A Data Driven approach for the measurement of ^{10}Be/^{9}Be in Cosmic Rays with magnetic spectrometers

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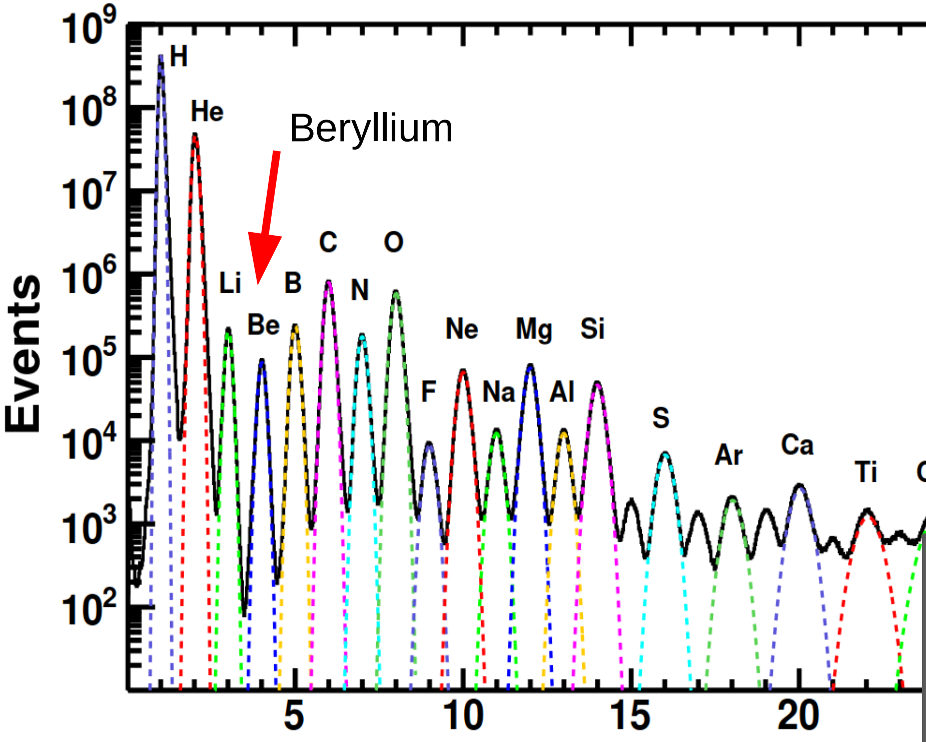
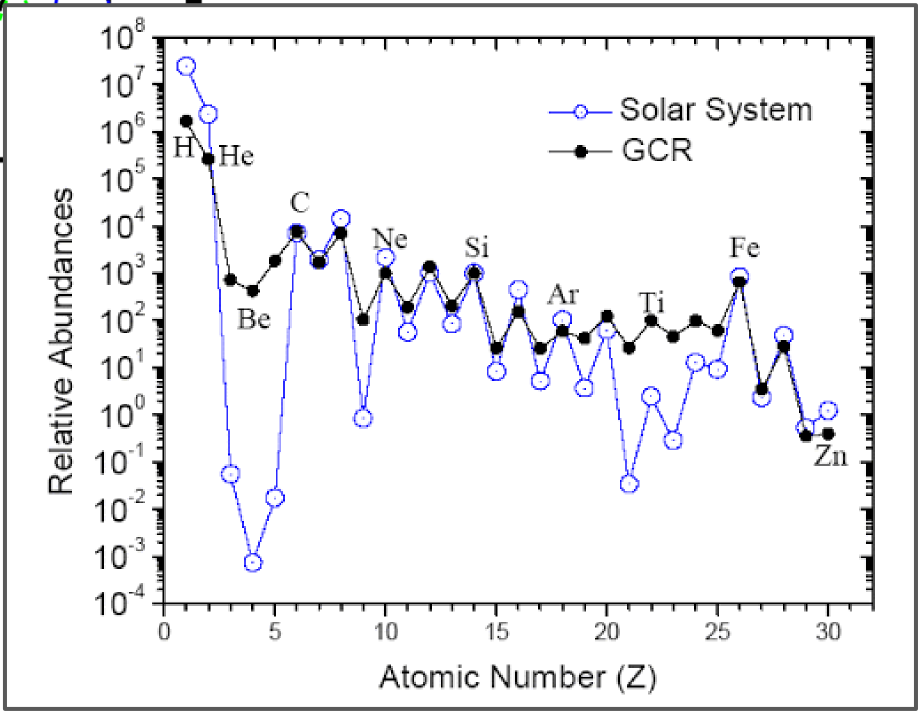
AMS-Italy 11/03/2021

Beryllium in cosmic rays



- Beryllium amount is very small in CR
- Why do we interest in it?

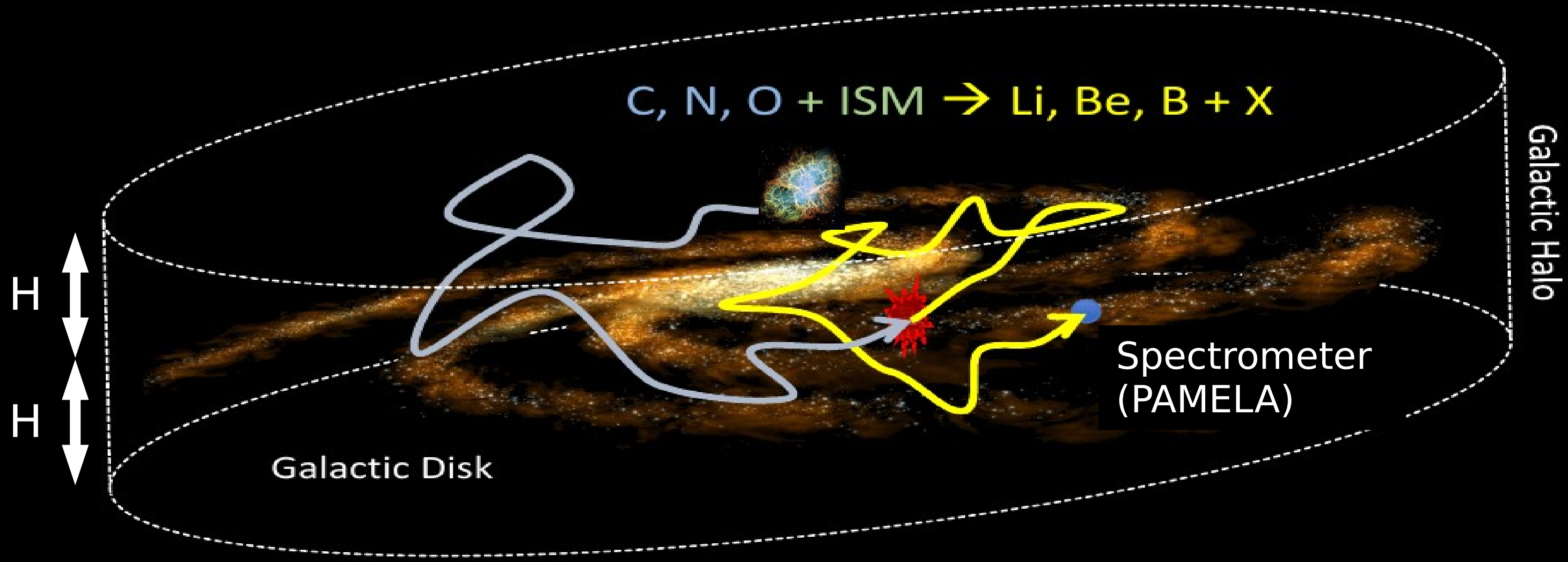


Beryllium (Li and B) are not produced in Stellar-Nucleo-Synthesis

Why they are so “abundant” in CR?

Secondary nuclei in CR

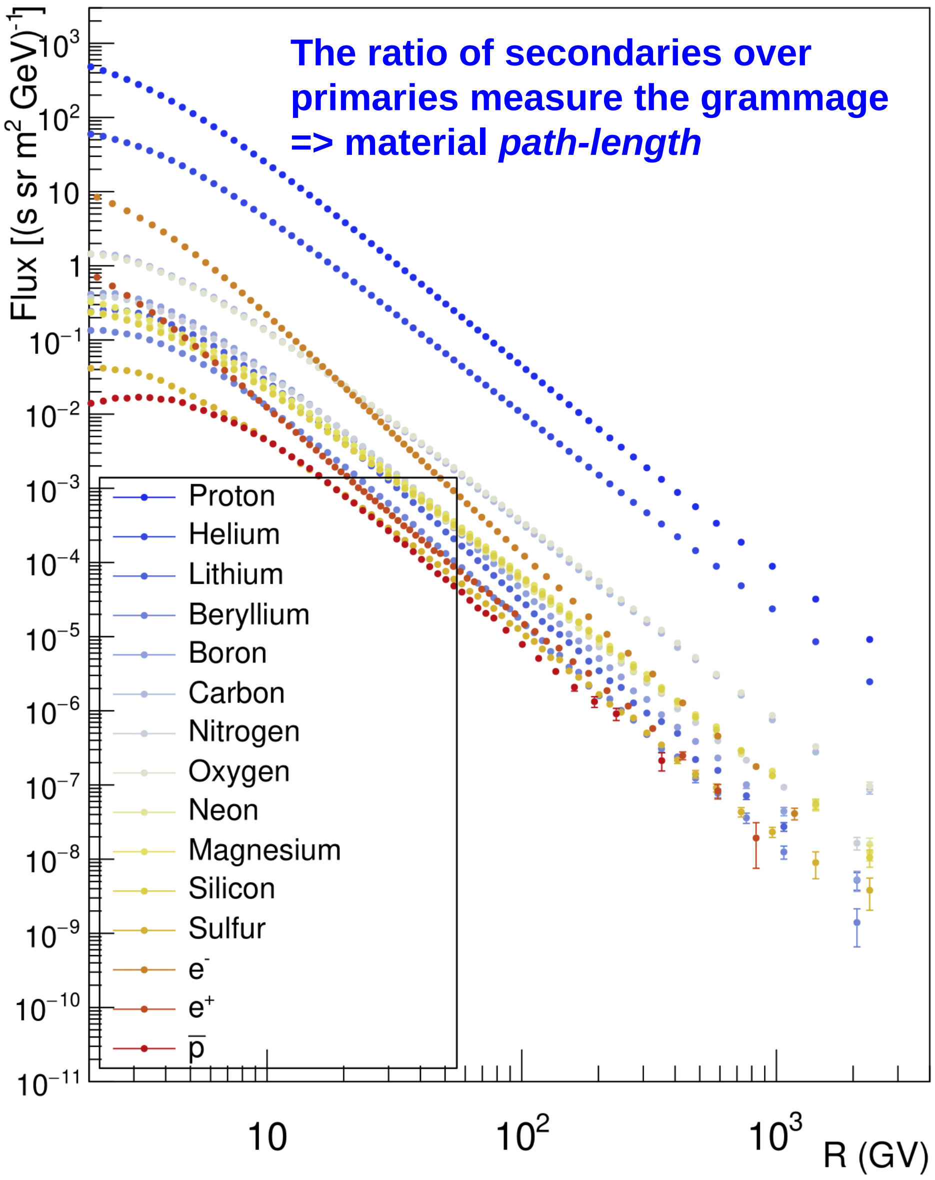
Secondary CR are produced from collisions of **primary CR** with the **interStellar medium (ISM)**



The fluxes of the secondary species are very important for the understanding of the origin and propagation of cosmic rays

- They carry information on the history of the travel and **properties of ISM,**
- Most abundant species: **Li, Be, B and light isotopes (**^{3}**He and D)**

