Possible cosmic ray tests of new physics

Kfir Blum
CERN & Weizmann Institute

Work with:
Boaz Katz, Eli Waxman,
Ryosuke Sato, Masahiro Takimoto, Kenny Ng,
Annika Reinert

1807.xxxxx, 1709.06507, 1709.04953, 1704.05431, 1305.1324, 1010.2836, 0907.1686

PACTS, Tallinn 2018

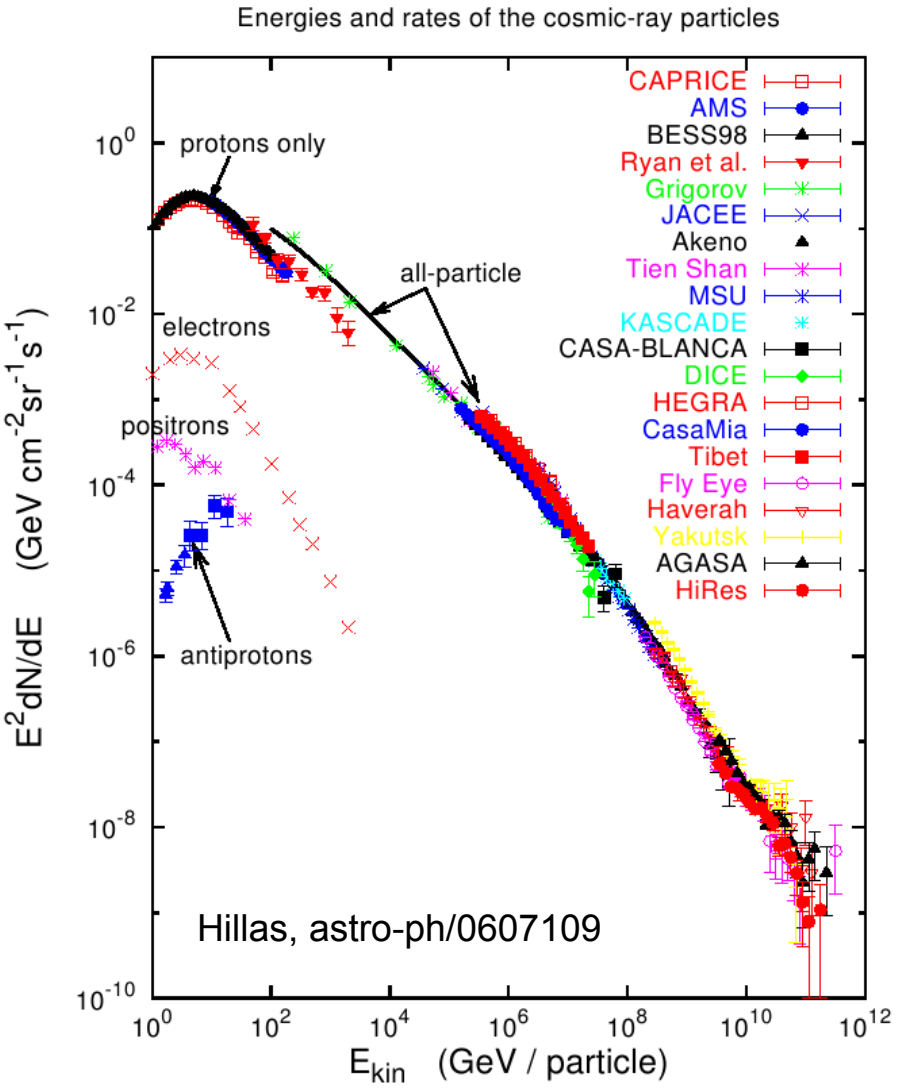
Cosmic ray antimatter is an interesting place to look for new physics.

Antiprotons

Positrons

Anti-He, anti-d

We could have, but we don't see (clear) hints for ~10 GeV thermal relic WIMPs in cosmic rays;
This does not mean we should stop looking.
(We don't see ~100 GeV SUSY at the LHC, but we shouldn't stop looking.)



Antiprotons

Antiprotons

Antiprotons are produced by CR proton collisions with interstellar matter (ISM).
The amount of antiprotons produced is proportional to the amount of ISM target.

How much ISM target is there?

Boron (B) is produced by fragmentation of CR C,N,O,… on ISM.
The amount of B produced is proportional to the amount of ISM target.

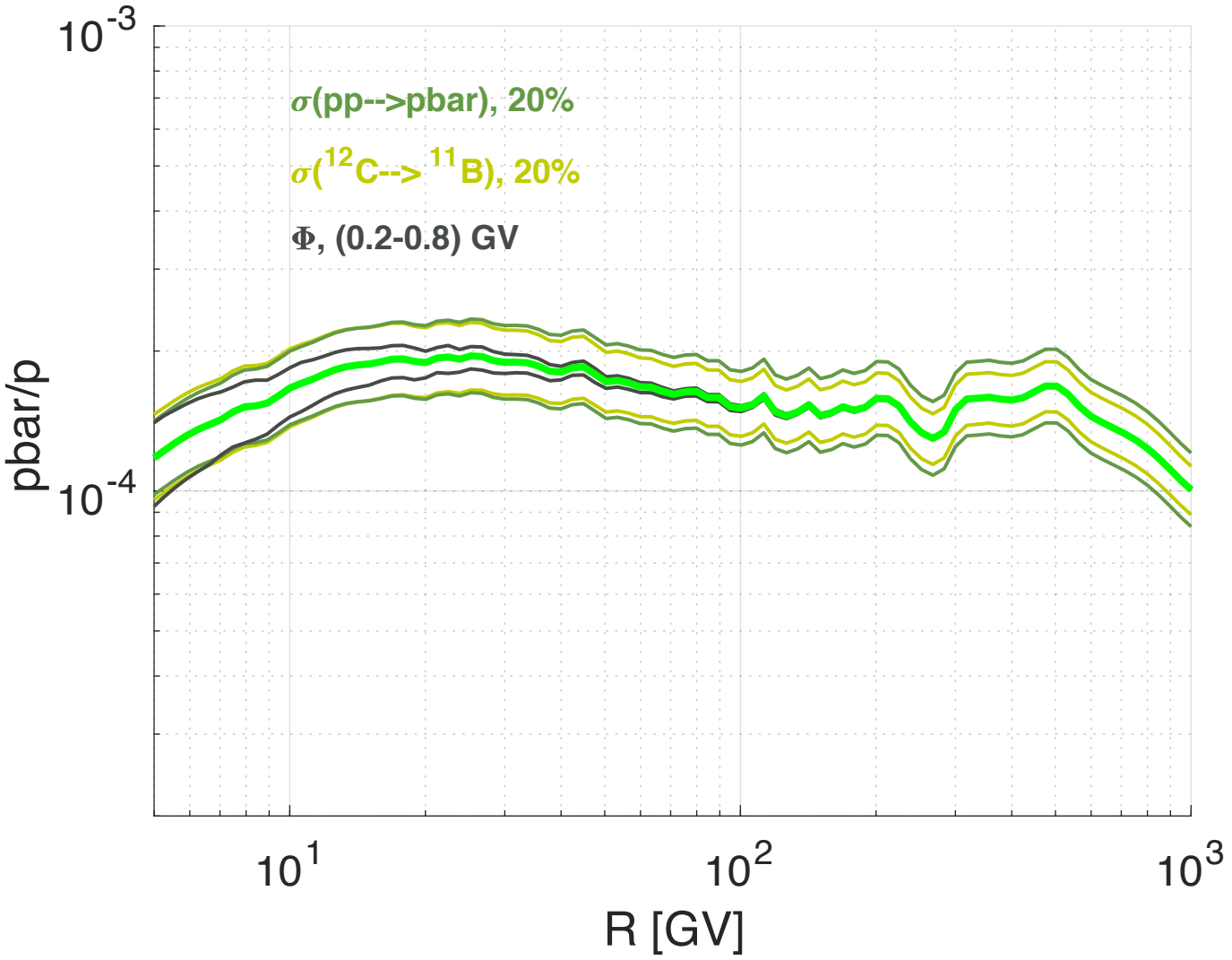
Simplest possibility:
Protons and C,N,O,… traverse roughly the same amount of ISM target.

Prediction:

$$n_{\bar{p}}(\mathcal{R}) \approx \frac{n_{\mathrm{B}}(\mathcal{R})}{Q_{\mathrm{B}}(\mathcal{R})} Q_{\bar{p}}(\mathcal{R})$$

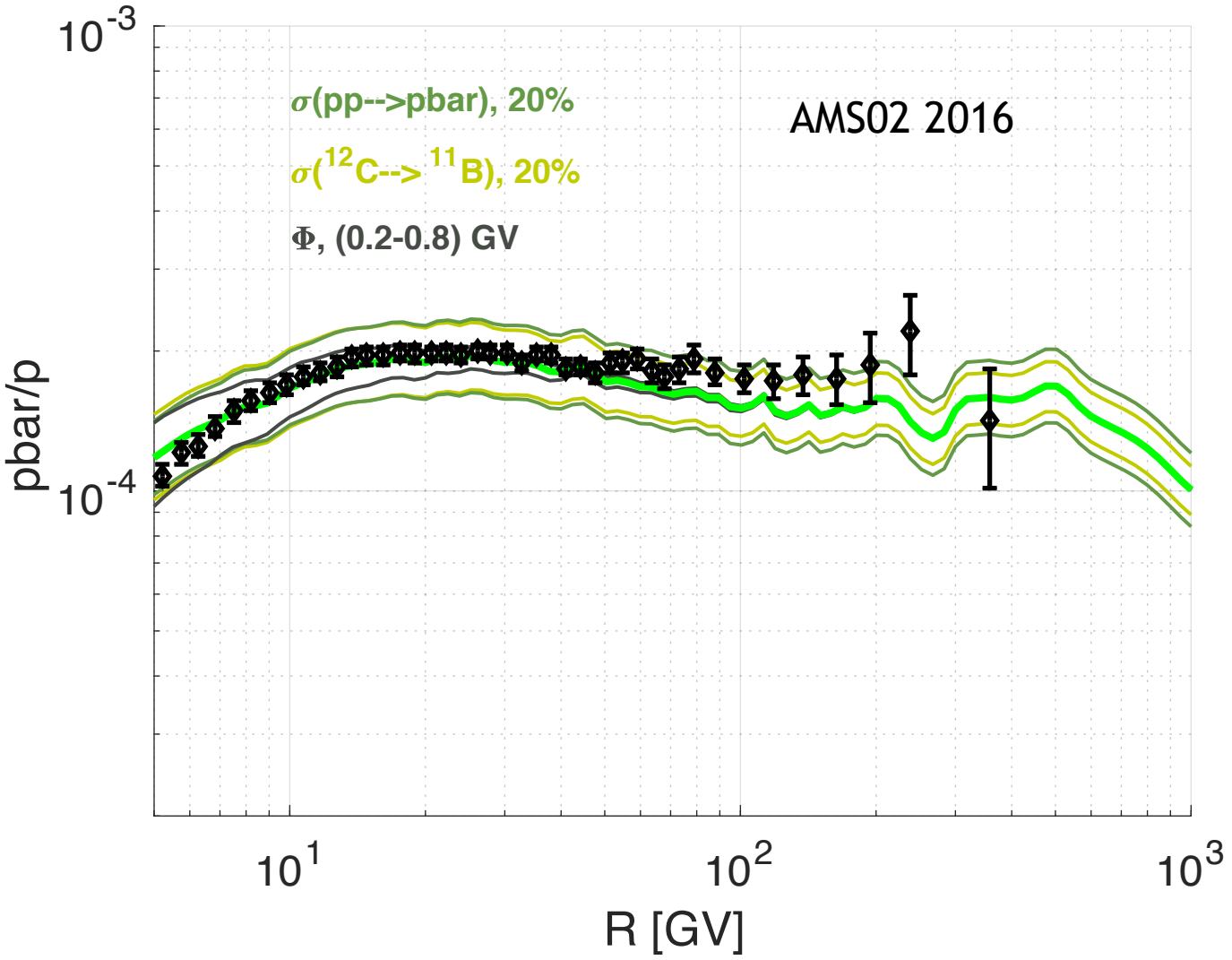
Antiprotons

$$n_{\bar{p}}(\mathcal{R}) \approx \frac{n_{\mathrm{B}}(\mathcal{R})}{Q_{\mathrm{B}}(\mathcal{R})} Q_{\bar{p}}(\mathcal{R})$$



Antiprotons

$$n_{\bar{p}}(\mathcal{R}) \approx \frac{n_{\mathrm{B}}(\mathcal{R})}{Q_{\mathrm{B}}(\mathcal{R})} Q_{\bar{p}}(\mathcal{R})$$



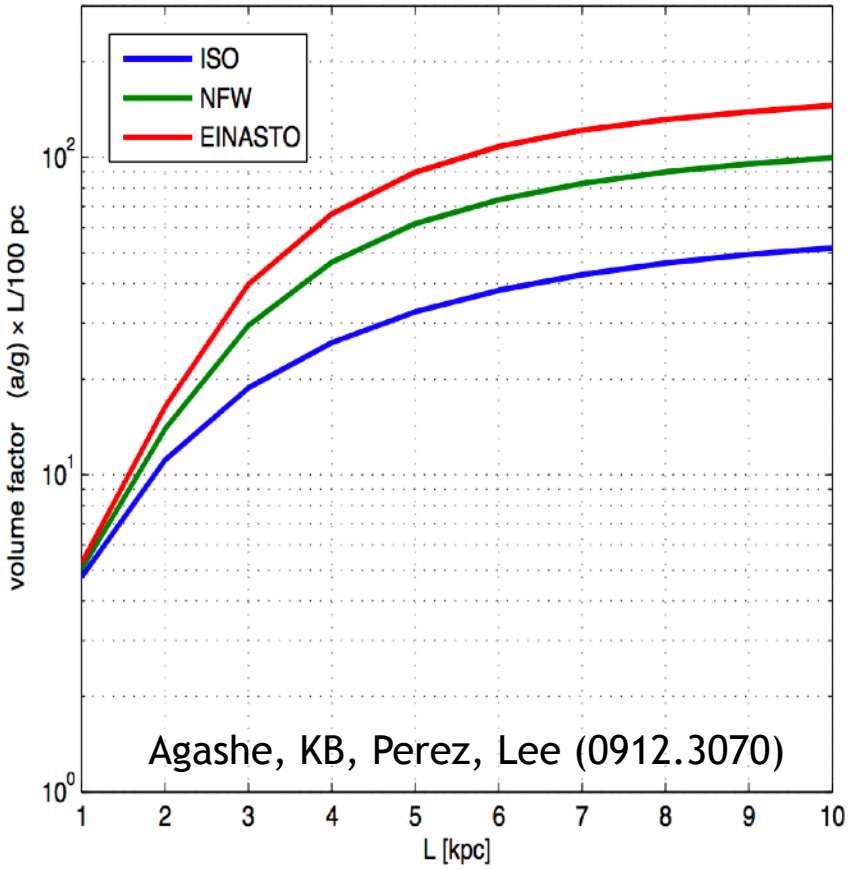
Antiproton constraints on dark matter annihilation?

No robust way to compute DM annihilation constraints from antiproton data.

Source terms distributed very differently:
DM halo and CR halo thought to extend to **multi-kpc** scales,
secondary CR sources confined to ~ **100 pc.**

Uncertain enhancement factor, ~ 1-100, to "DM signal".

Many authors set constraints, parametrising this uncertain enhancement… somehow

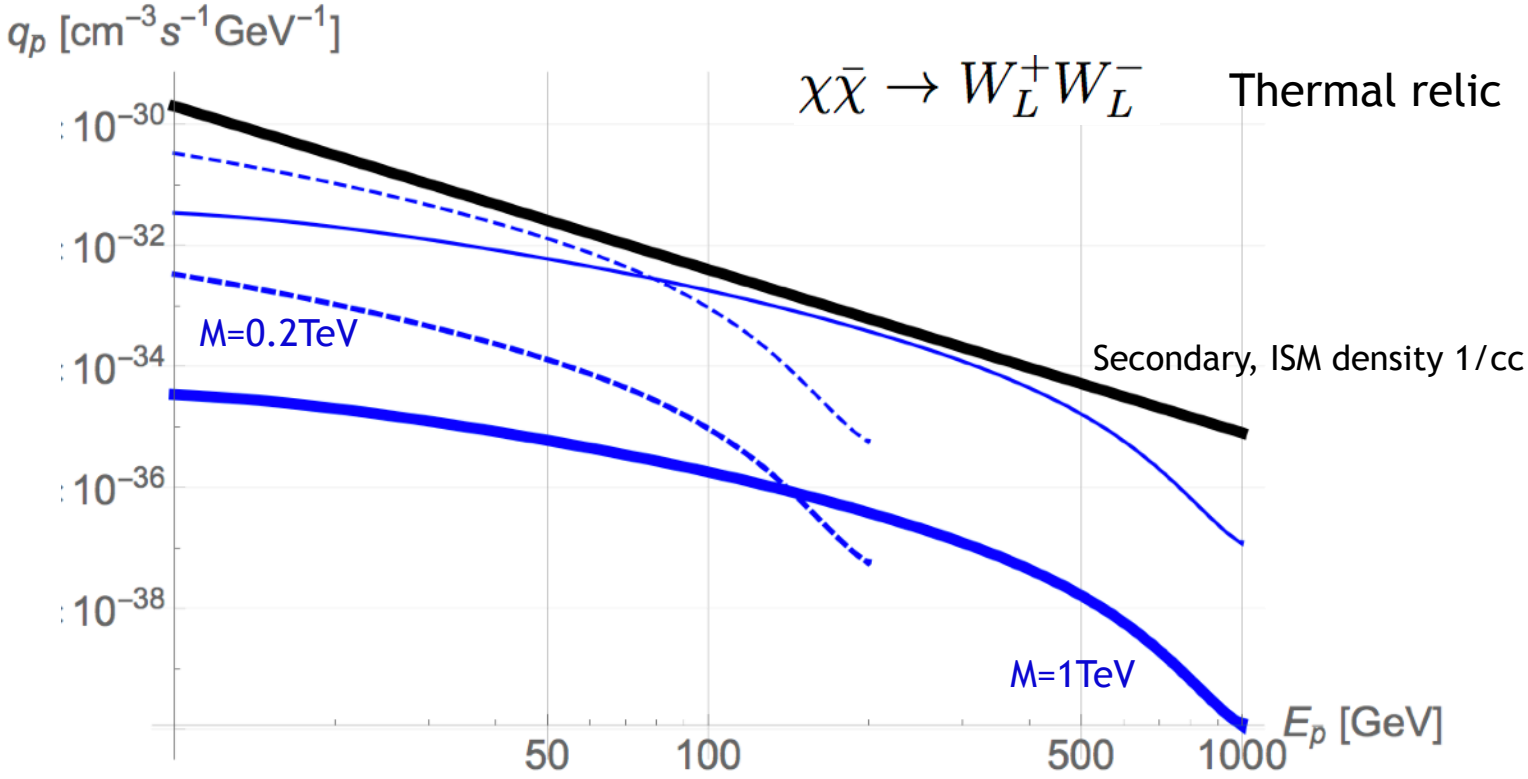


Antiproton constraints on dark matter annihilation?

Reasonably conservative:

DM injection rate density $q_{\bar{p},\mathrm{DM}} = \frac{n_\chi^2(\vec{r})\,\overline{\sigma v}}{4}\frac{dN_{\bar{p}}}{dE}$

should not exceed secondary injection rate density $q_{\bar{p},\mathrm{sec}} = \rho_{ISM} c\, Q_{\bar{p}}$
in a typical region in the MW gas disc

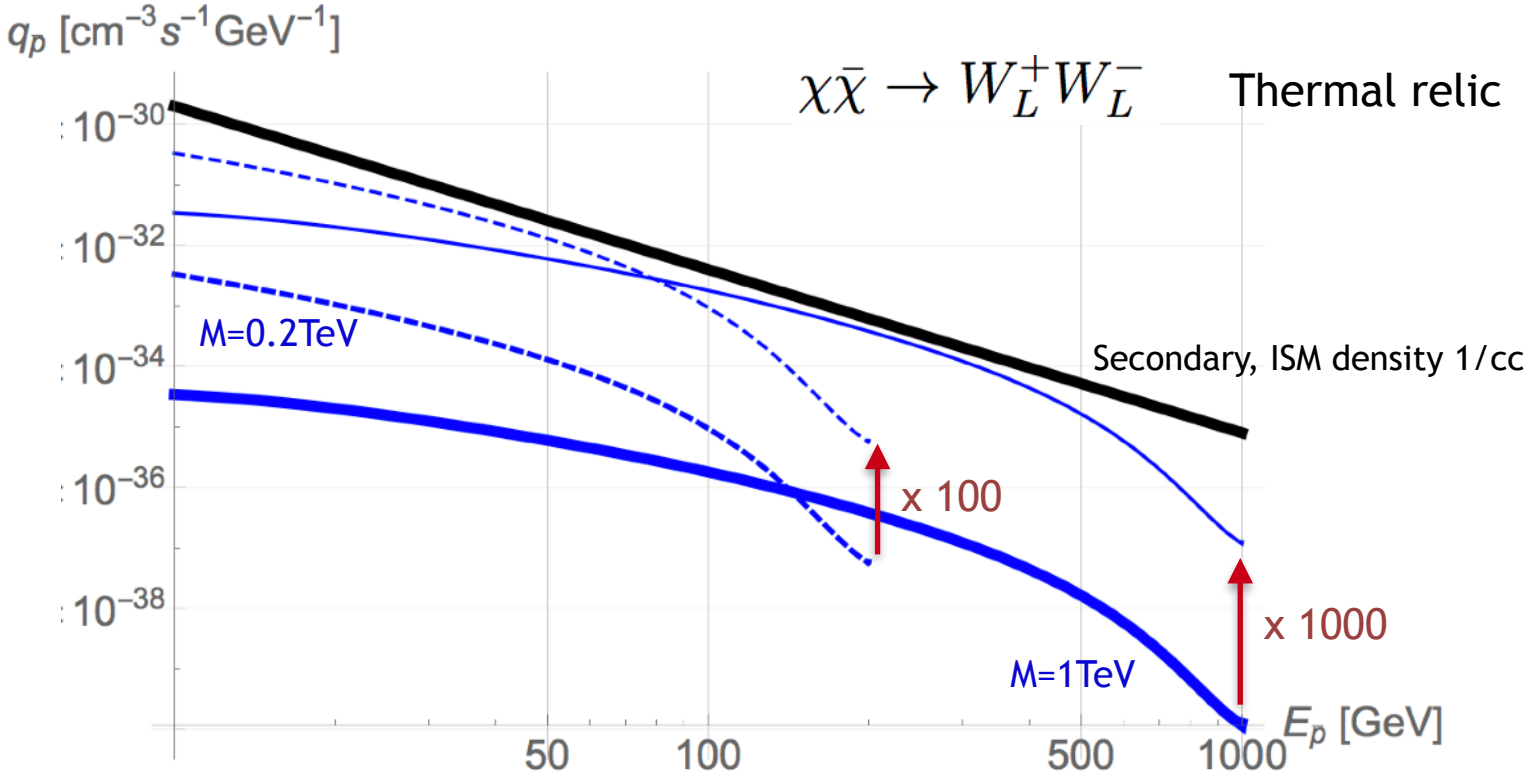


Antiproton constraints on dark matter annihilation?

Reasonably conservative:

DM injection rate density $q_{\bar{p},\mathrm{DM}} = \frac{n_\chi^2(\vec{r})\,\overline{\sigma v}}{4}\frac{dN_{\bar{p}}}{dE}$

should not exceed secondary injection rate density in a typical region in the MW gas disc $q_{\bar{p},\mathrm{sec}} = \rho_{ISM} c\, Q_{\bar{p}}$



Positrons

Positrons

e+ are produced by CR proton collisions with interstellar matter (ISM).
We can calibrate the amount of ISM target from B/C data.

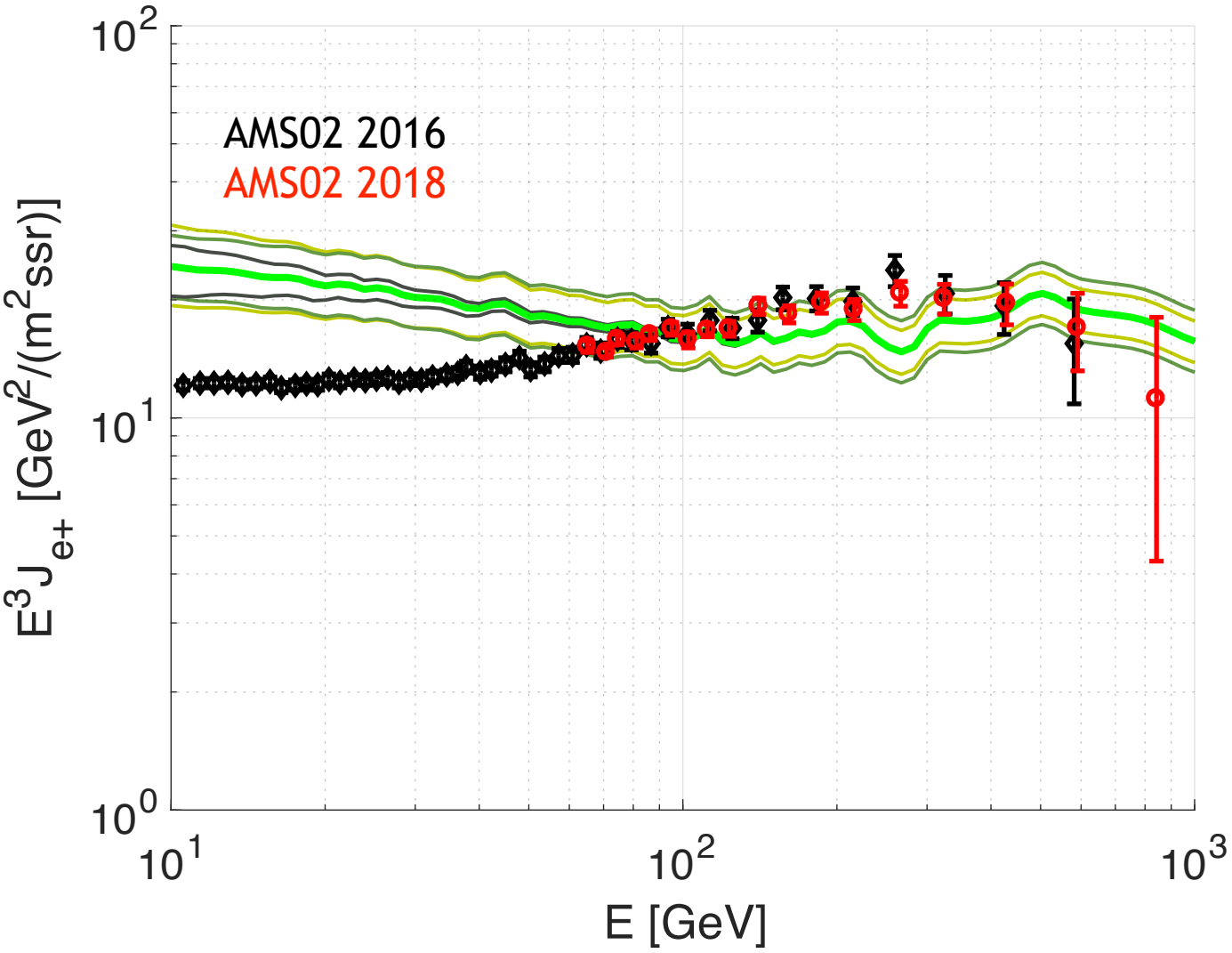
e+ loose energy during propagation.
So, some of the secondary flux should be lost.

