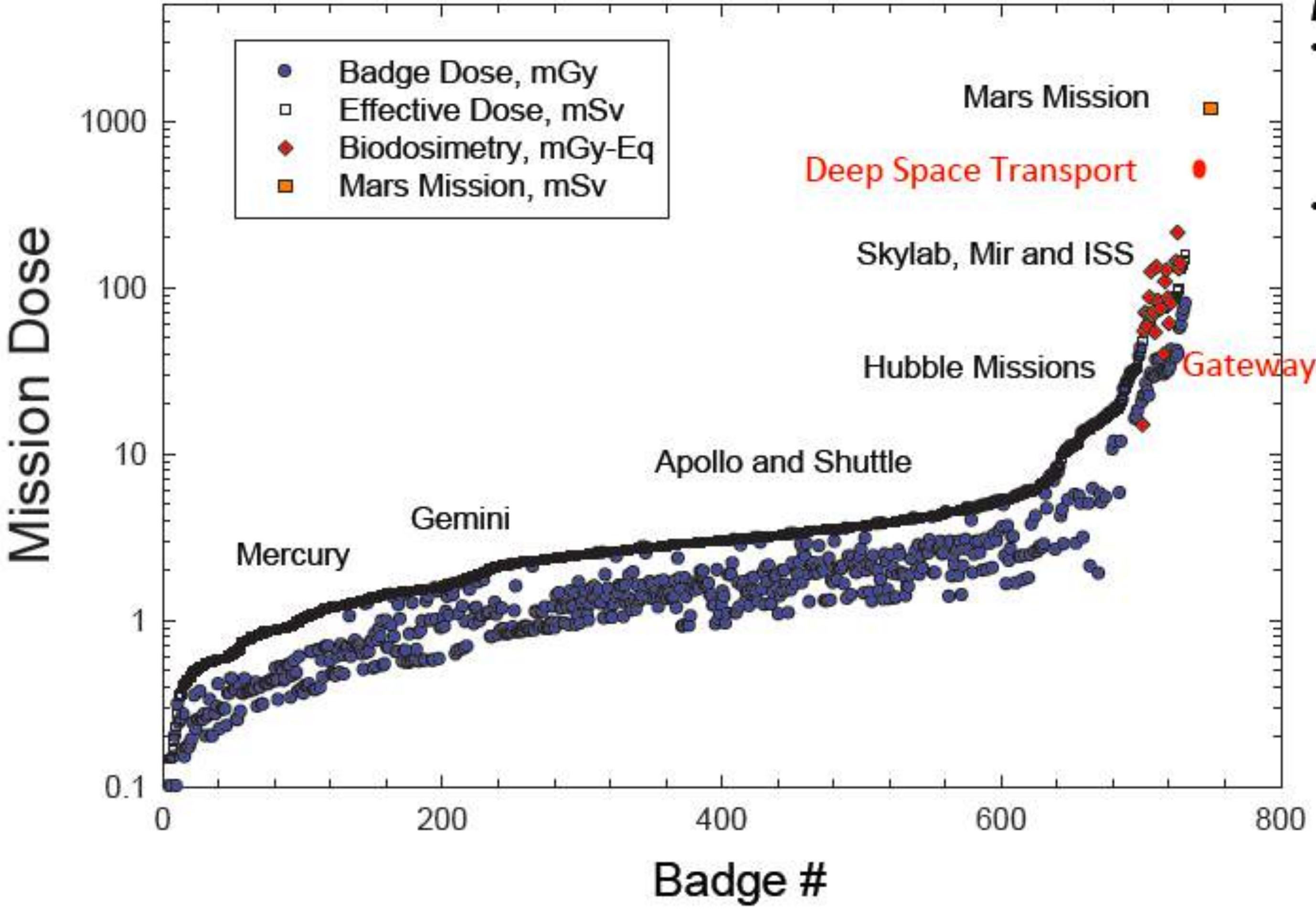
AMS & Exploration

B.Bertucci,
University & INFN Perugia

NASA Crew Mission Doses



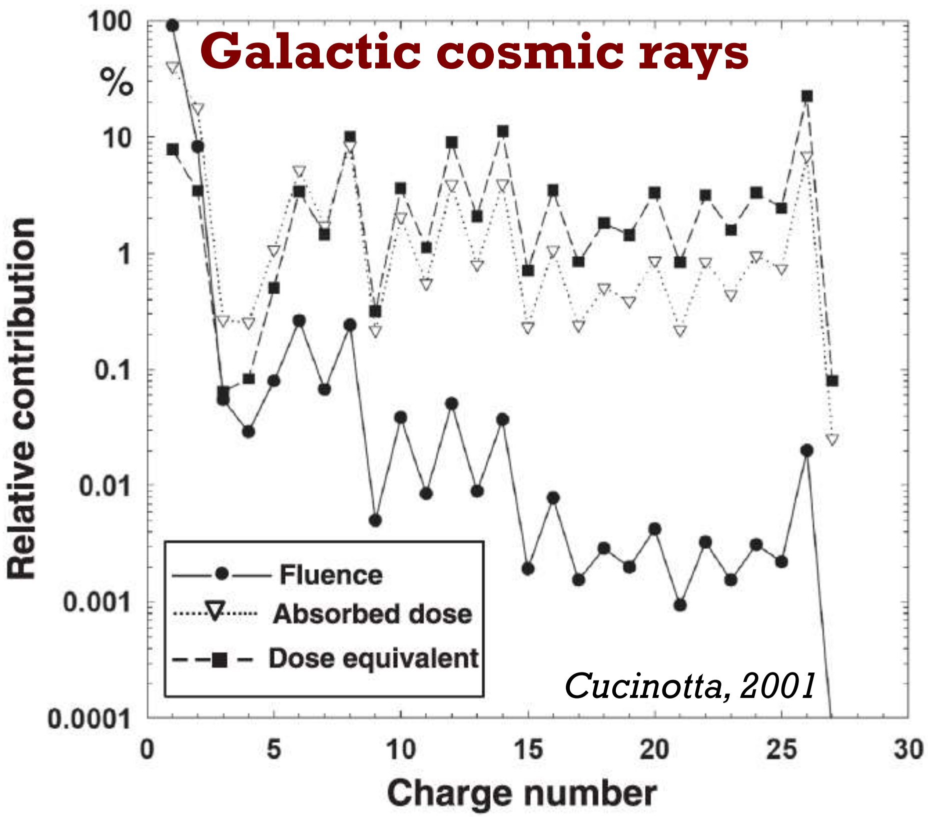
***NASA Experience**:*

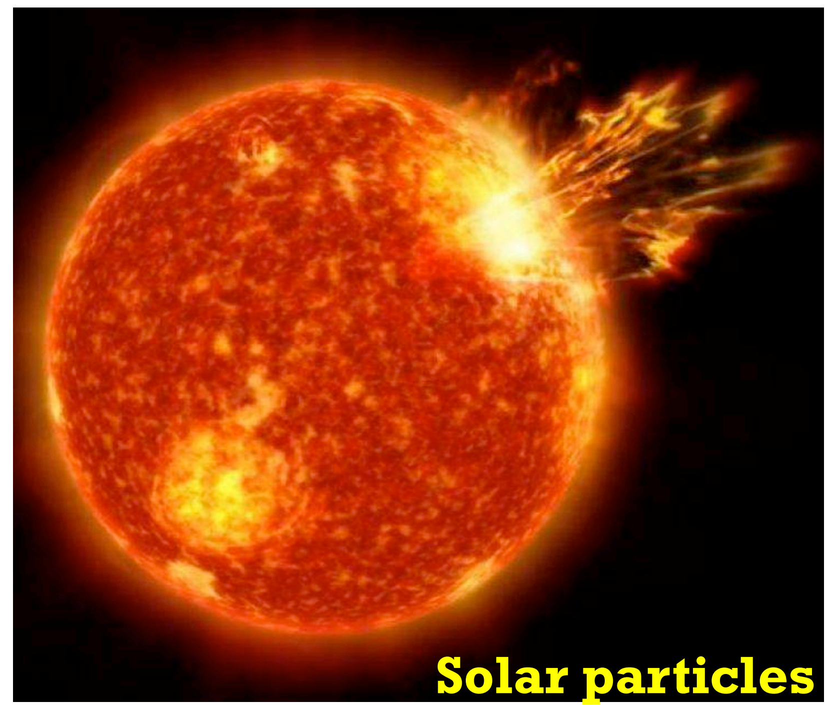
- *Single ISS mission approximately 1/10 of Mars mission exposure*
- *Crew with multiple missions have accumulated 30% of Mars exposure risk*

Update from Cucinotta et al. Radiat Res (2008)

Space exploration & radiation

Knowledge of radiation is a key point for planning long term manned missions out of the earth magnetosphere.





Most important source of dose (≈90 rem/yr)
Difficult to shield

+ A sensitivity analysis *(Slaba & Blattnig 2014)*

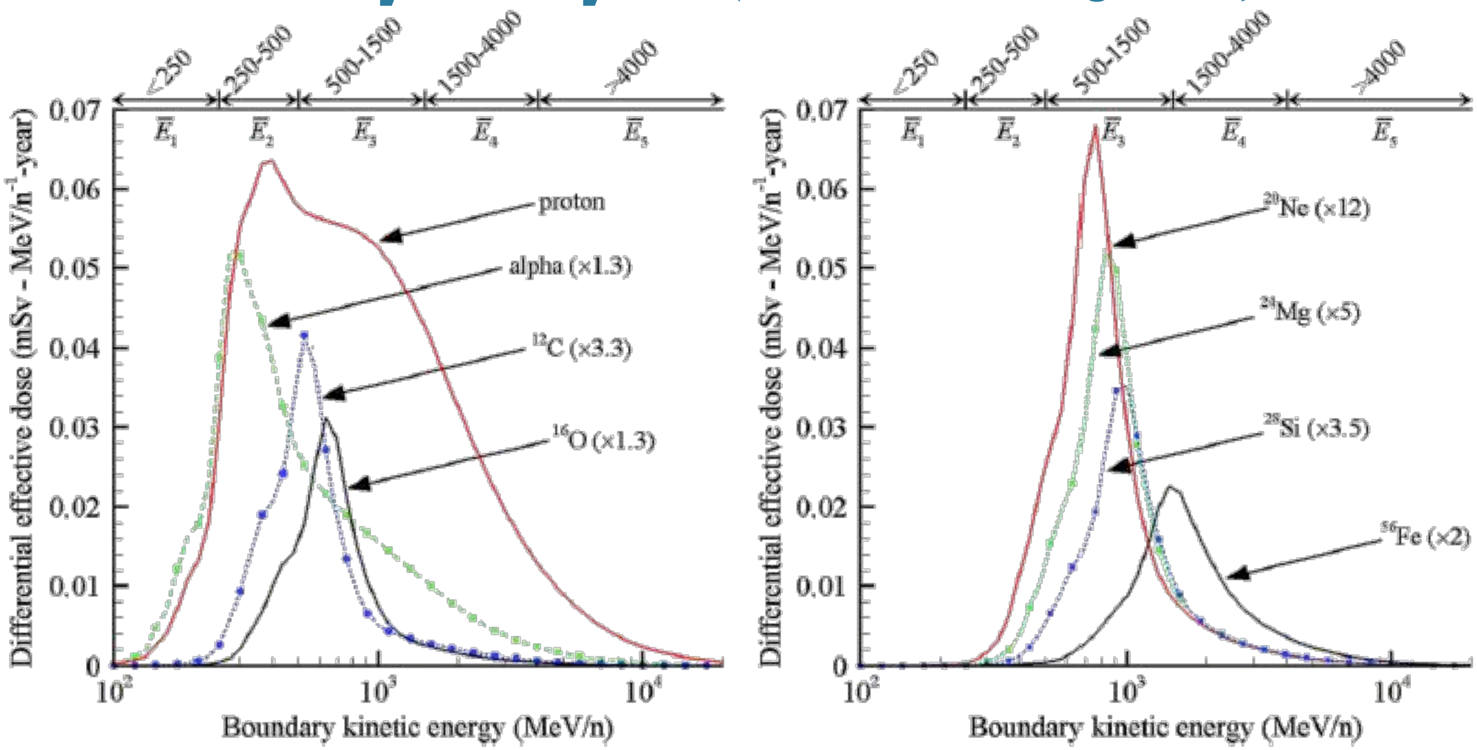
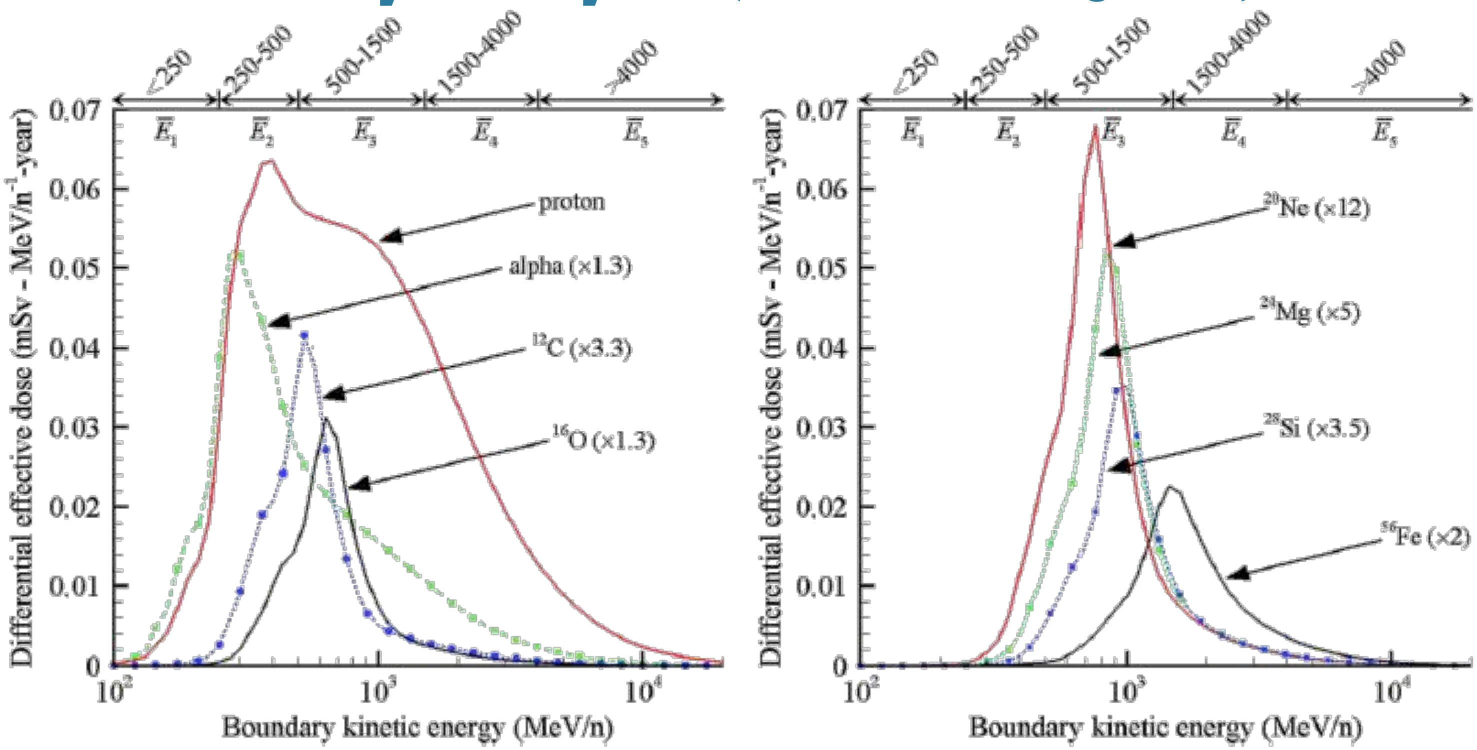


Table 2. Relative Contribution (×100) of GCR Boundary Energy and Charge Groups to Effective Dose With 20 g/cm² Aluminum Shielding[a]

	$\overline{E}_1$	$\overline{E}_2$	$\overline{E}_3$	$\overline{E}_4$	$\overline{E}_5$	Total
$Z = 1$	1.2	5.4	18.2	18.4	14.8	58.1
$Z = 2$	1.2	2.2	4.1	2.9	1.7	12.2
$Z = 3$–10	0.0	3.3	3.8	1.3	0.8	9.1
$Z = 11$–20	0.0	0.2	6.6	2.0	1.1	10.0
$Z = 21$–28	0.0	0.0	4.7	3.8	2.1	10.6
Totals	2.5	11.1	37.4	28.4	20.5	100.0

[a] A value of 0.0 indicates that the relative contribution is less than 0.1%. The BON2010 GCR model was used for these results during solar minimum conditions.

