



Voyager 1 Observations of Galactic Cosmic Ray Isotopes in the Very Local Interstellar Medium: Evidence for Primary ${}^2\text{H}$ and B

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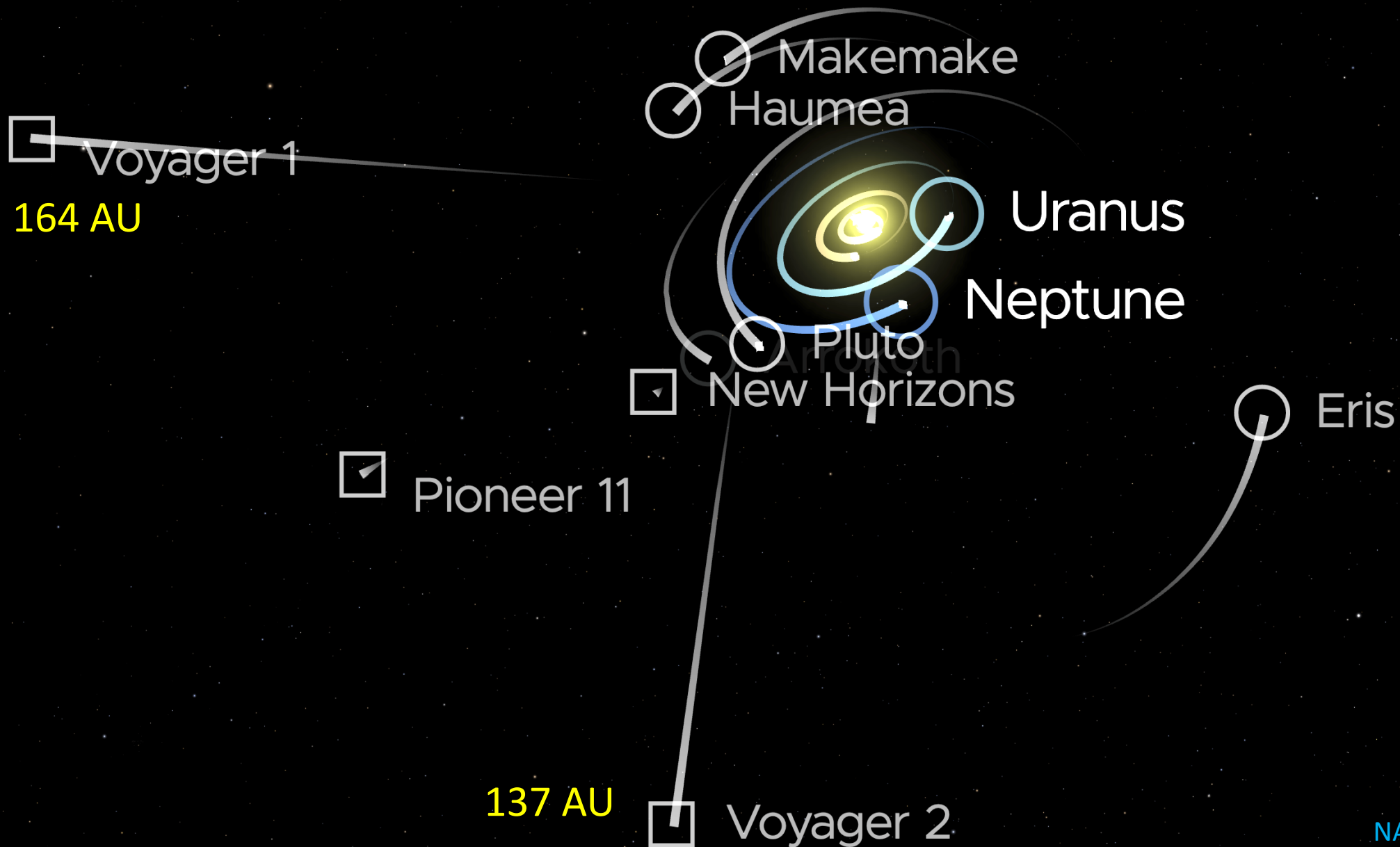
Dedicated to the memory of Ed Stone, the PI of V1 & V2



Ed Stone & Voyager 1

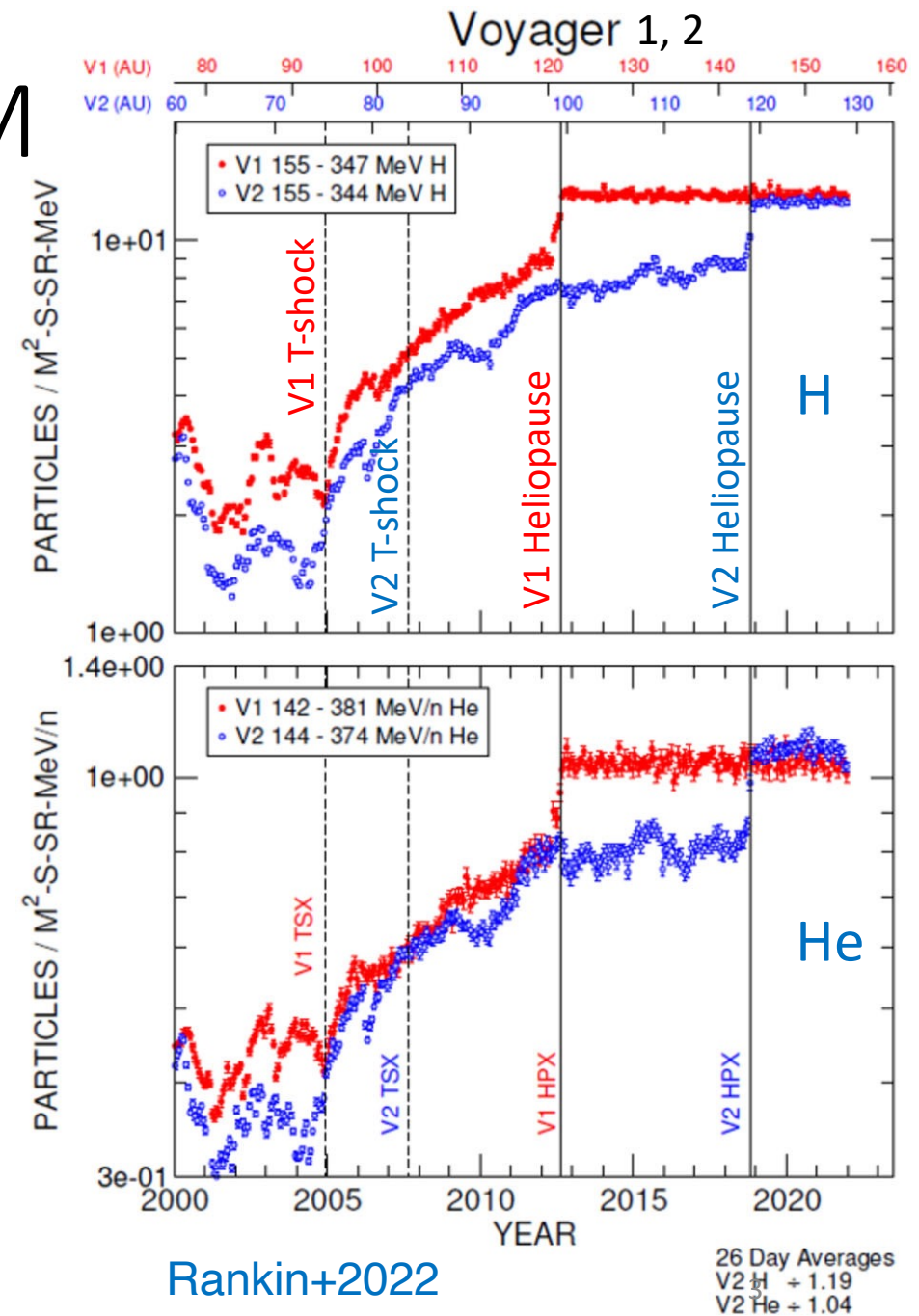
Current position

☐ Pioneer 10
137 AU



Cosmic rays in the very local ISM

- 26-day averages of GCR Hydrogen and Helium measured by **Voyager 1** and **Voyager 2** as a function of time and radial distance in the heliosheath and VLISM
- After the Heliopause crossing, the cosmic ray flux remains constant





