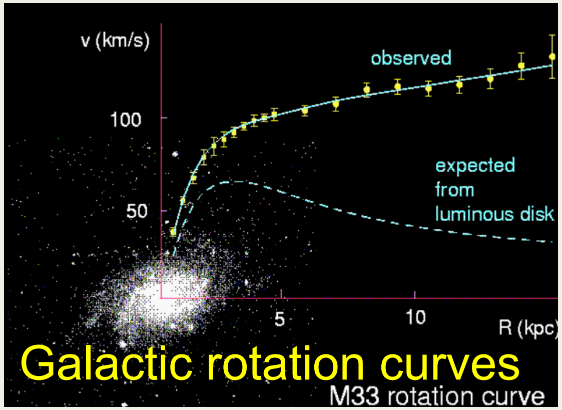
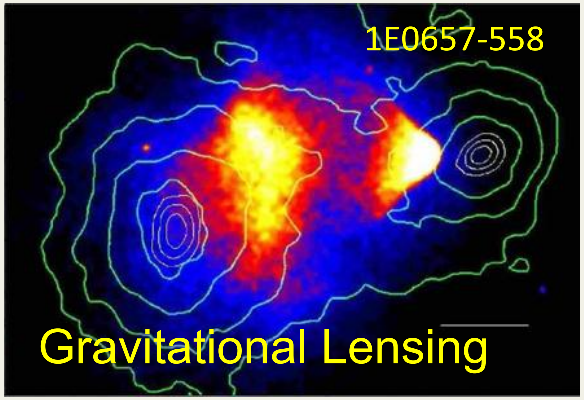
Dark Matter Indirect Searches

Yu-Feng Zhou

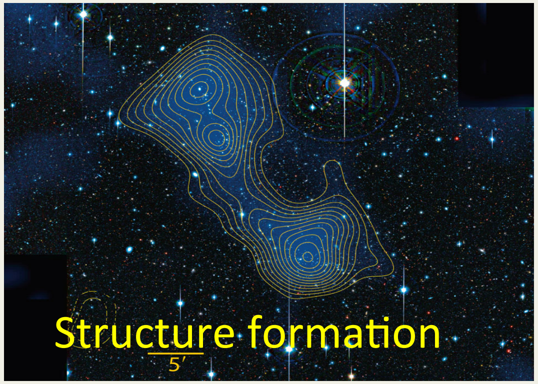
ITP-CAS

DM (so far) revealed (only) from observations

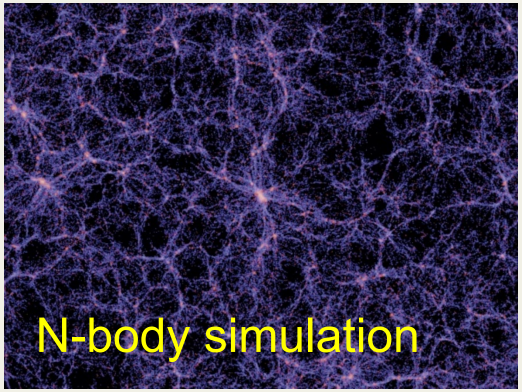




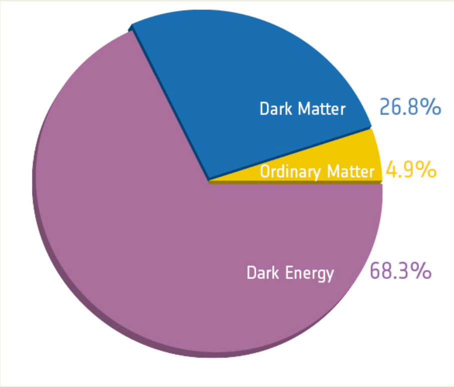
Tucker,etal, APJ,496,L5(1998)

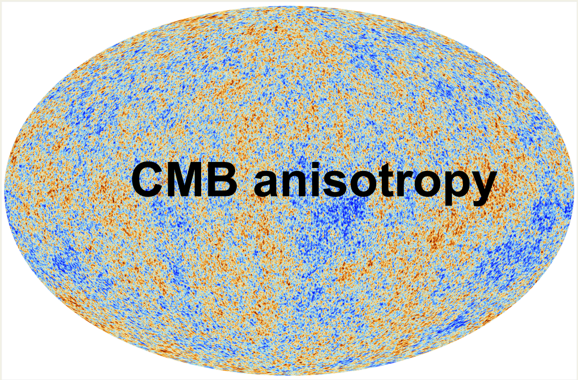


J.P. Dierich etal, 1207.8089, Nature



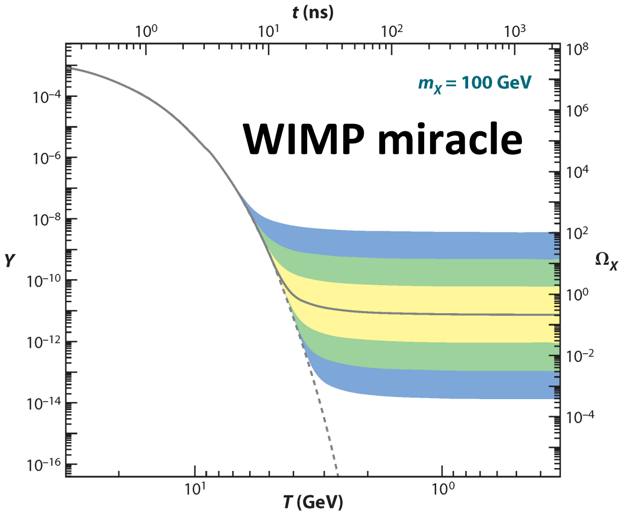
Millennium Simulation

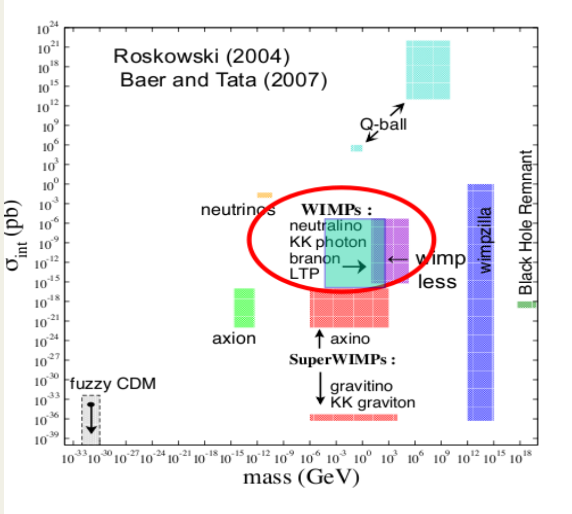


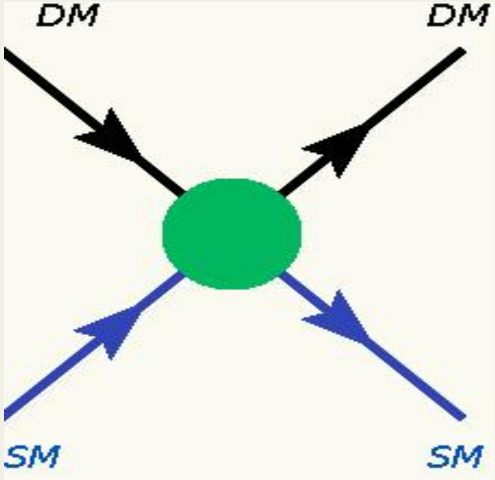


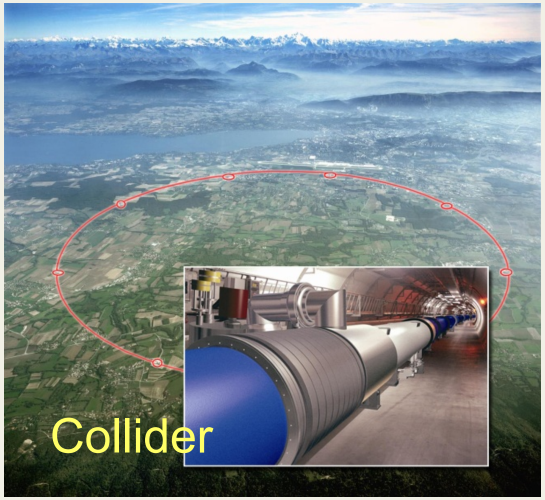
Planck, arXiv:1303.5062

Search for particle dark matter



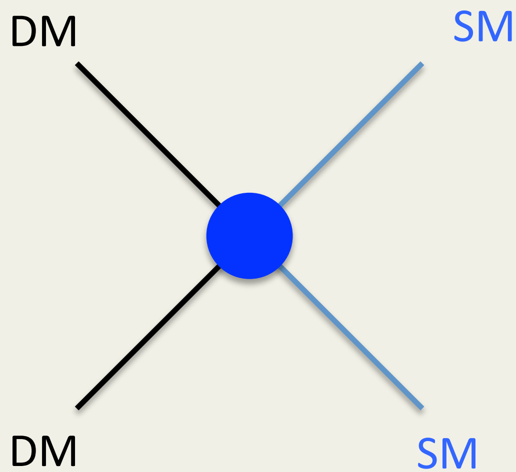






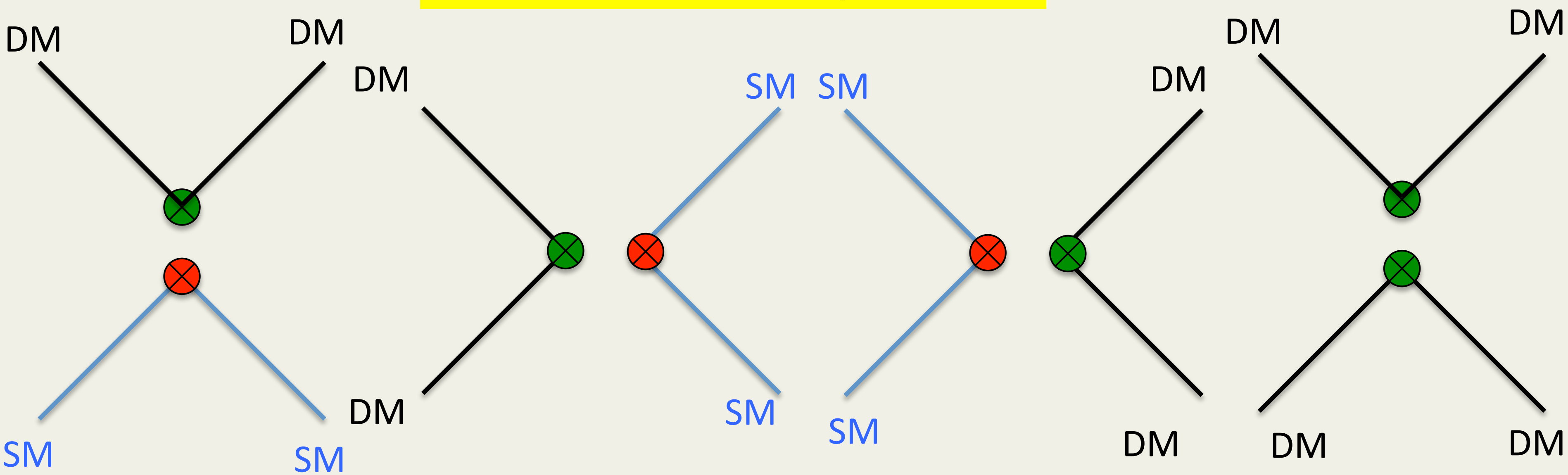
Connecting the dark matter search approaches

Effective Theory description ?



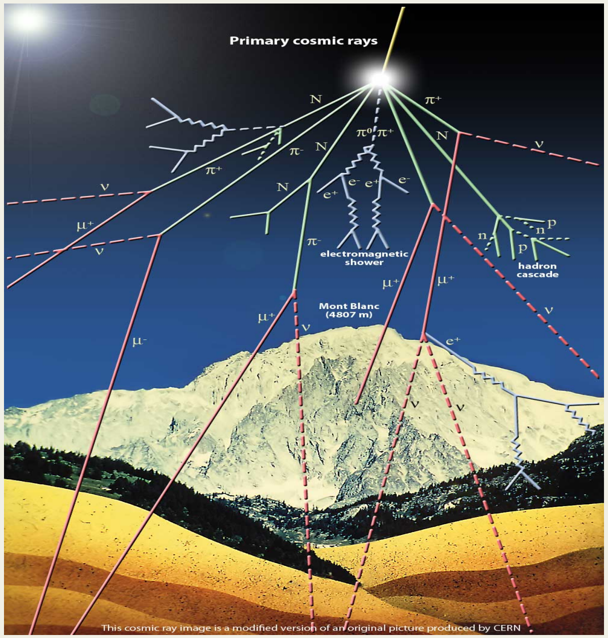
Typical energy scales vary from MeV to TeV

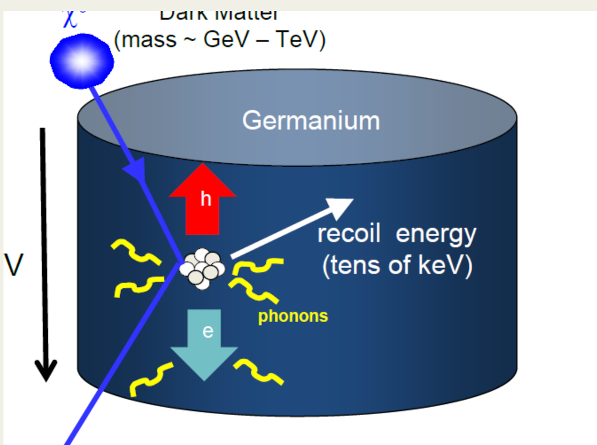
No one-to-one correspondence



Direct **Indirect** **Collider** **Structure Formation**

DM direct (underground) searches





Advantages

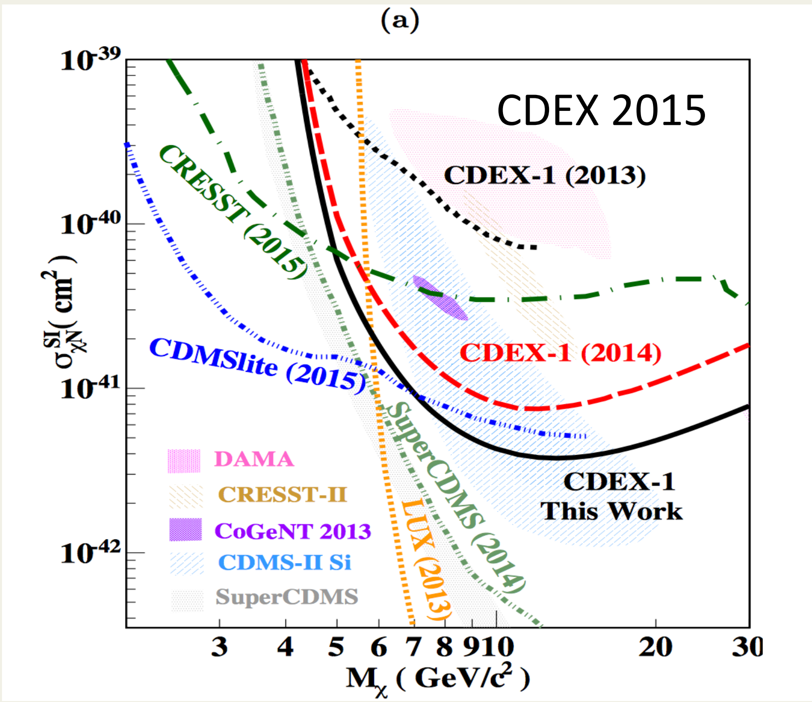
- probe DM interaction *directly*
- controlled backgrounds (lab exp.)
- can probe the motion of DM particle (annual modulation)
- can probe DM particles without annihilate or decay (e.g asymmetric DM)

