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

Based on:
Maurin *et al.*, AdSpR 55, 363 (2015)
Ghelfi *et al.*, A&A 591, 94 (2016) and AdSpR 60 (2017)

1. Introduction
2. ϕ time series from CR data
3. ϕ time series from NM data
4. Discussion and perspectives

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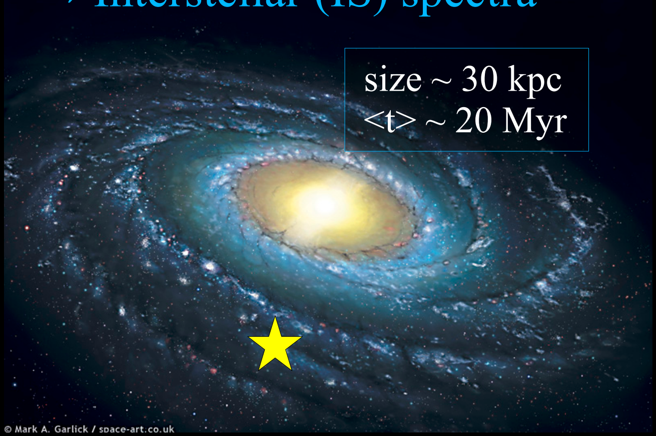
Washington DC
26 April 2017

1. Introduction: cosmic rays (CRs)

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



[time-independent]

1. Introduction: CRs + solar modulation

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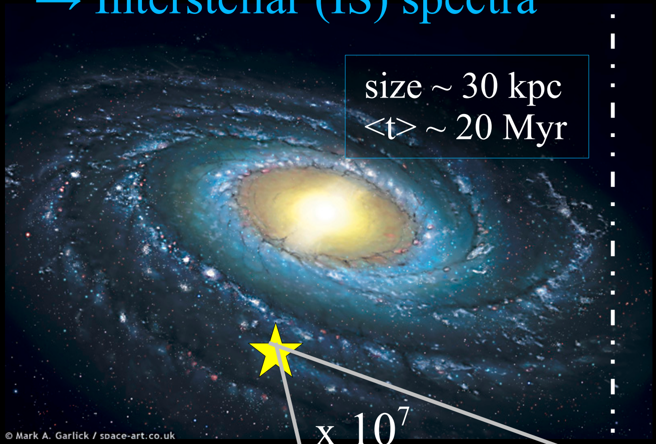
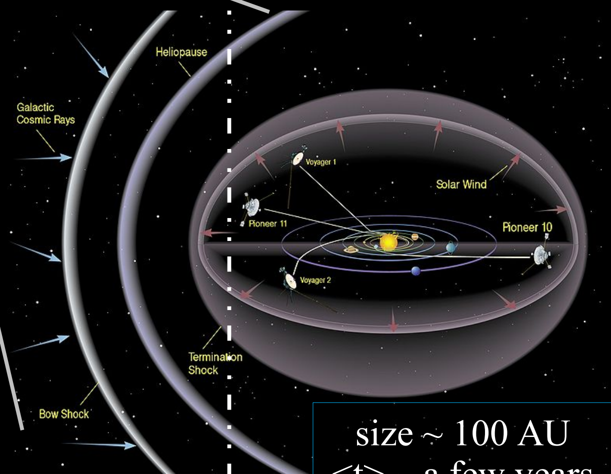
→ Interstellar (IS) spectra



size ~ 30 kpc
<t> ~ 20 Myr

x 10^7



size ~ 100 AU
<t> ~ a few years

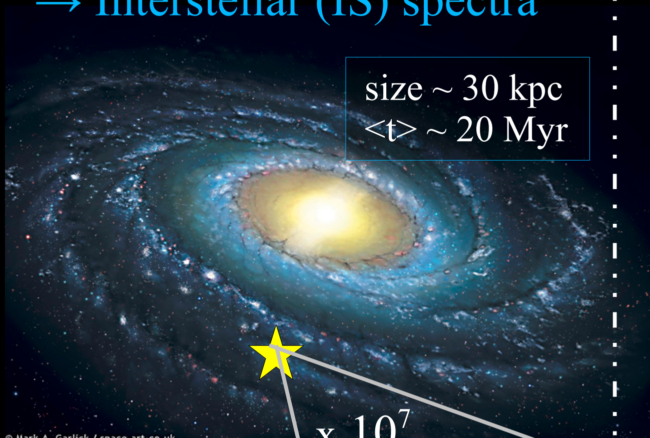
2. Transport in the Solar cavity
→ modulate CRs (< 10 GeV/n)

[time-independent]

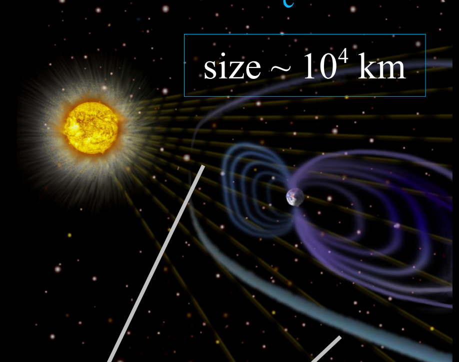
[time-dependent]

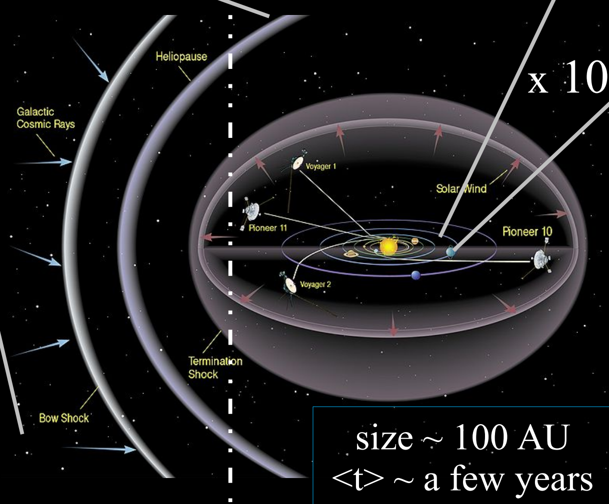
1. Introduction: CRs + modulation + rigidity cut-off (Rc)

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



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



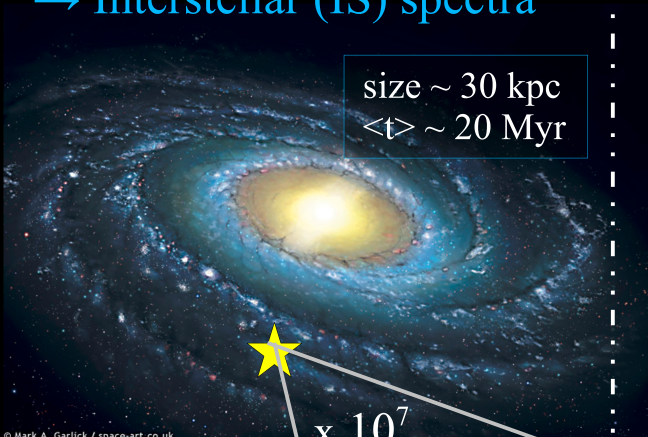


2. Transport in the Solar cavity
→ modulate CRs (< 10 GeV/n)

[time-independent] **[time-dependent]**

1. Introduction: CRs + modulation + Rc + atmosphere

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



x 10^7

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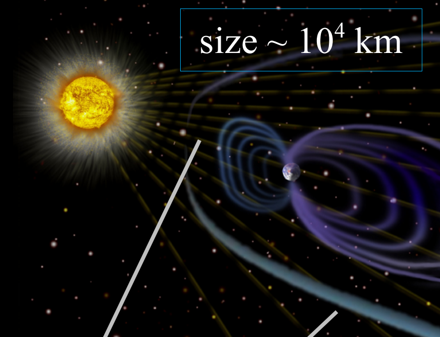
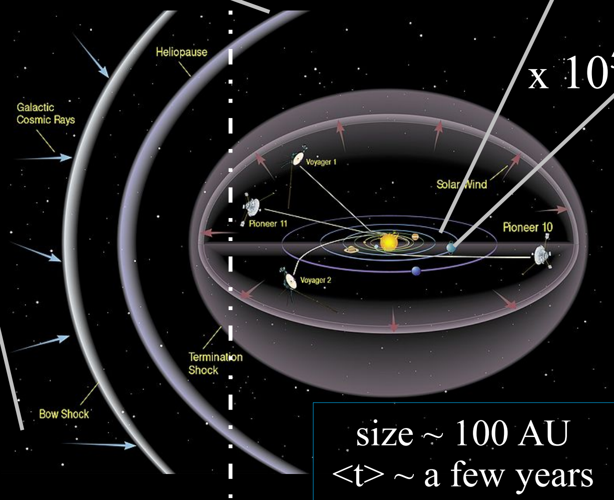


x 10^5



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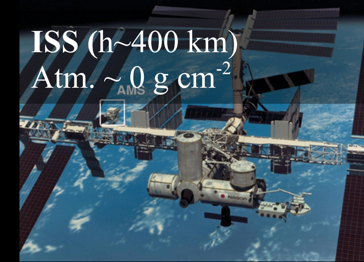
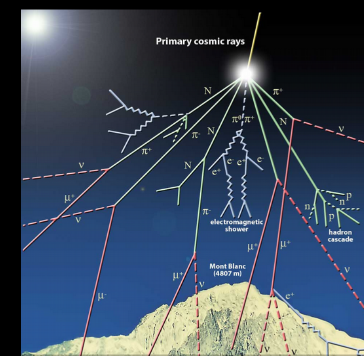
[time-independent]



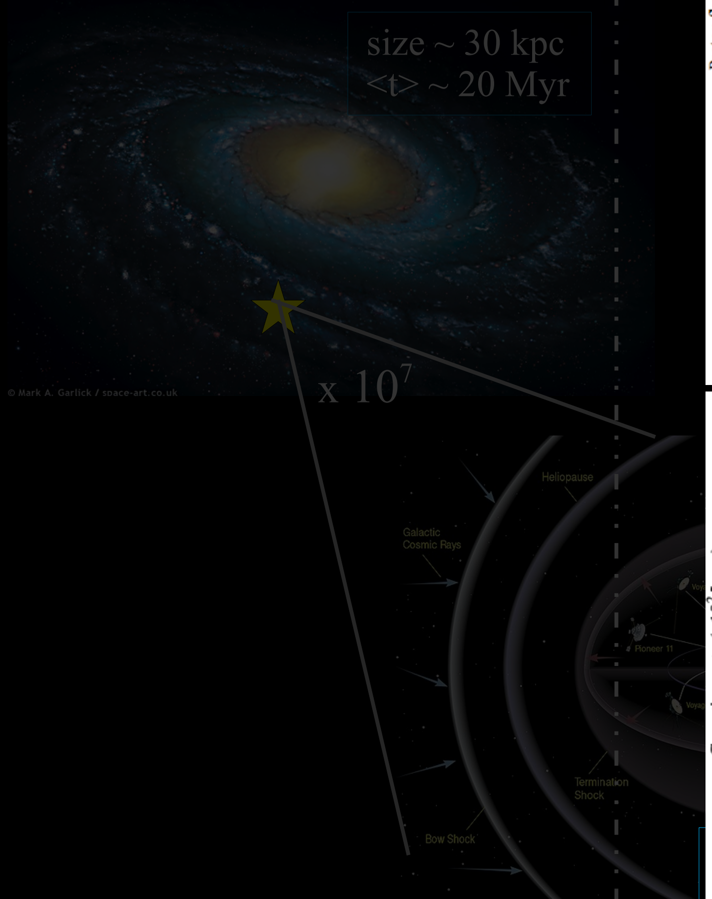


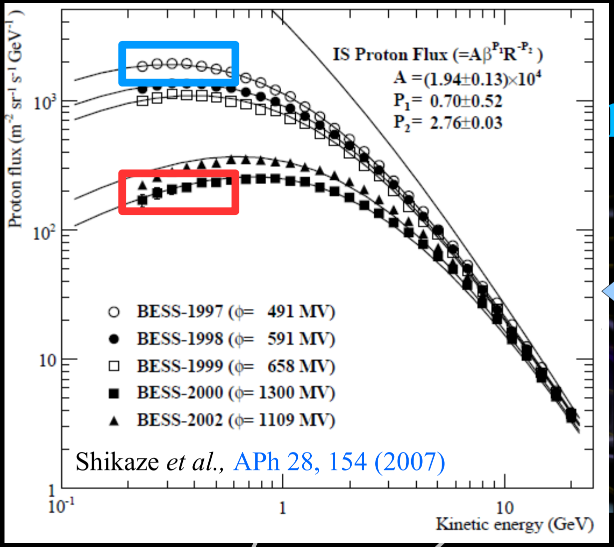
4. Atmosphere
→ CR showers

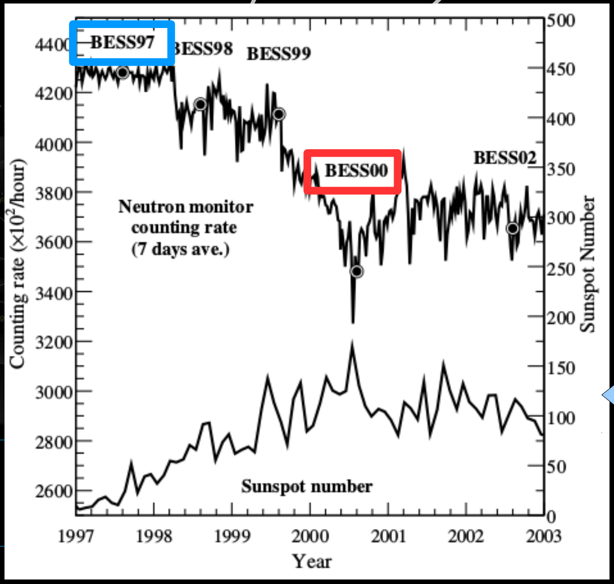
[time-dependent]