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

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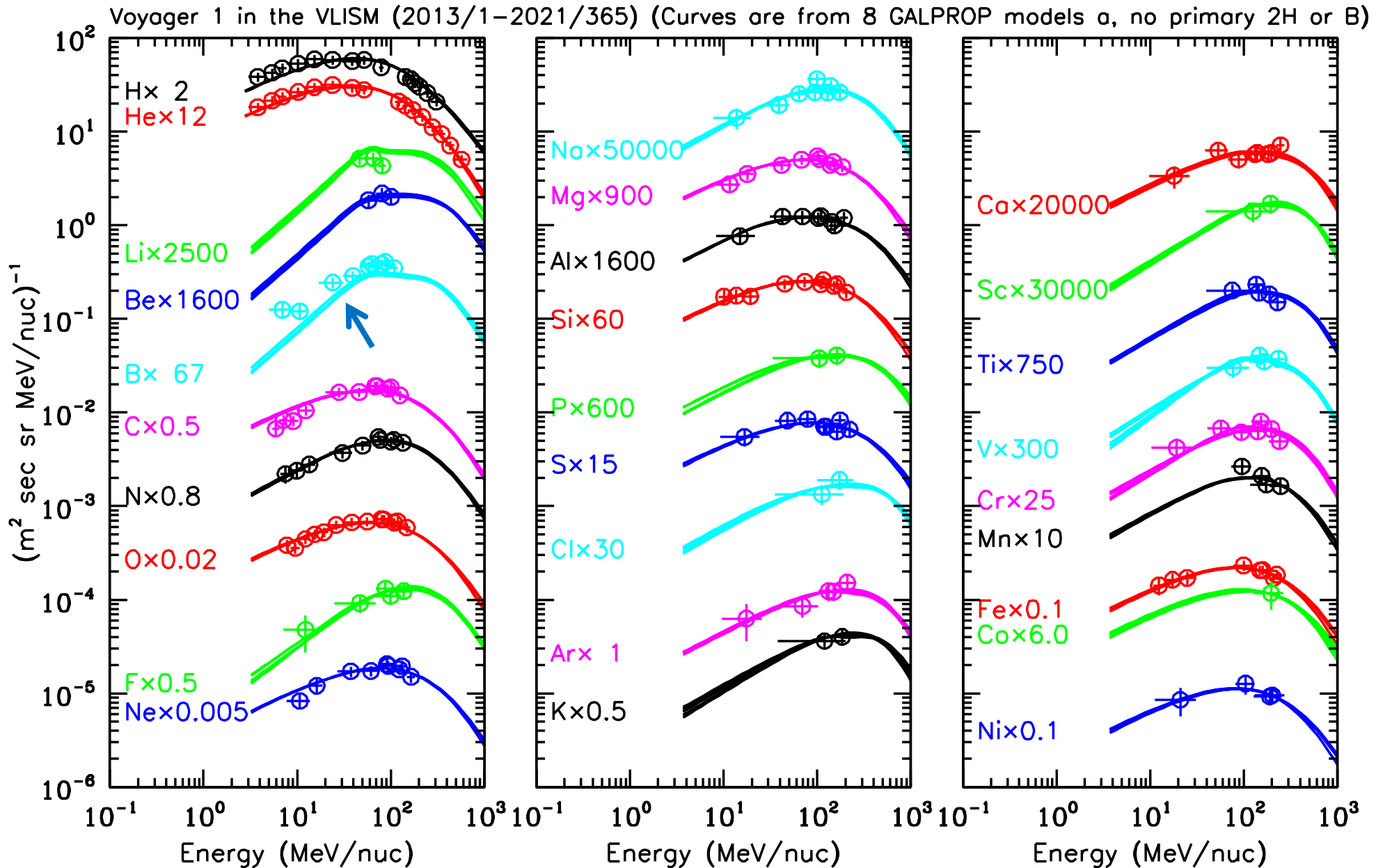
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- **2016 paper:** Data collected 2012/342 through 2015/181 ~ **2.5 years**
- **2024 paper:** Updated data set 1/1/2013 through 12/31/2021 = **9 years**

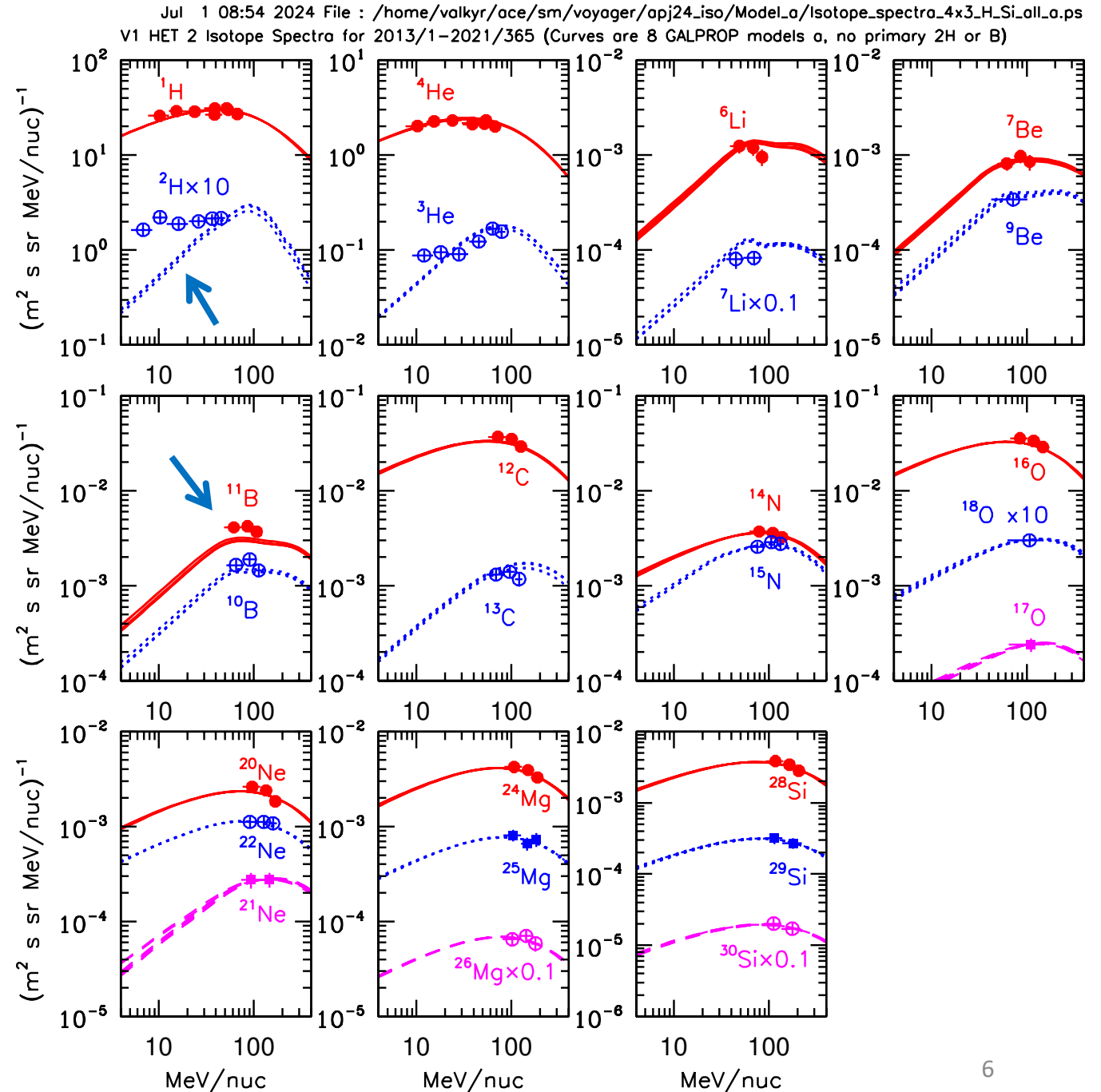
Elemental spectra

- Agree well with standard plain diffusion GALPROP models, except for the Boron excess at $\sim 2-4\sigma$
- Details of the GALPROP models are in the following slides



Isotopic spectra

- Although, **8 GALPROP models** have different propagation parameters derived independently, the isotopic spectra are all consistent
- Source abundances (conventional):
 ^2H , ^3He , Li, Be, B = 0
- The agreement is good, except for ^2H and $^{11}\text{B}+^{10}\text{B}$
- Tried many options including increased weight of B data points (up to x100) – do not work well (e.g. C becomes crazy)
- Origin of ^2H and B excess:
 - Errors in the cross sections/propagation models
 - ^2H , B are produced in the instrument
 - Primary components



GALPROP models

- Use only Voyager 1 data, but tuned to match LIS (Boschini+2020) at higher energies
- Fast ionization energy losses – reacceleration and convection are slow processes
- Plain diffusion – less parameters
- Single injection index for all species
- 8 models to cover available options in cross sections = 2 options for isotopic production cross sections × 4 options for total inelastic cross sections
- Source distribution: pulsar distribution by Lorimer+2006
- CO, H I, H II gas – standard distributions
- $X_{\text{CO}}(R) = 10^{19.6+0.066R} \text{ mol. cm}^{-2}/(\text{K km s}^{-1})$
- Updated cross sections (see following slides) – this work gave us more confidence, but did not eliminate the ^2H and B excesses

Total inelastic cross sections

Existing data cover the energy range of interest:
~10 MeV/n – 100 MeV/n

Parameterizations:

$p+A$, $\alpha+A$

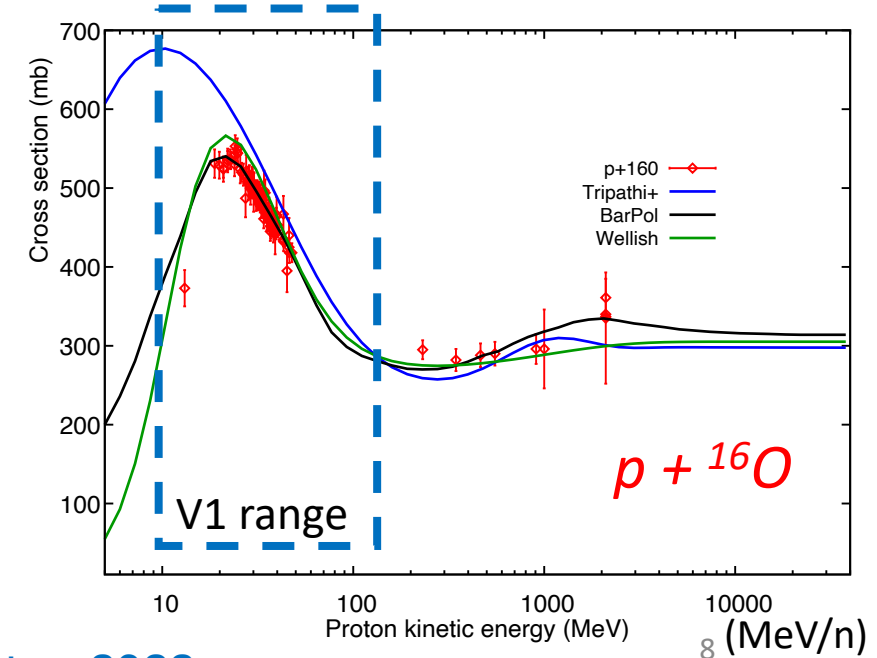
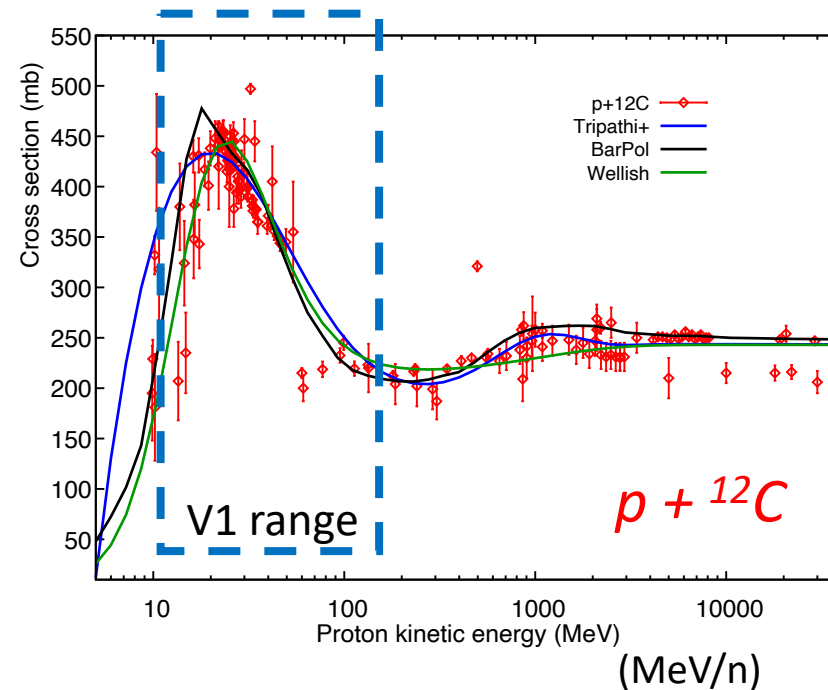
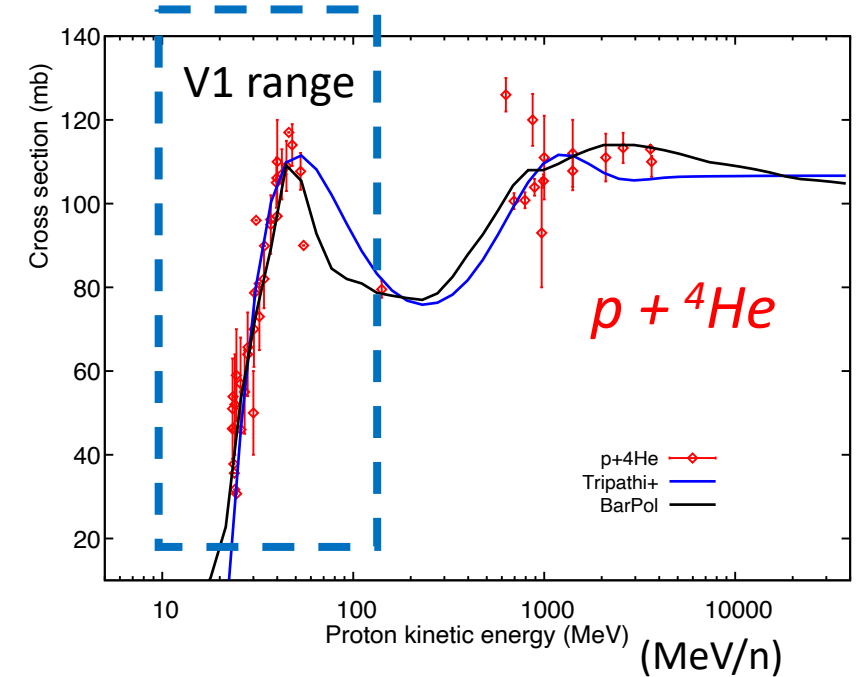
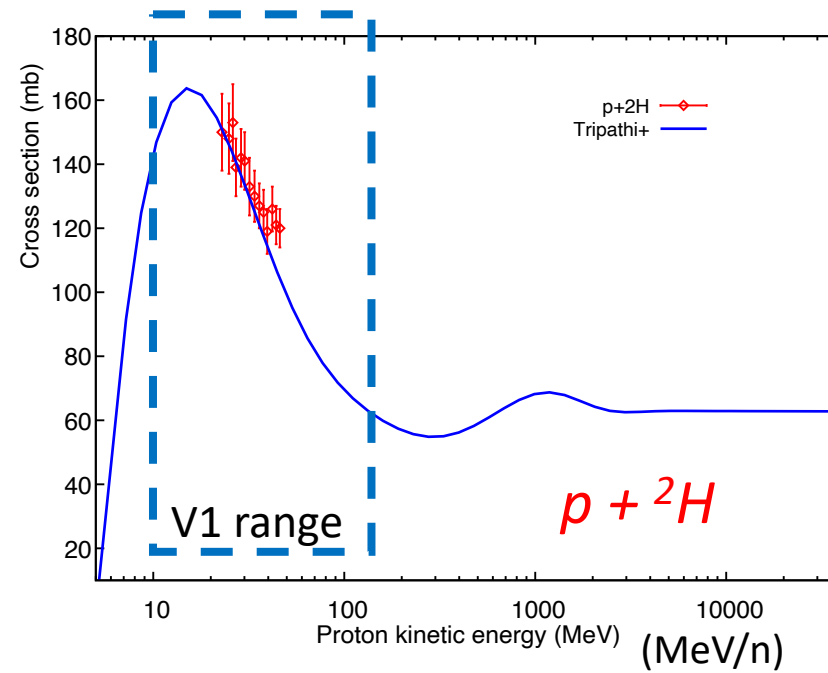
Tripathi+

Barashenkov & Polansky

$p+A$

Wellisch & Axen 1996

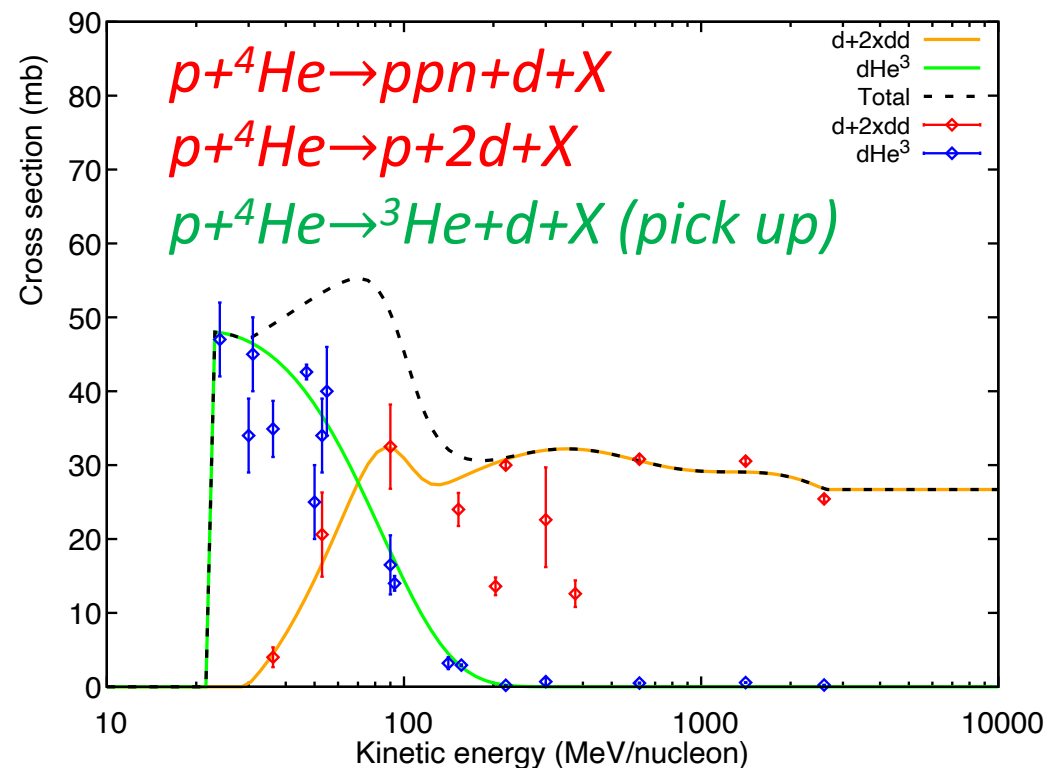
Use their combinations to cover all proj+targets



Porter+2022

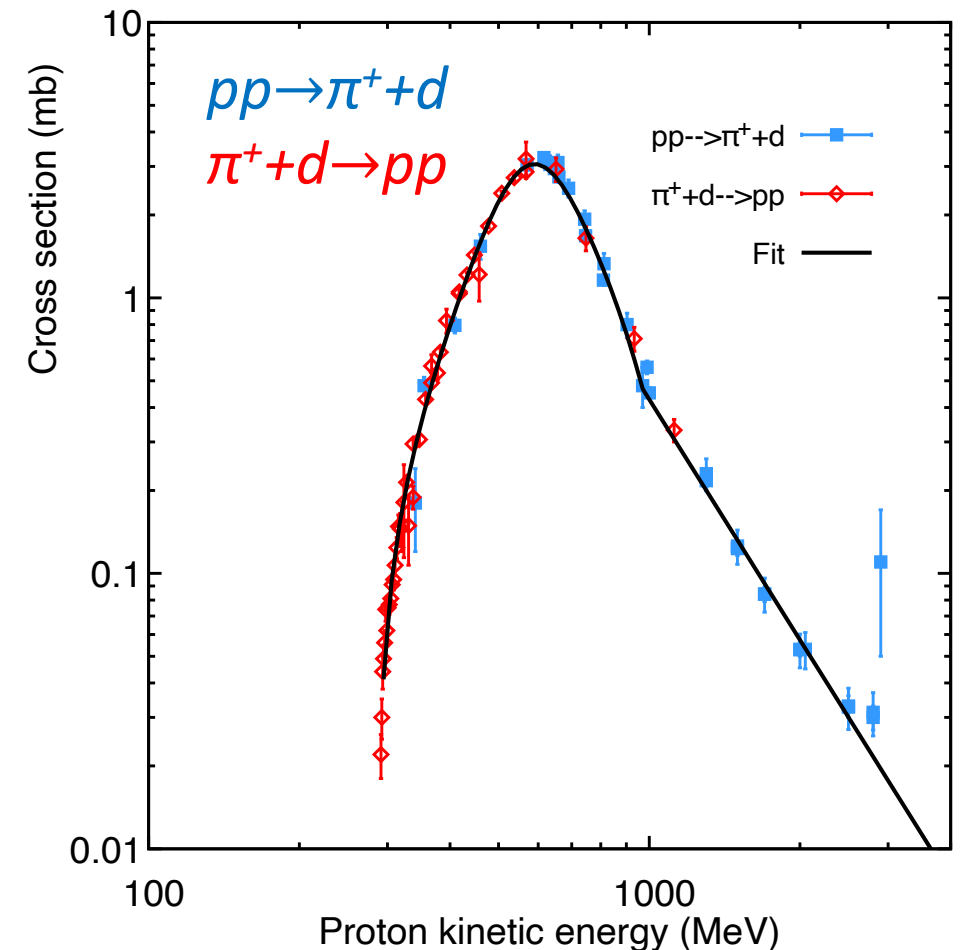
Deuteron production cross sections (GALPROP v57)

