Technische Universität München

SEARCHING FOR BOXES IN THE GAMMA-RAY SKY

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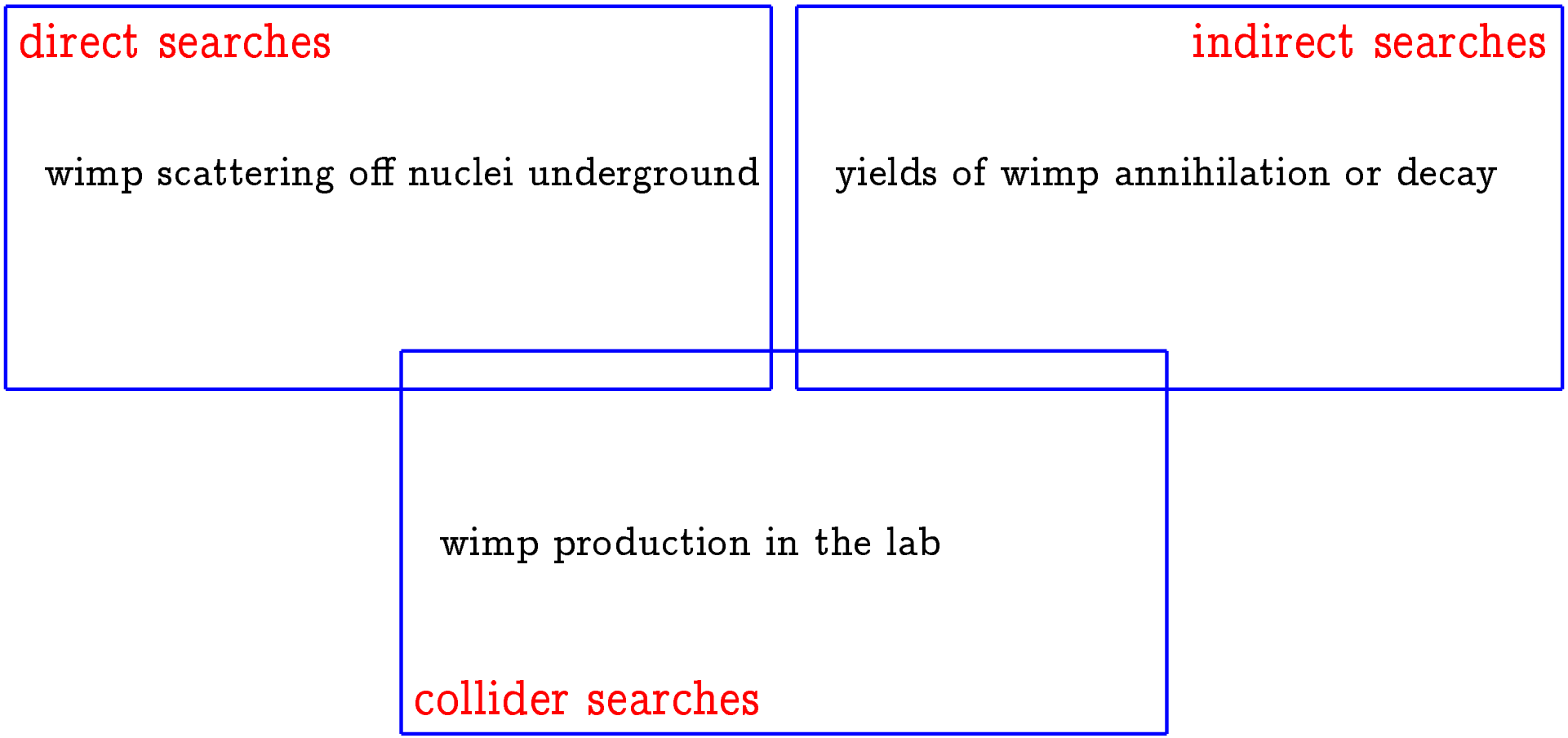
with Alejandro Ibarra, Hyun Min Lee, Sergio López Gehler and Wan-Il Park

[JCAP07(2012)043, arXiv:1205.0007] [JCAP05(2013)016, arXiv:1303.6632]

MITP Workshop, Mainz, June 30th 2013

1. THE QUEST FOR WIMPS

long-awaited data are being collected as we speak...



complementarity and uncertainty are key for wimp identification

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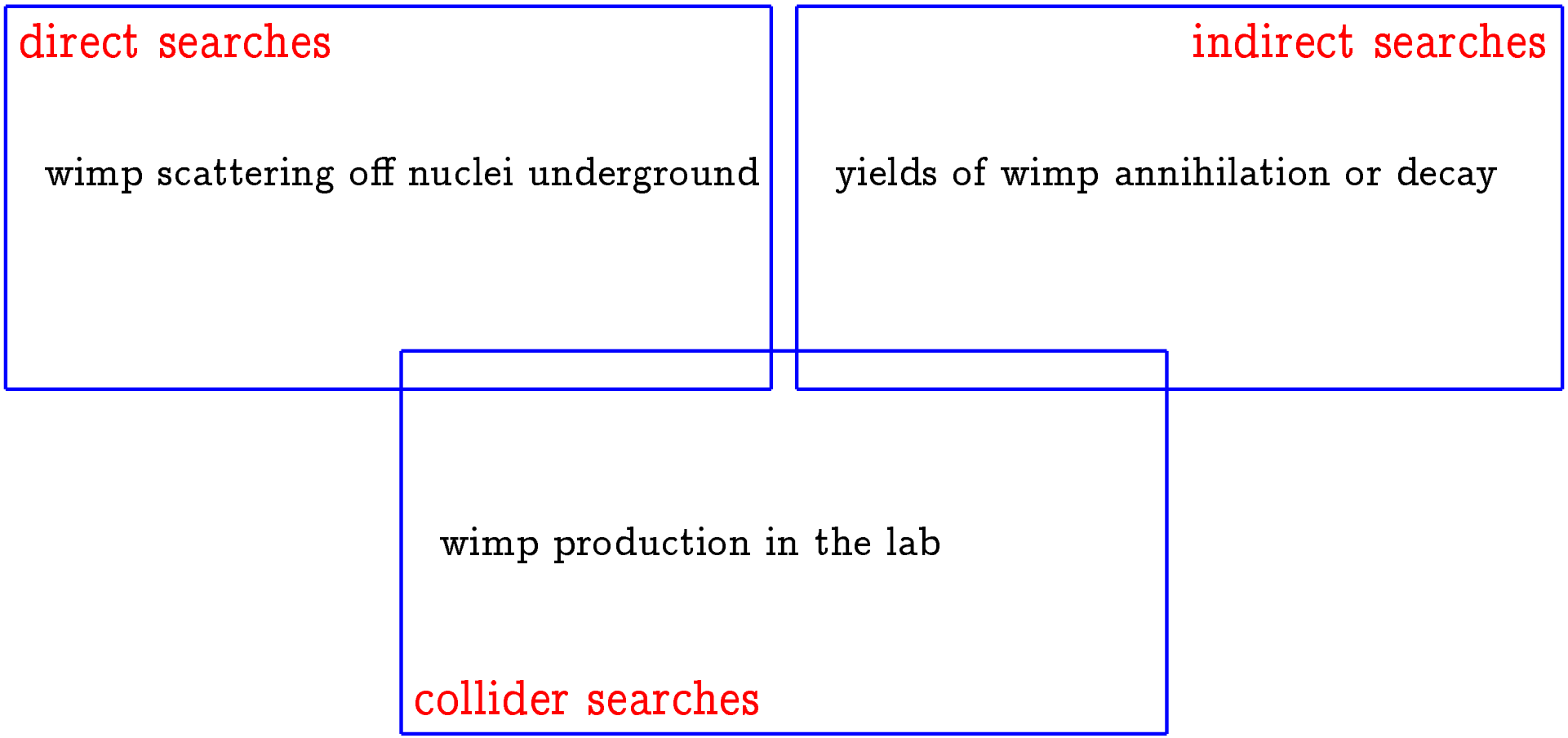

lots of unexplored data with extensive constraining power

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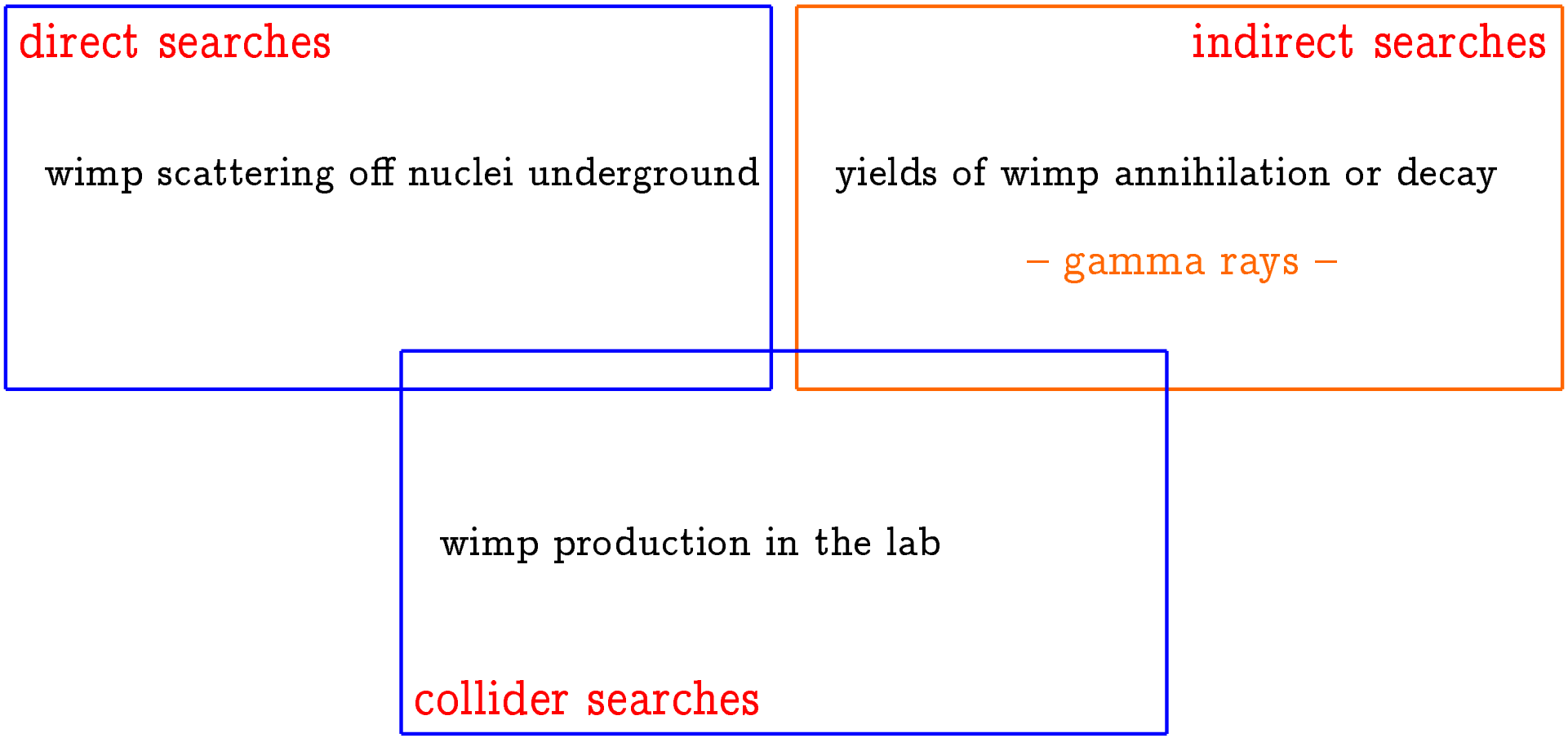

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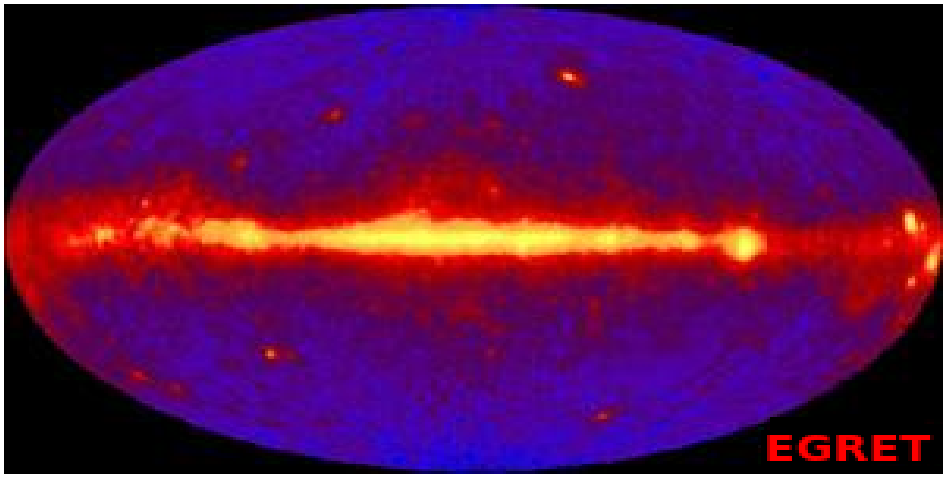
1. THE QUEST FOR WIMPS

the paradigmatic case of gamma rays

100 MeV – 100 GeV



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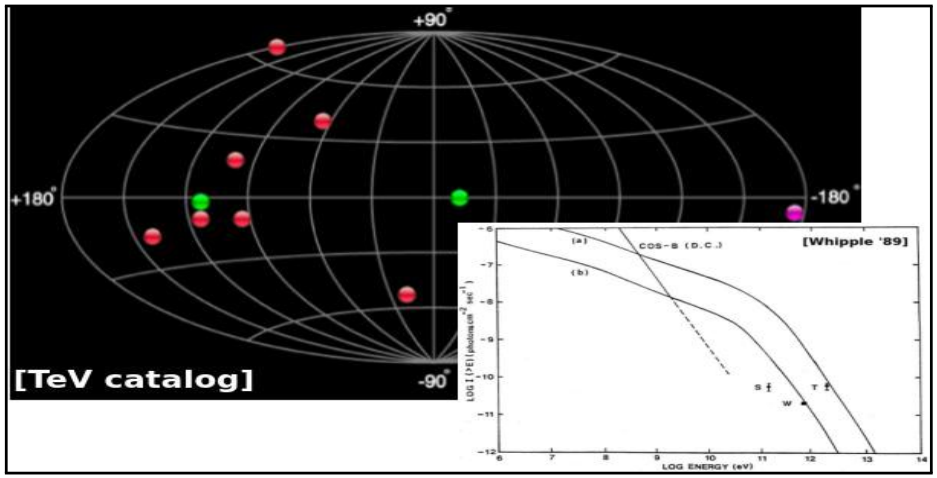

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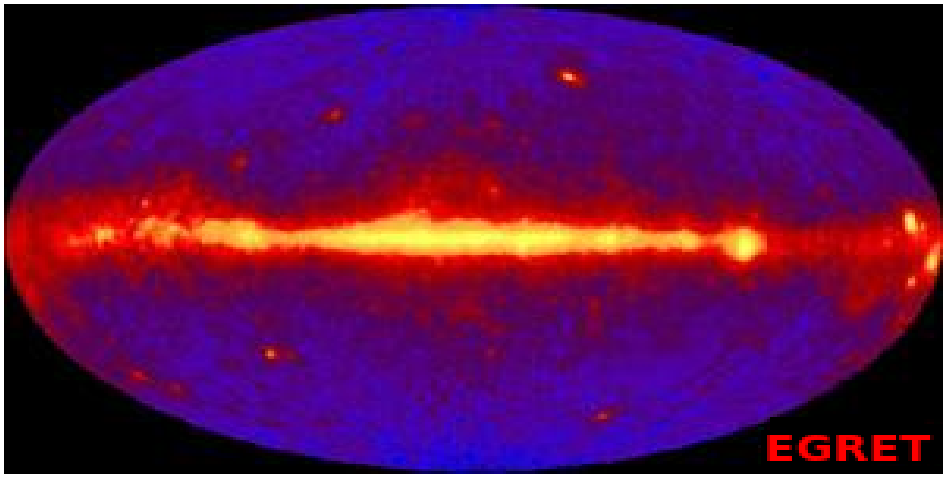

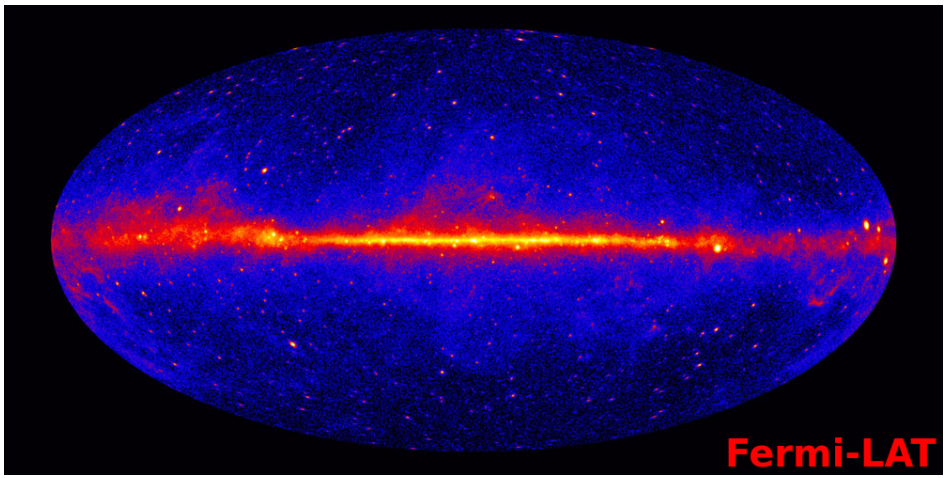

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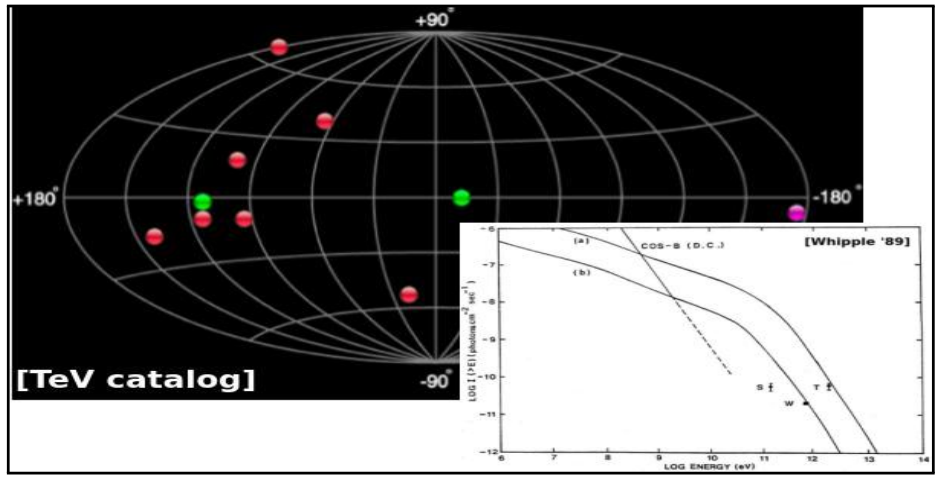
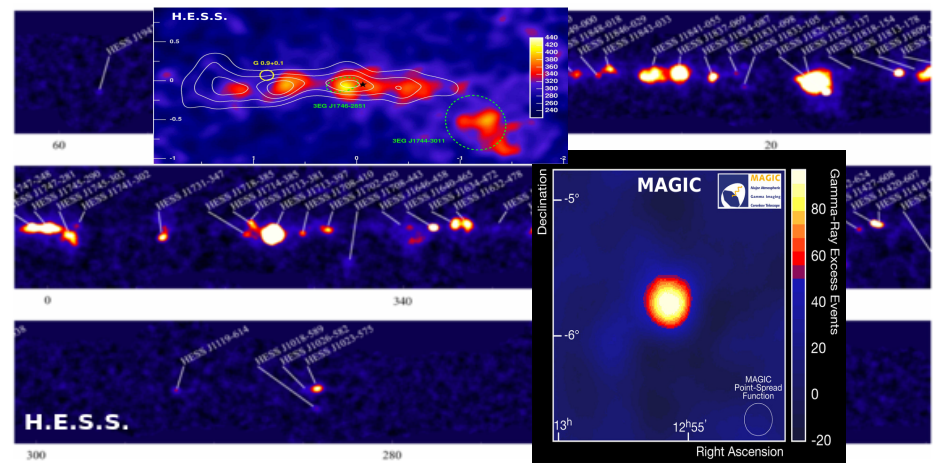




