RECENT ADVANCES IN ASTROPHYSICS OF COSMIC RAYS AND GAMMA-RAY ASTRONOMY

IGOR V MOSKALENKO – STANFORD
Not talking today about:


Inference of the Local Interstellar Spectra of Cosmic-Ray Nuclei $Z \leq 28$ with the GALPROP-HELMOD Framework
ApJS 250 (2020) 27


Deciphering the Local Interstellar Spectra of Secondary Nuclei with the Galprop/Helmod Framework and a Hint for Primary Lithium in Cosmic Rays

Karwin, Christopher M.; Murgia, Simona; Campbell, Sheldon; Moskalenko, Igor V.
Fermi-LAT Observations of $\gamma$-Ray Emission toward the Outer Halo of M31
The discovery of cosmic rays

Victor Hess, an Austrian scientist, took a radiation counter (a simple electroscope) on a balloon flight. He rose to 5200 m (without oxygen) and measured that the amount of radiation increases as the balloon climbed. Hess correctly concluded that the ionization was caused by highly penetrating radiation coming from outside the atmosphere. The results by Hess were later confirmed by the Kolhörster in a number of flights up to 9200 m.

Victor Hess flight on August 7, 1912
Nobel Prize: 1936
Spectrum of Cosmic Rays – 20th century

- All particle CR spectrum:
  - The knee (Kulikov & Christiansen 1958)
  - The ankle (Linsley 1963, Fly’s eye 1990s)
  - GZK cutoff (predicted Greisen-Zatsepin-Kuzmin 1966)

GZK cutoff:

\[ p \rightarrow \pi^0 \rightarrow \gamma + \gamma \]
Spectrum of Cosmic Rays – about now

✧ Are these features transient?
✧ Which type of sources are producing them?
✧ Are they typical for the whole Galaxy?
✧ What are the consequences if they do or they do not?

Gaisser, Stanev, Tilav 2013
Notice also a shift in our understanding of the subject of CRs!

“…this ionization might be attributed to the penetration of the earth’s atmosphere from outer space by hitherto unknown radiation of exceptionally high penetrating capacity…” – V. Hess
Decade of discoveries in astrophysics of cosmic rays
PAMELA discovery: Rising positron fraction

✧ TS93 (Golden+’96): flat positron fraction $0.078 \pm 0.016$ in the range 5-60 GeV

✧ HEAT-94,95,00 (Beatty+’04): “a small positron flux of nonstandard origin”

✧ AMS-01 (Aguilar+’07, 1998 flight) confirmed HEAT results

✧ PAMELA team reported a clear and very significant rise in the positron fraction compared to the “standard” model predictions

✧ “Standard” model:
  – Secondary production in the ISM
  – Steady state
  – Smooth CR source distribution

Take home:
✧ New physics may appear early (at the current exp. limits)
✧ Need a model to compare
AMS-02 data on $e^+$

✧ The raise of the positron fraction over the expectations of the secondary production model was confirmed by Fermi-LAT and AMS-02

✧ AMS-02 extended the measurements up to ~900 GeV

✧ A cutoff above 300 GeV?

✧ What are the sources?

✧ How does the positron fraction change with time if it does?

✧ Is it uniform in space?
The positron flux is the sum of low-energy part from cosmic ray collisions plus a high-energy part from a new source or dark matter both with a cutoff energy $E_s$.

$$\Phi_{e^+}(E) = \frac{E^2}{E'^2} \left[ C_d \left( \frac{E}{E_1} \right)^{\gamma_d} + C_s \left( \frac{E}{E_2} \right)^{\gamma_s} \exp(-\frac{E}{E_s}) \right]$$

- AMS positrons
All types of structures can be found

Pairs of instruments (AMS-02 & CALET) and (Fermi-LAT, DAMPE, HESS) confirm each other!

Do we expect to see the same e-spectrum throughout the Galaxy?

What are the expected signatures of the time dependence?
Break in the spectra of CR nucleons

Ahn+'2010, Yoon+'2011

\[ \gamma_{\text{CREAM}} = 2.58 \pm 0.02 \]

\[ \gamma_{\text{AMS-01}} = 2.74 \pm 0.01 \]

\[ \gamma_{\text{He}} < 200 \text{ GeV/n} = 2.77 \pm 0.03 \]

\[ \gamma_{\text{He}} > 200 \text{ GeV/n} = 2.56 \pm 0.04 \]

Adriani+'2011

\[ p \]

Breaks are at the same rigidity

PAMELA

First noticed in the data by CREAM “Discrepant hardening observed in cosmic-ray elemental spectra” (Ahn+'2010) and ATIC-2 (Panov+'2009)

 Initially looked like an energy calibration issue...

