# Dark matter in the Galaxy

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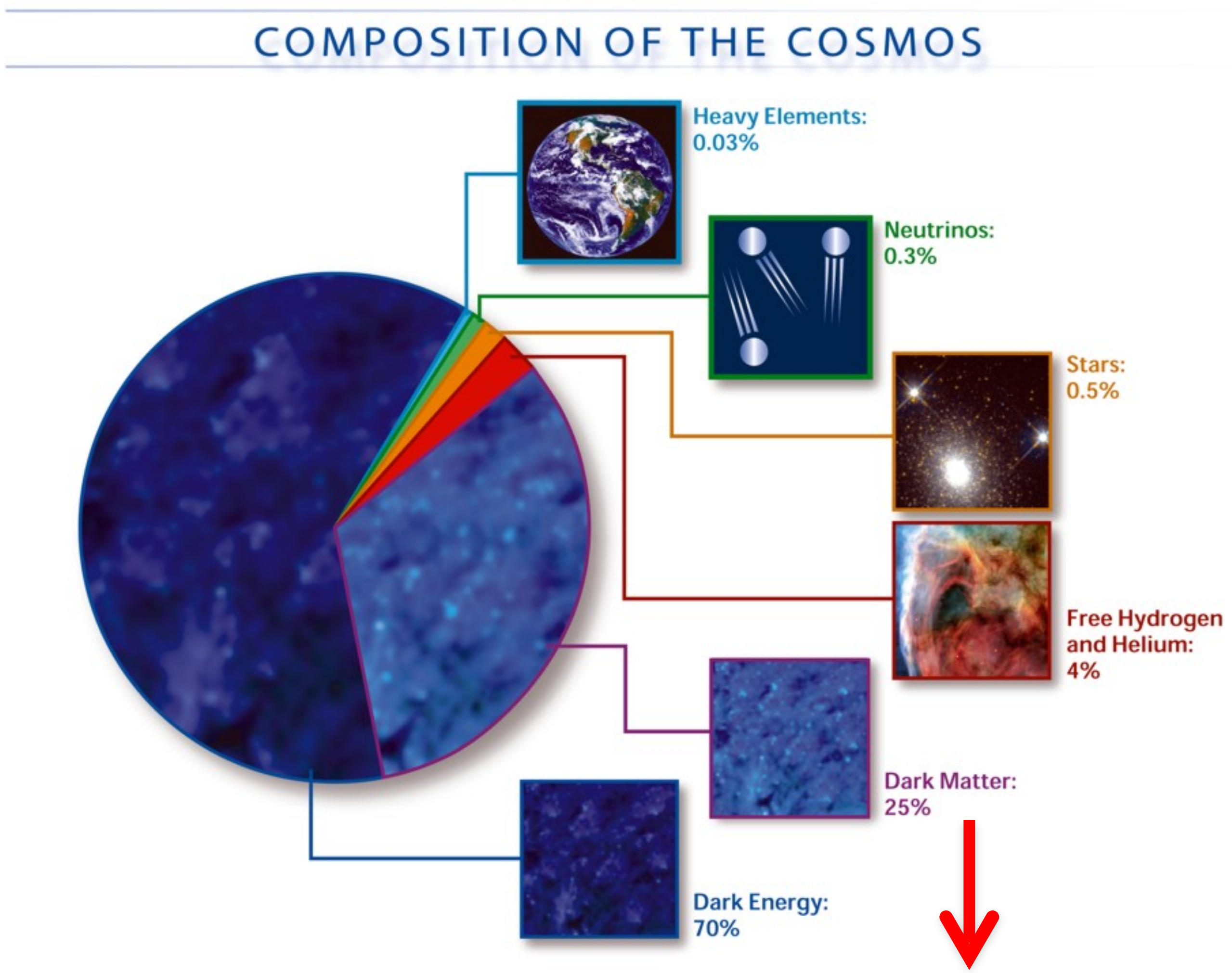
Queen Mary London, Feb 28, 2019

# The composition of the Universe




One possible hypothesis: the solution is a particle, a WIMP (weakly interacting massive particle)

# SIGNALS from RELIC WIMPs

**<u>Direct searches</u> (deeply underground experiments) :**

elastic scattering of a WIMP off detector nuclei
Measure of the recoil energy
Annual modulation and directionality of the measured rate

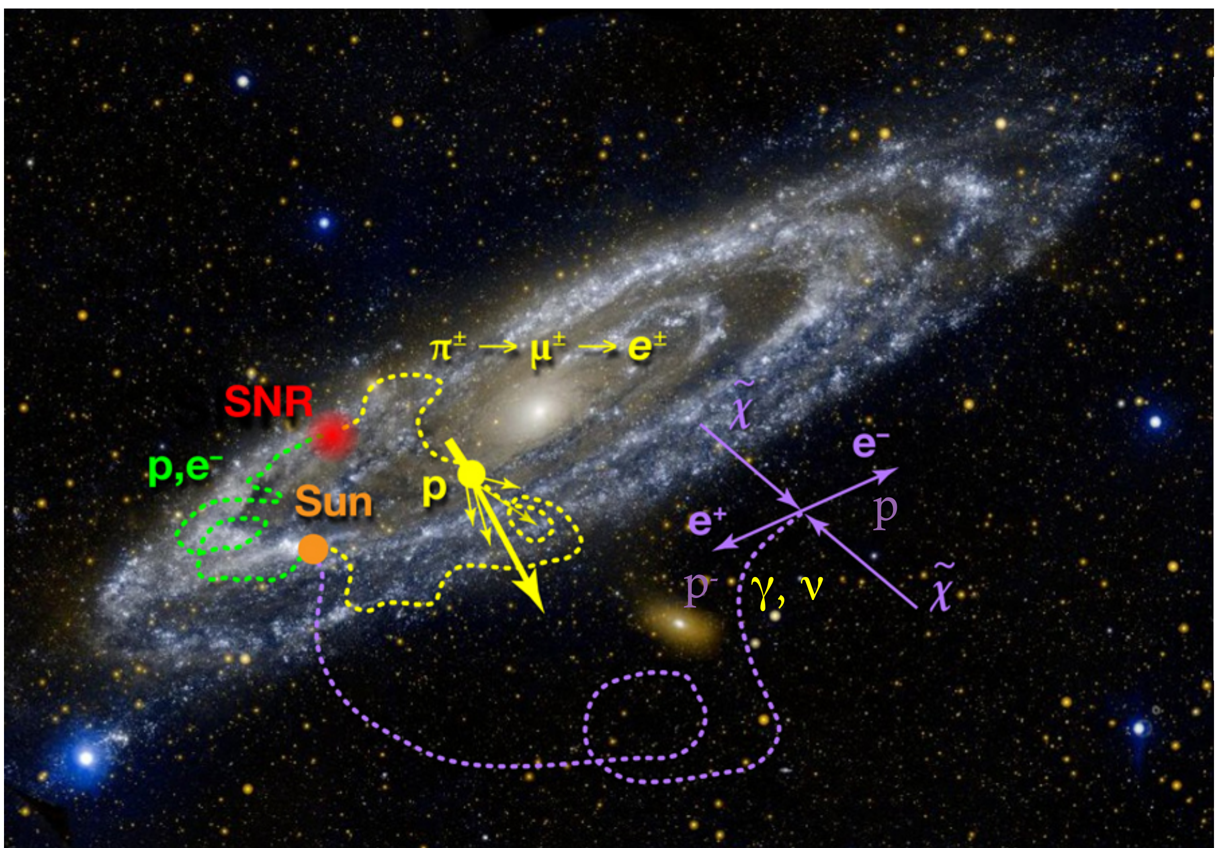
**<u>Indirect searches</u>: in Cosmic Rays (mostly space based experiments)**

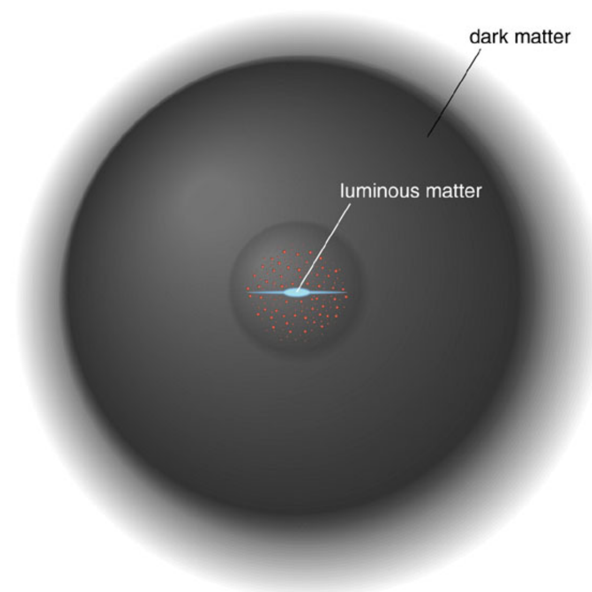
signals due to annihilation of accumulated $\chi\chi$ in the of Sun/Earth
(neutrinos)
signals due to $\chi\chi$ annihilation in the galactic halo
(antimatter, gamma-rays)

New particles are searched at colliders but we cannot say anything about being the solution to the DM in the Universe!

# Indirect DARK MATTER searches

Dark matter can annihilate in pairs with standard model final states.
Low background expected for cosmic **ANTIMATTER**, and for **NEUTRINOS** and **GAMMA RAYS** coming from dense DM sites



# Antimatter or γ-rays sources from DARK MATTER

Annihilation $$\mathcal{Q}_{\rm ann}(\vec{x},E) = \epsilon\left(\frac{\rho(\vec{x})}{m_{DM}}\right)^2 \sum_f \langle\sigma v\rangle_f \frac{dN^f_{e^\pm}}{dE}$$

Decay $$\mathcal{Q}_{\rm dec}(\vec{x},E) = \left(\frac{\rho(\vec{x})}{m_{DM}}\right) \sum_f \Gamma_f \frac{dN^f_{e^\pm}}{dE}$$

- $\rho(\vec{x})$ DM density in the halo of the MW
- $m_{DM}$ DM mass
- $\langle\sigma v\rangle_f$ thermally averaged annihilation cross section in SM channel f
- $\Gamma_f$ DM decay time
- e+, e- energy spectrum generated in a single annihilation or decay event

# Primary and secondary CRs in the Galaxy

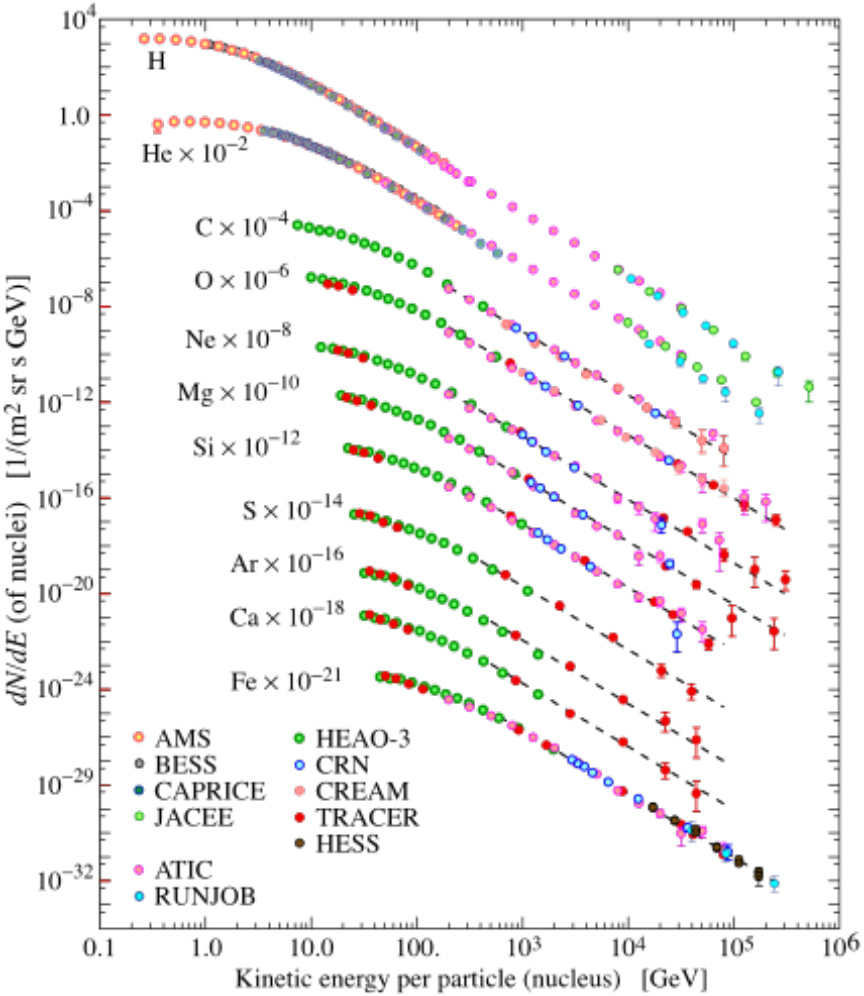
Primaries: produced in the sources (SNR and Pulsars)
H, He, CNO, Fe; e−, e+; possibly $e^+$, $p^-$, $d^-$ from Dark Matter annihilation

Secondaries: produced by spallation of primary CRs (p, He,C, O, Fe) on the interstellar medium (ISM): Li, Be, B, sub-Fe, [...], (radioactive) isotopes ; $e^+$, $p^-$, $d^-$

At first order, we understand fluxes at Earth as shaped by few, simple, isotropic effects:

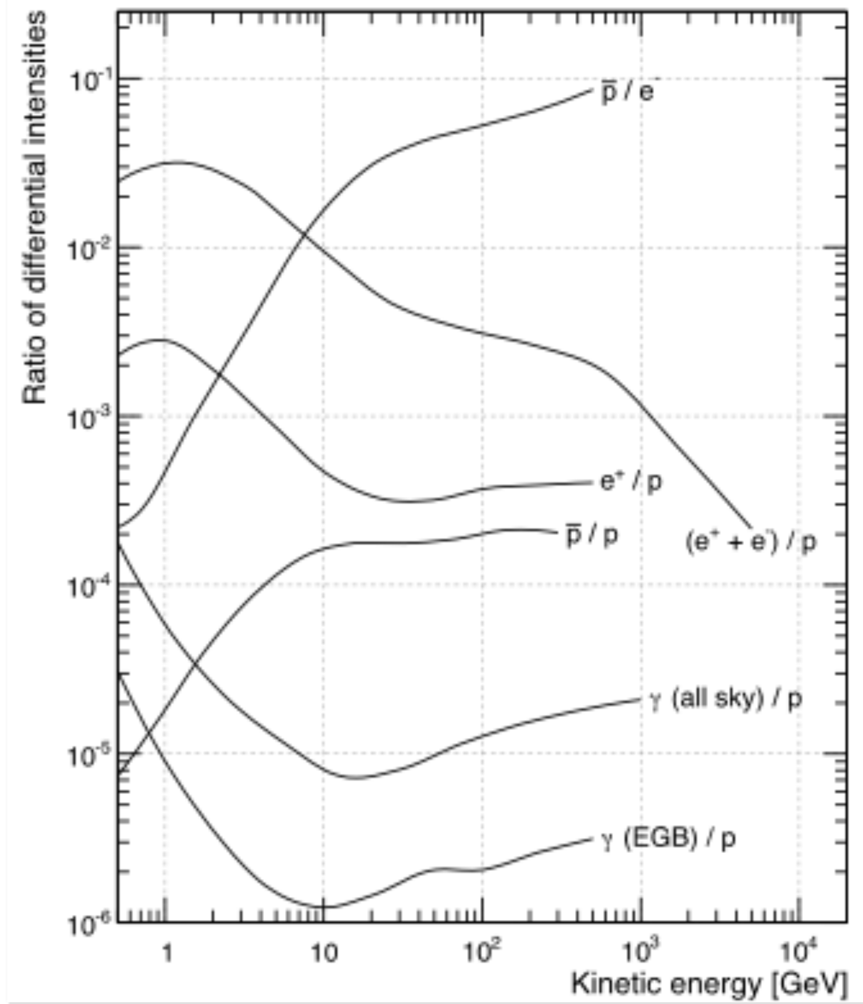
- acceleration in shocked stellar environments (SNR, PWN)
- particle interactions between CRs and ISM
- diffusion of the galactic magnetic fields
- particle energy losses

# Charged cosmic rays intensity




PDG, Fig. created by
P. Boyler and D. Muller

Rare CRs and γ-rays




L Baldini, 1407.7631

**Primaries** = present in sources:

Nuclei: H, He, CNO, Fe; e-, (e+) in SNR (& pulsars)