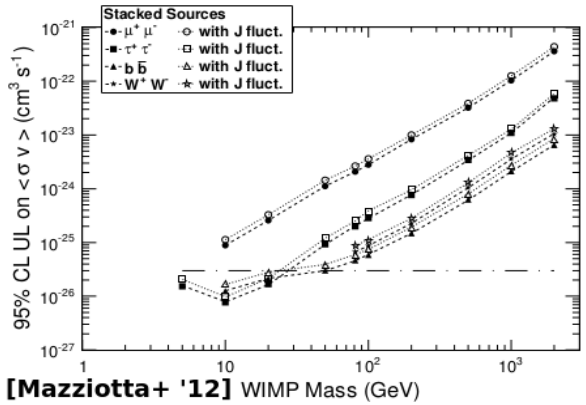
widely-used data but not fully explored yet

need to make the best of the available data

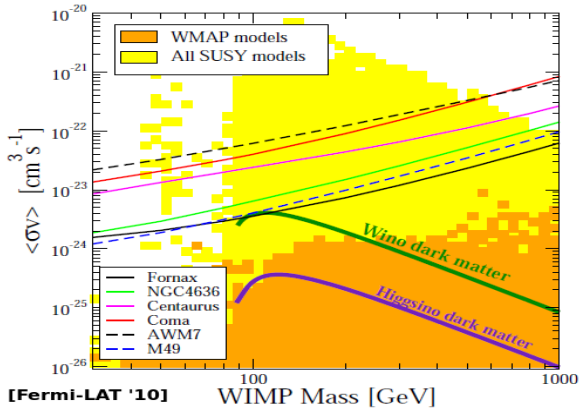
2. INDIRECT SEARCHES VIA GAMMA RAYS

target/constraint misc

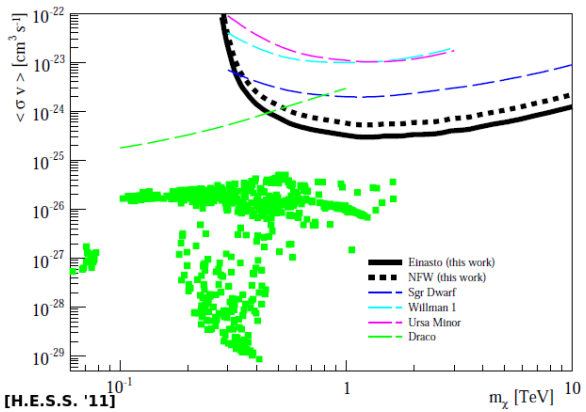
dwarfs



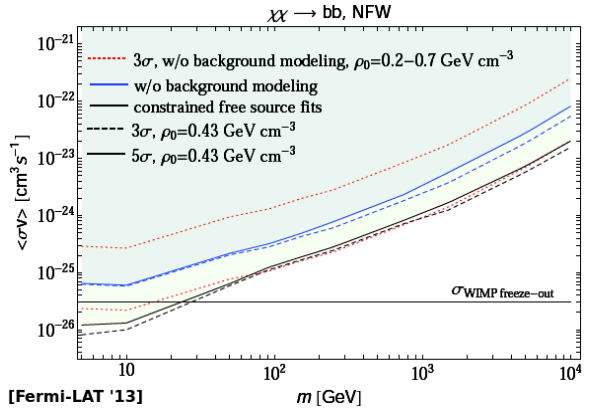
galaxy clusters



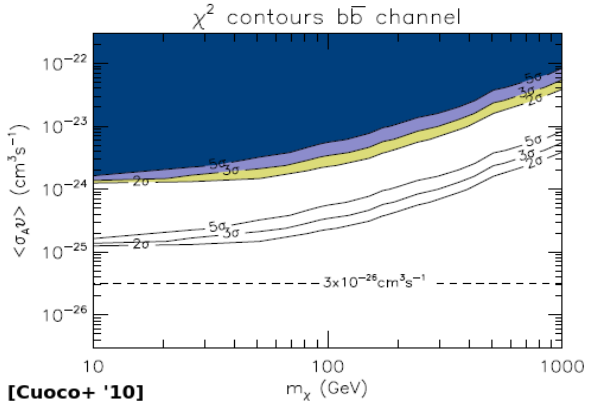
galactic centre



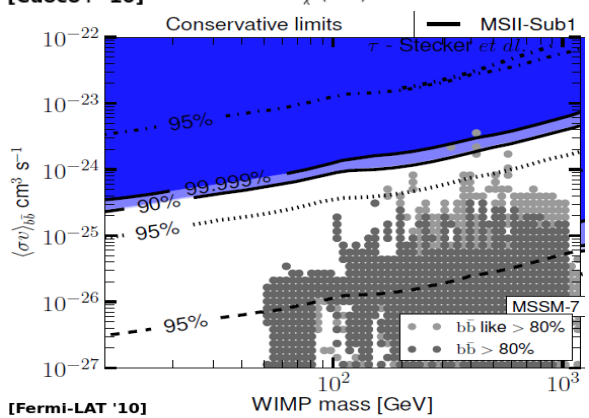
diffuse



anisotropies



extragalactic



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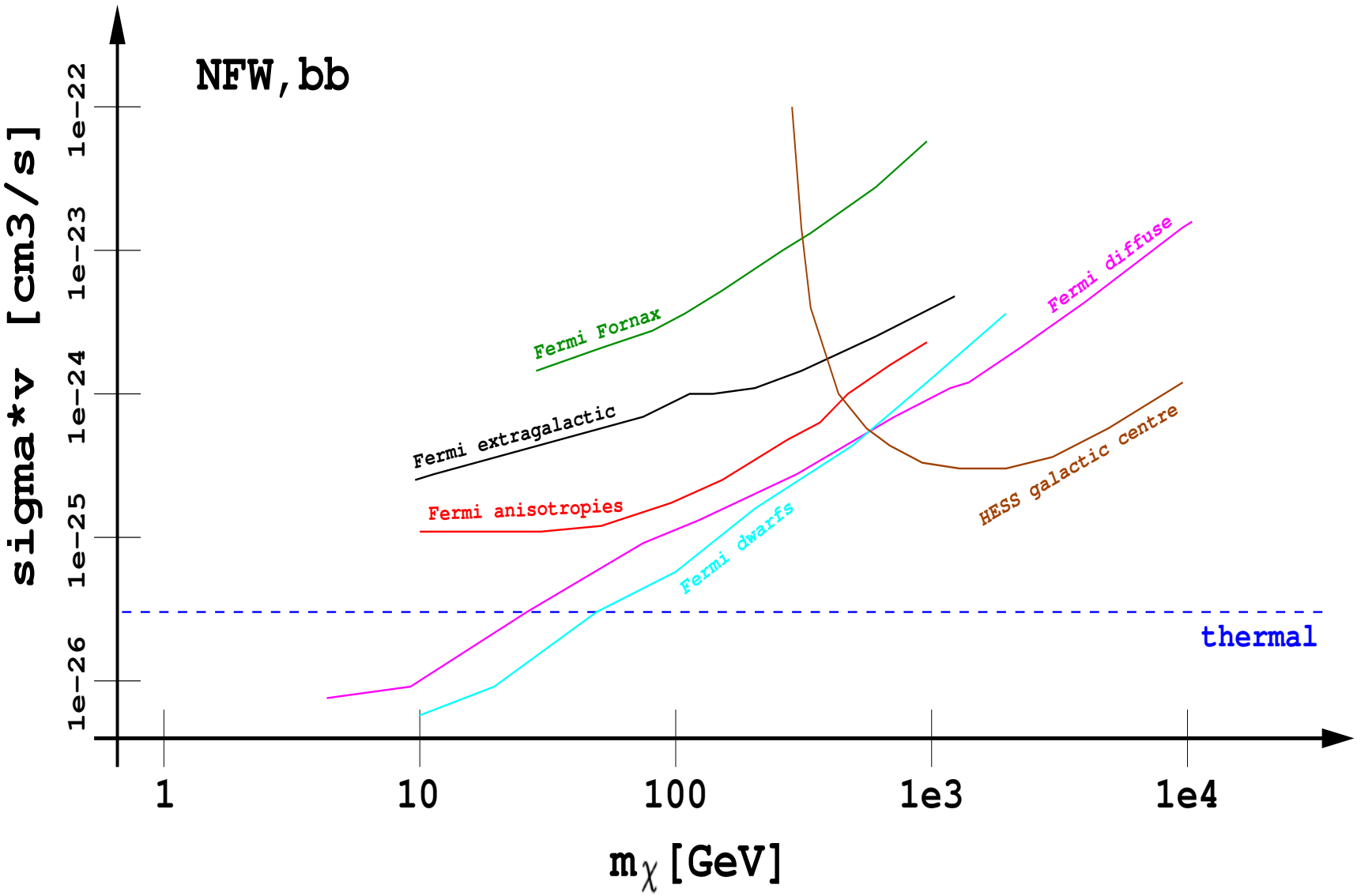

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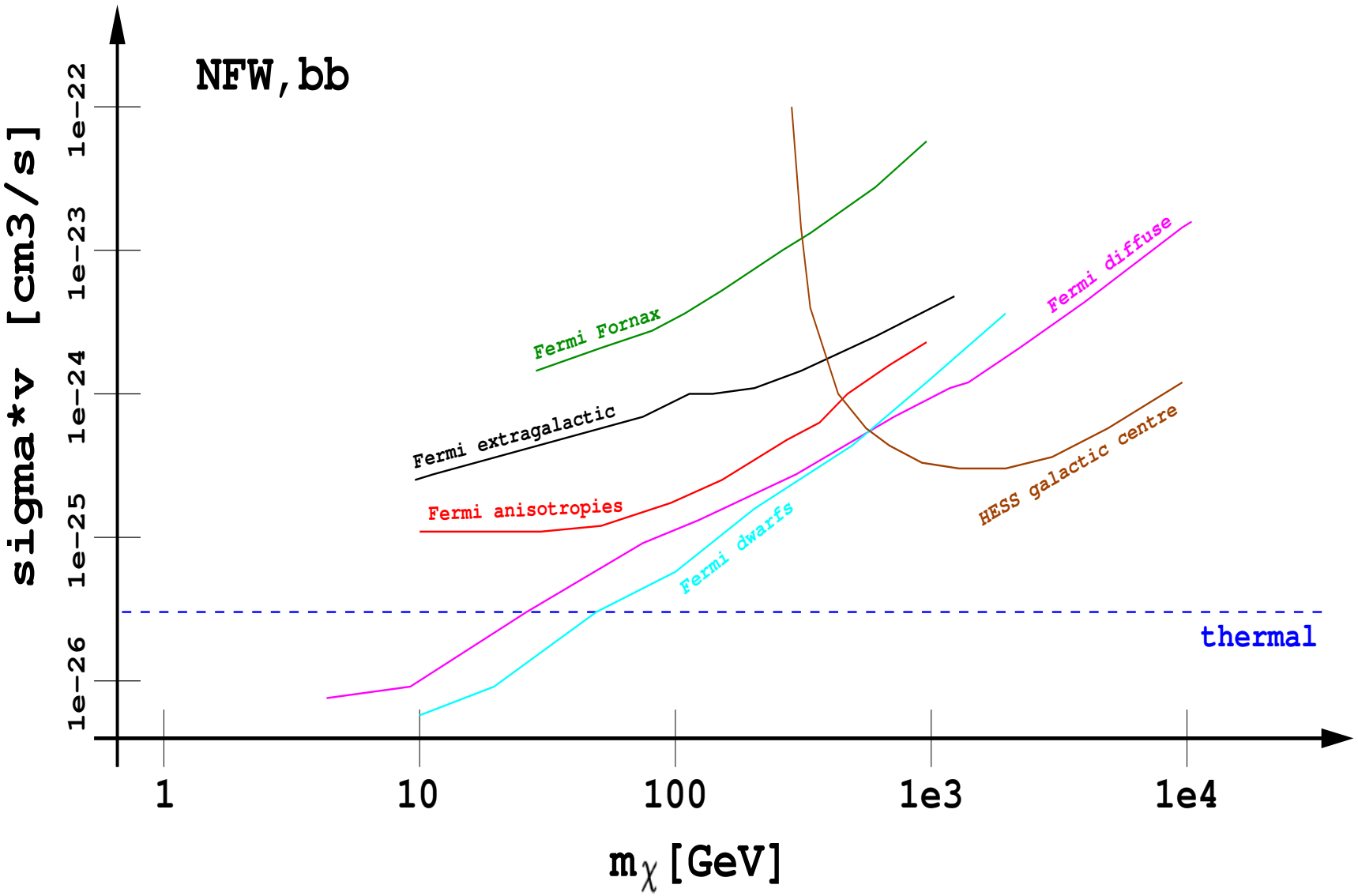

... but these are all for integrated fluxes

2. INDIRECT SEARCHES VIA GAMMA RAYS

$$\phi_\gamma = \frac{1}{4\pi\eta m_\chi^2} \sum_f \langle\sigma v\rangle_f \frac{dN_\gamma^f}{dE_\gamma} \frac{1}{\Delta\Omega} \int_{\Delta\Omega} d\Omega\, J_{\rm ann}$$

for sources in the open window, we can pinpoint injection spectrum

$\downarrow$

look for spectral features

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astrophysical backgrounds at high energies

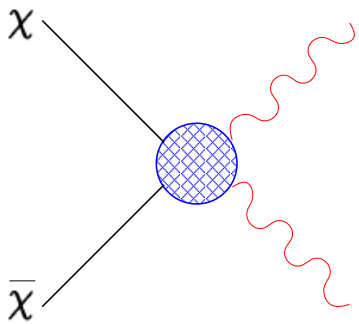
inverse Compton	$\propto E_\gamma^{-(p+1)/2}$	(caveat: monoen e in KN)
synchrotron	$\propto E_\gamma^{-(p+1)/2}$	
bremsstrahlung	$\propto E_\gamma^{-p}$	
pion decay	$\propto E_\gamma^{-p}$	$p \gtrsim 2$

anything harder than E_γ^{-2} and at high energies will stick out
and can be cleanly looked for

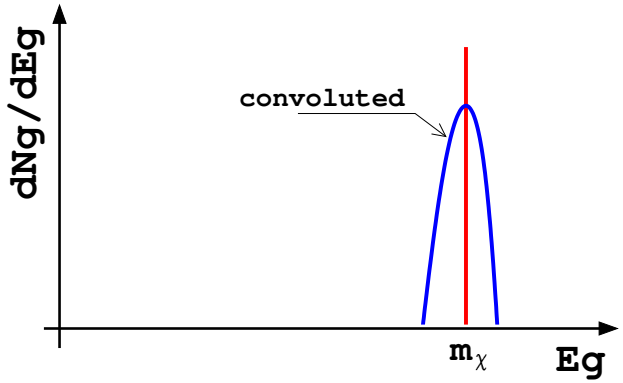
2. GAMMA-RAY SPECTRAL FEATURES

1 lines

[Srednicki+ '86, Rudaz+ '86, Bergström & Snellman '88]



$$\frac{dN_\gamma}{dE_\gamma} \propto \delta(E_\gamma - m_\chi)$$



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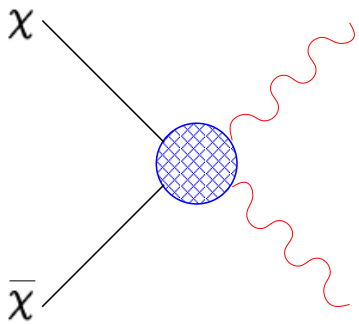

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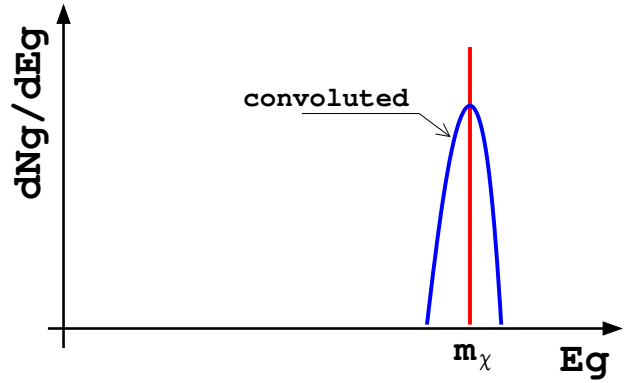
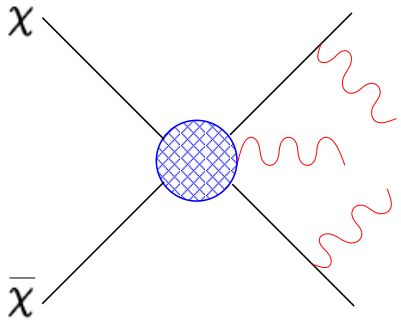


2 internal bremsstrahlung

[Bergström '89, Flores+ '89, Bringmann+ '07]



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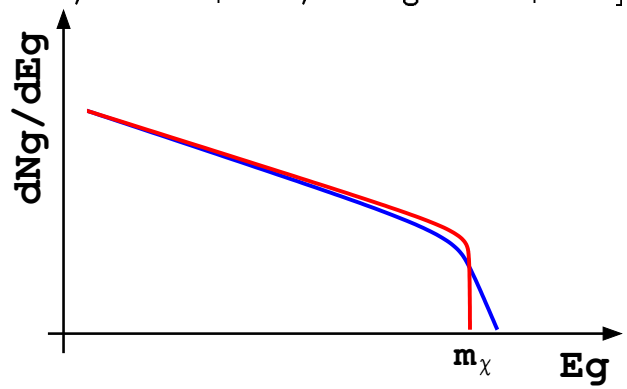
"hard" in astroph



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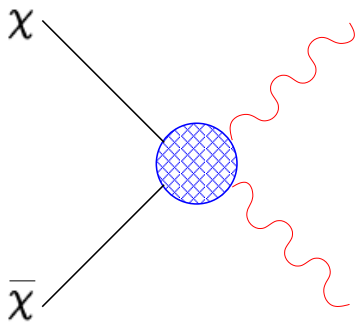

