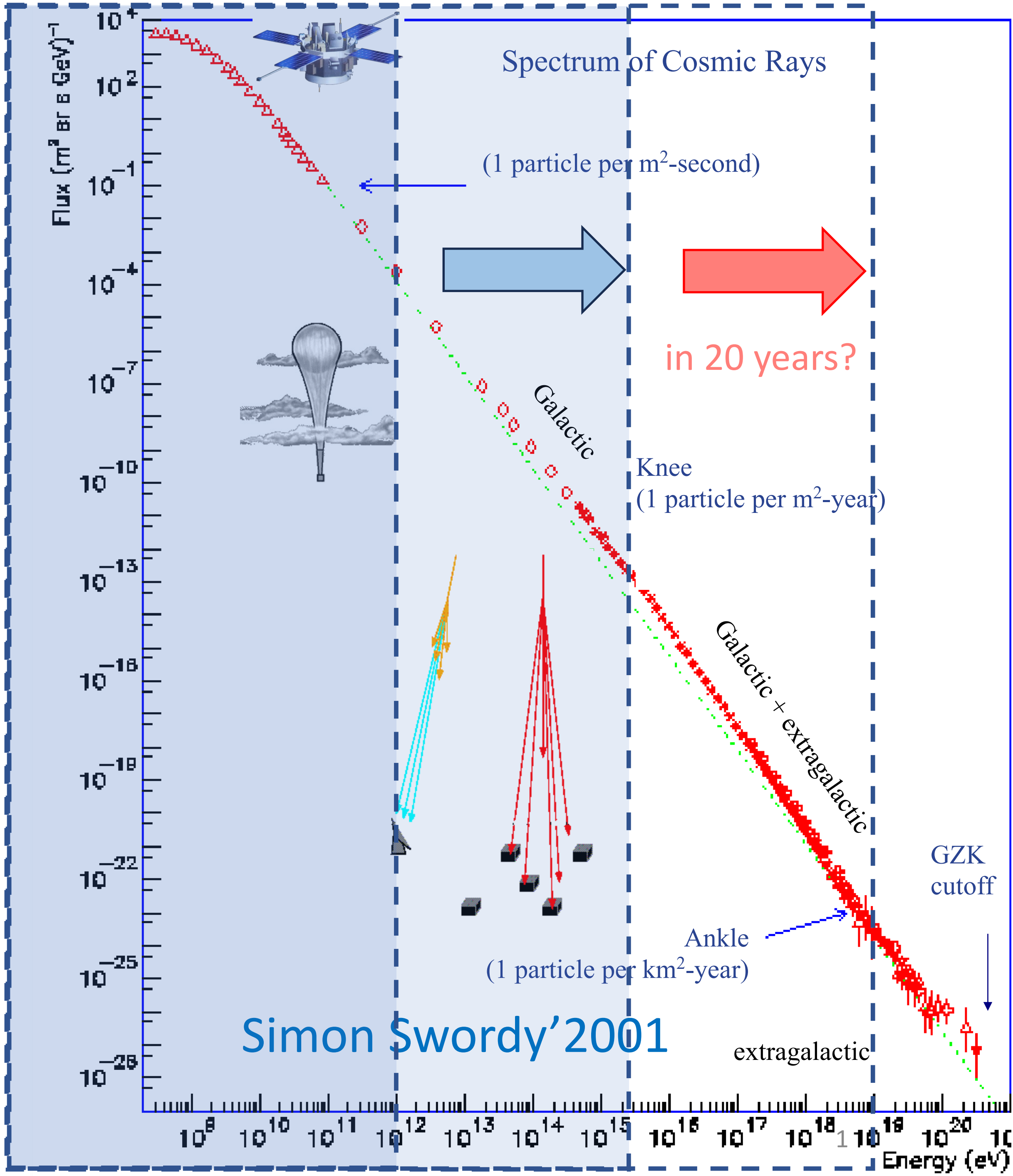
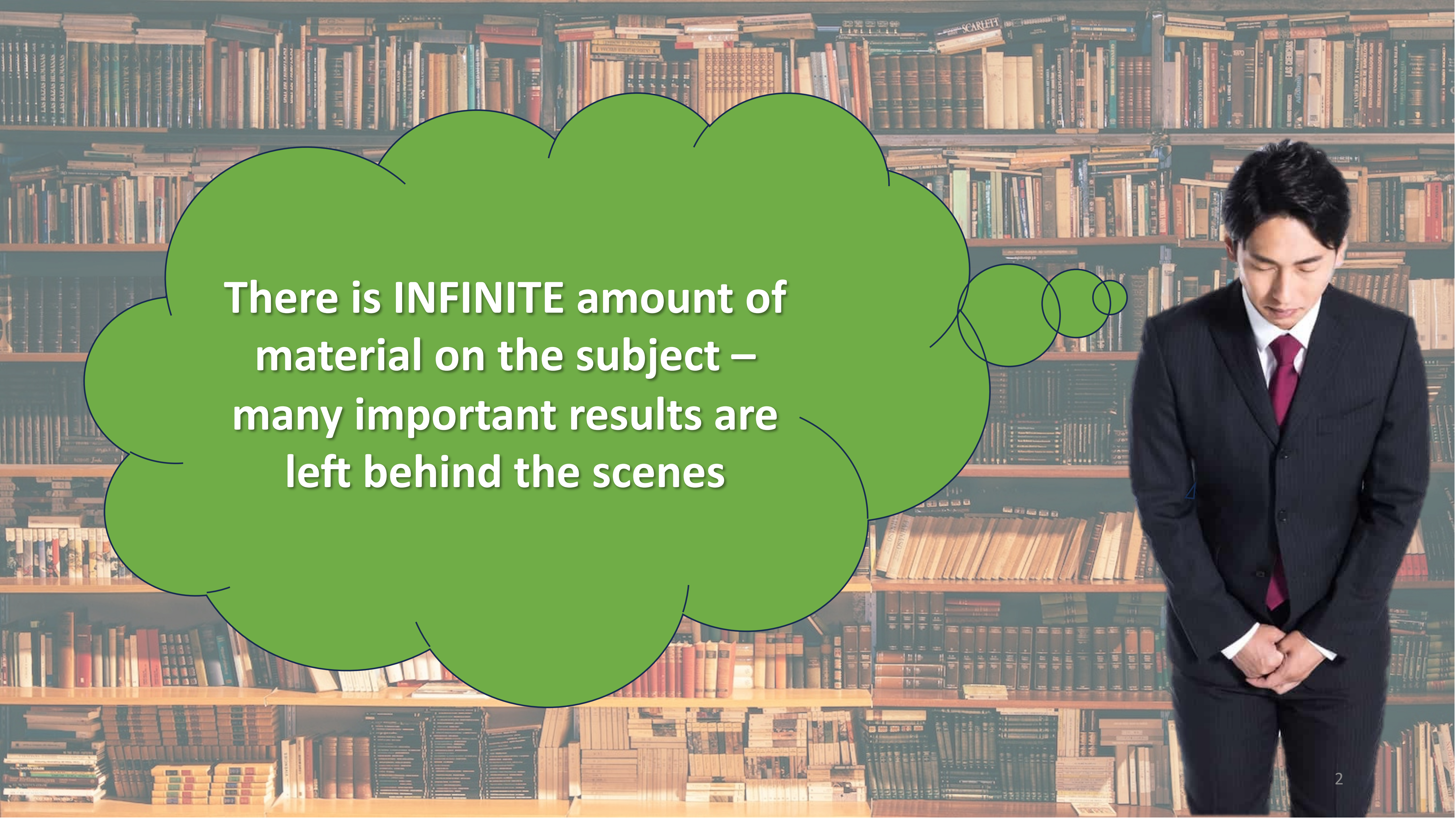
ICRC2023
38th International Cosmic Ray Conference
The Astroparticle Physics Conference

Direct measurements of cosmic rays and their possible interpretations

Igor V Moskalenko / Stanford U.



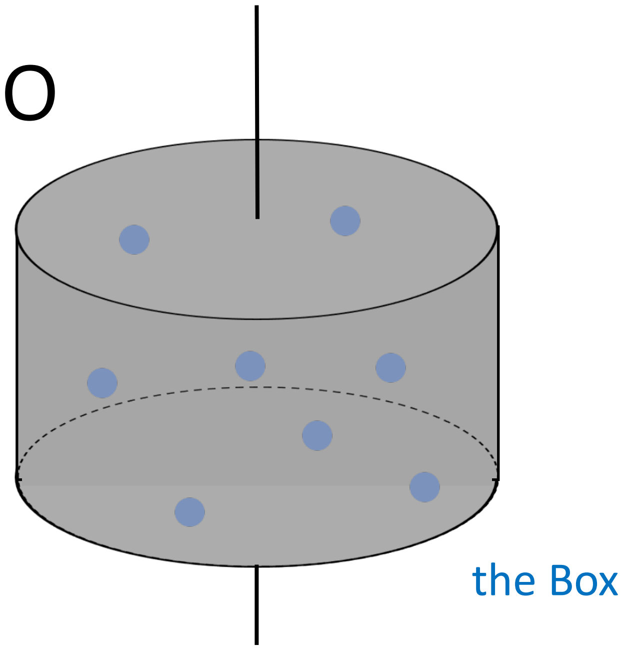

There is INFINITE amount of material on the subject – many important results are left behind the scenes

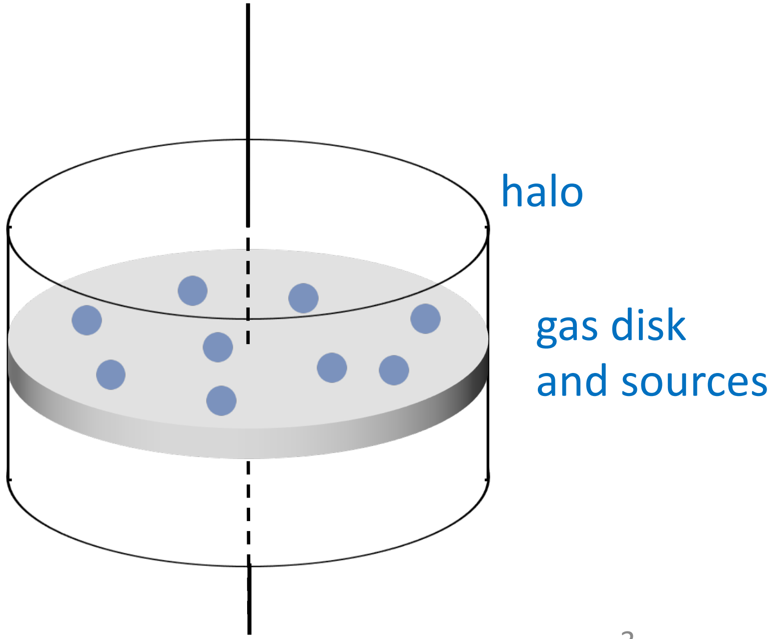
Leaky Box and a Galaxy with large halo

Two models were popular for most of the 20th century:

- the Leaky Box (simplest)
  - Considered the Galaxy as a volume uniformly filled with gas, sources, and cosmic rays and a small leakage – here is the name the LEAKY BOX
  - Tuned to the local measurements, it can correctly reproduce the fluxes of stable nuclei in one single point in the Galaxy
- a galaxy with large halo (a realistic model)
  - Considered the Galaxy as a volume filled with cosmic rays
  - The gas and sources are distributed in the disk
  - Cosmic rays escape into the intergalactic space through the boundaries

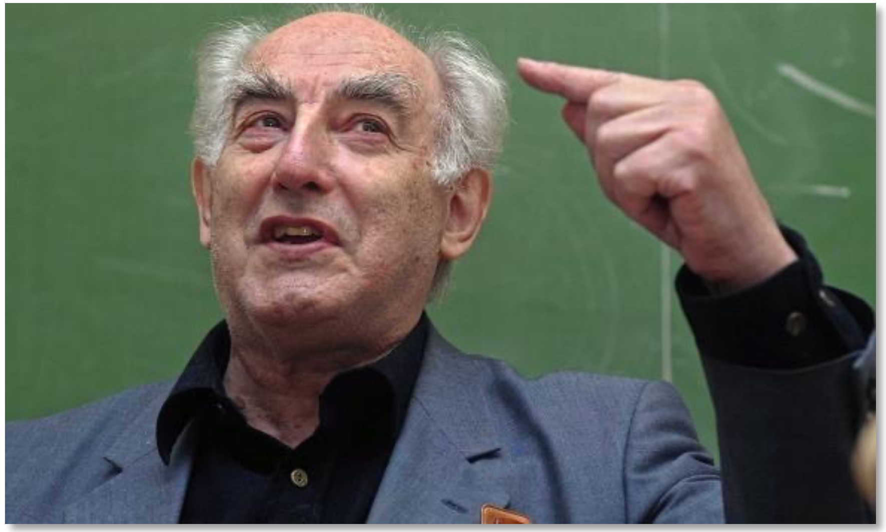
Both models were able to reproduce main features observed in cosmic rays

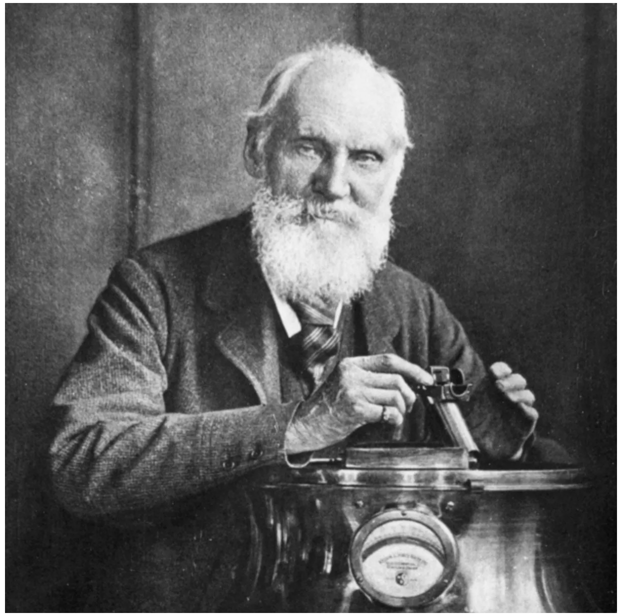




Reminiscent of the popular view 100 years ago

In respect of CR with $E_{CR}<10^{15}$-10^{16} eV there generally remain some vague points, but in the whole the picture is clear enough…
— V.L. Ginzburg, 1999

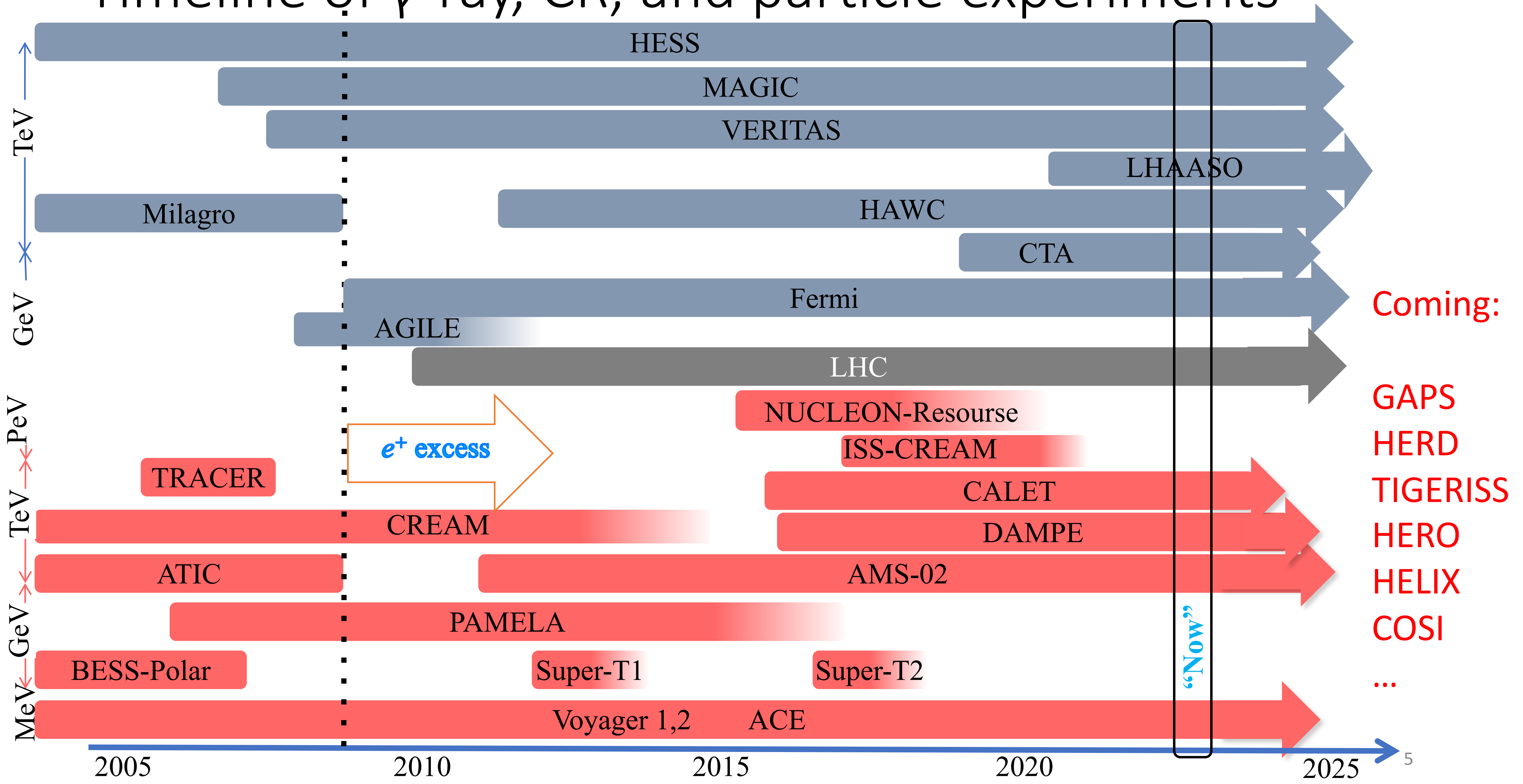




There is nothing new to be discovered in physics now. All that remains is more and more precise measurement… — Lord Kelvin (William Thomson), 1900

- Nowadays we have such excellent data that the whole picture becomes completely unclear
- This means that all theoretical breakthroughs are still ahead!

Timeline of γ-ray, CR, and particle experiments

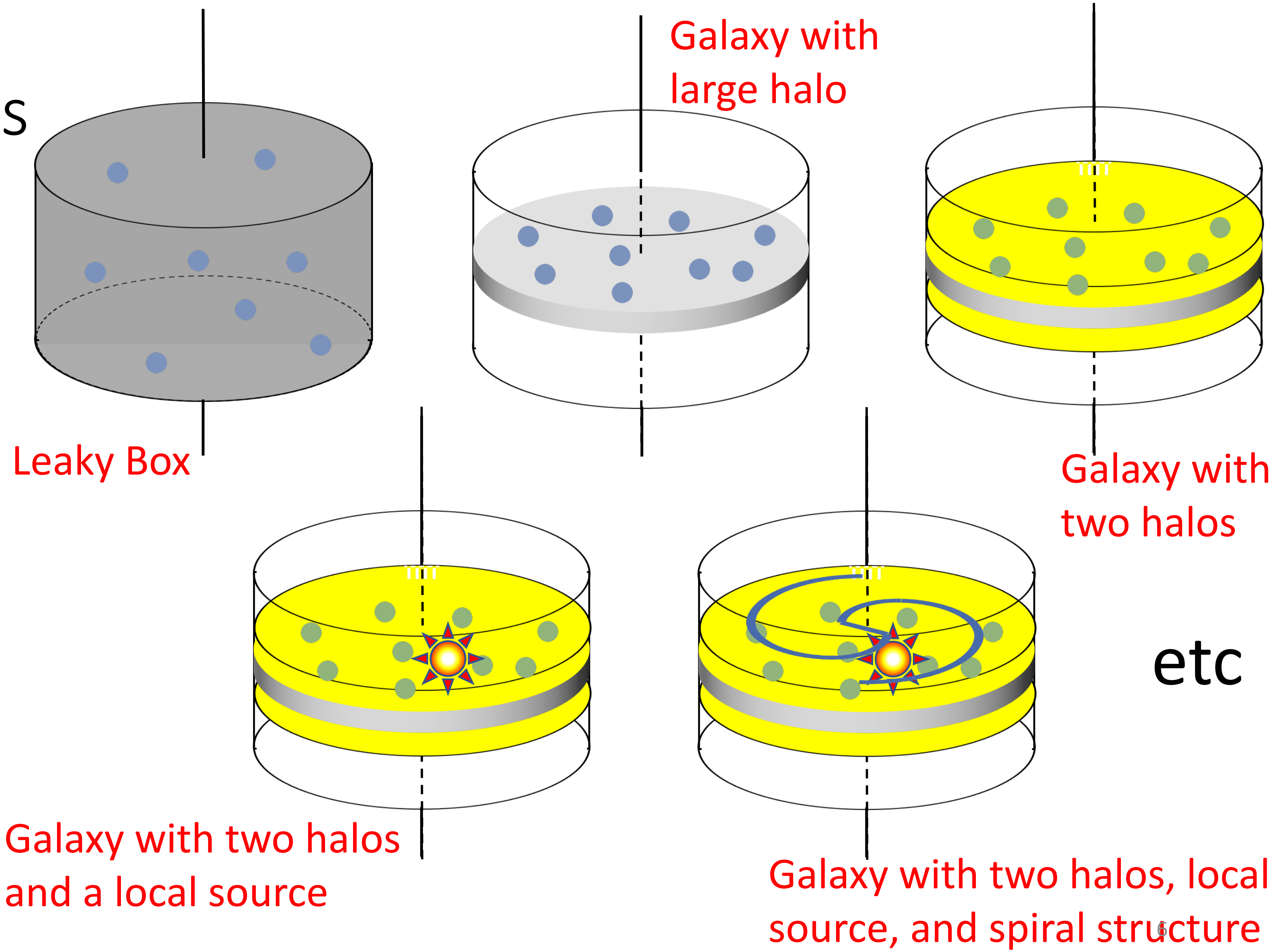


Evolution of Galactic models

- This evolution leads to better fits of the data at the cost of dramatic increase in the number of free parameters, but not necessarily better understanding

Time-tested wisdom:

- Occam's razor: “if you have two competing ideas to explain the same phenomenon, you should prefer the simpler one”
- A. Einstein: “Everything should be made as simple as possible, but not simpler”



Low energy features

(Iron offers some clues)

^{60}Fe as a tracer of SN activity in the solar neighborhood

✧ The evidence of the past SN activity in the local ISM is abundant (Fry+2015; Wallner+2016; Breitschwerdt+2016)

✧ Indications of several SNe between ~1.5 and ~3 Myr ago within 100 pc of the Sun

✧ The Local Bubble is a low-density region of the size of ~200 pc filled with hot H II gas that itself was formed in a series of SN explosions

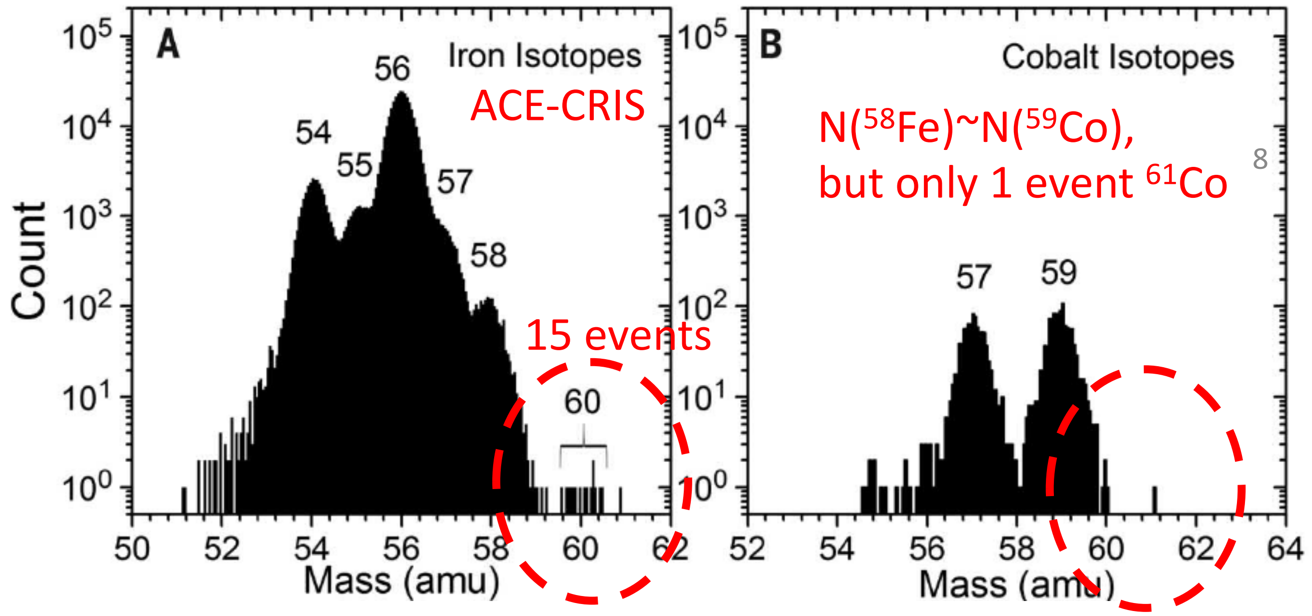
✧ ^{60}Fe: a half-life 2.6 Myr, β^- decay

✧ Excess of radioactive ^{60}Fe in deep ocean sediments (Knie+'1999, 2004; Ludwig+'2016; Wallner+'2016)

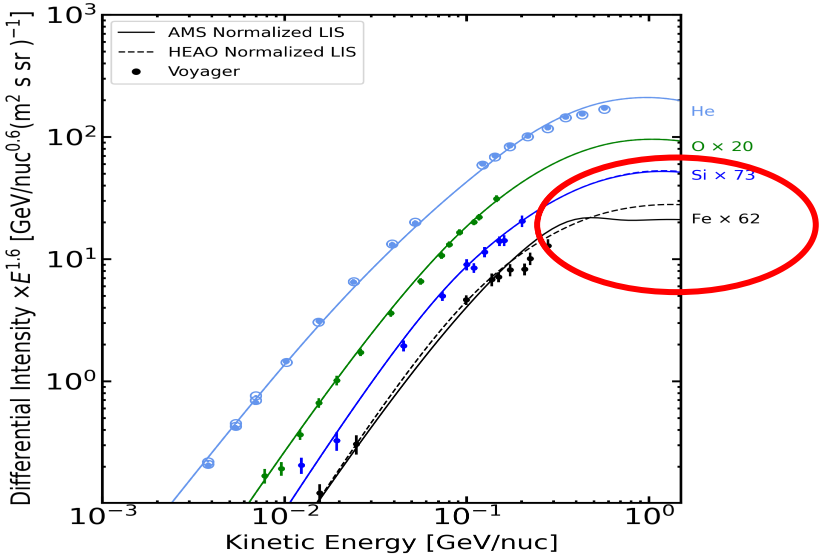
✧ Antarctic snow (Koll+'2019).

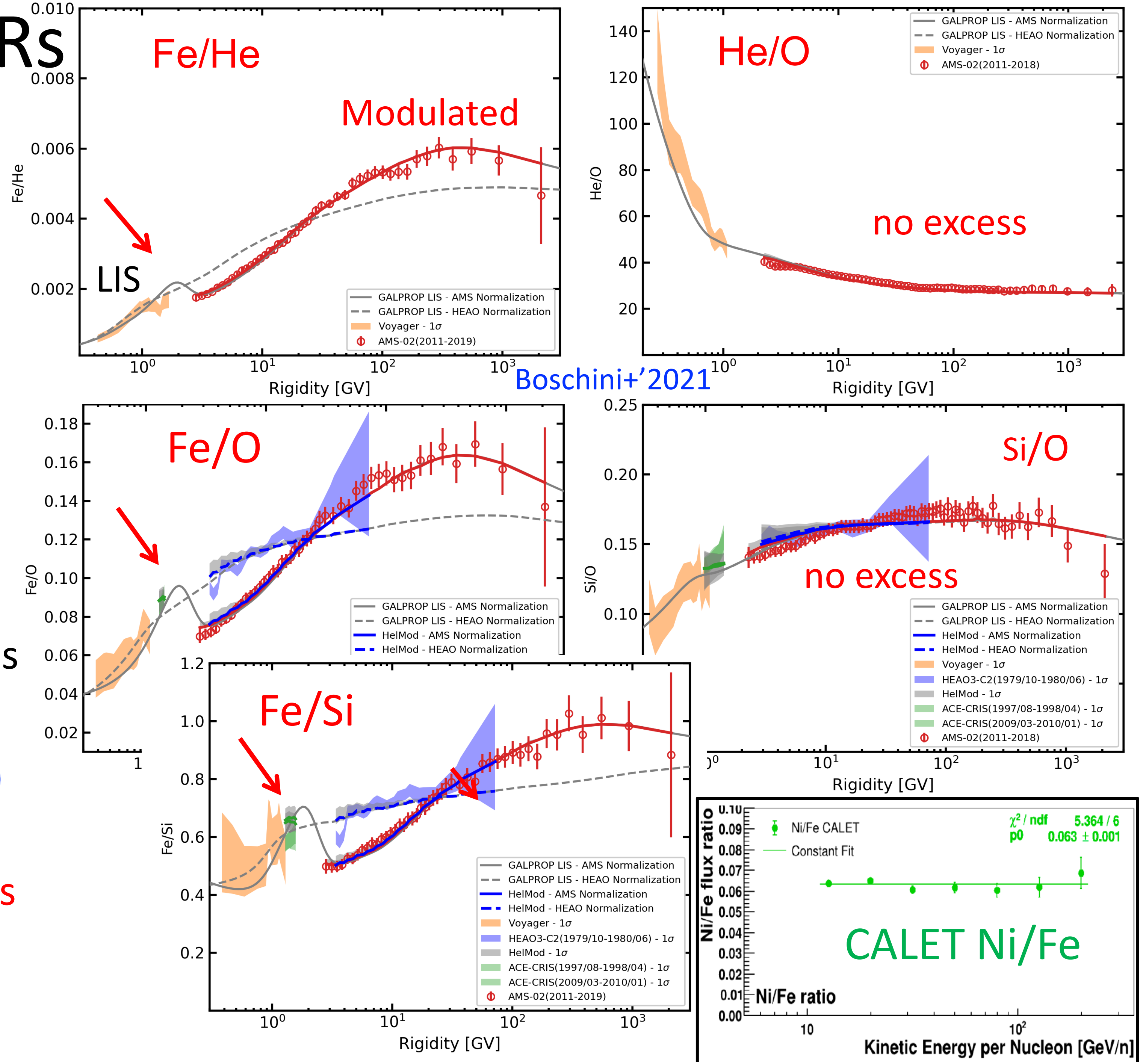
✧ Lunar regolith samples (Cook+'2009; Fimiani+'2012, 2014)

✧ ACE-CRIS observations of ^{60}Fe (Binns+'2016)



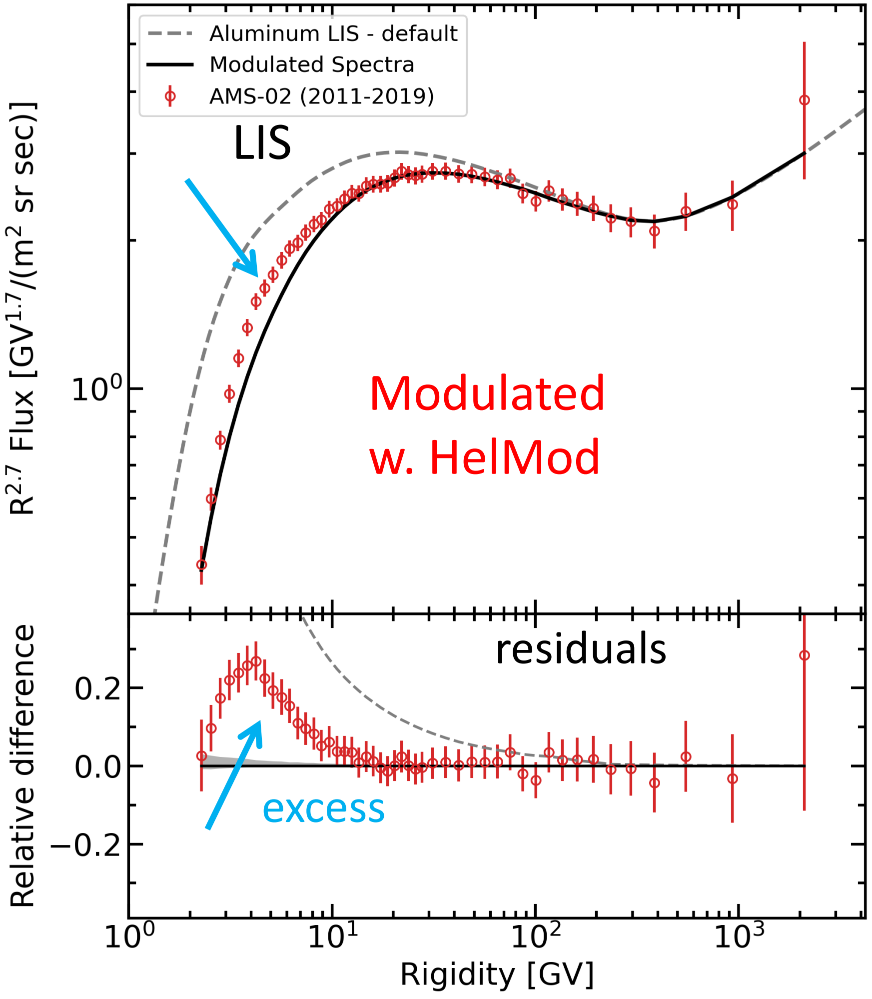
Iron excess/deficit in CRs



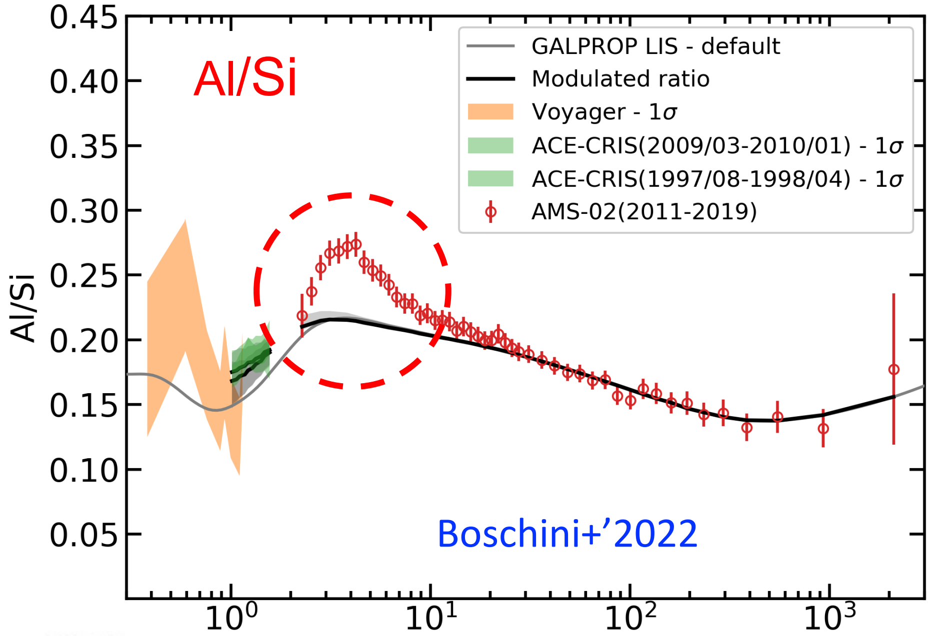


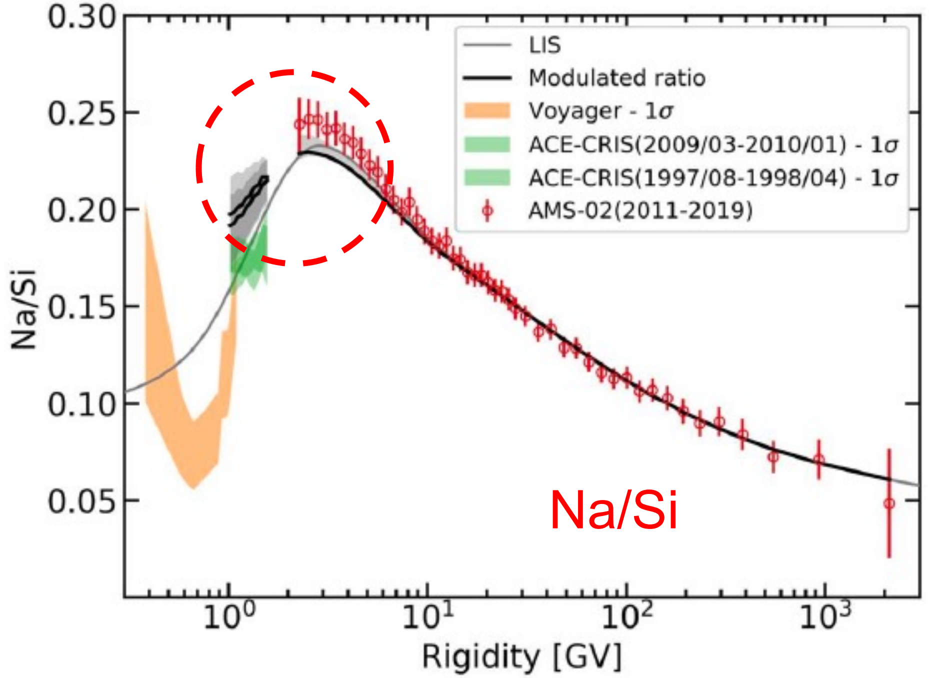
- ✧ The excess in iron – comparison of Voyager 1, ACE-CRIS, and AMS-02 data
- ✧ Most visible in Fe/He, Fe/O, Fe/Si ratios
- ✧ Absent in He/O and Si/O ratios
- ✧ Falls in line with other evidences (^{60}Fe)
- ✧ Local sources: large fragmentation cross sections and fast ionization losses
- ✧ Fe group: Ni/Fe = const (CALET)
- ✧ Important to measure sub-Fe/Fe ratio

Aluminum excess



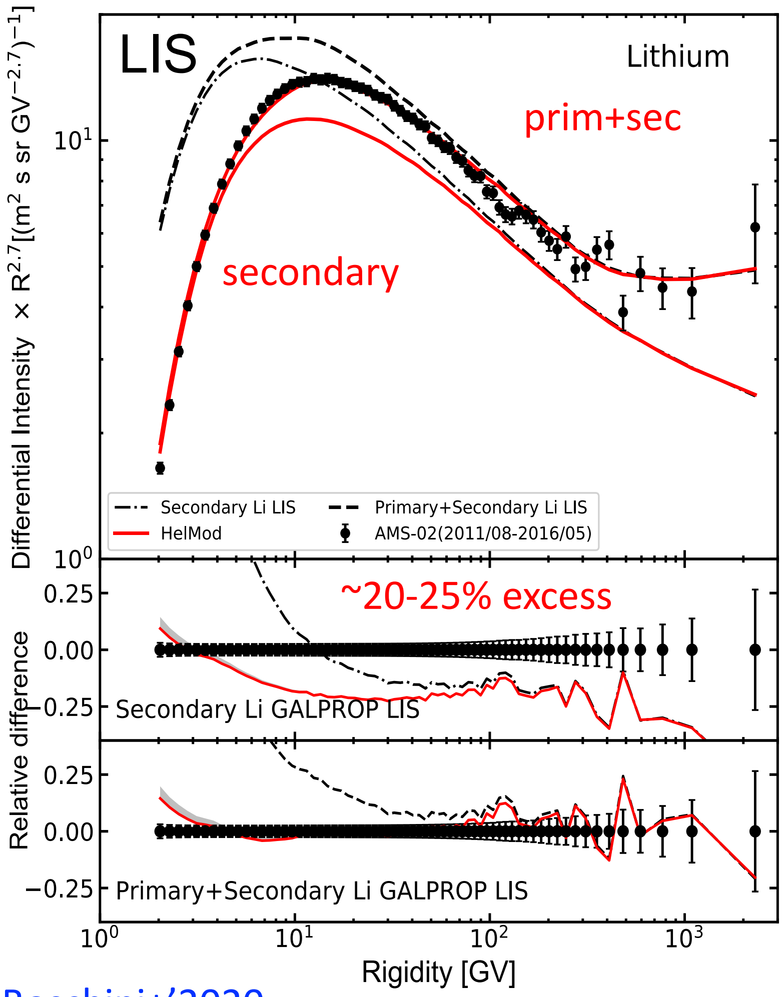
- An excess in aluminum becomes clearly visible when we compare the Al/Si ratio with model predictions
- A similar feature in Na/Si ratio is absent
- The excess is observed in a narrow region 3-10 GV (~0.8-4 GeV/n), where the production cross sections are mostly flat
- Indicates a presence of low-energy Al component, perhaps associated with local sources (massive stars?)



