Indirect searches for Dark Matter

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WIMP DM Indirect Searches

Annihilation inside celestial bodies:

→ ν at ν telescopes as up-going μ's

$$\Phi_\mu^{(\mathrm{Earth,Sun})} \propto < \sigma_{\mathrm{ann}} v > \frac{\rho_\chi}{m_\chi}$$

Annihilation in the galactic halo(s):

→ Photons (γ-rays, radio,…)

→ $e^+, \ \bar{p}, \ \bar{D}$

$$\Phi^{(\bar{p},\bar{D},e^+,\gamma)} \propto < \sigma_{\mathrm{ann}} v > \left(\frac{\rho_\chi}{m_\chi}\right)^2$$

ν and γ keep directionality

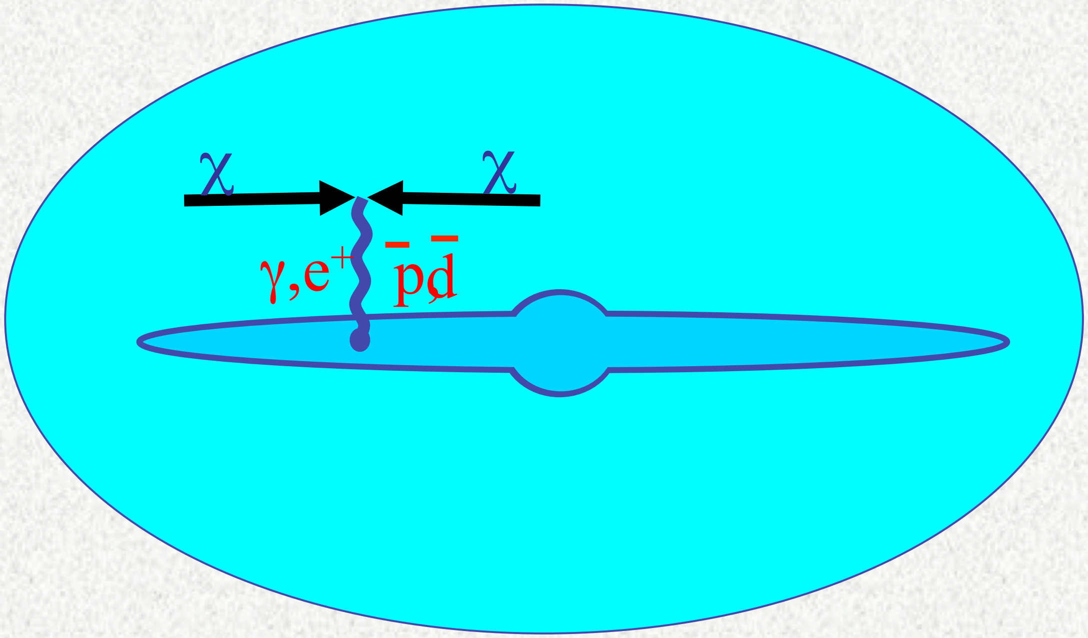
can be detected only if emitted from high χ density regions

Charged particles diffuse in the galactic halo

antimatter searched as rare components in cosmic rays (CRs)

For specific WIMP DM models: see talk by David Cerdeño

Dark Matter Indirect Detection



We look for an "exotic" contribution from
<u>**DARK MATTER PAIR ANNIHILATION**</u>
in a low astrophysics background of:

γ-rays:
Special ingredient is DM space distribution ρ(r)
Antiprotons, antideuterons, positrons:
special need is the astrophysics of charged cosmic rays

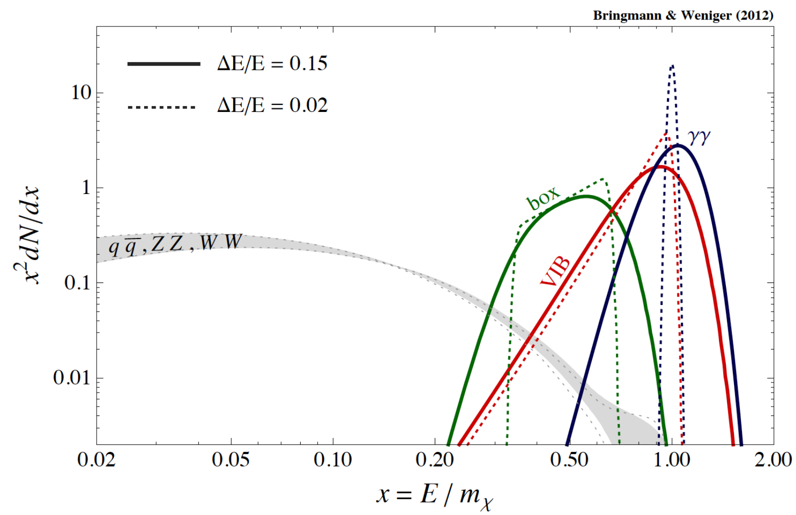
γ-rays from WIMP Dark Matter (DM)

$$\Phi_\gamma = \frac{1}{4\pi}\frac{<\sigma_{ann}v>_0}{2m_\chi^2}\frac{dN_\gamma}{dE_\gamma}I(\Psi)$$

- Particle Physics term:

$$\frac{\langle\sigma v\rangle}{m_\chi^2}$$ acts as a normalization

$\chi\chi \rightarrow \pi^0 \rightarrow 2\gamma$
$\chi\chi \rightarrow$ 1-loop $\rightarrow \gamma\,\gamma$, $Z\gamma$
Radiative corrrections
Inverse Compton



- Cosmological term

$$I(\Psi) = \int_{l.o.s.}\rho^2(r(\lambda,\psi))d\lambda$$

→ see talk by Risa Wechler

Integral along the line-of-sight of DM density distribution $\rho(r)$

Derived from numerical simulations of cosmological structures

γ-ray potential DM targets in the sky

Galactic center (GC)

☺ may be an over-dense region, spectral features could emerge

☹ high background

Galactic halo:

☺ low background at high galactic latitudes

☹ less concentrated DM environment

Galactic sub-structures:

☺ Could show spatial features (anisotropies)

☹ small objects, unknown position, number, …

Dwarf spheroidal MW satellites:

☺DM dominated

☹ Small number, some are distance-suppressed

Extra-galactic substructures:

☺ High DM density

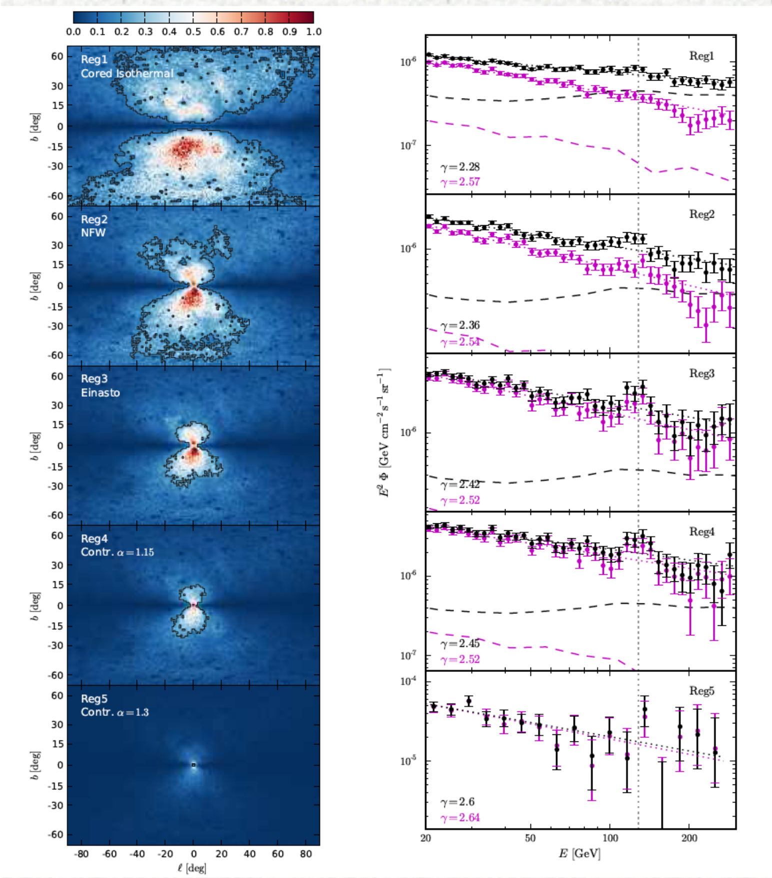
☹ High theoretical uncertainties / faint fluxes

γ-ray line in Fermi-LAT data at the galactic center

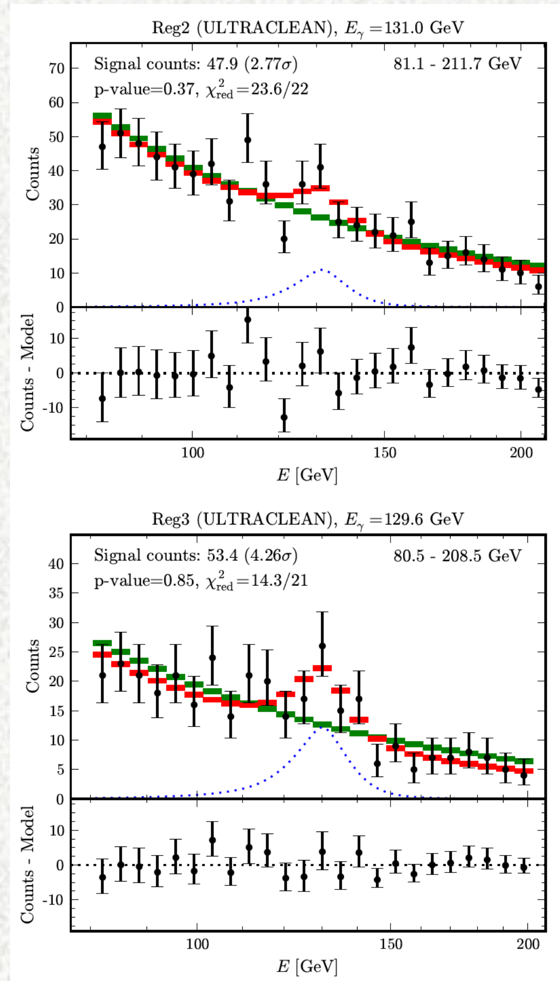
Bringmann+ 2012, Weniger 2012

Su&Finkbeiner, Tempel+, Buchmueller&Garny, Boyarsky+; Cholis+; Buckley & Hooper , Weiner&Yavin;…2012