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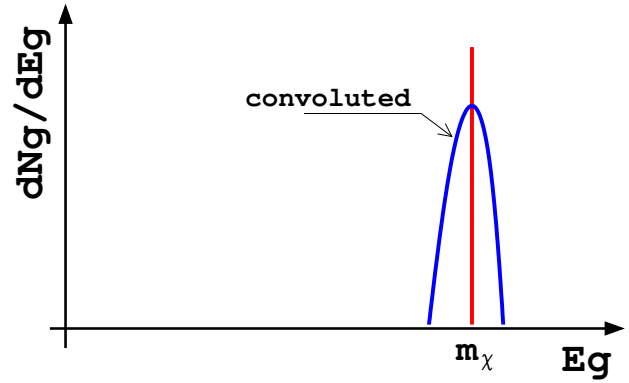

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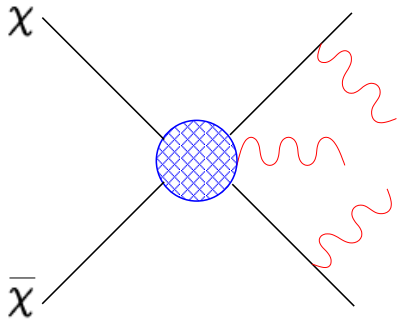

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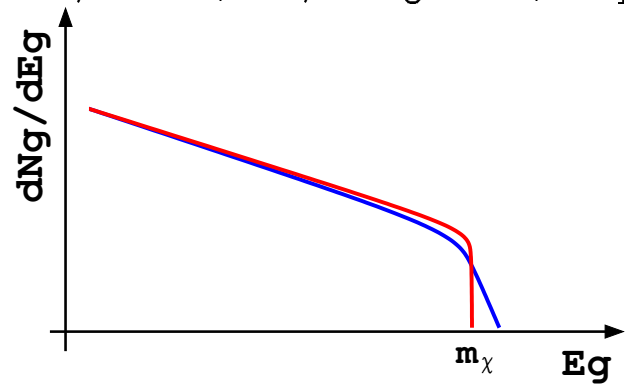

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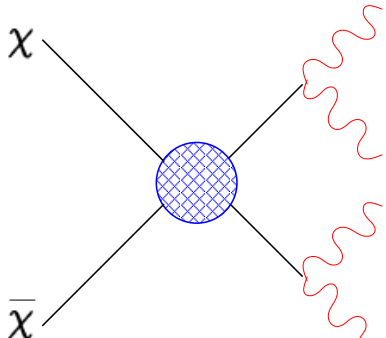

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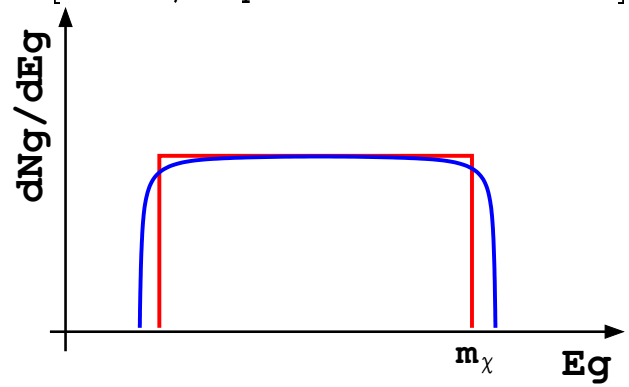

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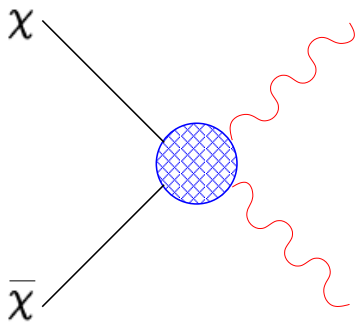

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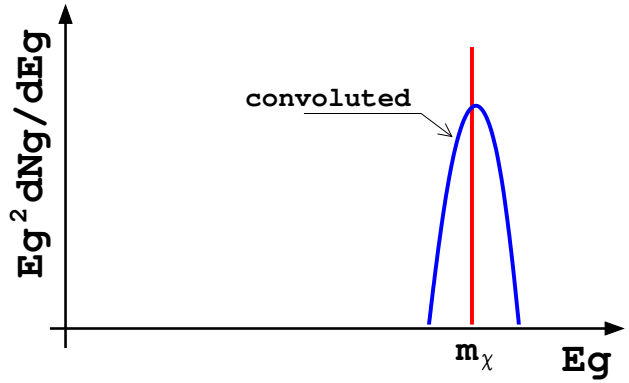

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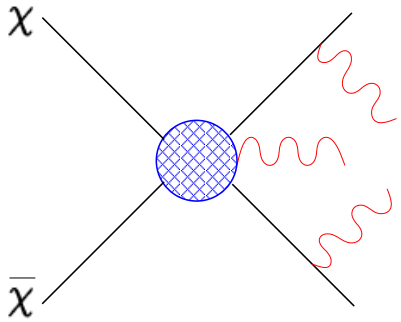

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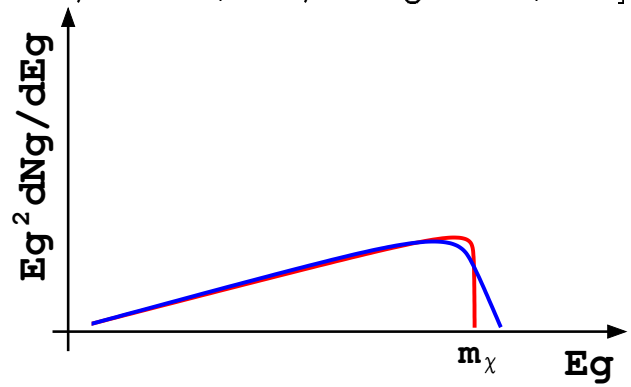

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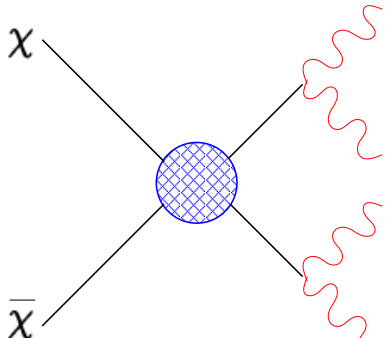

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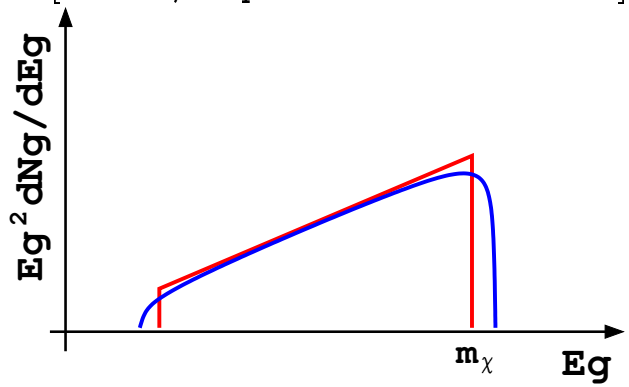

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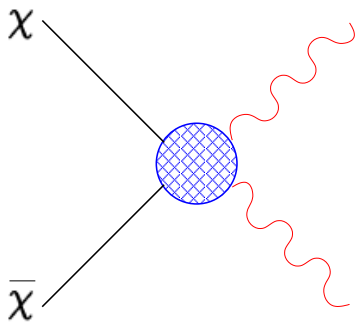

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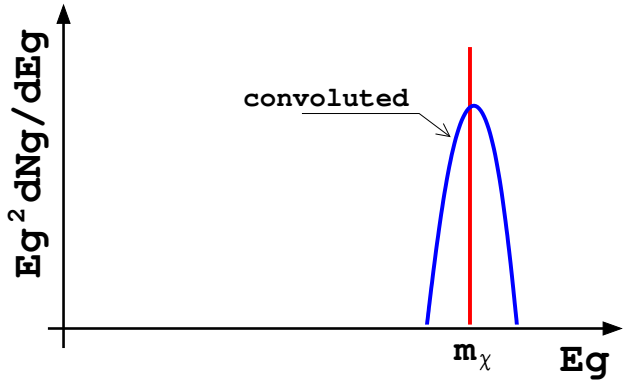

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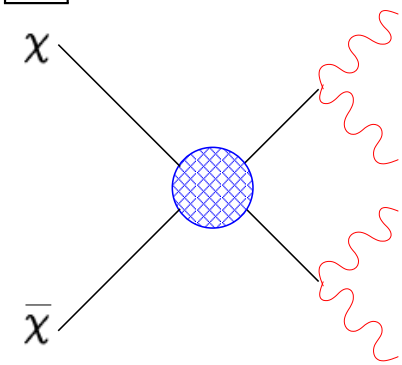

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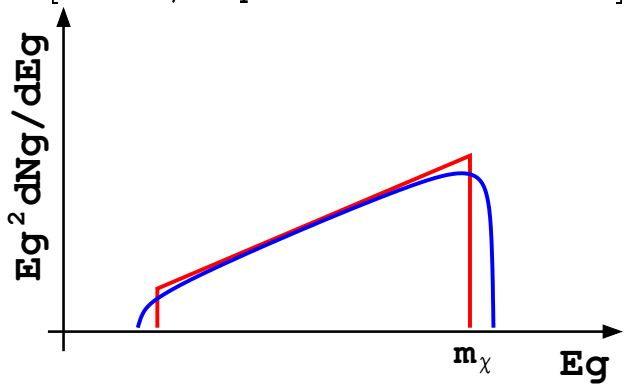

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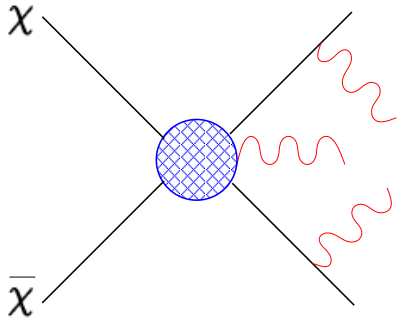

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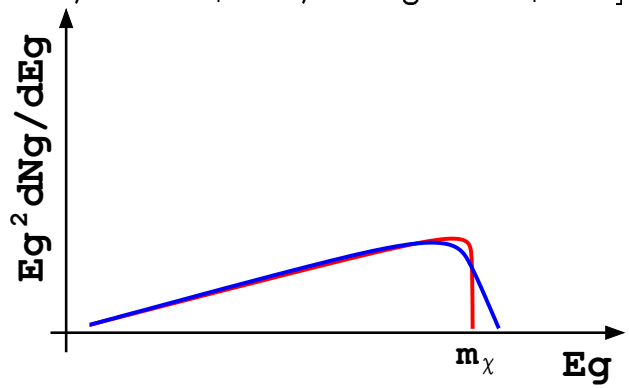

hardness

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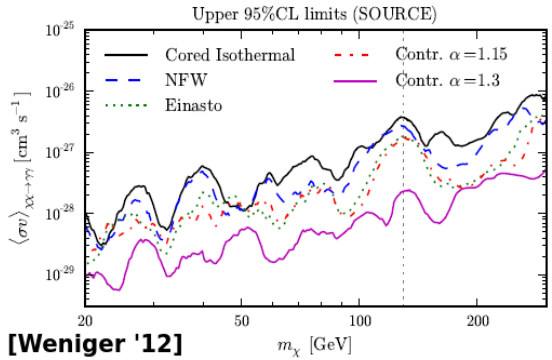

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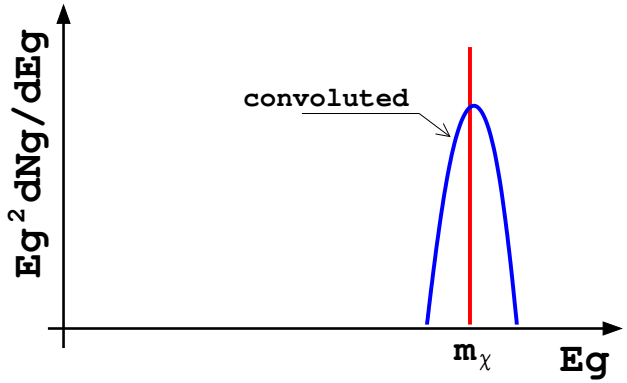

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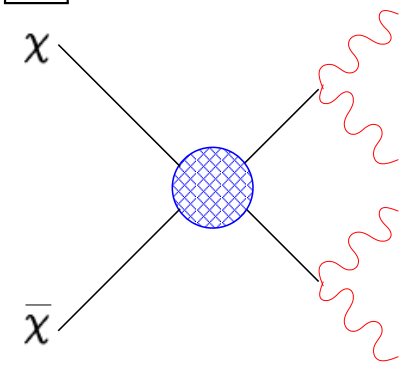

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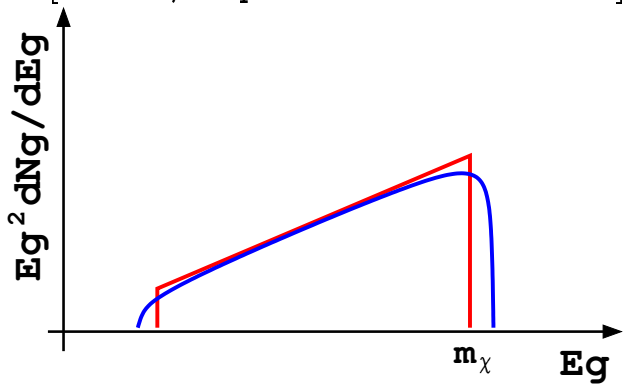

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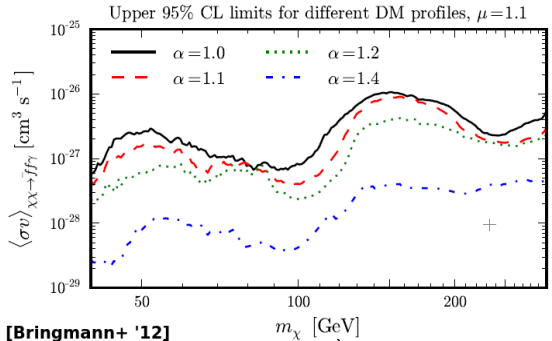

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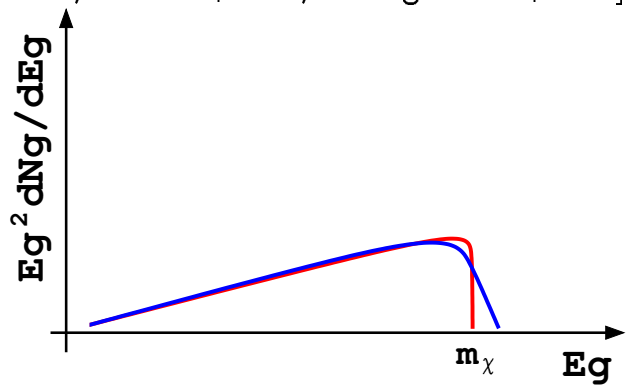

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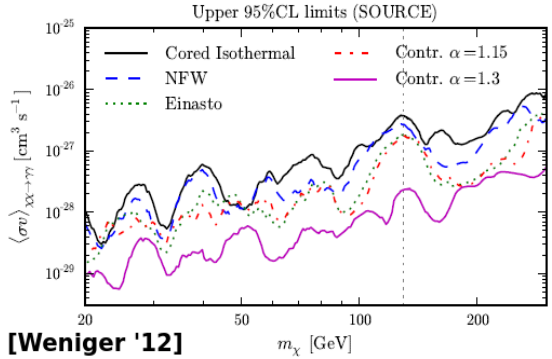

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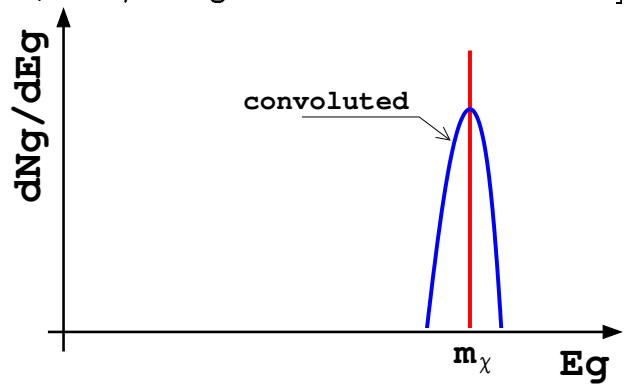
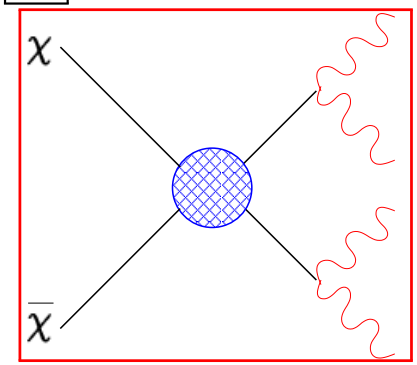


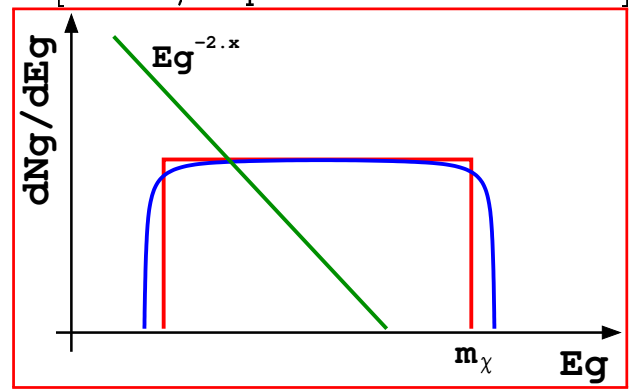
2 boxes



hard and up to HE

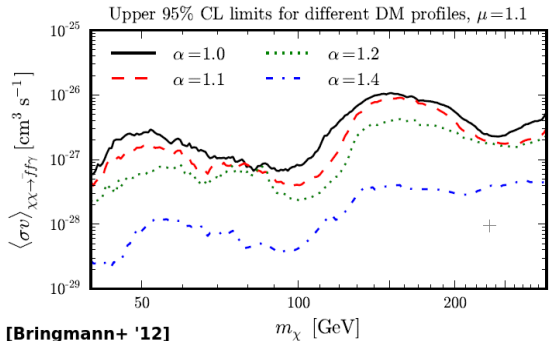
$$\frac{dN_\gamma}{dE_\gamma} \propto \text{const}$$

[Ibarra, López Gehler & MP '12]



3 internal bremsstrahlung

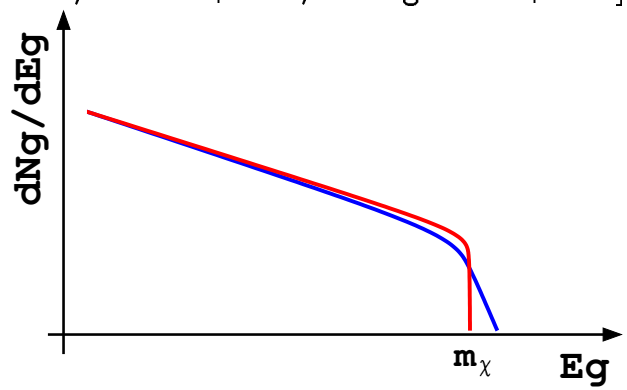
[Bergström '89, Flores+ '89, Bringmann+ '07]



