Cosmic-ray propagation and dark matter indirect detections

Yu-Feng Zhou

State Key Laboratory of Theoretical Physics

Kavli Institute for Theoretical Physics

Institute of Theoretical Physics, Chinese Academy of Sciences

H.B.Jin, Y.LWu, YFZ, arXiv:1410.0171

2ND WORKSHOP ON PARTICLE PHYSICS AND COSMOLOGY AFTER HIGGS AND PLANCK, OCT 08-11

OUTLINE

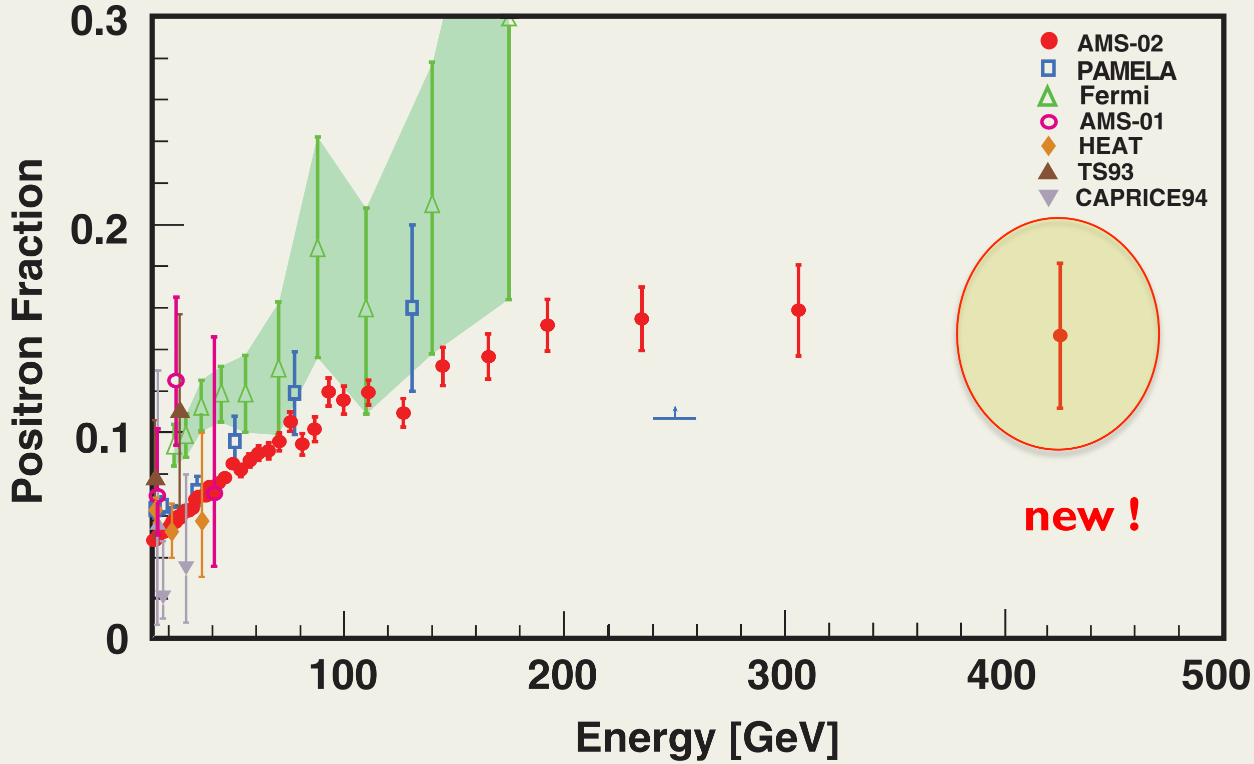
- Introduction
  - the latest AMS-02 results
  - CR propagation in the Galaxy
- Constraining the CR propagation models using AMS-02 data
  - propagation parameters
  - uncertainties in backgrounds
- Uncertainties in predictions from DM annihilations
  - Positrons and electrons
  - antiproton fluxes from DM
- Prediction for the CR antiprotons
  - Upper limits on antiproton flux from PAMELA data
  - Projections for the AMS-02 antiproton results
    - mock data of AMS-02 three-year data taking
    - Reconstruction capability

AMS-02 positron fraction (2014)

PRESS RELEASE
AMS Collaboration
CERN, Geneva, 18 September 2014

New results from the Alpha Magnetic Spectrometer on the International Space Station

The new results on energetic cosmic ray electrons and positrons are announced today. They are based on the first 41 billion events measured with the Alpha Magnetic Spectrometer (AMS) on the International Space Station (ISS). These results provide a deeper understanding of the nature of high energy cosmic rays and shed more light on the dark matter existence.



AMS-02, PRL113,121101(2014)

A closer look at the new data point

AMS-02, PRL113,121101(2014)

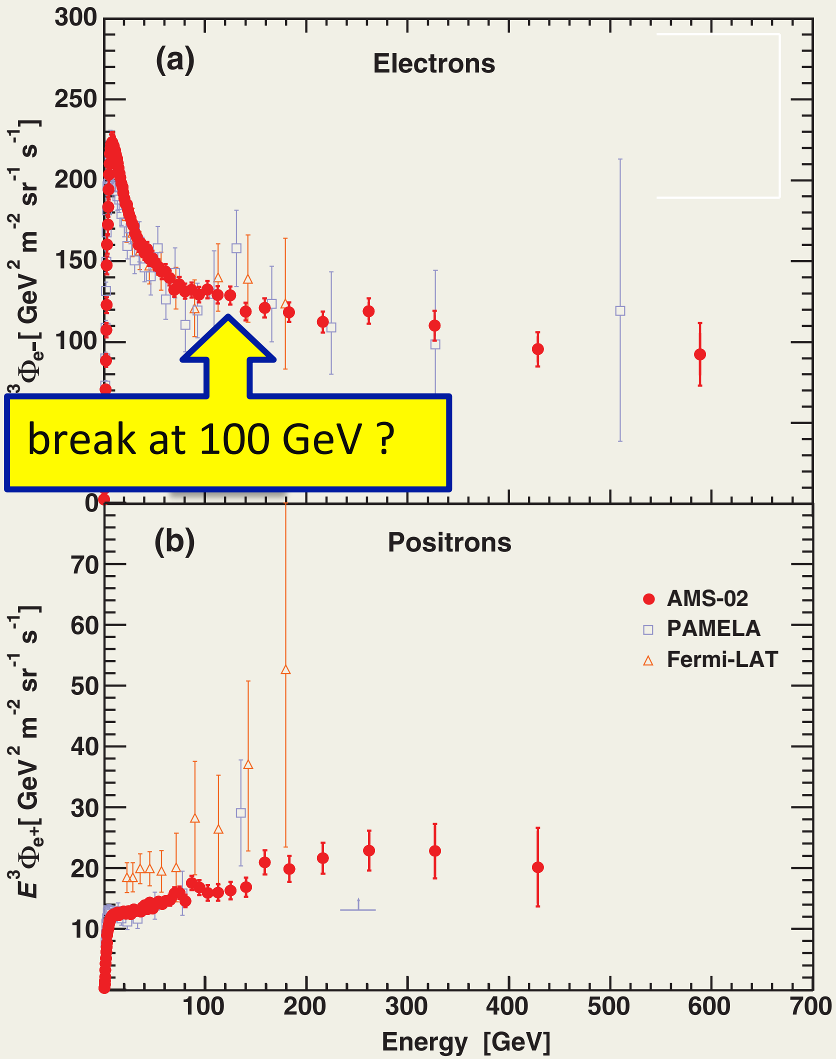
Energy [GeV]	N_{e^+}	Fraction	$\sigma_{stat.}$	$\sigma_{syst.}$
74.30–80.00	450	0.0963	0.0047	0.0014
80.00–86.00	381	0.1034	0.0056	0.0015
86.00–92.50	398	0.1207	0.0063	0.0016
92.50–100.0	358	0.1169	0.0063	0.0018
100.0–115.1	524	0.1205	0.0054	0.0021
115.1–132.1	365	0.1110	0.0062	0.0026
132.1–151.5	271	0.1327	0.0083	0.0032
151.5–173.5	228	0.1374	0.0097	0.0040
173.5–206.0	225	0.1521	0.0109	0.0053
206.0–260.0	178	0.1550	0.0124	0.0084
260.0–350.0	135	0.1590	0.0168	0.0132
350.0–500.0	72	0.1471	0.0278	0.0194