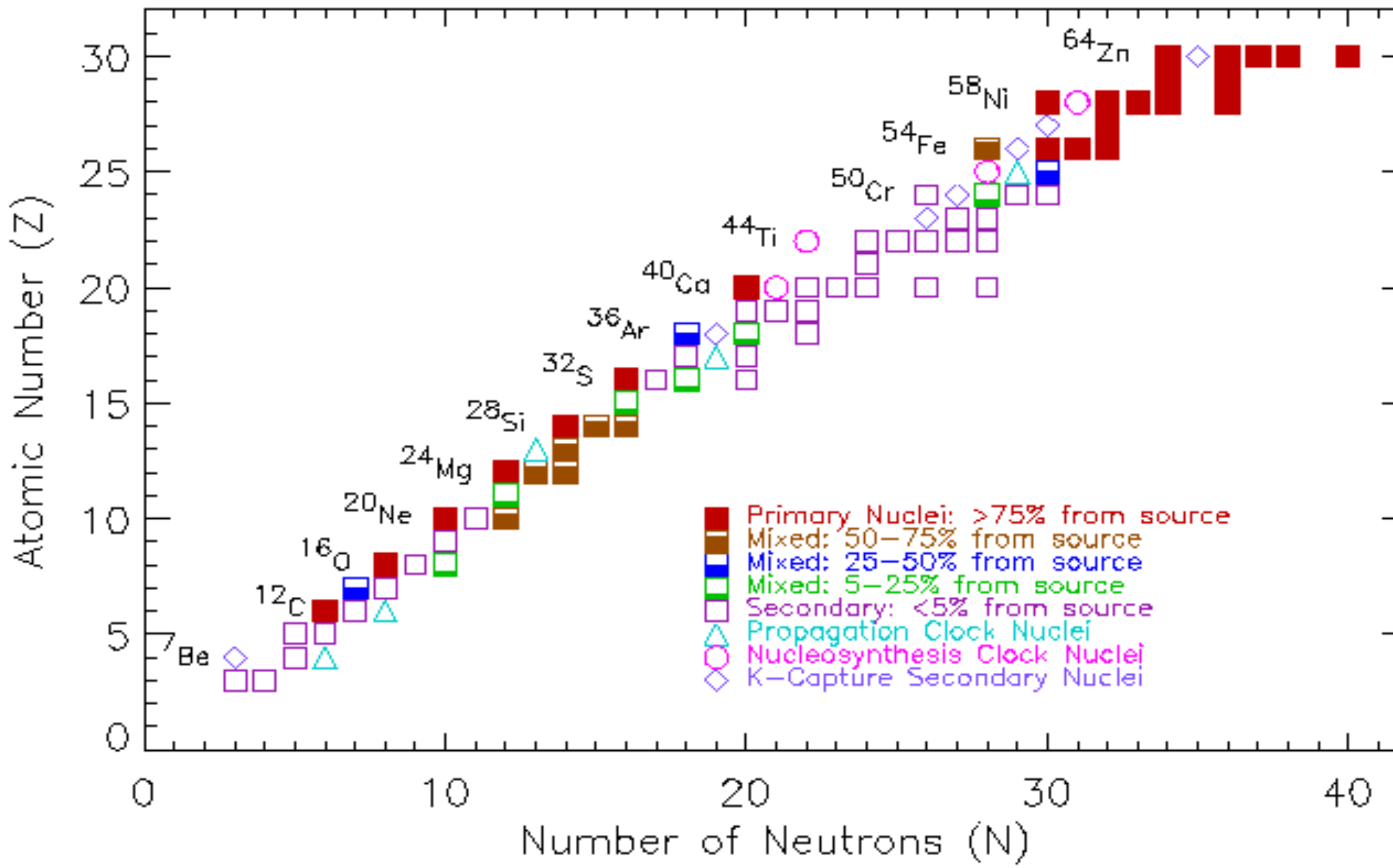
$e^+$, $p^+$, $d^+$ from Dark Matter annihilation

**Secondaries** = NOT present in sources, thus produced by

**spallation** of primary CRs (p, He, C, O, Fe) on ISM

Nuclei: LiBeB, sub-Fe, … ;

$e^+$, $p^+$, $d^+$; … from inelastic scatterings



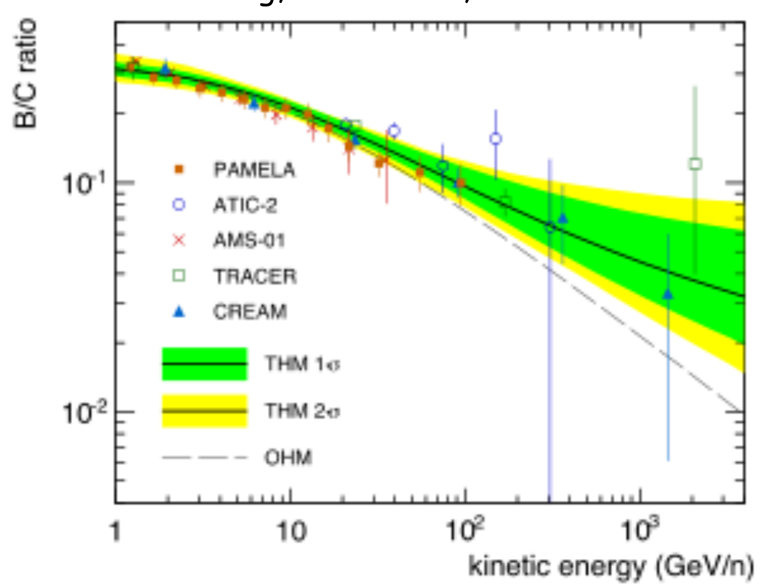
# The SOURCES of CRs cannot be tested by CRs

| SPECIES | SOURCES | TEST |
| --- | --- | --- |
| Primary nuclei, e- | Supernova remnants | EM: radio, X-rays, gamma-rays + simulations |
| Primary e- & e+ | Pulsar Wind Nebulae | EM (more difficult) + simulations |
| Secondary nuclei & leptons | CRs on the ISM | Colliders |
| Antimatter, Gamma rays | Dark Matter | Colliders (hopefully) |

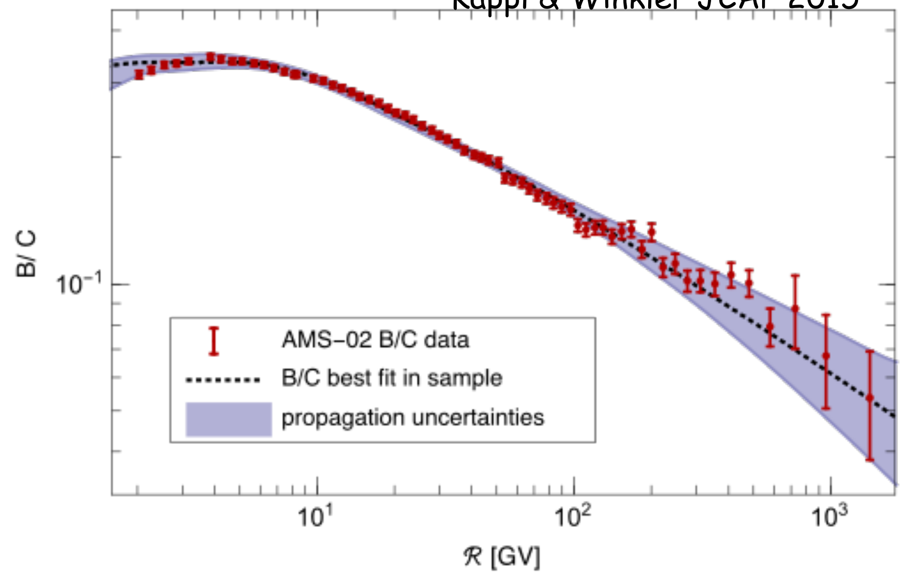
# Boron-to-Carbon: a "standard candle" for fixing GALACTIC PROPAGATION

- Li, Be, B are produced by fragmentation of heavier nuclei (mostly C, N, O) on H and He: production cross sections
- B/C is very sensitive to **propagation effects**, kind of standard candle

Feng, Tomassetti, Oliva PRD 2016




Kappl & Winkler JCAP 2015




**B/C (AMS, PRL 117, 2016) does not show features at high energies**

At first order, we understand B/C within Fermi acceleration and isotropic diffusion. This may be no longer sufficient when dealing with data at higher energies, gamma-ray data, other species

# The case for

# antiprotons

# Cosmic antiprotons

Antiprotons are produced in the Galaxy by **fragmentation**
of proton and He (and marginally heavier nuclei)
on the interstellar medium (ISM)

These secondary antiprotons would be the background to
an exotic component due to

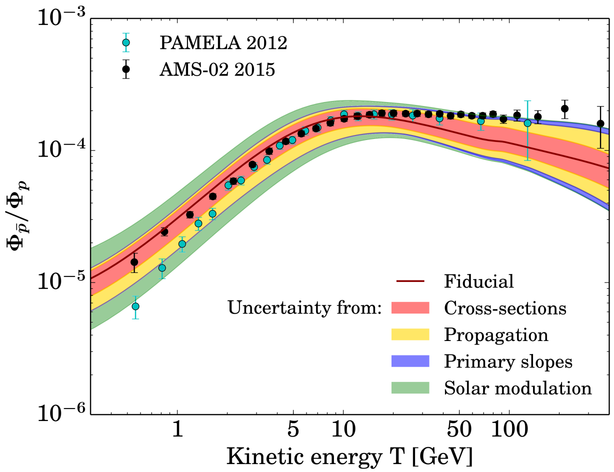
**dark matter annihilation**

in the galactic halo (**primary antiprotons**).

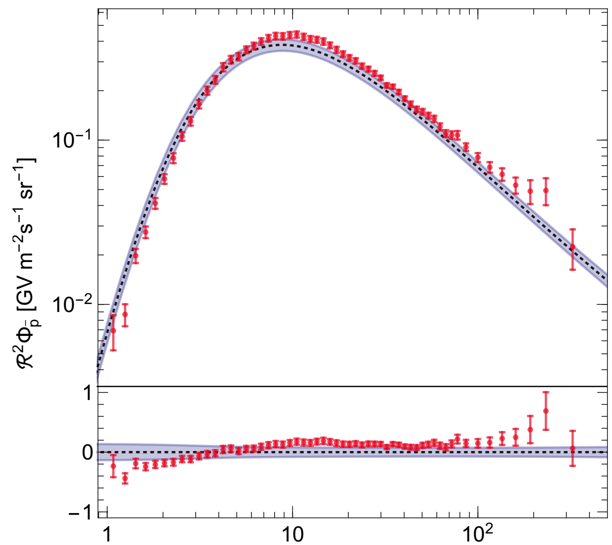
N. B. Thousands of cosmic antiprotons have already been
detected by balloon-borne (Bess, Caprice,….)
or satellite experiments (Pamela), and AMS-01,
and 290000 (out of 54 billion events) from AMS-02 on the ISS

# Antiproton flux at high energy: do secondaries fit all?

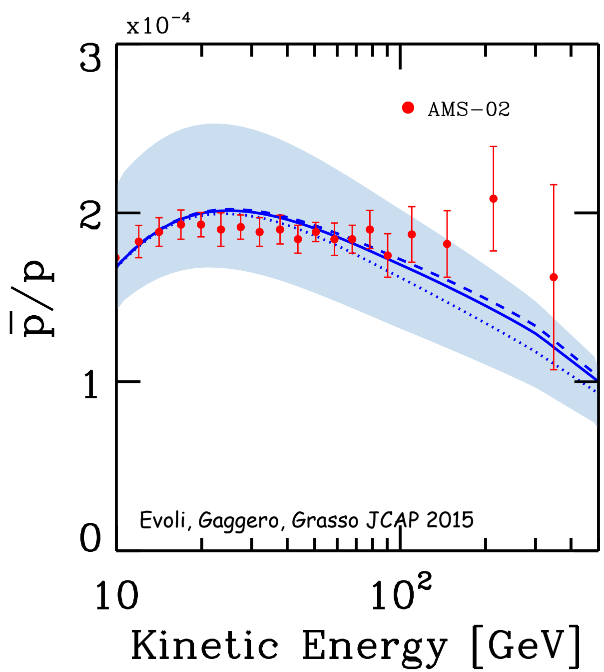
Giesen + JCAP 2015




Reinert & Winkler JCAP 2018




Propagation models fitted on AMS-02 B/C data.




Secondary antiprotons from

**(p, He)$_{CR}$ + (H, He)$_{ISM}$**

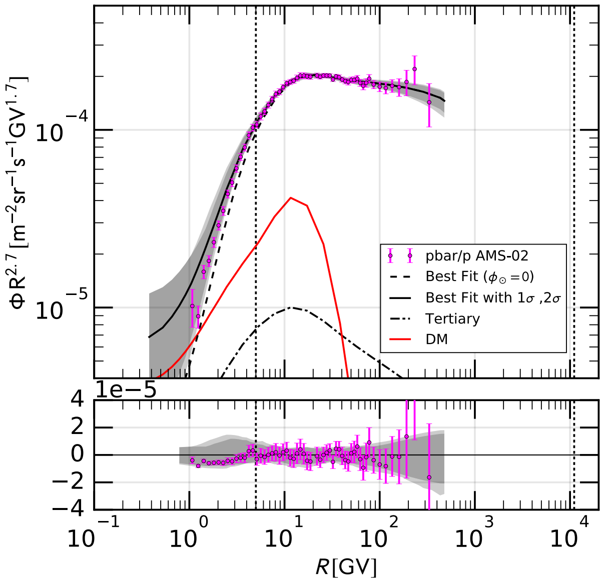
can explain data naturally, mainly because

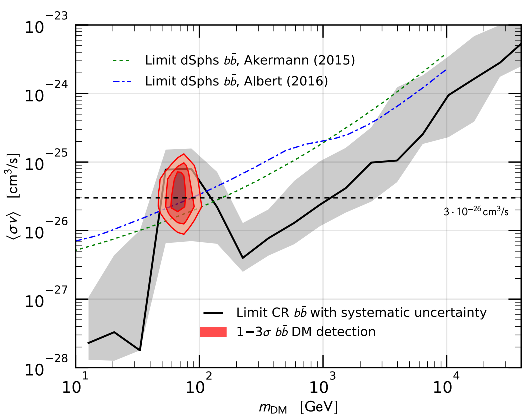
of the small diffusion coefficient slope indicated by B/C.

