Radiative seesaw and Dark Matter

A two-loop Radiative seesaw with multi-component DM explaining the Gamma Excess in the Higgs Decay and at the Fermi LAT

arXiv:

ON JAN.13 AT THE UNIV. OF TOYAMA

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IN COLLABORATION WITH
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HIROSHI TAKANO(KU)

PLAN

I A brief review on radiative seesaw models and DM

II A two-loop model with two or three DM

III By products:

* 135 gamma-ray line at the Fermi LAT

* Enhancement of h-> two gammas

IV Conclusion

I Radiative Seesaw and DM

Radiative Neutrino Mass Generation

(Zee,80;86; Wolfenstein,80;
Babu,88, etc)

$\neq$

Radiative Seesaw Mechanism

(Kraus, Nasri + Trodden,02; Ma,06; Aoki, Kanemura+ Seto,08; etc)

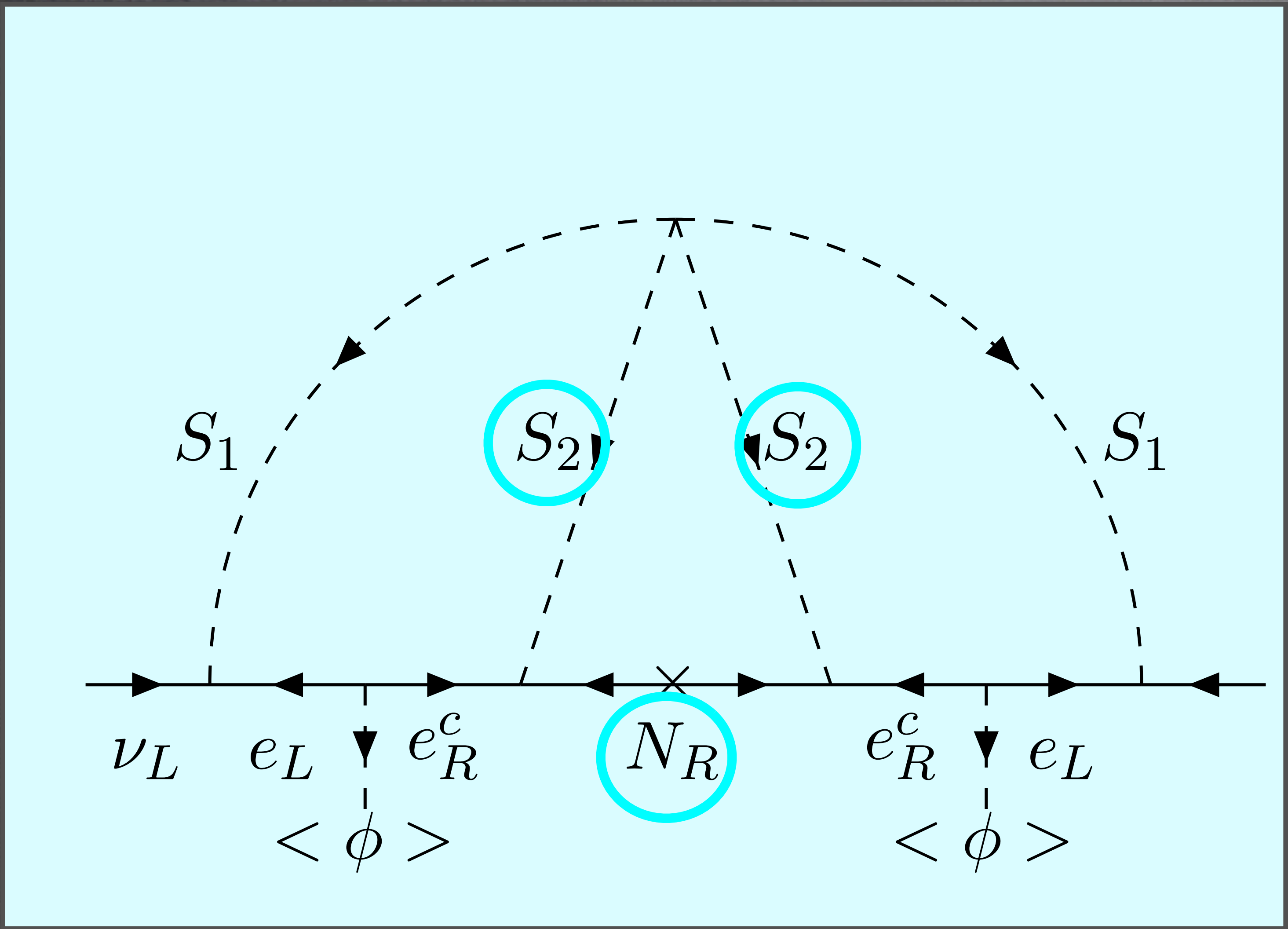
Unbroken discrete symmetry to forbid the Dirac masses

