Neutron Monitors (NM) for solar modulation studies: systematic uncertainties and ϕ time series

Workshop

"Solar Energetic Particles (SEP), Solar Modulation and Space Radiation: New Opportunities in the AMS-02 Era"

1. Introduction
2. ϕ from CR data or ground-based detectors
3. Count rates: uncertainties on ingredients
4. Δ(ingredients) → $\Delta N/N$ → $\Delta\phi/\phi$
5. Determination of ϕ : normalization issues
6. Conclusion and perspectives

Based on

Maurin *et al.*, AdSpR 55, 363 (2015)

Ghelfi *et al.* (in prep.)

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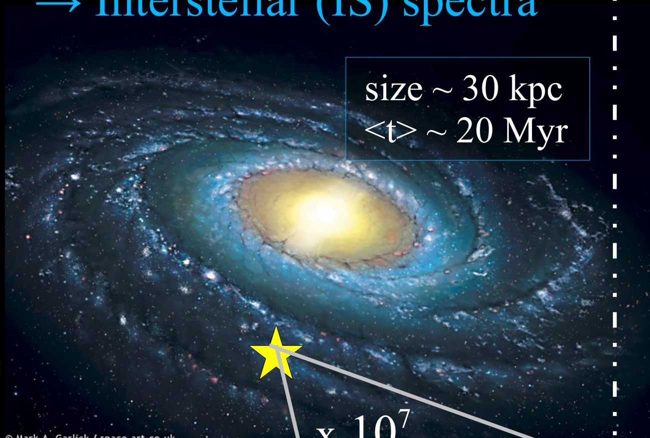
10/20/2015

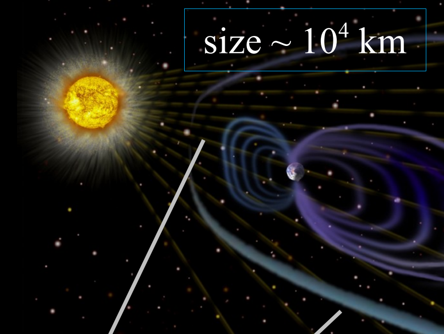
1. Introduction: CRs + modulation + Rc + atmosphere

1. Transport in the Galaxy
→ Interstellar (IS) spectra

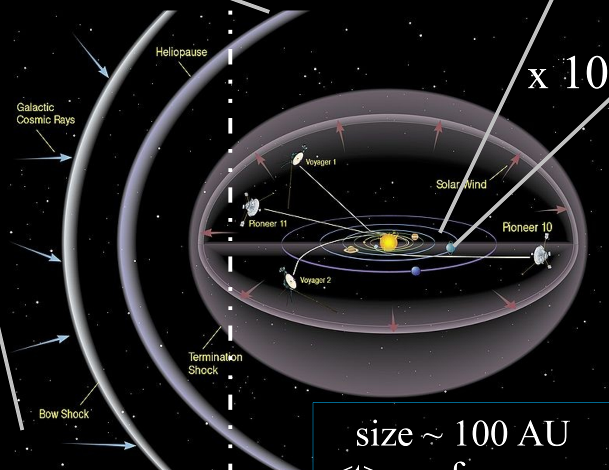


x 10^7

3. Earth magnetic shield
→ Cut-off rigidity R_c (at Earth)

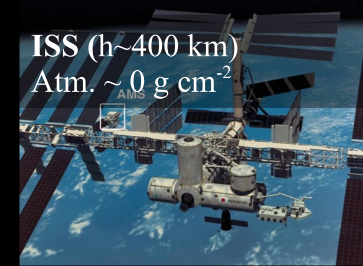


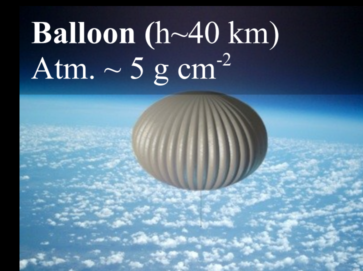
x 10^5

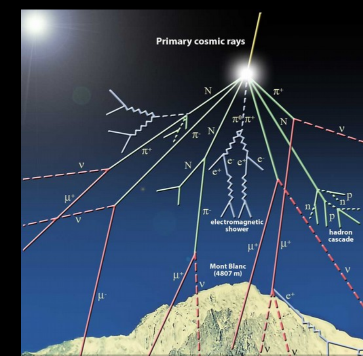


size ~ 100 AU
<t> ~ a few years

2. Transport in the Solar cavity
→ modulate CRs (< 10 GeV/n)







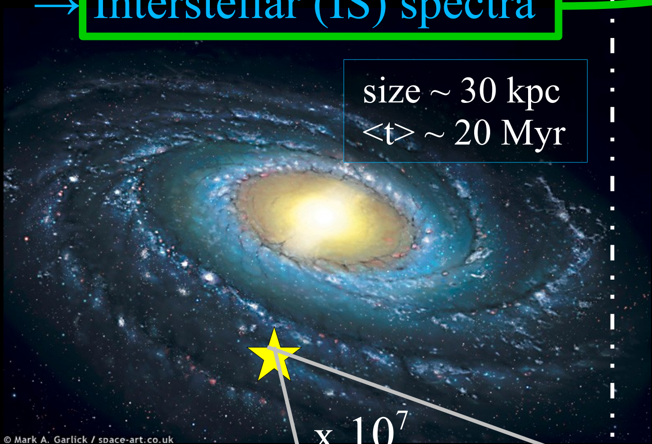
4. Atmosphere
→ CR showers

[time-independent]

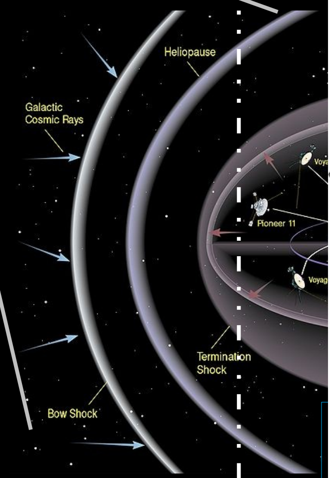
[time-dependent]

1. Introduction: IS fluxes, TOA fluxes, and count rates

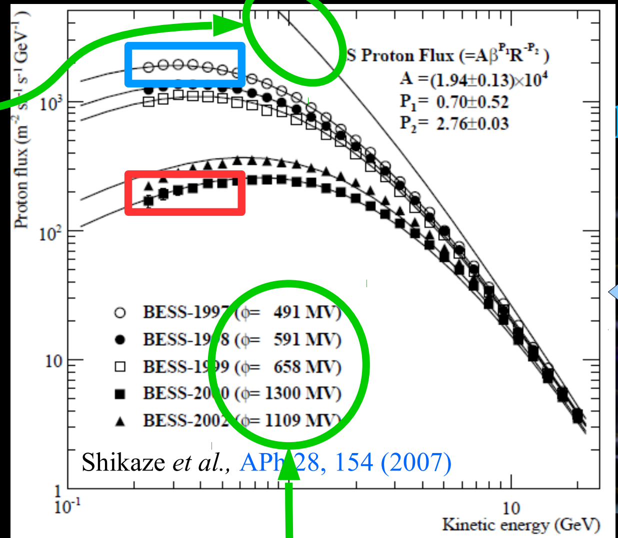
1. Transport in the Galaxy
→ Interstellar (IS) spectra

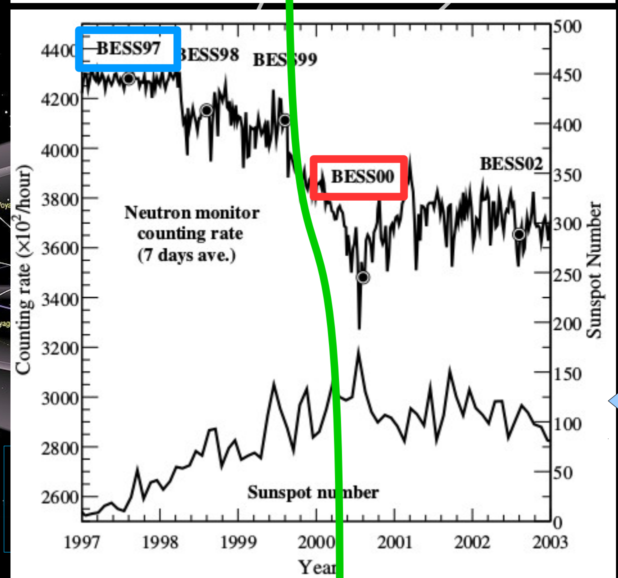


x 10^7

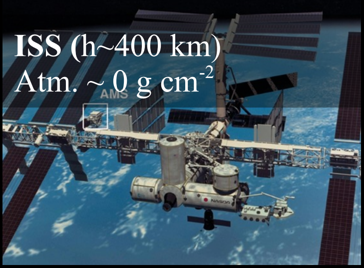


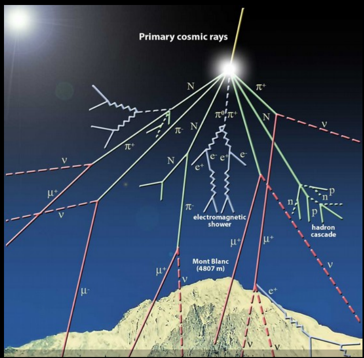
[time-independent]





2. Transport in the Solar cavity
→ modulate CRs (< 10 GeV/n)





4. Atmosphere
→ CR showers
[time-dependent]

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3. Count rates: uncertainties on ingredients
4. Δ(ingredients) $\rightarrow \Delta N/N \rightarrow \Delta\phi/\phi$
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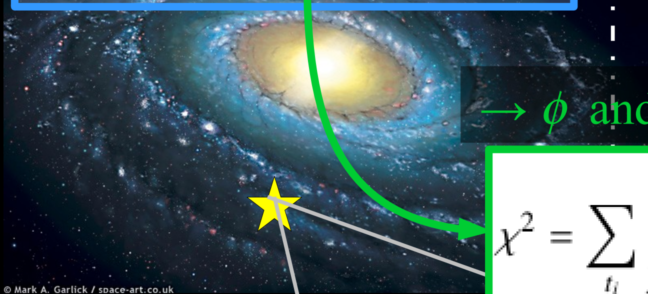
Reference textbooks (NMs): Dorman (1974, 2004, 2009)
Reference papers:
- ϕ from NMs: Usoskin *et al.* (1999, 2002, 2005, 2011)
- Solar activity times series: Usoskin, Liv. Rev. Sol. Phys. (2013)

