Cosmic ray nuclei and antinuclei in the Galaxy: new insights in the precision era

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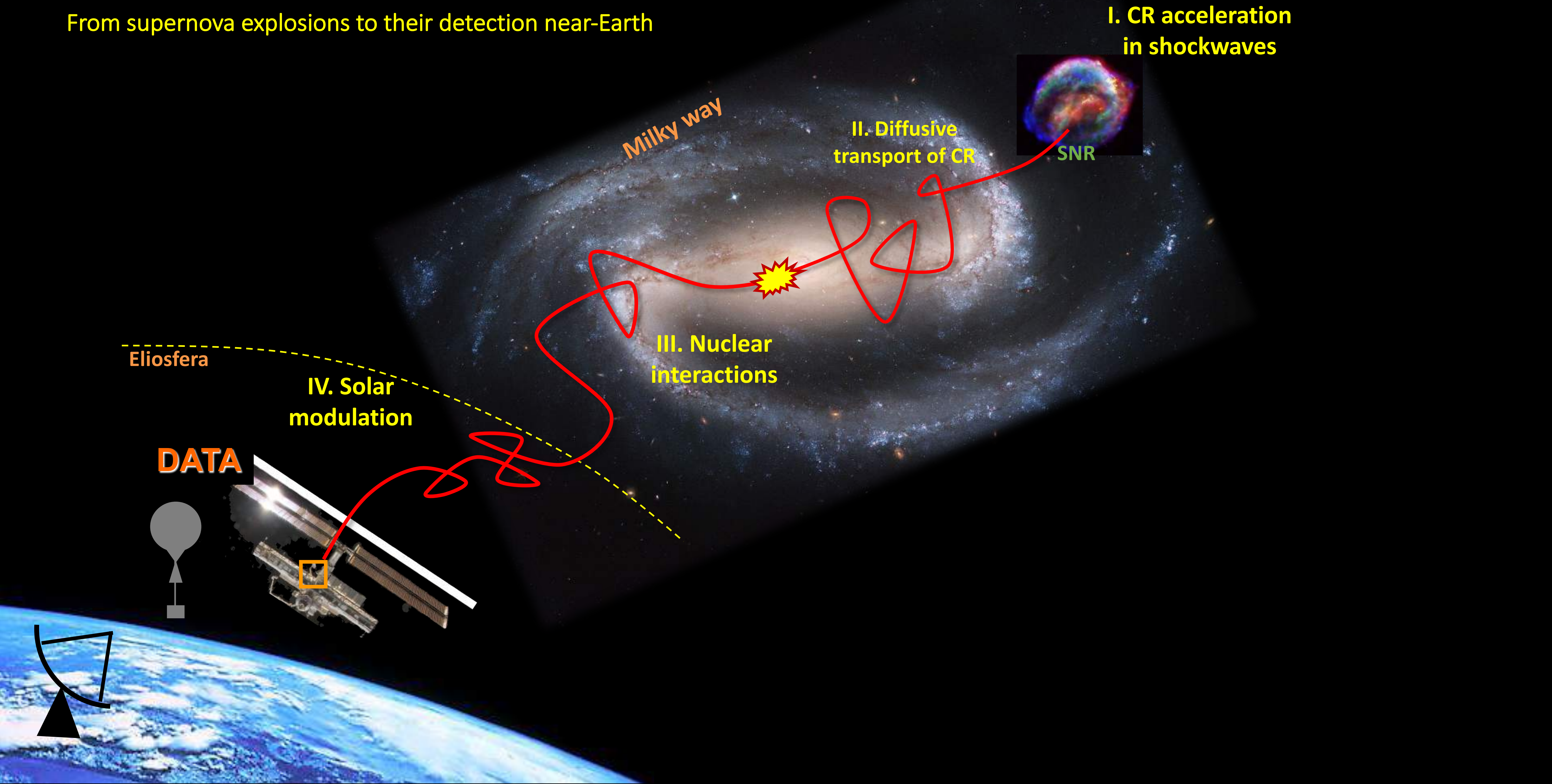
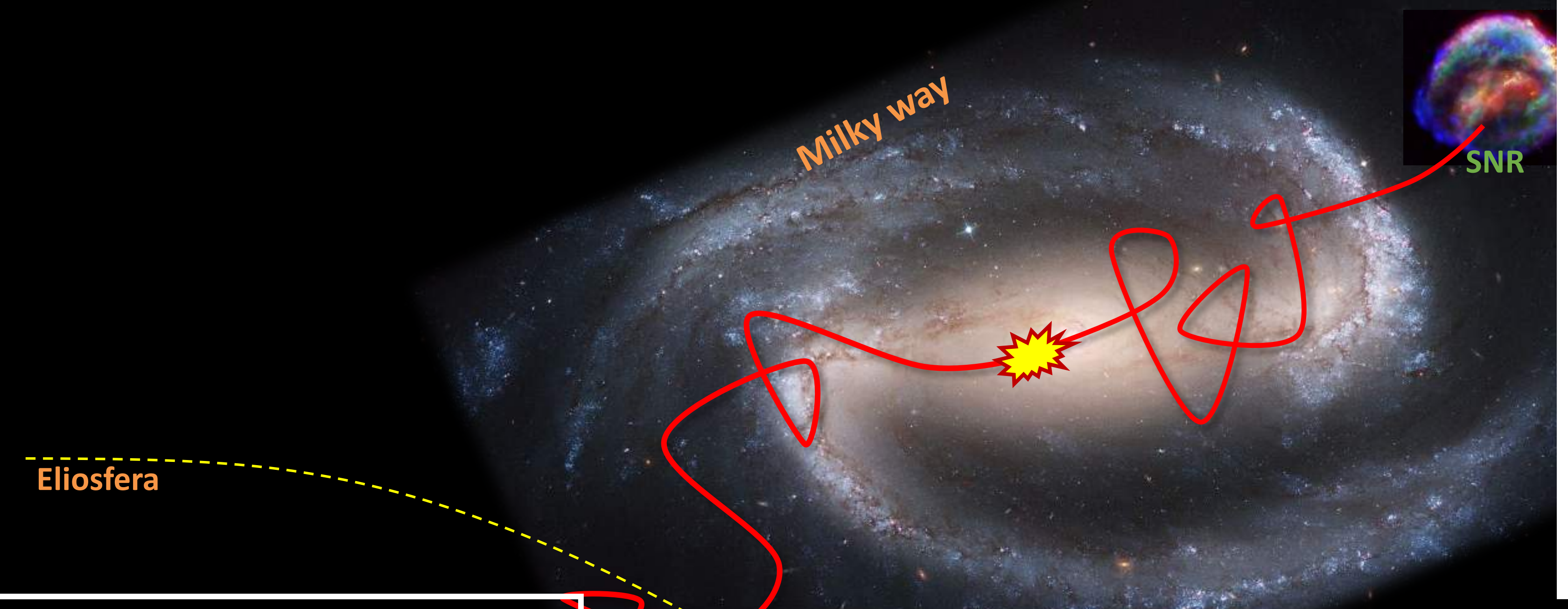
Cosmic rays, galactic messengers

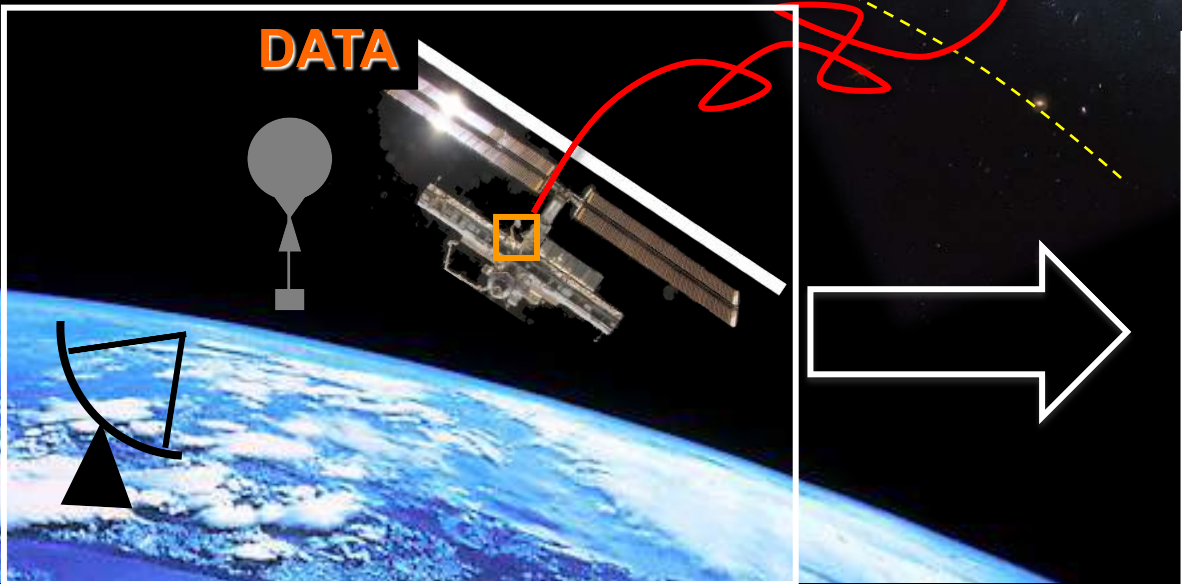
From supernova explosions to their detection near-Earth

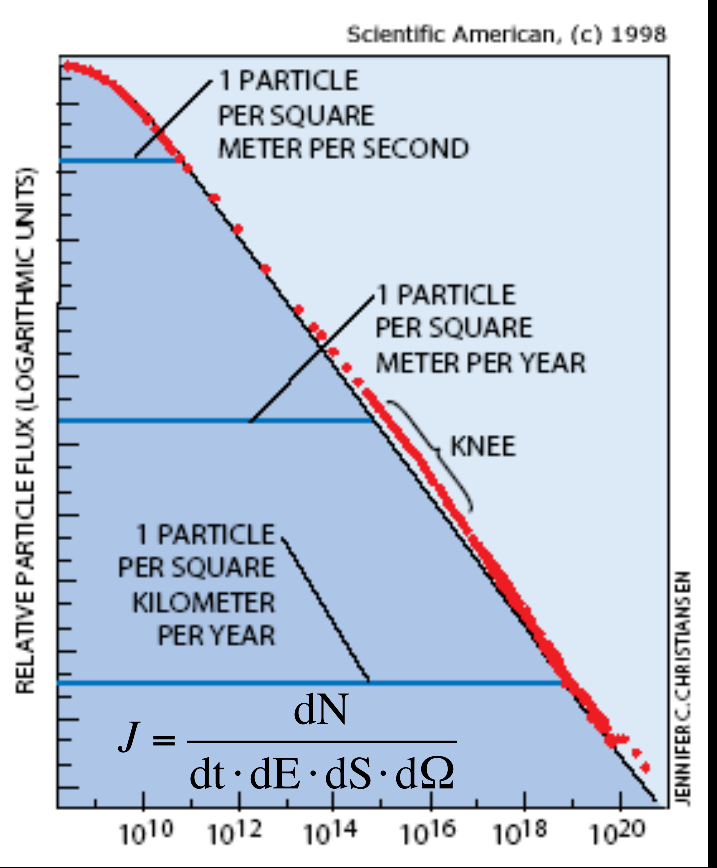


Observations

From ground telescopes, balloons and space experiments

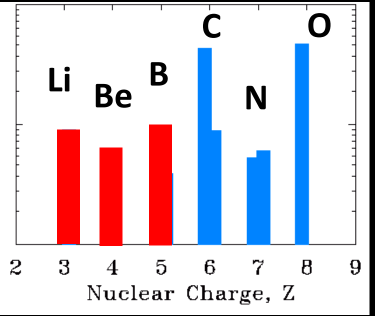


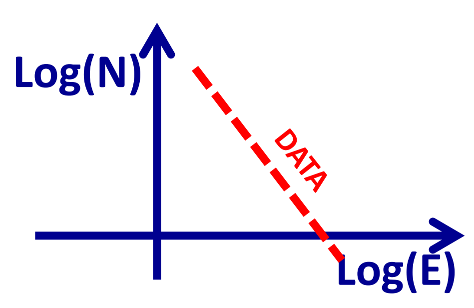




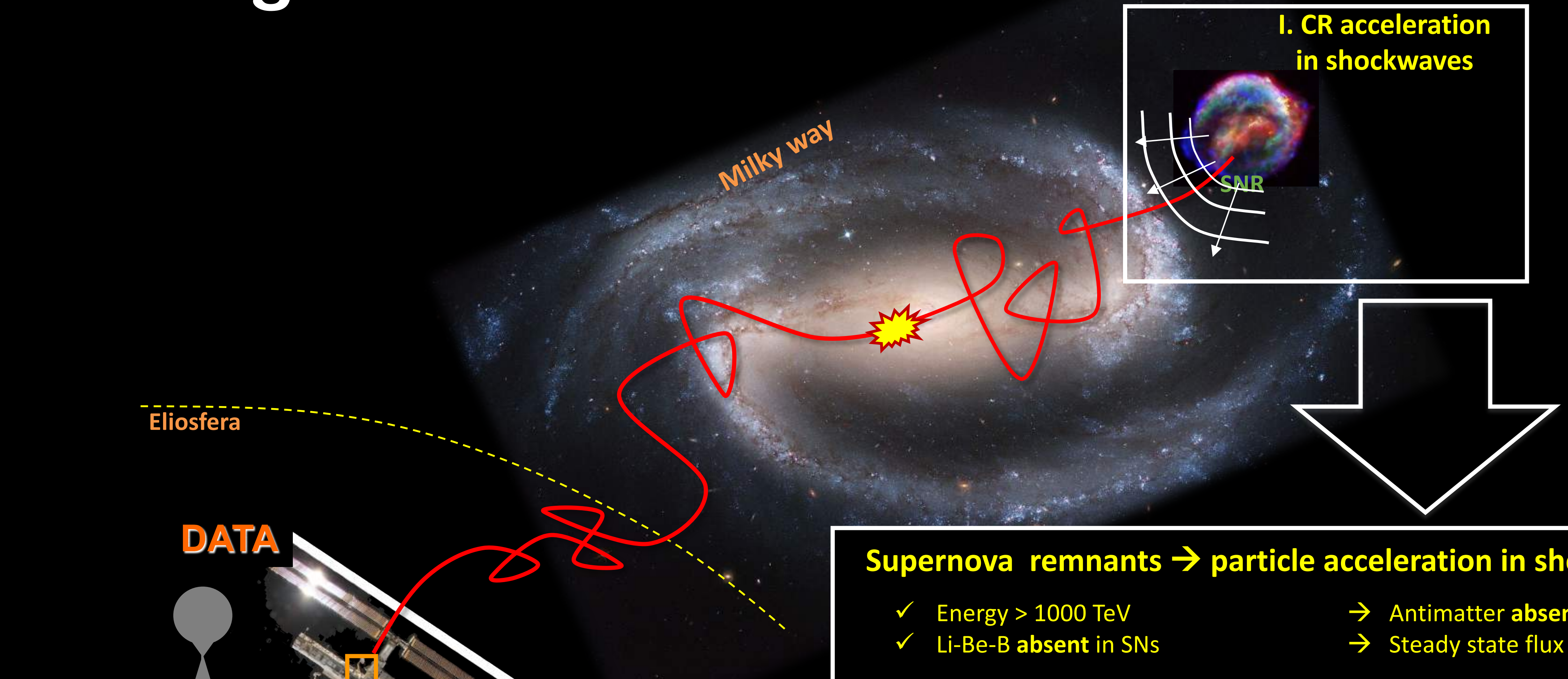
Basic observations

- ✓ Power-law spectrum to very high-energy
- ✓ **Energy density ~ 1 eV /cm3**
- ✓ All elements + antimatter
- ✓ High degree of isotropy
- ✓ Near-earth flux varies with time



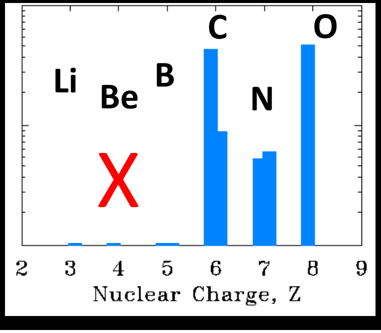


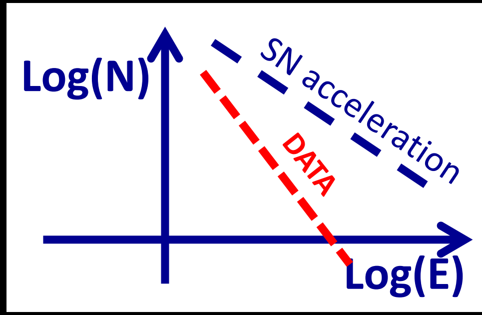
I. Origin and acceleration



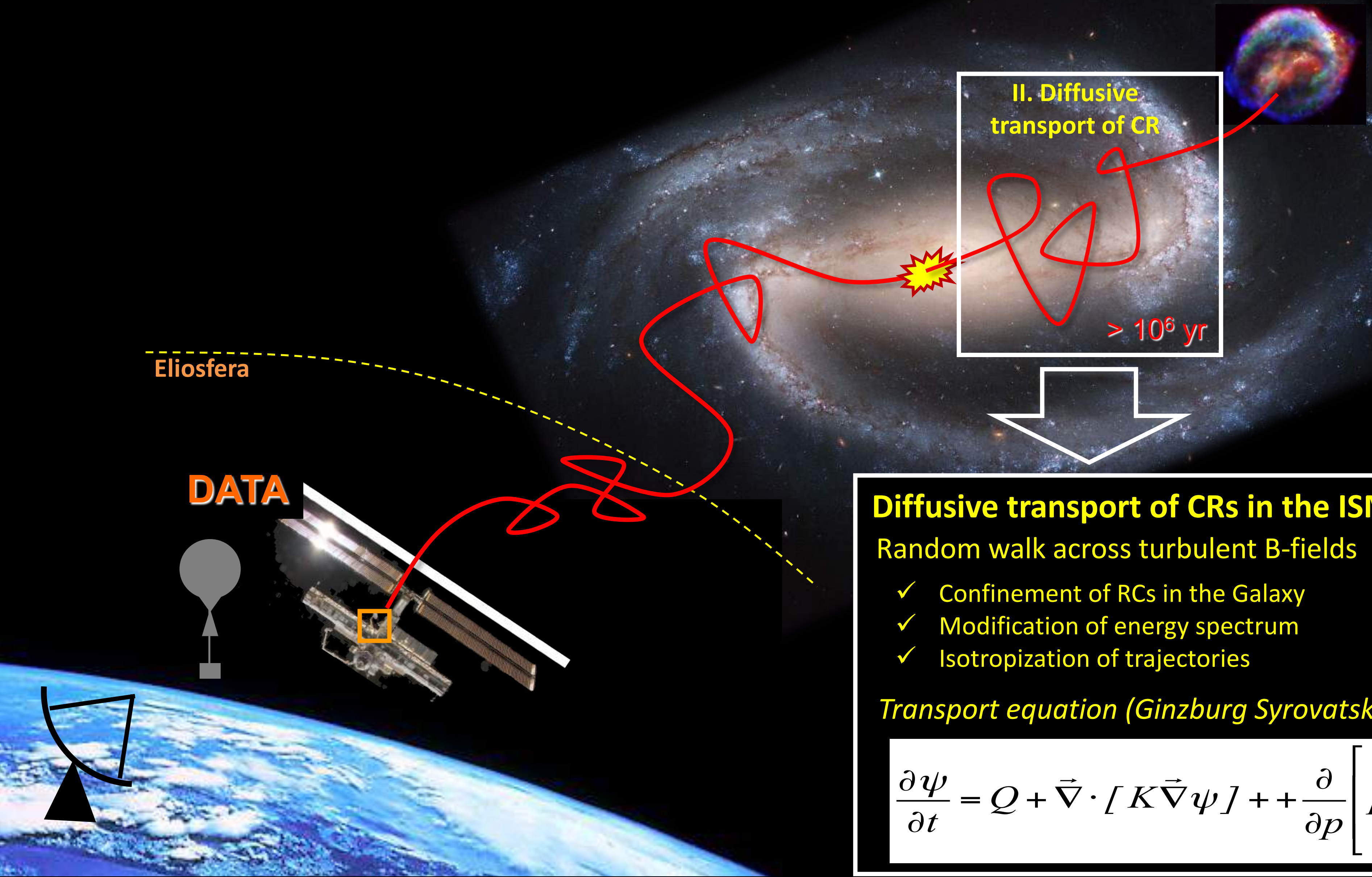
Supernova remnants → particle acceleration in shockwaves

- ✓ Energy > 1000 TeV
- ✓ Li-Be-B **absent** in SNs
- → Antimatter **absent** in SNs
- → Steady state flux





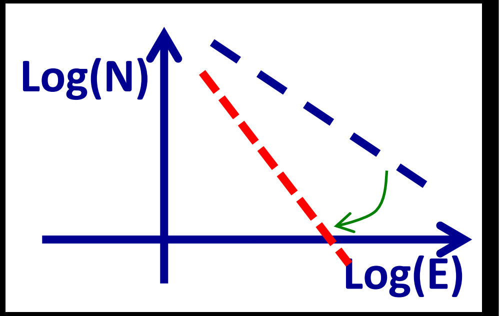
II. Diffusive transport



Diffusive transport of CRs in the ISM

Random walk across turbulent B-fields

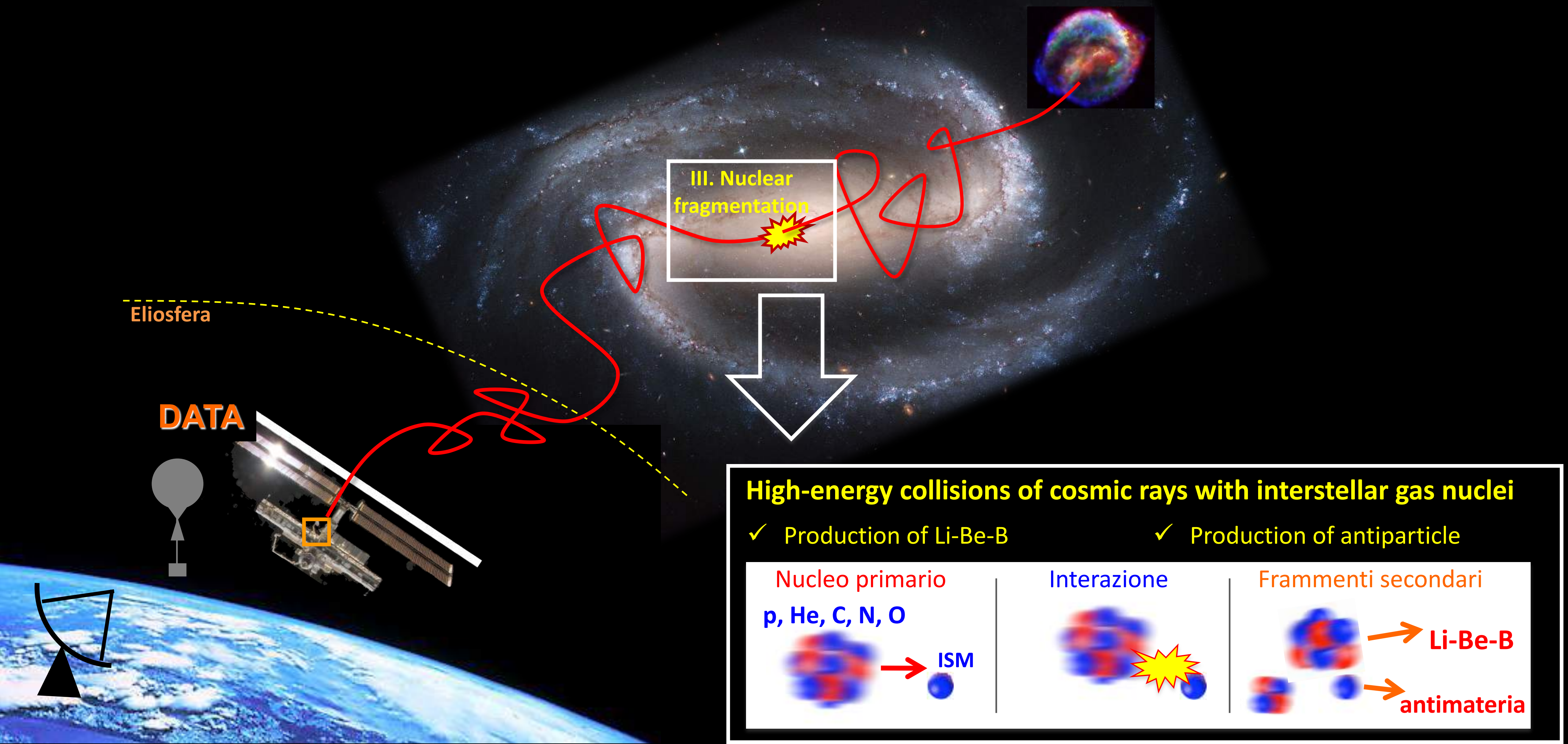
- ✓ Confinement of RCs in the Galaxy
- ✓ Modification of energy spectrum
- ✓ Isotropization of trajectories



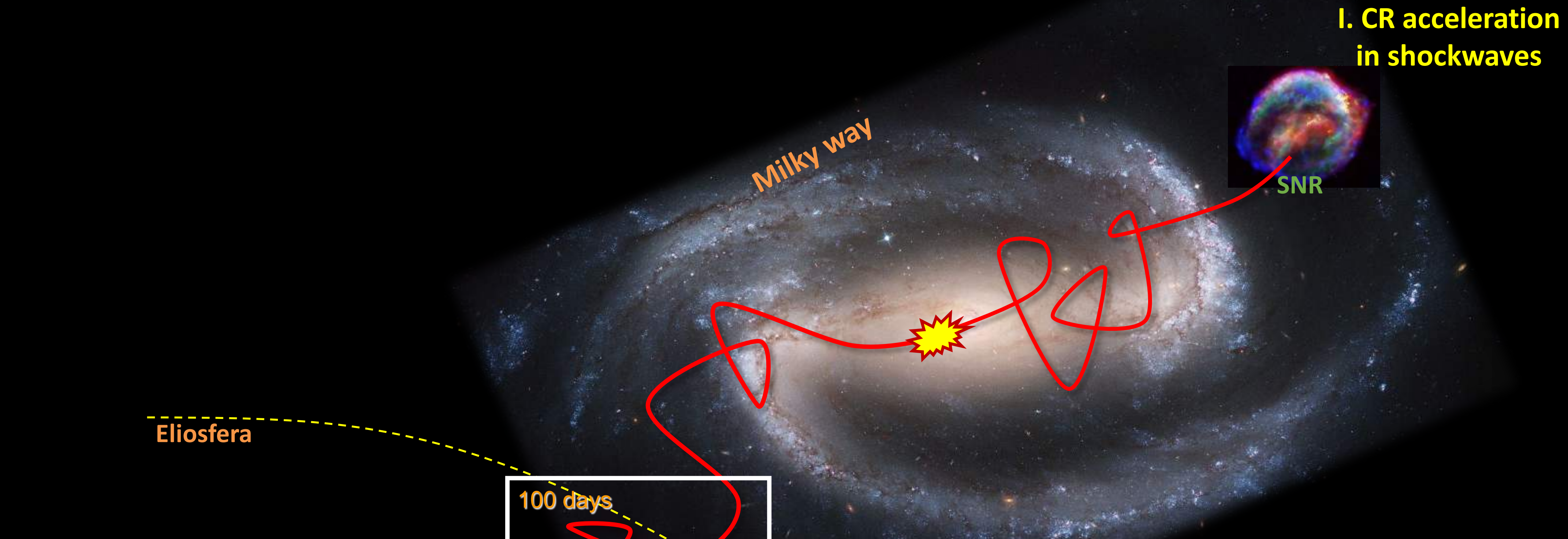
Transport equation (Ginzburg Syrovatsky)

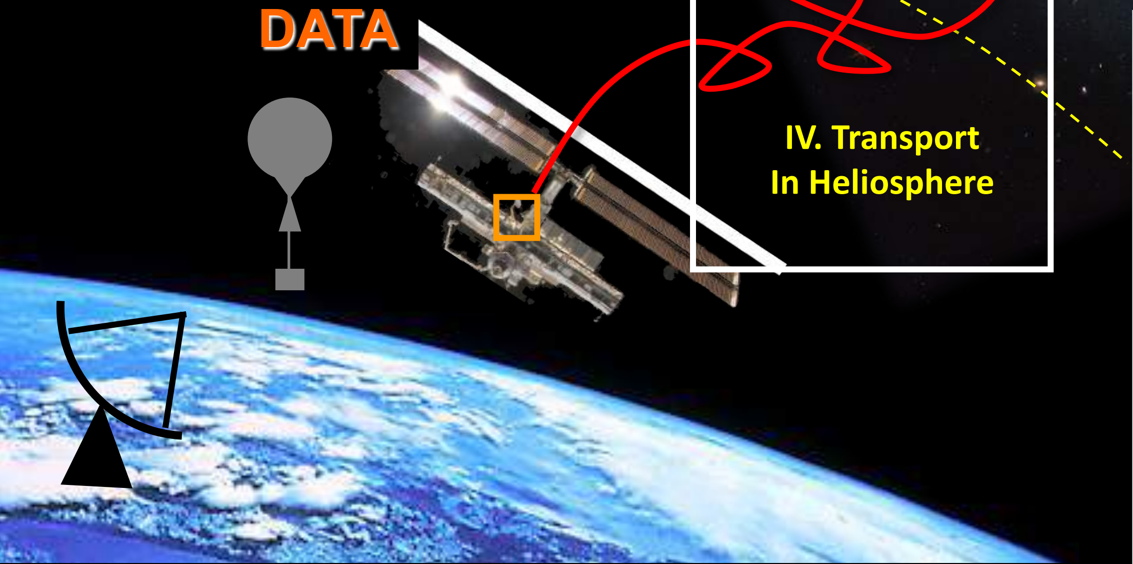
$$\frac{\partial \psi}{\partial t} = Q + \vec{\nabla} \cdot [\, K \vec{\nabla} \psi \,] + + \frac{\partial}{\partial p} \left[p^2 K_{pp} \frac{\partial}{\partial p} \frac{\psi}{p^2} - \dot{p} \psi \right] + - \Gamma_d \psi$$

III. Nuclear interactions



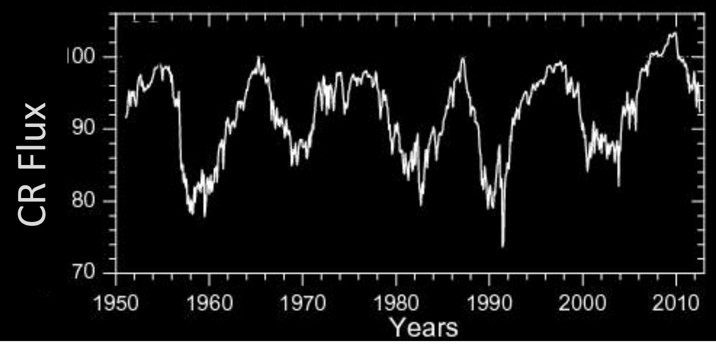
IV. Solar modulation

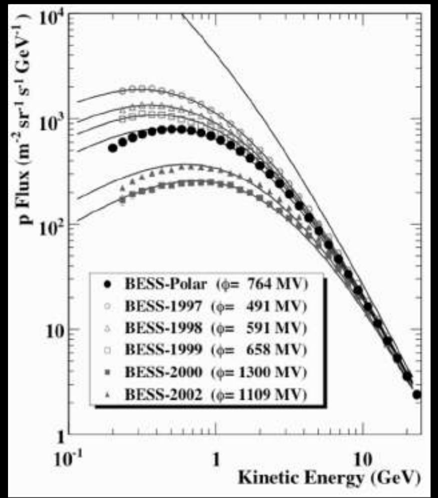




Interaction of cosmic rays with Solar plasma

- ✓ **Variability,** following the 11-year Sun's activity cycle
- ✓ Influence on the low-energy part of the CR spectrum





Toward consistent theory of CR origin and propagation in Galaxy

Observations

- ✓ Energy spectrum and intensity
- ✓ High degree of isotropy
- ✓ Presence of Li-Be-B and antimatter
- ✓ Temporal variability of the CR flux intensity

Established physics mechanisms

I. Nonthermal acceleration in Galactic sources
II. Diffusive transport in Galactic turbulence
III. Nuclear interactions with interstellar gas
IV. Transport and losses in the helisophere

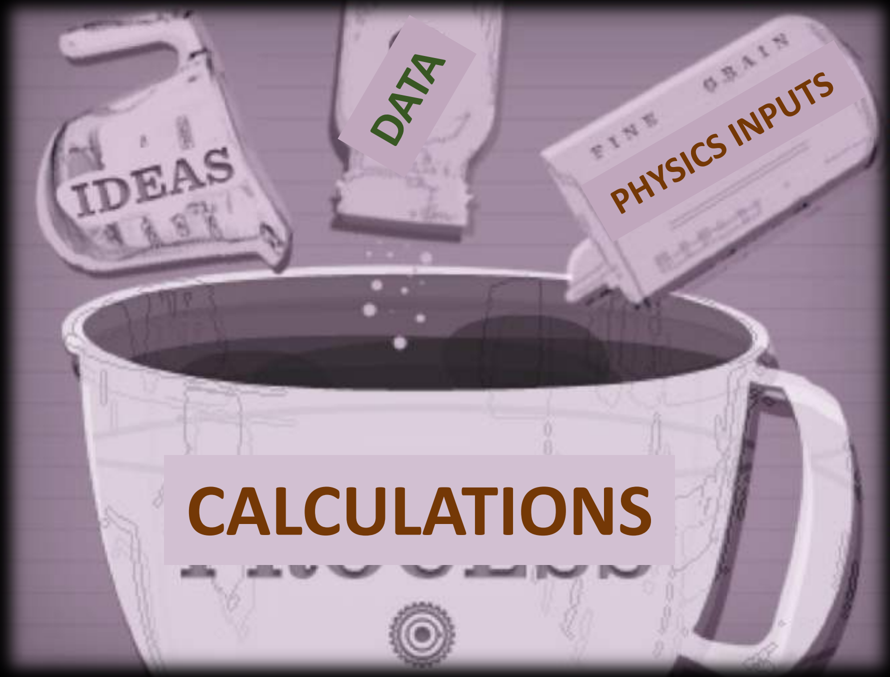
Present epoch: golden age of CR measurements
→ We are continuously challenged by the data

Opportunity to advance in open problems

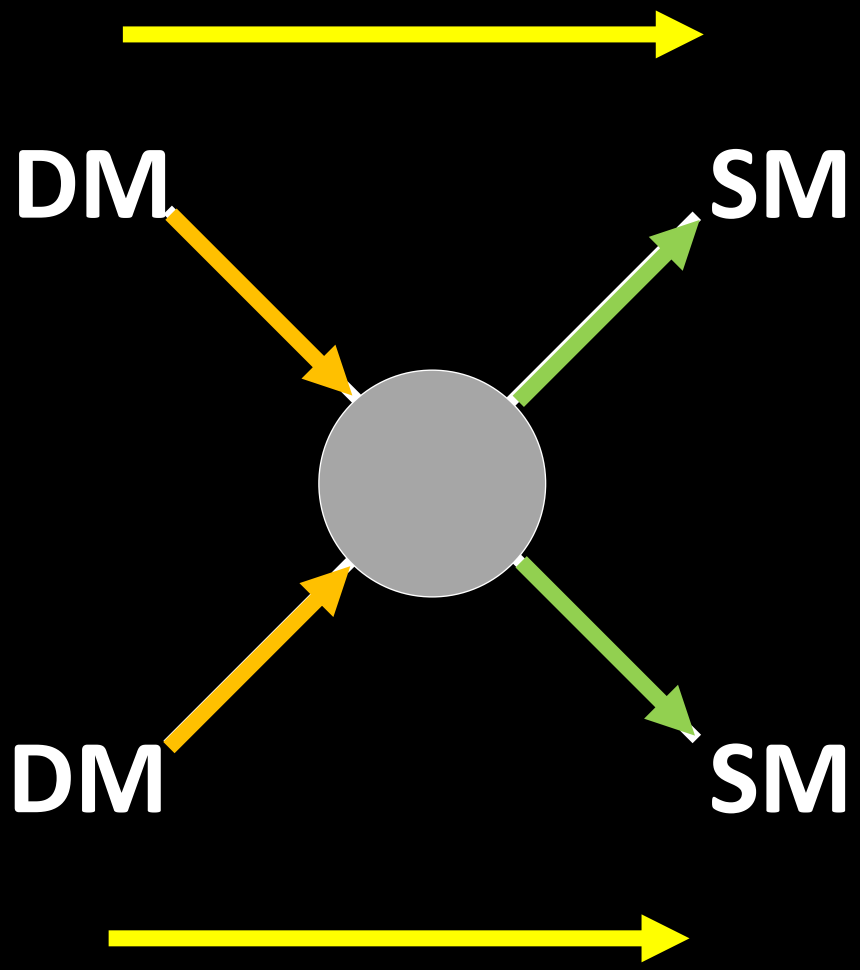
- Origin of cosmic rays
- Origin of cosmic antimatter
- Nature of dark matter

Interesting connections with other fields

- Cosmology and relativistic astrophysics
- Nuclear and particle physics
- Plasma physics, solar science, space weather