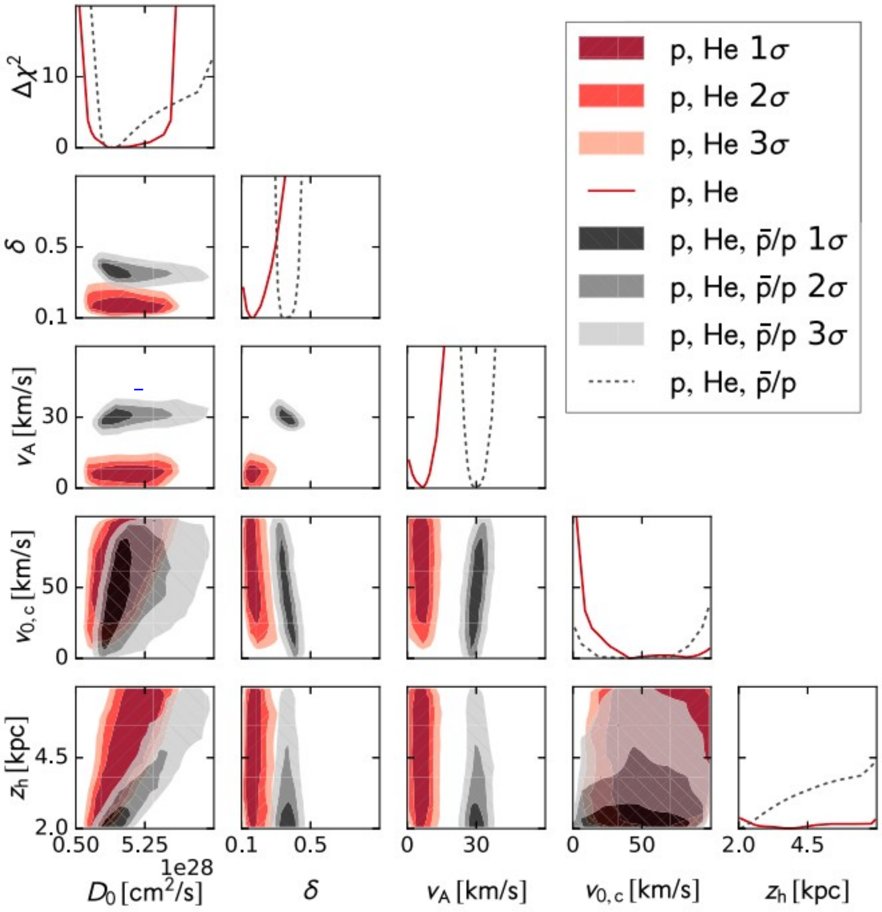
Cosmic Ray Propagation parameters



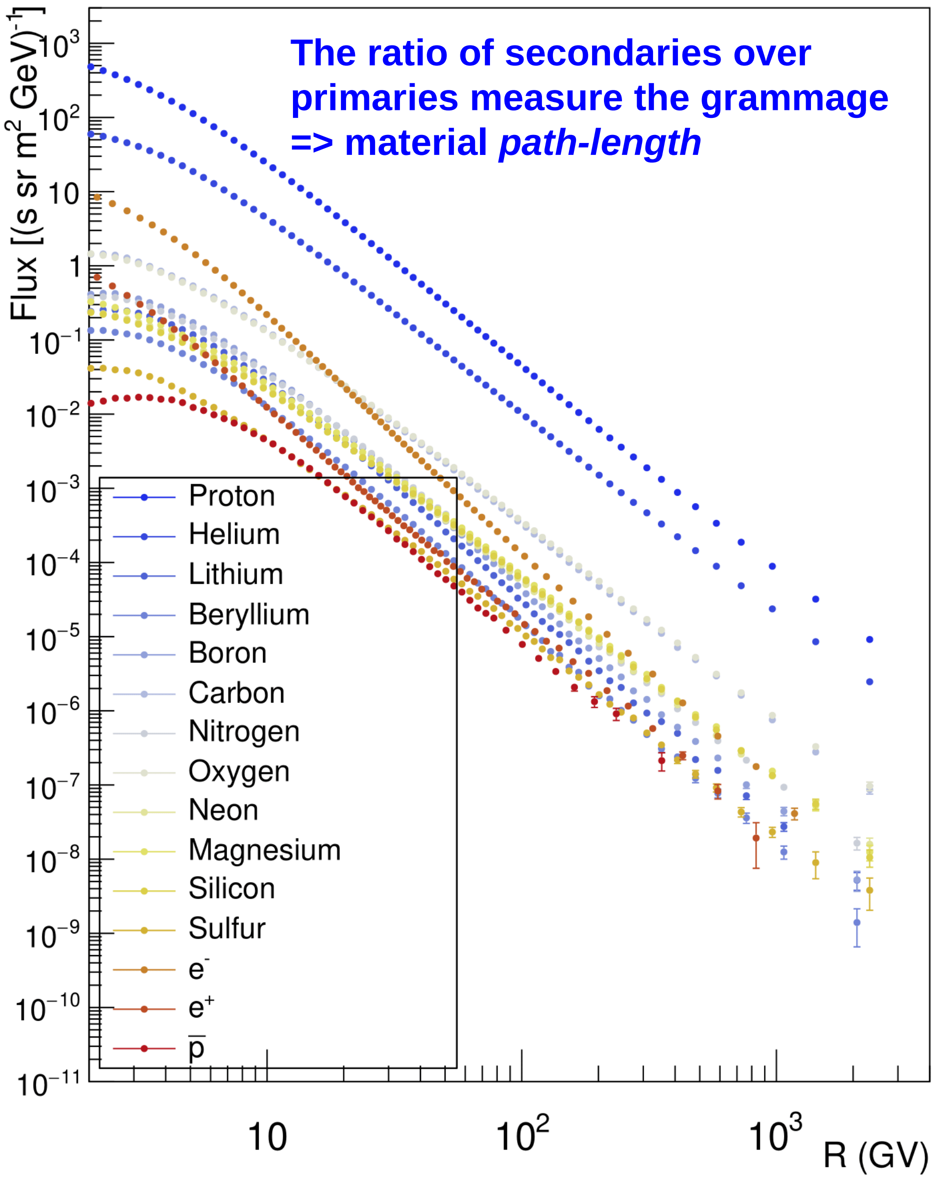
The ratio of secondaries over primaries measure the grammage => material *path-length*

The measurement of all the fluxes is useful to model the Cosmic Ray propagation

Example: M. Korsmeier & A. Cuoco
Phys. Rev. D 94.12 (2016), p. 123019



Cosmic Ray Propagation parameters



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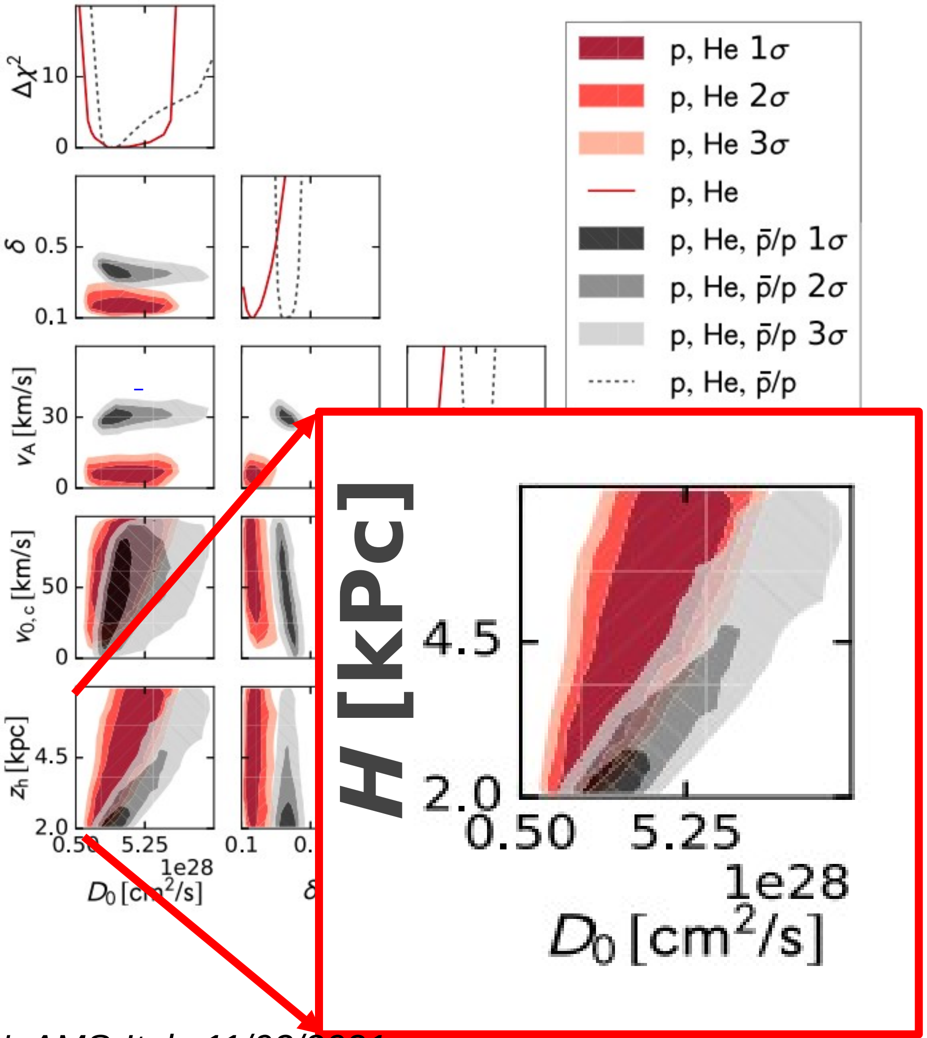

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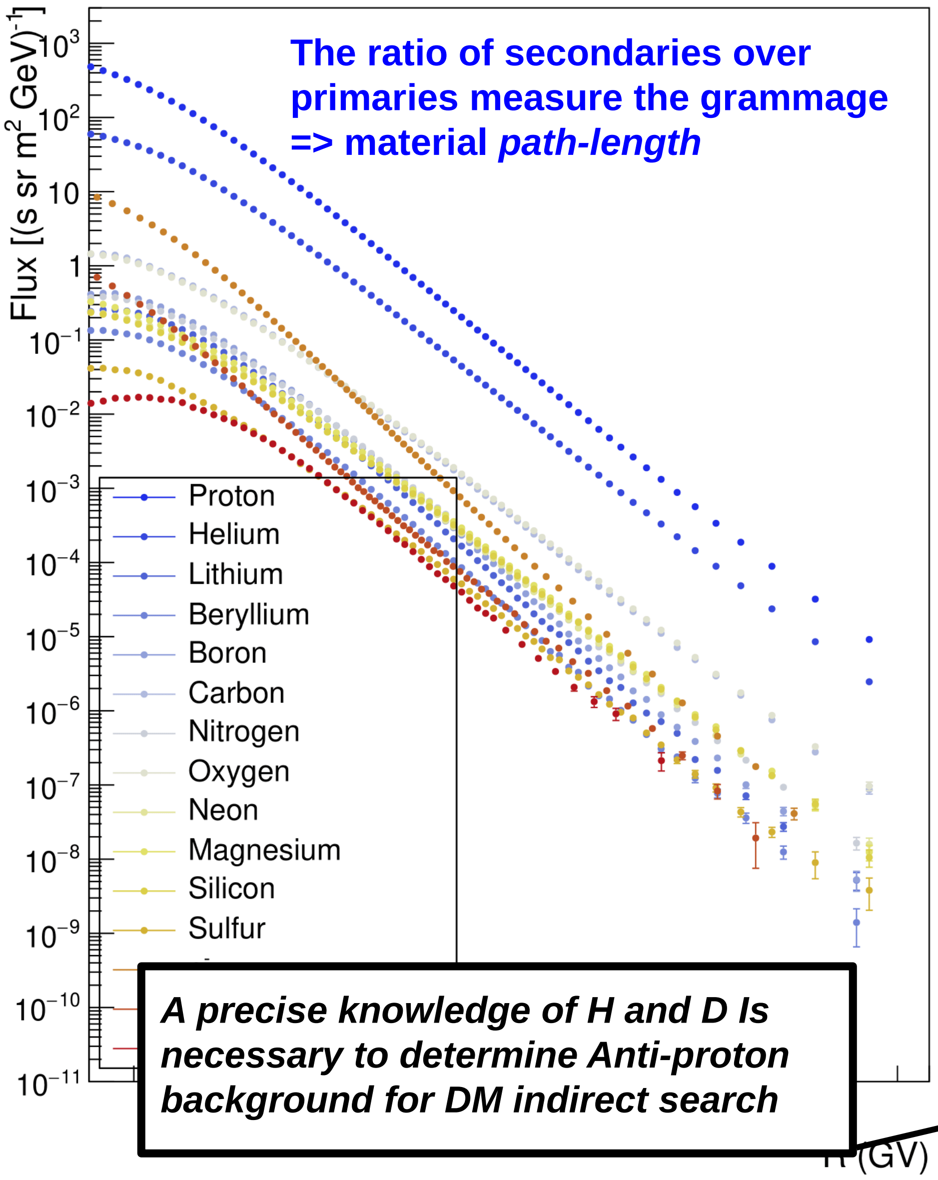
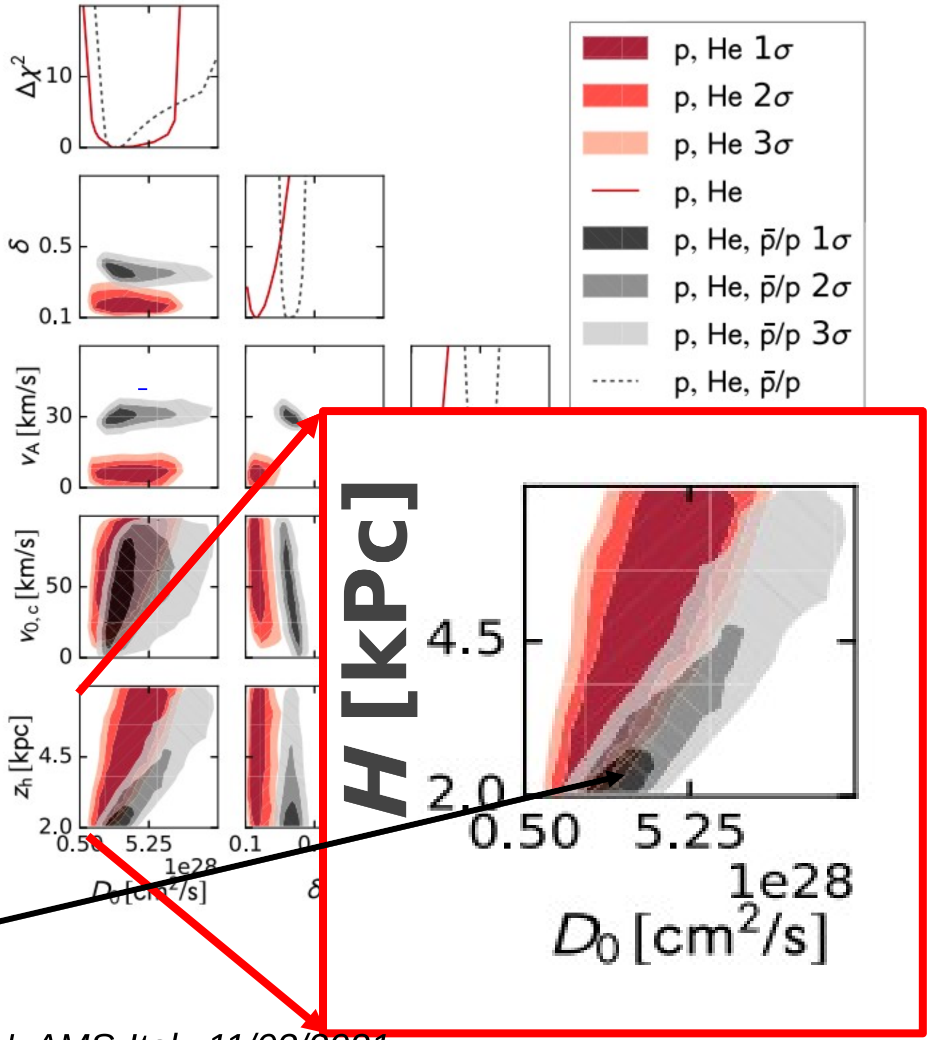


The ratio of secondaries over primaries measure the grammage => material *path-length*

A precise knowledge of H and D Is necessary to determine Anti-proton background for DM indirect search

The measurement of all the fluxes is useful to model the Cosmic Ray propagation

Example: M. Korsmeier & A. Cuoco Phys. Rev. D 94.12 (2016), p. 123019



Radioactive Cosmic Rays

Radioactive isotopes are sensitive to CR residence time in the Galaxy.
Used as cosmic clocks, they constrain H^2/D solving the existing H/D degeneracy.