5 ROI optimized on S/B and 5 ρ(r)



Weniger 2012



Interpretation in terms of particle physics model is not straightforward
(see also talk by T. Toma)

LAT Collaboration line search studies

(arxiv: 1305.5597) (See talk by A. Albert)

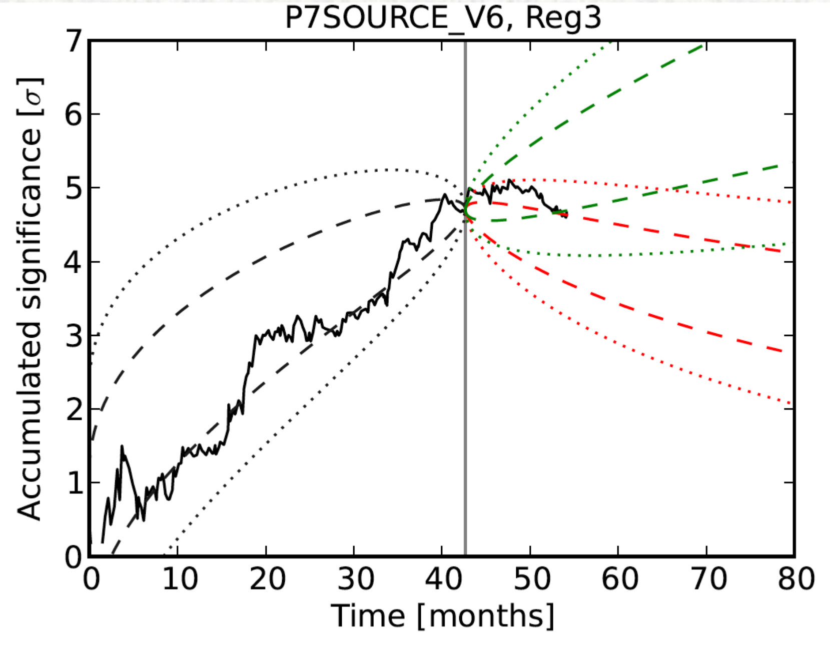
- Analysis with improved calibration constants, in 5 spatial regions
- No globally significant lines found ($<2\sigma$)
- In a region of $3^o \times 3^o$ around the GC finds positive excess around 133 GeV, with global significance $\sim 1.6\sigma$
- Excess $\sim 2\sigma$ found also for Limb photons (produced by cosmic ray interactions in the upper atmosphere), searched for in a very narrow range of zenith angles. Not compatible with DM interpretation
- No excess in the inverse GC region
- Unexpected dependence of 133 GeV line on incidence (w.r.t. the detector) angles, both for GC and Limb photons
- Set limits to $\langle\sigma v\rangle_{\gamma\gamma}$ which do not disfavor the WIMP DM hypothesis in general

130 GeV γ-ray line: current status

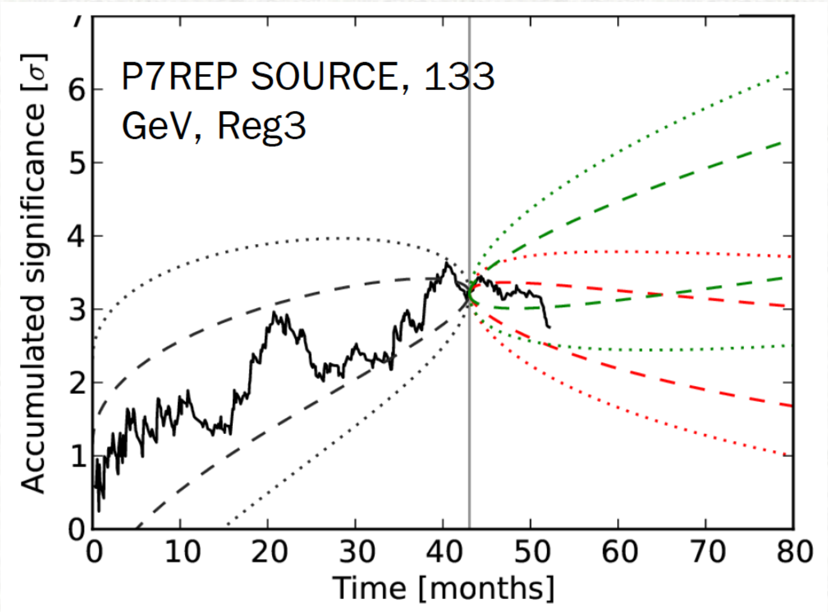
Weniger 1303.1798, July 2013*

Time evolution of the accumulated significance w.r.t. expectations

Analysis until July 2013



Reprocessed data, July 2013



68%(95%) CL: real signal, statistical fluke, steady source in the past
Solid: feature in the real Fermi-LAT data

4.6σ in P7V6

2.8σ (2.4σ) in P7REP 1-D(2-D)

N.B.: Also Limb feature drops from 3σ to ~2σ.

* http://fermi.gsfc.nasa.gov/ssc/proposals/alt_obs/white_papers_eval.html

γ-ray spectral line: perspectives

(http://fermi.gsfc.nasa.gov/ssc/proposals/alt_obs/obs_modes.html)

Fermi-LAT default observation is all sky coverage (each 3 hours) since launch (5 yrs). *Fermi* has solicited white papers for alternate observation strategies for specific science drivers

The Recommended Alternative: coverage of the Galactic center region

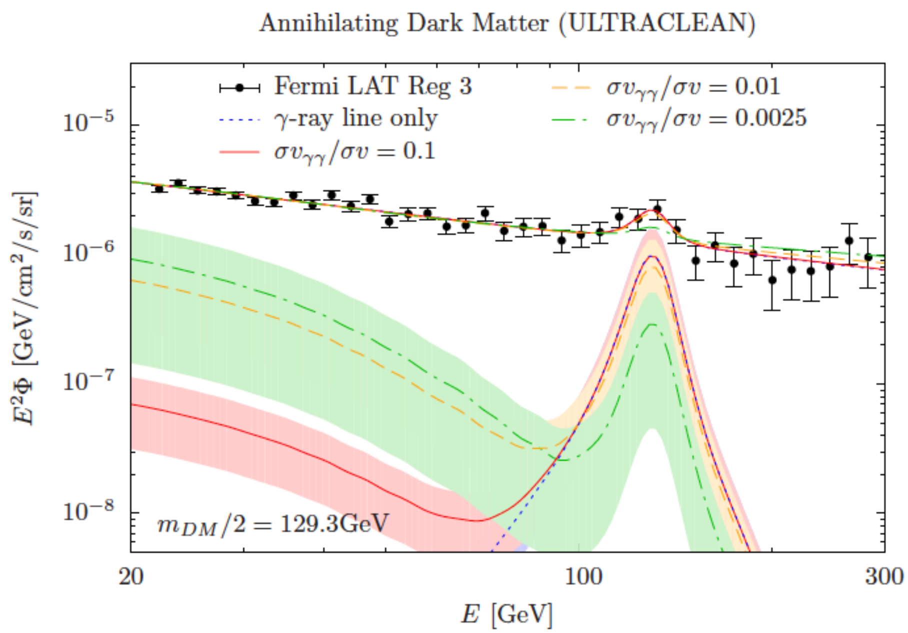
- Implementation should occur by December 2013
- Doubled the rate of accumulation w.r.t present data toward the GC
- The modified observing strategy should run for one year.
- After one year is up, the Fermi Project Scientist will organize a review to decide whether to maintain the modified observing strategy or return to survey mode.

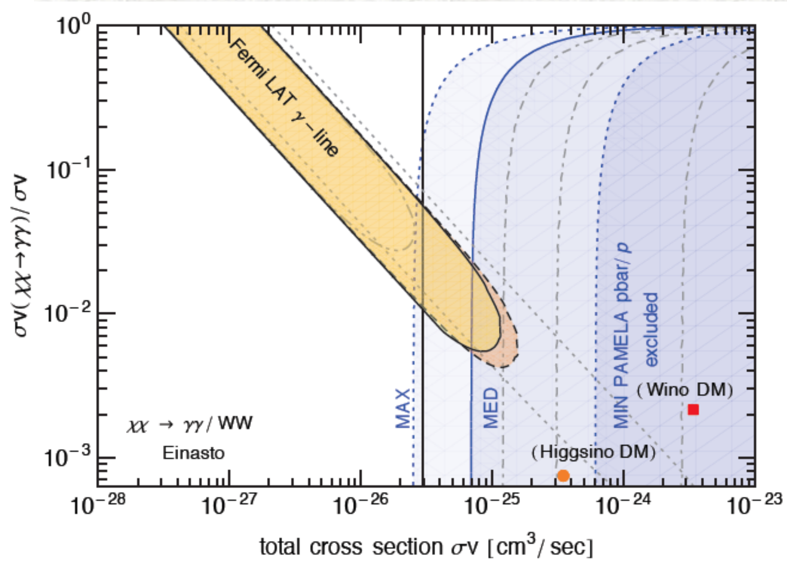
Good perspectives also with Hess-II, Cerenkov Telescope Array (CTA), GAMMA-400 (Bergstrom et al. 2012)

γ-ray line: constraints from continuum

γ-ray line: annihilation cross section is quite large
Models predict low BR for this 1-loop channel (DM is EM neutral, it cannot annihilate directly into photons)

Reasonable to expect a large γ-ray continuum associated to the line, even if with a harder spectrum and less pronounced spatial distribution



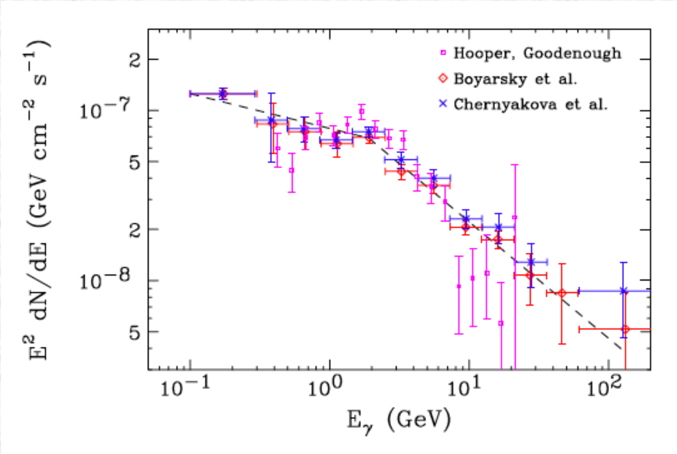


Buchmueller & Garny, JCAP 2012
Cohen, Lisanti, Slatyer, Wacker

γ-ray from the GC: astrophysics or DM?