**Greatest uncertainty set by nuclear cross sections.**

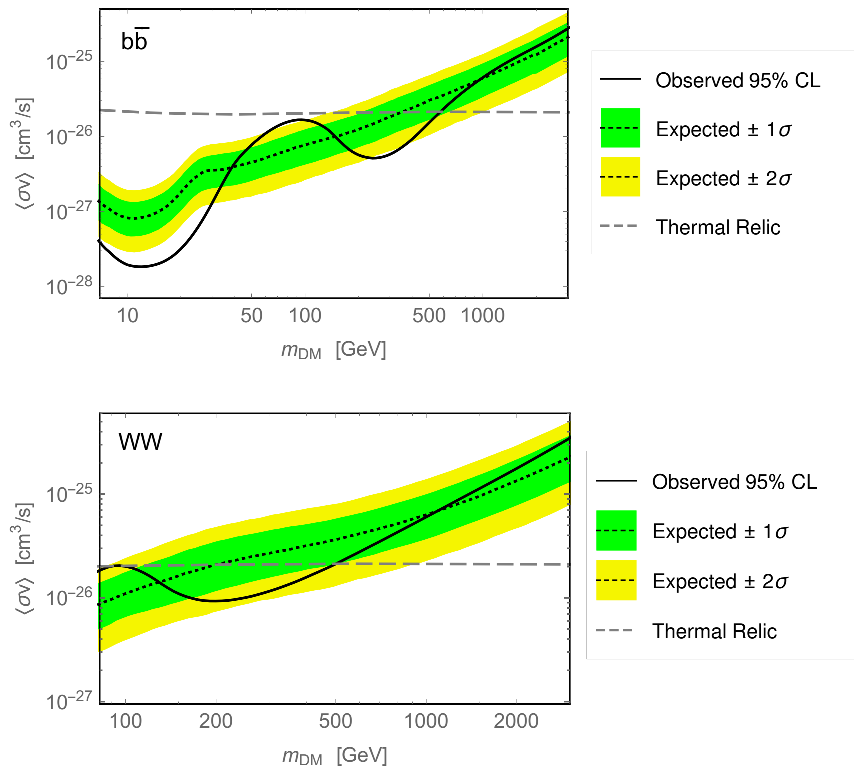
# Possible contribution from dark matter

Cuoco, Korsmeier, Kraemer PRL 2017




Reinert & Winkler JCAP2018




Antiproton data are so precise that permit
to set strong upper bounds on
the dark matter annihilation cross section,
or to improve the fit w.r.t. to the secondaries
alone adding a tine DM contribution

# **Production** cross sections in the galactic cosmic ray modeling

H, He, C, O, Fe,... are present in the supernova remnant surroundings, and directly accelerated into the interstellar medium (ISM)

All the other nuclei (Li, Be, B, p-, and e+, gamma, ...) are produced by spallation of heavier nuclei with the atoms (H, He) of the ISM

We need all the cross sections $\sigma^{kj}$ - from Nichel down to proton - for the production of the j-particle from the heavier k-nucleus scattering off the H and He of the ISM

**Remarkable for DARK MATTER signals :**
**antiproton, antideuteron, positron and gamma rays.**

# The role of high energy particle physics in CR physics

$$N^j(r,z) = \exp\left(\frac{V_c z}{2K}\right) \sum_{i=0}^{\infty} \frac{\bar{Q}_i^j}{A_i^j} \frac{\sinh\left[\frac{S_i^j (L-z)}{2}\right]}{\sinh\left[\frac{S_i^j L}{2}\right]} J_0\left(\zeta_i \frac{r}{R}\right)$$

$$\bar{Q}_i^j = q_0^j Q(E) \hat{q}_i + \sum_k^{m_k > m_j} \tilde{\Gamma}^{kj} N_i^k(0)$$

$$S_i^j = \left(\frac{V_c^2}{K^2} + 4\frac{\zeta_i^2}{R^2} + 4\frac{\Gamma_{rad}^{N^j}}{K}\right)^{1/2}$$

$$A_i^j = 2h\tilde{\Gamma}^{tot}_{N^j} + V_c + K S_i^j \coth\left(\frac{S_i^j L}{2}\right)$$

$\Gamma^{kj} = n_{ISM}\, \boldsymbol{\sigma}^{kj}\, v$

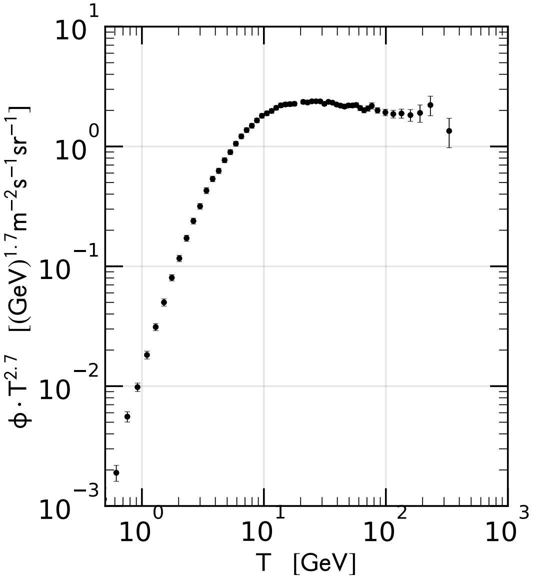
**Production cross section**

$\Gamma^{kj} = n_{ISM}\, \boldsymbol{\sigma}^{tot}\, v$

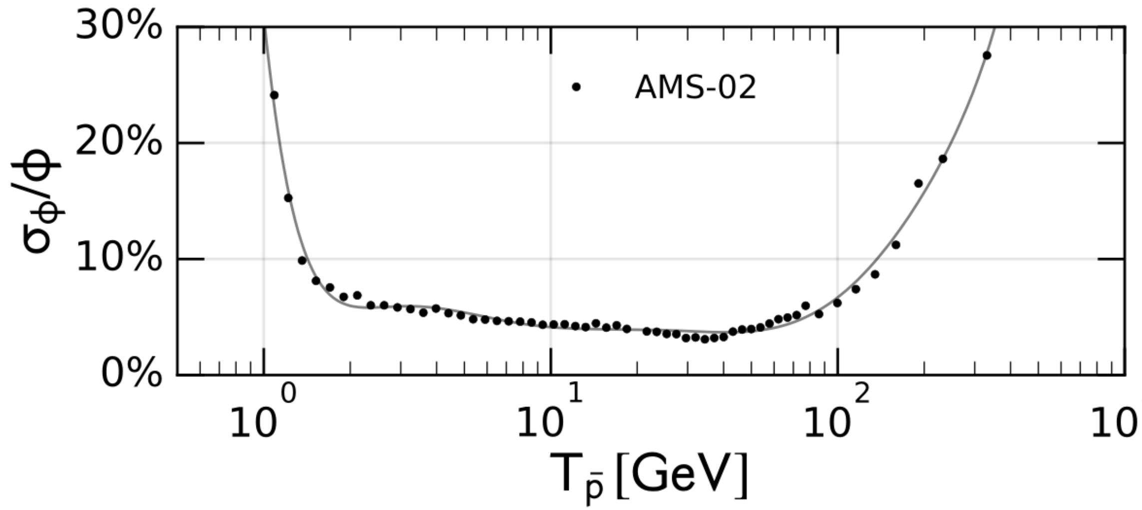
Destruction cross section

# Requirement on the phase space for the pp→pX cross section

FD, Korsmeier, Di Mauro PRD 2017




M. Aguilar et al., 2016. DOI: 10.1103/PhysRevLett.117.091103

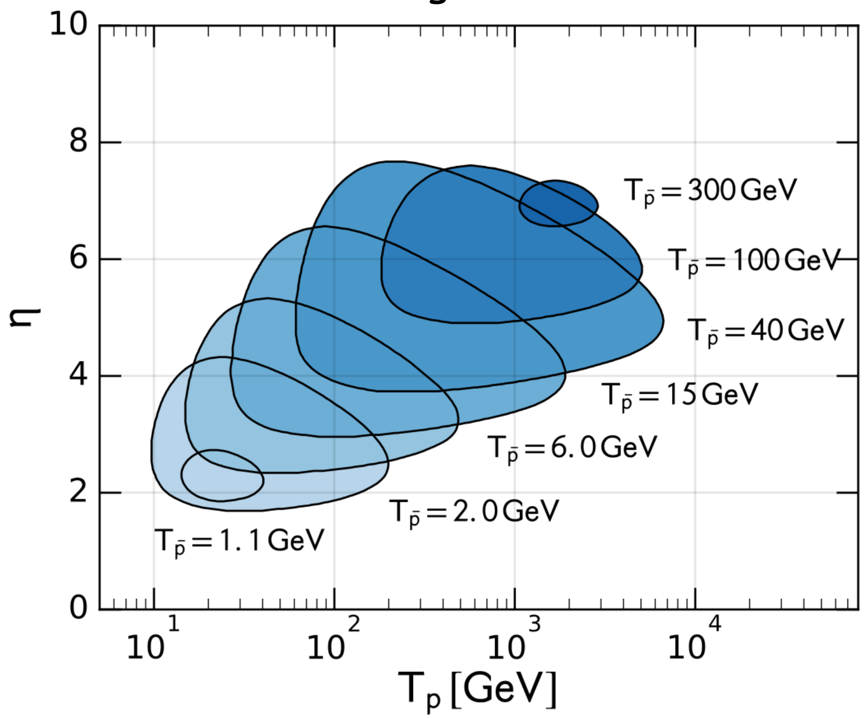



Which level of accuracy on cross sections do we need in order to match (not exceed) the accuracy in CR data?

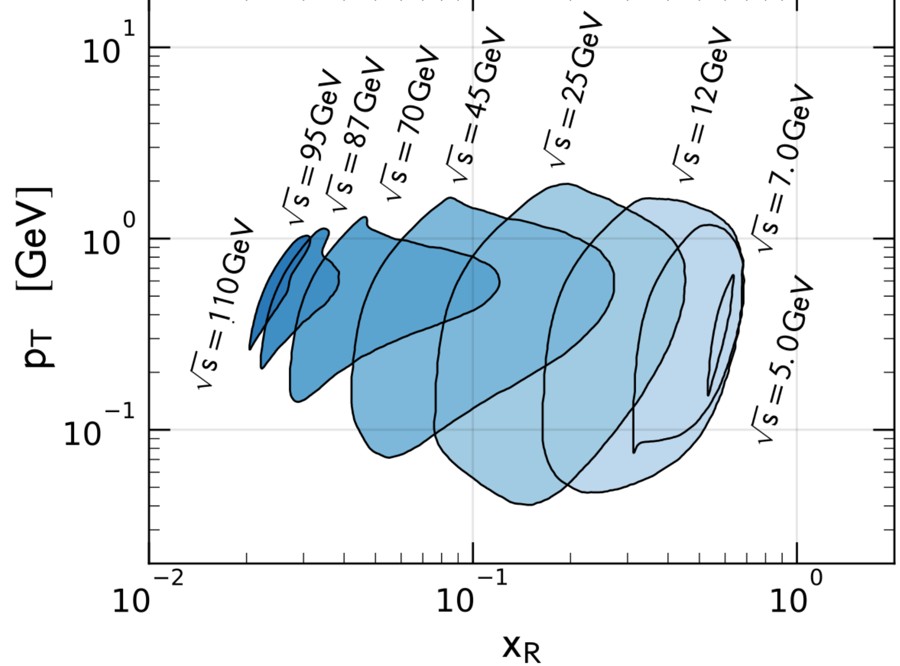
Bias towards AMS-02 data

# Parameter space to be covered

Fixed target




Lab frame



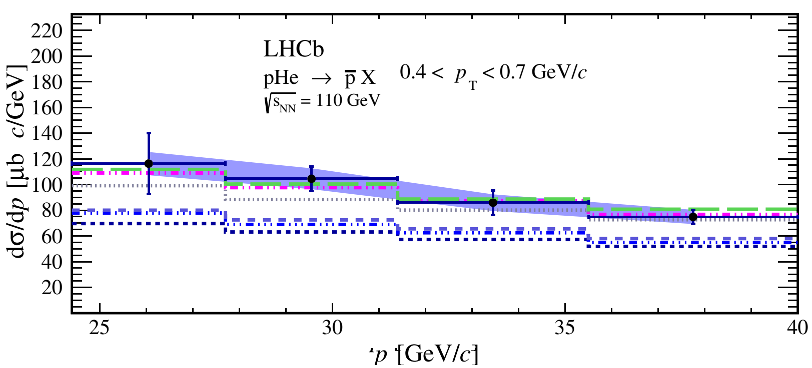

AMS02 accuracy is reached if pp→pbar cross section is measured with 3% accuracy inside the regions, 30% outside.

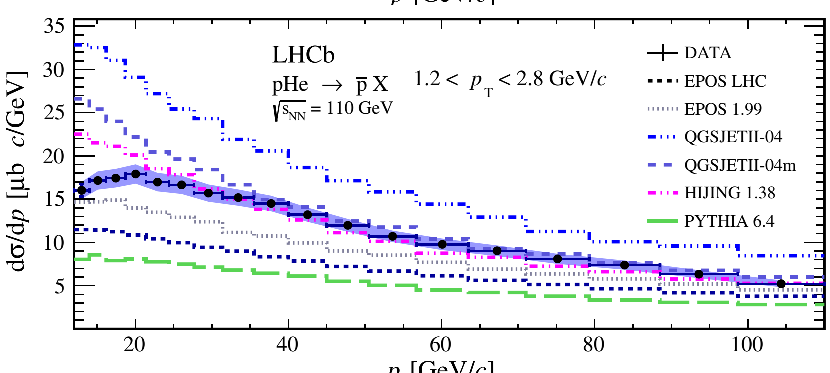
PHYSICAL REVIEW LETTERS **121,** 222001 (2018)

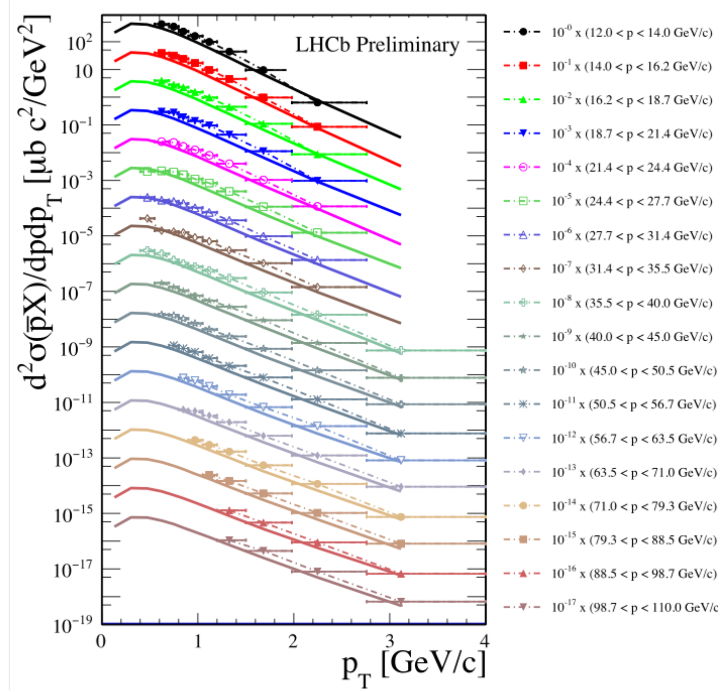
# Measurement of Antiproton Production in $p$-He Collisions at $\sqrt{s_{NN}} = 110$ GeV

R. Aaij *et al.**
(LHCb Collaboration)

The cross section for prompt antiproton production in collisions of protons with an energy of 6.5 TeV incident on helium nuclei at rest is measured with the LHCb experiment from a data set corresponding to an integrated luminosity of 0.5 $nb^{-1}$. The target is provided by injecting helium gas into the LHC beam line at the LHCb interaction point. The reported results, covering antiproton momenta between 12 and 110 GeV/$c$, represent the first direct determination of the antiproton production cross section in $p$-He collisions, and impact the interpretation of recent results on antiproton cosmic rays from space-borne experiments.



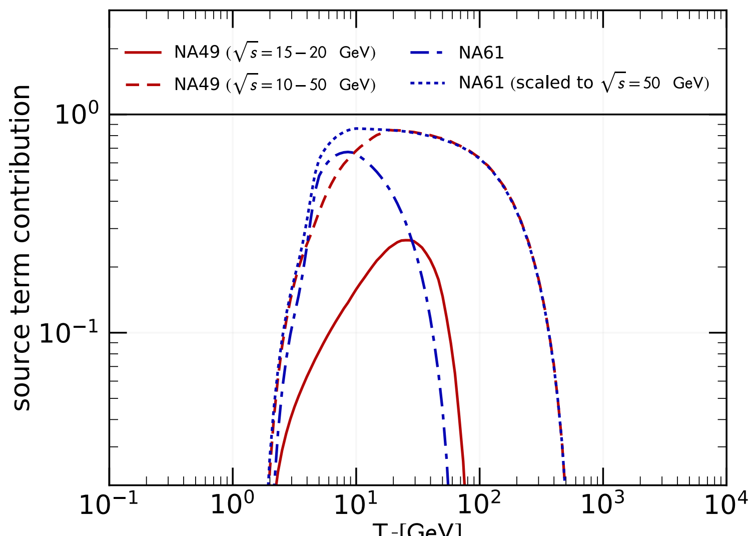



# New fixed-target data for the antiproton XS

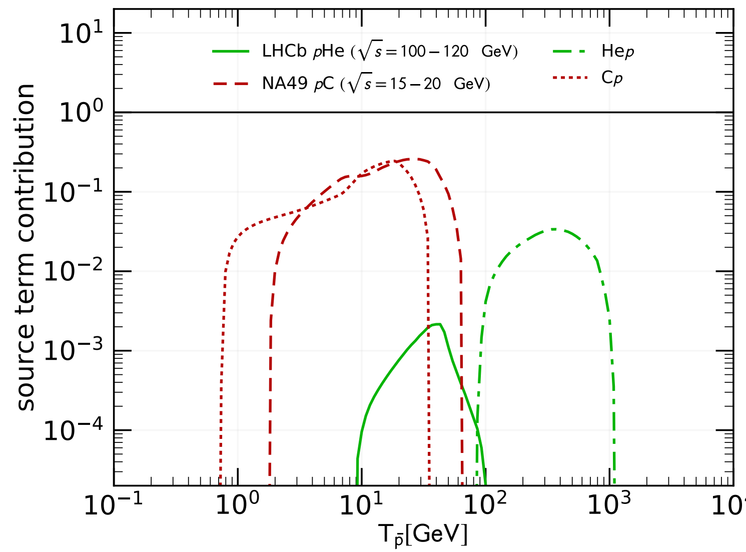
Korsmeier, FD, Di Mauro PRD 2018

| pp —> pbar+X | pHe —> pbar + X |
| --- | --- |
| **NA61** (Eur. Phys. J. C77 (2017)) | **LHCb** (PRL121 (2018)) |
| $\sqrt{s}$=7.7, 8.8, 12.3 and 17.3 GeV | $\sqrt{s}$ = 110 GeV |
| $T_p$ = 31, 40, 80, 158 GeV | $T_p$ = 6.5 TeV |

