Decaying vs Annihilating Dark Matter (and γ-ray features)

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Recontre de Blois, 26. – 31.05.2013

based on works in collaboration with Wilfried Buchmüller; Alejandro Ibarra, Miguel Pato, Stefan Vogl

Decaying vs Annihilating Dark Matter (and γ-ray features)

- Sharp gamma features at weak/TeV-scale energies are not expected from astrophysical processes. Famous ‘smoking gun’ for Dark Matter annihilation (or decay!)

e.g. Bergstrom, Snellman PRD37 (1988) 3737

- Typically loop suppressed, expect tiny cross-sections (‘holy grail’)

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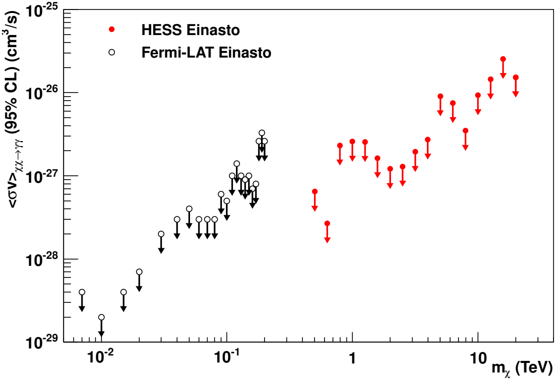
- Typically loop suppressed, expect tiny cross-sections (‘holy grail’)
- Detection could yield a wealth of information with major impact for particle- and astrophysics
    - Dark Matter mass
    - cross-section(s) to $\gamma\gamma$, γZ (or partial width/life-time!)
    - profile, morphology
    - sub-structures, ...

Limits from galactic centre/halo observations

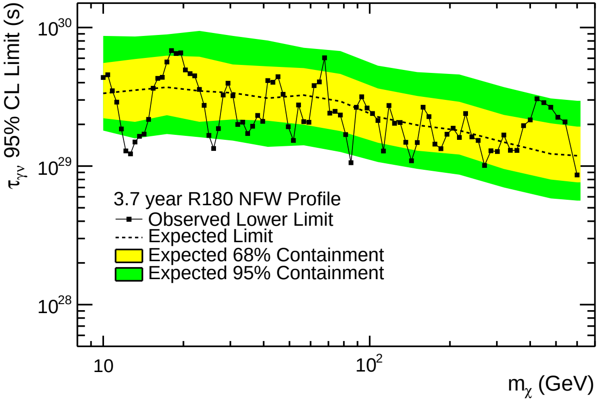
- Fermi, H.E.S.S. sensitivity of order $\sigma v_{\gamma\gamma} \lesssim 10^{-28}..10^{-26}\mathrm{cm}^3/\mathrm{sec}$



Fermi LAT 1205.2739 (23 months galactic halo); H.E.S.S. 1301.1173 (112h CGH within 4yr)

Limits from galactic centre/halo observations

- Fermi, H.E.S.S. sensitivity of order $\tau_{\gamma\nu} \gtrsim 10^{30}..10^{28}$sec



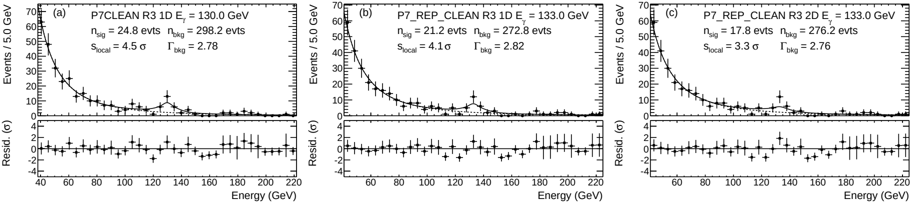
Fermi LAT 1305.5597 (3.7 yr galactic halo)

H.E.S.S. $\tau_{\gamma\nu} \gtrsim \mathcal{O}(10^{28})$sec

Gustaffson, Hambye, Scarna 1303.4423; H.E.S.S. 1301.1173

Tentative gamma-ray line from Galactic Centre

Bringmann, Ibarra, Vogl, Weniger 1203.1312; Weniger 1204.2797 *see also Hektor, Raidal, Tempel (12); Finkbeiner, Su (12); Boyarsky, Malyshev, Ruchayskiy (12); Linden, Profumo (12);...*



Fermi LAT GC 3° 4.5/4.1/3.3σ local for P7/P7rep/P7rep + P_E (improved description of energy reconstruction), 1.9σ global *Fermi LAT 1305.5597*

Decaying vs Annihilating DM (and γ-ray features)

Interplay of various channels (continous gamma rays, antiprotons; . . .)

- Generic model-independent analysis motivated by well-known dark matter candidates
    - Annihilating DM (line(s), e.g. wino/Higgsino)

$$\chi\chi \to \gamma\gamma, \gamma Z \quad \text{vs.} \quad \chi\chi \to WW, ZZ$$

    - Decaying DM (line, e.g. gravitino with RPV)

$$\psi_{3/2} \to \gamma\nu \quad \text{vs.} \quad \psi_{3/2} \to W\ell, Z\nu, h\nu$$

- Prospects 50 GeV - 10 TeV

Continuum Gamma Rays

- Line + continuum, $\mathrm{BR}_\gamma = \sigma v_{\gamma\gamma}/\sigma v \ (\tau/\tau_{\gamma\nu})$, $N_\gamma = 2(1)$

$$\frac{dJ}{dE} = \alpha \left(\delta(E - E_\gamma) + \frac{dN_{EG}}{dE} + \frac{1 - \mathrm{BR}_\gamma}{N_\gamma \, \mathrm{BR}_\gamma} \frac{dN^\gamma_{cont}}{dE} \right) + \beta \left(\frac{E}{E_\gamma} \right)^{-\gamma}$$

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- Extragalactic contribution *e.g. Bertone, Buchmüller, Ibarra*

$$\frac{dN_{EG}}{dE} = \frac{\Omega_{DM} \rho_{c0}}{\sqrt{\Omega_M} (H_0/c) \bar{J}_\psi} \frac{E^{1/2}}{E_\gamma^{3/2}} \left(1 + \frac{\Omega_\Lambda}{\Omega_M} \left(\frac{E}{E_\gamma} \right)^3 \right)^{-1/2} \Theta(E_\gamma - E)$$

