Introduction to

Galactic Cosmic Rays

...in the era of AMS-02

Yoann Génolini

NA61/SHINE autumn school
October 27th, 2020

Galactic Cosmic Rays

...in the era of AMS-02

Definition here:

Cosmic charged particles with energies up to the PeV.

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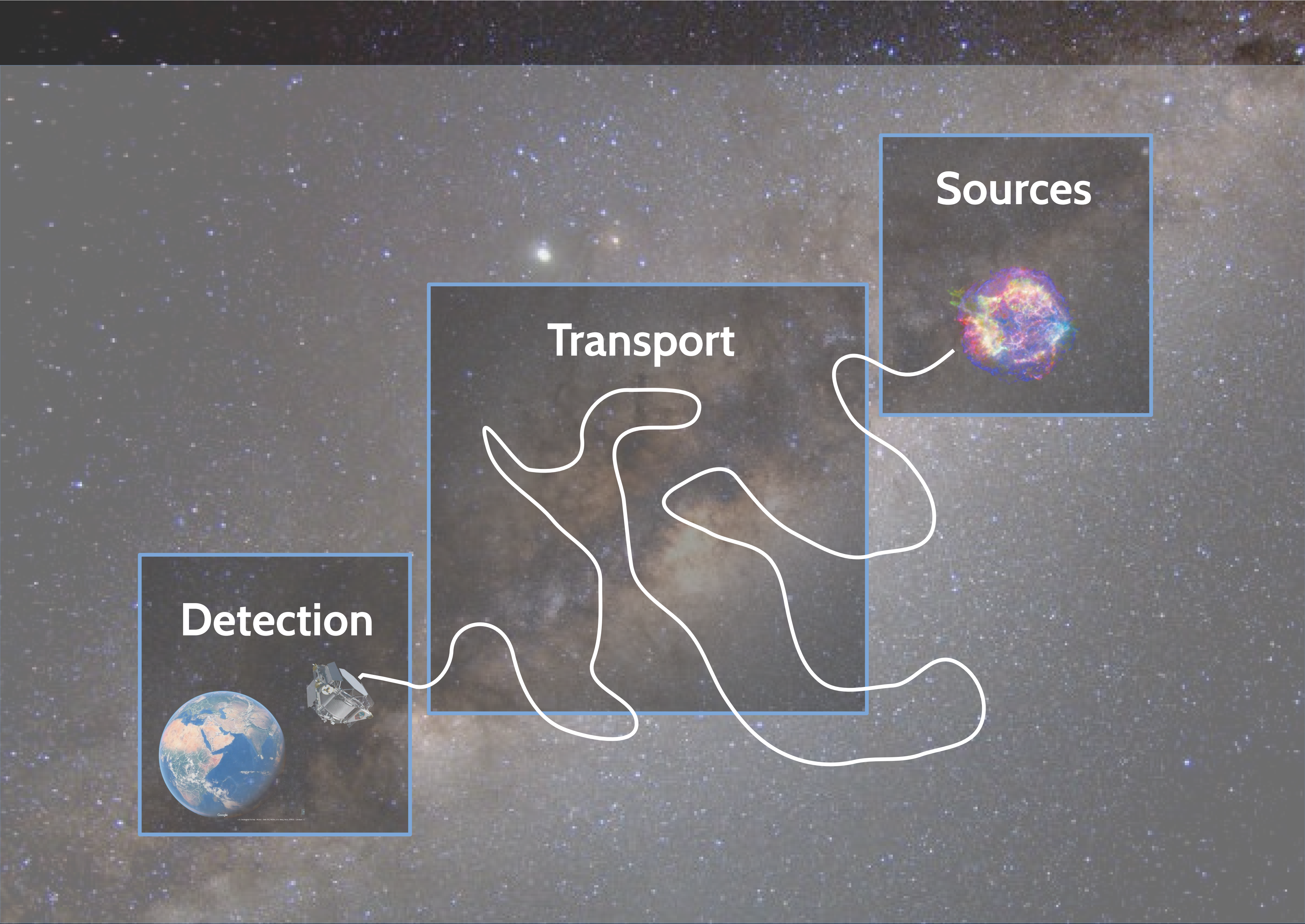

Sources
Transport
Detection

I – Detection and observables

II – Sources

III – Transport

IV – Some nuclear physics!

I – Detection and observables

II – Sources

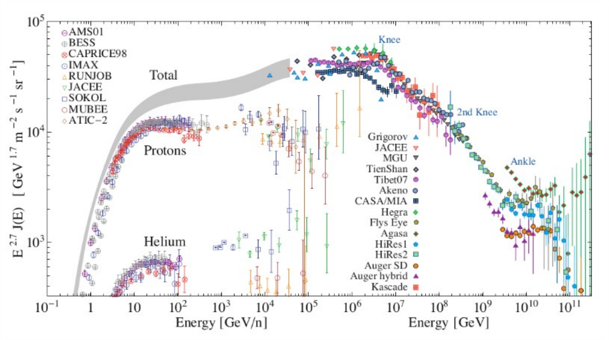
III – Transport

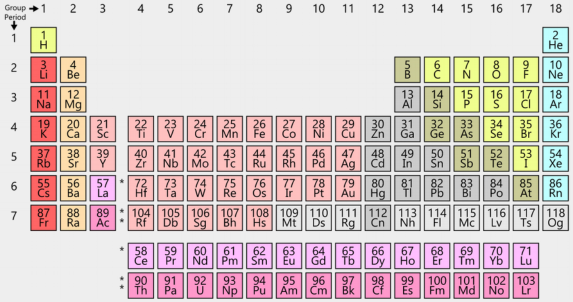
IV – Some nuclear physics!

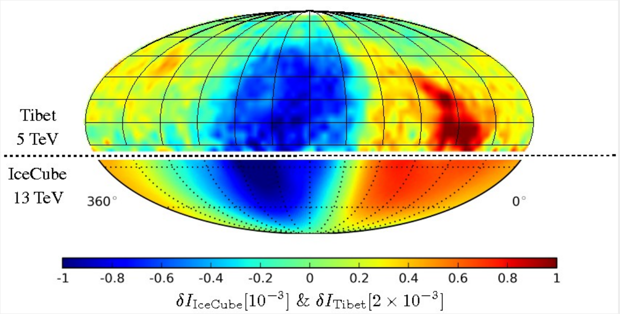
A - Charged cosmic-ray observables at Earth:

$$\Psi_i = \frac{dN_i}{dE\, dT\, d\Omega\, dS}$$

Energy | **Composition** | **Direction**







B – Direct detection experiments :

V. Hess (1912)

CR observations lead to particle discoveries :

-> C.D. Anderson : positron and muon (1932, 1936)
-> C. Powell : charged pions (1947)
-> G.D.Rochester, C.C.Butler : strange particles (1947-1950)

D.V. Skobeltsyn near his cloud chamber (1924)

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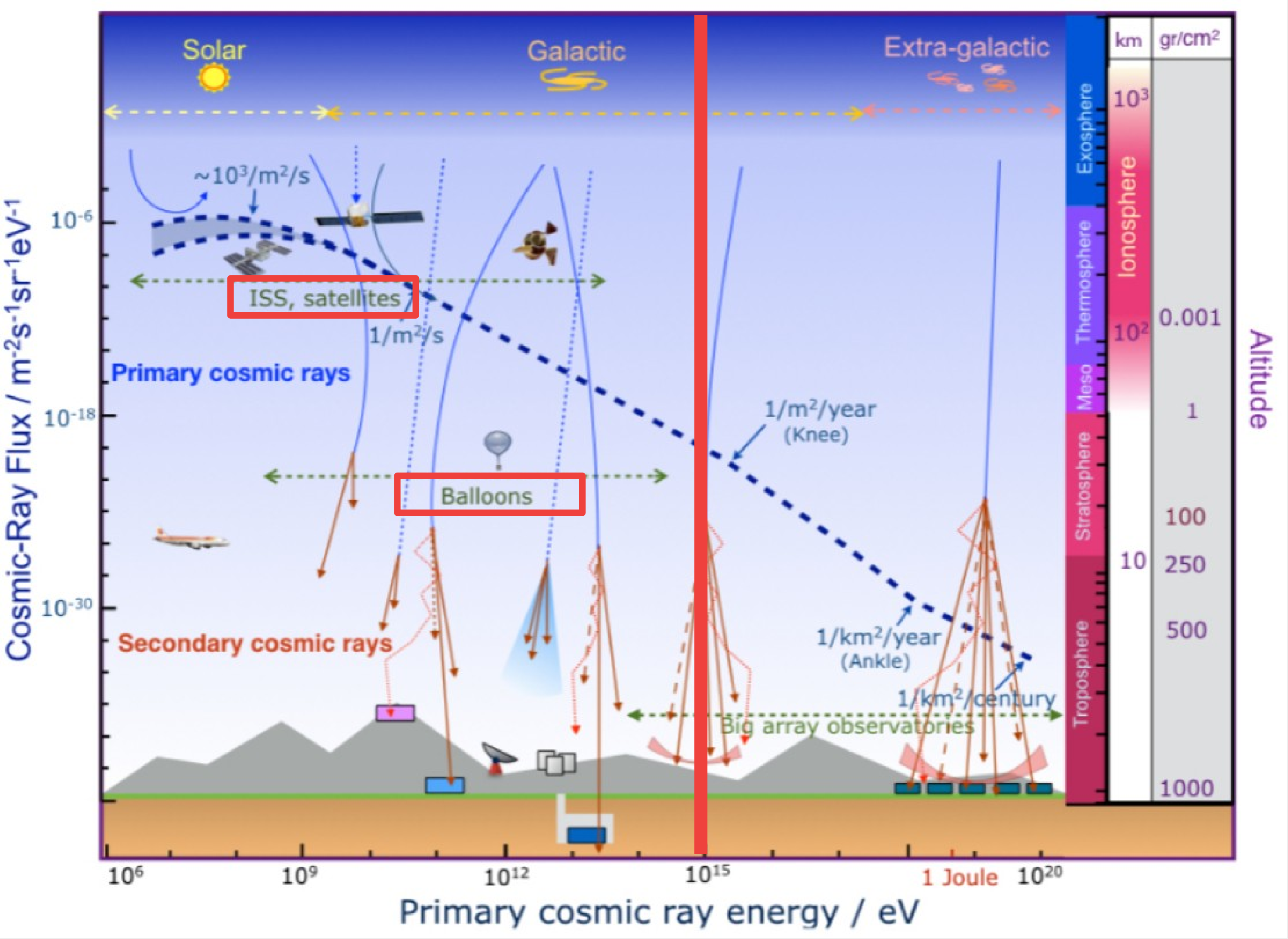
Sensitive to sub-products of interactions of CR with the atmosphere !

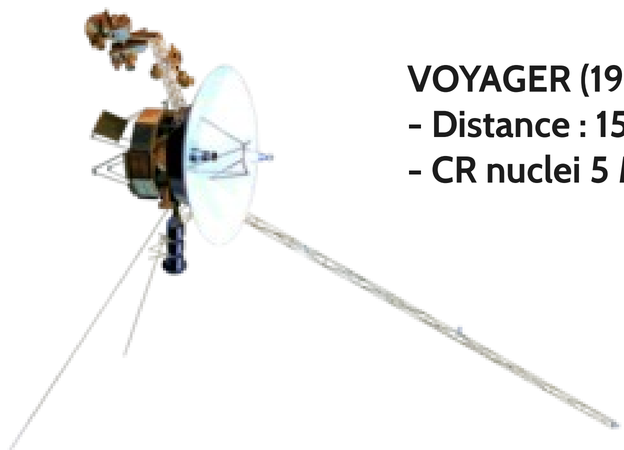
B – Direct detection experiments :



Garzón et al, XXV ECRS 2016 Proceedings

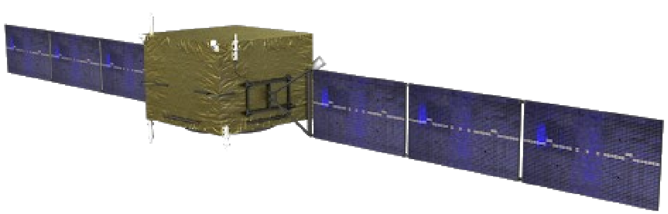
B – Direct detection experiments :

Some satelites … (~500km)



VOYAGER (1977)
- Distance : 151 AU !
- CR nuclei 5 MeV – 500 MeV

PAMELA (2006)
-Spectrometer !
- CR nuclei 1 GeV – 1.2 TeV



DAMPE (2015)
- CR nuclei 50 GeV – 500 TeV

NUCLEON (2014)
- CR nuclei 100 GeV – 1 PeV

B – Direct detection experiments :

Some detectors onboard ISS ... (~400km)

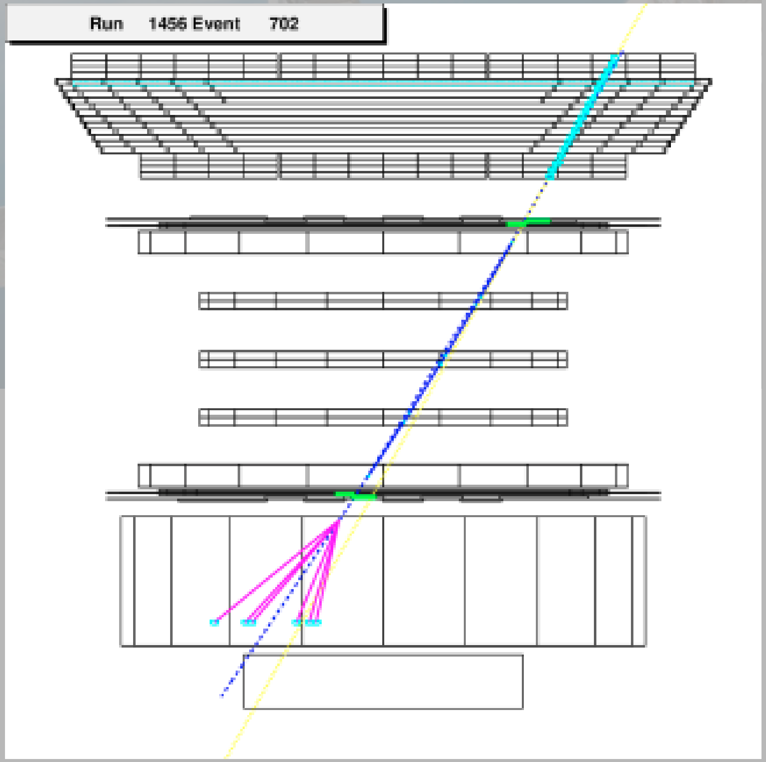
AMS-02 (2011)
- Spectrometer !
- CR nuclei 1 GeV – 1.9 TeV

CALET (2015)
- CR nuclei 10 GeV – 1 PeV

B – Direct detection experiments :

Some detectors onboard ISS … (~400km)

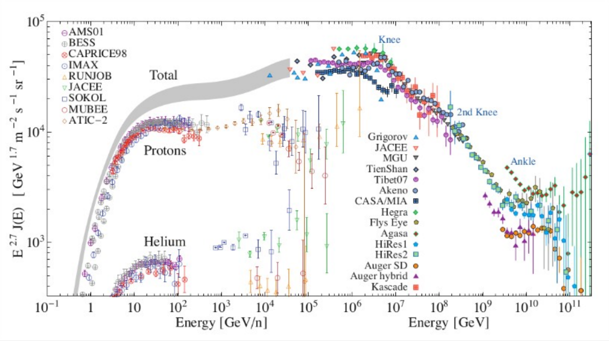
Exemple : AMS-02 event

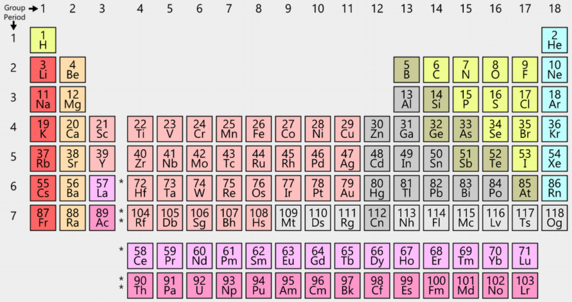


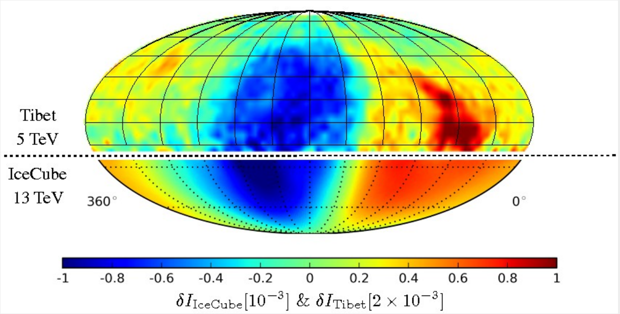
C – Main features in cosmic-ray observables at Earth:

$$\Psi_i = \frac{dN_i}{dE\,dT\,d\Omega\,dS}$$

Energy | **Composition** | **Direction**







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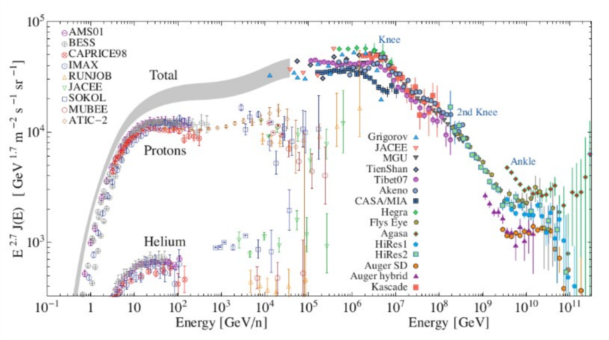

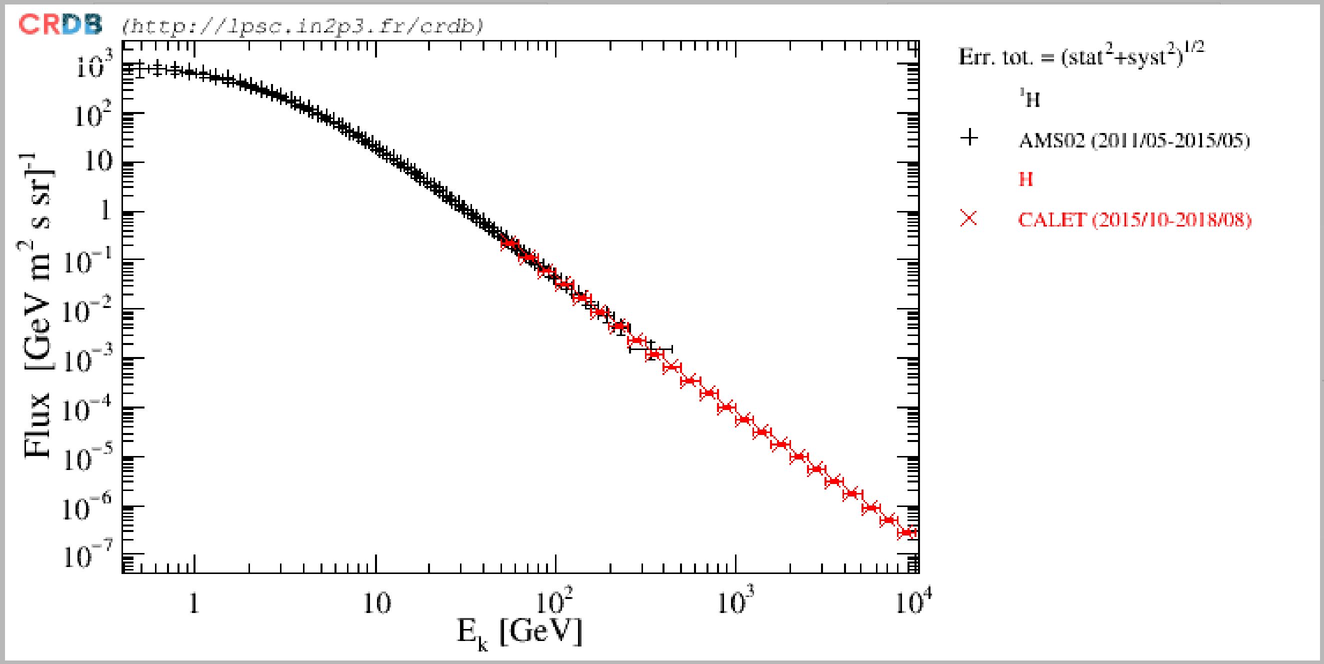

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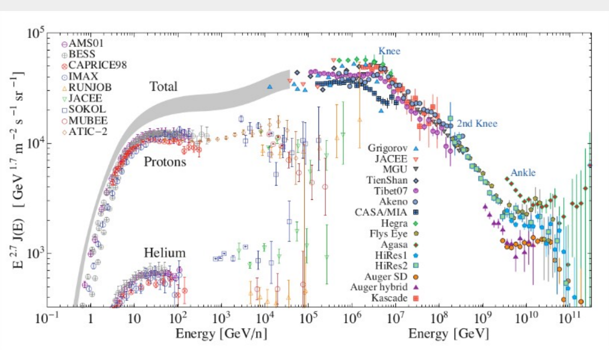