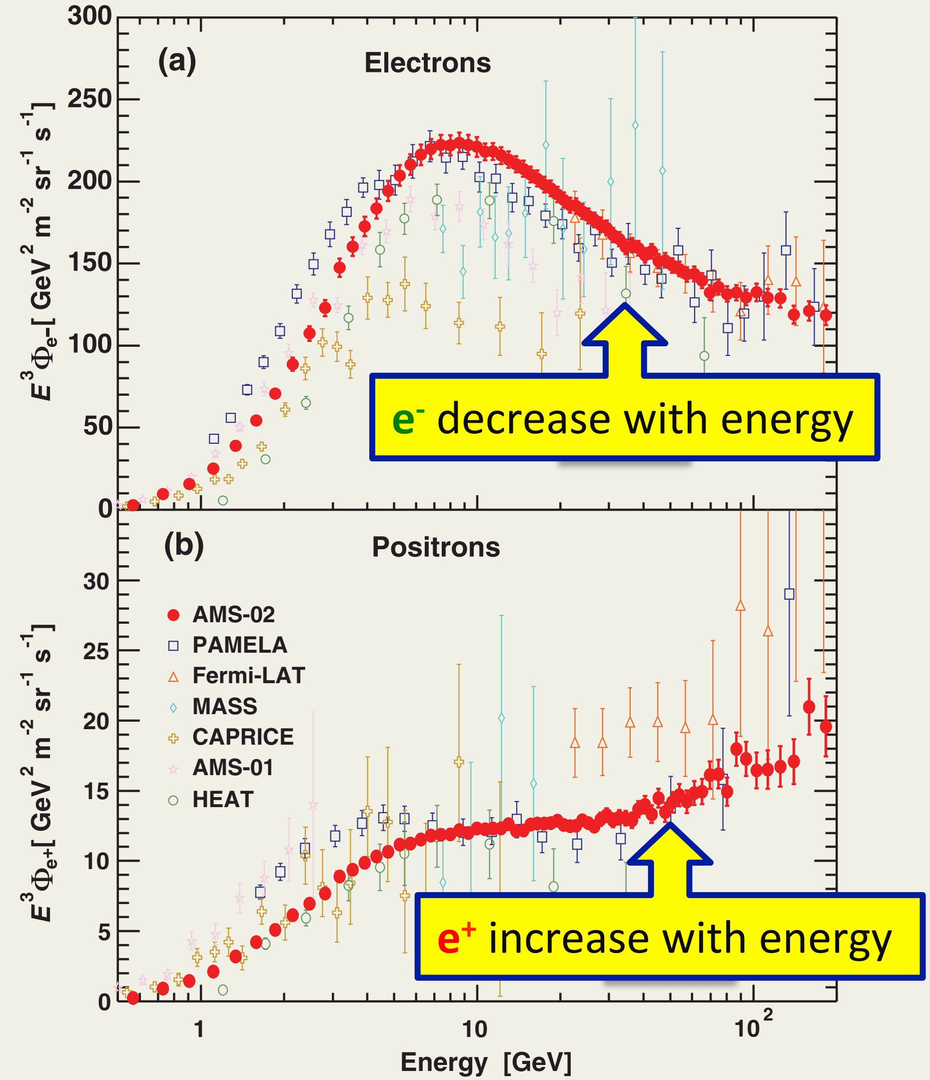
bin-width 150 GeV

Stat. ~19%

Syst. ~13%

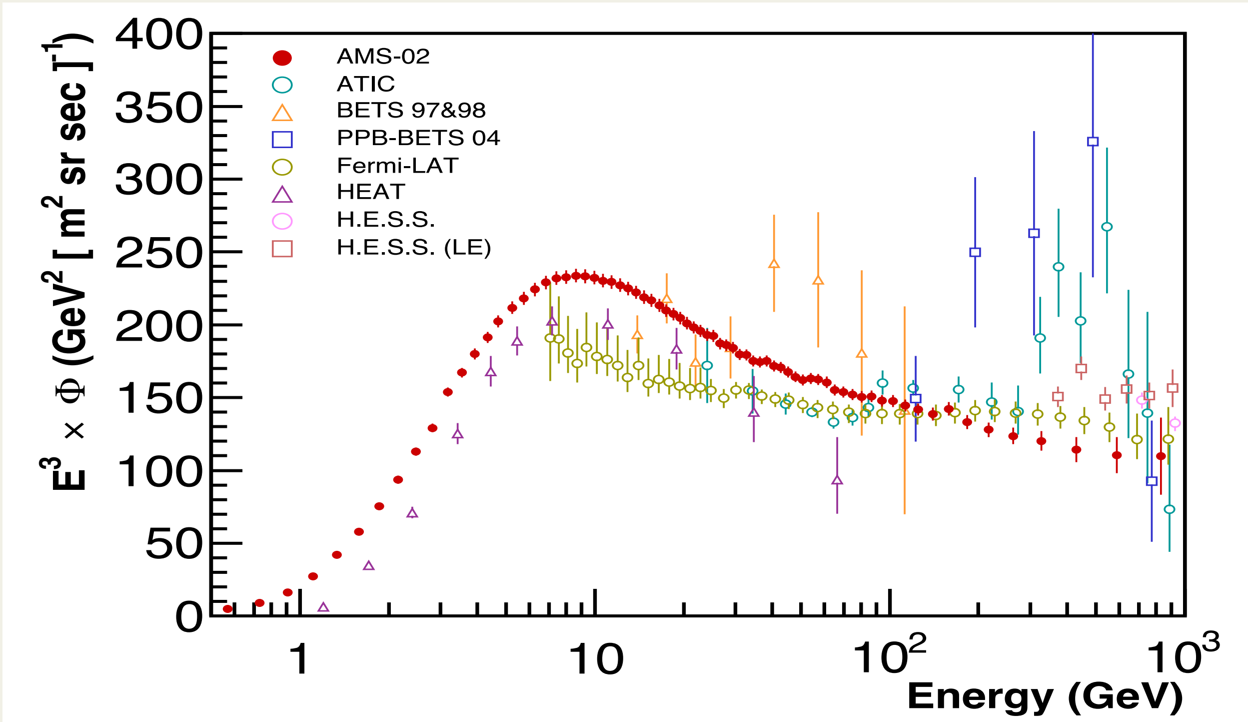
AMS-02 e^+ and e^- fluxes (2014)

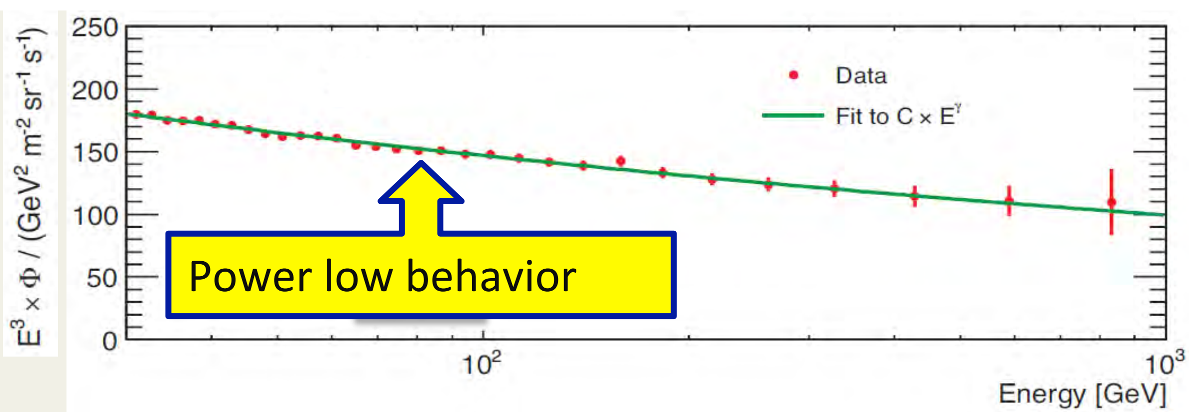




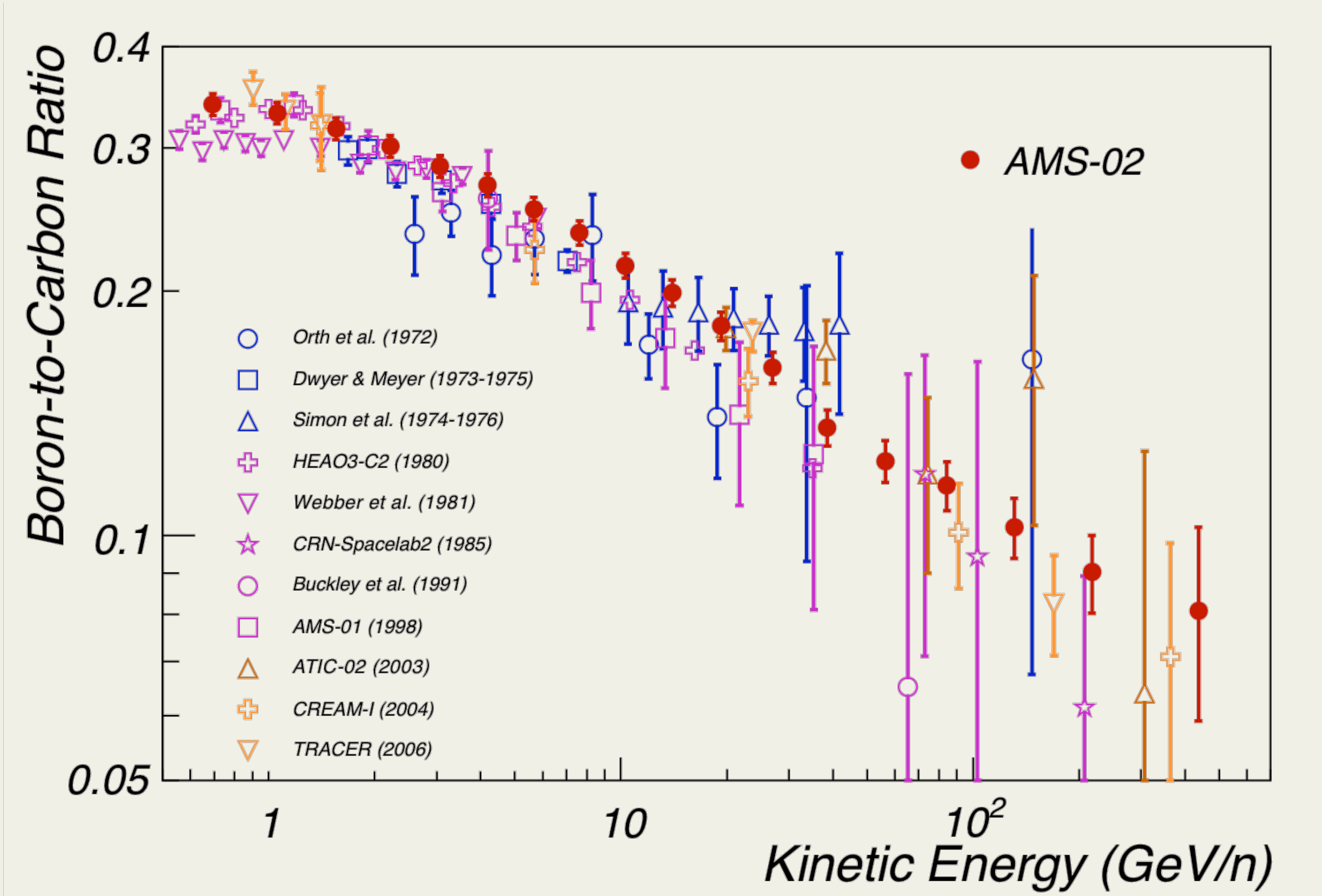
AMS-02, PRL113,121102(2014)

AMS-02 (e^++e^-) flux (2014)

