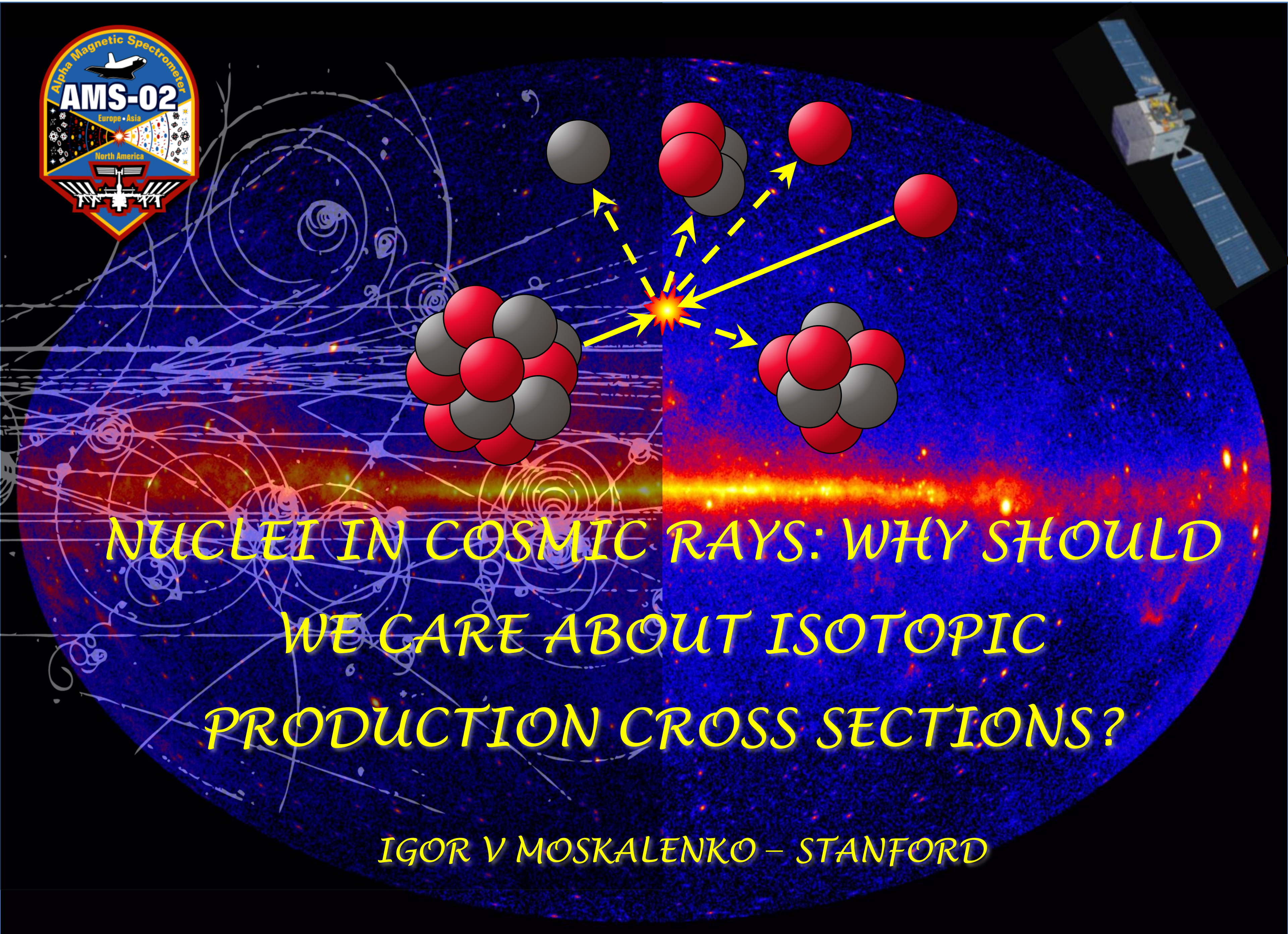
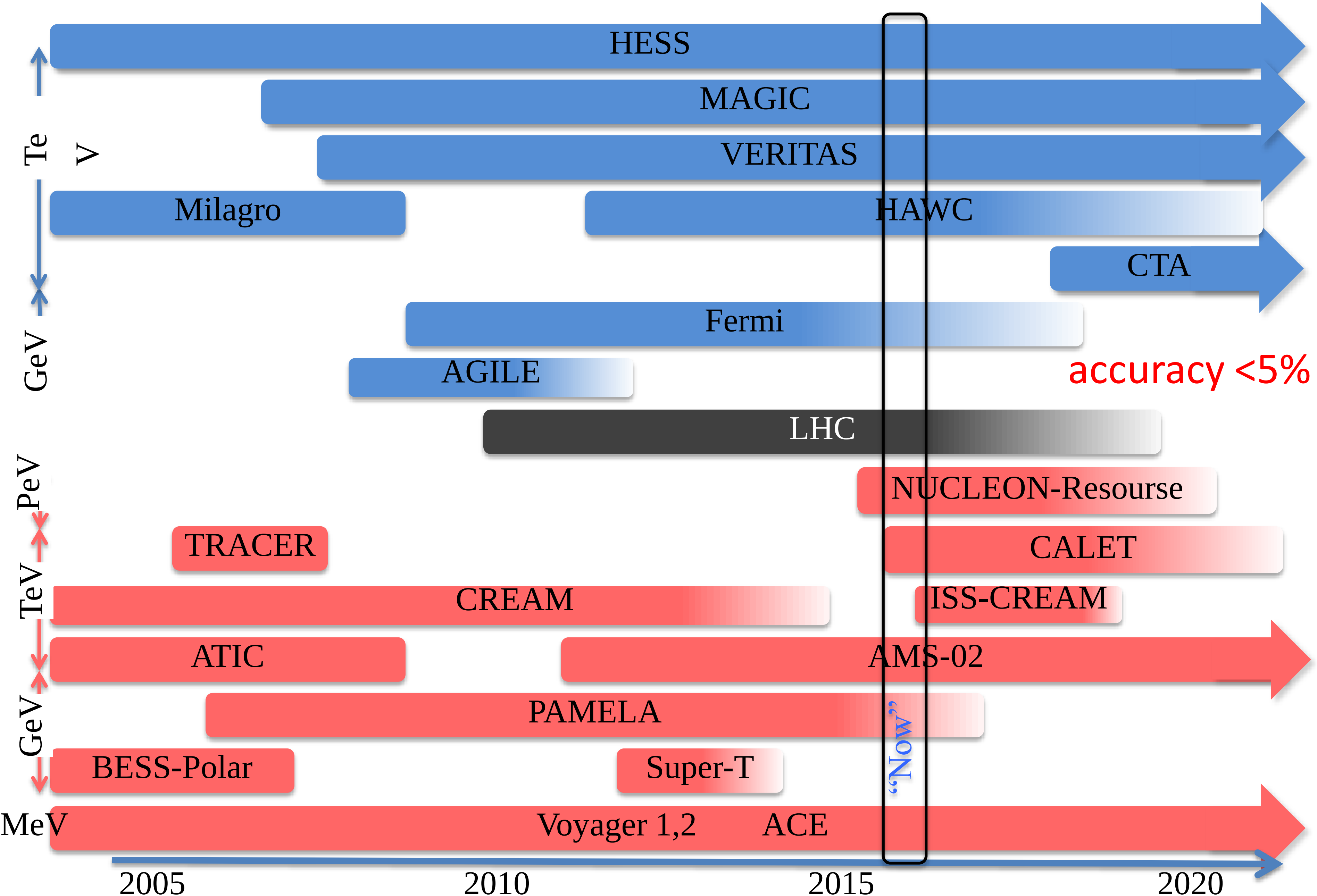


NUCLEI IN COSMIC RAYS: WHY SHOULD WE CARE ABOUT ISOTOPIC PRODUCTION CROSS SECTIONS?

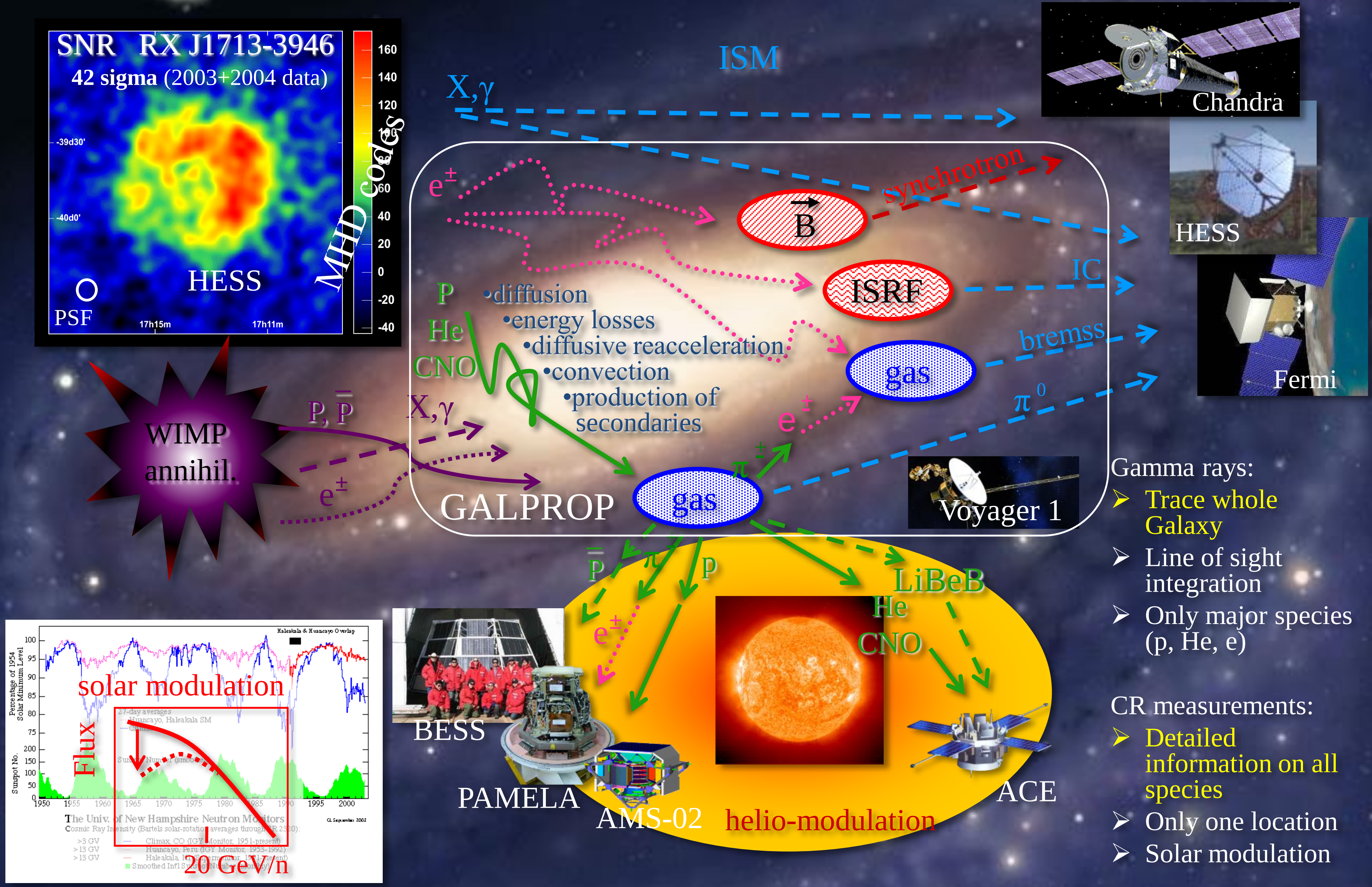
IGOR V MOSKALENKO – STANFORD

Timeline of γ-ray, CR, and particle experiments



accuracy <5%

CRs in the interstellar medium



Gamma rays:

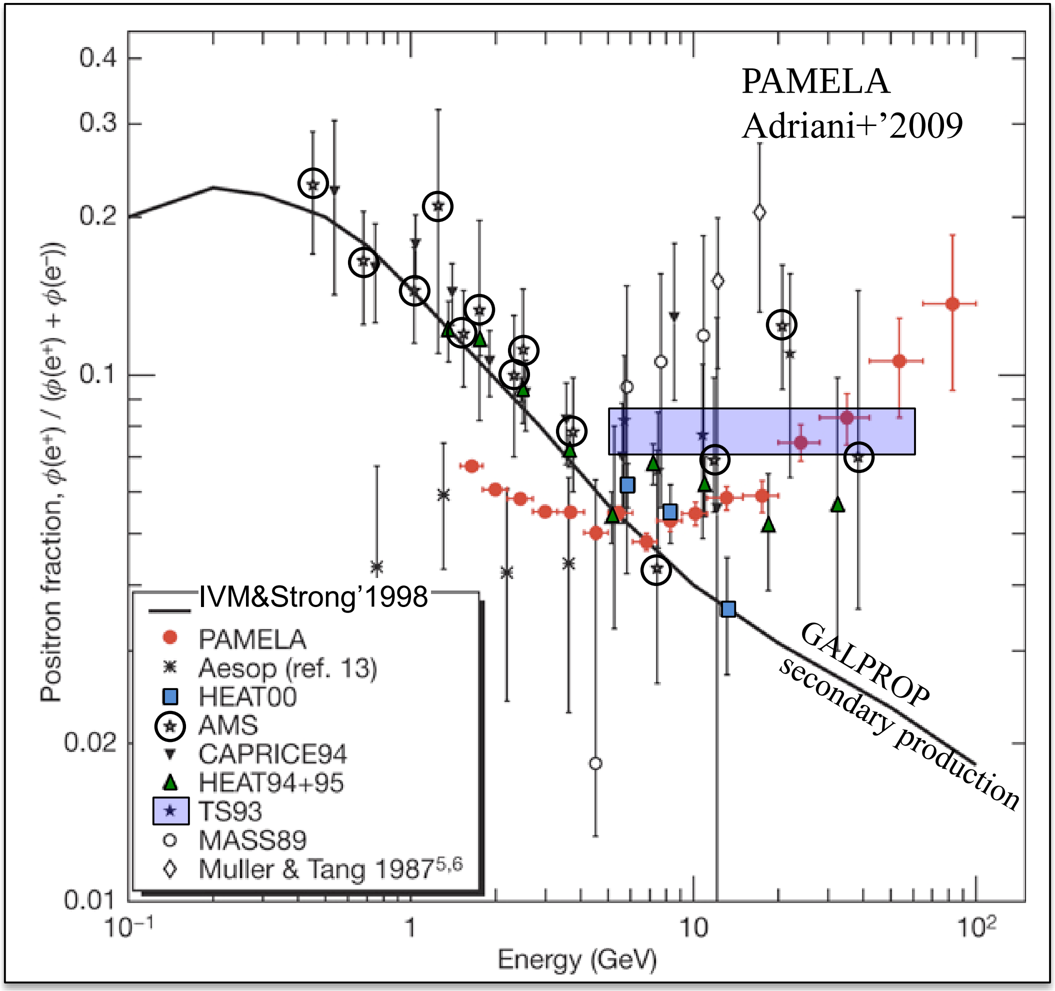
- ➢ Trace whole Galaxy
- ➢ Line of sight integration
- ➢ Only major species (p, He, e)

CR measurements:

- ➢ Detailed information on all species
- ➢ Only one location
- ➢ Solar modulation

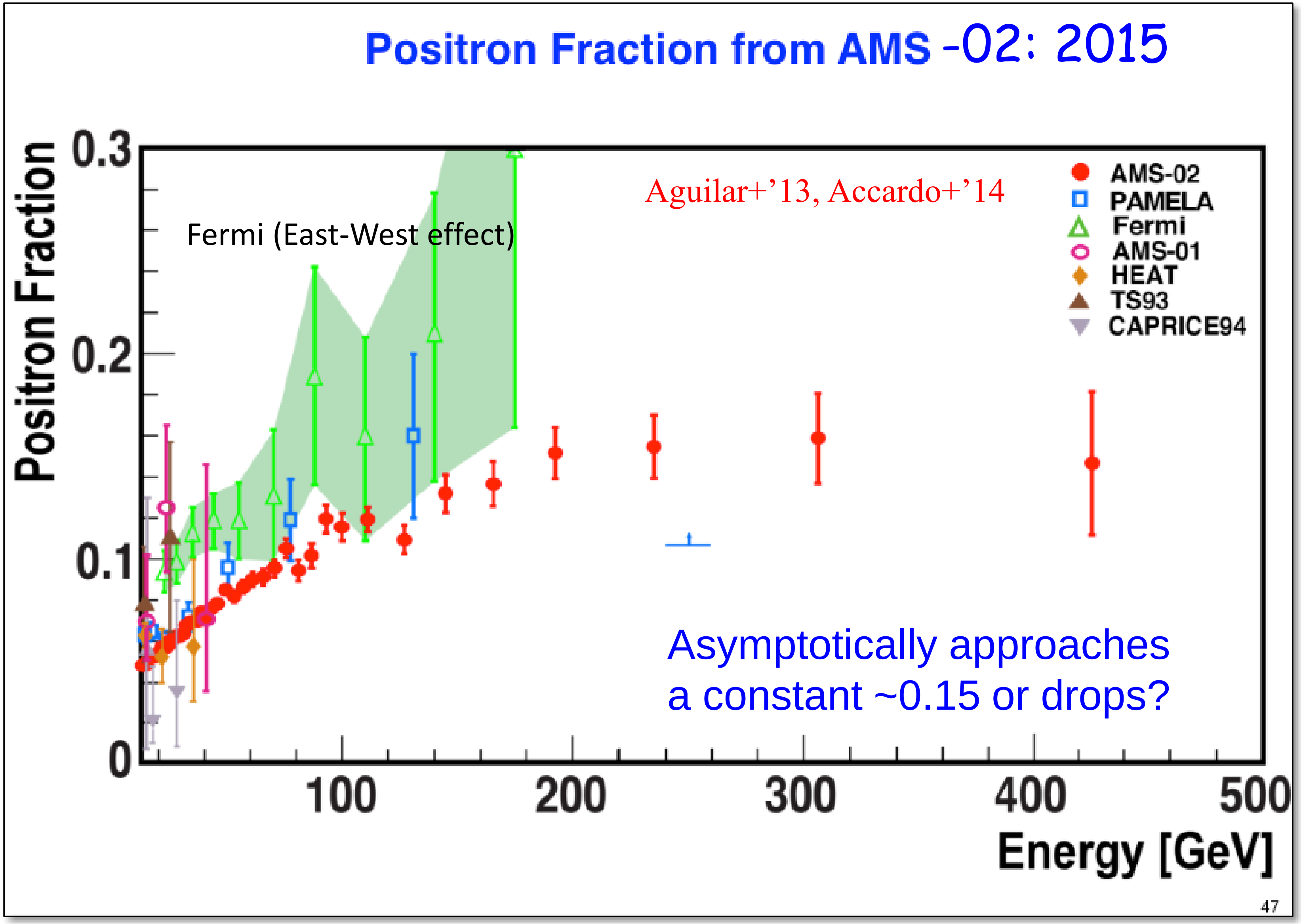
Modeling is a must!

PAMELA discovery: Rising positron fraction



- ✧ TS93 (Golden+'96): flat positron fraction 0.078±0.016 in the range 5-60 GeV
- ✧ HEAT-94,95,00 (Beatty+'04): "a small positron flux of nonstandard origin"
- ✧ PAMELA team reported a clear and very significant rise in the positron fraction compared to the "standard" model predictions
- ✧ "Standard" model:
  - ✦ Secondary production in the ISM
  - ✦ Steady state
  - ✦ Smooth CR source distribution

AMS-02: measurement of the positron fraction

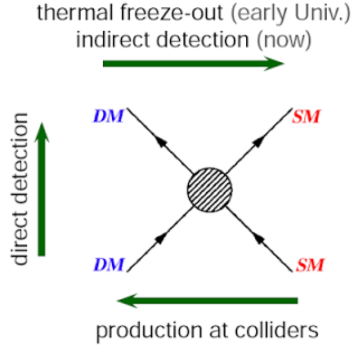


Aguilar+’13, Accardo+’14

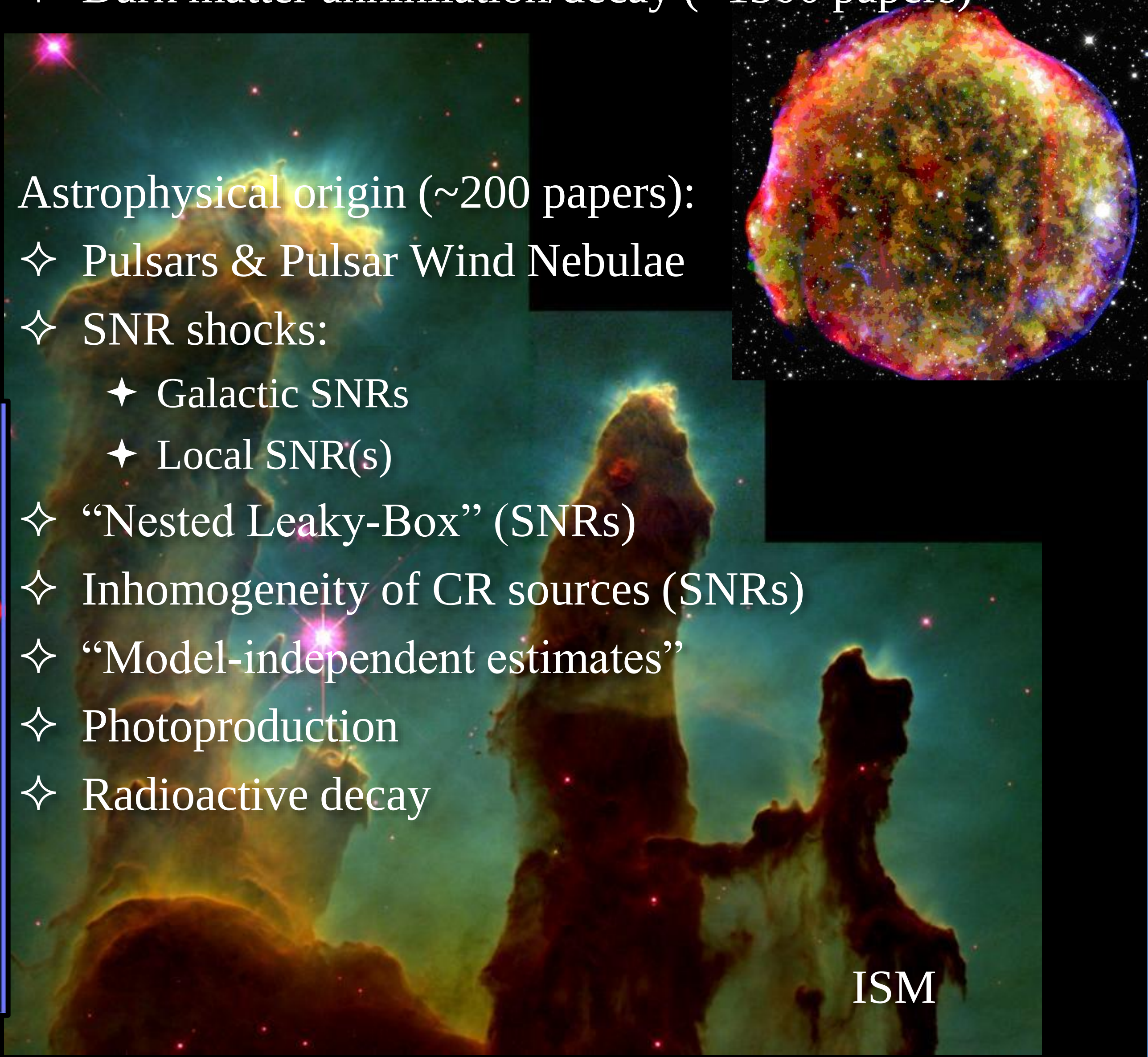
Fermi (East-West effect)

Asymptotically approaches a constant ~0.15 or drops?

