ON GAMMA RAY SIGNATURES FROM SCALAR DARK MATTER

Michel H.G. Tytgat
Université Libre de Bruxelles (ULB)
Belgium

SCALARS 2013 - September 12-16 2013 - Warsaw, Poland

I. GAMMA RAY SPECTRAL FEATURES

II. PROBLEM & MOTIVATION

III. MAJORANA DM

IV. REAL SCALAR DM

V. PROSPECTS

Based on work done in collaboration with
F. Giacchino and L. Lopez Honorez
(arXiv:1307.6480, to be published in JCAP)

I. GAMMA RAY SPECTRAL FEATURES

II. PROBLEM & MOTIVATION

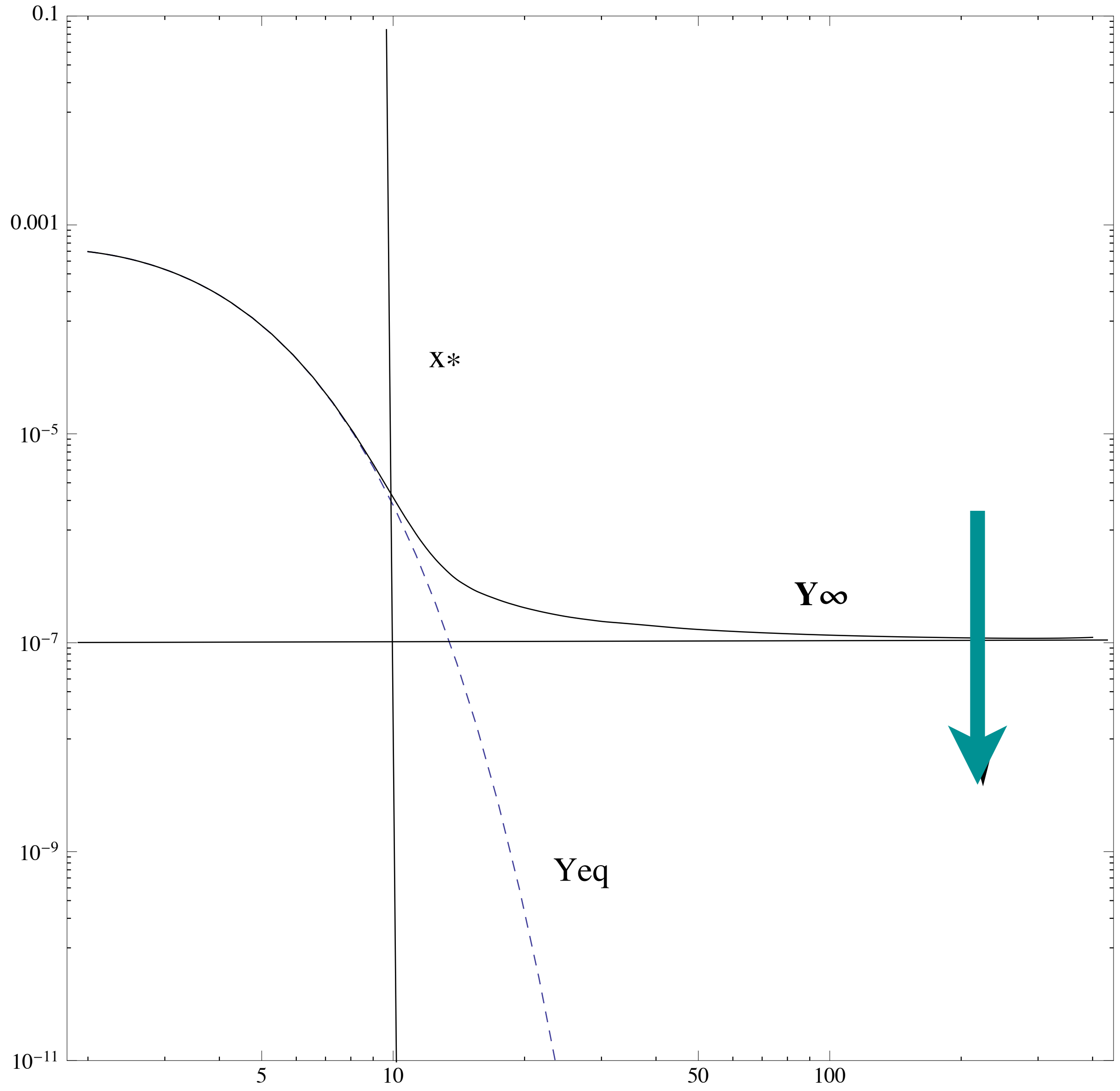
III. MAJORANA DM

IV. REAL SCALAR DM

V. PROSPECTS

I ASSUME THAT DM IS MADE OF WIMPS
(*i.e.* Relic Abundance from Thermal Freeze-out)

$$Y = \frac{n_X}{s}$$



$$x = \frac{m}{T}$$

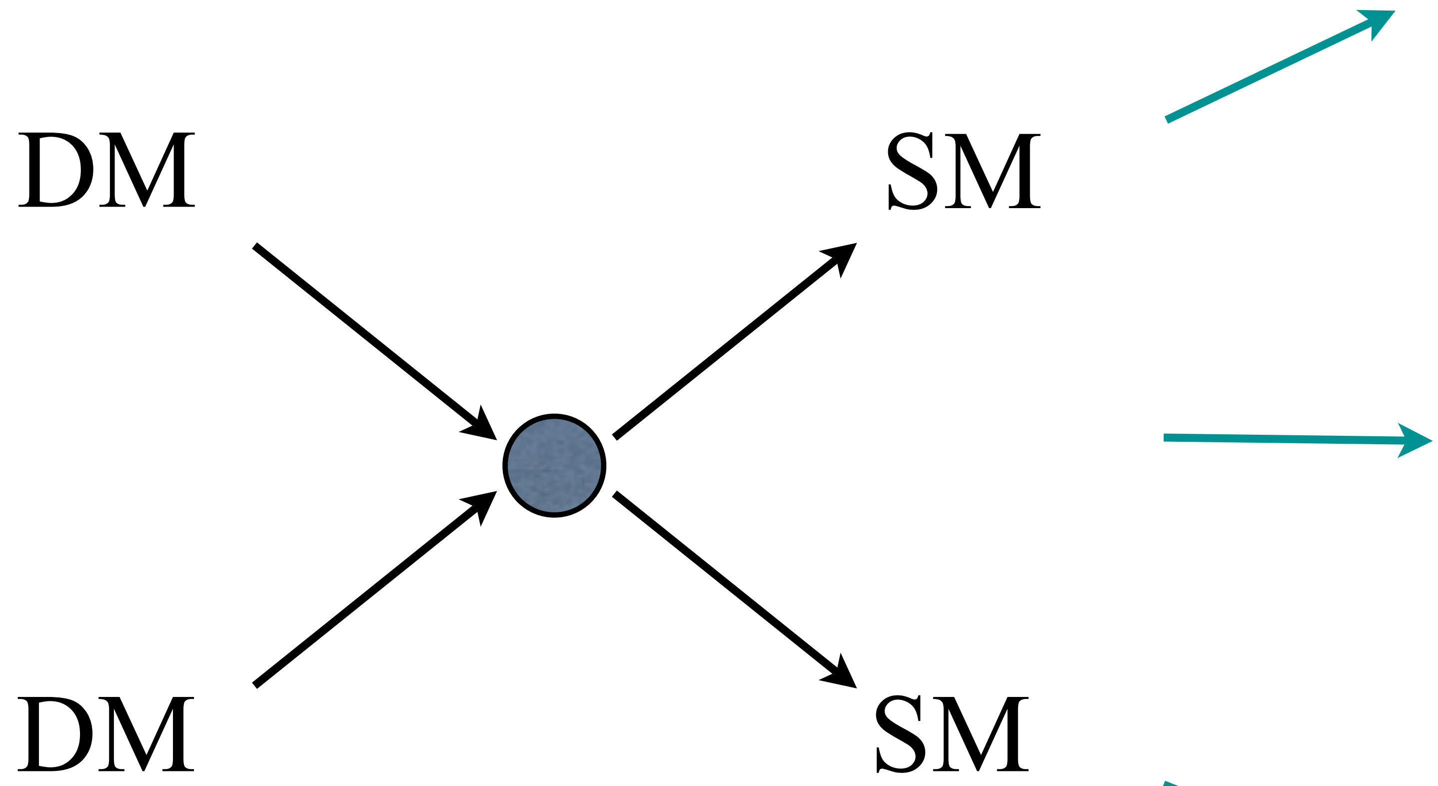
Relic abundance

$$Y_\infty = \frac{x_*}{\langle \sigma v \rangle} \; \frac{H}{s}\bigg|_{x=1}$$

WMAP/Planck require

$$\langle \sigma v \rangle \approx 3 \cdot 10^{-26} \mathrm{cm}^3 \cdot \mathrm{s}^{-1}$$

WIMP INDIRECT SEARCHES



$\pi^0 \to \gamma\gamma$

gamma rays

$\pi^+ \to \mu^+ + \nu$

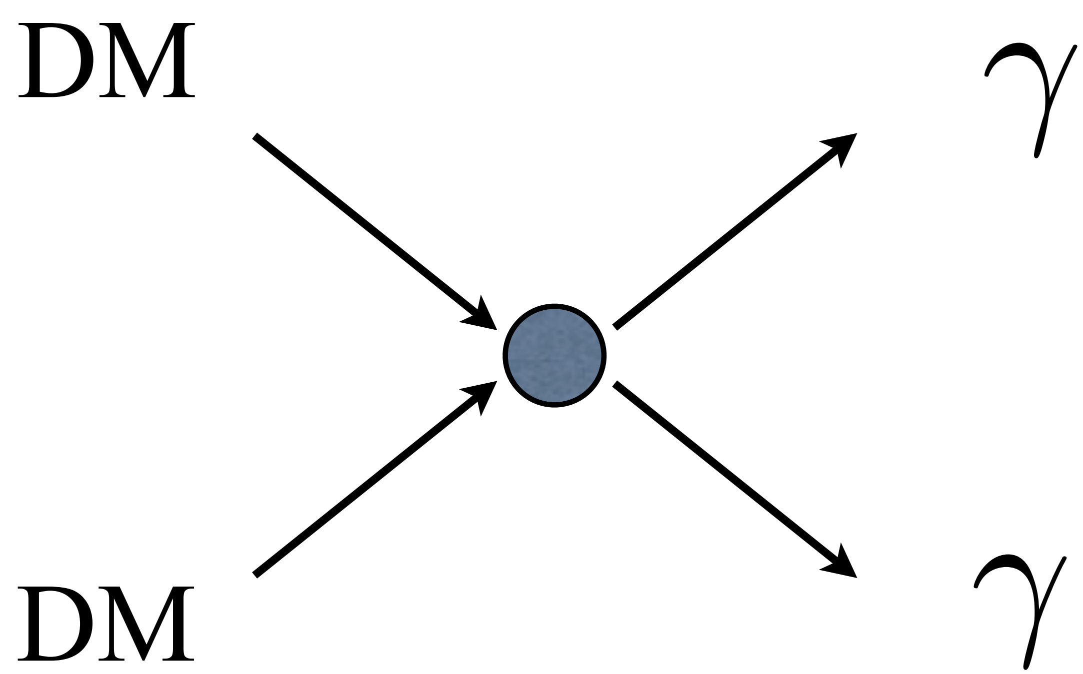
neutrinos

$e^+, \ \bar{p}, \ \bar{d}$

anti-matter

Problem: astrophysical backgrounds

WIMP INDIRECT SEARCHES



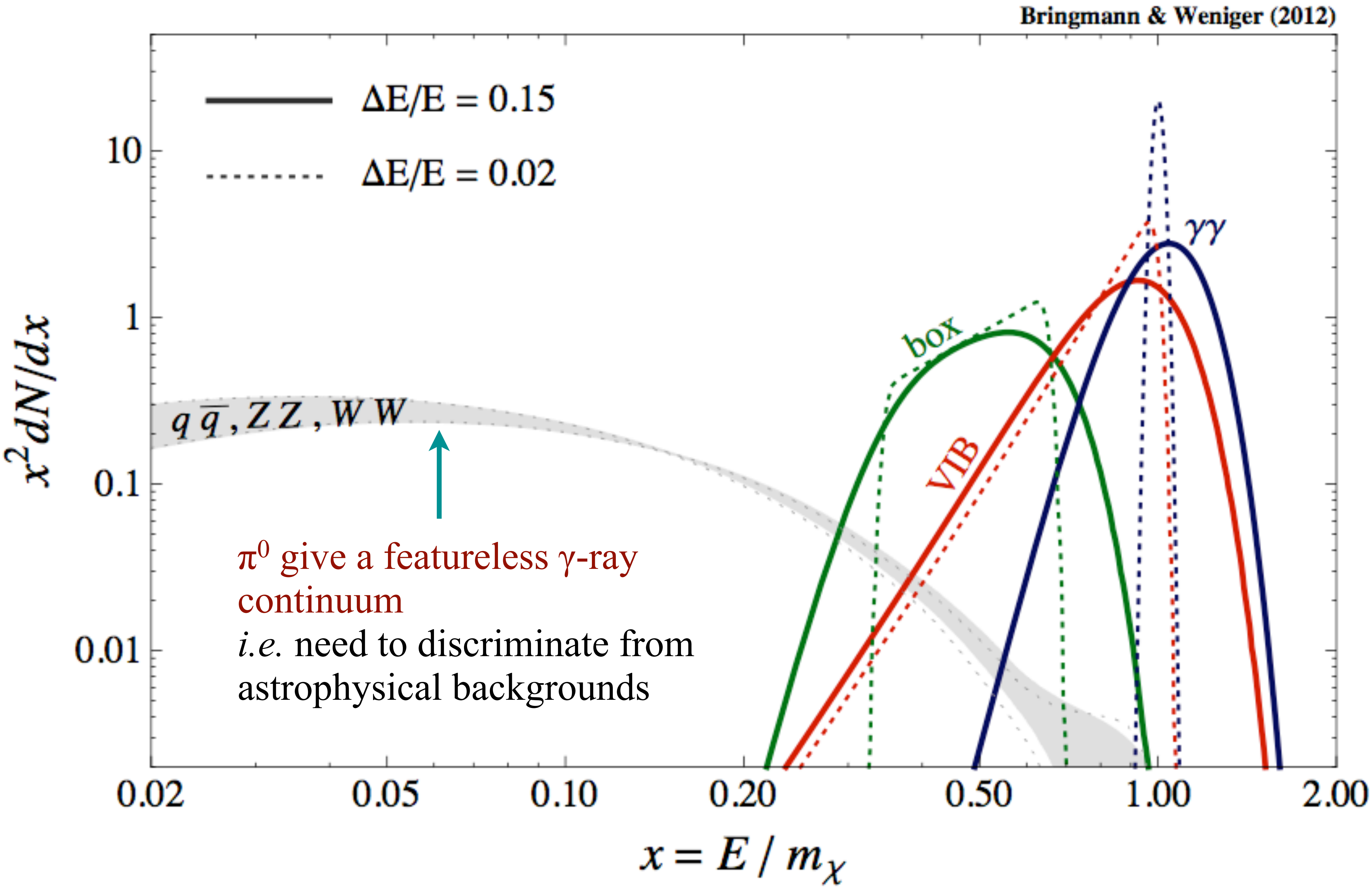
gamma ray lines

1. no (?) astrophysical counterparts

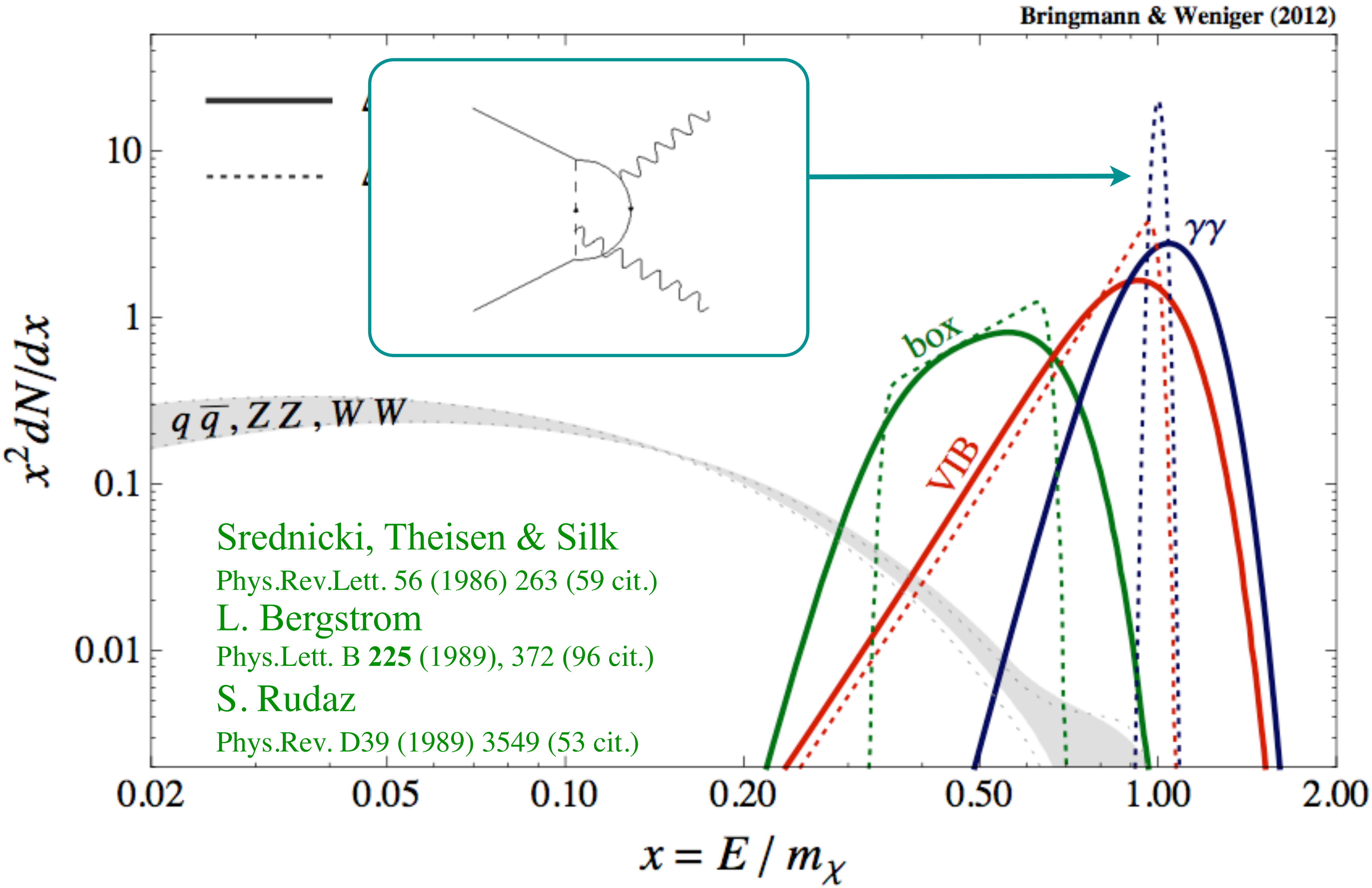
2. $M_{DM} = E_\gamma$

More generally search for SPECTRAL FEATURES

POSSIBLE GAMMA RAY FEATURES?

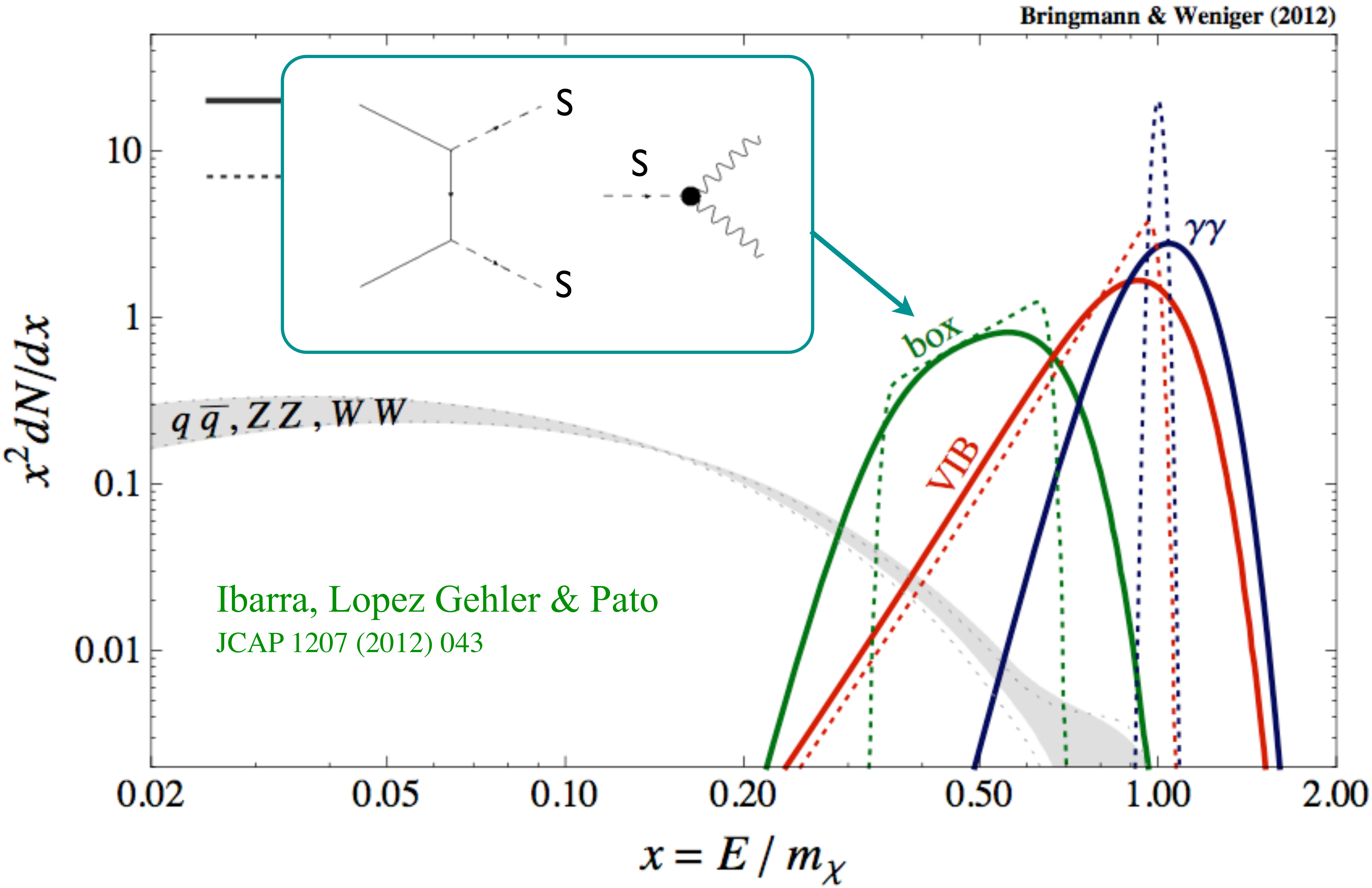


POSSIBLE GAMMA RAY FEATURES?



