Indirect Dark Matter Searches with Gamma-Ray Lines

Christoph Weniger

Max-Planck-Institut für Physik, München

Project Review MPP 2010

Based on **JCAP 1003 (2010) 024** and **arXiv:1011.3786**
(with Chiara Arina, Mathias Garny, Thomas Hambye, Alejandro Ibarra, David Tran)
and on ongoing work with **Gilles Vertongen** (to appear soon)

20 Dec 2010

Outline

I. Introduction

II. Theory

Three decaying dark matter scenarios

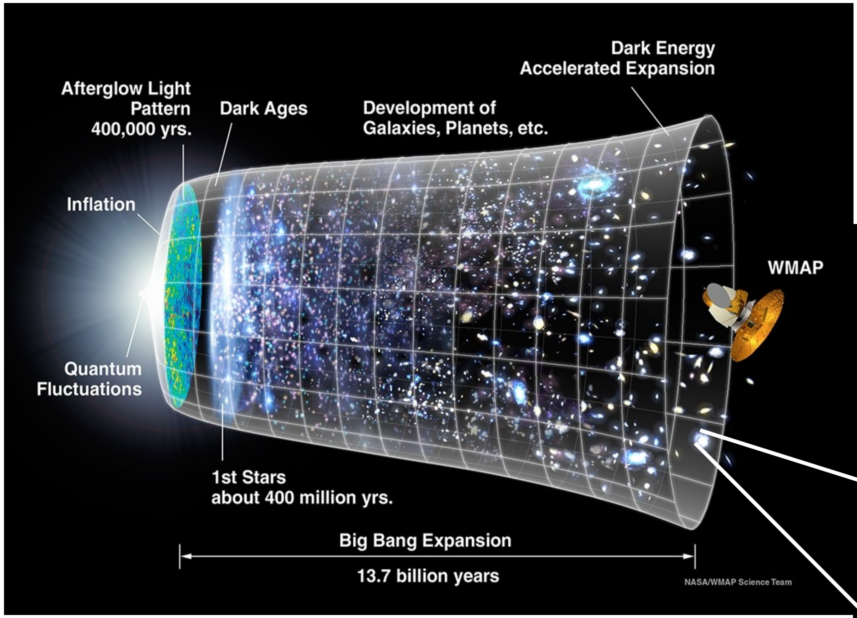
III. Experiment

Searching for gamma-ray lines with Fermi LAT

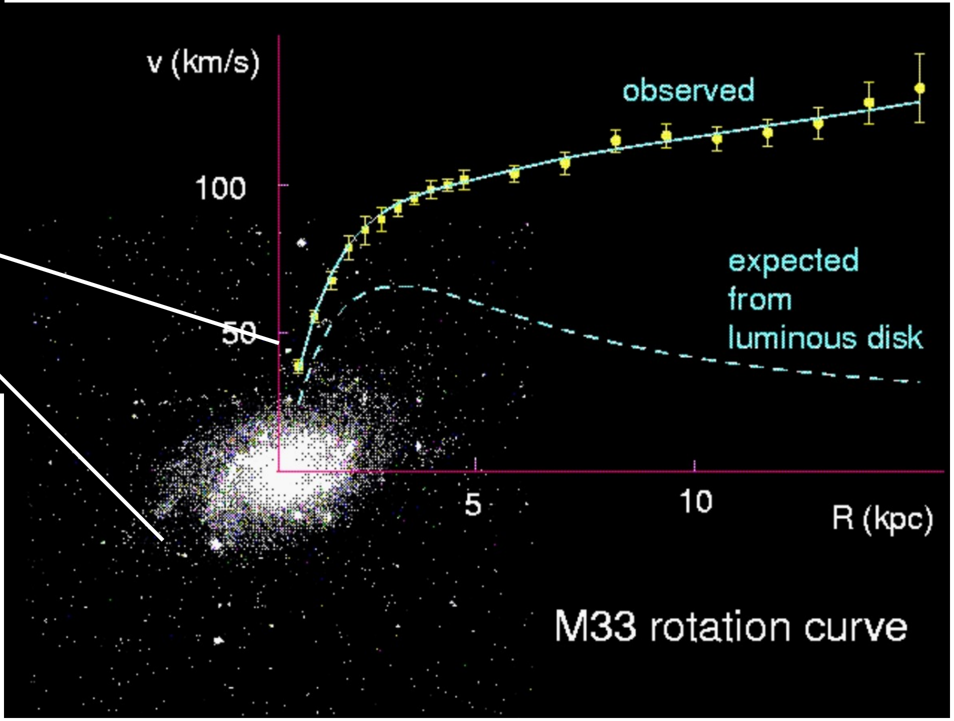
IV. Conclusions

I. Introduction

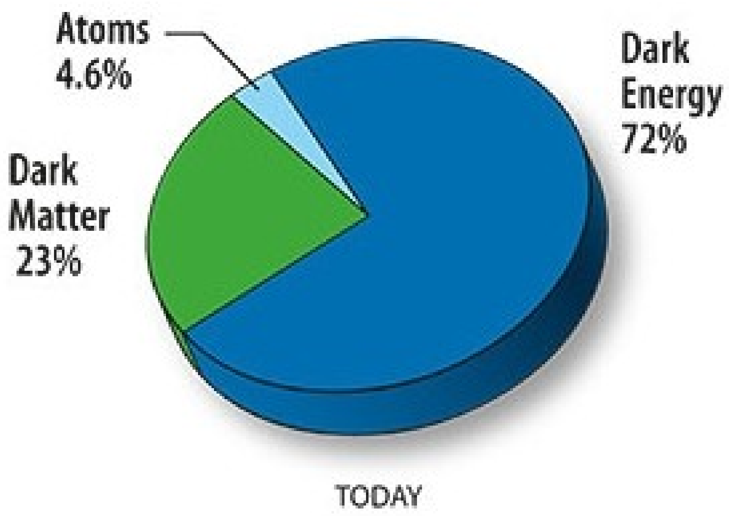
Evidence for non-baryonic Dark Matter



- CMB anisotropies vs LSS today
- Rotation curves in spiral galaxies
- ...



