Nuclear fragmentation and GCR phenomenology

I. GCR propagation and nuclear physics
II. Cross-section models used and issues
III. How uncertainties impact on GCR physics
IV. Conclusions and other issues

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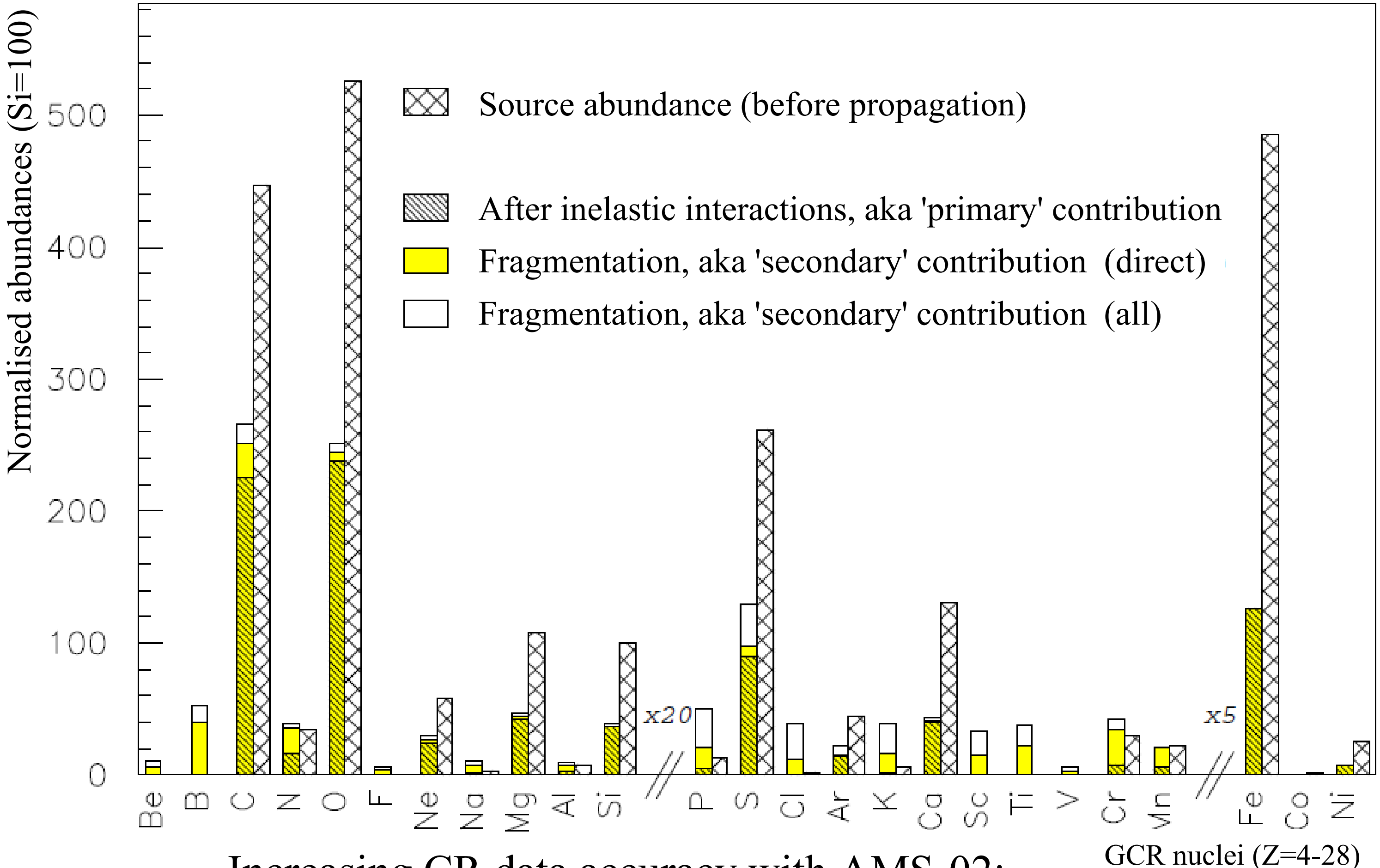
Nuclear physics for GCRs in the AMS-02 era
3/12/2012

Primary and secondary content in GCRs (1 GeV/n)

NB: at higher energy, grammage decreases
(escape rate from Galaxy > interaction rate)



Increasing CR data accuracy with AMS-02:

→ requires better precision on X-sections

→ rarer channels must be taken into account

(main channels depend on [GCR abund * ISM abund * x-sec])

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Inelastic cross sections ($\sigma_R = \sigma^{tot} - \sigma^{tot}_{ela}$)