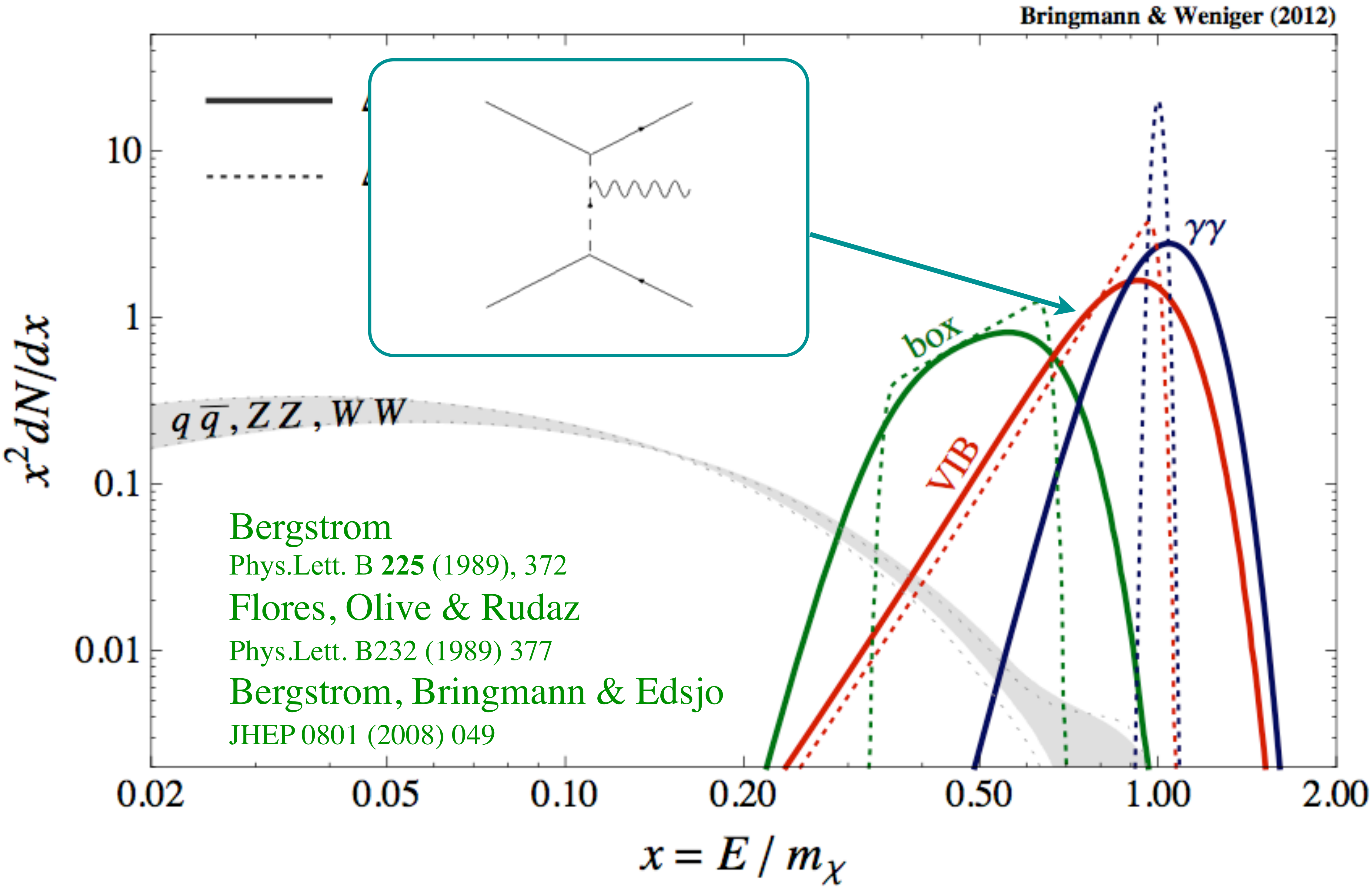
MONO-CHROMATIC GAMMA RAYS

POSSIBLE GAMMA RAY FEATURES



SECLUDED DM, BOX SHAPED SPECTRUM

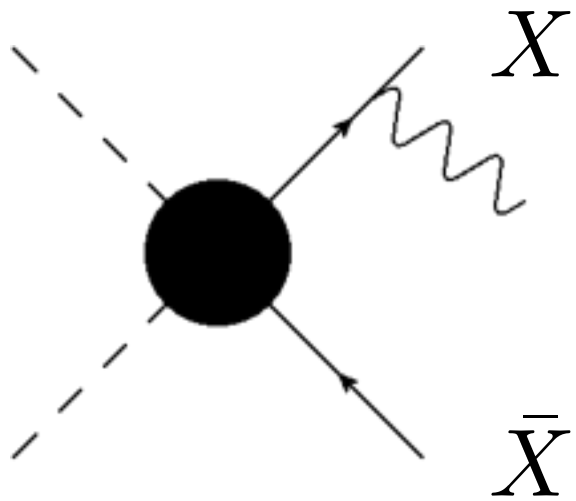
POSSIBLE GAMMA RAY FEATURES



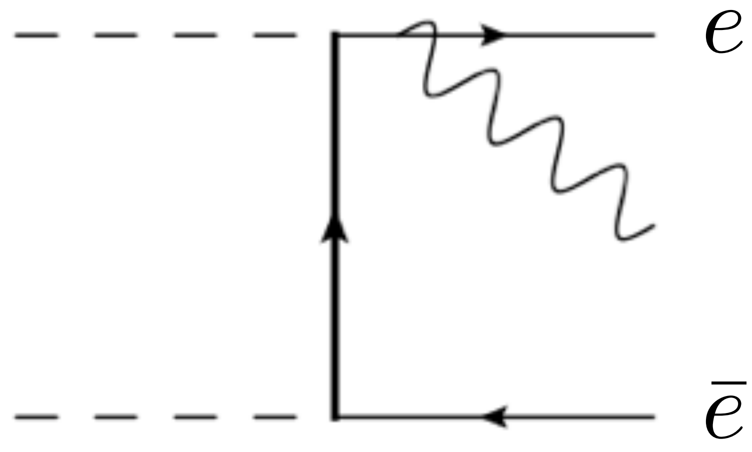
VIRTUAL INTERNAL BREMSSTRAHLUNG

VIRTUAL INTERNAL BREMSSTRAHLUNG?

annihilation of DM into charged particles



e.g.



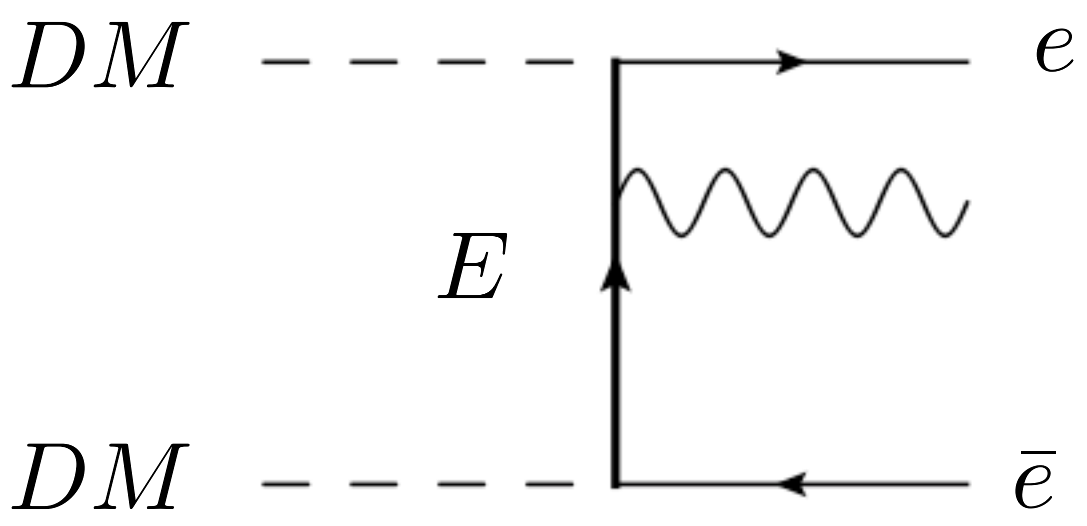
→ Final State Radiation (FSR)

$$\frac{d\sigma(\chi\chi \to X\bar{X}\gamma)}{dx} \approx \frac{\alpha Q_X^2}{\pi} \mathcal{F}_X(x) \log\left(\frac{s(1-x)}{m_X^2}\right) \sigma(\chi\chi \to X\bar{X})$$

IR dominated, collinear emission
universal feature encoded in splitting function

Birkedal, Matchev, Perelstein and Sprey (2005)

VIRTUAL INTERNAL BREMSSTRAHLUNG



$$\mathcal{M} \propto ((p_{DM} - p_{\bar{e}})^2 - M_E^2)^{-1} \sim (M_{DM}^2 - M_E^2 - 2M_{DM}E_{\bar{e}})^{-1}$$

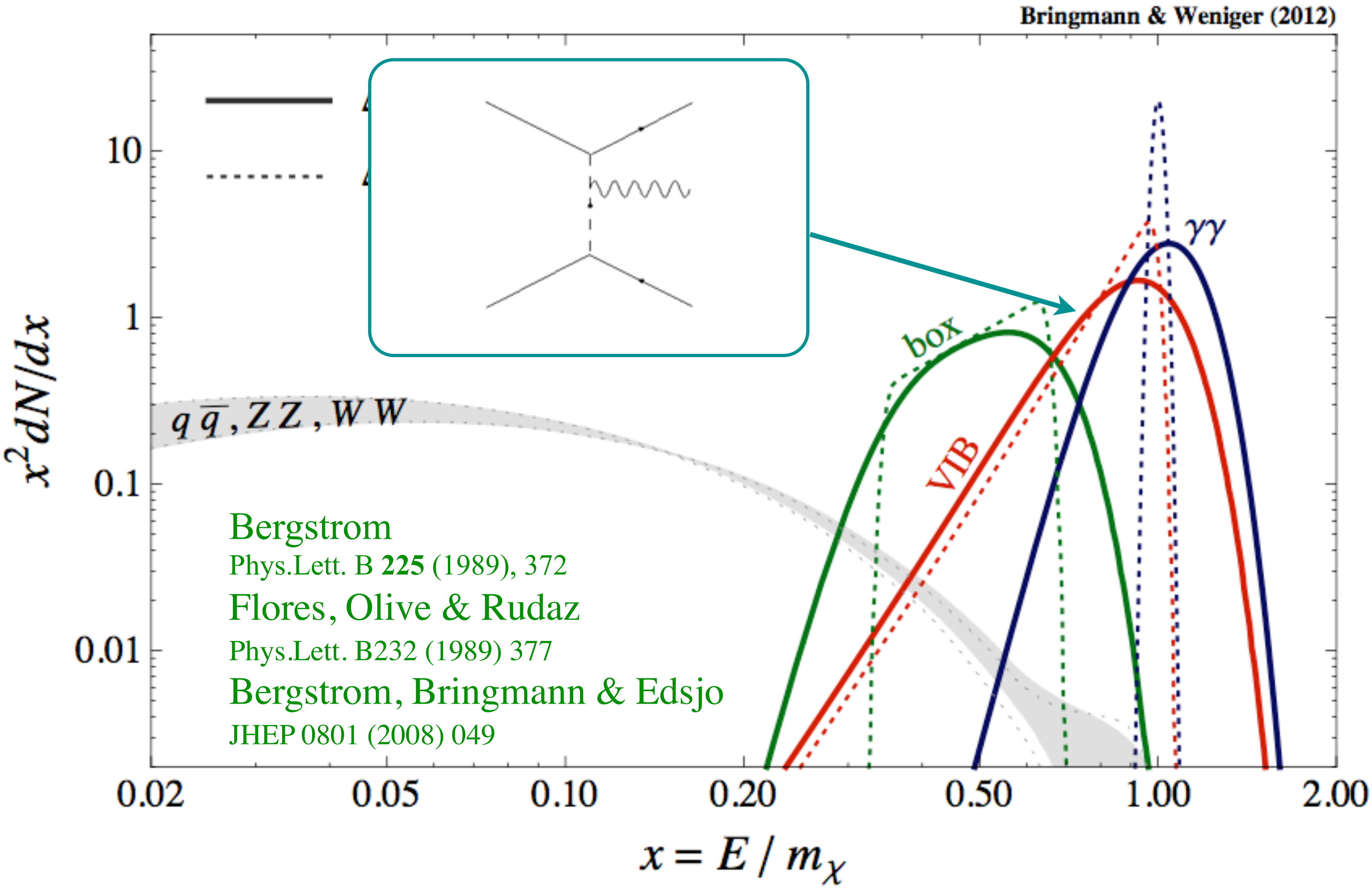
POTENTIALLY **VERY LARGE** ENHANCEMENT IF $M_{DM} \sim M_E$

FOR $E_{\bar{e}} \sim 0$ CORRESPONDING TO $E_\gamma \sim M_{DM}$

Bergstrom
Phys.Lett. B **225** (1989), 372

Bergstrom, Bringmann & Edsjo
JHEP 0801 (2008) 049

POSSIBLE GAMMA RAY FEATURES



VIRTUAL INTERNAL BREMSSTRAHLUNG

I. GAMMA RAY SPECTRAL FEATURES

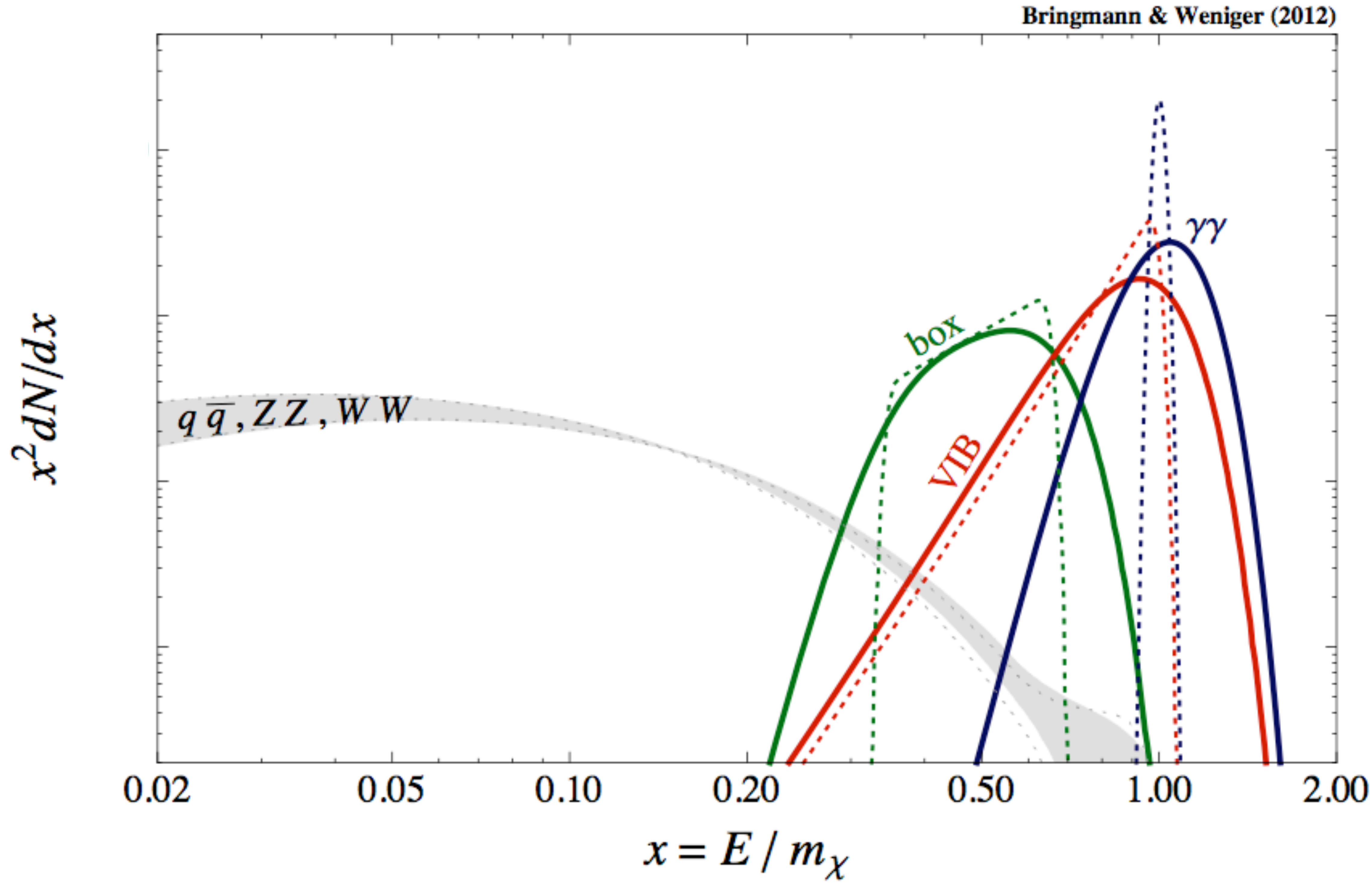
II. PROBLEM & MOTIVATION

III. MAJORANA DM

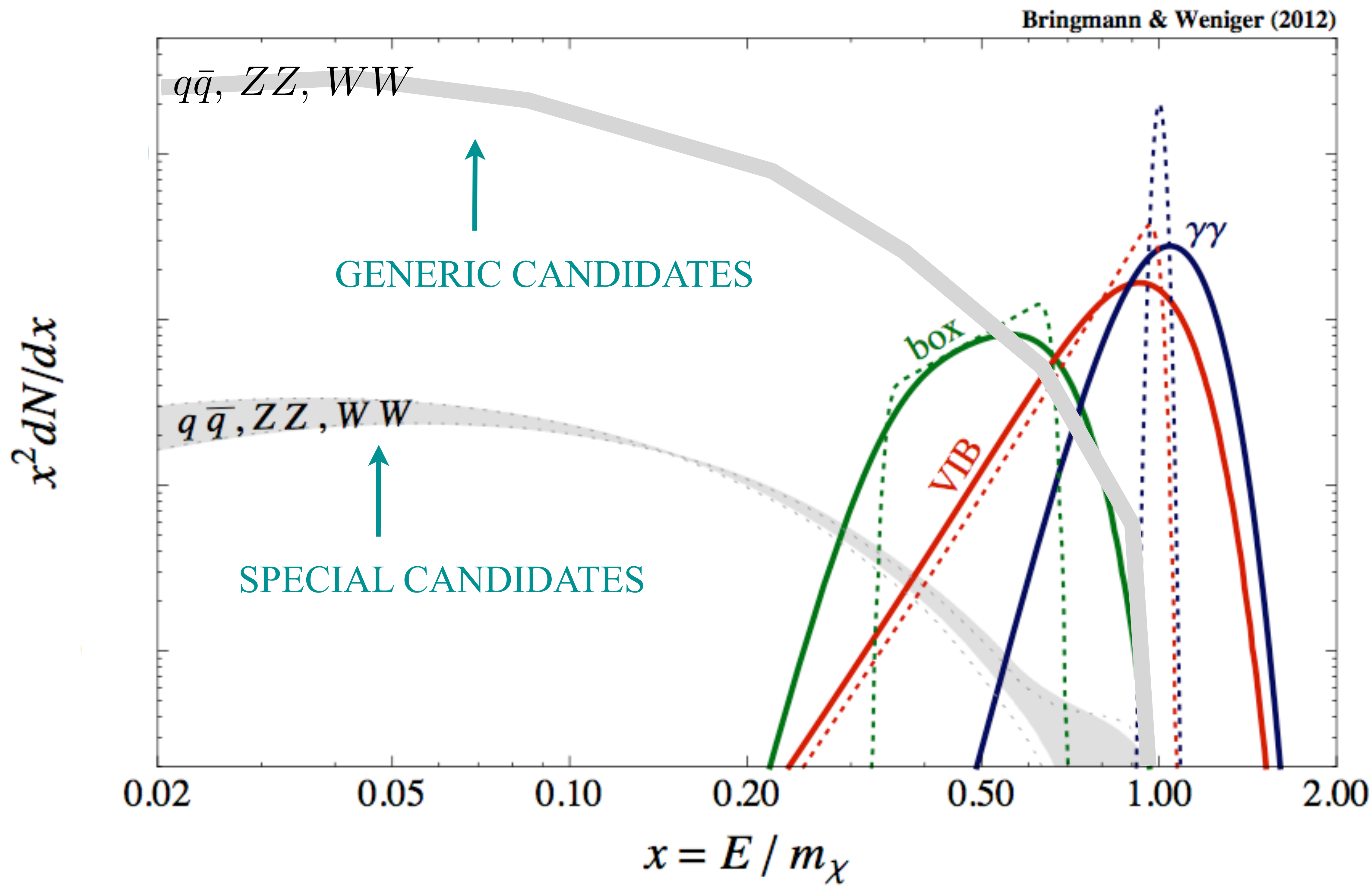
IV. REAL SCALAR DM

V. PROSPECTS

THE TROUBLE WITH GAMMA RAY FEATURES

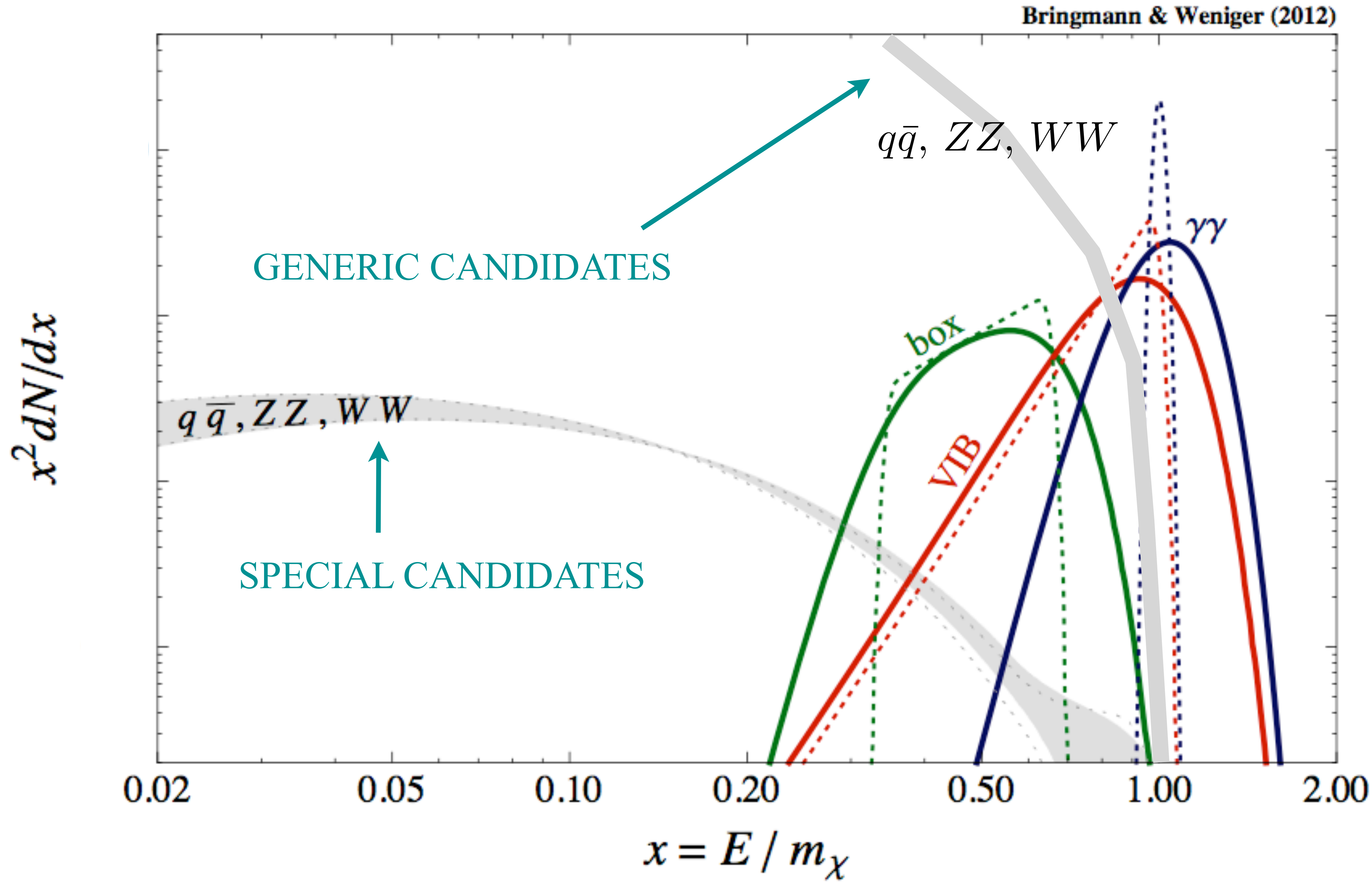


THE TROUBLE WITH GAMMA RAY FEATURES



expected to be small, *e.g.* γγ $\mathcal{O}(\alpha^2)\ \langle\sigma v\rangle_{2-\mathrm{body}} \sim 10^{-30}\mathrm{cm}^3 \cdot \mathrm{s}^{-1}$

THE TROUBLE WITH GAMMA RAY FEATURES



expected to be small, *e.g.* γγ $\mathcal{O}(\alpha^2)\,\langle\sigma v\rangle_{2-\mathrm{body}} \sim 10^{-30}\mathrm{cm}^3\cdot\mathrm{s}^{-1}$

PROBLEM:

HOW TO GET <u>SIGNIFICANT</u>
GAMMA RAY FEATURES?