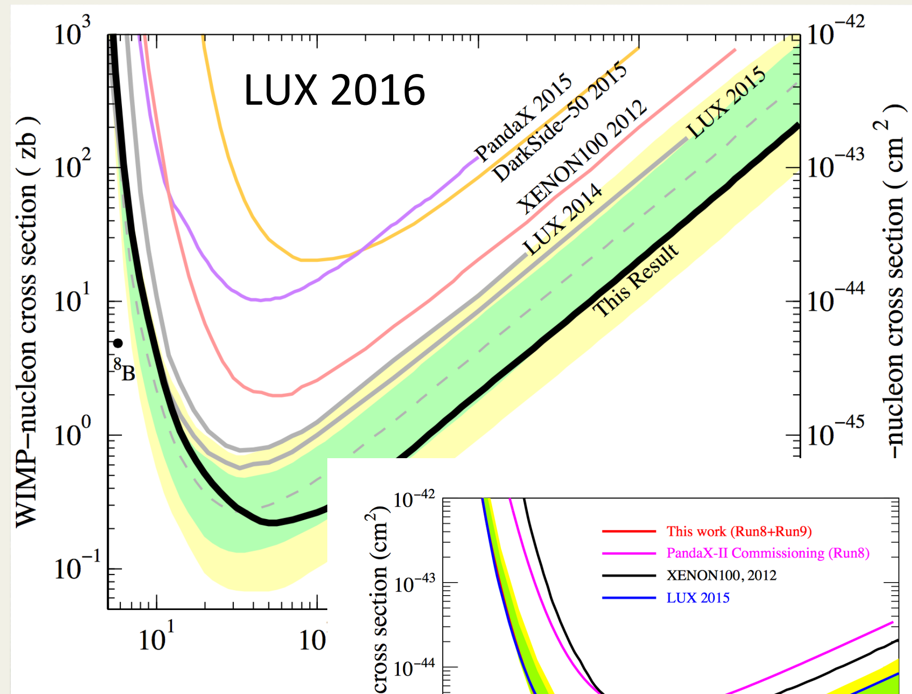
Challenges

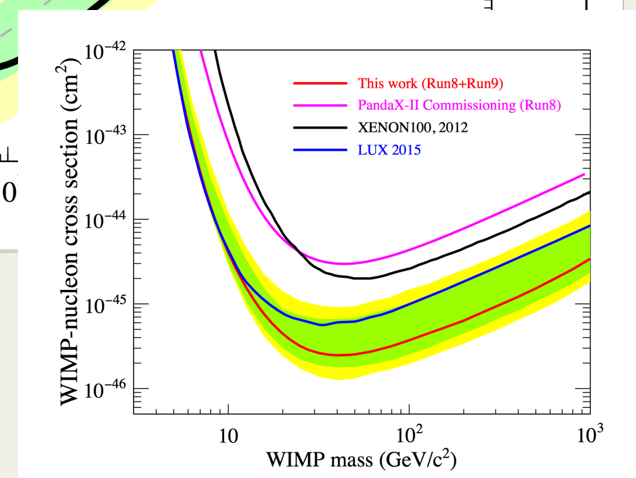
- tiny scattering cross sections
- need astrophysics inputs (e.g. local DM density, velocity)
- need nuclear physics inputs (e.g. form factors)
- model dependent interpretation:

  contact interactions, elastic scattering, isospin-conserving interaction, etc.,

Status of DM direct detections







PandaX 2016

Hints of "excesses" and "annual modulation"

- DAMA, CDMS-II, CoGeNT,

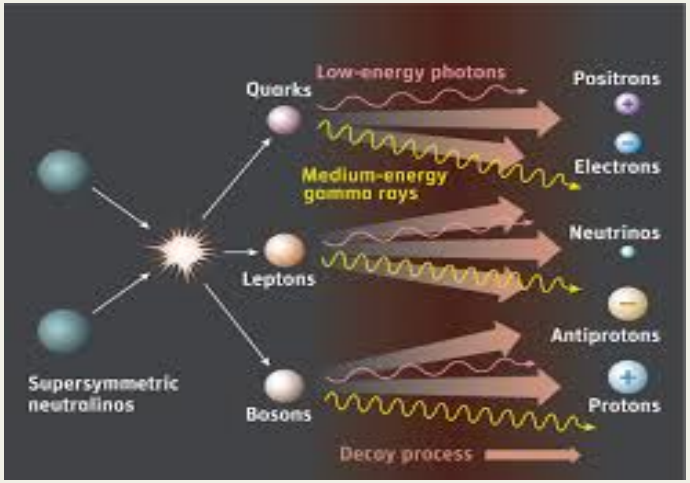
Stringent exclusion limits inconsistent with these hints

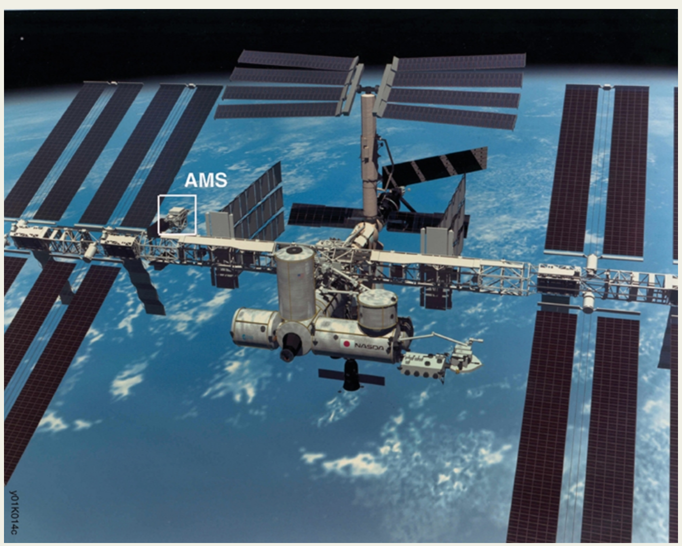
- LUX/PandaX: ~ 10^{-46} cm^2 @ 50 GeV
- CDMSlite, CRESST: ~ 10^{-41} cm^2 @ 5 GeV, CDEX ruled out CoGeNT excess
- XMASS: no sign of annual modulation

WIMPs on death row ?

No! connecting DM annihilation to DM-nucleon scattering highly model dependent !

DM indirect searches





Advantages

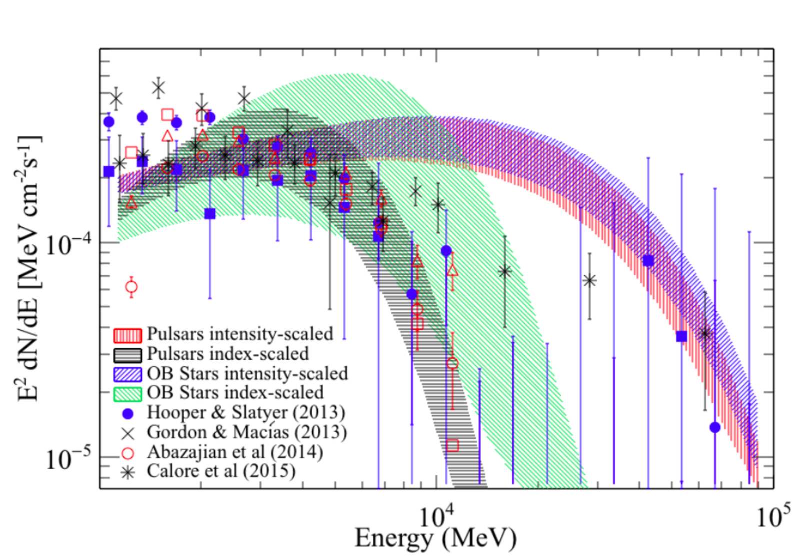
- can probe DM annihilation/decay, important to understand the origin of DM density.
- Tiny signals enhanced by huge volume of the DM halo
- can probe *both* energy spectral and morphology
  - line vs. continuum,
  - peaky vs. featureless power law,
  - extended signal in space vs. point-like source.

Challenges

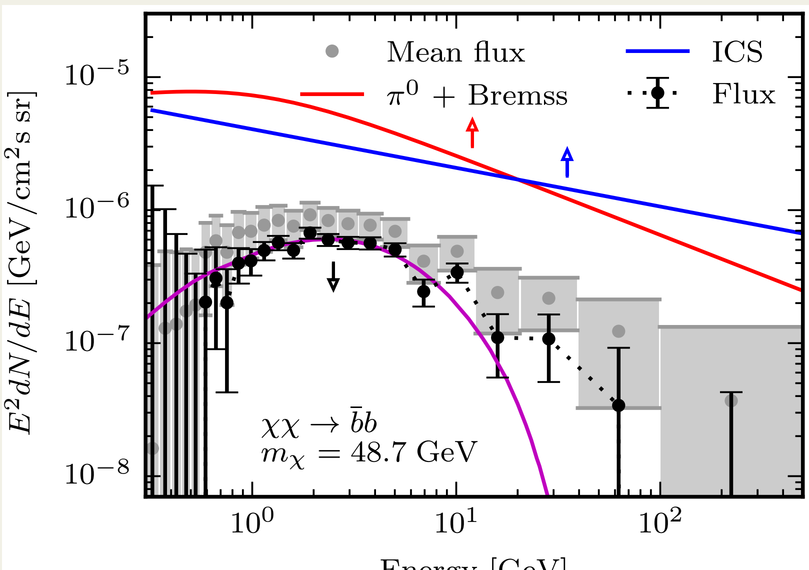
- always difficult to distinguish from astrophysical backgrounds ("backgrounds" not well undstood)
- Information loss during propagation
  - spectrum change du to E-dependent propagation, convection, re-acceleration, E-loss
  - anisotropic source -->isotropic signals
- Large uncertainties in theoretical predictions

  origin/propagation of CRs, Solar modulation, hadronic interaction cross sections

Established “anomaly”: GC γ-ray excess



Fermi-LAT, 1511.02938



Calore, etal, 1411.4647

Spectrum

- Smooth bump peaks at ~ 2 GeV

Morphology

- Consistent with a spherical emission profile expected from DM annihilation
- r-dependence consistent with a NFW DM profile with inner slope γ=1.2-1.3

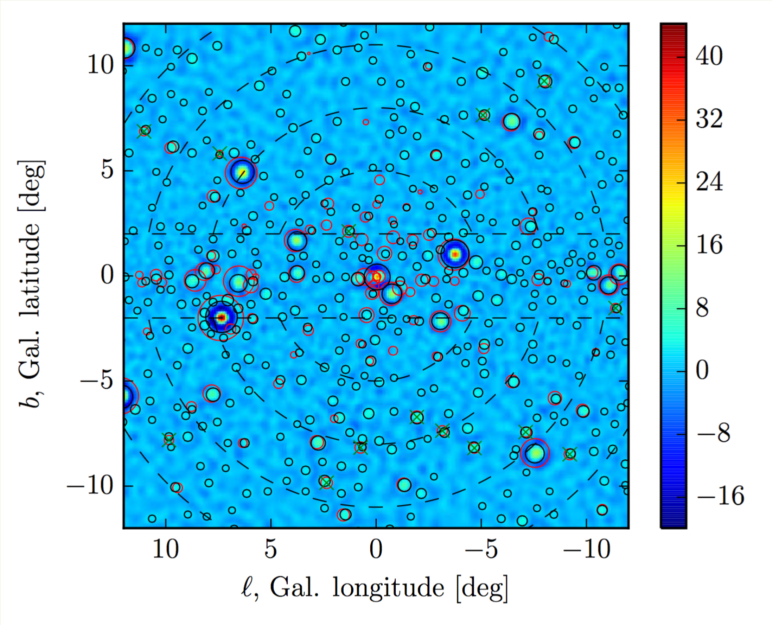
DM interpretation

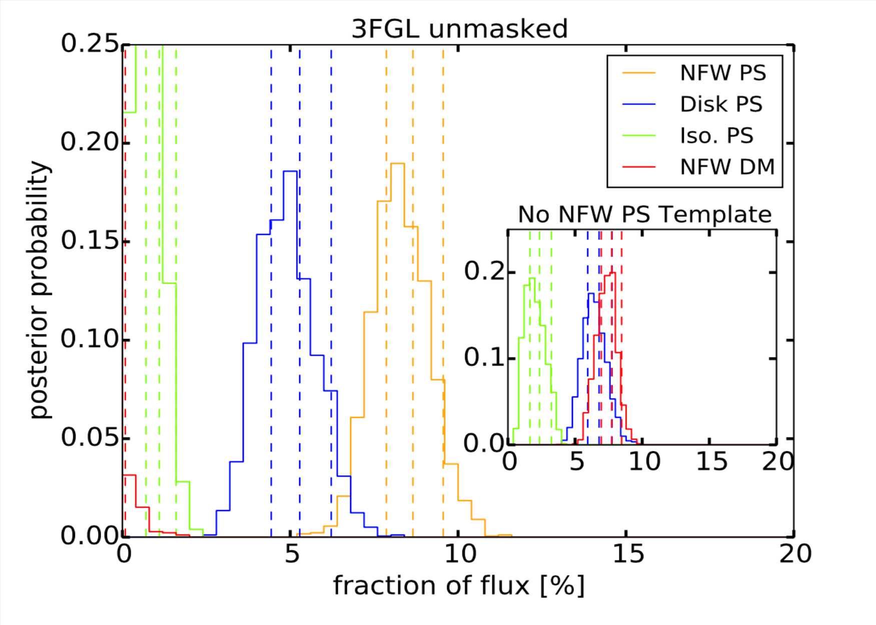
- DM annihilation with mass ~ 50 GeV
- typical thermal cross section
- 2b/2g final states favored
- Other channels also possible with lower p-values