⇩

N_R, Inert Higgs, etc are DM candidates.

Three-loop Model

Kraus, Nasri + Trodden, 02



Z_2-odd SM singlet

N_R can be DM.

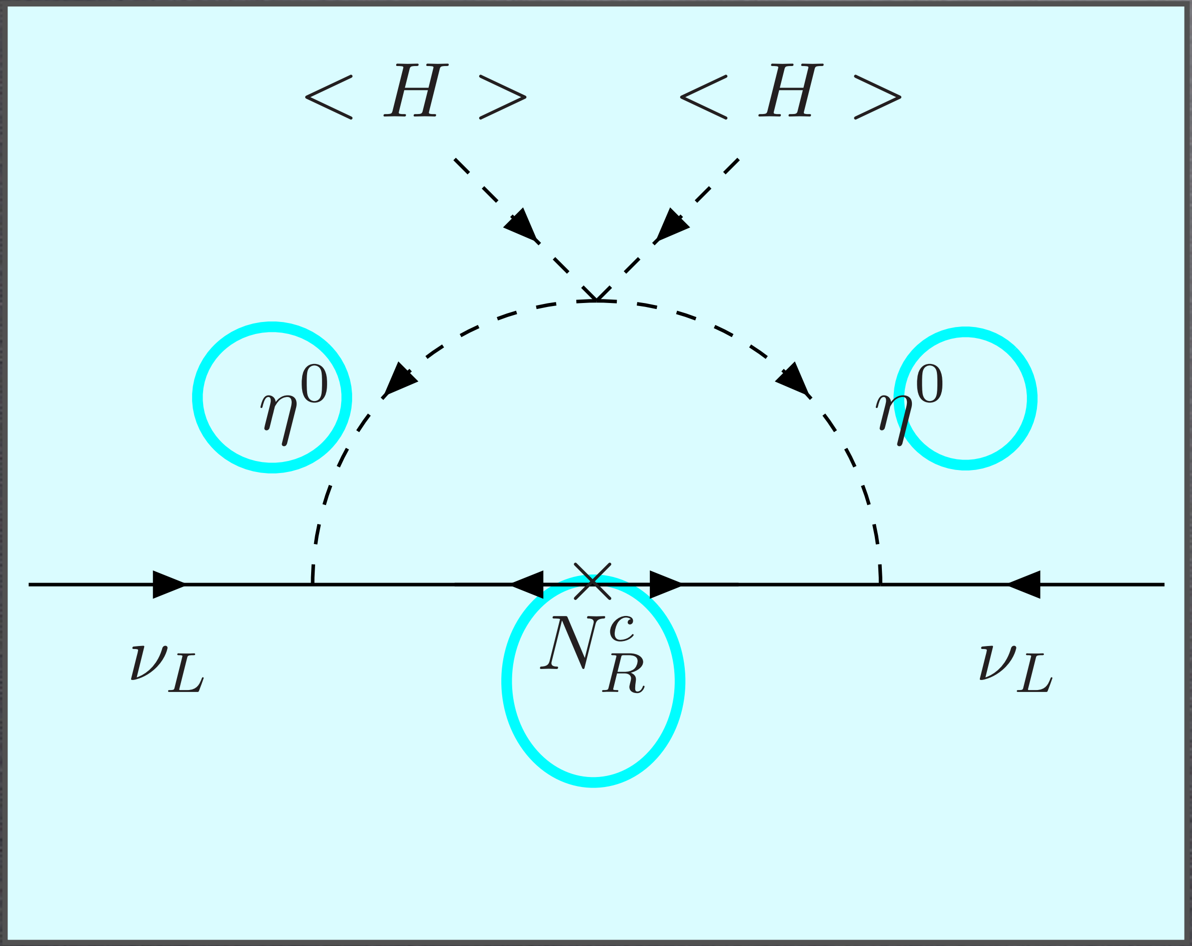
$$\mathbf{m}_\nu = \begin{pmatrix} 0 & 0 \\ 0 & M \end{pmatrix} \rightarrow \begin{pmatrix} m^2/M & 0 \\ 0 & M \end{pmatrix}$$

