AMS-02 Antiprotons Reloaded

Rolf Kappl

Bethe Center for Theoretical Physics & Physikalisches Institut der Universität Bonn

based on RK, Annika Reinert, Martin Wolfgang Winkler
JCAP **10** (2015) 034, arXiv:1506.04145

Theory Seminar ULB Brussels,
October 23th 2015

Outline

Motivation

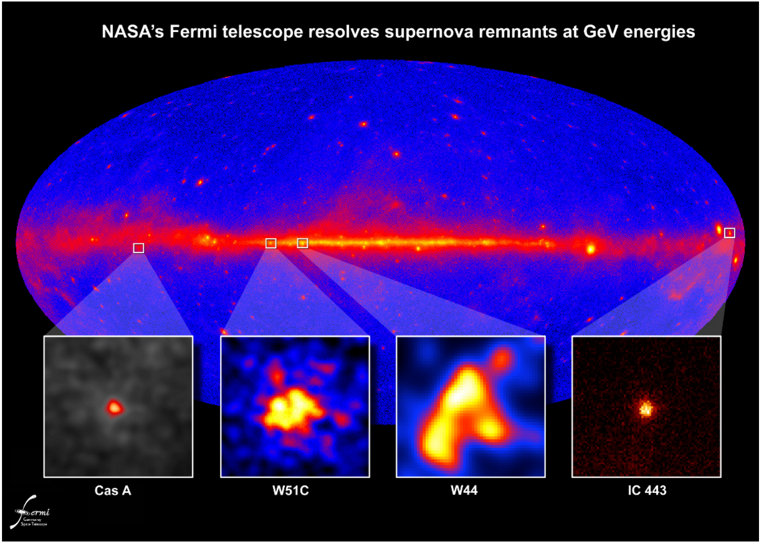
Cosmic Ray Propagation

Antiprotons Reloaded – Dark Matter Under Siege

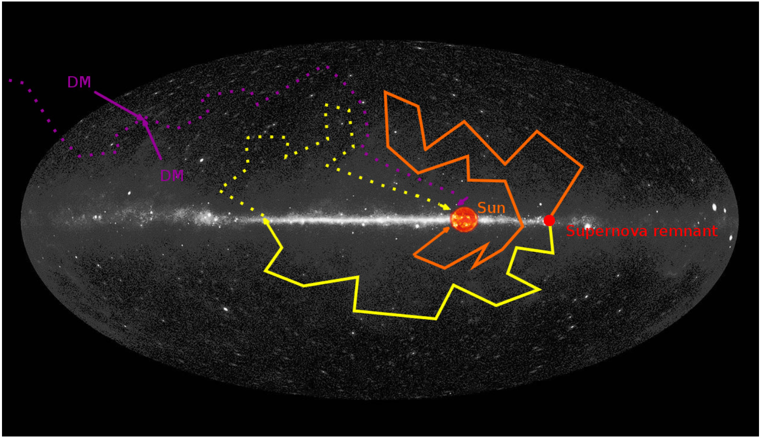
Conclusions

AMS-02 – A Precision Experiment For Cosmic Rays

Origin Of Cosmic Rays – Astrophysics At Work

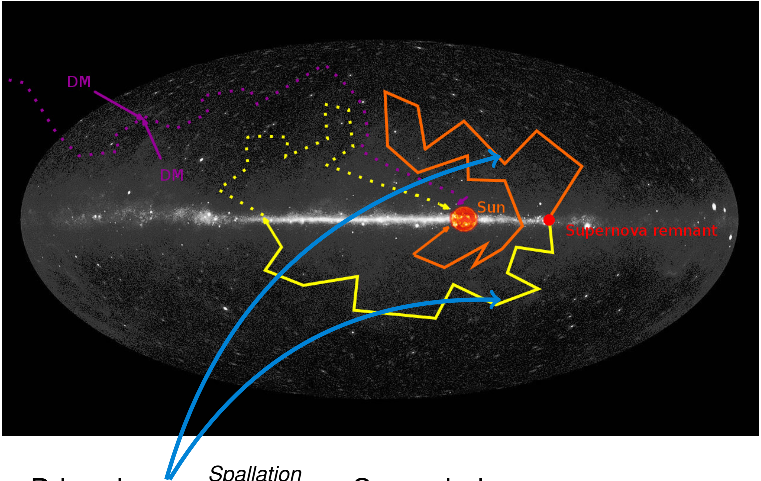


Primaries vs. Secondaries – Dark Matter?