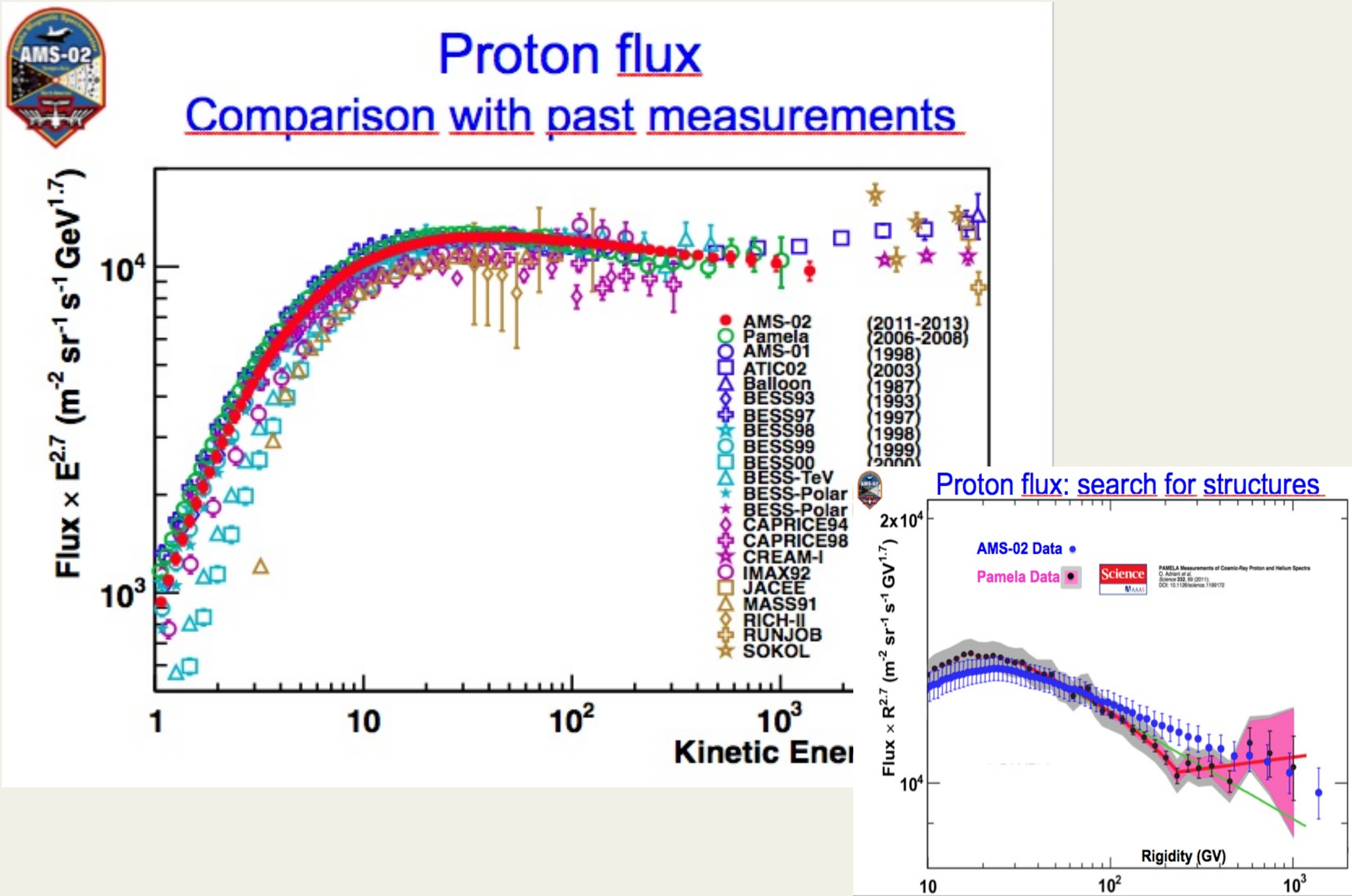




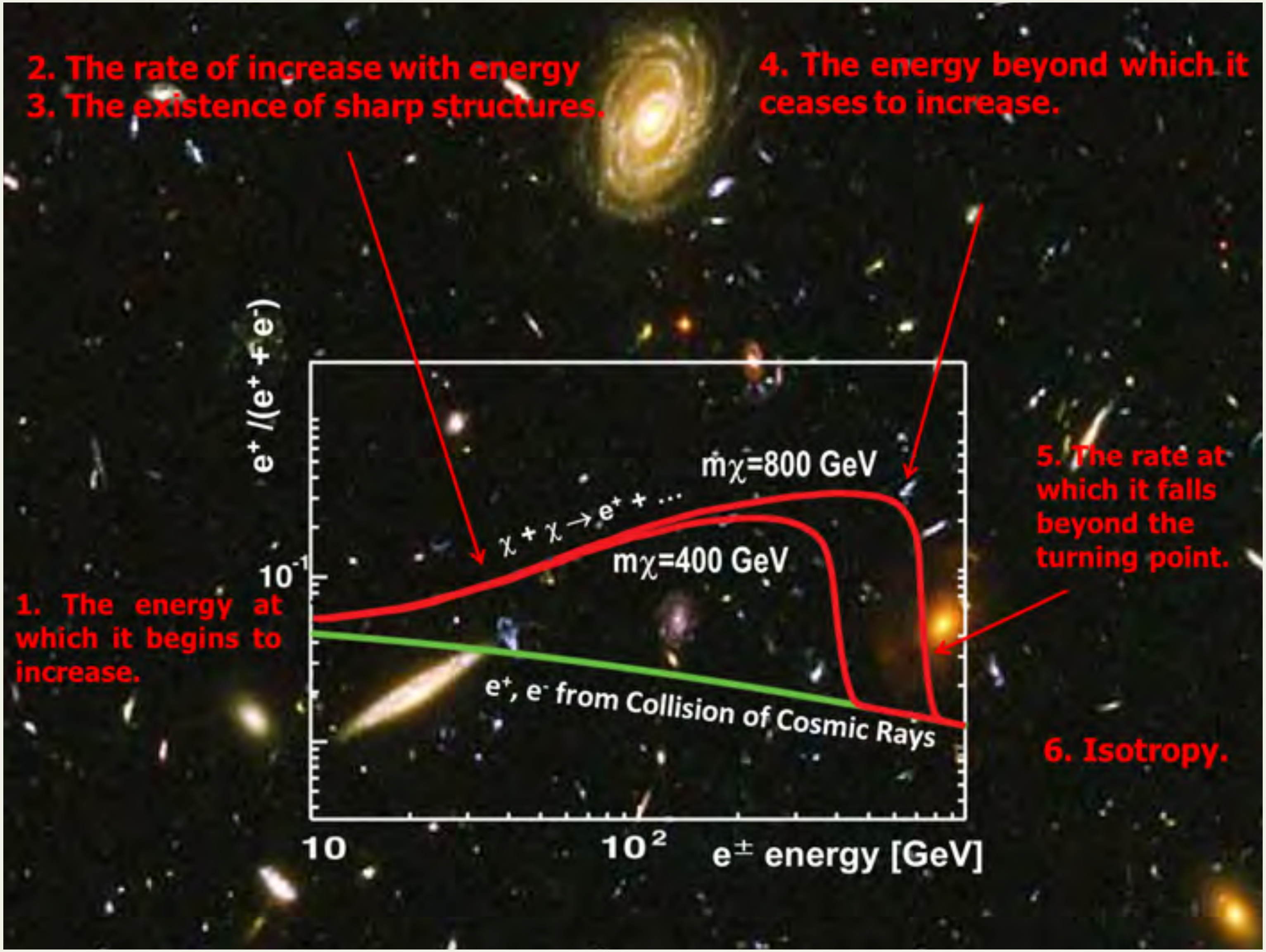
AMS-02 B/C ratio (2013)

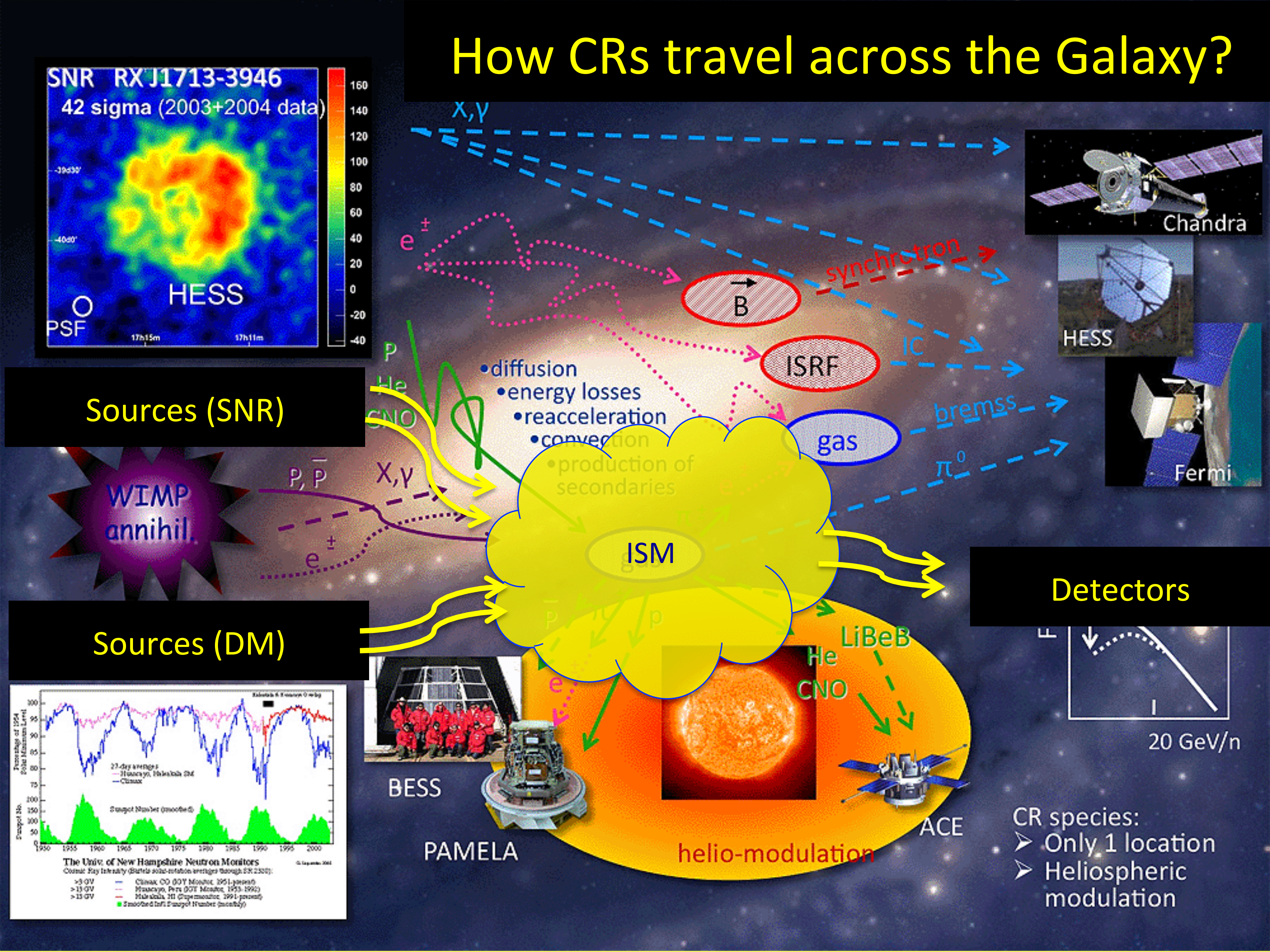


AMS-02 proton flux (2013)



Can we precisely predict the CR spectra?