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- Continuum gamma spectrum (from PYTHIA)

$$\frac{dN^\gamma_{cont}}{dE} \equiv \frac{1}{\sum_{f\neq\gamma} \mathrm{BR}_f} \sum_{f\neq\gamma} \mathrm{BR}_f \frac{dN^\gamma_f}{dE}$$

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e.g. Bertone, Buchmüller, Ibarra

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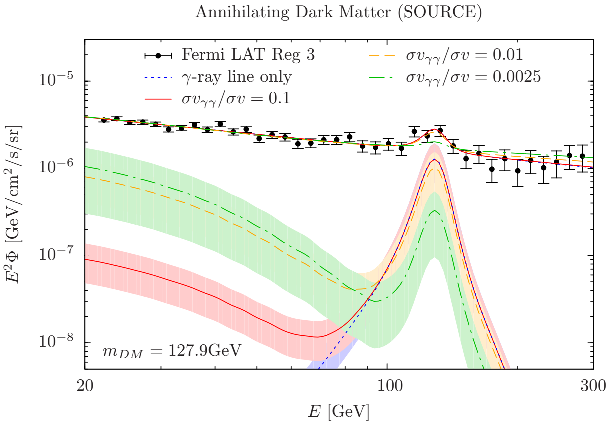
$$\frac{dN^\gamma_{cont}}{dE} \equiv \frac{1}{\sum_{f\neq\gamma}\mathrm{BR}_f}\sum_{f\neq\gamma}\mathrm{BR}_f\,\frac{dN^\gamma_f}{dE}$$

- Independent of DM distribution and CR propagation, assume power-law bkg model $20 - 200\,\mathrm{GeV}$

Continuum Gamma Rays

$\chi\chi \to \gamma\gamma, WW$



Reg	$\sigma v_{\gamma\gamma}$ $[10^{-27}\mathrm{cm}^3/\mathrm{s}]$									
	γ-ray line only		$\mathrm{BR}_{\gamma\gamma} = 0.1$		$\mathrm{BR}_{\gamma\gamma} = 0.01$		$\mathrm{BR}_{\gamma\gamma} = 0.0025$		$\mathrm{BR}_{\gamma\gamma} = 0.001$	
3 S	$1.25^{+0.65}_{-0.58}$	4.5σ	$1.24^{+0.64}_{-0.58}$	4.5σ	$0.99^{+0.52}_{-0.49}$	4.1σ	$0.32^{+0.21}_{-0.23}$	2.7σ	0.10	1.7σ
4 S	$1.24^{+0.68}_{-0.62}$	4.3σ	$1.21^{+0.68}_{-0.61}$	4.2σ	$0.86^{+0.51}_{-0.48}$	3.6σ	0.22	1.9σ	0.05	0.8σ

Constraints from PAMELA $\bar{p}/p$ measurement

- Rate of $\bar{p}$ per unit of kinetic energy and volume

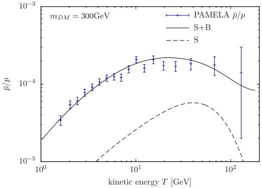
$$Q(T,\vec{r}) = \frac{1}{2}\frac{\rho^2(\vec{r})}{m_\chi^2}\sum_f \langle\sigma v\rangle_f \frac{dN^f_{\bar{p}}}{dT}$$

- Einasto profile with $\alpha_E = 0.17$, $r_s = 20\text{kpc}$, $\rho(r_\odot) = 0.39\text{GeV}/\text{cm}^3$
- Propagation: two-zone diffusion model compatible with B/C ratio, three parameter sets corresponding to MIN, MED, MAX $\bar{p}$ flux

$$0 = \frac{\partial f_{\bar{p}}}{\partial t} = \nabla\cdot(K(T,\vec{r})\nabla f_{\bar{p}}) - \nabla\cdot(\vec{V}_c(\vec{r})f_{\bar{p}}) - 2h\delta(z)\Gamma_{\rm ann} f_{\bar{p}} + Q(T,\vec{r})$$

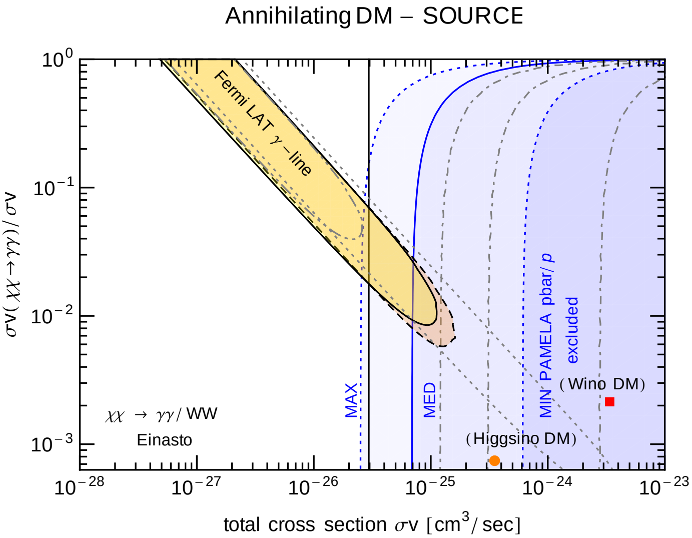
Model	δ	$K_0\,(\mathrm{kpc}^2/\mathrm{Myr})$	$L\,(\mathrm{kpc})$	$V_c\,(\mathrm{km/s})$
MIN	0.85	0.0016	1	13.5
MED	0.70	0.0112	4	12
MAX	0.46	0.0765	15	5

- secondary $\bar{p}$ flux from *Donato, Maurin, Salati, Barrau, Boudoul, Taillet 01*
- solar modulation in force field approximation $\phi_F = 500MV$