Dark matter search with cosmic rays



Annihilation in space

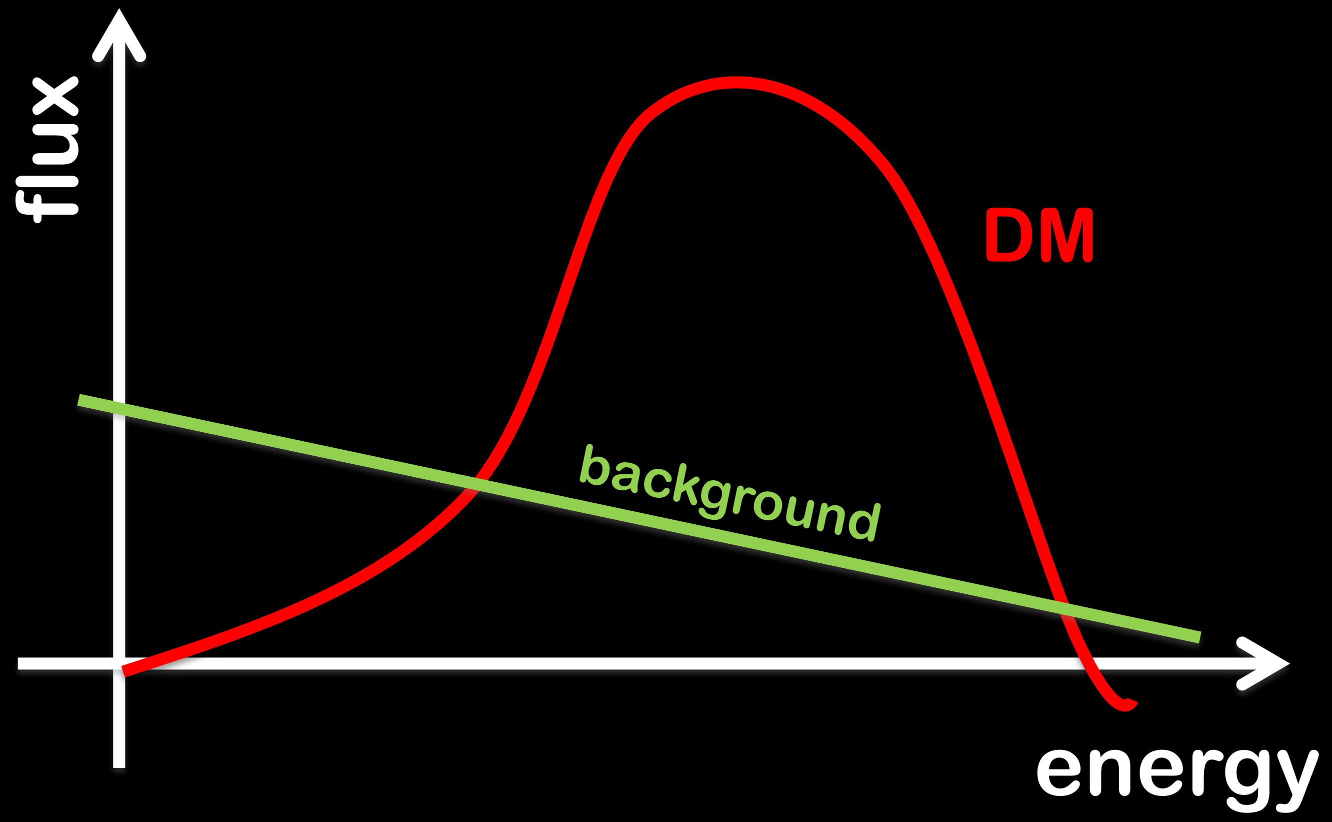
DM+DM --> (…) --> SM + SM

- ✓ Known particles
- ✓ Detectable
- ✓ Otherwise rare

AMS-02, GAPS, PAMELA, CALET, DAMPE

Dark matter search with cosmic rays

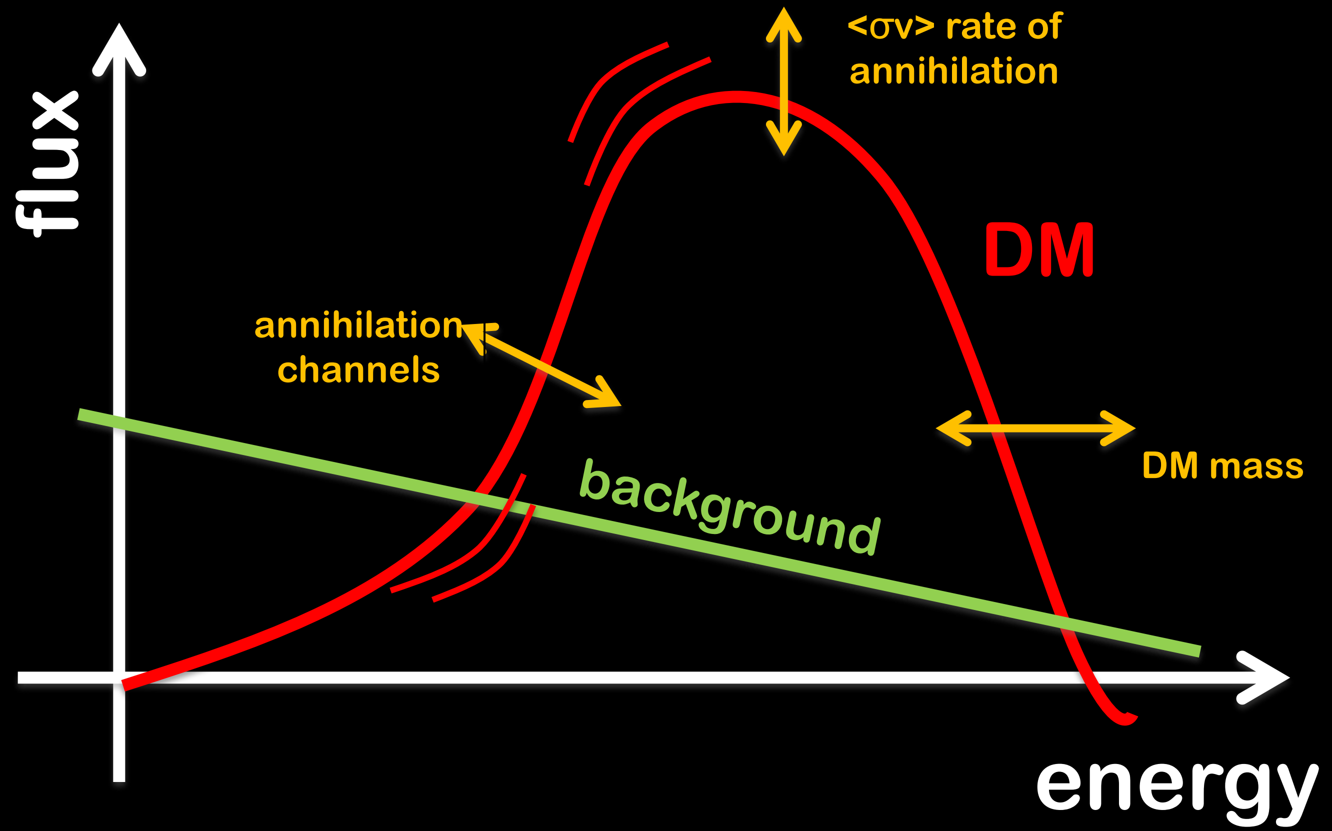
$$\chi + \chi \longrightarrow (\dots) \longrightarrow e^{\pm}, \overline{p}, \overline{d}, \overline{He}$$



We search for a signal excess over the astrophysical background

Dark matter search with cosmic rays

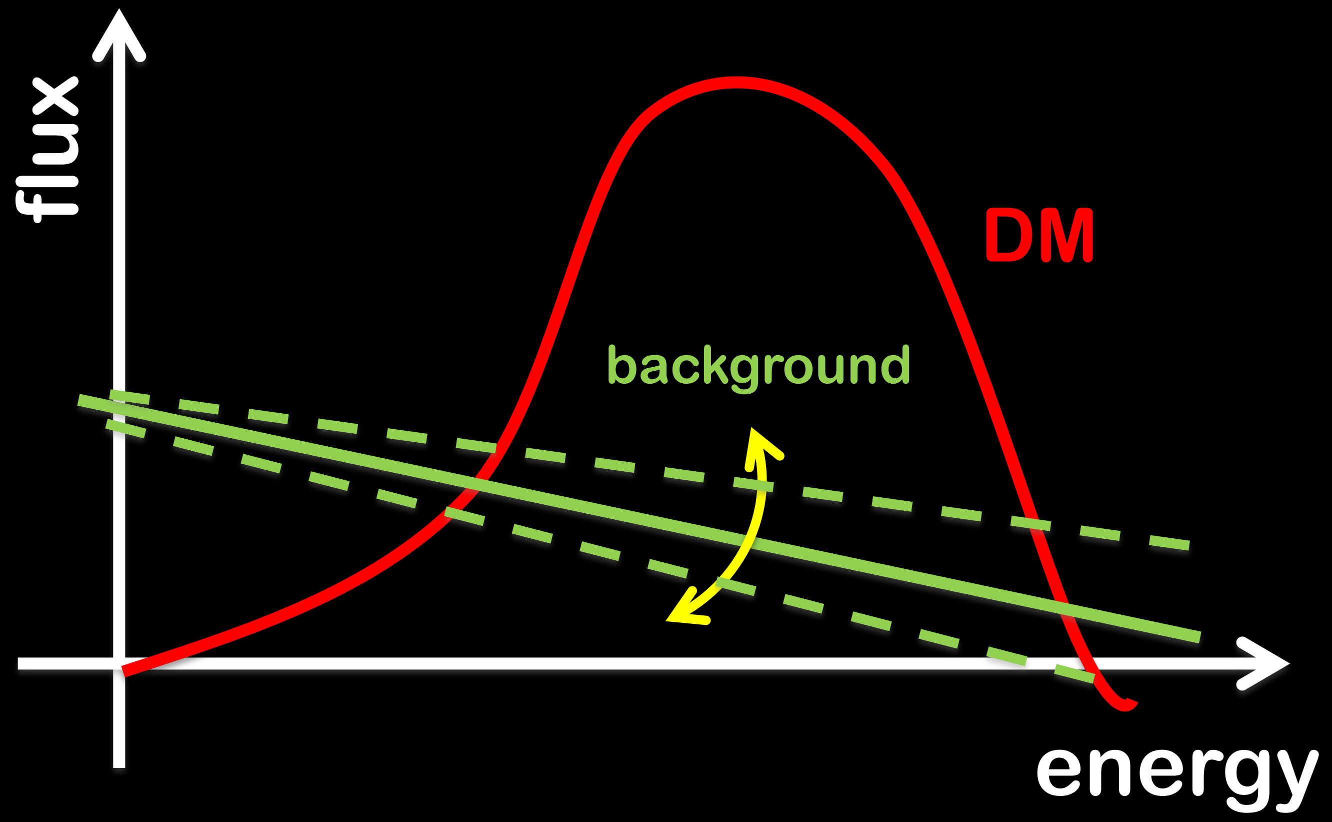
$$\chi + \chi \longrightarrow (\ldots) \longrightarrow e^{\pm}, \overline{p}, \overline{d}, \overline{He}$$



The spectral shape of the signal depends on the DM properties

Dark matter search with cosmic rays

$$\chi + \chi \longrightarrow (\ldots) \longrightarrow e^{\pm}, \bar{p}, \bar{d}, \overline{He}$$



The BG relies on astrophysical models of CR propagation -> nuclear data e.g. B/C

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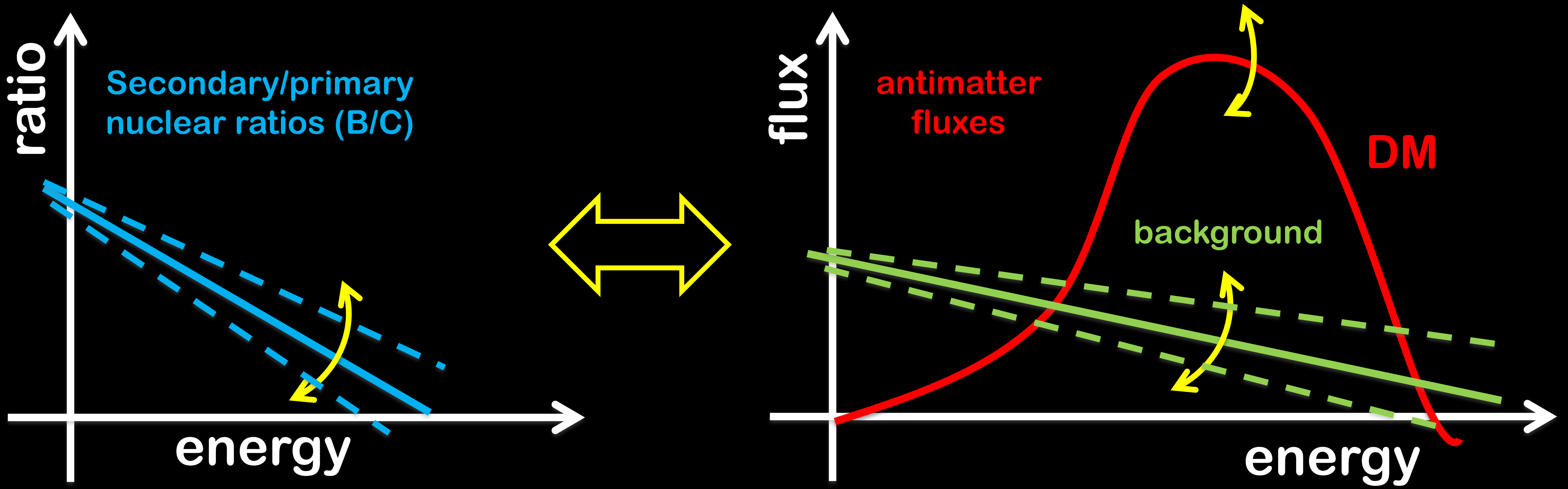


The BG relies on astrophysical models of CR propagation -> nuclear data e.g. B/C

The physical picture

Standard paradigm based on three pillars

- Shock acceleration in SNRs: p-He-C-O
- Diffusive transport within a magnetic halo
- Interactions with ISM gas→ Li-Be-B & antimatter

Implicit assumptions: homogenity, isotropy, stationarity, linearity

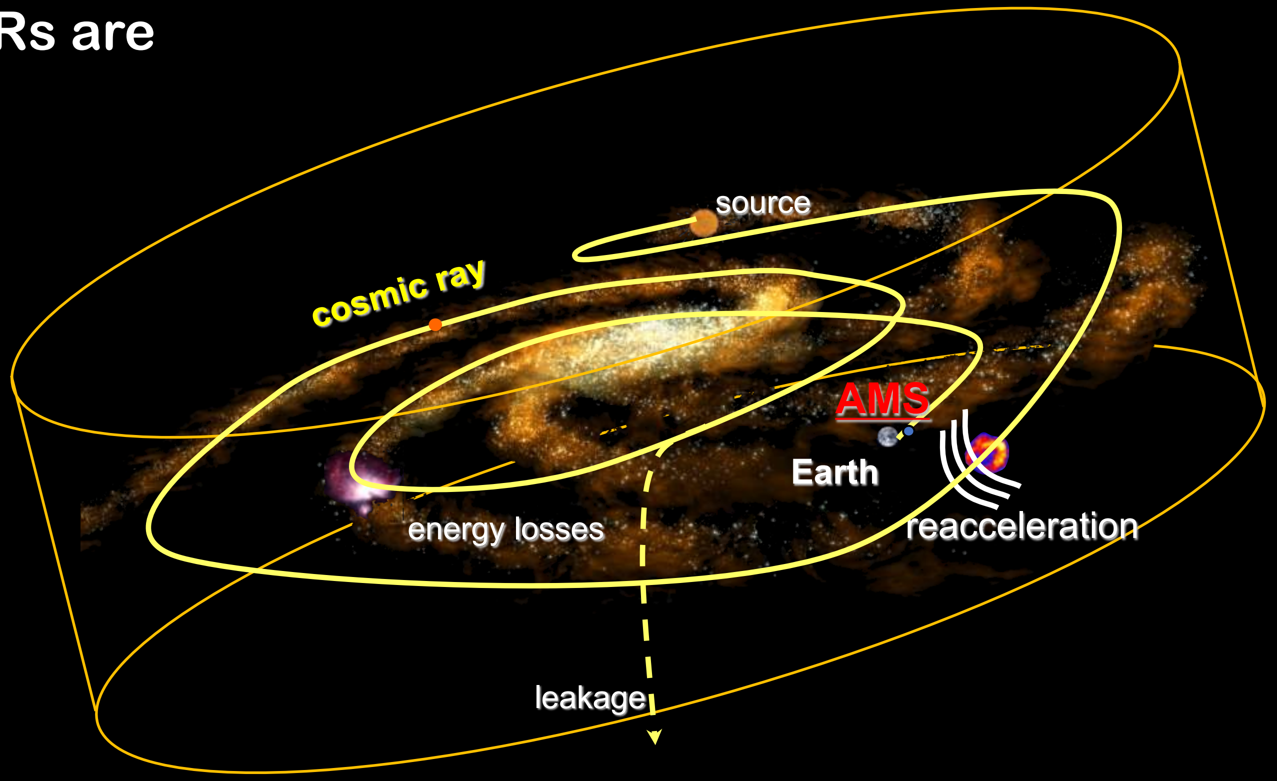
After accelerated and injected in the ISM, CRs are confined in the Galaxy, with $T \approx L^2/K$

They spend millions of years in the Galaxy before escape or destruction

Their diffusion becomes faster with increasing rigidity R = p/Z

$$K = \frac{v}{3}\lambda(R) \sim R^{\delta}$$

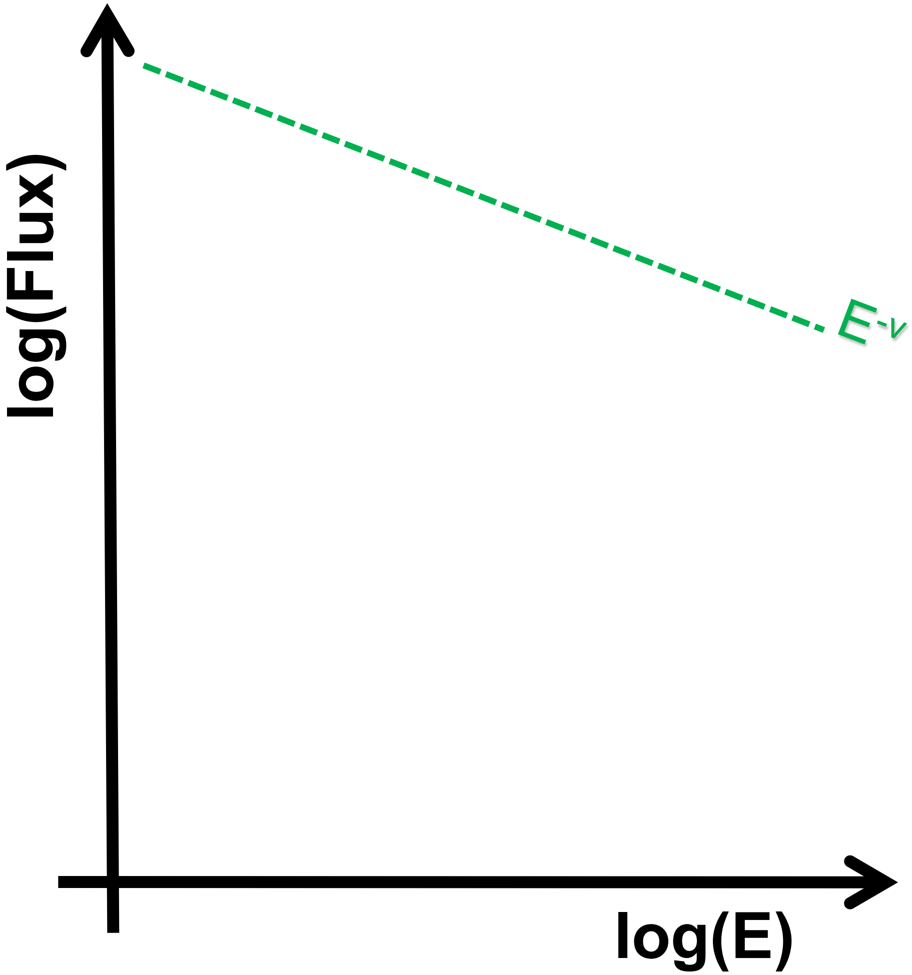
Particles with higher R (E) escape faster

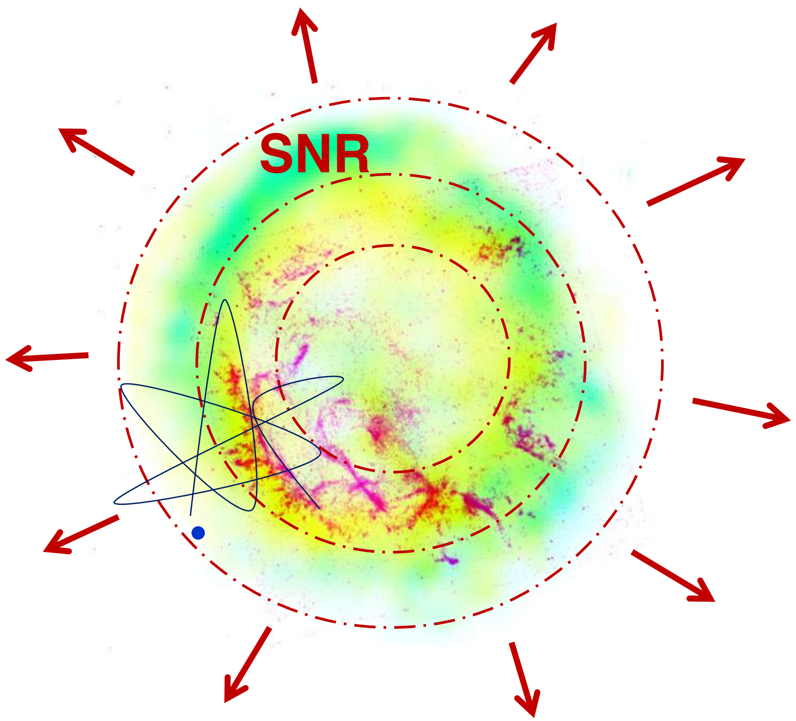


What makes the cosmic-ray energy spectra

Shock accelerated primaries: N(p) ~ $E^{-\nu}$

Primary particles, synthetized in stellar processes: **p, He, C-N-O, Si, Fe**





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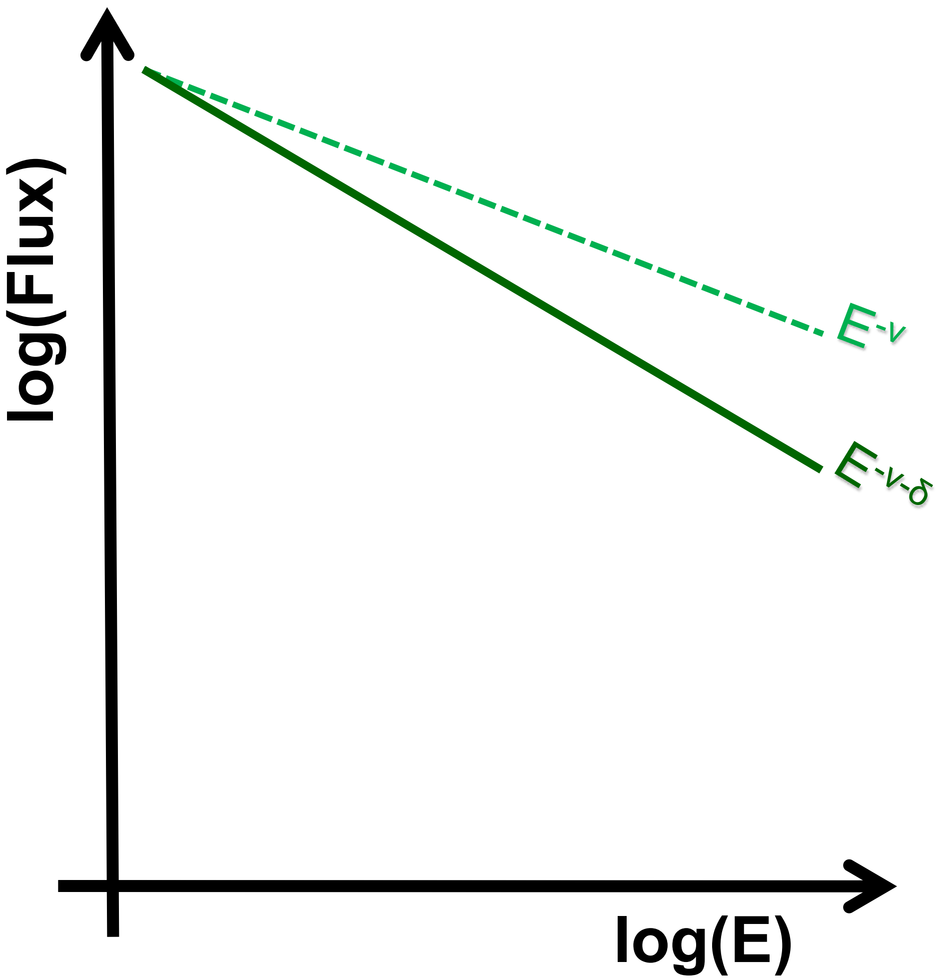
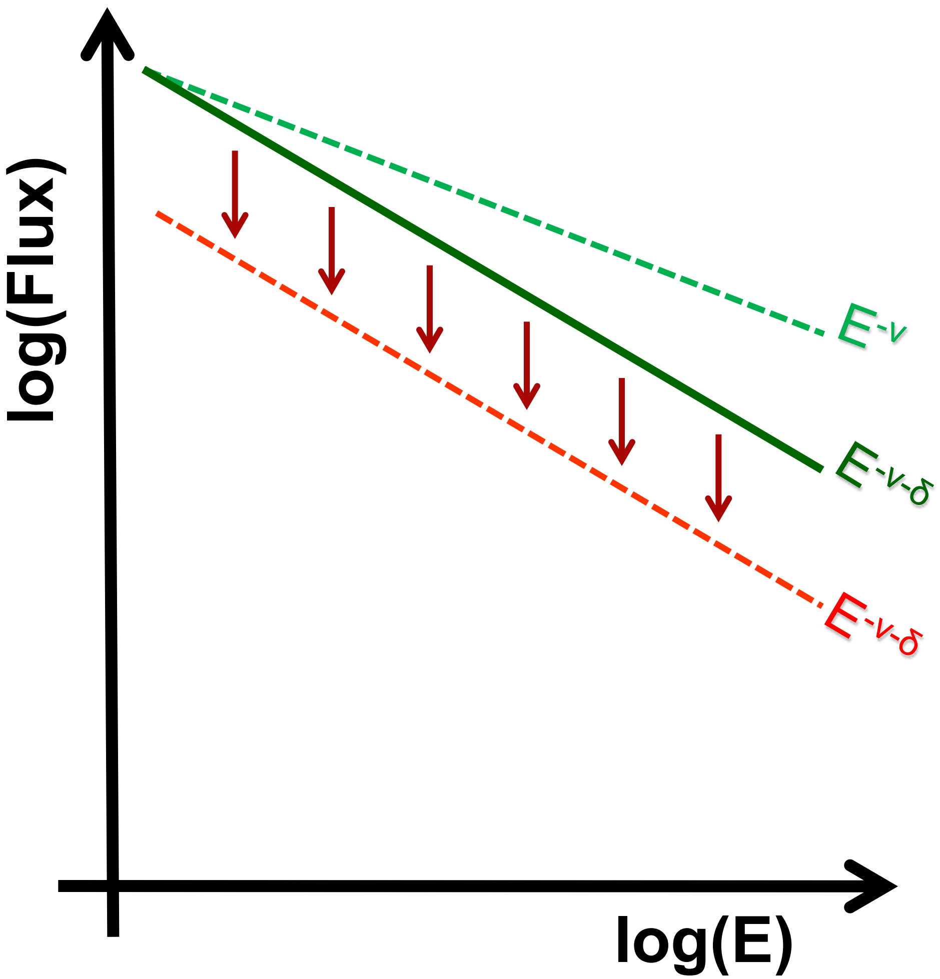


Shock accelerated primaries: $N(p) \sim E^{-\nu}$

Primaries at equilibrium: $N(p) \sim E^{-\nu-\delta}$

(diffusion coefficient in galaxy $K(E) \sim E^{+\delta}$)

What makes the cosmic-ray energy spectra



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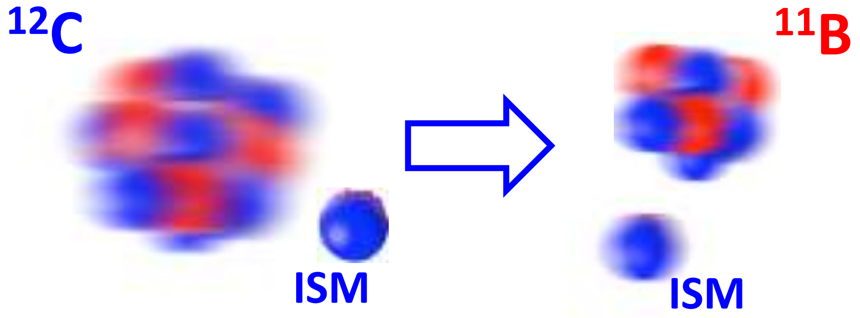
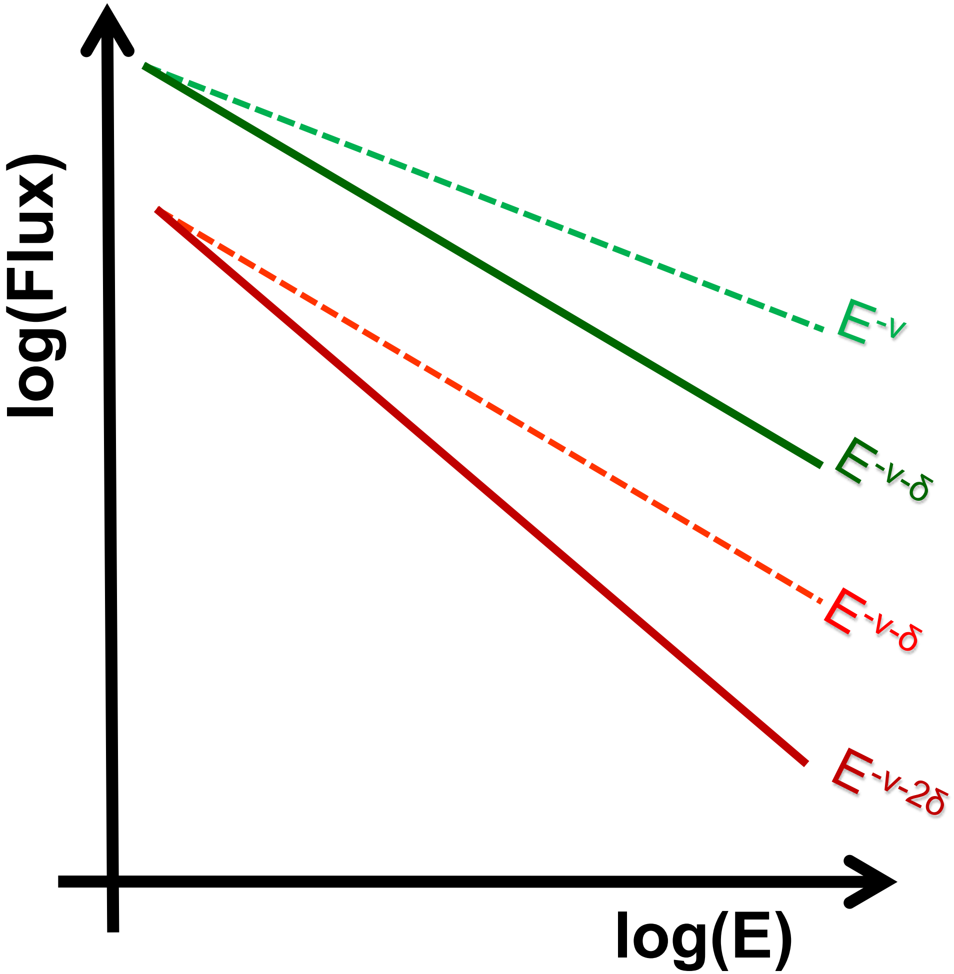
Secondaries generated from spallation: n(p) ~ $E^{-\nu-\delta}$



Straight ahead fragmentation
→ KE/nucleon is conserved

2H, 3He, Li-Be-B, F, Ti, V

What makes the cosmic-ray energy spectra



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Secondaries from spallation at equilibrium: $n(p) \sim E^{-\nu-2\delta}$

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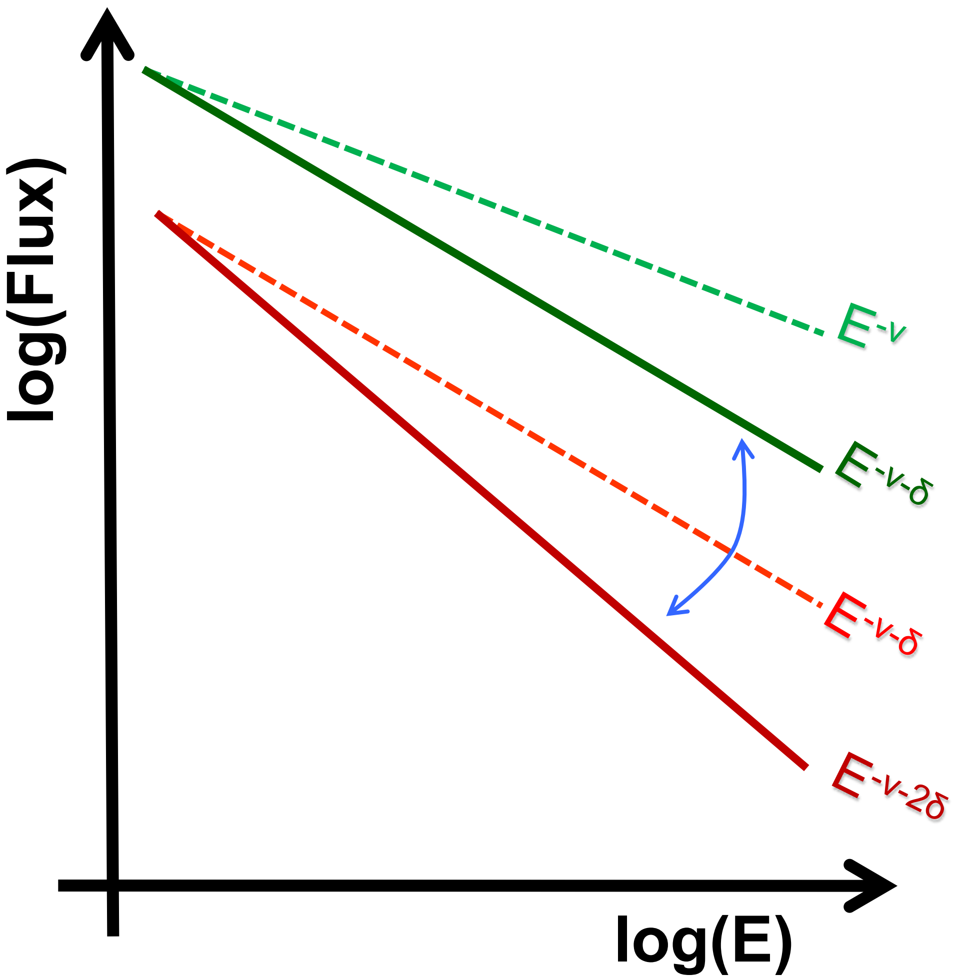
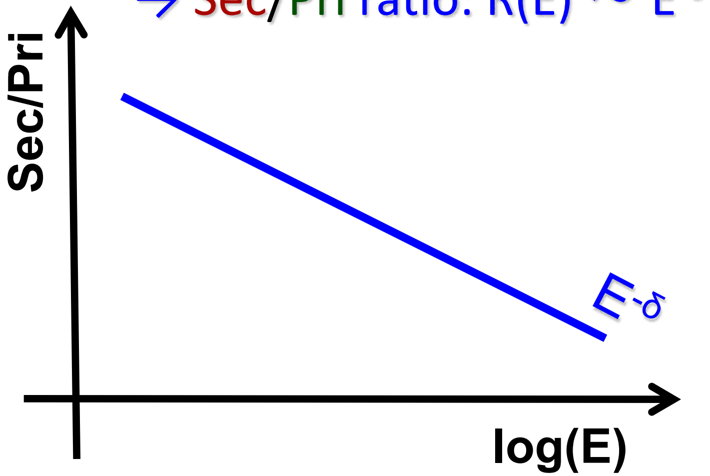
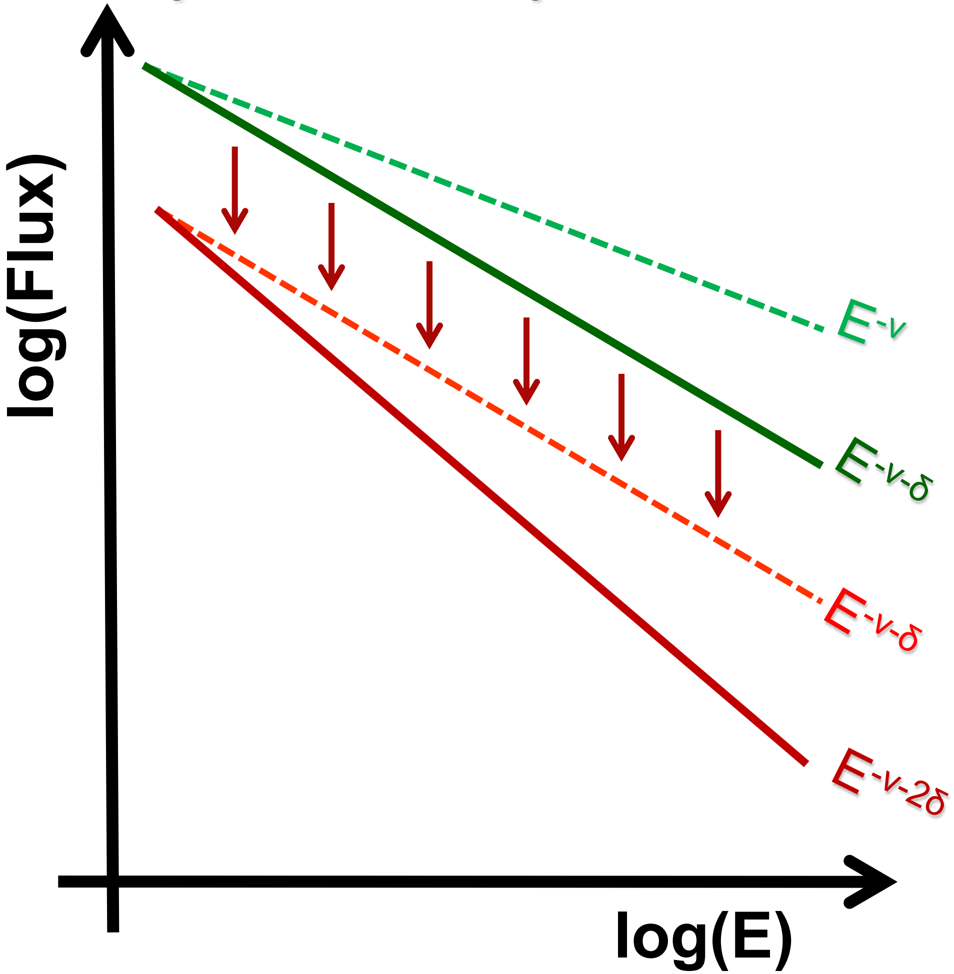