...until it was confirmed by PAMELA and with more statistics by AMS-02

UMD colloquium • College Park • Oct.19, 2020 :: IVM 12
AMS-02: Breaks in the spectra of CR species

- Spectral shapes of primary species are similar
- Spectral shapes of secondary species are similar, but different from primaries
- Spectra of secondaries are steeper than primaries in the whole energy range

△ If the flattening would be the effect of harder spectra coming from different sources, it would be difficult is to have so well correlated behavior (vs rigidity) of all primary and all secondary species because of very much different fragmentation and production cross sections
Latest data from AMS-02

Spectra of Ne, Mg, Si are a bit steeper than the spectra of He, C, O, but overall are very close. The error bars are still large.

Aguilar+’2020
AMSI-02 data

✧ Spectra of CR species from AMS-02:
  ♦ Primary
  ♦ Intermediate
  ♦ Secondary (steeper spectra)

✧ Local Interstellar Spectra (LIS) – dashed lines

✧ Primary Li at HE?

Boschini+’2020
Direct measurement of proton spectrum by CALET

CALET covers the range 50 GeV to 10 TeV with THE SAME INSTRUMENT confirming the existence of proton spectral hardening with a deviation from a single power law by more than 3σ.

Yet another break at 10TV?

Adriani’2019

He

10 TV

NUCLEON Atkin’2018

All particles

DAMPE An’2019
A collection of data indicates two breaks in H and He spectra

diamond Apparently, there are 2 breaks that very close to each other
Positron excess & electrons

The positron flux is the sum of low-energy part from cosmic ray collisions plus a high-energy part from a new source or dark matter both with a cutoff energy $E_s$.

$$
\Phi_{e^+}(E) = \frac{E^2}{E_s^2} \left[ C_d \left( \frac{E}{E_1} \right)^{\gamma_d} + C_s \left( \frac{E}{E_2} \right)^{\gamma_s} \exp \left( -\frac{E}{E_s} \right) \right]
$$

• AMS positrons

Positrons from Cosmic Ray Collisions

Positrons from New Source or Dark Matter

Energy [GeV]
What does this mean?

There are ~2,000 answers!

- Dark matter annihilation/decay (>1500 papers)

Astrophysical origin (~250 papers):

- SNR shocks:
  - Galactic SNRs
  - Local SNR(s)
  - SNR shocks interacting with clouds
  - “Nested Leaky-Box” (SNRs)

- Pulsars & Pulsar Wind Nebulae
  - Pulsar bow shocks
  - “Model-independent estimates”
  - Inhomogeneity of CR sources (SNRs, pulsars)
  - Time-dependent effects
Reinvention of the Nested Leaky-Box – SNRs

✧ Cowsik & Wilson 1974 “The nested Leaky-Box model for Galactic cosmic rays”

✧ Berezkho’+2003 “Cosmic ray production in supernova remnants including reacceleration: The secondary to primary ratio”

✧ Blasi’2009 “Origin of the Positron Excess in Cosmic Rays” and other authors

“The ‘inner box’ of cosmic ray confinement, corresponding to the region immediately surrounding the source, is assumed to have energy-dependent life time...”

“...we shall in addition take the effect of nuclear spallation inside the sources into account. The energy spectrum of these source secondaries is harder than that of reaccelerated secondaries. Therefore it plays a dominant role at high energies for a high density ISM...”

B/C

n = 1 cm⁻³
n = 0.3 cm⁻³
n = 0.003 cm⁻³
Astro: Secondary production in a SNR shock

- A rise in all secondary products
- Time- and spatially-dependent (?)