Astrophysical interpretations

- Unresolved millisecond pulsars
- CR Interactions with interstellar gas

Astrophysical sources: millisecond pulsars





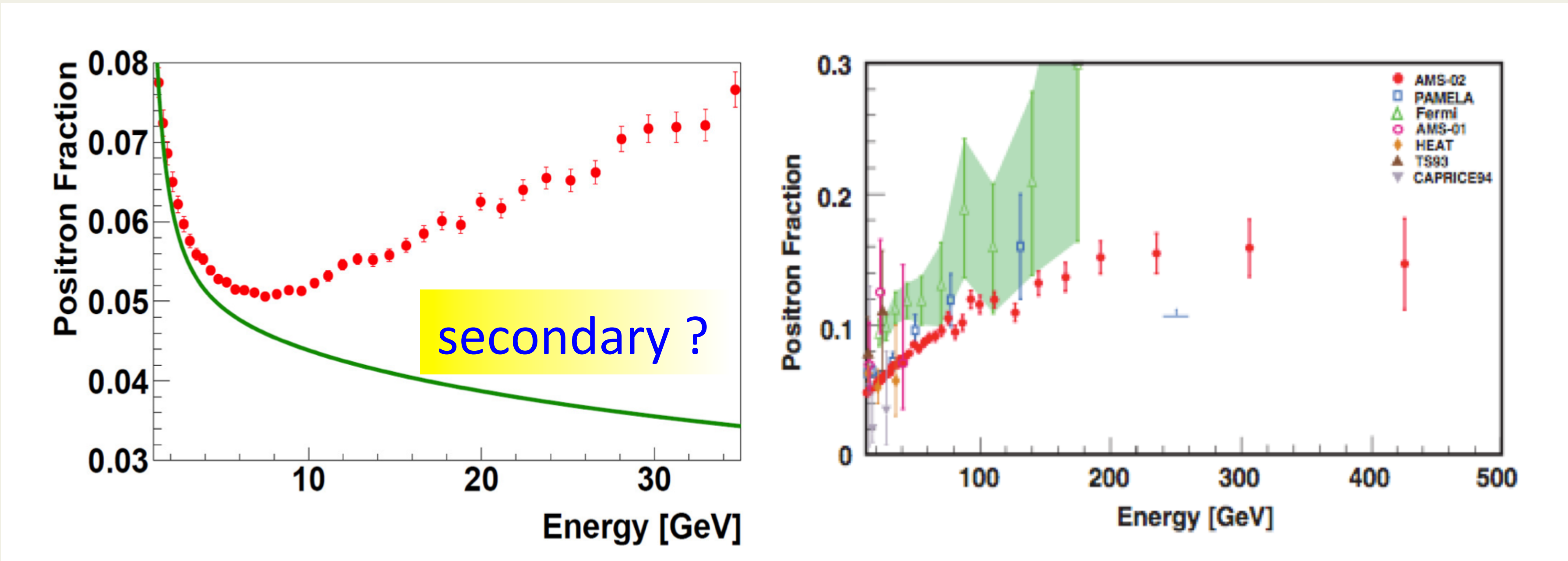
Wavelet analysis, R. Bartels, etal, 1506.05104

NonPoisonian analysis, S.K.Lee, etal, 1506.05124

Astrophysical sources

- Millisecond pulsars
- Interactions between CRs and interstellar molecular gas

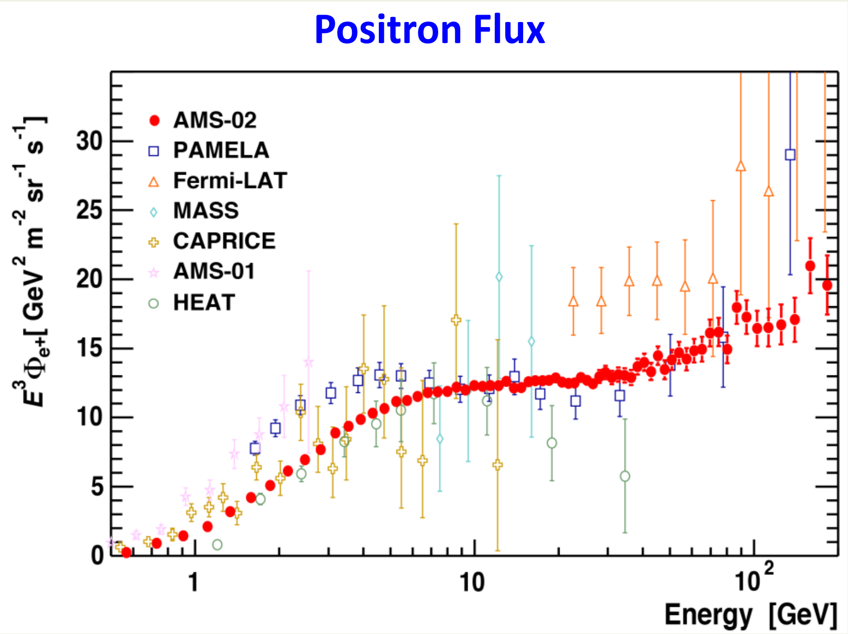
Established "anomaly": positron excess

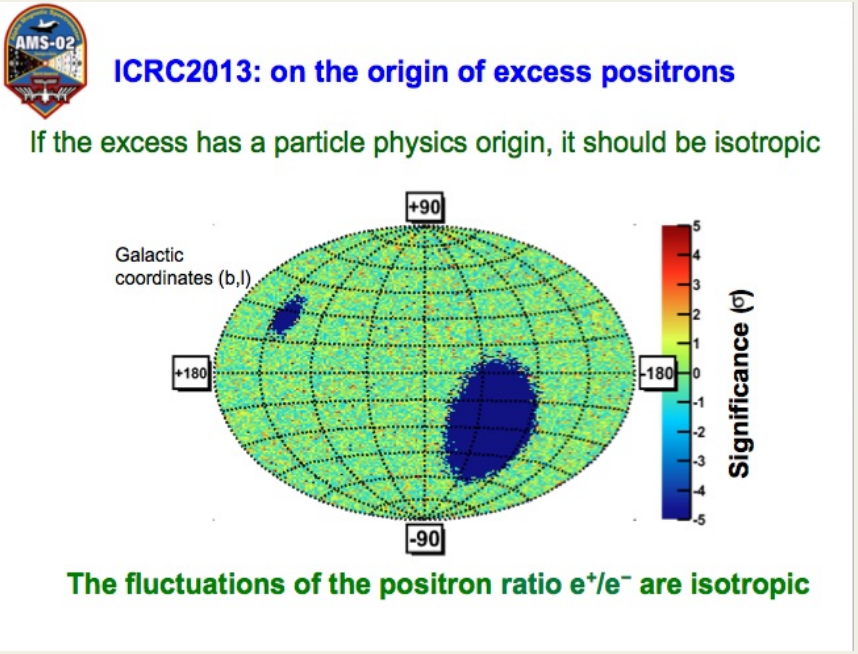


AMS-02, Phys.Rev.Lett. 113 (2014) 121101

- Positron fraction rises and reaches the maximal at energy ~270 GeV (expected to fall with energy, as secondaries)
- The high energy data points set the scale of DM mass and annihilation cross section /decay life-time (or energy cut-off for pulsar sources)

Positron flux and anisotropy

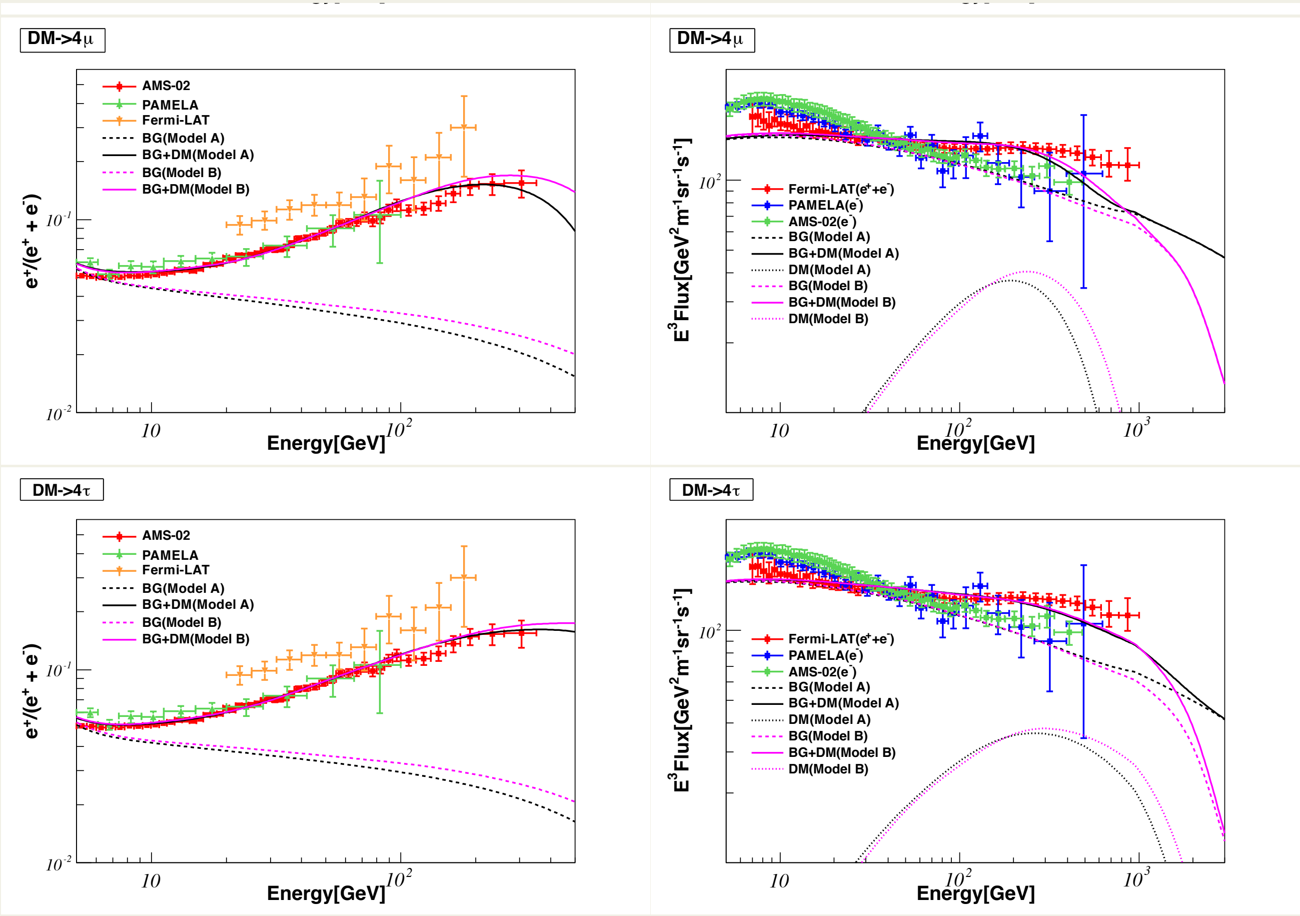




AMS-02, Phys.Rev.Lett. 113 (2014) 121102

- The rise in positron fraction is due to more positrons rather than less electrons
- Limits on the amplitude of a dipole anisotropy <0.03 at 95% C.L
  consistent with DM interpretation, cannot ruled astrophysical contributions

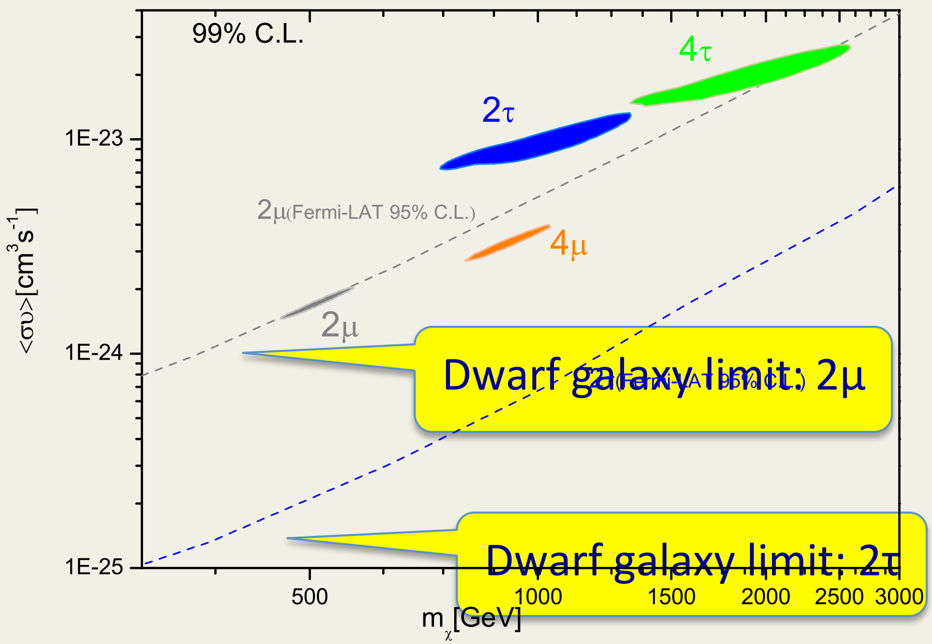
DM interpretations



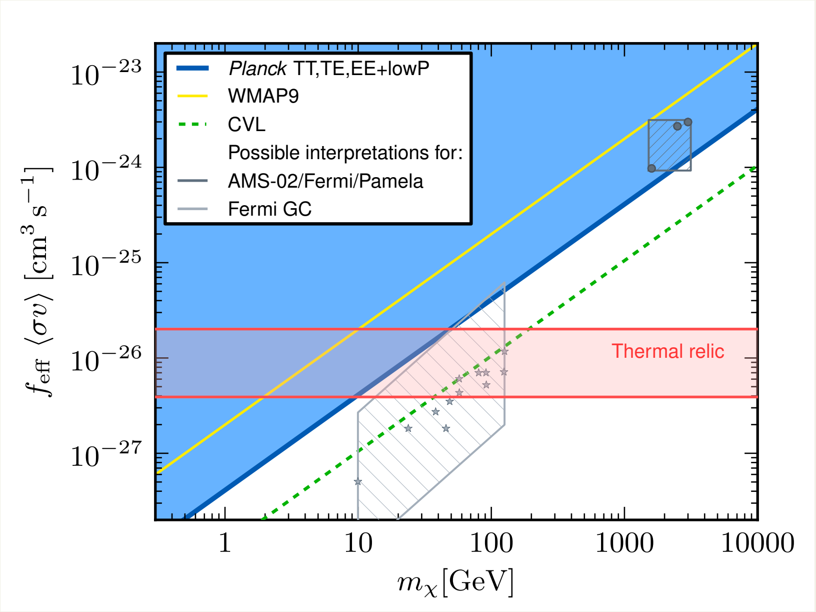
- Large annihilation cross sections, boost factor 100-1000
- Large cross sections to leptons, not quarks/gauge bosons
- AMS-02 data favour 4τ > 2τ >4μ > 2μ
- Annihilation slightly favoured over decay