Radiative Seesaw

One-loop Model

Ma, 06

Z 2-odd



Inert SU(2) doublet Higgs

$$< \eta > = 0$$

N_R and eta are DM candidates.

Eta DM studied by

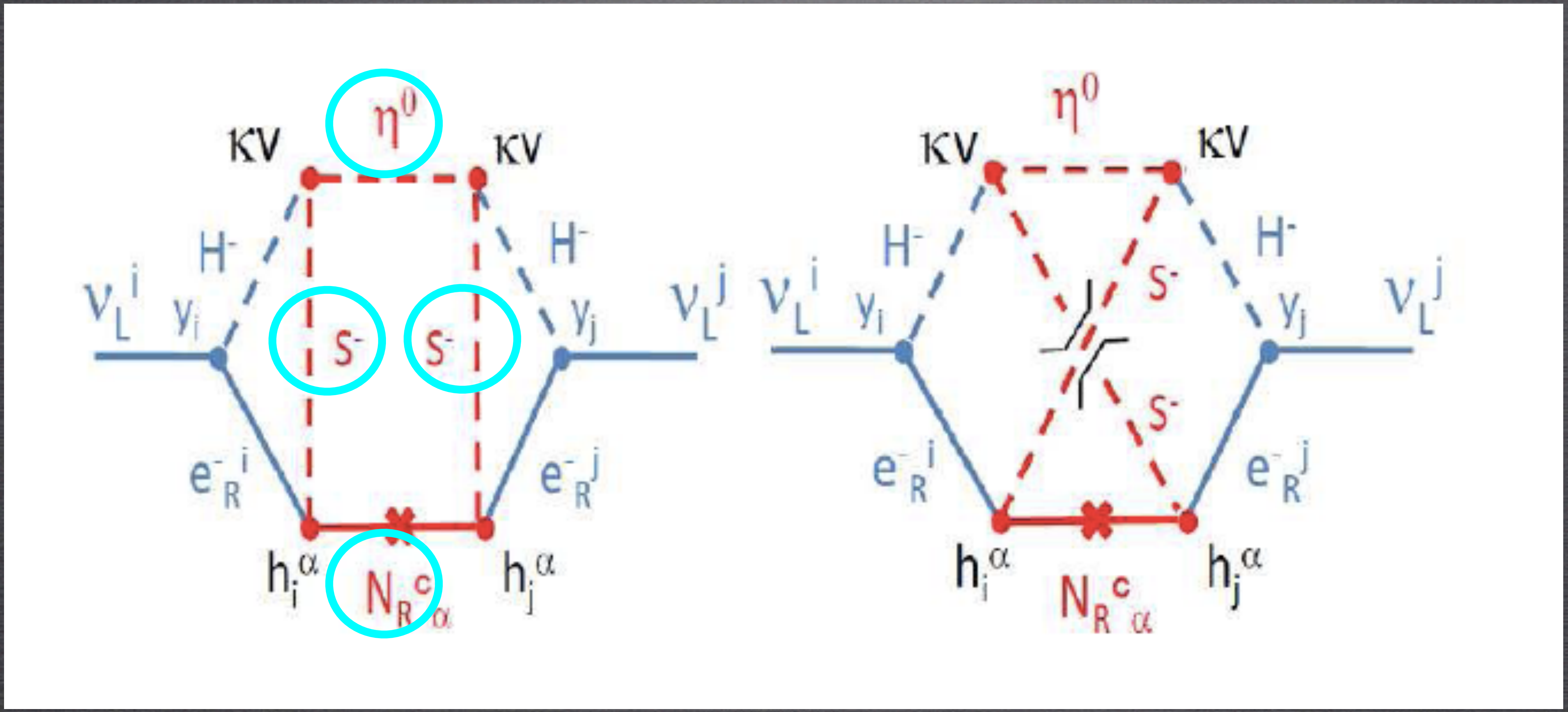
Barbieri, Hall + Rychkov, 06;
Lopez, Oliver + Tytgat,06;
Dolle + Su,09 etc