How CRs travel across the Galaxy?
SNR RX J1713-3946
42 sigma (2003+2004 data)
HESS
PSF
160
140
120
100
80
60
40
20
0
-20
-40
Sources (SNR)
WIMP annihil.
Sources (DM)
X,γ
e ±
B
synchrotron
ISRF
IC
gas
bremss
π 0
P
He
CNO
•diffusion
•energy losses
•reacceleration
•convection
•production of secondaries
P, P̄
X,γ
e ±
ISM
Detectors
Chandra
HESS
Fermi
LiBeB
He
CNO
20 GeV/n
BESS
PAMELA
ACE
helio-modulation
CR species:
➢ Only 1 location
➢ Heliospheric modulation
The Univ. of New Hampshire Neutron Monitors
27-day averages
Sunspot Number (smoothed)

Cosmic ray propagation equation

$$\frac{\partial \psi}{\partial t} = \nabla(D_{xx}\nabla\psi - \mathbf{V}_c\psi) + \frac{\partial}{\partial p}p^2 D_{pp}\frac{\partial}{\partial p}\frac{1}{p^2}\psi - \frac{\partial}{\partial p}\left[\dot{p}\psi - \frac{p}{3}(\nabla\cdot\mathbf{V}_c)\psi\right] - \frac{1}{\tau_f}\psi - \frac{1}{\tau_r}\psi + q(\mathbf{r}, p),$$

diffusion
convection
E-loss
reaccelaration
spallation
decay
source

Processes involved

- Diffusion (magnetic field)
- Convection (galactic wind)
- Reacceleration
- Energy loss
    - Ionization/Coulomb scattering
    - Adiabatic energy loss due to convection
    - Inverse Compton scattering
    - Synchrotron/bremsstrahlung
    - ….
- Fragmentation/Spallation
- Radioactive decay
- Solar modulation

Sources of CR particles

- Primary sources from SNR, pulsars
- Secondary source from spallation of primary CR nuclei
- DM annihilation/decay

Approaches

- Semi-analytical solution base on two-zone diffusion model.
- Fully numerical solution using real astrophysical data.

  GALPROP/Dragon code

Processes involved in CR diffusion

Diffusion (magnetic field)

$$\hat{\mathcal{L}}_D\psi = \nabla(D_{xx}\nabla\psi)$$

$$D_{xx} = \beta D_0 \left(\frac{\rho}{\rho_0}\right)^{\delta_1,\delta_2},$$

In general D_0 should be spatial dependent

Larger diffusion const. at higher energy,

Kolmogorov: $\delta = 1/3$

Convection (galactic wind)

$$\nabla V_c\psi(r,z) - \frac{\nabla V_c}{3}\frac{1}{p^2}\frac{\partial}{\partial p}(p^3\psi(r,z))$$

$$\left(\frac{dE}{dt}\right)_{\rm Adiab} = -E\left(\frac{2m+E}{m+E}\right)\frac{V_c}{2h}$$

Reacceleration (disturbances)

$$\frac{\partial}{\partial p}p^2 D_{pp}\frac{\partial}{\partial p}\frac{1}{p^2}\psi$$

relation between D_{pp} and D_{xx}

$$D_{pp} = \frac{4V_a^2p^2}{3D_{xx}\delta\left(4-\delta^2\right)\left(4-\delta\right)w},$$

Processes involved in CR diffusion

Energy loss

For nuclei

- Ionization/Coulomb scattering

For electrons

- Inverse Compton scattering
- Synchrotron

ISM gas distribution

- simple parametrizations
- Using real data

ISM magnetic field

$$B_0 \exp\left(-\frac{R-R_\odot}{R_B}\right)\exp\left(-\frac{|z|}{z_B}\right),$$

Spallation/secondary

$$N_1 + (\mathrm{H},\mathrm{He}) \to N_2 + X$$

e.g.

$^{11}C+H \rightarrow {}^{11}B+X$

Solar modulation

force-field approximation

$$\Phi^{\mathrm{TOA}}(T_{\mathrm{TOA}}) = \left(\frac{2mT_{\mathrm{TOA}}+T_{\mathrm{TOA}}^2}{2mT+T^2}\right)\Phi(T),$$

$$T_{\mathrm{TOA}} = T - \phi_F$$

Sources of CRs

- **Primary sources** (SNR)

Power low in rigidity

$$\frac{dq_A(p)}{dp} \propto \left(\frac{\rho}{\rho_{As}}\right)^{\gamma_A}$$

Spatial distribution

$$q_0 \left(\frac{R}{R_\odot}\right)^{\eta} \exp\left[-\xi \frac{R - R_\odot}{R_\odot} - \frac{|z|}{0.2 \text{ kpc}}\right] ,$$

- **Secondary sources**

$$q(p) = \beta c n_i \sum_{i=\mathrm{H,He}} \int dp' \frac{\sigma_i(p,p')}{dp'} n_p(p')$$

- **DM sources** (annihilation)

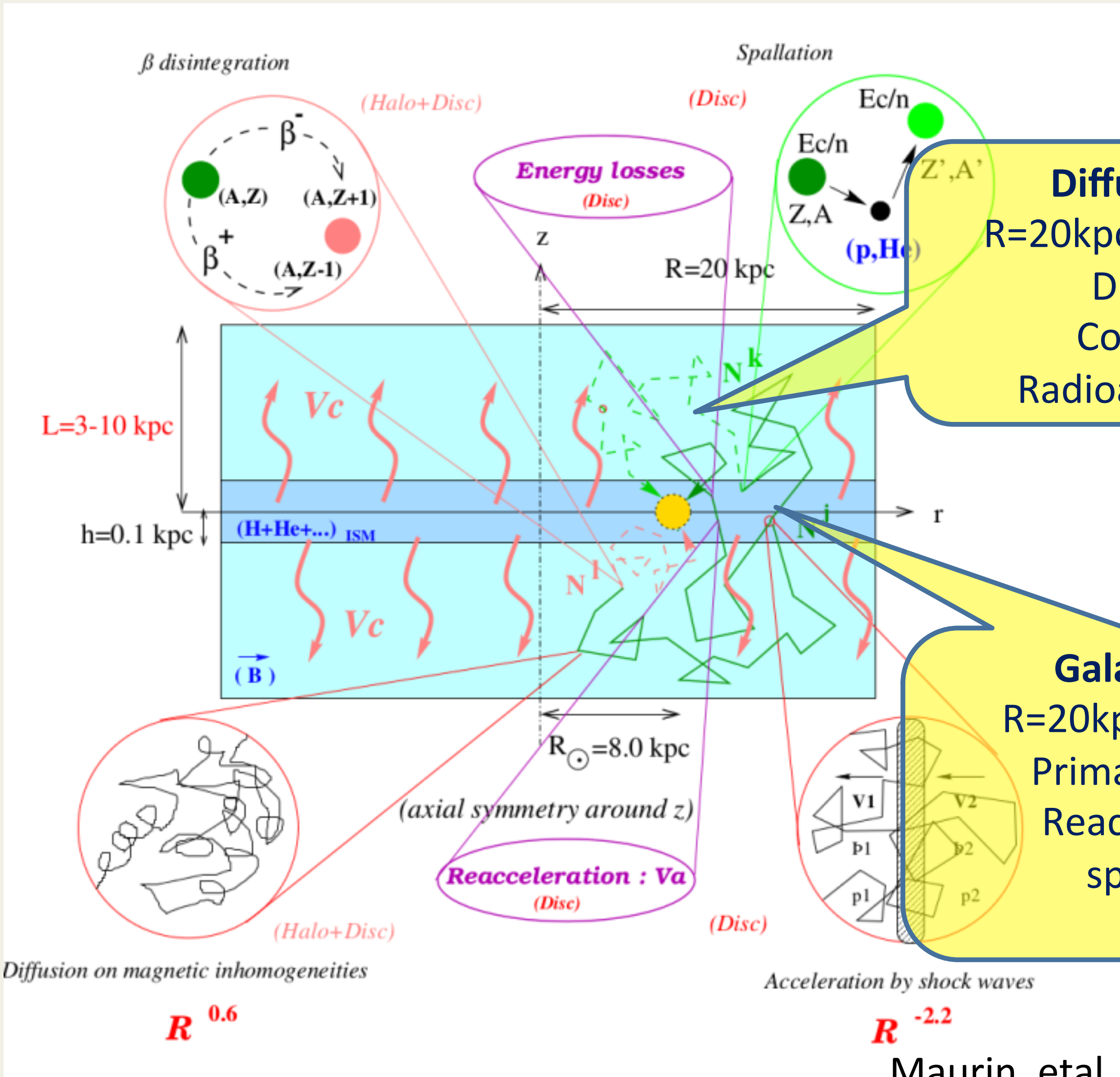
$$q(\boldsymbol{r}, p) = \frac{\rho(\boldsymbol{r})^2}{2m_\chi^2} \langle \sigma v \rangle \sum_X \eta_X \frac{dN^{(X)}}{dp},$$

DM profiles

$$\rho_\odot \left(\frac{r}{r_\odot}\right)^{-\gamma} \left(\frac{1 + (r_\odot/r_s)^\alpha}{1 + (r/r_\odot)^\alpha}\right)^{(\beta-\gamma)/\alpha}$$

	α	β	γ	r_s(kpc)
NFW	1.0	3.0	1.0	20
Isothermal	2.0	2.0	0	3.5
Moore	1.5	3.0	1.5	28.0

Simplified two-zone diffusion model



Diffusion halo
R=20kpc, Zh=1-10 kpc
Diffusion,
Convection
Radioactive decay

Galactic disk,
R=20kpc, h=0.1 kpc
Primary sources
Reaccelaration
spallation

Maurin, etal, astro-ph/0212111

Approximate solutions

For the source in the disk $q(r,z) = q(r)\delta(z)$ Hisano, hep-ph/0511118

Solution in Bessel expansion

$$\psi(r,z) = \exp\left(\frac{V_c z}{2K}\right) \sum_{i=0} \frac{Q_i}{A_i} \frac{\sinh[S_i(L-z)/2]}{\sinh[S_i L/2]} J_0(\zeta_i r_i/R)$$

with

$$A_i = 2h\Gamma_{inel} + V_c + K S_i \coth(S_i L/2)$$

$$S_i^2 = \frac{4\zeta^2}{R^2} + \frac{V_c^2}{K^2} + \frac{4\Gamma_{inel}}{K}$$

For DM sources (e.g. positrons) Maurin, astro-ph/0212111

Solution in Bessel and Fourier double expansion

$$\psi(r,z) = \sum_{n,m=1} A_{nm} J_0(\zeta_n r/R) \sin[m\pi(z-L)/2L]$$

$$A_{nm} = \int E' Q_{nm}(E') \frac{\tau}{E^2} \exp\left[\left(\frac{\zeta_n^2}{R} + \frac{m^2\pi^2}{4L^2}\right) K_0 \tau \left(\frac{E^{\delta-1}}{\delta-1} - \frac{E'^{\delta-1}}{\delta-1}\right)\right]$$