The e+ flux should be lower than the flux we would get, if losses were not important.

A simple *upper bound* prediction:

$$n_{e^+}(\mathcal{R}) \lesssim \frac{n_{\rm B}(\mathcal{R})}{Q_{\rm B}(\mathcal{R})} Q_{e^+}(\mathcal{R})$$

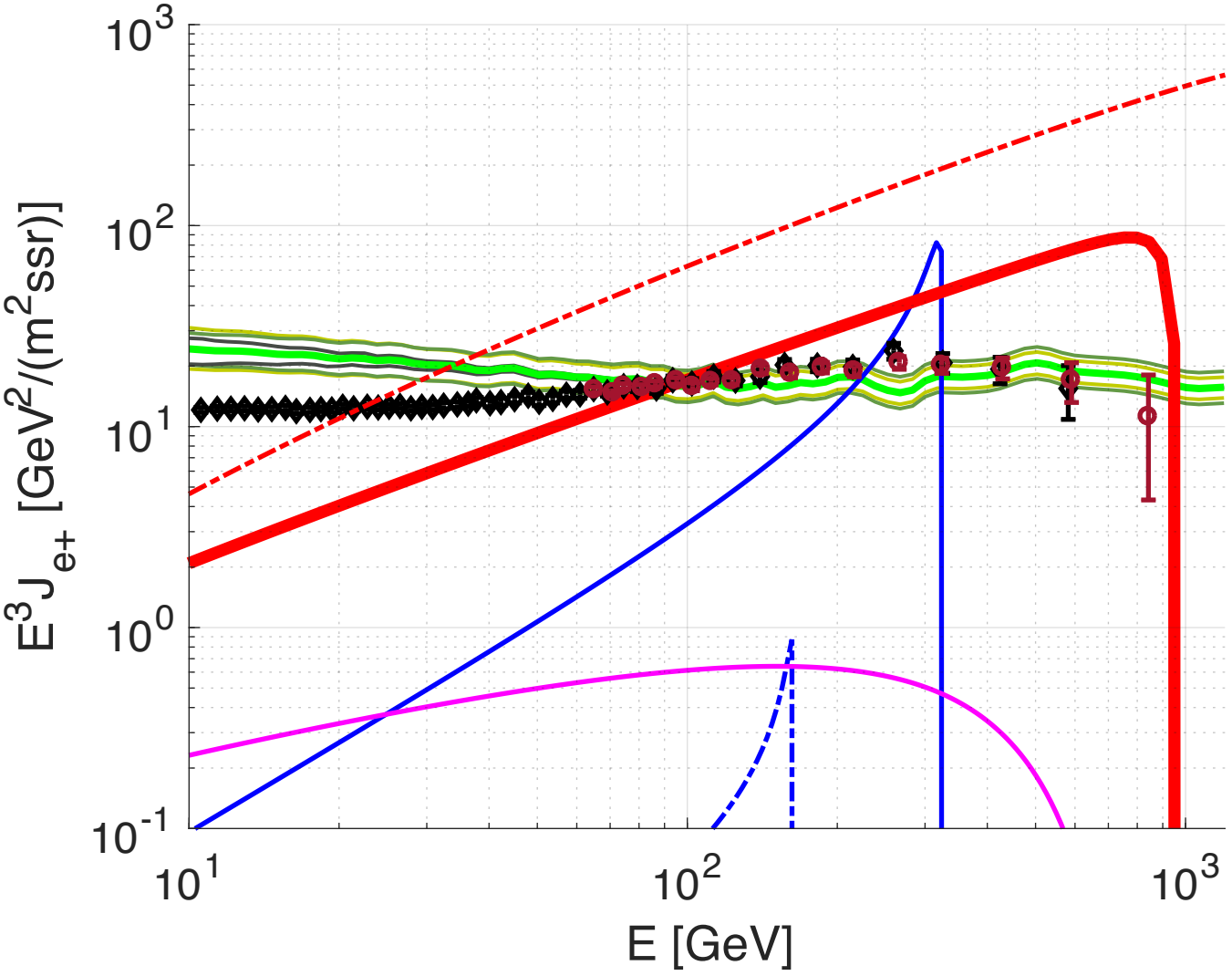
0907.1686



e+ upper bound predicted in Katz et al (**0907.1686**),

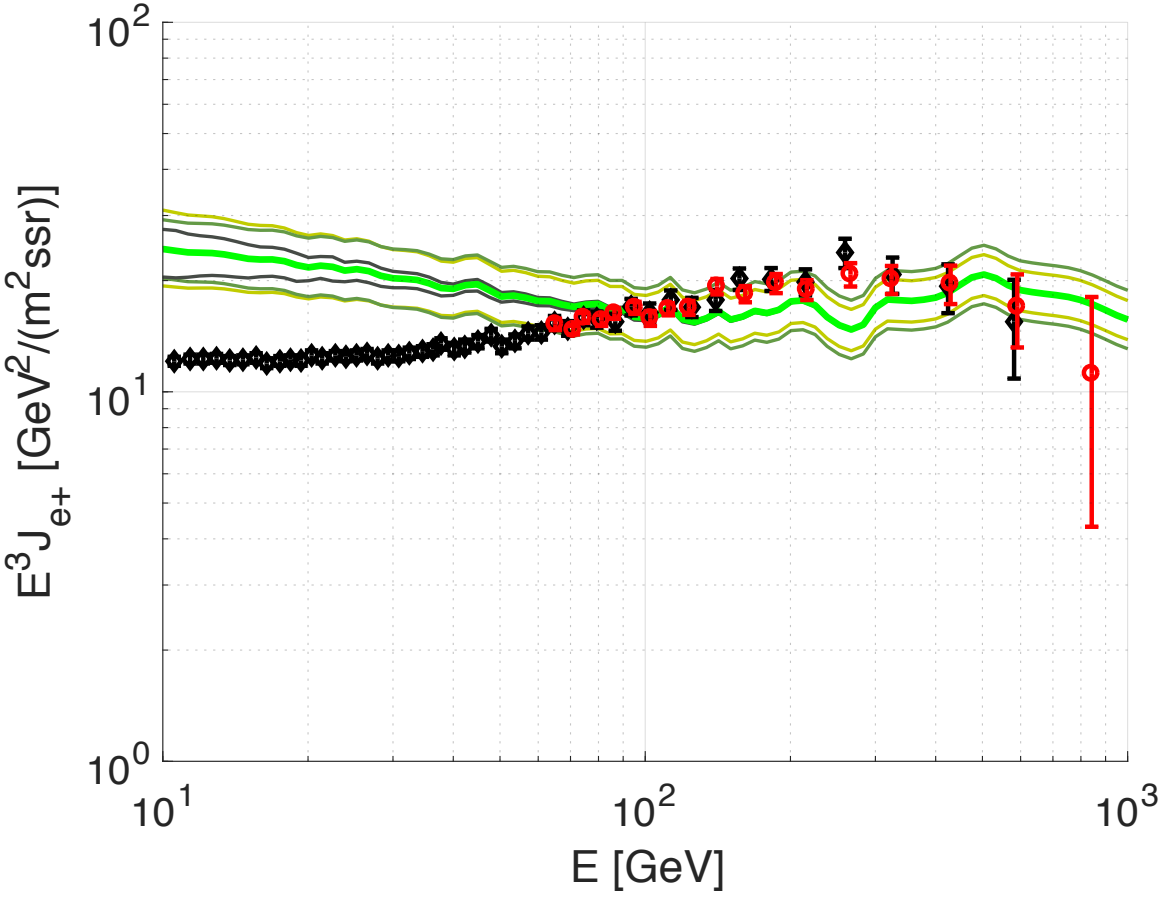
Evaluated with latest cross section and CR nuclei data (1709.06507, 1709.04953)

Why would dark matter or pulsars inject ***this*** e+ flux? 1709.06507



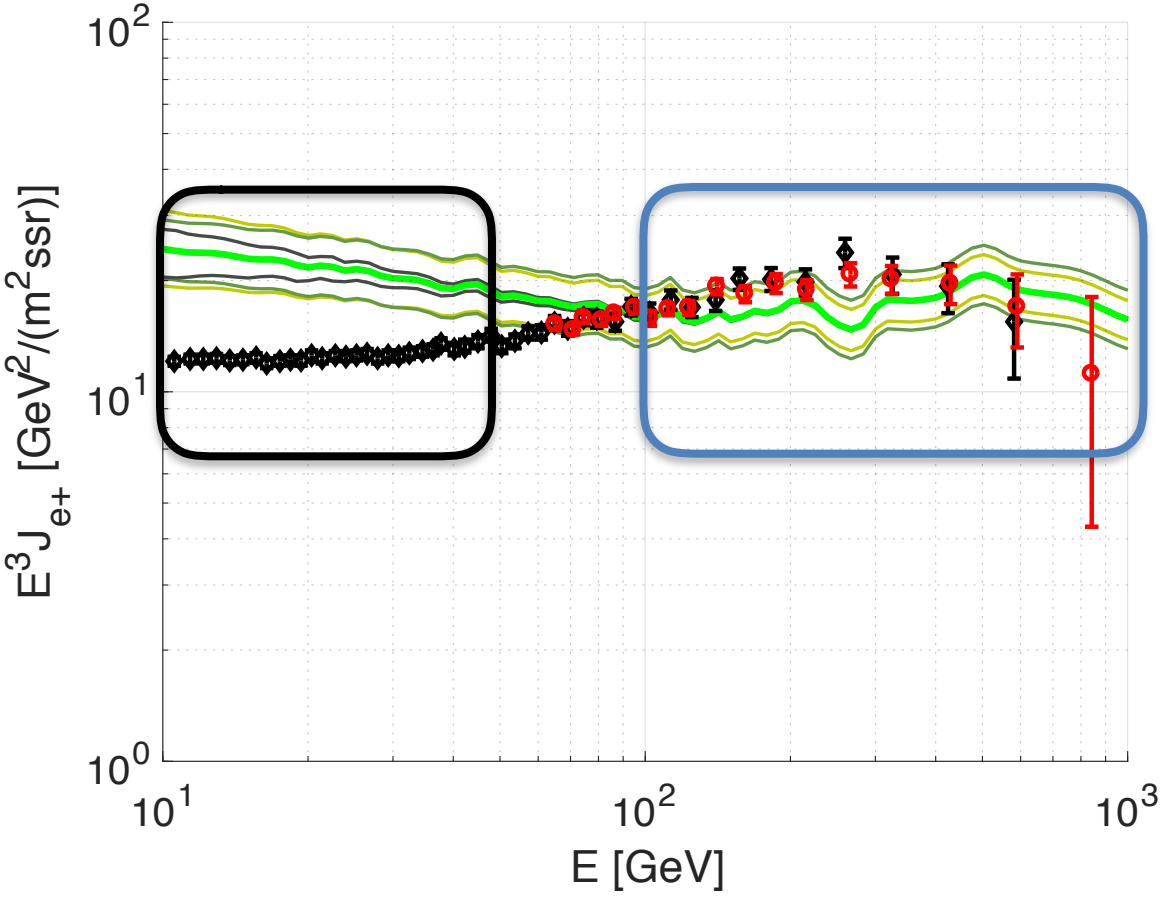
Pulsar model: D. Malyshev, I. Cholis, and J. Gelfand, Phys. Rev. **D80**, 063005 (2009)

So what is the issue with e+?



So what is the issue with e+?

1. Can it be that the flux of TeV e+ is **not** suppressed by energy losses?
2. Can it be that the flux of 100GeV e+ is **not** suppressed, while that of 10GeV **is**?

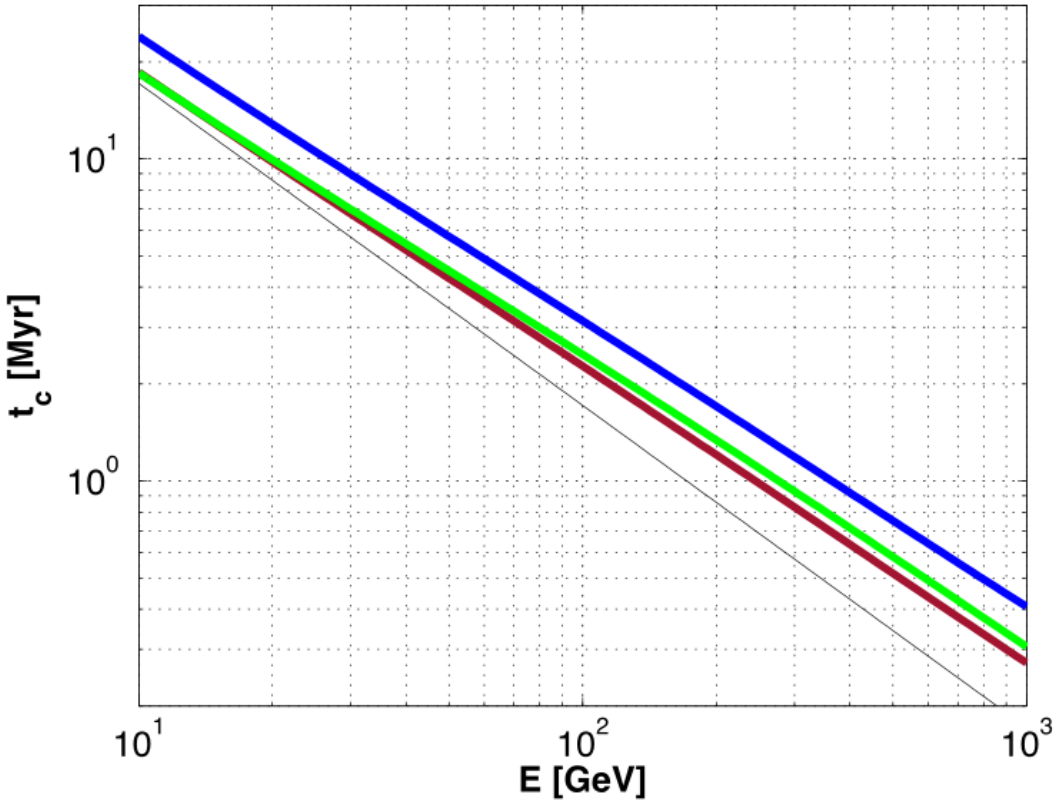


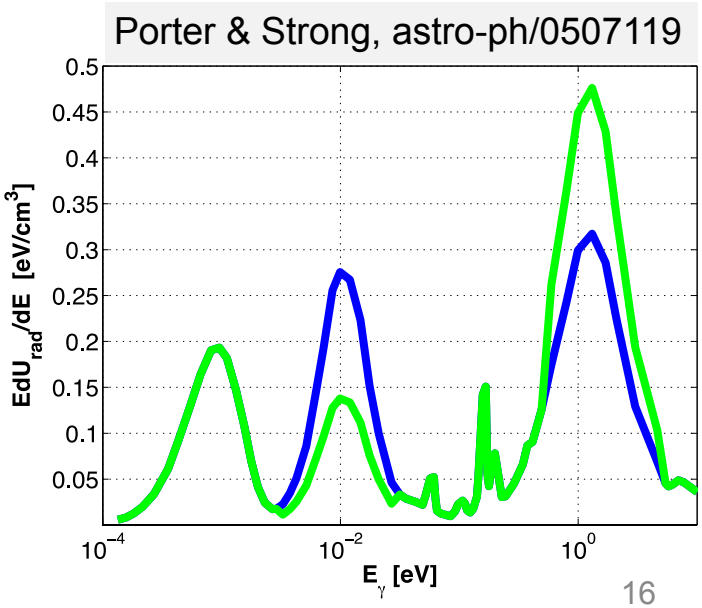
So what is the issue with e+?

1. Can it be that the flux of TeV e+ is not suppressed by energy losses?

Energy losses suppress the flux, if the cooling time is shorter than the propagation time.

@TeV cooling time ~ 0.3 Myr ==> TV propagation time ~ 0.3 Myr?

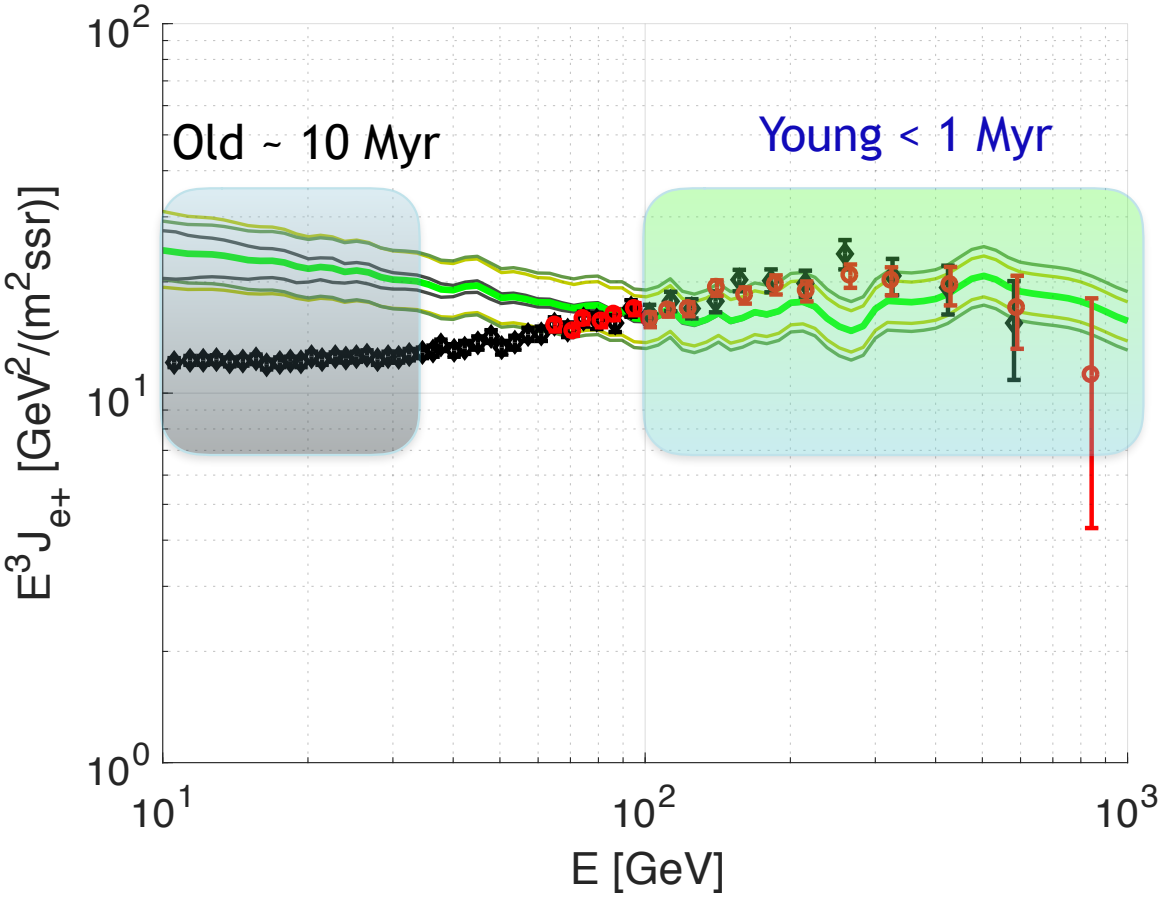




So what is the issue with e+?

2. Can it be that the flux of 100GeV e+ is not suppressed, while that of 10GeV is?

Cooling time ~ 1/E ==> propagation time ~ 1/R?
…cannot continue much beyond TV; bi-modal CR age contributions?



So what is the issue with e+?

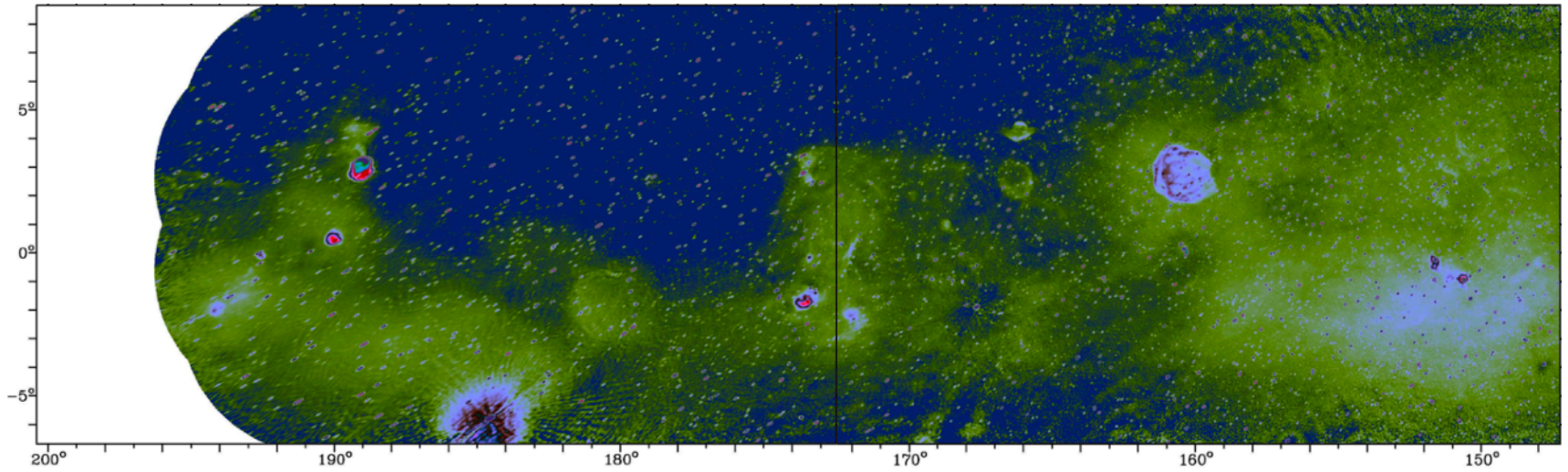
1. Can it be that the flux of TeV e+ is **not** suppressed by energy losses?
2. Can it be that the flux of >100GeV e+ is **not** suppressed, while that of <100GeV **is**?

I don't know of any contradiction of 1,2 with theory or observations.

Some ideas in the literature, e.g., recent CR injection by SNR

e.g. Ahlers, Mertch, Sarkar (0909.4060), Mertch & Sarkar (1402.0855), Kachelrie, Neronov, Semikoz (1504.06472), Thomas et al (1605.04926)

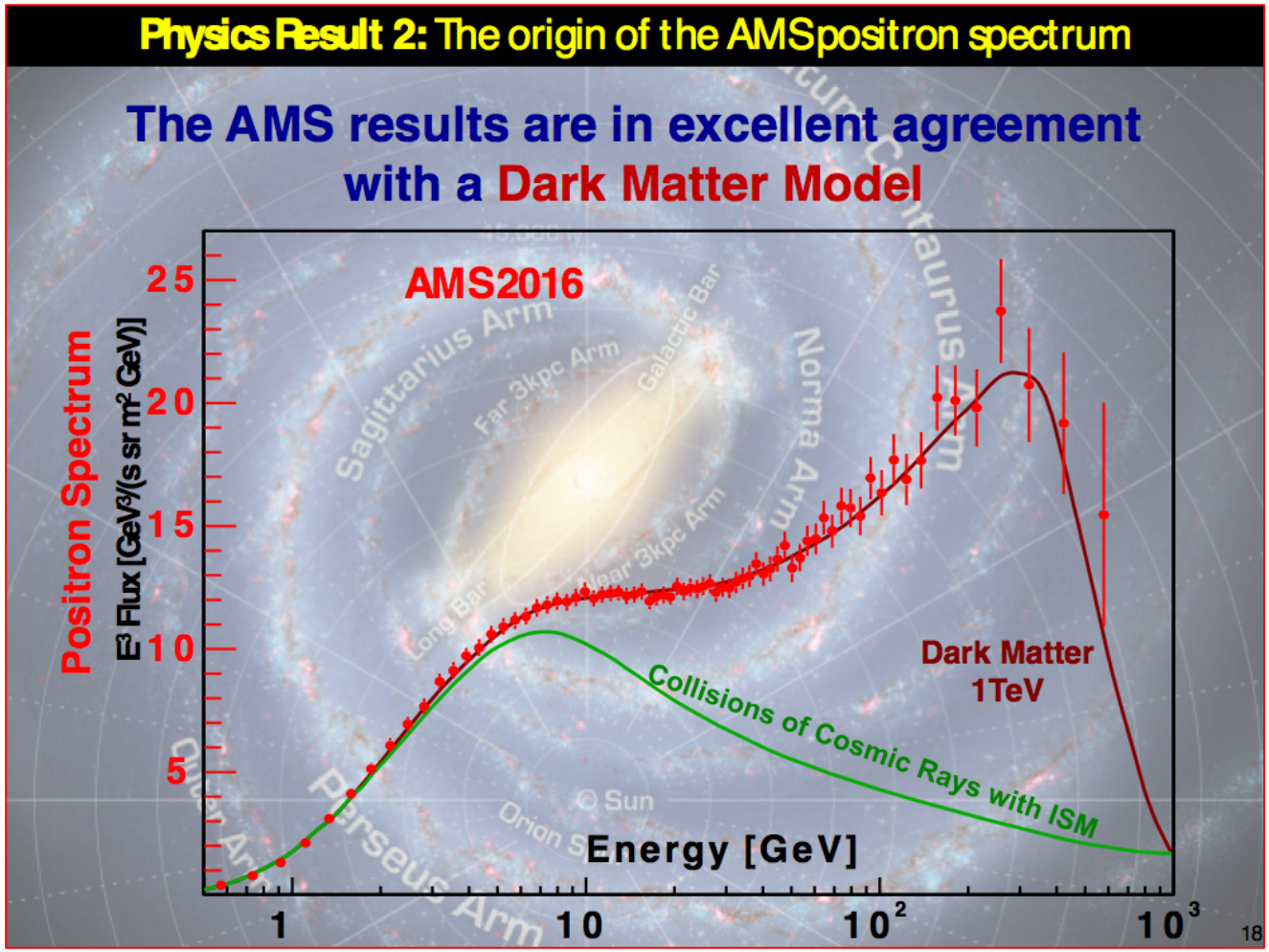
1708.04316, 408MHz (CGPS)



Perhaps e+ is evidence of new physics, CR unknowns make it difficult to assess.
How do we test this further?

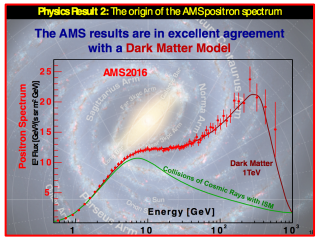
Perhaps e+ is evidence of new physics, CR unknowns make it difficult to assess.
How do we test this further?

Sharp spectral features?