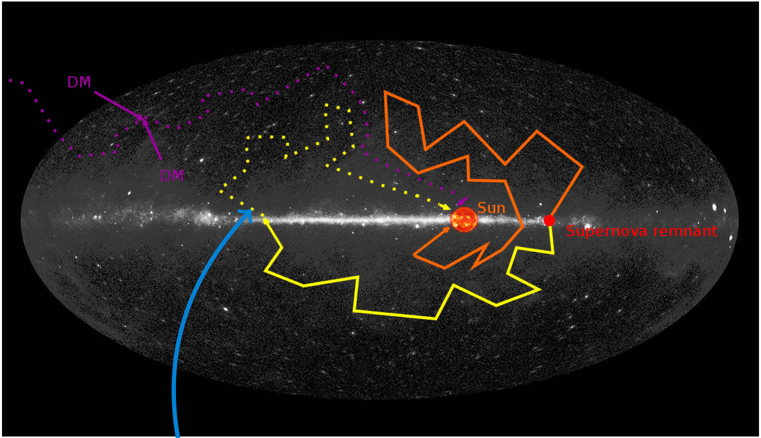
- Primaries $\xrightarrow{\textit{Spallation}}$ Secondaries
- Dark matter annihilation

Primaries vs. Secondaries – Dark Matter?



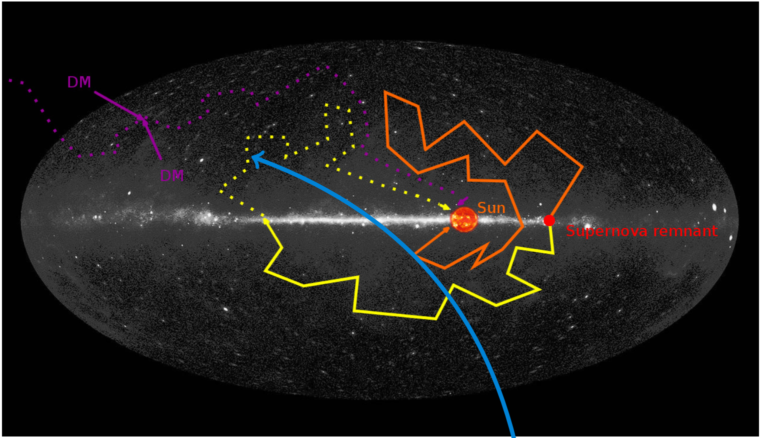
- Primaries $\xrightarrow{\textit{Spallation}}$ Secondaries
- Dark matter annihilation

Primaries vs. Secondaries – Dark Matter?



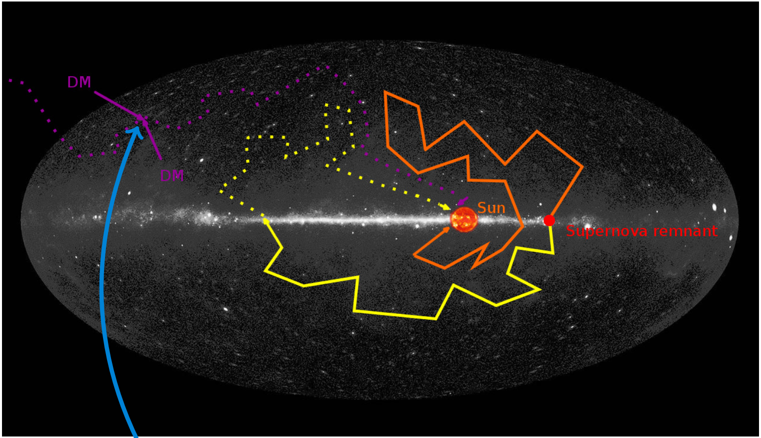
- Primaries $\xrightarrow{\textit{Spallation}}$ Secondaries
- Dark matter annihilation

Primaries vs. Secondaries – Dark Matter?



