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Conservative upper limits on WIMP annihilation cross section from Fermi-LAT gamma rays*

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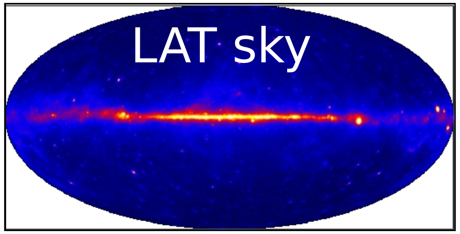
* arXiv: 1105.4230

The Isotropic Diffuse Gamma-Ray Emission



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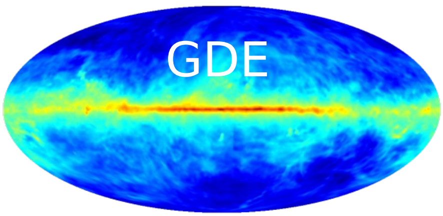

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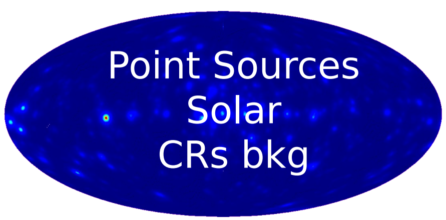

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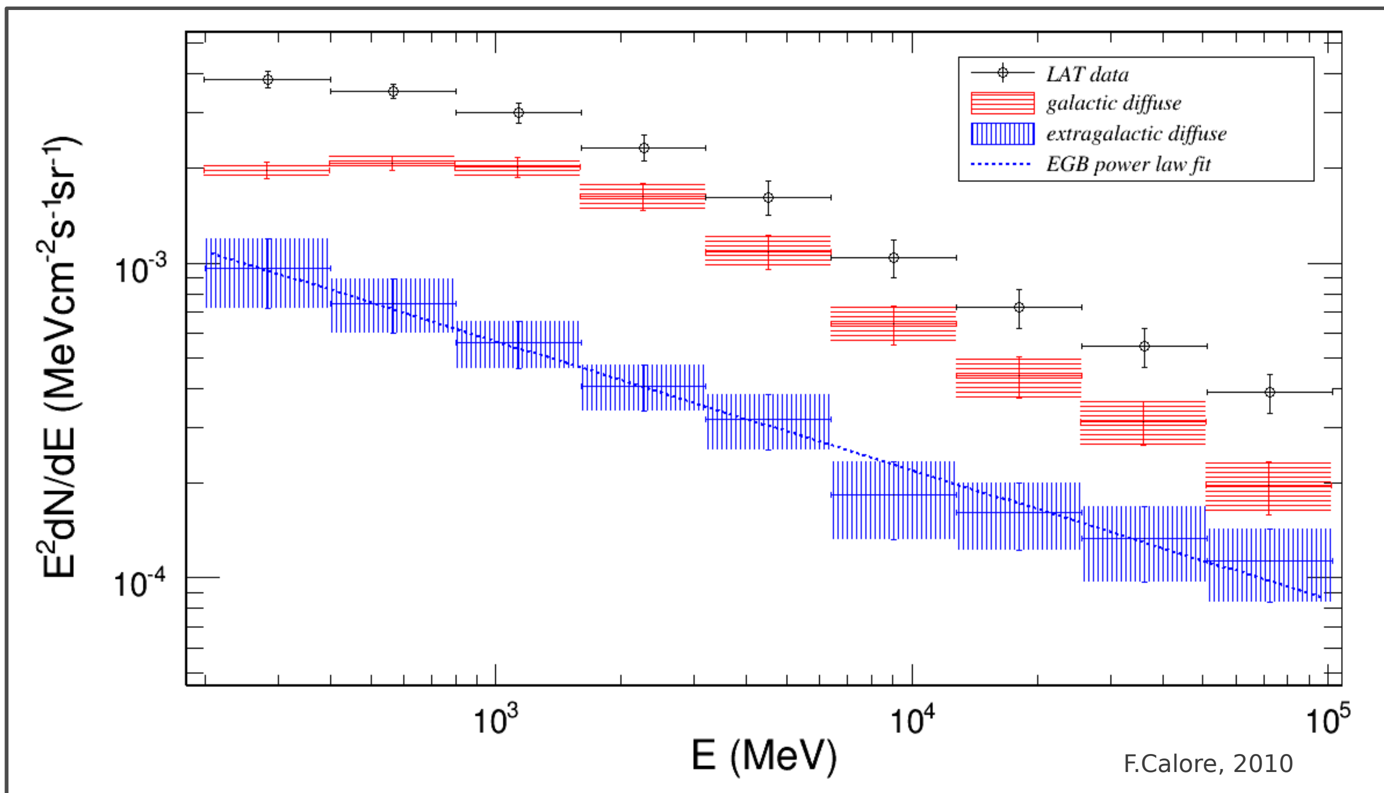
Isotropic Diffuse Gamma-Ray or "Extragalactic" Background (EGB)

The Spectrum of the Isotropic Diffuse Gamma-Ray Emission Derived From First-Year Fermi Large Area Telescope Data, The Fermi-LAT Collab. Phys. Rev. Lett. 104 (2010):

- Energy range: 200 MeV – 100 GeV.
- Observational region: |b| > 10° (high-latitude).
- Energy spectrum:

$$\frac{dN}{dE} = 1.45\, x\, 10^{-7} \left(\frac{E}{100\, MeV} \right)^{-2.41} MeV^{-1}\, cm^{-2}\, s^{-1}\, sr^{-1}$$



Overview: Constraining DM with the EGB

1. Understanding of the astrophysical background:

   Contributions (controversial but guaranteed):

   - Unresolved pointlike sources extragalactic (*e.g.* AGN, normal and starbursts galaxies, GRBs, Clusters of Galaxies) and galactic (Pulsars and Millisecond Pulsars);
   - Truly diffuse processes (*e.g.* LSS formation signature, UHECRs vs CMB, cascades of VHE gamma-rays from point sources).

2. Selection of the main contributions:

   Estimation of a residual extragalactic bkg.

3. Conservative upper limits on WIMP annihilation cross section.

(1) The non-DM astrophysical bkg: guaranteed contributions

1. Unresolved blazars: FSRQs and BL Lacertae objects;
2. Millisecond Pulsars;
3. Normal StarForming Galaxies.

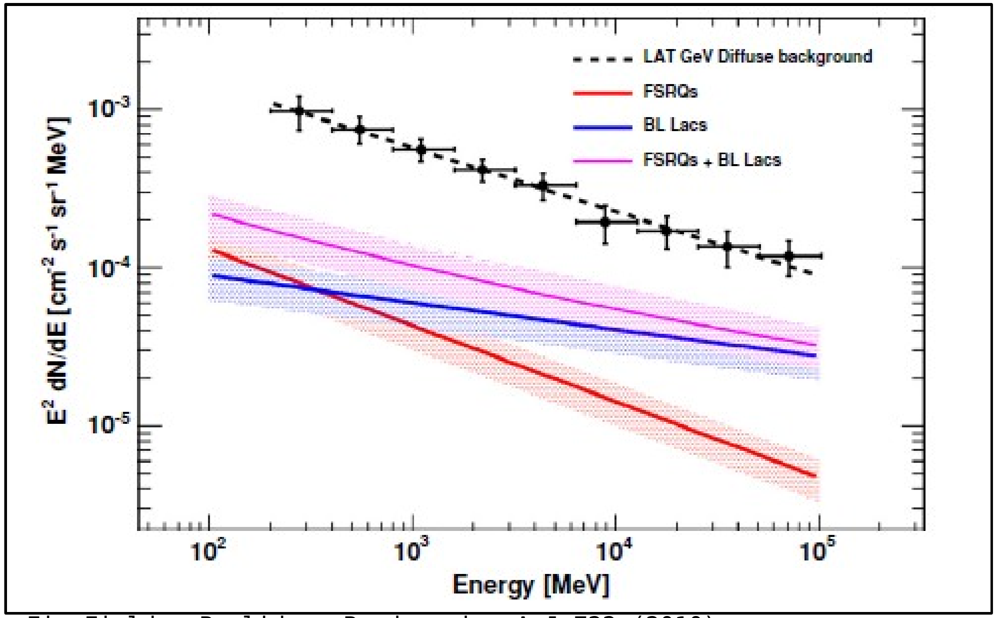


Fig:Fields, Pavlidou, Prodanovic, ApJ 722 (2010)

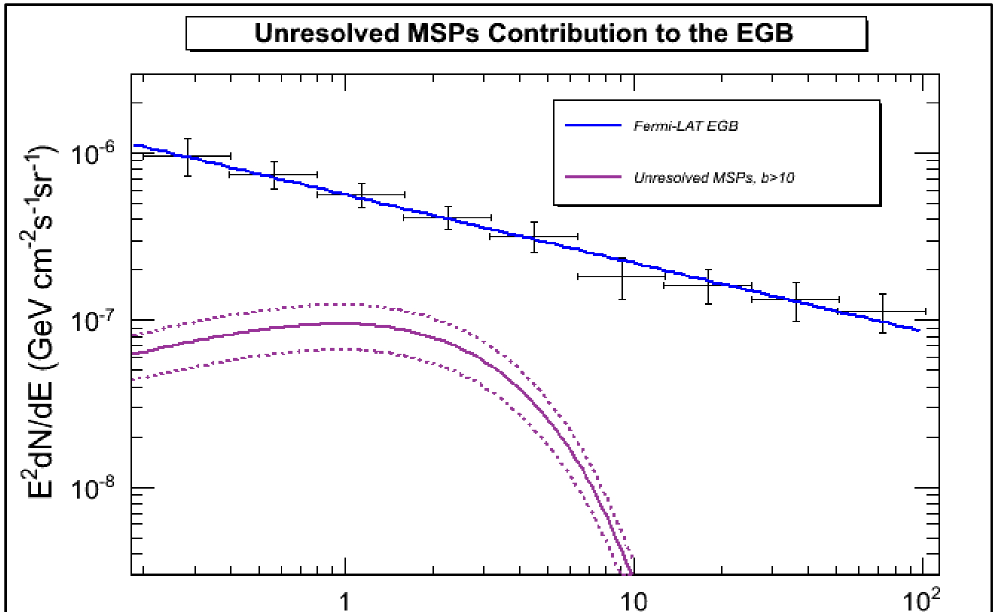


Fig: F.Calore (2011)