- Bradt & Peters (1950)

$$\sigma_R = \pi r_o^2 (A_{proj}^{1/3} + A_{cible}^{1/3} - b_0)^2$$

- Letaw *et al.* (1970-2000): accuracy <2% for 2<Z<30 and E>300MeV/n

S.Barshay & al, Phys.Lett **51B**, 5 (1974)
J.R.Letaw & al, ApJSS **51**, 271 (1983)
R.Silberberg & C.H Tsao, Phys.Rep. **191**, 351 (1990)
L.Sihver & al, Phys.Rev.C **47**, 1225 (1993)
H.P.Wellish & D.Axen, Phys.Rev.C **54**, 1329 (1996)
R.Silberberg & al, ApJ **501**, 911 (1998)
C.H.Tsao & al, ApJ **501**, 920 (1998)

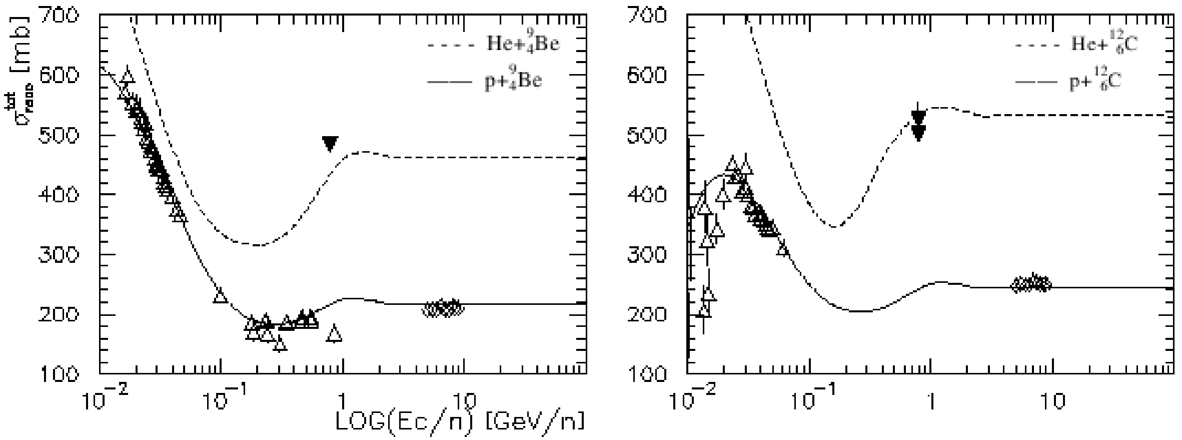
$$\sigma_R(E_k) = \sigma_R^{HE} \left[1 - 0.62 \exp(-E_k/200) \sin(10.9 E_k^{-0.28})\right] \ (mb)$$

$$\sigma_R^{HE} = 45 A^{0.7} \left[1 + 0.016 \sin(5.3 - 2.63 \ln A)\right] \ (mb)$$

- Tripathi *et al.* (~2000): ~ or better (at low E) than Letaw *et al.*, valid for all N+N reaction!

R.K.Tripathi & al, NASA, Technical Paper **3621**, (1997)
R.K.Tripathi & al, NASA, Technical Paper **3656**, (1997)
R.K.Tripathi & al, NASA, Technical Paper **209726**, (1999)

$$\sigma_R = \pi r_0^2 \left(A_{proj}^{1/3} + A_{cible}^{1/3} + \delta_E\right)^2 \left(1 - R_c \frac{B}{E_{cm}}\right) X_m$$



Data from compilations:
Bobchenko 79, Tanihata 85,
Bauhoff 86, Carlson 96

→ Tripathi *et al.* is the one generally used in the field

Production cross sections (straight-ahead approx.)

$$\int_0^\infty n_{\rm H}\, v' N^k(T')\sigma^{kj}(T,T')dT' = \int_0^\infty n_{\rm H}\, v' N^k(T')\sigma^{kj}(T)\delta(T-T')dT' = n_{\rm H}\, v N^k(T)\sigma^{kj}(T)$$

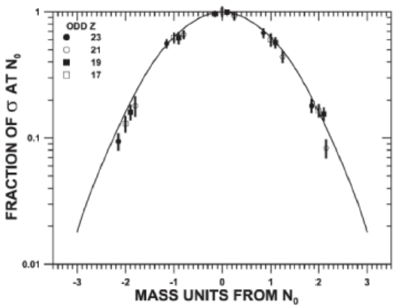
- Semi-empirical approach [Silberberg et Tsao]

- for any Proj. + Targ. → Frag.
- better than Webber if extrapolation (Z>30)