N_R DM studied by

Kubo, Ma + Suematsu, 06;
Aristizabal Sierra, Kubo, Restrepo, Suematsu +Zapata, 08;
Gelmini, Osoba+ Palomares-Ruiz, 09, etc

Three-loop Model

Aoki, Kanemura+Seto, 08



Z 2 ODD

Inert SU(2) doublet Higgs

	Q^i	u^i_R	d^i_R	L^i	e^i_R	Φ_1	Φ_2	$S^{\pm}$	η	N^α_R
Z_2 (exact)	+	+	+	+	+	+	+	−	−	−
$\tilde{Z}_2$ (softly broken)	+	−	−	+	+	+	−	+	−	+

$$< \eta >= 0$$

Non-susy Models of radiative generation of m_ν

Model	L-violating dim.	No. of loops	ν_R	No. of stable DMs
[1]	3 (tri-linear scalar coupling)	1	No	0
[2, 3, 21]	3 (tri-linear scalar coupling)	2	No	0
[15]	3 (tri-linear scalar coupling)	1	No	1
[22]	3 (tri-linear scalar coupling))	2	Yes	2
[4, 5, 11]	3 (Majorana mass)	3	Yes	1
[6–9, 12, 14, 23, 24]	3 (Majorana mass)	1	Yes	1
[13]	3 (Majorana mass)	1	Yes ($SU(2)_L$ triplet)	1
[17]	4 (quartic scalar coupling)	1	No	1
[19]	No L-violation	1	Yes	0
[18]	Spontaneous violation	2	No	1
[20]	Sponataneos violation	2	Yes	1
[16]	Spontaneous violation	1	Yes	1
[10]	2 (scalar mass)	1	Yes	0
Our model	2 (scalar mass)	2	Yes	**2** or **3**

[1] A. Zee, Phys. Lett. B **93** (1980) 389 [Erratum-ibid. B **95** (1980) 461].
[2] A. Zee, Nucl. Phys. B **264** (1986) 99.
[3] K. S. Babu, Phys. Lett. B **203** (1988) 132.
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[7] J. Kubo and D. Suematsu, Phys. Lett. B **643** (2006) 336 [hep-ph/0610006].
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[10] N. Sahu and U. Sarkar, Phys. Rev. D **78** (2008) 115013 [arXiv:0804.2072 [hep-ph]].
[11] M. Aoki, S. Kanemura and O. Seto, Phys. Rev. Lett. **102** (2009) 051805 [arXiv:0807.0361 [hep-ph]]; Phys. Rev. D **80** (2009) 033007 [arXiv:0904.3829 [hep-ph]].
[12] D. Aristizabal Sierra, J. Kubo, D. Restrepo, D. Suematsu and O. Zapata, Phys. Rev. D **79** (2009) 013011 [arXiv:0808.3340 [hep-ph]].
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[17] M. Aoki, S. Kanemura and K. Yagyu, Phys. Lett. B **702** (2011) 355 [Erratum-ibid. B **706** (2012) 495] [arXiv:1105.2075 [hep-ph]].

[18] M. Lindner, D. Schmidt and T. Schwetz, Phys. Lett. B **705** (2011) 324 [arXiv:1105.4626 [hep-ph]].

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[20] S. Kanemura, T. Nabeshima and H. Sugiyama, Phys. Rev. D **85** (2012) 033004 [arXiv:1111.0599 [hep-ph]].

[21] K. S. Babu and J. Julio, Phys. Rev. D **85** (2012) 073005 [arXiv:1112.5452 [hep-ph]].