→ Sec/Pri ratio: $R(E) \sim E^{-\delta}$



What makes the cosmic-ray energy spectra

Pri + ISM -> Sec + X
production processes



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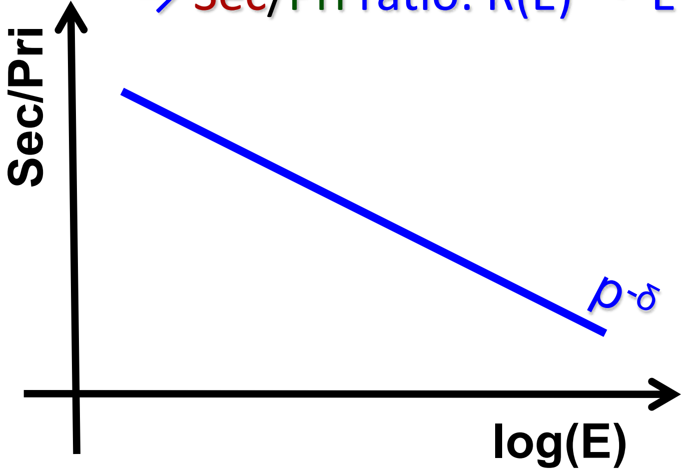
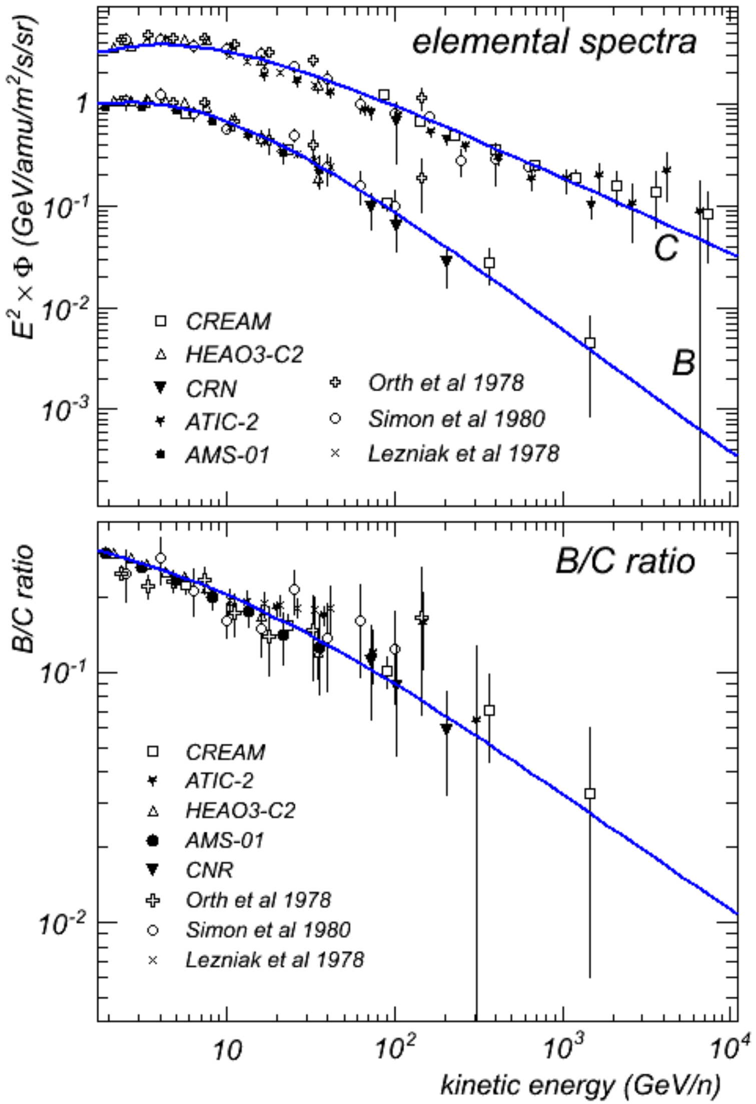
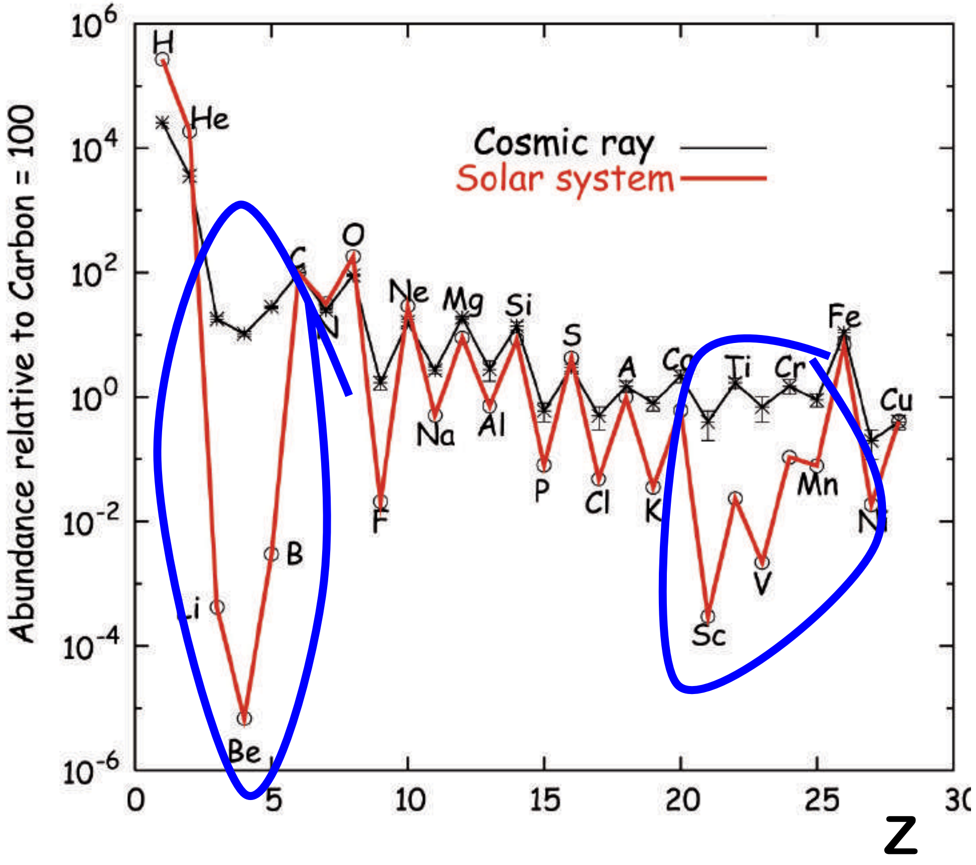
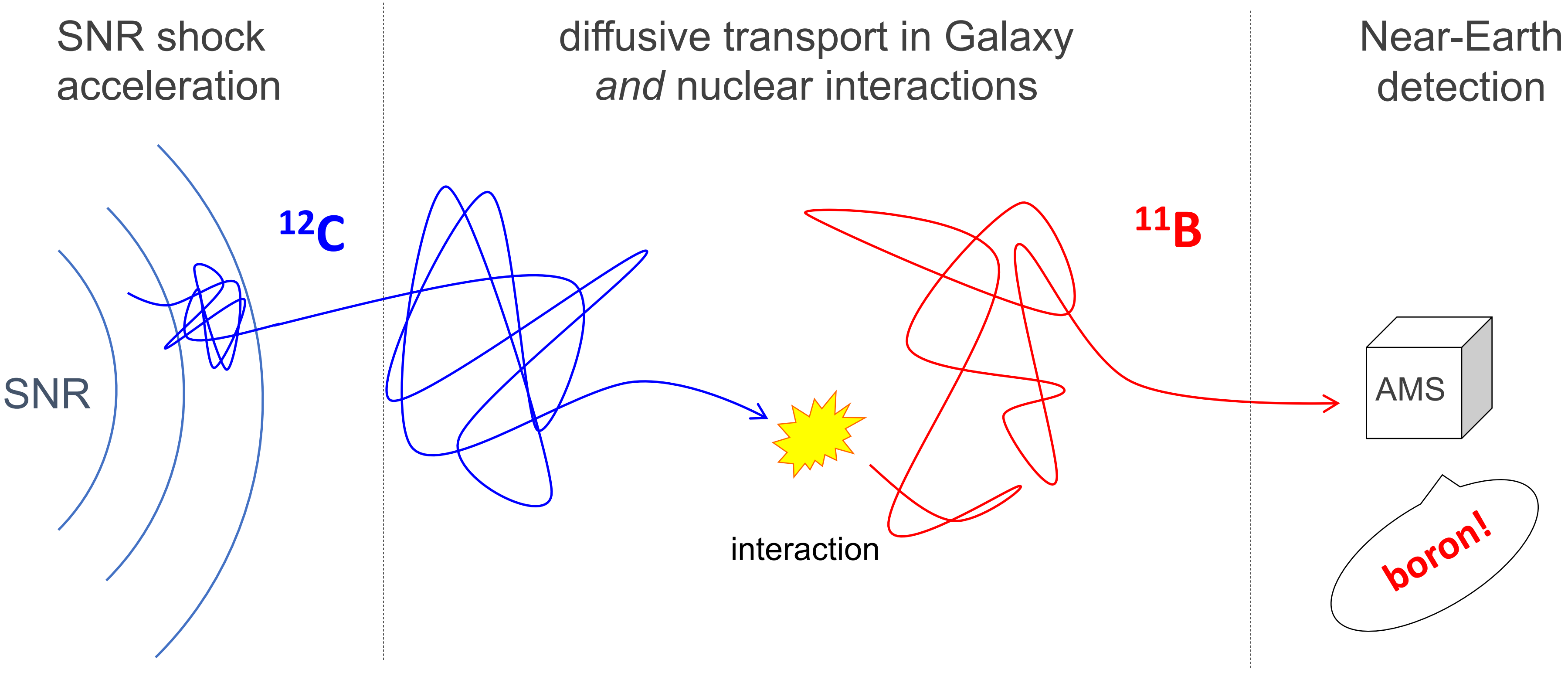


Basic predictions: secondary nuclei abundance

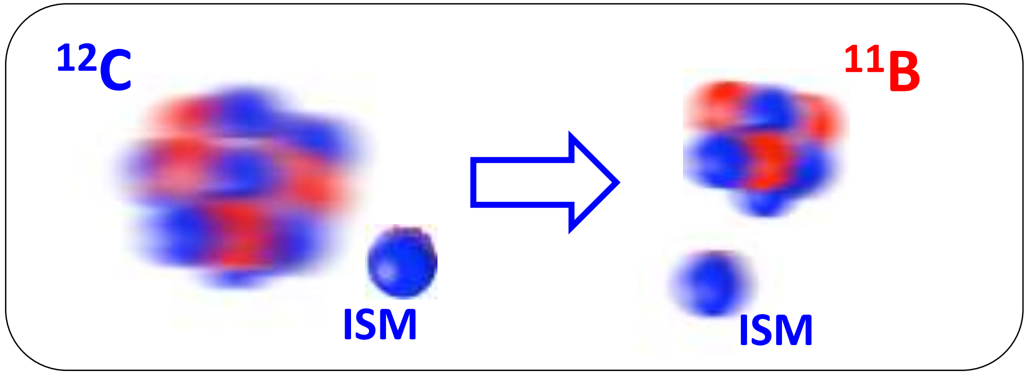




The physical picture

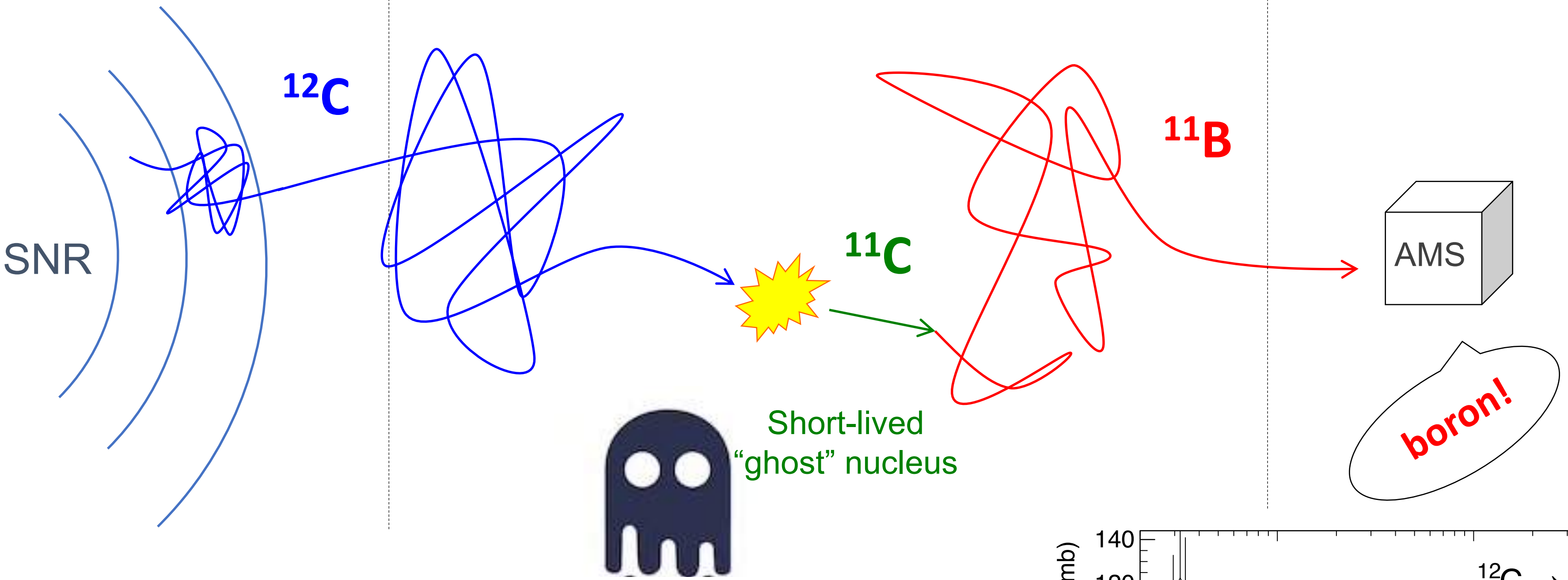


^{12}C+ISM ---> $^{10,11}B$
^{16}O+ISM ---> $^{10,11}B$
^{15}N+ISM ---> $^{10,11}B$
^{28}Si+ISM ---> $^{10,11}B$



The physical picture

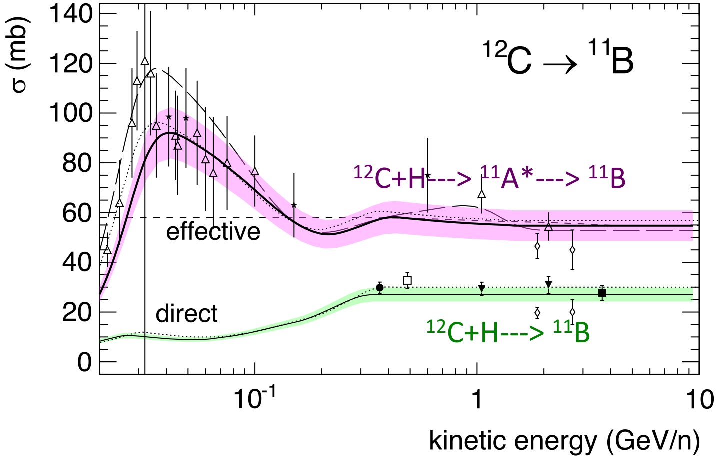
SNR shock acceleration | diffusive transport in Galaxy *and* nuclear interactions | Near-Earth detection



- Acting as virtual particles for CR propagation
- Effective (cumulative) cross-sections used

^{12}C+ISM ---> ^{11}B

^{12}C+ISM ---> ^{11}C* --->^{11}B



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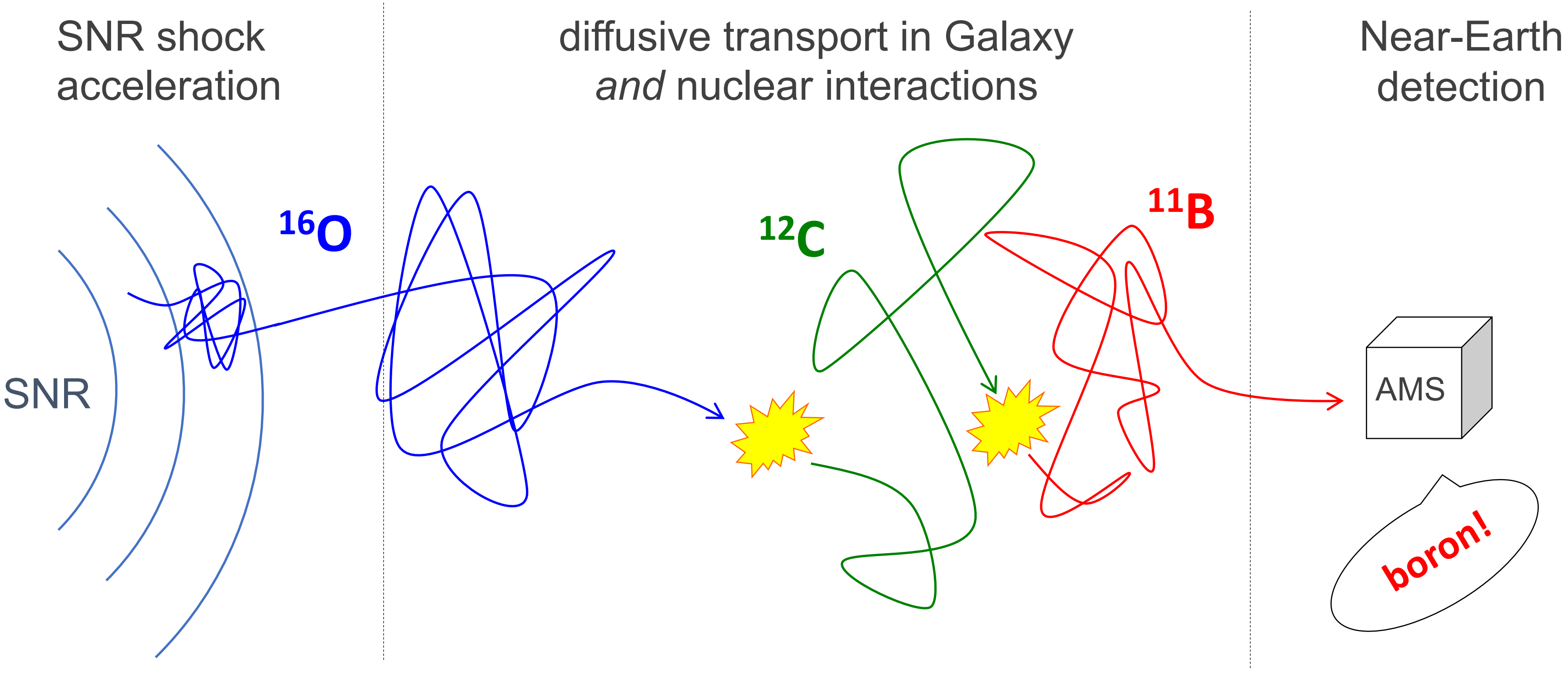
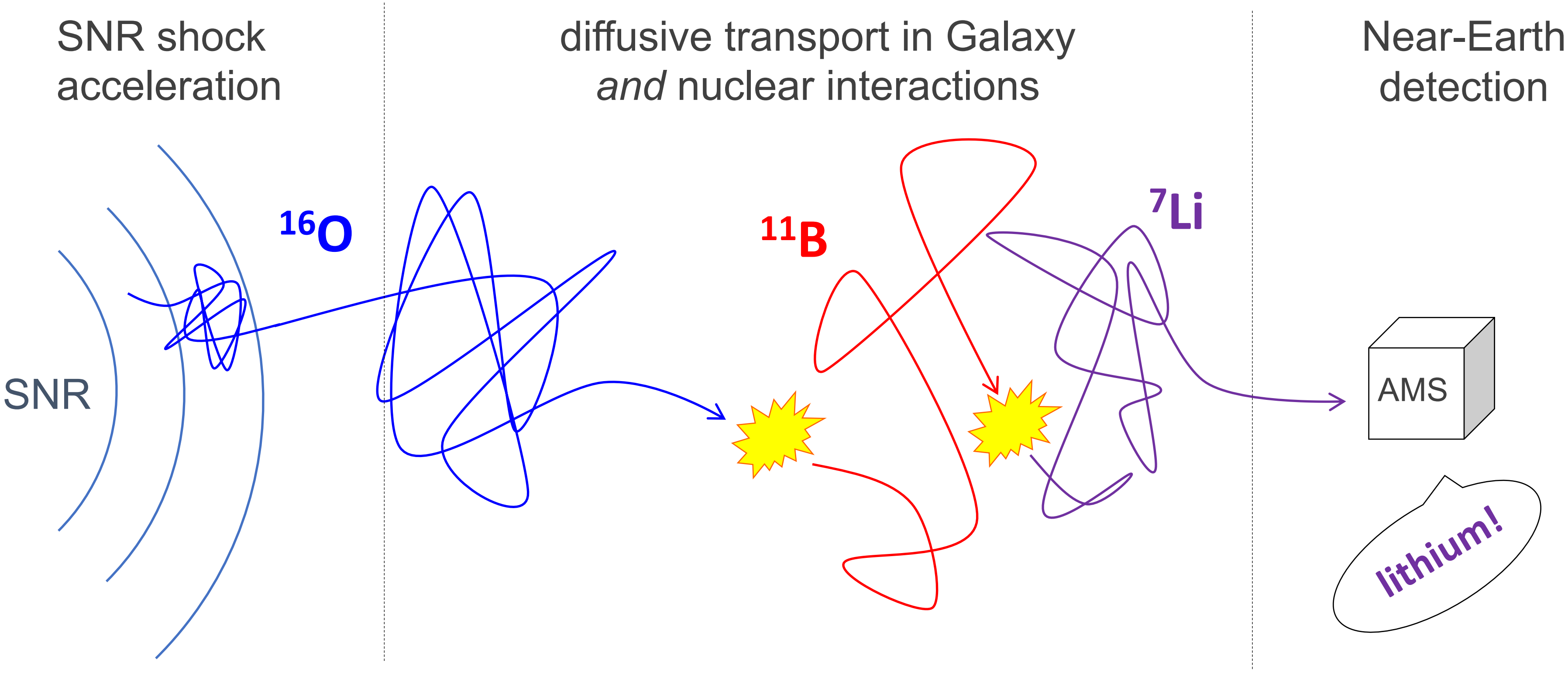


- Long-lived (or stable) intermediate nuclei
- CR propagation must be accounted
- Multi-step nature of fragmentation

Stable, interacting again with the gas

The physical picture



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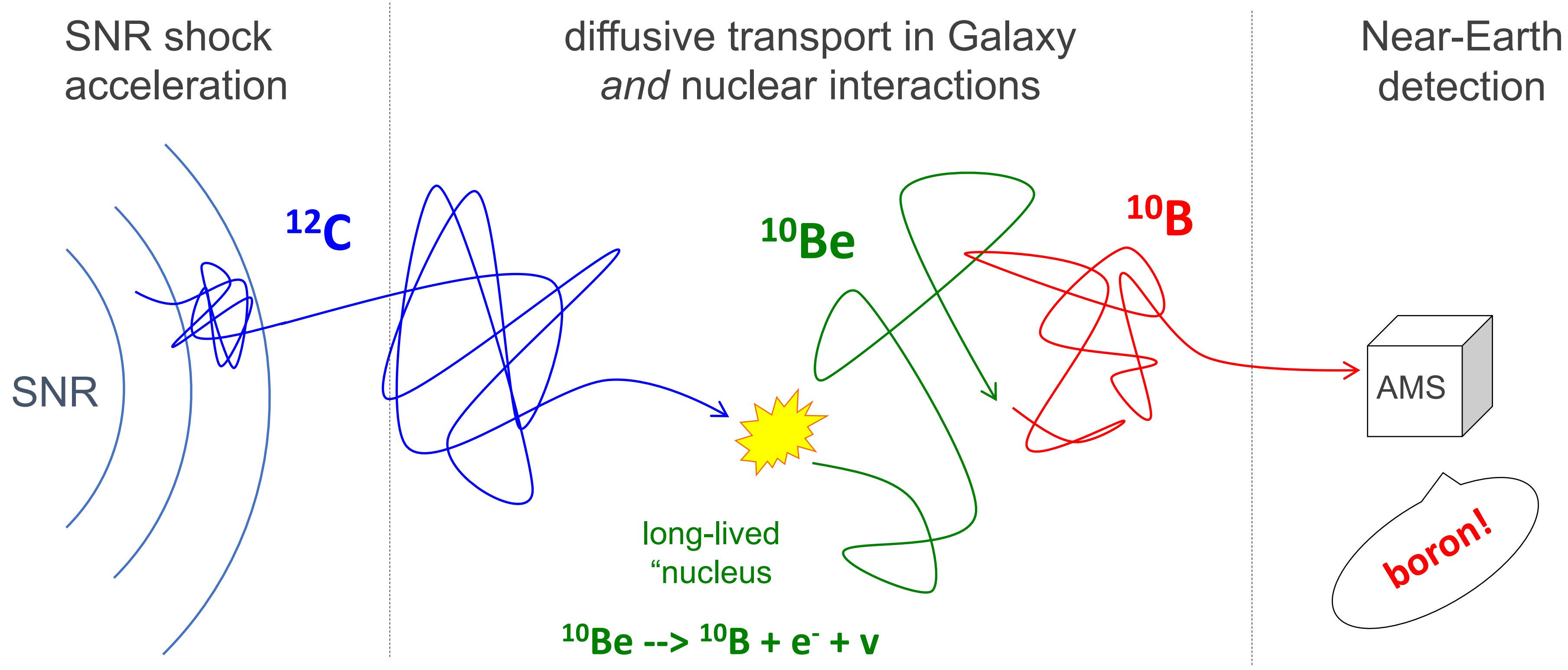


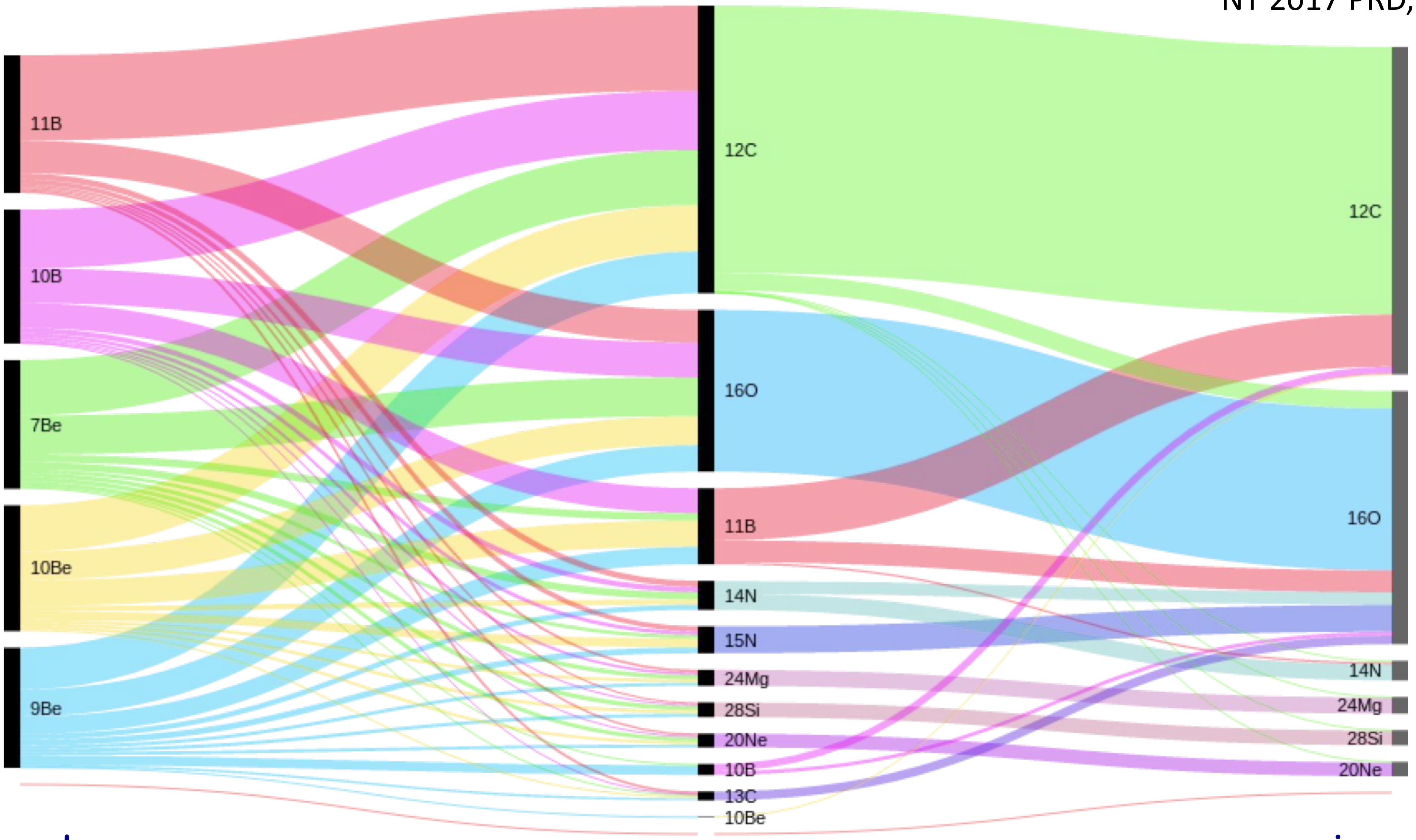
- Long-lived (or stable) intermediate nuclei
- CR propagation must be accounted
- Multi-step nature of fragmentation

Radioactive with T~1.5Myr

Decay occurs in the halo

Multi-step nature of cosmic ray fragmentation

NT 2017 PRD, 1707.06917



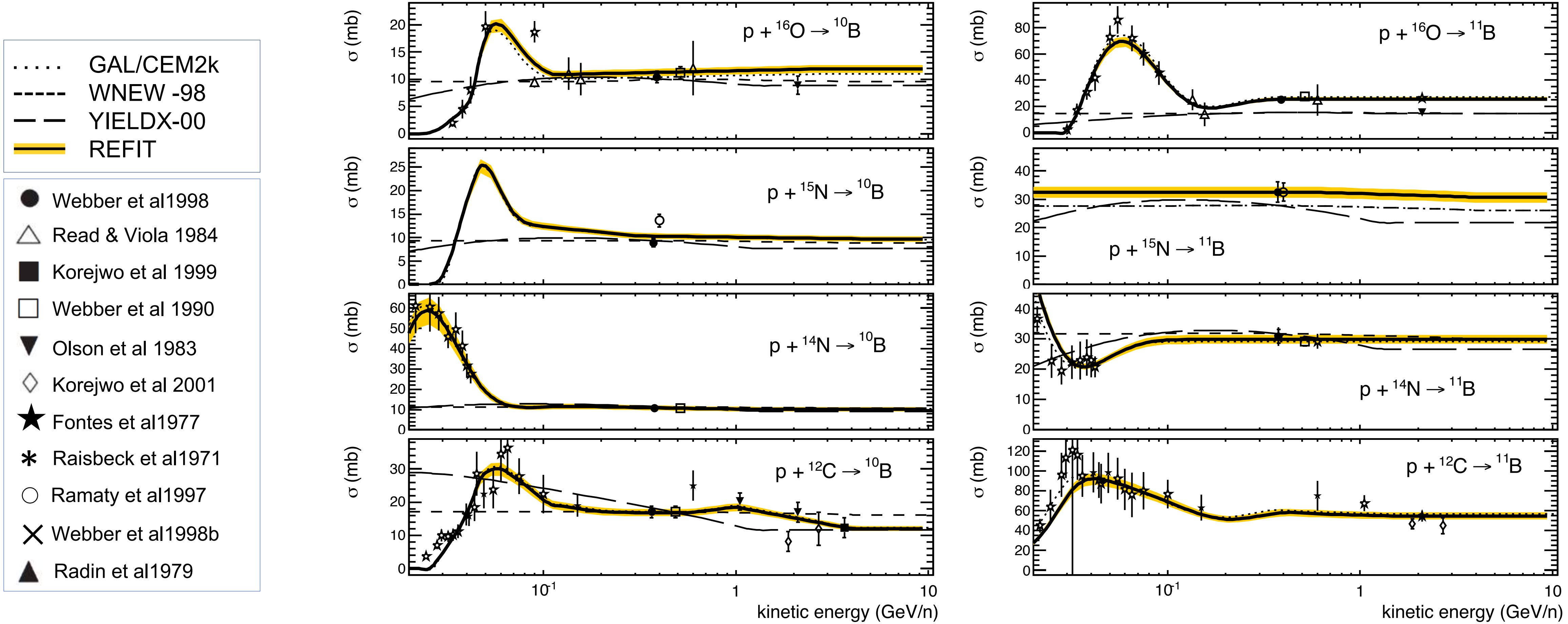
secondary **primary**

Fragmentation cross-section channels

- Data collected in ~1970's – early 2000. Available at E = 20MeV/n – 10GeV/n
- Semi-empirical parametrizations: Webber 98 + Sielberberg & Tsao 2000 + GALPROP

$$Q_S(E) = \sum_{CR} \sum_{ISM} \int_{E_{Th}}^{\infty} \beta c \, n_{ISM} \frac{d\sigma_{CR+ISM \to S}^{ISM}}{dE'} N_{CR}(E') dE' \quad \sim \Gamma_{CR \to S} N_{CR}$$

NT 2015 PRC, 1509.05776



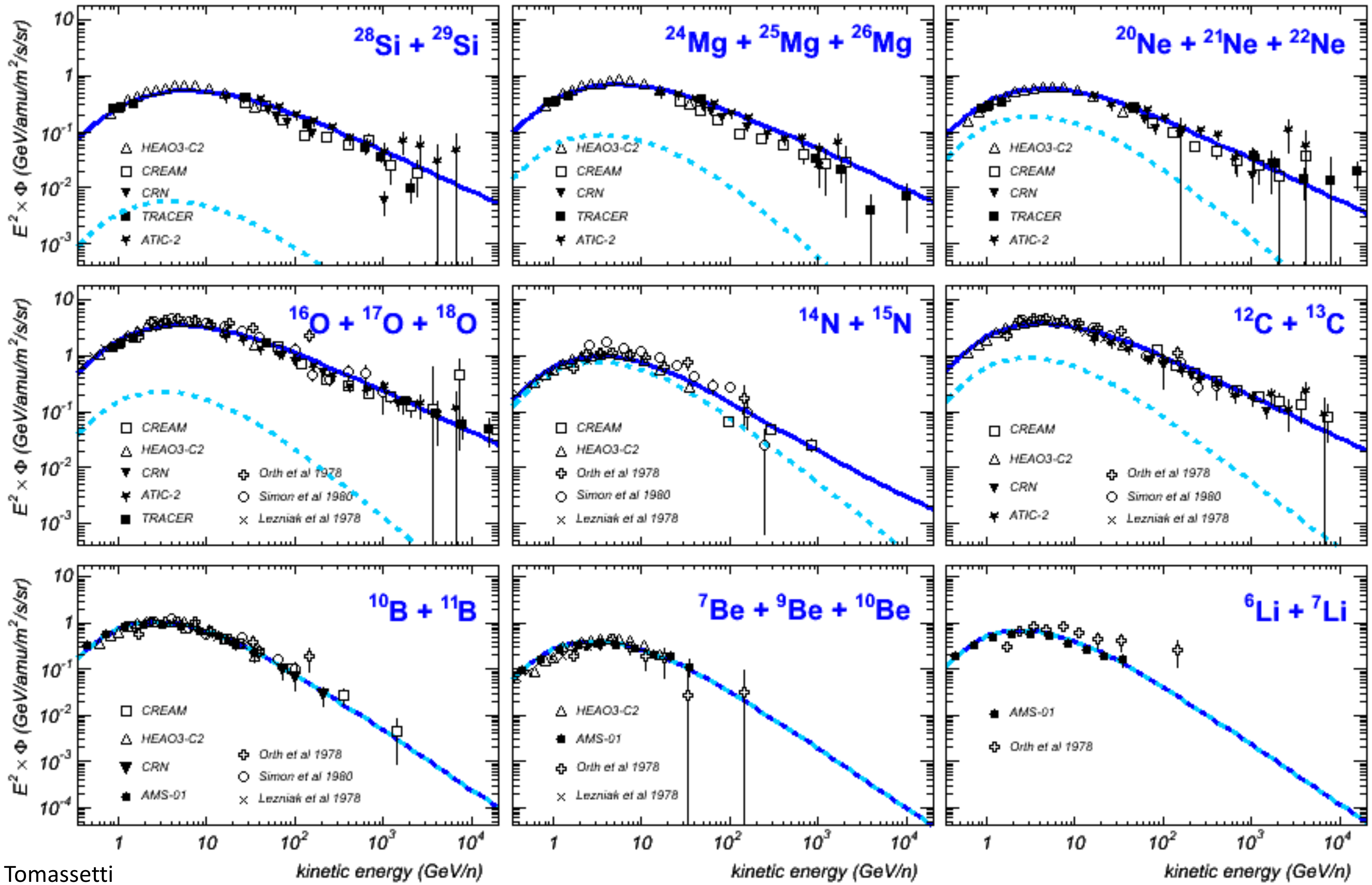
Standard predictions

Blue: total elemental spectra

Cyan: secondary component

Standard CR Spectra. Full nuclear network up to Silicon (Z=14)

NT & Donato A&A 2012 [1203.6094]



N . Tomassetti

One dimensional diffusion model

1D transport equation for j-the species

$$\frac{\partial N_j}{\partial t} = \frac{\partial}{\partial t}\left[K \frac{\partial}{\partial z} N_j \right] - 2h\delta(z)\Gamma_j N_j + 2h\delta(z) Q_j$$

diffusion

$$K_{zz}(E) \sim E^{\delta}$$

spallation

$$\Gamma = \beta c n \sigma_{int}$$

sources

$$Q^{j}{}_{pri} \sim E^{-\alpha}$$

$$Q^{k\to j}{}_{sec} \sim \Gamma_{k\to j} N_k$$

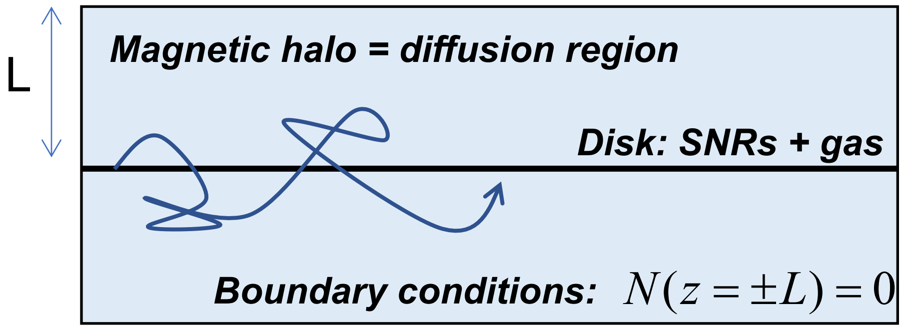
Equation coupling

Steady state solution

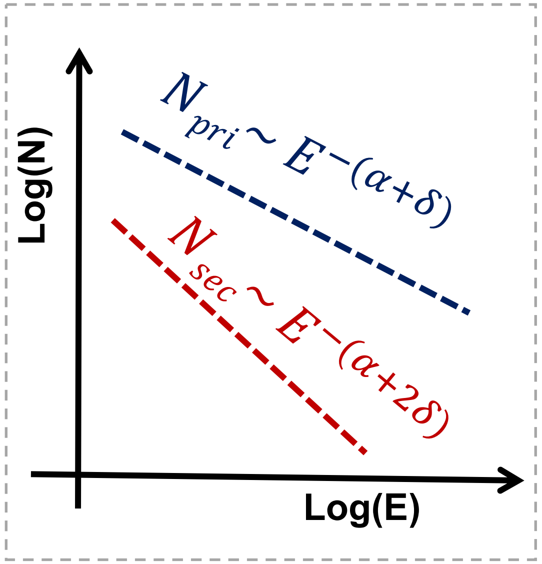
$$N(E,z) = \frac{Q(E)}{\frac{K(E)}{hL} + \Gamma(E)} \times \left[1 - \frac{|z|}{L}\right]$$

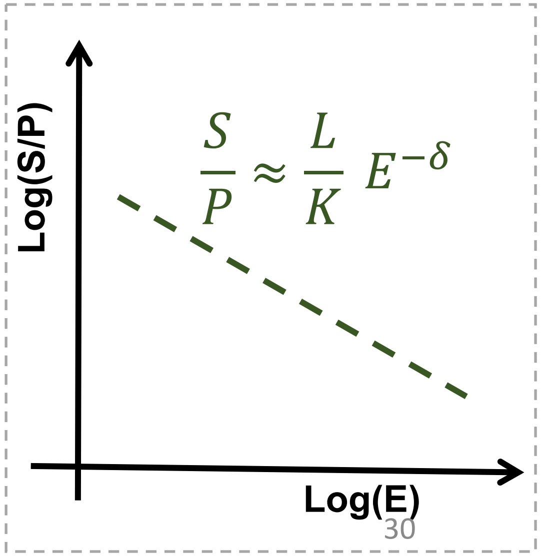
$$N_{pri}(E) \approx \frac{L}{K} Q_{pri} \sim E^{-(\alpha+\delta)}$$

$$N_{sec}(E) \approx \frac{L}{K} Q_{sec} \sim E^{-(\alpha+2\delta)}$$



$$\partial N / \partial t = 0$$





One dimensional diffusion model

1D transport equation

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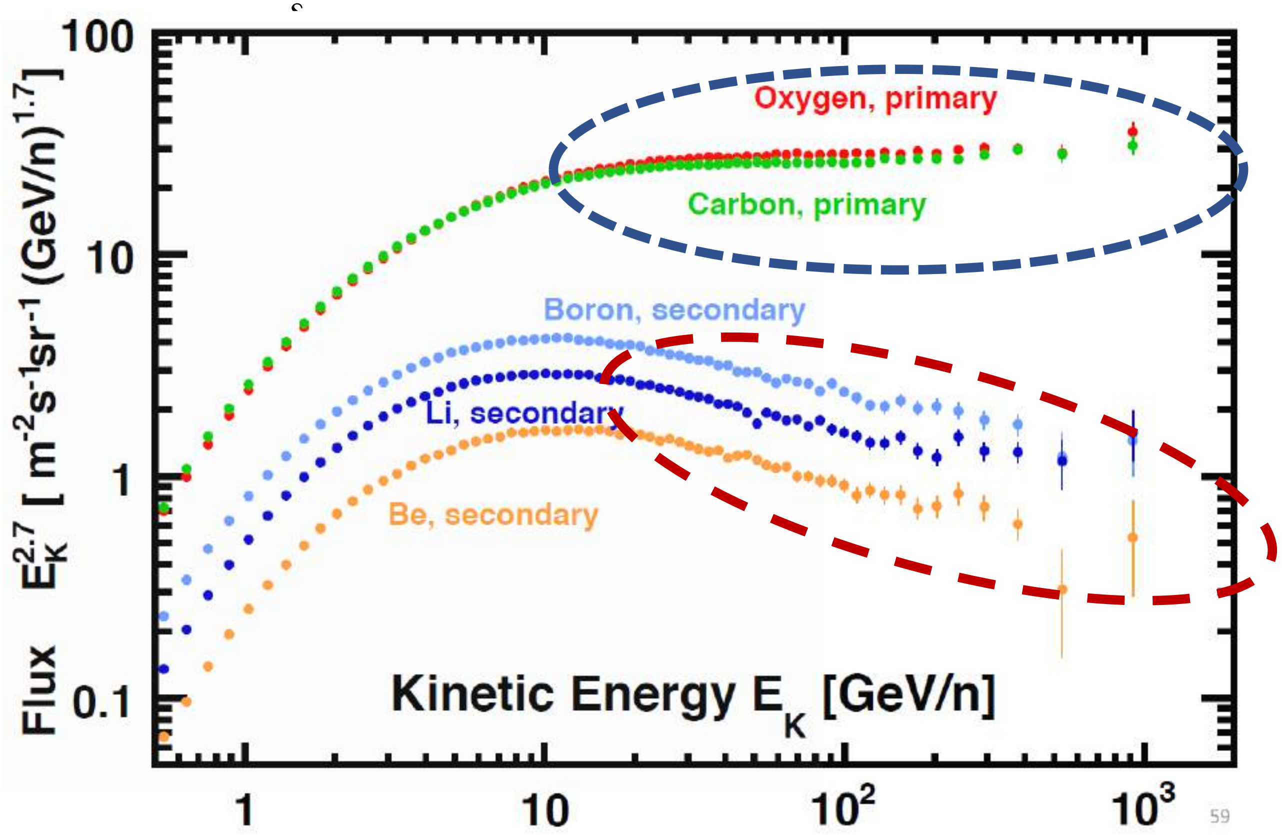
diffusion spallation sources