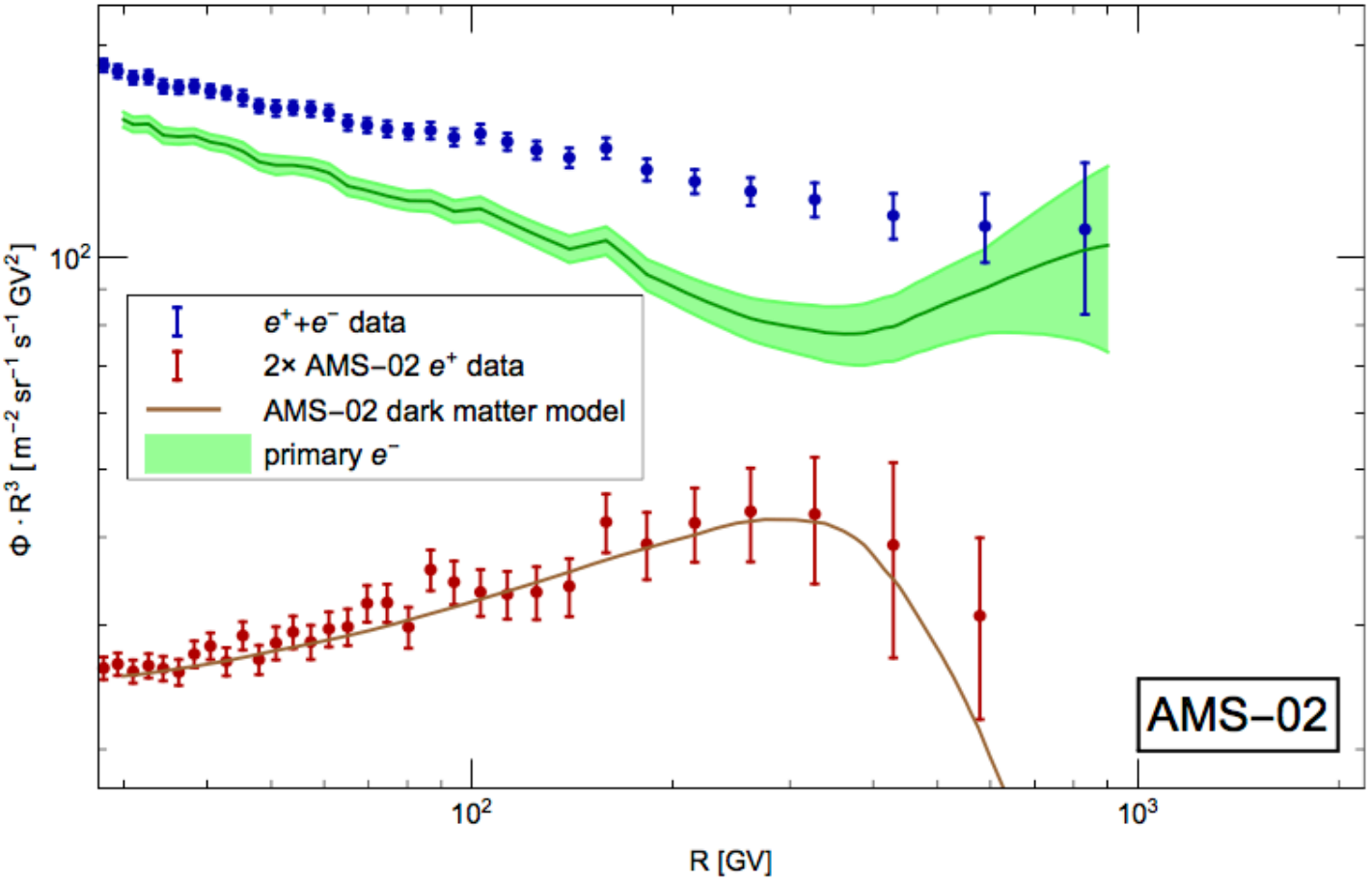
Perhaps e+ is evidence of new physics, CR unknowns make it difficult to assess.
How do we test this further?

Sharp spectral features?



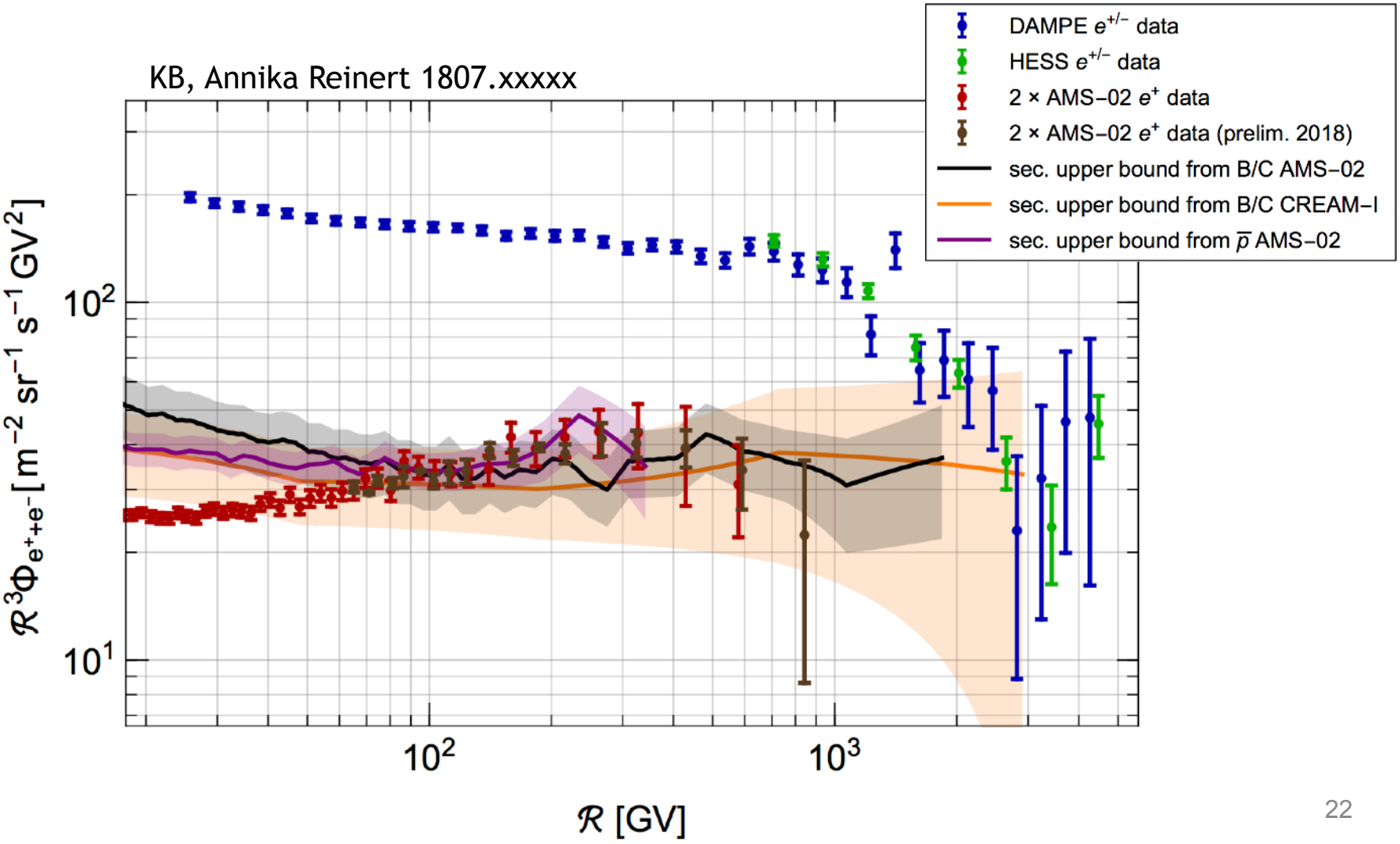
With current data, sharp spectral features in e+ are unlikely:
The total e flux is very smooth.

KB, Annika Reinert, 1807.xxxxx



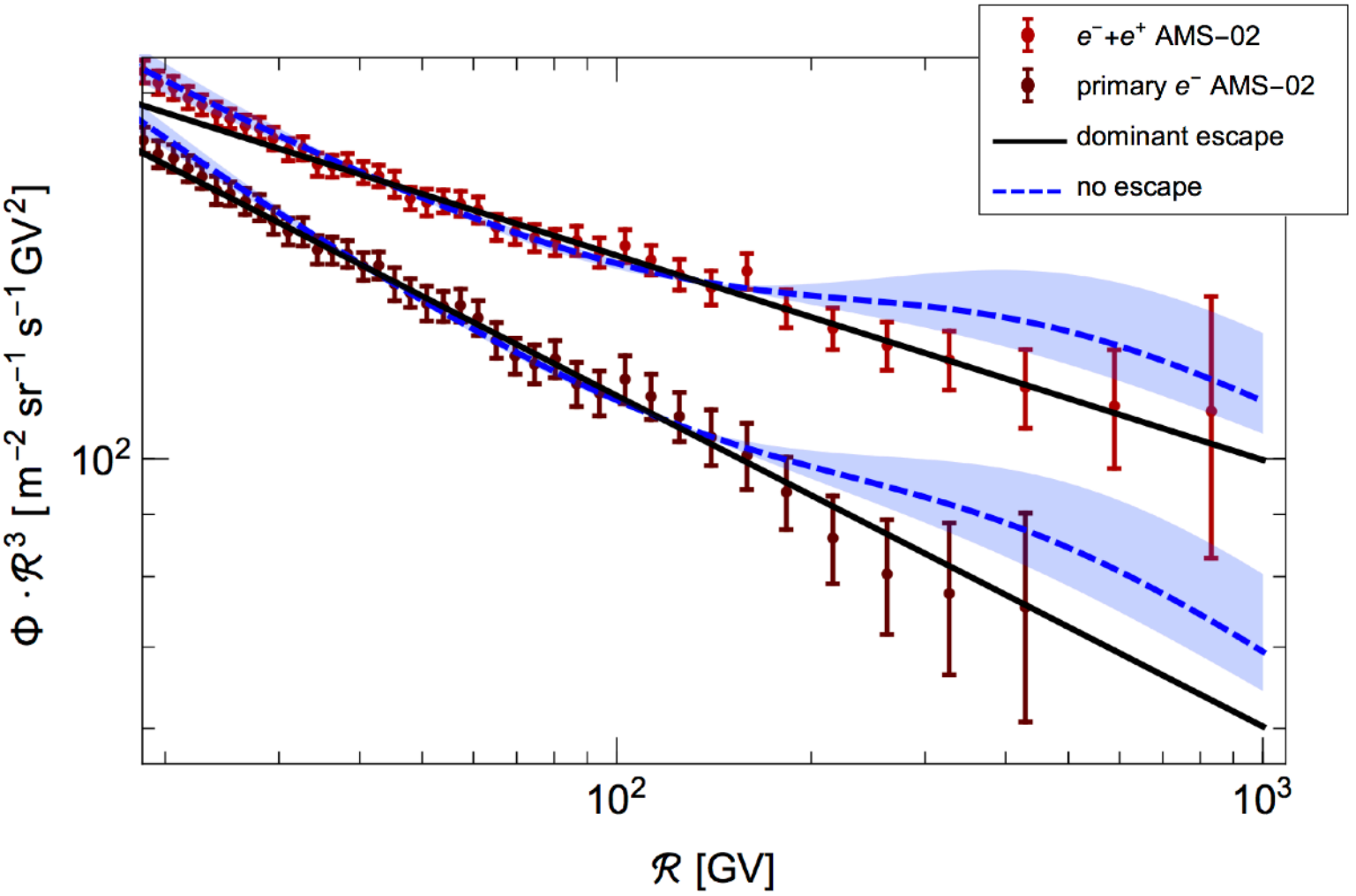
If no sharp feature, then what?

HESS/DAMPE/CALET total e flux at E~3 TeV consistent w/ secondary flux.



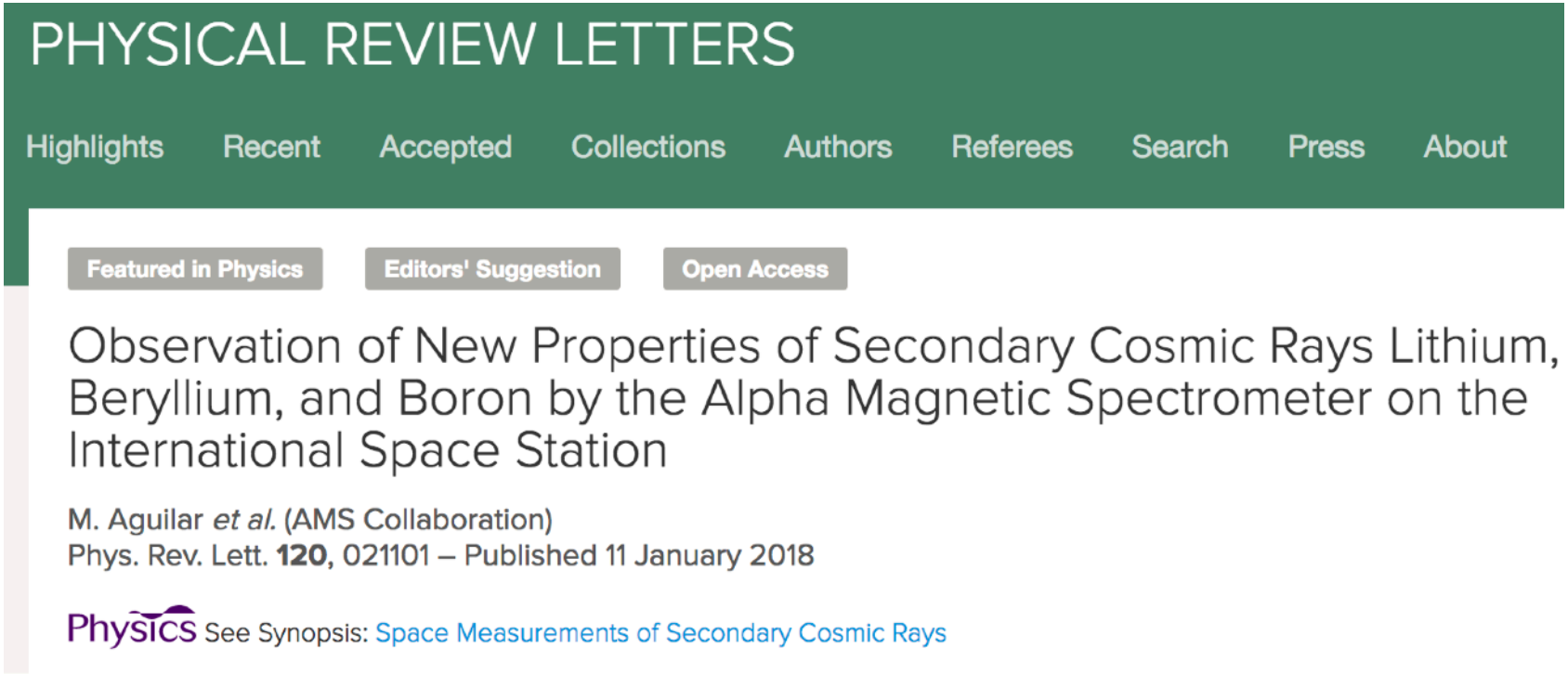
Perhaps e+ is evidence of new physics, CR unknowns make it difficult to assess.
How do we test this further?

Very precise e- and e+ measurements: KN steps?



Perhaps e+ is evidence of new physics, CR unknowns make it difficult to assess.
How do we test this further?

Radioactive nuclei



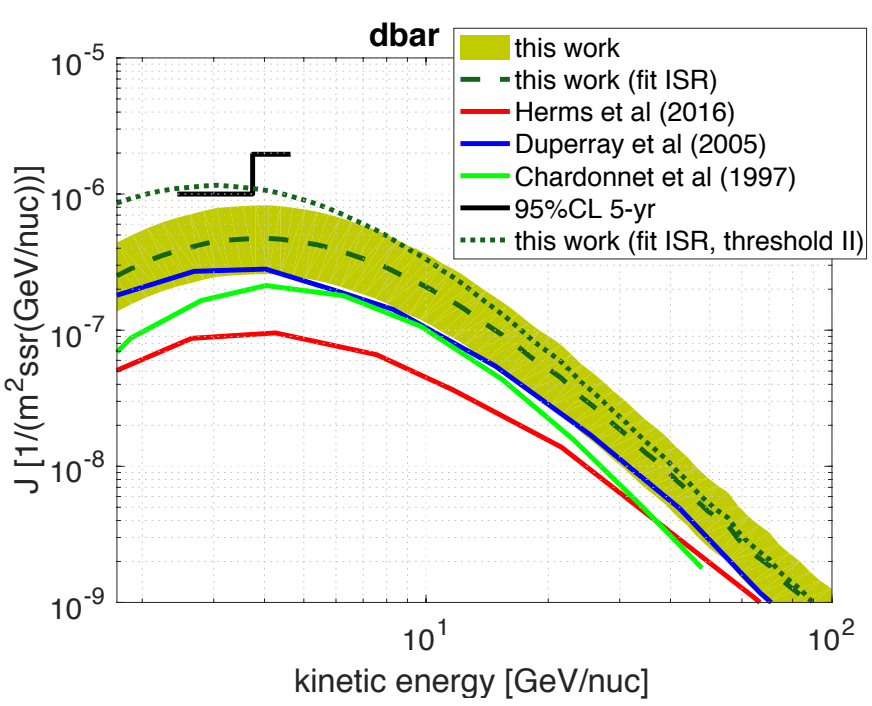
Anti-He and anti-d

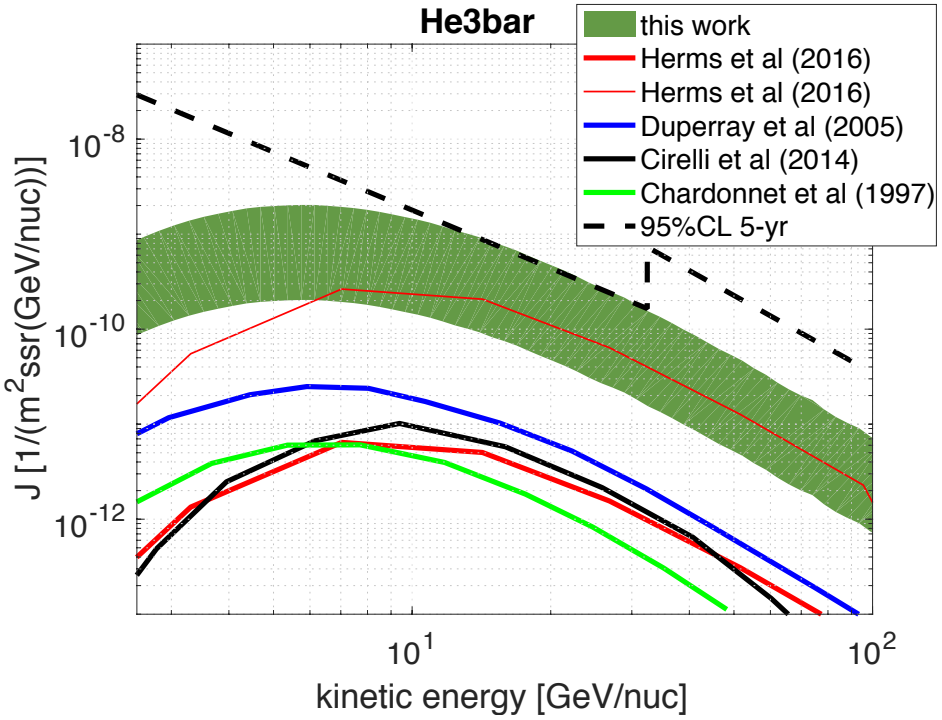
Anti-He and anti-d

The calculation of CR anti-nuclei is similar to that for antiprotons.

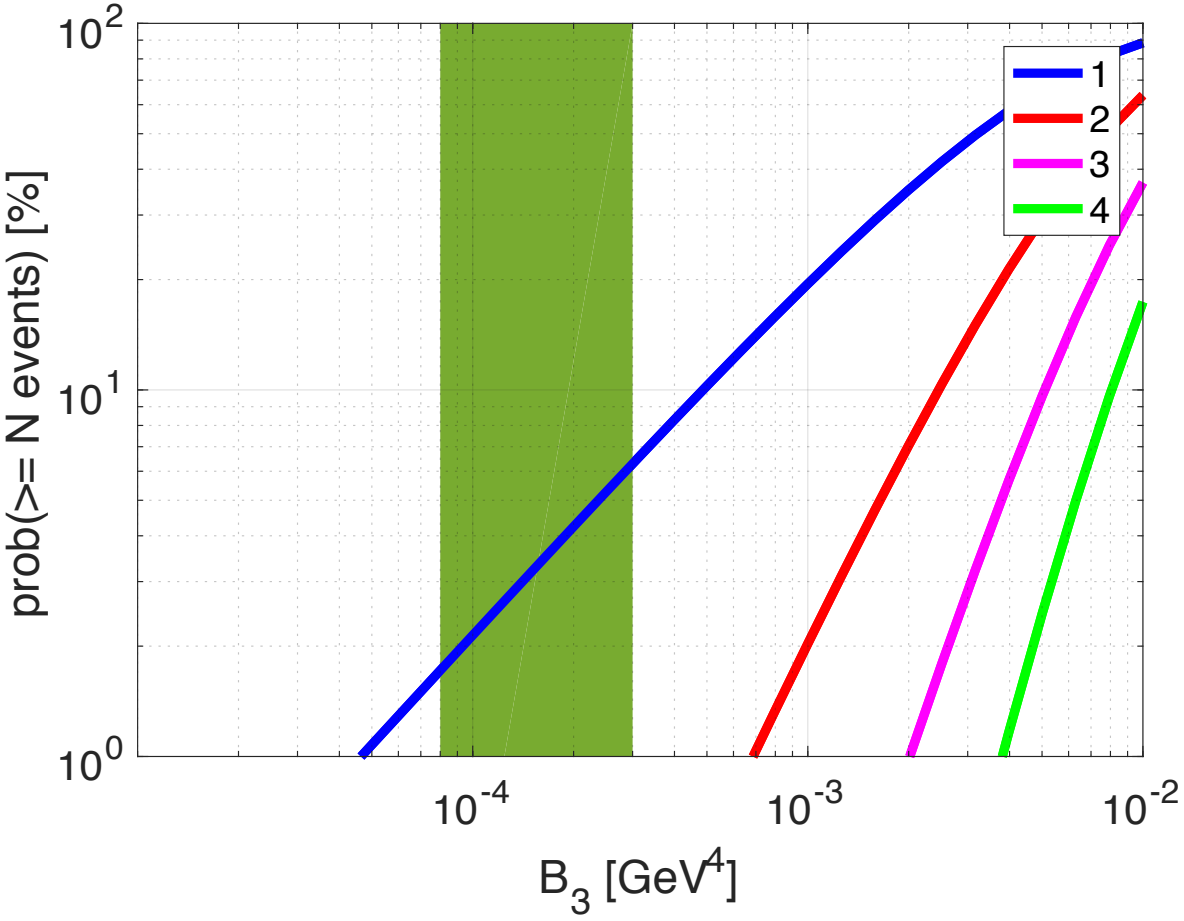
The uncertainty (at relativistic energies, R>few GV) is *not* from CR propagation, but from *production cross sections*.

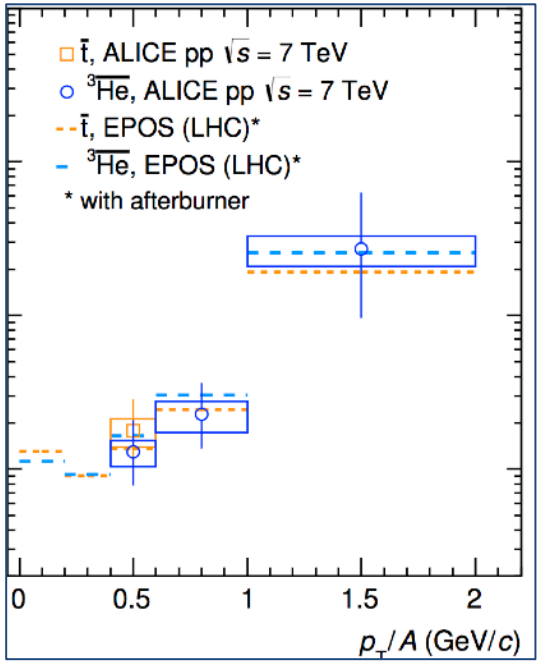
1704.05431





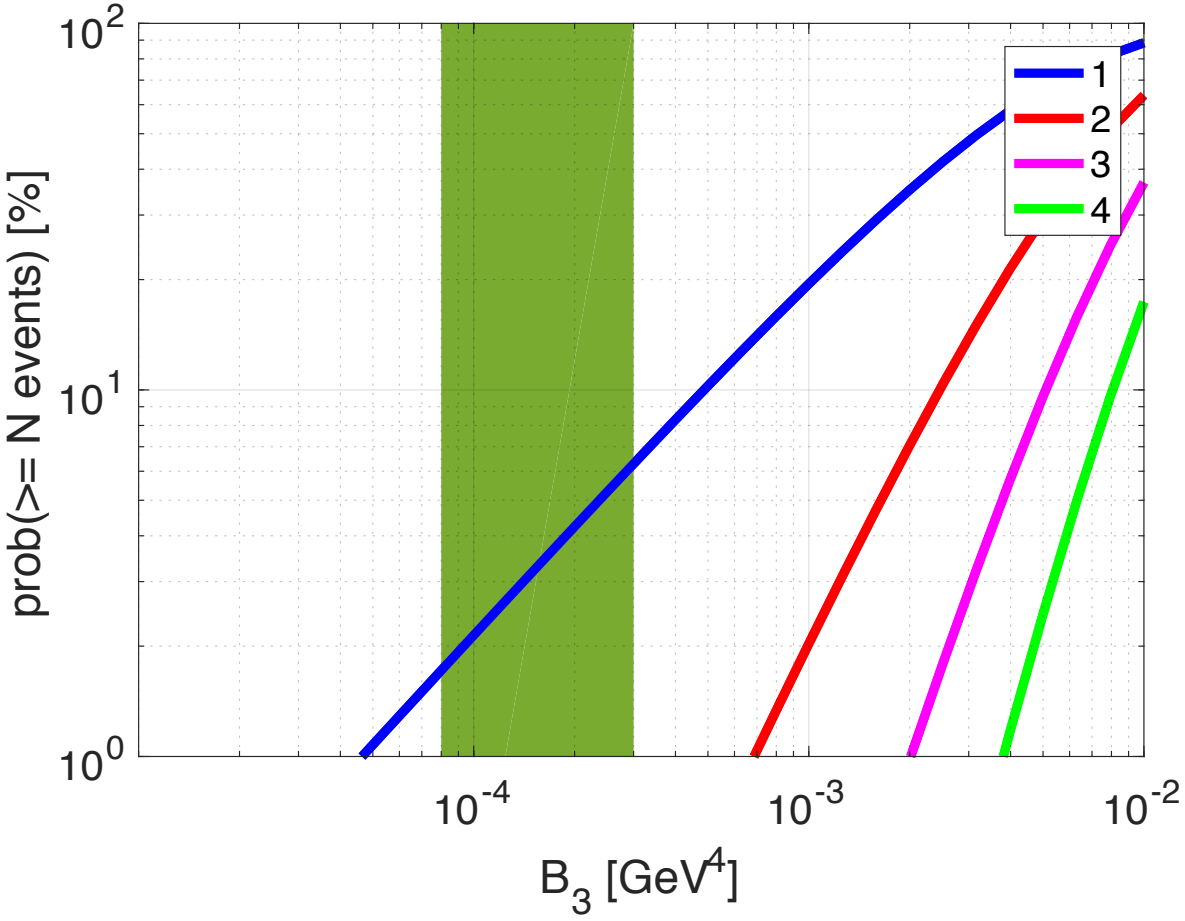
Anti-He3


prob(>= N events) [%]
10^2
10^1
10^0
10^{-4}
10^{-3}
10^{-2}
B_3 [GeV^4]
1
2
3
4


$\bar{t}$, ALICE pp $\sqrt{s}$ = 7 TeV
$^3\overline{He}$, ALICE pp $\sqrt{s}$ = 7 TeV
$\bar{t}$, EPOS (LHC)*
$^3\overline{He}$, EPOS (LHC)*
* with afterburner
0
0.5
1
1.5
2
p_T/A (GeV/c)

Anti-He3

AMS02, 2018, CERN colloquium: **6 anti-He3 events in ~7 years exposure** (anti-He3/He4 ~ 1/10^8)

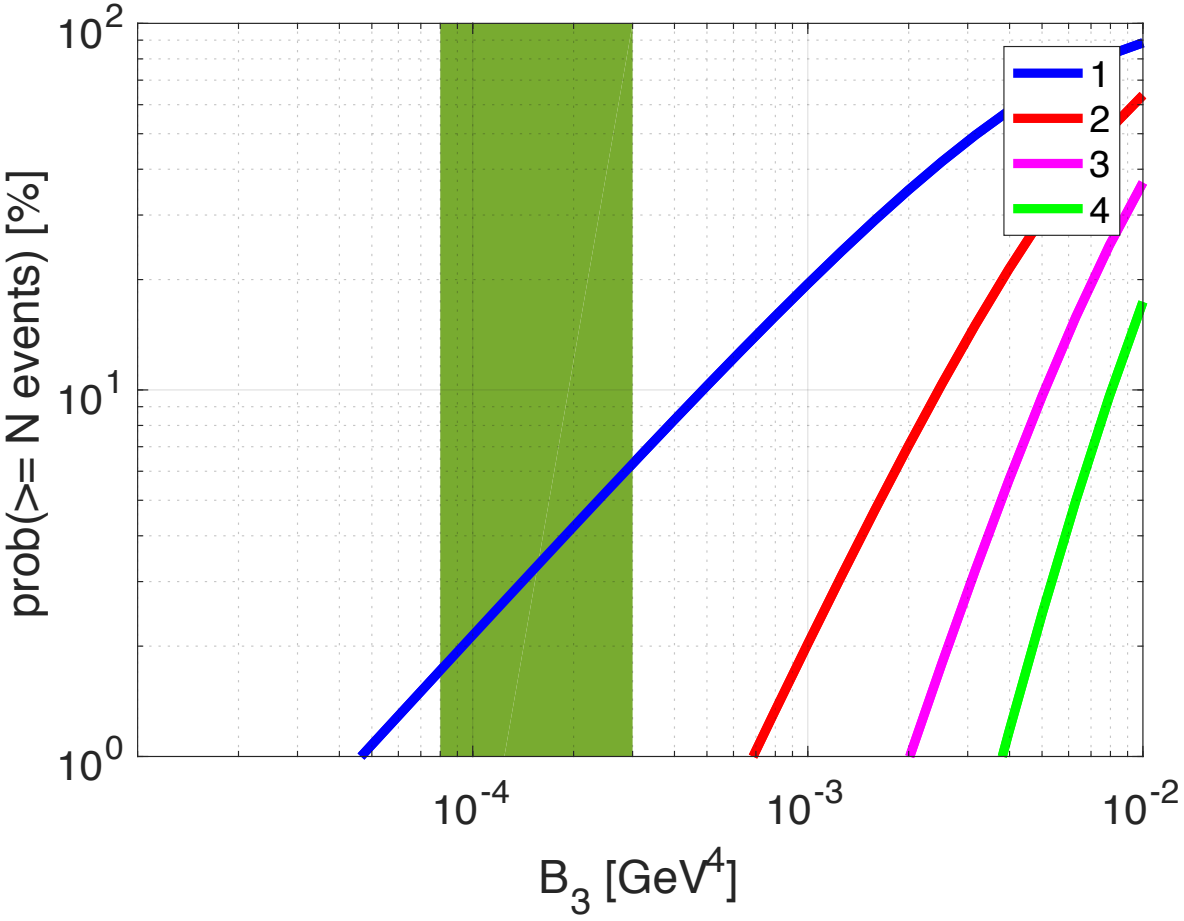


New physics?

