Recent results with the public USINE and CLUMPY codes

CLUMPY: https://lpsc.in2p3.fr/clumpy
USINE: https://lpsc.in2p3.fr/usine
CRDB: https://lpsc.in2p3.fr/crdb

CR = cosmic rays
CRDB = CR data base
DM = dark matter
XS = cross section

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Journées Théories du PNHE
IAP
1 Octobre 2018

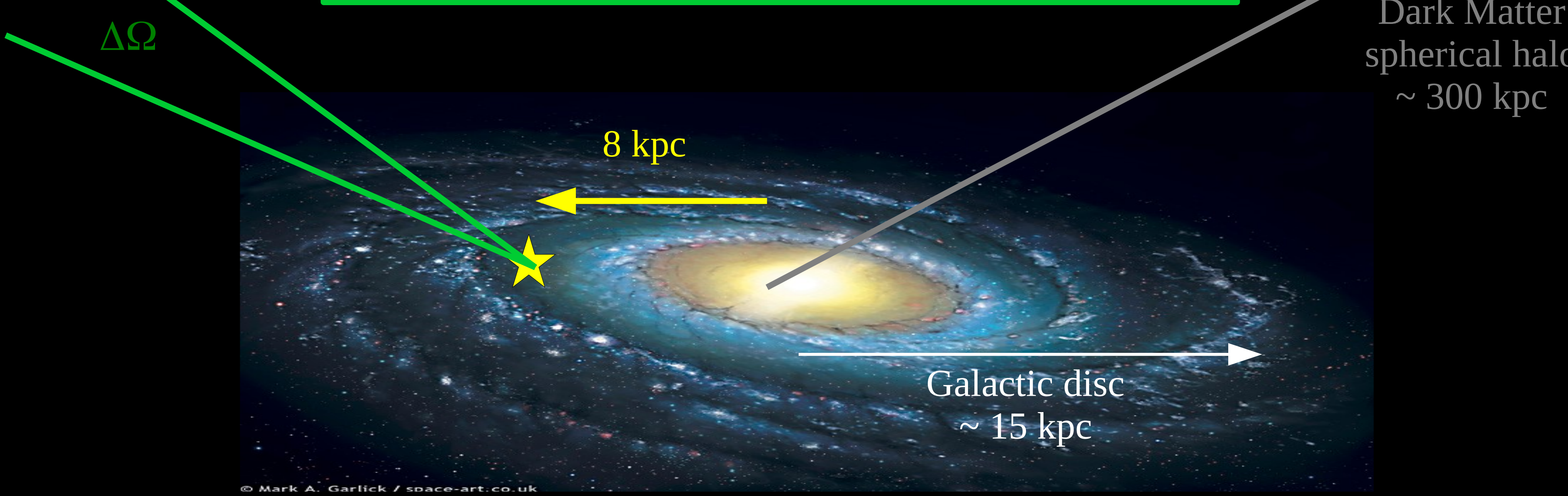
I. Cosmic rays and dark matter

Neutral particles

- propagate in straight line
- absorption ~ negligible at GeV-TeV in the Galaxy

→ *Observables* = skymaps + spectra

→ *Calculation* = line-of-sight integration on $\Delta\Omega$



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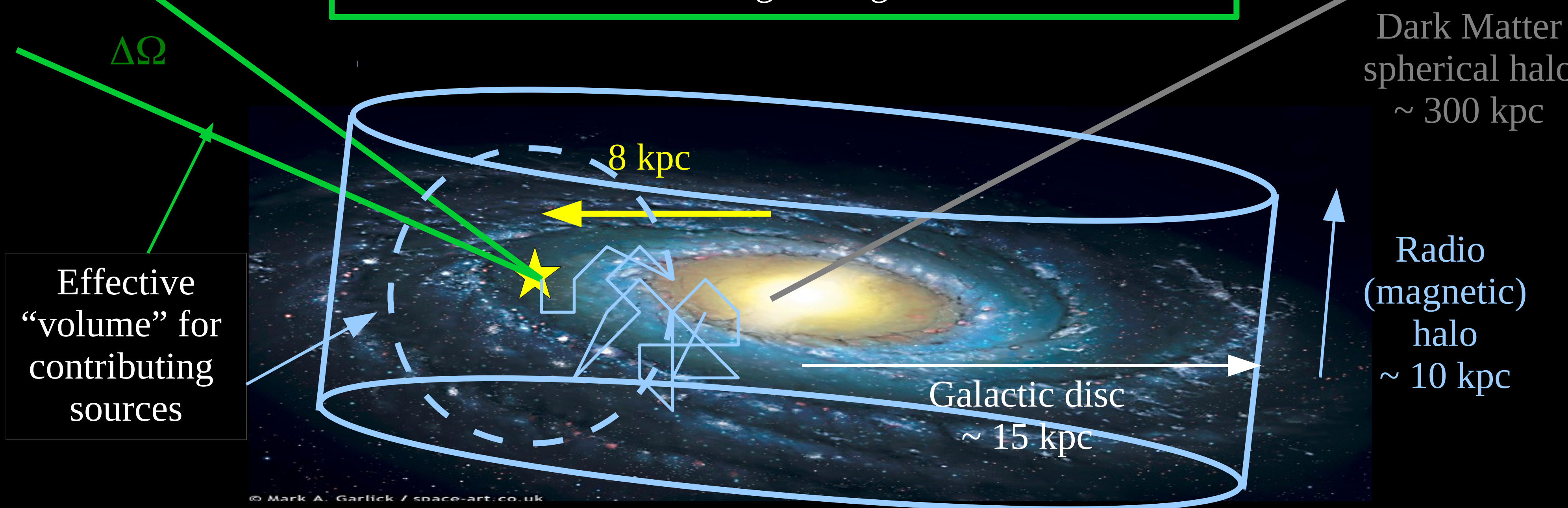


Charge particles
- diffusion in turbulent B
- continuous and catastrophic losses

→ *Observables* = spectra (all species) + anisotropy
→ *Calculation* = diffusion equation (same for DM)

A code for DM indirect detection signals in γ-rays and ν

CLUMPY

CR = cosmic rays
CRDB = CR data base
DM = dark matter
XS = cross section

Collaborators (over the years)

- France: **V. Bonnivard, A. Charbonnier, C. Combet, E. Nezri**, E. Pointecouteau
- Europe: J. Hinton, **M. Hütten**, S. Sarkar, M. Wilkinson…
- US: A. Geringer-Sameth, M. Walker...

II.1. Introduction

γ-ray (prompt) or ν flux from WIMP-DM annihilations:

Particle physics

Astrophysical J-factor

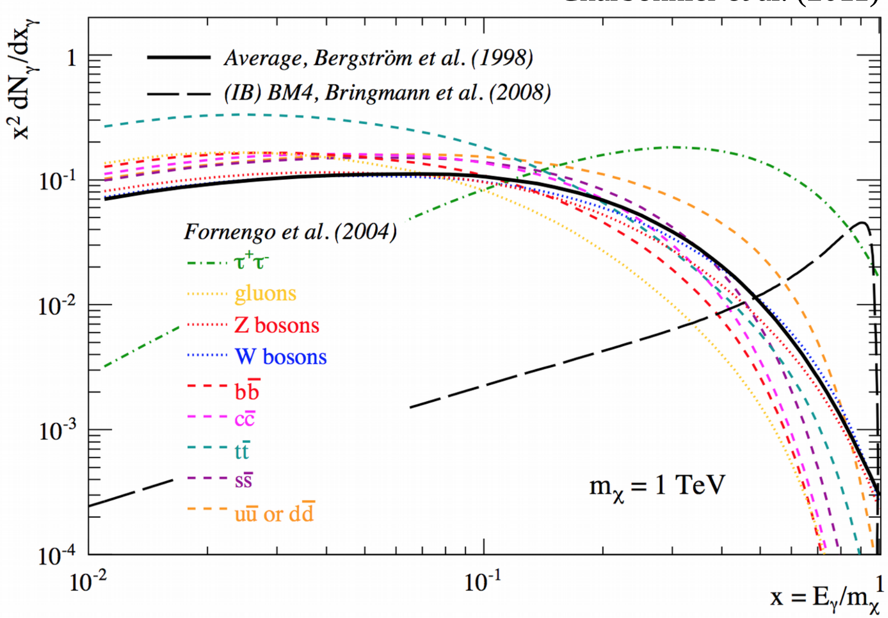
$$\frac{d\Phi}{dE}(E,\vec{k},\Delta\Omega(\alpha_{\rm int})) = \boxed{\frac{\langle\sigma v\rangle}{4\pi\;\delta\; m_{\rm DM}^2}\sum_f \frac{dN^f}{dE}B_f} \times \boxed{\int_0^{2\pi} d\beta \int_0^{\alpha_{\rm int}} \sin\alpha d\alpha \int_0^{l_{\rm max}} \rho^2(\vec{k}\;l,\alpha,\beta)\;dl}$$

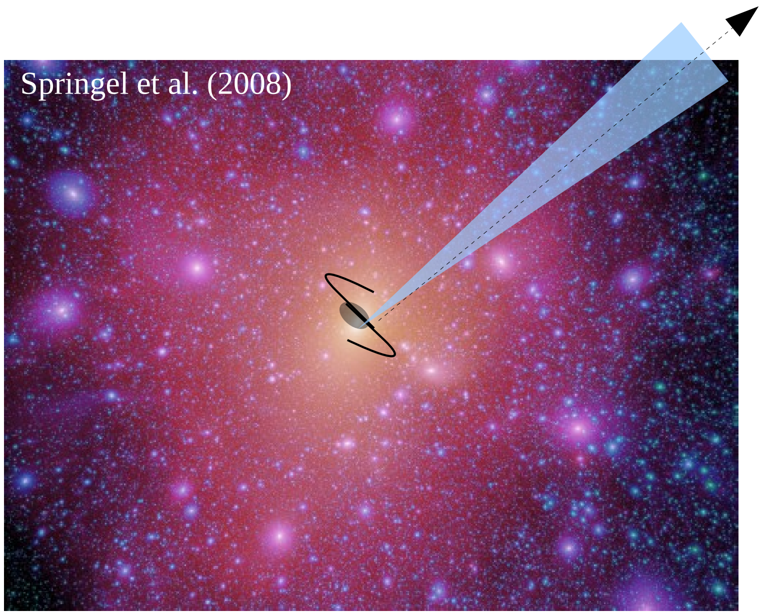
DM particle properties:
→ Mass
→ Annihilation XS