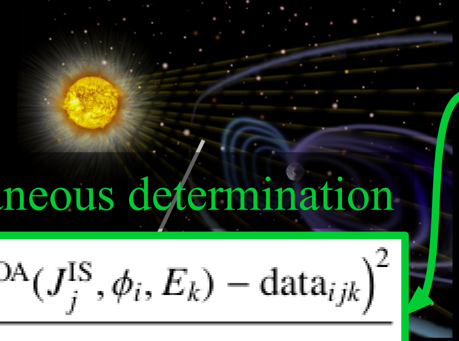
2. Modulation level: from TOA data [see Ghelfi's poster]

1. Transport in the Galaxy
→ Interstellar (IS) spectra

$$J^{\rm IS}\left(E^{\rm IS}\right)$$

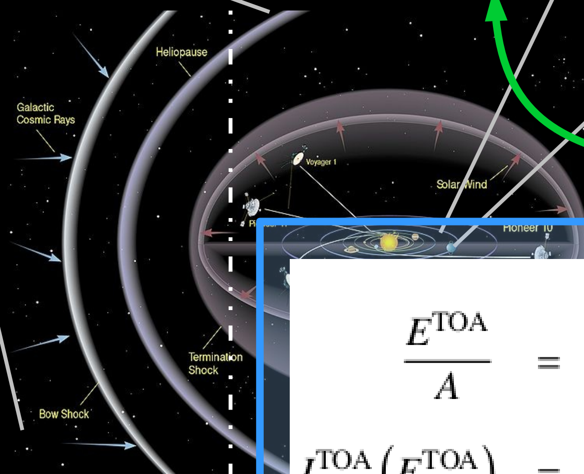


CRDB (Maurin *et al.*, 2014)
https://lpsc.in2p3.fr/crdb/



→ ϕ and $J^{\rm IS}$ simultaneous determination

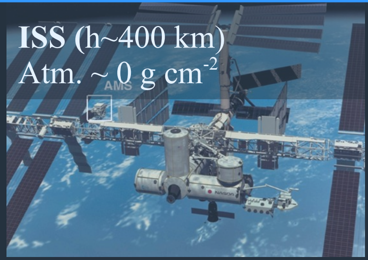
$$\chi^2 = \sum_{t_i}\sum_{N_j(i)}\sum_{E_k(i,j)} \frac{\left(J^{\rm TOA}(J_j^{\rm IS},\phi_i,E_k) - {\rm data}_{ijk}\right)^2}{\sigma_{ijk}}$$



$$\frac{E^{\rm TOA}}{A} = \frac{E^{\rm IS}}{A} - \frac{|Z|}{A}\phi,$$

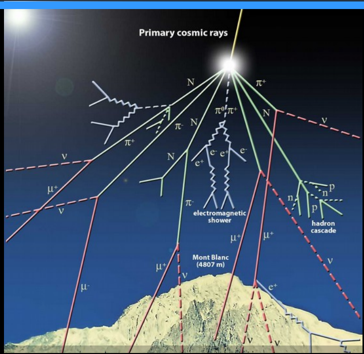
$$J^{\rm TOA}\left(E^{\rm TOA}\right) = \left(\frac{p^{\rm TOA}}{p^{\rm IS}}\right)^2 \times J^{\rm IS}\left(E^{\rm IS}\right),$$

2. Transport in the Solar cavity
→ Force-Field approximation (here)



ISS (h~400 km)
Atm. ~ 0 g cm^{-2}

Balloon (h~40 km)
Atm. ~ 5 g cm^{-2}



Neutron monitor (h<2 km)
Atm. ~ 600-1000 g cm^{-2}

4. Atmosphere
→ CR showers

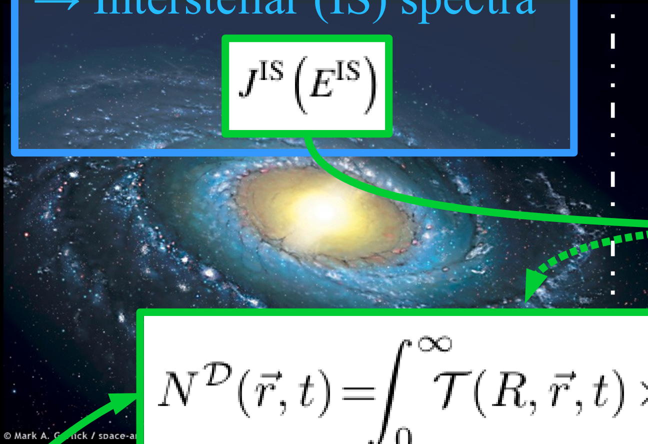
[time-independent]

[time-dependent]

2. Modulation level: from count rate detectors

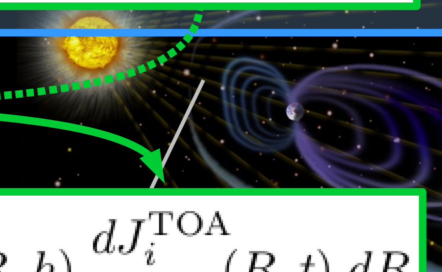
1. Transport in the Galaxy
→ Interstellar (IS) spectra

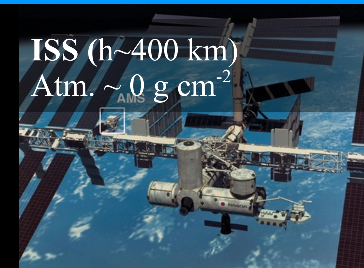
$J^{\text{IS}}\left(E^{\text{IS}}\right)$



3. Earth magnetic shield
→ Cut-off rigidity R_c (at Earth)

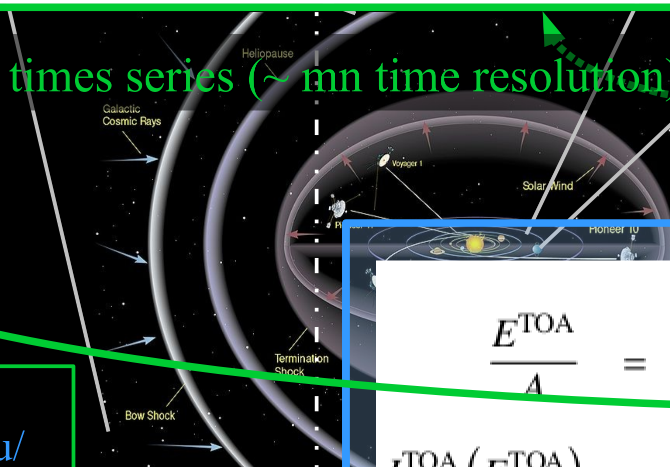
transmission function

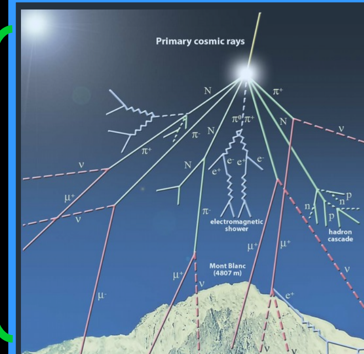




$$N^{\mathcal{D}}(\vec{r},t)=\int_0^\infty \mathcal{T}(R,\vec{r},t)\times\sum_{i=\text{CRs}}\mathcal{Y}_i^{\mathcal{D}}(R,h)\,\frac{dJ_i^{\text{TOA}}}{dR}(R,t)\;dR,$$

→ ϕ times series (~ mn time resolution)





NMDB
http://www.nmdb.eu/

$$\frac{E^{\text{TOA}}}{A} = \frac{E^{\text{IS}}}{A} - \frac{|Z|}{A}\phi,$$

$$J^{\text{TOA}}\left(E^{\text{TOA}}\right) = \left(\frac{p^{\text{TOA}}}{p^{\text{IS}}}\right)^2 \times J^{\text{IS}}\left(E^{\text{IS}}\right),$$

2. Transport in the Solar cavity
→ Force-Field approximation (here)

4. Atmosphere
→ CR showers

[time-independent]

[time-dependent]

Based on
Maurin *et al.*, AdSpR 55, 363 (2015)
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3. Count rates: ingredients and parameters

1. Transport in the Galaxy
$\longrightarrow$ Interstellar (IS) spectra

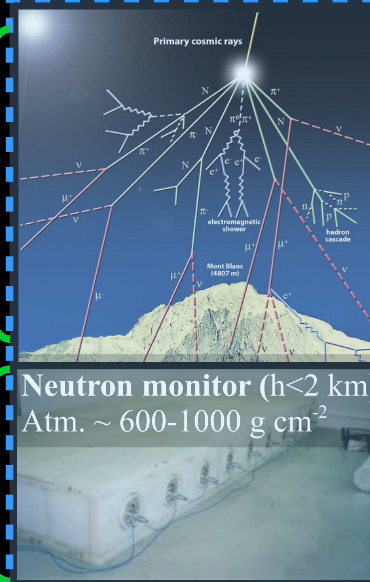
$J^{\rm IS}\left(E^{\rm IS}\right)$

3. Earth magnetic shield
$\longrightarrow$ Cut-off rigidity R_c (at Earth)

transmission function

$$N^{\mathcal{D}}(\vec{r},t)=\int_0^\infty \mathcal{T}(R,\vec{r},t)\times\sum_{i={\rm CRs}}\mathcal{Y}_i^{\mathcal{D}}(R,h)\,\frac{dJ_i^{\rm TOA}}{dR}(R,t)\,dR$$

