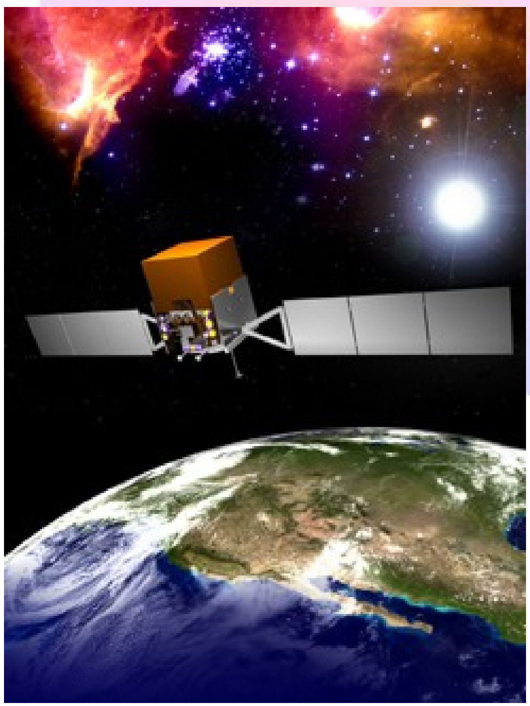
ULB PhysTh seminar

Université Libre de Bruxelles, March 22, 2011

Ultimate sensitivity of Fermi-LAT to Dark Matter



With Kev Abazajian and Pat Harding
ArXiv:1011.5090 ; 1012:1247

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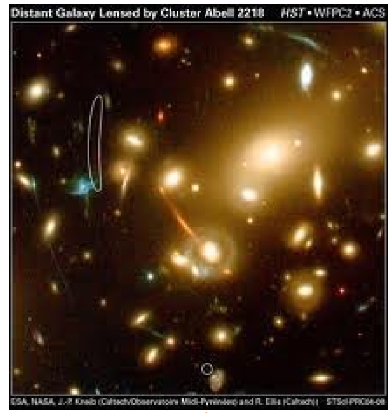
Dark Matter – the Unknown

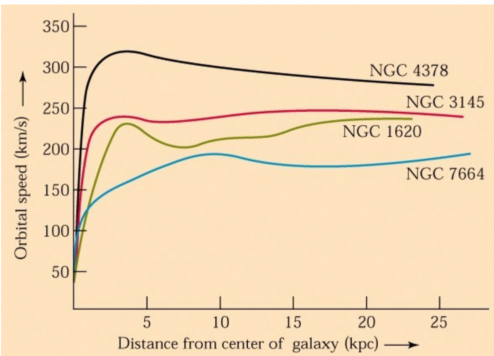
As we know,
There are known knowns.
There are things we know we know.
We also know
There are known unknowns.
That is to say
We know there are some things
We do not know.
But there are also unknown unknowns,
The ones we don't know
We don't know.

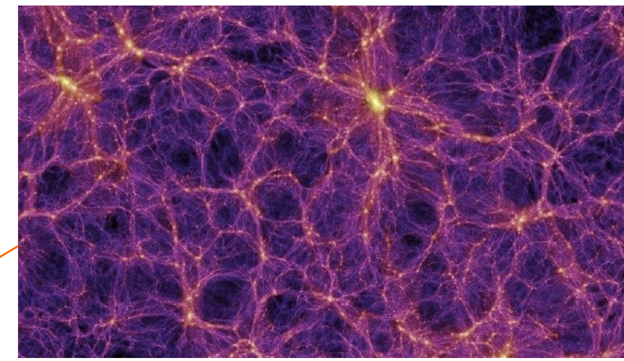
— Donald Rumsfeld, Feb. 12, 2002, Department of Defense news briefing

Dark Matter

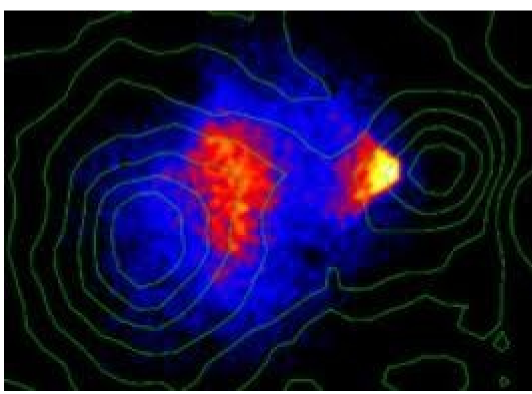
- A wealth of experimental evidence points at the presence of dark matter.

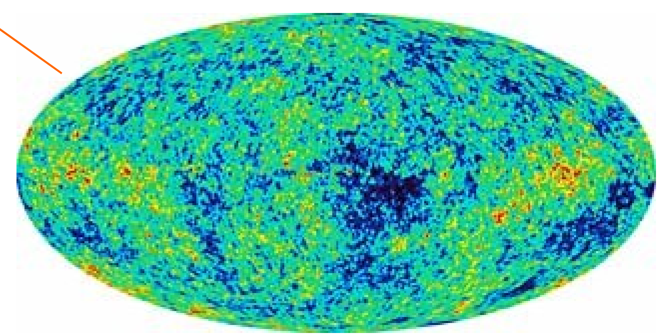






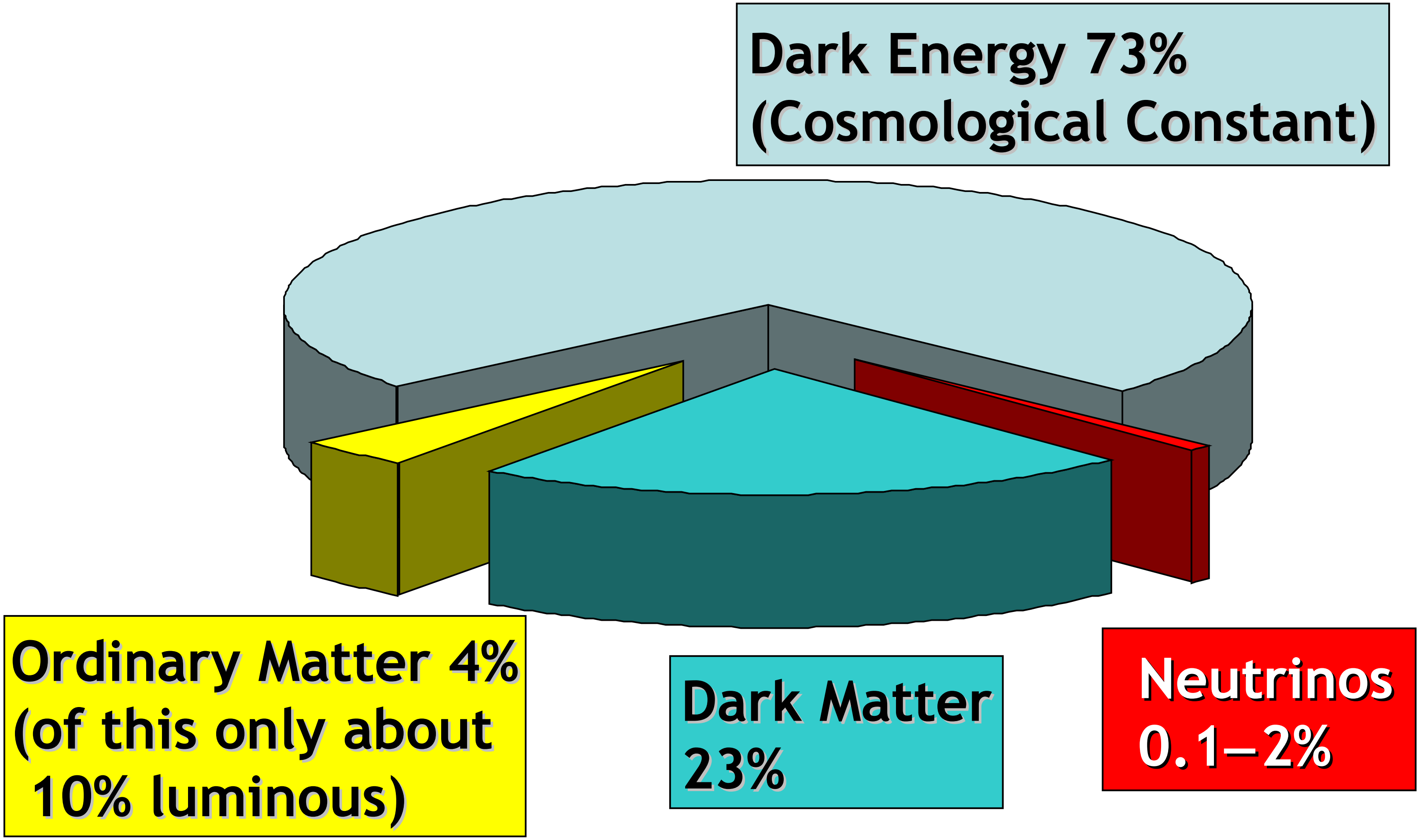
ΛCDM paradigm





Dark Matter

★ The energy content of the Universe has been accurately measured



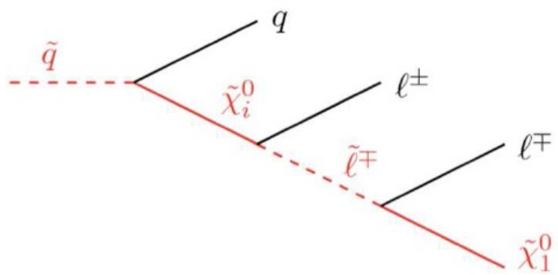
Dark Matter

- We want to believe dark matter is a particle which has to fit in a consistent quantum field theory.
- Many such theories exist (supersymmetry, extradimensions, many minimal extensions of the SM,…), and any candidate shares the following features:
  - It is stable on cosmological timescales
  - It is neutral
  - It must have been produced in the Early Universe so that it has now the right relic abundance (e.g. WIMP miracle)
  - It must be ‚cold‘ enough, i.e. cannot free-stream much

Dark Matter Detection

★ There are many ways to try and detect a WIMP

- In particle colliders like the LHC, search for large missing transverse energy in decay chains.



- In laboratory experiments, search for rare interactions of the DM particle with target nuclei. The recoil energy can be measured via scintillation light, ionization, or slight temperature increase (phonons). Two types of experiment:

➡ Detection of single unambiguous dark matter interactions. Background rejection crucial (CDMS, XENON, etc.)

➡ Look for an intrinsic property of the DM signal, for instance annual modulation. Need high stability and statistics (DAMA)

DIRECT DETECTION

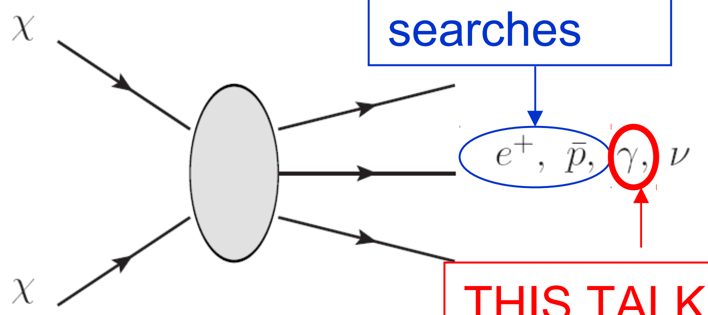
Dark Matter Detection

★ Indirect detection is also a promising possibility

In regions of high DM density in the Universe, DM can annihilate emitting photons, positrons, antiprotons or neutrinos.

[Dark matter can also simply decay and produce these particles.]

Antimatter searches



THIS TALK!

★ Favourable targets for DM indirect detection with photons include:

- Galactic center: large DM density, but large astrophysical uncertainty and background!
- Dwarf spheroidal galaxies (Draco, Ursa Minor,…): DM-rich environments but low fluxes
- Galaxy clusters (Fornax, Coma,…): large DM densities and low background… but far away!
- Isotropic diffuse gamma-ray background

THIS TALK!

Outline

- The Isotropic Diffuse Gamma-Ray Background observed by Fermi-LAT
- Blazar model and fit to the Fermi data
- Predictions from the blazar model for 5-year Fermi observations
- Calculation of the contribution to the IDGRB by DM annihilations in our Milky Way, as well as extragalactic: prompt and Inverse Compton components!
- Forecast for Fermi's 5-year sensitivity to DM annihilation cross-sections and decay lifetimes
- Comment on models explaining cosmic-ray anomalies, as well as on the possible hints in direct detection in view of our results.