DM global properties:
→ DM density/distribution

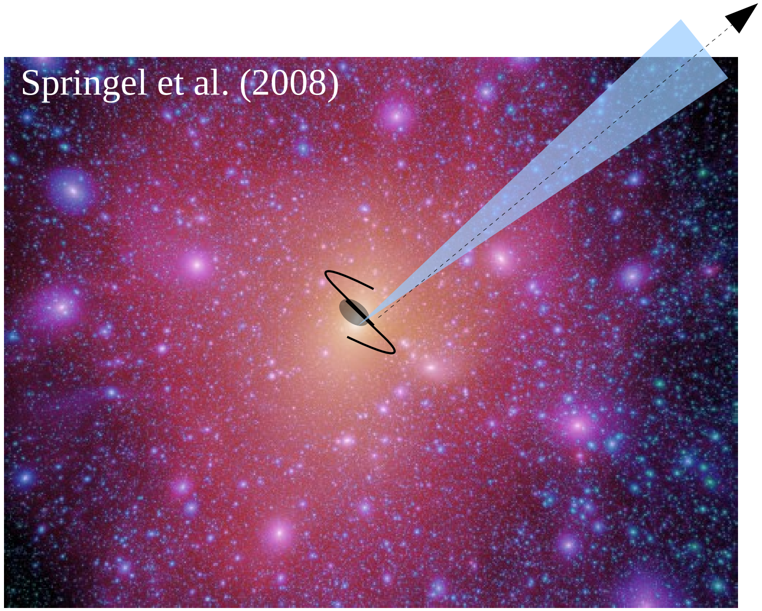
$k = (\psi,\theta)$

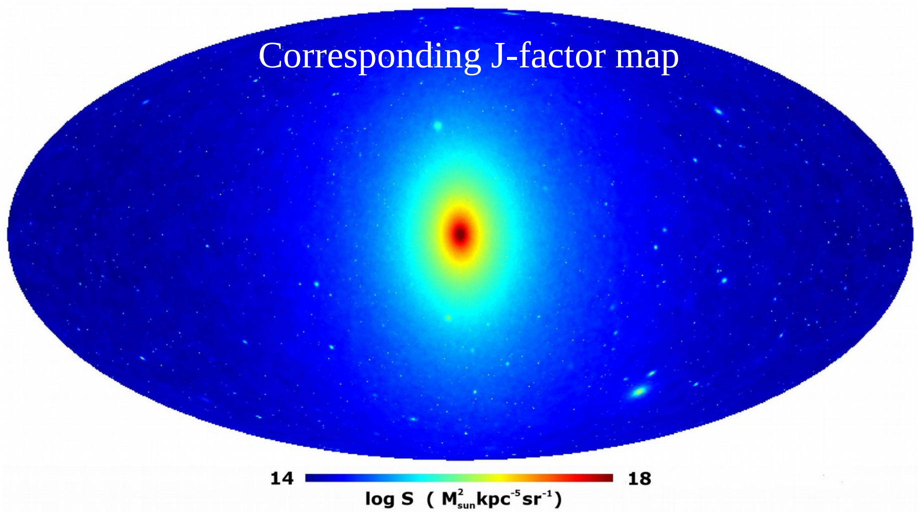
Charbonnier et al. (2011)





II.2. Rationale behind CLUMPY





- J-factors/exotic γ-ray skymaps useful for experiments (IACTs, Fermi-LAT)
- Simulations (DM-only, hydro) → similar yet differing results regarding DM properties (profiles, mass/spatial distributions of subhalos, halo concentration)

The origin of CLUMPY – Bridge between simulations and experiments

→ Emulator of the end-product of simulations in terms of DM annihilation/decay signals (fast, flexible, user-friendly, etc.), down to the smallest mass scales

→ Single halo or skymap mode

II.2. CLUMPY: development timeline and features

- 2011 – 2012: 1st release [ROOT]
  - → J-factors of MW halo + individual halos
  - → Small J-factor skymaps (flat sky approximation)

Charbonnier, Combet, Maurin, CPC 183, 656 (2012)

Used in: Charbonnier et al. (2011), Walker et al. (2011), Combet et al. (2012), Nezri et al. (2012), Maurin et al. (2012)

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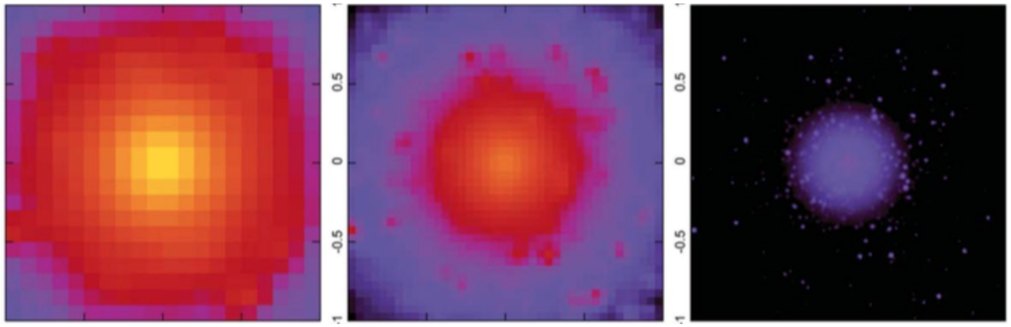

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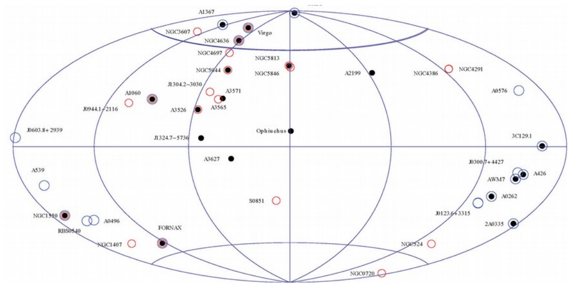

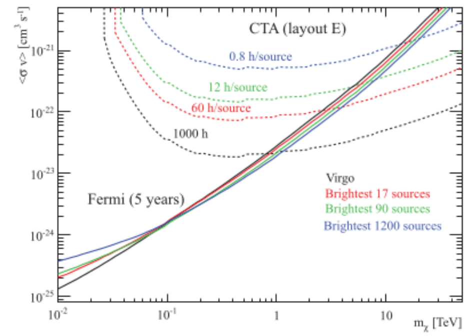

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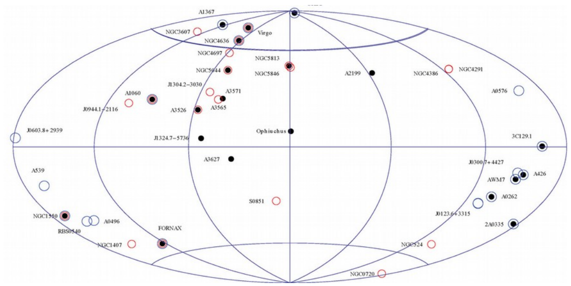
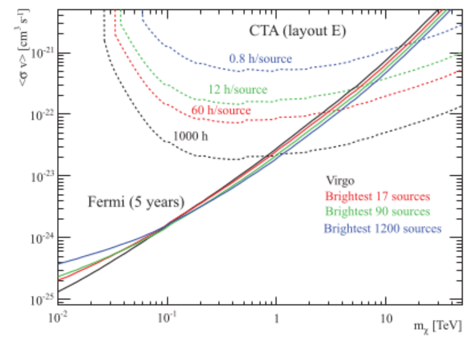
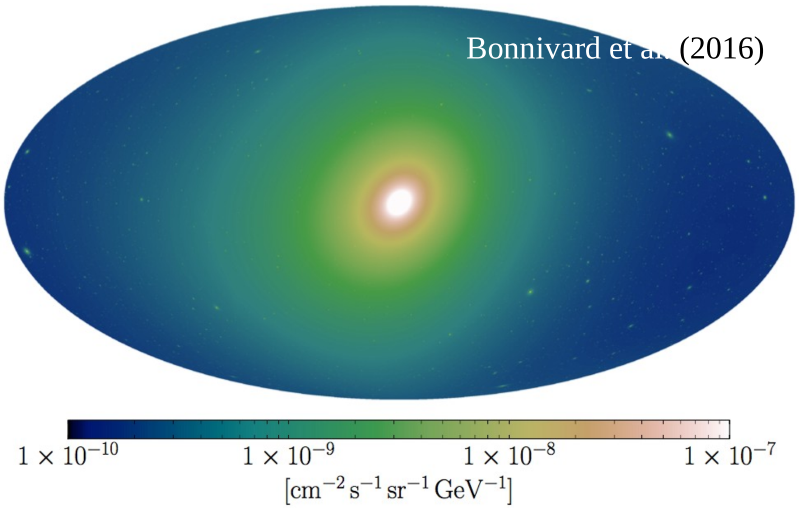




- 2015 – 2016 : 2nd release [ROOT, CFITSIO, HEALPix, GreAT]
  - → Jeans analysis module for dSph galaxies (MCMC)
  - → Triaxiality
  - → Fullsky maps (Healpix and related, e.g. APS)
  - → γ-ray and ν spectra (PPPC4DM)

Bonnivard, Hütten, Nezri, Charbonnier, Combet, Maurin, CPC 200, 336 (2016)

Used in: Bonnivard et al. (2015a,b,c, 2016), Hütten et al. (2016), Hütten & Maier (2018)



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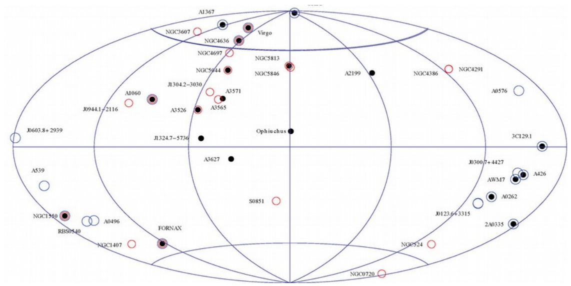

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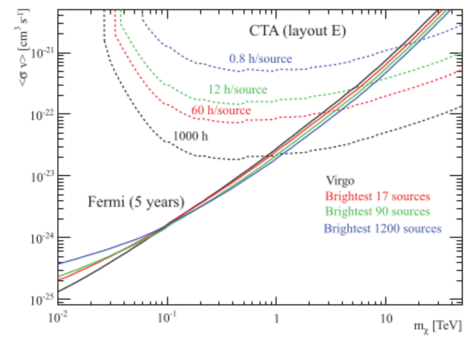

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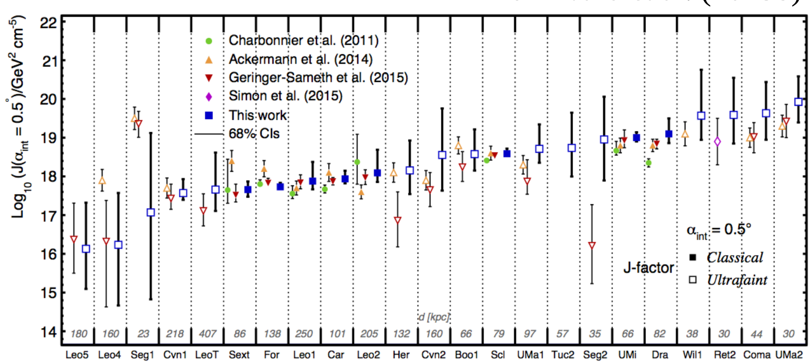
Bonnivard et al. (2015b)