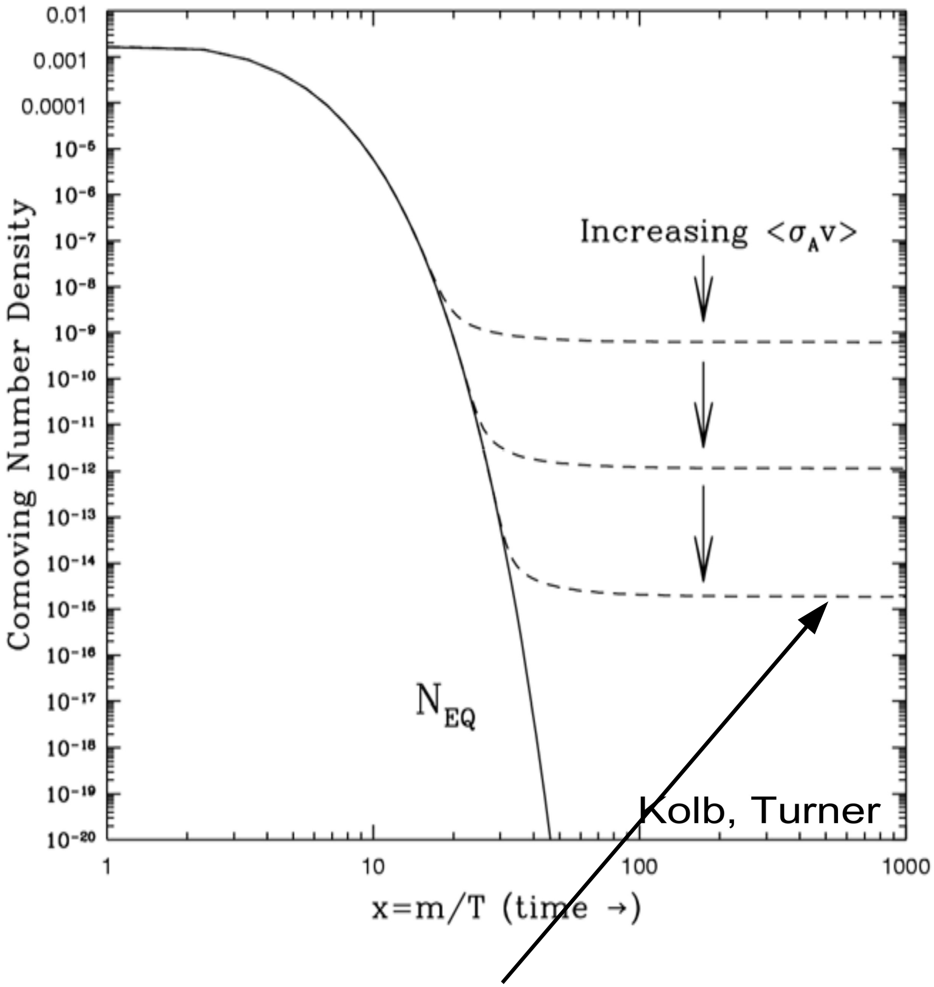
Total Energy in the Universe:



==> Suggests **new elementary particles**, beyond the realms of the Standard Model of particle physics

[see Amsler *et al.* (2009)]

The "WIMP Miracle"



A Weakly Interacting Massive Particle (WIMP), initially in thermal equilibrium with the rest of the Universe, freezes out with a relic density given by

$$\Omega_X \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{M_X^2}{\alpha^2}$$

$$M_X \simeq 100\ \mathrm{GeV} \Rightarrow \Omega_X \sim 0.1$$

==> WIMPs naturally reproduce the observed relic density.

Annihilation never stopped and is potentially observable in the cosmic-ray signals today $e.g.$ via $XX \to b\bar{b}, \gamma Z, \ldots$

WIMPs and gamma-ray lines

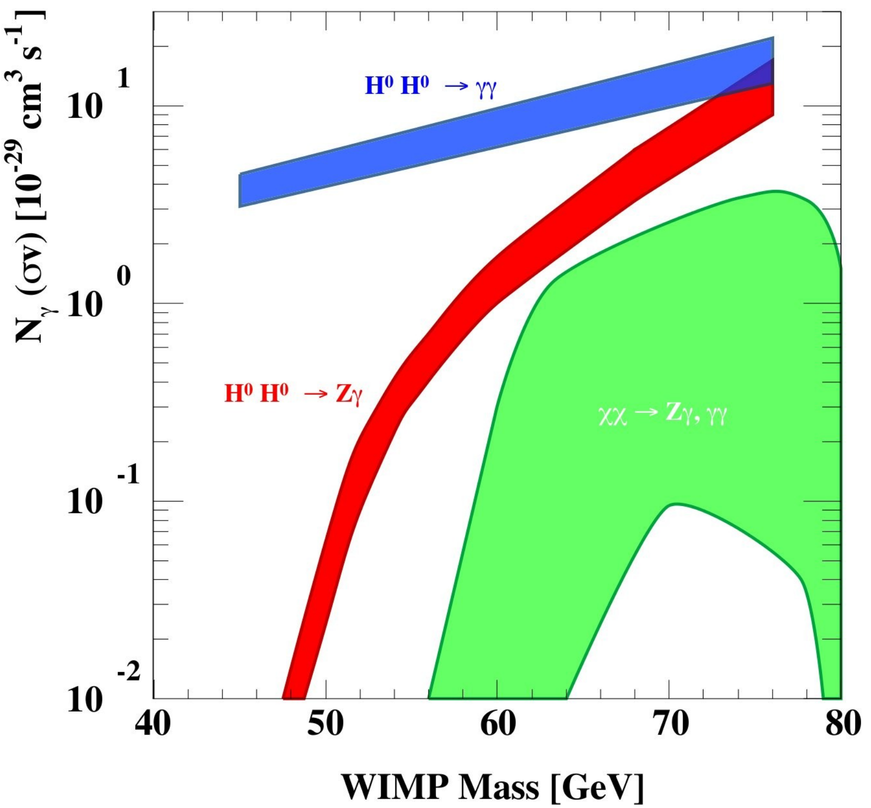
Gamma-ray line
→ new physics
(no astrophysical background)

MSSM neutralino annihilates into gamma-ray lines only **at one loop** via

$$\chi_1^0\chi_1^0 \to \gamma\gamma, Z\gamma$$

→ difficult to observe

[Rudaz et al. (1991),
Bergstrom et al. (1997), ...]



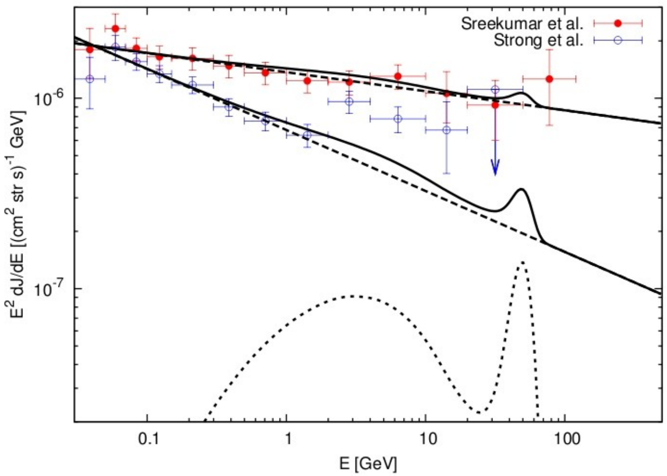
[Gustafsson et al. (2010)]

Many scenarios with enhanced lines exist:
- 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. (2010)]
- Kaluza-Klein dark matter in UED scenarios [Bertone et al. (2009)]

Decaying Dark Matter and Gamma-ray lines

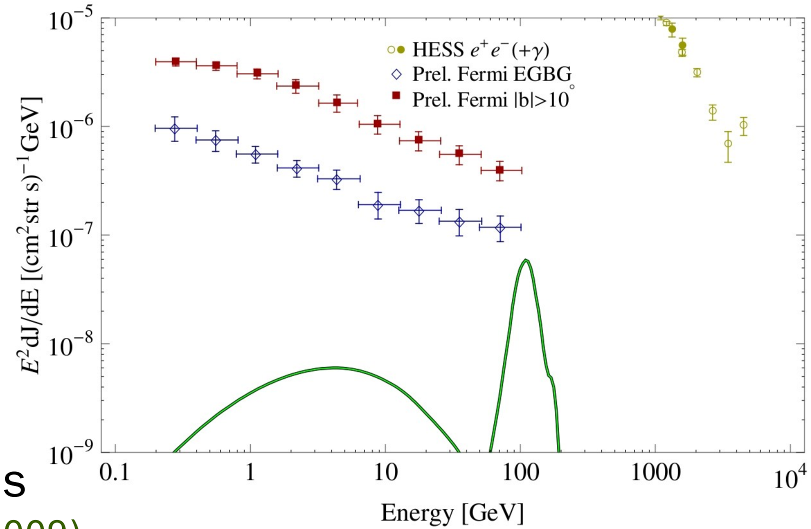
Gravitino and R-parity violation

[Buchmüller et al. (2009)]



