Gamma-ray lines & Co.
Indirect searches for dark matter

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Torsten Bringmann, Francesca Calore, Xiaoyuan Huang,
Alejandro Ibarra, Gilles Vertongen, Stefan Vogl

JCAP 1105 (2011) 027; Phys. Rev. D84 (2011) 103525;
arXiv:1203.1312; ongoing work

Christoph Weniger
Max-Planck-Institut für Physik, München

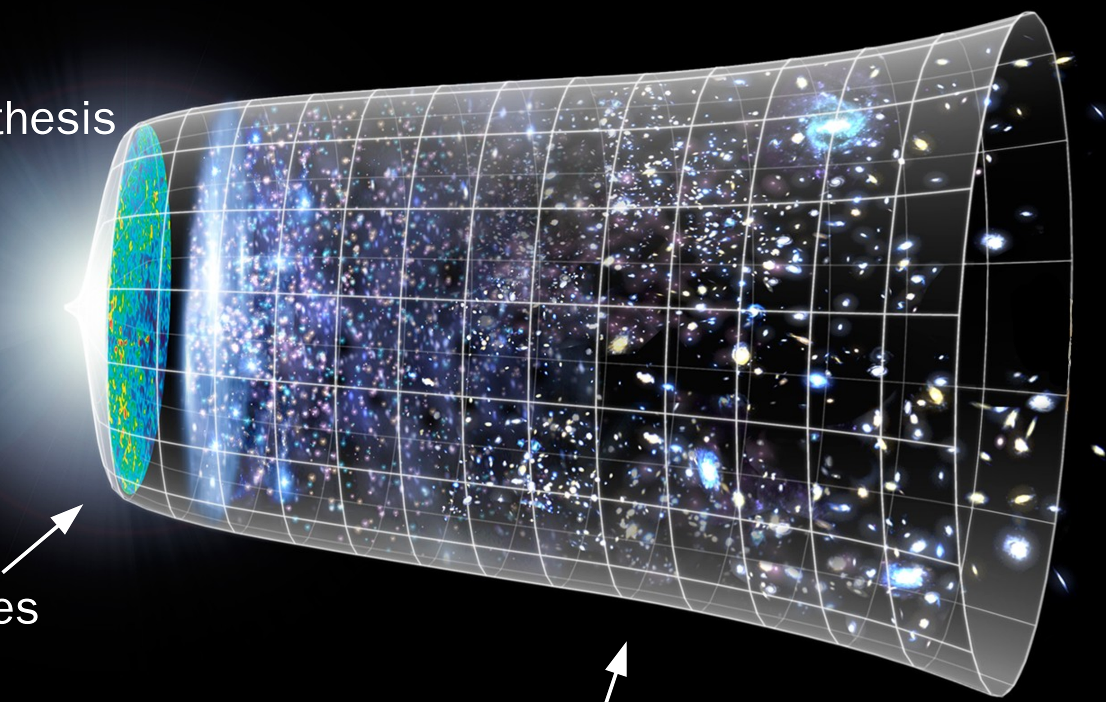
Lago di Resia - Südtirol

Outline

- Introduction
- Searching Spectral Sigantures from DM Annihilation with the Fermi LAT
  - Gamma-ray lines (Jan 2011)
  - Internal Bremsstrahlung (Mar 2012)
  - Gamma-ray lines again (Mar 2012) and a hint at 130 GeV
- Prospects for Atmospheric Cherenkov Telescopes
- Conclusions

Todays View on Dark Matter

Primordial
Nucleosynthesis



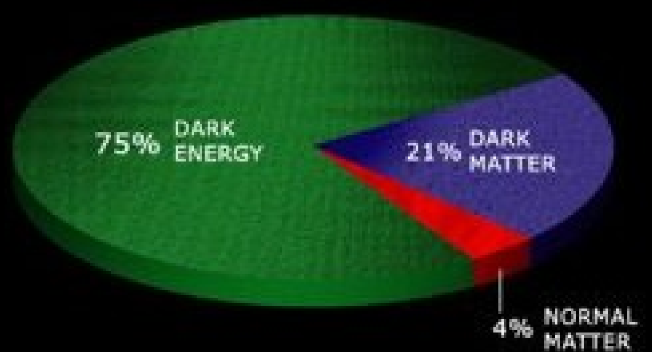
CMB Anisotropies

Microlensing
„Bullet Cluster“

Structure Formation
Large Scale Structures

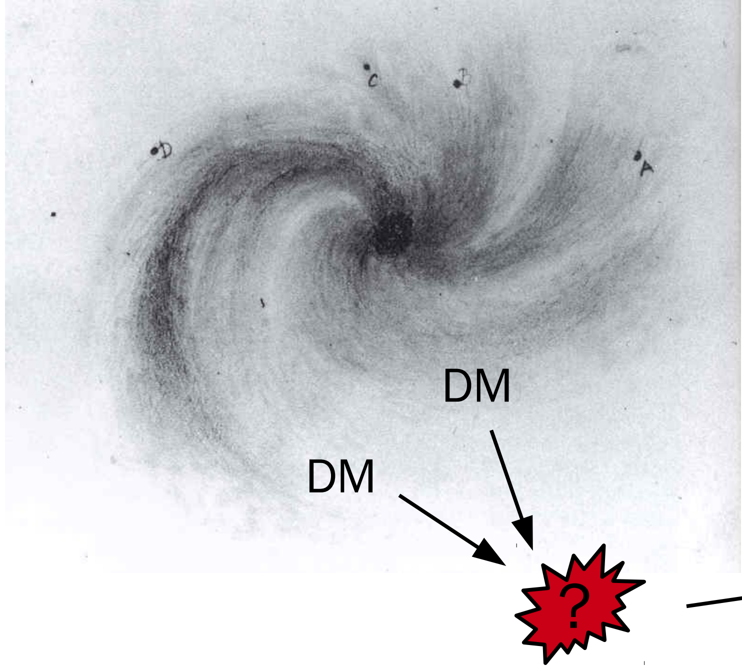
Galaxy Clusters & X-rays
Spiral Galaxy rotation curves
Dwarf Galaxies Tidal Stripping

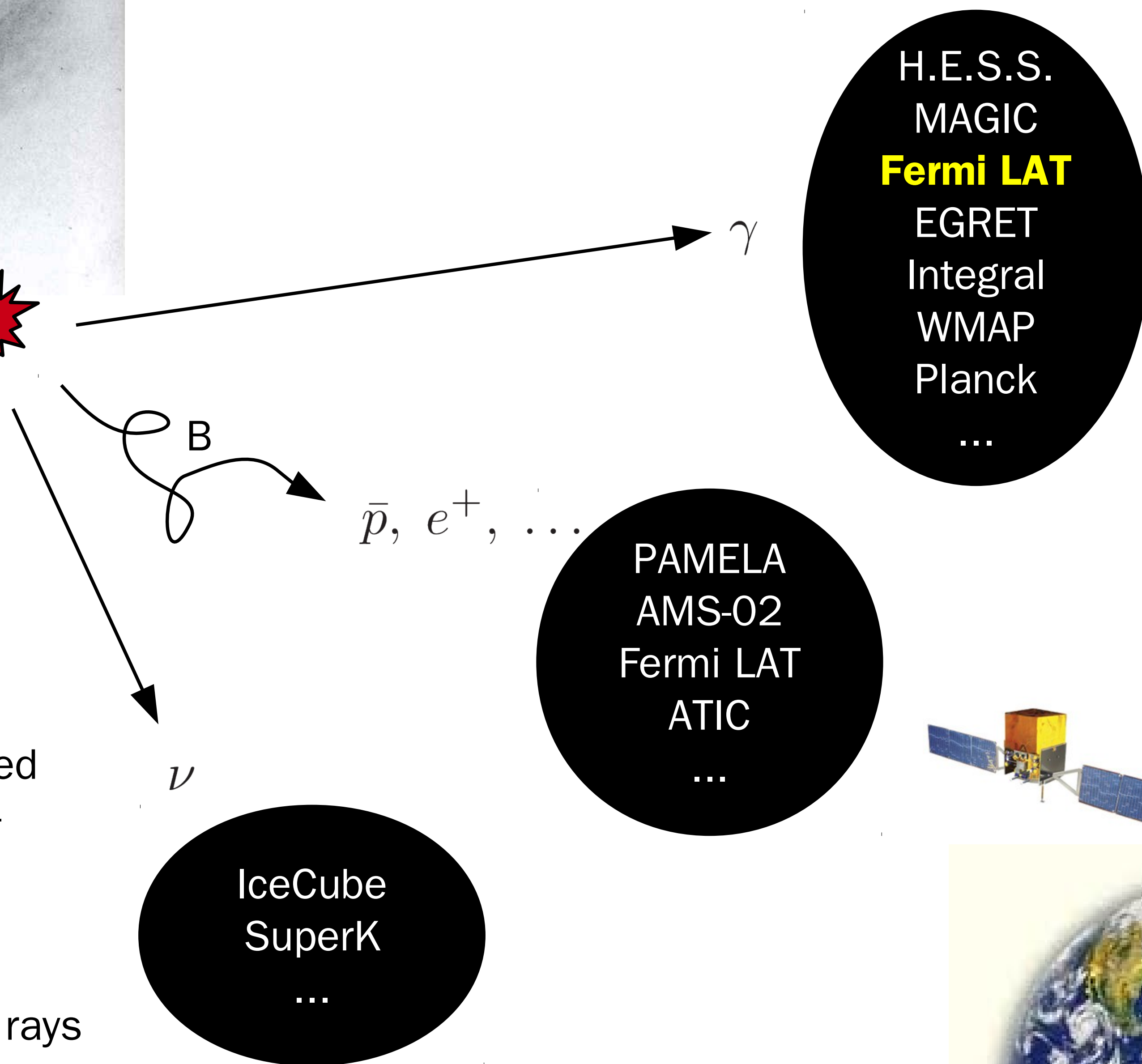
Energy budget today:



→ Motivation to search for Physics beyond the SM

Indirect Dark Matter Searches

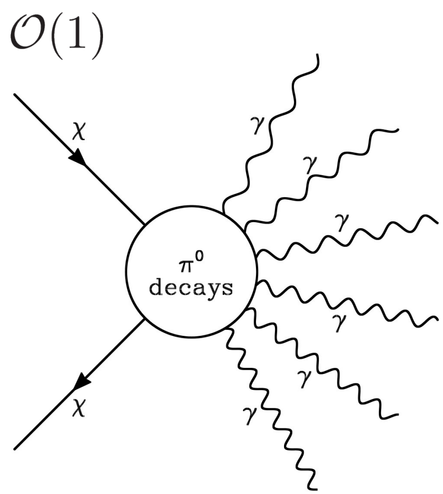


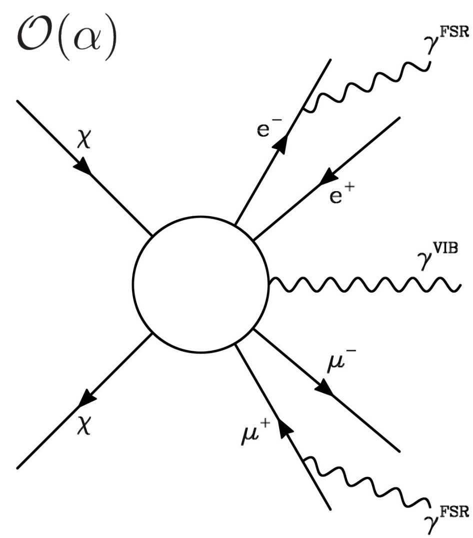


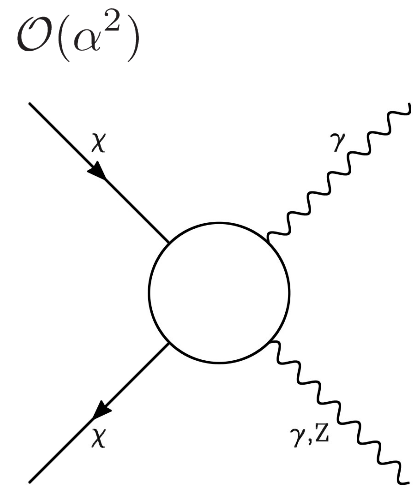
Searching WIMPs

- „Weakly Interacting Massive Particles“
- Compatible with observed relic density due to self-annihilation in early Universe
- Still annihilate today → contribute to cosmic rays

Components of the photon energy spectrum







Secondary photons

- Produced in the fragmentation of quarks/bosons (pi0 decay)
- <u>Soft</u> spectrum
- Difficult to distinguish from astrophysical fluxes

Internal Bremsstrahlung (IB)

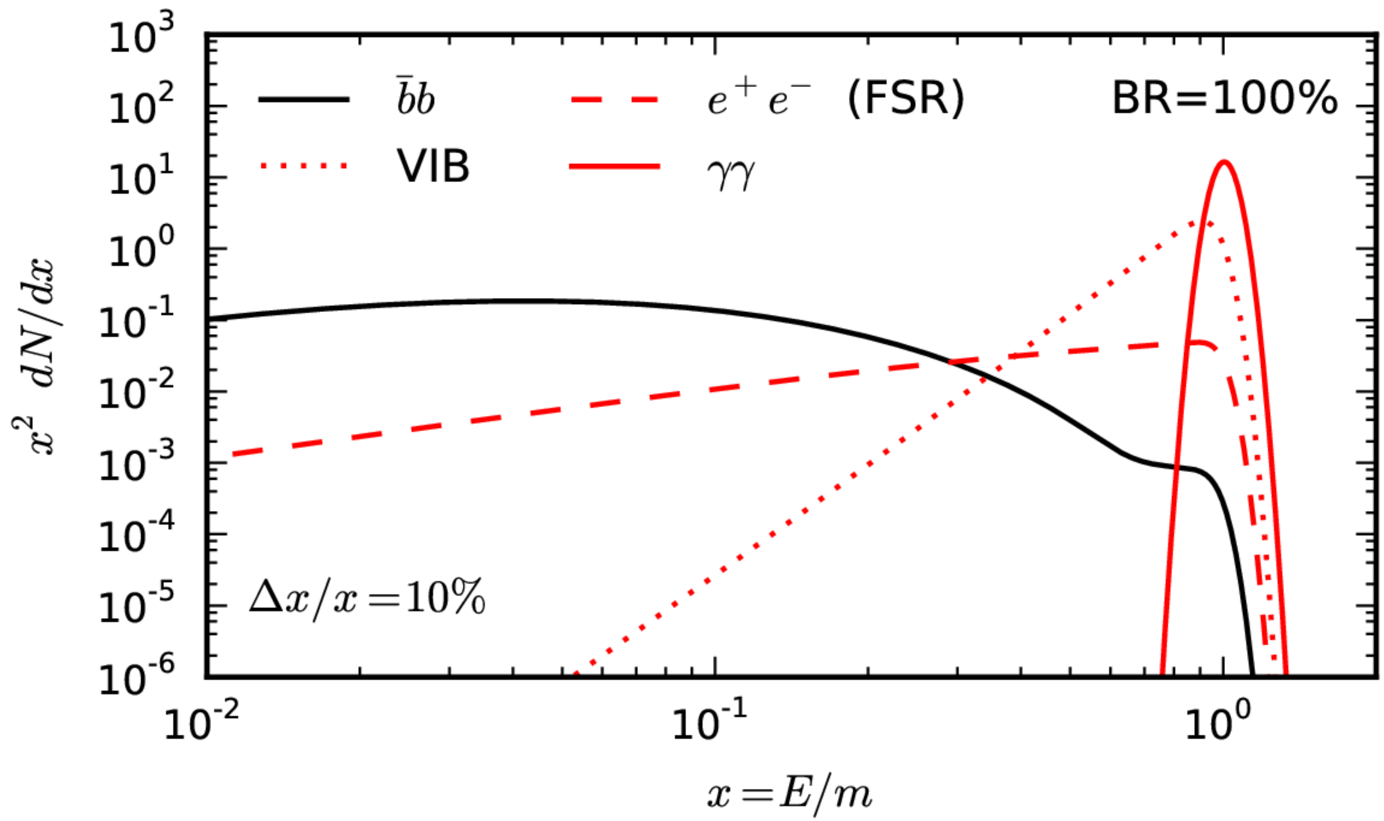
- Accompanies charged final states
- Appears at O(α)
- <u>Harder</u> spectrum
- IB = Final State Radiation (FSR) + Virtual Internal Bremsstrahlung (VIB)