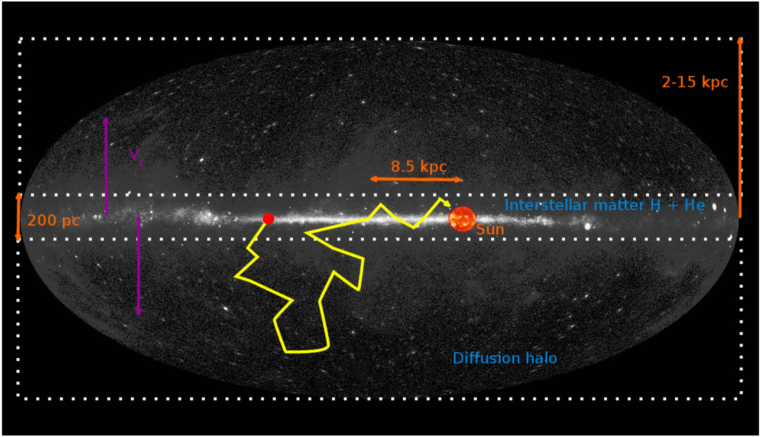
- Primaries $\xrightarrow{\textit{Spallation}}$ Secondaries
- Dark matter annihilation

Primaries vs. Secondaries – Dark Matter?



- Primaries $\xrightarrow{\textit{Spallation}}$ Secondaries
- Dark matter annihilation

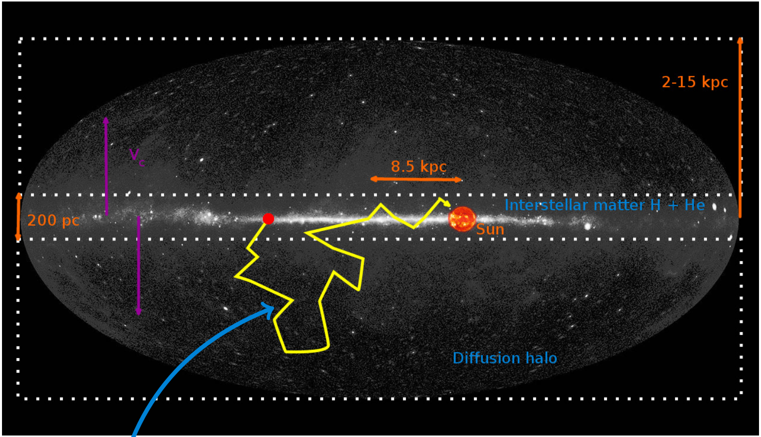
Transport Of Cosmic Rays – Fokker-Planck



- Two-zone diffusion model

$$\nabla(-K\,\nabla N_i + \mathbf{V}_c\,N_i) + \partial_E(b_{\text{tot}}\,N_i - K_{EE}\,\partial_E N_i) + \Gamma_{\text{ann}}\,N_i \;=\; q_i$$

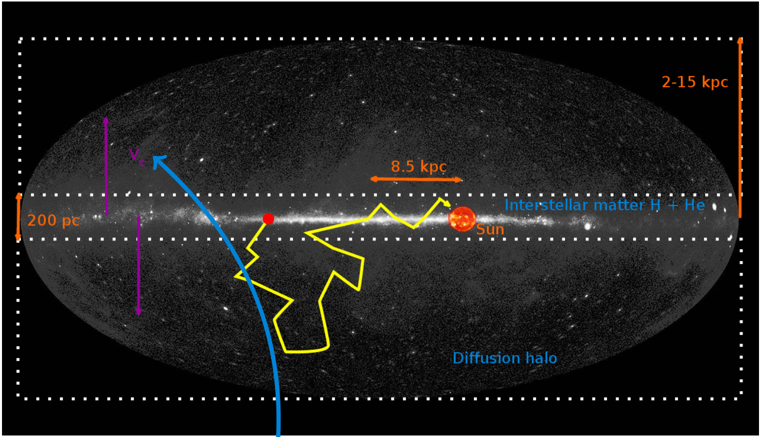
Transport Of Cosmic Rays – Fokker-Planck