- Includes all $p+A$ and $\alpha+A$ reactions
- ^4He is the main progenitor



Principle of detailed balance
(direct & inverse reactions):

$$\frac{\sigma_{pp}}{\sigma_{\pi d}} = 2 \frac{(2S_{\pi} + 1)(2S_d + 1)}{(2S_p + 1)^2} \frac{p'^2_{\pi}}{p'^2_p} = \frac{3}{2} \frac{p'^2_{\pi}}{p'^2_p}$$



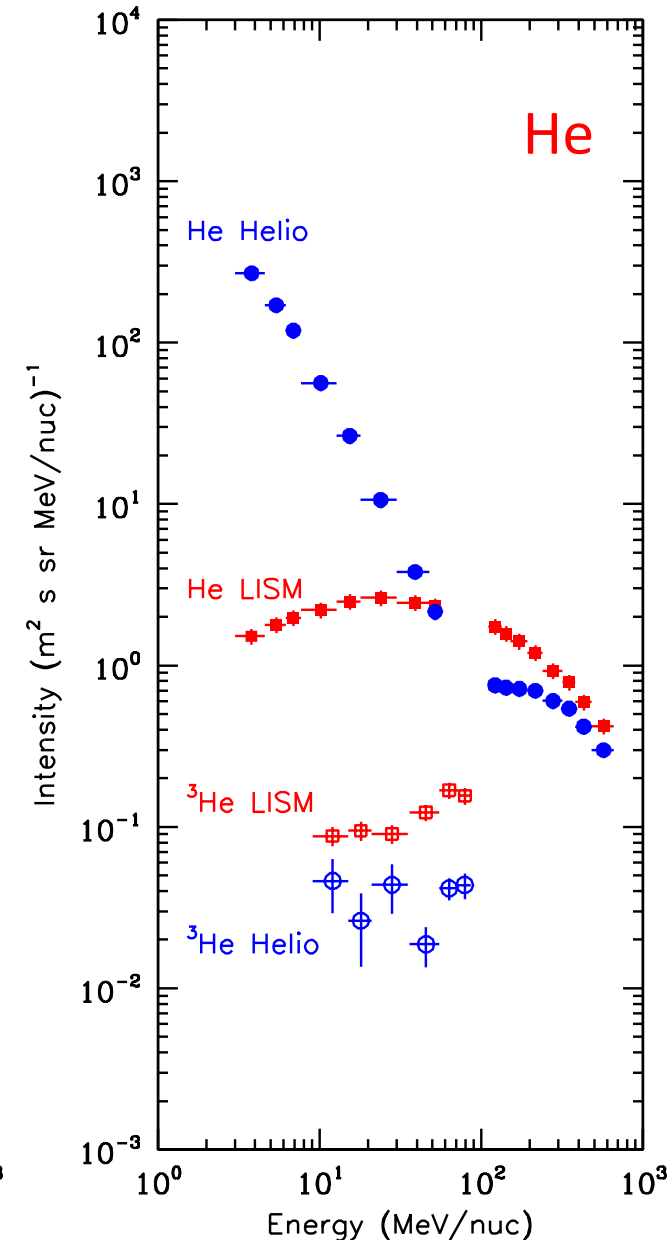
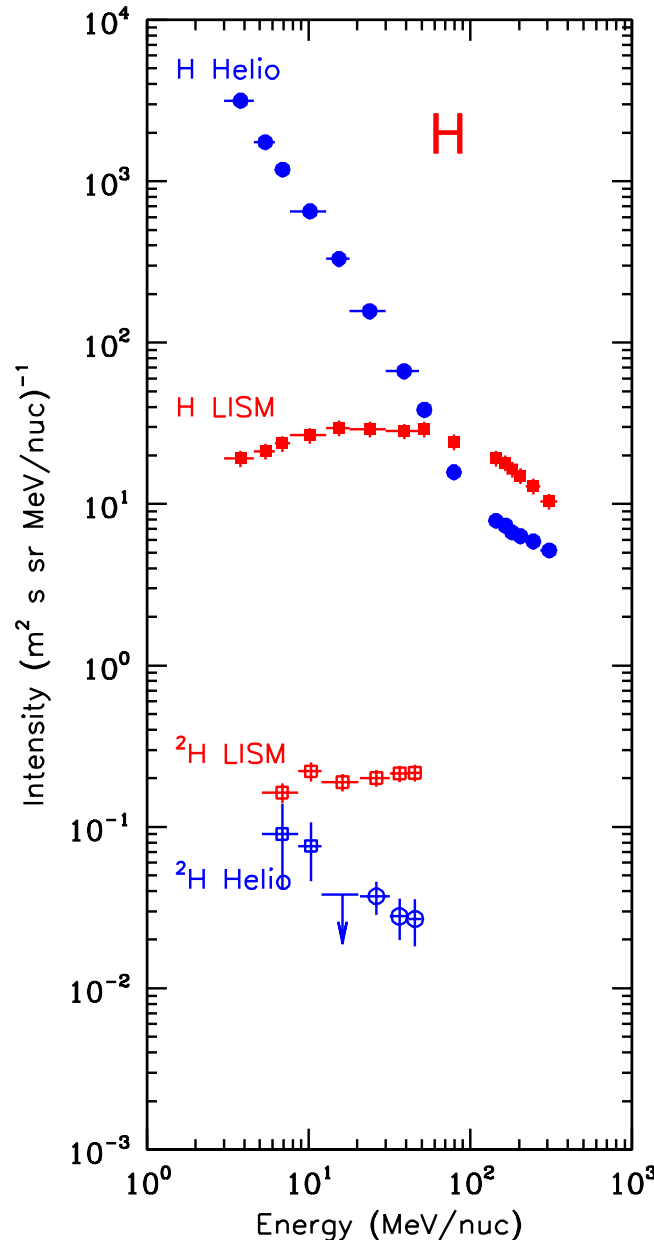
Updated isotopic production cross sections

Targets	$p + A \rightarrow B$	Products	Final Element
${}^7\text{Li}, {}^7,{}^9\text{Be}, {}^{10,11}\text{B}, {}^{12,13}\text{C}, {}^{14,15}\text{N}, {}^{16}\text{O}, {}^{56}\text{Fe}$	$\rightarrow$	${}^{6,7}\text{Li}, {}^7\text{Be}$	Li
${}^9\text{Be}, {}^{10,11}\text{B}, \text{nat},{}^{12,13}\text{C}, \text{nat},{}^{14,15}\text{N}, \text{nat},{}^{16}\text{O}, \text{nat},{}^{24}\text{Mg}, \text{nat},{}^{28}\text{Si}, \text{nat},{}^{32}\text{S}, \text{nat},{}^{56}\text{Fe}$	$\rightarrow$	${}^{7,9,10}\text{Be}, {}^{10}\text{B}, {}^{10}\text{C}$	Be
${}^{11}\text{B}, \text{nat},{}^{12,13}\text{C}, \text{nat},{}^{14,15}\text{N}, \text{nat},{}^{16}\text{O}, {}^{20,22}\text{Ne}, \text{nat},{}^{24}\text{Mg}, \text{nat},{}^{28}\text{Si}, \text{nat},{}^{56}\text{Fe}$	$\rightarrow$	${}^{10}\text{Be}, {}^{10,11}\text{B}, {}^{10}\text{C}$	B
$\text{nat},{}^{14,15}\text{N}, \text{nat},{}^{16}\text{O}, {}^{20,22}\text{Ne}, \text{nat},{}^{24}\text{Mg}, \text{nat},{}^{28}\text{Si}, \text{nat},{}^{56}\text{Fe}$	$\rightarrow$	${}^{13}\text{C}, {}^{13}\text{N}$	C
$\text{nat},{}^{16}\text{O}, {}^{20,22}\text{Ne}, \text{nat},{}^{24}\text{Mg}, \text{nat},{}^{28}\text{Si}, \text{nat},{}^{32}\text{S}, \text{nat},{}^{56}\text{Fe}$	$\rightarrow$	${}^{15}\text{N}, {}^{15}\text{O}$	N
${}^{19}\text{F}, {}^{20,22}\text{Ne}, {}^{23}\text{Na}, \text{nat},{}^{24}\text{Mg}, {}^{27}\text{Al}, \text{nat},{}^{28}\text{Si}, \text{nat},{}^{32}\text{S}, \text{nat},{}^{56}\text{Fe}$	$\rightarrow$	${}^{17}\text{C}, {}^{17}\text{N}, {}^{17,18}\text{O}, {}^{17,18}\text{F}, {}^{17,18}\text{Ne}$	O
${}^{20,22}\text{Ne}, {}^{23}\text{Na}, \text{nat},{}^{24}\text{Mg}, \text{nat},{}^{28}\text{Si}, \text{nat},{}^{32}\text{S}, \text{nat},{}^{56}\text{Fe}$	$\rightarrow$	${}^{19}\text{F}, {}^{19}\text{Ne}$	F
$\text{nat},{}^{24}\text{Mg}, {}^{27}\text{Al}, \text{nat},{}^{28}\text{Si}, \text{nat},{}^{56}\text{Fe}$	$\rightarrow$	${}^{21,22}\text{Ne}, {}^{21,22}\text{Na}$	Ne
$\text{nat},{}^{48,49}\text{Ti}, \text{nat},{}^{52}\text{Cr}, \text{nat},{}^{56}\text{Fe}$	$\rightarrow$	${}^{45}\text{Ca}, {}^{45}\text{Sc}, {}^{45}\text{Ti}$	Sc
$\text{nat},{}^{52}\text{Cr}, {}^{55}\text{Mn}, \text{nat},{}^{56}\text{Fe}$	$\rightarrow$	${}^{47}\text{Ca}, {}^{46,47,48,49,50}\text{Sc}, {}^{44,46,47,48,49,50,51}\text{Ti}, {}^{46,47,48,49,50,51}\text{V}, {}^{48,49,51}\text{Cr}, {}^{49,51,54}\text{Mn}$	Ti, V