Steady state solution

$$N(E,z) = \frac{Q(E)}{\frac{K(E)}{hL} + \Gamma(E)} \times \left[1 - \frac{|z|}{L}\right]$$



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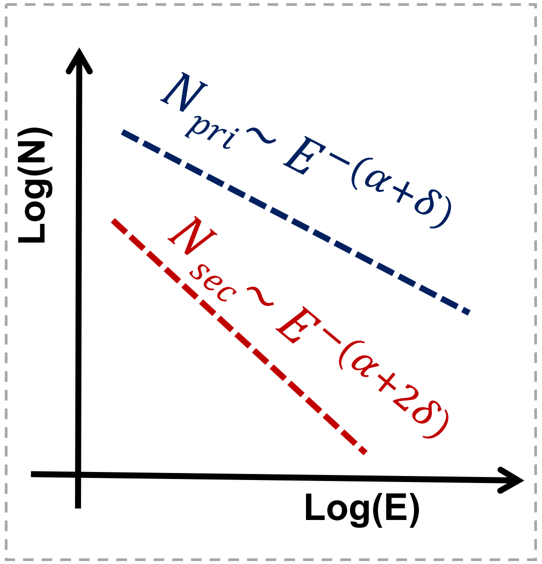
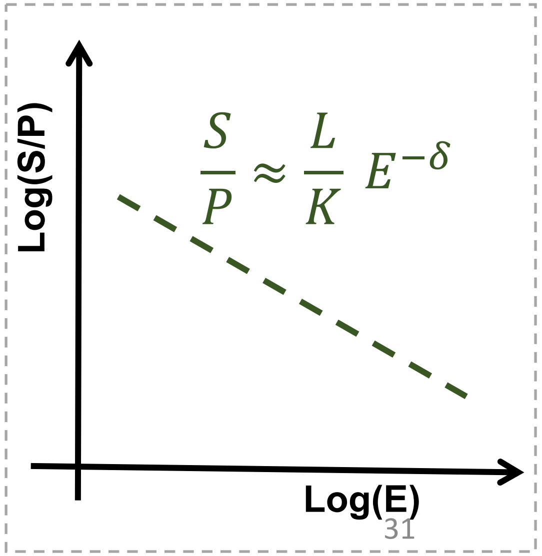




Old problems

Strong Moskalneko Ptuskin 2007, A&A Review

✓ *Acceleration spectrum:* $Q(E) \sim E^{-\alpha}$

✓ *Diffusion coefficient scaling:* $K(E) \sim E^{\delta}$

✓ *Equilibrium spectra HE:* $J(E) \sim Q/K = E^{-(\alpha+\delta)}$

From diffusive-shock-acceleration theory: $\alpha \sim 2$

From Kolmogorov: δ=1/3. [Kraichnan: δ =1/2]

Thumb rule $\gamma = \alpha + \delta$ Observed: $\gamma \sim$2.7

Challenge: found numerical value of parameters = relevance of effects

- ✓ B/C ratio is too steep (δ>1/3)
- ✓ Anisotropy too large
- ✓ Source spectra too steep (a>2)
- ✓ Discrepancy in p/p vs B/C ratios

Two common models

Diffusive-Reacceleration model [e.g. Trotta+2011]

- ❖ *Strong reacceleration, vA~30-40 km/s (!)*
- ✓ *B/C ratio fitted with δ ~1/3. Anisotropy ~ OK*
- ❖ *Steep source spectra α~2.4 (+ low-energy breaks)*
- ❖ *Trouble with antiprotons (need of ad-hoc terms)*

Plain diffusion model DR [e.g. Di Bernardo+ 2010]

- ✓ *Moderate reacceleration (vA<10 km/s)*
- ❖ *B/C ratio fitted with δ ~1/2. Anisotropy too large*
- ✓ *Reasonable source spectra α~2.2 (no breaks needed)*
- ✓ *Natural agreement with antiprotons*

New problems: anomalies

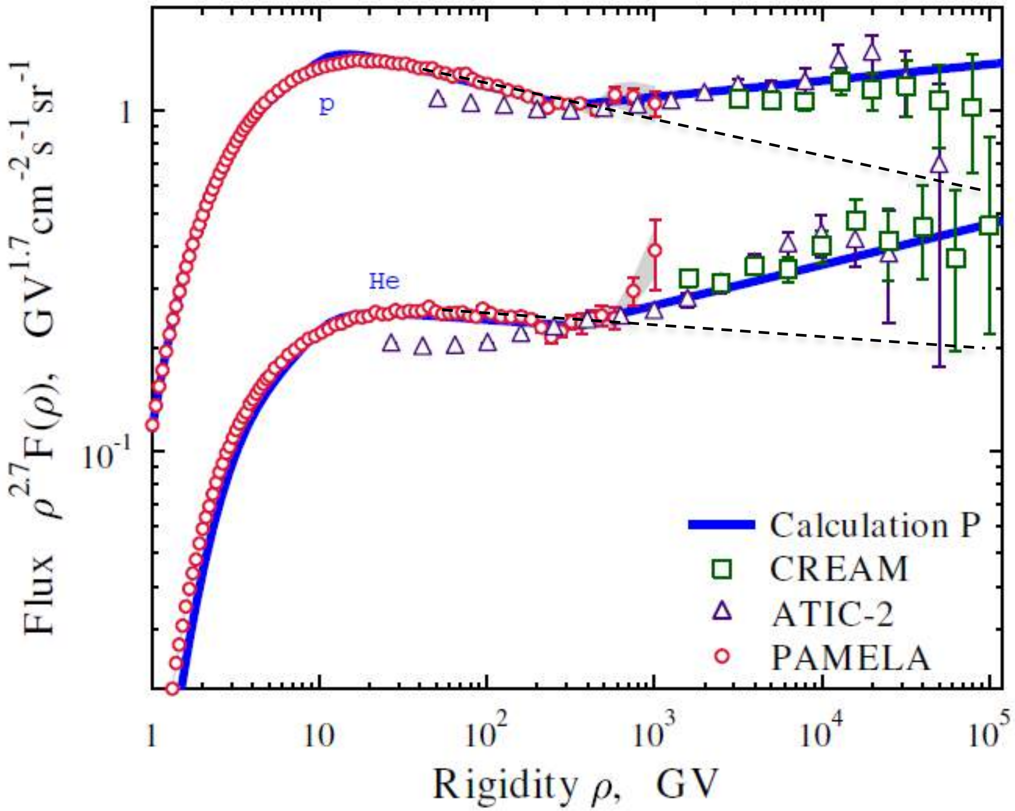
New era of CR dedtection in space (PAMELA, Fermi, AMS-02, DAMPE, CALET, ISSCREAM)

High precision → new unexpected features -> opportunity to get clues on origin & propagation of CRs

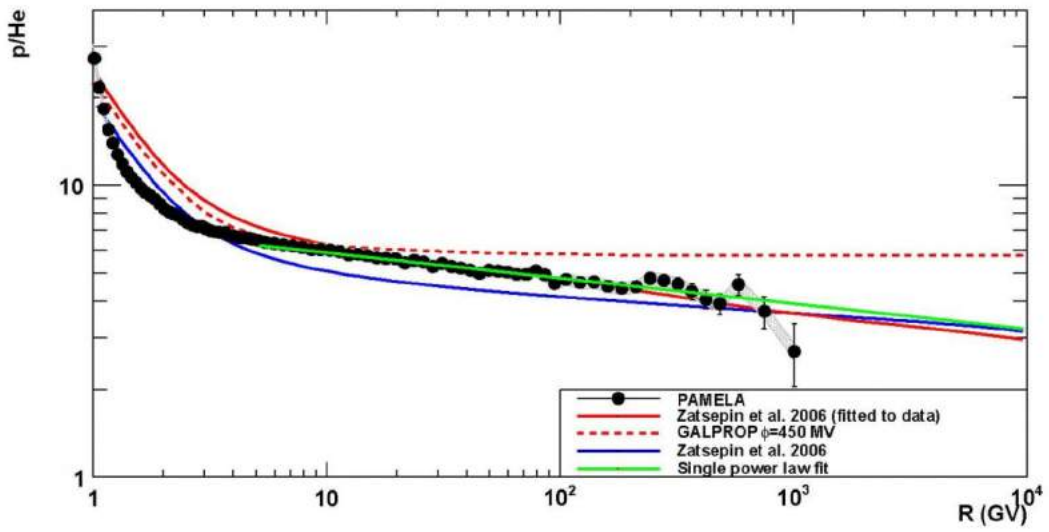
"These data challenge the current paradigm of cosmic-ray acceleration in supernova remnants followed by diffusive propagation in the Galaxy".

Adriani et al. Science 2011

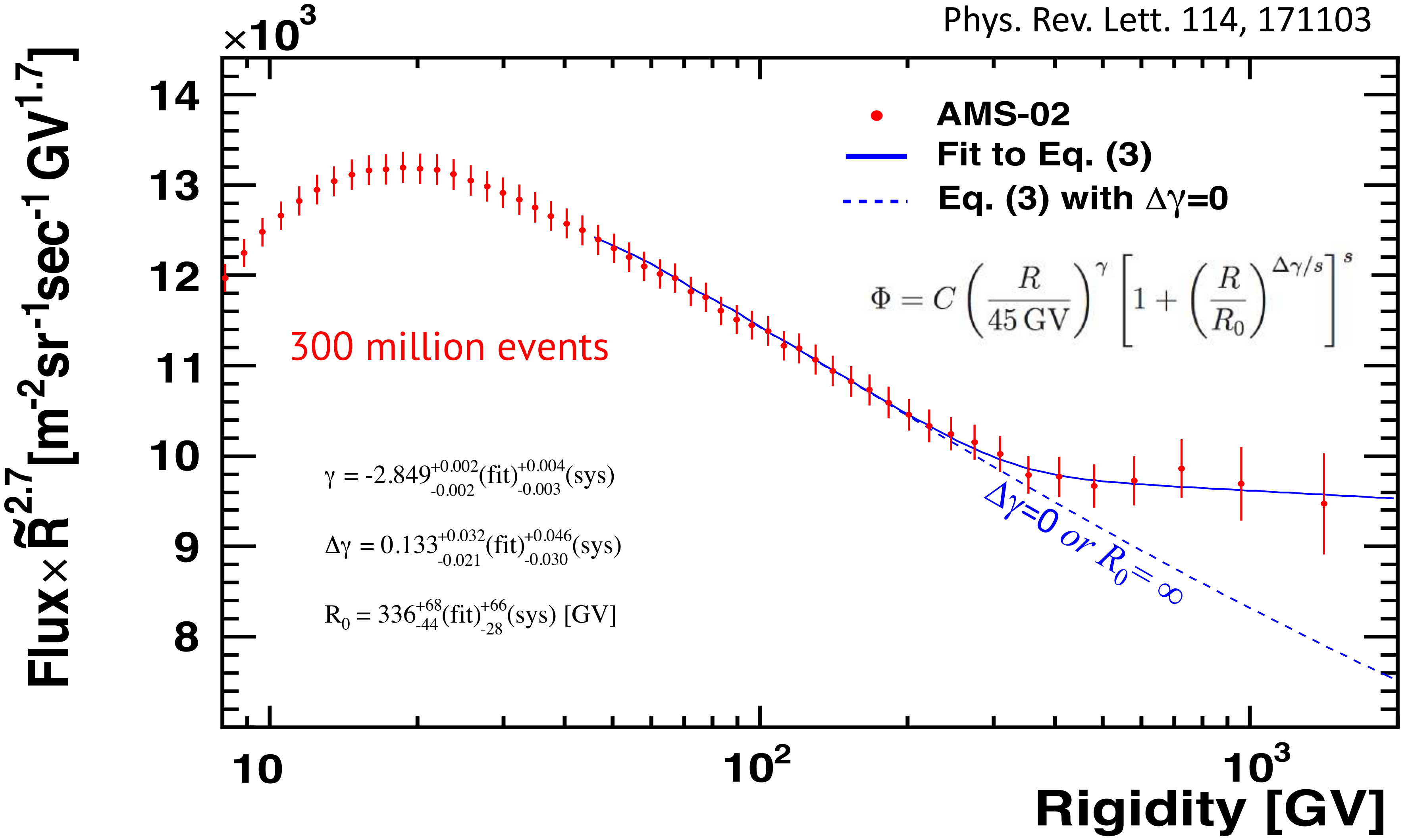
Spectral hardening at ~100 GeV energies



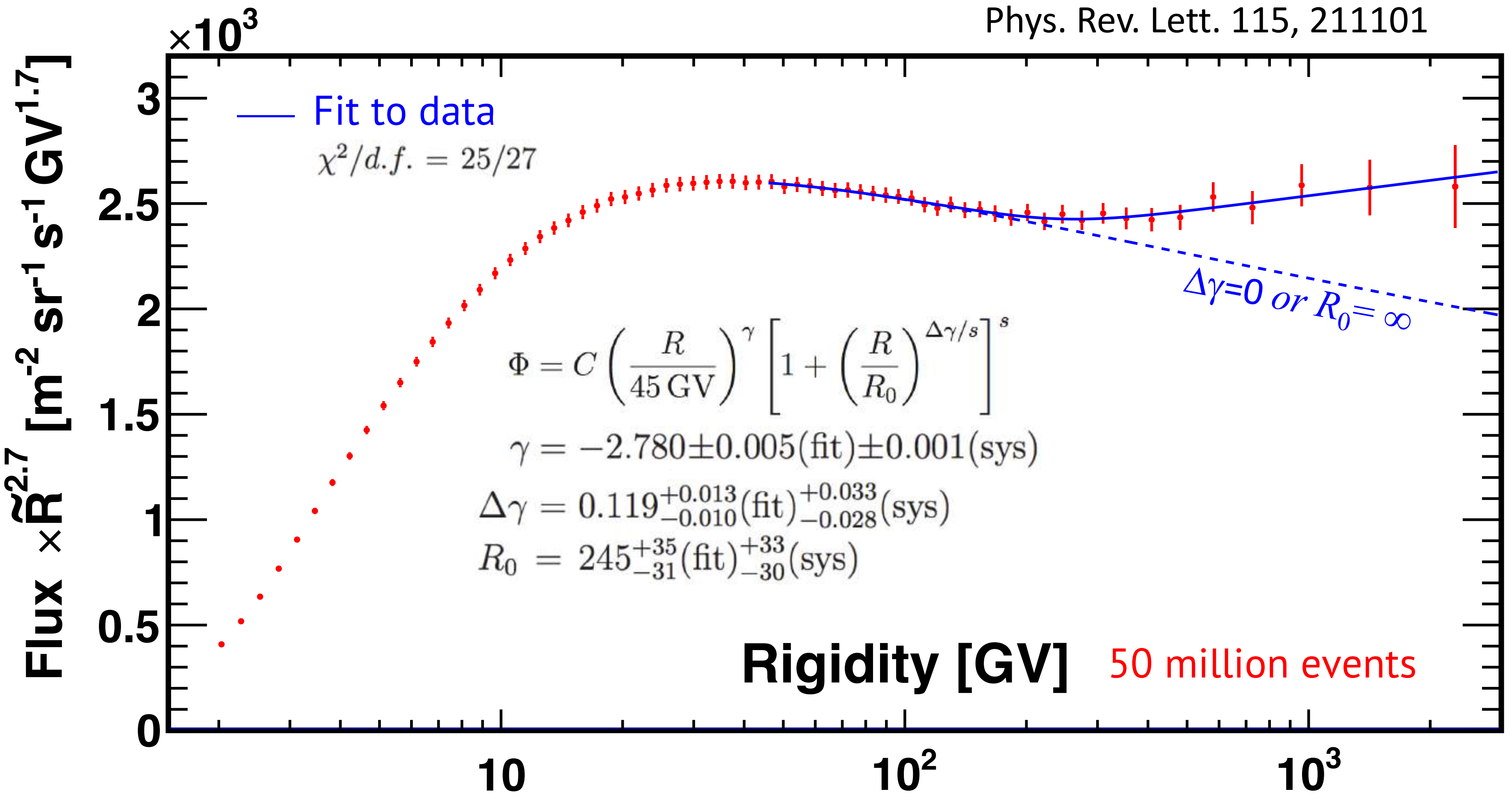
High-energy decrease of the p/He ratio



Proton Flux from AMS-02

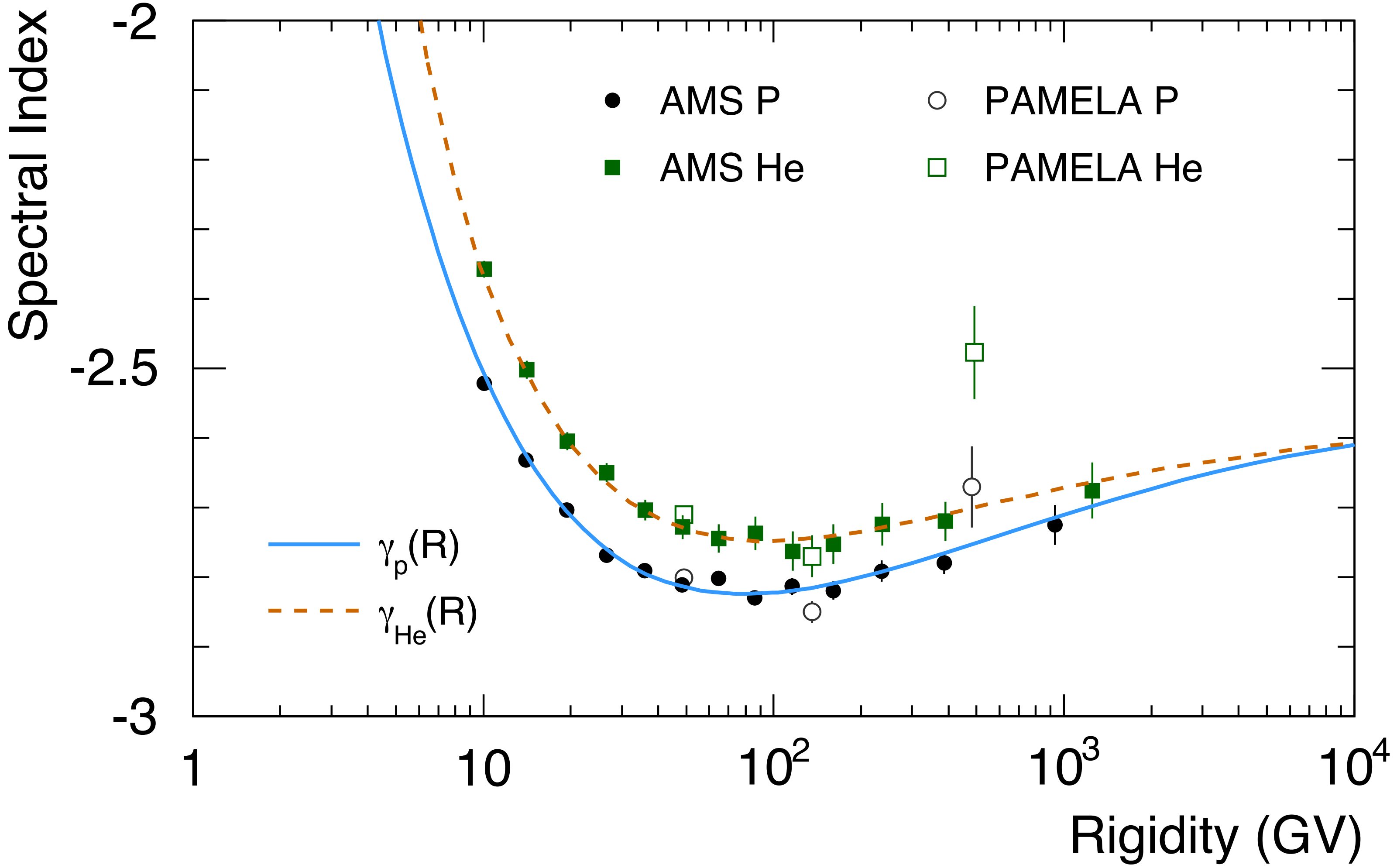


Helium Flux from AMS-02



Differential spectral index

$$\gamma(R) = -\frac{\partial \log J_0}{\partial \log R}$$



The spectral index increases with increasing rigidity R=p/Z

p/He ratio from AMS-02

The He spectrum is harder than the proton spectrum. The p/He ratio decreases as R^-1
The p/He ratio decreases without structures, while the p and He spectra harden at ~300 GV

Not explained by standard acceleration theory: the DSA mechanism is composition blind!

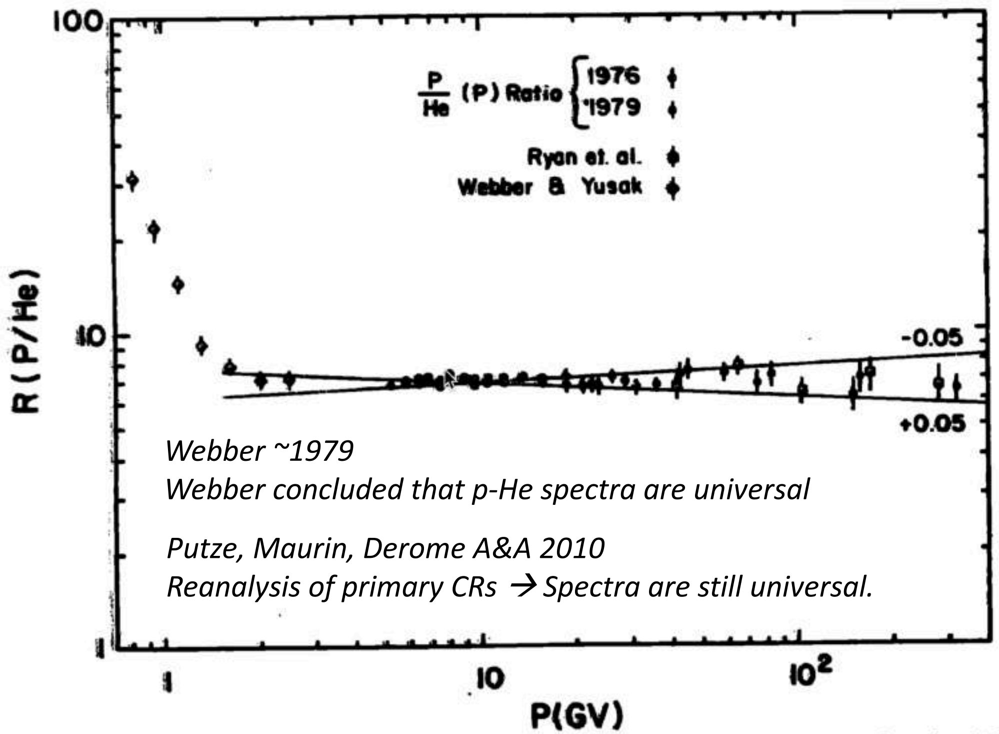
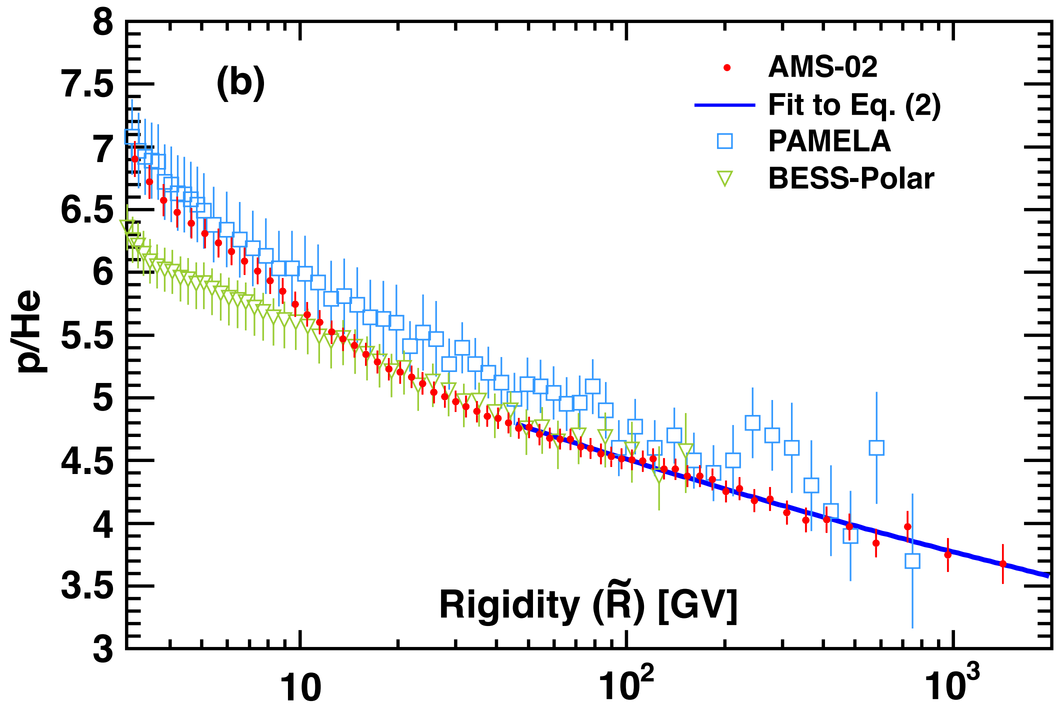


Figure 3. Proton to Helium ratio as a function of rigidity.



CREAM [2011] PAMELA [2011], AMS-02 [2015], BESS [2016]
Spectral differences between proton and He are established

Physics scenarios behind spectral anomalies

Basic predictions (E~ 10 GeV – 100 TeV)

- ✓ ***DSA@SNRs: power-law (α~ 2.0 – 2.2)*** $Q(E) \sim E^{-\alpha}$
- ✓ ***QLT: power-law diffusivity (δ~ 0.3 - 0.6)*** $K(E) \sim E^{\delta}$
- ✓ ***Equilibrium spectra (E>>GeV)*** $J(E) \sim Q/K = E^{-(\alpha+\delta)}$

Departure from power-law -> revisitation of standard mechanisms of DSA or diffusion.

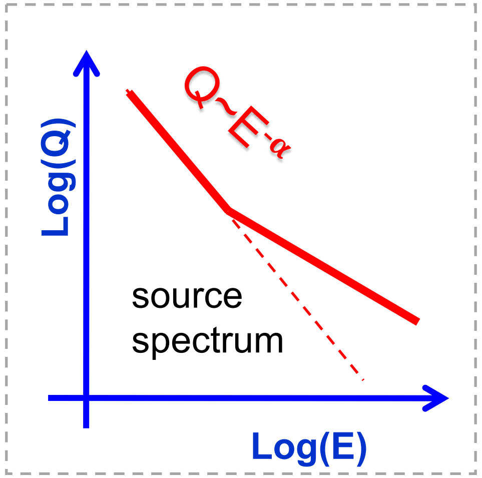
Serpico 2015 [1509.04233]

Vladimirov+ 2012 [1108.1023]

→ *Rejection of some assumptions: homogenity, isotropy, stationarity, linearity*

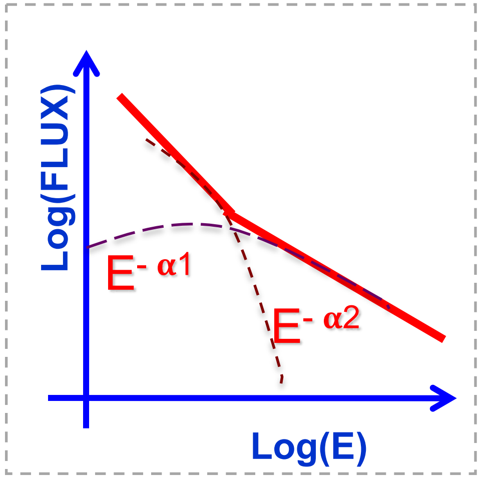
→ *Three main scenarios:*

Acceleration, Q(E)



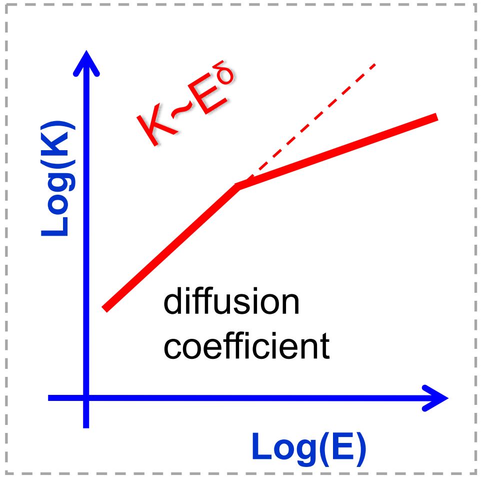
- *Non-linear DSA*
- *Mach number time-evolution*

Nearby sources



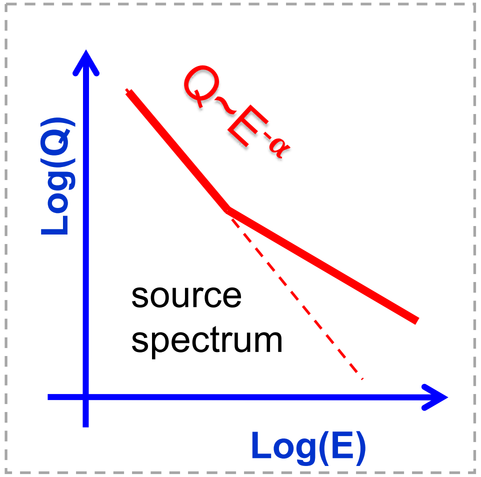
- *Local SNR + Galactic ensemble*
- *Reacceleration in weak shocks*

Propagation, K(E)



- *Transport in CR-induced turbulence*
- *Spatial dependent diffusion K(z,E)*

Q(E): revisited CR acceleration



Several acceleration effects may cause a deviation from power-law

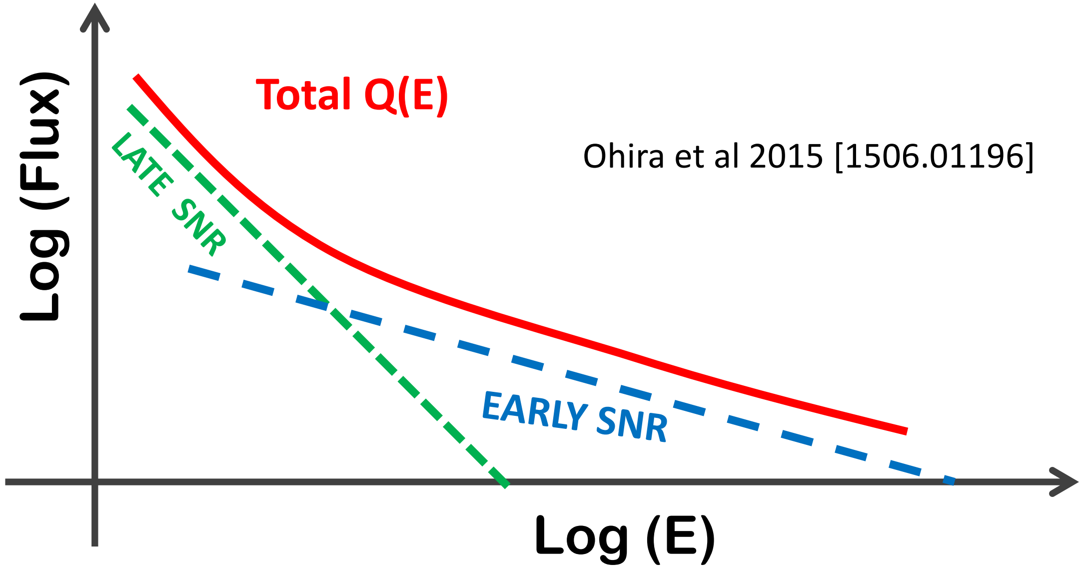
- Non-linear DSA due to CR feedback: concavity in acceleration spectra — *Ptuskin+ 2013 [1212.0381]*
- Time-dependent DSA with evolving shock and decreasing Emax — Ohira+ 2015 [1506.01196]
- Reacceleration of pre-existing CRs from weak shockwaves — *Thoudam+ 2013 [1308.1357]*

An example

EARLY SNR STAGE [M>>1]
Strong shock, hard spectrum

LATE SNR STAGE [M~1]
Weak shock, steep spectrum

$$\alpha = 2\frac{M^2+1}{M^2-1}$$



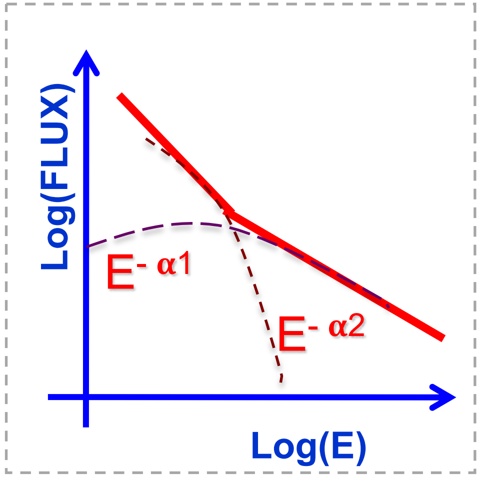
Ohira et al 2015 [1506.01196]

No realistic modeling of this scenario seems to fit well the fluxes

✓ **p/He ratio anomaly: good explanations, good fits**

- *Particle-dependent injection* — *Malkov et al. 2012 PRL*
- *Non-uniform He distribution* — *Ohira et al. 2016 [1506.01196]*

Nearby sources, but where?

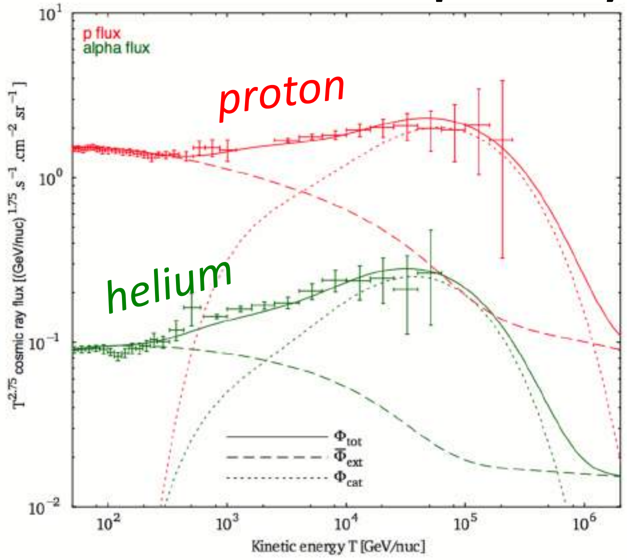


--> In the high-energy spectrum

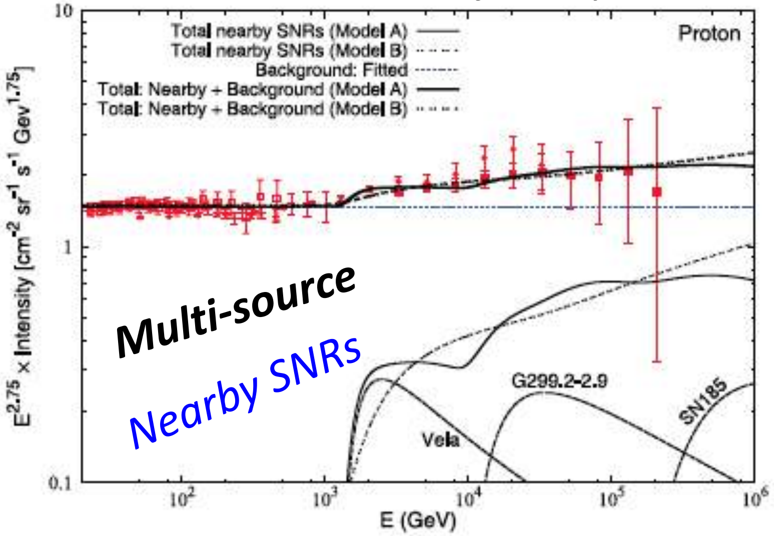
Galactic CR background at low-energy (100 MeV-100 GeV)
Nearby young SNR at high-energy (100 GeV – 10 PeV)

→ Fits to all spectra. But, lack of predictivity (many unknown, many parameters…)
X Impact for diffusive gamma-ray emission, related to a SOFT GCR background

Bernard et al 2013 [1207.4670]

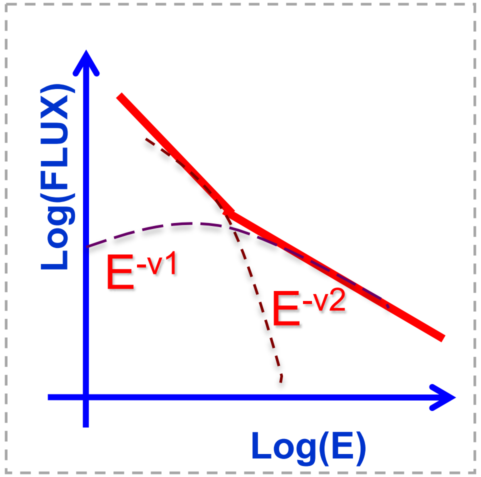


Thoudam & Horandel, january 2012



Bernard et al 2013 [1207.4670]
Thoudam & Horandel 2013[1304.140
Erlikin & Wolfendale 2012 [.]

Nearby sources, but where?