R.Silberberg & C.H.Tsao, ApJSS **25**, 315 (1973)
R.Silberberg & C.H.Tsao, ApJSS **35**, 129 (1977)
R.Silberberg & C.H.Tsao, ApJSS **35**, 137 (1977)
R.Silberberg & al, ApJSS **58**, 877 (1985)
R.Silberberg & C.H Tsao, Phys.Rep. **191**, 351 (1990)
L.Sihver & al, Phys.Rev.C **47**, 1225 (1993)
C.H.Tsao & al, Phys.Rev.C **47**, 1257 (1993)
C.J.Waddington, ApJ **470**, 1218 (1996)
R.Silberberg & al, ApJ **501**, 911 (1998)
C.H.Tsao & al, ApJ **501**, 920 (1998)
C.H.Tsao & al, ICRC **26**, HE.1.1.04 (1999)

- Empirical approach [Webber et al.]

- for Proj. + H/He → Frag.
- better than Silberberg on 'data' (Z<30)



P.Ferrando & al, Phys.Rev.C **37**, 1490 (1988)
W.R.Webber, J.C.Kish, D.A.Schrier, Phys.Rev C 41
W.R.Webber & al, ApJ **508**, 940 (1998-a)
W.R.Webber & al, ApJ **508**, 949 (1998-b)
W.R.Webber & al, Phys.Rev.C **58**, 3539 (1998-c)
W.R. Webber et al., ApJSS 144, 153 (2003)

More this afternoon?

- More recent empirical codes

- EPAX2 *http://www-w2k.gsi.de/hellstr/asp/gsi/epaxv21m.asp*
- PHITS *phits.jaea.go.jp*

- Microscopic description

- LAQGSM (Los Alamos Quark Gluon String Model)
- NUCFRG2 (semi-empirical abrasion-ablation model)

L.W.Townsend & al, NASA, Technical Paper **3310**, (1993)
F.A.Cucinotta, NASA, Technical Paper **3354**, (1993)
J.P.Bondorf & al, Phys.Rep. **257**, 133 (1995)
J.W.Wilson & al, NASA, Technical Paper **3533**, (1995)
F.A.Cucinotta & al, NASA, Technical Paper **3594**, (1996)
C.R.Ramsey & al, Phys.Rev.C **57**, 982 (1998)
Zeitlin et al., Phys. Rev. C **77**, 034605 (2008)
Zeitlin et al., AdSR 46, 728 (2010)
Zeitlin et al., Phys. Rev. C **83**, 034909 (2011)

→ Webber *et al.* is the one generally used in the field (but for Z<3 nuclei) with claimed uncertainties <10% (fragments from Li → O) or <20% (from Fe)

NB: it is not straightforward to go from nuclear data/models to X-sec for GCRs

From nuclear data to prod. X-sec used in GCRs

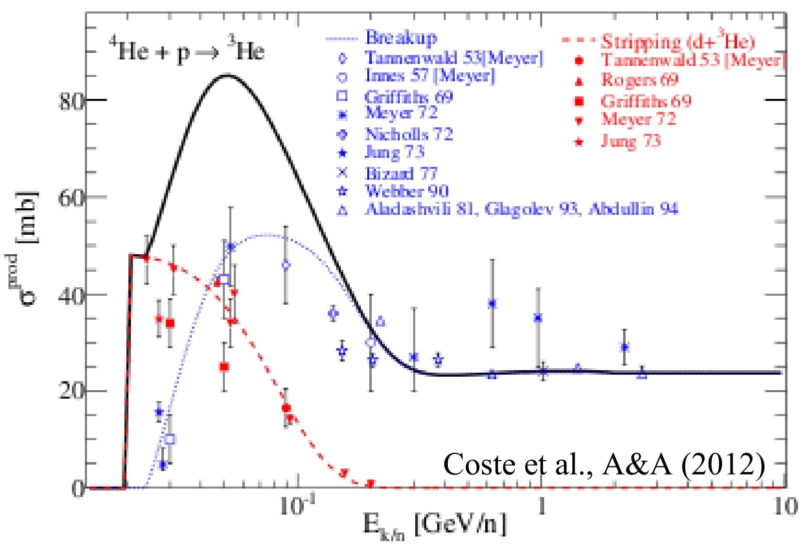
- **Step 1**: build decay chains from 'raw' nuclear properties
[e.g., Letaw et al., ApJSS 51, 271 (1983), Maurin (2001)]