Anti-He3

AMS02, 2018, CERN colloquium: **6 anti-He3 events in ~7 years exposure** (anti-He3/He4 ~ 1/10^8)

AMS02, the same CERN colloquium: **2 anti-He4 events…** (anti-He4/anti-He3 ~ 1/3)



Experimental problem?

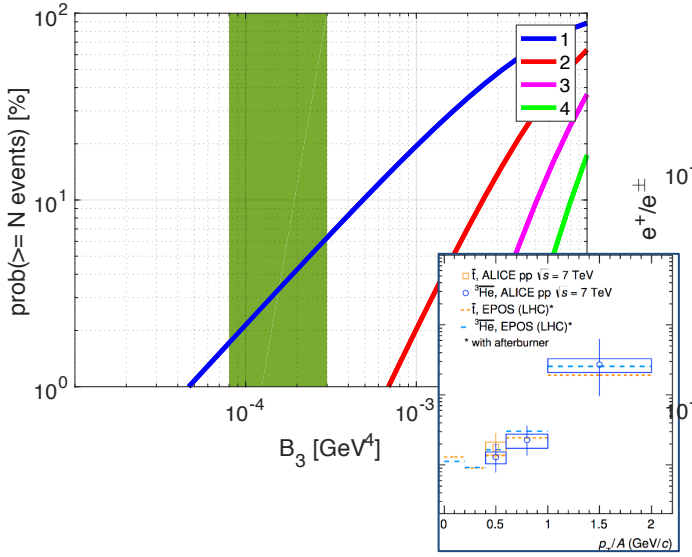
Summary

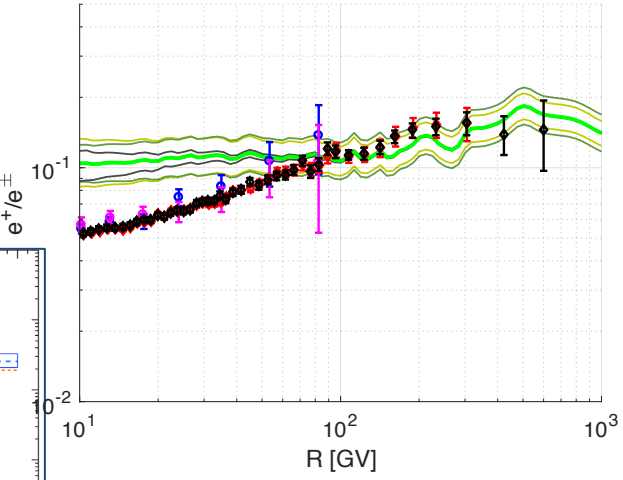
DM annihilation *could have* showed up naturally for O(10GeV) WIMPs…

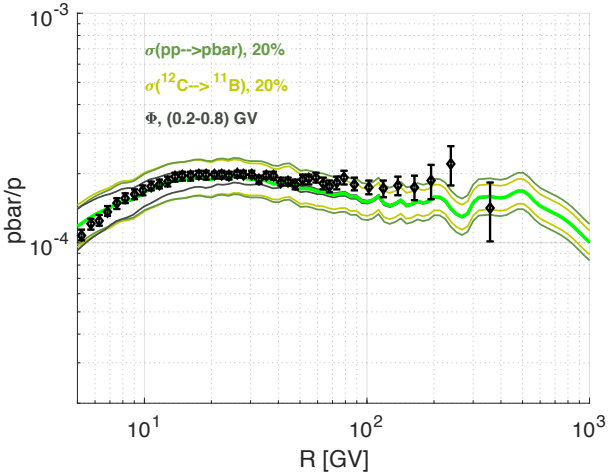
A lot of information, and more is coming.

Antiprotons and e+ look secondary.
If e+ are secondary, it entails serious revision to CR propagation stories.
Several ways to test in the next few years (precision TeV e data, radionuclei).

If AMS02 anti-He is not an experimental issue, it may be new physics
(of extreme and surprising nature… how to make anti-He4/anti-He3 ~ 1/3 ?)



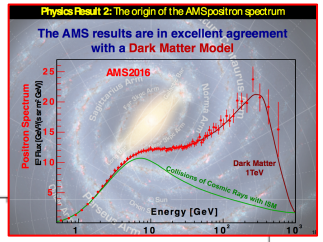


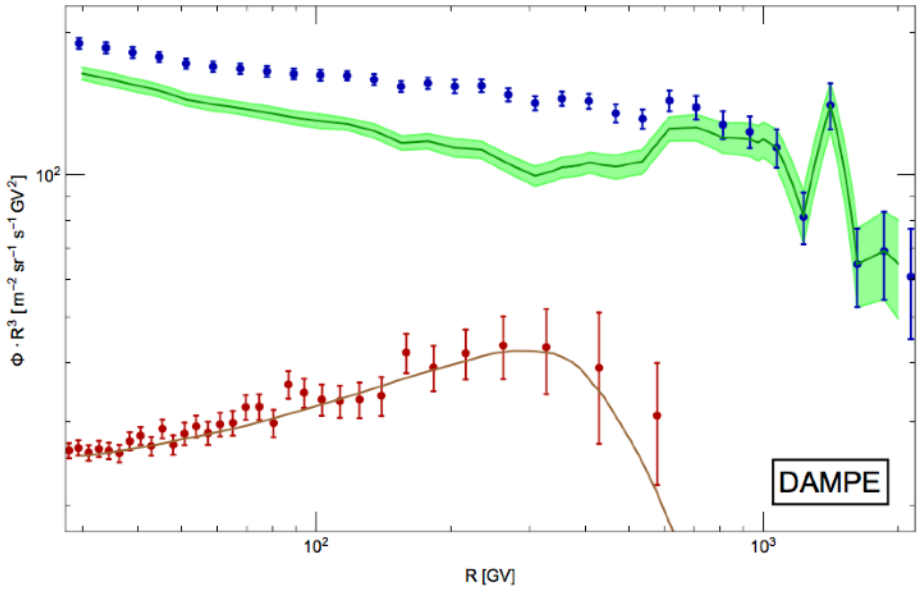


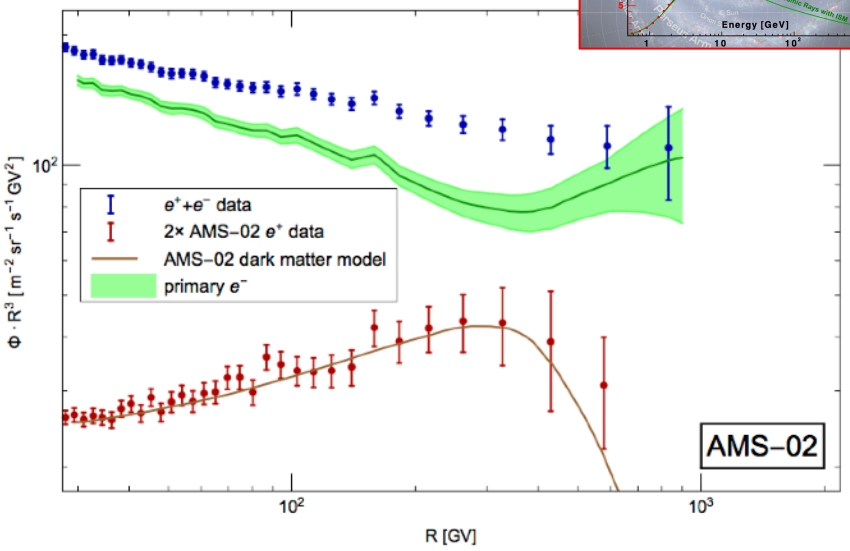
Xtra

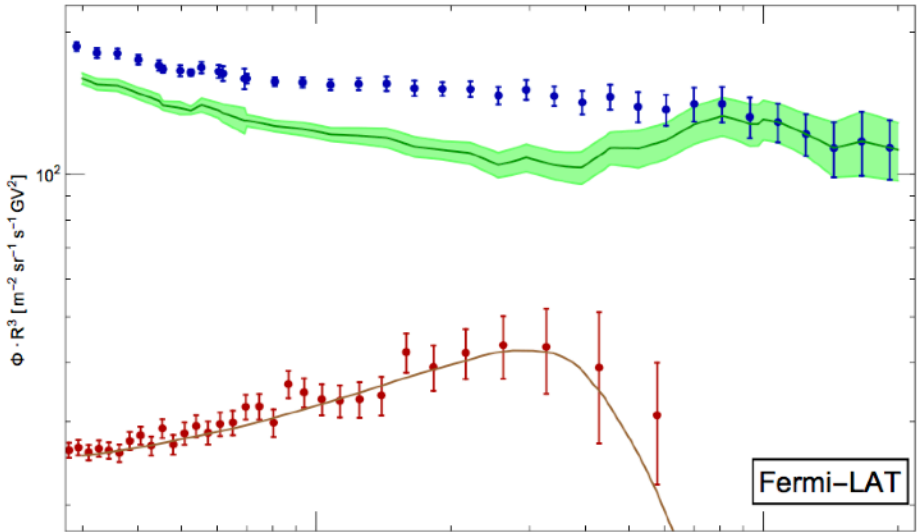
Perhaps e+ is evidence of new physics, CR unknowns make it difficult to assess.
How do we test this further?

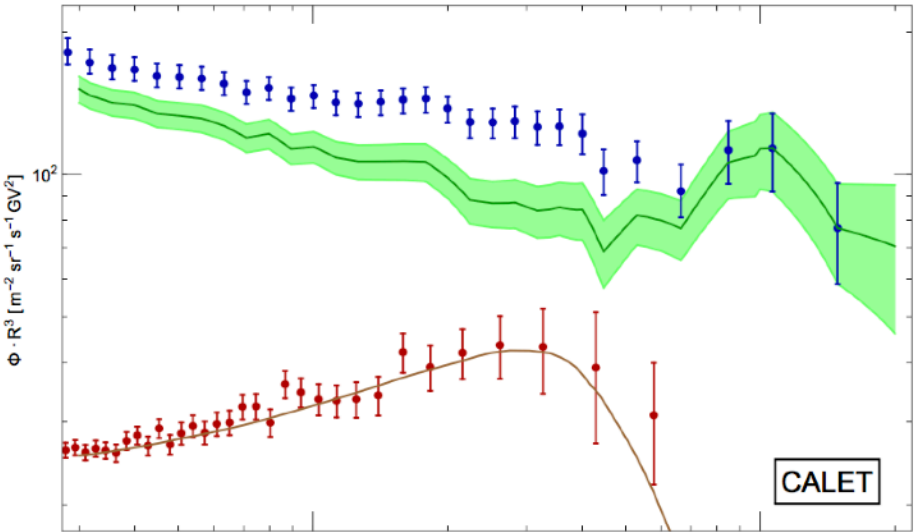
Sharp spectral features?





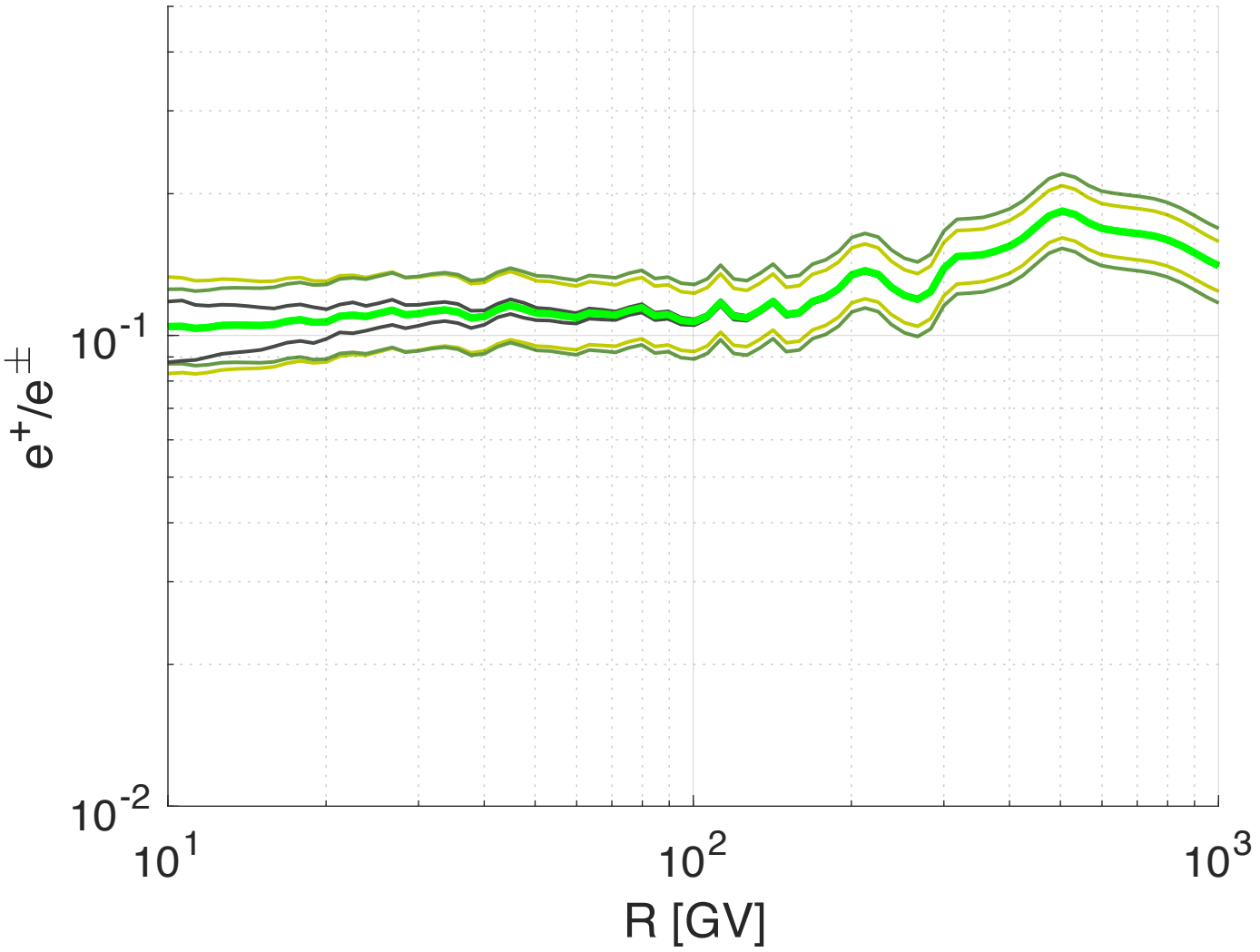






Secondary *upper bound* (Based on B/C)

$$n_{e^+}(\mathcal{R}) \lesssim \frac{n_{\rm B}(\mathcal{R})}{Q_{\rm B}(\mathcal{R})} Q_{e^+}(\mathcal{R})$$

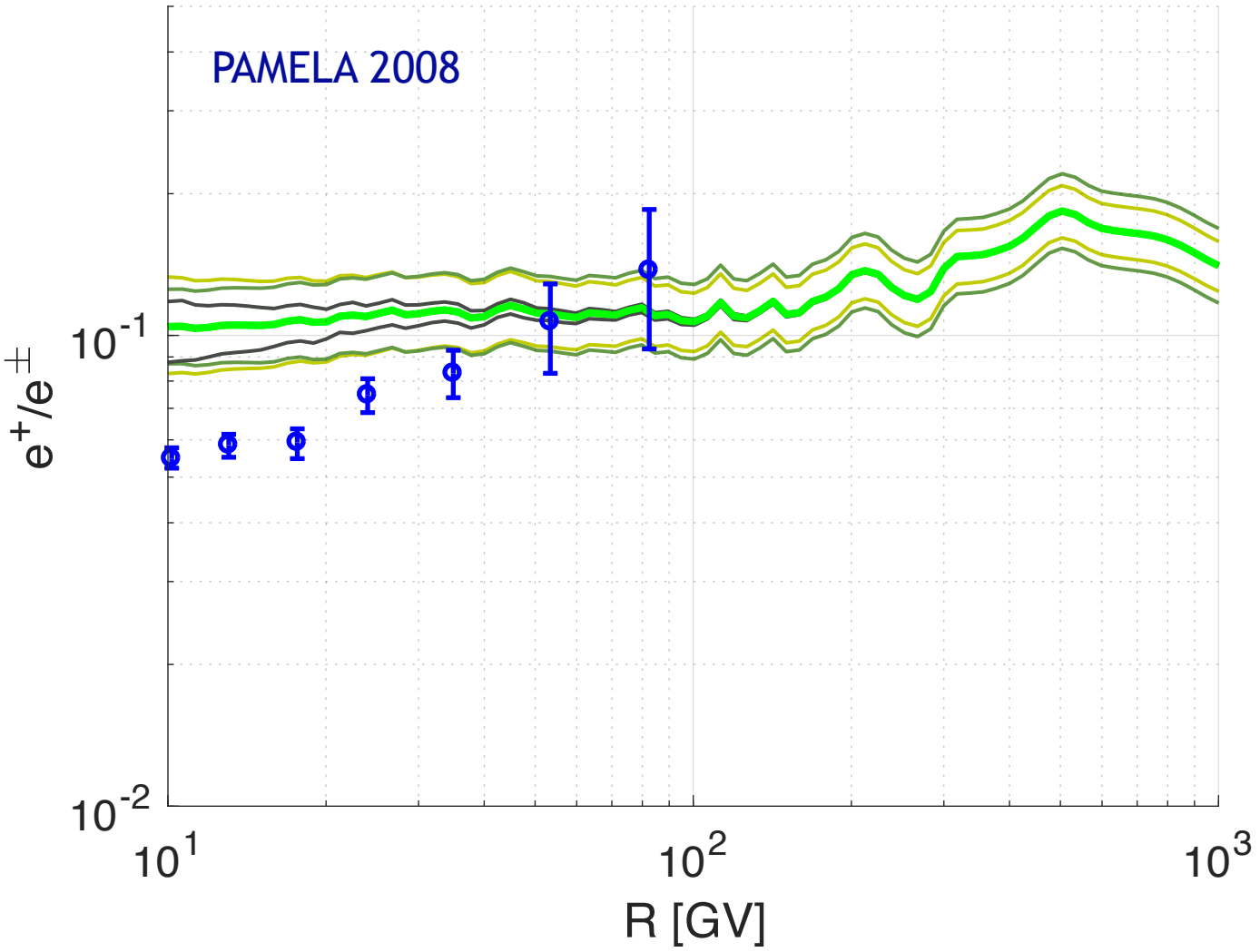


e+ upper bound predicted in Katz et al (**0907.1686**),

Evaluated with latest cross section and CR nuclei data (1709.06507, 1709.04953)

Secondary *upper bound* (Based on B/C)

$$n_{e^+}(\mathcal{R}) \lesssim \frac{n_{\rm B}(\mathcal{R})}{Q_{\rm B}(\mathcal{R})} Q_{e^+}(\mathcal{R})$$

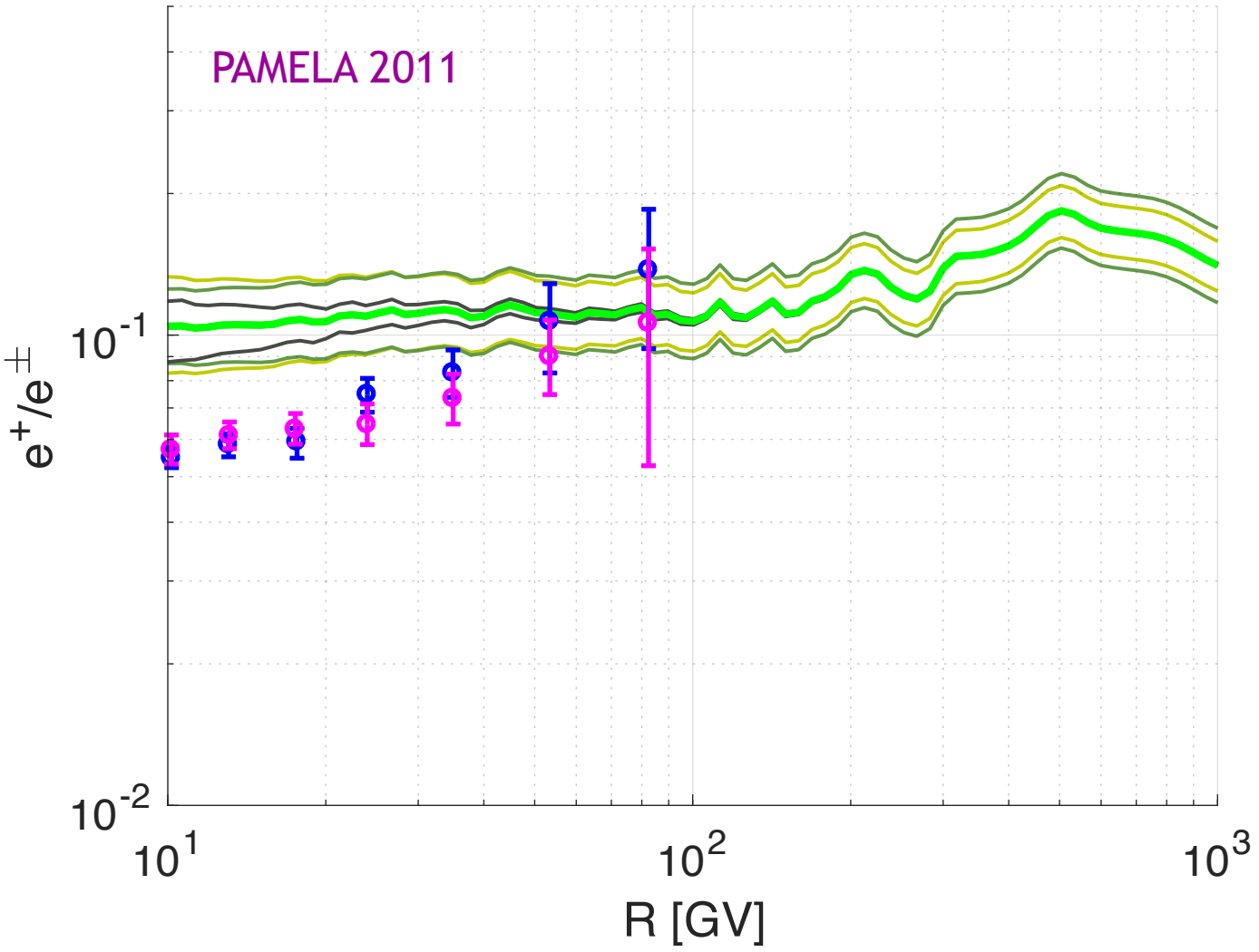


e+ upper bound predicted in Katz et al (**0907.1686**),

Evaluated with latest cross section and CR nuclei data (1709.06507, 1709.04953)

Secondary *upper bound* (Based on B/C)

$$n_{e^+}(\mathcal{R}) \lesssim \frac{n_{\rm B}(\mathcal{R})}{Q_{\rm B}(\mathcal{R})} Q_{e^+}(\mathcal{R})$$