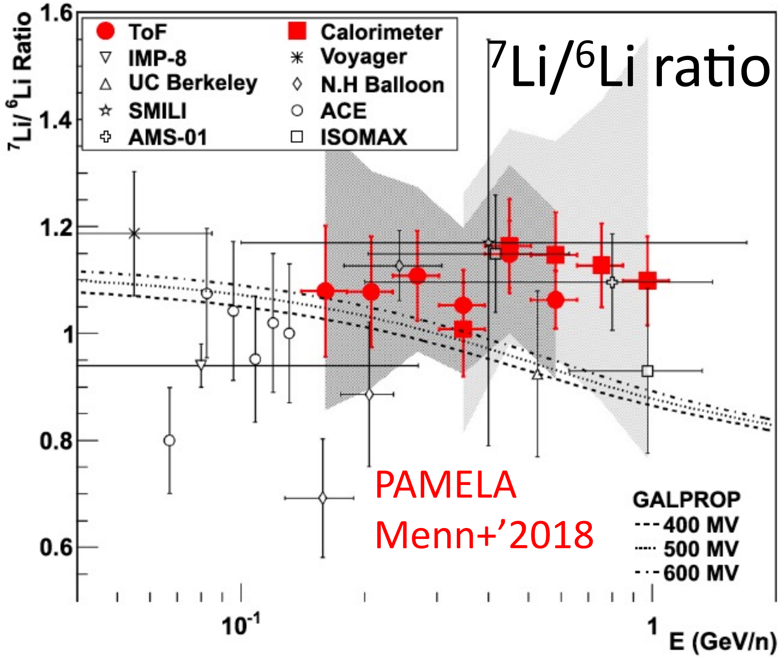


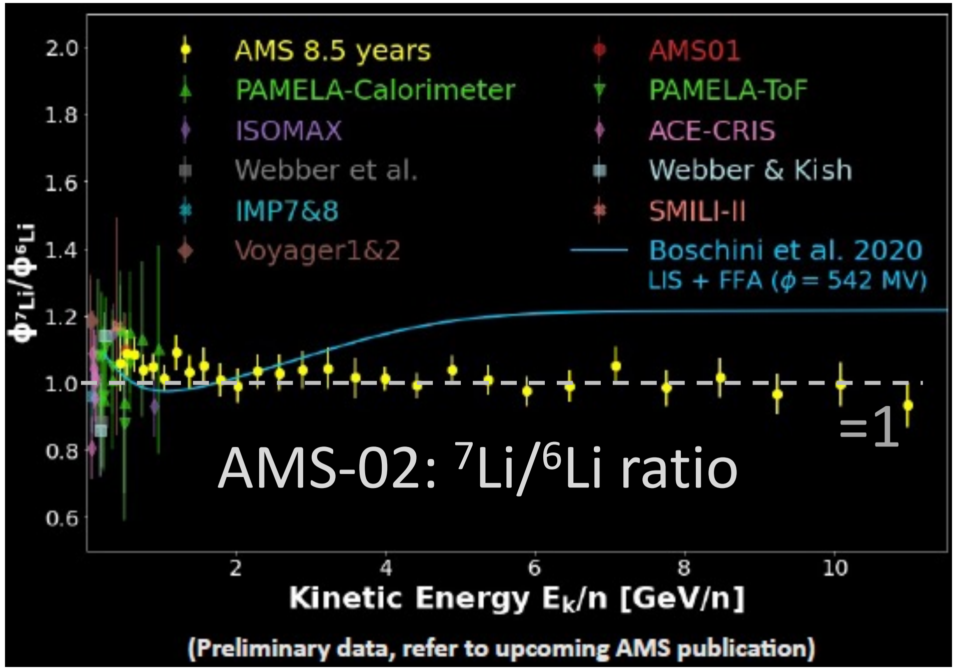
Lithium excess

- A comparison of the model calculation with AMS-02 data shows an excess above ~5-10 GV; the origin of this excess is unclear
- Xsections are flat above ~1 GeV/n, the excess is at >1.5 GeV/n (5 GV)
- Proposed that some primary ^{7}Li may come from nova explosions (^{7}Be decay), but perhaps there could be other sources of ^{6,7}Li
- Usually assumed ^{7}Li/^{6}Li ~1, but it may change at higher rigidity; measurements of the isotopic ratio can shed light on the origin of Lithium in CRs



Boschini+'2020



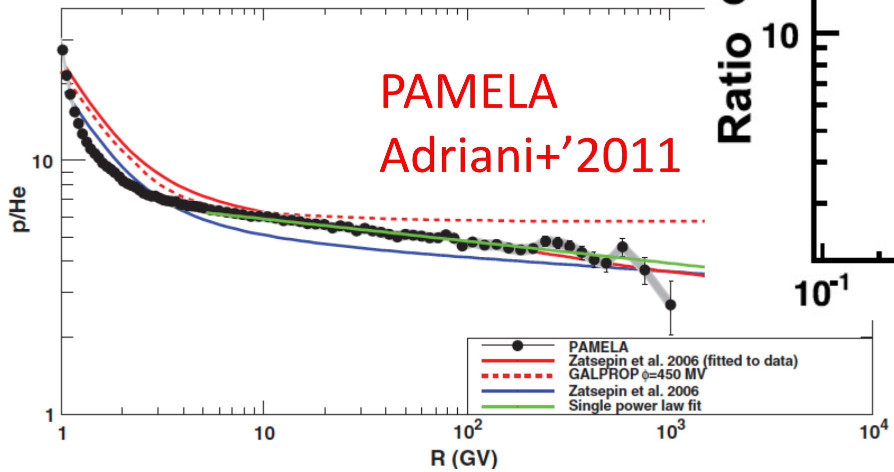


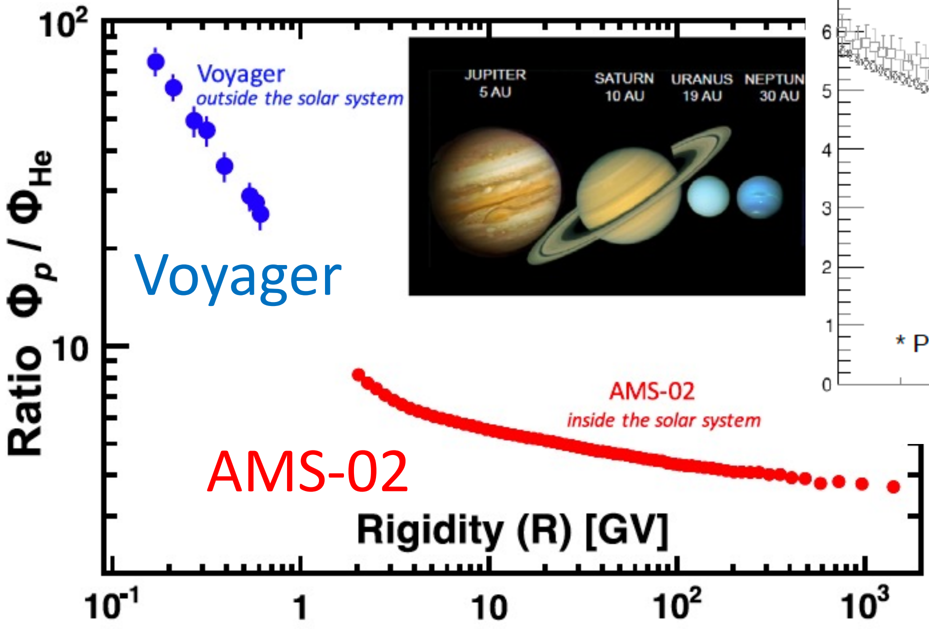
Inventory of Galactic cosmic ray sources

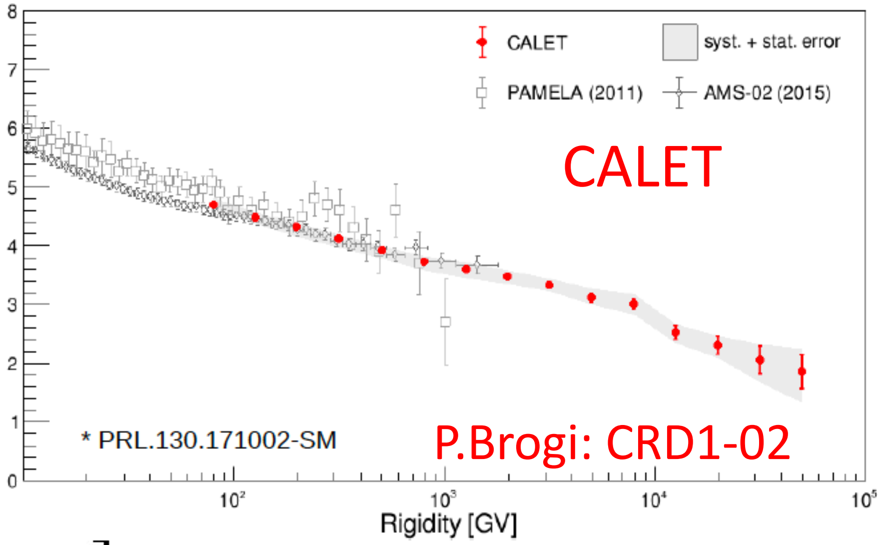
Type	Ejecta E_{kin}, erg	Frequency	Observed number (MW)
Supernova	10^{51}	~0.03/year Last 1604	294 (Green Catalogue)
Wolf-Rayet wind	10^{51} -over the lifetime		354
O star wind	10^{50} (0.01 $L_{☆}$)-over 5 Myr winds (2-4)x10^3 km/s		20,000
Pulsar (Crab)	~4x10^{49} (total E_{rot})		~1500
Nova	10^{45}	~30-40 per year	350
Stellar flare	10^{36}		
Solar flare	10^{32}-10^{33}	Some 10 per year	

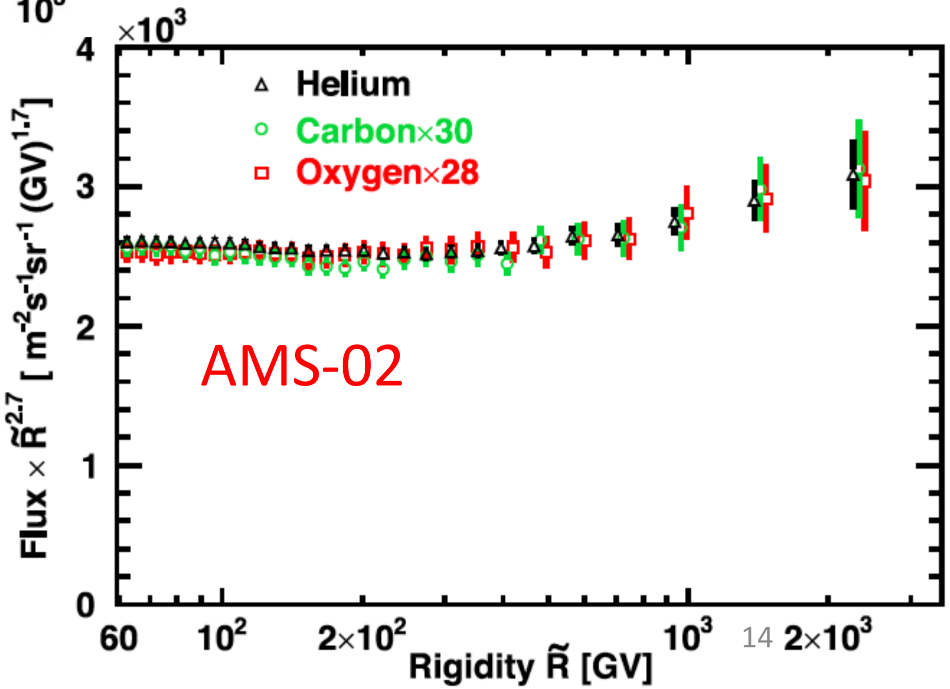
H/He ratio

Protons/Helium ratio







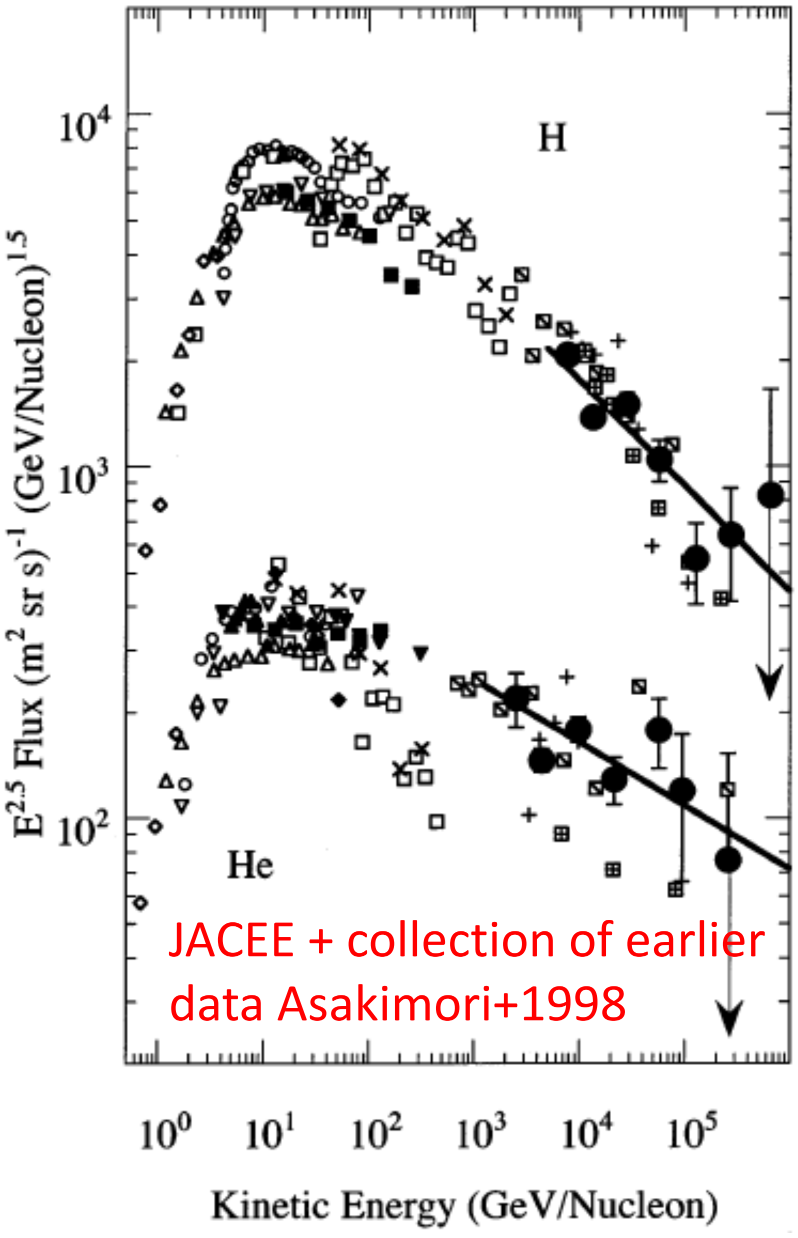


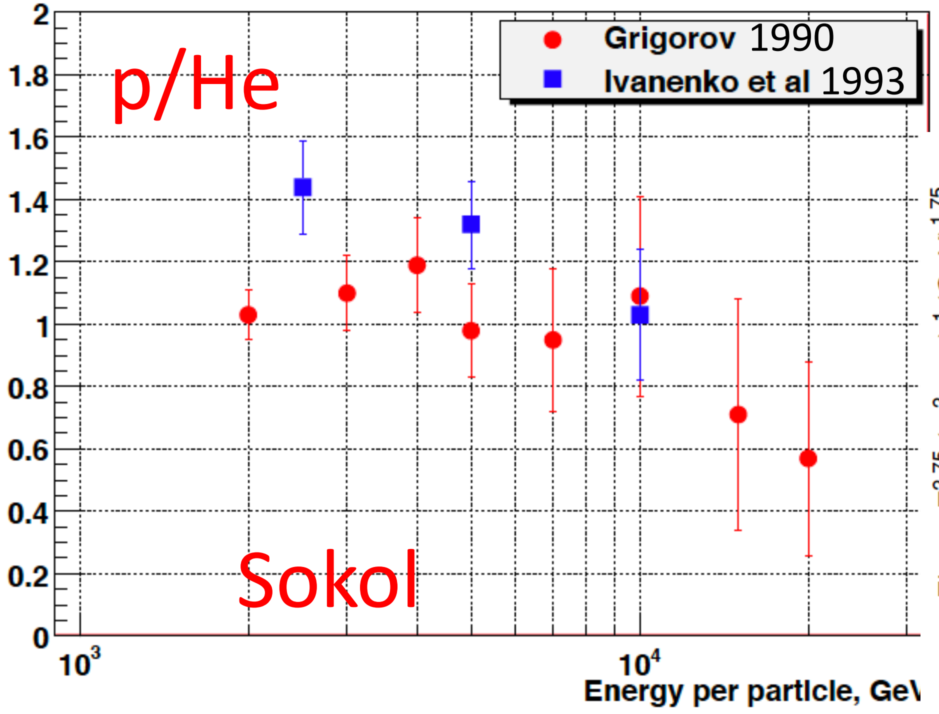
- The monotonic decrease of the H/He ratio when plotted vs Rigidity was clearly noticed in PAMELA data and confirmed by other experiments
- Helium, Carbon and Oxygen spectral indices are about the same above ~60 GV
- A/Z (protons)=1, A/Z (He,C,O)=2. A/Z ratio dependence?

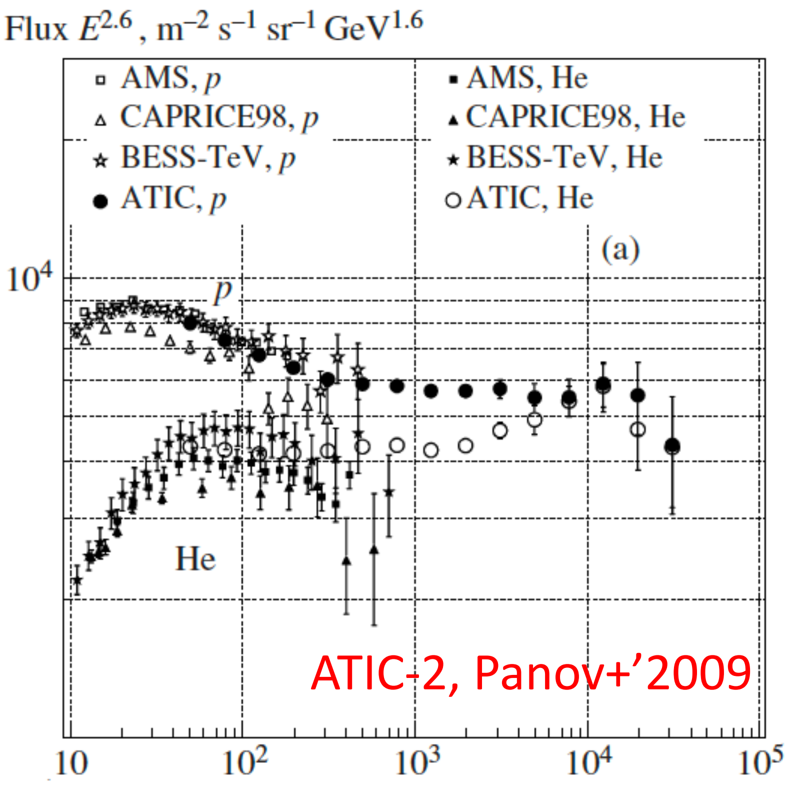
H/He ratio

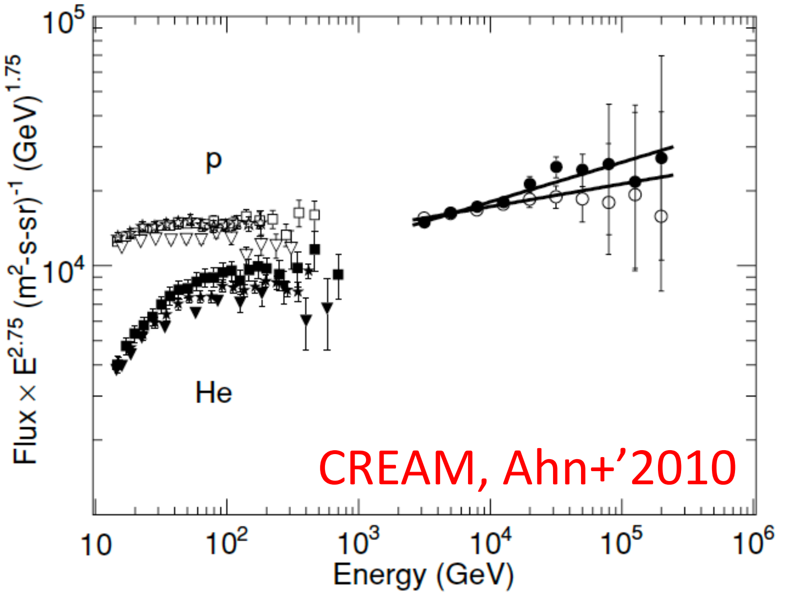
Paying tribute to earlier experiments

- The flatter spectrum of He (vs H) was observed while back, but theory told us that the spectral indices in rigidity do not depend on the nature of species
- This difference was attributed by many to systematic effects







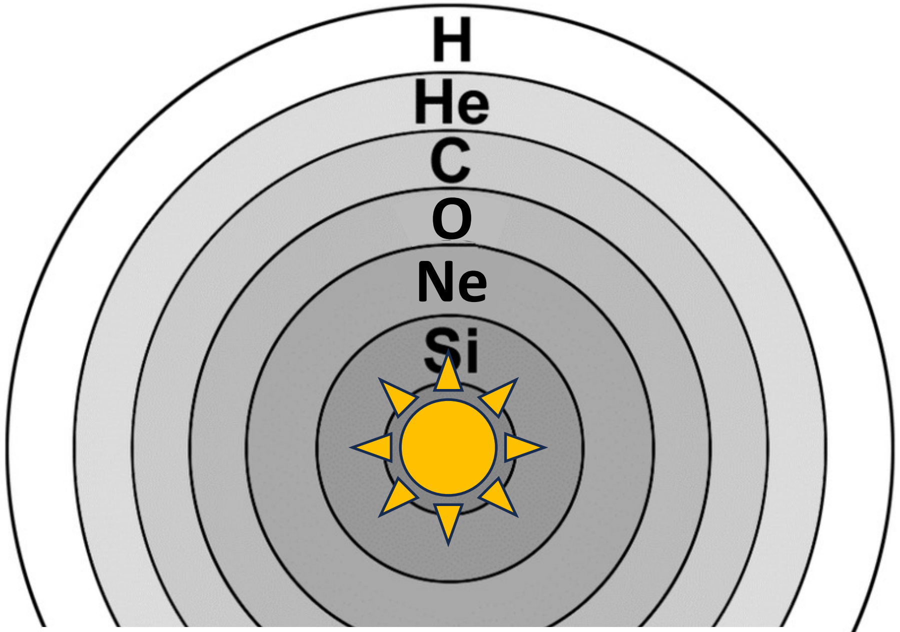


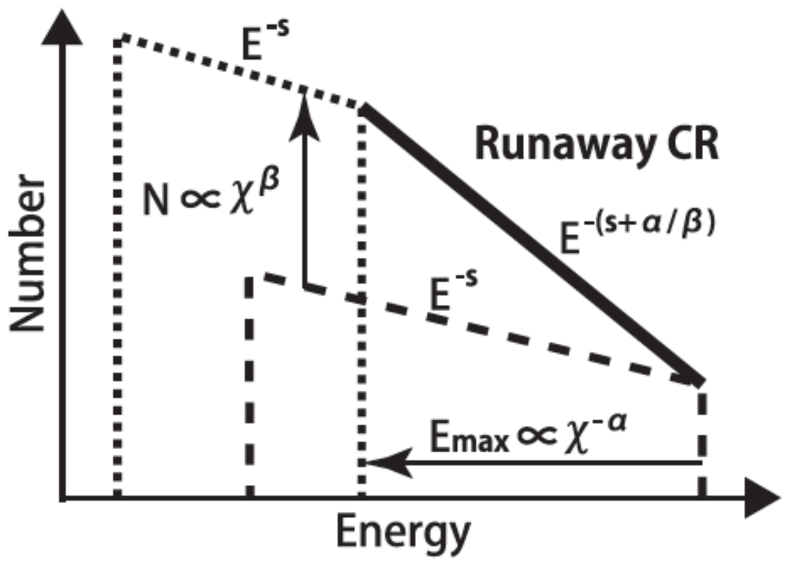
Hypothesis of the spatial distribution of elements

- Ohira, Ioka 2011, Ohira+2016:
  - SN explodes in pre-SN wind, which consists of lighter elements when the star is young, but becomes enriched with heavier and heavier elements at the final stages
  - The young SN shell accelerates heavier elements when young, and lighter elements when it fates
- Contribution from several SNRs
  - Similar scenario when enrichment with heavier elements is created by several SNe in a bubble

Cons:

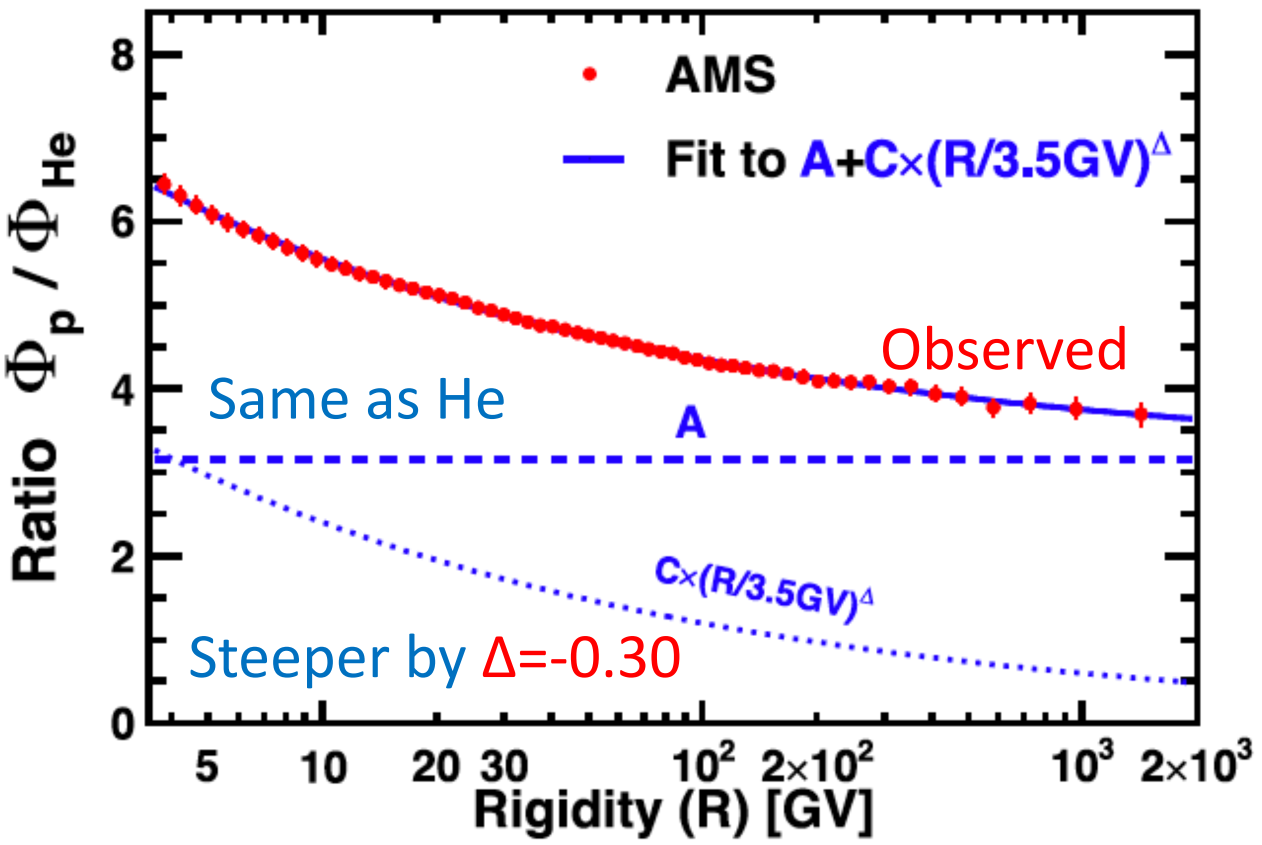
- Spectra of He, C, O have the same index
- Spectra of Ne, Mg, Si are somewhat steeper





Hypothesis of two components in the H spectrum

- Empirical hypothesis (Aguilar+2021)
  - Two types of sources inject distinctly different proton spectra into the ISM
  - One of them injects the spectrum similar to He, and another one injects a steeper (by 0.3) spectrum
  - Yang & Aharonian'2019 proposed that harder spectrum sources are surrounded by gas to reproduce the observed excess e^+



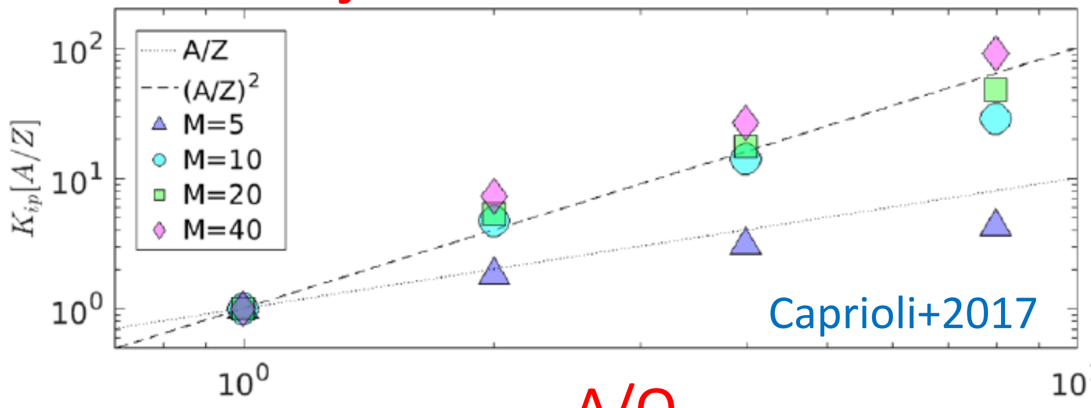
Cons

- Requires two types of distinctly different sources unique for protons
- Not observed in other species

Hypothesis of different acceleration efficiency

- Acceleration efficiency (Hanush+2019, Caprioli+2017):
  - Most of the particles in the shock are protons (A/Z=1), which generate Alfven waves and became frozen into the generated turbulence
  - Nuclei with A/Z>1 or A/Q>1 are not in synch with Alfven waves generated by protons and are more efficiently injected into the shock and accelerated