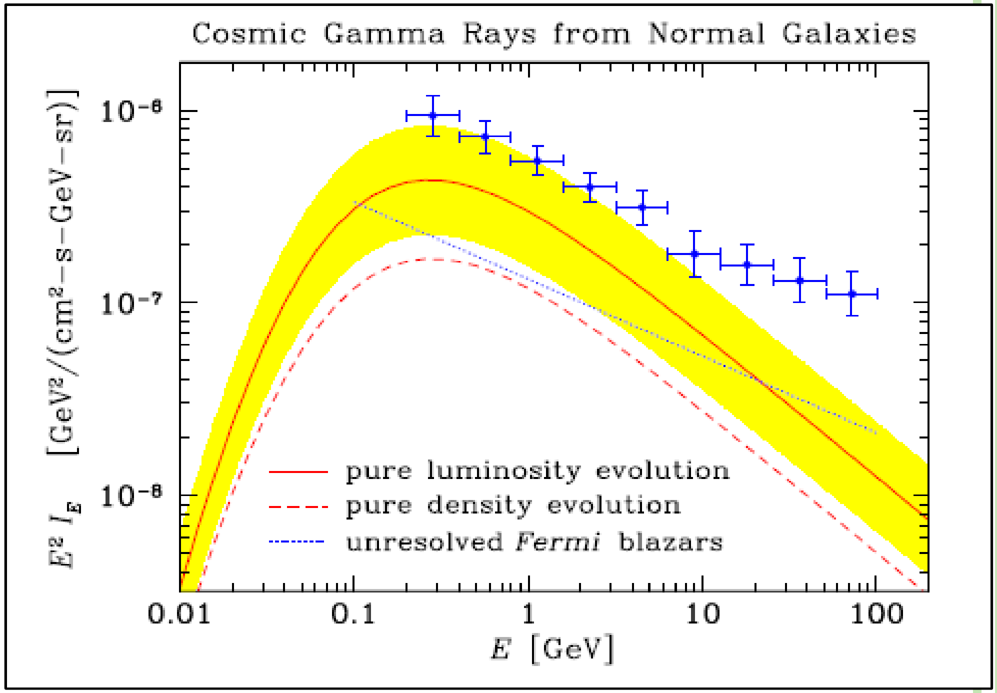


Fig:Fermi-LAT Collab. ApJ, 720 (2010)

(1) The non-DM astrophysical bkg: guaranteed contributions

1. Unresolved blazars: FSRQs e BL Lacertae objects.
2. Millisecond pulsars.
3. Normal Starforming Galaxies.
4. Gamma-rays from UHECRs:
   - *Truly diffuse emission*:

     $p + \gamma_{CMB} \rightarrow p + e^{+} + e^{-}$

     $\gamma\gamma_{b} \rightarrow e^{+}e^{-}$ (PP); $e^{\pm}\gamma_{b} \rightarrow e^{\pm}\gamma$ (ICS)
   - *Theoretical uncertainties*: injection spectrum of primary protons and source evolution.

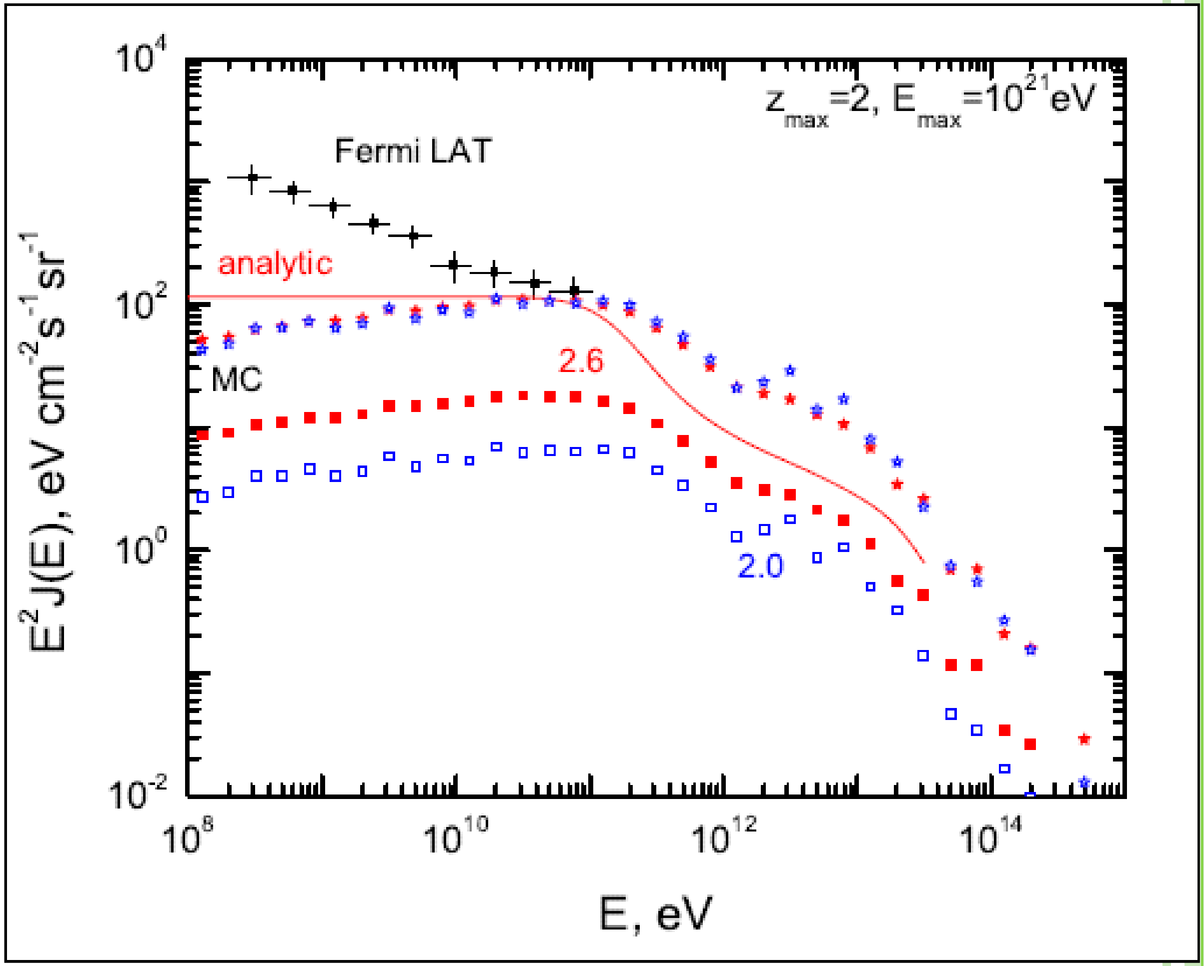


Fig:Berezinsky et al. Phys.Lett. B695 (2011)

(2) Residual Extragalactic Background

- **Identified contributions** must be subtracted from the LAT data in order to obtain a residual EGB.

- Great uncertainties both theoretical and observational, **two scenarios** :

  In **Model I** we subtracted:

  (a) Blazars: FSRQs and BL Lac objects;