^{10}Be ($T_{1/2}$=1.39My) ^{26}Al ($T_{1/2}$=0.72My) ^{36}Cl ($T_{1/2}$=0.30My) ^{53}Mg ($T_{1/2}$=3.74My) ^{60}Fe($T_{1/2}$=2.6My)

Among them Beryllium is the most promising for isotope separation at high energy

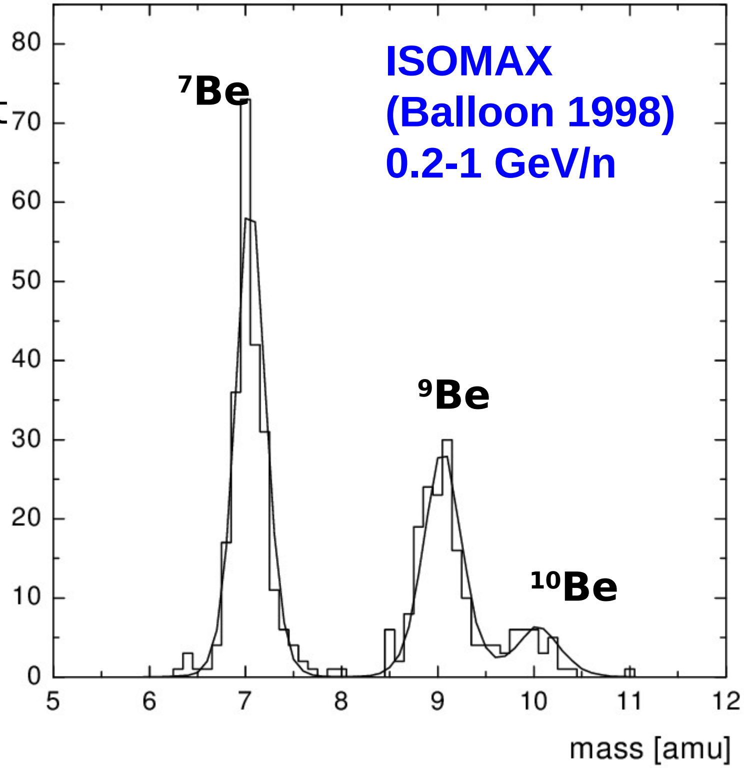
Be isotope composition in CR:

- **^{7}Be** decays through e^- capture, on Earth it has a $T_{1/2}$~ 55 days, but it's stable in CR because is totally ionized
- **^{9}Be** is stable
- **^{10}Be** is β-unstable: $T_{1/2}$= 1.39 My

^{10}Be→^{10}B+e^- + anti-ν

NOTE:

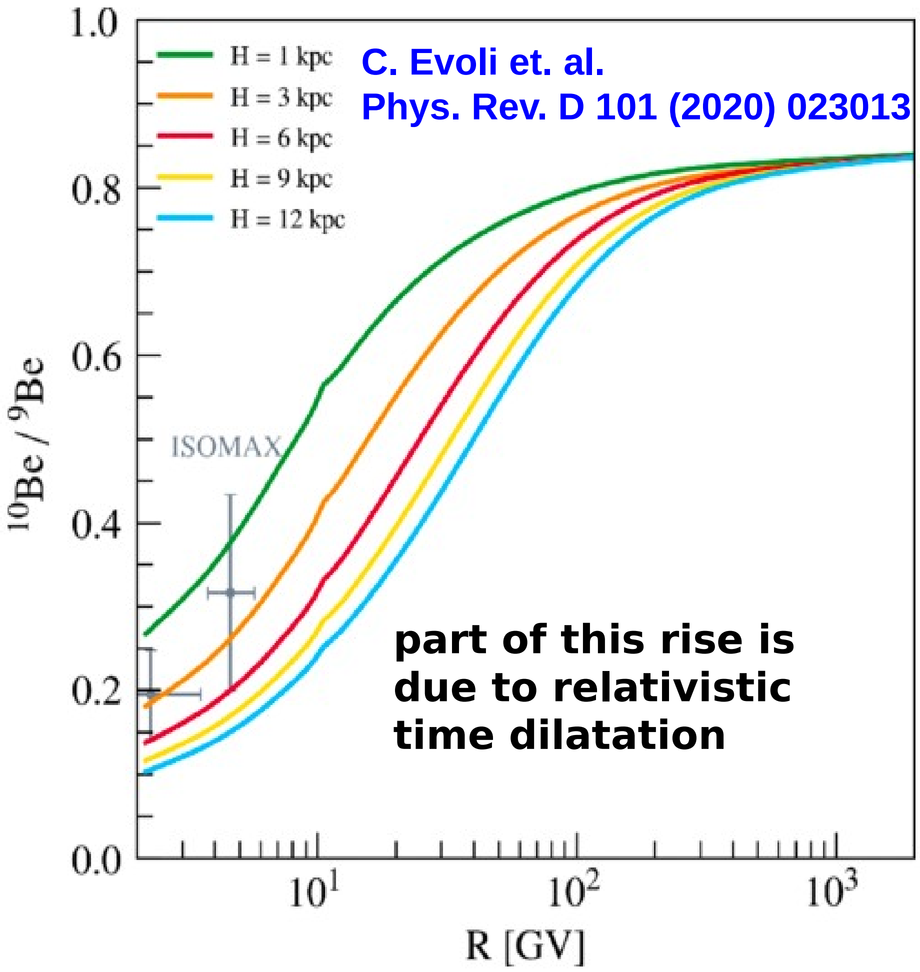
^{8}Be ($T_{1/2}$~ 8 × 10^{-17} s) "hole" is very useful for THIS measurement



^{10}Be/^{9}Be sensitive to the halo thickness ⇒ can remove the H/D degeneracy

but current measurements are:

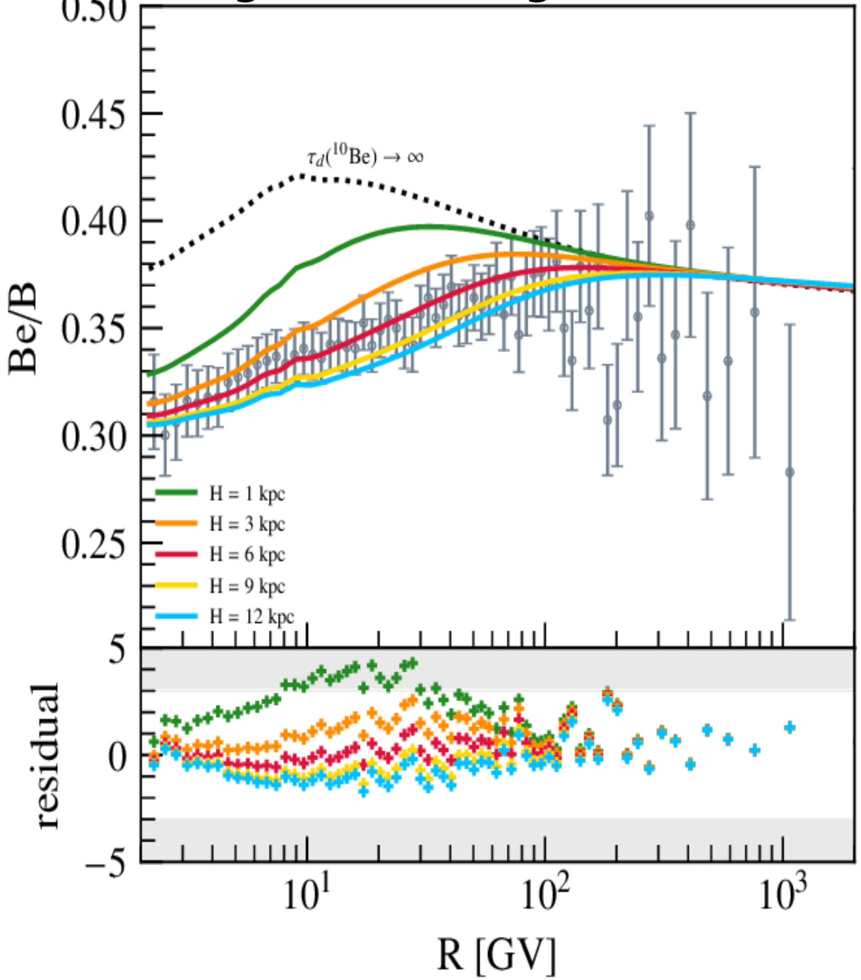
- **affected by large uncertainties**
- **limited to low energies**



C. Evoli et. al.
Phys. Rev. D 101 (2020) 023013

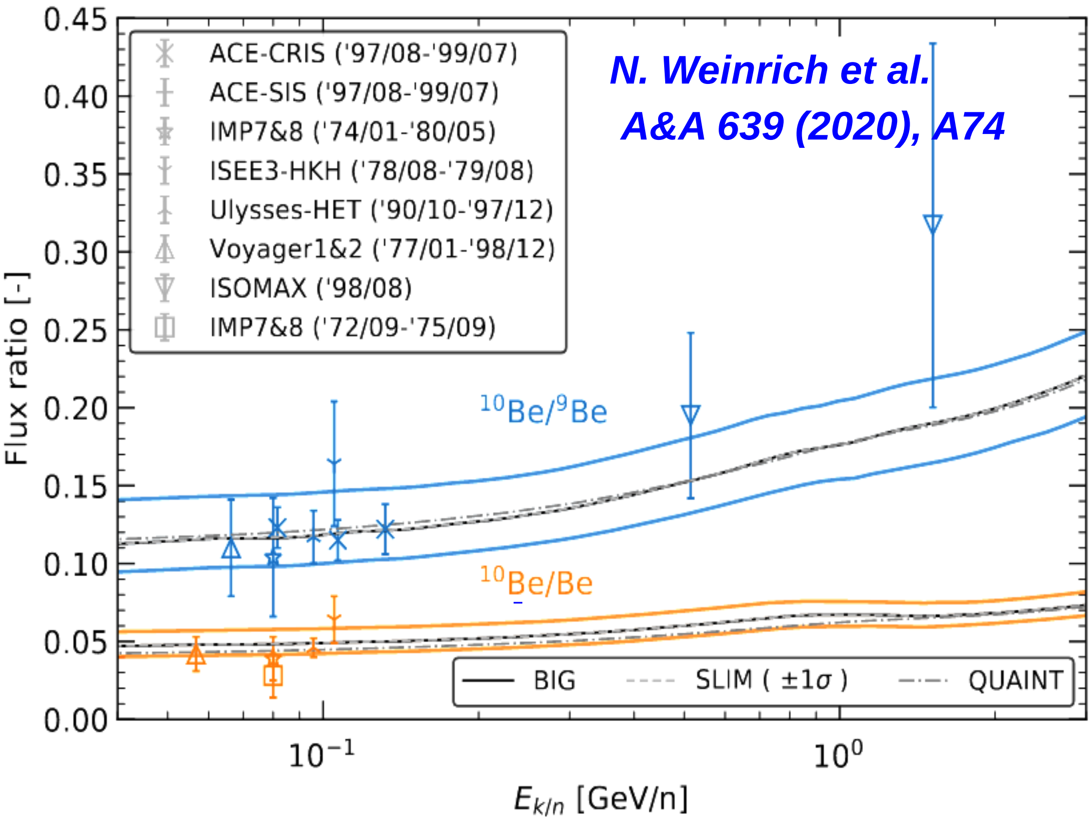
part of this rise is due to relativistic time dilatation

(some information encoded in Be/B being ^{10}B the daughter of ^{10}Be)

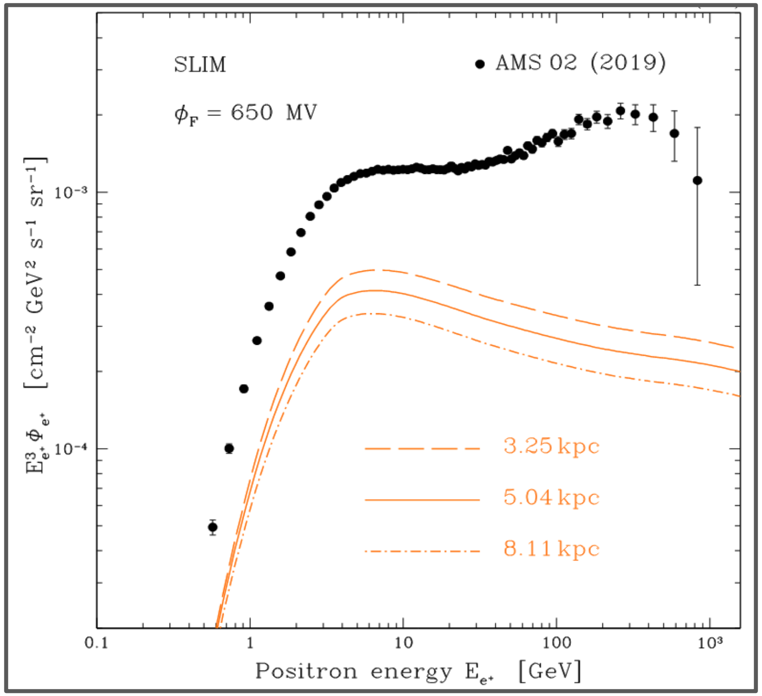


^{10}B status and impact on antimatter background

AMS-02 data Li/C B/C and Be/B used to tune USINE
(semi analytical propagation model)