Will be available with the next version of GALPROP

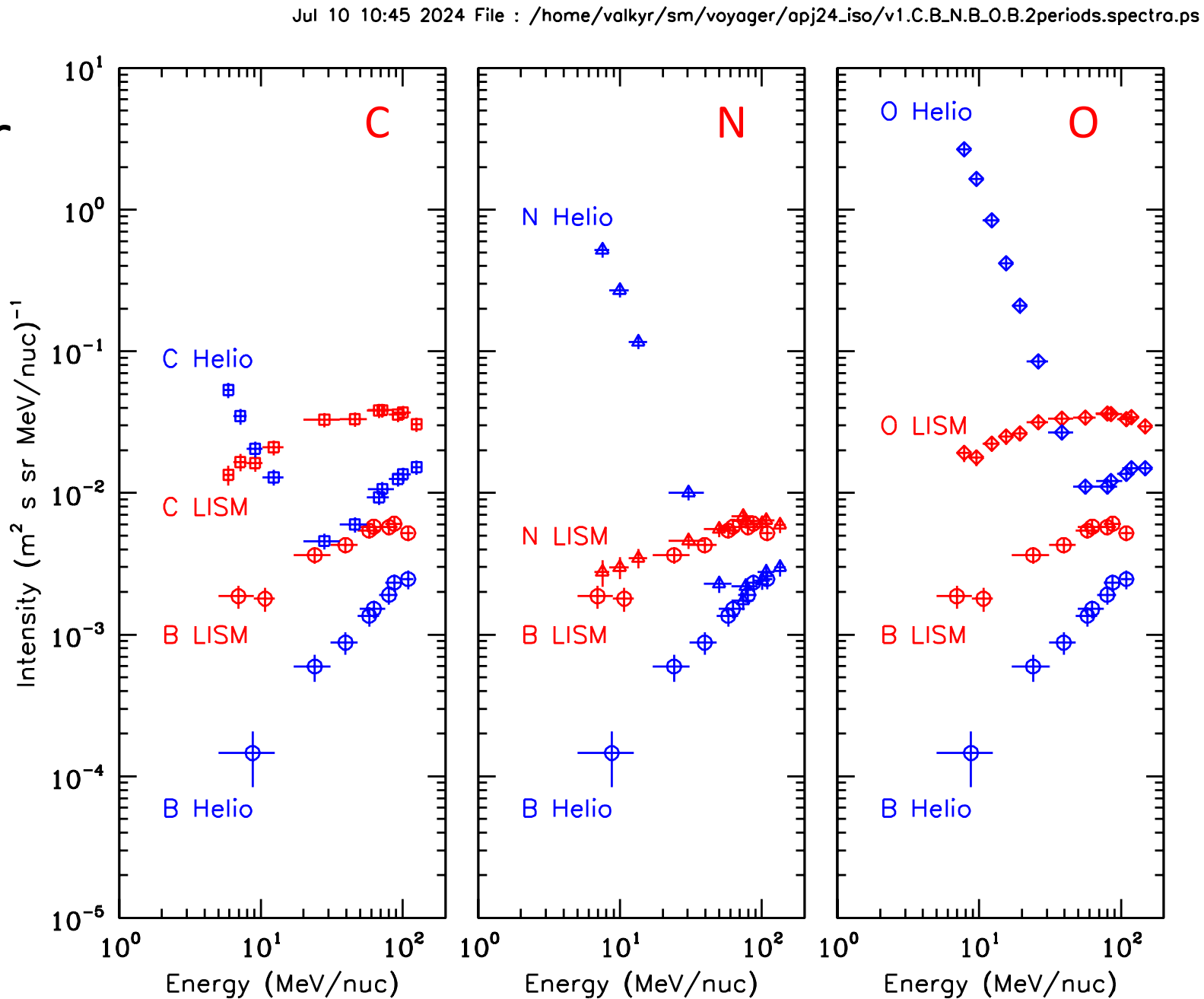
Why ^2H excess is not instrumental

- Energy spectra in the heliosheath (blue) and in the VLISM (red)
- Below 50 MeV/nuc the anomalous CR (ACR) He intensity in the heliosheath is much larger than the GCR intensity in the VLISM
- ^4He is the main progenitor of ^2H (and ^3H) in CRs. Assume same for mylar/sheldahl windows
- Yet, with higher ACR He intensity below 50 MeV/nuc, the ^2H intensity in the heliosheath is lower, not higher, than in the VLISM!
- This is the strongest argument as to why nuclear interactions in the windows are not responsible for the excess ^2H



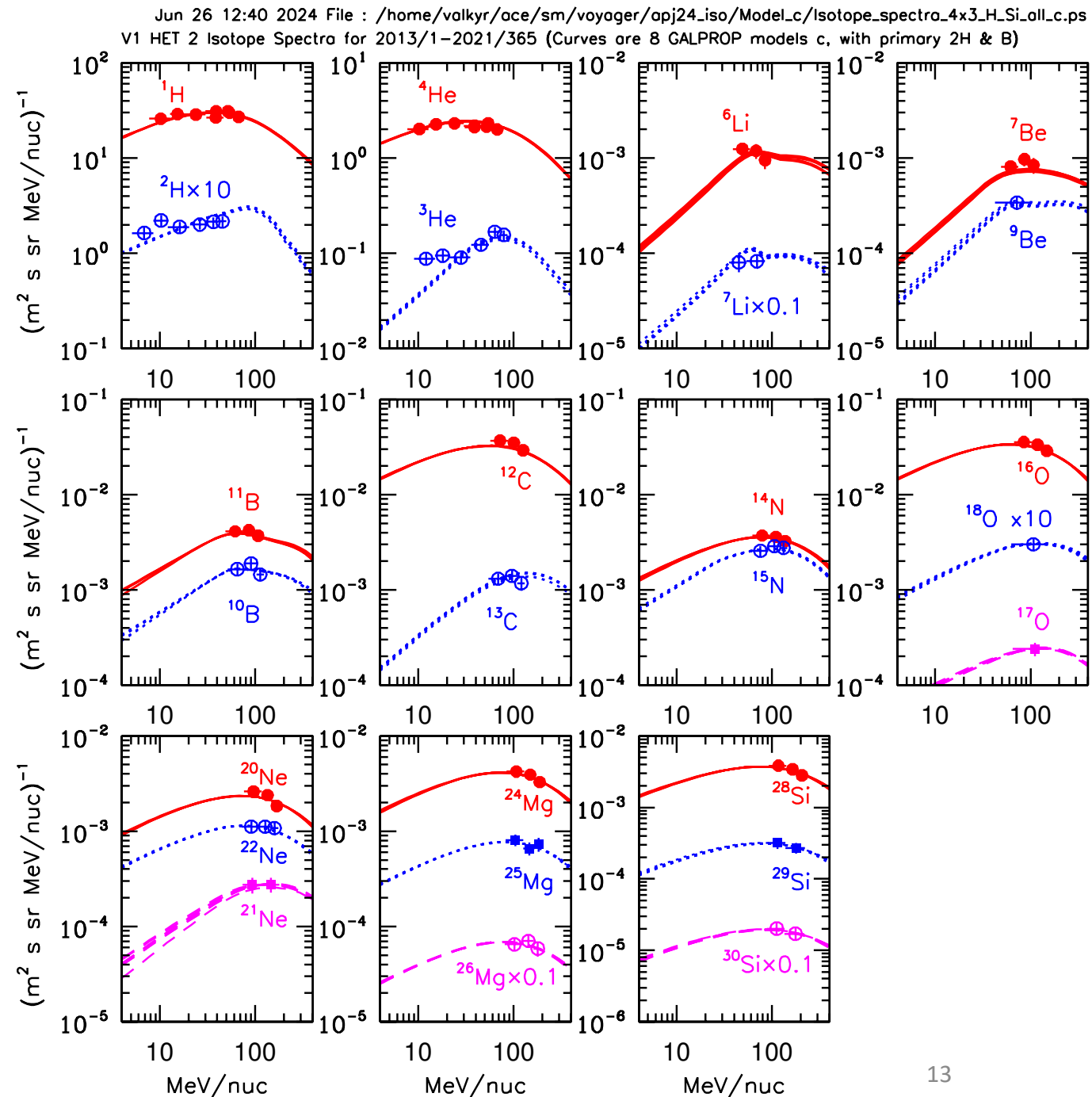
B is not instrumental either

- Energy spectra in the heliosheath (blue) and in the VLISM (red)
- Below 50 MeV/nuc the anomalous CR (ACR) CNO intensity in the heliosheath is much larger than the GCR intensity in the VLISM
- CNO are the main progenitors of B
- Yet, with higher ACR CNO intensity below 50 MeV/nuc, the B intensity in the heliosheath is lower, not higher, than in the VLISM!
- This is the strongest argument as to why nuclear interactions in the windows are not responsible for the excess B