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

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







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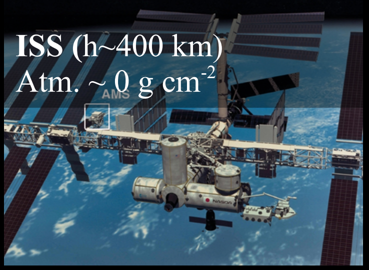
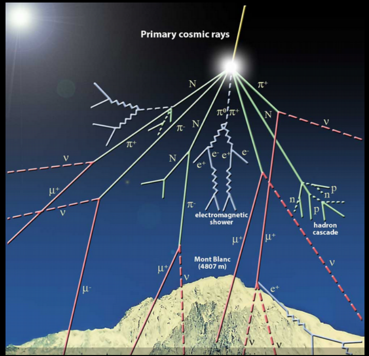




4. Atmosphere
→ CR showers

[time-independent]

[time-dependent]

1. Introduction: motivation and approach

1. Transport in the Galaxy

ϕ time series

Main motivation

ϕ at any t, for CR data interpretation:
→ consistently derived ϕ for all CR data
→ publicly available values

ϕ determination from

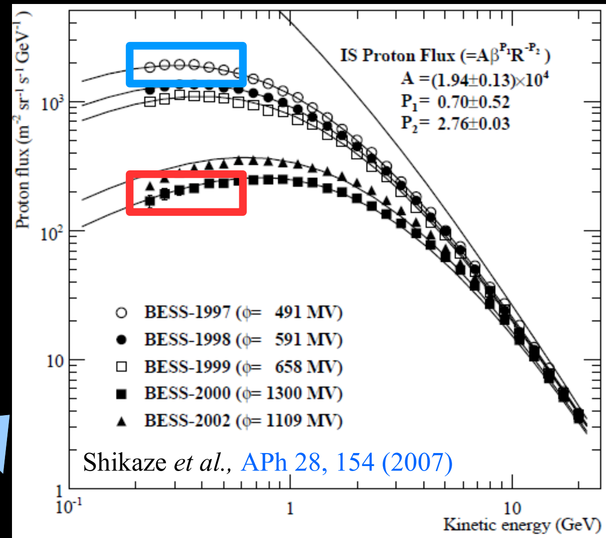
- *CR data:* depends on IS flux
  - Pros: full spectral info on E
  - Cons: sampling limited in time
- *NM data*: depends on IS flux, yield...
  - Pros: sampling (mn), #stations
  - Cons: integral measurement, uncertainties on many ingredients

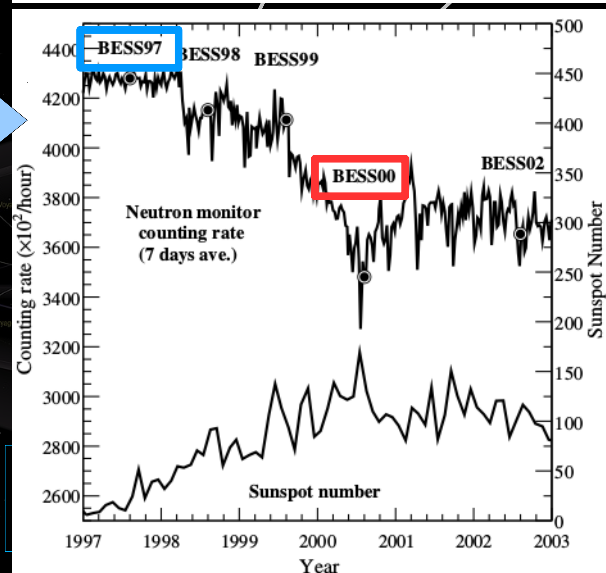
Main novelties

- Cross-check between two approaches
- Assess fully uncertainties in both cases

→ Conclude on robustness of ϕ values

[time-independent]





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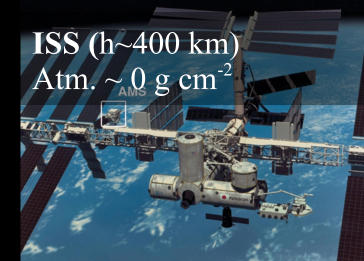

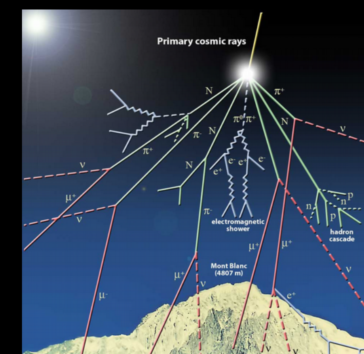

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[time-dependent]

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Ghelfi *et al.*, A&A 591, 94 (2016)
and AdSpR 60 (2017)

2. ϕ from CR data: principle

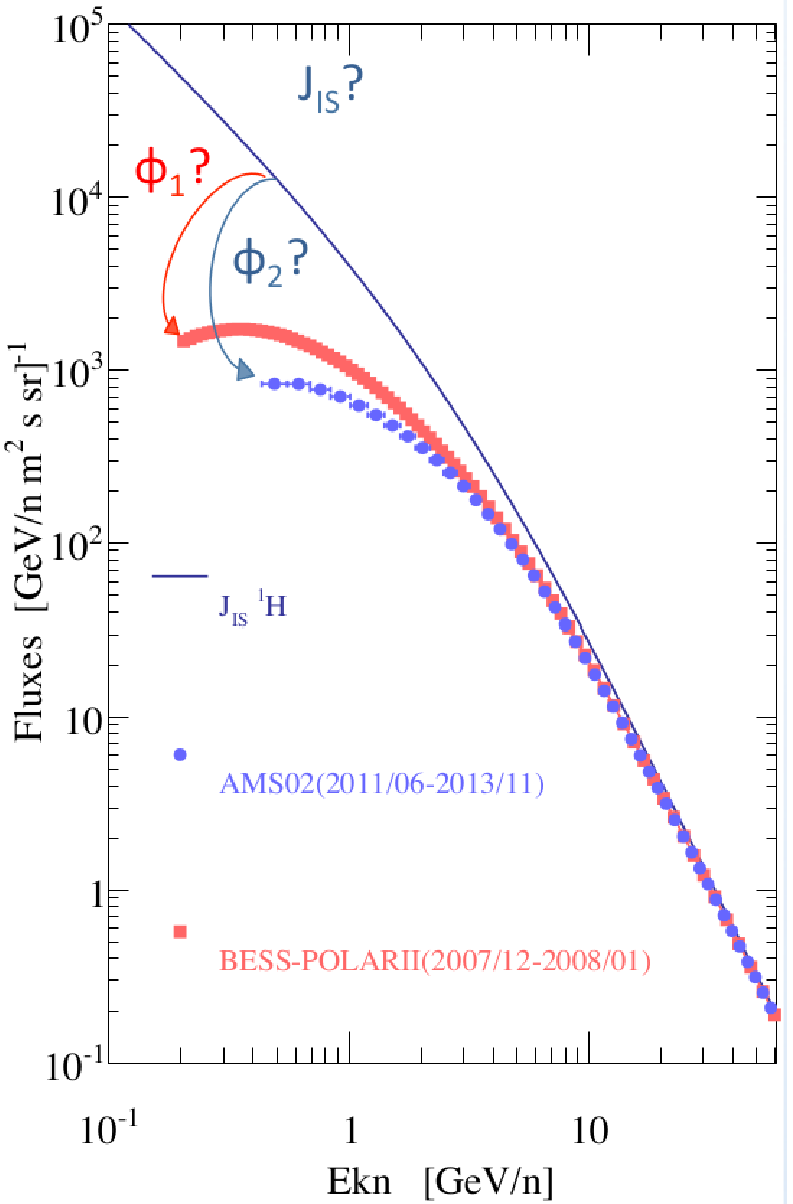
Simultaneous determination of ϕ and J^{IS}

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

→ Minimise model/data for all measured "Ek"

- *For each CR species "j"*: time-indep. params (IS flux)
- *For each CR data exp. "t"*: time-dep. modulation level

N.B.: beware of degeneracies between ϕ and J^{IS}
→ **use most abundant species H and He (best-measured) and as many data as possible**



2. ϕ from CR data: full analysis

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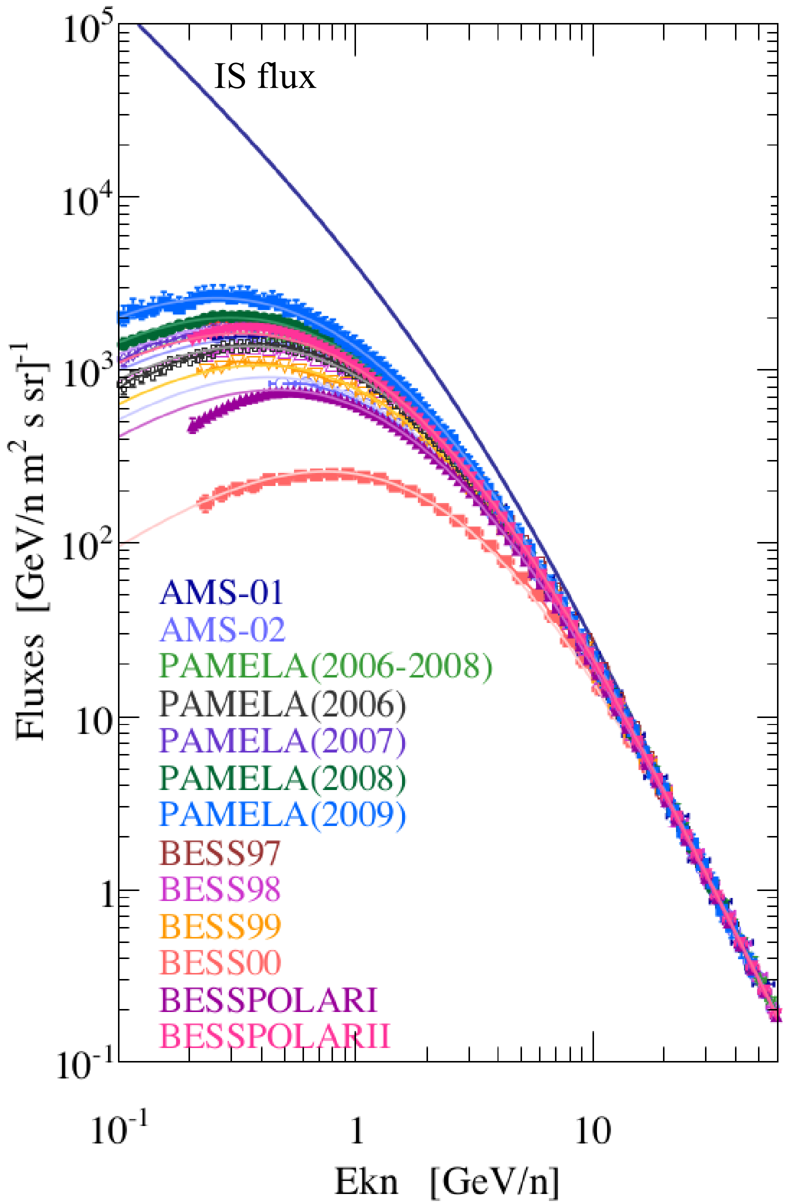
Inputs and analysis

Modulation model: Force-Field approximation
IS flux: cubic spline (piecewise continuous function)

- more flexibility than power-laws
- enable non-parametric fit



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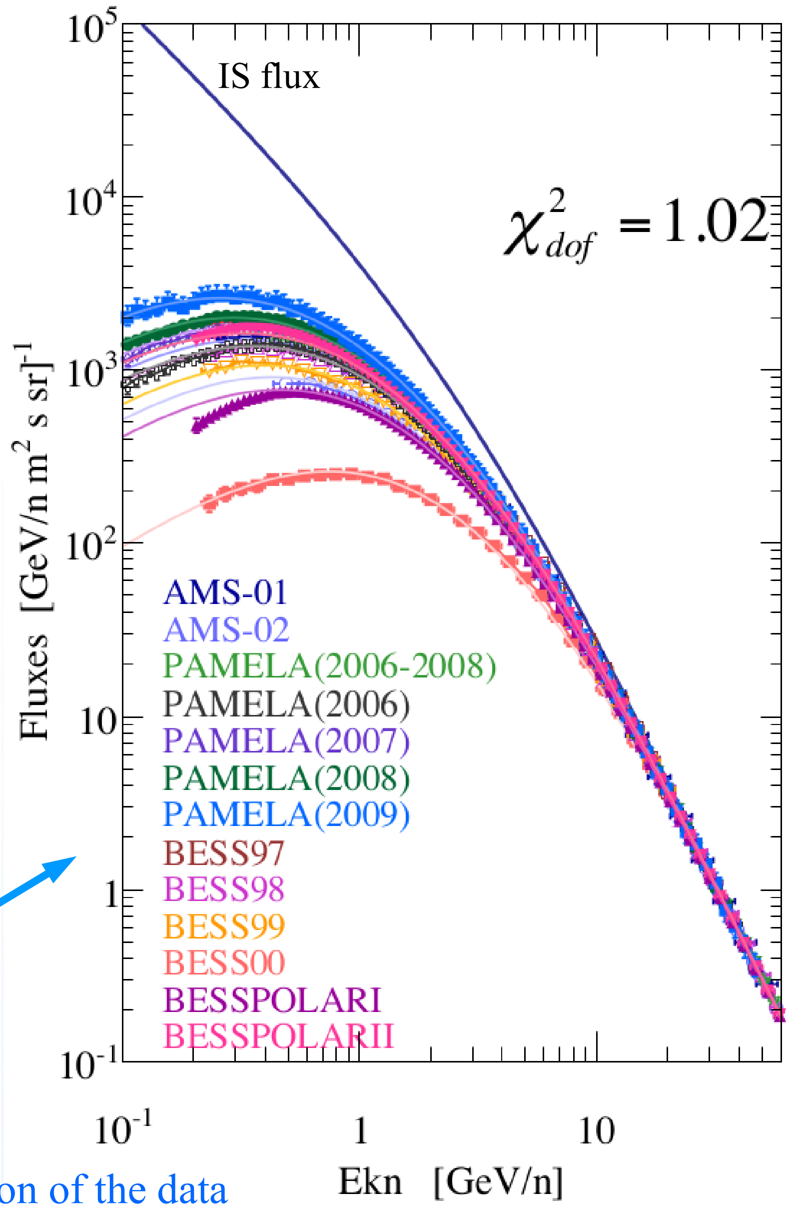
1. *Iterative χ2 analysis*: best data sample (remove inconsistent data)



