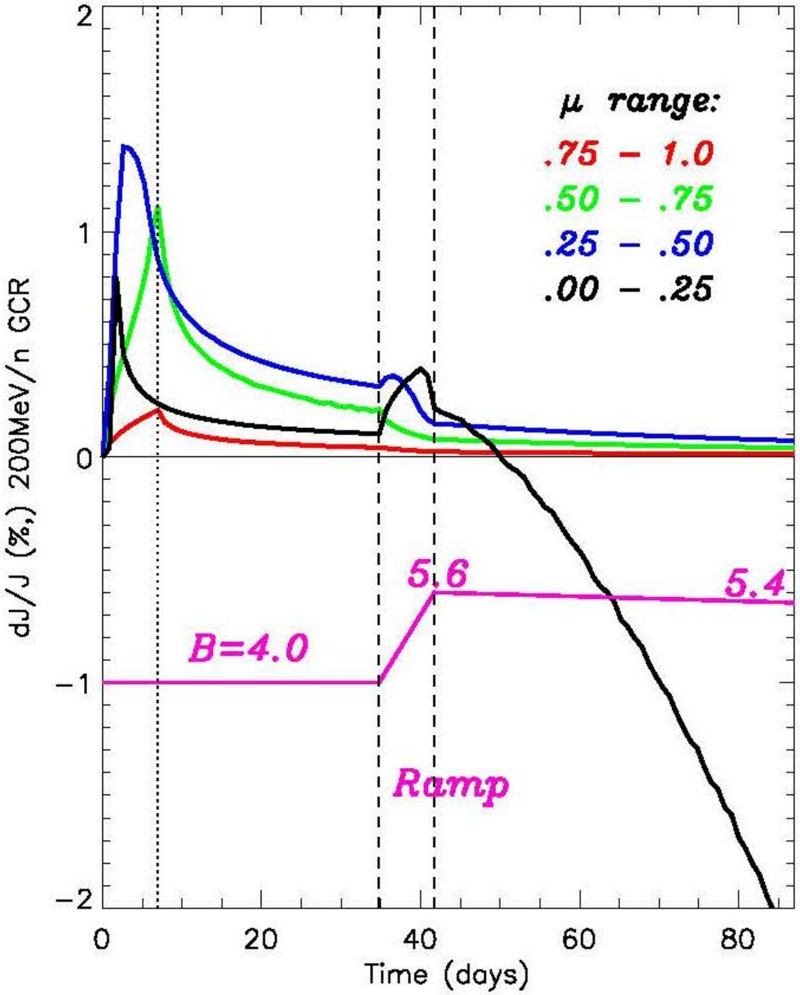


Figure 3. Simulation results obtained for a spherical shell of compression with a gradual increase of B (see text). Shown are the time profiles of the excess flux of 200 MeV GCRs predicted for *V1* in four pitch-angle segments. Note the decreasing trend of GCR flux for $\mu \approx 0$ starting around day 40, when *V1* moves into the expanding downstream region (II). The magenta line indicates the assumed profile of B as seen at *V1*.

Results are generally consistent with model of Kota and Jokipii, ApJ, 2017.

Idea is that particles are trapped downstream of the shock where the magnetic field strength is declining, resulting in energy loss, which leads to intensity decrease.

Intensity drops for pitch angles in range 0.00 – 0.25 but not for others, similar to the observations.

Particles with near 90° pitch-angle spend the most time trapped and lose the most energy.

THE ASTROPHYSICAL JOURNAL, 863:188 (8pp), 2018 August 20 https://doi.org/10.3847/1538-4357/aad3cf

Magnetic Mirroring and Focusing of Cosmic Rays

Kedron Silsbee[1], Alexei V. Ivlev[1], Marco Padovani[2], and Paola Caselli[1]

THE ASTROPHYSICAL JOURNAL, 863:188 (8pp), 2018 August 20

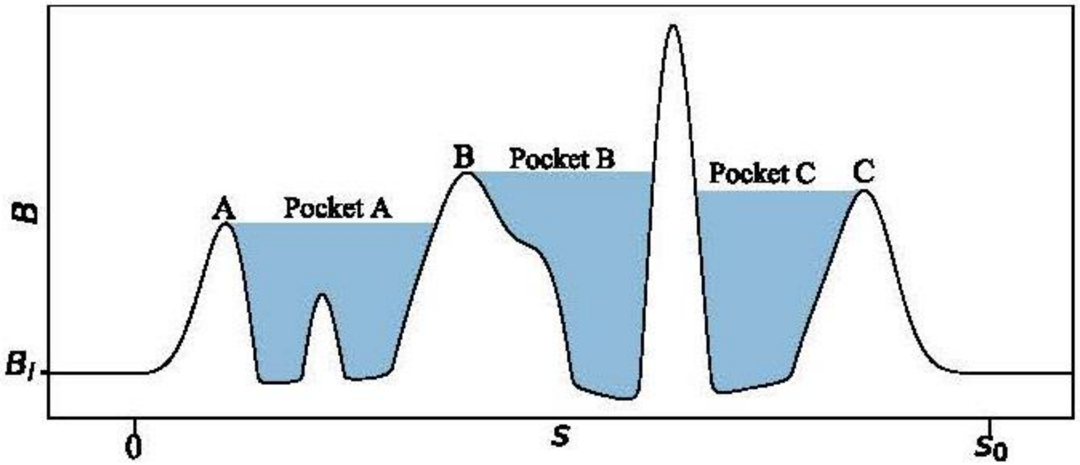


Figure 2. Situation where the magnetic field has multiple maxima along the field line. This results in multiple magnetic pockets, indicated by the shading.

$$\frac{\sin^2 \alpha}{B(s)} = \frac{\sin^2 \alpha_i}{B_i}, \tag{1}$$

$$\frac{n(s)}{n_i} = 1 - \sqrt{1 - \frac{B(s)}{B_l}}. \tag{6}$$

Magnetic pockets of low cosmic ray density form between local maxima in the strength of the magnetic field. Similar scenario to Rankin et al., 2019, but two differences: a) Silsbee et al. claim the density is controlled in a region by the largest fields in the sequence, but Rankin et al. say the notch is controlled by the weakest; b) Silsbee et al. do not invoke an energy loss mechanism to produce their reduced densities.

Summary

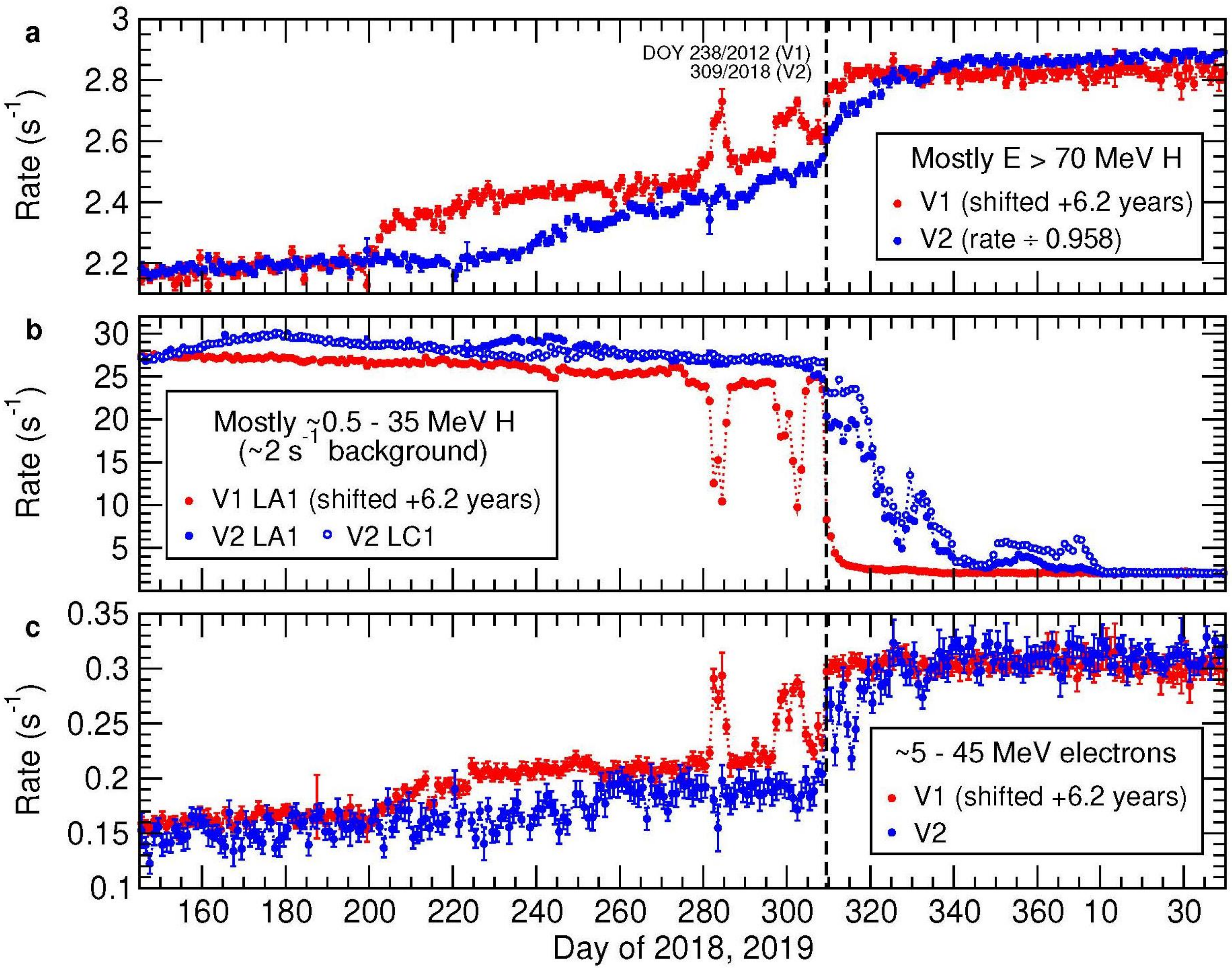
- Voyager 2 has joined Voyager 1 in the VLISM.
- H and He spectra are essentially the same at V1 and V2 implying no significant gradient over ~167 AU in the VLISM.
- The spectra roll-over at low energies, likely due to ionization energy losses.
  - H/He = 12.2 ± 0.9 from 3-346 MeV/nuc.
    - H and He spectra peak at the same energy/nuc implying spectra are not affected by solar modulation.
    - Supports idea that Voyager is observing GCR spectra from VLISM.
  - GCR electron ($e^+ + e^-$) spectrum is also ~same at V1 and V2 and is ~$E^{-1.3}$ from ~3-74 MeV.
    - GCR e/p ratio in the VLISM is ~50 at 3 MeV.
  - Models of VLISM energy spectra:
    - Model spectra at ≥ 3 MeV/nuc used to find ionization rate of atomic H is in range 1.51-1.64 x 10^{-17} s^{-1}
      - Factor of ~11-12 below astrochemistry results for diffuse interstellar clouds.
      - Possibilities to explain include more contribution from electrons below 3 MeV (but not likely enough), and variation of the GCR spectra in the Galaxy (more likely).
    - Model spectra at ≥ 3 MeV/nuc used to find energy density of GCRs is in range 0.83-1.02 eV/cm^3
  - Isotopes
    - Observed spectra of isotopes from V1 in the LISM:
      - Li - Ne look ~OK with respect to models.
      - Big discrepancy between models and observations for 2H and 3He.

Summary (continued)

- **V1 observed long periods (up to months, years) of depressed intensities for particles with pitch angles near 90°.**
  - **Remains to be investigated at V2.**

The End

Comparison of V1 and V2 rates near heliopause crossings (HPXs)



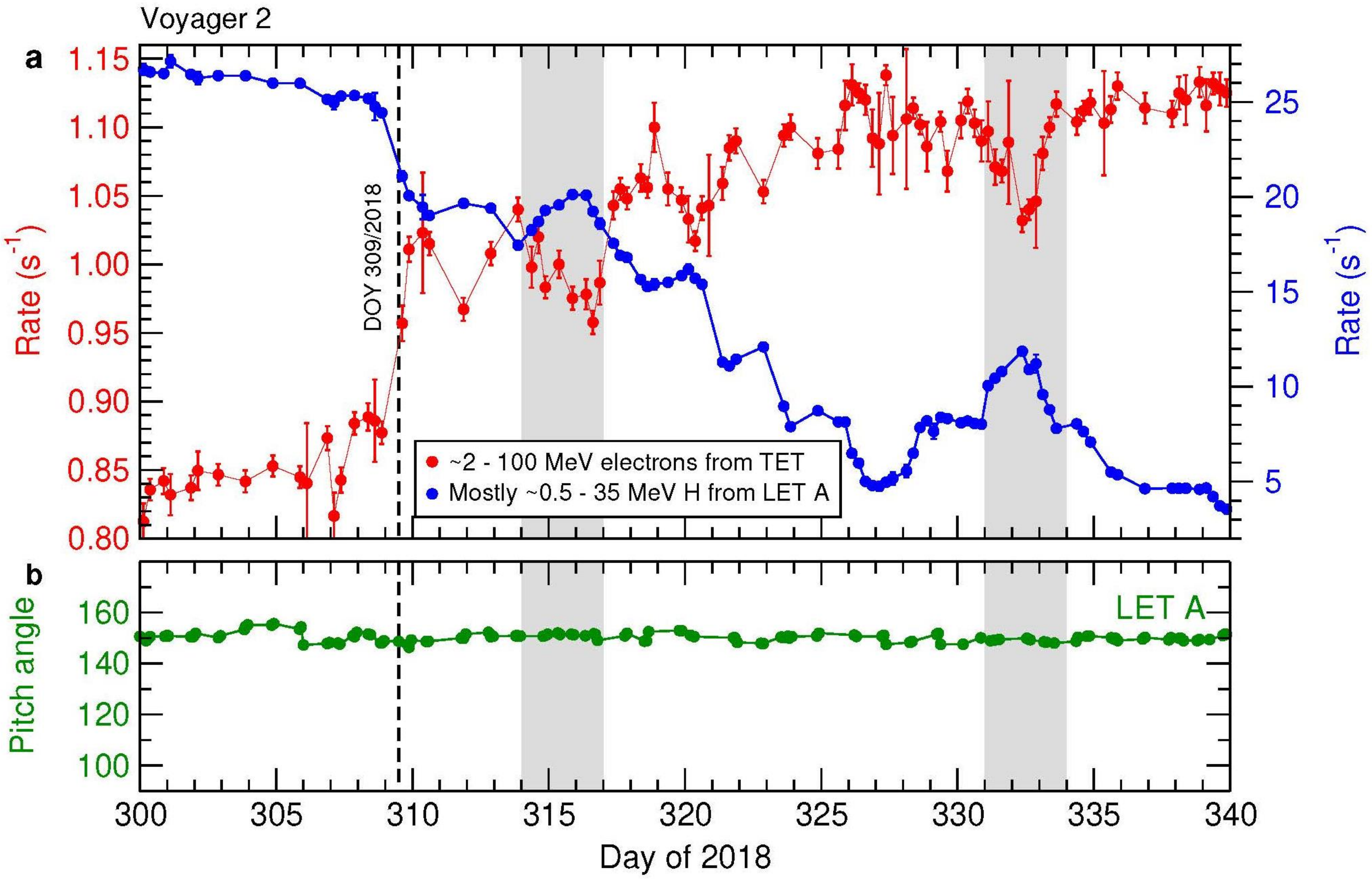
There is a boundary layer having GCR modulation prior to HPX for V1 and V2, and a smaller one after HPX for V2. Caution: relative velocities of S/C and HP could be different in the 2 cases.