Primary ^2H and B

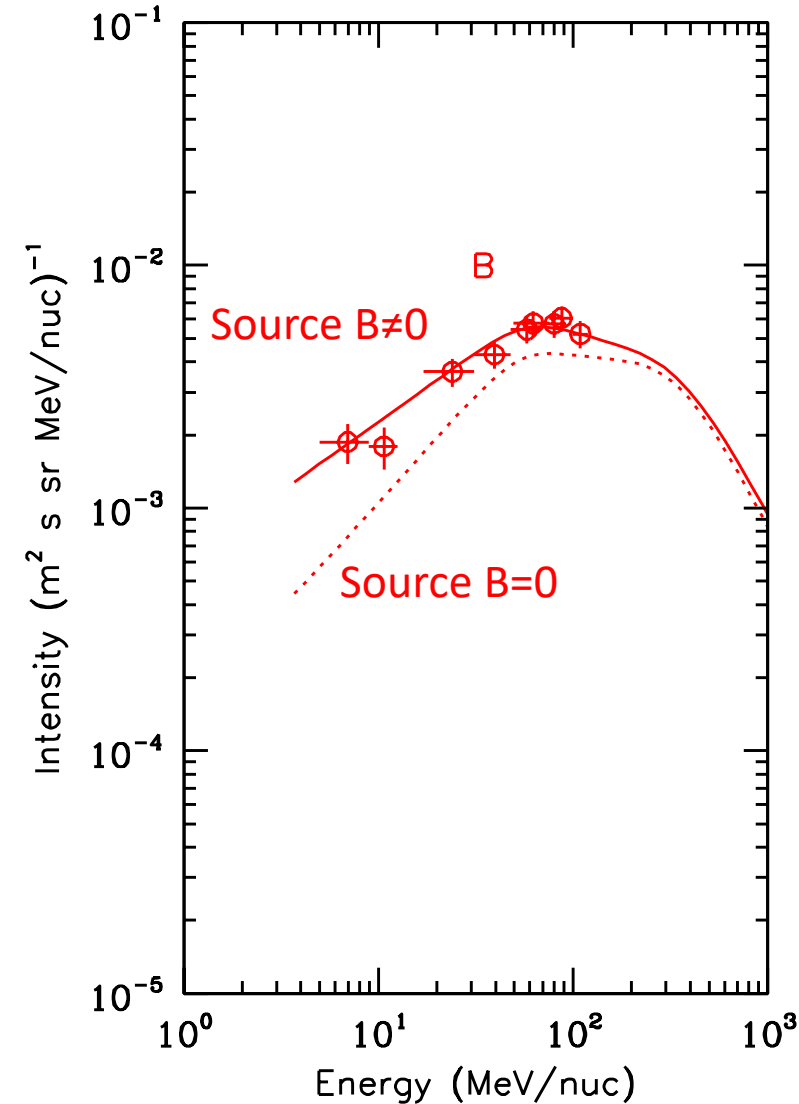
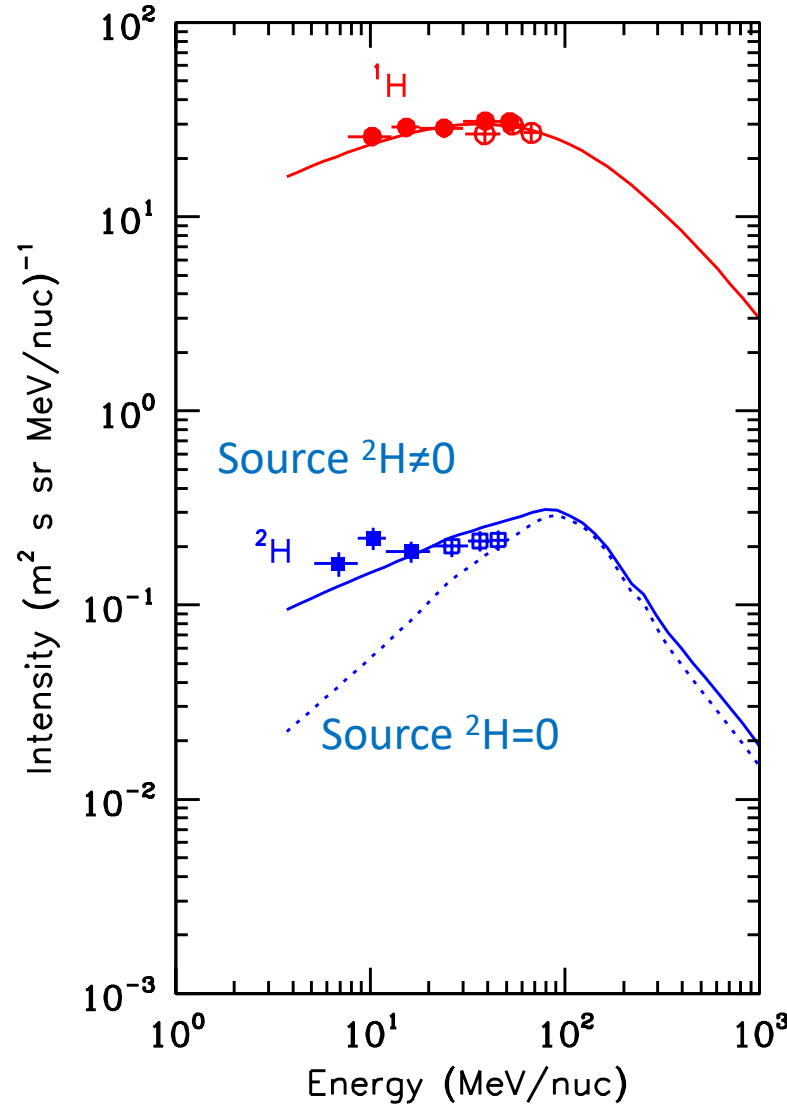
- Allow free abundances of ^2H and B (^3He , Li, Be = 0)
- Good fit for all species for all 8 models including ^2H and B
- Origin of primary ^2H (Caselli & Ceccarelli 2012)
 - Deuteration of organic molecules and dust grain surfaces
 - Deuterium release under heating or passing shock (Linsky+2006)



Primary ^2H & B

Jul 1 12:31 2024 ~sm/voyager/apj24_iso/v1.1H.2H.B.spectra_UL4022co.ps

- $^2\text{H}/^1\text{H}$ abundance ratio can vary by orders of magnitude in different environments
- In the gas phase $^2\text{H}/^1\text{H}$ ratio is $\sim 10^{-5}$ – close to the primordial ratio
- Organic molecules and dust grain surfaces show enhancements of the $^2\text{H}/^1\text{H}$ ratio of up to **13 orders of magnitude** with respect to the elemental $^2\text{H}/^1\text{H}$ abundance ratio (i.e. in the form of H, D, H_2 , D_2 , HD)
- $^2\text{H}/^1\text{H} \sim 0.1\text{--}1$ values are quite common
- The origin of such enhancements and the complex deuterium chemistry on the dust grain surfaces is widely discussed in the literature ([Caselli & Ceccarelli 2012](#))



AMS-02 reports of the primary component in ^2H

PHYSICAL REVIEW LETTERS **132**, 261001 (2024)

Editors' Suggestion

Featured in Physics

Properties of Cosmic Deuterons Measured by the Alpha Magnetic Spectrometer

M. Aguilar,²⁹ B. Alpat,³⁵ G. Ambrosi,³⁵ H. Anderson,¹⁰ L. Arruda,²⁷ N. Attig,²⁴ C. Bagwell,¹⁰ F. Barao,²⁷ M. Barbanera,³⁵

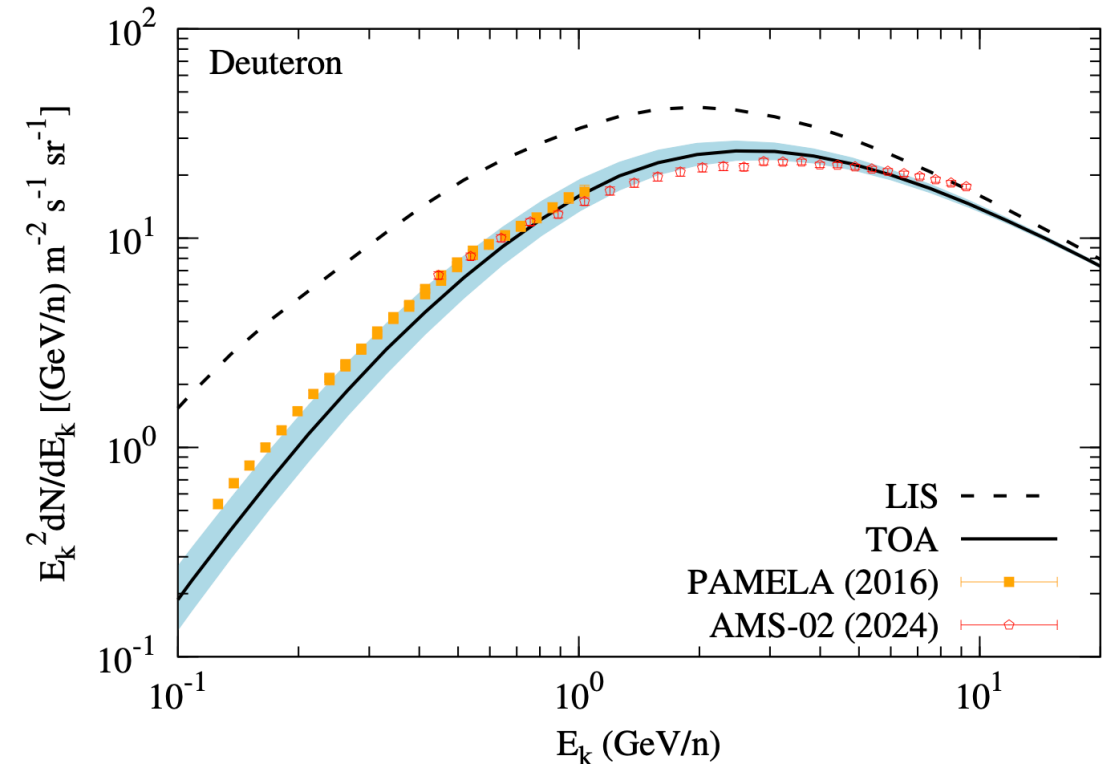
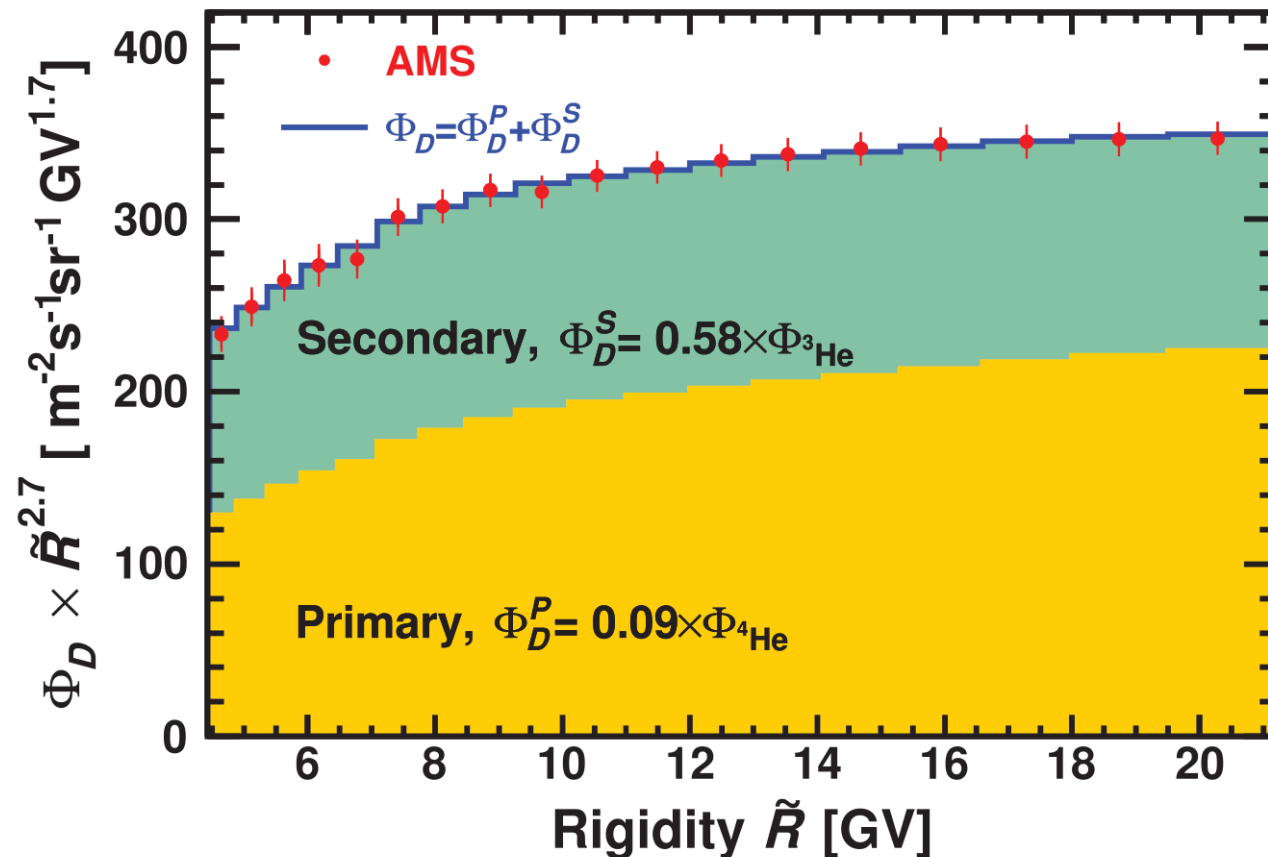
Above ~ 13 GV we find a nearly identical rigidity dependence of the D and p fluxes with a D/p flux ratio of 0.027 ± 0.001 . These unexpected observations indicate that cosmic deuterons have a sizable primarylike component. With a method independent of cosmic ray propagation, we obtain the primary component of the D flux equal to $9.4 \pm 0.5\%$ of the ^4He flux and the secondary component of the D flux equal to $58 \pm 5\%$ of the ^3He flux.