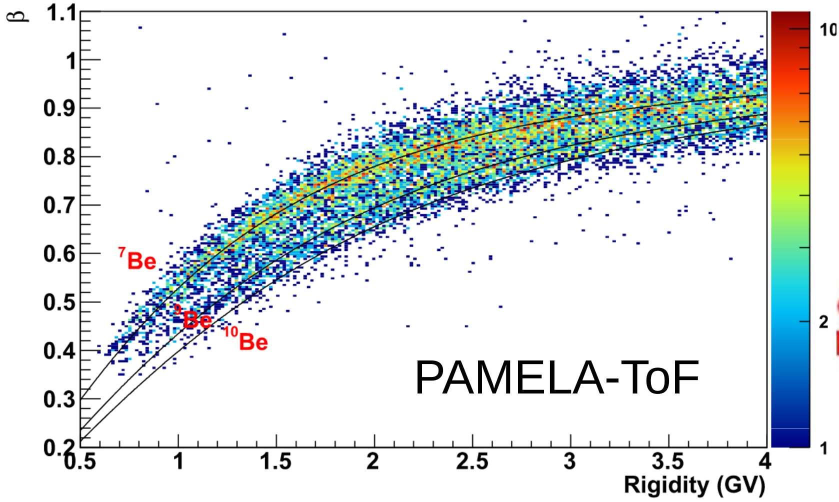
N. Weinrich et al.
A&A 639 (2020), A74

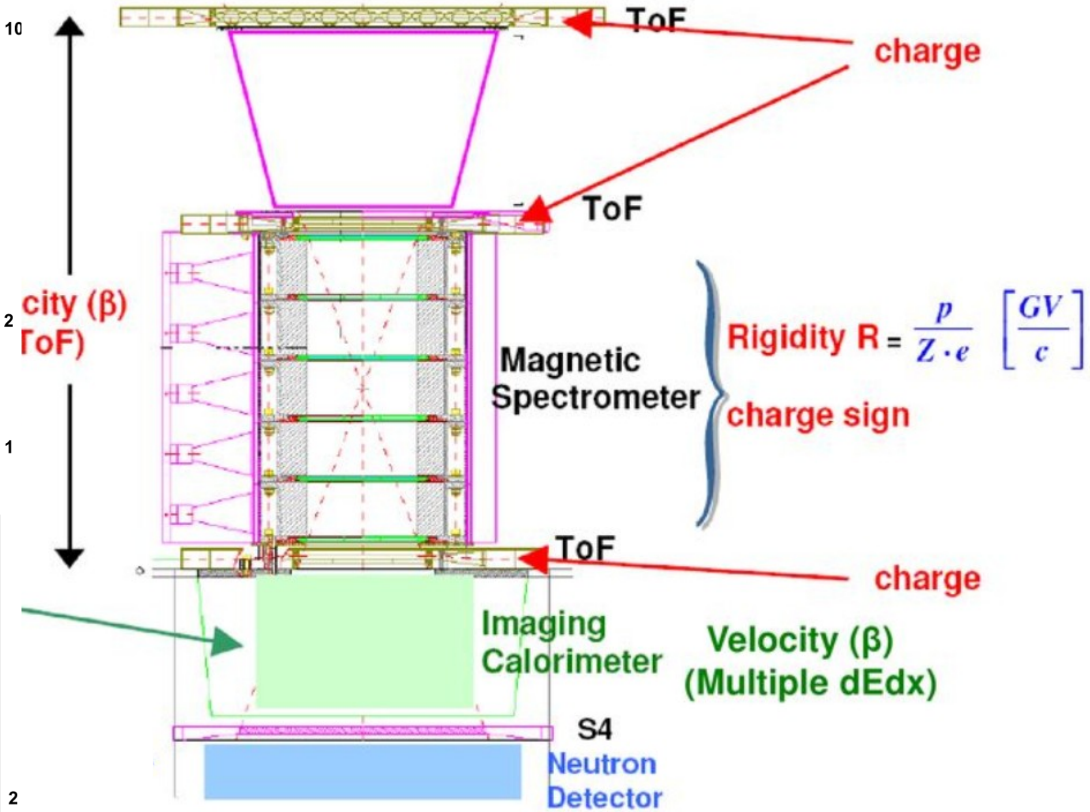


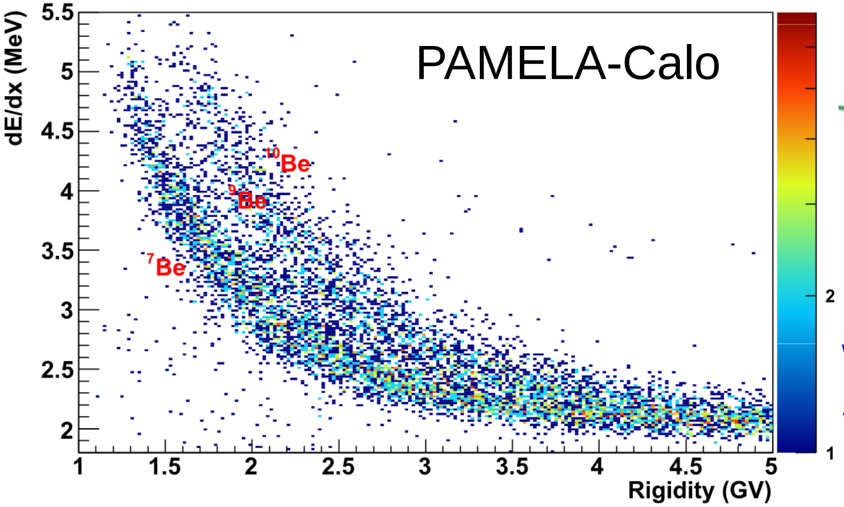
^{10}Be/^{9}Be can be predicted by model with uncertainties much larger than the direct measurement obtained by MAGNETIC SPECTROMETERS in SPACE

Example of the impact of uncertainty in halo thickness parameter H, on the expected secondary positron flux.
An improved knowledge of H will help in the study of the unknown Positron source (Pulsar, DM, … ?)

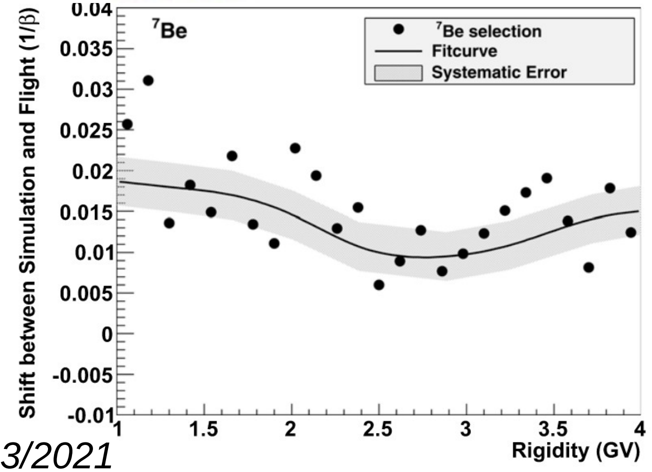
Example: Beryllium measured by PAMELA Spectrometer







W. Menn et. al.
APJ 862 (2018) 141



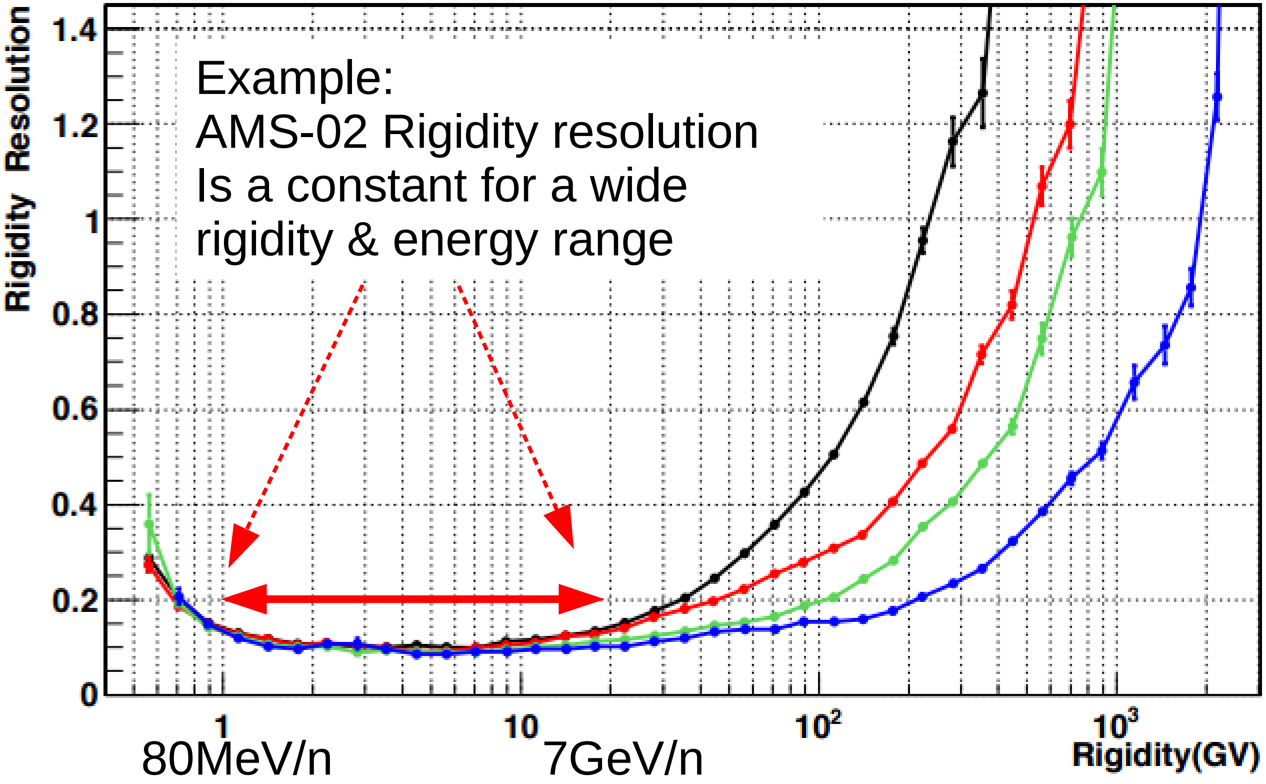
Due to a **NON-perfect Monte-Carlo simulation** ↔
PAMELA was not able to measure ^{10}Be/^{9}Be
but only the complementary ^{7}Be/(^{9}Be+^{10}Be)

The mass resolution in magnetic spectrometers

$$\frac{\delta M}{M} = \sqrt{\boxed{\left(\frac{\delta R}{R}\right)^2} + \boxed{\gamma^4 \left(\frac{\delta\beta}{\beta}\right)^2}}$$

This term is constant for fixed β
(i.e. within the same E_k/n bin)

This term is dominated by Multiple Coulomb Scattering
i.e. is constant in a wide kinetic energy range



Example:
AMS-02 Rigidity resolution
Is a constant for a wide
rigidity & energy range

therefore:
the mass resolution
is
=> CONSTANT <=
(for a fixed E_k/n)

… this allows to get rid of Monte Carlo predictions of the isotope mass distributions ...

The “Data Driven” approach (all the boring Math)

A 3x3 equation system of the unknown “templates”: T_7, T_9, T_{10} (fixing isotopic fractions f_x)

$$
\begin{aligned}
D(x) &= f_7 T_7 + f_9 T_9 + f_{10} T_{10} \\
A_{7,9} D(x) &= f_7 T_9 + f_9 A_{7,9} T_9 + f_{10} A_{7,9} T_{10} \\
A_{7,10} D(x) &= f_7 T_{10} + f_9 A_{7,10} T_9 + f_{10} A_{7,10} T_{10}
\end{aligned}
$$

=> Measured mass distribution

=> $A_{7,9}$ known dilatation (7=>9)

=> known dilatation (7=>10)

Can be solved iteratively knowing that $f_7 > f_9 > f_{10}$:

$$
\begin{aligned}
T_7 &= \frac{1}{f_7}\left[D - \frac{f_9}{f_7} A_{7,9} D - \frac{f_{10}}{f_7} A_{7,10} D\right] + \\
&+ \frac{f_9 f_9}{f_7^2} T_{G1} + \frac{f_9 f_{10}}{f_7^2} T_{G2} + \frac{f_{10} f_9}{f_7^2} T_{G3} + \frac{f_{10} f_{10}}{f_7^2} T_{G4}
\end{aligned}
$$

(main and “known” quantities)

(small corrections: “ghost”)

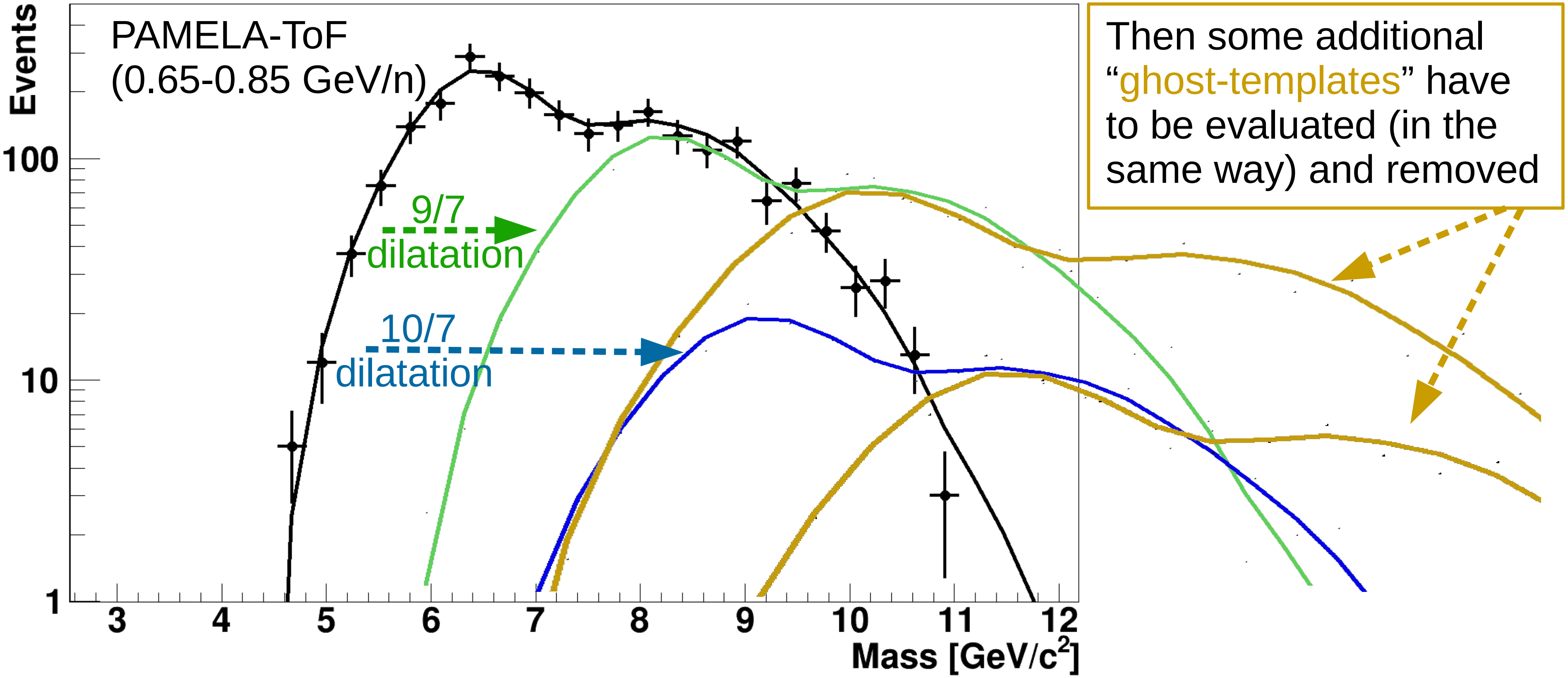
$$
\left.
\begin{aligned}
T_{G1} &= A_{7,9} T_9 \simeq L_{7,x_{G1}} T_7 \quad \text{@ 11.5 amu} \\
T_{G2} &= A_{7,9} T_{10} \simeq L_{7,x_{G2}} T_7 \quad \text{@ 13 amu} \\
T_{G3} &= A_{7,10} T_9 \simeq L_{7,x_{G3}} T_7 \quad \text{@ 13 amu} \\
T_{G4} &= A_{7,10} T_{10} \simeq L_{7,x_{G4}} T_7 \quad \text{@ 14 amu}
\end{aligned}
\right\}
$$