A source of photons with soft spectrum seems to be present at the GC

(Hooper&Goodenough2011, Linden&Hooper 2011, Abazazjian&Kaplinghat 2012, Hooper+2013,Gordon,Macias 2013)



Residuals emission from 5° around the GC (Linden&Hooper 2011)

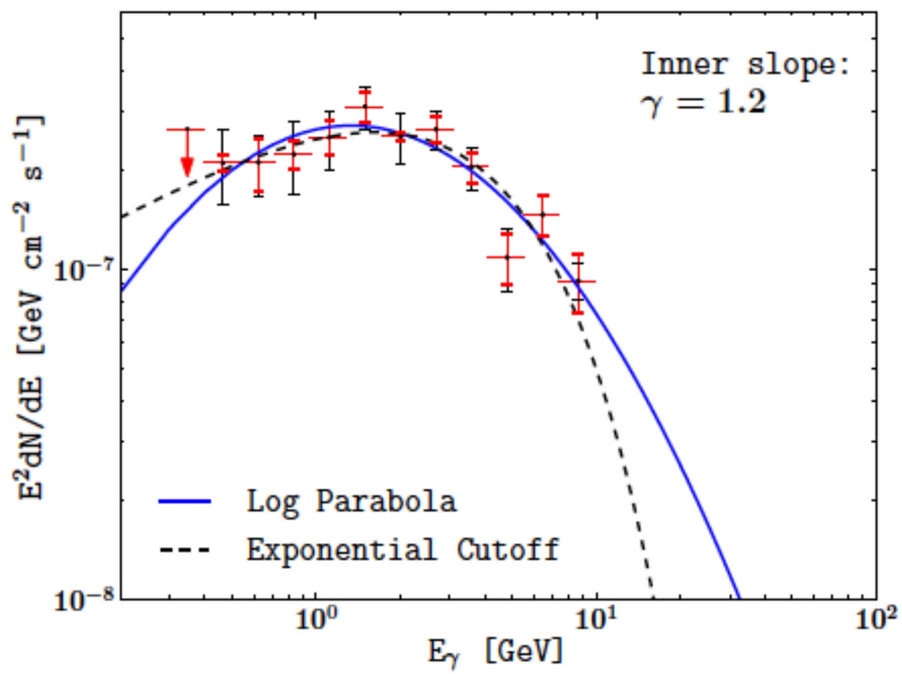
The GC is a very crowded place: emission from the Sgr A central black hole or from milli-second pulsars can be a viable astrophysical explanation

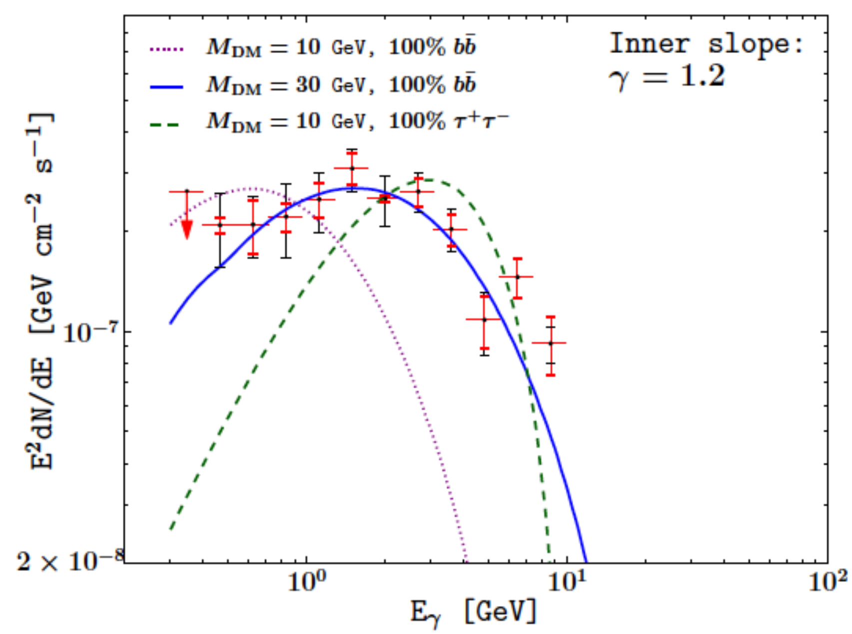
Also, preferably light (10-30 GeV) DM could explain the observed spectrum

The observed spectrum can also be used to set constraints on annihilation cross section, but the background subtraction is not trivial

γ-ray from the GC: astrophysics or DM?

Gordon&Macias 2013 (see also Abazjian&Kaplinghat 2012)





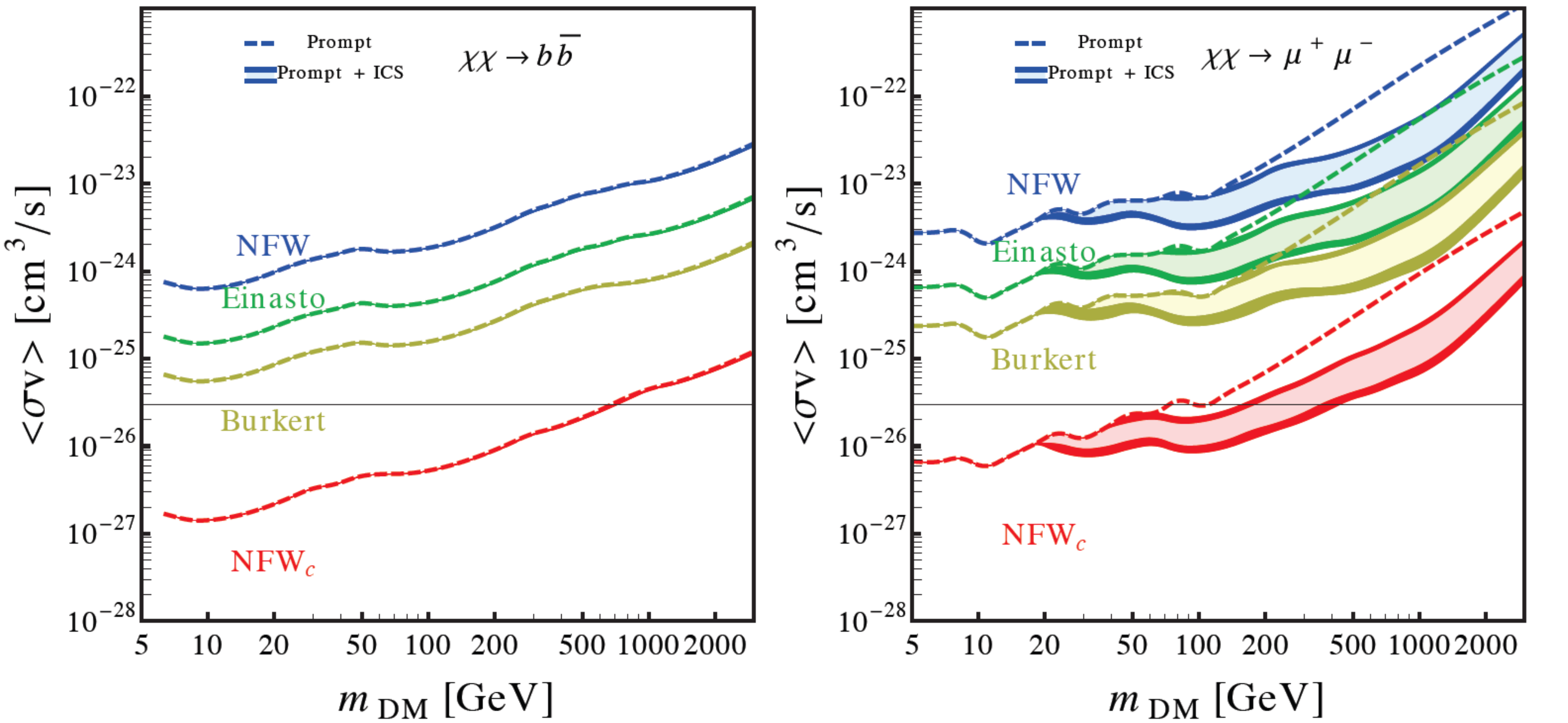
Fit with typical unresolved milli-second pulsars at he GC

Fit with self-annihilating DM, cross section close to thermal (10^{-26} cm^3/s) and steep (1.2) NFW DM profile (!)

Astrophysical interpretation is possible (and model dependent)
DM interpretation is possible as well, but highly model dependent
N.B. astrophysical sources ARE there