Interpretations



✧ Dark matter annihilation/decay (>1300 papers)



Astrophysical origin (~200 papers):

✧ Pulsars & Pulsar Wind Nebulae

✧ SNR shocks:

  ✦ Galactic SNRs

  ✦ Local SNR(s)

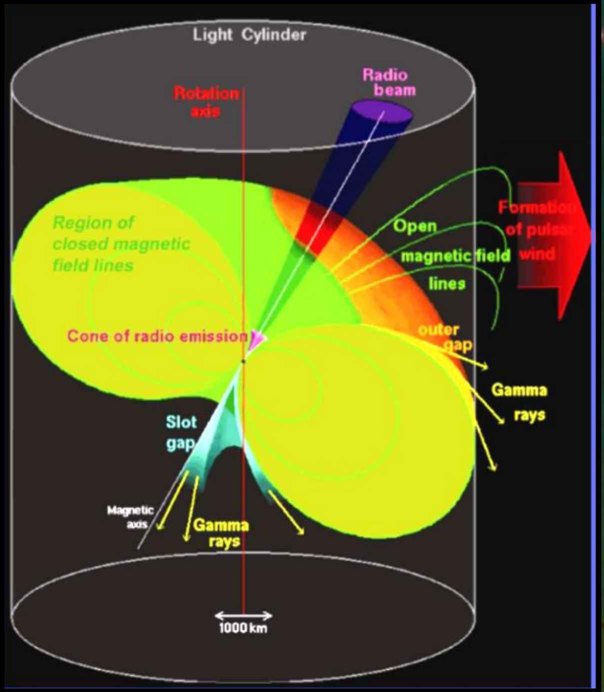
✧ “Nested Leaky-Box” (SNRs)

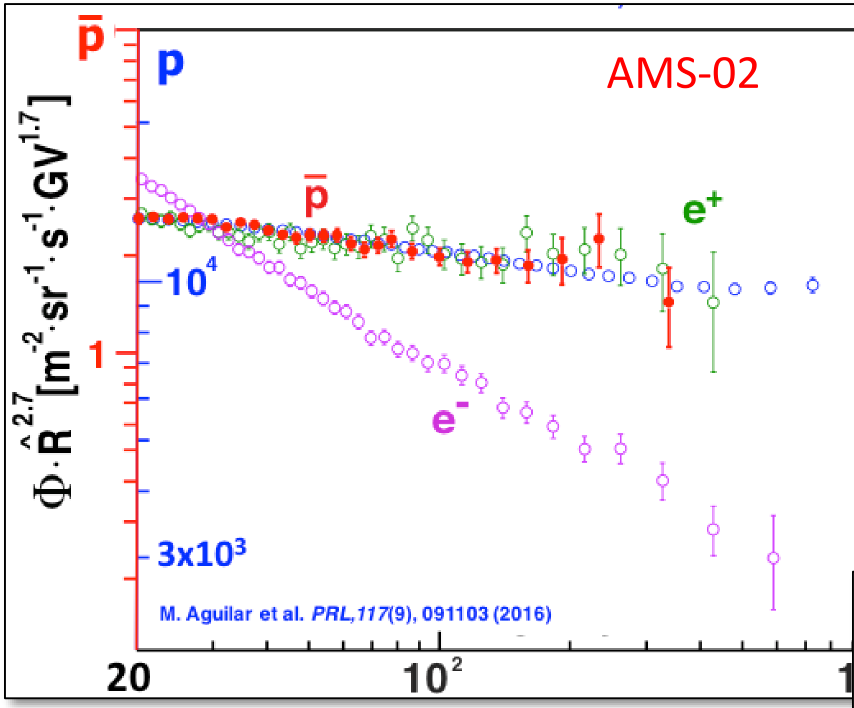
✧ Inhomogeneity of CR sources (SNRs)

✧ “Model-independent estimates”

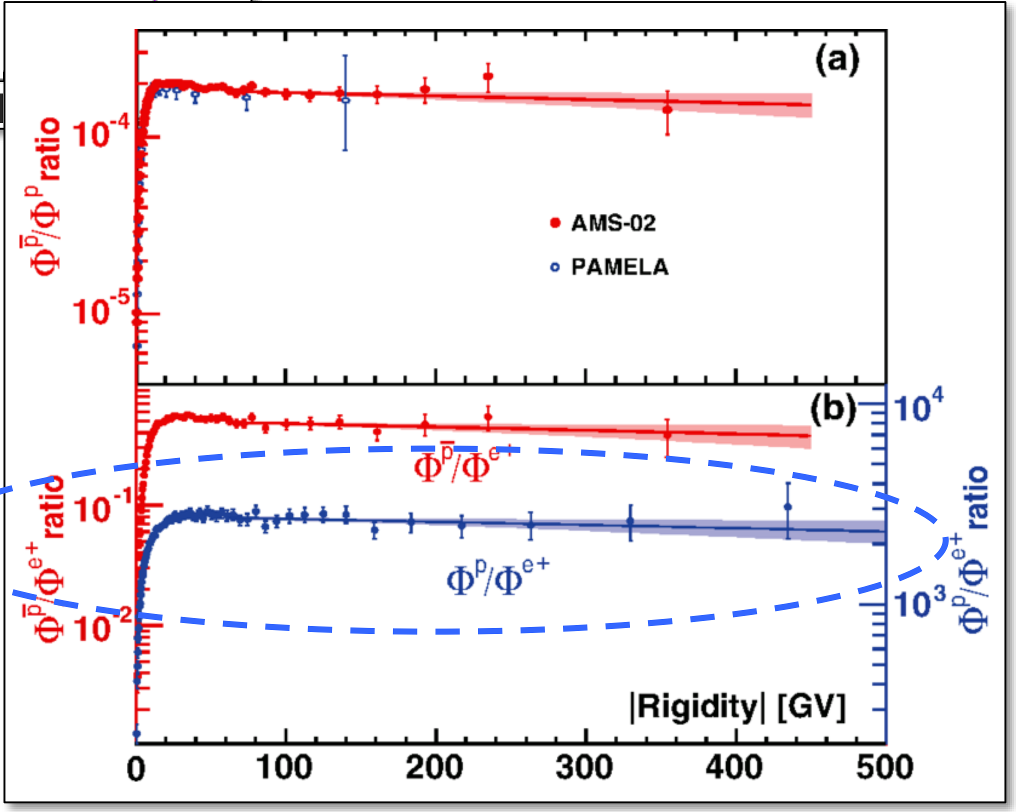
✧ Photoproduction

✧ Radioactive decay



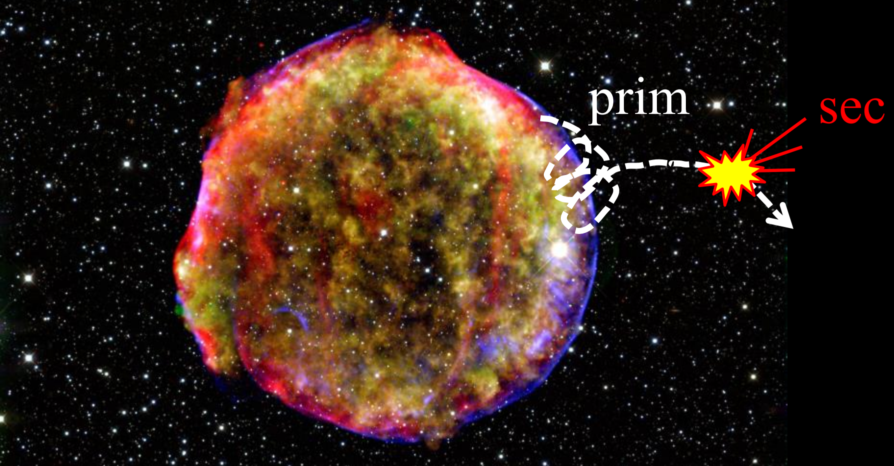


AMS-02: New measurements of CRs

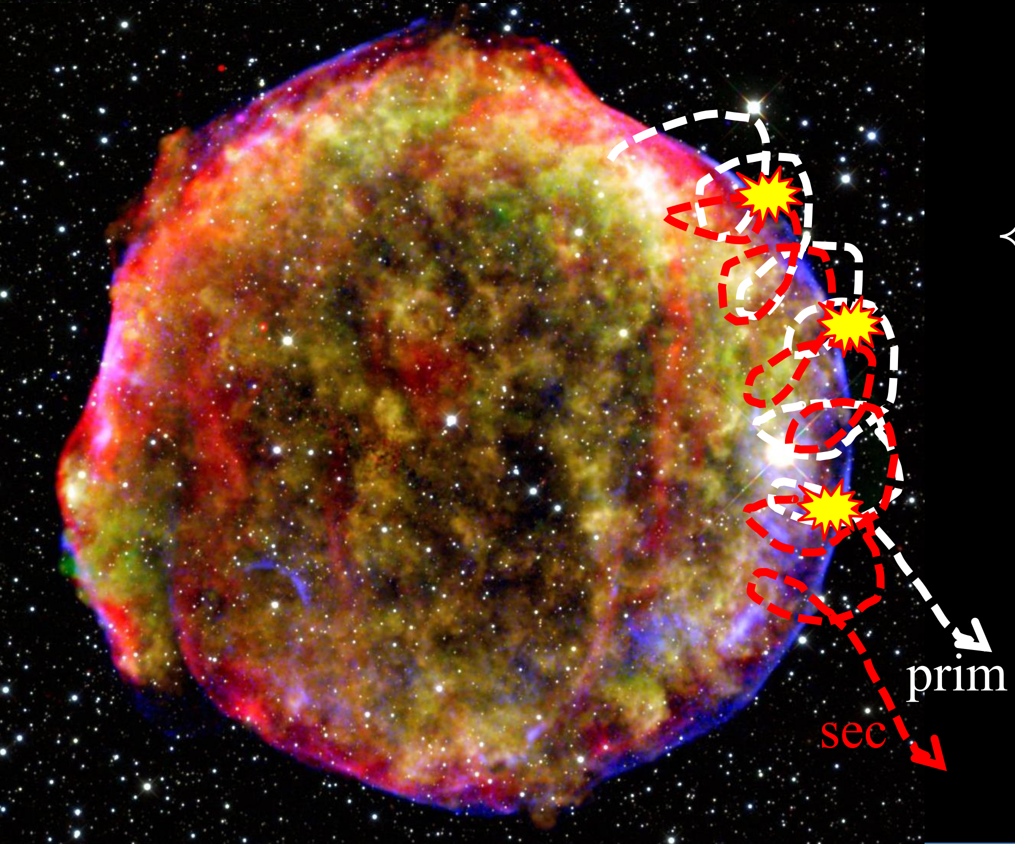


- ✧ If excess positrons are produced in pulsars or DM decays why the p/e$^+$ ratio is flat?
- ✧ Makes pulsar and DM interpretations problematic
- ✧ The flat p/e$^+$ ratio perhaps indicates a common origin of p and e$^+$!

Production of secondaries at the shock



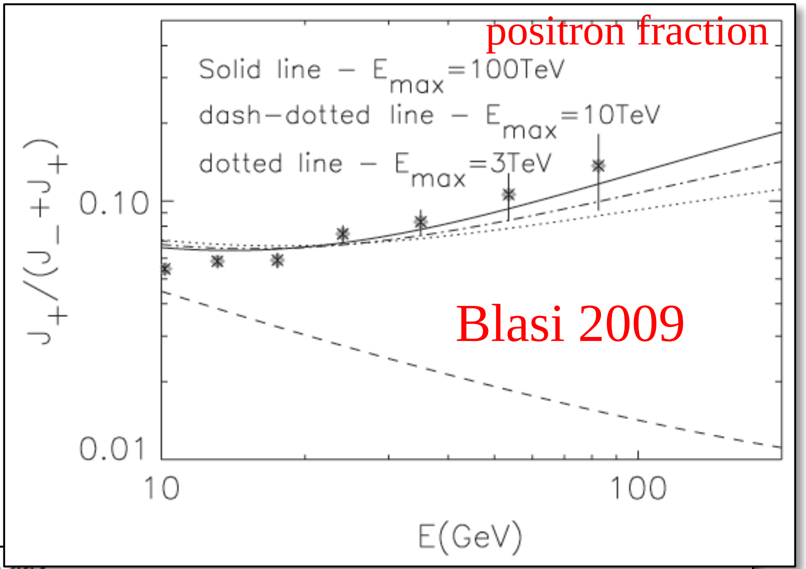
✧ In the “standard” scenario, secondary species are produced in the interstellar medium – softer spectrum at all energies

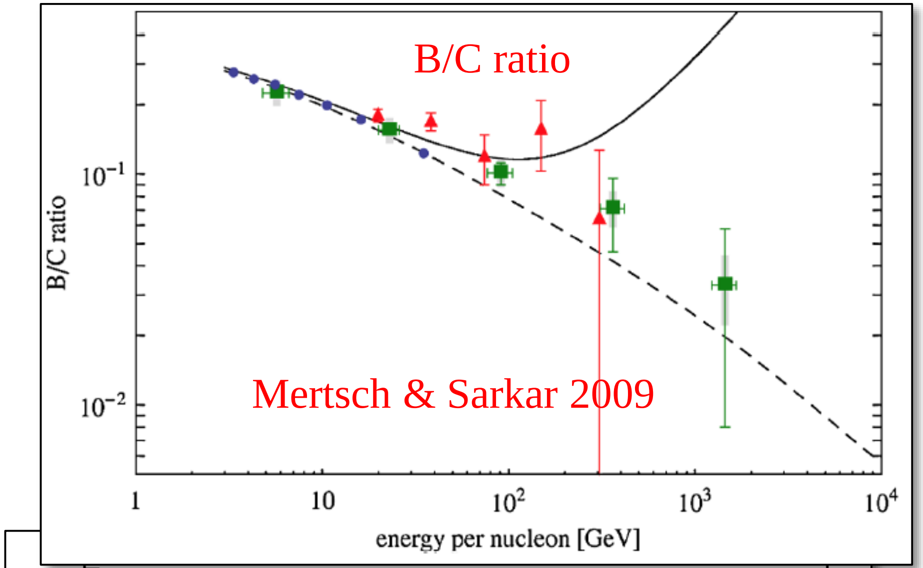


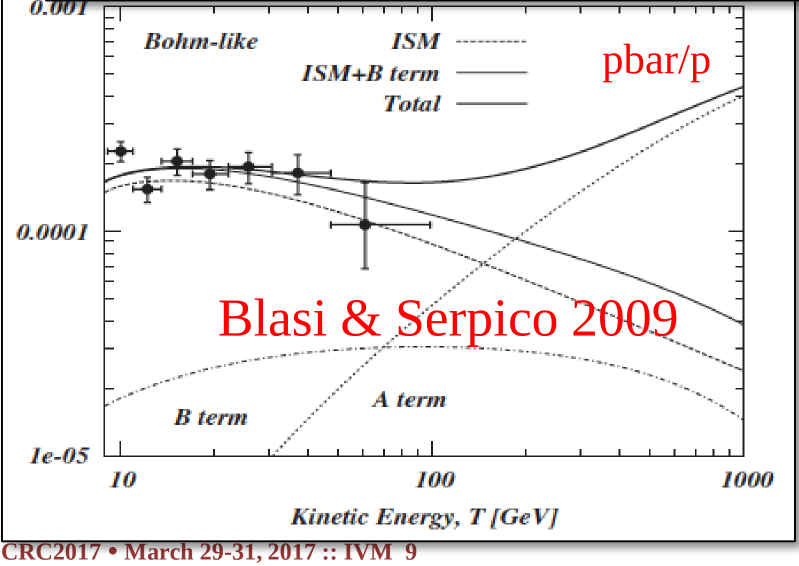
✧ In the SNR scenario, some proportion of secondary species is produced in the shock and then accelerated together with primary species – harder spectrum at high energies

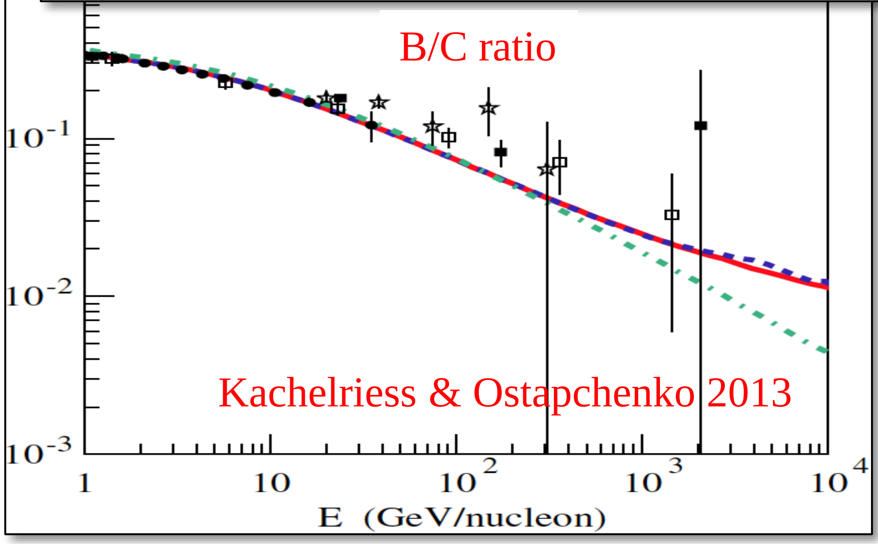
Secondary production in a SNR shock

- ✧ The model assumptions are somewhat different, but all models predict a rise in the secondary products
- ✧ The rise in pbar/p and B/C ratios become more subtle as the higher energy data become available



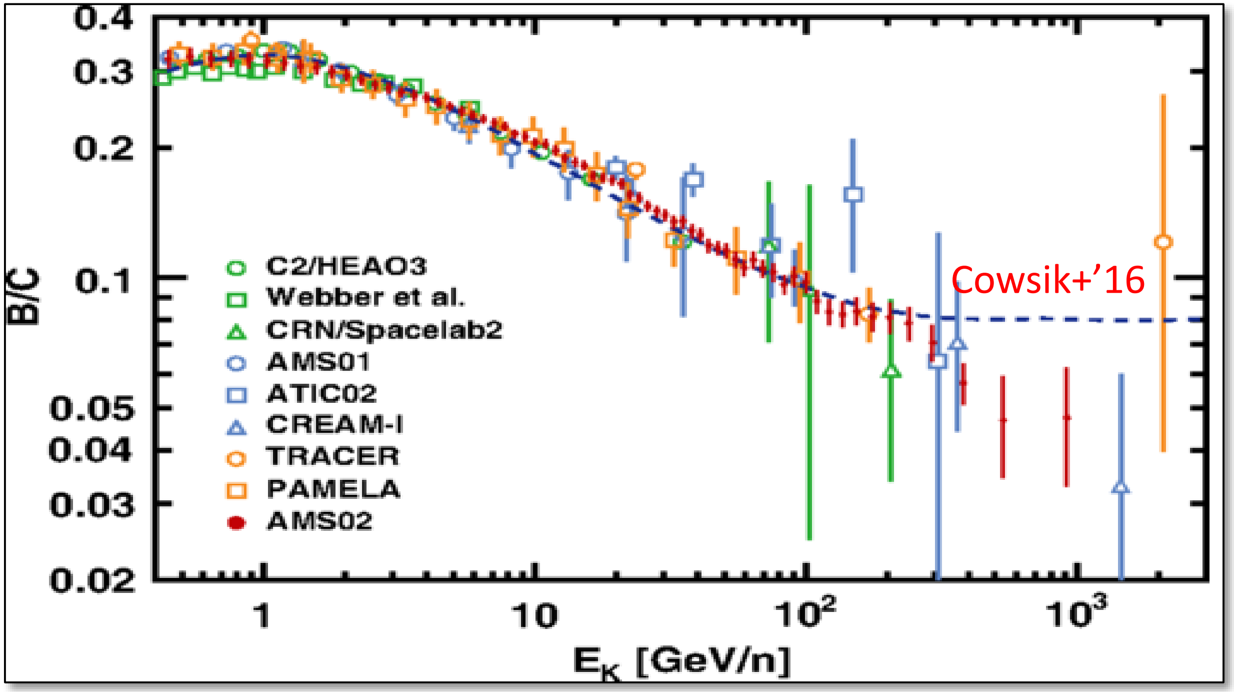


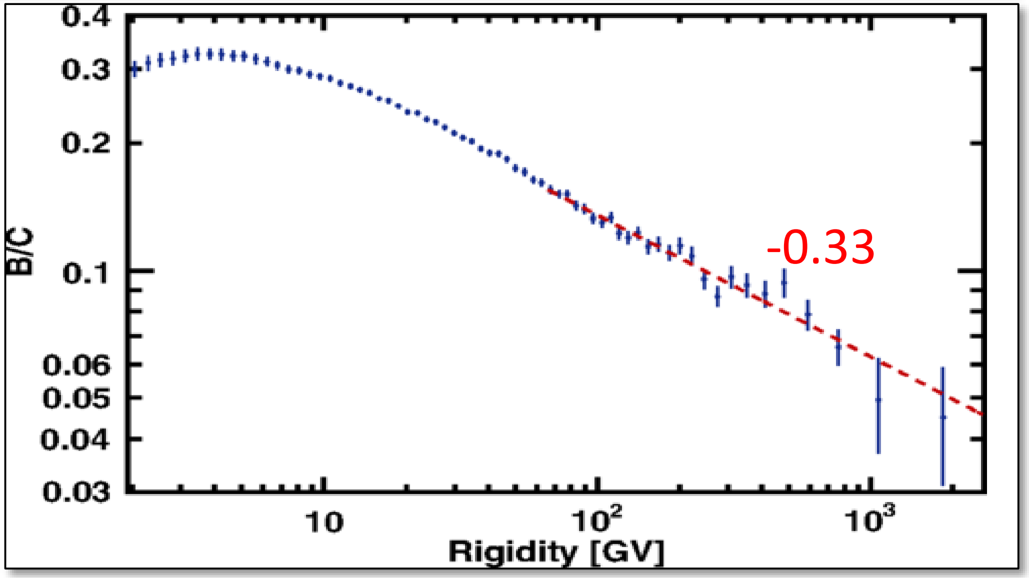




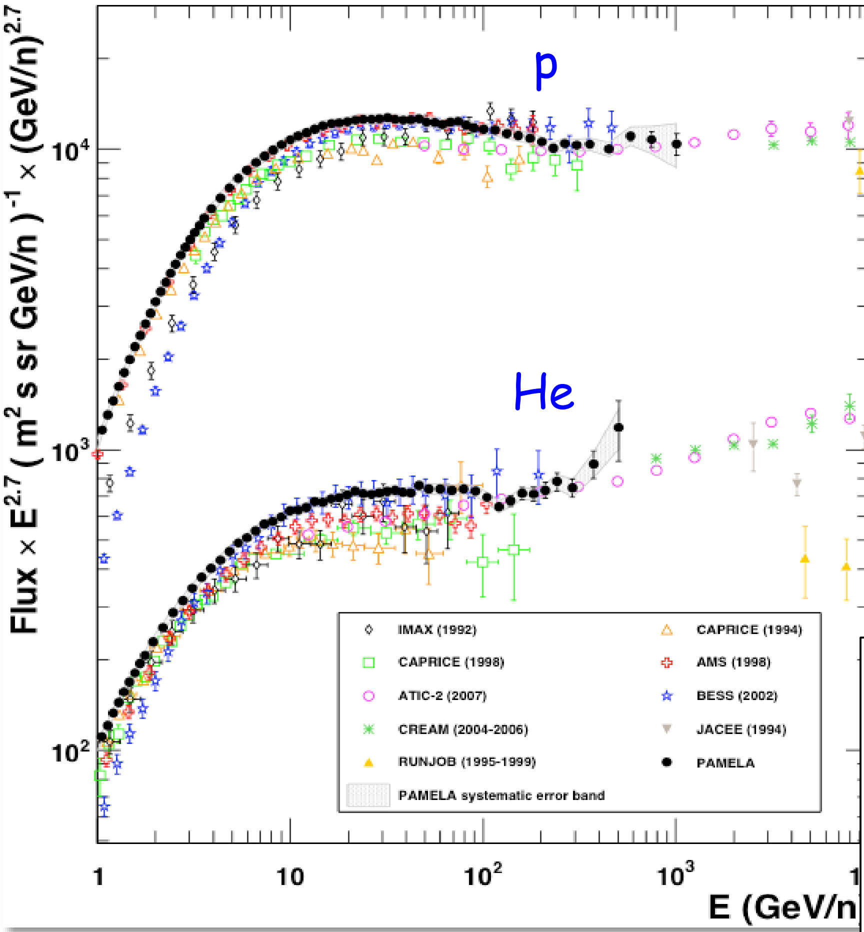
AMS-02: B/C ratio

- ✧ Contrary to expectations, the B/C ratio is monotonically falling up to 2 TV
- ✧ The “structure” is not significant
- ✧ The dashed red line is a fit that yields an index 0.3333 (classical Kolmogorov index is 1/3)