H.B.Jin, Y.L.Wu, YFZ, 1304.1997

Constraints from gamma rays



Fermi limits from dSphs

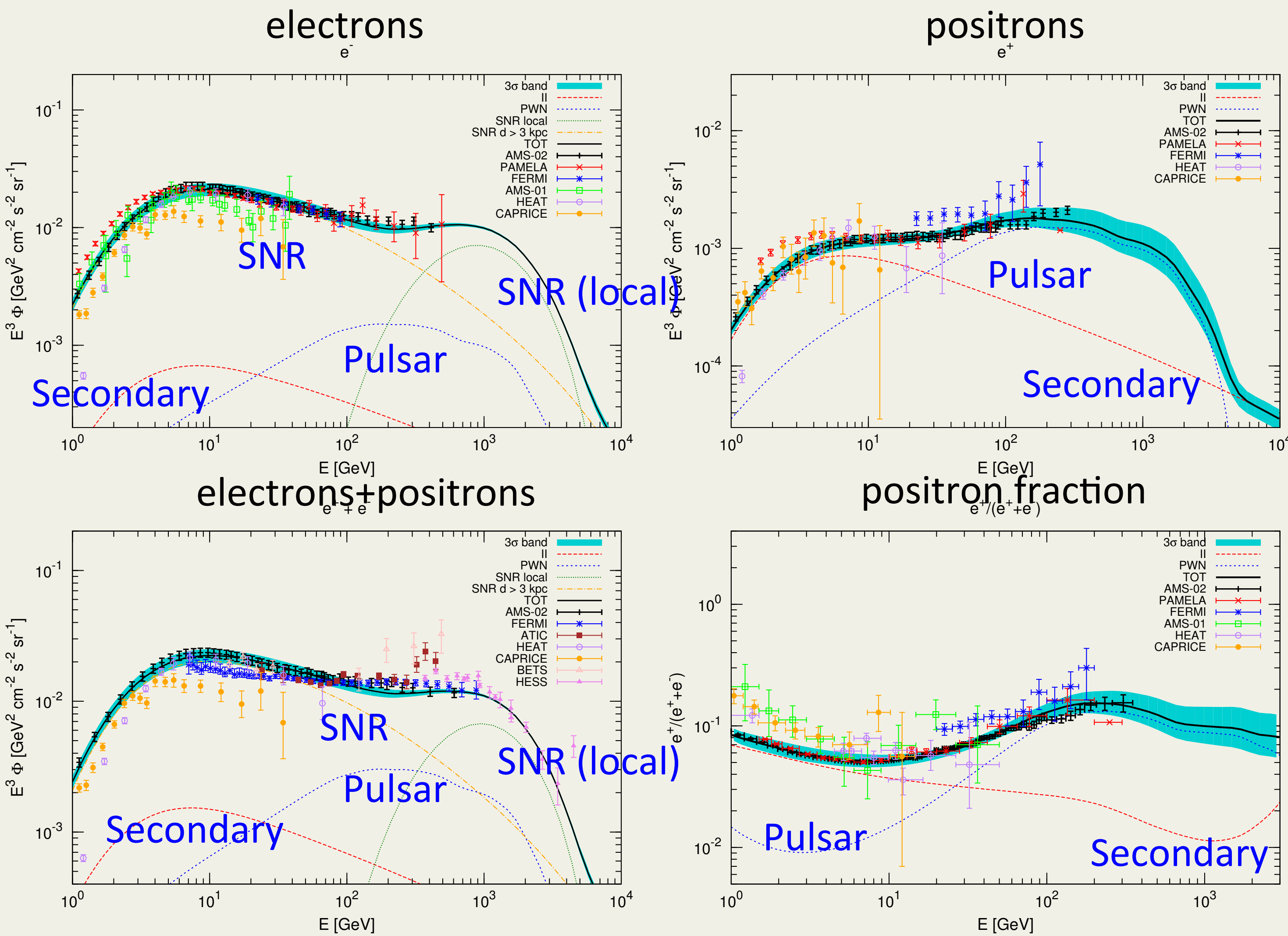


PLANK limits

Only DM annihilating into muon-final states are consistent with the dSphs limit

H.B.Jin, Y.L.Wu, YFZ, arXiv:1410.0171,JCAP

Astrophysical explanations



Mauro etal, 1402.0321

Towards a precise determination of the CR backgrounds

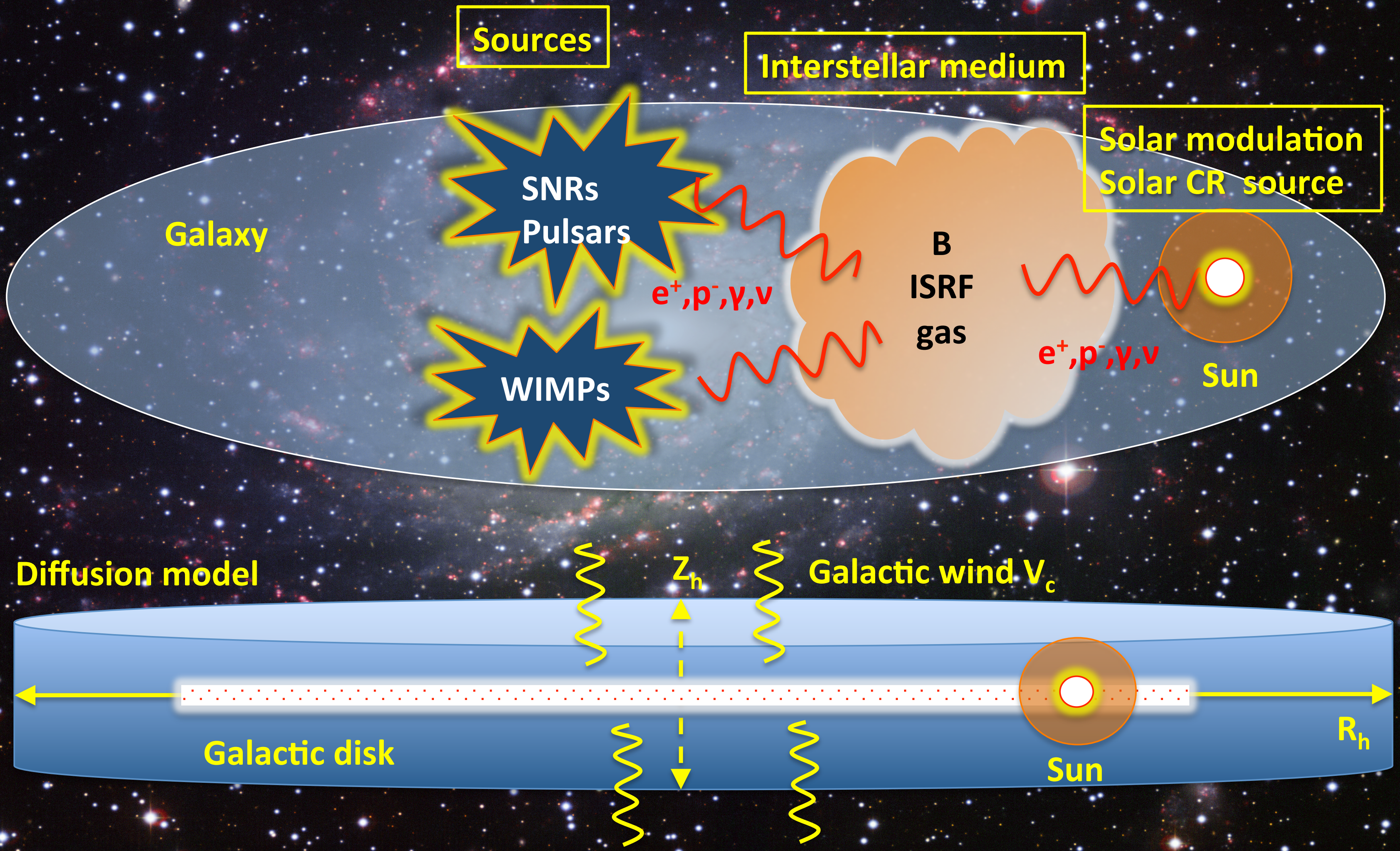
Astrophysical background modeling

- **Primary CR:** injection spectrum, power-law with cutoff
  (Fermi diffusive shock-wave acceleration)
- **Secondary CR**: pp cross-sections, densities of ISM gas
- **Propagation**: assume diffusive propagation,
  fit to some "non-anomalous" cosmic-ray data (B/C, $^{10}Be/^{9}Be$, etc.)

Uncertainties in propagation parameters are crucial for DM prediction

- Significant propagation parameter degeneration in B/C,
  but NOT in DM DM → e^+ and pbar
- Primary source terms also degenerate with propagation parameters

Origin and propagation of CRs



Cosmic-ray transportation equation

diffusion · convection · E-loss · reaccelaration · spallation · decay · source

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

Sources of CRs

- Primary sources from SNR, pulsars
- Primary sources from WIMP
- Secondary source from CR fragmentation

Processes in Propagation

- Diffusion (random B field)
- Convection (galactic wind)
- Reacceleration (turbulence)
- Energy loss: Ionization, IC, Synchrotron, bremsstrahlung
- Fragmentation (inelastic scattering)
- Radioactive decay (unstable species)

Solar modulation

Uncertainties

- Distribution of primary sources
- Parameters in the diffusion equation
- Cross sections for nuclei fragmentation
- Distribution of B field
- Distribution of gas

Approaches

- Semi-analytical, two-zone diffusion model.
- Numerical solution using realistic astrophysical data. GALPROP/Dragon code

Cosmic-ray propagation processes

Diffusion (constant)

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

Main source of uncertainty

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

In general D_0 should be spatial dependent (Dragon code)

e.g, larger diffusion const. at higher energy,

Kolmogorov: $\delta = 1/3$

Boundary Condition

flux vanishes at (R_h, Z_h)

Main source of uncertainty

Convection

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

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

Reacceleration

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

Relation between Dpp and Dxx

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

determine the propagation models

Observables

1) Secondary/Primary

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

  sensitive to combination D_0/Z_h

2) Radioactive species (cosmic clock)

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

  sensitive to diffusive halo size

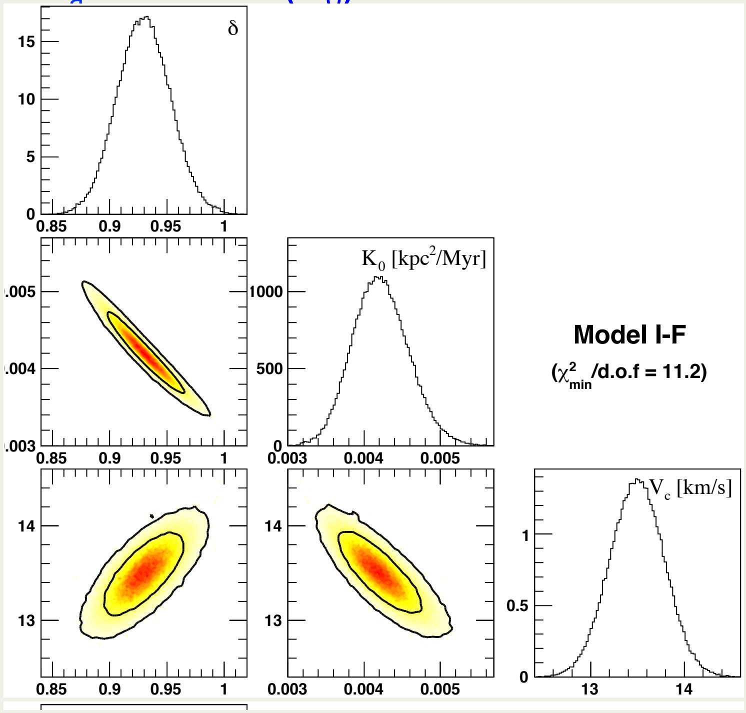
3) Stable primaries

- Proton and electron fluxes

  sensitive to primary sources

Degeneracies between parameters

1. **D_0 / Z_h , (diffusion/halo size) most relevant for DM**
2. $\delta + \gamma_{p2} = 2.7$
3. V_a scales as $(D_0)^{1/2}$



Trotta, etal, arXiv:1011.0037

Maurin, etal, astro-ph/0212111

A new analysis framework

The Standard approach: B/C+ ^{10}Be/^{9}Be

pros: B/C is source independent, only constrain D_0/Z_h,

^{10}Be: τ_{Be10} =1.4 Myr, sensitive to D_0 only, break the D_0/Z_h degeneracy

corns: low precision ^{10}Be/^{9}Be data (from ACE, ISOMAX)

data come from different exps., different solar activity periods, complicate the solar modulation estimation