Constraining the propagation models from the CR data

Observables

-- Secondary/Primary

- B/C and sub-Fe(Sc+V+Ti)/Fe

  sensitive to combination D_0/Z_h

-- Radioactive species

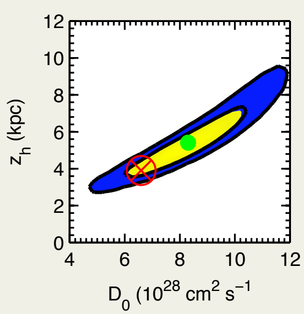
- $^{10}Be/^{9}Be$, $^{36}Cl/Cl$, $^{26}Al/^{27}Al$

  sensitive to diffusive halo size

-- Stable primaries

- Proton and Helium fluxes

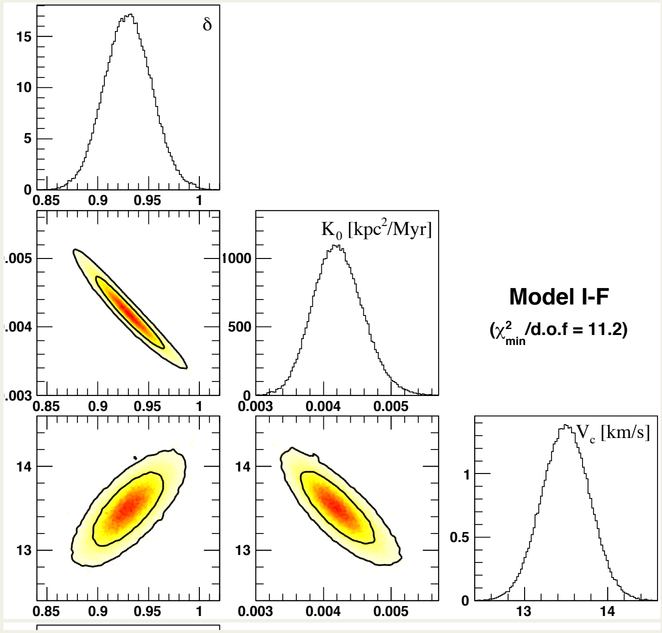
  sensitive to primary sources



Trotta, etal, arXiv:1011.0037

Degeneracies in parameters

- D_0 and Z_h are almost degenerate
- V_a scales as $(D_0)^{1/2}$
- $\delta + \gamma_{p1}$ close to 2.72



Maurin, etal, astro-ph/0212111

Analysis using AMS-02 data alone

Previous analyses relay on combinations of B/C, $^{10}Be/^{9}Be$, etc. from from different experiments

Our Motivations:

1. AMS-02 is measuring the CRs with unprecedented accuracies
2. Avoiding combination of syst. errors in different experiments
3. All data from the same period, easy to model solar modulation effects
4. Now, it is possible to determining the major parameters from AMS-02

$$\boldsymbol{\theta} = \{Z_h, D_0, \delta, V_a, \gamma_{p1}, \gamma_{p2}\}.$$

Data Set: only B/C ratio + Proton flux

$$D = \{D_{B/C}^{\mathrm{AMS}}, D_p^{\mathrm{AMS}}\}.$$

proton flux is not just a power low in energy

(break at 10 GeV imposes constraints on V_a)

B/C → D_0/Z_h, Va, δ

Proton → γ_1, γ_2, V_a

Proton flux spectrum constrains V_a, breaks V_a-- D_0 degeneracy, and enables the determination of Z_h

Method: Bayesian inference

- Bayes's Theorem

$$p(\theta|D) = \frac{\mathcal{L}(D|\theta)\pi(\theta)}{p(D)}$$

- Bayesian evidence (quality of fit)

$$p(D) = \int_V \mathcal{L}(D|\theta)\pi(\theta)d\theta.$$

- Marginal distribution

$$p(\theta_1, \ldots, \theta_n)_{\rm marg} = \int p(\theta|D) \prod_{i=n+1}^{m} d\theta_i$$

- Priors (uniform)

$$\pi(\theta_i) \propto \begin{cases} 1, & \text{for} \quad \theta_{i,\min} < \theta_i < \theta_{i,\max} \\ 0, & \text{otherwise} \end{cases}$$

Likelihood function

$$\prod_i \frac{1}{\sqrt{2\pi\sigma_i^2}} \exp\left(-\frac{(f_{\rm th}(\theta) - f_{{\rm obs},i})^2}{2\sigma_i^2}\right)$$

Numerical methods

- MCMC sampling
- Metropolis-Hasting
- CosmoMC package

Results

with 2.6x10^4 MCMC samples

Trotta, 1011.0037
Fit B/C+^{10}Be/^{9}Be

Quantity	Prior range	Best-fit value	Posterior mean and Standard deviation	Posterior 95% range	Ref. [23]
Z_h(kpc)	[1, 11]	3.2	3.3±0.6	[2.1, 4.6]	5.4±1.4
D_0/Z_h	[1, 3]	2.02	2.00±0.07	[1.82, 2.18]	(1.54±0.48)
δ	[0.1, 0.6]	0.29	0.29±0.01	[0.27, 0.32]	0.31±0.02
$V_a(\mathrm{km}\cdot\mathrm{s}^{-1})$	[20, 70]	44.7	44.6±1.2	[41.3, 47.5]	38.4±2.1
γ_{p1}	[1.5, 2.1]	1.79	1.78±0.01	[1.75, 1.81]	1.92±0.04
γ_{p2}	[2.2,2.6]	2.46	2.45±0.01	[2.43,2.47]	2.38±0.04

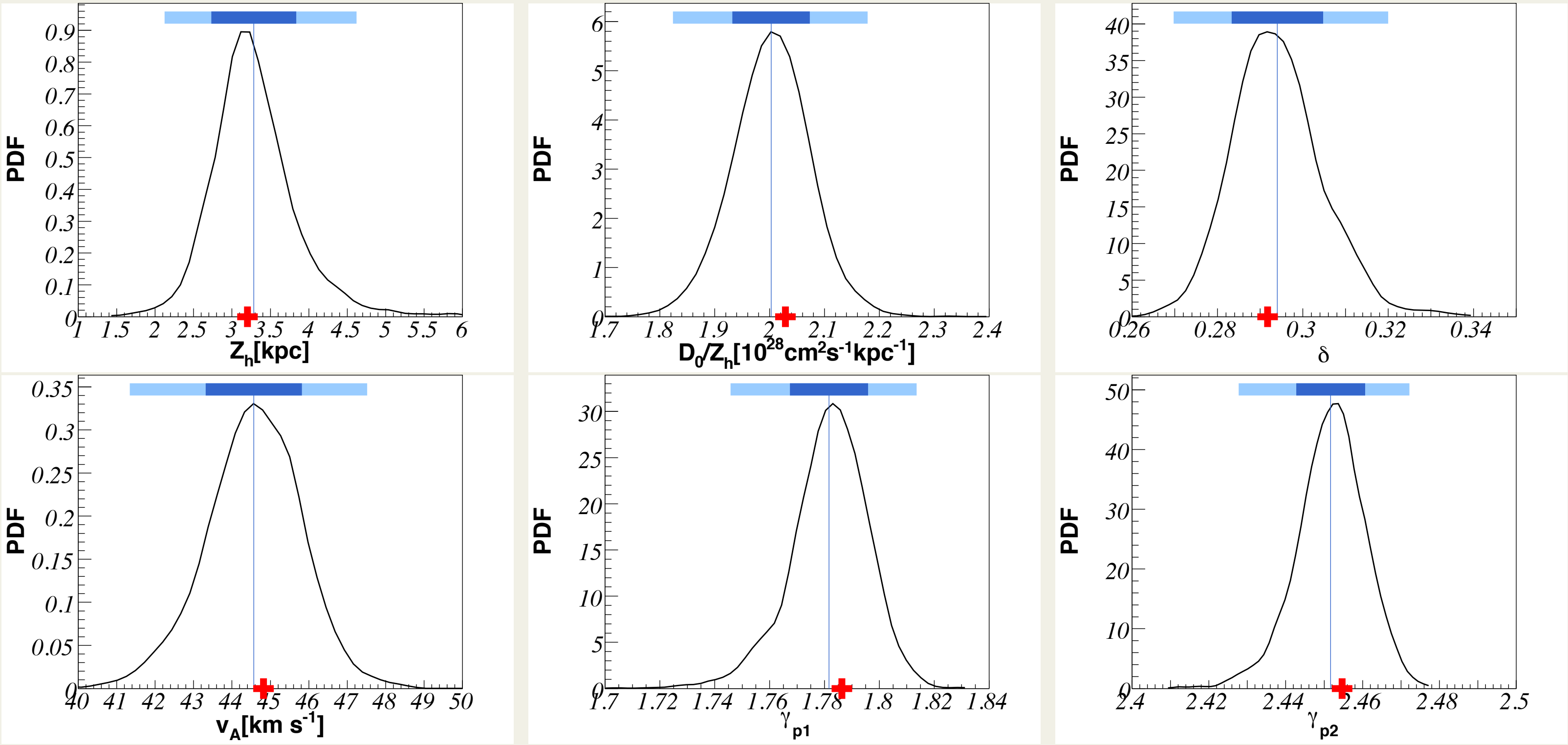
D_0/Z_h is precisely determined (err <5%)