- Blasi 2009: Positron fraction
- Mertsch & Sarkar 2009: B/C ratio
- Blasi & Serpico 2009: pbar/p
- Kachelriess & Ostapchenko 2013: B/C ratio
Astro: Nested Leaky-Box – cocoon model

- The model includes a cocoon around SNR with most of the grammage
- Secondaries are produced in cocoons
- ISM - small energy independent grammage

The diffuse gamma-ray emission predicted by the model would be very faint

- The model also contradicts to the most recent B/C data
- Hypothesis rejected?
🎀 The B/C ratio as measured by AMS-02 (2018) agrees pretty well with the model calculations.
🎀 Does not exhibit any significant excess.
Positron excess: Old friends – pulsars

✧ Jon Arons 1981 “Particle acceleration by pulsars”

✧ Harding & Ramaty 1987 “The pulsar contribution to Galactic cosmic ray positrons”

✧ Ahmed Boulares 1989 “The nature of the cosmic-ray electron spectrum, and supernova remnant contributions”

“Therefore, the only role observed pulsars might play as direct cosmic ray sources is in providing positrons and electrons…”

3 components:
✧ Secondary e\(^{+/−}\)
✧ Primary e\(^−\) from SNR
✧ Primary e\(^{+/−}\) from pulsars
Pulsars as sources of CR positrons (& electrons)

Example: Cholis & Hooper ‘13

Pulsar spectrum is parametrized as:

\[
\frac{dN}{dE} \sim E^{-\alpha} e^{\left(\frac{-E}{E_c}\right)}
\]

✧ \(\alpha, E_c\) – free parameters
✧ Free injection spectrum of electrons from SNRs

Good:

✓ Affects only electrons and positrons, does not affect other CR species
✓ Given enough free parameters, it is possible to fit the positron fraction

Bad:

– Pulsar-only-model cannot reproduce all-e spectrum and the cutoff in \(e^+\) spectrum at \(\sim 300\) GeV
What do pulsars know about CR protons?

- If excess positrons are produced in pulsars or DM decays why the $p/e^+$ ratio is flat?
- The flat $p/e^+$ ratio perhaps indicates a common origin of the spectra of $p$ and $e^+$!
• Bow shocks – a shock at the place of interaction of the stellar wind with interstellar gas
• Large proper motion speed of pulsars – due to the kick at birth
Pulsar bow shock model by A. Bykov et al. (2017)

- Pulsars with high spin-down power produce relativistic winds.
- Some of the PWNe are moving relative to the ambient ISM with supersonic speeds producing bow shocks.
- Ultrarelativistic particles accelerated at the termination surface of the pulsar wind may undergo reacceleration in the converging flow system → produces universal spectrum, same as for protons.
- Similar spectra for electrons and positrons.
The 5.7 millisecond pulsar PSR J0437-4715

- Distance: 156.79±0.25pc
- Closest and brightest millisecond pulsar (MSP), in a binary system with a white dwarf companion and an orbital period of 5.7 days
- Velocity ~100 km/s
- Observed in optical, far-ultraviolet (FUV), and X-ray bands
- It exhibits the greatest long-term rotational stability of any pulsar
- It is the first pulsar for which the full three-dimensional orientation of the binary orbit was determined, enabling a new test of General Relativity

Optical image of the binary system containing PSR J0437-4715
Accelerated leptons from the nebula of PSR J0437-4715 can be responsible both for:

◇ the enhancement of the positron fraction above a few GeV detected by PAMELA and AMS-02 spectrometers

◇ the TeV range lepton fluxes observed with H.E.S.S., VERITAS, Fermi, CALET, and DAMPE
Break in the spectra of CR nucleons

First noticed in the data by CREAM and ATIC
Initially looked like an energy calibration issue...
...until it was confirmed by PAMELA and with more statistics by AMS-02
B/C in different scenarios

- **I**njec**K**on
- **R**eference scenario
- **P**ropagation mild flattening
- **1 TeV/n**
- **H**E source

Vladimirov'2012
Interstellar turbulence and the diffusion coeff.

- 300 GV break: A transition from the self-generated turbulence to the cascading of externally generated turbulence (for instance due to supernova bubbles) from large spatial scales to smaller scales.

- The agreement with AMS-02 data is pretty good, but does not explain the difference between the spectra of $p$ and heavier species (He-O).