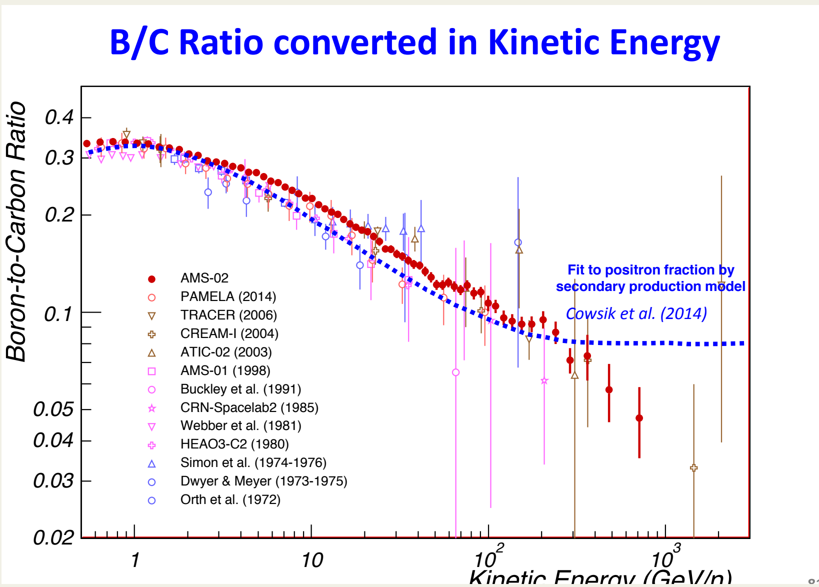
The new approach: B/C + Proton flux

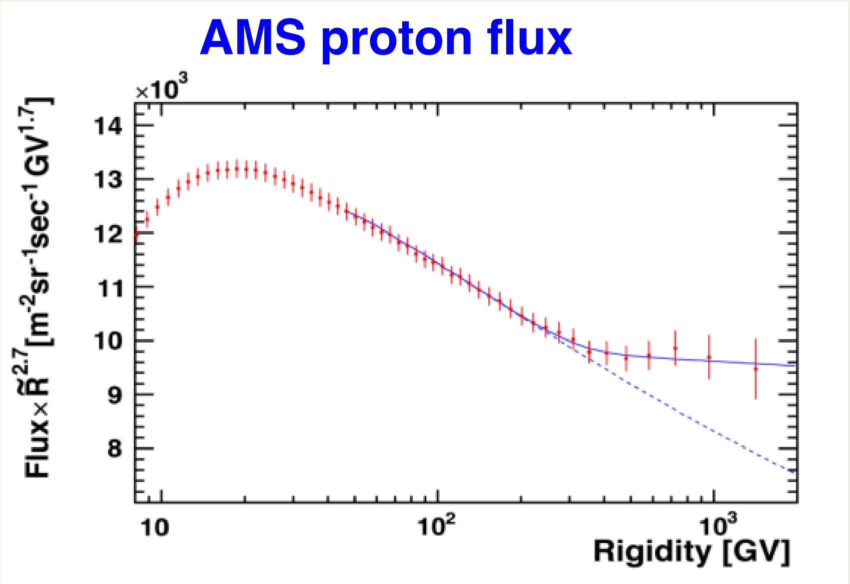
- Proton flux carries nontrivial information of CR propagation
- B/C + Proton forms a complete set for determining all the propagation parameters.
- Both have been measured by the same experiment: AMS-02
  - Very precisely measured
  - Avoiding combination of syst. errors in different experiments
  - All data from the same period, easy to model solar modulation effects

H.B.Jin, Y.L.Wu, YFZ, JCAP 1509 (2015) 09, 04

A global Markov-Chain Monte-Carlo Bayesian determination of propagation parameters

Input: AMS-02 data on B/C ratio and proton flux





AMS-02, Phys.Rev.Lett. 114 (2015) 171103

Approach: Bayesian statistic analysis + Markov Chain Monte Carlo

Results

(using data from AMS02, ICRC2013)

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
$V_a(\mathrm{km \cdot s^{-1}})$	[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%)

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

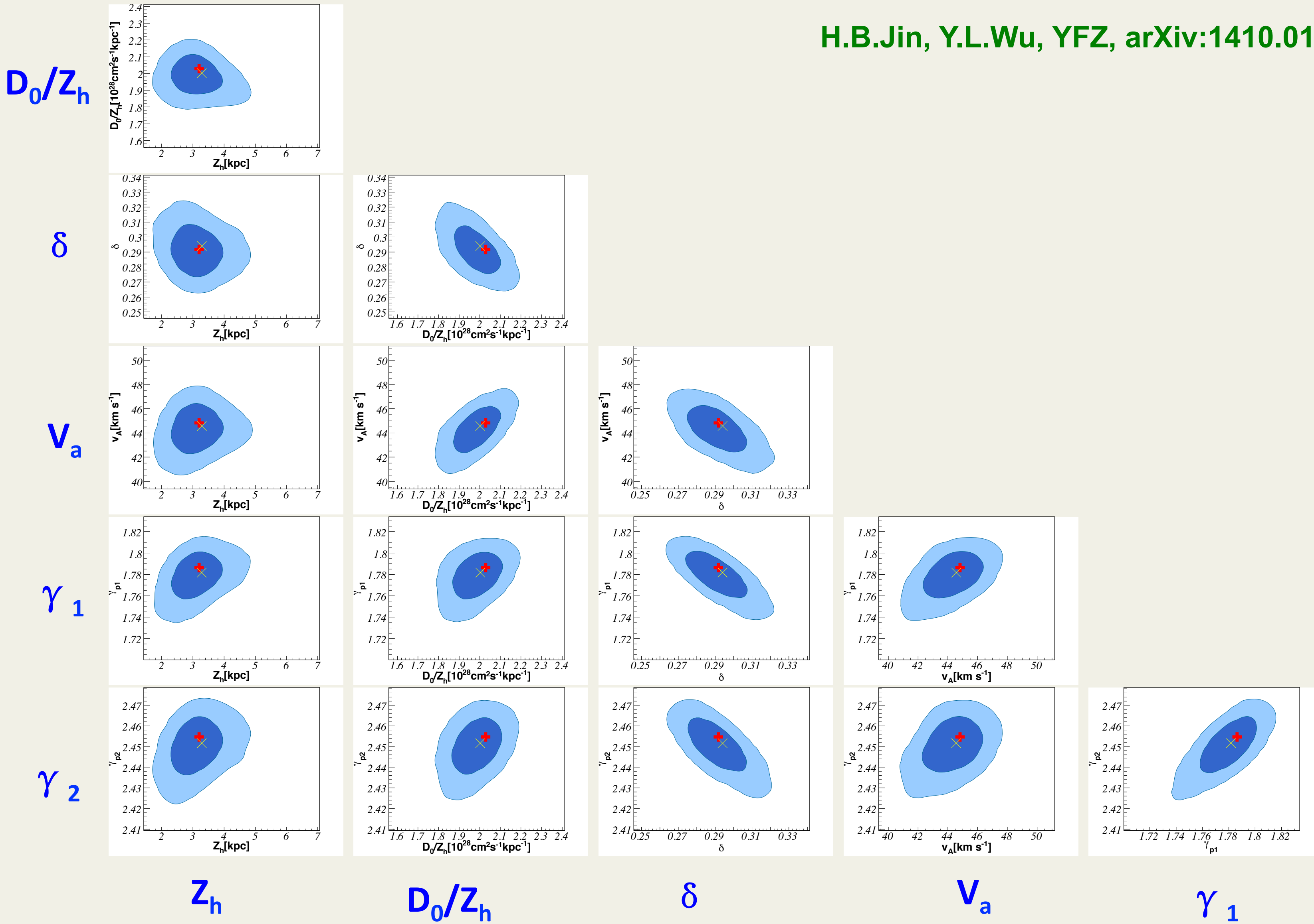
A lower Z_h favored

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

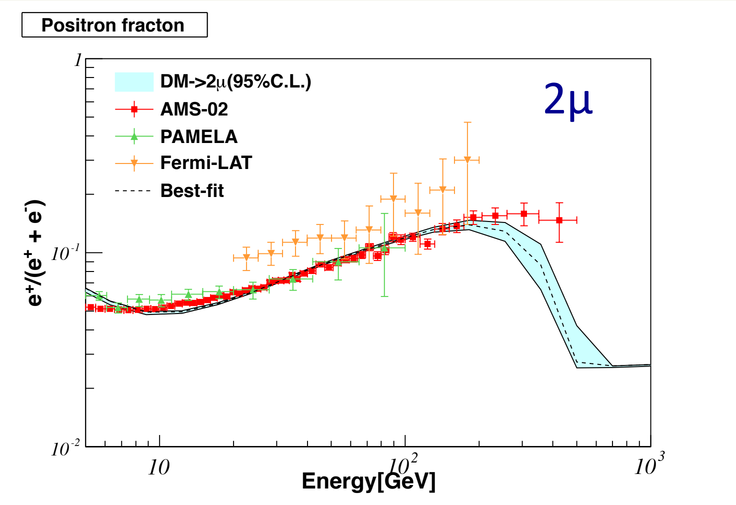
H.B.Jin, Y.L.Wu, YFZ, arXiv:1410.0171,JCAP

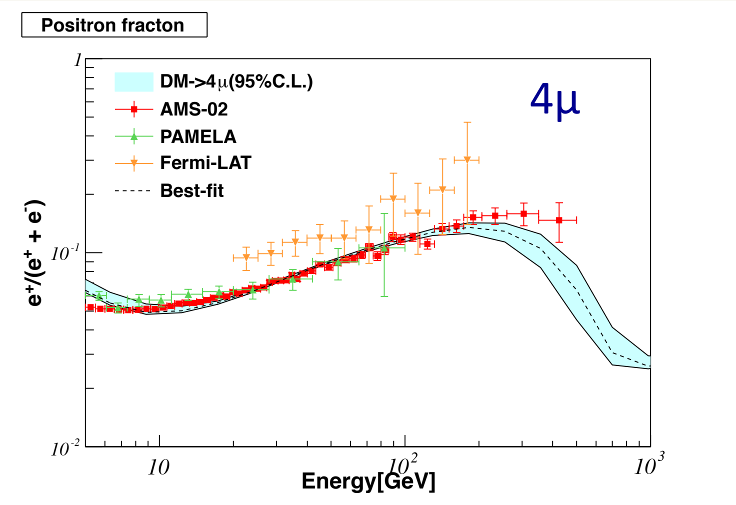
Correlations between parameters

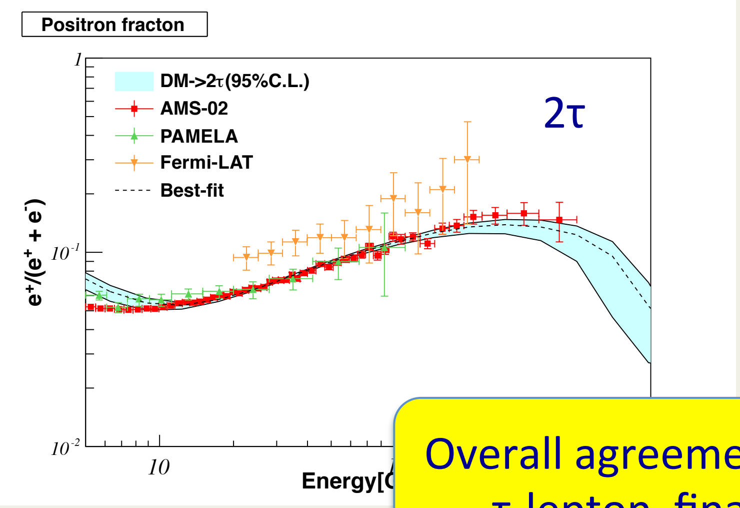
H.B.Jin, Y.L.Wu, YFZ, arXiv:1410.0171,JCAP

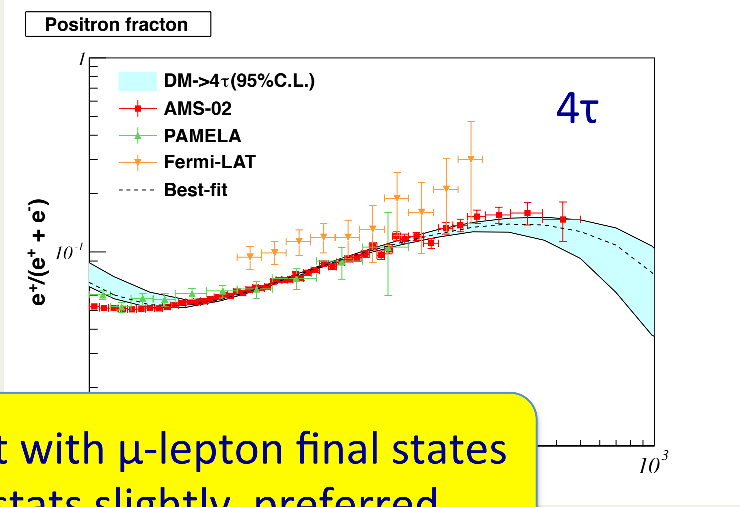


DM fits including propagation uncertainties



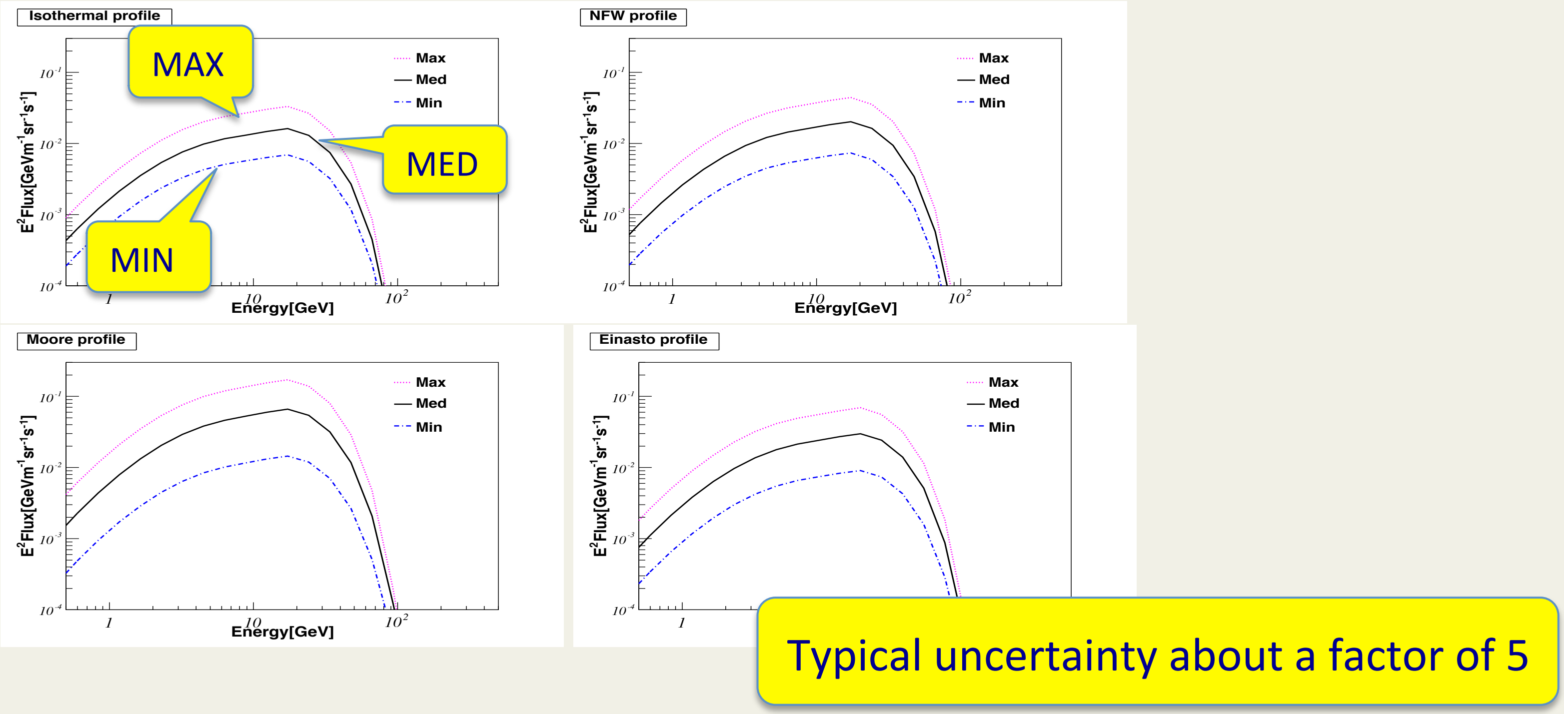






Overall agreement with μ-lepton final states
τ-lepton final stats slightly preferred