[22] S. S. C. Law and K. L. McDonald, Phys. Lett. B **713** (2012) 490 [arXiv:1204.2529 [hep-ph]].

[23] Y. Farzan and E. Ma, Phys. Rev. D **86** (2012) 033007 [arXiv:1204.4890 [hep-ph]].

[24] S. Kashiwase and D. Suematsu, arXiv:1301.2087 [hep-ph].

II The model

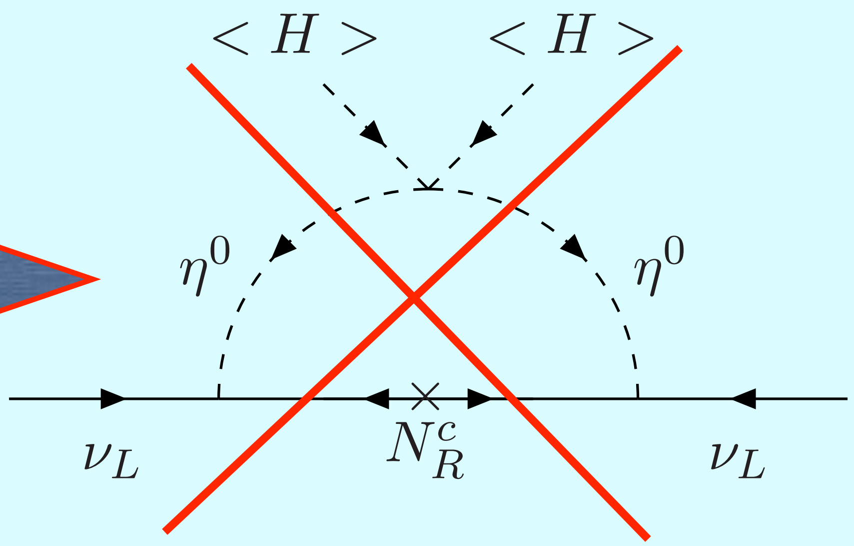
Model	L-violating dim.	No. of loops	ν_R	No. of stable DMs
Our model	2 (scalar mass)	2	Yes	**2** or **3**