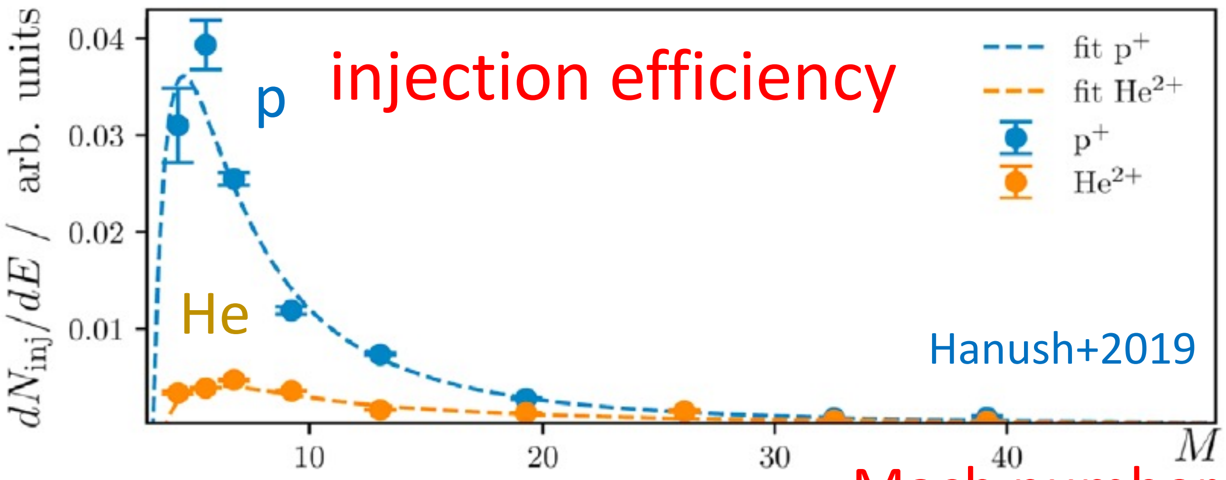
injection enhancement



A/Q

Predictions

- Injection of heavier species increases relatively to protons with increase of the Mach number and the increase of A/Q
- Same is true for all species A/Q>1

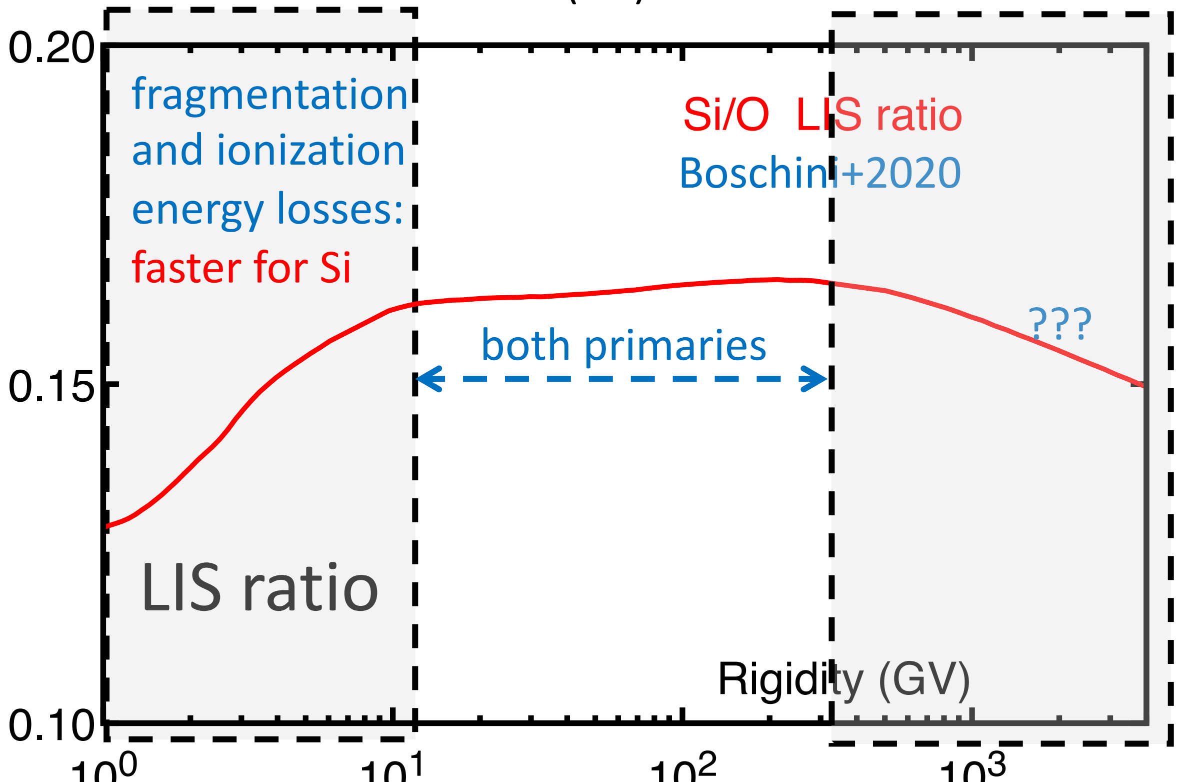


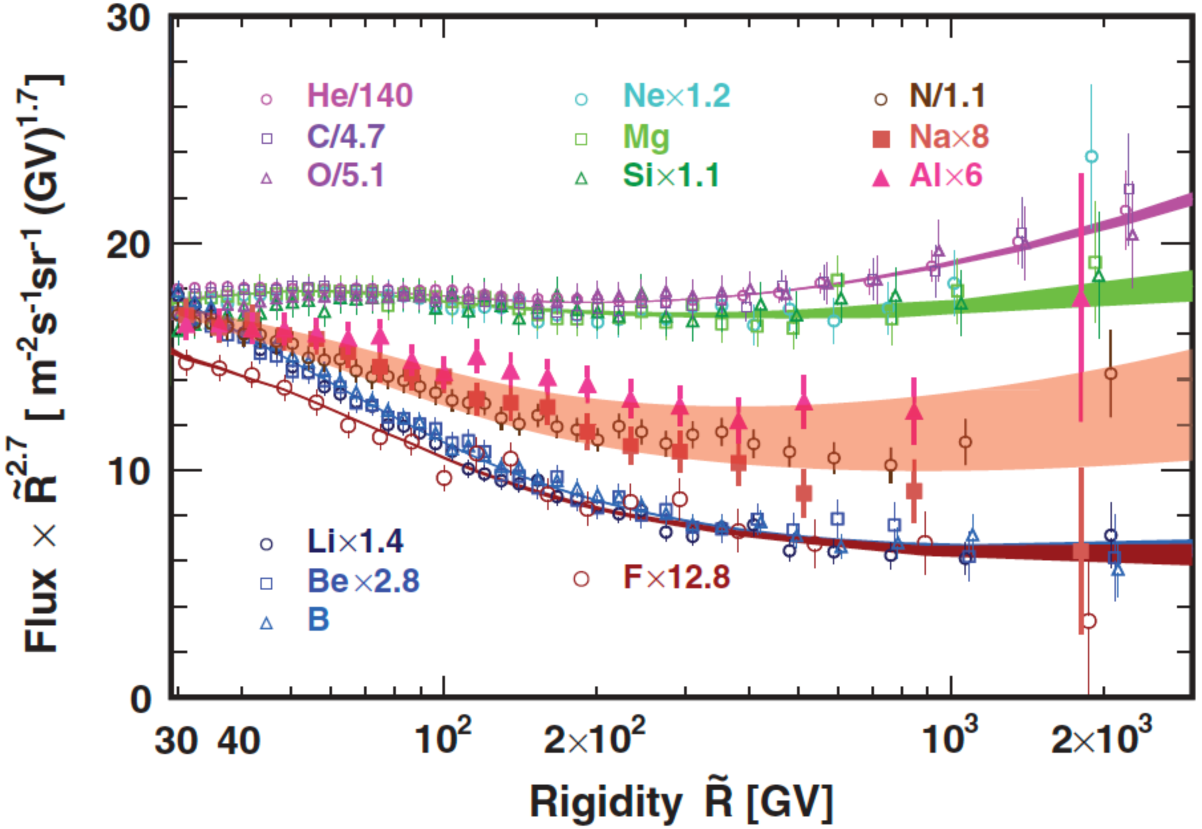
* Q is the charge of partly ionized atom

Silicon puzzle

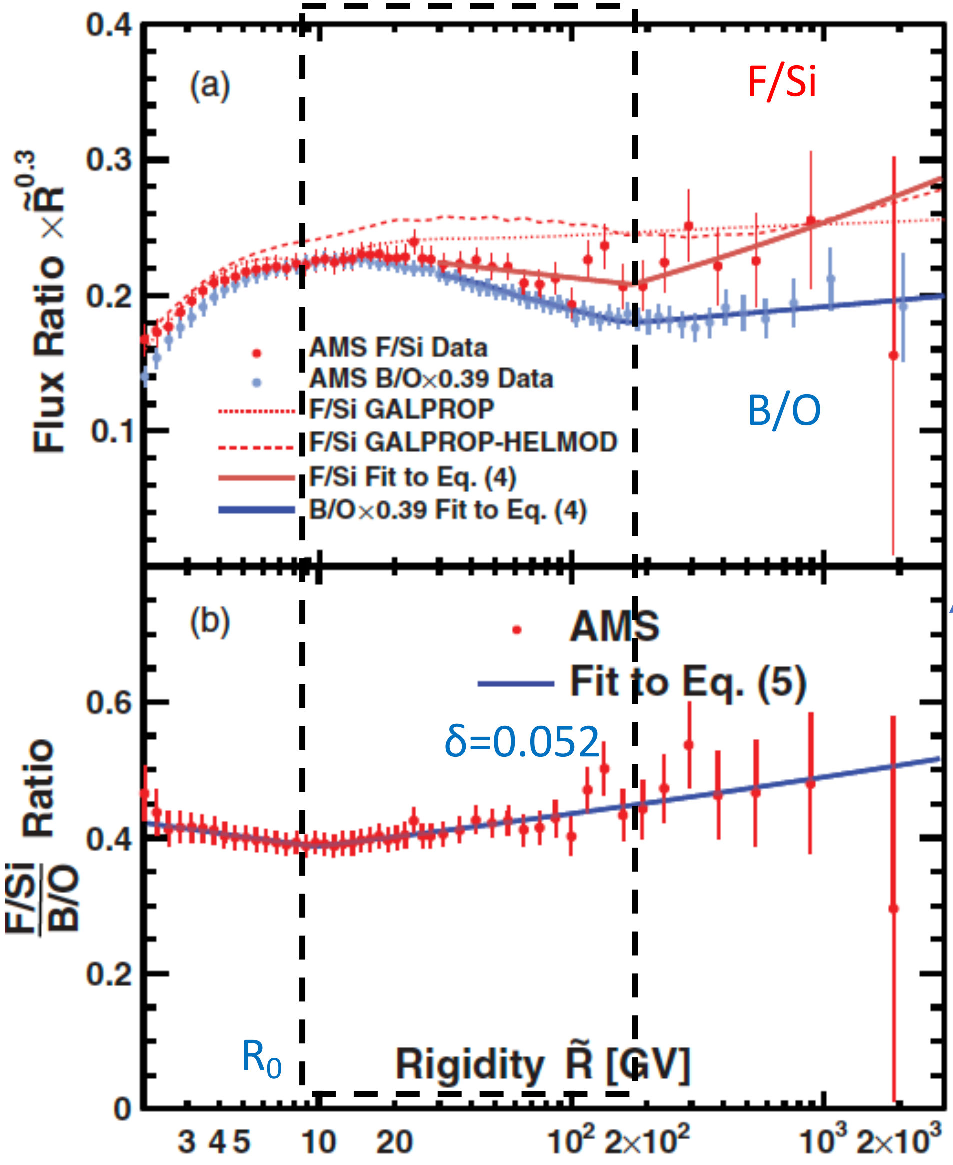
- O and Si are both primaries with A/Z=2
- Low energies: Si – large fragmentation Xsec and faster ionization energy losses
- Middle range: O and Si are mostly primaries, Si/O ~ const
- High energies: Oxygen spectrum is flatter. Why? Points to different origin or propagation

Local interstellar ratio (LIS) – removes modulation



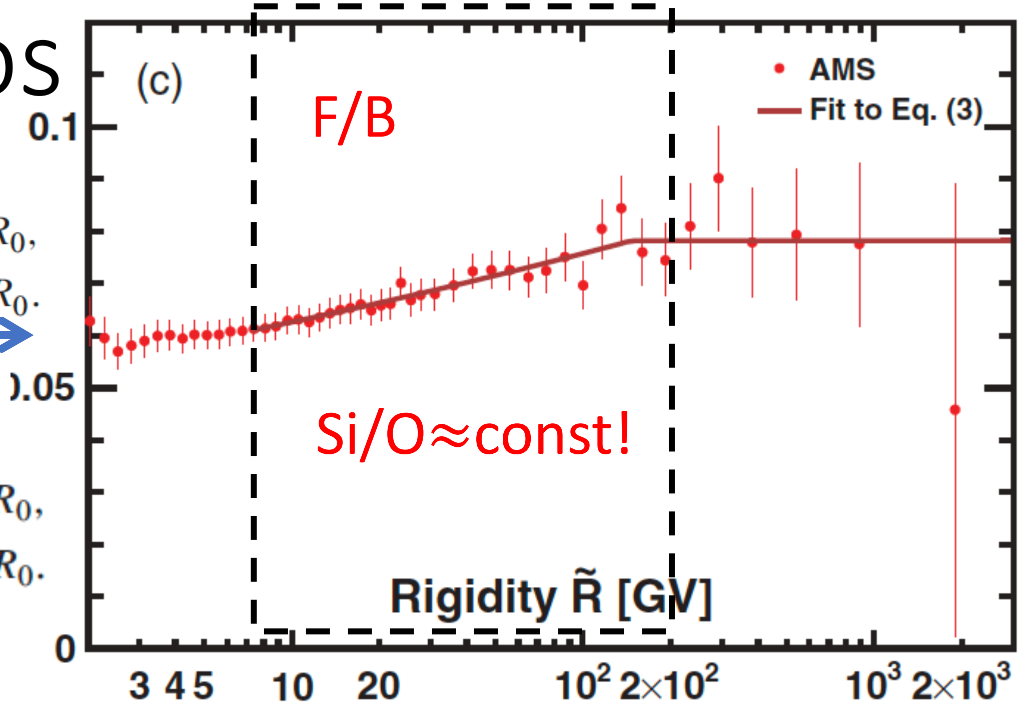


Fluorine puzzle & B/*, F/Si ratios



$$\mathrm{F/B} = \begin{cases} \kappa (R/R_0)^{\Delta}, & R \le R_0, \\ \kappa, & R > R_0. \end{cases}$$

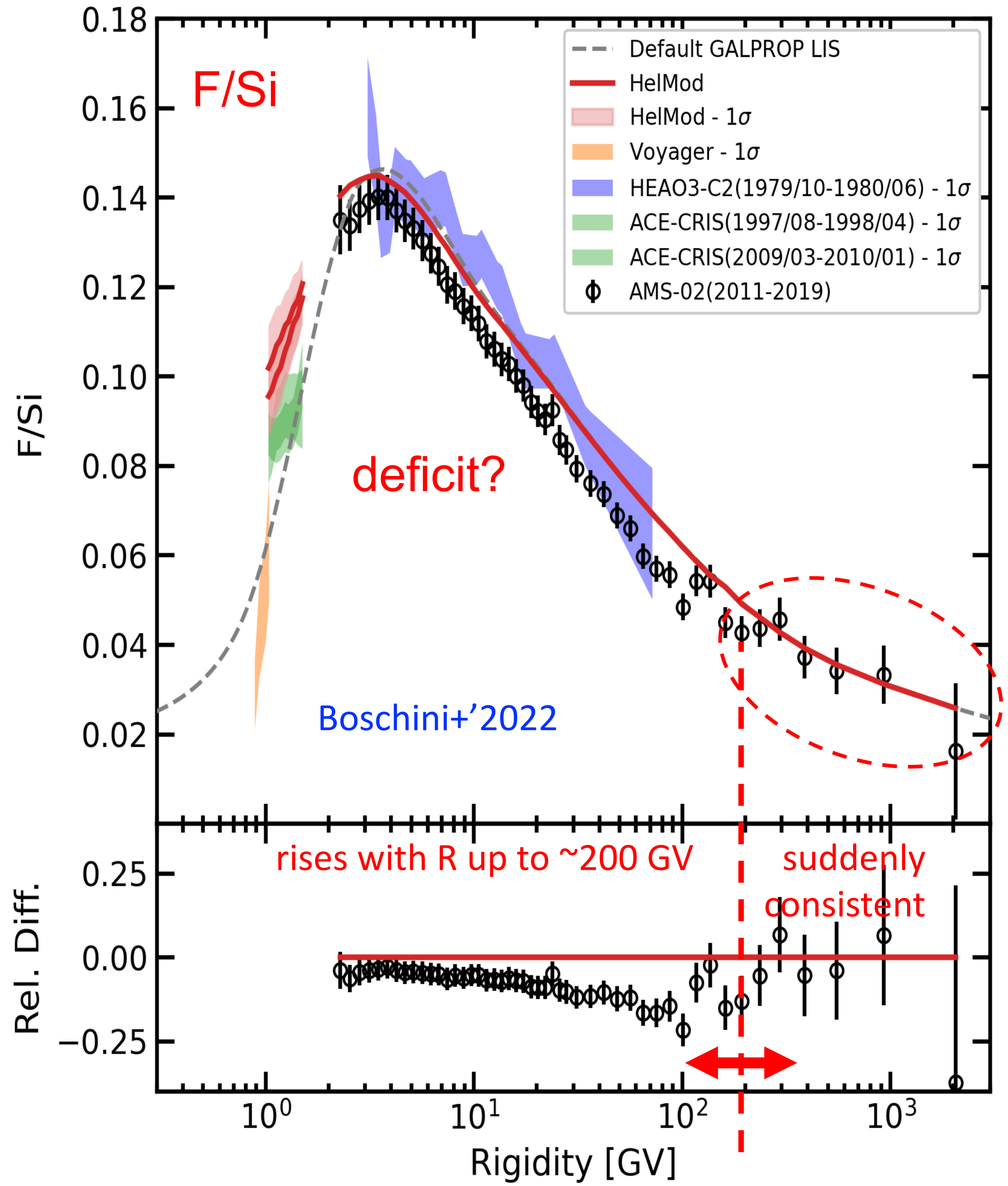
$$\frac{\mathrm{F/Si}}{\mathrm{B/O}} = \begin{cases} k (R/R_0)^{\delta_l}, & R \le R_0, \\ k (R/R_0)^{\delta}, & R > R_0. \end{cases}$$



- We look at the middle range from a few GV to ~200 GV, where O/Si ~ const
- F/B ratio rises as Δ=0.083±0.007 (<150 GV)
- F/Si ratio is flatter than B/O ratio by δ=0.052±0.007
- => Fluorine has a different origin or different propagation or a non-negligible primary component
- Interesting to see other ratios P/S and sub-Fe/Fe!

Fluorine puzzle – another view

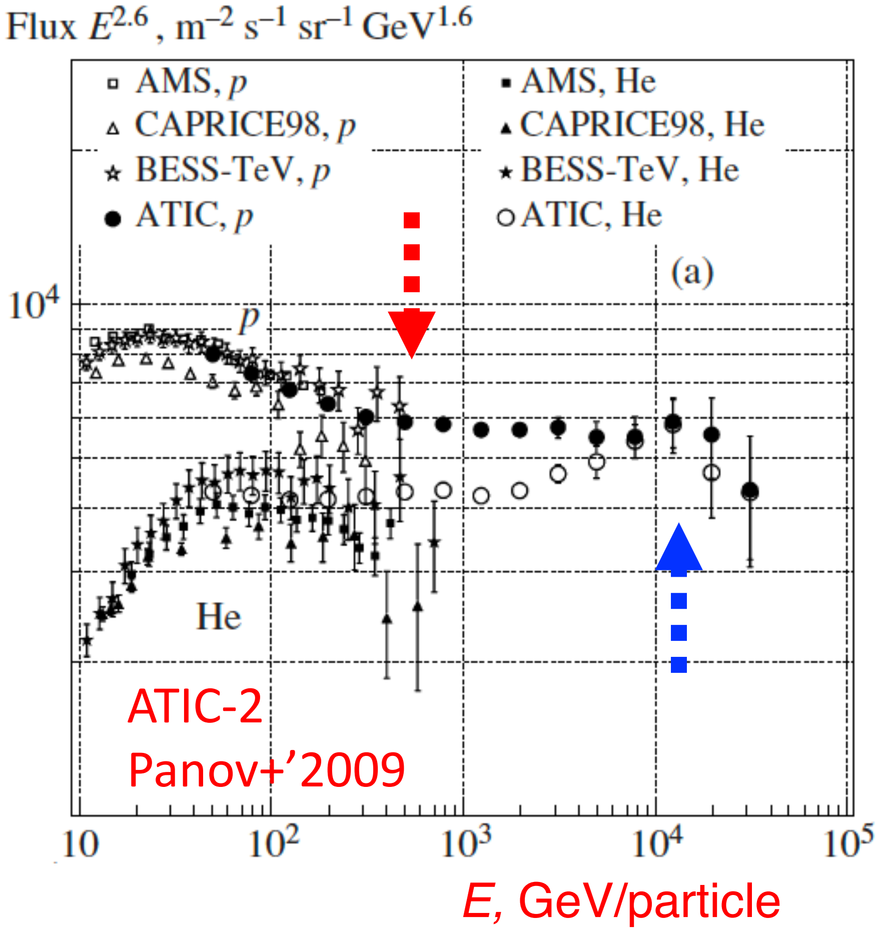
- A comparison of standard propagation calculations with data shows a deficit in secondary Fluorine, which rises with rigidity up to the break at 200 GV
- BUT consistent with the B/O ratio above 200 GV albeit with large error bars
- This is a serious issue, which cannot be cured by renormalization of the cross sections – the latter are flat above ~1-2 GeV/n
- This R-dependent discrepancy implies a different origin of Si group and CNO group or difference in propagation

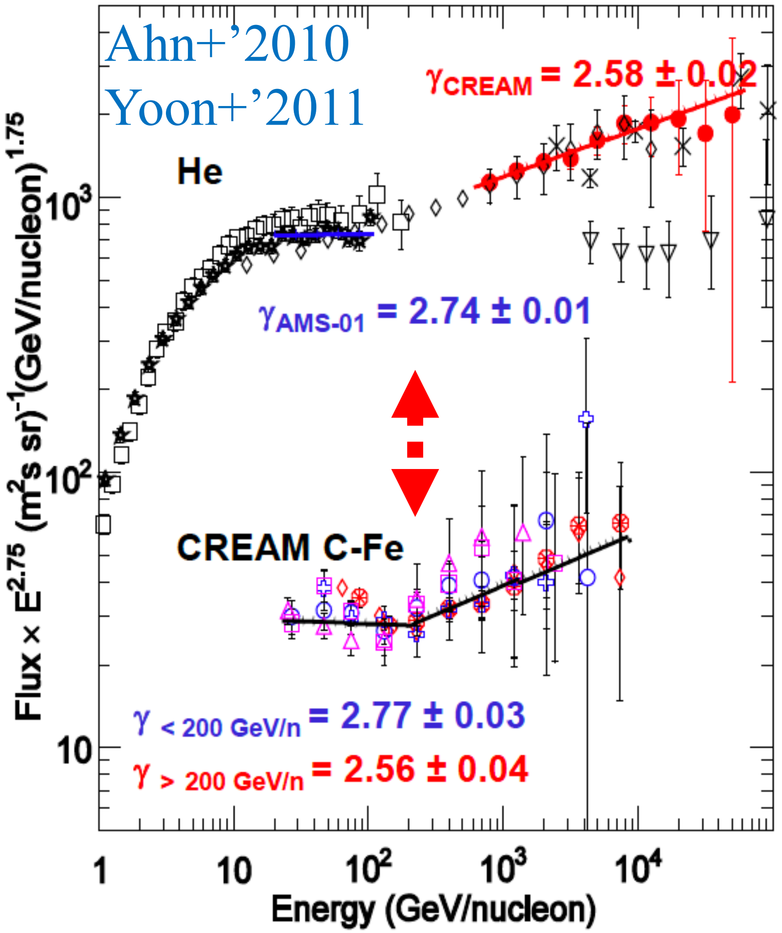


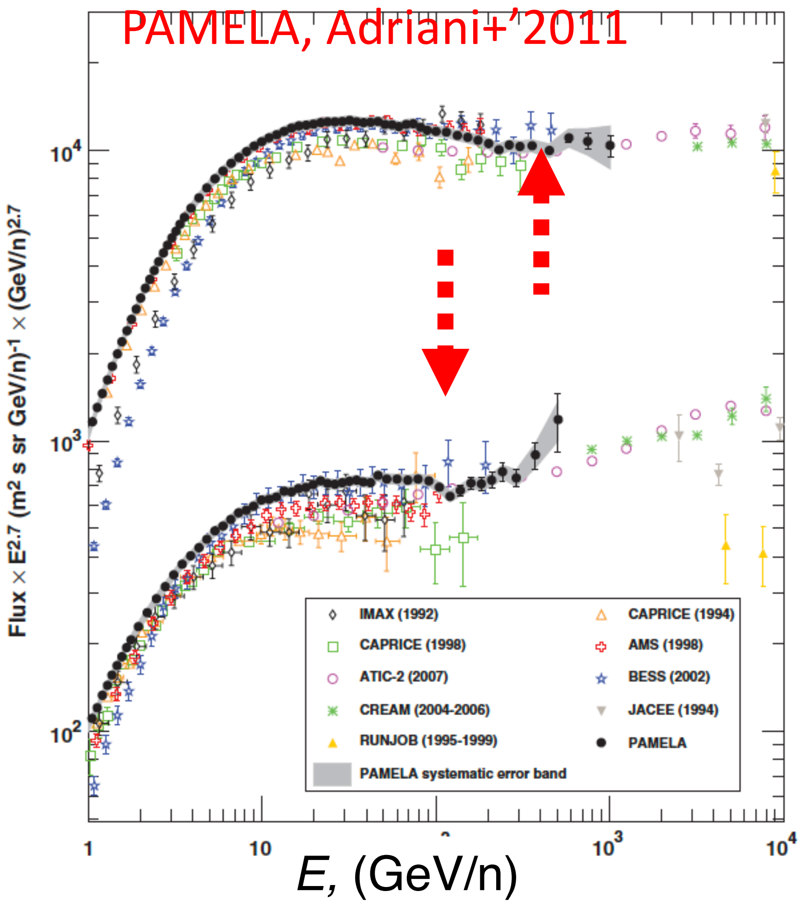
~200 GV & 10 TV breaks or TV bump

200 GV break in nucleon spectra

- ATIC-2 (Panov+'2009) and CREAM "*Discrepant hardening observed in cosmic-ray elemental spectra*" (Ahn+'2010)
- Initially looked like a calibration issue between <200 GeV and >200 GeV instruments
- Beautifully outlined by PAMELA (went up to 1 TeV)
- Do not be confused, plots have different units: GeV/particle, GeV/nucleon

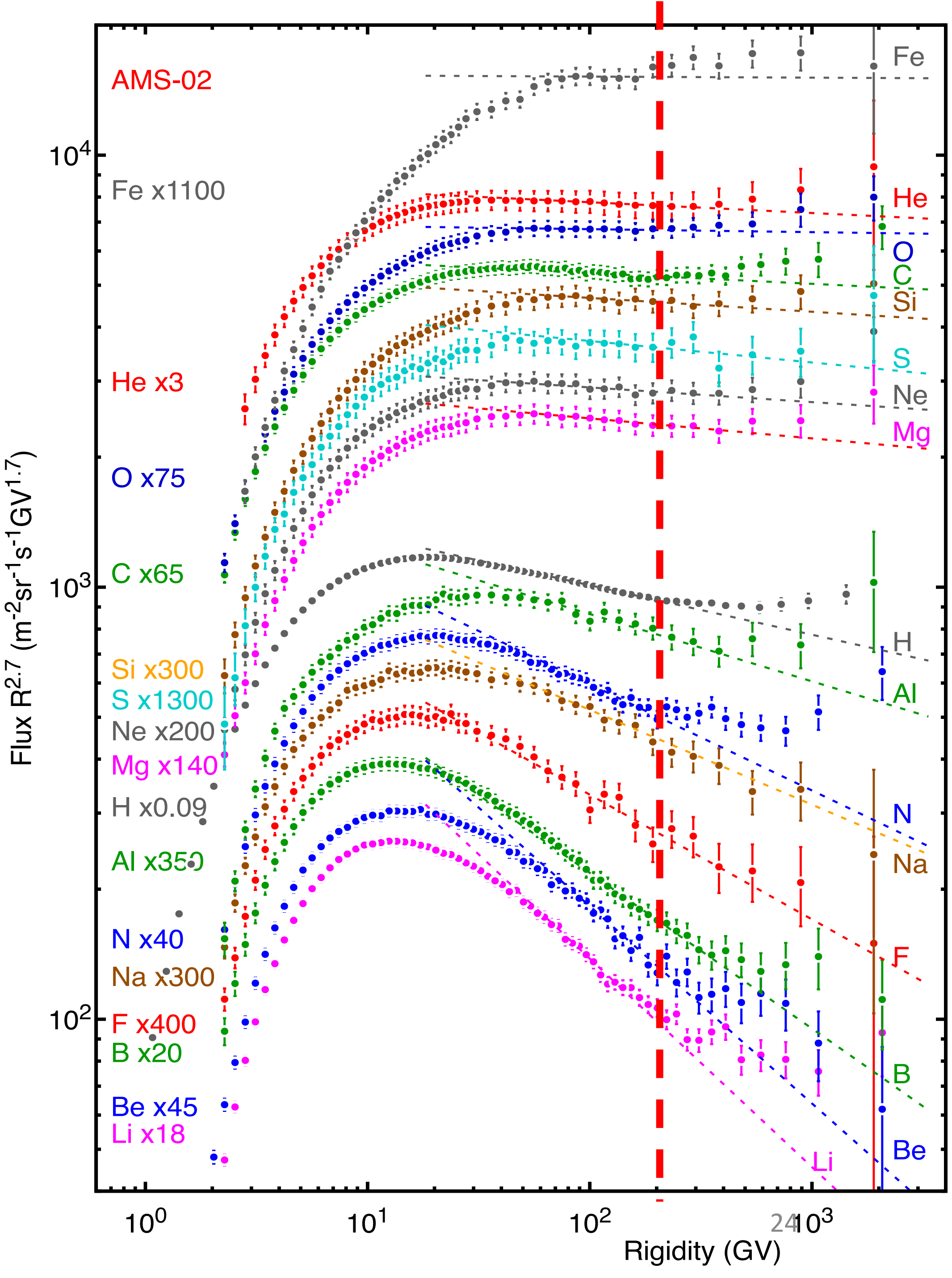




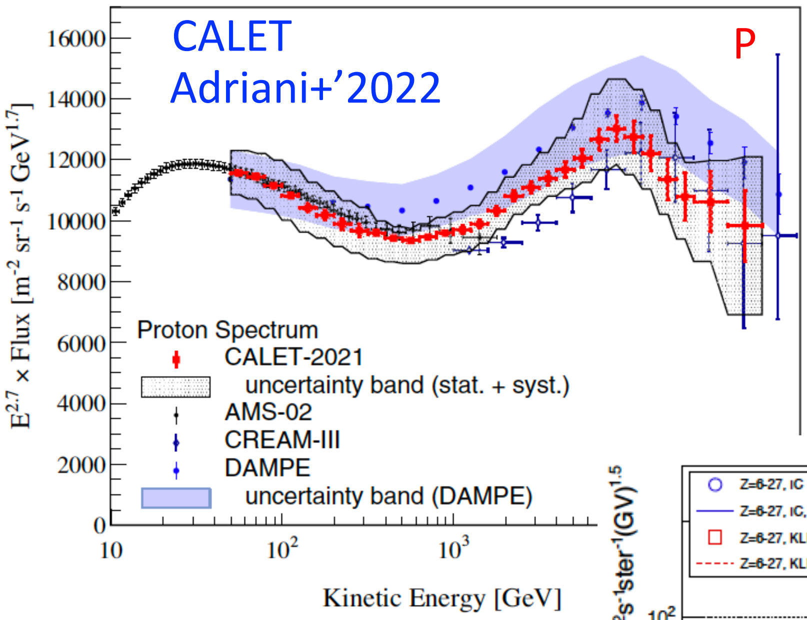


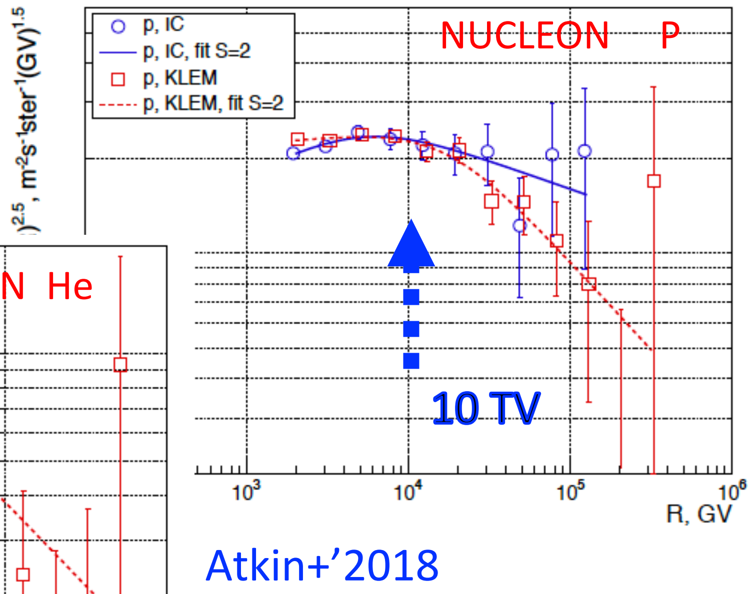
AMS-02 measurements of the break

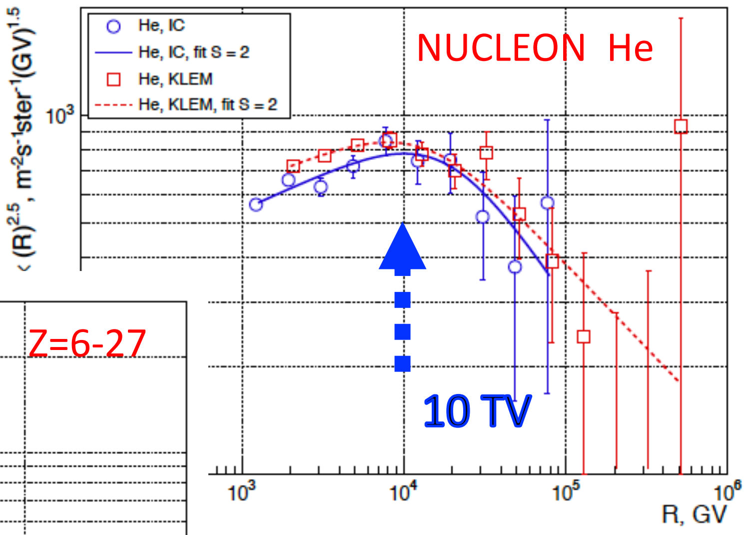
- It is most clearly seen in AMS-02 data, which cover this range
- CR species are sorted by approximate order of their spectral index in 50-200 GV range
- Fe has the flattest spectrum followed by He, O, C, and then Si, S, Ne, Mg
- The steeper spectra are observed in H, Al, N, Na, F, B, Be, and the steepest is Li (partly tertiary)
- Fluorine is flatter than Boron, and may indicate a different origin or a presence of the primary component