Continuum Gamma Rays + Antiprotons

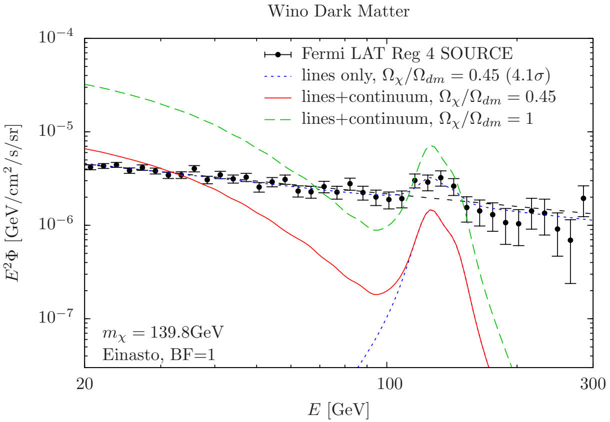
$\chi\chi \to \gamma\gamma, WW$



[Fermi dwarf 1108.3546 $\sigma v_{WW} \lesssim 10^{-25}$cm^3/s]

Buchmüller, MG 1206.7056

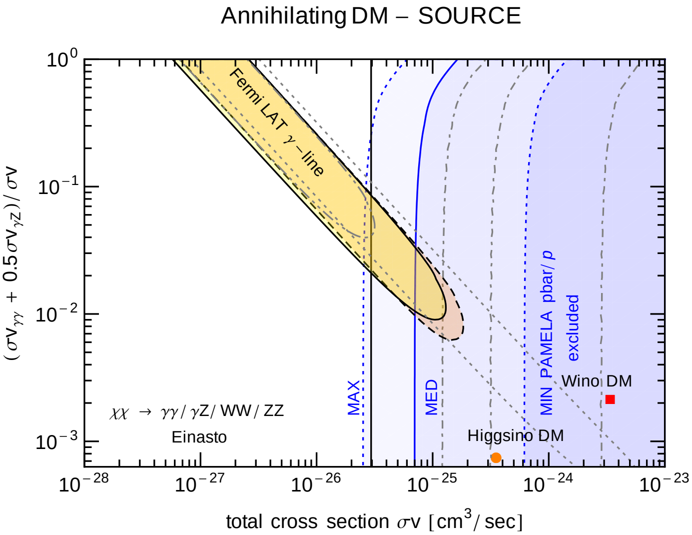
Continuum Gamma Rays (Wino)



Buchmüller, MG 1206.7056

Annihilating DM (two lines)

$\chi\chi \to \gamma\gamma, \gamma Z, WW, ZZ$



(assume $\sigma v_{\gamma Z}/(2\sigma v_{\gamma\gamma}) = 1.7$ like for Higgsino)

Buchmüller, MG 1206.7056

Annihilating DM (line(s))

- Constraints from secondary continous gamma and antiproton flux require

$$\mathrm{BR}_\gamma \quad = \quad \frac{\sigma v_{\gamma\gamma} + 0.5\sigma v_{\gamma Z}}{\sigma v} \gtrsim 0.5\%$$

- Example: Higgsino (H) and wino-like (W) LSP

	μ	M_2	$m_{\chi_0^1}$	$m_{\chi_0^2}$	$m_{\chi_\pm^1}$	$\sigma v_{\gamma\gamma}(\sigma v_{\gamma Z})$	$\sigma v_{WW}(\sigma v_{ZZ})$
H	139	1000	135.89	144.44	139.20	$1.0(3.4) \cdot 10^{-28}$	$2.1(1.4) \cdot 10^{-25}$
W	400	143	139.79	408.08	139.94	$2.0(10.9) \cdot 10^{-27}$	$3.4(0.0) \cdot 10^{-24}$

$$\mathrm{BR}_\gamma \quad \sim \quad 0.08\%(0.2\%)$$

see e.g. refs in 1305.4710, 1208.5481 for models with enhanced line signal

alternatives: internal bremsstrahlung (previous talk), box-shaped gamma features (e.g. 1205.0007)

Decaying dark matter

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BARYOGENESIS WITHOUT GRAND UNIFICATION

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Received 8 March 1986

A mechanism is pointed out to generate cosmological baryon number excess without resorting to grand unified theories The lepton number excess originating from Majorana mass terms may transform into the baryon number excess through the unsuppressed baryon number violation of electroweak processes at high temperatures

The current view ascribes the origin of cosmological baryon excess to the microscopic baryon number violation process in the early stage of the Universe [1,2]. The grand unified theory (GUT) of particle in-

conserving baryon number violation processes as in the standard SU(5) GUT. (Baryon numbers would remain, if the baryon production takes place at low temperatures $T \lesssim O(100\text{ GeV})$, e.g., after reheating

Gravitino

- Consistent cosmology with leptogenesis ($T_R \sim 10^9$ GeV), gravitino dark matter ($\Omega_{3/2}h^2 = 0.11$) and BBN ($\tau_{NLSP} \lesssim t_{BBN}$)

$$\Omega_{3/2}h^2 \simeq 0.27 \left(\frac{T_R}{10^9\,\mathrm{GeV}}\right)\left(\frac{10\,\mathrm{GeV}}{m_{3/2}}\right)\left(\frac{m_{\widetilde{g}}}{1\,\mathrm{TeV}}\right)^2$$

Buchmüller, Bolz, Brandenburg hep-ph/0012052

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Buchmüller, Bolz, Brandenburg hep-ph/0012052

- Gravitino meta-stable due to bilinear R-parity violation

$$\tau_{3/2}(\psi \to \gamma\nu) \quad \simeq \quad 10^{27}\mathrm{s}\left(\frac{\zeta}{10^{-7}}\right)^{-2}\left(\frac{M_1}{100\ \mathrm{GeV}}\right)^2\left(\frac{m_{3/2}}{10\ \mathrm{GeV}}\right)^{-3}$$

Buchmüller, Covi, Hamaguchi, Ibarra, Yanagida 07; Bobrovski, Buchmüller, Hajer 1007.5007

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Buchmüller, Covi, Hamaguchi, Ibarra, Yanagida 07; Bobrovski, Buchmüller, Hajer 1007.5007

- Lifetimes of this order can be probed by indirect detection

Buchmüller, Ibarra, Shindou, Takayama, Tran 09; Ibarra, Tran, Grefe; ...