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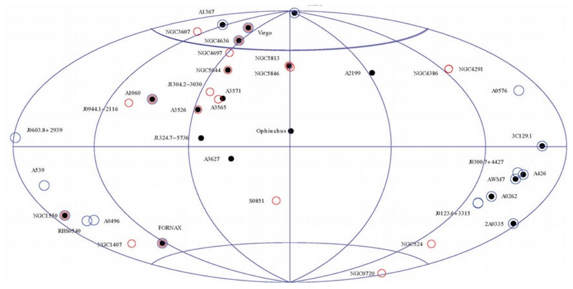

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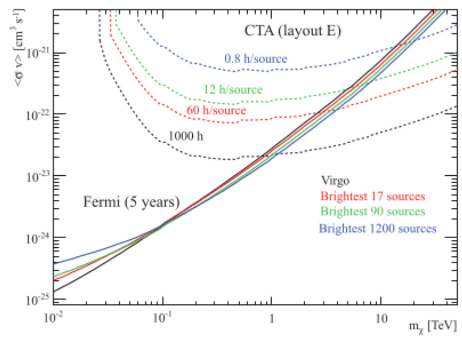

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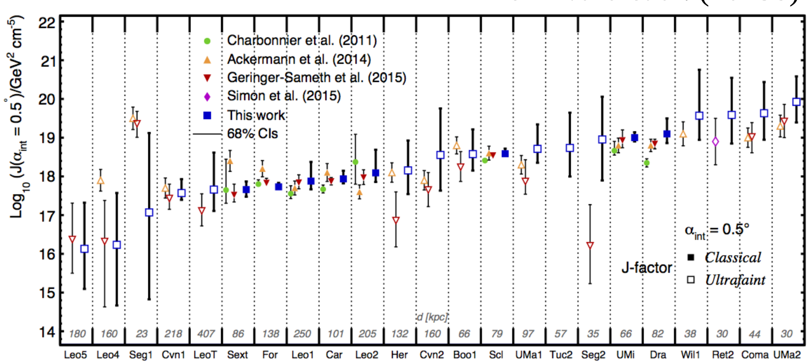
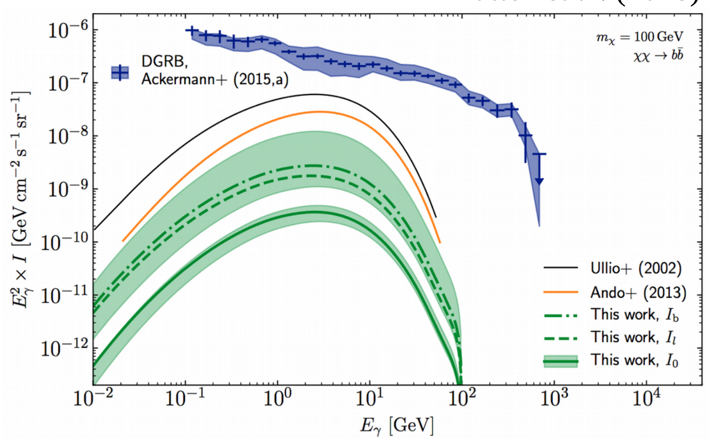


- 2018: 3rd release [ROOT, CFITSIO, HEALPix, GreAT, GSL, CLASS]
  - → ‘Cosmology’, halo mass function
  - → Mean extragalactic contribution to the exotic γ-ray flux
  - → Improved user-friendliness (easier install)

Hütten, Combet, Maurin, to appear in CPC (arXiv:1806.08639)

Used in: Hütten, Combet, Maurin (2018)

Hütten et al. (2018)



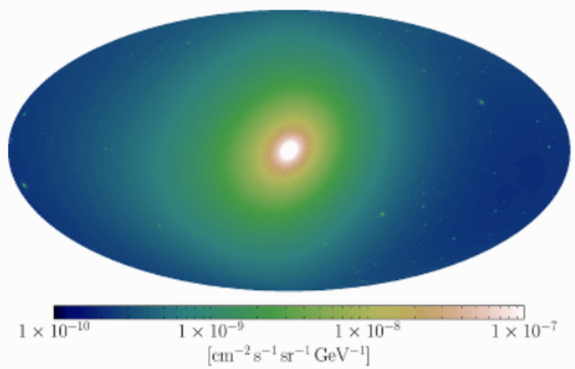
II.2. CLUMPY: `GitLab` and `Sphinx` documentation

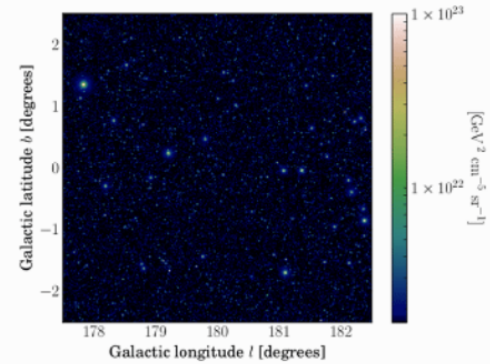
CLUMPY

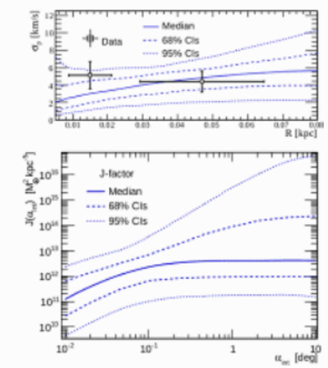
version 3.0

Search docs

Home » **CLUMPY** user documentation   Edit on GitLab







CLUMPY user documentation

We hope you will enjoy using **CLUMPY** whether you are:

- *an experimental astroparticle physicist* looking for *J*-factors or synthetic 2D γ-ray or ν skymaps from dark matter decay or annihilation, to calculate your instrumental sensitivity or to use in model/template analyses;
- *a theoretical astroparticle physicist* wishing to explore the γ-ray or ν flux in the Galaxy, dSphs, or galaxy clusters for your preferred particle physics model;
- *an astrophysicist* working on the DM content of dSphs and wishing to perform a Jeans analysis on your kinematic data;
- *a cosmologist* wishing to compute halo mass functions for any cosmology, redshift, and overdensity definition Δ.

II.3. Conclusions

Public code for γ-ray and ν signals from DM (sub-)structures

- Started in 2008
  - *3 public releases so far*
  - *Versatile (γ and ν, from local to extragalactic halos)*
  - *On gitlab, fully documented*

- Several reference results in the literature
  - *J factors in dwarf spheroidal galaxies*
  - *J-factors from galaxy clusters (and stacking strategy)*
  - *Prospective studies for CTA (dark clumps)*
  - *Extragalactic...*

- … and used by teams/collaborations (ANTARES, HAWC, CTA)

Future developments

- Improving/upgrading existing modules
  - *Pixel statistics for extragal (F. Calore), velocity-dep. XS (J. Lavalle)*
  - *Technical: python wrappers (M. Hütten)*

- New module (?): *Sunyaev-Zel'dovich (F. Ruppin)*

A code for galactic cosmic-ray propagation

… and a cosmic-ray data base

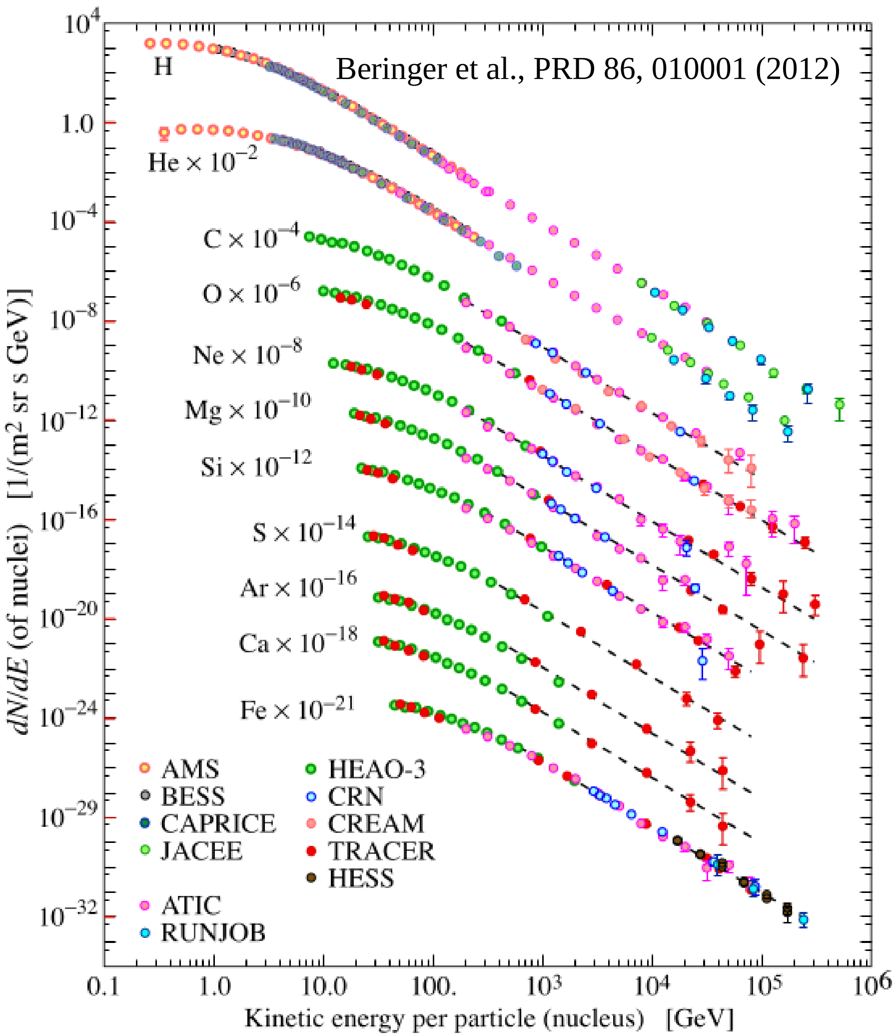
CR = cosmic rays
CRDB = CR data base
DM = dark matter
XS = cross section

Collaborators (over the years)

- France: M. Boudaud, Y. Génolini…+ Derome, Lavalle, Melot, Taillet, Salati, Serpico... (+ many PhD/postdoc who left academia)
- Europe: F. Donato, N. Fornengo, M. Vecchi...