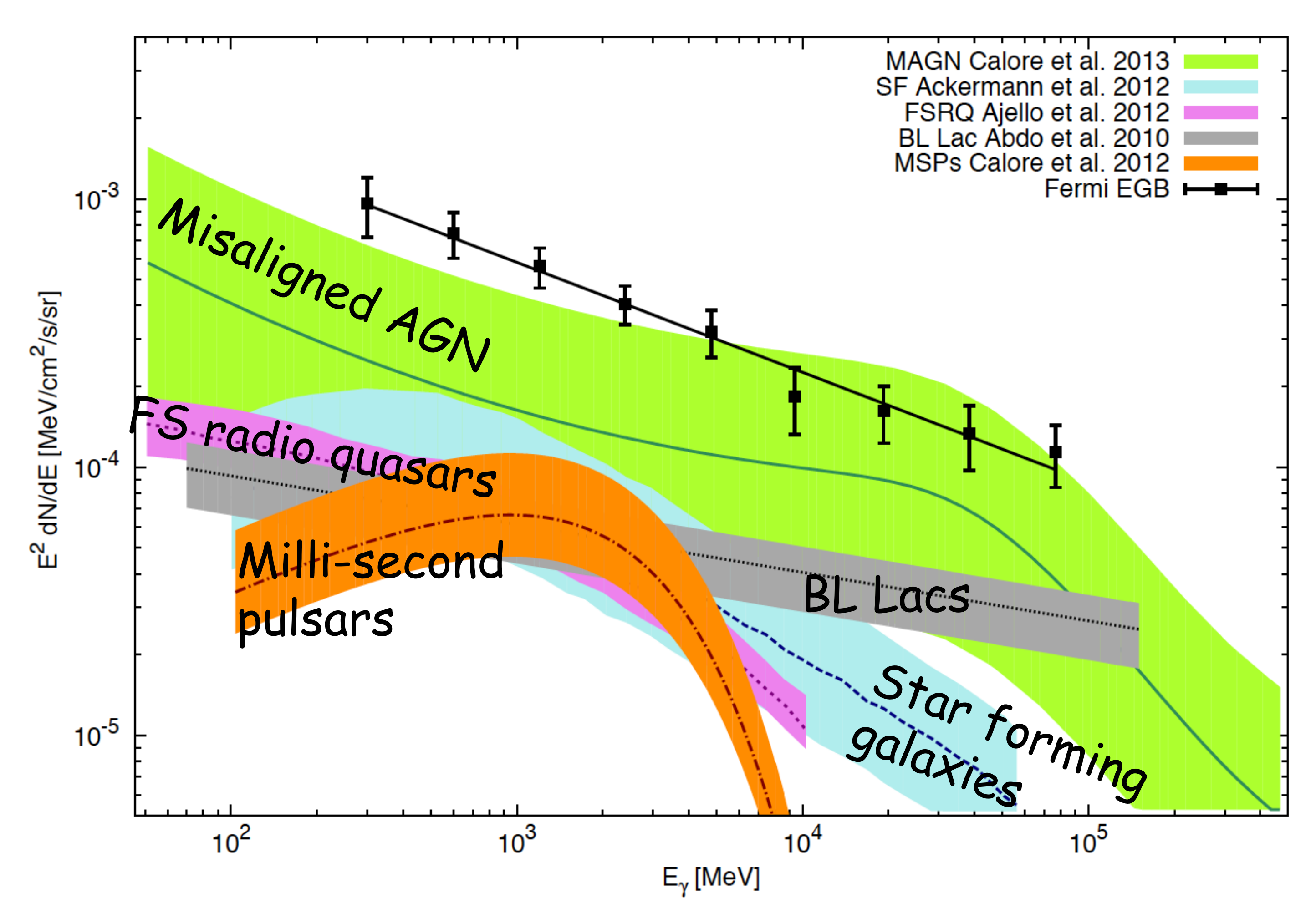
γ-rays from the inner Galaxy: bounds

Gomez-Vargas et al., 1308.3515



Regions of interest around the GC (40°x40° with masks) selected by maximizing S/N

Diffuse γ-ray emission from high galactic latitudes: the role of backgrounds from unresolved sources

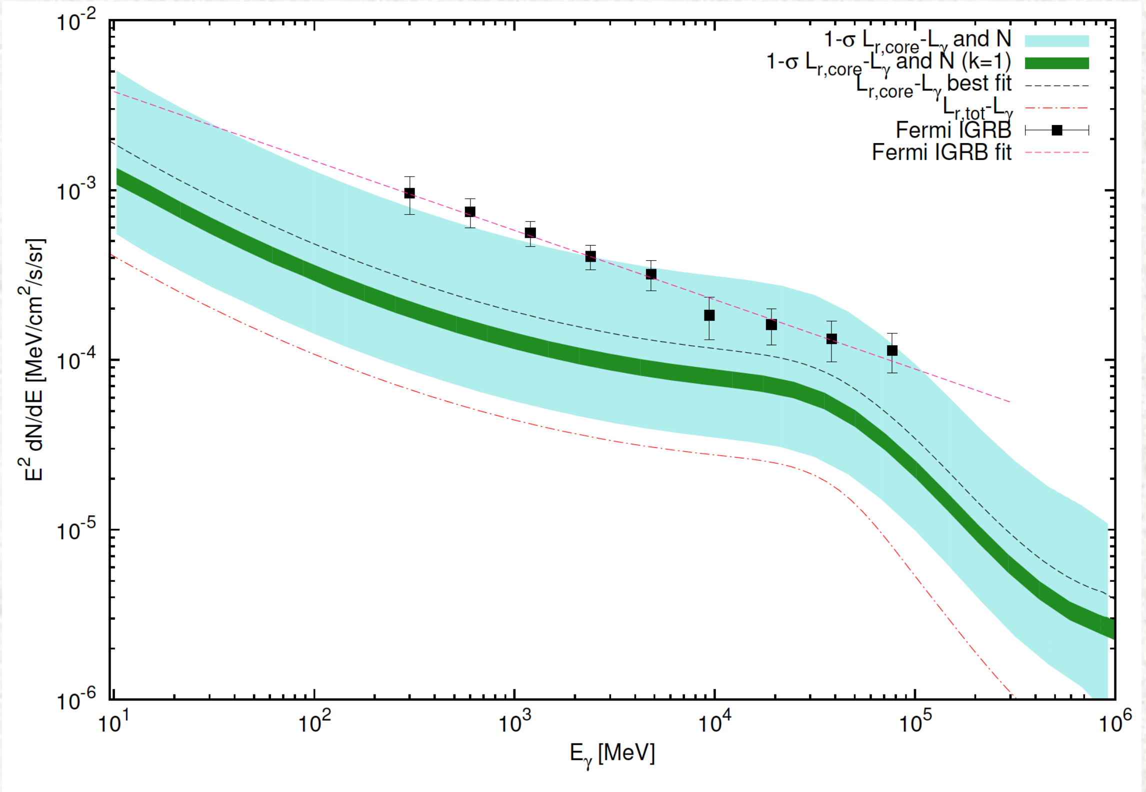


Bringmann, Calore, Di Mauro, FD 1303.3284

Isotropic γ-ray flux: contribution from unresolved misaligned AGN

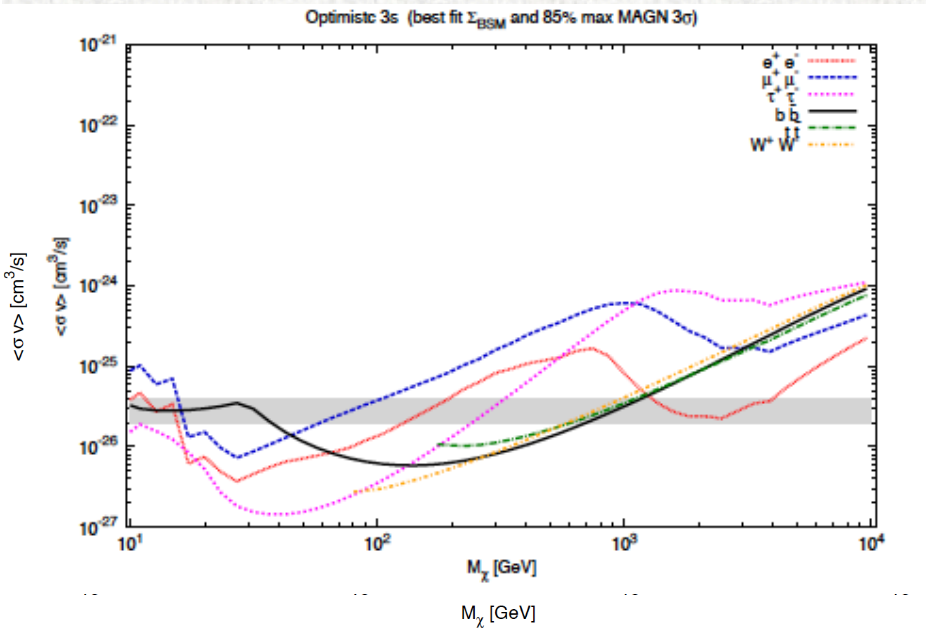
Di Mauro,Calore,FD, Ajello, Latronico 2013

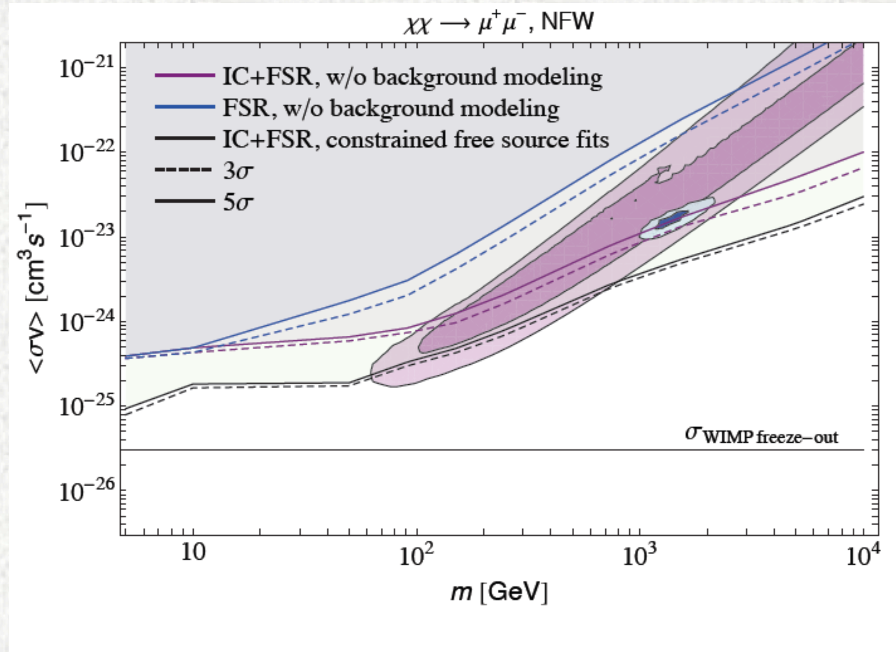
Best fit MAGN diffuse flux: 20-30% Fermi-LAT IGRB, |b|>10°
(MAGN might explain almost all the IGRB up 100 GeV)



Estimated uncertainty band: factor 10

Constraints to DM from diffuse γ-ray emission





High latitude data: |b|>10:

Bringmann, Calore, Di Mauro, FD 2013

- <u>Negligible</u> the choice for ρ(r)
- <u>crucial</u> the backgrounds from extra-galactic unresolved sources

Halo 5<|b|<15,|l|<80:

Fermi-LAT Coll. 1204.6474

-Models for the diffuse galactic emission <u>improve</u> the limits
- <u>Important</u> the choice for ρ(r)