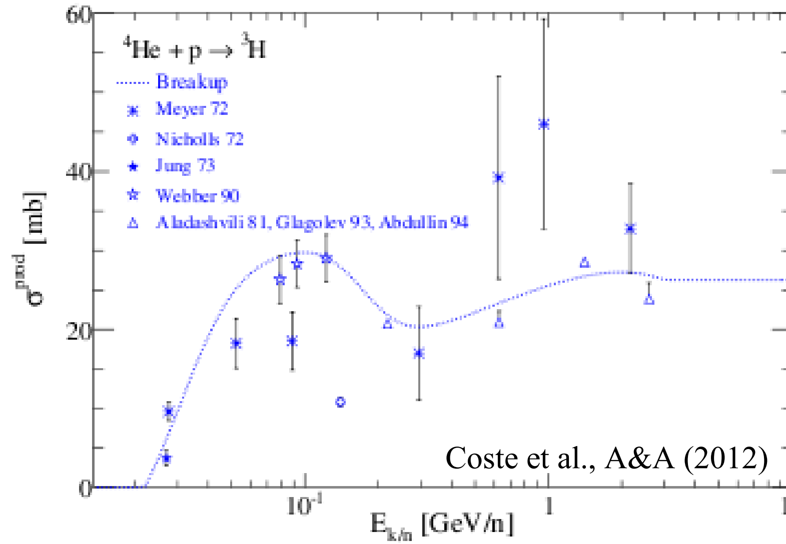
NUBASE: a database of nuclear and decay properties,
Audi et al., Nuclear Physics A 624, 1 (2003)

$$\sigma_{\rm cumul}^{\rm Proj+Targ \rightarrow X}(t_{\rm cumul}, E) = \sigma^{\rm P+T \rightarrow X} + \sum_i \mathcal{B}r(i)\, \sigma^{\rm P+T \rightarrow X_i \xrightarrow{(t_{1/2}<t_{\rm cumul})} X}(E)$$

- **Step 2**: calculate cumulative X-sec from decay chains and model/parameterisation

$$\rightarrow \text{A simple case: } \sigma_{\rm cumul}^{\rm 3He}(t_{\rm confinement\sim 20Myr}) = \sigma^{\rm 3He} + \sigma^{\rm 3H \xrightarrow[100\%]{12.2\,yr} 3He}$$





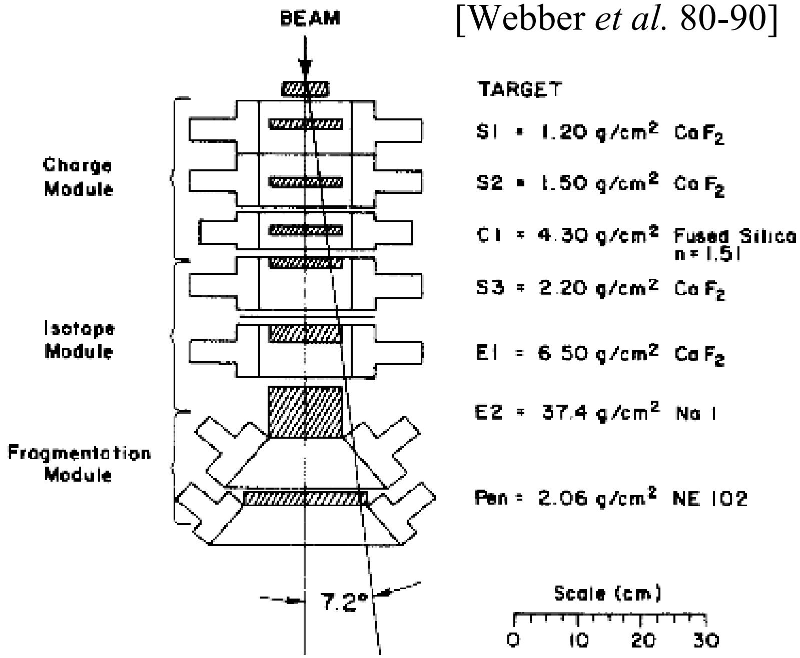
NB: Models are based on data that are themselves cumulative X-sections: caution is required!

But what exactly is measured?

- Different time-of-flight → not the same cumulative cross section measured
- Target not always the one we need → indirect 'measurement'

- LBL Bevalac: CH2, He, C

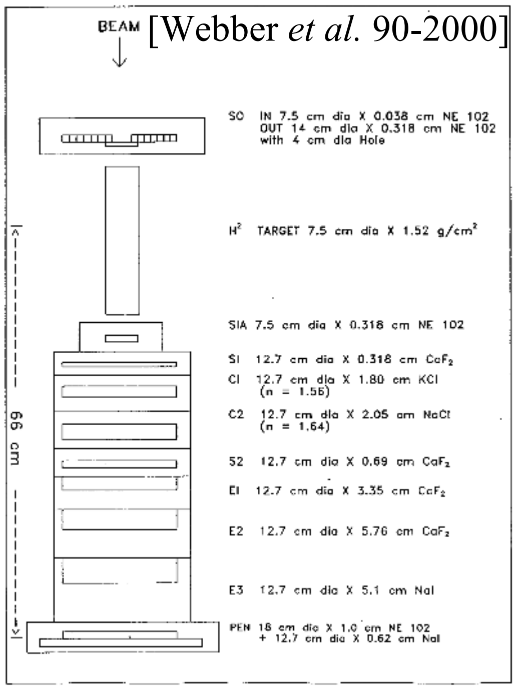
[Webber *et al.* 80-90]