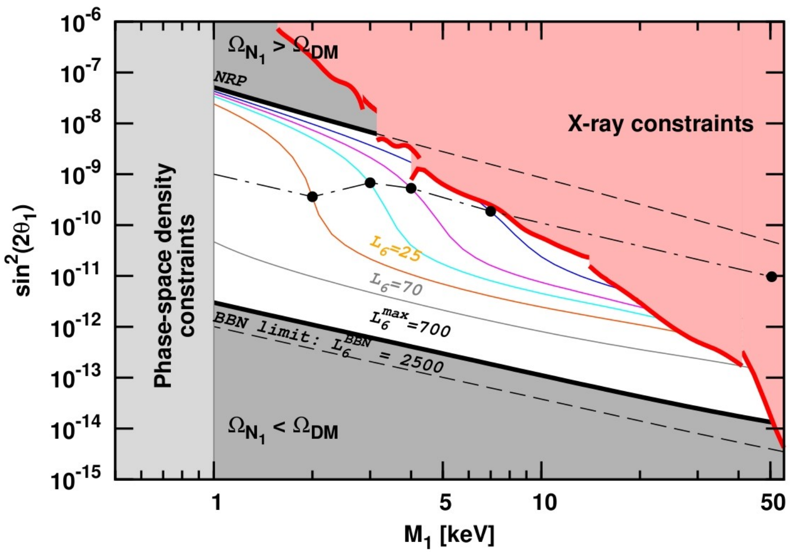
Hidden SU(2) vector DM

[Arina, Hambye, Ibarra, CW (2009)]



Sterile Neutrinos

[Boyarsky et al. (2009), Loewenstein & Kusenko (2009)]



II. Theory

Three decaying dark matter scenarios

A) Gravitino Dark Matter

Gravitino dark matter with R-parity violation

- Gravitinos: spin-3/2 fermions predicted in super-gravity
- Gravitino LSPs are very good **non-WIMP dark matter** candidates

- If reheating temperature of Universe is high (e.g. thermal leptogenesis scenarios), overclosure bound implies $m_{3/2} \gtrsim 10\mathrm{GeV}$
  → this gives rise to **long-lived NLSPs in conflict with BBN**
- The NLSP problem can be solved by allowing a **small violation of R-parity**

[Buchmüller et al. (2007)]

$$W \simeq \lambda_{ijk} L_i L_j e_k^c \qquad 10^{-14} \lesssim \lambda \lesssim 10^{-7}$$

I) Allows **decay of NLSP** before onset of BBN
II) Implies that **gravitino is unstable** with cosmological lifetimes

[Takayama et al. (2000), Bertone et al. (2007)]

Decay channels of NLSP (e.g. stau):

$\tilde{\tau}_1 \to \tau\nu$ (LHC)

Decay channels of gravitino:

$\psi_{3/2} \to \gamma\nu$ (cosmic rays)

$\psi_{3/2} \to W^{\pm}\ell^{\mp}$ [Ibarra, Tran (2008)]

...

Linked by strength of R-parity violation

B) The “dim-6 miracle” of DM decay

Is there a <u>generic</u> reason for a DM lifetime close to experimental limit (~10^{27}s)?

If the symmetry stabilizing dark matter is violated by **dim-6 operators at** the **Grand Unification scale**, the corresponding DM lifetime is automatically in the ball park of what is **accessible by cosmic-ray experiments!**

$$\tau_{\rm DM} \sim 8\pi \frac{M_*^4}{M_{\rm DM}^5} \simeq 3 \times 10^{27}\ {\rm s} \left(\frac{M_*}{2\times 10^{16}\ {\rm GeV}}\right)^4 \left(\frac{1\ {\rm TeV}}{M_{\rm DM}}\right)^5$$

[Eichler (1989), Arvanitaki et al. (2009), ...]

Example: SU(2)$_X$ Vector Dark Matter

Setup: SM + hidden SU(2)$_X$ gauge group with hidden higgs

$$\mathcal{L} = \mathcal{L}^{SM} - \underbrace{\frac{1}{4g_\phi^2} F^{\mu\nu} \cdot F_{\mu\nu} + (\mathcal{D}_\mu \phi)^\dagger (\mathcal{D}^\mu \phi) - \mu_\phi^2 \phi^\dagger \phi - \lambda_\phi (\phi^\dagger \phi)^2}_{\text{"hidden sector"}} - \underbrace{\lambda_m \phi^\dagger \phi H^\dagger H}_{\text{connection SM/HS}}$$

- SU(2)$_X$ breaks when hidden higgs condenses: $\mu_\phi^2 < 0$
- A **custodial SO(3)$_X$ symmetry** survives → SU(2)$_X$ **vector bosons** remain stable and are **WIMP dark matter**
- **Custodial symmetry** in general **broken** by higher dim. operators:

$$\frac{1}{\Lambda^2} \mathcal{D}^\mu \phi^\dagger \phi \, \mathcal{D}_\mu H^\dagger H \qquad \frac{1}{\Lambda^2} \mathcal{D}_\mu \phi^\dagger \mathcal{D}_\nu \phi \, F^{\mu\nu Y} \qquad \frac{1}{\Lambda^2} \phi^\dagger F_{\mu\nu}^a \frac{\tau^a}{2} \phi F^{\mu\nu Y}$$

Decay channels include **tree-level gamma-ray lines**

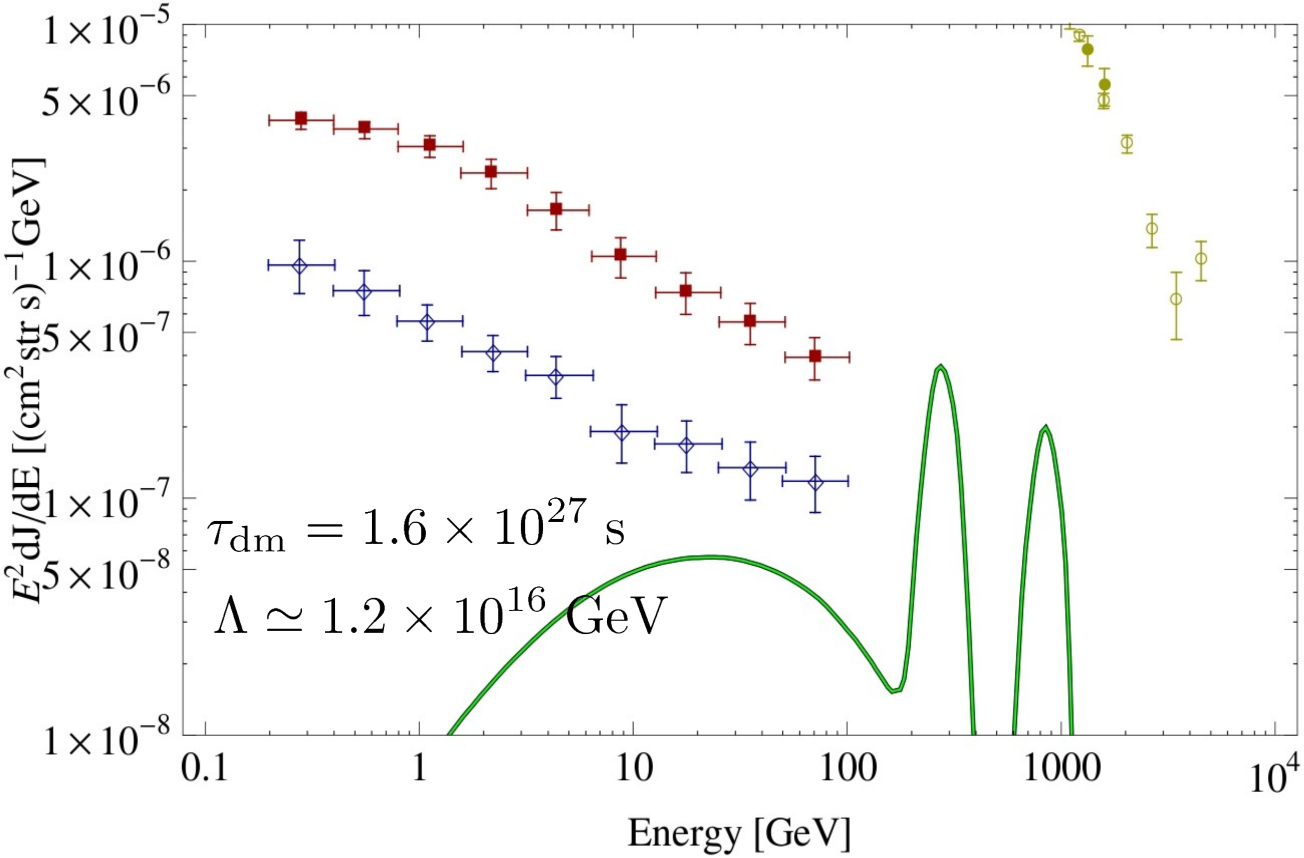
$$A_i \to \gamma\eta, \gamma h, Z\eta, \; Zh, \; W^+W^-, \; \nu\bar{\nu}, \; e^+e^-, \; \ldots$$