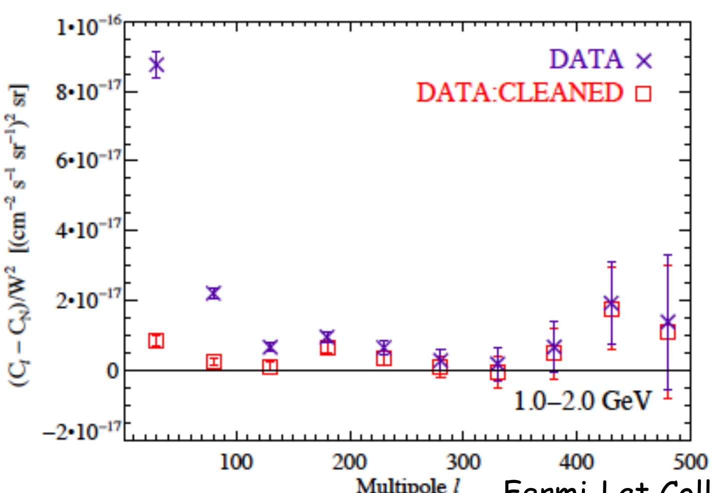
Anisotropies in γ-rays

Peculiar DM over-dense regions may imprint spatial signatures in high resolution data

$$\Delta_{\mathbf{flux}}(\Psi) = \frac{d\Phi}{dE}(\Psi) - \left\langle \frac{d\Phi}{dE} \right\rangle = \sum_{l=0}^{\infty} \sum_{m=-l}^{m=l} a_{lm} Y^{*}_{lm}(\Psi)$$

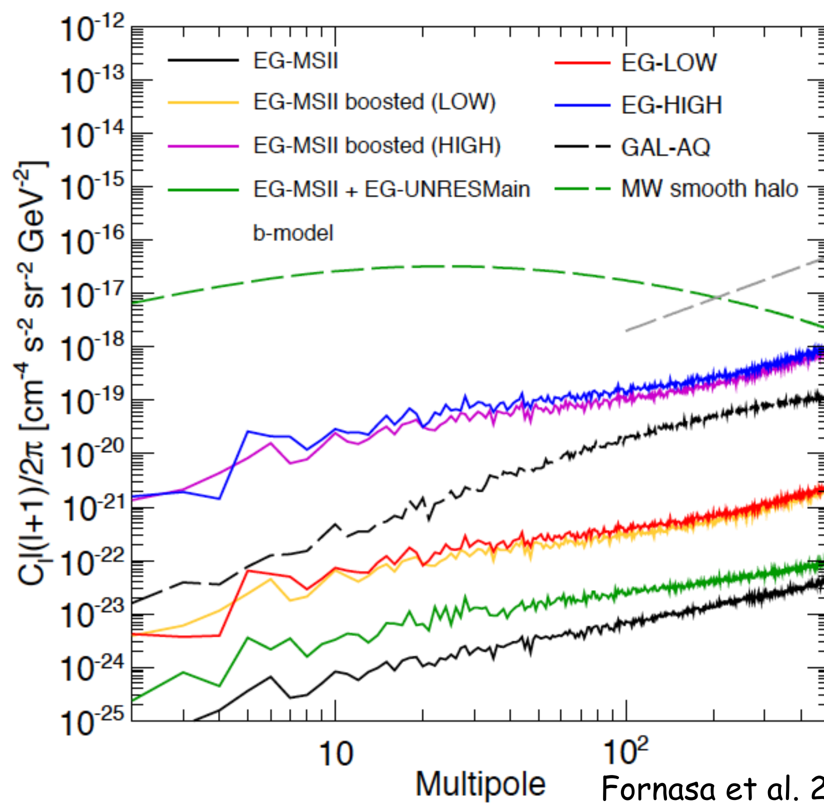
$$C_\ell = \frac{1}{2\ell+1} \left(\sum_{|m|\geqslant\ell} |a_{\ell m}|^2 \right),$$

Fermi-LAT: detected angular power >3σ in 1-10 GeV range at high l



Fermi-Lat Coll. 1202.2856

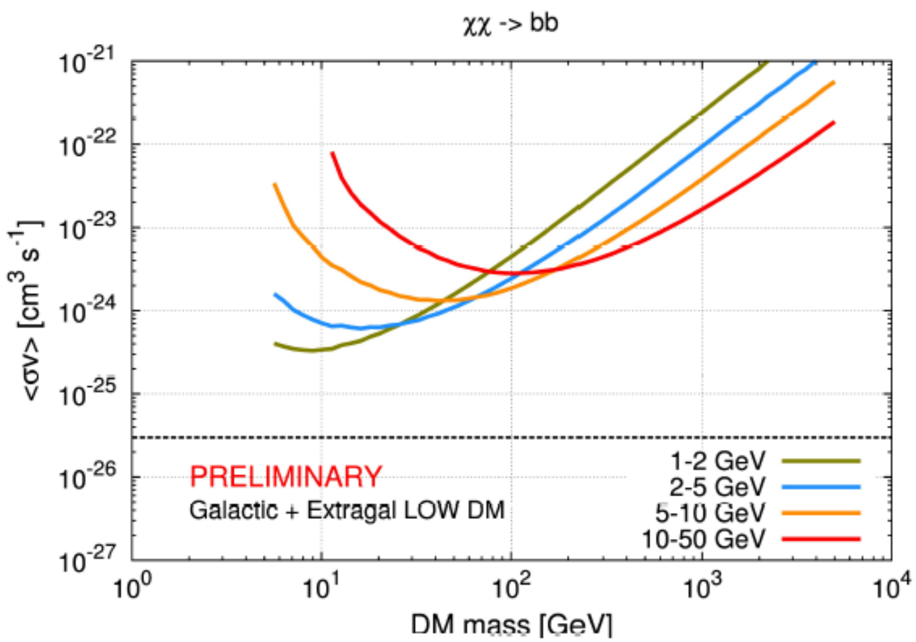
Predicted angular power spectrum: galactic and extragalactic

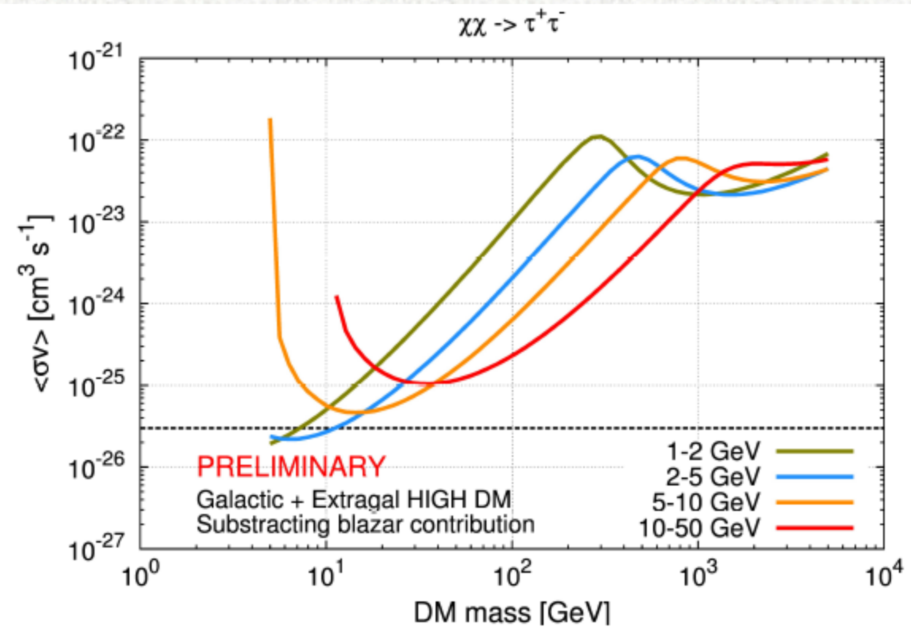


Fornasa et al. 2012

Anisotropies in γ-rays: DM constraints
From angular power spectrum

Gomez-Vargas et al, 1303.2154



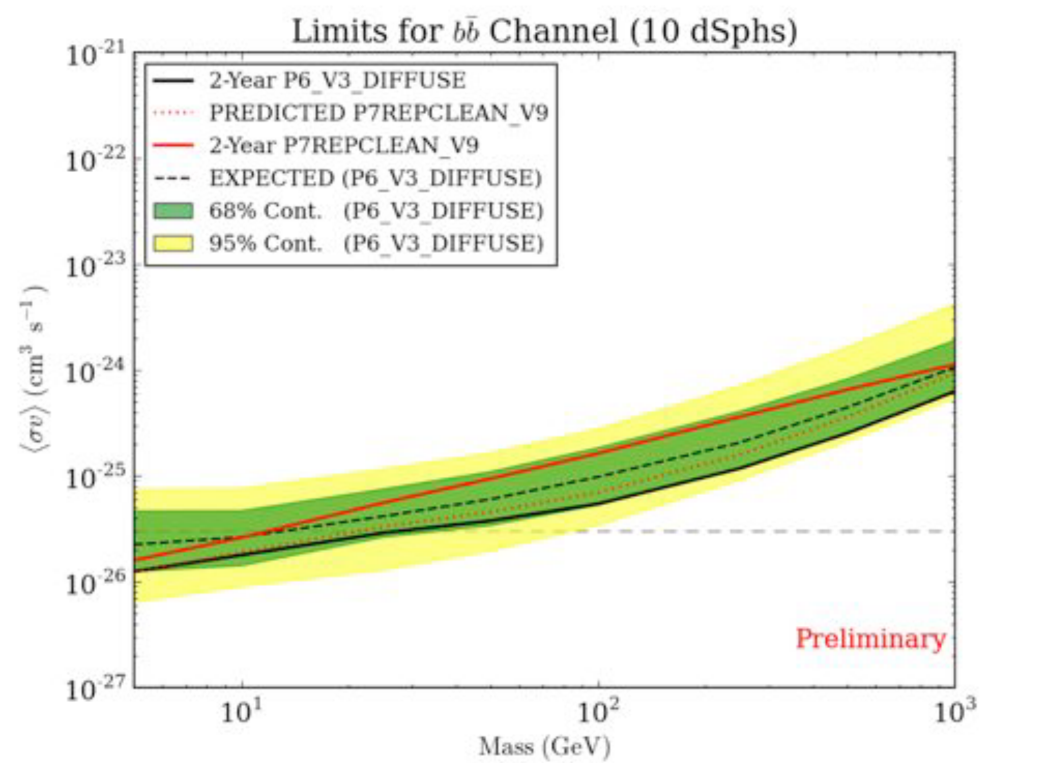


Bounds depend on modeling the low-mass subhalos,
below the simulations numerical resolution.
Strongest limits are obtained if blazars
angular power spectrum is subtracted.