$$\frac{D_0}{Z_h} = (2.00 \pm 0.07)\ \mathrm{cm^2 s^{-1} kpc^{-1}}.$$

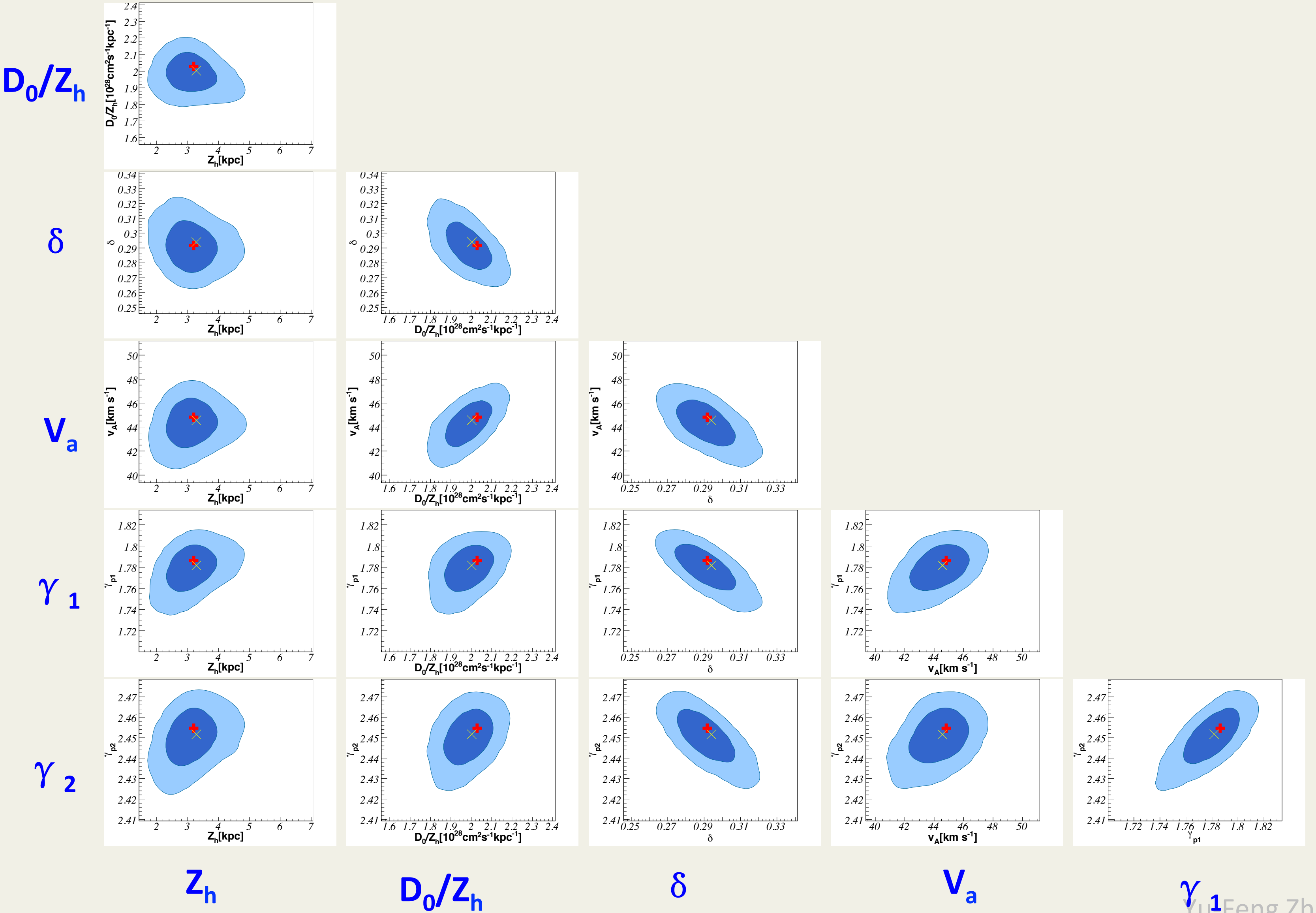
Z_h is determined with err up to ~ 20% (smaller than the fit to B/C+^{10}Be/^{9}Be)

$$Z_h = 3.3 \pm 0.6\mathrm{kpc}$$

1D posterior PDFs



Correlations between parameters

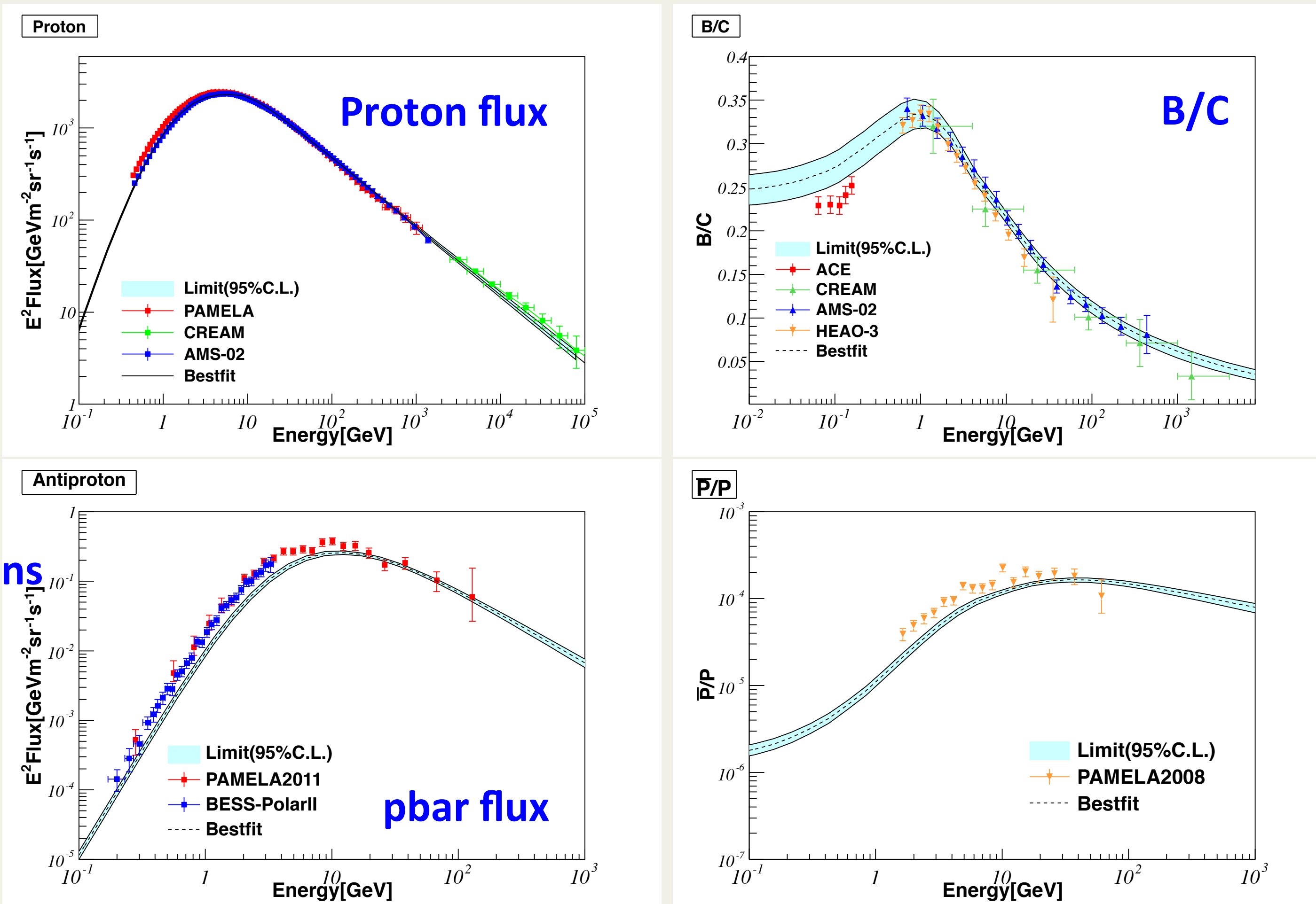


Yu-Feng Zhou, ITP-CAS

Best-fits & predictions for backgrounds

Best fits

Predictions

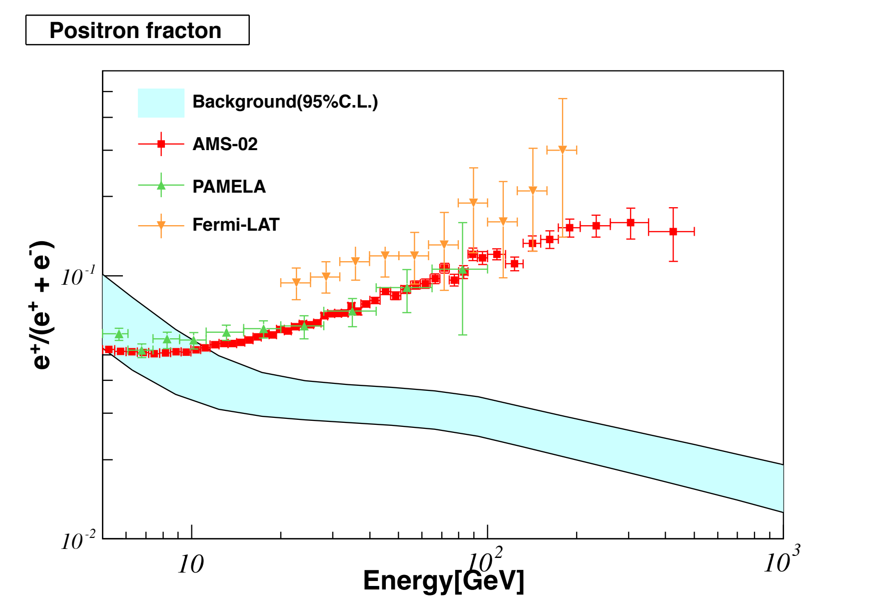


antiproton/proton

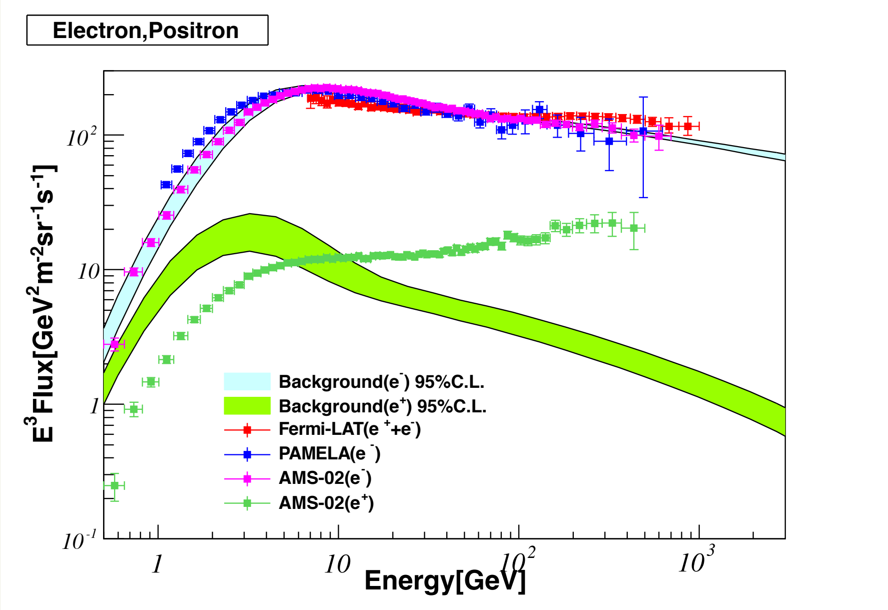
Uncertainties in positron backgrounds

Through scanning the whole parameters space allowed at 95%CL, the uncertainties of the backgrounds are obtained

