Desired nuclear cross-sections (XS) for Galactic Cosmic-Ray (GCR) data

1) GCRs and production cross sections
2) Ranking of quantities of interest
3) Propagating XS uncertainties & forecasts

Y. Génolini, DM, I. Moskalenko, M. Unger

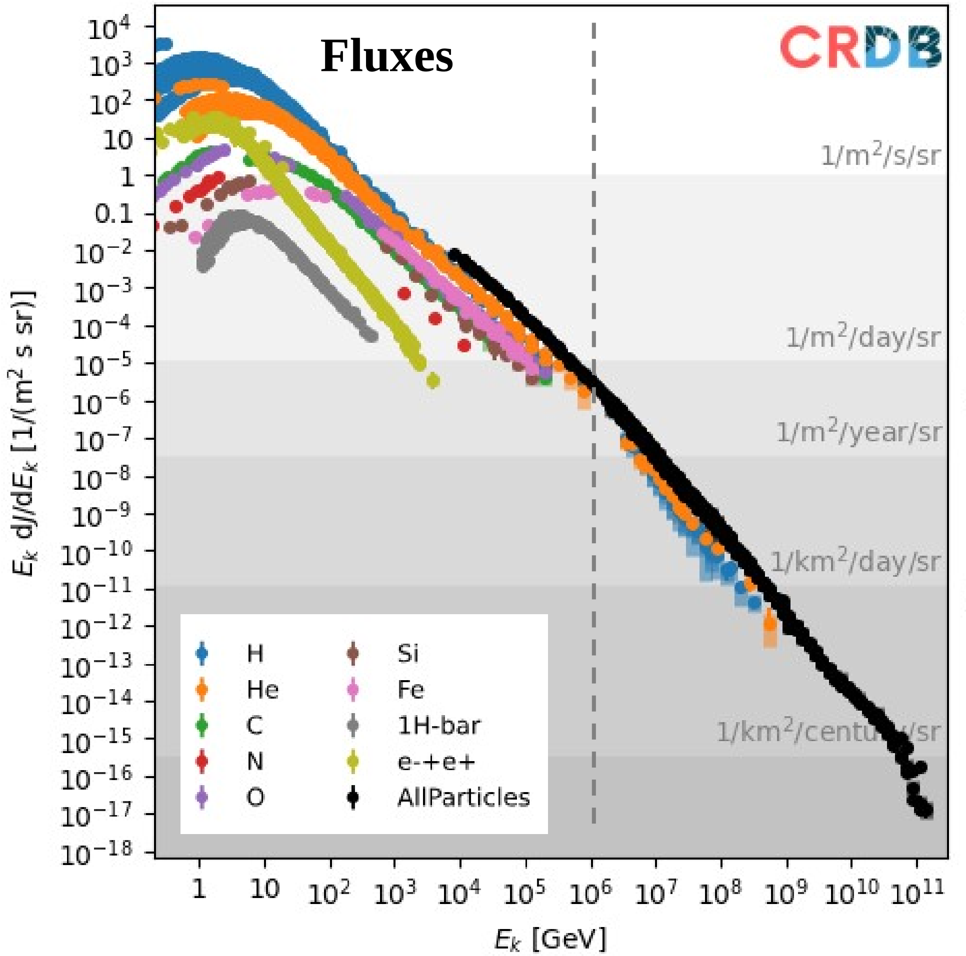
- Paper I: Lithium to Oxygen (PRC 98, 034611, 2018), *Editor's Suggestion*
- Paper II: Fluorine to Silicon (PRC 109, 064914, 2024)
- Paper III and IV (in prep.): [^{1}H, ^{2}H, ^{3}He and ^{14}He] then [Z=15-30]

David Maurin
(LPSC)
dmaurin@lpsc.in2p3.fr

Journées théorie du PNHE
6 novembre 2024

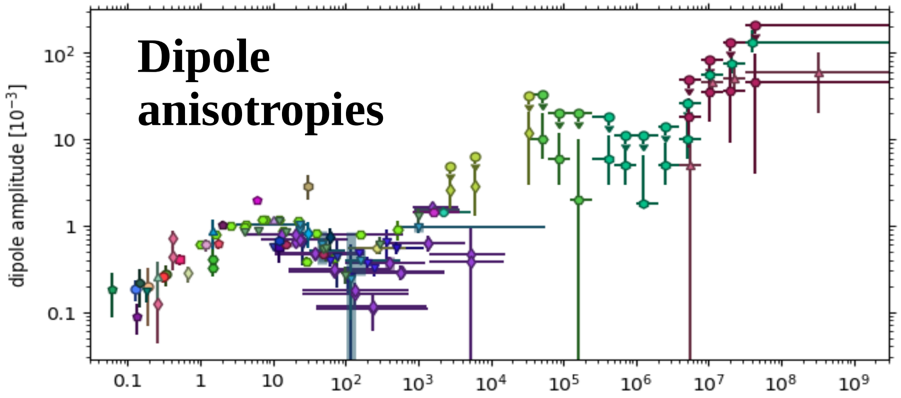
1) CR data

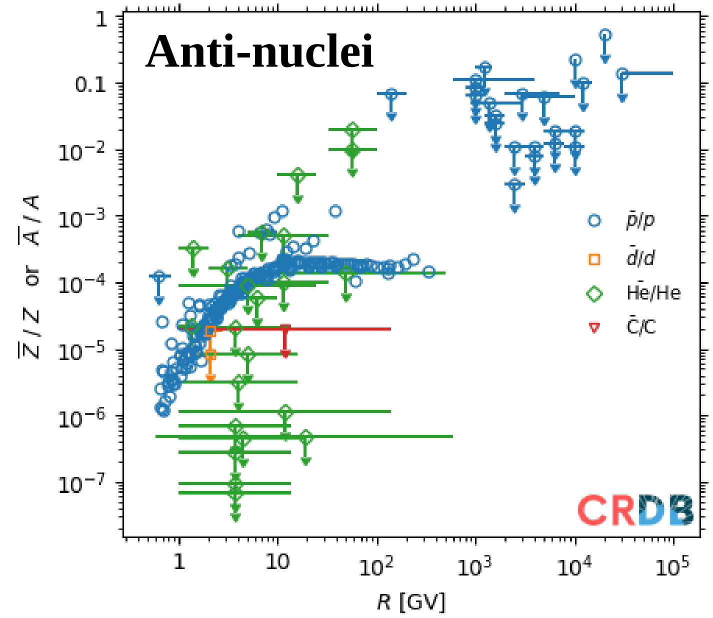
Galactic CRs Extragalactic CRs

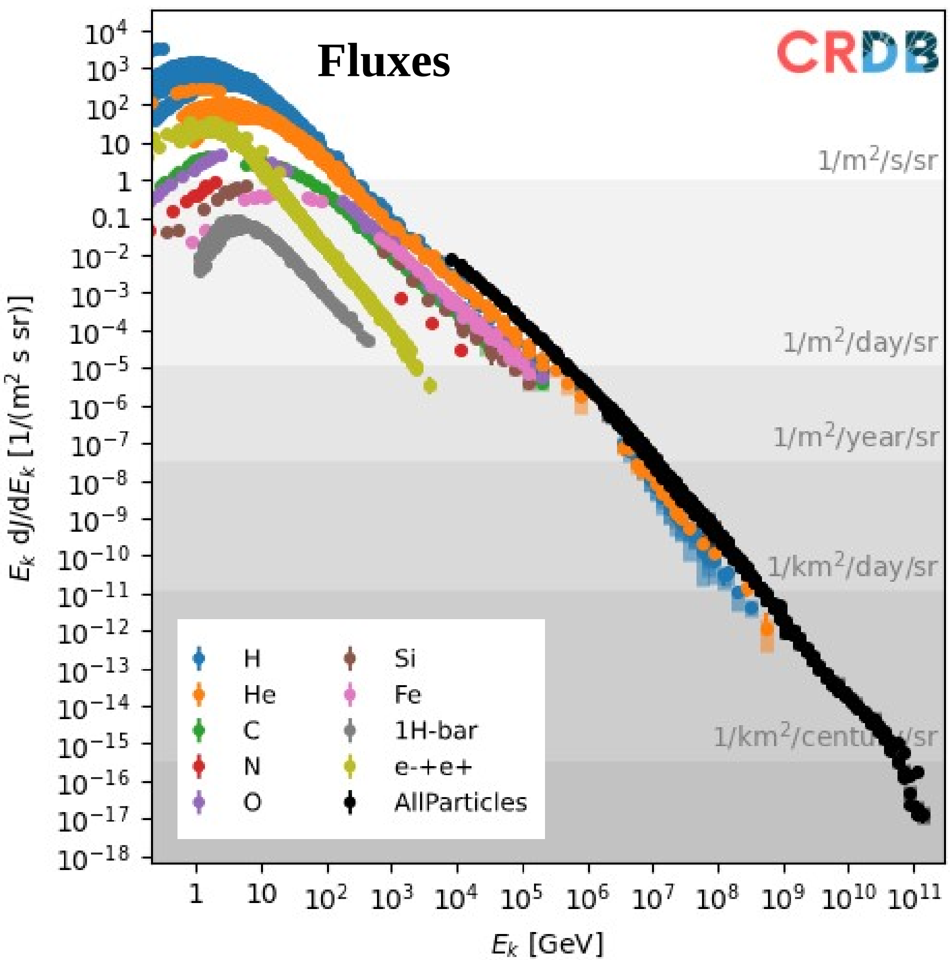


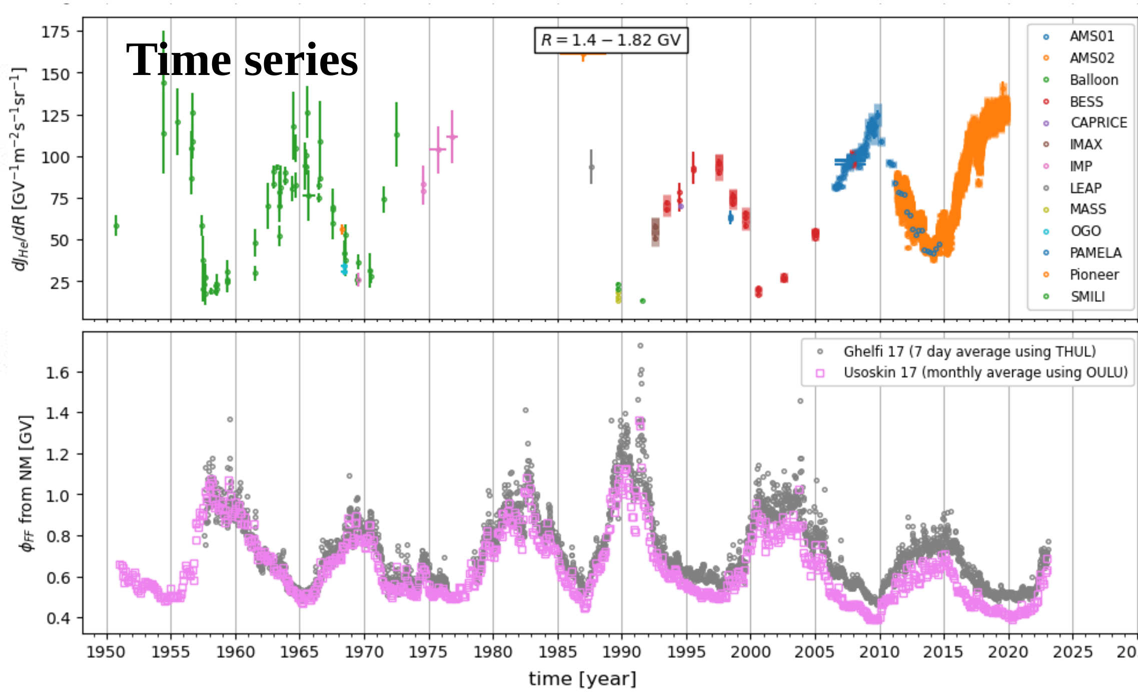
1) CRDB (https://lpsc.in2p3.fr/crdb)

DM et al. (*2014*, *2020*, *2023*)
- Meta-data (refs, dates, infos)
- Plots (online+notebooks+pip-installable)





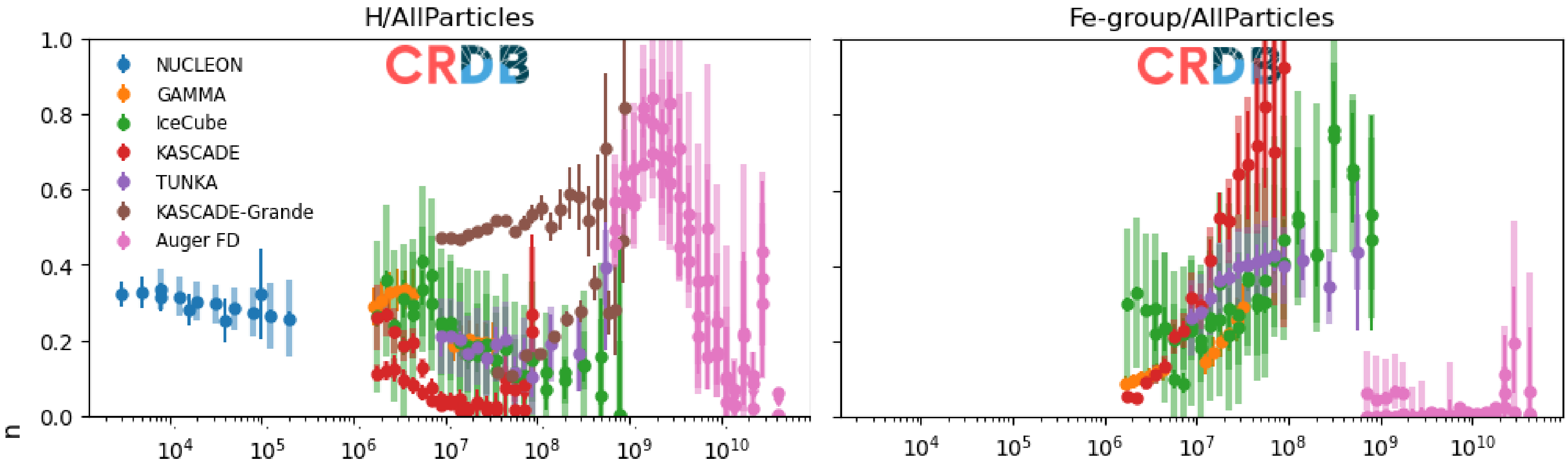


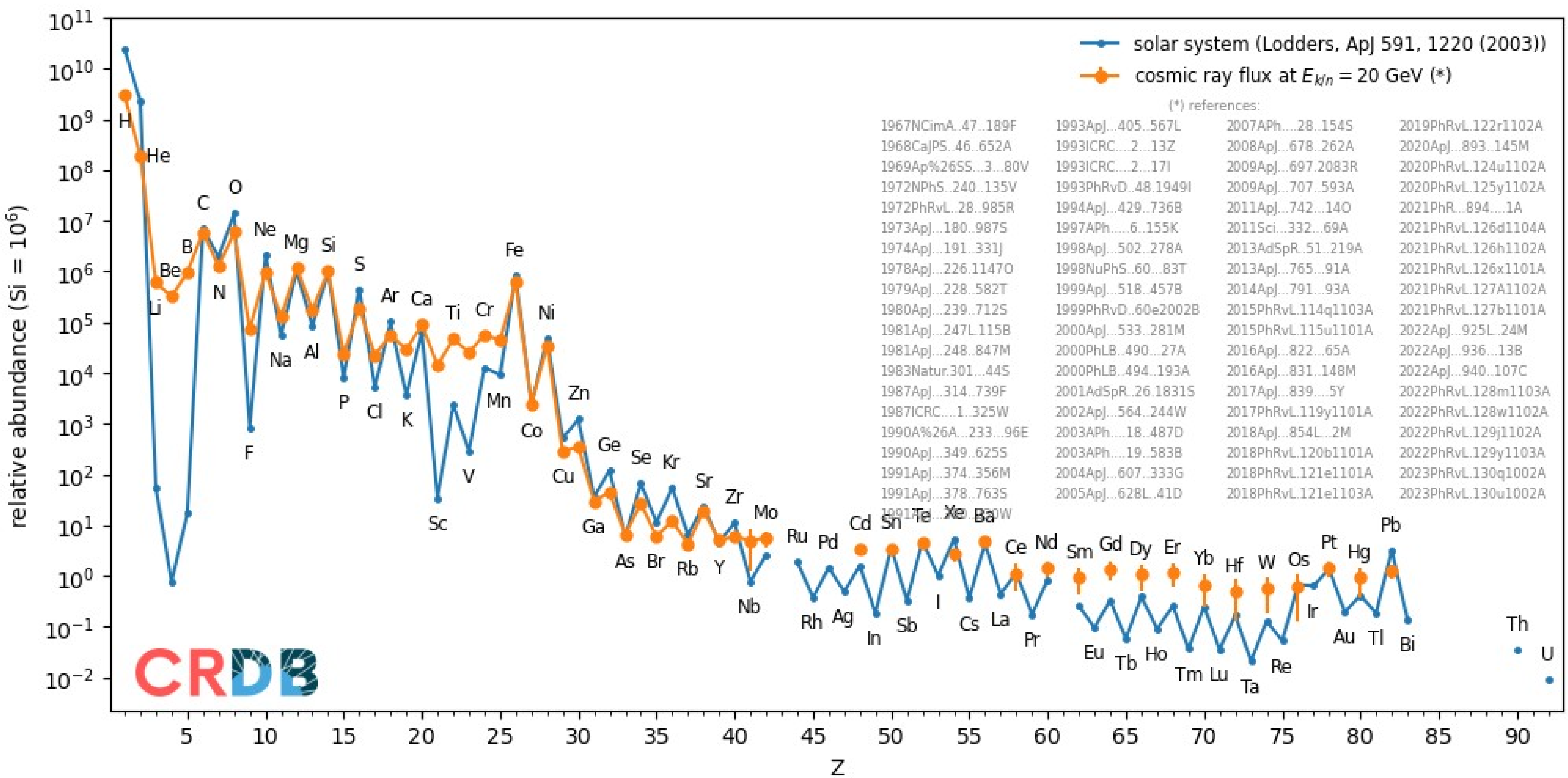


1) CRDB (https://lpsc.in2p3.fr/crdb)

DM et al. (2014, 2020, 2023)

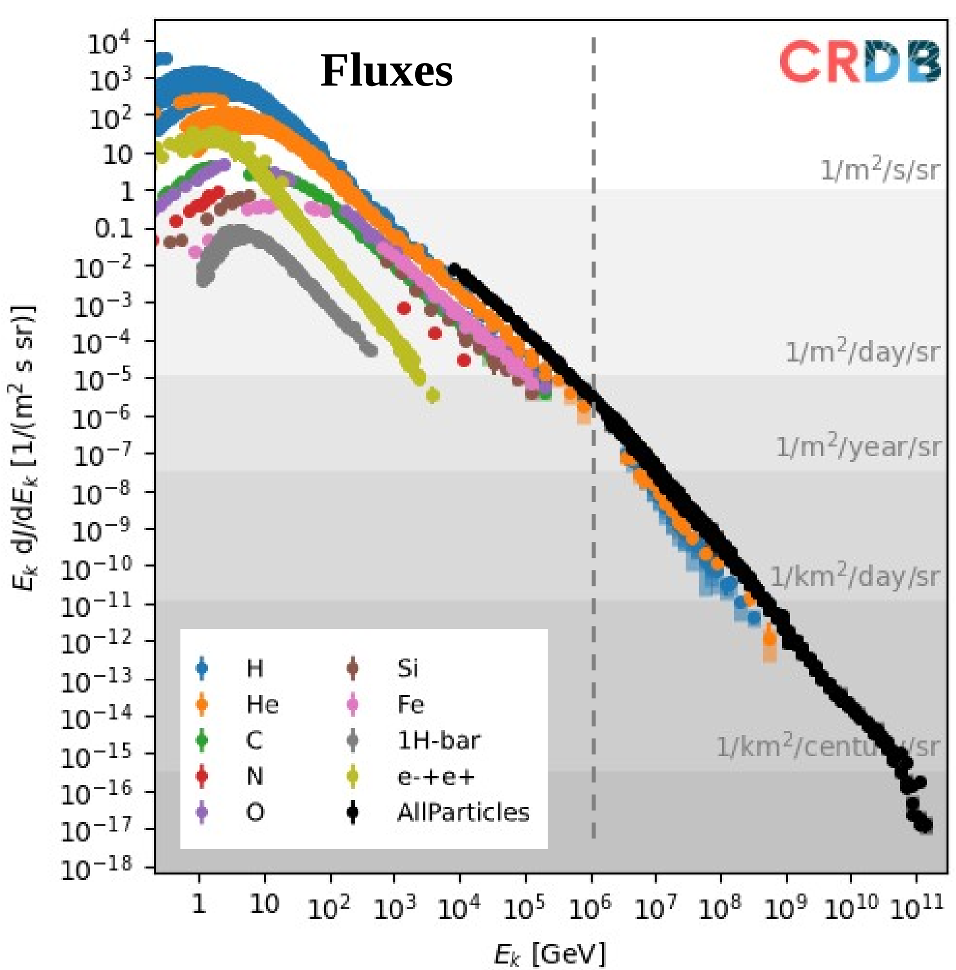
- Meta-data (refs, dates, infos)
- Plots (online+notebooks+pip-installable)





1) GCR data: challenges

Galactic CRs Extragalactic CRs



Astrophysical challenges

- Sources: origin, abundances, E_{max}
- Transport: turbulence, anisotropies ($\delta<10^{-3}$)
- Origin of quasi-universal power law ($E^{-2.8}$)

Primary Li in GCRs?
Inconsistency of modelled 2H, Li and F with data?
Residual grammage at source (gas cocoons) ?

Dark-matter related challenges

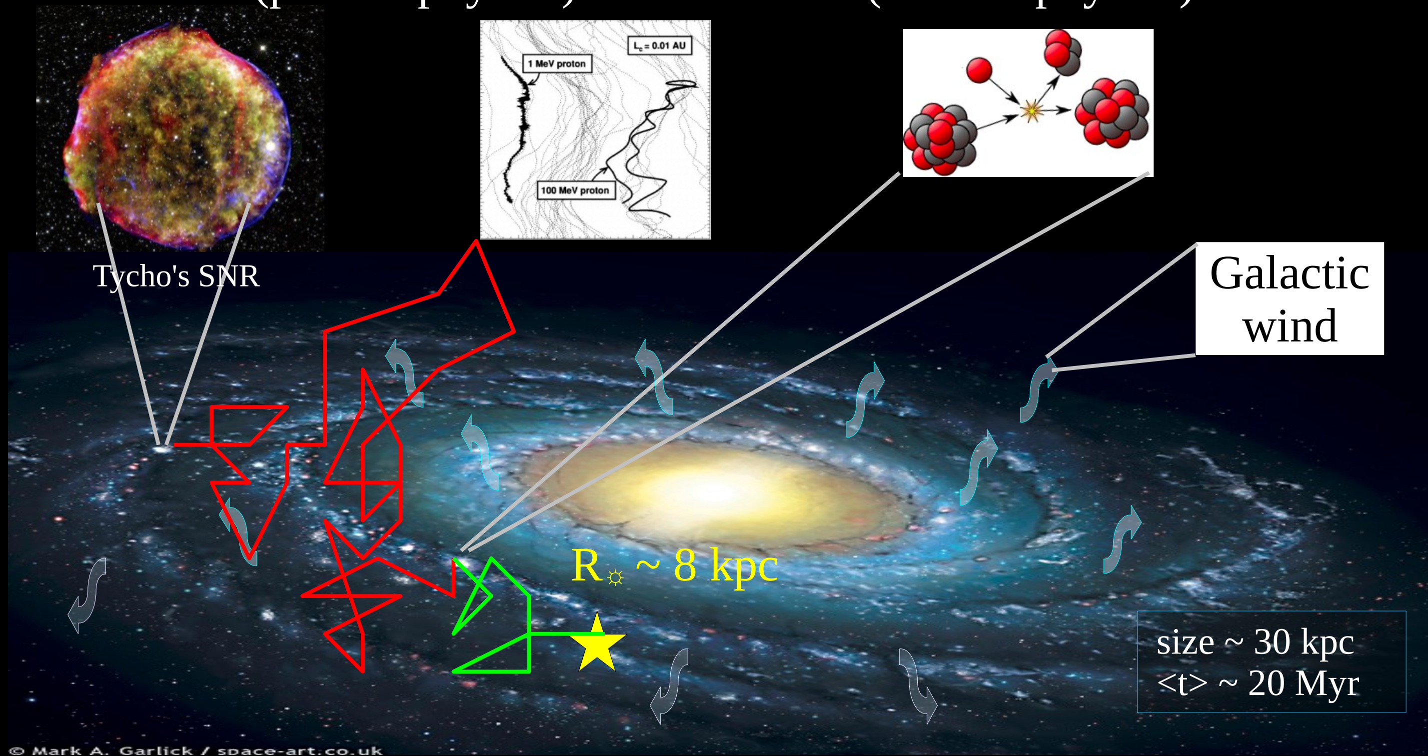
(in rare CRs = e^+, pbar, diffuse γ-rays)

- How well do we know astro. prod.?
- Are there primary sources?

Excess in pbar at 10 GeV/n?
Anti-helium in AMS-02 data?