Gamma-ray lines

- Produced in two-body annihilatino into photons or photon+Z/h boson
- Appears at O(α^2)
- <u>Hardest</u> spectrum

[Figs. from Kuhlen (2010)]

Different components in comparison



Radiative corrections produce characteristic features at kinematic cutoff. They

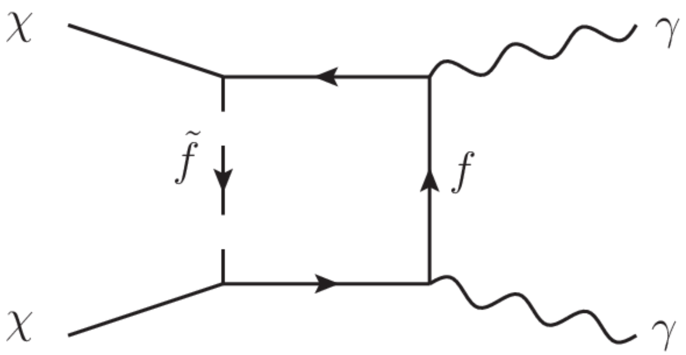
- appear as lines, bumps, sharp cutoffs
- are "smoking gun" signatures
- provide a measure of the dark matter mass

Gamma-Ray Lines

Characteristic Features

- Are produced in two-body annihilation

$$\chi\chi \to \gamma\gamma,\ \gamma Z,\ \gamma h$$



- Simple energy spectrum

$$\frac{dN}{dE} \propto \delta(E - E_\gamma) \quad \text{with} \quad E_\gamma \leq m_\chi$$

- Process is one-loop suppressed

$$\mathrm{BR}(\chi\chi \to \gamma\gamma) \sim \alpha_{\mathrm{em}}^2$$

Some models with enhanced lines:

- Singlet Dark Matter [Profumo et al. (2010)]
- Hidden U(1) dark matter [Mambrini (2009)]
- Effective DM scenarios [Goodman et al. (2010)]
- "Higgs in Space!" [Jackson et al. (2010)]
- Inert Higgs Dark Matter [Gustafsson et al. (2007)]
  $\to$ W bosons close to kin. threshold running in the loop
- Kaluza-Klein dark matter in UED scenarios [Bertone et al. (2009)]

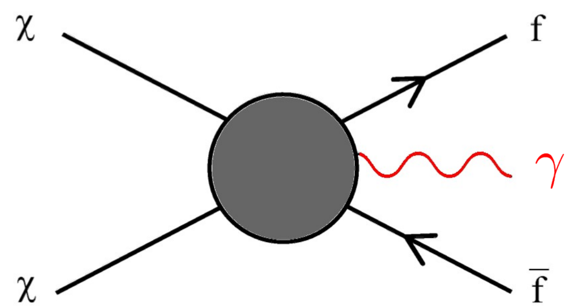
...

Internal Bremsstrahlung

Charged final states give rise to **internal bremsstrahlung (IB)**

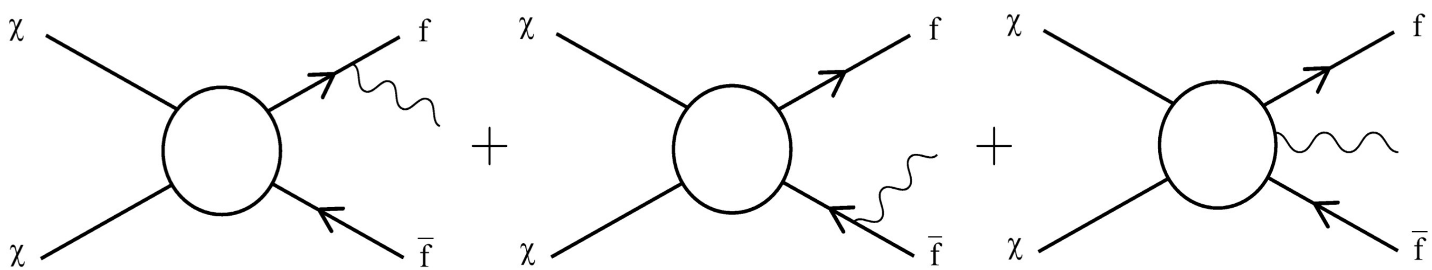
$$\chi\chi \to f\bar{f} \qquad \overset{\mathcal{O}(\alpha)}{\Longrightarrow}$$

(here: χ is a Majorana fermion)



Splits up into two contributions:

=



"Final State Radiation"

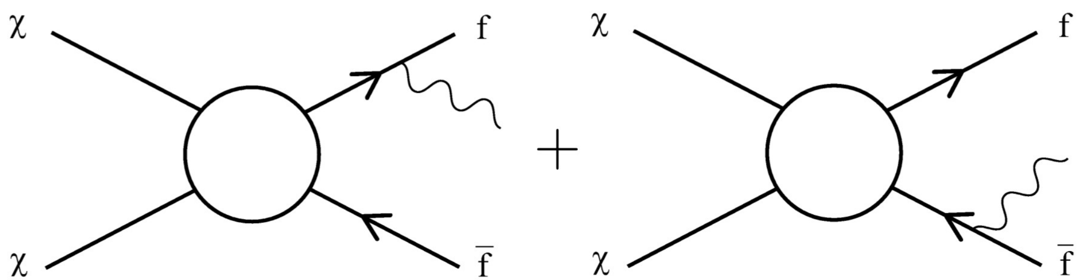
"Virtual Internal Bremsstrahlung"

1^{st} order in $(m_f/m_\chi)^2$

0^{th} order in $(m_f/m_\chi)^2$

[Figs. from T. Bringmann]

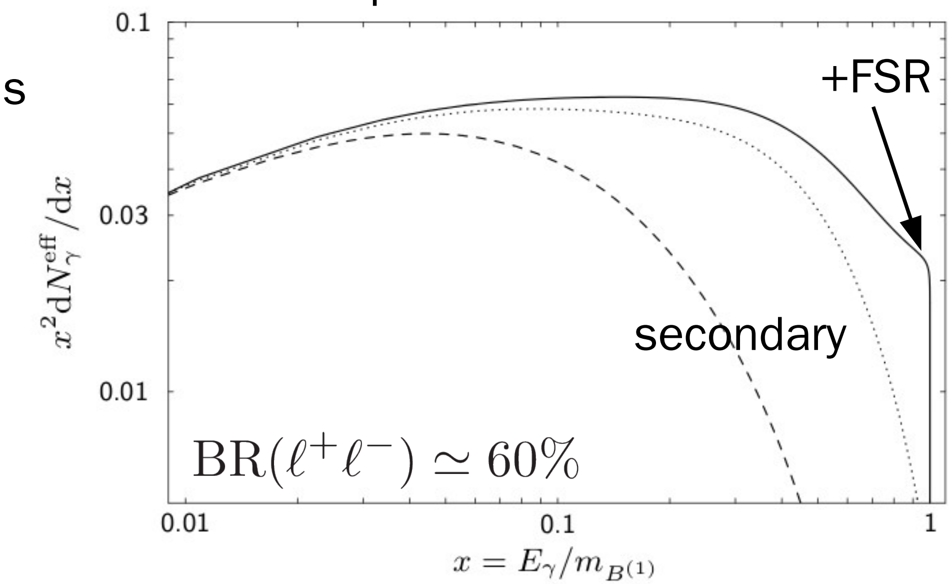
Final State Radiation (FSR)



Characteristic features

- log-enhancement for light fermions
- universal spectrum
- generates sharp cutoff at dark matter mass

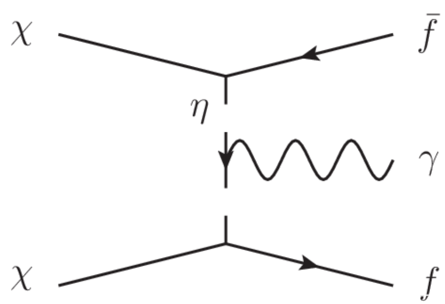
Example: Kaluza-Klein DM



- Important when branching ratio into leptons is large

[Bergström et al., 2004]

Virtual Internal Bremsstrahlung (VIB)



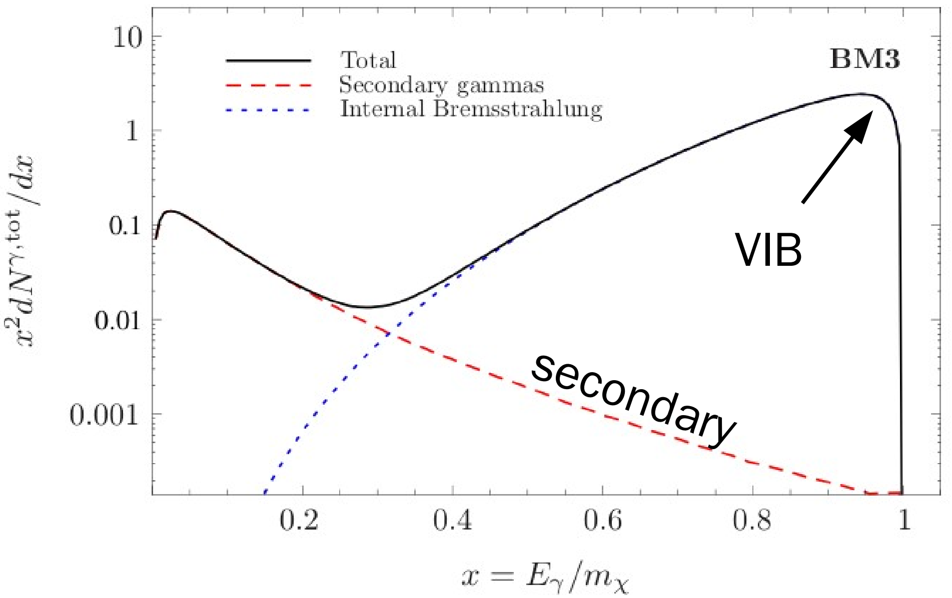
t-channel

Characteristic features

- dominates FSR when
  - 3-body final state lifts e.g. helicity suppression
  - final states are scalars
- model-dependent spectrum
- produces “bumps”

- Important in models with degenerate mass spectrum (LSP DM in coannihilation region)

Example: stau coannihilation region

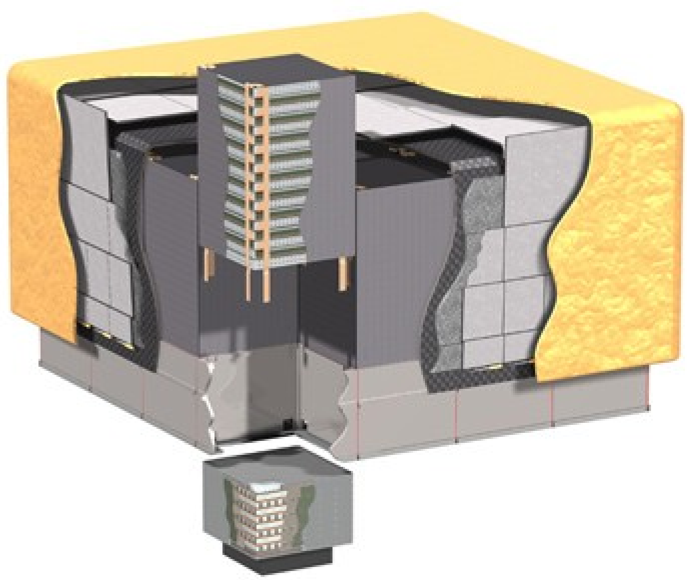


[Bringmann et al., 2004]

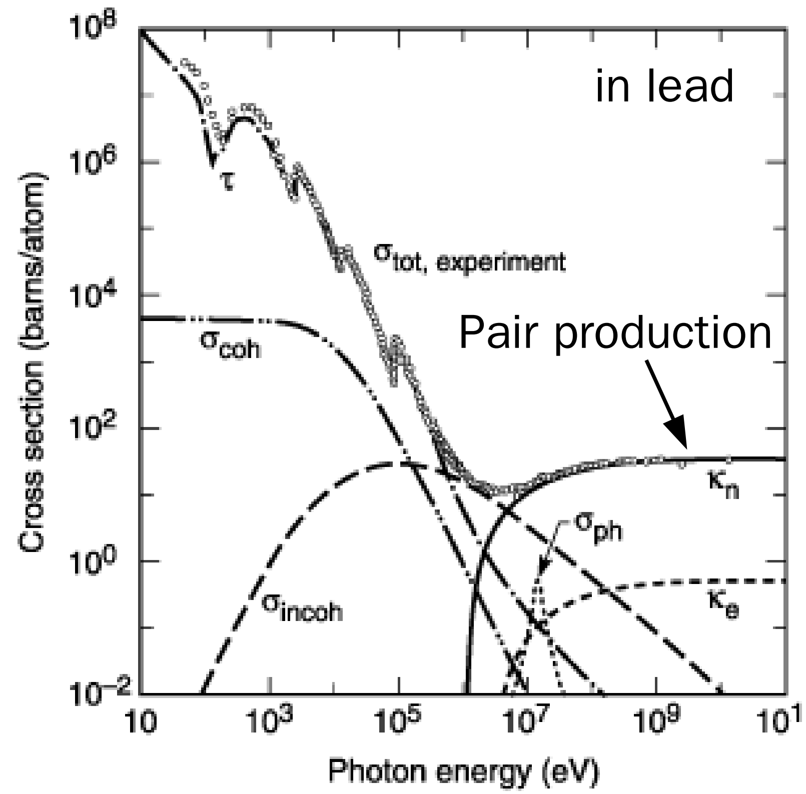
Indirect Dark Matter Searches with the Large Area Telescope (LAT)