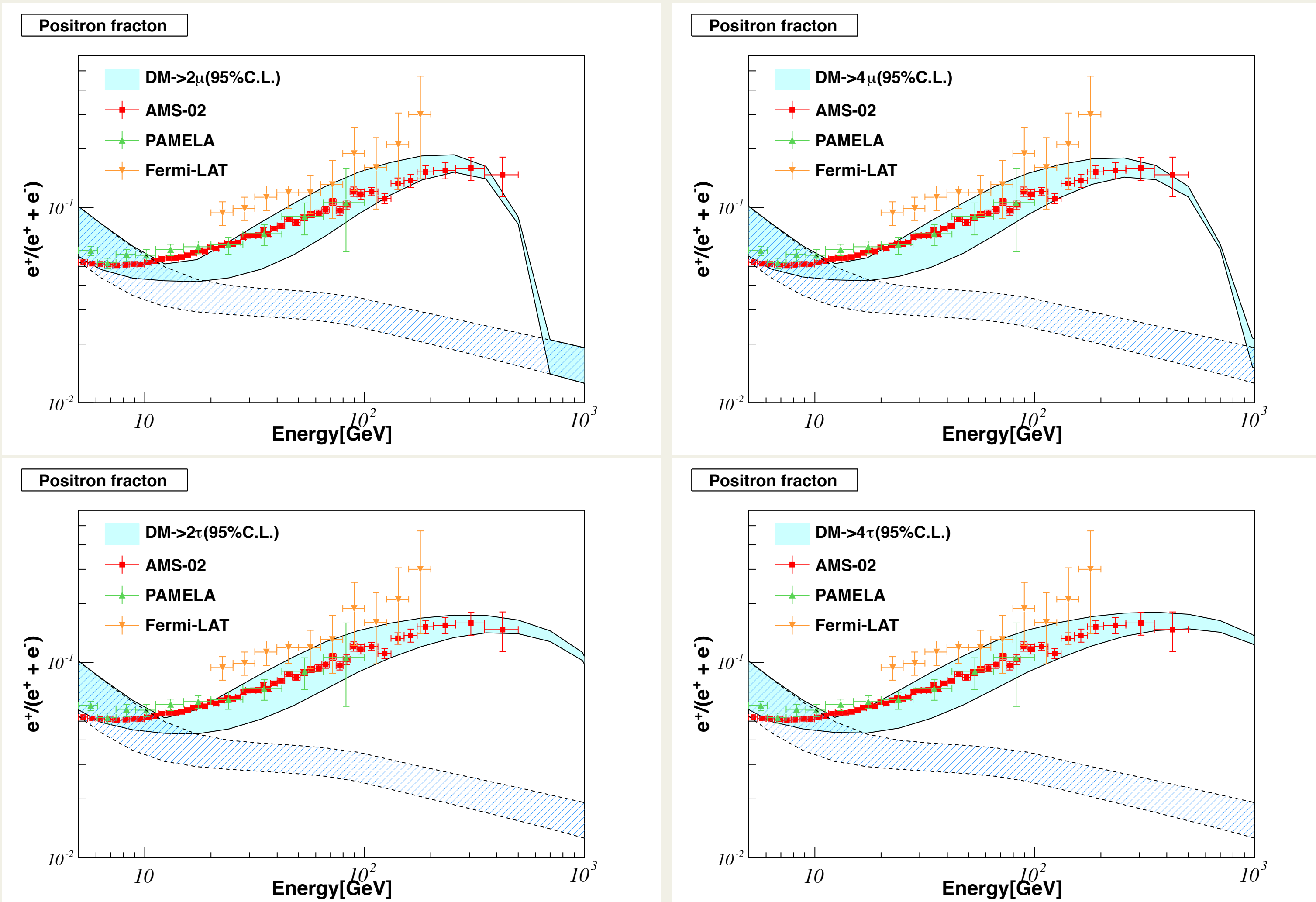
Positron fraction



electron and positron fluxes



Uncertainties in positron fraction from DM annihilation



Typical uncertainties are within O(2), much smaller above 200 GeV

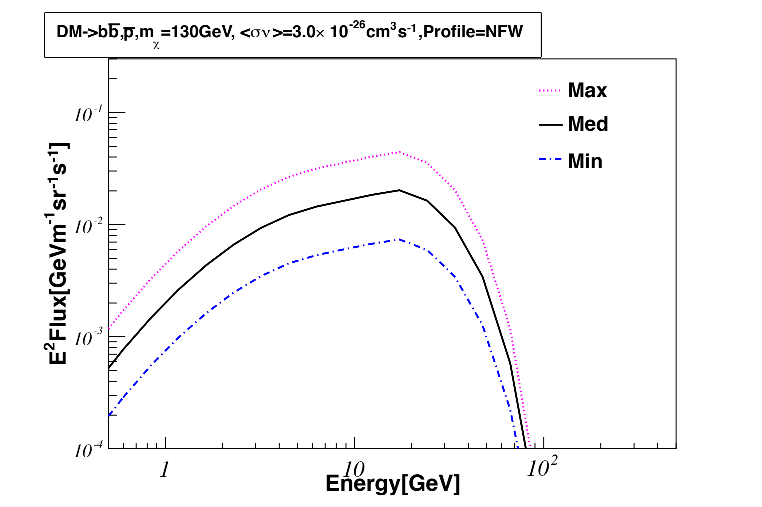
Previous analyses: uncertainties ~O(10), e.g T.Delahaye, etal, arXiv:0712.2312

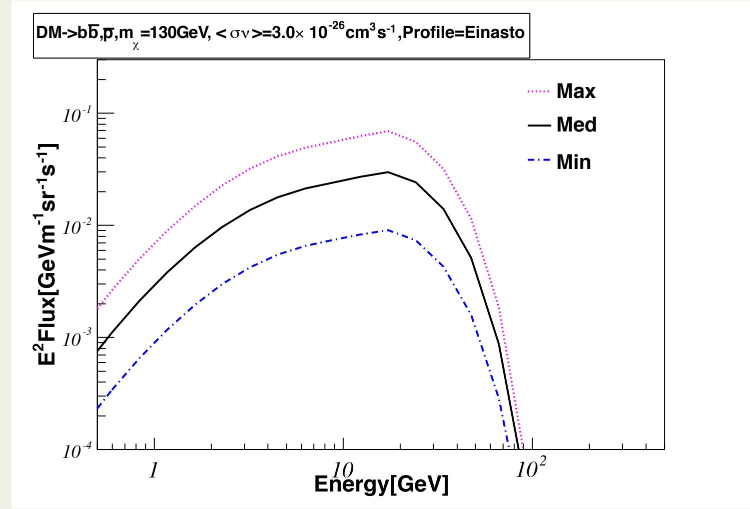
Uncertainties in antiproton flux from DM annihilation

- Reference propagation models

minimal, median and maximal fluxes

parameters	Min	Med	Max
$Z_h(\mathrm{kpc})$	1.8	3.2	6.0
D_0/Z_h	1.96	2.03	1.77
δ	0.30	0.29	0.29
$V_a(\mathrm{km}\cdot\mathrm{s}^{-1})$	42.7	44.8	43.4
γ_{p1}	1.75	1.79	1.81
γ_{p2}	2.44	2.45	2.46





- At 95% CL, the difference between min and max configuration is within O(10).

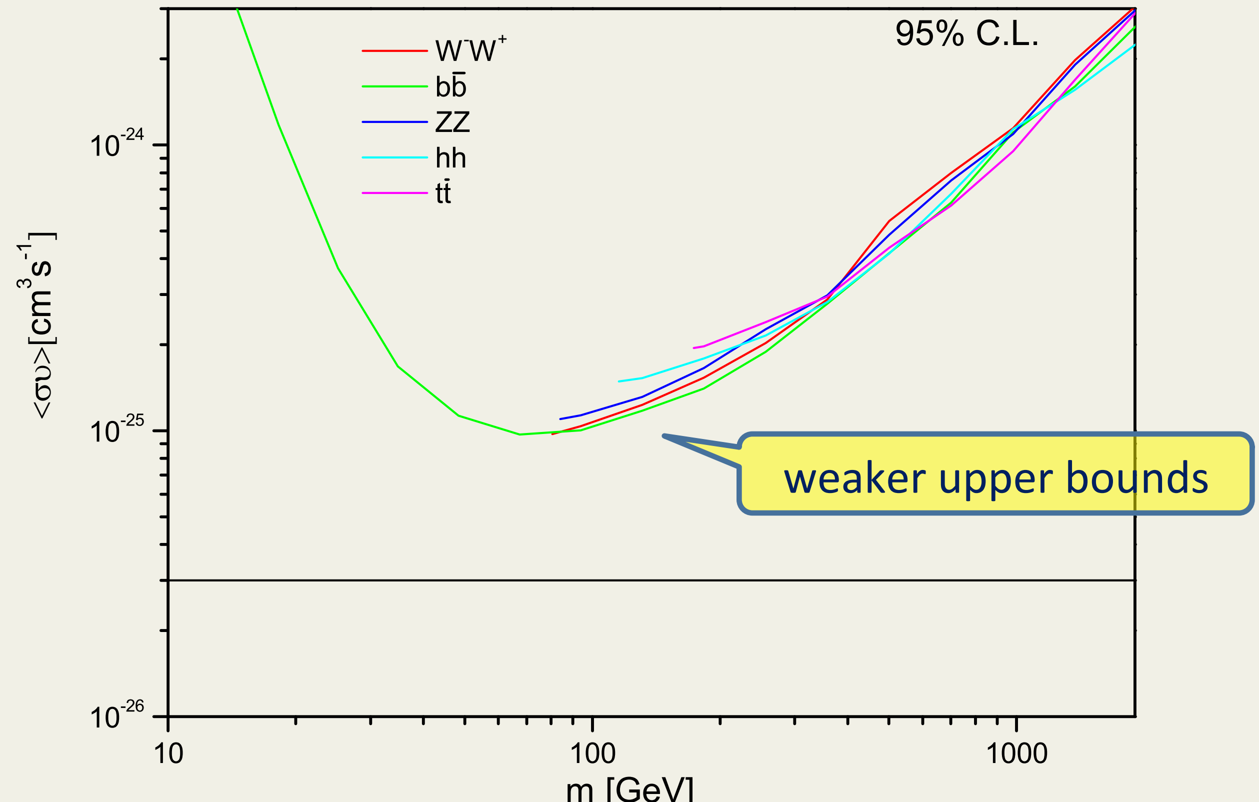
Previous analyses: uncertainties ~O(100), e.g. F.Donato, etal, astro-ph/0306207