→ Force-field approximation provides an excellent description of the data (same conclusions adding monthly PAMELA data)

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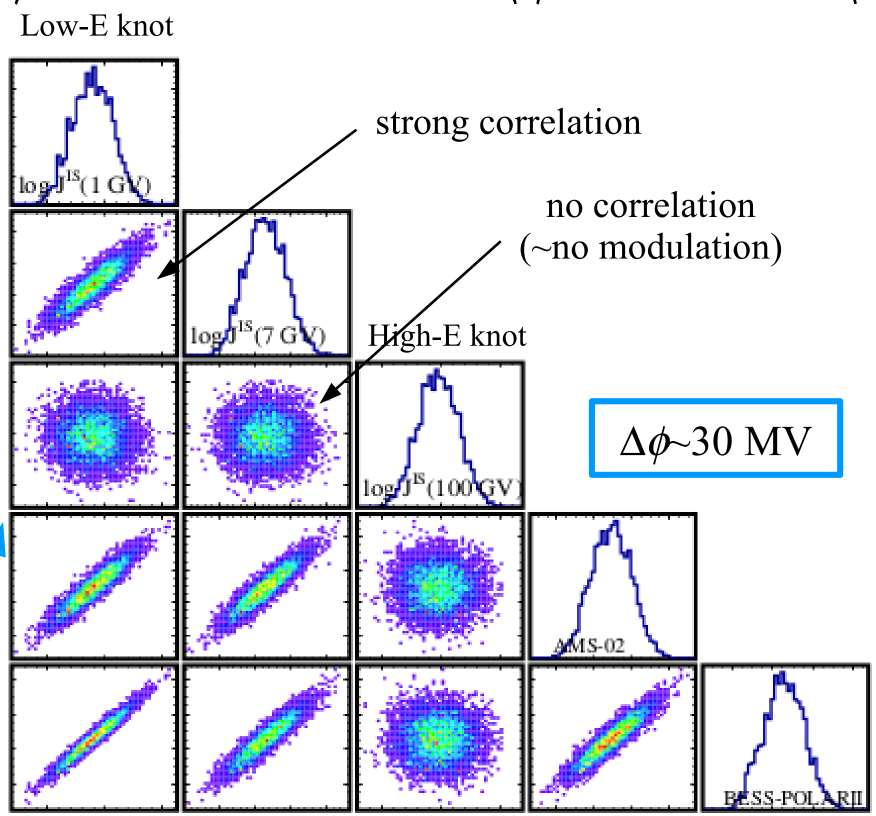
1. *Iterative χ2 analysis*: best data sample (remove inconsistent data)

2. *Markov Chain Monte Carlo*: PDF on ϕ and spline (efficient sample of parameter space)

Sub-sample of parameters
(probability density function and correlations)

IS flux parameters | *ϕ parameters*



$\Delta\phi$~30 MV

→ All parameters ~gaussian distributed
[N.B.: ~ +30 MV bias from ^{2}H (^{3}He) in H (He)]

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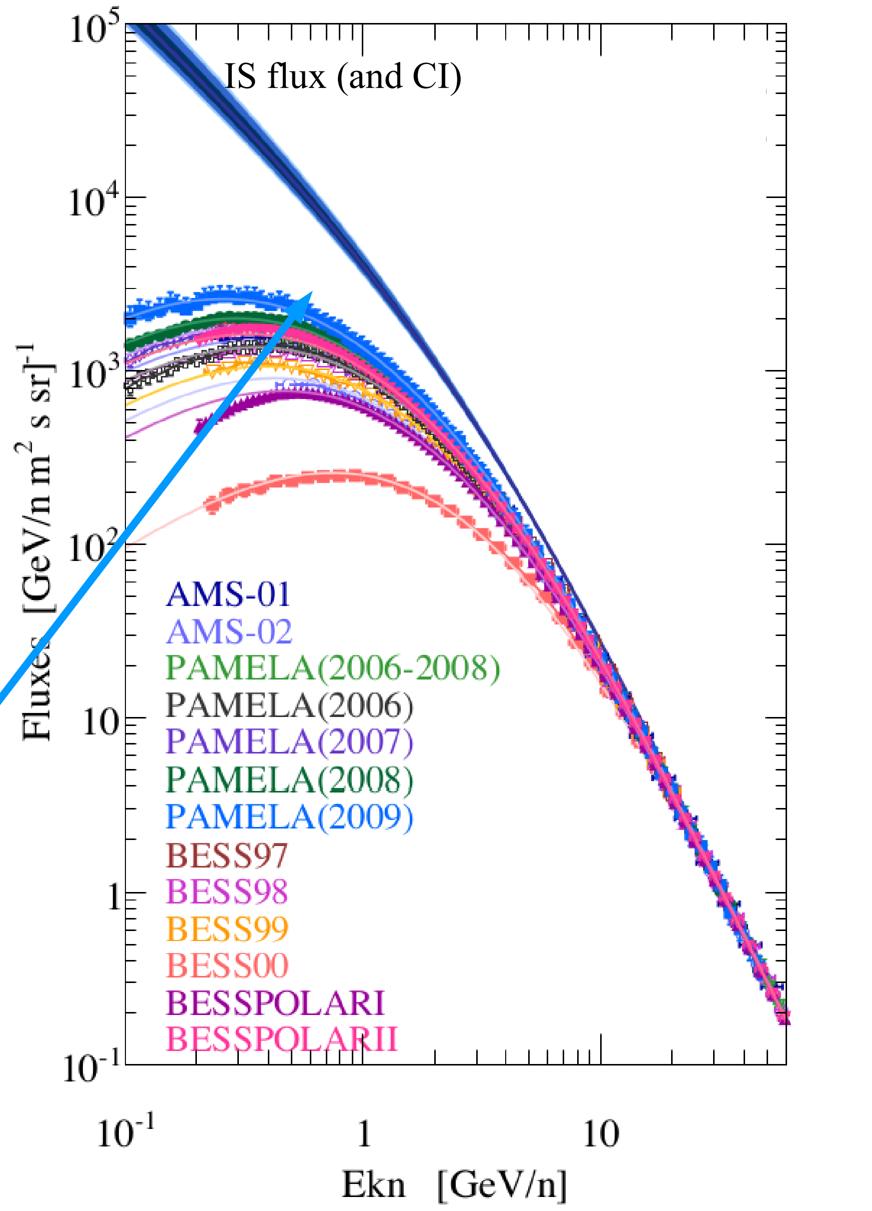
2. *Markov Chain Monte Carlo*: PDF on ϕ and spline (efficient sample of parameter space)
3. *Credible intervals*: on ϕ and J^{IS}

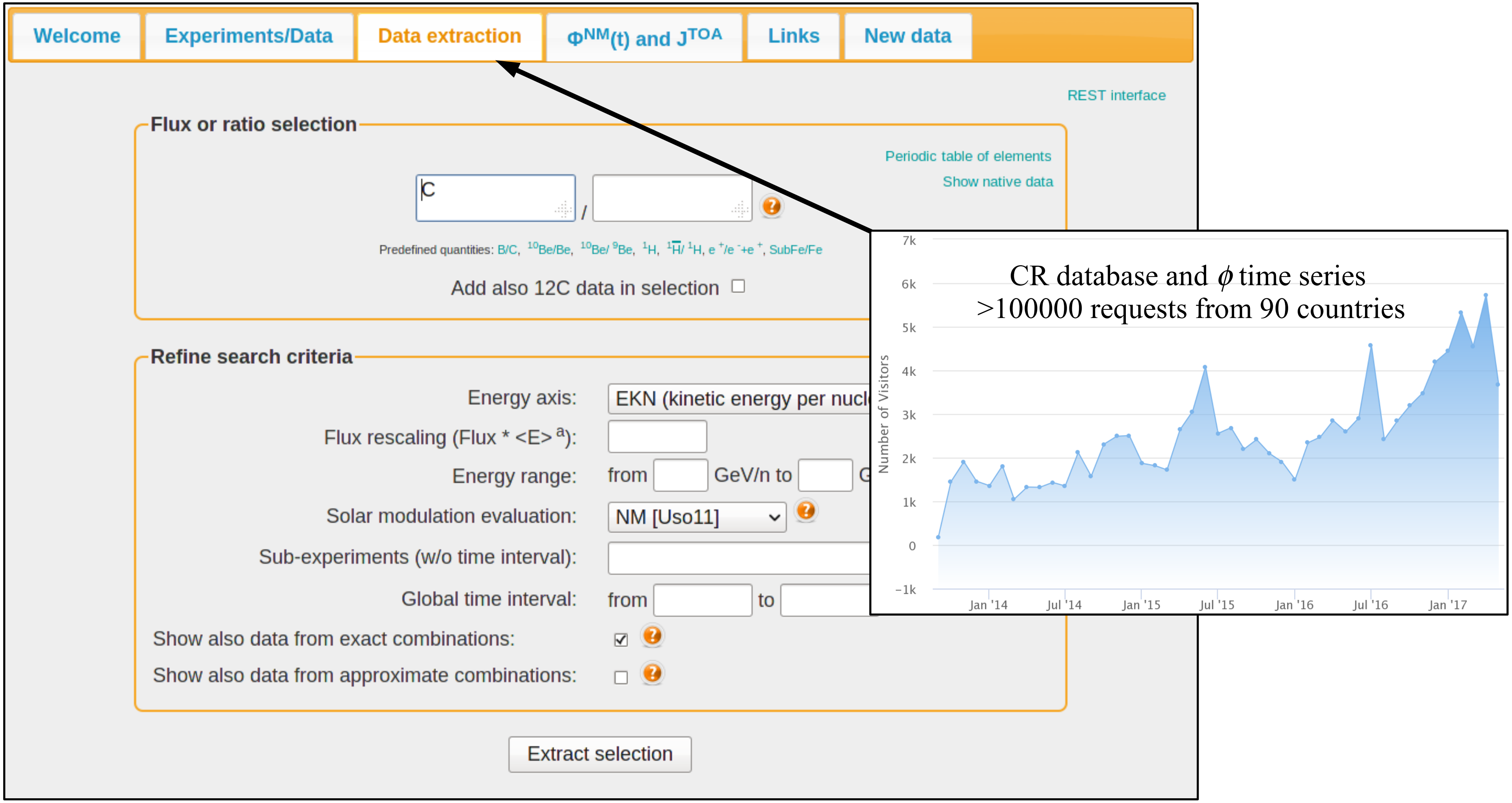


2. ϕ from CR data: time series

CRDB: http://lpsc.in2p3.fr/crdb
Maurin *et al.*, A&A 569, 32 (2014)

Fit of ϕ for each CR (fixed J^{IS})

→ retrieve H and He data from CRDB (cosmic-ray database)
→ Uncertainty on JIS propagated



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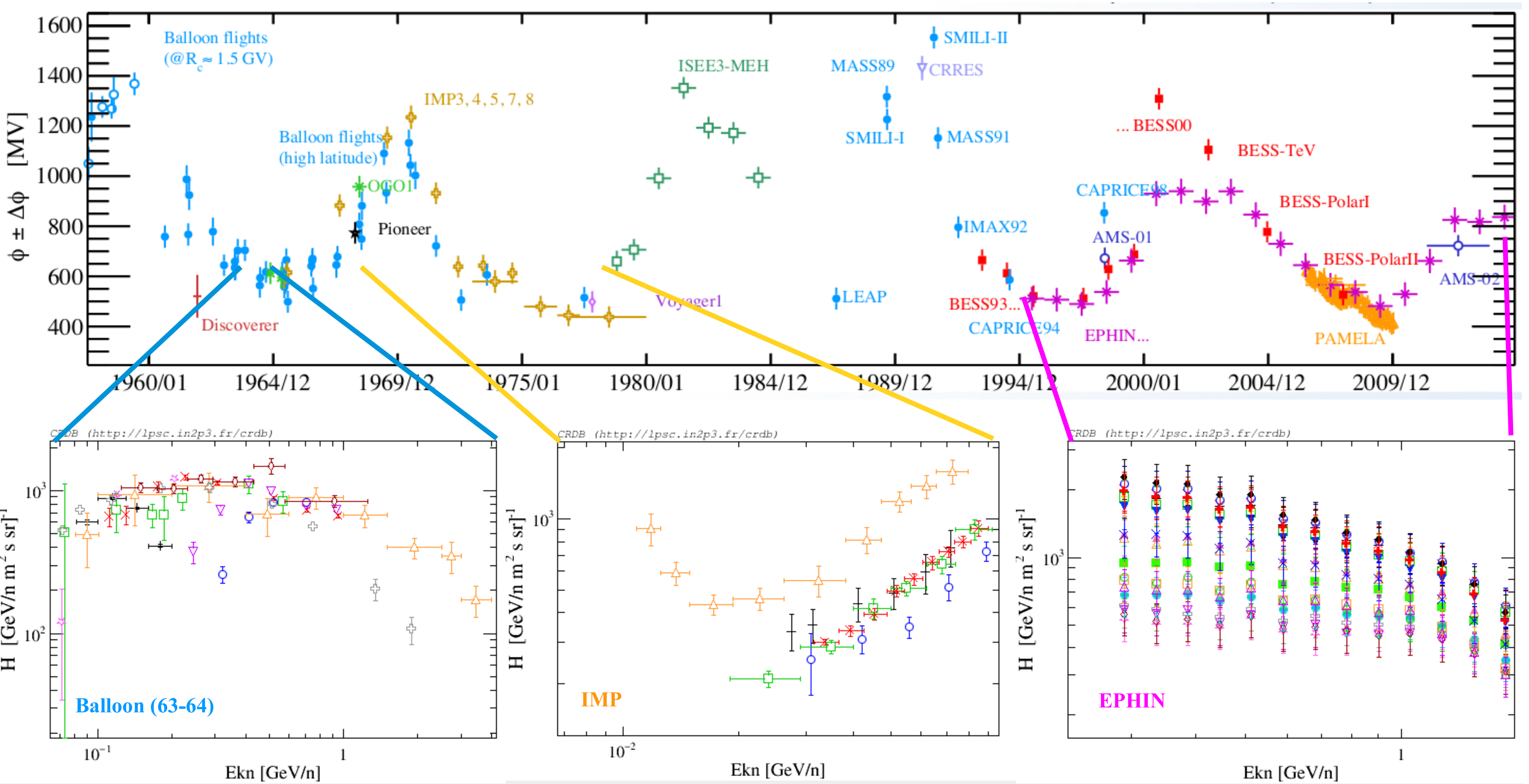
→ **Solar cycle seen from first balloon-borne experiments (in the 50's)**