Launch: June 2008

- Main Instrument on the **Fermi Gamma-Ray Space Telescope**
- Pair conversion instrument
- 30 MeV to >300 GeV energy range
- 2.4 sr field of view



Main components (in 16 towers)
- Plastic anticoincidence detector
- Tungsten conversion foils
- Silicon strip detectors
- Cesium Iodine Calorimeter



High-level data is publicly available
http://fermi.gsfc.nasa.gov

Search for

Spectral Signatures

from DM Annihilation

with the Fermi LAT

Take-away messages

- Spectral signatures are <u>excellent targets</u>
- It requires some <u>extra effort</u> to exploit these features (and it requires, as always, some extra luck to find them)

- Current searches with Fermi LAT
  - constrain DM models with intense gamma-ray lines
  - do not constrain DM models with intense IB radiation
  - we find a weak indication for a possible signal at ~130 GeV

The Gamma-Ray Signal

The gamma-ray flux from dark matter annihilation at a certain energy in a certain direction is given by:

$$\frac{dJ_{\text{ann.}}}{d\Omega dE} = \frac{\langle \sigma v \rangle}{8\pi m_{\text{dm}}^2} \frac{dN}{dE} \times \int_{\text{l.o.s.}} ds \; \rho(\vec{r}[s, \Omega])^2$$

„Particle Physics Factor“

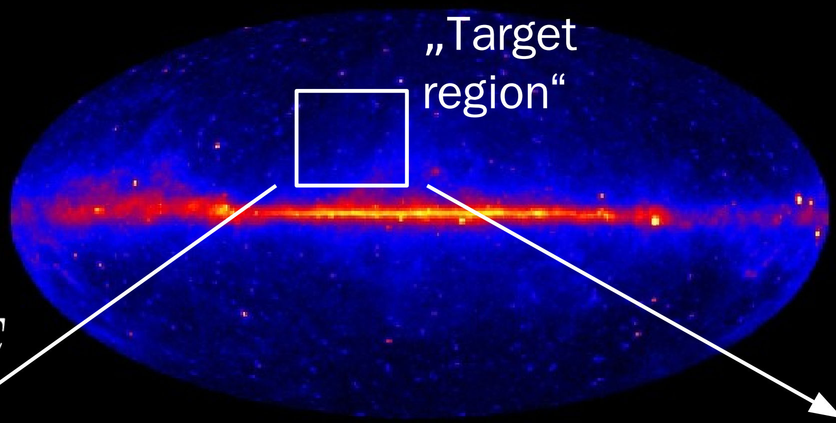
Characteristic **Energy Spectrum**

„Astrophysics Factor“

Characteristic **Spatial Dependence** (point-like or extended)

Signal/Background Discrimination

Measured Events:
$(E_i,\ \Omega_i)$

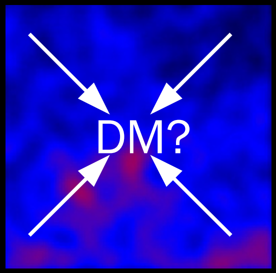


„Target region“

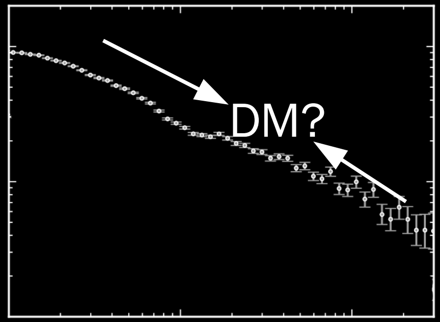
$$\int_{E_0}^{E_1} dE$$

$$\int_{\Delta\Omega} d\Omega$$

Countmap:



Energy spectrum:



Spatial BG extrapolation

- Dwarf Galaxy Limits
- Galaxy Cluster Limits
- Angular power spectrum
- EGBG
- …

Pro: works for **all signal spectra**
Con: Need to understand bg. well

Spectral BG extrapolation

- Gamma-ray lines
- *Internal Bremsstrahlung*

Pro: works **everywhere**
Con: only lines/IB

1) Search for 1-300 GeV gamma-ray lines (Jan 2011)

2) Search for Internal Bremsstrahlung features (Mar 2012)

3) Improved search for 30-300 GeV gamma-ray lines (now)

Differences

- Amount of LAT data
- Event selection
- <u>Target regions</u>

1) Search for 1-300 GeV gamma-ray lines (Jan 2011)

2) Search for Internal Bremsstrahlung features (Mar 2012)

3) Improved search for 30-300 GeV gamma-ray lines (now)

General strategy in Line/IB searches

- Select **target region** (or, better, multiple target regions)
- Perform a detailed **spectral analysis** of the gamma-ray flux, scan through different models, target regions etc.

Gamma-ray lines or IB radiation are expected to be **faint**. Although they are „smoking gun“ signatures, they deserve and require dedicated efforts and analyses.

Target Regions: Selection

A good target region features:

1) sufficient **exposure** (uniform at Fermi LAT)

2) large **signal-to-noise** ratio, to minimize <u>statistical</u> errors S/N

$$S \propto \int_{\Delta\Omega} d\Omega \frac{dJ_{\mathrm{signal}}}{d\Omega} \qquad B \propto \int_{\Delta\Omega} d\Omega \frac{dJ_{\mathrm{bg}}}{d\Omega} \qquad N \propto \sqrt{S+B} \approx \sqrt{B}$$

3) large **signal-to-background** ratio S/B, to minimize <u>systematical</u> errors,

4) understandable **backgrounds** (no big problem when looking for lines)

Here:

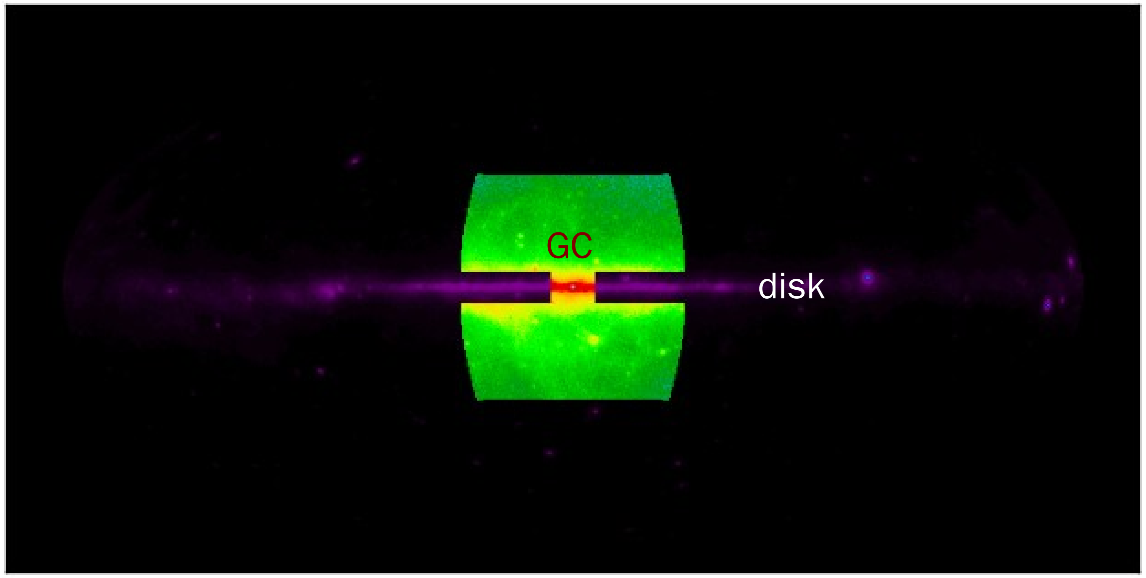
- **Signal** morphology from Galactic Dark Matter Halo (Isothermal, NFW, Einasto profiles)
- **Background** morphology derived from measured LAT events at ~1 GeV

Target Regions for Fermi LAT (Version I)

Target region for DM annihilation

Shape: tilted H (obtained by trial and error); Size: obtained from three parameter fit

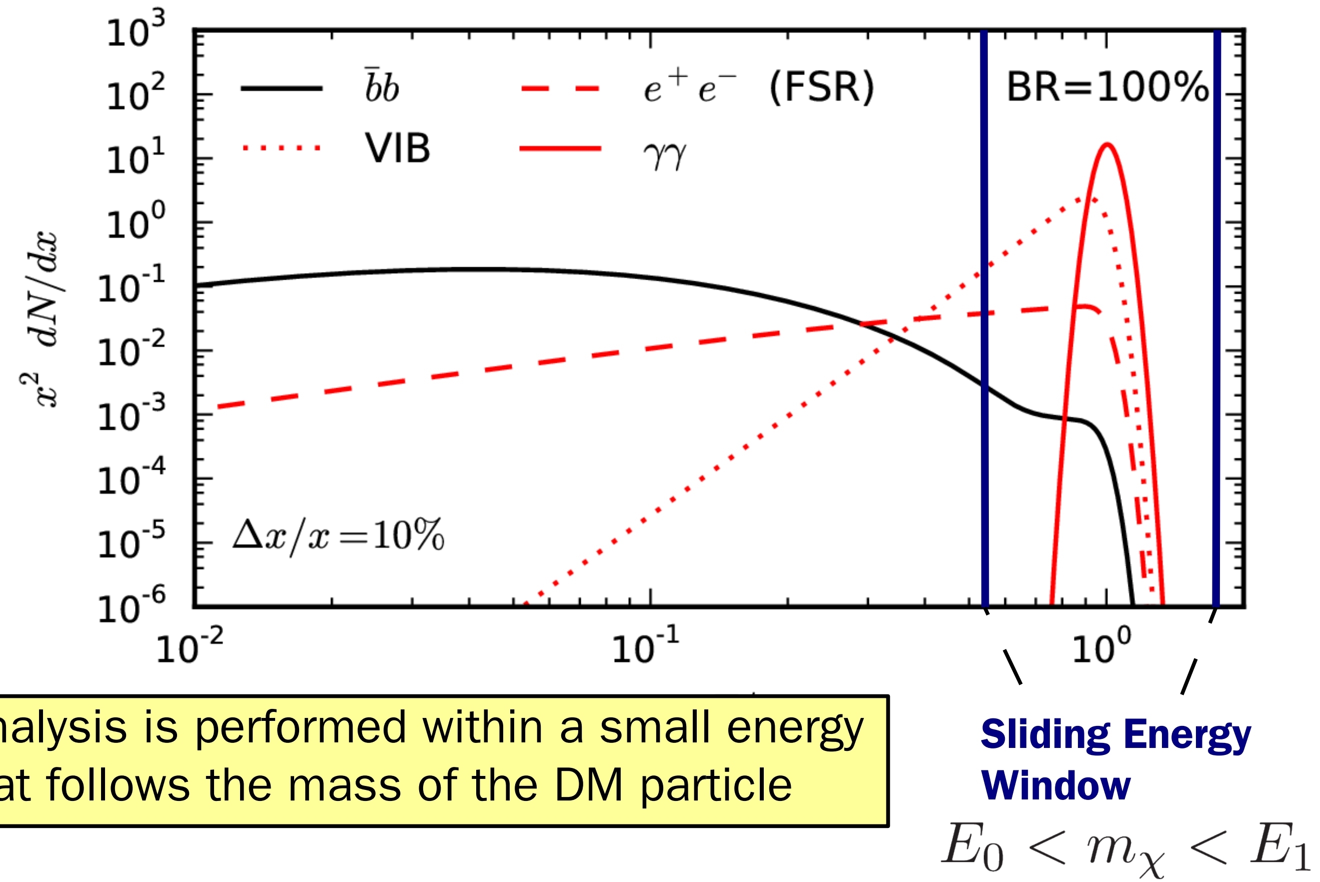
Optimized for large S/N for isothermal, NFW and Einasto profiles



$$-36^\circ < \ell < 36^\circ,\ 7^\circ < |b| < 36^\circ$$
$$\text{plus} \quad |\ell|,\ |b| < 7^\circ$$

(This will be further optimized below, but is a good first approximation)

Spectral Analysis: Sliding Energy Window



All spectral analysis is performed within a small energy window that follows the mass of the DM particle

Main features:

- Secondary photons in DM signal can be (in almost all cases) neglected
- Astrophysical bg. fluxes can be (in many cases) approximated by power-laws

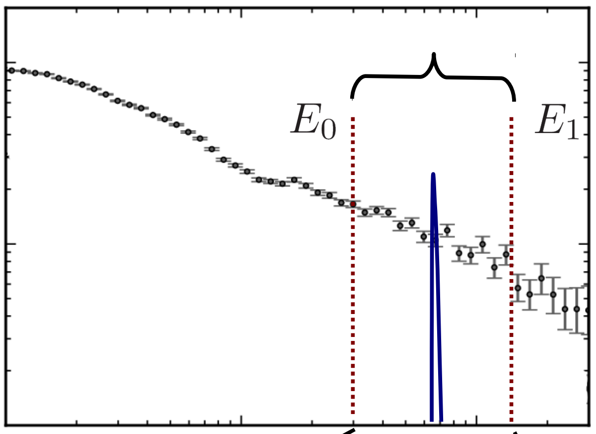
Main challenge:

- What size is reasonable? [depends on statistics & true bg. Curvature]
  here: few times energy resolution < 10 GeV, increases to factor 10 at 300 GeV