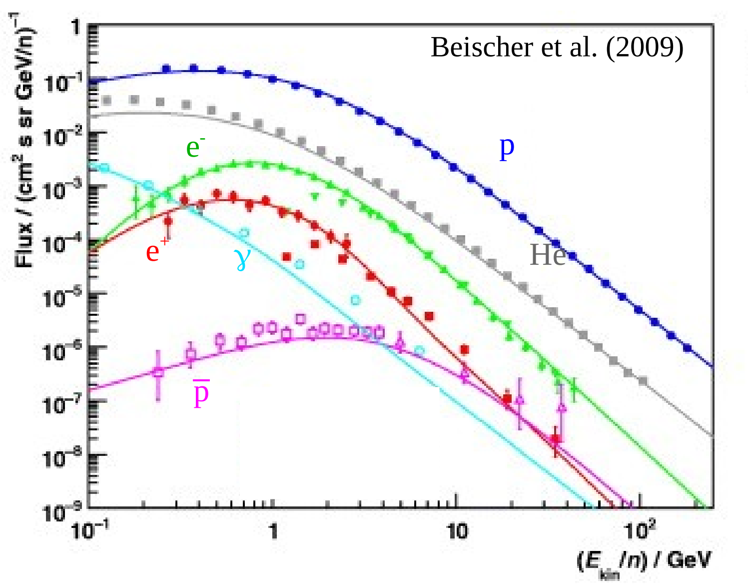
III.1. Introduction: Galactic cosmic rays (GCR)

Elemental spectra



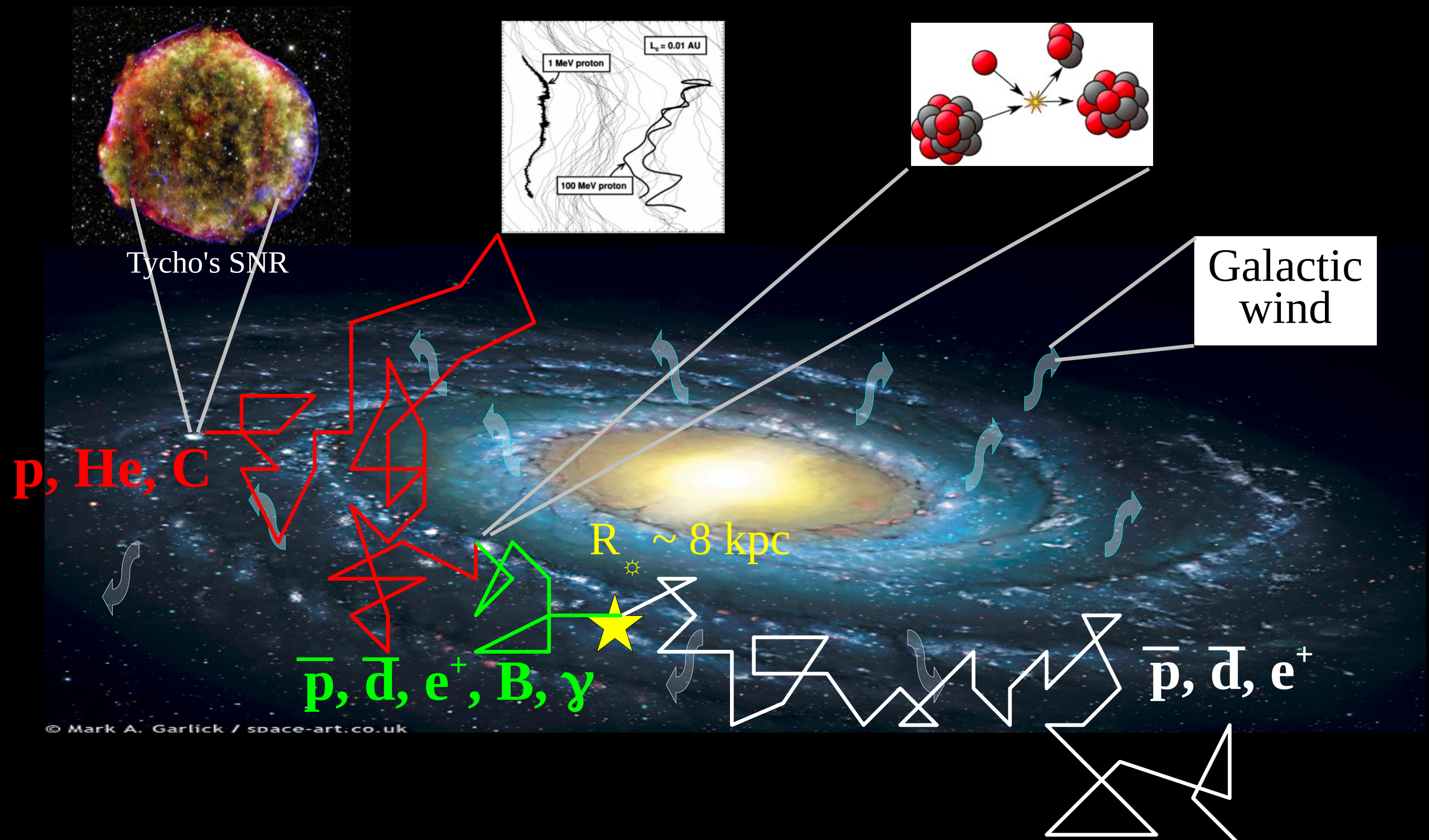
→ Origin of 'universal' power law ($E^{-2.8}$)?
→ Abundances of elements/isotopes?
→ CR anisotropy ($\delta<10^{-3}$)

Protons and He
vs
diffuse γ-rays, pbar, e^- and e^+



N.B.: rare CRs produced by H,He + ISM
→ How well do we know the astro. production?
→ Is it a good place to look for dark matter?

III.1. Introduction: GCR journey



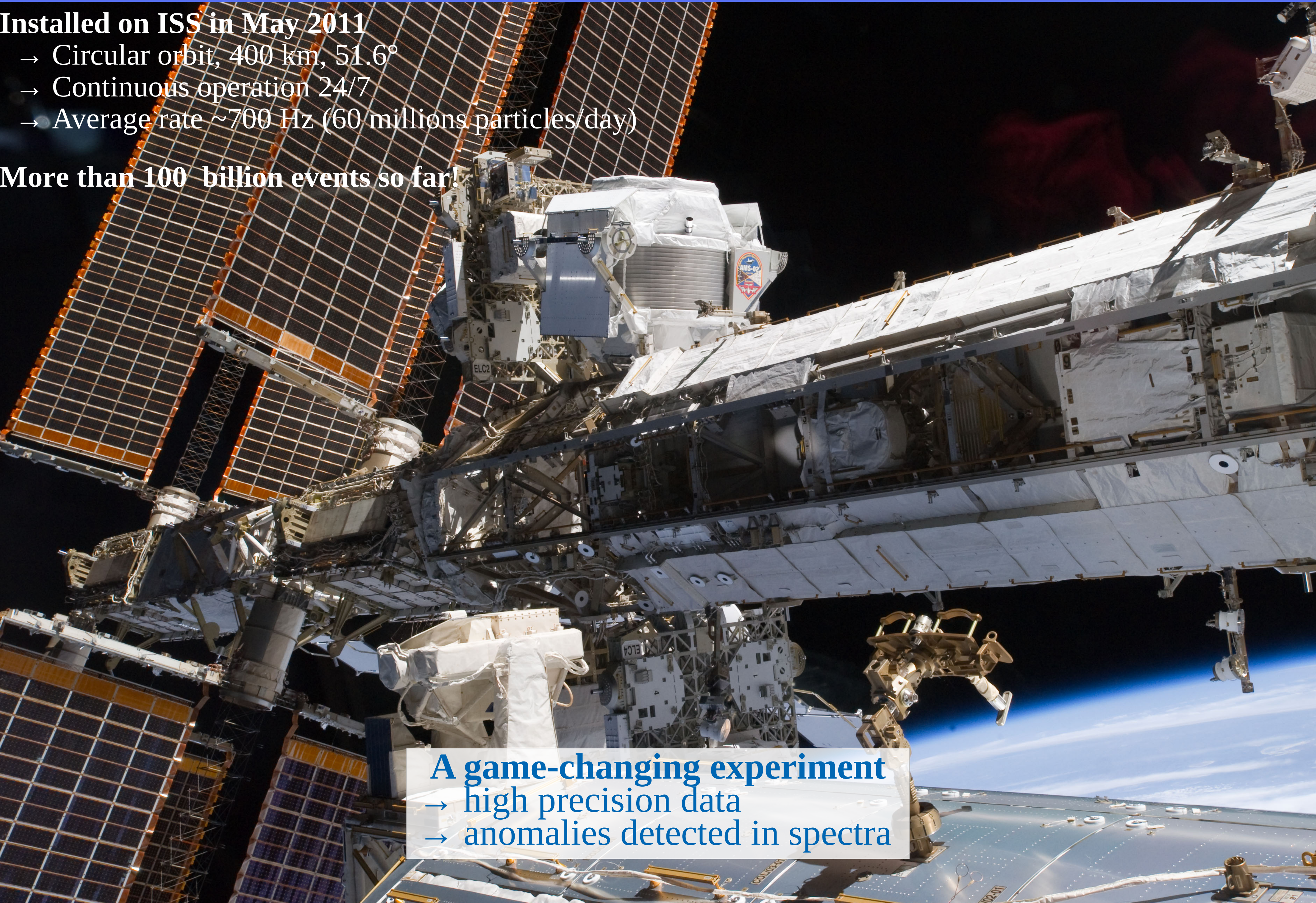
Milky-Way dark matter halo

- ~ spherical halo
- radius ~300 kpc

III.1. Introduction: AMS experiment

Installed on ISS in May 2011
→ Circular orbit, 400 km, 51.6°
→ Continuous operation 24/7
→ Average rate ~700 Hz (60 millions particles/day)

More than 100 billion events so far!