Typical uncertainties in antiproton flux



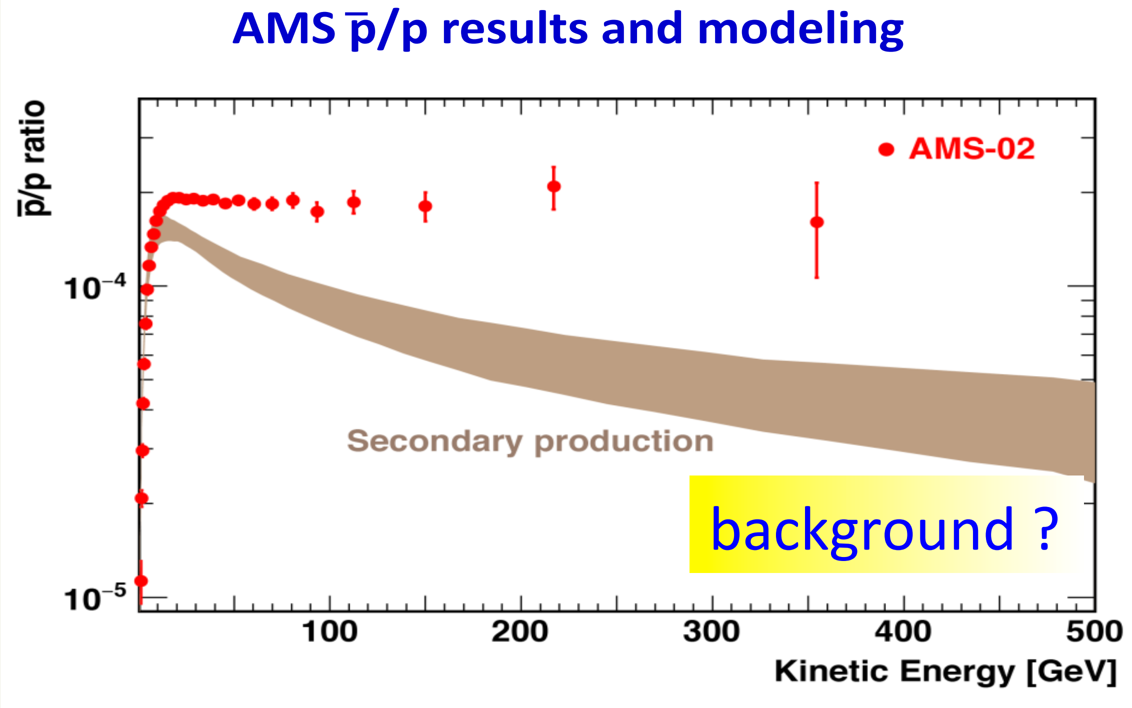
model	R(kpc)	Z_h(kpc)	D_0	ρ_0	δ_1/δ_2	V_a(km/s)	ρ_s	γ_{p1}/γ_{p2}
Conventional	20	4.0	5.75	4.0	0.34/0.34	36.0	9.0	1.82/2.36
MIN	20	1.8	3.53	4.0	0.3/0.3	42.7	10.0	1.75/2.44
MED	20	3.2	6.50	4.0	0.29/0.29	44.8	10.0	1.79/2.45
MAX	20	6.0	10.6	4.0	0.29/0.29	43.4	10.0	1.81/2.46

The “new” MIN, MED, MAX models in GALPROP approach

An "anomaly" in antiproton ?

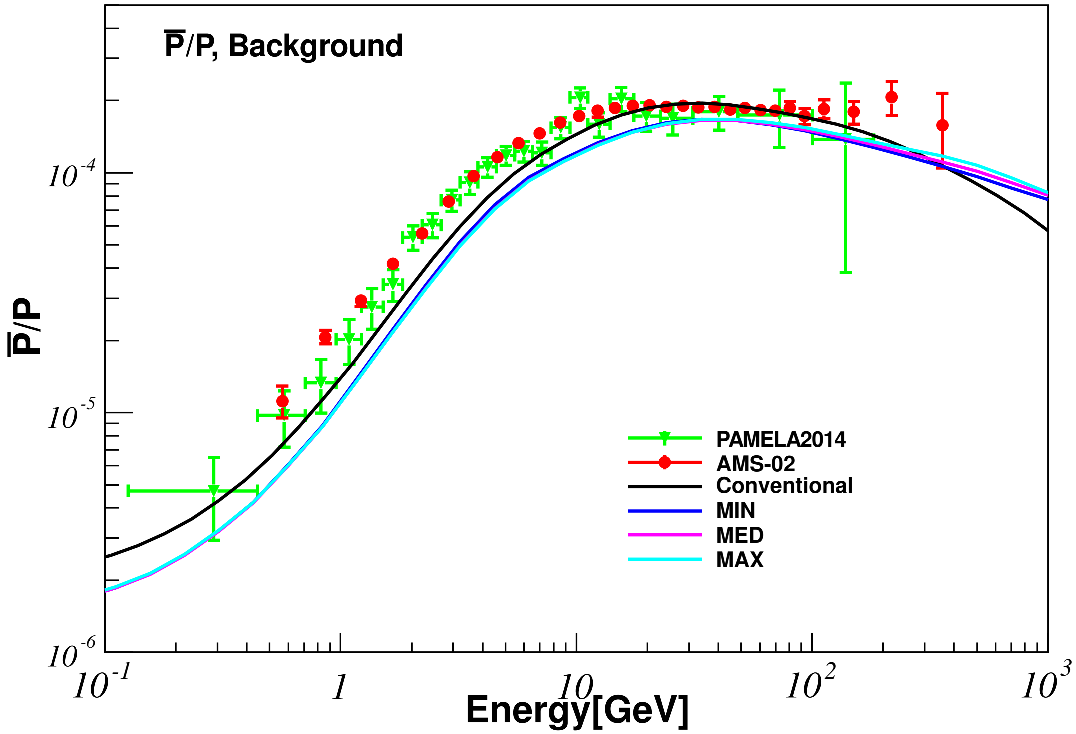
Importance of CR antiproton

- unlikely to be produced by pulsars
- produced in nonstandard SNR theories
- much less energy loss during propagation (compared with CR electrons)
- more sensitive to propagation parameters, and DM profile



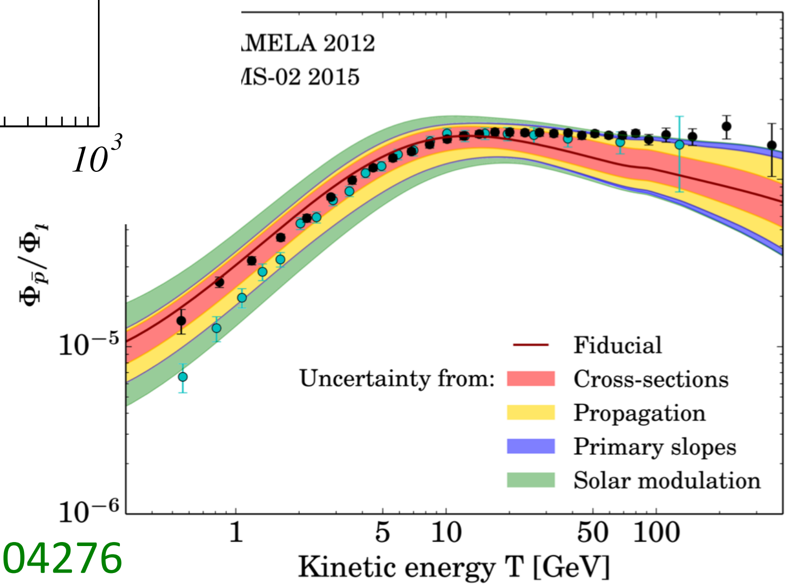
S.Ting "AMS-02 days at CERN", April 15-17, 2014， CERN

AMS-02 data (almost) consistent with background



Giesen, 1504.04276
Ibe, 1504.05554
Hamaguchi, 1404.05937
Lin, 1504.07230
Chen, 1504.07848
Chen,1505.00134

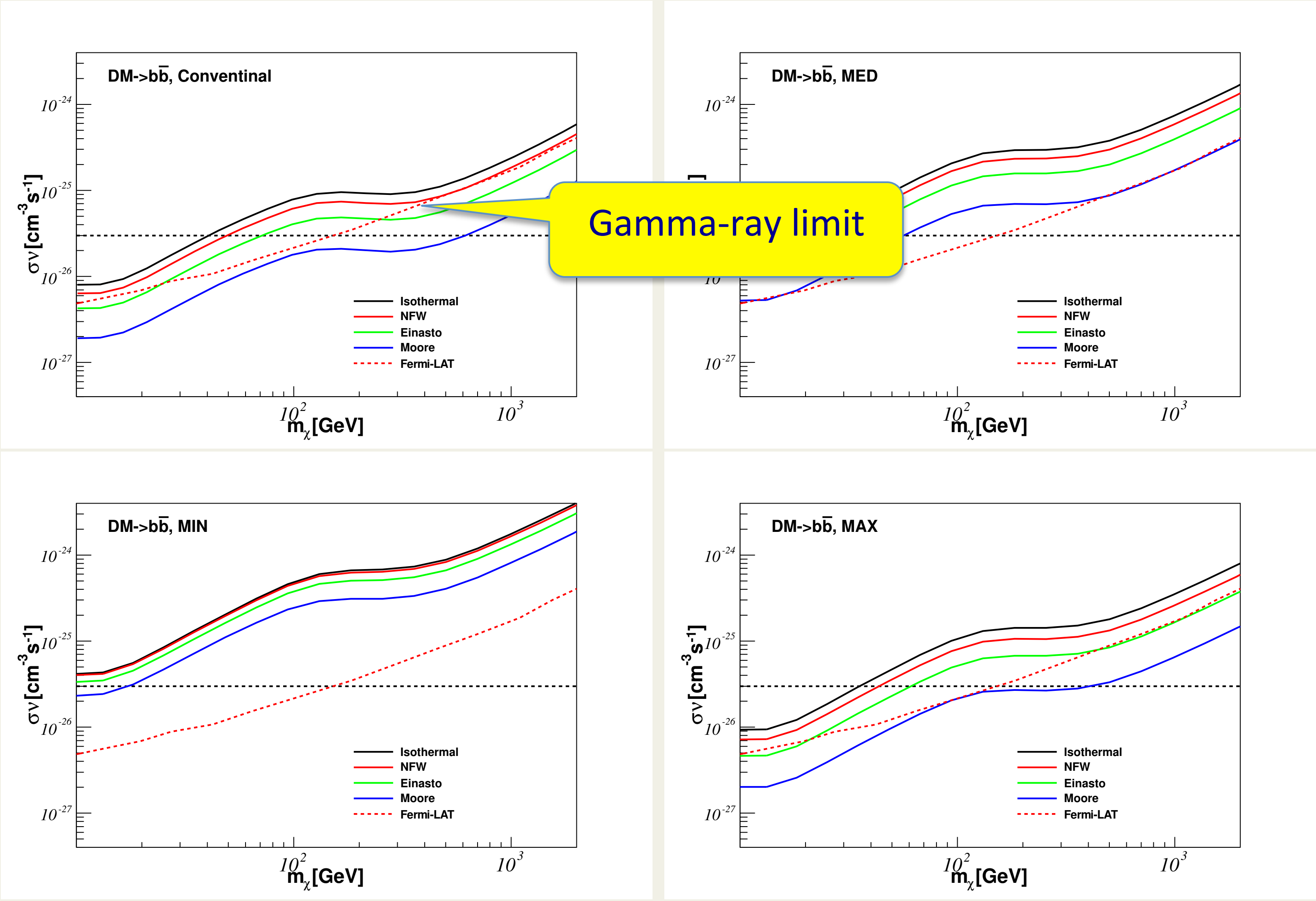
H.B.Jin, Y.L.Wu, YFZ arXiv:1504.04601, PRD



Giesen, 1504.04276

AMS-02 pbar data set stringent limits

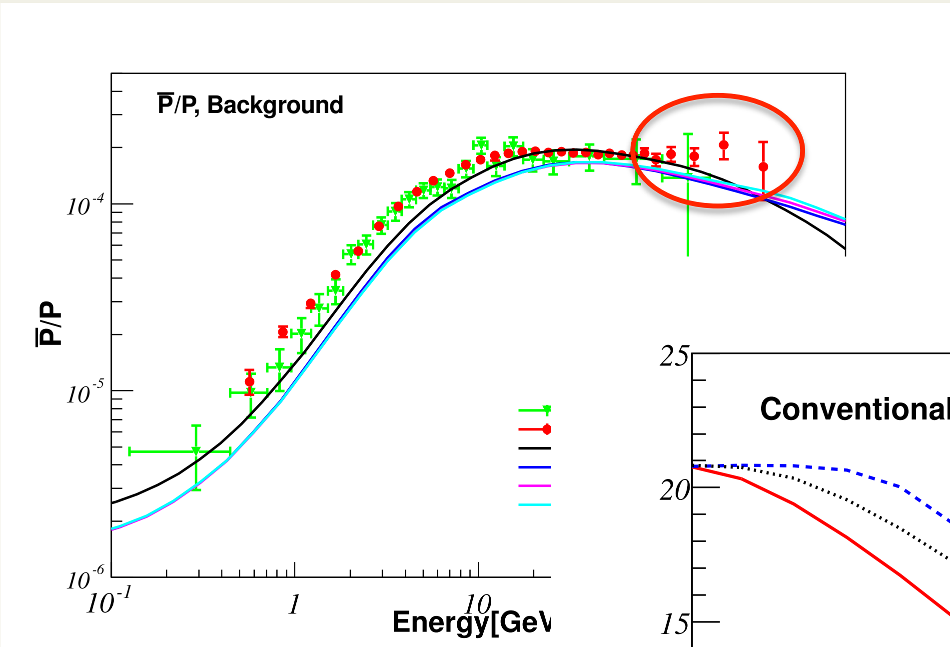
(bb channel)