Fraction of the pp source term covered by the kinematical parameters space



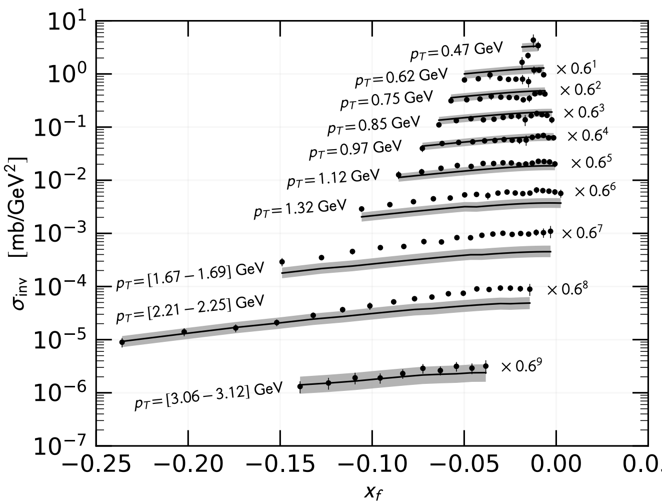

Fraction of the p-nucelus source term covered by the kinematical parameters space

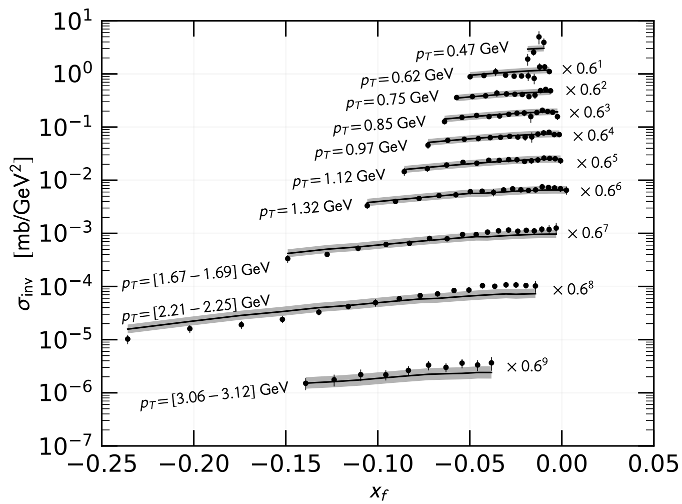


# Antiproton production cross section data analysis

Korsmeier, FD, Di Mauro, PRD 2018

1. Fit to NA61 pp —> pbar + X data
2. Calibration of pA XS on NA49 pC —> pbar + X data
3. Inclusion of LHC pHe —> pbar + X data

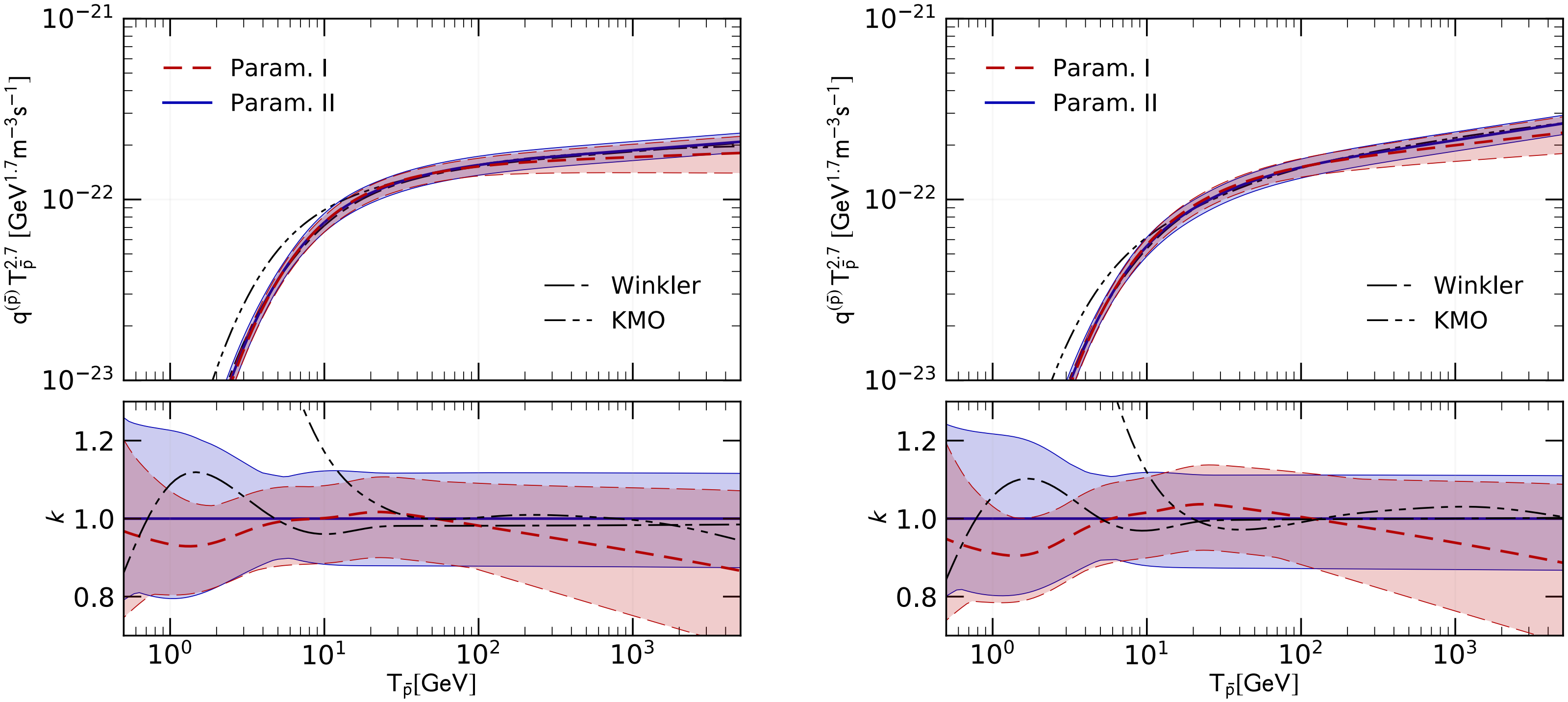



LHCb data agree better with one of the two pp parameterizations.
They select the high energy behavior of the Lorentz invariant cross section

# The antiproton source spectrum

Korsmeier, FD, Di Mauro PRD 2018




Param II is preferred by the fits.

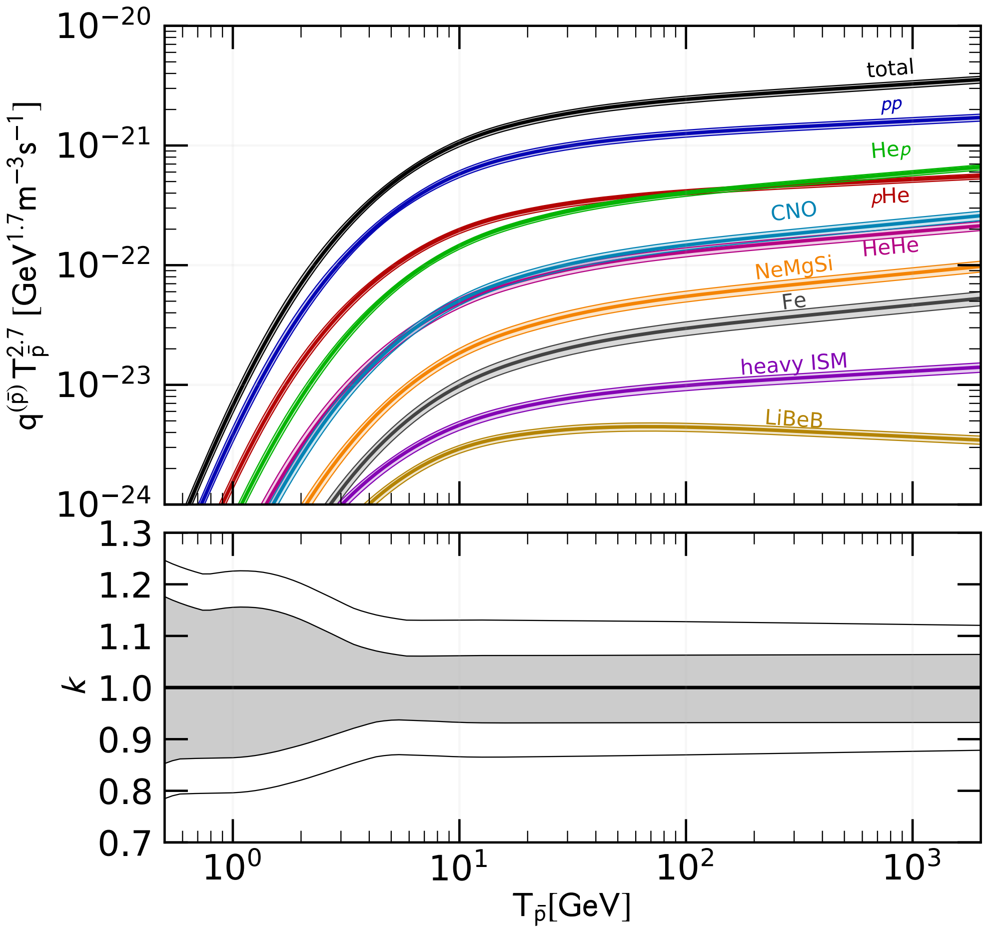
The effect of LHCb data is to select a h.e. trend of the pbar source term.

**A harder trend at high energies is preferred.**

Uncertainties still range about 20%, and increase at low energies.

# Effects on the total pbar production

Korsmeier, FD, Di Mauro, PRD 2018




The higher nuclei (CNO) in CRs

with uncertainties in the hyperon correction and isospin violation

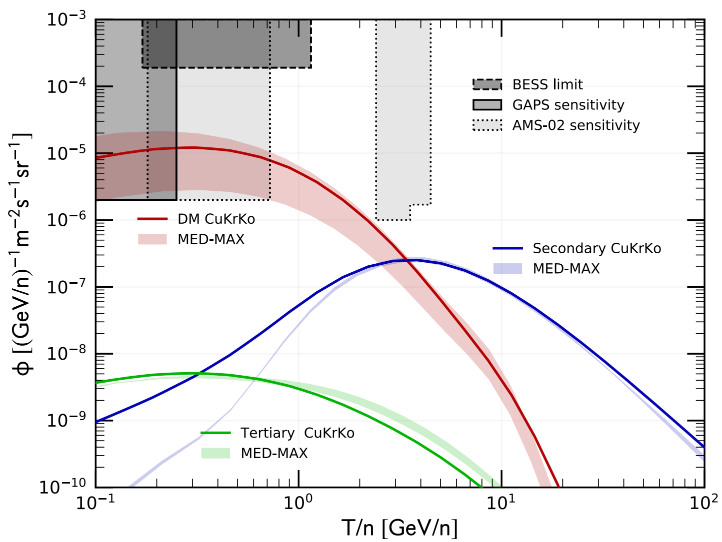
The antiproton source term - is affected by uncertainties of +- 10% from cross sections. Higher uncertainties at very low energies

# COSMIC ANTIDEUTERONS

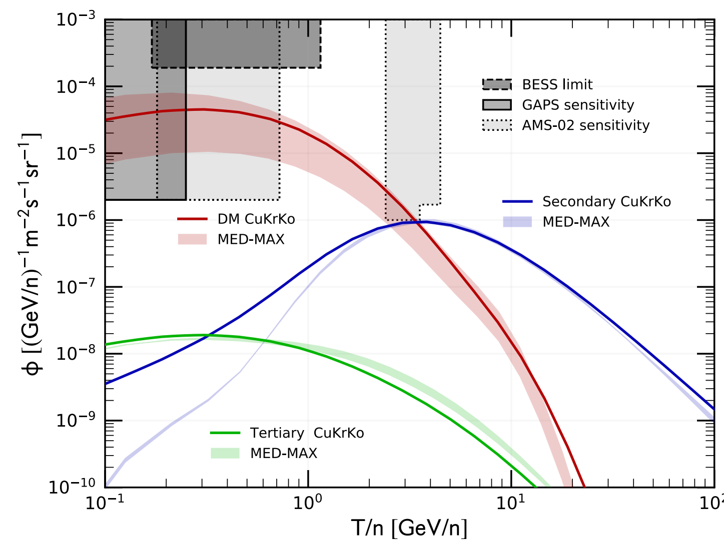
# Possible **antideuteron** verification of Dark Matter hint in antiprotons

FD, Fornengo, Korsmeier, PRD 2018

$P_{coal}$ = 124 (62) MeV




$P_{coal}$ = 248 (124) MeV

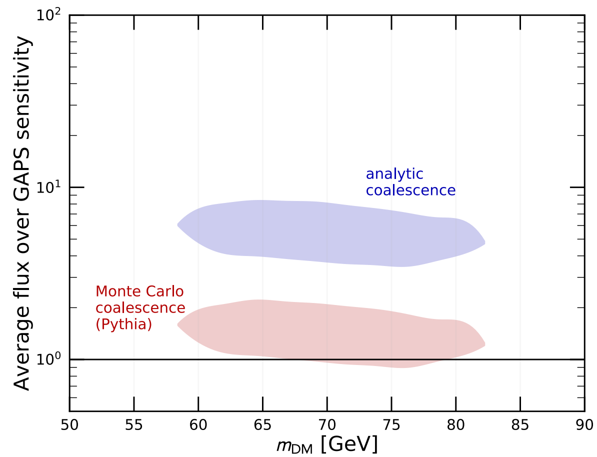



DM antiprotons possibly hidden in AMS data are potentially testable by AMS and GAPS

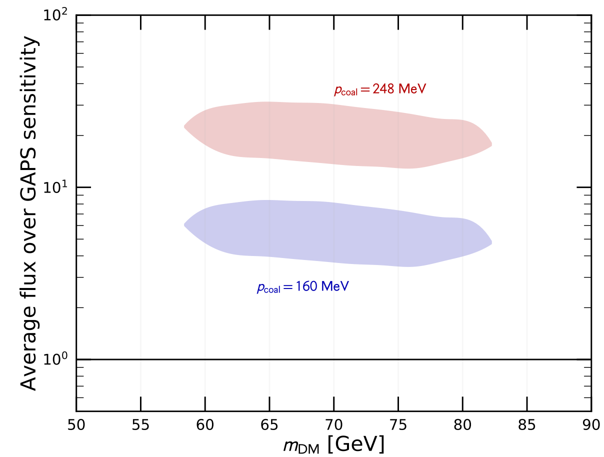
# Uncertainties on the detection predictions