1) GCR transport

(plasma physics) (nuclear physics)



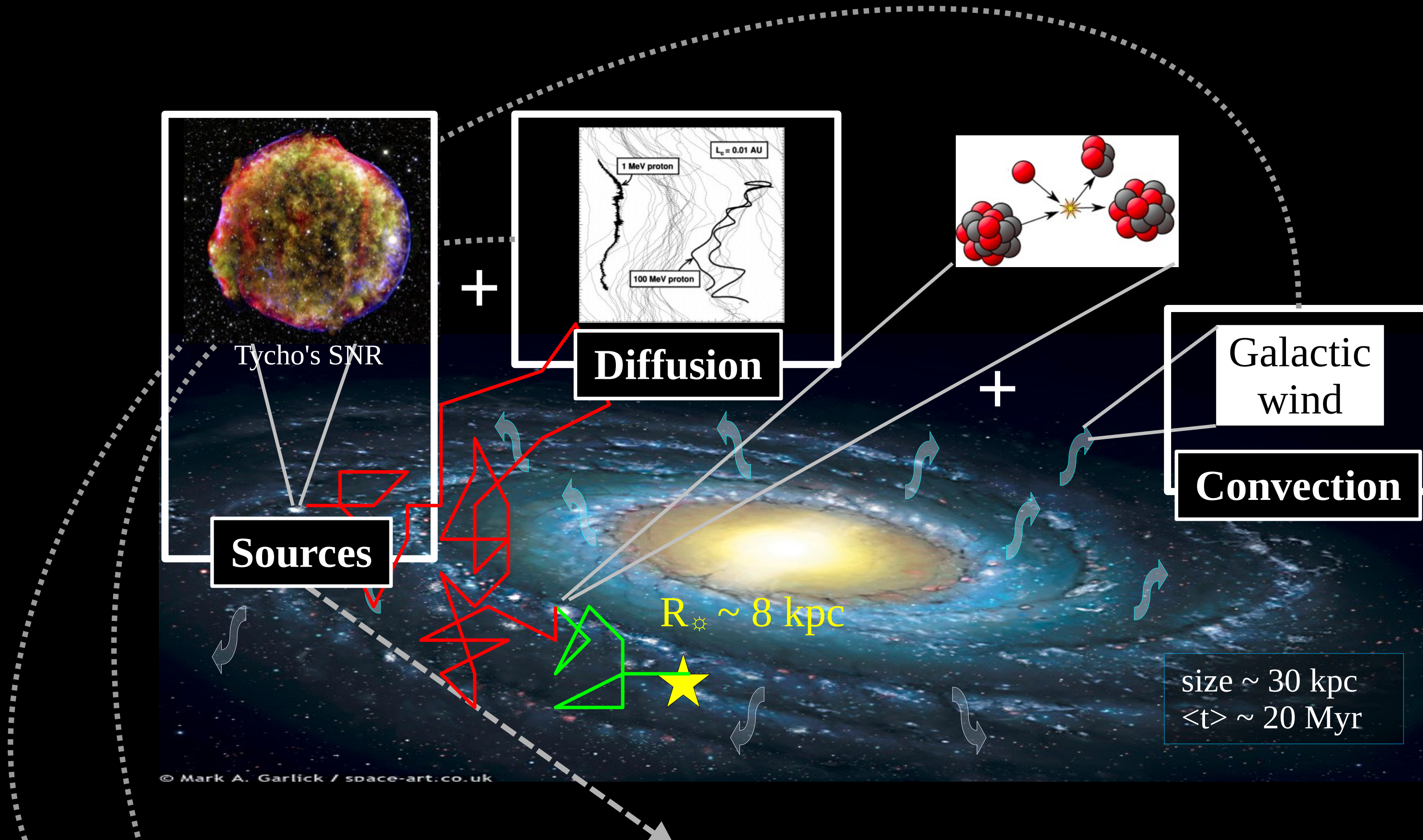
(astrophysics + particle physics)

→ Phenomenological transport models to interpret CR data (DRAGON, GALPROP, PICARD, *USINE*)

DM, CPC (2020)
https://dmaurin.gitlab.io/USINE/

N.B: microphysics-based approaches make progress!
(e.g., moving-mesh MHD code AREPO)

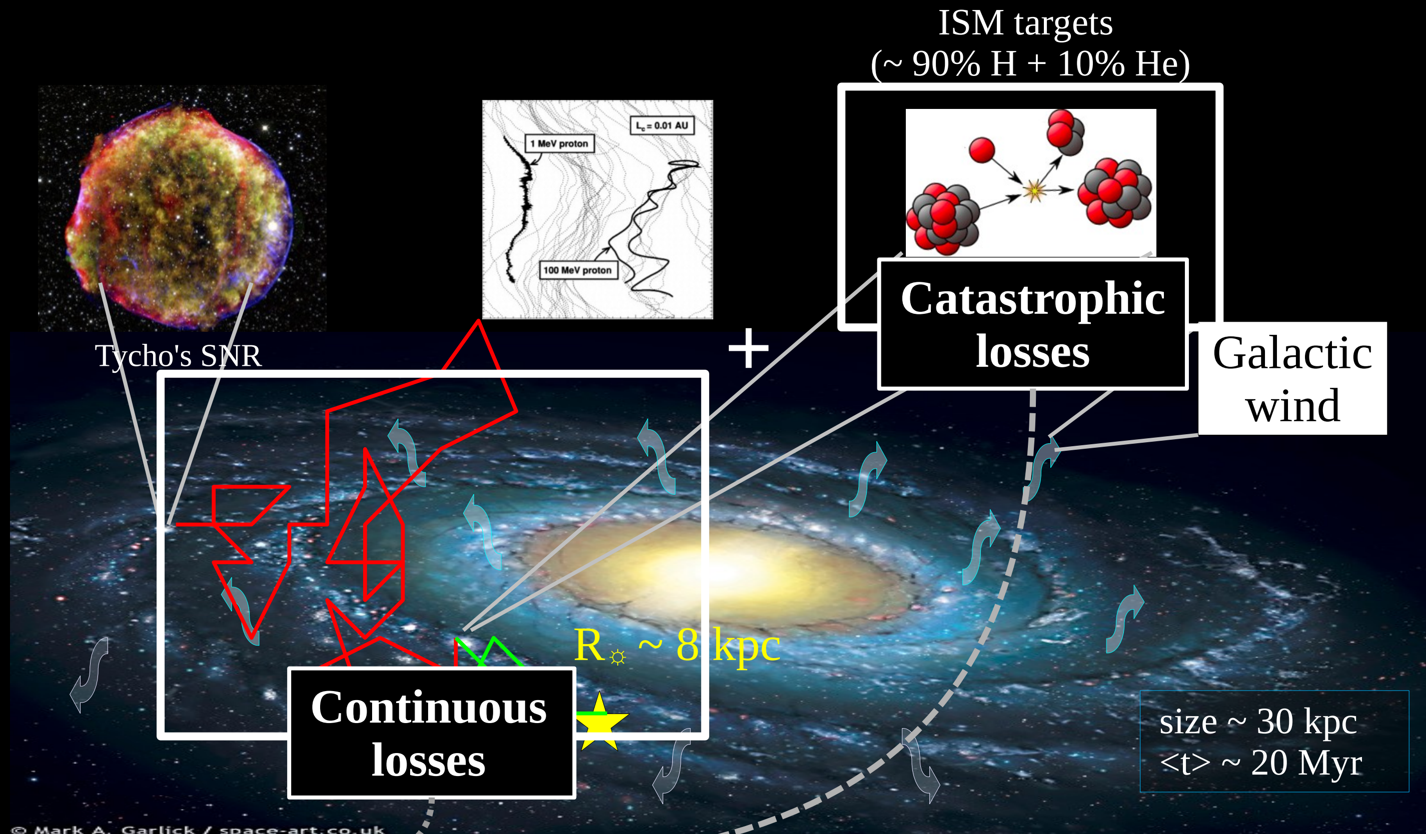
1) GCR transport: model parameters



$$\left(\mathcal{L}^{\vec{r}} + \mathcal{L}^{\rm E} + \mathcal{L}^{\rm sink}\right)\begin{bmatrix}N_n\\ N_{n-1}\\ \vdots\\ N_0\end{bmatrix} = \begin{bmatrix}Q^p_n\\ Q^p_{n-1}\\ \vdots\\ Q^p_0\end{bmatrix} + \sum_{\rm ISM} n_{\rm ISM}\, v \begin{bmatrix}0 & \dots & \dots & 0\\ \sigma^{\rm cumul}_{n\to(n-1)} & \ddots & & \vdots\\ \vdots & \ddots & \ddots & \vdots\\ \sigma^{\rm cumul}_{n\to 0} & \dots & \sigma^{\rm cumul}_{1\to 0} & 0\end{bmatrix}\begin{bmatrix}N_n\\ N_{n-1}\\ \vdots\\ N_0\end{bmatrix}$$

Source and transport parameters
= free parameters to determine from GCR data

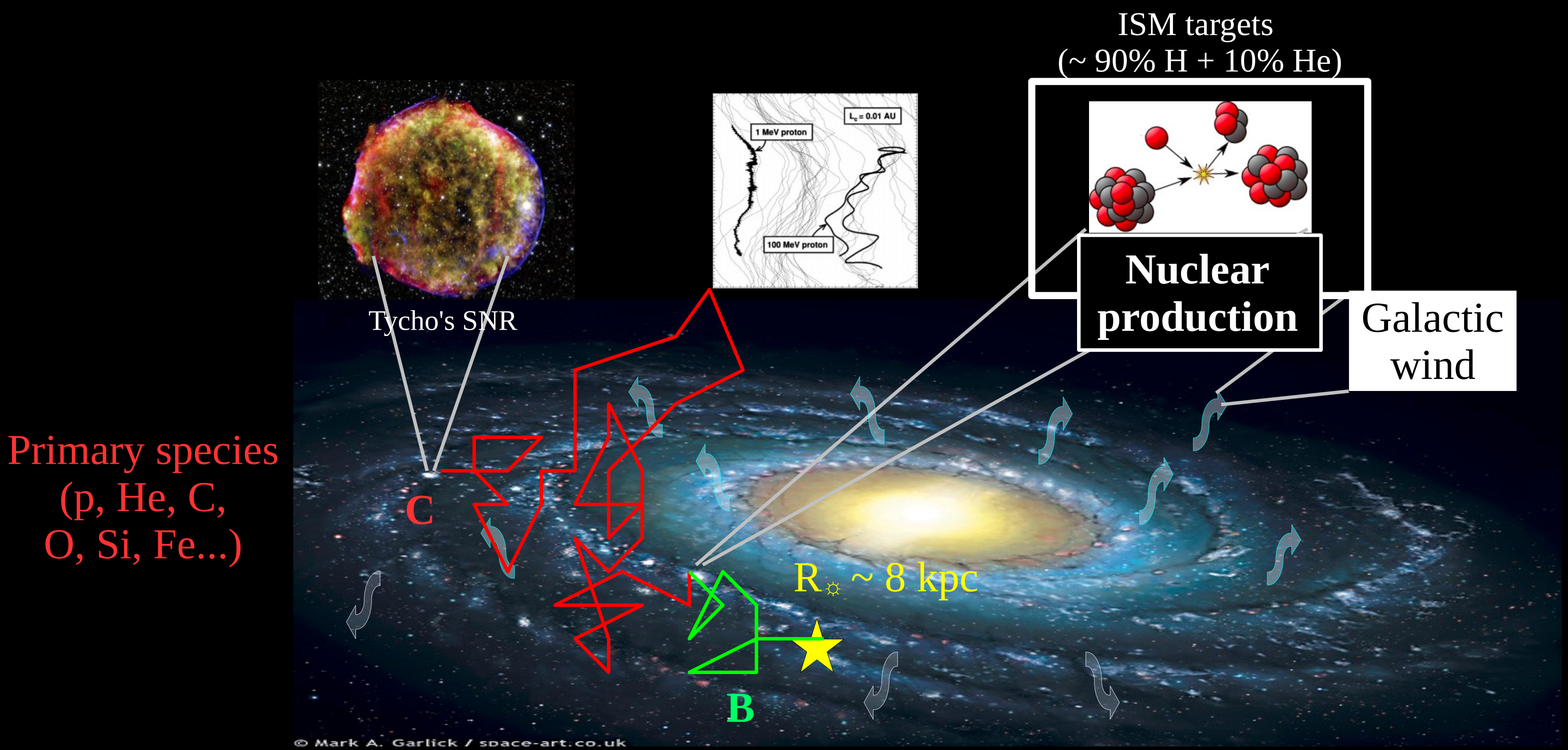
1) GCR transport: XS key ingredient



$$(\mathcal{L}^{\vec{r}} + \mathcal{L}^{\rm E} + \mathcal{L}^{\rm sink}) \begin{bmatrix} N_n \\ N_{n-1} \\ \vdots \\ N_0 \end{bmatrix} = \begin{bmatrix} Q^p_n \\ Q^p_{n-1} \\ \vdots \\ Q^p_0 \end{bmatrix} + \sum_{\rm ISM} n_{\rm ISM}\, v \begin{bmatrix} 0 & \dots & \dots & 0 \\ \sigma^{\rm cumul}_{n\to(n-1)} & \ddots & & \vdots \\ \vdots & \ddots & \ddots & \vdots \\ \sigma^{\rm cumul}_{n\to 0} & \dots & \sigma^{\rm cumul}_{1\to 0} & 0 \end{bmatrix} \begin{bmatrix} N_n \\ N_{n-1} \\ \vdots \\ N_0 \end{bmatrix}$$

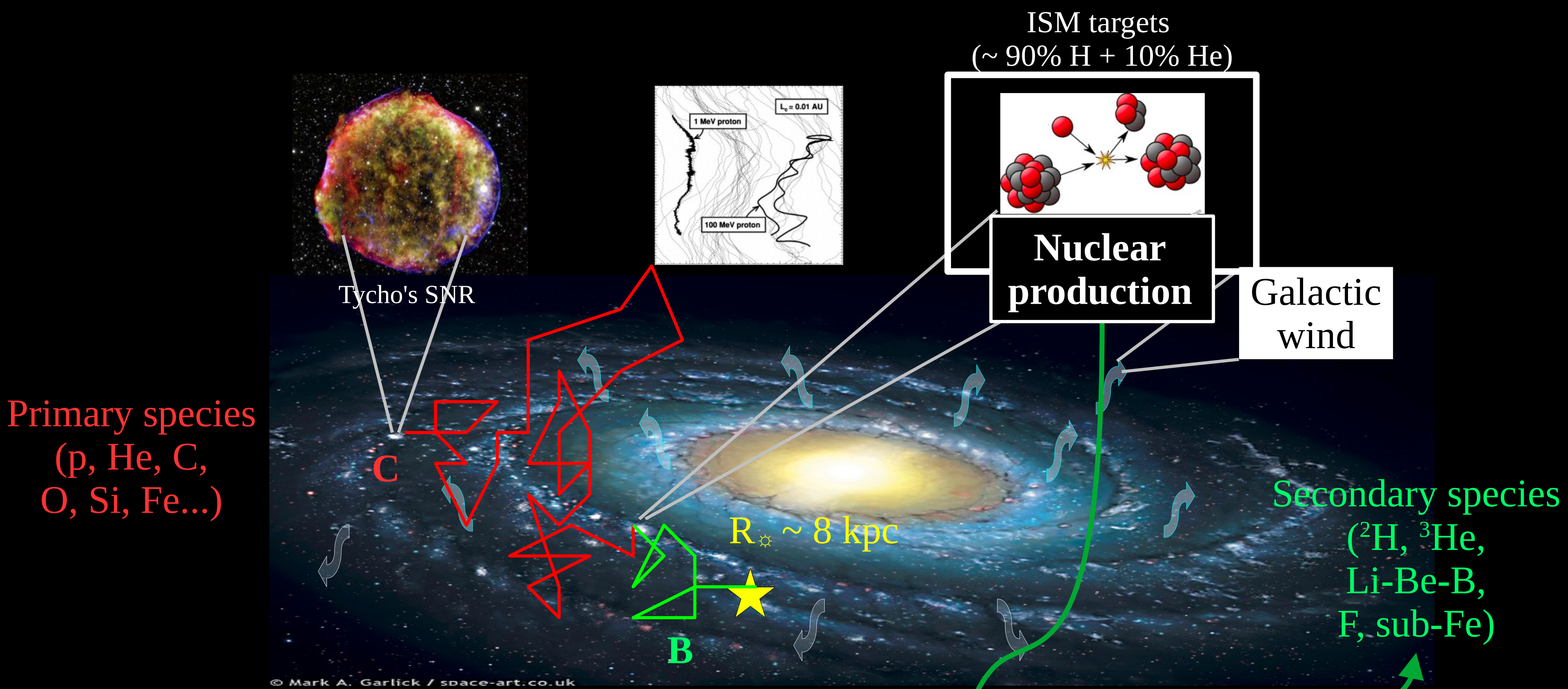
Continuous and **catastrophic losses**
= input ingredients of the GCR calculation

1) GCR transport: uncertainties from production XS



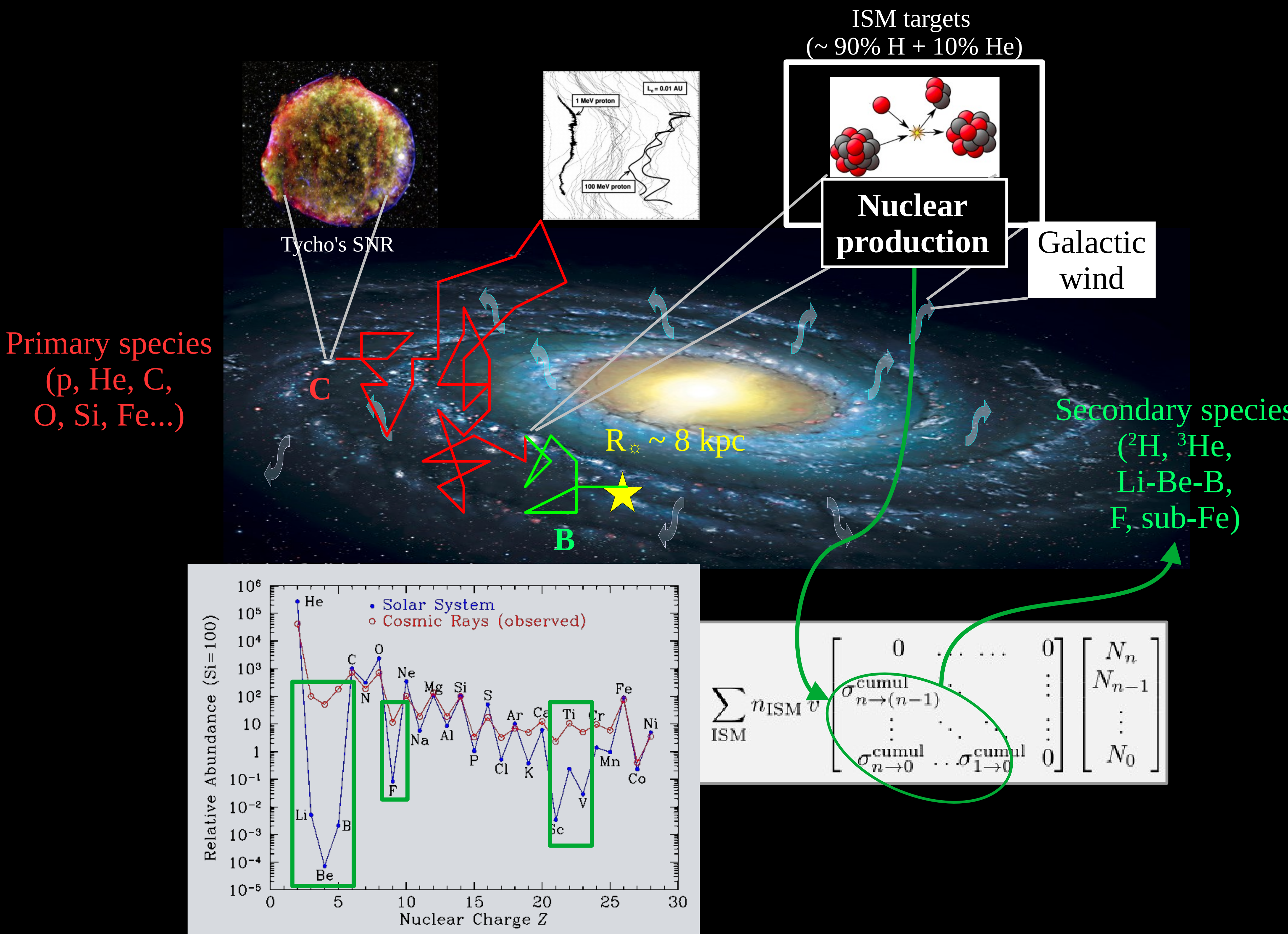
$$\left(\mathcal{L}^{\vec{r}} + \mathcal{L}^{\rm E} + \mathcal{L}^{\rm sink}\right) \begin{bmatrix} N_n \\ N_{n-1} \\ \vdots \\ N_0 \end{bmatrix} = \begin{bmatrix} Q^p_n \\ Q^p_{n-1} \\ \vdots \\ Q^p_0 \end{bmatrix} + \sum_{\rm ISM} n_{\rm ISM}\, v \begin{bmatrix} 0 & \dots & \dots & 0 \\ \sigma^{\rm cumul}_{n\to(n-1)} & \ddots & & \vdots \\ \vdots & \ddots & \ddots & \vdots \\ \sigma^{\rm cumul}_{n\to 0} & \dots & \sigma^{\rm cumul}_{1\to 0} & 0 \end{bmatrix} \begin{bmatrix} N_n \\ N_{n-1} \\ \vdots \\ N_0 \end{bmatrix}$$

1) GCR transport: uncertainties from production XS

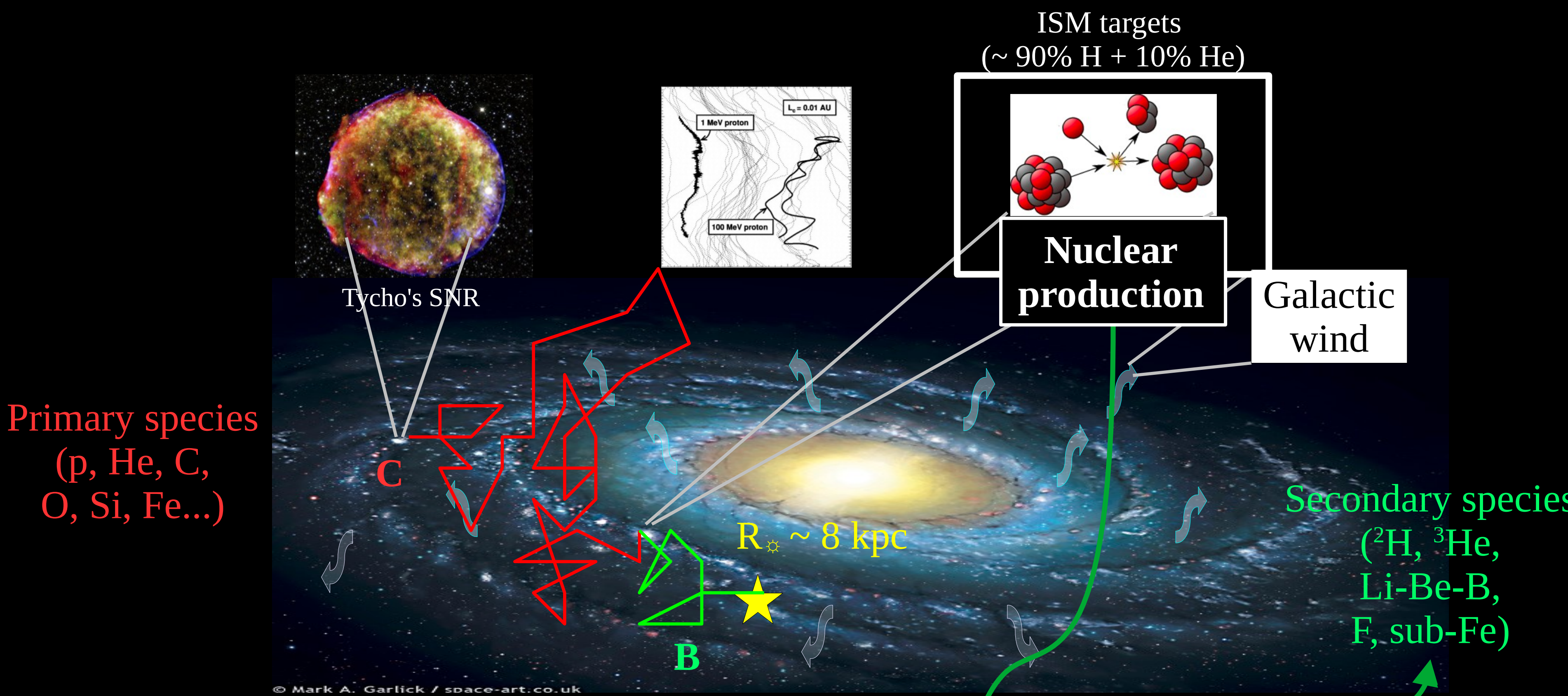


$$\left(\mathcal{L}^{\vec{r}} + \mathcal{L}^{\rm E} + \mathcal{L}^{\rm sink}\right) \begin{bmatrix} N_n \\ N_{n-1} \\ \vdots \\ N_0 \end{bmatrix} = \begin{bmatrix} Q^p_n \\ Q^p_{n-1} \\ \vdots \\ Q^p_0 \end{bmatrix} + \sum_{\rm ISM} n_{\rm ISM}\, v \begin{bmatrix} 0 & \dots & \dots & 0 \\ \sigma^{\rm cumul}_{n\to(n-1)} & \ddots & & \vdots \\ \vdots & \ddots & \ddots & \vdots \\ \sigma^{\rm cumul}_{n\to 0} & \dots & \sigma^{\rm cumul}_{1\to 0} & 0 \end{bmatrix} \begin{bmatrix} N_n \\ N_{n-1} \\ \vdots \\ N_0 \end{bmatrix}$$