[Arina, Hambye, Ibarra, CW (2009)]

Exemplary gamma-ray spectrum

$$\frac{1}{\Lambda^2}\,\mathcal{D}_\mu\phi^\dagger\mathcal{D}_\nu\phi\;F^{\mu\nu Y}$$

$$M_A = 1550\,\mathrm{GeV}\quad M_\eta = 1245\,\mathrm{GeV}\quad M_h = 153\,\mathrm{GeV}\quad \sin\beta \approx 0.25$$



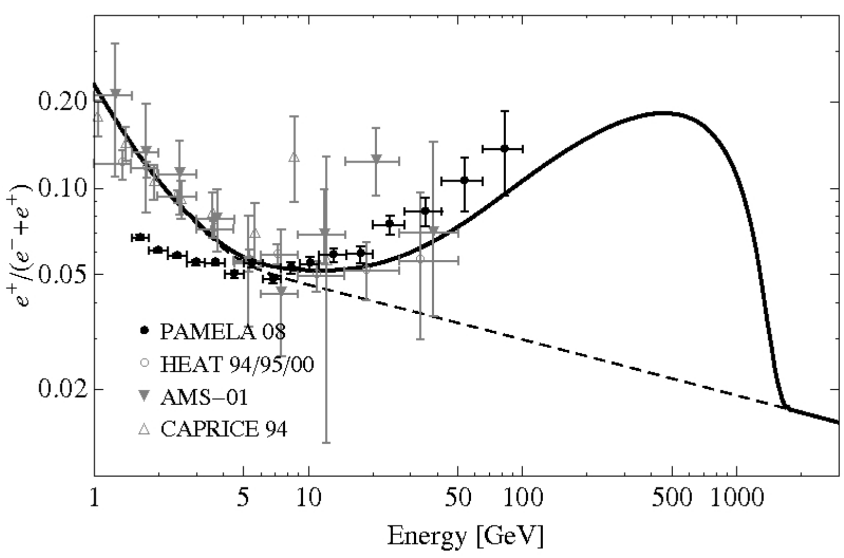
C) Models motivated by PAMELA anomaly

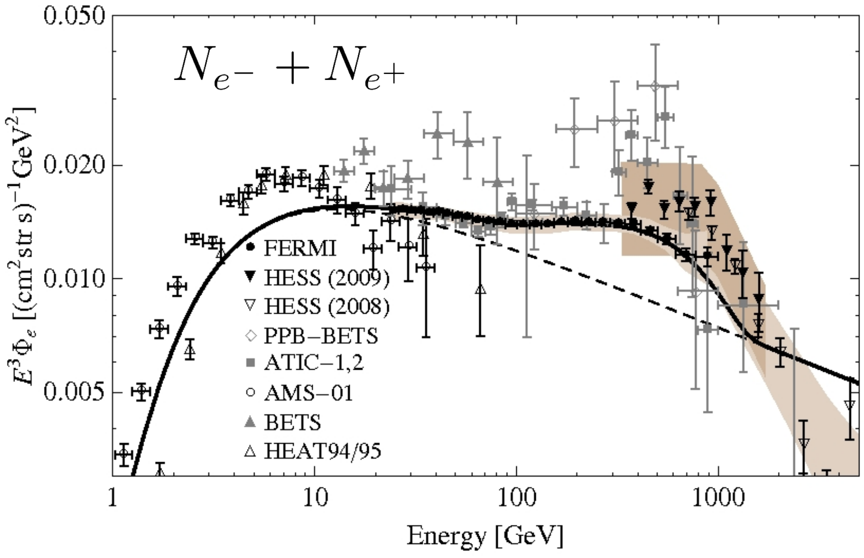
Ad-hoc decay channel:

$$\psi_{\rm DM} \to \mu^+\mu^-\nu$$

$$M_{\rm DM} \simeq 3.5 \text{ TeV}$$

$$\tau_{\rm DM} \simeq 1.1 \times 10^{26} \text{ s}$$





Other possible explanations

- Dark Matter annihilation
- Nearby Pulsars
- Non-standard cosmic-ray propagation
- ...

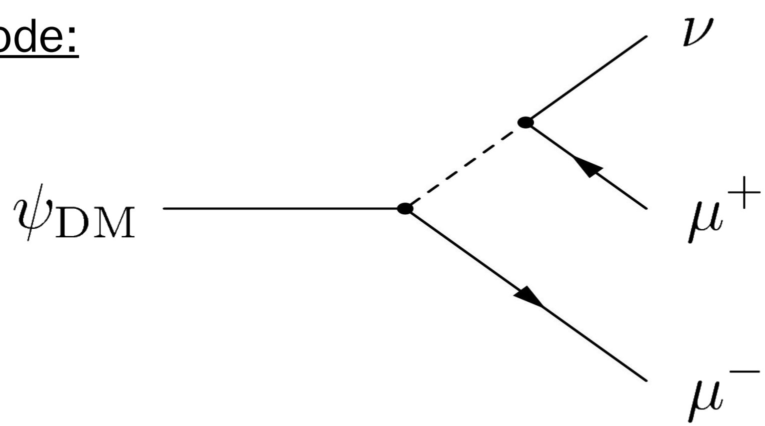
[Ibarra, Tran, CW (2009)]

Gamma-Ray Lines: Closing the loop

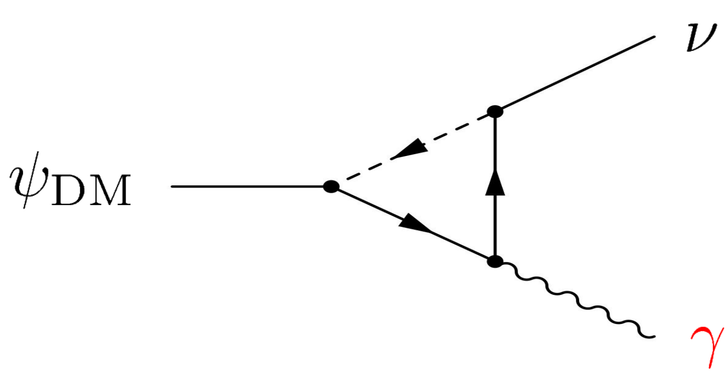
Monochromatic gamma rays can be produced on one-loop level.