$\longrightarrow$ ϕ times series (~ mn time resolution)



$$\frac{E^{\rm TOA}}{A} = \frac{E^{\rm IS}}{A} - \frac{|Z|}{A}\phi,$$

$$J^{\rm TOA}\left(E^{\rm TOA}\right) = \left(\frac{p^{\rm TOA}}{p^{\rm IS}}\right)^2 \times J^{\rm IS}\left(E^{\rm IS}\right),$$

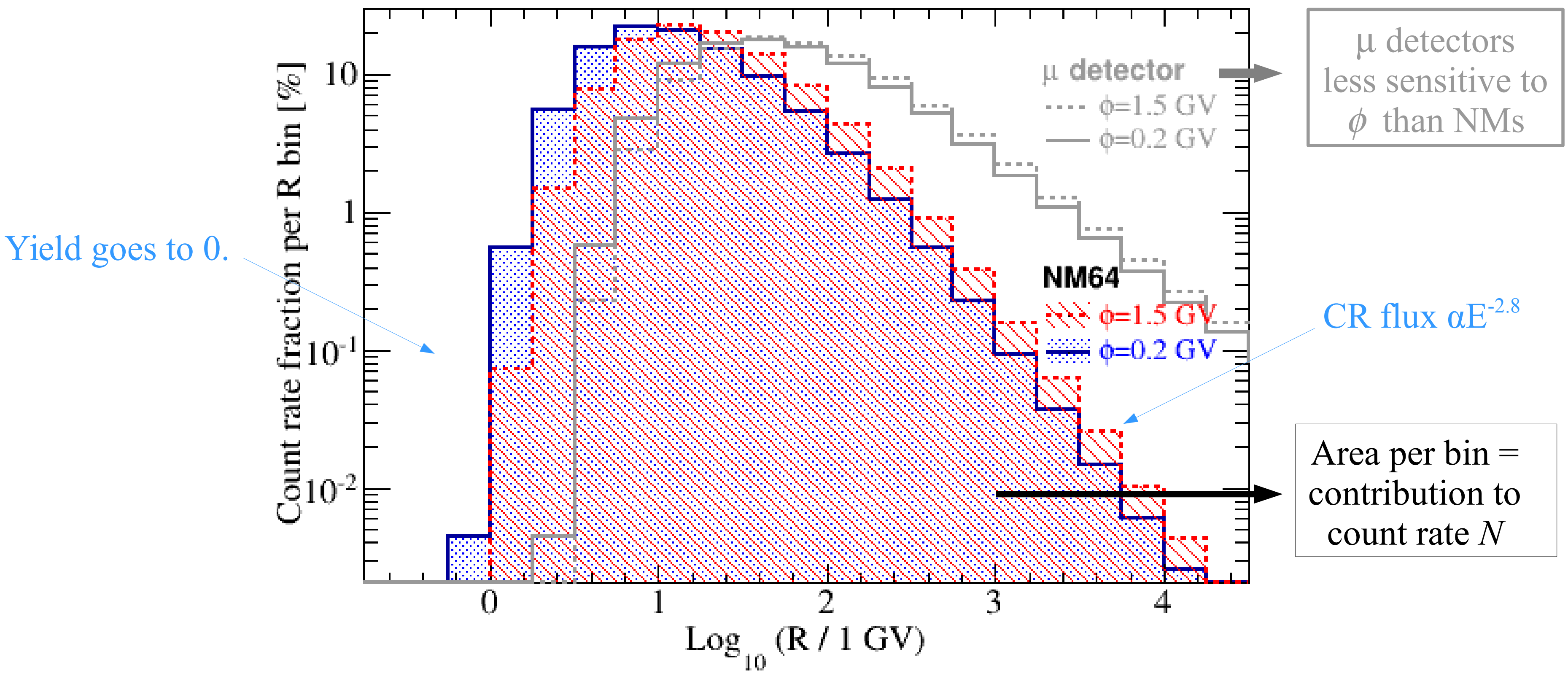
2. Transport in the Solar cavity
$\longrightarrow$ Force-Field approximation (here)

$\longrightarrow$ Key ingredients
(source of uncertainties)

Free parameter $\phi(t)$

3. Count rates: contributions per log(R) bin

$$N^{\mathcal{D}}(\vec{r},t)=\int_0^\infty \mathcal{T}(R,\vec{r},t)\times\sum_{i=\mathrm{CRs}}\mathcal{Y}_i^{\mathcal{D}}(R,h)\,\frac{dJ_i^{\mathrm{TOA}}}{dR}(R,t)\,dR,$$



→ NM64: sensitive to CRs in range 5 GV – 500 GV

→ Muons detectors: sensitive to CRs in range 10 GV – 1 TeV

3. Count rates: contribution from CRs heavier than He

$$N^{\mathcal{D}}(\vec{r},t)=\int_0^\infty \mathcal{T}(R,\vec{r},t)\times\sum_{i=\mathrm{CRs}}\mathcal{Y}_i^{\mathcal{D}}(R,h)\,\frac{dJ_i^{\mathrm{TOA}}}{dR}(R,t)\,dR,$$

sum over all CR species *i*

Ansatz: in sum, only consider **^{1}H and $(1+s_{Z>2})^4$He**

- ^{1}H and ^{4}He most abundant species in CRs
- ^{1}H and ^{4}He modulated differently: $(A/Z)_p=1$ whereas $(A/Z)_{4He}= 2$
- Heavier than He assimilated to ^{4}He: $(A/Z)_{Z>2}\sim 2$

Calculate $s_{Z>2}$

- Extract IS flux for all species: fit on TOA fluxes (using CRDB)
- Use scaling $\mathcal{Y}_A^{\mathcal{D}}(R,h)=\frac{A}{4}\times\mathcal{Y}_{^4\mathrm{He}}^{\mathcal{D}}(R,h)$ from Mishev & Velinov (2001)
- Calculate $s_{Z>2}$ and its uncertainties (+ check how good the scaling is)

→ $s_{Z>2}$ = 0.611 (+0.016, -0.009)
compared to previously used value 0.428

N.B.: the relative weight of He to H in N(r,t) increases → matters for ϕ determination

3. Count rates: Transfer function T

$$N^{\mathcal{D}}(\vec{r},t) = \int_0^\infty \mathcal{T}(R,\vec{r},t) \times \sum_{i=\mathrm{CRs}} \mathcal{Y}_i^{\mathcal{D}}(R,h)\, \frac{dJ_i^{\mathrm{TOA}}}{dR}(R,t)\, dR,$$

Definition: transmission function in the geomagnetic field, which depends on the detector location (and can vary with time)

N.B.: in the most general case, T and Y are entangled (complex structure of B plus dependence of T and Y on the primary particle incident angle)

Ansatz:

- Average Y over a few incident angles
- Use vertical cut-off rigidity → step function $T=\theta(R-Rc)$
  [Cooke *et al.*, 1991] for various cut-off definitions
  [Smart and Shea (2003, 2008a,b, 2009)] for Rc(**r**,t) calculations

→ these approximations lead to significant uncertainties (see further)

3. Count rates: Yield function – calculation

$$N^{\mathcal{D}}(\vec{r},t)=\int_0^\infty \mathcal{T}(R,\vec{r},t)\times\sum_{i=\mathrm{CRs}}\mathcal{Y}_i^{\mathcal{D}}(R,h)\frac{dJ_i^{\mathrm{TOA}}}{dR}(R,t)\,dR,$$

Definition: the yield function at altitude *h*, is the detector response (in count m^2 sr) to a unit intensity of primary CR species *i* at rigidity *R*

Calculate Y

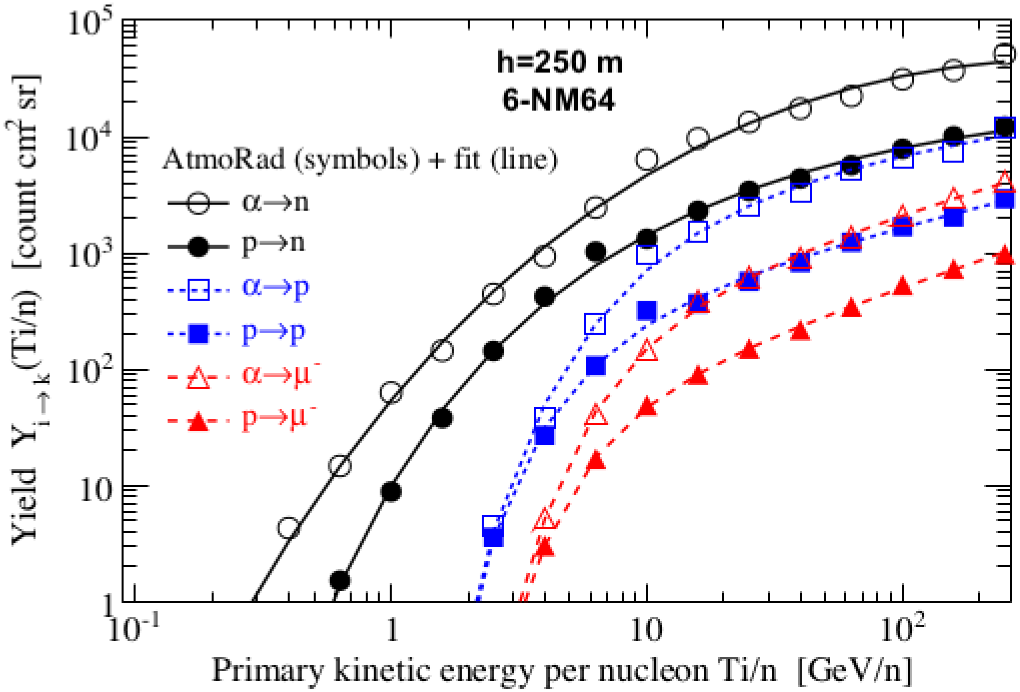
- *MC-based yield functions*
  – Atmosphere response (e.g., Clem & Dorman 2000) + Mishev et al. (2013)
  – Detector response
- *NM 'count rate'-based formulae* (e.g., Caballero-Lopez & Moraal, 2012)
  → use *Rc* to reconstruct Yield from count rates of NM at different latitudes