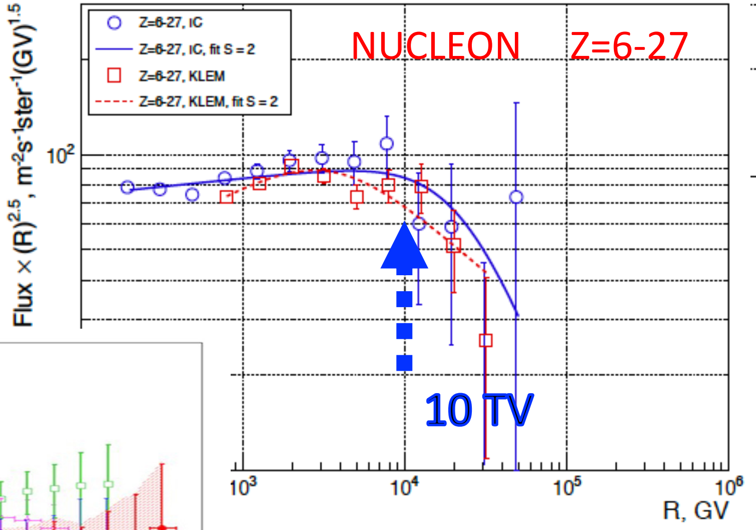


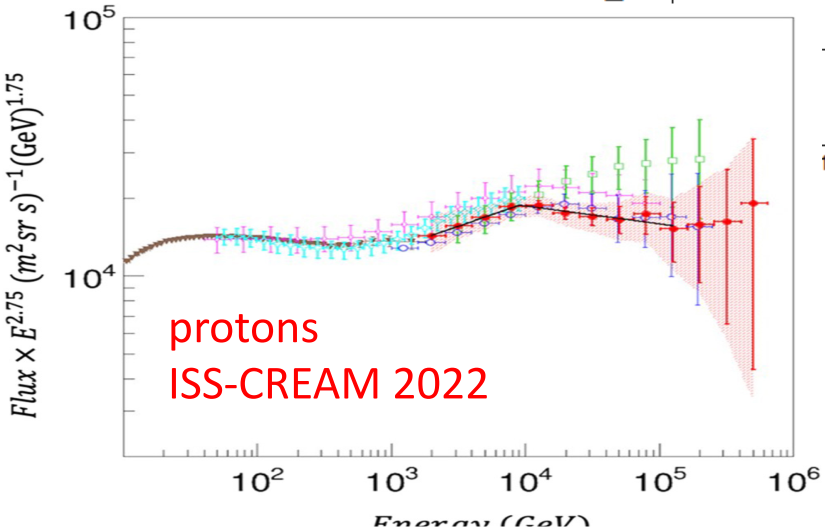
Yet another break at 10 TV

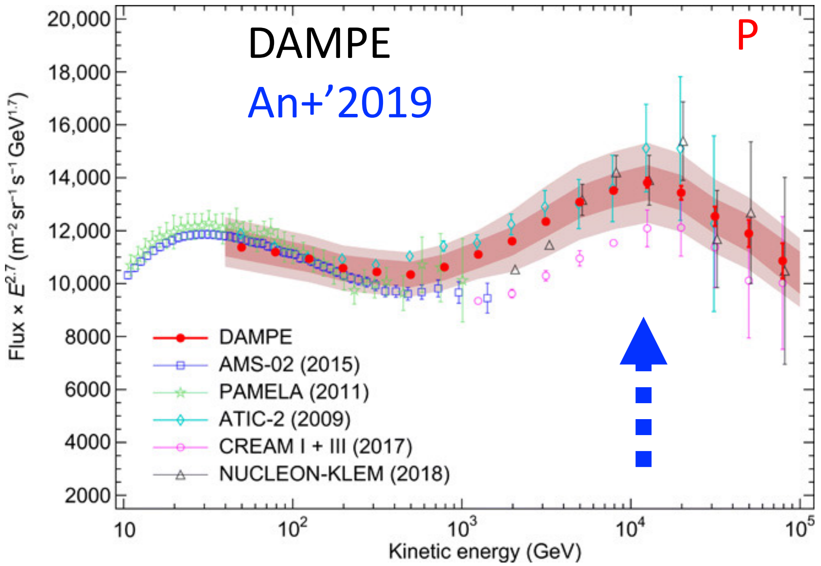






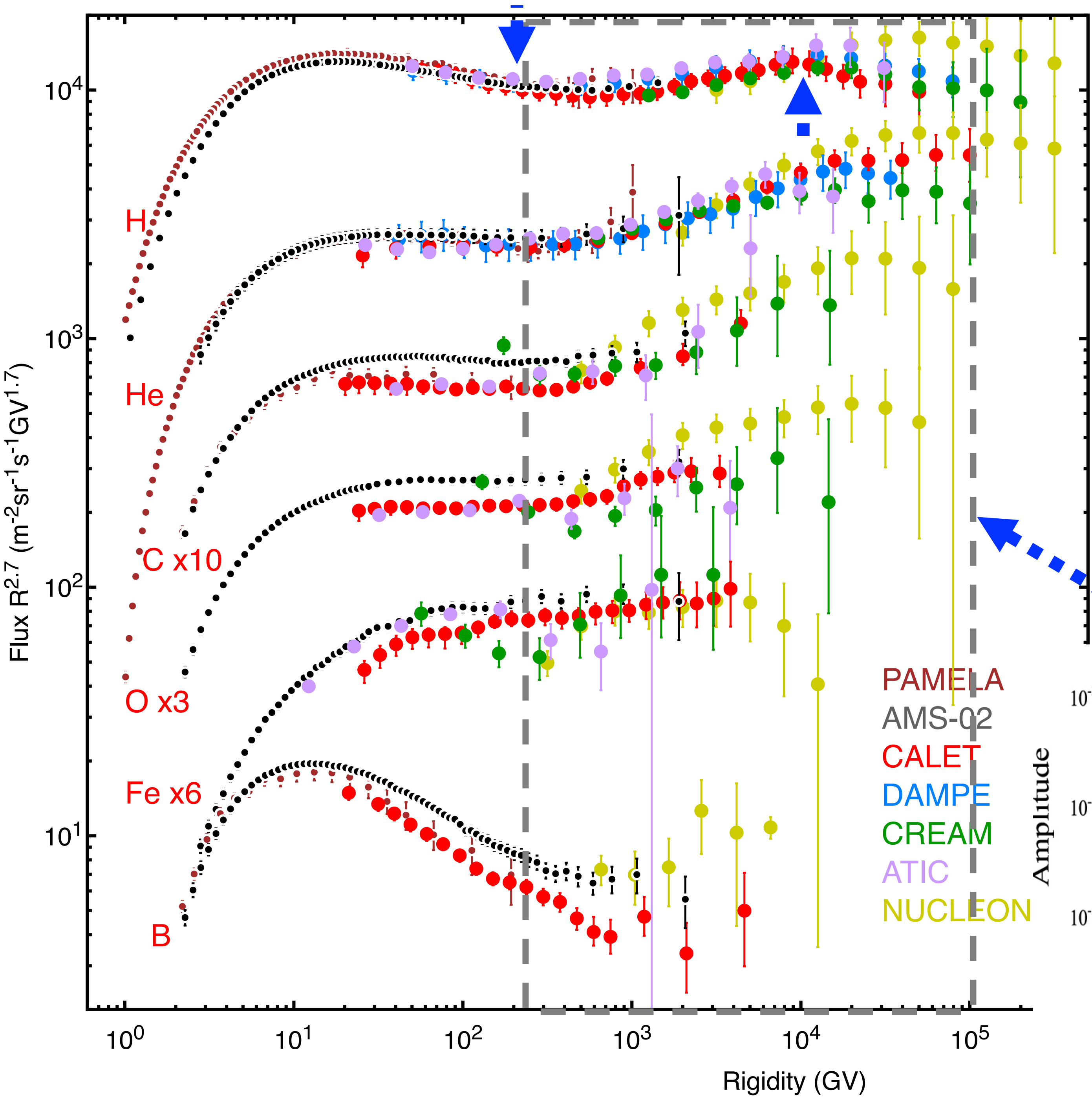




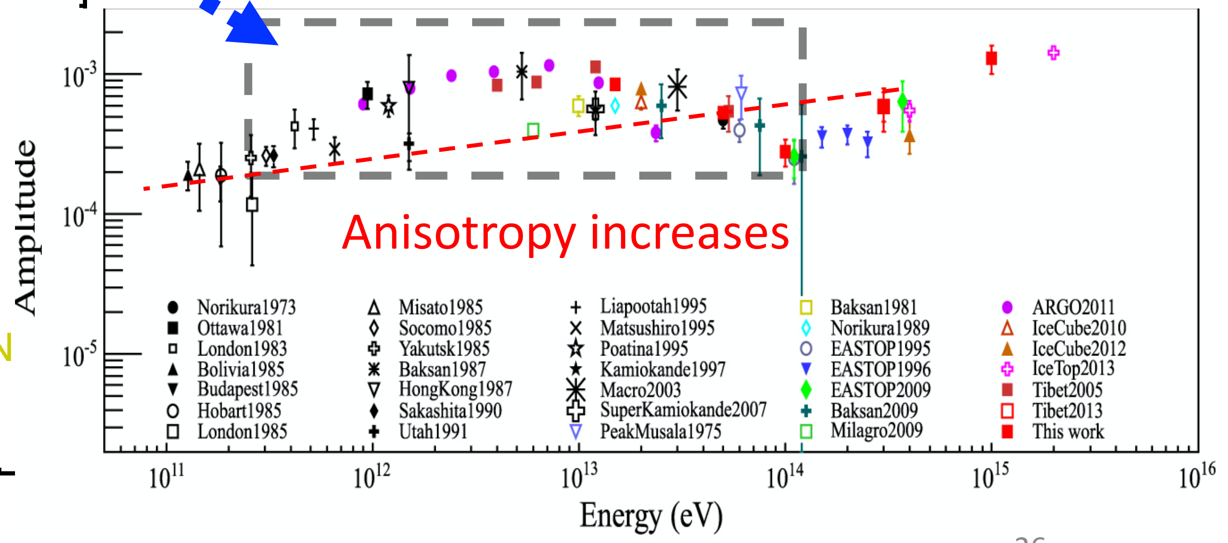


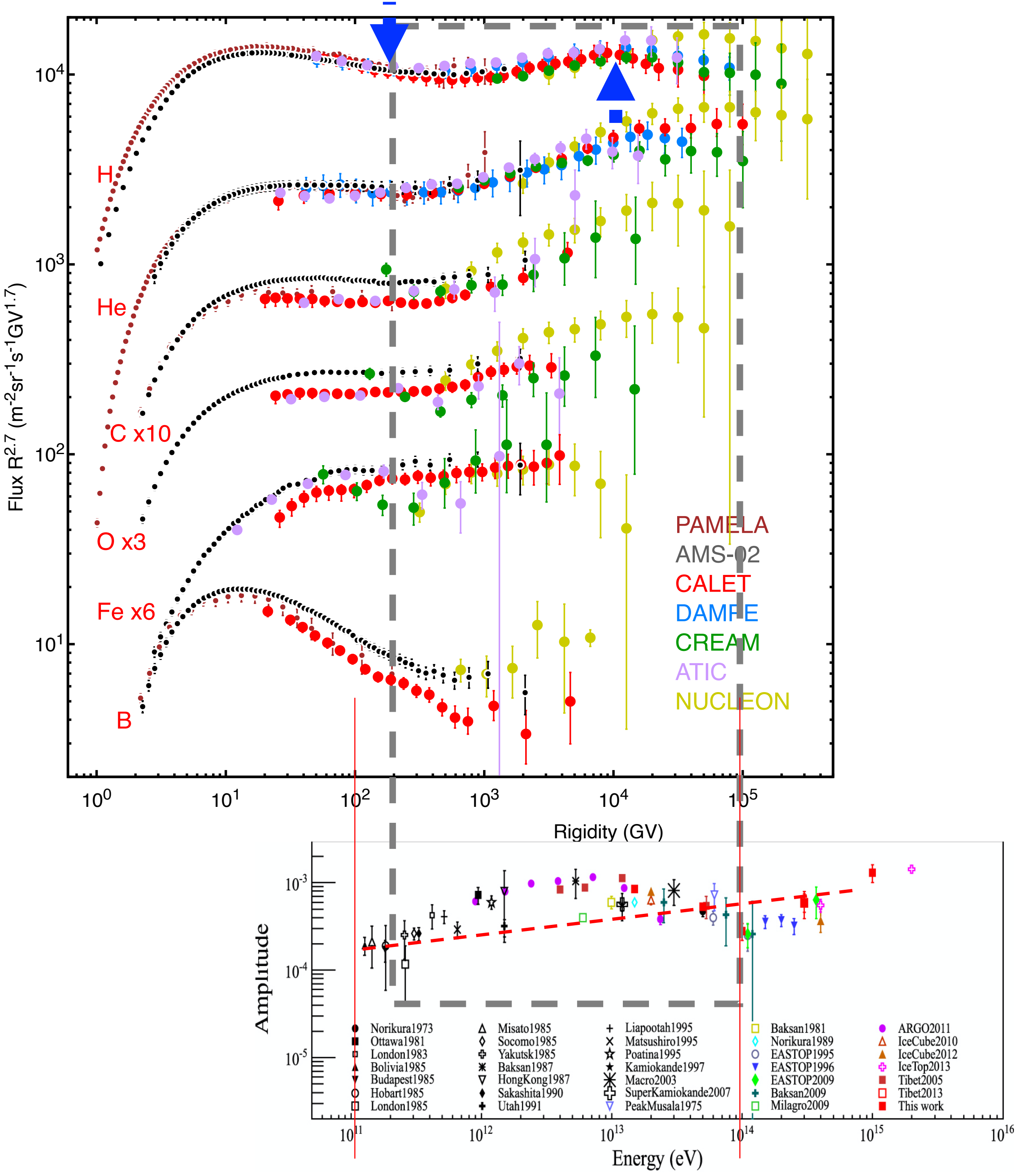
- Was also observed by ATIC, but no claim was made

TeV bump



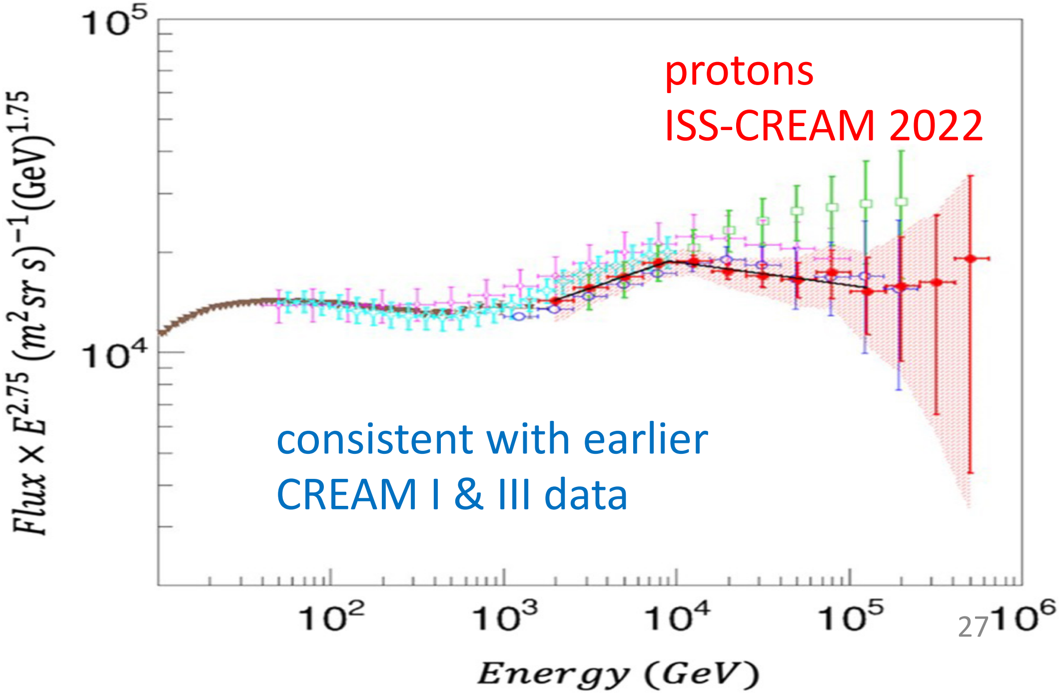
- The TeV bump is now confirmed by several instruments
- The two breaks, at ~0.2 TV and 10 TV, plus anisotropy increase indicate a single structure rather than two separate features
- Protons are dominant: Rigidity ≈ Kinetic Energy per Particle (in TeV range)





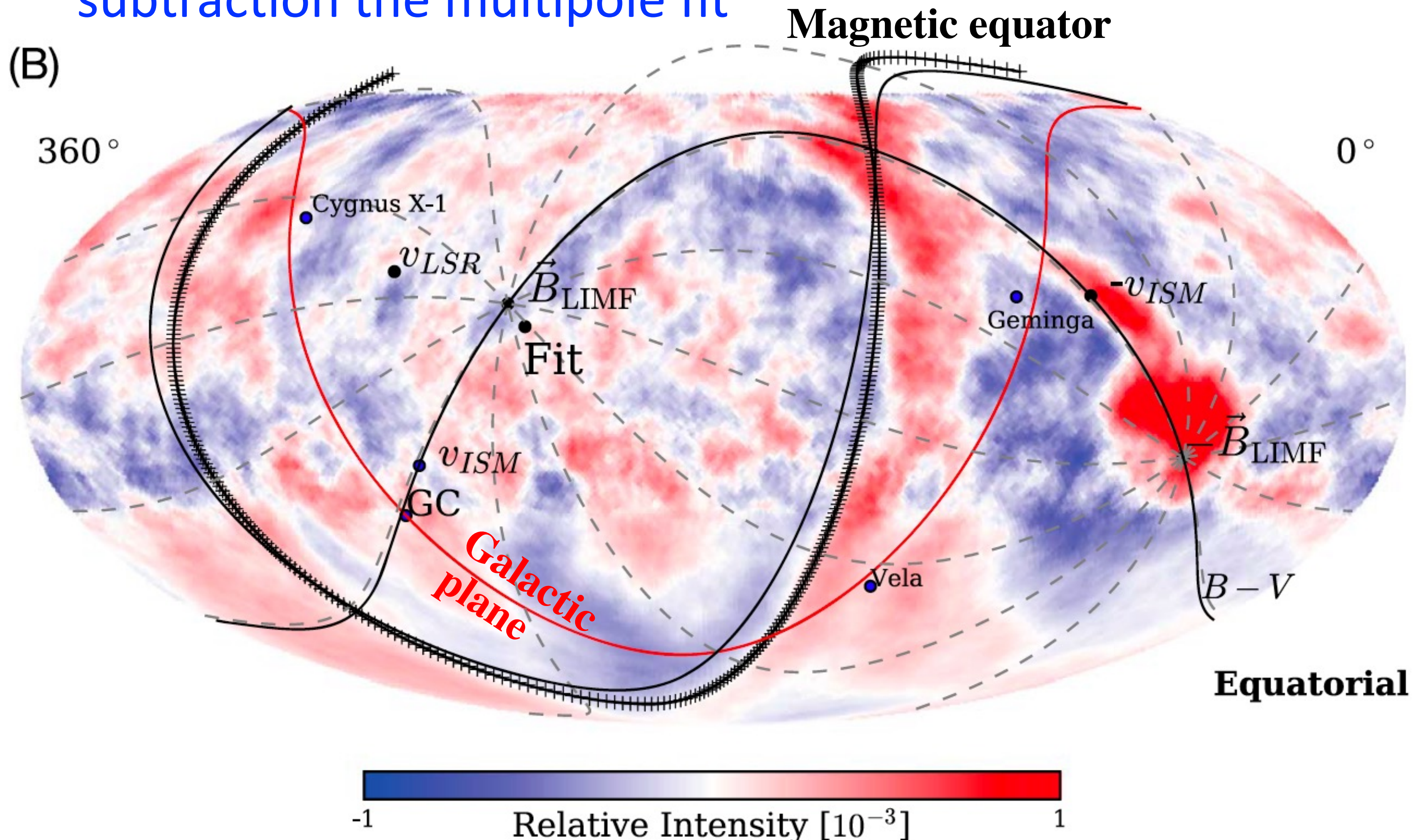
TeV bump

- The TeV bump is now confirmed by several instruments
- The two breaks, at ~0.2 TV and 10 TV, plus anisotropy increase indicate a single structure rather than two separate features
- Protons are dominant: Rigidity ≈ Kinetic Energy per Particle (in TeV range)



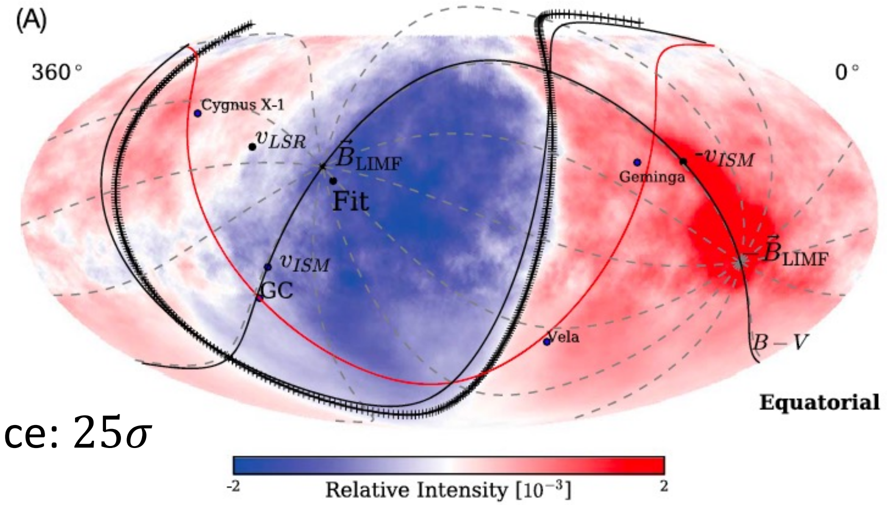
Small-scale anisotropy @ 10 TeV & local B field

Relative intensity after subtraction the multipole fit



- Very sharp jump in anisotropy across the magnetic equator – a hint at the proximity of the source
- The direction to the source coincides with the Galactic anticenter, the direction of the local B-field, and about 45° off the "tail" of the heliosphere

Relative intensity



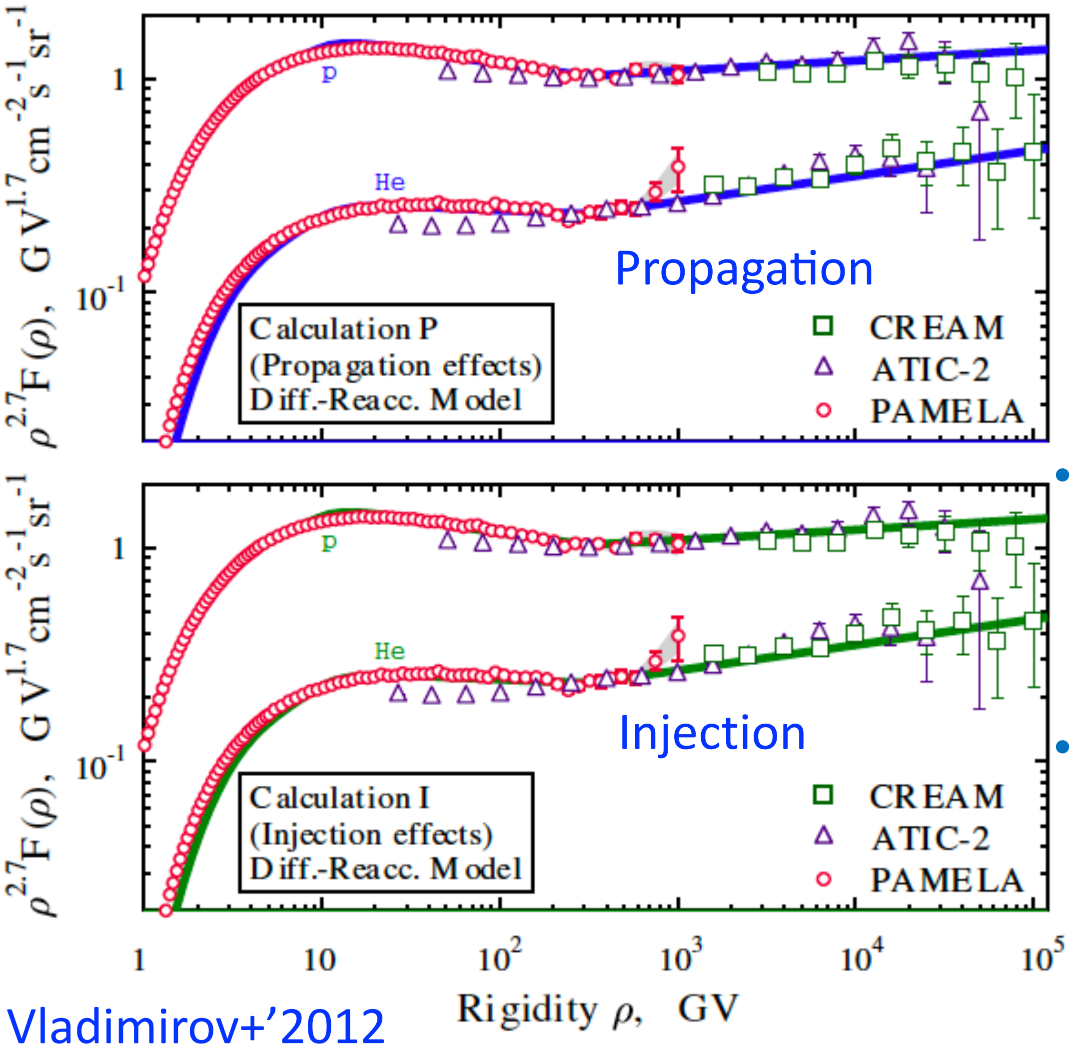
IceCube+HAWC
Abeysekara+2019

See a presentation by Malkov, CRD4-05

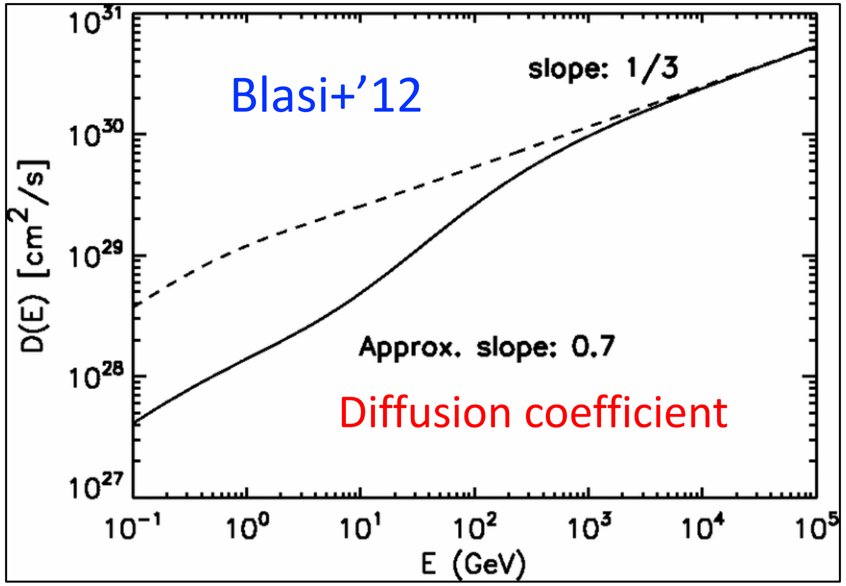
Significance: 25σ

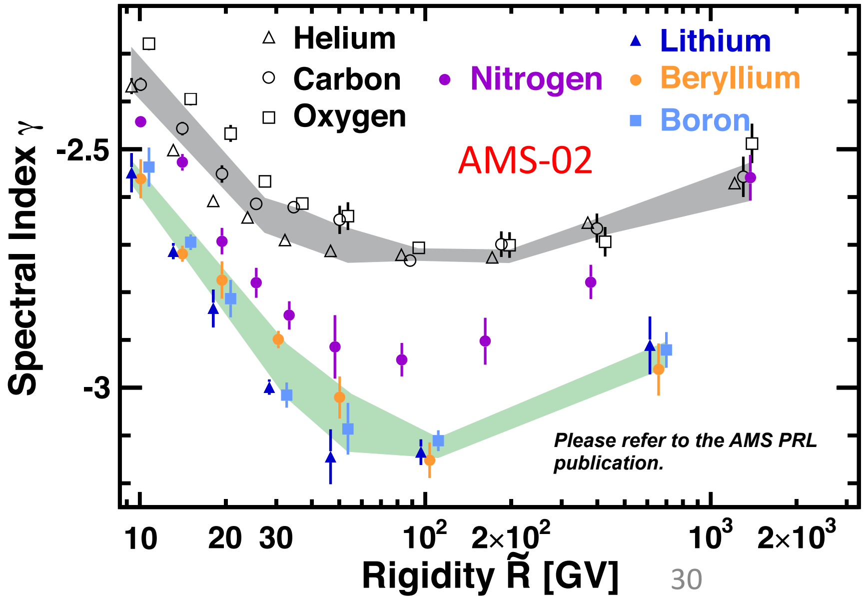
Models of the TeV bump

Early hypotheses of the origin of ~200 GV break



- Vladimirov+2012 proposed 4 distinct scenarios: Propagation, Injection, Local Source at low or high energies. Propagation scenario (break in the diffusion coeff.) was a favorite
- Blasi+12 proposed physical motivation for the break in the diffusion coefficient
- The diffusion coeff. scenario reproduced the observed difference between spectra of primary and secondary species

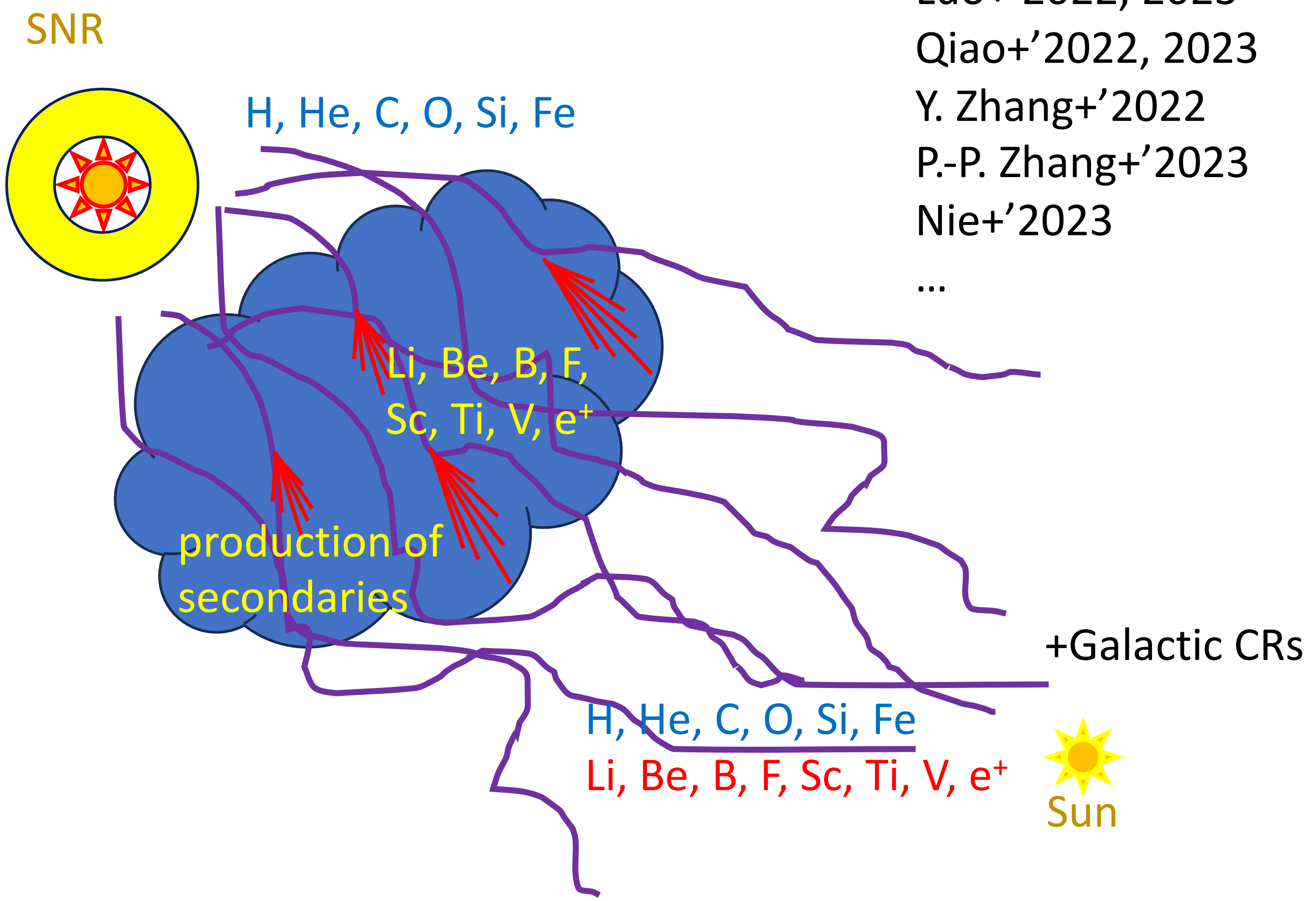




Local SNR + gas cloud models

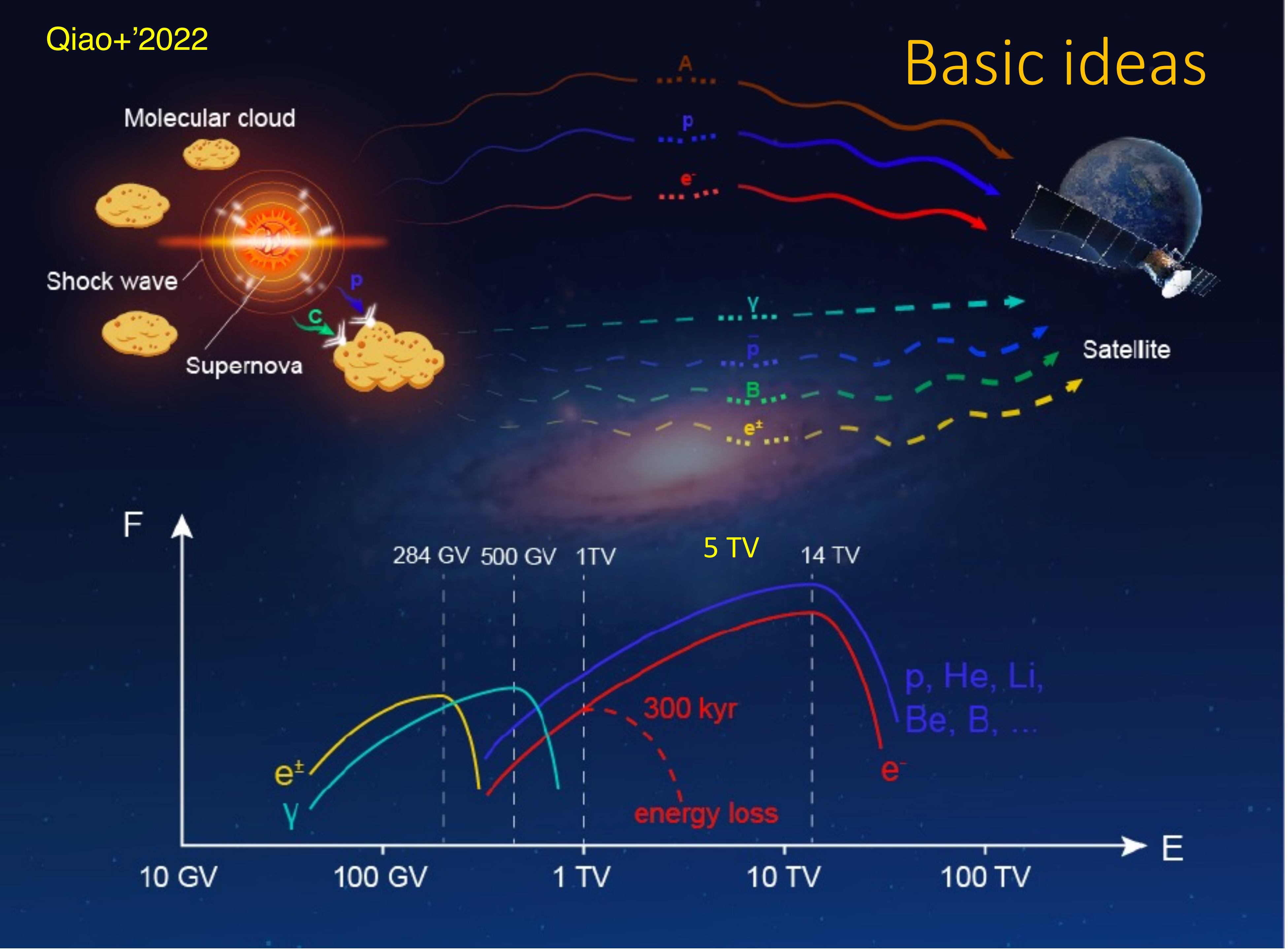
Claimed to reproduce all observed features in CR nuclei, $e^{\pm}$, pbars