MOTIVATION:

MODEL BUILDING

EXPERIMENT(ALIST)S

«Significant gamma-ray line from Inert Doublet»

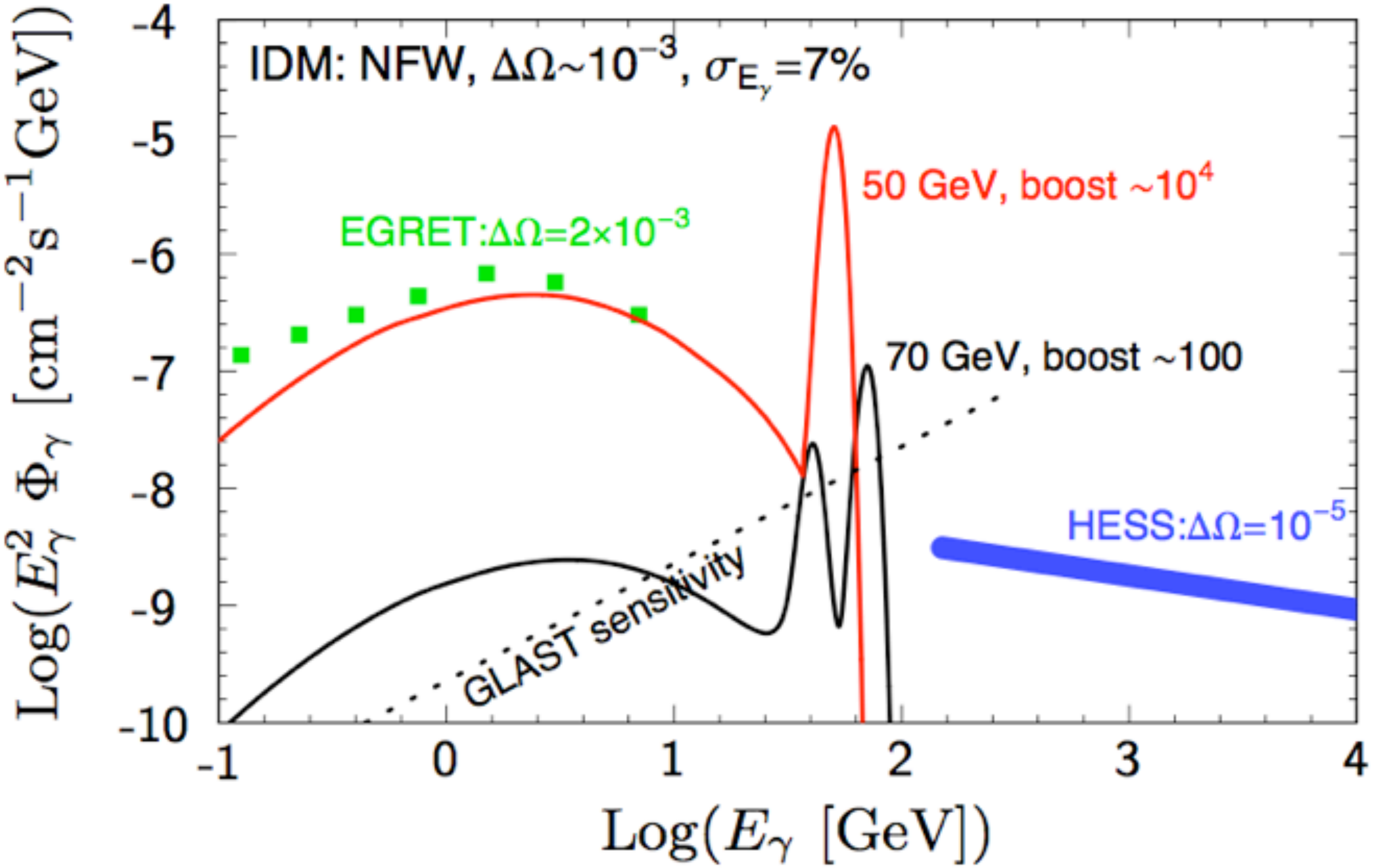


TABLE II: *IDM benchmark model results.*

Model	$v\sigma_{tot}^{v\to 0}$ $[\mathrm{cm}^3\mathrm{s}^{-1}]$	Branching ratios [%]: $\gamma\gamma$	$Z\gamma$	$b\bar{b}$	$c\bar{c}$	$\tau^+\tau^-$	$\Omega_{\mathrm{CDM}}h^2$
I	1.6×10^{-28}	36	33	26	2	3	0.10
II	8.2×10^{-29}	29	0.6	60	4	7	0.10
III	8.7×10^{-27}	2	2	81	5	9	0.12
IV	1.9×10^{-26}	0.04	0.1	85	5	10	0.11

Gustafsson, Bergstrom, Lundstrom & Edsjo
Phys.Rev.Lett. 99 (2007) 041301

«Significant gamma-ray line from Inert Doublet»

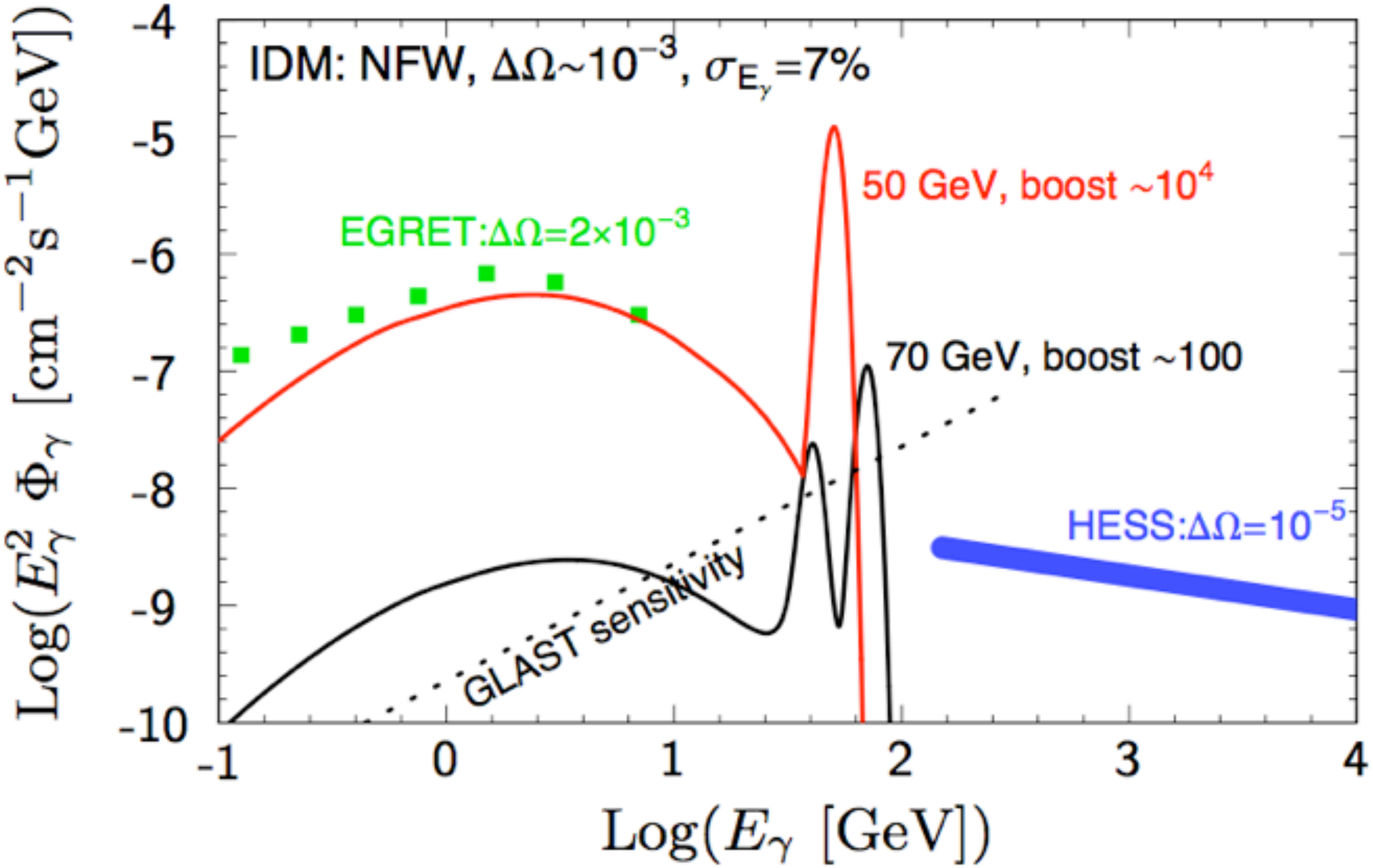


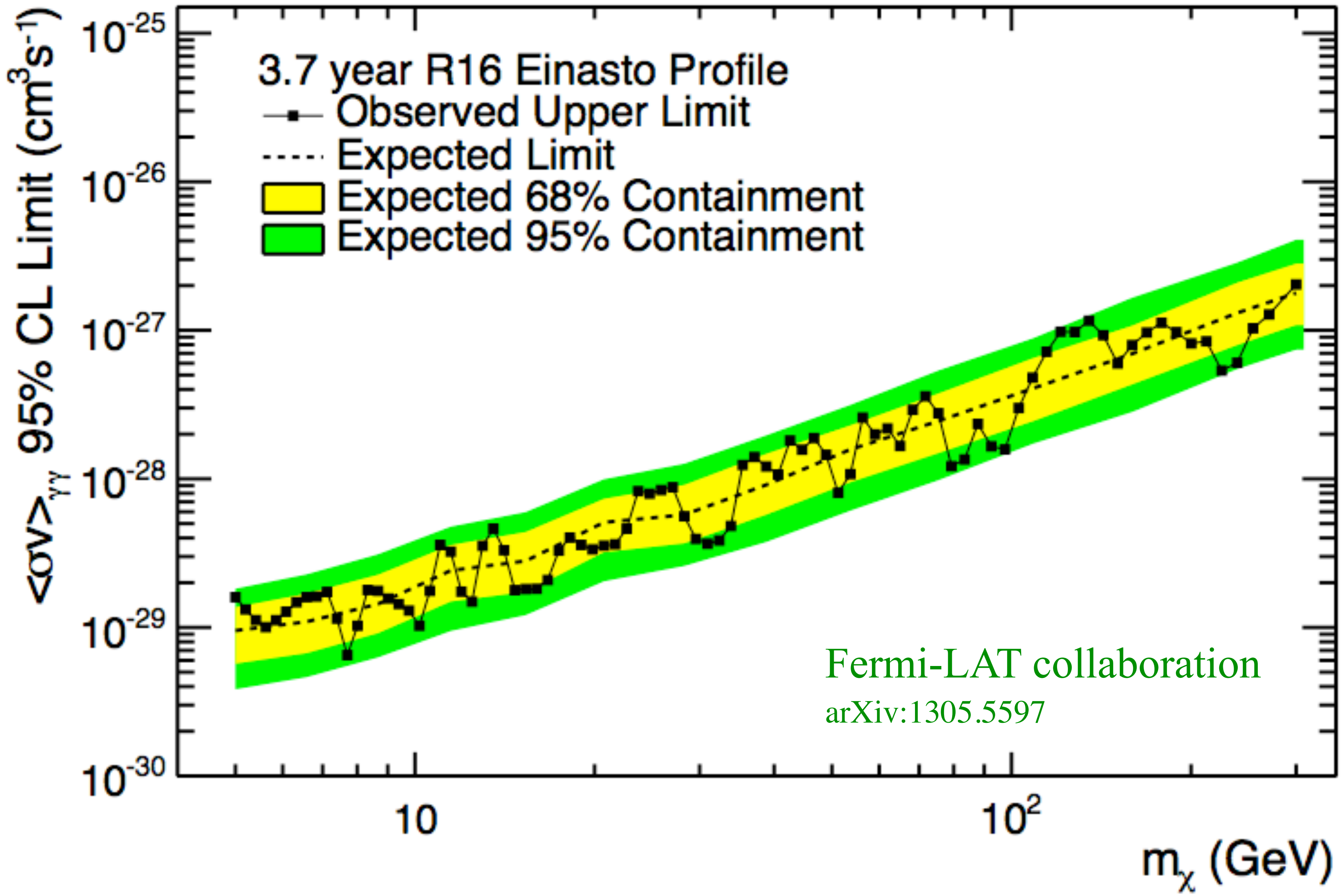
TABLE II: *IDM benchmark model results.*

Model	$v\sigma_{tot}^{v\to0}$ [$\mathrm{cm}^3\mathrm{s}^{-1}$]	Branching ratios [%]: $\gamma\gamma$	$Z\gamma$	$b\bar{b}$	$c\bar{c}$	$\tau^+\tau^-$	$\Omega_{\mathrm{CDM}}h^2$
I	1.6×10^{-28}	36	33	26	2	3	0.10
II	8.2×10^{-29}	29	0.6	60	4	7	0.10
III	8.7×10^{-27}	2	2	81	5	9	0.12
IV	1.9×10^{-26}	0.04	0.1	85	5	10	0.11