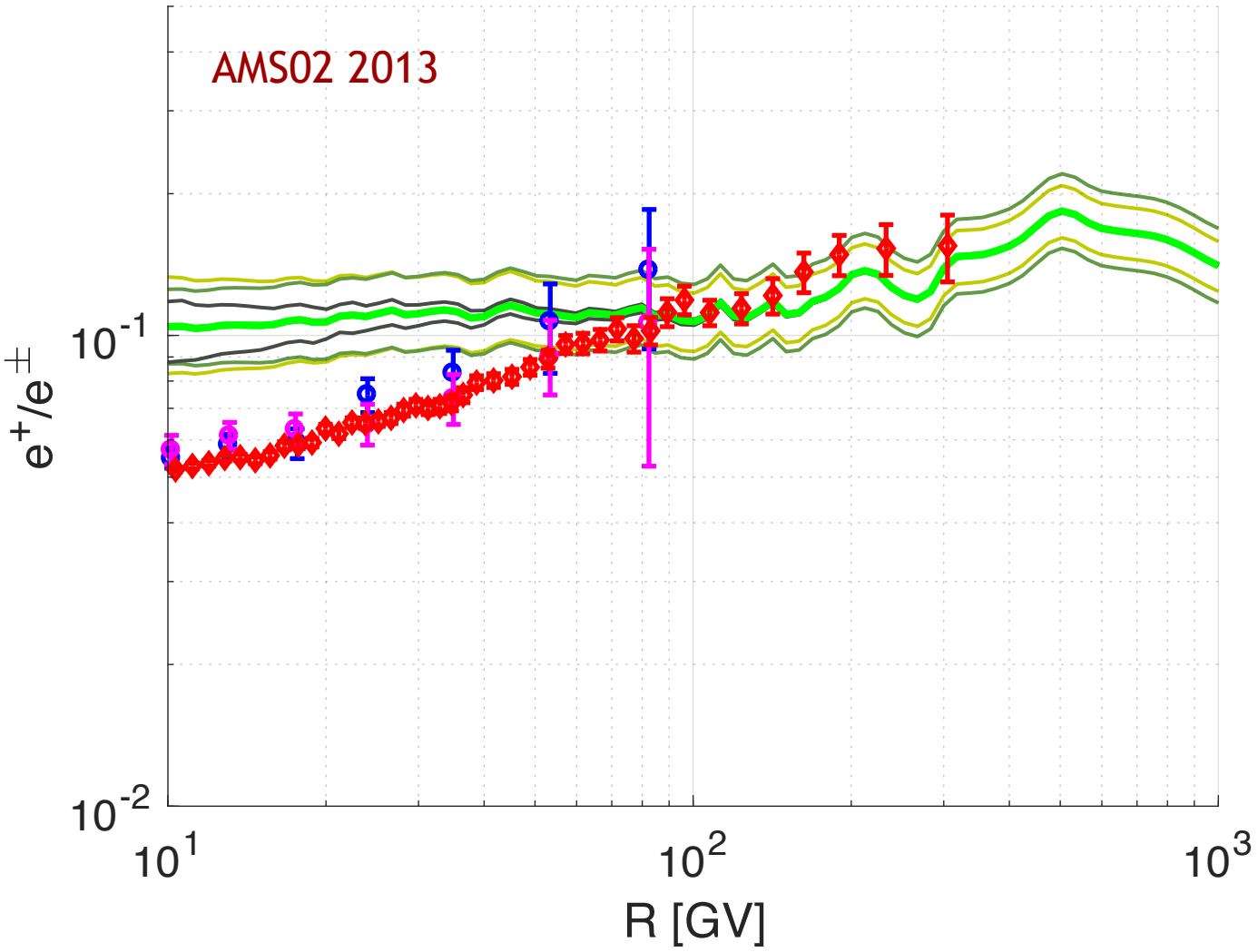


e+ upper bound predicted in Katz et al (**0907.1686**),

Evaluated with latest cross section and CR nuclei data (1709.06507, 1709.04953)

Secondary *upper bound* (Based on B/C)

$$n_{e^+}(\mathcal{R}) \lesssim \frac{n_{\rm B}(\mathcal{R})}{Q_{\rm B}(\mathcal{R})} Q_{e^+}(\mathcal{R})$$

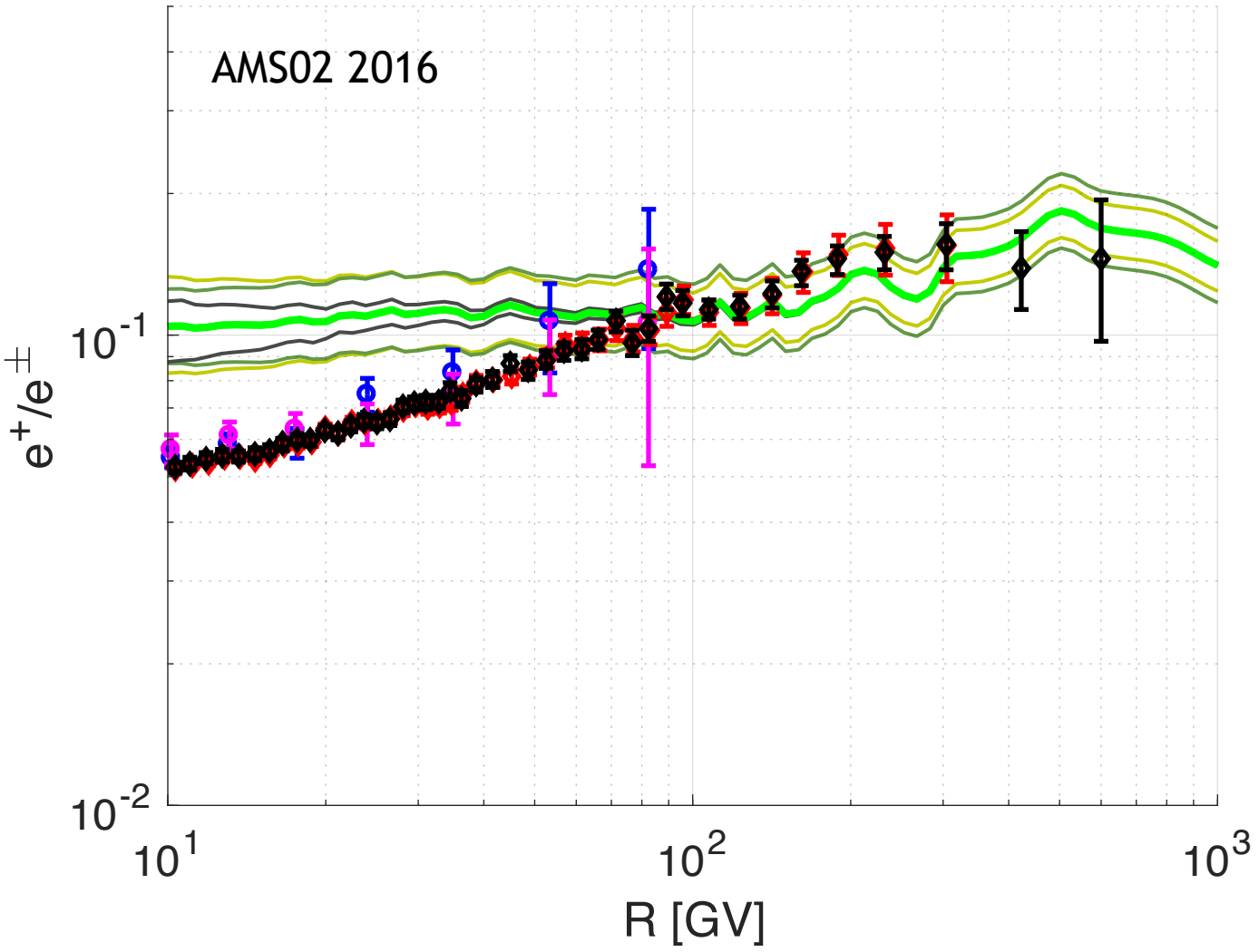


e+ upper bound predicted in Katz et al (**0907.1686**),

Evaluated with latest cross section and CR nuclei data (1709.06507, 1709.04953)

Secondary *upper bound* (Based on B/C)

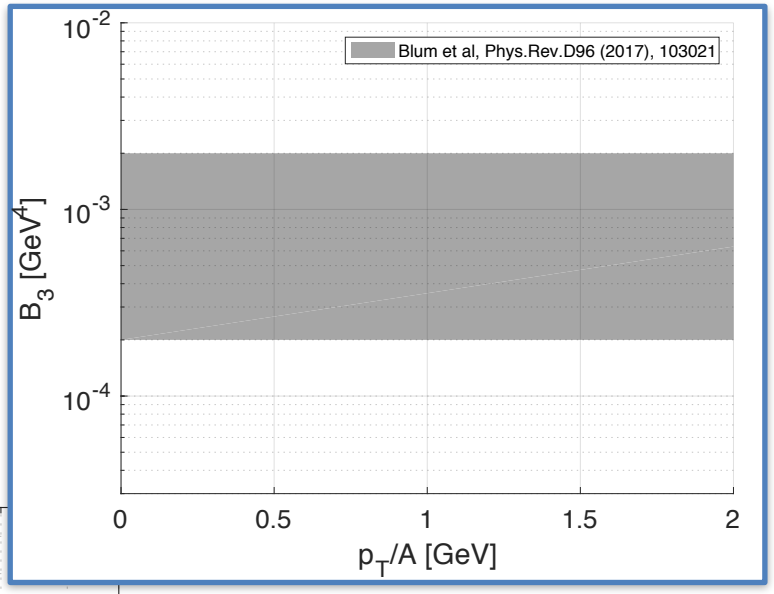
$$n_{e^+}(\mathcal{R}) \lesssim \frac{n_{\rm B}(\mathcal{R})}{Q_{\rm B}(\mathcal{R})} Q_{e^+}(\mathcal{R})$$

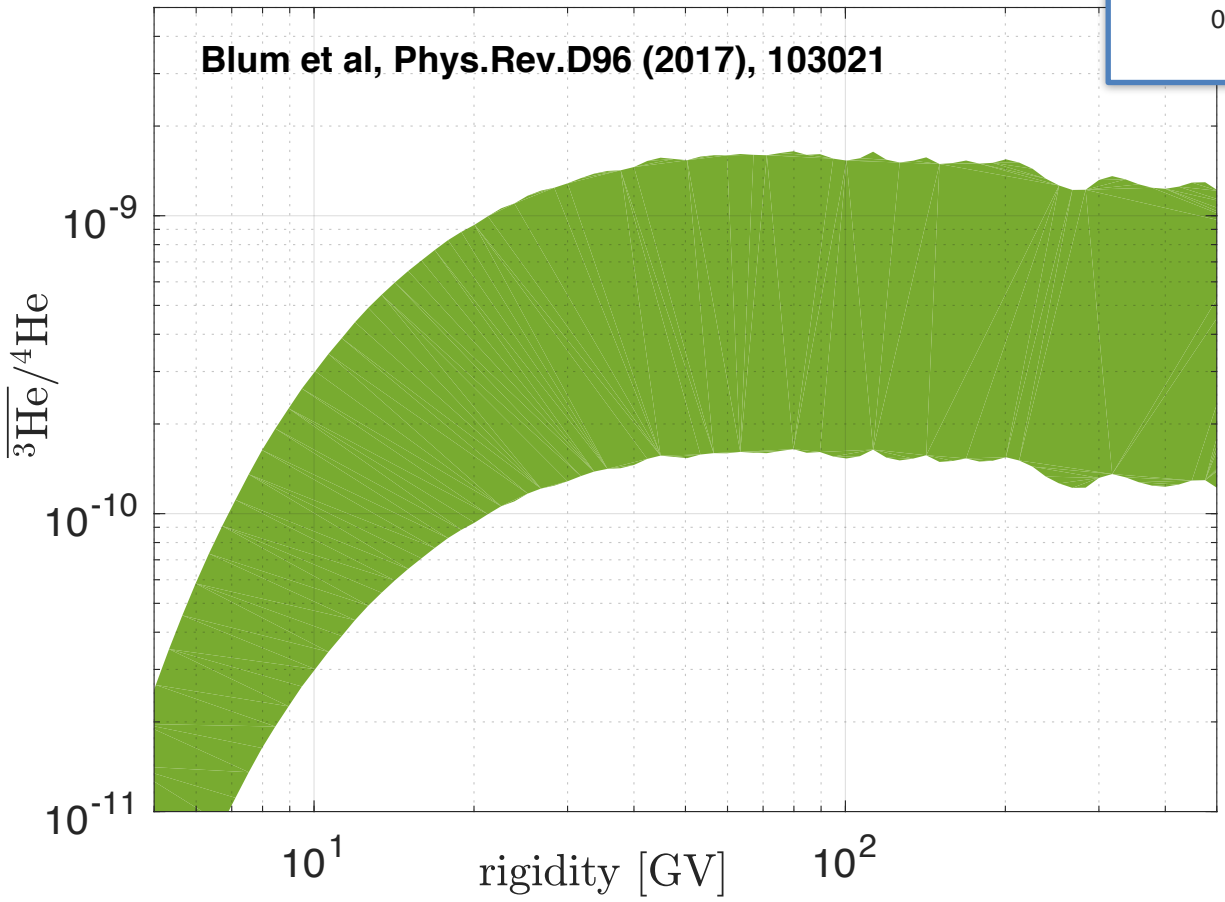


e+ upper bound predicted in Katz et al (**0907.1686**),

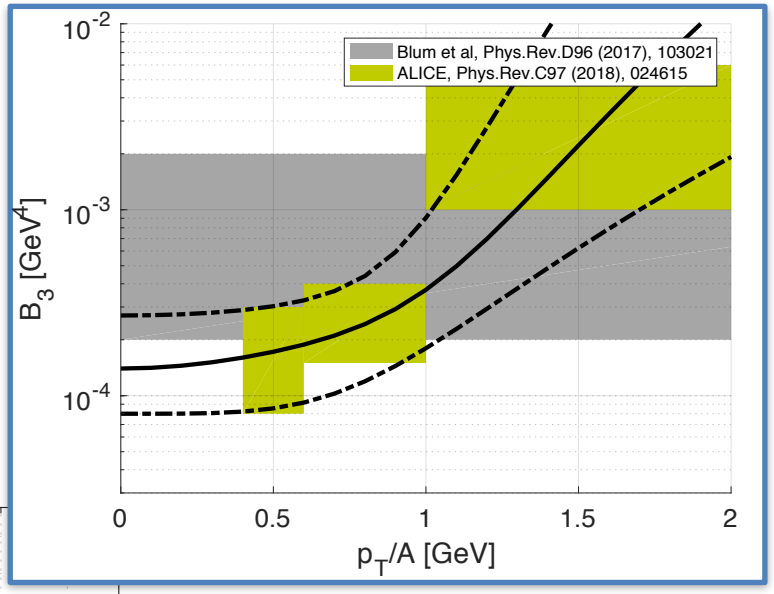
Evaluated with latest cross section and CR nuclei data (1709.06507, 1709.04953)

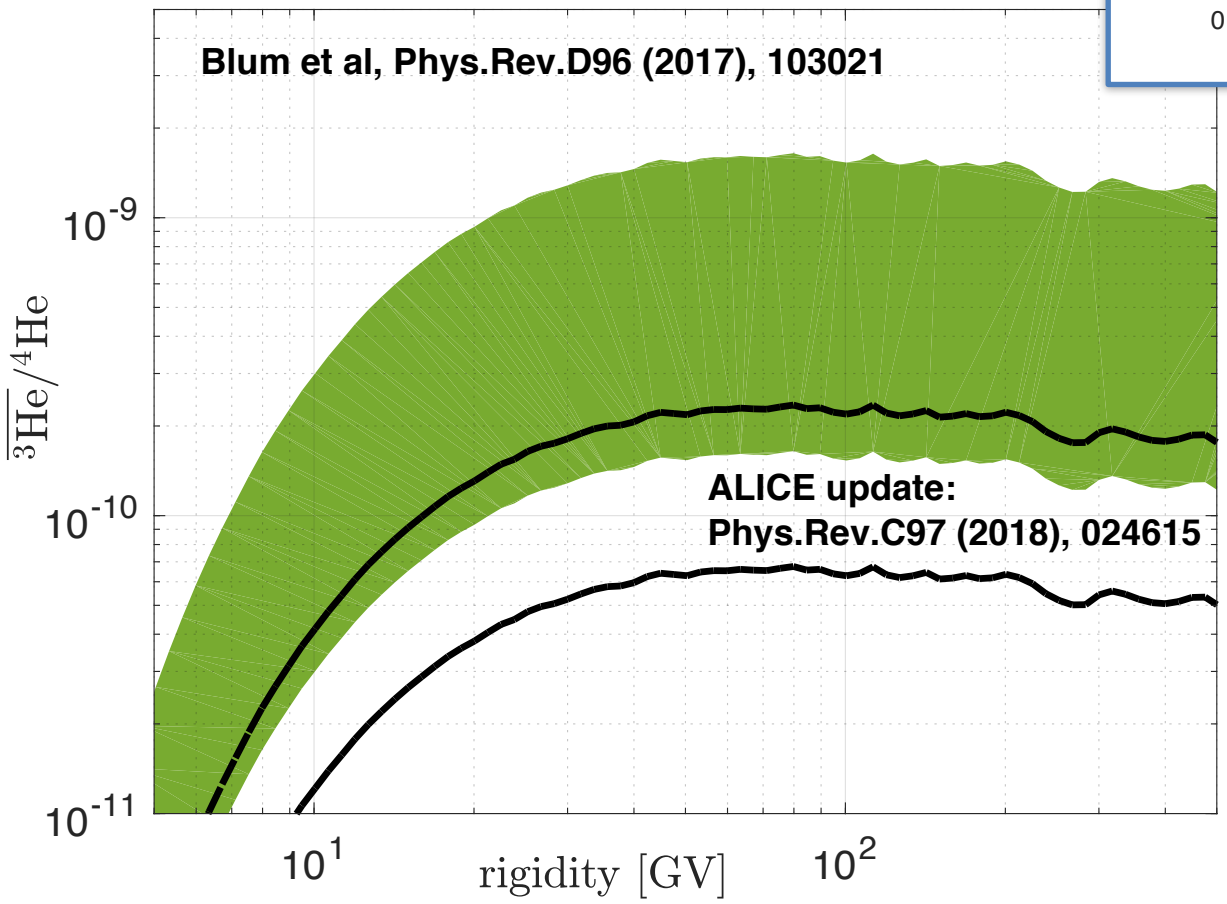
Anti-He


Blum et al, Phys.Rev.D96 (2017), 103021
10^{-2}
10^{-3}
10^{-4}
B_3 [GeV^4]
0
0.5
1
1.5
2
p_T/A [GeV]


Blum et al, Phys.Rev.D96 (2017), 103021
10^{-9}
10^{-10}
10^{-11}
$\overline{^3\mathrm{He}}/^4\mathrm{He}$
10^1
rigidity [GV]
10^2

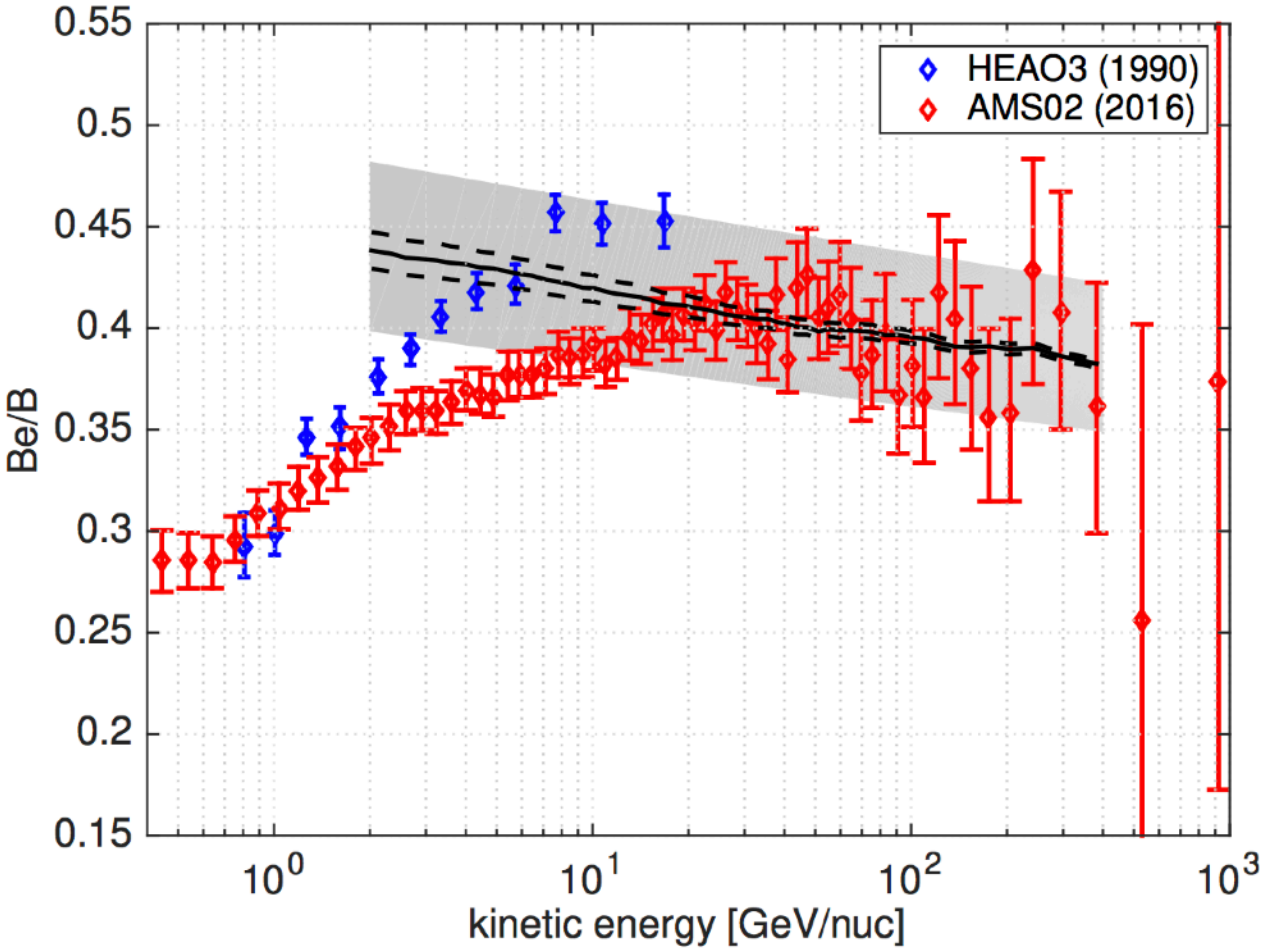
Anti-He


Blum et al, Phys.Rev.D96 (2017), 103021
ALICE, Phys.Rev.C97 (2018), 024615
B_3 [GeV^4]
p_T/A [GeV]


Blum et al, Phys.Rev.D96 (2017), 103021
ALICE update:
Phys.Rev.C97 (2018), 024615
$\overline{^3\mathrm{He}}/^4\mathrm{He}$
rigidity [GV]

Perhaps e+ is evidence of new physics, CR unknowns make it difficult to assess.
How do we test this further?

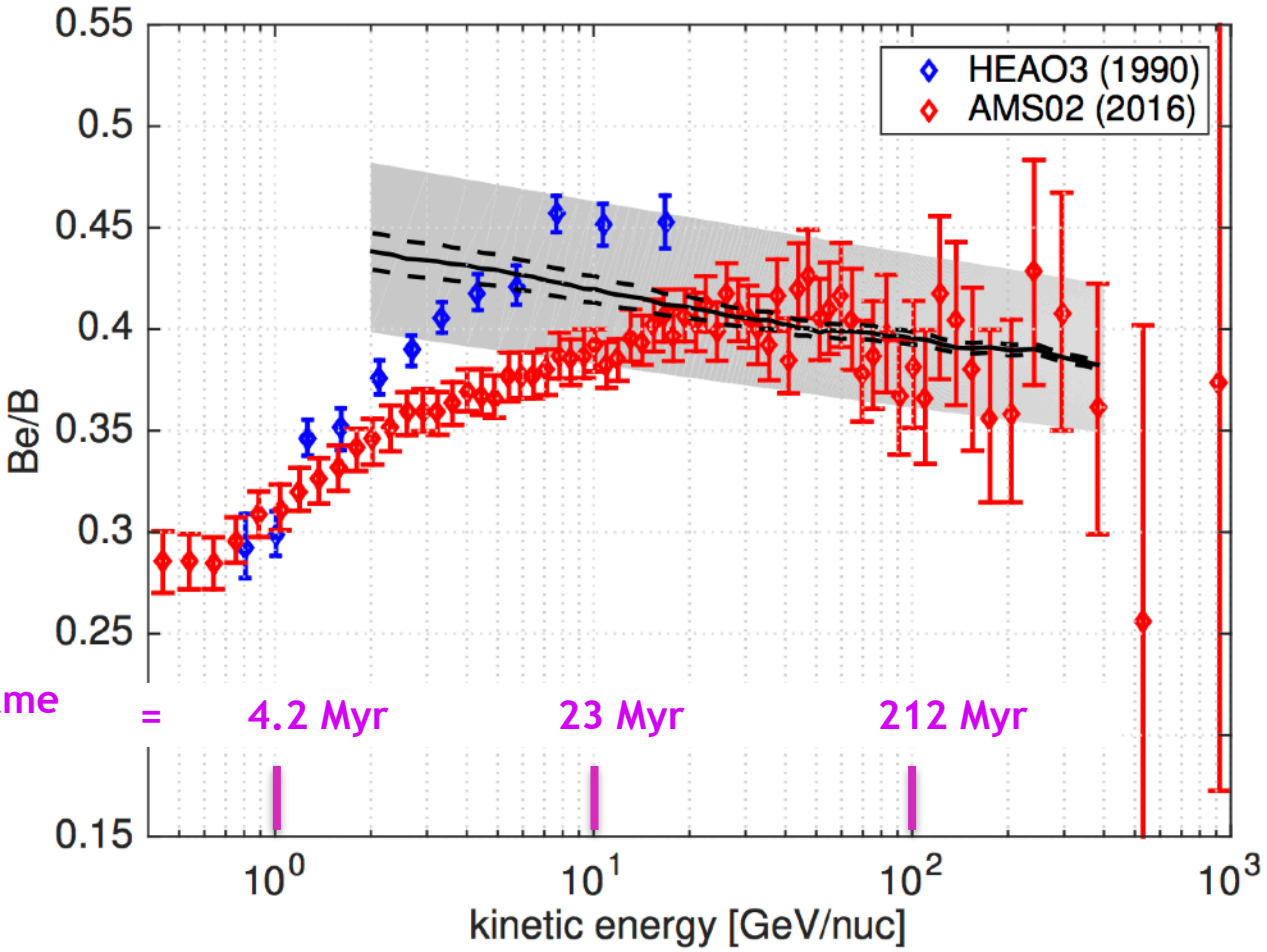
Radioactive nuclei



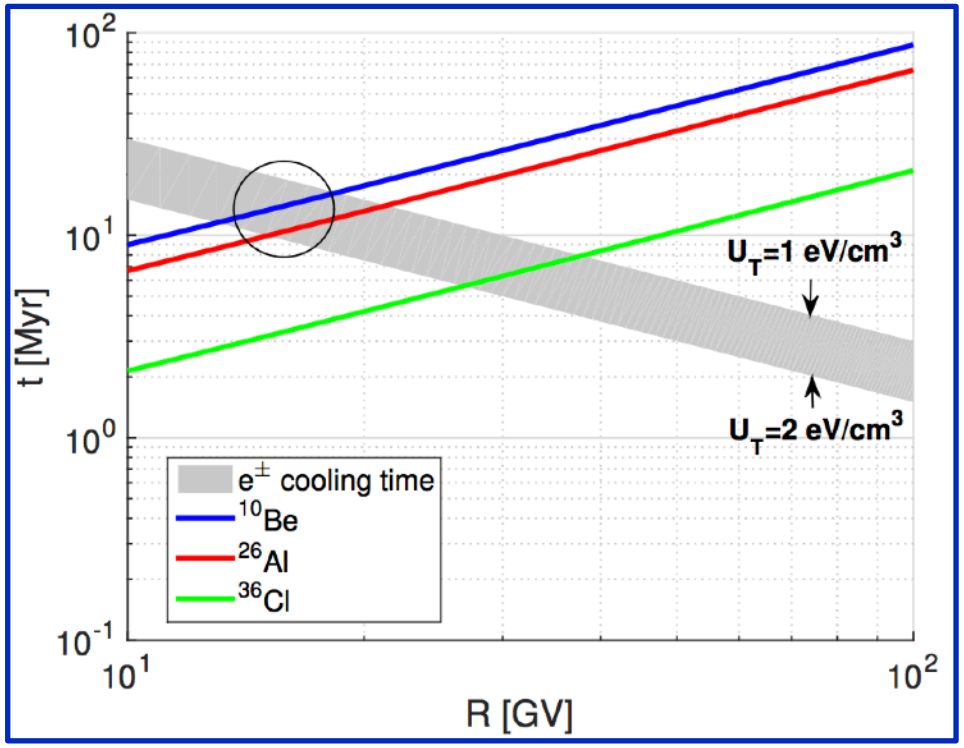
Perhaps e+ is evidence of new physics, CR unknowns make it difficult to assess.
How do we test this further?