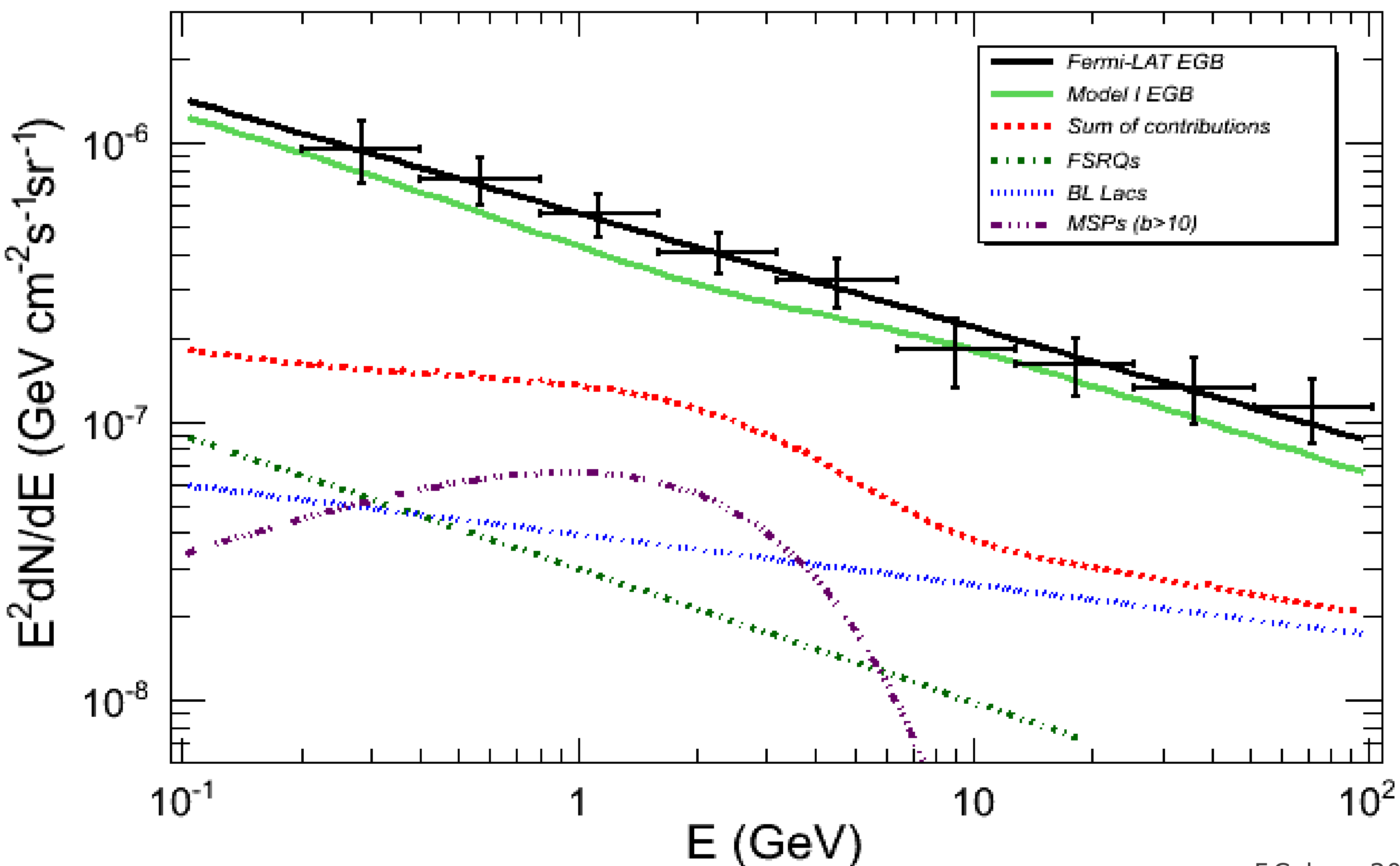
  (b) MSPs population at $|b| > 10°$.

  In **Model II** we further subtracted:

  (c) Normal star forming galaxies : pure density evolution model;

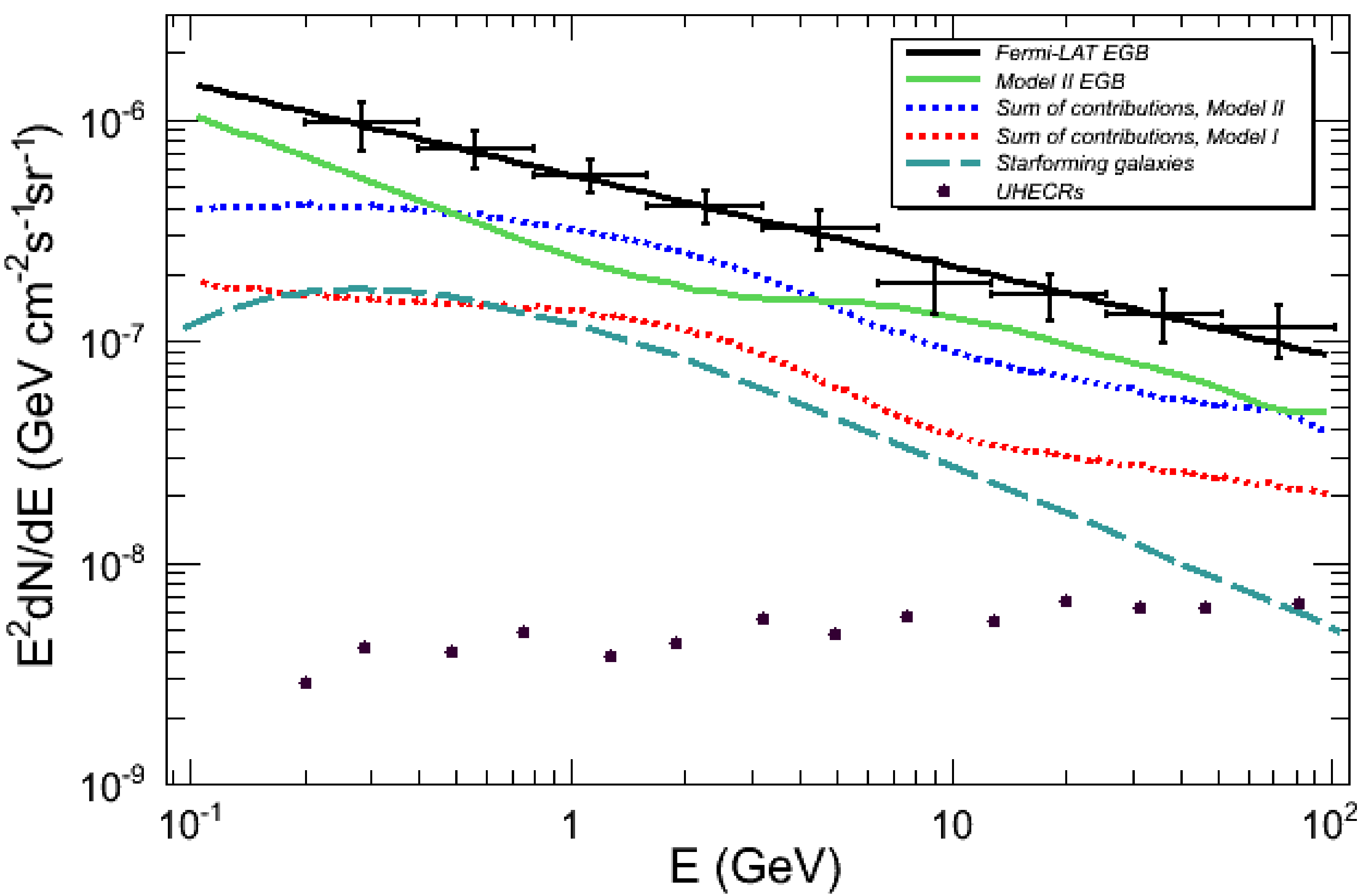
  (d) Gamma rays from UHECRs : ankle model (2.0).

(2) Residual EGB: Model I



F.Calore, 2010

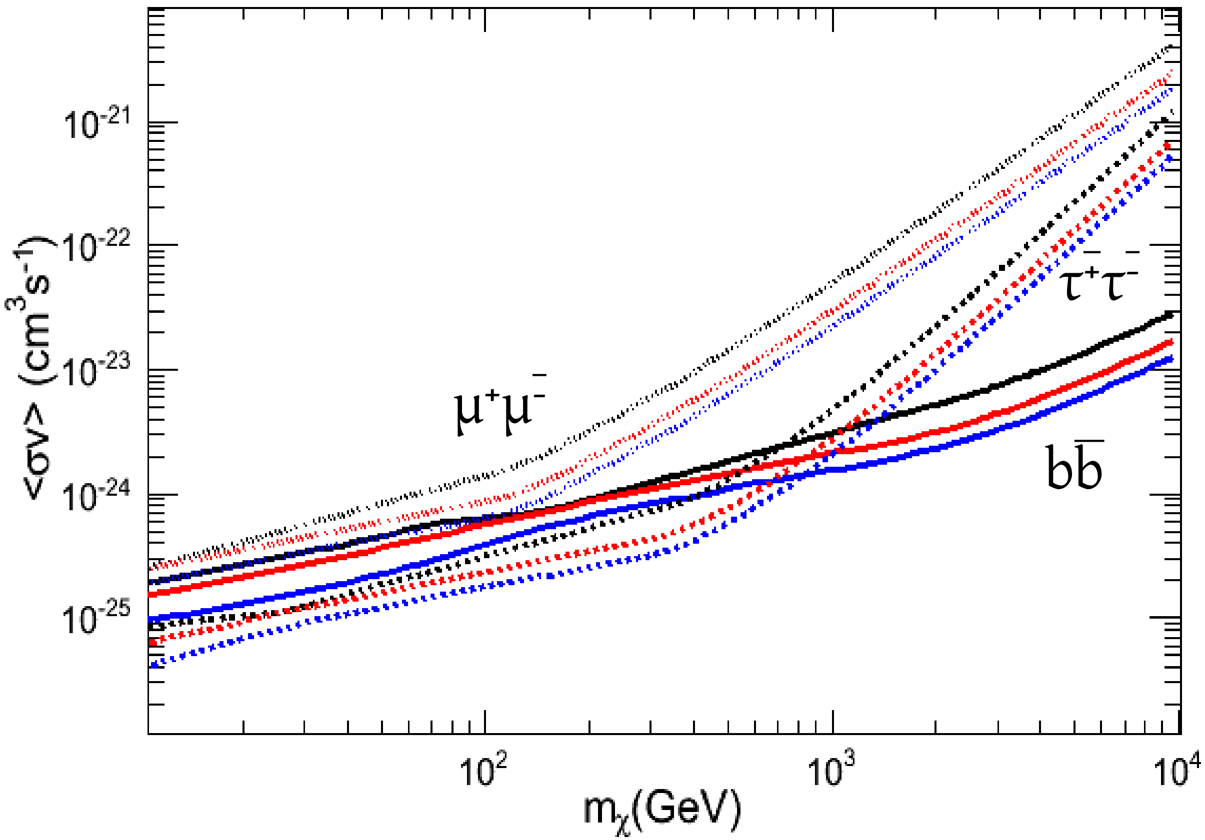
(2) Residual EGB: Model II



F.Calore, 2010

Conservative upper limits on <σv>

- Cored isothermal density profile for the Galactic halo;
- Smooth halo (no clumpiness);
- DM final states: $b\bar{b}$, $\mu^+\mu^-$, $\tau^+\tau^-$