Blasi+’12

Approx. slope: 0.7

Diffusion coefficient

Aloisio+’15

$E_k^{2/3} J(E_k) \text{(GeV}^{1/3} \text{m}^2 \text{s}^{-1})$

$H=4.0 \text{ Kpc}, h_y=0.15 \text{ kpc}, \mu=2.4 \text{ mg/cm}^2$

$B_0=1 \mu \text{G}, l_c=50 \text{ pc}, \eta_B=0.075, \zeta_{\text{CR}}=0.045$

$\eta_t=0.02 \text{ cm}^3, \phi_{\text{SDR}}=500 \text{ MV}$

$\gamma_{\text{prot}}=4.20, \gamma_{\text{nucl}}=4.15$
Effect of interstellar propagation

Such behavior was predicted (Vladimirov+’12, Blasi+’12):

$$\Delta \gamma_{\text{sec}} \sim 2 \Delta \gamma_{\text{prim}}$$

if the break is due to the break in the spectrum of interstellar turbulence.
Direct measurement of proton spectrum by CALET

Adriani+’2019

Yet another break at 10TV?

Adriani+’2019

He

10 TV

Atkin+’2018

Z=6-27

Is this also due to the break in the diffusion coefficient or a local source or what?

He

10 TV

All particles

An+’2019
Local SNR?

The TeV bump has to be made of the preexisting CRs with all their primaries and secondaries that have spent millions of years in the Galaxy! – weak local shock that reaccelerates CR particles

Local SNR scenario is proposed by:
Fang et al. 2020,
Fornieri et al. 2020,
Yuan et al. 2020

◇ Local SNR as an accelerator of primary species from the interstellar gas is ruled out
◇ A fine-tuned scenario of many sources (Niu 2020) looks unrealistic too
Local SNR scenario

Please refer to the AMS PRL publication.

Fresh primary component from local SNR

Local SNR produces no secondaries

Nitrogen Flux has peculiar Rigidity Dependence

Primary + Secondary

Primary

Secondary

Nitrogen x 130
Boron x 145
Beryllium x 200
Lithium x 400
Carbon x 30
Oxygen x 28

Flux \times \tilde{R}^{2.7} \left[ \text{m}^2\text{s}^{-1}\text{sr}^{-1}(\text{GV})^{1.7} \right]

Rigidity \tilde{R} [\text{GV}]
Galactic Loops

✧ WMAP K-band polarization intensity map
✧ Unsharp mask version of the Haslam et al. (1982) map
✧ The origin of the Loops is unknown
✧ If these are old SNRs, accelerated particles may still be present in the shell
✧ Signatures of the past (recent?) activity in the Solar neighborhood
✧ How strong does this past activity affect the current fluxes of CR species?
Bow shocks – a shock at the place of interaction of the stellar wind with interstellar gas

Large proper motion speed of pulsars – due to the kick at birth
Bow shock of a passing star or just a weak shock

CRs propagate along the magnetic flux tube while self-generating turbulence;

Distance-size relationship $\zeta_{\text{obs}}(\text{pc}) \sim 10^2 \sqrt{l_\perp (\text{pc})}$;

Assuming $l_\perp = 10^{-3}-10^{-2}$ pc, we find the path length along the magnetic field lines of $\zeta_{\text{obs}} = 3$-10 pc.
Bow shock nearby

✧ Weak shock to reaccelerate CR particles: small Mach number
✧ Weak shock – must be nearby
✧ Sharp breaks – no diffusion, propagation along the magnetic field lines (the flux tube)
✧ The effect on secondaries is similar to the Propagation scenario

Ad hoc bump fit requires six parameters

Our predicted CR spectrum depends on two parameters, \( M \) – the shock Mach number, and \( R_0 \) – and the bump rigidity
Anisotropy

CR anisotropy has an enhancement in exactly the range of the bump
The Kolmogorov or Bohm type of diffusion produce deviations from the observed spectrum.
Passing Stars: Scholtz Star & Epsilon Indi

double Scholtz Star, passed near the sun ~70–80 kyr ago

triple Epsilon Indi

K4.5V

Mₐ~0.77M☉

Mₐ~0.095M☉

Mₕ~0.095M☉

Mₔ~0.072M☉

Mₔ~0.063M☉

Mₕ~0.072M☉

Mₔ~0.067M☉

~1500 au

~2 au

~100 km/s

6.8 pc

82.4 km/s

11 yr orbit

8 yr orbit

~0.77M☉

~0.072M☉

~0.067M☉

~0.095M☉

~0.063M☉

~0.072M☉

~0.067M☉
Prediction: Possible time dependence

✧ Lateral gradient scale of the flux tube is $10^{15}-10^{16}$ cm
  ~100-1000 au
✧ Relative speed of the Sun and the star ~100 km/s
✧ Expected time dependence is 3-30 years
✧ AMS-02 (2011-2014) – break rigidity ~450 GV
✧ Situation with ~10 TV break is unclear as the error bars are large
Thanks!
Andromeda galaxy M31 – a closest spiral