The AMS-02 cosmic ray deuteron flux is consistent with a secondary origin

Qiang Yuan^{1,2,*} and Yi-Zhong Fan^{1,2,†}

arXiv: 2406.19315

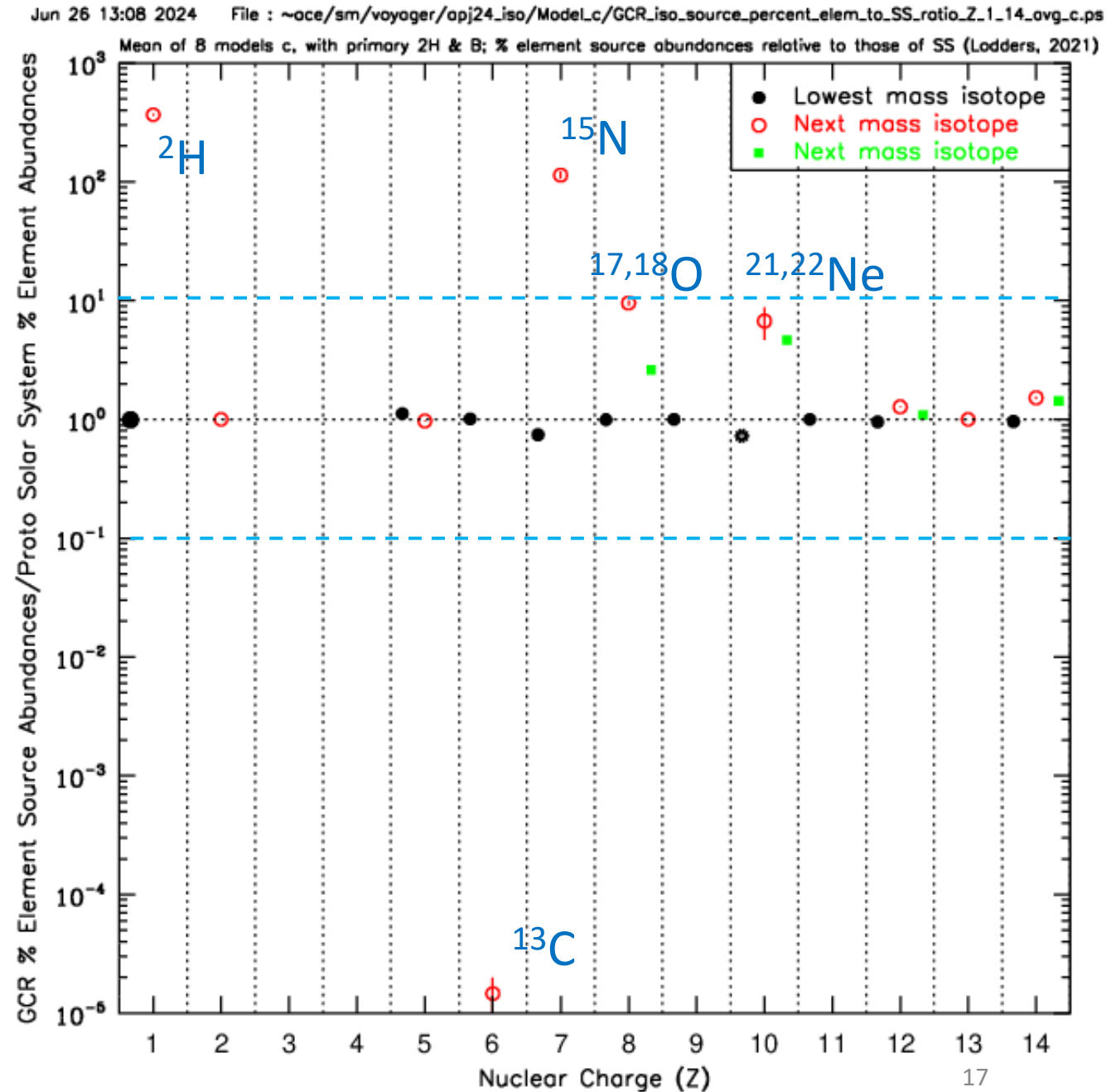
AMS-02, PRL 2024



GALPROP v56 with D cross sections updated
Contributions of H-Fe are important

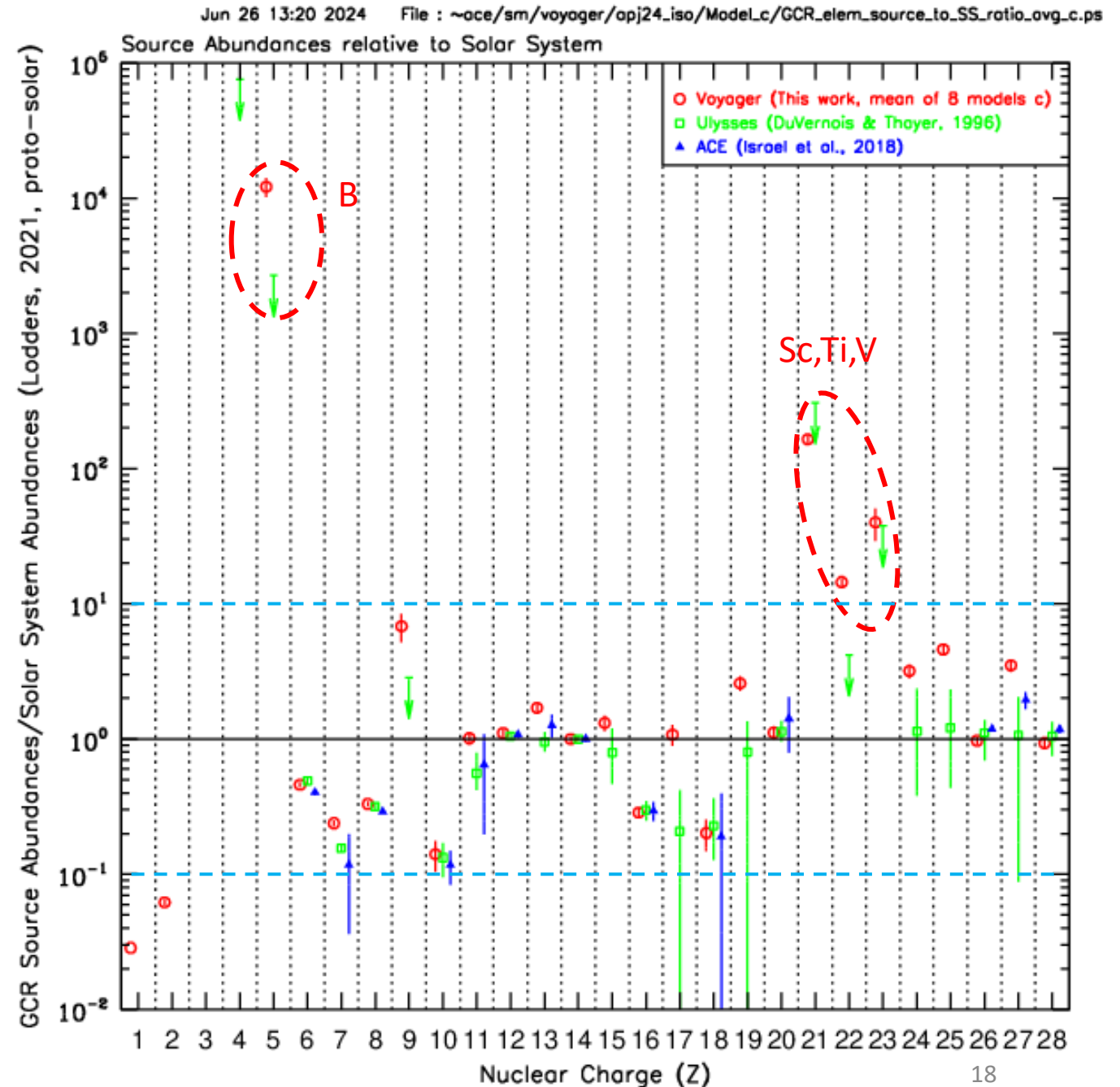
Source isotopic distributions

- Relative distribution of isotopes within an element compared to the Solar system abundances by Lodders 2021
- Obvious outliers: ^2H , ^{13}C , ^{15}N , $^{17,18}\text{O}$, $^{21,22}\text{Ne}$
- Seems that abundances ^{15}N and ^2H correlate ([Caselli & Ceccarelli 2012](#))
- ^{13}C – consistent with zero
- ^{22}Ne overabundance is well-known