FD, Fornengo, Korsmeier, 1711.08465 subm. PRD

**Coalescence Model:**
**a factor > 10**
(does not affect pbar flux)

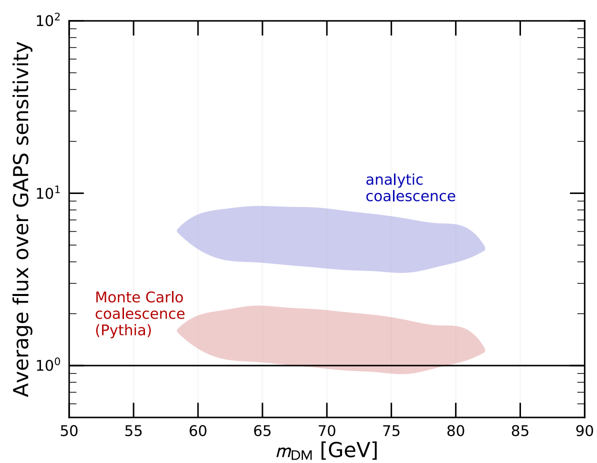


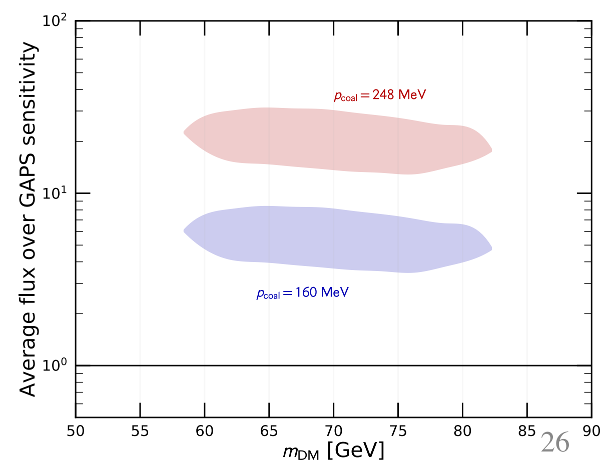

(a) Coalescence model



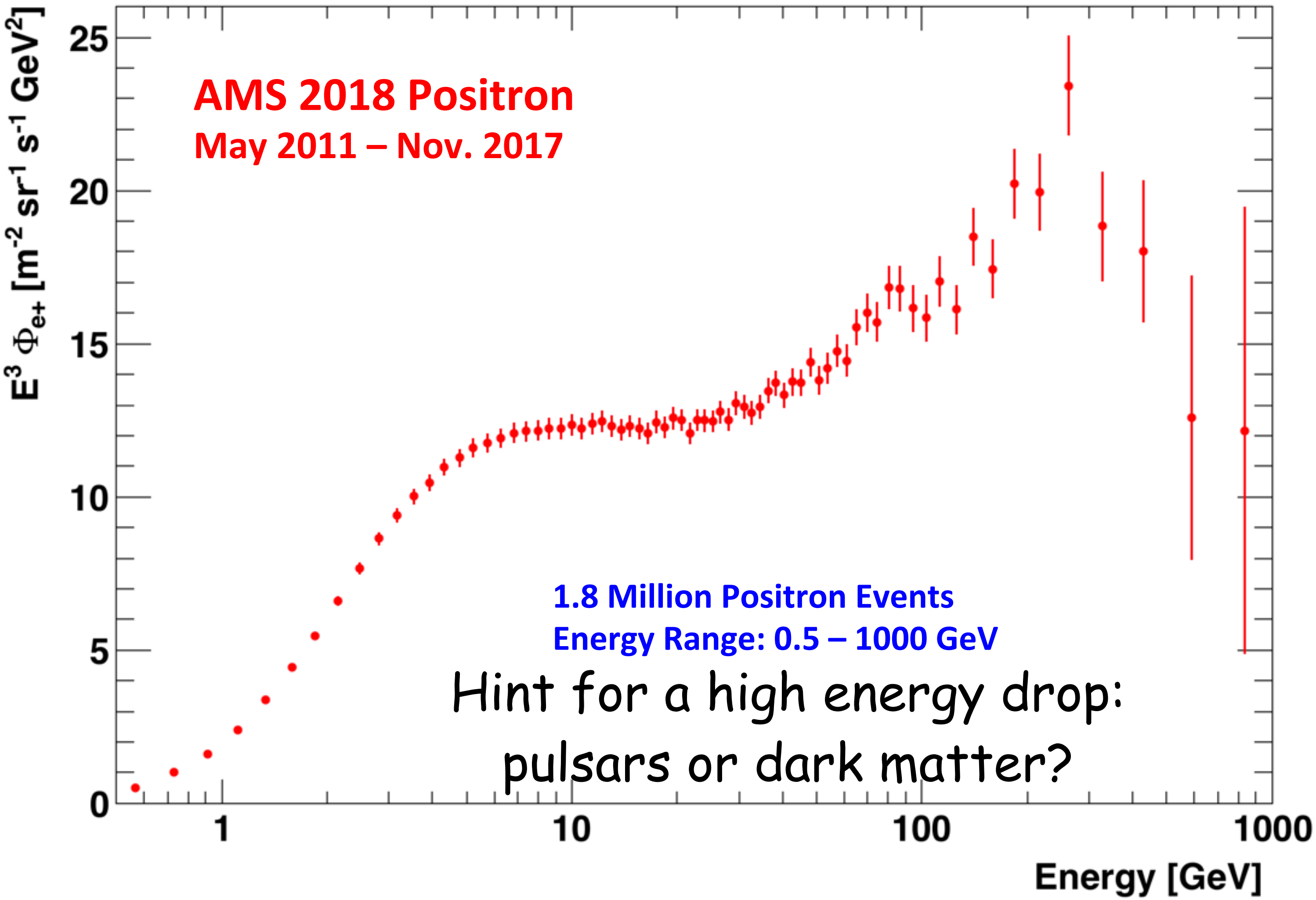

(b) Coalescence momentum

**Propagation models:**
**a factor > 10**
(affects pbar flux)



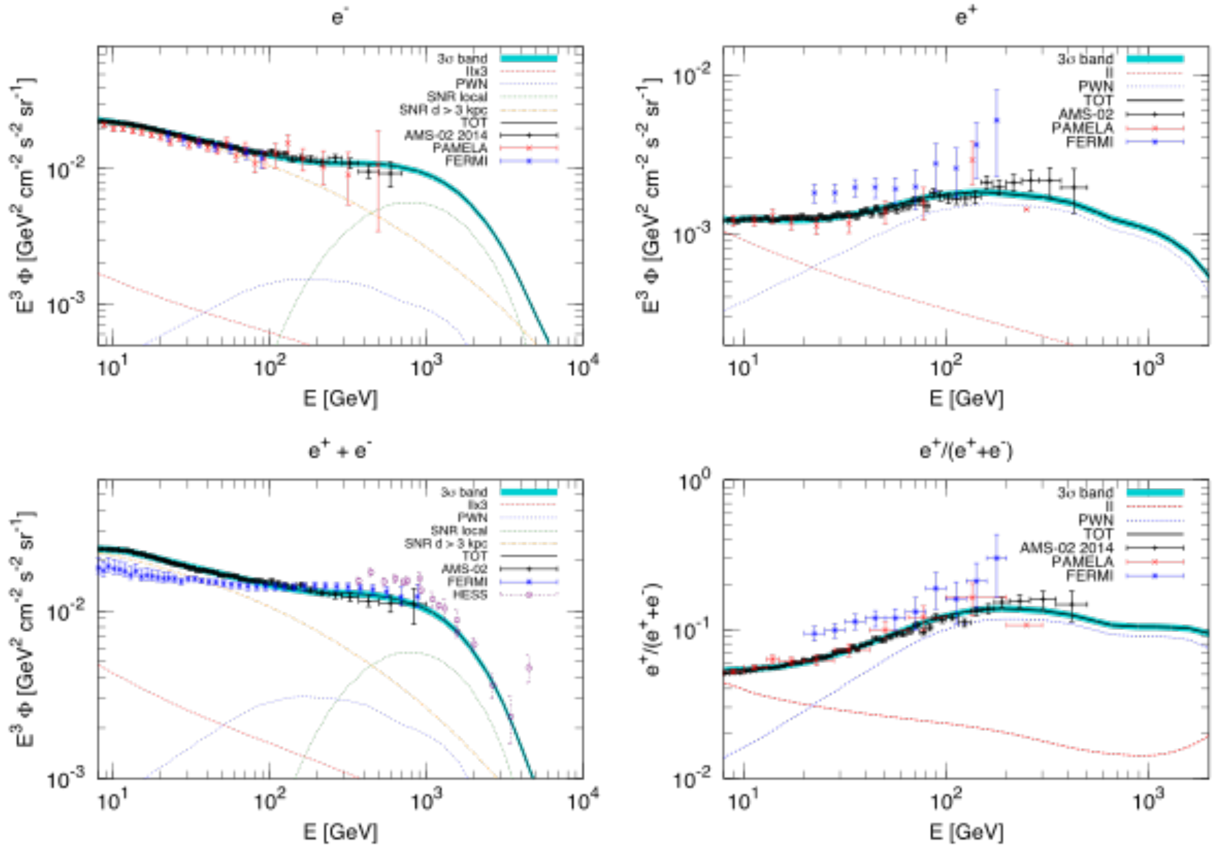
# The cosmic positrons




Hint for a high energy drop:
pulsars or dark matter?

# AMS lepton data: an astrophysical interpretation

Di Mauro, FD, Fornengo, Vittino JCAP 2016

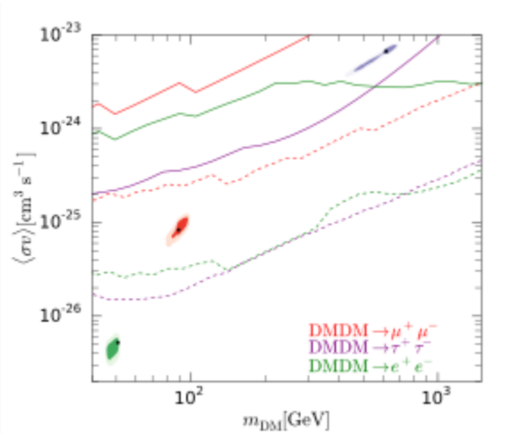


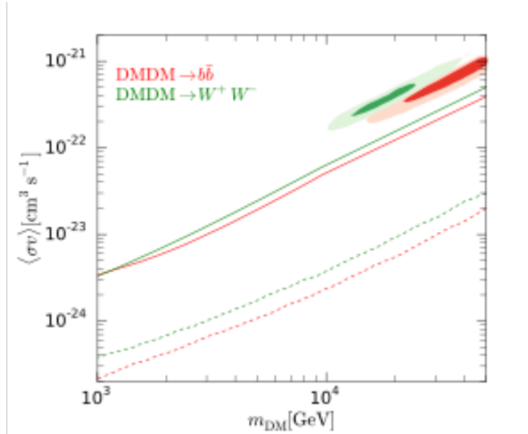

TH: Secondaries + supernovae + pulsars

EXP: AMS data precise on wide range

Small features can bring strong information

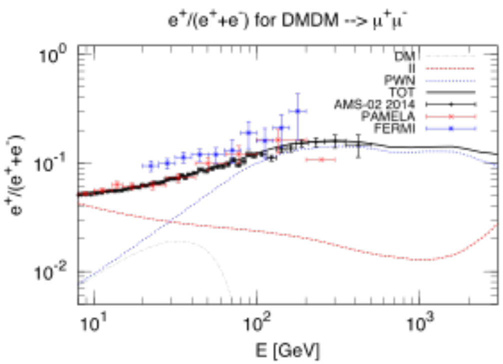
# Searching for a DM signal

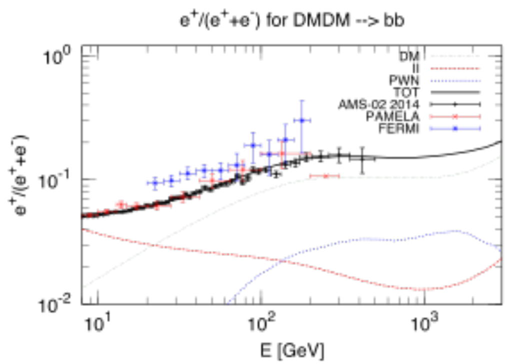



Upper bounds are from Fermi-LAT gamma ray data at latitudes > 20

(Di Mauro&FD PRD2015)




Positron fraction vs detected energy: DM component is added to secondary and PWN spectra

When also $m_{DM}$ is let free to vary, the fit with **DM improves** w.r.t the scenario with astrophysical contributions only.

Leptonic (hadronic) annihilation channels are compatible (in tension) with upper bounds from DM searches in high latitude Fermi-LAT gamma rays

# A multi-wavelength, multi-messenger analysis

S. Manconi, M. Di Mauro, FD 1803:01009 PRD subm.

We build a model for the production and propagation of e- and e+ in the Galaxy and test it against 3 observables:

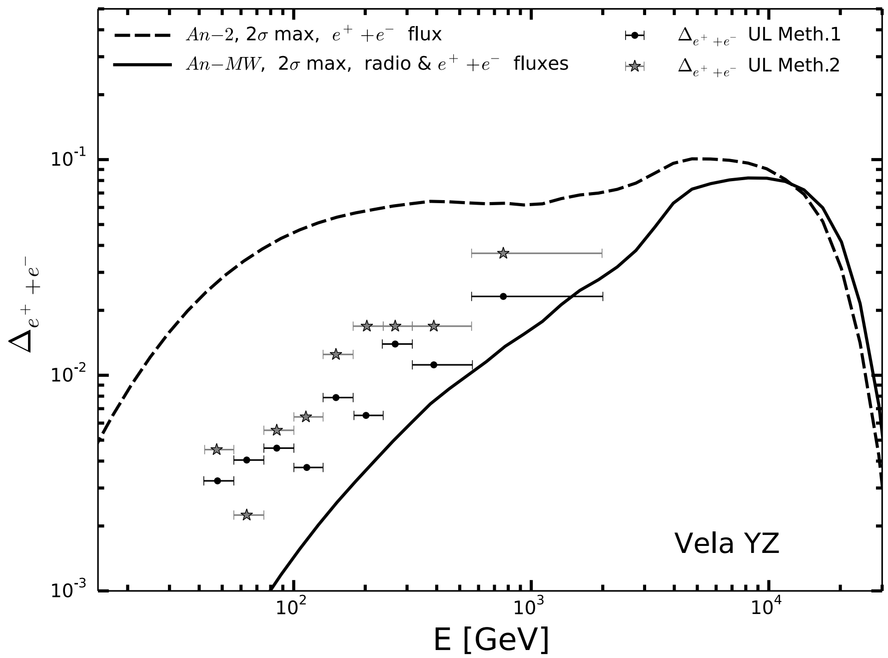
1. **Radio brightness data** from Vela YZ and Cygnus Loop at all frequencies.
   The radio emission is all synchrotron from e- accelerated by the source

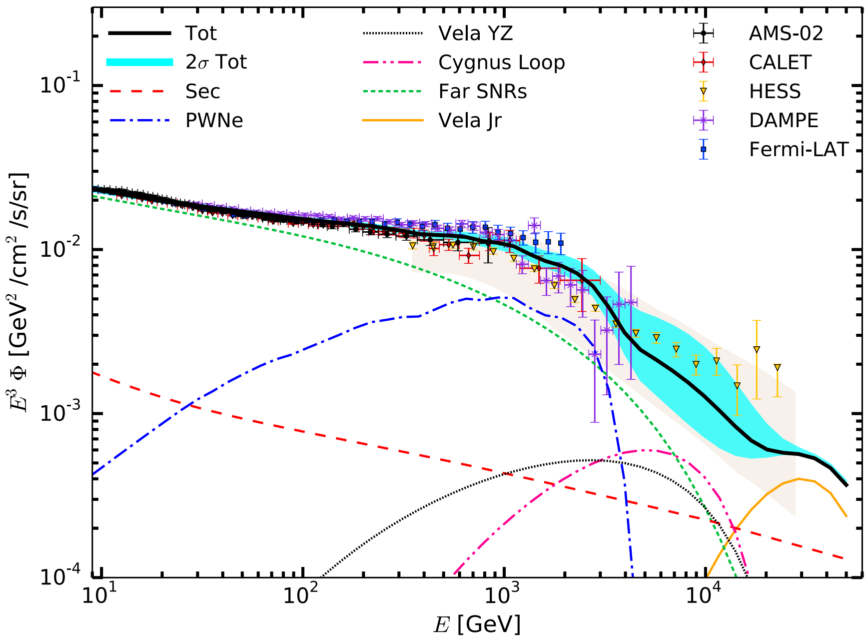
2. **e+e- flux** from 5 experiments, e+ flux from AMS
   Far and near SNRs, near SNRs and PWNe, secondaries for e+e-.
   The e+ flux constrains the PWN emission.
   e+e- data taken with their uncertainty on the energy scale.

3. e+e- **dipole anisotropy** upper bounds from Fermi-LAT
   Test on the power of this observable on the closest SNRs.