- Two-zone diffusion model

$$\nabla(-K\,\nabla N_i + \mathbf{V}_c\,N_i) + \partial_E(b_{\rm tot}\,N_i - K_{EE}\,\partial_E N_i) + \Gamma_{\rm ann}\,N_i \;=\; q_i$$

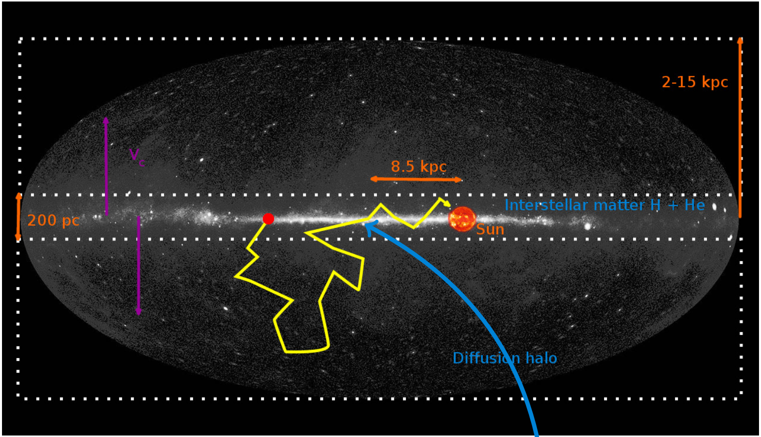
Transport Of Cosmic Rays – Fokker-Planck



- Two-zone diffusion model

$$\nabla(-K\,\nabla N_i + \mathbf{V}_c\,N_i) + \partial_E(b_{\rm tot}\,N_i - K_{EE}\,\partial_E N_i) + \Gamma_{\rm ann}\,N_i \;=\; q_i$$

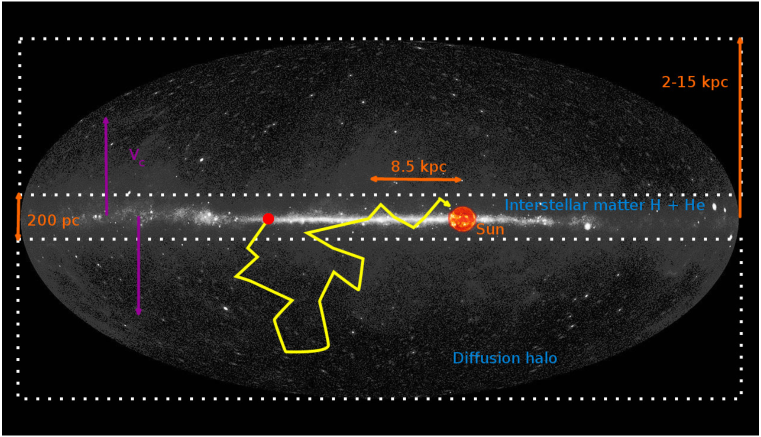
Transport Of Cosmic Rays – Fokker-Planck



- Two-zone diffusion model

$$\nabla(-K\,\nabla N_i + \mathbf{V}_c\,N_i) + \partial_E(b_{\mathrm{tot}}\,N_i - K_{EE}\,\partial_E N_i) + \Gamma_{\mathrm{ann}}\,N_i = q_i$$

Transport Of Cosmic Rays – Fokker-Planck



- Two-zone diffusion model

$$\nabla(-K\,\nabla N_i + \mathbf{V}_c\,N_i) + \partial_E(b_{\text{tot}}\,N_i - K_{EE}\,\partial_E N_i) + \Gamma_{\text{ann}}\,N_i = \boxed{q_i}$$