- Experiments are very sensitive to gamma-ray lines → this can potentially compensate the loop-suppression of the decay

Main decay mode:

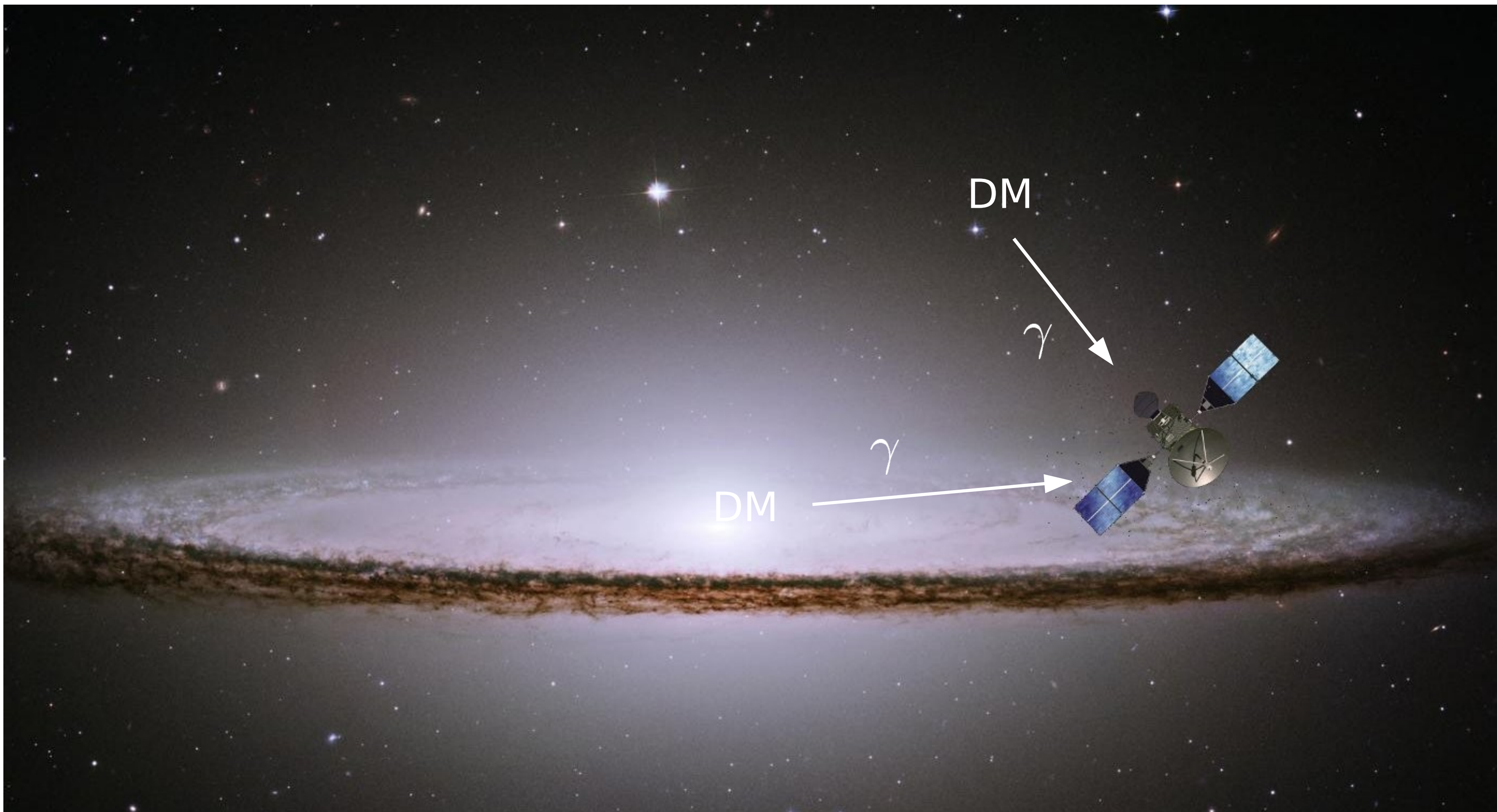


One-loop decay:



III. Experiment

Searching for gamma-ray lines with Fermi LAT



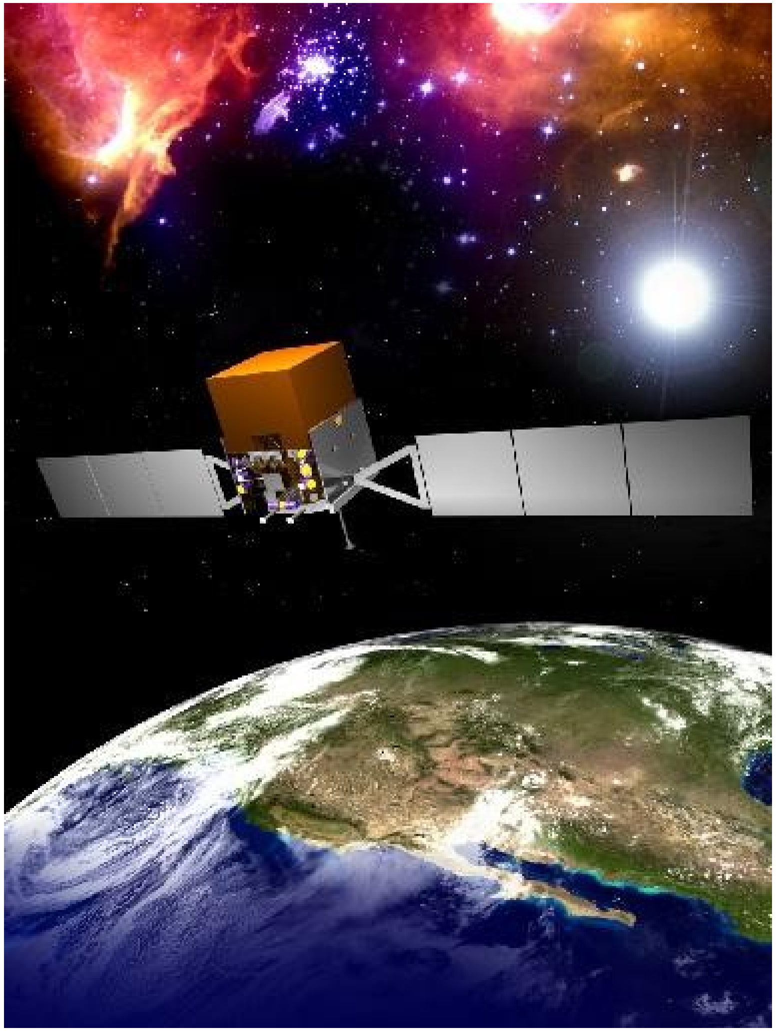
The Fermi Large Area Telescope

Fermi Large Area Telescope (LAT) Overview:

- Pair conversion detector
- The LAT is the main instrument of on board of the **Fermi Gamma-Ray Space Telescope**

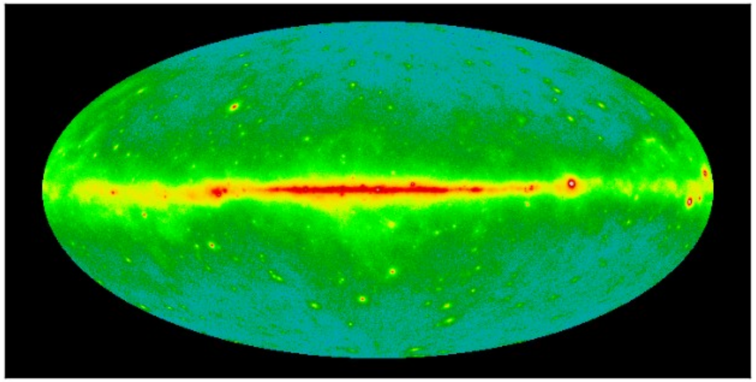
- Main energy range: **30 MeV – 300 GeV**
- Good **energy resolution: ~10%**
- Large field of view: **FOV ~ 2.4sr**
- Is taking data **since Aug 2008**

Data as well as analysis software publicly available!