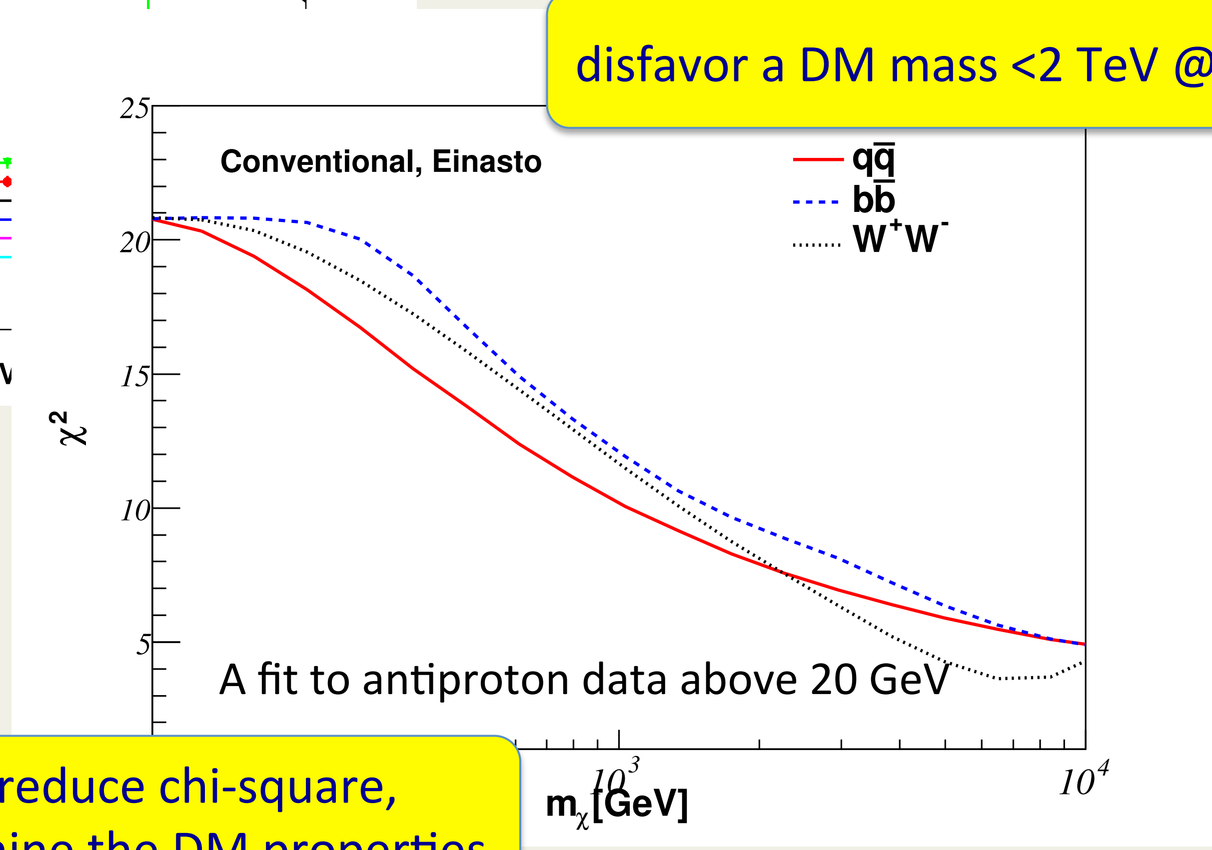
Upper limits from antiproton could be compatible with that from dwarf galaxies

Hints for DM ?

H.B.Jin, Y.L.Wu, YFZ, arXiv:1504.04601,PRD



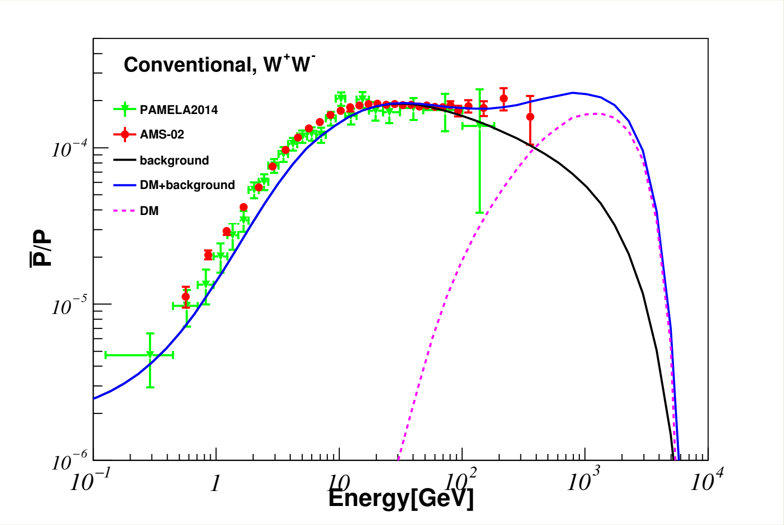
disfavor a DM mass <2 TeV @2σ

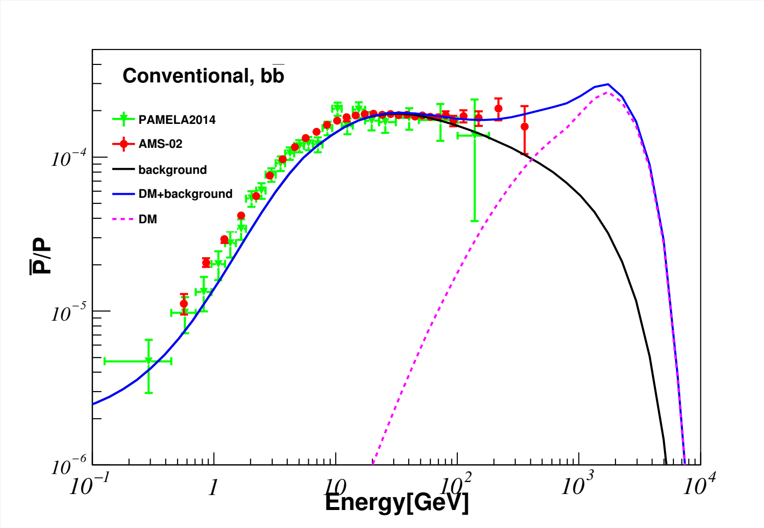


Introducing DM can reduce chi-square,
but so far cannot determine the DM properties

heavy DM not yet excluded

H.B.Jin, Y.L.Wu, YFZ, arXiv:1504.04601, PRD

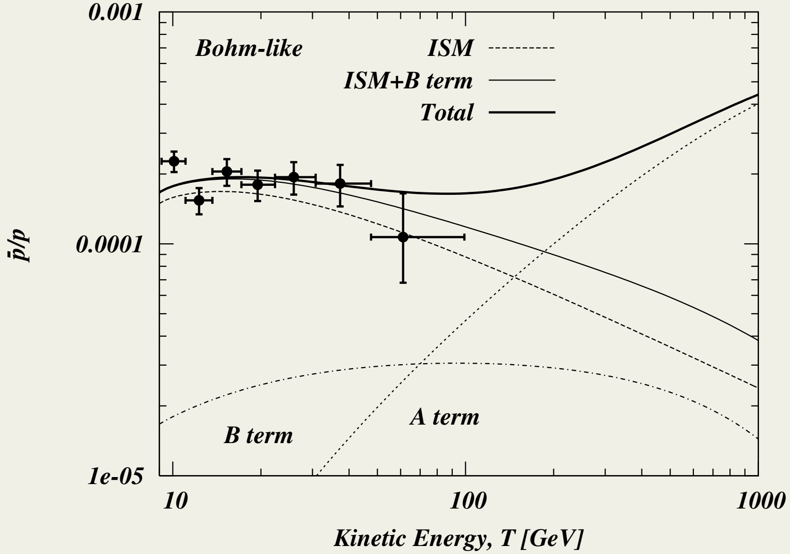




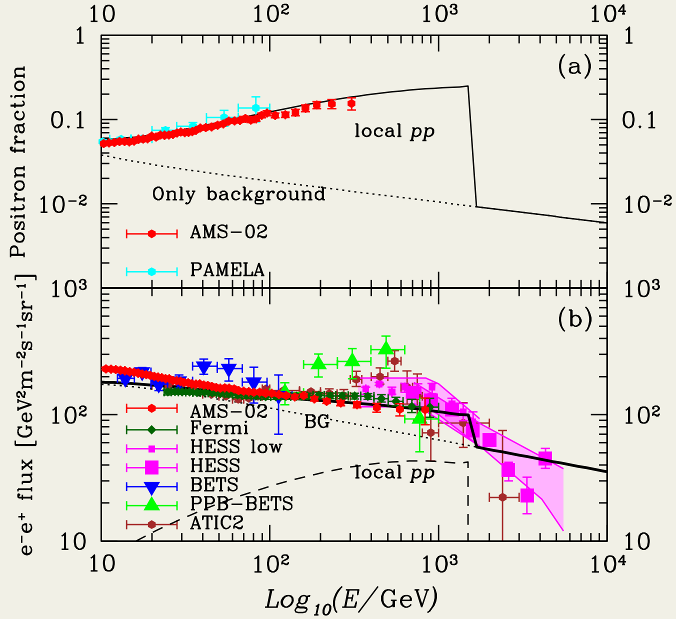
Eg. a 10 TeV DM contribution with
Boost factor ~100

Antiproton data at high energies will be crucial
AMS-02 see ~one antiproton/month, due to limited acceptance & rigidity resolution
Call for next generation magnet spectrometer

Astrophysical explanations (nonstandard)



Blasi, 0904.0871



Kohri, 1505.01236

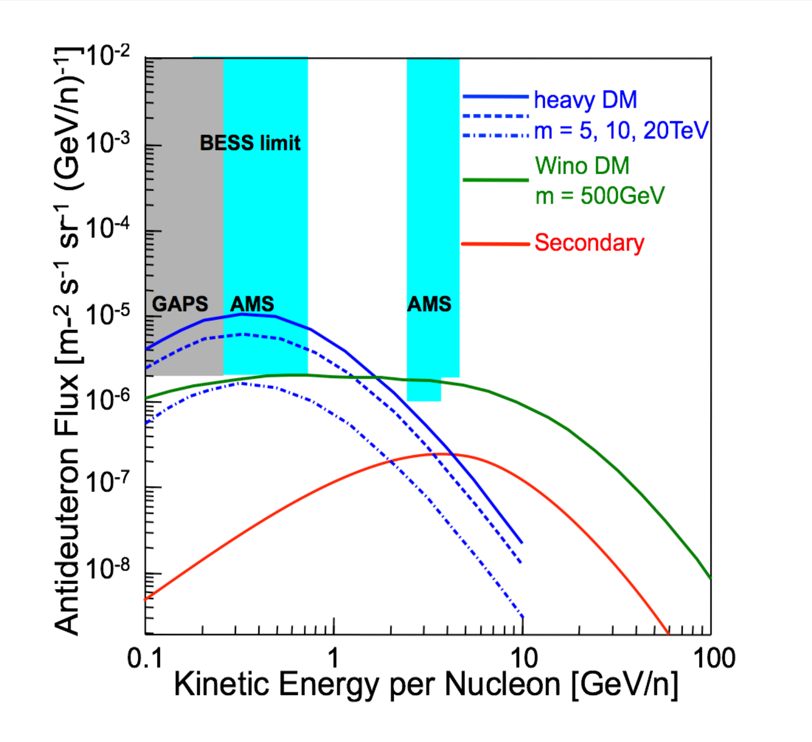
Astrophysical explanations

- Secondary produced inside SNRs,
  predicts flattening or weak rising of pbar spectrum
- Local SNR surrounded by dense cloud, with pbar generated
  by pp-collisions.

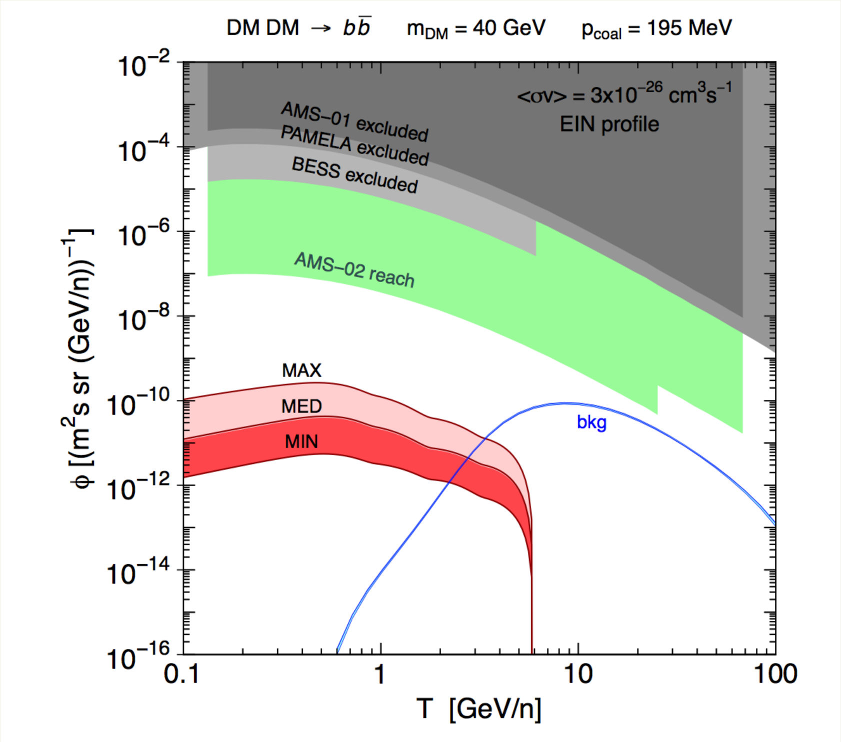
Both predict enhanced positron fraction.