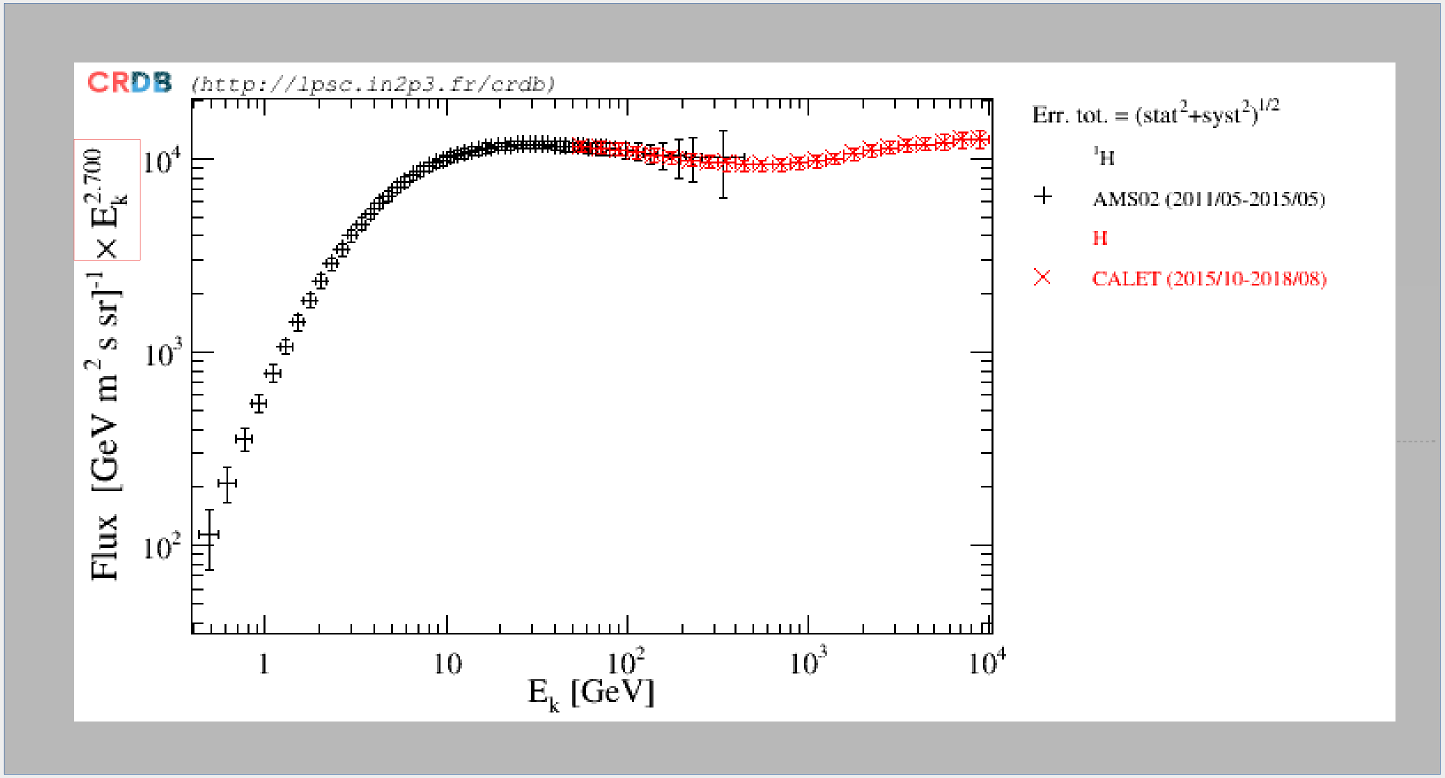

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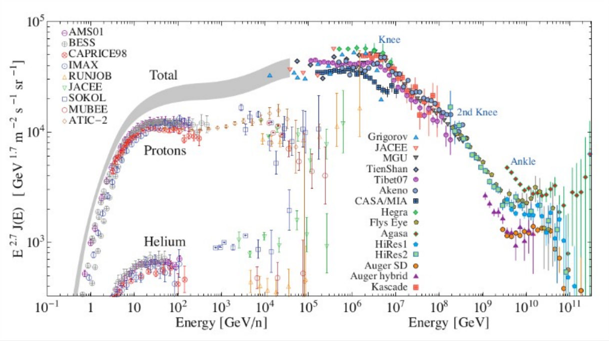

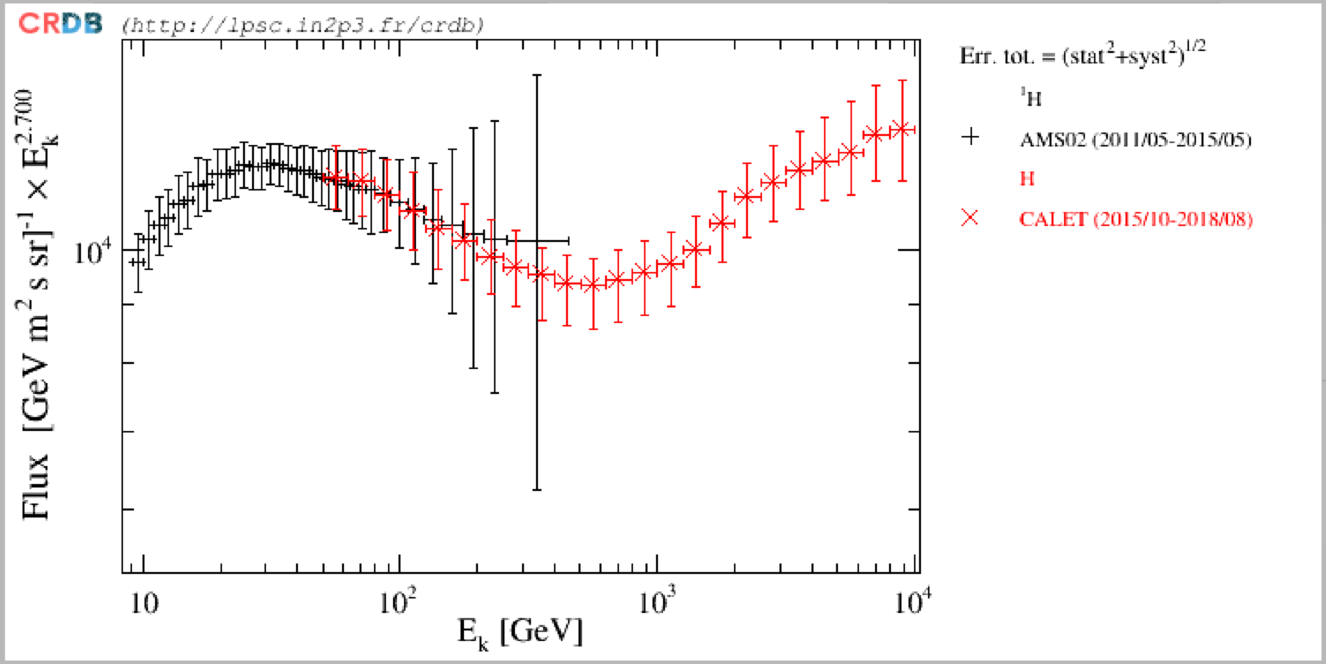

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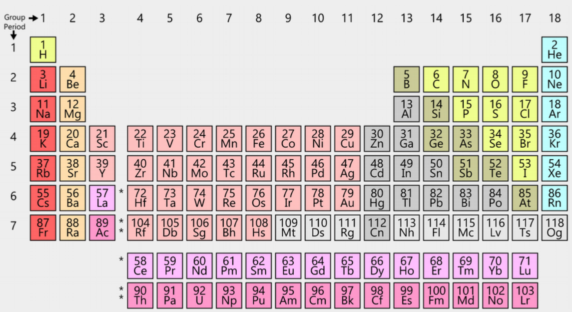

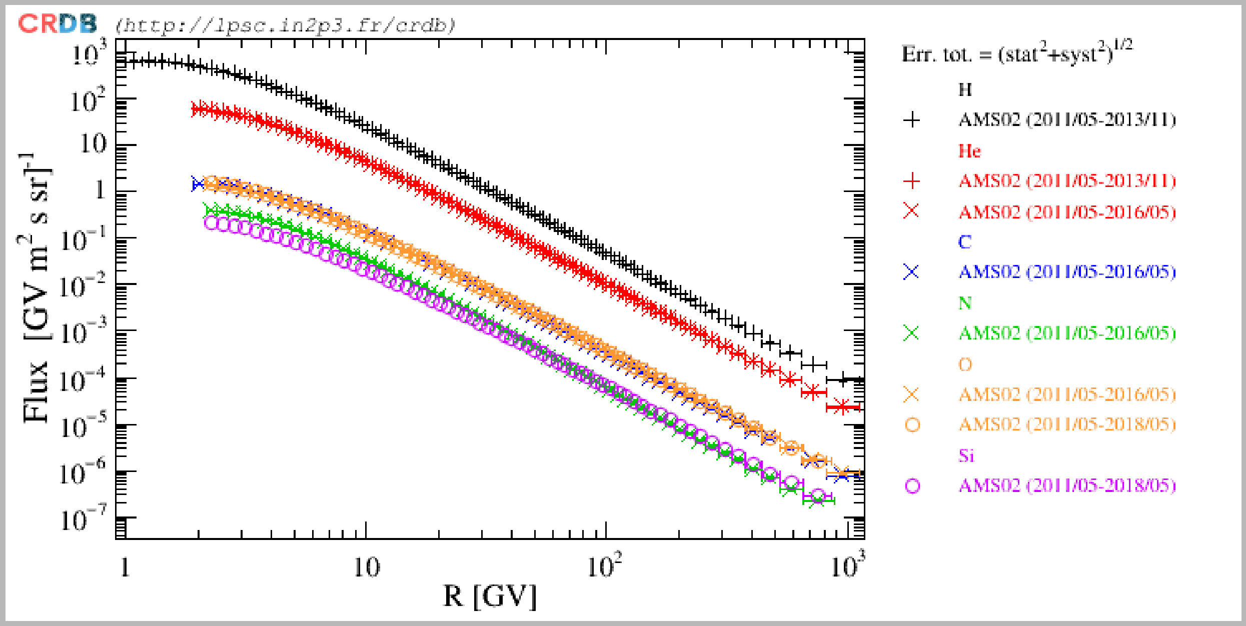

Protons: 85 % / Helium 12.5 % / Heavier nuclei 1 %

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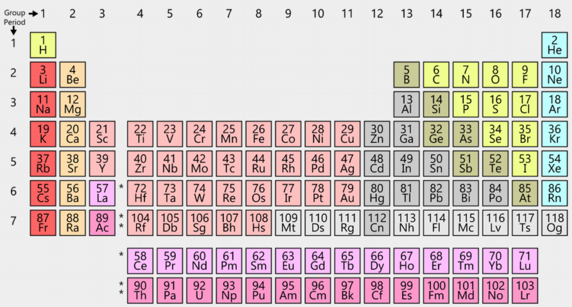

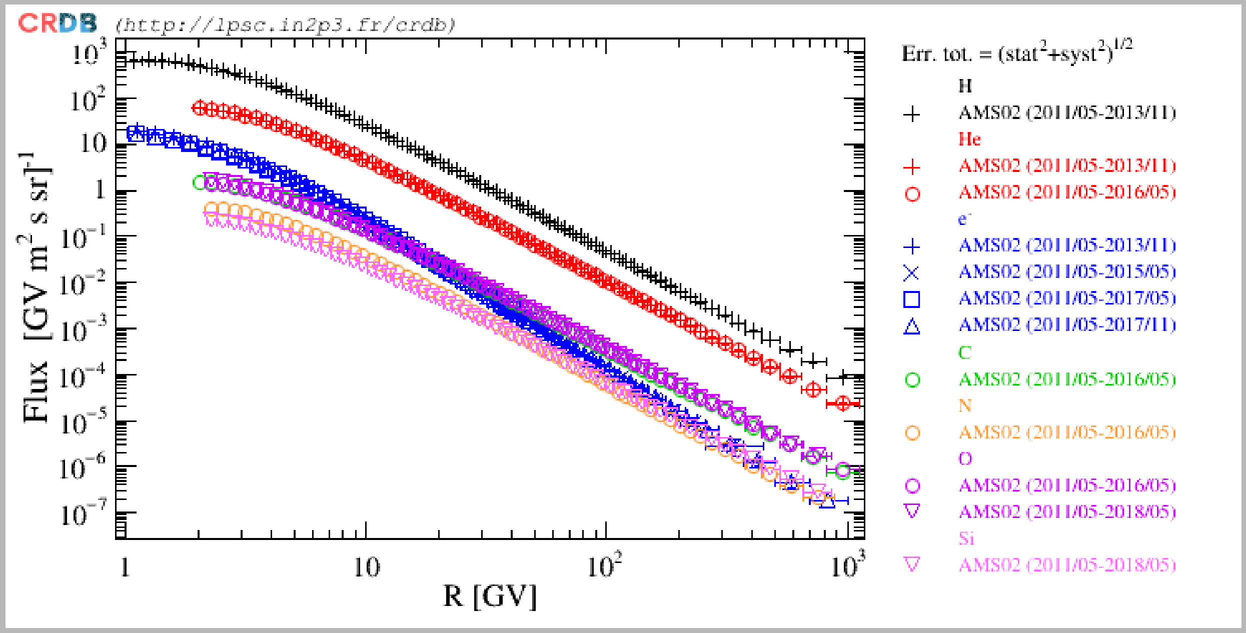

Protons: 85 % / Helium 12.5 % / Heavier nuclei 1 %

Electrons 1.5 %

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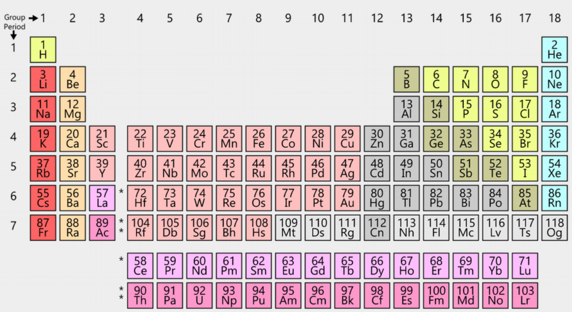
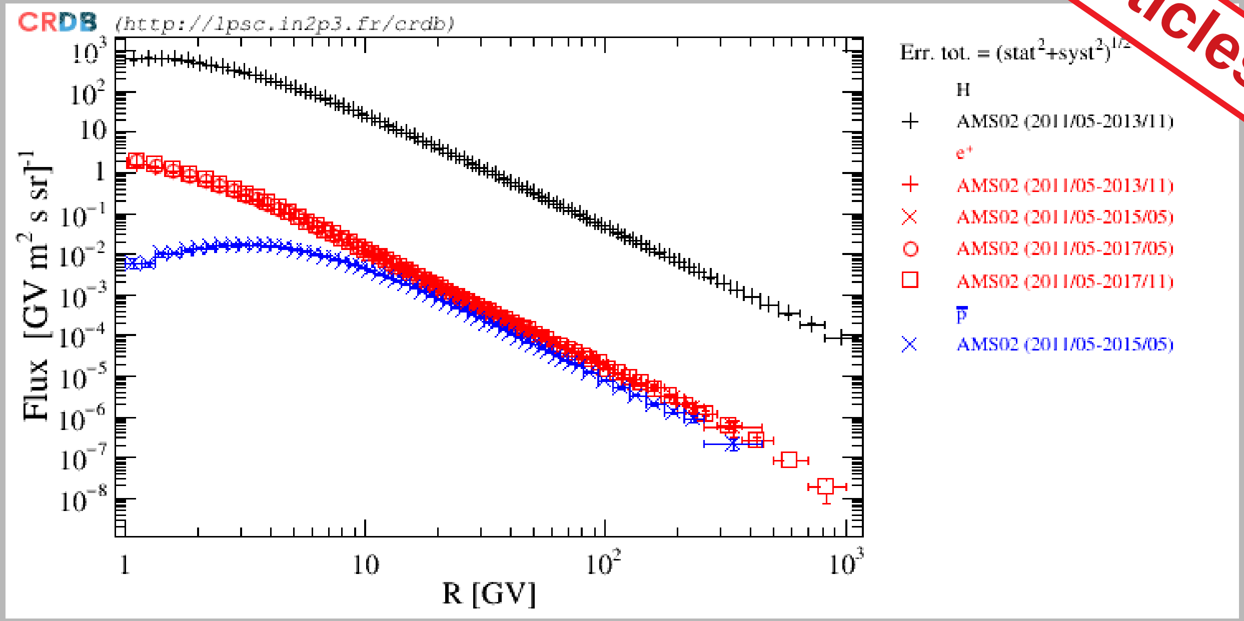


Antiparticles !



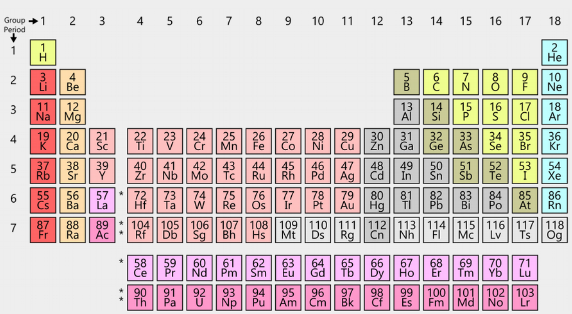
1 positron / 10^3 protons ! 1 antiproton / 10^4 protons !!

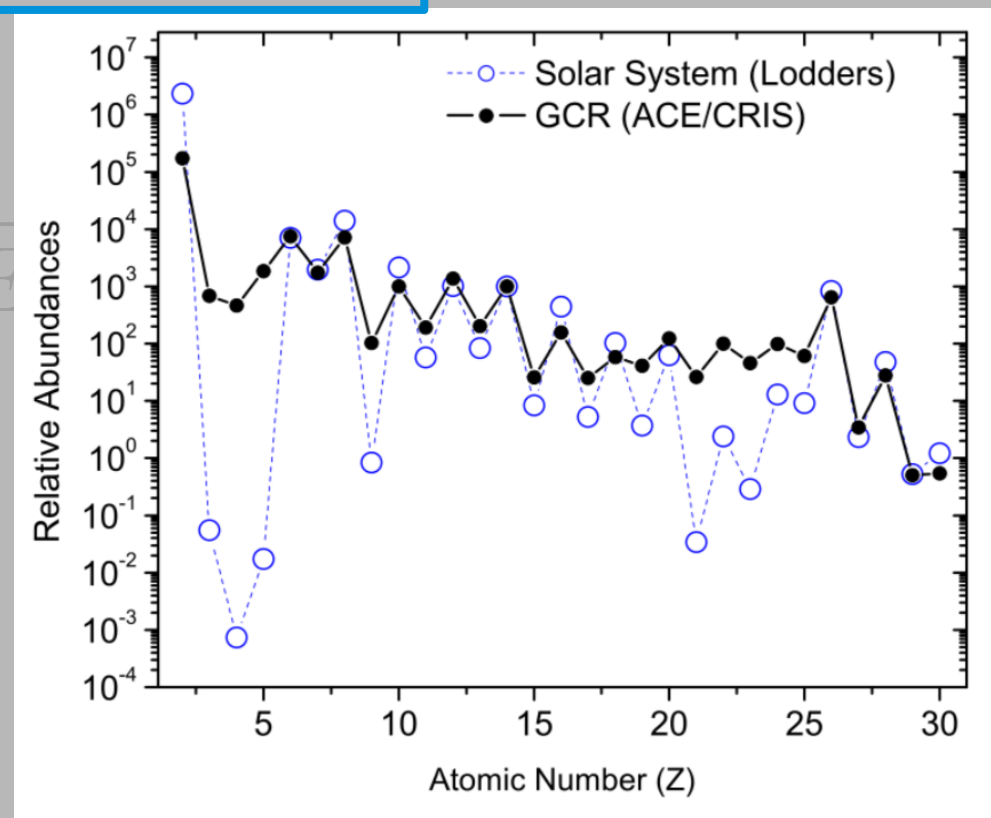
C – Main features in cosmic-ray observables at Earth:

Secondary cosmic-rays!

$$\Psi_i = \frac{\quad}{dE}$$

Composition





Collaboration ACE., Nuclear Physics A, Vol. 758 (2005)

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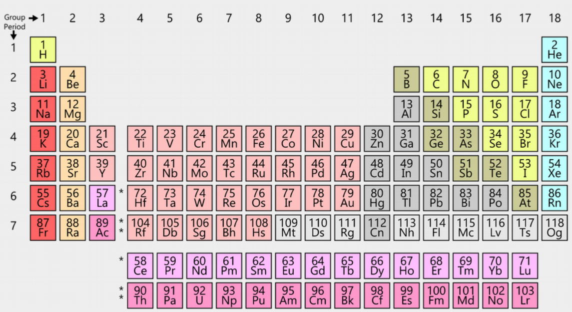

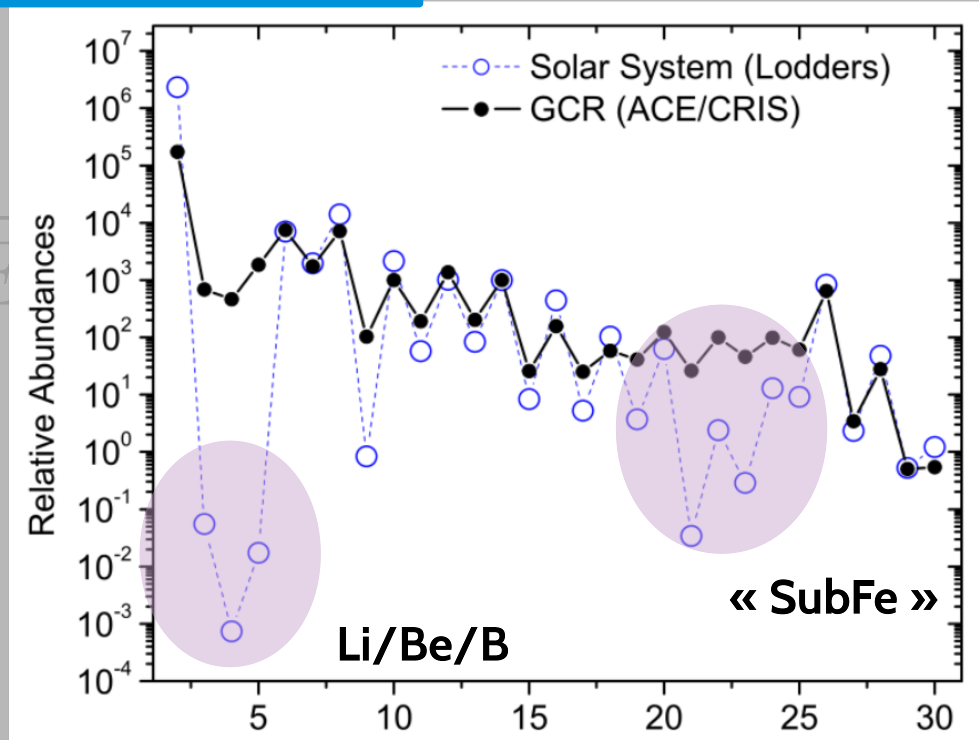

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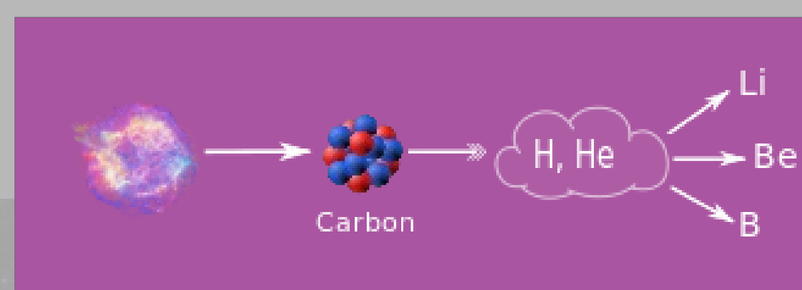