# A multi-messenger analysis

S. Manconi, M. Di Mauro, FD 1803:01009



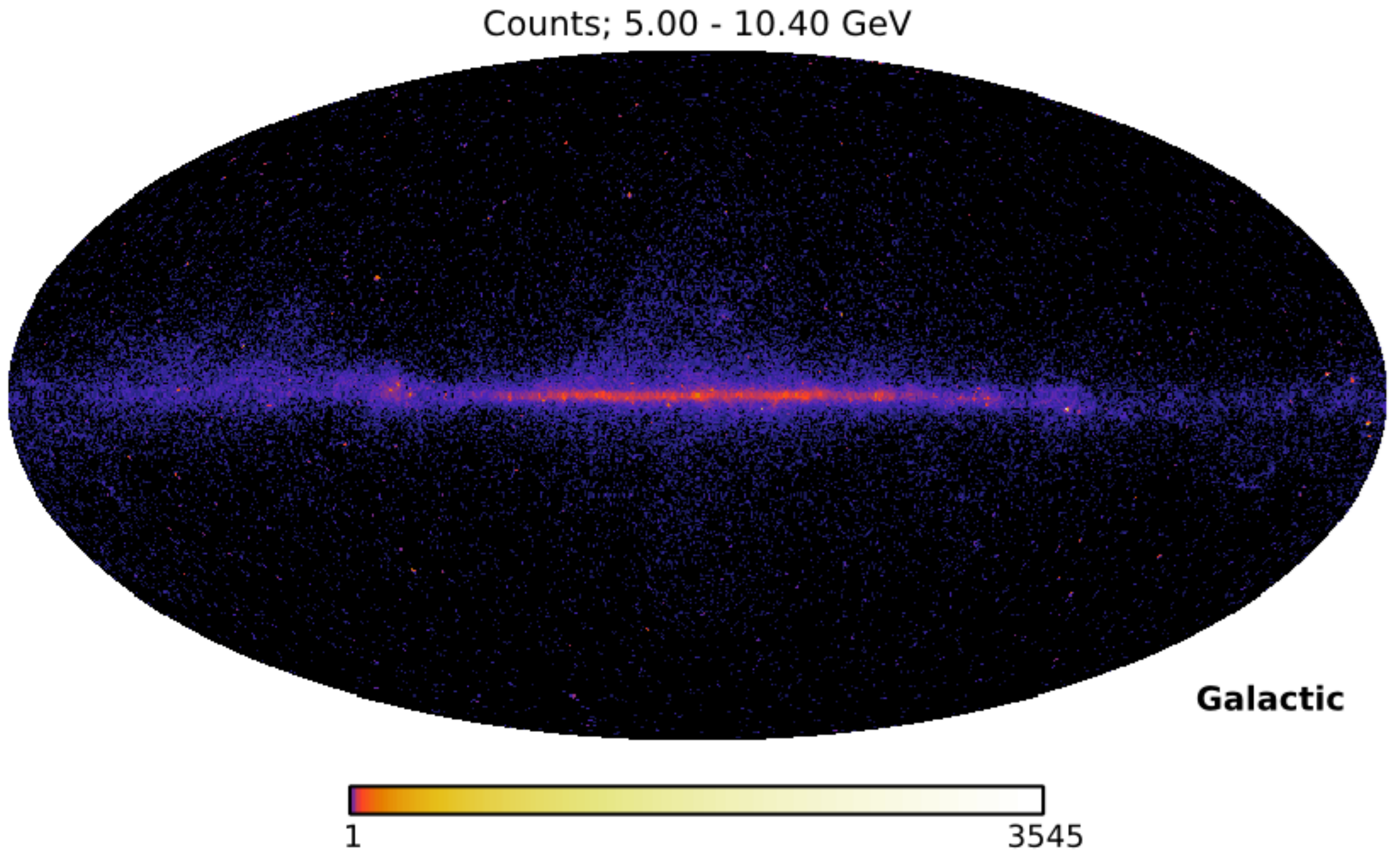




We can fit the whole data with a consistent model [provided that the proper systematic errors on the **energy scale** of each experiment are included].

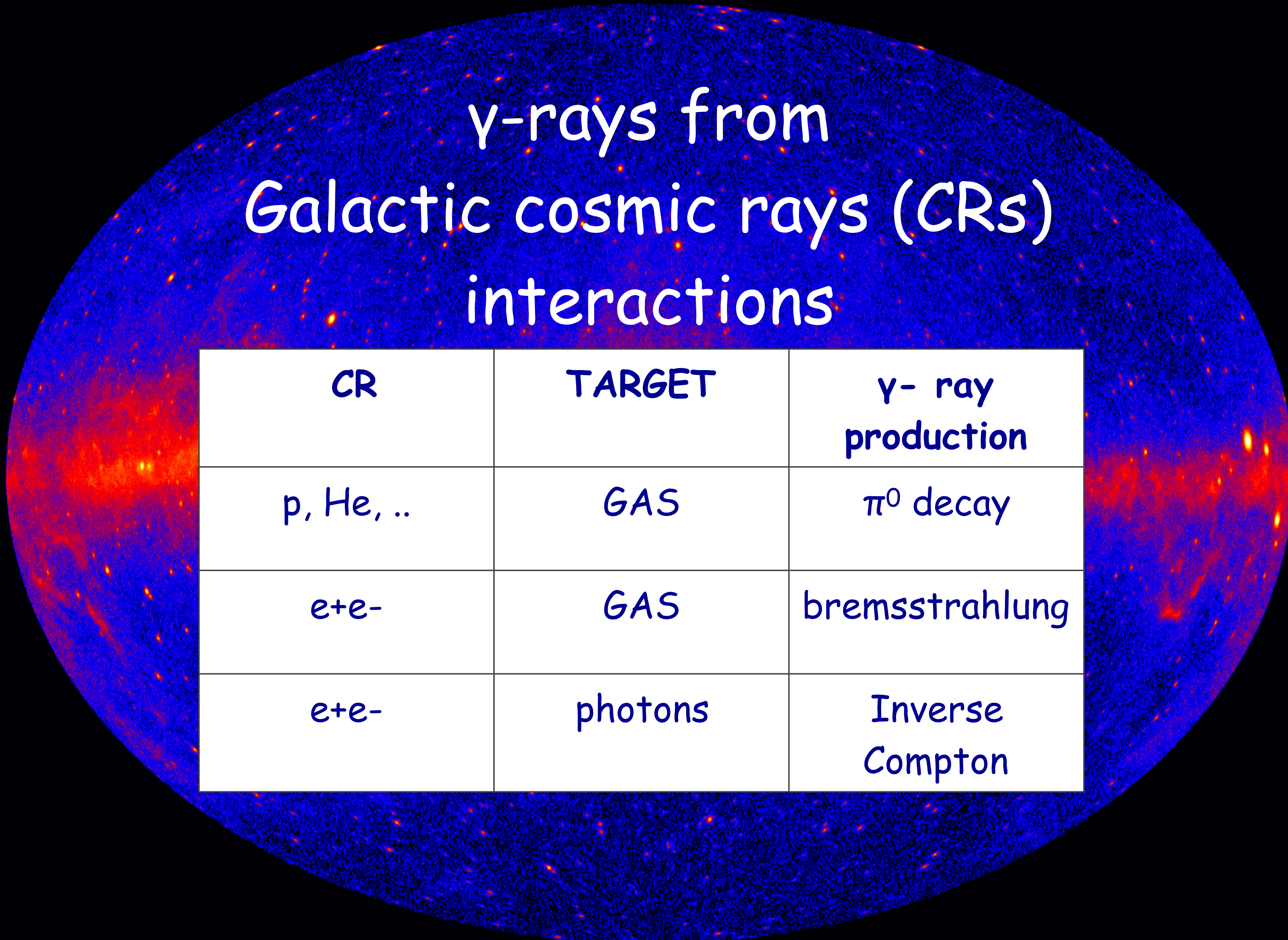
Anisotropies from charged particles start to be constraining

Different physical contributions shape **non trivial slope changes**

# The invaluable gamma-ray sky

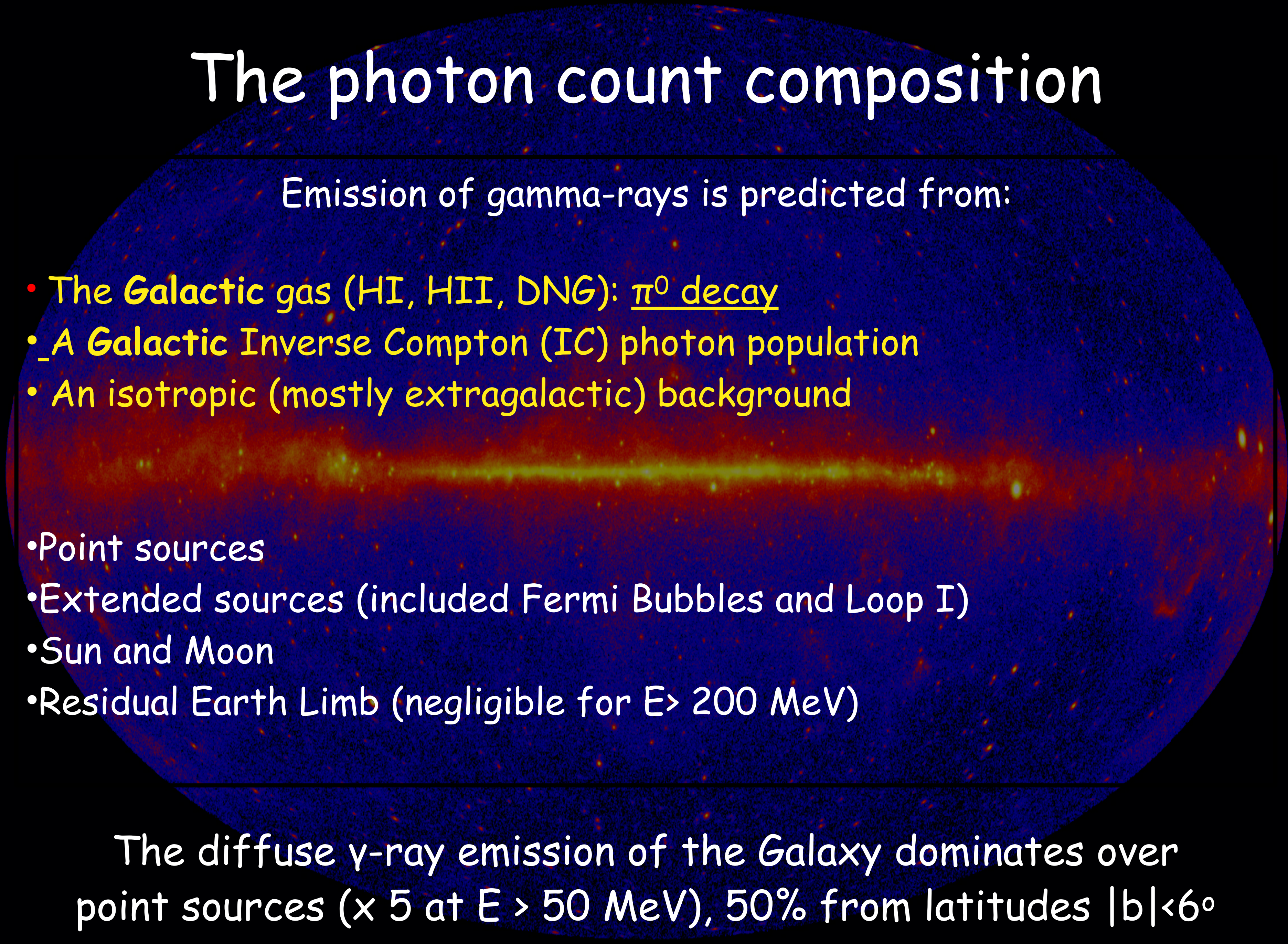


# γ-rays from Galactic cosmic rays (CRs) interactions



| **CR** | **TARGET** | **γ- ray production** |
|---|---|---|
| p, He, .. | GAS | $\pi^0$ decay |
| e+e- | GAS | bremsstrahlung |
| e+e- | photons | Inverse Compton |

# The photon count composition



Emission of gamma-rays is predicted from:

- The **Galactic** gas (HI, HII, DNG): $\pi^0$ decay
- A **Galactic** Inverse Compton (IC) photon population
- An isotropic (mostly extragalactic) background

- Point sources
- Extended sources (included Fermi Bubbles and Loop I)
- Sun and Moon
- Residual Earth Limb (negligible for E> 200 MeV)

The diffuse γ-ray emission of the Galaxy dominates over point sources (x 5 at E > 50 MeV), 50% from latitudes $|b|<6^{o}$

# Photon statistics:

## pushing the γ-ray source count distribution below the Catalog detection thresholds

Zechlin, Cuoco, FD, Fornengo, Vittino ApJS 2016, Zechlin, Cuoco, FD, Fornengo, Regis ApJ 2016

The **1-point probability distribution function (1p-PDF)** :

•**MEASURE** the source count (N) distribution dN/dS as a function of the flux S

•**EXTEND** the sensitivity for dN/dS BELOW the 3FGL

•**DECOMPOSE** the total gamma-ray sky into:

i) Point sources,
ii) Galactic foreground,
iii) Isotropic diffuse background
iv) Further components (i.e. dark matter)?

Lee, Ando Kamionkowski 2009; Baxter, Dodelson,Koushiappas, Strigari 2009; Dodelson, Belikov, Hooper, Serpico 2009; Malyshev&Hogg 2011; Feyereisen, Ando, Lee 2015; Lee, Lisanti, Safdi 2015; Lee, Lisanti, Safdi, Slatyer 2015; Linden, Rodd, Safdi, Slatyer 2016; Vernstrom+ 2014; Vernstrom, Norris, Scott, Wall 2015;Lisanti+ 2016; Feyereisen, Tamborra, Ando 2017

# 1p-PDF analysis

Zechlin, Cuoco, FD, Fornengo, Vittino ApJS 2016,

1p-PDF == $p_k$, the probability to find k photons in a given pixel

$n_k$ is the number of pixels counting k photons

Exploit the method of generating functions (Malyshev & Hogg 2011)

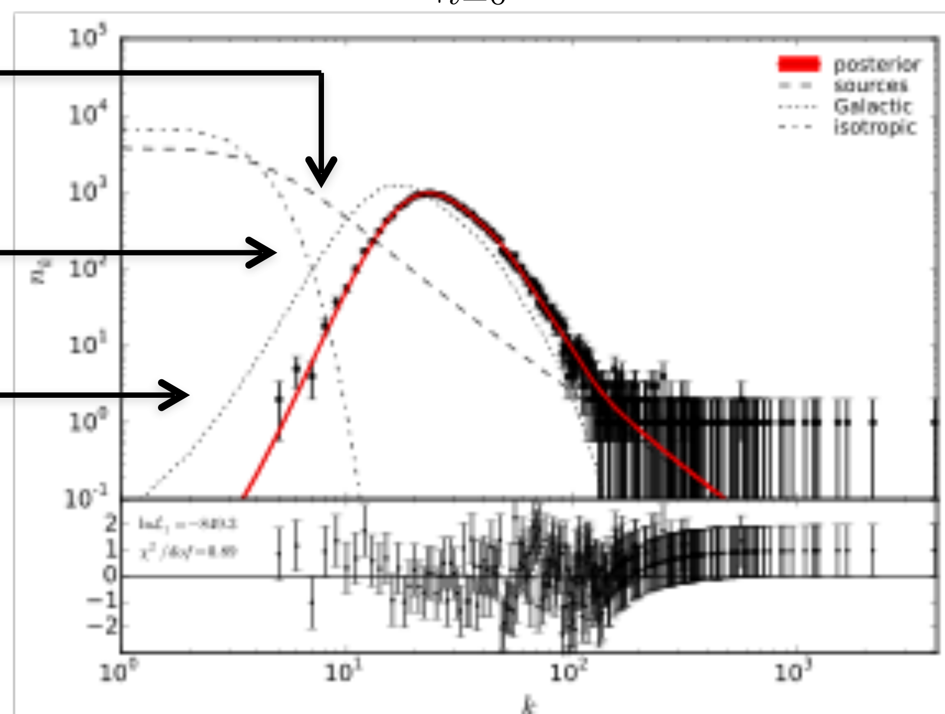
$$\mathcal{P}^{(p)}(t) = \sum_{k=0}^{\infty} p_k^{(p)} t^k$$

$$p_k^{(p)} = \frac{1}{k!} \frac{\mathrm{d}^k \mathcal{P}^{(p)}(t)}{\mathrm{d}t^k}\Bigg|_{t=0}$$