Yang & Aharonian'2019
Liu+'2019
Fang+'2021
Fornieri+'2021
Yuan+'2021
Zhao+'2022, 2022
Luo+'2022, 2023
Qiao+'2022, 2023
Y. Zhang+'2022
P.-P. Zhang+'2023
Nie+'2023
…



- Many models are speculating on the idea of a local SNR (~300 pc, Geminga SNR)
- Consider a combination of the Galactic CRs with concave spectra + sharp peak from the local SNR
- Secondary species are produced in gas cloud(s)
- Propose to reproduce antiprotons, electrons, positrons
- Proposed to reproduce CR anisotropy

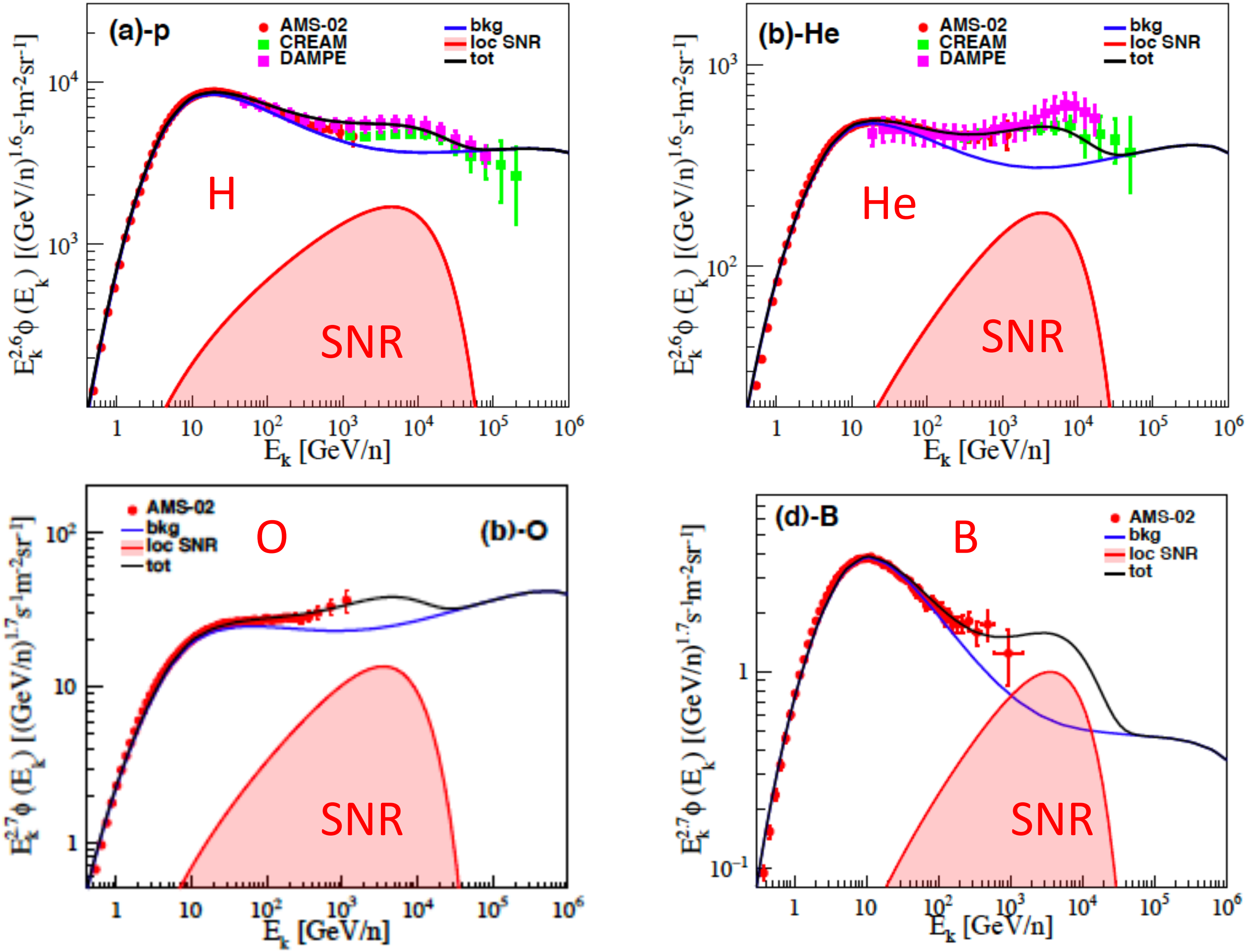
Basic ideas

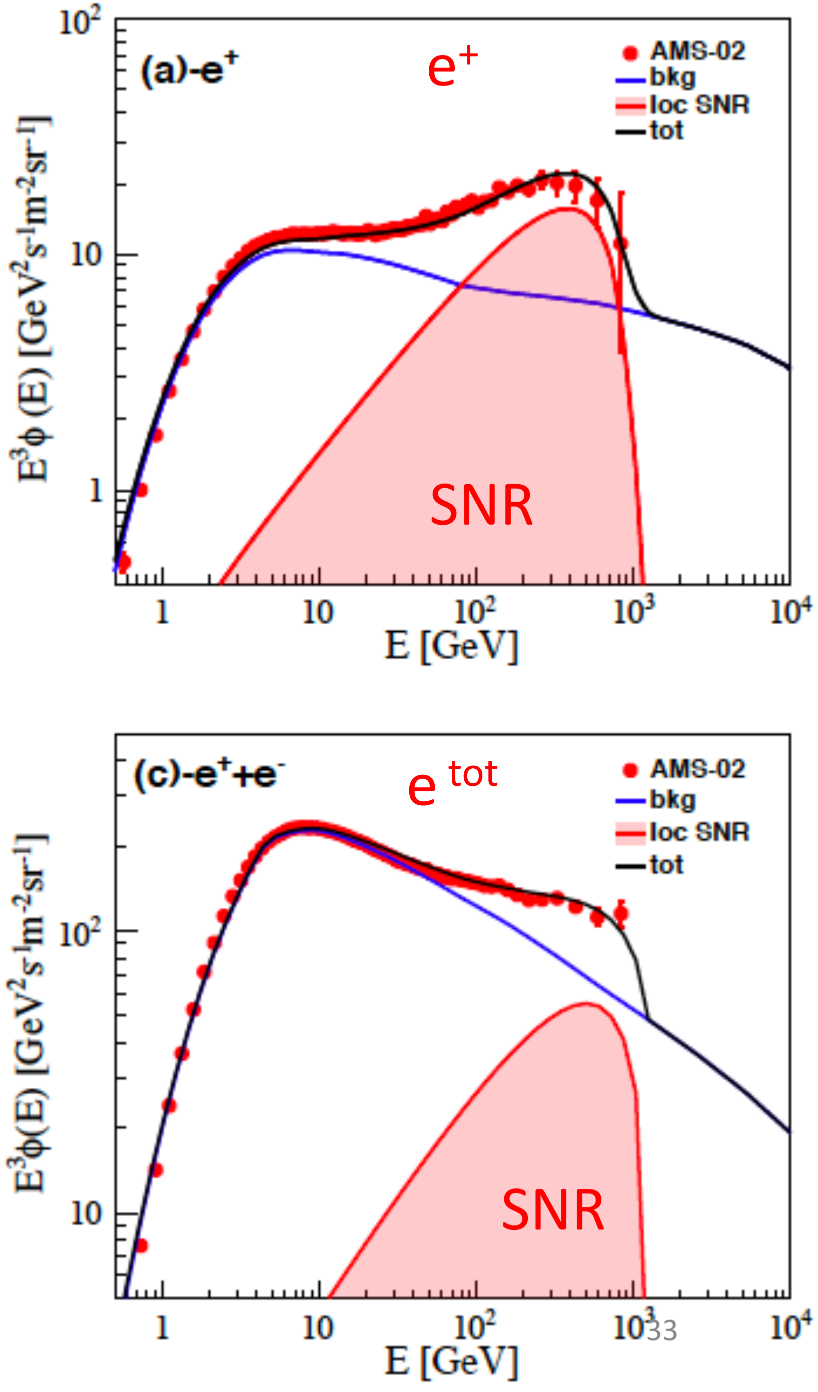


- SNR accelerates particles (primary nuclei, e^-) with a cutoff at 5 TV
- They produce secondaries (LiBeB, $e^{\pm}$) in the cloud
- Primary e^- loose energy to make a break at 1 TV
- $e^{\pm}$ are produced with a cutoff at 300 GV (5 TV cutoff in protons)
- Proposed source Geminga SNR, age 330 kyr at 330 pc

Example spectra in the SNR model

Red area shows SNR contribution





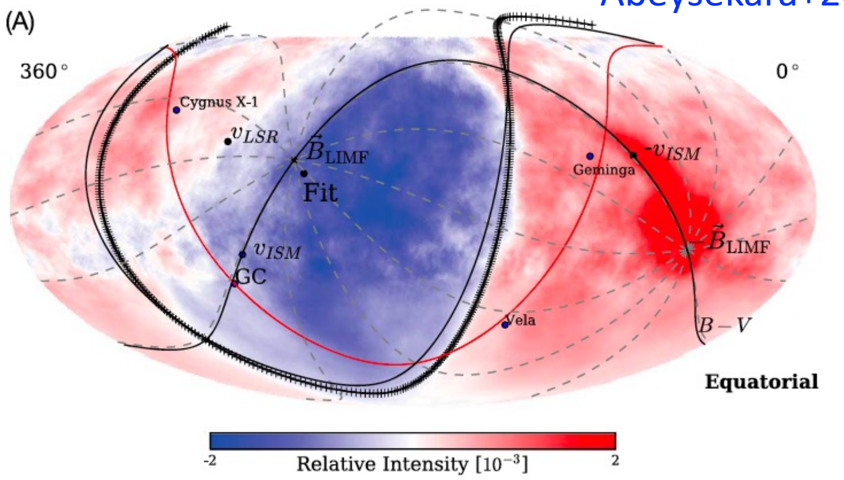
Some issues with local SNR model

- A lot of fine tuning
- To make a room for the SNR component, one has to make a concave spectrum of the Galactic CRs. I.e. one has to make a dip in the Galactic CR spectrum and a peak in SNR component at the same energy simultaneously
- Used a modified Tomassetti's (2015) two-halo scenario
- 8 transport parameters + 6 spectral parameters + individual normalization for Galactic (28) and SNR (28) components for each species + 7 parameters for primary e^- + gas cloud grammage ≈ 45-50 free parameters (not counting Galactic CR normalizations)
- Cannot reproduce the sharp jump in anisotropy along the magnetic equator

Diffusion length and anisotropy

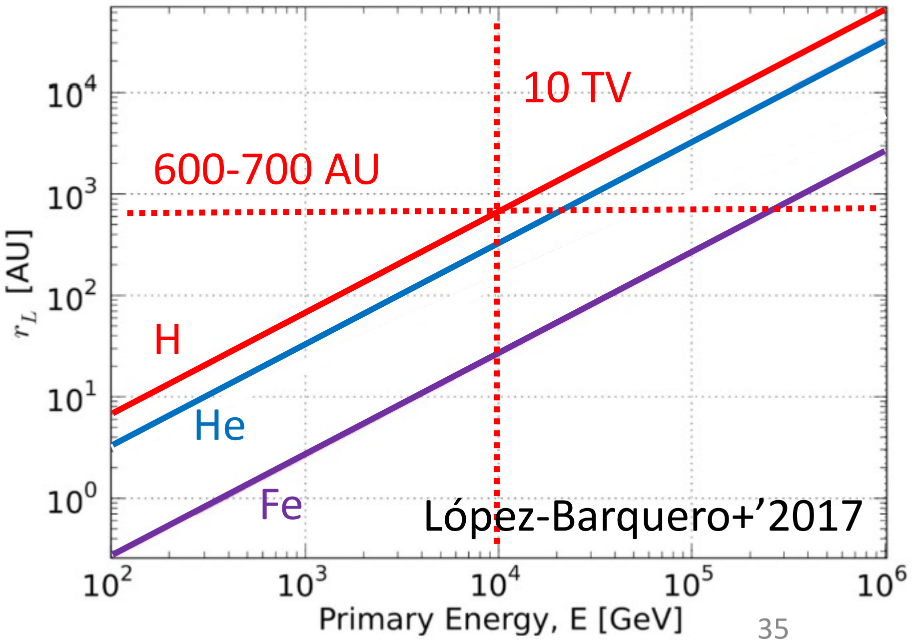
- The gyroradius of a particle with rigidity 10 TV in the interstellar 3 μG magnetic field is 600-700 AU ~ (3-4) $\times 10^{-3}$ pc
- Geminga SNR is at ~330 pc
- This is ~10^5 mean free paths – there is no way to see such sharp anisotropy at such a distance
- The observed anisotropy exhibits very sharp break at the magnetic equator
- All global models of the TV bump have this problem
- Conclusion: the source should be close

IceCube+HAWC
Abeysekara+2019



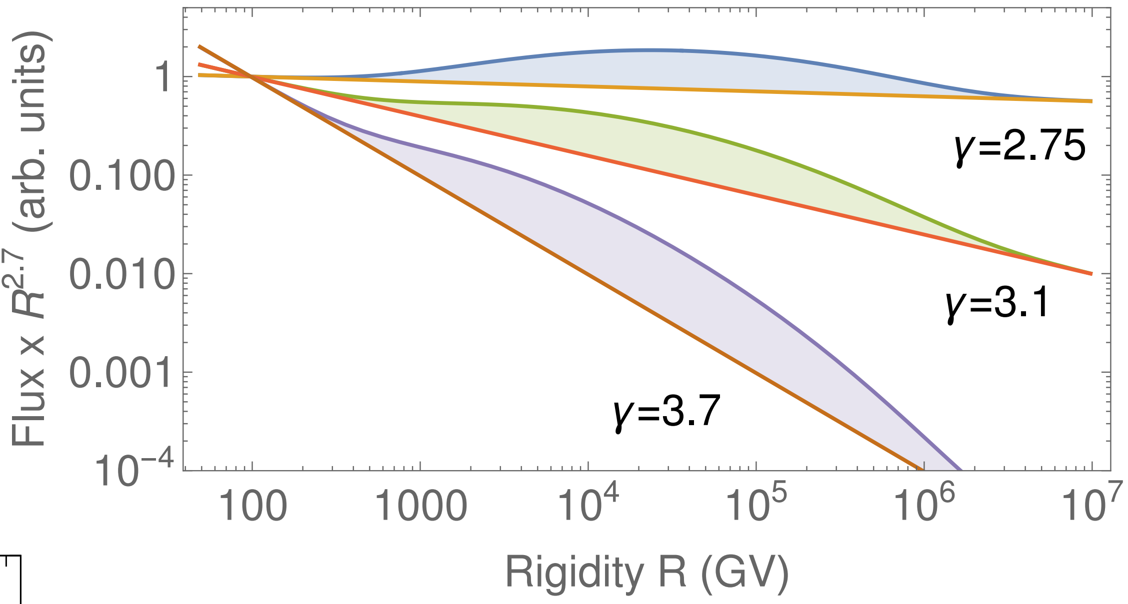
Relative intensity

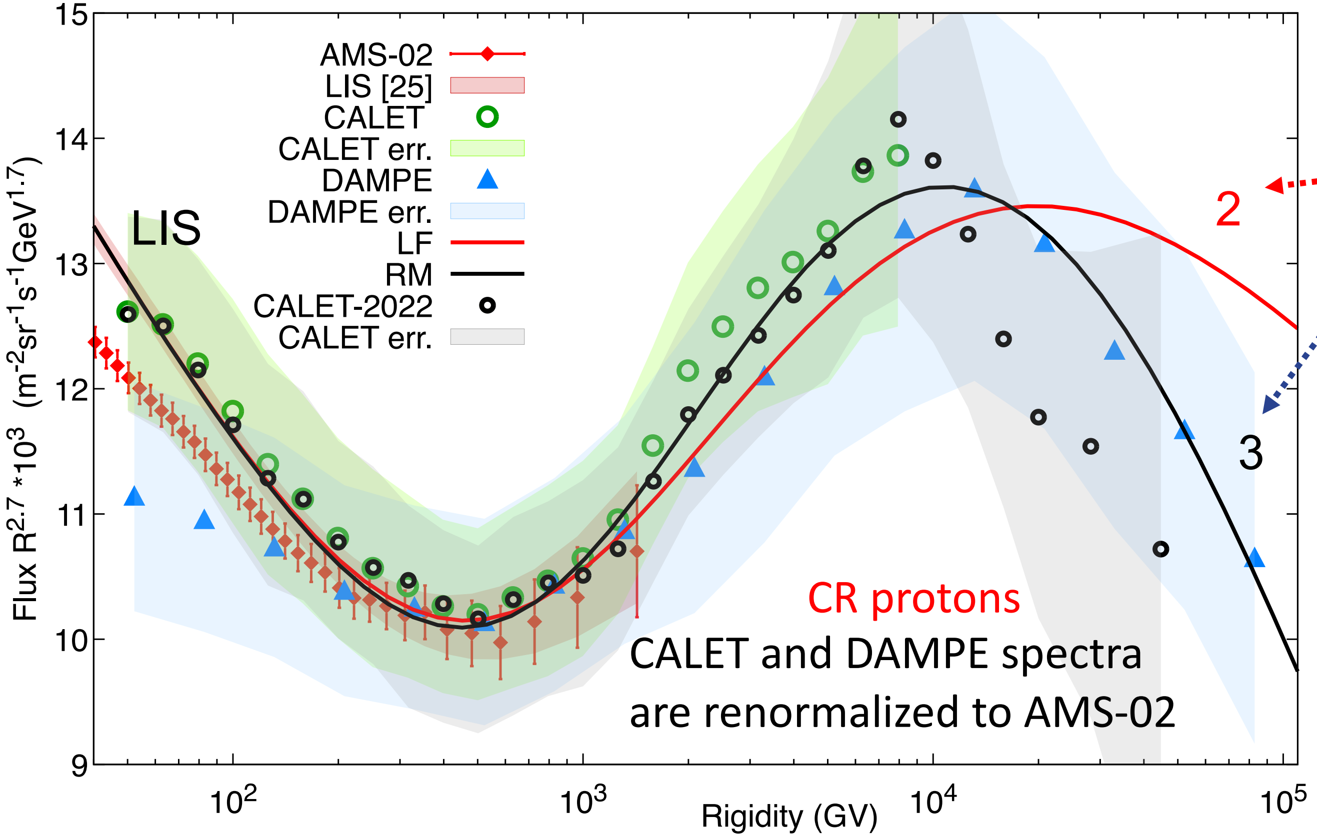
Gyroradius in B=3 μG



Reacceleration bump

- ✧ Moderate reacceleration, Mach number ~1.5
- ✧ Low-energy particles do not reach us as they are convected downstream by the ISM flow
- ✧ High-energy particles lost from the flux tube





- ✧ Only 2 (3) free parameters – fixed from CR proton spectrum
- ✧ Use local interstellar spectrum (LIS) below the bump
- ✧ The steeper the spectrum of ambient particles – that larger the bump

Malkov & IVM'2021, 2022
see a presentation by Malkov, CRD4-05

Parameters

Table 1. Model parameters and fit results for the proton spectrum.

Parameter (St. err. %)	R_0(GV)	R_L(GV)	q	$K=(\gamma+2)/(q-\gamma)$	$\chi^2_{\min}$/dof	dof
Realistic Model (RM)	5878 (3.5%)	2.24×10^5 (28%)	4.2	3.59 (4.9%)	0.10	76-3
Loss-Free Model (LF)	4795 (3.2%)	∞	4.7	2.58 (2.9%)	0.19	76-2

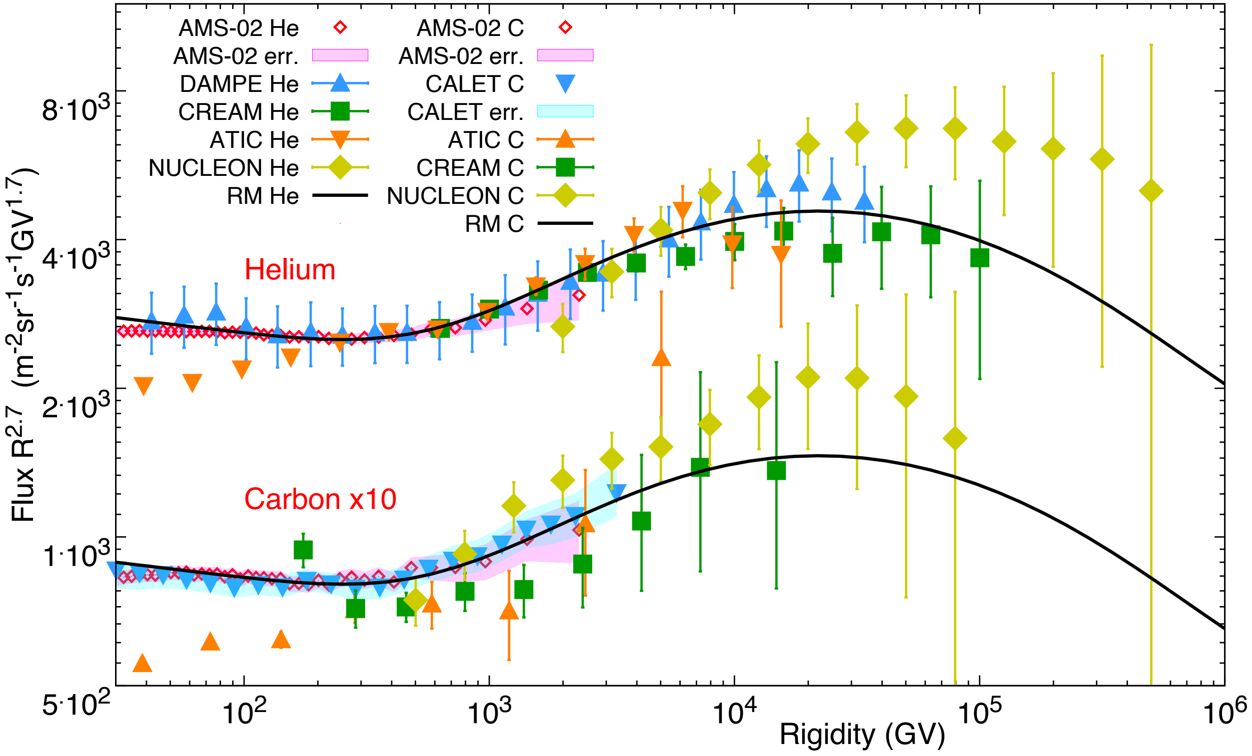
q=3r/(r-1)

$$f_s(R) = A_s R^{-\gamma_s}\left\{1+\frac{\gamma_s+2}{q-\gamma_s}\exp\left[-\sqrt{\frac{R_0}{R}}-\sqrt{\frac{R}{R_L}}\right]\right\}$$

○ - parameters fixed from CR proton spectrum

Table 2. Input parameters for CR species derived from their LIS (Boschini et al. 2020b).

Parameters	protons	helium	boron	carbon
A_s (m^{-2} s^{-1} sr^{-1} GV^{-1})	2.32×10^4	3410	79	109
γ_s	2.85	2.76	3.1	2.76



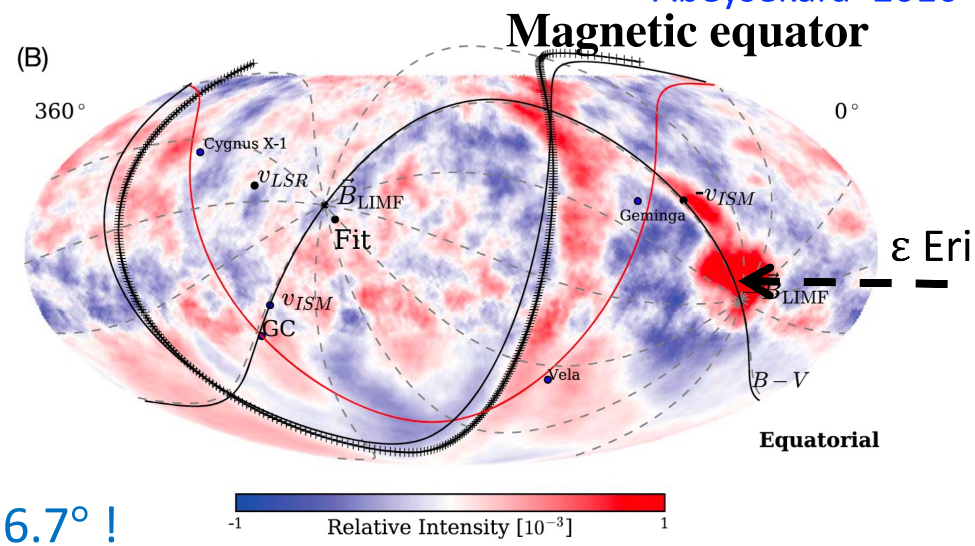
Malkov & IVM'2021, 2022

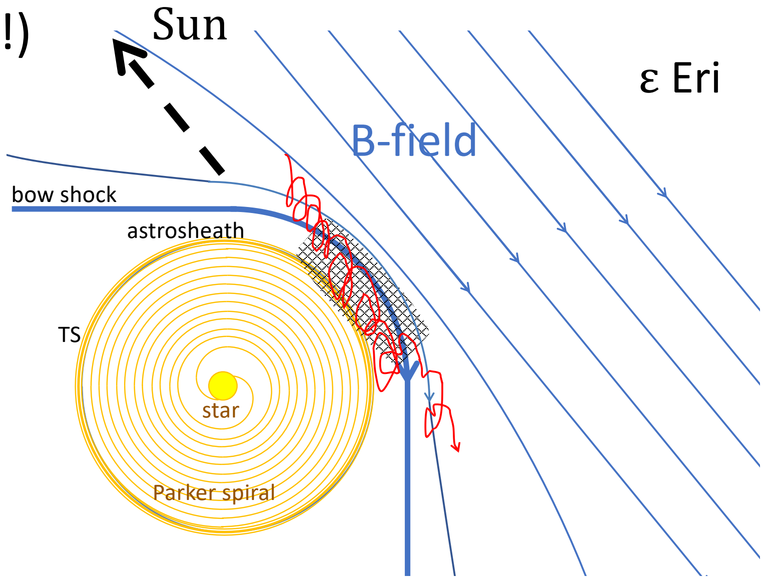
- ✧ A_s, γ_s – fixed normalization and spectral index of the LIS below the bump (individual for each species)
- ✧ LIS for H-Ni are given in Boschini+'2020
- ✧ Model reproduces spectra of ALL CR species with only 2 (3) parameters fixed from the proton spectrum

Epsilon Eridani and passing stars

- Distance-shock-size relation: $\zeta_{obs}(pc) \sim 100\sqrt{L_\perp(pc)}$; for sufficiently large bow shocks, $L_\perp = 10^{-3}$-10^{-2} pc, then the distance is ζ_{obs} = 3-10 pc (Malkov & IVM'2021, 2022)
- Any local shock with a small Mach number ~1.5
- ε Eri: K2 dwarf (5 000 K), 0.82 $M_\odot$, 0.74 $R_\odot$ (preferred)
- Distance – 3.2 pc
- Speed – 20 km/s (a bit small, but has a strong stellar wind)
- Mass loss rate – 30-1500 $\dot{M}_\odot$!
- Well aligned with the direction of the local magnetic field – within 6.7° !
- Huge astrosphere – 8000 au, 47' as seen from Earth (larger than the Moon!)
- ε Indi: triplet K4.5V (0.77 $M_\odot$) + T1.5 (0.072 $M_\odot$) + T6 (0.067 $M_\odot$)
- Distance – 3.6 pc
- Speed – 40.4 km/s (radial)
- Scholz's Star: duplet M9.5 (0.095 $M_\odot$) + T5.5 (0.063 $M_\odot$)
- Distance – 6.8 pc
- Speed – 82.4 km/s (radial)