$t_{flight} \sim 1$ ns

- SATURNE Saclay: liquid H^2

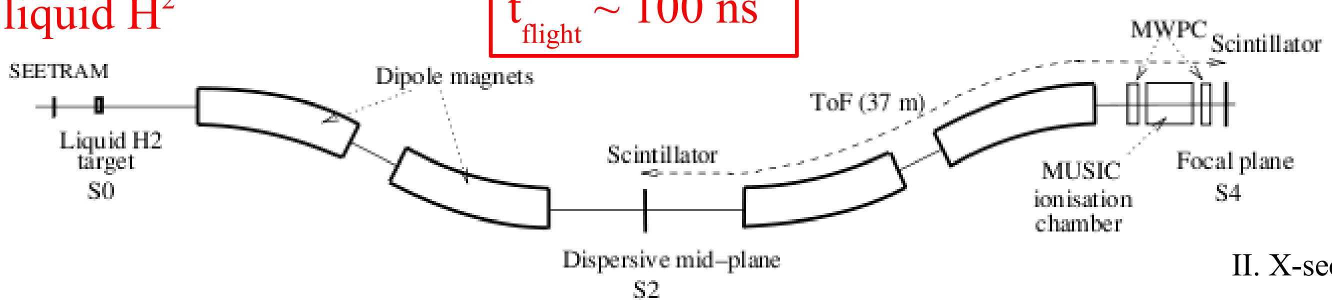
[Webber *et al.* 90-2000]



- GSI Darmstadt: liquid H^2

[Villagrasa *et al.* 2007]

$t_{flight} \sim 100$ ns



+ irradiation measurements and tricky isomers!

- Irradiated targets and chemical extraction (meteorite community)

Michel et al., NIMPR B 103, 183 (1995)

- systematic investigation (700 thin-target cross sections) of p-induced reactions (0.8-2.6 GeV)
-Target elements (C, N, 0, ..., Ni, Cu...Au), LAMPF/Los Alamos and Saturne/Saclay

→ residual nuclides investigated cover γ-emitting radionuclides with half-lives between 15 h and 50 yrs, and long-lived ^{10}Be, ^{26}Al and ^{36}Cl...

- Irradiation vs direct (Michel vs Webber): radioactive GCR clock ^{26}Al

- ^{26}Al (τ~0.87 Myr) has an isomeric state ^{26}Al* with a decay time of 6.3 s

$\rightarrow \sigma^{28Si\rightarrow 26Al,\ 27Si\rightarrow 26Al}$ (Michel) ~ 0.72 $\sigma^{28Si\rightarrow 26Al,\ 27Si\rightarrow 26Al}$ (Webber)

NB: mess with the cumulative if (i) return to fundamental which is a long-lived state; (ii) returns to a different nucleus.

- Most measurements within 10%–15%
- ^{26}Al, ^{22}Na, ^{21}Ne, ^{20}Ne, ^{7}Be fragments ~ 30% or more
- Presence of long-lives isomers ^{26}Al, ^{44}Sc, and possibly ^{57}Ni

NB: monitor cross sections (^{22}Na, ^{7}Be) used in Michel [EU] to determine the integrated beam intensities differs from those measured by Webber [US]

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X-sec uncertainties: impact on GCR model parameters

Input: X-sections → **Minimisation**: Propagation model: free parameters δ, K_0, V_a; GCR data: B/C data from HEAO-3 (1979) → **Output**: Best-fit parameters

Maurin, Putze & Derome, A&A **516**, 67(2010)