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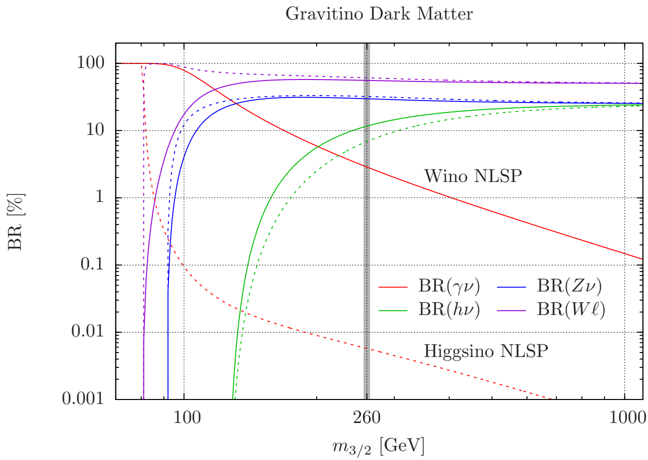
Buchmüller, Ibarra, Shindou, Takayama, Tran 09; Ibarra, Tran, Grefe; ...

- Two-body decay channels $\psi \to \gamma\nu, Z\nu, W\ell, h\nu$

$$\mathcal{L} = \underbrace{\frac{i}{\sqrt{2}M}\left(\overline{\chi}\gamma^\nu\gamma^\mu(D_\mu\phi)\psi_\nu + \mathrm{c.c.}\right)}_{\psi \to Z\nu,\, W\ell,\, h\nu} - \underbrace{\frac{1}{4M}\overline{\lambda}\gamma^\nu\sigma^{\mu\rho}\psi_\nu F_{\mu\rho}}_{\psi \to \gamma\nu}$$

Gravitino



Branching ratios of two-body gravitino decays for two representative examples
Wino NLSP: $M_2 = 1.1\ m_{3/2},\ M_1 = \mu = 10\ m_{3/2}$

Higgsino NLSP: $\mu = 1.1\ m_{3/2},\ M_1 = 10\ m_{3/2},\ M_2 = 1.9\ M_1$.

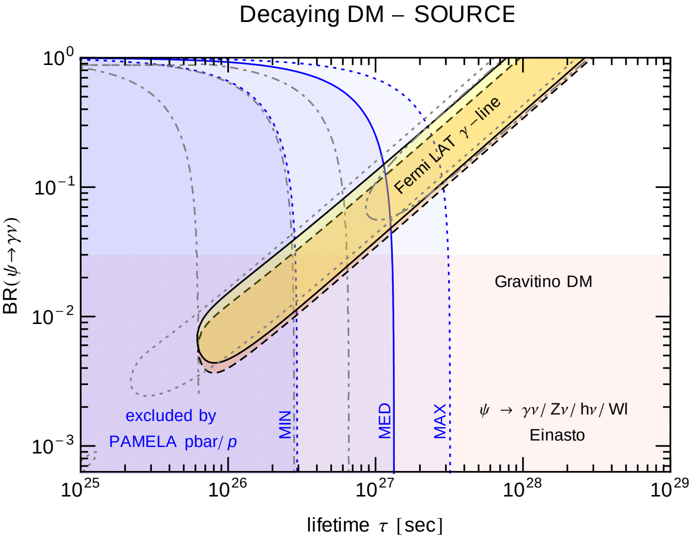
Gravitino

Branching ratio for $\psi \to \gamma\nu$ for Wino NLSP

$$\mathrm{BR}_{\gamma}^{\max} \simeq \frac{3\pi\alpha}{2\sqrt{2}G_F m_{3/2}^2} \simeq 3\% \text{ for } m_{3/2} \simeq 260 \text{ GeV}$$

Continuum Gamma Rays + Antiprotons

$\psi \to \gamma\nu, Z\nu, W\ell, h\nu$



Buchmüller, MG 1206.7056

Morphology

- Shape depends on line-of-sight integral over DM distribution (squared)

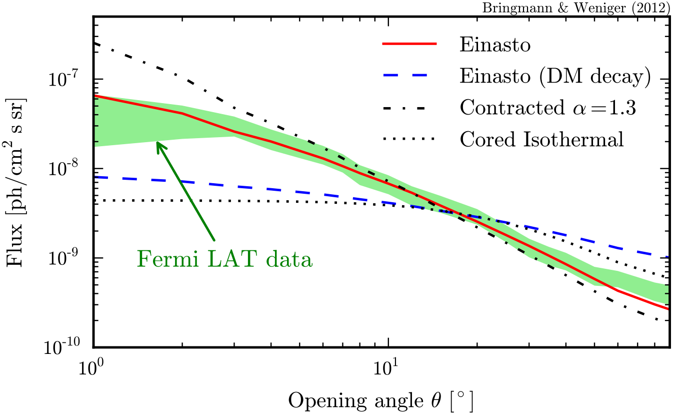
$$\frac{dJ_\gamma}{dEd\Omega} = \frac{1}{4\pi}\delta(E-E_\gamma)\begin{cases} \dfrac{1}{\tau_{\gamma\nu}\, m_{DM}} \displaystyle\int_{l.o.s.} ds\, \rho_{dm}(r) & \text{decay} \\ \dfrac{2\sigma v_{\gamma\gamma}}{m_{DM}^2} \displaystyle\int_{l.o.s.} ds\, \frac{1}{2}\, \rho_{dm}(r)^2 & \text{annihilation} \end{cases}$$

- NFW or Einasto profile

$$\rho_{dm}(r) \propto \frac{1}{(r/r_s)^\alpha (1+r/r_s)^{3-\alpha}}, \qquad \exp\left(-\frac{2}{\alpha_E}(r/r_s)^{\alpha_E}\right)$$

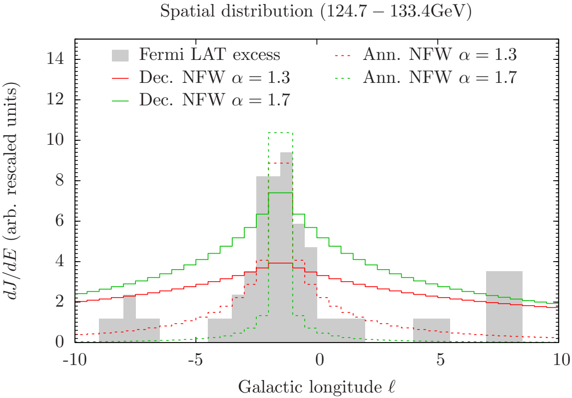
with $\alpha_E = 0.17$, $\alpha \geq 1$ and scale radius $r_s = 20\text{kpc}$