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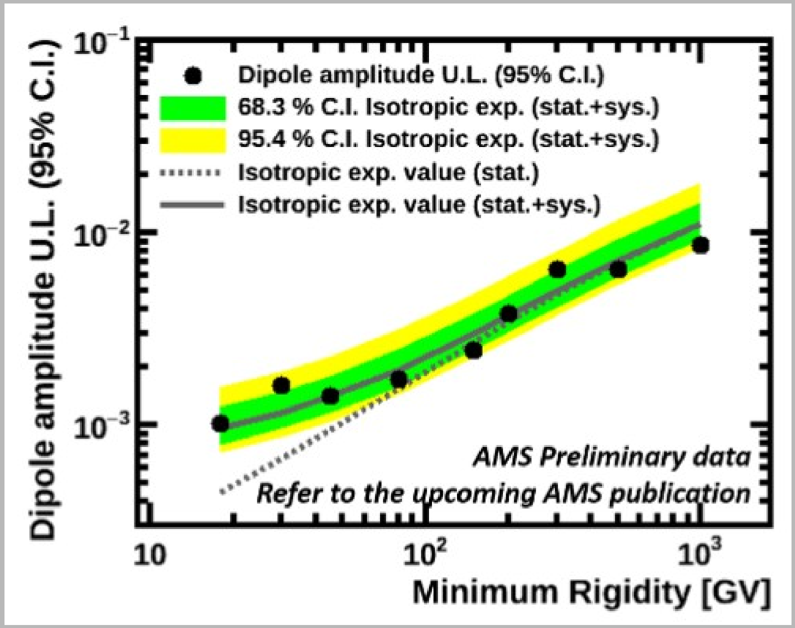
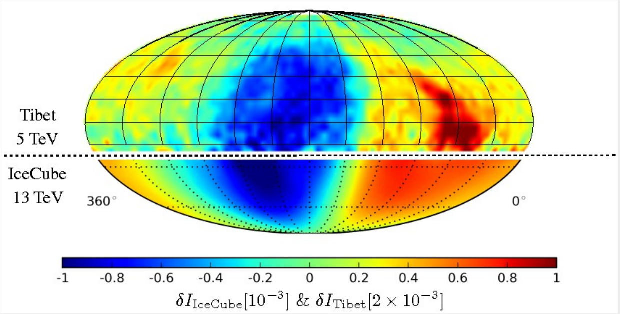


M A Velasco et al. TAUP 2019

Direction



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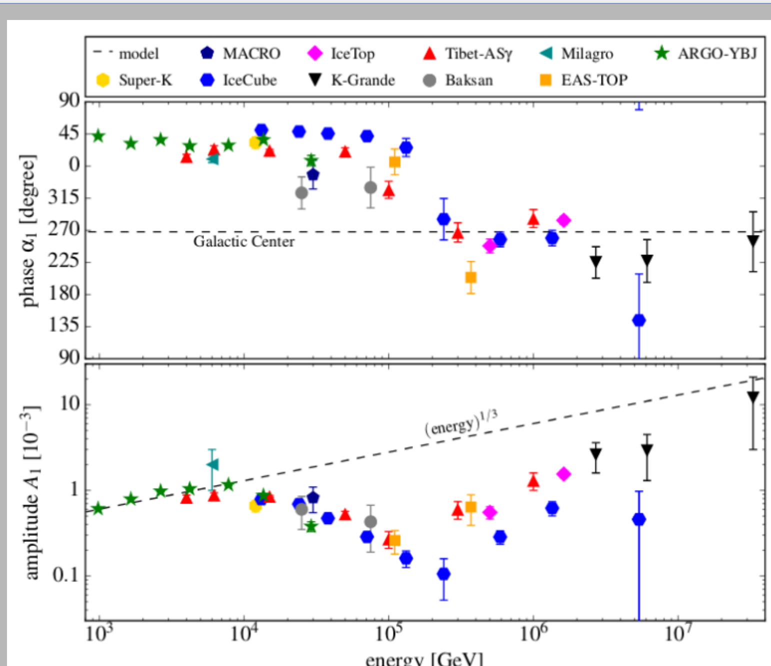

M. Ahlers & P. Mertsch (PPNP, 2016)

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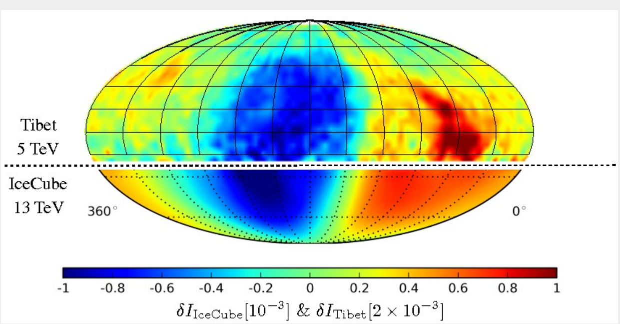
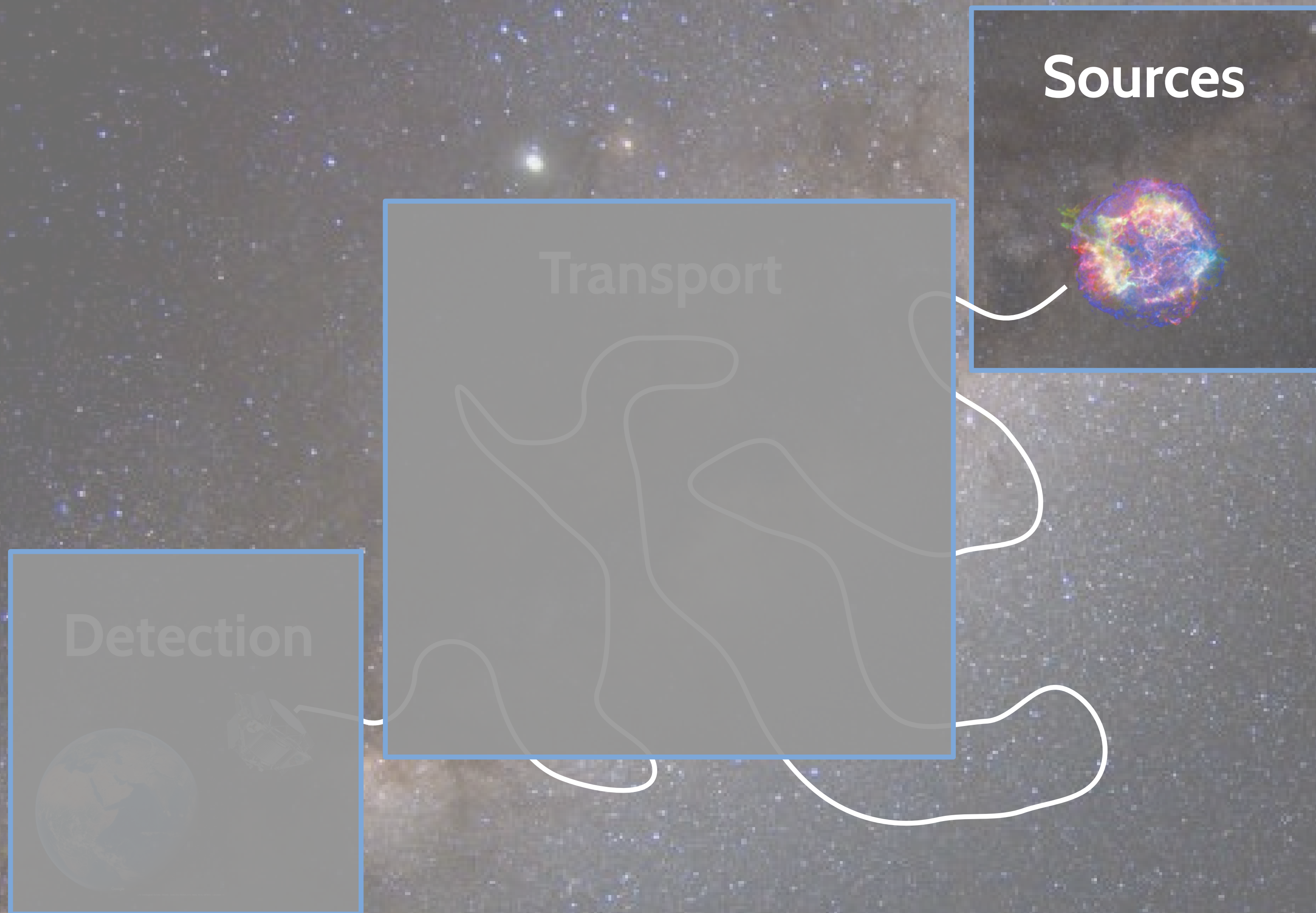


-> CRs arrival direction is quasi-isotrope.


Sources
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I – Detection and observables

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IV – Some nuclear physics!

A – The energetic argument..

Cosmic ray energy density is large!

Thermal pressure of gas in clouds	$0.3\ \mathrm{eV.cm^{-3}}$
Starlight density	$0.5\ \mathrm{eV.cm^{-3}}$
Magnetic fields	$0.6\ \mathrm{eV.cm^{-3}}$
Gas kinetic motion	$1\ \mathrm{eV.cm^{-3}}$
Cosmic-rays	$1.5\ \mathrm{eV.cm^{-3}}$

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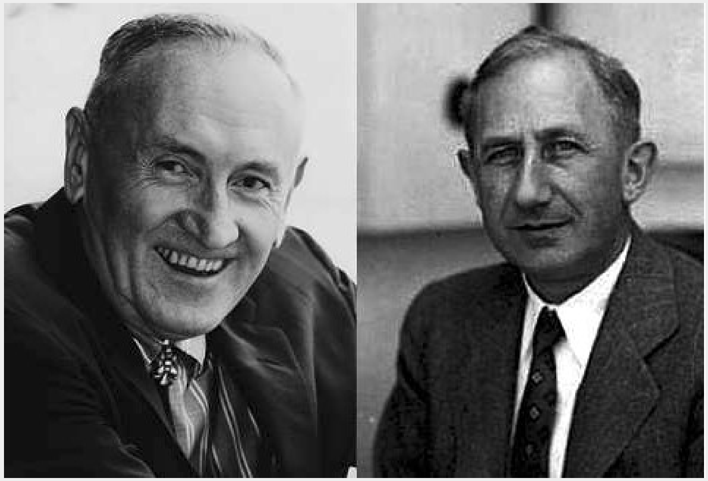
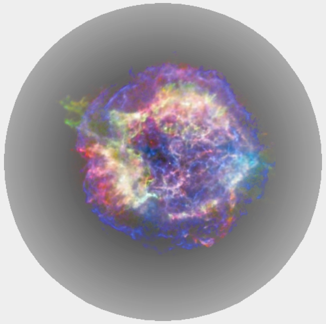


F. Zwicky W. Baade

were the first to postulate that SNR could be possible sources of CRs.

W. Baade and F. Zwicky Phys. Rev. 46, 76 (1934)

$$\mathcal{P}_{CR} \approx \frac{U_{CR} V_{CR}}{\tau_{res}} \approx 10^{40}\,\mathrm{erg\,s^{-1}}$$



10% of

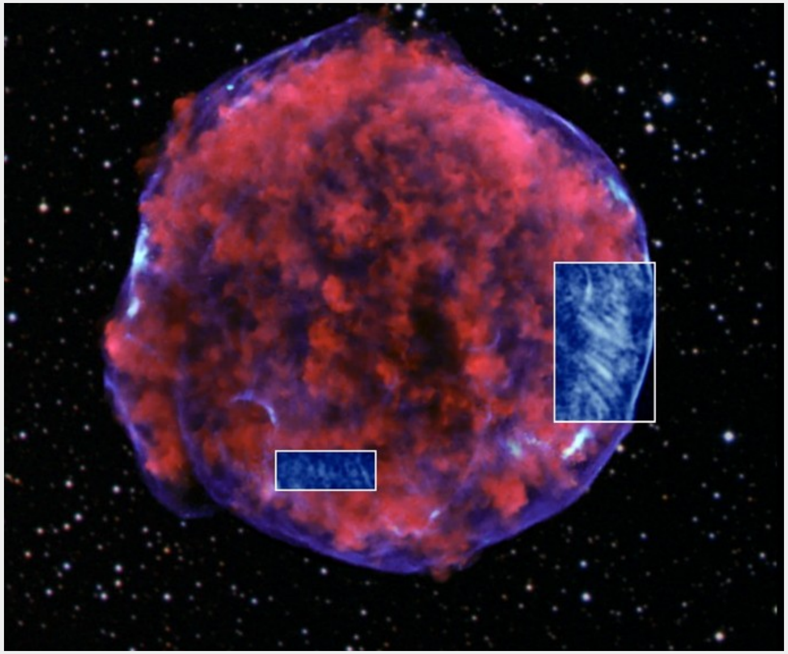
$$\mathcal{P}_{SNR} = \nu_{SNR}\,\mathcal{E}_{SNR} \approx 10^{41}\,\mathrm{erg\,s^{-1}}$$

A conversion of about 10% of the SNR energy into particle acceleration is sufficient to accomodate CR energetics

Argument worked out in: V. L. Ginzburg, S. I. Syrovatskii, The origin of cosmic rays, (1969).

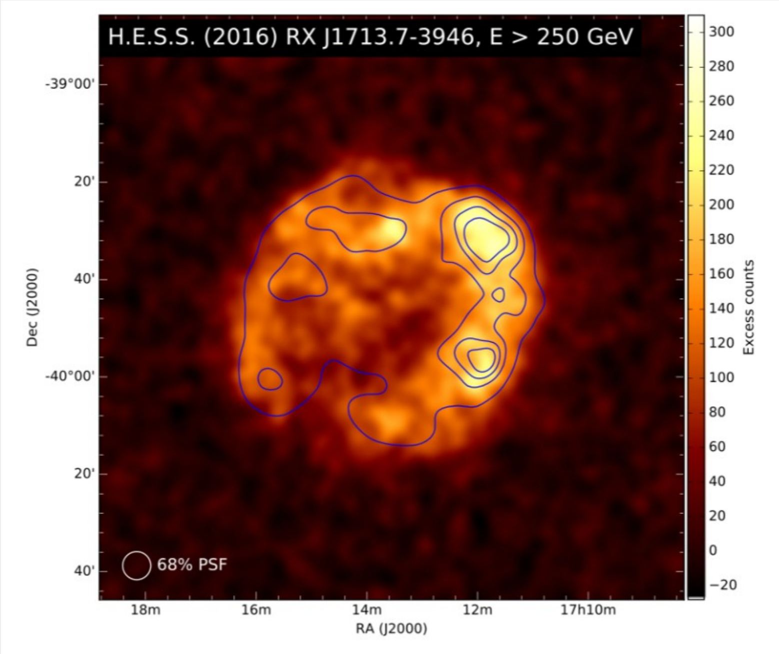
B – Observation of SNRs → Non thermal emissions

X-rays



Chandra observation of Tycho SNIa

Gamma rays



Collaboration, H. E. S. S., A&A 612, A6 (2018).

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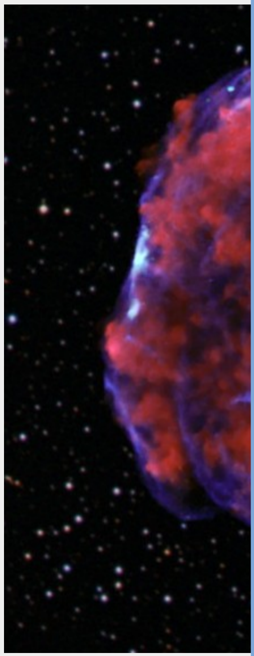
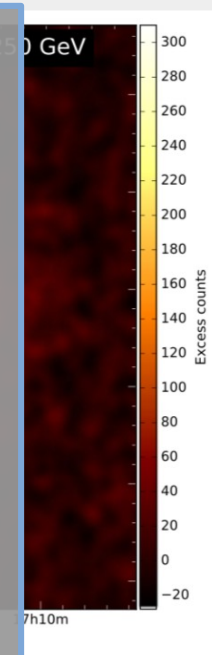
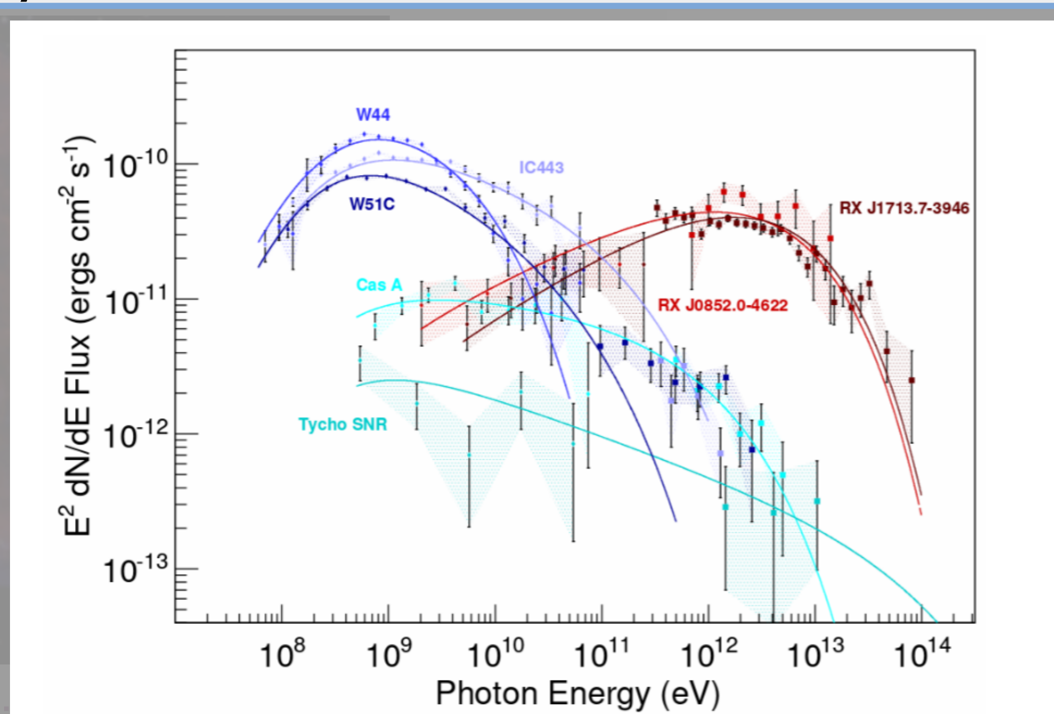
X-rays **Gamma rays**







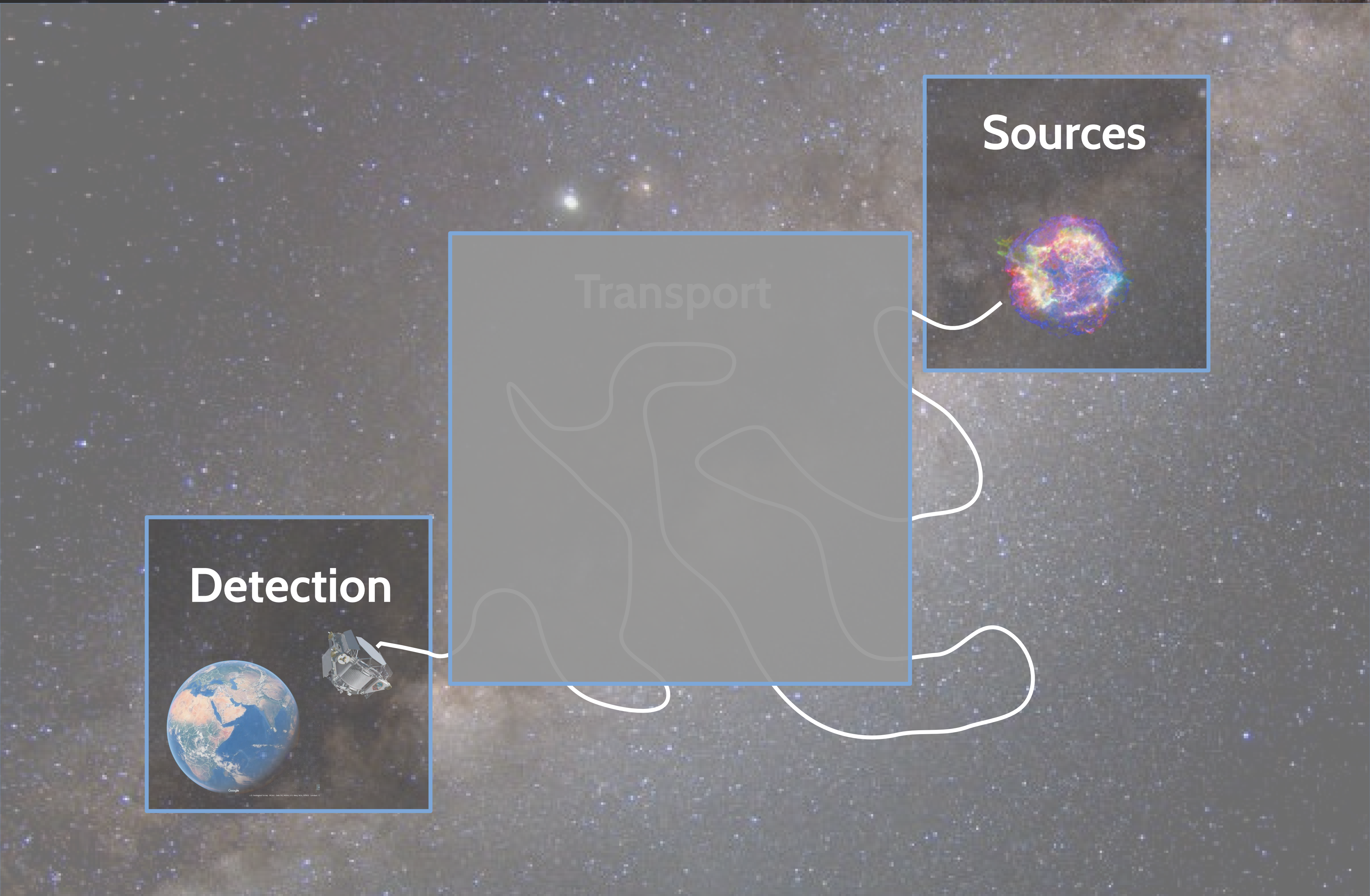
Chandra ... 2, A6 (2018).