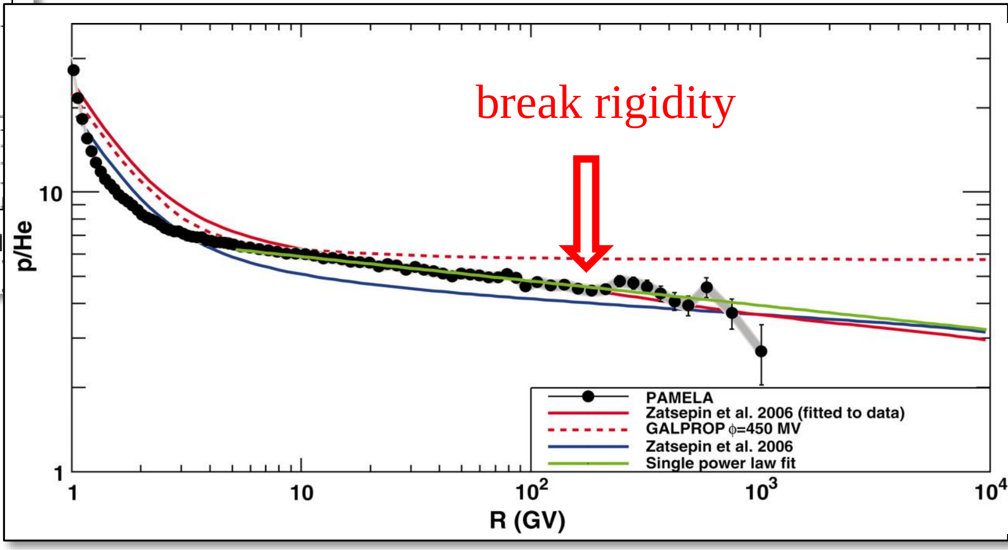




PAMELA: definitive evidence of the breaks



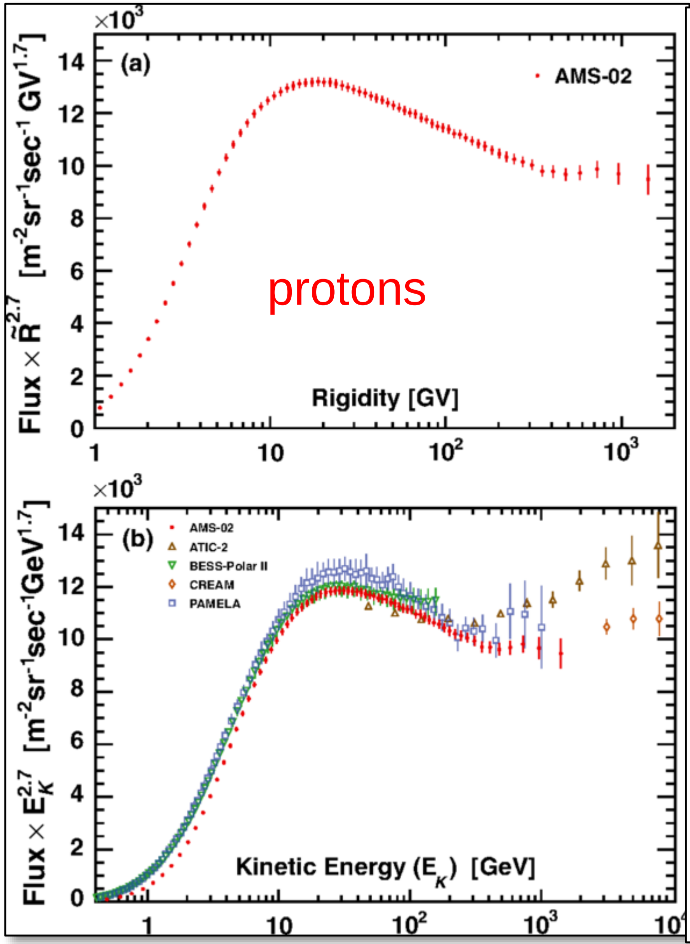
- ✧ Breaks are at the same rigidity pointing to the same origin of the breaks

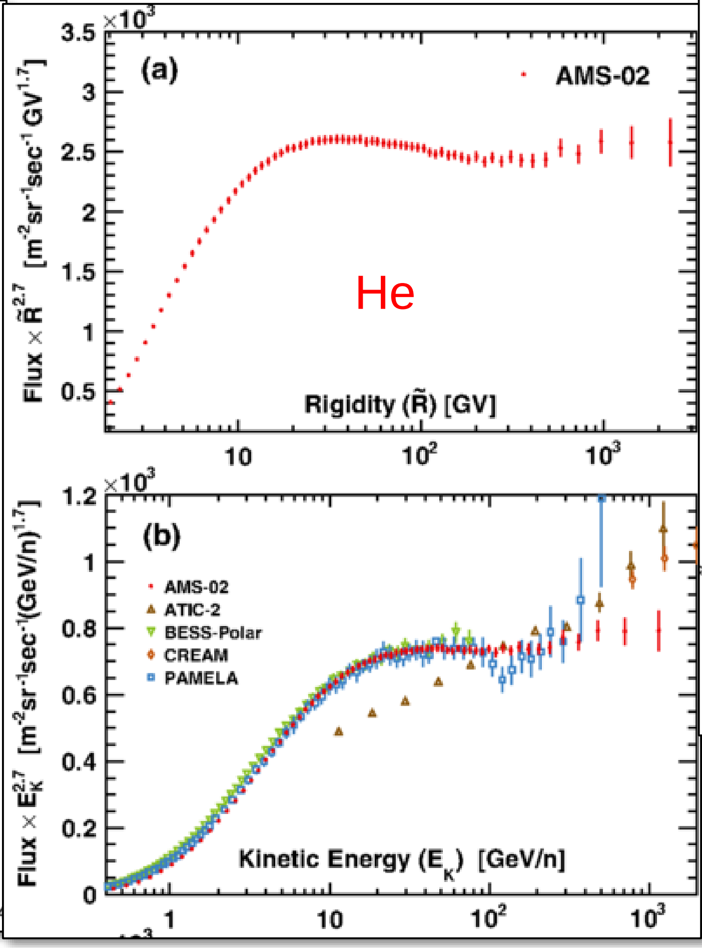


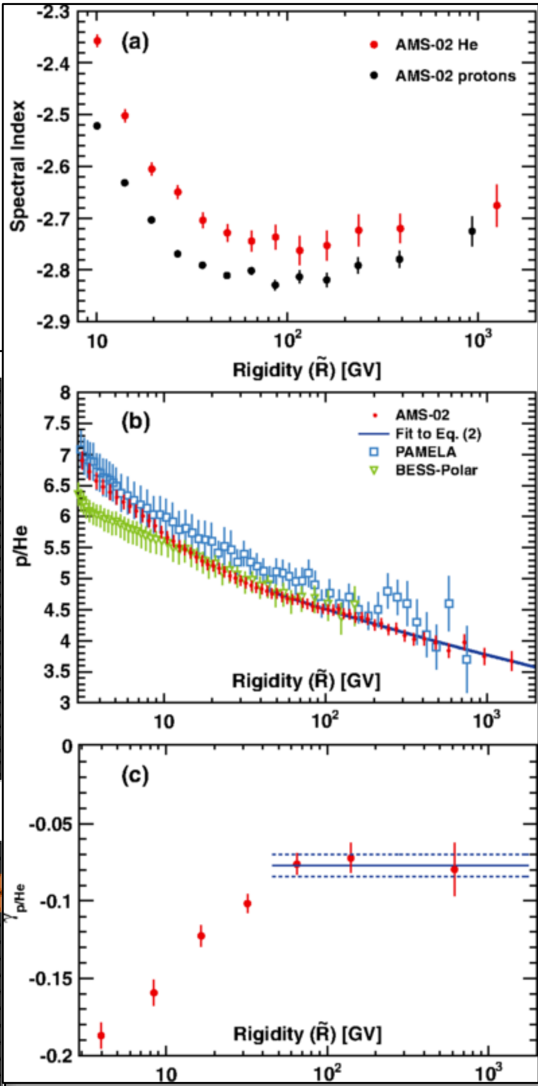
AMS-02 study of the break structure

- ✧ Breaks are smooth at the same rigidity
- ✧ p/He ratio shows no structure

- ✧ Difference in indices of p, He: Δδ ~0.1 over large energy range
- ✧ Why?

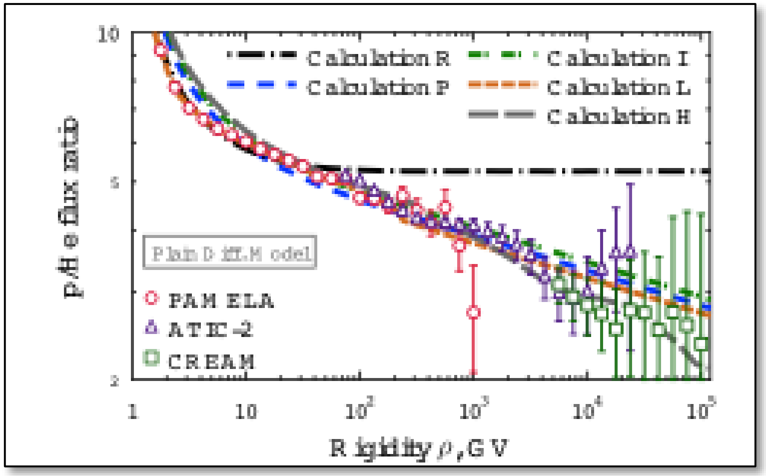


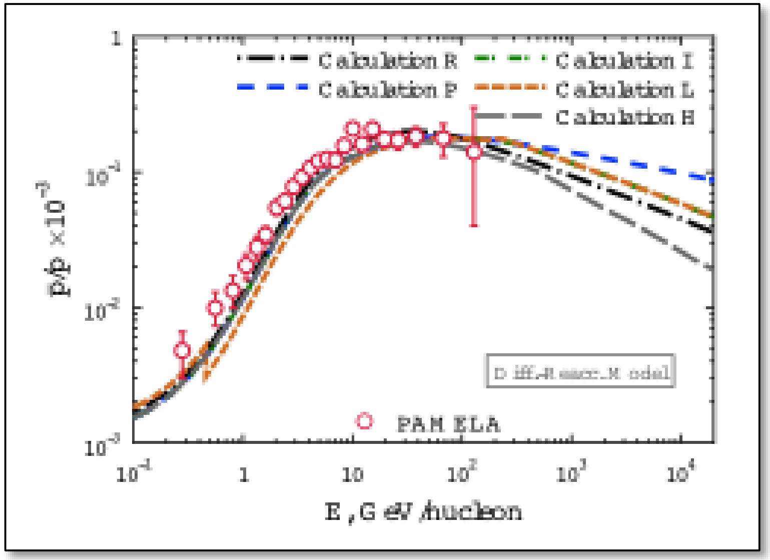


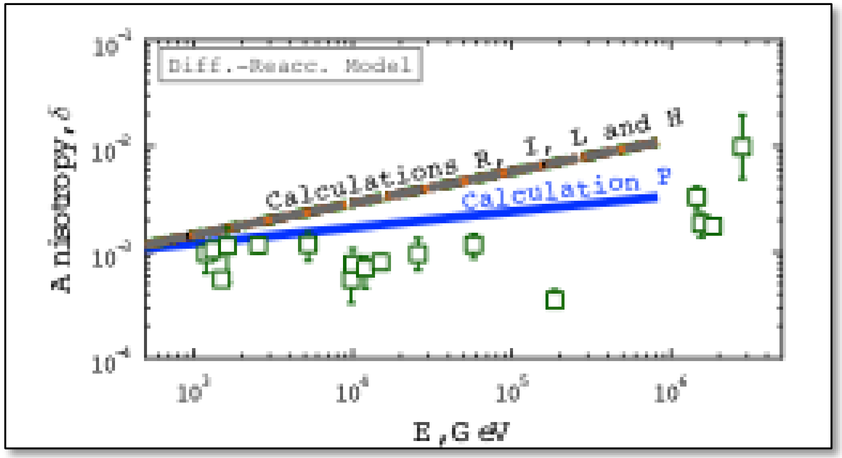


Possible interpretations

- The p/He ratio is correctly reproduced in all scenarios except the Reference scenario:
    - Propagation (P)
    - Injection (I)
    - Local source at Low Energies (L) or at High Energies (H)
- Different composition vs. Energy
- Measured pbar/p ratio is in a better agreement with propagation scenario (P)
- Only propagation scenario (P) is in an agreement with anisotropy data



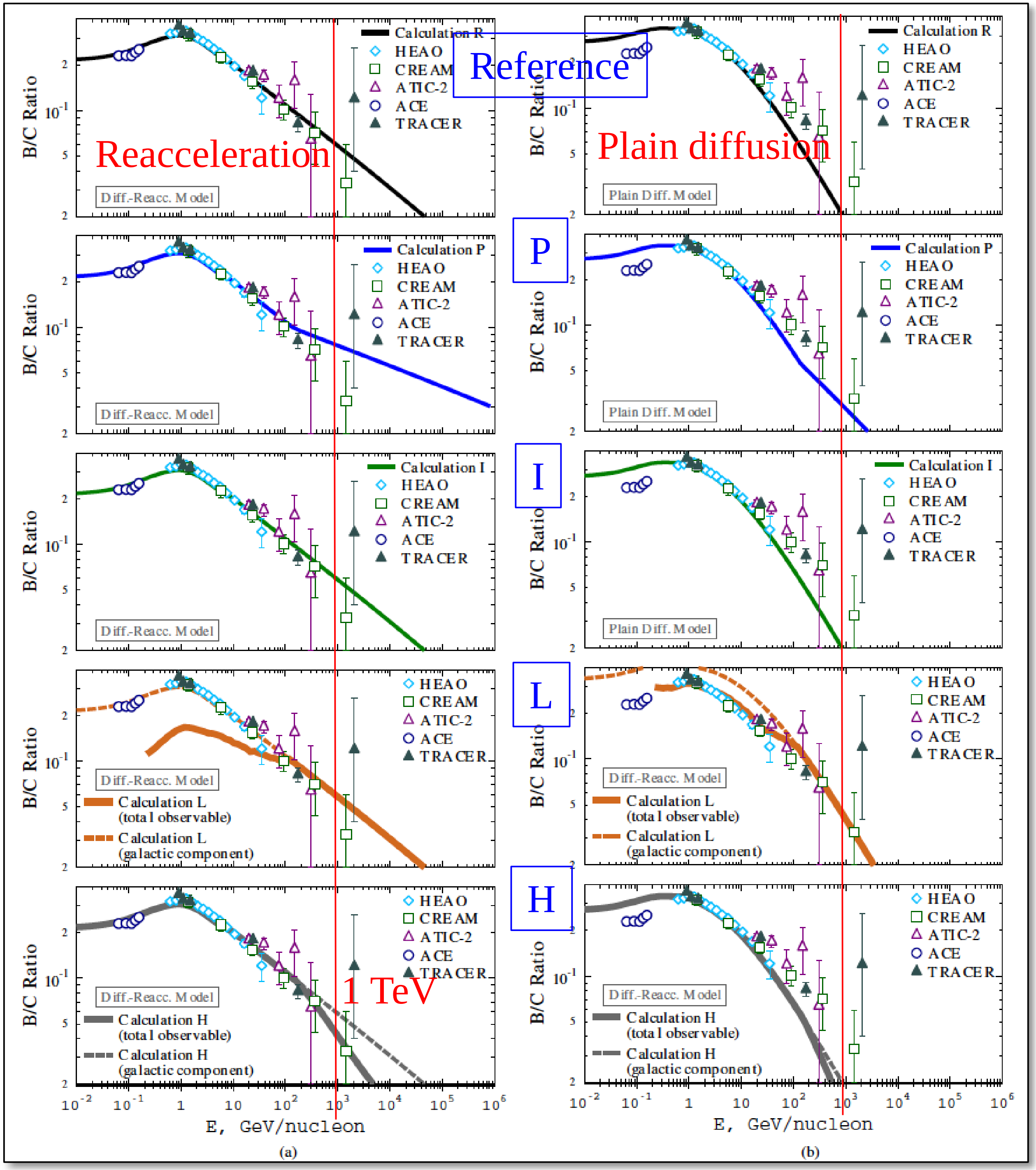




GALPROP:
Vladimirov+’2012, ApJ 752, 68

B/C ratio

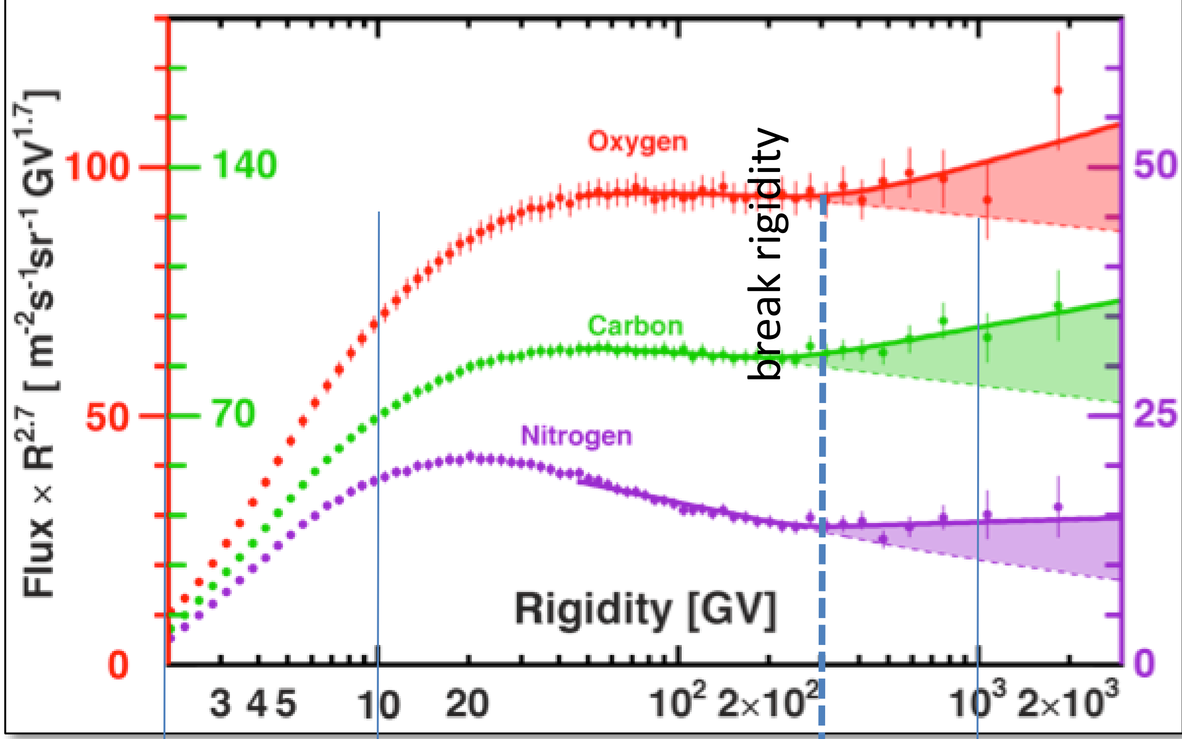
- ✧ Two models: reacceleration and plain diffusion
- ✧ Scenario (P) predicts a break in the B/C ration at ~150 GeV/n (~300 GV)
- ✧ The plots are using PAMELA data; AMS-02 point to less sharp break