Point sources distributed as dN/dS

Isotropic diffuse background

Galactic foreground template



# Modeling the γ-ray contributions

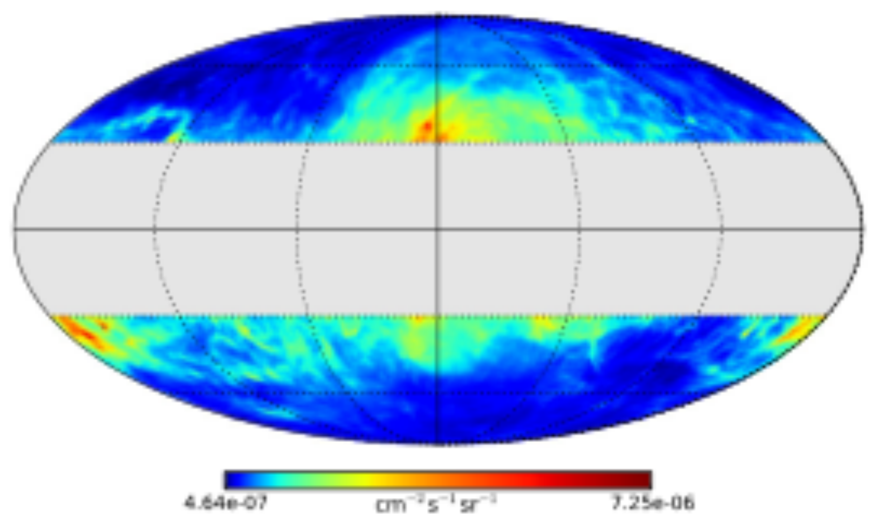
**Point sources have an integrated FLUX S** following a multi-broken power law (MBPL)

$$\frac{\mathrm{d}N}{\mathrm{d}S} \propto \begin{cases} \left(\frac{S}{S_0}\right)^{-n_1} & , S > S_{\mathrm{b}1} \\ \left(\frac{S_{\mathrm{b}1}}{S_0}\right)^{-n_1+n_2} \left(\frac{S}{S_0}\right)^{-n_2} & , S_{\mathrm{b}2} < S \leq S_{\mathrm{b}1} \\ \vdots & \vdots \\ \left(\frac{S_{\mathrm{b}1}}{S_0}\right)^{-n_1+n_2} \left(\frac{S_{\mathrm{b}2}}{S_0}\right)^{-n_2+n_3} \cdots \left(\frac{S}{S_0}\right)^{-n_{N_{\mathrm{b}}+1}} & , S \leq S_{\mathrm{b}N_{\mathrm{b}}} \end{cases}$$

Diffuse emission included as:

- Galactic diffuse background: template from Fermi Science Tool (gll_iem_v05_rev1.fit)

- Isotropic diffuse background follows $E^{-2.3}$ (we fix its integral)




Galactic diffuse emisison

# Data fitting procedure

Likelihood can be defined in two ways:

•Simple 1p-PDF, assuming Poisson statistics (Malyshev&Hogg, 2011):

$$\mathcal{L}_1(\mathbf{\Theta}) = \prod_{k=0}^{k_{\max}} \frac{\nu_k(\mathbf{\Theta})^{n_k}}{n_k!} e^{-\nu_k(\mathbf{\Theta})}$$

•Pixel dependent, for full exploitation of spatial templates:

$$\mathcal{L}_2(\mathbf{\Theta}) = \prod_{p=1}^{N_{\rm pix}} P(k_p)$$

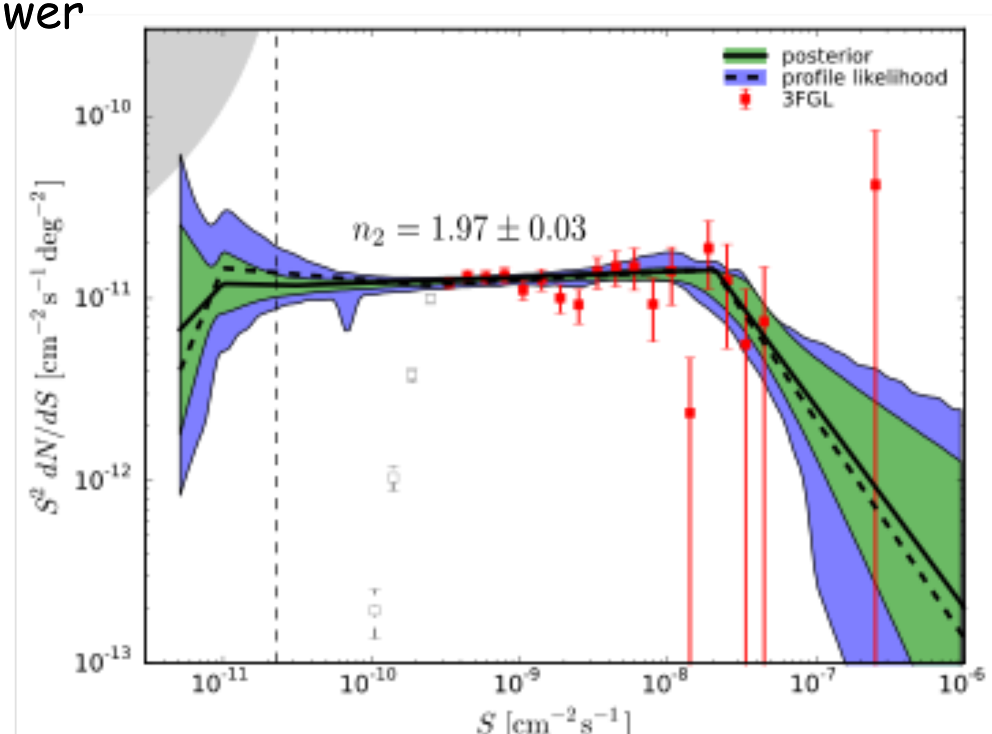
•Sampling with MCMC (Multinest, Feroz&Hobson 2008)

•Parameter estimation: likelihood profiles and bayesian inference

•All results are presented for $L_2$, account pixel dependence

# The source number count in 1-10 GeV

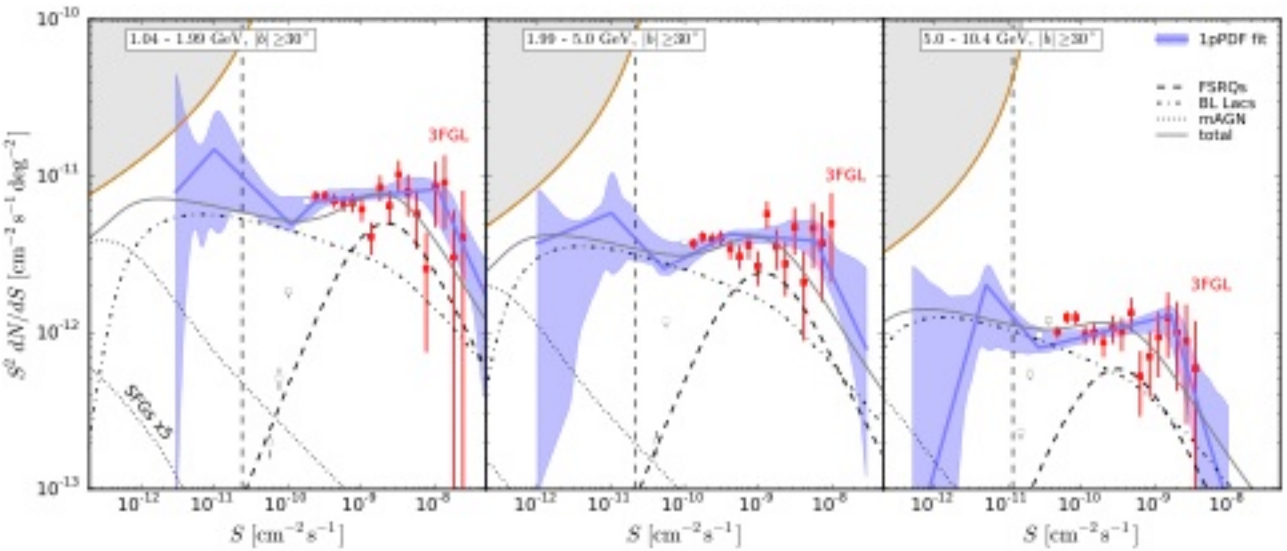
- Measure dN/dS down to fluxes $S \sim 2 \times 10^{-11}$ $cm^{-2} s^{-1}$, **~x10 below 3FGL catalog**
- dN/dS described by a single broken power
- Break for bright sources
- Tested against a systematics (pixel size, bright source masking, galactic foreground, latitude, galactic mask)



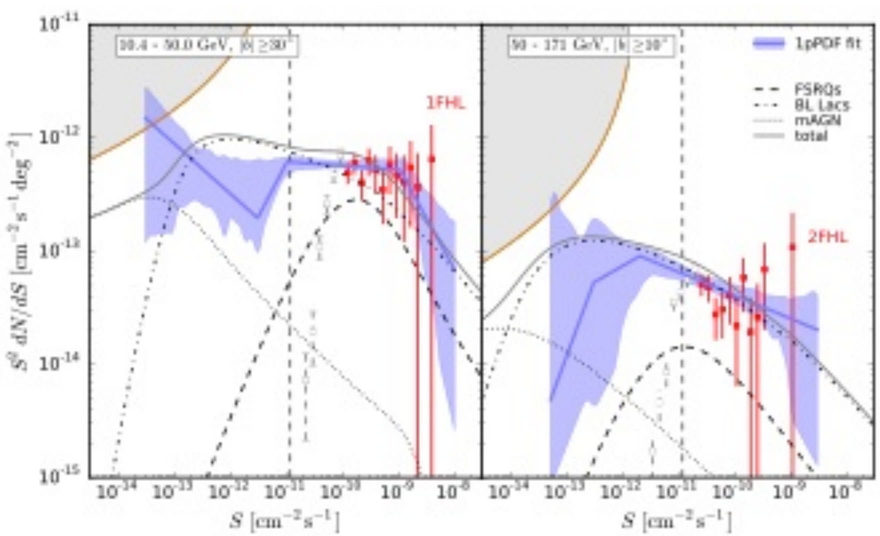

High latitude sky composed:
**25%** point sources | **69%** diffuse galactic | **6%** diffuse isotropic

# 1p-PDF, results on the energy binning

Zechlin, Cuoco, FD Fornengo, Regis ApJ2016




Measure down to ~ $10^{-11}$ cm$^{-2}$s$^{-1}$, close to sensitivity




- We use the MBPL and then the hybrid approach (to fix the node)
- The models are just state-of-the-art predictions. They indicate that our measure can have physical interpretation

Constraining Galactic dark matter with gamma-ray pixel counts statistics

PRD 2018

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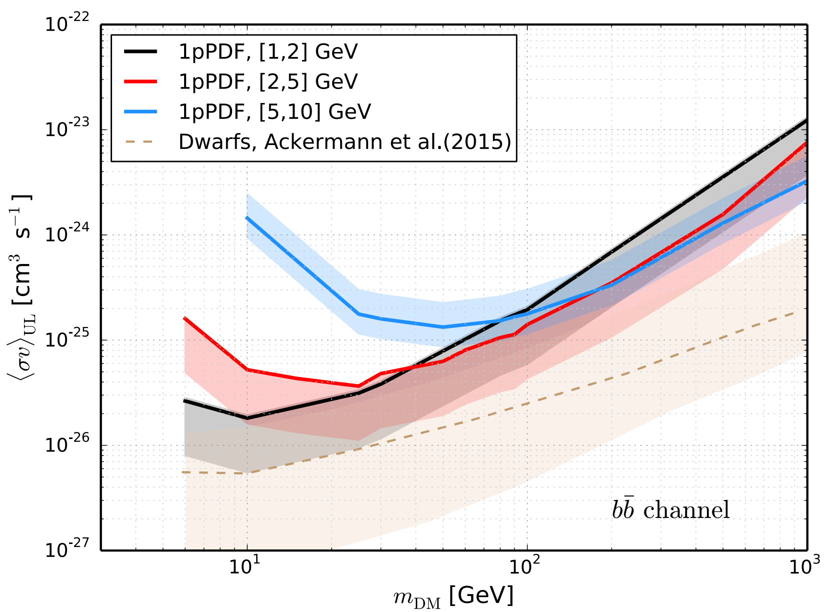



i) point sources,

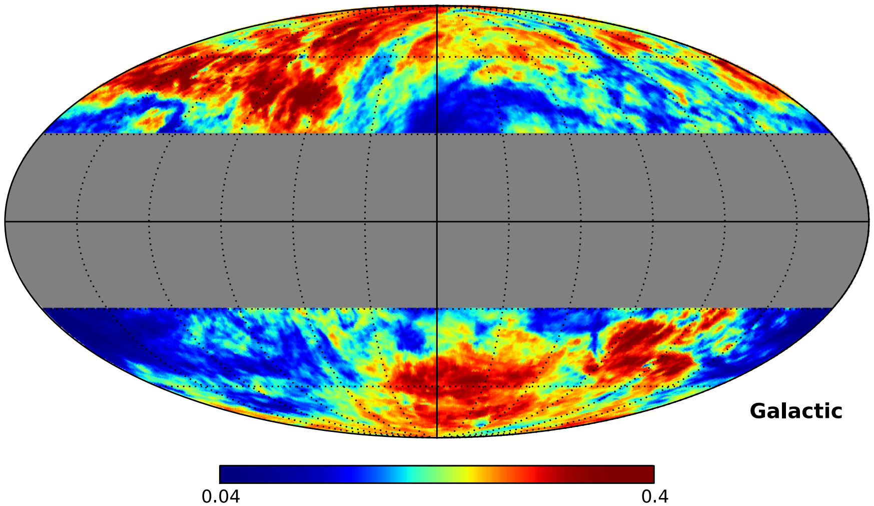
ii) galactic diffuse emission,

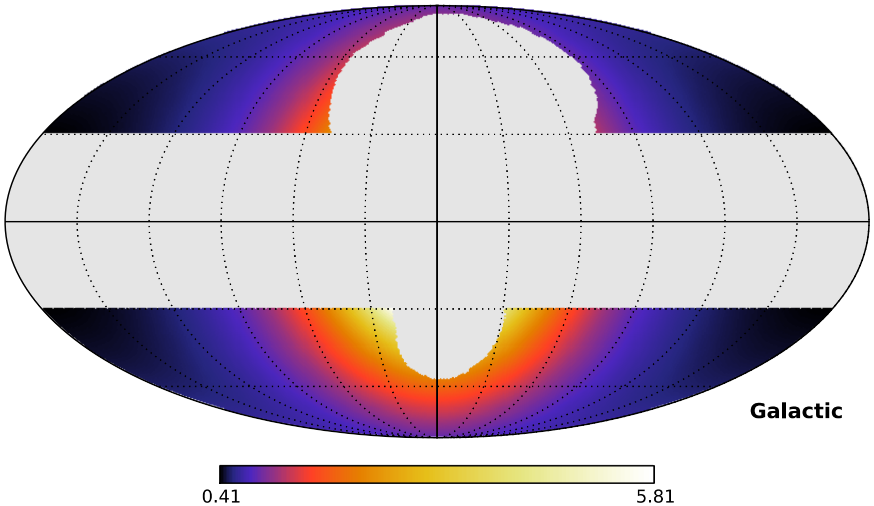
iii) isotropic bkd,

**iv) Dark matter annihilating in the galactic halo**

Strong bounds, < dSph

# Inspecting the gamma-ray sky



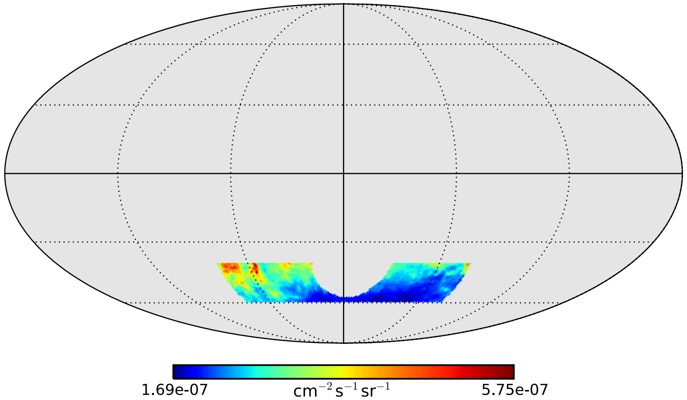




Relative difference between two models for the galactic diffuse emission: still an uncertainty prior to any DM searches