Bethe's Legacy – Boron As A Tracer

Bethe Center for Theoretical Physics

MARCH 1, 1939 PHYSICAL REVIEW VOLUME 55

Energy Production in Stars*

H. A. Bethe
Cornell University, Ithaca, New York

(Received September 7, 1938)

It is shown that the *most important source of energy in ordinary stars is the reactions of carbon and nitrogen with protons*. These reactions form a cycle in which the original nucleus is reproduced, *viz.* $C^{12}+H=N^{13}$, $N^{13}=C^{13}+\epsilon^+$, $C^{13}+H=N^{14}$, $N^{14}+H=O^{15}$, $O^{15}=N^{15}+\epsilon^+$, $N^{15}+H=C^{12}+He^4$. Thus carbon and nitrogen merely serve as catalysts for the combination of four protons (and two electrons) into an α-particle (§7).

The carbon-nitrogen reactions are unique in their cyclical character (§8). For all nuclei lighter than carbon. integration of the Eddington equations gives 19. For the brilliant star Y Cygni the corresponding figures are 30 and 32. This good agreement holds for all bright stars of the main sequence, but, of course, not for giants.

For fainter stars, with lower central temperatures, the reaction $H+H=D+\epsilon^+$ and the reactions following it, are believed to be mainly responsible for the energy production. (§10)

It is shown further (§5–6) that *no elements heavier than* He^4 *can be built up in ordinary stars*. This is due to the fact.

Bethe, Phys.Rev. 55 (1939) 434-456

- CNO cycle shows that boron is not produced in stars
- Boron is produced by spallation of interstellar matter
- Injected boron $q_B \xrightarrow{\textit{Propagation}}$ Measured boron at AMS-02
- Task:

$$q_B = 4\pi \sum_{i\in\{C,N,O,Ne,Mg,Si\}} \int dT' \frac{d\sigma}{dT} n_{ISM}\, \Phi_i(T')$$

Bethe's Legacy – Boron As A Tracer

Bethe Center for Theoretical Physics

MARCH 1, 1939 PHYSICAL REVIEW VOLUME 55

Energy Production in Stars*

H. A. Bethe
Cornell University, Ithaca, New York

(Received September 7, 1938)

It is shown that the *most important source of energy in ordinary stars is the reactions of carbon and nitrogen with protons*. These reactions form a cycle in which the original nucleus is reproduced, *viz.* $C^{12}+H=N^{13}$, $N^{13}=C^{13}+\epsilon^+$, $C^{13}+H=N^{14}$, $N^{14}+H=O^{15}$, $O^{15}=N^{15}+\epsilon^+$, $N^{15}+H=C^{12}+He^4$. Thus carbon and nitrogen merely serve as catalysts for the combination of four protons (and two electrons) into an α-particle (§7).

The carbon-nitrogen reactions are unique in their cyclical character (§8). For all nuclei lighter than carbon. integration of the Eddington equations gives 19. For the brilliant star Y Cygni the corresponding figures are 30 and 32. This good agreement holds for all bright stars of the main sequence, but, of course, not for giants.

For fainter stars, with lower central temperatures, the reaction $H+H=D+\epsilon^+$ and the reactions following it, are believed to be mainly responsible for the energy production. (§10)

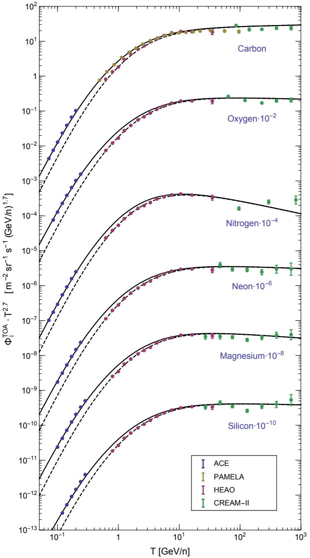
It is shown further (§5–6) that *no elements heavier than* He^4 *can be built up in ordinary stars*. This is due to the fact.