Gustafsson, Bergstrom, Lundstrom & Edsjo
Phys.Rev.Lett. 99 (2007) 041301

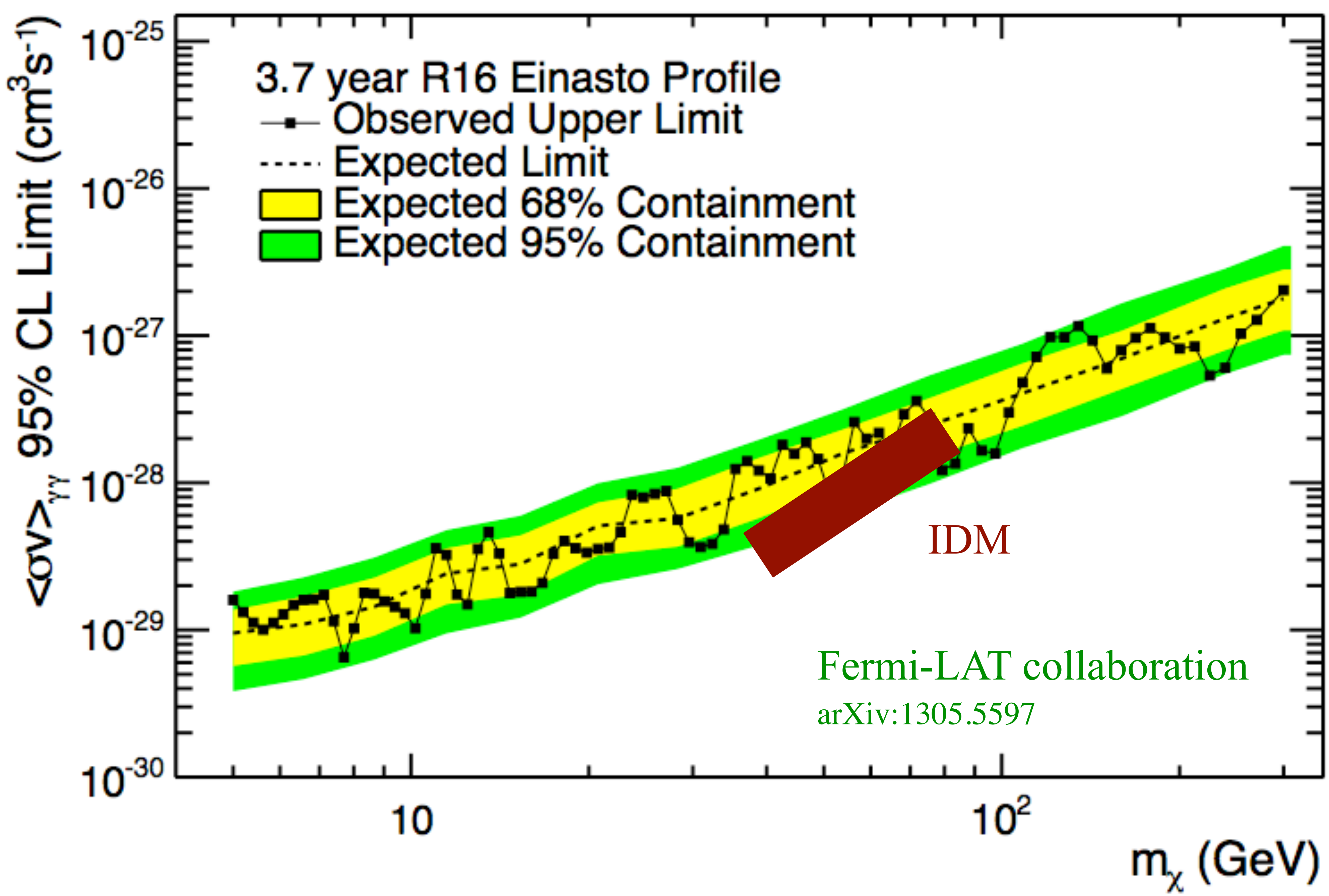
$M_{higgs} \sim$ 500 GeV

CURRENT EXPERIMENTAL LIMITS



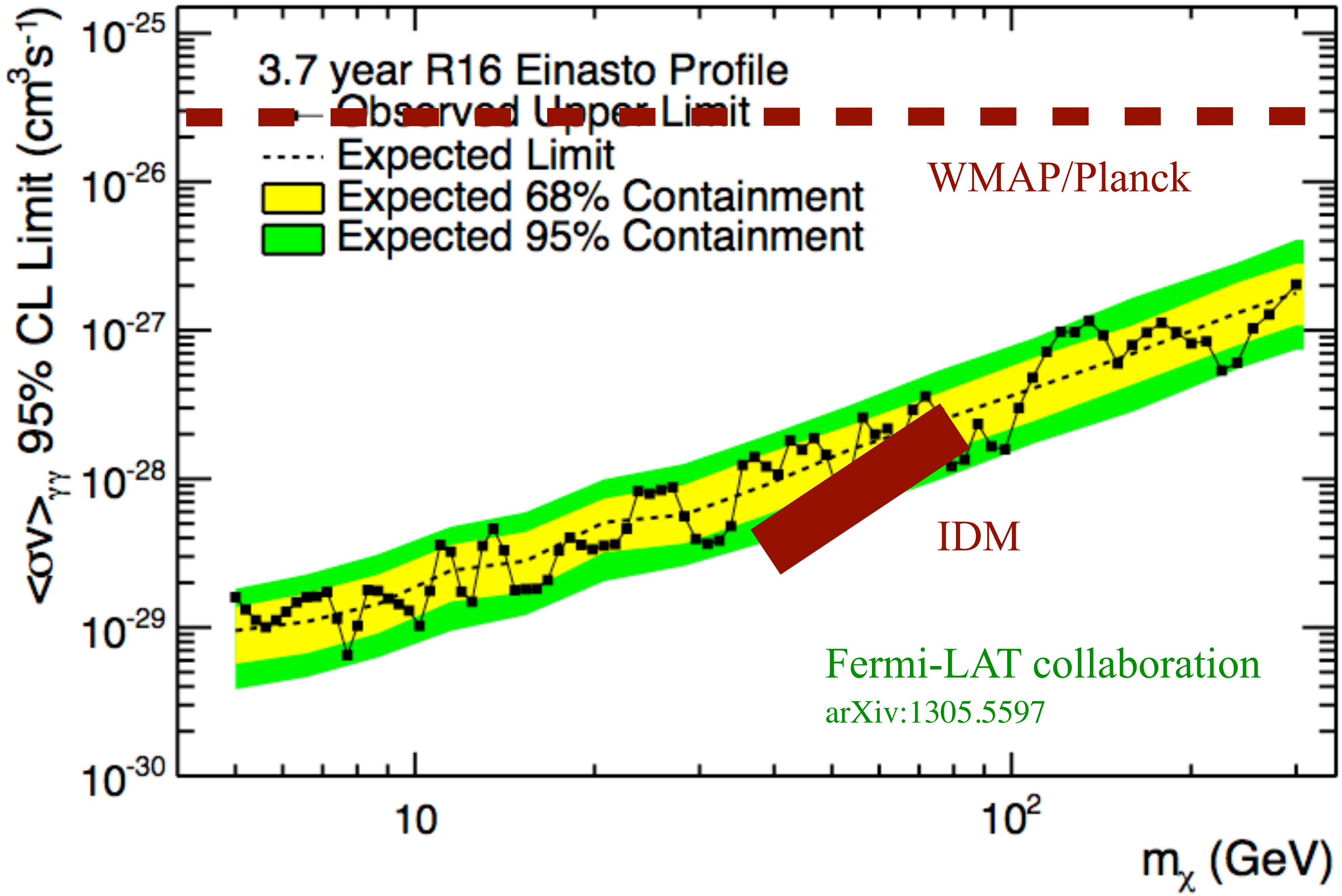
Fermi-LAT limits on gamma ray lines

CURRENT EXPERIMENTAL LIMITS



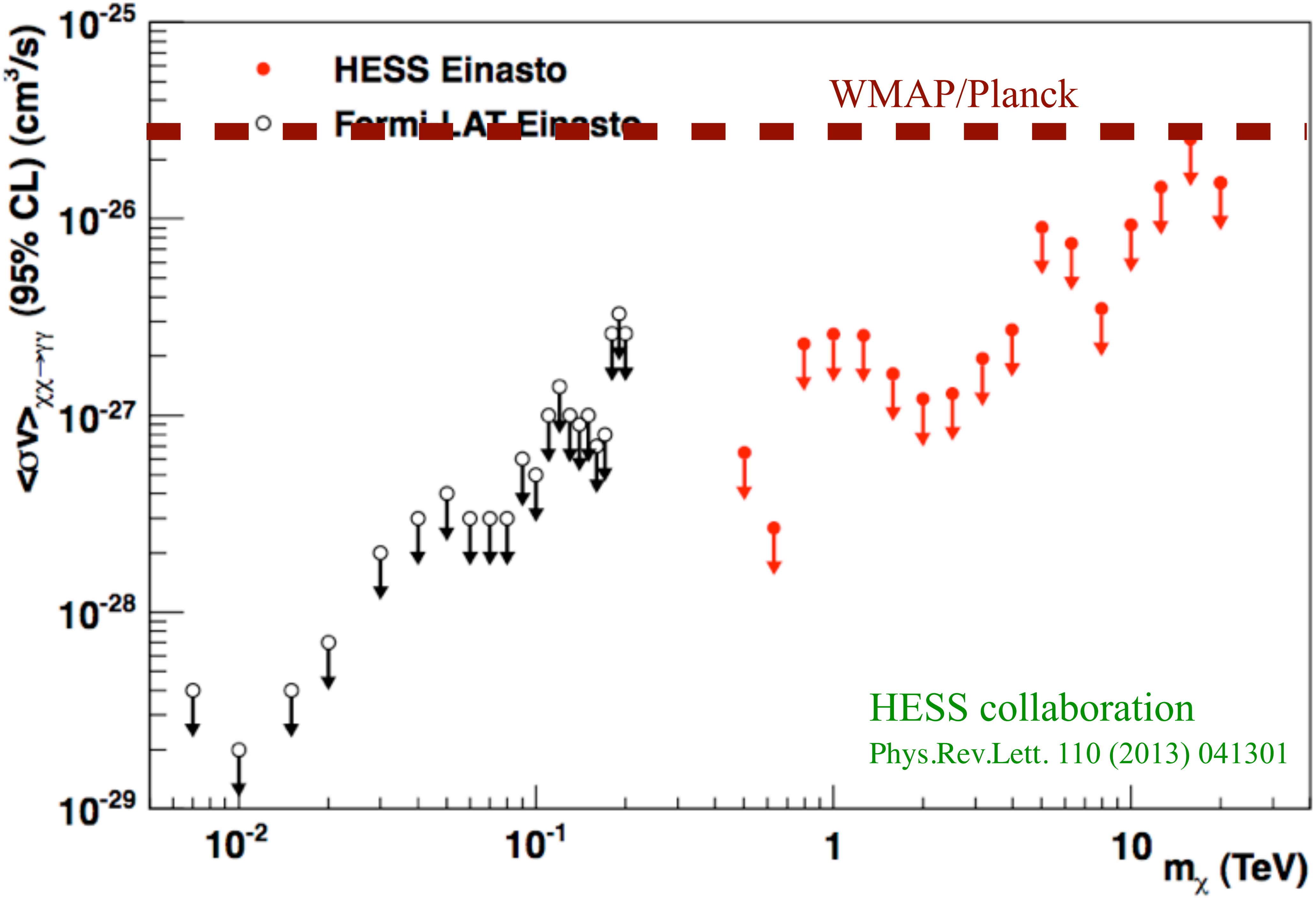
Fermi-LAT limits on gamma ray lines

CURRENT EXPERIMENTAL LIMITS



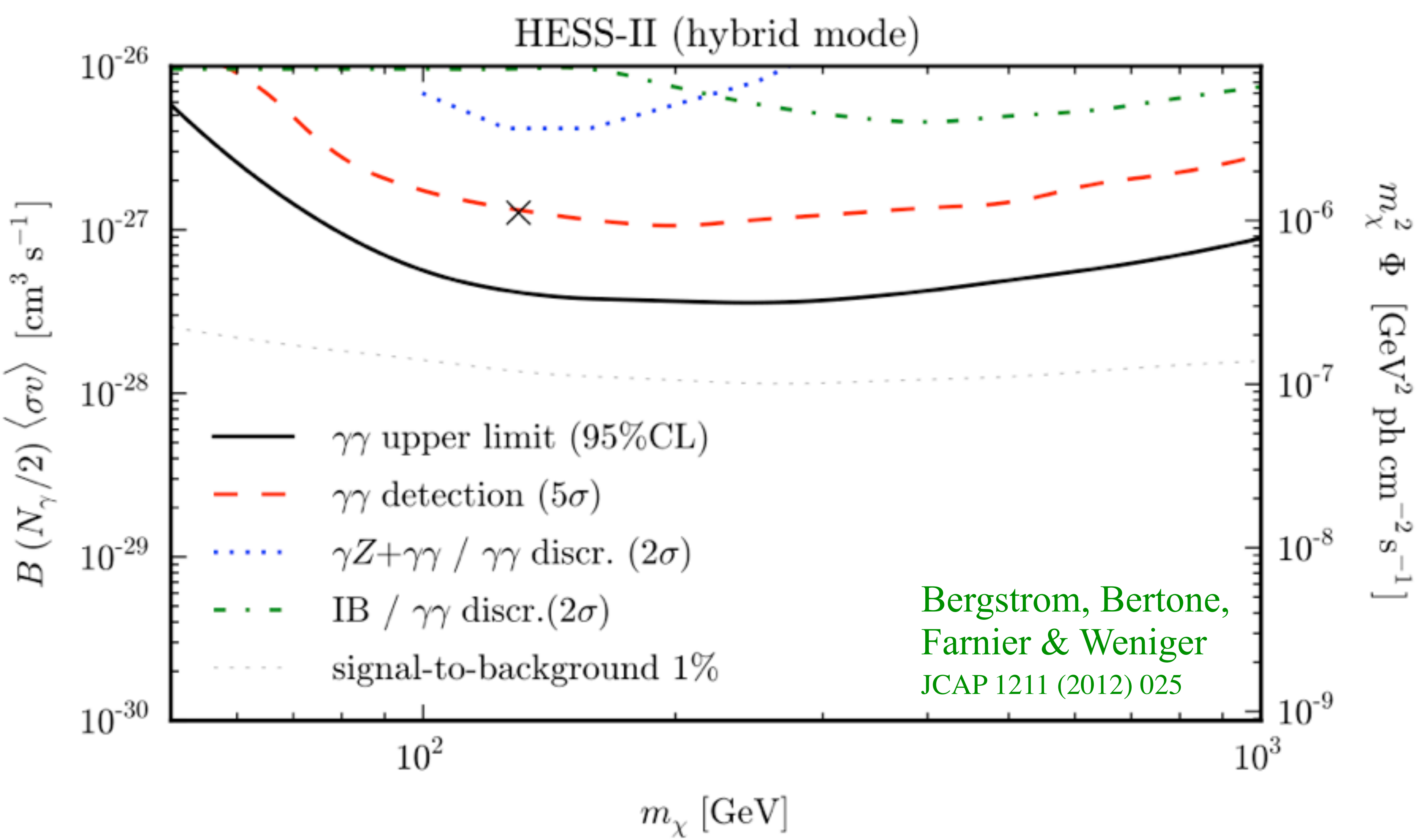
Fermi-LAT limits on gamma ray lines

CURRENT EXPERIMENTAL LIMITS



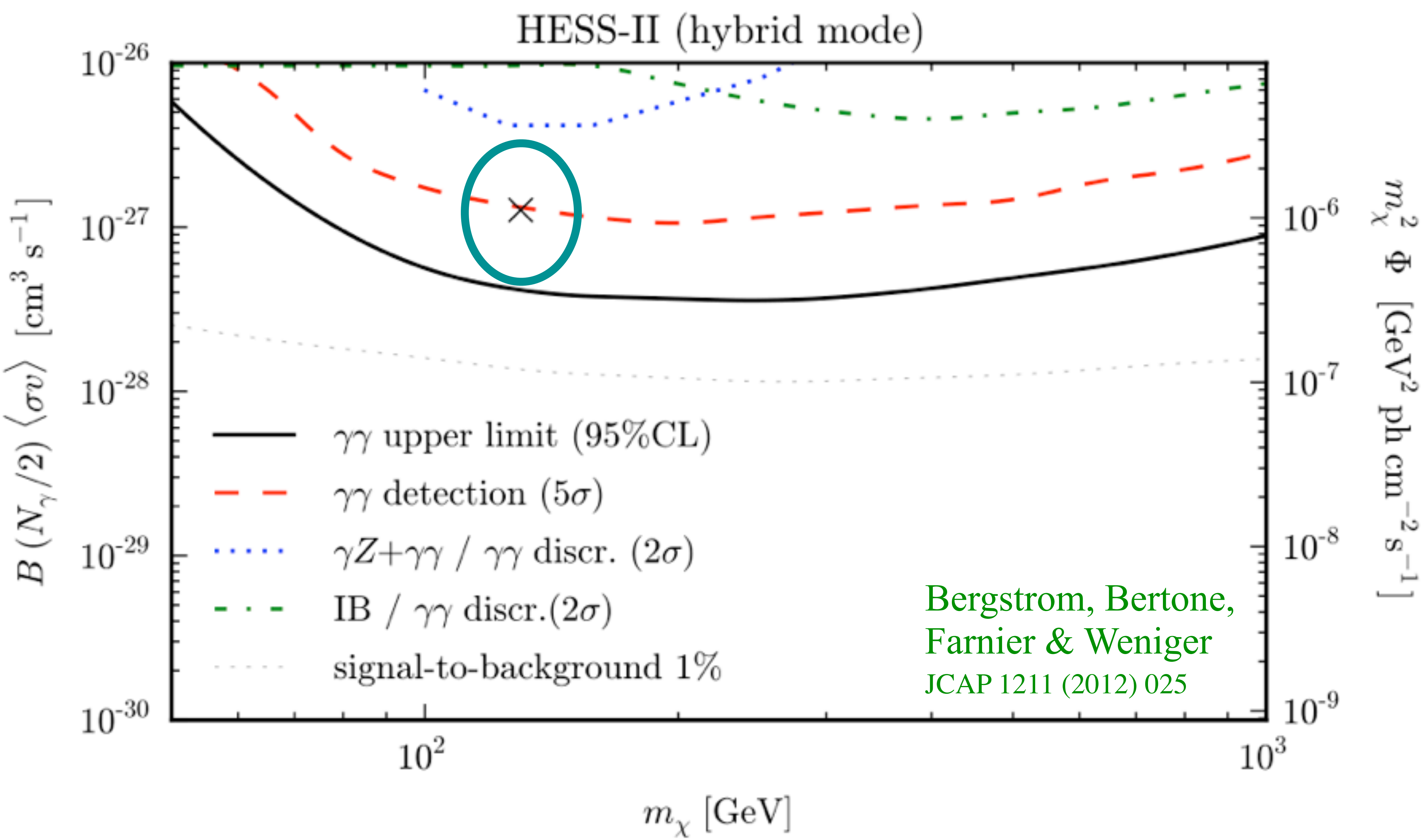
HESS limits on gamma ray lines

NEAR FUTURE LIMITS



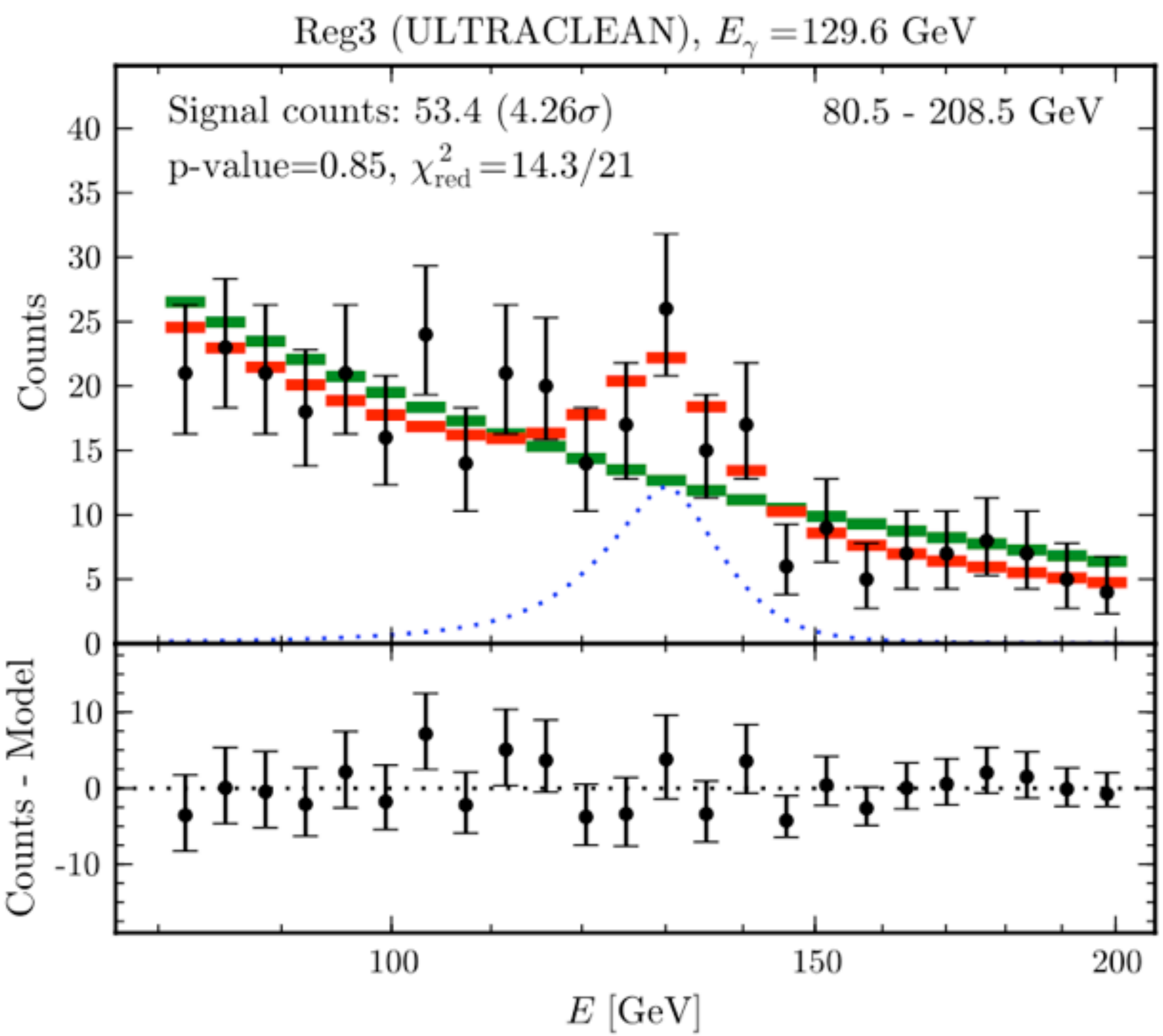
HESS-II will fill the gap between Fermi-LAT and HESS (2014?)

NEAR FUTURE LIMITS



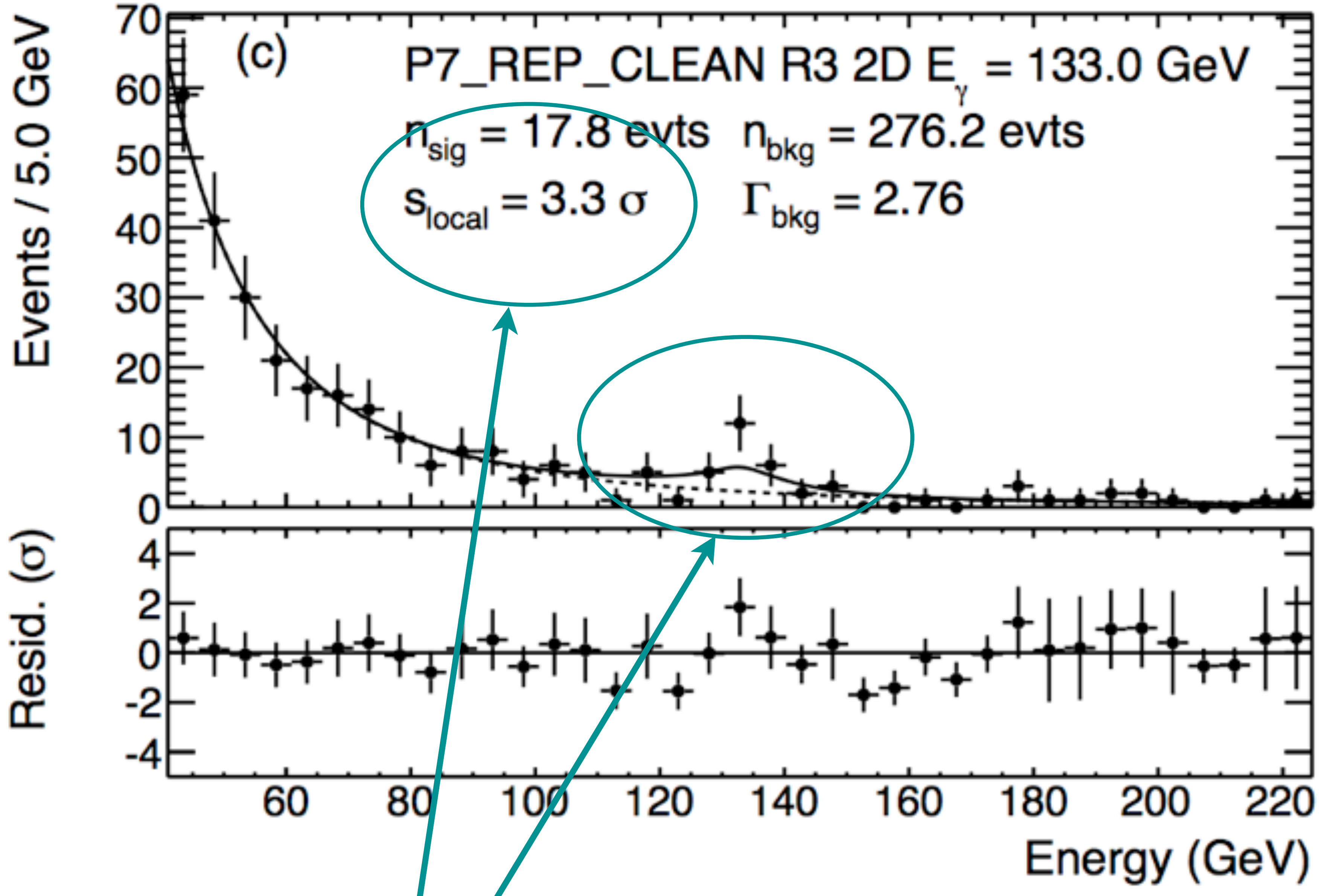
HESS-II will fill the gap between Fermi-LAT and HESS (2014?)

the Fermi-LAT/Weniger 130 GeV line



Weniger
JCAP 1208 (2012) 007
See also Brigmann, Huang, Ibarra, Vogl & Weniger
JCAP 1207 (2012) 054

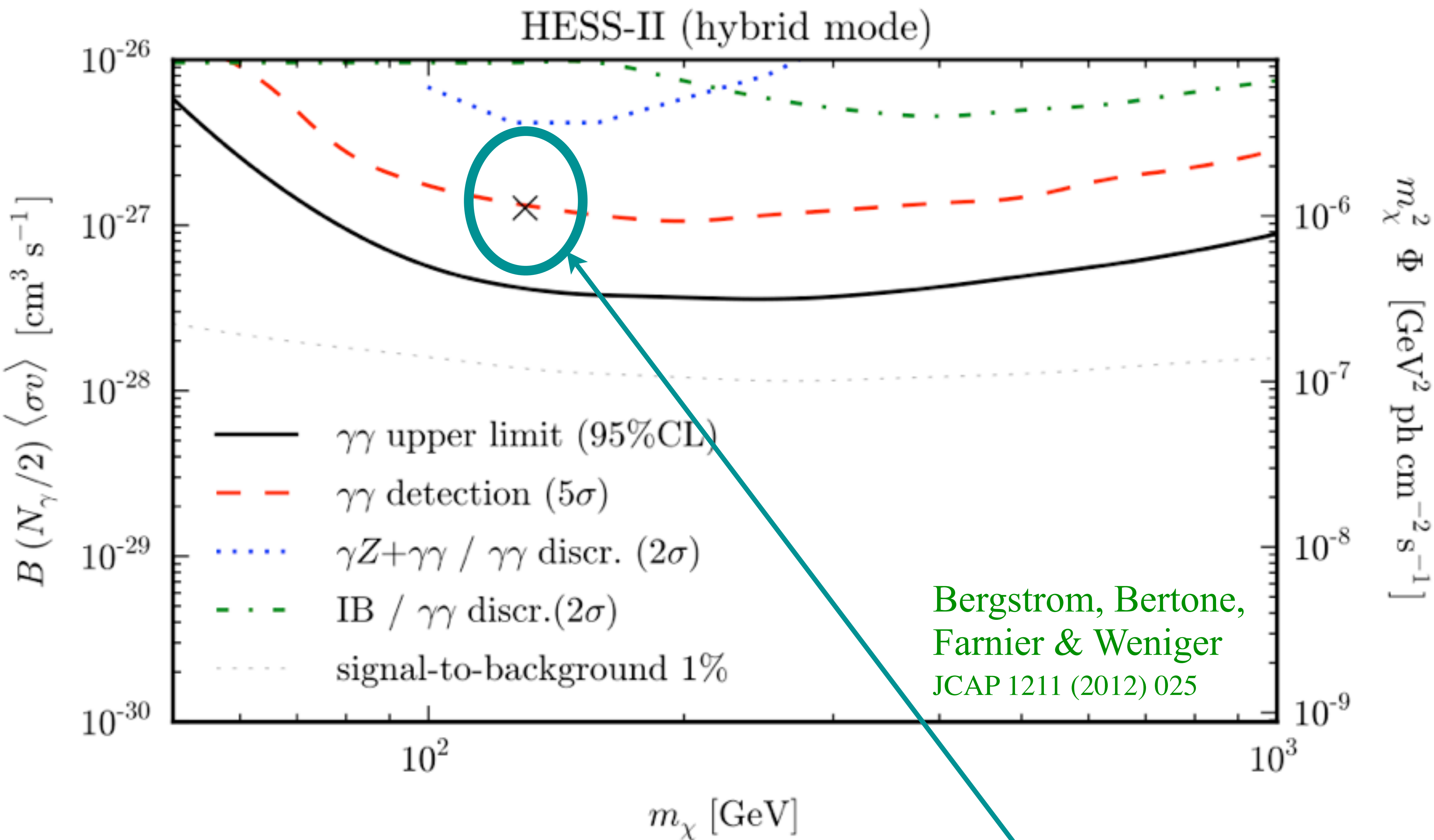
the Fermi-LAT/Weniger 130 GeV line



Fermi-LAT collaboration
arXiv:1305.5597

global significance (LEE) is less than 2σ

NEAR FUTURE LIMITS



will also test the 130 GeV line at the GC (2014?)

I. GAMMA RAY SPECTRAL FEATURES

II. PROBLEM & MOTIVATION

III. MAJORANA DM

IV. REAL SCALAR DM

V. PROSPECTS

$$DM\ DM \rightarrow SM\ SM$$

WMAP/Planck REQUIRE

$$\langle \sigma v \rangle \approx 3 \cdot 10^{-26} \mathrm{cm}^3 \cdot \mathrm{s}^{-1}$$

THAT MAY BE IN THE EARLY UNIVERSE

MAY BE MUCH SMALLER*
AT THE GALACTIC CENTRE

* For that matter, it may be larger *e.g.* through resonant annihilation or Sommerfeld enhancement. This is not considered here.

EARLY UNIVERSE

s-wave p-wave

$$\langle \sigma v \rangle = a + b\langle v^2 \rangle + c\langle v^4 \rangle + \ldots = a + 6\, b\, x_f + 60\, c\, x_f^2 + \ldots$$

with $x_f = \dfrac{T_{fo}}{M_{DM}}$ $\qquad \langle v^2 \rangle \approx 0.3$ at freeze-out

GALACTIC CENTRE

$$v \sim 10^{-3}$$

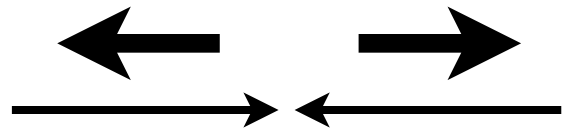
IF S-WAVE (a) SMALL $\longrightarrow$ $\langle \sigma v \rangle_{GC} \ll \langle \sigma v \rangle_{fo}$

ANNIHILATION OF MAJORANA DM INTO LIGHT FERMIONS

Goldberg
«Constraint on the Photino mass from cosmology»
Phys.Rev.Lett. 50 (1983) 1419

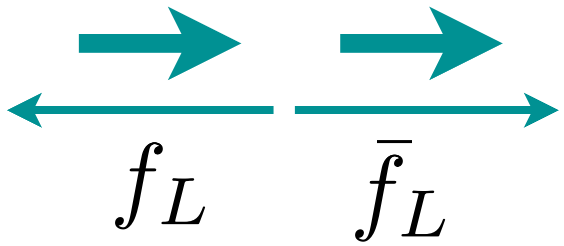
$$\chi\chi \to f\bar{f}$$

S-WAVE INITIAL STATE



CP-ODD

FINAL STATE



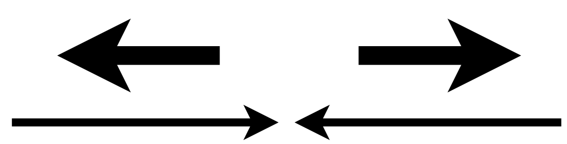
CP-EVEN

ANNIHILATION OF MAJORANA DM INTO LIGHT FERMIONS

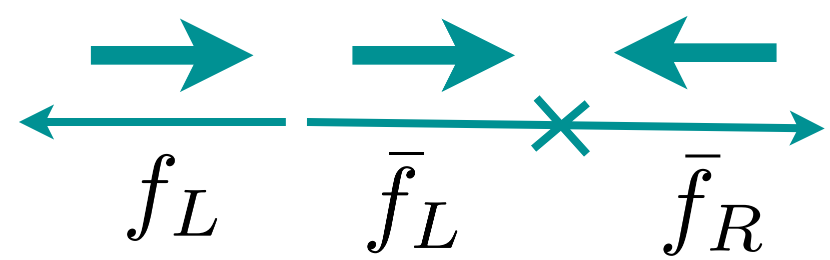
Goldberg
«Constraint on the Photino mass from cosmology»
Phys.Rev.Lett. 50 (1983) 1419

$$\chi\chi \to f\bar{f}$$

S-WAVE INITIAL STATE



FINAL STATE



S-WAVE ANNIHILATION
IS CHIRALLY SUPPRESSED

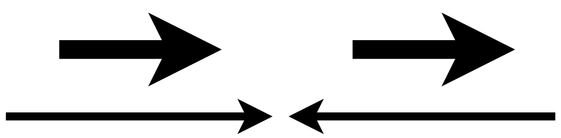
$$\boxed{\sigma v \propto y_f^4 \frac{m_f^2}{M_\chi^4}}$$

ANNIHILATION OF MAJORANA DM INTO LIGHT FERMIONS

Goldberg
«Constraint on the Photino mass from cosmology»
Phys.Rev.Lett. 50 (1983) 1419

$$\chi\chi \to f\bar{f}$$

P-WAVE INITIAL STATE



FINAL STATE

$f_L \quad \bar{f}_L$

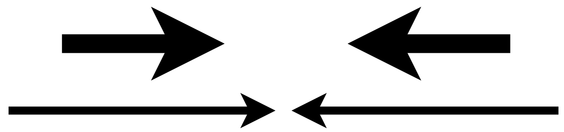
P-WAVE SUPPRESSED
IN CHIRAL LIMIT

$$\boxed{\sigma v \propto y_f^4 \frac{v^2}{M_\chi^2}}$$

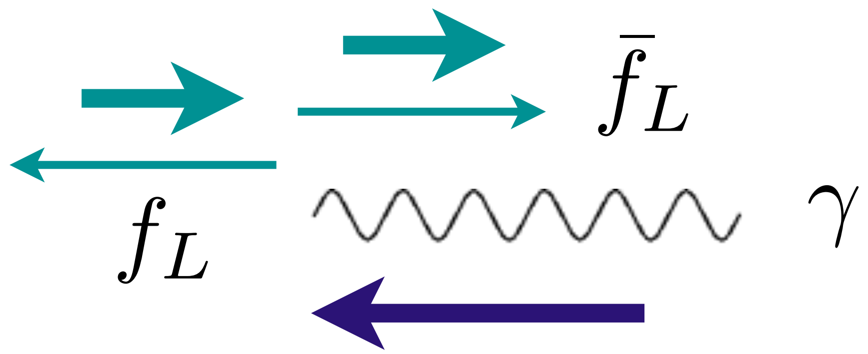
VIRTUAL INTERNAL BREMSSTRAHLUNG IS S-WAVE! *

$$\chi\chi \to f\bar{f}\gamma$$

S-WAVE INITIAL STATE



FINAL STATE



VIB suppressed by α_{em} (and phase-space) but otherwise dominant process at GC!!!