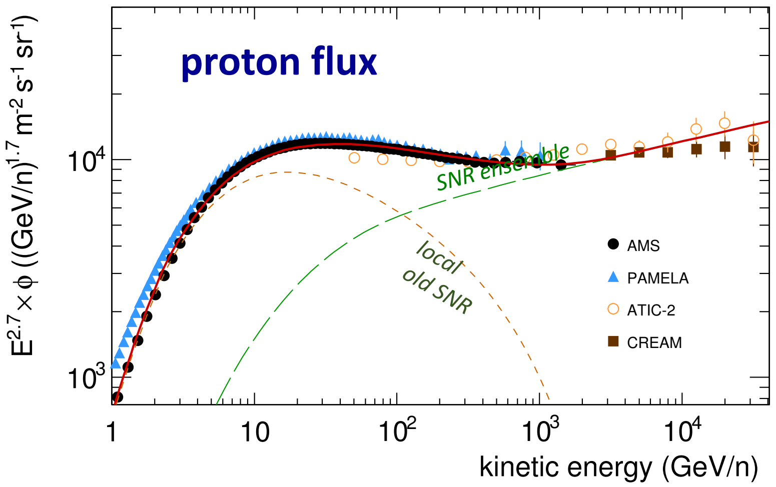


--> In the low-energy spectrum

Galactic CR background at high-energy (100 GeV-10 PeV)
Nearby young SNR at high-energy (100 MeV – 100 GeV)

→ Fits to all spectra. Still lack of predictivity (many unknown, many parameters…)
X Impact for diffusive gamma-ray emission, related to HARD GCR background

NT & Donato 2015 [1502.06150]

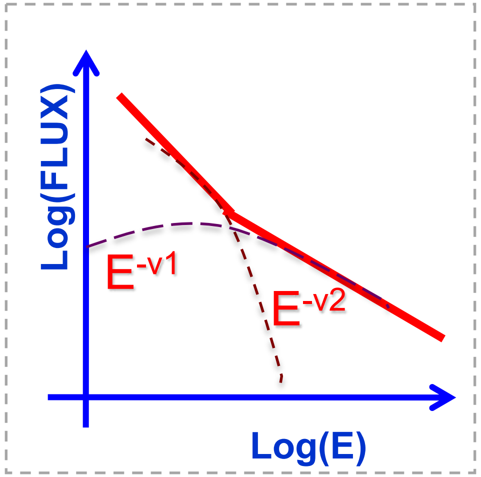


Explanation to several anomalies is possible

Connection w/ e+ excess	*Kachelriess et al 1504.06472*
Explanation for p/He	*NT 2015, 1511.04460*
Implications for O/Fe	*NT 2015, 1509.05774*
TeV anisotropy signatures	*Kachelriess et al 1505.02720*

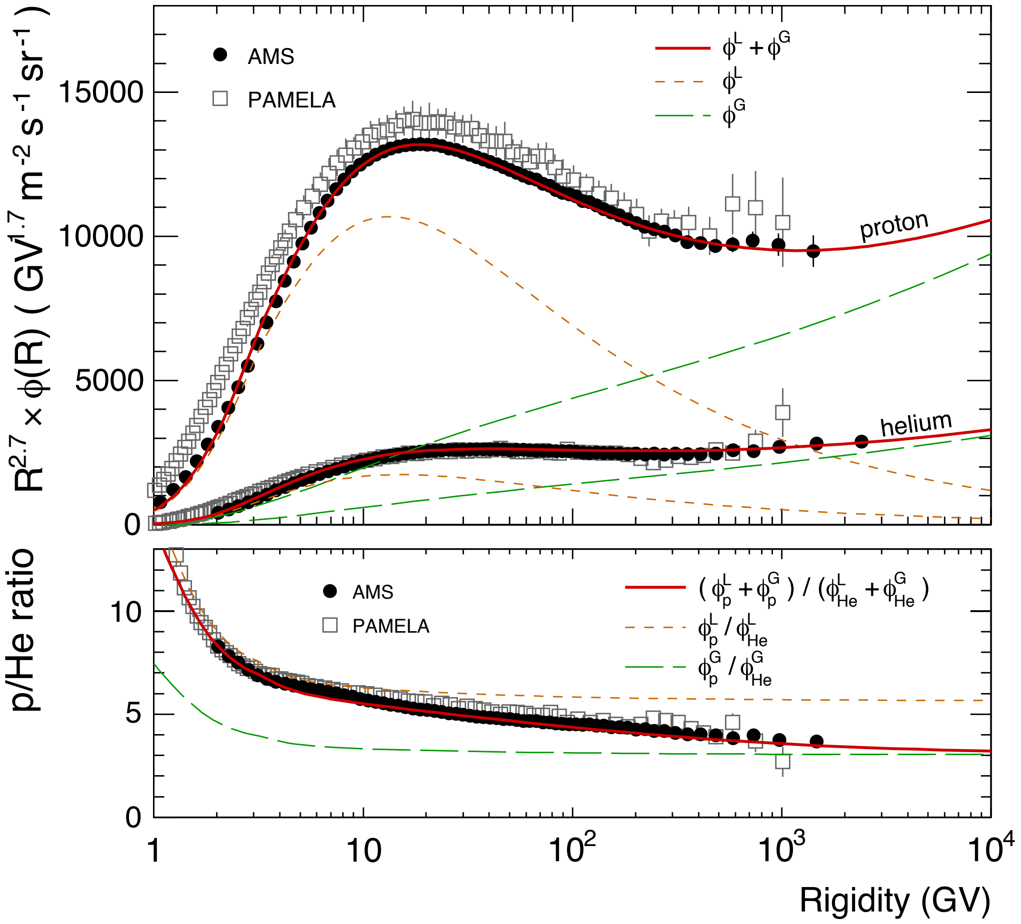
IT remains unlikely that a powerful source dominate that GeV-TeV spectrum.
Unclear what we should expect for secondary/primary ratios.
Impact for diffusive gamma-ray emission, related to HARD GCR background.

Nearby sources, but where?



Standard: sources are continuously distributed in space and time.

Rejecting stationarity -> stochasticity -> appearance of nearby SNRs

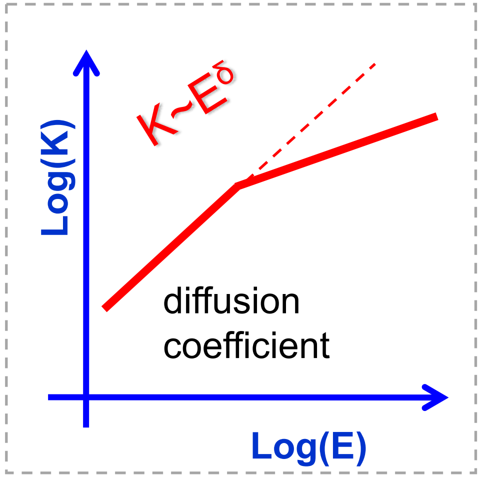


The idea. Two different classes of sources contribute to the CR flux. Each class has different spectra and composition.

Fluctuation in composition of H and He may explain the decrease of the p/He ratio and the high-energy hardening

If the local sources has particular properties, it may also explain antiprotons and positron spectra

K(E): Revisited CR transport

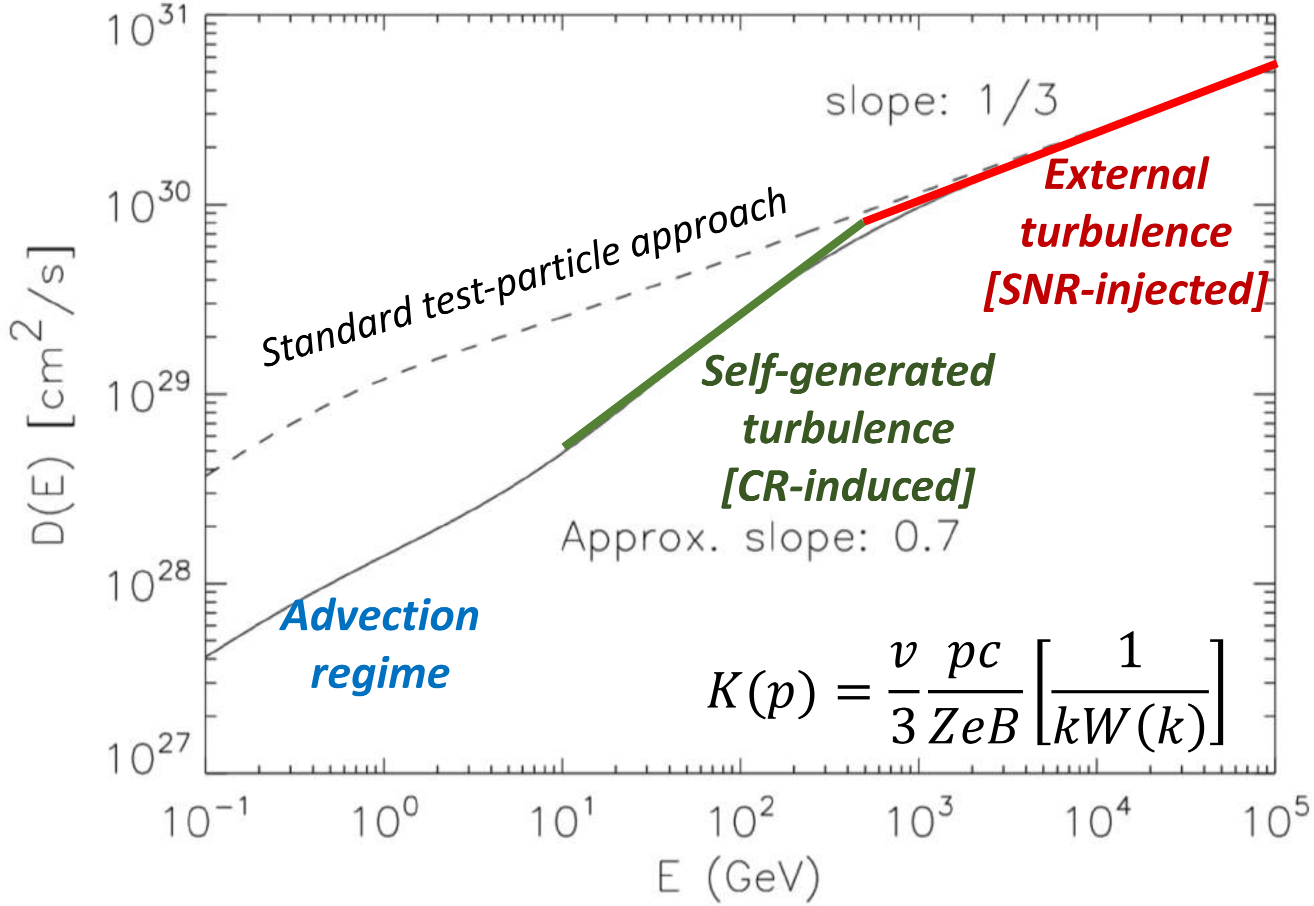


Cosmic-ray induced turbulence

Blasi+ 2012 [1207.3706] | Aloisio+ 2015 [1507.00594]

Spectral breaks as a signature of cosmic ray induced turbulence in the Galaxy

Self-generated turbulence steepens the CR diffusion at rigidity below ~300 GV



$$K(p) = \frac{v}{3}\frac{pc}{ZeB}\left[\frac{1}{kW(k)}\right]$$

K(E): Revisited CR transport *Inhomogeneous K(z,E)*

Non-homogeneous diffusion $K = K(E, z)$ →

$$N(E,z) \approx \frac{Q(E)}{\frac{K_0(E)}{h\Lambda(\mathrm{E})} + \Gamma} \times \left[1 - \frac{\lambda(E,z)}{\Lambda(E)}\right]$$

→ *similar solution*

But the halo size L is replaced by Λ, effective halo size

$$L \longrightarrow \Lambda(E) = \lambda(E, L) = \int_0^L \frac{K_0(E)}{K(E,z)} dz$$

Factorizable in E-z: $K(E,z) = f(z) \times k(E)$

E.g. Di Bernardo+ 2010 [0909.4548] $f(z) = e^{z/z_t}$

→ *Λ = const* → *same phenomenology in the disk (z=0)*

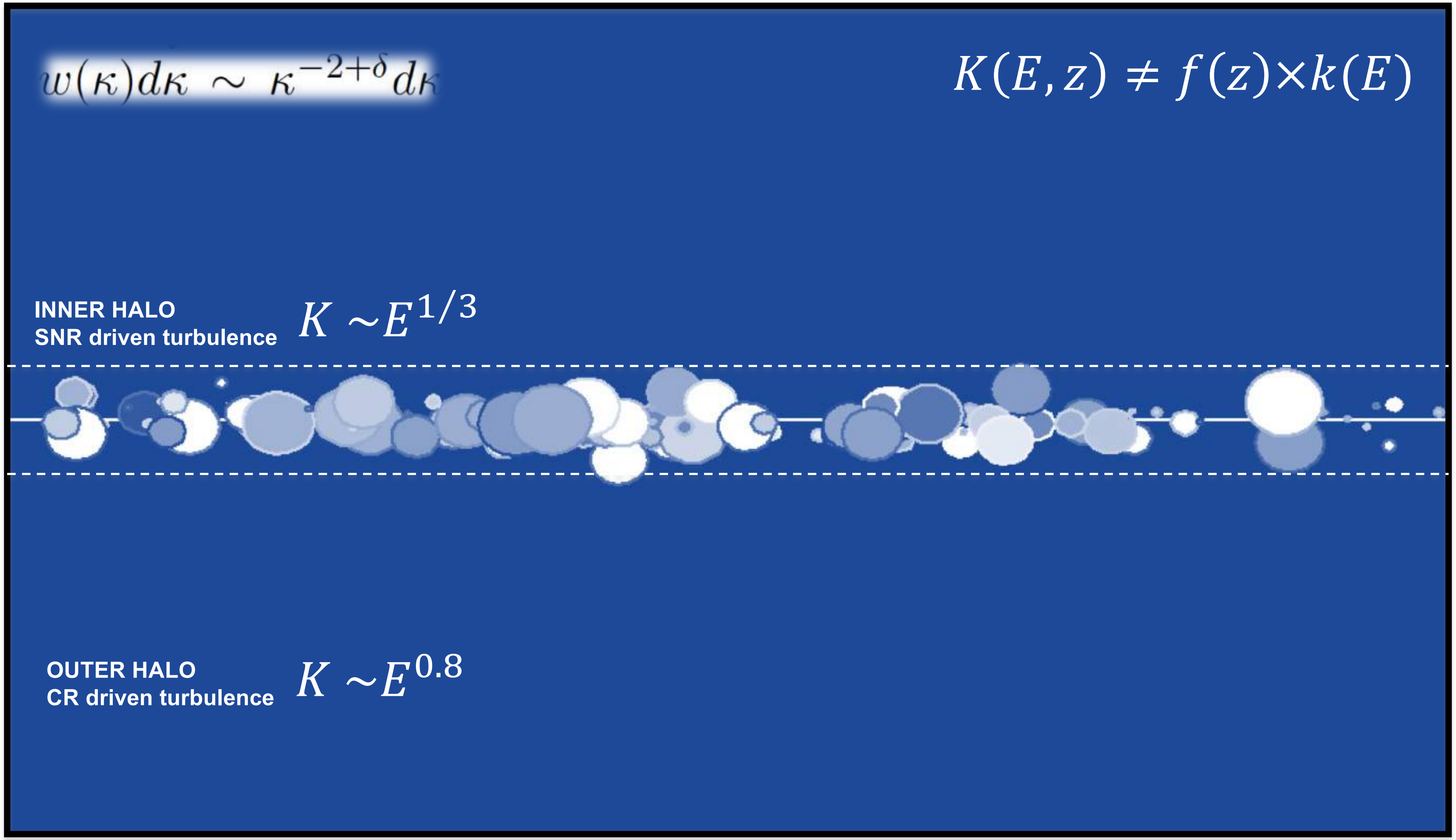
$$N_0(E) \approx \frac{\Lambda}{K_0(E)} Q(E)$$

Non-Factorizable : $K(E,z) \neq f(z) \times k(E)$

→ *Λ = Λ(E) : fluxes are no longer power law*

$$N_0(E) \approx \frac{\Lambda(\mathrm{E})}{K_0(E)} Q(E)$$

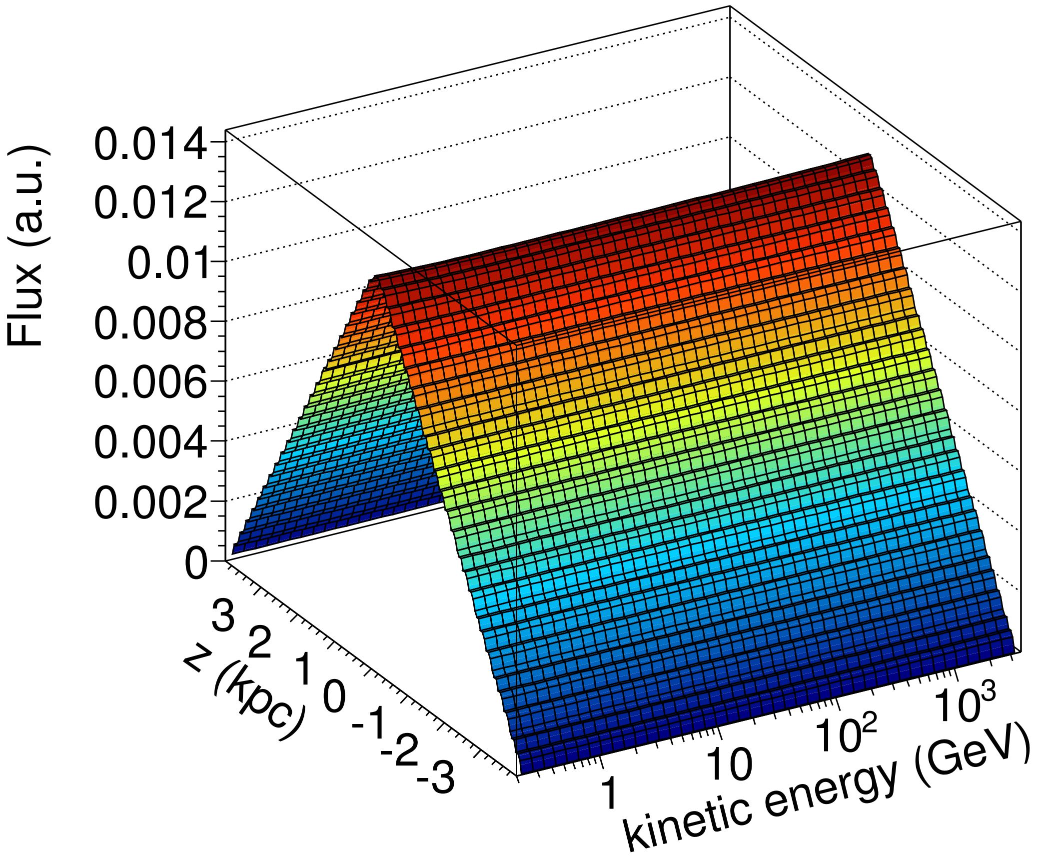
Simplest non-factorizable K(z,E) : two diffusive regimes at works



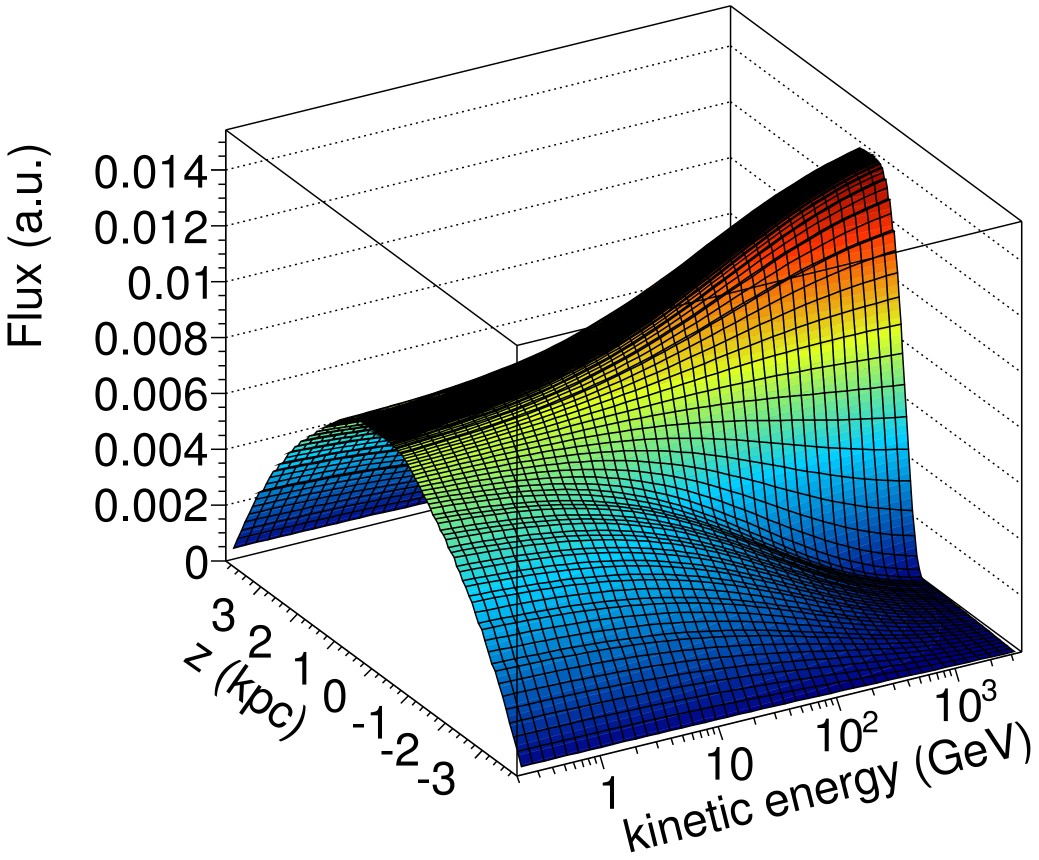
Simplest non-factorizable K(z,E) : two diffusive regimes at works

Spatial distribution of CRs at equilibrium – w/ Dragon

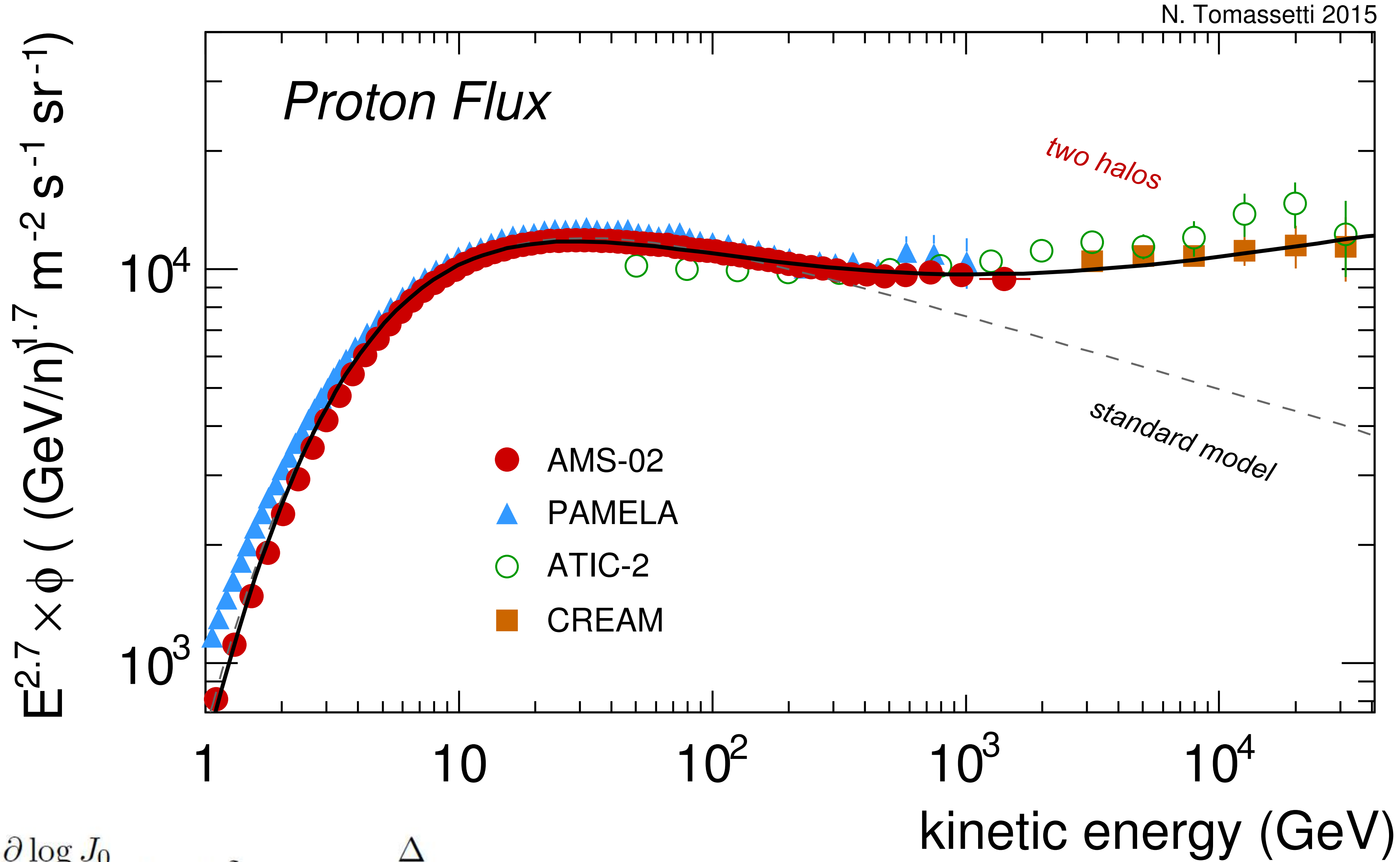
Homogeneous K(E)



Two-halo K(E)



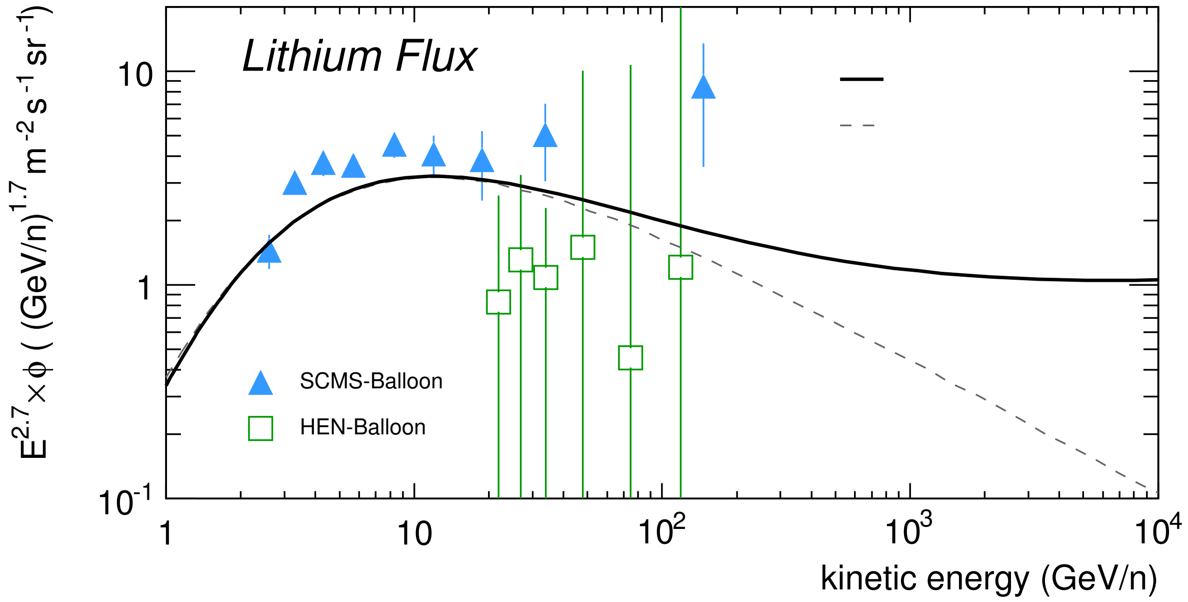
Primary spectra: universal hardening

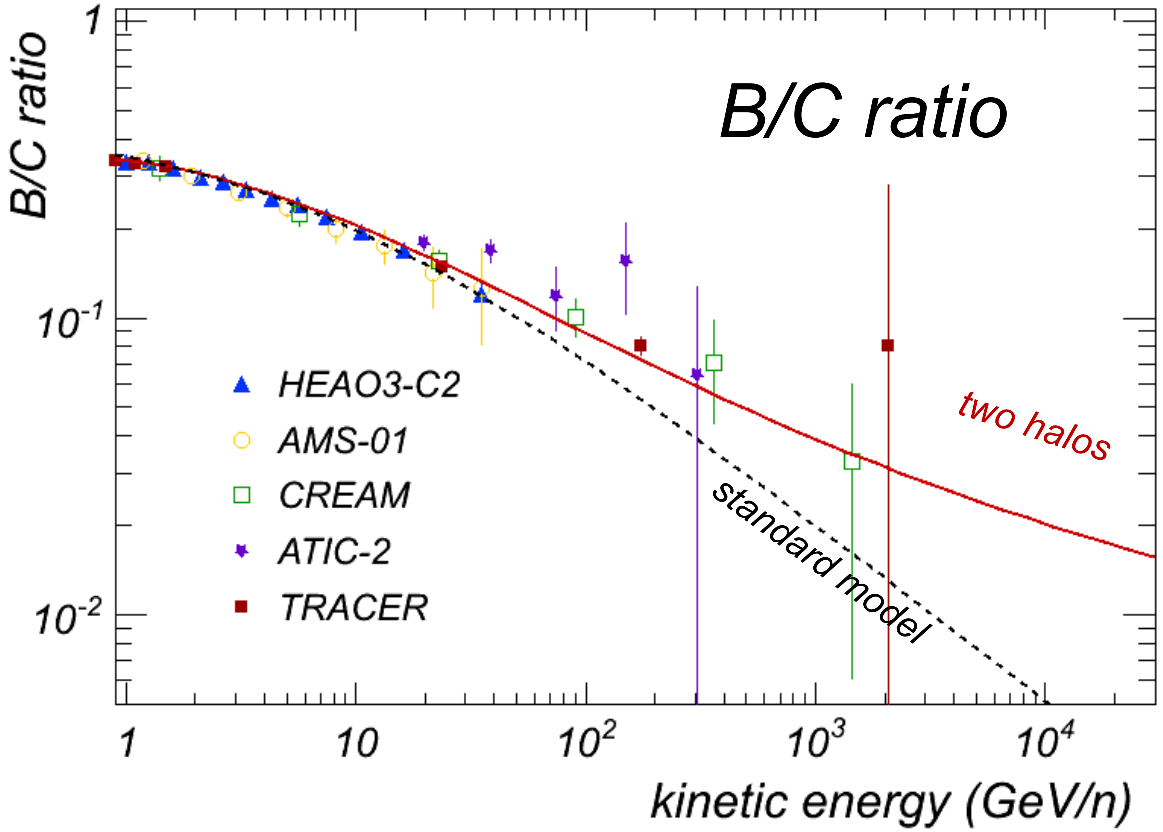


$$\gamma(R) = -\frac{\partial \log J_0}{\partial \log R} \approx \nu + \delta + \frac{\Delta}{1 + \frac{\xi}{1-\xi}(R/R_0)^{\Delta}}$$

Secondary spectra and secondary/primary ratios

- ✓ **All spectra of secondary nuclei must harden twice**
- ✓ **Secondary/primary ratios must harden as well**
- ✓ **Better agreement with anisotropy data**





Physics scenarios behind anomalies

Models with revised acceleration

- ✓ Can hardly explain a pronounced spectral hardening. Testable with high-energy gamma-rays.
- ✓ No implications for secondary/primary ratios nor for anisotropy.
- ✓ Acceleration in SN-II or superbubble can explain the p/He ratio

Models with nearby sources

- ✓ Can explain several anomalies with proper tuning. Weak predictive power.
- ✓ Supported by indications SN explosions occurred ~2Myr ago. But the required properties seem unlikely.
- ✓ Softening of secondary/primary ratios is a possible signature. Unclear impact for gamma rays
- ✓ There must be an impact on cosmic-ray anisotropy, but it is difficult to estimate.

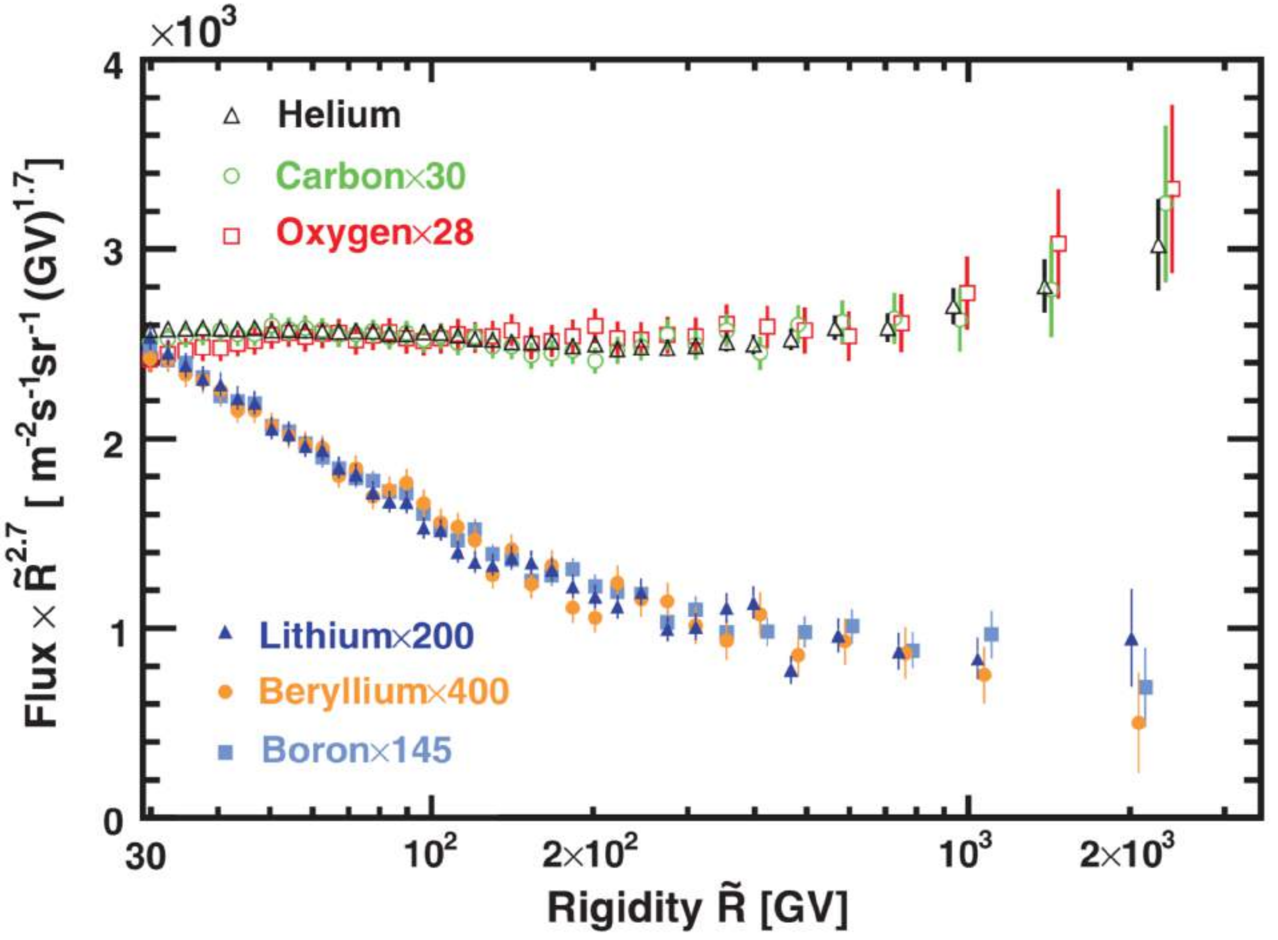
Models with revised transport (non-linear or spatial-dependent diffusion)

- ✓ Can explain spectral hardening as universal features of all CR spectra. High predictive power
- ✓ Clear signature in secondary/primary ratios and antimatter/matter ratios.
- ✓ Observational tests with gamma-ray data.
- ✓ Lead to small anisotropy amplitude at multi-TeV energy.

origin of the CR hardening	Pri spectra	Sec spectra	Pri/Sec ratios
from nearby sources	Yes	No	No
from acceleration	Yes	Yes	No
from transport	Yes	Yes	Yes

Data: news from AMS

the rigidity dependences of primary cosmic rays and secondary cosmic rays are unique and distinct



- ✓ **Two elemental groups Li-Be-B vs He-C-O**
- ✓ **Universal spectral hardening at rigidity R~O(100 GV)**
- ✓ **Different changes of slopes Li-Be-B break > He-C-O**

Data: news from AMS

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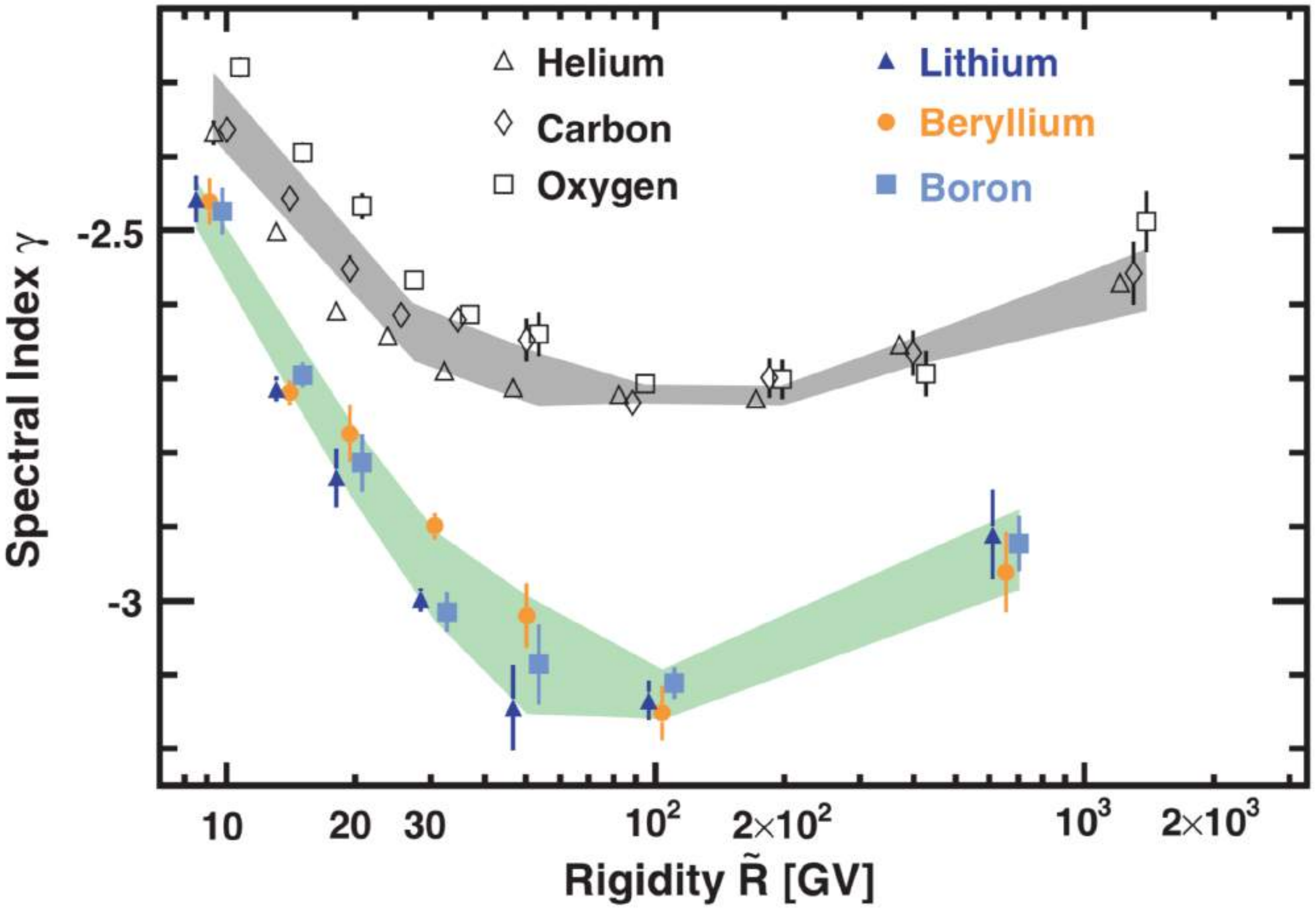