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3. ϕ from NM data: count rate and ingredients

$$N_s^{\rm data}(t) = k_{s,y}^{\rm corr} \times \int_0^\infty \mathcal{T}_s(R, \overrightarrow{r}, t) \times \sum_{i={\rm CRs}} \mathcal{Y}_{i\,s}^{\mathcal{D}}(R, h)\, \frac{dJ_i^{\rm TOA}}{dR}(R, t)\, dR$$

Count rate in NM station s

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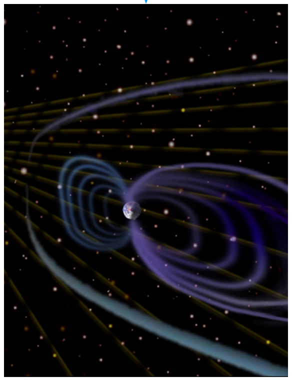
Count rate in NM station s

Transmission function: here, simple Rc



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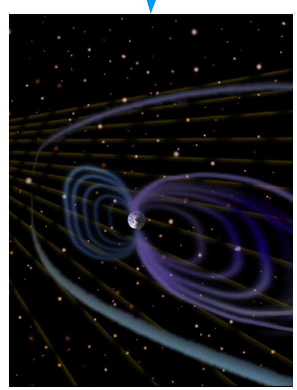
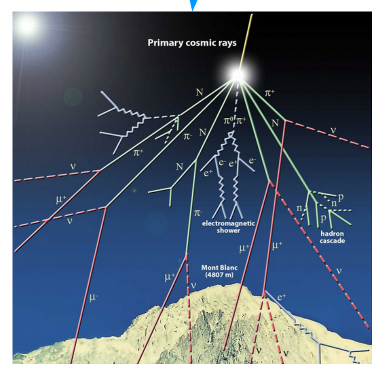


Yield function: #counts in detector per CR



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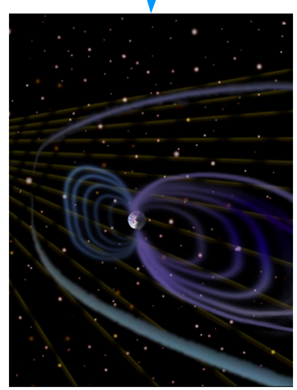

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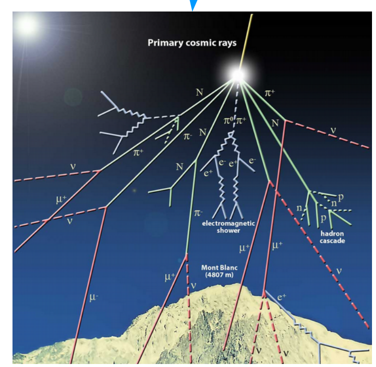
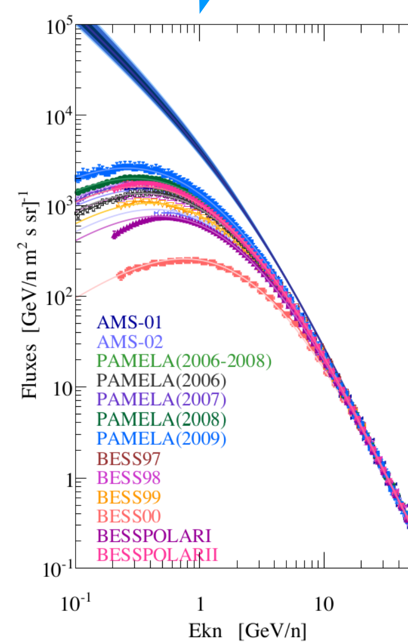


IS flux + fitted parameter ϕ



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Count rate in NM station s

Calibration factor (account for local environment)

Transmission function: here, simple Rc

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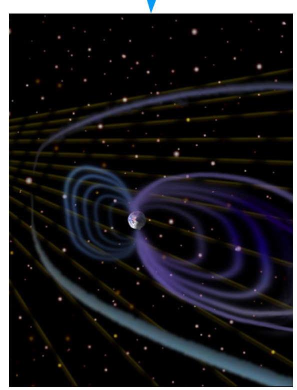
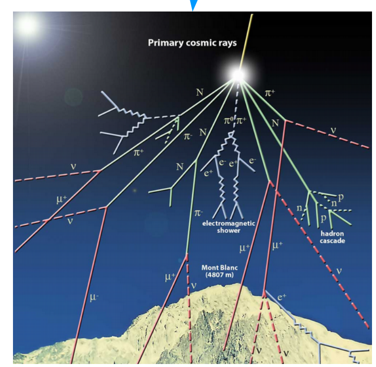
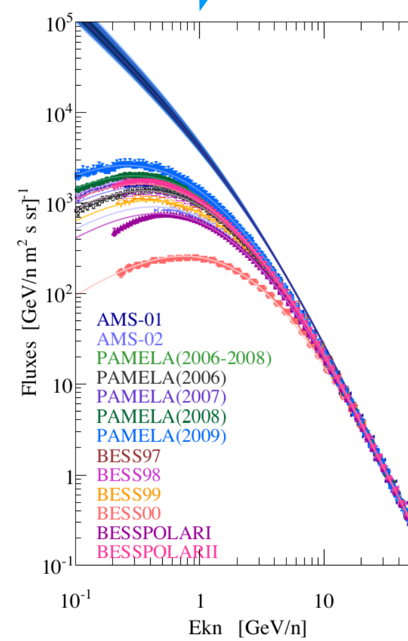
$$k_{s,y,{\rm exp}}^{\rm corr} = \frac{\langle N_s^{\rm data} \rangle_{\rm exp}}{N_{s,y,{\rm exp}}^{\rm calc}\left(J_{\rm H,He}^{\rm TOA}\right)}$$







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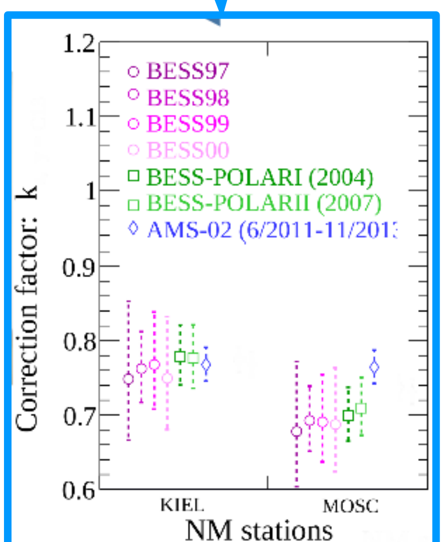

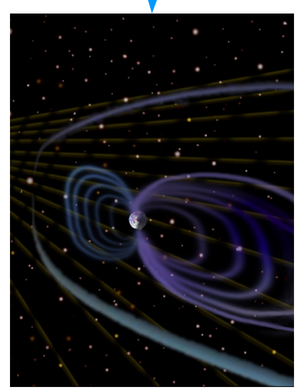

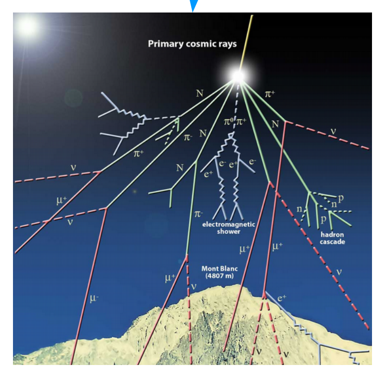

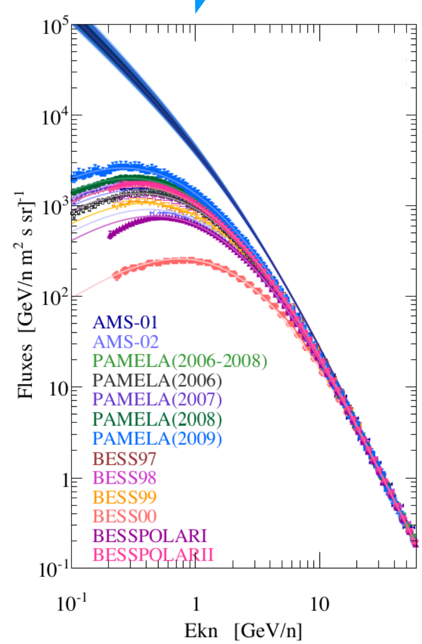

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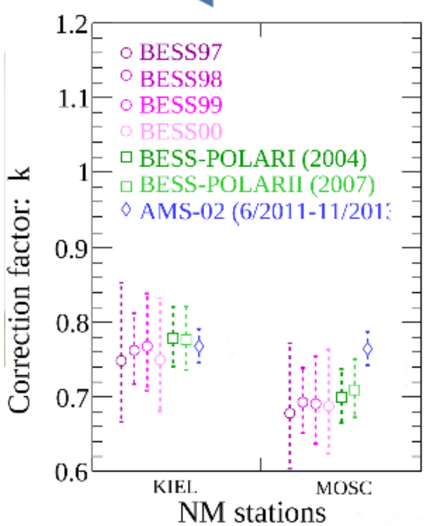
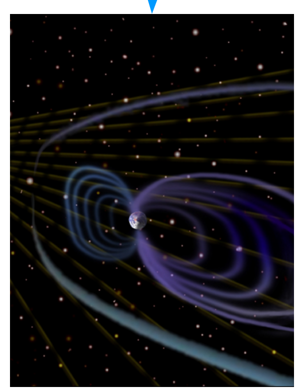
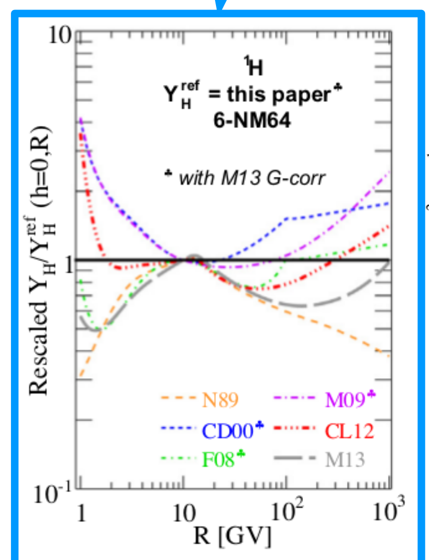
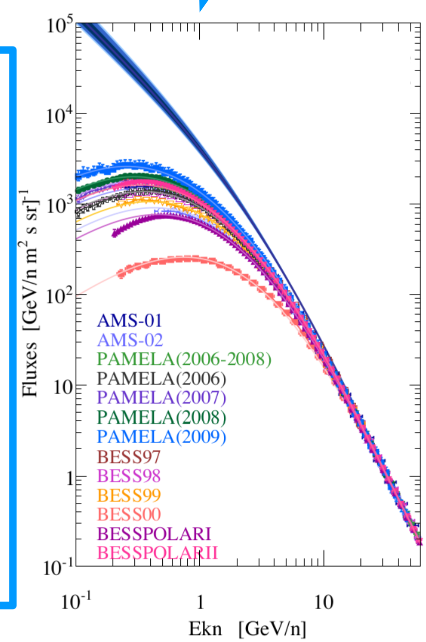








3. ϕ from NM data: count rate and ingredients

$$N_s^{\rm data}(t) = k_{s,y}^{\rm corr} \times \int_0^\infty \mathcal{T}_s(R, \vec{r}, t) \times \sum_{i={\rm CRs}} \mathcal{Y}_{i\,s}^{\mathcal{D}}(R, h)\, \frac{dJ_i^{\rm TOA}}{dR}(R, t)\, dR$$

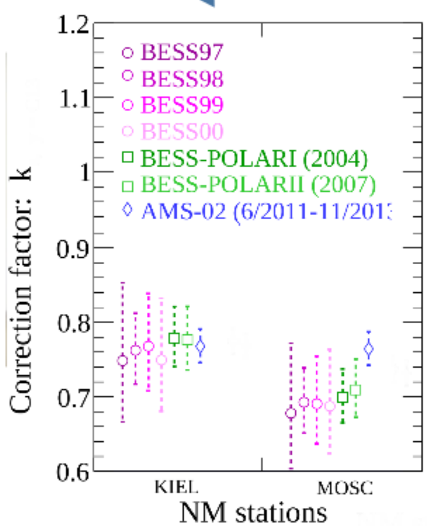
Count rate in NM station s

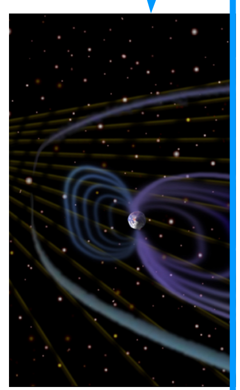
Calibration factor (account for local environment)