+ A sensitivity analysis *(Slaba & Blattnig 2014)*



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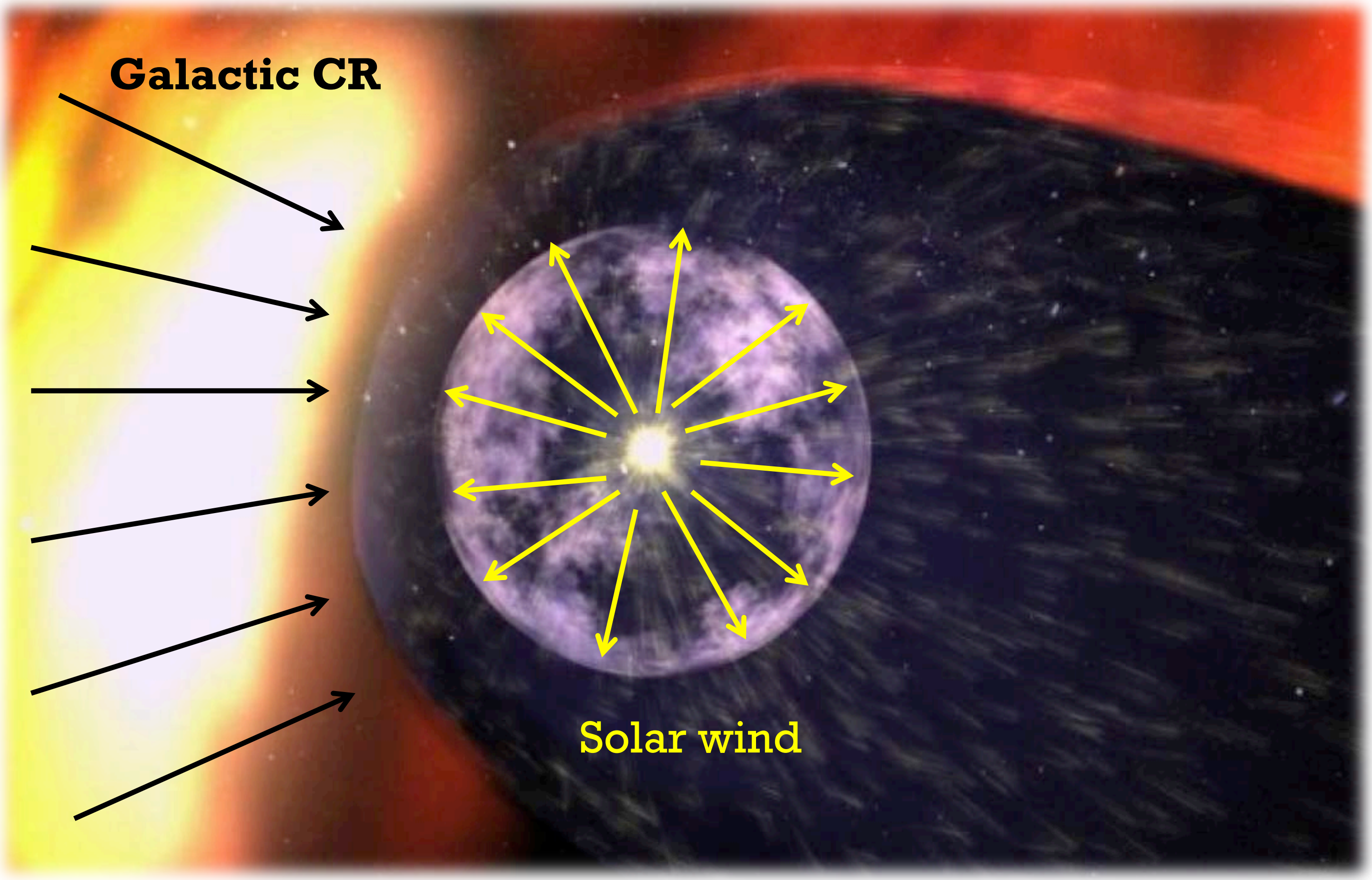
- ✓ Z>1 contribute with 42 % : ions are relevant
- ✓ bulk of the dose comes from CR with E/n > 500 MeV

+ Galactic CR & the Heliosphere

A turbulent solar wind with an embedded Heliospheric Magnetic Field influence the spectrum of Galactic CR up to several GeVs.



Modeling CR transport in Heliosphere

$$\frac{\partial f}{\partial t} = \nabla \cdot [\mathbf{K} \cdot \nabla f] - \mathbf{V} \cdot \nabla f - \langle \mathbf{v}_D \rangle \cdot \nabla f + \frac{1}{3}(\nabla \cdot \mathbf{V}) \frac{\partial f}{\partial \ln p} + Q(r, p, t)$$

Flux **Diffusion** **Convection** **Particle drift** **Energy losses** **Source**

Parker Equation

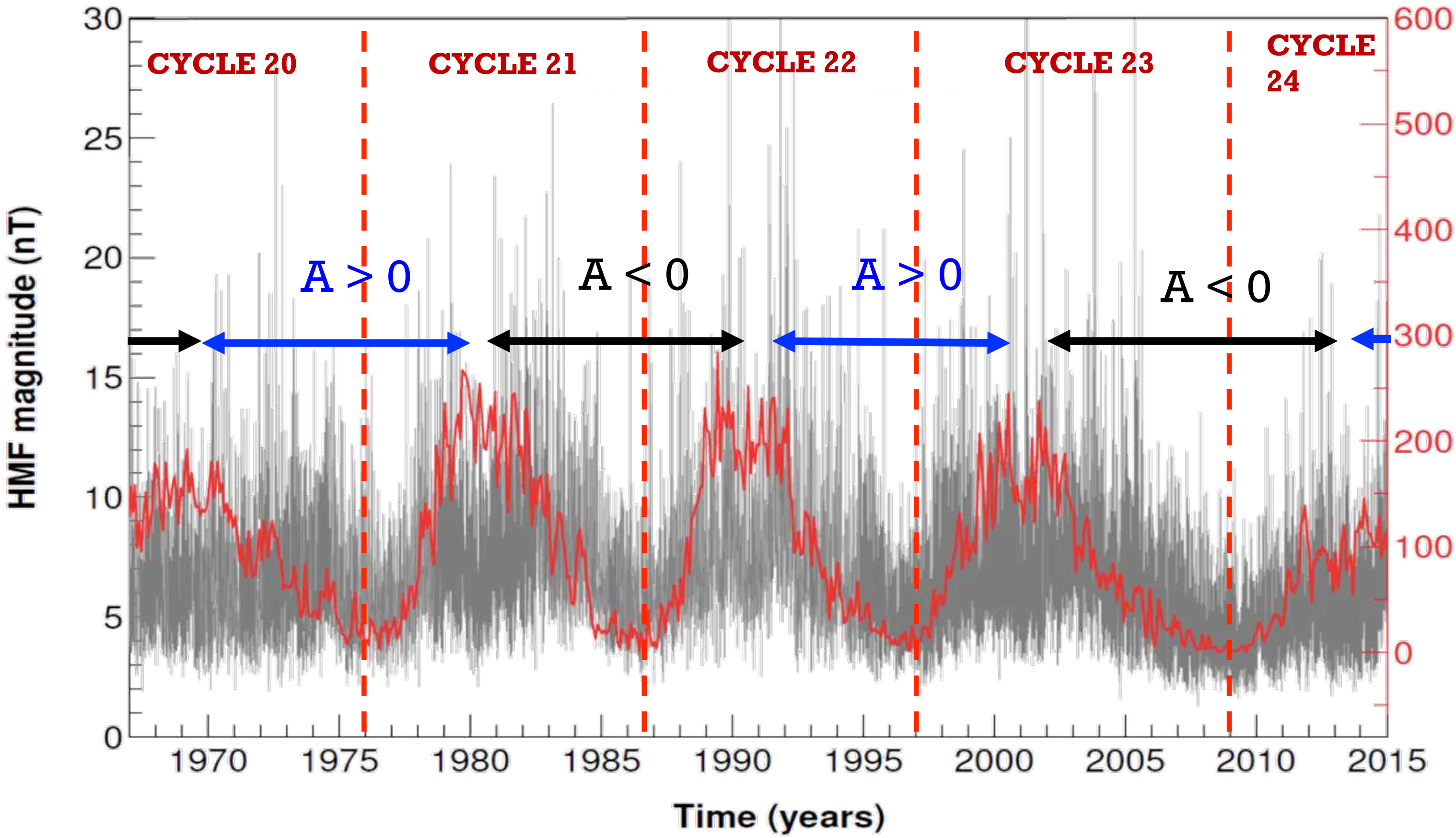
+ Modeling CR transport in Heliosphere

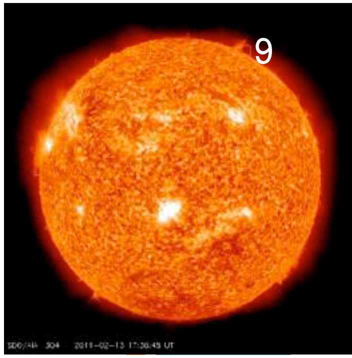
$$\frac{\partial f}{\partial t} = \nabla \cdot [\mathbf{K} \cdot \nabla f] - \mathbf{V} \cdot \nabla f - \langle \mathbf{v}_D \rangle \cdot \nabla f + \frac{1}{3}(\nabla \cdot \mathbf{V}) \frac{\partial f}{\partial \ln p} + Q(r, p, t)$$

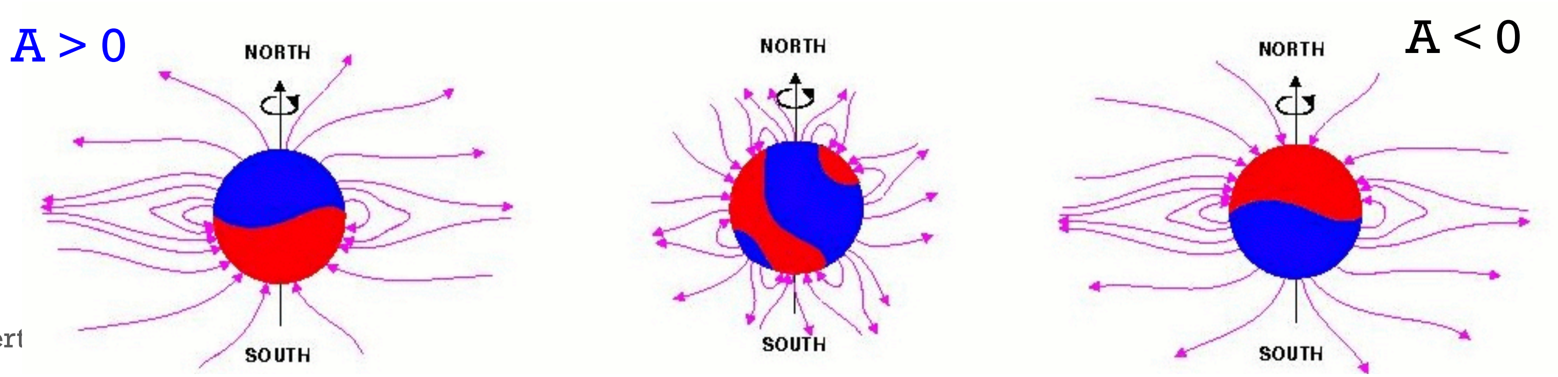
Flux — **Diffusion** — **Convection** — **Particle drift** — **Energy losses** — **Source**

- **Diffusion**: Small Scale Magnetic Field irregolarities
- **Convection**: Effect of the solar wind moving out from the Sun
- **Particle drift**: Large Scale structure of magnetic field (gradients & curvature)
- **Energy losses**: Adiabatic expansion of the solar wind
- **Source**: GCR particles

+ Continuous solar changing conditions

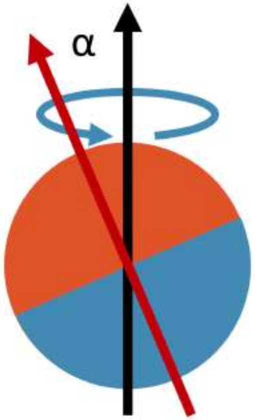


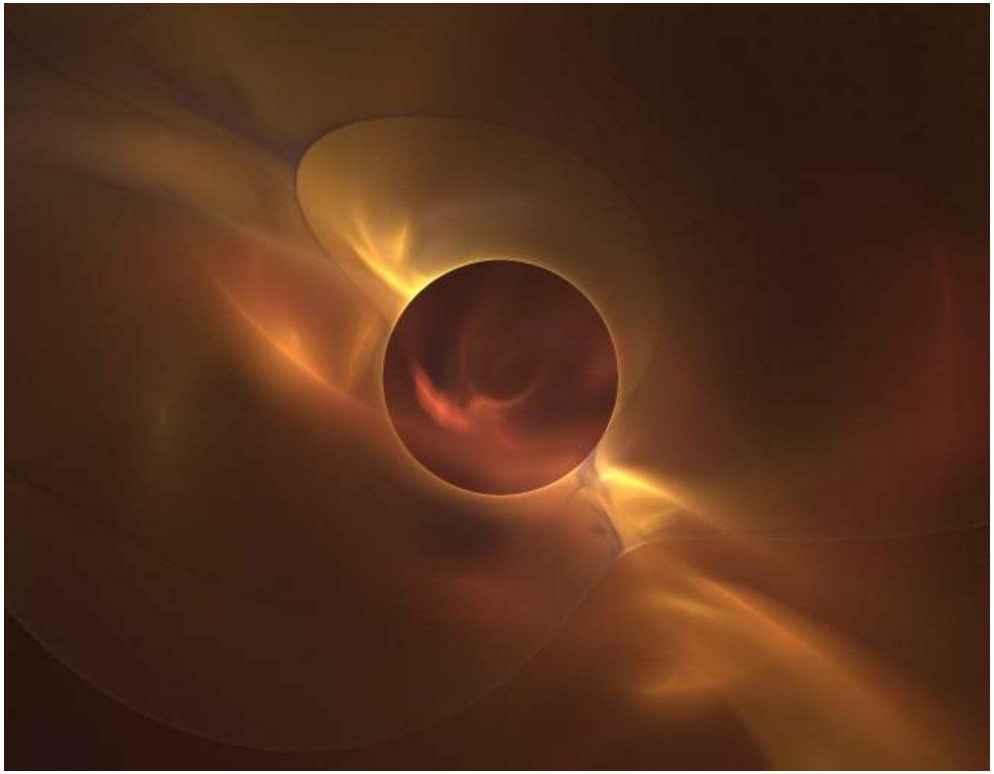


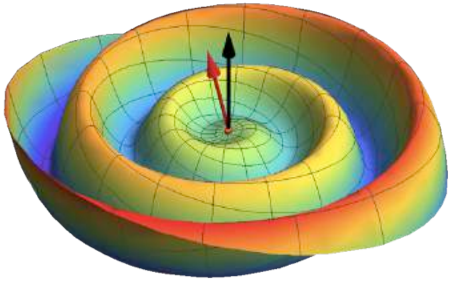


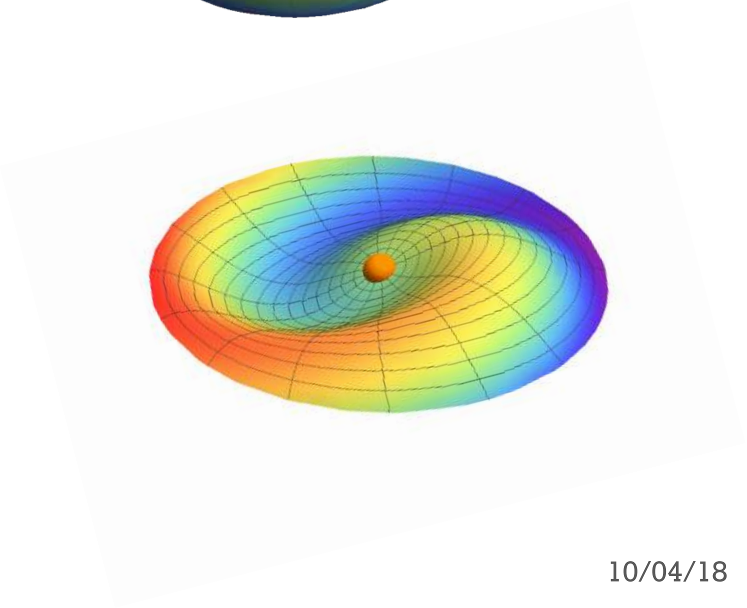
+ A complex magnetic field

- Latitude dependence and Archimedeal spiral due to sun rotation
- Intensity / Polarity changing in time : undefined in solar max
- A wavy neutral current sheet changing with tilt angle









+ A plethora of approaches/methods

Space Agencies:
forecasting for mission planning
effective parametric models driven by observations relating model parameters to solar activity indicators.