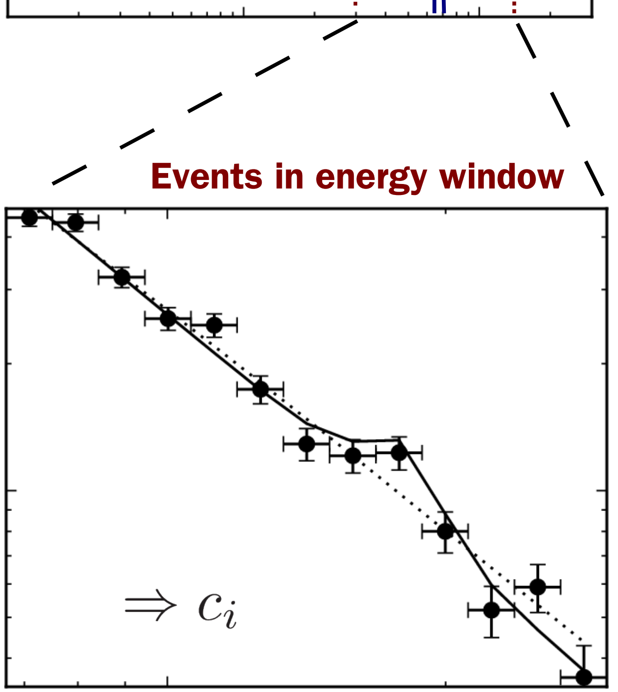
Spectral Analysis – Likelihood analysis

Event extraction:

Energy spectrum in target region



Events in energy window



(sketch)

We perfrom a **binned likelihood analysis**, using the likelihood function

$$\mathcal{L} = \prod_i P(c_i|\mu_i)$$

where

c_i : observed events

μ_i : expected events

$$P(c|\mu) = \frac{\mu^c e^{-\mu}}{c!}$$

The model:

$$\frac{dJ}{dE} = S\ \delta(E - E_\gamma) + \beta E^{-\gamma}$$

convolved with energy dispersion and exposure

$$\mu_i = \int_{\Delta E_i} dE \int dE'\ \mathcal{D}(E, E')\mathcal{E}(E')\frac{dJ}{dE'}$$

$\mathcal{D}(E, E')$: LAT energy dispersion

$\mathcal{E}(E)$: LAT exposure

Spectral Analysis – Likelihood analysis

Significance of a line contribution for fixed m_χ follows from the TS value

$$TS = -2\ln\frac{\mathcal{L}_{\text{null}}}{\mathcal{L}_{\text{alt}}}$$

$$\mathcal{L}_{\text{alt}}: \text{ Best-fit model with DM}, S \geq 0$$

$$\mathcal{L}_{\text{null}}: \text{ Best-fit model without DM}, S = 0$$

$$(\Rightarrow \mathcal{L}_{\text{alt}} \geq \mathcal{L}_{\text{null}})$$

$$\text{Significance without trial correction}: \sqrt{TS}\sigma$$

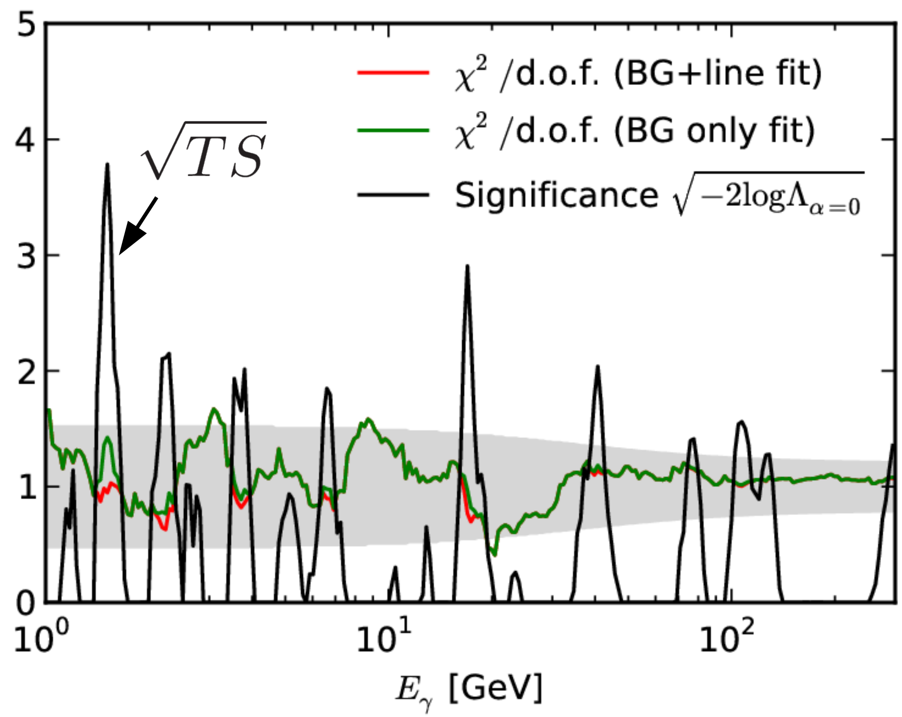
But: look-elsewhere effect has to be included

95% CL upperlimits are derived using the **profile likelihood method:**
increase S until $\Delta(-2\ln\mathcal{L}) = 2.71$, while refitting (profiling over) the other parameters

Searching lines in the Fermi LAT data

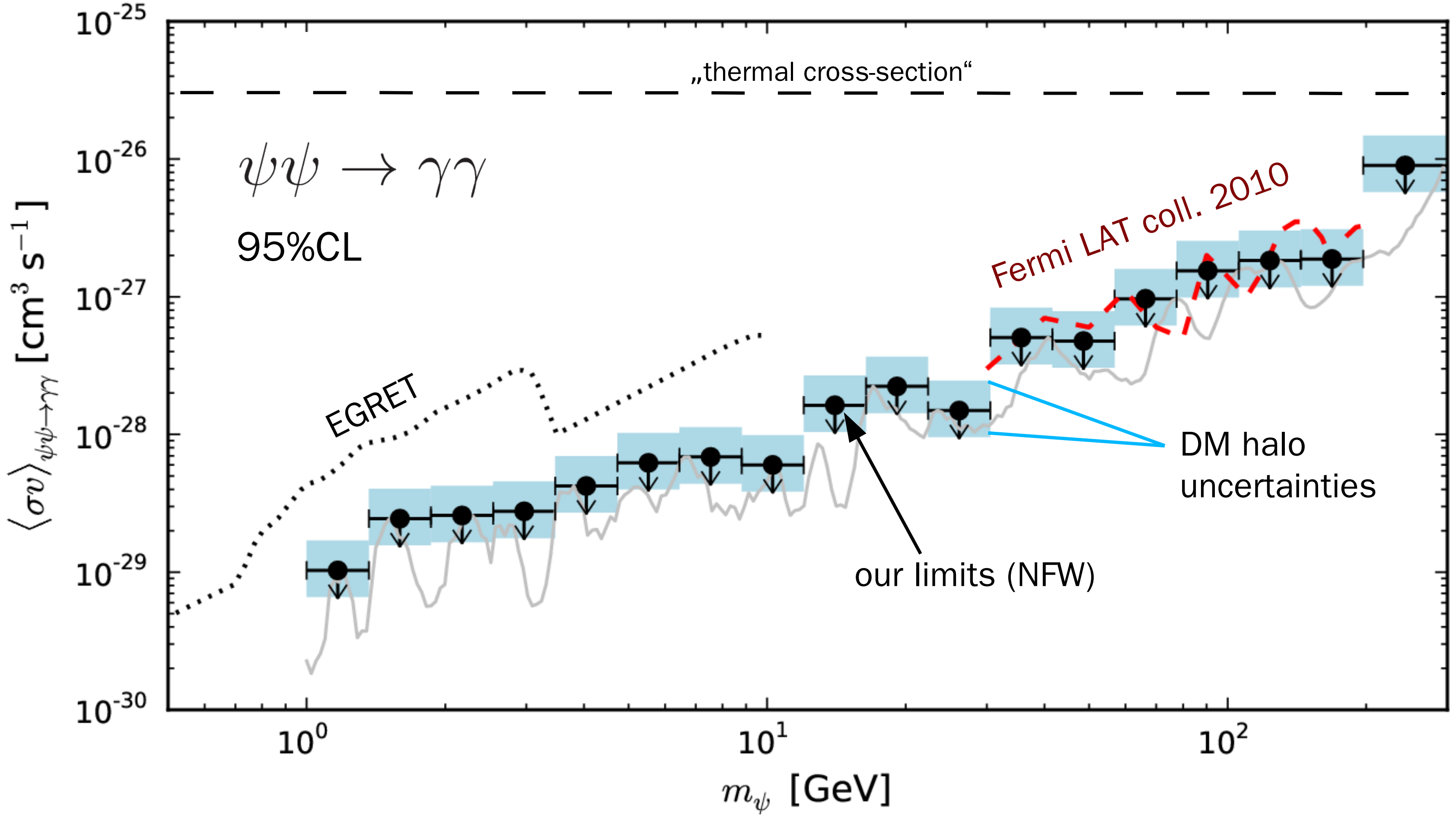
Our Jan 2011 analysis:

- Fermi LAT data from Aug 08 – Nov 10
- P6CLEAN_V3 events
- Energies between 1 – 300 GeV (using public CTBBestEnergy information)



- **No 5σ signal found**
- Goodness-of-fit (green and red lines) in agreement with expectations
- "Signals" below 20 GeV are very problematic, as they are systematics dominated! The 10-20 GeV "excess" was later identified with an artifact in the effective area (by now corrected)
- Nothing exciting above 20 GeV, where limits and TS values are statistics limited

Limits on Lines from DM Annihilation



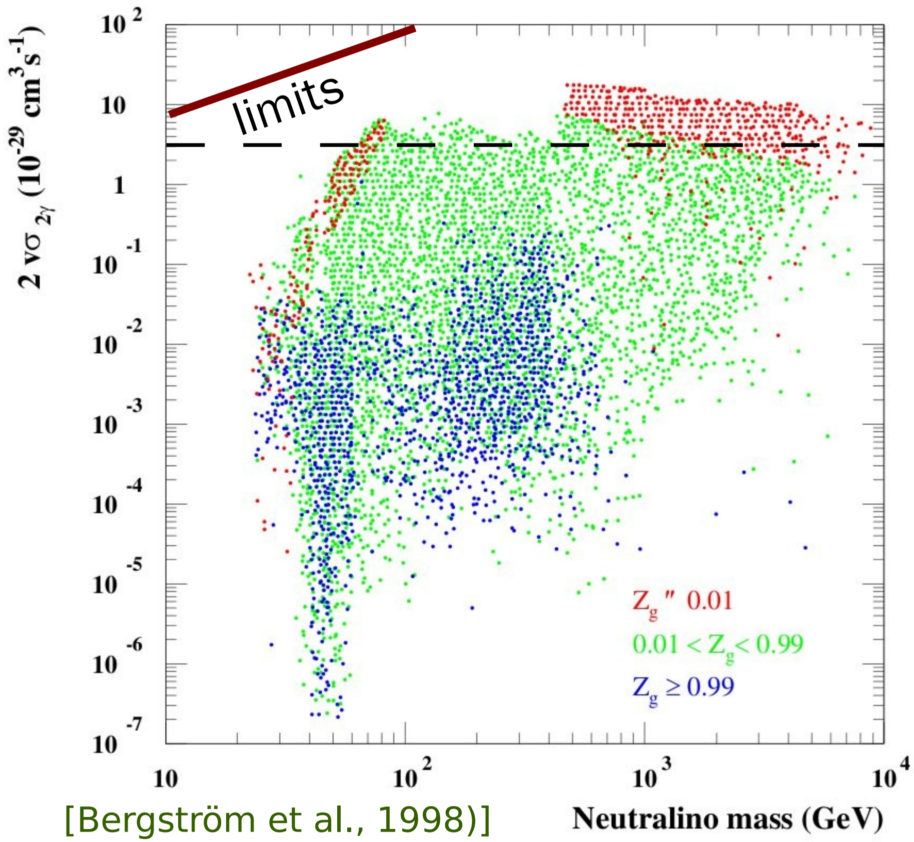
Consequences?

Some DM models that are already tested:

- Singlet Dark Matter [Profumo et al. (2010)]
- Hidden U(1) dark matter [Mambrini (2009)]
- Effective DM scenarios [Goodman et al. (2010)]
- “Higgs in Space!” [Jackson et al. (2010)]
- Inert Higgs Dark Matter [Gustafsson et al. (2007)]
- ...

DM models that are <u>not</u> affected:

MSSM neutralinos remain unconstrained



[Bergström et al., 1998)]

→ need to work harder!

1) Search for 1-300 GeV gamma-ray lines (Jan 2011)

2) Search for Internal Bremsstrahlung features (Mar 2012)

3) Improved search for 30-300 GeV gamma-ray lines (now)

Limits on Internal Bremsstrahlung: A simple toy model

Features

- inspired by **MSSM** coannihilation region $(\eta \to \tilde{f}_R \quad \text{and} \quad y \propto g_{1,2})$
- intense **virtual internal bremsstrahlung**
- reduced to the essential parameters