1) GCR transport: uncertainties from production XS



1) GCR transport: uncertainties from production XS



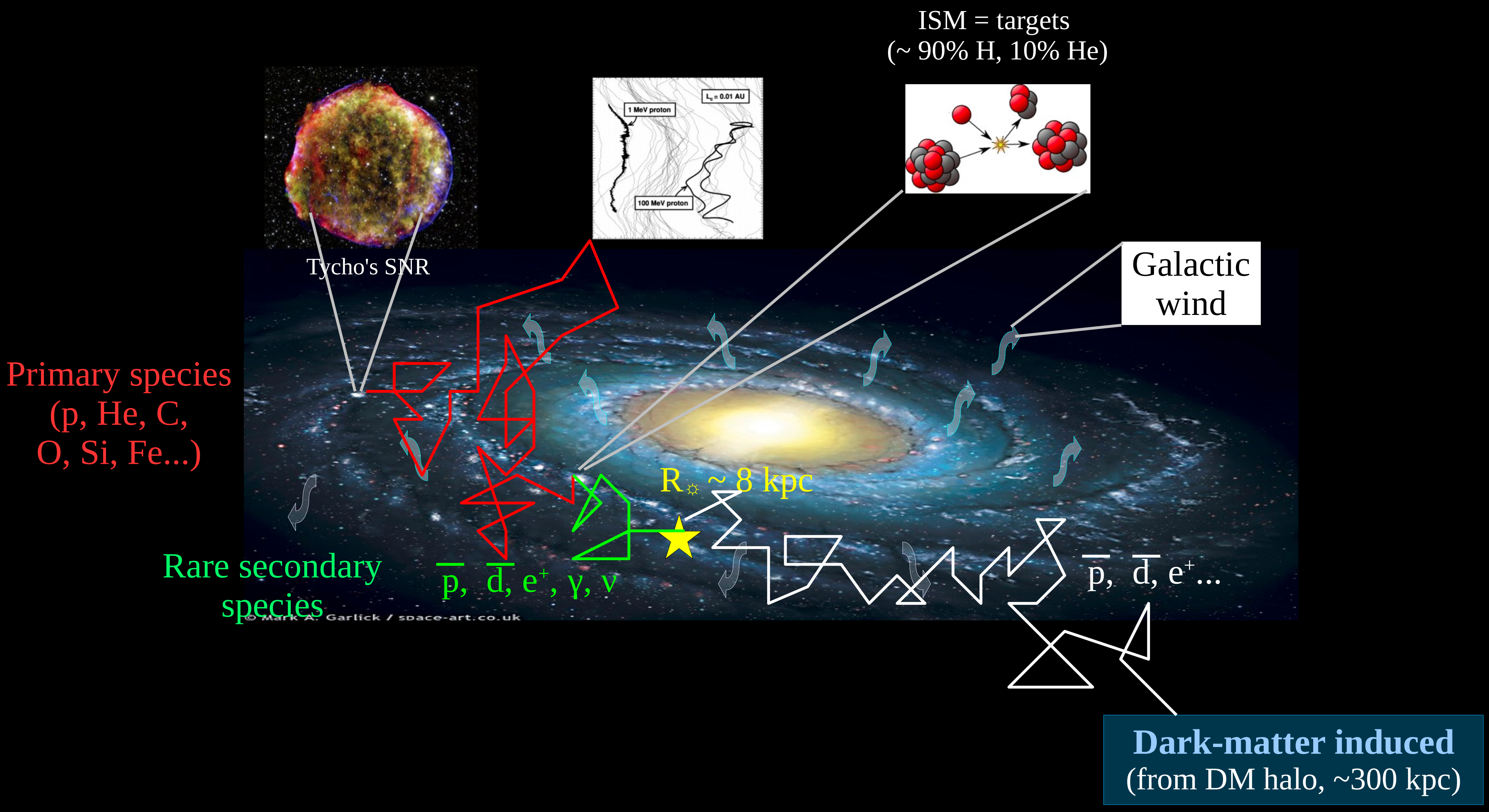
@HE

$$\left(\mathcal{L}^{\vec r} + \cancel{\mathcal{L}^{E}} + \cancel{\mathcal{L}^{\rm sink}}\right)\begin{bmatrix} N_n \\ N_{n-1} \\ \vdots \\ N_0 \end{bmatrix} = \begin{bmatrix} Q^p_n \\ Q^p_{n-1} \\ \vdots \\ Q^p_0 \end{bmatrix} + \sum_{\rm ISM} n_{\rm ISM}\, v \begin{bmatrix} 0 & \dots & \dots & 0 \\ \sigma^{\rm cumul}_{n\to(n-1)} & \ddots & & \vdots \\ \vdots & \ddots & \ddots & \vdots \\ \sigma^{\rm cumul}_{n\to 0} & \dots & \sigma^{\rm cumul}_{1\to 0} & 0 \end{bmatrix} \begin{bmatrix} N_n \\ N_{n-1} \\ \vdots \\ N_0 \end{bmatrix}$$

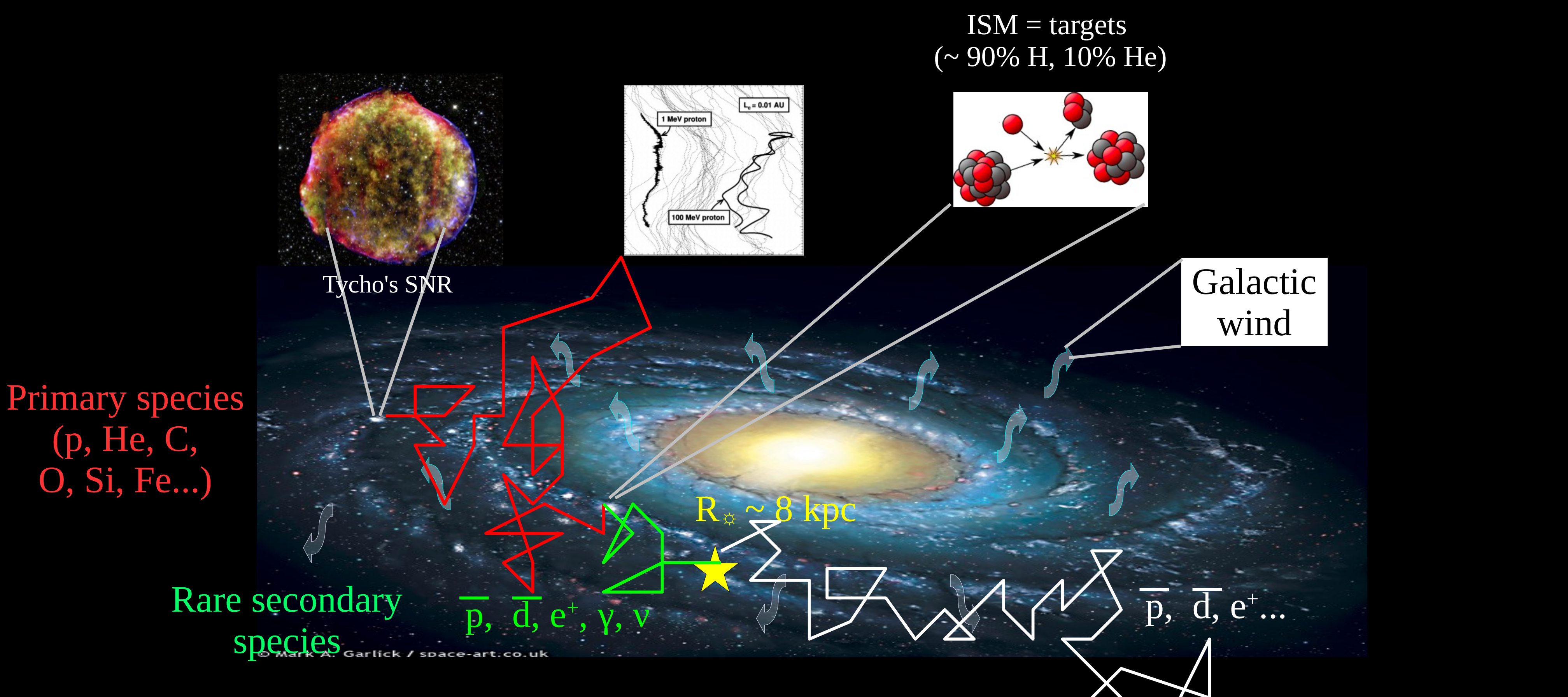
→ Sec./prim. (B/C, F/Si…) constrain transport parameters
[e.g. Weinrich et al., 2020; Ferronato Bueno et al., 2024]

Transport uncertainties dominated by production XS ones

2) Dark matter searches: uncertainties from XS



2) Dark matter searches: uncertainties from XS



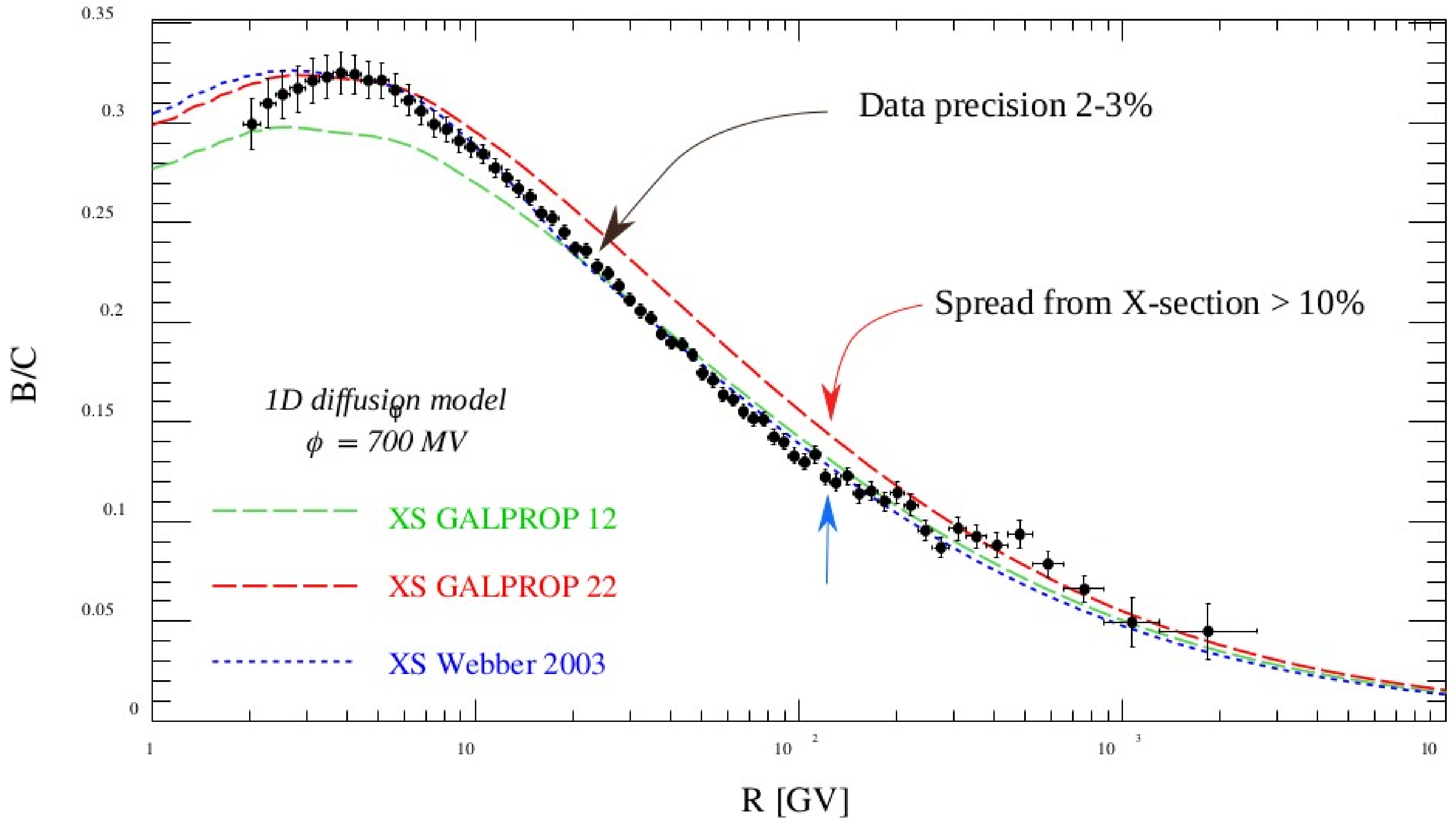
(1) Astro. background uncertainties from:
- → direct production XS
- → nuclear production XS (via transport parameters fixed from LiBeB/C)

(2) DM signal uncertainties from:
- → nuclear production XS (diffusive halo size L determined from $^{10}Be/^{9}Be$ data and XS)

2) XS uncertainties: illustration

Modelling (from XS) vs GCR uncertainties

[XS sets based on same nuclear data]



→ *AMS-02 high-precision cannot be fully exploited*

→ *DM discovery/constraints can be significantly improved with better XS data*

Which nuclear data to improve to model GCR at AMS-02 precision?
→ Motivation for ranking production XS

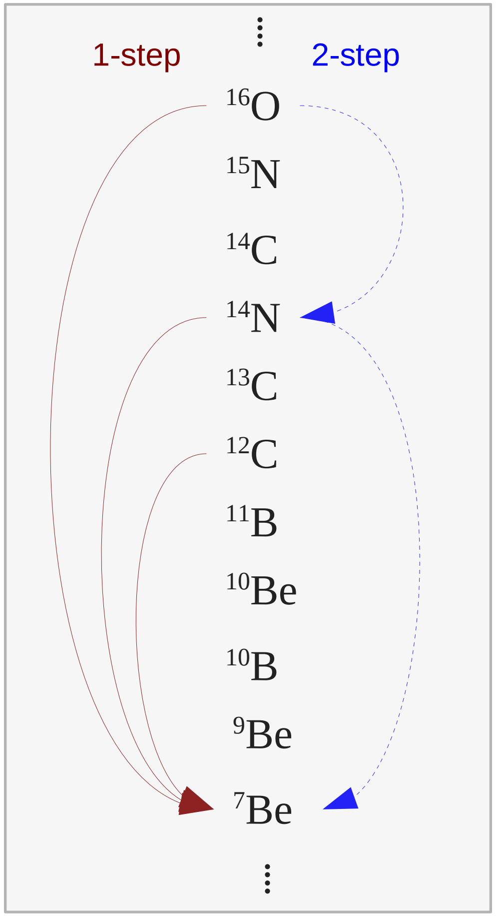
1) GCRs and production cross sections

2) Ranking of quantities of interest

3) Propagating XS uncertainties & forecasts

2) Ranking of production paths ($P^{1\ldots n\text{-step}}$ coefficients)

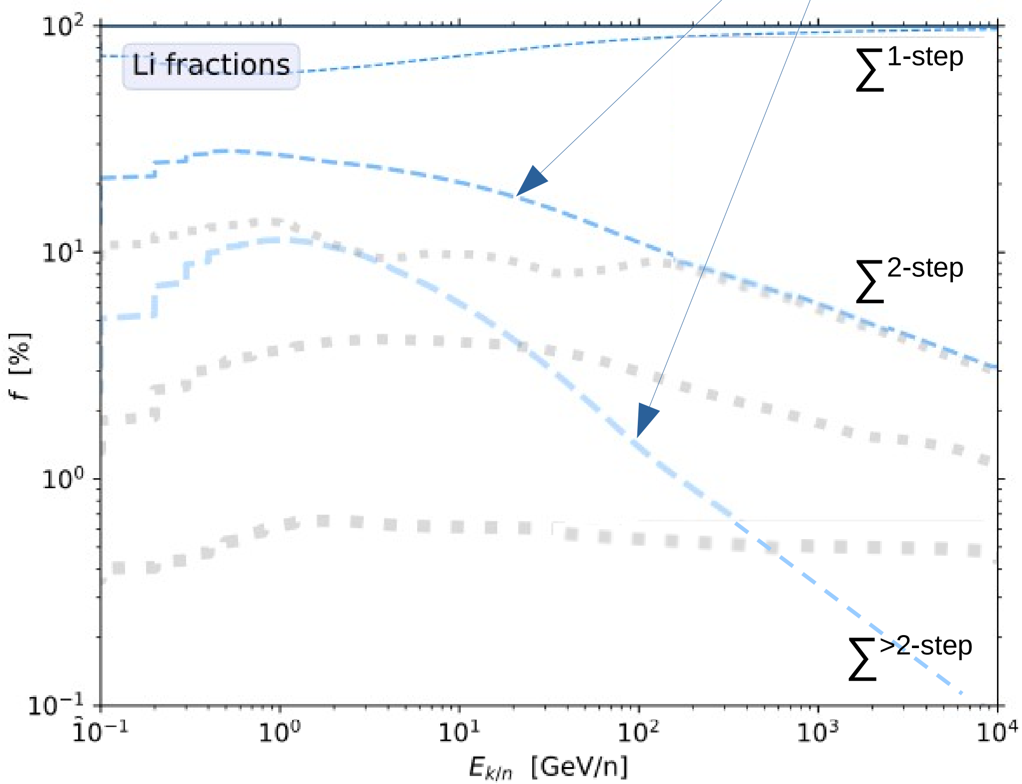
Qty / ranking	Definition	Property
Relative weight of a single production path (1-step or multi-step) linking CR i to j = *channels*	$\begin{cases} P_{ij}^{1-\mathrm{step}} \equiv \dfrac{\psi_{\mathrm{sec}}^{j,\,\sigma_{m\to n}^{\mathrm{cumul}}=0\ \forall(m,n)\neq(i,j)}}{\psi_{\mathrm{sec}}^{j,\,\mathrm{ref}}} \\ P_{ikj}^{2-\mathrm{step}} \equiv \dfrac{\psi_{\mathrm{sec}}^{j,\,\sigma_{m\to n}^{\mathrm{cumul}}=0\ \forall(m,n)\neq\{(i,k),(k,j)\}}}{\psi_{\mathrm{sec}}^{j,\,\mathrm{ref}}} \\ P_{ikpj}^{3-\mathrm{step}} \equiv \ldots \\ \ldots \end{cases}$ $P_j^{>2-\mathrm{step}} \equiv 1 - \sum_i^{i>j}\left(P_{ij}^{1-\mathrm{step}} + \sum_k^{i>k>j} P_{ikj}^{2-\mathrm{step}}\right)$	$\sum_i^{i>j}\left(P_{ij}^{1-\mathrm{step}} + \sum_k^{i>k>j}\left(P_{ikj}^{2-\mathrm{step}} + \sum_p^{i>k>p>j}(\ldots)\right)\right) = 1$ ⇒ *Uniqueness and completeness of paths* $\dfrac{P_{i\ldots\ldots j}^{(n+1)-\mathrm{step}}}{P_{i\ldots\ j}^{n-\mathrm{step}}} \propto R^{-\delta}$ (diffusion coeff. slope $\delta \approx 0.5$)

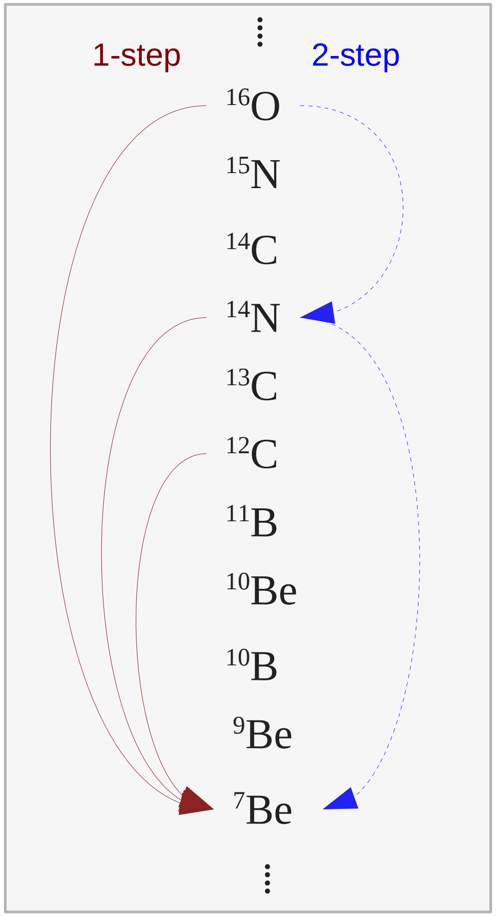


2) Ranking of production paths ($P^{1\ldots n\text{-step}}$ coefficients)

Qty / ranking	Definition	Property
Relative weight of a single production path (1-step or multi-step) linking CR i to j = *channels*	$P^{1-\rm step}_{ij} \equiv \frac{\psi_{\rm sec}^{j,\,\sigma^{\rm cumul}_{m\to n}=0\ \forall(m,n)\neq(i,j)}}{\psi_{\rm sec}^{j,\,\rm ref}}$ $P^{2-\rm step}_{ikj} \equiv \frac{\psi_{\rm sec}^{j,\,\sigma^{\rm cumul}_{m\to n}=0\ \forall(m,n)\neq\{(i,k),(k,j)\}}}{\psi_{\rm sec}^{j,\,\rm ref}}$ $P^{3-\rm step}_{ikpj} \equiv \ldots$ $\ldots$	$\sum_i^{i>j}\left(P^{1-\rm step}_{ij} + \sum_k^{i>k>j}\left(P^{2-\rm step}_{ikj} + \sum_p^{i>k>p>j}(\ldots)\right)\right) = 1$ ⇒ *Uniqueness and completeness of paths* $\frac{P^{(n+1)-\rm step}_{i......j}}{P^{n-\rm step}_{i...\,j}} \propto R^{-\delta}$ (diffusion coeff. slope $\delta \approx 0.5$)

$$P^{>2-\rm step}_{j} \equiv 1 - \sum_i^{i>j}\left(P^{1-\rm step}_{ij} + \sum_k^{i>k>j} P^{2-\rm step}_{ikj}\right)$$



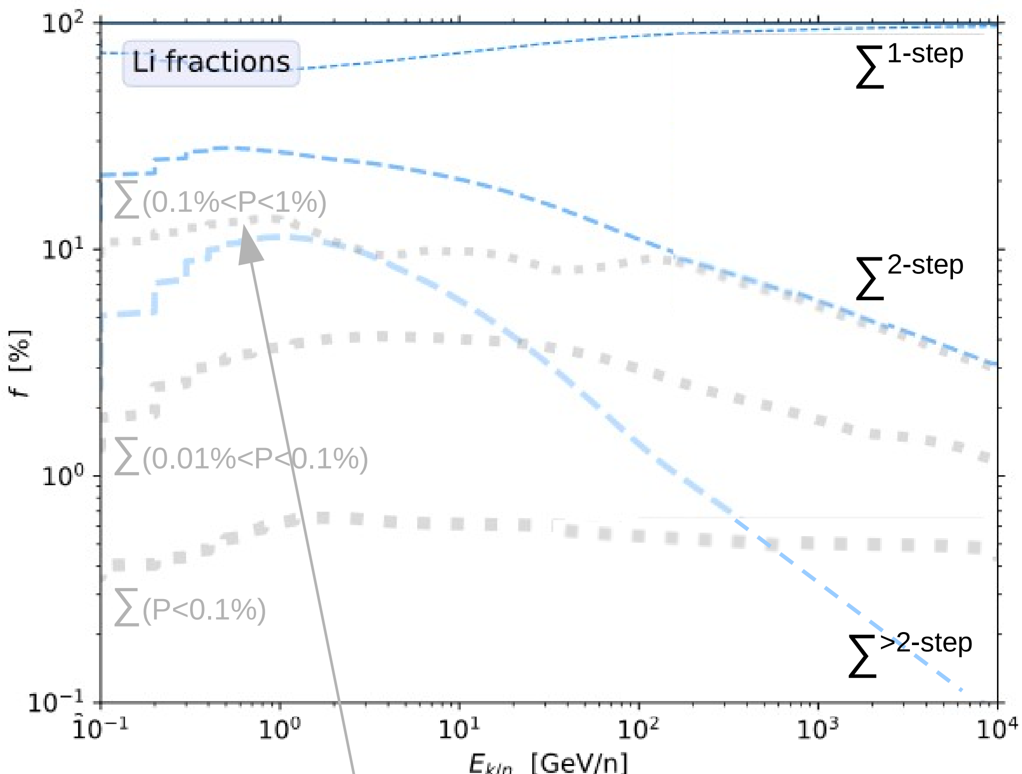


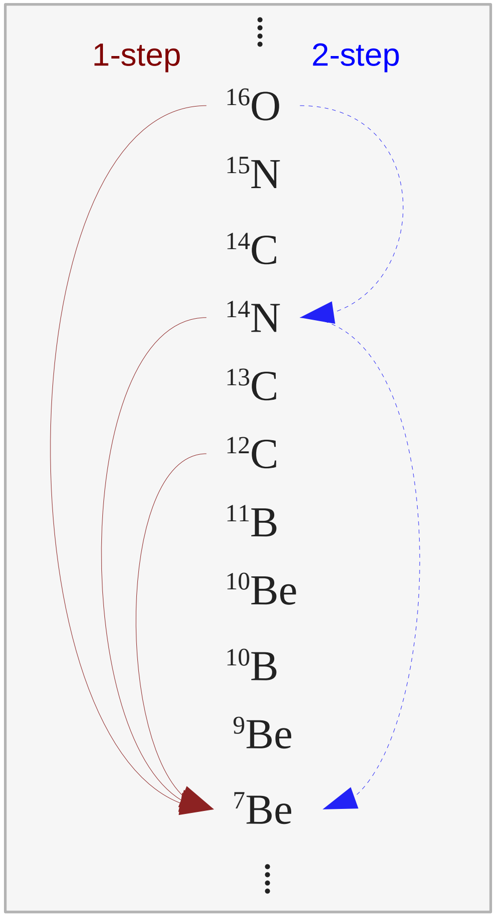
→ Multi-step reactions contribute to up to 40% of Li in GCRs
→ Impact of **n**-step reactions go as $R^{(n-1)/2}$ (peaks at a few GeV/n)

2) Ranking of production paths ($P^{1\ldots n\text{-step}}$ coefficients)

Qty / ranking	Definition	Property
Relative weight of a single production path (1-step or multi-step) linking CR i to j = *channels*	$P_{ij}^{1-\text{step}} \equiv \dfrac{\psi_{\text{sec}}^{j,\,\sigma^{\text{cumul}}_{m\to n}=0\ \forall(m,n)\neq(i,j)}}{\psi_{\text{sec}}^{j,\,\text{ref}}}$ $P_{ikj}^{2-\text{step}} \equiv \dfrac{\psi_{\text{sec}}^{j,\,\sigma^{\text{cumul}}_{m\to n}=0\ \forall(m,n)\notin\{(i,k),(k,j)\}}}{\psi_{\text{sec}}^{j,\,\text{ref}}}$ $P_{ikpj}^{3-\text{step}} \equiv \ldots$ $\ldots$	$\sum_i^{i>j}\left(P_{ij}^{1-\text{step}} + \sum_k^{i>k>j}\left(P_{ikj}^{2-\text{step}} + \sum_p^{i>k>p>j}(\ldots)\right)\right) = 1$ ⇒ *Uniqueness and completeness of paths* $\dfrac{P_{i\ldots\ldots j}^{(n+1)-\text{step}}}{P_{i\ldots\ j}^{n-\text{step}}} \propto R^{-\delta}$ (diffusion coeff. slope $\delta \approx 0.5$)

$$P_j^{>2-\text{step}} \equiv 1 - \sum_i^{i>j}\left(P_{ij}^{1-\text{step}} + \sum_k^{i>k>j} P_{ikj}^{2-\text{step}}\right)$$





→ Channels contributing <1% individually amount to up to 10% collectively

2) Ranking of production XS (f_{abc} coefficients)

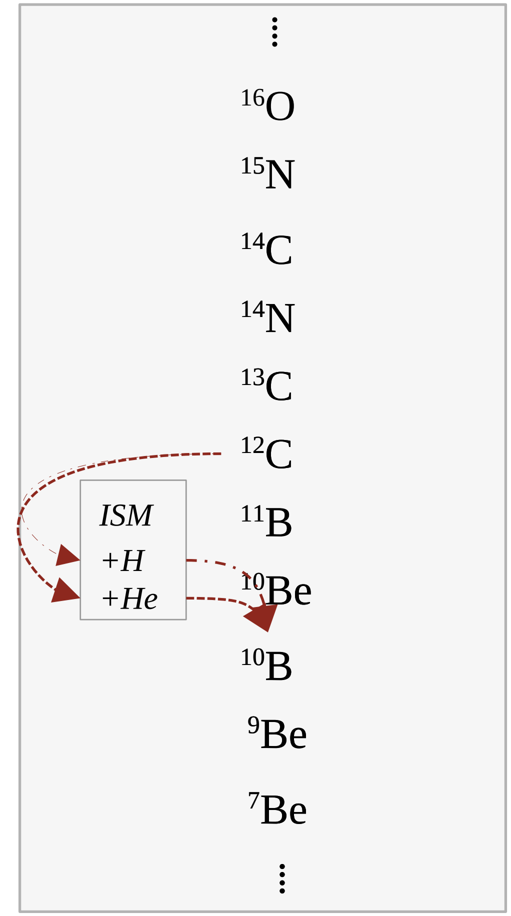
Qty / ranking	Definition	Property
Impact of individual XS on CR flux = *flux impact*	$f^j_{abc} \equiv \frac{\psi^{j,\,\mathrm{ref}}_{\mathrm{sec}} - \psi^{j,\,\sigma_{a+b\to c}=0}_{\mathrm{sec}}}{\psi^{j,\,\mathrm{ref}}_{\mathrm{sec}}}$	$\sum_{\forall(a,b,c)} f^j_{abc} \gtrsim 1$

But… each coeff. is not a fraction: double counting!