CR / DM :
retrieving the LIS spectrum
effective models to unveil the LIS-GCR spectra.Minimal parameters, minimal computing time. Basic physics insights on the modulation process

Solar :
understanding the Heliosphere
all models are solution of the Parker equation, different approaches and focus studies on dedicated aspects of the problem

+ A plethora of approaches/methods

Space Agencies:
forecasting for mission planning
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from I.Moskalenko talk

GALPROP/HelMod

- Goal #1: reliable local interstellar spectra of all CR species (>100 MeV/n)
- Goal #2: reliable heliospheric modulation for an arbitrary epoch in the past
- GALPROP/HelMod
  - Boschini, et al., ApJ 840 (2017) 115 (p, He, $\bar{p}$)
  - – – – ApJ 854 (2018) 94 (e^-)
  - – – – ApJ 2018, in press (He, C, O)
  - – – – ApJ 2018, in preparation

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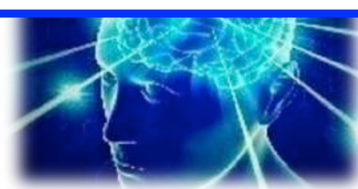

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Analytical solutions:

- *only convection (CDA)*
- *Force-Field Approximation (FFA) + modified FFA*
- *1D analytical*

Parametric models:

- *universal LIS shape*
- *FFA inspired modulation parameters as a function of SSN + time-lag*

Numerical integration:

- *1D: radial-dependent features*
- *2D/3D : drift effects, polar dependences,asymmetries.*

Stochastic random-walk:

- *MC propagation of a large number of pseudo-particle trajectories*
- *2D/3D*
- *steady state / time-dependent*

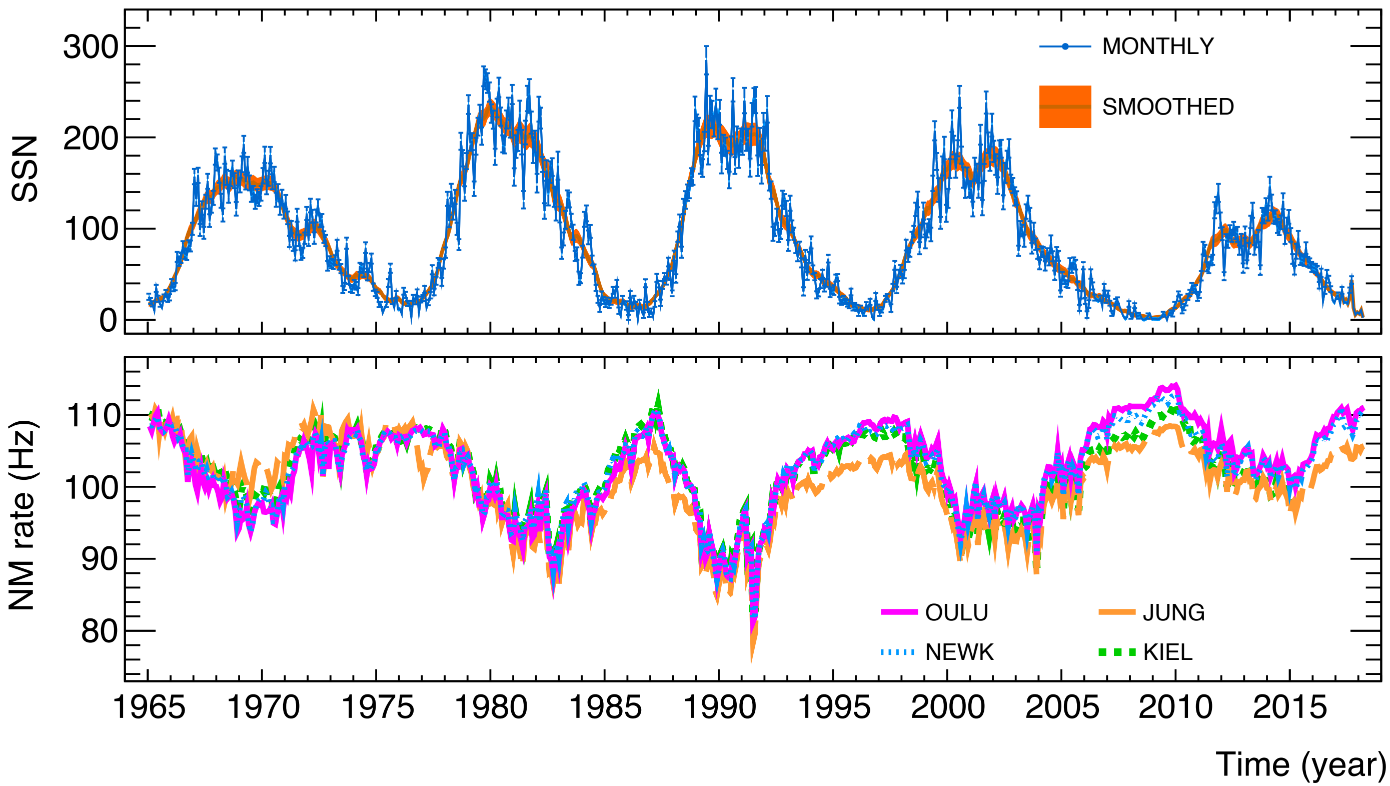
+ Fitting the models? (Input/Test on CR data)

Global trends studied by Neutron Monitors:

- inexpensive : many NM & long term measurements

BUT

- indirect: no info on different components or energy spectrum
- different "normalizations" depending on the geomagnetic cutoff



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Direct measurements?

Long term measurements of Z=1,2,>2 by different probes (ACE, PIONEER, VOYAGER): different nuclei but limited to low energies …

Higher energies not continuously monitored, PAMELA (2006-2016) only p/e fluxes…

….

Only AMS can provide continuous measurements of different CR species above GeV

+ AMS & new opportunities for modeling GCR in the heliosphere

- Refinement of Local Interstellar Spectra

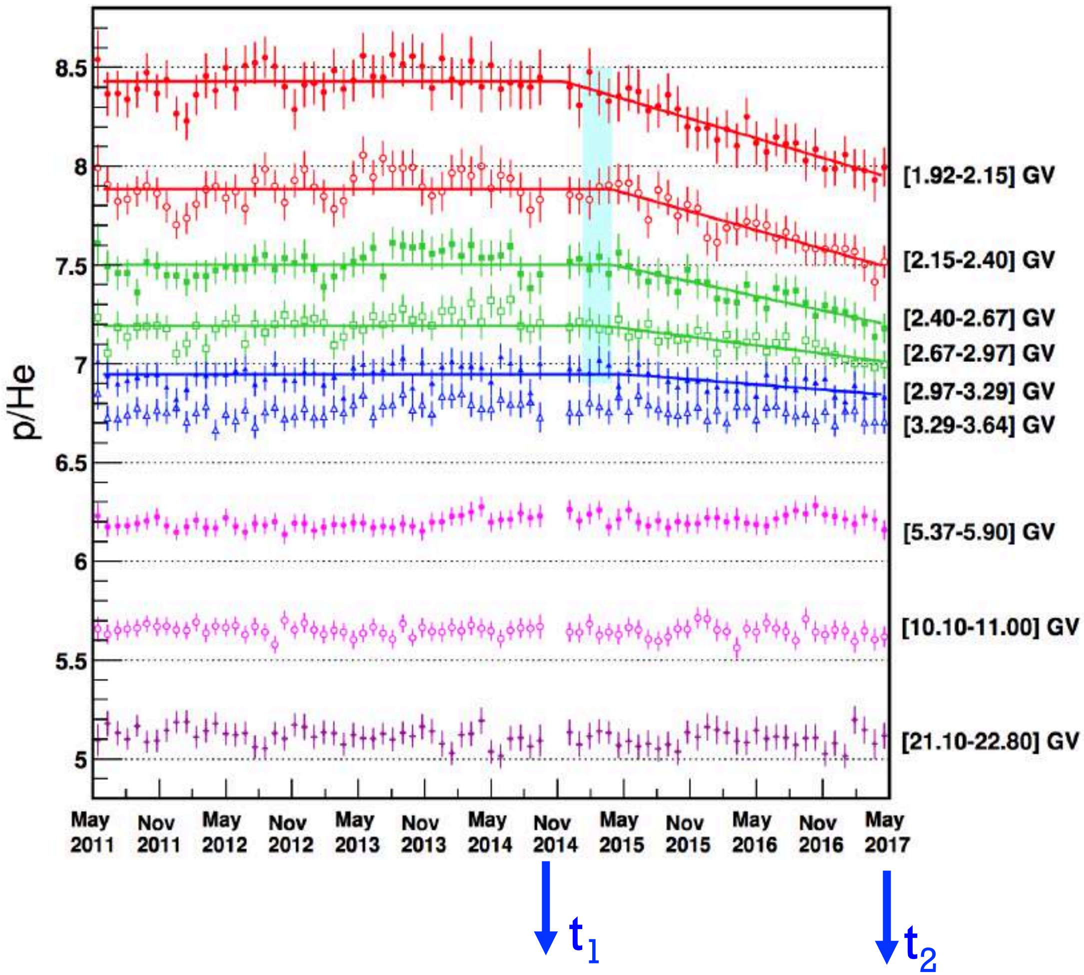
- Continuous & accurate measurement of time dependent structures:
  - ✓ in a wide energy range
  - ✓ for different ions
  - ✓ for positive and negative CR components+/- particles

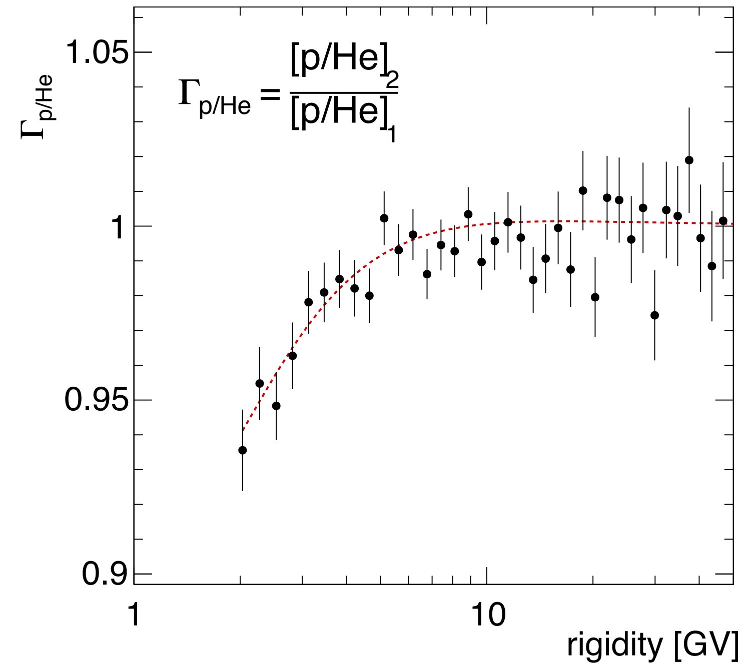
Better understanding of Heliospheric effects on GCR → increase sensitivity to signals for fundamental physics research

Better tuning of parametric models → increase reliability and predictive power

+ p/He modulation in the light of AMS-02

→ A clear trend of the p/He flux ratio as a function of rigidity





Why ?

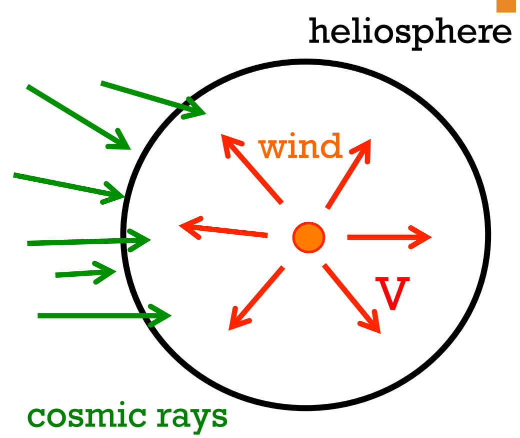
+ 1D numerical approach *(Pg-Lisbon)*

$$\frac{\partial f}{\partial t} = \nabla \cdot [\mathbf{K}\cdot\nabla f] - \mathbf{V} \cdot \nabla f - \langle \mathbf{v}_D \rangle \cdot \nabla f + \frac{1}{3}(\nabla \cdot \mathbf{V})\frac{\partial f}{\partial \ln p} + Q(r,p,t)$$

Some simplifications:

+ steady state solution @ given time

+ Radial & homogeneus diffusion. No drift.



$$k\frac{\partial^2 f}{\partial r^2} + \left(-V + \frac{2k}{r} + \frac{\partial k}{\partial r}\right)\frac{\partial f}{\partial r} + \left(\frac{2V}{3r} + \frac{1}{3}\frac{\partial V}{\partial r}\right)\frac{\partial f}{\partial \ln p} = 0$$

Focus on the diffusion parameter:

$K(R) = (\mathbf{v}/3)\, \lambda\, (R)$ $\lambda\, (R)$ = universal "composition-blind" mean free path