3. Count rates: Yield function (MC-based) for NM64

Total yield: $\mathcal{Y}_i^{\mathcal{D}}(T_i,h) = \sum_{k=\mathrm{n,p},\mu\ldots} \mathcal{Y}_{ik}^{\mathcal{D}}(T_i,h)$

[efficiency] [fluence]

Partial yields: $\mathcal{Y}_{ik}^{\mathcal{D}}(T_i,h) = S_T \sum_{l=1}^{3} \Omega^{(\theta_l,\theta_{l+1})} \times \int_0^\infty \mathcal{E}_k^{\mathcal{D}}(T_k) \times \boxed{\varphi_{ik}^{l}(h, T_i \to T_k)} dT_k$

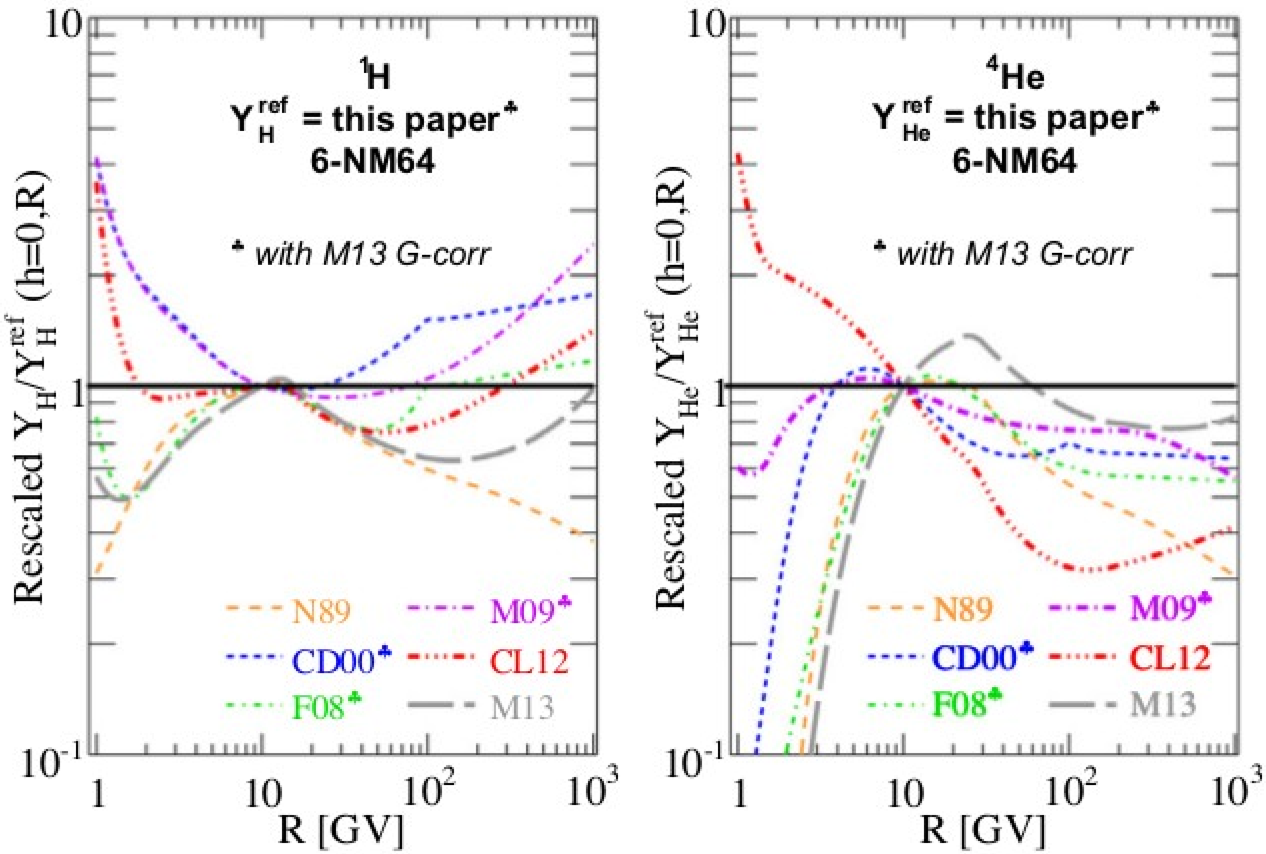


ϕ [GV]	$N^{\text{6-NM64}}$ [s^{-1}]	N_k/N [%]			
		n	p	μ^+	μ^-
0.4	91	87.2	7.9	0.2	4.7
1.5	57	87.4	8.0	0.2	4.4

→ in NM count rates, mostly n, but also p and μ^-

3. Count rates: Yield function uncertainties for NM64

$$N^{\mathcal{D}}(\vec{r},t)=\int_0^\infty \mathcal{T}(R,\vec{r},t)\times\sum_{i=\text{CRs}}\mathcal{Y}_i^{\mathcal{D}}(R,h)\frac{dJ_i^{\text{TOA}}}{dR}(R,t)\,dR,$$



→ Large differences between various teams (R-dependent)

→ Simulations should be extended above 100 GV (important for count rates calculation

[N.B.: for MC-based yields, better results obtained with Mishev et al. (2013) correction]

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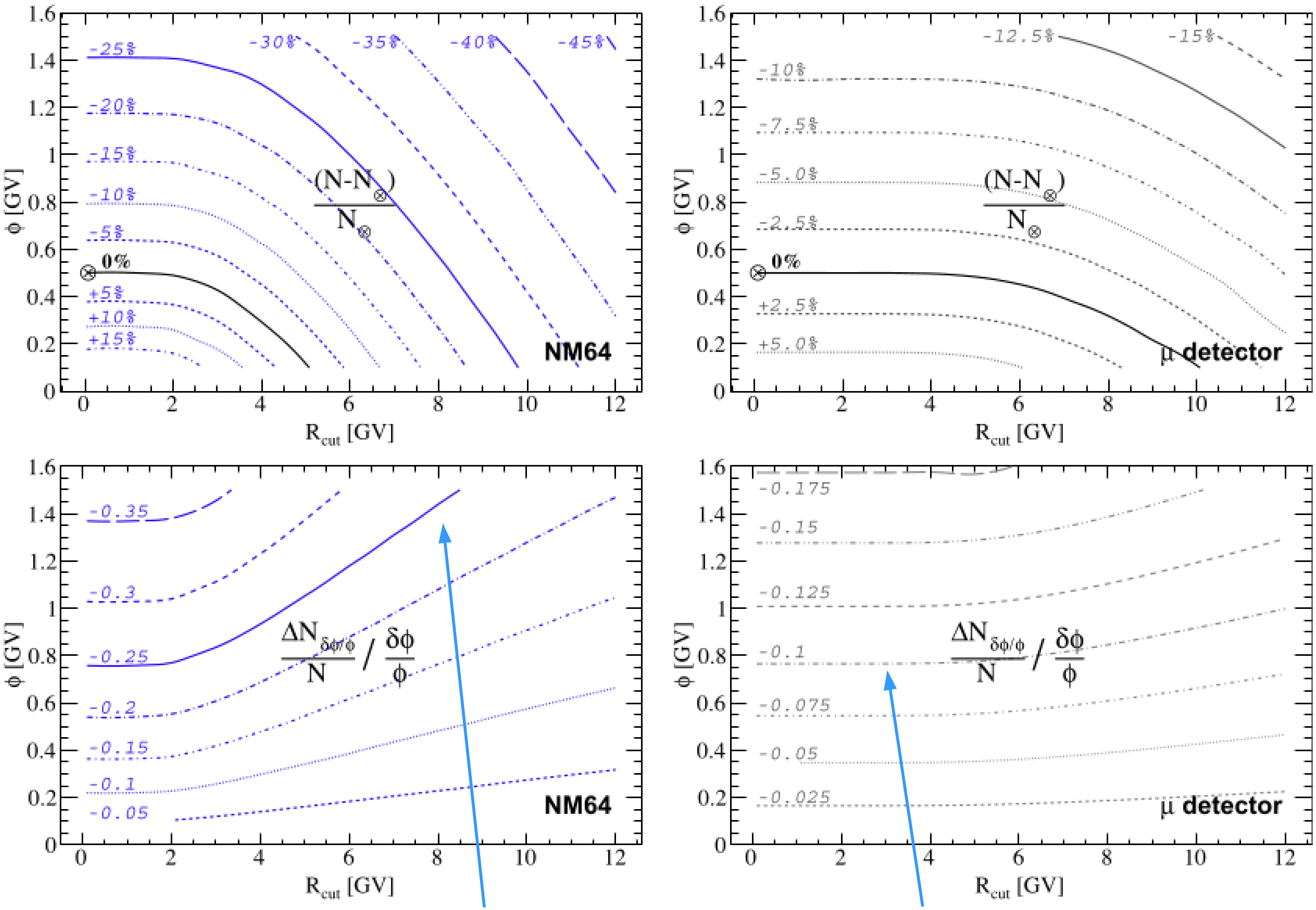
4. Abacus for $\Delta N/N$ and $\Delta\phi/\phi$

Top: count rate variation when varying *Rc* or ϕ



Bottom: $\Delta\phi/\phi = -4\ \Delta N/N$ (NM) or $\Delta\phi/\phi = -10\ \Delta N/N$ (μ)