One to one correspondence between f_{abc} and $\sigma_{a+b\to c}$

$f_{12C\ H\ 10Be}$

$f_{12C\ He\ 10Be}$



2) Ranking of production XS (f_{abc} coefficients)

Qty / ranking	Definition	Property
Impact of individual XS on CR flux = *flux impact*	$f^j_{abc} \equiv \frac{\psi^{j,\,\mathrm{ref}}_{\mathrm{sec}} - \psi^{j,\,\sigma_{a+b\to c}=0}_{\mathrm{sec}}}{\psi^{j,\,\mathrm{ref}}_{\mathrm{sec}}}$	$\sum_{\forall(a,b,c)} f^j_{abc} \gtrsim 1$

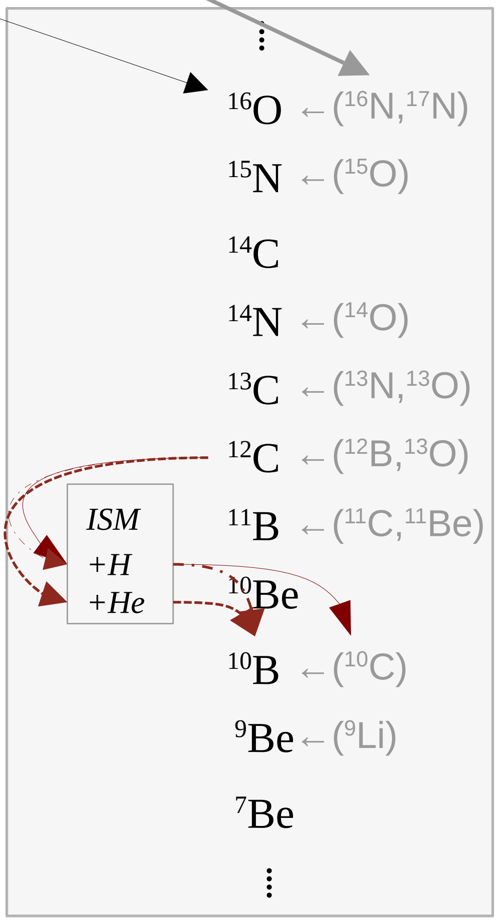
But… each coeff. is not a fraction: double counting!

→ Network of ~1000 reactions (up to ^{56}Fe) to rank!

[N.B.: CR fluxes use cumulative XS (account for short-lived nuclei)]

$$\sigma^{\mathrm{cumul}}_{a+b\to c} = \sigma_{a+b\to c} + \sum_g \mathcal{B}r_g \cdot \sigma_{a+b\to g}$$

Ghosts (=short-lived) nuclei



One to one correspondence between f_{abc} and $\sigma_{a+b\to c}$

$f_{12C\ H\ 10Be}$

$f_{12C\ He\ 10Be}$

$f_{12C\ H\ 10C}$

2) Ranking of production XS (f_{abc} coefficients)

Qty / ranking	Definition	Property
Impact of individual XS on CR flux = *flux impact*	$f^j_{abc} \equiv \frac{\psi^{j,\,\rm ref}_{\rm sec} - \psi^{j,\,\sigma_{a+b\to c}=0}_{\rm sec}}{\psi^{j,\,\rm ref}_{\rm sec}}$	$\sum_{\forall(a,b,c)} f^j_{abc} \gtrsim 1$

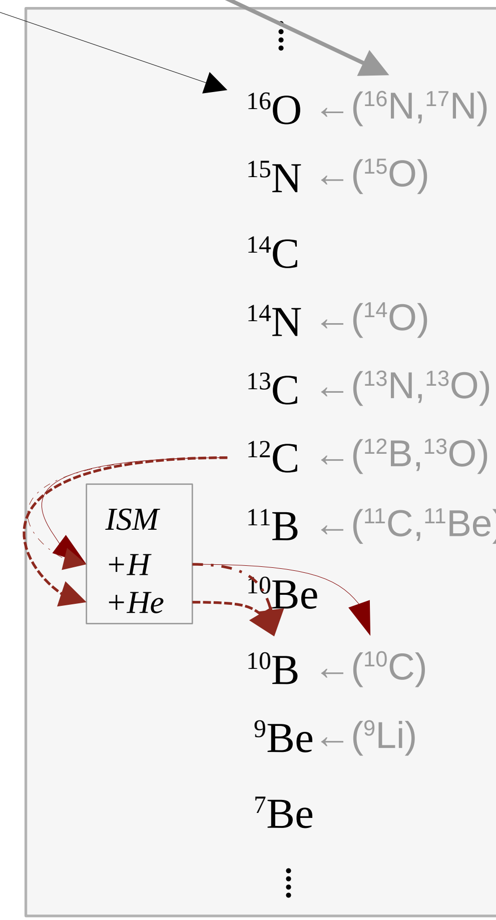
But… each coeff. is not a fraction: double counting!

→ Network of ~1000 reactions (up to ^{56}Fe) to rank!

[N.B.: CR fluxes use cumulative XS (account for short-lived nuclei)]

$$\sigma^{\rm cumul}_{a+b\to c} = \sigma_{a+b\to c} + \sum_g \mathcal{B}r_g \cdot \sigma_{a+b\to g}$$

Ghosts (=short-lived) nuclei



	Flux impact f_{abc}	σ (mb)	
Reaction	**Mean**	[Min,Max]	Data
^{16}O + H → ^{6}Li	**15.2**	[13.0, 18.4]	√
^{12}C + H → ^{6}Li	**12.5**	[14.0, 15.4]	√
^{12}C + H → ^{7}Li	**9.93**	[11.9, 12.6]	√
^{16}O + H → ^{7}Li	**9.74**	[10.7, 11.2]	√
^{11}B + H → ^{7}Li	**2.92**	[21.5, 21.5]	√
^{16}O + He → ^{6}Li	**2.86**	[20.6, 31.8]	
^{12}C + He → ^{6}Li	**2.14**	[21.6, 23.7]	
^{7}Li + H → ^{6}Li	**2.11**	[31.5, 31.5]	√
^{13}C + H → ^{7}Li	**2.05**	22.1	
^{56}Fe + H → ^{7}Li	**2.03**	[23.0, 23.0]	√
^{15}N + H → ^{7}Li	**1.95**	18.6	√
^{16}O + H → ^{15}N	**1.88**	34.3	√
^{16}O + He → ^{7}Li	**1.82**	[17.8, 18.6]	
^{56}Fe + H → ^{6}Li	**1.74**	[17.8, 22.5]	√
^{12}C + He → ^{7}Li	**1.71**	[18.4, 19.4]	

…

Ranking
- Top 10 reacs ~ 80%
- Next 100 ~ 15%
- All the rest ~ 5%

About the nuclear data
- No data for many reacs
- Many with 1 or 2 pts
- Very partial E coverage
- Inconsistent data
- …

One to one correspondence between f_{abc} and $\sigma_{a+b\to c}$

$f_{12C\ H\ 10Be}$

$f_{12C\ He\ 10Be}$

$f_{12C\ H\ 10C}$

→ We have ranked the reactions, but when to stop in the list?

1) GCRs and production cross sections

2) Ranking of quantities of interest

3) Propagating XS uncertainties & forecasts

N.B.: f_{abc} coeff. link XS uncertainties to modelled flux uncertainties

3) Error on flux: qualitative improvement

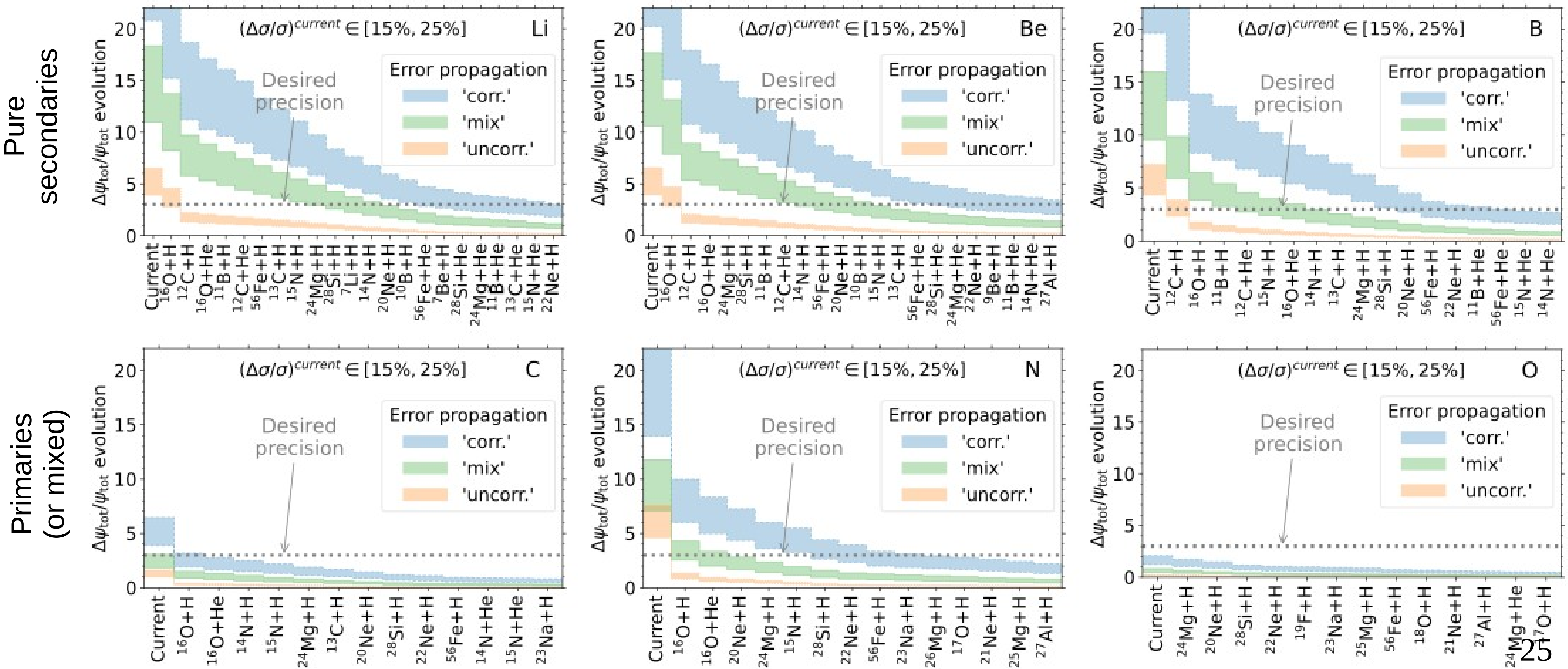
Assuming that in a+b all c measured perfectly → **estimate improvement on flux modelling precision**

Assumption on existing or future XS uncertainties	Error propagation formula on propagated flux
Fully correlated = similar bias on all XS (*over pessimistic for current XS*)	$\left(\frac{\Delta\psi_{\rm tot}}{\psi_{\rm tot}}\right)^{\rm corr} \approx f_{\rm sec} \sum_{a,b,c} f_{abc} \frac{\Delta\sigma_{a+b\to c}}{\sigma_{a+b\to c}}$
Fully uncorrelated = all XS data independent (*over optimistic for current XS*)	$\left(\frac{\Delta\psi_{\rm tot}}{\psi_{\rm tot}}\right)^{\rm uncorr} \approx f_{\rm sec} \sqrt{\sum_{a,b,c} \left(f_{abc} \frac{\Delta\sigma_{a+b\to c}}{\sigma_{a+b\to c}}\right)^2}$
Partially correlated = same bias for all XS of any given proj. (*most likely for current XS*)	$\left(\frac{\Delta\psi_{\rm tot}}{\psi_{\rm tot}}\right)^{\rm mix} \approx f_{\rm sec} \sum_{a} \sqrt{\sum_{b,c} \left(f_{abc} \frac{\Delta\sigma_{a+b\to c}}{\sigma_{a+b\to c}}\right)^2}$

3) Error on flux: qualitative improvement

Assuming that in a+b all c measured perfectly → **estimate improvement on flux modelling precision**

Assumption on existing or future XS uncertainties	Error propagation formula on propagated flux
Fully correlated = similar bias on all XS (*over pessimistic for current XS*)	$\left(\frac{\Delta\psi_{\rm tot}}{\psi_{\rm tot}}\right)^{\rm corr} \approx f_{\rm sec} \sum_{a,b,c} f_{abc} \frac{\Delta\sigma_{a+b\to c}}{\sigma_{a+b\to c}}$
Fully uncorrelated = all XS data independent (*over optimistic for current XS*)	$\left(\frac{\Delta\psi_{\rm tot}}{\psi_{\rm tot}}\right)^{\rm uncorr} \approx f_{\rm sec} \sqrt{\sum_{a,b,c} \left(f_{abc} \frac{\Delta\sigma_{a+b\to c}}{\sigma_{a+b\to c}}\right)^2}$
Partially correlated = same bias for all XS of any given proj. (*most likely for current XS*)	$\left(\frac{\Delta\psi_{\rm tot}}{\psi_{\rm tot}}\right)^{\rm mix} \approx f_{\rm sec} \sum_{a} \sqrt{\sum_{b,c} \left(f_{abc} \frac{\Delta\sigma_{a+b\to c}}{\sigma_{a+b\to c}}\right)^2}$



3) Error on flux: quantitative improvement

Assumption on existing or future XS uncertainties	Error propagation formula on propagated flux
Fragments multinomially distributed = all fragments of interaction measured in exp. *(precision better than ξ on $(\Delta\psi_{\rm tot}/\psi_{\rm tot})$ for minimal number of interactions $N_{\rm tot}=\sum_{a,b}N_{ab}$ if each N_{ab} ensures $N_{ab}\geq(f^2_{\rm sec}/\xi^2)\times C_{ab}\times\sum_{a,b}C_{ab}$*	$\left(\frac{\Delta\psi_{\rm tot}}{\psi_{\rm tot}}\right)^{\rm multi}\approx f_{\rm sec}\sqrt{\sum_{a,b}\frac{1}{N_{ab}}C^2_{ab}}$ with $C^2_{ab}\equiv\sum_c f^2_{abc}\frac{\sigma^{\rm inel}_{a+b}}{\sigma_{a+b\to c}}$

Even better...
→ forecast for # of reacs (beam time calc.) to reach 3% precision on modelled flux (to be on par with AMS-02)

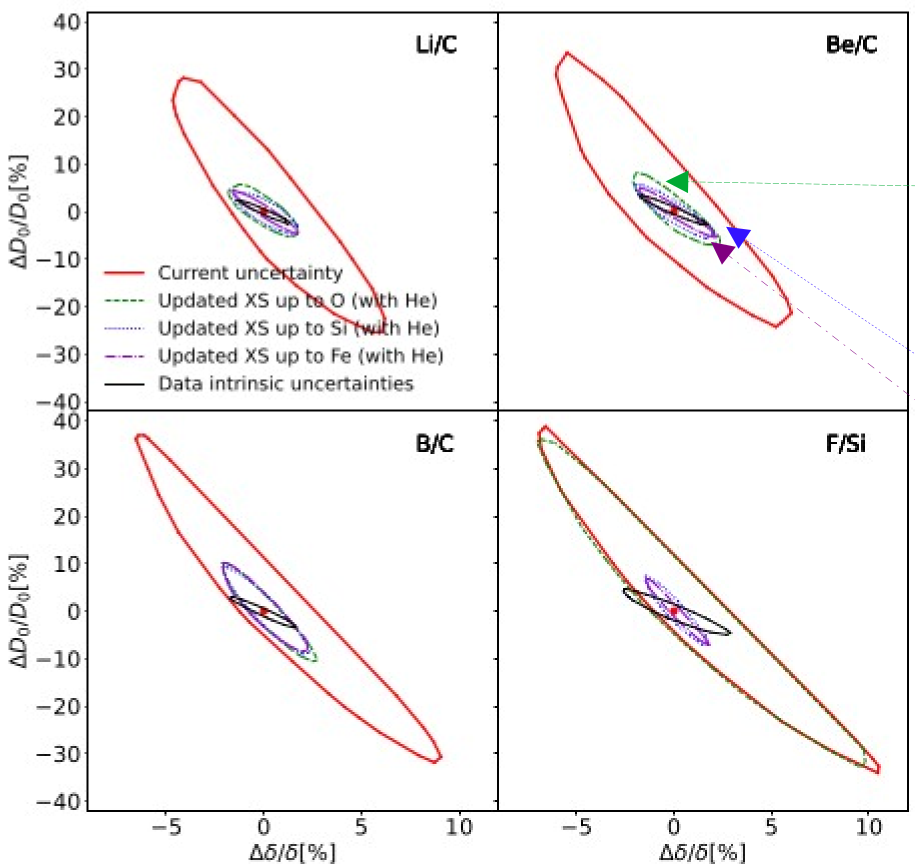
Reaction	$N_{\rm int}$
^{16}O + H	60k
^{12}C + H	50k
^{16}O + He	20k
^{11}B + H	10k
^{15}N + H	10k
^{14}N + H	10k
^{12}C + He	10k
^{10}B + H	5k
^{13}C + H	5k
^{7}Li + H	5k
	$N(\leqslant \rm O)=1.9\times10^5$
^{28}Si + H	50k
^{24}Mg + H	50k
^{20}Ne + H	50k
^{22}Ne + H	20k
^{28}Si + He	10k
^{27}Al + H	10k
^{26}Mg + H	10k
^{24}Mg + He	10k
^{23}Na + H	10k
^{25}Mg + H	10k
^{21}Ne + H	10k
^{20}Ne + He	10k
^{32}S + H	5k
^{29}Si + H	5k
^{22}Ne + He	5k
	$N(\leqslant \rm Si)=3.8\times10^5$
^{56}Fe + H	30k
^{56}Fe + He	10k
	$N(\leqslant \rm Fe)=4.2\times10^5$

3) Error on flux: forecast on transport parameters

Assumption on existing or future XS uncertainties	Error propagation formula on propagated flux
Fragments multinomially distributed = all fragments of interaction measured in exp. (*precision better than* ξ *on* $(\Delta\psi_{\rm tot}/\psi_{\rm tot})$ *for minimal number of interactions* $N_{\rm tot}=\sum_{a,b}N_{ab}$ *if each* N_{ab} *ensures* $N_{ab}\geq(f_{\rm sec}^2/\xi^2)\times C_{ab}\times\sum_{a,b}C_{ab}$	$\left(\frac{\Delta\psi_{\rm tot}}{\psi_{\rm tot}}\right)^{\rm multi}\approx f_{\rm sec}\sqrt{\sum_{a,b}\frac{1}{N_{ab}}C_{ab}^2}$ with $C_{ab}^2\equiv\sum_c f_{abc}^2\frac{\sigma_{a+b}^{\rm inel}}{\sigma_{a+b\to c}}$

1000 MC realisation of XS values + fit of GCR data
→ sample estimate of 1σ contours on parameters

[Following Génolini et al 2019, DM et al., 2022b]



Reaction	$N_{\rm int}$
^{16}O + H	60k
^{12}C + H	50k
^{16}O + He	20k
^{11}B + H	10k
^{15}N + H	10k
^{14}N + H	10k
^{12}C + He	10k
^{10}B + H	5k
^{13}C + H	5k
^{7}Li + H	5k
	$N(\leqslant \mathrm{O}) = 1.9\times10^5$
^{28}Si + H	50k
^{24}Mg + H	50k
^{20}Ne + H	50k
^{22}Ne + H	20k
^{28}Si + He	10k
^{27}Al + H	10k
^{26}Mg + H	10k
^{24}Mg + He	10k
^{23}Na + H	10k
^{25}Mg + H	10k
^{21}Ne + H	10k
^{20}Ne + He	10k
^{32}S + H	5k
^{29}Si + H	5k
^{22}Ne + He	5k
	$N(\leqslant \mathrm{Si}) = 3.8\times10^5$
^{56}Fe + H	30k
^{56}Fe + He	10k
	$N(\leqslant \mathrm{Fe}) = 4.2\times10^5$

3) Error on flux: forecast on pbar flux and L (halo size)

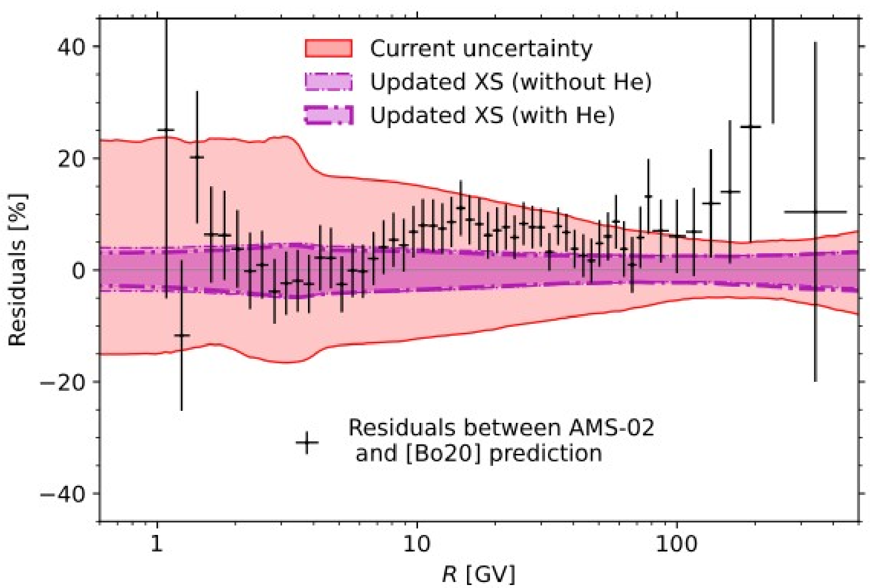
Assumption on existing or future XS uncertainties	Error propagation formula on propagated flux
Fragments multinomially distributed = all fragments of interaction measured in exp. *(precision better than ξ on $(\Delta\psi_{\rm tot}/\psi_{\rm tot})$ for minimal number of interactions $N_{\rm tot}=\sum_{a,b}N_{ab}$ if each N_{ab} ensures $N_{ab}\geq(f_{\rm sec}^2/\xi^2)\times C_{ab}\times\sum_{a,b}C_{ab}$*	$\left(\frac{\Delta\psi_{\rm tot}}{\psi_{\rm tot}}\right)^{\rm multi}\approx f_{\rm sec}\sqrt{\sum_{a,b}\frac{1}{N_{ab}}C_{ab}^2}$ with $C_{ab}^2\equiv\sum_c f_{abc}^2\frac{\sigma_{a+b}^{\rm inel}}{\sigma_{a+b\to c}}$

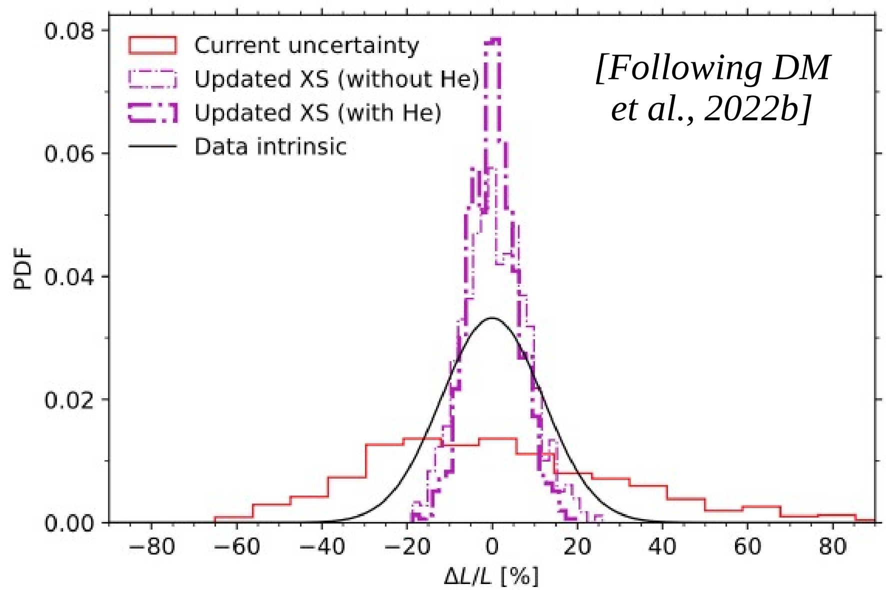
1000 MC realisation of XS values + fit of GCR data
→ sample estimate of 1σ contours on parameters

Reaction	$N_{\rm int}$
$^{16}O+H$	60k
$^{12}C+H$	50k
$^{16}O+He$	20k
$^{11}B+H$	10k
$^{15}N+H$	10k
$^{14}N+H$	10k
$^{12}C+He$	10k
$^{10}B+H$	5k
$^{13}C+H$	5k
$^{7}Li+H$	5k

$N(\leqslant O)=1.9\times10^5$

[Following Boudaud et al., 2020]





→ New nuclear XS measurements
low risk / high benefit (game changer for GCRs)
NA61: pilot test in 2018 (Unger et al.)
+ run in coming weeks!