Upper limits from PAMELA

Global fit including PAMELA antiproton data

- Method: Bayesian updating

$$P(\boldsymbol{\theta}', \boldsymbol{\theta}|D') = \frac{\mathcal{L}(D'|\boldsymbol{\theta}', \boldsymbol{\theta})\pi(\boldsymbol{\theta}')\tilde{\pi}'(\boldsymbol{\theta})}{\int \mathcal{L}(D'|\boldsymbol{\theta}', \boldsymbol{\theta})\pi(\boldsymbol{\theta}')\tilde{\pi}(\boldsymbol{\theta})d\boldsymbol{\theta}'d\boldsymbol{\theta}},$$



Considering the uncertainties in all the propagation parameters, the upper limits from PAMELA pbar data are weakened by ~O(10)

Sensitivity of AMS-02 on antiproton

- Number of events, uncertainty

$$N = \epsilon a(T_i)\phi(T_i)\Delta T_i \Delta t, \qquad \Delta\phi(T_i)_{\rm sta} = \sqrt{\frac{\phi(T_i)}{\epsilon a(T_i)\Delta T_i \Delta t}}.$$

$$\Delta\phi(T_i) = \sqrt{\Delta\phi(T_i)^2_{\rm sta} + \Delta\phi^2_{\rm sys}}. \qquad \Delta\phi_{\rm sys} = 8\%.$$

- Acceptance, efficiency

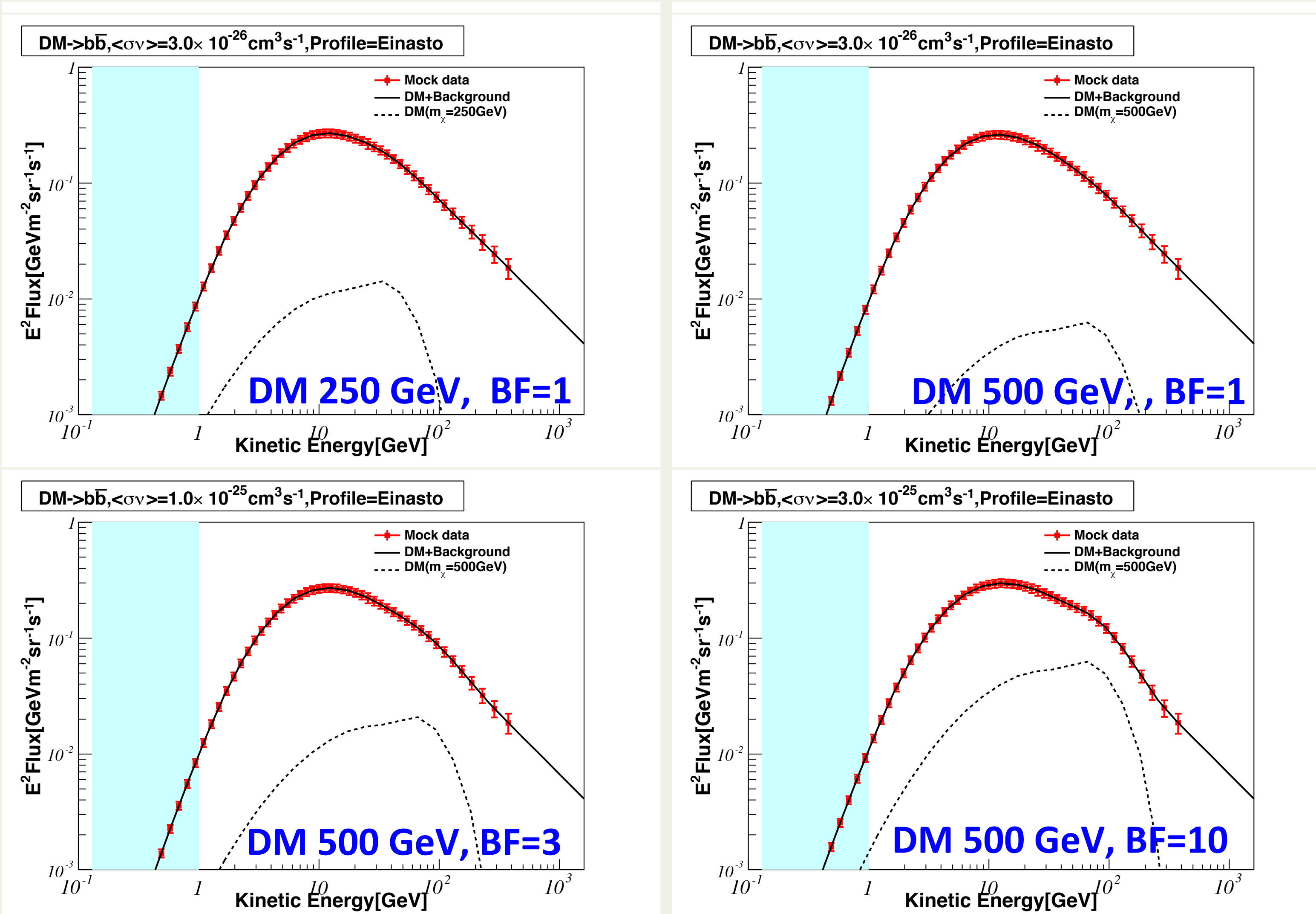
  a(T) =0.0147 m^2 , (1– 11 GeV), 0.03 m^2, (11– 150 GeV)

  ε=90%, (> 1 GeV)

- Data binning, according to AMS-02 rigidity resolution

$$\frac{\Delta R}{R} = 0.000477 \times R + 0.103. \qquad \frac{\Delta T}{T} = \left(\frac{T+2m_p}{T+m_p}\right)\frac{\Delta R}{R},$$

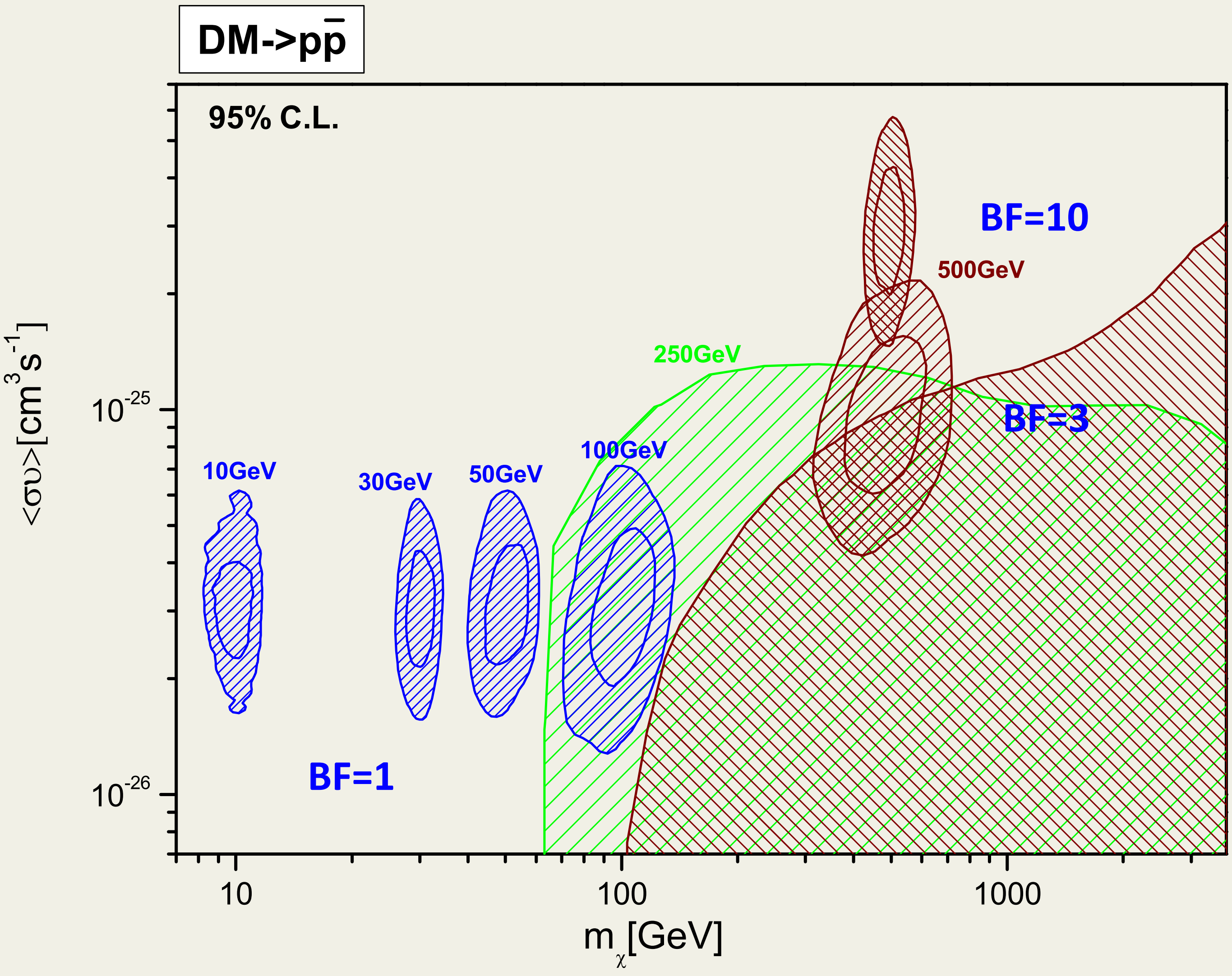
AMS-02 antiproton mock data



$$\langle \sigma v \rangle = \mathrm{BF} \times (3 \times 10^{-26} \mathrm{cm}^3 \mathrm{s}^{-1})$$

Yu-Feng Zhou, ITP-CAS

Reconstruction of DM properties



The cross section can be reconstructed within O(2), masses O(30%) at 95% for light DM (<100 GeV) and BF=1. Reconstruction is possible for heavy DM with large BF

CONCLUSIONS

- Accurate prediction for DM-induced CR signals requires better understanding of the propagation of CR particles.
- We determine the major CR propagation parameters use the AMS-02 data alone (B/C ratio + proton flux).

  e.g. the uncertainty in D0/Zh is within 5%.
- The uncertainties in positron fraction is constrained to O(2) and that in antiproton is ~O(10), both are significantly smaller than the analyses prior to AMS-02.
- The projection for AMS-02 sensitivity on antiproton

  for DM <200 GeV with thermal σv, the cross section can be reconstructed within ~O(2) for 3-year data taking.

Thank you !