“ghost” templates are small corrections of the tail of T_7 and are “far” (placed above T_{10})

The “Data Driven” approach (how to get rid of MC)

A self-consistent approach to extract isotope mass distributions from data itself.
(it is a solution of the 3x3 equation system of the mass distributions: “templates”)

An intuitive/graphical view: The unknown templates are related by: δM/M = constant
Linear transf. approximation: templates are related by (known) coordinate dilatation



Then some additional “ghost-templates” have to be evaluated (in the same way) and removed

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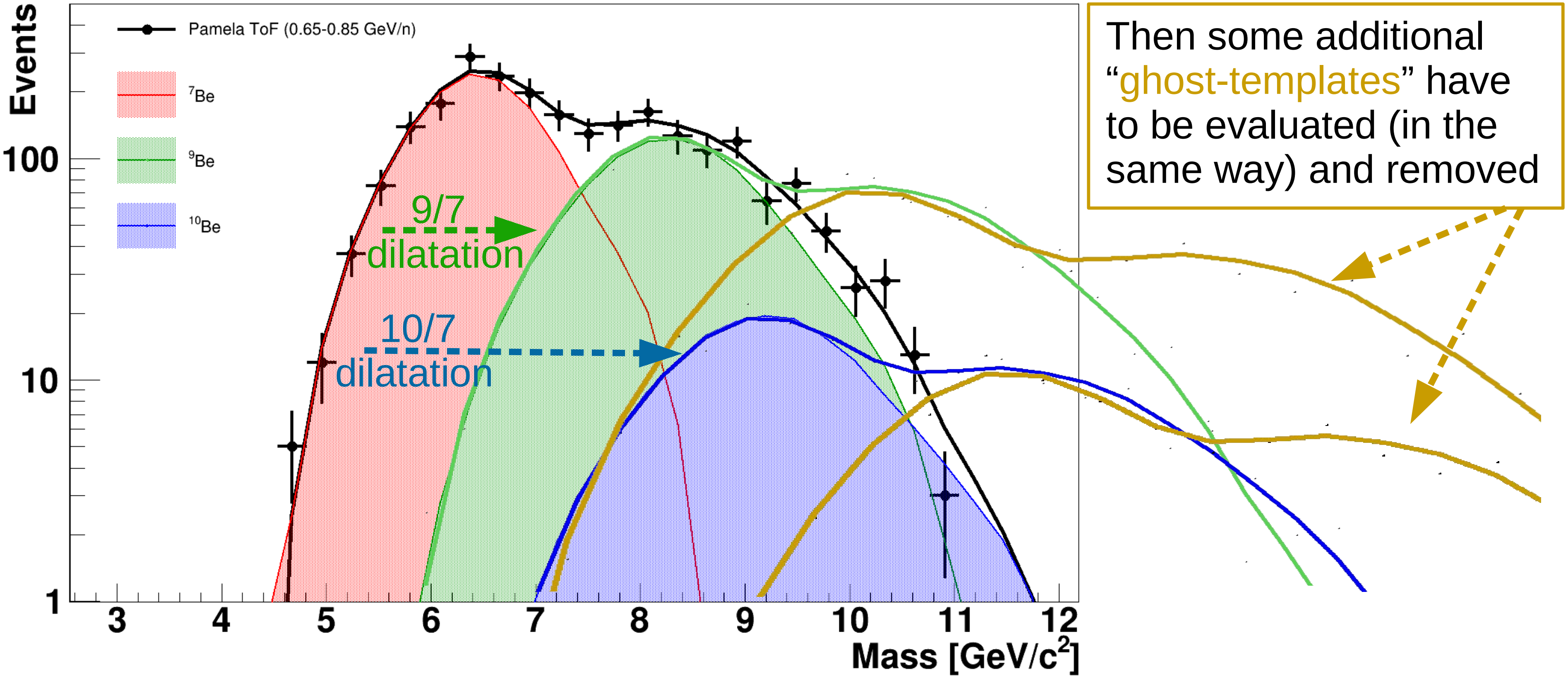

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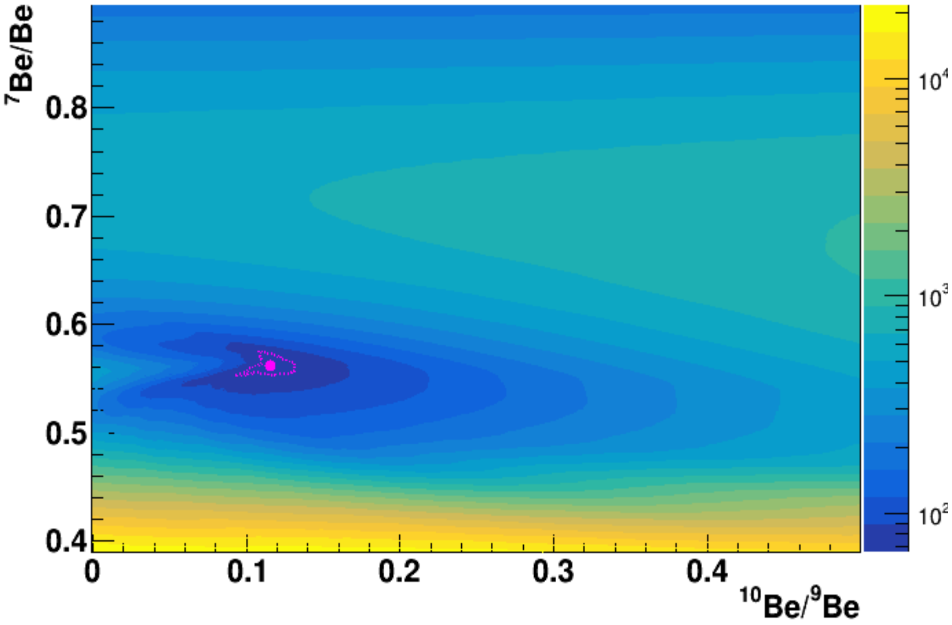
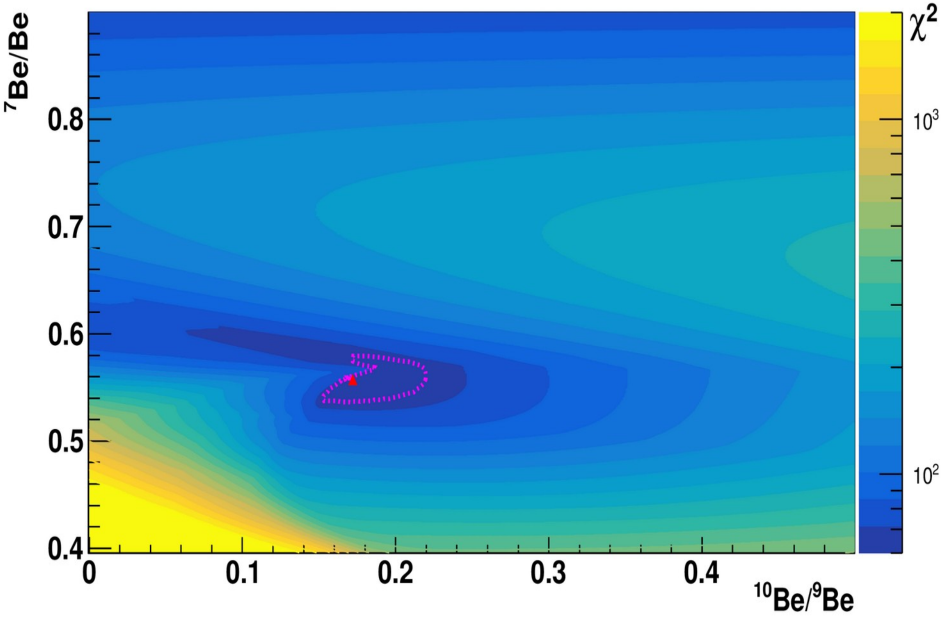
The map of χ^2 configurations

A χ^2 value can be evaluated for each configuration in the plane $< f_7$ and $f_{10}/f_9 >$ leading to a 2D confidence interval of the physical minimum.

PAMELA-Calo 0.2-0.52 GeV/n

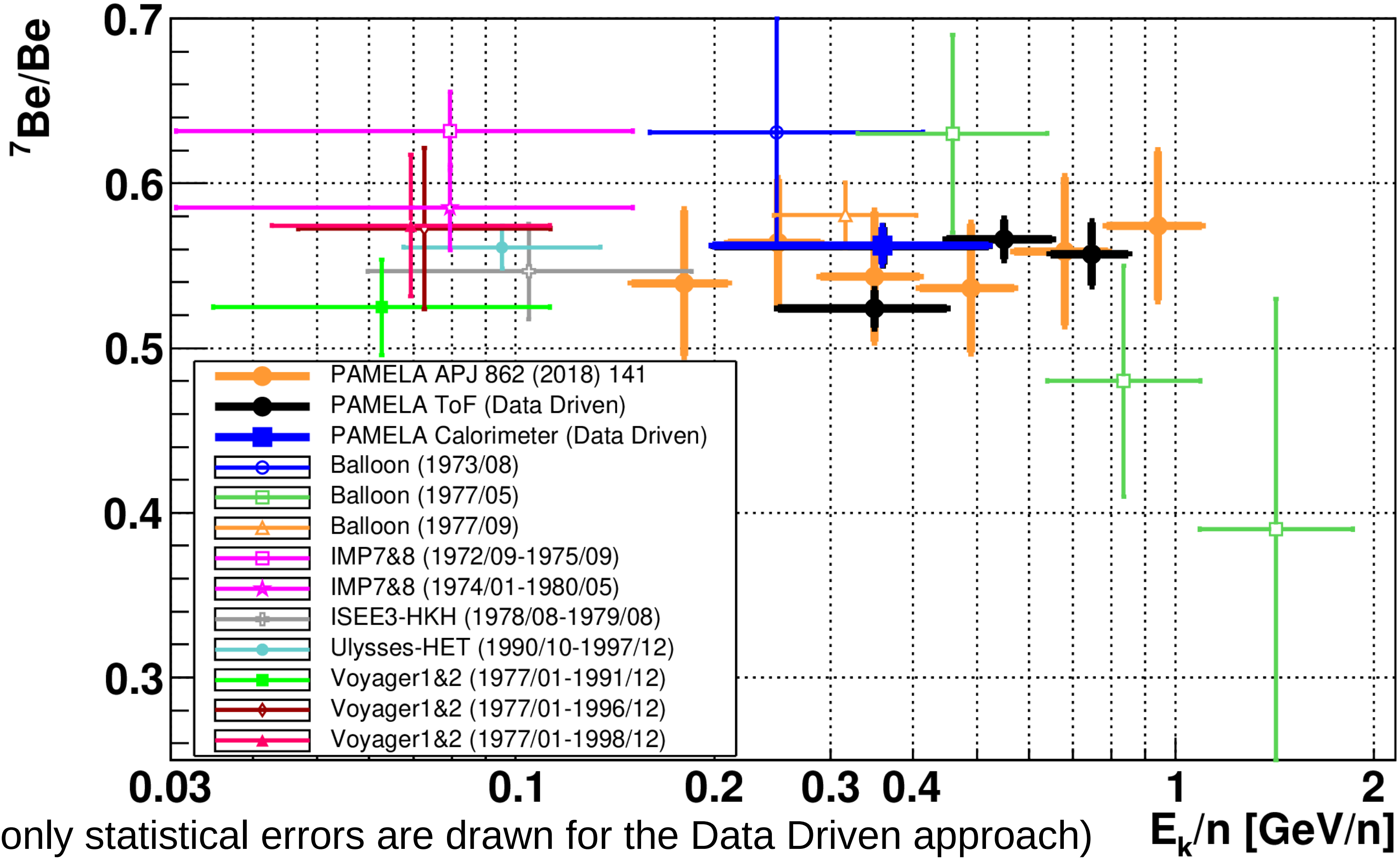


PAMELA-ToF 0.65-0.85 GeV/n



statistical bootstrap performed to treat the naive un-physical solutions: $f_7=1$, $f_9=1$, $f_{10}=1$ (characterized by a null χ^2 value) this is a detail important only for scarce statistics.

Comparison with previous measurements ^{7}Be/Be

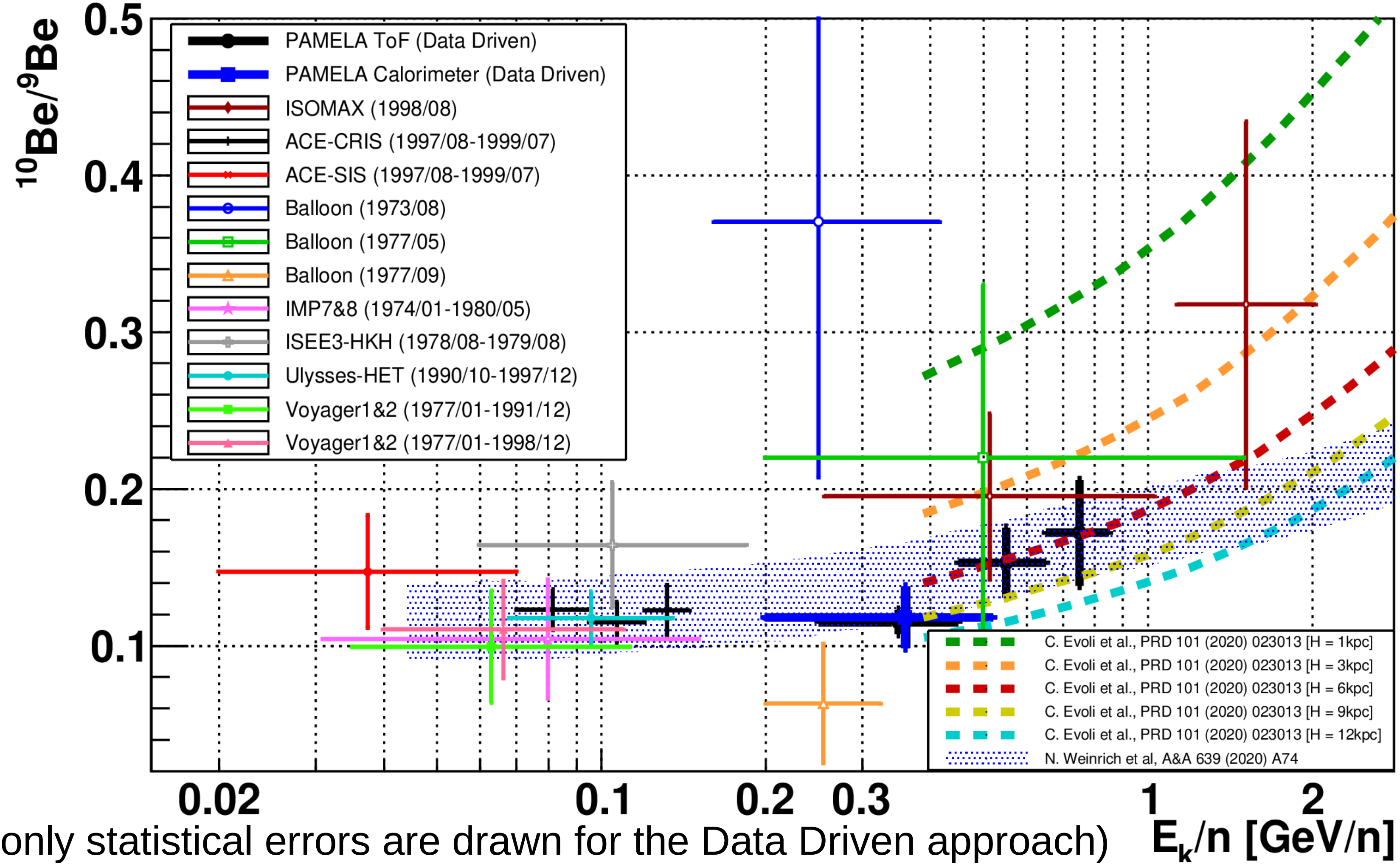


(only statistical errors are drawn for the Data Driven approach)