V1 saw interstellar flux tubes invading the heliosheath; V2 saw structures in the VLISM just after HPX. Transition time for heliospheric particles (ACRs) to background longer in the case of V2.

Electrons behave similarly to GCR H so these are GCR electrons.

Stone et al., Nature Astronomy, 2019 (submitted)

Anti-correlation of V2 GCR electrons and heliospheric (ACR) H intensities in VLISM

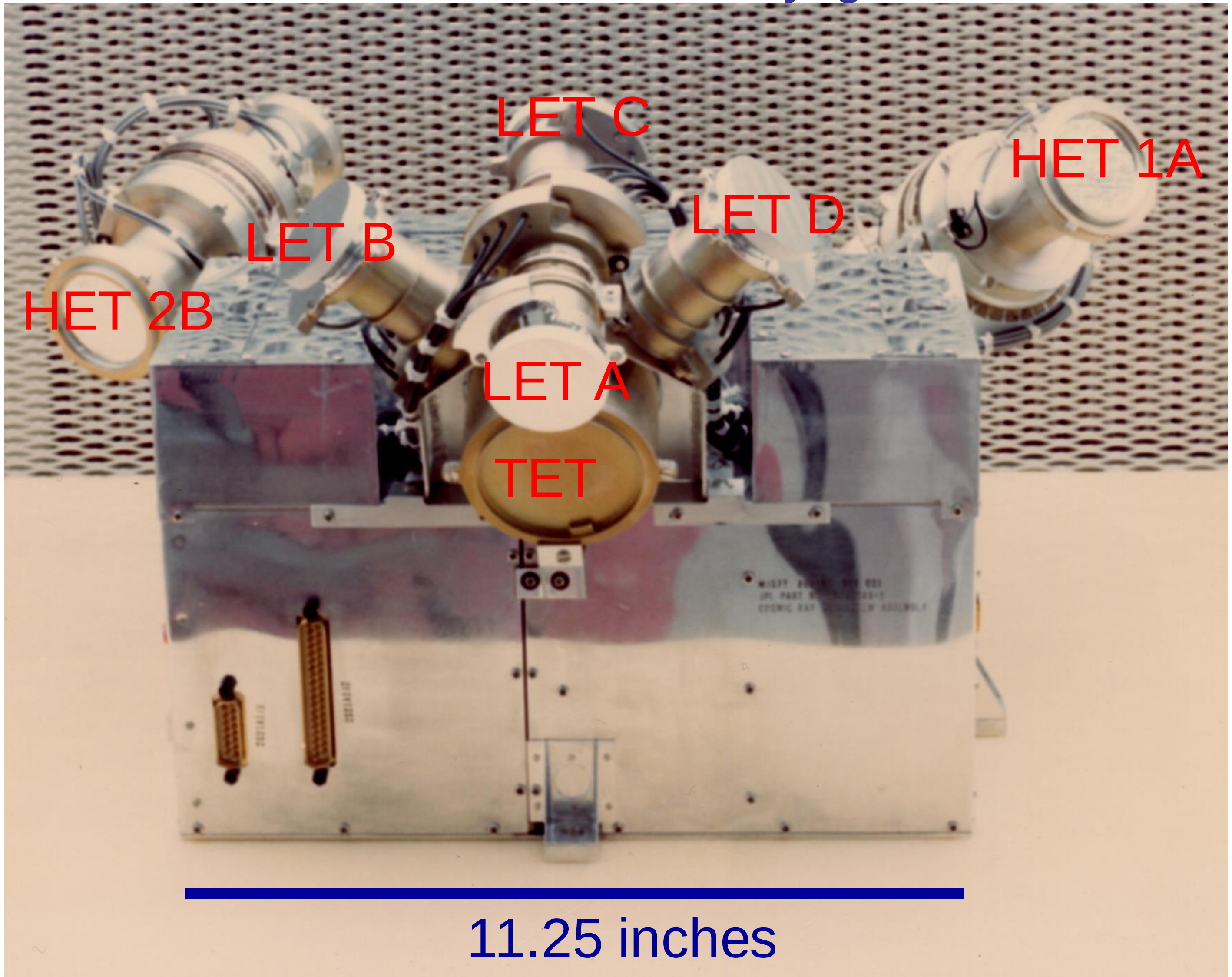


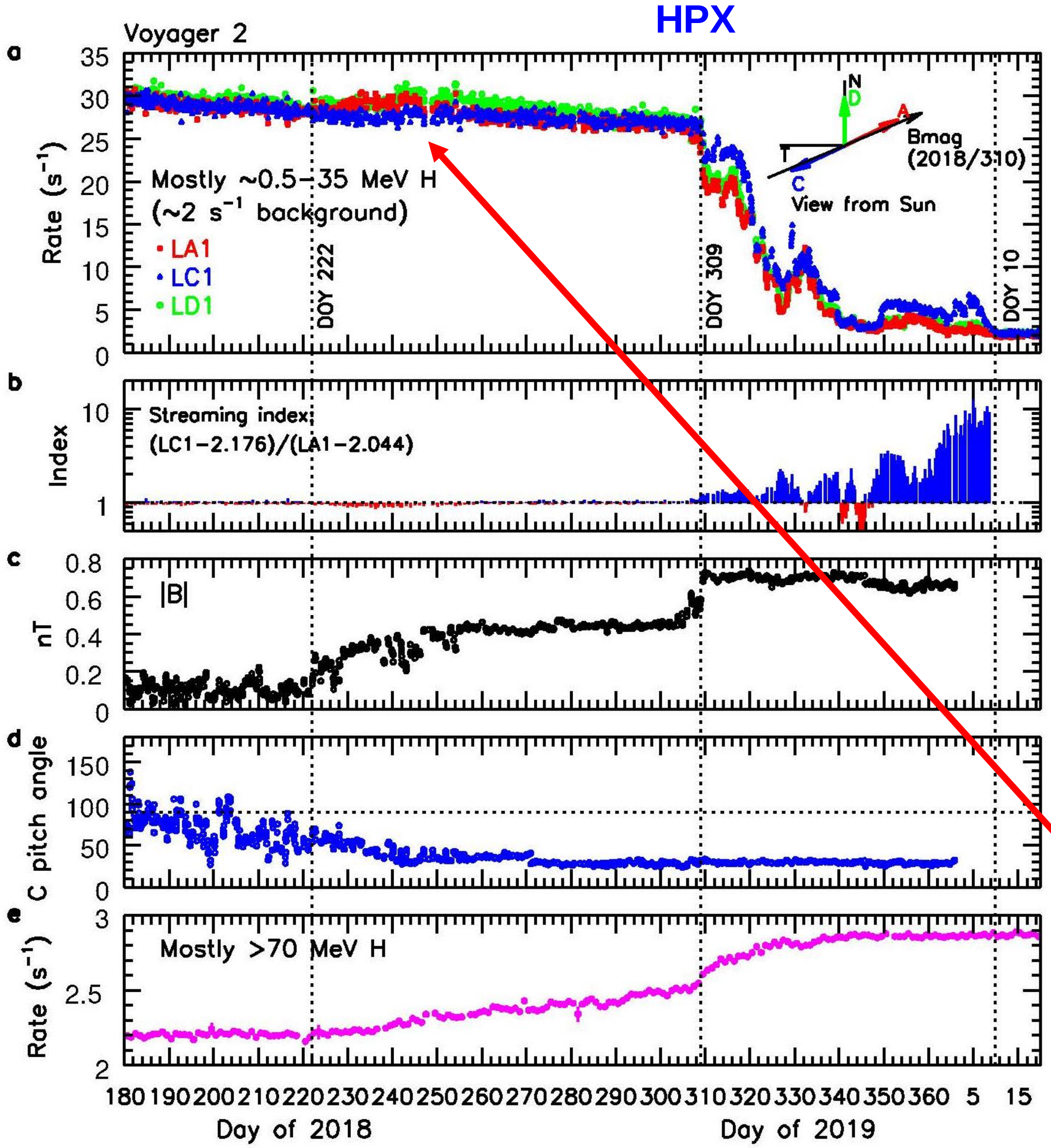
Gray bands highlight most prominent anti-correlations but there are others.

Local magnetic field direction not changing (lower-panel); suggests local field not governing the phenomenon.

Stone et al., Nature Astronomy, 2019 (submitted)

CRS instrument on Voyager 1





Particle streaming in VLISM for V2

LETs A and C are mounted back to back and LET D is pointed perpendicular to that line, so rate differences indicate anisotropies.

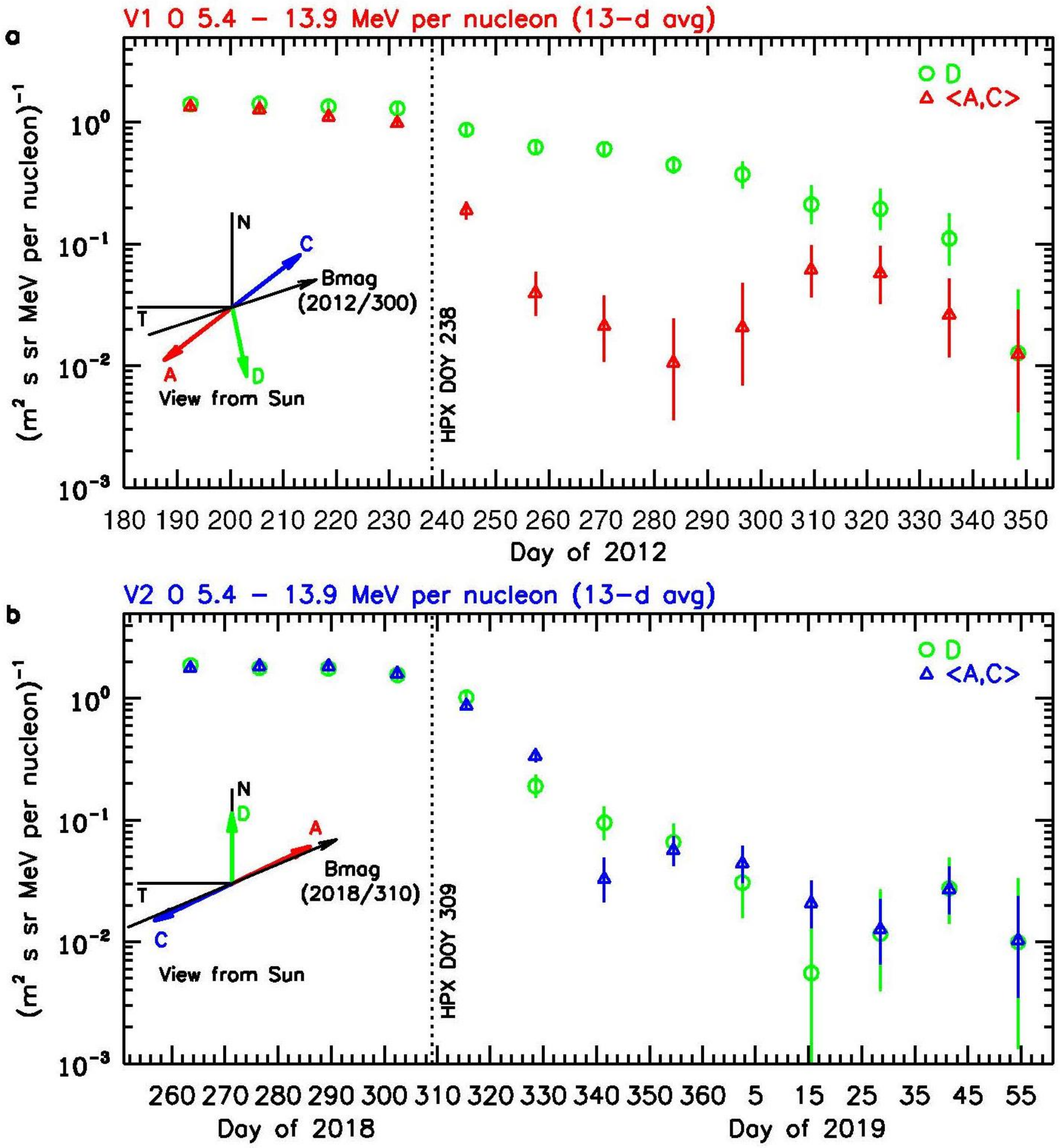
LC1/LA1 ratio reaches 10 and then on day 10 of 2019 the rates suddenly drop to GCR background levels.

Taken together with anti-correlations of GCRs and ACRs, it suggests that the field lines V2 are on are connected or in close proximity to the heliopause back along the flank.

The connection was lost on day 10 of 2019.

Small anisotropies seen earlier prior to HPX occurred in the magnetic barrier.

Stone et al., Nature Astronomy, 2019 (submitted)



Another V1, V2 Difference

For V1, heavier ACR ions (e.g., O) persisted longer than lighter ones in the VLISM and ones that had pitch angles near 90º persisted the longest. This was explained as either a gradient drift in a non-uniform magnetic field (Florinski et al., 2015) or a particular pitch-angle dependence of the perpendicular diffusion coefficient (Strauss & Fichtner, 2014)

Not the case for V2.

Stone et al., Nature Astronomy, 2019 (submitted)

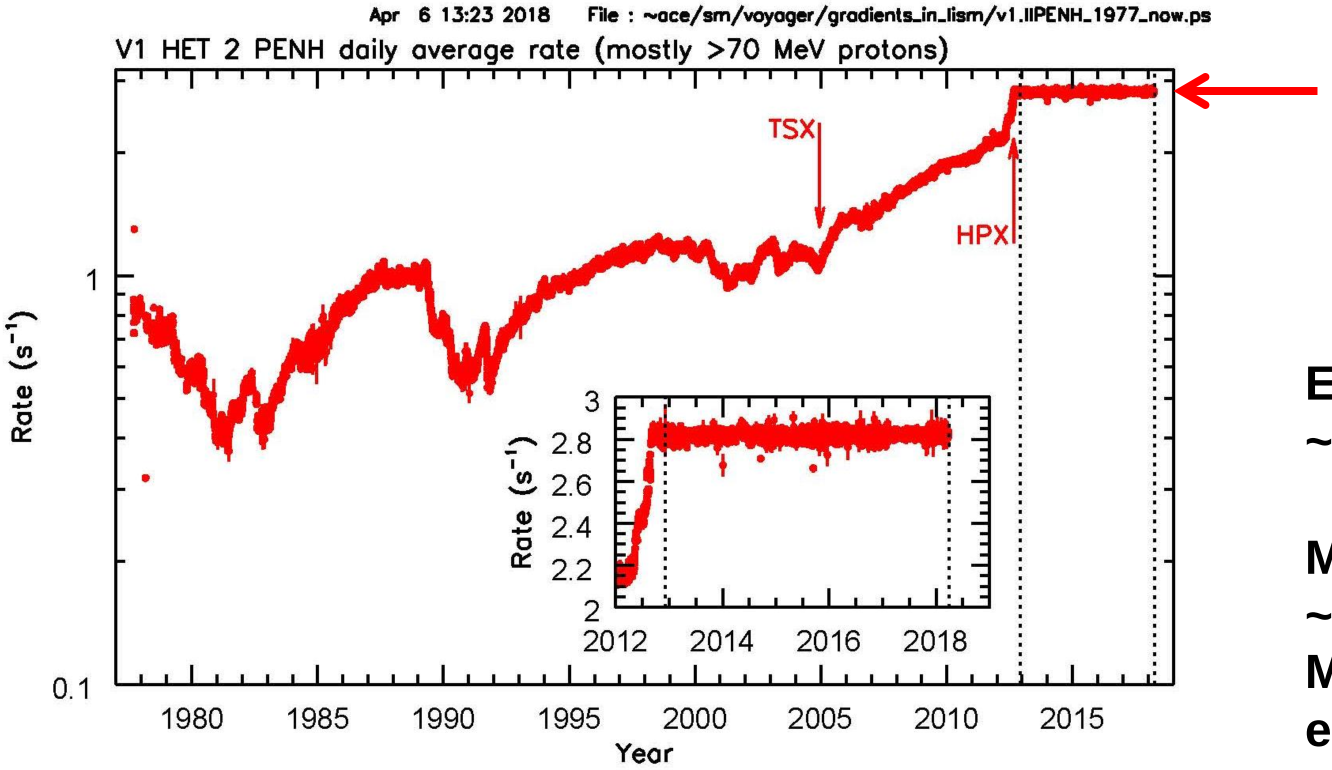
Summary (continued)

- The V1 and V2 heliopause crossings revealed some differences with respect to cosmic rays:
  - V2 saw invading interstellar flux tubes; V2 did not.
    - V2 saw a similar kind of structure but on other side of HP in VLISM.
    - Appears to be a flux tube with magnetic connection back to heliopause on the flank
  - V2 saw a GCR modulation boundary layer on outside of HP; V1 did not.
  - Both saw a GCR modulation region just inside heliopause.
  - V2 saw a strong streaming region just beyond HP; V1 saw a different type of anisotropy.
  - Persistence of ACRs in VLISM different for the two Voyagers.