DM in Dwarf Spheroidal satellite Galaxies

Dsph Galaxies are very interesting DM targets:

1. Most DM dominated objects in the Universe
2. Multi-λ observations do not motivate astrophysical backgrounds
3. Quite close (25-150 kpc) sources
4. Located at high latitudes (low galactic foreground)



A.Drlica-Wagner, Fermi Symposum 2012

Preliminary:
4-year Pass7 data yield higher bounds than 2 years Pass6: statistical fluctuations in the event classification

Strong bounds
Mildly model dependent

Fermi-LAT Coll, PRL 2011;
A.Drlica-Wagner, Fermi Symposum 2012

Also: Charbonnier+ 2011; Walker+ 2011
Geringer-Sameth&Koushiappas 2011

Radio signals from DM

Colafrancesco, Profumo,Ullio 2007; Regis Ullio 2008; Fornengo, Linerso, Regis, PRL2011,JCAP2011a,b

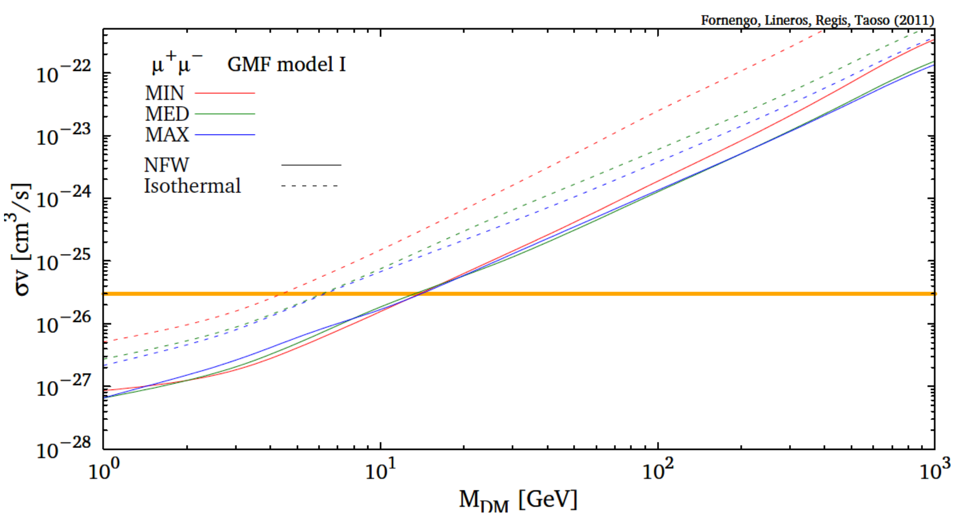
e^+e^- from DM annihilating can induce radio signals by **synchrotron emission**

$$\nu_{\mathrm{GHz}} \sim B_{\mu\mathrm{G}} \left(\frac{E}{15\,\mathrm{GeV}} \right)^2$$

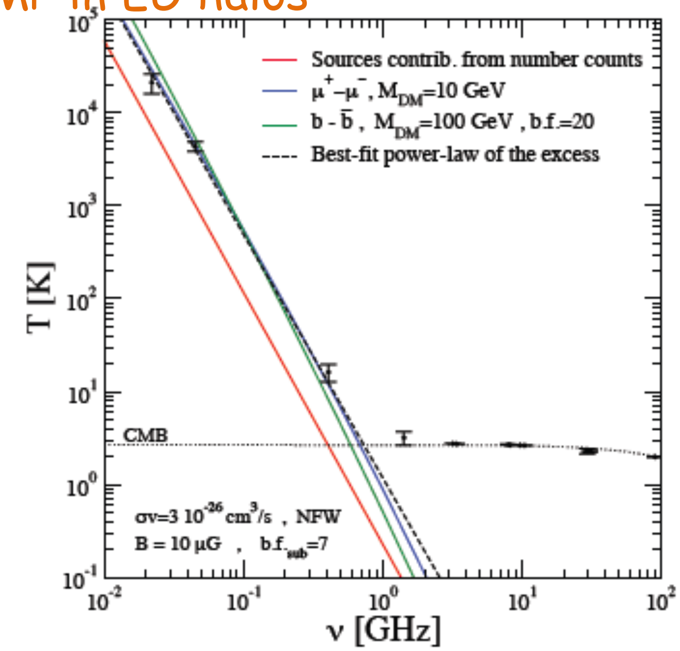
in galactic and extragalactic magnetic field

Arcade excess w.r.t. EG sources:
+ WIMP in EG halos

All sky, 5 bands survey



Fornengo, Lineros, Regis, Taoso JCAP 2012

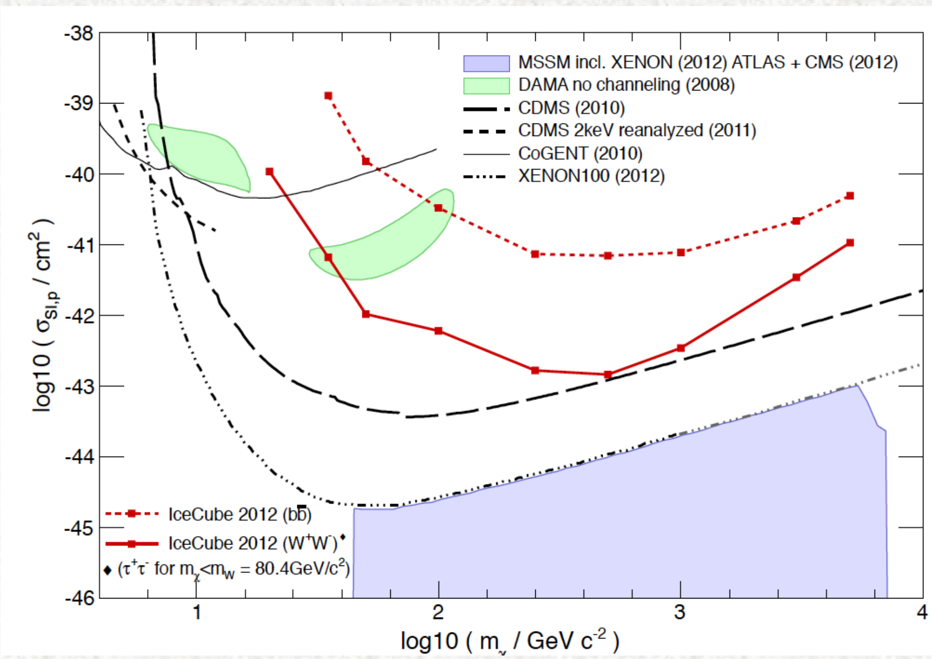


Fornengo, Lineros, Regis, Taoso PRL 2012

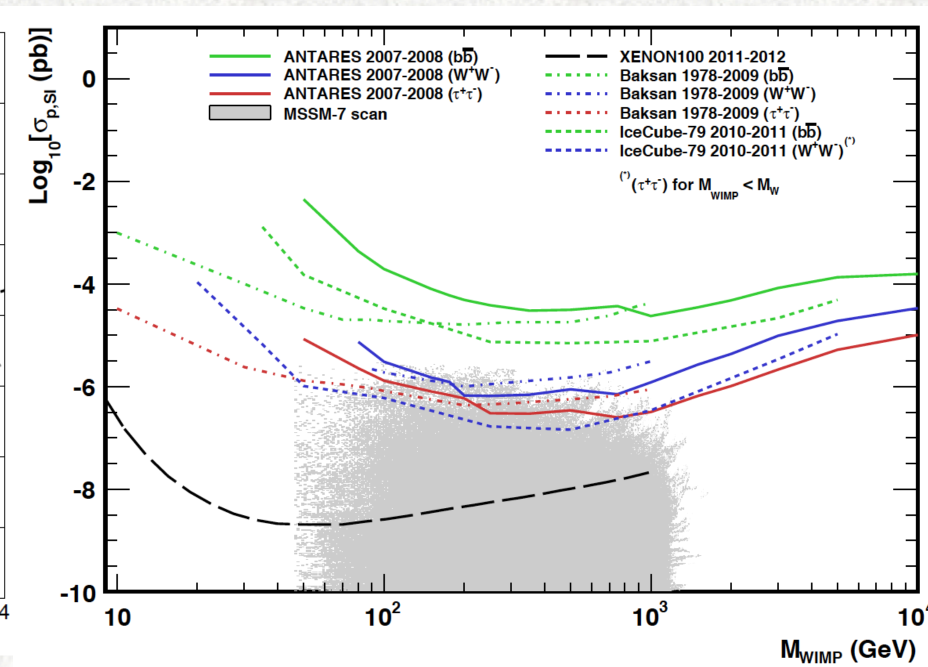
Neutrinos from DM annihilation in the Sun: current upper limits

WIMP DM gravitationally accumulates in the center of the Sun and Earth
→ annihilate into neutrinos (almost unabsorbed in the Sun)
→ detectable at neutrino telescopes