The Isotropic Diffuse GRB

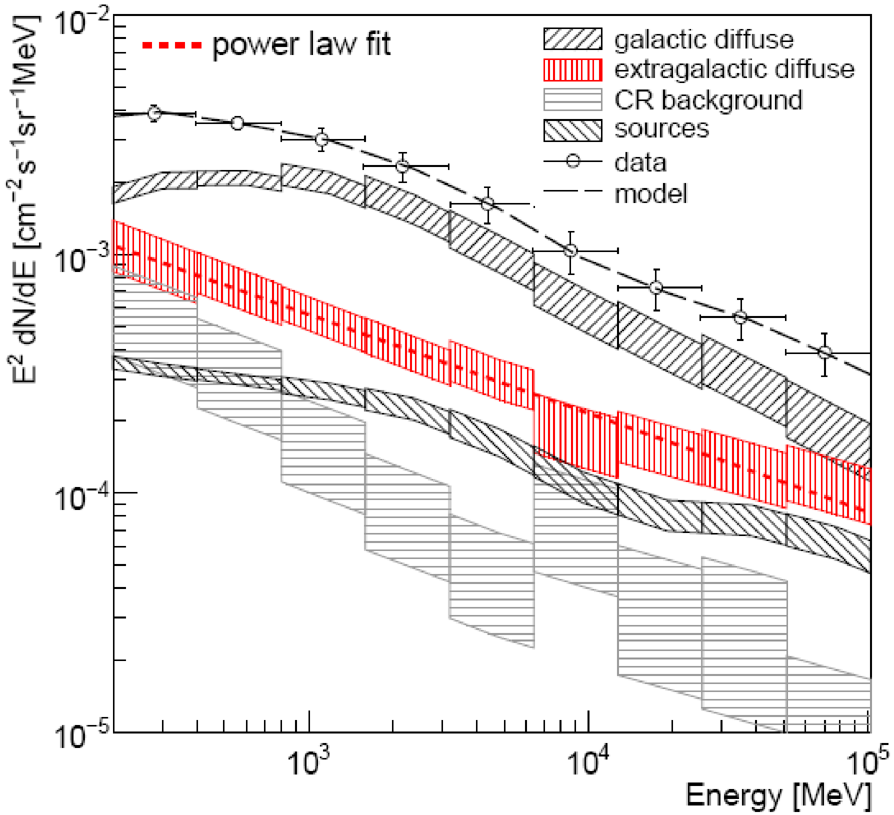
- An isotropic diffuse component in the gamma-ray sky was first discovered in the range 35 keV to a few 100 MeV by the satellite SAS-2 in 1975, and later confirmed by EGRET up to about 30 GeV.

- This component is sometimes referred to as the Extragalactic Gamma-ray Background (EGB), although the „extragalactic“ nature of this component is not clear. For instance, diffuse emission processes within our halo also contribute.

- The first-year data of the Large Array Telescope (LAT) aboard the Fermi Gamma-Ray Space Telescope (launched in June 2008) measured this component with a much better precision, and extended the energy range to 100 GeV.

Fermi-LAT and the EGB

★ The first 10 months data from Fermi-LAT lead to a precise ‚measurement‘:

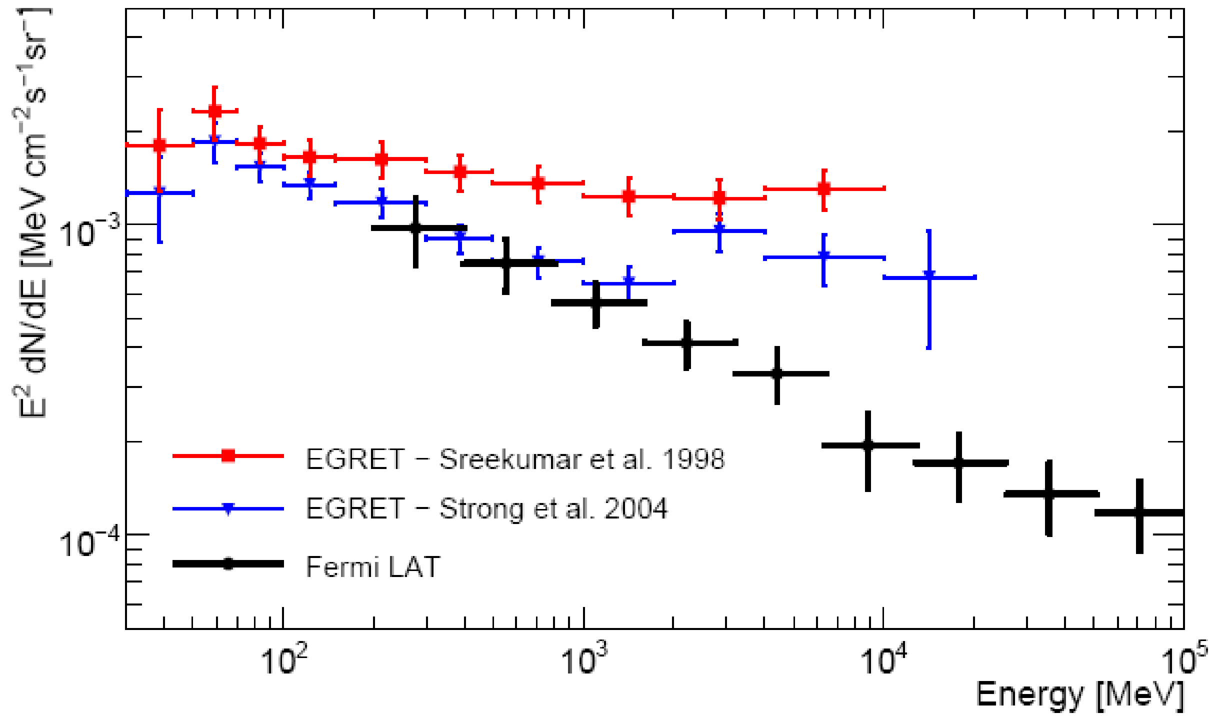


[Abdo, et al., 1002.3603]

➡ The isotropic diffuse component represents roughly 25% of the total flux (for $|b| > 10°$).

Fermi-LAT and the EGB

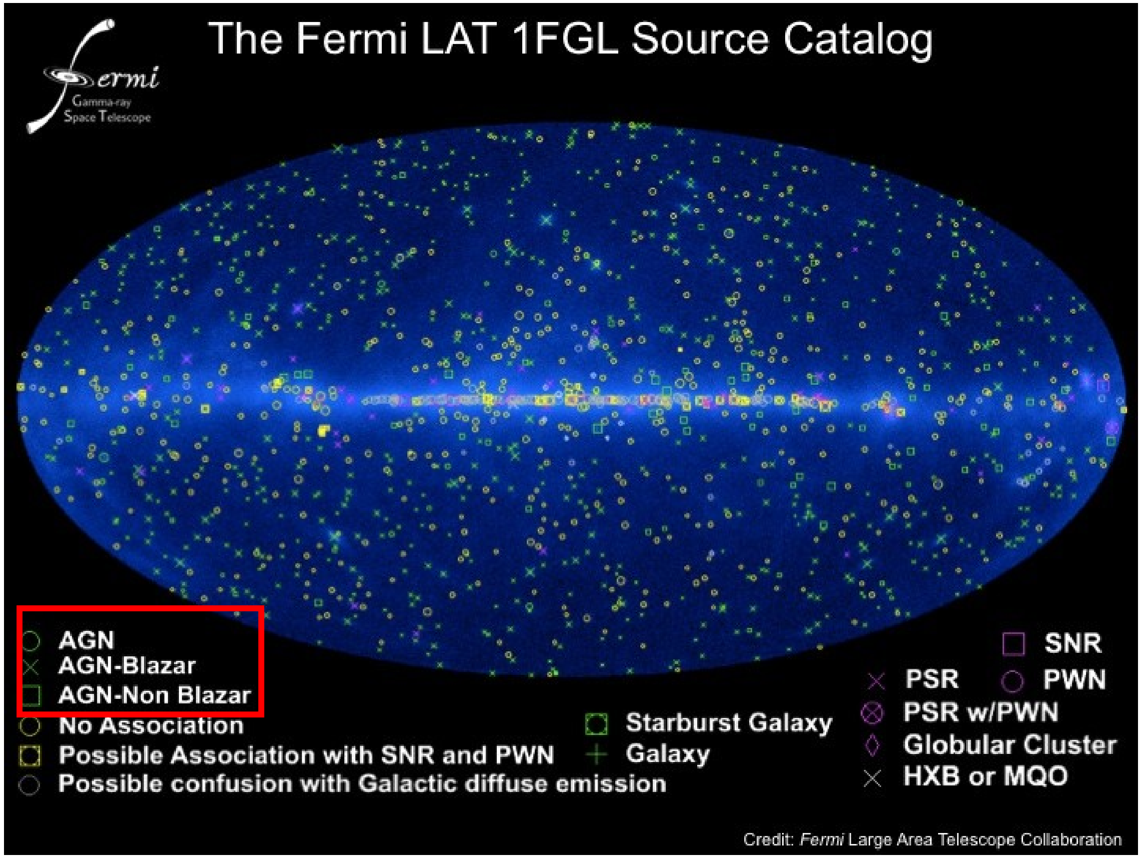
★ The measured spectrum of the EGB follows a featureless power law with an index 2.41, notably softer than what was found by the EGRET collaboration.



[Abdo, et al., 1002.3603]

Fermi-LAT and the EGB

- The ‚measurement' of the isotropic diffuse background is actually quite indirect. It is extracted from the total flux measured by Fermi by subtracting the galactic diffuse component (calculated using GALPROP) and the known sources.



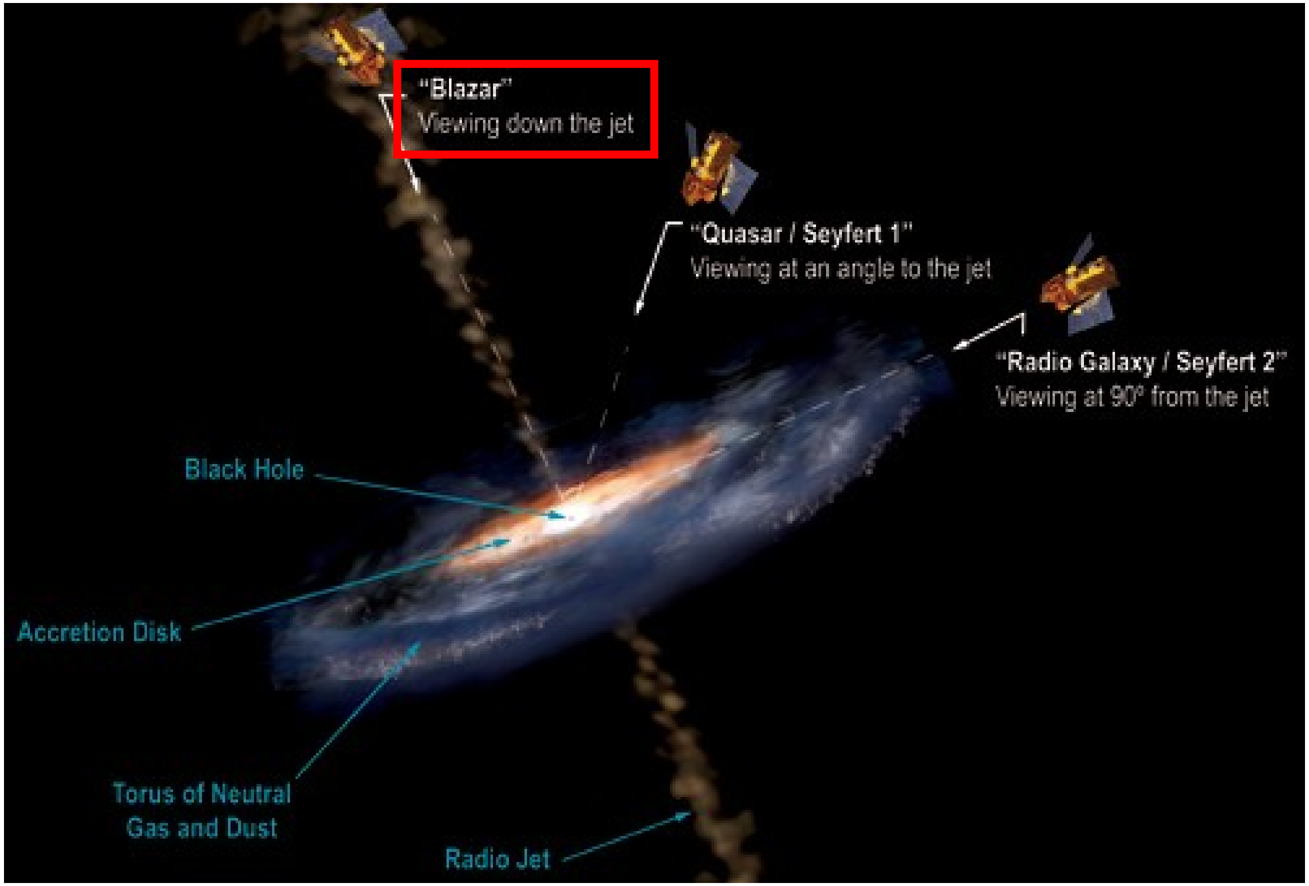
Models for the EGB

- Non-blazar Active Galactic Nuclei (AGN): Good for 10 keV-100 MeV, but too low at GeV.
- Star-forming galaxies: too low above 10 GeV.
- Dark matter annihilation (in the Milky Way or extragalactic): typically flux too low, and no features seen
- Blazars
  - They are the most numerous point-source objects in EGRET and Fermi catalogues.
  - They make up 15% of the total gamma-ray flux
  - Their stacked spectrum has a similar index to the EGB

⇒ They are likely candidates for the bulk of the EGB emission!