Bethe, Phys.Rev. 55 (1939) 434-456

- CNO cycle shows that boron is not produced in stars
- Boron is produced by spallation of interstellar matter
- Injected boron $q_B \xrightarrow{\text{Propagation}}$ Measured boron at AMS-02
- Task:

$$q_B = 4\pi \sum_{i\in\{C,N,O,Ne,Mg,Si\}} \int dT' \frac{d\sigma}{dT} n_{ISM} \boxed{\Phi_i(T')}$$

Cosmic Ray Primaries

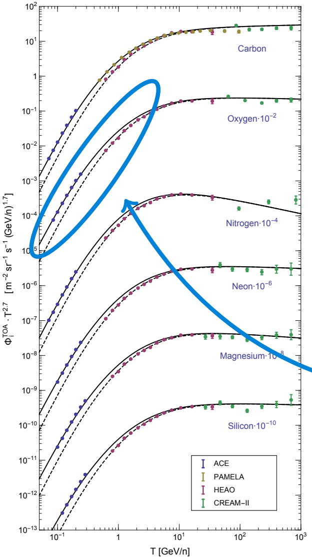


- We considered C, N, O, Ne, Mg, Si as the main contributions for boron production
- Fits to measured fluxes

$$\Phi_i(T) = A \left(\frac{T}{T+b} \right)^c T^{-\gamma}$$

- Yet no AMS-02 data
- Solar modulation

Cosmic Ray Primaries

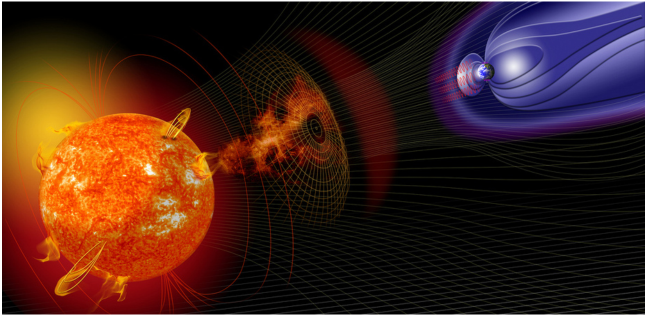


- We considered C, N, O, Ne, Mg, Si as the main contributions for boron production
- Fits to measured fluxes

$$\Phi_i(T) = A\left(\frac{T}{T+b}\right)^c T^{-\gamma}$$

- Yet no AMS-02 data
- Solar modulation

Interlude – Cosmic Rays In The Heliosphere



- Force field approximation for solar modulation

$$\Phi^{\mathrm{TOA}}(T - Z\phi) = \frac{(T - Z\phi)^2 + 2m(T - Z\phi)}{T^2 + 2mT}\Phi^{\mathrm{IS}}(T)$$

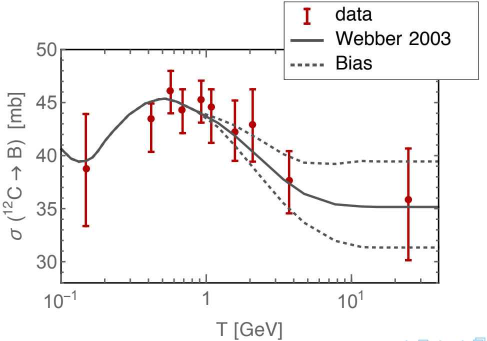
- Force field parameter ϕ takes care of the solar activity

Back To The Injection – Cross Sections Reloaded

- Source term:

$$q_B = 4\pi \sum_{i\in\{C,N,O,Ne,Mg,Si\}} \int dT' \boxed{\frac{d\sigma}{dT}} n_{ISM} \Phi_i(T')$$

- Parametrization from Webber et al., AJSS **144** (2003) 153
- Large uncertainties, poor experimental data