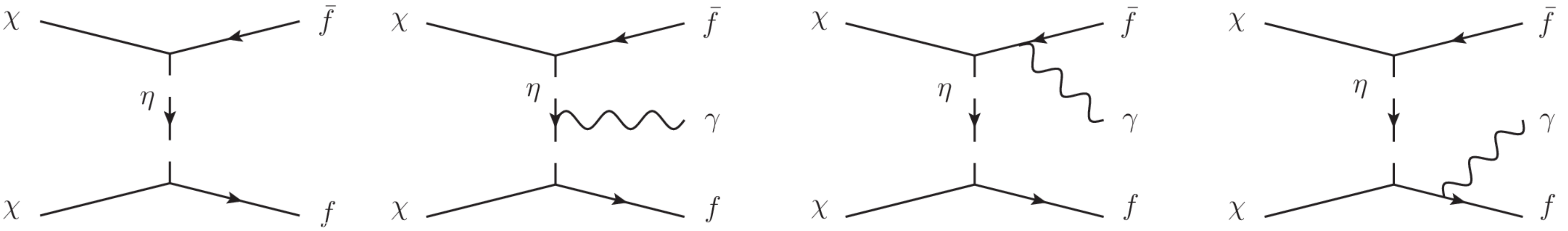
Fields: Majorana DM χ Scalar mediator η

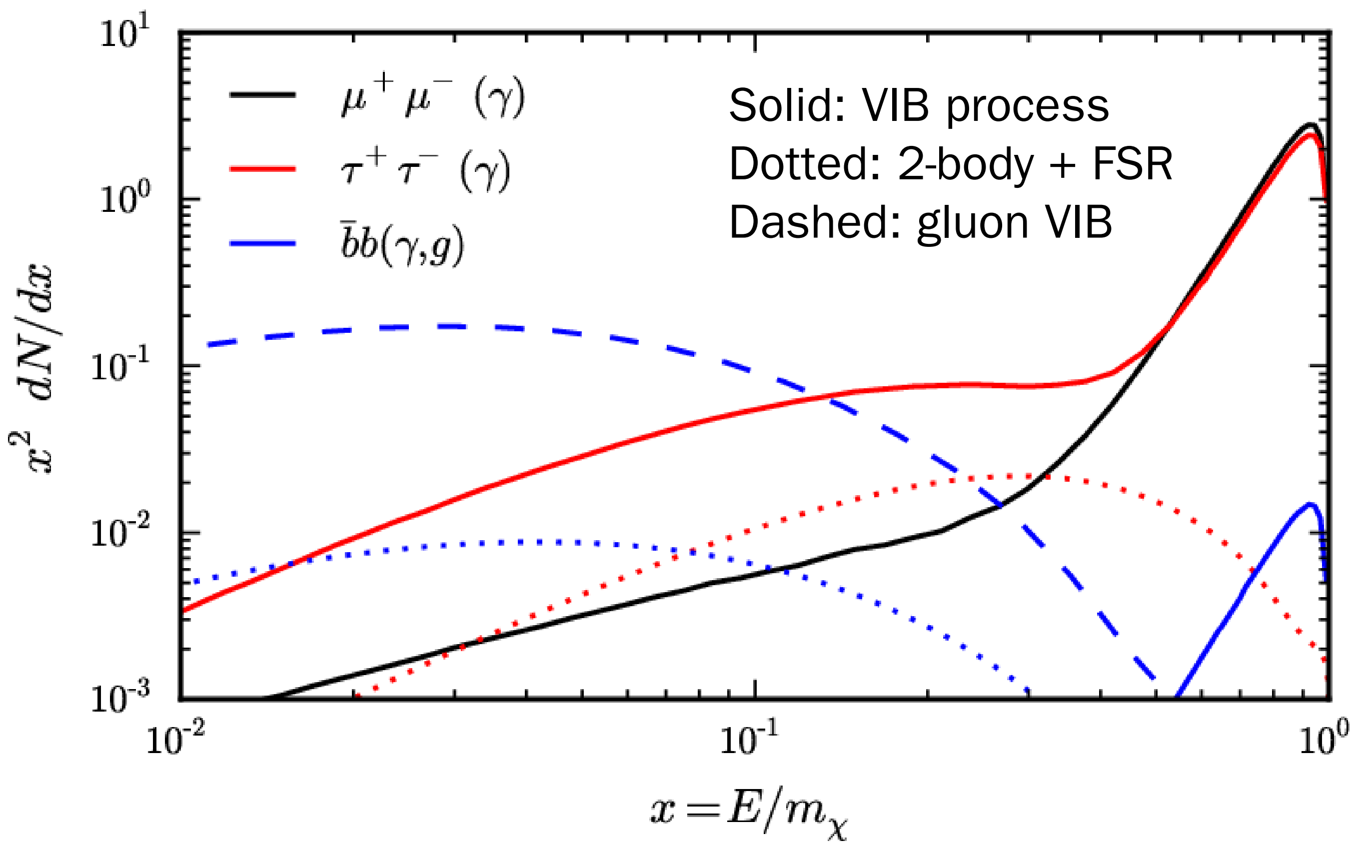
Yukawa- Interaction: $\mathcal{L}_{\text{int}} = y \cdot \bar{\chi}\psi_R\eta \; + \; \text{h.c.}$ $(\psi_R \to \mu_R, \; \tau_R, \; b_R)$

Parameters: $y, \; m_\chi, \; m_\eta$ with $\mu \equiv \frac{m_\eta^2}{m_\chi^2}$ $40 \text{ GeV} < m_\chi < 300 \text{ GeV}$

Gamma-ray spectra of toy model

Dark Matter annihilation: 2 body + VIB + FSR





Improved target regions (Version II)

Target region selection:

- **Background** morphology estimated from gamma-ray data at 1 to 40 GeV
- **Signal** shape derived from generalized NFW profile with free inner slope (to account for baryon induced contraction)

$$\rho_{\mathrm{dm}}(r) \propto \frac{1}{r^{\alpha}(1 + r/r_s)^{3-\alpha}}$$

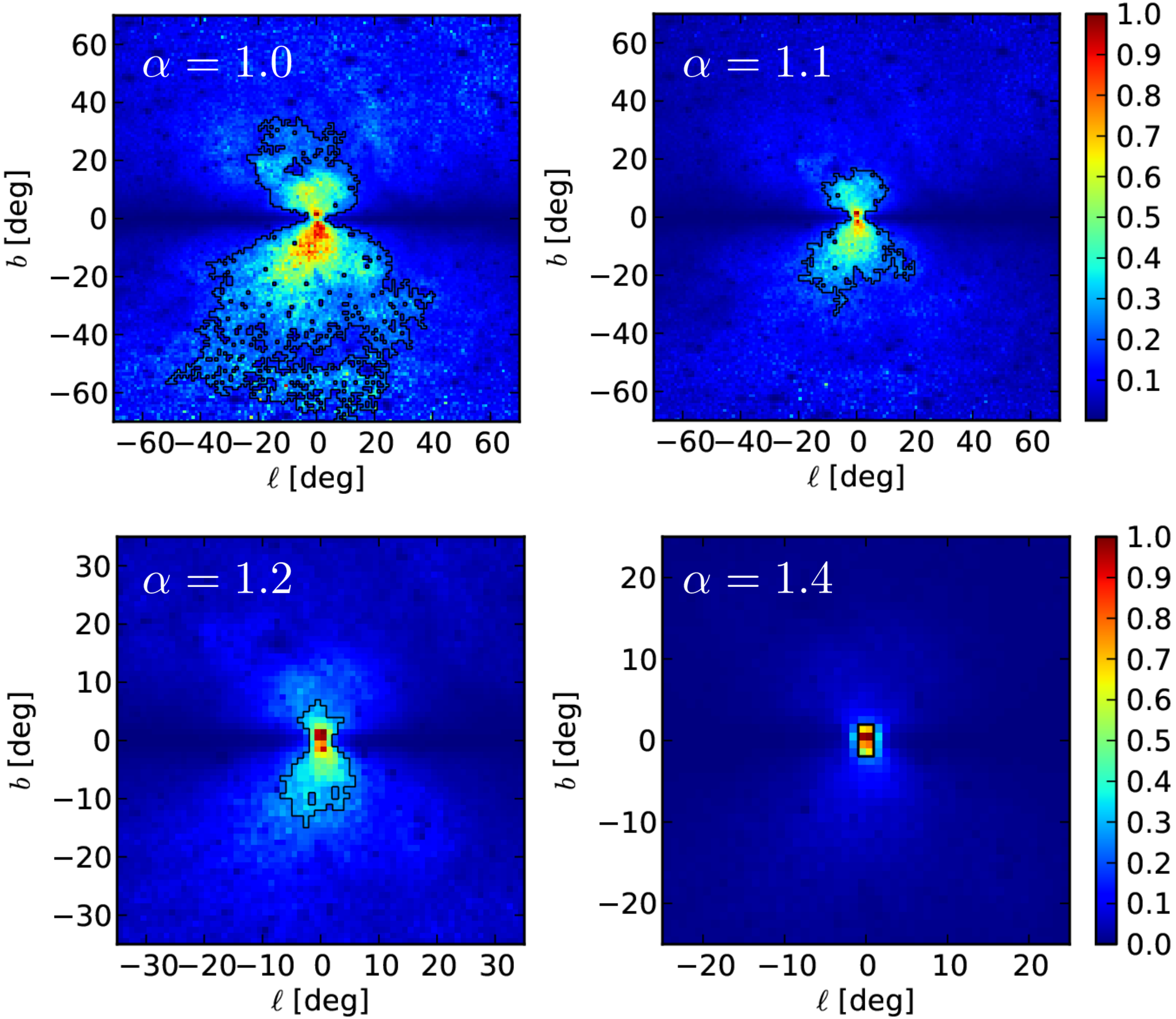
- Target regions are optimized **pixel-by-pixel** (one square degree size)

$$\mathcal{R}_T = \frac{\sum_{i\in T} \mu_i}{\sqrt{\sum_{i\in T} c_i^{1\mathrm{to}40\mathrm{GeV}}}}$$

Furthermore

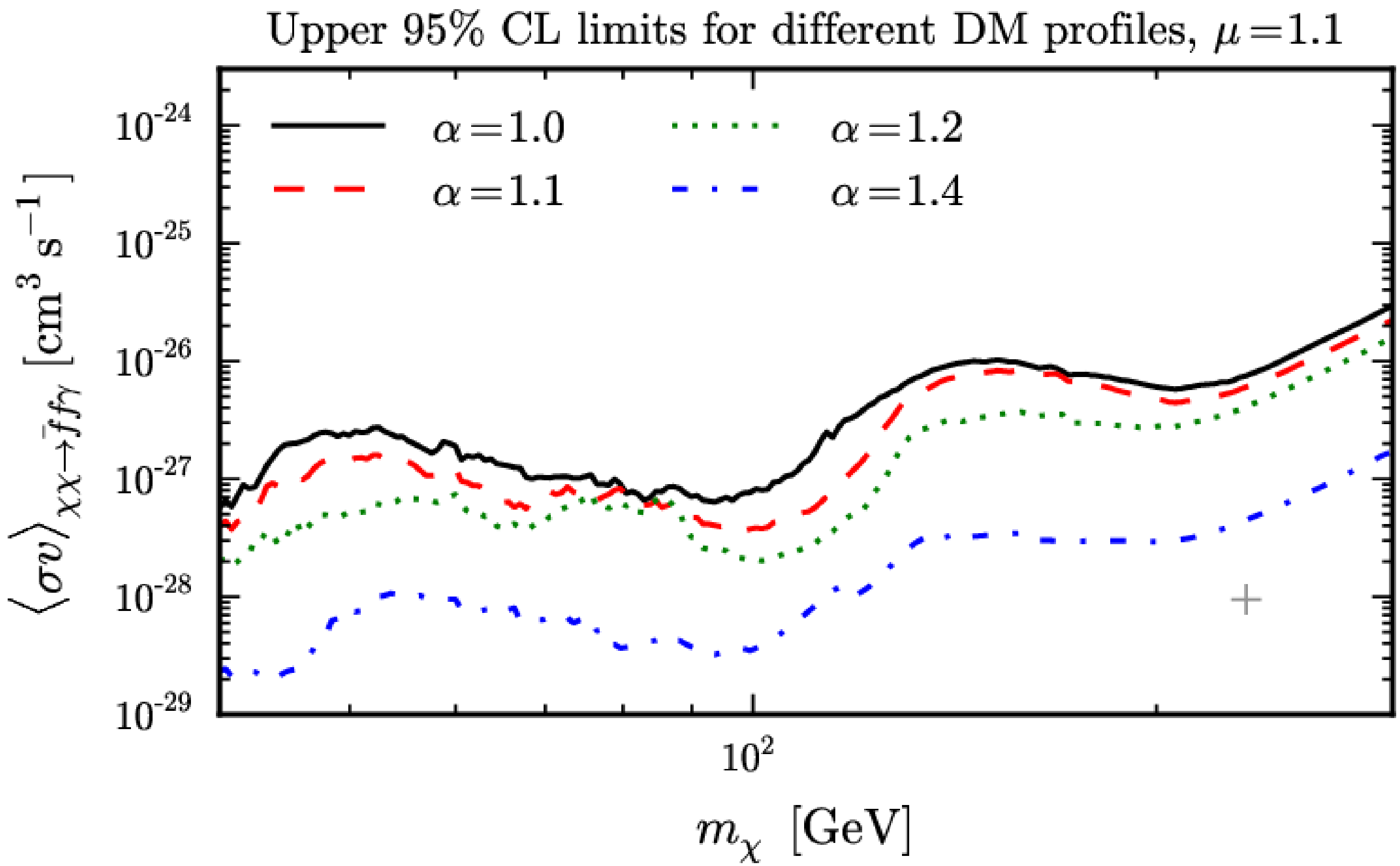
- we updated to **43 month of data**
- we updated to the **new event selection** P7CLEAN_V6

Improved target regions (Version II)



Resulting limits on VIB cross-section

$$\langle \sigma v \rangle = \langle \sigma v \rangle_{\chi\chi \to f\bar{f}} + \langle \sigma v \rangle_{\chi\chi \to f\bar{f}\gamma}$$

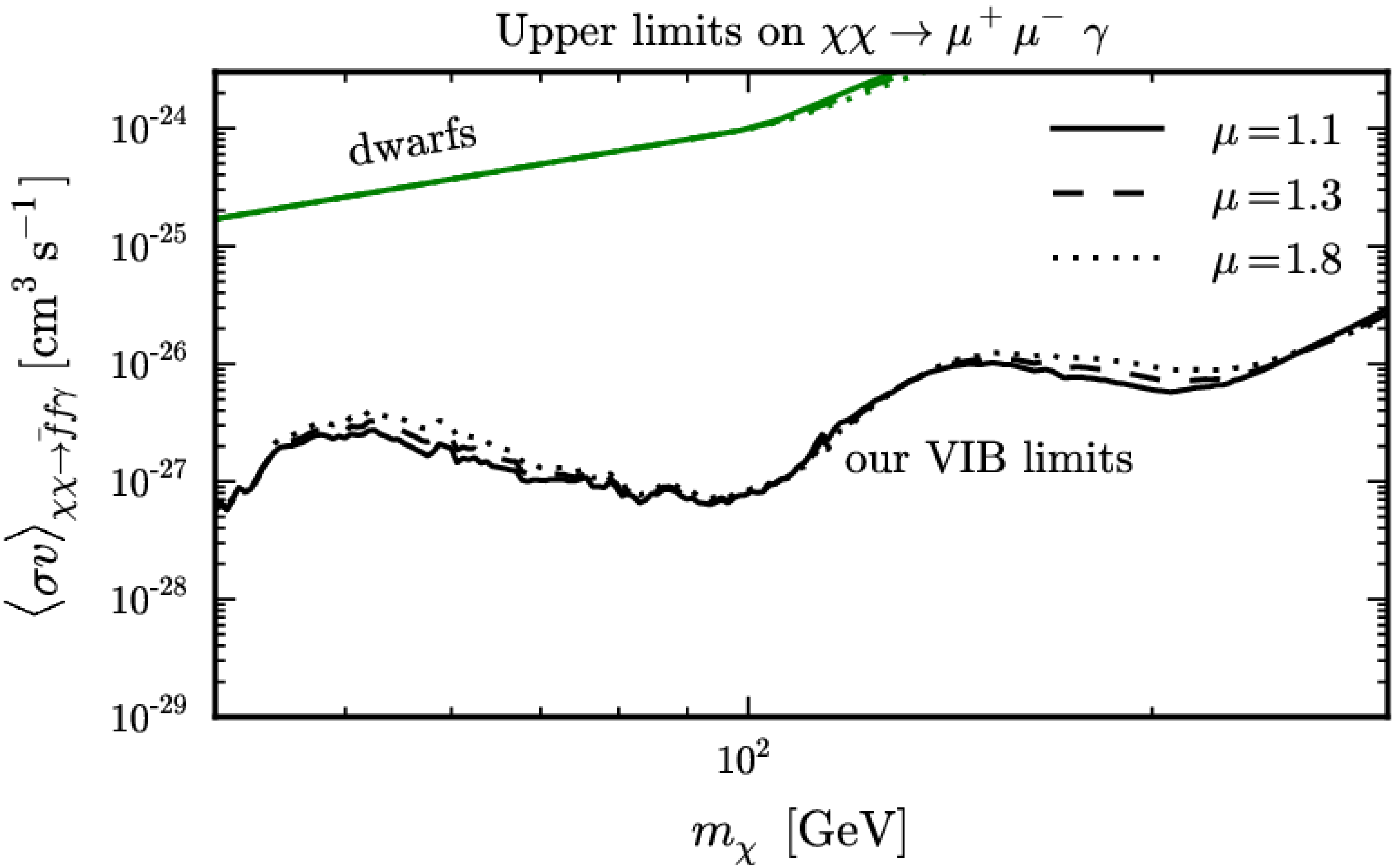


$3 \cdot 10^{-26} \mathrm{cm}^3/\mathrm{s}$

No 5σ signal found!