What are blazars?

★ THIS:



i.e. it is an AGN with the jet pointing towards us, perpendicular to the accretion disk

What are blazars?

- ★ There are two types of blazars, distinguished based on their optical properties:

  - Flat-spectrum radio quasars (FSRQs)
    - Rest-frame equivalent width of the strongest emission line < 5 Å
    - Domination of continuum/No emission lines

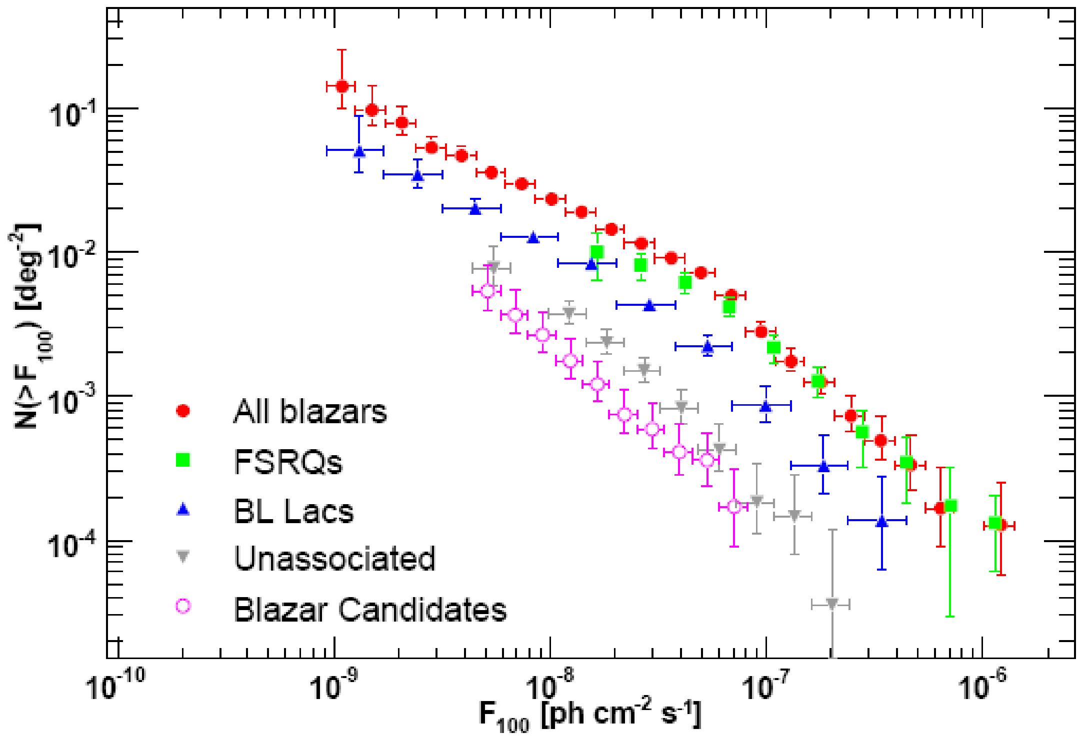
  - BL Lacertae objects (BL Lacs)
    - Rest-frame equivalent width of the strongest emission line > 5 Å
    - Spectral index in radio band smaller than 0.5
    - Emission lines

- ★ General properties of blazars:
  - Bolometric luminosity dominated by gamma-ray luminosity
  - Great time variability and strong polarization
  - Dominating jet component, relativistically beamed vs. Isotropic from accretion disk
  - FSRQs are generally more luminous than BL Lacs

Blazar measurements by Fermi

- In 11 months of running, Fermi-LAT detected 296 FSRQs, 300 BL Lacs, as well as 72 of unknown type [Abdo, et al., 1002.0150].

- The photon index of FSRQs was measured to be 2.48, softer than than that of BL Lacs, 2.07, which explains the detection of the latter at lower fluxes than FSRQs:



[Abdo, et al., 1003.0895]

Blazar model

★ It consists of two parts:

1. The Spectral Energy Distribution (SED) → the luminosity of blazars as a function of energy.

$$\nu L_\nu(x, P)$$

$x \equiv \log(\nu/\mathrm{Hz})$

where ν is the blazar frequency

Bolometric luminosity

$\int L_\nu d\nu$

2. The gamma-ray luminosity function → the density of blazars per unit luminosity.

$$\rho_\gamma(L_\gamma, z)$$

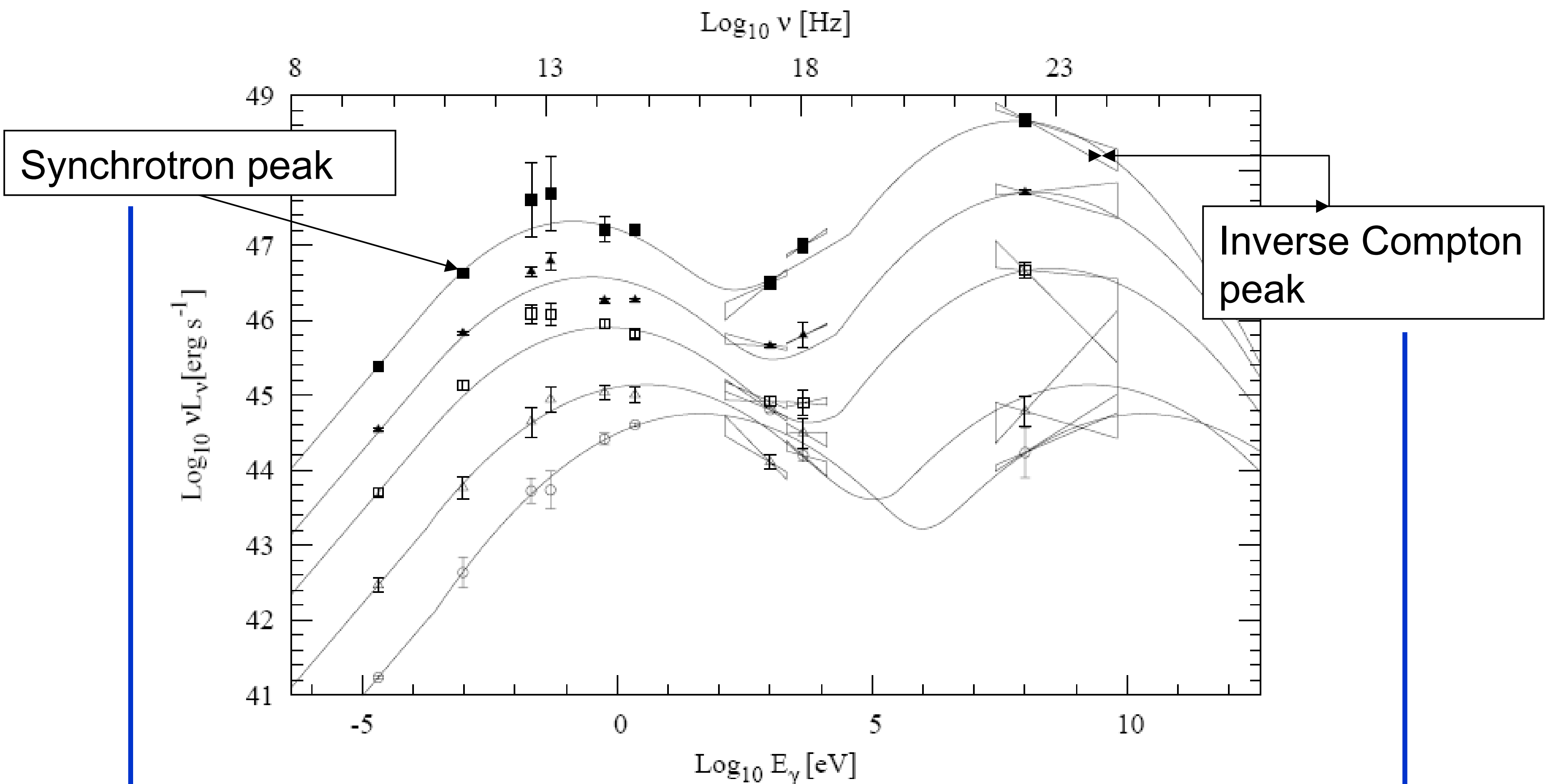
Gamma-ray luminosity defined as

νL_ν at $h\nu = 100$ MeV

Redshift of the blazar

1. SED sequence

★ We use the SED sequence from Inoue and Totani (0810.3580):



From the same nonthermal electron population accelerated in the relativistic jet!

2. Gamma-ray luminosity function

★ The gamma-ray luminosity can be related to the X-ray luminosity of the accretion disk, L_X, through the bolometric luminosity P :

$$P = 10^q L_X$$

where q is a scaling parameter.

★ The comoving number density of AGNs (including blazars) per unit L_X, , was parameterized by Ueda et al., astro-ph/0308140.

$$\rho_X(L_X, z)$$

★ The comoving number density of blazars per unit L. is given by

$$\rho_\gamma(L_\gamma, z) = \kappa \frac{dL_X}{dL_\gamma} \rho_X(L_X, z)$$

★ The GLF has three free parameters: q, · and the faint-end index °1, which will be fitted to the Fermi observation.