XSCRC2024: Cross sections for Cosmic Rays @ CERN

16–18 oct. 2024
CERN
Fuseau horaire Europe/Zurich

Series of XSCRC workshop (2017, 2019, 2024)
(Cross Sections for Cosmic-Rays at CERN)
https://indico.cern.ch/event/1377509/

- Accueil
- Ordre du jour
- Inscription
- Liste des participants
- Liste des contributions
- Recueil des résumés
- Liste des orateurs
- Appel à contribution
- Code of Conduct
- Practical information
  - Accommodation
  - Health insurance, visa
  - Directions to and inside CERN
  - Wi-fi connection
  - Child care

Cosmic-ray (CR) physics in the GeV-TeV range has entered a precision era with recent data from space-based experiments. However the poor knowledge of nuclear reactions (production of antimatter and …

In brief
~60 participants (~30 presentations)
+ dedicated discussion sessions

Goal: bring together
- GCR experts on phenomenology and data (AMS-02, DAMPE...)
- Particle physicists (ALICE, AMBER, LHCb…)
- Nuclear physics facilities (FAIR@GSI, HIAF@China...)
- Synergies on needs (space rad. protection, hadrontherapy, nuclear codes)

Outputs (past and future)
- Collaborations between different communities
- Measurements of pbar, dbar, He-bar inelastic production XS
- Measurement of nuclear production XS

→ **White paper (in progress)**

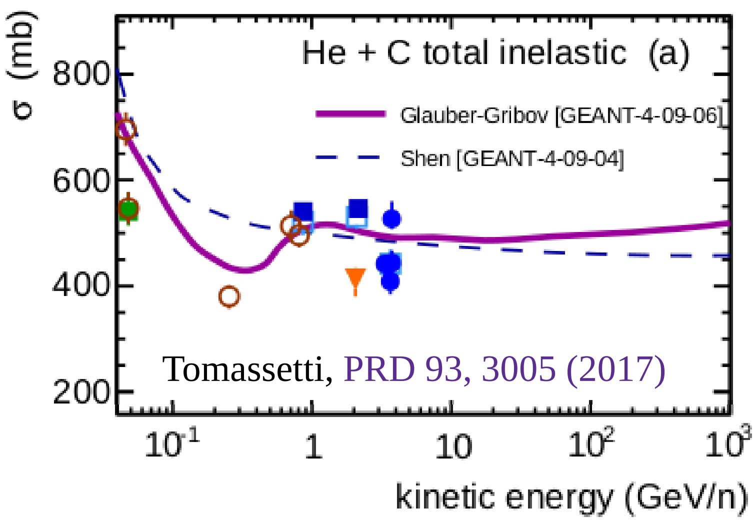
Organizing Committee: Fiorenza Donato (chair), Saverio Mariani (co-chair), David Maurin (co-chair)

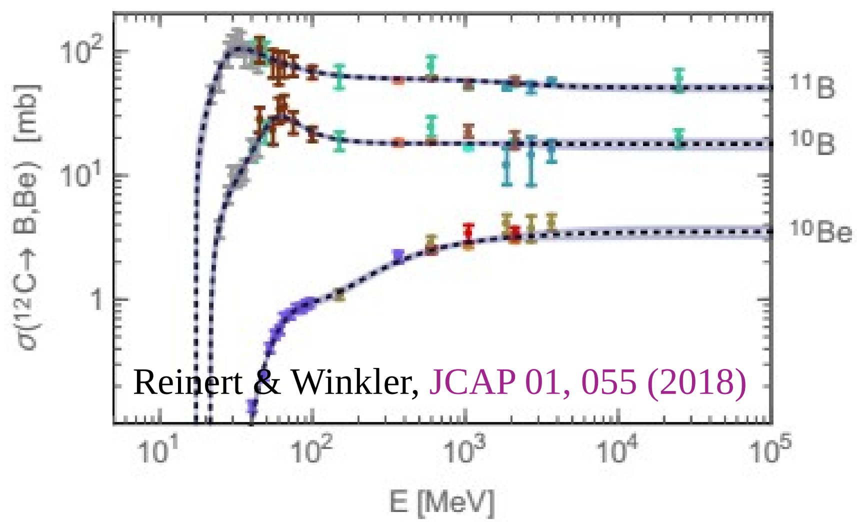
XS for GCRs and their typical uncertainties

Reaction cross sections
(CR destruction)

Production cross sections
(creation of secondary species)

on targets
(ISM = 90% H+10% He)





Uncertainties ~ 5-10% (on H)
→ **mostly OK in AMS02 era**

Uncertainties ~ 10-20% (on H)
→ **big issue in AMS02 era!**

XS parametrisations and EXFOR data base

XS Parametrisations

Two "historical" groups/codes

- WNEW (Webber et al., up to 2003): semi-empirical formula based on "regularities" observed in data
- YIELDX (Tsao & Silberberg, up to 2000): semi-analytical formula "driven" by theory

Model parameters = global fit on all data
YIELDX better than WNEW for XS reaction with "no data"

GALPROP implementation

Use of WNEW and YIELDX + rescaling on existing data (Moskalenko & Mashnick, 2003):

- Galp-opt12: starts from WNEW
- Galp-opt22: starts from YIELDX

XS extraction: EXFOR database
https://www.nndc.bnl.gov/exfor/exfor.htm

Type of measured reactions

- Direct: beam on H (or using CH2 − C subtraction technique)
- Indirect: target irradiated by proton beam (γ-spectrometry or mass spectrometry after chemical extraction)

Relevant publications for Fe

- Napolitani et al. (2004)
- Herbach et al. (2006)
- Villagrasa-Canton et al. (2007)
- Titarenko et al. (2008,2011)

In practice

- update all relevant XS for relevant progenitors (see Génolini et al., 2018): ^{56}Fe, ^{28}Si, ^{24}Mg, ^{20}Ne, ^{16}O, ^{14,15}N, 12C…
- Apply rescaling procedure

Most significant differences in updated XS

DM et al. (2022)

Beware: cumulative XS required in CRs
(must account for short-lived nuclei, aka ghosts)

$$\sigma^c(X+H\to Y) \;=\; \sigma(X+H\to Y) + \sum_{G\,\in\,\mathrm{ghosts}} \sigma(X+H\to G)\cdot \mathcal{B}r\,(G\to Y)\,,$$

For Fe in LiBeB, overall:
- Galp-opt12 (left factor) undershoots
- Galp-opt12 (right factor) overshoots

x = no data

	Li				Be					B					
	^{6}Li	^{7}Li	^{6}He (100%)	^{8}He (16%)	^{7}Be	^{9}Be	^{10}Be	^{11}Li (85%)	^{9}Li (49%)	^{10}B	^{11}B	^{11}C (100%)	^{10}C (100%)	^{11}Be (97%)	^{11}Li (7.8%)
^{56}Fe	∞|0.8	∞|1	∞|0.6	$\times$	15|0.8	21|1.4	19|0.7	$\times$	∞|0.3	20|0.8	15|1	2.0|1.7	$\times$	$\times$	$\times$
^{28}Si	$\times$	$\times$	$\times$	$\times$	1	1.05	1.02	$\times$	0.4	$\times$	$\times$	0.5|1.2	$\times$	$\times$	$\times$
^{24}Mg	$\times$	$\times$	$\times$	$\times$	1.04	2.04	0.95	$\times$	0.6	$\times$	$\times$	0.5|1.1	$\times$	$\times$	$\times$
^{20}Ne	$\times$	$\times$	$\times$	$\times$	$\times$	$\times$	$\times$	$\times$	$\times$	$\times$	$\times$	0.95	1	$\times$	$\times$
^{16}O	1.4	0.96	∞	$\times$	0.98	1.41	1.18	$\times$	0.7	0.96	0.4	∞	∞	∞	$\times$
^{15}N	1	1	$\times$	$\times$	1	1	1	$\times$	0.5	1.34	1.17	1	$\times$	$\times$	$\times$
^{14}N	1	1	∞	$\times$	1.18	0.94	1.02	$\times$	0.8	0.91	0.6	∞	∞	$\times$	$\times$
^{12}C	1.1	0.94	∞	$\times$	0.94	0.91	1.04	$\times$	∞	1.08	0.92	1.04	0.7	$\times$	$\times$
^{11}B	1	1	$\times$	$\times$	1.06|1.16	1.04	0.4	$\times$	0.97	0.93	...	∞|0.7	∞|1.16	$\times$	$\times$
^{10}B	$\times$	$\times$	$\times$	$\times$	0.94	$\times$	$\times$	...	$\times$	...	...	...	∞|1.75	...	...
^{10}Be	$\times$	$\times$	$\times$	$\times$	$\times$	$\times$	...	...	$\times$	$\times$	...	...	$\times$	...	...
^{9}Be	1	1	$\times$	$\times$	1	...	...	...	$\times$	...	...	...	...	...	...
^{7}Be	$\times$	$\times$	$\times$	...	...	...	...	...	...	...	...	...	...	...	...
^{7}Li	1	...	$\times$	...	∞	...	...	...	...	...	...	...	...	...	...

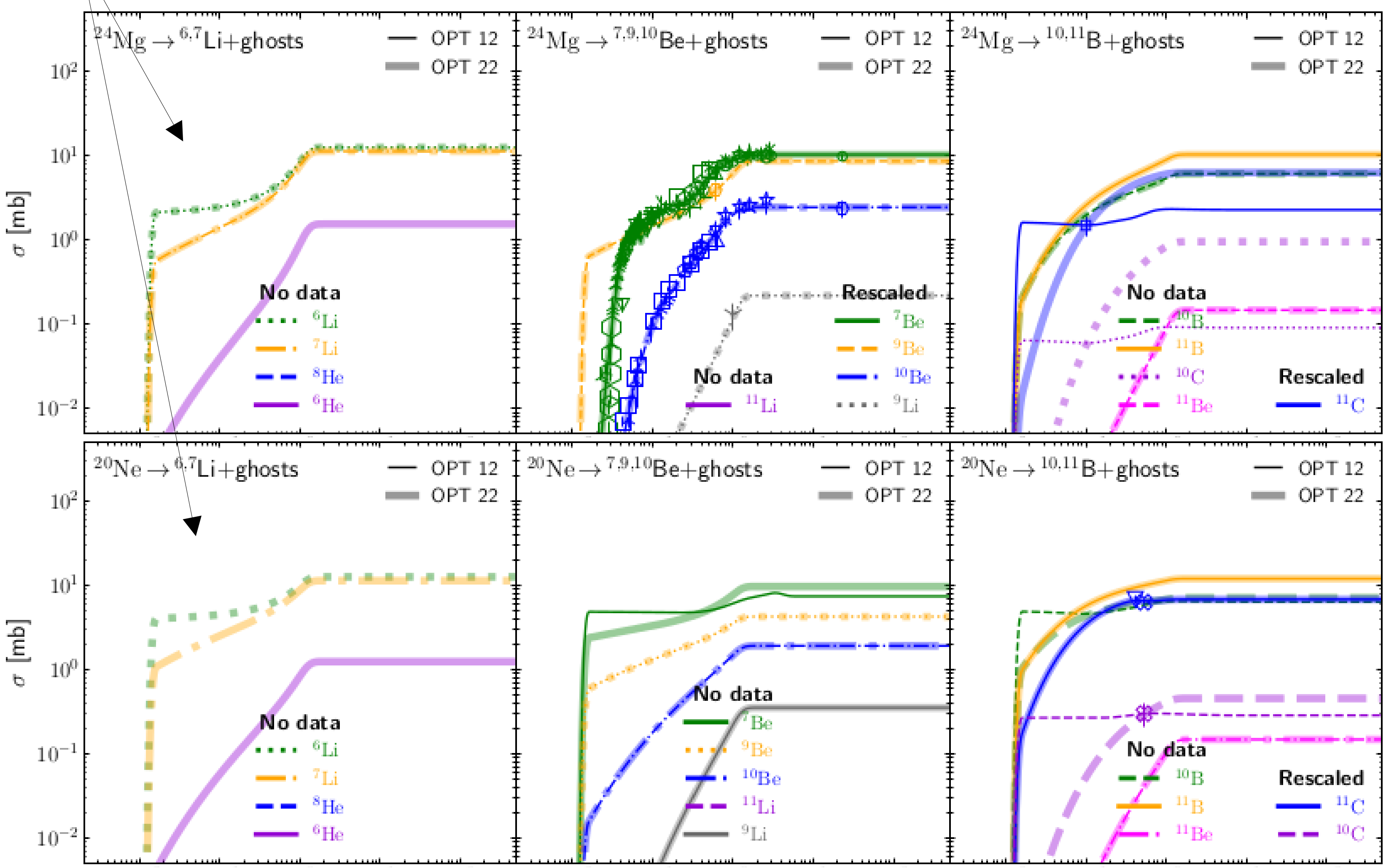
For O in LiBeB (dominant progenitor, ~50% of total):
- Significant differences after update

Scare/no data for important reactions...

Beware: cumulative XS required in CRs
(must account for short-lived nuclei, aka ghosts)

$$\sigma^c(X+H\rightarrow Y) = \sigma(X+H\rightarrow Y) + \sum_{G\,\in\,\text{ghosts}} \sigma(X+H\rightarrow G)\cdot \mathcal{B}r(G\rightarrow Y)\,,$$

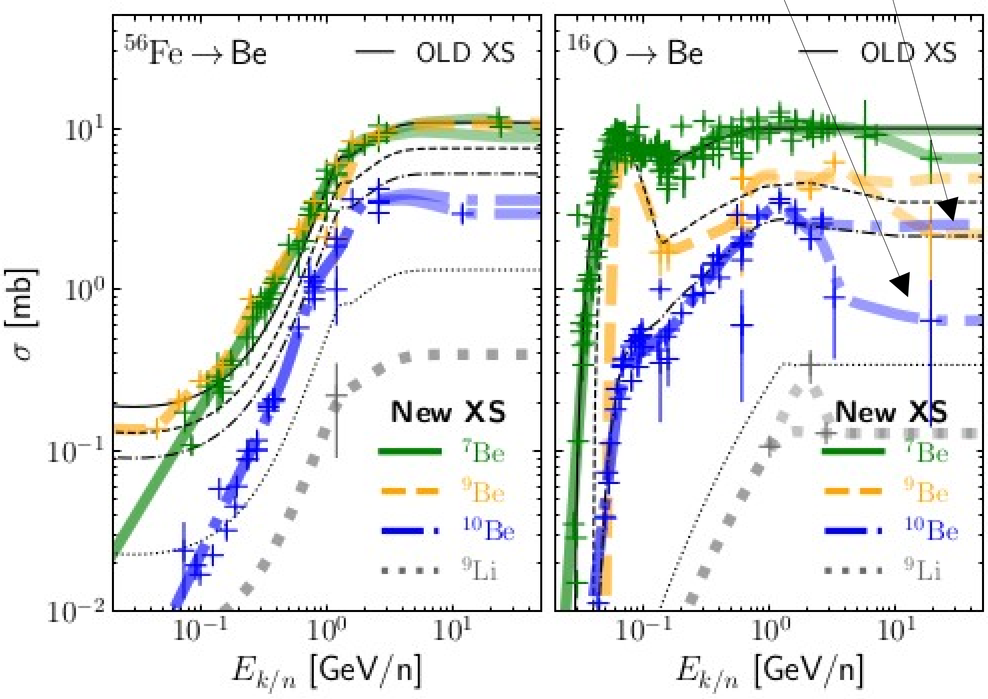
No data for many progenitors into Li!



Large discrepancies for 10Be production XS

Extra- uncertainty at high energy:

- assume constant above 1.5 GeV/n?
- try to pass through all data?



References for LiBeB production XS

(direct and inverse kinematics, activation,
gamma-detection, subtraction CH4-C, ...)

[Ba19]	[Ba05]	[Fa98]	[Sh93]	[Mi86]	[Fo77]	[La73]	[St68]	[Re65]	[La63]	[Pa60]
[Ma18]	[Ya04]	[Si97]	[Bo93]	[RV84]	[Ka76]	[Ra72]	[Ra68]	[Do65]	[Li62]	[Ho60]
[Ge17]	[Na04]	[Mi97]	[Si92]	[Ol83]	[In76]	[Bu72]	[Do68]	[Be65]	[Ga62]	[Hi60]
[Ma16]	[Ke04]	[Le97]	[We90]	[Re81]	[Ho76]	[Am72]	[An68]	[Wa64]	[Fo62]	[Be60]
[Du13]	[Ko02]	[Fa97]	[Ko90]	[Ra79]	[He76]	[St71]	[Wi67]	[Ra64]	[Cu62b]	[Ba58]
[Ak13]	[Ki02]	[We96]	[Di90b]	[Mo79]	[Re75]	[Ra71]	[Me66]	[Po64]	[Cu62a]	[Sy57]
[Ti11]	[imos]	[Si96]	[Di90a]	[Iz78]	[Ra75b]	[Fo71]	[La66]	[Ka64]	[Br62]	[Pr57]
[Ti08]	[Ko99]	[Sc96]	[Al90]	[Go78]	[Ra75]	[Bi71]	[Ga66]	[Ho64]	[Le61]	[Bu55]
[He06]	[We98a]	[Pa96]	[Mi89]	[Sc77]	[Ra74]	[Ba71]	[Va65]	[Va63]	[Cl61]	[Di50]
[Ge05]	[NU98]	[Mi95]	[Ki89]	[Ra77]	[Ja74]	[Da70]				

Improvement of new XS data on transport parameters

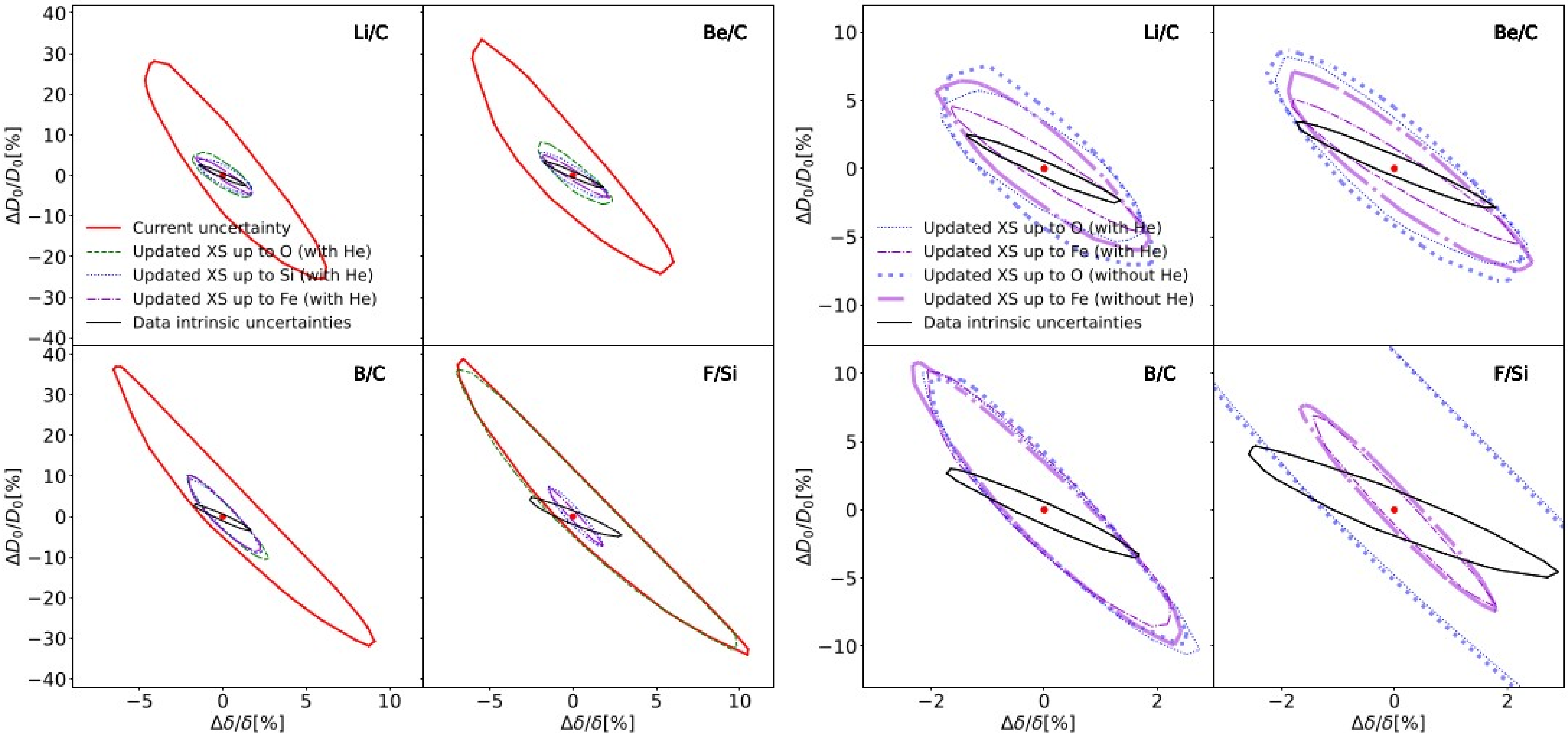
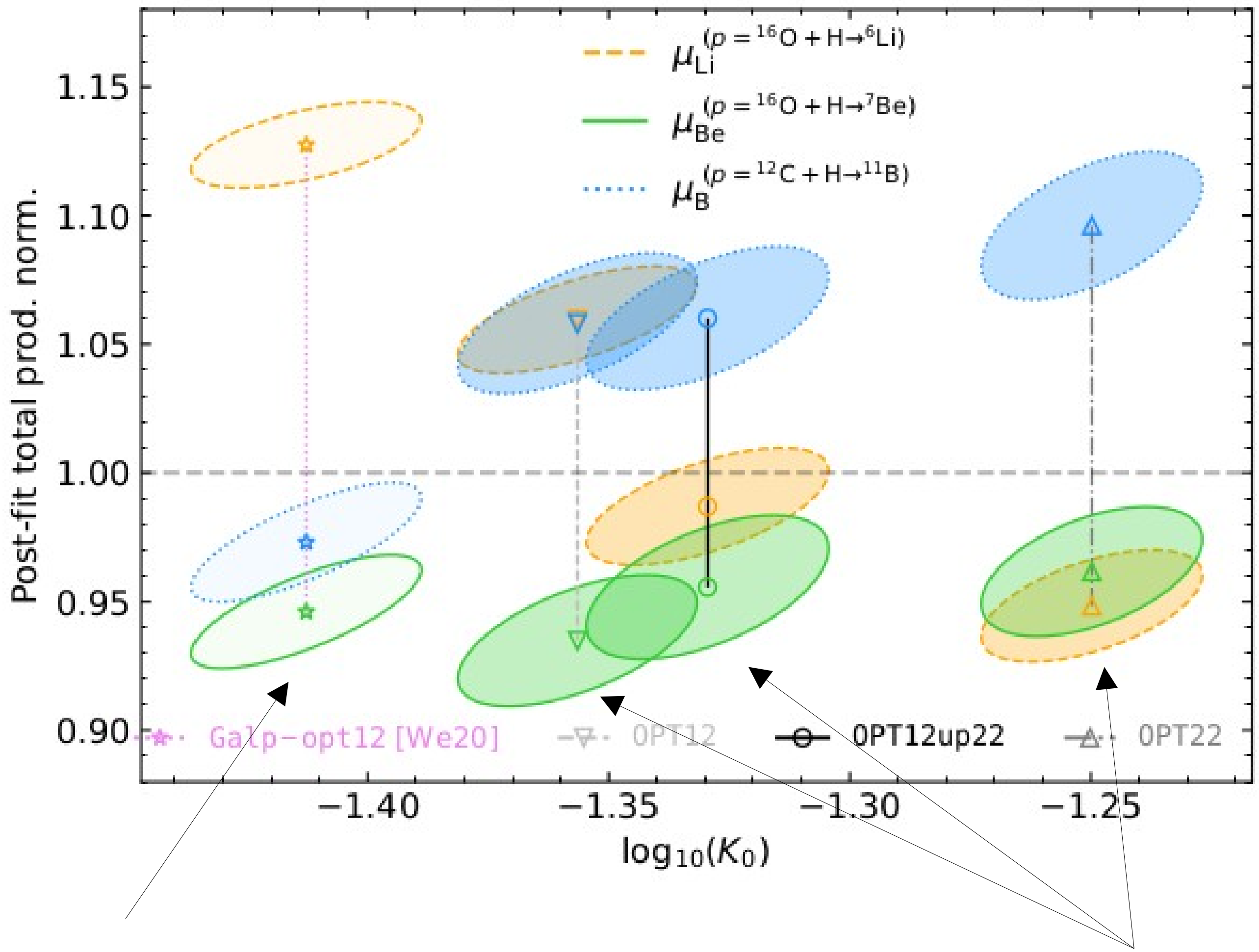


FIG. 4. Forecast of transport parameters determination from new cross-section measurement campaigns. Each figure shows 1σ contours in the (D_0, δ) relative error plane in different scenarios. The *left panel* shows the estimated current uncertainty (solid red line) and three cases were a subsets of cross sections have been updated according to our proposition Table IV, increasing the mass of the heavier progenitor from O to Fe. Finally, for comparison, we show the irreducible/intrinsic data uncertainty (solid black line). The *right panel* is a zoom of the left one and compares subcases where we would not measure the fragmentations of Table IV on a helium target. More details on how these bounds were computed can be found in the text.