- Limits stronger than traditional thermal cross-section (like for gamma-ray lines)

Galactic Center vs Dwarf Galaxies

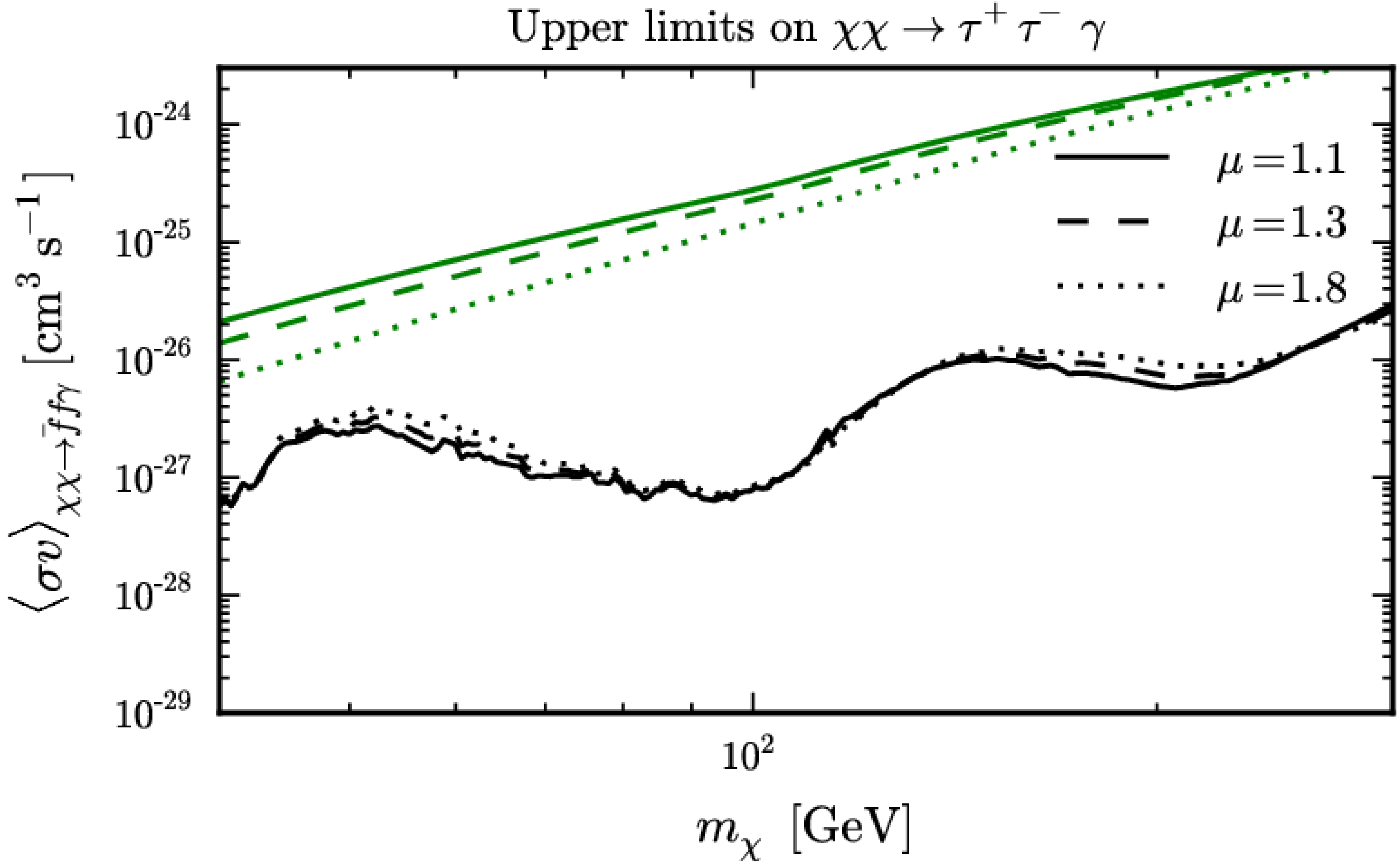


Approximate Dwarf Galaxy Limits (stacked analysis of dwarf galaxies at Fermi LAT)

[Geringer-Sameth et al. (2011)]

- are up to O(10-100) **weaker** than our IB limits
- Become stronger for heavier or colored fermions

Galactic Center vs Dwarf Galaxies



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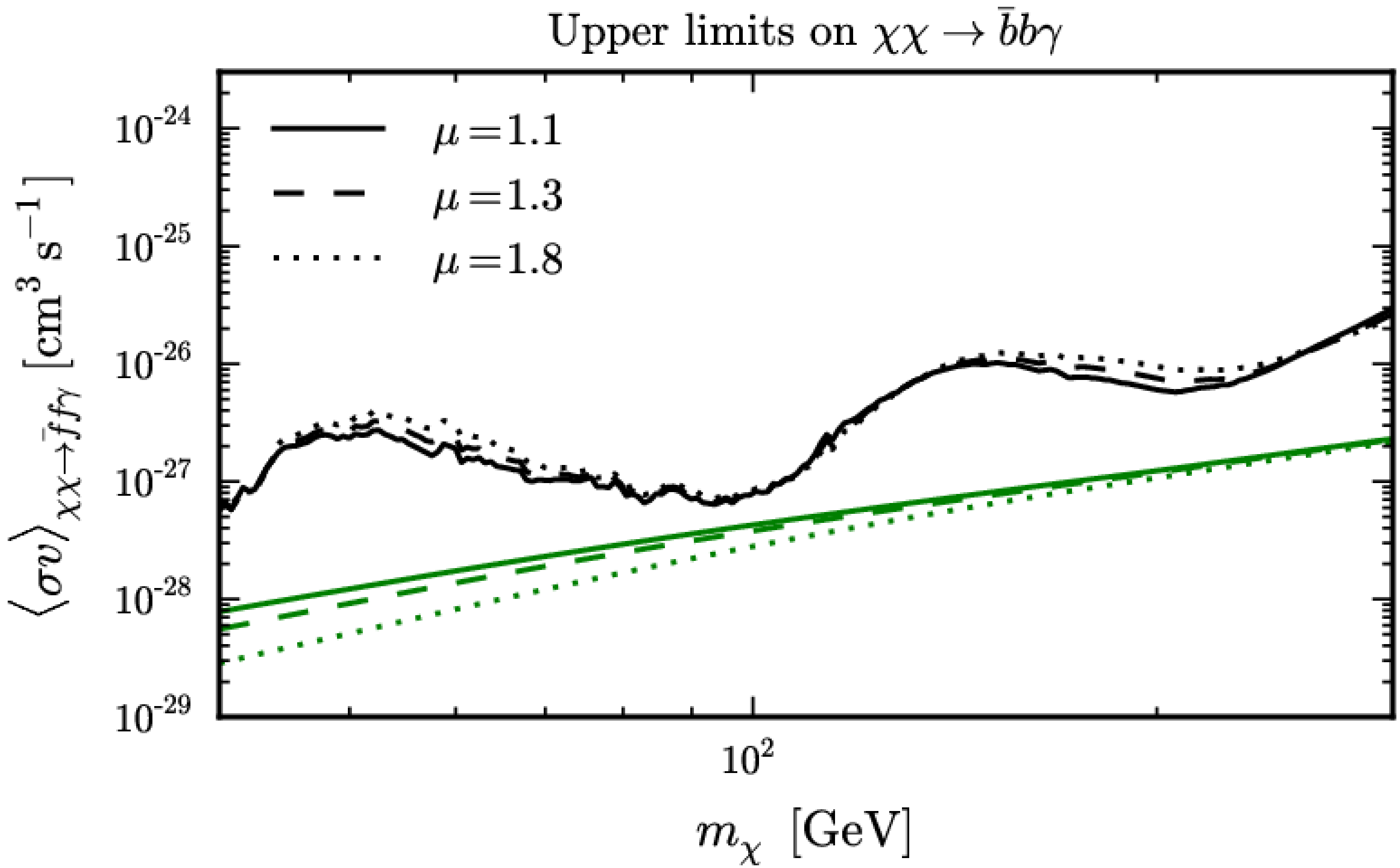
Galactic Center vs Dwarf Galaxies



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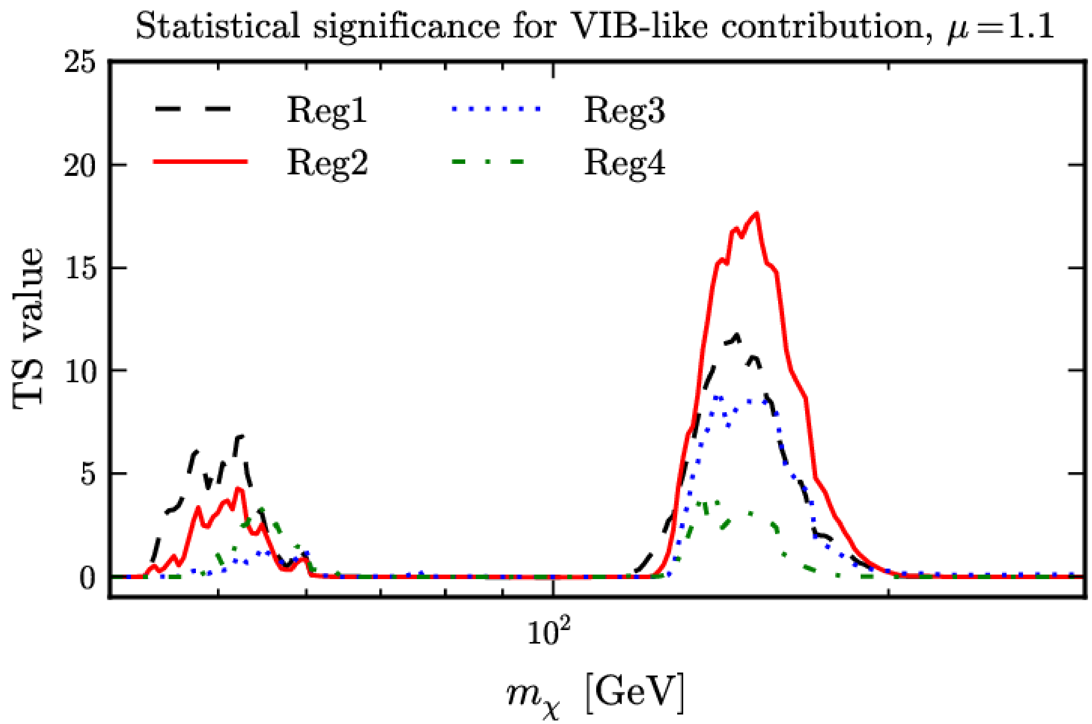
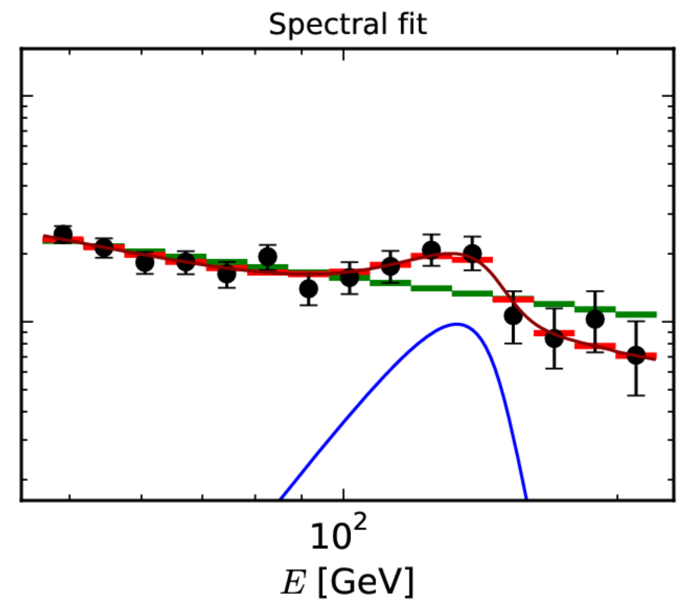
Signal Significance





Weak indication for signal

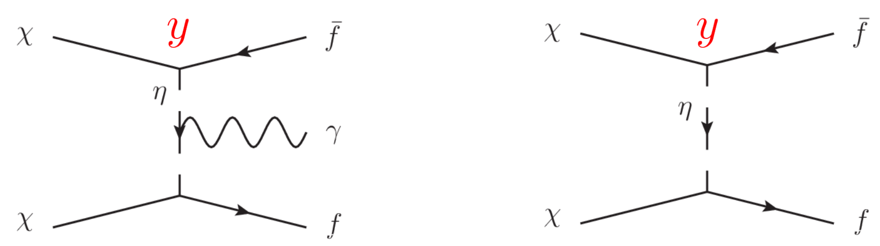
- Strongest in Reg2
- After look-elsewhere effect: 3.2σ
- Best-fit values:

$$\langle \sigma v \rangle_{\chi\chi \to \bar{f} f \gamma} \simeq 6 \times 10^{-27} \mathrm{cm}^3 \mathrm{s}^{-1} \qquad m_\chi \simeq 150 \text{ GeV}$$

- But: cross-section much larger than expected for VIB (if we want DM to be a thermal relic)

The thermal cross-section

Annihilation cross-section: $\langle \sigma v \rangle = a + b v^2$



$$\Rightarrow \frac{a}{b} \sim \mathcal{O}\left(\frac{\alpha}{\pi}\right)$$

Velocities at freeze-out:

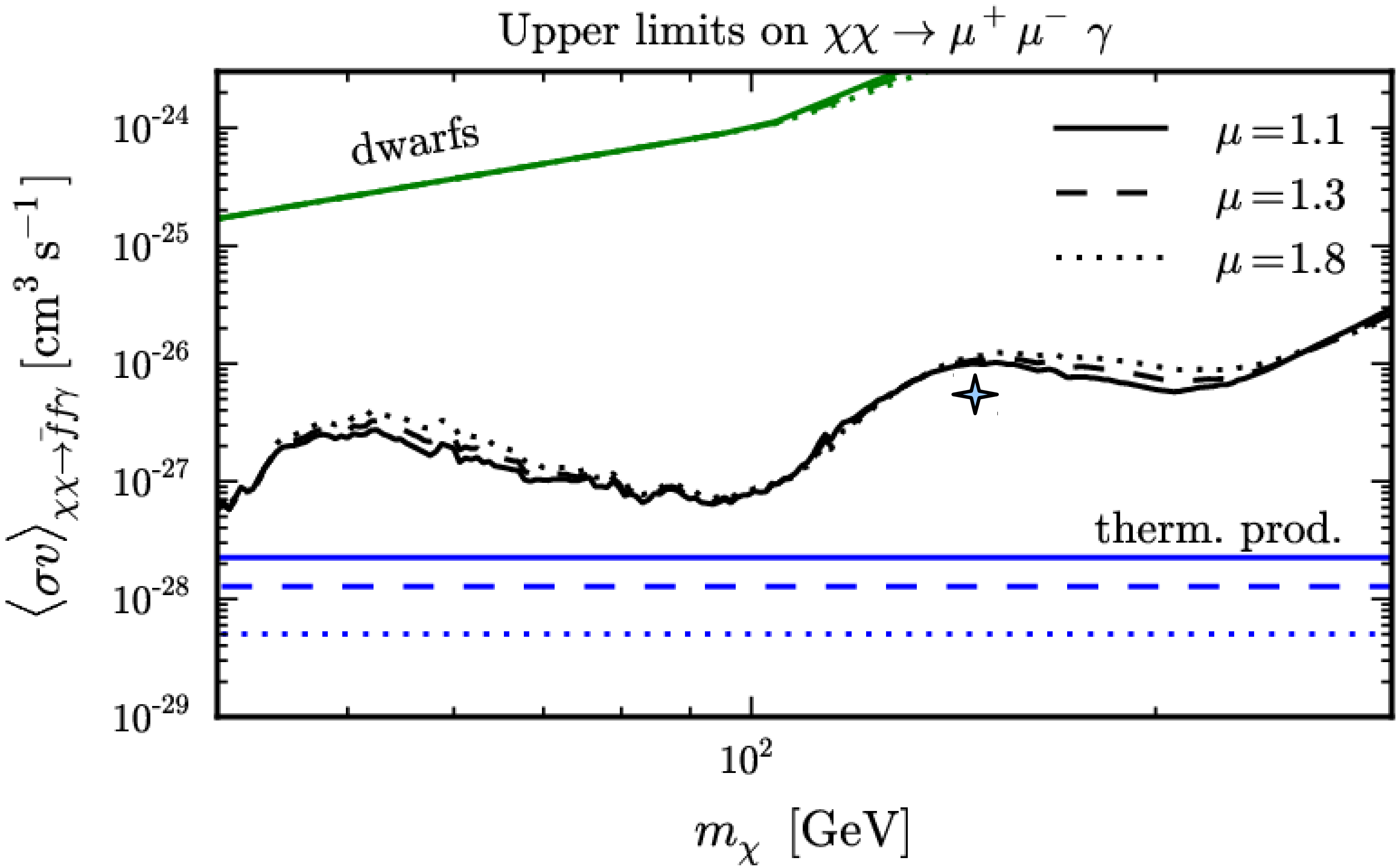
$$v_{\mathrm{f.o.}}^2 \approx 6 \frac{T_f}{m_\chi} \sim 0.3$$

It follows:

$$\frac{\langle \sigma v \rangle_{\mathrm{VIB}}}{3 \times 10^{-26} \mathrm{cm}^3/\mathrm{s}} \approx \frac{a}{a + b v_{\mathrm{f.o.}}^2} \sim \frac{a}{b v_{\mathrm{f.o.}}^2} \sim \frac{\alpha}{0.3\pi} \sim 10^{-2}$$

→ **Natural VIB cross-section:** $\langle \sigma v \rangle_{\mathrm{VIB}} \sim \mathcal{O}(10^{-28} \mathrm{cm}^3/\mathrm{s})$

Relic density constraints



Relic density constraint

- Values depend <u>strongly</u> on mass-splitting
- Fermi LAT IB limits still factor O(10) away from expected cross-sections

1) Search for 1-300 GeV gamma-ray lines (Jan 2011)

2) Search for Internal Bremsstrahlung features (Mar 2012)

3) Improved search for 30-300 GeV gamma-ray lines (now)

Target Regions at Fermi LAT (Version III)

For our current gamma-ray line analysis, we use **<u>five</u> target regions,** Reg1…Reg5

Recall that we optimize pixel-by-pixel:

$$\mathcal{R}_T = \frac{\sum_{i\in T}\mu_i}{\sqrt{\sum_{i\in T} c_i^{1\mathrm{to}40\mathrm{GeV}}}}$$