Bergstrom
Phys.Lett. B **225** (1989), 372

Bergstrom, Bringmann & Edsjo
JHEP 0801 (2008) 049

* NB: FSR is $\propto \langle \sigma v \rangle_{f\bar{f}}$ hence negligible in this scenario

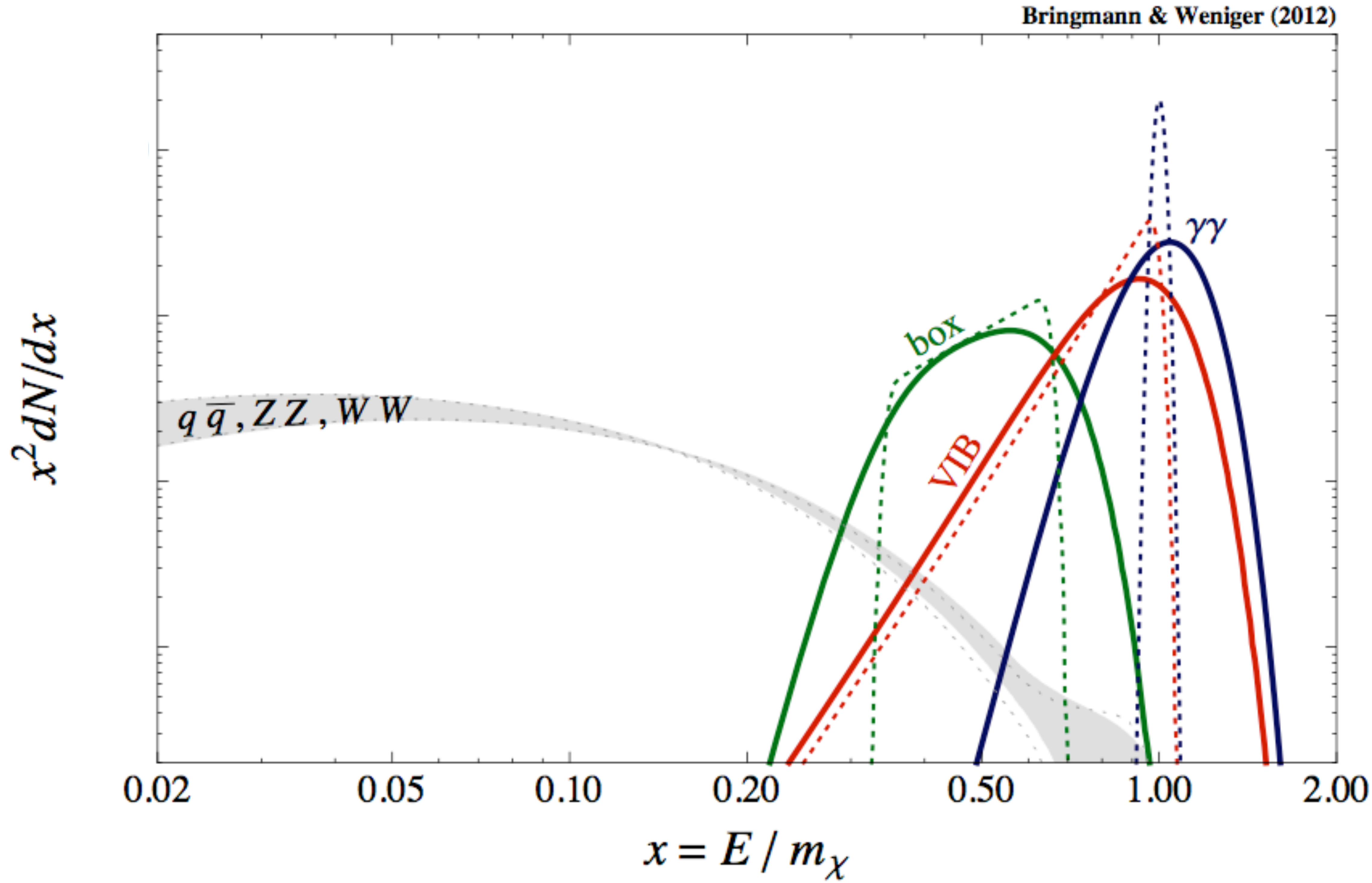
SUMMARY MAJORANA DM

EARLY UNIVERSE

$$\langle \sigma v \rangle_{fo} \approx b \langle v^2 \rangle \approx 0.3\, b \qquad\qquad \chi\chi \to f\bar{f}$$

GALACTIC CENTRE

$$\langle \sigma v \rangle_{GC} = \mathcal{O}(\alpha) \qquad\qquad \chi\chi \to f\bar{f}\gamma$$


Bringmann & Weniger (2012)
$x^2 dN/dx$
$q\,\bar{q}\,,ZZ\,,WW$
box
VIB
$\gamma\gamma$
0.02
0.05
0.10
0.20
0.50
1.00
2.00
$x = E\,/\,m_\chi$

MANY WORKS ON MAJORANA CASE

NEUTRALINO (of course)

See for instance

Torsten Bringmann & Francesca Calore
«Significant enhancement of neutralino dark matter annihilation»
arXiv:1308.1089

ALSO MERE TOY MODELS

See for instance

Mathias Garny, Alejandro Ibarra & Stefan Vogl
«Dark matter annihilation into two light fermions and one gauge boson»
arXiv:1112.5155

«The 130 GeV Fingerprint of Right-handed Neutrino Dark Matter»

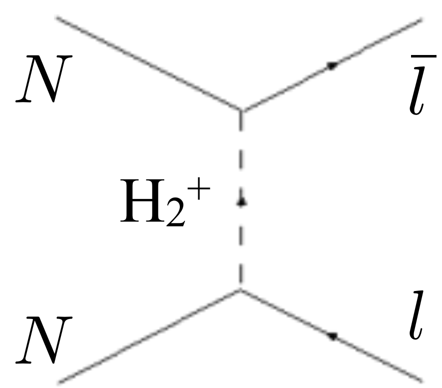
L. Bergstrom, arXiv:1208.6082

$$\mathcal{L} \supset y_l \bar{L} H_2 N + M_N N^T C N + h.c.$$

E. Ma, hep-ph/06011225

INERT DOUBLET (actually Krauss-Nasri-Trodden model, but does not matter)

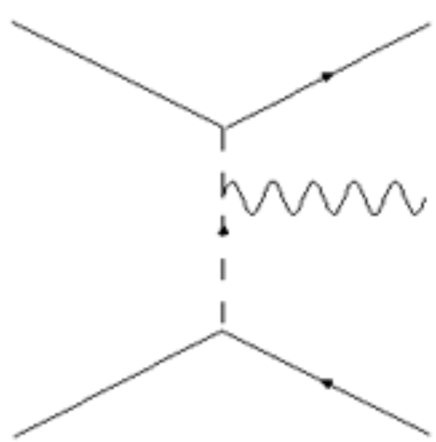
EARLY UNIVERSE

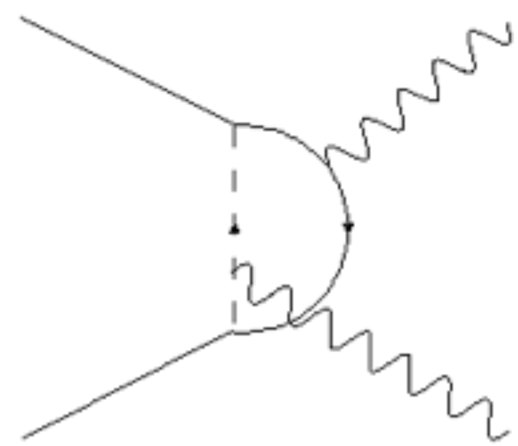


$$\sigma v \propto \frac{y_l^4}{M_H^4} \left(\cancel{m_l^2} + 2/3 M_N^2 \beta^2\right)$$

$$\langle \sigma v \rangle \approx 3 \cdot 10^{-26}\, \mathrm{cm}^3 \cdot \mathrm{s}^{-1}$$

GALACTIC CENTRE





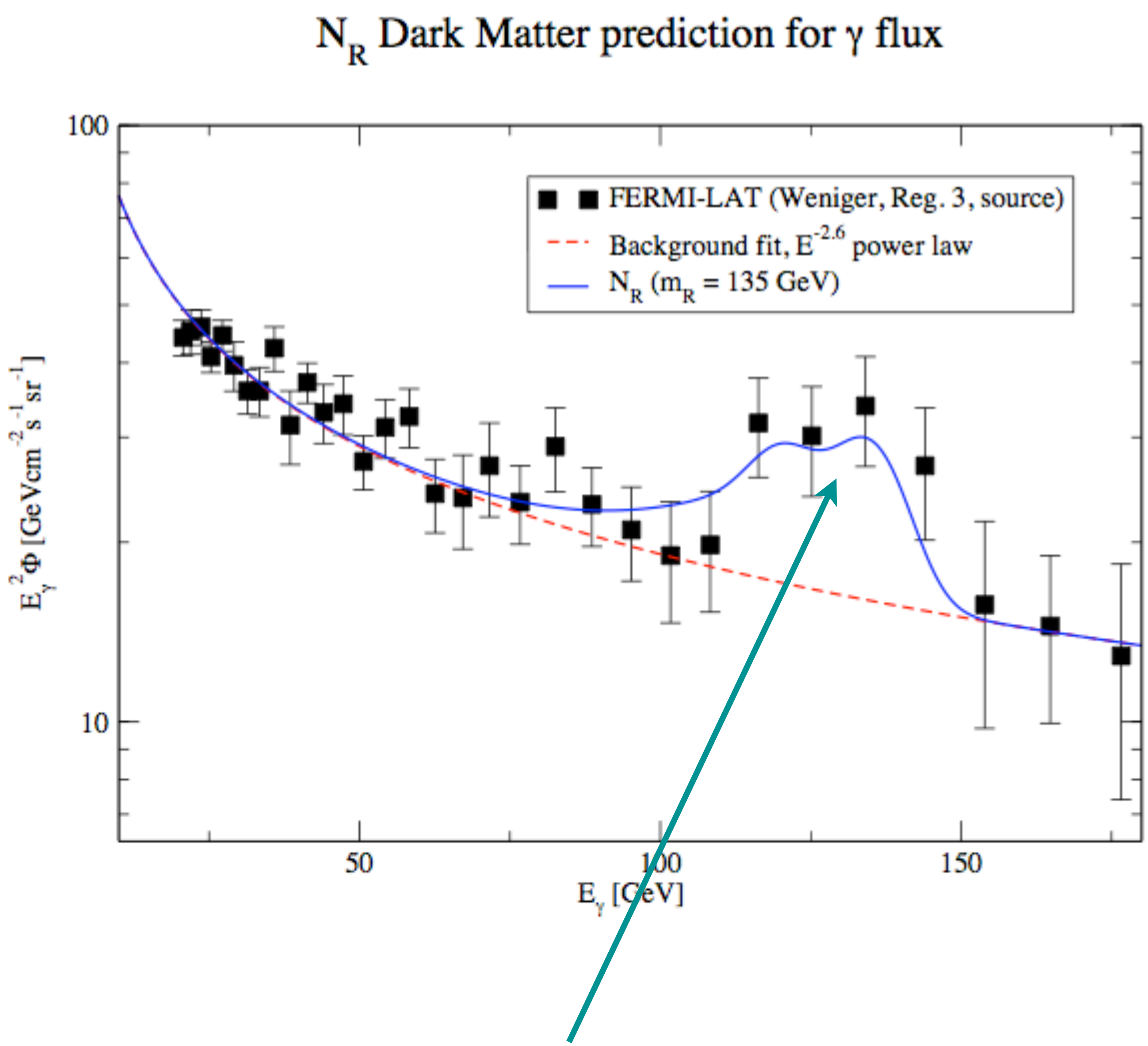
Bergstrom & Baltz, 2002

$$\langle \sigma v \rangle \approx 6.7 \cdot 10^{-29} \mathrm{cm}^3 \mathrm{s}^{-1}$$

$$\langle \sigma v \rangle \approx 2.3 \cdot 10^{-29} \mathrm{cm}^3 \mathrm{s}^{-1}$$

«The 130 GeV Fingerprint of Right-handed Neutrino Dark Matter»

L. Bergstrom, arXiv:1208.6082



NEED AN *O*(10) BOOST FACTOR

(Einasto profile)

I. GAMMA RAY SPECTRAL FEATURES

II. PROBLEM & MOTIVATION

III. MAJORANA DM

IV. REAL SCALAR DM

V. PROSPECTS

ANNIHILATION OF REAL SCALAR DM INTO LIGHT FERMIONS

toy model $\mathcal{L} \supset y_l \, S \, \bar{\Psi} \, l_R + h.c.$

real singlet scalar

vector-like heavy lepton

$$S \longrightarrow -S$$

Z_2 symmetry

S dark matter

$$\Psi \longrightarrow -\Psi$$

➡ VECTOR-LIKE PORTAL

P. Fileviez Perez, M.B. Wise
arXiv:1303.1452

ANNIHILATION OF REAL SCALAR DM INTO LIGHT FERMIONS

$SS \to f\bar{f}$ is <u>d-wave</u> suppressed

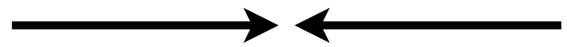
Takashi Toma
arXiv:1307.6181 (July 23)
Giacchino, Lopez Honorez & M.T.
arXiv:1307.6480 (July 24)

$$\sigma v(SS \to l\bar{l}) = \frac{y_l^4}{60\pi}\frac{v^4}{M_S^2}\frac{1}{(1+r^2)^4}$$

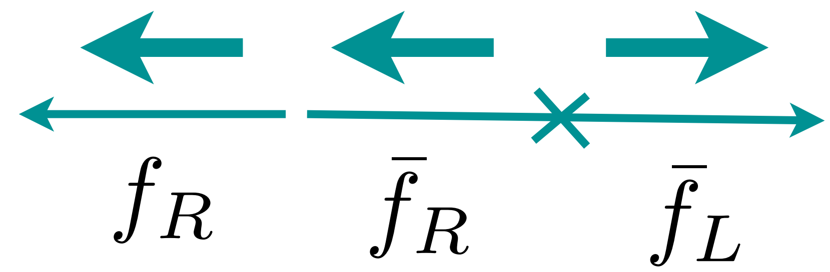
$$r = \frac{M_\Psi}{M_S} > 1$$

$$\langle v^4 \rangle = 60\, x_f^2 \sim 0.1 < \langle v^2 \rangle$$

S-WAVE INITIAL STATE

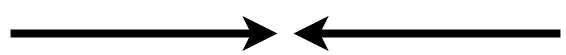


FINAL STATE

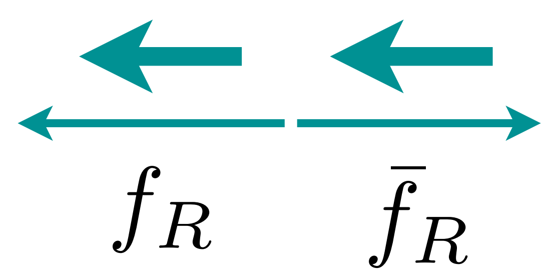


$$\mathcal{O}_S = m_f \, S^2 \, \bar{\psi}_f \psi_f$$

P-WAVE INITIAL STATE



FINAL STATE



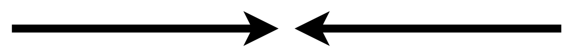
CP-ODD

CP-EVEN

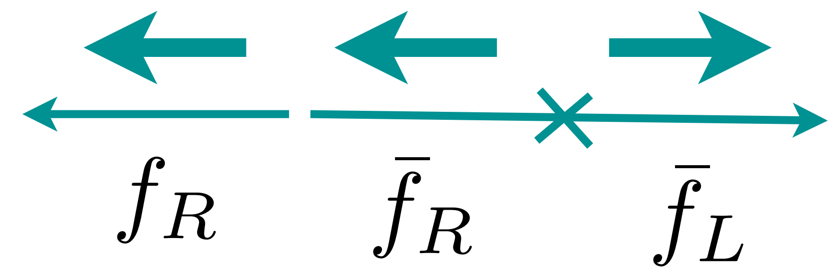
$$\mathcal{O}_P = \cancel{A} \partial_\mu S \, \bar{\psi}_f \gamma^\mu \psi_f$$

a complex scalar would have p-wave annihilation

S-WAVE INITIAL STATE

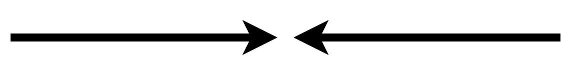


FINAL STATE

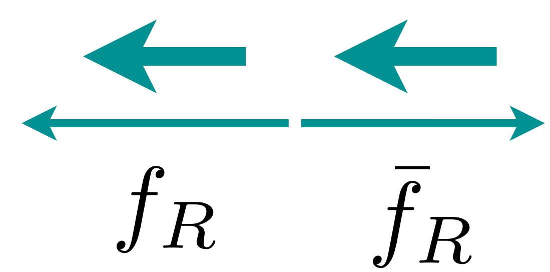


$$\mathcal{O}_S = m_f\, S^2\, \bar{\psi}_f \psi_f$$

D-WAVE INITIAL STATE



FINAL STATE



CP-EVEN

CP-EVEN

$$\mathcal{O}_T = \partial_\mu S \partial_\nu S\, \Theta^{\mu\nu}_{f_R}$$

FERMION
STRESS-ENERGY TENSOR

$$\sigma v(SS \to l\bar{l}) = \frac{y_l^4}{60\pi}\frac{v^4}{M_S^2}\frac{1}{(1+r^2)^4}$$

vs

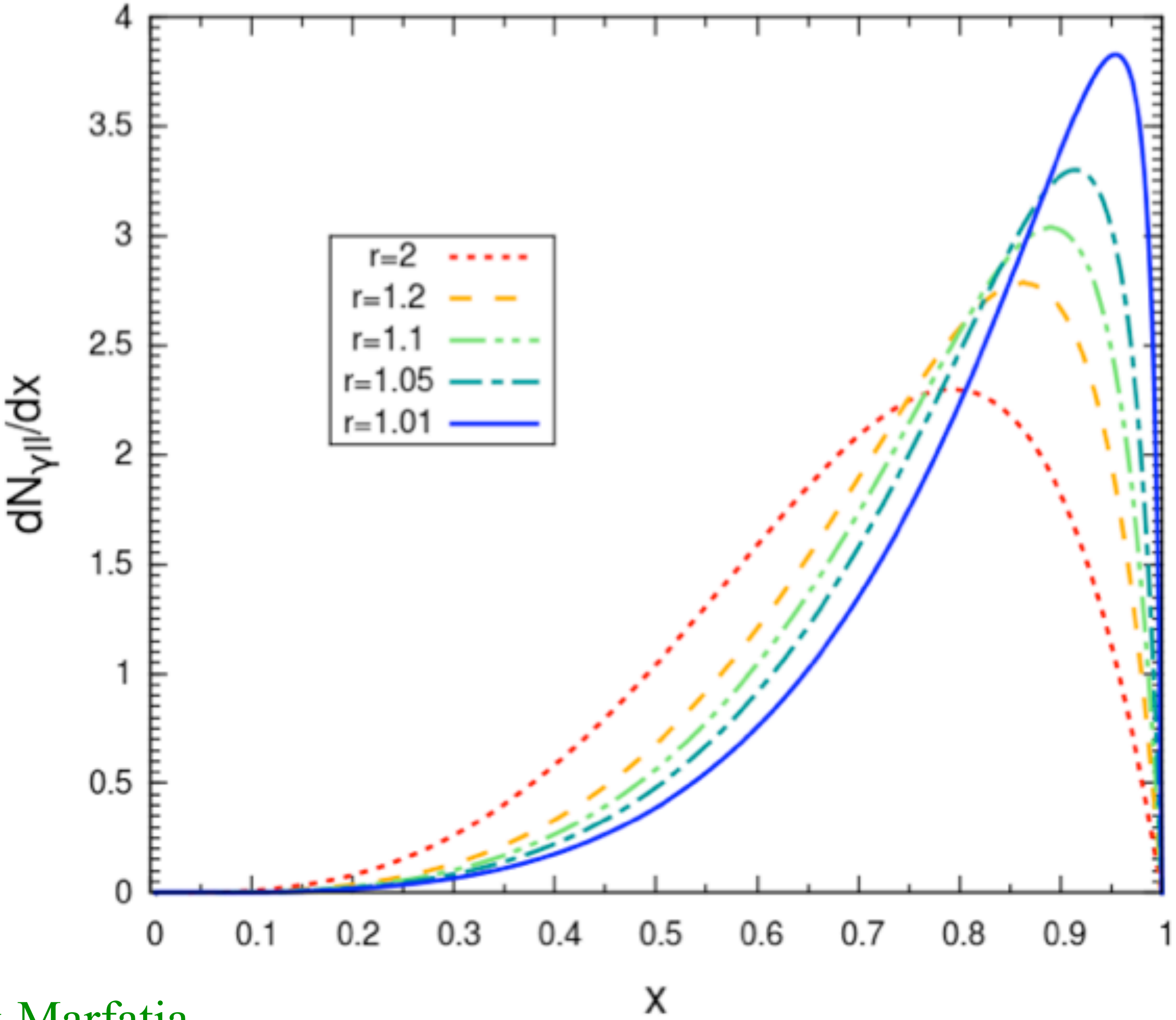
$$r = \frac{M_\Psi}{M_S} > 1$$

$$\sigma v(\chi\chi \to l\bar{l}) = \frac{g_l^4}{48\pi}\frac{v^2}{M_\chi^2}\frac{1+r^4}{(1+r^2)^4}$$

$$\rightarrow \quad \frac{\langle\sigma v\rangle_S}{\langle\sigma v\rangle_\chi} = \frac{4y_l^4\langle v^4\rangle}{5g_l^4\langle v^2\rangle(1+r^4)} < 0.16\,\frac{y_l^4}{g_l^4} \qquad \text{for r =1}$$

Thus, *mutatis mutandis,* it takes a **larger coupling** for S than for χ to match WMAP/Planck

gamma ray spectrum precisely the same as for $\chi\chi \to f\bar{f}\gamma$



Barger, Keung & Marfatia
arXiv:1111.4523

Takashi Toma
arXiv:1307.6181

Giacchino, Lopez Honorez & M.T.
arXiv:1307.6480

How come? An effective interaction perspective

SCALAR

$$\mathcal{O}_S = \left(\partial_\mu \bar{l} \gamma_\nu l_R + \bar{l}_R \gamma_\nu \partial_\mu l_R\right) F^{\mu\nu}$$

MAJORANA

$$\mathcal{O}_\chi = \left(\partial_\mu \bar{l}_R \gamma_\nu l_R + \bar{l}_R \gamma_\nu \partial_\mu l_R\right) \tilde{F}^{\mu\nu}$$

merely amounts to $\vec{E} \rightarrow \vec{B}$

but there is a factor of 8

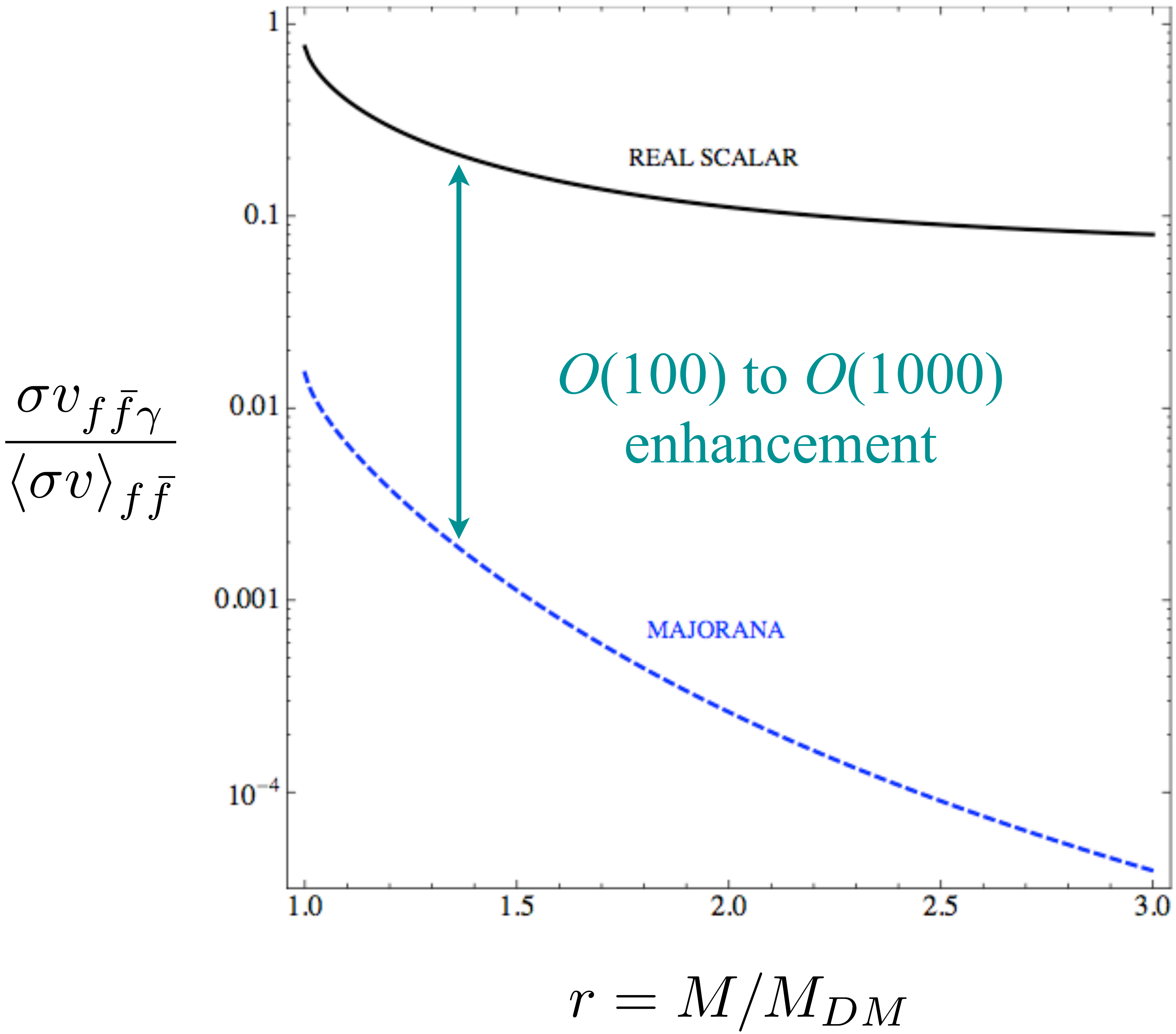
$$\frac{\sigma(SS \to f\bar{f}\gamma)}{\sigma(\chi\chi \to f\bar{f}\gamma)} = \frac{8y_l^4}{g_l^4}$$

while

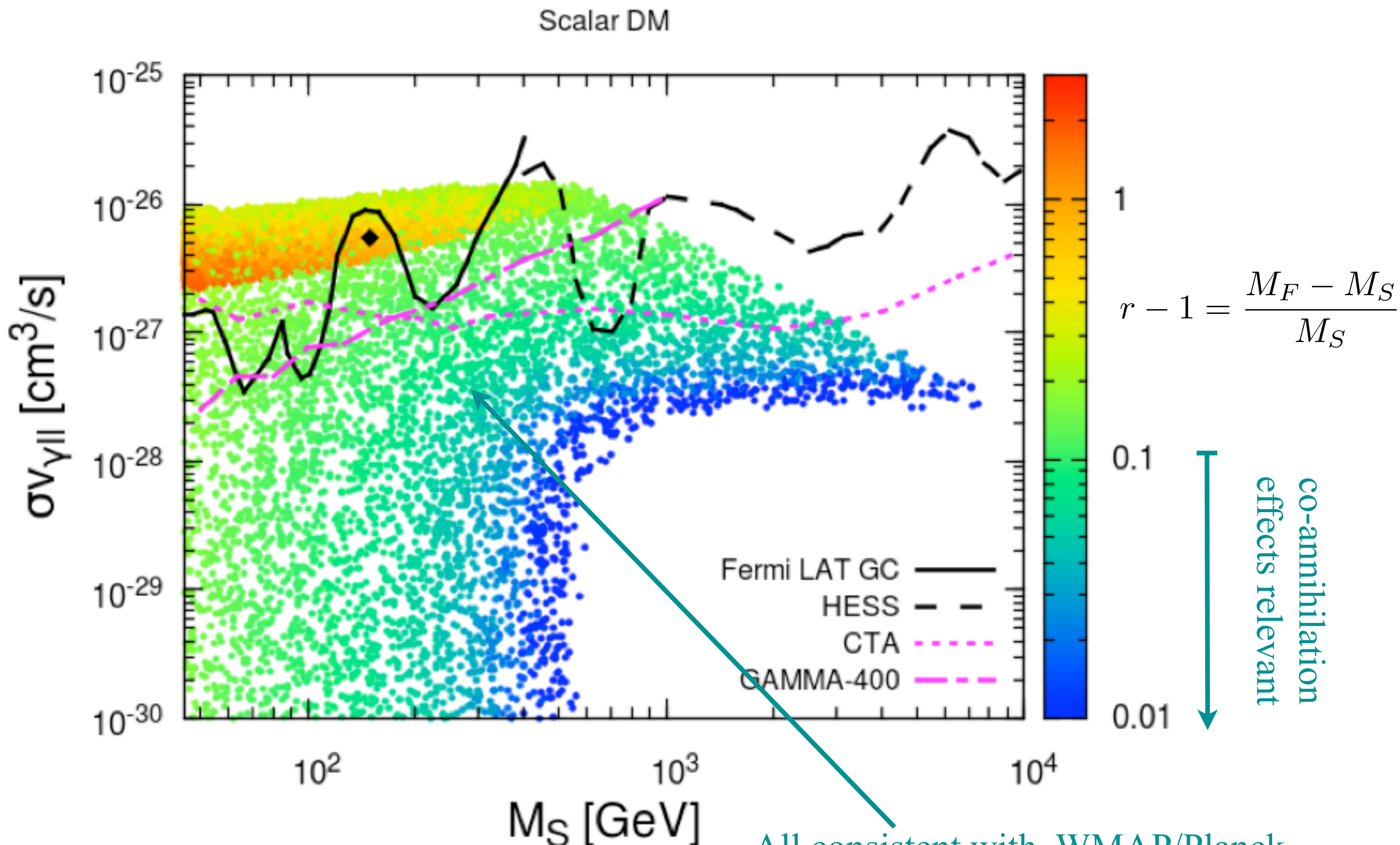
$$\frac{\langle\sigma v\rangle_{SS\to f\bar{f}}}{\langle\sigma v\rangle_{\chi\chi\to f\bar{f}\gamma}} < 0.16\,\frac{y_l^4}{g_l^4}$$

bottom-line: significant VIB signal for real scalar!