4. Uncertainties for $\Delta N/N$ and $\Delta\phi/\phi$

$\Delta N/N \sim 1\% \;\rightarrow\; \Delta\phi \sim 40$ MV

Ingredient	Effect	$\frac{\Delta N}{N}$ NM	$\frac{\Delta N}{N}$ μ	$\Delta\phi^*$ [MV] NM	$\Delta\phi^*$ [MV] μ	Comment
Solar modulation	$\phi \in [0.2, 1.5]$ GV	[+15,-25]%	[+5,-10]%	–	–	w.r.t. $\phi = 0.5$ GV
Cut-off rigidity	$R_c \in [0, 10]$ GV	[+10,-20]%	[0,-5]%	–	–	w.r.t. $R_c = 5$ GV
TOA flux	p and He CR data	$\pm 2\%$	$\pm 2\%$	± 66	± 140	(t, R_c, ϕ)-independent
	IS flux dispersion[a]	$\pm 6\%$	$\pm 8\%$	± 200	± 570	(without AMS-02) $\Downarrow$
	Heavy species	$\pm 0.6\%$	$\pm 0.6\%$	± 20	± 40	Global norm. factor[◇]
Yield function	Dispersion	$\lesssim \pm 4\%$	$< 0.2\%$	$\lesssim 120$	$\lesssim 14$	(R_c, ϕ) dependent
Transfer function	Sigmoid$(R_c, x = +\frac{\sigma}{0.1})$	-2x%	-0.5x%	+66x	+35x	For $R_c \gtrsim 5$ GV
	$H(R_c + \Delta R_c) : x = \frac{(\Delta R_c/R_c)}{0.05}$	-2x%	-x%	+66x	+71x	For $R_c \gtrsim 5$ GV
	- $R_c(t) : \frac{\Delta R}{R} \lesssim +0.2\%$/yr	-0.4%/yr	-0.1%/yr	+13/yr	+7/yr	Depends on location
	- $R_c^{\rm eff} \rightarrow R_c^{\rm app} : +3\%$	-1.2%	-0.3%	+40	+21	Depends on R_c
Time-dep. effects[†]	Pressure	$\pm 0.2\%$	$\pm 0.2\%$	± 6	± 14	After correction
	Temperature	$\pm 0.5\%$	$\pm 4\%$	± 15	± 290[‡]	Not corrected
	Vapour water	$\pm 0.3\%$	$\pm 0.1\%$	± 10	± 8	Not corrected
	Snow coverage ($T = 1$ yr)	-7%	–	+230	–	Not corrected
NM detector effects	Temperature	+0.05%/°C	–	-1.5/°C	–	(t, R_c, ϕ)-independent
	nNM6 vs mNM64	few %	–	~ 100	–	$\Downarrow$
	Surroundings (hut)	few %	–	~ 100	–	Global norm. factor[◇]

→ IS flux uncertainty: global shift in ϕ time series (will improve with AMS-02 data)

→ Yield uncertainty: main source of uncertainty for ϕ

→ Rigidity cut-off uncertainty: also important source of uncertainty for ϕ

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5. Determination of ϕ

Questions in the AMS-02 context

- **From AMS-02 point of view**
  - → Can we predict AMS-02 flux time-variability from NMs?
  - → Consistency between AMS-02 and NM-derived ϕ ?

and for TOA CR data interpretation

- → "Experiment-dependent" ϕ value (based on ≠IS fluxes, ≠modulation models)
- → Need "consistently-derived" values for all data (CR or dark matter interpretation)

- **More globally, in the context of Solar modulation**
  - → Access to IS spectra and fit of Solar modulation parameters
  - → Study of charge dependence for Solar modulation

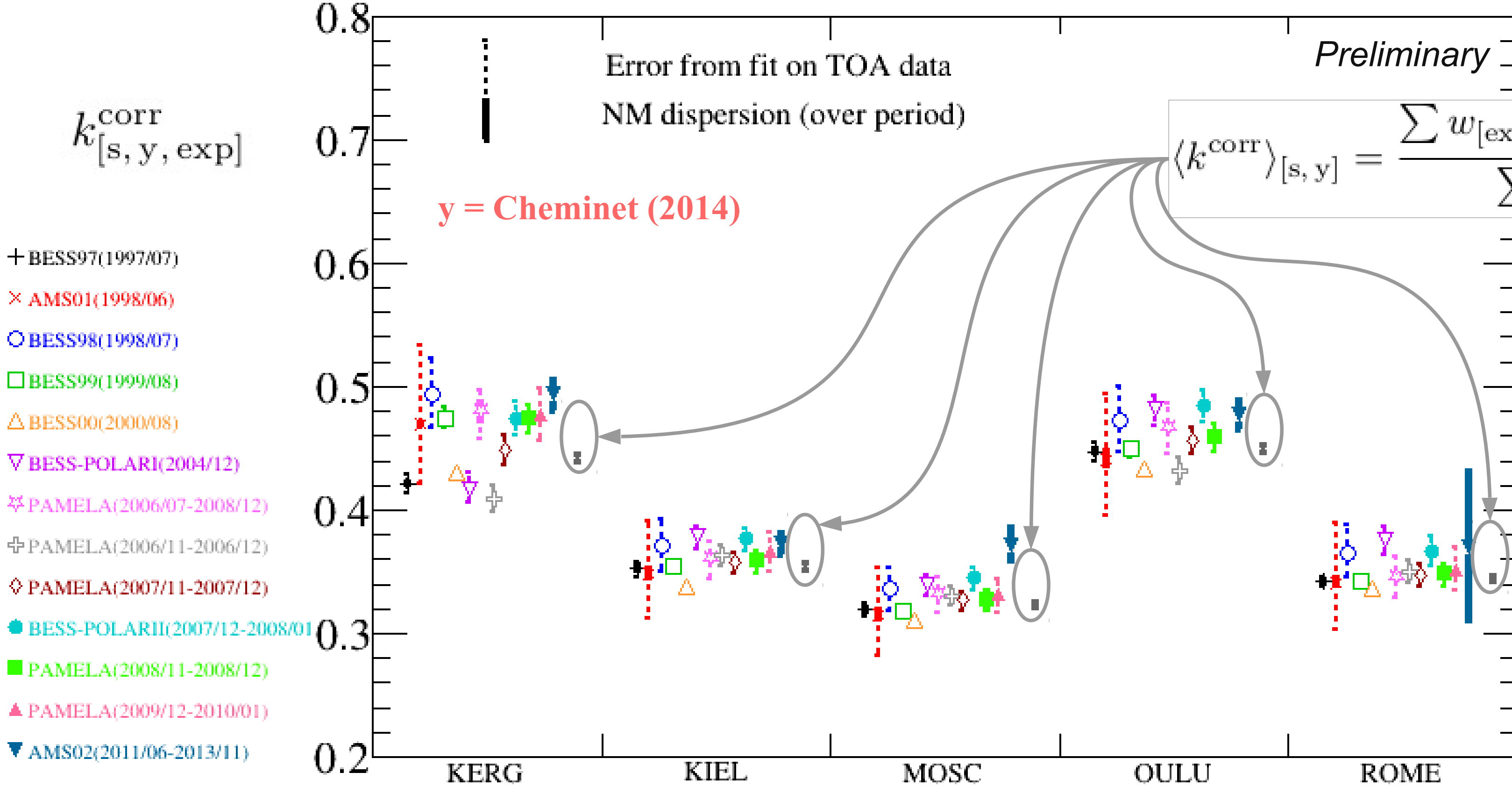
- **For the space weather community (over short and long periods)**
  - → AMS-02 protons is another monitor of the Solar activity
  - → Cross-calibration between TOA CR data and NM/μ detectors?

5. Determination of ϕ : normalisation issues

$$N^{\rm calc}(R_c,h) = k^{\rm corr} \int_{R_c}^{\infty} \sum_{i={\rm CRs}} \mathcal{Y}_i(R,h)\, \frac{dJ_i^{\rm TOA}}{dR}(R,t)\, dR, \quad \Rightarrow \quad k^{\rm corr}_{\rm [s,\,y,\,exp]} = \frac{N^{\rm calc}_{\rm [s,\,y,\,exp]}}{\langle N^{\rm measured}_{\rm [s]} \rangle_{\rm exp.\ date}}$$

k = individual NM's efficiency factor (accounts for the local environment)

$$\langle k^{\rm corr} \rangle_{\rm [s,\,y]} = \frac{\sum w_{\rm [exp]} \times k^{\rm corr}_{\rm [s,\,y,\,exp]}}{\sum w_{\rm [exp]}}$$



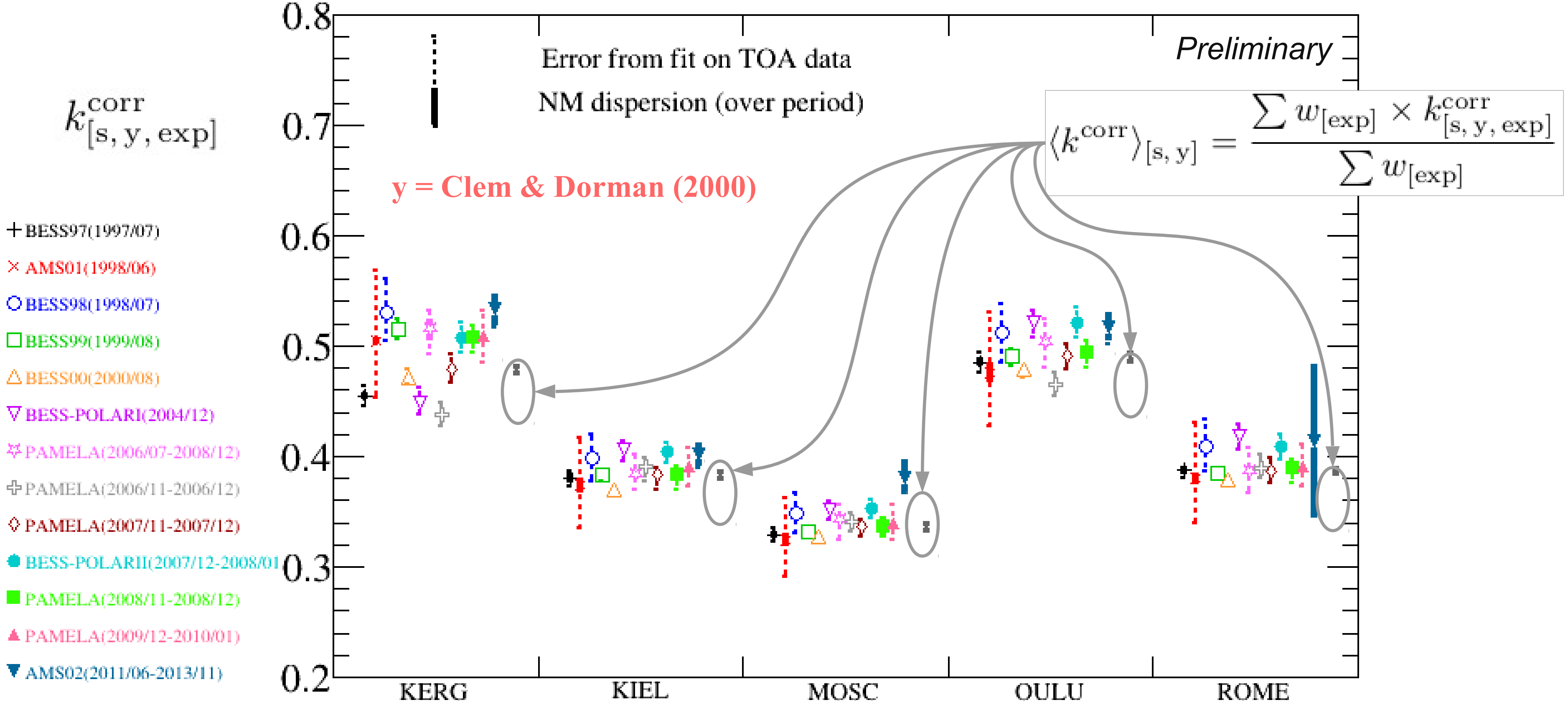
→ Correction factor well constrained from selected TOA CR data (see Ghelfi's poster)