-Data Driven results for PAMELA-ToF and PAMELA-Calo are in reasonable agreement

-Both are compatible with published (MC based) PAMELA result.

a “new” measurement for ^{10}Be/^{9}Be

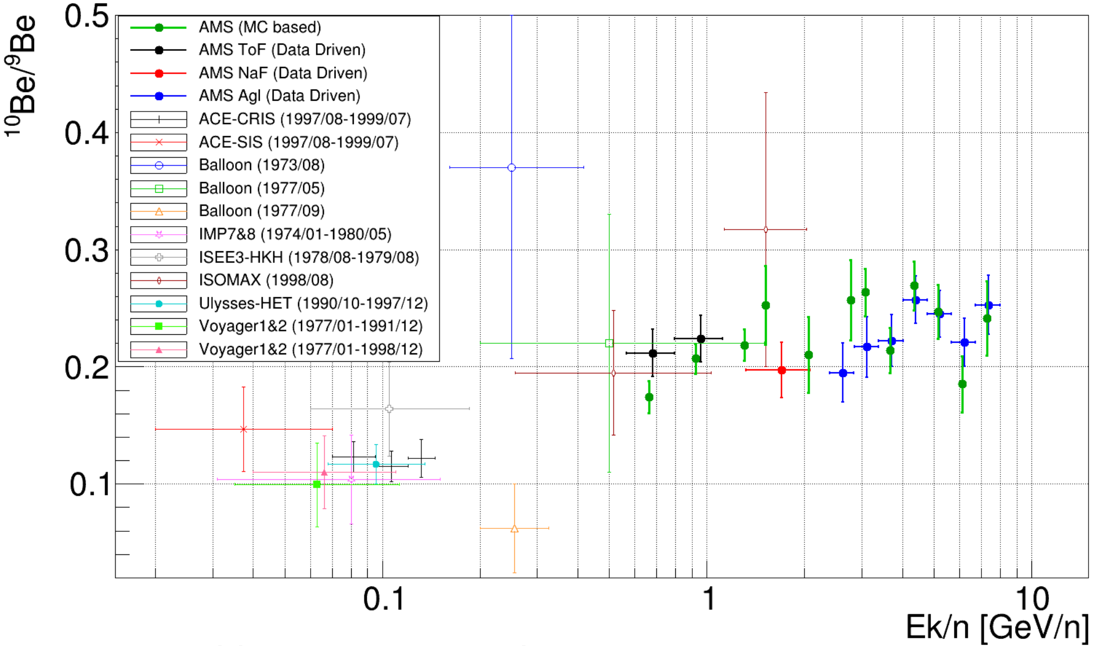


(only statistical errors are drawn for the Data Driven approach)

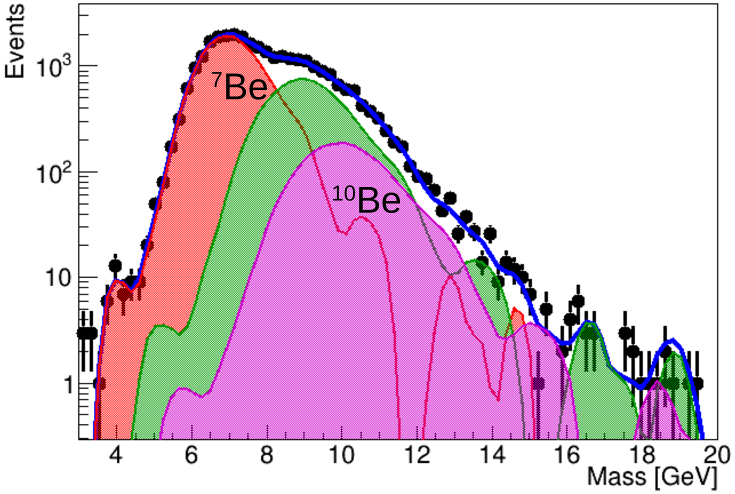
-Data Driven results for PAMELA improves our knowledge of ^{10}Be/^{9}Be at “high-Energy”

-Compatibility with theoretical expectations

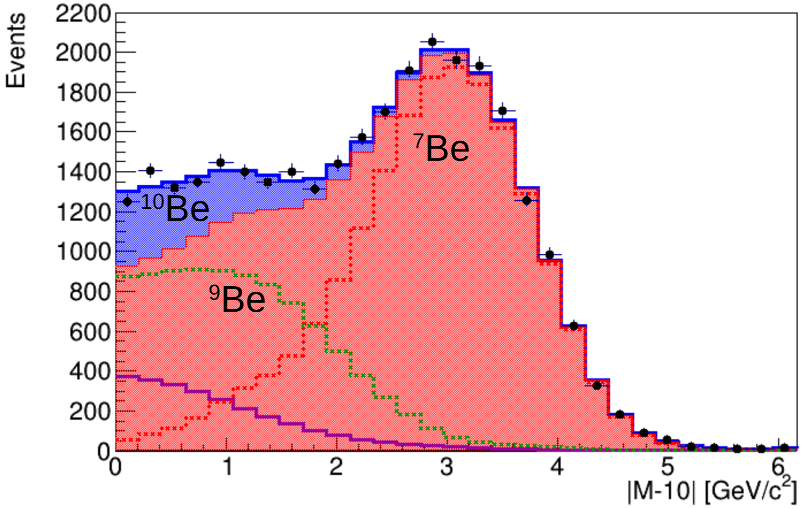
Application to AMS-02 Beryllium

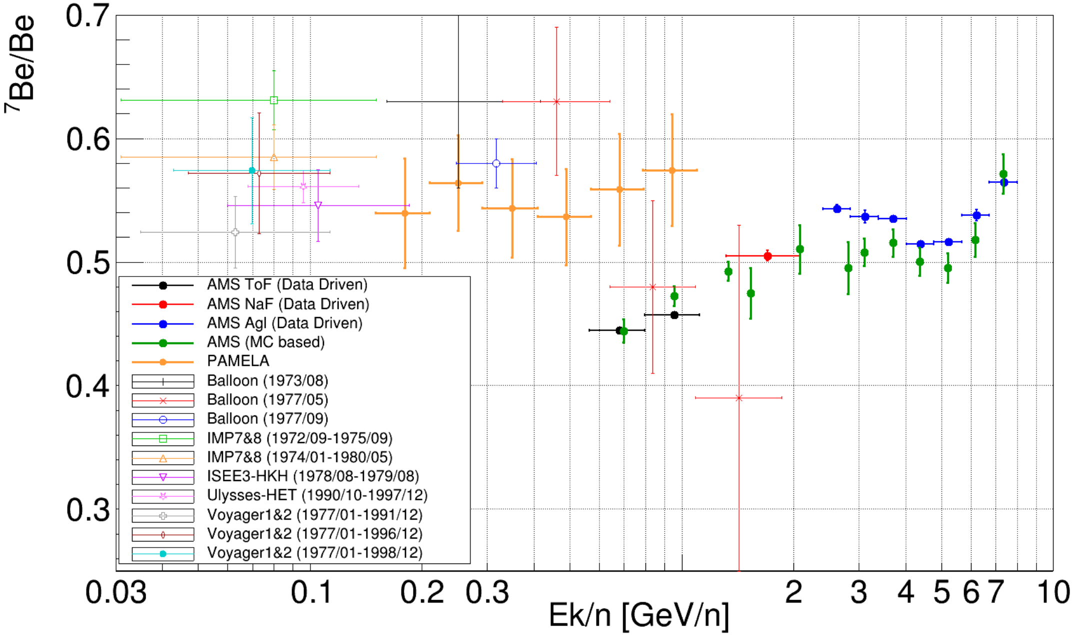


Last bin of Agl: Data Driven templates



Last bin of Agl: Data Driven templates
a stacked representation





conclusions

Be isotopic composition is a key quantity to improve CR propagation models

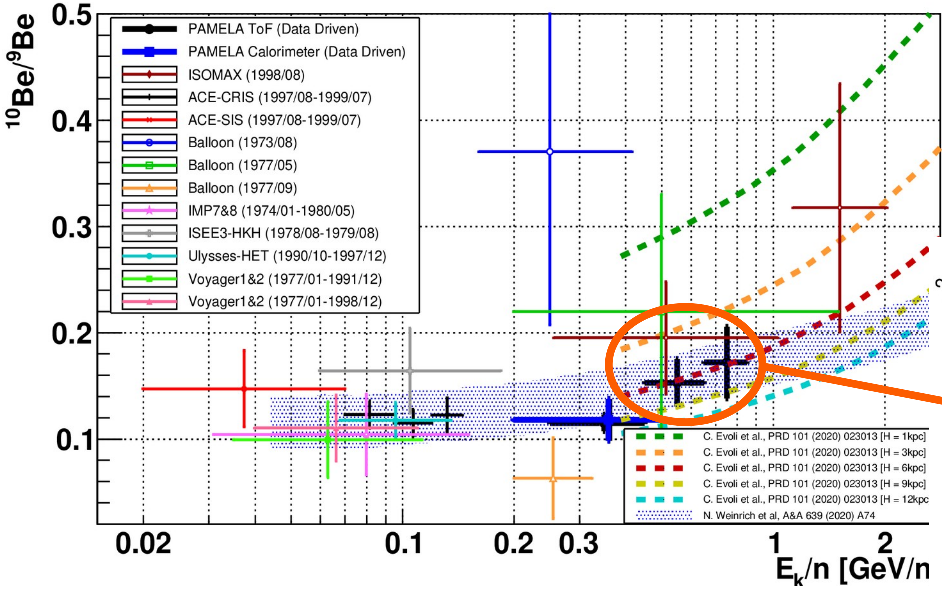
^{10}Be is subdominant, its measurement requires a very good MC simulation

As an example, the very good Beryllium data collected by PAMELA experiment has not provided the important ^{10}Be/^{9}Be measurement because of a not perfect MC simulation

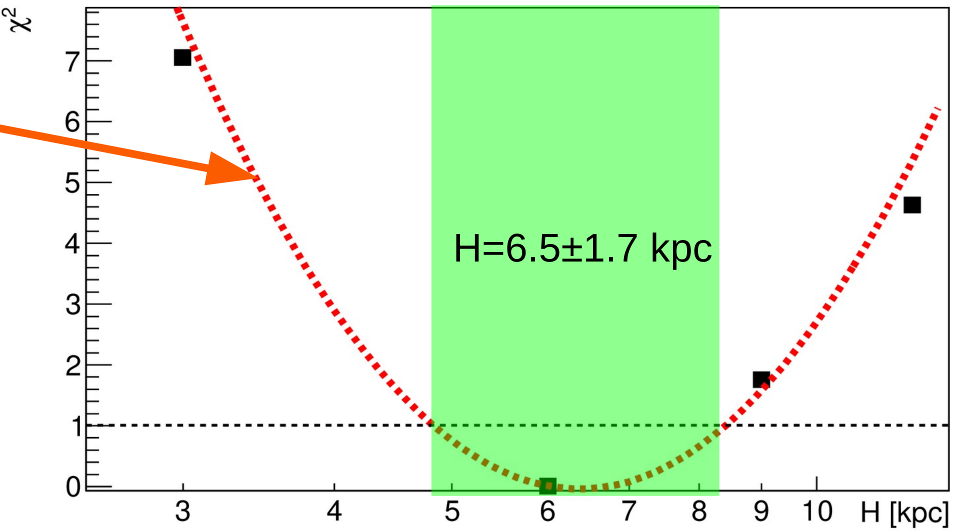
Developed a “Data Driven” approach to measure ^{10}Be/^{9}Be without the use of MC

….in the following some qualitative/naive comparison with THEORY

Example of sensitivity to Halo thickness: PAMELA

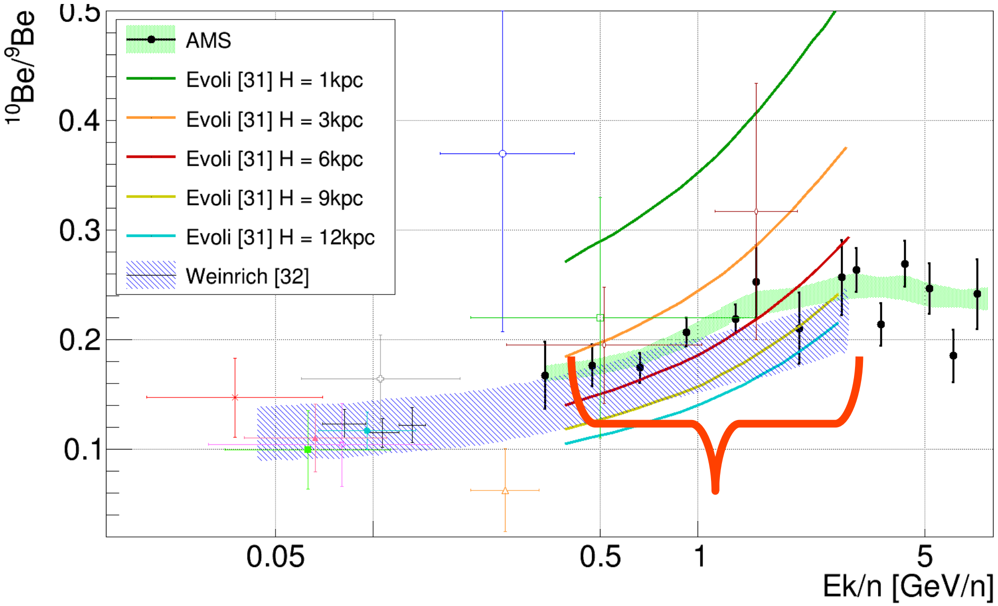


Example: assuming the model of C. Evoli [Phys. Rev. D 101 (2020) 023013] fitting the sub-range 0.45-0.85 GeV/n