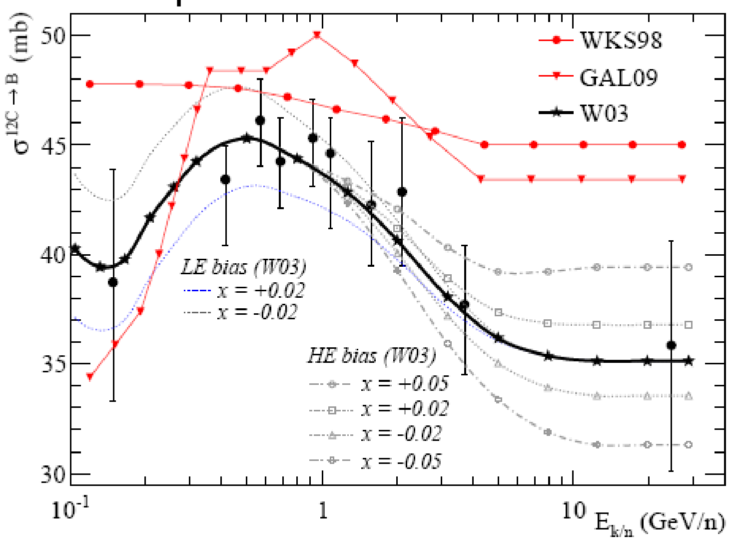
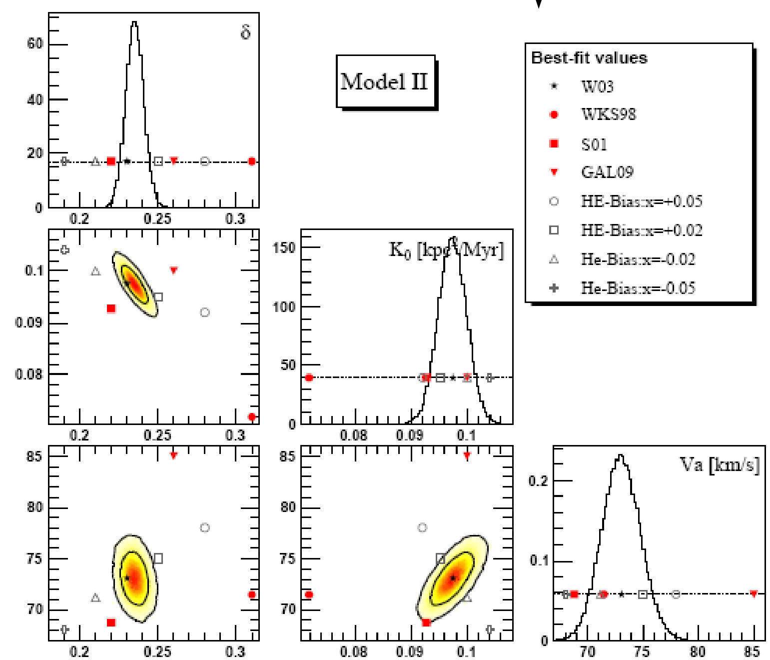


Fig. 3. Production cross-section for ^{12}C+H→^{10,11}B (adapted from Webber et al. 2003). The standard sets are shown as solid lines (WKS98: red dots; GAL09: red down triangles; W03: black stars), and the biased sets in dotted ($|x| = 0.02$) and dashed ($|x| = 0.05$) lines.



- W03 and WKS98 are parameterisations of the same 'data' (energy bias)
- GAL09: modern nuclear codes normalised to LANL database [Moskalenko & Mashnik, astro-ph/0306367]

→ Systematics uncertainties (from X-sec) > statistical uncertainties (from GCR data)

… and AMS-02 is at least 100 better than HEAO-3!

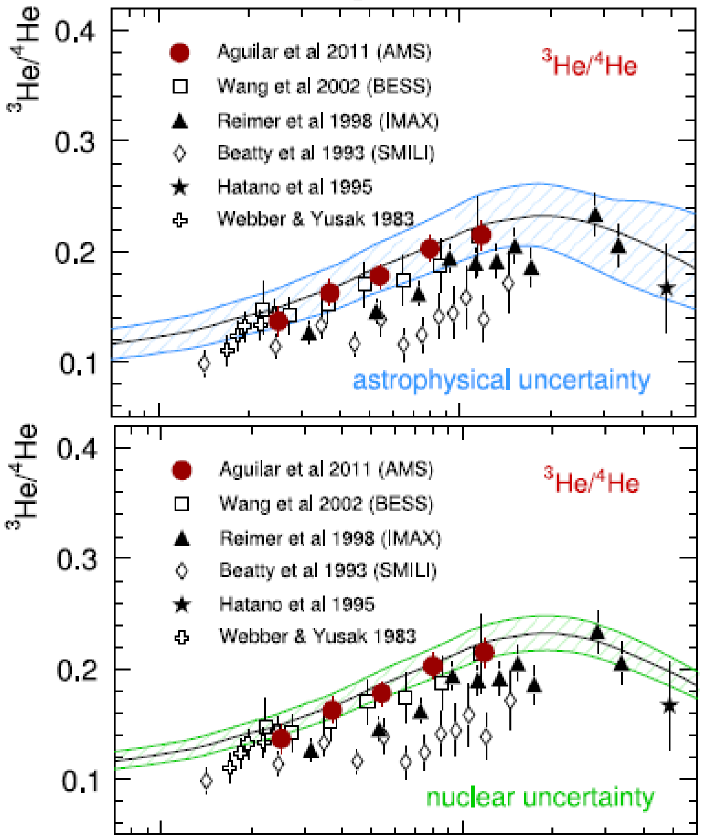
III. Uncertainties are too large!