→ assume a dependence on the particle β

→ assume a dependence on R

→ time dependence and normalization of the coefficient included in $k_0(t)$

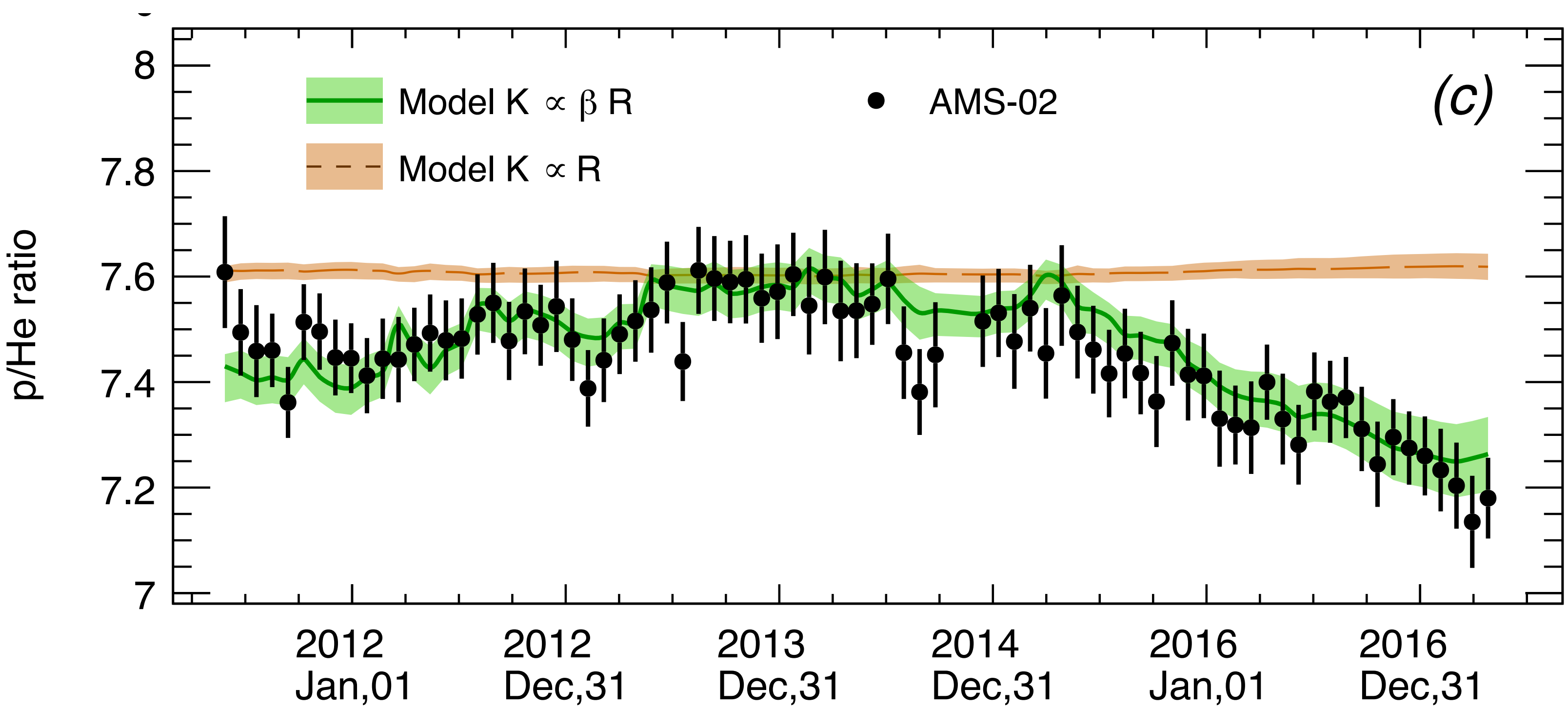
$K(R,t) = \beta \times k_0(t) \times R$

Solve Parker equation numerically & retrieve $k_0(t)$ from the fit to proton fluxes

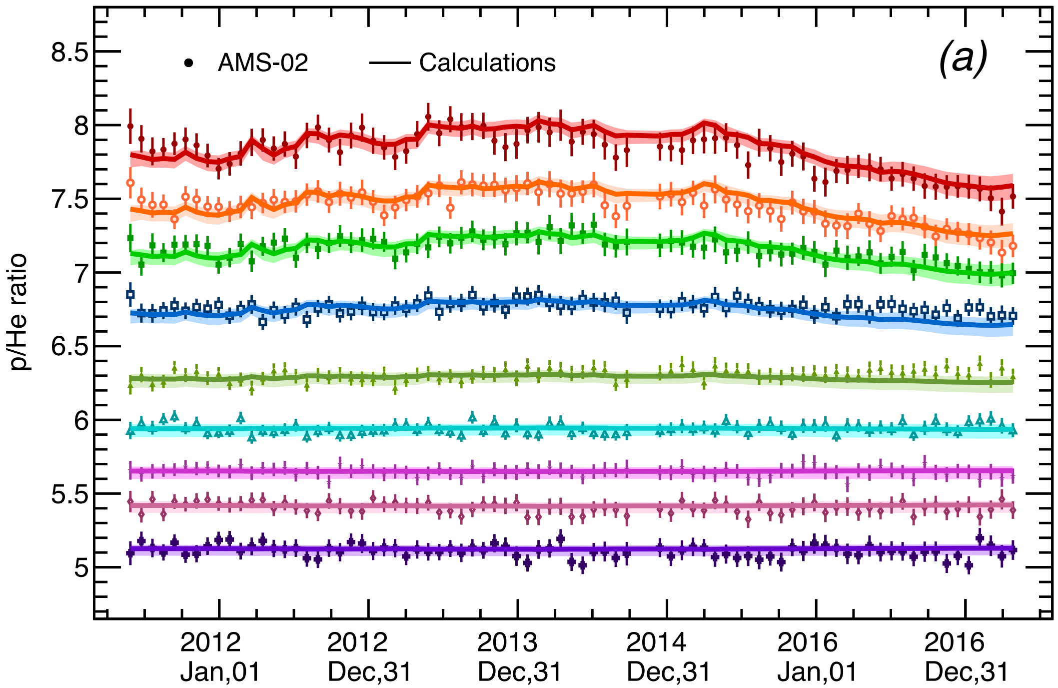
Use the same $k_0(t)$ to predict He fluxes

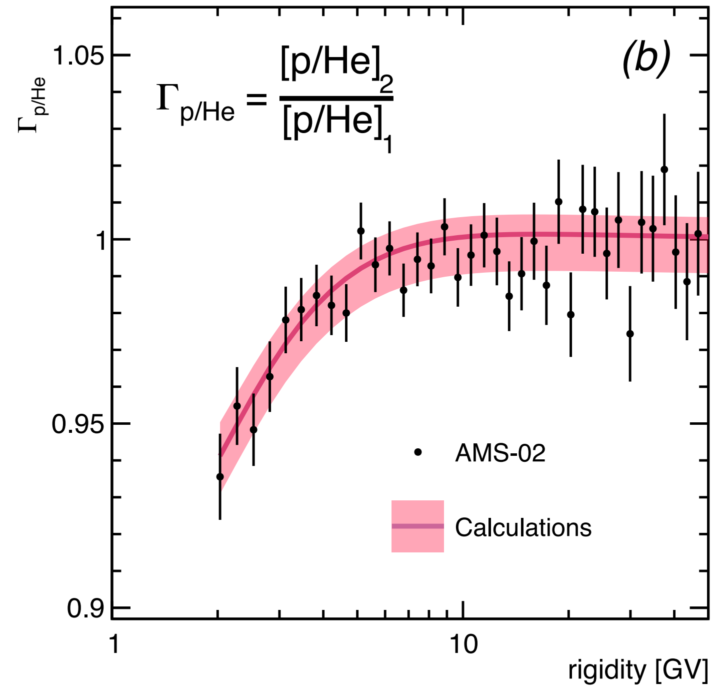
+ Comparison to AMS-02 data

- Different p-He LIS and their uncertainties accounted
- Isotopic composition accounted
- Tested different expressions for the diffusion coefficients



p/He modulation

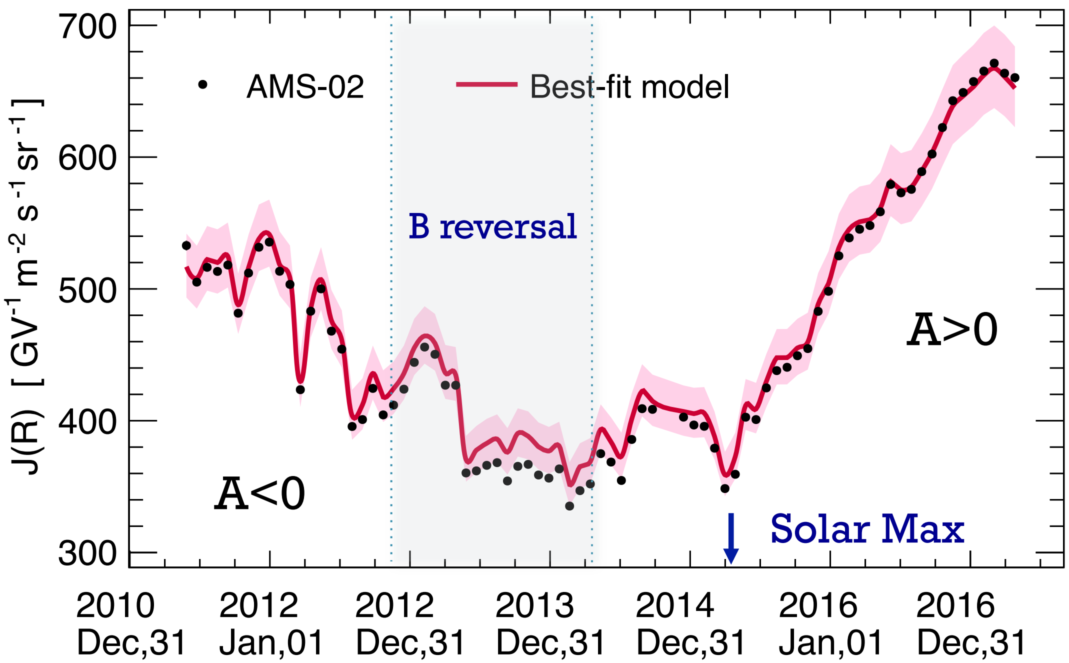


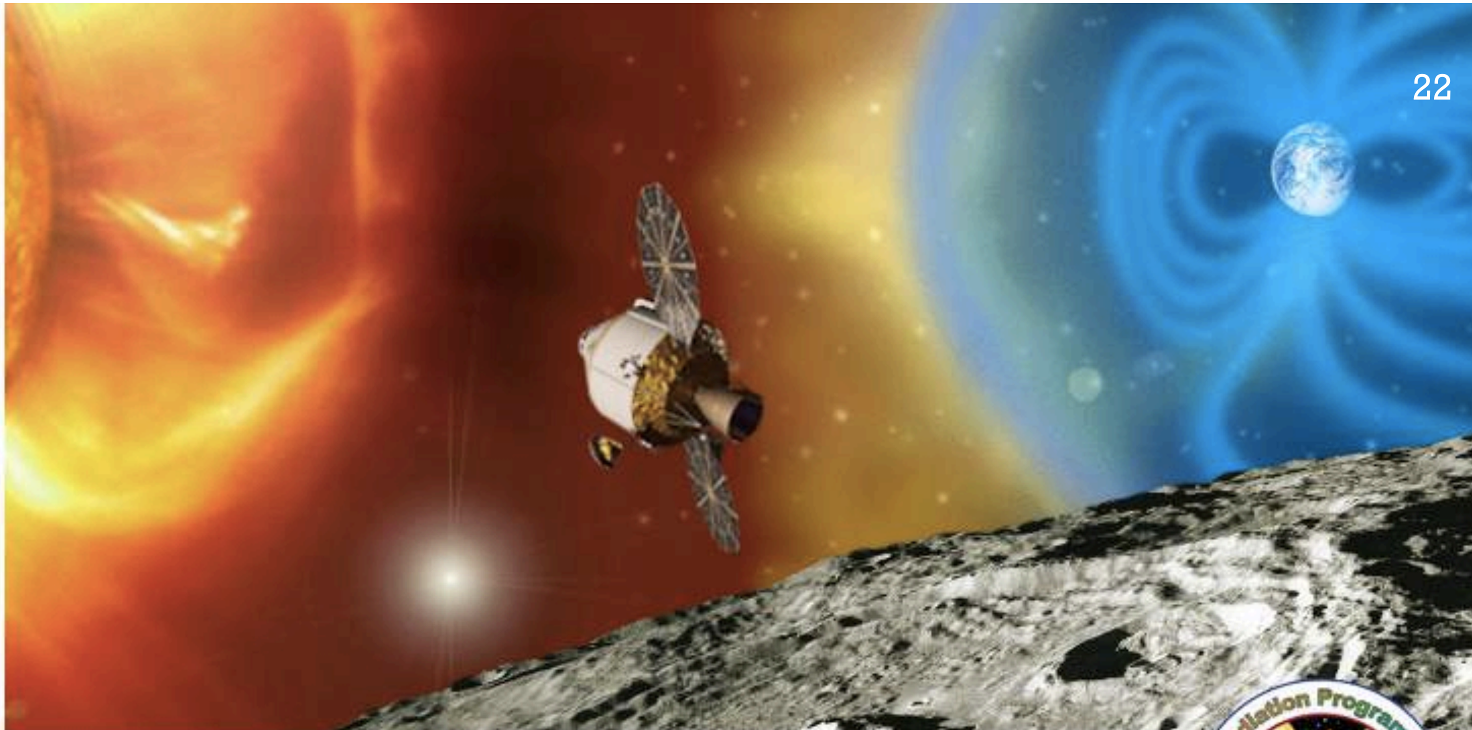


The p/He long-term structure is a signature of the universality of the CR mean free paths λ (R)

+ Conclusion 1)

- Simple 1D models can give insight to specific features in the solar modulation effects
  - cannot be used for forecasting → time dependence on solar parameters effectively accounted from fit to reference data
  - cannot account for more complex effects arising from change of B field polarity → i.e. drift effects





Following the NASA-STD-7009 prescription

OLTARIS
On-Line Tool for the Assessment of Radiation In Space

2.3 References

1. ? NASA Standard 7009
2. ? [2.0 2.1 2.2 2.3 2.4 2.5 2.6 2.7] P. M. O'Neill et al., Badhwar-O'Neill Galactic Cosmic Ray Model Update Based on Advanced Composition Explorer (ACE) Energy Spectra from 1977 to Present, Advances in Space Research 37 (2006) 1727-1733.
3. ? , F.F. Badavi et al., A Dynamic/Anisotropic Low Earth Orbit (LEO) Ionizing Radiation Model?, NASA-TP-2006-214533, 2006.

Newest Features

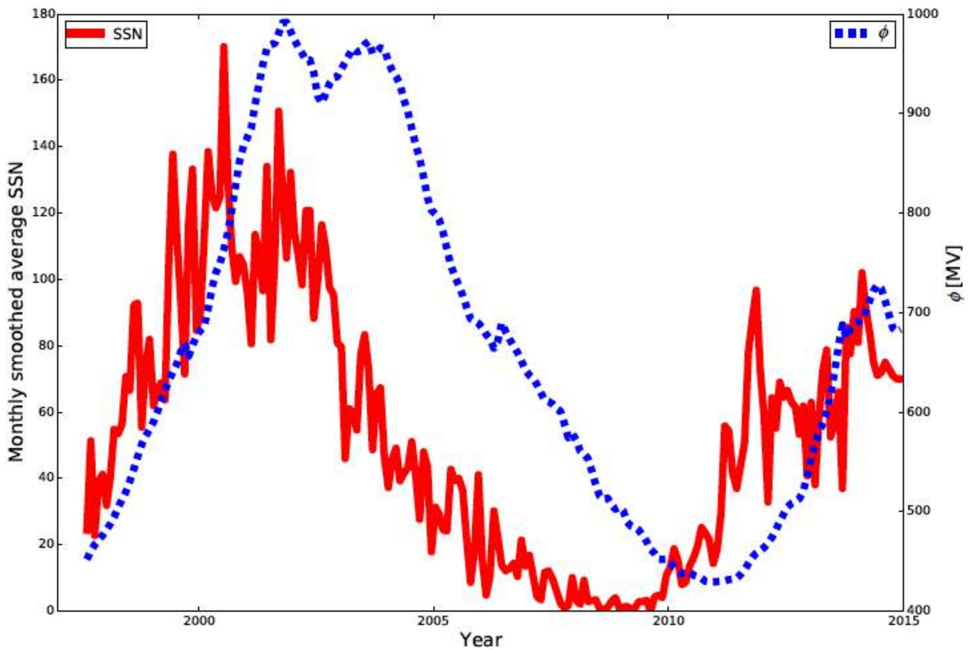
- Added NASA-Q quality factors for dose equivalent response and NASA tissue weighting factors for effective dose calculation.
- Added gray equivalent response. Computes the PEL (Permissible Exposure Limit) quantities for Lens, Skin, BFO, CNS (Hippocampus), and CNS (Z>10) (Hippocampus).
- **Added Badhwar-O'Neill 2014 GCR model.**

e.g. solar modulation in BON-2014

Time dependence of the diffusion in the heliosphere described by the same decelerating potential ϕ (aka solar modulation parameter) for all species.