The future: heavier CR antiparticles ?

antideuteron



antihelium



Cirelli, etal, 1401.4017

- Low signal event rates, but backgrounds also low (> GeV)

Summary

- DM as revealed from astrophysical observations is one of the clear indications of new physics beyond the SM.
- DM direct detections have set stringent limits on some type of DM interactions with the SM, waiting for xenon-1T or the next generation detectors.
- "Anomalies" in cosmic gamma-rays (GC region) and antiparticles (positrons) exist, can be linked to DM but plausible astrophysical explanations (PWN, SNR) exist. It is crucial to improve the understanding of the CR background.
- hint of "Anomalies" in CR antiprotons need to be confirmed, if true can be related to DM or nonstandard interactions of SNRs.
- Future anti-deuteron and anti-helium can shed new light on the search for DM

Thank you !

Backup slides

Sources of cosmic rays

- **Primary sources** (SNR)

Assume power low in rigidity

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

Spatial distribution (pulsar survey)

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

- **Secondary sources** (cross sections)

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

only a few, very old pp-,pA-collision data

- **Primary DM sources** (spectrum)

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

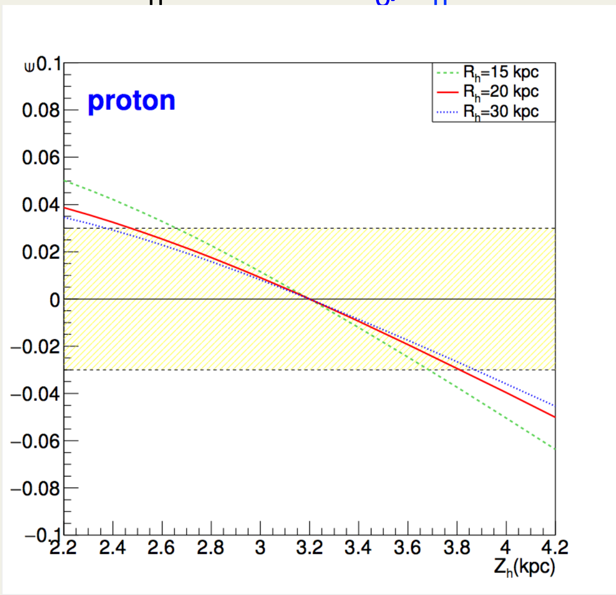
DM profiles (N-body simulations)

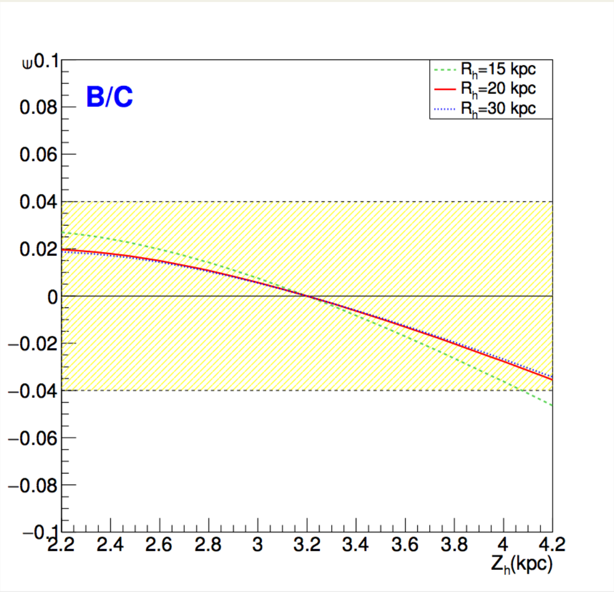
$$\rho_\odot \left(\frac{r}{r_\odot}\right)^{-\gamma} \left(\frac{1+(r_\odot/r_s)^\alpha}{1+(r/r_\odot)^\alpha}\right)^{(\beta-\gamma)/\alpha}$$

	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

Proton flux contains important information on CR propagation

Proton flux breaks the D_0/Z_h degeneracy (in 2D diffusion model)
Relative change with Z_h for fixed D_0/Z_h





Analytic solution in 2D two-zone model

$$\psi_i(0) = \frac{2hq_i}{V_c + 2h/\tau_f + D_{xx} S_i \coth(S_i Z_h/2)},$$

$$S_i^2 = \frac{V_c^2}{D_{xx}^2} + \frac{4}{D_{xx}\tau_r} + \frac{4\zeta_i^2}{R_h^2}.$$

Breaking term

$$D_{xx} S_i \coth(S_i Z_h/2) \approx \left(\frac{D_{xx}}{Z_h}\right)\left(2 + \frac{V_c^2 Z_h^2}{6D_{xx}^2} + \frac{2Z_h^2}{3D_{xx}\tau_r} + \boxed{\frac{2Z_h^2}{3R_h^2}\zeta_i^2}\right).$$

D0/Zh degeneracy is broken in stable CR fluxes

- For proton ~5%, data err ~3%
- For B/C ~2%, data error ~4%

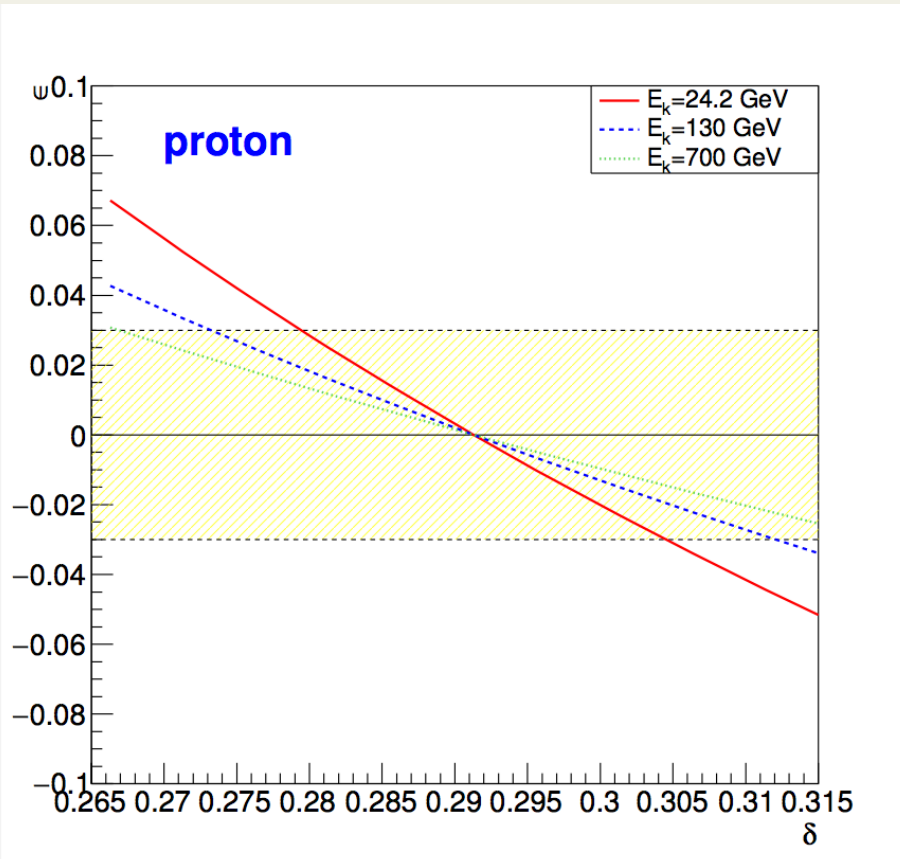
Thus

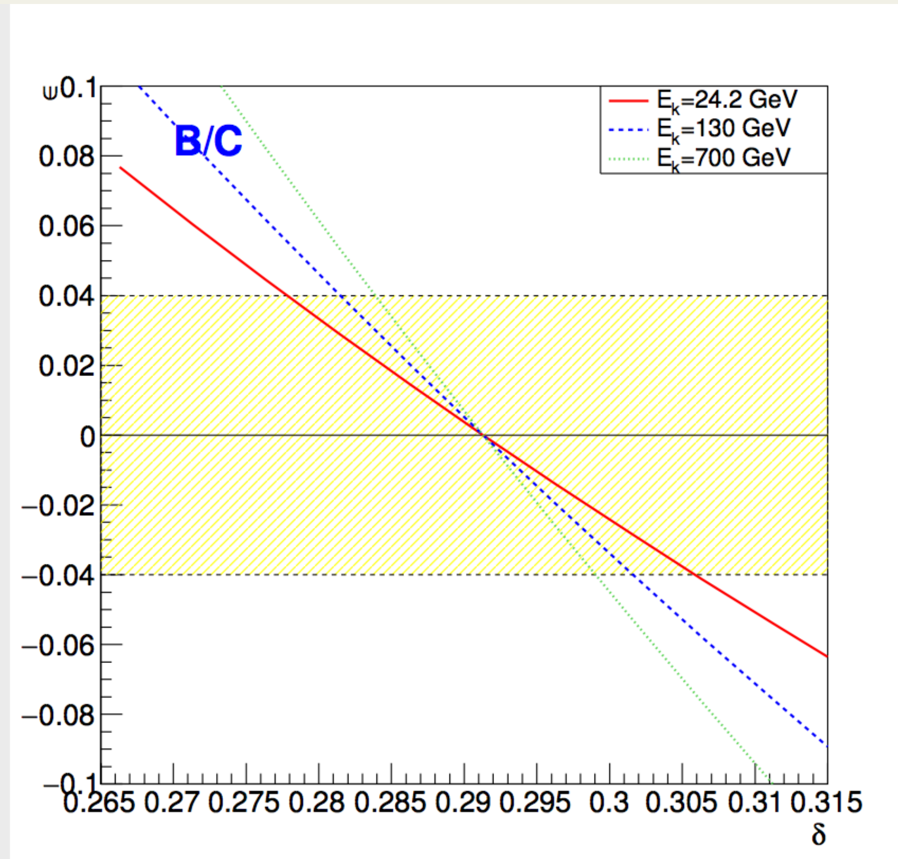
- B/C determines D0/Zh
- Proton flux determines Zh

H.B.Jin, Y.L.Wu, YFZ, arXiv:1410.0171,JCAP

Proton flux also breaks the γ+δ degeneracy

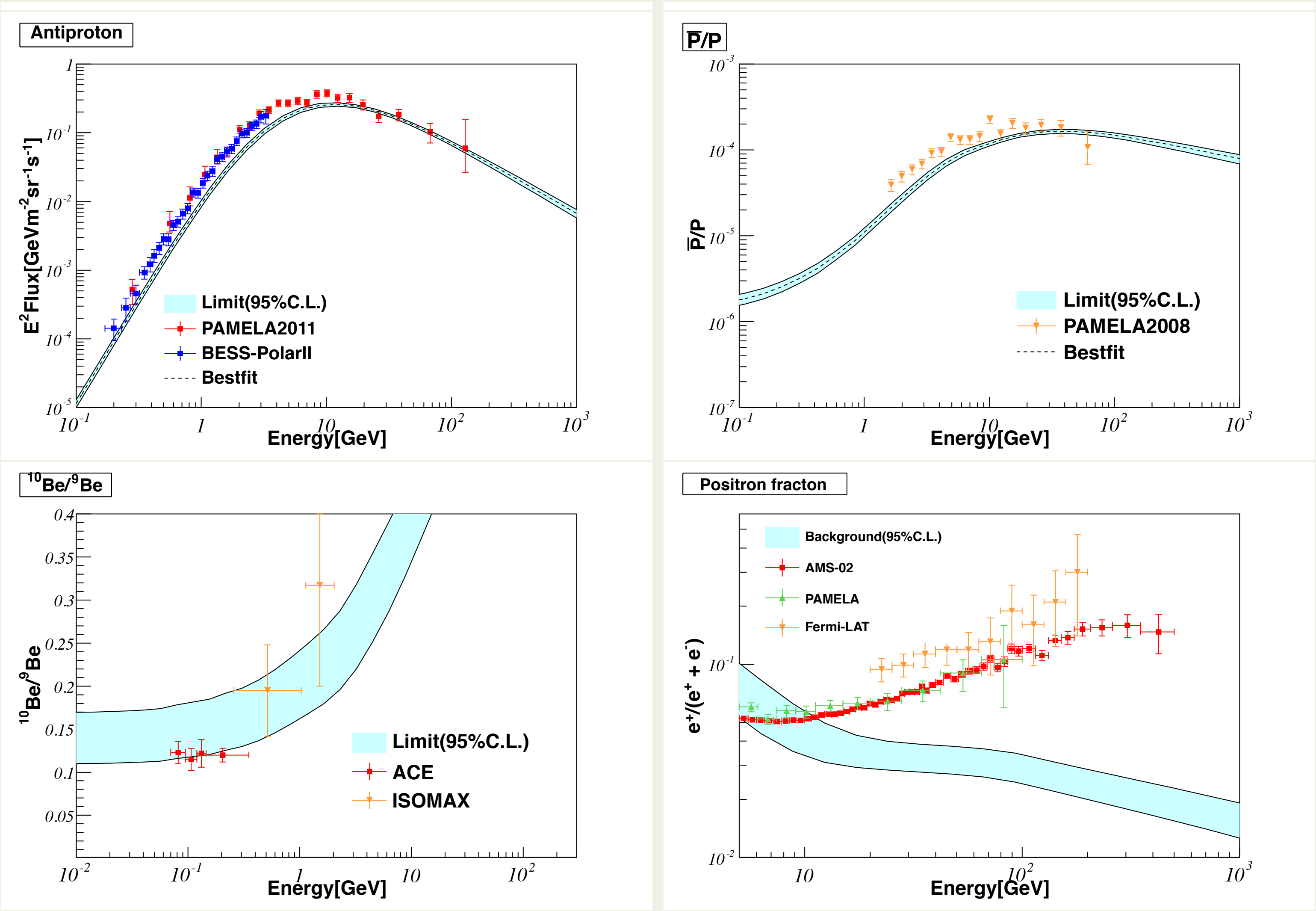
Relative changes with δ for fixed γ+δ = 2.7





H.B.Jin, Y.L.Wu, YFZ, arXiv:1410.0171,JCAP

Predicted backgrounds



$e^+/(e^+ + e^-)$ uncertainty within a factor of ~2

$^{10}Be/^{9}Be$ as prediction, rather than input