Impact of updated XS: Li primary source?

DM et al. (2022)

Interpretation of post-fit nuisance XS parameters



Old XS dataset

→ Need a ~13% increase of Li production to match the data

→ Alternative (Boschini et al., 2020): need primary source of Li

New XS datasets

→ Depending on XS dataset, need to increase or decrease Li production

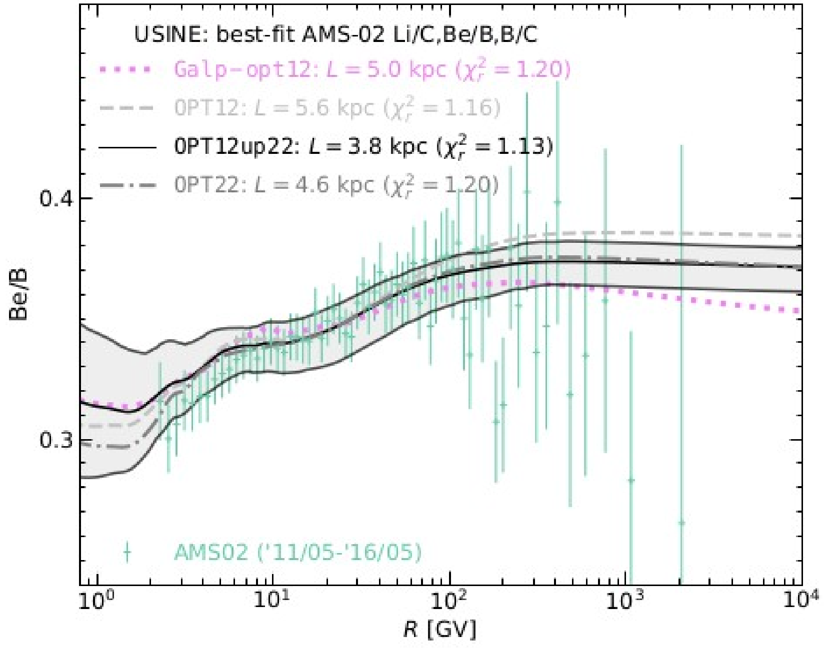
→ Need for Li primary source alleviated: any claim for primary Li, Be, or B source cannot be significant (XS too uncertain)

Impact of updated XS: halo size of the Galaxy

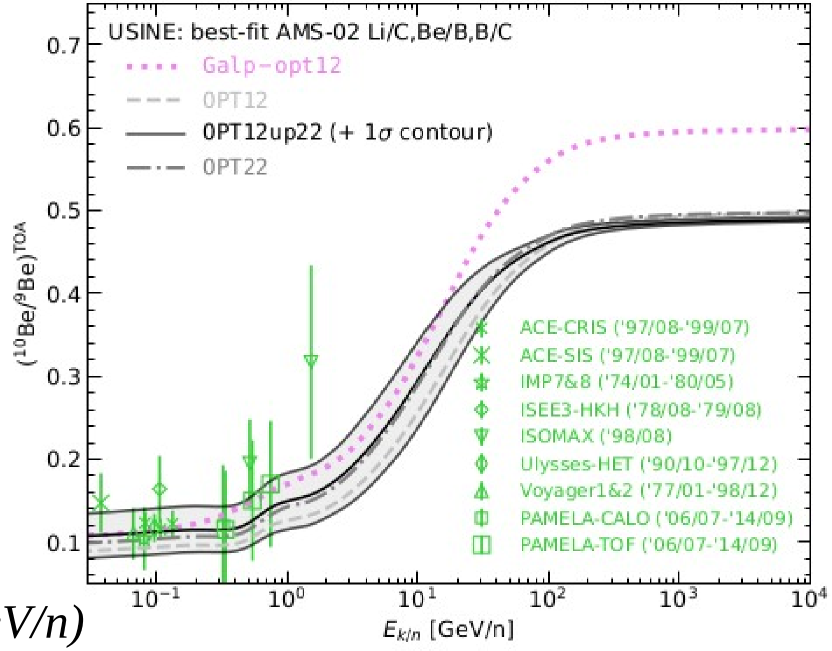
Halo size (*determined from radioactive CR ^{10}Be*)
critical parameter for dark matter searches
(e.g., Génolini et al., PRD 2021)

DM, E. Ferronato Bueno, and L. Derome
https://arxiv.org/abs/2203.07265

Fit Li/C+Be/B+B/C with USINE		
Cross-section set	L [kpc]	χ^2_r
Galp-opt12	$5.0^{+3.0}_{-1.8}$	1.20
OPT12	$5.6^{+5.6}_{-2.5}$	1.16
OPT12up22	$3.8^{+2.8}_{-1.6}$	1.13
OPT22	$4.6^{+4.0}_{-2.1}$	1.20



Fit ^{10}Be/^{9}Be (analytical)		
Cross-section set	L [kpc]	χ^2_r
Galp-opt12	5.1 ± 0.6	0.46
OPT12up22	2.8 ± 0.3	0.40



→ Also impacted by XS uncertainties

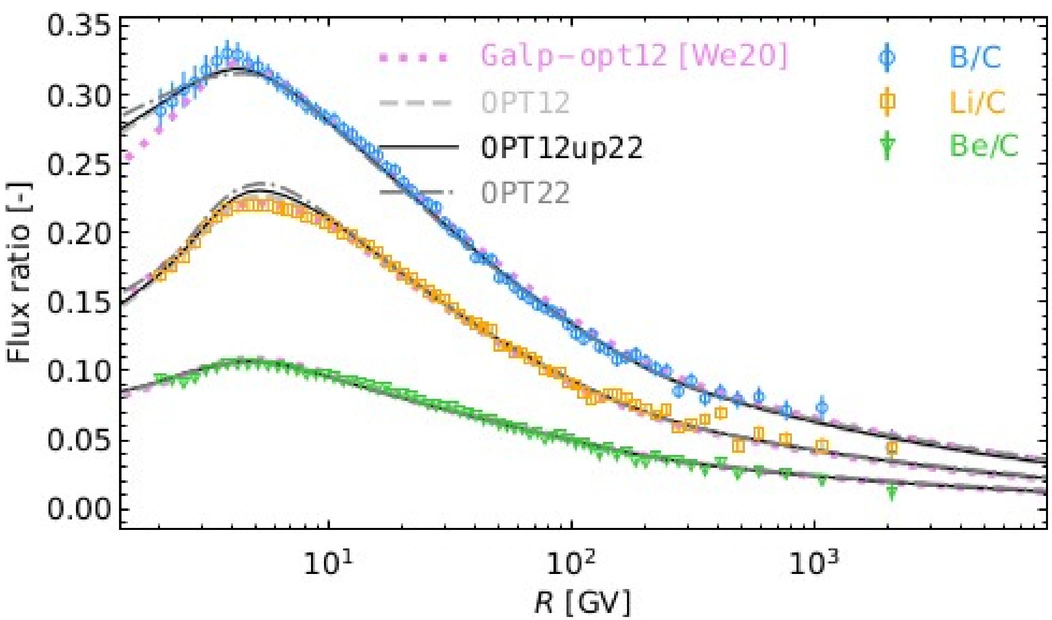
N.B.: ^{10}Be/^{9}Be data soon by AMS-02 and HELIX (up to 10 GeV/n)

2) XS for GCRs vs AMS-02 data

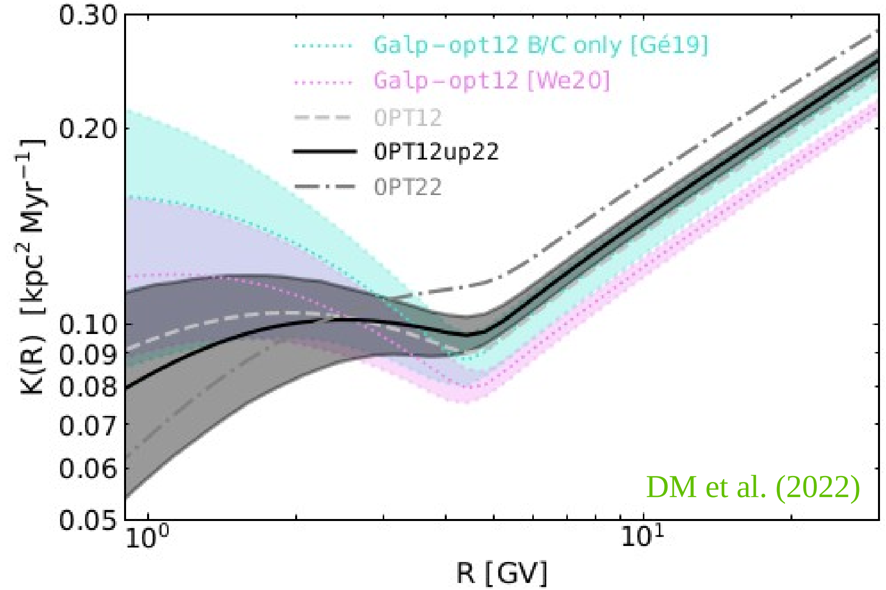
Modelling systematics (from XS) vs CR data uncertainties

[N.B.: XS parametrizations rely on same nuclear data]

Fit to AMS-02 data
[including nuisance parameters on XS]



Uncertainty on diffusion coefficient
[including OPT12up22 XS model updated on unaccounted for 2003-2022 XS data]

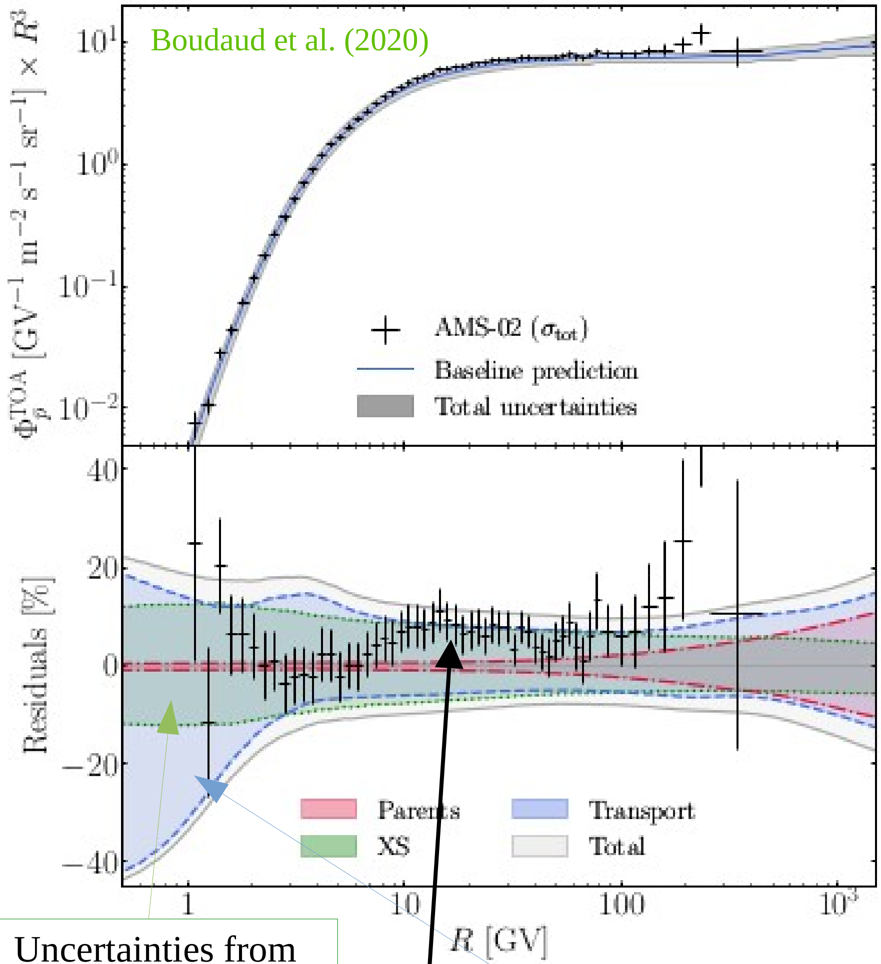


Universality of transport?
→ Yes within current nuclear uncertainties
(no need for source of primary Li)

But to fully exploit CR data, new/better XS data are needed… but which ones?

2) Nuclear XS for dark matter searches

Background (astro. contrib.)



Uncertainties from pbar production $(p,He)_{CR}$ + $(H,He)_{ISM}$

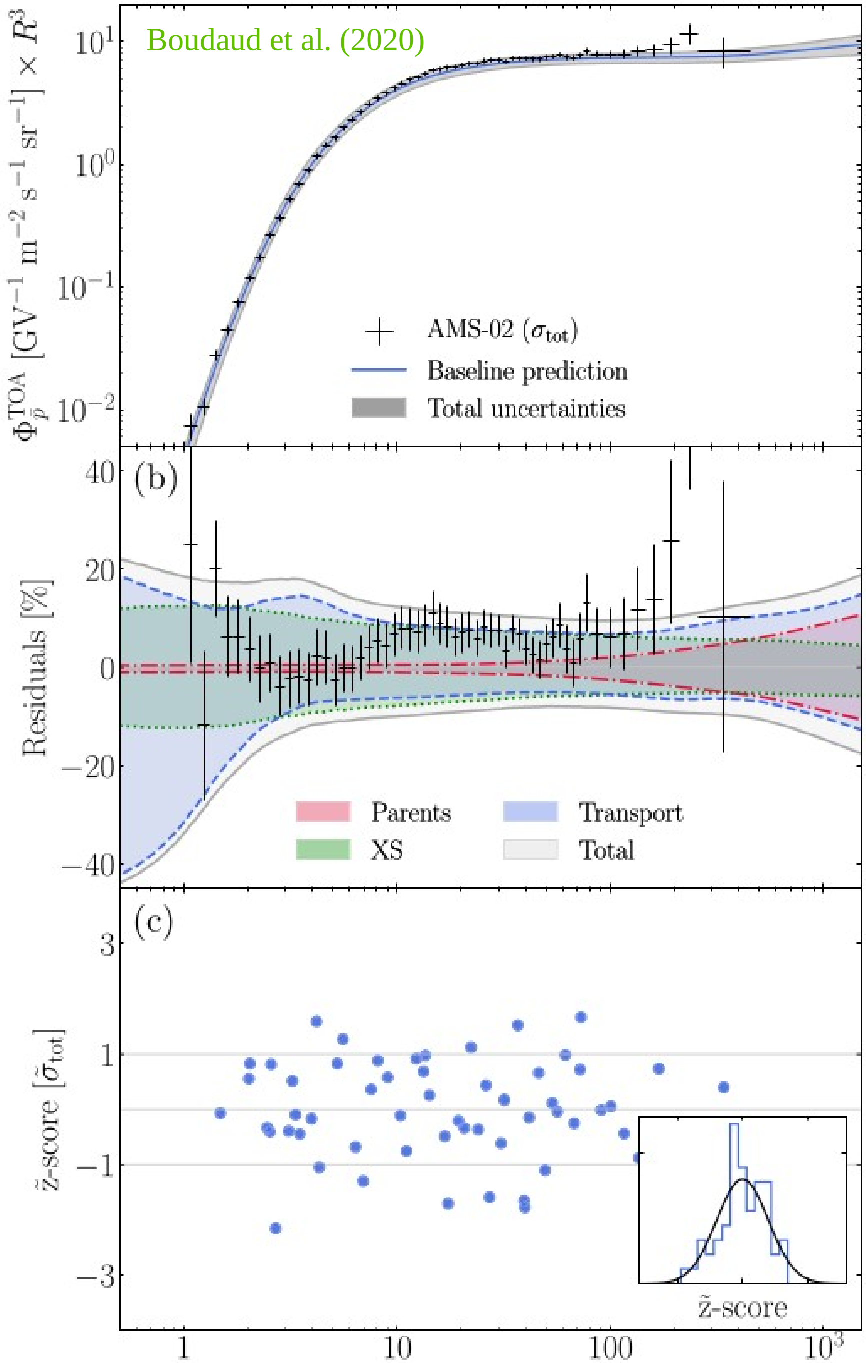
Uncertainties from LiBeB nuclear XS

Cannot take full benefit of AMS-02 high-precision data

[N.B.: any future improvement on pbar data moot if no better XS!]

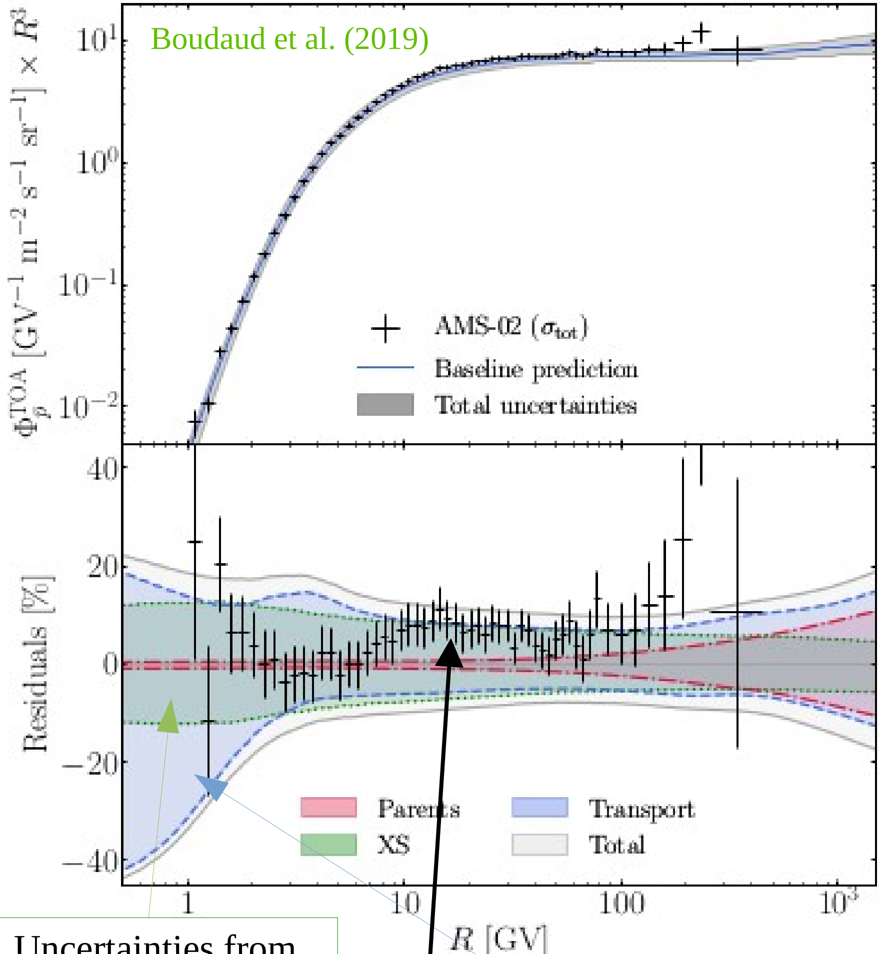
2) Nuclear XS for dark matter searches

Background (astro. contrib.)



2) Nuclear XS for dark matter searches

Background (astro. contrib.)



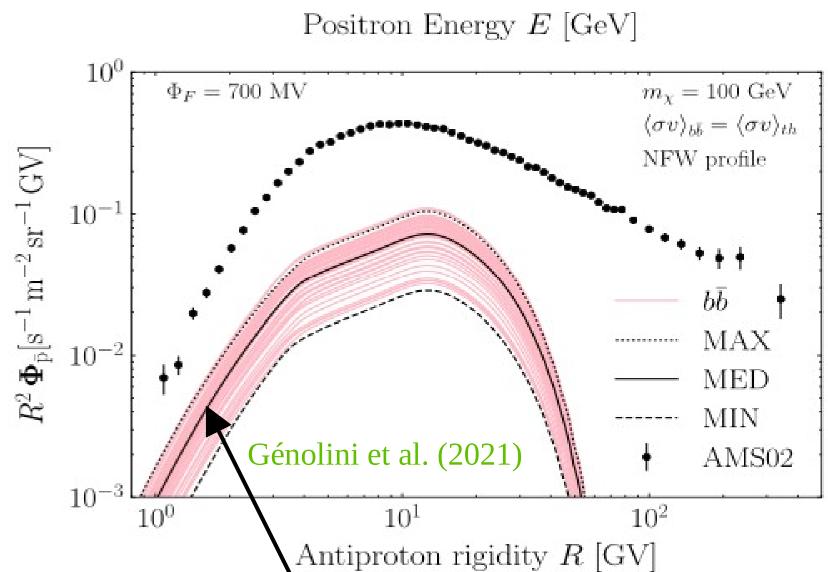
Uncertainties from pbar production $(p,He)_{CR} + (H,He)_{ISM}$

Uncertainties from LiBeB nuclear XS

Cannot take full benefit of AMS-02 high-precision data

[N.B.: any future improvement on pbar data useless if no better XS!]

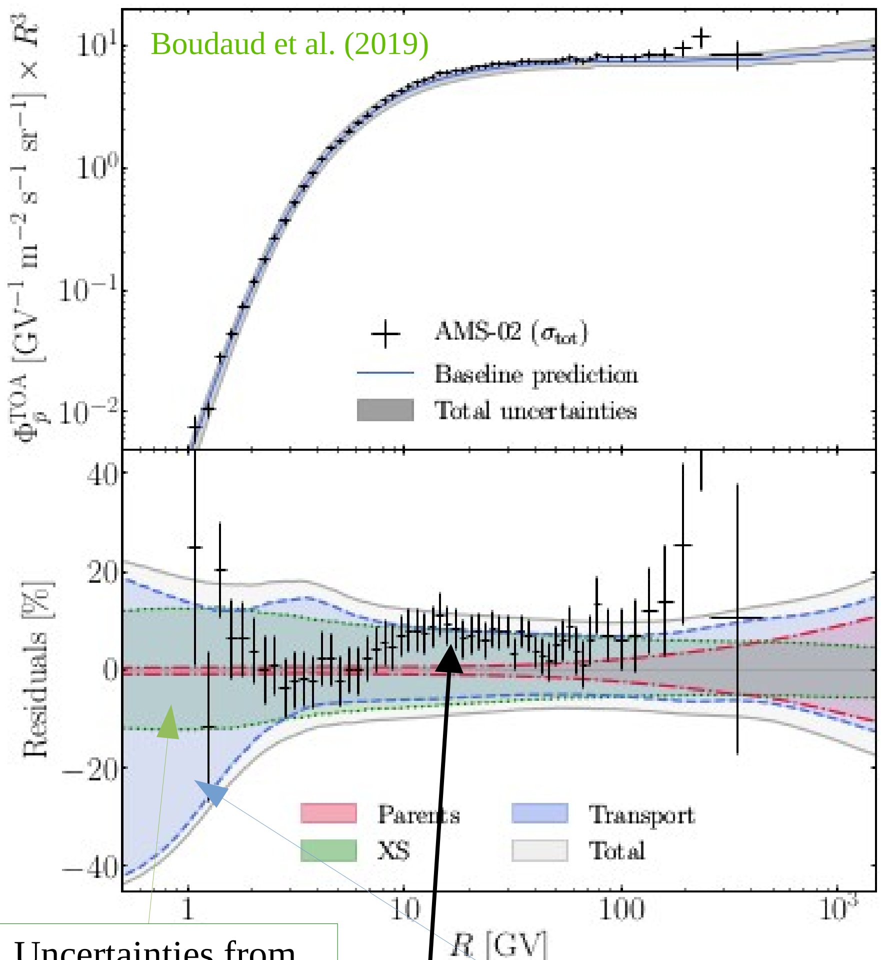
Signal (dark matter contrib.)



Signal uncertainty directly related to L (diffusive halo size)

2) Nuclear XS for dark matter searches

Background (astro. contrib.)