Fit to different data sets using as input the Sun Spot Number + time delay

Flux predictions based on the effective relation between ϕ and SSN



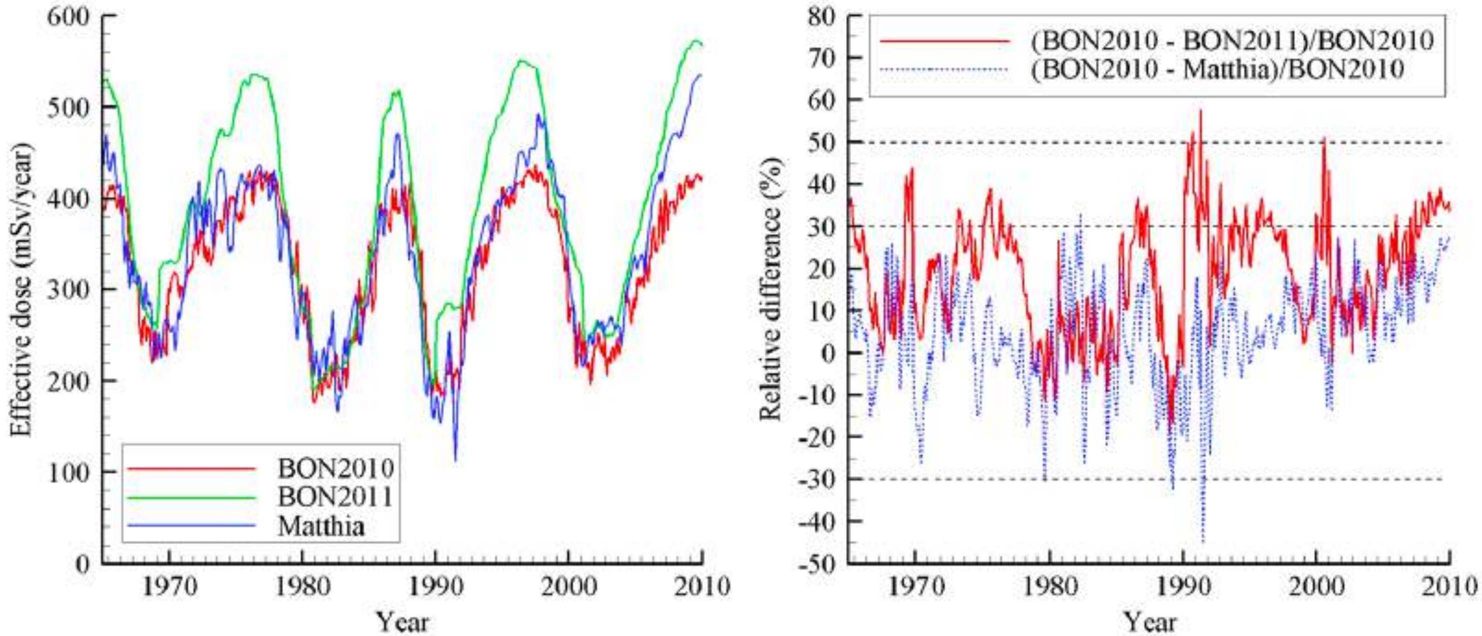
Input experimental data

e.g. Data sets in parametric BON-2014model

Name	Flight	Time	Ions (Z)	Energy [GeV/n]
ACE/CRIS [18]	Satellite	1998 - Present	5 - 28	0.05 - 0.5
AMS [19, 20]	STS-91	1998	1, 2	0.1 - 200.0
ATIC-2 [21]	Balloon	2002	1 - 26†	4.6 - 10.0
BESS [22]	Balloon	1997 - 2000, 2002	1, 2	0.2 - 22.0
CAPRICE [23, 24]	Balloon	1994, 1998	1, 2	0.15 - 350.0
CREAM-II [25]	Balloon	2005	6 - 26†	18.0 - 10.0
HEAO-3 [26]	Satellite	1979	4 - 28	0.62 - 35.0
IMAX [27]	Balloon	1992	1, 2	0.18 - 208.0
IMP-8 [28]	Satellite	1974	6 - 14†	0.05 - 1.0
LEAP [29]	Balloon	1987	1, 2	0.18 - 80.0
MASS [30]	Balloon	1991	1, 2	1.6 - 100.0
PAMELA [31, 32]	Satellite	2006 - 2009	1, 2	0.08 - 10.0
TRACER [33]	Balloon	2003	8 - 26†	0.8 - 10.0
Lezniak et al. [34]	Balloon	1974	4 - 26†	0.35 - 52.0
Minagawa et al. [35]	Balloon	1975	26, 28	1.3 - 10.0
Muller et al. [36]	STS-51	1985	6 - 14†	50.0 - 10.0
Simon et al. [37]	Balloon	1976	5 - 8	2.5 - 10.0

† Not all ion data are available in the provided range.

Accuracy vs data sets *(Slaba & Blattnig 2014)*

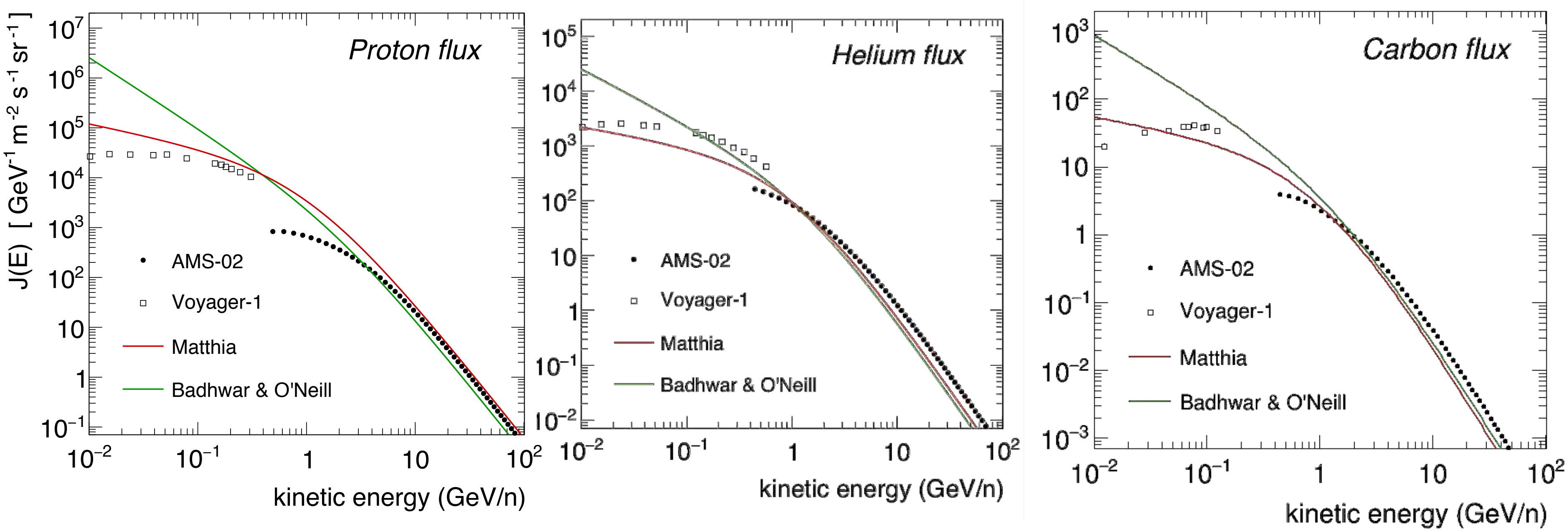


Most of the tuning with low energy (ACE/CRIS) data sets:
30-50% discrepancy when comparing different models over the full spectrum.

+ Input LIS: H, He, C

NASA & DLR radiation models:

- **BON model:** O'Neill et al., NASA/TP–2015–218569 (2015)
- **Matthia model:** Matthia et al. Adv. Space Res. 51, 329-338 (2013)



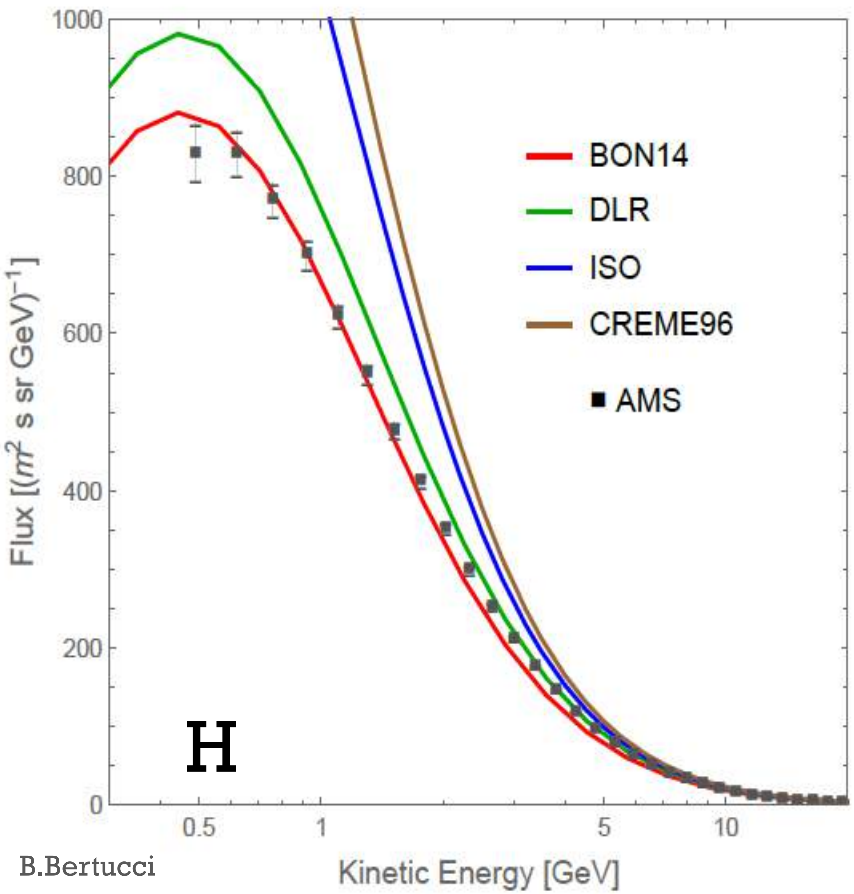
Data :

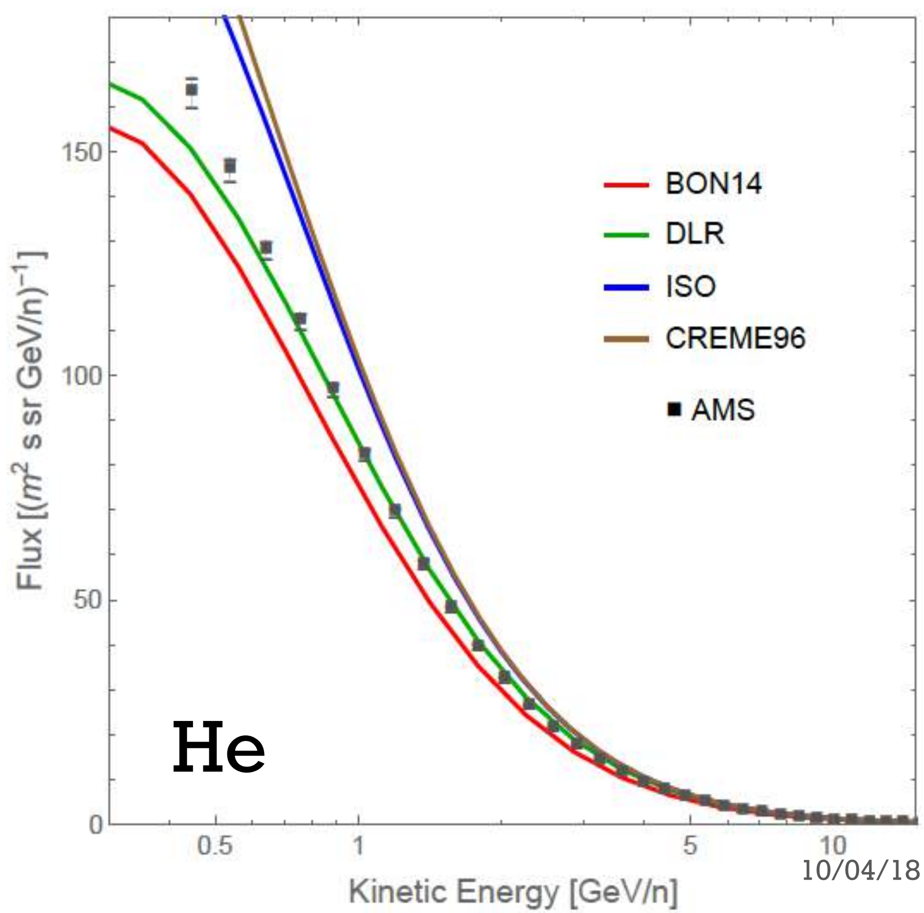
✓ **AMS-02** from Aguilar et al. Phys. Rev. Lett. 119 (2017) 251101 [in the heliosphere]

✓ **Voyager-1** from Cummings et al. ApJ 831, 18 (2016) [in the interstellar space]

Models compared to data *(J.Norbury 2016)*

- **BON model:** O'Neill et al., NASA/TP–2015–218569 (2015)
- **Matthia model:** Matthia et al. Adv. Space Res. 51, 329-338 (2013)
- **ISO:** *https://www.iso.org/standard/37095.html*
- **CREME96:** *https://creme.isde.vanderbilt.edu/*





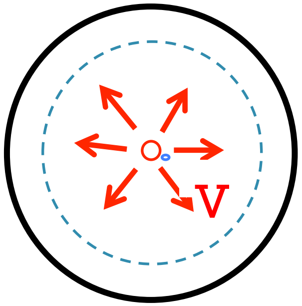
Conclusion 2)

- The parametric models used for dose evaluation are the most sensitive to the availability of new set of data, expected improvements from AMS:

  - Different input spectra (maybe from FFA fits?) for different species
  - Continuous time dependent data series for global fit of model parameters
  - different parameters ?

+ Forecast & time lag

It takes few months to propagate the magnetic properties of the Sun in the Heliosphere: modulation of CR is delayed of a DT.



Typical speed V~400-700 km/s
Typical size d~100-120 AU

⇒ $\Delta T \sim$ 6-12 months

Relating time delay effects to solar observables can be used to forecast CR intensity.