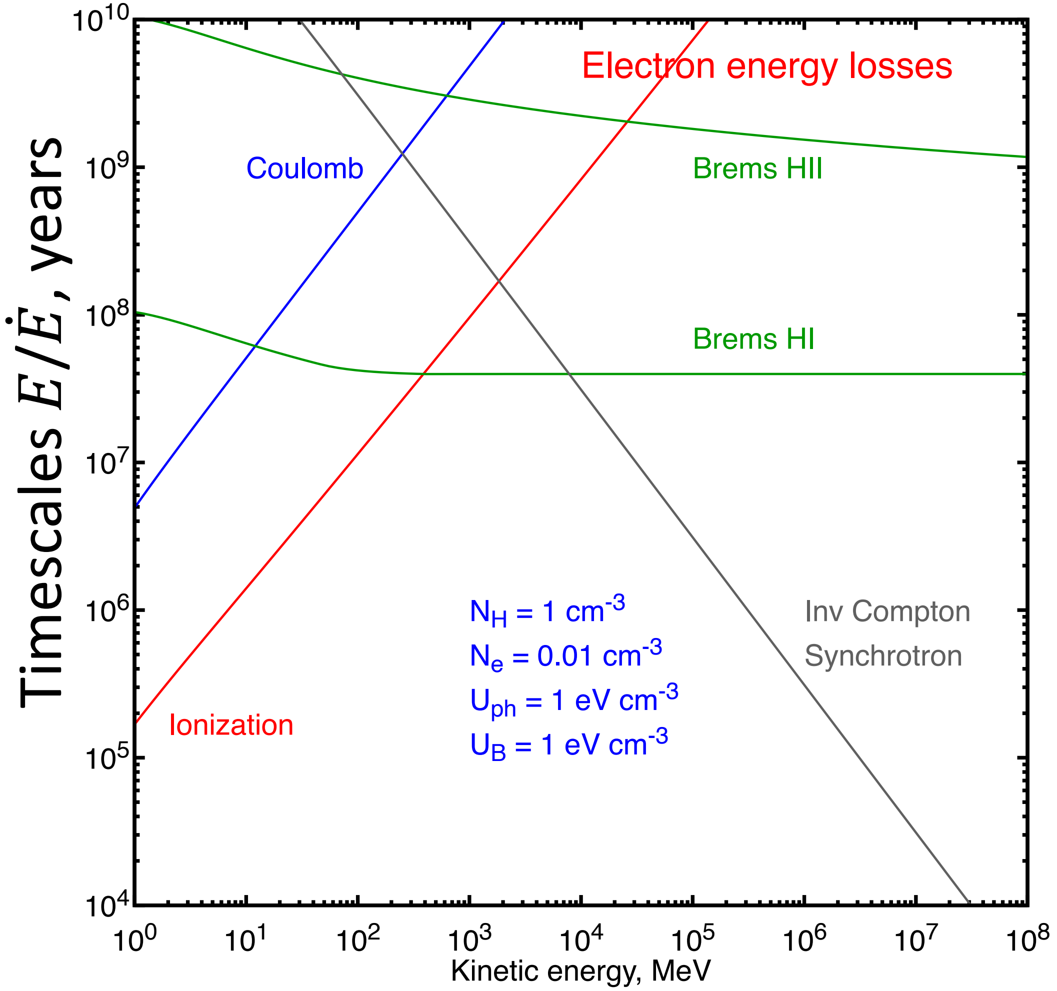
IceCube+HAWC Abeysekara+2016

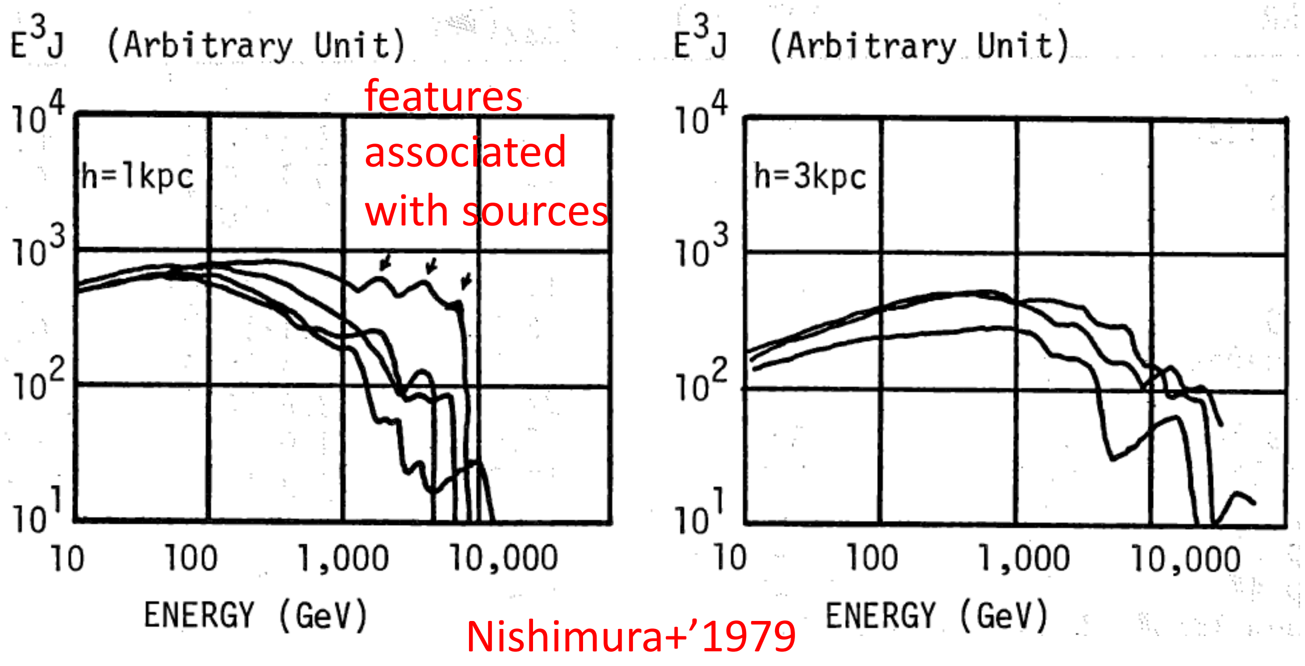




Cosmic ray electrons

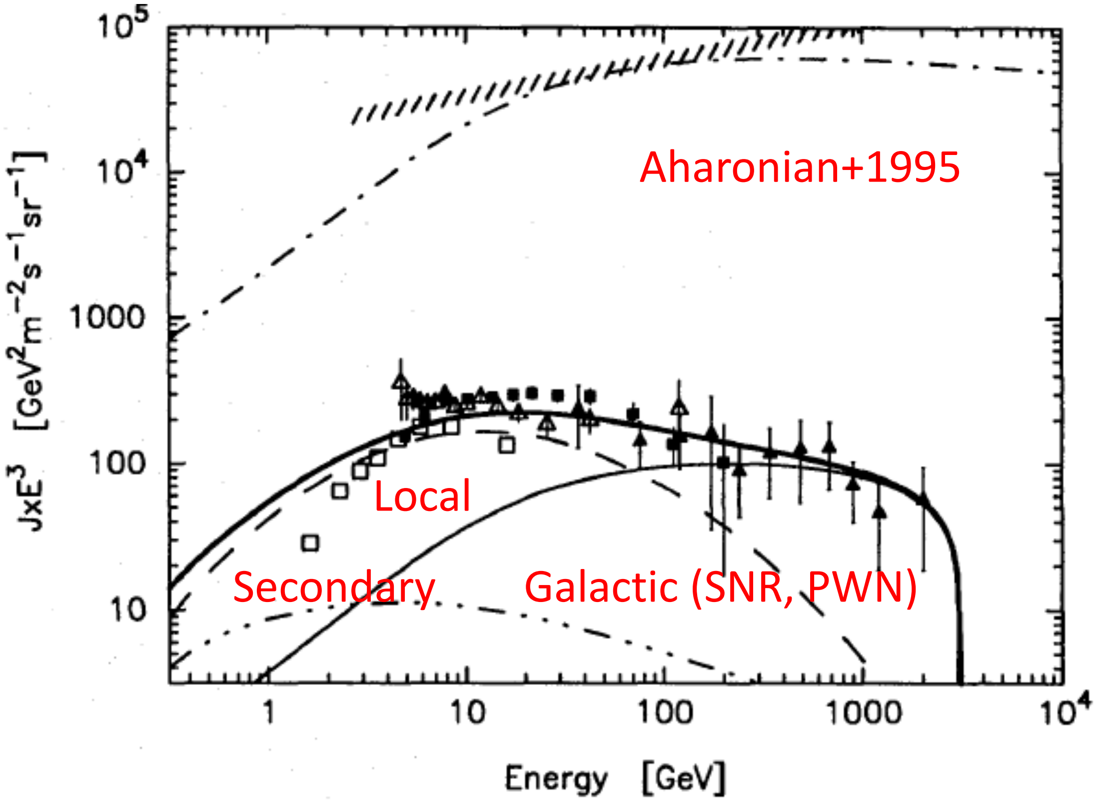
CR electrons

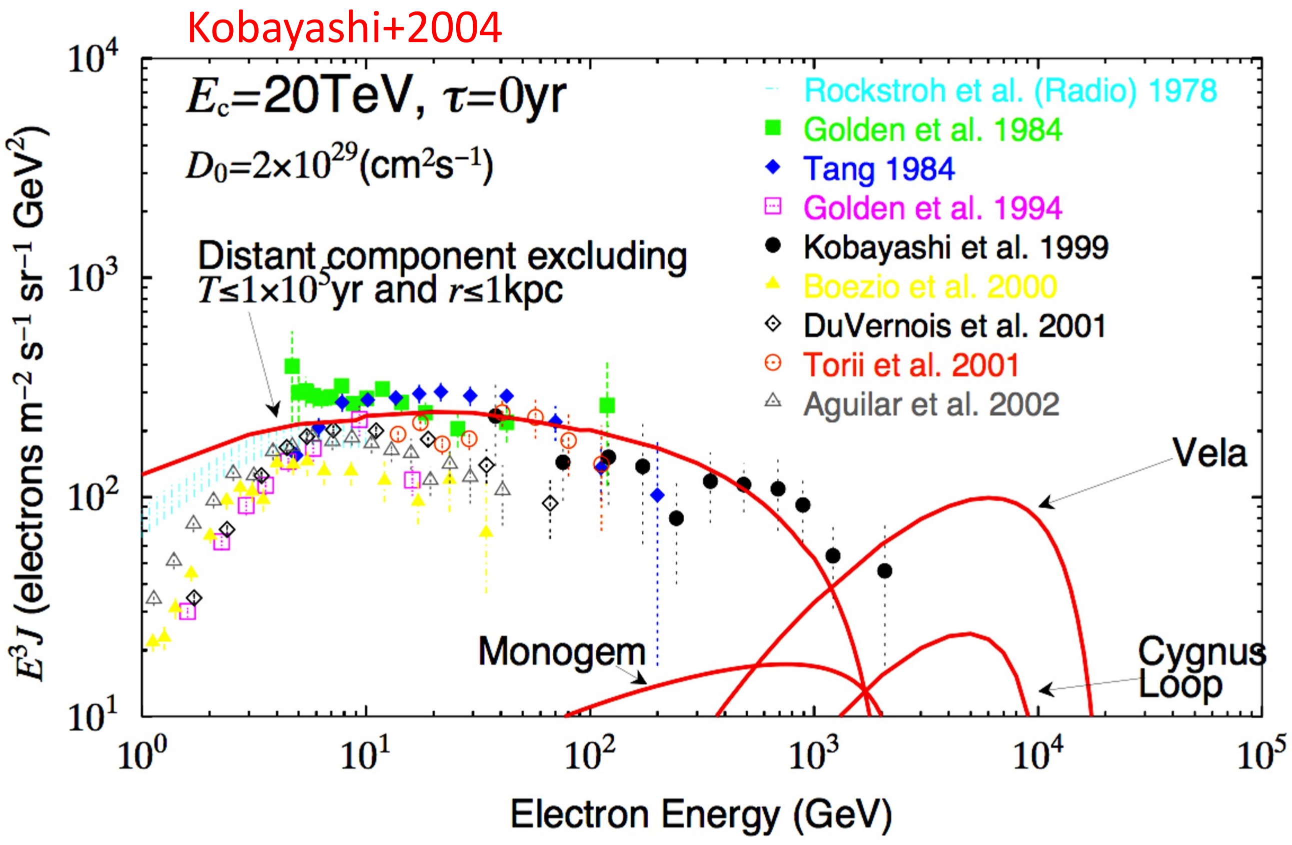




- Electrons in CRs are subject to severe energy losses at all energies. The fastest losses are at low (ionization) and high (inverse Compton & synchrotron) energies.
- Therefore, the sources of VHE electrons should be close and relatively young
- Perhaps Nishimura+'1979 was first to propose that "the electron spectrum in TeV region would deviate from smooth power law behavior due to small number of sources which are capable of contributing to the observed flux… several bumps would be observed in the spectrum correlating to each source…"

CR electrons

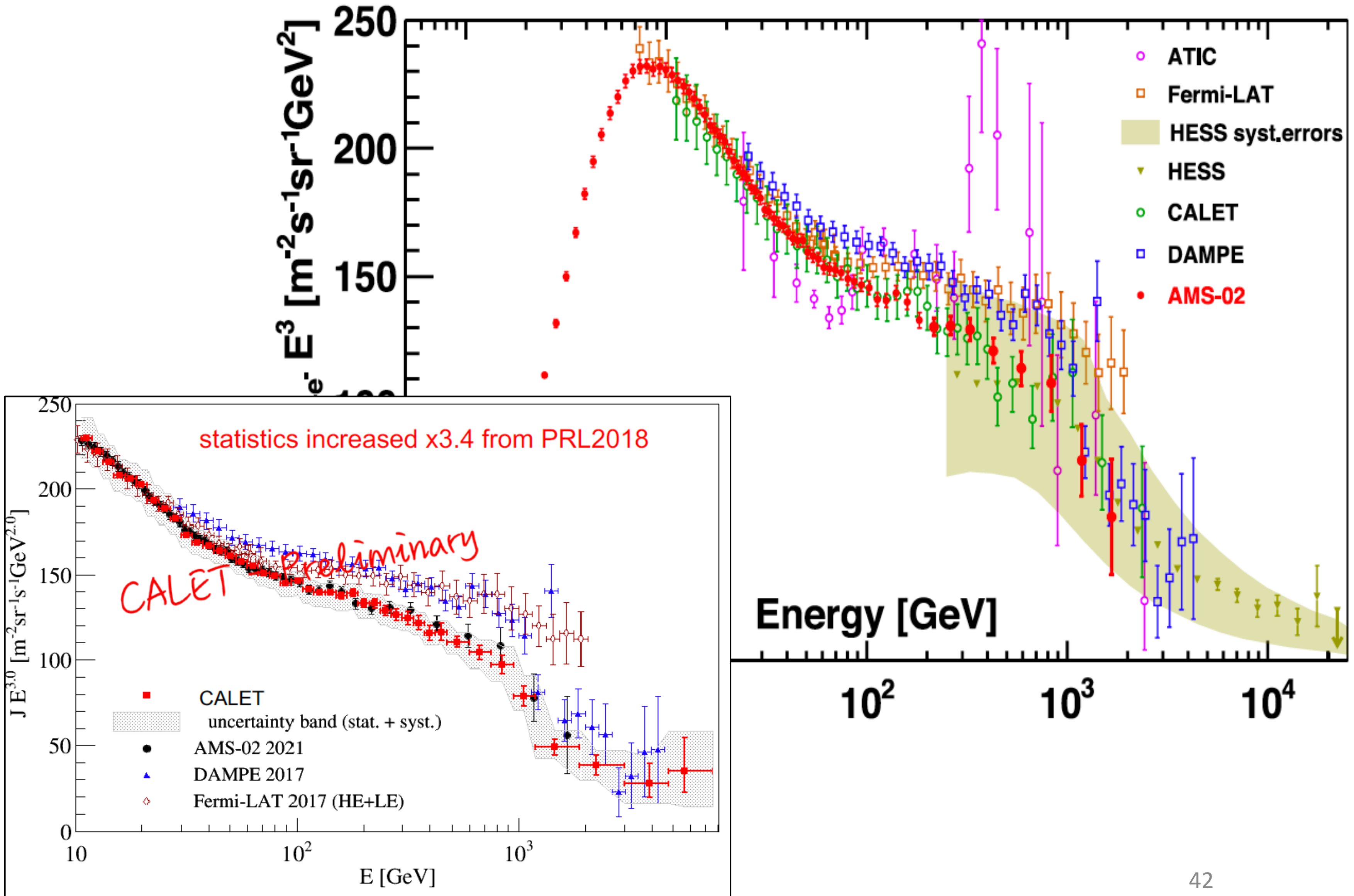




- Early papers show possible contribution of local sources
- Follow up papers discussed the origin of the observed spectrum and simulated contribution of the local sources beyond 1 TeV

Precise measurement of Electrons ($e^+ + e^-$)

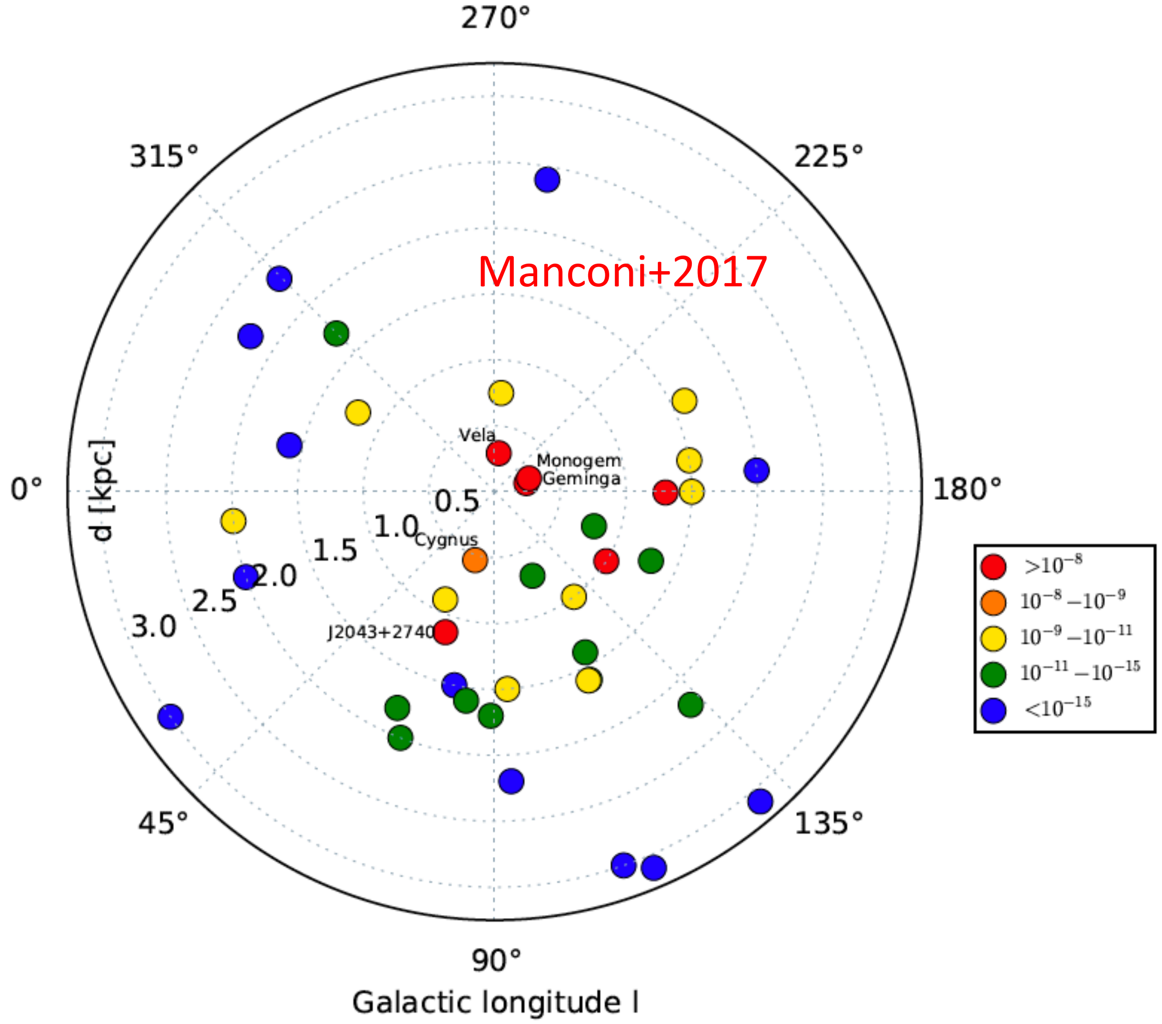
- Several experiments have measured the electron spectrum, they agree within ~20%
- It becomes clear that the spectrum cannot be reproduced with a single component
- It has a sharp decrease at ~1 TeV, partly due to the fast energy losses
- The high-energy part >1 TeV does not exhibit signatures of local sources yet putting significant constraints on the sources
- Slow diffusion zones ???

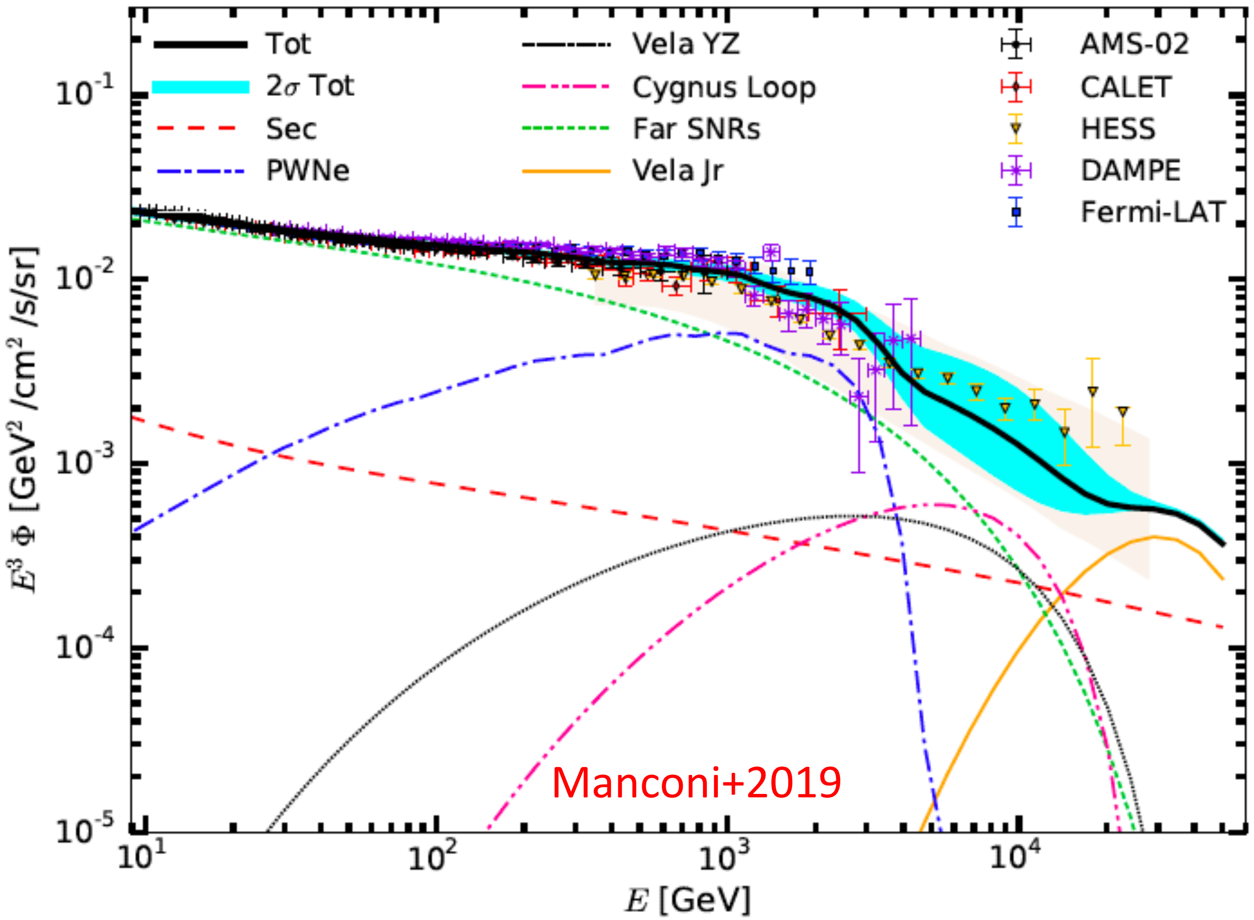


The Astroparticle Physics Conference (ICRC2023) Nagoya, Japan, Jul 26 – Aug 3, 2023

Models with contributions from local sources

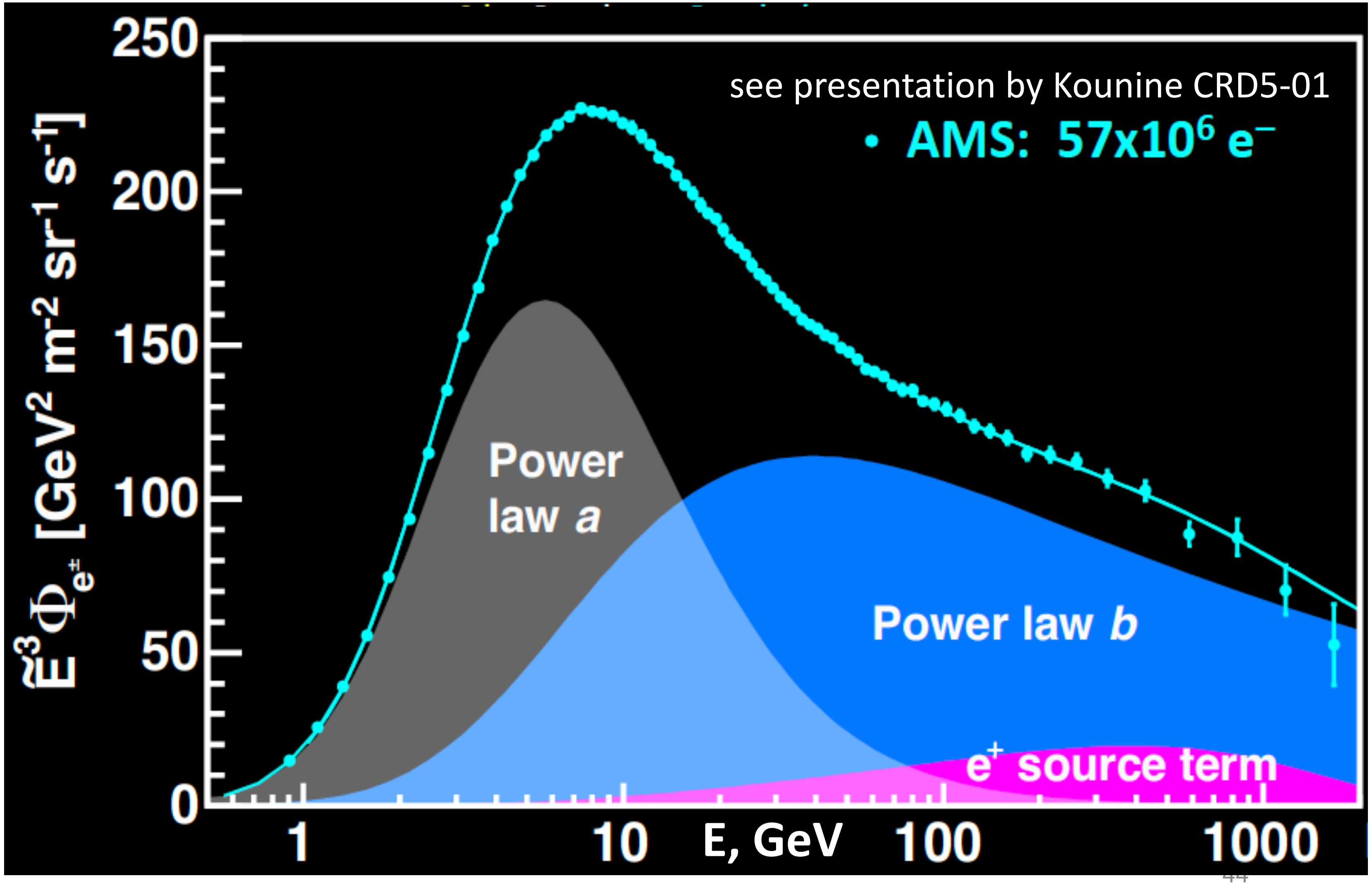
- Multicomponent models include Galactic component from distant sources, local source catalog (SNRs, PWNe), and may use the observed radio spectral indices of the local SNRs





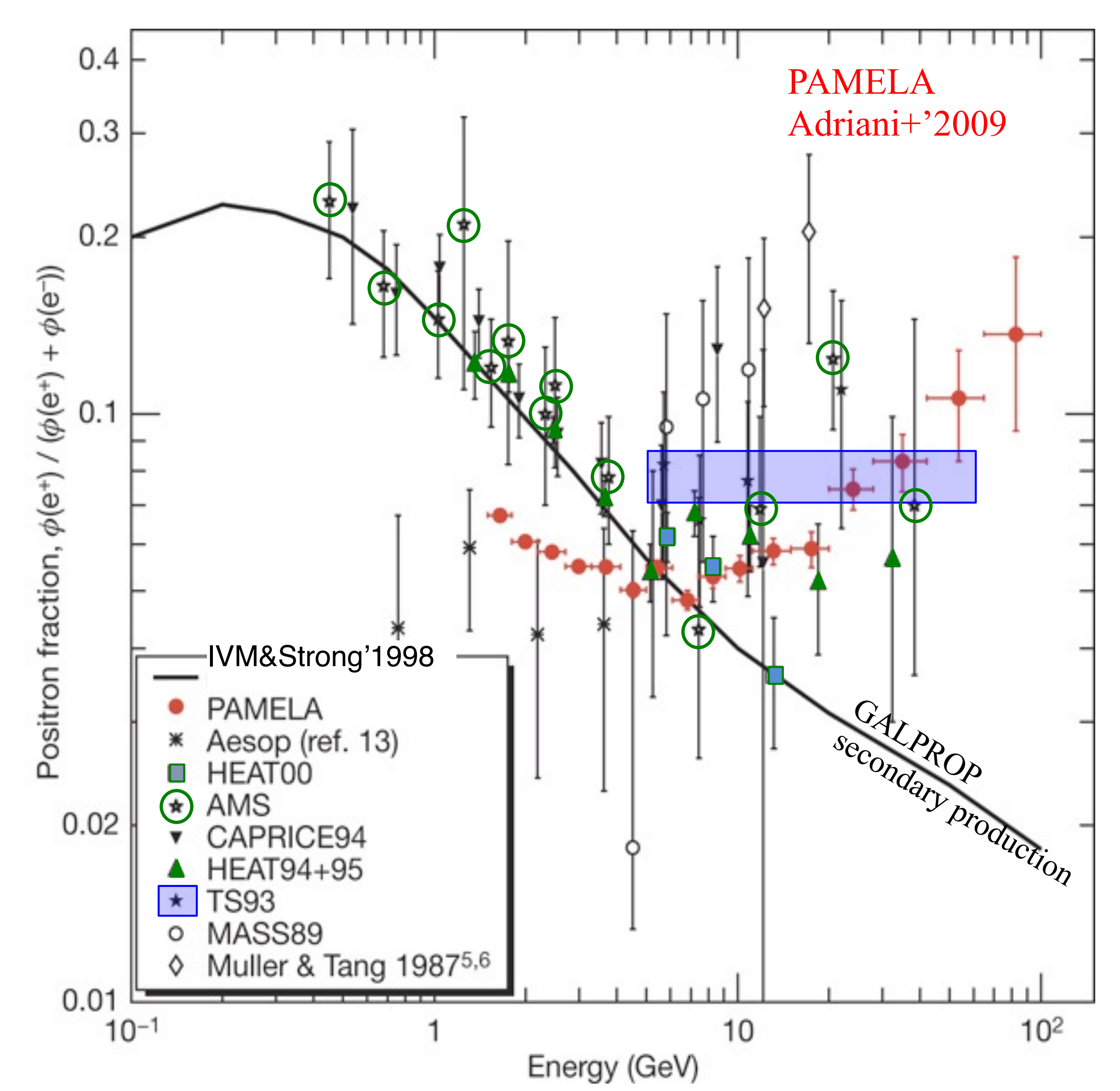
AMS-02 spectrum of electrons (e^-) & clues to the positron excess

- AMS-02 data on electrons (e^-) offers a clue to the origin of the break at ~1 TeV and on the source of excess positrons
- A three-component fit: low-energy power-law, high-energy power-law, and e^+ source term
- The break in the all-electron spectrum at ~1 TeV is related to the cutoff in e^+ plus a corresponding e^- component
- Implies charge-symmetric source of excess e^+ (DM, pulsars, hadronic interactions)
- Need more accurate data to test if the charge-symmetry is exact (e.g., hadronic processes do not produce identical $e^\pm$ spectra)



Cosmic ray positrons

Rising positron fraction



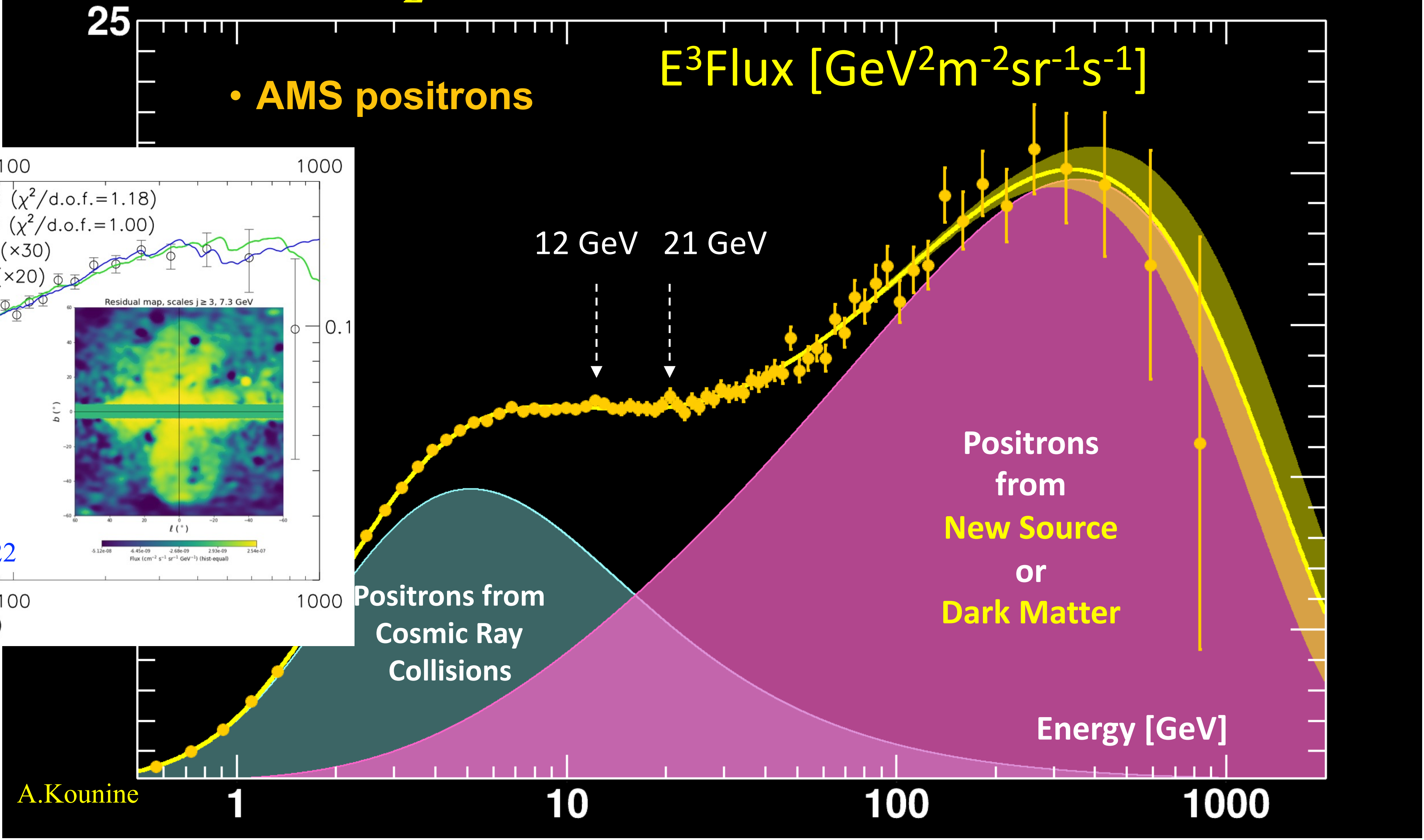
- TS93 (Golden+'96): flat positron fraction 0.078±0.016 in the range 5-60 GeV
- HEAT-94,95,00 (Beatty+'04): "a small positron flux of nonstandard origin"
- PAMELA team reported a clear and very significant rise in the positron fraction compared to the "standard" model predictions
- "Standard" model:
  - Secondary production in the ISM
  - Steady state
  - Smooth CR source distribution

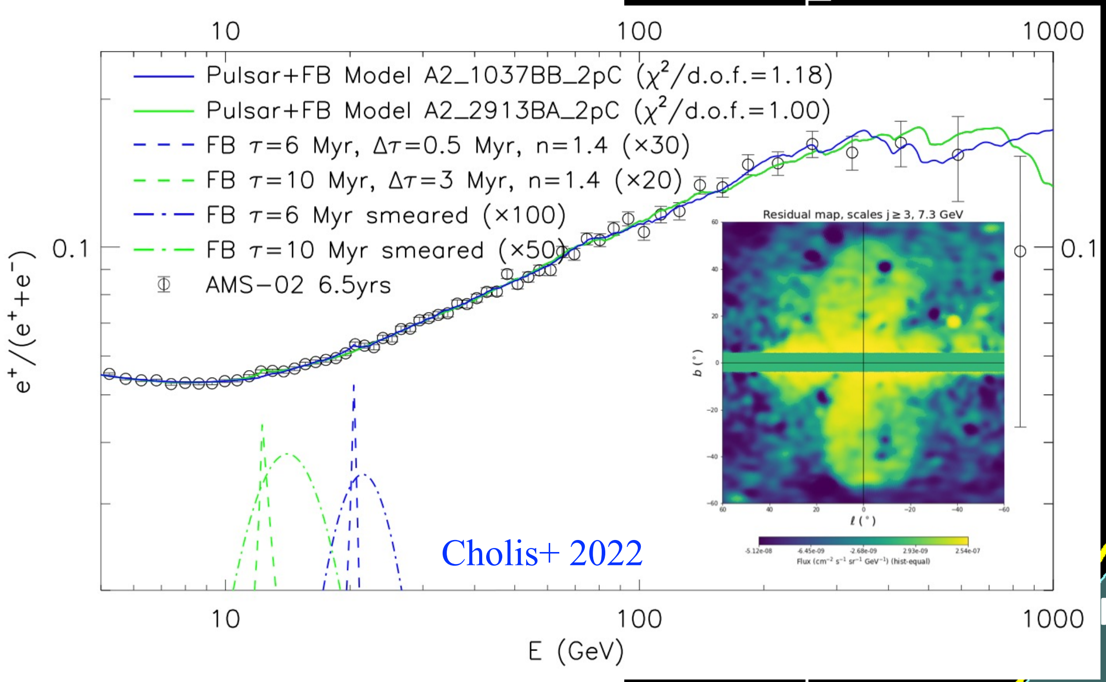
Unexpected Positrons

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.