5. Determination of ϕ : normalisation issues

$$N^{\rm calc}(R_c,h) = k^{\rm corr} \int_{R_c}^{\infty} \sum_{i={\rm CRs}} \mathcal{Y}_i(R,h)\, \frac{dJ_i^{\rm TOA}}{dR}(R,t)\, dR,$$

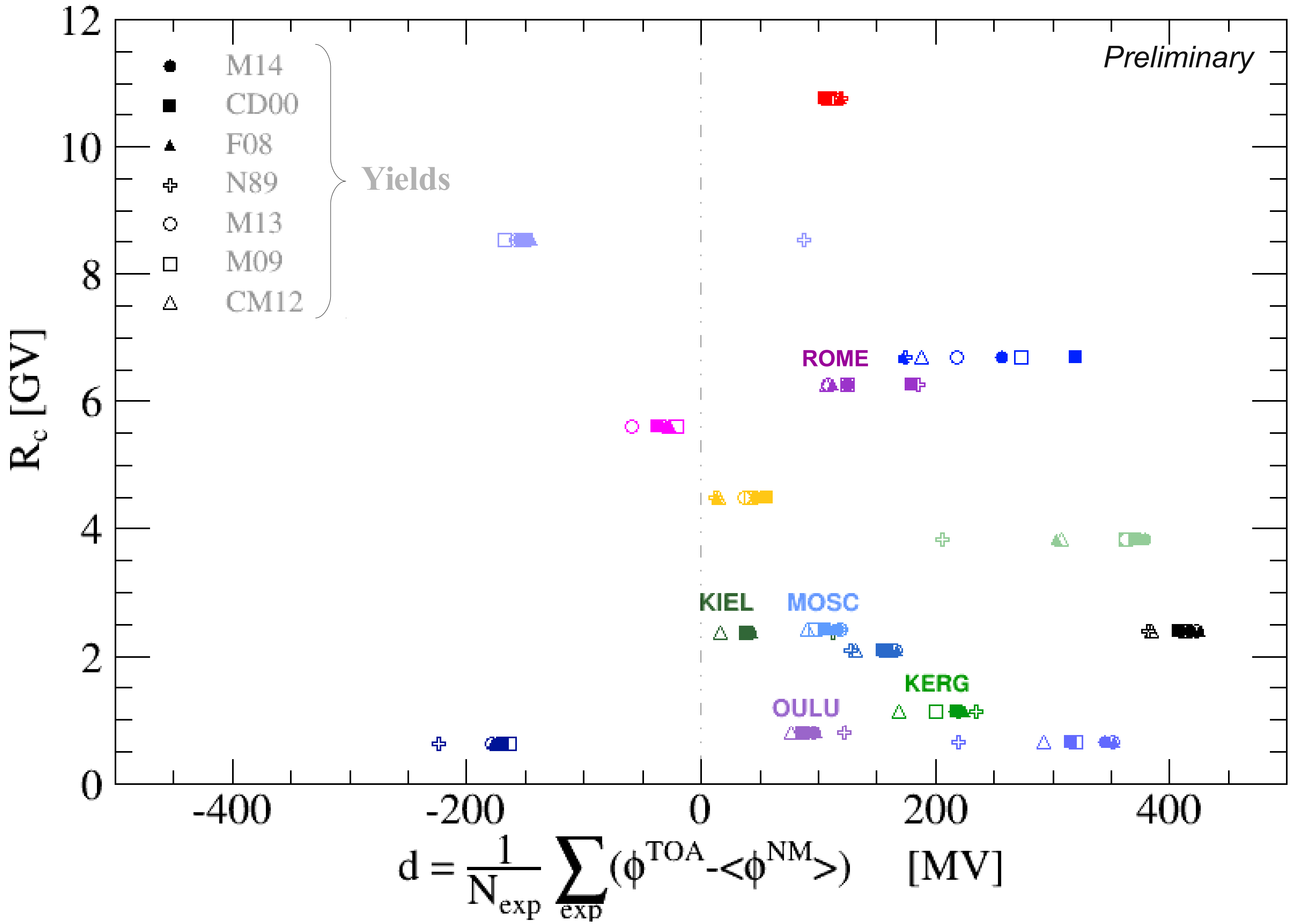
$$k^{\rm corr}_{\rm [s,\,y,\,exp]} = \frac{N^{\rm calc}_{\rm [s,\,y,\,exp]}}{\langle N^{\rm measured}_{\rm [s]} \rangle_{\rm exp.\,date}}$$

k = individual NM's efficiency factor (accounts for the local environment)



→ k differs from Usoskin *et al.* (2011) values (e.g., 0.82 for KIEL)
[this difference is not understood at this moment]

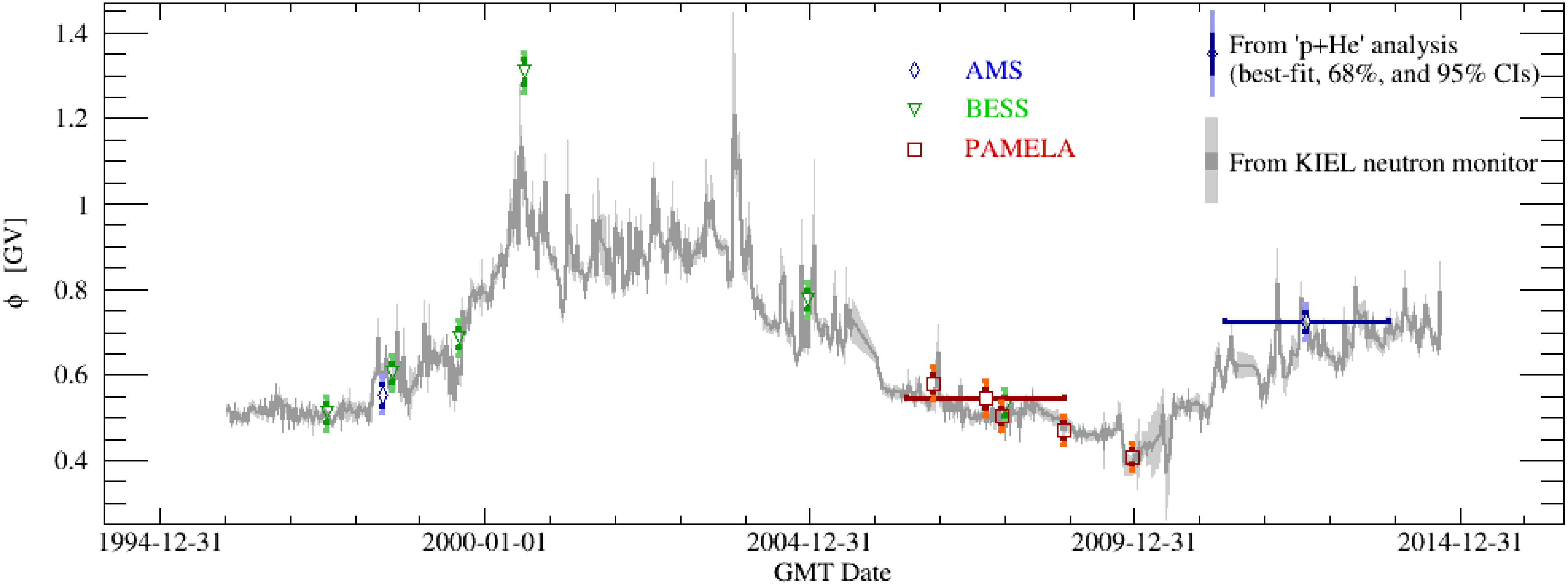
5. Determination of ϕ : ϕ(TOA)-ϕ(NM) over exp. dates



→ Still large differences between different stations: related to Rc?

6. Conclusion and perspectives

Can we provide accurate ϕ time series from NM data?



To do list:

- Find best combination of IS flux/Yield function/NM station matching ϕ^{TOA}
- Combine/compare from reconstruction from μ detectors
- Investigate more realistic modulation models and see impact on ϕ^{TOA} and ϕ^{NM}

→ **Time series from NM:** Ghelfi *et al.* (in prep.)