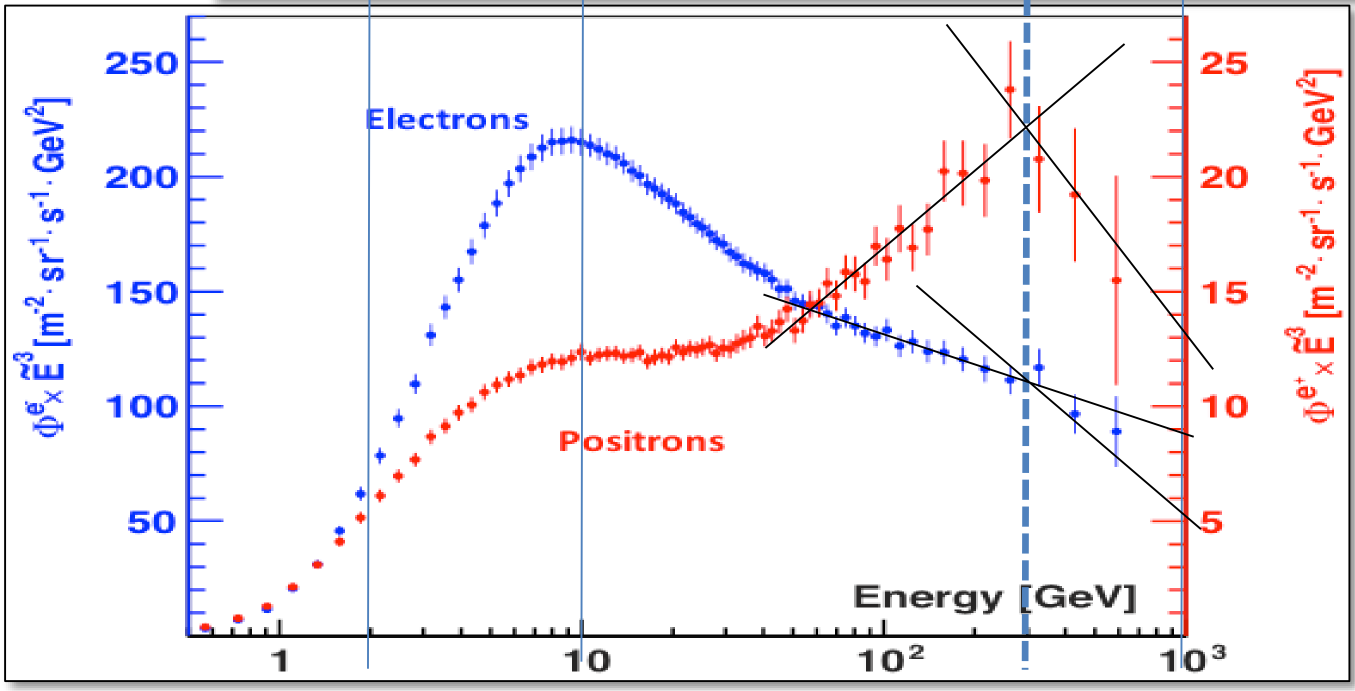


GALPROP:
Vladimirov+'2012, ApJ 752, 68

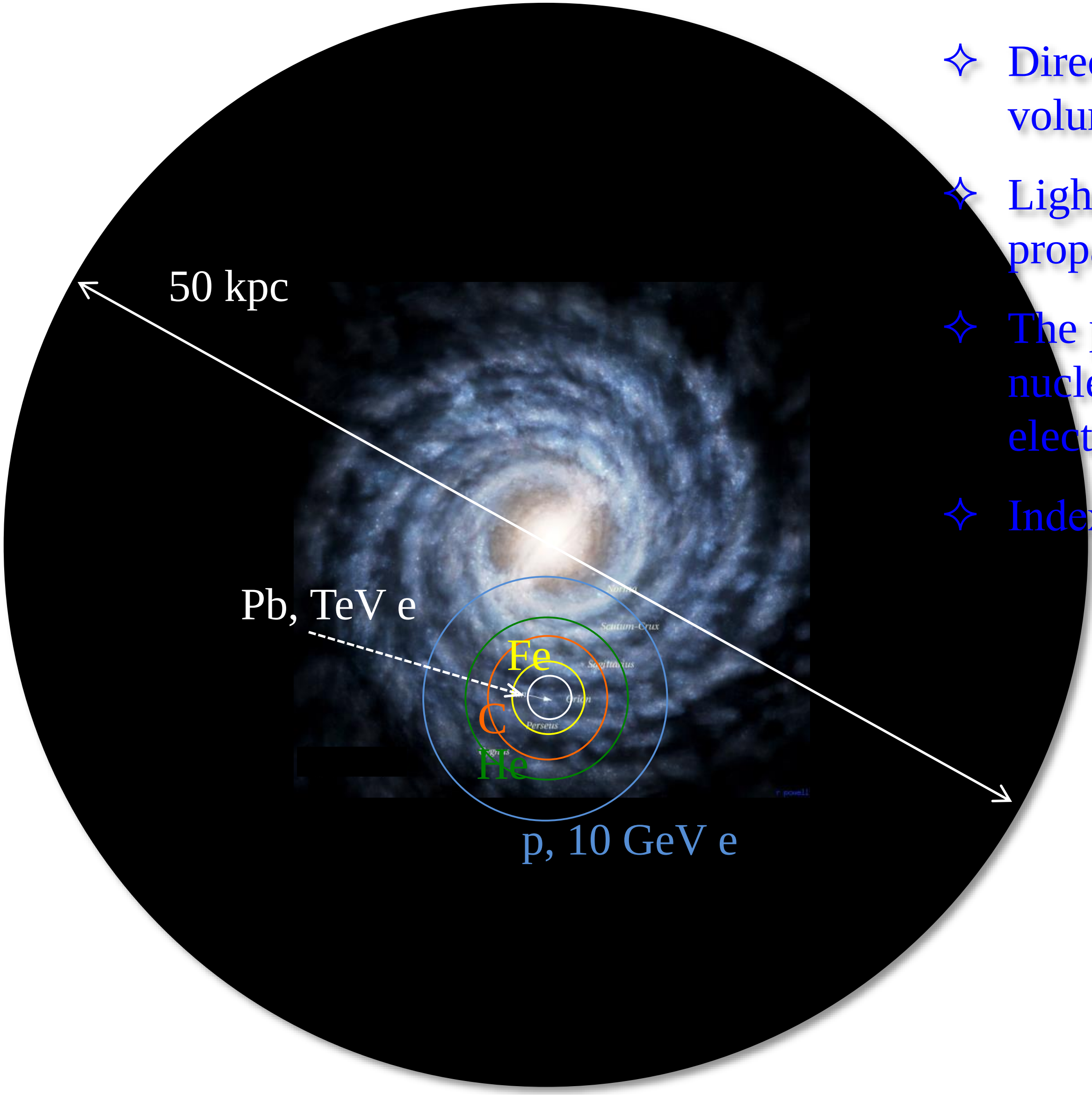
More on breaks

- ✧ The breaks are at the same rigidity – indicates that the same (unknown) mechanism works for p, He, and heavier elements
- ✧ What’s about electrons and/or positrons?
- ✧ The breaks are rather opposite – spectral steepening (I am not saying that they are significant)
- ✧ Why?





Direct probes of CR propagation



- Direct measurements probe a very small volume of the Galaxy
- Light & heavy nuclei probe different propagation volume
- The propagation distances are shown for nuclei for rigidity ~1 GV, and for electrons ~1 TeV
- Index of the diffusion coefficient $\delta \sim 0.33$

Effective propagation distance:

$\langle X \rangle \sim \sqrt{6D\tau} \sim 2.7\ \text{kpc}\ R^{\delta/2} (A/12)^{-1/3}$

Helium: $\sim 3.6\ \text{kpc}\ R^{\delta/2}$

Carbon: $\sim 2.7\ \text{kpc}\ R^{\delta/2}$

Iron: $\sim 1.6\ \text{kpc}\ R^{\delta/2}$

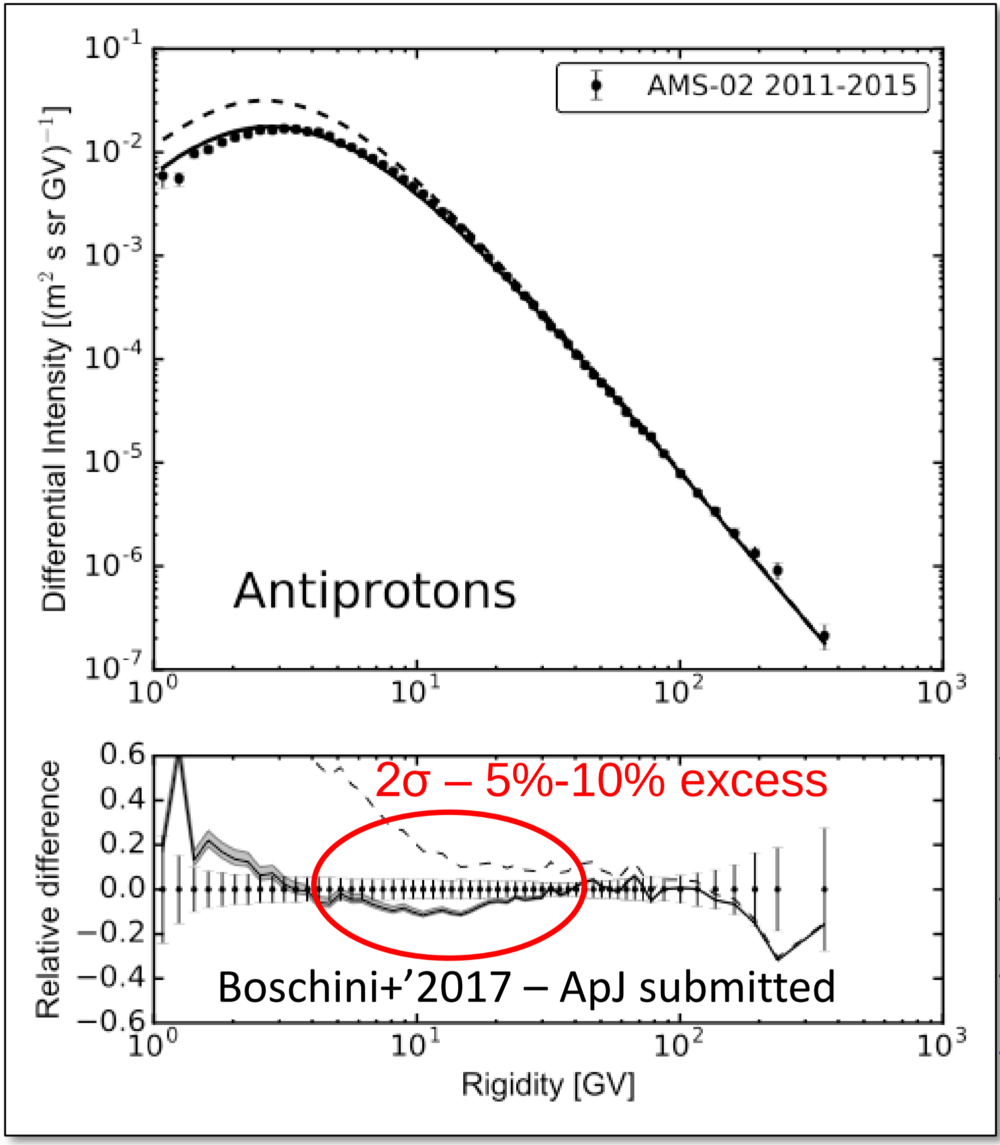
Lead: $\sim 1.0\ \text{kpc}\ R^{\delta/2}$

(anti-) protons: $\sim 5.6\ \text{kpc}\ R^{\delta/2}$

Electrons $\sim 1\ \text{kpc}\ E_{12}^{-\delta/2}$

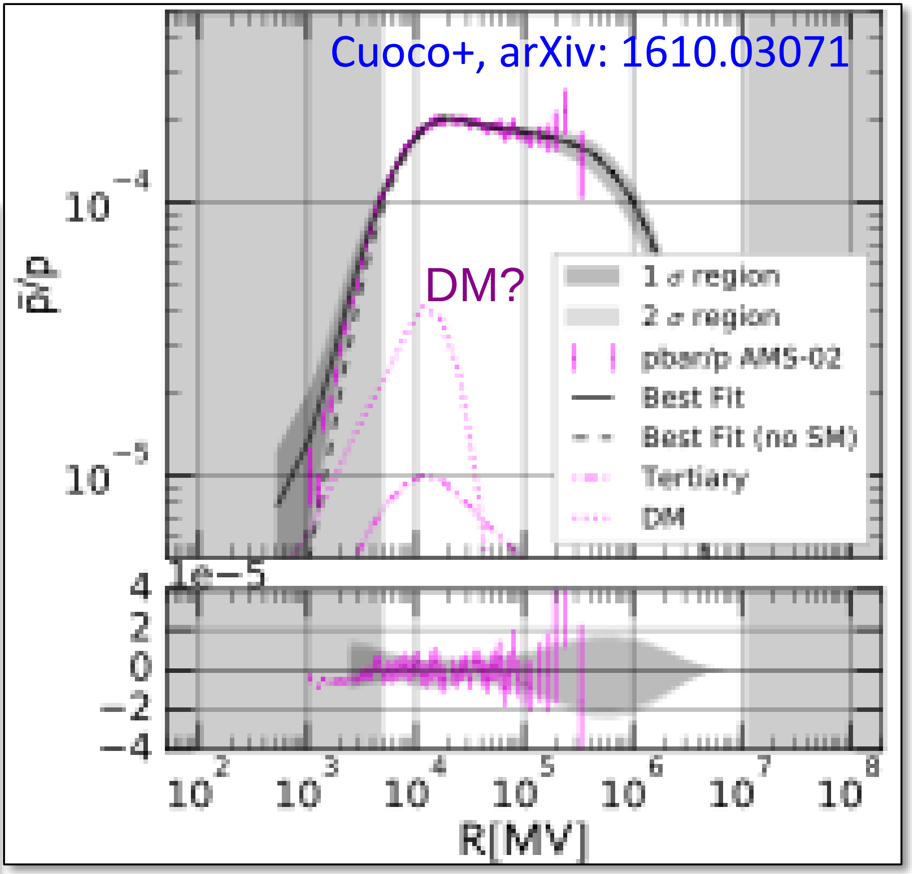
γ-rays: detailed information about *p*,*e* spectra in the whole Galaxy ~50 kpc

Excess in pbars?


Antiprotons

2σ – 5%-10% excess

Boschini+'2017 – ApJ submitted


Cuoco+, arXiv: 1610.03071

DM?

- ✧ Do we know pbar production cross section to <5% accuracy?
- ✧ Propagation/injection errors?
- ✧ Real DM signal?
- ✧ Must measure the cross sections to say for sure

Fermi-LAT: Inner Galaxy

- ✧ Cylindrically symmetrical model
- ✧ Gas distribution, its emissivity, and γ-ray emission from inverse Compton scattering are divided into 6 Galactocentric rings. Their relative normalization is determined from a fit to the Fermi-LAT data
- ✧ Point sources, isotropic emission and Loop I are tuned to the data in iterations
- ✧ Fitting starts from the outer Galaxy and the normalizations of the rings are consequently fixed
- ✧ Extracting emission from the central part of the Galaxy

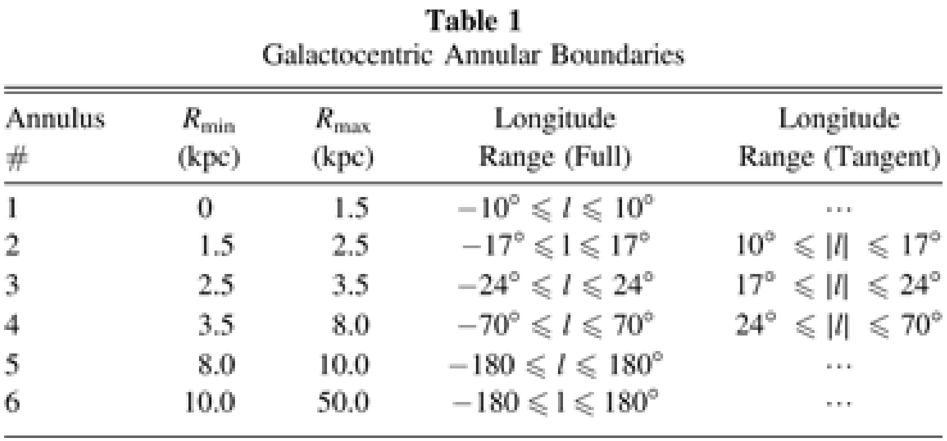
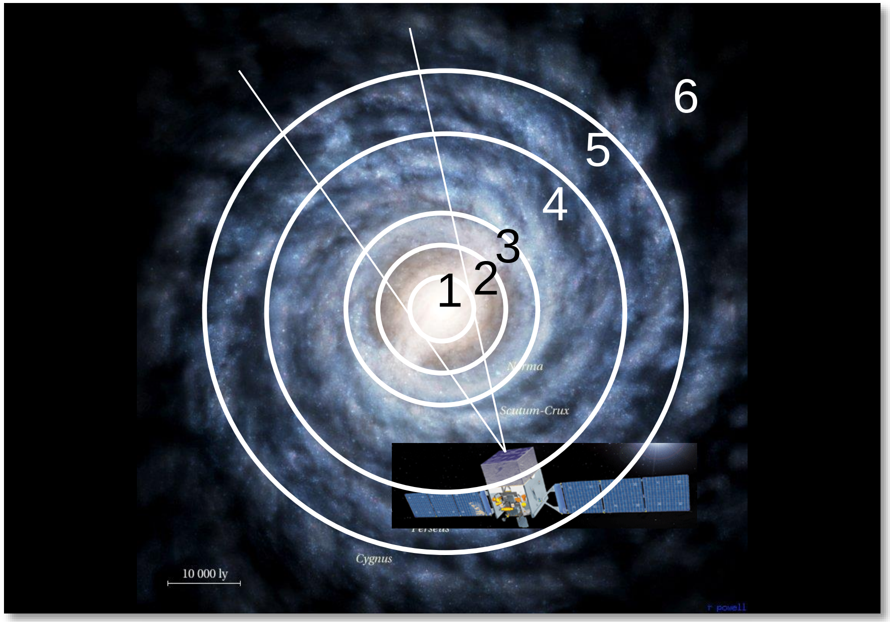


Table 1
Galactocentric Annular Boundaries

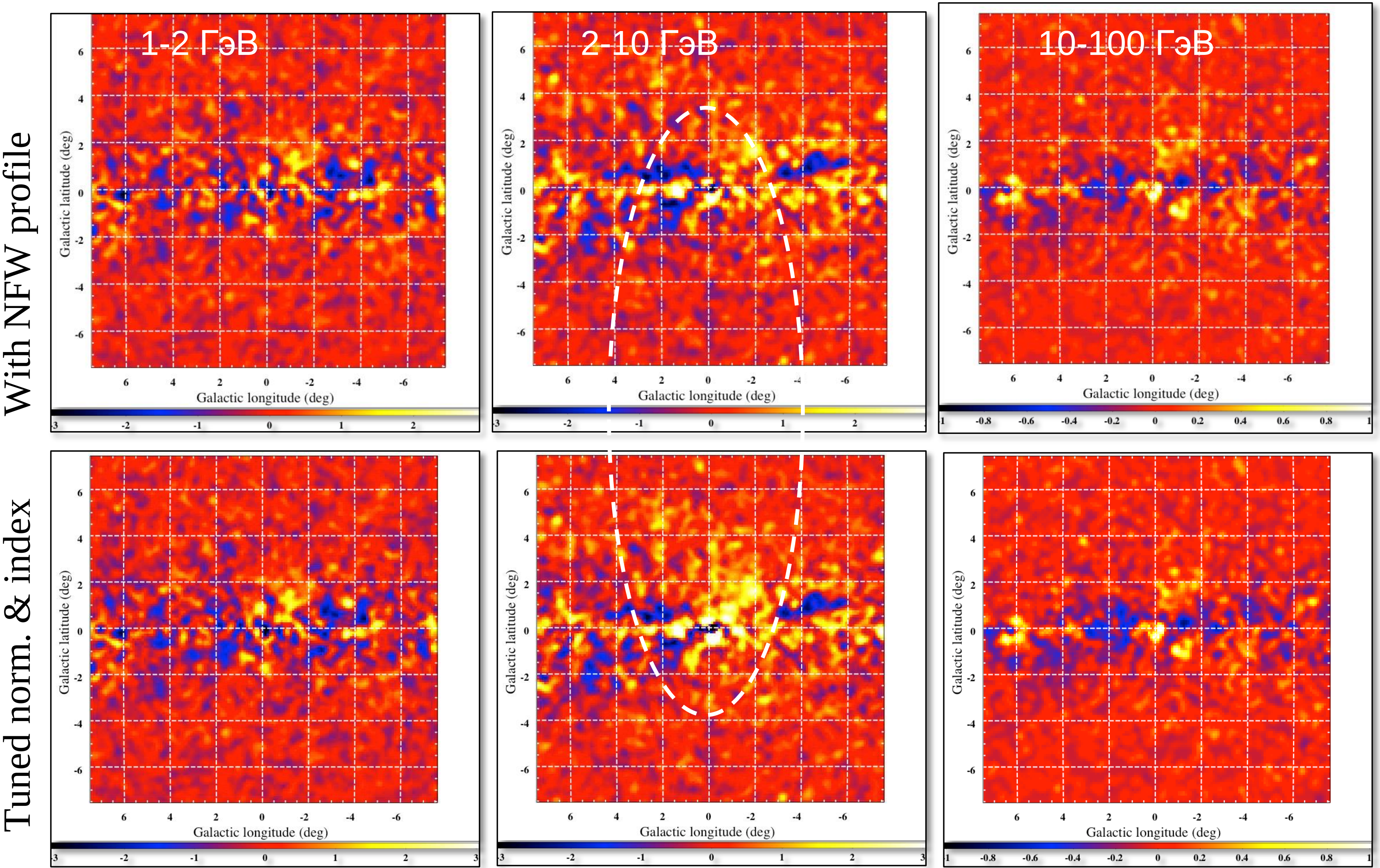
Annulus #	$R_{\rm min}$ (kpc)	$R_{\rm max}$ (kpc)	Longitude Range (Full)	Longitude Range (Tangent)
1	0	1.5	$-10° \leqslant l \leqslant 10°$	...
2	1.5	2.5	$-17° \leqslant l \leqslant 17°$	$10° \leqslant \|l\| \leqslant 17°$
3	2.5	3.5	$-24° \leqslant l \leqslant 24°$	$17° \leqslant \|l\| \leqslant 24°$
4	3.5	8.0	$-70° \leqslant l \leqslant 70°$	$24° \leqslant \|l\| \leqslant 70°$
5	8.0	10.0	$-180 \leqslant l \leqslant 180°$	...
6	10.0	50.0	$-180 \leqslant l \leqslant 180°$	...