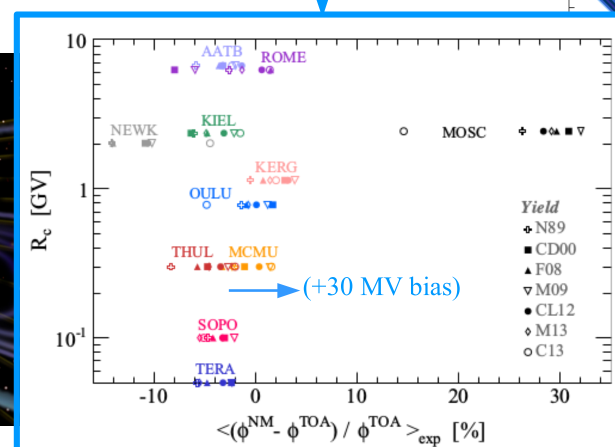
Transmission function: here, simple Rc

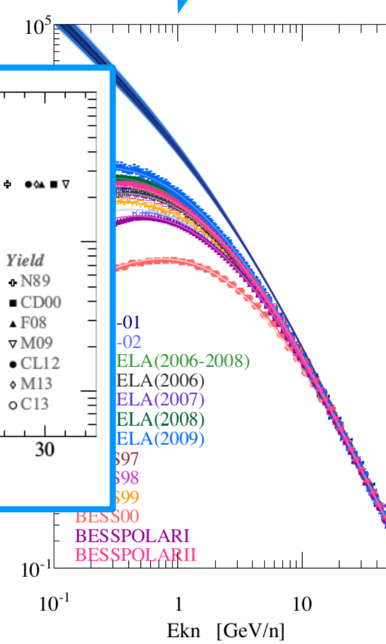
Yield function: #counts in detector per CR

IS flux + fitted parameter ϕ







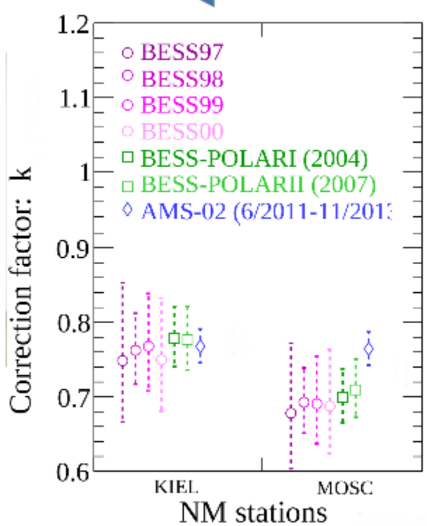


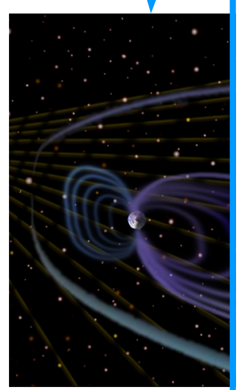
3. ϕ from NM data: count rate and ingredients

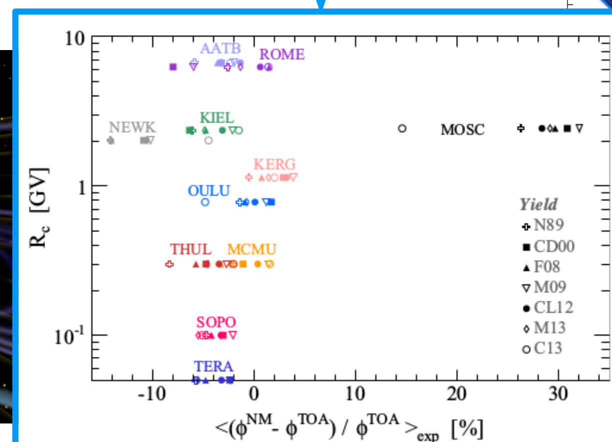
N.B.: 5% variation in count rate → 25% variation on ϕ

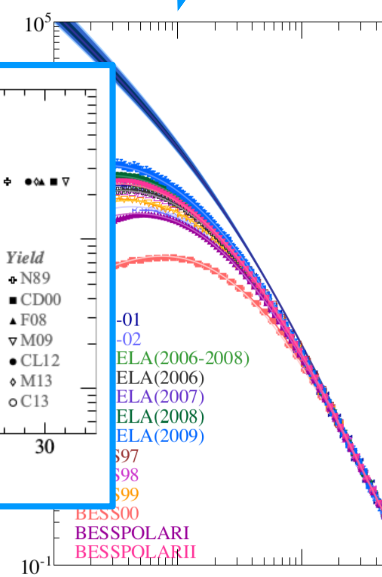
$$N_s^{\rm data}(t) = k_{s,y}^{\rm corr} \times \int_0^\infty \mathcal{T}_s(R, \vec{r}, t) \times \sum_{i={\rm CRs}} \mathcal{Y}_{i\,s}^{\mathcal{D}}(R,h)\, \frac{dJ_i^{\rm TOA}}{dR}(R,t)\, dR$$

- Count rate in NM station s
- Calibration factor (account for local environment)
- Transmission function: here, simple Rc
- Yield function: #counts in detector per CR
- IS flux + fitted parameter ϕ





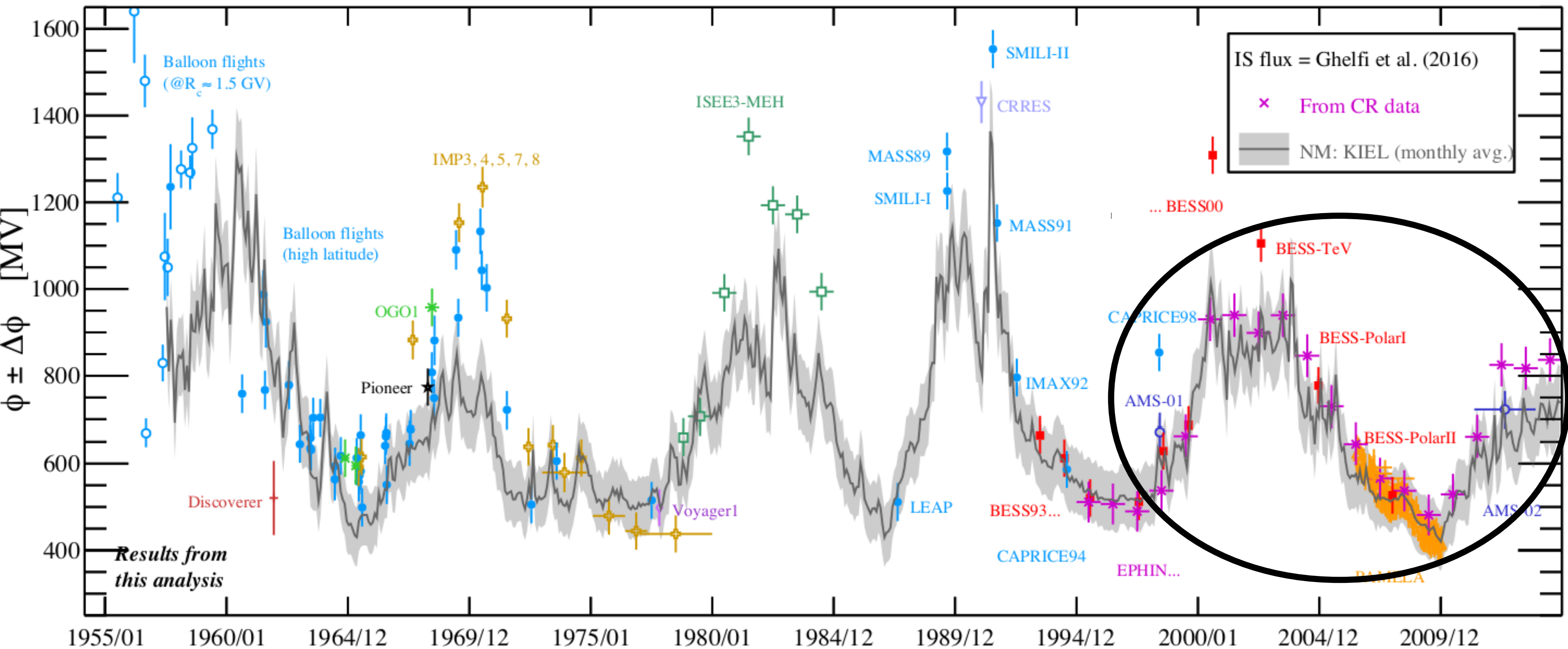




Contribution to $\Delta\phi/\phi$: ~10% ~6% ~5%

3. ϕ from NM data: results

Illustration on KIEL data (monthly averaged)



→ Good agreement for 'calibration' data (AMS, BESS…) and after ~1990

→ Fair agreement before 1990 (CR data, NM data/calculation, modulation model?)

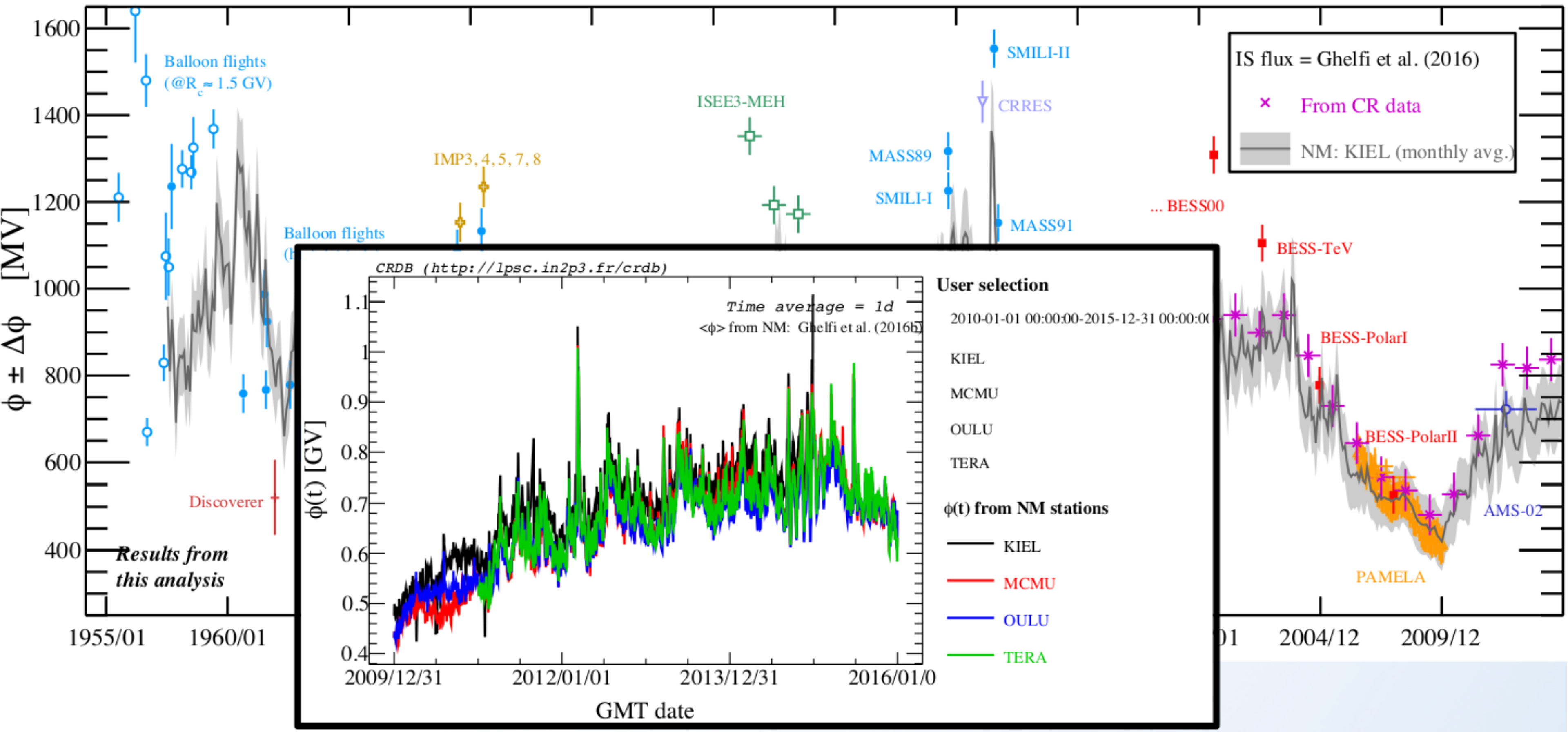
→ $\Delta\phi$ ~ 50-100 MV (NM data) to compare to $\Delta\phi$ ~30 MV (CR data)

3. ϕ from NM data: online on CRDB

CRDB: http://lpsc.in2p3.fr/crdb

ϕ online on CRDB

1. Retrieve NM data daily from NMDB (www.nmdb.eu)
2. Run analysis presented and update ϕ on CRDB interface



→ several stations available, several time average

→ need to extend to other stations (added in NMDB)