Morphology



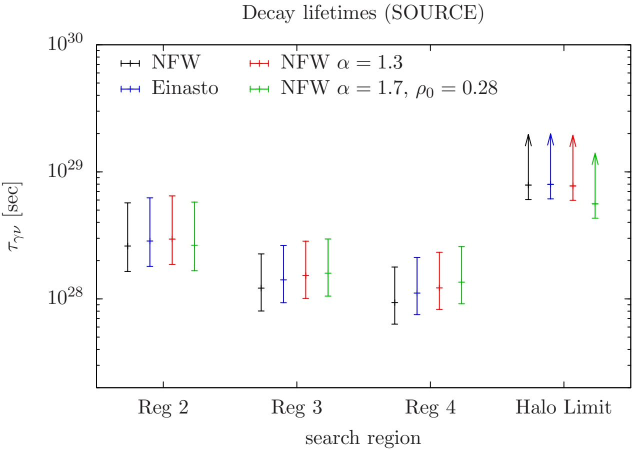
Bringmann, Weniger 1208.5481

Morphology



Finkbeiner, Su 1206.1616

Morphology



Buchmüller, MG 1206.7056

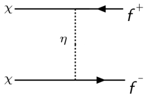
Prospects

- Future IACTs (HESS-II, CTA $A_{eff} \sim 10^5 - 10^6 \mathrm{m}^2$) and space telescopes (Gamma400, $\delta E/E \sim 1 - 3\%$) can probe the tentative Fermi excess at 130 GeV *Bergstrom, Bertone, Weniger (1207.6773)*
- Start to probe potentially interesting regions in 100 GeV - few TeV range
- Interplay with various ID, DD and Collider searches

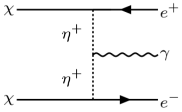
Prospects (annihilating DM, internal bremsstrahlung)

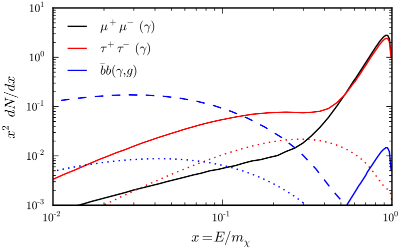
Bergstrom 89; Flores, Olive, Rudaz 89

$$\sigma v_{\chi\chi\to f\bar{f}} \propto \left\{\frac{m_f^2}{m_{DM}^2}, \frac{v^2}{c^2}\right\} \times \left(\frac{m_{DM}}{m_\eta}\right)^4$$



$$\sigma v_{\chi\chi\to f\bar{f}\gamma(g)} \propto \frac{\alpha_{em(s)}}{\pi}\left(\frac{m_{DM}}{m_\eta}\right)^8$$

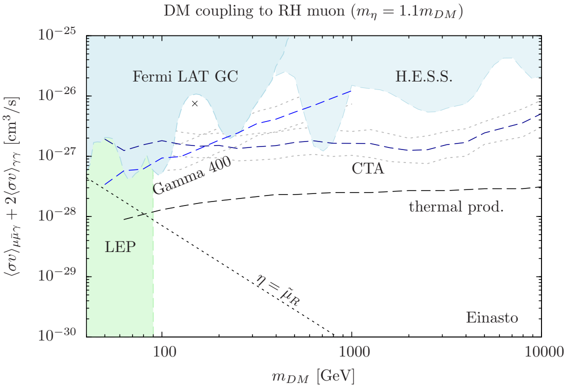




Bringmann, Ibarra, Vogl, Weniger 1203.1312

Prospects (annihilating DM, internal bremsstrahlung)

$\chi\chi \to \mu_R \bar{\mu}_R \gamma$ via charged scalar η, $m_\eta / m_{DM} \lesssim 2 - 3$



CTA (50h GC 2° MPIK setting); Gamma400 (GC+Halo-Disk 20° within 5yr)

MG, Ibarra, Pato, Vogl (in prep.); see Bergstrom, Bertone, Weniger (1207.6773) for γ-line

Prospects (annihilating DM, internal bremsstrahlung)

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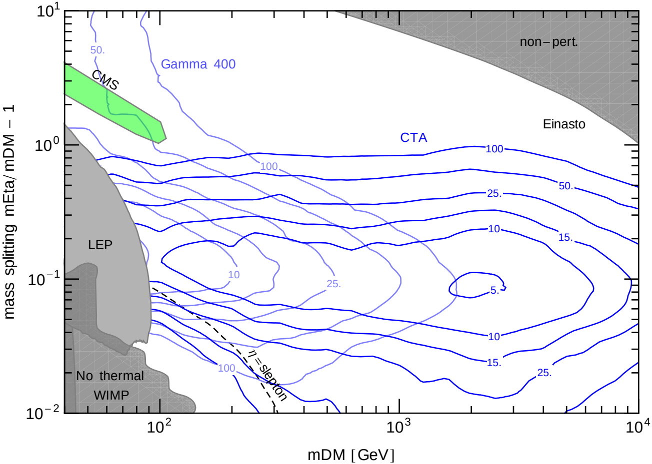
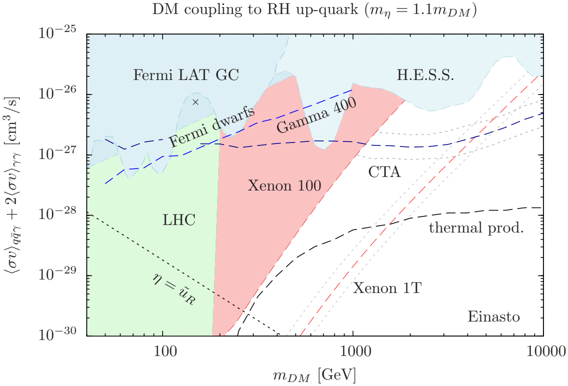
DM coupling to RH muon (thermal production)



MG, Ibarra, Pato, Vogl (in prep.)