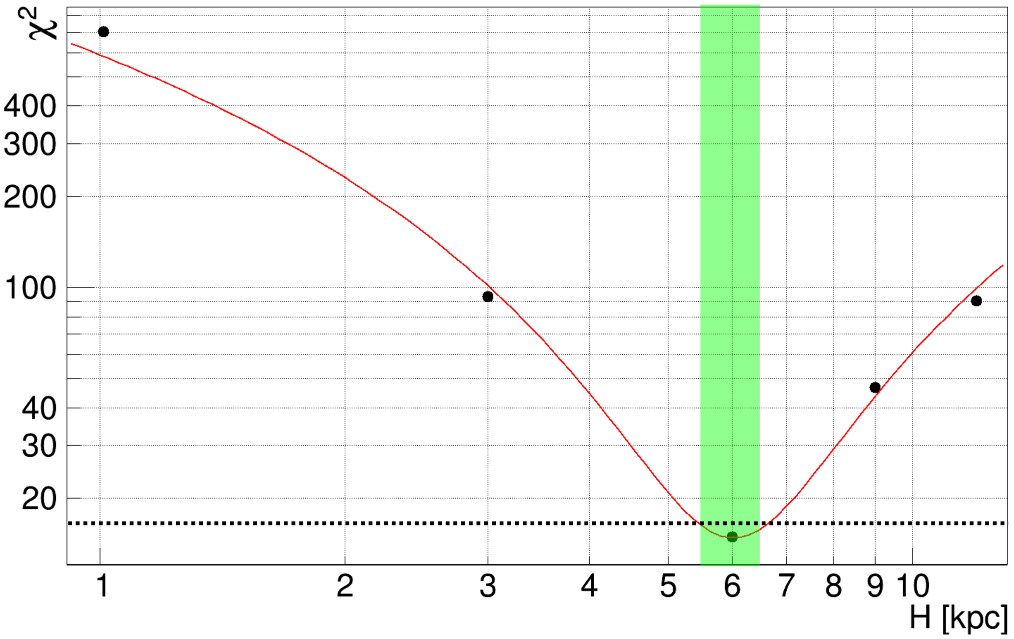
The comparison of ^{10}Be/^{9}Be (and the complementary ^{7}Be/Be) with theory models (once tuned accounting for these measured ratios) will provide a ~ 25% precision measurement for H parameter that is currently affected by large uncertainties. (currently H = 3-8 kpc)

Example of sensitivity to Halo thickness: AMS



Example: assuming the model of C. Evoli
[Phys. Rev. D 101 (2020) 023013]
fitting the sub-range 0.4-3.5 GeV/n

H=6.0±0.5 kpc



The behavior of $^{10}Be/^{9}Be$ seems flattening for E > 3.5GeV/n
This is very interesting.

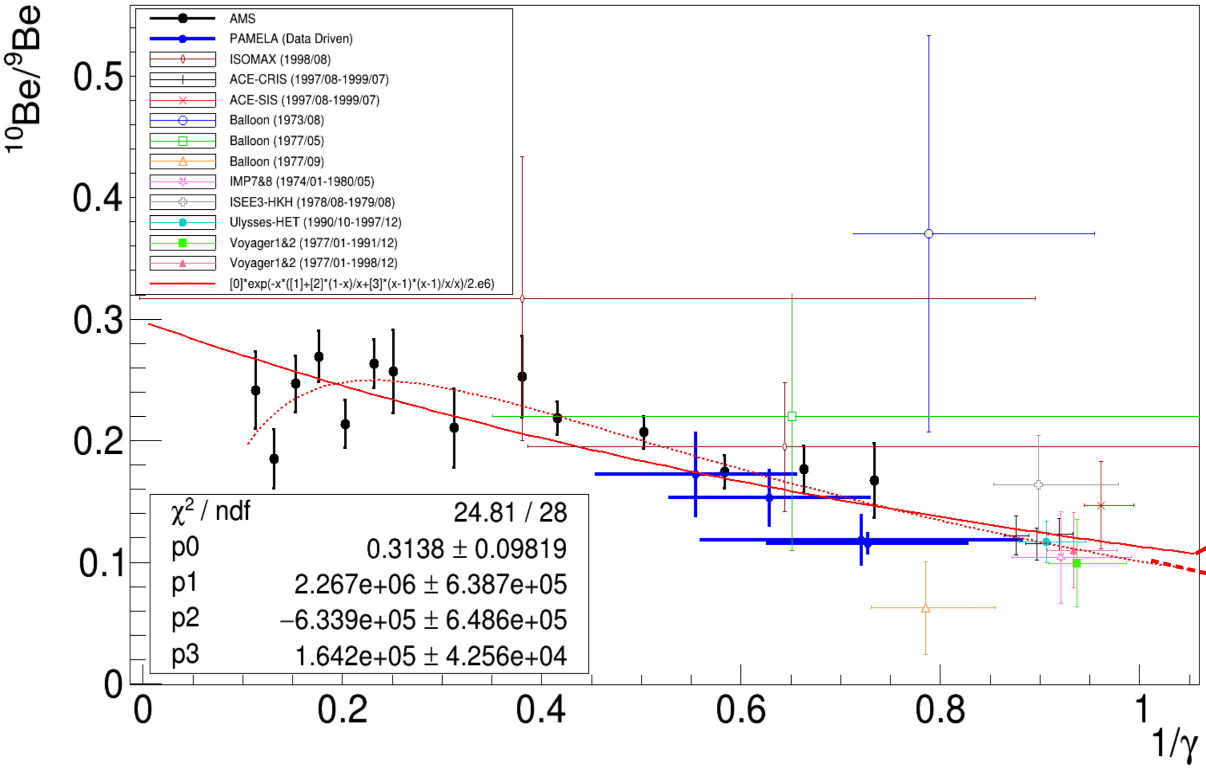
It is useful to study also the comparison with $^{7}Be/Be$ theoretical expectations

a naive/toy model

Energy dependence modeled as
a Relativistic Time Dilatation: $\tau = T_{1/2}/\log(2) \approx 2\,My$

$$\frac{^{10}Be}{^{9}Be}(\gamma) = \left.\frac{^{10}Be}{^{9}Be}\right|_{T=0} e^{-\frac{T(\gamma)}{\gamma\tau}}$$

$$T(\gamma) = \underset{\substack{\uparrow \\ \text{Low energy avg residence time}}}{T_0} + \underbrace{(\gamma-1)T_1 + (\gamma-1)^2 T_2 + \dots}_{\text{Propagation effects (energy dependent)}}$$



$T_0 = 2.3 \pm 0.6\,My$

$T_1 = -0.6 \pm 0.6\,My$

$T_2 = 0.16 \pm 0.04\,My$

Exponential “pure Time Dilatation”:
T_0 = 1.94 ±0.15My; T_1=0; T_2=0

Time Dilation + Propagation effects

Relativistic Dilatation effect seems important:
Low energy average residence time:
T_0 = 1.7-2.9 My   Production fraction 0.3±0.1

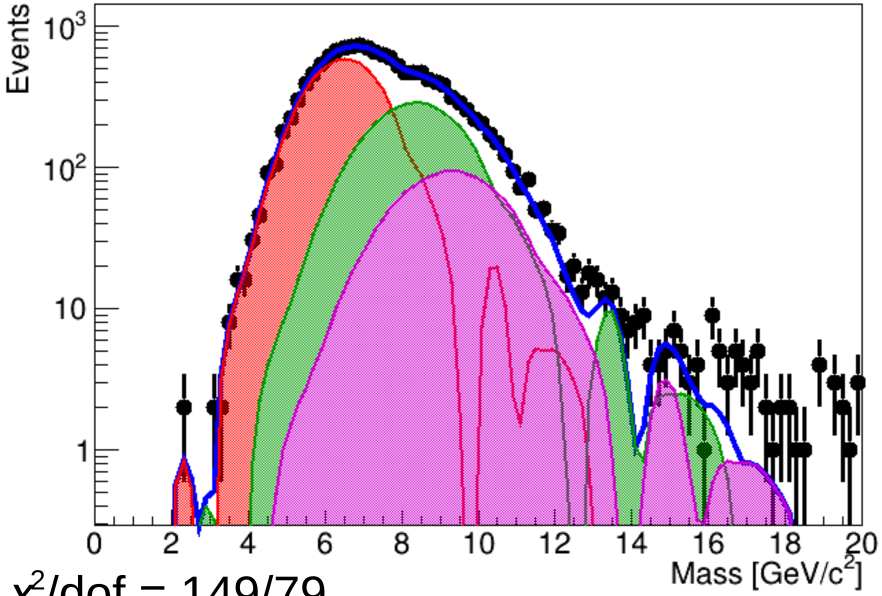
Some TEST of the Data Driven fitting method

method verification with a Toy model

toy-experiment generated by gaussian + a power-law right tail

same statistics & same signal

14kevents ^{9}Be/Be = 0.314 ^{10}Be/Be = 0.13



x^2/dof = 149/79

^{9}Be/Be = 0.340 ^{10}Be/Be = 0.123

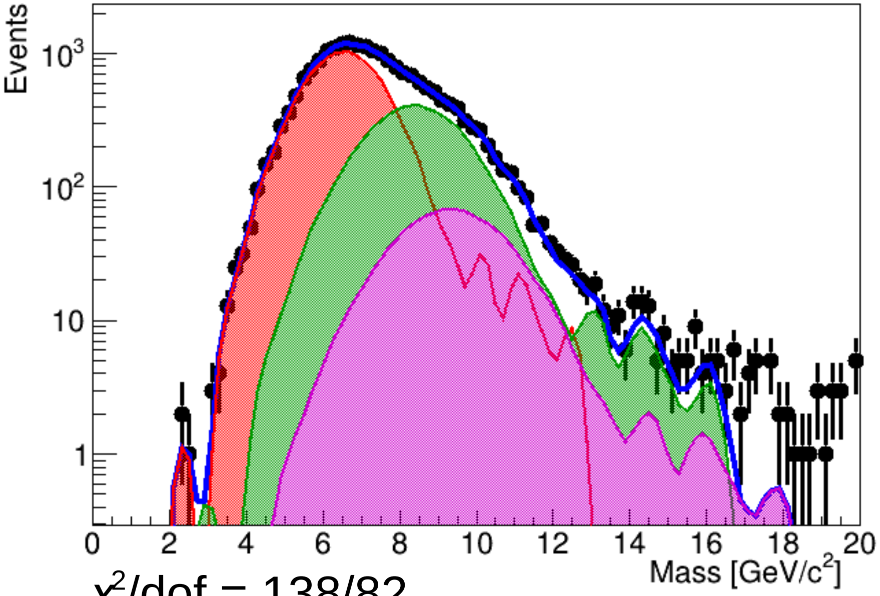
Unbiased 1σ (68% C.L.) intervals:

$0.086 <$ ^{10}Be/Be < 0.131 RMS 0.01

$0.304 <$ ^{9}Be/Be < 0.354 RMS 0.007

3/2 statistics & 1/2 signal

21kevents ^{9}Be/Be = 0.314 ^{10}Be/Be = 0.065



x^2/dof = 138/82

^{9}Be/Be = 0.318 ^{10}Be/Be = 0.059

Unbiased 1σ (68% C.L.) intervals:

$0.046 <$ ^{10}Be/Be < 0.069 RMS 0.005

$0.310 <$ ^{9}Be/Be < 0.331 RMS 0.006

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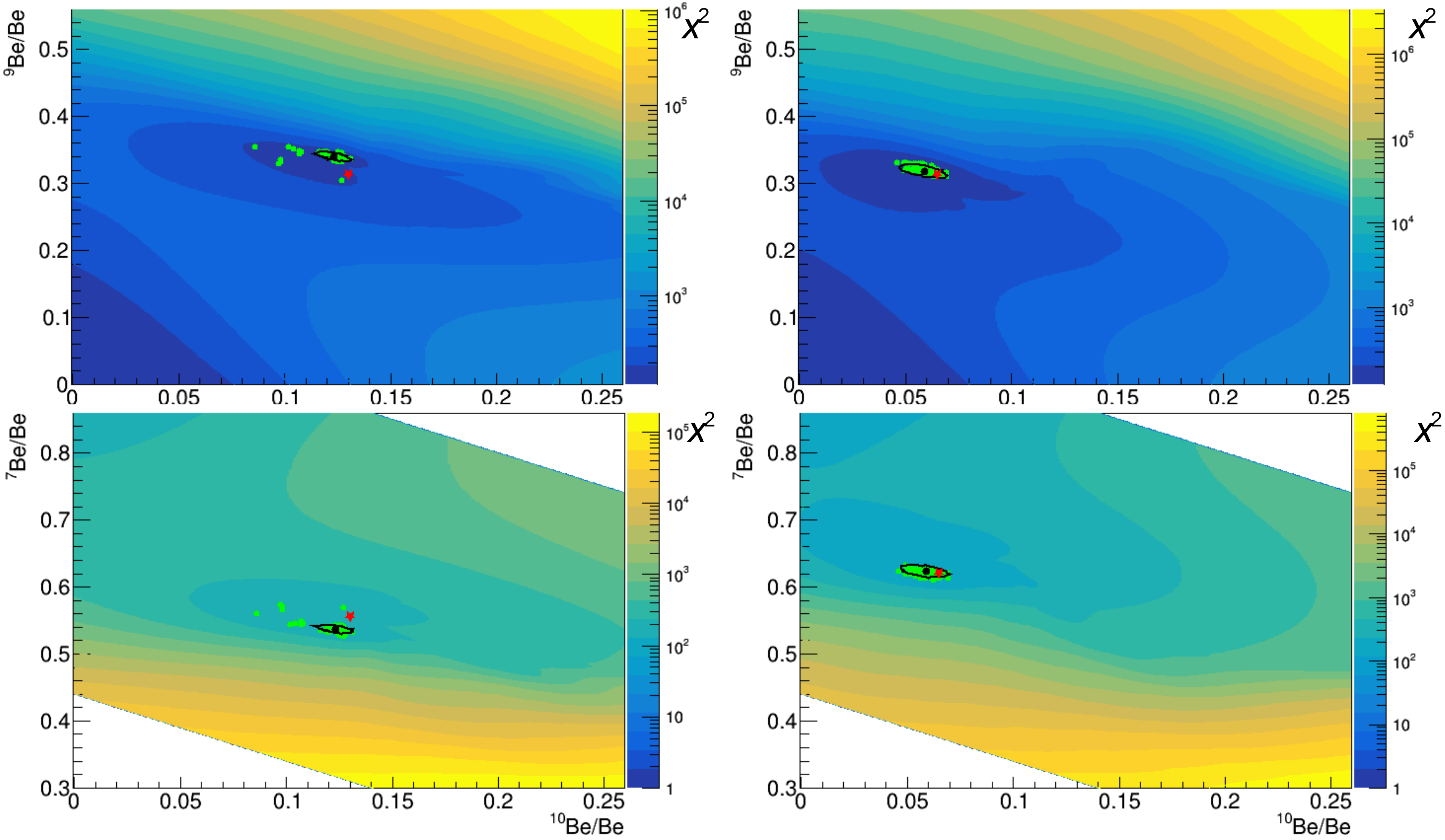
Toy-model confidence intervals