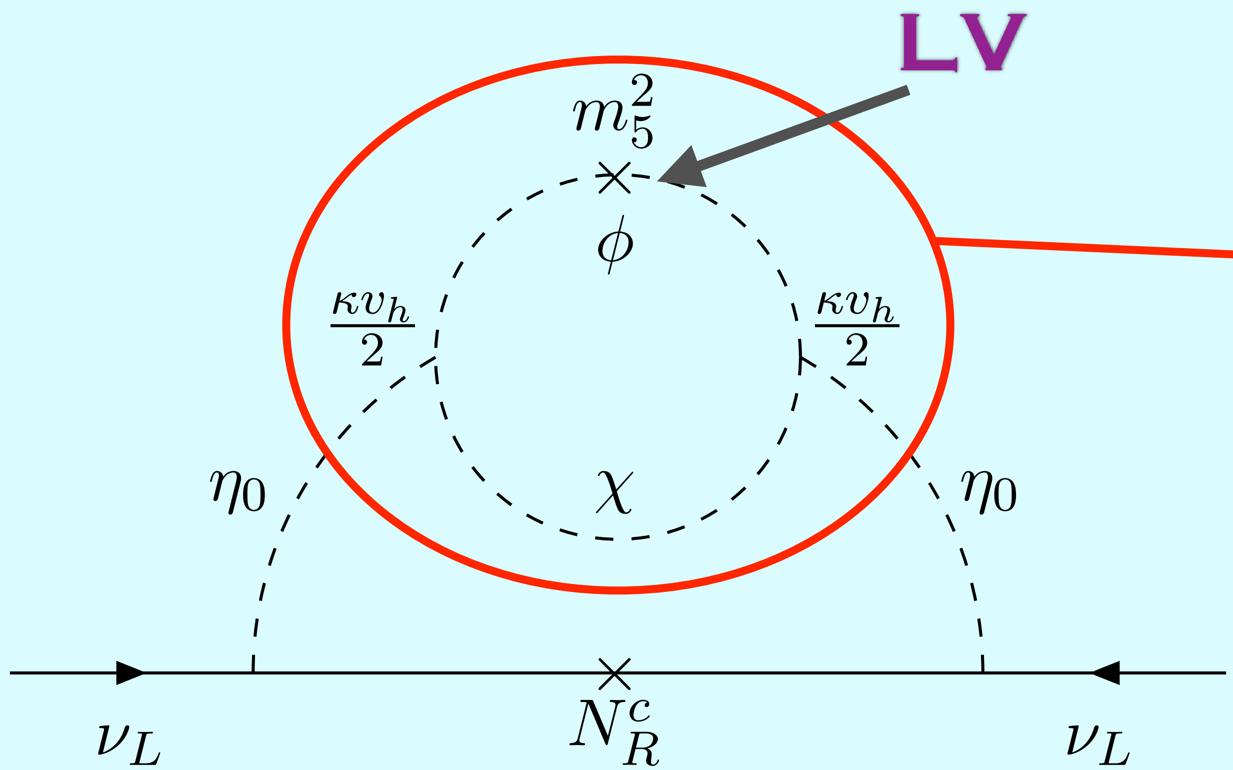
Ma

field	statistics	$SU(2)_L$	$U(1)_Y$	L	Z_2	Z_2'	D_{2N}
$(\nu_L, l_)$	F	2	$-1/2$	1	$+$	$+$	$\mathbf{1}$
l^c	F	1	1	1	$+$	$+$	$\mathbf{1}$
N_R^c	F	1	1	0	$-$	$+$	$\mathbf{1}''$
$H = (H^+, H^0)$	B	2	$1/2$	0	$+$	$+$	$\mathbf{1}$
$\eta = (\eta^+, \eta^0)$	B	2	$1/2$	-1	$-$	$+$	$\mathbf{1}''$
χ	B	1	0	0	$+$	$-$	$\mathbf{1}'$
ϕ	B	1	0	1	$-$	$-$	$\mathbf{1}'''$

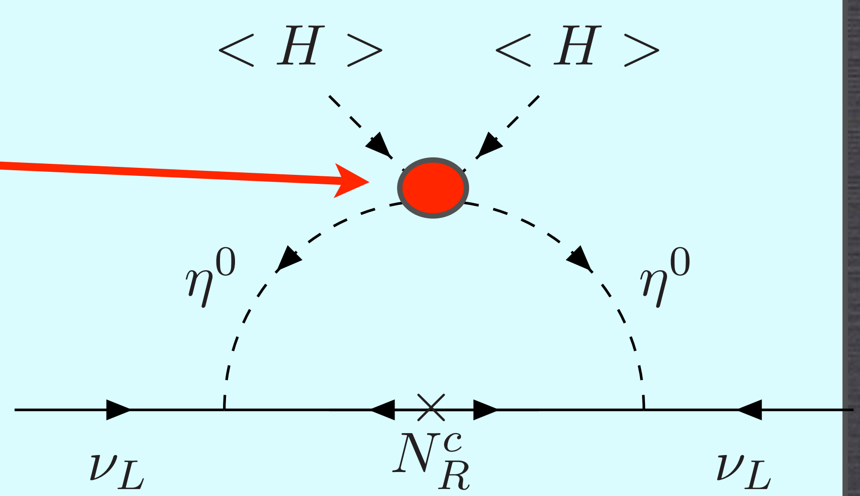
Matter content
(Minimal extension)

NO “λ_5 term”, $(1/2)\lambda_5(H^\dagger\eta)^2$





TWO LOOP SEESAW



ONE LOOP SEESAW

$$m_\nu \sim \left(\frac{\kappa}{16\pi^2}\right)^2 \frac{m_D^2}{M_R} \sim 10^{-7}\ \frac{m_D^2}{M_R}\ \textbf{for}\ \kappa = 0.1$$