Number of blazars and flux

★ We now have all the tools to calculate fluxes! First, the flux from a given blazar observed on Earth (or by Fermi) is given by:

$$F_\gamma(z,P) = \frac{1+z}{4\pi d_L(z)^2} \int_{E_{\mathrm{min,obs}}(1+z)/h}^{\infty} d\nu \frac{L_\nu(\nu,P)}{h\nu}$$

Luminosity distance

Minimum photon energy observable by Fermi, 100 MeV

★ The number count of blazars detected above sensitivity F_γ

$$N(>F_\gamma) = 4\pi \int_0^{z_{\mathrm{max}}} dz \frac{dV}{dz} \int_{L_\gamma^{\mathrm{lim}}(z,F_\gamma)}^{\infty} dL_\gamma \rho_\gamma(L_{\gamma,z})$$

Luminosity below which a blazar at redshift z is no longer detectable for the sensitivity F_γ

Number of blazars and flux

★ The diffuse flux coming from unresolved blazars is given by:

$$\frac{dN}{dE_\gamma dA dt d\Omega} = \frac{1}{4\pi}\int_0^{z_{\rm max}} dz \frac{dr}{dz}\int_{L_{\gamma,\rm min}}^{L_\gamma^{\rm lim}(F_{\gamma,z})} dL_\gamma \rho_\gamma(L_\gamma, z)$$

$$\times \frac{1+z}{h}\frac{L_\nu(E_\gamma(1+z)/h, P)}{E_\gamma(1+z)} e^{-\tau(z,E_\gamma)}$$

Photon energy, area, time and solid angle

Line-of-sight integral over the comoving distance

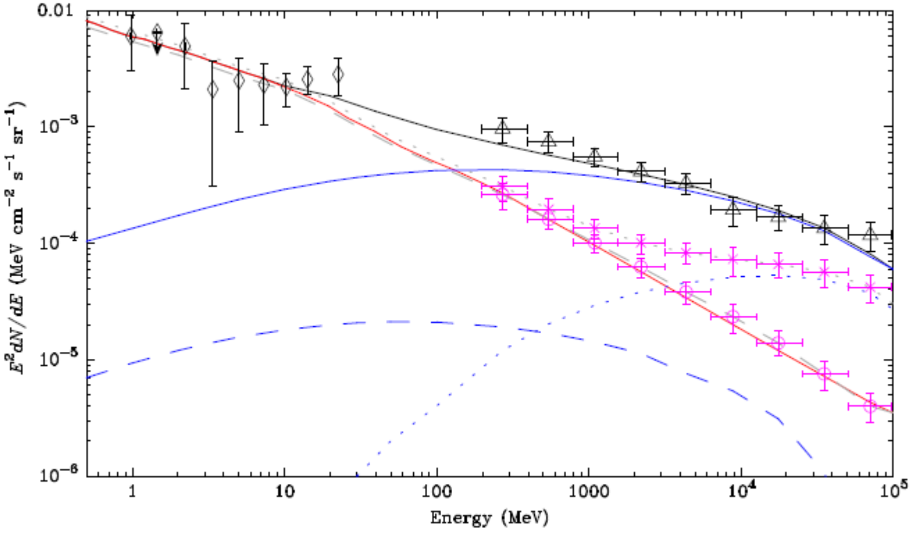
Photon absorption on the way to Earth

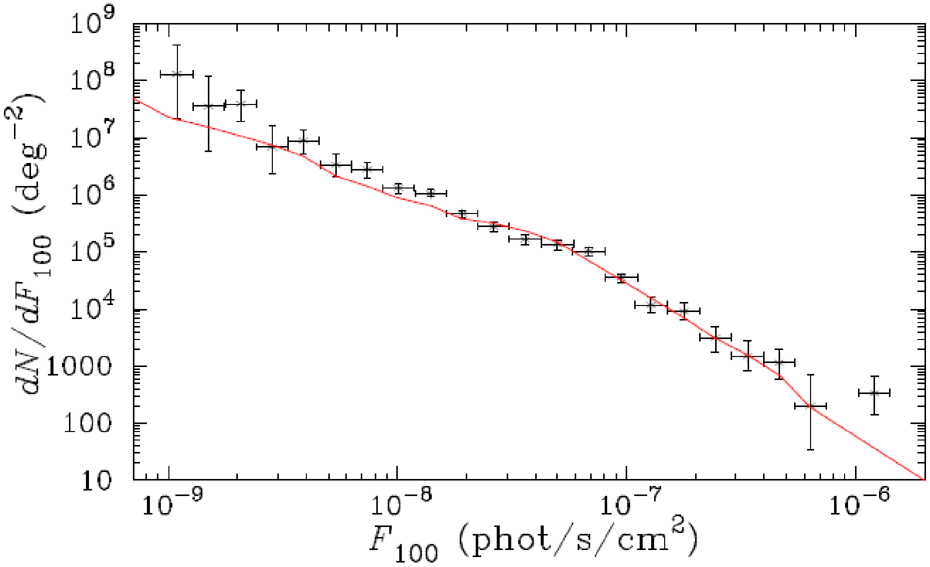
★ There is an additional non-blazar AGN contribution which will be important at energies smaller than 100 MeV. The combination of both the blazar and non-blazar AGN contribution will provide a good fit to the observed photon background from 0.01 MeV to 100 GeV!

Fits

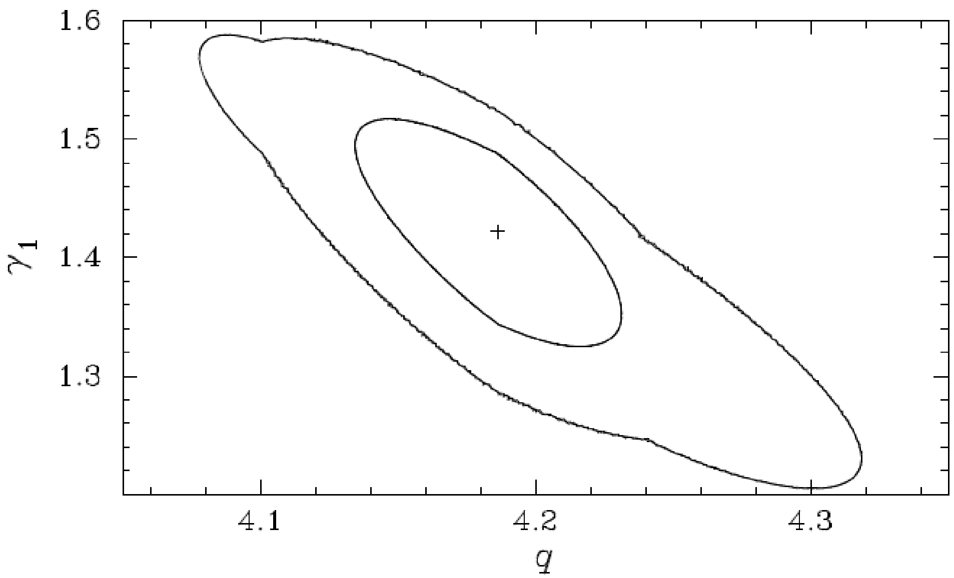
★ We are fitting simultaneously to dN/dF and to the diffuse flux, which was calculated by Fermi down to a sensitivity of 10^{-9} ph cm^{-2} s^{-1}.

$\chi^2/\mathrm{DOF} = 0.79$





- The 68% and 95% confidence level regions for the faint-end index and the luminosity scale (out of 3 total parameters) are:



➡ The value of q indicates that the bolometric luminosity is roughly 15‘000 times higher than the X-ray luminosity from the disk.

➡ The value °1>1 indicates that low-luminosity blazars have a significant contribution to the total blazar flux.

➡ The fraction $\kappa = 2.5 \times 10^{-6}$ 400‘000 AGNs there is 1 blazar observable in gamma-rays.

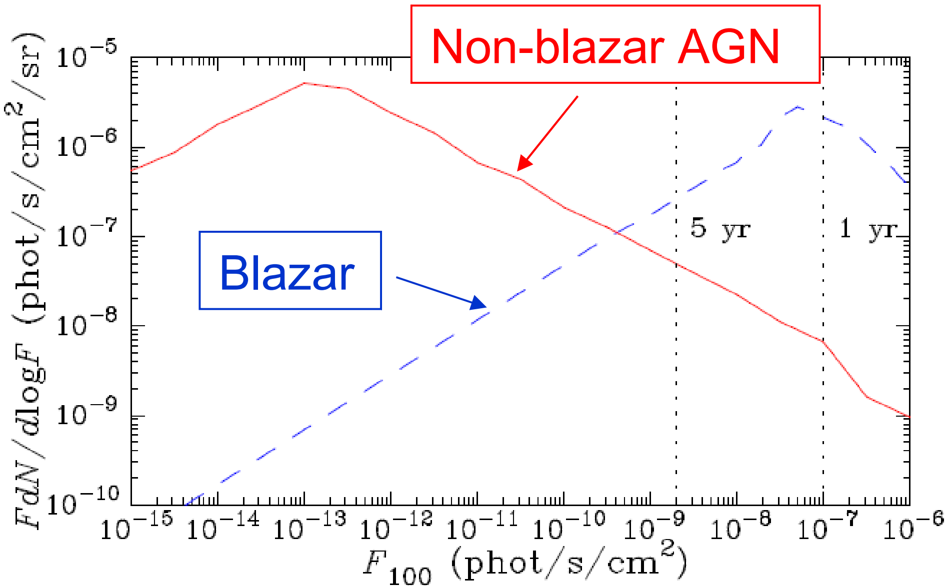
Predictions

★ The fits to Fermi data at the sensitivity of 10^{-7} ph cm^{-2} s^{-1} played the role of the ‚normalization' of our model. With this, we can now make predictions for the 5-year sensitivity of Fermi, 2×10^{-9} ph cm^{-2} s^{-1}.

1. $98.45^{+0.45}_{-0.07}\%$ of total blazar flux will be resolved by Fermi after 5 yrs

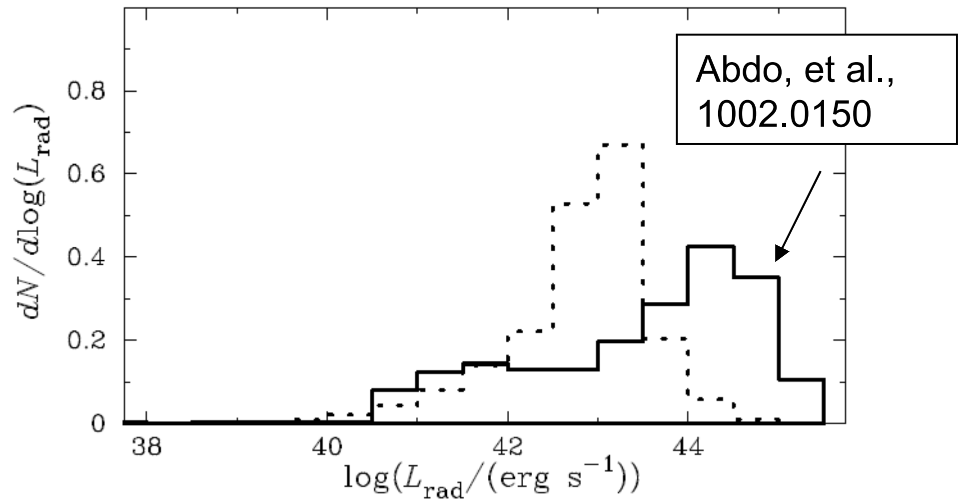
2. 1630^{+320}_{-400} blazars should be resolved by Fermi after 5 yrs