The End, Really

Accounting for the PENH rate

The 4 model LISM nuclei spectra and the Potgieter et al. 2015 electron spectrum are used to calculate energy density and ionization rate of atomic H in the LISM. Can they reproduce the rate of penetrating particles in the HET telescope?



Answer = Yes

Table 4
Composition of observed PENH rate = 2.82 s^{-1}

Propagation Model for Nuclei	H	He	Li-Ni	e	Total	Ratio
	Calculated PENH rate (s^{-1})					
LBM	1.83	0.11	0.009	0.75	2.69	0.95
DR	1.98	0.13	0.011	0.75	2.86	1.01
PD1	2.14	0.12	0.010	0.75	3.02	1.07
PD2	2.14	0.12	0.010	0.75	3.01	1.07

Electrons account for ~25% of rate

Median nuclei energy ~500 MeV/nuc
Median electron energy ~60 MeV

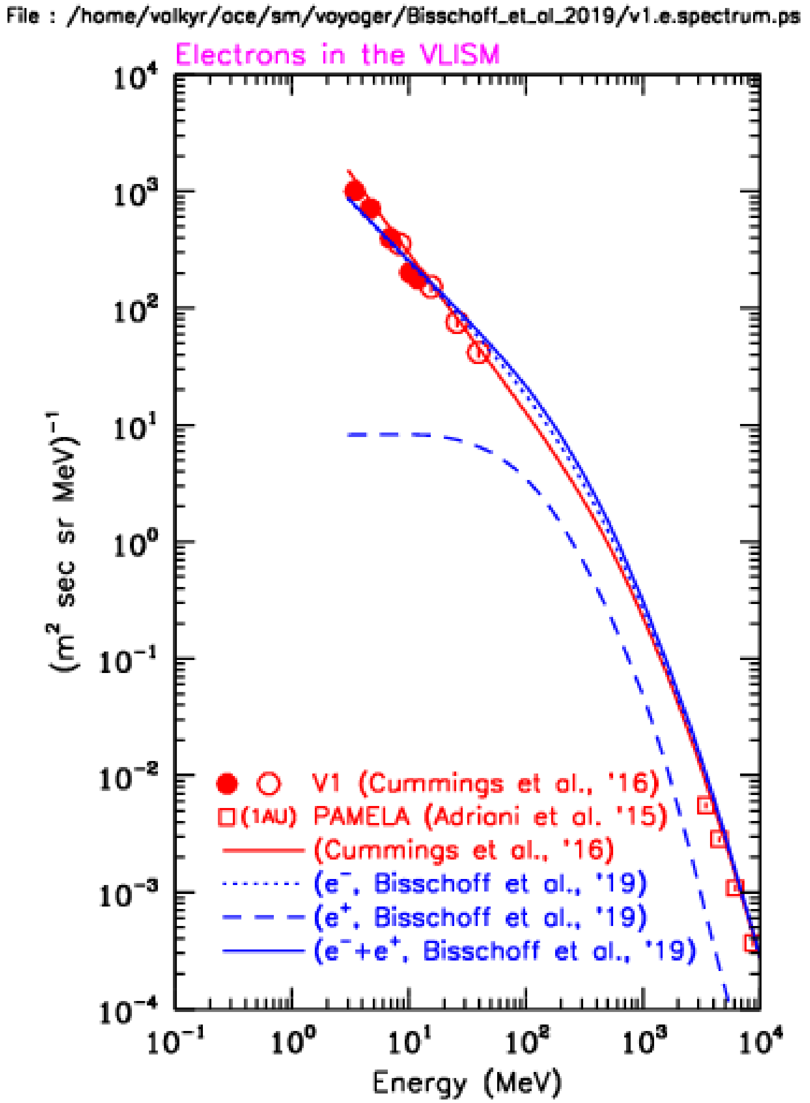
This rate is closely related to PGH rate on the Voyager CRS website

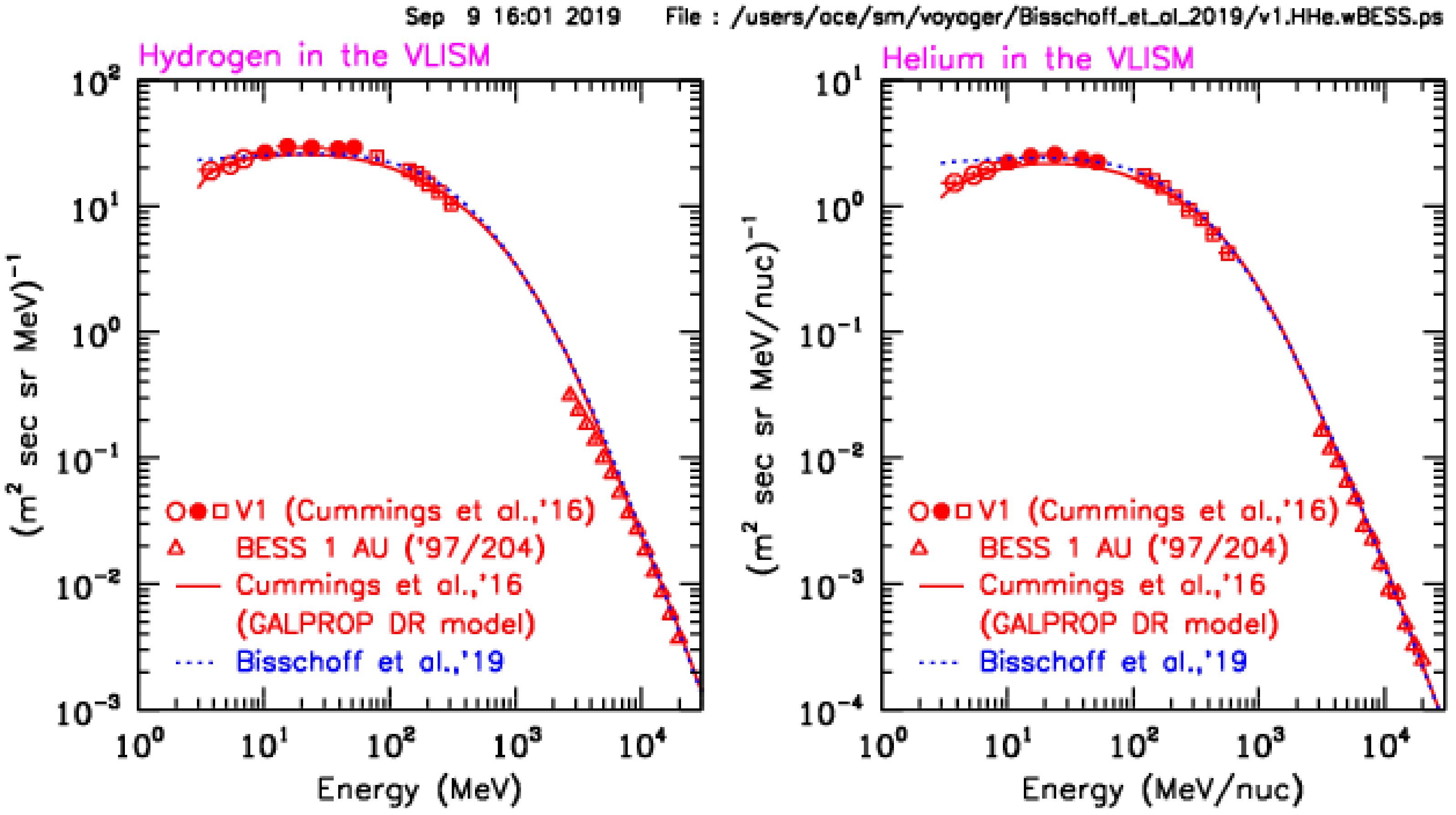
The Astrophysical Journal, 878:59 (8pp), 2019 June 10
https://doi.org/10.3847/1538-4357/ab1e4a

New Very Local Interstellar Spectra for Electrons, Positrons, Protons, and Light Cosmic Ray Nuclei

D. Bisschoff, M. S. Potgieter, and O. P. M. Aslam
ce Research, North-West University, 2520 Potchefstroom, South Africa; driaan.b@gmail.com
'19 February 22; revised 2019 April 18; accepted 2019 April 29; published 2019 June 13

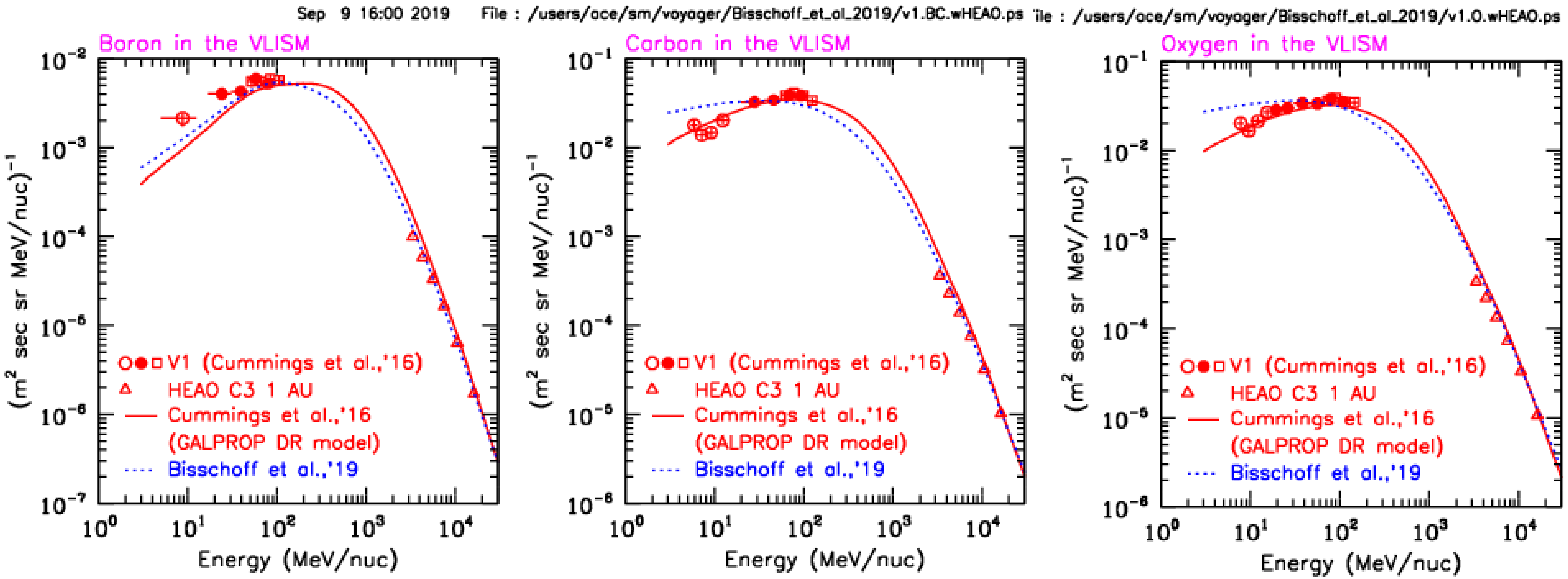
Based on GALPROP models.



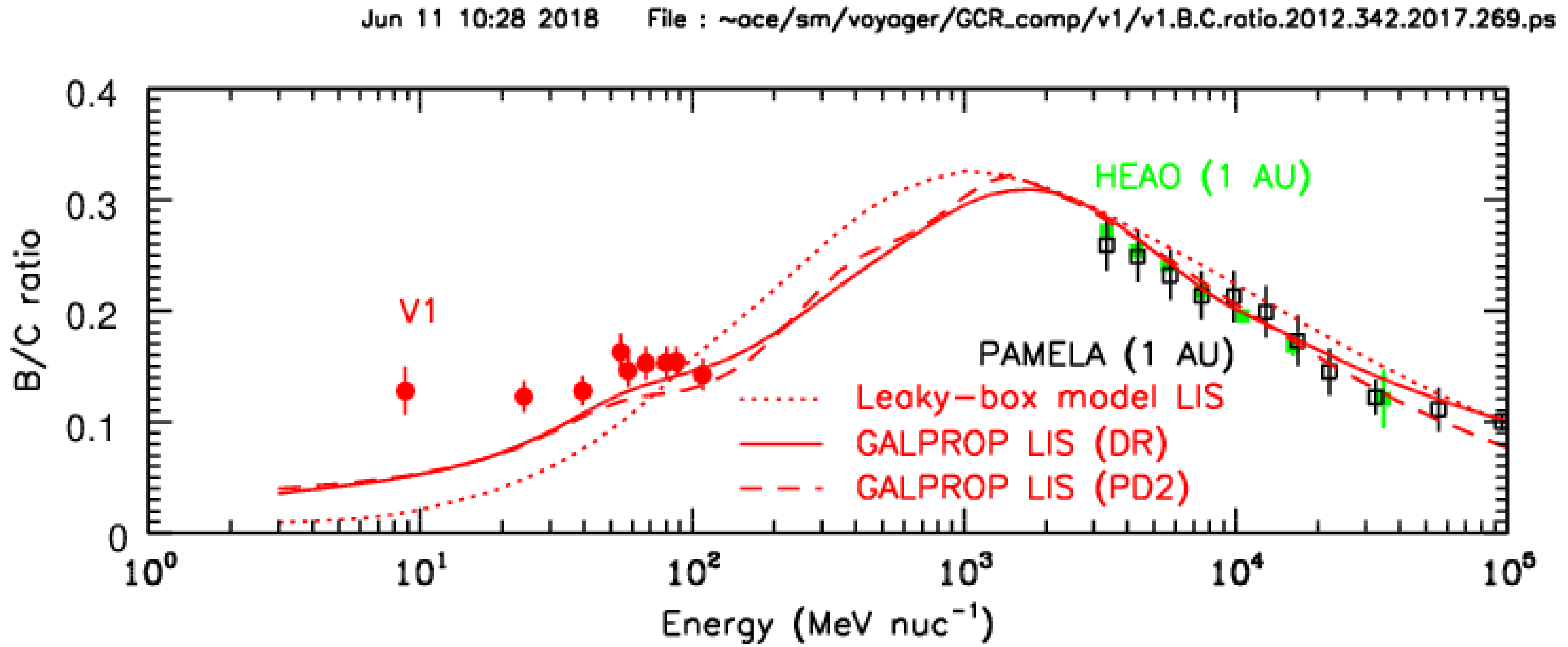


New VLISM spectra from Bisschoff et al., 2019 don't significantly change energy densities or ionization rate results from Cummings et al., 2016.