Funk, S. (2015). An. Rev. of Nuc. and Part. Sci., 65, 245-277.

- Pion decay from p-p colisions.
- IC and Synchrotron form high-energy electrons.

Infered spectrum of accelerated particles: $\boxed{q(E) \propto E^{-\alpha}, \alpha \in [2, 2.5]}$

Consistent with the theory of Diffusive shock acceleration (DSA)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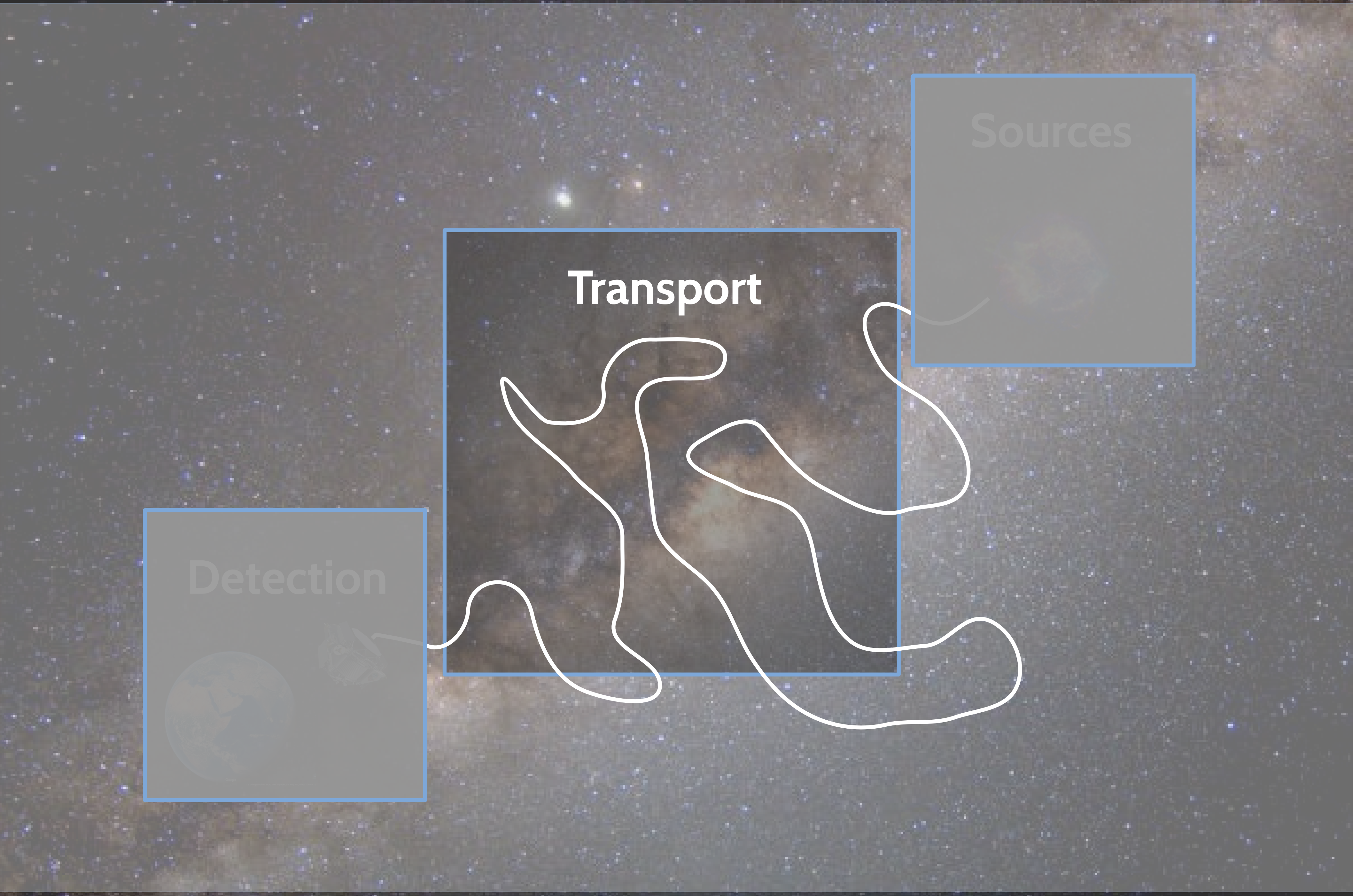

Sources
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I – Detection and observables

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IV – Some nuclear physics!

A – Diffusion

Some observations supporting diffusion:

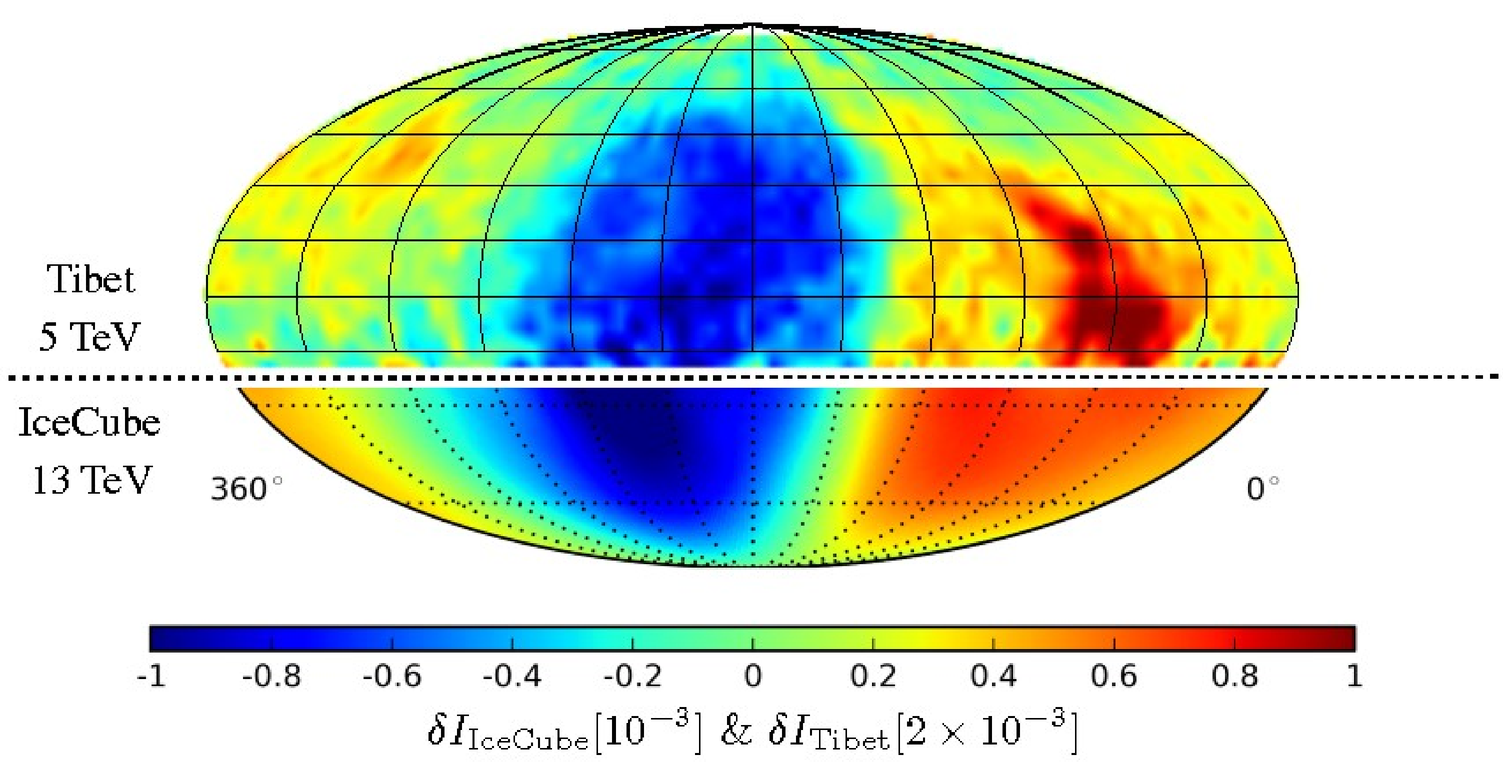
1- Isotropy of arrival directions

Perseus Double Cluster, visible light.

A – Diffusion

Some observations supporting diffusion..

1- Isotropy of arrival directions



M. Ahlers & P. Mertsch (PPNP, 2016)

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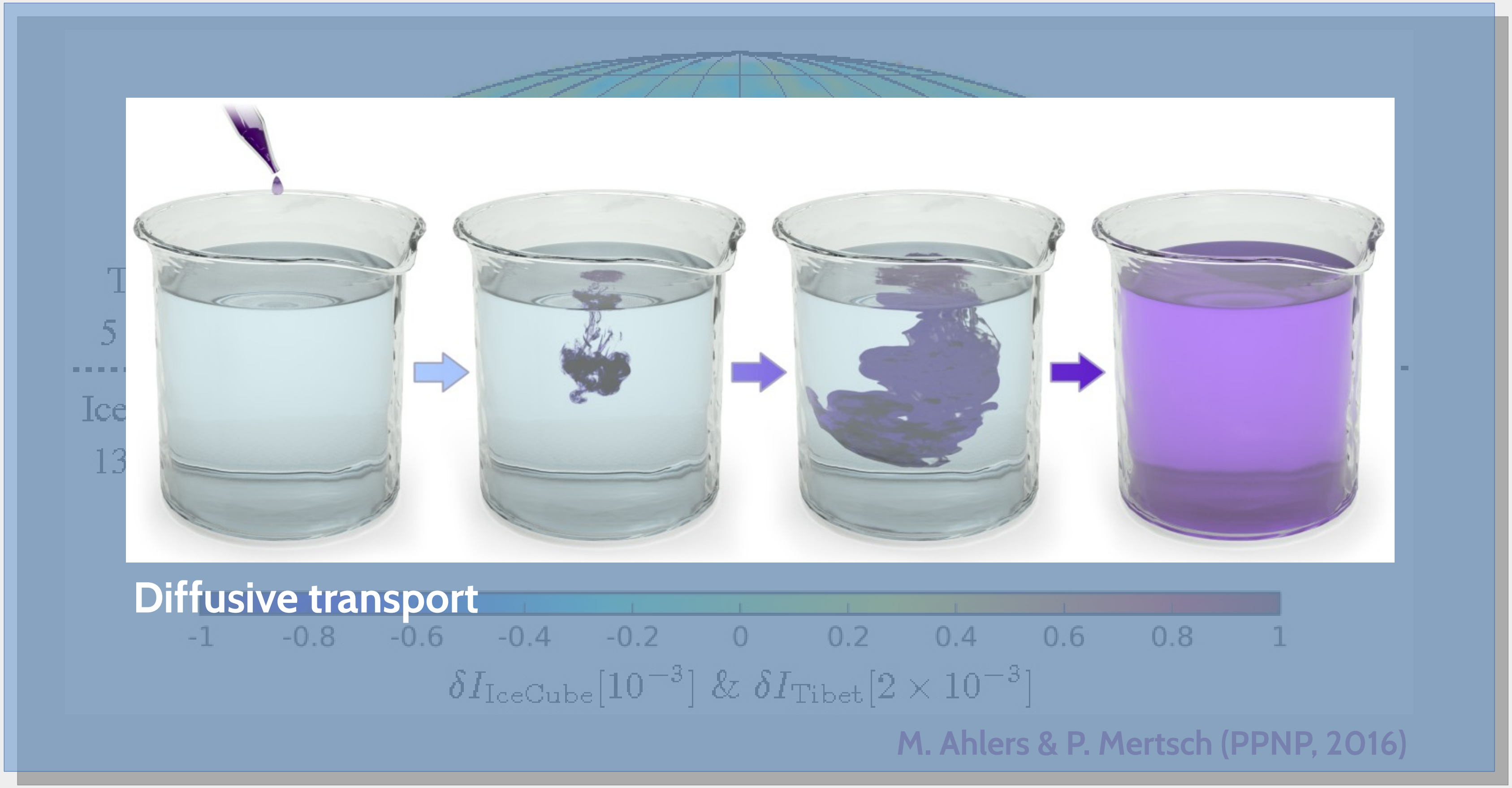
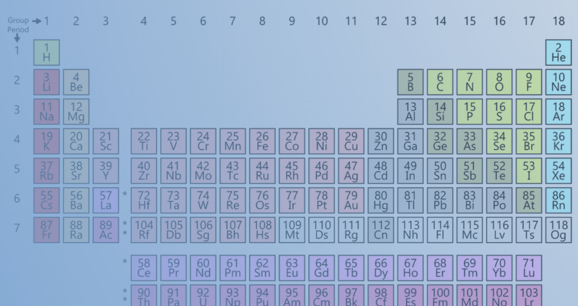


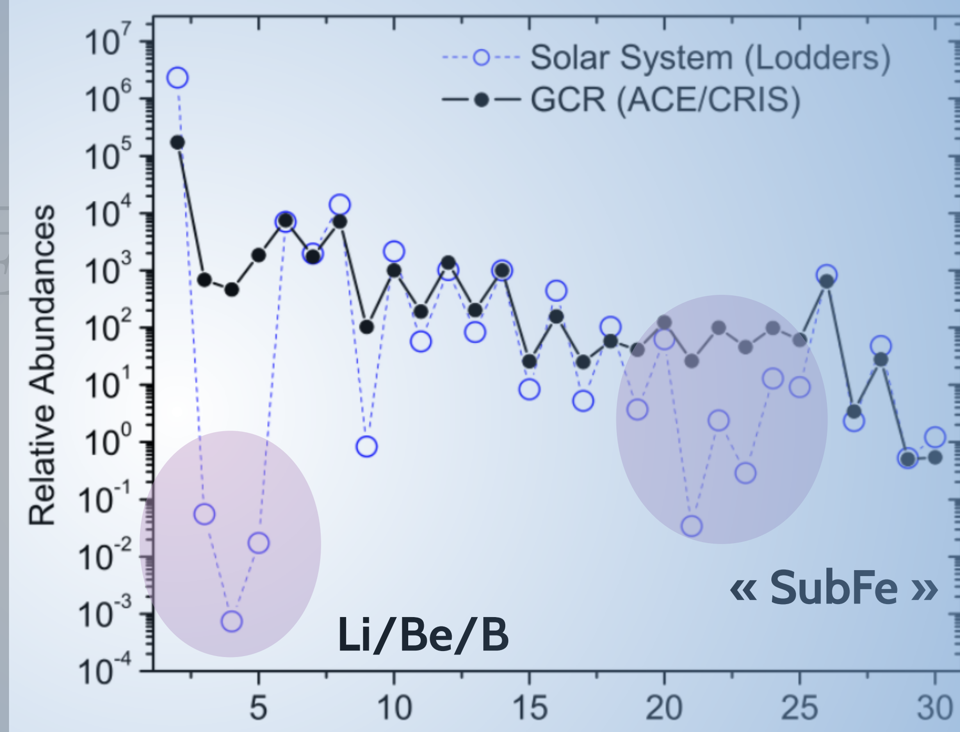
C – Main features in cosmic-ray observables at Earth:

Reminder

Composition

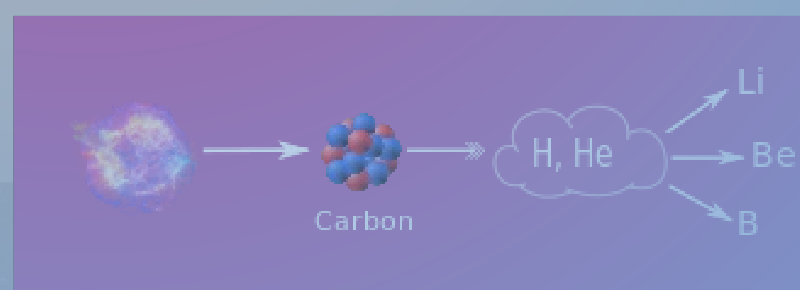


Secondary cosmic-rays!



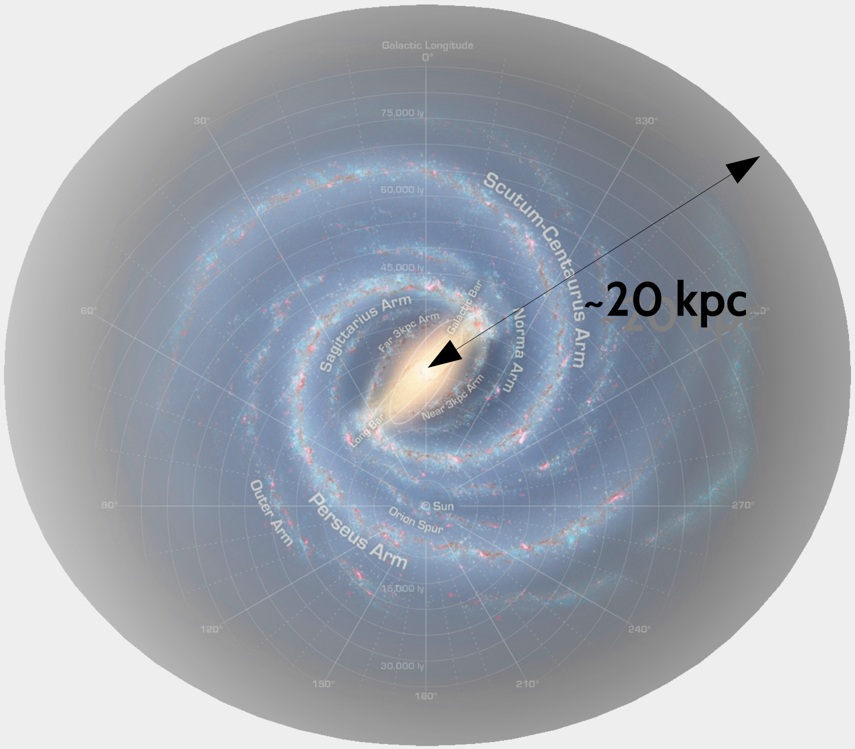
Produced by spallation of heavier nuclei

Collaboration ACE., Nuclear Physics A, Vol. 758 (2005)

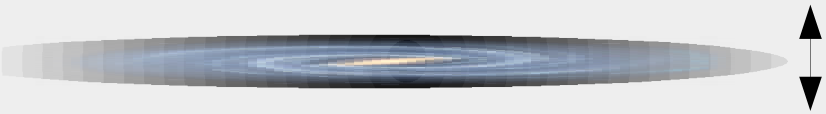


A – Diffusion

2- Abundance of light elements



face-on



edge-on

~0.2 kpc

Milky Way modelling

A – Diffusion

2- Abundance of light elements

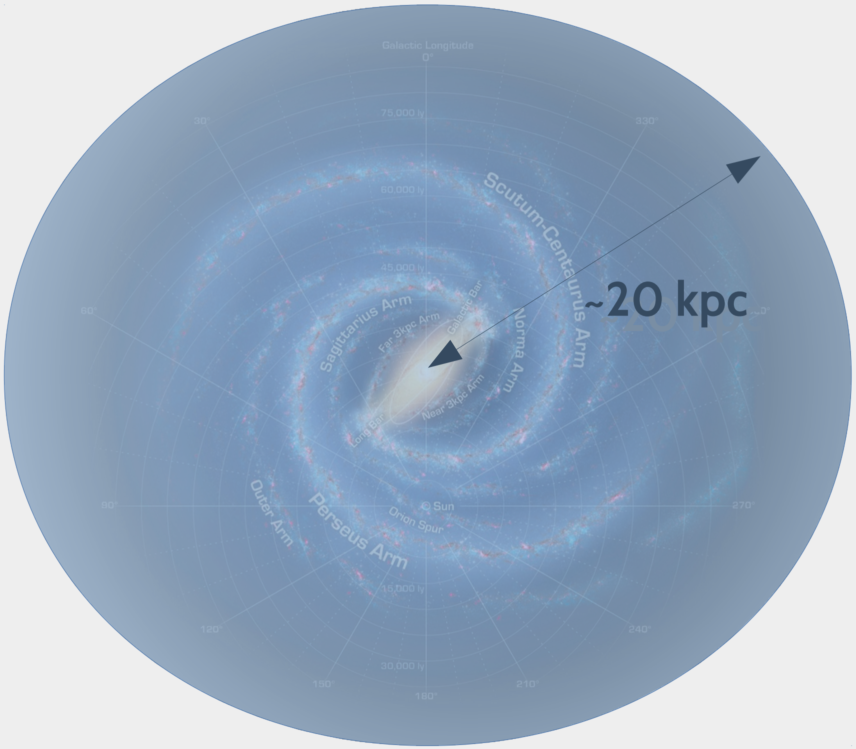
Cylindrical box with typical escape time: τ_{esc}

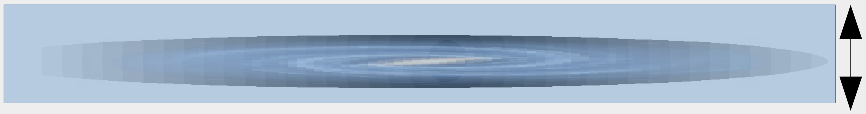
$$\psi_{\mathrm{C}} = \mathcal{Q}_{\mathrm{C}} \times \tau_{esc}$$