[Bringmann+ '12]

$$\frac{dN_\gamma}{dE_\gamma} \propto E_\gamma^{-1}$$

"hard" in astroph

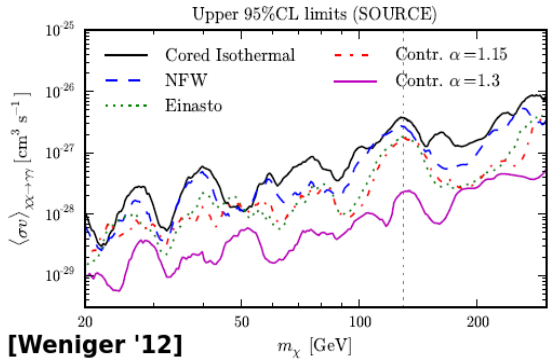


hardness

2. GAMMA-RAY SPECTRAL FEATURES

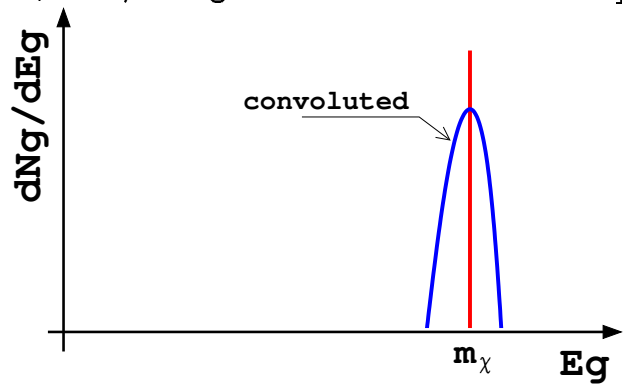
1 lines

[Srednicki+ '86, Rudaz+ '86, Bergström & Snellman '88]



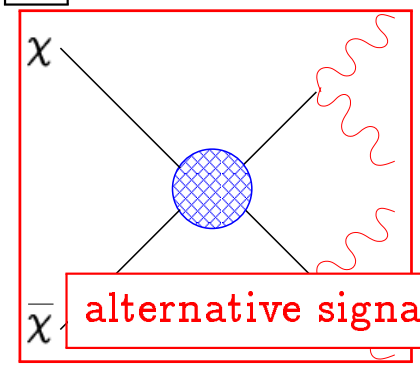
[Weniger '12]

$$\frac{dN_\gamma}{dE_\gamma} \propto \delta(E_\gamma - m_\chi)$$



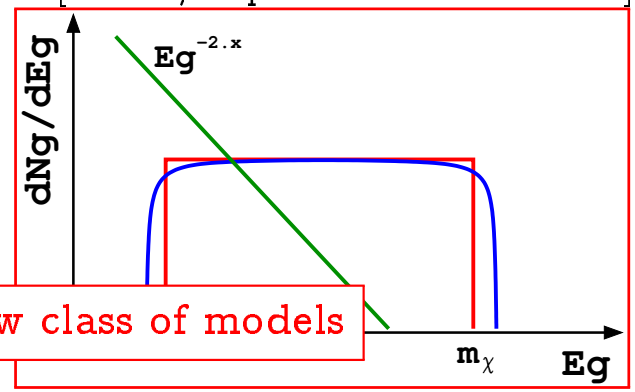
2 boxes

[Ibarra, López Gehler & MP '12]



hard and up to HE

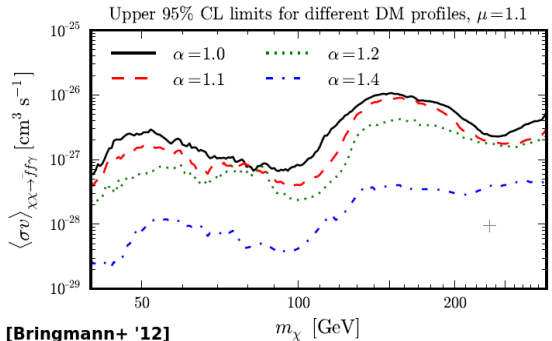
$$\frac{dN_\gamma}{dE_\gamma} \propto \text{const}$$



alternative signature with implications for a new class of models

3 internal bremsstrahlung

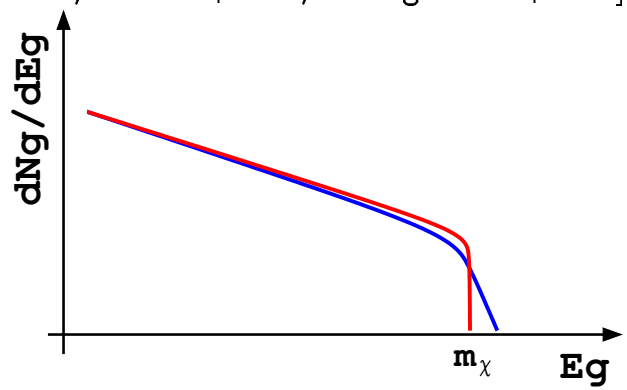
[Bergström '89, Flores+ '89, Bringmann+ '07]



[Bringmann+ '12]

$$\frac{dN_\gamma}{dE_\gamma} \propto E_\gamma^{-1}$$

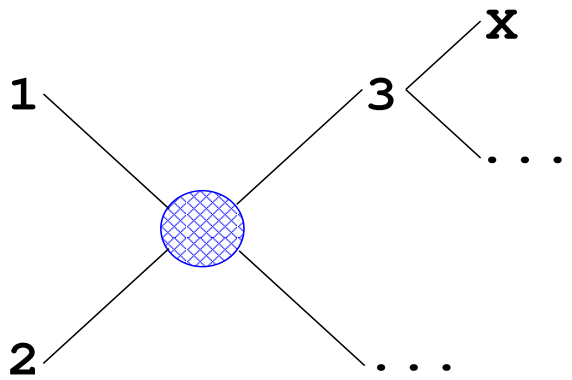
"hard" in astroph



hardness

2. BOX PHENOMENOLOGY

1-step cascades

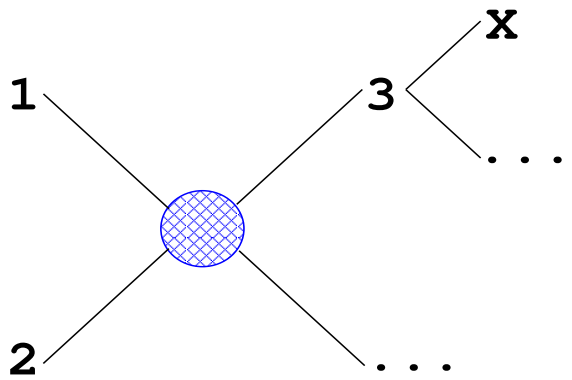


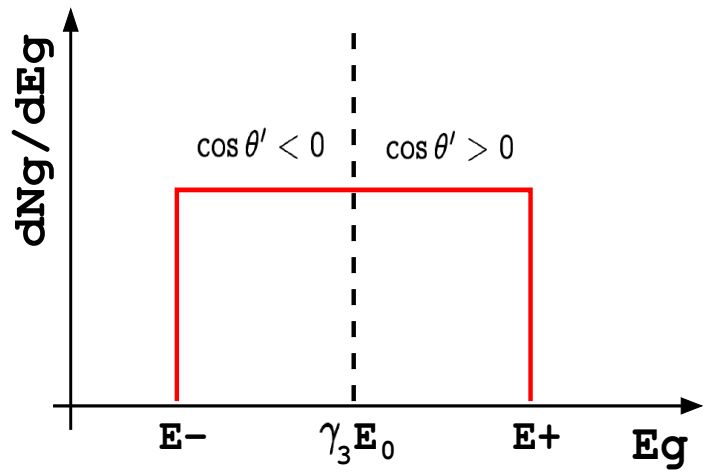
$$E_X = \gamma_3 (E'_X + \beta_3 p'_X \cos\theta') \qquad \text{(isotropic emission)}$$

$$\frac{dN_X}{dE_X} = \int dE_3 \, \frac{dN_3}{dE_3} \int_{-1}^{1} \frac{d\cos\theta'}{2} \int dE'_X \, \frac{dN_X}{dE'_X} \, \delta(E_X - \gamma_3 (E'_X + \beta_3 p'_X \cos\theta'))$$

2. BOX PHENOMENOLOGY

1-step cascades





$$E_X = \gamma_3 (E'_X + \beta_3 p'_X \cos\theta')$$

(isotropic emission)

$$\frac{dN_X}{dE_X} = \int dE_3 \, \frac{dN_3}{dE_3} \int_{-1}^{1} \frac{d\cos\theta'}{2} \int dE'_X \, \frac{dN_X}{dE'_X} \, \delta(E_X - \gamma_3 (E'_X + \beta_3 p'_X \cos\theta'))$$

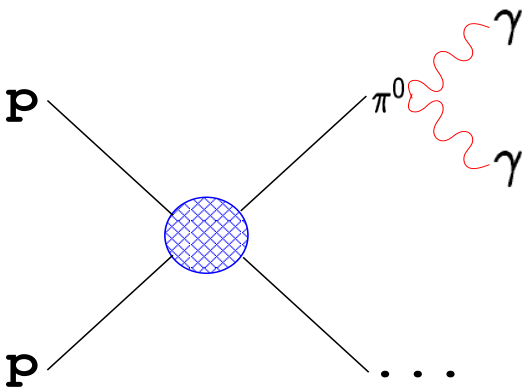
$$= \frac{AB}{2\beta_3 \gamma_3 E_0} \mathcal{F}_{box}[E_0 \gamma_3 (1-\beta_3), E_0 \gamma_3 (1+\beta_3)]$$

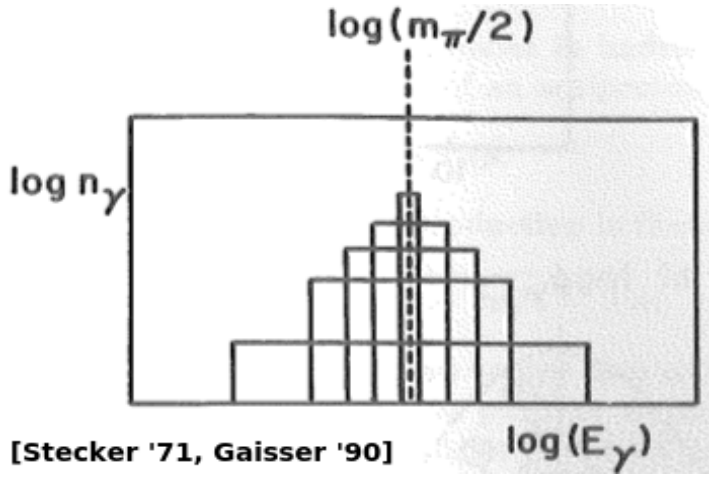
$$dN_3/dE_3 = A\delta(E_3 - E_3^*)$$

$$dN_X/dE'_X = B\delta(E'_X - E_0)$$

2. BOX PHENOMENOLOGY

boxes are realised in nature!





$$E_\gamma = E'_\gamma \gamma_\pi (1 + \beta_\pi \cos\theta')$$

$$\frac{dN_\gamma}{dE_\gamma} = \int dE_\pi \, \frac{dN_\pi}{dE_\pi} \, \frac{2}{2\beta_\pi \gamma_\pi m_\pi/2} \mathcal{F}_{box}[m_\pi \gamma_\pi (1-\beta_\pi)/2, m_\pi \gamma_\pi (1+\beta_\pi)/2]$$

$$\propto \begin{cases} E_\gamma^p & \text{if } E_\gamma \ll m_\pi/2 \\ E_\gamma^{-p} & \text{if } E_\gamma \gg m_\pi/2 \end{cases}$$

$$dN_\pi/dE_\pi \propto E_\pi^{-p}$$

$$dN_\gamma/dE'_\gamma = 2\delta(E'_\gamma - m_\pi/2)$$

2. BOX PHENOMENOLOGY

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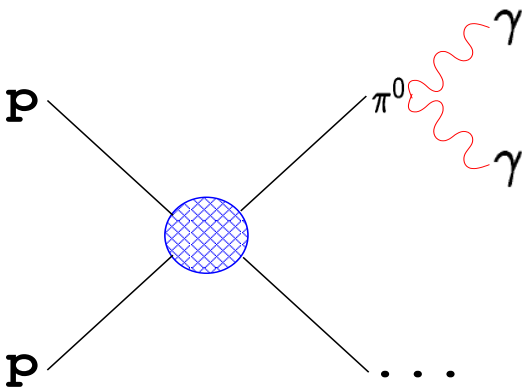

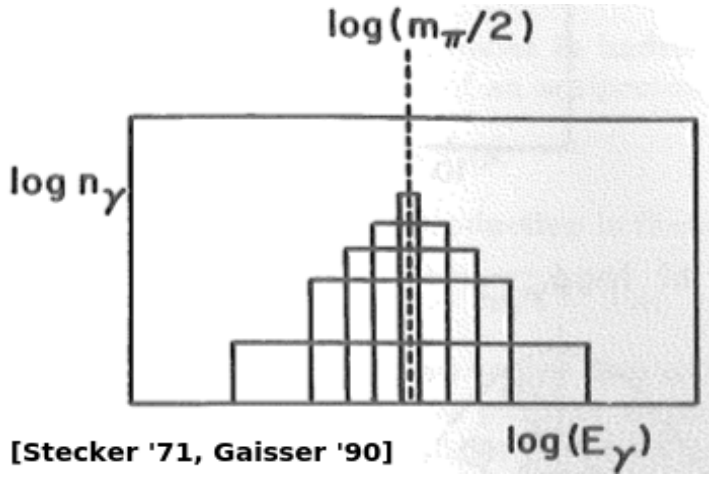

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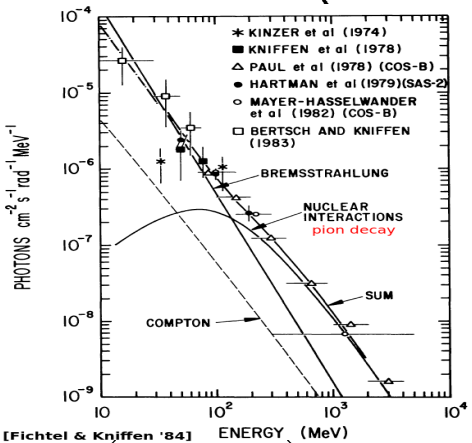
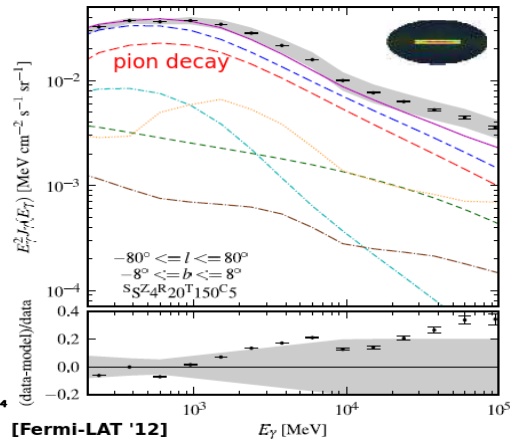
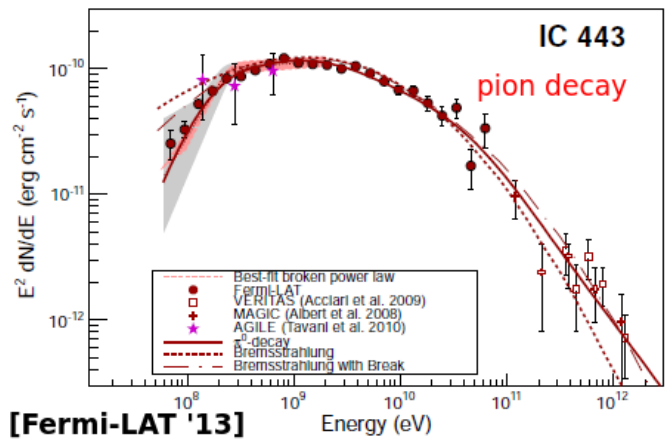
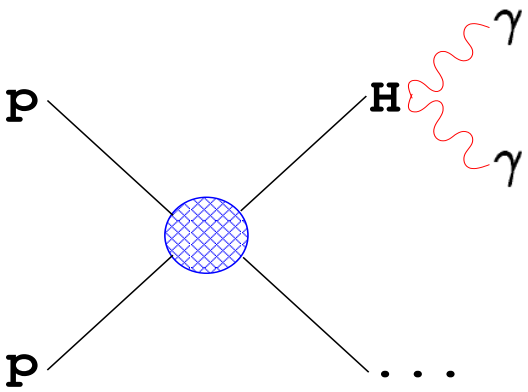


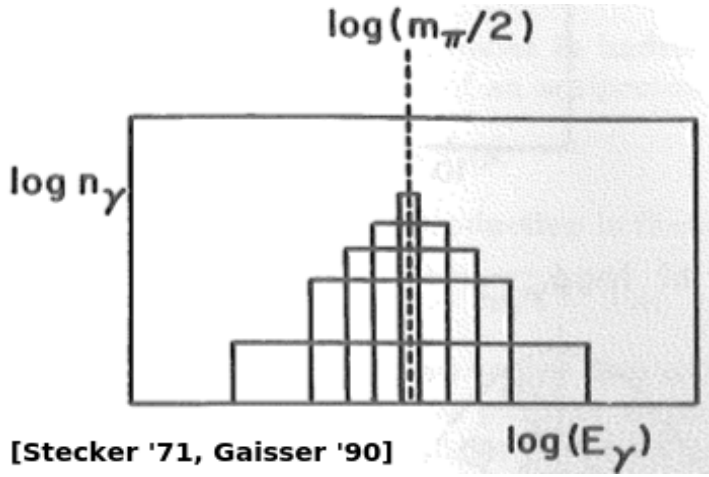




2. BOX PHENOMENOLOGY

boxes are realised in nature!