3. The bulk of the non-blazar AGN population will only be resolved if the sensitivity improves by 4 orders of magnitude:

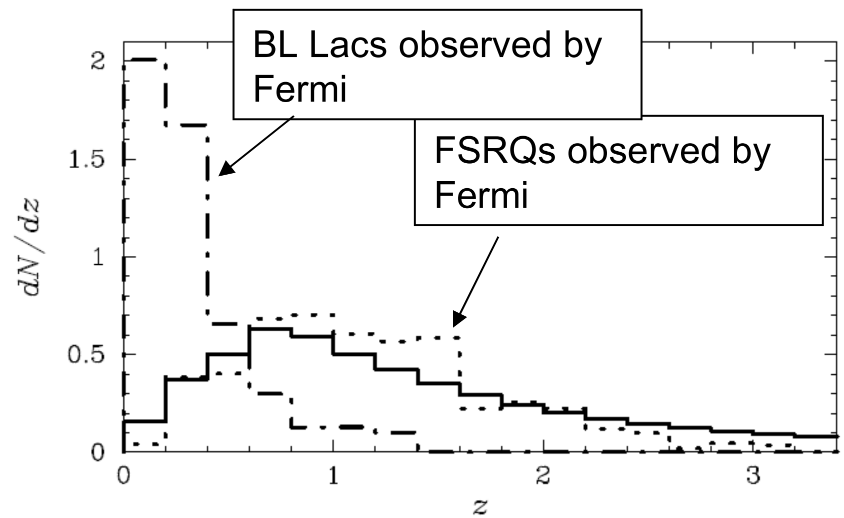


Predictions

4. We also predict the distributions of blazar in radio luminosity:

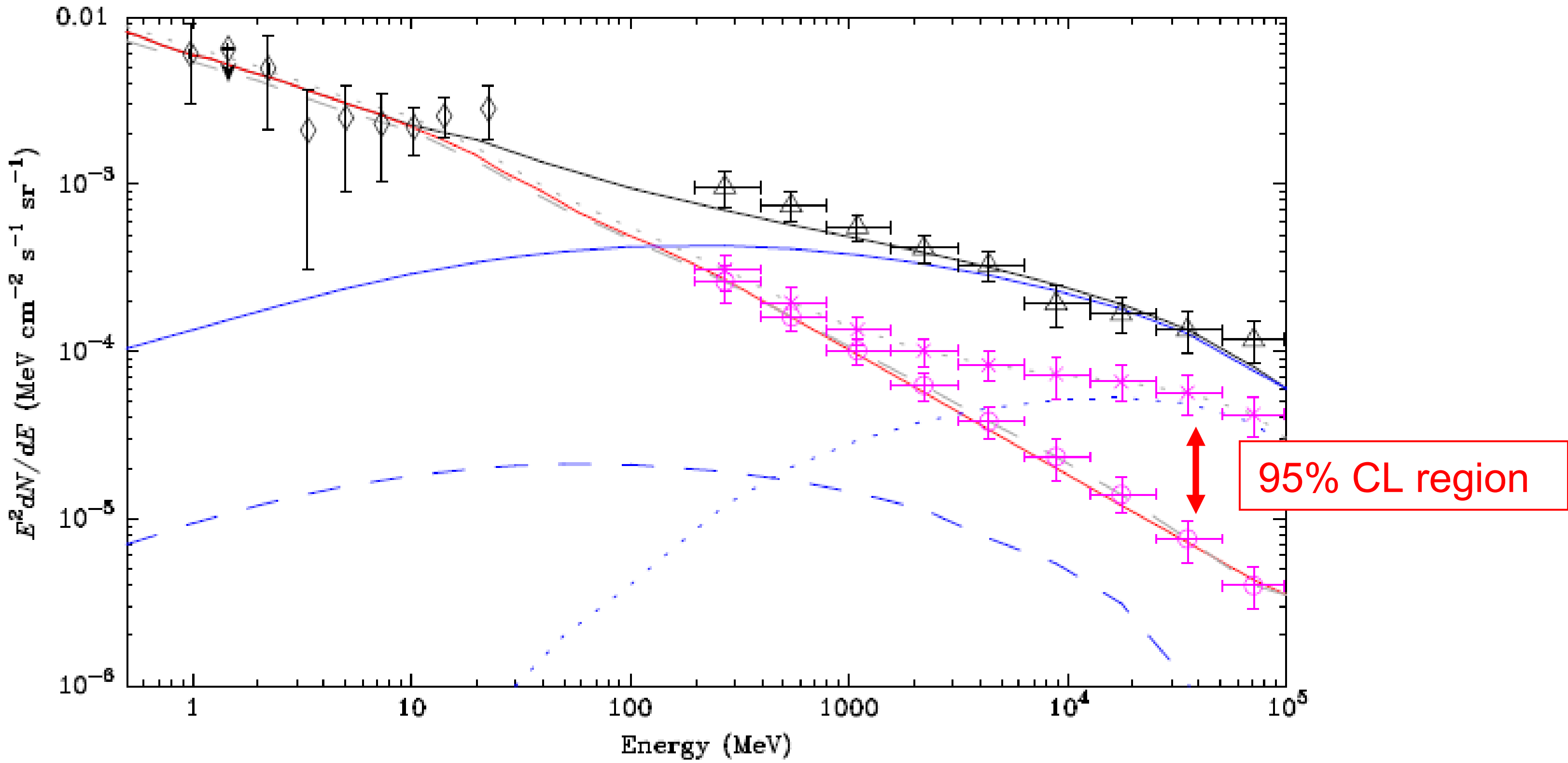


5. As well as the redshift distribution:



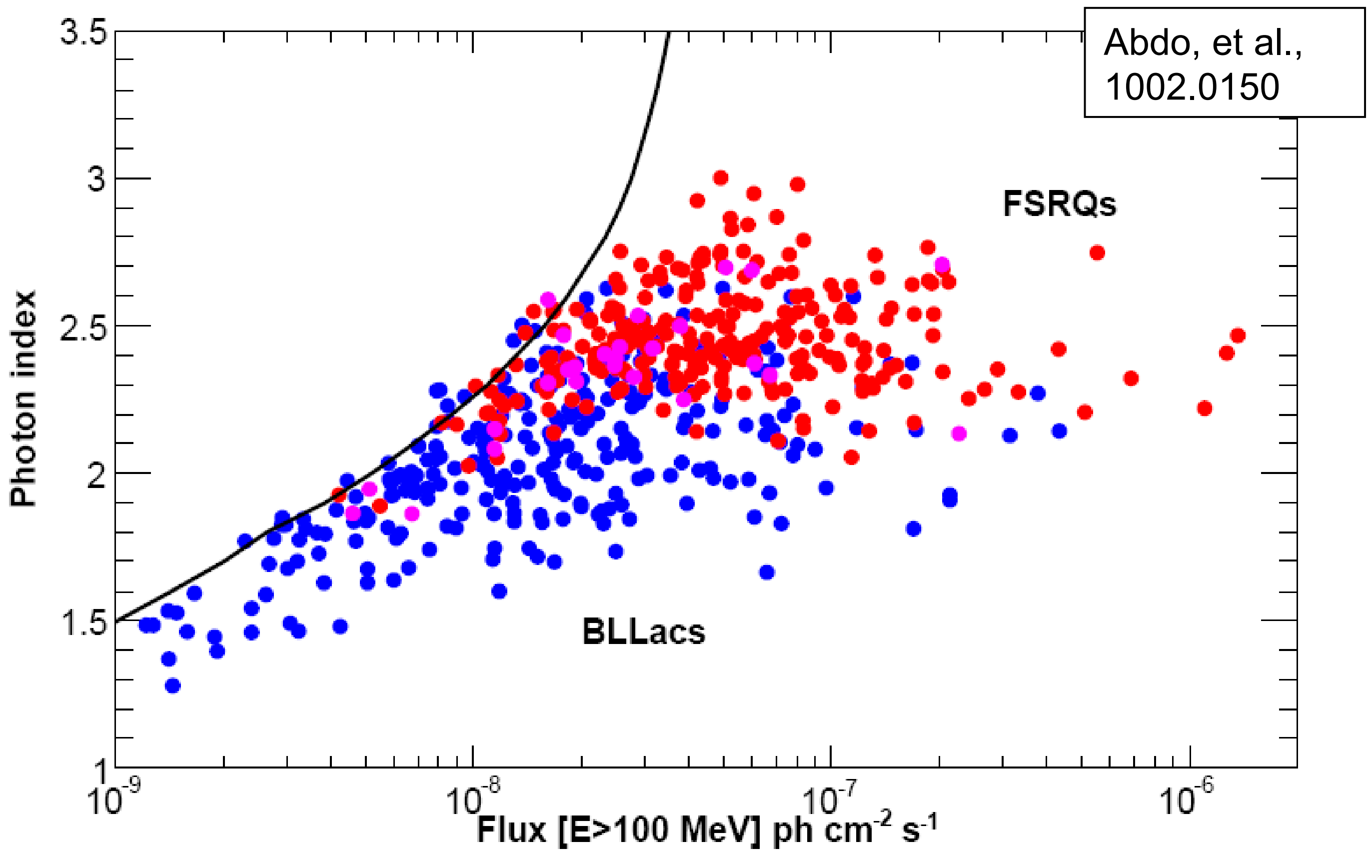
Predictions

6. Finally, we predict the improved EGB given by the unresolved fraction of blazars at Fermi's sensitivity after 5 yrs:



Spectral-dependent detection

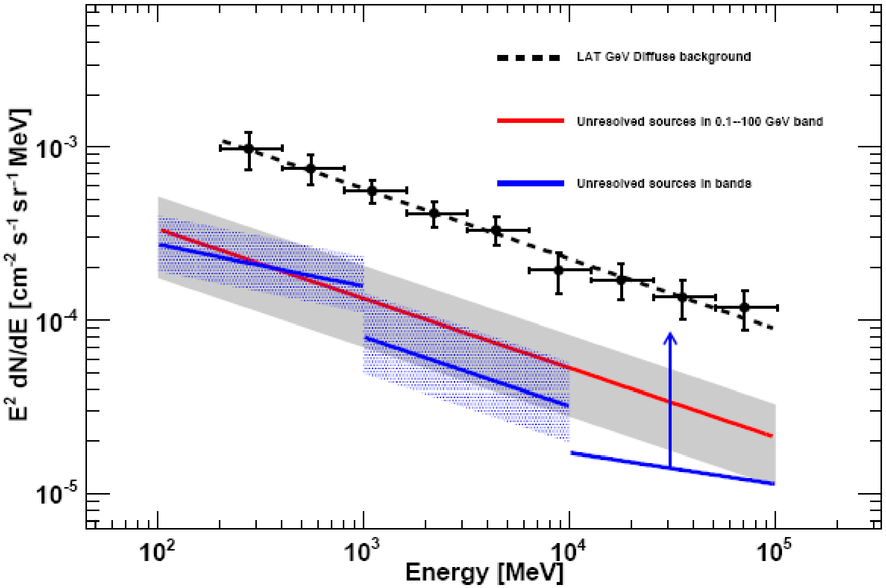
- ★ We are currently updating our predictions using the spectral-dependent flux limit below. This effect is (unfortunately) important, leading to the revision of the improvement to a factor 2-3, instead of 3-10.

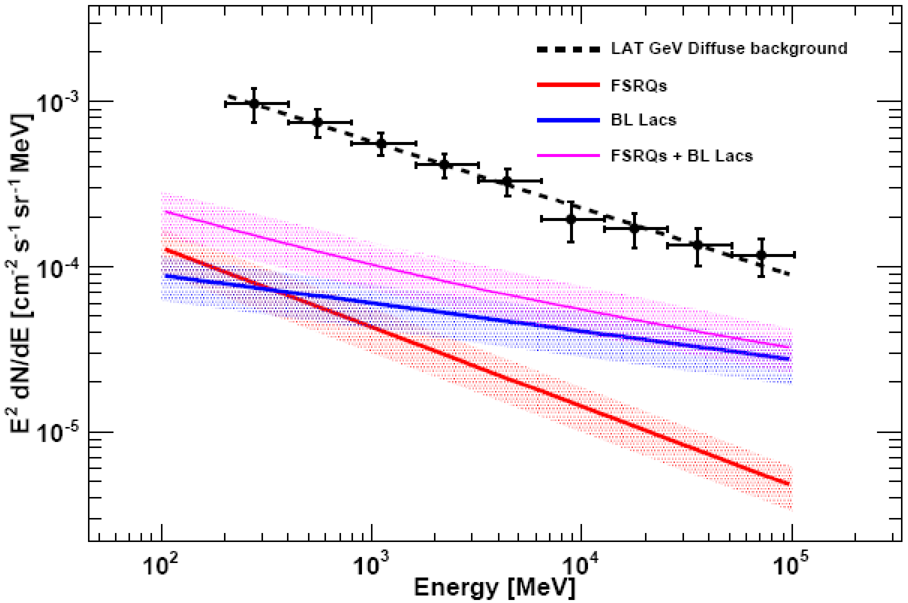


Results from Fermi Collaboration

★ In a recent paper [Abdo, et al., 1003.0895] the Fermi collab studied the contribution to the EGB from unresolved point sources.

★ They conclude that at most 20% of the EGB can be provided by unresolved sources like blazars.





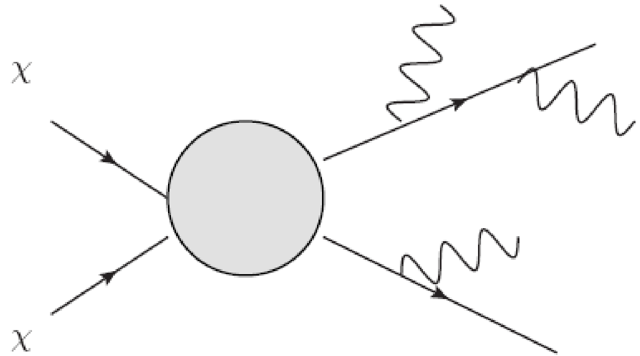
1. Power law spectrum assumed does not fit observed spectra well.
2. The average spectral properties of blazars might change with flux and/or redshift.