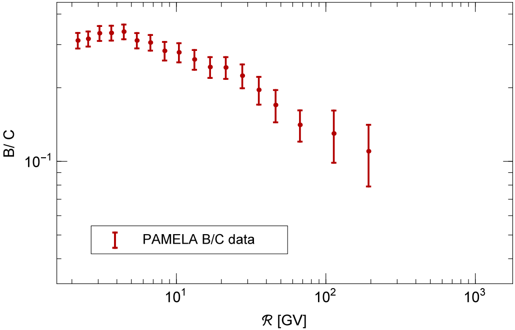


Nuclear Physics Meets Astrophysics

- Source term q_B for boron determined
- Fokker-Planck equation solved with semi-analytical approach in two dimensions Maurin et al., Astrophys.J. **555** (2001) 585-596
- With the fit to the carbon flux $\Rightarrow$ B/C ratio computed (Secondary/Primary ratio)
- Scanned over a sample of random propagation parameters and kept only configurations which passed χ^2 test

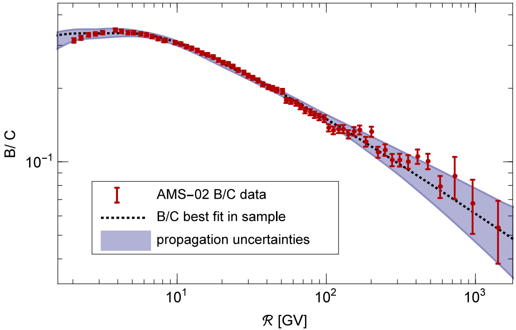
Propagation parameters fixed with highest precision!

B/C Before AMS-02



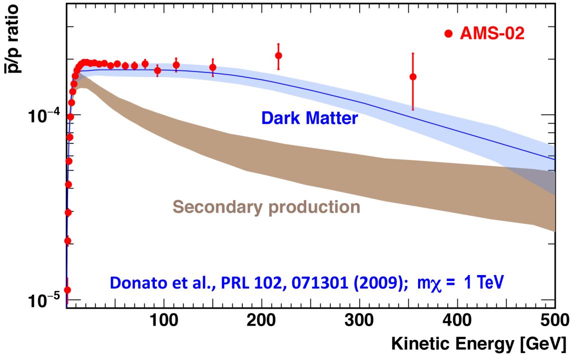
- Best data before AMS-02 from the PAMELA experiment Adriani et al., Astrophys. J. **791** (2014), 93
- Clear trend but still large uncertainties

B/C In The AMS-02 Precision Era



- Low experimental errors and data up to high rigidities
- Still preliminary data $\Rightarrow$ Data quality will further increase

$\bar{p}/p$ Ratio With Old Propagation Parameters

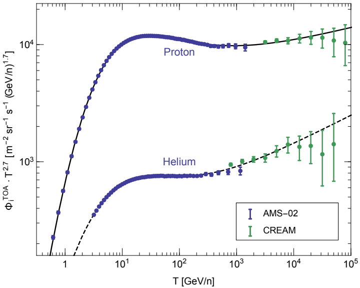


- $\bar{p}/p$ ratio computed with outdated (unknown?) propagation parameters

Protons And Helium – Primaries Reloaded

- Source term for $\bar{p}$ production:

$$q_{\bar{p}} = 4\pi \sum_{i \in \{H, He\}} \int dT' \frac{d\sigma}{dT} n_{ISM} \boxed{\Phi_i(T')}$$