Prospects (annihilating DM, internal bremsstrahlung)

$\chi\chi \to u_R\bar{u}_R\gamma, u_R\bar{u}_R g$ via colored scalar η



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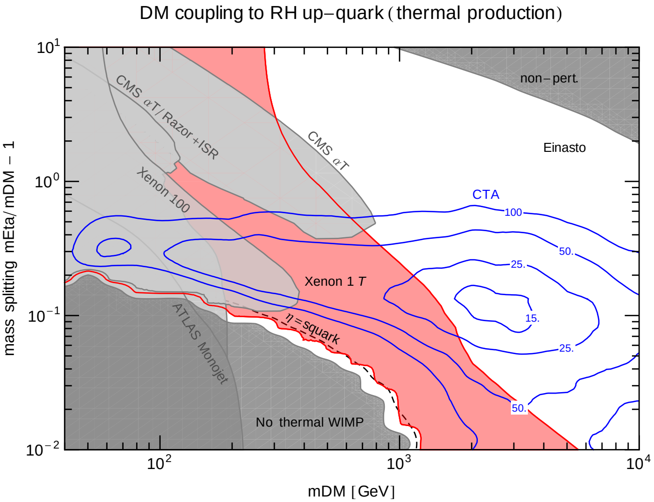
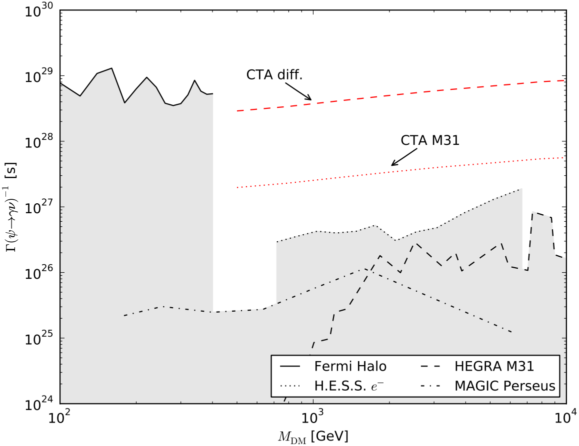


MG, Ibarra, Pato, Vogl (in prep.)

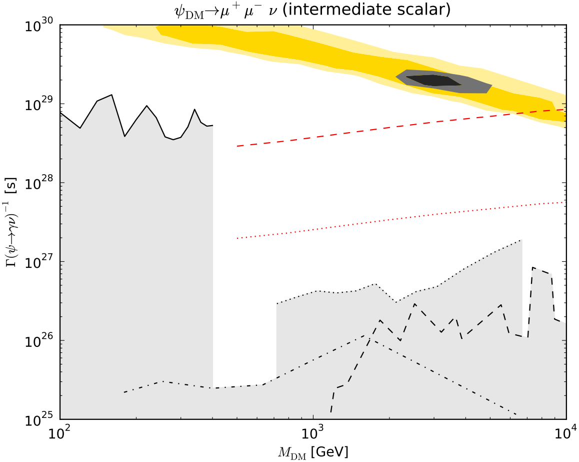
Prospects (decaying DM)



MG, Ibarra, Tran, Weniger 2011

Prospects (decaying DM)

Radiative decay $\psi \to \gamma\nu$ induced by $\psi \to \mu\bar{\mu}\nu$



MG, Ibarra, Tran, Weniger 2011

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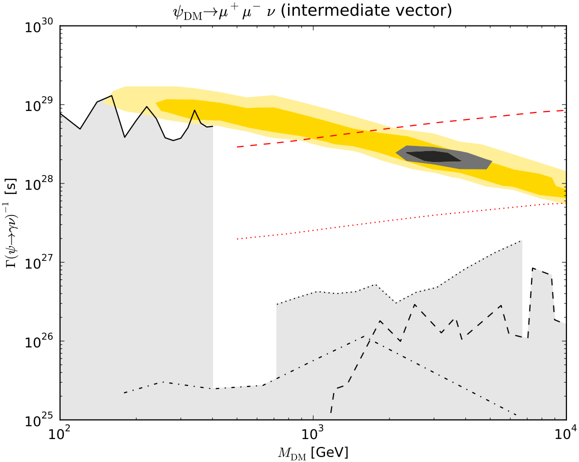

MG, Ibarra, Tran, Weniger 2011

Conclusion

- Detection of a line-like signal in gamma ray spectrum could yield a wealth of information on dark matter. Future IACTs and space telescopes start to probe interesting regions in 100 GeV - few TeV range

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thank you!

Annihilating DM (internal bremsstrahlung)

- For Majorana dark matter, the annihilation rate in the Milky Way halo into light fermions is strongly suppressed (e.g. MSSM neutralino annihilating via squark/slepton, here called $\eta \in \tilde{\ell}, \tilde{q}$)

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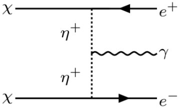
- The helicity suppression is lifted by the associated emission of a gauge boson, $\chi\chi \to f\bar{f}V$, $V = \gamma, W, Z, g$

$$\sigma v_{\chi\chi\to f\bar{f}\gamma} \quad \propto \quad \frac{\alpha_{em}}{\pi}\left(\frac{m_{DM}}{m_\eta}\right)^4$$



Bergstrom 89; Flores, Olive, Rudaz 89; Drees, Jungman, Kamionkowski Nojiri 93

- Characteristic gamma spectrum peaked at $E_\gamma \sim 0.8 - 0.9 m_{DM}$, particularly important for $m_\eta \gtrsim m_{DM}$ (e.g. coannihilation regions)

Bringmann, Bergstrom, Edsjo 07

Annihilating DM (internal bremsstrahlung)

- Consider toy model with 'Bino' DM χ and 'squark' (or 'slepton') η close in mass ('coannihilation region'); generalize Yukawa interaction strength f with RH SM fermion $\psi_R \in \ell, u, d$

$$\mathcal{L} = f\,\bar{\chi}\psi_R\eta + \text{h.c.}$$

- In susy case couplings f fixed by $U(1)_Y$ couplings

	$\psi = \ell$	$\psi = u$	$\psi = d$
MSSM	$\eta = \tilde{\ell}_R$ $f = 0.5$	$\eta = \tilde{u}_R$ $f = 0.33$	$\eta = \tilde{d}_R$ $f = 0.16$
Fermi line	$f \simeq 2.0$	$f \simeq 1.8$	$f \simeq 2.6$