same statistics & same signal

3/2 statistics & 1/2 signal

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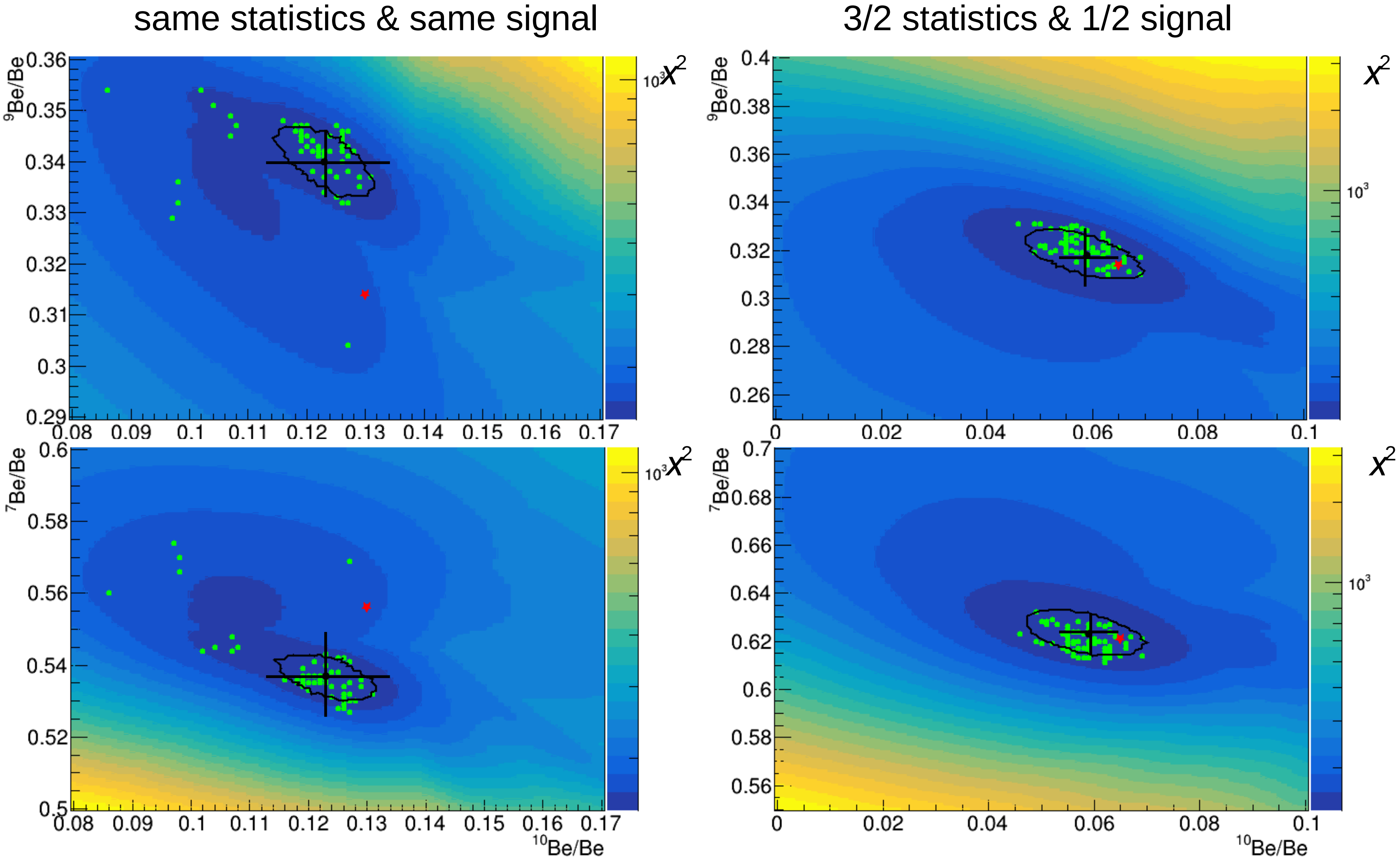
Toy-model confidence intervals: zoom



same statistics & same signal

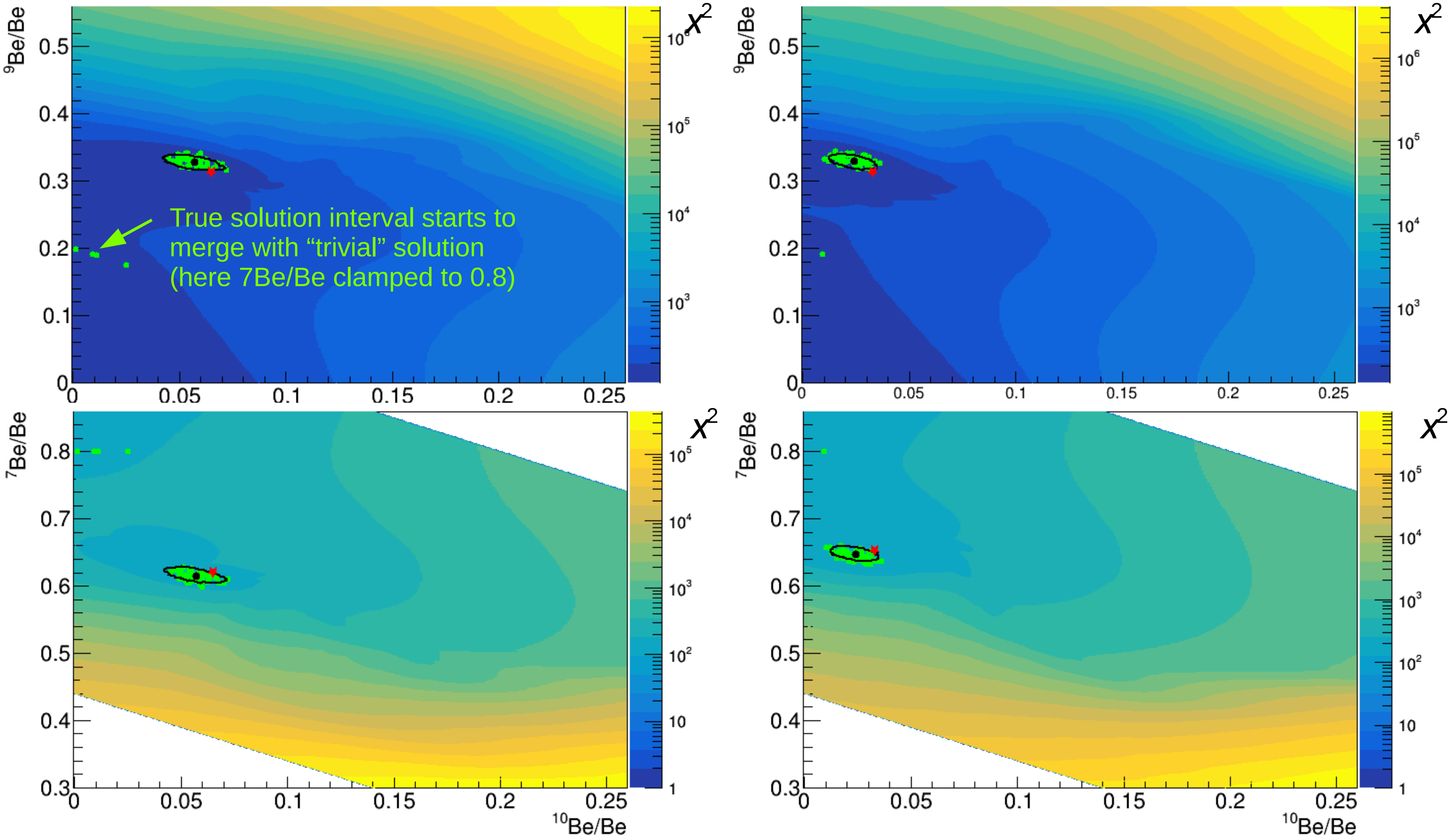
3/2 statistics & 1/2 signal

F. Nozzoli – INFN/Trento

Toy-model confidence intervals: hard task

same statistics & 1/2 signal

3/2 statistics & 1/4 signal

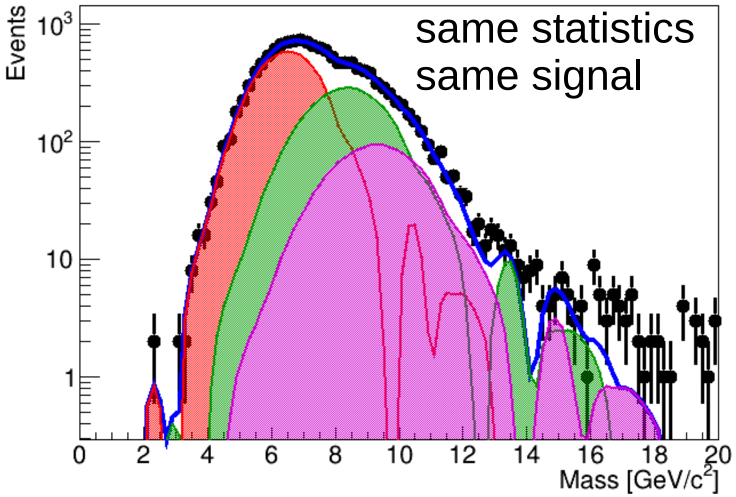


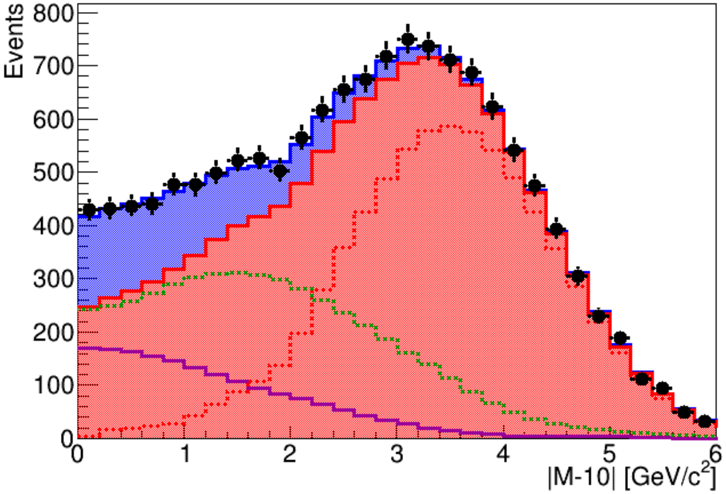
True solution interval starts to merge with “trivial” solution (here 7Be/Be clamped to 0.8)

F. Nozzoli – INFN/Trento

The “stacked” plot

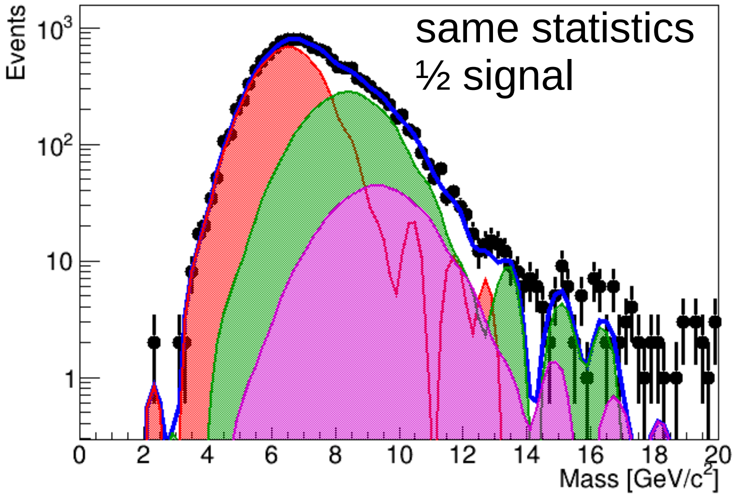
We know that the evidence for ^{10}Be is NOT VISUALLY CONVINCING

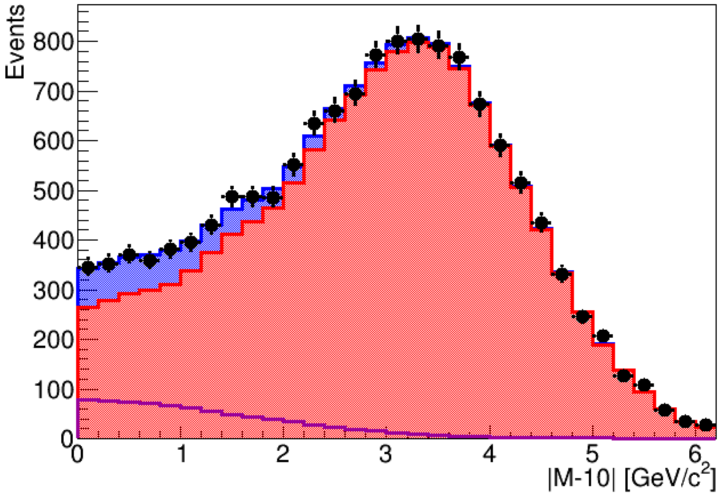




both are not “convincing”

“same” statistical evidence but “convincing”





F. Nozzoli – INFN/Trento