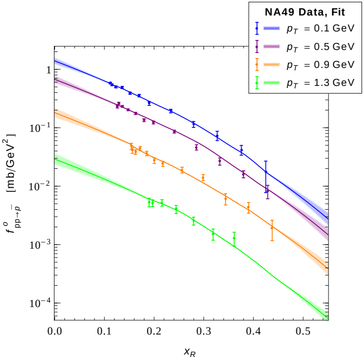
- Fits to measured fluxes with spectral break

$$\Phi_i(T) = \left(\frac{T}{T+b}\right)^c \sum_k A_k T^{-\gamma_k}$$

New $\bar{p}$ Production Cross Sections

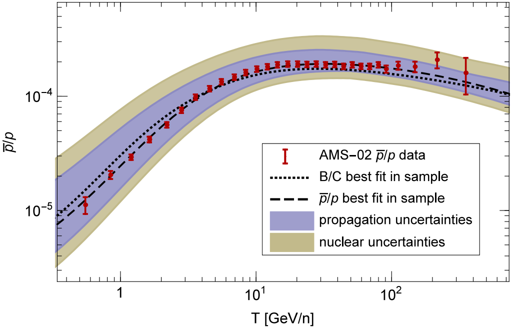
- Source term for $\bar{p}$ production:

$$q_{\bar{p}} = 4\pi \sum_{i \in \{H,He\}} \int dT' \boxed{\frac{d\sigma}{dT}} n_{ISM} \Phi_i(T')$$



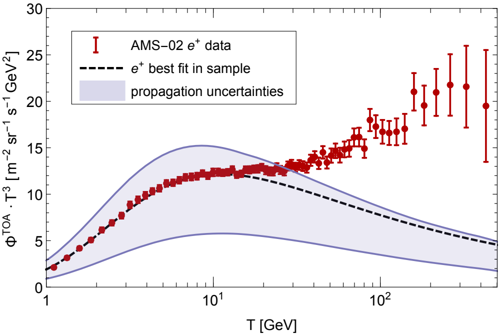
- New results from NA49 experiment with huge phase space coverage
  Anticic et al., Eur. Phys. J. **C65** (2010) 9
- Tracking of uncertainties, hyperon 'feed-down' effects, isospin effects, ...
  RK and Winkler, JCAP **09** (2014) 051

$\bar{p}/p$ Ratio With New Propagation Parameters



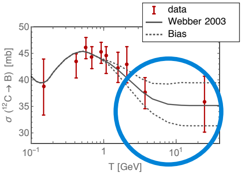
- $\bar{p}/p$ ratio computed with new cross sections
- New propagation parameters derived from boron $\Rightarrow$ Good agreement for antiprotons
- No need for antiprotons from dark matter annihilation $\Rightarrow$ Good probe to constrain dark matter models

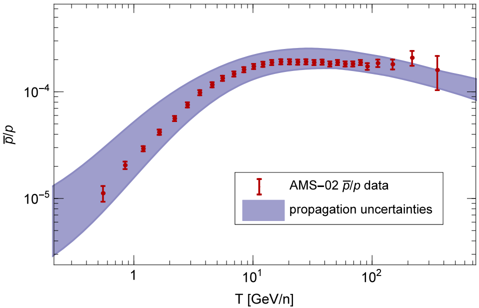
Outlook – Positrons, Better Cross Section Data, . . .



- Data on positrons can be used to further constrain propagation parameters

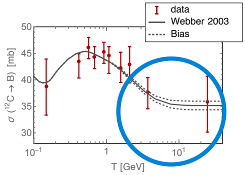
Outlook – Positrons, Better Cross Section Data, . . .

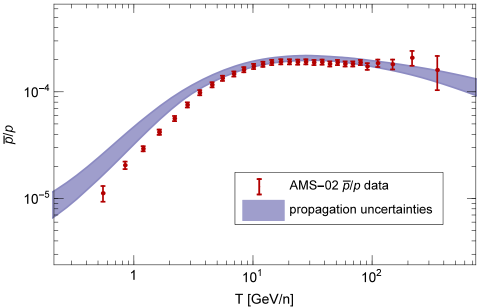




- New cross section measurements would dramatically decrease the uncertainty

Outlook – Positrons, Better Cross Section Data, . . .





- New cross section measurements would dramatically decrease the uncertainty

Conclusions

- With AMS-02 the precision era for indirect dark matter detection started
- We estimated the antiproton background with very high precision
- The new antiproton data together with our background calculation will be a perfect probe for dark matter models

Thank you for your attention!