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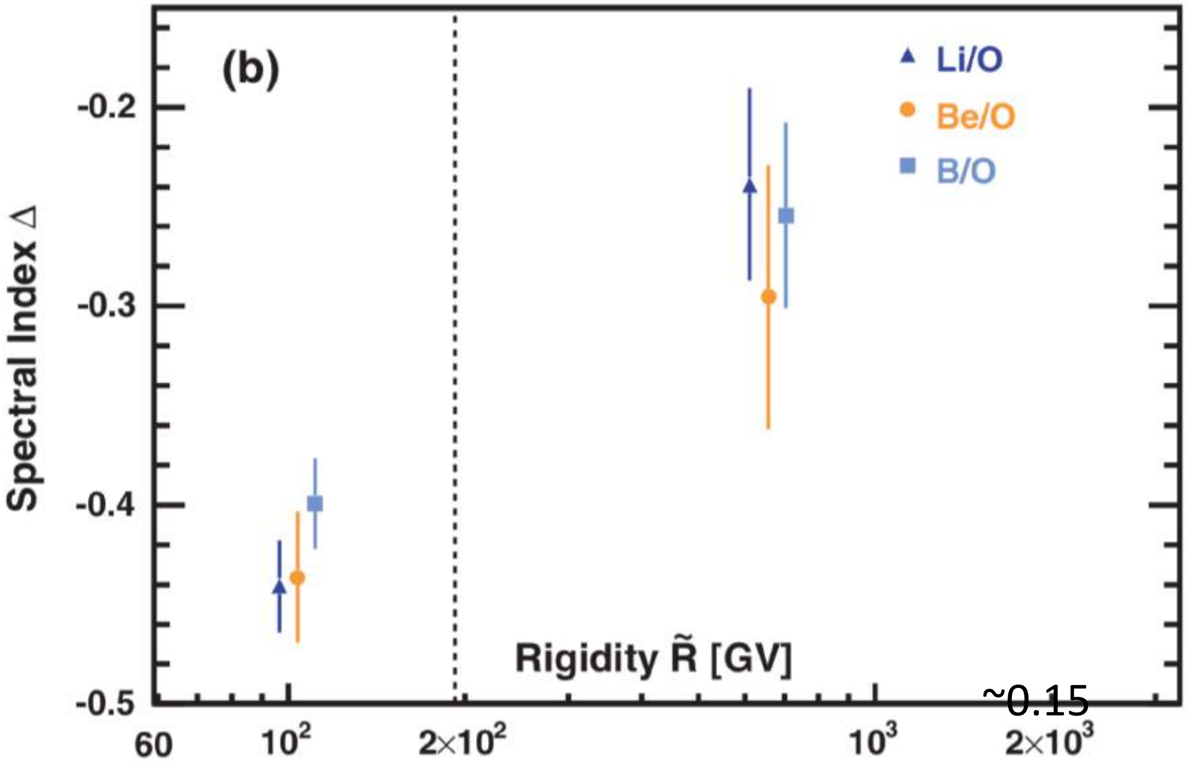
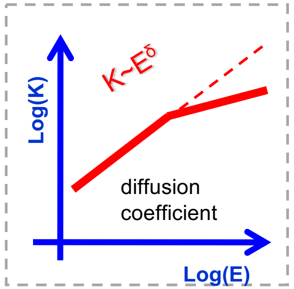


- ✓ **Two elemental groups Li-Be-B vs He-C-O**
- ✓ **Universal spectral hardening at rigidity R~O(100 GV)**
- ✓ **Different changes of slopes Li-Be-B break > He-C-O**

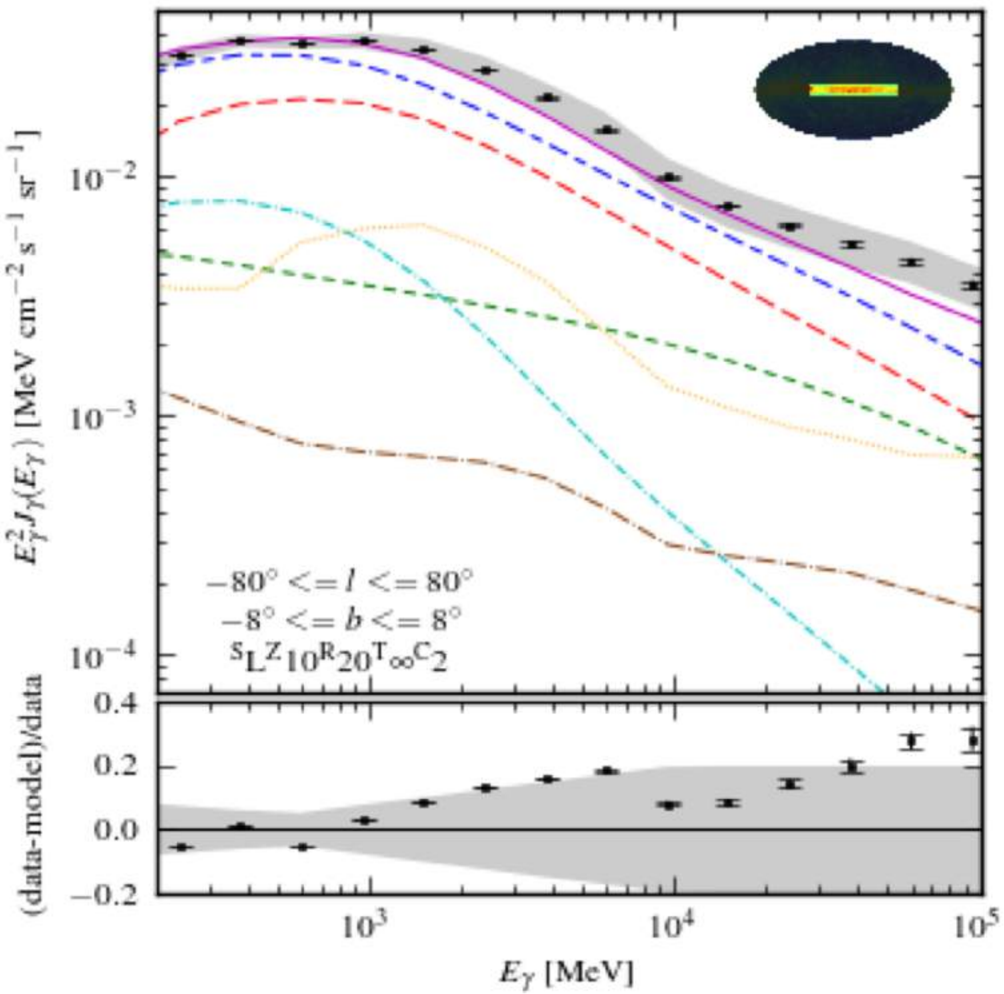
→ AMS data support models with revised CR transport

- Genolini+ 2017 [1706.09812]: *Evidence for break in K(R) from the B/C ratio*
- *AMS-02 2018: breaks found in all secondary/primary ratios Li-Be-B / C-O*



Evidence for spatial-dependent CR transport: Gamma-rays

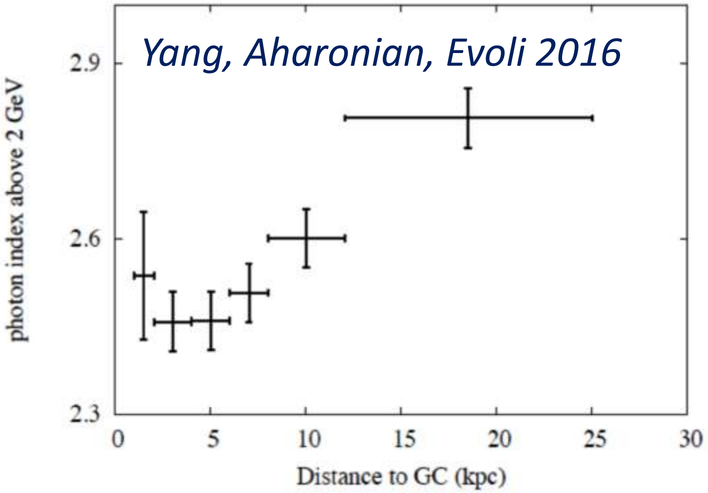
Ackermann et al. ApJ 2012



From similar considerations, we also expect <u>radial</u> dependence of K(E)

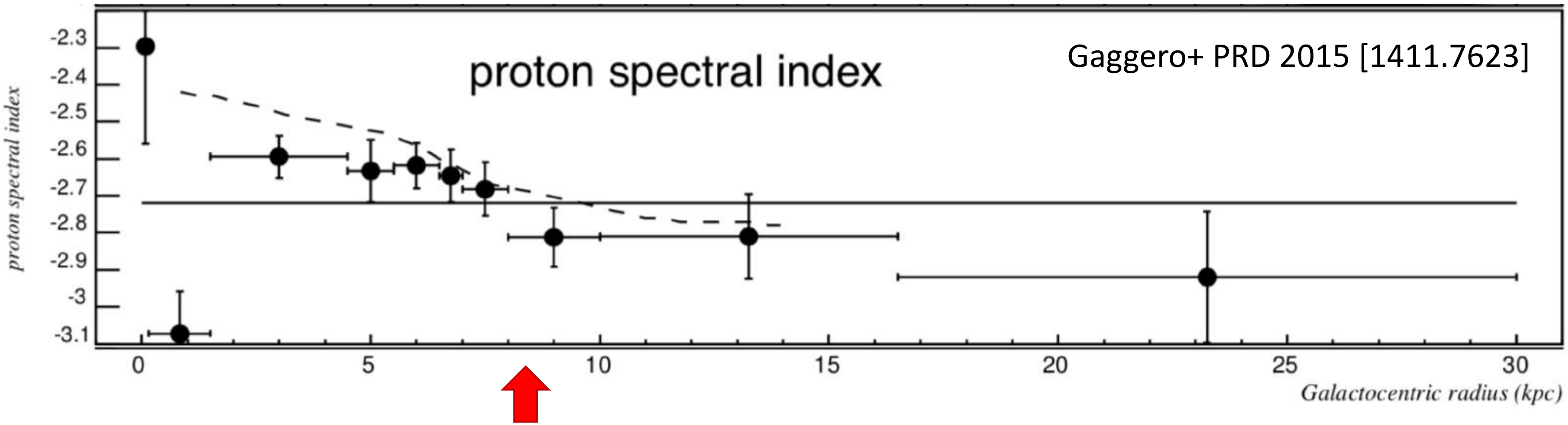
Gaggero+ PRD 2015 [1411.7623]
Erlykin & Wolfendale [1212.2760]

Fermi data on DGE -> harder spectra in the inner galaxy, unaccounted by standard models



Evidence for spatial-dependent CR transport: Gamma-rays

Radial dependence of K(E) → progressive steepening of proton spectral index
In practice: K~E^d with d=d(r) linearly increasing with Galactic radius



→ CR proton index in the whole Galaxy
→ CR density gradient
→ Implications for neutrinos from GC

What if…

Secondary nuclei are not entirely secondary?

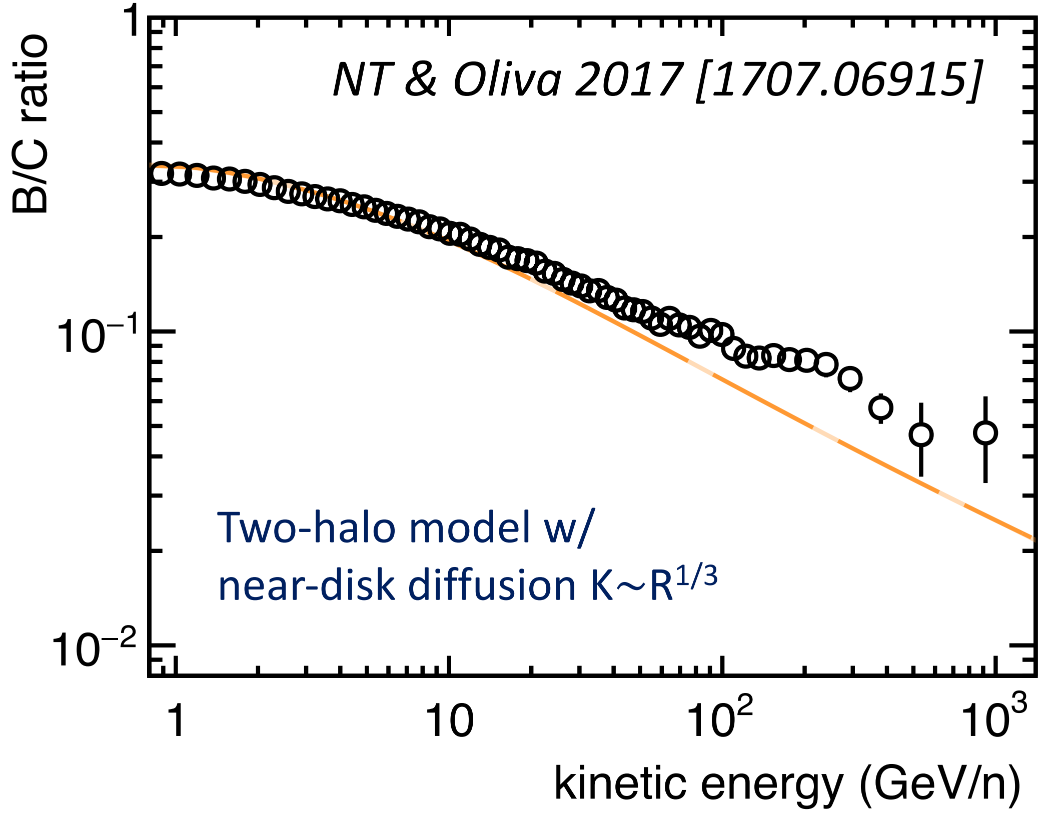
Known mechanisms for acceleration of secondary CRs

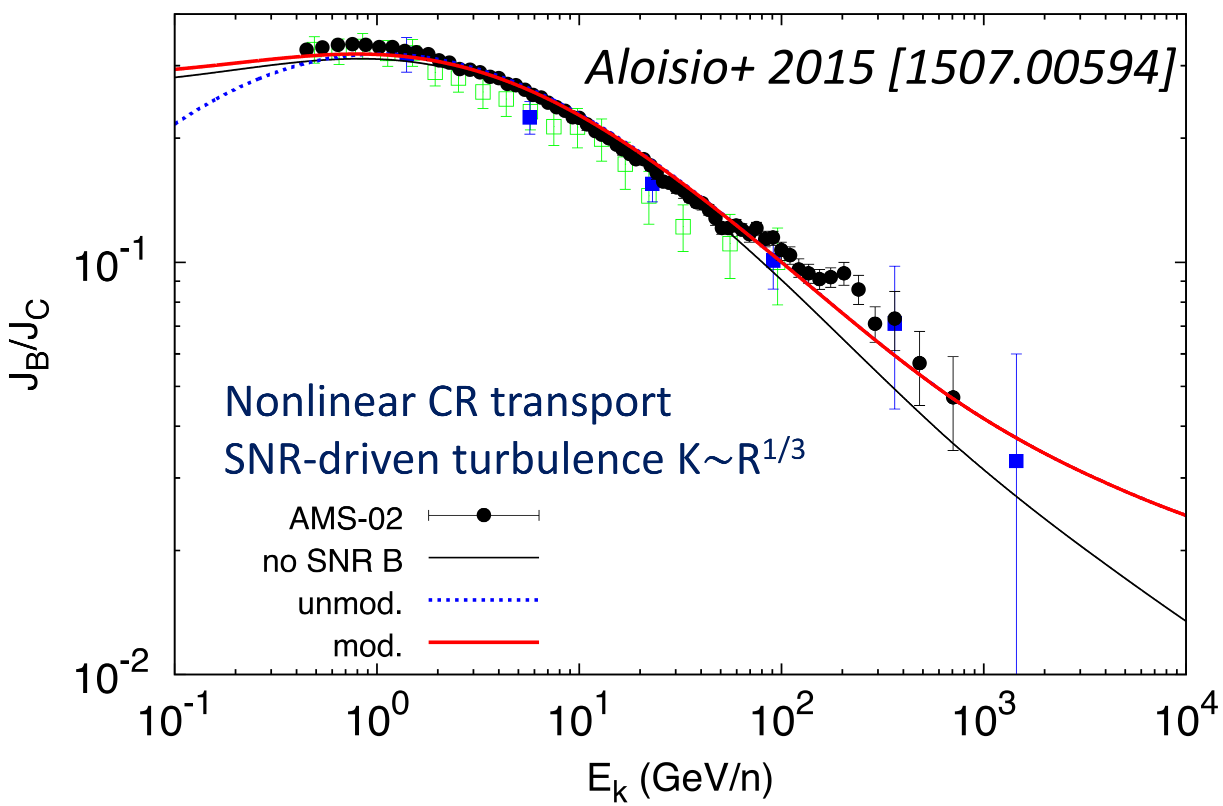
Distributed reacceleration

Hadronic interactions inside sources

Motivations →

Testing with AMS data: *Missing boron?*



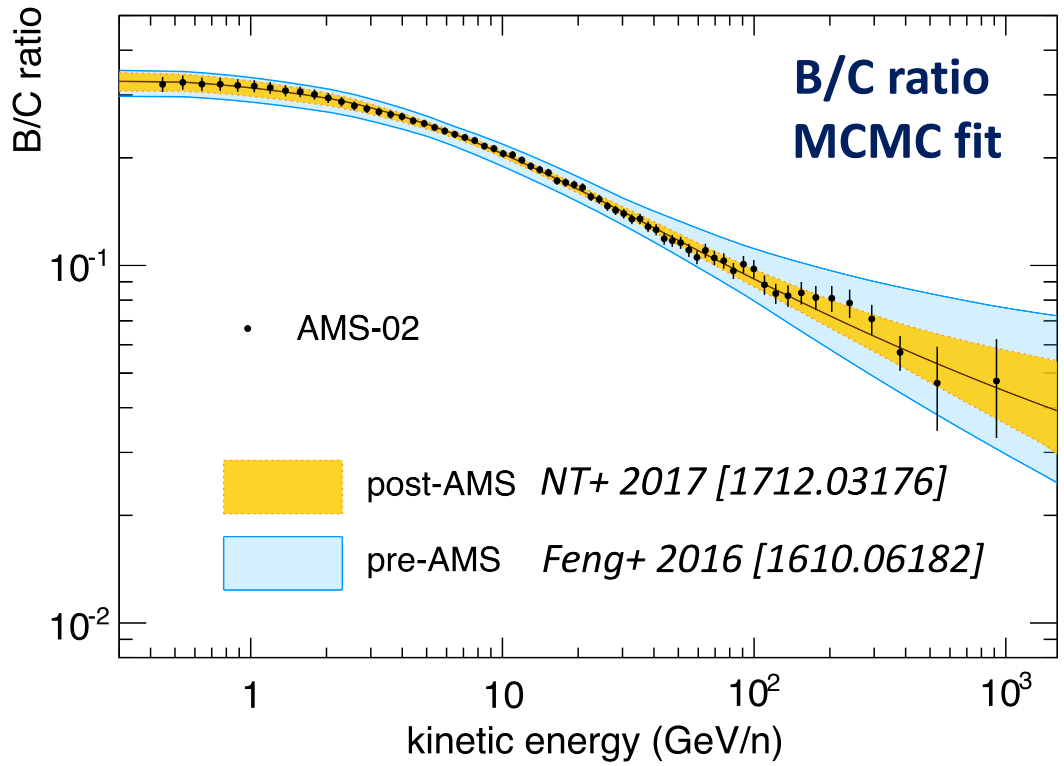


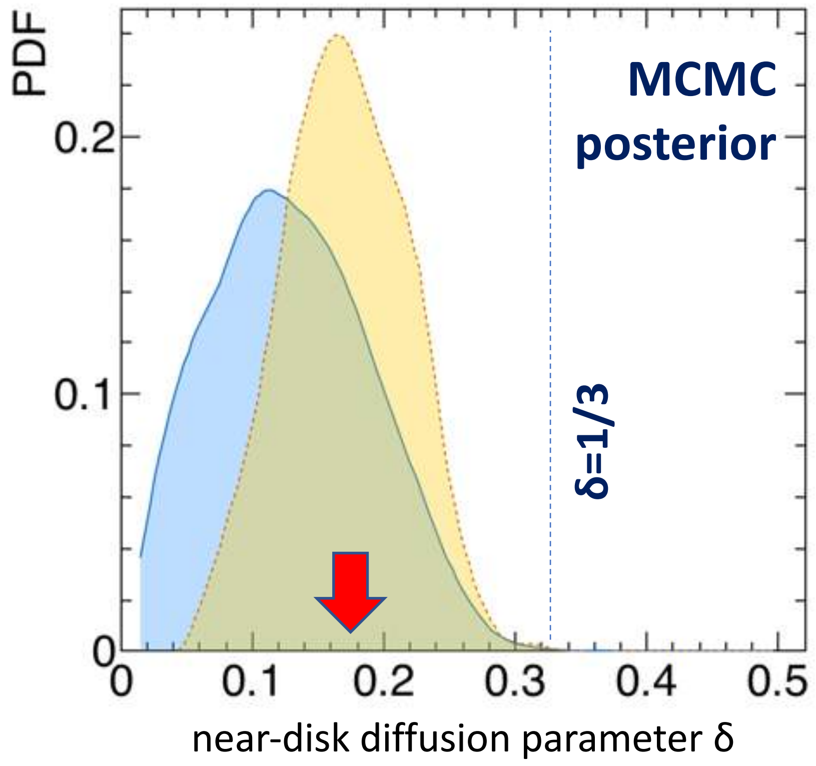
Assumed Kolmogorov-like SNR-driven turbulence -> B/C is underpredicted at TeV energy

This may hint at some «*source component*» of CR boron

⚠

Testing with AMS data *Markov Chain Monte-Carlo global analysis*





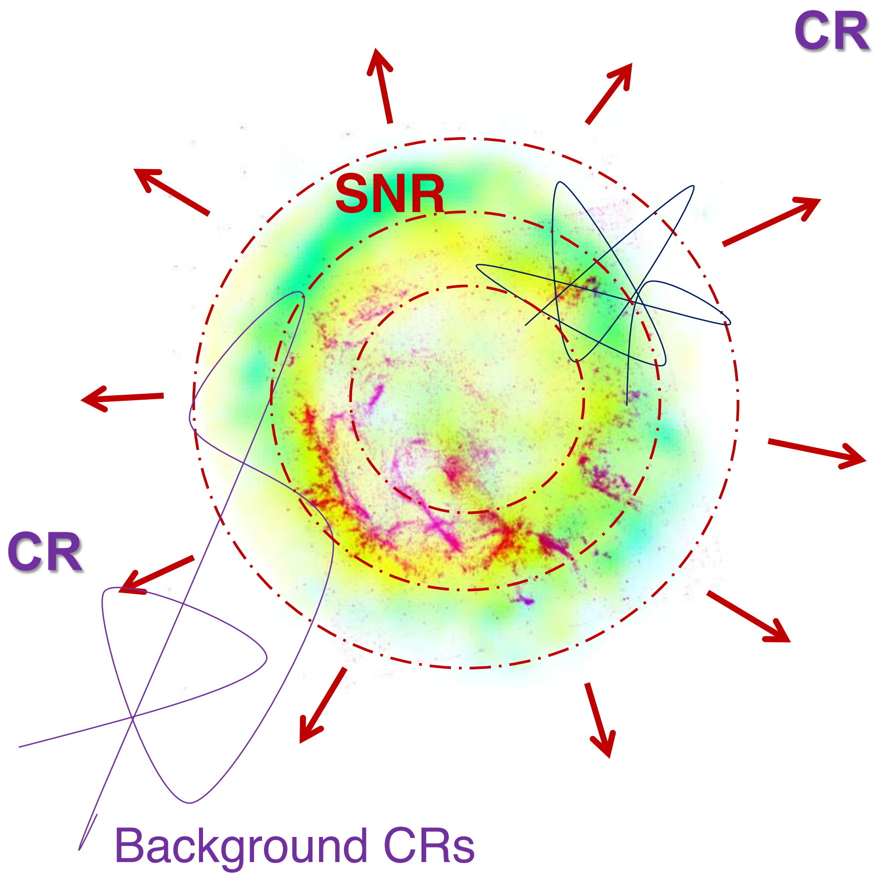
Leaving the near-disk diffusion scaling as free parameter: $\delta = 0.18 \pm 0.2$ (posterior mean)

- Voyager-1 in the LISM confirms expectations $P \sim k^{-5/3}$ [Burlaga+ ApJ 804(2015)L31]
- Within a two-halo scenario, **$\delta=1/3$ is excluded** @ 95%CL w/ AMS02 [NT+ 1712.03176]

Secondary CRs from sources: known mechanisms

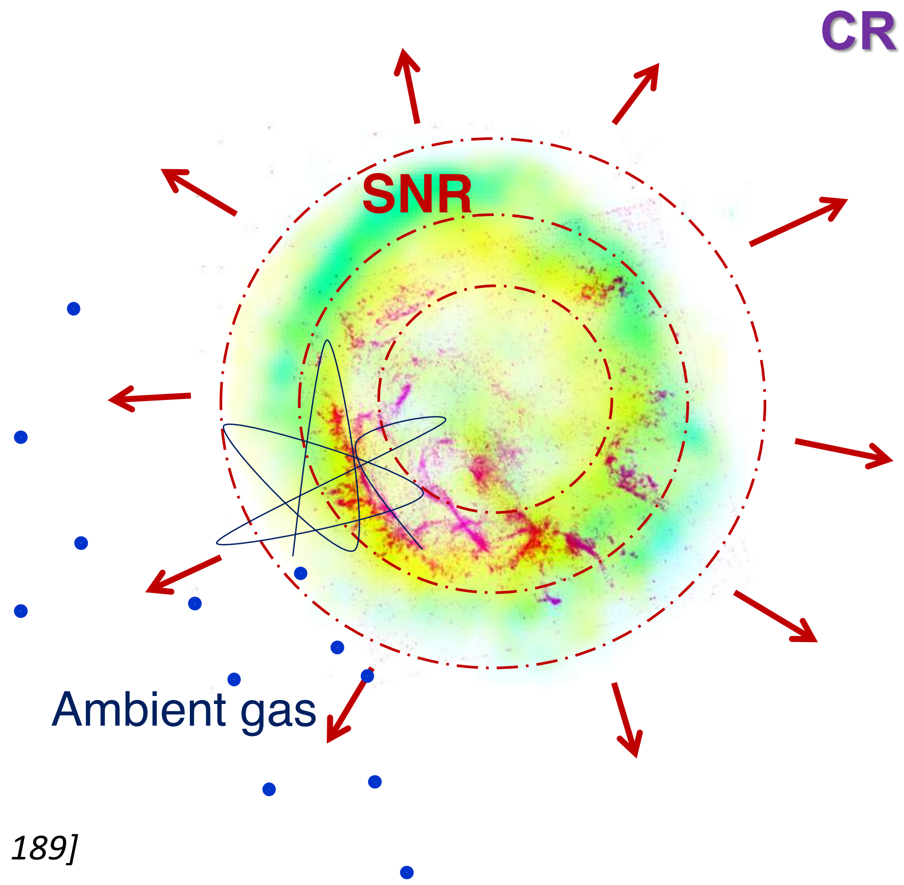
Distributed reacceleration

DSA of preexisting CRs (pri & **sec**) that occasionally encounter SN shocks when traveling in the Galaxy



Fragmentation in SNRs

Production (and DSA) of secondary CRs inside SNRs from collisions of primary CRs with ambient gas

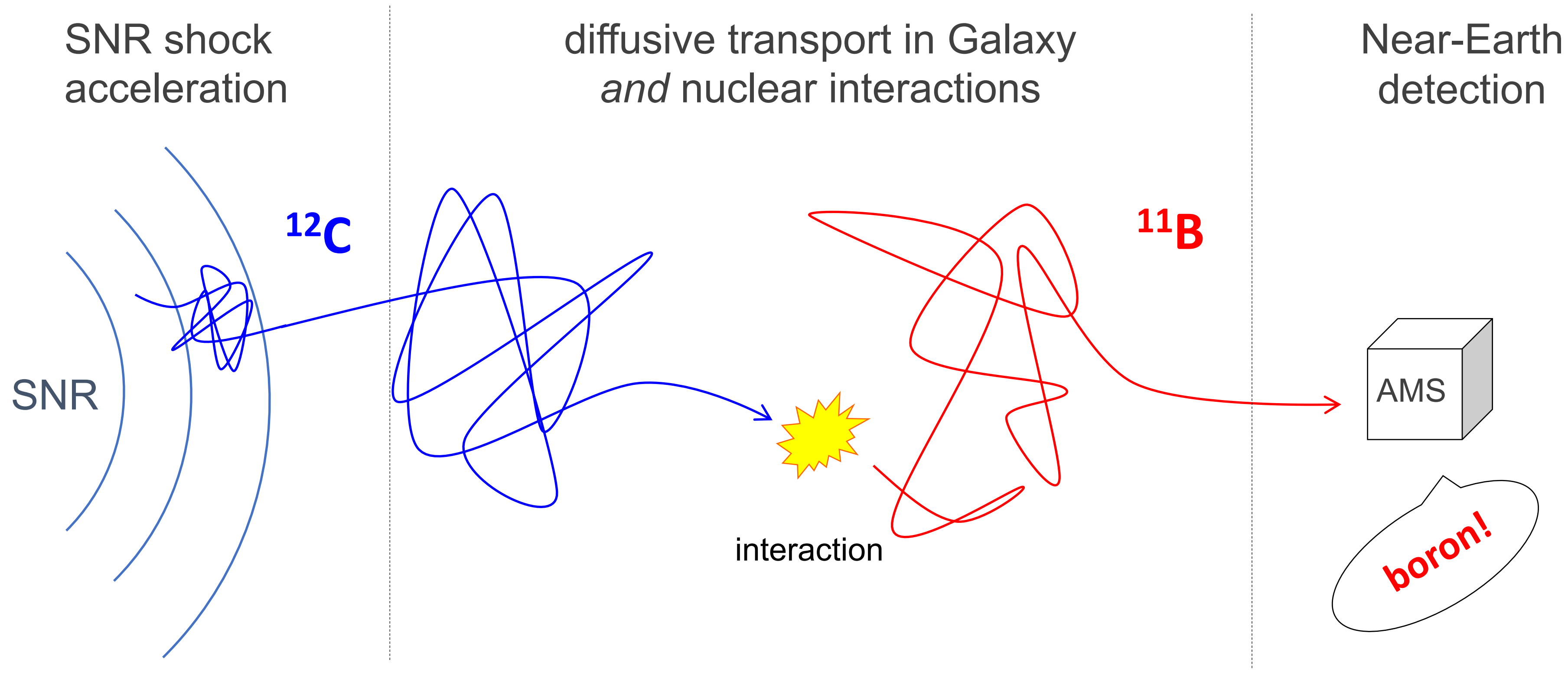


Berezko+ 2003 [A&A 410, 189]

NT & Donato A&A 2012 [1203.6094]

The physical picture

Standard picture

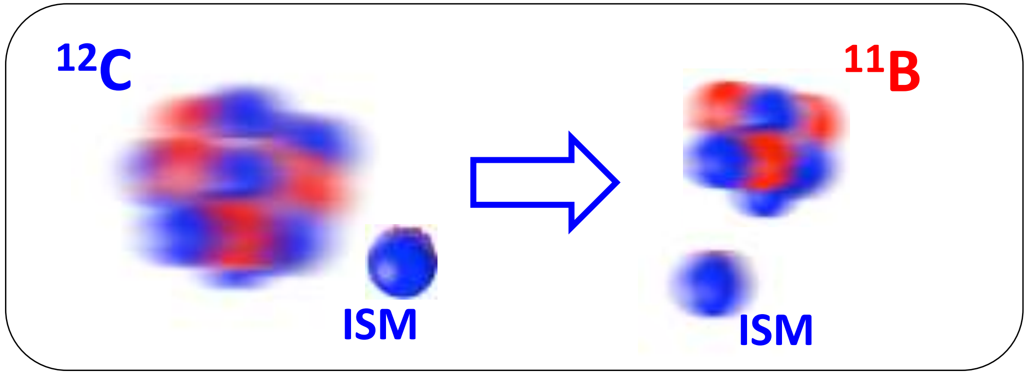


$^{12}C + ISM \dashrightarrow {}^{10,11}B$

$^{16}O + ISM \dashrightarrow {}^{10,11}B$

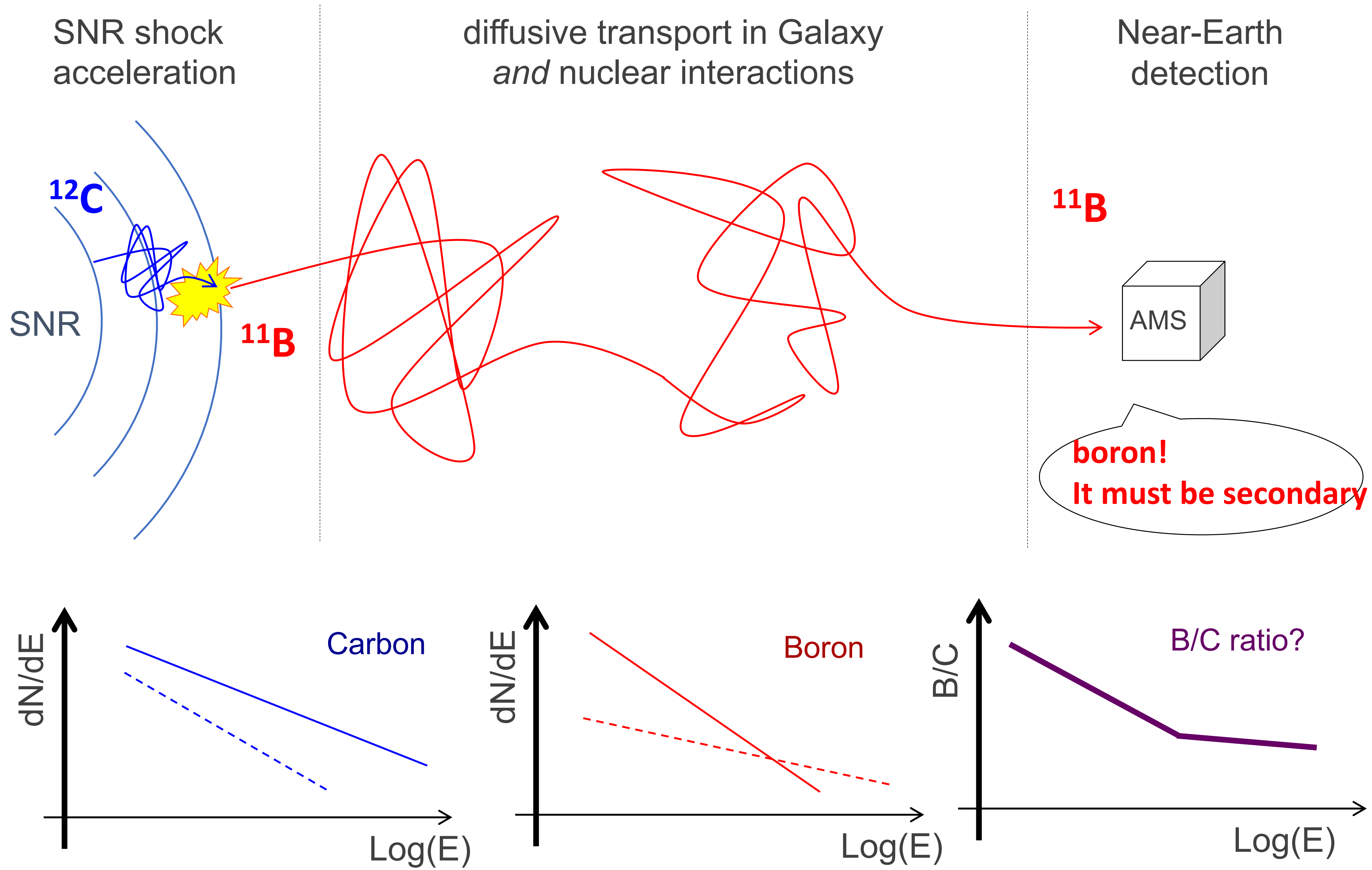
$^{15}N + ISM \dashrightarrow {}^{10,11}B$