- Similar to the Milky Way at 778 kpc
- Provides an external view on our own Galaxy
- Large size on the sky $3^\circ \times 1^\circ$ – easy to resolve
- The rotation curve remains constant over large distances – large content of DM
- Virial radius $\sim 300$ kpc

Rubin & Ford 1970

from Vera Rubin, 2006
The interstellar emission model for the MW (1-100 GeV):
π⁰-decay + (anisotropic) inverse Compton + Bremsstrahlung

“Square” region is M31 field (28°×28°)

“TR” labels the test region

Schematic of the eight concentric circles which define the annuli (A1-A8) in the MW foreground model. Only A5-A8 contribute to the Galactic foreground emission for the field used in this analysis.
γ-ray maps for $\pi^0$-decay for different rings (GALPROP) – 1

HI gas

H I gas

H II, H$_2$ gas

H II, H$_2$ gas
γ-ray maps for anisotropic IC for different rings (GALPROP) – 2

(Local)

Anisotropic Inverse Compton Emission, A5

Anisotropic Inverse Compton Emission, A6-A7

Anisotropic Inverse Compton Emission, A8

AIC/IC Flux Ratio

Anisotropic/isotropic ratio illustrates the importance of the effect that reaches a factor of 1.7 for certain directions and is non-uniform on the sky.
Spectral fits in TR and FM31

✧ Flux and fractional count residuals for the fit in the TR and FM31
✧ The fractional residuals (FM31) show an excess between 3-20 GeV reaching a level of 4%
✧ Residuals at HE is due to the spectral approximation of the 3FGL sources
Spectrum of the excess and interpretation

- Spectral shape is not resembling other CR-related components
- FM31: properties of the extended (DM?) halo remain highly uncertain
- Consistent with DM interpretation of the Galactic center excess (requires a large boost factor)
- Decaying DM looks more natural
3FGL sources: Spectral changes at HE

3FHL J0617.2+2234e (IC443)

3FHL J0205.5+6449 (PSR J0205+6449)

3FHL J1104.4+3812 (Mkn 421, $z = 0.03$)

3FHL J0222.6+4302 (3C 66A)
Test region demonstrates spatially uniform distribution of the residuals
- The fit is used to fix the isotropic background normalization
- The isotropic background derived in different regions shows moderate spectral variations, while overall shape remains the same
FM31: Spatial residuals

- Spatial count residuals (data – model) resulting from the baseline fit in FM31 for three different energy bands. Smoothed using 1° Gaussian kernel. The pixel size is 0.2°×0.2°
- The “arc” structure is clearly seen in the 1st and 2nd pixels (see the Arc Template on the left)
- M33 is in the bottom left angle
- Dashed circle – “spherical halo” of 117 kpc radius (8.5°)
FM31: Spatial residuals

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Arc flux and residuals

Simultaneous fit of the arc template with other components

Power-law (left) and power-law with exponential cutoff (right) spectral fits are unable to flatten the residuals in the range 3-20 GeV

The right panel shows a separate fit of two parts of the arc (North and South)

The index of the arc emission has a value ~2.0-2.4, notably flatter than other components
2D residuals after the Arc fit

✧ Subtraction of the Arc template flattens the 2D residuals, which show no obvious residual structure
What is the arc? Loops, loops, loops…

- There are ~17 so-called Loops found on the sky in radio and polarized radio emission; some of them are seen in γ-rays (e.g., famous Loop I).
- Loops or Spurs are large structures covering a significant part of the sky – their origin is unknown.
- A part of the shell of Loop III seems to be associated with the north part of the arc, and Loops II and IIIIs are covering the entire ROI.
- The Arc could be a part of the old Loop III or other Loops; hard spectrum – particle acceleration.
Adding M31 components: all-component fit

- Three spherically symmetric templates centered at M31 are added to the model: inner galaxy (IG), spherical halo (SH), and far outer halo (FOH).
- Templates are given PLEXP spectral models and fit simultaneously with other components of the IEM, including the arc template. Two fit variations are performed, amounting to two different variations in the arc template: full arc with PL, arc north and south with PLEXP.
- IG, SH, and FOH are detected at the significance levels of 7σ, 7σ, and 5σ, respectively. Results for the two fit variations are similar.
- Spectral shapes (SH, FOH) are noticeably different from other components.