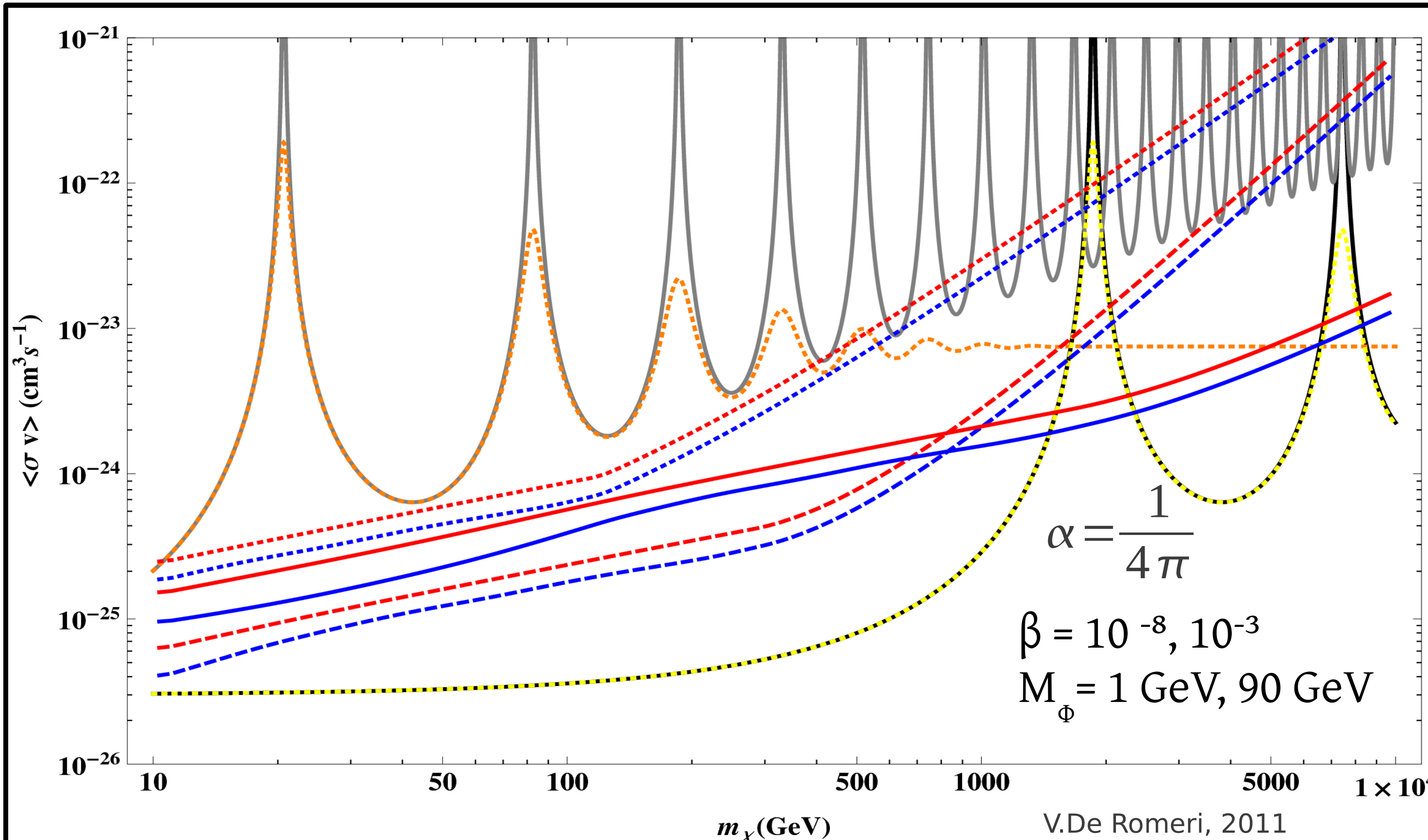
F.Calore, 2011

- Little dependence on DM distribution;
- Conservative limits;
- Mild differences due to final states;
- Advantages of indirect detection through gamma rays (propagation not affected by the Galaxy)

Bounds on the Sommerfeld enhanced <σv>

Recent claims on the excess of CR positrons have stimulated the interpretation of data in terms of annihilating DM with fairly large <σv>:

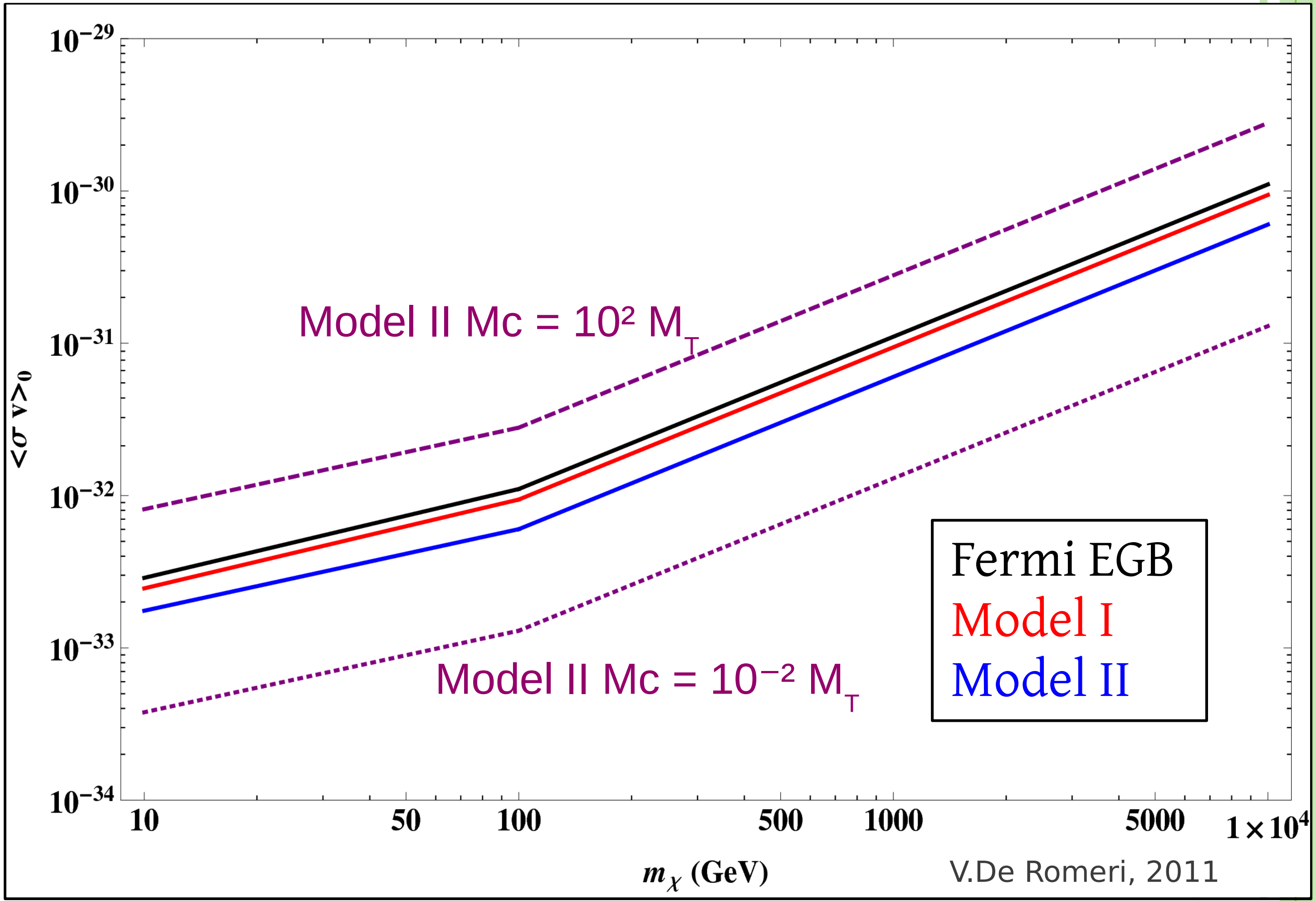
One way of boosting is through the Sommerfeld enhancement.