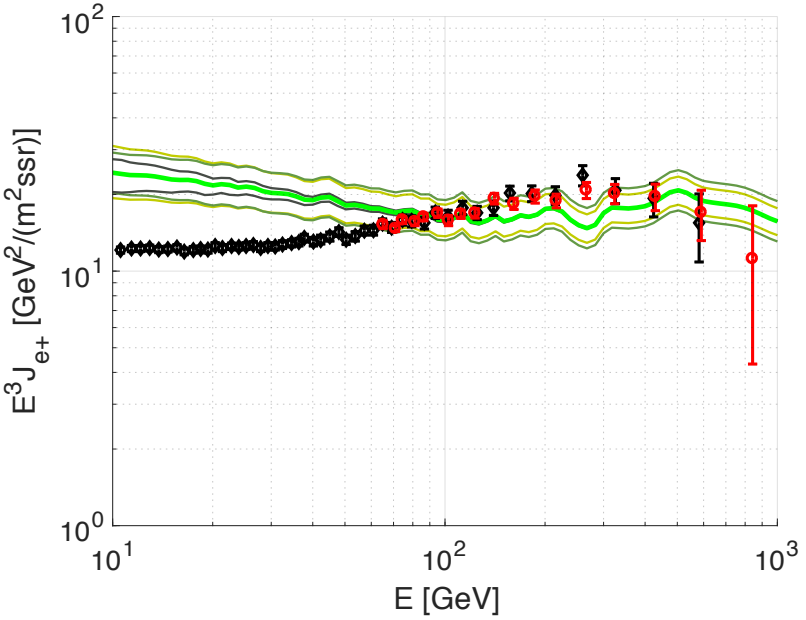
Radioactive nuclei

At rigidity R~20GV,
CR age is of order 10 Myr.



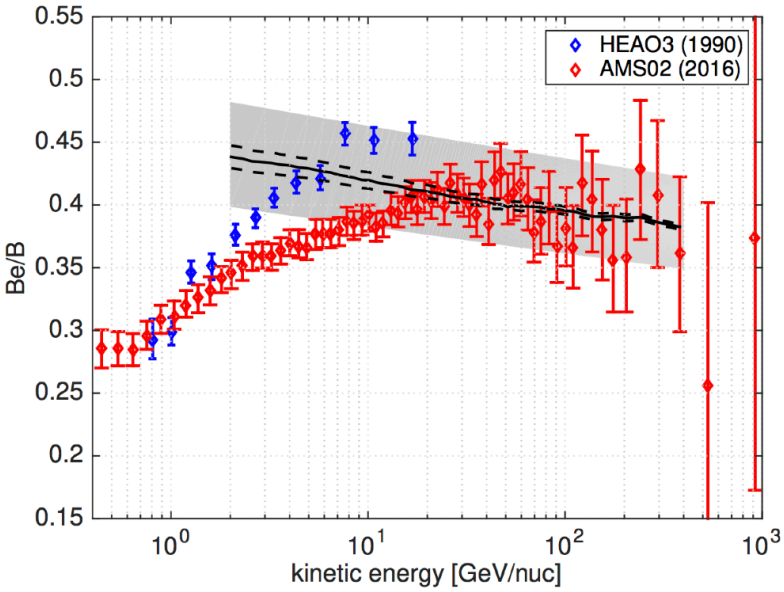
Perhaps e+ is evidence of new physics, CR unknowns make it difficult to assess.
How do we test this further?





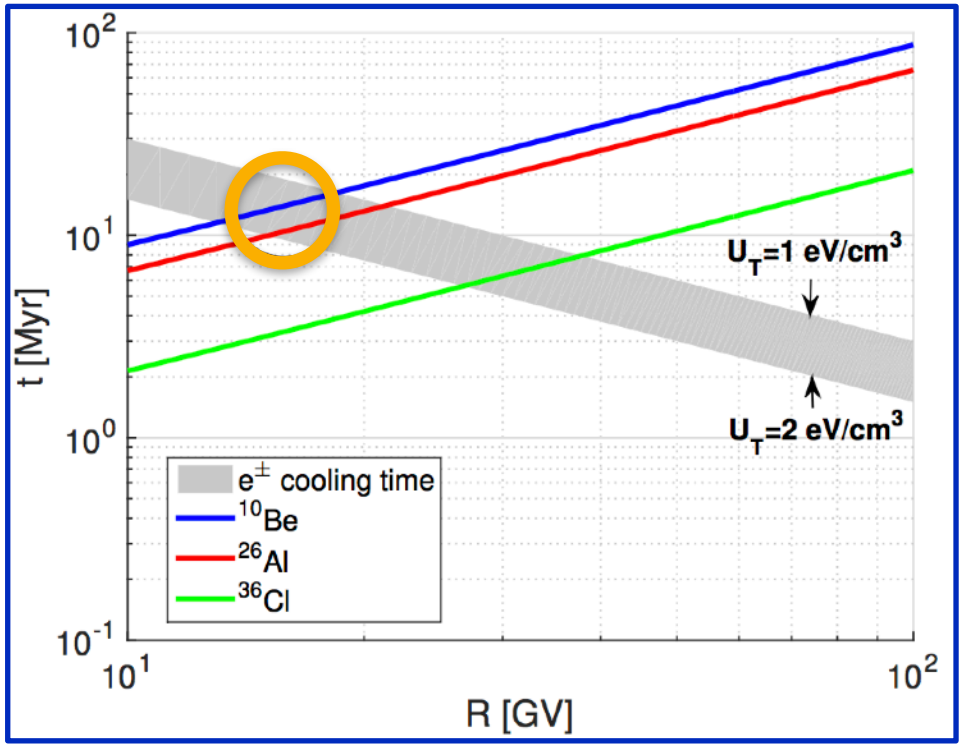
$$f_{^{10}\mathrm{Be}}(15\ \mathrm{GV}) \sim 0.3 - 0.4$$

$$f_{e^+}(15\ \mathrm{GV}) \sim 0.4 - 0.5$$



Katz et al (**0907.1686**), from HEAO3 data

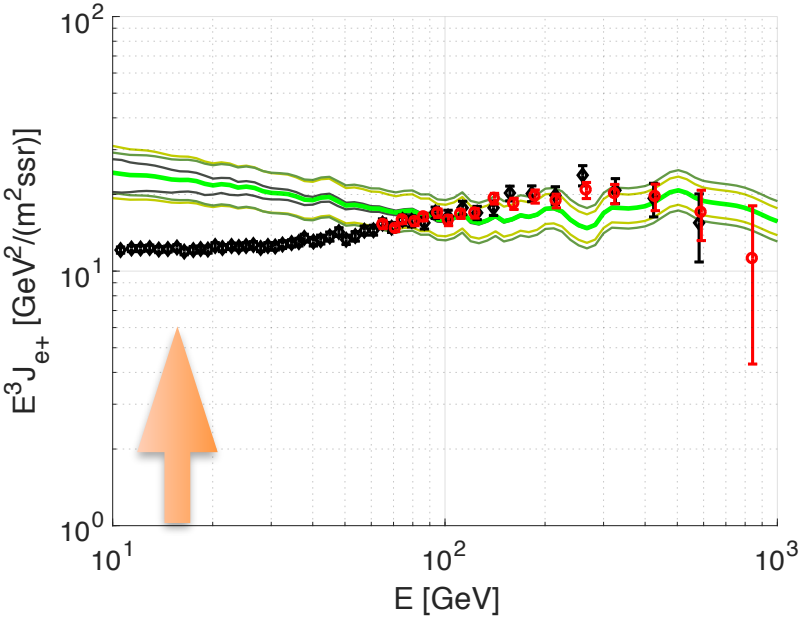
Perhaps e+ is evidence of new physics, CR unknowns make it difficult to assess.
How do we test this further?

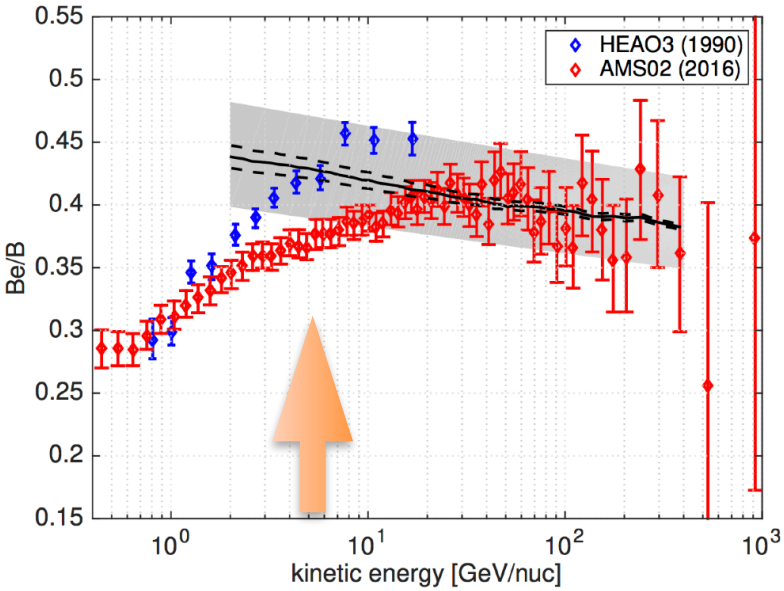


$$f_{^{10}\mathrm{Be}}(15\ \mathrm{GV}) \sim 0.3 - 0.4$$

$$f_{e^+}(15\ \mathrm{GV}) \sim 0.4 - 0.5$$

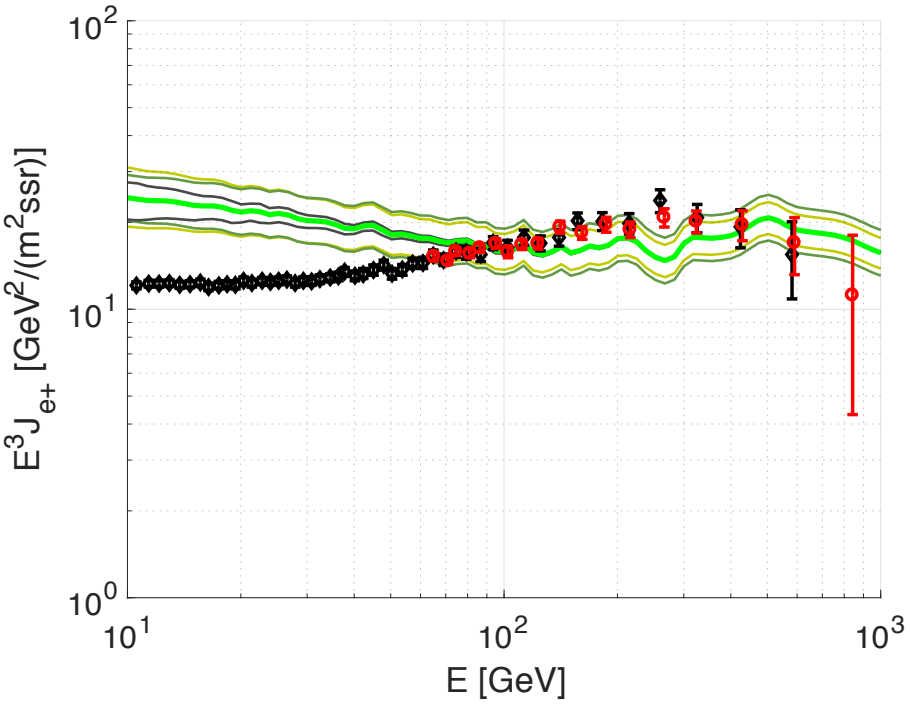
Katz et al (**0907.1686**), from HEAO3 data

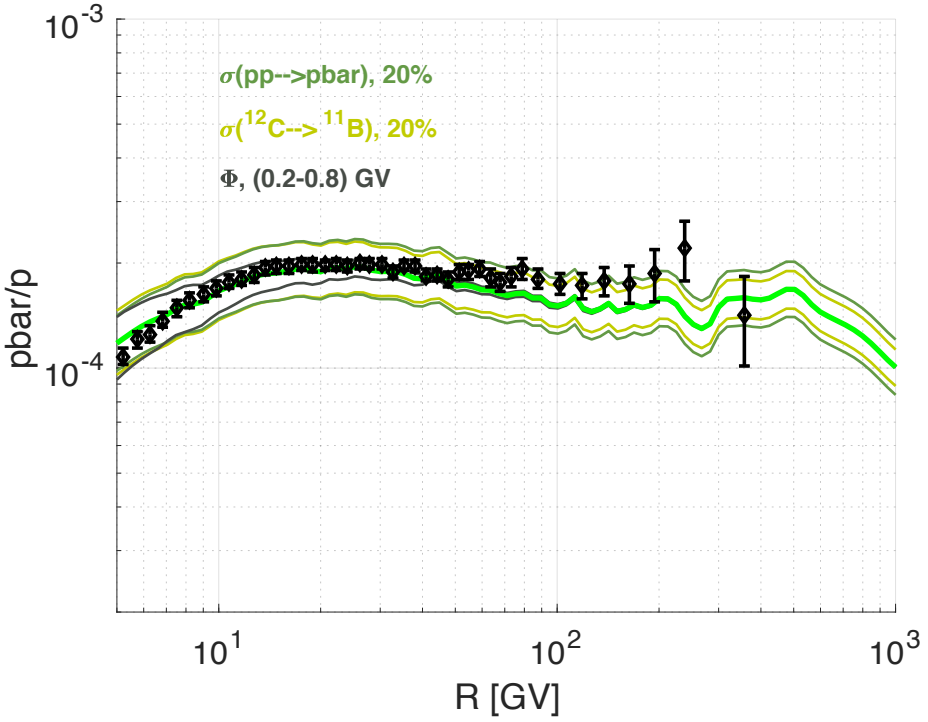




The data supports the simple possibility, that CR nuclei (C,N,O,…) have similar propagation histories as CR p, He, and that fragmentation occurs w/ CR spectra similar to those observed locally.

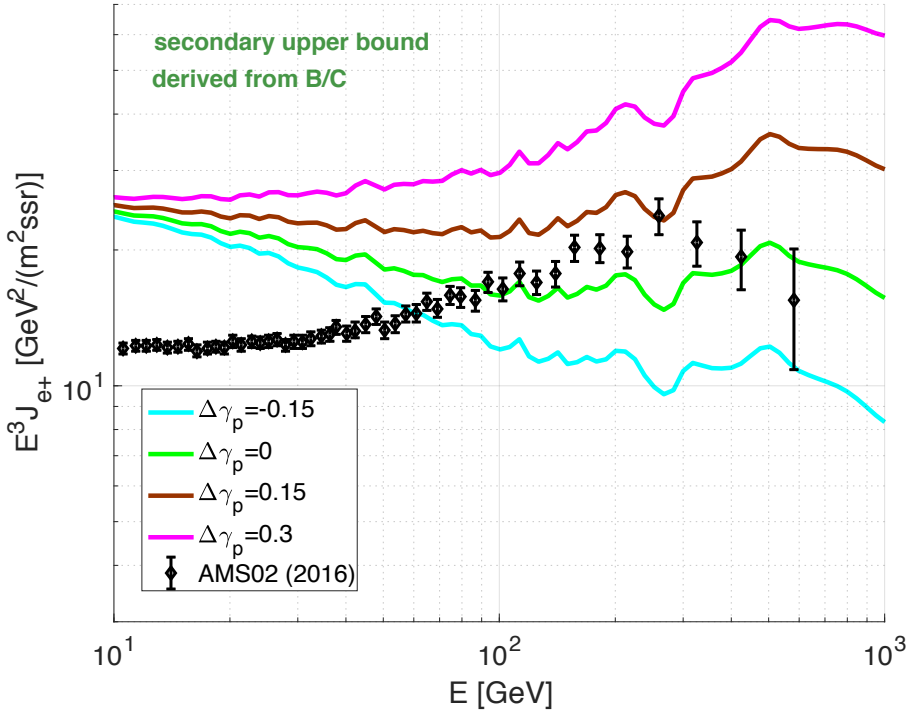
But this simple possibility is not guaranteed from theory, and could be violated to some extent.

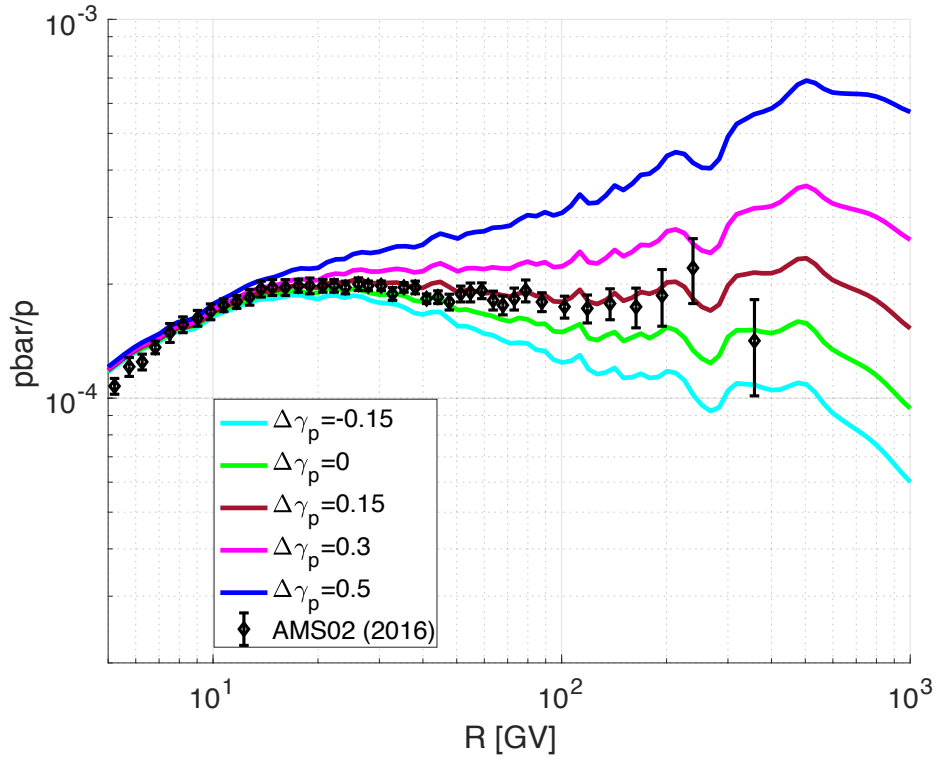




The data supports the simple possibility, that CR nuclei (C,N,O,…) have similar propagation histories as CR p, He, and that fragmentation occurs w/ CR spectra similar to those observed locally.

But this simple possibility is not guaranteed from theory, and could be violated to some extent.



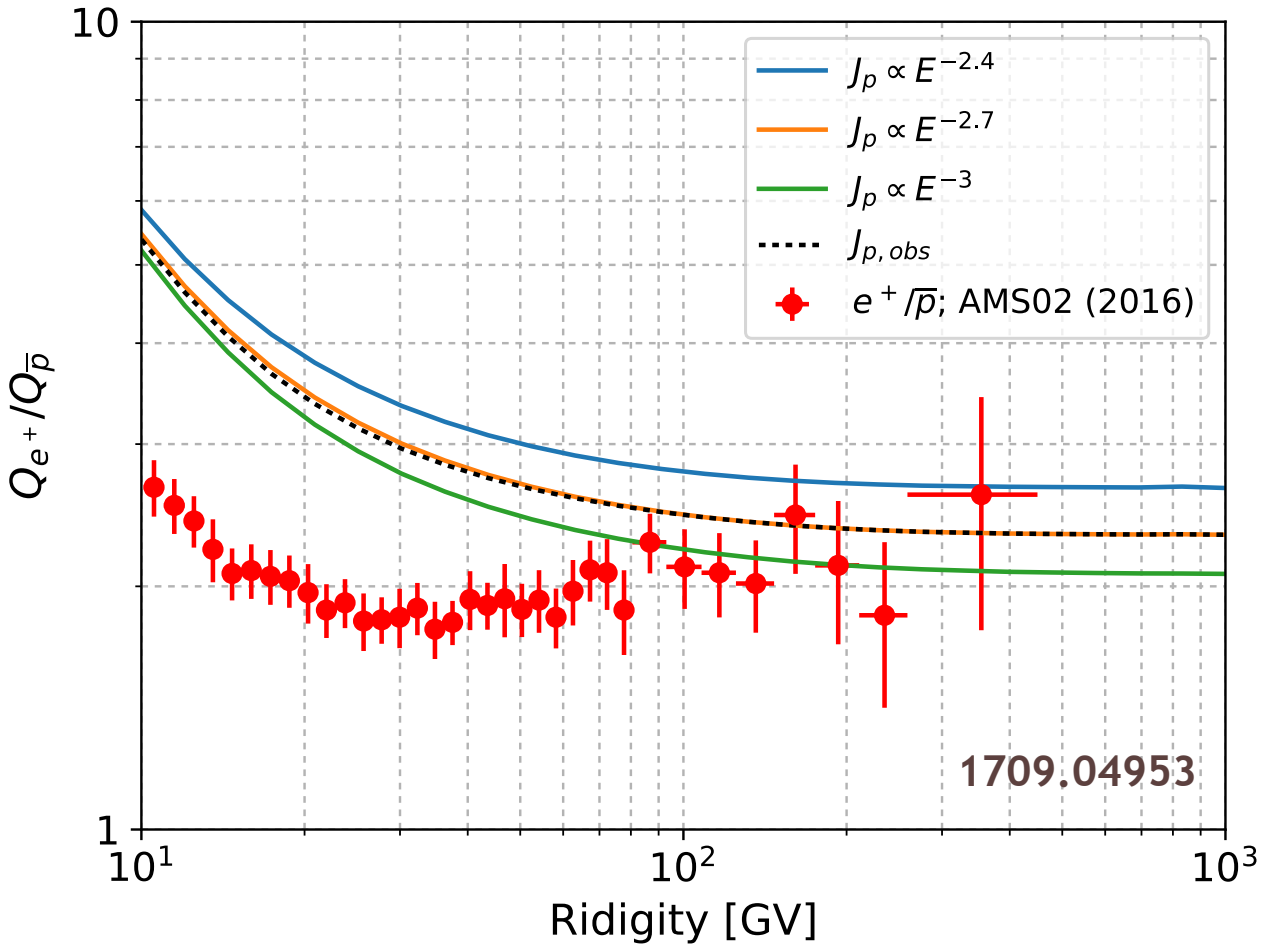


A more robust derivation:

Skip B/C, relate e+ directly to pbar

$$\frac{n_{e^+}}{n_{\bar{p}}} = f_{e^+}(\mathcal{R})\frac{Q_{e^+}(\mathcal{R})}{Q_{\bar{p}}(\mathcal{R})}$$

$$\boxed{f_{e^+}(\mathcal{R}) \leq 1}$$

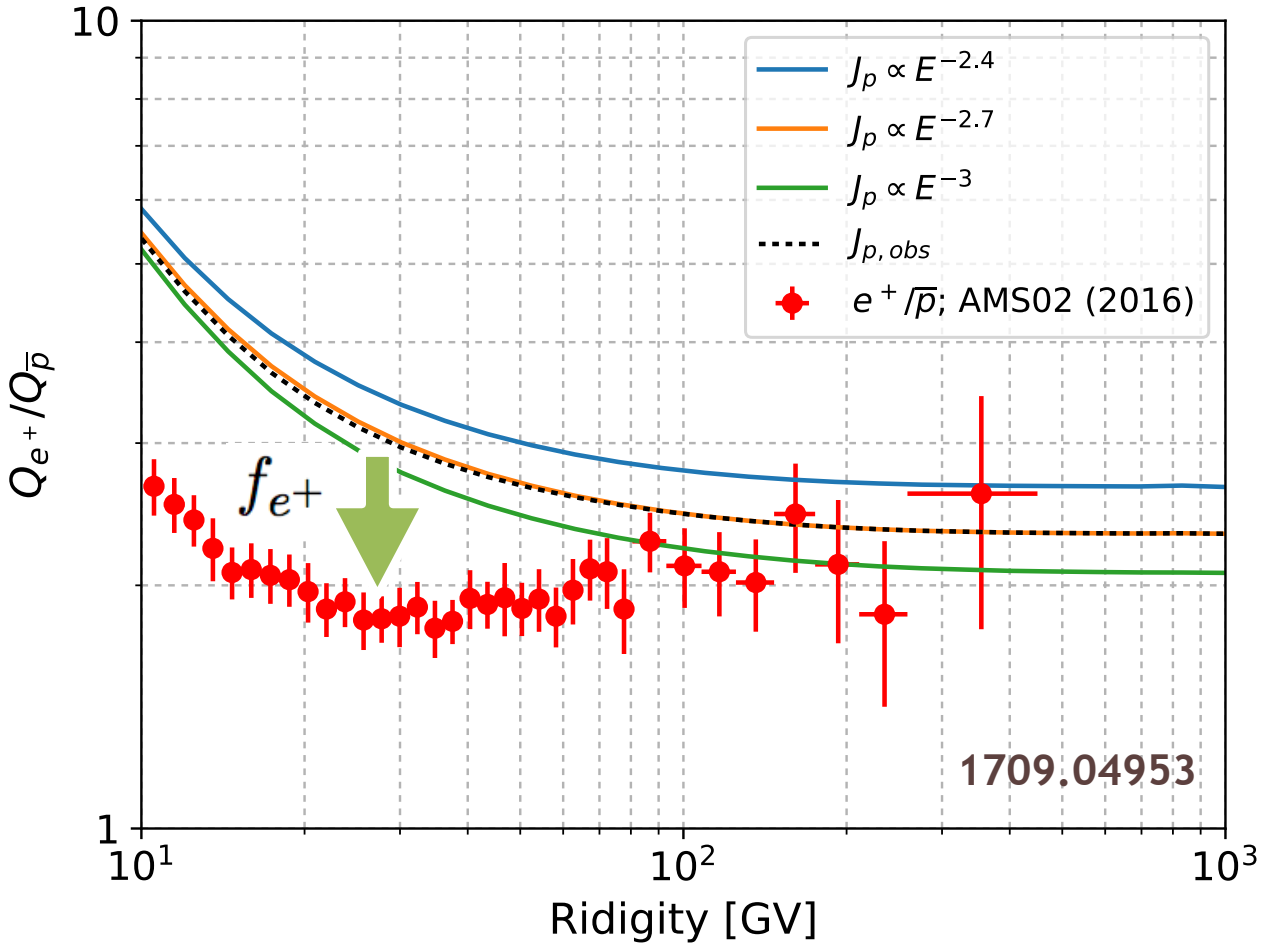


A more robust derivation:

Skip B/C, relate e+ directly to pbar

$$\frac{n_{e^+}}{n_{\bar{p}}} = f_{e^+}(\mathcal{R})\frac{Q_{e^+}(\mathcal{R})}{Q_{\bar{p}}(\mathcal{R})}$$

$$f_{e^+}(\mathcal{R}) \leq 1$$

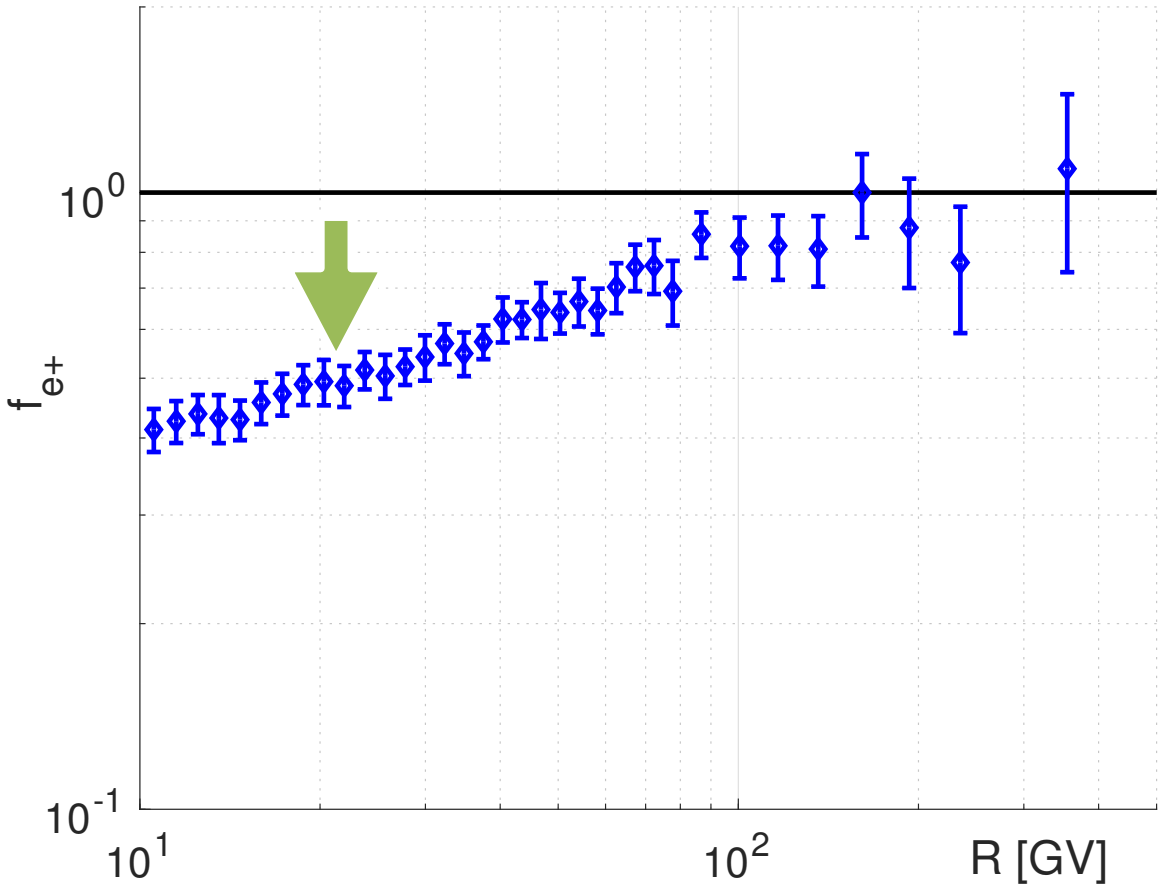


A more robust derivation:

Skip B/C, relate e+ directly to pbar

$$\frac{n_{e^+}}{n_{\bar{p}}} = f_{e^+}(\mathcal{R})\frac{Q_{e^+}(\mathcal{R})}{Q_{\bar{p}}(\mathcal{R})}$$

$$f_{e^+}(\mathcal{R}) \leq 1$$

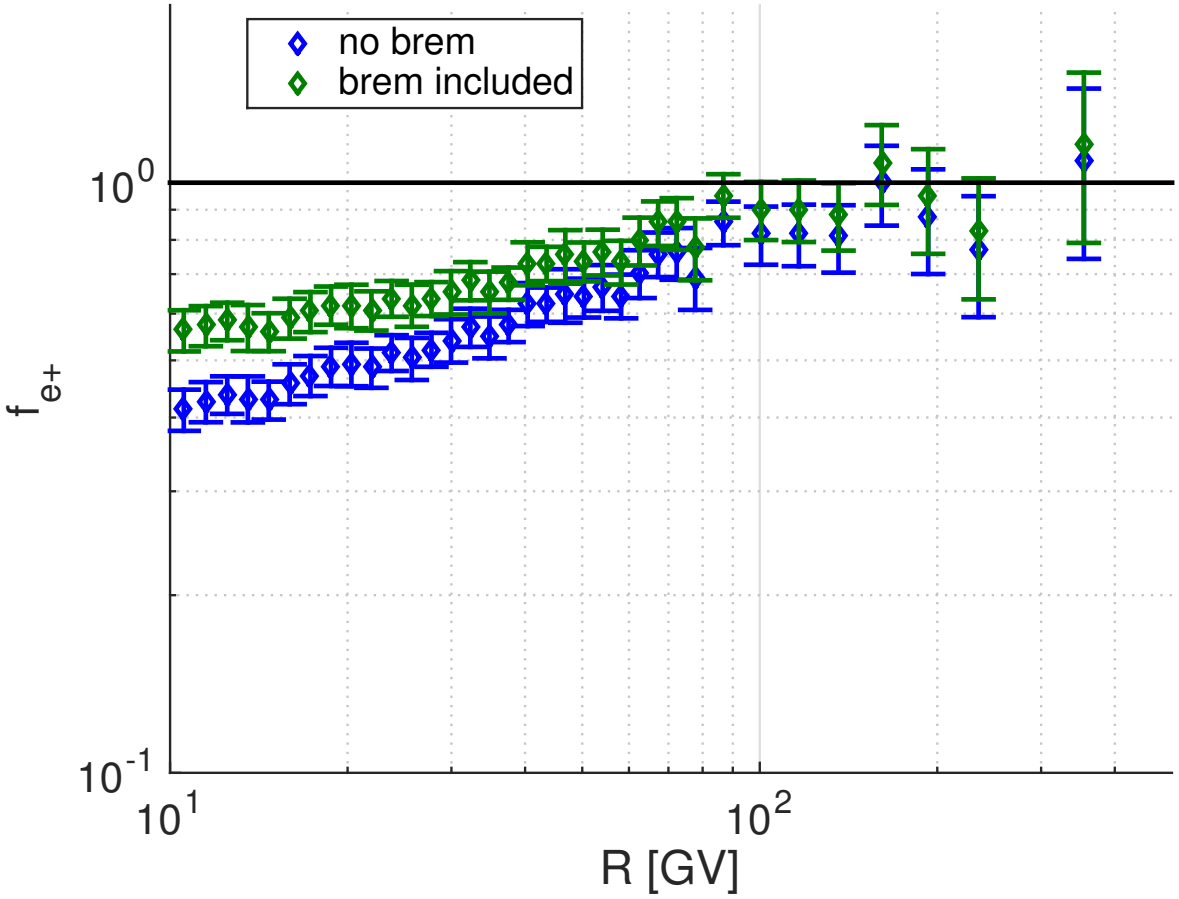


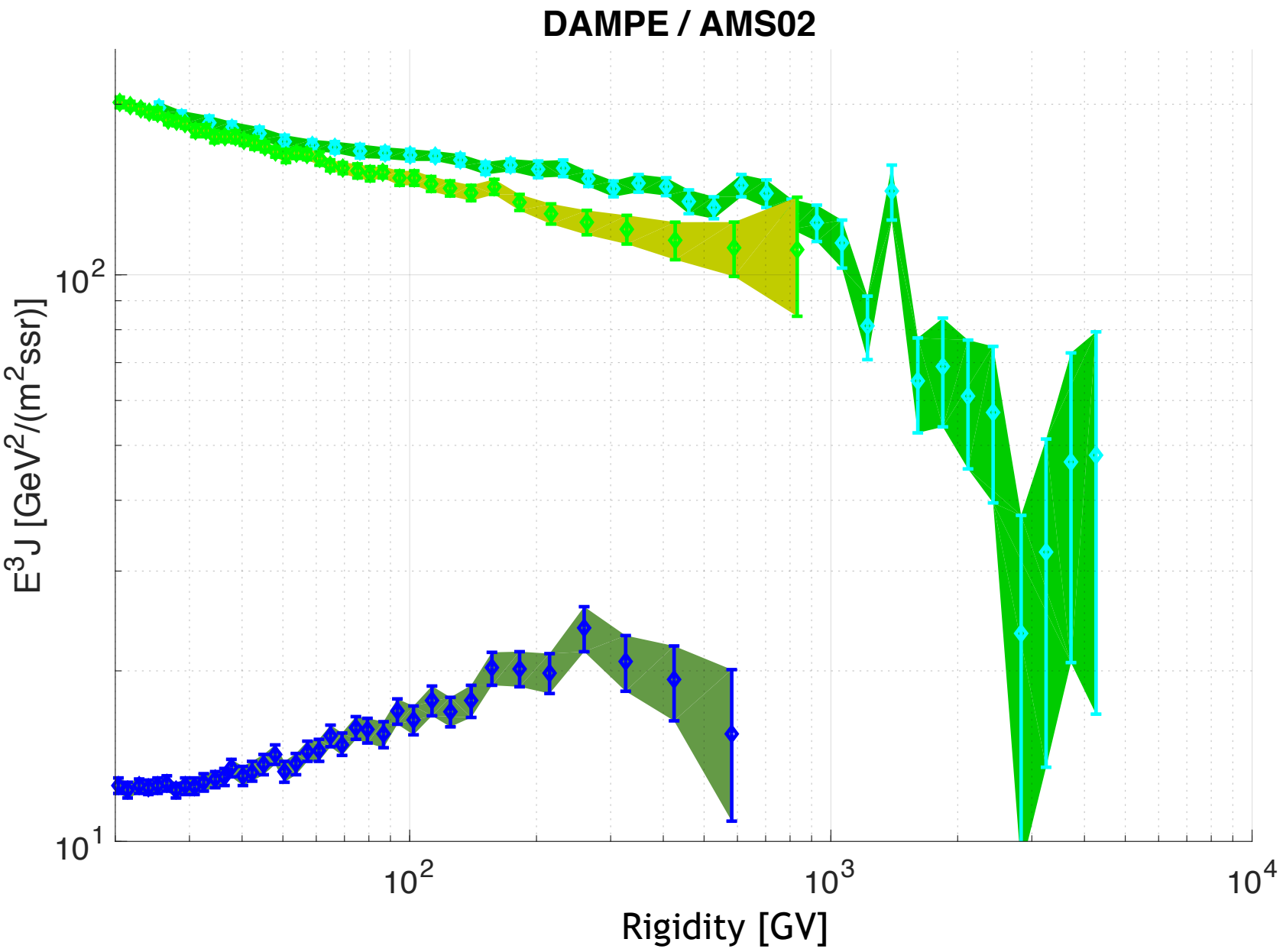
A more robust derivation:

Skip B/C, relate e+ directly to pbar

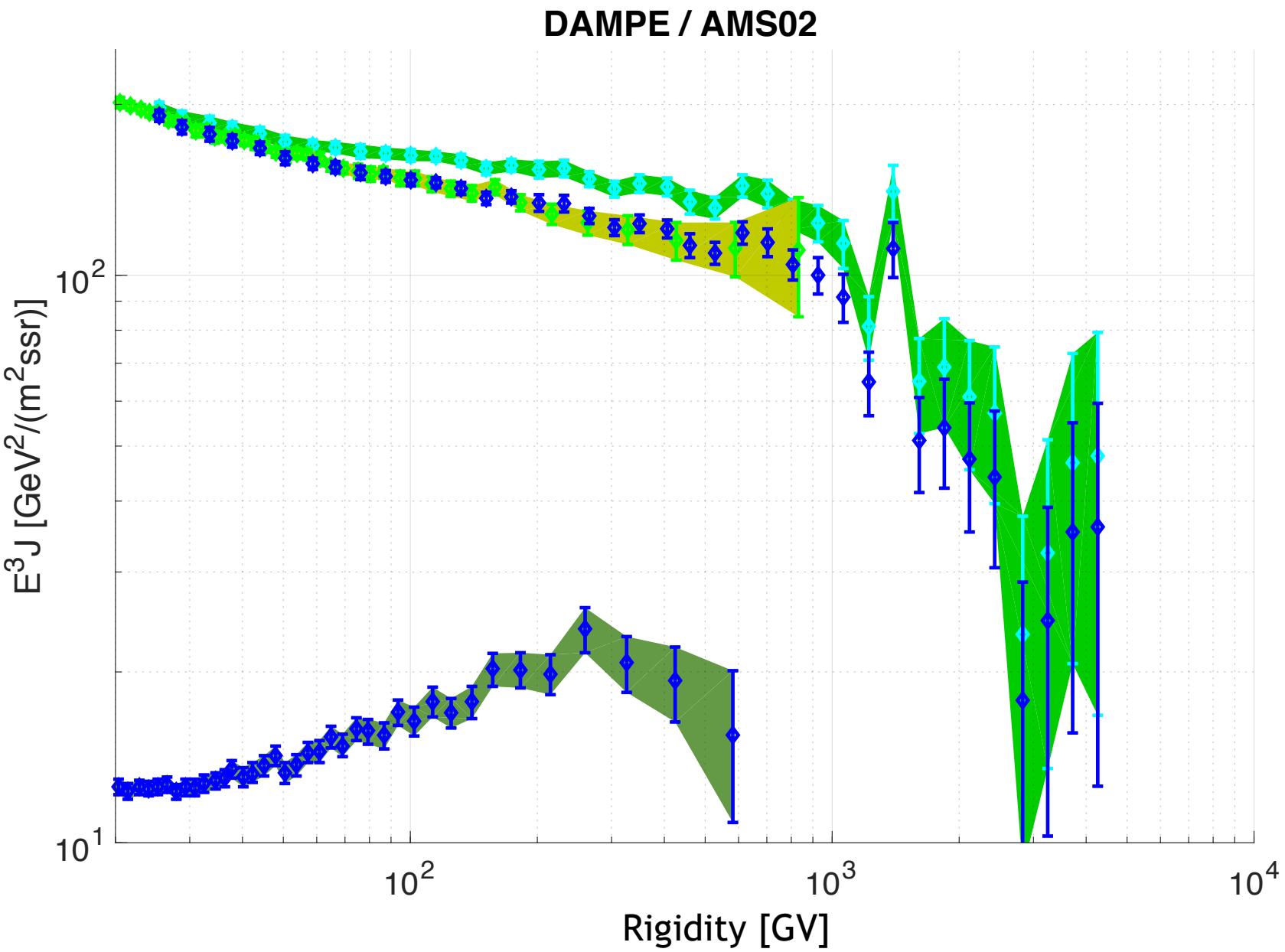
$$\frac{n_{e^+}}{n_{\bar{p}}} = f_{e^+}(\mathcal{R})\frac{Q_{e^+}(\mathcal{R})}{Q_{\bar{p}}(\mathcal{R})}$$

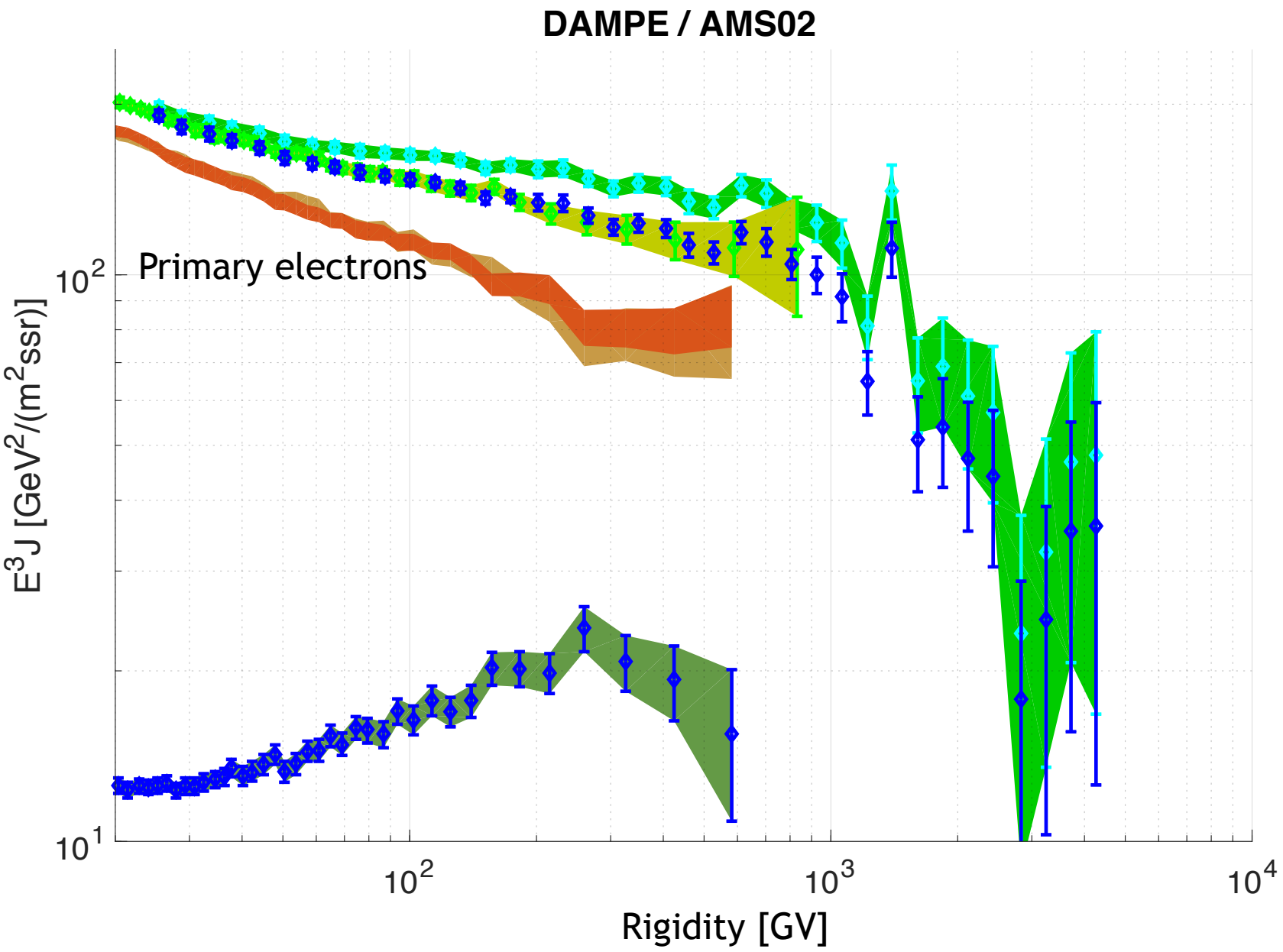
$$f_{e^+}(\mathcal{R}) \leq 1$$

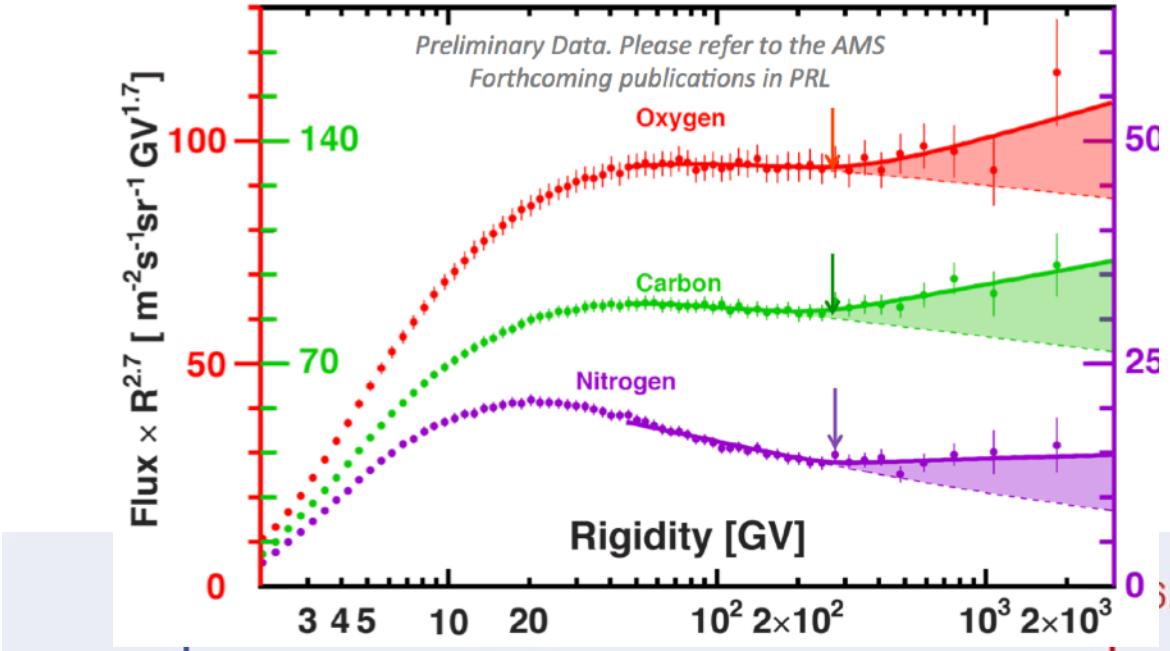


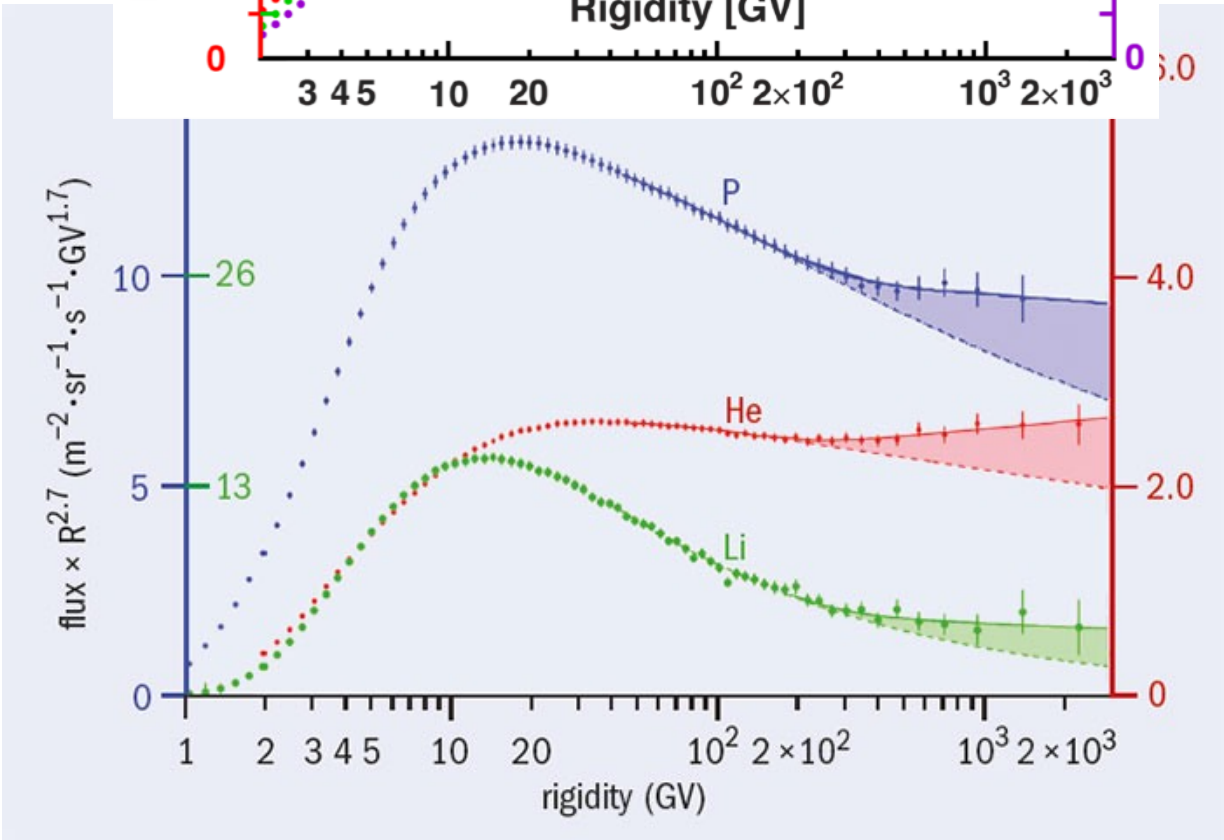

DAMPE / AMS02
$E^3 J$ [GeV^2/(m^{2}ssr)]
10^2
10^1
10^2
10^3
10^4
Rigidity [GV]

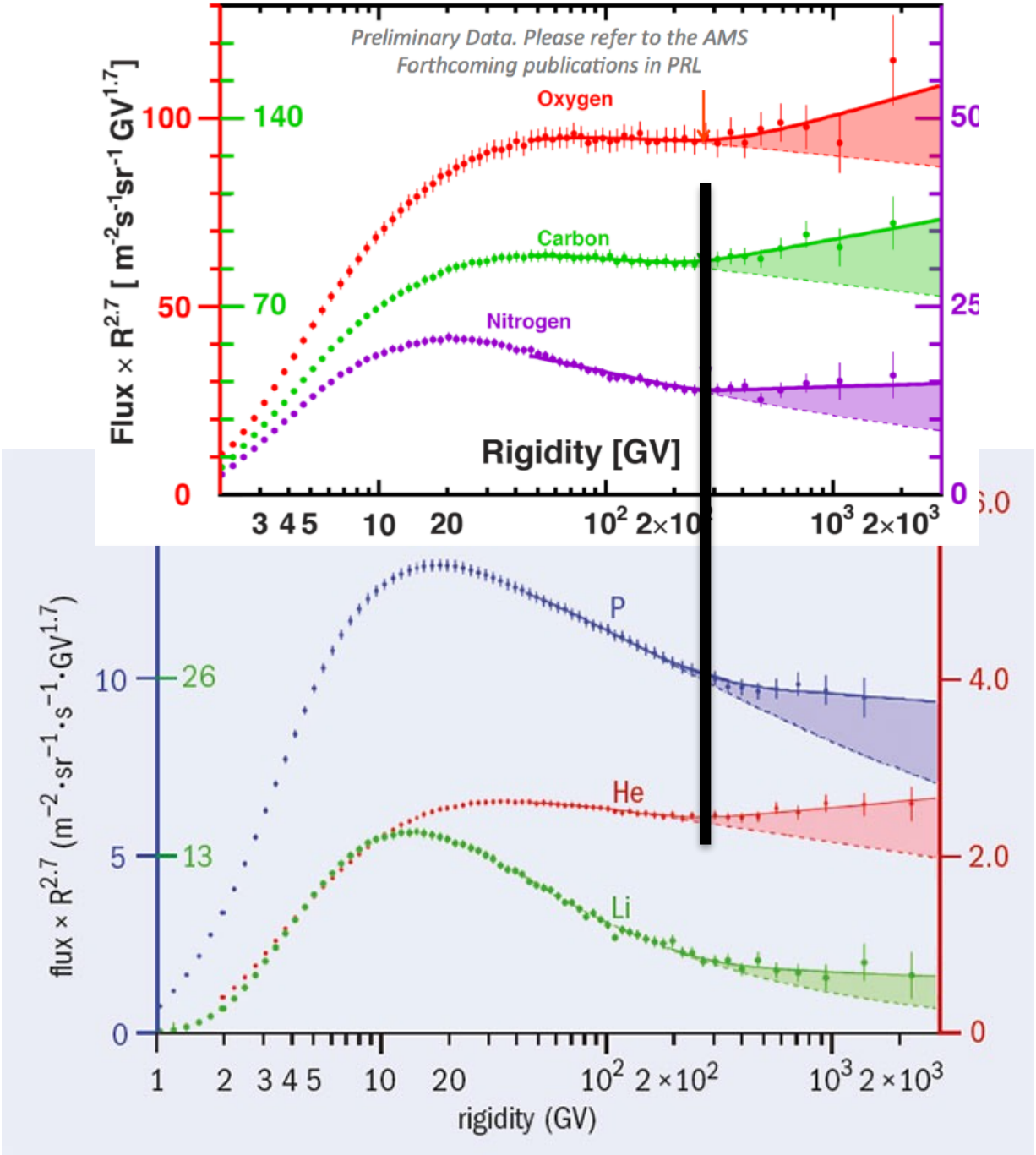
Rescale DAMPE to match AMS02 (sorry China)