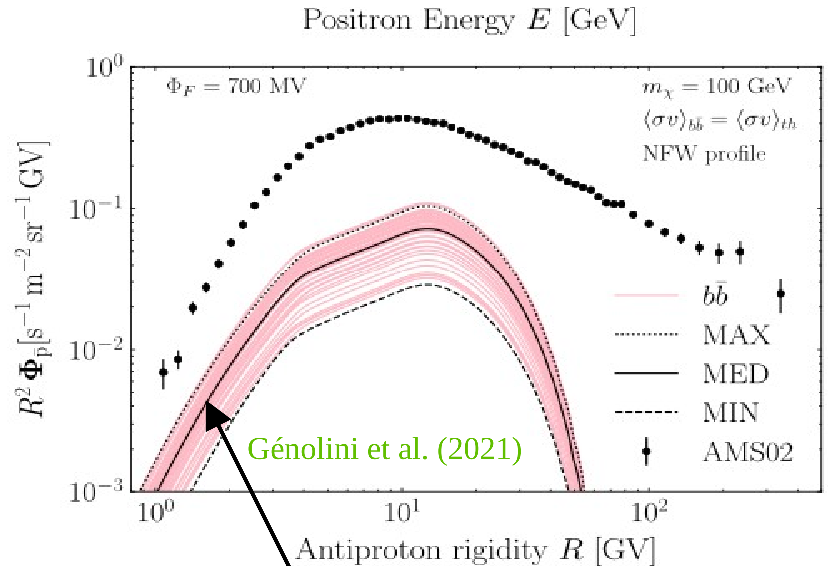
Uncertainties from pbar production $(p,He)_{CR}$ + $(H,He)_{ISM}$

Uncertainties from LiBeB nuclear XS

Cannot take full benefit of AMS-02 high-precision data

[N.B.: any future improvement on pbar data moot if no better XS!]

Signal (dark matter contrib.)



Signal uncertainty directly related to L (diffusive halo size)

Fit $^{10}Be/^{9}Be$ (analytical)		
Cross-section set	L [kpc]	χ^2_r
DM et al. (2022b)		
`Galp-opt12`	5.1 ± 0.6	0.46
`OPT12up22`	2.8 ± 0.3	0.40

Uncertainty on L large because of uncertain Be isotopic production XS

[N.B.: will plague interpretation of AMS-02 and HELIX measurement of this ratio]

1) CR data

CRDB (Cosmic Ray Data Base)
https://lpsc.in2p3.fr/crdb
DM et al. (*2014*, *2020*, *2023*)

- Charged CR and anisotropy data
- Meta-data (references, dates, infos)
- Plots (online+pip lib.+jupyter notebooks)
- Solar mod. (down to 10 mn interval)

Cosmic-Ray Data Base (CRDB)

Main developers: D. Maurin, F. Melot, and H. Dembinski (+ log
Contributors: M. Ahlers, J. Gonzalez, A. Haungs, P.-S. Mangea
Taillet, D. Wochele, J. Wochele
Partners: KCDC project
Publications (please cite): V2.1, V4.0, V4.1

[Acknowledgements / Contact us / Funding support]

[Gallery from CRDB.py and notebook]

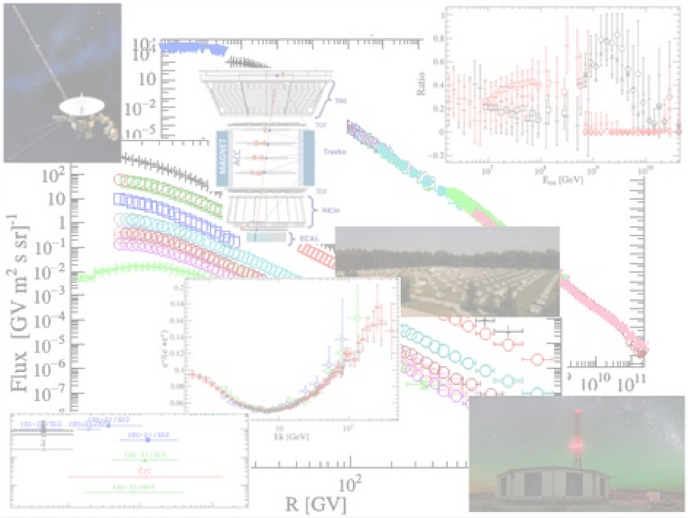
Data and user interfaces

CRDB compiles cosmic-ray data and meta-data from 10^6 eV to 10^{21} eV:

→ *Leptons*: e^-, e^+, e^-+e^+, $e^+/(e^-+e^+)$, and e^+/e^-
→ *Nuclei:* fluxes and ratios of isotopes, elements, and groups of elements
→ *Anti-nuclei:* anti-protons, limits on anti-deuterons and anti-nuclei
→ *Anisotropy*: dipole phase and amplitude

These contextualised data can be retrieved from a pip-installable python library (see also the example notebooks) or from this website:

- Caveats/Tips: warnings on some datasets and info on data transformations
- Data extraction: plot, save, and export user-selected CR quantities
- Experiments/Data: sorted lists of experiments, publications, and their data
- REST/CRDB.py: REST interface (query from script) and python library
- Solar modulation: Force-Field modulation level time series (and REST access)
- Submit data: submit data and their associated meta-data
- Useful links: links to other CR databases or resources



You can also export in one go the DB content (USINE, GALPROP, csv, or csv-asimport format) and the associated ADS bibtex entries and Latex cite (sorted by sub-experiment).

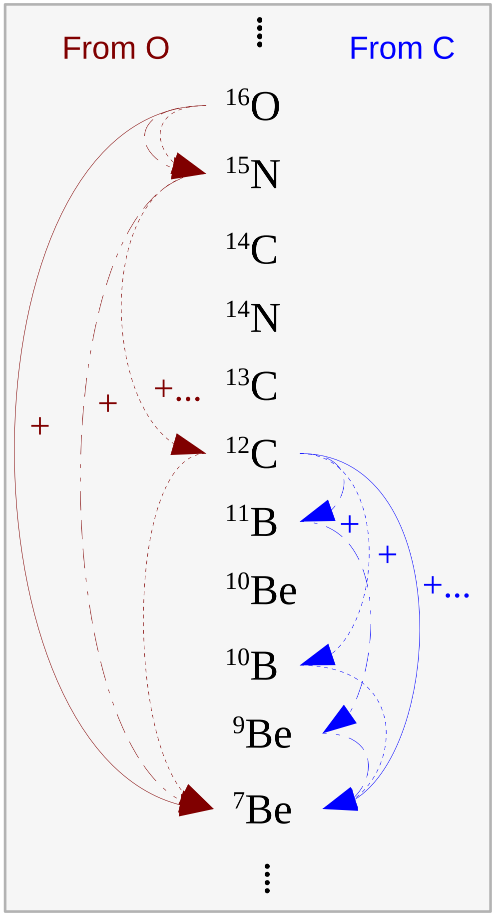
Behind the scene

- *Architecture:* LAMP solution (Linux OS, Apache HTTP server, MySQL database, PHP Hypertext PreProcessor) hosted at LPSC on a virtual server
- *Web pages:* PHP language, AJAX, sorting and displays with jquery (and jquery-ui, jquery.cluetip, table-sorter), and Rest interfaces enabled
- *Scripts and codes:* c++ and ROOT CERN library for plots, cron job scheduler for meta-data and modulation data updates
- *Data extraction:* extensive use of the ADS system, DataThief, and a lot of patience!

2) Ranking of progenitors (P coefficients)

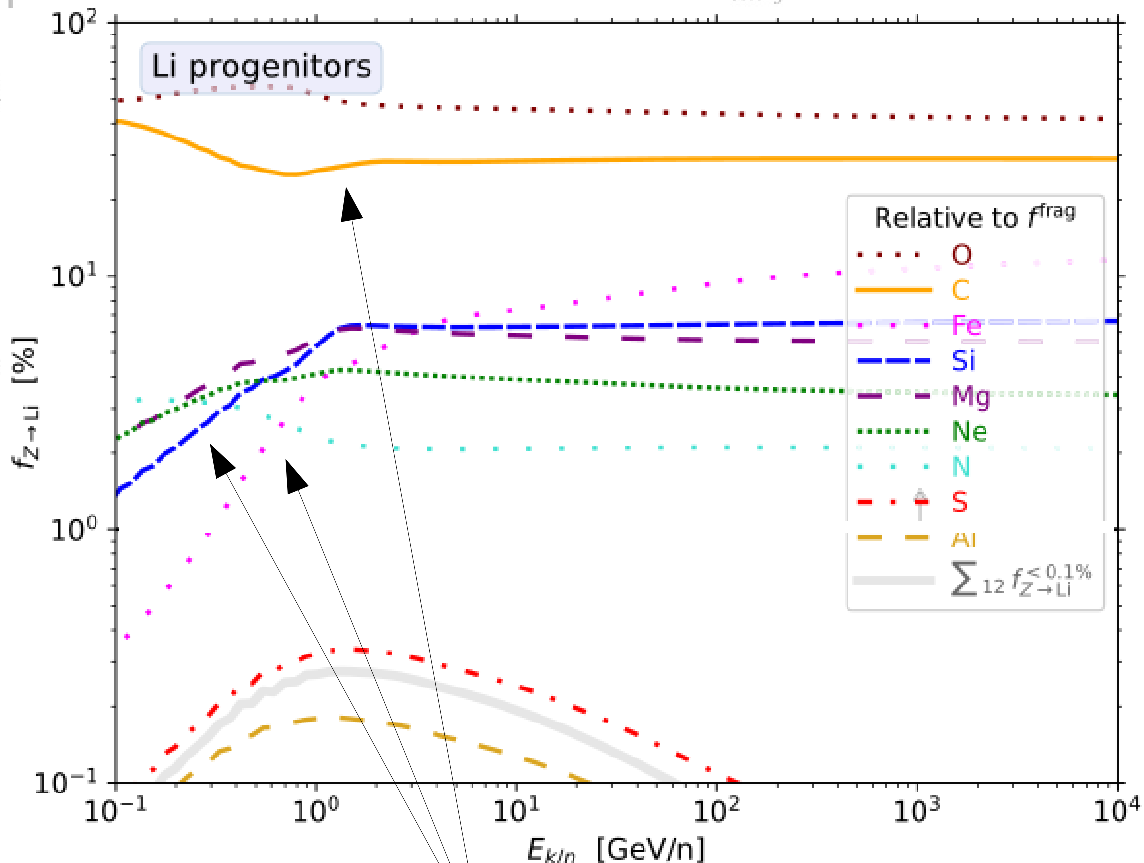
Qty / ranking	Definition	Property
Relative weight of a single production path (1-step or multi-step) linking CR i to j = *channels*	$\begin{cases} P_{ij}^{1-\text{step}} \equiv \dfrac{\psi_{\text{sec}}^{j,\,\sigma_{m\to n}^{\text{cumul}}=0\ \forall(m,n)\neq(i,j)}}{\psi_{\text{sec}}^{j,\,\text{ref}}} \\ P_{ikj}^{2-\text{step}} \equiv \dfrac{\psi_{\text{sec}}^{j,\,\sigma_{m\to n}^{\text{cumul}}=0\ \forall(m,n)\neq\{(i,k),(k,j)\}}}{\psi_{\text{sec}}^{j,\,\text{ref}}} \\ P_{ikpj}^{3-\text{step}} \equiv \dots \\ \dots \end{cases}$ $P_j^{>2-\text{step}} \equiv 1 - \sum_i^{i>j} \left(P_{ij}^{1-\text{step}} + \sum_k^{i>k>j} P_{ikj}^{2-\text{step}} \right)$	$\sum_i^{i>j} \left(P_{ij}^{1-\text{step}} + \sum_k^{i>k>j} \left(P_{ikj}^{2-\text{step}} + \sum_p^{i>k>p>j} (\dots) \right) \right) = 1$ $\dfrac{P_{i\dots\dots j}^{(n+1)-\text{step}}}{P_{i\dots\,j}^{n-\text{step}}} \propto R^{-\delta}$ (diffusion coeff. slope $\delta \approx 0.5$)
Cumulative weight of all paths linking $i \to j$ = *direct+indirect prod. of j from primary flux i*	$\begin{cases} P_{i\to j} \equiv \begin{cases} P_{ij}^{1-\text{step}} + \sum_k^{i>k>j} \left(P_{ikj}^{2-\text{step}} + \sum_p^{i>k>p>j} \left(P_{ikpj}^{3-\text{step}} + \dots \right) \right) \\ = \dfrac{\psi_{\text{sec}}^{j,\,\sigma_{k\to p}=0\ \forall k>i,\,\forall p} - \psi_{\text{sec}}^{j,\,\sigma_{i\to k}=0\ \forall k}}{\psi_{\text{sec}}^{j,\,\text{ref}}} \end{cases} \\ P_{Z_i\to Z_j} \equiv \dfrac{1}{n_{Z_i} n_{Z_j}} \times \sum_{i\in Z_i} \sum_{j\in Z_j} P_{i\to j} \end{cases}$	$\begin{cases} \sum_i P_{i\to j} = 1 \\ \sum_{Z_i} P_{Z_i\to Z_j} = 1 \end{cases}$

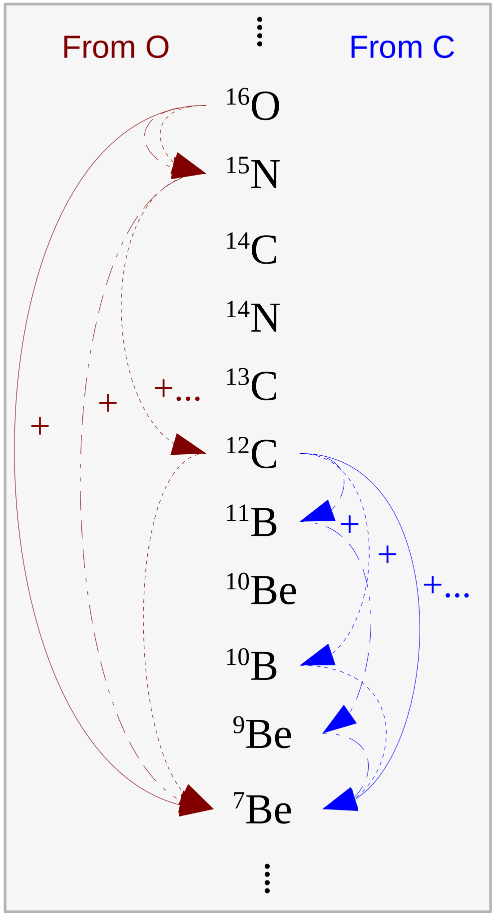
Uniqueness and completeness of P coefficients



2) Ranking of progenitors (P coefficients)

Qty / ranking	Definition	Property
Relative weight of a single production path (1-step or multi-step) linking CR i to j = *channels*	$P^{1-\text{step}}_{ij} \equiv \frac{\psi_{\text{sec}}^{j,\,\sigma^{\text{cumul}}_{m\to n}=0\ \forall(m,n)\neq(i,j)}}{\psi_{\text{sec}}^{j,\,\text{ref}}}$ $P^{2-\text{step}}_{ikj} \equiv \frac{\psi_{\text{sec}}^{j,\,\sigma^{\text{cumul}}_{m\to n}=0\ \forall(m,n)\neq\{(i,k),(k,j)\}}}{\psi_{\text{sec}}^{j,\,\text{ref}}}$ $P^{3-\text{step}}_{ikpj} \equiv \dots$	$\sum_{i}^{i>j}\left(P^{1-\text{step}}_{ij}+\sum_{k}^{i>k>j}\left(P^{2-\text{step}}_{ikj}+\sum_{p}^{i>k>p>j}(\dots)\right)\right)=1$ $\frac{P^{(n+1)-\text{step}}_{i\dots\dots j}}{P^{n-\text{step}}_{i\dots\, j}} \propto R^{-\delta}$ (diffusion coeff. slope $\delta \approx 0.5$)
Cumulative weight of all paths linking $i \to j$ = *direct+indirect prod.* of j from *primary flux* i		

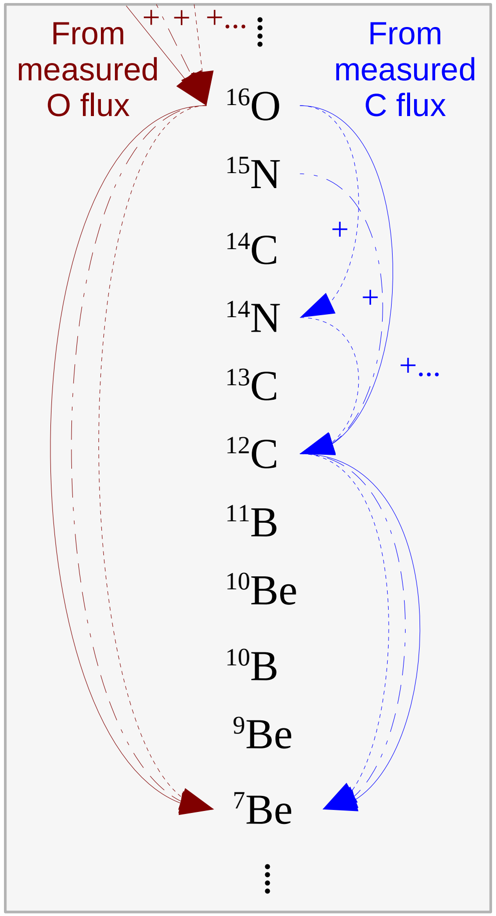




→ Importance of heavier species grows with E ($\Gamma^{\text{inel}} \sim A^{2/3}$)
→ Highlight relative importance of source terms

2) Ranking of direct production (D coefficients)

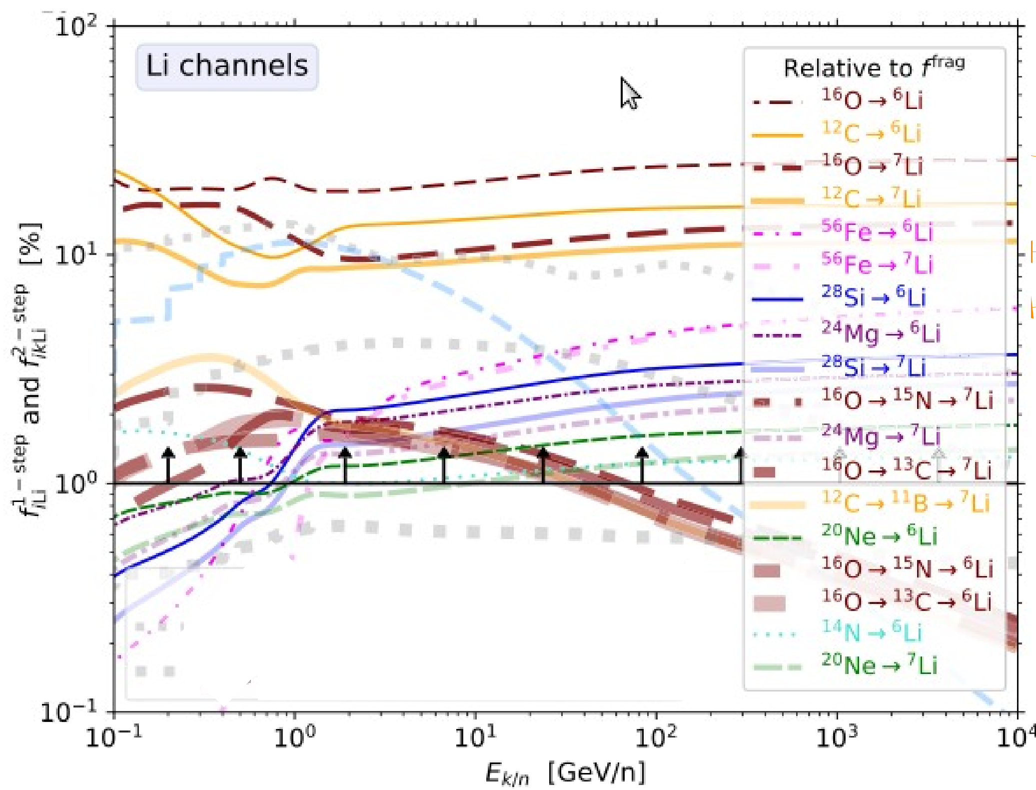
Qty / ranking	Definition	Property
Relative weight of a single production path (1-step or multi-step) linking CR i to j = *channels*	$\begin{cases} P^{1-\text{step}}_{ij} \equiv \dfrac{\psi_{\text{sec}}^{j,\, \sigma^{\text{cumul}}_{m\to n}=0\ \forall(m,n)\neq(i,j)}}{\psi_{\text{sec}}^{j,\,\text{ref}}} \\ P^{2-\text{step}}_{ikj} \equiv \dfrac{\psi_{\text{sec}}^{j,\, \sigma^{\text{cumul}}_{m\to n}=0\ \forall(m,n)\neq\{(i,k),(k,j)\}}}{\psi_{\text{sec}}^{j,\,\text{ref}}} \\ P^{3-\text{step}}_{ikpj} \equiv \dots \\ \dots \end{cases}$ $P^{>2-\text{step}}_{j} \equiv 1 - \sum_i^{i>j}\left(P^{1-\text{step}}_{ij} + \sum_k^{i>k>j} P^{2-\text{step}}_{ikj}\right)$	$\sum_i^{i>j}\left(P^{1-\text{step}}_{ij} + \sum_k^{i>k>j}\left(P^{2-\text{step}}_{ikj} + \sum_p^{i>k>p>j}(\dots)\right)\right) = 1$ $\dfrac{P^{(n+1)-\text{step}}_{i\dots\dots j}}{P^{n-\text{step}}_{i\dots\, j}} \propto R^{-\delta}$ (diffusion coeff. slope $\delta \approx 0.5$)
Cumulative weight of all paths linking $i \to j$ = *direct+indirect prod.* of j from *primary flux* i	$P_{i\to j} \equiv \begin{cases} P^{1-\text{step}}_{ij} + \sum_k^{i>k>j}\left(P^{2-\text{step}}_{ikj} + \sum_p^{i>k>p>j}\left(P^{3-\text{step}}_{ikpj} + \dots\right)\right) \\ = \dfrac{\psi_{\text{sec}}^{j,\, \sigma_{k\to p}=0\ \forall k>i, \forall p} - \psi_{\text{sec}}^{j,\, \sigma_{i\to k}=0\ \forall k}}{\psi_{\text{sec}}^{j,\,\text{ref}}} \end{cases}$ $P_{Z_i\to Z_j} \equiv \dfrac{1}{n_{Z_i} n_{Z_j}} \times \sum_{i\in Z_i}\sum_{j\in Z_j} P_{i\to j}$	$\begin{cases} \sum_i P_{i\to j} = 1 \\ \sum_{Z_i} P_{Z_i\to Z_j} = 1 \end{cases}$
Cumulative weight of all paths whose last 2 steps are $i \to j$ = *direct production* of j from *measured flux* i	$D_{i\to j} \equiv \begin{cases} P^{1-\text{step}}_{ij} + \sum_k^{k>i>j}\left(P^{2-\text{step}}_{kij} + \sum_p^{k>p>i>j}\left(P^{3-\text{step}}_{kpij} + \dots\right)\right) \\ = \dfrac{\psi_{\text{sec}}^{j,\,\text{ref}} - \psi_{\text{sec}}^{j,\, \sigma^{\text{cumul}}_{i\to j}=0}}{\psi_{\text{sec}}^{j,\,\text{ref}}} \end{cases}$ $D_{Z_i\to Z_j} \equiv \dfrac{1}{n_{Z_i} n_{Z_j}} \times \sum_{i\in Z_i}\sum_{j\in Z_j} D_{i\to j}$	$\begin{cases} \sum_i D_{i\to j} = 1 \\ \sum_{Z_i} D_{Z_i\to Z_j} = 1 \end{cases}$ ⇩ *Uniqueness and completeness of D coefficients*

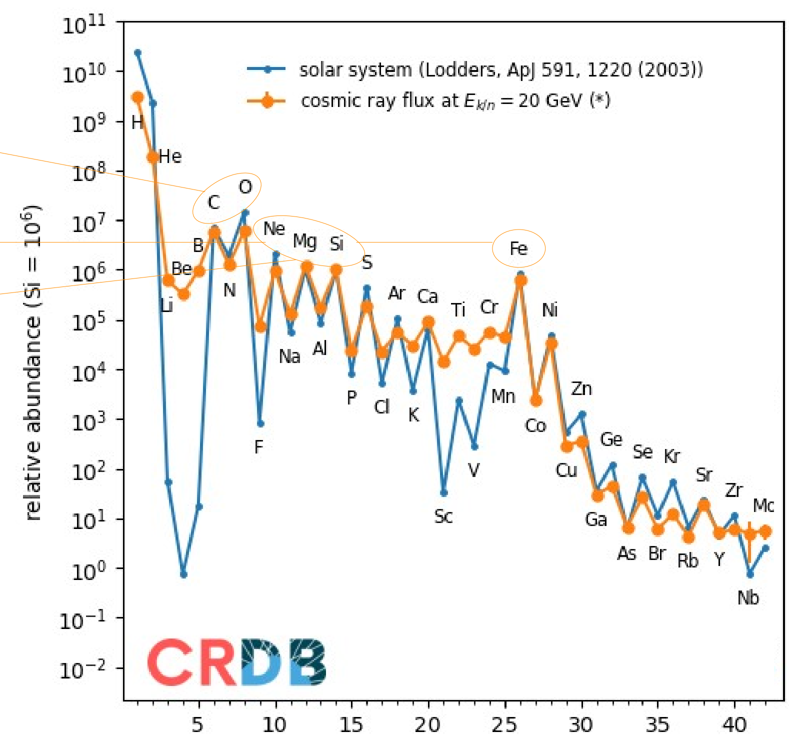


2) Ranking of production paths ($P^{1\ldots n\text{-step}}$ coefficients)