- Can explain Fermi 'line' for $m_\chi \simeq 150\text{GeV}$, $\sigma v_{f\bar{f}\gamma} \simeq 7 \cdot 10^{-27}\text{cm}^3/\text{s}$
- In tension with bounds from Fermi dwarfs and Pamela antiproton data for $\chi\chi \to q\bar{q}\gamma$ due to secondary gamma/$\bar{p}$ flux from $\chi\chi \to q\bar{q}g$; ruled out by Xenon100/LHC limits on charged scalars
- Viable explanation for $\chi\chi \to \ell\bar{\ell}\gamma$, compatible with continuum gamma, antiproton, Xenon100 and LHC data

Virtual Internal Bremsstrahlung

- $2 \to 2$ annihilation

$$\sigma v_{\chi\chi\to f\bar{f}} \quad = \quad \left[\mathcal{O}(v^0)\mathcal{O}\left(\frac{m_f}{m_{DM}}\right)^2 + \mathcal{O}(v^2)\right]\mathcal{O}\left(\frac{m_{DM}}{m_\eta}\right)^4$$

- $2 \to 3$ annihilation via FSR from nearly on-shell $e^\pm$ (soft/collinear)

$$\sigma v^{FSR}_{\chi\chi\to f\bar{f}\gamma} \quad \simeq \quad \frac{\alpha_{em}}{\pi}\int_0^1 dx \frac{1-x}{x}\log[4m_{DM}^2(1-x)/m_f^2] \times \sigma v_{\chi\chi\to f\bar{f}}$$

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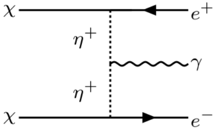
- $2 \to 3$ annihilation via VIB and FSR from off-shell $e^\pm$

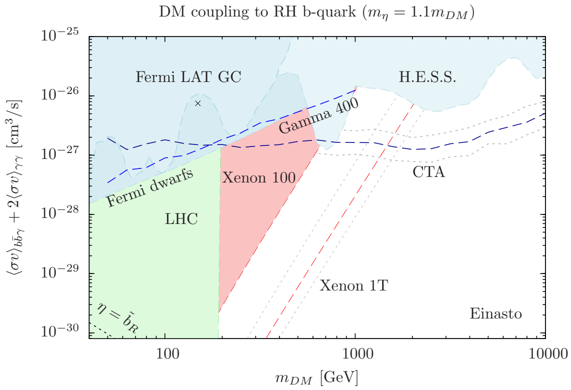
$$\sigma v^{VIB/FSR}_{\chi\chi \to f\bar{f}\gamma} \quad = \quad \frac{\alpha_{em}}{\pi} \left[\mathcal{O}(v^0)\mathcal{O}\left(\frac{m_{DM}}{m_\eta}\right)^8 + \mathcal{O}(v^2)\mathcal{O}\left(\frac{m_{DM}}{m_\eta}\right)^4 \right]$$



Bergstrom 89; Flores, Olive, Rudaz 89

Prospects (annihilating DM, internal bremsstrahlung)

$\chi\chi \to b_R \bar{b}_R \gamma, b_R \bar{b}_R g$ via colored scalar η



MG, Ibarra, Pato, Vogl (in prep.)

Gravitino

$\Delta W = \mu_i H \ell_i, \Delta \mathcal{L} = B_i H_u \tilde{\ell}_i + m_{id}^2 \tilde{\ell}_i^\dagger H_d$

$$\zeta_i = \frac{\epsilon_i' v_d + \epsilon_i'' v_u}{v}$$

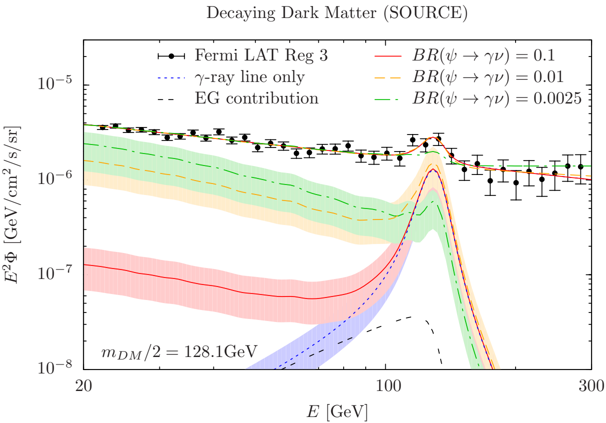
$$\epsilon_i' = -\frac{B_i' B + m_{id}^{2\prime} \left(\widetilde{m}_{li}^2 - m_u^2\right)}{\left(\widetilde{m}_{li}^2 - m_u^2\right)\left(\widetilde{m}_{li}^2 - m_d^2\right) - B^2}$$

$$\epsilon_i'' = \frac{B_i' \left(\widetilde{m}_{li}^2 - m_d^2\right) + B m_{id}^{2\prime}}{\left(\widetilde{m}_{li}^2 - m_u^2\right)\left(\widetilde{m}_{li}^2 - m_d^2\right) - B^2}$$

Bobrovski, Buchmüller, Hajer 1007.5007

Continuum Gamma Rays

$\psi \to \gamma\nu, Z\nu, W\ell, h\nu$



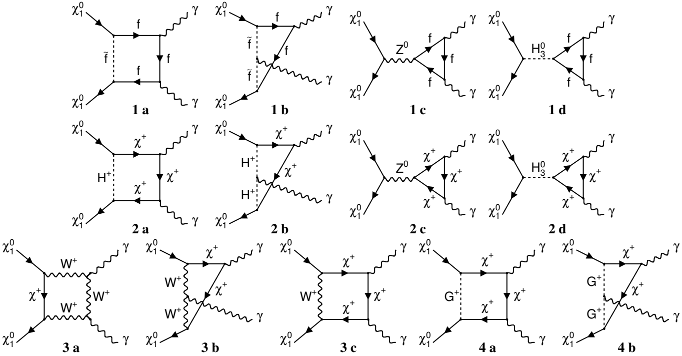
Buchmüller, MG 1206.7056

Annihilating DM (line)

$$\chi\chi \to \gamma\gamma \qquad E_\gamma = m_{DM}$$

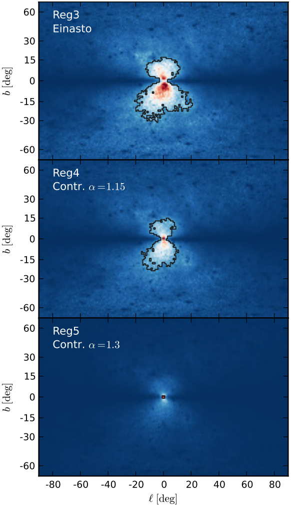
$$\chi\chi \to \gamma Z \qquad E_\gamma = m_{DM}\left(1 - \frac{M_Z^2}{4m_{DM}^2}\right)$$