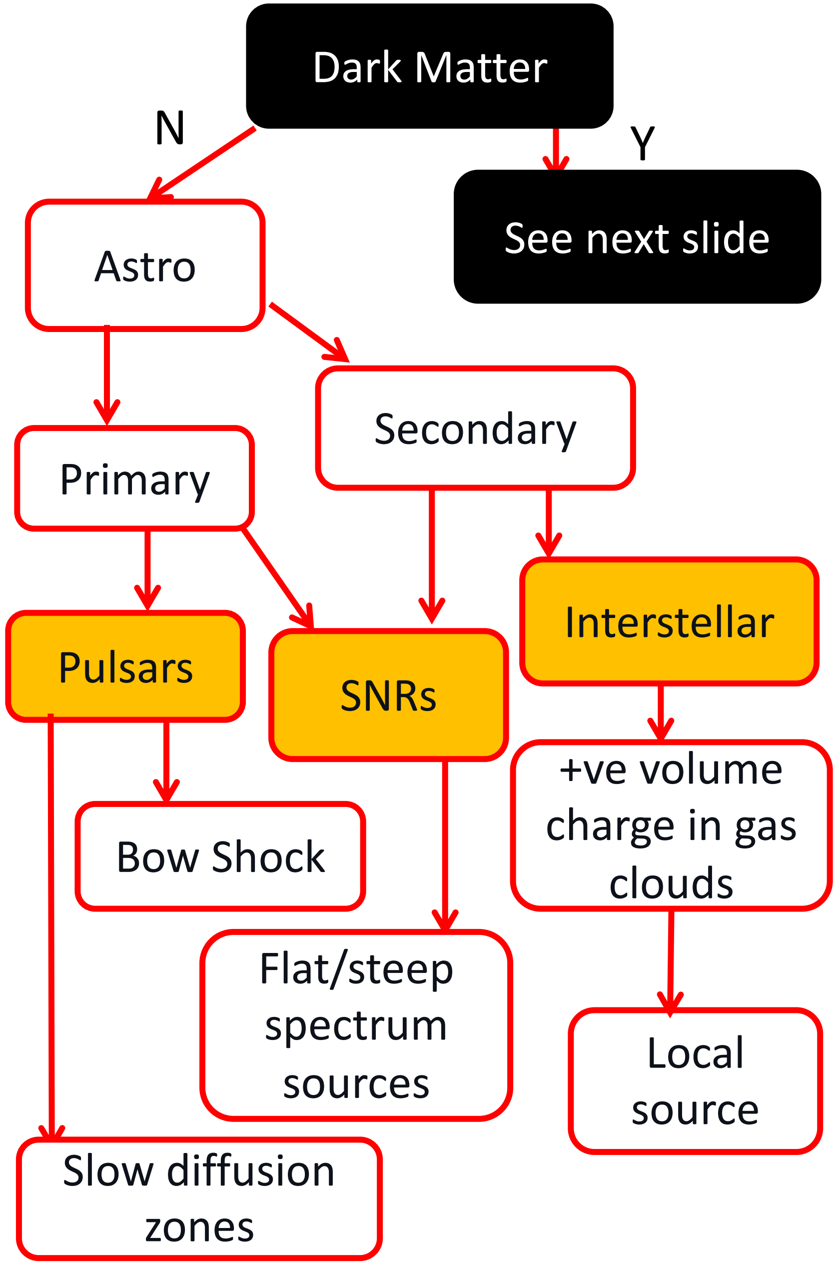
Collisions — New Source or Dark Matter

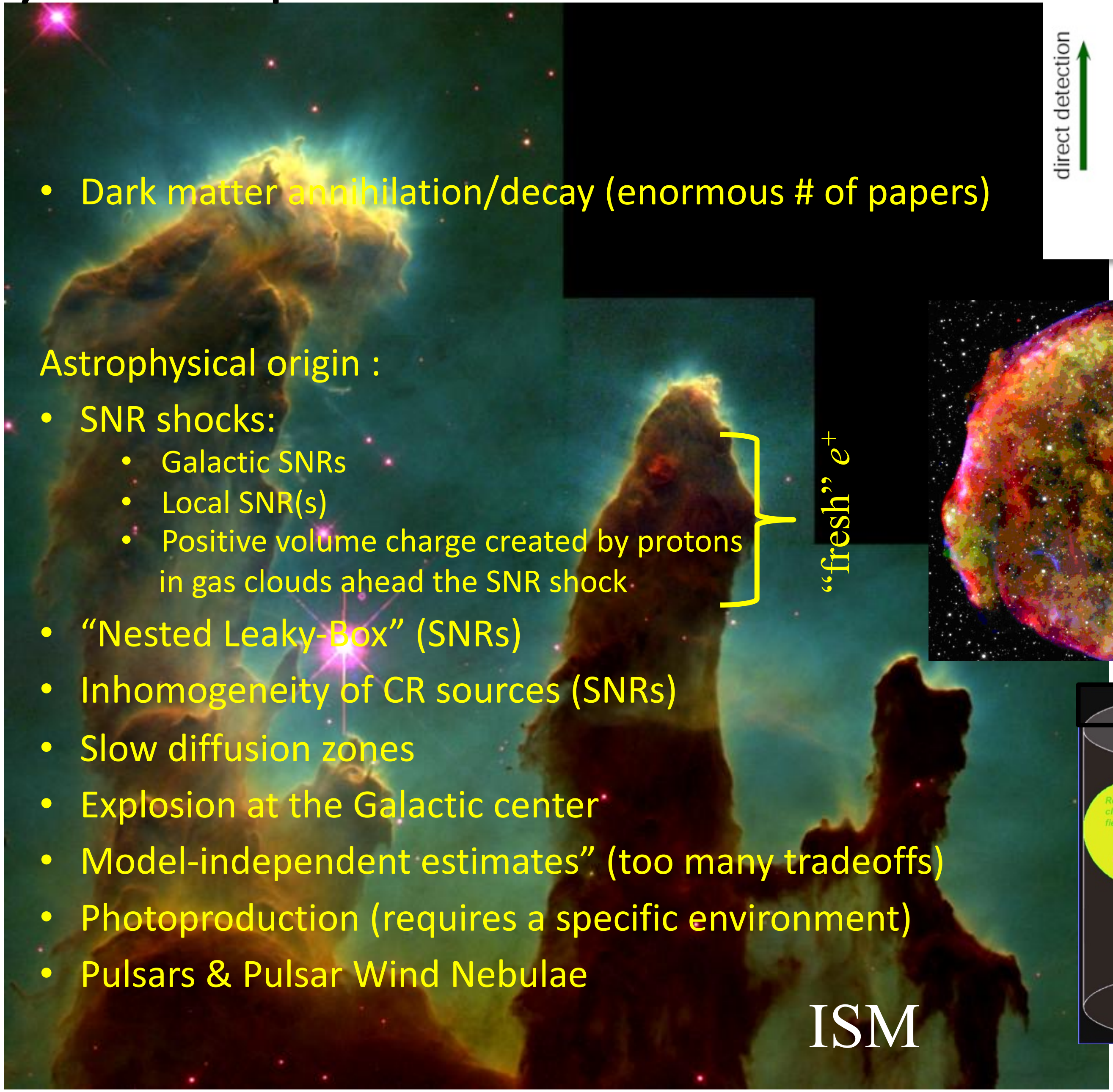
$$\Phi_{e^+}(E) = \frac{E^2}{\hat{E}^2}\left[C_d(\hat{E}/E_1)^{\gamma_d} + C_s(\hat{E}/E_2)^{\gamma_s}\exp(-\hat{E}/E_s)\right]$$





Positron Anomaly Interpretations



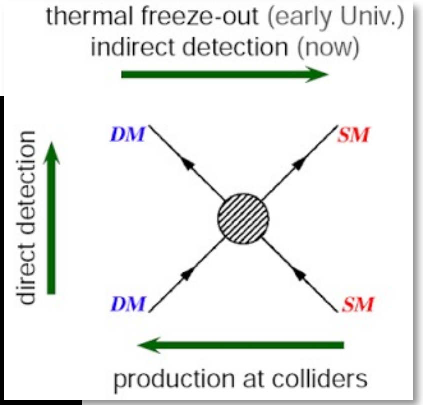


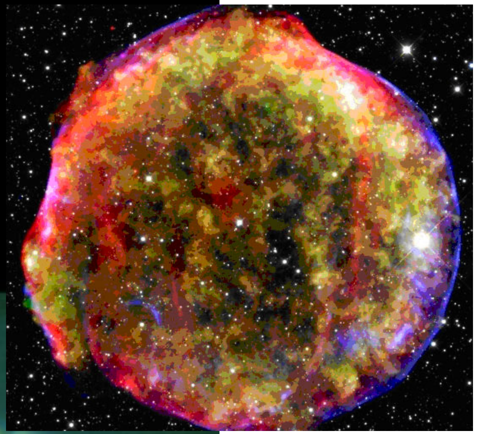
- Dark matter annihilation/decay (enormous # of papers)

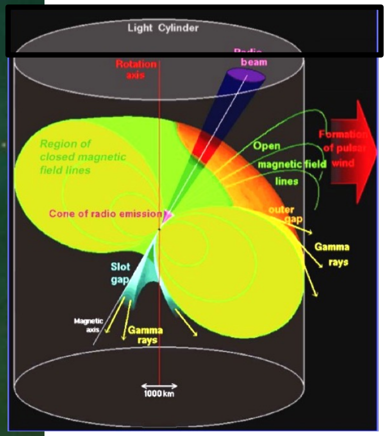
Astrophysical origin :

- SNR shocks:
  - Galactic SNRs
  - Local SNR(s)
  - Positive volume charge created by protons in gas clouds ahead the SNR shock

  } "fresh" e^+
- "Nested Leaky-Box" (SNRs)
- Inhomogeneity of CR sources (SNRs)
- Slow diffusion zones
- Explosion at the Galactic center
- Model-independent estimates" (too many tradeoffs)
- Photoproduction (requires a specific environment)
- Pulsars & Pulsar Wind Nebulae



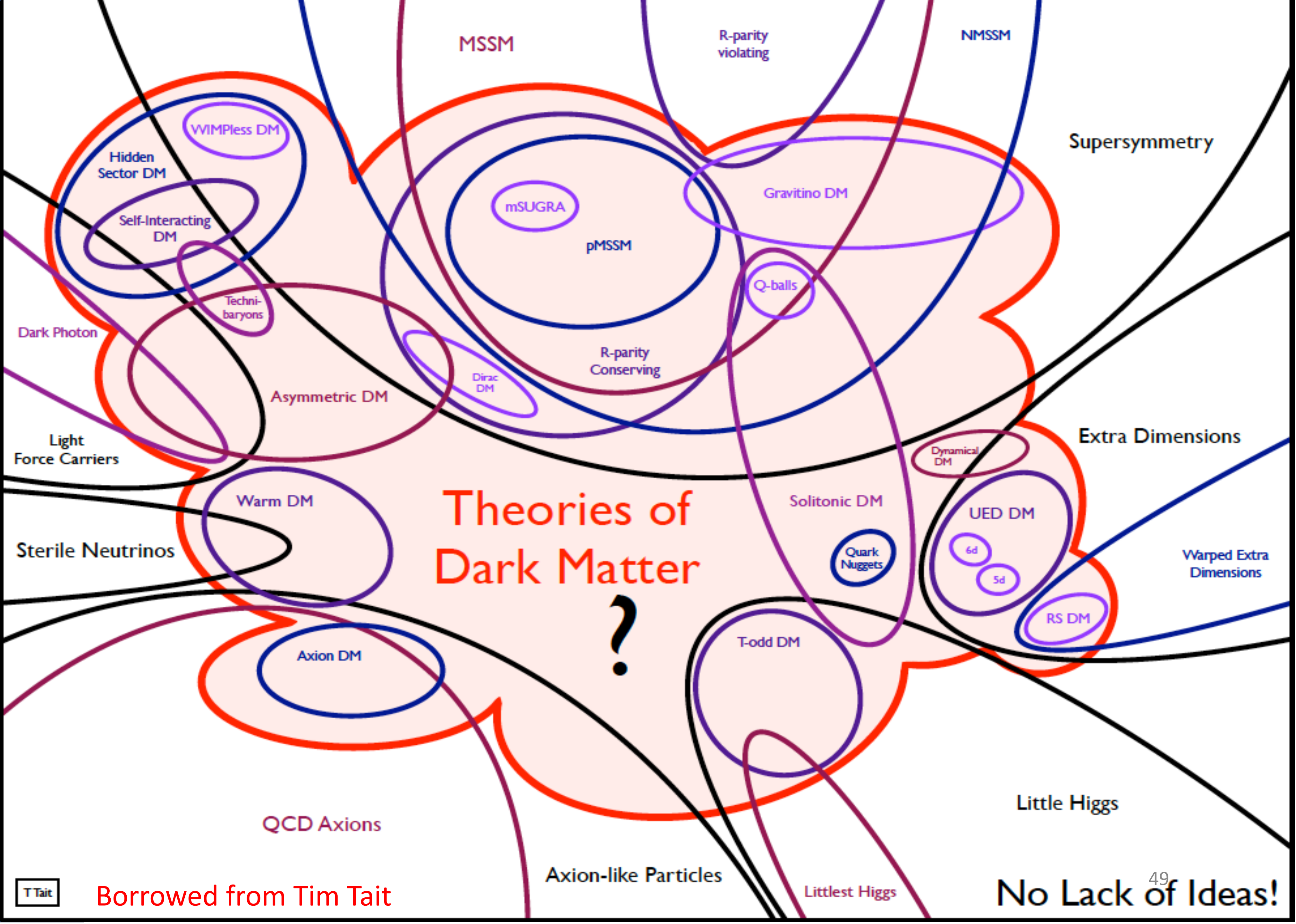




Current view on Dark Matter in astro-physics

Addressed a review talk by Francesca Calore:

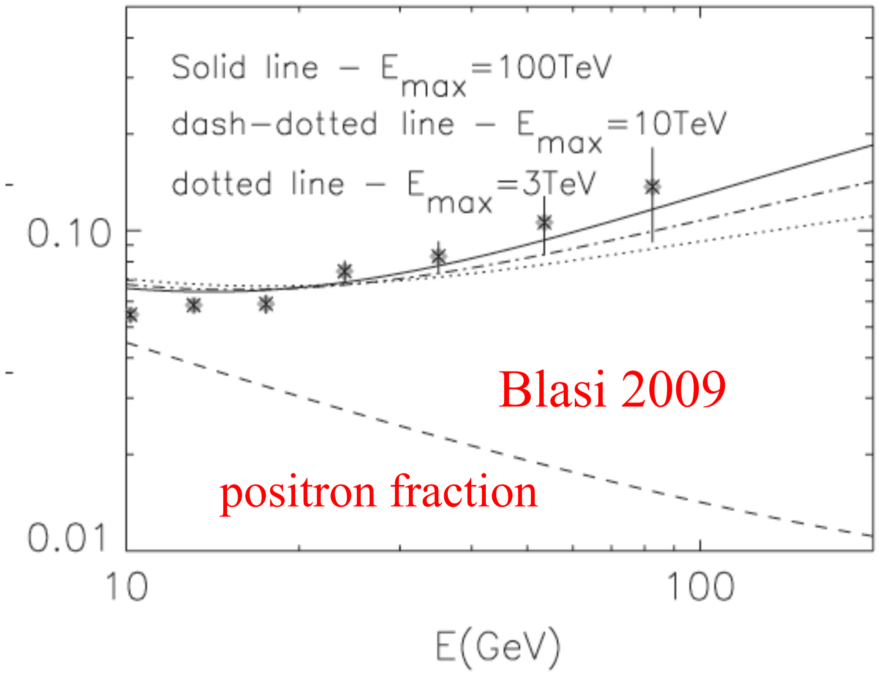
Review1-02

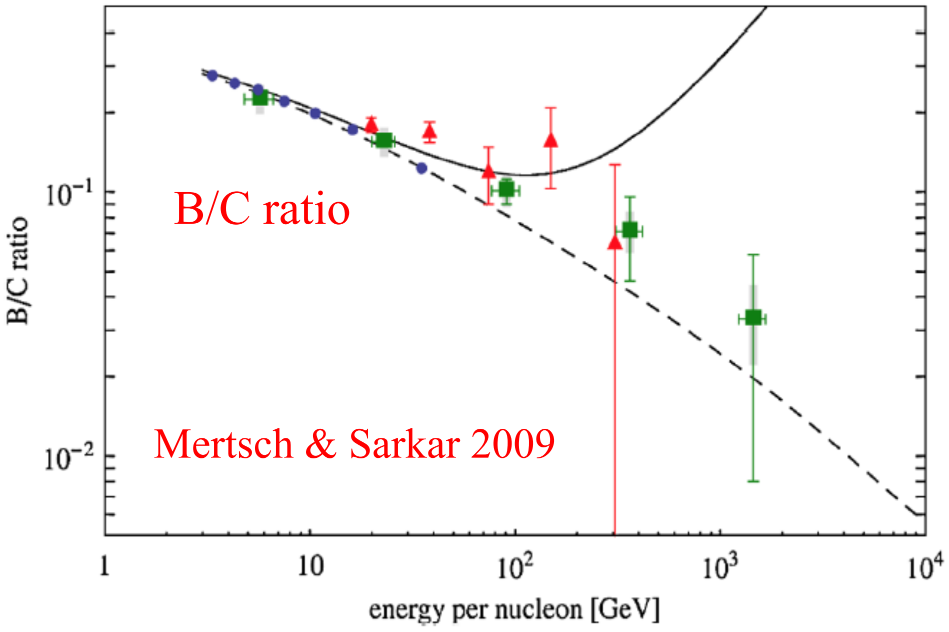


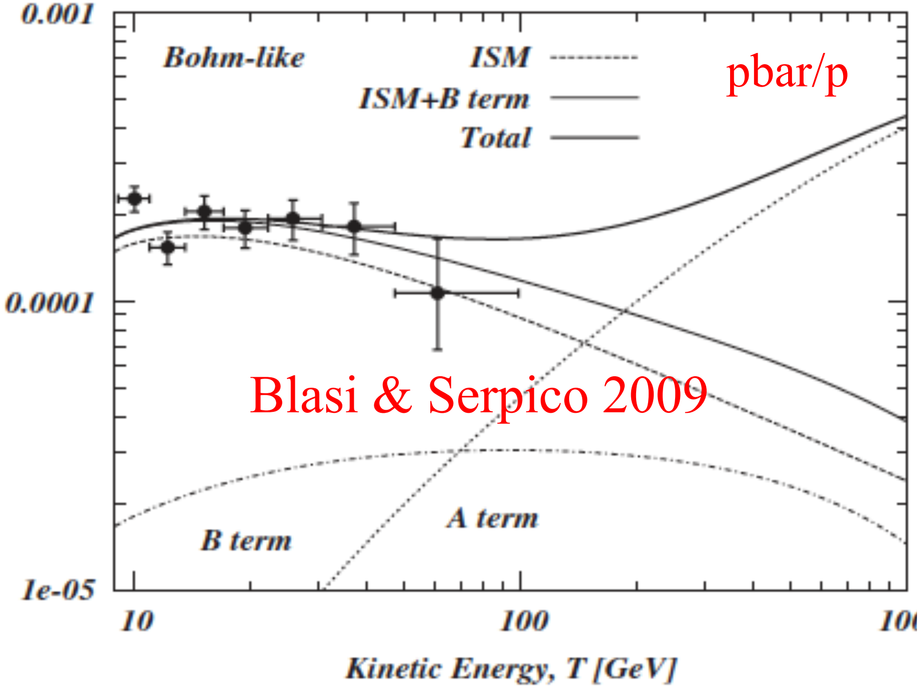
Borrowed from Tim Tait

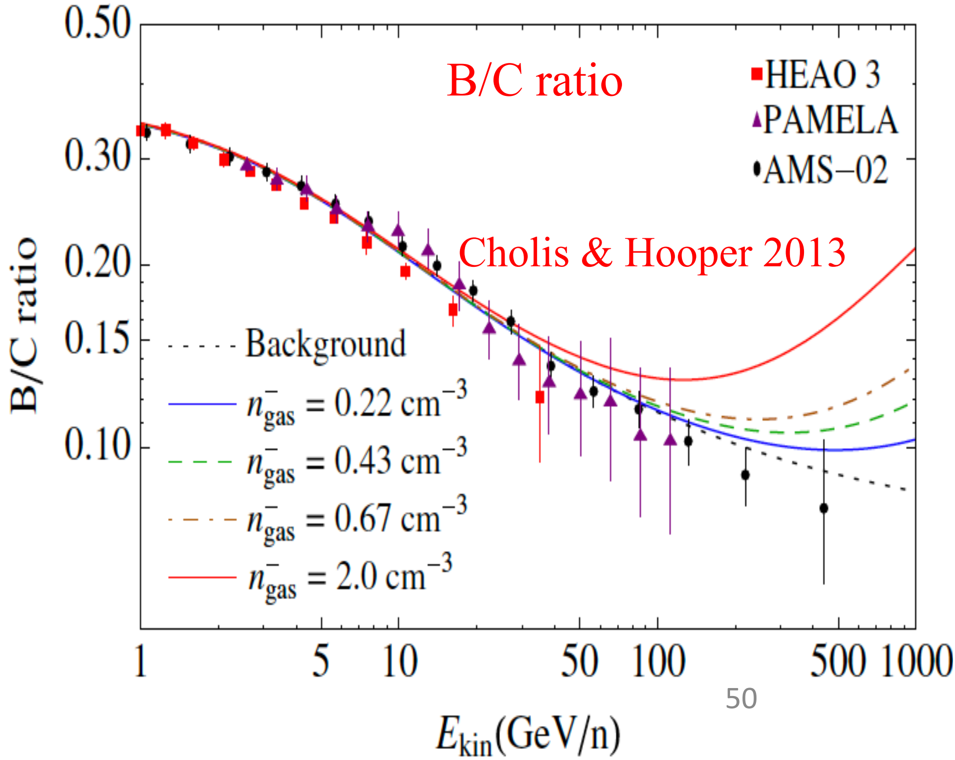
Positron production in Galactic SNR shocks

- First models speculated on the idea of production of secondary species in the SNR shock (proposed by Berezkho+2004)
- Soon it becomes clear that other secondaries (pbars, B) should rise too, which may contradict to observations



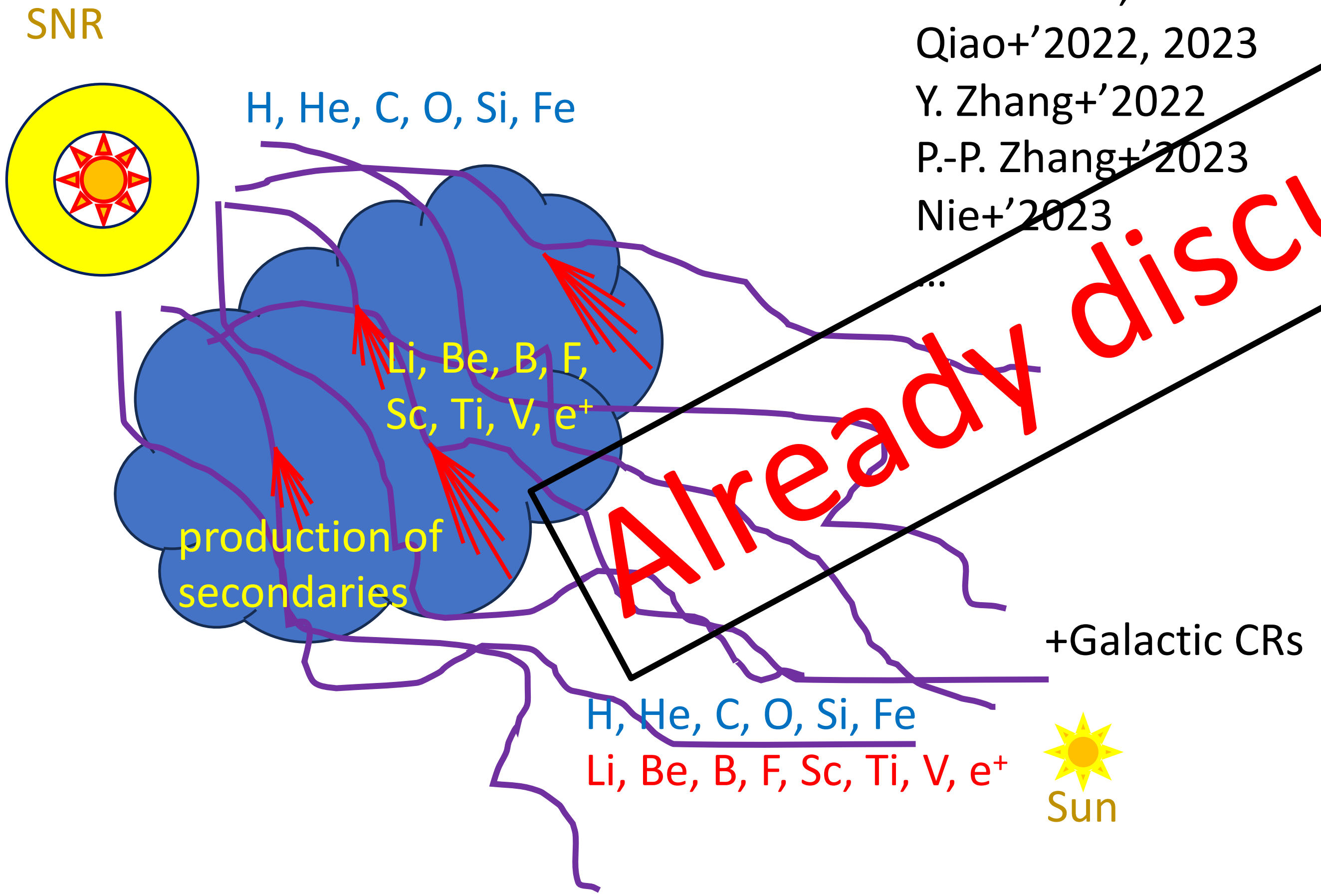






Local SNR + gas cloud models

Claimed to reproduce all observed features in CR nuclei, $e^{\pm}$, pbars



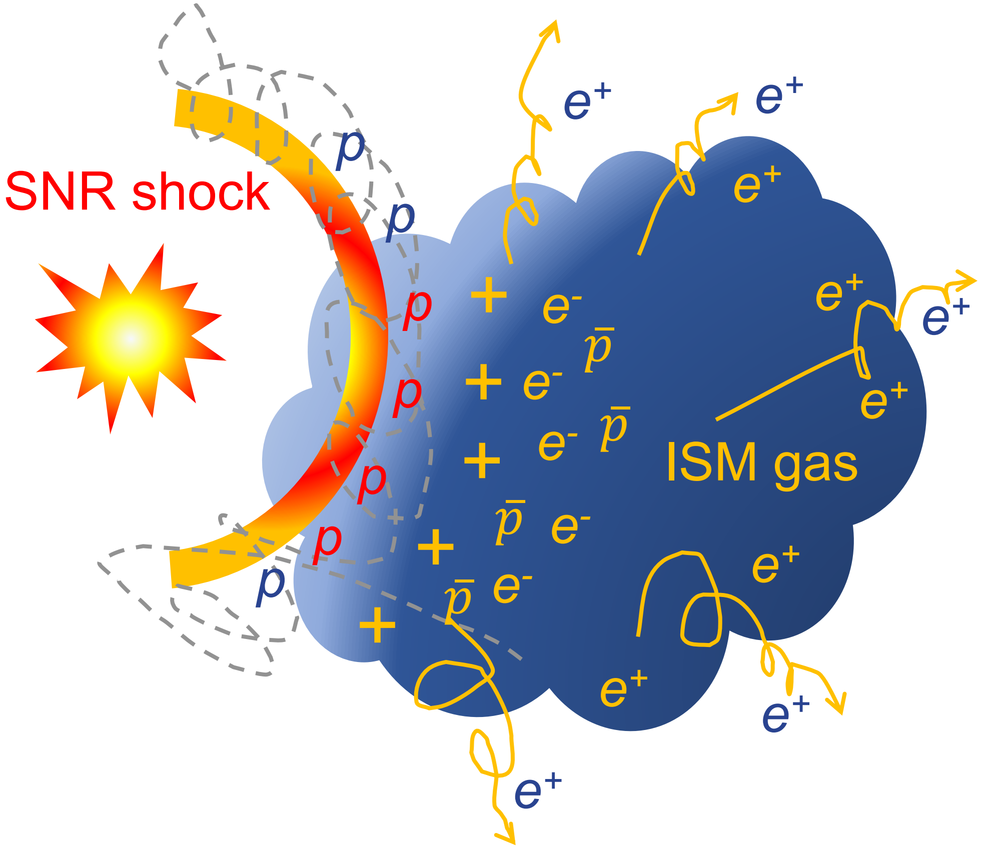
Yang & Aharonian'2019
Liu+'2019
Fang+'2021
Fornieri+'2021
Yuan+'2021
Zhao+'2022, 2022
Luo+'2022, 2023
Qiao+'2022, 2023
Y. Zhang+'2022
P.-P. Zhang+'2023
Nie+'2023
…

- Many models are speculating on the idea of a local SNR (~300 pc, Geminga SNR)
- Consider a combination of the Galactic CRs with concave spectra + sharp peak from the local SNR
- Secondary species are produced in gas cloud(s)
- Propose to reproduce antiprotons, electrons, positrons
- Proposed to reproduce CR anisotropy

Already discussed

Volume charge model by M. Malkov

- Protons accelerated in a SNR shell are interacting with the interstellar gas
- Produce secondary particles ($\bar{p}$, e^-, e^+) in hadronic interactions and develop a positive electric volume charge
- Electric charge preferentially expels secondary positrons into the interstellar medium
- Passing SNR shock picks up positrons from interstellar medium → produces the same spectrum as protons

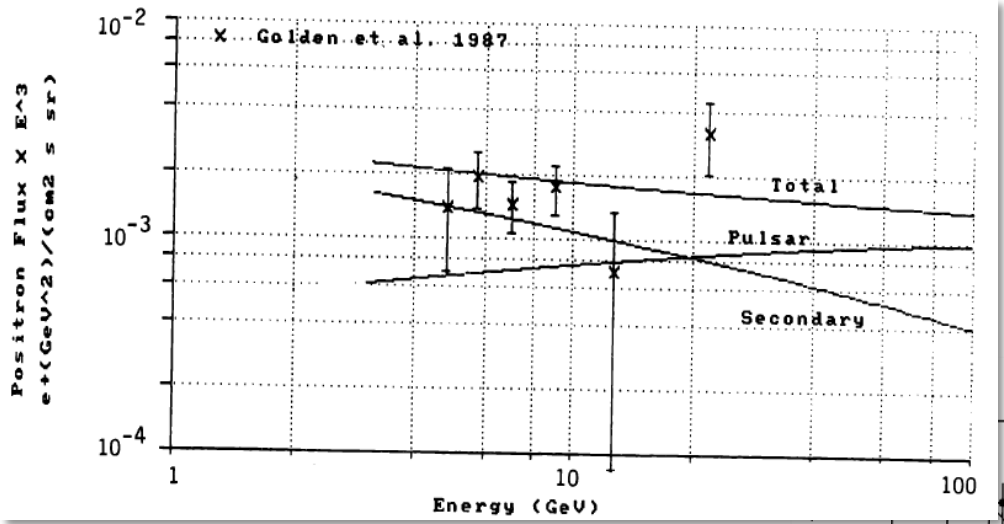


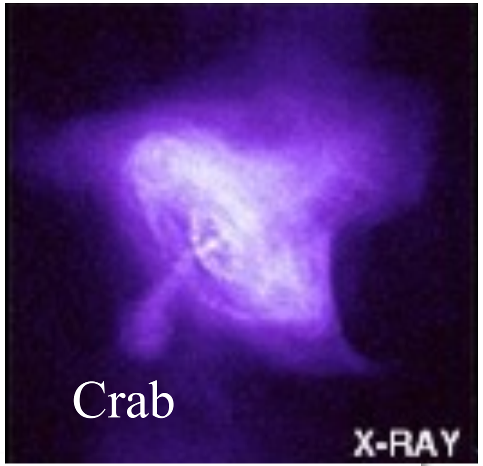
- There are also other sources of positrons in the ISM, such as radioactivity

Pulsars

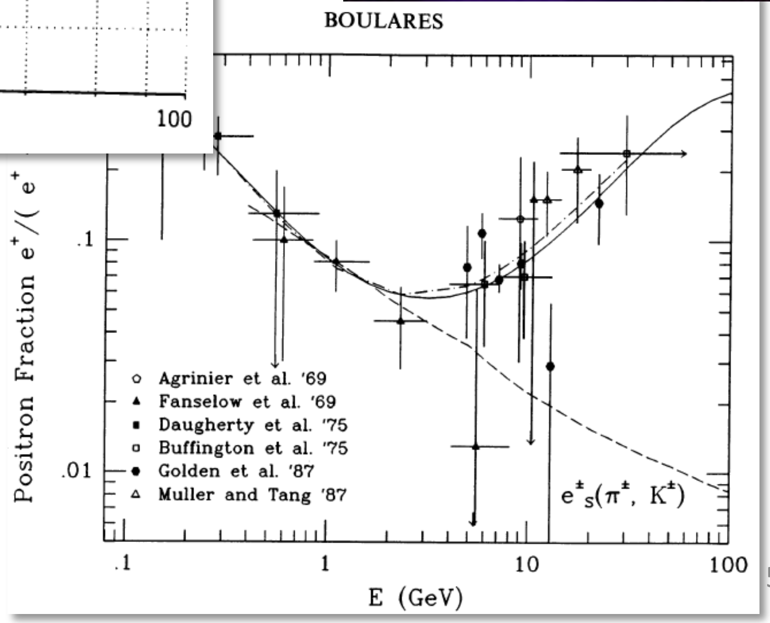
- Arons 1981 “Particle acceleration by pulsars”
- Harding & Ramaty 1987 “The pulsar contribution to Galactic cosmic ray positrons”
- Boulares 1989 “The nature of the cosmic-ray electron spectrum, and supernova remnant contributions”

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



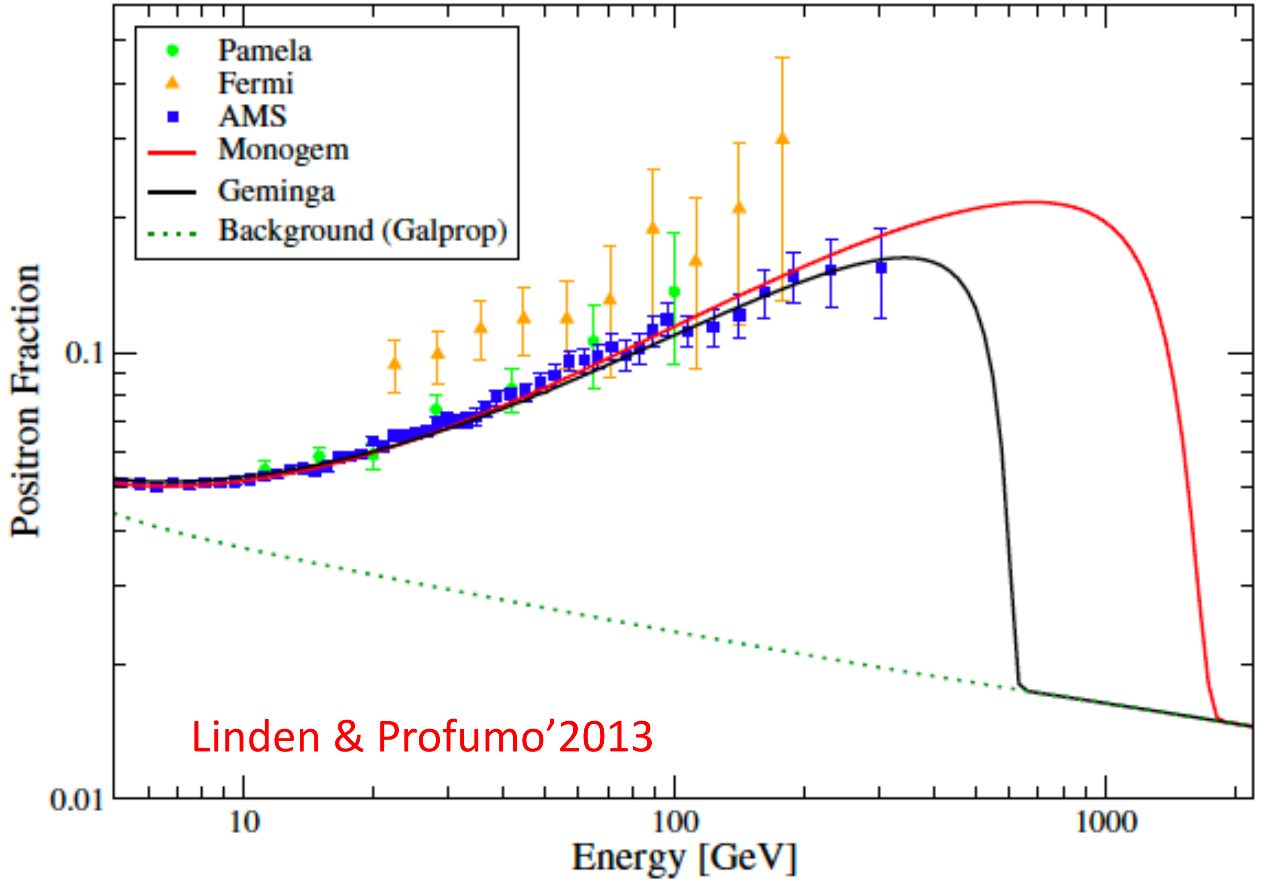


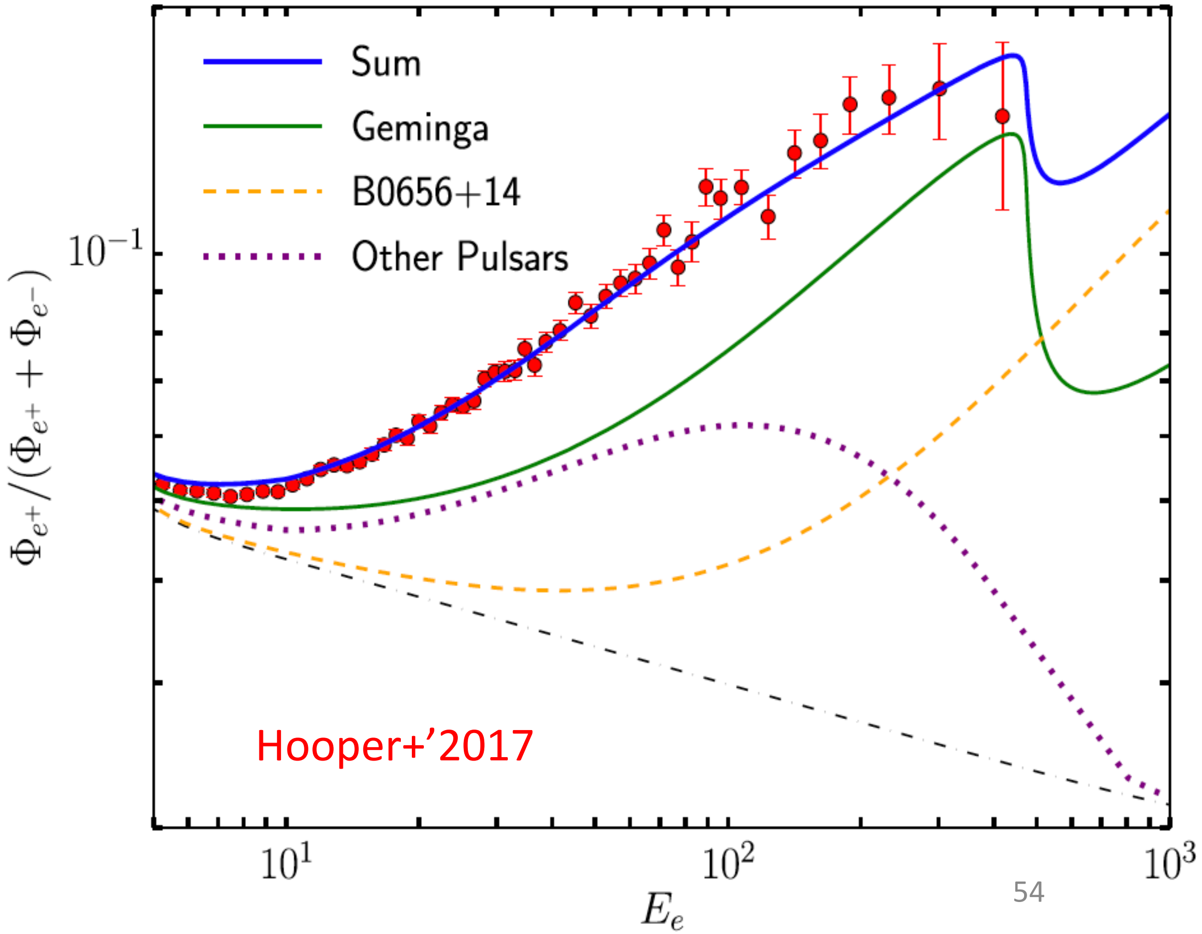
3 components:
✧ Secondary $e^{+/-}$
✧ Primary e^- from SNR
✧ Primary $e^{+/-}$ from pulsars