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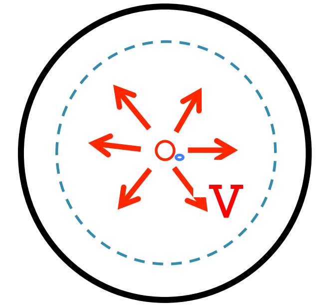

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⇨ ΔT ~ 6-12 months

Relating time delay effects to solar observables can be used to forecast CR intensity.

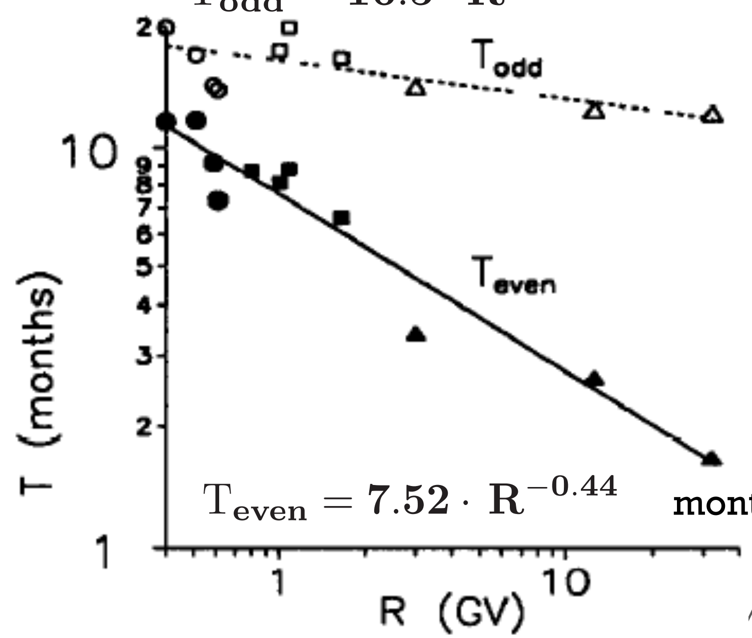
Known effect since the 60*s* (Dorman).
Use of NM & Balloon data to study time-lag as a function of the SSN (Nymmick 2000)

→ dependence on the cycle
- even/odd, min/max SSN

→ dependence on the rigidity

used in: ISO model, BON 14 model

$T_{odd} = 16.5 \cdot R^{-0.10}$ months

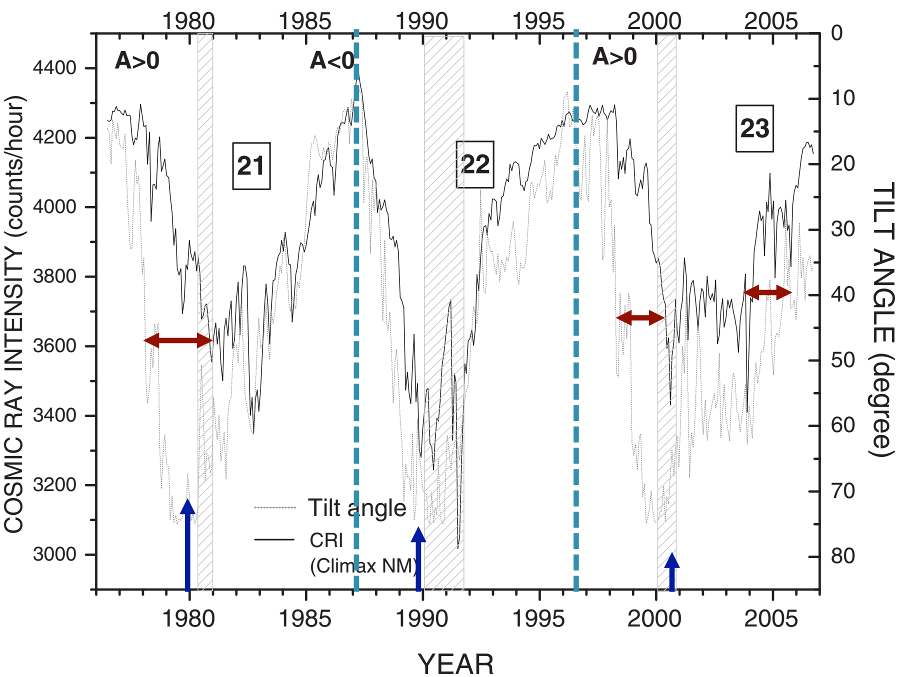


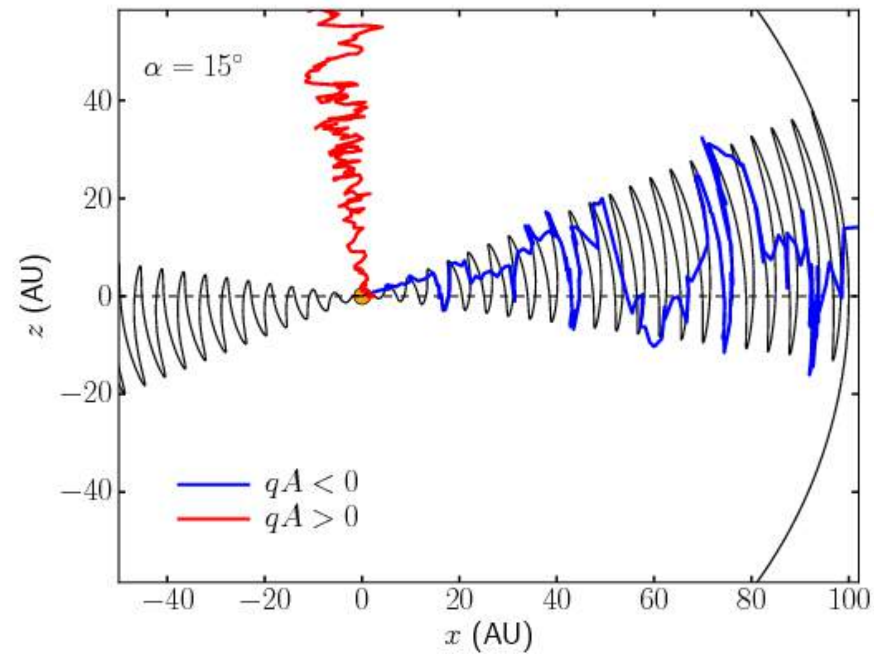
$T_{even} = 7.52 \cdot R^{-0.44}$ months

+ Time lag wrt tilt angle

Time lag of CR count rates are also related to the dynamics of transport for positive charged particles for different polarities of the B field

Badruddin et al., A&A 466, 697-704 (2007)





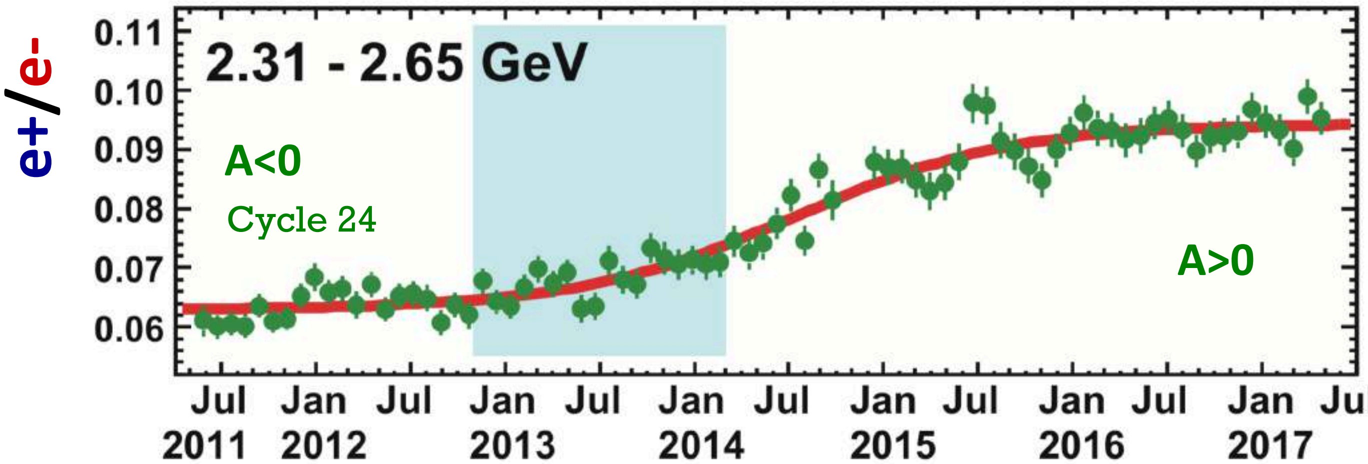
Cholis, Hooper, Linden, PRD 93, 043016 (2016)

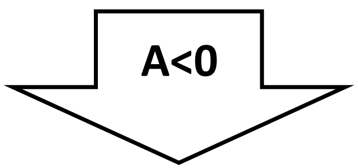
Understanding drift effects :

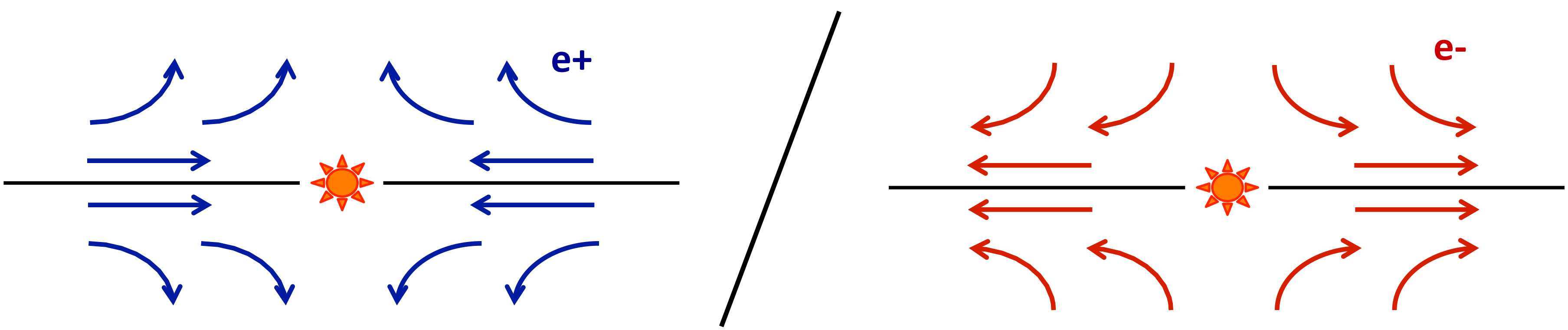
a) modeling of the time-lag — flux forecast !

b) modeling of different charge sign particle behaviour (e-/anti-p) — DM signals !

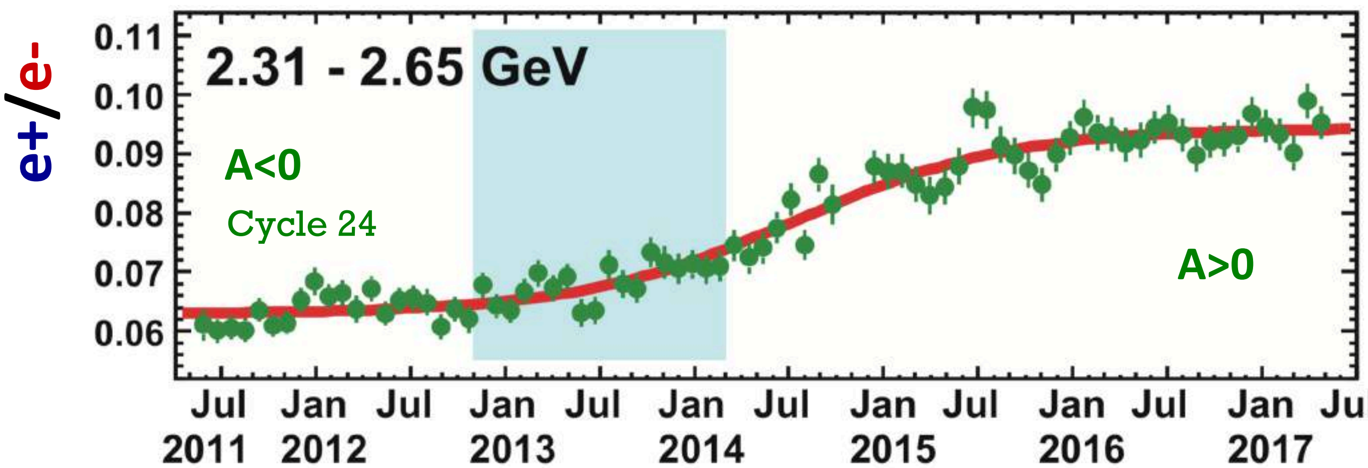
Same physics behind e+/e- time evolution

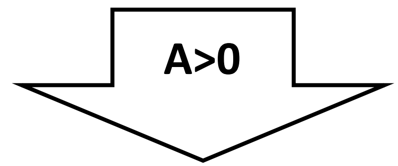


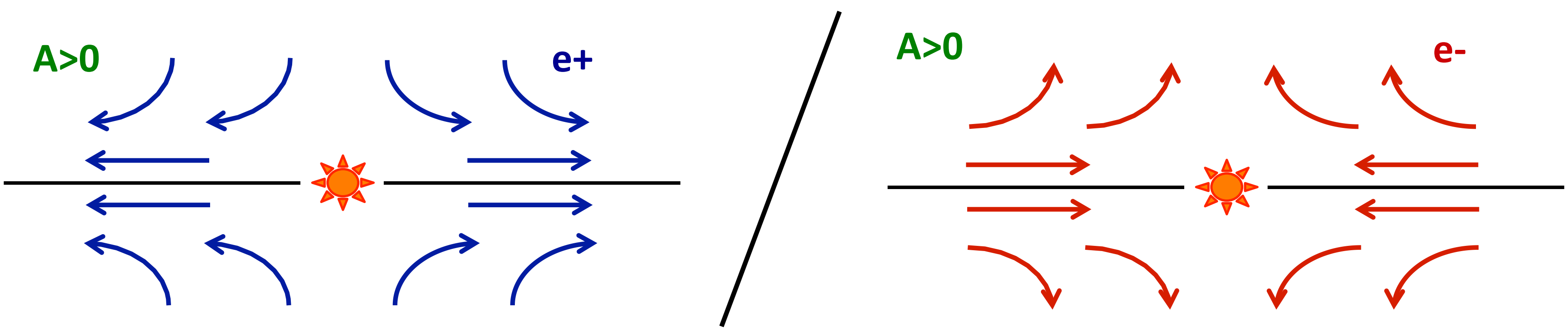




Same physics behind e+/e- time evolution







+ Example: Time lag fitting with pre-AMS data

Different models to approach the problem:
2D/3D numerical codes (e.g. Burger, Potgieter)
2D/3D stochastic random-walk solutions (more and more popular)

Basic stochastic models [2D and steady-state]

- ***SolarProp*** *(BCTP-Bonn): public, unmantained. 2D basic, customizable [Kappl 1601.02832]*
- ***HelioProp*** *(TUM-Munchen): similar to SolarProp. Under development [Vittino+ 1707.09003]*
- ***HelMod*** *(Milan): 2D w/ detailed wind/diffusion/drift. GALPROP interface [Boschini+ 2017]*
- ***NWU*** *models (NWU, South-Africa) [Strauss et al. Astrophys. Space Sci 339, 223 (2012)]*

....

Advanced stochastic models [3D or time-dependent]

- *Strauss et al. ApJ 735, 83 (2011): 3D, focus study on Jovian Electrons.*
- *Strauss et al. A&A 522, A35 (2010): focus on ACR Oxygen and modulation in heliosheath*
- *Zhang ApJ 541, 428 (2000): 3D, skew propagation, DSA at TS, anisotropic diffusion.*
- *Wawrzynczak+, J. Phys. Conf. Ser. 574, 012078 (2015): time-dependent CR transport*
- *Pei et al. J. Geophys. Res. 115, 12107 (2010): time-dependent CR transport*

....