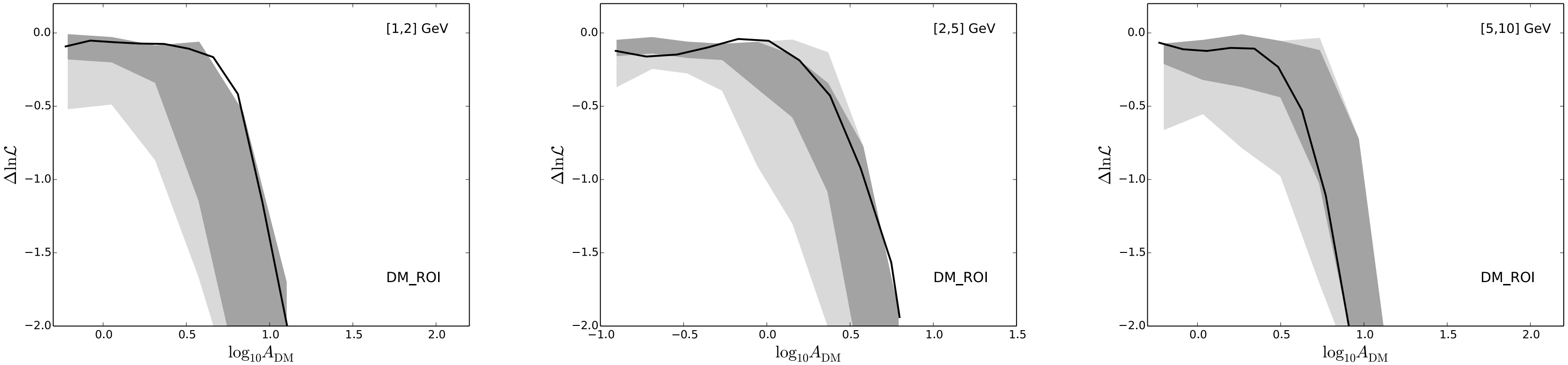
The gamma-ray sky map due to DM annihilation

$$\mathcal{J}(\psi) = \frac{1}{r_\odot} \int_{\rm los} \left( \frac{\rho[r(l)]}{\rho_\odot} \right)^2 {\rm d}l(\psi)$$

# Optimization of the ROI

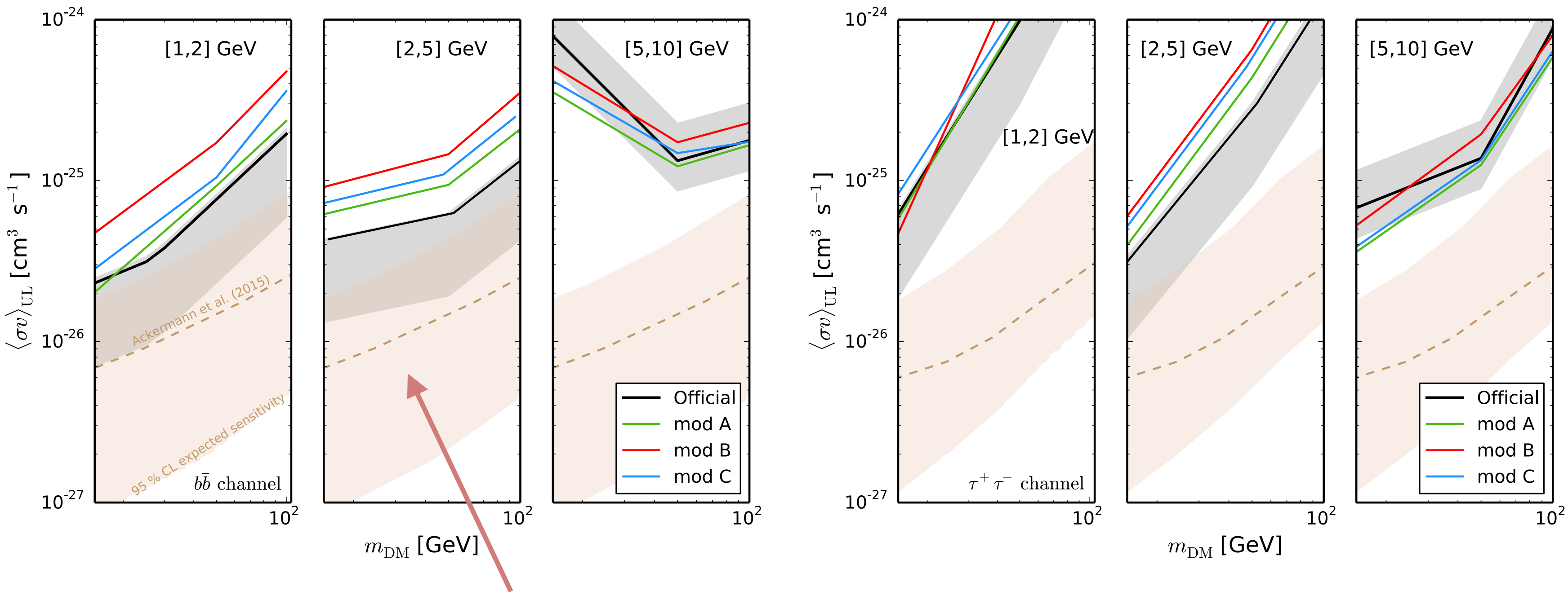



The Region of Interest (ROI)
Found empirically, must be stable against sky simulation




Likelihood on the null hypothesis (no DM) - Solid line: actual flight data
The method is reliable, the ROI is reliable

# The diffuse Galactic emission, a major systematics




Fermi Coll. upper bounds from dwarf spheroidal galaxies (Ackermann et al. PRL 2015)

The intensity of a (diffuse) galactic dark matter annihilation component is very sensitive to models for γ-ray DGE models

# Conclusions

Existing data on antimatter and gamma-rays do not necessarily require exotic (DM) interpretation, but need a highly precise astrophysical treatment of the backgrounds and

the regions in which they are produced and propagated.

- POSITRONS are well fitted by known, powerful galactic sources.

  DM interpretation still open, but less natural

- ANTIPROTONS are a powerful constraining means on the DM annihilation intensity

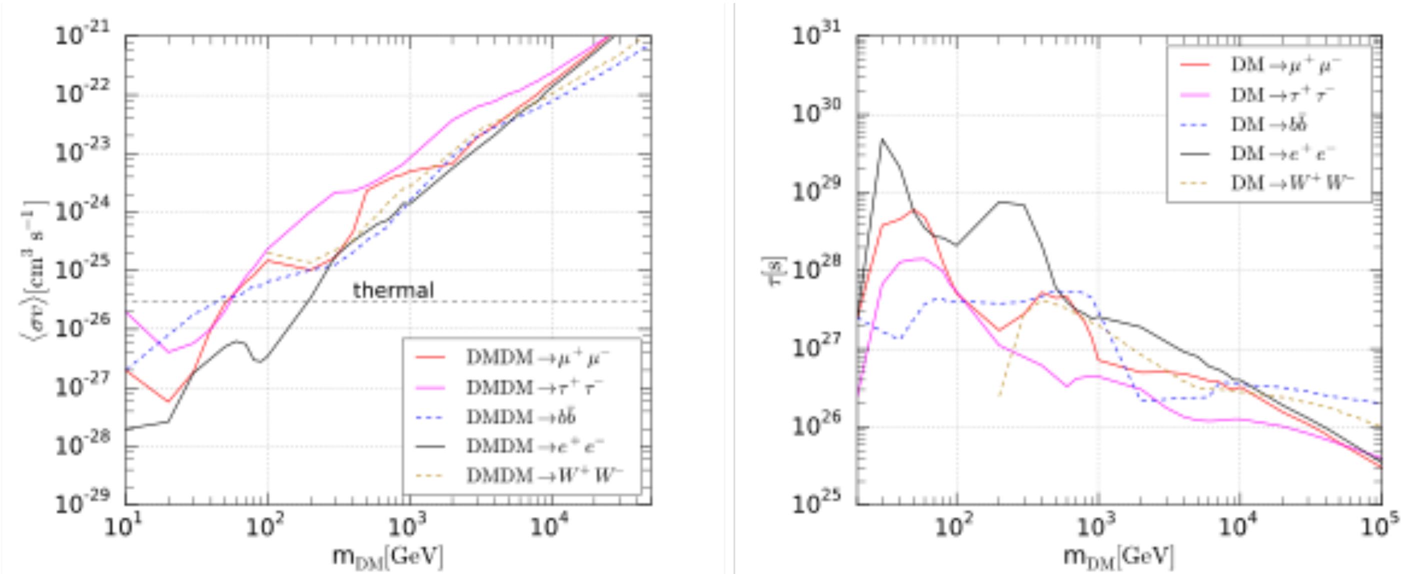
- ANTIDEUTERONS are challenging, but with the highest detection potentials

- GAMMA-RAY are now extremely powerful. A major limit is the ubiquitous galactic diffuse emission

# Adding a Dark Matter component:

## Upper bounds on annihilation cross section/decay time from fitting AMS-02 lepton data

Di Mauro, FD, Fornengo, Vittino JCAP 2016




The upper bounds are obtained with astrophysical components AND a contribution from Dark Matter annihilation / decay

(MED propation model, Einasto DM radial density profile).

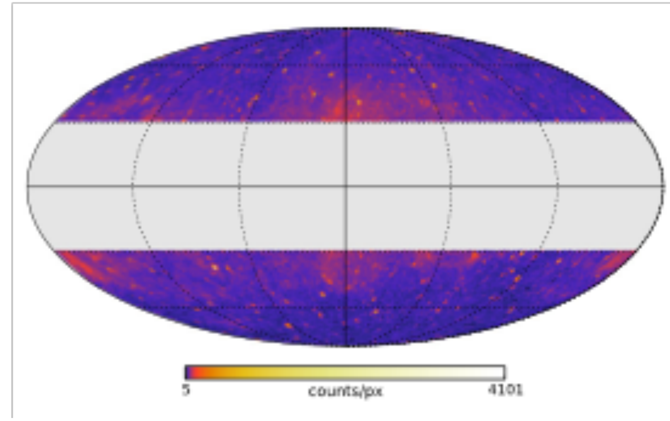
Limits on annihilation cross section at the thermal value

For m<200 GeV and $e^+e^-$ annihilation channel

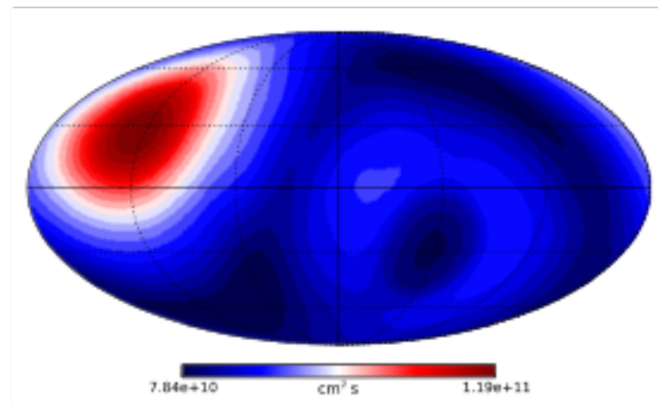
# The Fermi-LAT data

- 6 years **Data** (P7REP, standard selection cuts, front event only)
- Latitude |b|>30°
- Single bin: 1-10 GeV
- Correction for point spread function (PSF) smearing
- Correction for **EXPOSURE** inhomogeneities performed on 20 equally-spaced regions

The photon map

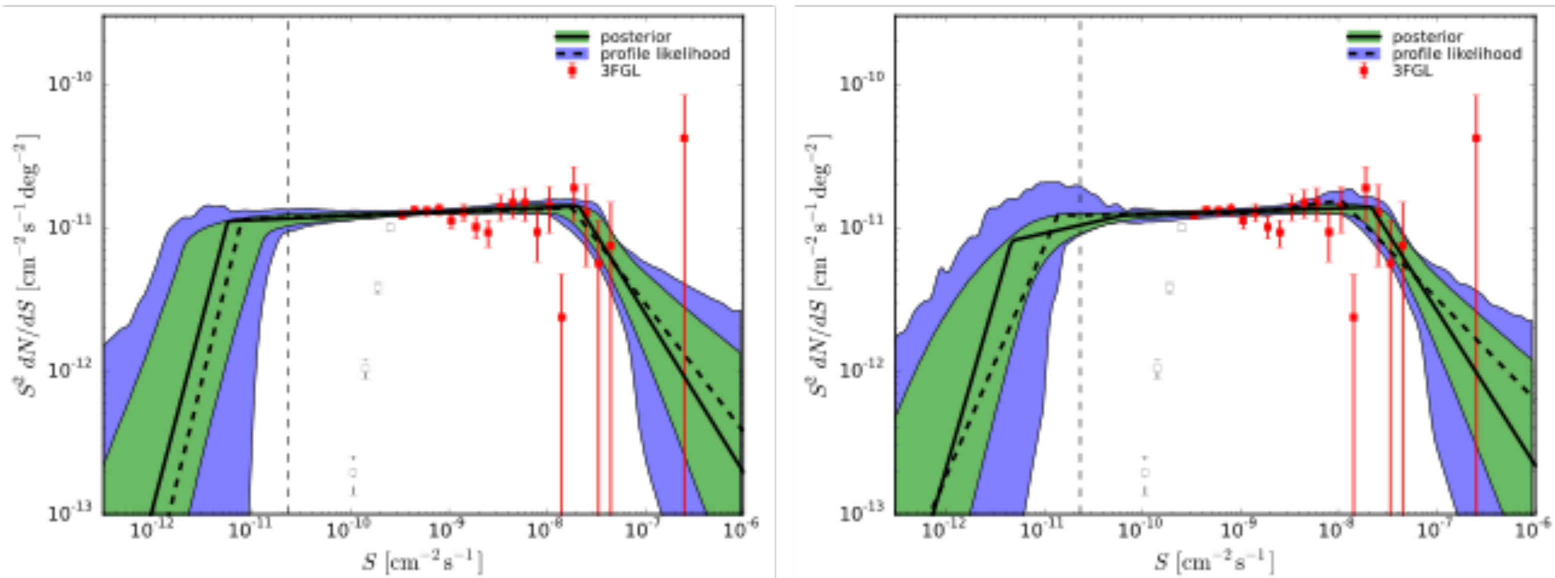



The exposure map



# The MBPL approach

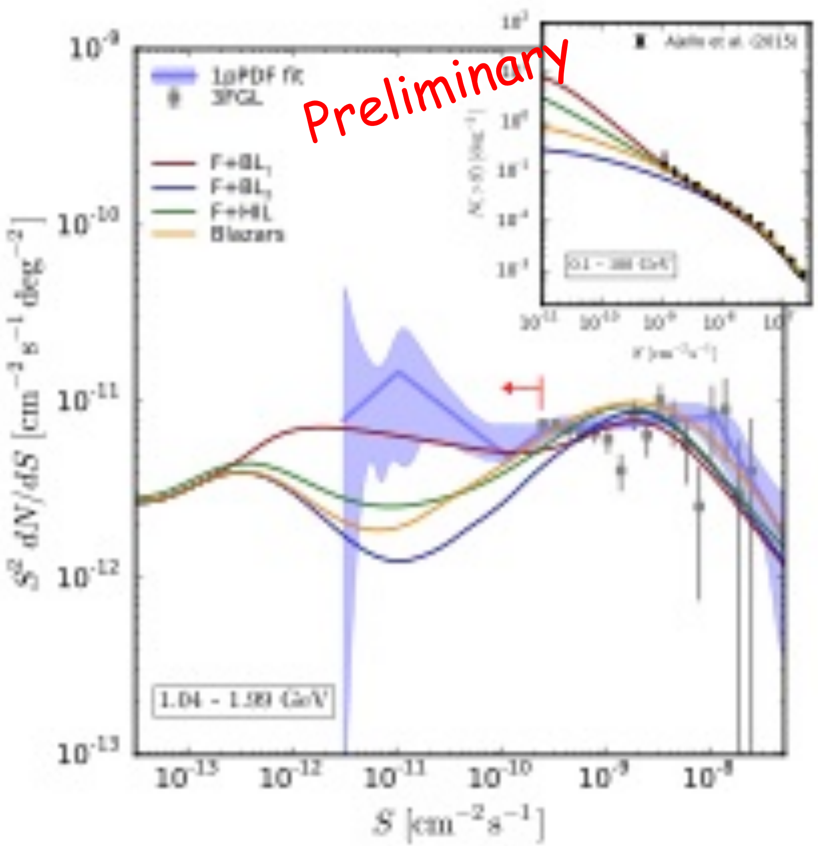
Fits over $2N_b+4$ parameters: $(A_S, S_{b1}, \ldots, S_{bN_b}, n_1, \ldots, n_{N_b+1}, A_{gal}, F_{iso})$




(a) MBPL, $N_b = 2$ (b) MBPL, $N_b = 3$

- 2 free breaks are sufficient to fit the dN/dS
- $n_2$=1.97 ±0.03: the intermediate ($10^{-10}$-$10^{-8}$ cm$^{-2}$s$^{-1}$) flux region is extremely well constrained (due to high statistics)
- $A_{gal}$ ~ 1 for the galactic foreground, fitted at per mille level (i.e. 1.073±0.004)
- Cut-off at faint sources can be intrinsic or a sensitivity limit

# 1p-PDF, power of the energy binning




Different models for the gamma-ray luminosity of BL Lacs can lead to significant differences in the non resolved flux region.

The 1p-PDF method will be a powerful tool to constrain models for extragalactic sources