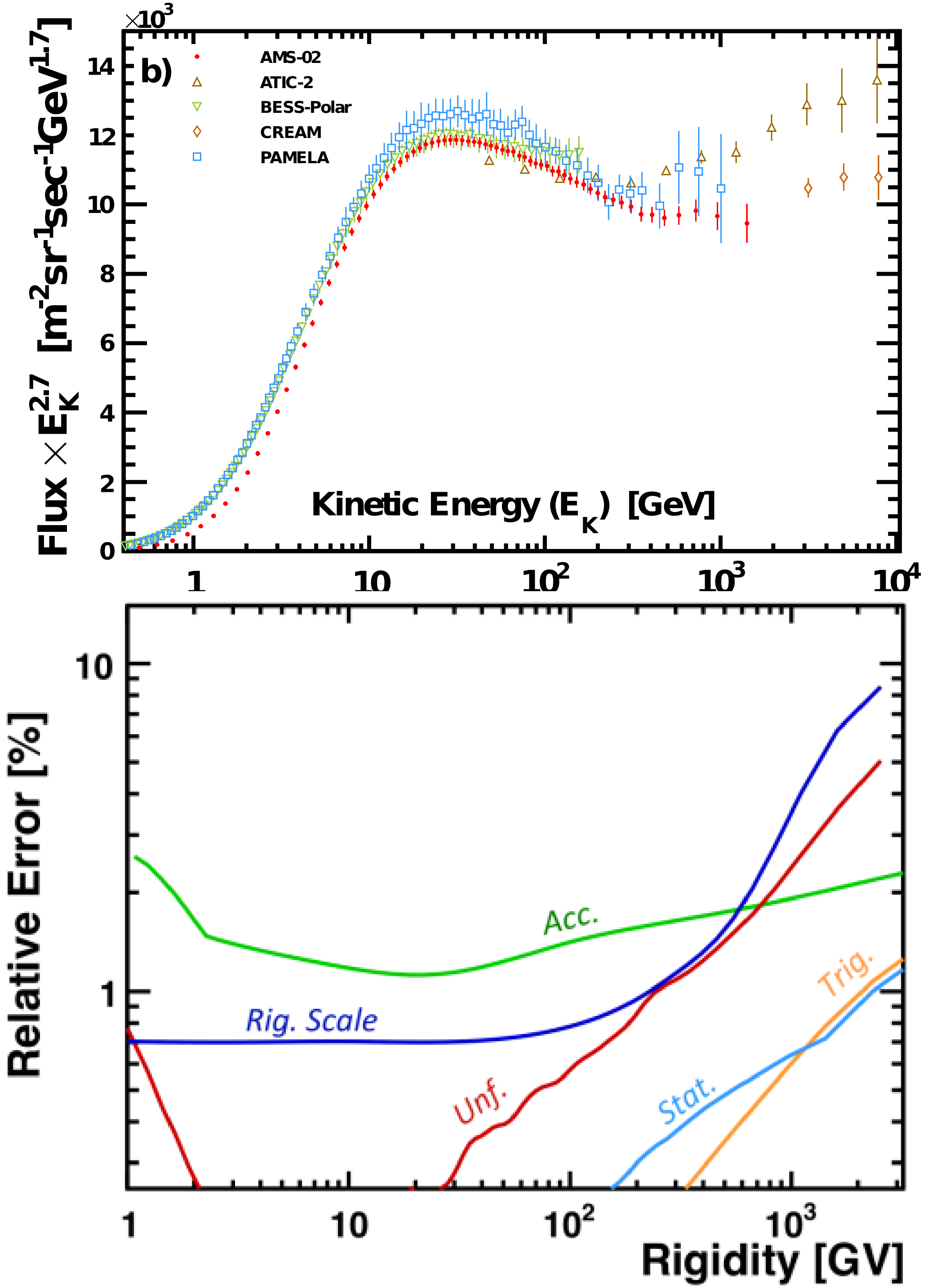
A game-changing experiment
→ high precision data
→ anomalies detected in spectra

III.1. Introduction: AMS data → 3% accuracy!

AMS-02 proton flux

Aguilar et al., PRL 114 (2015)

→ *based on 300 million events*

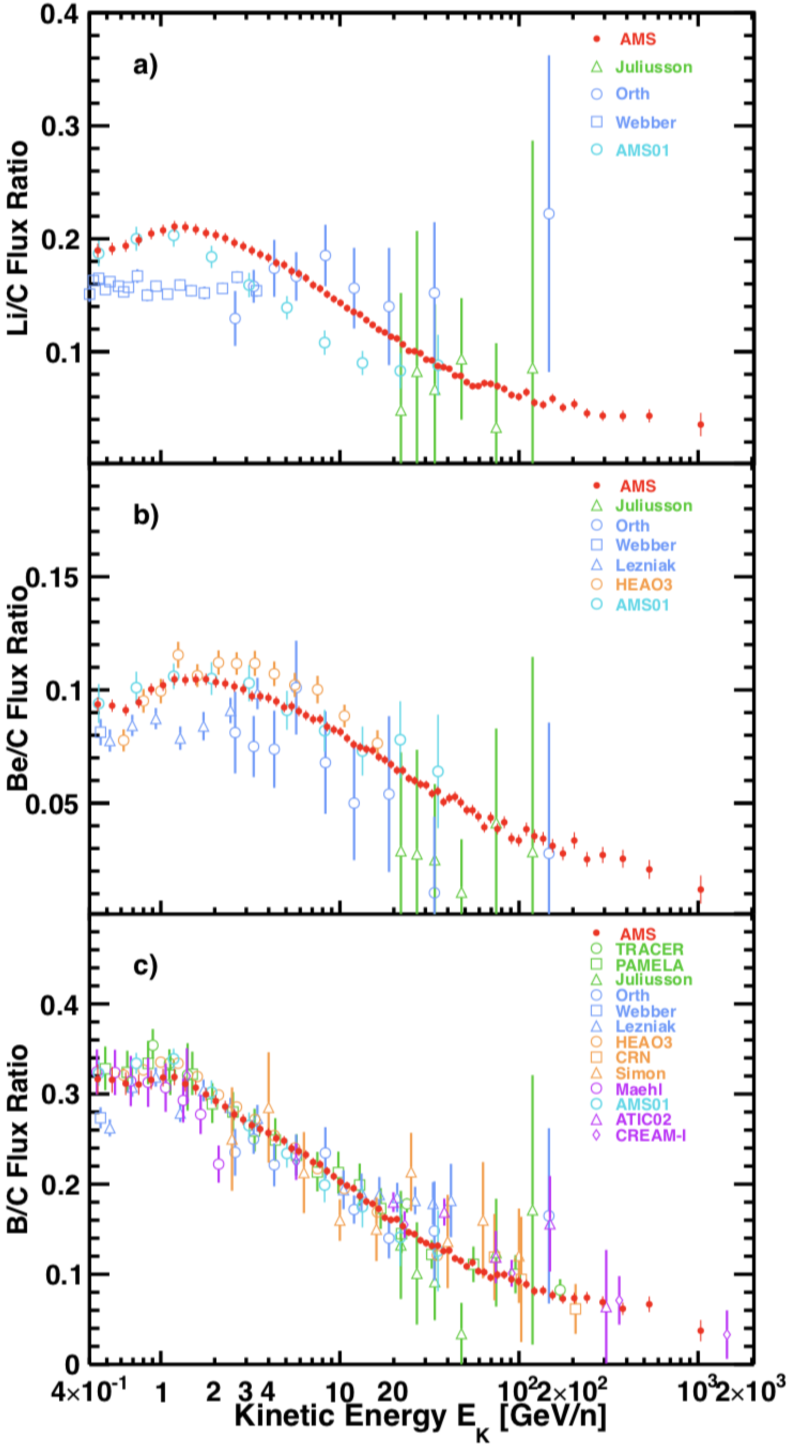


… and uncertainties

→ most difficult part of the analysis

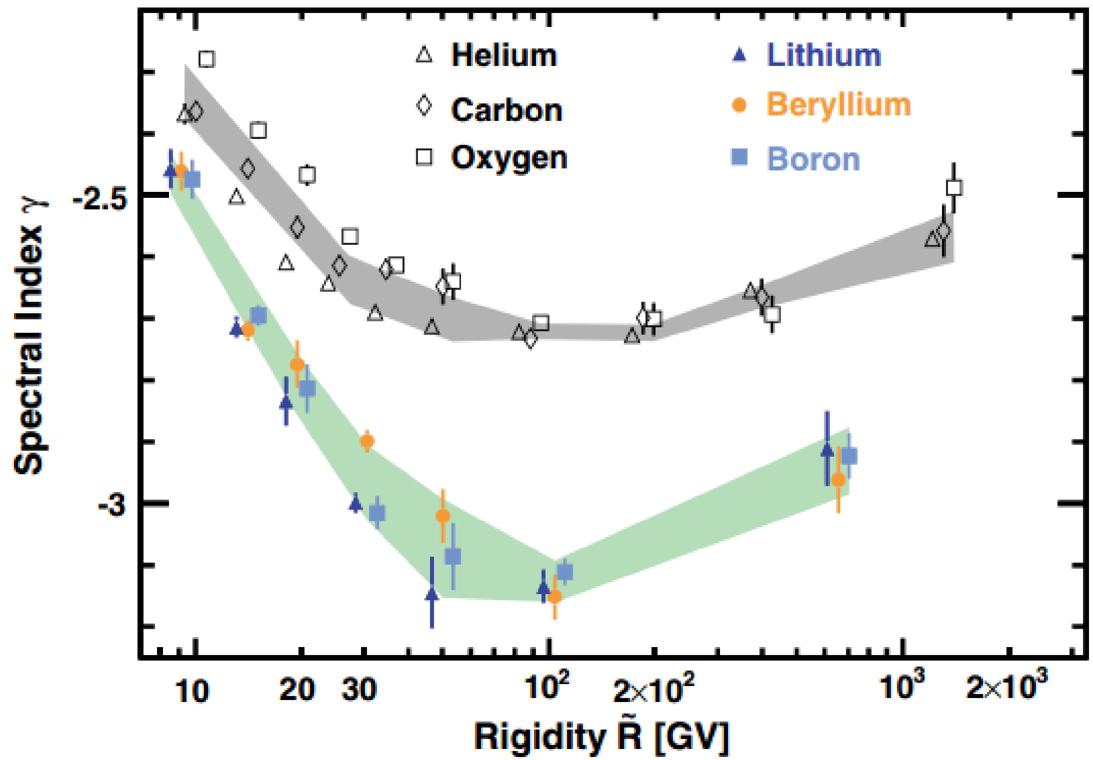
→ stat. uncertainties sub-dominant

III.1. Introduction: AMS data → spectral breaks!