Takashi Toma
arXiv:1307.6181
Giacchino, Lopez Honorez & M.T.
arXiv:1307.6480

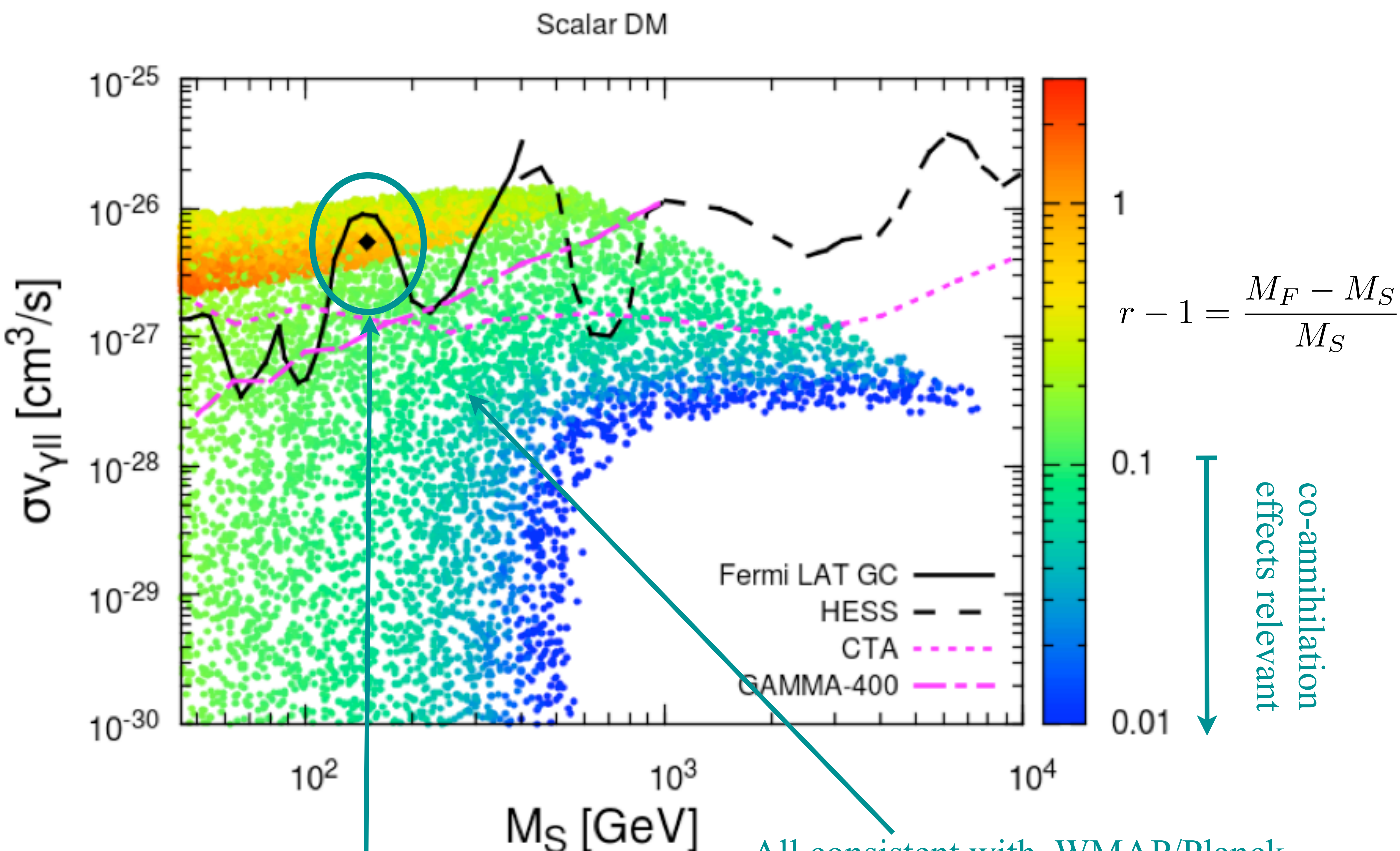


REAL SCALAR
MAJORANA
$O(100)$ to $O(1000)$
enhancement
$\frac{\sigma v_{f\bar{f}\gamma}}{\langle \sigma v \rangle_{f\bar{f}}}$
$r = M/M_{DM}$
1
0.1
0.01
0.001
10^{-4}
1.0
1.5
2.0
2.5
3.0



All consistent with WMAP/Planck

Also $SS \to \gamma\gamma$,γZ etc...

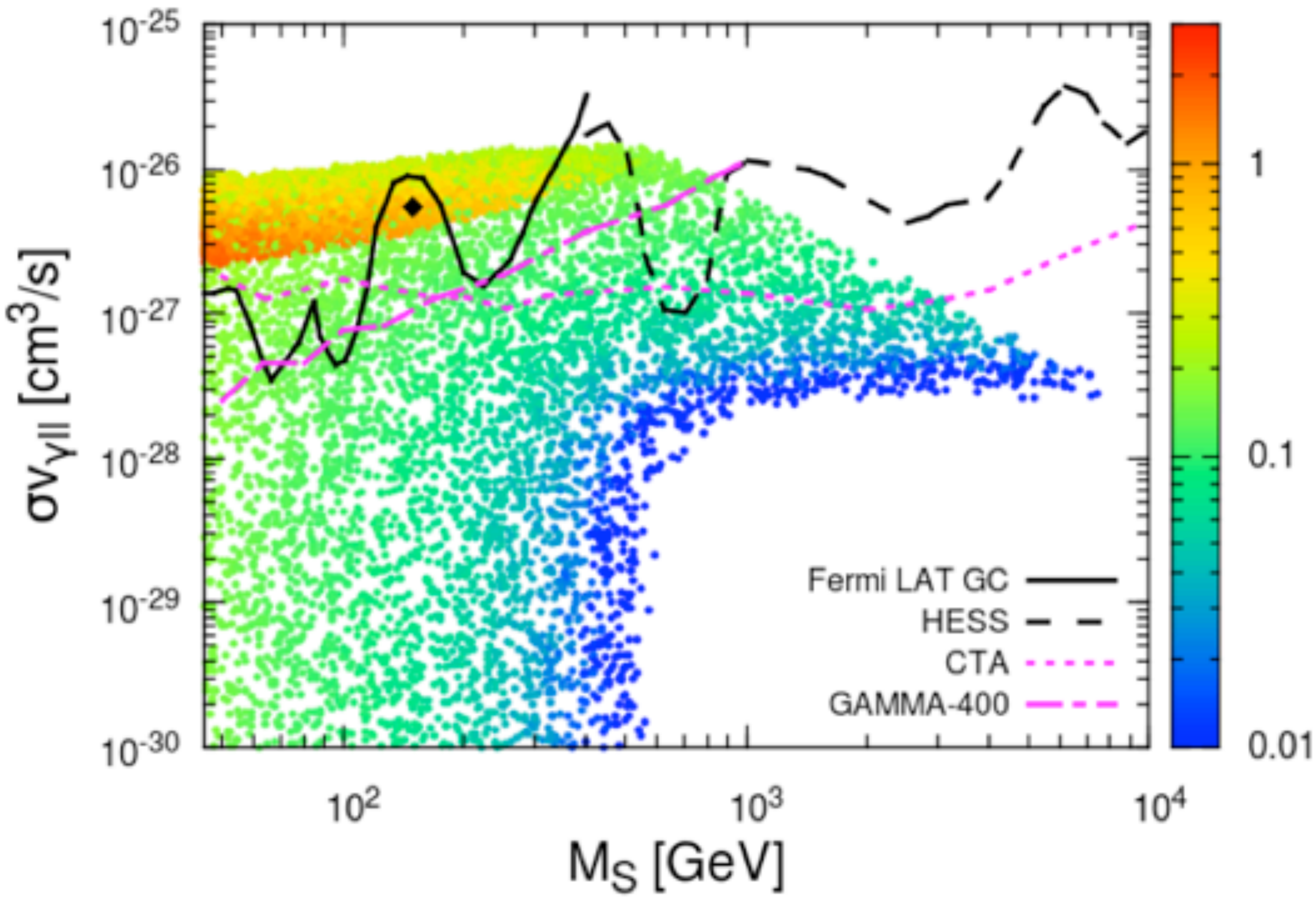


All consistent with WMAP/Planck
Also $SS \to \gamma\gamma$,γZ etc...

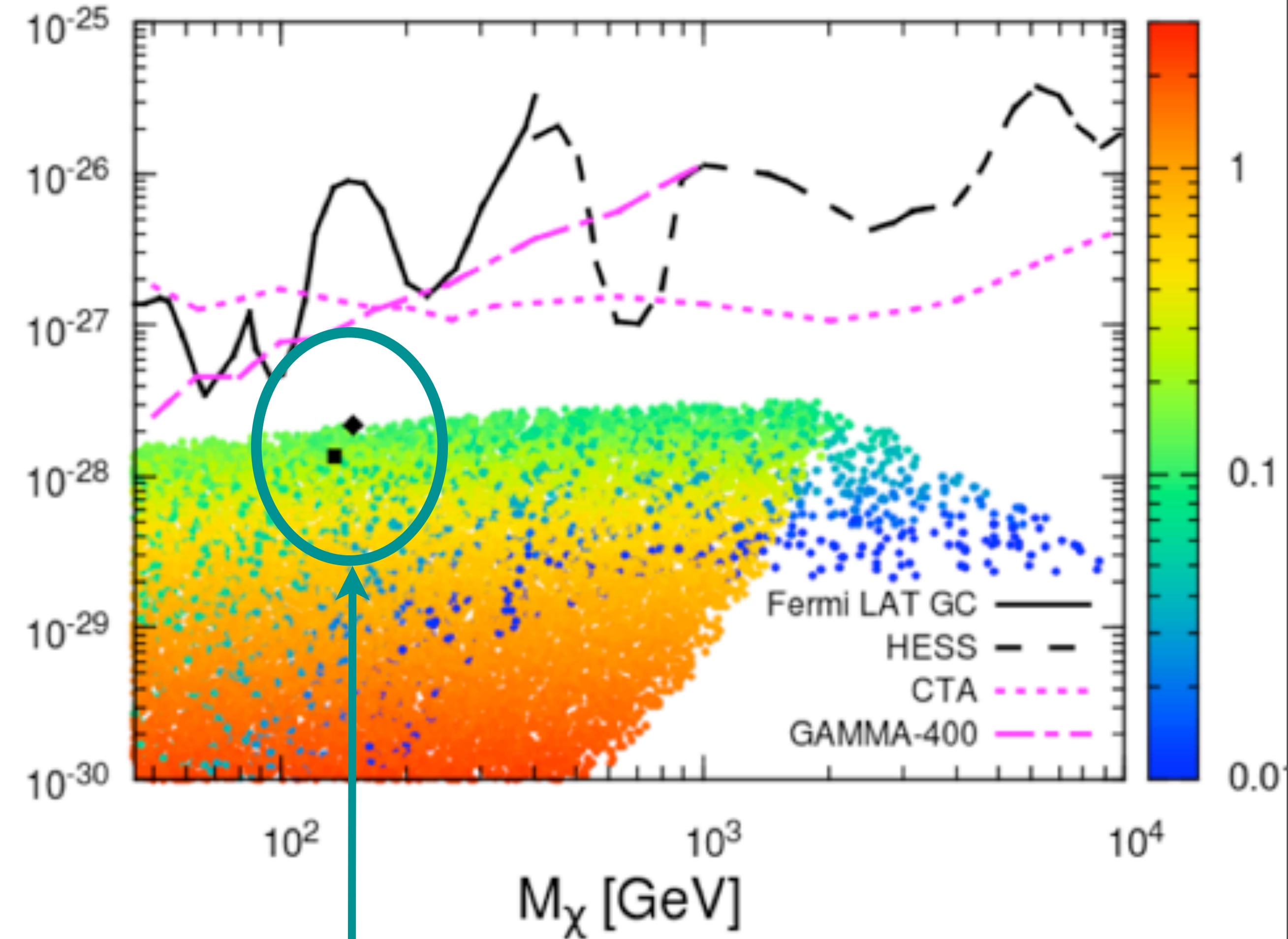
145 GeV candidate
(~130 GeV Fermi-LAT excess)

See also
Takashi Toma
arXiv:1307.6181

SCALAR

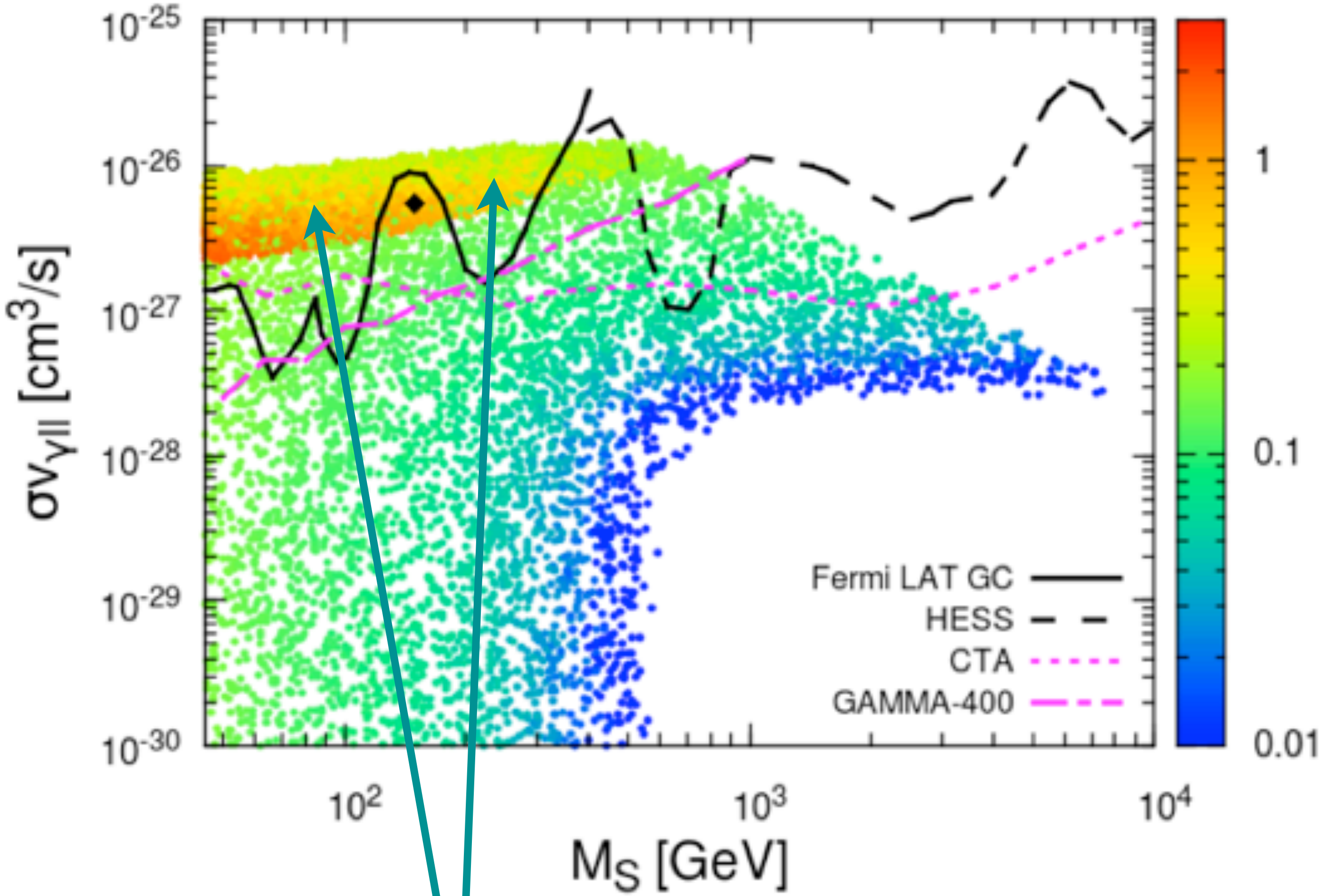


MAJORANA

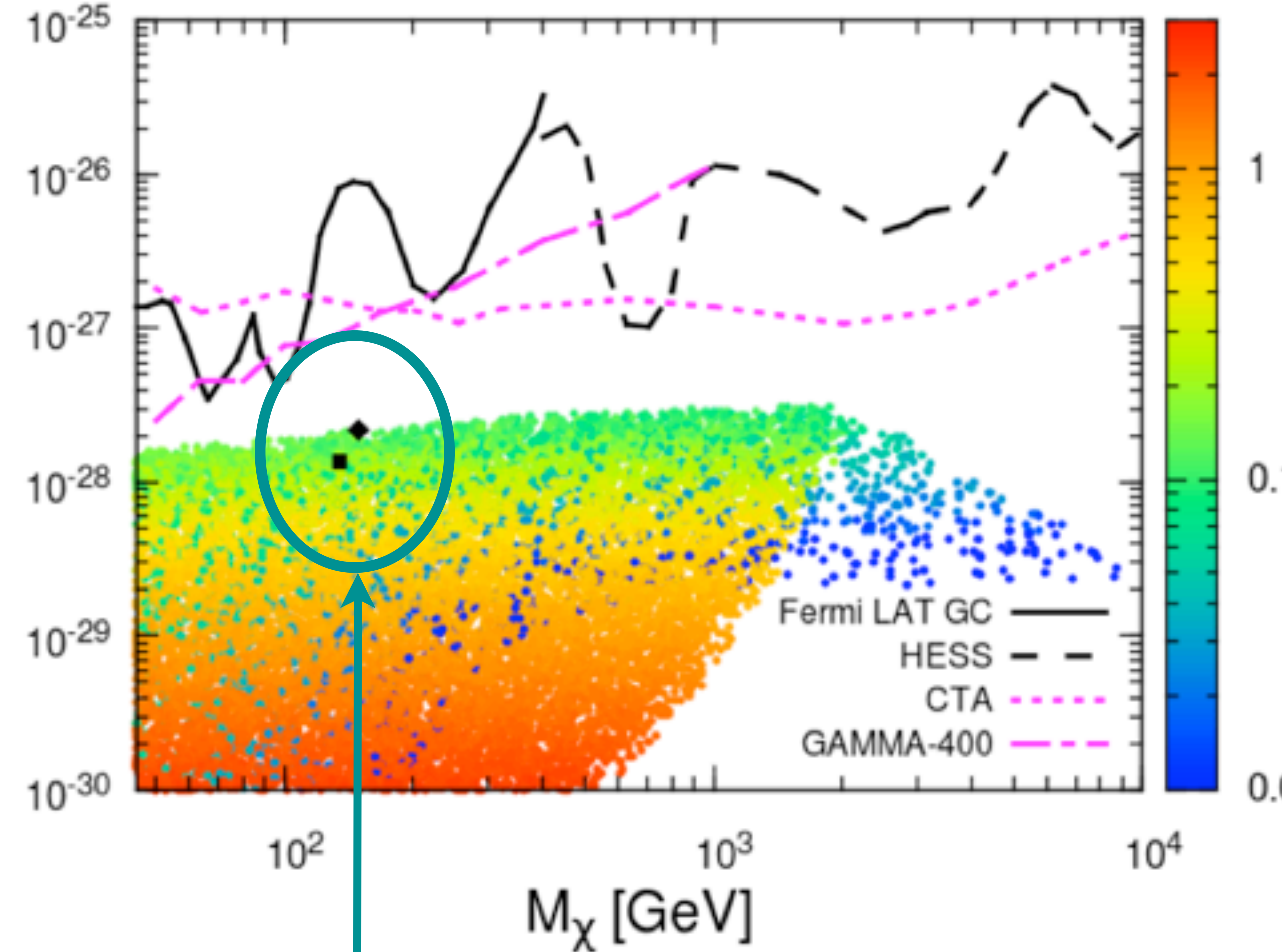


need an O(10) boost
(Bergstrom)

SCALAR



MAJORANA



excluded, but we neglected
coupling to the Higgs
(*i.e.* much larger viable parameter
space in practice)

need an $O(10)$ boost
(Bergstrom)

I. GAMMA RAY SPECTRAL FEATURES

II. GOAL & MOTIVATION

III. MAJORANA DM

IV. REAL SCALAR DM

V. PROSPECTS

$$\mathcal{L} \supset y_l \, S \, \bar{\Psi} \, l_R + h.c.$$

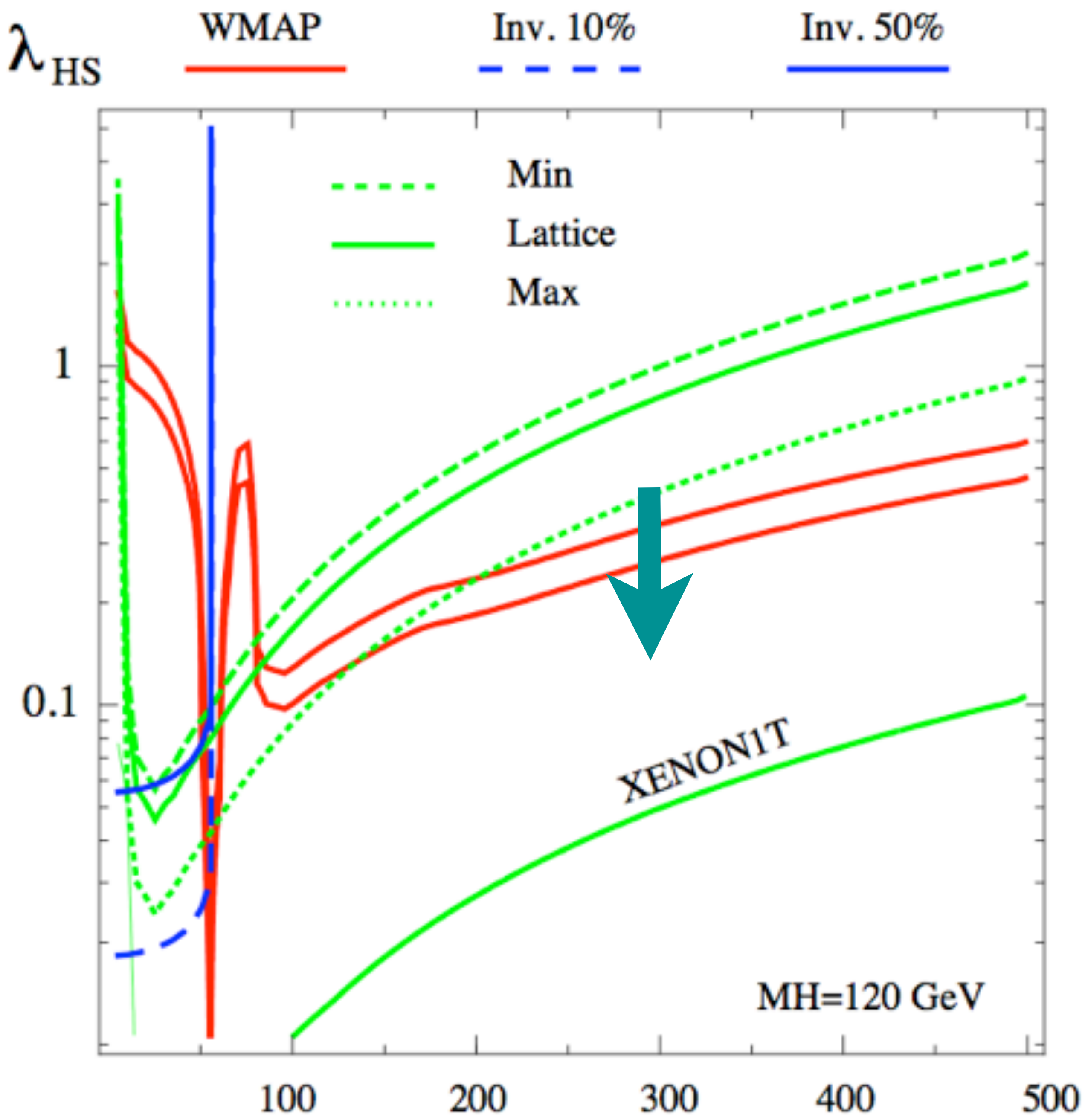
A SINGLET SCALAR

$$\mathcal{L} \supset y_l \, S \, \bar{\Psi} \, l_R + h.c.$$

A SINGLET SCALAR

$$\mathcal{L} \supset \lambda_{HS} S^2 |H|^2$$

Silveira & Zee
Yndurain & Veltman
McDonald
Burgess, Pospelov & ter Veldhuis
...