$M_R \sim$**1 TeV is a natural scale.**

The Z2 x Z2 x L invariant quartic couplings

$$
\begin{aligned}
V_\lambda = {} & \lambda_1(H^\dagger H)^2 + \lambda_2(\eta^\dagger\eta)^2 + \lambda_3(H^\dagger H)(\eta^\dagger\eta) + \lambda_4(H^\dagger\eta)(\eta^\dagger H) \\
& + \frac{1}{4}\gamma_1\chi^4 + \gamma_2(H^\dagger H)\chi^2 + \gamma_3(\eta^\dagger\eta)\chi^2 + \gamma_4|\phi|^4 + \gamma_5(H^\dagger H)|\phi|^2 \\
& + \gamma_6(\eta^\dagger\eta)|\phi|^2 + \gamma_7\chi^2|\phi|^2 + \frac{\kappa}{2}[\,(H^\dagger\eta)\chi\phi + h.c.\,]\ .
\end{aligned}
$$

The Z2 x Z2 invariant scalar mass terms

$$
V_m = m_1^2 H^\dagger H + m_2^2\eta^\dagger\eta + \frac{1}{2}m_3^2\chi^2 + m_4^2|\phi|^2 + \frac{1}{2}m_5^2[\,\phi^2 + (\phi^*)^2\,]
$$

breaks L.