Qty / ranking	Definition	Property
Relative weight of a single production path (1-step or multi-step) linking CR i to j = *channels*	$P_{ij}^{1-\text{step}} \equiv \dfrac{\psi_{\text{sec}}^{j,\,\sigma_{m\to n}^{\text{cumul}}=0\ \forall(m,n)\neq(i,j)}}{\psi_{\text{sec}}^{j,\,\text{ref}}}$ $P_{ikj}^{2-\text{step}} \equiv \dfrac{\psi_{\text{sec}}^{j,\,\sigma_{m\to n}^{\text{cumul}}=0\ \forall(m,n)\neq\{(i,k),(k,j)\}}}{\psi_{\text{sec}}^{j,\,\text{ref}}}$ $P_{ikpj}^{3-\text{step}} \equiv \ldots$ $\ldots$	$\sum_i^{i>j}\left(P_{ij}^{1-\text{step}} + \sum_k^{i>k>j}\left(P_{ikj}^{2-\text{step}} + \sum_p^{i>k>p>j}(\ldots)\right)\right) = 1$ ⇨ *Uniqueness and completeness of paths* $\dfrac{P_{i\ldots\ldots j}^{(n+1)-\text{step}}}{P_{i\ldots\ j}^{n-\text{step}}} \propto R^{-\delta}$ (diffusion coeff. slope $\delta \approx 0.5$)

$$P_j^{>2-\text{step}} \equiv 1 - \sum_i^{i>j}\left(P_{ij}^{1-\text{step}} + \sum_k^{i>k>j} P_{ikj}^{2-\text{step}}\right)$$





→ Ranking favours most abundant CR species (weighted by production XS)

2) Ranking of P vs D coefficients (for Z=3-12 fluxes)

$\log_{10} = \begin{cases} 2.0 \rightarrow 100\% \\ 1.5 \rightarrow 31\% \\ 1.0 \rightarrow 10\% \end{cases}$

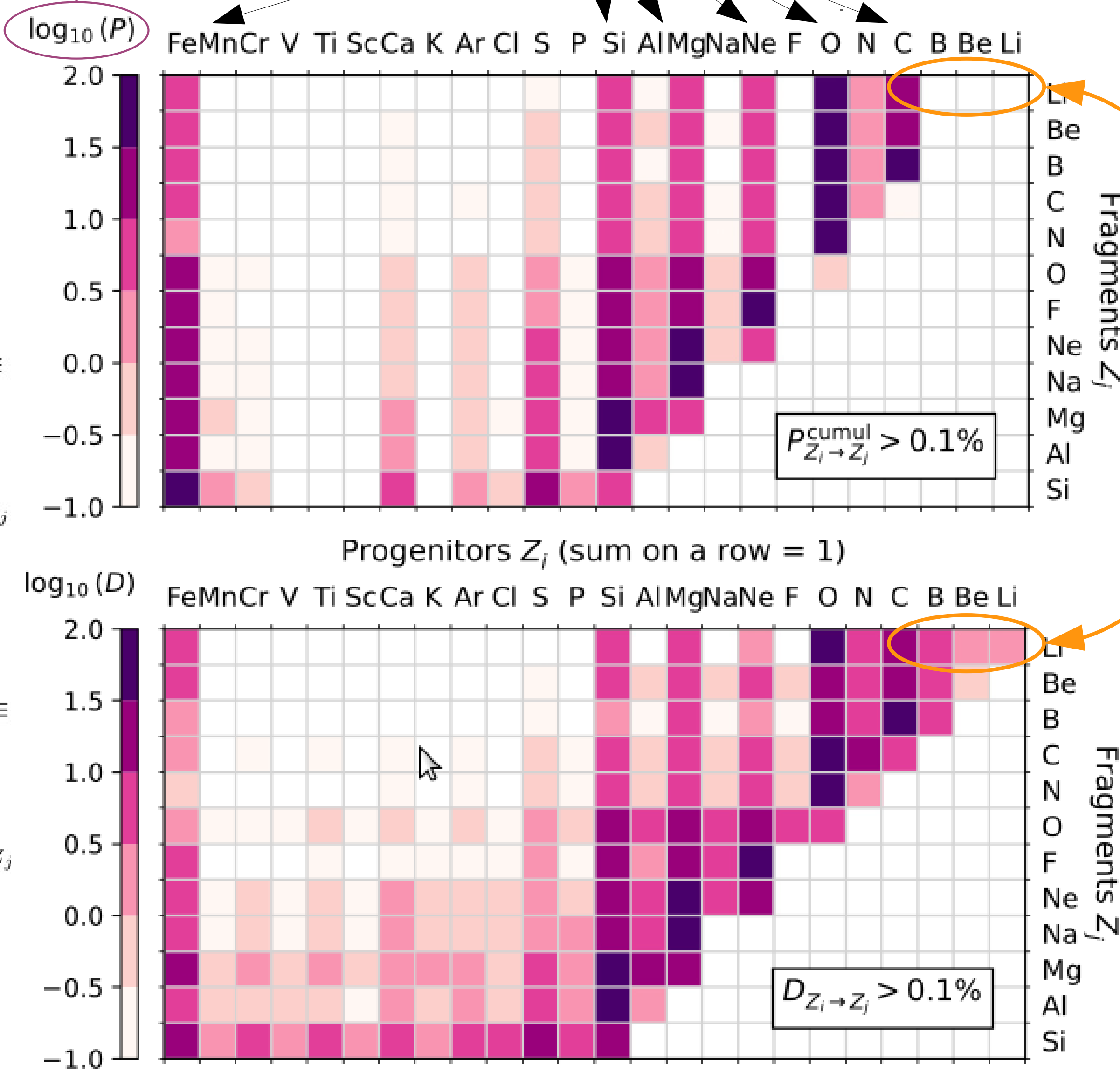
→ Primary species C, O, Ne, Mg, Si, and Fe most important progenitors

Cumulative weight of all paths linking $i \rightarrow j$ = *direct+indirect prod.* of j from *primary flux* i

$P_{i \rightarrow j} \equiv P_{Z_i \rightarrow Z_j}$

Cumulative weight of all paths whose last 2 steps are $i \rightarrow j$ = *direct production* of j from *measured flux* i

$D_{i \rightarrow j} \equiv D_{Z_i \rightarrow Z_j}$



LiBeB are pure secondaries... not in P but in D coeffs

2) Ranking of P vs D coefficients (for Z=3-12 fluxes)

$\log_{10} = \begin{cases} 2.0 \rightarrow 100\% \\ 1.5 \rightarrow 31\% \\ 1.0 \rightarrow 10\% \end{cases}$

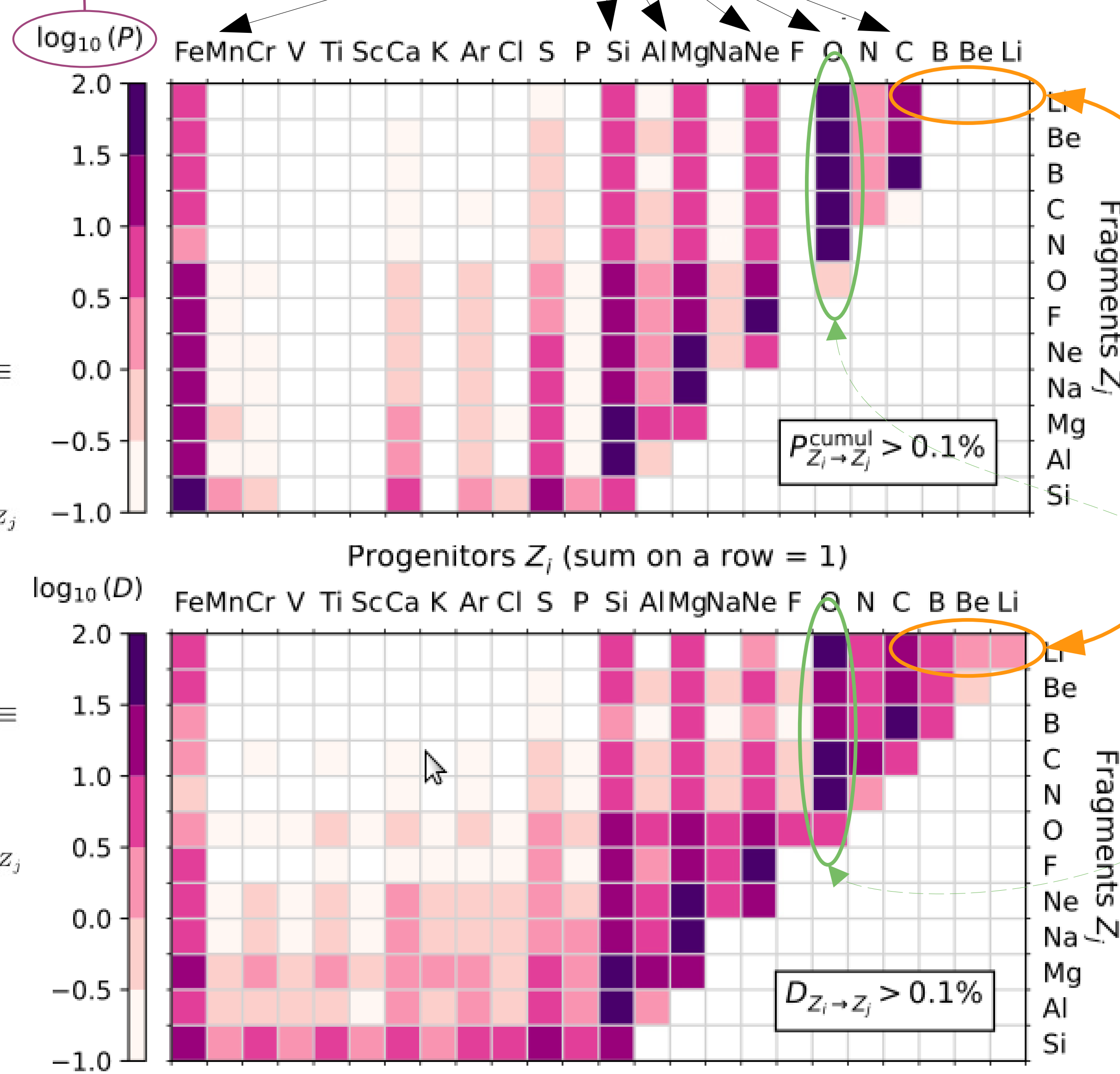
→ Primary species C, O, Ne, Mg, Si, and Fe most important progenitors

Cumulative weight of all paths linking $i \rightarrow j$ = *direct+indirect prod.* of j from *primary flux* i

$P_{i \rightarrow j} \equiv P_{Z_i \rightarrow Z_j}$

Cumulative weight of all paths whose last 2 steps are $i \rightarrow j$ = *direct production of* j *from measured flux* i

$D_{i \rightarrow j} \equiv D_{Z_i \rightarrow Z_j}$



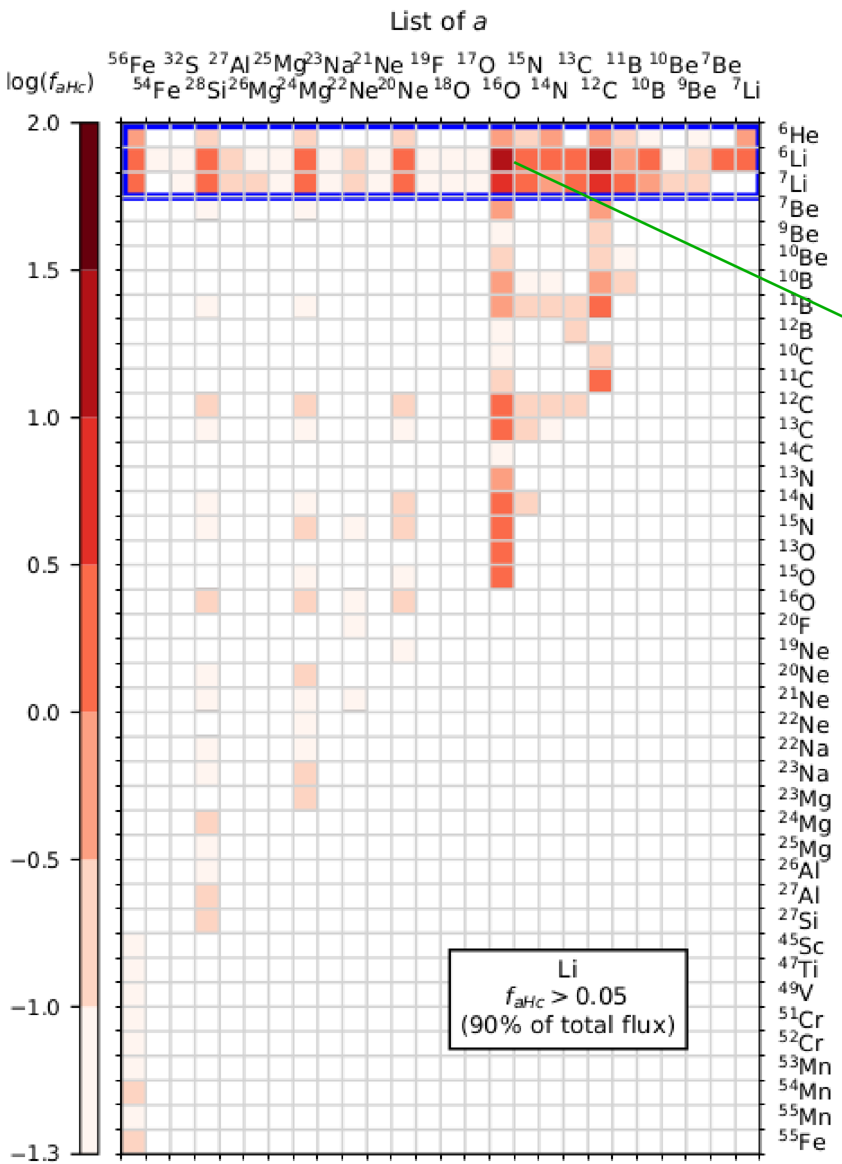
LiBeB are pure secondaries... not in P but in D coeffs

Primary O main progenitor of BeB, not seen in looking at D

2) Ranking of production XS (f_{abc} coefficients)

→ Network of ~1000 reactions (up to ^{56}Fe) to rank!

cumulative XS (account for short-lived nuclei)]

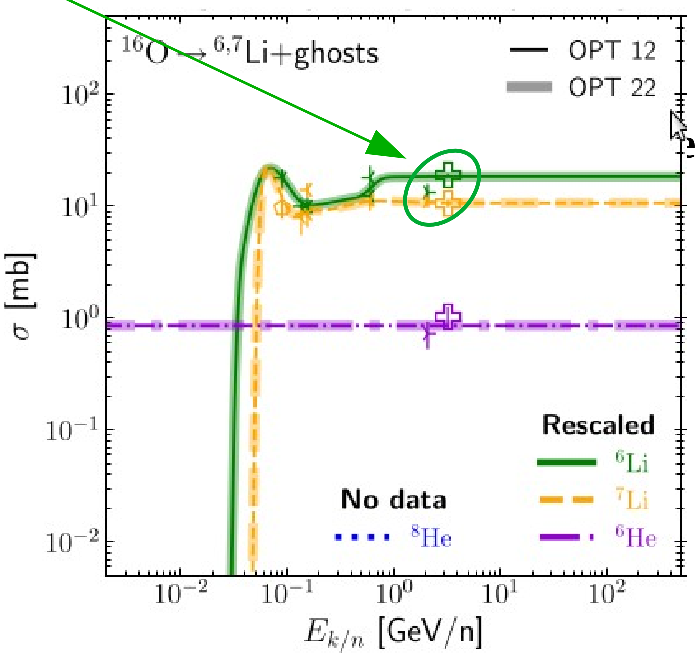


Impact of individual XS on CR flux = *flux impact*

$$f^j_{abc} = \frac{\psi^{j,\,\mathrm{ref}}_{\mathrm{sec}} - \psi^{j,\,\sigma_{a+b\to c}=0}_{\mathrm{sec}}}{\psi^{j,\,\mathrm{ref}}_{\mathrm{sec}}}$$

$$\sigma^{\mathrm{cumul}}_{a+b\to c} = \sigma_{a+b\to c} + \sum_g \mathcal{B}r_g \cdot \sigma_{a+b\to g}$$

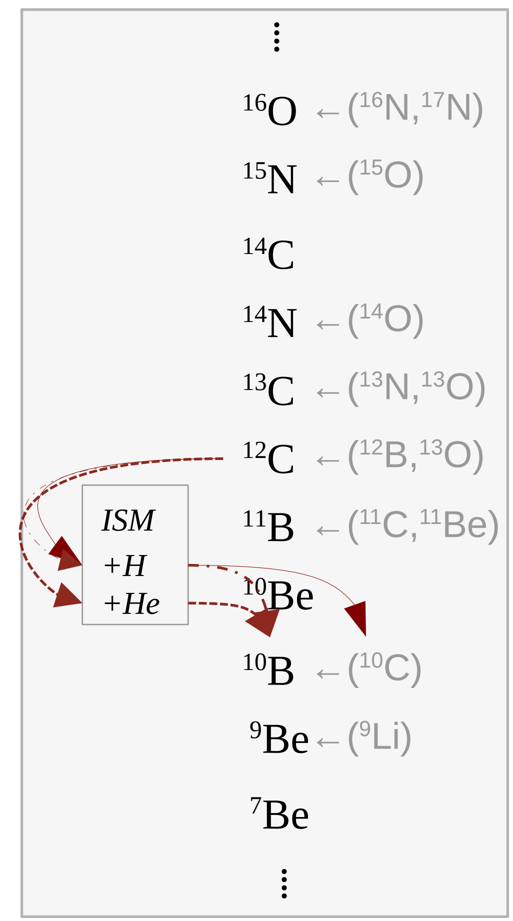
Illustration of limitation of current nuclear data and models



^{16}O+H → ^{6}Li (σ~20 mb) ⇔ 16% of Li

→ **based on 2 inconsistent data**

Ghosts (=short-lived) nuclei



$$\sum_{\forall(a,b,c)} f^j_{abc} \gtrsim 1$$

(owing to double counting in multi-step prod.)

3) Error on flux: quantitative improvement

Assumption on existing or future XS uncertainties	Error propagation formula on propagated flux
Fragments multinomially distributed = all fragments of interaction measured in exp. *(precision better than ξ on $(\Delta\psi_{\rm tot}/\psi_{\rm tot})$ for minimal number of interactions $N_{\rm tot}=\sum_{a,b} N_{ab}$ if each N_{ab} ensures $N_{ab}\geq (f_{\rm sec}^2/\xi^2)\times C_{ab}\times\sum_{a,b} C_{ab}$*	$\left(\frac{\Delta\psi_{\rm tot}}{\psi_{\rm tot}}\right)^{\rm multi}\approx f_{\rm sec}\sqrt{\sum_{a,b}\frac{1}{N_{ab}}C_{ab}^2}$ with $C_{ab}^2\equiv\sum_c f_{abc}^2\frac{\sigma_{a+b}^{\rm inel}}{\sigma_{a+b\to c}}$

→ C_{ab} for more realistic estimate of flux improvement
→ forecast for # of reacs (beam time calc.) to reach 3% precision on modelled flux (to be on par with AMS-02)

3) Error on flux: quantitative improvement

Assumption on existing or future XS uncertainties	Error propagation formula on propagated flux
Fragments multinomially distributed = all fragments of interaction measured in exp. (*precision better than* ξ *on* $(\Delta\psi_{\rm tot}/\psi_{\rm tot})$ *for minimal number of interactions* $N_{\rm tot}=\sum_{a,b}N_{ab}$ *if each* N_{ab} *ensures* $N_{ab}\geq(f^2_{\rm sec}/\xi^2)\times C_{ab}\times\sum_{a,b}C_{ab}$)	$\left(\frac{\Delta\psi_{\rm tot}}{\psi_{\rm tot}}\right)^{\rm multi}\approx f_{\rm sec}\sqrt{\sum_{a,b}\frac{1}{N_{ab}}C^2_{ab}}$ with $C^2_{ab}\equiv\sum_c f^2_{abc}\frac{\sigma^{\rm inel}_{a+b}}{\sigma_{a+b\to c}}$

→ C_{ab} for more realistic estimate of flux improvement
→ forecast for # of reacs (beam time calc.) to reach 3% precision on modelled flux (to be on par with AMS-02)

Li		Be		B		C	
$a+b$	C_{ab}	$a+b$	C_{ab}	$a+b$	C_{ab}	$a+b$	C_{ab}
^{16}O + H	0.841	^{16}O + H	1.079	^{12}C + H	0.802	^{16}O + H	1.054
^{12}C + H	0.684	^{12}C + H	0.928	^{16}O + H	0.690	^{16}O + He	0.185
^{16}O + He	0.176	^{16}O + He	0.216	^{12}C + He	0.147	^{24}Mg + H	0.125
^{56}Fe + H	0.165	^{28}Si + H	0.200	^{16}O + He	0.130	^{15}N + H	0.116
^{28}Si + H	0.143	^{24}Mg + H	0.200	^{11}B + H	0.103	^{28}Si + H	0.110
^{12}C + He	0.140	^{56}Fe + H	0.188	^{28}Si + H	0.098	^{14}N + H	0.104
^{24}Mg + H	0.135	^{12}C + He	0.181	^{24}Mg + H	0.098	^{20}Ne + H	0.092
^{11}B + H	0.114	^{11}B + H	0.147	^{15}N + H	0.093	^{13}C + H	0.083
^{15}N + H	0.105	^{14}N + H	0.120	^{56}Fe + H	0.085	^{56}Fe + H	0.068
^{13}C + H	0.098	^{20}Ne + H	0.117	^{14}N + H	0.082		
^{14}N + H	0.091	^{15}N + H	0.115	^{13}C + H	0.074		
^{20}Ne + H	0.086	^{13}C + H	0.092	^{20}Ne + H	0.066		
^{10}B + H	0.057	^{10}B + H	0.078				
^{7}Li + H	0.057	^{56}Fe + He	0.058				
^{56}Fe + He	0.053	^{22}Ne + H	0.054				

3) Error on flux: quantitative improvement

Assumption on existing or future XS uncertainties	Error propagation formula on propagated flux
Fragments multinomially distributed = all fragments of interaction measured in exp. (*precision better than* ξ *on* $(\Delta\psi_{\rm tot}/\psi_{\rm tot})$ *for minimal number of interactions* $N_{\rm tot}=\sum_{a,b} N_{ab}$ *if each* N_{ab} *ensures* $N_{ab}\geq(f^2_{\rm sec}/\xi^2)\times C_{ab}\times\sum_{a,b} C_{ab}$)	$\left(\frac{\Delta\psi_{\rm tot}}{\psi_{\rm tot}}\right)^{\rm multi}\approx f_{\rm sec}\sqrt{\sum_{a,b}\frac{1}{N_{ab}}C^2_{ab}}$ with $C^2_{ab}\equiv\sum_c f^2_{abc}\frac{\sigma^{\rm inel}_{a+b}}{\sigma_{a+b\to c}}$

→ C_{ab} for more realistic estimate of flux improvement
→ forecast for # of reacs (beam time calc.) to reach 3% precision on modelled flux (to be on par with AMS-02)

Li $a+b$	Li C_{ab}	Be $a+b$	Be C_{ab}	B $a+b$	B C_{ab}	C $a+b$	C C_{ab}
^{16}O + H	0.841	^{16}O + H	1.079	^{12}C + H	0.802	^{16}O + H	1.054
^{12}C + H	0.684	^{12}C + H	0.928	^{16}O + H	0.690	^{16}O + He	0.185
^{16}O + He	0.176	^{16}O + He	0.216	^{12}C + He	0.147	^{24}Mg + H	0.125
^{56}Fe + H	0.165	^{28}Si + H	0.200	^{16}O + He	0.130	^{15}N + H	0.116
^{28}Si + H	0.143	^{24}Mg + H	0.200	^{11}B + H	0.103	^{28}Si + H	0.110
^{12}C + He	0.140	^{56}Fe + H	0.188	^{28}Si + H	0.098	^{14}N + H	0.104
^{24}Mg + H	0.135	^{12}C + He	0.181	^{24}Mg + H	0.098	^{20}Ne + H	0.092
^{11}B + H	0.114	^{11}B + H	0.147	^{15}N + H	0.093	^{13}C + H	0.083
^{15}N + H	0.105	^{14}N + H	0.120	^{56}Fe + H	0.085	^{56}Fe + H	0.068
^{13}C + H	0.098	^{20}Ne + H	0.117	^{14}N + H	0.082		
^{14}N + H	0.091	^{15}N + H	0.115	^{13}C + H	0.074		
^{20}Ne + H	0.086	^{13}C + H	0.092	^{20}Ne + H	0.066		
^{10}B + H	0.057	^{10}B + H	0.078				
^{7}Li + H	0.057	^{56}Fe + He	0.058				
^{56}Fe + He	0.053	^{22}Ne + H	0.054				

Reaction	$N_{\rm int}$
^{16}O + H	60k
^{12}C + H	50k
^{16}O + He	20k
^{11}B + H	10k
^{15}N + H	10k
^{14}N + H	10k
^{12}C + He	10k
^{10}B + H	5k
^{13}C + H	5k
^{7}Li + H	5k
	$N(\leqslant {\rm O}) = 1.9\times10^5$
^{28}Si + H	50k
^{24}Mg + H	50k
^{20}Ne + H	50k
^{22}Ne + H	20k
^{28}Si + He	10k
^{27}Al + H	10k
^{26}Mg + H	10k
^{24}Mg + He	10k
^{23}Na + H	10k
^{25}Mg + H	10k
^{21}Ne + H	10k
^{20}Ne + He	10k
^{32}S + H	5k
^{29}Si + H	5k
^{22}Ne + He	5k
	$N(\leqslant {\rm Si}) = 3.8\times10^5$
^{56}Fe + H	30k
^{56}Fe + He	10k
	$N(\leqslant {\rm Fe}) = 4.2\times10^5$