#part.cm $^{-3}$ #part.cm $^{-3}$.s $^{-1}$

$$\psi_{\mathrm{B}} = \frac{\psi_{\mathrm{C}}}{\tau_{int}} \times \tau_{esc}$$

$$\frac{1}{\sigma_{\mathrm{C}\rightarrow\mathrm{B}} n_{ISM} c}$$





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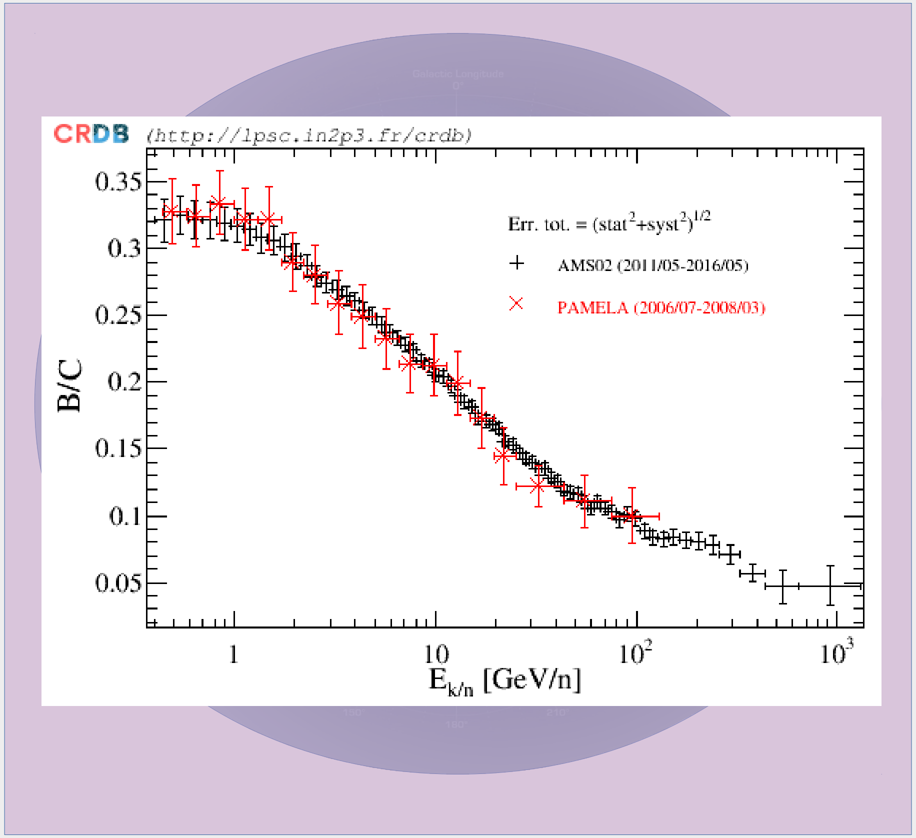
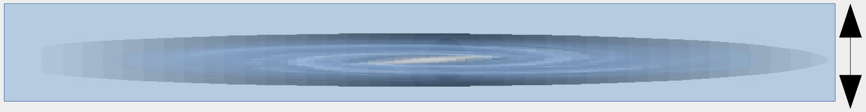
@ 1GeV : $\frac{\psi_{\mathrm{B}}}{\psi_{\mathrm{C}}} \approx 0.3$

$$\tau_{esc} \approx 0.3 \times \tau_{int} \approx 1\,\mathrm{Myr}$$





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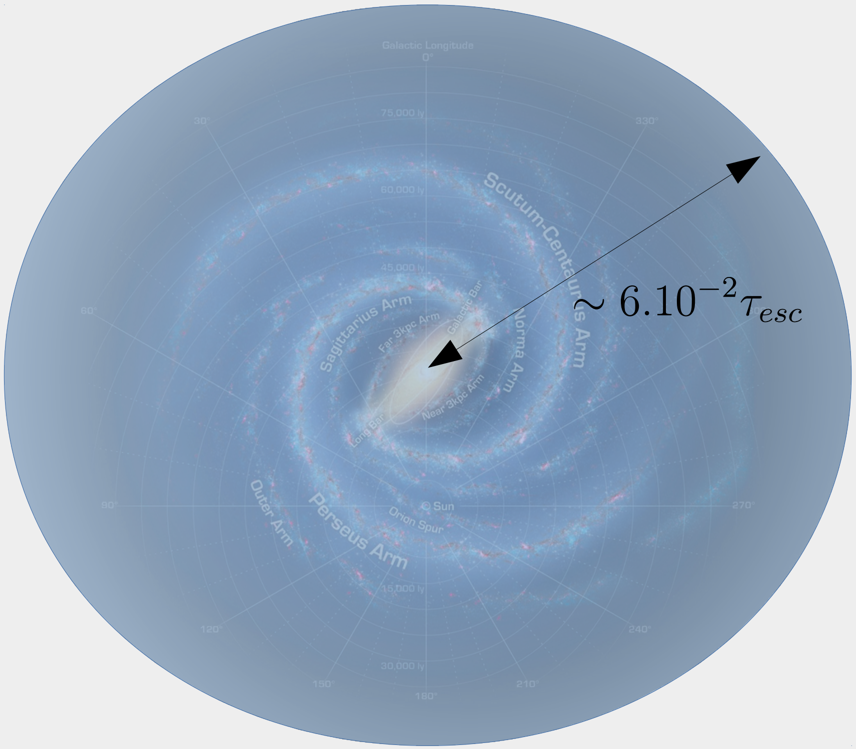
$$\psi_{\mathrm{B}} = \frac{\psi_{\mathrm{C}}}{\tau_{int}} \times \tau_{esc}$$

$$\frac{1}{\sigma_{\mathrm{C}\to\mathrm{B}} n_{ISM} c}$$

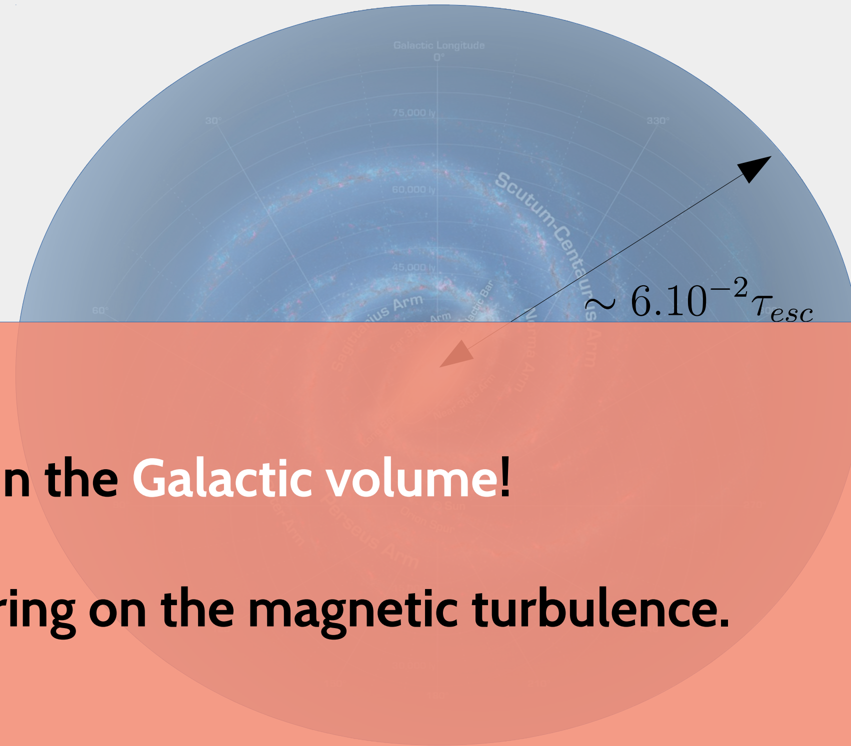
@ 1GeV : $\frac{\psi_{\mathrm{B}}}{\psi_{\mathrm{C}}} \approx 0.3$

$$\tau_{esc} \approx 0.3 \times \tau_{int} \approx 1\,\mathrm{Myr}$$



Milky Way modelling

A - Diffusion



$\sim 6.10^{-2}\tau_{esc}$

2- Abundance of light elements

Cylindrical box with typical escape time: τ_{esc}

$$\psi_{\rm C} = Q_{\rm C} \times \tau_{esc}$$

#part.cm^{-3} #part.cm^{-3}.s^{-1}

Cosmic rays are confined in the Galactic volume!

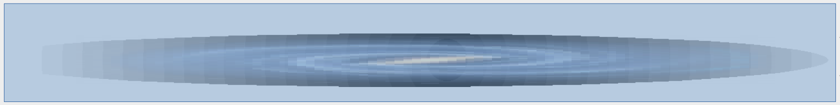
They undergo a random walk scattering on the magnetic turbulence.

$$\psi_{\rm B} = \frac{\psi_{\rm C}}{\tau_{int}} \times \tau_{esc}$$

$$\frac{1}{\sigma_{\rm C\to B}\, n_{ISM}\, c}$$

@ 1GeV : $\dfrac{\psi_{\rm B}}{\psi_{\rm C}} \approx 0.3$

$$\tau_{esc} \approx 0.3 \times \tau_{int} \approx 1\,\mathrm{Myr}$$



$\sim 6.10^{-4}\tau_{esc}$

Milky Way modelling

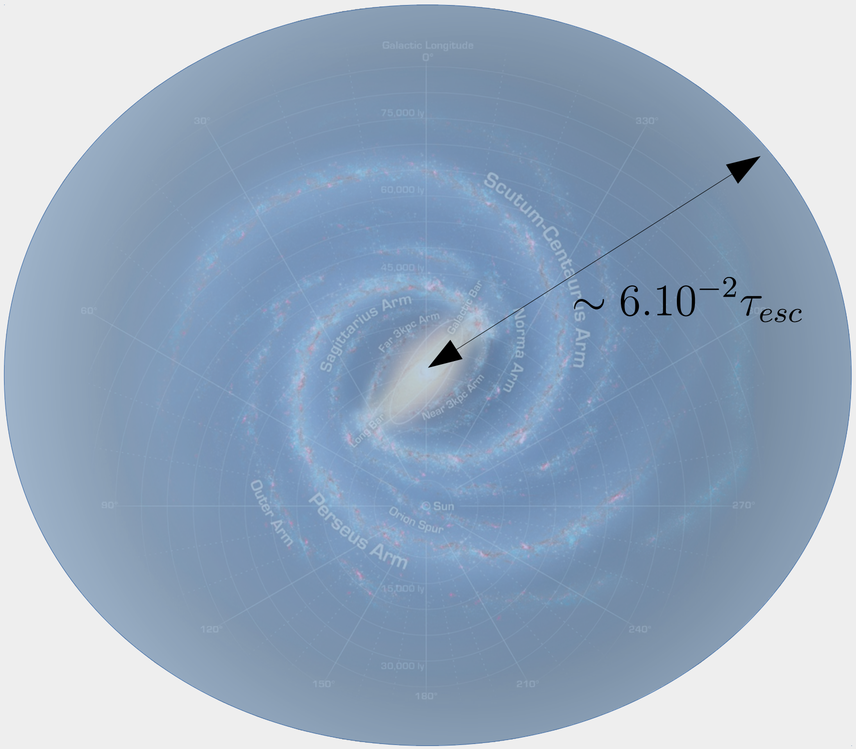
A – Diffusion

2- Abundance of light elements

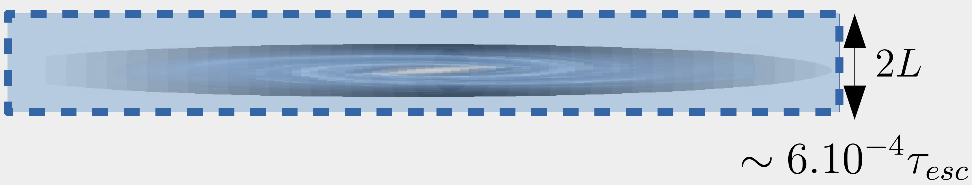
Galactic volume: what is the size of the box?

Assuming diffusion in the box:

$$\frac{\partial \psi}{\partial t} = K \Delta \psi \longrightarrow \tau_{esc} = \frac{L^2}{K}$$



The smallest sacle defines the escape time.



Milky Way modelling

A – Diffusion

2- Abundance of light elements

Galactic volume: what is the size of the box?

Assuming diffusion in the box:

$$\frac{\partial\psi}{\partial t} = K\Delta\psi \longrightarrow \tau_{esc} = \frac{L^2}{K}$$

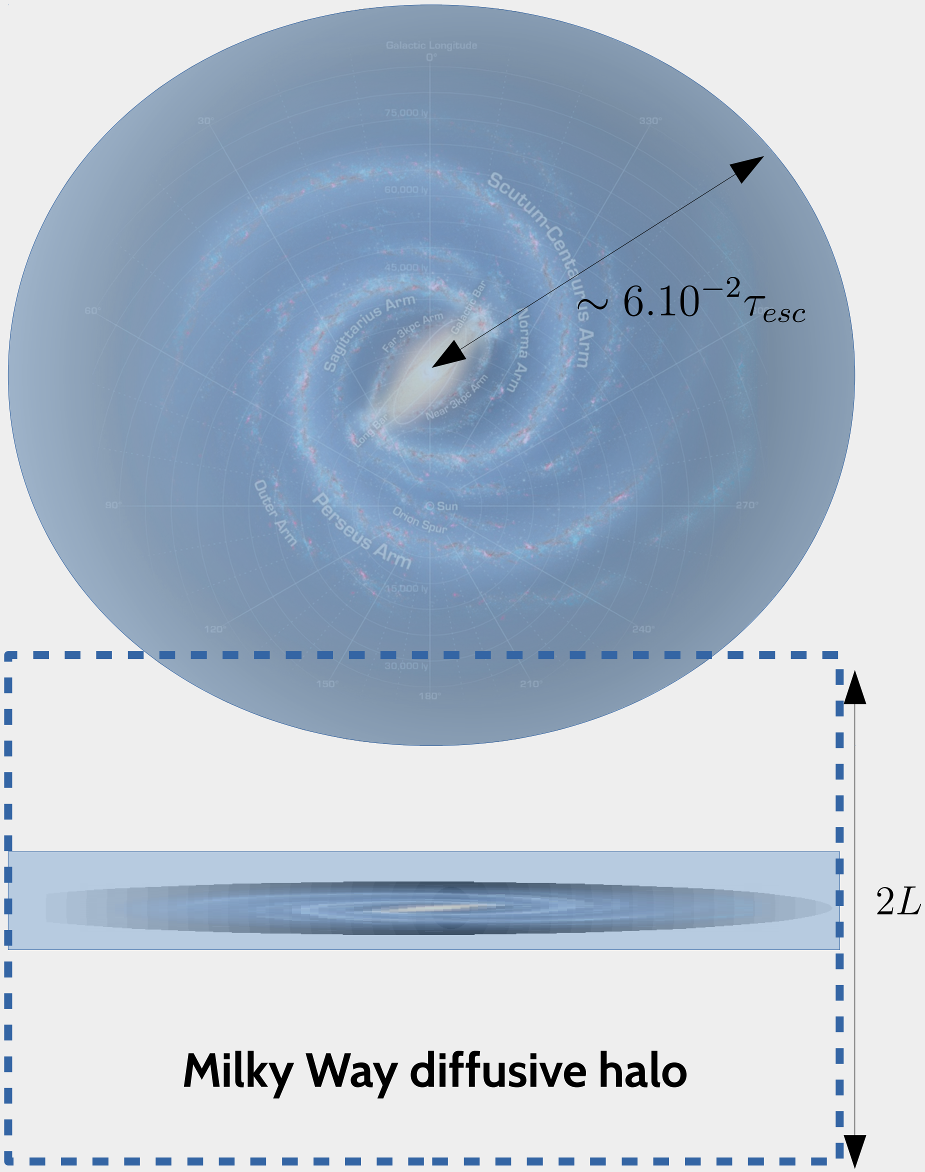
Size of the box given by long-lived radioisotopes:

$$\tau_{1/2}(^{10}\mathrm{Be}) = 1.4\,\mathrm{Myr} \longrightarrow \lambda_{1/2} = \sqrt{K\tau_{1/2}\gamma}$$

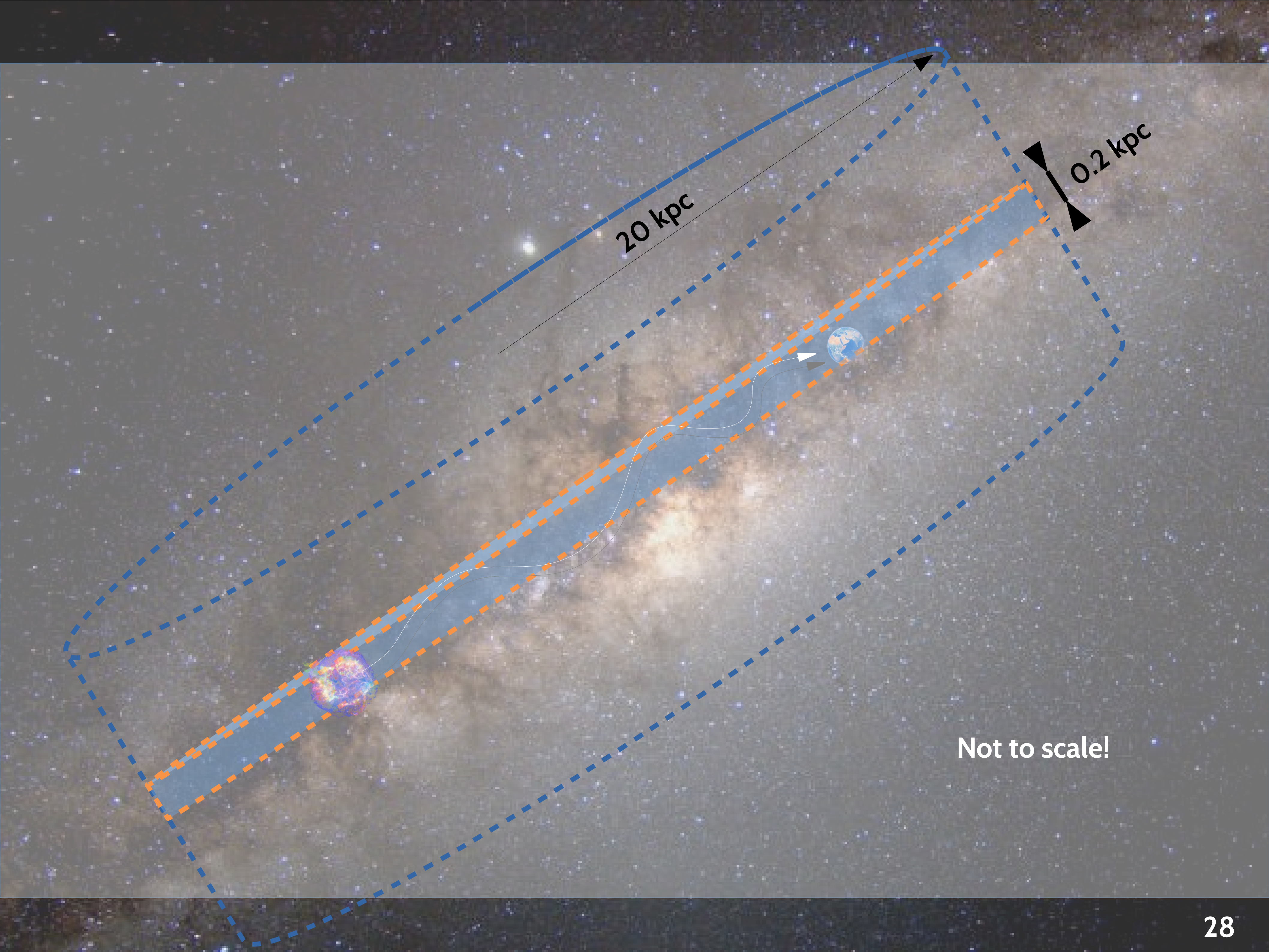
$$\psi_{^{10}\mathrm{Be}} = f(L/\lambda_{1/2})$$

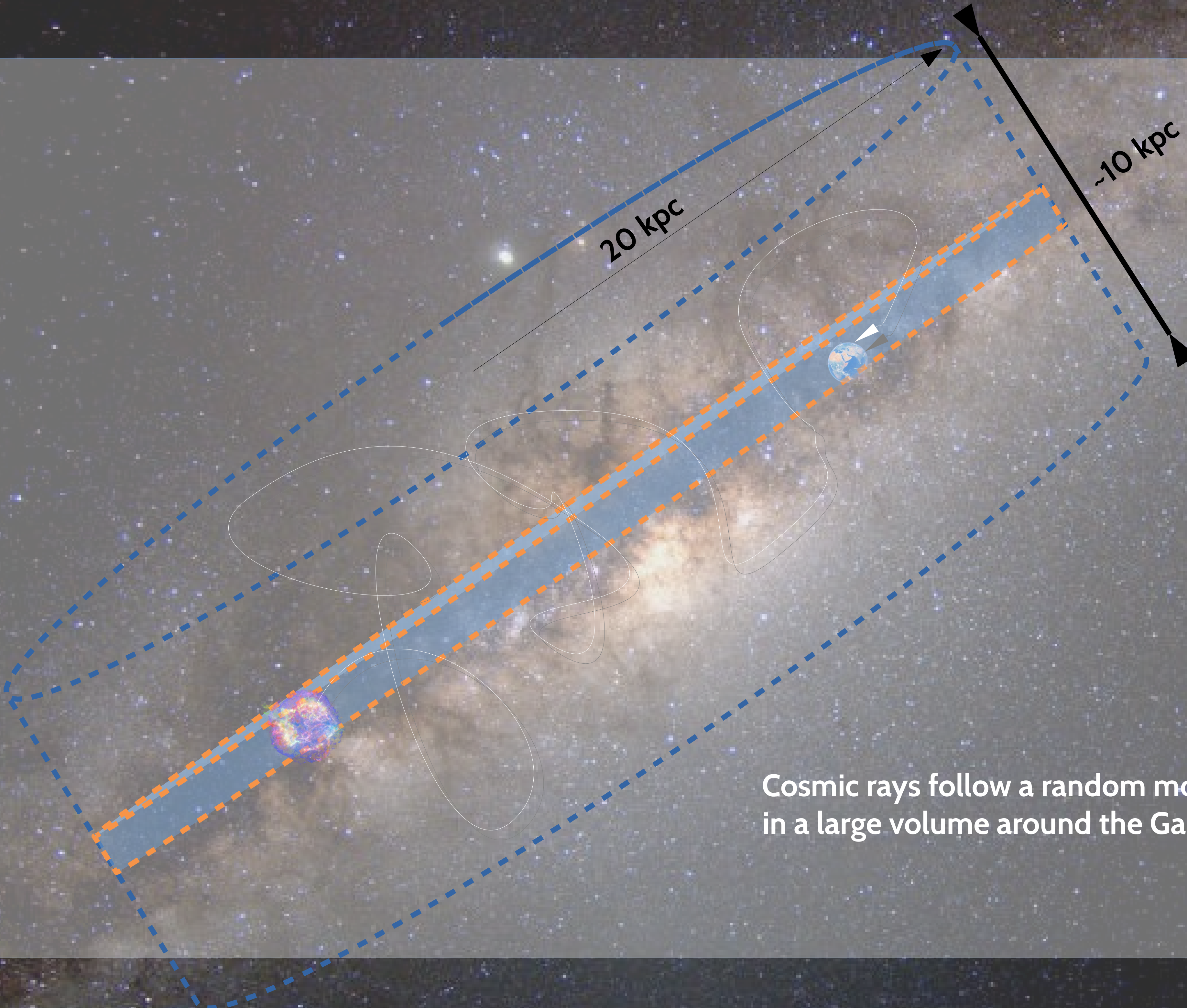
Data on radioactive Be give:

$$L \approx 5\,\mathrm{kpc}$$



Evoli et al. PRD 101, 023013 (2020)
Weinrich et al. A&A 639, A74 (2020)

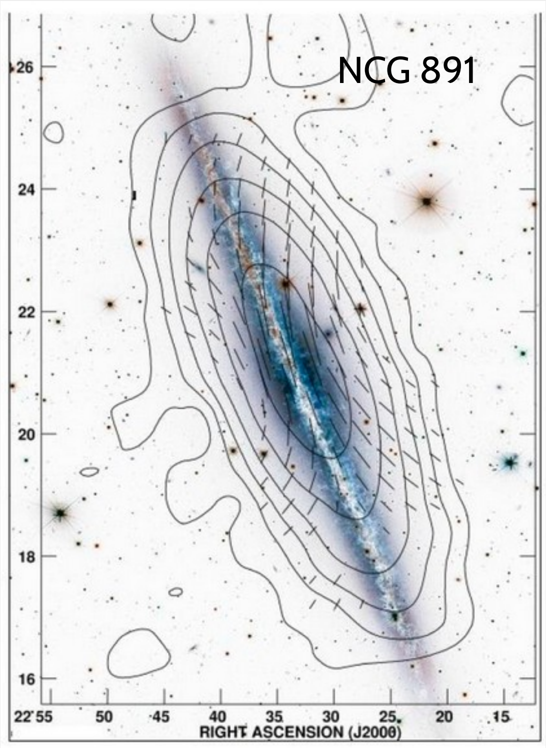

20 kpc
0.2 kpc
Not to scale!