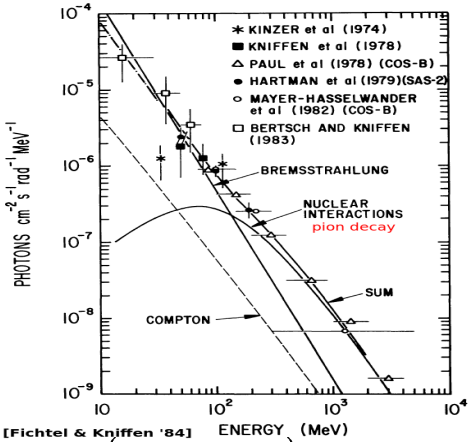


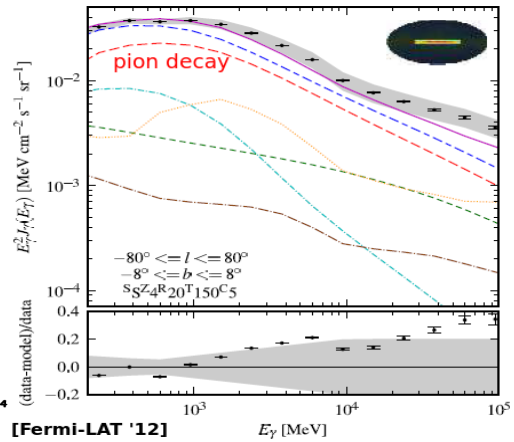


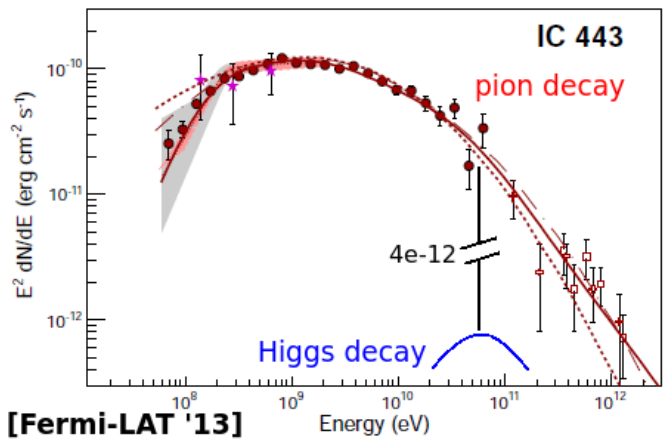
same for Higgs actually, but:

$$\sigma(pp \to H^0 X)/\sigma(pp \to \pi^0 X) \simeq 20\ \text{pb}/100\ \text{mb}$$

$$\text{BR}(H^0 \to \gamma\gamma)/\text{BR}(\pi^0 \to \gamma\gamma) \simeq 2 \times 10^{-3}/1$$

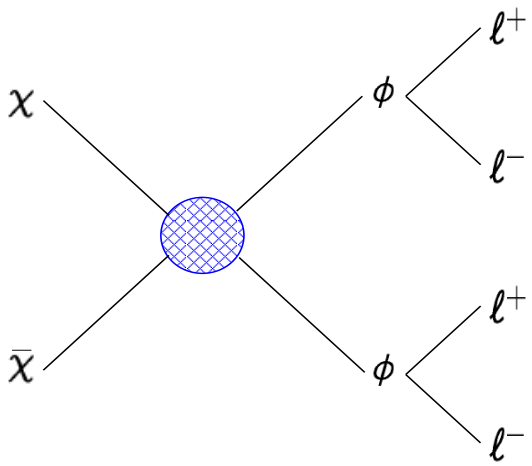




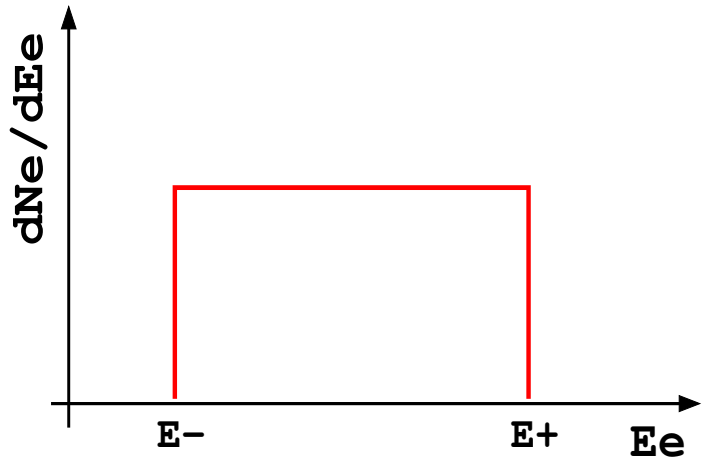


2. BOX PHENOMENOLOGY

wimpy boxes



[Nomura & Thaler '08, Mardon+ '09 x2]



$$E_\ell = \gamma_\phi (E'_\ell + \beta_\phi p'_\ell \cos\theta')$$

$$\frac{dN_\ell}{dE_\ell} = \frac{4}{\Delta E}\mathcal{F}_{box}[E_-, E_+]$$

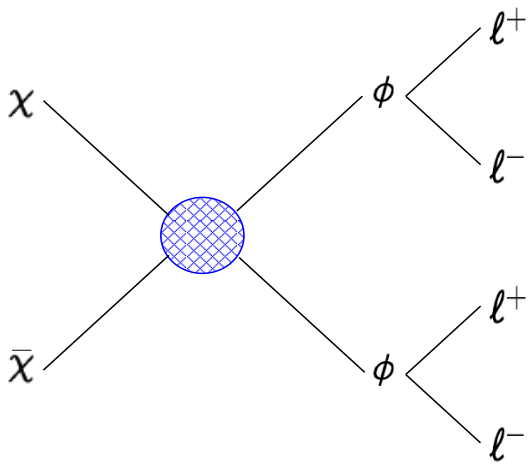
$$E_\pm = m_\chi/2\left(1 \pm \sqrt{1 - m_\phi^2/m_\chi^2}\right) \qquad \Delta E = E_+ - E_-$$

$$dN_\phi/dE_\phi = 2\delta(E_\phi - m_\chi)$$

$$dN_\ell/dE'_\ell = 2\delta(E'_\ell - m_\phi/2)$$

2. BOX PHENOMENOLOGY

wimpy boxes



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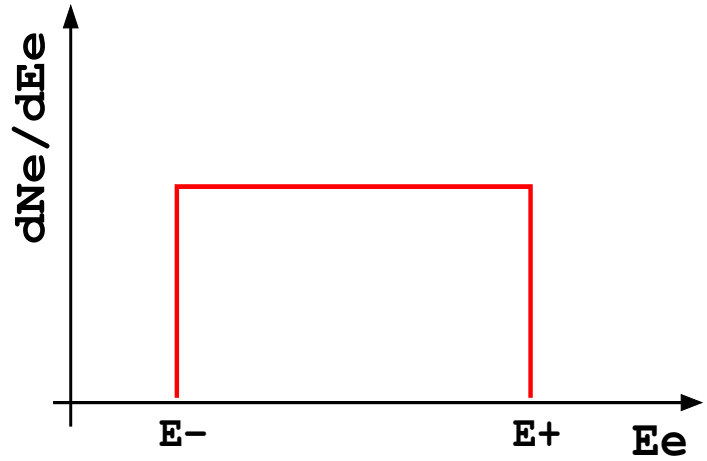

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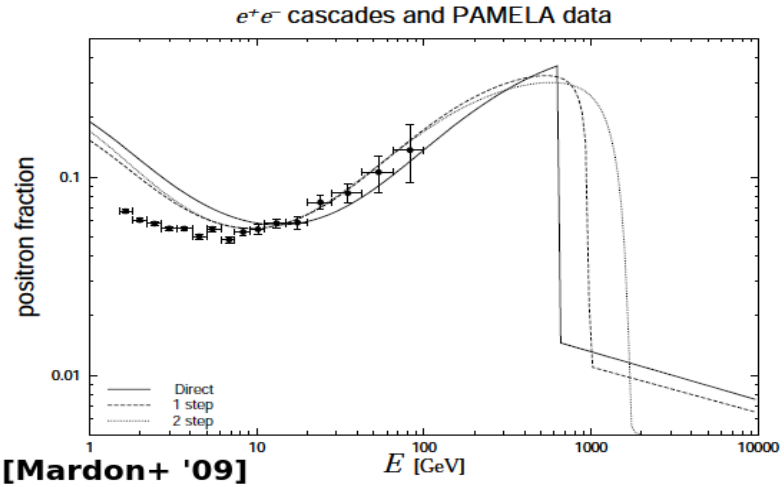
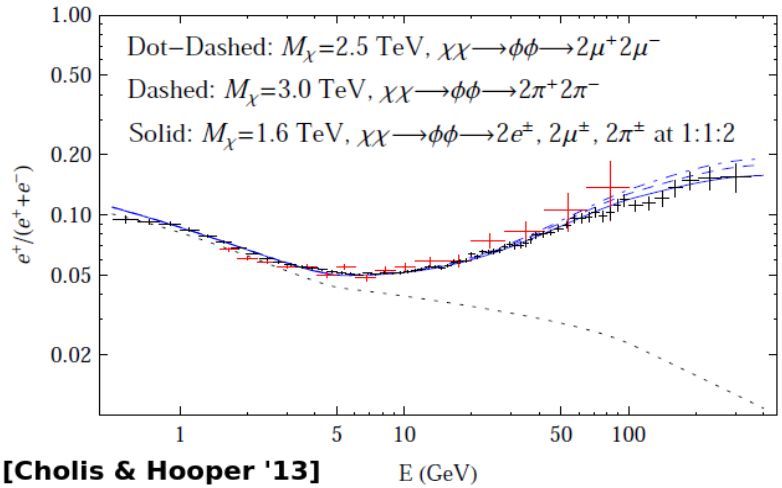


[Mardon+ '09]

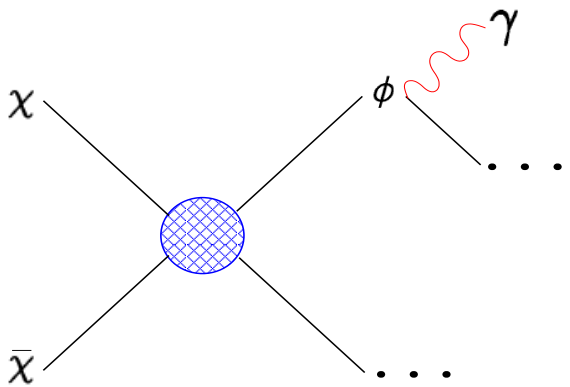


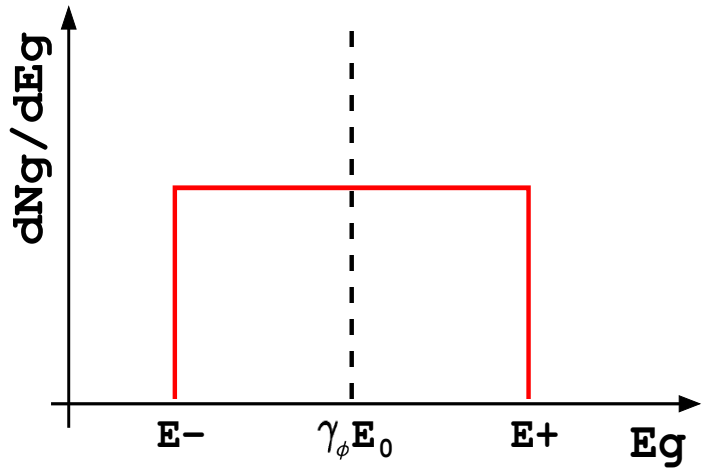
[Cholis & Hooper '13]

2. BOX PHENOMENOLOGY

gamma-ray boxes

[Ibarra, Gehler & MP '12; Ibarra, Lee, Gehler, Park & MP '13]





$$E_\gamma = E'_\gamma \gamma_\phi (1 + \beta_\phi \cos\theta')$$

$$\frac{dN_\gamma}{dE_\gamma} = \frac{AB}{\Delta E} \mathcal{F}_{box}[E_-, E_+]$$

$$E_\pm = E_0 \gamma_\phi (1 \pm \beta_\phi) \qquad \Delta E = E_+ - E_-$$

$$dN_\phi / dE_\phi = A\delta(E_\phi - E^*_\phi)$$
$$dN_\gamma / dE'_\gamma = B\delta(E'_\gamma - E_0)$$

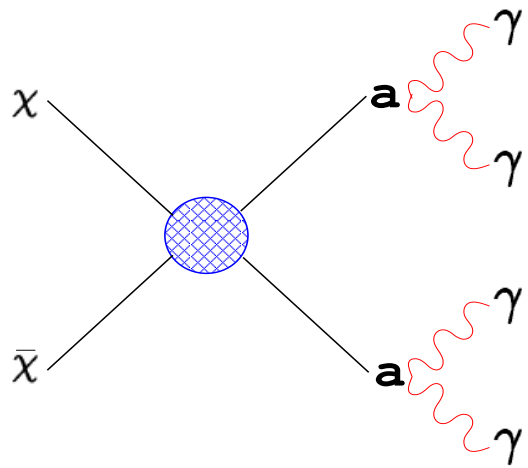
box requirements:

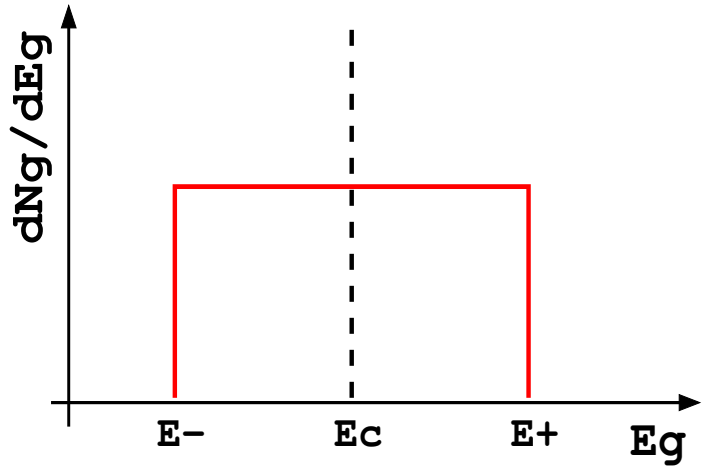
final state γ, monochromatic dN_ϕ/dE_ϕ and dN_γ/dE'_γ

2. BOX PHENOMENOLOGY

gamma-ray boxes

[Ibarra, Gehler & MP '12; Ibarra, Lee, Gehler, Park & MP '13]





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$$dN_a/dE_a = 2\delta(E_a - m_\chi)$$

$$dN_\gamma/dE'_\gamma = 2\delta(E'_\gamma - m_a/2)$$

$$E_\pm = \frac{m_\chi}{2}\left(1 \pm \sqrt{1 - \frac{m_a^2}{m_\chi^2}}\right) \qquad E_c = \frac{m_\chi}{2}$$

2. BOX PHENOMENOLOGY

gamma-ray boxes

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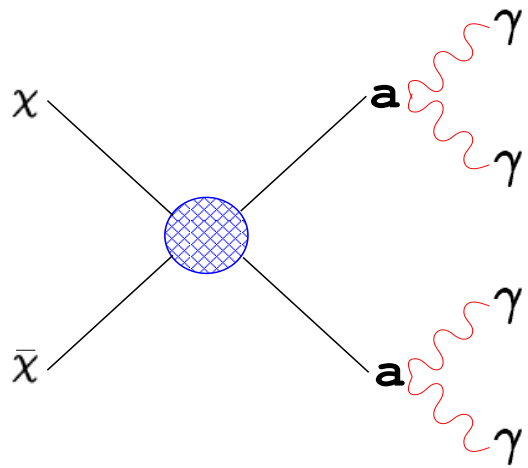

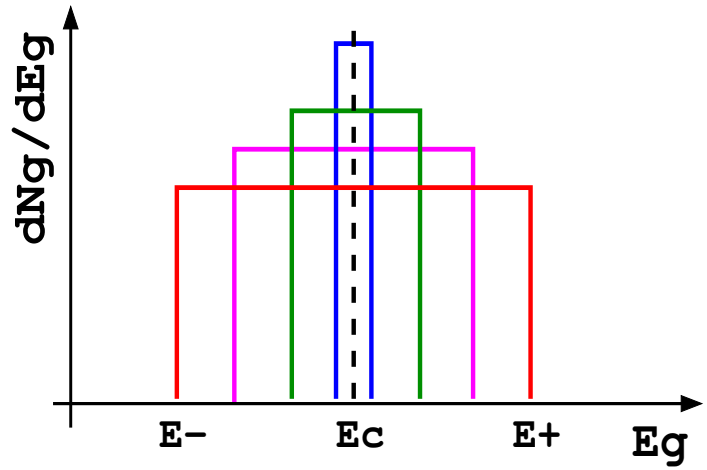

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$$E_\pm = \frac{m_\chi}{2}\left(1 \pm \sqrt{1 - \frac{m_a^2}{m_\chi^2}}\right) \qquad E_c = \frac{m_\chi}{2}$$

.. as $m_a \to m_\chi$: $\beta_a \sim 0$, $E_+ \sim E_-$, $\Delta E \sim 0$ line at $m_\chi/2$

.. as $m_a \to 0$: $\beta_a \sim 1$, $E_+ \sim m_\chi$, $E_- \sim 0$ box ending at m_χ

3. METHODOLOGY

fluxes at the Earth

[Ibarra, Gehler & MP '12; Ibarra, Lee, Gehler, Park & MP '13]

$$\tilde{\phi}_\gamma(E_\gamma) \equiv \frac{d^4 N_\gamma}{dE_\gamma\, dS d\Omega\, dt} = \frac{\langle \sigma v \rangle}{4\pi \eta m_{DM}^2} \frac{dN_\gamma}{dE_\gamma} \frac{1}{\Delta\Omega} \int_{\Delta\Omega} d\Omega\, J_{ann}$$

$\eta = 2\,(4)$ for Majorana (Dirac)

$$J_{ann} = \int_{l.o.s.} ds\, \rho_{DM}^2$$

3. METHODOLOGY

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Einasto profile with $\rho_0 = 0.4$ GeV/cm^3

3. METHODOLOGY

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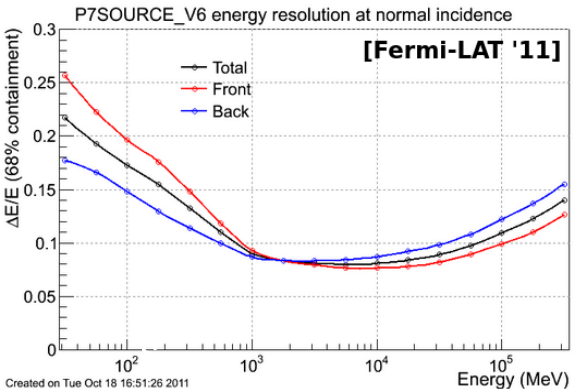
Einasto profile with $\rho_0 = 0.4$ GeV/cm^3



$$\phi_\gamma(E_\gamma) = \int dE'_\gamma\; \tilde{\phi}_\gamma(E'_\gamma) \frac{1}{\sqrt{2\pi}\sigma(E'_\gamma)} \exp\left(-\frac{(E'_\gamma - E_\gamma)^2}{2\sigma^2(E'_\gamma)}\right)$$

3. METHODOLOGY

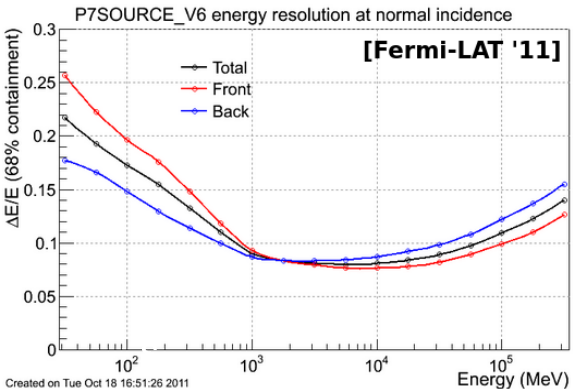
fluxes at the Earth

[Ibarra, Gehler & MP '12; Ibarra, Lee, Gehler, Park & MP '13]

$$\tilde{\phi}_\gamma(E_\gamma) \equiv \frac{d^4 N_\gamma}{dE_\gamma\, dS d\Omega\, dt} = \frac{\langle \sigma v \rangle}{4\pi \eta m_{DM}^2} \frac{dN_\gamma}{dE_\gamma} \frac{1}{\Delta\Omega} \int_{\Delta\Omega} d\Omega\, J_{ann}$$

$\eta = 2\,(4)$ for Majorana (Dirac) $\qquad J_{ann} = \int_{l.o.s.} ds\, \rho_{DM}^2$