Fermi-LAT: Ajello+’2016

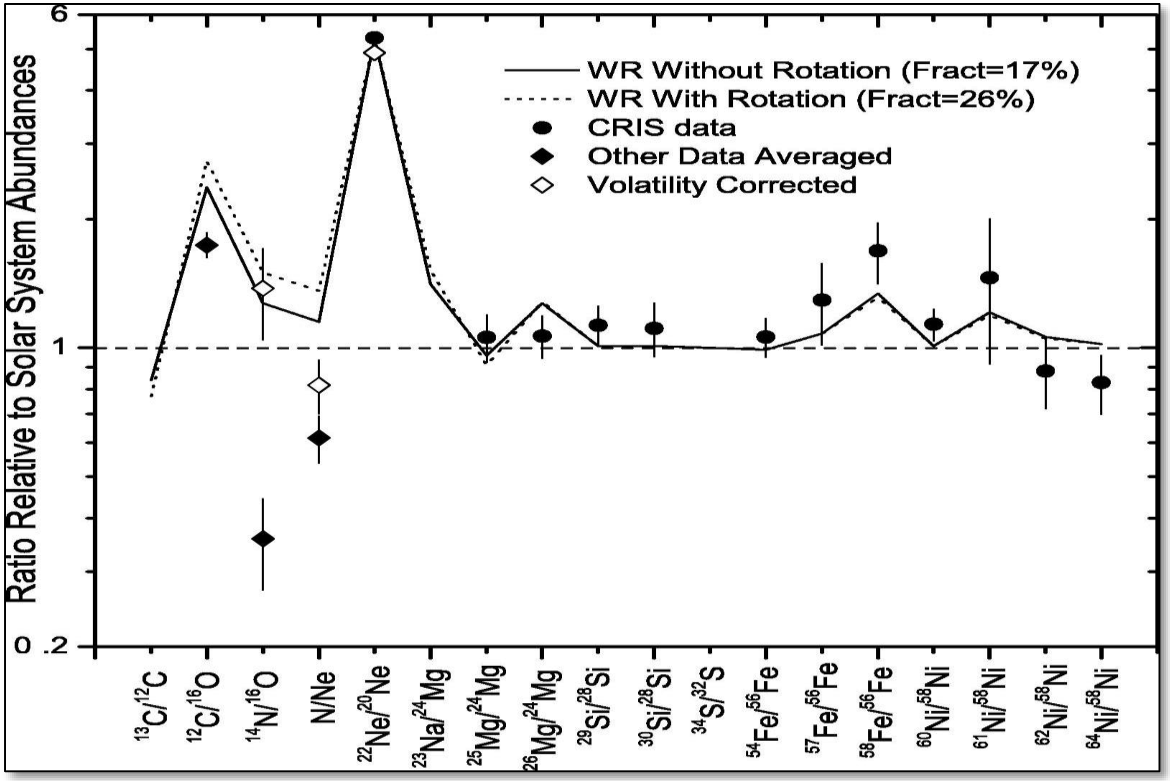
Results of the fit with the NFW profile

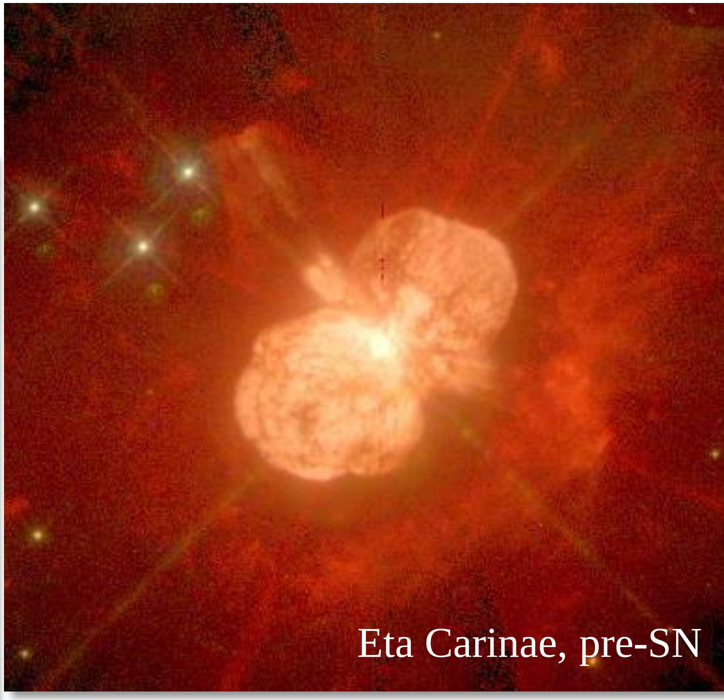
(Data-model): sources – pulsar distribution, point sources removed



Events per pixel 0.1° × 0.1°

Sources of cosmic rays



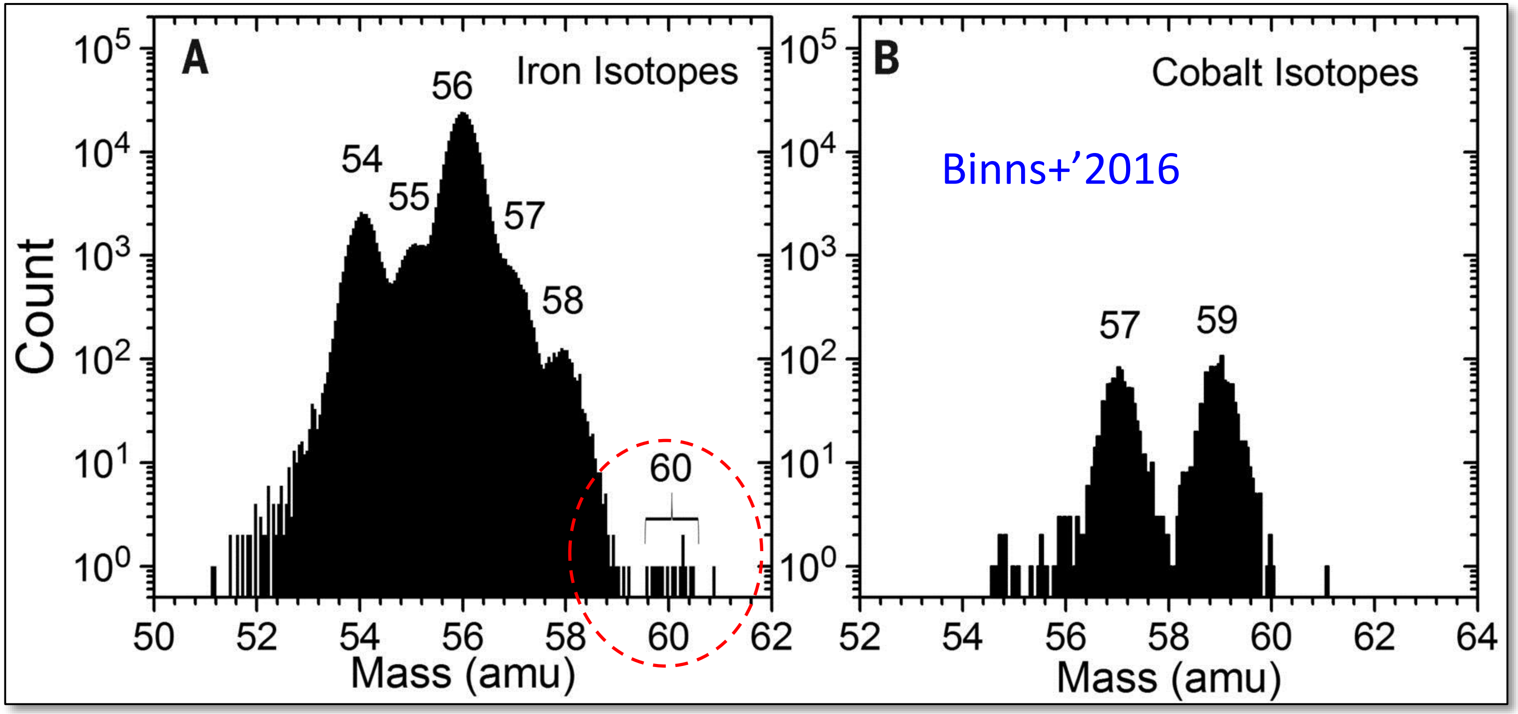


Eta Carinae, pre-SN

Tycho’s Supernova 1572

- Some isotopes in CRs have anomalous abundances
- Ne^{22}/Ne^{20} excess indicates that about ~20% of CRs are accelerated dense winds of massive stars (e.g. Wolf-Rayet)
- ACE data: ≤500 MeV/n

ACE: Primary 60Fe in cosmic rays



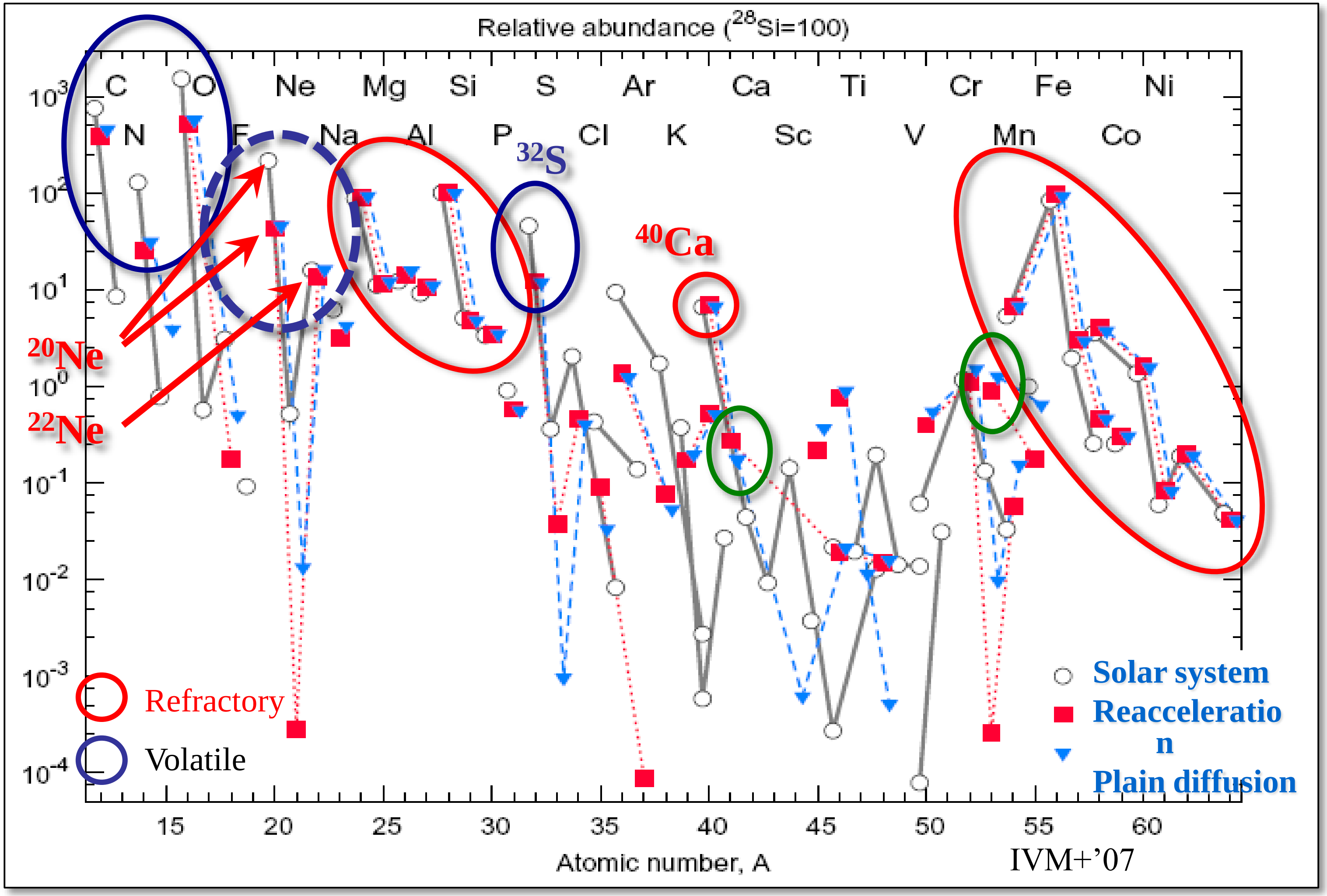
- ✧ β⁻ decay with a half-life of 2.62 Myr
- ✧ Supports a hypothesis of a "recent" SN explosion in the Solar system neighborhood

CR source isotopic abundances

- ✧ Source abundances of refractories agree with solar
- ✧ Volatiles are suppressed at the sources
- ✧ Radioactive ^{41}Ca (EC, ~0.1 Myr) and ^{53}Mn (EC, ~3.7 Myr) are present at the sources
- ✧ True or errors in the cross sections?
- ✧ Main channel:

^{56}Fe->^{53}Mn (~80%)

^{56}Fe->^{41}Ca (~50%)

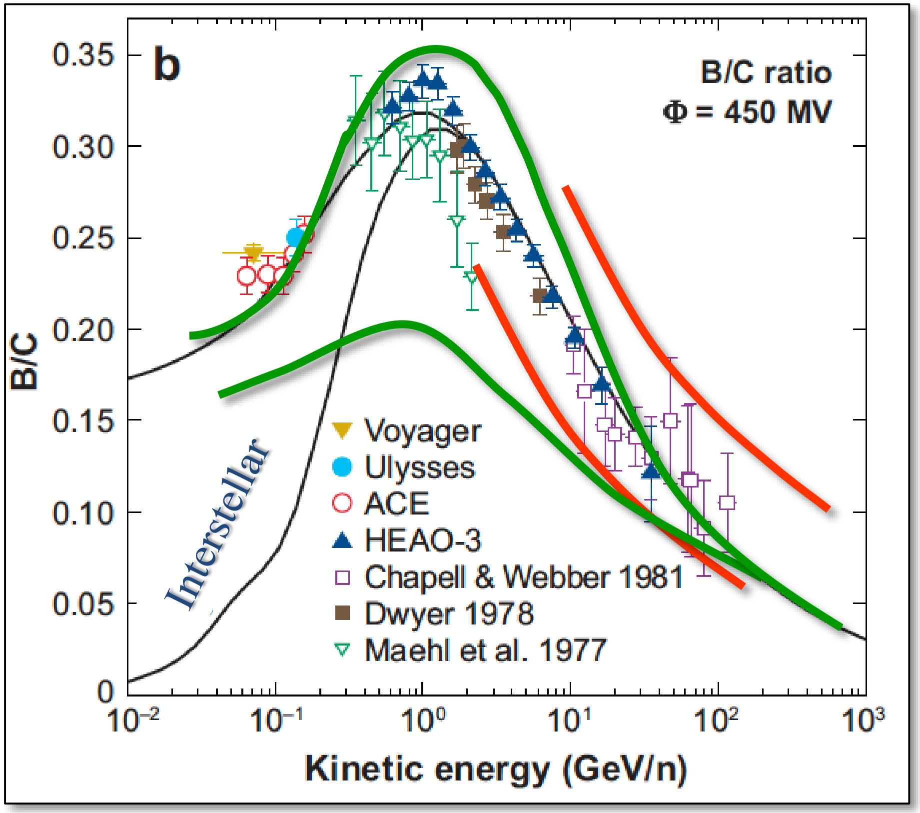


GALPROP-based derivation of source isotopic abundances using ACE data at ~200 MeV/n

Global impact of low energy data & nuclear cross sections

- Even though we may be looking at high energy data, the low energy data and their interpretation is critically important
- Low energies:
  - The most accurate measurements of elemental and isotopic composition
  - LOW ENERGY DATA are used in the models to derive the propagation parameters that then extrapolated to ALL ENERGIES and to the WHOLE GALAXY
- Most of CR physics is about the origins of CRs and their propagation
- Correct interpretation of low energy data is the top priority
- The accuracy of the isotopic production cross sections is affecting the accuracy of our predictions!

Secondary/primary nuclei ratio & CR propagation

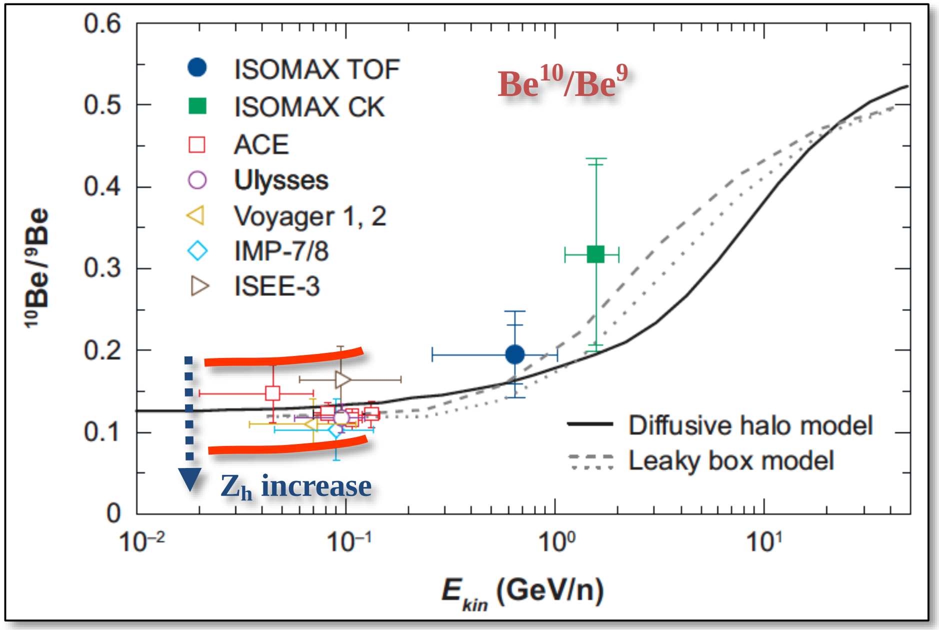


Typical parameters (model-dependent):

$D \sim 10^{28}\,(\rho/1\text{ GV})^{\alpha}\ \text{cm}^2/\text{s}$

$\alpha \approx 0.3\text{-}0.6$

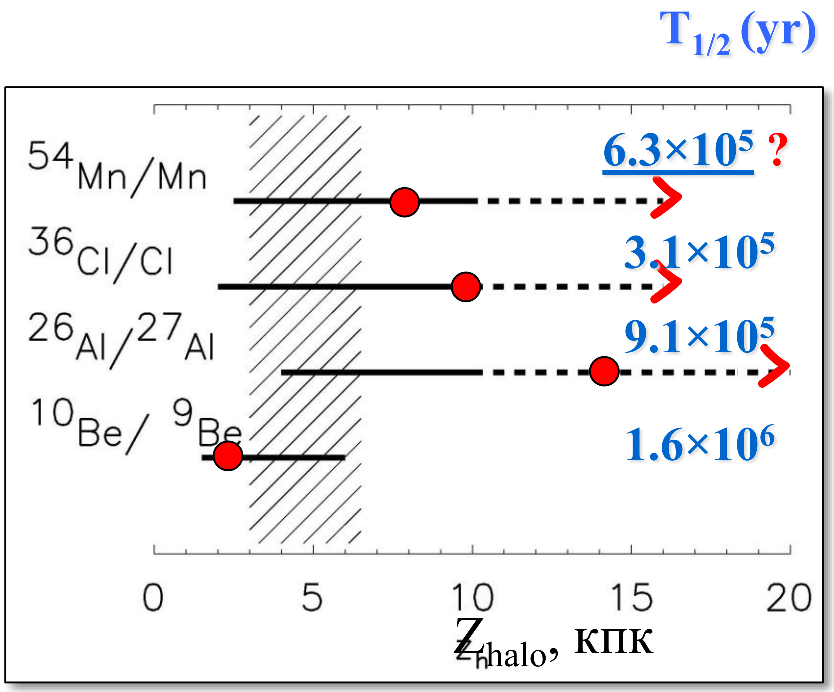
$Z_h \sim 4\text{-}6$ kpc; $V_A \sim 30$ km/s



Using secondary/primary nuclei ratio (B/C) & radioactive isotopes (e.g. Be^{10}):

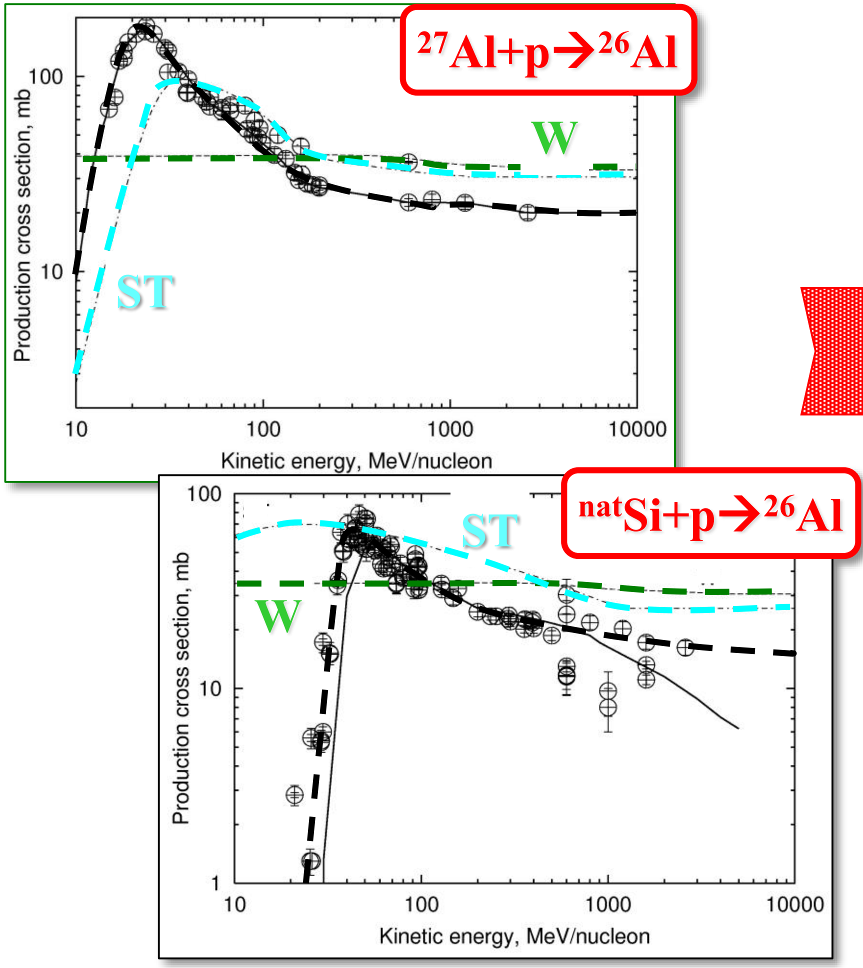
- ✧ Diffusion coefficient and its index
- ✧ Galactic halo size Z_h
- ✧ Propagation mode and its parameters (e.g., reacceleration V_A, convection V_z)
- ✧ Propagation parameters are model-dependent

Derivation of the halo size using radioactive clocks

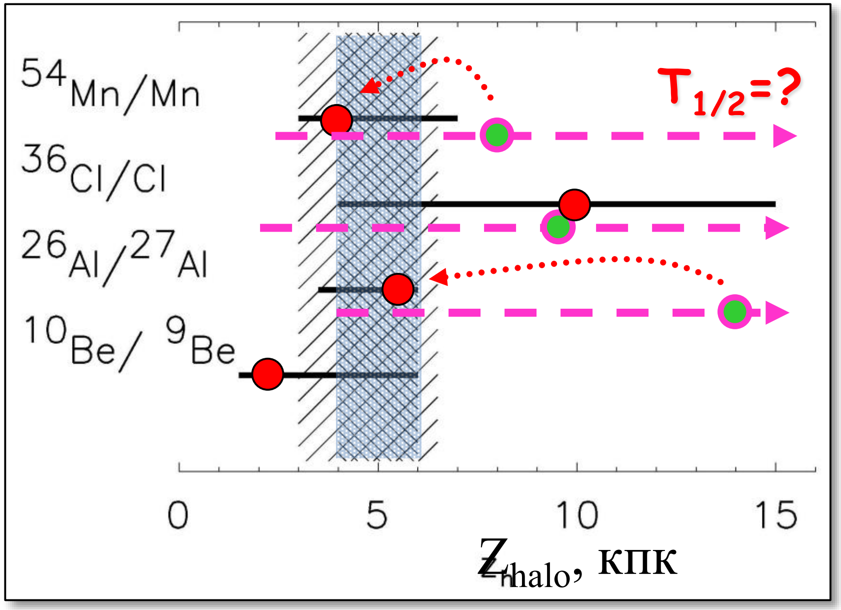


- ✧ Large dispersion between different isotopes
- ✧ Upper limit is underfined
- ✧ Possible reasons:
  - ✦ Instrumental and/or data analysis errors
  - ✦ Errors in the calculations of the cross sections
  - ✦ Errors in the life-time estimates
  - ✦ Different origin of elements (local vs. global)