$^{28}Si + ISM \dashrightarrow {}^{10,11}B$



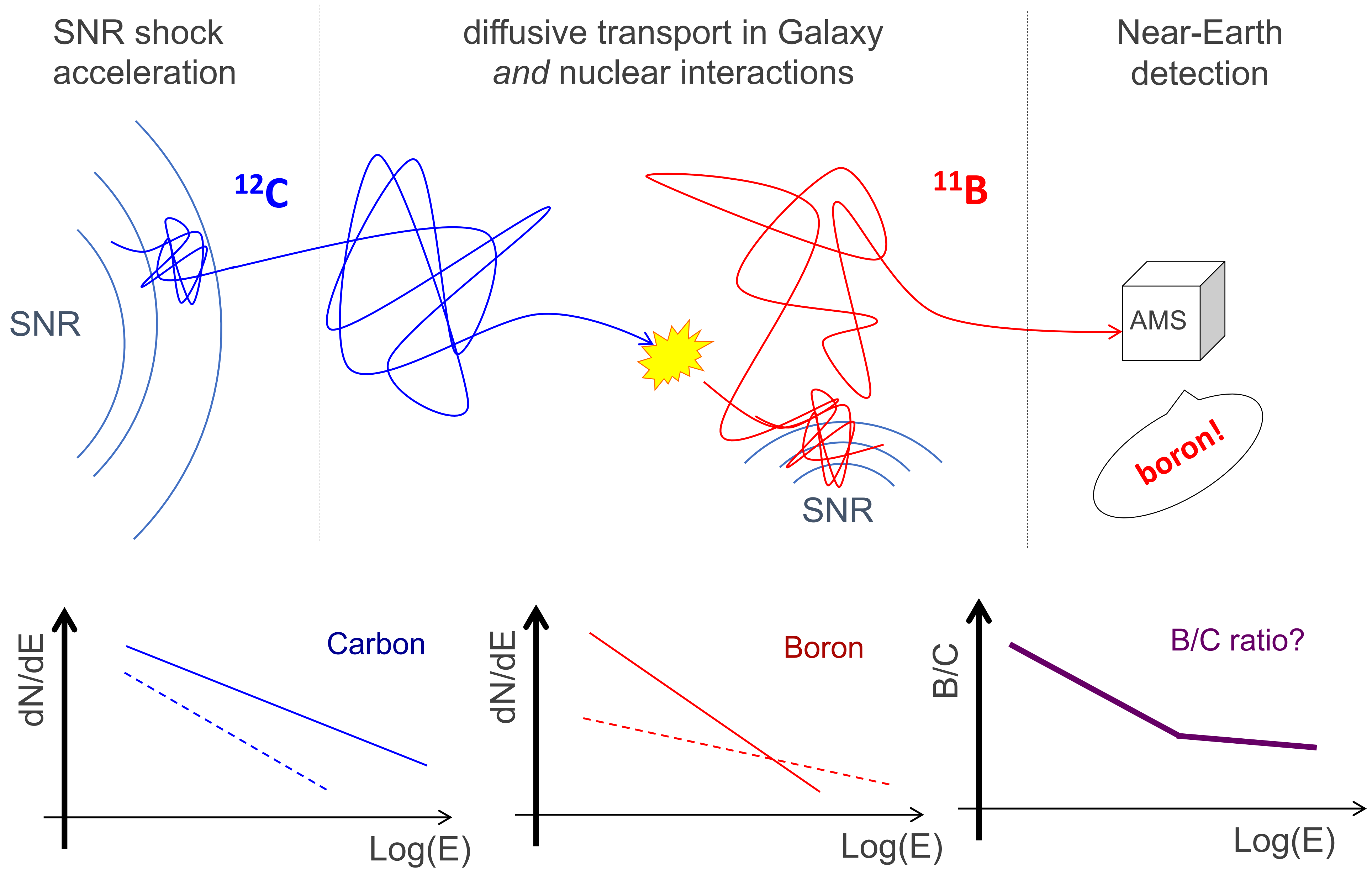
The physical picture

Fragmentation in SNRs



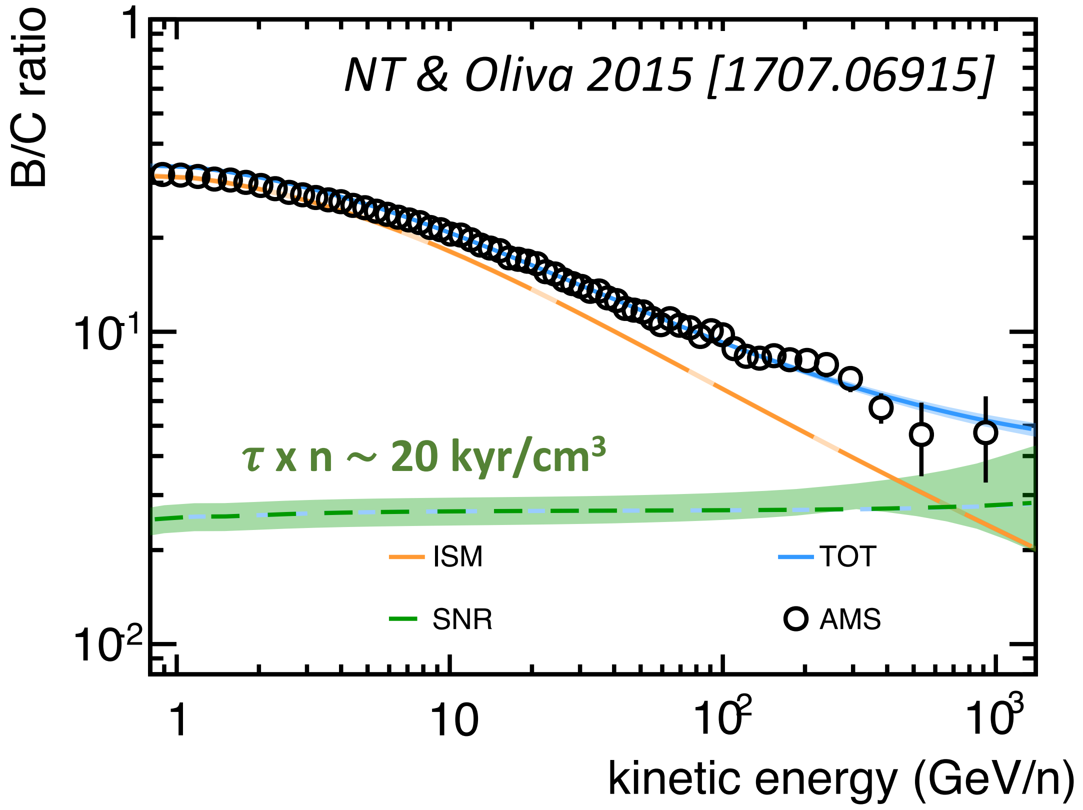
The physical picture

Distributed reacceleration

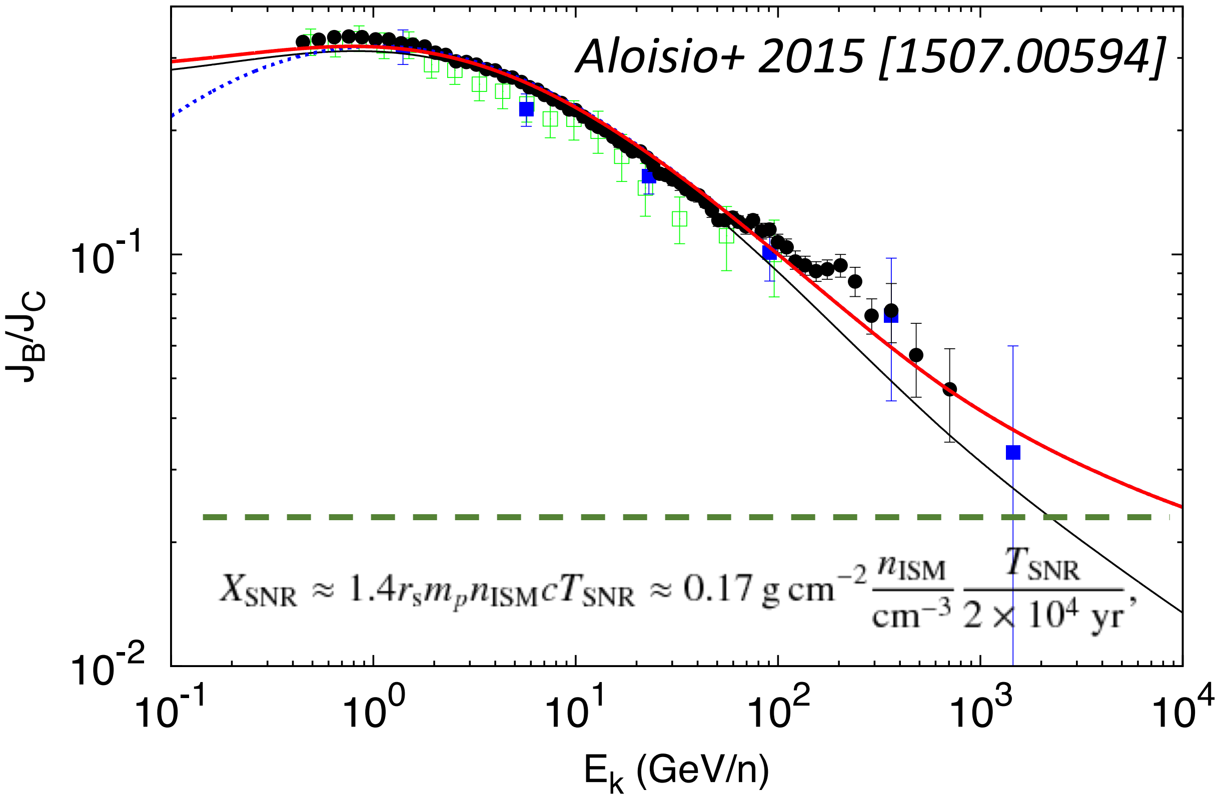


New Test with the AMS data *Secondary B from SNRs*

Two-halo to account for primary fluxes
Near-disk diffusion scaling fixed to 1/3



Nonlinear CR transport model
SNR-driven turbulence ~R^1/3



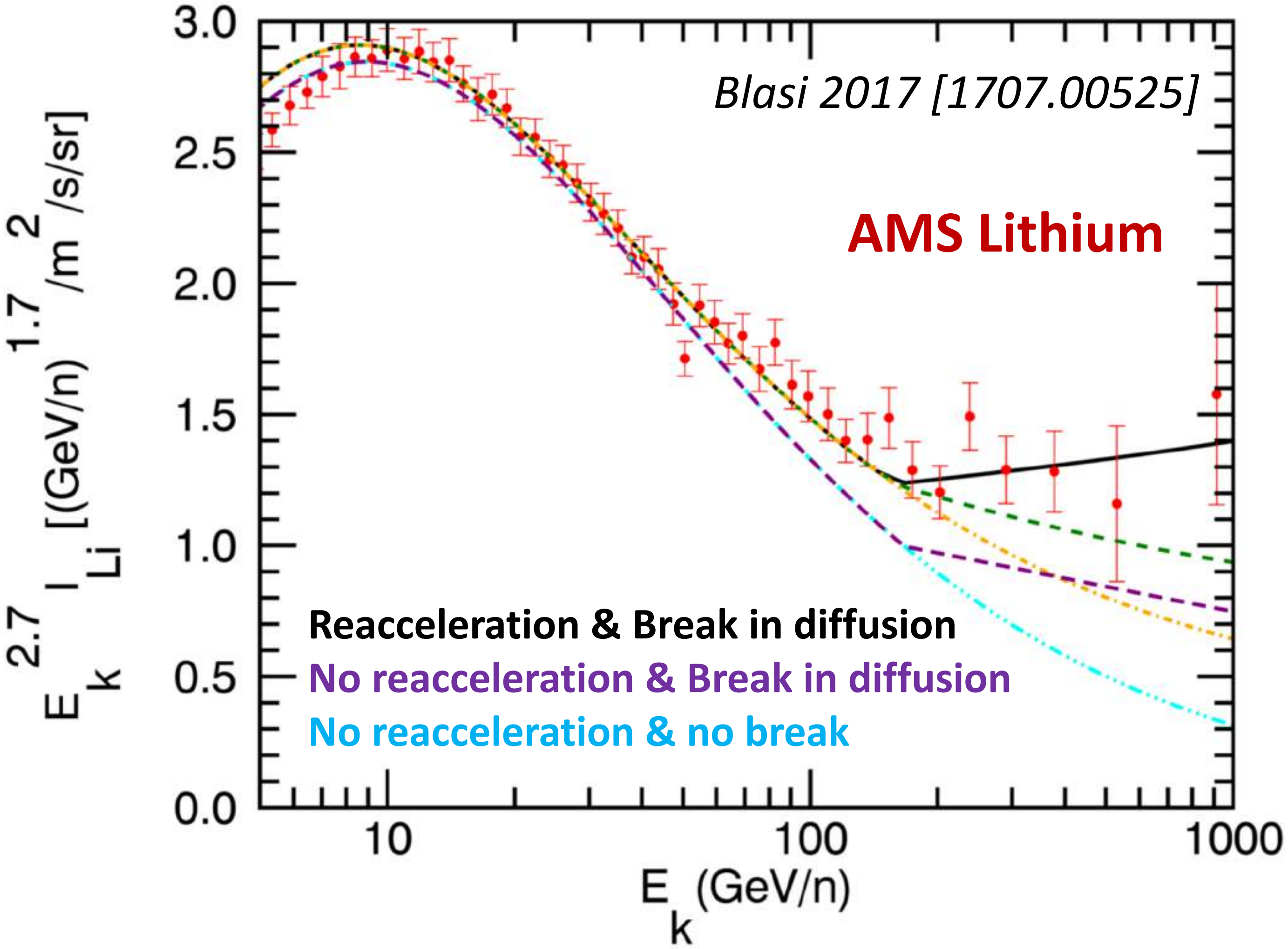
→ Consistent with SNRs of age <T> ~ 20 kyr expanding over the regular ISM ($n \sim 1 cm^{-3}$)

Test with the AMS data *Shock accelerated Li-Be-B*

Break in diffusion w/ HE scaling fixed to 1/3

+ Reacceleration at work

Li-Be-B data support distributed reacceleration



AMS antiproton data: a new anomaly?

✓ **Expectations:**
decrease of pbar/p ratio, similar to the decrease of B/C ratio

✓ **Data:**
the measured antiproton flux is as hard as the proton flux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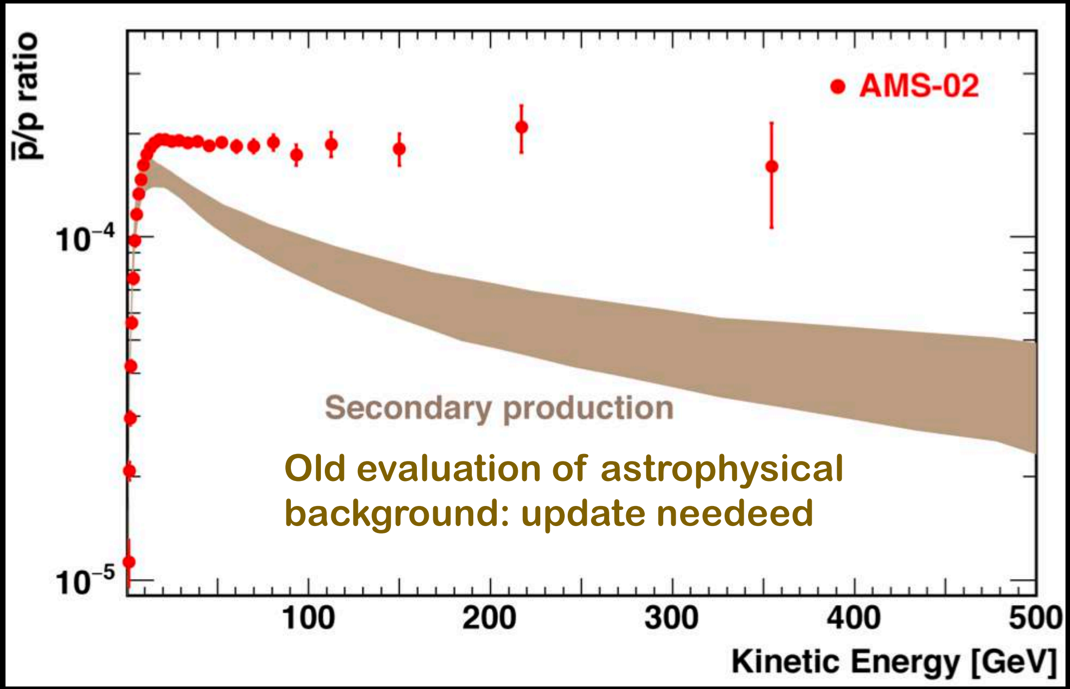
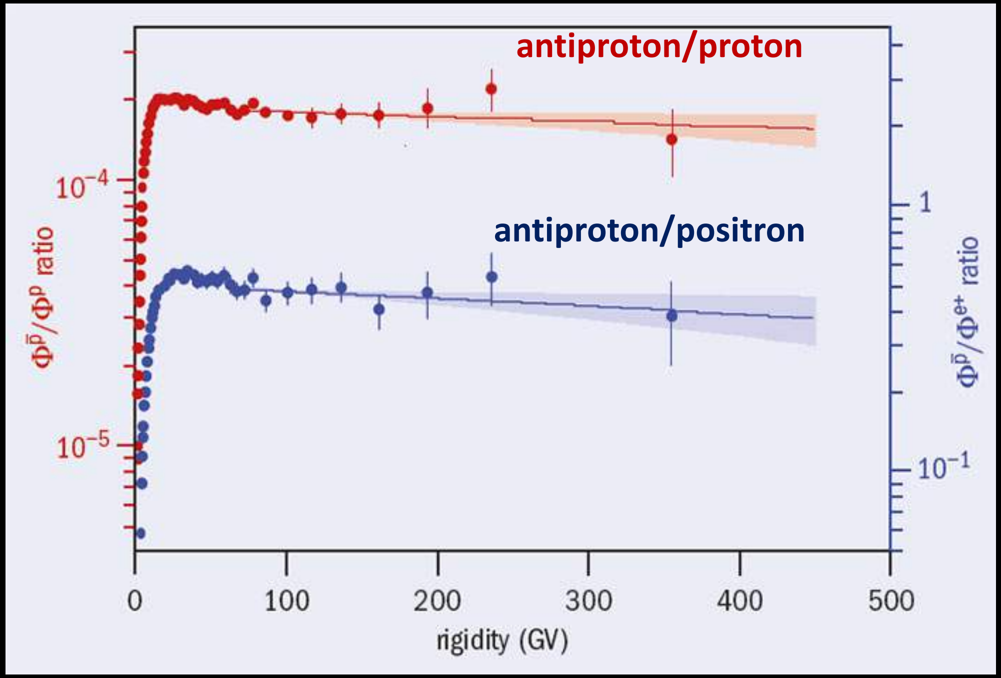
FEATURE

Cosmic rays continue to confound

11 November 2016

Five years of data from the AMS experiment on board the International Space Station reveal intriguing features.

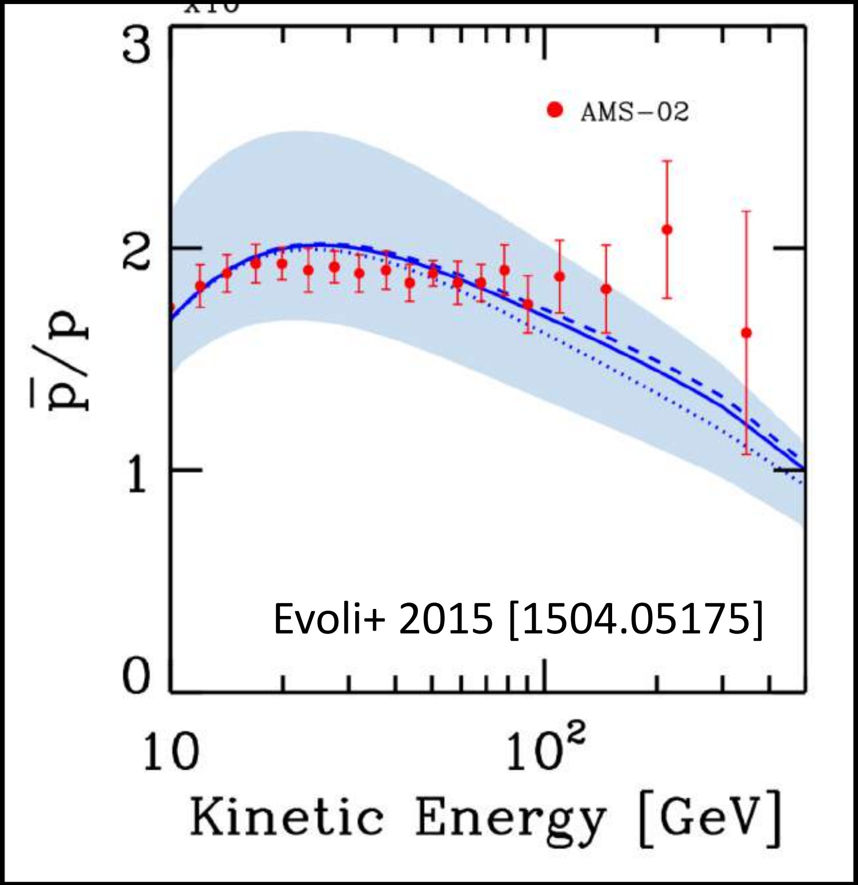


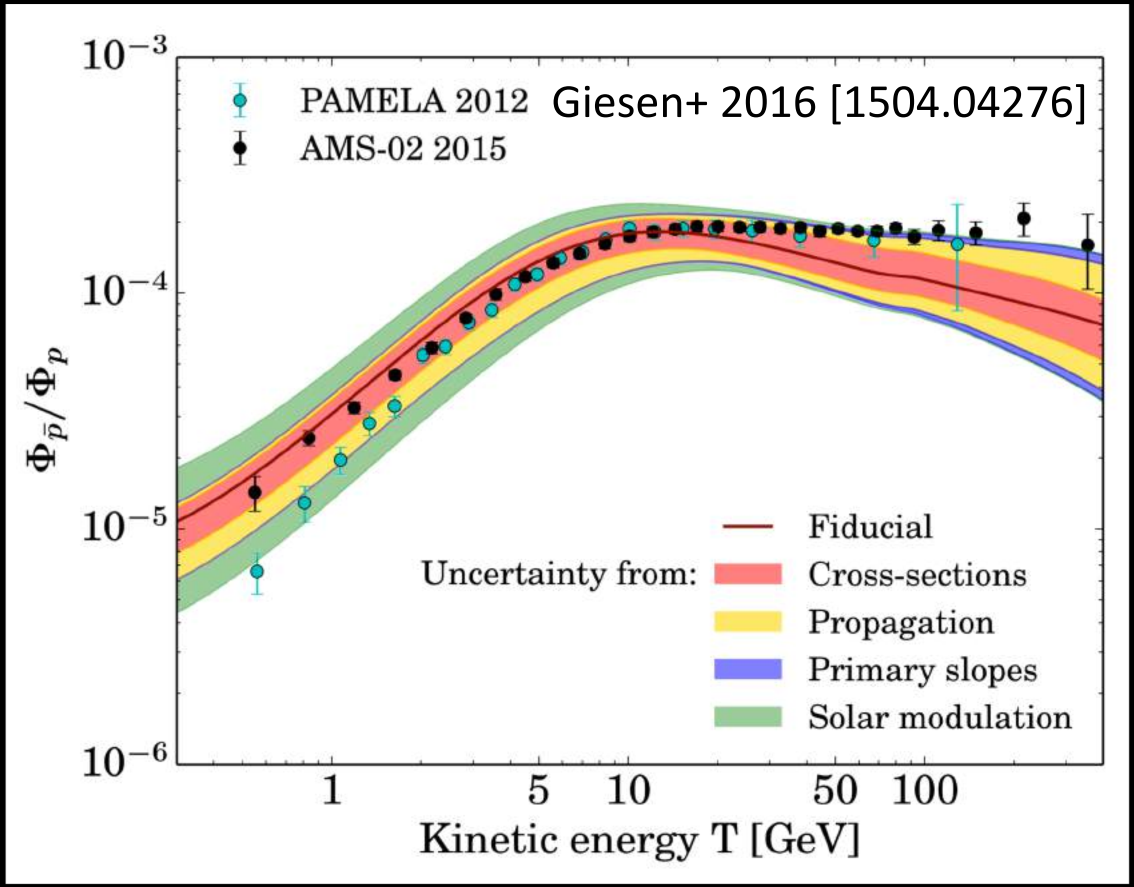


AMS antiproton data: a new anomaly?

Conservative estimates of all uncertainties → no clear excess

But, no good agreement between data an calculations





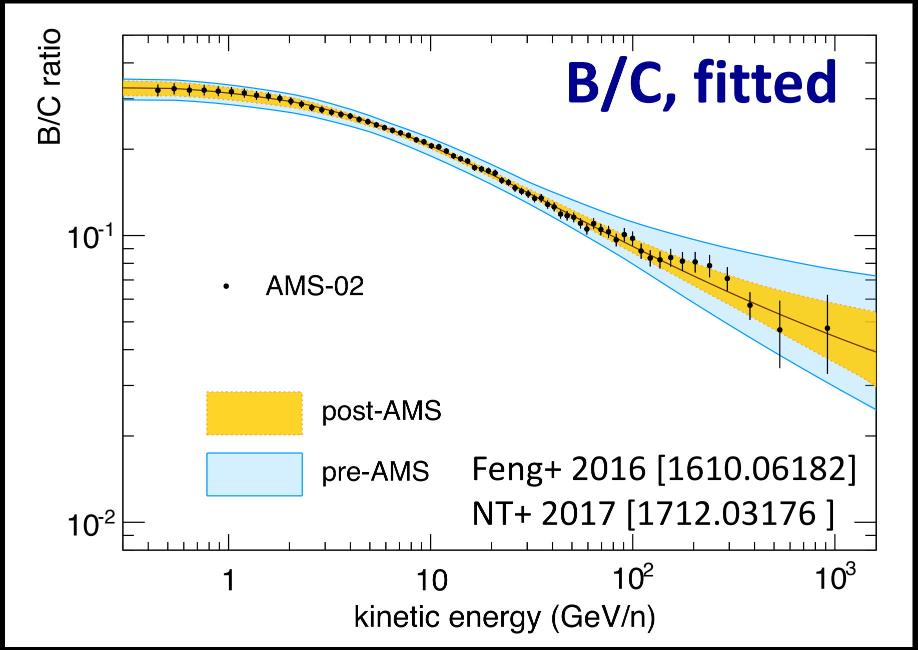
AMS antiproton data: a new anomaly?

Conservative estimates of all uncertainties → no clear excess

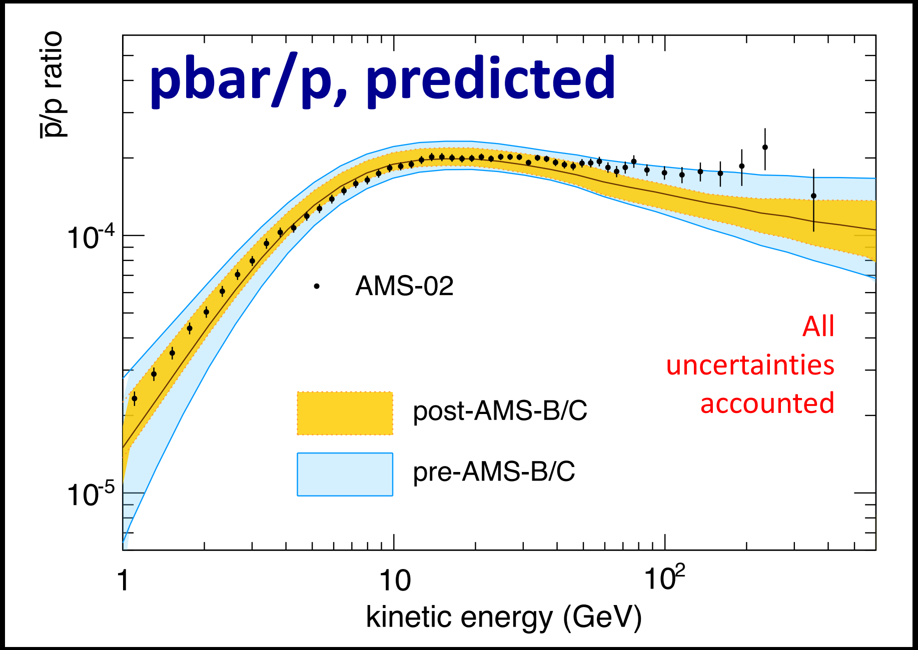
But, no good agreement between data an calculations

Use of AMS-02 B/C ratio data (2016) → Updated prediction of secondary p

Useof Bayesian MCMC techniques → A clear tension starts to emerge

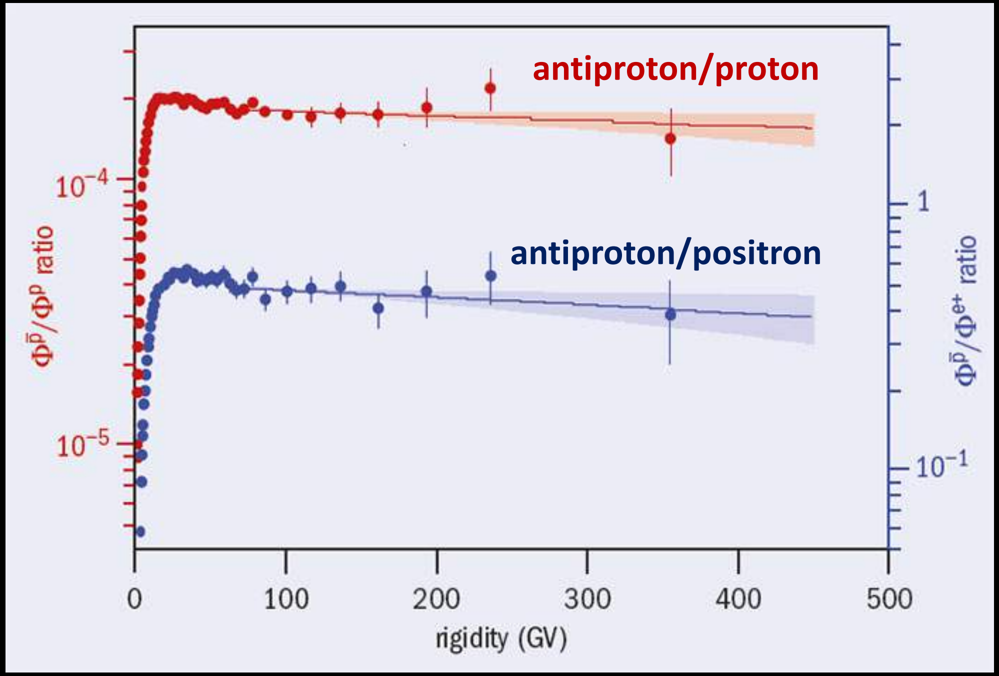


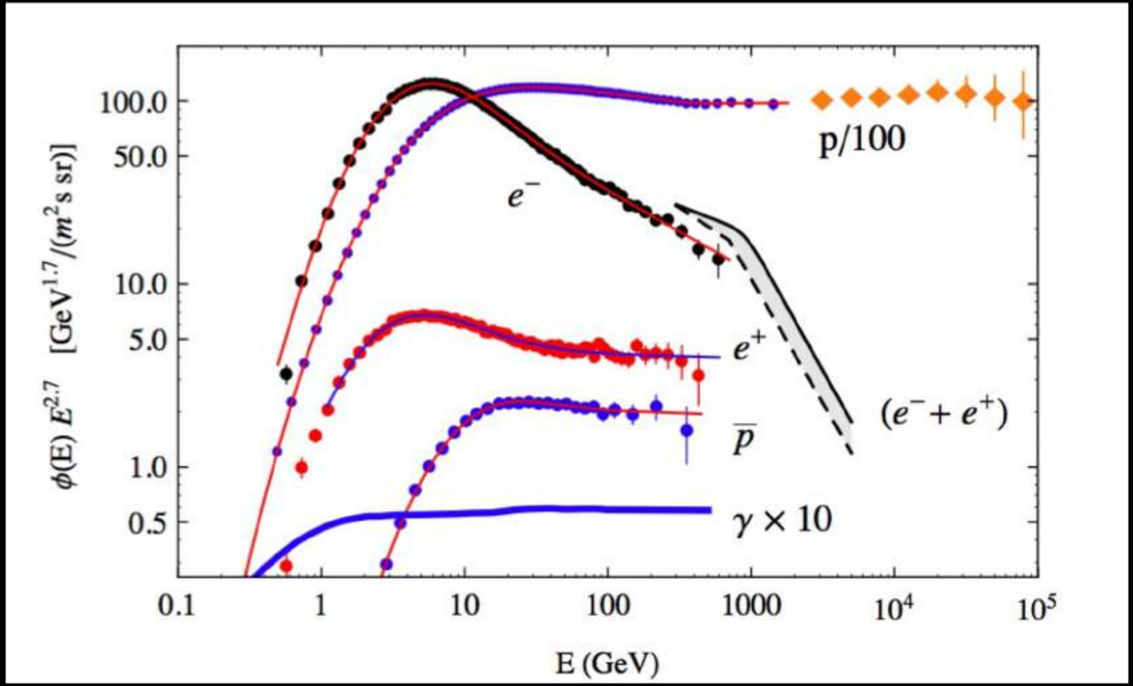
MCMC Global Bayesian Analysis



AMS antiproton data: a new anomaly?

Proton, antiproton, positron spectra: a remarkable coincidence





Standard picture

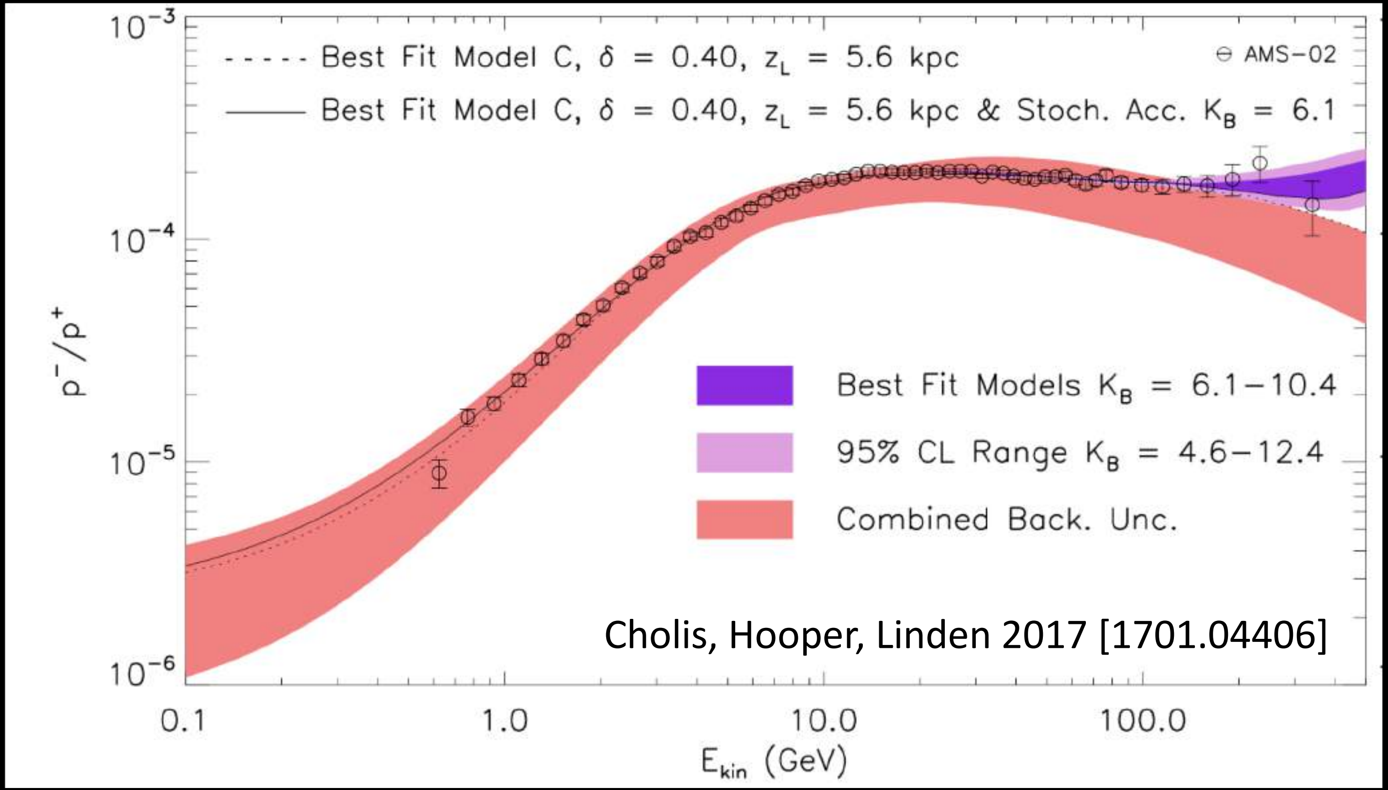
- Very long lifetime for cosmic rays
- Lepton/hadron diferences between due to propagation
- New hard source of positrons is required
- Secondary production occurs in interstellar space

→ **The spectra of p, p, and e+ are similar by coincidence**

Lipari 2017 PRD [1608.02018]

- Much shorter lifetime for cosmic rays
- Electron/proton difference is due to their accelerators
- Antiprotons and positrons of secondary origin
- Secondary production occurs inside accelerators

Shock accelerated antiprotons?



Pbar/P "excess" explained by production and acceleration of hard antiprotons inside supernova remnants

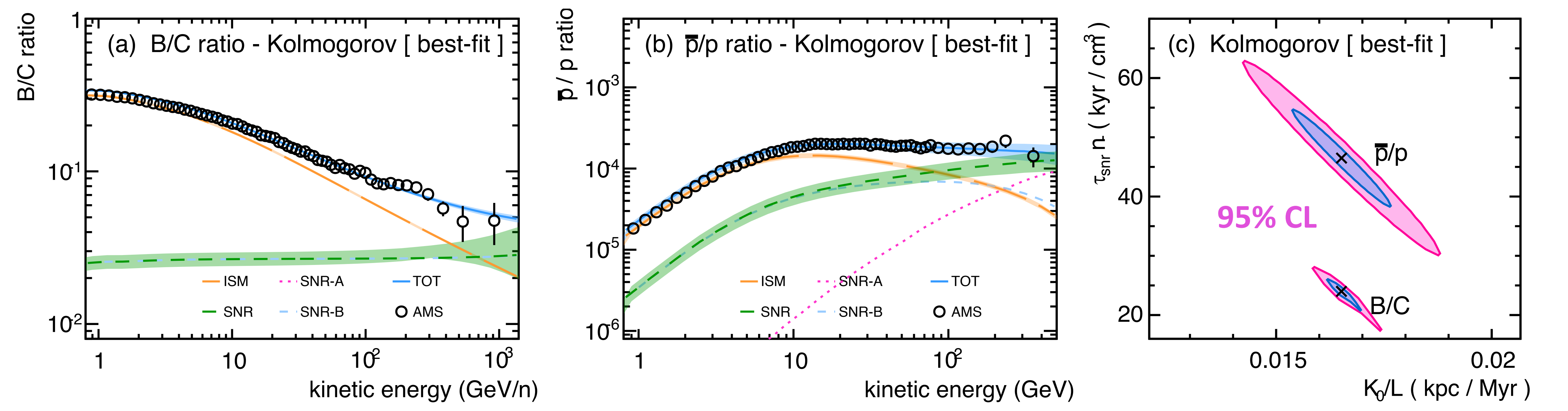
Shock accelerated antiprotons?

NT &Oliva 2017
[1707.06915]

→ Good fit, but still inconsistent with B/C ratio.
→ Antiproton production and acceleration in SNRs does not resolve the tension between B/C and pbar/p

Unless… p-He and metals are accelerated by different sources

→ Break of connection between B/C and pbar/p. → B/C ratio is no longer a diagnostic tool.
→ Ideal diagnostic: high-energy deuterons. Same progenitors as antiprotons [NT & Feng 1612.05651]

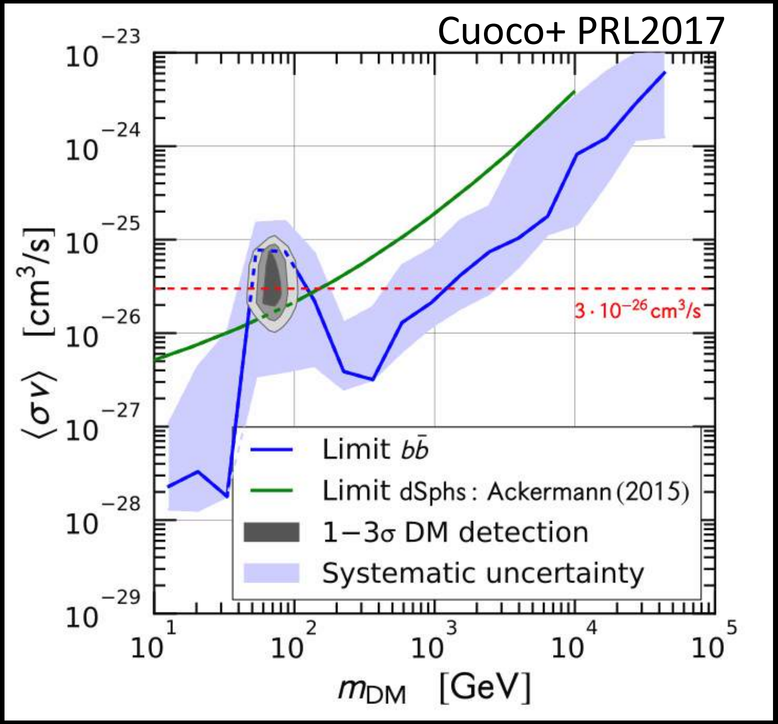


Antiprotons from dark matter?