For electrons, H, He, C, and O, Cummings et al., 2016 VLISM spectra agree better with low-energy Voyager data than does Bisschoff et al., 2019. Both have trouble matching Voyager B data.



B/C ratio



V1 data is for new longer period, 2012/342-2017/269 to get better statistics at low energies.
Models underestimate the B/C ratio below 20 MeV/nuc.

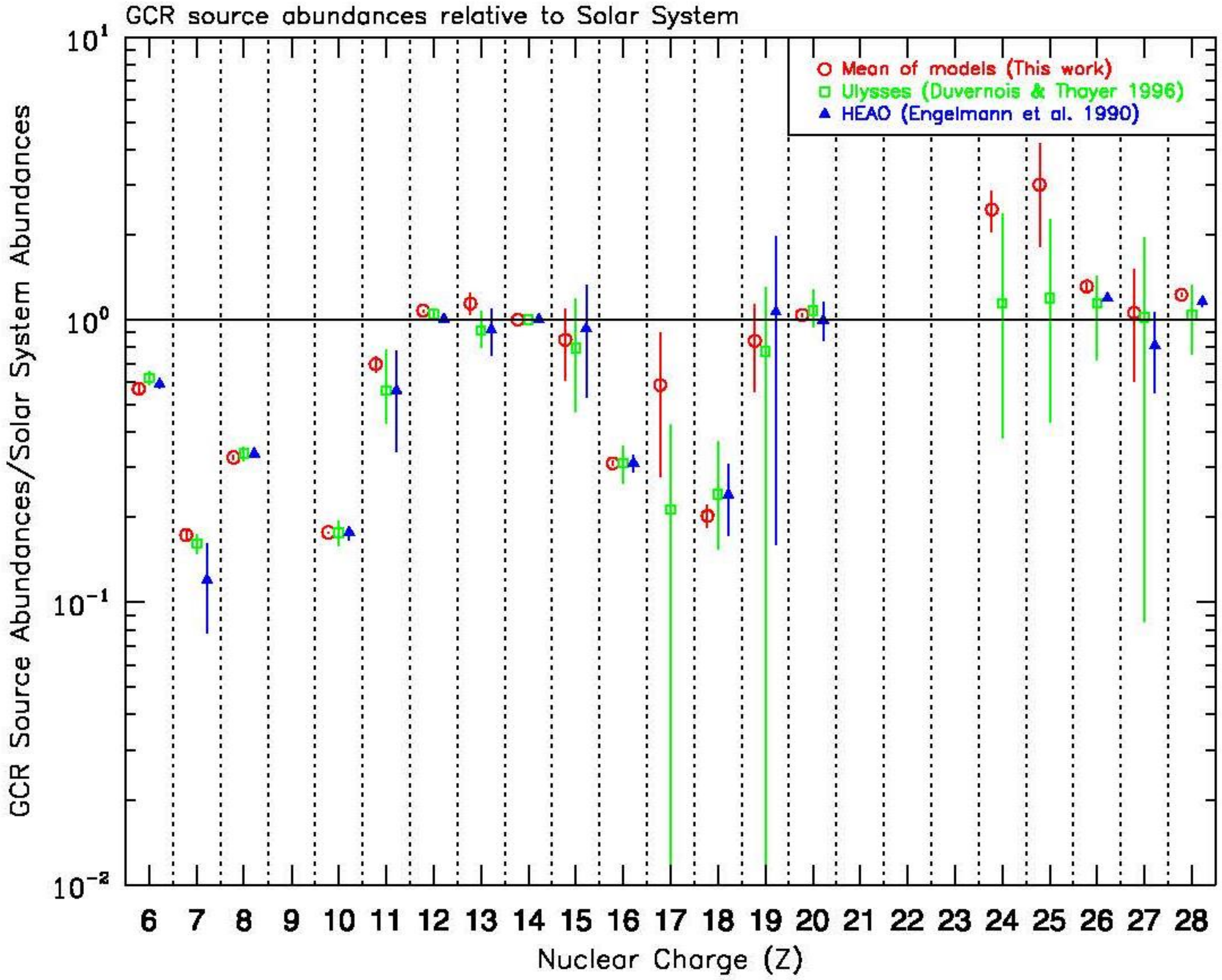
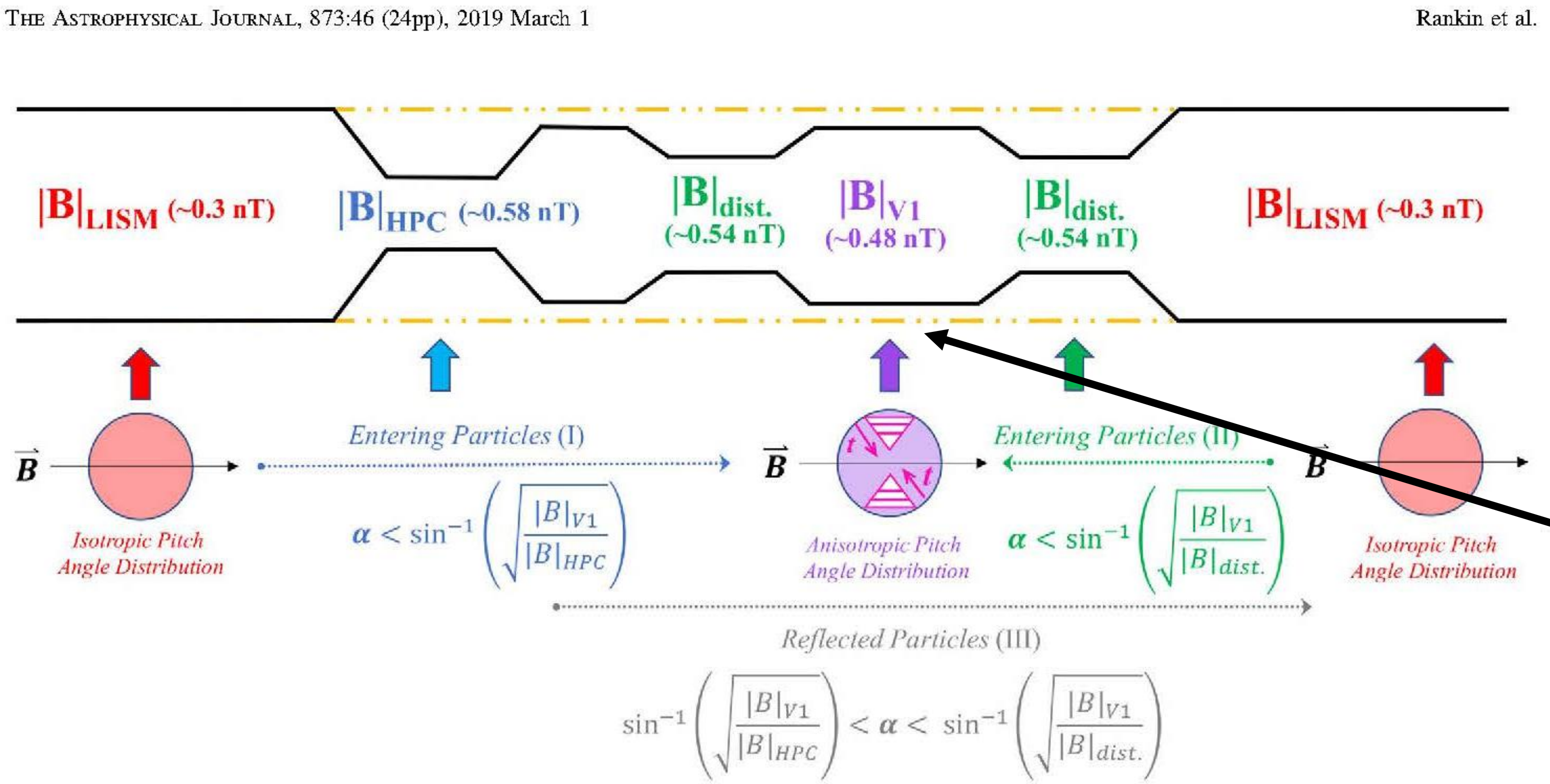


Figure 11. GCR elemental source abundances relative to solar system abundances as described in the text. The solar system abundances are taken from Table 6 of Lodders et al. (2009) and their uncertainties have not been taken into account in forming the ratios.

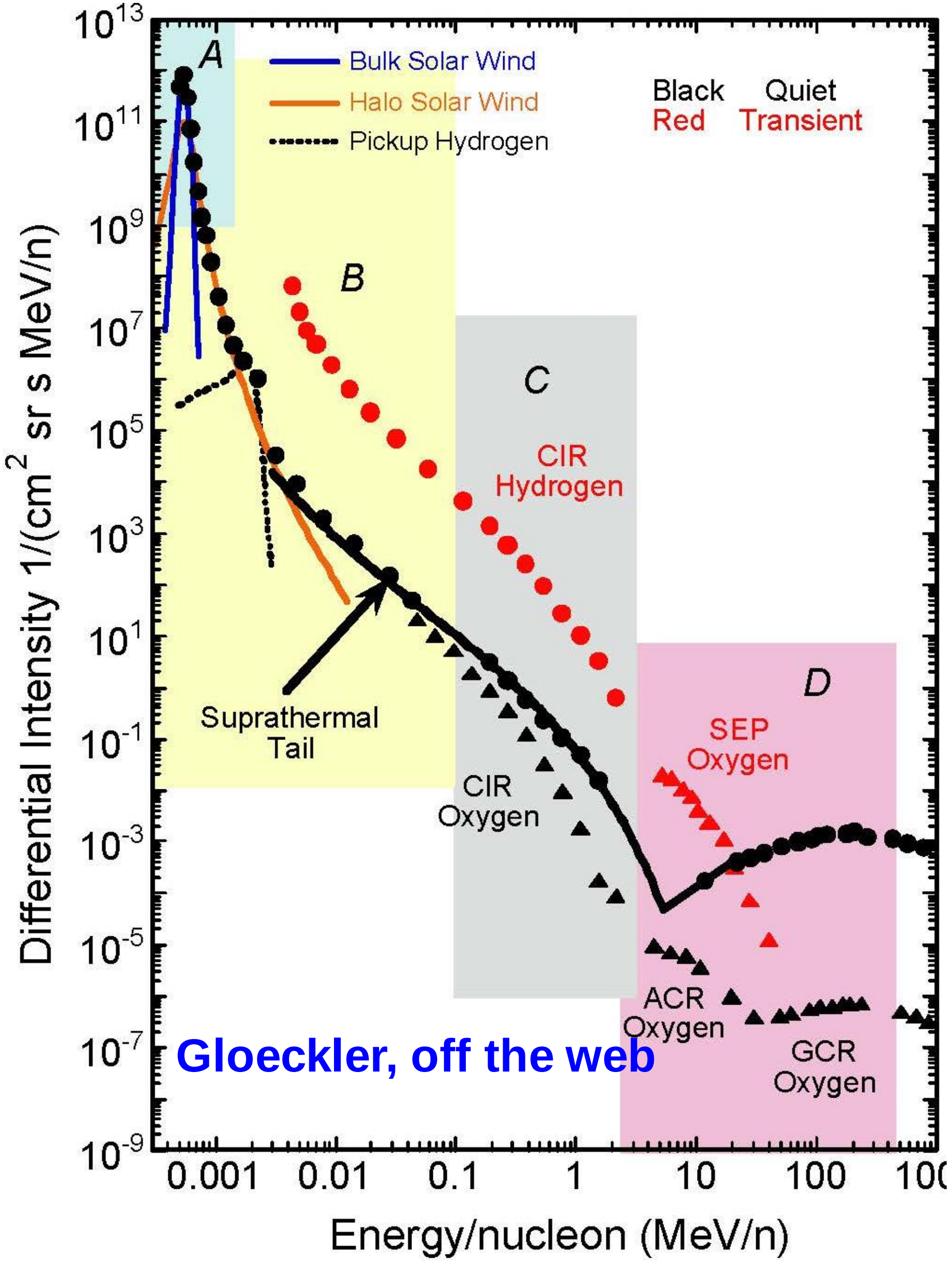
GCR source abundance generally consistent with previous determinations, with generally smaller uncertainties.