Mambrini
arXiv:1108.0671

$$\mathcal{L} \supset y_l \, S \, \bar{\Psi} \, l_R + h.c.$$

A SINGLET SCALAR

$$\mathcal{L} \supset y_l \bar{L} H_2 N + M_N N^T C N + h.c.$$

Ma's INERT DOUBLET MODEL

$$\updownarrow$$

$$\mathcal{L} \supset y_l \bar{L}_H \tilde{H}_2 l_R + M_{L_H} \bar{L}_H L_H$$

A (NOT SO) INERT DOUBLET

$$\mathcal{L} \supset y_l \, S \, \bar{\Psi} \, l_R + h.c.$$

A SINGLET SCALAR

$$\mathcal{L} \supset y_l \bar{L} H_2 N + M_N N^T C N + h.c.$$

Ma's INERT DOUBLET MODEL

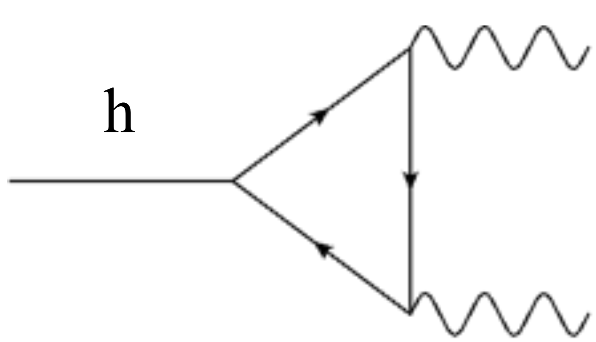
$$\updownarrow$$

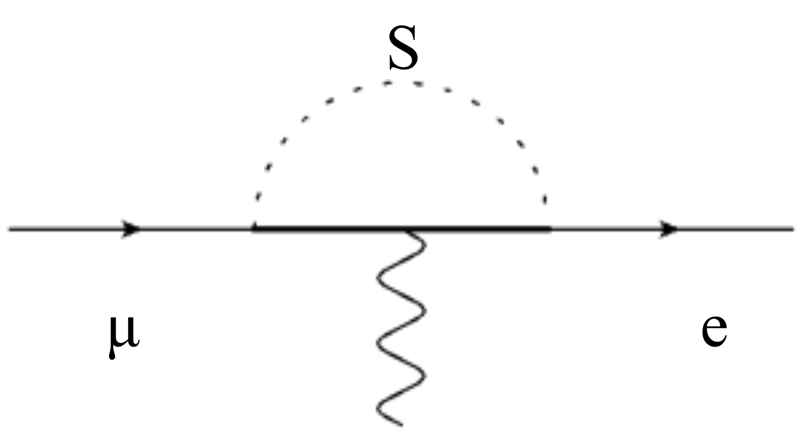
$$\mathcal{L} \supset y_l \bar{L}_H \tilde{H}_2 l_R + M_{L_H} \bar{L}_H L_H$$

A (NOT SO) INERT DOUBLET

$$\mathcal{L} \supset y_l \bar{L}_H \tilde{H} l_H + M_{L_H} \bar{L}_H L_H + M_{l_H} \bar{l}_H l_H$$

etc...





$$\mathcal{L} \supset y_l \, S \, \bar{\Psi} \, l_R + h.c.$$

A SINGLET SCALAR

$$\mathcal{L} \supset y_q \, S \, \bar{\Psi} q_R + h.c.$$

$$\frac{\langle \sigma v \rangle_{g\bar{q}q}}{\langle \sigma v \rangle_{\gamma\bar{q}q}} = \frac{N_c^2 - 1}{2N_c} \frac{\alpha_s}{Q^2 \alpha}$$

~ 40 (up-like quarks)

~ 150 (down-like quarks)

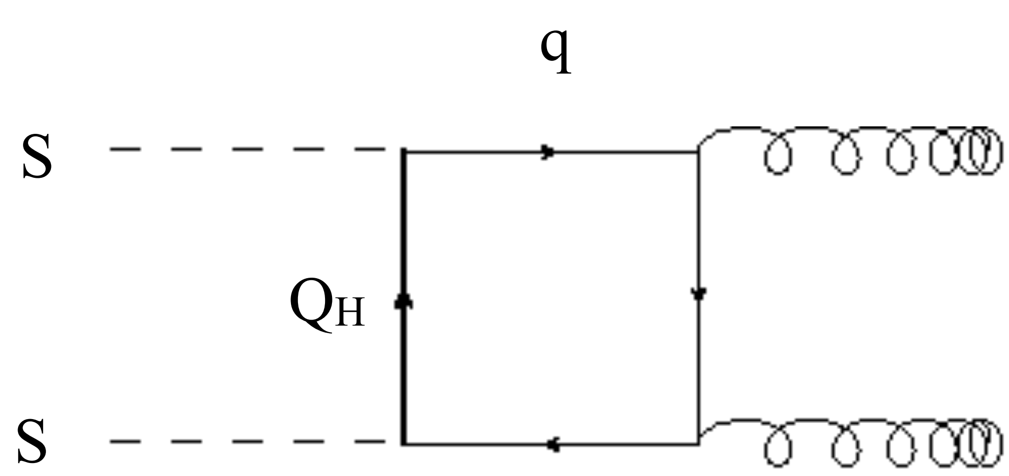
ABUNDANCE FROM (GLUON) BREMSSTRAHLUNG

+ DIRECT DETECTION

+ CONSTRAINTS FROM CR ANTI-PROTONS

+ LHC constraints

etc...

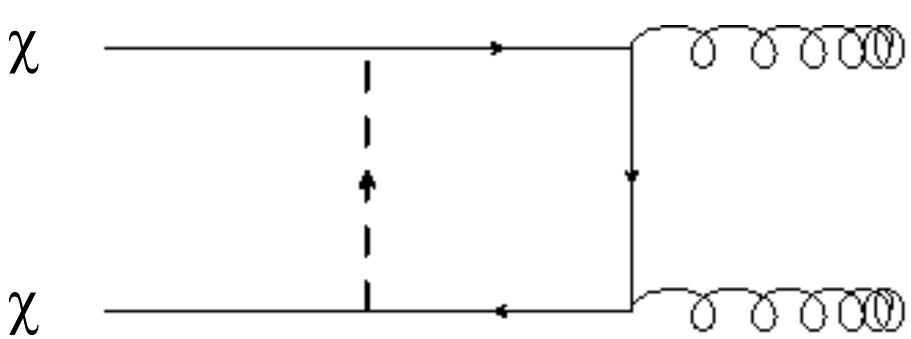


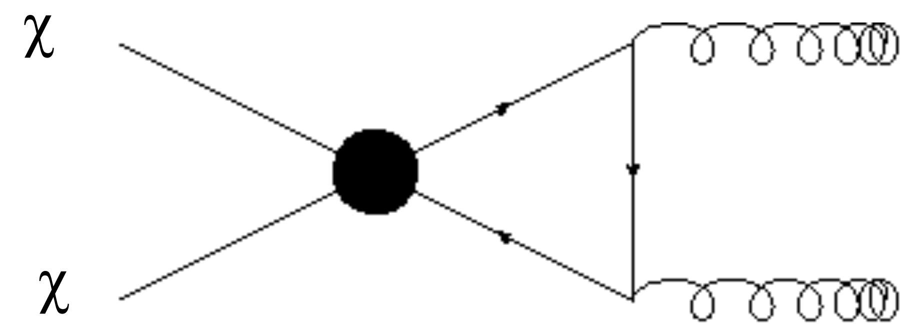
DIRECT
DETECTION ?

neutralino case:
DREES & NOJIRI
PRD 47 (1993) 4226

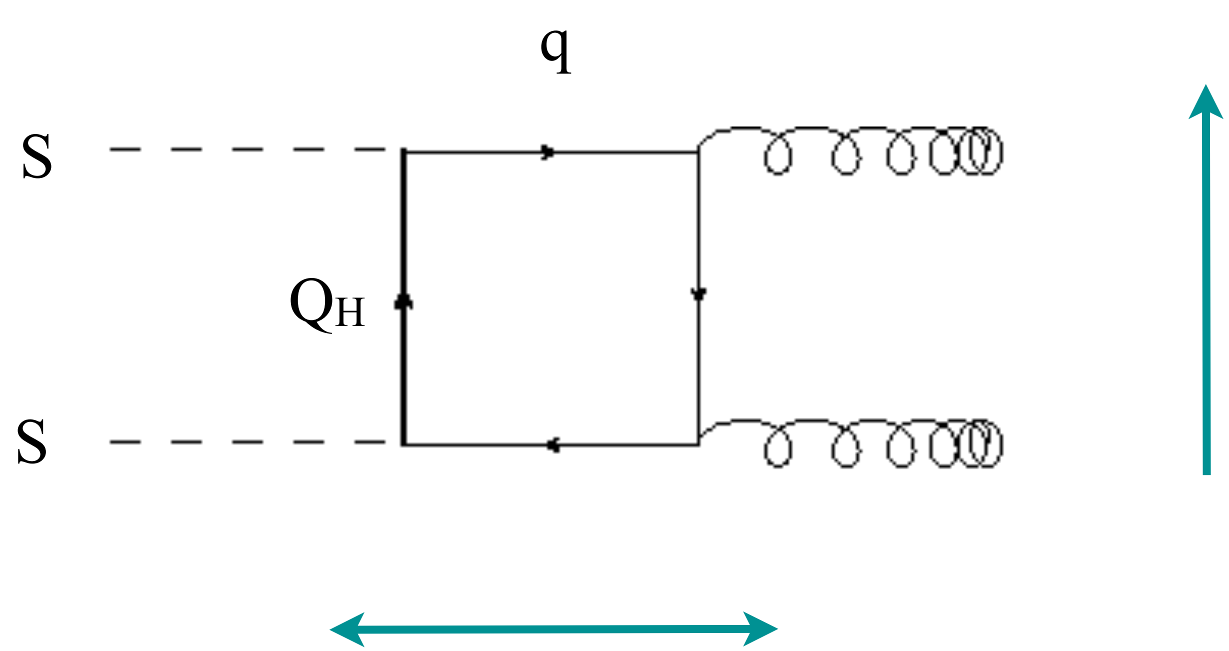
ANNIHILATION

A CHIRAL ANOMALY



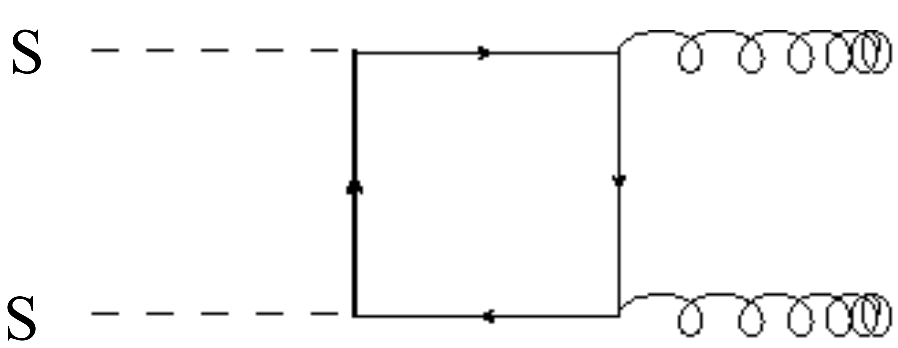


S. Rudaz
Phys.Rev. D39 (1989) 3549

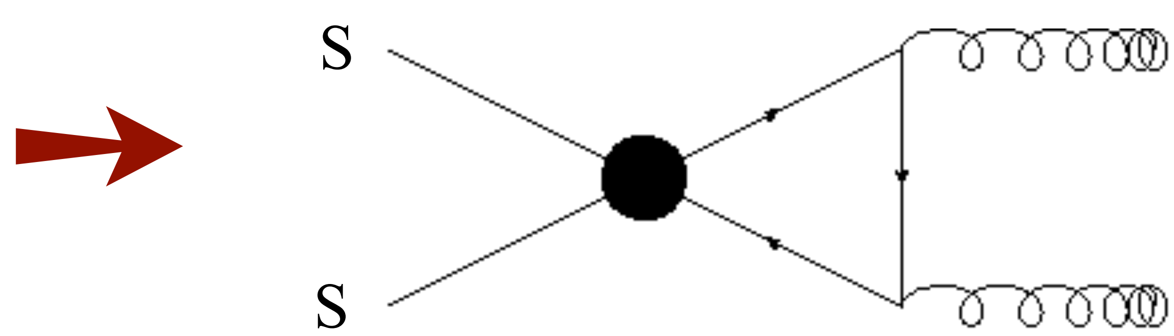


DIRECT
DETECTION ?

ANNIHILATION/PRODUCTION



TRACE ANOMALY? HUM, NOT QUITE

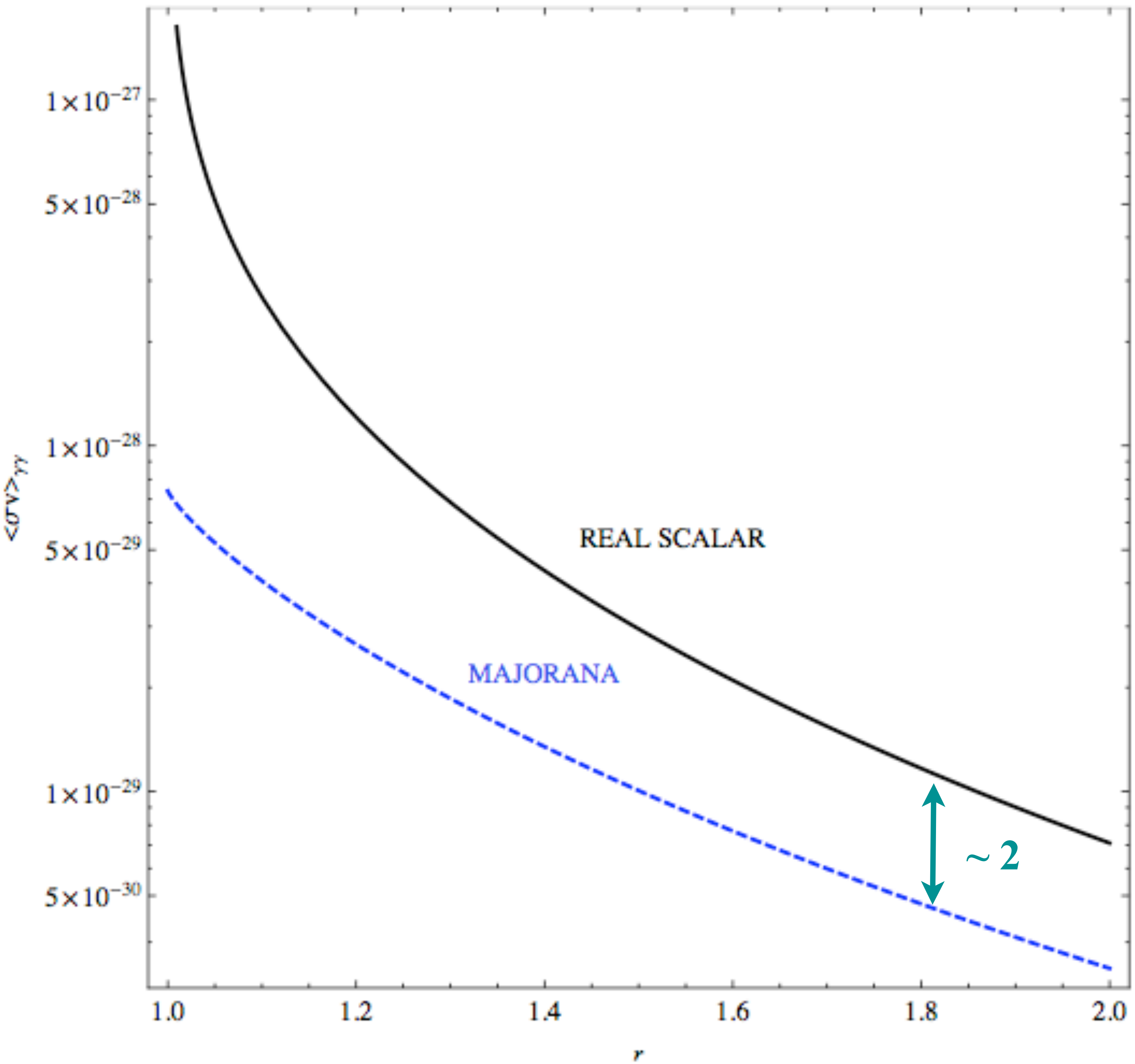


CONCLUSIONS

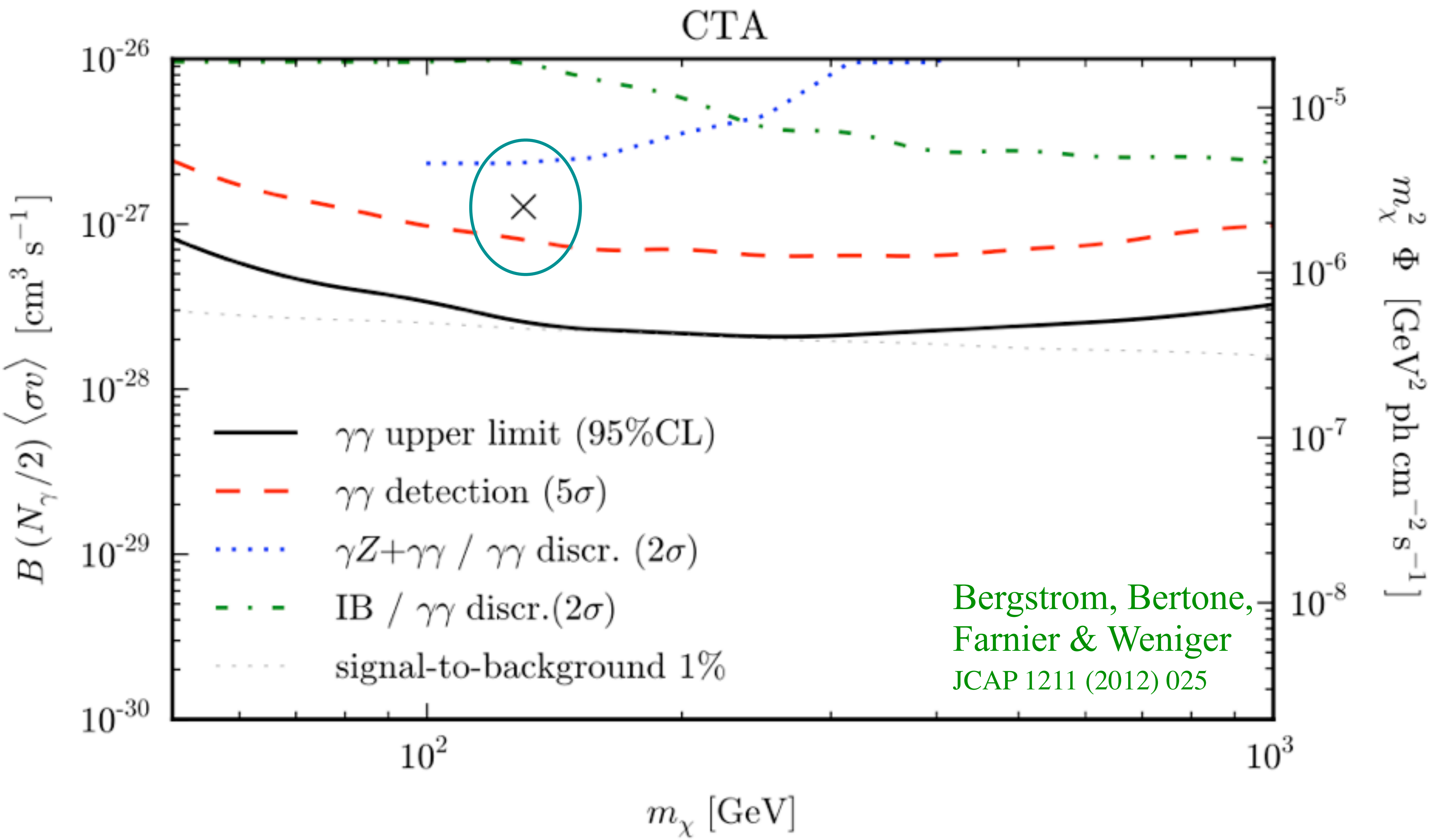
A simple model (scalar DM through vector-like portal) with a <u>very</u> significant gamma ray signature (VIB) (not very common)

May be of some interest for model building (*e.g.* model resuscitation, CP violation,...) at the price of introducing many new parameters (Yukawa couplings).

BACKUP SLIDES

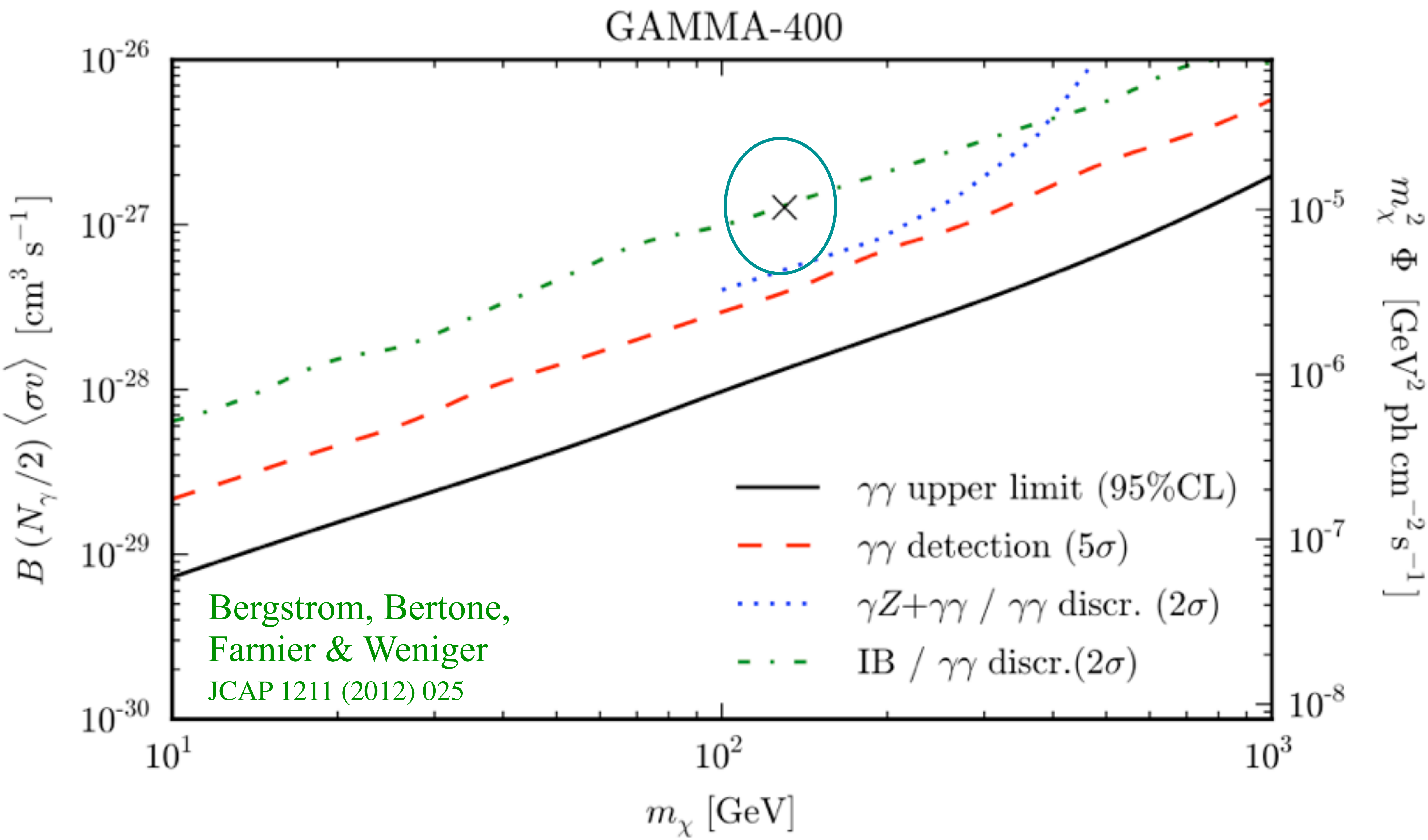

1×10^{-27}
5×10^{-28}
1×10^{-28}
5×10^{-29}
1×10^{-29}
5×10^{-30}
$<\sigma v>_{\gamma\gamma}$
REAL SCALAR
MAJORANA
~ 2
1.0
1.2
1.4
1.6
1.8
2.0
r

PLANNED EXPERIMENTS



improved sensitivity (a factor ~10), perhaps 2018 (?)