Einasto profile with $\rho_0 = 0.4$ GeV/cm^3



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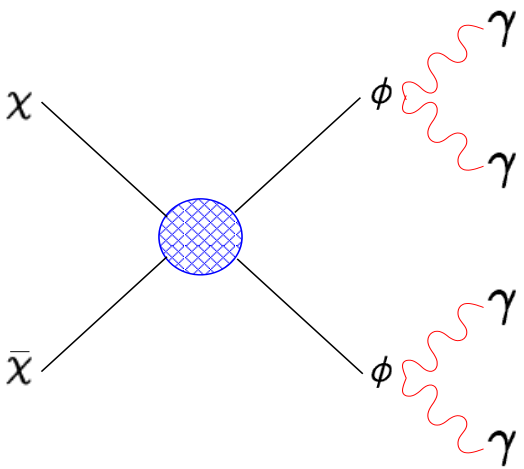
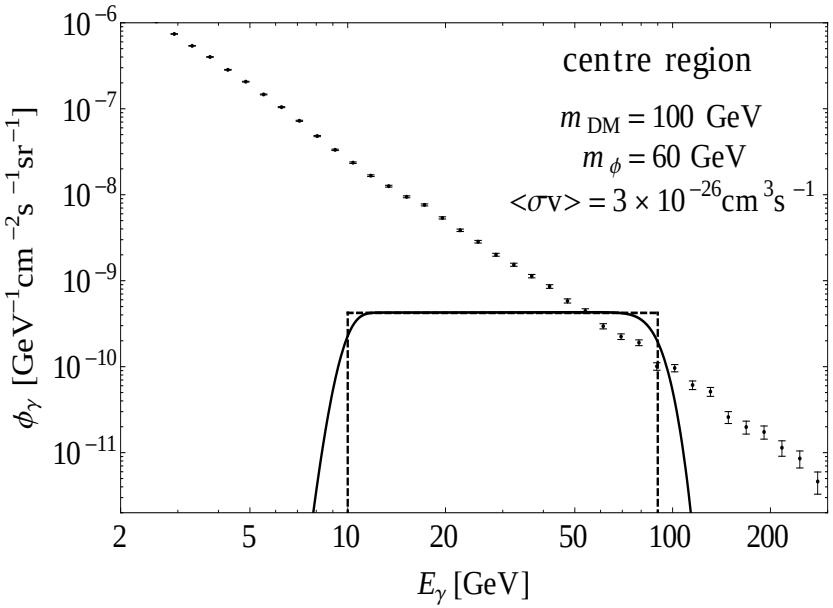
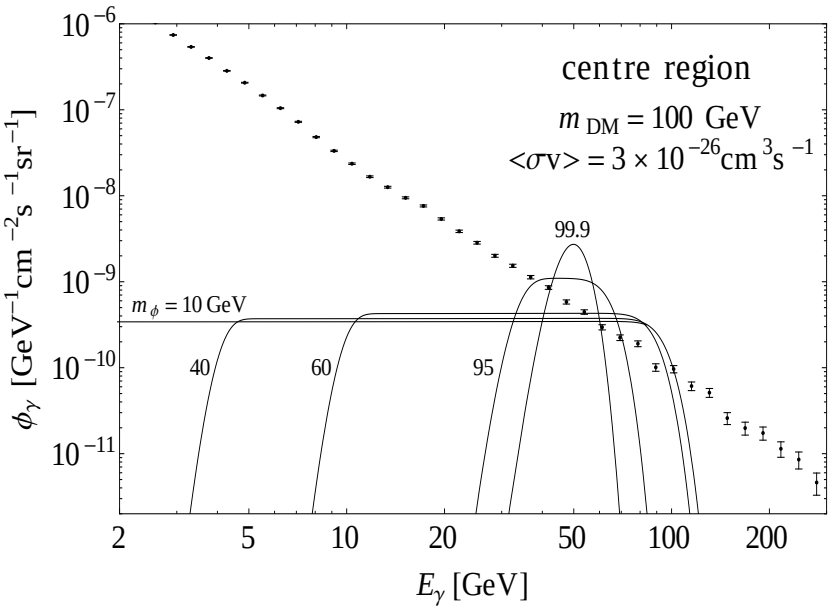




3. METHODOLOGY

[Ibarra, Gehler & MP '12; Ibarra, Lee, Gehler, Park & MP '13]



narrow box

$m_\phi \simeq m_\chi$: moderate fine-tuning

line at $m_\chi/2$ with 4γ

(usual line is at m_χ with 2γ)

wide box

$m_\phi \ll m_\chi$: no fine-tuning at all

high-energy shoulder at m_χ

amplitude saturation as $m_\phi \to 0$

.. narrow box is harder, but wide box extends to higher energies
$\to$ similar constraints (!)

.. sub-thermal constraints in both cases (!)

3. METHODOLOGY

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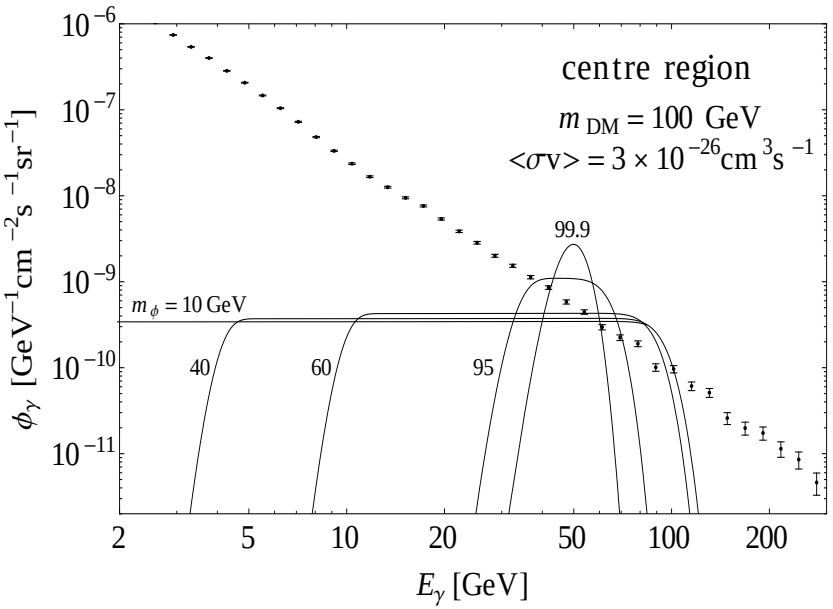

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derivation of constraints

(i) conservative: no background, $\phi_{\gamma,b} = 0$

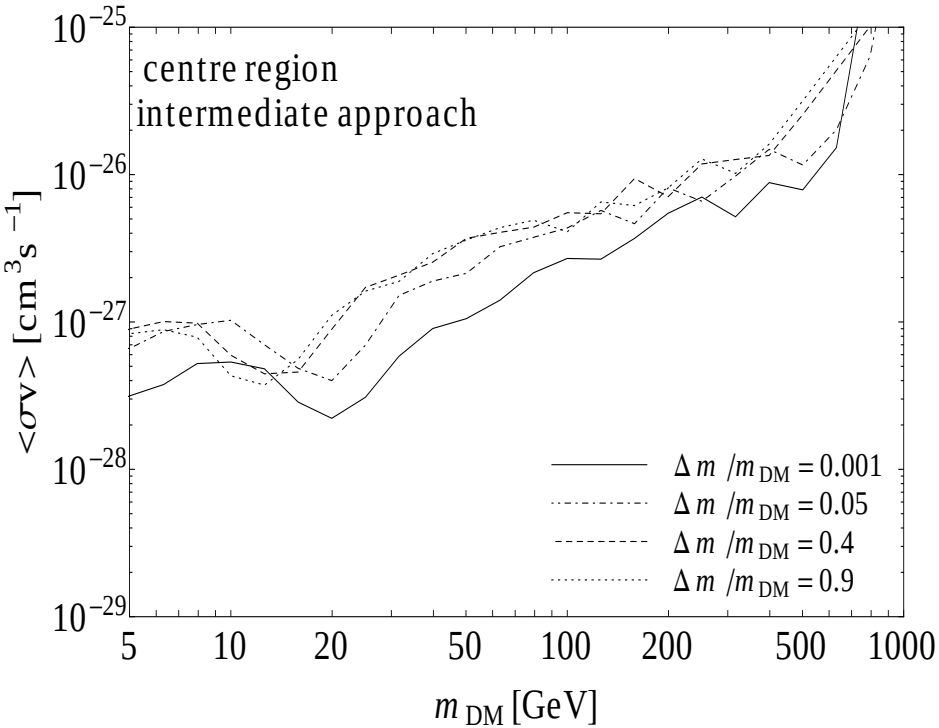
(ii) intermediate: scaled-down background fit $\phi_{\gamma,b} \propto E_\gamma^{-\nu}$

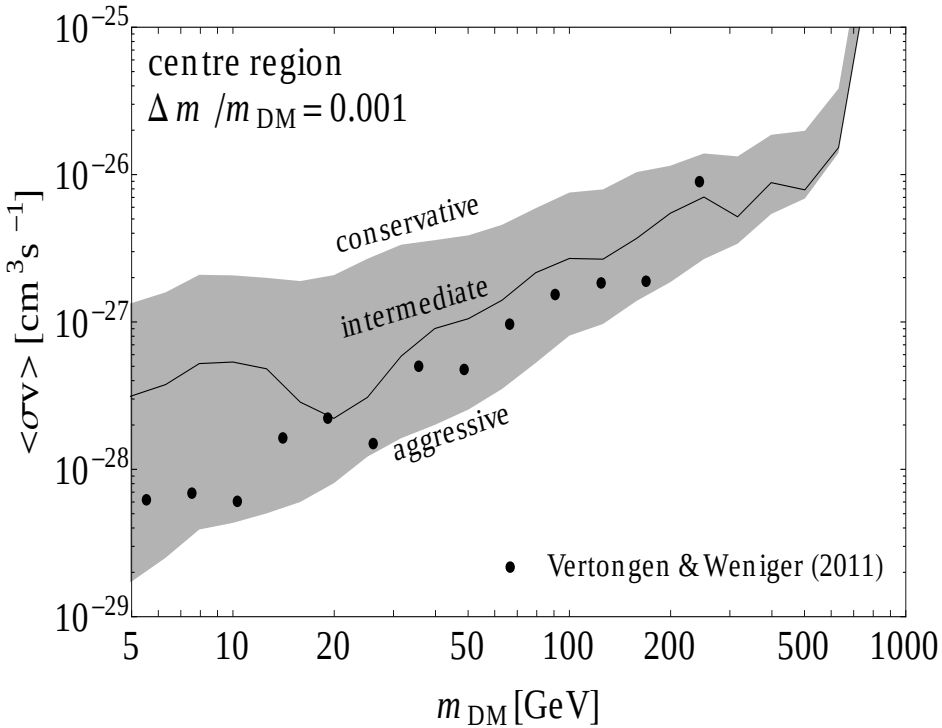
(iii) aggressive: background meets measurements, error-dominated

4. RESULTS: CONSTRAINTS

target: $|l| \in [0, 36]^\circ$, $|b| \in [5, 36]^\circ$; $|l| \in [0, 7]^\circ$, $|b| \in [0, 5]^\circ$
(Fermi-LAT centre region; Vertongen & Weniger '11)

$$\chi\chi \to \phi\phi \to 4\gamma$$





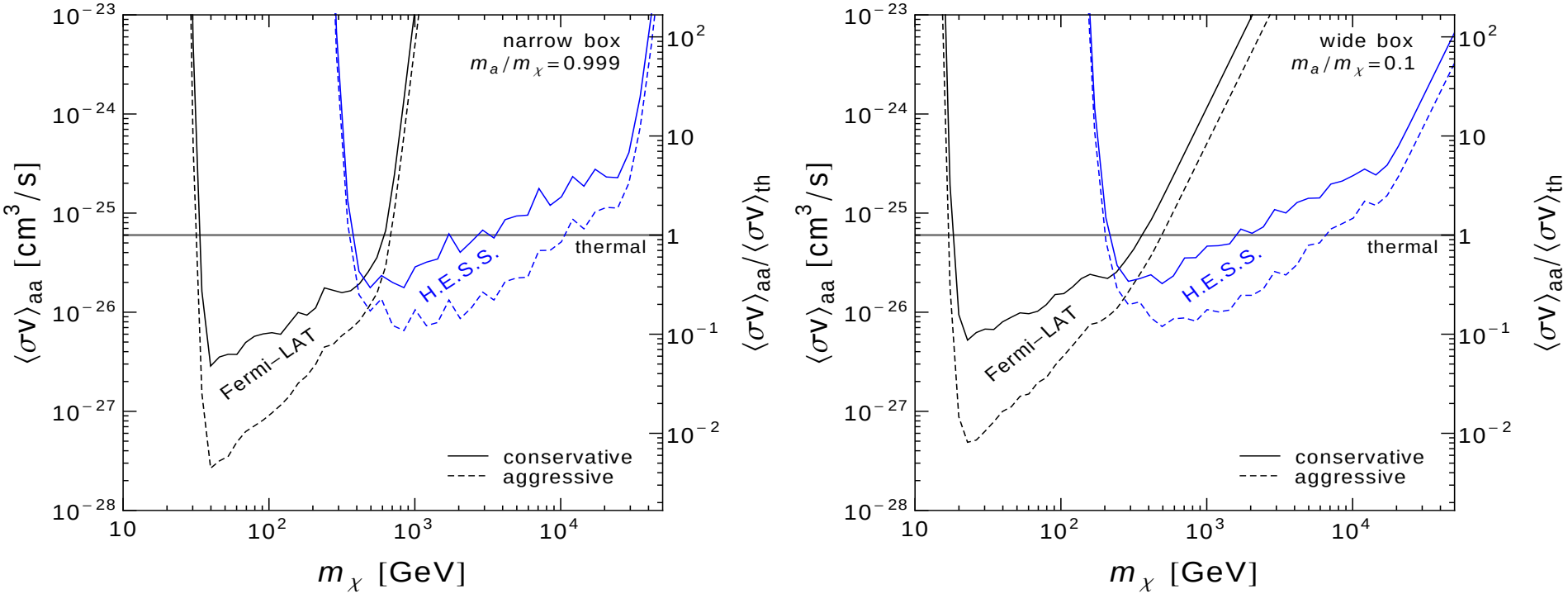
[Ibarra, Gehler & MP '12]

.. saturation of constraints as $m_\phi \to 0$
.. constraints across parameter space, not only in fine-tuned regions
.. background modelling important at small m_χ
.. no direct comparison to usual lines, but similar results

4. RESULTS: CONSTRAINTS

target: Region 3 (Fermi-LAT; Weniger '12)
$|l| < 0.8°$, $|b| < 0.3°$ (H.E.S.S. '06)

$$\chi\bar{\chi} \to aa \to 4\gamma$$



[Ibarra, Lee, Gehler, Park & MP '13]

.. H.E.S.S. meets Fermi-LAT and extends to multi-TeV

.. first ever gamma-ray box constraints at TeV energies

.. thermal x-sec probed for $m_\chi \simeq 10$ GeV – few TeV

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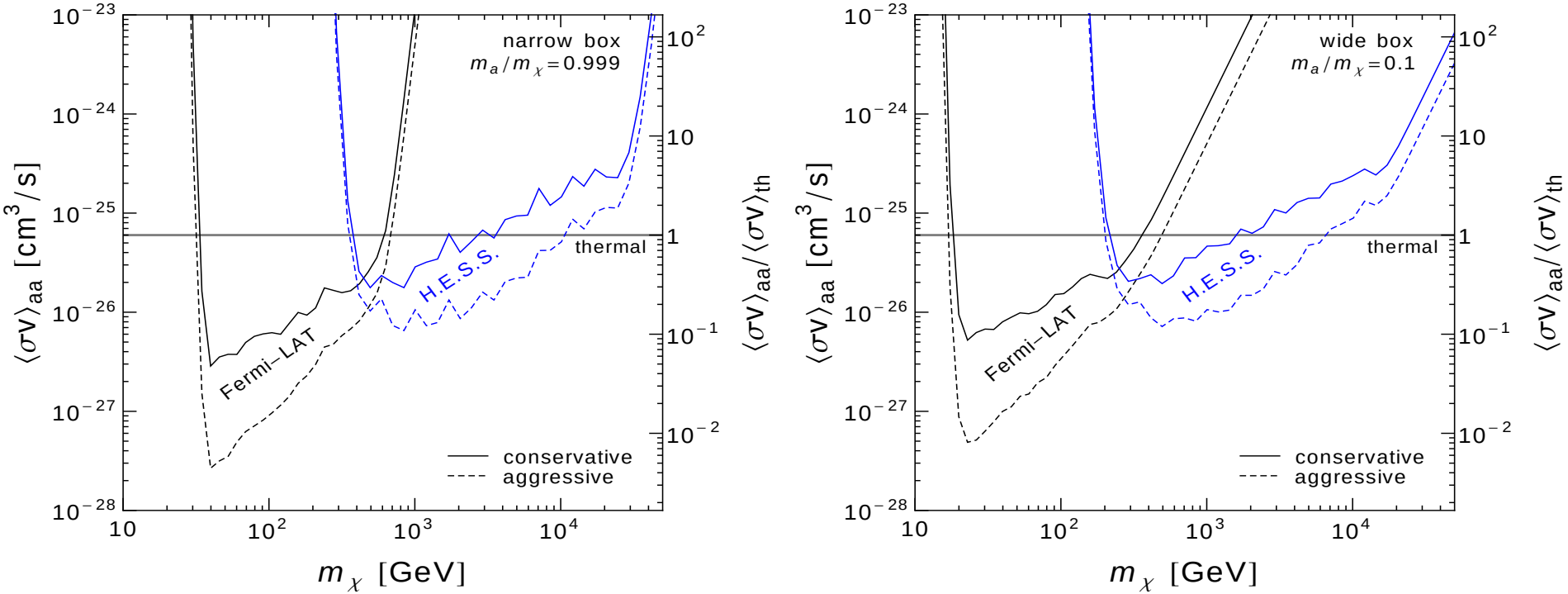

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.. H.E.S.S. meets Fermi-LAT and extends to multi-TeV

.. first ever gamma-ray box constraints at TeV energies

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future ACTs can probe boxes from thermal x-sec above 10 TeV,
a region hardly accessible to direct, collider and other indirect searches