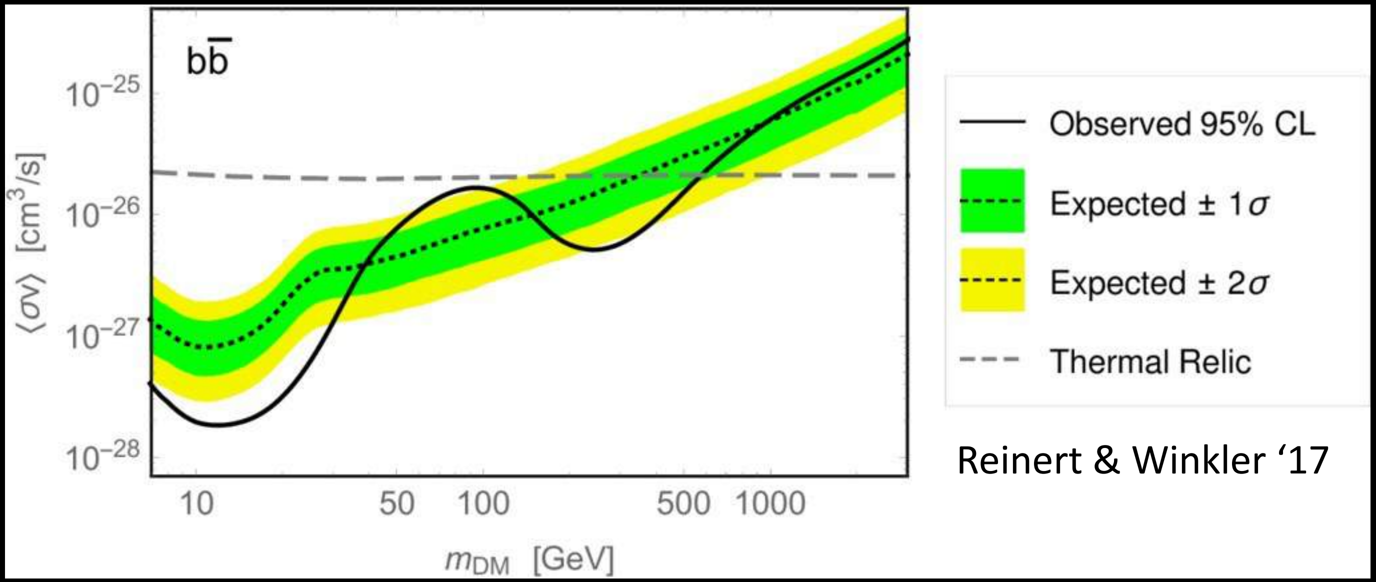
AMS-02 data (2015): remarkably hard antiproton/proton ratio
Old evaluation of astrophysical background: update needeed

Cuoco et al. 2017 + Cui et al. 2017: evidence for DM excess

- Consistent w/ gamma-ray excess
- At the level of thermal annihilation rate

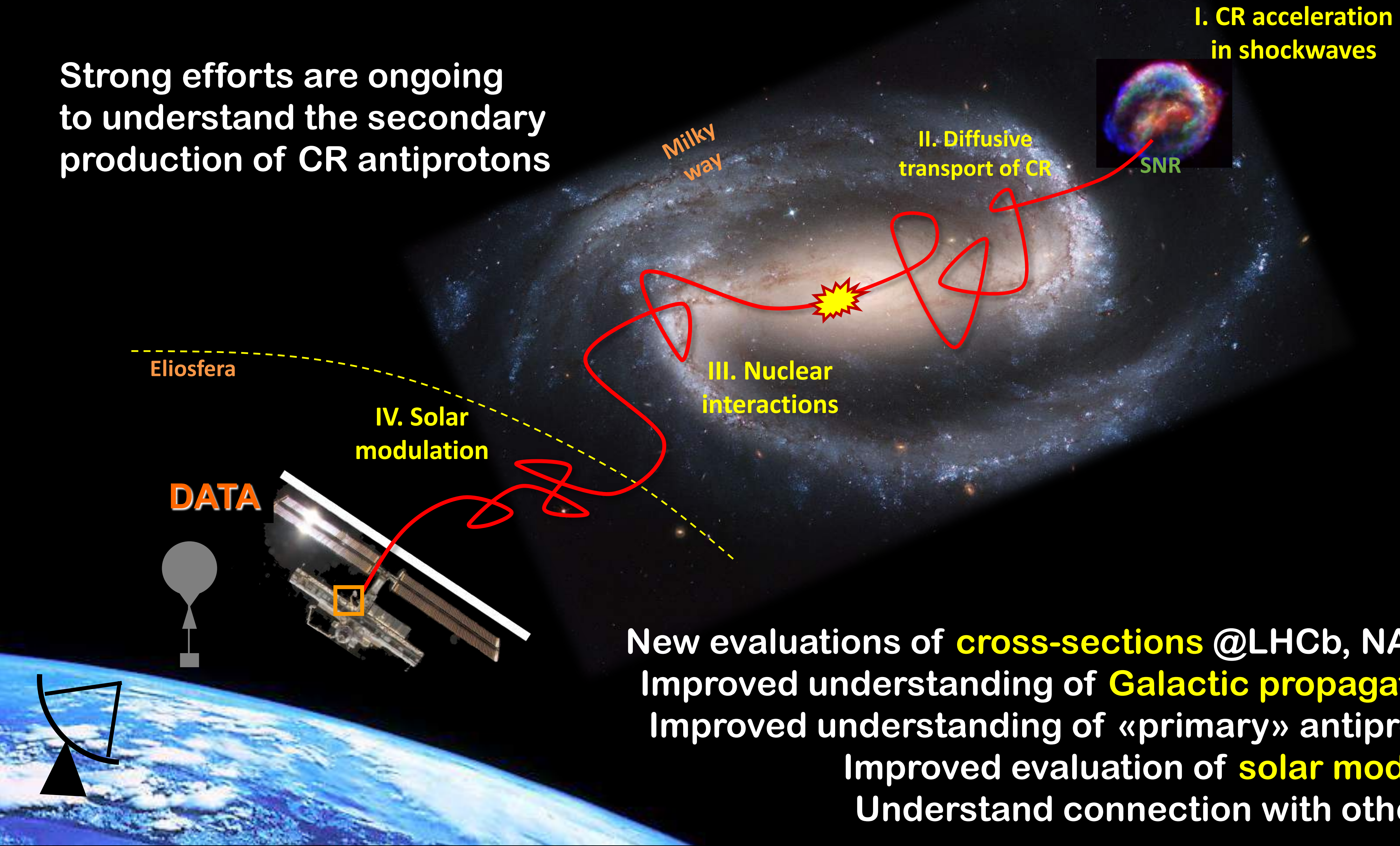


All uncertainties accounted → wait, it's just 1-sigma



Antiprotons: summary

Strong efforts are ongoing to understand the secondary production of CR antiprotons



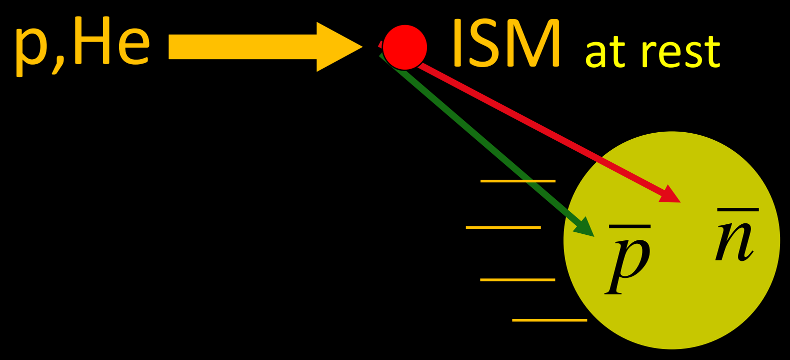
New evaluations of cross-sections @LHCb, NA61, COMPASS
Improved understanding of Galactic propagation processes
Improved understanding of «primary» antiprotons sources
Improved evaluation of solar modulation effects
Understand connection with other messengers

Next milestone: antinuclei

Never detected in cosmic rays → Next milestone [→ AMS-02, GAPS]
Nuclear coalescence of antinucleons: $\bar{d}=\{\bar{p},\bar{n}\}$, $\overline{He}=\{\bar{p},\bar{p},\bar{n}\}$ [→ ALICE]

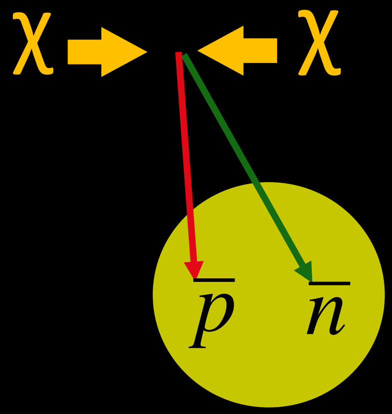
Favorable signal/background ratio, due to kinematics

Antideuterons from CR collisions

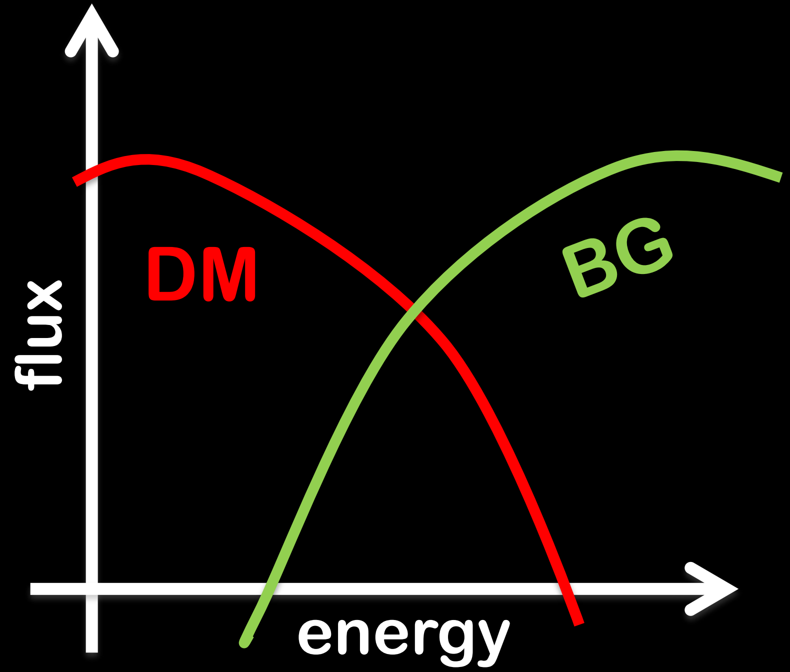


Collisions of RC with interstellar gas
Secondary deuterons produced at HE

Antideuteron from DM-DM



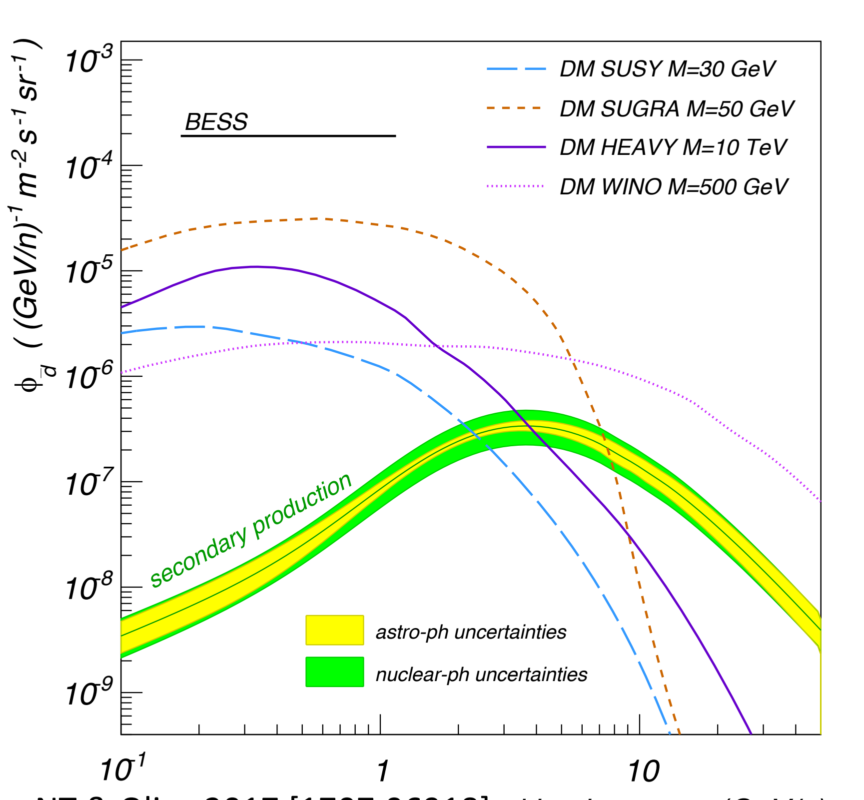
Collisions χ+ χ -> had -> d-bar
Galactic frame ~ CM frame



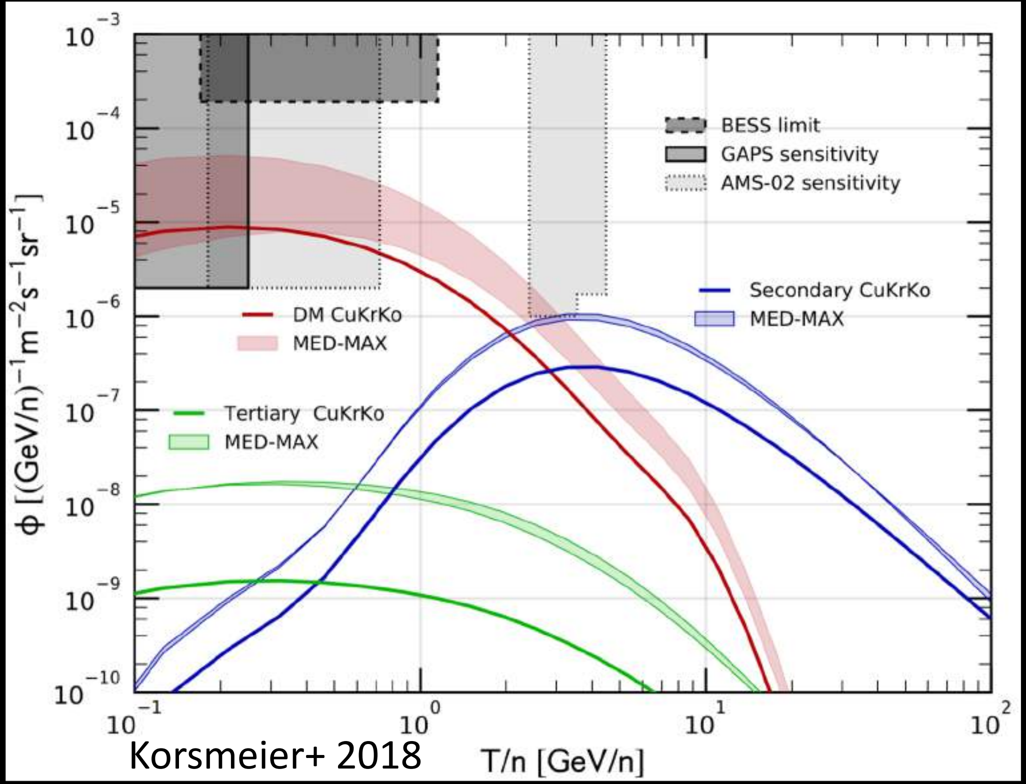
Next milestone: antinuclei

The sub-GeV region is very promising to probe ~100 GeV scale DM

anti-deuteron



NT & Oliva 2017 [1707.06918]



Korsmeier+ 2018

Next milestone: antinuclei

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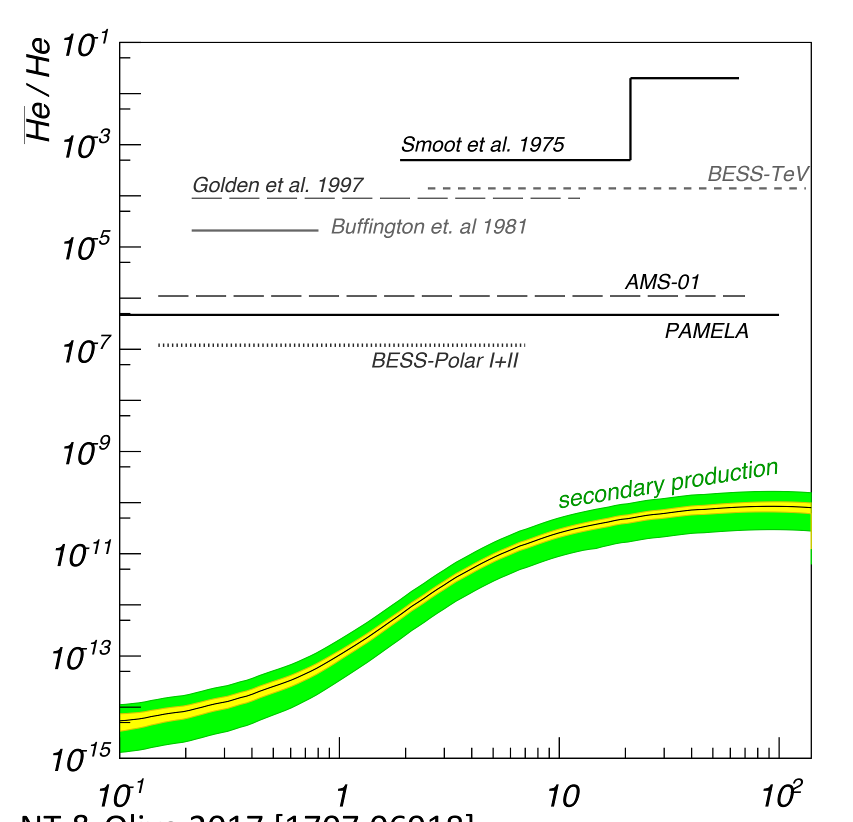
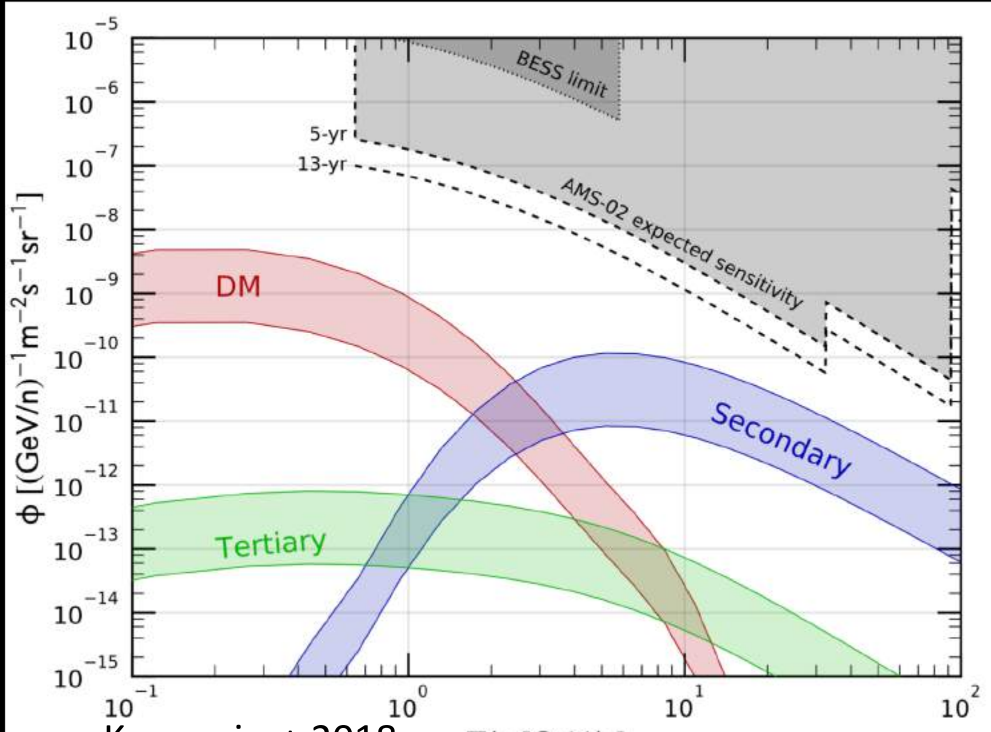
anti-helium



NT & Oliva 2017 [1707.06918]



Korsmeier+ 2018

Antihelium enhancement?

$pp \rightarrow p\,p\,p\,n\,\bar{p}\,\bar{n}$

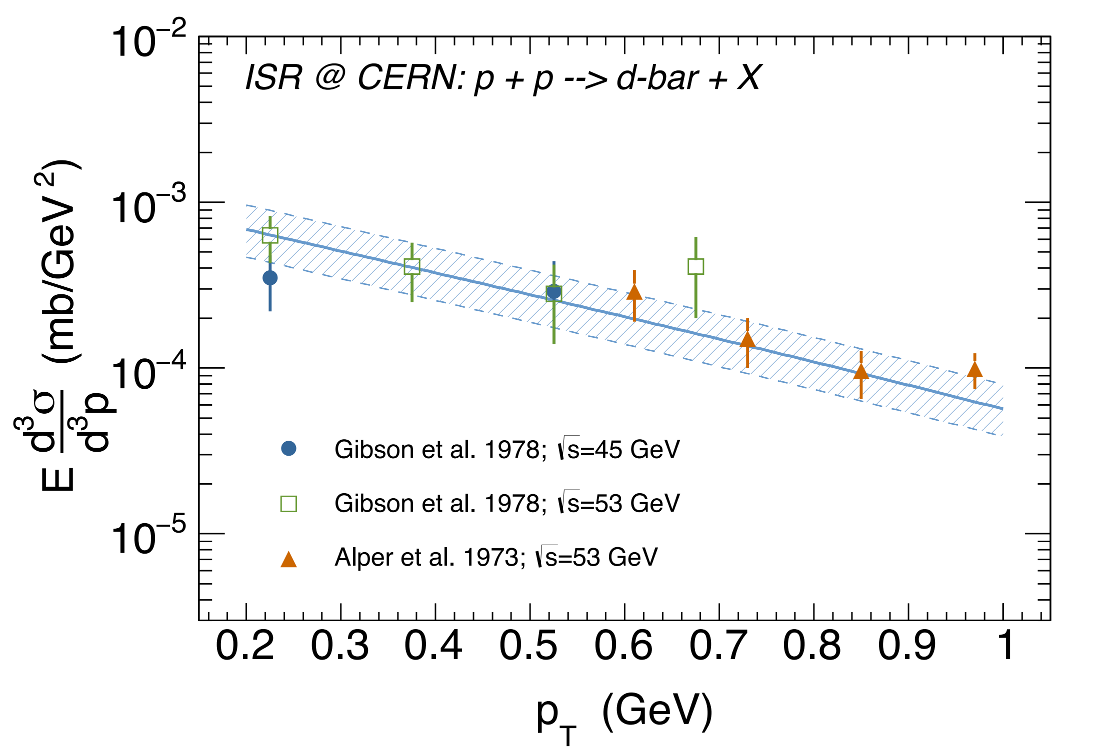
$$E_A \frac{d^3\sigma_A}{dp^3} = B_A \left(E_N \frac{d^3\sigma_N}{dp^3} \right)^A_{p_N = p_N/A}$$

Coalescence model, standard approach.

The coalescence parameter is constrained against cross-section data pp-> dbar+X

No valuable data for antihelium
→ Assumed same coalescence momentum.
→ Checked against p+Be or p+Al data

anti-deuteron XS's



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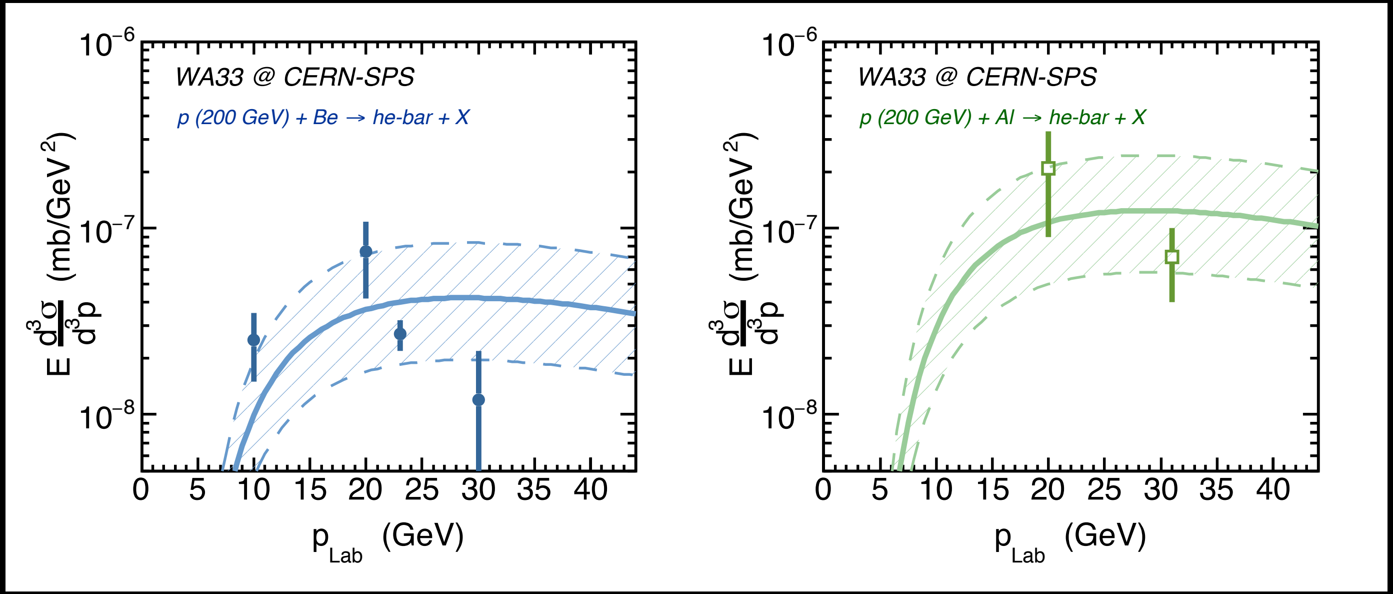
anti-helium XS @SPS

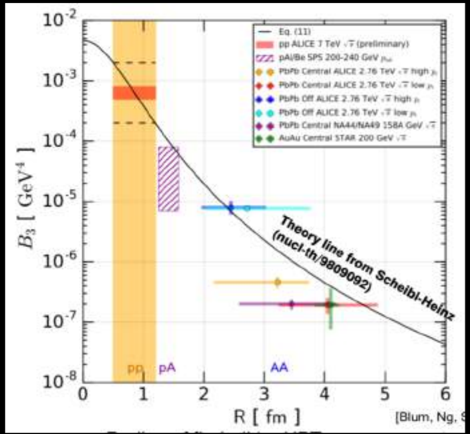


Antihelium enhancement?

Blum, Ng, Sato, Takimoto(201)7

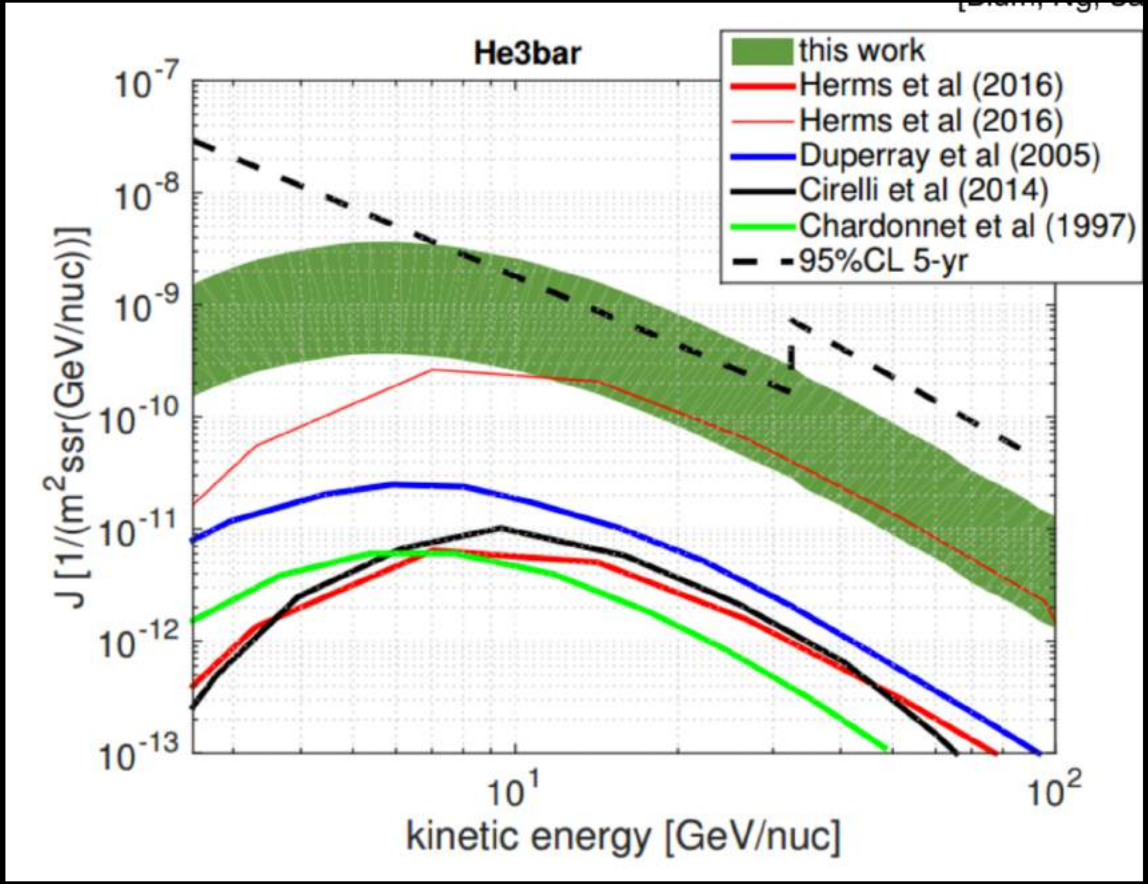
$$E_A \frac{d^3\sigma_A}{dp^3} = B_A \left(E_N \frac{d^3\sigma_N}{dp^3} \right)^A_{p_N = p_N/A}$$

Blum+ 2017: alternative model for nuclear coalescence into antihelium



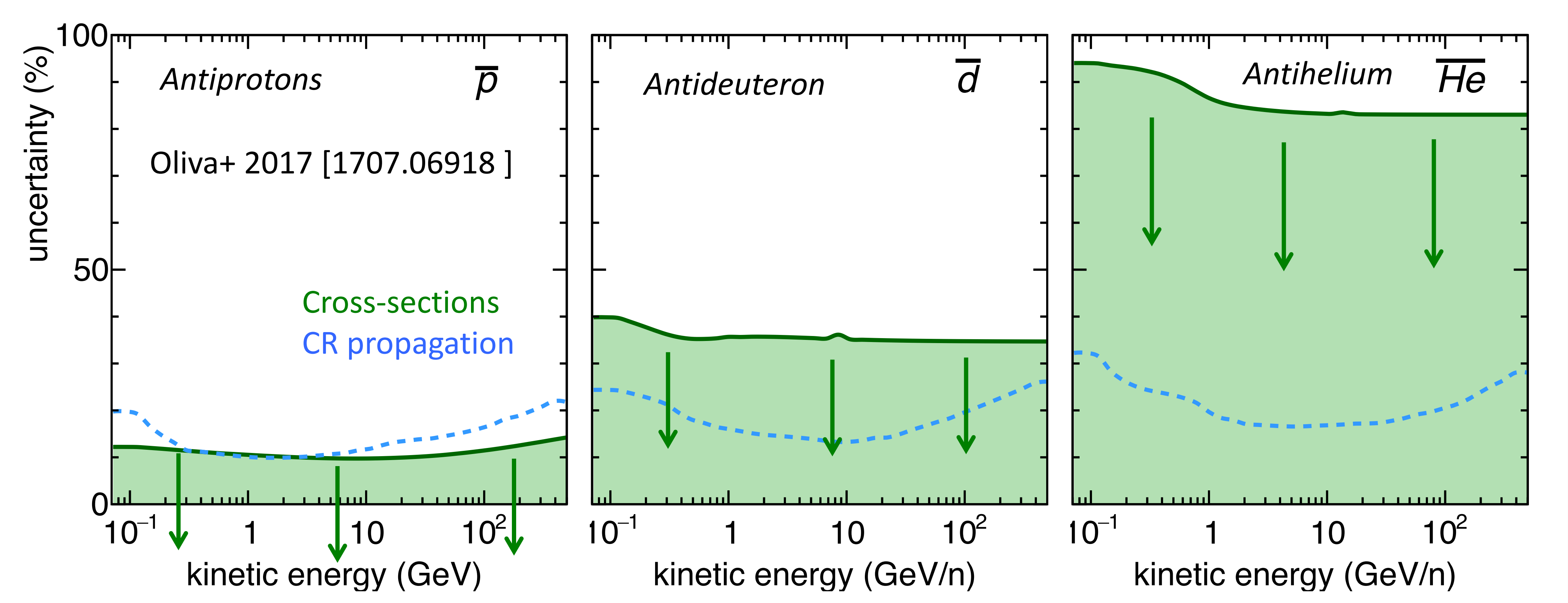
Enhanced antihelium production by a factor ~100.

anti-helium



→ To be verified with new cross-section data from ALICE [Acharya+ 2018 PRC]

Propagation VS cross-section uncertainties



New crosss-section data from LHC.

Work in progress

Received: 28 August 2017 | Revised: 10 September 2017 | Accepted: 13 September 2017
DOI: 10.1002/asna.201713446

ORIGINAL ARTICLE

LHC

Astronomische Nachrichten

Measurement of antiproton production in *p*–He collisions at LHCb to constrain the secondary cosmic antiproton flux

G. Graziani* | on behalf of the LHCb collaboration

PHYSICAL REVIEW C **97**, 024615 (2018)

ALICE

Production of deuterons, tritons, ^{3}He nuclei, and their antinuclei in *pp* collisions at $\sqrt{s}$ = 0.9, 2.76, and 7 TeV

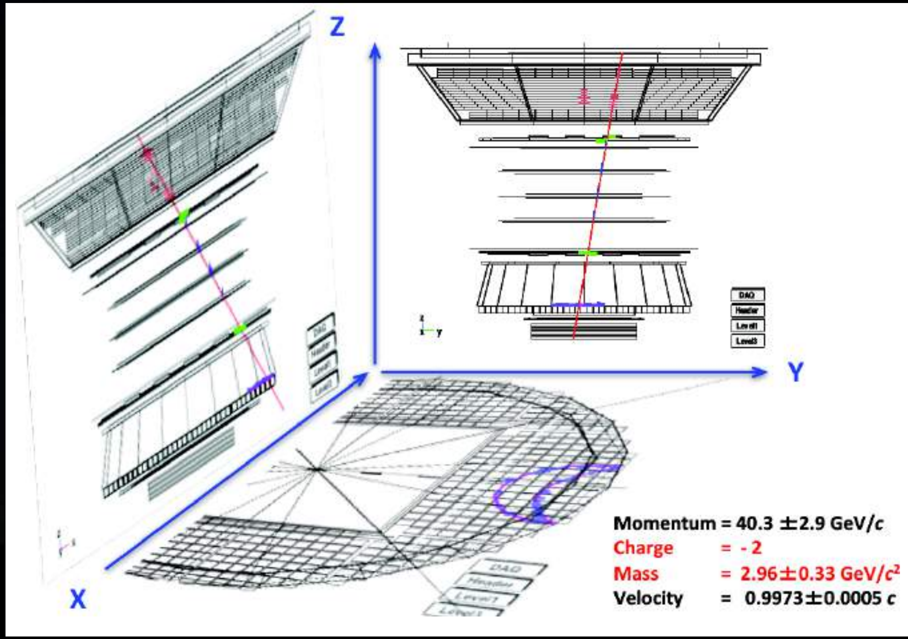
S. Acharya *et al.**
(ALICE Collaboration)

(Received 23 October 2017; published 21 February 2018)

Antinuclei search

The AMS sensitivity to D-bar is approaching the theoretical calculations. Results on d-bar search at 0.1-5 GeV to be released soon.

The search for antihelium is ongoing as well Z=-2 event candidates are under verification.



GAPS experiment has been approved for a 2020 flight on Antartica

Background is dominated by nuclear uncertainties (coalescence)
→ New constraints from LHC data on production cross-section

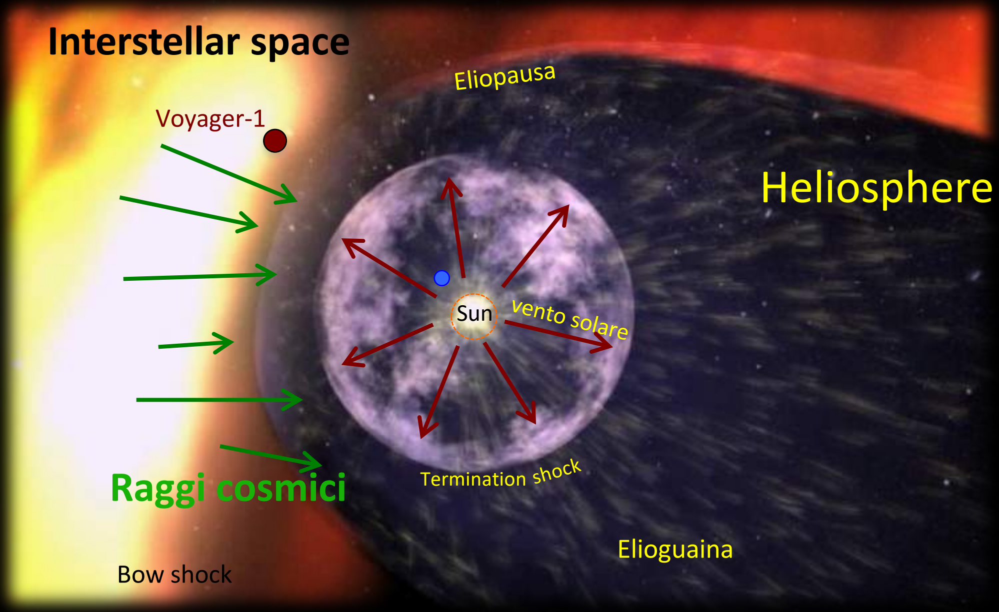
Cosmic rays in the Heliosphere: solar modulation

For long-time, CR physicists used very simple models to describe the solar modulation effect of CRs. The interpretation of high-precision data requires a better modeling approach.

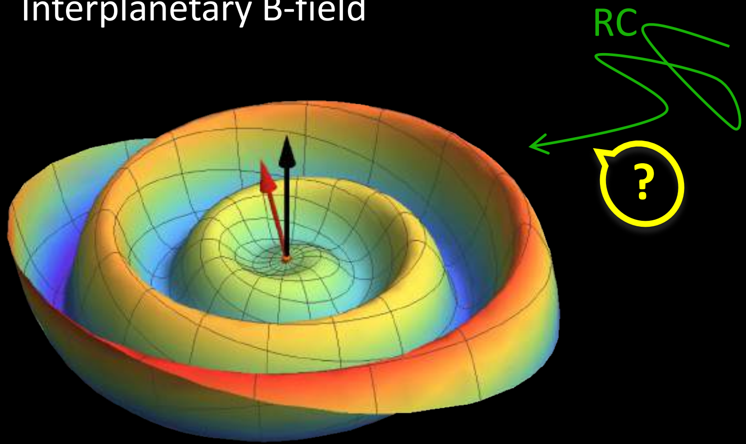
A large wealth of data for the investigation of solar modulation is now available

- New multi-channel data from AMS-02 & PAMELA on CR particles and antiparticles.
- Long time-series of solar data from CRIS-ACE, EPHIN-SOHO, and Voyager-1 in interstellar space
- Solar data from ground-and space-based observatories, e.g. WSO, and Parker Solar Probe

matisse.web.cern.ch



Interplanetary B-field



CR transport across the parker spiral
Charge-sign dependence from the current sheet

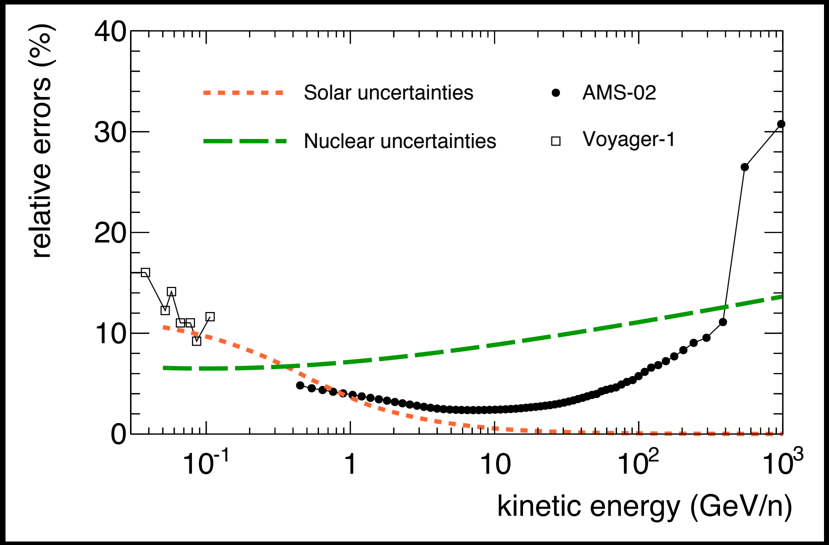
Fragmentation cross sections for cosmic-ray physics

Precision measurements in space → new phenomena to be explained

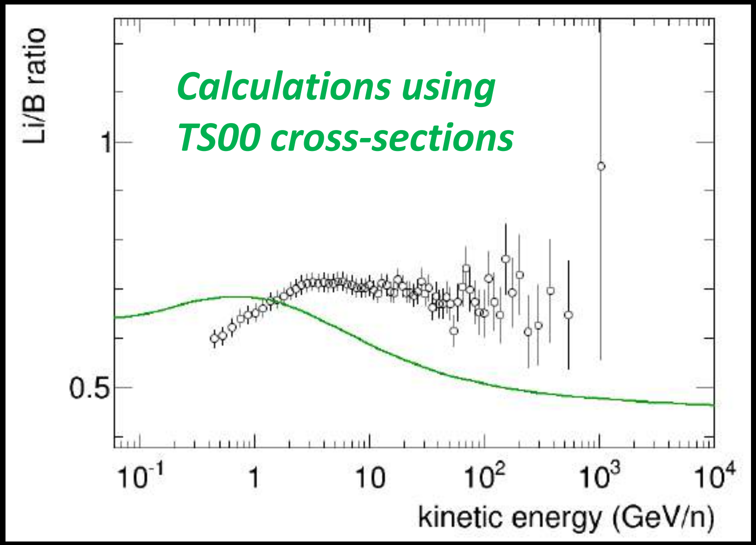
→ precision in physics models required

- ✓ ***B/C ratio: nuclear uncertainties are dominants over experimental errors***
- ✓ ***Li-Be production XS's are poorly known. They limit the interpretation of CR data***
- ✓ ***Better data and calculations for antiproton, antineutron production, nuclear coalescence***

Data/Nuclear/Solar uncertainties in B/C ratio



Calculations for the Li/B ratio



Uncertainties in antiproton flux calculations