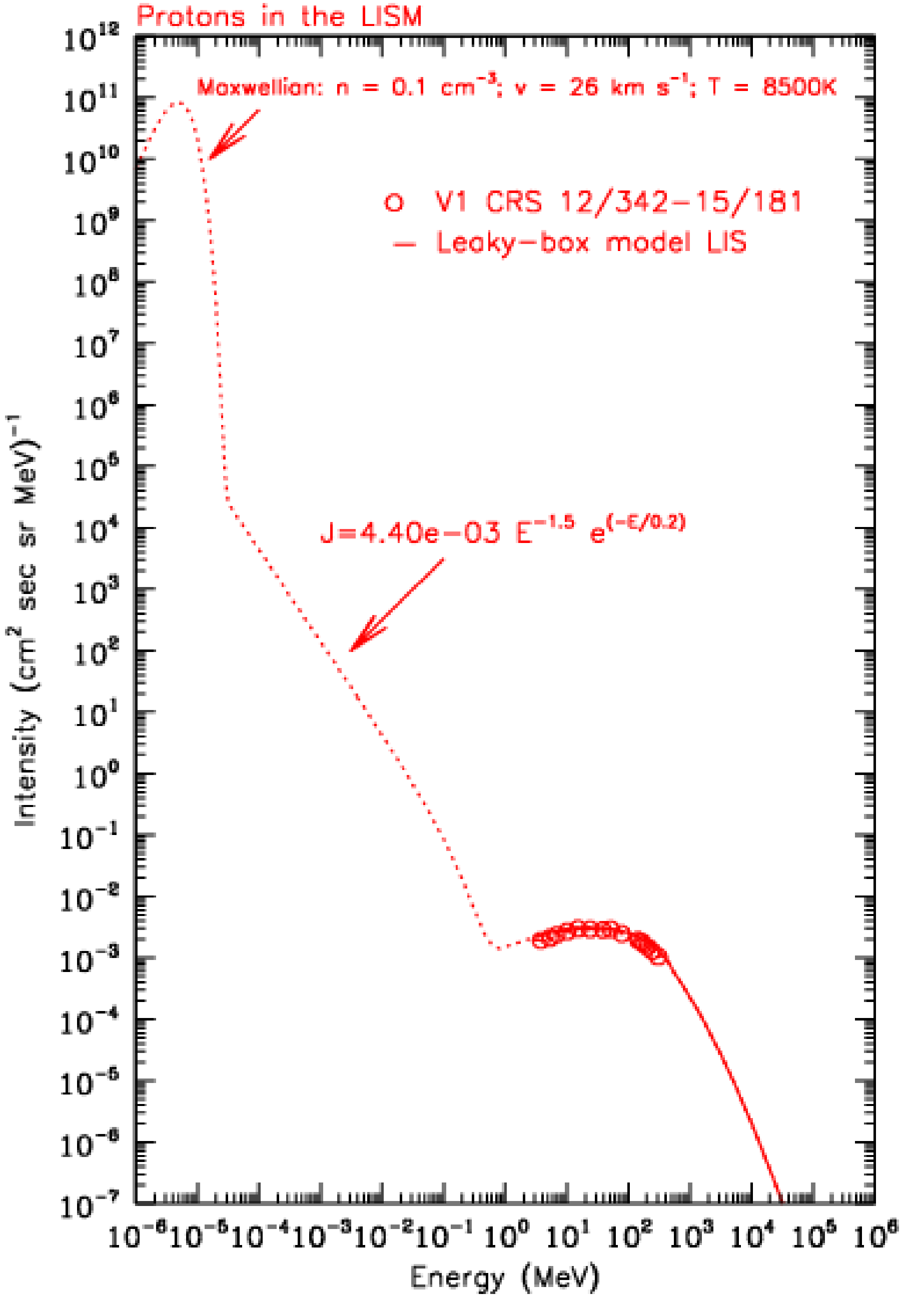


$$\frac{n(s)}{n_i} = 1 - \sqrt{1 - \frac{B(s)}{B_l}}. \qquad (6)$$

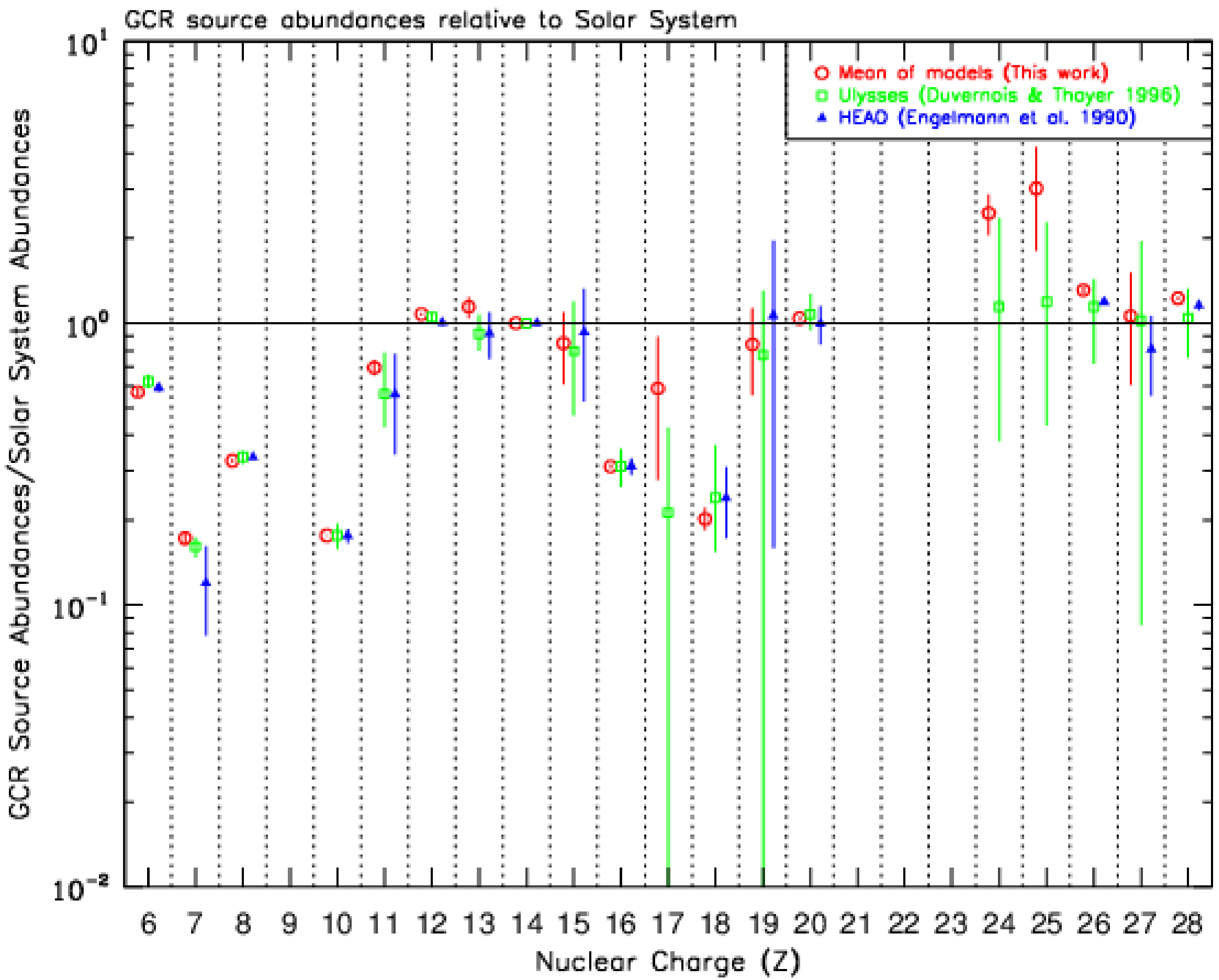
= 0.80 for $B(s)$ = 0.5 nT and B_i = 0.48 nT

Apply equation 6 to Rankin et al. observations. Calculated density reduction for the Rankin et al. example above based on formulation in Silsbee et al., 2018, is much bigger than the observed intensity decrease, which is a few percent. Mechanism does not appear to be the same as in Kota and Jokipii, 2017.


Bulk Solar Wind
Halo Solar Wind
Pickup Hydrogen
Black Quiet
Red Transient
A
B
C
D
CIR Hydrogen
Suprathermal Tail
CIR Oxygen
SEP Oxygen
ACR Oxygen
GCR Oxygen
Gloeckler, off the web
Differential Intensity 1/(cm2 sr s MeV/n)
Energy/nucleon (MeV/n)


Protons in the LISM
Maxwellian: n = 0.1 cm-3; v = 26 km s-1; T = 8500K
o V1 CRS 12/342-15/181
— Leaky-box model LIS
J=4.40e-03 E-1.5 e(-E/0.2)
Intensity (cm2 sec sr MeV)-1
Energy (MeV)

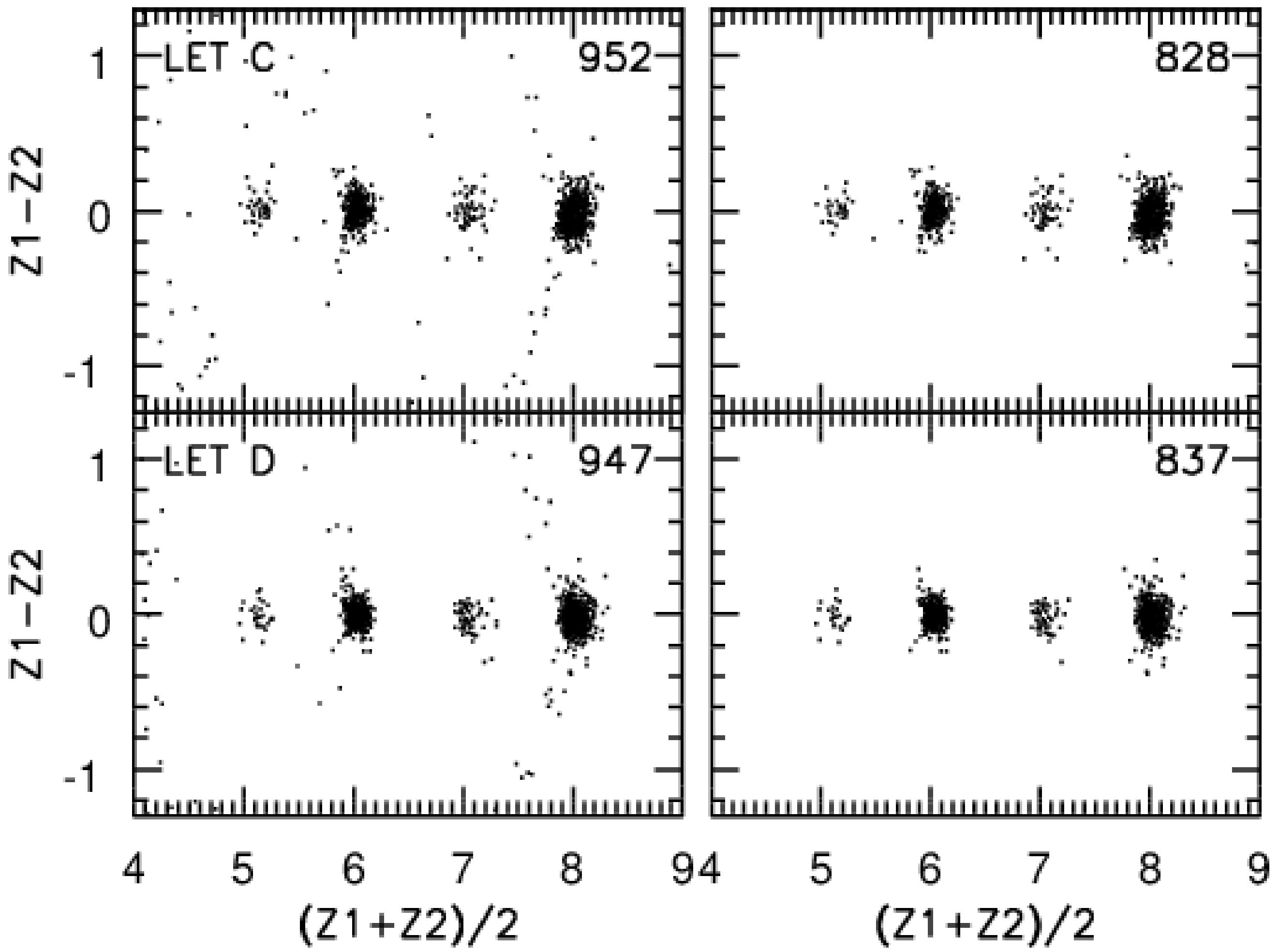
GCR elemental source abundances relative to Solar System



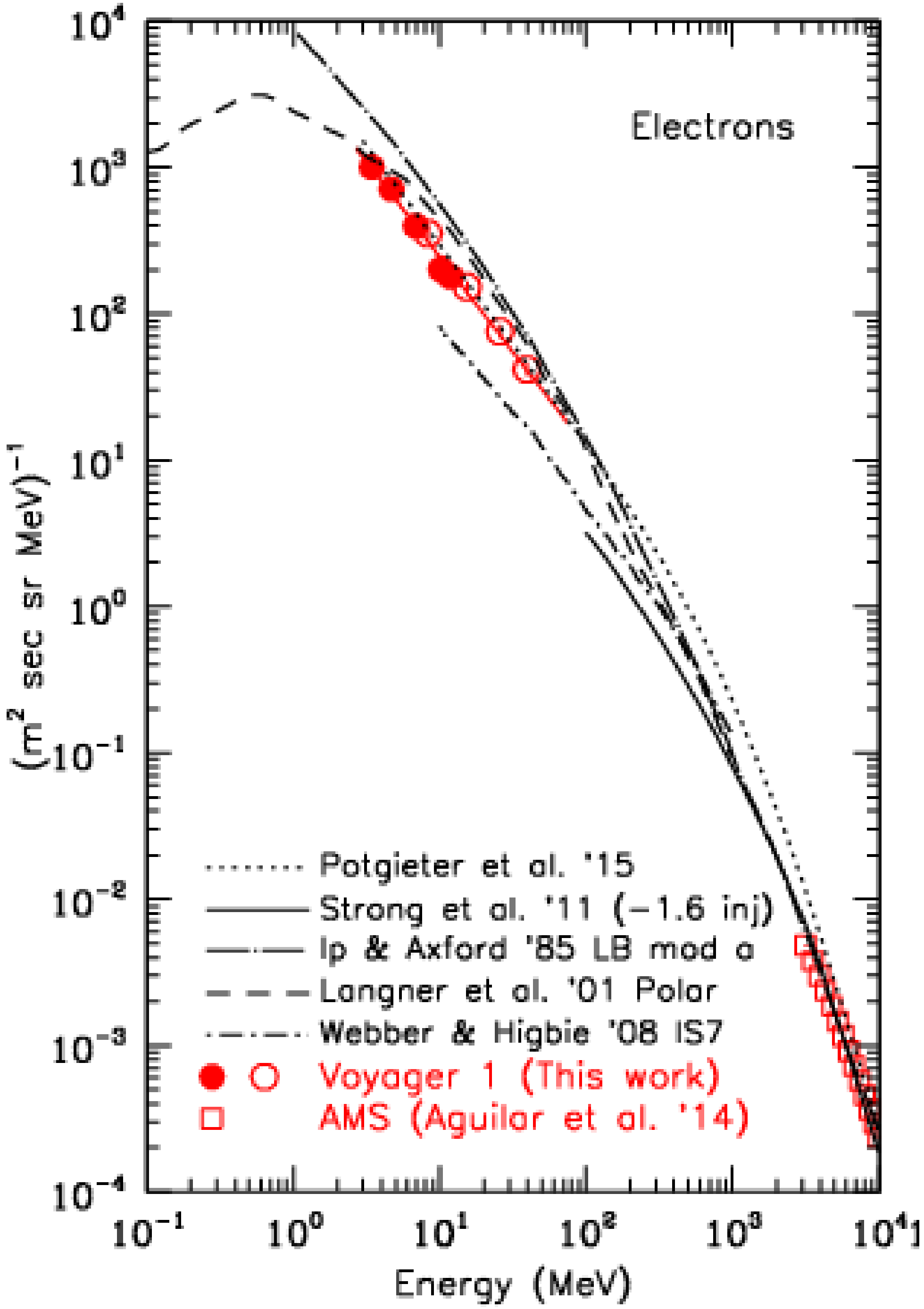
Red points are from this work – Mean of models.

Compares reasonably well to Ulysses and HEAO results with typically smaller uncertainties.

Diagnostic plots for lowest energy B/C point from LET C and D telescopes for 2012/342-2017/269



Easy to cleanly select B and C from data – no background problem.



Voyager 1 electron (e- + e+) spectrum (circles) and AMS (e- + e+) at 1 AU (squares).

Voyager 1:

$dJ/dE = A*(E/10 \text{ MeV})^b \ (m^2 \text{ s sr MeV})^{-1}$

$A = 246 \pm 9$

$b = -1.30 \pm 0.05$

Potgieter et al. 2015 electron energy spectrum is used for energy density and ionization rate calculations.