Icecube Coll. PRL 2013

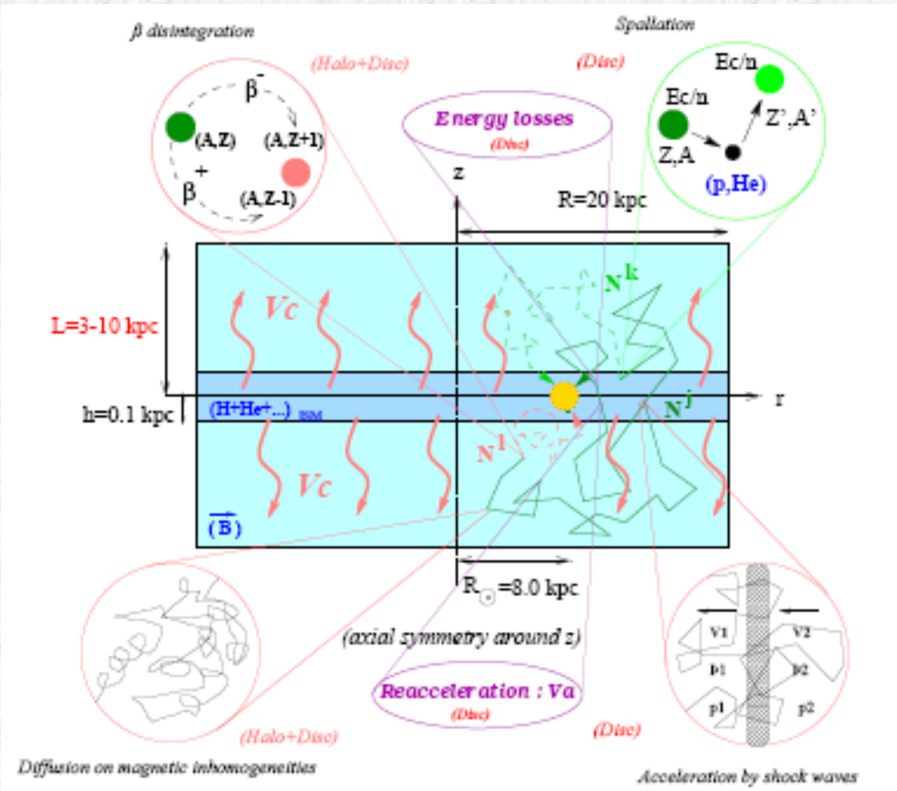


Antares Coll. 1302.6516



See talks by M. Spurio, K. Choi, M. Ackermann, M. Danninger

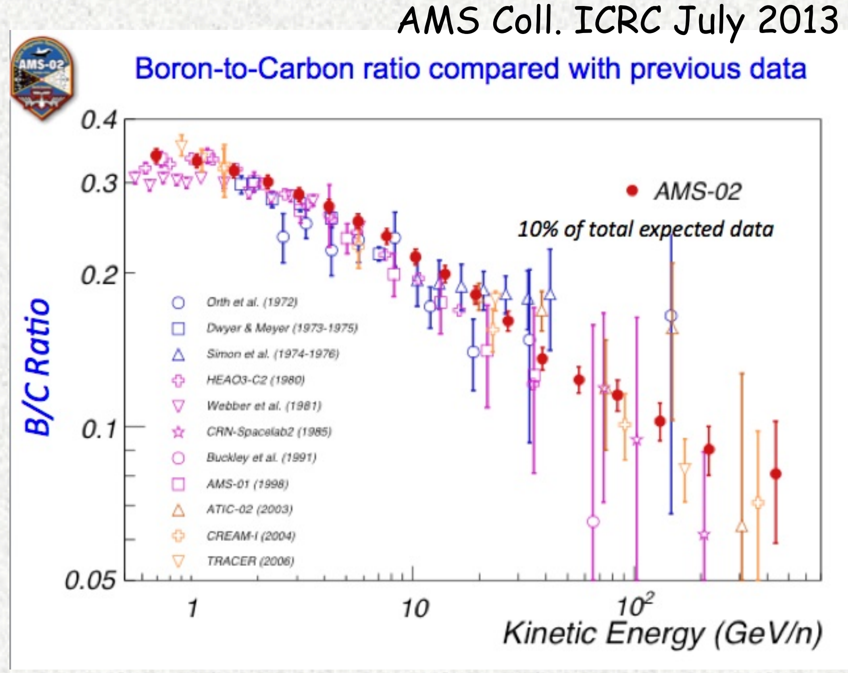
Cosmic antimatter fluxes from DM annihilation in the Milky Way halo



Diffusive models for CR propagation in the Galaxy

Jopikii & Parker 1970; Ptuskin & Ginzburg, 1976; Ginzburg, Khazan & Ptuskin 1980; Weber, Lee & Gupta 1992, ...; Maurin, FD, Taillet, Salati 2001; Maurin, Taillet, FD 2002; Putze, Derome, Maurin 2010; Strong & Moskalenko 1998; Moskalenko, Strong, Ormes, Potgieter,2002; Shibata, Hareyama, Nakazawa, Saito 2004; 2006;); Evoli, Gaggero, Grasso, Maccione 2008; Di Bernardo et al. 2010; …

AMS Coll. ICRC July 2013



AMS data on CRs: great step forward for fixing Propagation and source models!

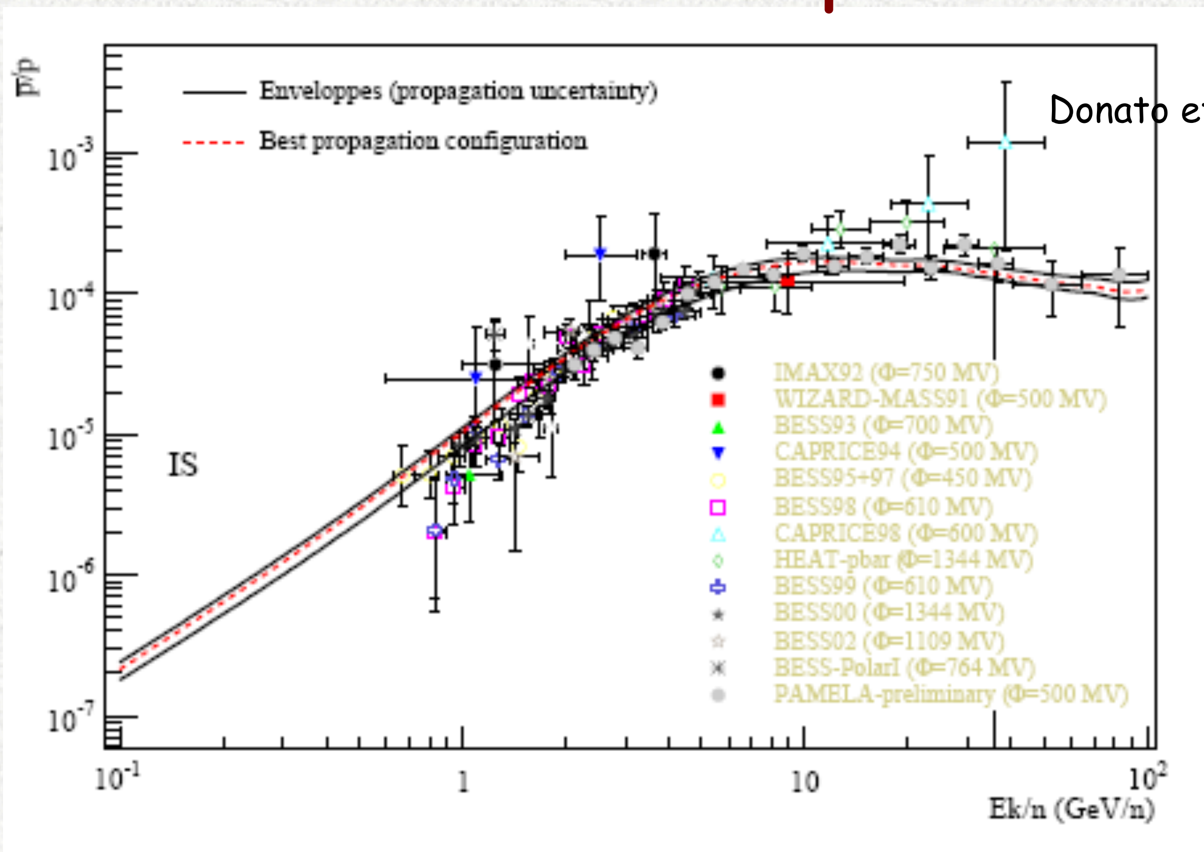
Antiproton in CRs: data and models

Theoretical calculations with the semi-analytical DM, compatible with stable and radioactive nuclei

NO need for new phenomena (astrophysical / particle physics)

→ Bounds to models

AMS-02 data expected ☺



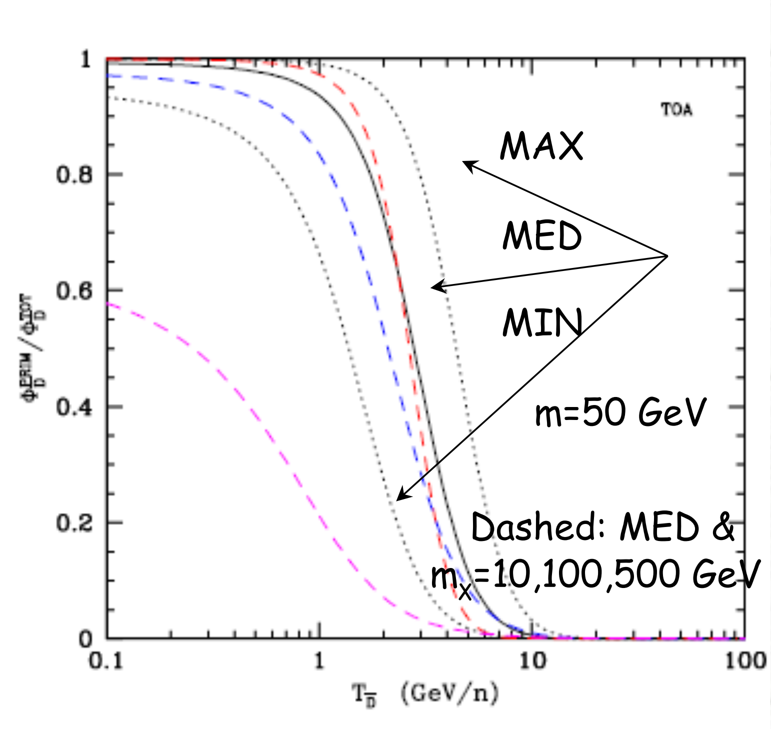
Donato et al. PRL 2009

(talk by M Grefe)

Antideuterons in Cosmic Rays

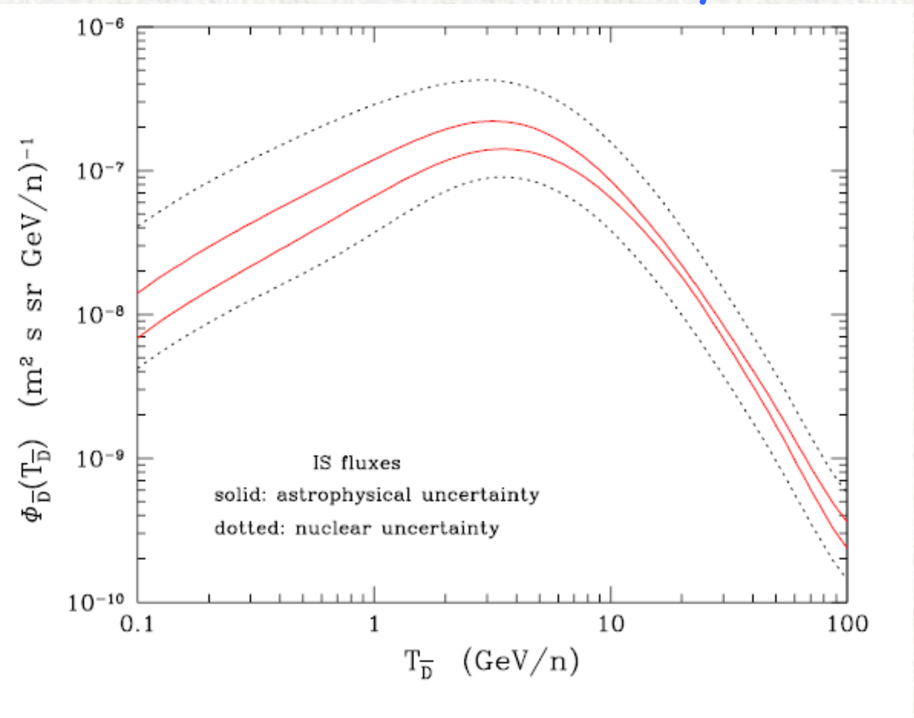
FD, Fornengo, Salati PRD 2000; FD, Fornengo, Maurin PRD 2008

Antideuterons may form by the fusion of an antiproton and an antineutron



Low energy antideuterons have a <u>high discrimination power</u>

Secondary antideuterons are predicted with sizeable nuclear uncertainty



Antideuterons: detection perspectives

AMS is in space
and performing very well!