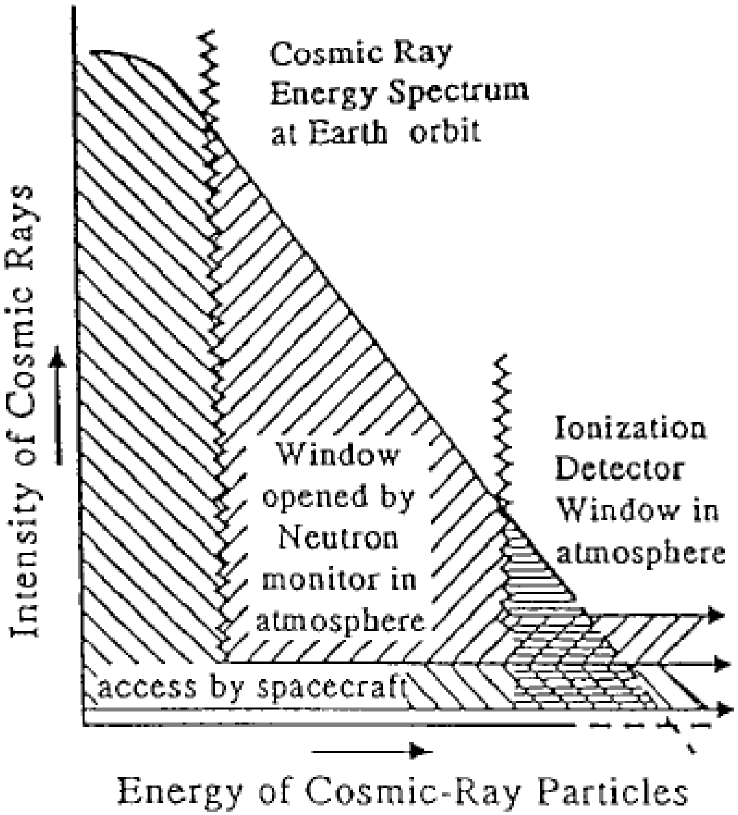
→ Need to improve "Yield functions + Rc + NM relative normalisation"

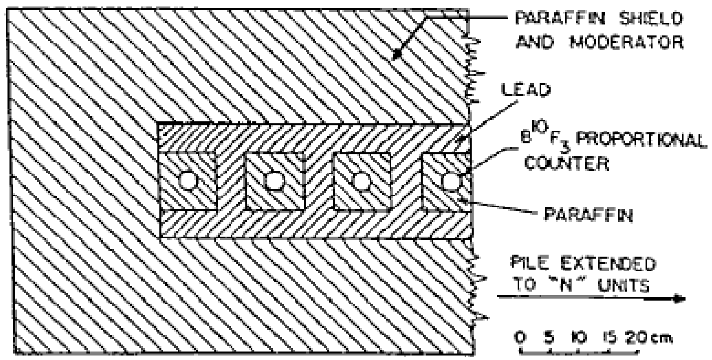
→ Monthly/weekly/daily AMS-02 data mandatory to go further…

[N.B.: Web interface to provide ϕ for any "past" time interval (CRDB website asap)]

The invention of NMs in the 50's (John A. Simpson)

Simpson, Space Sci. Rev. **93**, 11 (2000)





$$^{10}\mathrm{B} + \mathrm{n} \rightarrow {}^{11}\mathrm{B}^* \rightarrow {}^{7}\mathrm{Li} + {}^{4}\mathrm{He}^{++} + \mathrm{Q}\,.$$

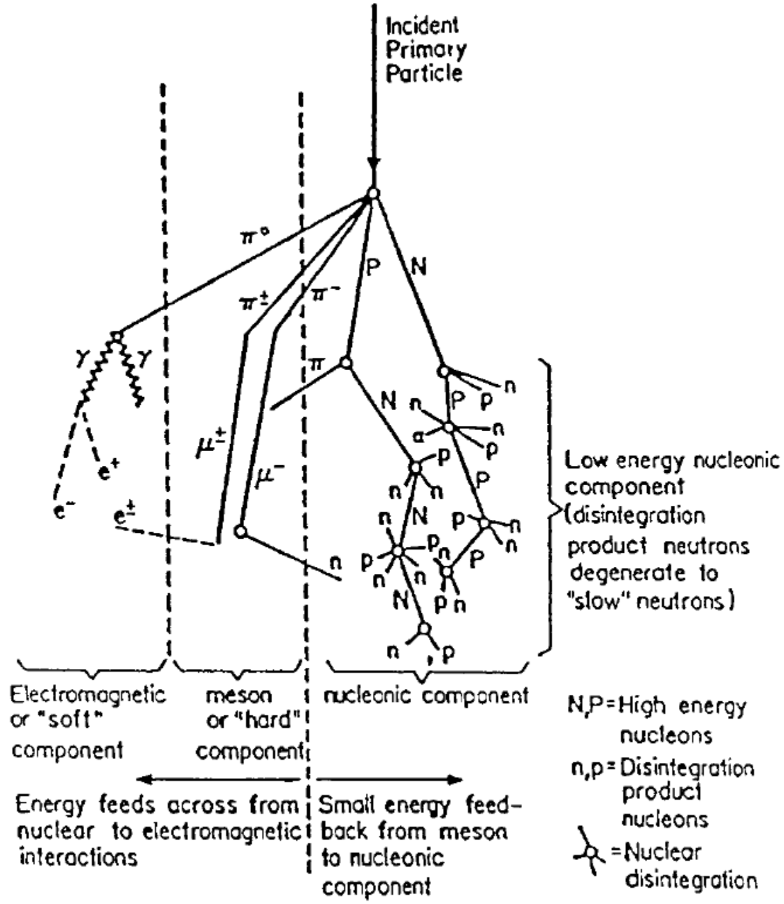
$$^{3}\mathrm{He}_2 \quad + \quad \mathrm{n} \quad \rightarrow \quad {}^{3}\mathrm{H}_1 \quad + \quad \text{proton}$$


Izmiran NMs (Russia)

→ NMs come “cheap”, insensitive to low energy SCRs,
Good time resolution, active since the 50's

CR showers and ground-based detectors

Simpson, Space Sci. Rev. **93**, 11 (2000)



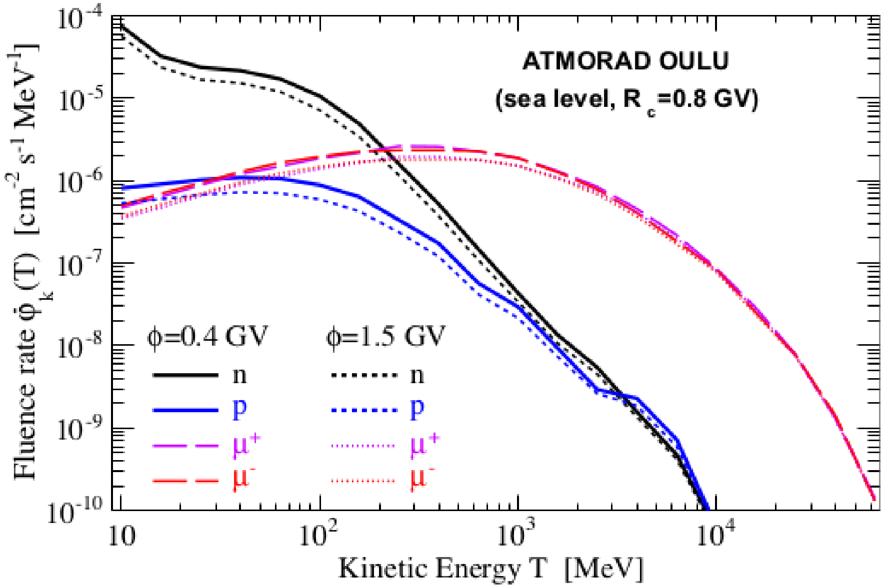
→ **Count rates:** neutron monitors (NMs), μ detectors (AUGER scaler data)
→ **Spectra**: neutron spectrometers (BSS)

Fluence rate from PLANETOCOSMICS (and setup)

(fluence rate) [fluence]

$$\dot{\varphi}_k(T_k,\vec{r},t) = S_T \times \sum_{l=1}^{3} \Omega^{(\theta_l,\theta_{l+1})} \sum_{i}^{\text{CRs}} \sum_{T_i^{\text{cut-off}}}^{T_i^{\max}} \Delta T_i \times J_i^{\text{TOA}}(T_i,\phi(t)) \times \boxed{\varphi_{ik}^{l}(h,\, T_i \;\rightarrow\; T_k)}$$

GEANT4 + atmosphere model (PLANETOCOSMIC)



Monte Carlo simulation setup

Parameter	Qty	Bins	Range	Unit
Primary i	H He	18	[0.1 – 251.2]	GeV/n
Secondary k	n p, $\mu^{\pm}$	70 25	$[10^{-3} - 10^{11}]$ $[10^{6} - 10^{11}]$	eV
Incidence	$[\theta_l, \theta_{l+1}]$	3	$\left\{0, \frac{\pi}{6}, \frac{\pi}{3}, \frac{\pi}{2}\right\}$	rad
Altitude	h	36	[0 – 30]	km asl

Adrien Cheminet, PhD thesis (2013)

→ **fluence rate** = secondary particule spectrum content at any depth given some TOA fluxes