The Astrophysical Journal, 831:18 (21pp), 2016 November 1
doi:10.3847/0004-637X/831/1/18

GALACTIC COSMIC RAYS IN THE LOCAL INTERSTELLAR MEDIUM: *VOYAGER 1* OBSERVATIONS AND MODEL RESULTS

A. C. Cummings[1], E. C. Stone[1], B. C. Heikkila[2], N. Lal[2], W. R. Webber[3], G. Jóhannesson[4],
I. V. Moskalenko[5], E. Orlando[5], and T. A. Porter[5]
[1] California Institute of Technology, Pasadena, CA 91125, USA
[2] Goddard Space Flight Center. Greenbelt, MD 20771, USA
[3] New Mexico State University, Las Cruces, NM 88003, USA
[4] University of Iceland, Reykjavik, Iceland
[5] HEPL and KIPAC, Stanford University, Stanford, CA 94305, USA
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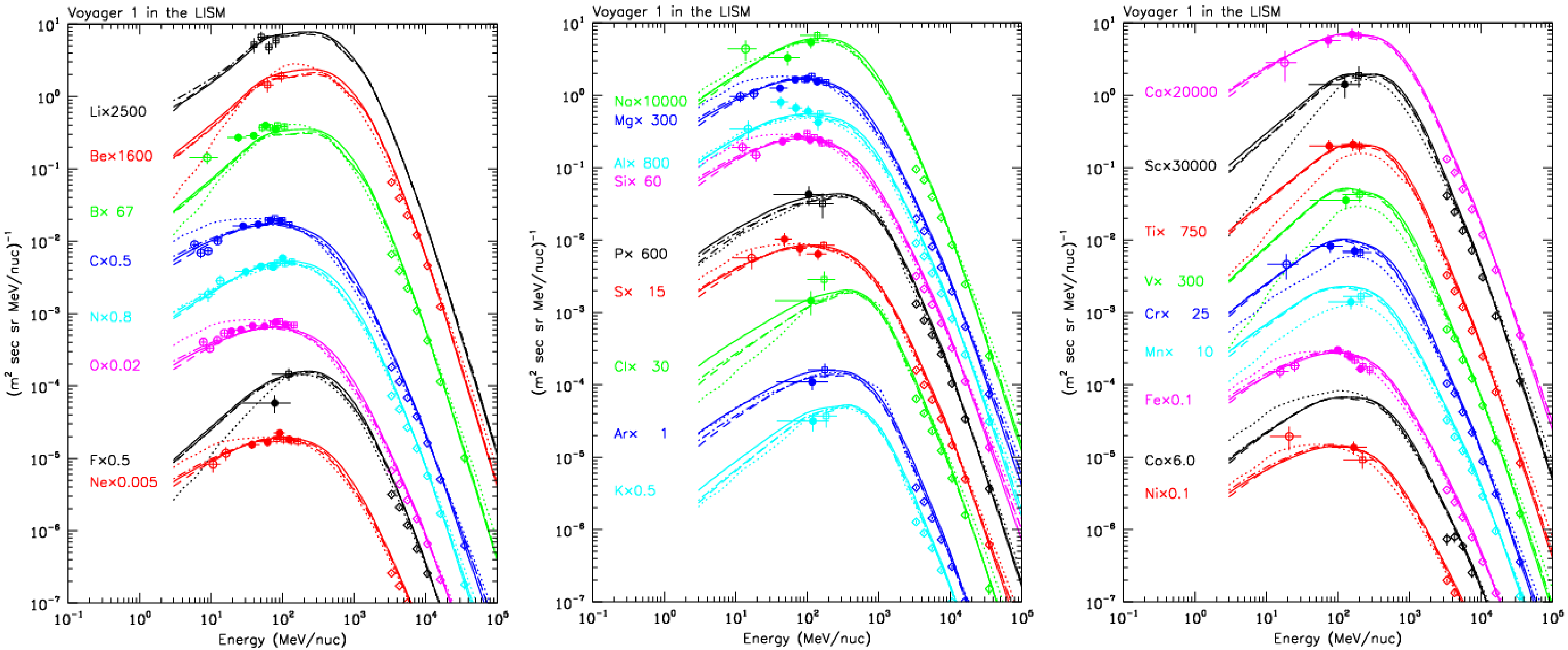
ABSTRACT

Since 2012 August *Voyager 1* has been observing the local interstellar energy spectra of Galactic cosmic-ray nuclei down to 3 MeV nuc^{-1} and electrons down to 2.7 MeV. The H and He spectra have the same energy dependence between 3 and 346 MeV nuc^{-1}, with a broad maximum in the 10–50 MeV nuc^{-1} range and a H/He ratio of 12.2 ± 0.9. The peak H intensity is ~15 times that observed at 1 AU, and the observed local interstellar gradient of 3–346 MeV H is $-0.009 \pm 0.055\%$ AU^{-1}, consistent with models having no local interstellar gradient. The energy spectrum of electrons ($e^- + e^+$) with 2.7–74 MeV is consistent with $E^{-1.30\pm0.05}$ and exceeds the H intensity at energies below ~50 MeV. Propagation model fits to the observed spectra indicate that the energy density of cosmic-ray nuclei with >3 MeV nuc^{-1} and electrons with >3 MeV is 0.83–1.02 eV cm^{-3} and the ionization rate of atomic H is in the range of $1.51–1.64 \times 10^{-17}$ s^{-1}. This rate is a factor >10 lower than the ionization rate in diffuse interstellar clouds, suggesting significant spatial inhomogeneity in low-energy cosmic rays or the presence of a suprathermal tail on the energy spectrum at much lower energies. The propagation model fits also provide improved estimates of the elemental abundances in the source of Galactic cosmic rays.

Key words: cosmic rays – ISM: abundances – ISM: clouds

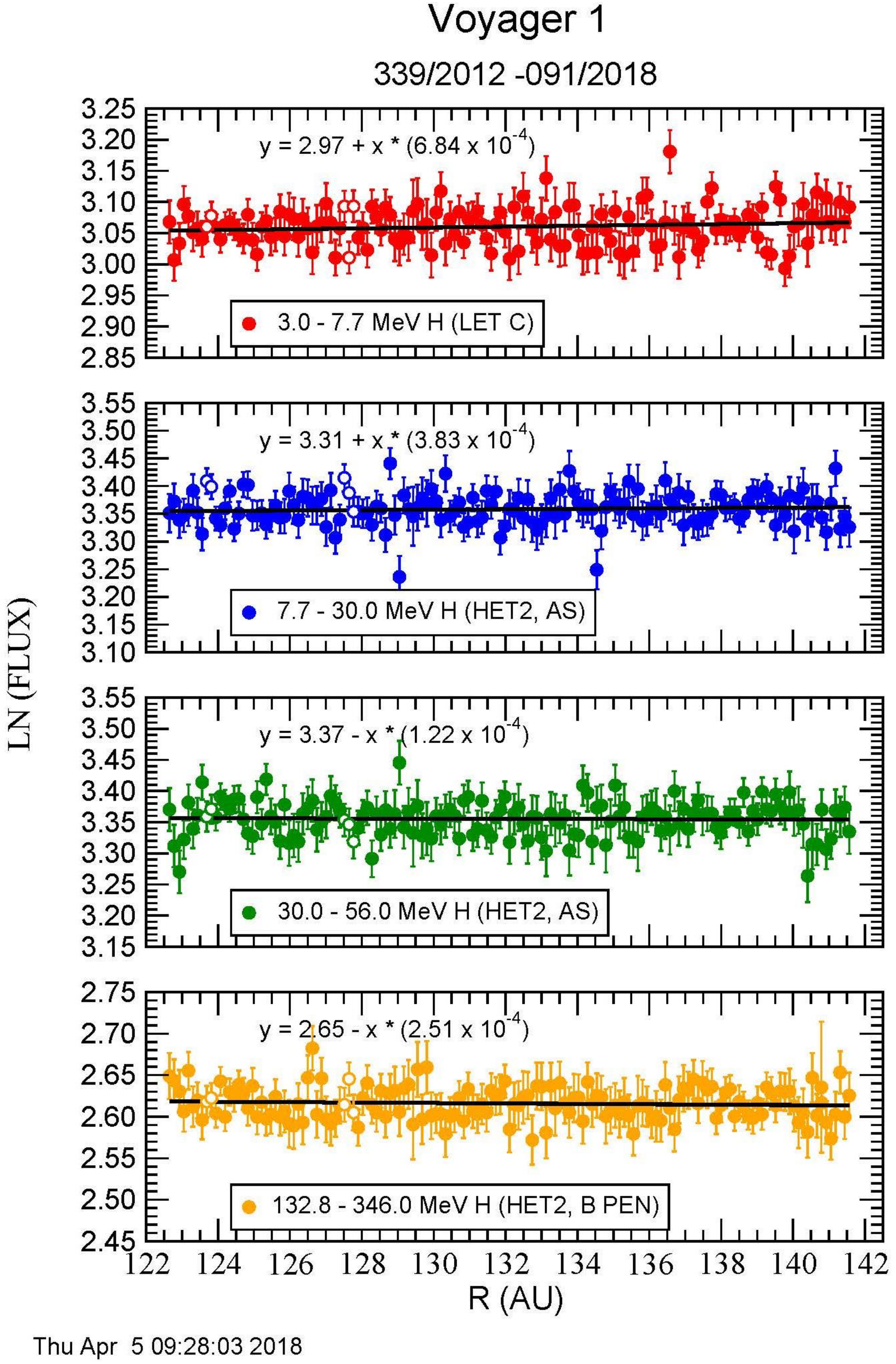
Supporting material: machine-readable tables



V1 spectra for 2012/342-2015/181 for Li – Ni, with exception of Co, together with high-energy portion of HEAO-3-C2 data (>= 3.35 GeV/nuc).

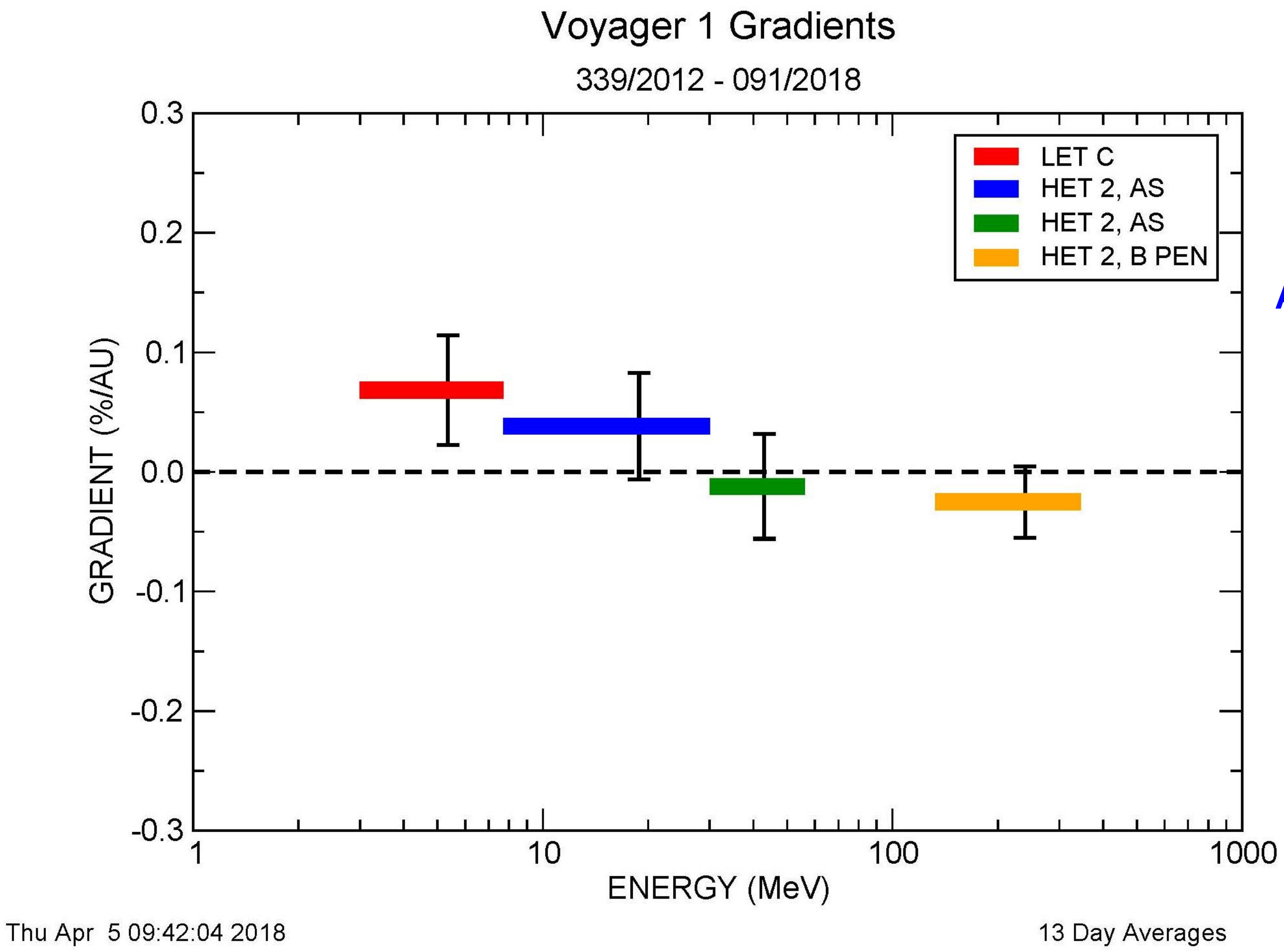
Models are constrained by the new Voyager observations and by data taken at 1 AU.

All calculations of ionization rate and energy density will use the models, starting at 3 MeV/nuc.



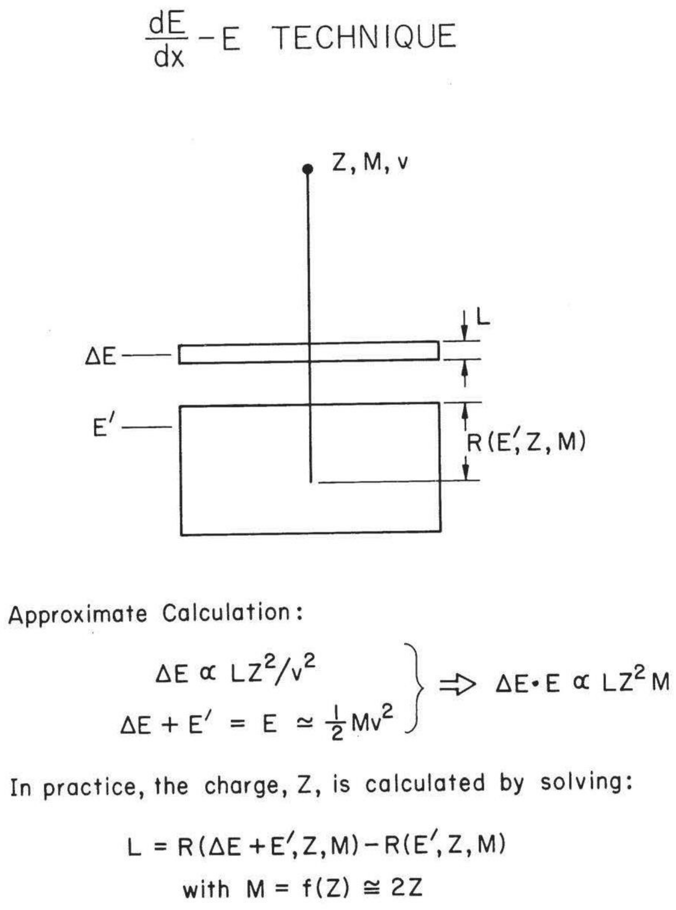
GCR H intensities in units of $(m^2\ s\ sr\ MeV)^{-1}$
in 4 energy bands
vs radial distance in the LISM
with fits that yield radial gradients.