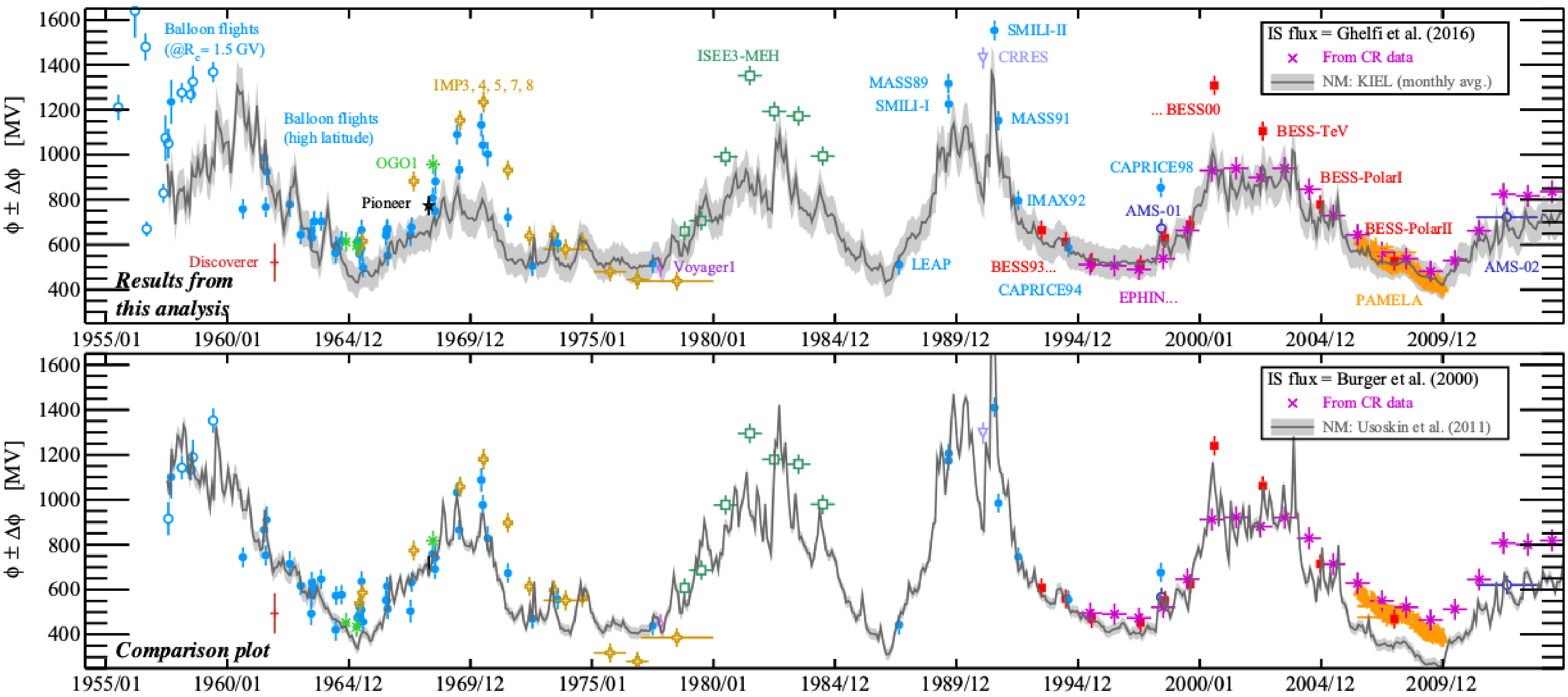
N.B.: not updated since nov. 2016 (script/format change in NMDB… only realised last week!)

Any suggestion/stuff you'd like to see in this interface?

3. ϕ from NM data: comparison Usoskin et al.

Comparison with reference values of Usoskin

http://cosmicrays.oulu.fi/phi/Phi_mon.txt



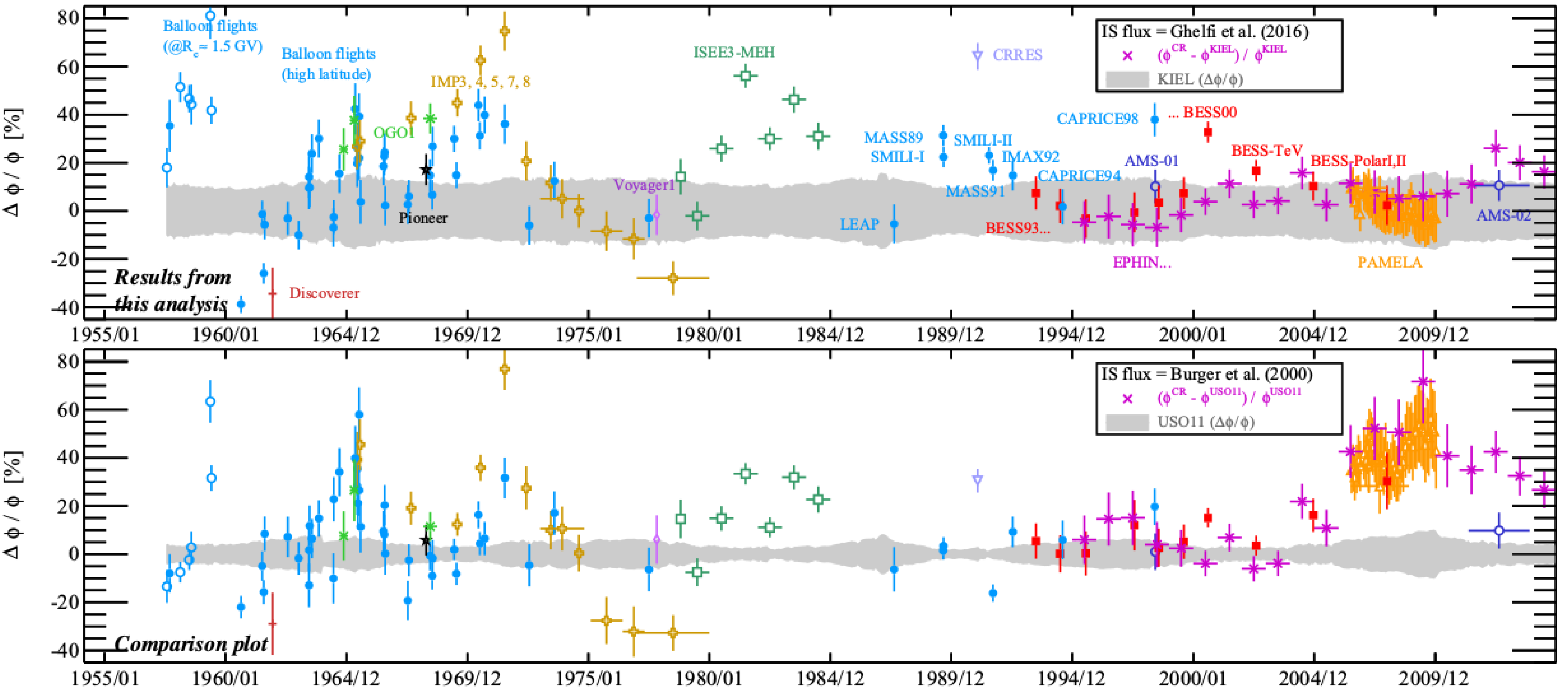
→ Usoskin provides a better match to pre-1990 data, but offset for recent data

→ Larger uncertainties in our analysis (from propagation of many uncertainties)

3. ϕ from NM data: residuals

Comparison with reference values of Usoskin

http://cosmicrays.oulu.fi/phi/Phi_mon.txt



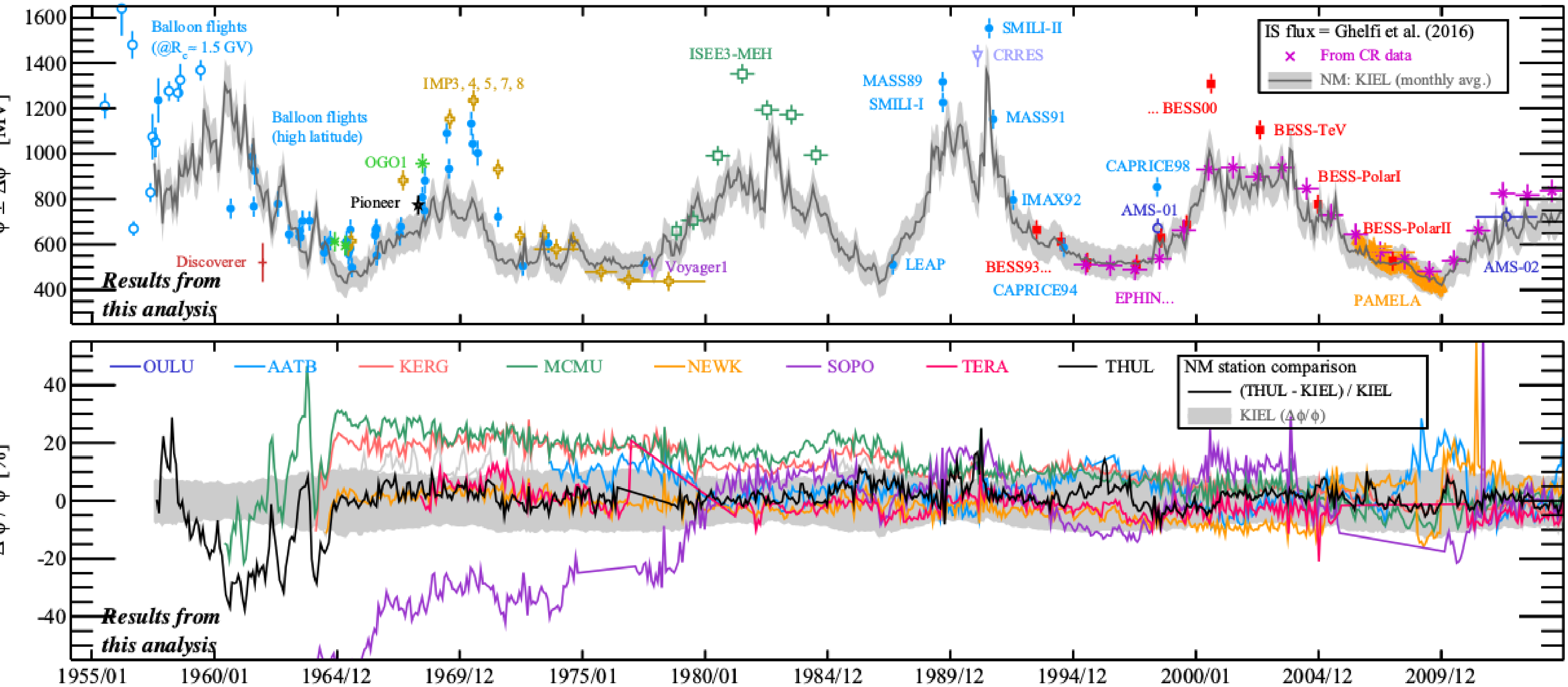
→ Usoskin provides a better match to pre-1990 data, but offset for recent data

→ Larger uncertainties in our analysis (from propagation of many uncertainties)

4. Discussion and perspectives (1/3)

Improvements in ϕ from NM data?

Residuals w.r.t. reference station (KIEL)



$$N_s^{\rm data}(t) = k_{s,y}^{\rm corr} \times \int_0^\infty \mathcal{T}_s(R, \vec{r}, t) \times \sum_{i={\rm CRs}} \mathcal{Y}_i^{\mathcal{D}_s}(R, h) \, \frac{dJ_i^{\rm TOA}}{dR}(R, t) \, dR$$

→ Time-dependence of Rc (e.g., Smart and Shea, 2008, 2009) + sigmoid?

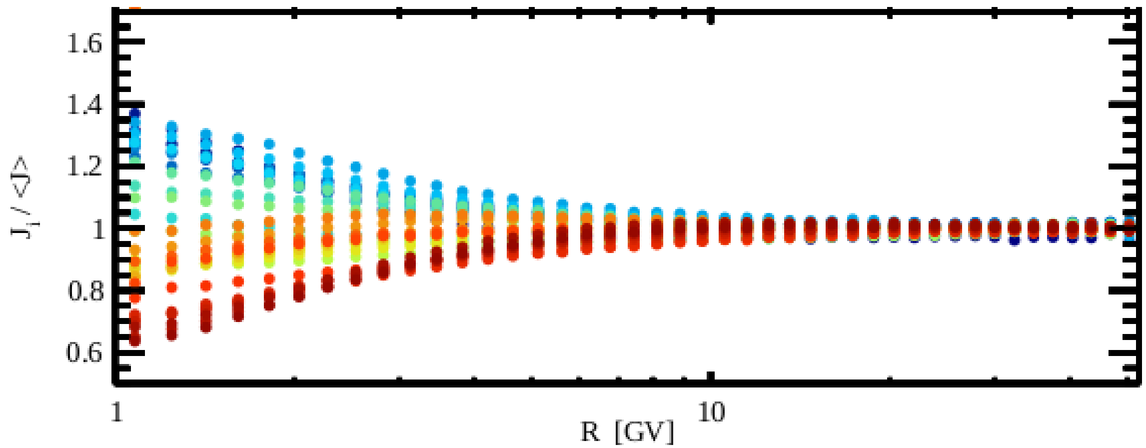
→ Use improved yield function (see next talk)

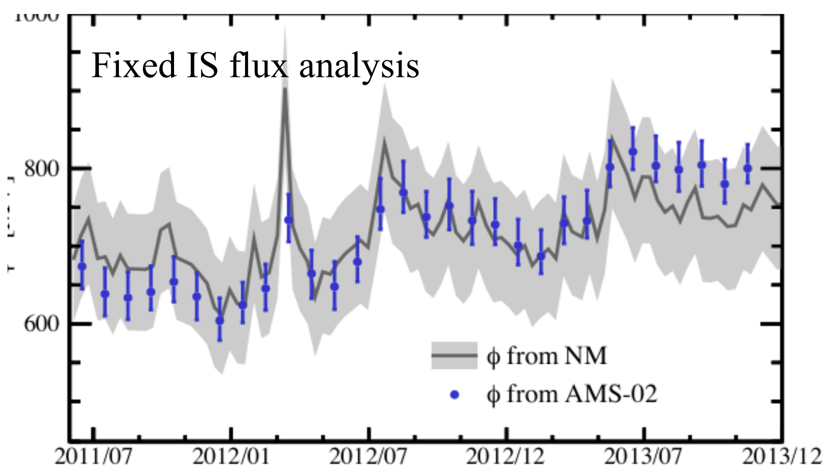
4. Discussion and perspectives (2/3)

A. Ghelfi (PhD thesis)

Is the Force-Field approximation still valid for AMS-02 data?