→ Break seen in all data
(primary and seconday species)

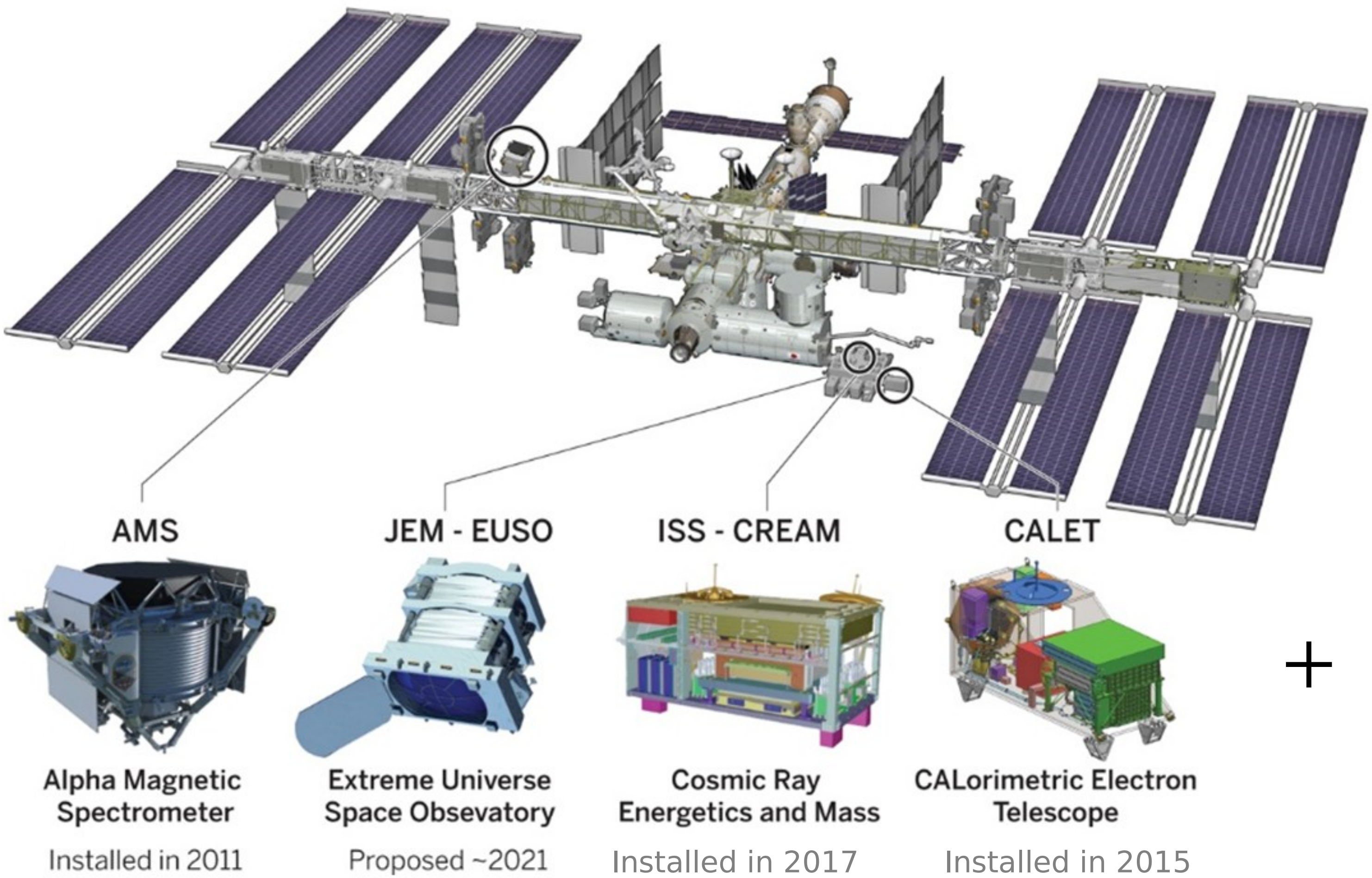
Aguilar *et al.*, PRL 120, 021101 (2018)



→ most likely transport (not source spectrum)
[coupling CR/B/gas via MHD]

III.1. Introduction: other ongoing experiments

→ A bright present (and near future)
for high-energy cosmic-rays



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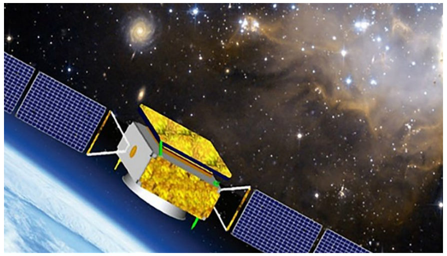


DAMPE satellite

Launched in 2015

… but data interpretation
limited by XS uncertainties!

III.2. Status of CRDB

Content

- Contextualised data (data points, experiments, references…)
- Plots and exports (REST interface)
- Z=1-30, antiprotons, leptons (all data since 1950)

190 125 web pages visited for 13568 different IP addresses (from 107 countries) since 2013-08-28.

Update (in progress)

- Add latest AMS-02, DAMPE, CALET, Voyager data...
- Add UHECR data (with H. Dembinski)
- Add Z>30 data
- Set phi_{FF} from NMDB back online…

III.3. Transport equation: techniques and codes

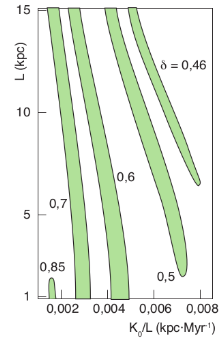
$$\overbrace{\frac{\partial N^j}{\partial t}}^{\text{Variation}} + \overbrace{\left(-\vec{\nabla}\cdot\left(K(E,\vec{r})\vec{\nabla}\right)+\vec{\nabla}\cdot\vec{V}(\vec{r})\right)}^{\text{Spatial transport: diffusion+convection}} N^j + \overbrace{\left(\Gamma_{\rm rad}+\Gamma_{\rm inel}\right)}^{\text{Catastrophic losses}} N^j + \overbrace{\frac{\partial}{\partial E}\left(b^j N^j - c^j\frac{\partial N^j}{\partial E}\right)}^{\text{E gains/losses}} = \overbrace{Q^j(E,\vec{r}) \quad + \sum_{m_i>m_j}\Gamma^{i\to j}N^i}^{\text{Source term: prim.+sec.}}$$

	Weighted-slab/LB	*(Semi-)analytical*	*Finite difference scheme*	*Monte Carlo*
Approach	Separate fragmentation: • Grammage dist. (PLD) • Integrate on grammage LB → PLD(X) = $e^{(-X/\lambda esc)}$	Simplify problem: • dominant effects • simple geometry	Discretize equation: • Numerical scheme (e.g., Crank-Nicholson) → Matrix inversion	Follow each particle: • N particles at t=0 • evolve each @ t+1 $1D : \Delta z = \pm\sqrt{2D\Delta t}$
Tools	• 1D numerical integr.	• Green functions • Fourier/Bessel • Diff. equations	• Num. recipes/solvers (NAG, GSL libraries)	• Stochastic diff. equations Markov process + MPI
Pros	• Simple	• Direct dep. in sol. • Fast (e.g. w/ MCMC)	• Simple algebra • Universal (any model)	• Stat. properties (along path) • t step (for/back)-ward
cons	• Leakage approx. fails (leptons and decay)	• “Effective” models • New eq. per model	• Slower / instabilities • RAM for high.res.	• N large (statistical errors) • Massively parallel
Codes and/ or references	Davis (1960) – Leaky box Ginzburg & Syrovatskii (1969) Jones/Ptuskin/Webber (70-01) Jones *et al.* (2001)	Ptuskin (1980+) Schlickeiser (1990+) USINE (2000+)	GALPROP (Strong *et al.*, 1998) DRAGON (Evoli *et al.*, 2008) PICARD (Kissmann *et al.*, 2013)	Webber & Rockstroh (1997) Farahat *et al.* (2008) Kopp, Büshing *et al.* (2012) CRPROPA3.1 (Merten *et al.*, 2017)
	↓ 0D	↓ 1D, 2D	↓ 3D, 3D+1	↓ 3D, 3D+1

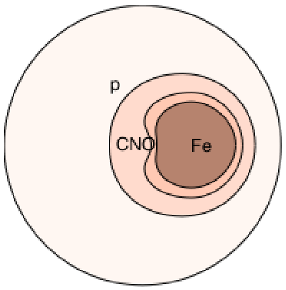
III.3. USINE: development timeline and features

- 1999 – 2003: 1st (unreleased) version
  - → Z=1-30 nuclei in 2D semi-analytical model

Maurin et al. (2001)



Taillet & Maurin (2003)

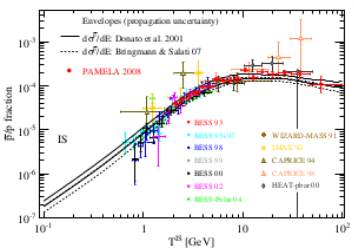


Donato et al. (2004)

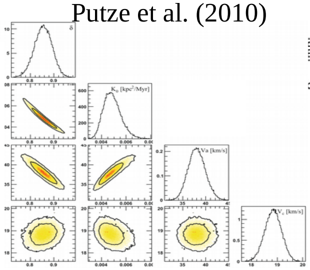
Case	δ	K_0 (kpc^2/Myr)	L (kpc
max	0.46	0.0765	15
med	0.70	0.0112	4
min	0.85	0.0016	1

- 2005 – 2012 : 2nd (unreleased) version
  - → Antiprotons and antideuterons (and DM)
  - → Interfaced with `CERN/ROOT`
  - → Interfaced with `GreAT` MCMC engine

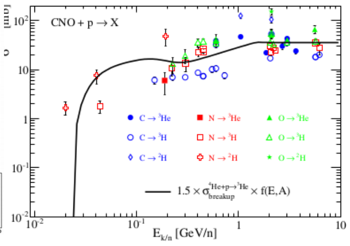
Donato et al. (2009)



Putze et al. (2010)



Coste et al. (2012)



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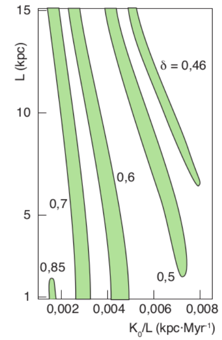
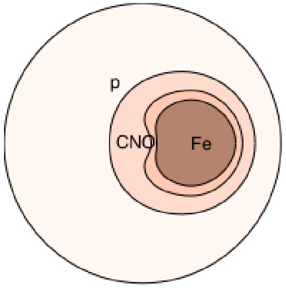
  → Z=1-30 nuclei in 2D semi-analytical model

Maurin et al. (2001)



Taillet & Maurin (2003)

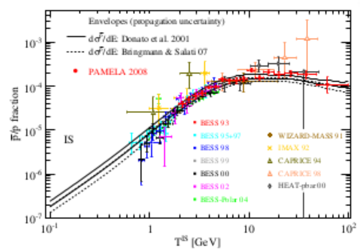


Donato et al. (2004)

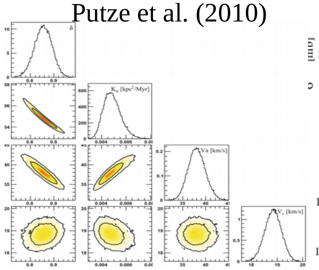
Case	δ	K_0 (kpc^2/Myr)	L (kpc
max	0.46	0.0765	15
med	0.70	0.0112	4
min	0.85	0.0016	1

- 2005 – 2012 : 2nd (unreleased) version
  → Antiprotons and antideuterons (and DM)
  → Interfaced with `CERN/ROOT`
  → Interfaced with `GreAT` MCMC engine