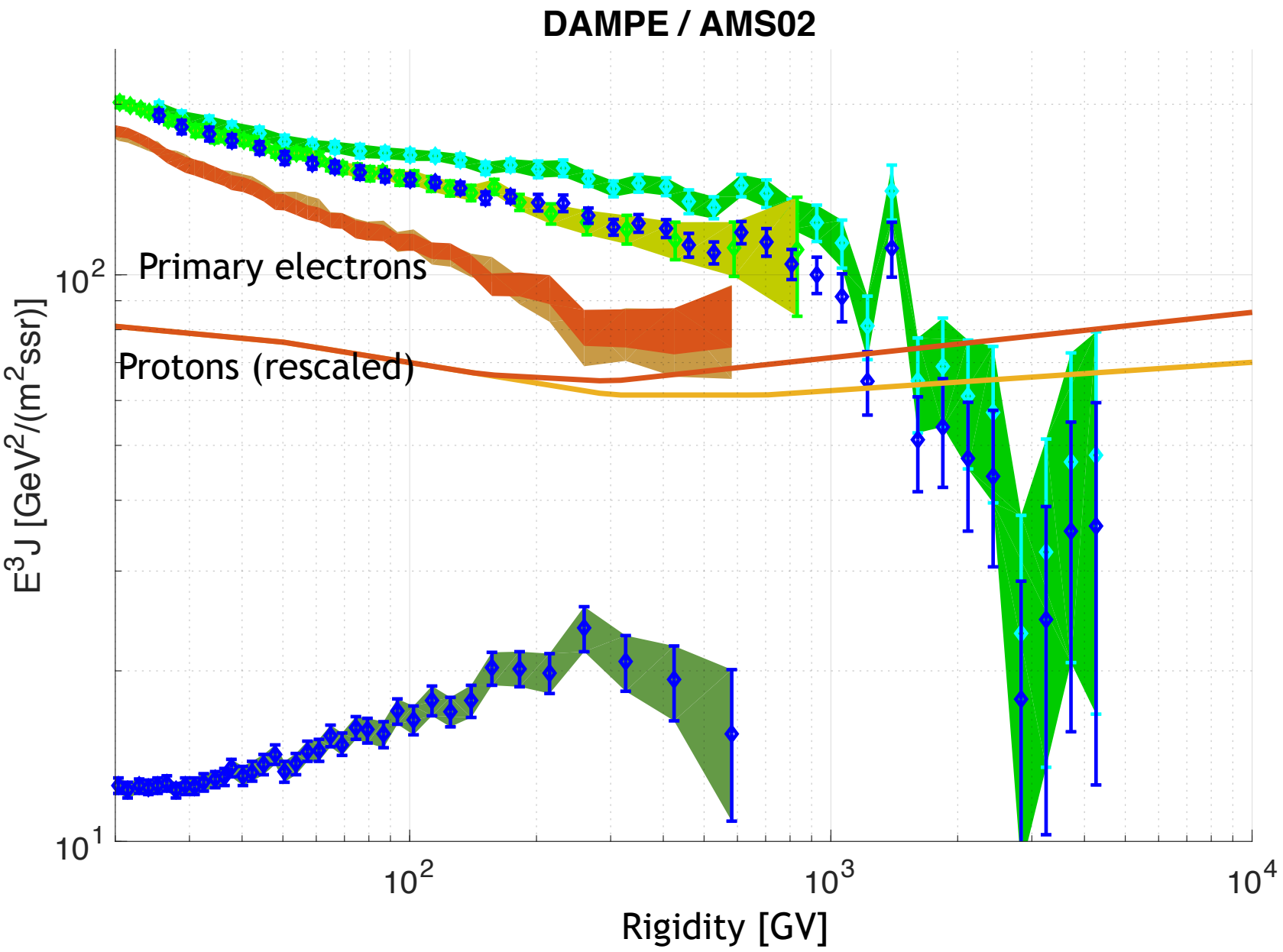


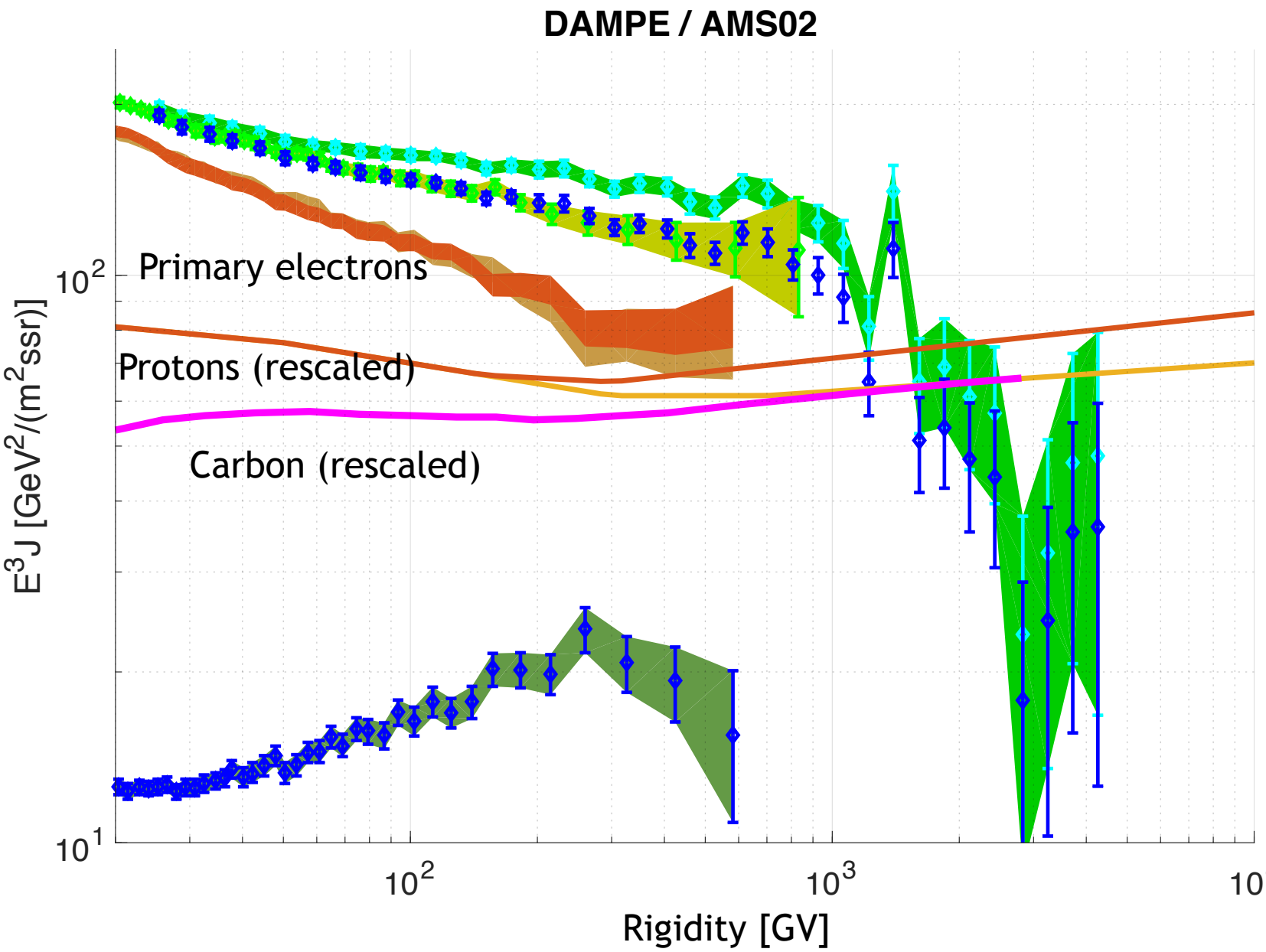

DAMPE / AMS02
Primary electrons
$E^3 J$ [GeV^2/(m^{2}ssr)]
10^2
10^1
10^2
10^3
10^4
Rigidity [GV]

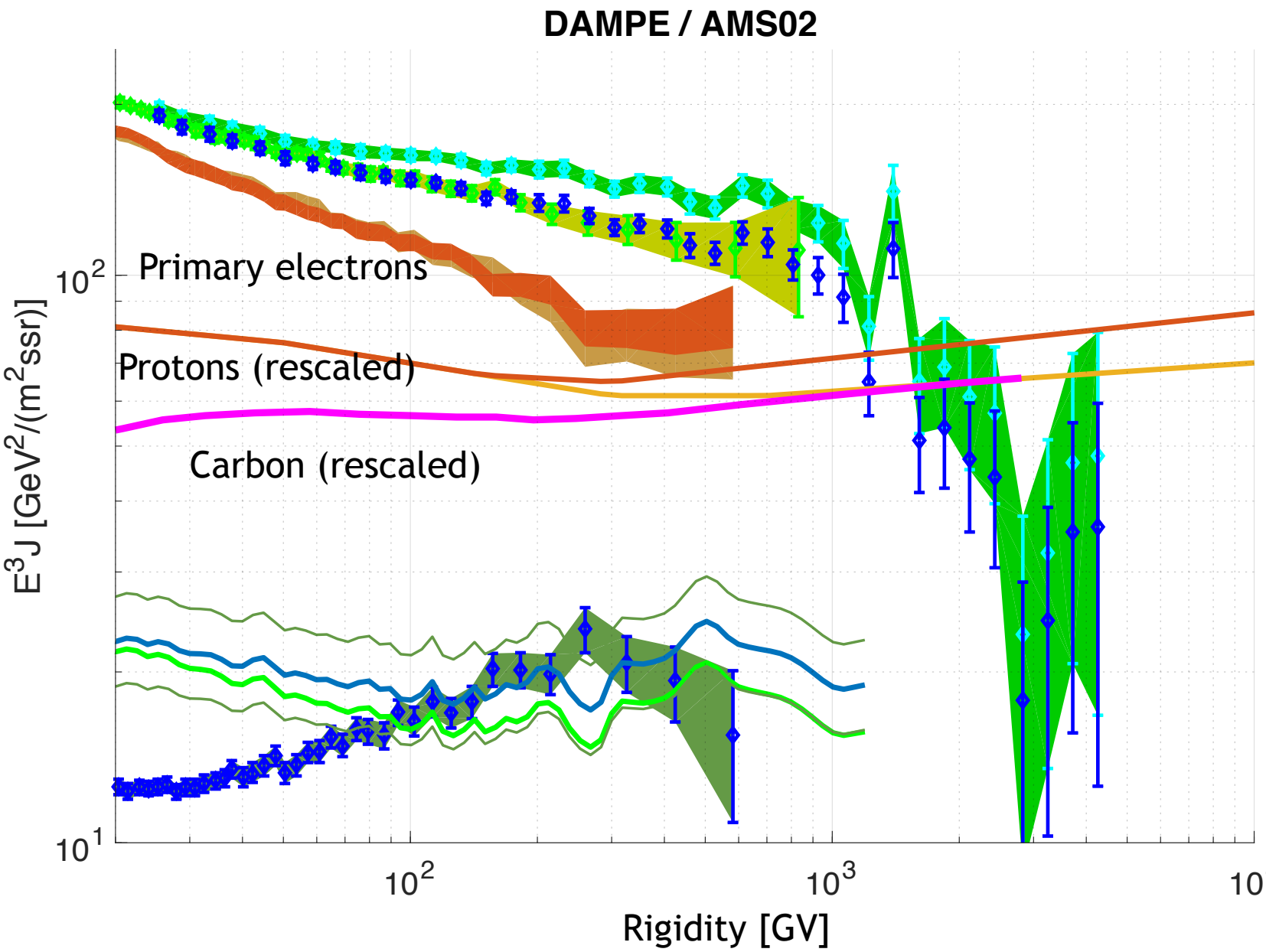

Preliminary Data. Please refer to the AMS
Forthcoming publications in PRL
Oxygen
Carbon
Nitrogen
Flux × R^2.7 [m^-2 s^-1 sr^-1 GV^1.7]
Rigidity [GV]
100
140
50
70
0
50
25
0
3 4 5
10
20
10^2
2×10^2
10^3
2×10^3

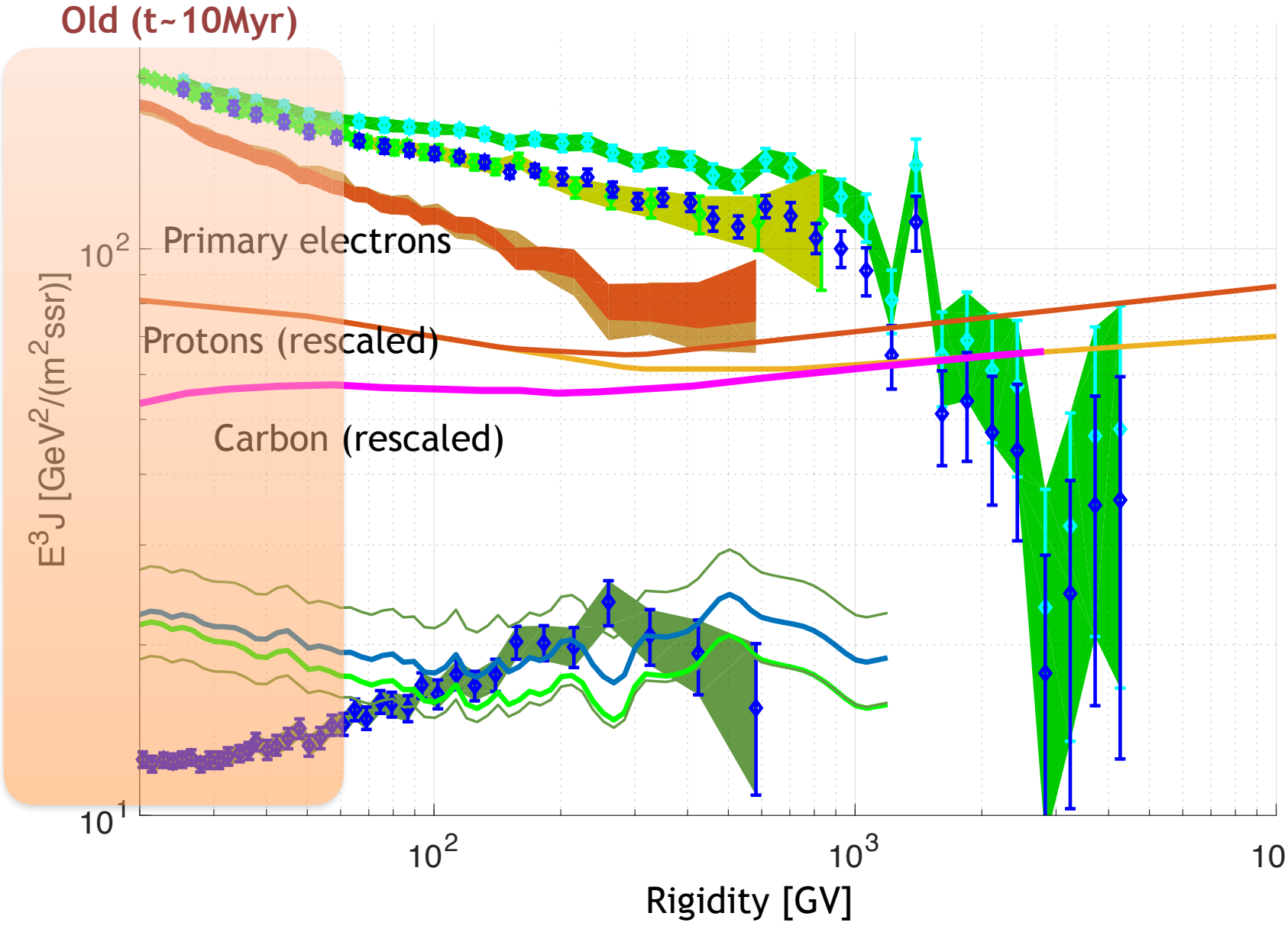

P
He
Li
flux × R^2.7 (m^-2 · sr^-1 · s^-1 · GV^1.7)
rigidity (GV)
10
26
5
13
0
4.0
2.0
0
1
2
3 4 5
10
20
10^2
2 ×10^2
10^3
2 ×10^3

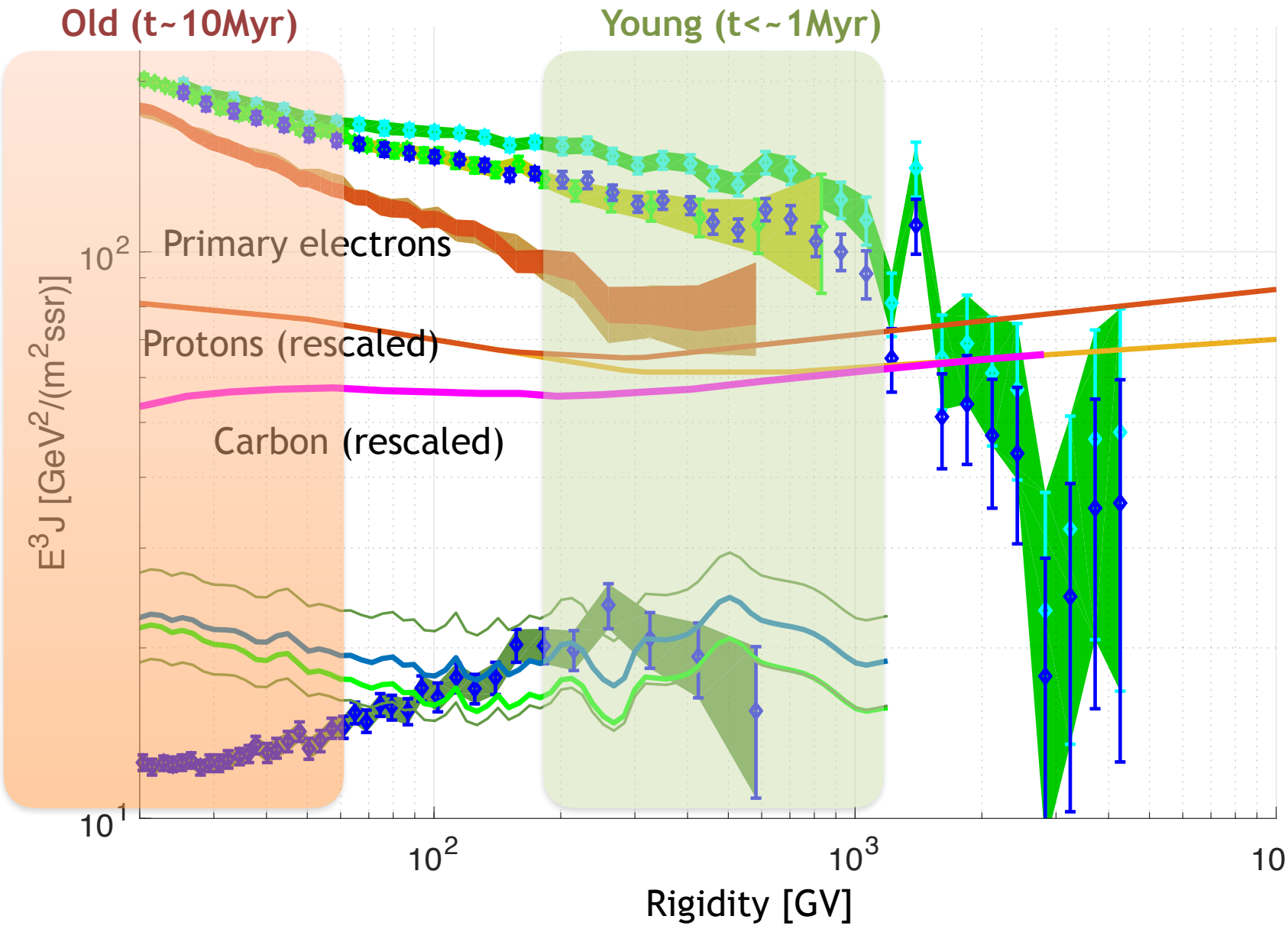

Preliminary Data. Please refer to the AMS
Forthcoming publications in PRL
Oxygen
Carbon
Nitrogen
Flux × R^2.7 [m^-2 s^-1 sr^-1 GV^1.7]
Rigidity [GV]
100
140
50
70
0
50
25
0
3 4 5
10
20
10^2
2×10^2
10^3
2×10^3
P
He
Li
flux × R^2.7 (m^-2 · sr^-1 · s^-1 · GV^1.7)
10
26
5
13
0
4.0
2.0
0
1
2
3 4 5
10
20
10^2
2 ×10^2
10^3
2 ×10^3
rigidity (GV)

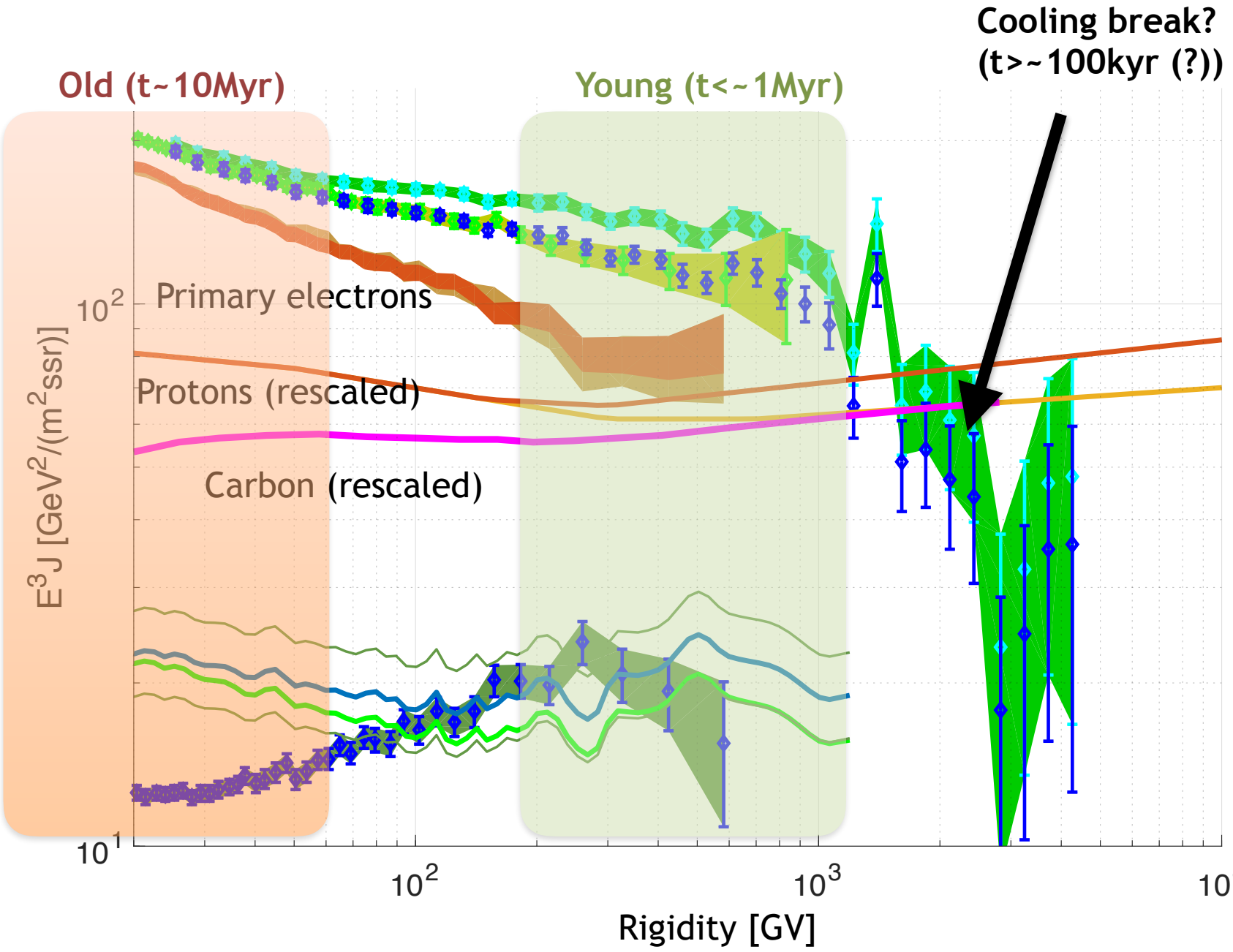

DAMPE / AMS02
Primary electrons
Protons (rescaled)
$E^3 J$ [GeV^2/(m^{2}ssr)]
10^2
10^1
10^2
10^3
10^4
Rigidity [GV]


DAMPE / AMS02
Primary electrons
Protons (rescaled)
Carbon (rescaled)
$E^3 J$ [GeV^2/(m^{2}ssr)]
10^2
10^1
10^2
10^3
10^4
Rigidity [GV]


DAMPE / AMS02
Primary electrons
Protons (rescaled)
Carbon (rescaled)
$E^3 J$ [GeV^2/(m^{2}ssr)]
10^2
10^1
10^2
10^3
10^4
Rigidity [GV]


Old (t~10Myr)
Primary electrons
Protons (rescaled)
Carbon (rescaled)
$E^3 J$ [GeV^2/(m^{2}ssr)]
10^2
10^1
10^2
10^3
10^4
Rigidity [GV]


Old (t~10Myr)
Young (t<~1Myr)
Primary electrons
Protons (rescaled)
Carbon (rescaled)
$E^3 J$ [GeV^2/(m^{2}ssr)]
10^2
10^1
10^2
10^3
10^4
Rigidity [GV]


Cooling break?
(t>~100kyr (?))
Old (t~10Myr)
Young (t<~1Myr)
Primary electrons
Protons (rescaled)
Carbon (rescaled)
$E^3 J$ [GeV^2/(m^{2}ssr)]
10^2
10^1
10^2
10^3
10^4
Rigidity [GV]