Gamma-rays from Dark Matter

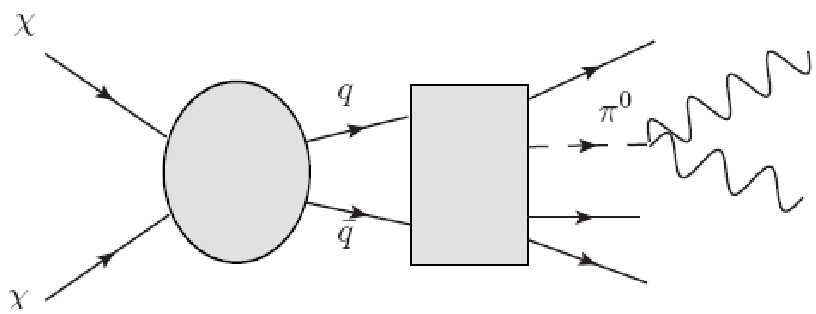
★ Dark matter annihilation or decay can emit photons in many ways:

1. PROMPT EMISSION

- DM can annihilate into products of charged particles, which can radiate off photons



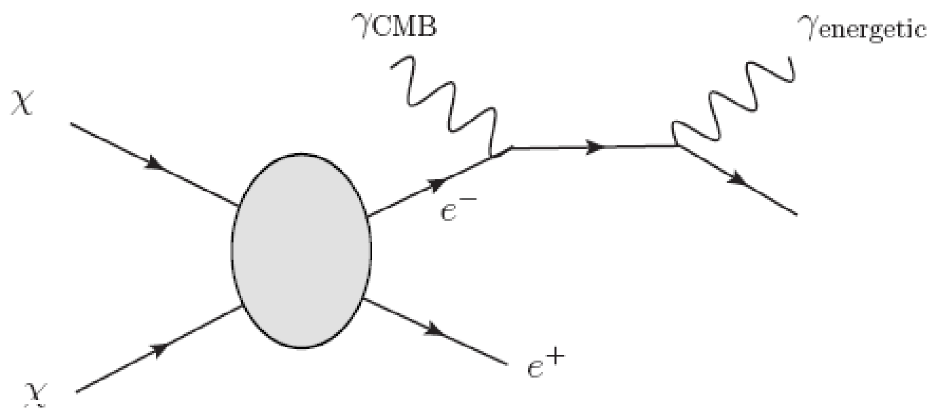
- If the annihilation products hadronize, they can produce neutral pions which decay into two photons:



Gamma-rays from Dark Matter

2. INVERSE-COMPTON COMPONENT

- If the final state contains an (energetic) electron, the Inverse Compton scattering of this electron off background photons is important!



Background photons can be :

✓ Starlight originating from stars in the galactic disk (at optical wavelengths)

✓ Infrared radiation produced by the absorption and re-emission of starlight by the galactic dust

✓ The Cosmic Microwave Background

Gamma-rays from Dark Matter

★ Dark matter annihilation or decay can occur in our galaxy or outside.

★ Note that there is an irreducible isotropic component in galactic DM annihilation coming from the anti-galactic center (AGC), which in our case is going to be dominant over the extragalactic contribution.

★ The differential flux of photons from DM annihilation within our galaxy is

Direct output from Pythia

$$\frac{\mathrm{d}\Phi^{\mathrm{ann}}_{\mathrm{halo}}}{\mathrm{d}\epsilon_1 \Delta\Omega} = \frac{\langle \sigma_{\mathrm{ann}} v \rangle}{8\pi} r_\odot \frac{\rho_\odot^2}{m_\chi^2} \bar{J}_{\mathrm{ann}} \left[\left(\frac{\mathrm{d}N}{\mathrm{d}\epsilon_1}\right)_{\mathrm{IC}} + \left(\frac{\mathrm{d}N}{\mathrm{d}\epsilon_1}\right)_{\mathrm{prompt}} \right]$$

$$\bar{J}_{\mathrm{ann}} = \frac{1}{\Delta\Omega} \int_{\Delta\Omega} \mathrm{d}\Omega \int_{\mathrm{l.o.s.}} \frac{\mathrm{d}s}{r_\odot} \left(\frac{\rho(r)}{\rho_\odot}\right)^2 \quad \text{with} \quad \rho(r) = \rho_{\mathrm{Einasto}} = \rho_s \exp\left[-\frac{2}{\alpha_E} \left(\left(\frac{r}{r_s}\right)^{\alpha_E} - 1 \right) \right]$$

Solid angle in the sky, which we take to be the AGC, at $b = 0^\circ,\ l = 180^\circ$ independent of profile!!

Minimal Einasto density profile for our Milky Way

$$\alpha_E = 0.22,\ r_s = 21\ \mathrm{kpc}$$
$$r_\odot = 8.28\ \mathrm{kpc},\ \rho_\odot = 0.385\ \mathrm{GeV/cm^3}$$

Gamma-rays from Dark Matter

★ The IC component is slightly more involved to compute [Cirelli & Panci, 0904.3830]:

$$\left(\frac{\mathrm{d}N}{\mathrm{d}\epsilon_1}\right)_{\mathrm{IC}} = \frac{1}{\epsilon_1}\int_{m_e}^{m_\chi} \mathrm{d}E \frac{\boxed{\mathcal{P}(\epsilon_1, E)}}{\boxed{\dot{\mathcal{E}}(E)}} Y(E)$$

Differential power emitted into photons of energy ϵ_1 by an electron of energy E

Total rate of electron energy loss due to IC scattering

# of electrons per DM annihilation generated with energy larger than E.

★ In order to get such a simple result, we are

- Neglecting the diffusion of the electrons, which is a good approximation away from the galactic center
- Assuming that the only losses for electrons are IC, which has been shown to be dominant in this environment
- Neglecting the dependence of the local number density of target photons on the spatial position: certainly true for CMB photons!

$$n_{\mathrm{CMB}}(\epsilon) = \frac{\epsilon^2}{\pi^2}\frac{1}{\exp(\epsilon/T_{\mathrm{CMB}}) - 1} \qquad T_{\mathrm{CMB}} = 2.725\ \mathrm{K}$$

Gamma-rays from Dark Matter

★ The extragalactic contribution is given by

$$\frac{\mathrm{d}\Phi^{\mathrm{ann}}_{\mathrm{cosm}}}{\mathrm{d}\epsilon_1 \Delta\Omega} = \frac{\langle \sigma_{\mathrm{ann}} v\rangle}{8\pi} \frac{c}{\boxed{H_0}} \frac{\Omega^2_{\mathrm{DM}} \rho^2_{\mathrm{crit}}}{m_{\chi^2}}$$

$$\int_0^\infty \mathrm{d}z (1+z)^3 \frac{\boxed{f(z)}\, \mathrm{e}^{-\tau(z,\varepsilon_1)}}{\boxed{\sqrt{\Omega_m (1+z)^3 + \Omega_\Lambda}}} \left[\left(\frac{\mathrm{d}N}{\mathrm{d}\epsilon_1}\right)_{\mathrm{IC}} + \left(\frac{\mathrm{d}N}{\mathrm{d}\epsilon_1}\right)_{\mathrm{prompt}} \right]_{\epsilon_1(1+z)}$$

Optical depth

Rescaling factor of DM density with redshift

In the line-of-sight integral, we make a change of integration variable from radius to redshift: $dr = cdz/[(1+z)H(z)]$

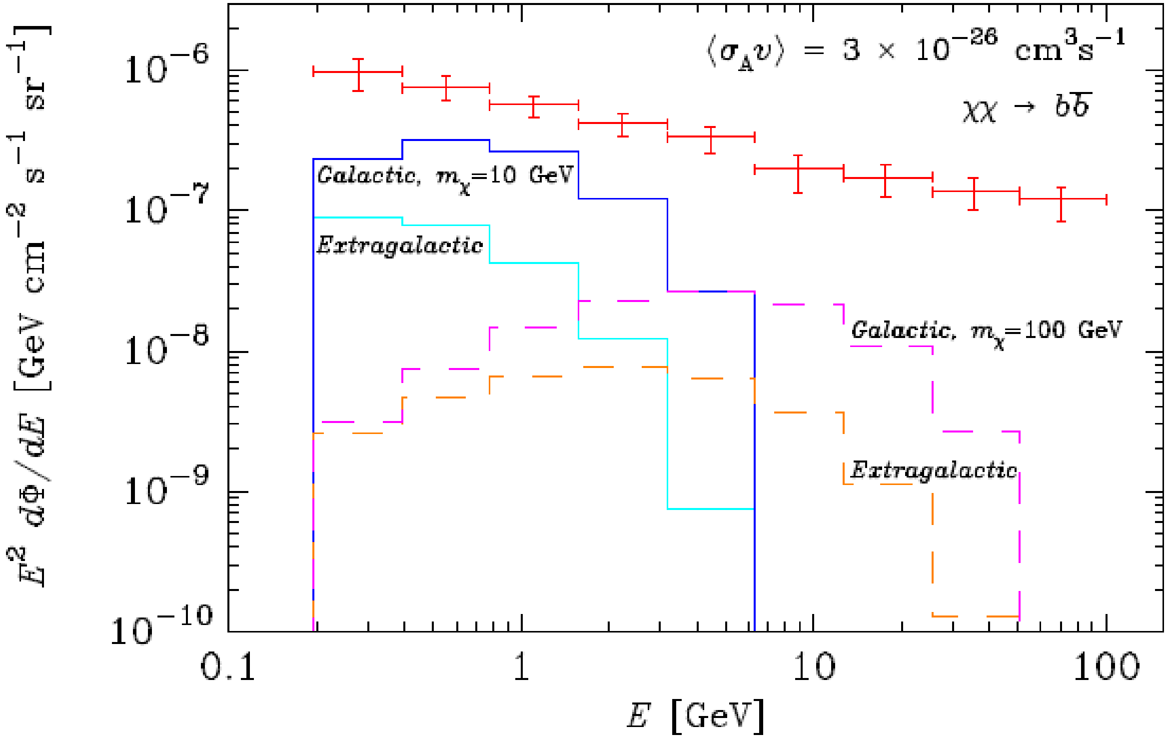
The Hubble function is $H(z) = H_0 \sqrt{\Omega_m (1+z)^3 + \Omega_\Lambda}$

The factor $f(z)$ accounts for the fact that DM is clustered into halos and subhalos rather than uniformly distributed, and for the redshift evolution of the halo mass function. We adopt the fit by Yüksel, et al. [arXiv:0707.0196]:
$f(z) = f_0 10^{0.9[\exp(-0.9z)-1]-0.16z}$ where $f_0 = 3 \times 10^4$ for the Einasto profile

Gamma-rays from Dark Matter

★ We are also including an irreducible boost factor of 3.3 in the direction of the anti-GC due to substructure, following Kamionkowski, Koushiappas and Kuhlen [1001.3144], where the density probability distribution function of cold DM was calibrated with Via Lactea II.

★ The contribution to the EGB from the MW is always found to be dominant compared to the extragalactic contribution.



[Abazajian, et al., 1002.3820]

Decaying Dark Matter

★ The particle constituting dark matter does not need to be absolutely stable. Its lifetime must just be long enough.