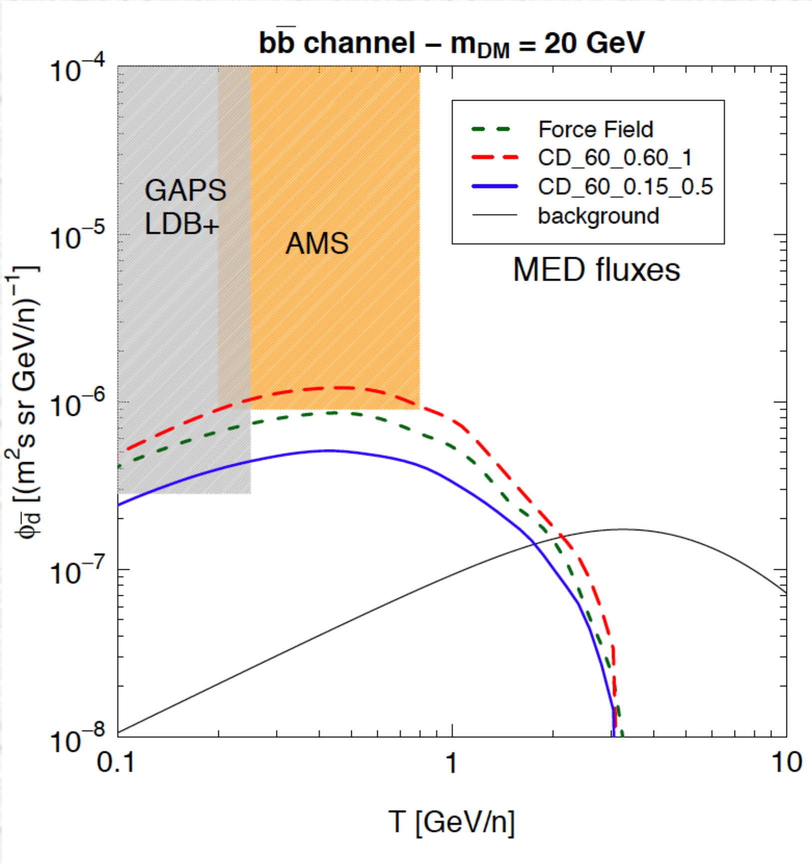
(see talk by Roberto Battiston)

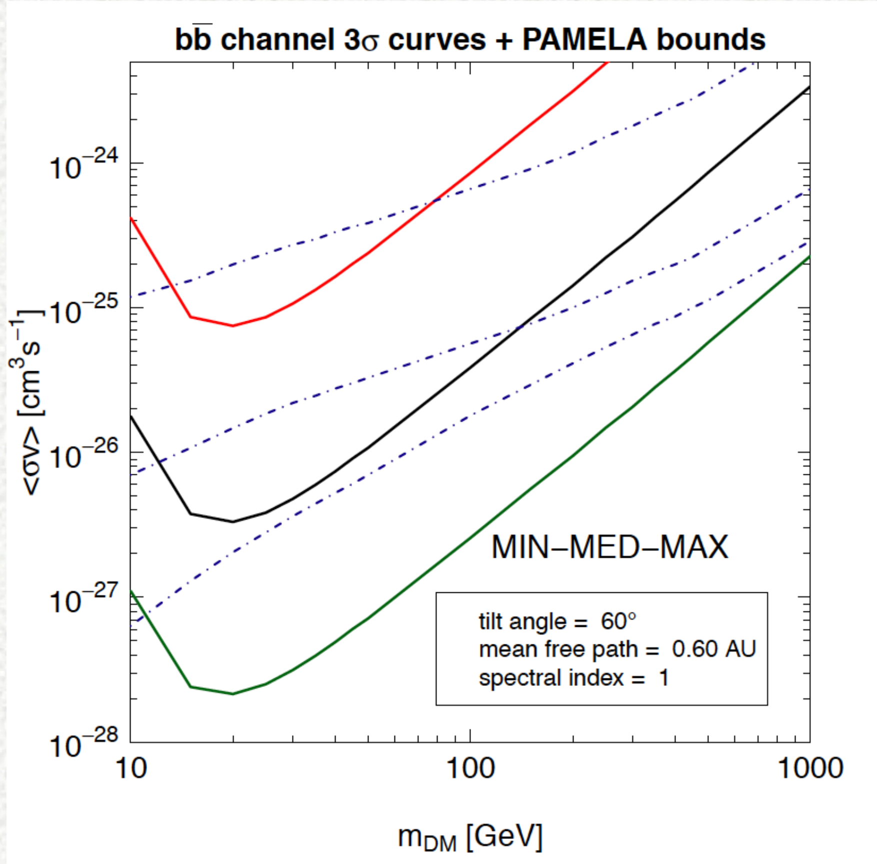
GAPS is a dedicated balloon experiment

Prototype flight 06.2012!
(1307.3538)

Antideuterons: detection perspectives

Fornengo, Maccione, Vittino 1306.4171



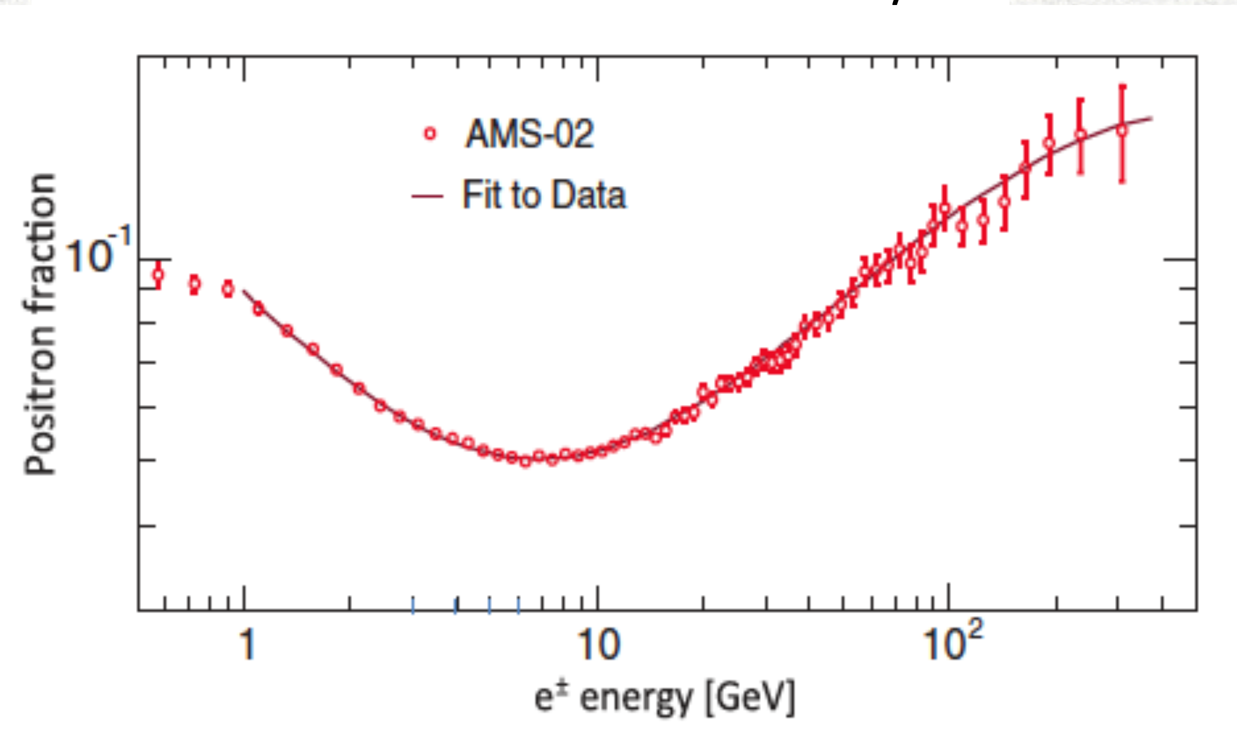


3σ expected sensitivities

Prospects for 3σ detection of antideuteron with GAPS (dotted lines are Pamela bounds from antiprotons)

Positron Fraction I: new data and ….

AMS Coll. PRL 2013 & Talk by R. Battiston



$$\Phi_{e^+} = C_{e^+} E^{-\gamma_{e^+}} + C_s E^{-\gamma_s} e^{-E/E_s}$$

$$\Phi_{e^-} = C_{e^-} E^{-\gamma_{e^-}} + C_s E^{-\gamma_s} e^{-E/E_s}$$

Excellent fit with diffuse-like spectra and a common, generic, cut-off source

Positron Fraction II: new data and … which models?

If DM invoked to explain high energy positron fraction data (Hooper+09, Regis&Ullio09,Bergstrom+09, Cirelli,Pnaci, Serpico09 …. hundreds of paper, indeed!!!):

- large DM masse
- high cross section
- hard final state spectrum
- Hadronic channels suppressed

If ASTROPHYSICS invoked: PULSARs (and SNRs) are there:

e^+ and e^-: pair production in the strong pulsar magnetoshpere

(Hooper,Blasi,Serpico09; Profumo0812.4457, Grasso+2009, Delahaye+2010;..)

- High energy e- are accelerated by the strong pulsar electric field
- e- synchrotron radiate gamma rays
- e^+/e^- are produced by pair conversion in strong magnetic fields of the PSR or scattering off of thermal X-rays

PULSARS CAN BE THE SOURCES OF ENERGETIC e^+e^-!

MORE DATA AND AT HIGHER ENERGIES ARE EXPECTED BY AMS-02

Conclusions and outlooks

- Indirect dark matter detection has entered a precision era, most recently thanks to Fermi-LAT and AMS-02
- Some intriguing hints are challenged by statistics and by alternative astrophysical interpretation
- Major effort is needed in the understanding astrophysical bounds
- A multiwavelength and multichannel approach - mandatory for backgrounds understanding – looks powerful also for DM searches

Indirect DM searches cannot proceed alone but are complemented by direct DM searches

and new particle production at colliders