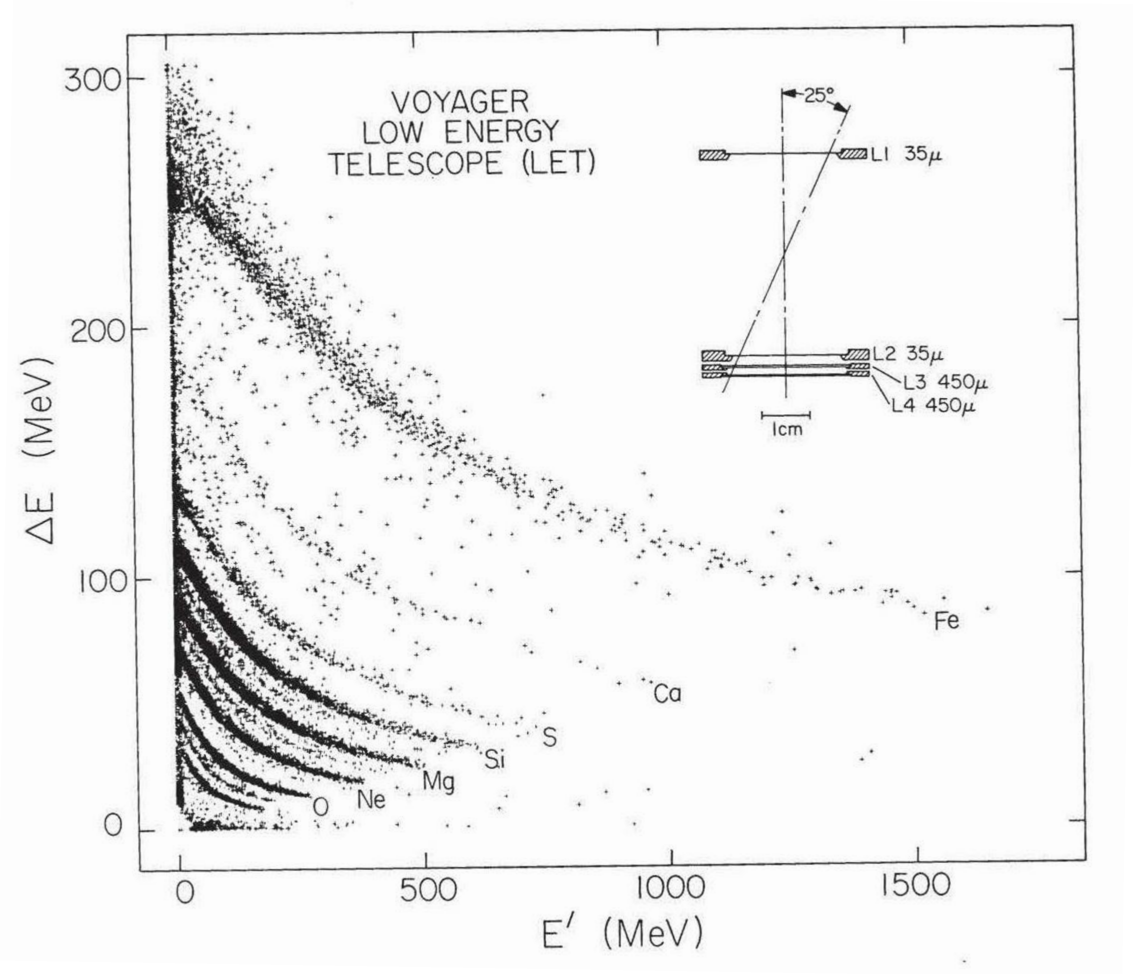
Some periods removed – known transient events and spacecraft maneuvers.



Average of four is 0.006 ± 0.020 %/AU

dE/dX vs E’ technique

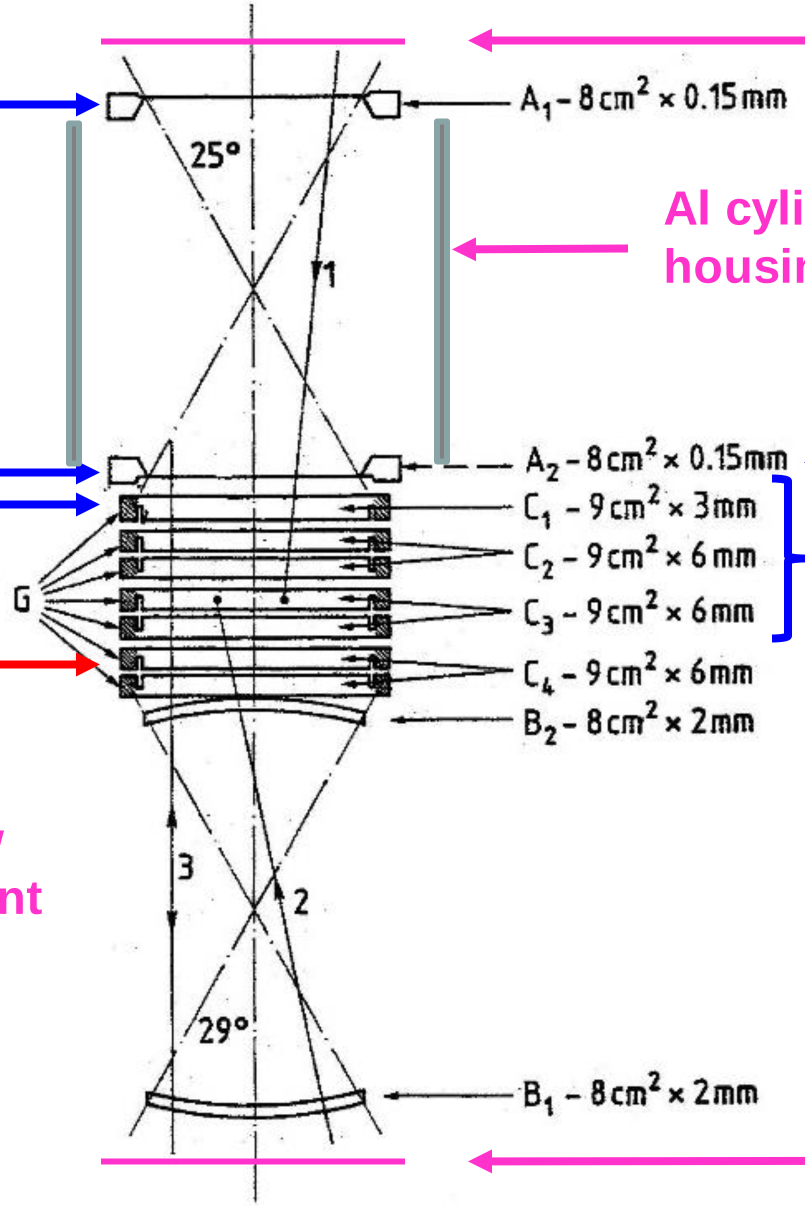




So, assuming M = 2*Z (for all but protons), can derive a fractional value of Z from two energy loss measurements and knowledge of L. Can do that in two semi-independent ways, by letting ΔE be either the energy loss from 1st detector or from the 2^{nd} detector. Further, can get two semi-independent estimates of the mass of the nucleus by selecting data that we know has Z = 1 or Z = 2.

CRS HET Telescope

Window/blanket:
2.75 mils mylar
equivalent



Al cylinder
housing

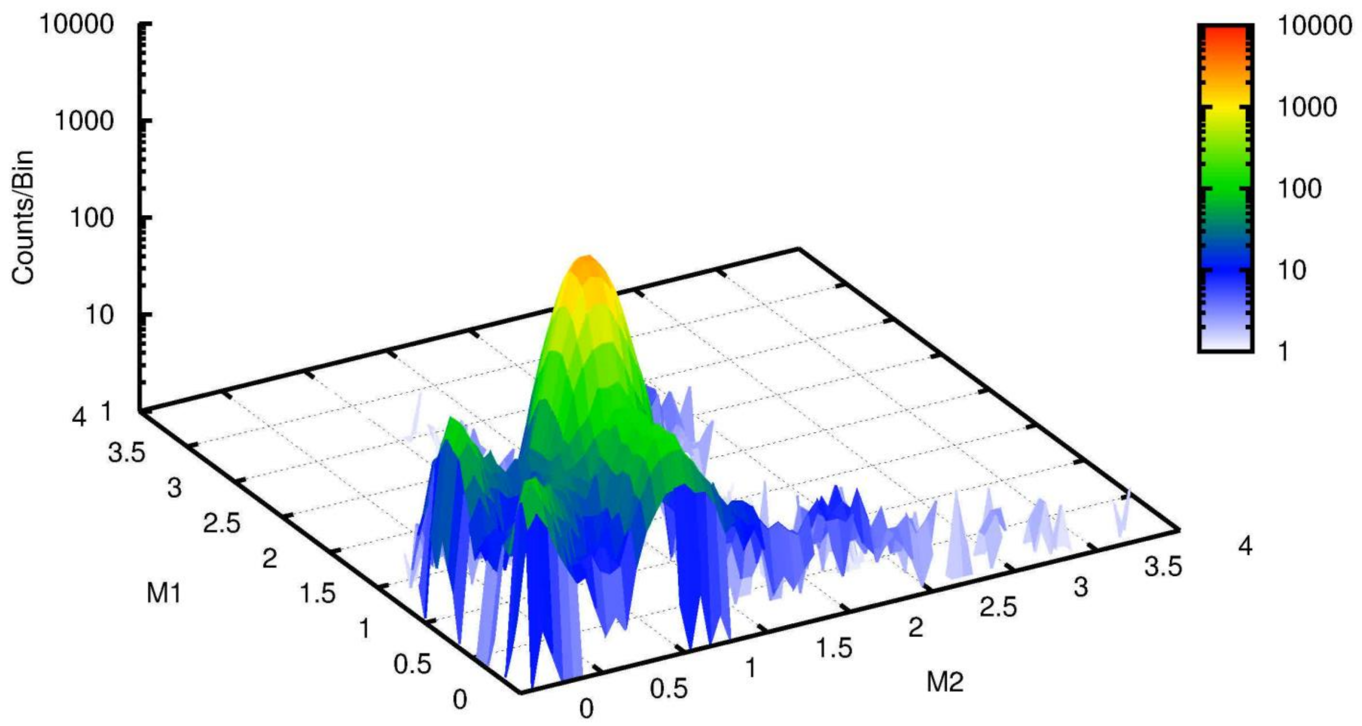
Trigger condition for
"A stopping" analysis:
A1.A2.C1.notC4

Energy losses returned:
A1, A2,
and C1+C2+C3 (sumC)

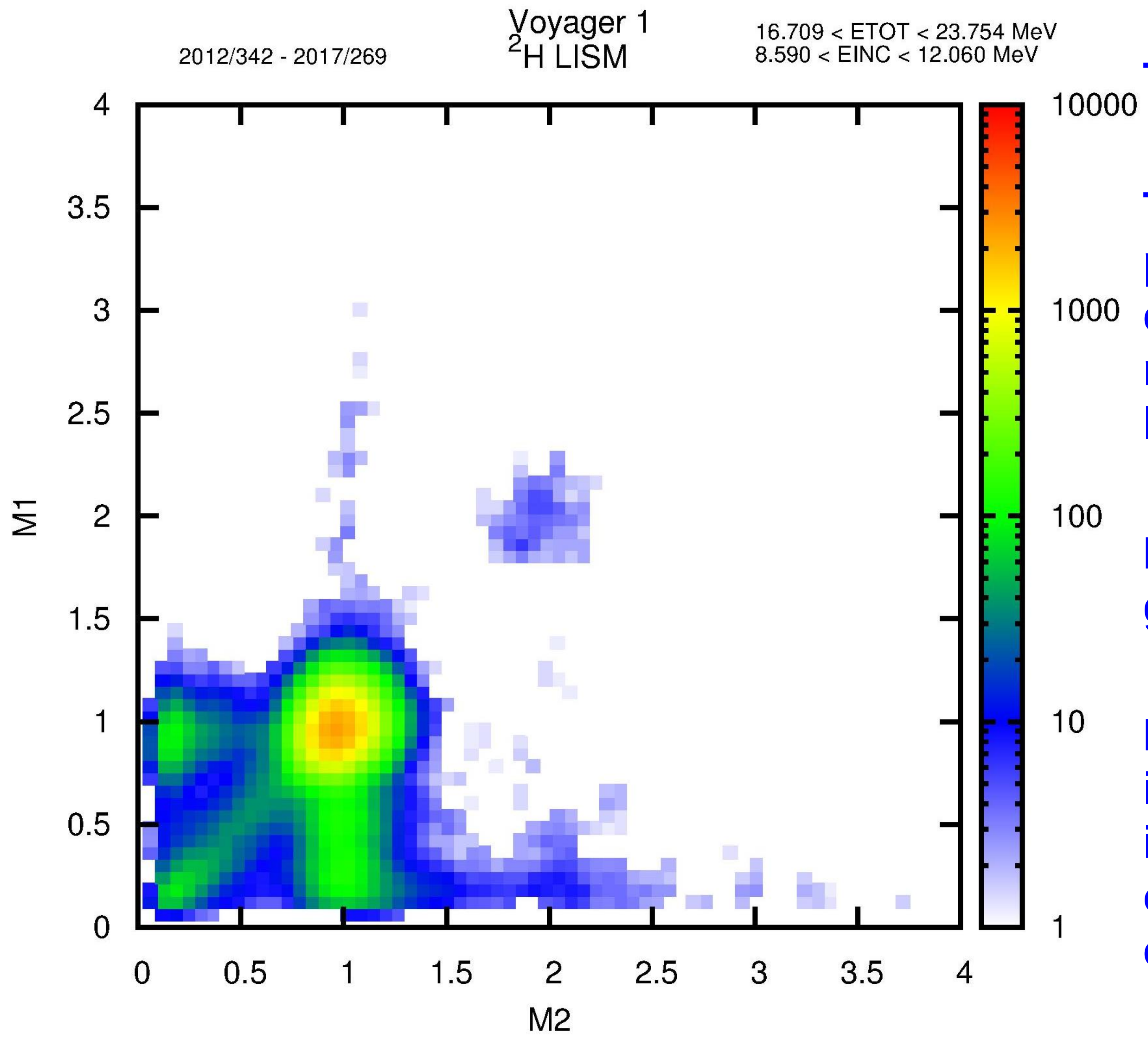
Window/blanket in FOV is a new
revelation and could be important
for the isotope analysis.

Window/blanket:
3.5 mils mylar
equivalent

V1 HET 2 ASHG 2H Energy Interval B (8.6 – 12.1 MeV/nuc)



Plot of two semi-independent mass estimates (M1 and M2) for each particle to look for blobs at 1,1 for protons and 2,2 for deuterons.



2D spectrogram version of M1 vs M2

There are features present near the 1H blob.

The vertical streak below 1,1 is due to particles going through A1, just beyond its edge, causing energy loss to be lower than nominal. Results in M1 being calculated as low.

Horizontal streak same, except particles going through A2 just beyond its edge.

Diagonal streak is due to particles stopping in a dead layer and higher energy particles interacting and not all the energy being collected. Causes E' to be low and both M's coming out low.