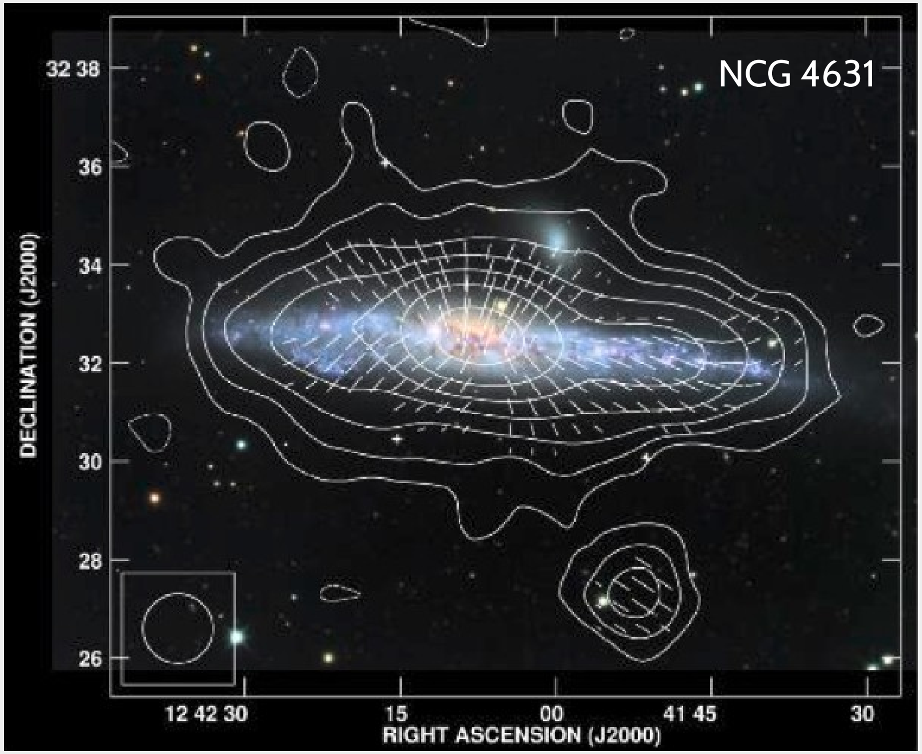


Cosmic rays follow a random motion in a large volume around the Galaxy!

A – Diffusion

Galactic diffusive halo: Consistent with the observation of other galaxies..





Max Planck Institute for radio astronomy. (taken from M Krause arxiv 0806.2060 and 0810.2923)

..extended synchrotron emission over kpc distances!

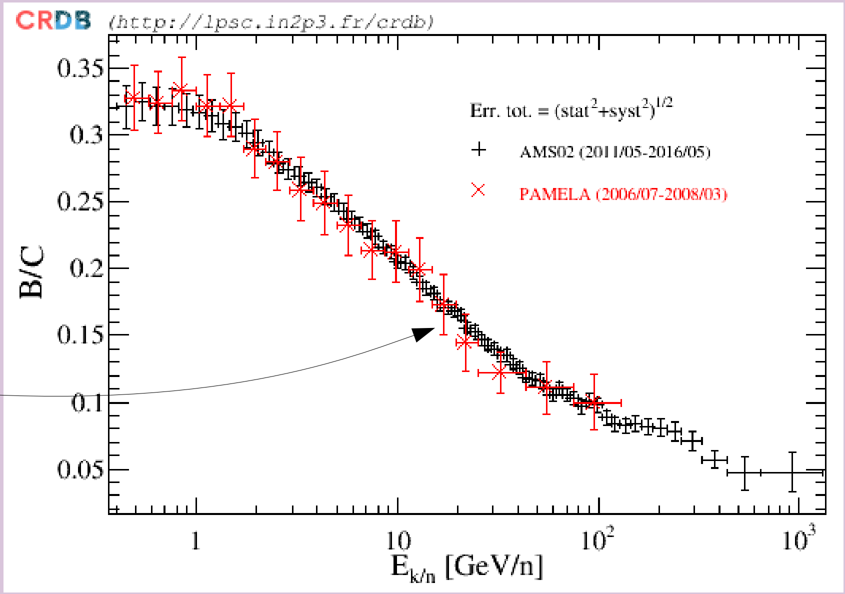
A – Diffusion

The escape time is a function of the energy.

@ 1GeV : $\dfrac{\psi_B}{\psi_C} \approx 0.3$

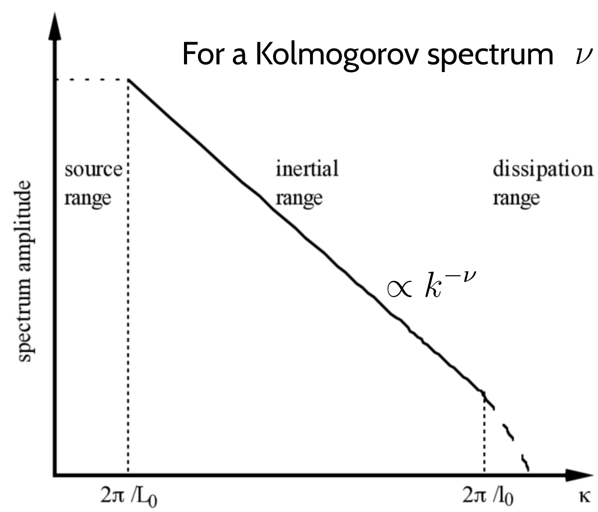
$$\tau_{esc} \approx 0.3 \times \tau_{int} \approx 1\,\mathrm{Myr}$$

$\tau_{esc} \propto 1/K(E) \searrow$ when $E \nearrow$



CRs scatter on the waves of a turbulent spectrum:

For a Kolmogorov spectrum $\nu = \dfrac{11}{3}$



Quasi-linear theory prediction

Jokipii, Astrophys.J. 146 480 (1966)

$$K(E) \propto E^{\delta}$$

$$\delta = 4 - \nu$$

For a Kolmogorov spectrum $\delta = 1/3$

B – Transport equation

$$\cancel{\frac{\partial \psi_\alpha}{\partial t}} - \vec{\nabla}_{\mathbf{x}} \left\{ K(E)\, \vec{\nabla}_{\mathbf{x}} \psi_\alpha - \vec{V}_{\rm c} \psi_\alpha \right\} + \frac{\partial}{\partial E} \left\{ b_{\rm tot}(E)\, \psi_\alpha - \beta^2 K_{pp} \frac{\partial \psi_\alpha}{\partial E} \right\}$$

$$+\sigma_\alpha\, v_\alpha\, n_{\rm ism}\, \psi_\alpha + \Gamma_\alpha\, \psi_\alpha = q_\alpha + \sum_\beta \{\sigma_{\beta\to\alpha} v_\beta n_{\rm ism} + \Gamma_{\beta\to\alpha}\}\, \psi_\beta \;.$$

Steady state!

B – Transport equation

$$\cancel{\frac{\partial \psi_\alpha}{\partial t}} - \vec{\nabla}_{\mathbf{x}} \left\{ K(E)\,\vec{\nabla}_{\mathbf{x}}\psi_\alpha - \vec{V}_c \psi_\alpha \right\} + \frac{\partial}{\partial E}\left\{ b_{\rm tot}(E)\,\psi_\alpha - \beta^2 K_{pp}\frac{\partial\psi_\alpha}{\partial E}\right\}$$
$$+\sigma_\alpha\, v_\alpha\, n_{\rm ism}\,\psi_\alpha + \Gamma_\alpha\,\psi_\alpha = q_\alpha + \sum_\beta \left\{\sigma_{\beta\to\alpha} v_\beta n_{\rm ism} + \Gamma_{\beta\to\alpha}\right\}\psi_\beta\,.$$

Steady state!

Diffusion Convection Energy losses Reacceleration

Destruction Decay Source Spallation Decay

Can be solved numerically (e.g. GALPROP or DRAGON codes) or semi-analytically (USINE code)

Predict the CR density in the Galaxy and compare with observations in order to understand the sources and the transport.

B – Transport equation

$$\cancel{\frac{\partial \psi_\alpha}{\partial t}} - \vec{\nabla}_{\mathbf{x}} \left\{ \boxed{K(E)} \vec{\nabla}_{\mathbf{x}} \psi_\alpha - \boxed{\vec{V}_c} \psi_\alpha \right\} + \frac{\partial}{\partial E} \left\{ \boxed{b_{\mathrm{tot}}(E)} \psi_\alpha - \beta^2 \boxed{K_{pp}} \frac{\partial \psi_\alpha}{\partial E} \right\}$$

$$+ \boxed{\sigma_\alpha} v_\alpha \boxed{n_{\mathrm{ism}}} \psi_\alpha + \boxed{\Gamma_\alpha} \psi_\alpha = q_\alpha + \sum_\beta \left\{ \boxed{\sigma_{\beta\to\alpha}} v_\beta \boxed{n_{\mathrm{ism}}} + \boxed{\Gamma_{\beta\to\alpha}} \right\} \psi_\beta \,.$$

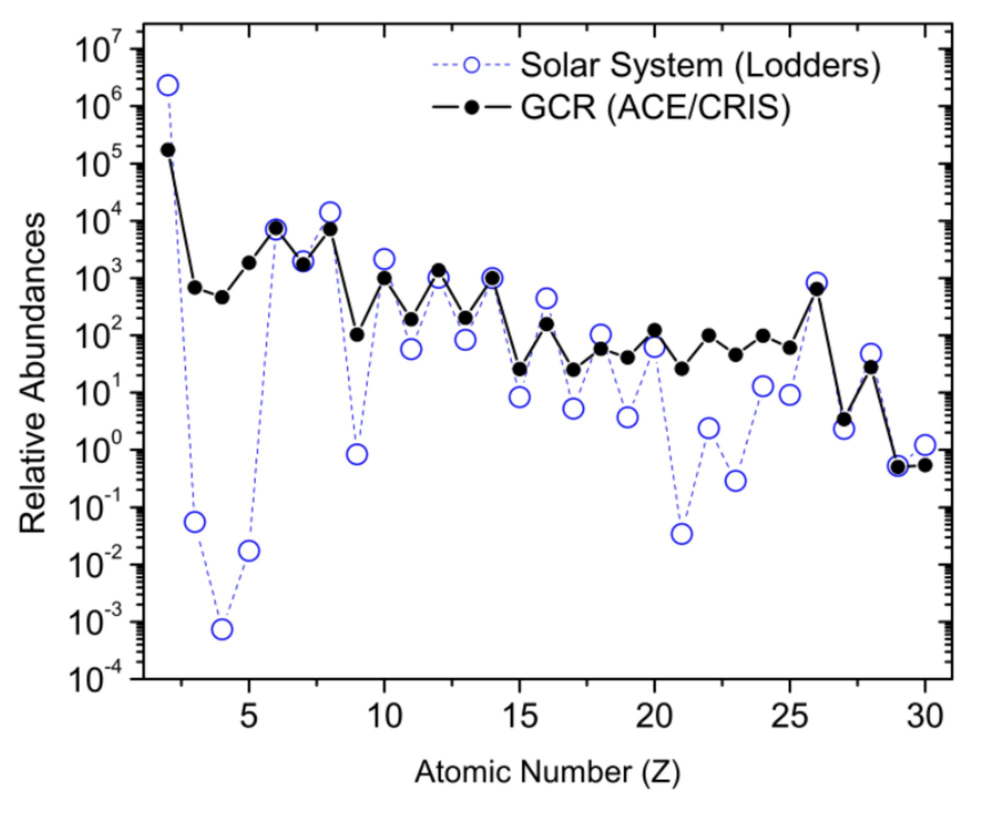
Steady state!

-Fixed by “Laboratory” experiments or simulations

-Fixed by cosmic ray fluxes, depends on the phenomenology

C – Transport parameters

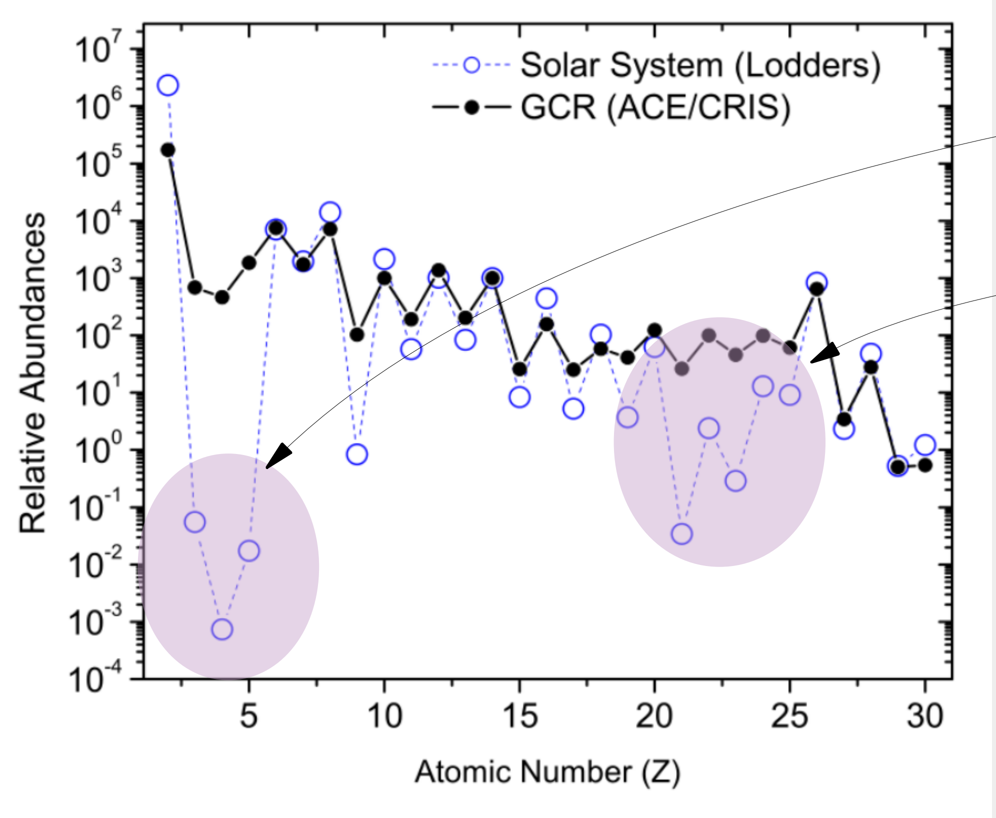
Secondary cosmic-rays!



Collaboration ACE., Nuclear Physics A, Vol. 758 (2005)

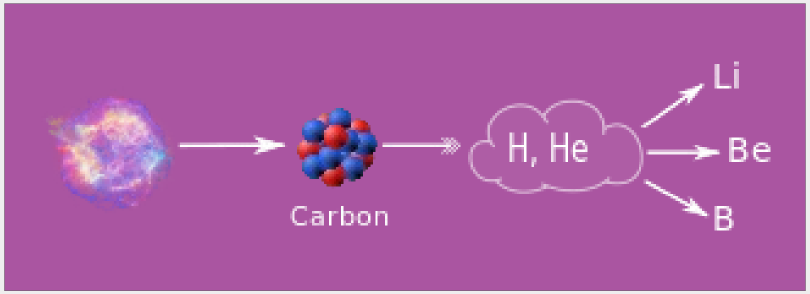
C – Transport parameters

Secondary cosmic-rays!



Collaboration ACE., Nuclear Physics A, Vol. 758 (2005)

Produced by spallation of heavier nuclei



C – Transport parameters

$$\cancel{\frac{\partial \psi_\alpha}{\partial t}} - \vec{\nabla}_{\mathbf{x}} \left\{ \boxed{K(E)}\, \vec{\nabla}_{\mathbf{x}} \psi_\alpha - \cancel{\vec{V}_c \psi_\alpha} \right\} + \frac{\partial}{\partial E} \left\{ \cancel{b_{\rm tot}(E)}\, \psi_\alpha - \beta^2 \cancel{K_{pp}} \frac{\partial \psi_\alpha}{\partial E} \right\}$$

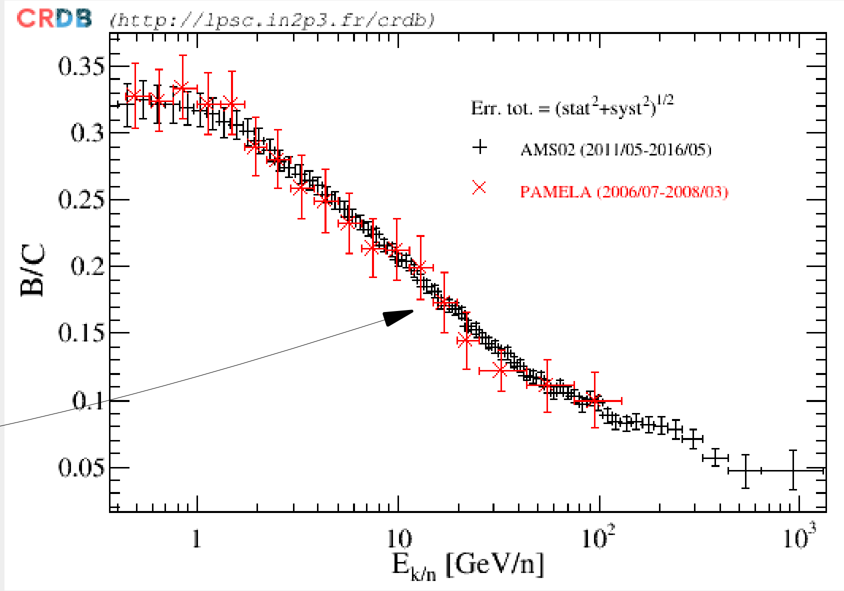
$$+\sigma_\alpha\, v_\alpha\, n_{\rm ism}\, \psi_\alpha + \cancel{\Gamma_\alpha}\, \psi_\alpha = q_\alpha + \sum_\beta \left\{ \sigma_{\beta\to\alpha} v_\beta n_{\rm ism} + \cancel{\Gamma_{\beta\to\alpha}} \right\} \psi_\beta \,.$$

Steady state!