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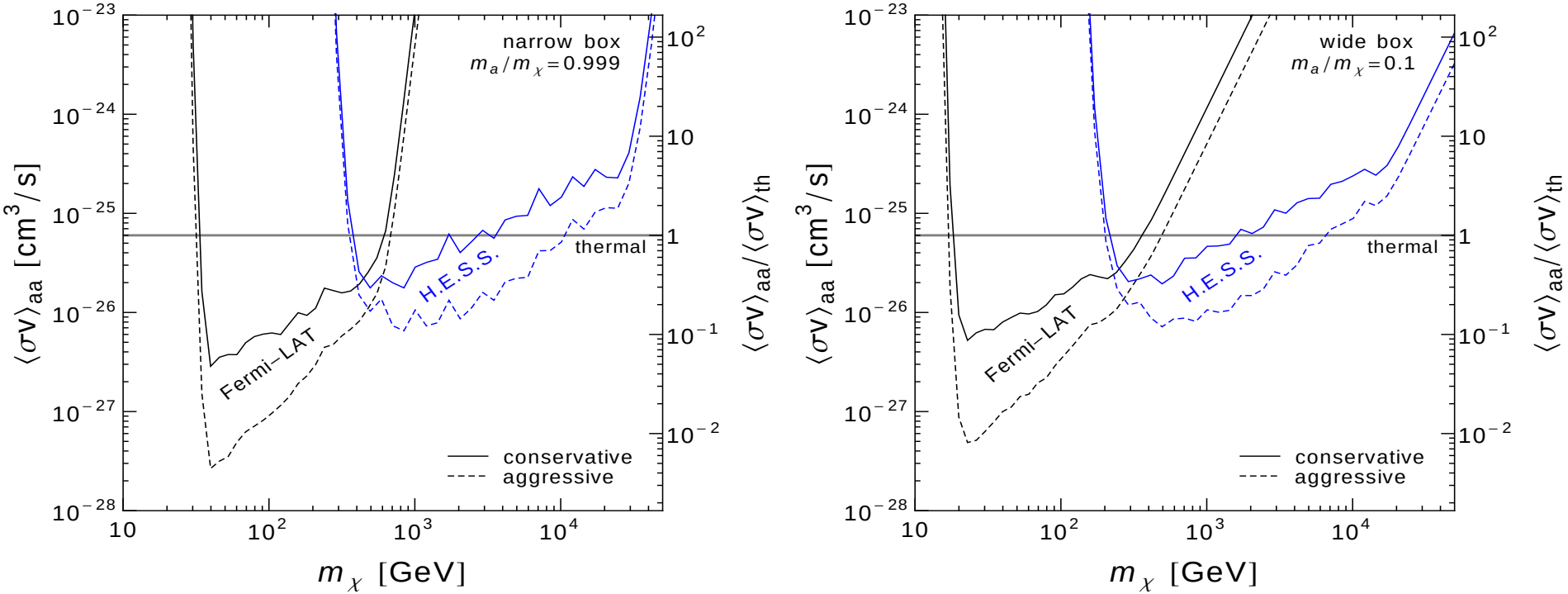

[Ibarra, Lee, Gehler, Park & MP '13]

$\mathrm{BR}(\chi\bar{\chi} \to aa \to 4\gamma) \lesssim 0.02 - 1$ for $m_\chi = \mathcal{O}(10)$ GeV – few TeV (wrt thermal)

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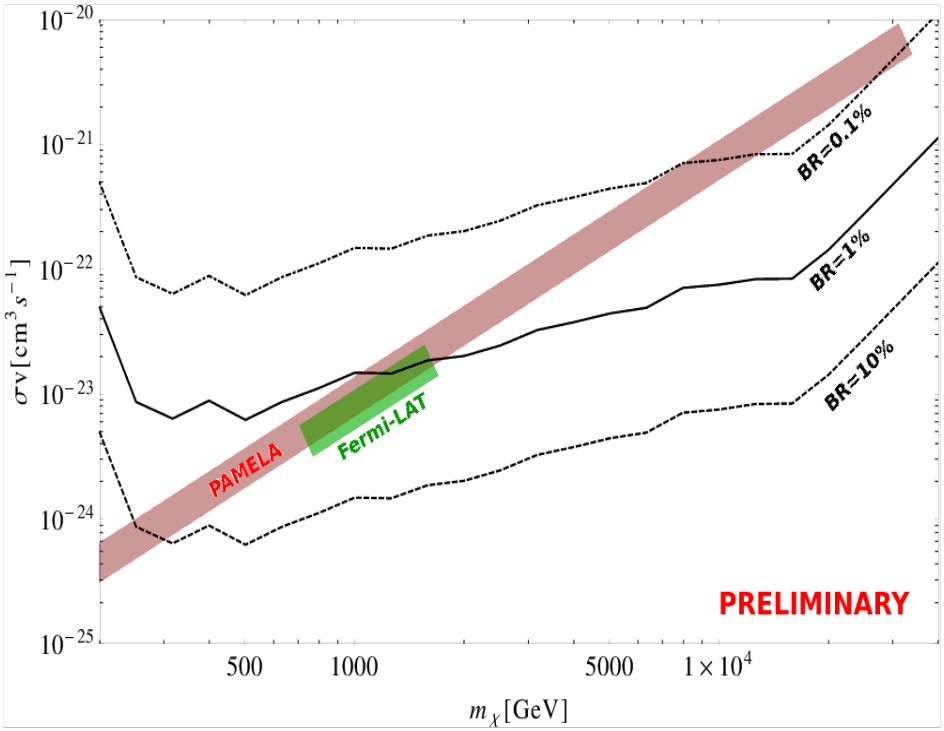

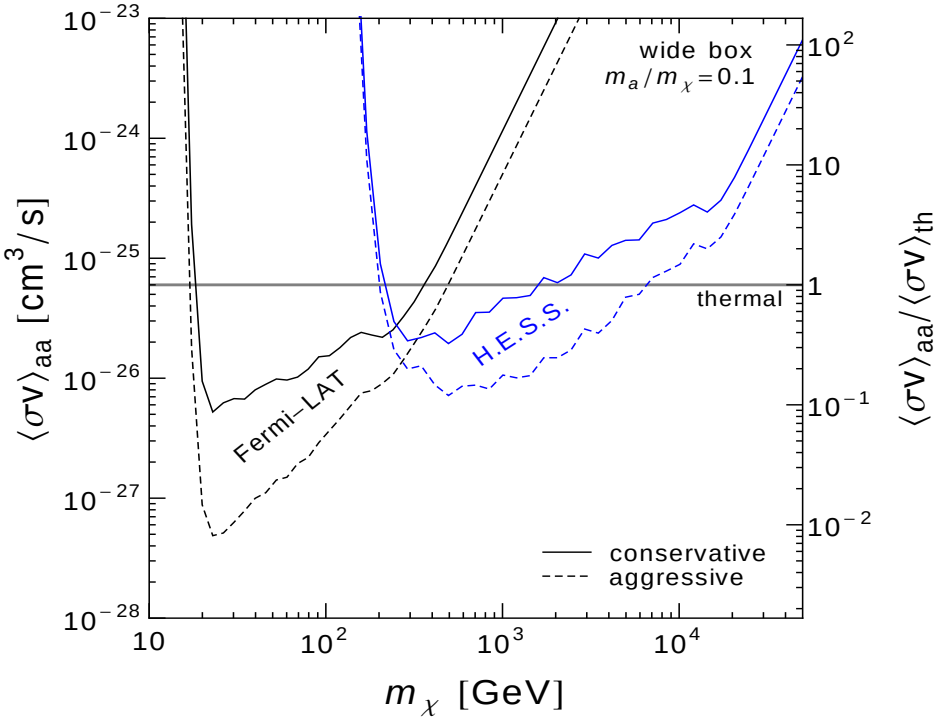

[Ibarra, Lee, Gehler, Park & MP '13]

$\mathrm{BR}(\chi\bar{\chi} \to aa \to 4\gamma) \lesssim 0.02 - 1$ for $m_\chi = \mathcal{O}(10)$ GeV – few TeV (wrt thermal)

$\mathrm{BR}(\chi\bar{\chi} \to aa \to 4\gamma) \lesssim 10^{-2}$ for $m_\chi \sim$ TeV (wrt PAMELA/AMS-02/Fermi-LAT)

if the $e^\pm$ excess is due to cascade annihilations, we should either see a gamma-ray box or else the decay to photons must be heavily suppressed

4. RESULTS: SIGNATURES

on the observability of gamma-ray boxes

$$\chi\bar{\chi} \to aa \to 4\gamma$$

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on the observability of gamma-ray boxes

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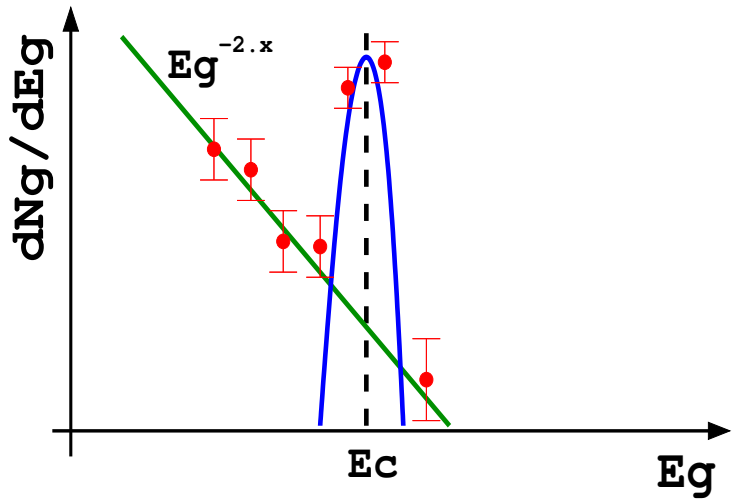
narrow box ($m_a \simeq m_\chi$)



$$E_c = m_\chi/2$$

measure $E_c \to$ infer m_χ, $m_a \simeq m_\chi$

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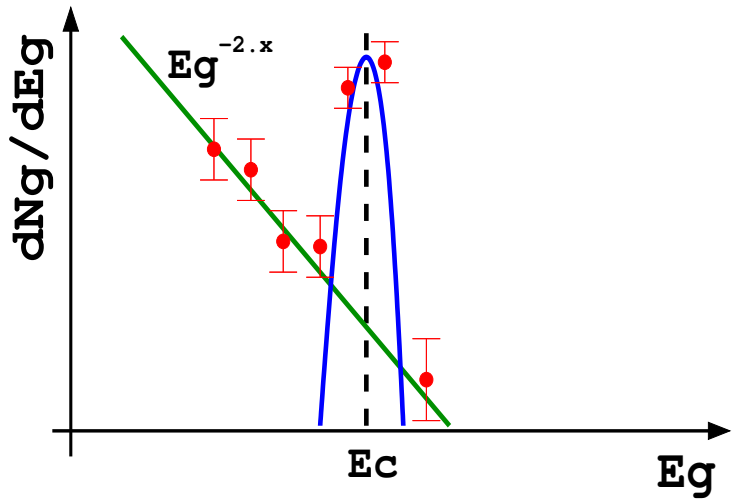

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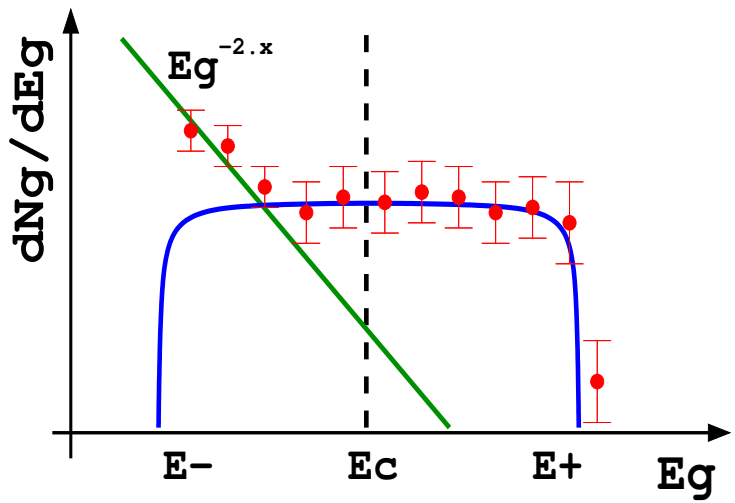
measure $E_c \to$ infer m_χ, $m_a \simeq m_\chi$

wide box ($m_a \ll m_\chi$)



$$E_c = \frac{m_\chi}{2} \qquad E_\pm = \frac{m_\chi}{2}\left(1 \pm \sqrt{1 - \frac{m_a^2}{m_\chi^2}}\right)$$

measure E_+, lower limit ΔE

$\to$ infer range on m_χ and upper limit on m_a

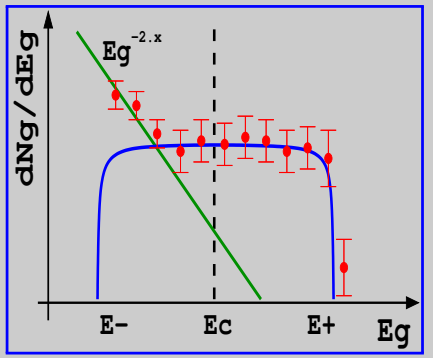
5. CONCLUSIONS

gamma-ray boxes

.. alternative feature with unique phenomenology

.. strong constraints across GeV–TeV with present observations

.. no fine-tuning required to exclude particle physics models



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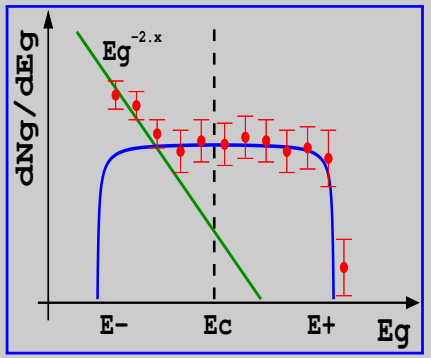


the way forward in dark matter searches

interplay direct+indirect+collider searches

accurate description of dark matter distribution

– fully explore all available data –

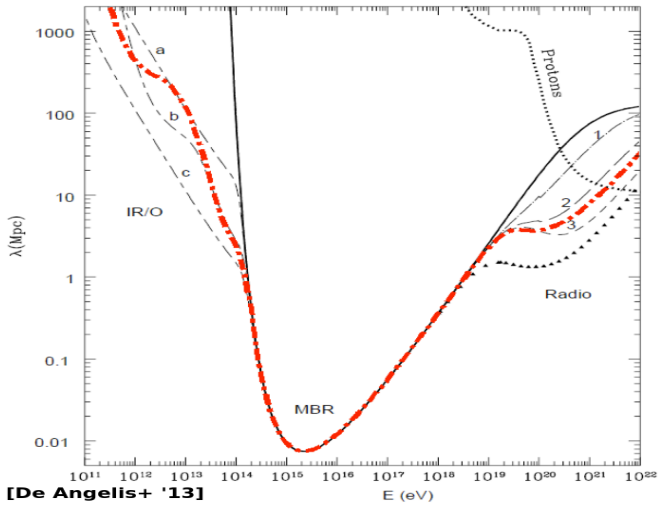
BACKUP SLIDES

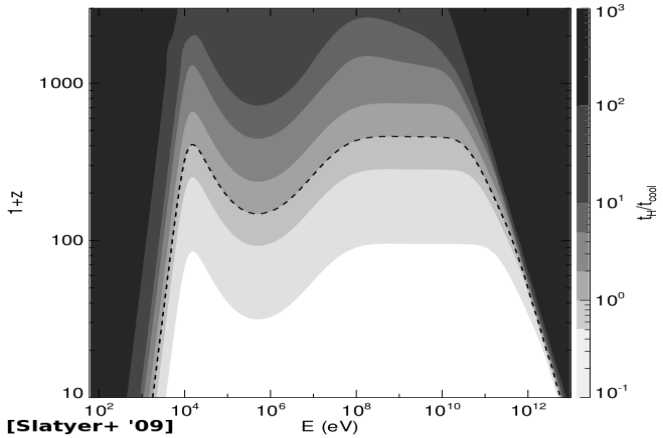
2. INDIRECT SEARCHES VIA GAMMA RAYS

rate $\Gamma_{ann}\, n_\chi = \frac{\langle \sigma v \rangle}{\eta} \frac{\rho^2}{m_\chi^2}$ $\Gamma_{dec}\, n_\chi = \tau_{dec}^{-1} \frac{\rho}{m_\chi}$

$\chi\bar{\chi} \to \text{SM} \ldots \to \ldots \gamma$ $\chi \to \text{SM} \ldots \to \ldots \gamma$

gamma-ray "propagation" $\gamma\gamma_{bkg} \to e^+e^-$ $\gamma\gamma_{bkg} \to \gamma\gamma$ $\gamma e^- \to \gamma e^-$





open window for $\lesssim$ 10 Mpc sources of < 100 TeV or $> 10^{20}$ eV photons
$\to$ no attenuation, no shift in energy nor direction

$$\phi_\gamma = \frac{1}{4\pi\eta m_\chi^2} \sum_f \langle \sigma v \rangle_f \frac{dN_\gamma^f}{dE_\gamma} \frac{1}{\Delta\Omega} \int_{\Delta\Omega} d\Omega\, J_{\text{ann}}$$

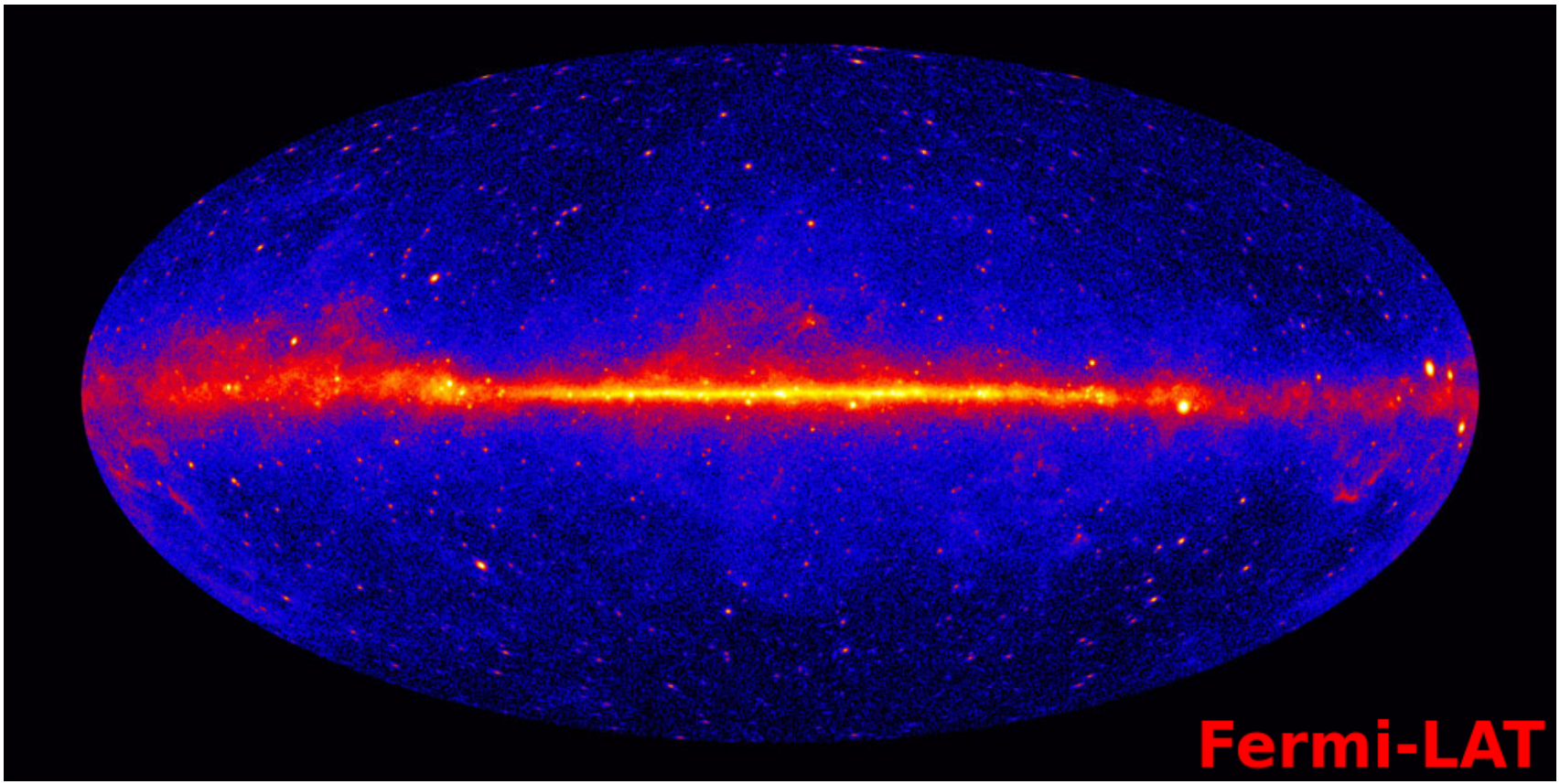
astrophysical backgrounds
IC, synchrotron, bremsstrahlung, pion decay...