★ There are a few candidates around, such as the gravitino, the sterile neutrino, and even within GUT theories, GUT-scale suppressed d=6 operators provide a long enough lifetime to certain particles [Arvanitaki, et al., 0812.2075]

★ The framework to calculate the gamma-ray contribution to the EGB is very similar to the annihilation case.

$$\frac{\mathrm{d}\Phi^{\mathrm{dec}}_{\mathrm{halo}}}{\mathrm{d}\epsilon_1 \Delta\Omega} = \frac{1}{4\pi\tau_\chi} r_\odot \frac{\rho_\odot}{m_\chi} \bar{J}_{\mathrm{dec}} \left[\left(\frac{\mathrm{d}N}{\mathrm{d}\epsilon_1}\right)_{\mathrm{IC}} + \left(\frac{\mathrm{d}N}{\mathrm{d}\epsilon_1}\right)_{\mathrm{prompt}} \right]$$

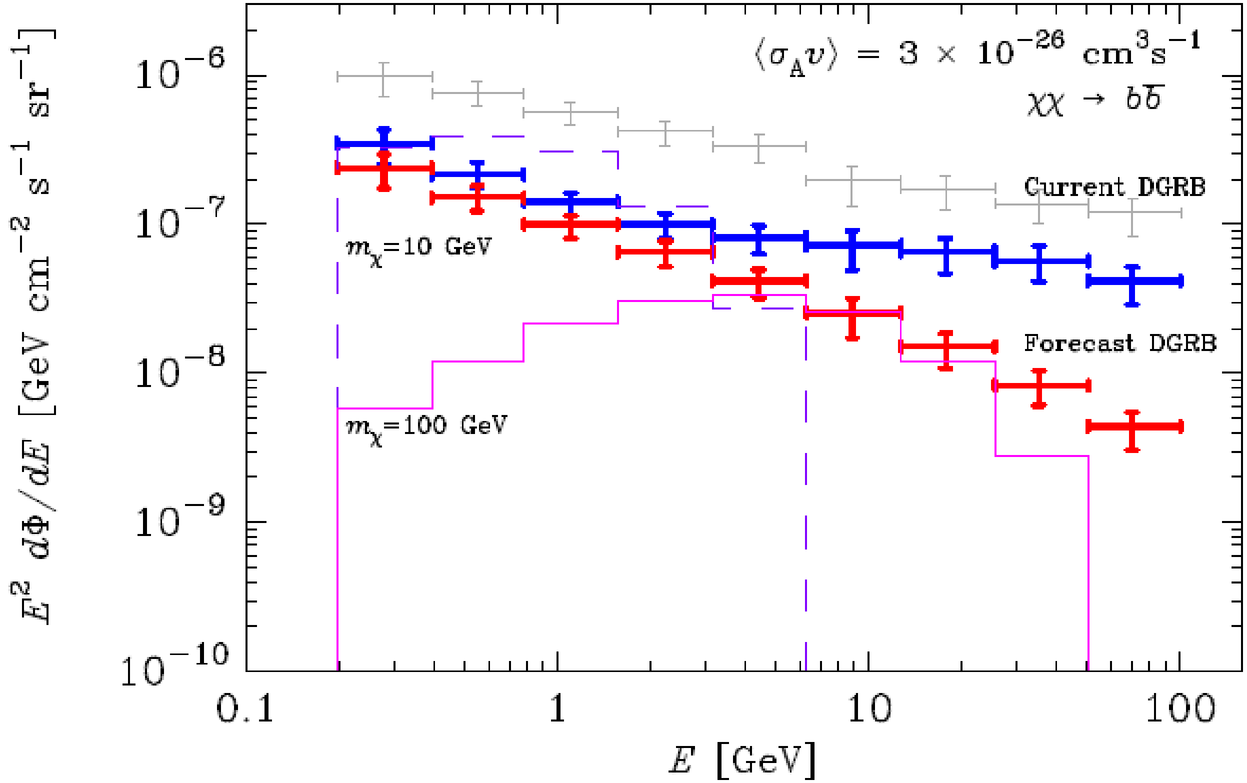
DM lifetime

with $$\bar{J}_{\mathrm{dec}} = \frac{1}{\Delta\Omega}\int_{\Delta\Omega}\mathrm{d}\Omega \int_{\mathrm{l.o.s.}} \frac{\mathrm{d}s}{r_\odot}\frac{\rho(r)}{\rho_\odot}$$

1. Linear in the density profile
2. No boost factor due to substructure

Constraints on DM models

- We can constrain DM models by requiring that the gamma-ray flux from DM annihilation (or decay) does not exceed the EGB measured by Fermi.
  - In particular, we can use our forecast limit for the Fermi EGB to place the most stringent constraints that can be obtained from Fermi (after 5 years).

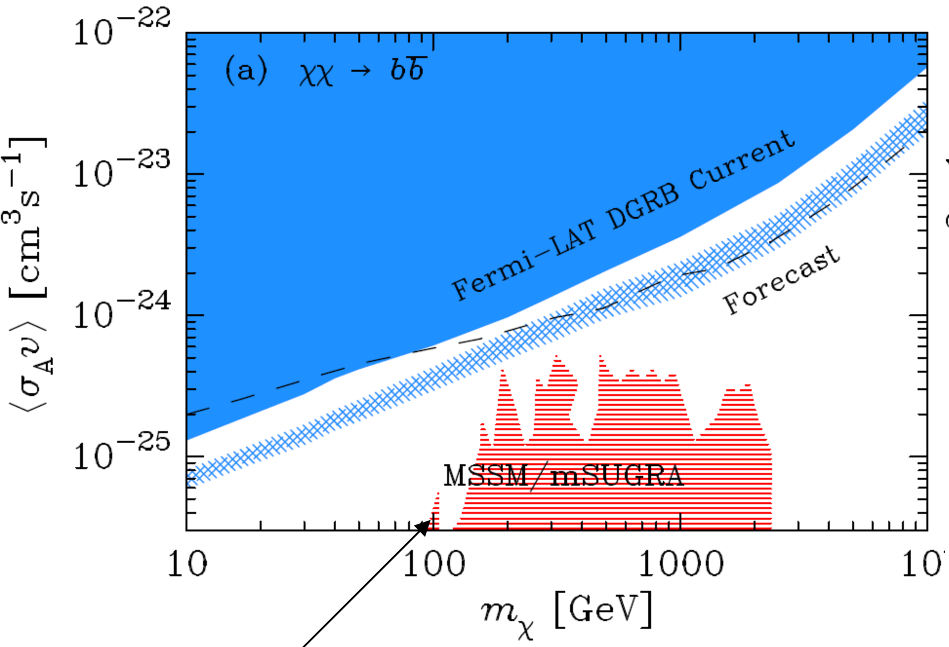


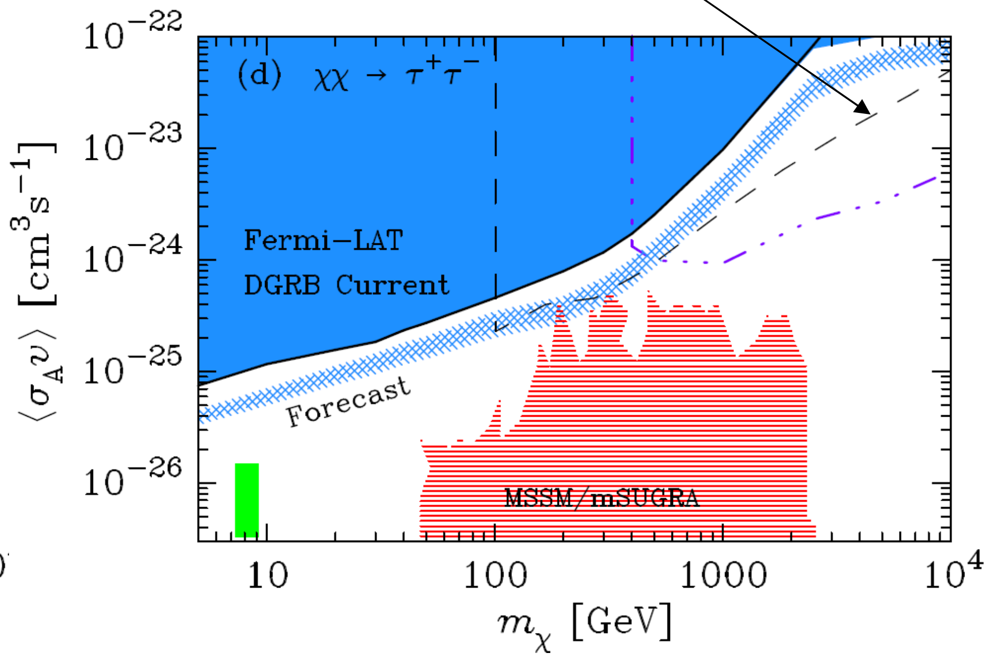
[Abazajian, et al., 1011.5090]

Constraints on DM models

★ The limits for annihilation cross-sections into typical channels with large hadronic activity are the following:

[Cirelli, Panci, Serpico, 0912.0663]

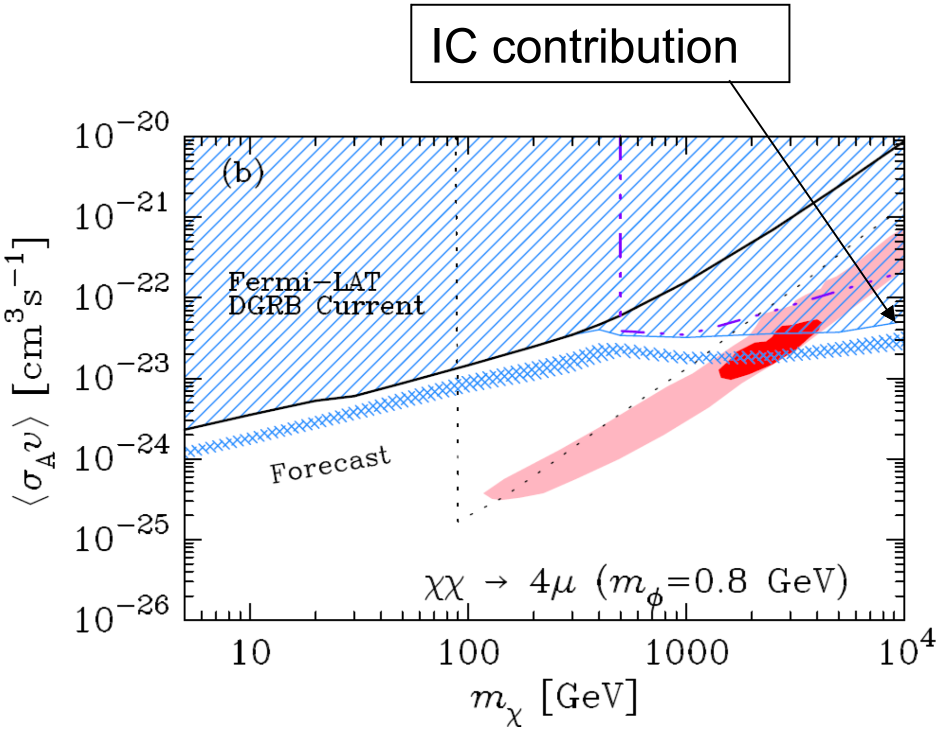




[Bergstrom, Bringmann, Edjsö, 1011.4514]

Constraints on DM models

- DM annihilation into four leptons have become popular in theories with a new GeV-scale mediator [Arkani-Hamed, et al., 0810.0713] . These models are quite constrained:

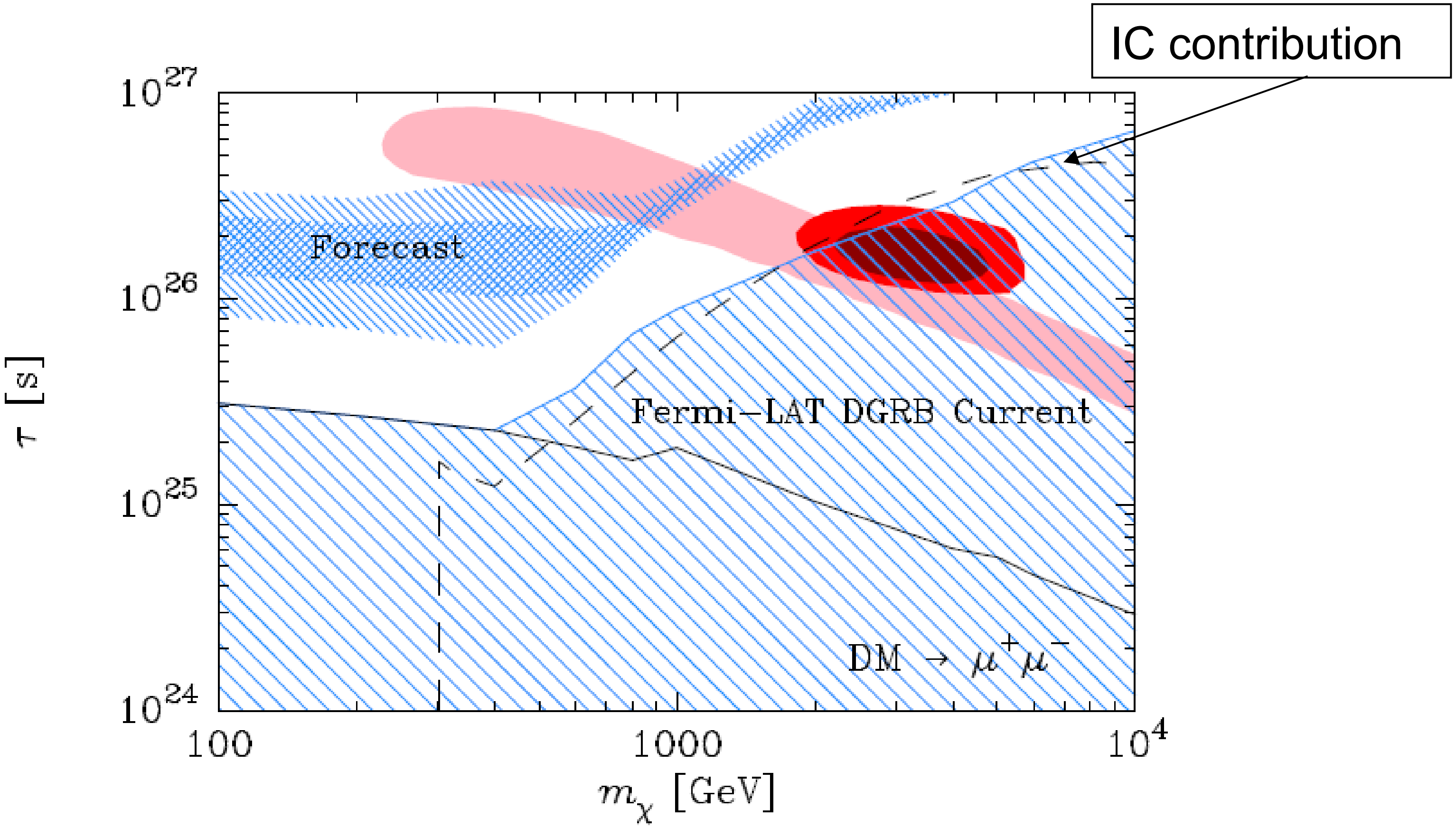


Pink region: where the PAMELA rise in positron fraction is explained (99% CL)