Conservative upper limits from early proto halos

A boosted production of gamma rays in models with <σv> depending on 1/v has been predicted for the first DM bound objects

$$\langle \sigma v \rangle = \langle \sigma v \rangle_0 \frac{c}{v} cm^3 / sec$$



Energy density in photons today from WIMP annihilation in protohalos:

$$\rho_\gamma = 5.28\times10^6 \left(\frac{M_c}{M_T}\right)^{-1/3} \left(\frac{1}{\beta}\right) < \sigma v >_0 B_{2.6} \left(\frac{m_\chi}{TeV}\right)^{-1} GeV\, cm^{-3}$$

Conclusions

- New estimation for a residual EGB, subtracting the emission from unresolved blazars and MSPs (conservative scenario) and, further, starforming galaxies and gamma rays from UHECRs (relaxed scenario).
- A conservative (i.e. it is unlikely that a higher cross section is compatible with the "true" extragalactic bkg) upper bound on $< \sigma v >$ is derived by assuming that the Model I and II EGB are entirely due to WIMPs pair-annihilating in the halo of our Galaxy.
- The bounds on $< \sigma v >$ have been interpreted in terms of Sommerfeld enhancement of the annihilation cross section. A Sommerfeld enhancement due to a force carrier of $m_\varphi < 1$ GeV ($\alpha = 1/4\pi$) is strongly excluded by Model I and II for the Fermi-LAT EGB data.
- We have explored the possibility that the residual gamma-ray EGB is entirely due to cosmological annihilation of DM in protohalos at high redshift. Very severe limits are thus derived for the velocity-independent part of the annihilation cross section, depending on the protohalo mass

Conclusions

- New estimation for a residual EGB, subtracting the emission from unresolved blazars and MSPs (conservative scenario) and, further, starforming galaxies and gamma rays from UHECRs (relaxed scenario).
- A conservative (i.e. it is unlikely that a higher cross section is compatible with the “true” extragalactic bkg) upper bound on $< \sigma v >$ is derived by assuming that the Model I and II EGB are entirely due to WIMPs pair-annihilating in the halo of our Galaxy. Values for $< \sigma v > \gtrsim 10^{-25} cm^3/s$ are strongly excluded for $m_\chi \simeq 10$ GeV.
- The bounds on $< \sigma v >$ have been interpreted in terms of Sommerfeld enhancement of the annihilation cross section. A Sommerfeld enhancement due to a force carrier of $m_\varphi < 1$ GeV ($\alpha = 1/4\pi$) is strongly excluded by Model I and II for the Fermi-LAT EGB data.
- We have explored the possibility that the residual gamma-ray EGB is entirely due to cosmological annihilation of DM in protohalos at high redshift. Very severe limits are thus derived for the velocity-independent part of the annihilation cross section, depending on the protohalo mass

Thanks for the attention

Backup slides

(1) The non-DM astrophysical bkg: guaranteed contributions

1. Unresolved blazars: FSRQs and BL Lacertae objects:
    1. Largest number of identified members (1FGL catalog).
    2. *Observed source count distribution analysis:* power-law spectrum.
    3. *Theoretical uncertainties* in the SED and luminosity function.

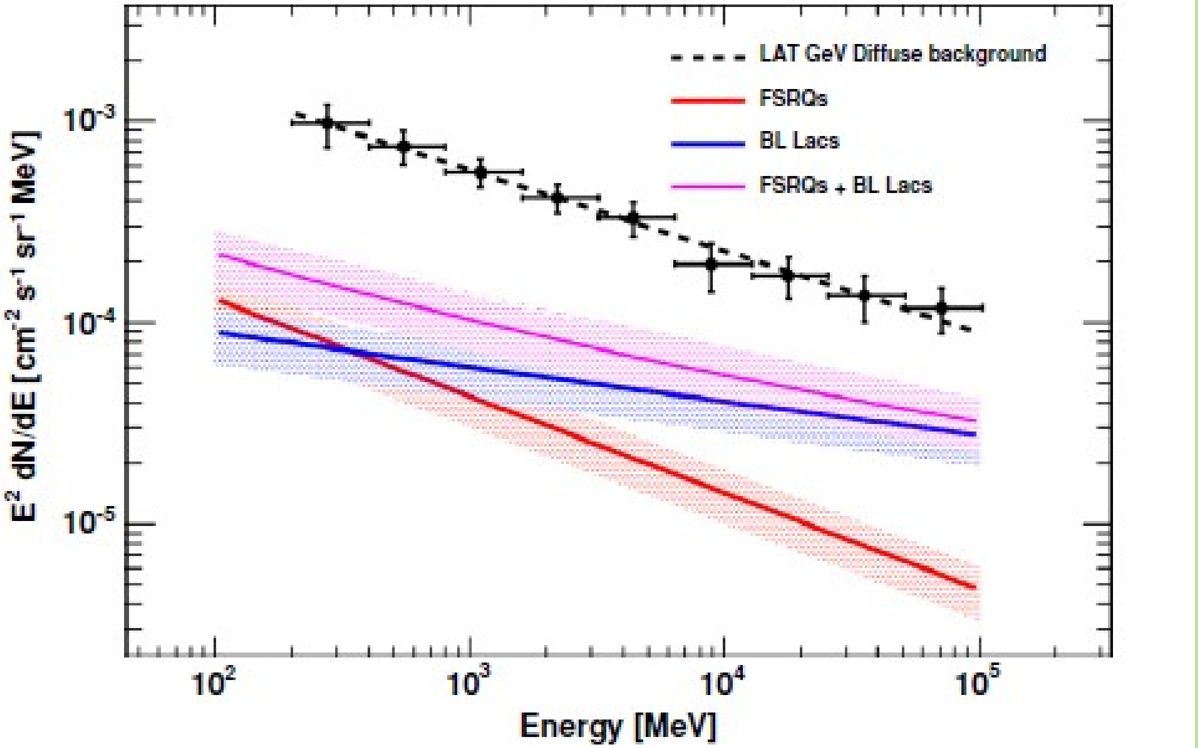


Fig:Fields, Pavlidou, Prodanovic, ApJ 722 (2010)

(1) The non-DM astrophysical bkg: guaranteed contributions

1. Unresolved blazars: FSRQs and BL Lacertae objects.
2. Millisecond Pulsars:
   - Galactic resolved pulsars and MSPs: second largest population (1FGL catalog).
   - *MSPs more prevalent* at high latitudes :

     Minimal guaranteed contribution from MSPs (|b| > 10°).

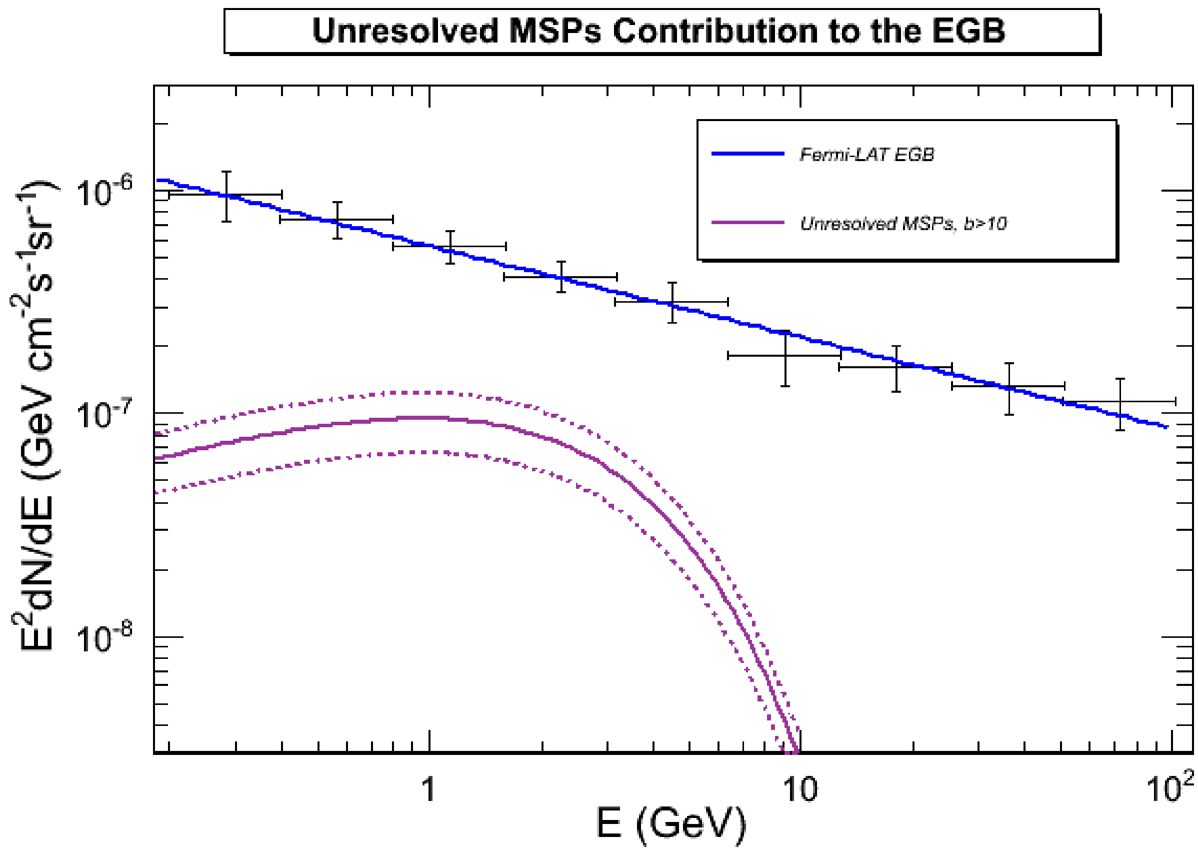


Fig: F.Calore (2011)

(1) The non-DM astrophysical bkg: guaranteed contributions

1. Unresolved blazars: FSRQs and BL Lacertae objects.
2. Millisecond Pulsars
3. Normal Starforming Galaxies:
   - *Gamma-ray emission*: CRs interactions with interstellar medium: *Theoretical uncertainties*.
   - *Limiting cases*: (a) pure luminosity evolution; (b) pure density evolution.