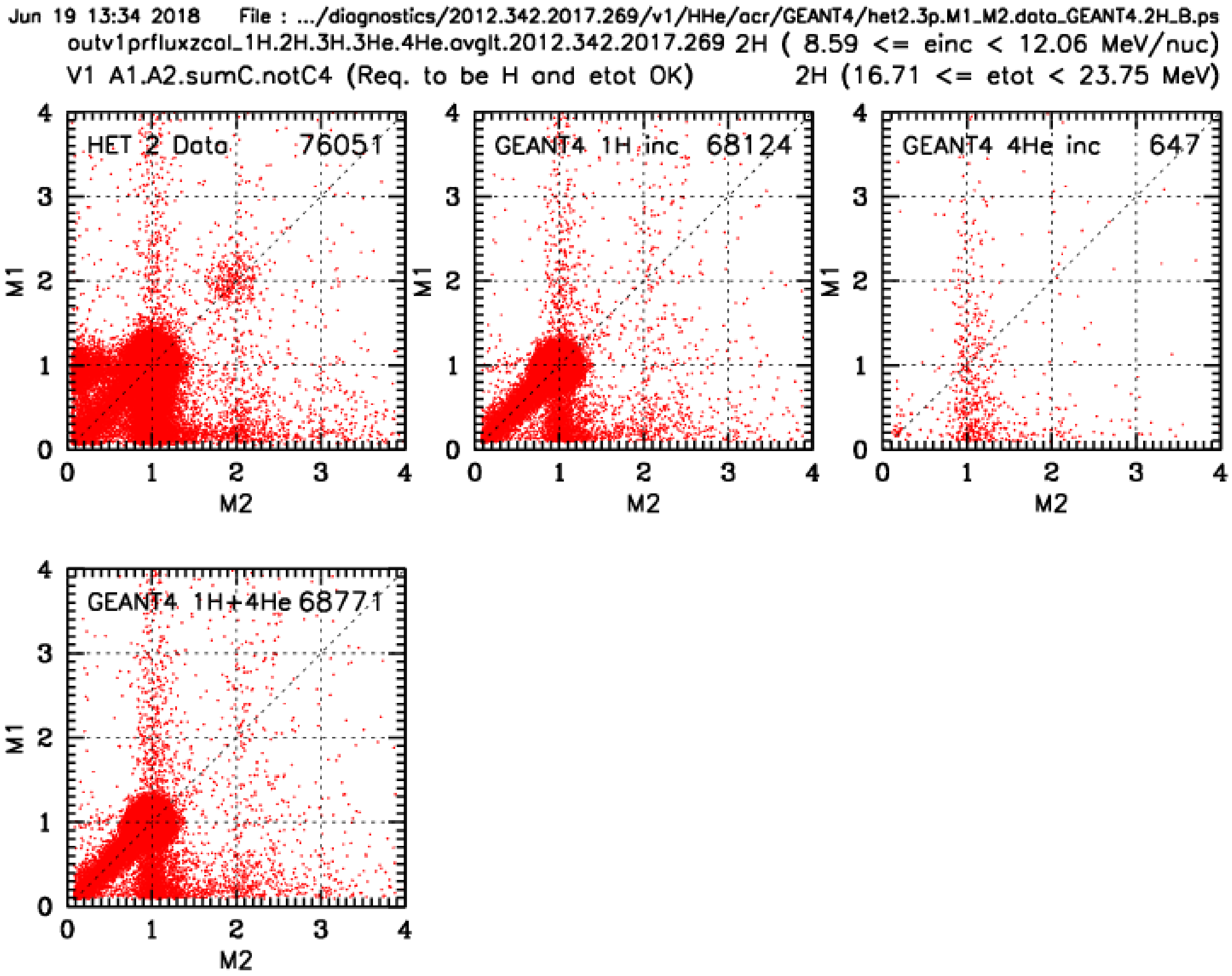
Same features will be present for the 2H blob.

Not time to go into how we remove background from the 2H blobs. It's under 10% for the B end and varies from 15-30% on the A end. Similar for 3He.

We are convinced we have a good measurement of both 2H and 3He.

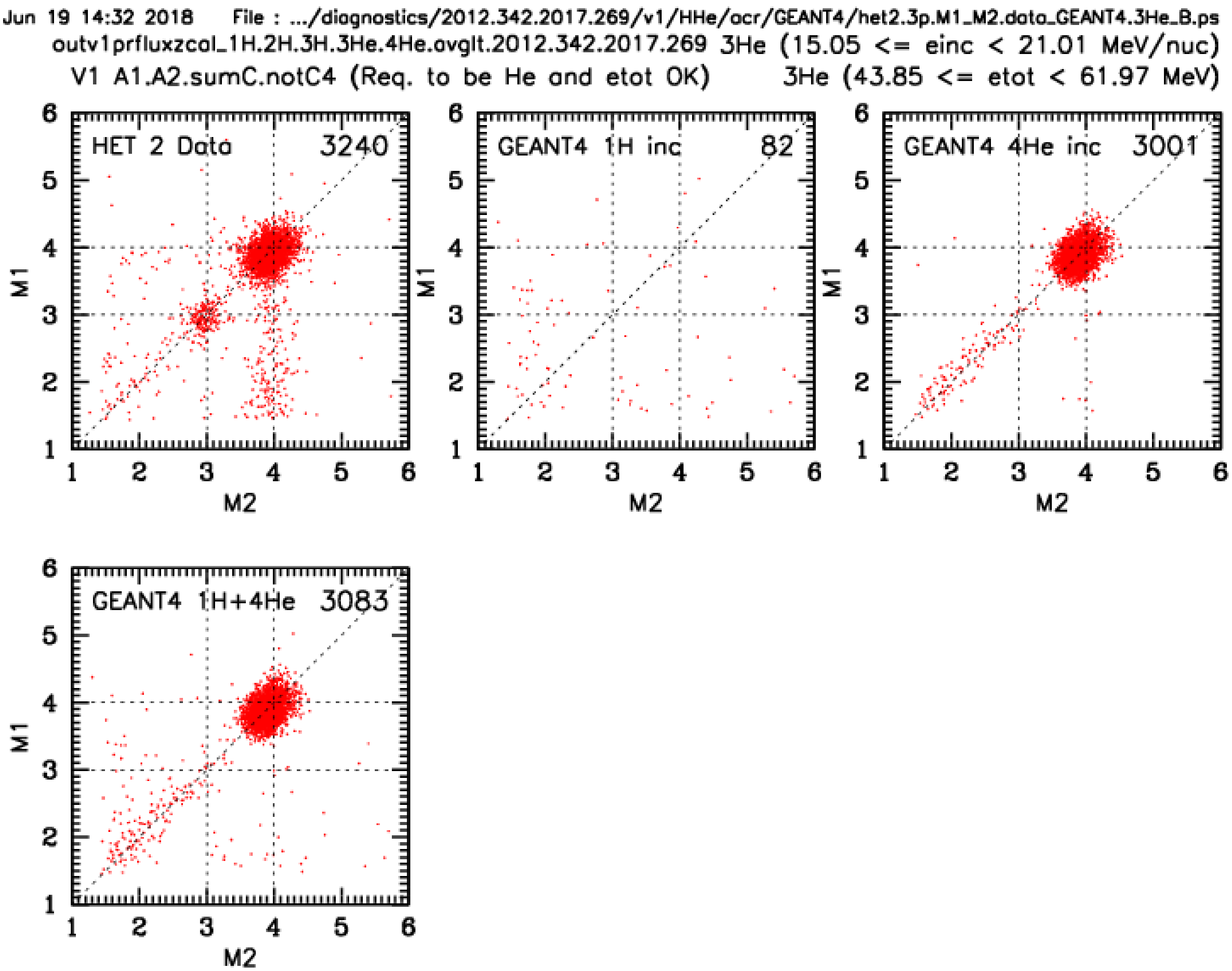
Is it from the LISM?

Recall there is the window/blanket material in the field of view. Nuclear interactions in that window from incident 1H or 4He could be producing the 2H and 3He we observe.



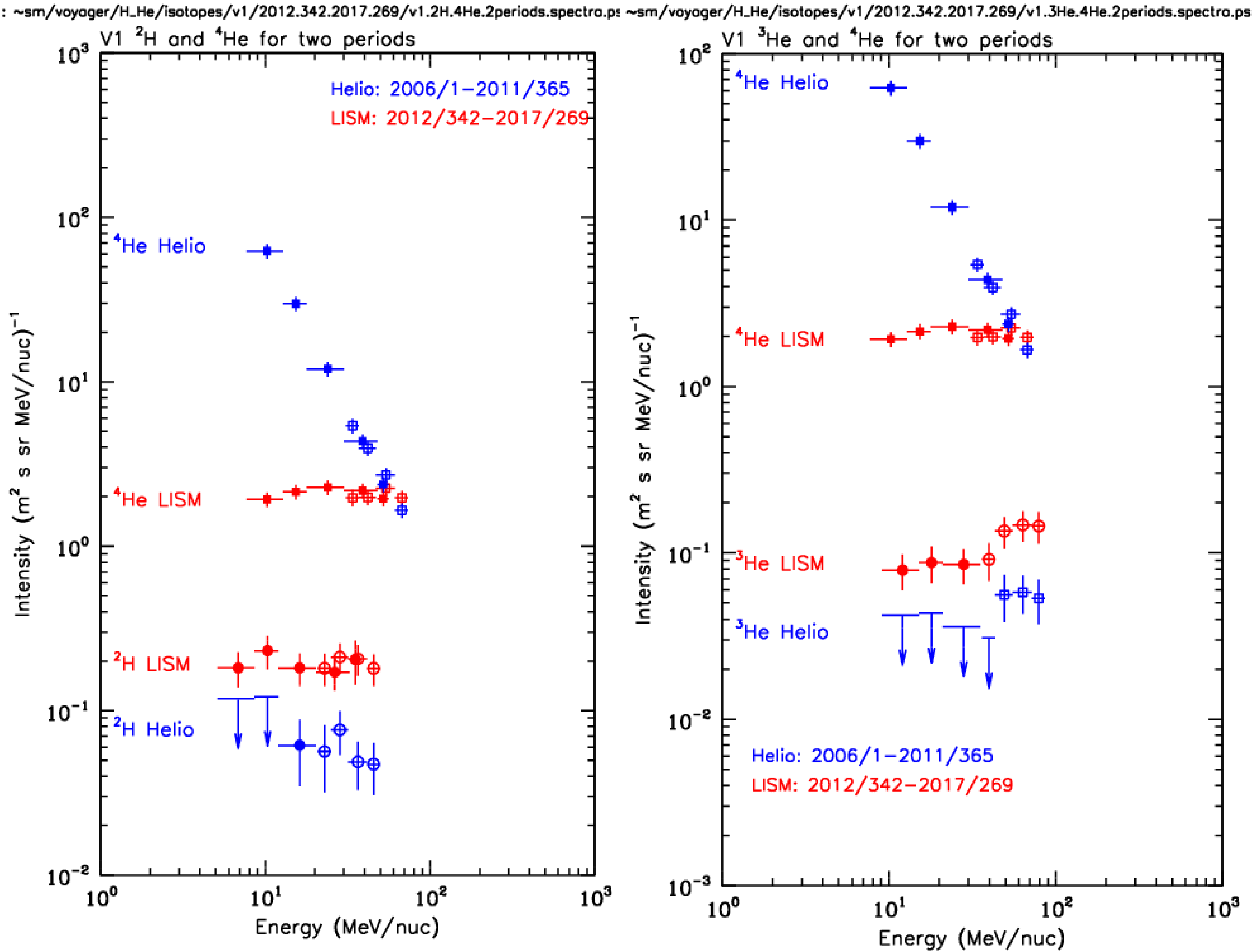
Modeled the HET telescope and included the window/blanket material and the Al cylinder separating the A1 and A2 detectors.

Ran two GEANT4 simulations with incident spectra from the GALPROP DR 1H and 4He models in Cummings et al., 2016. The simulation shown is for the same 2H energy interval shown in previous slides. Does not appear that 2H is being made in the telescope.



The simulation shown below is for the 15-1 – 21.0 MeV/nuc 3He energy interval.

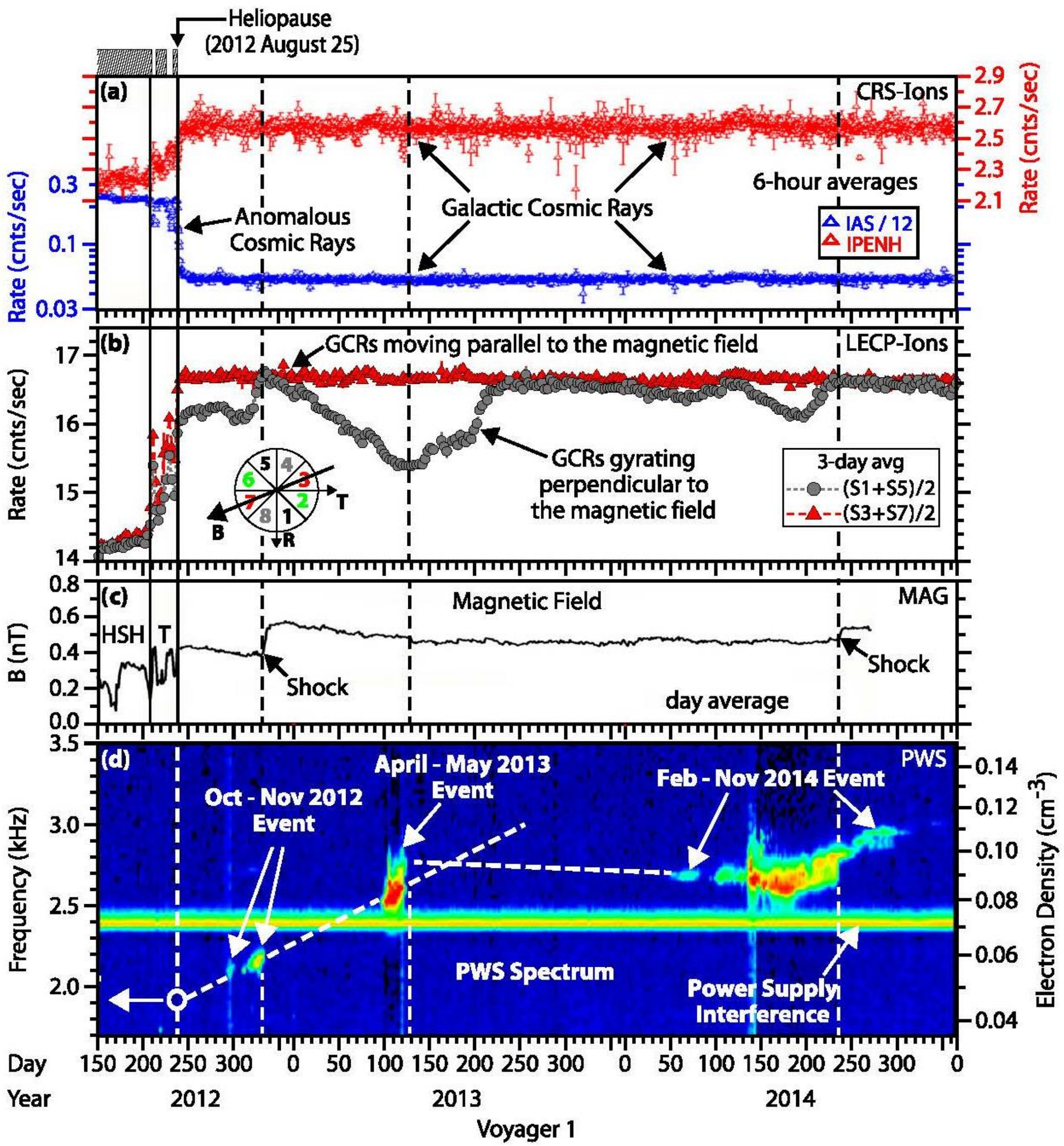
No significant 2H or 3He is being produced in the instrument according to these GEANT4 model runs.



But what if the cross sections are wrong in GEANT4?

Compare LISM spectra with ones from the heliosheath, where the intensities of 1H and 4He are dramatically higher in the energy range of interest due to ACRs.

The 2H and 3He intensities are not larger in the heliosheath, implying the LISM 2H and 3He is not being made in the window/thermal blanket material from progenitors with similar energies.



Sun is having an effect at position of Voyager 1 in LISM.

Figure is from Gurnett et al., 2015.

There is often an anisotropy of GCRs present, up to ~10% lower intensity if looking perpendicular to the magnetic field direction.

Shocks are observed.

Electron-plasma oscillations observed, the frequency of which give the local plasma density…