Solving this equation in a 1D geometry for a two nuclei system (B and C) leads to

$$\frac{\Psi_{\rm B}}{\Psi_{\rm C}} = \frac{\boxed{\sigma_{\rm C\to B}}}{\boxed{\mathcal{K}\, E^\delta} + \boxed{\sigma_{\rm B}(E)}}$$

$$\propto E^{-\delta}$$

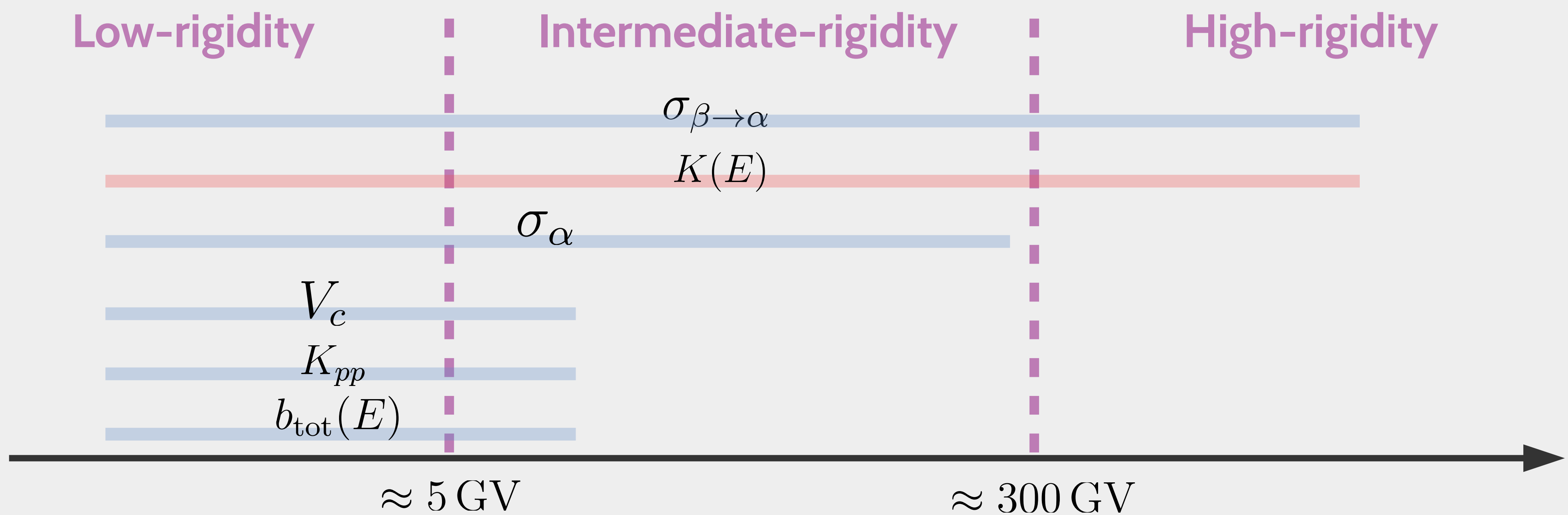


C – Transport parameters

We solve semi-analytically the famous propagation equation in a 1D geometry:

$$-\vec{\nabla}_{\mathbf{x}}\left\{K(E)\,\vec{\nabla}_{\mathbf{x}}\psi_\alpha - \vec{V}_{\rm c}\psi_\alpha\right\} + \frac{\partial}{\partial E}\left\{b_{\rm tot}(E)\;\psi_\alpha - \beta^2\,K_{pp}\,\frac{\partial\psi_\alpha}{\partial E}\right\}$$

$$+\sigma_\alpha\,v_\alpha\,n_{\rm ism}\,\psi_\alpha + \Gamma_\alpha\,\psi_\alpha = \;q_\alpha + \sum_\beta\left\{\sigma_{\beta\to\alpha}v_\beta n_{\rm ism} + \Gamma_{\beta\to\alpha}\right\}\,\psi_\beta\,.$$



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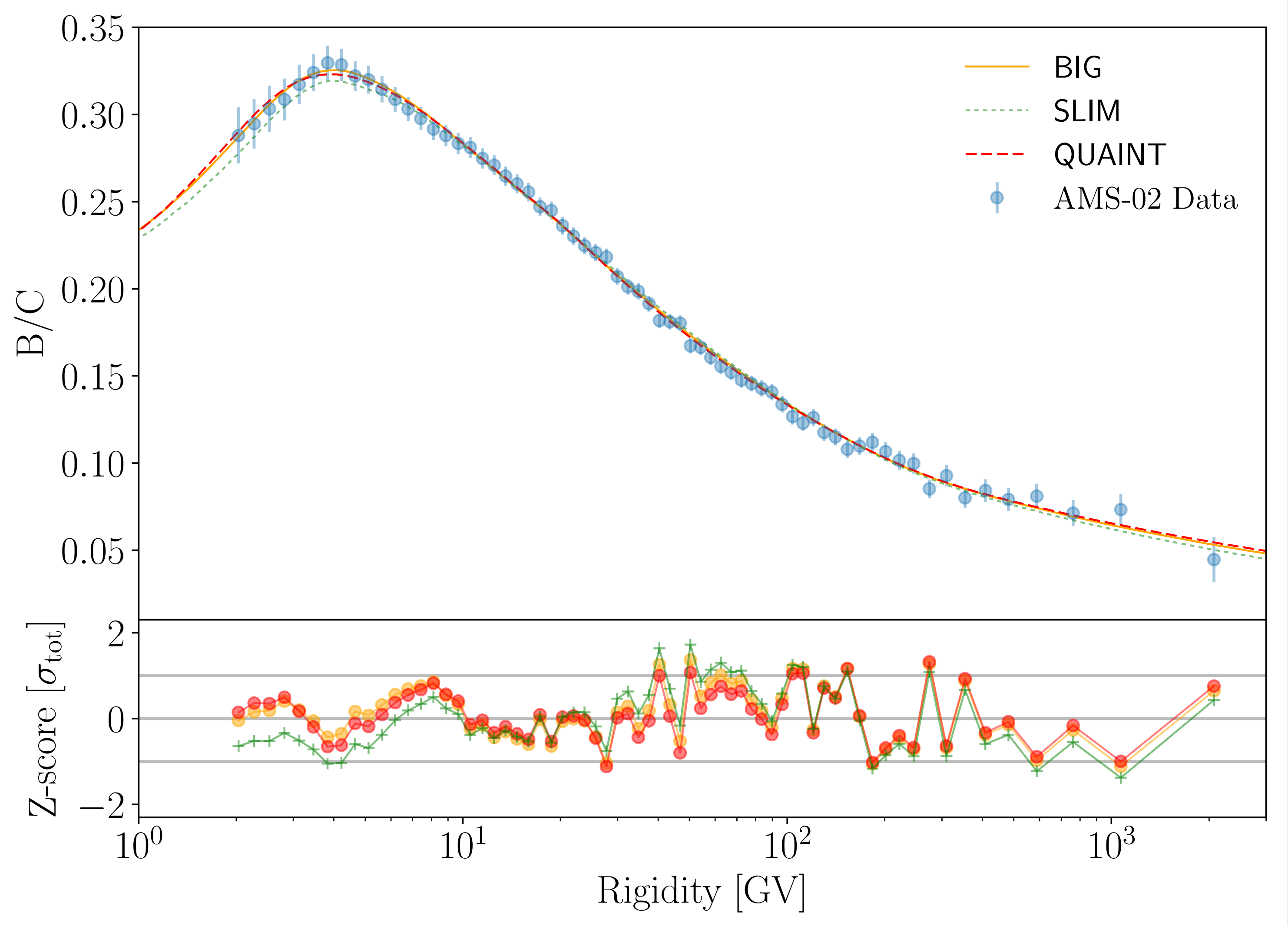
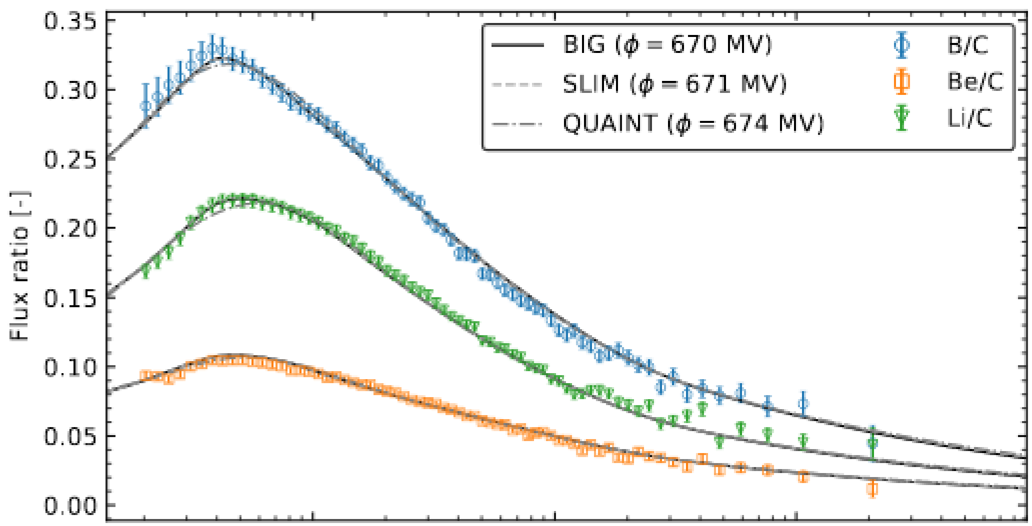
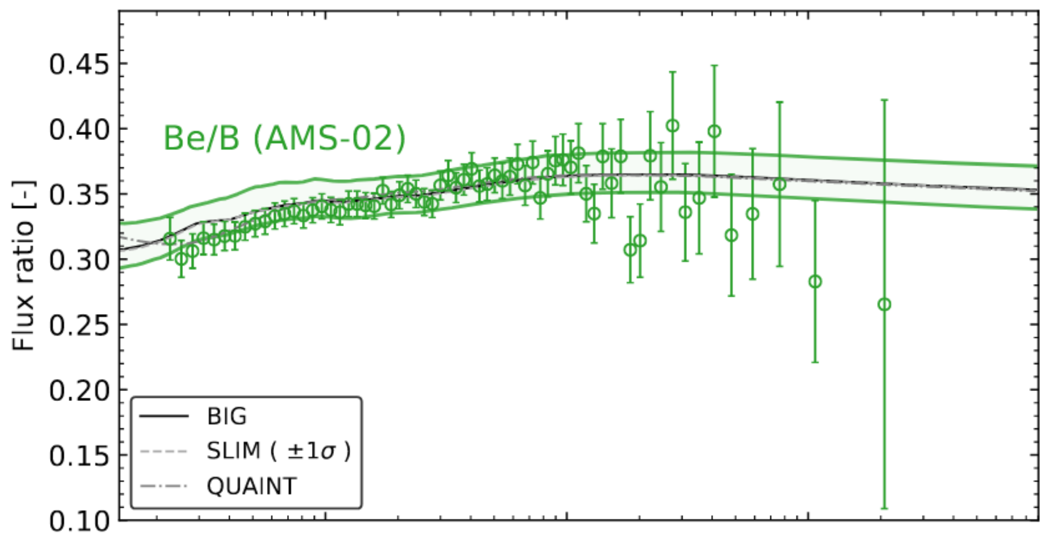


YG et al. Phys. Rev. D 99, 123028 (2019)

C – Transport parameters





Parameter [unit]	BIG	SLIM	QUAINT
Intermediate-rigidity parameters			
$\log_{10}\left(\frac{K_0}{1\ \mathrm{GV}}\right)^{\dagger}$ [-]	$-1.43^{+0.04}_{-0.06}$	$-1.41^{+0.02}_{-0.03}$	$-1.34^{+0.04}_{-0.05}$
δ [-]	$0.51^{+0.02}_{-0.02}$	$0.51^{+0.01}_{-0.01}$	$0.47^{+0.02}_{-0.02}$
Low-rigidity parameters			
V_c [km s^{-1}]	$0.7^{+2.0}_{-0.9}$	n/a	$0.0^{+2.5}$
V_a [km s^{-1}]	$0.0^{+12.2}$	n/a	$49.7^{+8.1}_{-9.7}$
η [-]	1 (fixed)	1 (fixed)	$-1.64^{+0.42}_{-0.52}$
δ_l [-]	$-0.75^{+0.18}_{-0.16}$	$-0.74^{+0.13}_{-0.14}$	n/a
R_l [GV]	$4.57^{+0.23}_{-0.20}$	$4.53^{+0.19}_{-0.18}$	n/a
χ^2 indicators‡			
$\chi^2_{\rm min}$/dof	$258.8^{\star}/195$	$258.3^{\star}/197$	$258.8/196$
$\chi^2_{\rm nui}/n_{\rm nui}$	21.9/16	22.3/16	19.8/16

	BIG	SLIM	QUAINT
Base & Be/B (AMS-02)			
L [kpc]	$4.96^{+2.97}_{-1.76}$	$5.04^{+3.07}_{-1.79}$	$4.79^{+3.19}_{-1.77}$
χ^2 / $n_{\rm dof}$	233.7 / 193	233.1 / 195	235.3 / 194
$\chi^2_{\rm nui}$ / $n_{\rm nui}$	17.4 / 20	17.4 / 20	15.8 / 20

YG et al. Phys. Rev. D 99, 123028 (2019), Derome et al. A&A 627, A158 (2019), Weinrich et al. A&A 639, A74 (2020), Weinrich, YG et al. A&A 639, A131 (2020).

D – Why are these transport parameters interesting?

Learn about the physics of the Galaxy:

→ Galactic Halo Turbulence properties.

→ Dynamic of the CRs and the gas.

→ To be compared with other observables.

Learn about exotic physics:

→ Compute predictions of secondaries antiparticles!

→ Precise estimation is needed, one of the limitation comes from nuclear cross-sections.

D – Why are these transport parameters interesting?

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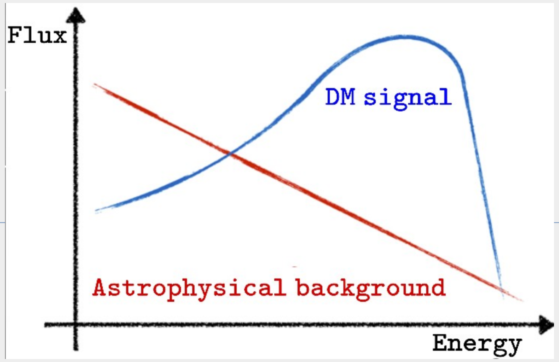

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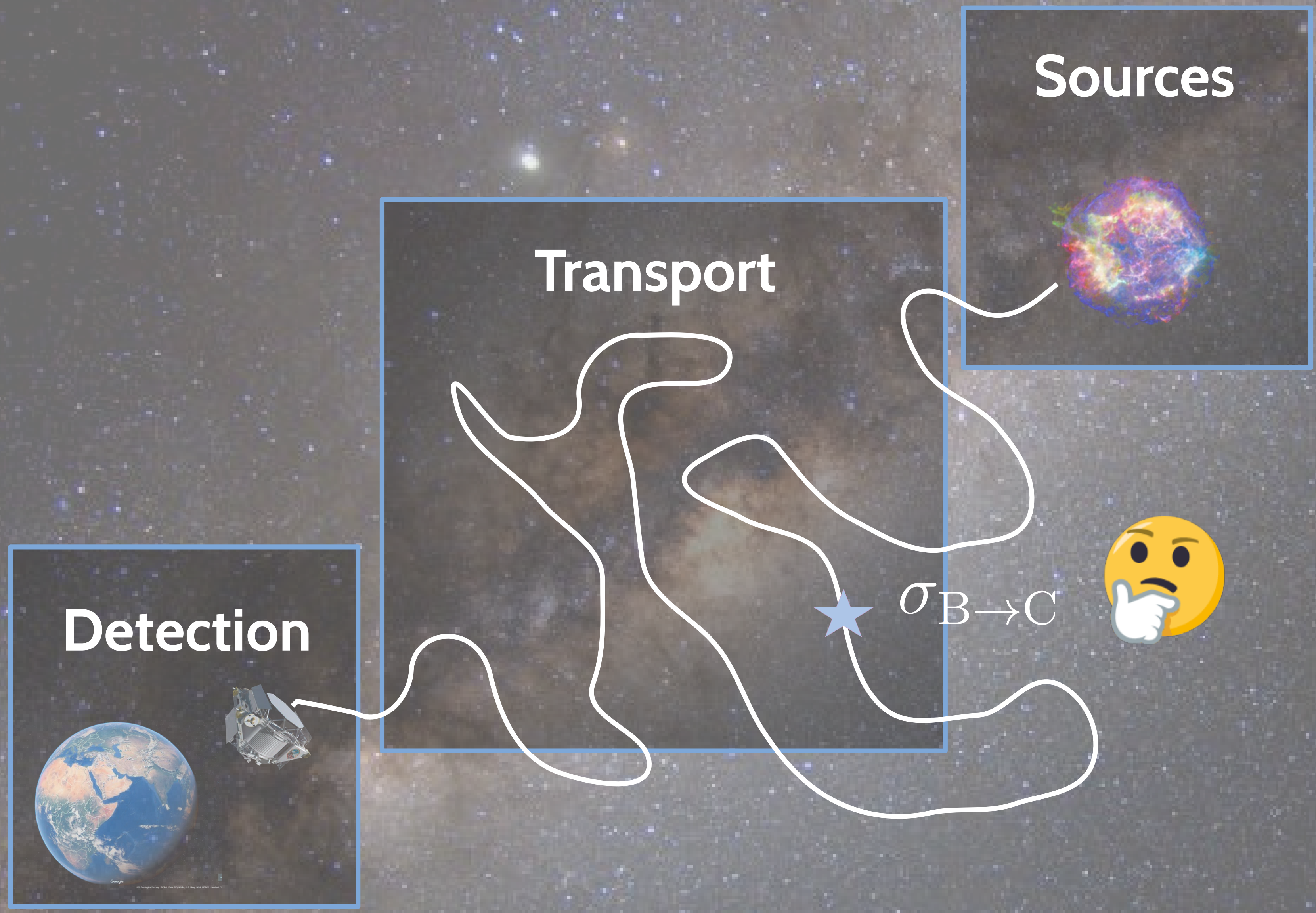

Sources
Transport
Detection
$\sigma_{\mathrm{B}\to\mathrm{C}}$

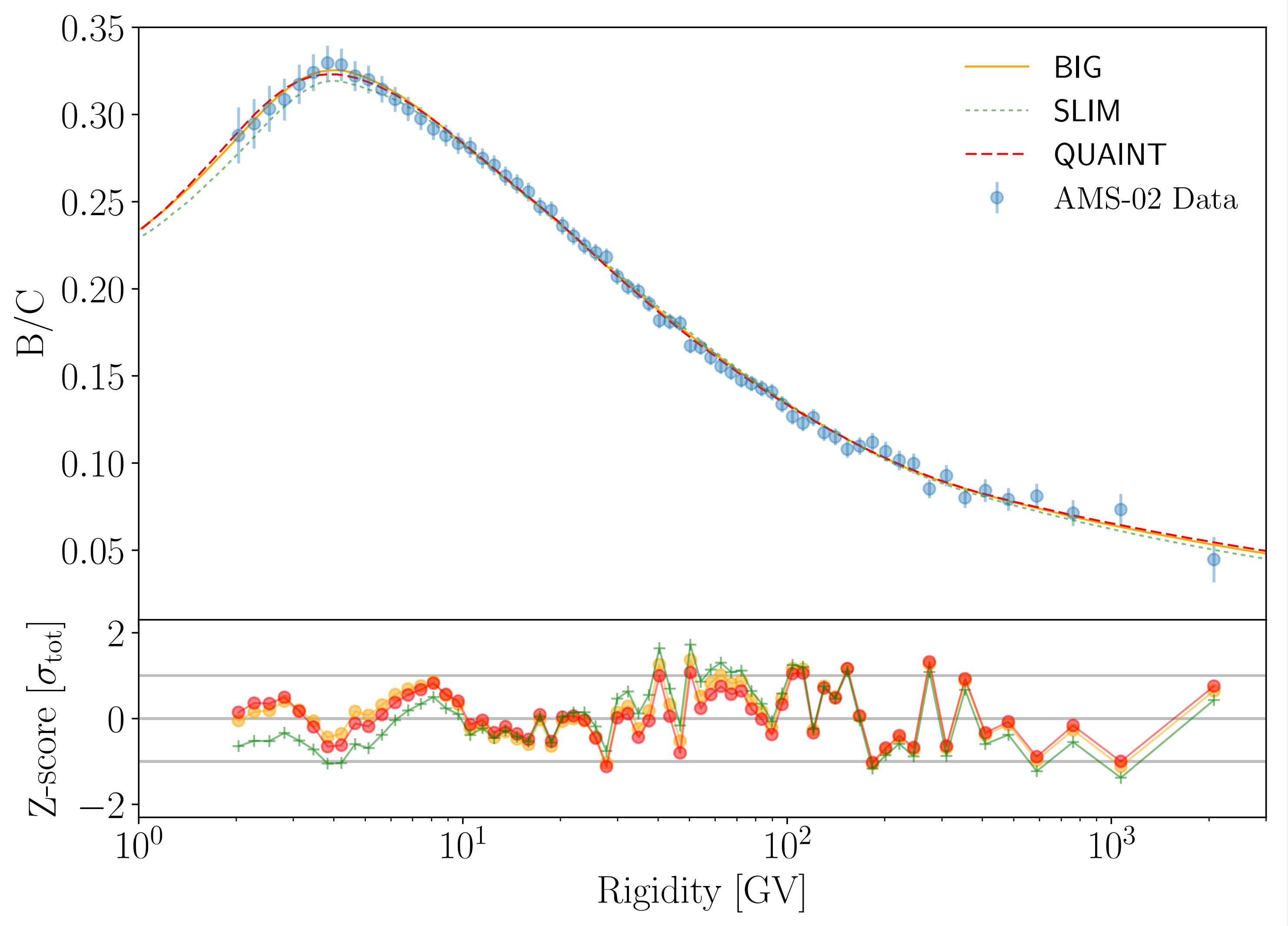
I – Detection and observables

II – Sources

III – Transport

IV – Some nuclear physics!

The case of the B/C..



AMS-02 data precision is close to the % level.

Secondary cosmic rays: the boron

$$\mathrm{B} = \boxed{{}^{10}\mathrm{B}}\,\boxed{{}^{11}\mathrm{B}}$$

30 % + 70 %

Secondary cosmic rays: the boron

$^{12}\mathrm{C}$ $^{13}\mathrm{C}$

$$\mathrm{B} = {}^{10}\mathrm{B} \quad {}^{11}\mathrm{B}$$

30 % + 70 %

$$\textcolor{red}{\Psi_{\mathrm{B}}} = \sum_{a>\mathrm{B}} \left(\frac{\sigma_{a\to{}^{10}\mathrm{B}}}{\mathcal{K}\ R^{\delta} + \sigma_{{}^{10}\mathrm{B}}(R)} + \frac{\sigma_{a\to{}^{11}\mathrm{B}}}{\mathcal{K}\ R^{\delta} + \sigma_{{}^{11}\mathrm{B}}(R)} \right) \textcolor{red}{\Psi_a}$$

Measured by detectors

Theoretical prediction in slab diffusion geometry

Measured isotopic flux

e.g. $^{12}\mathrm{C}$

Secondary cosmic rays: the boron

$$\mathrm{B} = \boxed{^{10}\mathrm{B}}\ \boxed{^{11}\mathrm{B}} \leftarrow \boxed{^{12}\mathrm{C}}\ \boxed{^{13}\mathrm{C}}$$

30 % + 70 %

Measured up to few percent!

$$\boxed{\Psi_{\mathrm{B}}} = \sum_{a>\mathrm{B}} \left(\frac{\sigma_{a\to^{10}\mathrm{B}}}{\mathcal{K}\ R^{\delta} + \sigma_{^{10}\mathrm{B}}(R)} + \frac{\sigma_{a\to^{11}\mathrm{B}}}{\mathcal{K}\ R^{\delta} + \sigma_{^{11}\mathrm{B}}(R)} \right) \boxed{\Psi_a}$$

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Secondary cosmic rays: the boron

$$\mathrm{B} = \boxed{{}^{10}\mathrm{B}}\ \boxed{{}^{11}\mathrm{B}} \qquad \boxed{{}^{12}\mathrm{C}}\ \boxed{{}^{13}\mathrm{C}}$$

30 % + 70 %

Measured up to few percent!