X-sec for light nuclei: similar issues + new ones

→ similar results shown for another secondary/primary GCR ratio

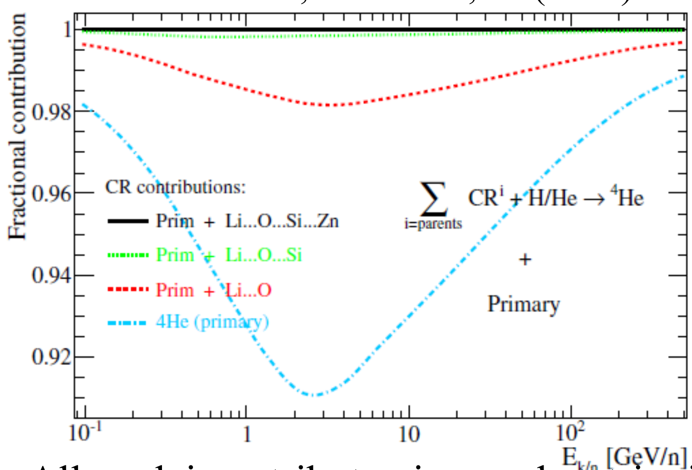
→ If GCR data accurate enough (<1%), secondary content of a 'primary' must also be accounted for!

Tomassetti, ApSS **342**, 131 (2012)



^4He

Coste et al., A&A **539**, 88 (2012)



^1H → All nuclei contribute via n and p stripping!

Webber *et al.* (2003)

1. For neutron stripping (σ in mbarn),

$$1n: \quad \sigma = (4.4 + 0.91 N_{Zi})(5.9 + 0.10 Z_i) \times \left[1 - \frac{Z_i - (16.5 + 1.6 N_{Zi})}{16.5}\right]$$

$$2n: \quad \sigma = 1.1\left[1 + (Z_i - 4)/20\left(11.4 - Z_i^{0.7}\right)0.7 N_{Zi}\right] ,$$

$$3n: \quad \sigma = 0.2\left[1 + \left(7.5 - Z_i^{0.5}\right) N_{Zi}\right] .$$

2. For proton stripping (σ in mbarn),

$$1p: \quad \sigma = 0.50 \sigma_{Zf} (0.68 - 0.04 N_{Zi}) ,$$

$$2p: \quad \sigma = 1.85 + [2.5(Z_f + 2) - 23.0](1 - 0.23 N_{Zi}) .$$

→ certainly too simplistic!

NB: considering different secondary/primary ratios ($^2H/^4He$, $^3He/^4He$, LiBeB/C, sub-Fe/Fe) is a way to 'keep under control' production cross sections uncertainties

Relaxing the straight-ahead approximation?

→ Energy of fragments follows a Gaussian?

Cucinotta et al., NASA-TR-3285 (1993)

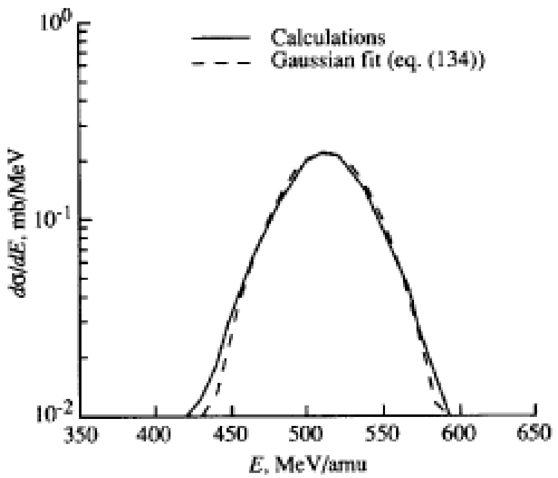
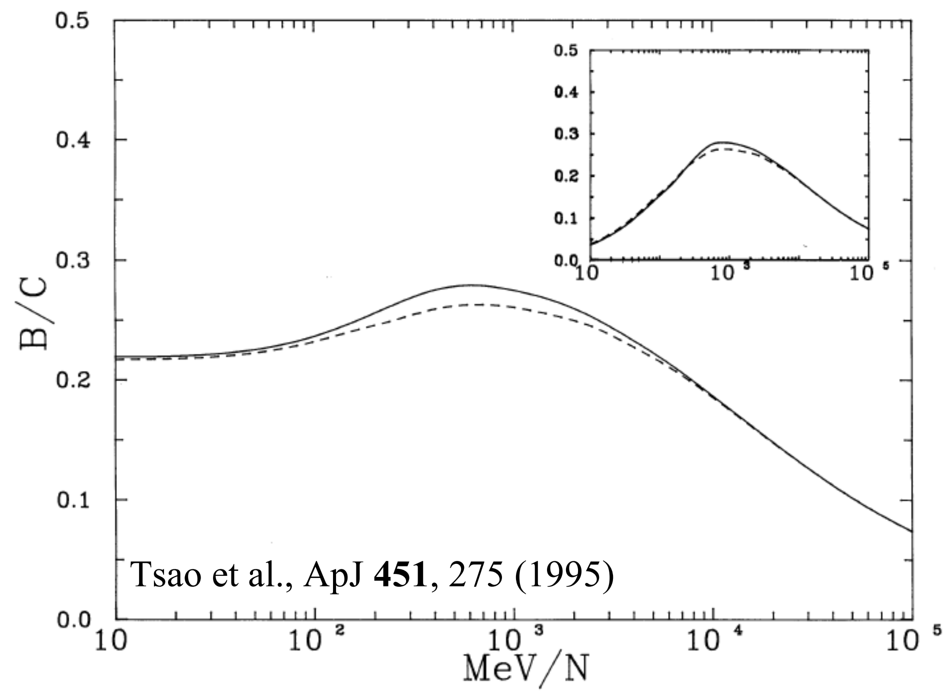