Effect of cross section improvements

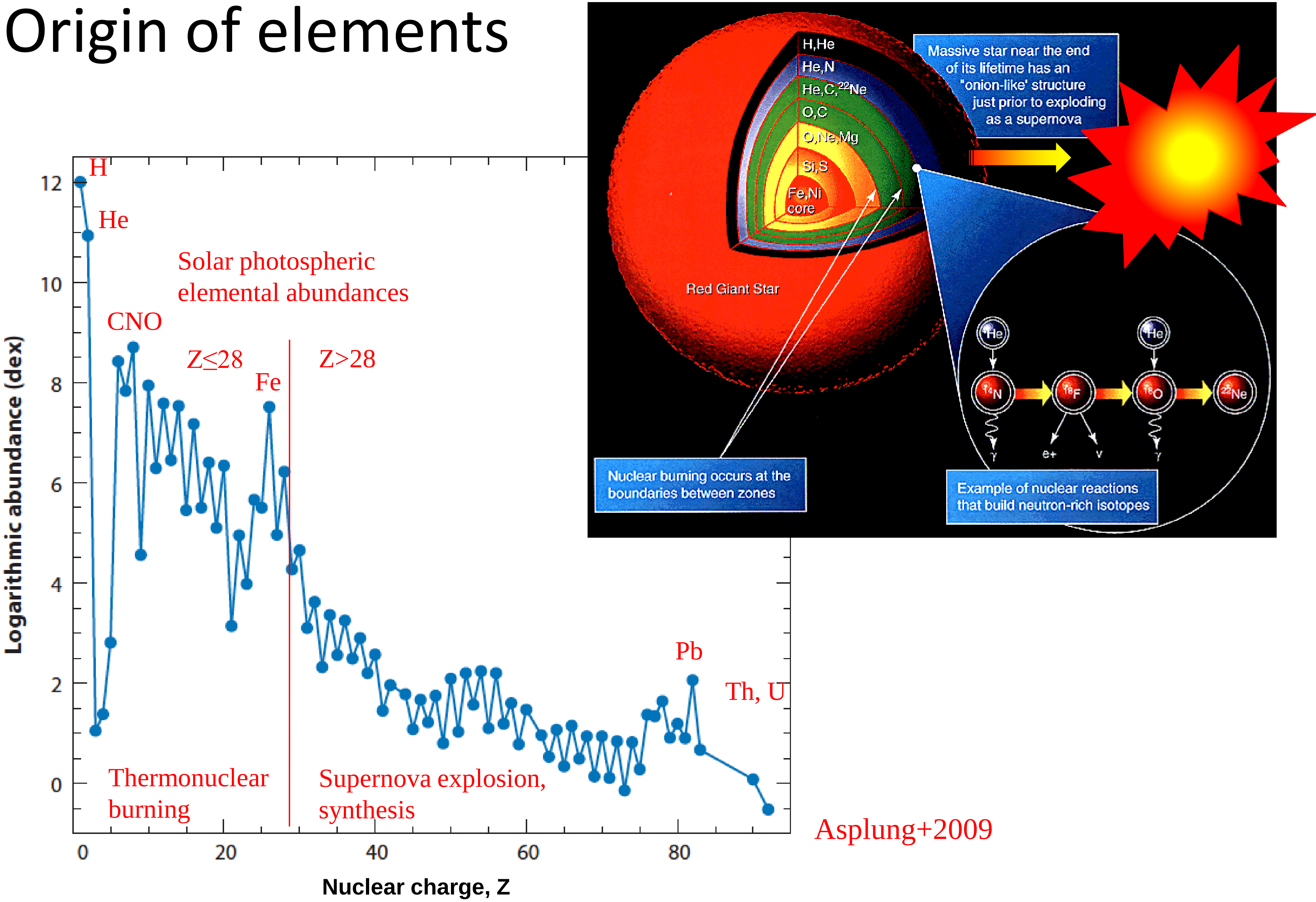


Moskalenko+’2001



- More accurate calculation of the cross sections reduces the errors and the scattering
- Halo size derived from different isotopic ratios becomes consistent

Origin of elements

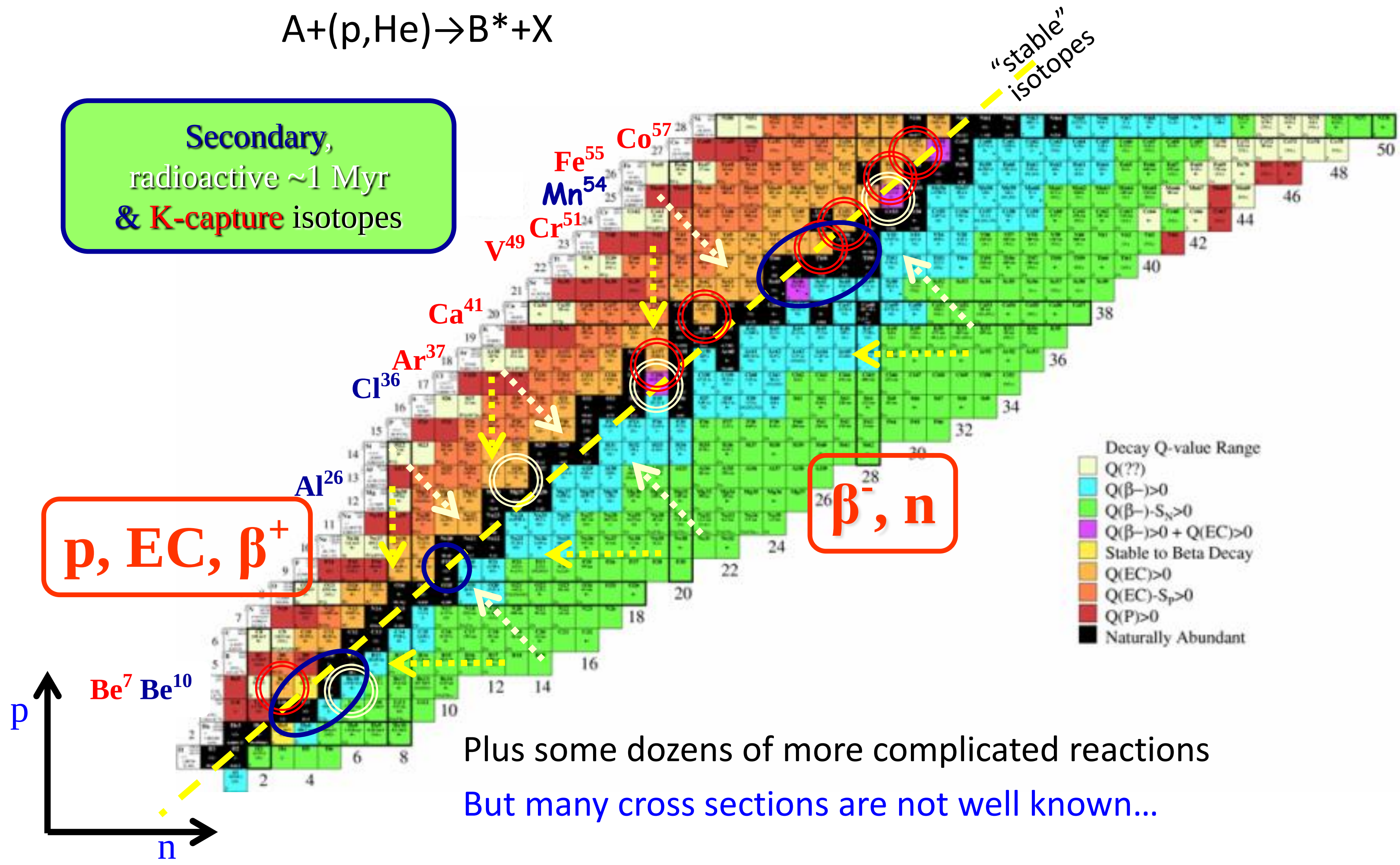


Asplung+2009

Nuclear Reaction Network + Cross Sections

Many different isotopes are produced via spallations of CR nuclei:

$A+(p,He)\rightarrow B^*+X$

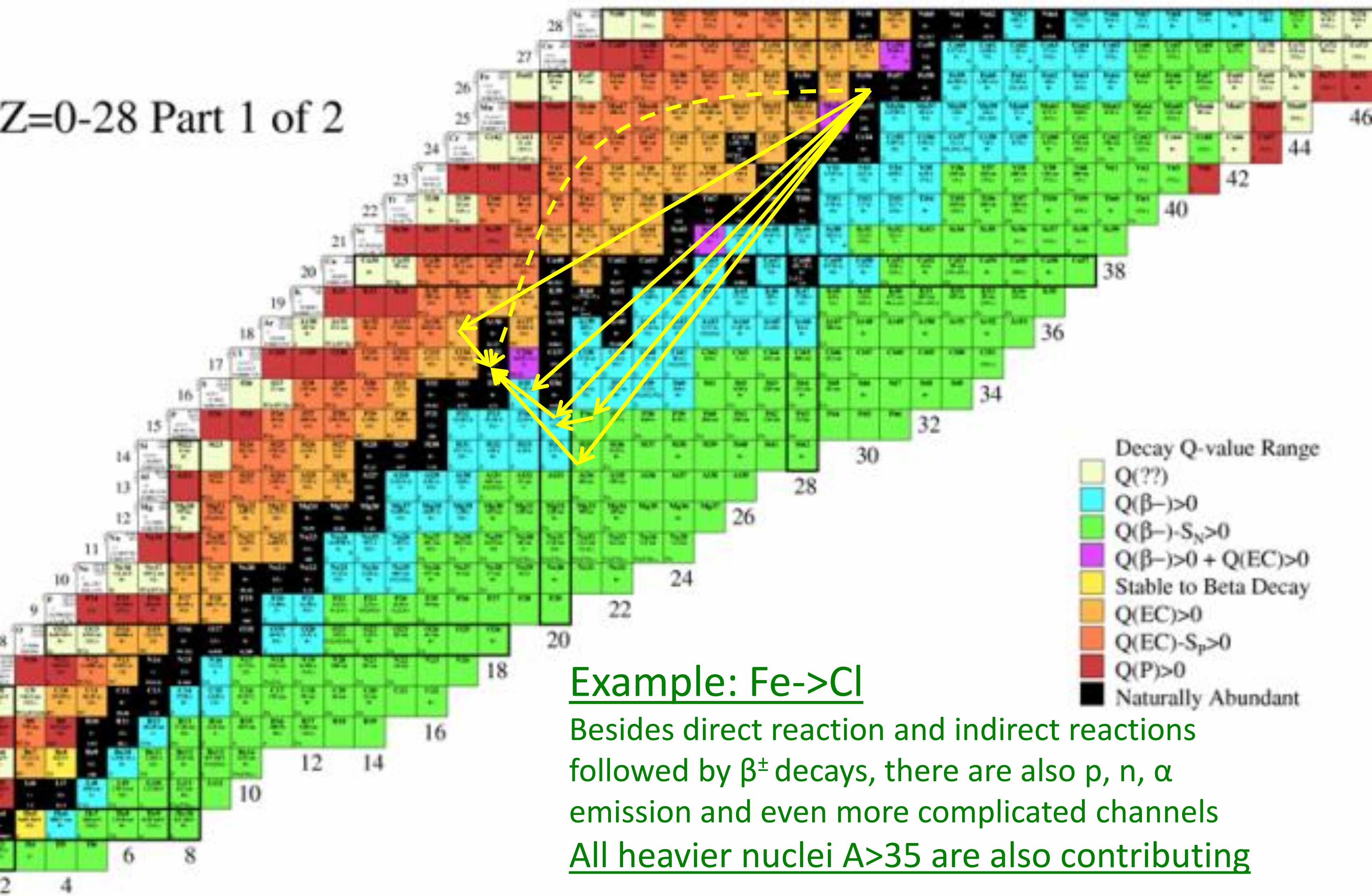


Secondary, radioactive ~1 Myr & **K-capture** isotopes

Plus some dozens of more complicated reactions

But many cross sections are not well known…

Nuclear Reaction Network + Cross Sections



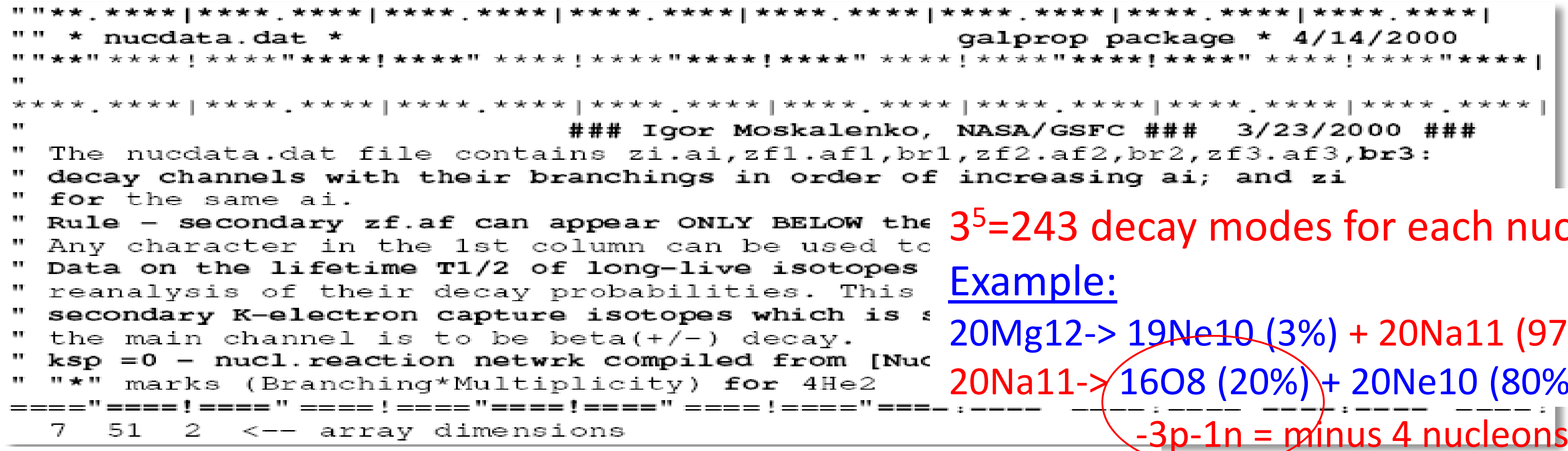
Example: Fe->Cl

Besides direct reaction and indirect reactions followed by $\beta^\pm$ decays, there are also p, n, α emission and even more complicated channels

All heavier nuclei A>35 are also contributing

Nuclear Reaction Network

nuc_package.cc



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****.****|****.****|****.****|****.****|****.****|****.****|****.****|****.****|
"                                ### Igor Moskalenko, NASA/GSFC ###  3/23/2000 ###
" The nucdata.dat file contains zi.ai,zf1.af1,br1,zf2.af2,br2,zf3.af3,br3:
" decay channels with their branchings in order of increasing ai; and zi
" for the same ai.
" Rule - secondary zf.af can appear ONLY BELOW the
" Any character in the 1st column can be used to
" Data on the lifetime T1/2 of long-live isotopes
" reanalysis of their decay probabilities. This
" secondary K-electron capture isotopes which is
" the main channel is to be beta(+/-) decay.
" ksp =0 - nucl.reaction netwrk compiled from [Nuc
" "*" marks (Branching*Multiplicity) for 4He2
===="====!===="====!===="====!===="====!===="===-:----  ----:----  ----:----  ----:
  7  51  2  <-- array dimensions
```

3^5=243 decay modes for each nuclide!

Example:

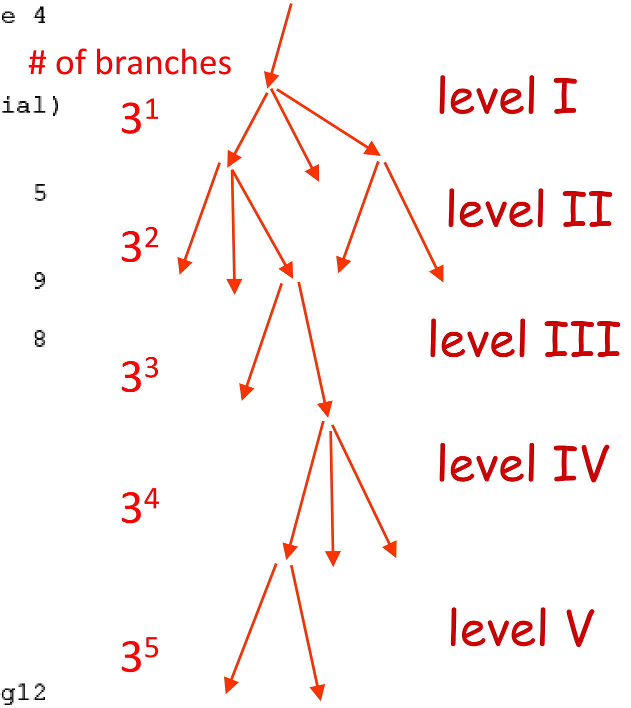
20Mg12-> 19Ne10 (3%) + 20Na11 (97%)

20Na11-> 16O8 (20%) + 20Ne10 (80%)

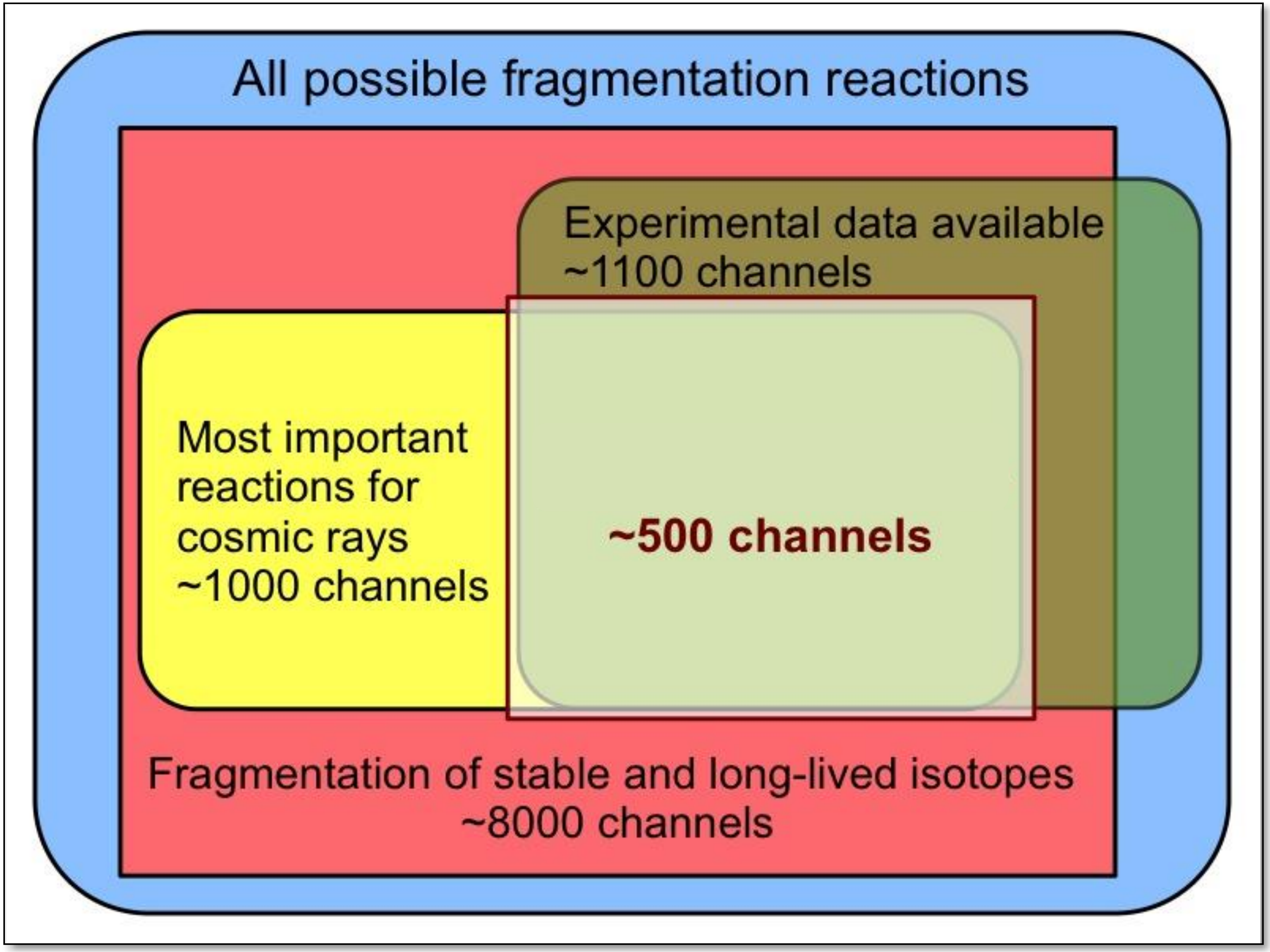
-3p-1n = minus 4 nucleons!!