Use a public model (SolarProp) explicitely introducing a "time-lag" parameter (Tomassetti et al, ApJL 2017)

Setting up of the model with a time-lag

$$\frac{\partial f}{\partial t} = \nabla \cdot [\mathbf{K} \cdot \nabla f] - \mathbf{V} \cdot \nabla f - \langle \mathbf{v}_D \rangle \cdot \nabla f + \frac{1}{3}(\nabla \cdot \mathbf{V}) \frac{\partial f}{\partial \ln p} + Q(r,p,t)$$

Quasi steady-state approach

$$\partial f / \partial t = 0$$

Stochastic differential Integration method

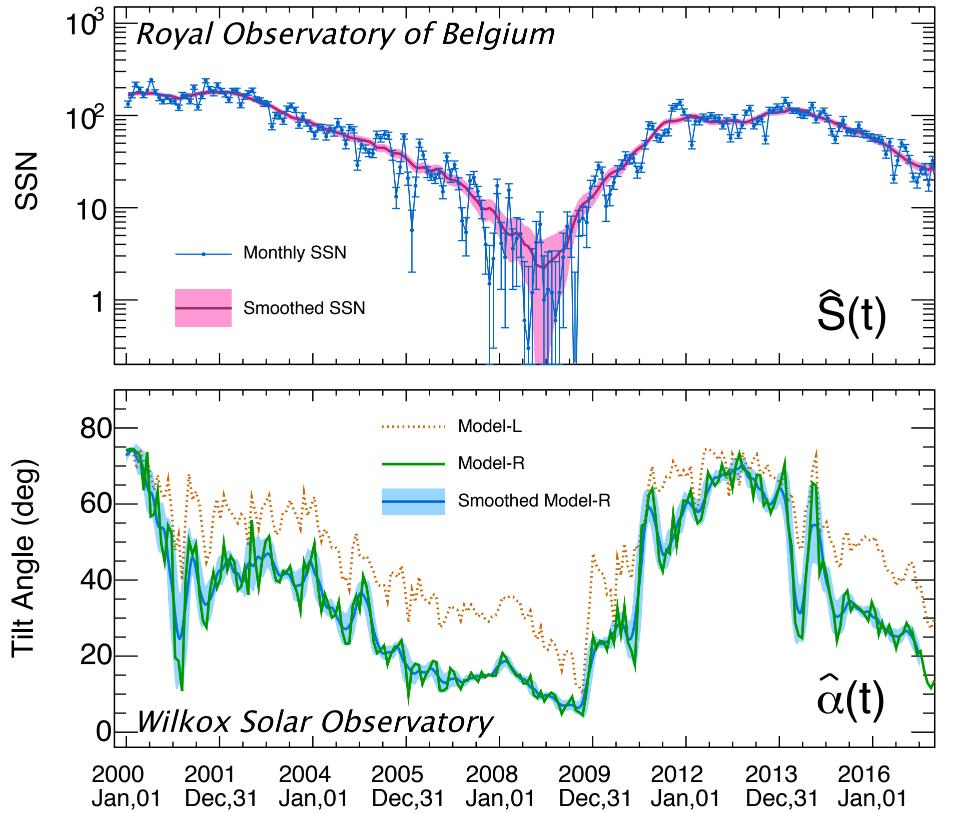
Use of "retarded" physics inputs

$$k(t) = a \cdot \log_{10}[\hat{s}(t - \Delta T) + b]$$
$$\alpha(t) = \hat{\alpha}(t - \Delta T)$$

Free parameters TBD by data

$$\chi^2 = \chi^2(a, b, \Delta T)$$

Solar inputs



+ Global fitting to space CR data

Proton flux data at negative polarity (A<0) between 2000 and 2012

- PAMELA: at E= 0.08 – 50 GeV, from 2006 to 2010 (3.5yrs) monthly resolved
- EPHIN/SOHO: at E=0.5-2 GeV, from 2000 to 2013, yearly resolved
- BESS-Polar I-II: at E=0.1-50 GeV, from two 15-day flights in 2004 and 2008

Global χ^2 estimator:

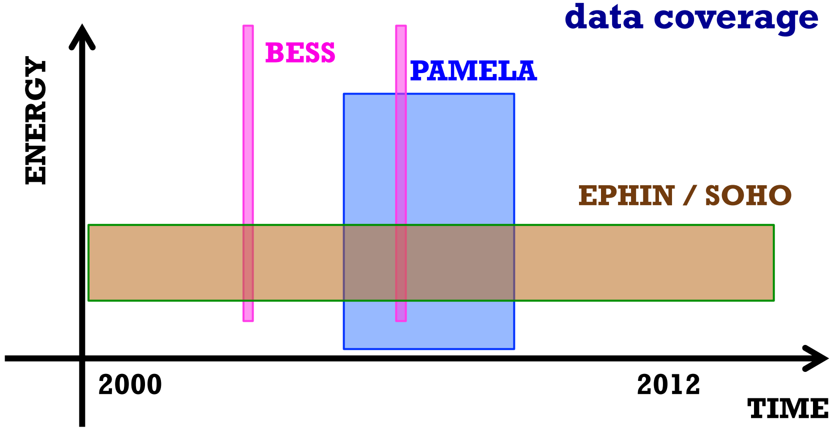
$$\chi^2 = \sum_t \sum_E \left[\frac{J(E,\alpha(t),\kappa(t)) - \hat{J}(E,t)}{\sigma_{tot}(E,t)} \right]^2$$

Three free parameters

$$\chi^2 = \chi^2(a,b,\Delta t)$$

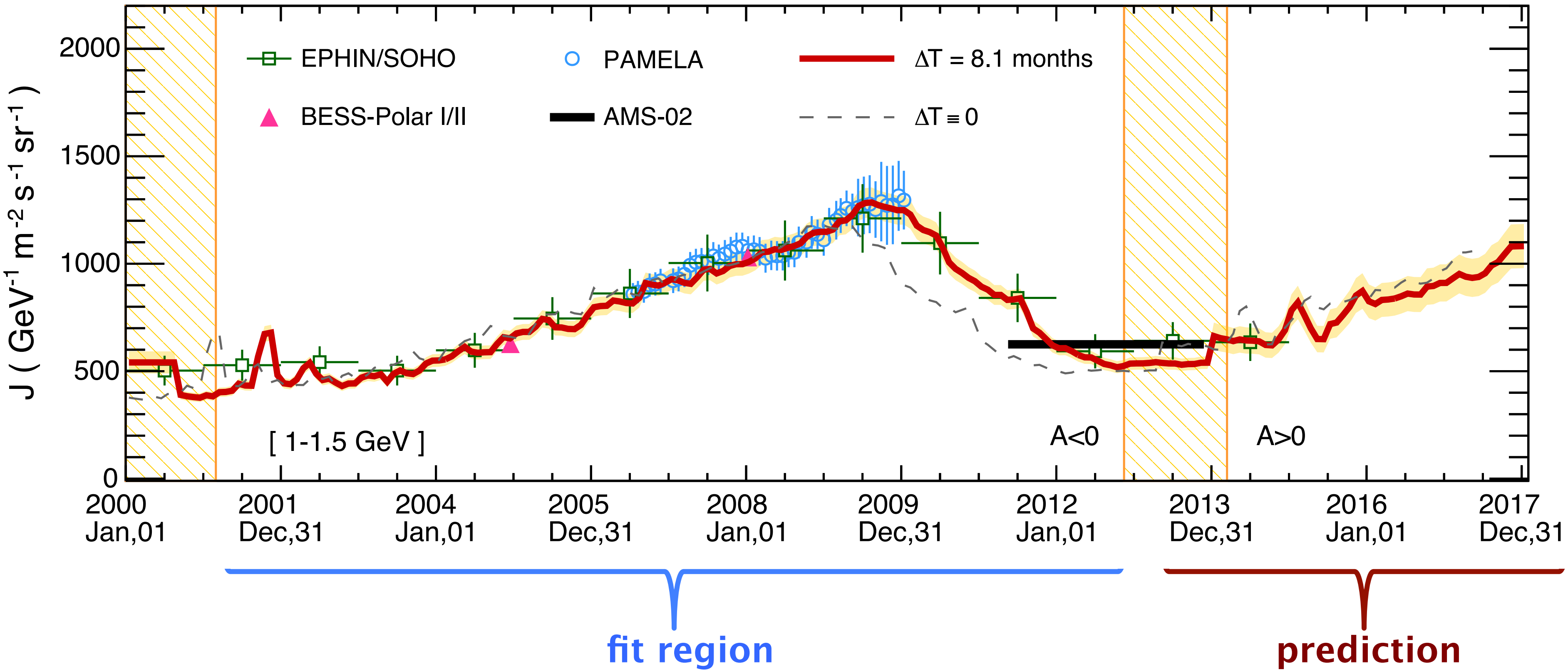
nearly 4000 data points

data coverage



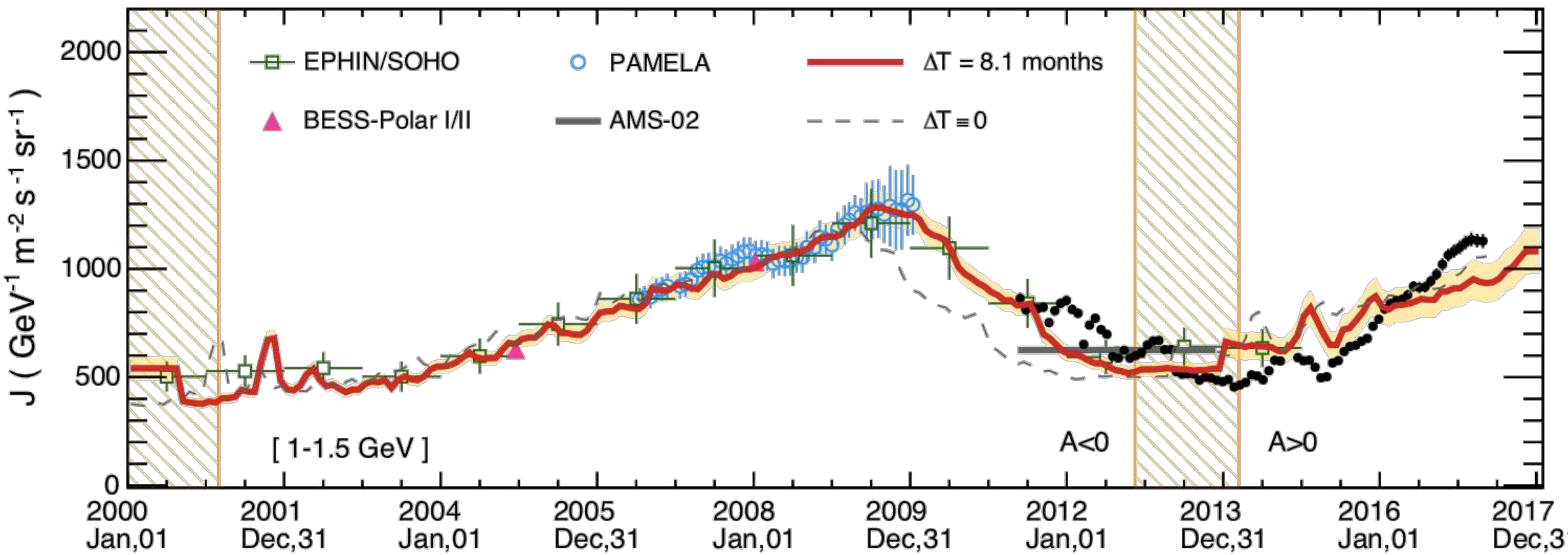
Proton flux time profile @ 1 GeV

Data are well described by a ΔT=8.1 months



✓ **Real-time solar-data → ability to *forecast* 8 months in advance**

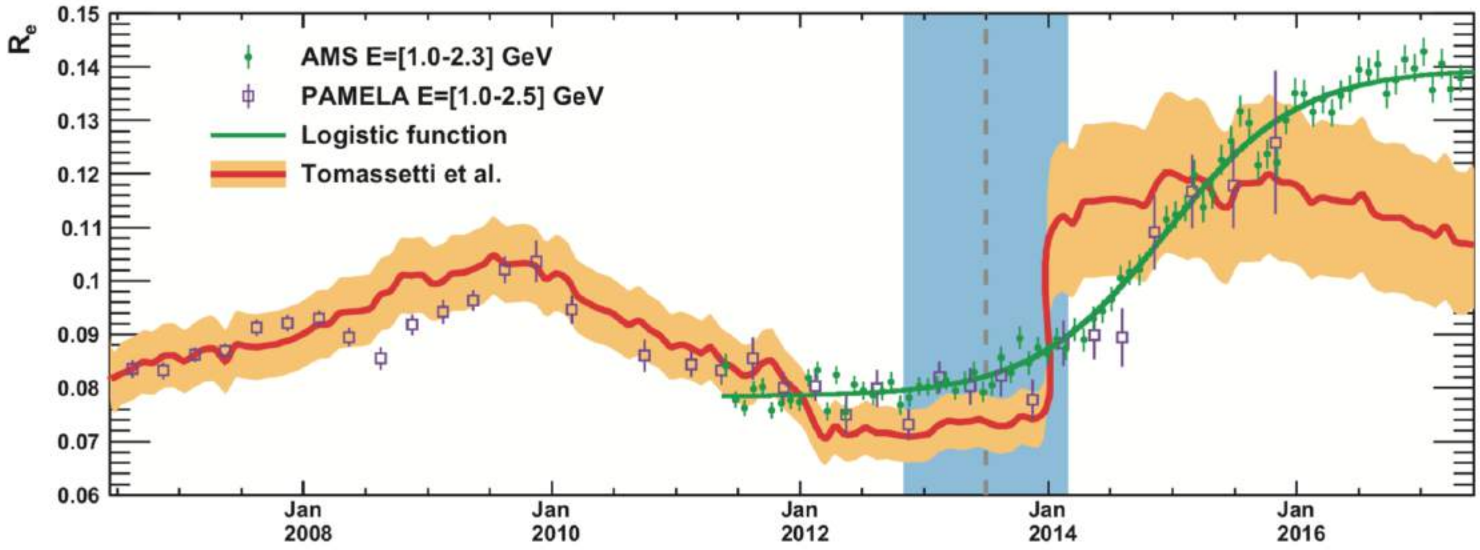
+ Prediction vs measurement?



Model needs to be recalibrated:

- more detailed description of drift(s) at the magnetic field reversal region ?
- different time lags at different energies?