Positrons from pulsars

Pulsars are the primary charge-symmetric suspects as they allow the origin of positrons to be disconnected from nuclear species, and therefore to avoid constraints

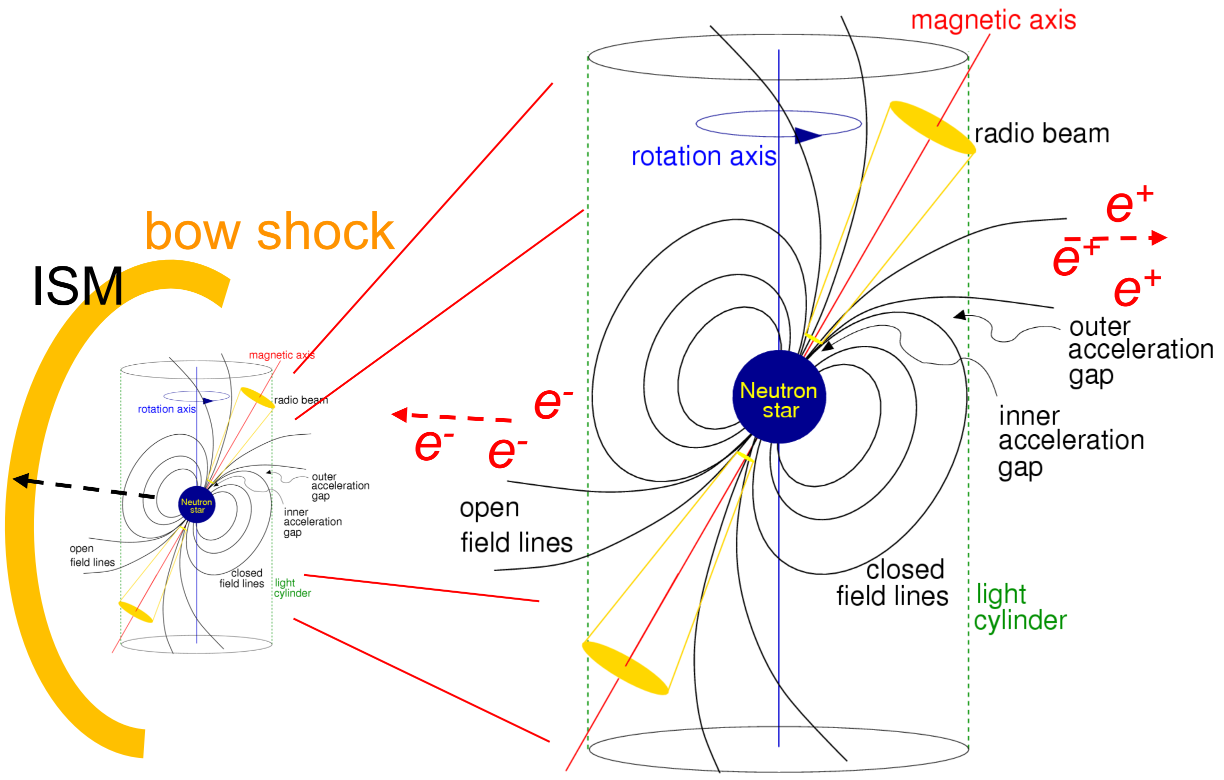




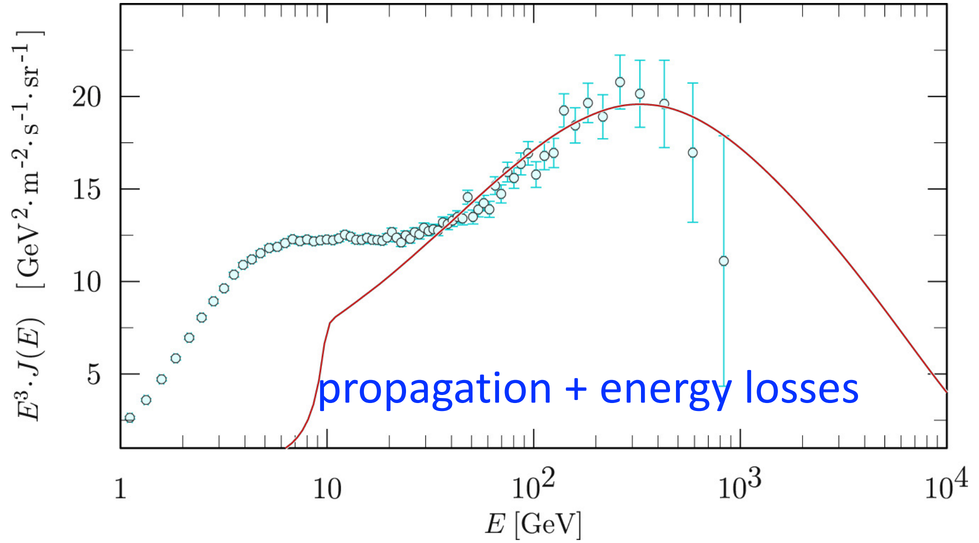
Pulsar bow shock model

- ✧ 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

See Bykov+'2017,2019, Petrov'+2020

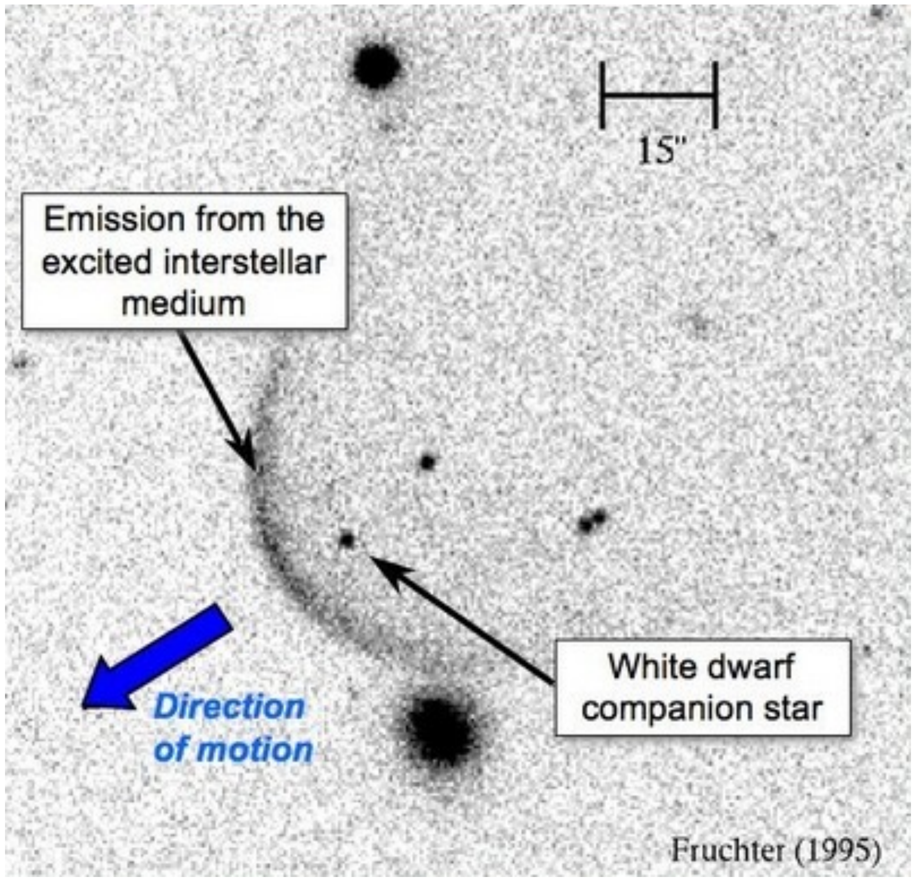


positrons from a millisecond pulsar PSR J0437-4715



The 5.7 millisecond pulsar PSR J0437-4715

- Distance: 156.79±0.25 pc
- 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

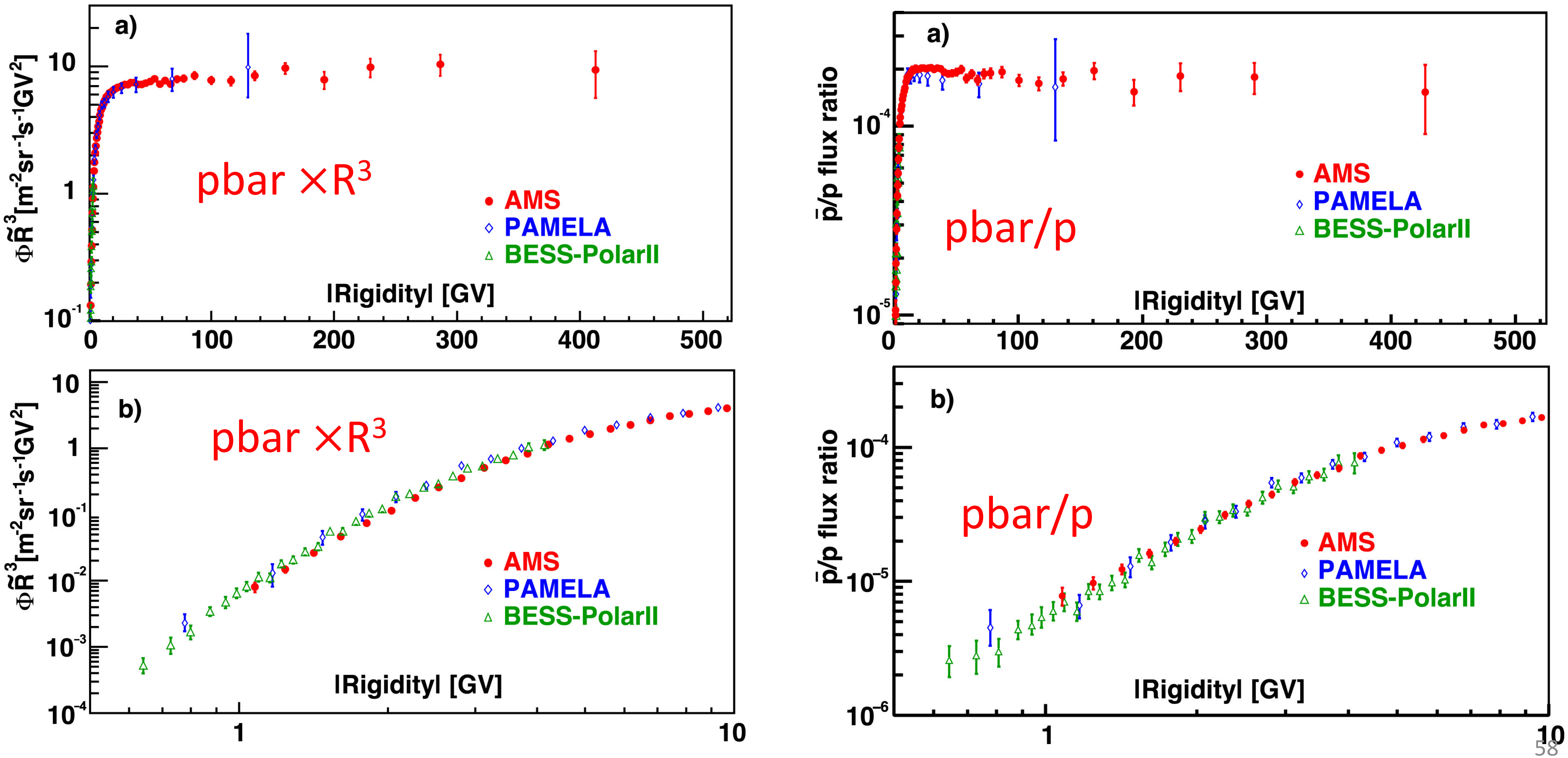


Optical image of the binary system containing PSR J0437-4715

Antiprotons

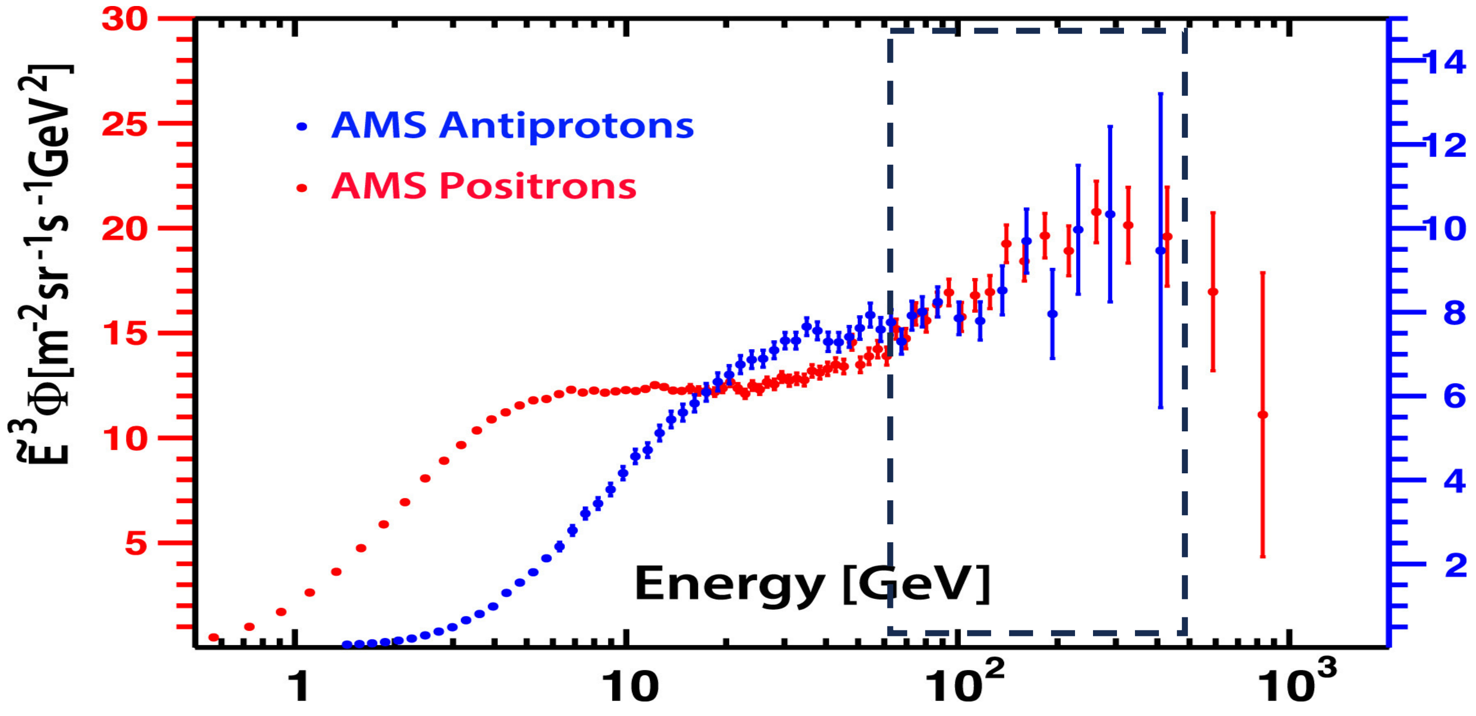
Antiprotons

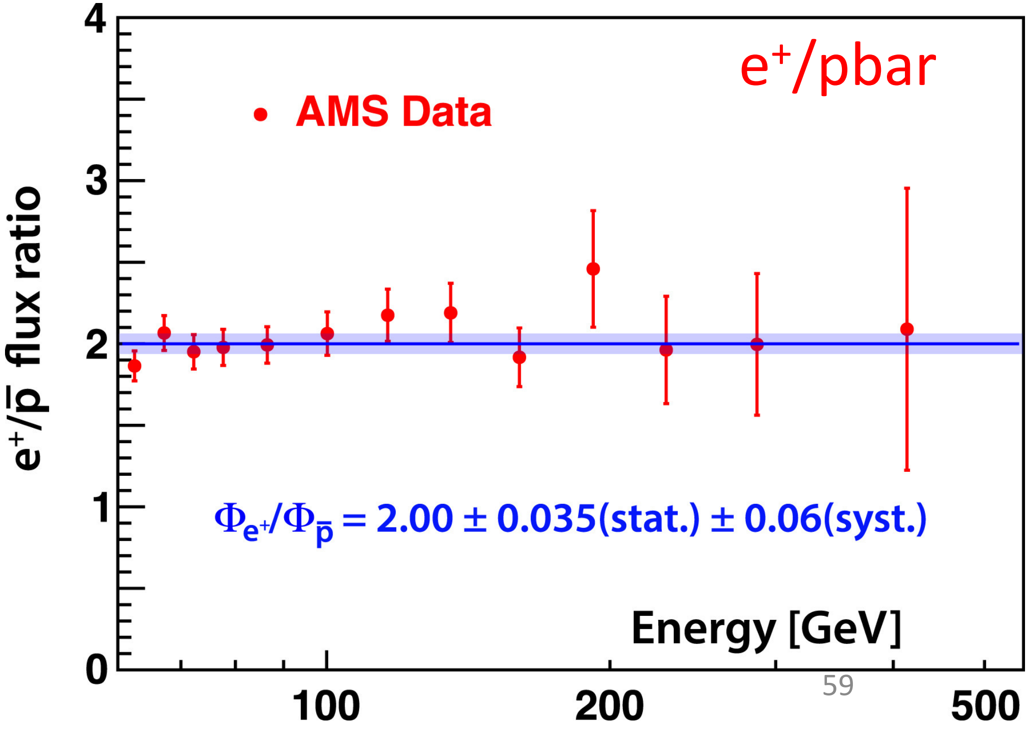
- Pbar spectrum is measured up to ~450 GV
- Rise at low energies due to the kinematics
- The ratio pbar/p is flat (constant) from 30 GV-450 GV



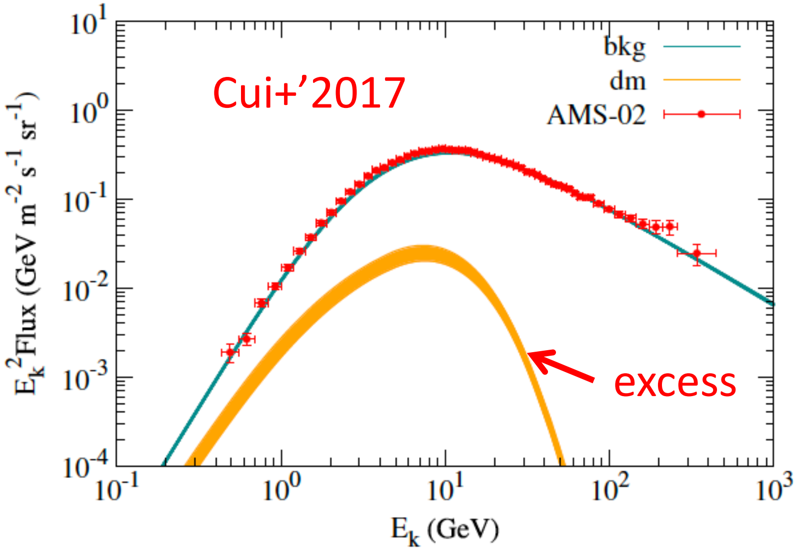
Antiprotons

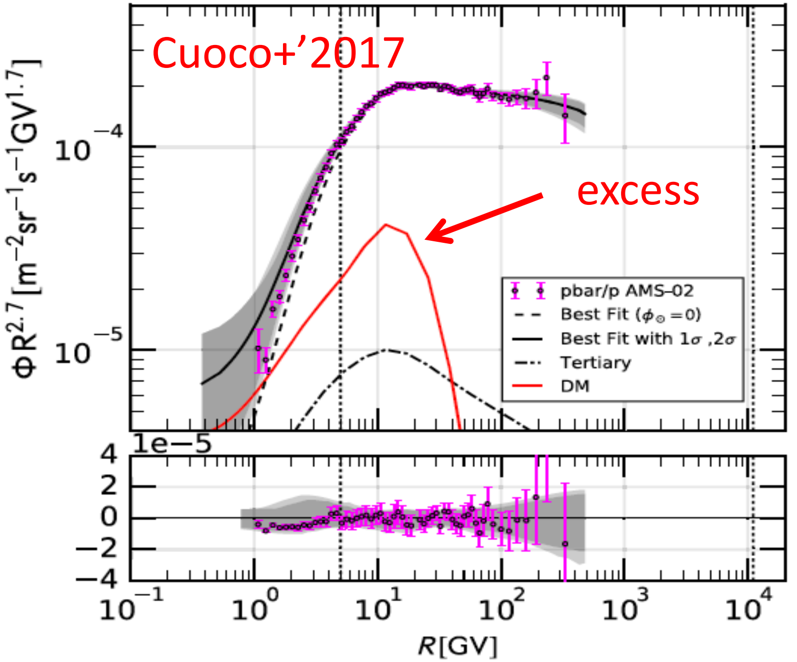
- Often repeated is a statement that e^+/pbar ratio is const and is exactly 2
- In fact, the published fit was made to a constant function
- The fit could be done in different ways
- Constraining are only several lower-energy points 60-150 GeV
- A calculation of the LIS spectra would extend the ratio to lower energies and allow us to check if it still holds



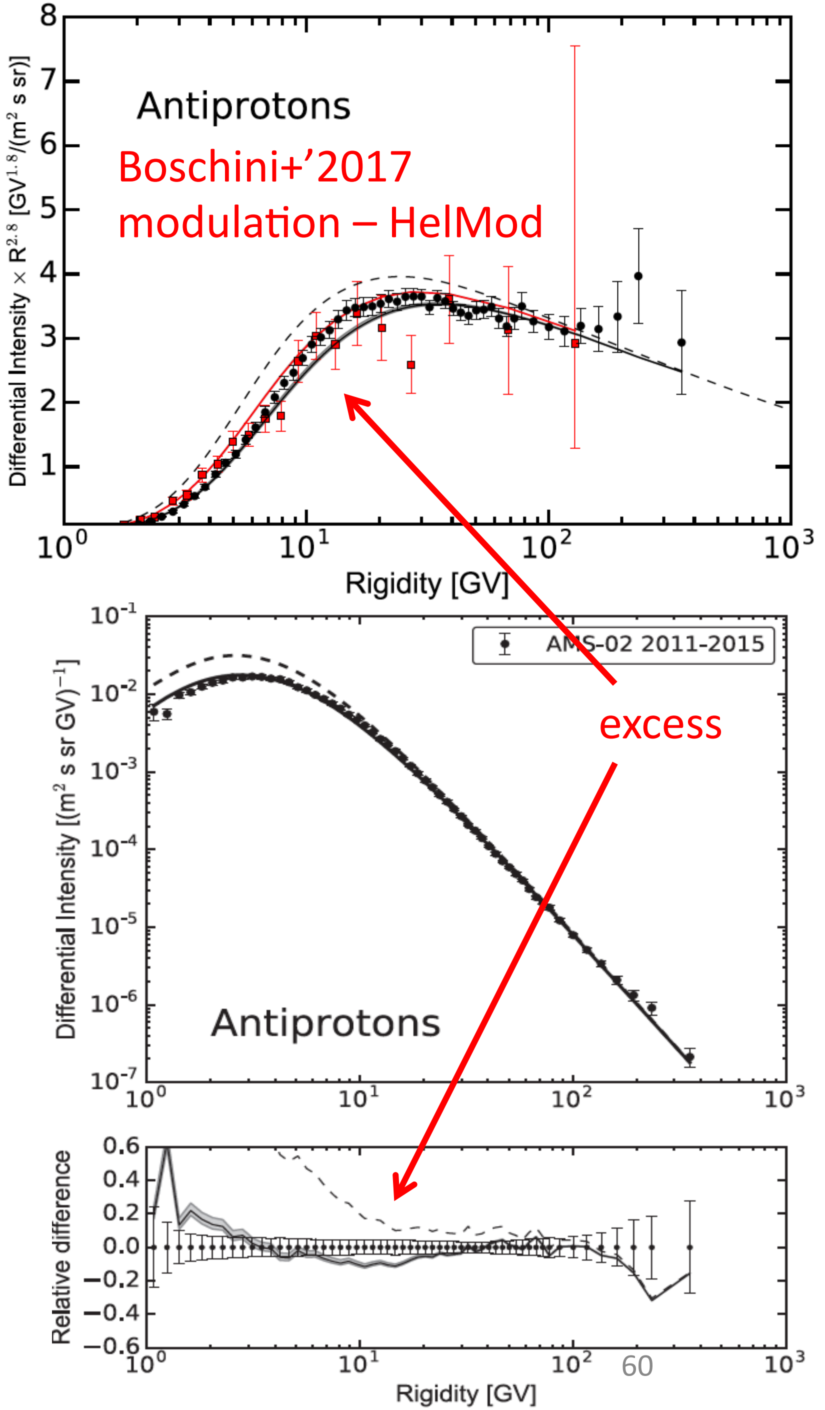


10 GeV antiproton excess





- After publication of AMS-02 antiproton data in 2016, several groups independently noticed an excess around 10 GeV
- All three papers are marked as published on May 10-12, 2017
- Cui+ and Cuoco+ interpretation was the dark matter
- Boschini+ pointed to increased systematics due to the high solar activity period during the data taking or due to the cross sections (see also Heisig+'2020; Engelbrecht & Di Felice'2020; Engelbrecht & Moloto'2021; Lv+'2023)



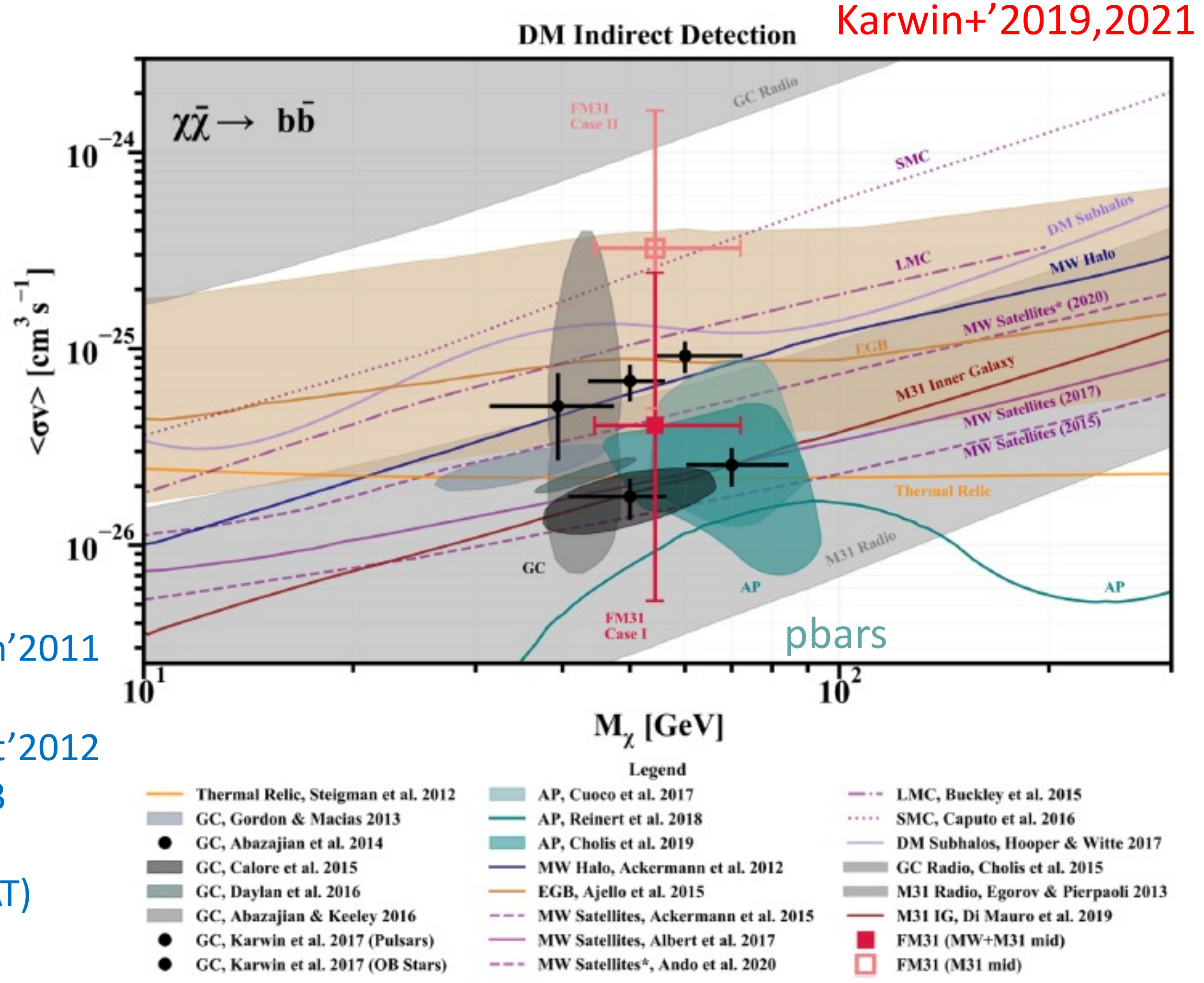
10 GeV antiproton excess

The two hypotheses remain, the (i) dark matter contribution and (ii) systematics due to the solar modulation/cross section uncertainties

(i) The same DM candidate (m_χ~50-100 GeV) can reproduce the antiproton excess, γ-ray excess from the Galactic center, and γ-ray emission from 400 kpc halo of the Andromeda galaxy

(ii) People like the DM hypothesis, but attempts are made to improve on the cross sections

Karwin+'2019,2021



Some cross section papers:

Kachelriess+'2015,2019,2023 (QGSJET-II-04m)

Winkler'2017

Donato+'2017

Korsmeier+2018

Aaij+2018 (LHCb Collaboration)

Some DM papers:

Hooper & Goodenouth'2011

Hooper & Linden'2011

Abazajian & Kaplinghat'2012

Gordon & Macias'2013

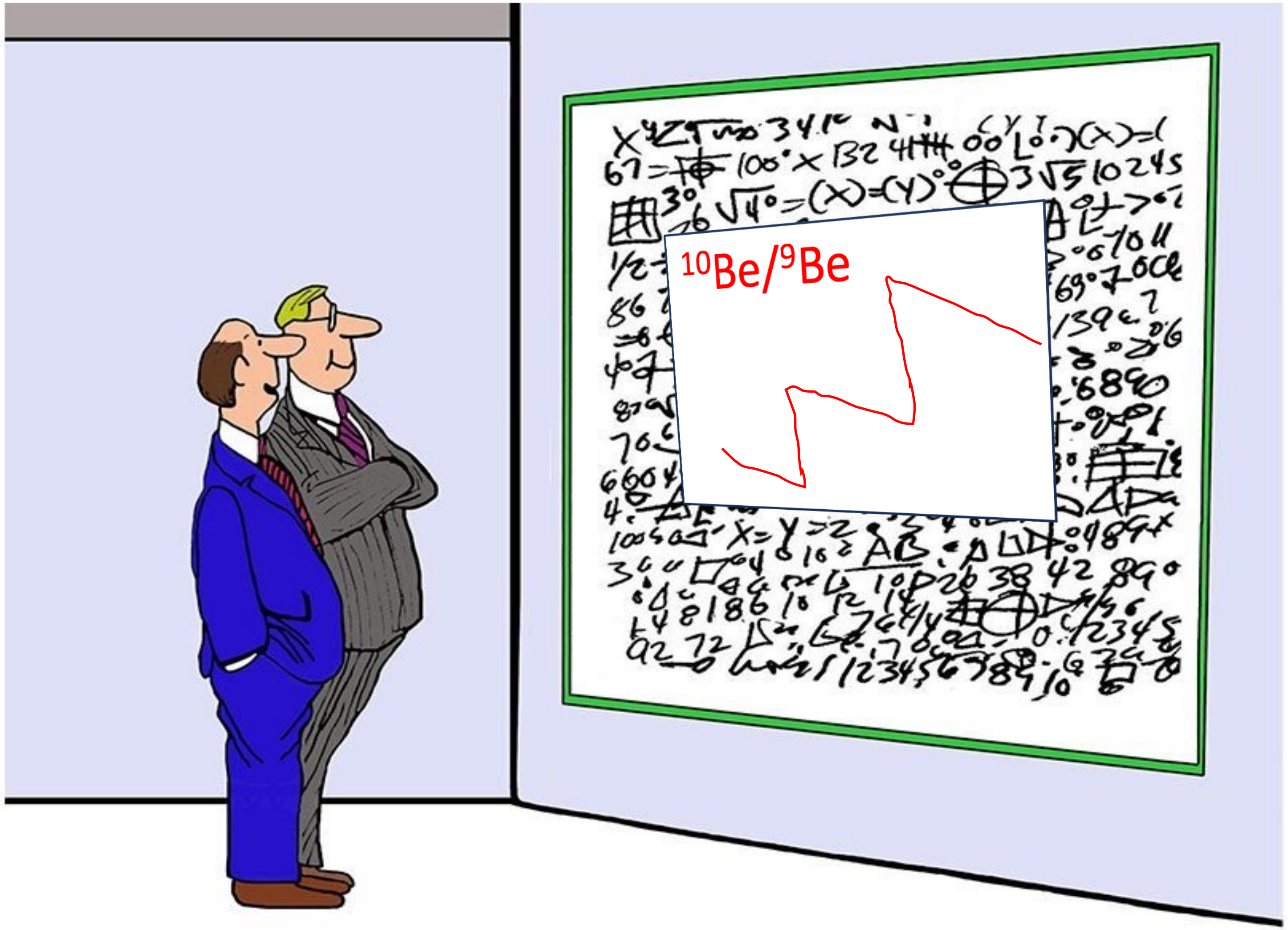
Galore+'2015

Ajello+'2016 (Fermi-LAT)

Cholis+'2019

Karwin+'2019,2021

Thanks!



When you put it like this, it makes complete sense