Where to look for gamma-ray lines?

<u>Target region</u> should maximize the signal-to-noise ratio S/N, depending on angular profile of expected signal



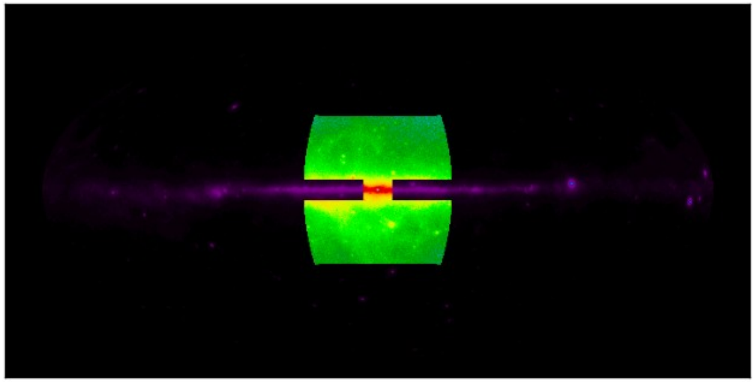
Target regions

DM annihilation

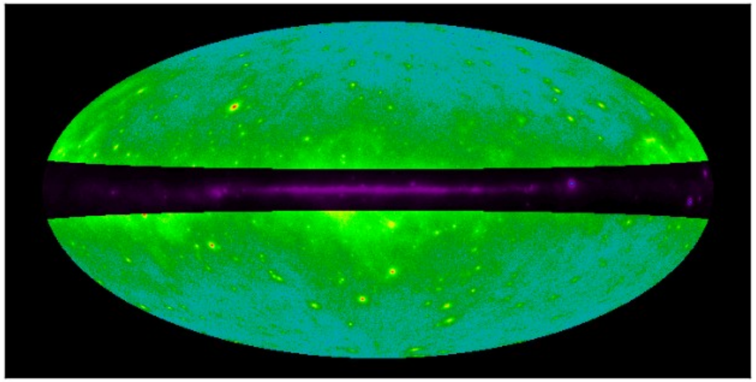
$$S \sim \int_{\mathrm{l.o.s.}} ds \rho_{\mathrm{dm}}^2(s)$$

DM decay

$$S \sim \int_{\mathrm{l.o.s.}} ds \rho_{\mathrm{dm}}(s)$$



DM signal peaked at galactic center



Mostly isotropic DM signal, dominates at high latitudes

Data analysis

Calculating limits mainly statistical problem

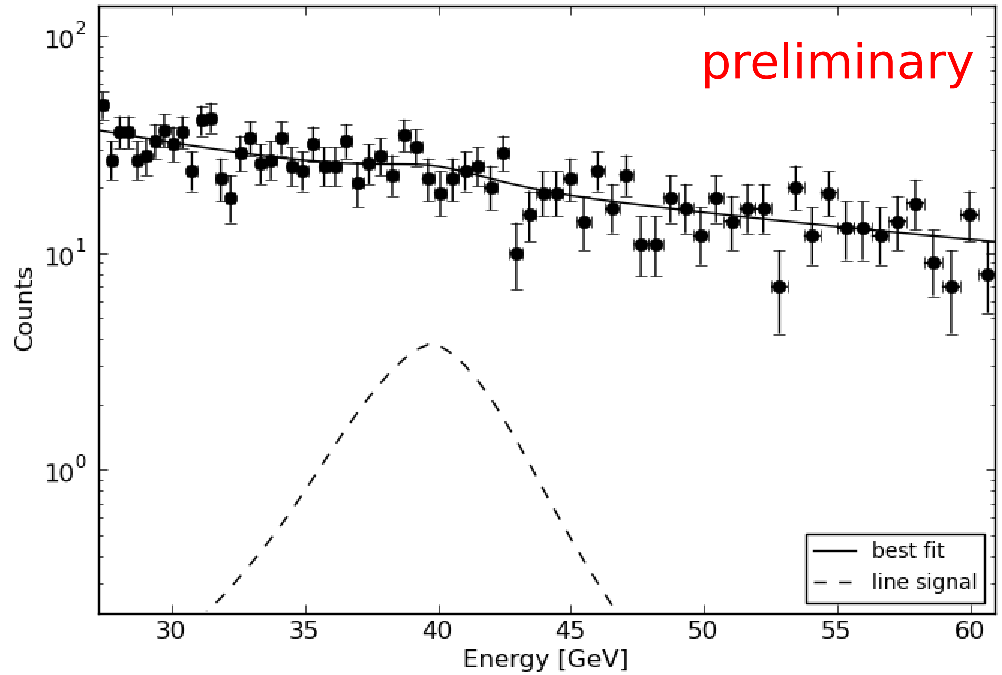
- Astrophysical backgrounds can be locally modeled by simple power-law
- Spectral shape of line signal completely determined by detector response to monochromatic photons

Model for BG (2 d.o.f.) and Line (1 d.o.f.): $$\frac{dJ}{dE} = \alpha E^{-\gamma} + \beta \mathcal{D}(E, E_\gamma)$$