AMS-02 data monthly variation:
6/2011 to 11/2013 (blue to red)





→ Fair agreement, but trend visible

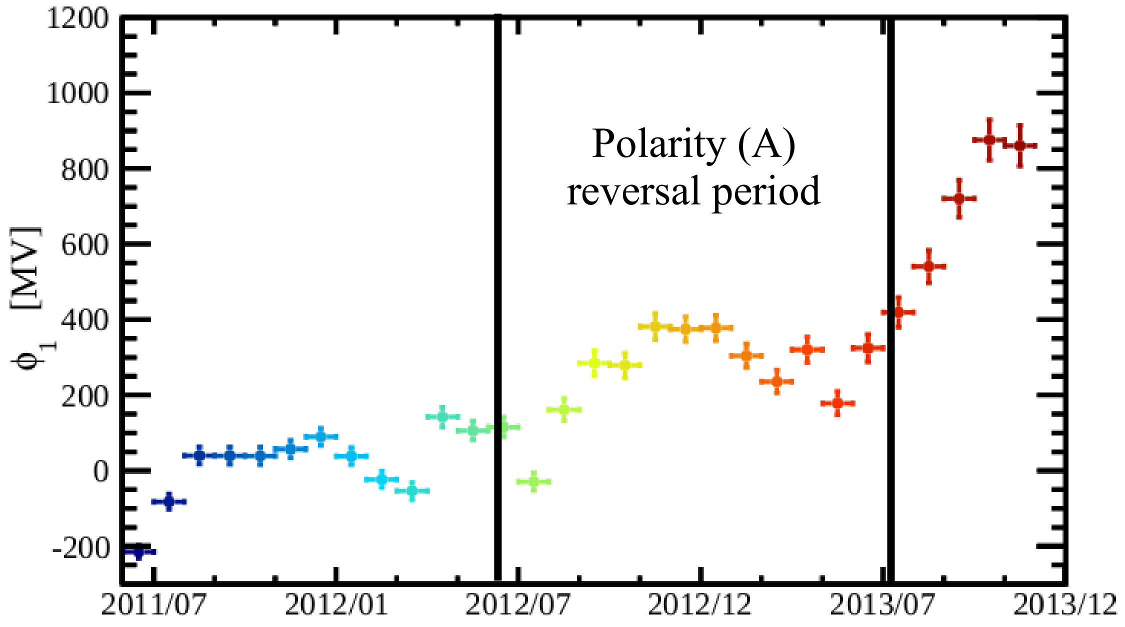
4. Discussion and perspectives (3/3)

A. Ghelfi (PhD thesis)

Is the Force-Field approximation still valid for AMS-02 data?

Beyond the FF approximation
Cholis *et al.* (2016)

$$\begin{cases} \phi(t) \rightarrow \phi(R,t) = \phi_0(t) + \phi_1(R,t) \\ \phi_1(R,t) = \begin{cases} 0 & \text{Si A<0} \\ a(t)f(R) & \text{Si A>0} \end{cases} \end{cases}$$



→ **Need more investigation, but confirms high potential of AMS-02 data for Solar physics (similar to PAMELA?)**

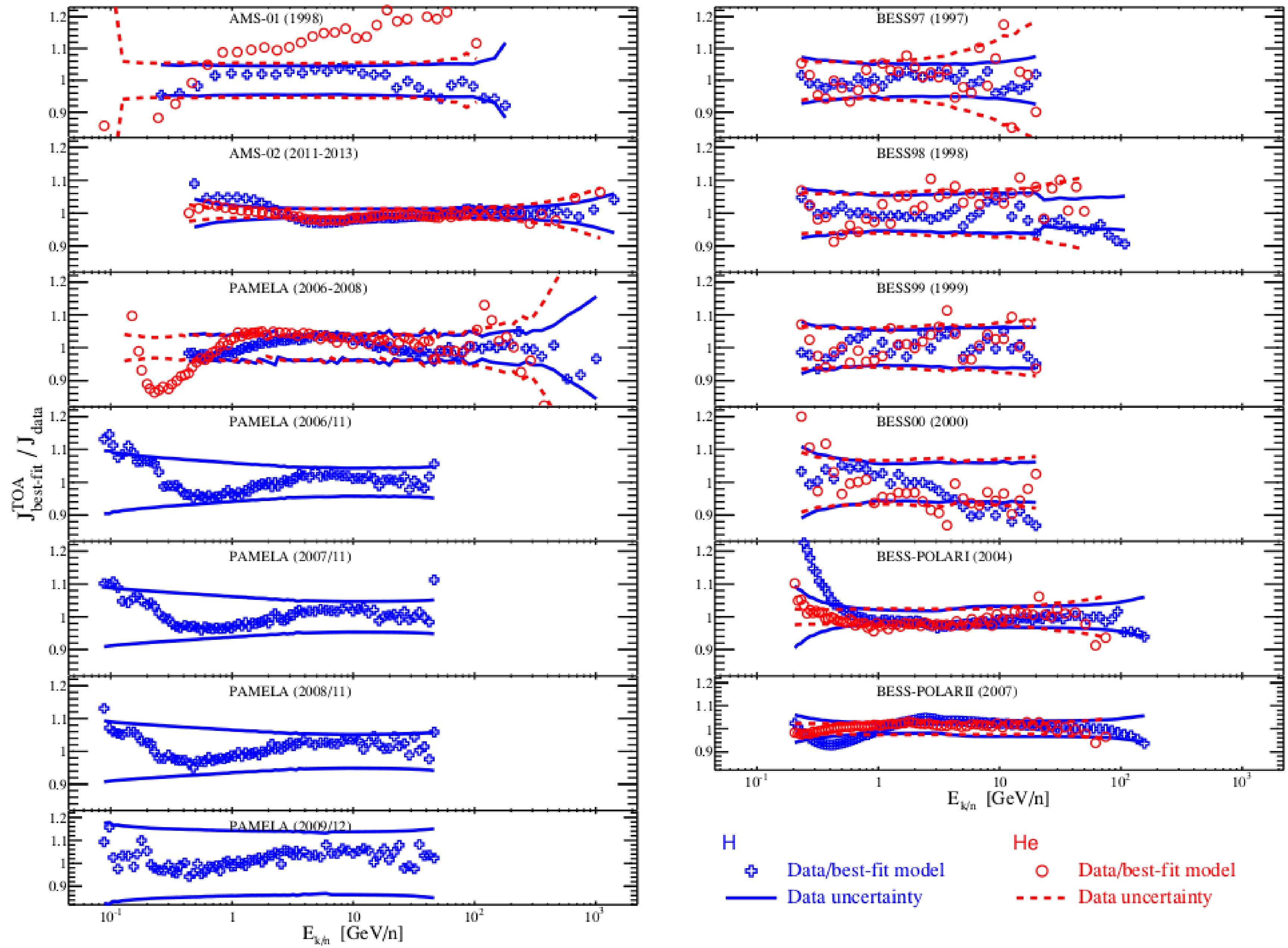


Fig. 1. Ratio of the best-fit model for p (filled black circles) and He (empty red circles) to data for the experiments passing our selection (see Table 1). The solid blue (dashed red) lines correspond to the uncertainties (statistical and systematics combined) on the p (He) measurements. We note that the AMS-01 (*top left panel*) and PAMELA (2006−2008) He data (red empty circles; *left panel*, *third row*) are excluded based on their χ^2 value (see Table 1) and are shown for illustration only.

Table 1. List of proton and helium data tested and rejected (*italics*) for the analysis.

Experiment (date)	$\chi^2_{\rm exp}(p)$ all → cut	$\chi^2_{\rm exp}$(He) all → cut
AMS-01 (1998)	0.38 → 0.37	7.6
AMS-02 (2011–2013)	1.4 → 1.2	0.71 → 0.66
BESS93 (1993)	*2.9*	*2.5*
BESS97 (1997)	0.12 → 0.11	0.44 → 0.44
BESS98 (1998)	0.45 → 0.43	0.64 → 0.65
BESS99 (1999)	0.24 → 0.23	0.44 → 0.44
BESS00 (2000)	1.1 → 1.0	0.83 → 0.82
BESS-TEV (2002)	*4.5*	*0.73*
BESS-POLARI (2004)	1.5 → 1.6	1.1 → 1.1
BESS-POLARII (2007)	1.6 → 1.5	0.46 → 0.49
CAPRICE98 (1998)	*6.9*	...
IMAX92 (1992)	*2.6*	*2.0*
PAMELA (2006–2008)	0.27 → 0.26	*4.5*
PAMELA (2006/11)	0.34 → 0.35	...
PAMELA (2007/11)	0.28 → 0.29	...
PAMELA (2008/11)	0.22 → 0.24	...
PAMELA (2009/12)	0.09 → 0.09	...

Notes. The left column provides the name and date of the experiments; the second column gives (i) $\chi^2_{\rm exp}$ value (see Eq. (4)) for proton fits using all the available data listed in this table and (ii) the same quantity, but only data for which the previous fit gives $\chi^2_{\rm exp}(p) \leq 2$; the third column is for $\chi^2_{\rm exp}$(He) values, the cut sample now demanding that both $\chi^2_{\rm exp}(p) \leq 2$ and $\chi^2_{\rm exp}(\rm He) \leq 2$.

References. References for the data are AMS (Alcaraz et al. 2000; Aguilar et al. 2015a,b), BESS (Wang et al. 2002; Shikaze et al. 2007; Abe et al. 2016), CAPRICE (Boezio et al. 2003), IMAX (Menn et al. 2000), PAMELA (Adriani et al. 2011, 2013a).

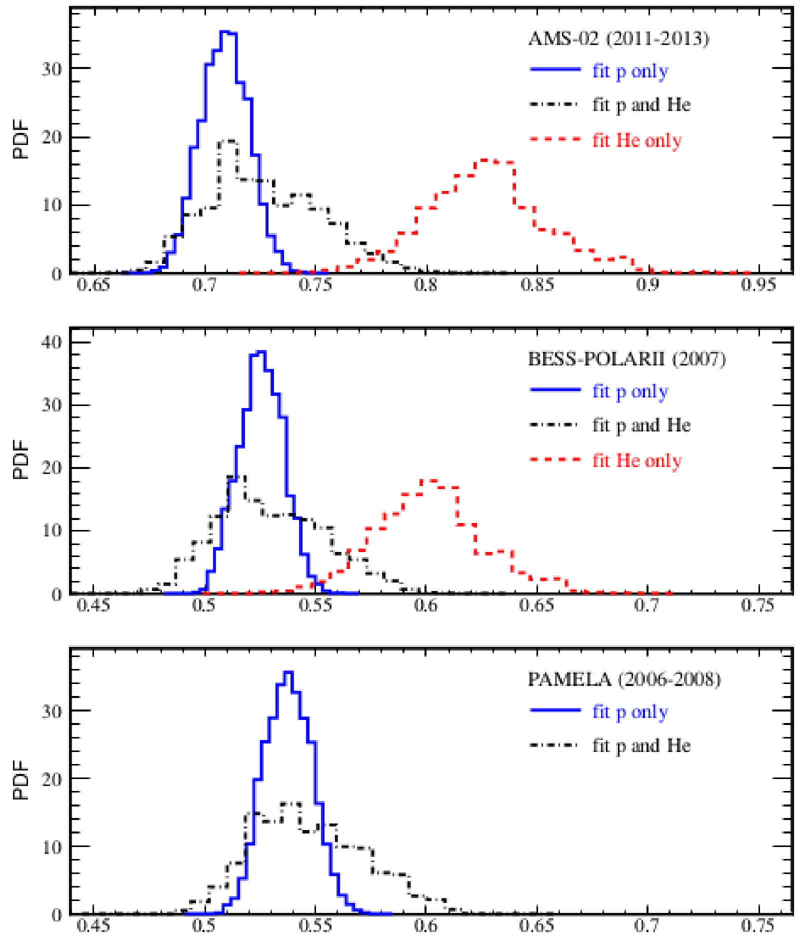


Fig. 3. PDF of the solar modulation level ϕ for the three most recent datasets with the highest statistics. We show the results for a fit on all selected data from Table 1, for p data alone (blue solid line), He data alone (red dashed line), and p and He data simultaneously (black dash-dotted line).

2. ϕ from CR data: full analysis

Simultaneous determination of ϕ and J^{IS}

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

→ Minimise model/data for all measured "Ek"

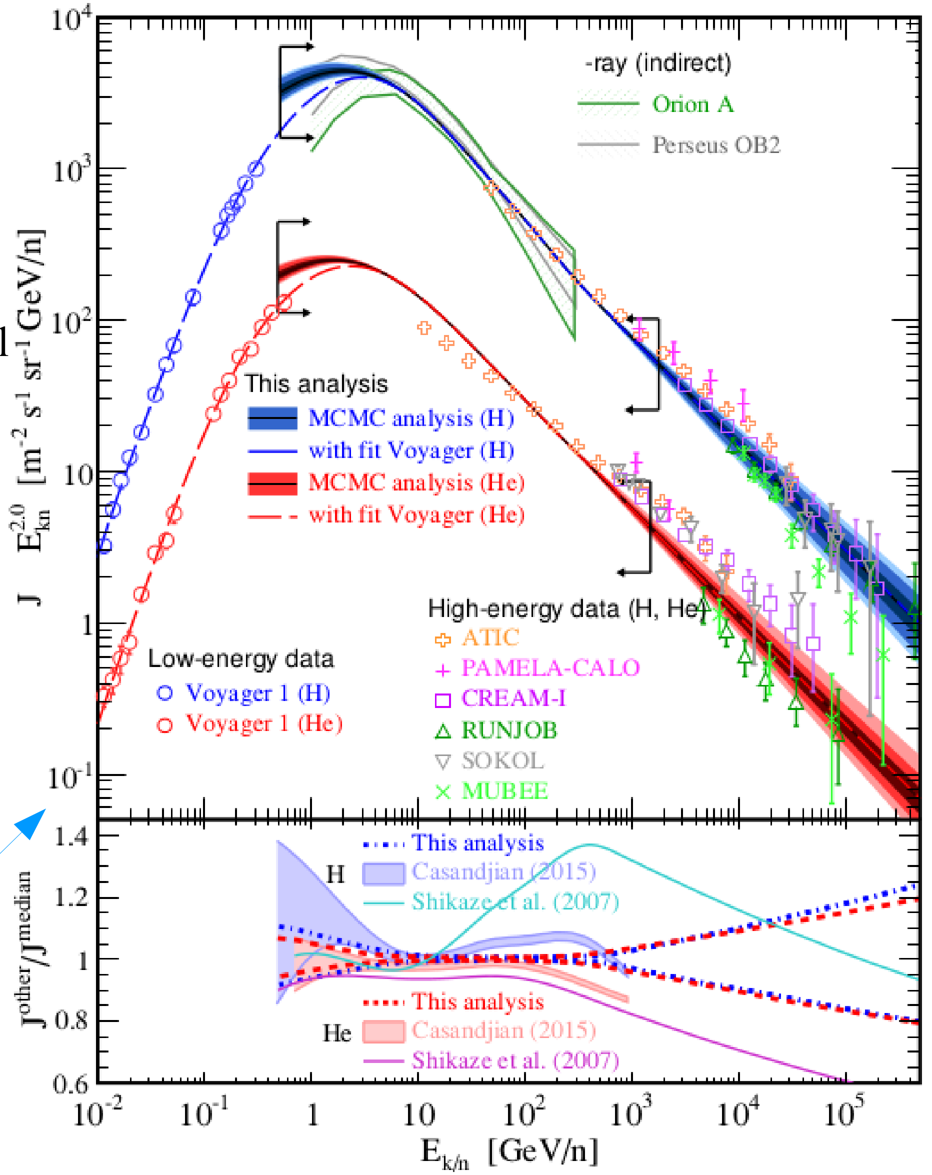
- *For each CR species "j"*: time-indep. params (IS flux)
- *For each CR data exp. "t"*: time-dep. modulation level