M31-related geometry: Uniform intensity templates centered at M31

- Inner Galaxy (IG): 0° < r ≤ 0.4° (5.5 kpc)
- Spherical Halo (SH): 0.4° < r ≤ 8.5° (117 kpc)
- Far Outer Halo (FOH): r > 8.5° (~200 kpc)
Excess in different foreground models

- A systematic excess is observed between 3–20 GeV at the level of 3–5% independently on the background (foreground) model used.

- Absent only in case of the foreground model that is built using the LAT data itself, yet with free index (FSSC index scaled).

- Interestingly, isotropic component has a “bump” in the same energy range as the observed excess.

- Dark Matter halo around the Milky Way?
The big picture (illustrative)

MW-M31-like pairs (example) from Garrison-Kimmel et al. (2018)
Primary Li in CRs

- Standard approach to fit:
  - Spectra of CR species
  - B/C ratio
- Use GALPROP for IS propagation
- Use HelMod for heliospheric propagation

- HelMod calcs correspond to the periods of data taking

Boschini+ arXiv: 1911.03108
Primary Li in CRs. II

- Two break scenarios: \( P \) – propagation, \( I \) – injection spectra

- \( \text{Be} \): the discrepancy <10 GV is most likely due to errors in total inelastic X sections
- \( \text{B} \): obvious is some systematics between AMS-02 and PAMELA
- \( \text{N} \): excellent
- \( \text{Li} \): obvious is an excess >4 GV that cannot be explained by the production X sections no by \( ^7\text{Be} \) decay; a hint on primary \( ^7\text{Li} \)
Sources of Li

✧ Small fraction of Li is primordial
✧ Most of Li is produced in CR interactions with interstellar gas (secondary)
✧ Observed stellar Li abundances indicate that some proportion of lithium is also produced in low-mass stars and nova explosions (primary)
✧ The \( \alpha \)-capture reaction of \(^7\text{Be} \) production \(^3\text{He}(\alpha, \gamma)^7\text{Be} \) was proposed by Cameron 1955 and Cameron & Fowler 1971
✧ A decay of \(^7\text{Be} \) (K-capture) with a half-life of 53.22 days yields \(^7\text{Li} \)
✧ But \(^7\text{Be} \) should be transported into cooler layers so that can decay to \(^7\text{Li} \) (Cameron-Fowler mechanism)
✧ Blue-shifted absorption lines of partly ionized \(^7\text{Be} \) were observed in the spectrum of classical novae V339 Del, V1369 Cen, V5668 Sgr, V2944 Oph, V407 Lupi, V838 Her (2015-2018)
✧ Total mass of \(^7\text{Li} \) in these novae is \(~10^{-9}M_\odot - 6 \times 10^{-9}M_\odot \) vs. the total mass of the ejecta \(~10^{-5}M_\odot - 10^{-4}M_\odot \)
✧ Nova ejecta Li/p \(~10^{-4} - 10^{-5}\) vs. CRs Li/p \(~10^{-4}\) → VERY CLOSE!
✧ Perhaps the 1\(^{st}\) direct evidence of primary Li in CRs (AMS-02 data)!
Fluxes of CR species

- Positrons and antiprotons are $10^4$-10$^6$ less abundant than protons – discriminating them especially at very high energies is a challenge.

- Electrons have a steep spectrum, so small energy calibration errors can lead to large errors in flux measurements.
Voyager 1 spectra for 2012/342-2014/365

Cummings+’2016

✧ Li – Ni: V1 spectra together with HEAO-3-C2 data (≥3.35 GeV/nuc)
✧ Calculations: GALPROP & Leaky-Box (W.Webber)
Voyager 1

- Spectra tuned to Voyager 1, ACE-CRIS, AMS-02
- Spectra of primary and secondary species are well aligned >1 GeV/n
- Intermediate: have significant secondary contribution
- At lower energies spectra exhibit some irregular behavior due to the energy losses, fragmentation and local sources

Boschini+’2020