Bergstrom, Ullio 97



Tentative gamma-ray line from Galactic Centre

Bringmann, Ibarra, Vogl, Weniger 1203.1312; Weniger 1204.2797



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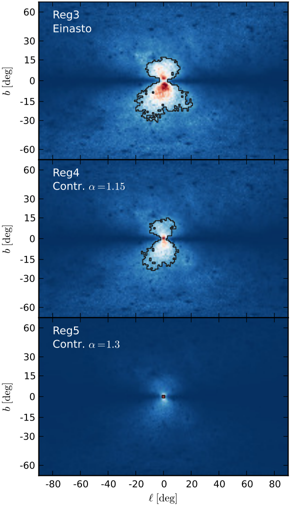
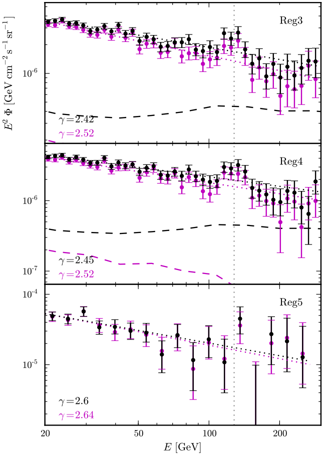
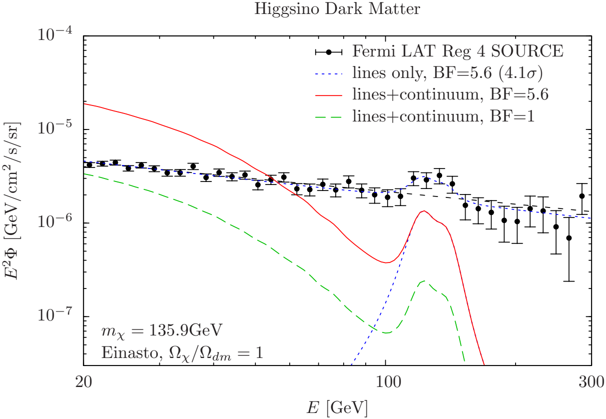




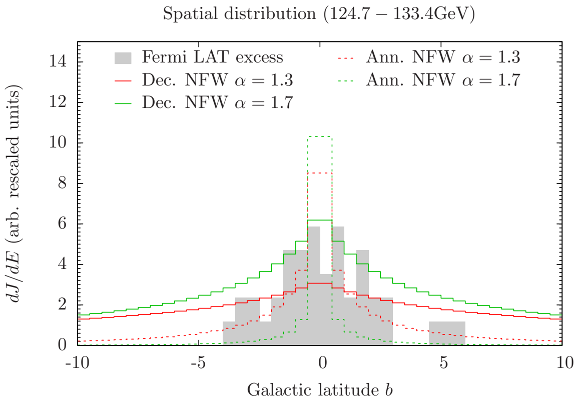
see also Hektor, Raidal, Tempel (12); Finkbeiner, Su (12); Boyarsky, Malyshev, Ruchayskiy (12); Linden, Profumo (12);...

Continuum Gamma Rays (Higgsino)



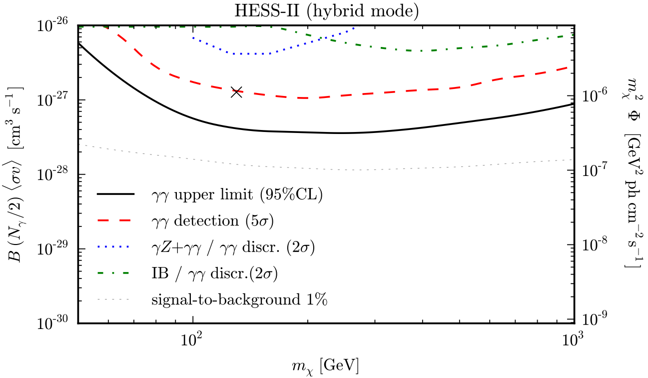
Buchmüller, MG 1206.7056

Morphology



Finkbeiner, Su 1206.1616

Prospects (annihilating DM, line)



see Bergstrom, Bertone, Weniger, 1207.6773

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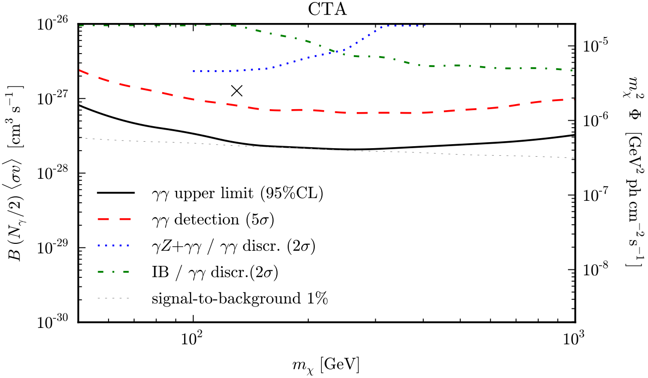

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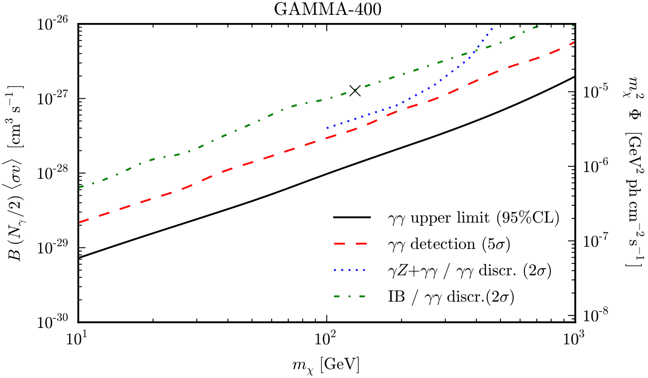

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