Red region: where the Fermi e+/e- feature is explained (99% CL)

Constraints on DM models

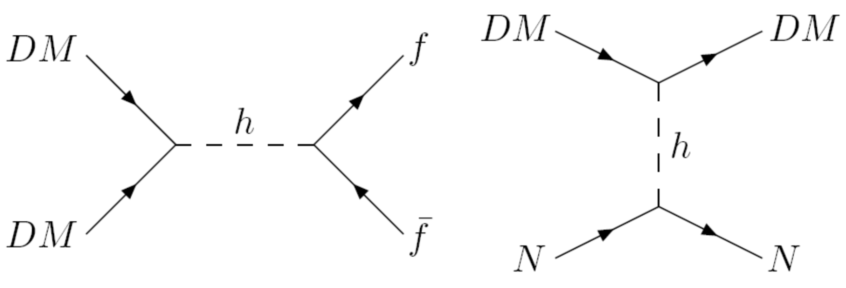
- Unstable DM candidates are also required to decay on very long timescales:



Constraints on DM models

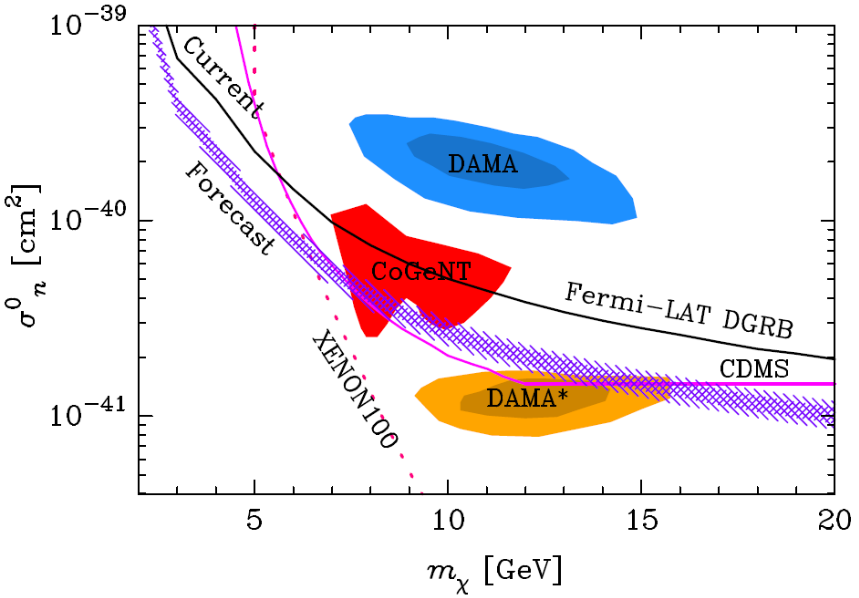
★ Minimal models of dark matter where interactions occur through the exchange of Higgs bosons („Higgs portal“) can explain possible „signals“ at direct detection experiments such as DAMA, CoGeNT and CDMS.

→ Light DM!



★ In these models, there is a one-to-one correspondance between the annihilation cross-section and the direct detection one. [Andreas, Hambye, Tytgat, 0808.0255]

→ We can compare limits from direct and indirect detection experiments!



Conclusions

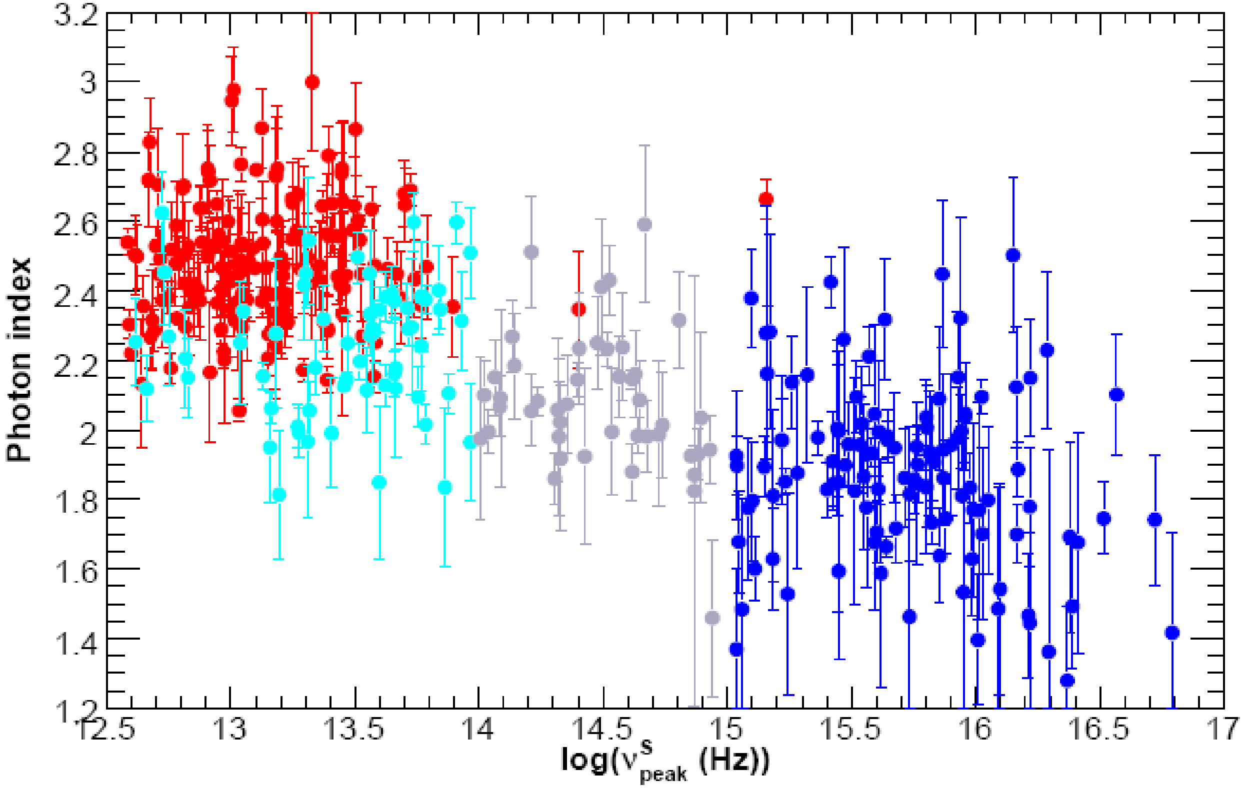
- ★ The nature of dark matter is still one of the great mysteries of physics.
- ★ Indirect detection does not need to be highly dependent on astrophysical parameters: constraints from the Isotropic Diffuse Gamma-Ray background are robust!
- ★ We have presented a blazar model based on the Spectral Energy Distribution (SED) sequence that has precise prediction for Fermi after 5 years of data-taking.
- ★ If this blazar model is correct, and no DM is seen by Fermi, the limits on annihilation cross-sections for DM will improve by a factor 2-3.
- ★ This would strongly constrain most of the PAMELA/Fermi explanations (large DM mass), as well as the DAMA/CoGeNT ones (light DM).

Decaying Dark Matter

★ The extragalactic contribution is given by:

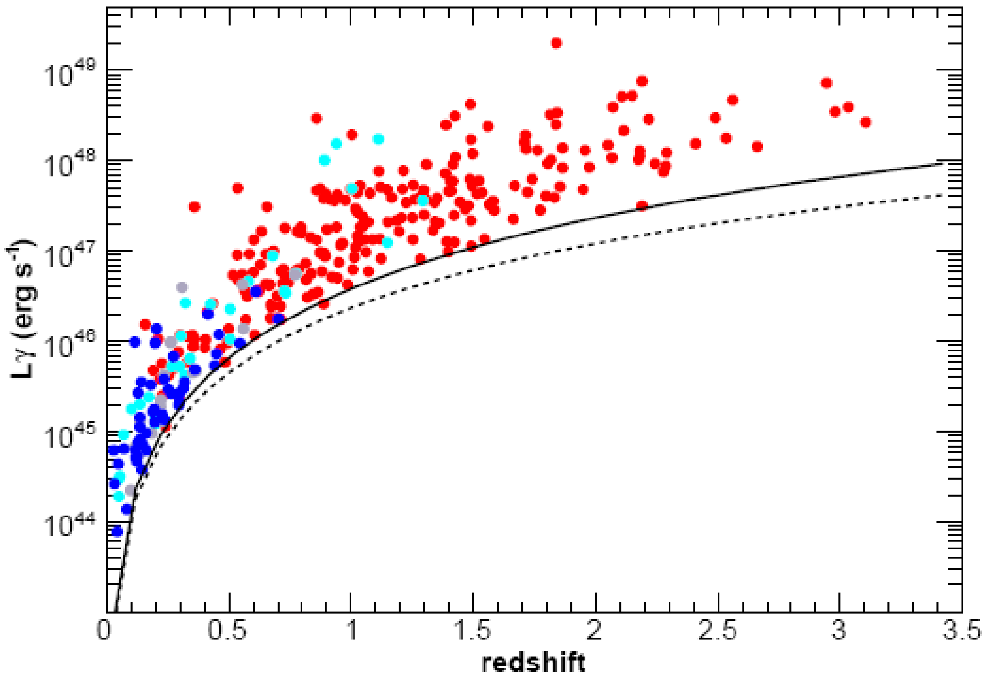
$$\frac{\mathrm{d}\Phi^{\mathrm{dec}}_{\mathrm{cosm}}}{\mathrm{d}\epsilon_1 \Delta\Omega} = \frac{1}{4\pi\tau_\chi}\frac{c}{H_0}\frac{\Omega_{\mathrm{DM}}\rho_{\mathrm{crit}}}{m_\chi}\int_0^\infty \mathrm{d}z \frac{\mathrm{e}^{-\tau(z,\varepsilon_1)}}{\sqrt{\Omega_m(1+z)^3+\Omega_\Lambda}}\left[\left(\frac{\mathrm{d}N}{\mathrm{d}\epsilon_1}\right)_{\mathrm{IC}} + \left(\frac{\mathrm{d}N}{\mathrm{d}\epsilon_1}\right)_{\mathrm{prompt}}\right]_{\epsilon_1(1+z)}$$

SED



Photon index
3.2
3
2.8
2.6
2.4
2.2
2
1.8
1.6
1.4
1.2
12.5
13
13.5
14
14.5
15
15.5
16
16.5
17
$\log(\nu^{s}_{peak}$ (Hz))

SED



Lγ (erg s⁻¹)
10^{49}
10^{48}
10^{47}
10^{46}
10^{45}
10^{44}
0
0.5
1
1.5
2
2.5
3
3.5
redshift