1 look at overdensities

2 look at low-background

maximise S/B

2. INDIRECT SEARCHES VIA GAMMA RAYS



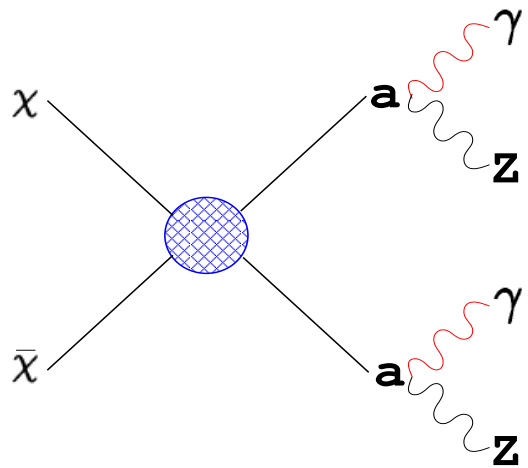
dwarf galaxies galaxy clusters clumps galactic centre

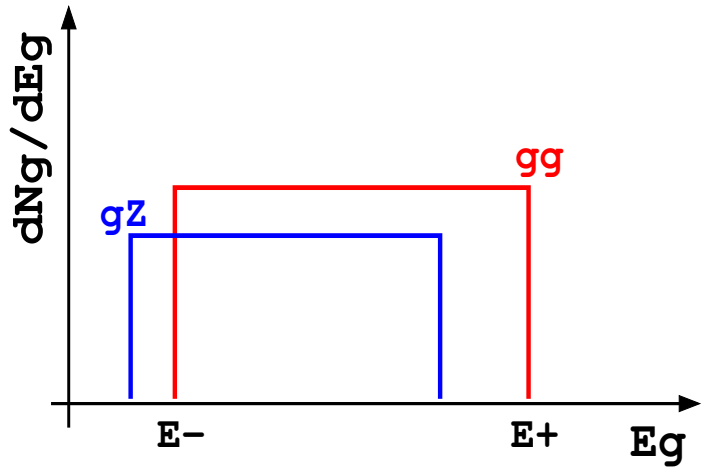
extragalactic halo anisotropies

2. BOX PHENOMENOLOGY

gamma-ray boxes

[Ibarra, Gehler & MP '12; Ibarra, Lee, Gehler, Park & MP '13]





$$E_\gamma = E'_\gamma \gamma_a (1 + \beta_a \cos\theta')$$

$$\frac{dN_\gamma}{dE_\gamma} = \frac{2}{\Delta E} \mathcal{F}_{box}[E_-, E_+]$$

$$dN_a/dE_a = 2\delta(E_a - m_\chi)$$

$$dN_\gamma/dE'_\gamma = \delta(E'_\gamma - m_a(1 - m_Z^2/m_a^2)/2)$$

$$E_\pm = \frac{m_\chi}{2}\left(1 - \frac{m_Z^2}{m_a^2}\right)\left(1 \pm \sqrt{1 - \frac{m_a^2}{m_\chi^2}}\right)$$

$$E_c = \frac{m_\chi}{2}\left(1 - \frac{m_Z^2}{m_a^2}\right)$$

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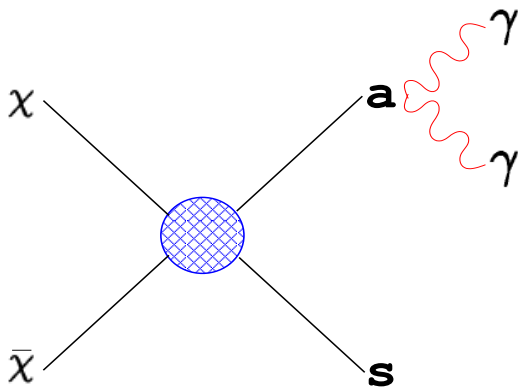

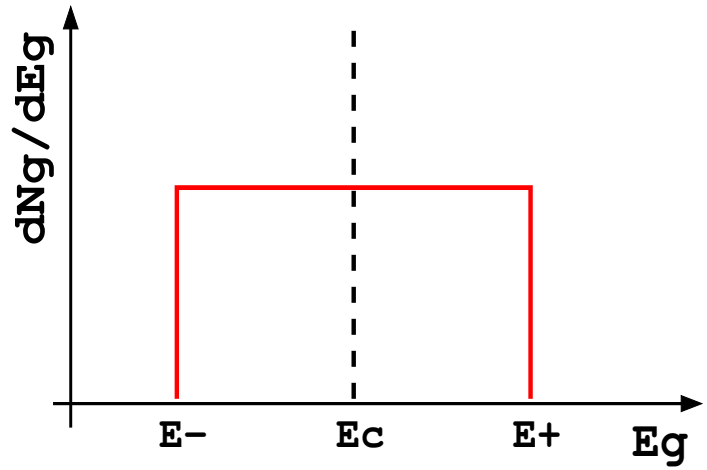

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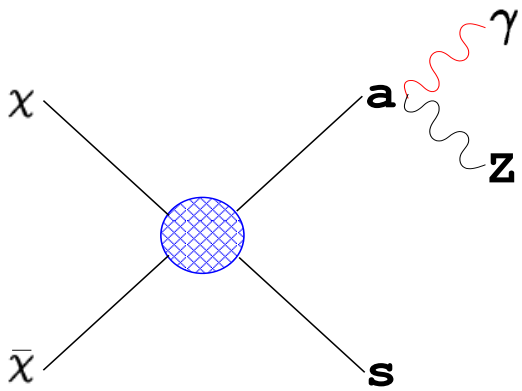

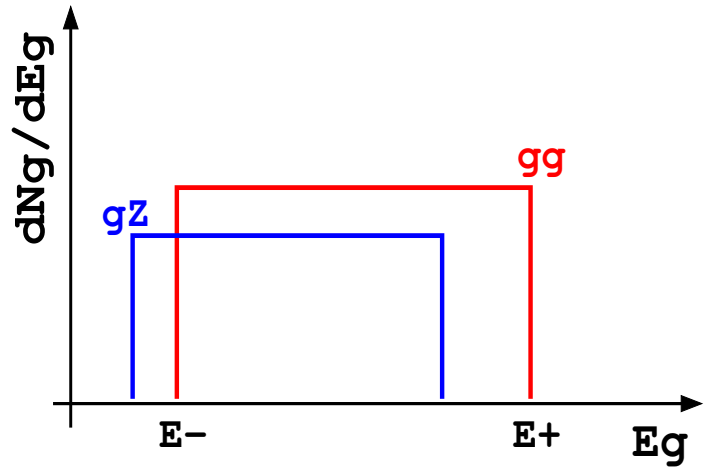

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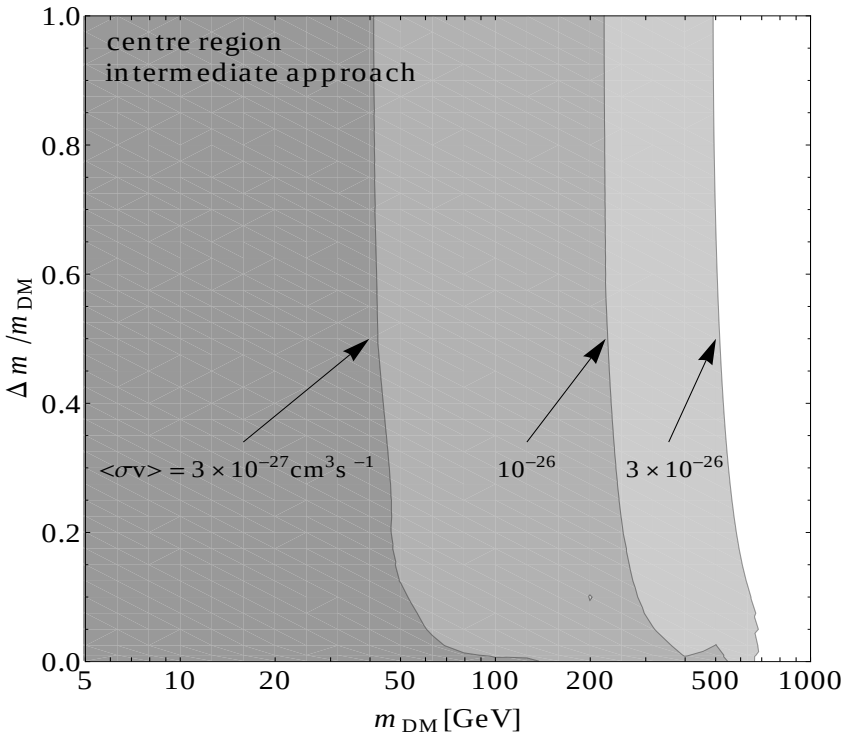
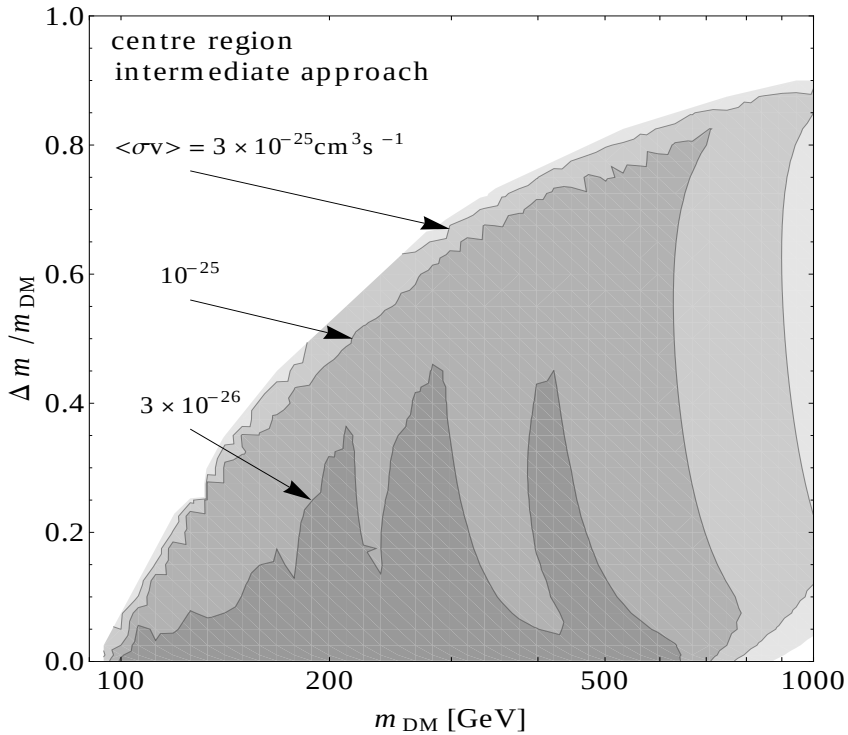


$\chi\chi \to \phi\phi \to 2\gamma 2Z$



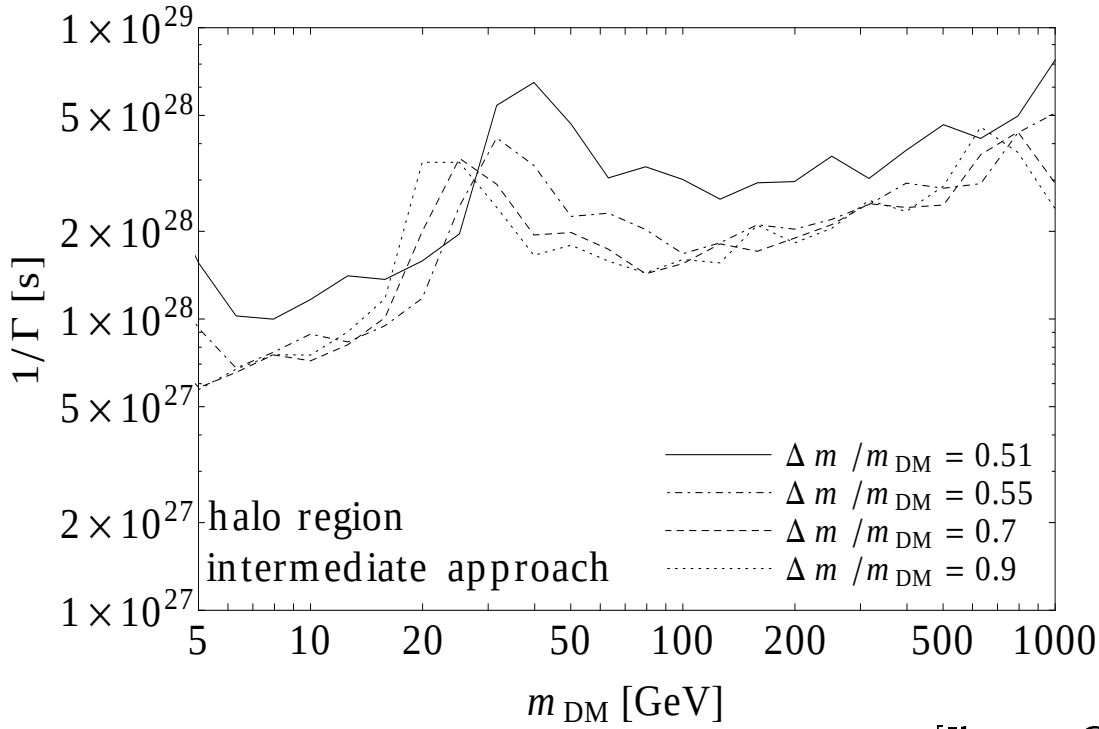
[Ibarra, Gehler & MP '12]

exclusion of thermal x-sec $m_\chi = 5 - 600$ GeV with $\Delta m/m_\chi \geq 5\%$

4. RESULTS: CONSTRAINTS

target: $|b| \geq 10^\circ$ (Fermi-LAT halo region; Vertongen & Weniger '11)

$$\chi \to \phi\phi \to 4\gamma$$



[Ibarra, Gehler & MP '12]

2–3 o.o.m. stronger than $\Gamma^{-1} \simeq 10^{26}$ s

4. RESULTS: SIGNATURES

target: Region 3 (Fermi-LAT; Weniger '12)

narrow box

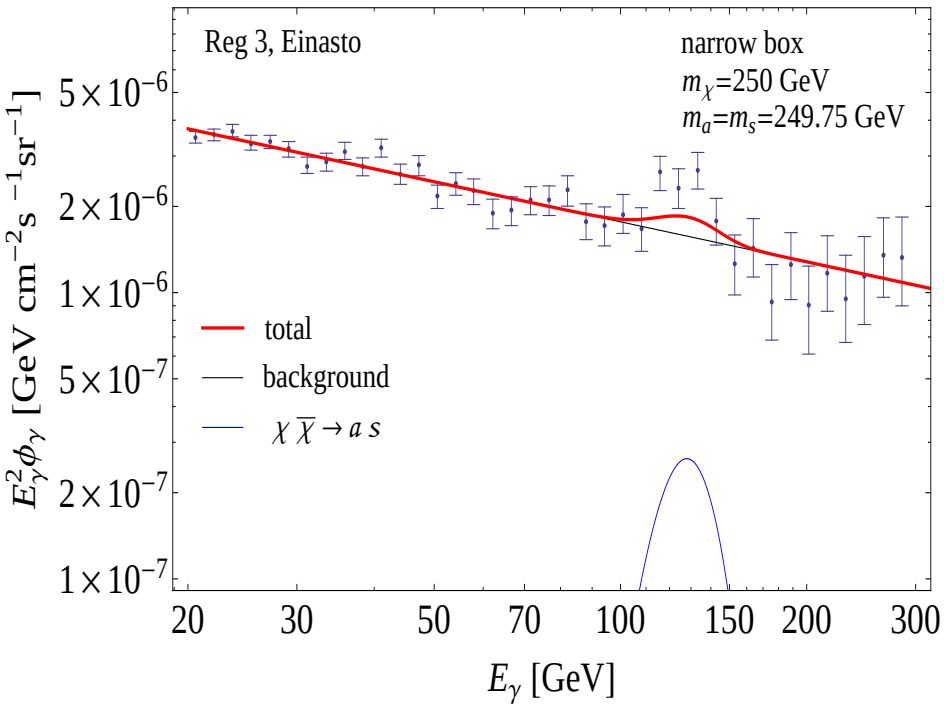
$\mathrm{BR}(\chi\bar{\chi} \to aa, as) \simeq 0, 1$

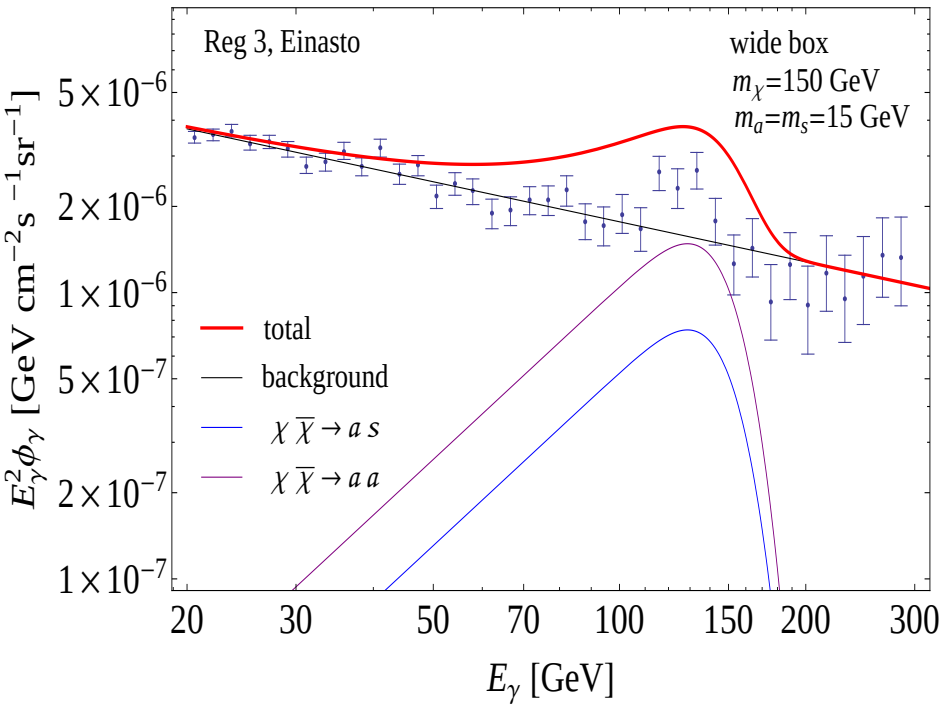
$\mathrm{BR}(a \to \gamma\gamma) \simeq 0.4$

wide box

$\mathrm{BR}(\chi\bar{\chi} \to aa, as) \simeq 0.25, 0.25$

$\mathrm{BR}(a \to \gamma\gamma) \simeq 1$





[Ibarra, Lee, Gehler, Park & MP '13]

boxes from thermal wimps easily produce observable fluxes without fine-tuning and are at the verge of being excluded