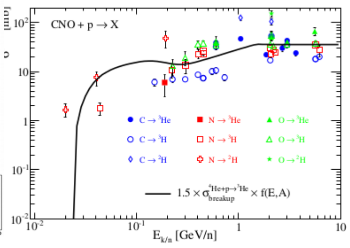
Donato et al. (2009)



Putze et al. (2010)

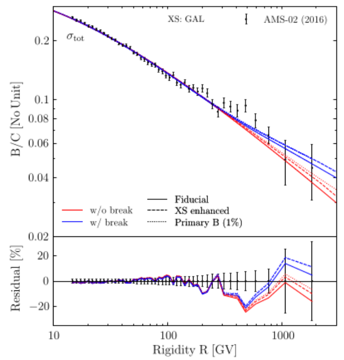


Coste et al. (2012)

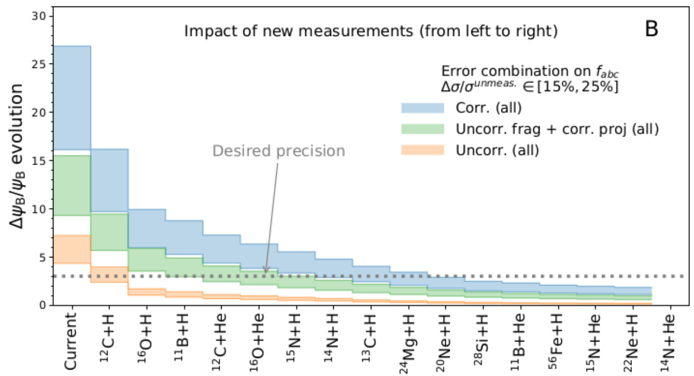


- 2018: V3.4, first public release
  → Full C++, static/dynamic tests, continuous integration
  → Improved χ^2 description (covariance, nuisance)
  → Improved user-friendliness (single `ASCII` initialisation file)

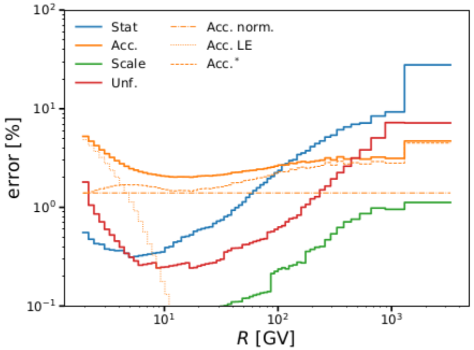
Génolini *et al.*
PRL 119, 241101 (2017)



Génolini *et al.* PRC 98, 034611 (2018)
(as an *Editors' Suggestion*)



Derome *et al.* (in prep)
Boudaud *et al.* (in prep.)



III.4. Conclusions

Public code for galactic cosmic-ray propagation (+ CR dabase)

- Started in 1999
  - *First public release this year!*
  - *Semi-analytical model: pedagogic value and still scientifically relevant!*
  - *On gitlab, fully documented*

- Several reference results in the literature
  - *Determination of transport parameters (w/ MCMC)*
  - *DM-related studies (anti-matter)*
  - *AMS-02 data analysis...*

- … and hopefully used by other teams soon!

Future developments

- Include electrons and positrons (with M. Boudaud)
- DM contributions for anti-nuclei and positrons (2D model)
- Interface with generic MCMC engine
- ...

4. Break in the diffusion coefficient?

Génolini, Serpico *et al.*, PRL 119, 241101 (2017)

Indications for a High-Rigidity Break in the Cosmic-Ray Diffusion Coefficient

Using cosmic-ray boron to carbon ratio (B/C) data recently released by the AMS-02 experiment, we find indications (*decisive evidence*, in Bayesian terms) in favor of a diffusive propagation origin for the broken power-law spectra found in protons (p) and helium nuclei (He). The result is robust with respect to

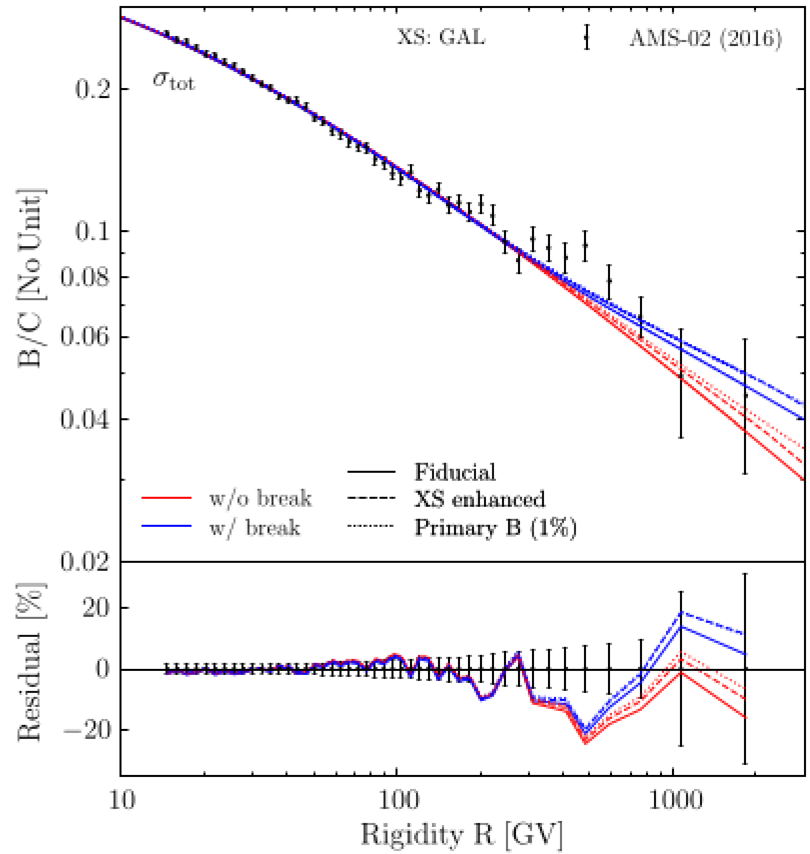
Test hypotheses

- Break in source: $K(R) = K_0 \beta (R/\mathrm{GV})^\delta$
- Break in diffusion: $$K(R) = K_0 \beta \frac{(R/\mathrm{GV})^\delta}{\{1 + (R/R_b)^{\Delta\delta/s}\}^s}$$

→ same number of free parameters (K_0, δ, V_c)

→ no extra parameters:

- R_s, $\Delta\delta$, and s from AMS-02 p and He break
- Correlations accounted for



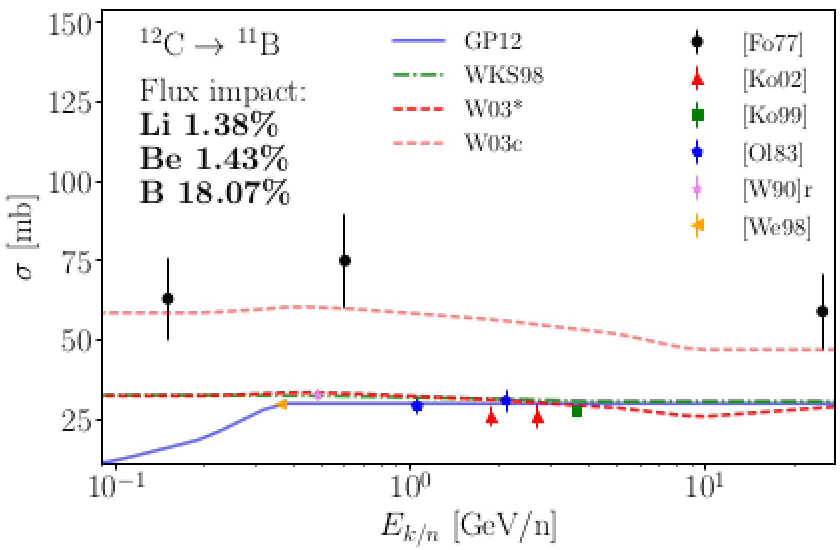
N.B.: difference not compelling by eye…
but that what statistics is for!

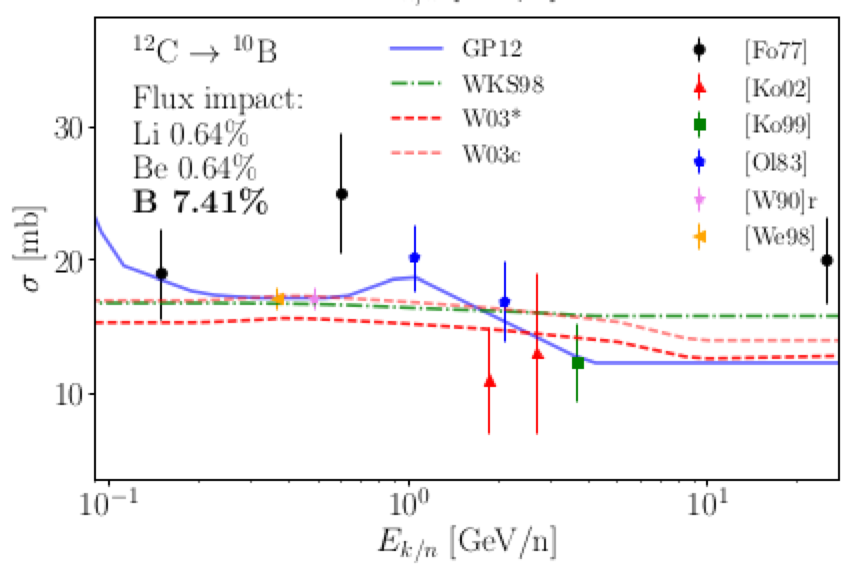
Robustness against

- Energy dependence of inelastic cross sections ($\propto \ln^2 E$)
- primary B fraction as high as 4.5% of the C (would already overshoot antiprotons)

5. Ranking XS: most important reactions for B (2)

This is what it looks like...