+ Same model : e+/e-



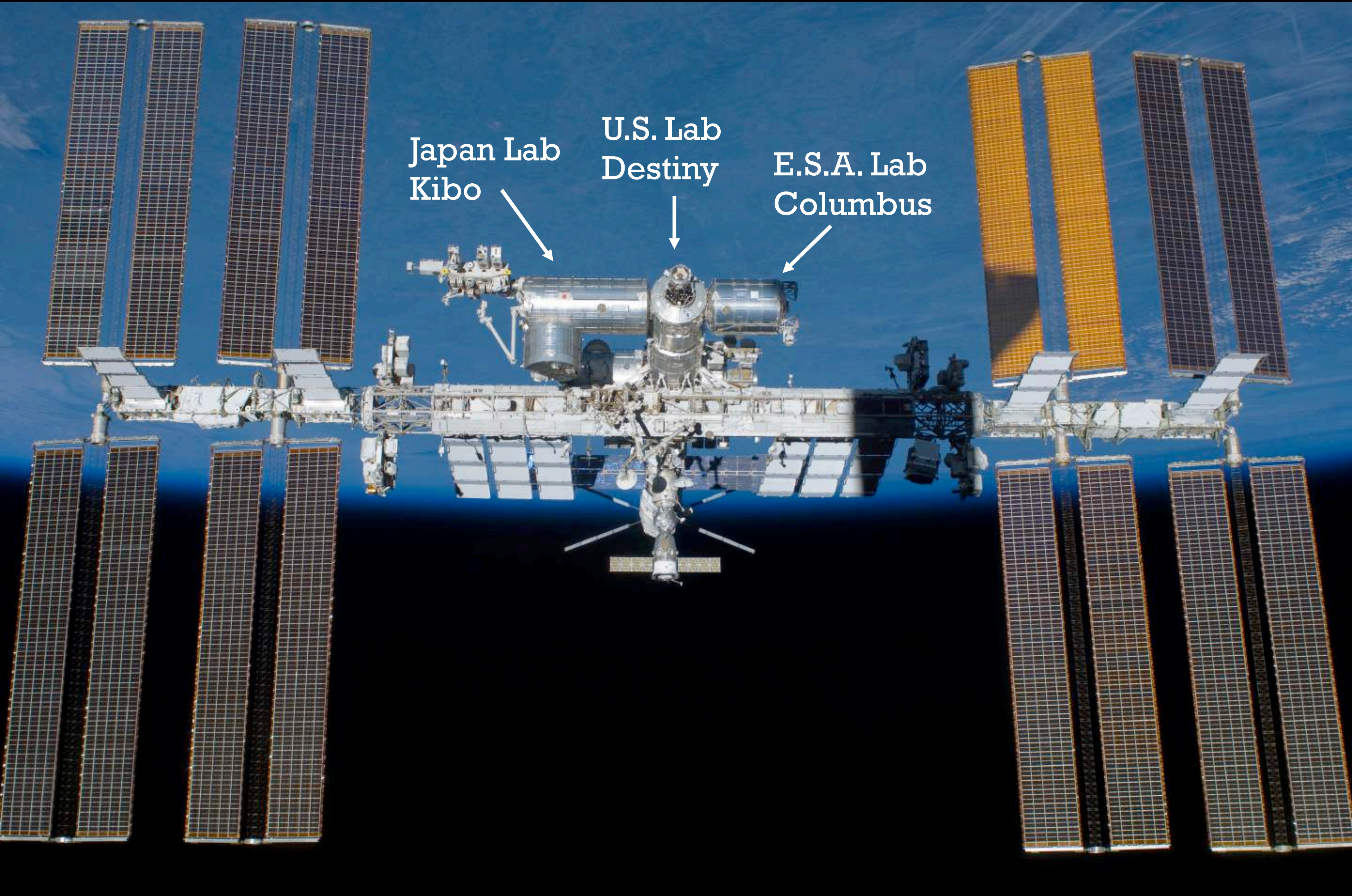
Only AMS data can really "stress" model predictions
→ long term measurements (at different crossing of B field reversal) are
of paramount importance to get reliable understanding of dynamics & forecasting

Conclusions (3)

- Pursuing a program of fundamental physics AMS is providing new and precise measurements on the radiation environment at 1 A.U.

- Long term measurements from AMS are fundamental to:
  - explore fundamental physics phenomena
  - explore Heliospheric effects on charged particles
  - improve risk assessment in manned exploration missions

Measuring doses on the ISS



Comparison of Silicon-Based Detectors
22nd Workshop for Radiation Monitoring on ISS

2017-09-06

R. Rios, Ph.D.

Space Radiation
Analysis Group **NASA**

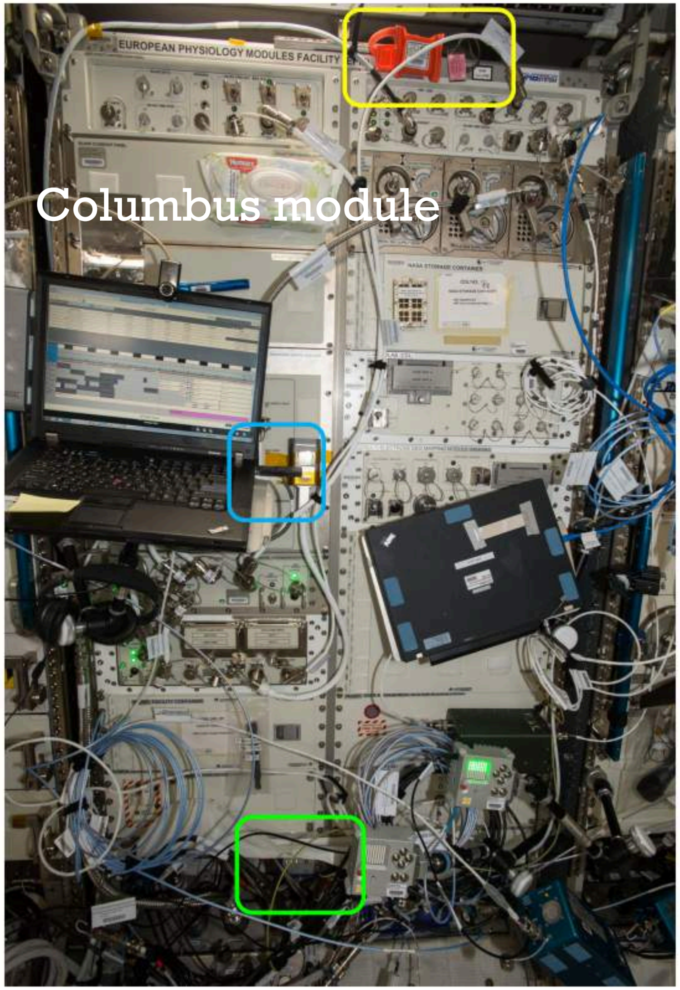


Figure 2: The Passive Detector Packages (PDP) from the DOSIS 3D project and the NASA RAM detectors (yellow); the NASA REM detector in the front of the EPM Rack (blue); the DOSIS-MAIN-BOX beneath the EPM rack (green) with three green status LEDs. (Image, caption courtesy T. Berger, DLR)

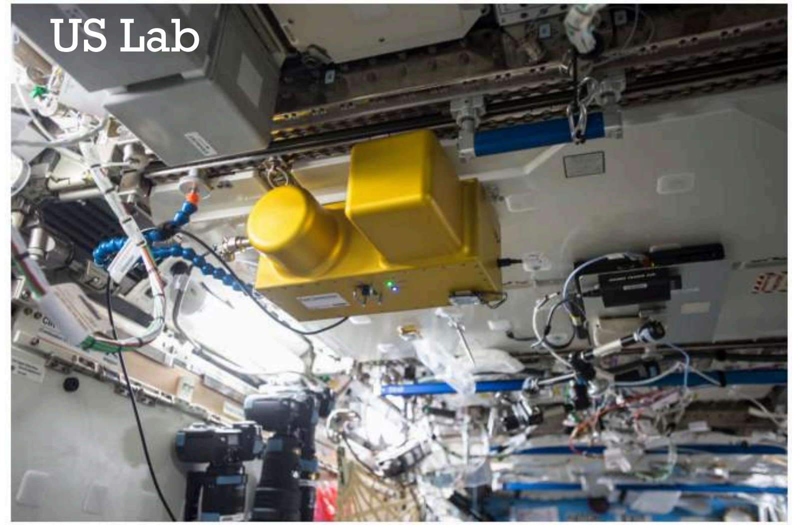
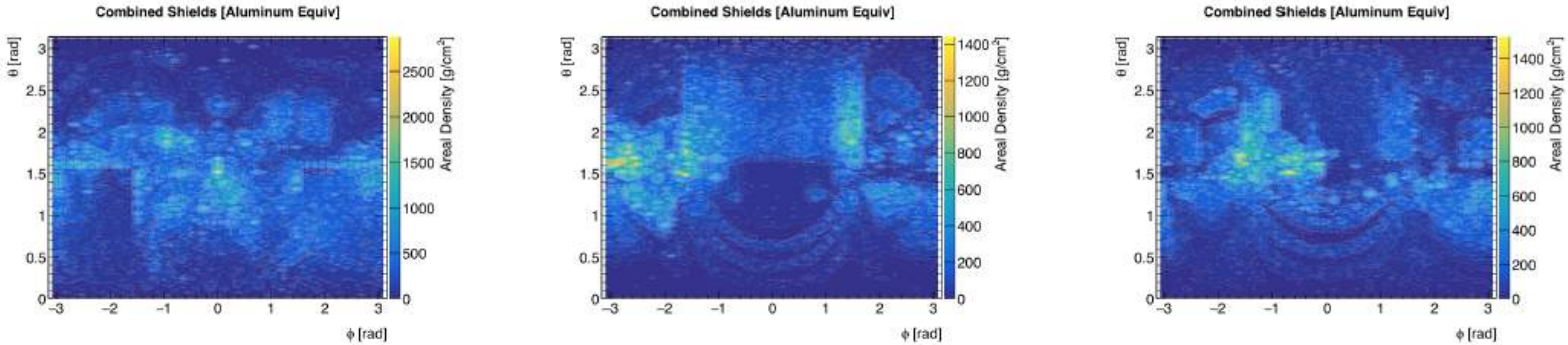


Figure 15: RAD at LAB1 O3.

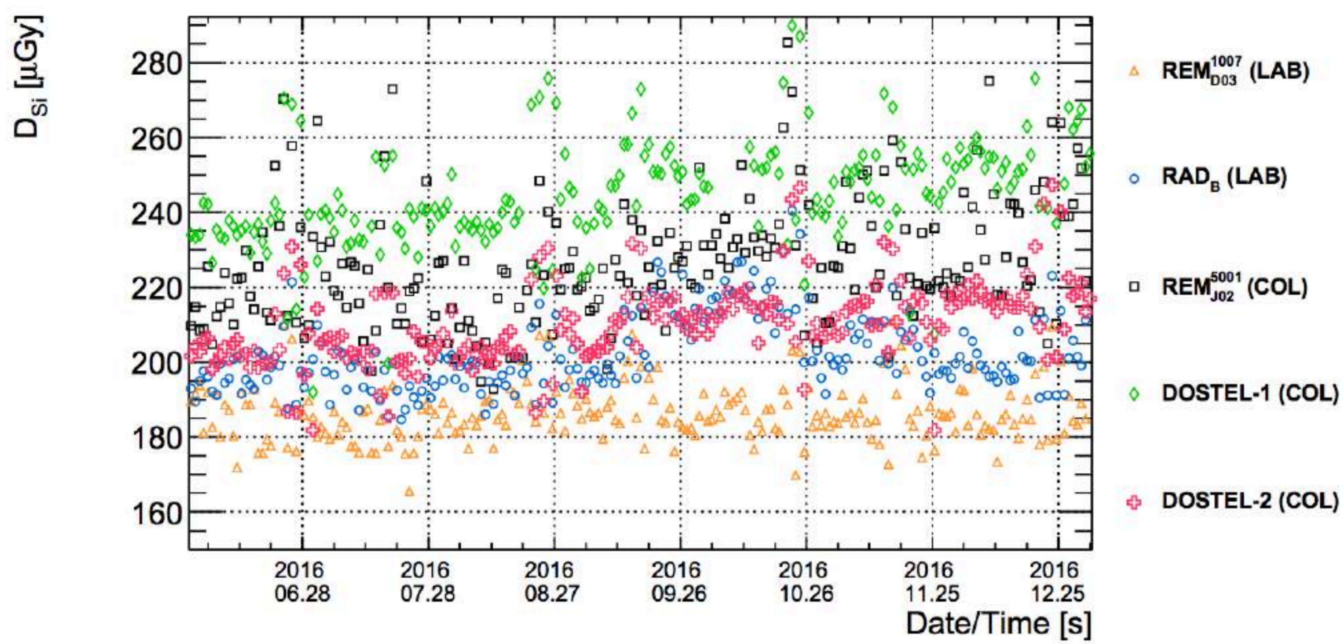
Figure 16: REM$^{1007}_{D03}$, in the orange box, on SSC9.



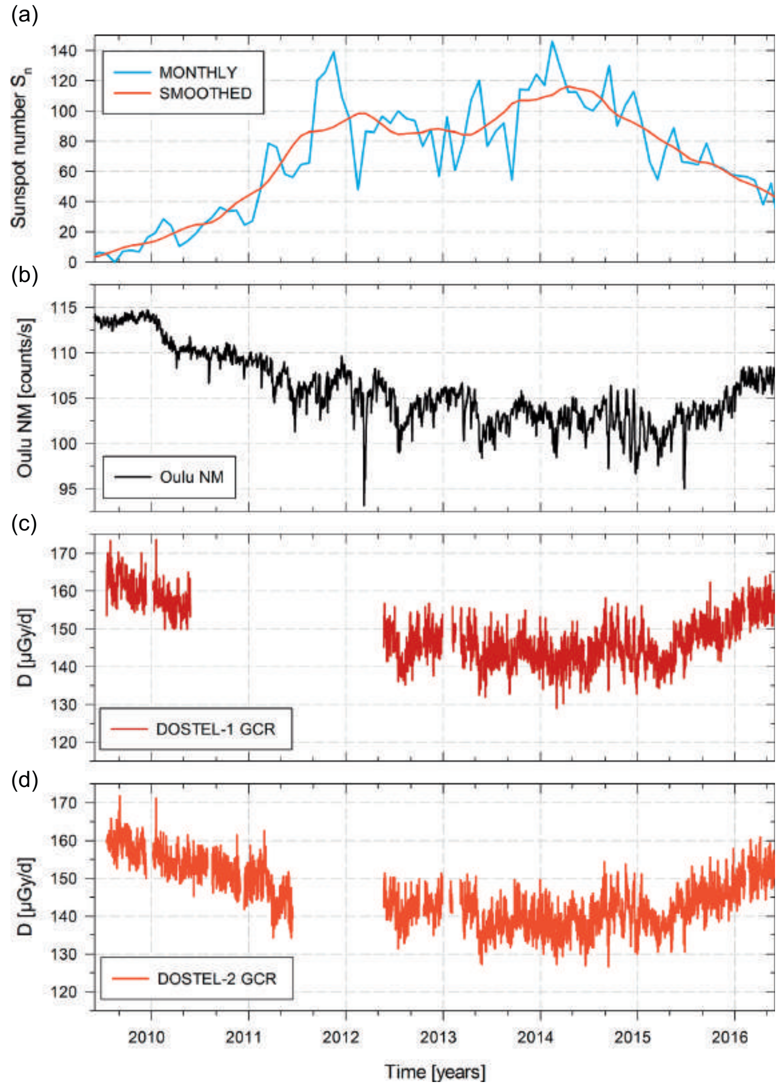
(a) TEPC, RAM, & RAD in US LAB1 O3, ρ_A=93.7g/cm^2 (Al-eq.)

(b) DOSTEL in COL1, ρ_A=50.1g/cm^2 (Al-eq.)

(c) RAM in COL1 A3, ρ_A=47.0g/cm^2 (Al-eq.)



+ Dose measurement aboard the ISS



AMS ?

Berger et al, 2017

Summary

Matthia @ WRMISS, 2017

- Output of DLR and BO-10/BO-14 model similar (<5%); differences in dose rates ≤ 5%
- Reasonable agreement between different transport models for many particles but severe differences for others
- Calculated total dose rates are compatible with measurements, but in some cases large discrepancies in the contribution of individual particle types

- Promising results for the parameterized model for dose rate in Si and tissue (long term trends)
- Short term behavior not nicely reproduced – What could be used instead of NM data for the primary GCR intensity…?

Continuous counting rates from AMS could be used in the study of active dosimeters on ISS

Conclusions (4)

- Long term measurements from AMS are fundamental to:
  - explore fundamental physics phenomena
  - explore Heliospheric effects on charged particles
  - improve risk assessment in manned exploration missions

- Continuous counting rates from AMS could be used in the study of active dosimeters on ISS