```
" ZI.AI    ZF.AF BR     ZF.AF BR     ZF.AF BR

   3.11    4.09 0.04    4.10 0.85    4.11 0.08 ! 11Li  3-> 9Be  4,10Be 4,11Be 4
   7.12    2.04 0.06    6.12 0.98    0.   0.   ! 12N   7-> 4He  2*2,12C 6 *
   5.12    2.04 0.06    6.12 0.98    0.   0.   ! 12B   5-> 4He  2*2,12C 6 *
   4.12    5.12 1.00    0.   0.      0.   0.   ! 12Be  4->12B   5 (12B -special)
   8.13    6.12 0.12    7.13 0.88    0.   0.   ! 13O   8->12C   6,13N 7
   4.13    4.12 1.00    0.   0.      0.   0.   ! 13Be  4->12Be  4
   4.14    5.12 0.05    5.13 0.81    5.14 0.14 ! 14Be  4->12B   5,13B  5,14B  5
   9.16    8.15 1.00    0.   0.      0.   0.   ! 16F   9->15O   8
   6.16    7.15 0.99    7.16 0.01    0.   0.   ! 16C   6->15N   7,16N  7
  10.17    7.13 0.03    8.16 0.96    9.17 0.01 ! 17Ne10->13N    5,16O  8,17F  9
   7.17    8.16 0.95    8.17 0.05    0.   0.   ! 17N   7->16O   8,17O  8
   7.18    6.14 0.12    8.17 0.14    8.18 0.74 ! 17N   7->14C   6,17O  8,18O  8
  11.19   10.18 1.00    0.   0.      0.   0.   ! 19Na11->18Ne10
   7.19    8.18 0.62    8.19 0.38    0.   0.   ! 19N   7->18O   8,19O  8
  11.20    8.16 0.20   10.20 0.80    0.   0.   ! 20Na11->16O    8,20Ne10
  12.20   10.19 0.03   11.20 0.97    0.   0.   ! 20Mg12->19Ne10,20Na11
   7.20    8.19 0.61    8.20 0.39    0.   0.   ! 20N   7->19O   8,20O  8
  12.21   10.20 0.29   11.21 0.71    0.   0.   ! 21Mg12->20Ne10,21Na11
   7.21    8.20 0.84    8.21 0.16    0.   0.   ! 21N   7->20O   8,21O 8
  14.24   12.23 0.07   13.24 0.93    0.   0.   ! 24Si14->23Mg12,24Al13
  11.28   12.27 0.01   12.28 0.99    0.   0.   ! 28Na11->27Mg12,28Mg12
  16.29   14.28 0.47   15.29 0.53    0.   0.   ! 29S 16->28Si14,29P 15
  11.29   12.28 0.22   12.29 0.78    0.   0.   ! 29Na11->28Mg12,29Mg12
  11.30   12.28 0.01   12.29 0.30   12.30 0.69 ! 30Na11->28Mg12,29Mg12,30Mg12
  15.32   16.32 1.00    0.   0.      0.   0.   ! 32P 15->32S 16          [TOI]
```



Big picture



All possible fragmentation reactions

Experimental data available
~1100 channels

Most important reactions for cosmic rays
~1000 channels

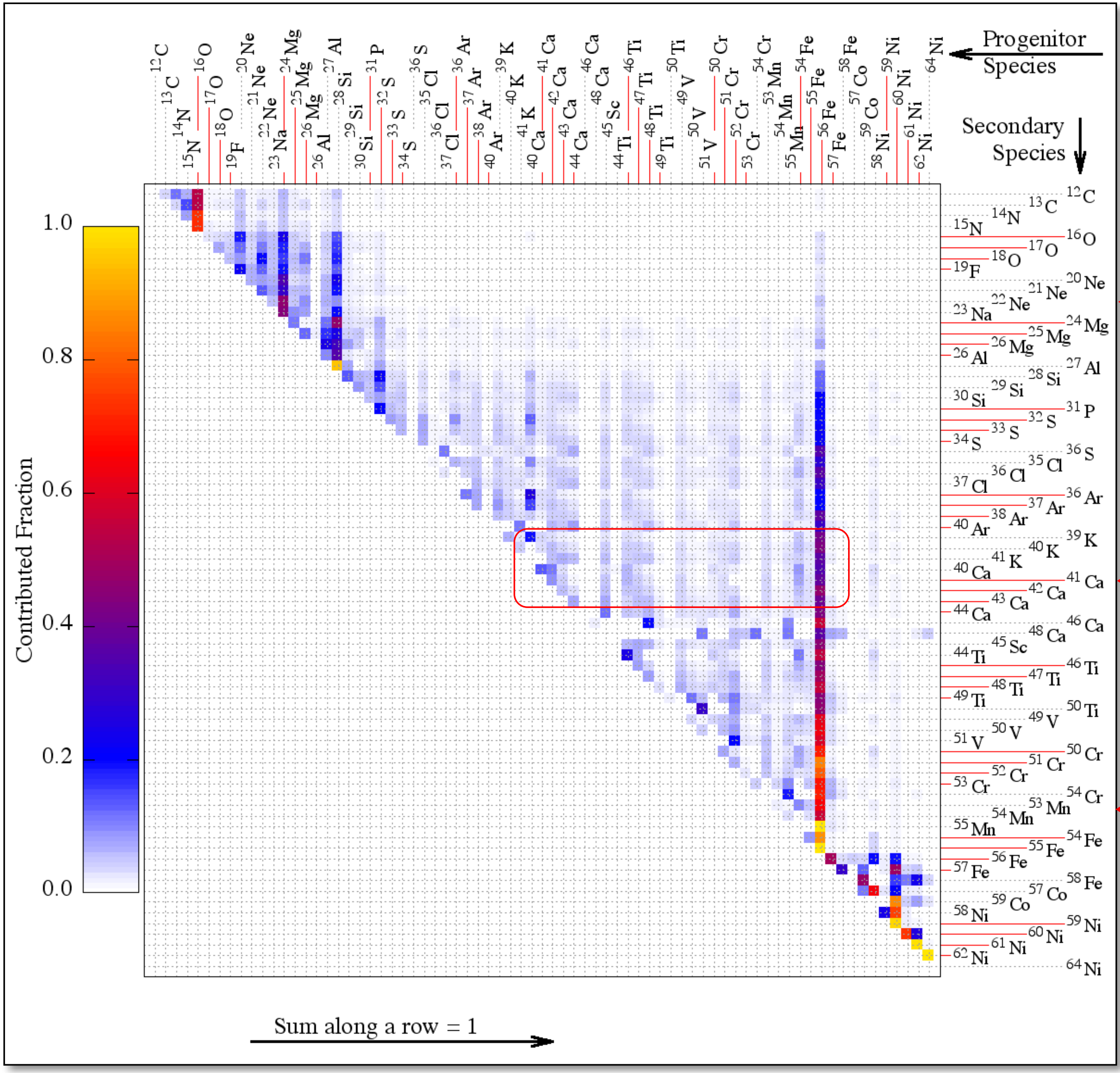
~500 channels

Fragmentation of stable and long-lived isotopes
~8000 channels

Available systematics and approximations

- Total inelastic cross sections:
  - Barashenkov, Polansky
  - Wellisch & Axen, 1996 (corrected)
  - Letaw, Silberberg, & Tsao, 1983
- Semi-empirical systematics for isotopic production cross sections:
  - Webber et al., 1990, 2003
  - Silberberg, Tsao, Barghouty, 1998
- Data fits and approximations
- Nuclear codes (Mashnik, Gudima, Toneev, Titarenko, и др.)
  - CEM – cascade-exciton model
  - LAQGSM – Los Alamos quark-gluon string model
  - ALICE – Particle Spectra from Compound Nucleus Decay
- GALPROP has the best available cross sections – cross checked when possible
  - Could use all approximations mentioned above

Cross section matrix



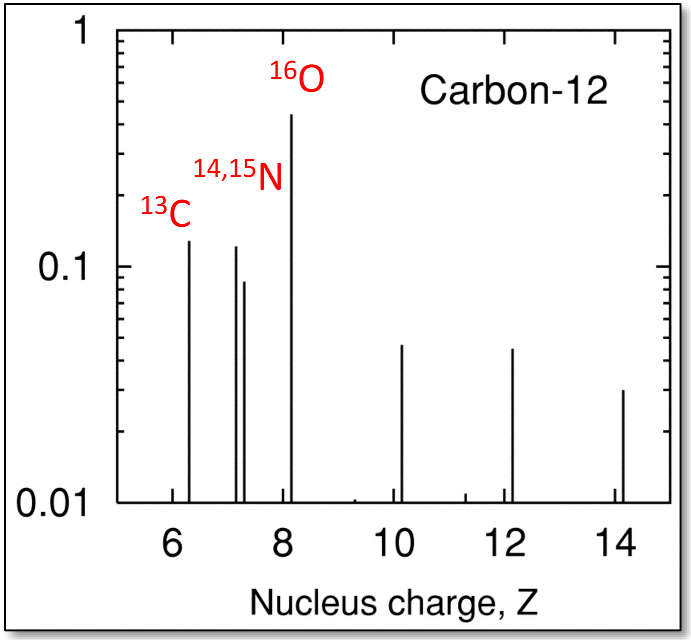
^{22}Ne

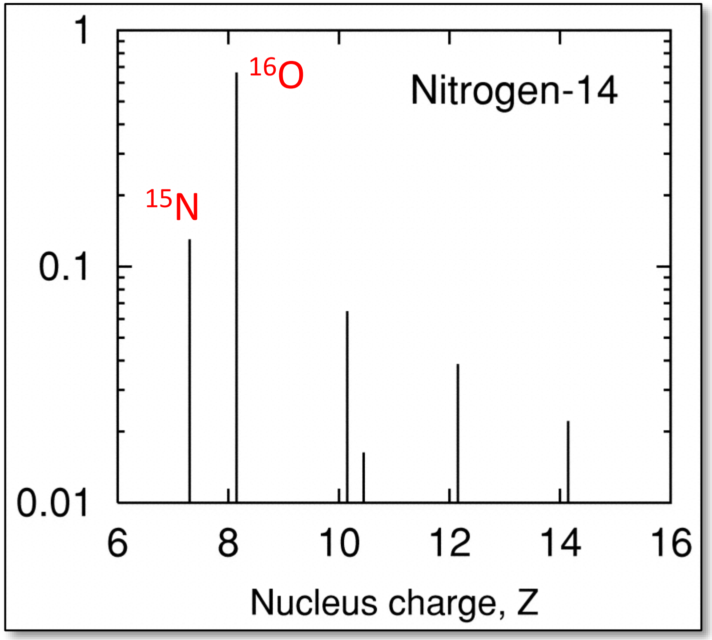
^{41}Ca

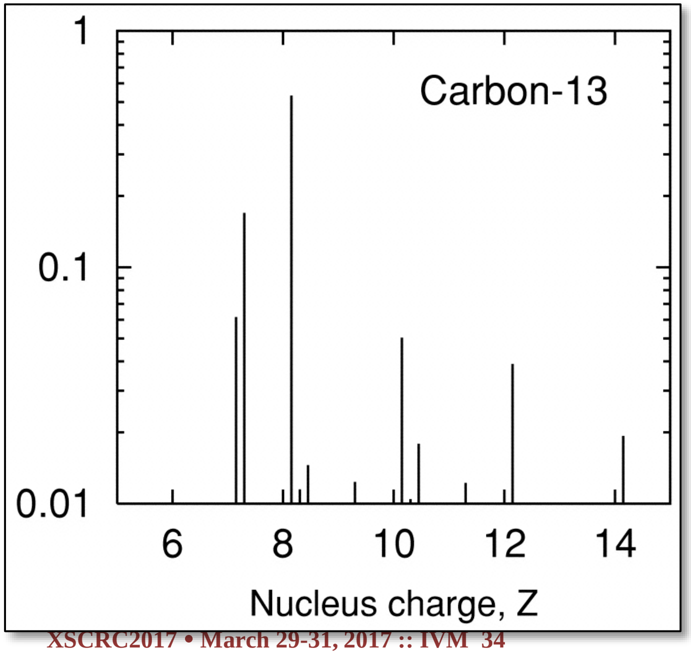
^{53}Mn

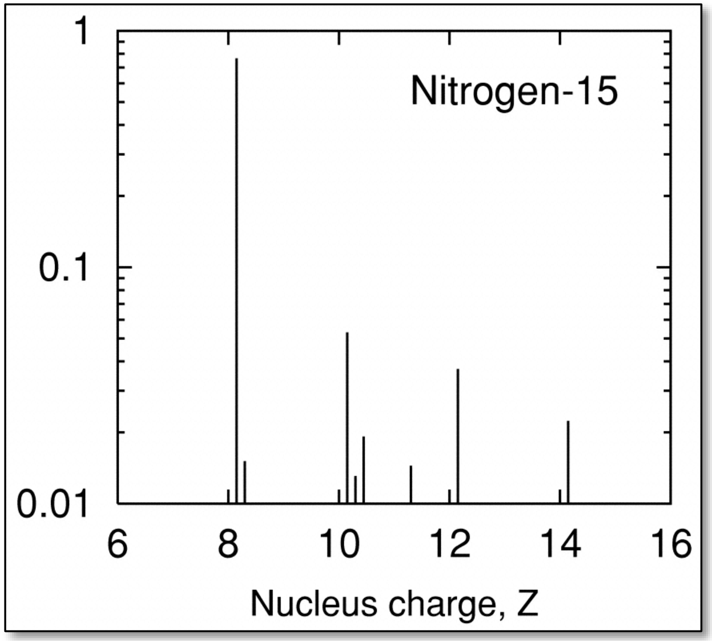
- ✧ Matrix = product of CR abundances (ACE) @ 200 MeV/n and production cross sections @ 500 MeV/n
- ✧ Each secondary isotope is produced through fragmentation and decays of heavier species
- ✧ Calculation of production of each isotope involves 100s of direct and indirect channels

Isotopic production







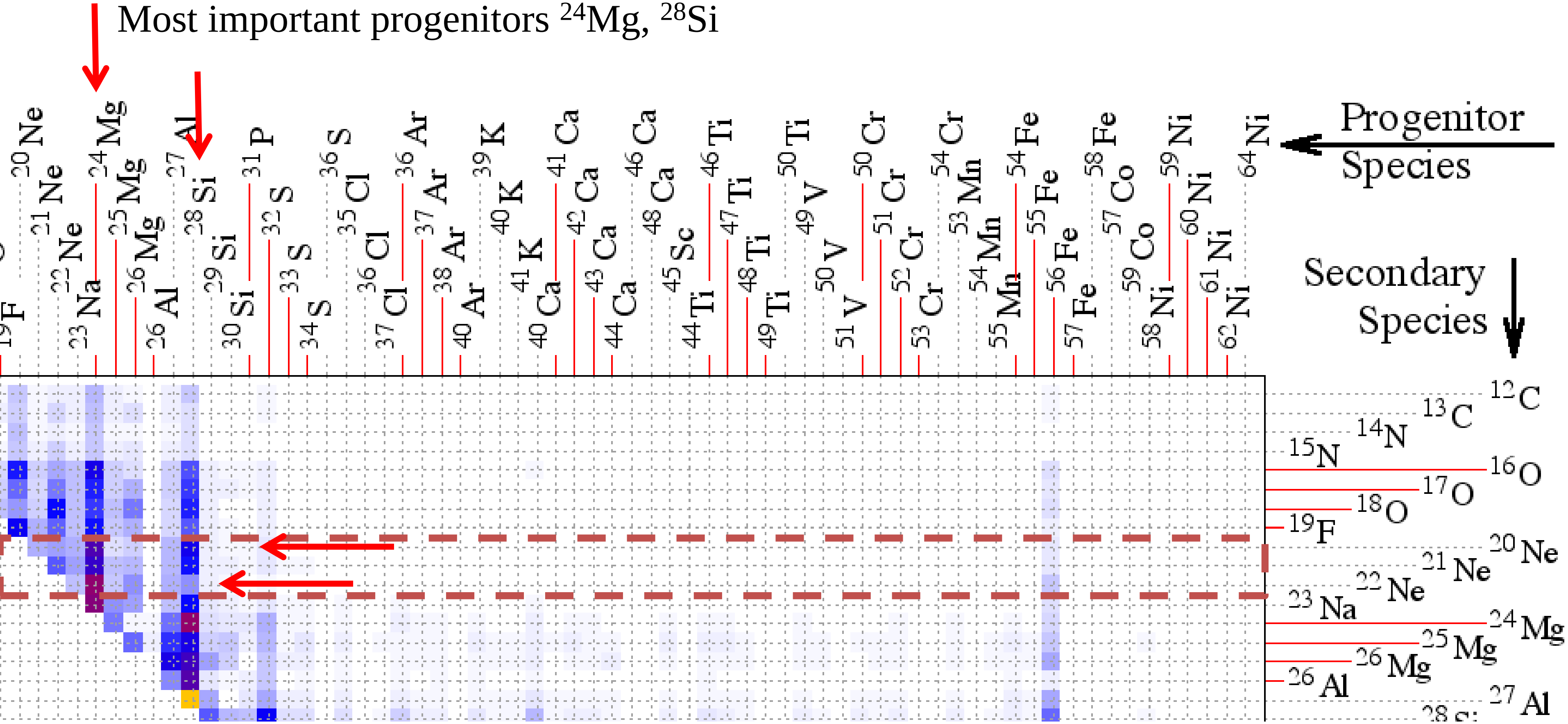


- ✧ Relative contributions of heavier isotopes to production of C and N isotopes