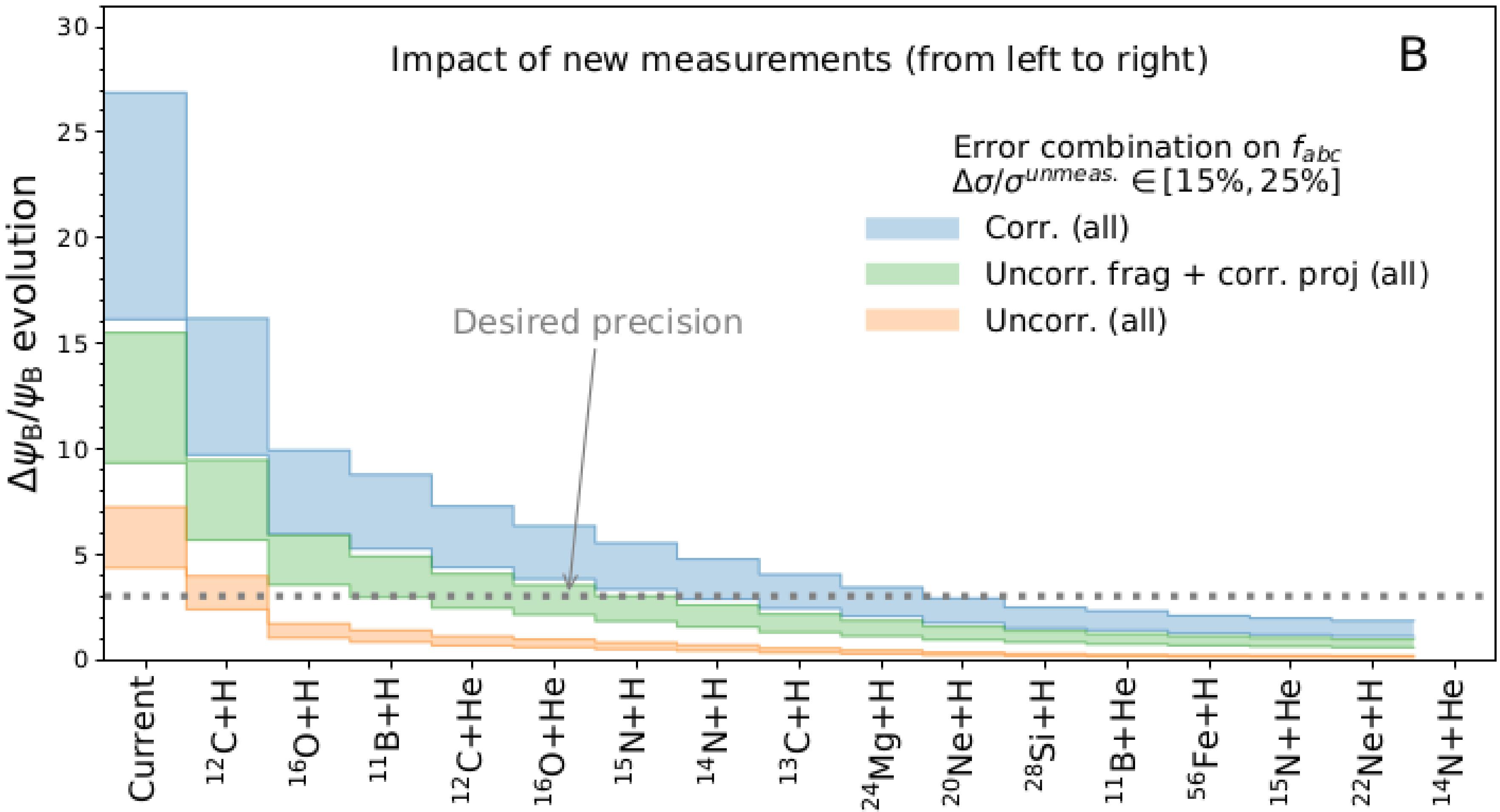


Reaction $a+b\to c$	Flux impact f_{abc} [%]			σ [mb]	Data	$\sigma\%\sigma$
	min	**mean**	max	range		
$\sigma(^{12}\mathrm{C}+\mathrm{H}\to{}^{11}\mathrm{B})$	18.0	**18.1**	19.0	30.0	✓	1.8
$\sigma(^{12}\mathrm{C}+\mathrm{H}\to{}^{11}\mathrm{C})$	16.0	**16.2**	17.0	26.9	✓	**n/a**
$\sigma(^{16}\mathrm{O}+\mathrm{H}\to{}^{11}\mathrm{B})$	11.3	**11.8**	12.0	18.2	✓	1.5
$\sigma(^{12}\mathrm{C}+\mathrm{H}\to{}^{10}\mathrm{B})$	7.20	**7.41**	7.60	12.3	✓	1.1
$\sigma(^{16}\mathrm{O}+\mathrm{H}\to{}^{10}\mathrm{B})$	6.82	**7.03**	7.21	10.9	✓	
$\sigma(^{16}\mathrm{O}+\mathrm{H}\to{}^{11}\mathrm{C})$	5.67	**5.89**	6.00	9.1		**n/a**
$\sigma(^{11}\mathrm{B}+\mathrm{H}\to{}^{10}\mathrm{B})$	4.00	**4.07**	4.20	38.9	✓	
$\sigma(^{12}\mathrm{C}+\mathrm{He}\to{}^{11}\mathrm{B})$	2.50	**2.59**	2.70	38.6		1.8
$\sigma(^{12}\mathrm{C}+\mathrm{He}\to{}^{11}\mathrm{C})$	2.10	**2.14**	2.20	32.0		**n/a**
$\sigma(^{15}\mathrm{N}+\mathrm{H}\to{}^{11}\mathrm{B})$	2.00	**2.03**	2.10	26.1	✓	1.2
$\sigma(^{12}\mathrm{C}+\mathrm{H}\to{}^{10}\mathrm{C})$	1.80	**1.87**	1.90	3.1	✓	**n/a**
$\sigma(^{16}\mathrm{O}+\mathrm{He}\to{}^{11}\mathrm{B})$	1.67	**1.75**	1.80	24.4		1.5
$\sigma(^{13}\mathrm{C}+\mathrm{H}\to{}^{11}\mathrm{B})$	1.50	**1.53**	1.60	22.2		1.7
$\sigma(^{12}\mathrm{C}+\mathrm{H}\to{}^{10}\mathrm{Be})$	1.40	**1.48**	1.50	4.0	✓	
$\sigma(^{14}\mathrm{N}+\mathrm{H}\to{}^{11}\mathrm{B})$	1.30	**1.34**	1.36	17.3	✓	1.7
$\sigma(^{12}\mathrm{C}+\mathrm{He}\to{}^{10}\mathrm{B})$	1.00	**1.06**	1.10	15.8		1.1
$\sigma(^{16}\mathrm{O}+\mathrm{He}\to{}^{10}\mathrm{B})$	0.99	**1.05**	1.09	14.6		
$\sigma(^{24}\mathrm{Mg}+\mathrm{H}\to{}^{11}\mathrm{B})$	0.98	**1.01**	1.00	10.4		1.6
$\sigma(^{14}\mathrm{N}+\mathrm{H}\to{}^{11}\mathrm{C})$	0.90	**0.92**	0.94	11.9		**n/a**
$\sigma(^{20}\mathrm{Ne}+\mathrm{H}\to{}^{11}\mathrm{B})$	0.87	**0.90**	0.93	12.0		1.7
$\sigma(^{16}\mathrm{O}+\mathrm{He}\to{}^{11}\mathrm{C})$	0.83	**0.88**	0.90	12.2		**n/a**
$\sigma(^{16}\mathrm{O}+\mathrm{H}\to{}^{10}\mathrm{Be})$	0.84	**0.87**	0.91	2.2	✓	
$\sigma(^{11}\mathrm{B}+\mathrm{H}\to{}^{10}\mathrm{Be})$	0.81	**0.83**	0.85	12.9	✓	
$\sigma(^{14}\mathrm{N}+\mathrm{H}\to{}^{10}\mathrm{B})$	0.77	**0.79**	0.82	10.3	✓	
$\sigma(^{15}\mathrm{N}+\mathrm{H}\to{}^{10}\mathrm{B})$	0.72	**0.74**	0.77	9.6	✓	
$\sigma(^{28}\mathrm{Si}+\mathrm{H}\to{}^{11}\mathrm{B})$	0.39	**0.63**	0.87	[4.0, 9.5]		2.1
$\sigma(^{13}\mathrm{C}+\mathrm{H}\to{}^{10}\mathrm{B})$	0.59	**0.62**	0.65	9.0		1.6
$\sigma(^{24}\mathrm{Mg}+\mathrm{H}\to{}^{10}\mathrm{B})$	0.58	**0.60**	0.62	6.2		
$\sigma(^{11}\mathrm{B}+\mathrm{He}\to{}^{10}\mathrm{B})$	0.57	**0.58**	0.59	50.0		
$\sigma(^{13}\mathrm{C}+\mathrm{H}\to{}^{11}\mathrm{C})$	0.54	**0.56**	0.59	8.2		**n/a**
$\sigma(^{20}\mathrm{Ne}+\mathrm{H}\to{}^{11}\mathrm{C})$	0.52	**0.54**	0.56	7.2	✓	**n/a**
$\sigma(^{24}\mathrm{Mg}+\mathrm{H}\to{}^{11}\mathrm{C})$	0.51	**0.53**	0.56	[5.1, 5.9]		**n/a**
$\sigma(^{20}\mathrm{Ne}+\mathrm{H}\to{}^{10}\mathrm{B})$	0.49	**0.51**	0.52	[6.4, 7.1]		
$\sigma(^{28}\mathrm{Si}+\mathrm{H}\to{}^{11}\mathrm{C})$	0.42	**0.44**	0.46	[4.3, 5.0]		**n/a**
$\sigma(^{15}\mathrm{N}+\mathrm{H}\to{}^{11}\mathrm{C})$	0.40	**0.41**	0.43	5.3	✓	**n/a**
$\sigma(^{28}\mathrm{Si}+\mathrm{H}\to{}^{10}\mathrm{B})$	0.27	**0.39**	0.52	[2.8, 5.7]		
$\sigma(^{56}\mathrm{Fe}+\mathrm{H}\to{}^{11}\mathrm{B})$	0.03	**0.35**	0.67	[0.4, 11.0]		3.3
$\sigma(^{15}\mathrm{N}+\mathrm{He}\to{}^{11}\mathrm{B})$	0.29	**0.29**	0.30	34.1		1.2
$\sigma(^{22}\mathrm{Ne}+\mathrm{H}\to{}^{11}\mathrm{B})$	0.27	**0.28**	0.30	[16.0, 18.0]	✓	1.2
$\sigma(^{13}\mathrm{C}+\mathrm{H}\to{}^{10}\mathrm{Be})$	0.24	**0.25**	0.26	5.9	✓	
$\sigma(^{12}\mathrm{C}+\mathrm{He}\to{}^{10}\mathrm{C})$	0.24	**0.25**	0.25	3.7		**n/a**
$\sigma(^{56}\mathrm{Fe}+\mathrm{H}\to{}^{10}\mathrm{B})$	0.01	**0.24**	0.47	[0.2, 7.8]		1.1
$\sigma(^{12}\mathrm{C}+\mathrm{He}\to{}^{10}\mathrm{Be})$	0.22	**0.23**	0.24	5.6		

N.B.: ranking robust against transport/source parameters

5. Ranking XS: error propagation

(projectile + target) to measure with high priority



→ Ordering insensitive on error assumption
→ Calculated for Li, Be, B, N, and C

New measurements at NA61 soon!