Significance of line

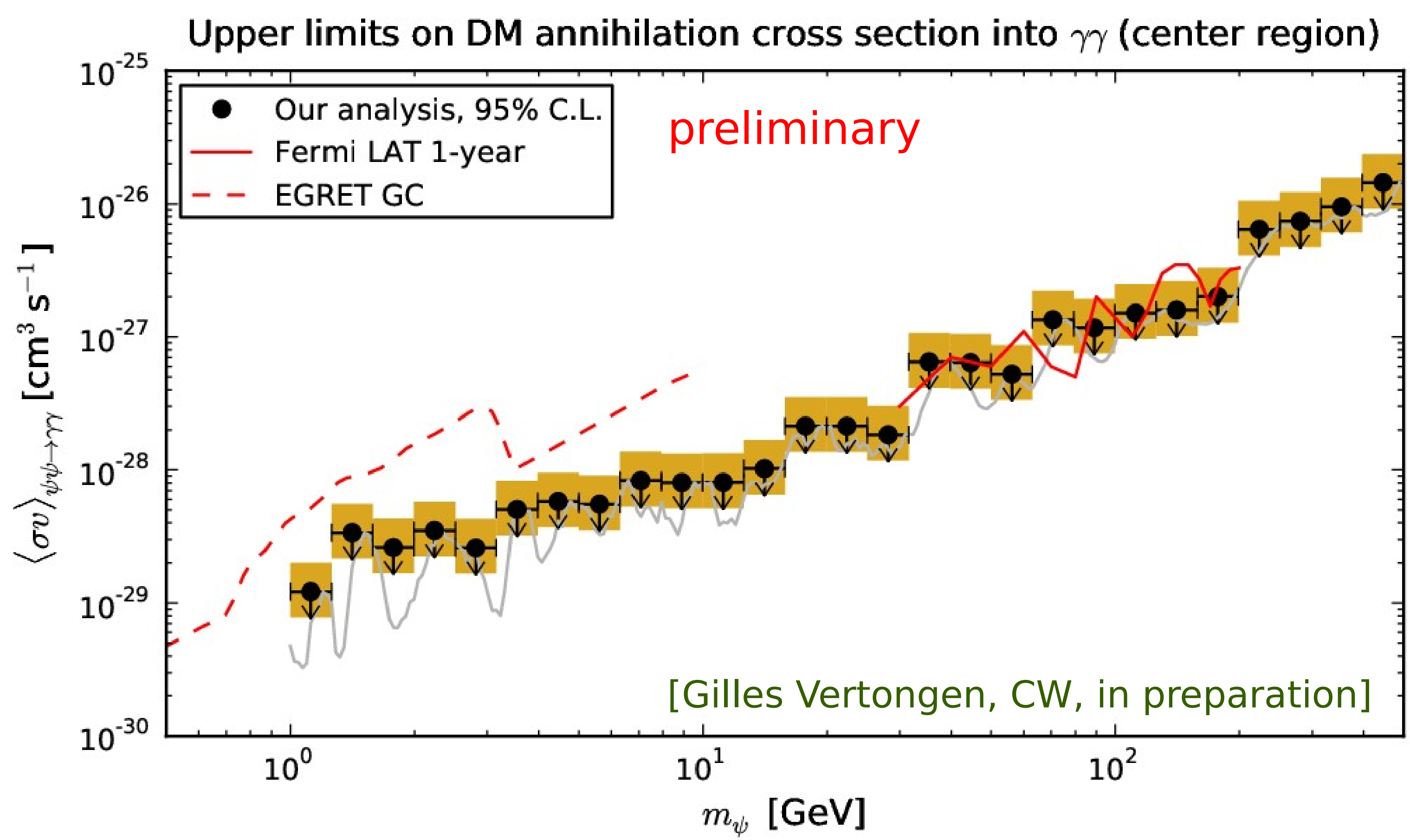
- can be calculated by profile-likelihood method
- e.g. 5-sigma line requires:

$$-2\log\frac{L^{\max}_{\beta=0}}{L^{\max}_{\beta\geq 0}} \gtrsim 25$$



No Line found between 1 and 500 GeV at 5σ level
→ we show limits at 2σ

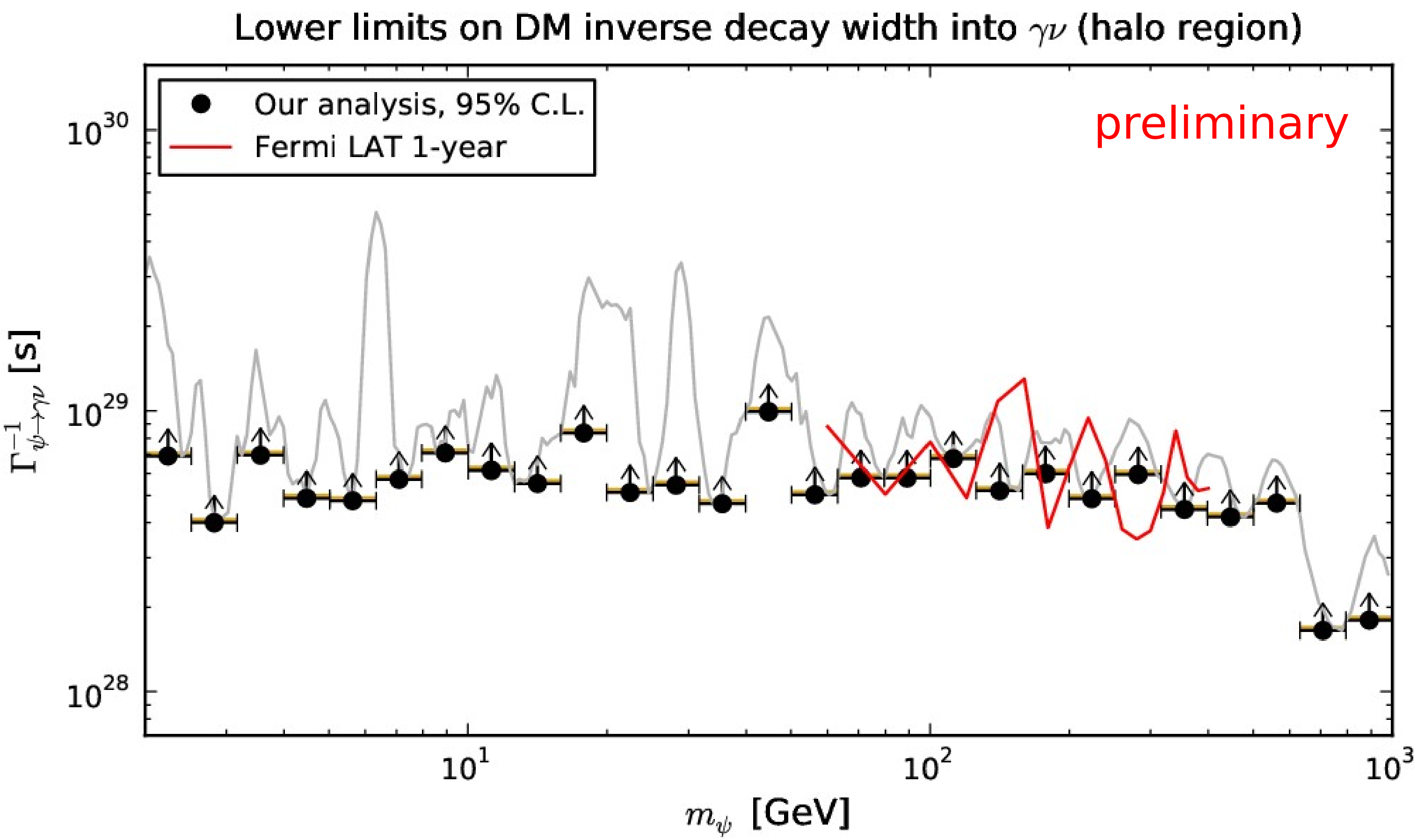
Limits on WIMP annihilation $\chi_1^0\chi_1^0 \to \gamma\gamma$



Limits on dark matter masses from 1 to 500 GeV

- Previous Fermi LAT results are extended to higher and lower energies
- Previous EGRET results at energies <10 GeV improved by a factor of a few