Cored Isothermal

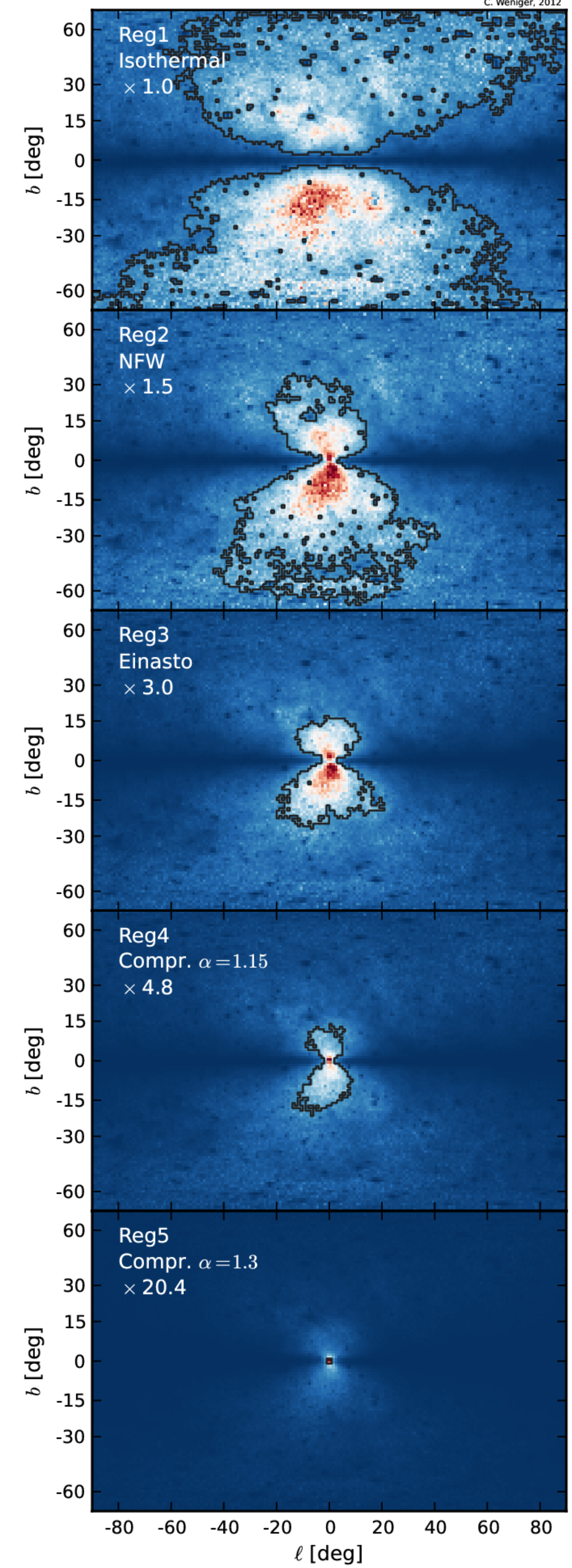
NFW

Einasto

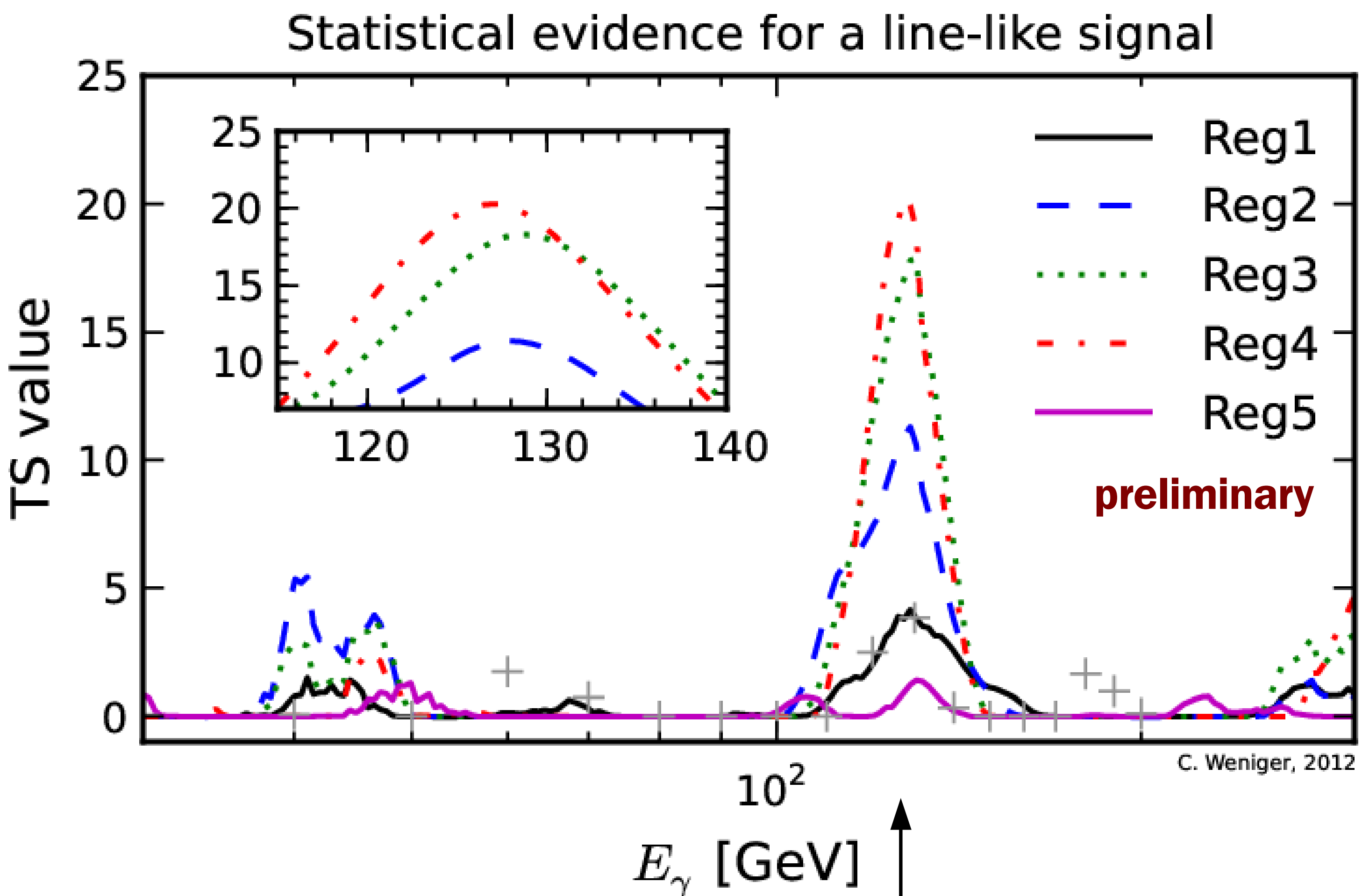
Contracted

$\alpha = 1.15$

$\alpha = 1.3$

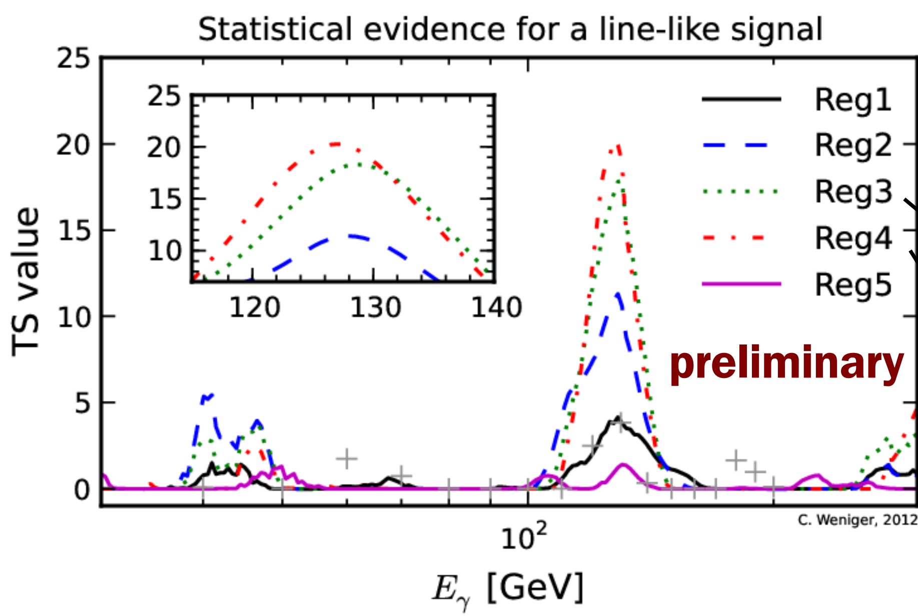


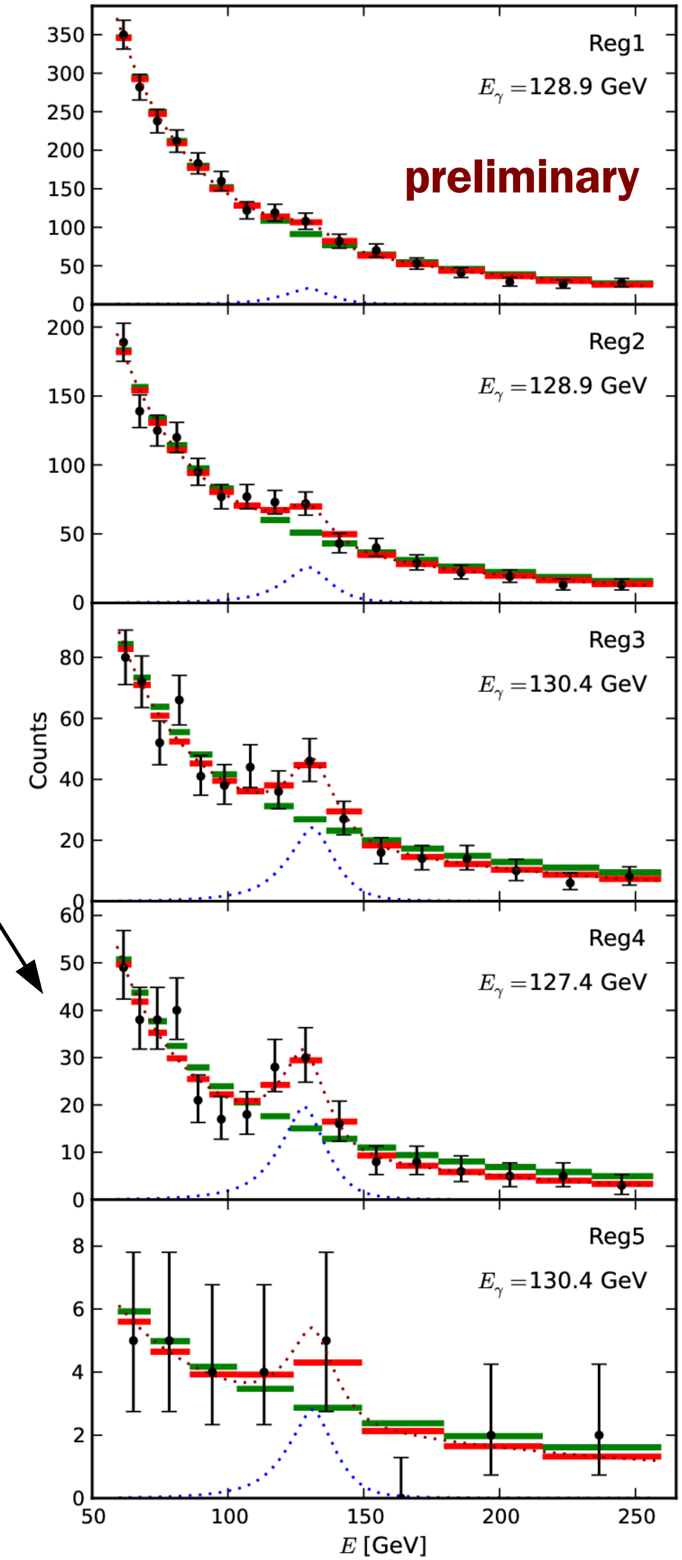
preliminary



We find again large TS values at around 130 GeV in Reg3 (Einasto) and in Reg4 (contracted NFW)

Fits vs data





Fits compared with (rebinned) data

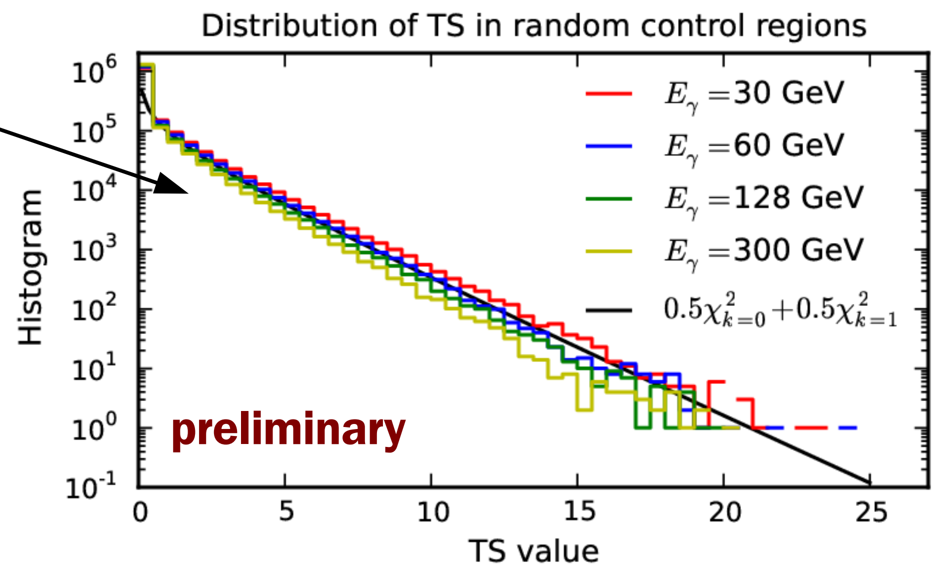
- Red: best-fit alternative model
- Green: best-fit null model (bg only)
- Blue: best-fit line signal

Different statistical checks

We performed different statistical tests to argue away the signal candidate:

- The signal does **not** appear in other sky regions. We checked this by
  - moving the target regions around
  - performing a bootstrap analysis of anti-galactic-center data

  → makes instrumetal cause less likely



- The TS value does **not** significantly depend on the details of the energy dispersion of the LAT

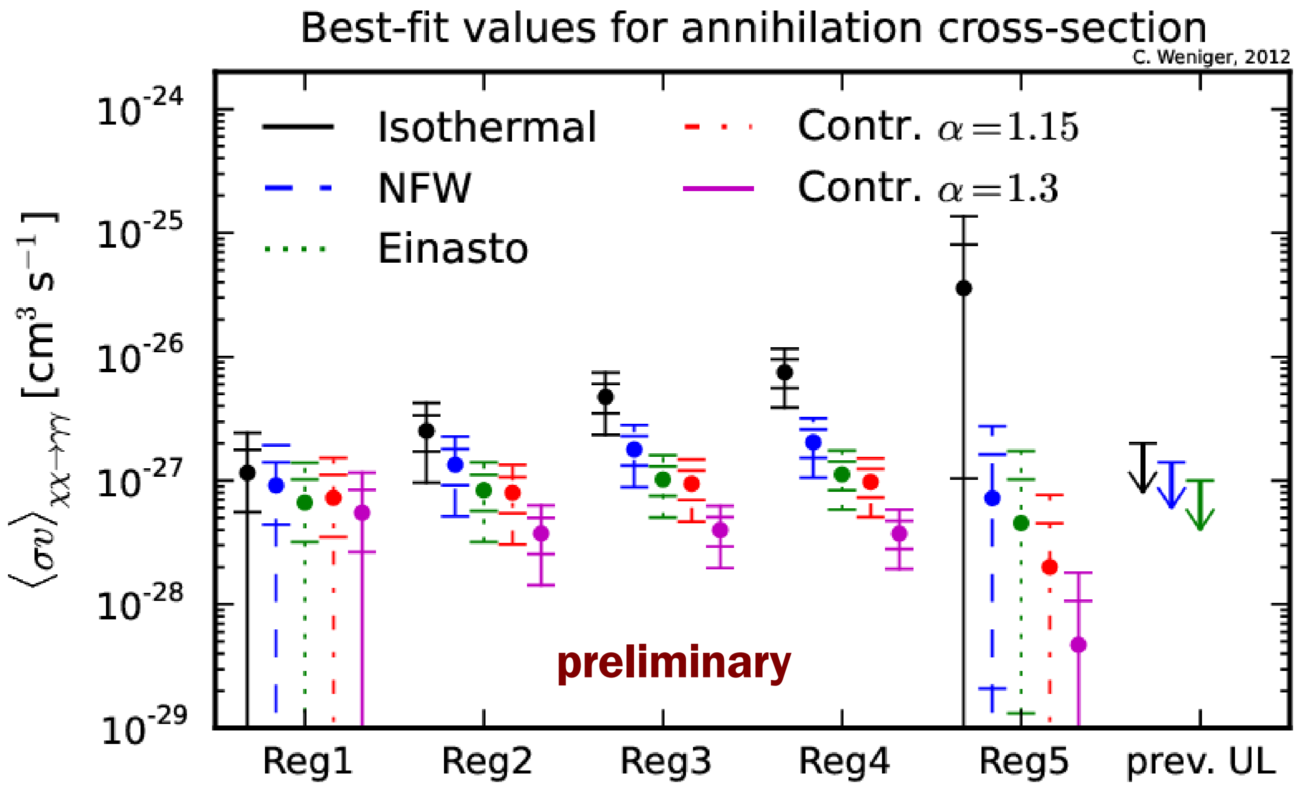
- The TS value changes with the window size (which is expected), but not enough to remove the signal

- Taking into account the look-elsewhere effect, the significance is about **3.2σ** (otherwise around 4.5σ)

- Beware: Analysis based on public data and public information only, instrumental cause appears unlikely, but cannot be excluded.

  → We need confirmation/rejection of signal from Fermi LAT collaboration

If we optimistically interpret the signature in terms of dark matter annihilation into photon pairs...



In each region Reg1 to Reg5, we derive best-fit values for the annihilation cross section for different DM profiles

- **Einasto** profile leads to **consistent** values
- **Isothermal** or **contracted profiles** with α=1.3 favour **inconsitent** values

- Upper Limits are previous results from Fermi LAT collaboration (May 2011) [Edmonds, thesis 2011]

Prospects

We concentrate here on prospects for **Atmospheric Cherenkov Telescopes** (ACTs)

- Pro (compared to Fermi LAT):
  - Reaches up to multi TeV energies
  - Much larger effective area, less statistical noise
- Con:
  - Much smaller field-of-view, shorter observational times
  - Potentially worse energy resolution
  - Difficult to reject backgrounds from charged cosmic rays

Prospects for Line/IB features at ACTs

Strategy

- For each instrument (here H.E.S.S. and CTA) we generate ~1000 mock data sets without DM signal
- We perform the spectral analysis and derive limits
- The experimental sensitivity to these models is ~O(5) weaker
- Energy window size is chosen such that limits should be accurate at 50% (tested with Monte Carlo)

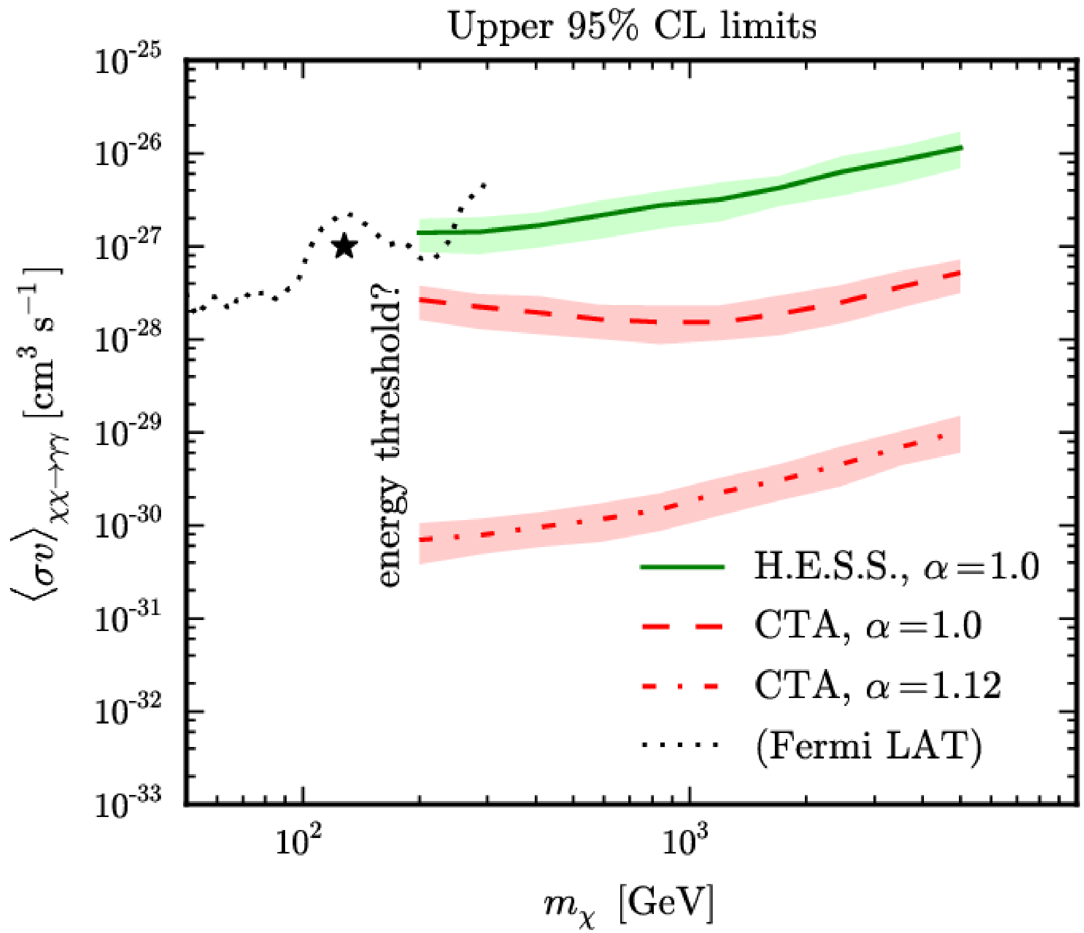
Relevant background fluxes

- Isotropic cosmic rays (essentially protons & electrons)
- The H.E.S.S. source at Galactic center
- Diffuse gamma rays from Galactic center region (also observed by H.E.S.S.)

Target region

- 2x2 deg^2 around the galactic center (Einasto)
- 0.2x0.2 deg^2 around the galactic center (contracted)

<u>Projected</u> Limits on Gamma-Ray Lines



Results

- H.E.S.S. limits would extend Fermi LAT limits to higher energies
- CTA will strengthen H.E.S.S. limits by ~10
- For <u>mildly</u> contracted profiles, limits/sensitivity already improves by ~100 !

- Our signal candidate should be in reach of e.g. H.E.S.S. II (if energy threshold is low enough)

Conclusions

- Gamma-ray lines and IB features are excellent targets for dark matter searches → unique opportunity for signal/background discrimination
- But: they are most likely very <u>faint</u>
  → careful selection of target regions, scan through different models

- Fermi LAT sets very strong limits on gamma-ray lines → excludes already some models of DM annihilation or decay (still not MSSM neutralinos)
- IB features, although generically stronger than lines, are <u>not</u> constrained
- <u>Weak indication</u> for a possible gamma-ray line at ~130 GeV

- ACTs can continue Fermi LAT limits to higher energies & test the signal candidate at ~130 GeV
- CTA should improve limits by another factor O(10)
- If astrophysics is kind (contr. profiles), ACTs can test even very small cross-sections