Heavier than He fraction: IS flux determination

$$\frac{dJ^{\mathrm{IS}}}{dR} = C_0 \times \beta^{C_1} \times R^{-C_2}$$

CR	C_0	C_1	C_2	$f_j = \frac{J_j}{\sum_i J_i}$
	$(\mathrm{m}^2\ \mathrm{s\ sr\ GV})^{-1}$	-	-	(%)
$\mathrm{H}^{\ddagger}$	23350 ± 184	2.10 ± 0.10	-2.839 ± 0.003	83.7
$^2\mathrm{H}$	838.5 ± 29.5	3.62 ± 0.08	-2.950 ± 0.060	2.21
$^3\mathrm{He}$	512.7 ± 2.0	6.70 ± 0.01	-3.045 ± 0.003	1.08
$\mathrm{He}^{\ddagger}$	$3657. \pm 38.5$	1.77 ± 0.04	-2.782 ± 0.003	14.6
Li	18.86 ± 0.86	4.58 ± 0.07	-3.200 ± 0.400	0.027
Be	22.09 ± 0.18	6.57 ± 0.08	-2.948 ± 0.003	0.054
B	72.77 ± 0.32	5.77 ± 0.01	-3.086 ± 0.002	0.132
C	116.5 ± 0.50	4.26 ± 0.01	-2.791 ± 0.002	0.438
N	45.7 ± 0.45	5.19 ± 0.02	-2.971 ± 0.004	0.112
O	95.5 ± 0.35	3.87 ± 0.01	-2.733 ± 0.002	0.413
F	35.73 ± 0.03	5.63 ± 0.02	-2.979 ± 0.005	0.084
Ne	16.75 ± 0.10	4.29 ± 0.02	-2.779 ± 0.003	0.065
Na	4.945 ± 0.034	5.02 ± 0.02	-2.922 ± 0.003	0.013
Mg	20.25 ± 0.10	4.03 ± 0.02	-2.755 ± 0.003	0.083
Al	4.165 ± 0.029	4.65 ± 0.02	-2.812 ± 0.004	0.015
Si	13.5 ± 0.10	3.86 ± 0.02	-2.681 ± 0.003	0.066
P	1.084 ± 0.014	5.99 ± 0.04	-2.938 ± 0.007	0.003
S	3.445 ± 0.025	4.87 ± 0.02	-2.785 ± 0.004	0.013
Cl	1.428 ± 0.015	6.65 ± 0.03	-3.052 ± 0.007	0.003
Ar	2.64 ± 0.04	6.24 ± 0.04	-3.075 ± 0.007	0.005
K	2.192 ± 0.005	6.37 ± 0.06	-3.110 ± 0.010	0.004
Ca	3.70 ± 0.03	5.24 ± 0.05	-2.991 ± 0.005	0.009
Sc	1.106 ± 0.019	5.68 ± 0.04	-3.120 ± 0.008	0.002
Ti	3.126 ± 0.032	4.96 ± 0.03	-3.062 ± 0.005	0.006
V	1.357 ± 0.014	4.82 ± 0.03	-2.995 ± 0.006	0.003
Cr	2.271 ± 0.019	4.51 ± 0.03	-2.919 ± 0.005	0.006
Mn	1.132 ± 0.014	4.11 ± 0.03	-2.776 ± 0.005	0.004
Fe	8.032 ± 0.046	3.37 ± 0.03	-2.600 ± 0.001	0.047
Co	0.0055 ± 0.0037	3.54 ± 0.03	-2.610 ± 0.010	$< 10^{-3}$
Ni	8.405 ± 0.019	4.50 ± 0.10	-2.600 ± 0.020	0.002

‡ H = ^{1}H+^{2}H, whereas He = ^{3}He+^{4}He.

Primary CR species

→ p, He most abundant species

→ flatter spectrum for heavier species (destruction in propagation)

Secondary CR species

→ steeper slope (relative fraction decreases with R w.r.t. primary species)

→ ^{2}H and ^{3}He not same A/Z as other heavy species (A/Z~2)

→ small fraction, but plenty of them...

Heavier than He fraction: IS flux determination

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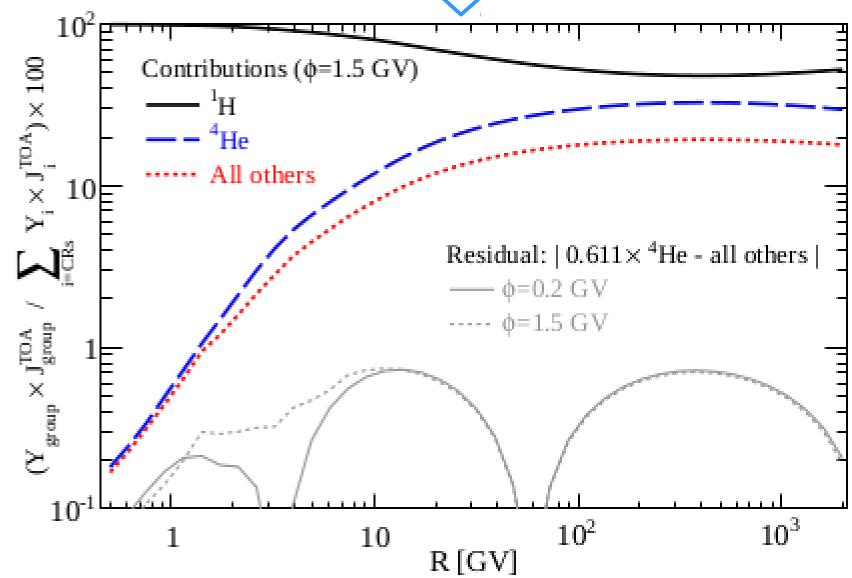
Small fraction in CRs, but yield µ A

$$\langle f_j\rangle_{\mathcal{Y}} = \frac{\mathcal{Y}_j(R)\times J_j^{\rm TOA}(R)}{\sum\limits_{i=\rm CRs}\mathcal{Y}_i(R)\times J_i^{\rm TOA}(R)} \approx \langle f_j\rangle_A$$

⇩

→secondary and heavy species contribute significantly to count rates!

⇩

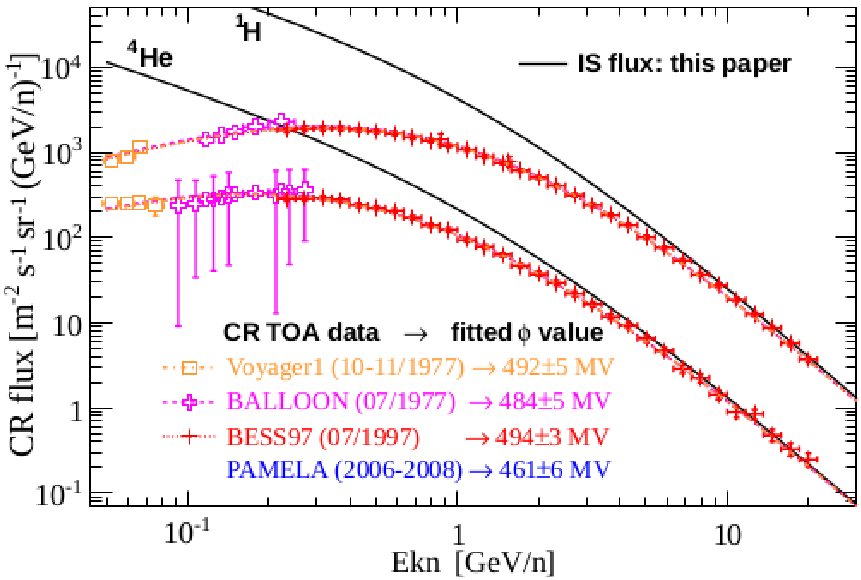


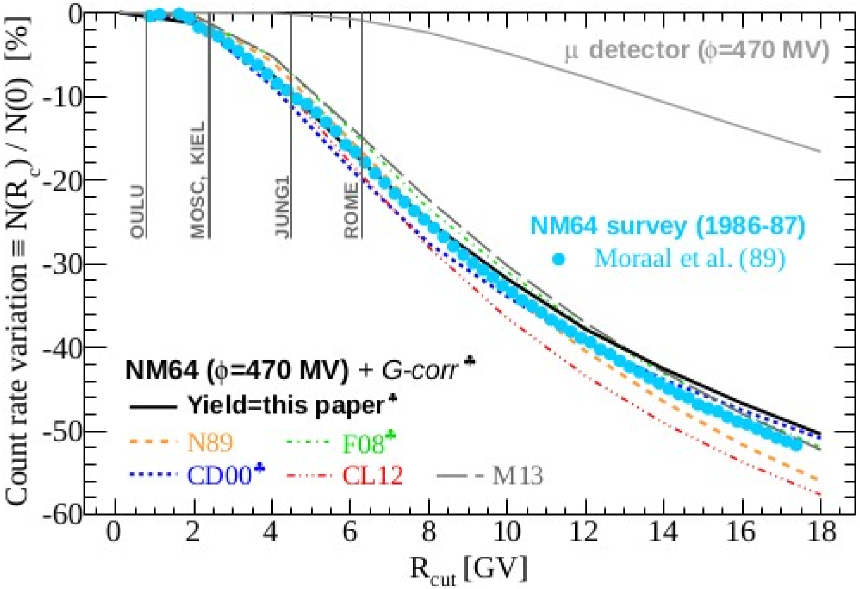
$$\boxed{s_{Z>2} \equiv \frac{J_{\rm CRs\text{-}(^1H,^4He)}}{J_{^4He}} = 0.611^{+0.016}_{-0.009}}$$

(0.428 in previous studies)

Validation of yield functions on NM latitude surveys

1. Latitude surveys (vs Rc) every 11 yr at solar minimum
2. Use CR data at same epoch to find ϕ
3. Check surveys with calculated count rates





→Up to 10 GV, our yield gives best fit
→Other yield functions more or less OK as well (dispersion)

Relaxing assumption on transfer function

$$N^{\mathcal{D}}(\vec{r},t)=\int_0^{\infty}\mathcal{T}(R,\vec{r},t)\times\sum_{i=\text{CRs}}\mathcal{Y}_i^{\mathcal{D}}(R,h)\,\frac{dJ_i^{\text{TOA}}}{dR}(R,t)\,dR,$$

- Rc varies in times: 10% in 50 yrs

- Transfer resembles a sigmoid (rather than step)

$$\mathcal{T}(R)=\frac{1}{2}\left[1+\text{erf}\left(\frac{R-R_c}{\sqrt{2}\,\Delta R}\right)\right]\qquad \sigma\equiv\frac{\Delta R}{R_c}$$

- Apparent cut-off rigidity rather than effective vertical cut-off rigidity

$$R_c^{\text{eff}}\approx R_{\text{upper}}-\sum_{i=R_c}^{R_{\text{upper}}}\Delta R_i^{\text{allowed}}$$

$$R_c^{\text{app}}(R_c)\equiv\frac{\int_0^{2\pi}d\phi\int_0^{\pi/2}R_c(\theta,\phi)\times\mathcal{Y}(R_c,\theta,\phi)\,d\theta}{\int_0^{2\pi}d\phi\int_0^{\pi/2}\mathcal{Y}(R_c,\theta,\phi)\,d\theta}.$$

→Variation depends on t, Rc, position
→Maximal variation < 10% on count rates