Figure 37. Comparison of calculation of energy spectrum for $^4He+^{12}C \rightarrow {}^3H+X$ at 520A MeV with Gaussian fit of equation (134).

→ Consequences on B/C: w/o straight-ahead approximation, difference ≤10%

Tsao et al., ApJ **451**, 275 (1995)
Kneller et al., ApJ **589**, 217 (2003)



→ Probably a good idea to investigate further

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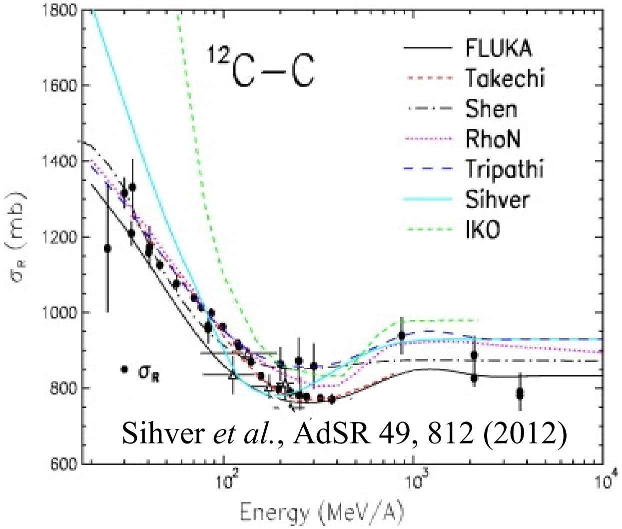
Conclusions and questions (I)

1. Inelastic

- Should we use Tripathi *et al.* or something else?
- Should we believe the claimed <2-5% accuracy, or is it a 5% accuracy on scattered data?

Unclear: what precision do we need for AMS-02 data?



Sihver *et al.*, AdSR 49, 812 (2012)

2. Fragmentation/spallation

- **Decay chains and cumulative**
  - Decay chain lists 'well' known (though confusions EC/β decay for Z>30)
  - In principle not that many isotopes contribute (strong interaction instantaneous < ms)
  - Do we know all long-lived isomeric states (probably not many existing)?

- **Cross sections**
  - Should we use Webber *et al.* or something else?
  - Should we believe the claimed <10% accuracy, or is it 5% on scattered data?
  - Issue of 'monitor' cross sections

To do: we have to establish systematically with current X-sec models, what are the channels required to reach, say a x% accuracy [work in progress]

Conclusions and questions (II)

- **Deserves further investigation**

- How to relax straight-ahead approximation?
- n and p stripping from Webber too simplistic (contributions to p GCR flux)

To do: evaluate whether these two ingredients are necessary or not [collaborations welcome!]

3. Other stuff (not presented)...

NB: X-sec for e^- attachment and stripping also useful!
EC-decay channel blocked (GCRs fully stripped above GeV/n)

G.M.Raisbeck & al, ICRC **15**, 67 (1978)
L.W.Wilson, ICRC **15**, 274 (1978)
J.R.Letaw & al, ApJSS **56**, 369 (1984)

⇨ Is there something better ?

We need experts to help us, because
- it is difficult to search in databases
- it is difficult to know what's relevant and what's not
- sometimes we just don't know what we don't know!

→ with expected accuracy of AMS-02 data, room for lot of improvement
→ collaborations welcome to tackle these problems