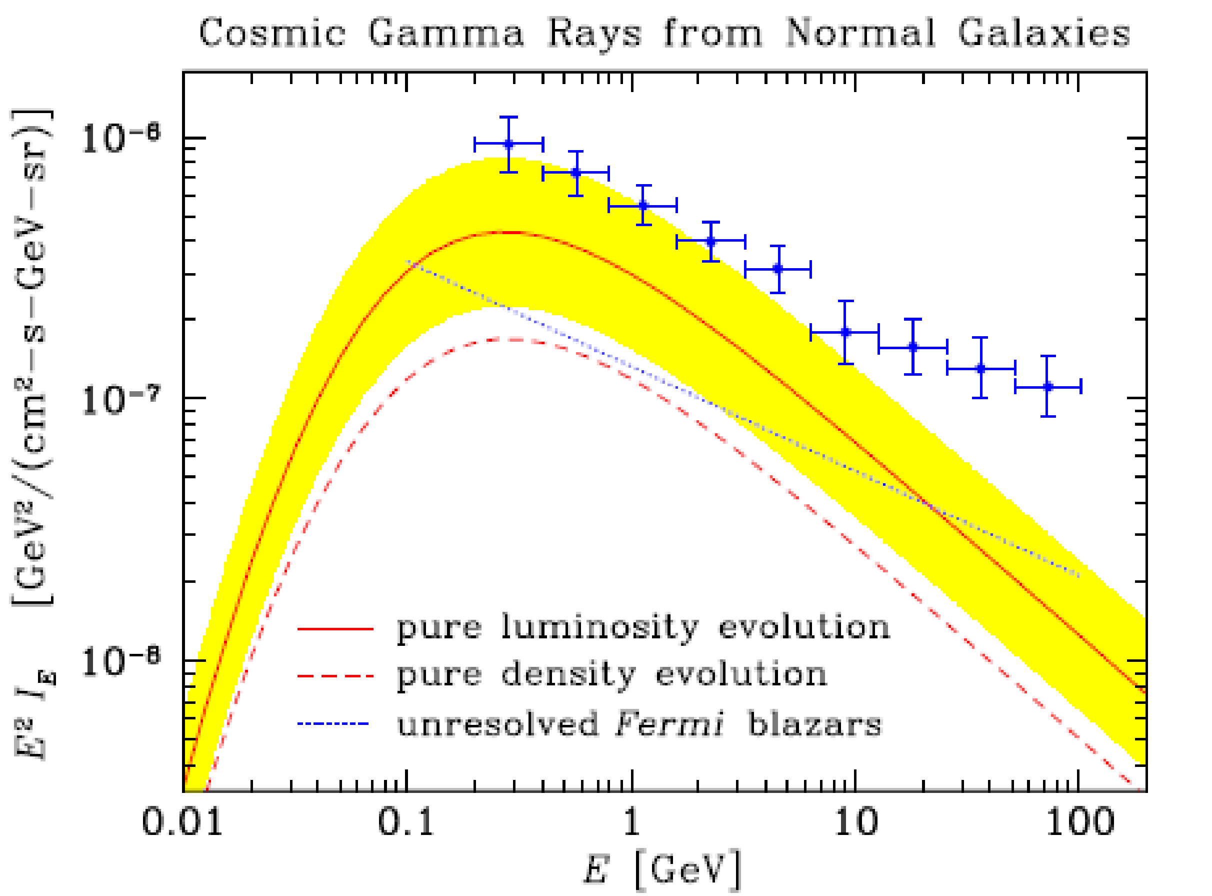


Fig:Fields, Pavlidou, Prodanovic, ApJ 722 (2010)

The Dark Matter Signal

- DM indirect detection through gamma-rays.
- Continuum spectrum of secondaries gamma-rays from hadronization of WIMP annihilation final states.
- Generic WIMP annihilating in the Galactic smooth halo.

Expected differential gamma ray flux from galactic DM annihilation:

$$\frac{d\Phi}{dE_\gamma}(E_\gamma, b, l) = \frac{d\Phi^{WIMP}}{dE_\gamma}(E_\gamma) \cdot \langle \Phi^{COSMO}(b, l) \rangle_{\Delta\Omega}$$

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Particle Physics

$$\frac{d\Phi^{WIMP}}{dE_\gamma}(E_\gamma) = \frac{1}{4\pi} \frac{\langle \sigma v \rangle_0}{2\mathrm{m}^2} \sum_f \left(\frac{dN_\gamma^f}{dE_\gamma}\right) B_f$$

- $B_f = 1$
- Different final states (gauge bosons, quarks)

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- Different final states (gauge bosons, quarks)

Astrophysics/Geometry

$$\langle \Phi^{COSMO}(b,l) \rangle_{\Delta\Omega} = \langle I(b,l) \rangle_{\Delta\Omega}$$

$$I(b,l) = \int_{l.o.s} \rho_{DM}^2(r(\lambda, b, l))\, d\lambda$$

- High latitude observational region
- Sensitivity to different DM halo profiles
- No galactic substructures

DM Constraints from the EGB

The Isotropic Diffuse Gamma Ray Background at high latitudes has a great potential for DM indirect searches:

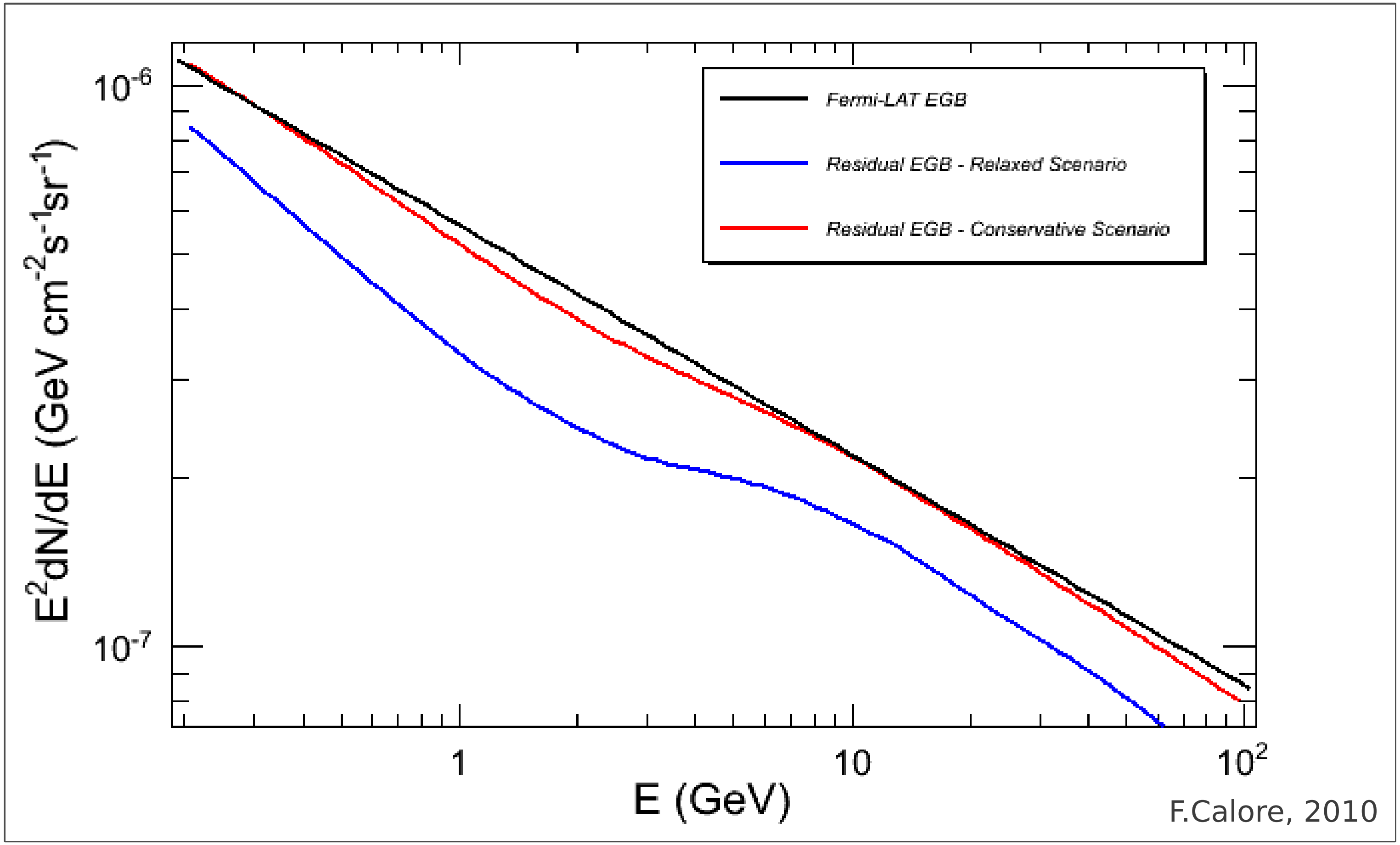
- Advantages of indirect detection through gamma rays (propagation not affected by the Galaxy).
- Weak dependence on uncertainties on the DM main halo distribution (high latitude emission comparable for diffent profile) and on the DGE model.
- Main uncertainties on the underlying astrophysical background.

Conservative upper limits on the WIMP annihilation cross section (for different final states).