Inputs!

$$\Psi_{\mathrm{B}} = \sum_{a>\mathrm{B}} \left(\frac{\sigma_{a\to {}^{10}\mathrm{B}}}{\mathcal{K}\, R^{\delta} + \sigma_{{}^{10}\mathrm{B}}(R)} + \frac{\sigma_{a\to {}^{11}\mathrm{B}}}{\mathcal{K}\, R^{\delta} + \sigma_{{}^{11}\mathrm{B}}(R)} \right) \Psi_{a}$$

Measured by detectors

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e.g. ${}^{12}\mathrm{C}$

Secondary cosmic rays: the boron

$$\mathrm{B} = {}^{10}\mathrm{B} \quad {}^{11}\mathrm{B} \qquad {}^{12}\mathrm{C} \quad {}^{13}\mathrm{C}$$

30 % + 70 %

Measured up to few percent!

Inputs!

$$\Psi_{\mathrm{B}} = \sum_{a>\mathrm{B}} \left(\frac{\sigma_{a\to{}^{10}\mathrm{B}}}{\mathcal{K}\,R^{\delta} + \sigma_{{}^{10}\mathrm{B}}(R)} + \frac{\sigma_{a\to{}^{11}\mathrm{B}}}{\mathcal{K}\,R^{\delta} + \sigma_{{}^{11}\mathrm{B}}(R)} \right) \Psi_a$$

Measured by detectors

Constraints on CR propagation parameters

Measured isotopic flux

e.g. ${}^{12}\mathrm{C}$

Secondary cosmic rays: the boron

$$\mathrm{B} = \boxed{{}^{10}\mathrm{B}}\ \boxed{{}^{11}\mathrm{B}} \leftarrow \boxed{{}^{12}\mathrm{C}}\ \boxed{{}^{13}\mathrm{C}}$$

30 % + 70 %

Measured up to few percent!

Inputs!.. large uncertainties

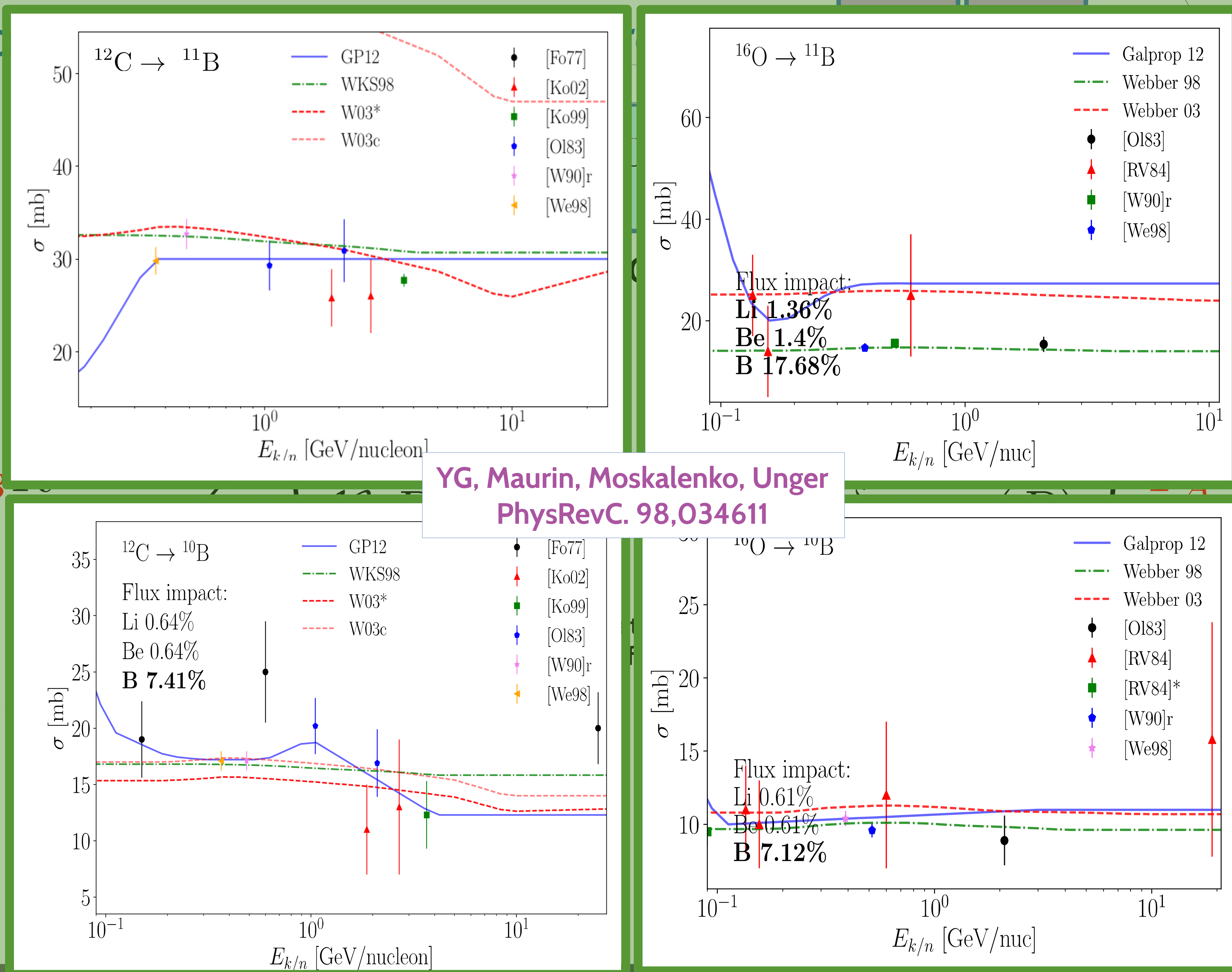
$$\Psi_{\mathrm{B}} = \sum_{a>\mathrm{B}} \left(\frac{\sigma_{a\rightarrow{}^{10}\mathrm{B}}}{\mathcal{K}\ R^{\delta} + \sigma_{{}^{10}\mathrm{B}}(R)} + \frac{\sigma_{a\rightarrow{}^{11}\mathrm{B}}}{\mathcal{K}\ R^{\delta} + \sigma_{{}^{11}\mathrm{B}}(R)} \right) \Psi_{a}$$

Measured by detectors

Measured isotopic flux

e.g. ${}^{12}\mathrm{C}$

Sec

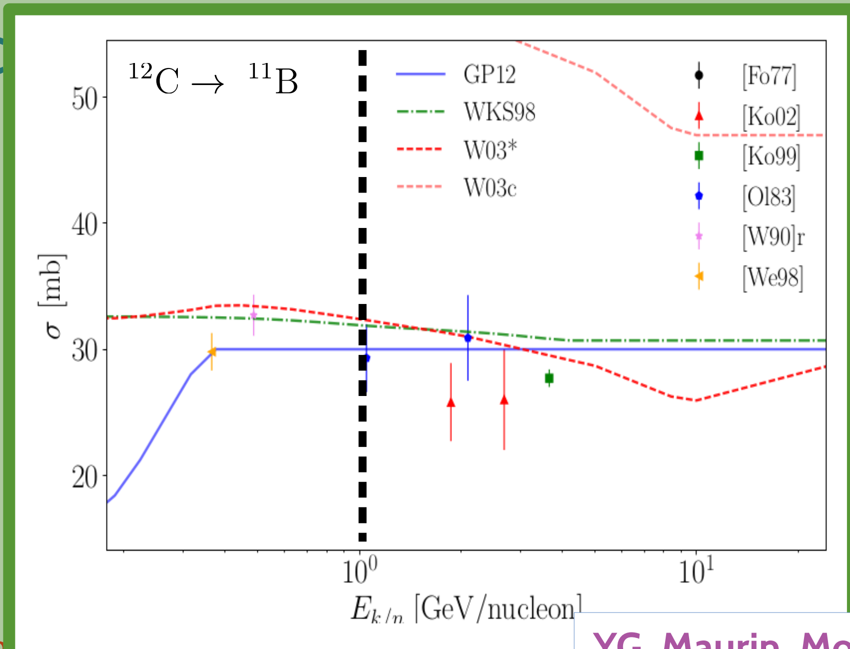


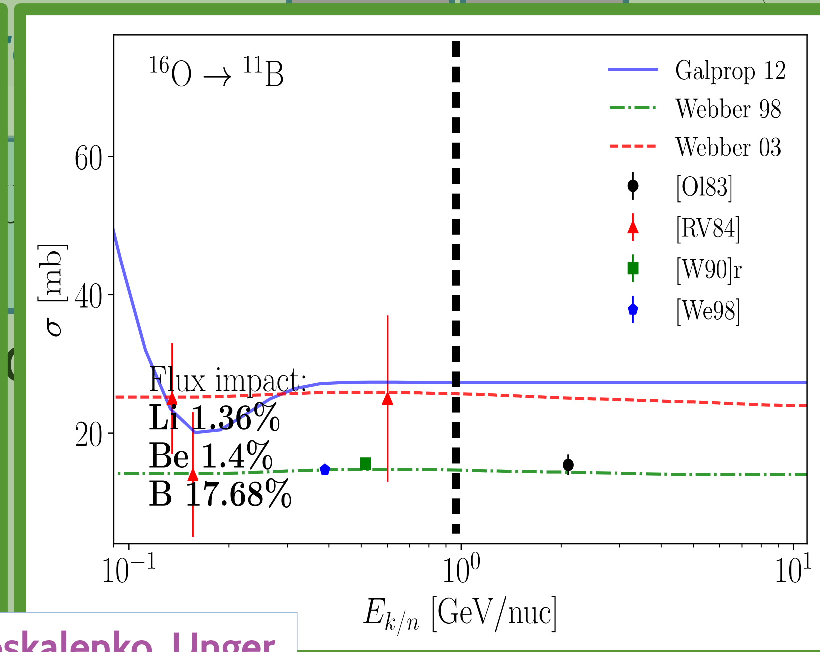
YG, Maurin, Moskalenko, Unger
PhysRevC. 98,034611

$\mathcal{N}_B$

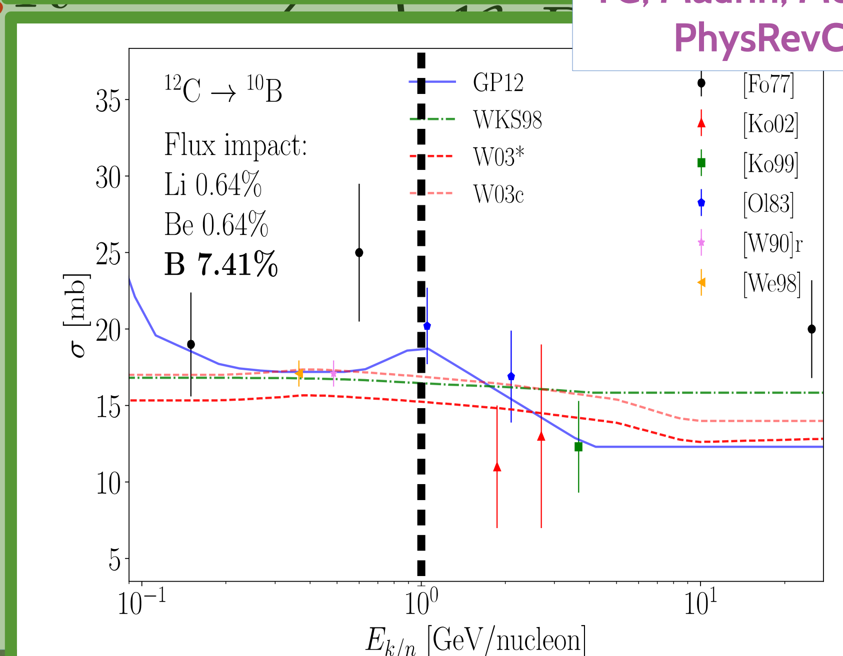
Ψ_B

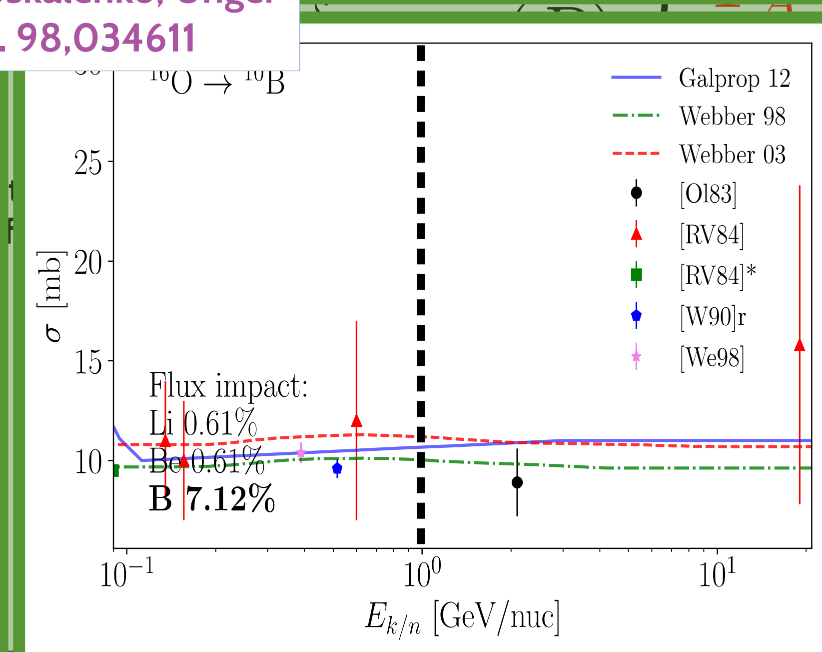
opic flux

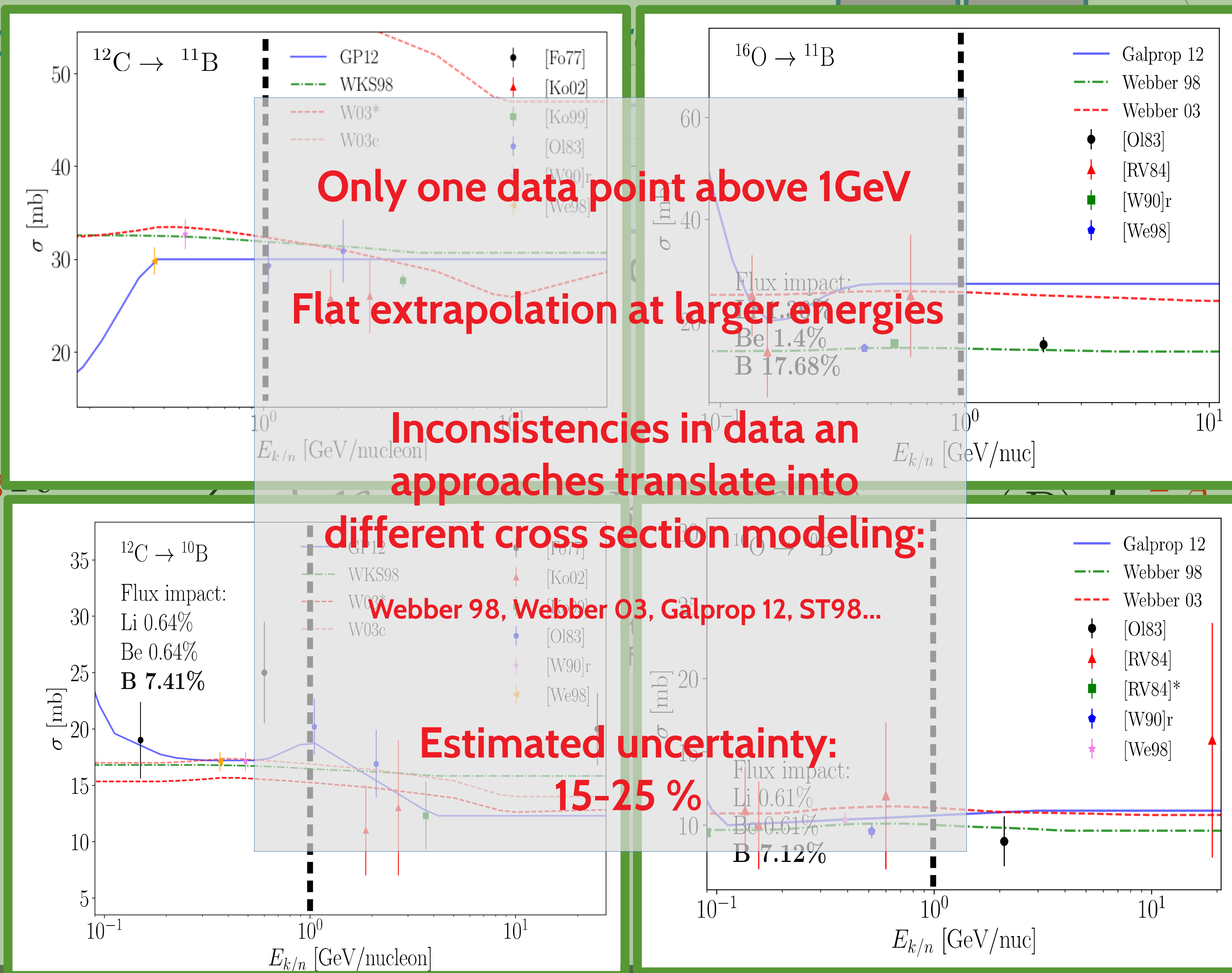




YG, Maurin, Moskalenko, Unger
PhysRevC. 98,034611







Only one data point above 1GeV

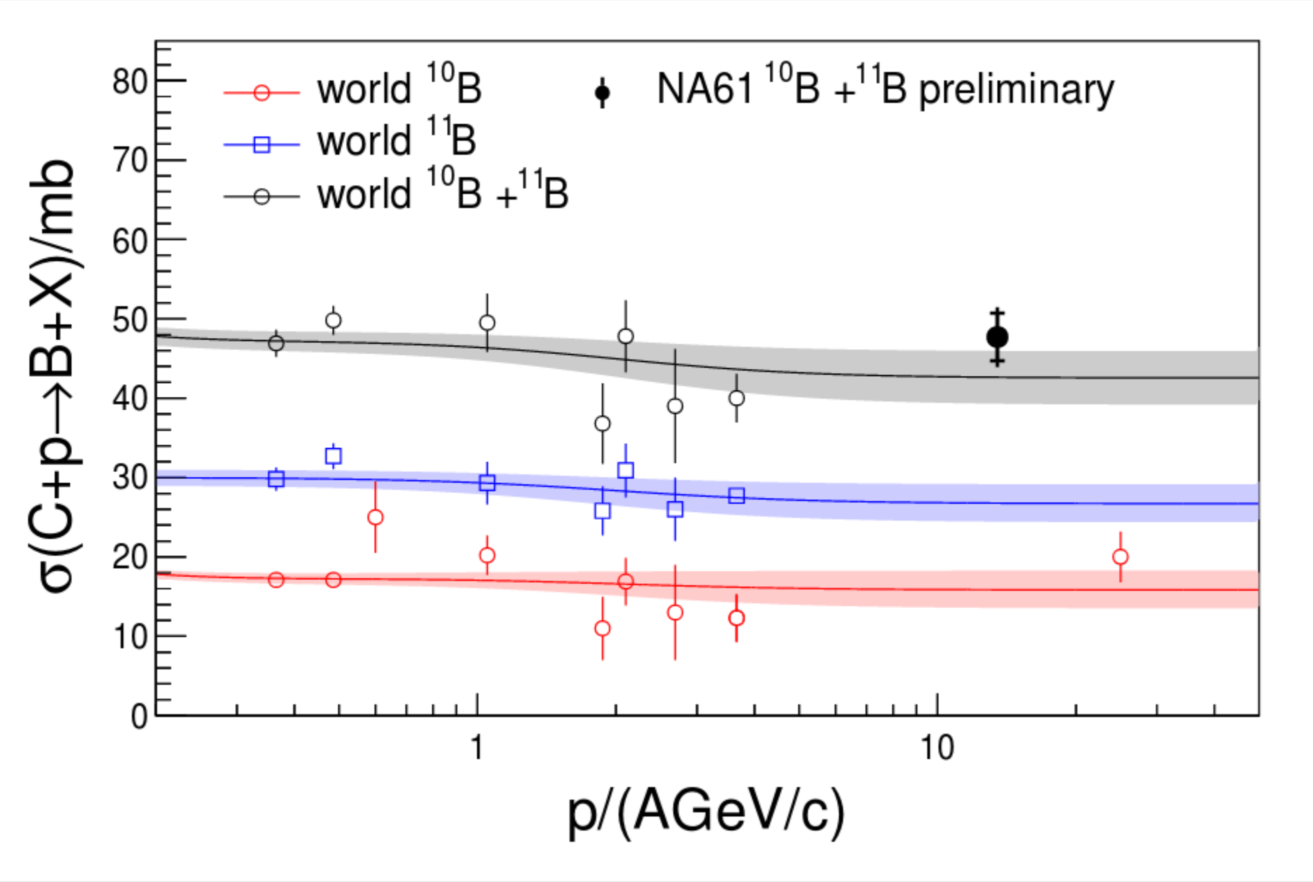
Flat extrapolation at larger energies

Inconsistencies in data an approaches translate into different cross section modeling:

Webber 98, Webber 03, Galprop 12, ST98...

Estimated uncertainty: 15-25 %

NA61 is already taking data!



M. Unger (NA61/SHINE Collaboration) Pos ICRC (2019) 446

PoS(ICRC2019)446

Take home messages!

→ Galactic cosmic rays are mesured with unprecedented precision.

Energy | **Composition** | **Direction**

→ New physics may arise from a detailed interpretation of these observables.

Keys ingredients to further improve the analyses:

→ Experimental covariance from the collaborations.

→ Reduce the uncertainties on spallation cross sections.