Source elemental abundances relative to the solar system

- The source abundances derived from **Voyager 1**, **Ulysses** and **ACE-CRIS** data are generally consistent
- There is a general trend “volatiles vs refractory” elements
- **Most elements fit into 0.1-10 band**
- Overabundance of B is significant
- Large deviations are observed for low-abundant Sc, Ti, V – perhaps the result of the errors in the cross sections

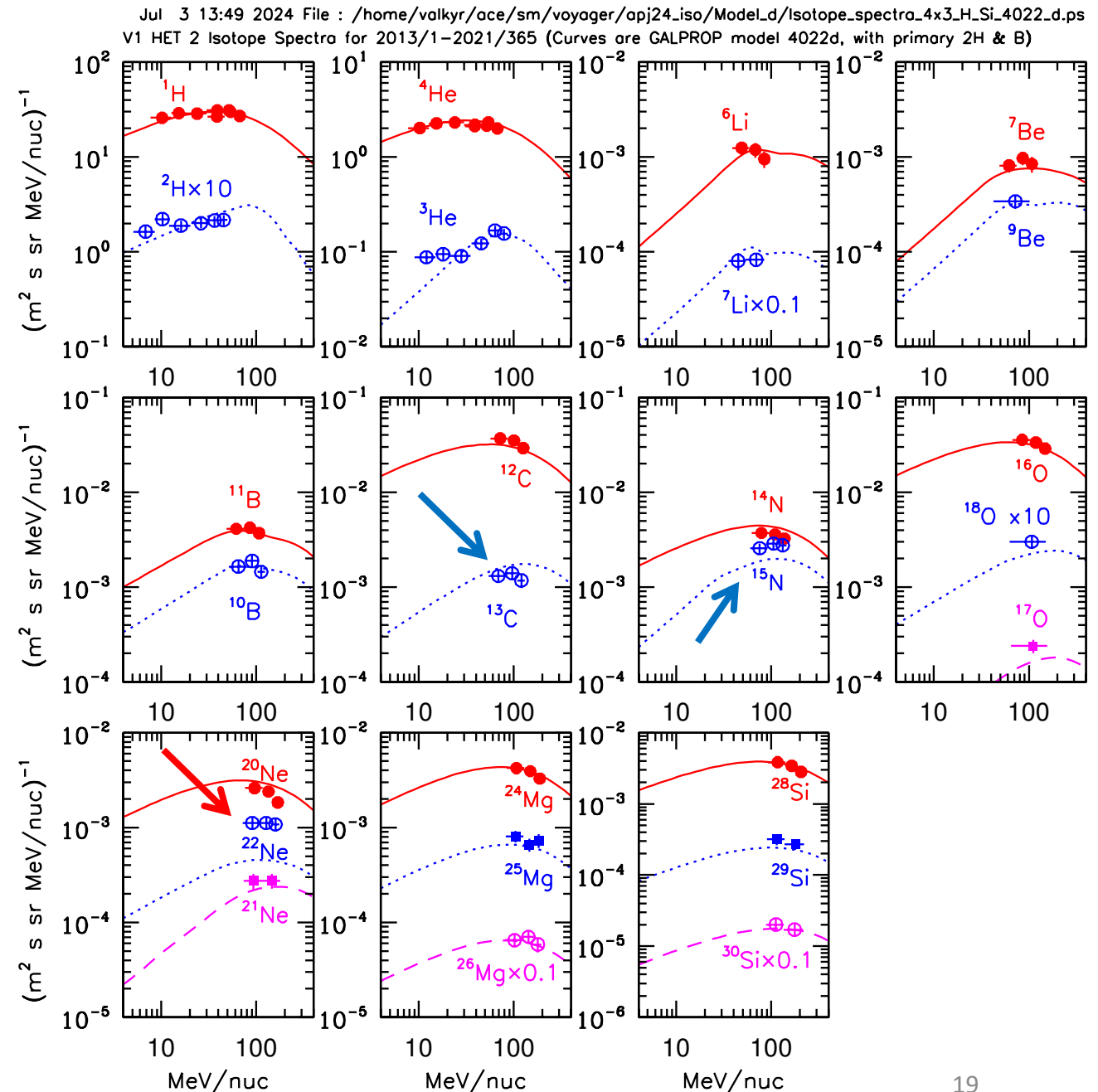


Consistency with Solar system abundances

If we normalize the **source isotopic abundances within an element** to the Solar system values, then

- ^{13}C , ^{15}N , $^{17,18}\text{O}$, $^{20,21}\text{Ne}$ – deviations from data are at the level of $\leq 2\sigma$
- ^{22}Ne – large deviation

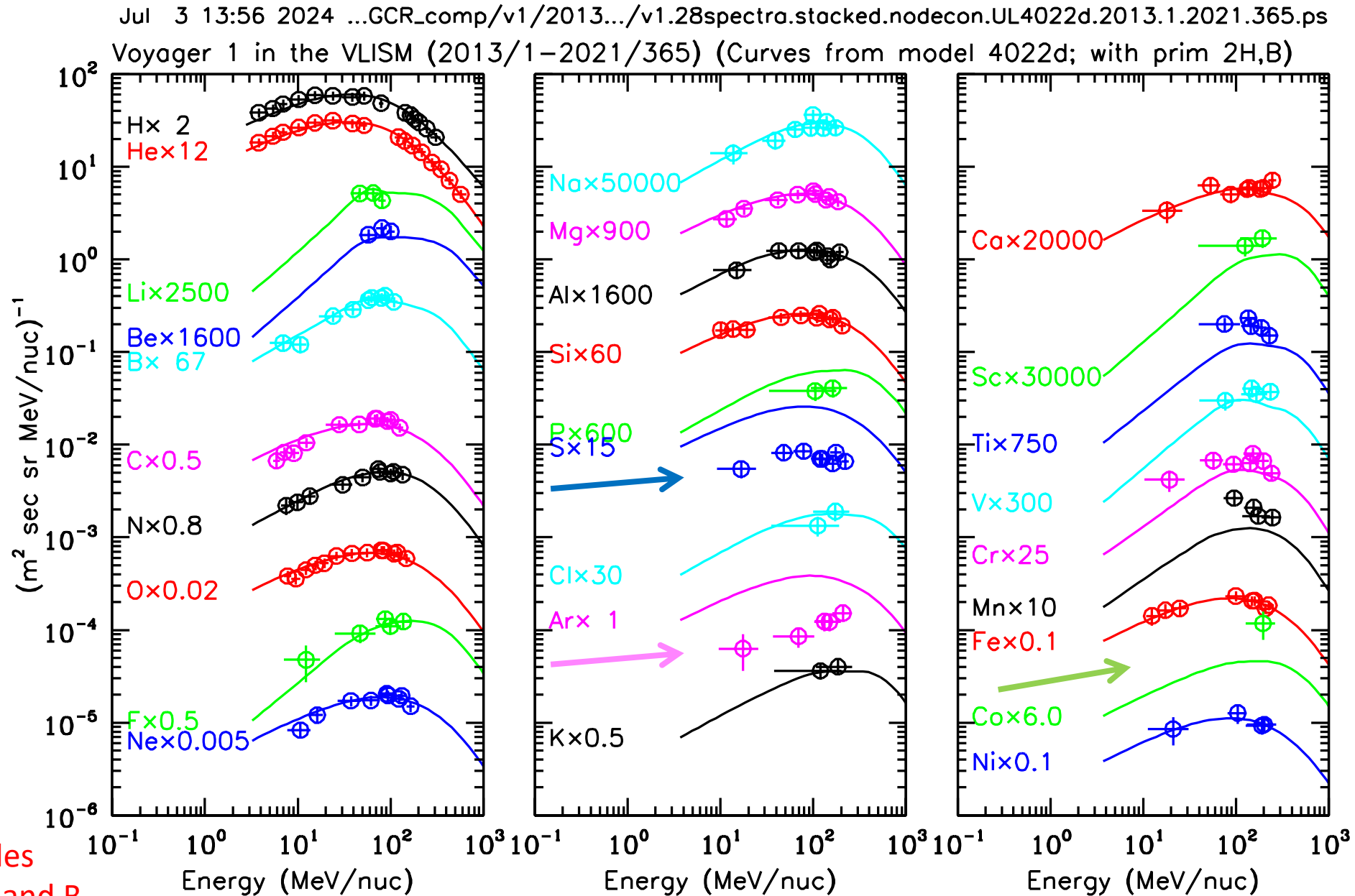
Note that this calculation includes the primary components for ^2H and B



Consistency with Solar system elem. abundances

- Sc, V – deviations from data are at the level of $\leq 2 \sigma$
- S, Ar, Co – large deviations
- Ti, Cr, Mn - between the two cases; larger deviations are observed in the two lowest energy points

Note that this calculation includes the primary components for ^2H and B



Conclusion

- The Voyager 1 unique dataset represents 9 years of data taking in the VLISM
- New data provide resolved spectra of the individual isotopes of elements $Z \leq 14$
- Primary component found in the ^2H spectrum and a hint for primary B – likely connected with the physics of the CR sources and/or ISM
- Derived source abundances for many elements/isotopes are different from solar system abundances; they can be used for source identification and origin of low-energy CRs
- Some of these differences can be attributed to the errors in the cross sections/propagation models
- If V1 is switched off in 2026 (~ 173 AU), the final V1 dataset will represent 14 years of data taken in the VLISM by an instrument that was built and launched in 1977!