Upper limits from the comparison with:

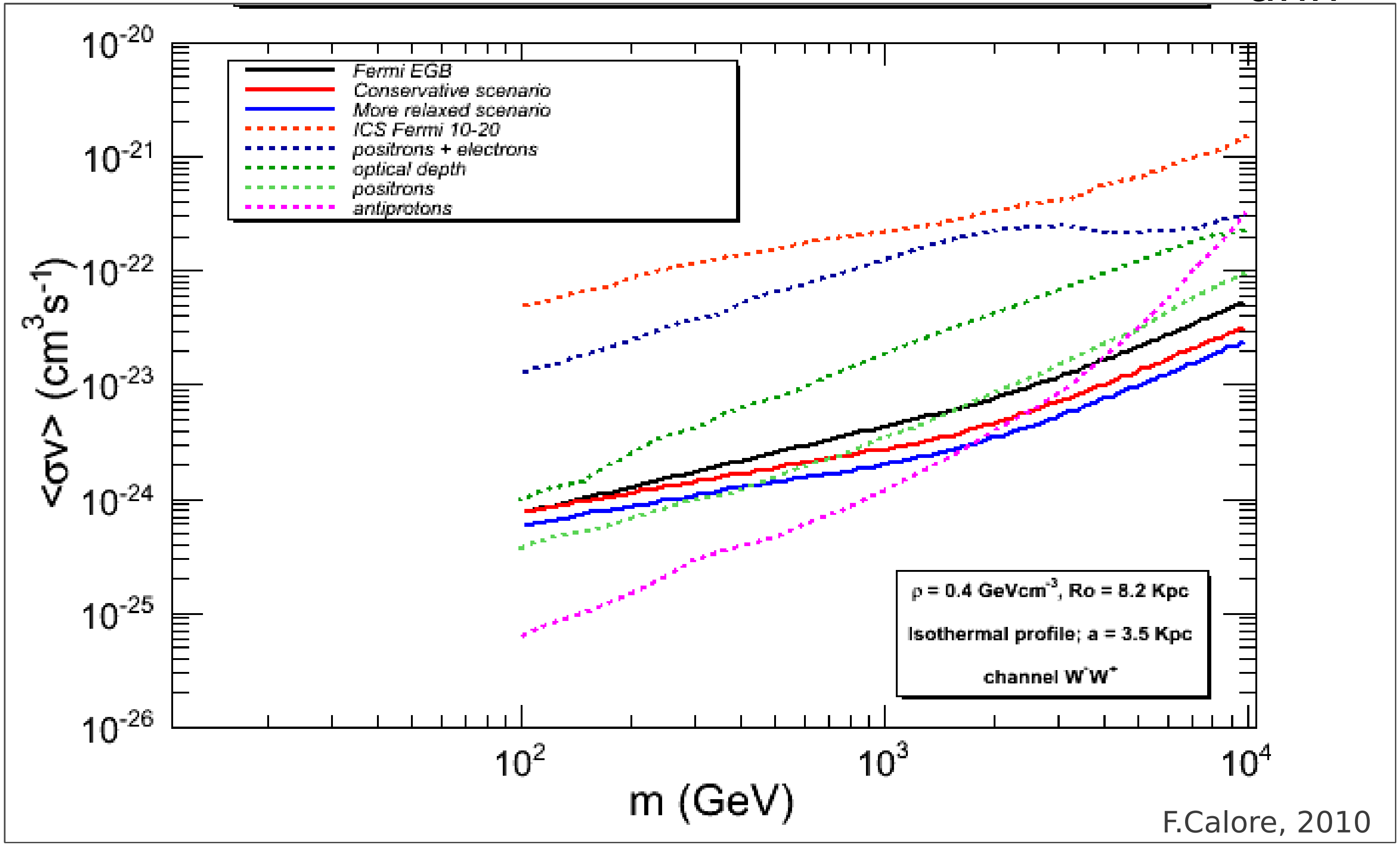
- EGB estimated by the Fermi-LAT Collaboration;
- EGB "Residual", further reduced by our analysis of the astrophysical bkg.

(2) Residual Extragalactic Background



Subtraction of the further non-DM astrophysical contributions from the Fermi EGB → estimation of a *RESIDUAL extragalactic bkg*: conservative residual EGB and relaxed residual EGB.

Conservative upper limits on $<\sigma_{ann} v>_0$



Annihilation channel W^-W^+. Upper limits on $<\sigma v>_0$ derived from:

- Different estimations of the EGB (solid lines): Fermi-LAT EGB, conservative residual EGB and more relaxed residual EGB.
- Other astrophysical signals (dashed lines) from `Catena et al. Phys. Rev. D 81(2010).`

→ Improvement of the bounds on the WIMP annihilation cross section for heavy WIMP

→ Relevance of the astrophysical bkg understanding.

Unresolved Point Sources

SOURCES	References	DOMINANT PHYSICAL PROCESSES	%	Notes
Blazars: BL Lacs & FSRQs	*A.A.Abdo&others, Submitted to ApJ. , 2010*	*IC emission and synchrotron radiation*	*16% - 23% (population analysis)*	*Fermi-LAT data and sources count distribution analysis*
Starforming Galaxies (normal & starburst)	*B.D.Fields, V.Pavlidou, T.Prodanovic, arXiv:1003.3647, 2010*	*Diffuse emission due to collisions of CR with IS gas → gamma-rays mainly from pion decay in flight or leptonic interactions (electrons)*	*63% - 19% at peak (0.3 GeV)*	*Fermi-LAT data*
Starburst Galaxies	*T.A.Thompson, E.Quataert, E.Waxman, Astrophys.J., 654, 2006*	*CR protons vs ISM nuclei, lose energy rapidly via inelastic scattering → resulting pions decaying in secondary particles and gamma-rays (gamma ray emission associated with pion production)*	*< 20%*	*Prediction based on EGRET data (some predictions fulfilled by Fermi-LAT observations)*
Clusters of Galaxies	*P.Blasi, S.Gabici, G.Brunetti, Int.J.Mod.Phys., A22, 2007*	*GeV-TeV gamma-ray fluxes from π^0 decays, ICS and UHE protons in the ICM*	*1% - 10%*	*Prediction based on EGRET data*
Pulsars	*C.A.Faucher-Giguère & A.Loeb, Phys.Rev.Lett., 1001, 2010*	*IC, curvature radiation and synchrotron radiation from electrons-positrons cascades*	*5% - 15% (MSPs)*	*Prediction based on EGRET data*

Truly Diffuse Emission Processes

SOURCES	References	DOMINANT PHYSICAL PROCESSES	%	Notes
Signature of LSS formation	*·S.Gabici & P.Blasi, Astroparticle Phys., 19, 2003* *·U.Keshet, E.Waxman, A.Loeb, Astrophys.J., 585, 2003*	*Shock waves produced in clusters mergers and LSS formation give rise to highly relativistic electrons → IC of the CMB photons to GeV energies*	*10%*	*Prediction based on EGRET data*
UHECRs	*O.Kalashev, D.Semikoz, G.Sigl, Phys. Rev. D, 79, 2009*	*Interactions of UHECRs with CMB photons → secondary electromagnetic cascades*	*1% - 50%*	*Prediction based on EGRET data and dependent from the primary cosmic rays flux*
VHE Gamma-Rays from Blazars	*T.M.Venter, arXiv:1001.1363, 2010*	*VHE gamma-rays from blazars vs soft photons of EBL → EM cascades*	*+50% of intrinc blazar spectra contribution*	*Dependence on blazar gamma-ray luminosity function and spectral properties*

(1) The non-DM astrophysical bkg: other sources explored, but neglected

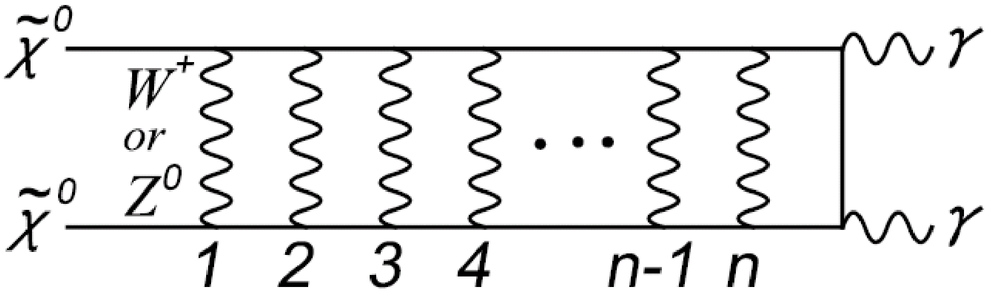
- RADIO QUIET AGN: contribution still uncertain (ApJ 672, L5, ApJ.702, 523);
- BL LAC OBJECTS and FSRQs whose jets are not aligned along the line of sight (Fanaroff and Riley radio galaxies I and II): high uncertanty in the model, few objects of the sample already subtracted in the Fermi-LAT EGB (arXiv: 1103.3946);
- GAMMA RAY BURSTS: less than the 1% contributes to the EGB (ApJ. 700, 10261033);
- STARBUST and Luminous Infrared galaxies (LIG): they may cover a significant fraction of the EGB (up to the 20%), but the model-dependance is still too high (ApJ. 654, 219);
- Gamma ray emission from nearby clusters of galaxies: in the first 18 months, no gamma rays have been detected yet;
- Gravitational induced shocked waves produced during cluster mergers and large-scale structure formation may contribute for some percent, via Inverse Compton scattering of highly relativistic electrons.