N.B.: beware of degeneracies between ϕ and J^{IS}
→ use most abundant species H and He (best-measured) and as many data as possible

Inputs and analysis

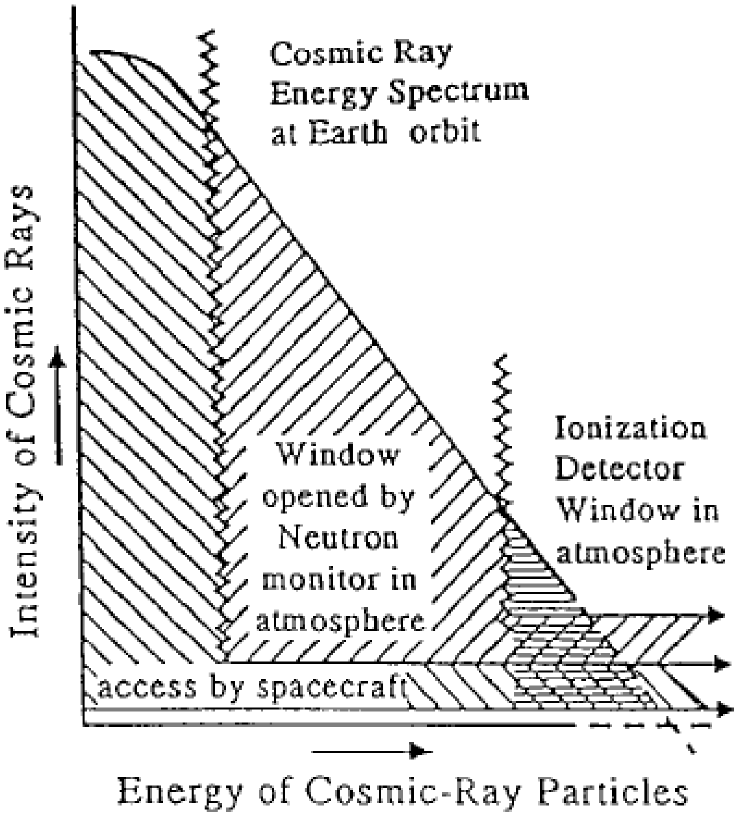
Modulation model: Force-Field approximation
IS flux: cubic spline (piecewise continuous function)
– more flexibility than power-laws
– enable non-parametric fit

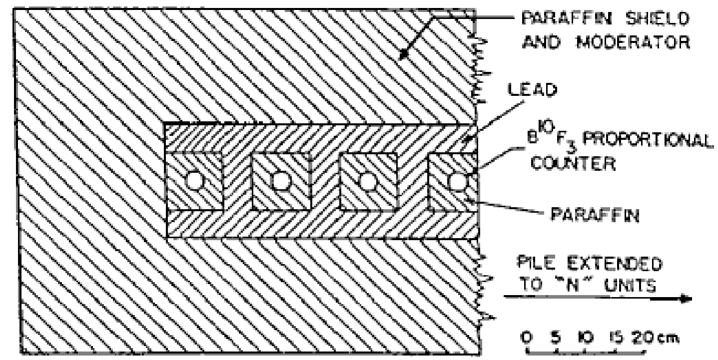
1. *Iterative χ2 analysis*: "golden data sample" (remove inconsistent data)
2. *Markov Chain Monte Carlo*: PDF on ϕ and spline (efficient sample of parameter space)
3. *Credible intervals*: on ϕ and J^{IS}



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

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





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

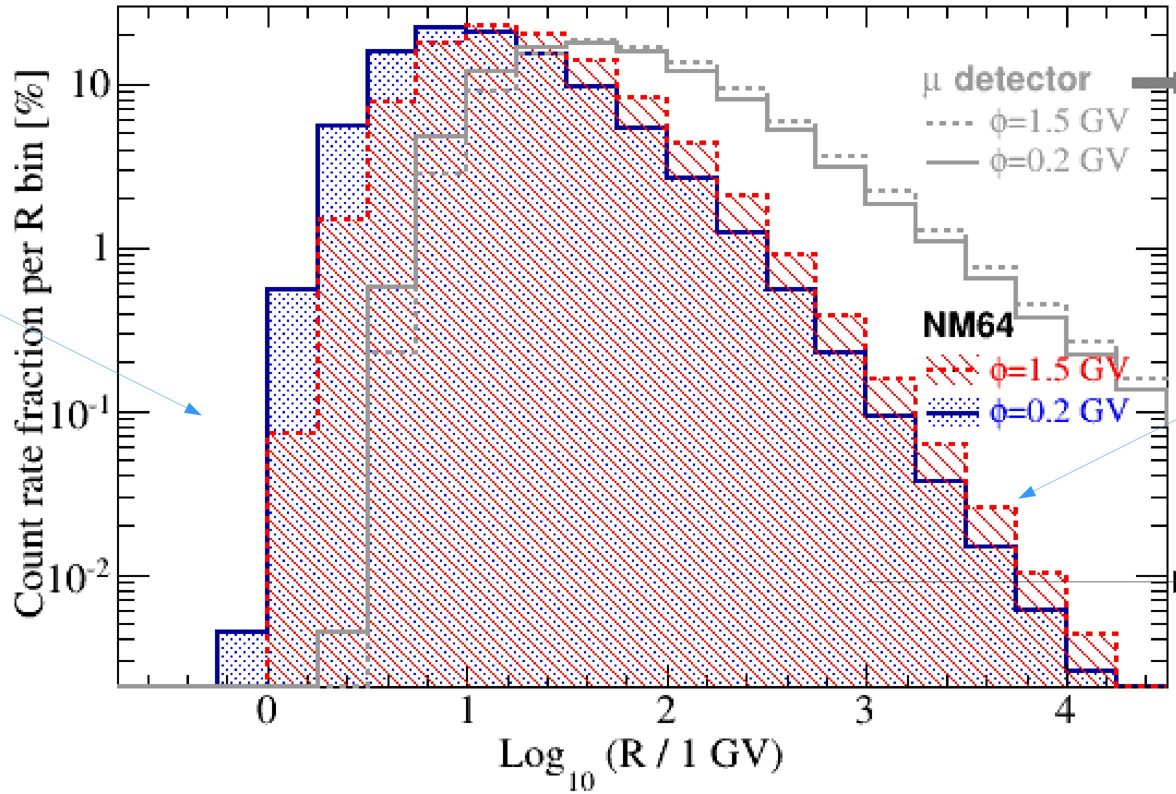
$$^{3}\mathrm{He}_2 \;+\; \mathrm{n} \;\rightarrow\; {}^{3}\mathrm{H}_1 \;+\; \mathrm{proton}$$


Izmiran NMs (Russia)

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

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

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



Yield goes to 0.

μ detectors less sensitive to ϕ than NMs

CR flux $\alpha E^{-2.8}$

Area per bin = contribution to count rate N

→ 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

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

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

→ $s_{Z>2}$ = 0.445 +/- 0.005 (IS fit) +/-0.03 (scaling approx)
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

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

$\Delta N/N \sim 1\% \;\longrightarrow\; \Delta\phi \sim 40$ 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) ⇓
	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	–	⇓
	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

Table 1
Weighted mean averaged correction factors $\langle k_{s,y}^{corr} \rangle_{exp}$ for various stations (ordered by decreasing R_c) and yield functions: N89 (Nagashima et al., 1989), CD00 (Clem and Dorman, 2000), F08 (Flückiger et al., 2008), M09 (Matthiä, 2009), CL12 (Caballero-Lopez and Moraal, 2012), M13 (Mishev et al., 2013), C13 (Paper I). The relative uncertainty on these factors is 2.2% (see Section 4.2). For comparison purpose, we show in square brackets the values obtained from a similar analysis by Usoskin et al. (2011) and in curly brackets by Gil et al. (2015). These authors use different TOA datasets for the normalisation. We have $\Delta k/k \approx 2.2\%$ from Eq. (12), whereas Gil et al. (2015) report $\Delta k/k \approx 0.1\%$.

Station	R_c [GV]	h [m]	$\langle k_{s,y}^{corr} \rangle_{exp}$						
			N89	*CD00*	*F08*	*M09*	*CL12*	*M13*	*C13*
Almaty	6.69	3340	0.751	0.712	0.687	0.570	0.476	0.562	0.861
Rome	6.27	60	0.787	0.802 [0.921]	0.599	0.643 [0.597]	0.540	0.639 {1.151}	0.731
Moscow	2.43	200	0.789	0.784	0.608	0.631	0.520	0.651 {1.241}	0.727
Kiel	2.36	54	0.828	0.817 [0.823]	0.637	0.663 [0.548]	0.570	0.686 {1.185}	0.770
Newark	2.02	50	0.906	0.899	0.697	0.724	0.624	0.750 {1.100}	0.852
Kerguelen	1.14	33	1.100	1.090 [0.990]	0.848	0.878 [0.662]	0.754	0.913 {0.971}	1.010
Oulu	0.78	15	1.070	1.060 [0.948]	0.821	0.850 [0.634]	0.743	0.885 {1.006}	0.963
McMurdo	0.30	48	1.320	1.300	1.010	1.050	0.909	1.090 {0.789}	1.220
Thule	0.30	26	1.210	1.200	0.935	0.968	0.834	1.010	1.120
SouthPole	0.10	2820	1.010	0.993	0.898	0.799	0.701	0.830	1.270
TerreAdelie	0.00	45	1.130	1.120	0.869	0.899	0.789	0.934	1.030

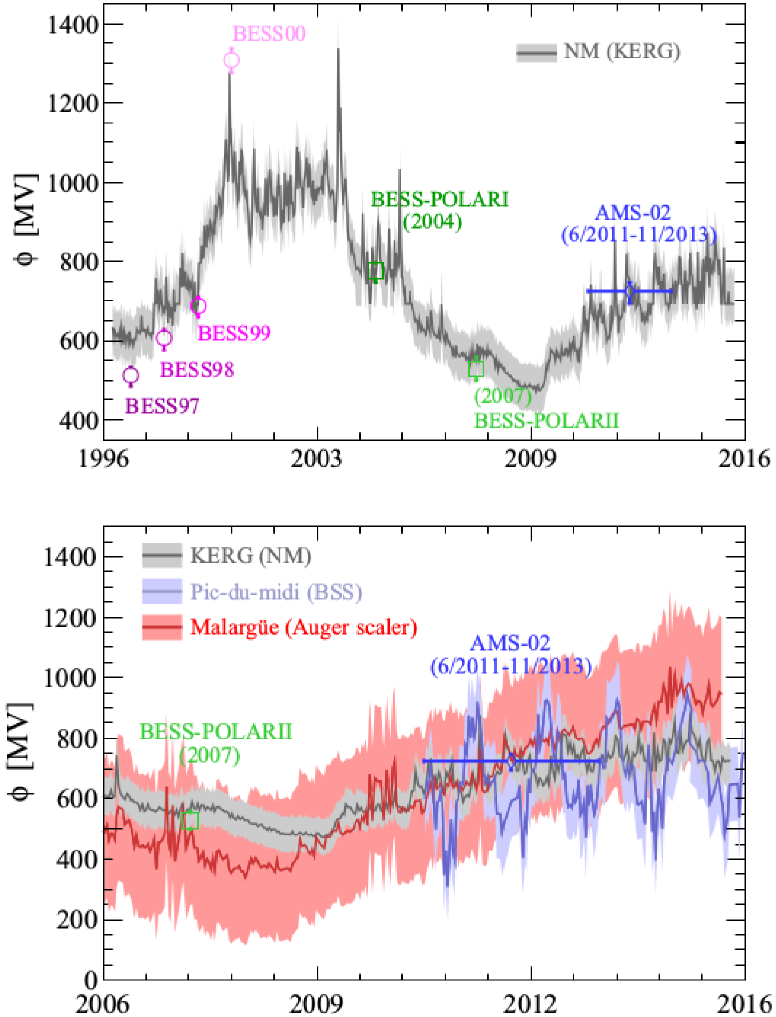


Fig. 4. *Top panel:* ten-days average $\langle \phi^{NM} \rangle$ time-series (solid line) and uncertainties (shaded area) displayed along with ϕ^{TOA} (Ghelfi et al., 2016) for illustration. We underline that ϕ^{NM} calculated on the exact BESS97 time interval is much lower than the 10-days average and in full agreement with ϕ^{TOA}. *Bottom panel:* comparison of ten-days average $\langle \phi^{NM} \rangle$ (grey), $\langle \phi^{scaler} \rangle$ (red), and $\langle \phi^{BSS} \rangle$ (blue) time-series. The symbols show the CR TOA data available to calculate the correction factor for BSS and Auger scaler data. See text for discussion. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)