- ✧ Less abundant isotopes may play important role, example: ^{15}N->^{14}N, ^{13}C^{14,15}N->^{12}C

Moskalenko+'2003

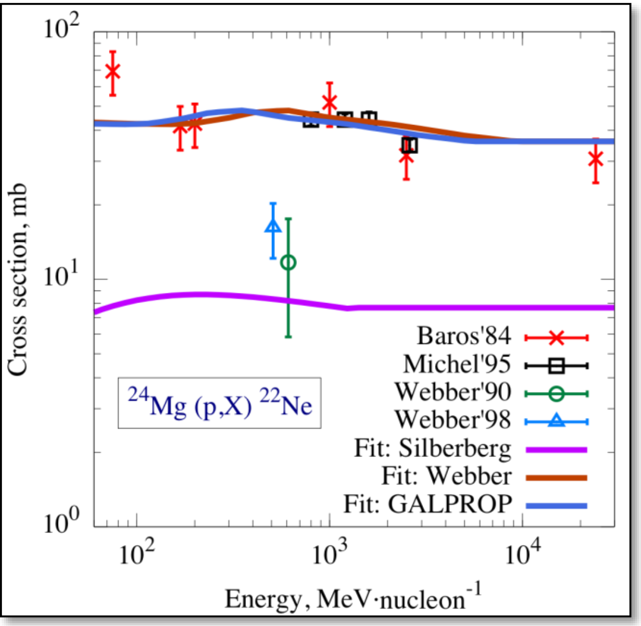
Cross section matrix – zooming in Ne-isotopes

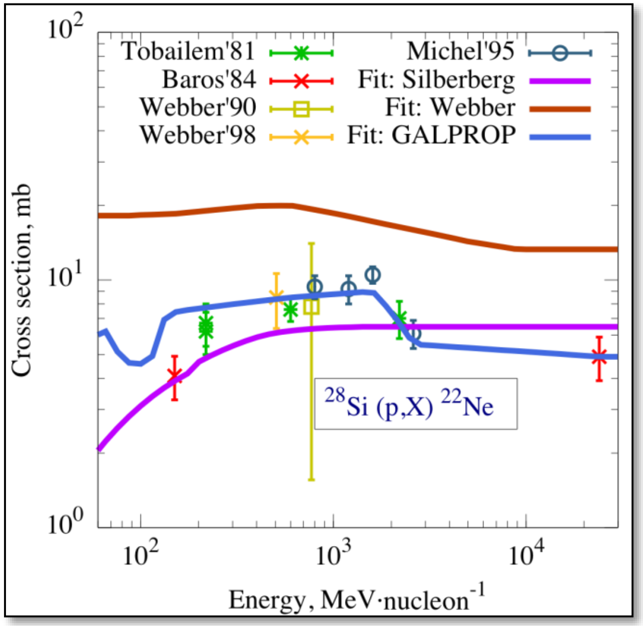
Most important progenitors ^{24}Mg, ^{28}Si

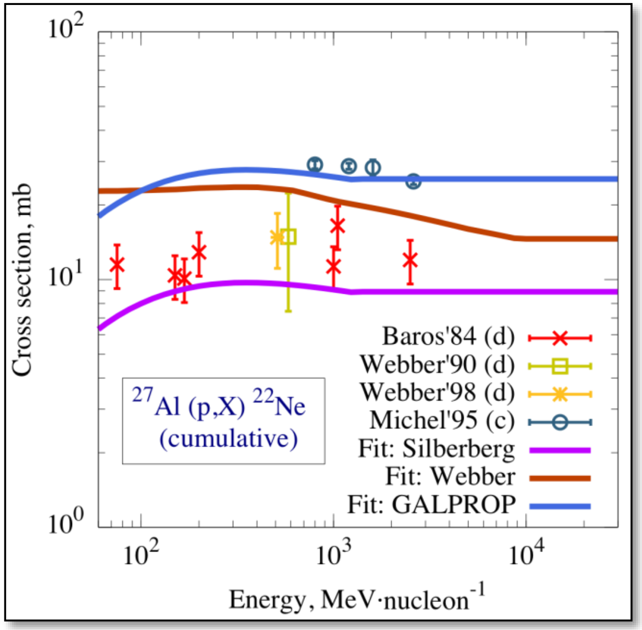


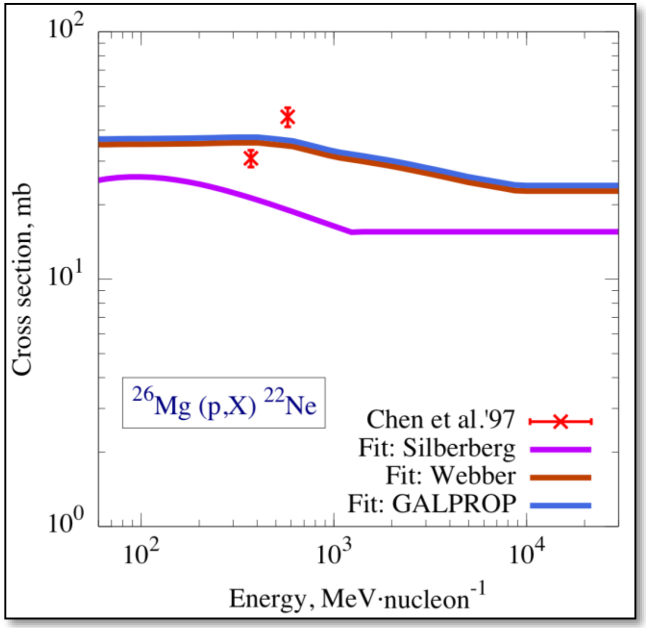
Production of ^{22}Ne

- Results depend on a chosen parameterization
- Could differ by a factor of 10 or more!
- Using ST systematics may lead to a significantly larger source abundance of ^{22}Ne

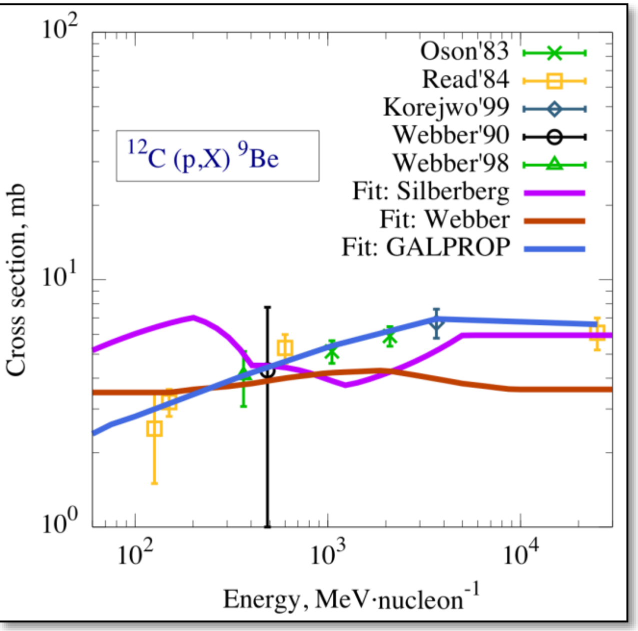


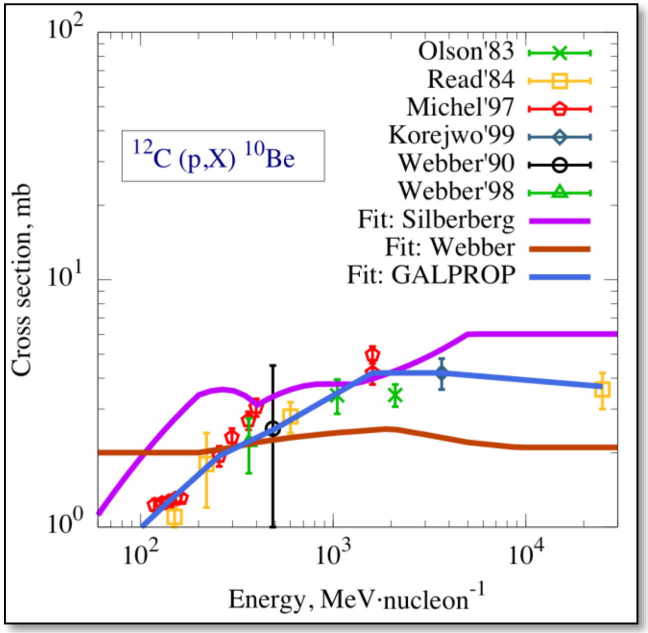




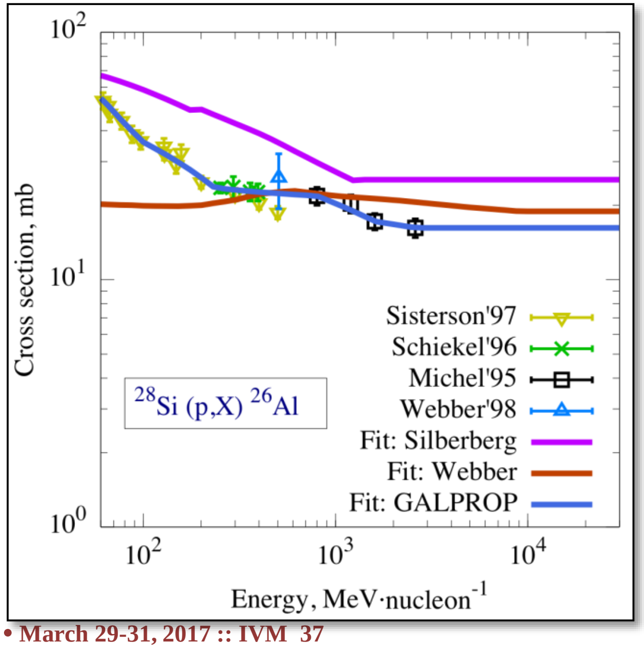


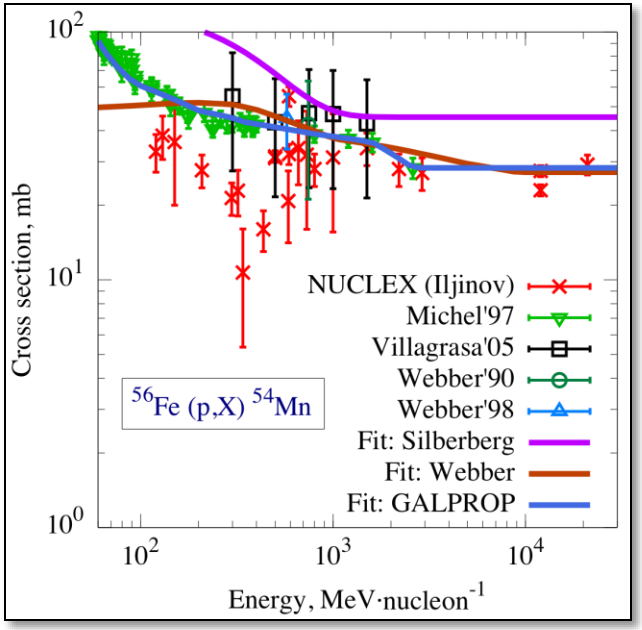
Production of radio isotopes



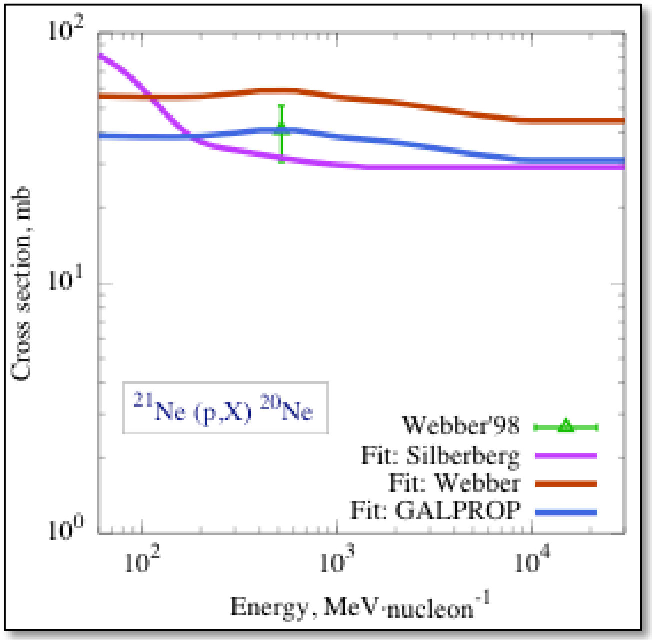


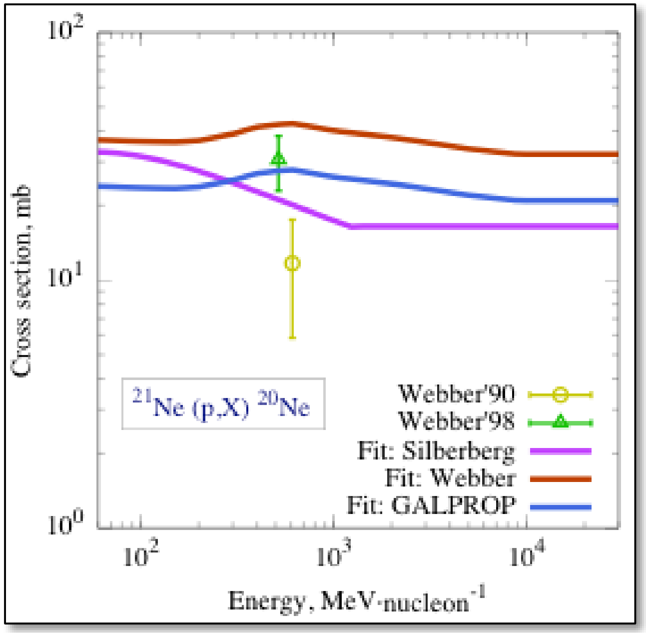
- Using different parameterizations may produce different energy dependence of the halo size

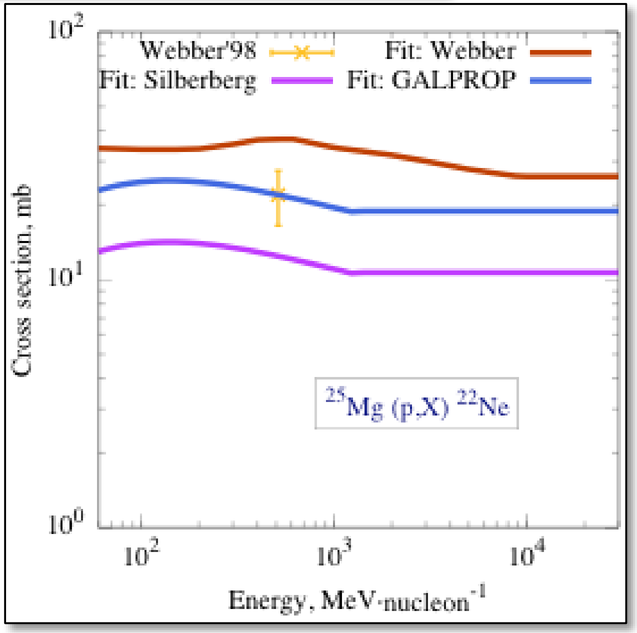




Some other examples

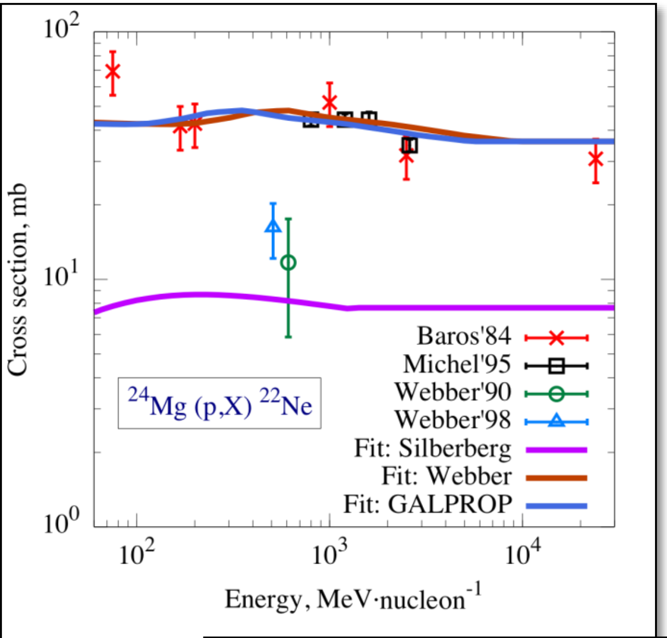


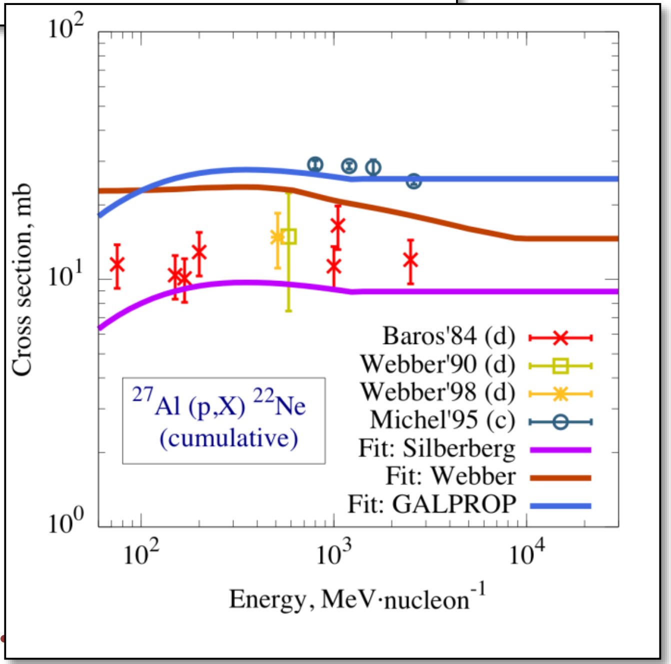




- ✧ Examples with one or two contradictory data points
- ✧ Good that these are not major production channels

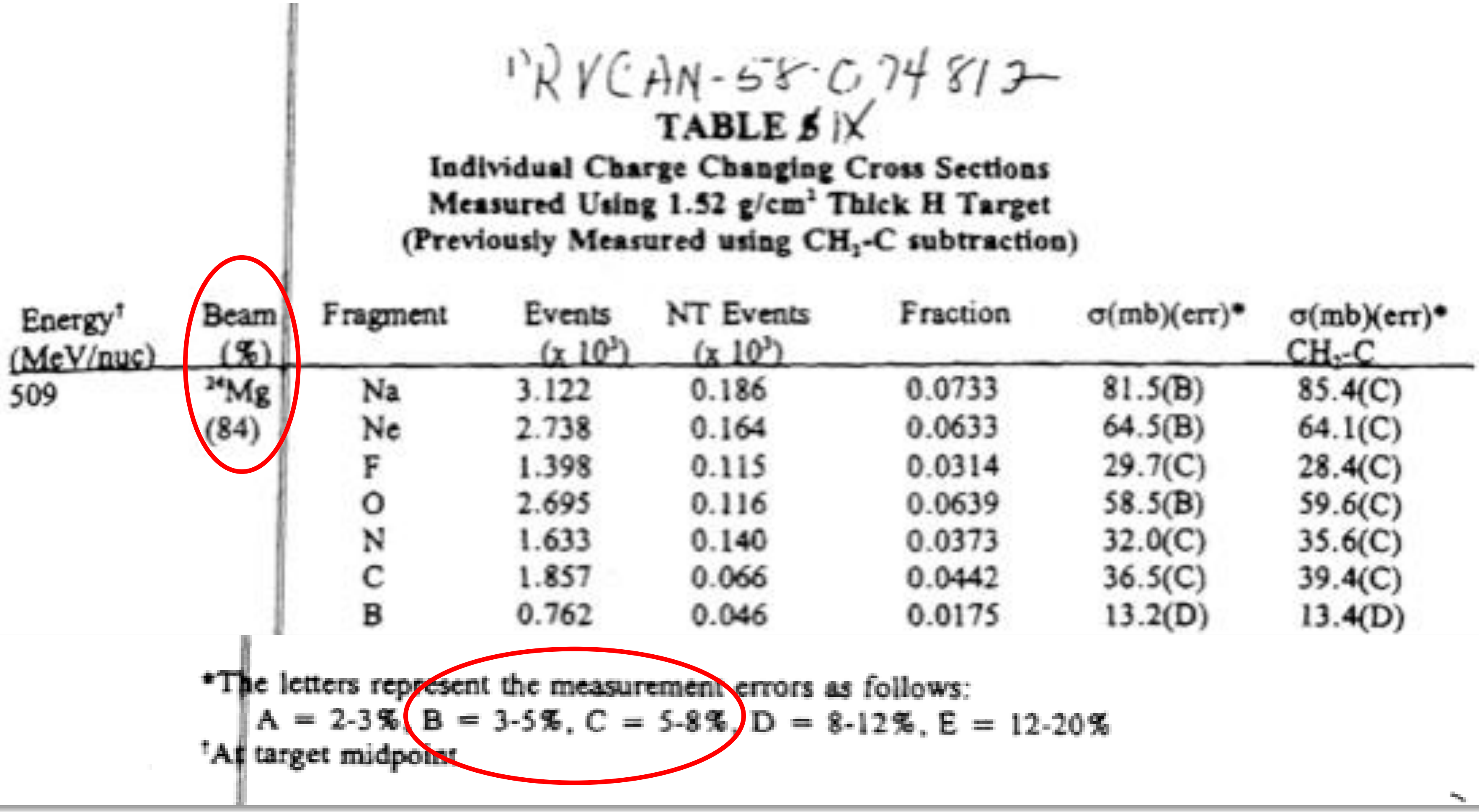
Evaluation procedure – very laborious





- Start with most important cross sections
- For each channel: collect data points if exist
- Look at individual experimental setups
- Look at what is measured:
  - individual isotopic cross sections
  - cumulative cross sections =$\Sigma_i(\beta_i\sigma_i)$
  - isobaric cross sections A=const
  - target isotopic composition: pure or natural
- Adjust exp. error! – see next slides
- Compare with calculations – choose the best one
- If well-measured – make a fit to the data
- If no data points exist – use nuclear codes or semi-phenomenological systematics
- Evaluate the accuracy using similar product nuclei

Example of measured cross sections



PRVCAN-58-074812

TABLE ~~5~~ IX

Individual Charge Changing Cross Sections
Measured Using 1.52 g/cm^2 Thick H Target
(Previously Measured using CH$_2$-C subtraction)

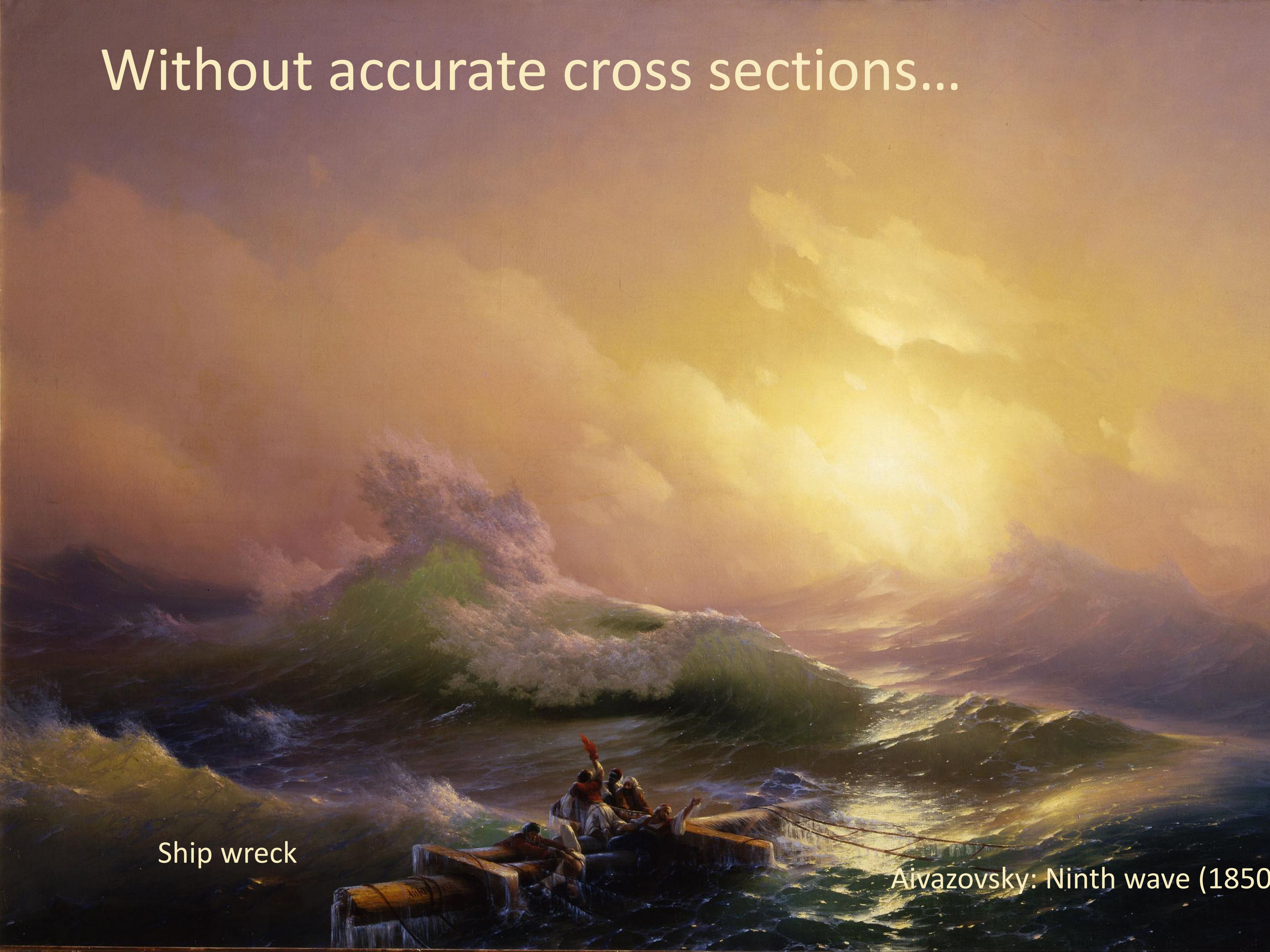
Energy† (MeV/nuc)	Beam (%)	Fragment	Events (x 10^3)	NT Events (x 10^3)	Fraction	σ(mb)(err)*	σ(mb)(err)* CH$_2$-C
509	^{24}Mg	Na	3.122	0.186	0.0733	81.5(B)	85.4(C)
	(84)	Ne	2.738	0.164	0.0633	64.5(B)	64.1(C)
		F	1.398	0.115	0.0314	29.7(C)	28.4(C)
		O	2.695	0.116	0.0639	58.5(B)	59.6(C)
		N	1.633	0.140	0.0373	32.0(C)	35.6(C)
		C	1.857	0.066	0.0442	36.5(C)	39.4(C)
		B	0.762	0.046	0.0175	13.2(D)	13.4(D)

*The letters represent the measurement errors as follows:
A = 2-3%, B = 3-5%, C = 5-8%, D = 8-12%, E = 12-20%

†At target midpoint

- ✧ Webber et al. 1998, PRC 58, 3539 (Suppl. tables: PRVCAN-58-074812 - 24)
- ✧ GALPROP nuc_package.cc – all Webber's error bars are increased to 15%-50%

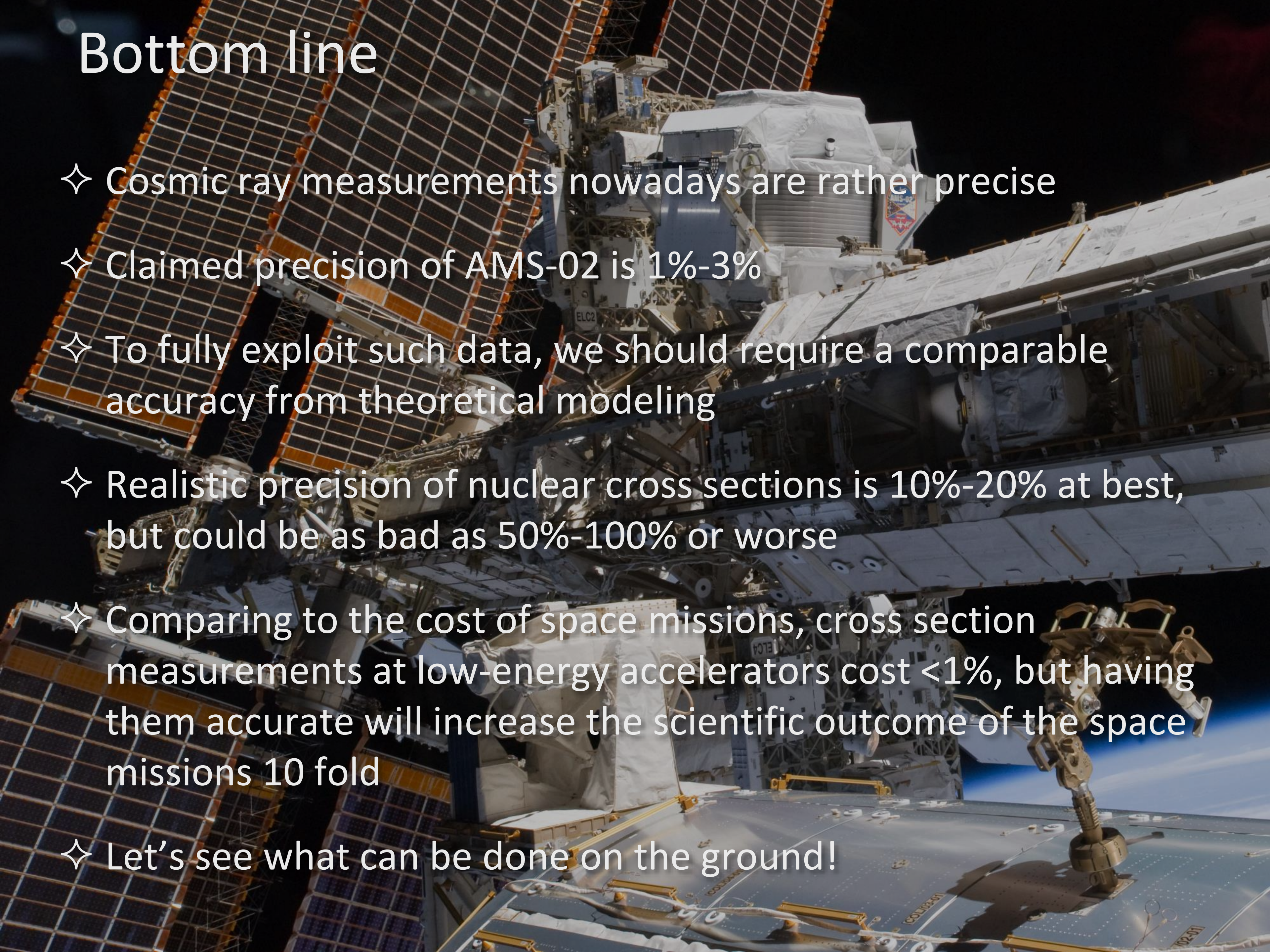
Without accurate cross sections…



Ship wreck

Aivazovsky: Ninth wave (1850

Bottom line



- Cosmic ray measurements nowadays are rather precise
- Claimed precision of AMS-02 is 1%-3%
- To fully exploit such data, we should require a comparable accuracy from theoretical modeling
- Realistic precision of nuclear cross sections is 10%-20% at best, but could be as bad as 50%-100% or worse
- Comparing to the cost of space missions, cross section measurements at low-energy accelerators cost <1%, but having them accurate will increase the scientific outcome of the space missions 10 fold
- Let’s see what can be done on the ground!