Sommerfeld enhancement

Through this mechanism it is possible to obtain the behaviour 1/v in the WIMPs annihilation cross section.
It's a non elementary effect in non relativistic quantum mechanics, which arises when the particles interact through a force in the presence of a potential and subsequentely their wave function comes out to be distorted.

$$\sigma v = S(\sigma v)_0$$

It may be depicted through two particles spreading in the space-time which interact by exchanging vector bosons before annihilating. This gives origin to non perturbative corrections in the cross section of the process considered.



In case of WIMPs annihilation the Sommerfeld enhancement is a consequence of the presence of a Yukawa potential and light force carriers.

Reff. Arnold J. W. Sommefeld. **Uber die Beugung und Bremsung der Elektronen**. Annalen der Physik, 403, 1931.
Nima Arkani-Hamed, Douglas P. Finkbeiner, Tracy R. Slatyer, and Neal Weiner. **A Theory of Dark Matter**., 2009.
Nojiri, Hisano, Matsumoto. **Explosive dark matter annihilation**. Physical Review Letter, 2004. ArXiv hepph/ 037216v1.

Let ψ(r) be the wave function describing the annihilation process;
in the non relativistic limit it obeys to the Schrodinger equation:

$$\frac{1}{m}\frac{d^2\psi(r)}{dr^2} - V(r)\psi(r) = -m\beta^2\psi(r)$$

$$S = \frac{|\psi(\infty)|^2}{|\psi(0)|^2}$$

Boundary conditions, as r →∞:

$$\frac{d\psi}{dr} = im\beta\psi \qquad \psi(r) = \sin(r)$$

The Schrodinger equation can be solved analitically for a Coulomb potential.

$$V(r) = -\frac{\alpha}{r} \quad \Longrightarrow \quad S = \frac{\pi\alpha}{\beta}\left(1 - e^{-\frac{\pi\alpha}{\beta}}\right)^{-1}$$

In the presence of a Yukawa potential, the equation is not analitically solvable. The behaviour of the enhancement in this case depends on the mass of the force carrier.

$$V(r) = -\frac{\alpha}{r}e^{-m_\phi r}$$

3)Analitical solution through the approximation with the Hulthèn potential

The third method for solving for the Schrodinger equation makes use the analytical approximation of the Yukawa potential with the Hulthèn potential :

$$V_Y \approx V_H = \frac{C\delta\, e^{-\delta r}}{1-e^{-\delta r}} \qquad \delta = \frac{\pi^2 m_\phi}{6}$$

$$S = \frac{\pi}{\varepsilon_v} \frac{\sinh\left(\dfrac{2\pi\varepsilon_v}{\pi^2\varepsilon_\phi/6}\right)}{\cosh\left(\dfrac{2\pi\varepsilon_v}{\pi^2\varepsilon_\phi/6}\right) - \cos\left(2\pi\sqrt{\dfrac{1}{\pi^2\varepsilon_\phi/6} - \dfrac{\varepsilon_v{}^2}{\left(\pi^2\varepsilon_\phi/6\right)^2}}\right)}$$

$$\varepsilon_v \equiv v/\alpha \quad \mathrm{e} \qquad \varepsilon_\phi \equiv m_\phi/(\alpha m_\chi)$$

Sebastian Cassel. **Sommerfeld factor for arbitrary partial wave processes**. ArXiv hep-ph/0903.5307v1.
Tracy R. Slatyer. **The Sommerfeld enhancement for dark matter with an excited state**. JCAP, 2010. ArXiv hepph/0910.5713.

Sommerfeld enhancement features

Under a Yukawa potential the characteristics of the Sommerfeld enhancements may be summarized introducing the parameter $\beta^* \equiv \sqrt{\alpha m_\phi / m_\chi}$ which sets the borderline velocity over which the approximation with the Coulomb potential is allowed:

1. When β*<<β<<α, the Coulomb approximation is valid and S ≈ πα/β;
2. For large velocities, β>>α the enhancement saturates S ~ 1;
3. For small velocities, as β<<β*, the potential energy dominates over the kinetic energy and we are in another regime, where the Schrodinger equation has the same form as the one describing the hydrogen atom, giving thus origin to bound states when:

$$m_\chi = \frac{4 m_\phi n^2}{\alpha} \qquad n = 1,2,3..$$

The behaviour close to the resonances is

$$S \cong \left(\frac{\beta^*}{\beta}\right)^2$$

Ref. Massimiliano Lattanzi and Joseph Silk. " **Can the WIMP annihilation boost factor be boosted by the Sommerfeld enhancement?"** Physical Review Letter, 2009. ArXiv astro-ph/0812.0360v2.

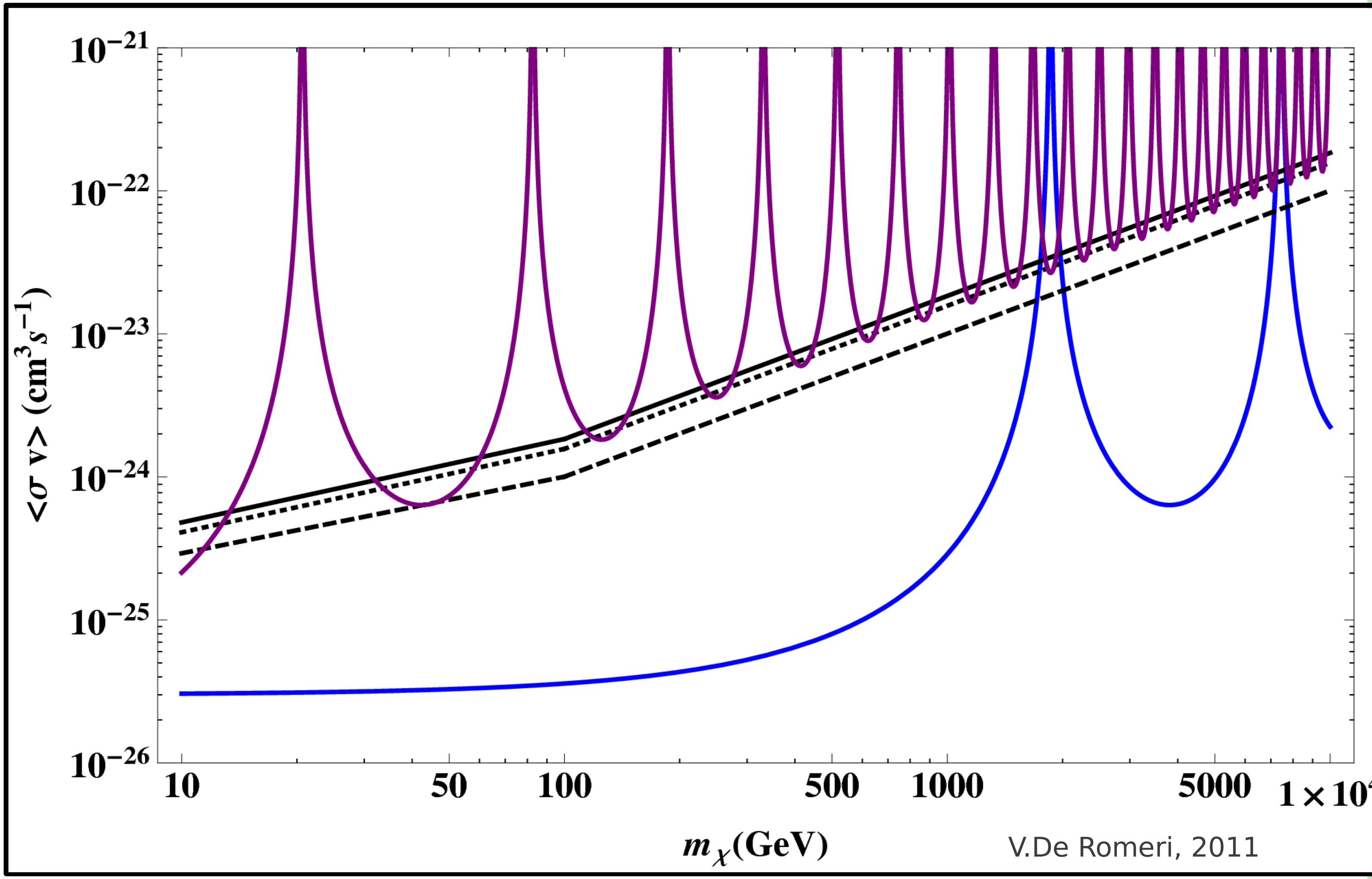
Upper limits from early proto halos

$$\rho_\gamma = 5.28\times10^6 \left(\frac{M_c}{M_T}\right)^{-1/3} \left(\frac{1}{\beta}\right) <\sigma v>_0 B_{2.6} \left(\frac{m_\chi}{TeV}\right)^{-1} GeV\, cm^{-3}$$

$$\langle \sigma v \rangle = \langle \sigma v \rangle_0 \frac{c}{v} cm^3/sec$$

Fermi LAT EGB
Model I
Model II

$\beta = 10^{-8}$
M_Φ = 1 GeV,
90 GeV
Zc = 200



Outlook

- Identification of unresolved astrophysical sources → reduction of potential DM contribution → further improvement of upper limits on $\langle \sigma v \rangle_0$.
- Optimal angular window ($10° < |b| < 20°$)→ strongest bounds on DM annihilation cross section.
- Not only galactic DM signal (main smooth halo) → Galactic substructures? Extragalactic DM signal?