PLANNED (?) EXPERIMENTS

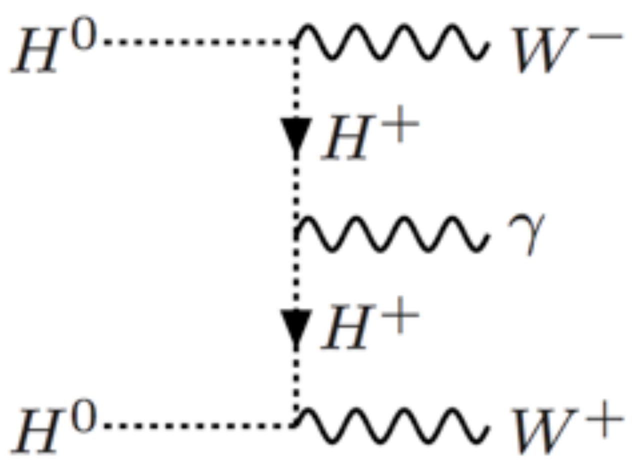


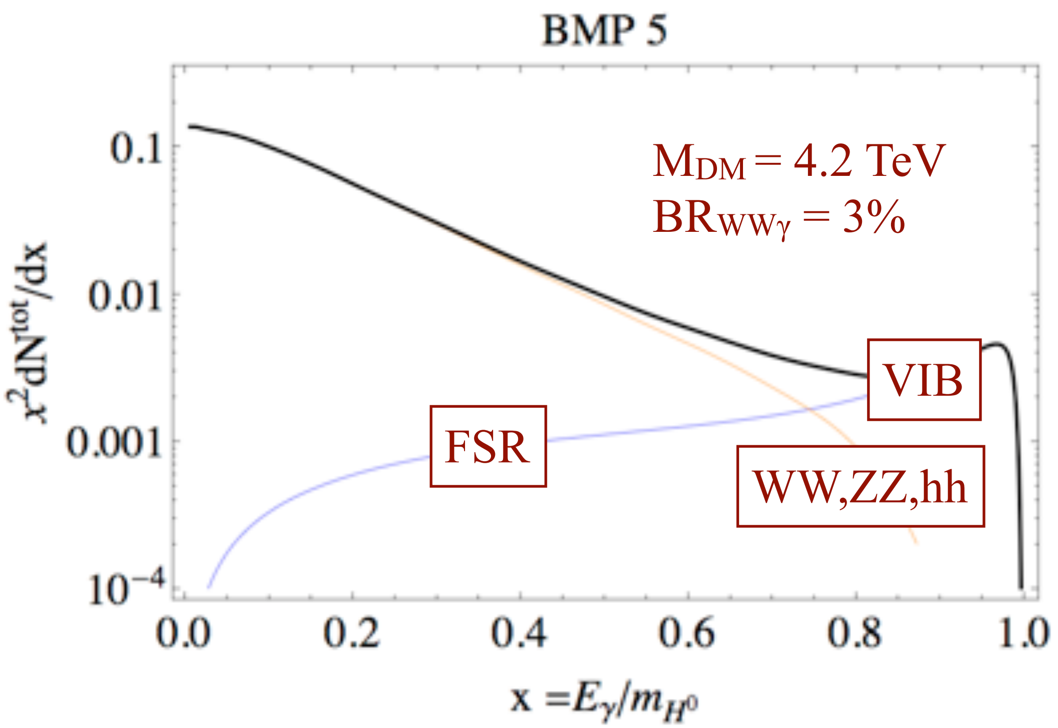
improved resolution (a factor ~10), launch perhaps 2018 (?)

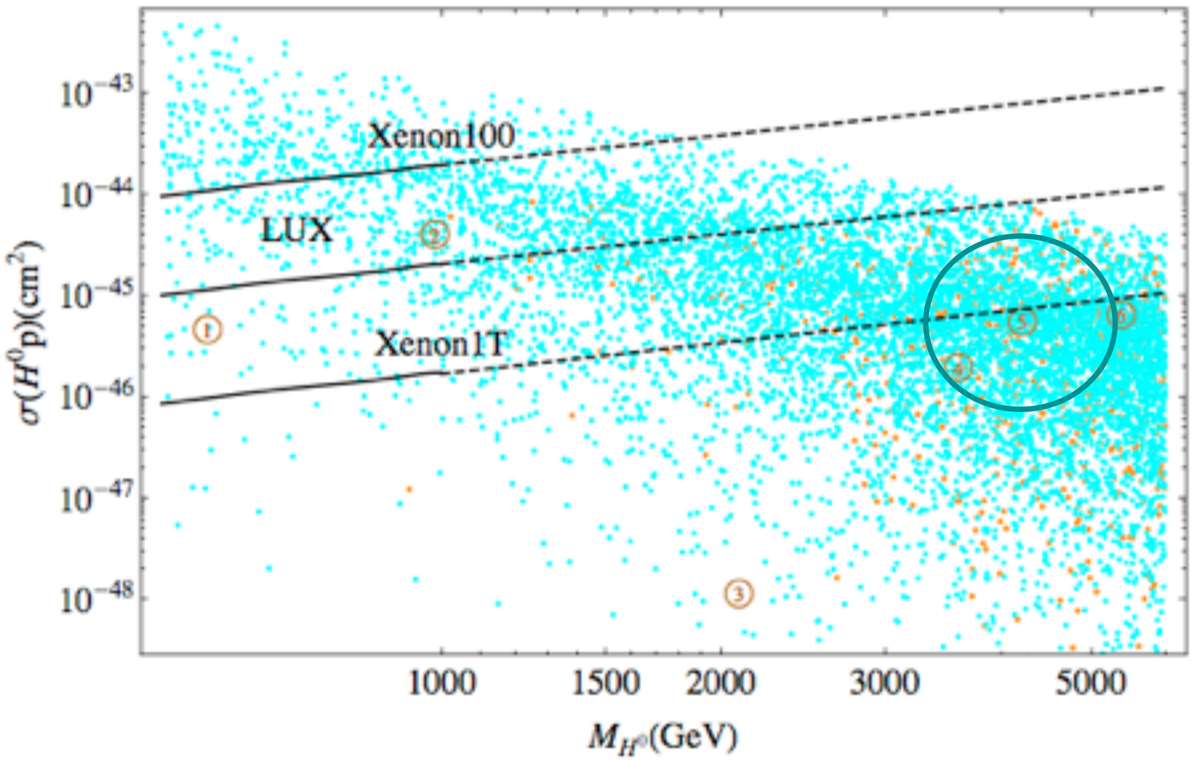
«Novel Gamma-ray Spectral Features in the Inert Doublet Model»

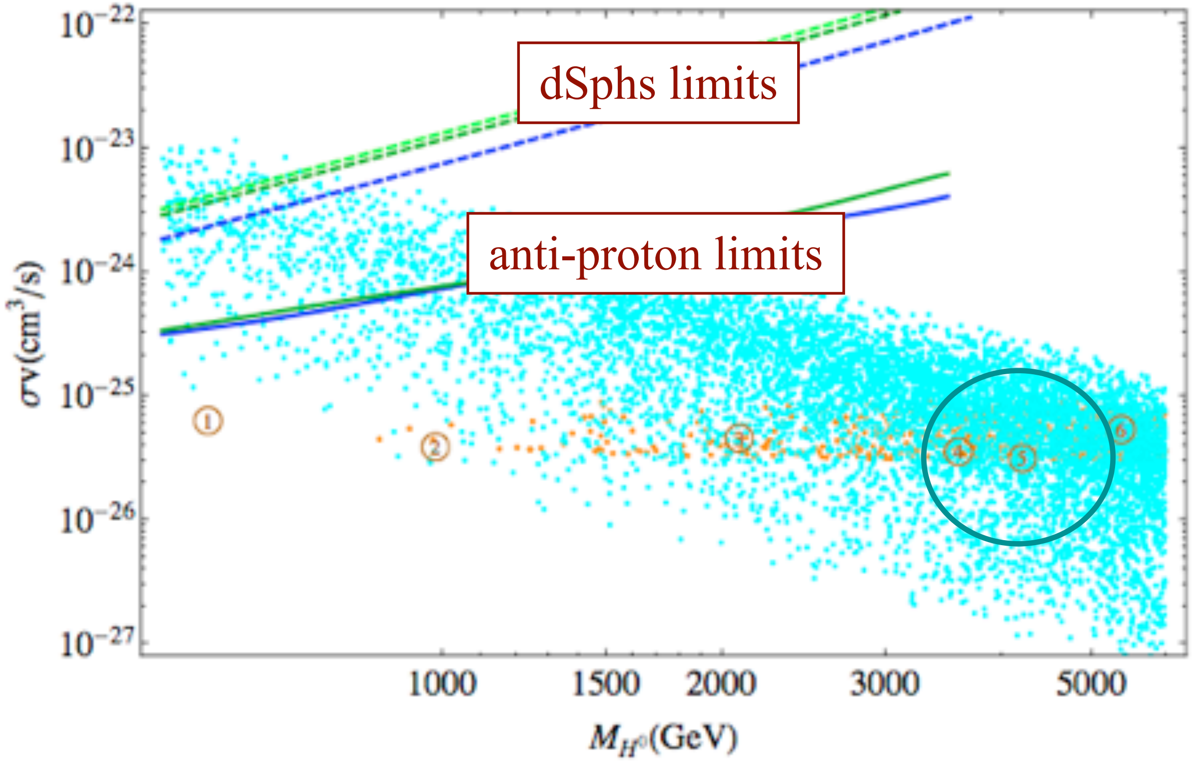
Garcia-Cely & Ibarra

arXiv:1306.4681









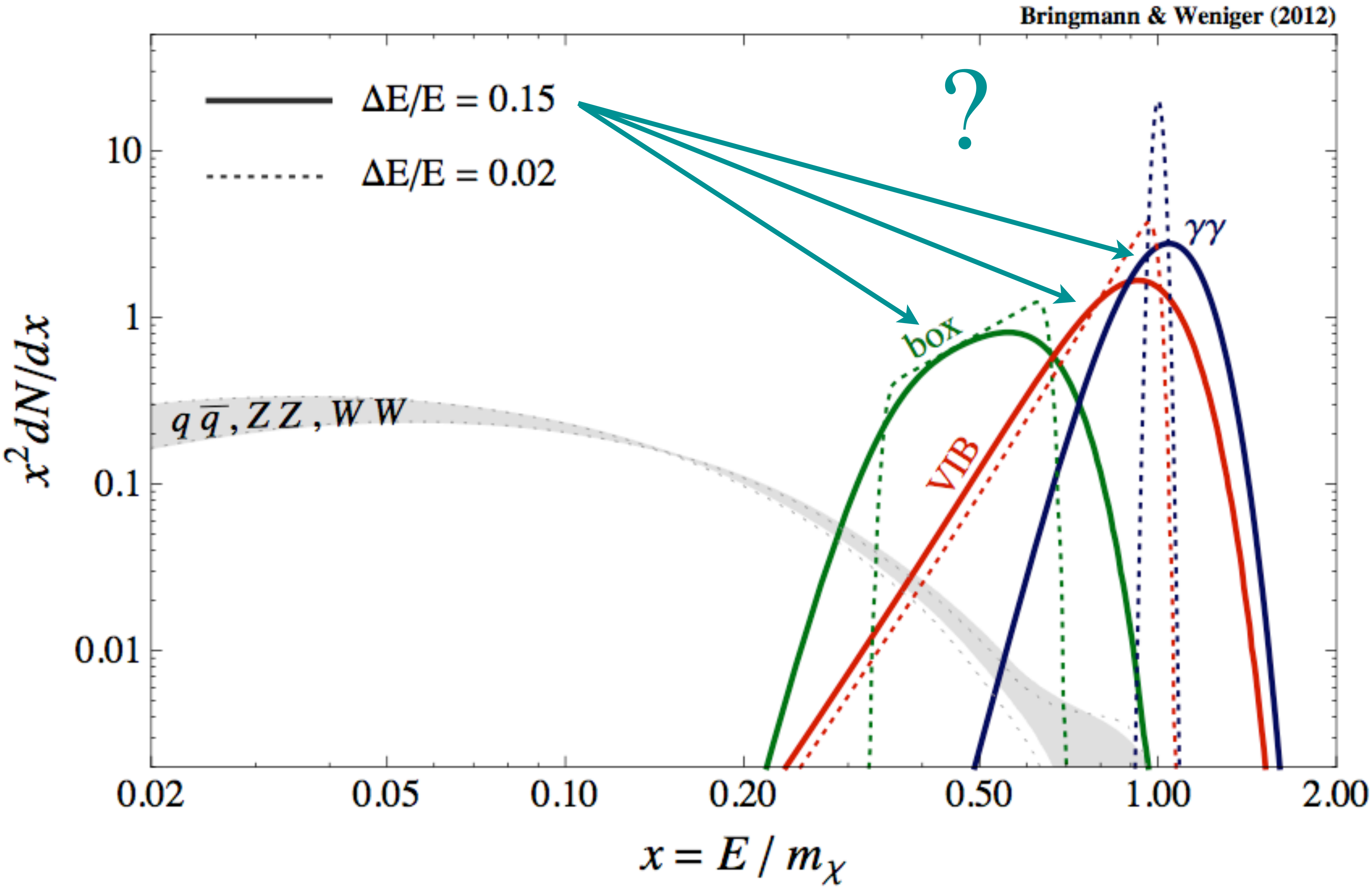
e.g. ANNIHILATION OF MAJORANA DM INTO LIGHT FERMIONS

the same, from an effective operator perspective

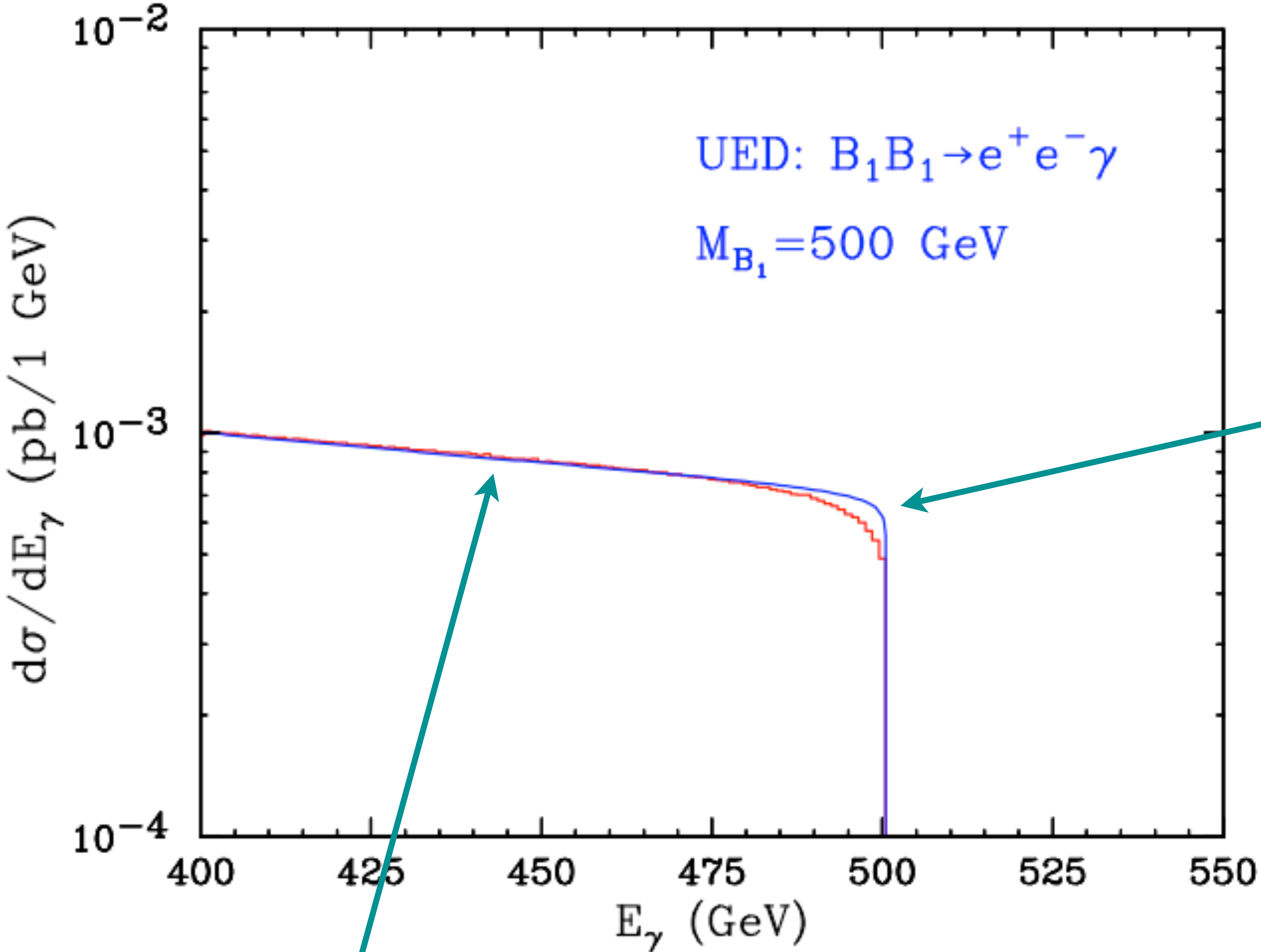
$$\mathcal{O}_S = m_f\, \bar{\chi}\chi\, \bar{\psi}_{f_L}\psi_{f_R} \quad \longrightarrow \quad \text{S-WAVE ANNIHILATION}$$

$$\mathcal{O}_P = \bar{\chi}\gamma_\mu\gamma_5\chi\, \bar{\psi}_{f_L}\gamma^\mu\psi_{f_L} \quad \longrightarrow \quad \text{P-WAVE ANNIHILATION}$$

POSSIBLE GAMMA RAY FEATURES



similar signatures, given the current resolution (*i.e.* Fermi-LAT)



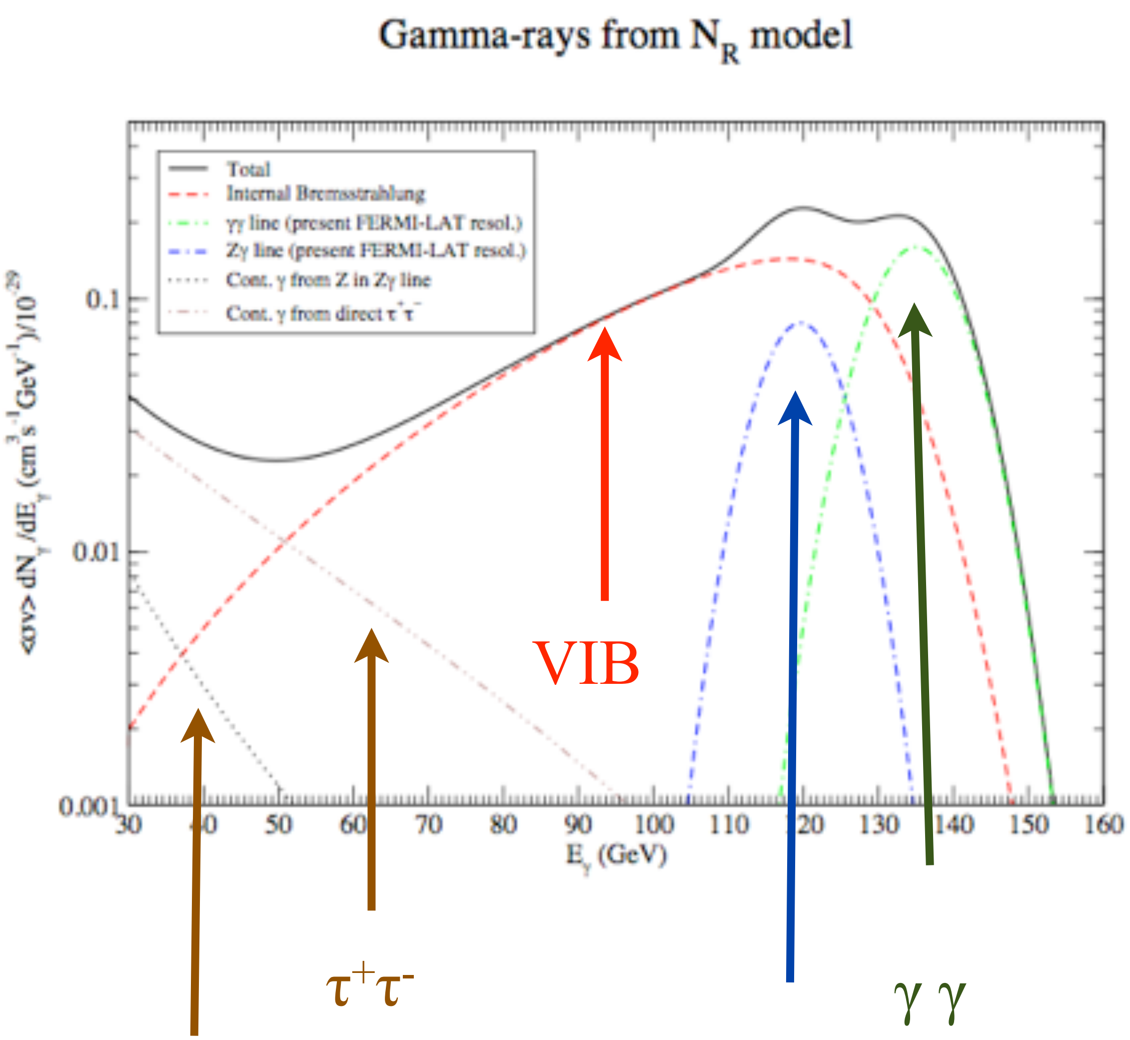
$\mathcal{F}_e \to 1$

$\mathcal{F}_e \propto \frac{1}{E_\gamma}$

Birkedal, Matchev, Perelstein and Sprey (2005)

«The 130 GeV Fingerprint of Right-handed Neutrino Dark Matter»

L. Bergstrom, arXiv:1208.6082

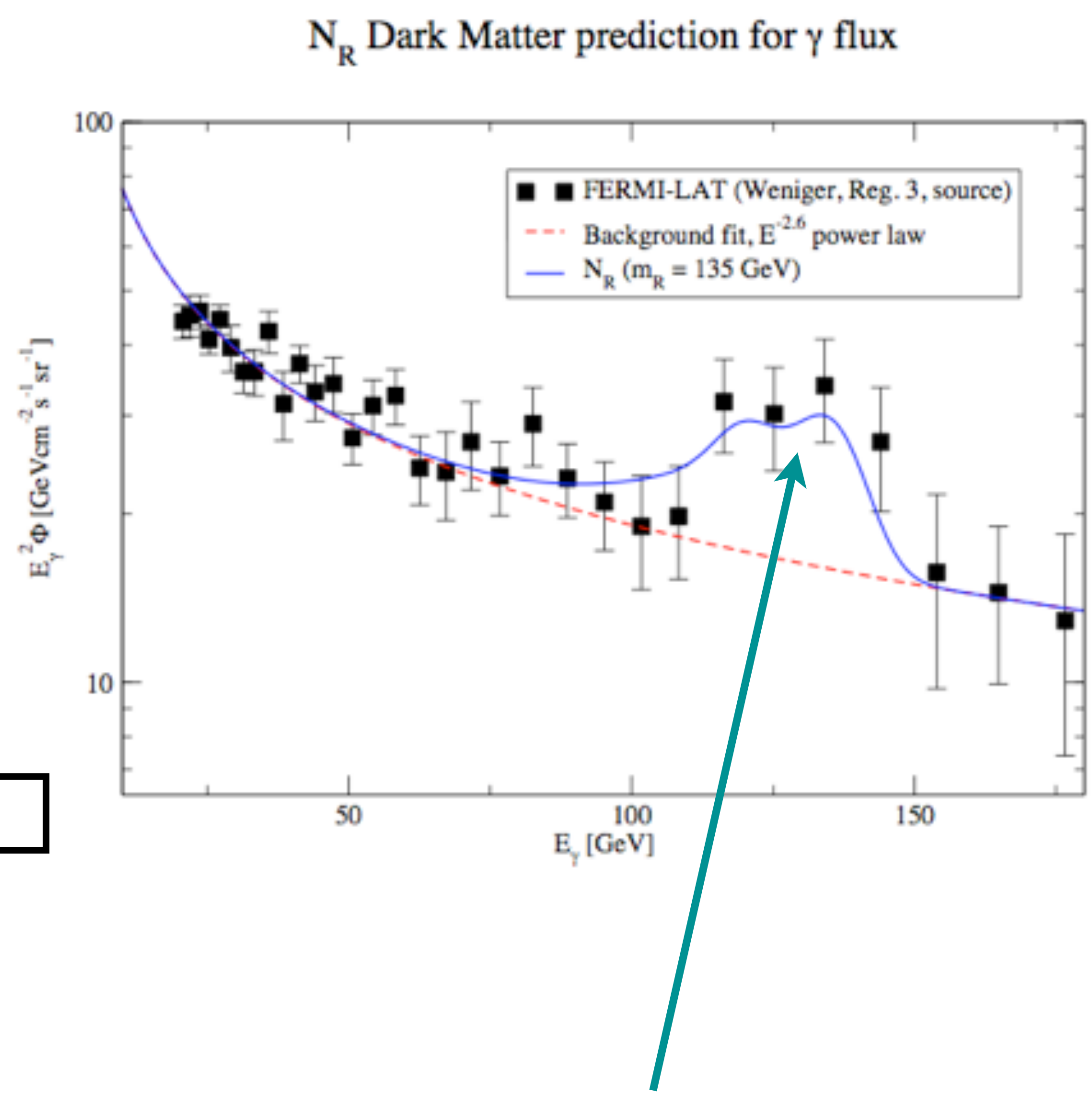


continuum from Z in γZ

γZ

Continuum
(negligible)

M_N ~135 GeV «fingerprint»



NEED A BOOST FACTOR O(10)
(Einasto profile)