Limits on dark matter decay $\psi_{\mathrm{dm}} \to \gamma\nu$

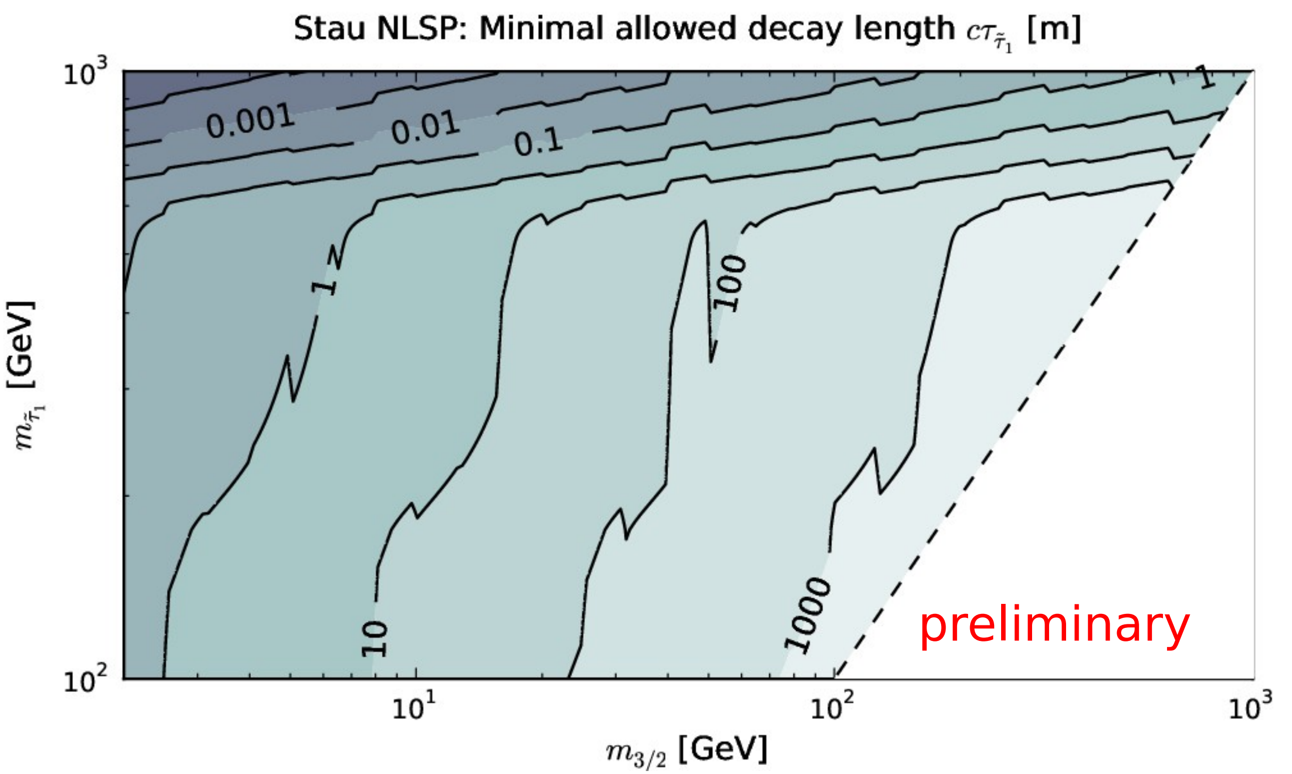


Limits on dark matter masses from 2 GeV to 1 TeV

- Previous Fermi LAT results are extended to higher and lower energies
- New limits below masses of 60 GeV are relevant for gravitino dark matter: lower limits on **gravitino lifetime** → upper limits on **R-parity violation**

Gravitino dark matter with stau NLSP

Lower limits on **stau NLSP** decay length:



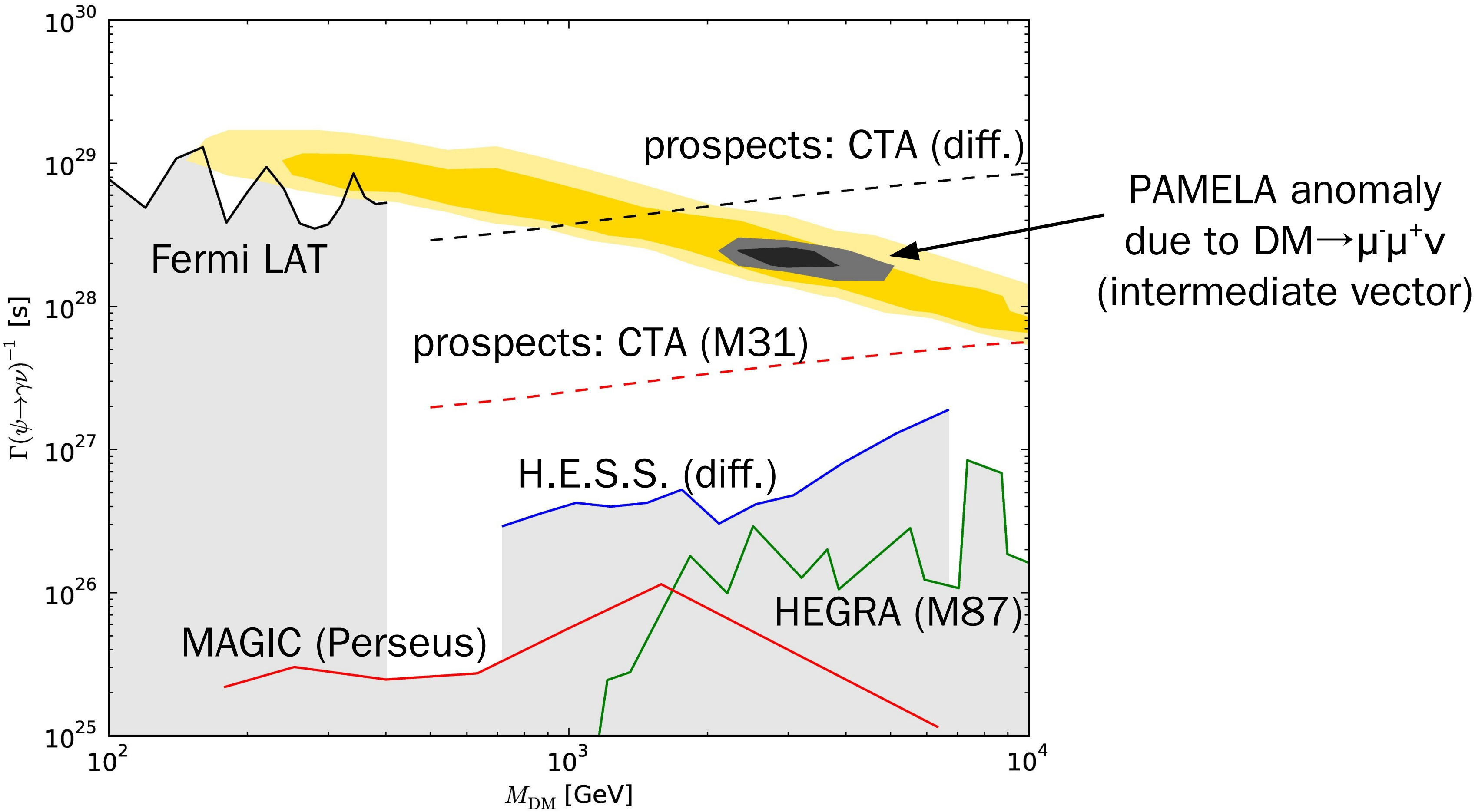
Long lived stau at LHC

- shows up as ionizing track
- decay visible via displaced vertex, decay lengths up to few km can be detected (since some particles decay inside collider) [Ishiwata et al. (2008)]
- Fermi LAT bounds → for typical masses and light (~10 GeV) gravitinos decay lengths down to O(10 m) possible

Beyond 500 GeV: Gamma-ray lines at CTA?

Beyond 500 GeV Air Cherenkov Telescopes become important

- High energies relevant for DM interpretation of PAMELA positron anomaly
- Observing gamma-ray signals from DM <u>decay</u> is very difficult: DM signal is mostly isotropic ↔ difficult to reject cosmic-ray background



- Future **Cherenkov Telescope Array** (CTA) might improve limits considerably

[Garny, Ibarra, Tran, CW (2010)]

IV. Conclusions

Conclusions

- Gamma-ray lines are very clean indirect dark matter signatures
- Sizable lines are predicted in many dark matter models
- Decaying dark matter examples include: Gravitinos, SU(2) vector dark matter, lines at one-loop level
- Analysis of Fermi LAT data shows no significant lines between 1 and 500 GeV; 2σ limits on DM cross section and lifetime were derived
- Gravitino dark matter scenario: Fermi LAT implies minimal NLSP decay lengths of O(10m) and below → accessible at the LHC

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Thank you & merry Christmas