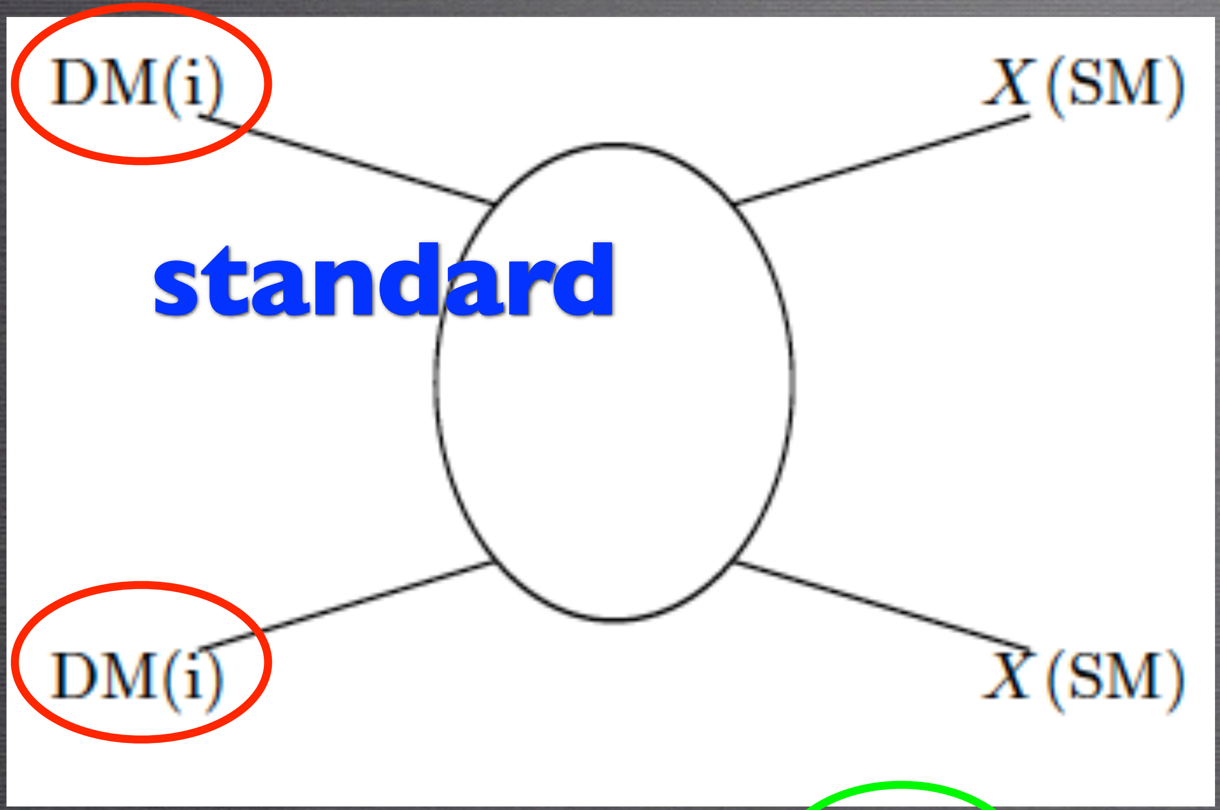
Cold Dark Matter candidates

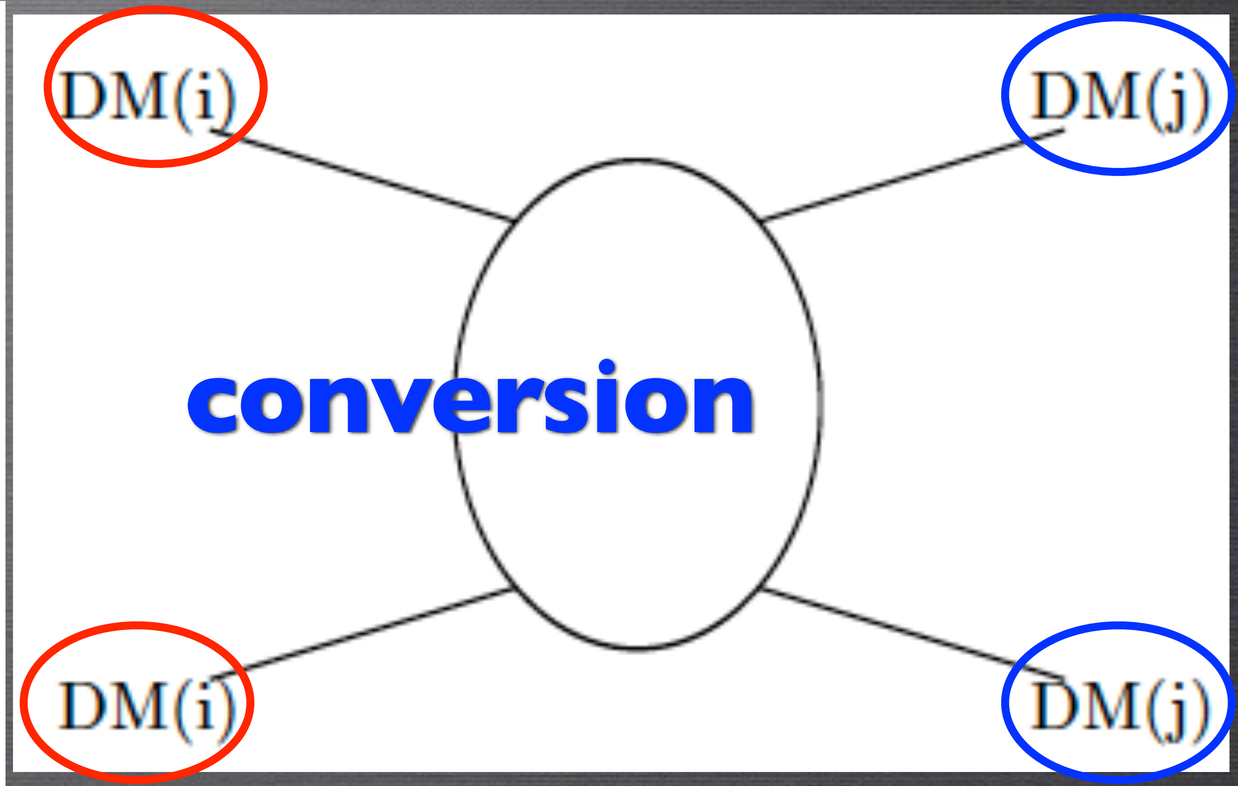
field	statistics	$SU(2)_L$	$U(1)_Y$	L	Z_2	Z'_2	D_{2N}
$(\nu_L, l_)$	F	2	$-1/2$	1	$+$	$+$	$\mathbf{1}$
l^c	F	1	1	1	$+$	$+$	$\mathbf{1}$
N_R^c	F	1	1	0	$-$	$+$	$\mathbf{1}''$
$H = (H^+, H^0)$	B	2	$1/2$	0	$+$	$+$	$\mathbf{1}$
$\eta = (\eta^+, \eta^0)$	B	2	$1/2$	-1	$-$	$+$	$\mathbf{1}''$
χ	B	1	0	0	$+$	$-$	$\mathbf{1}'$
ϕ	B	1	0	1	$-$	$-$	$\mathbf{1}'''$

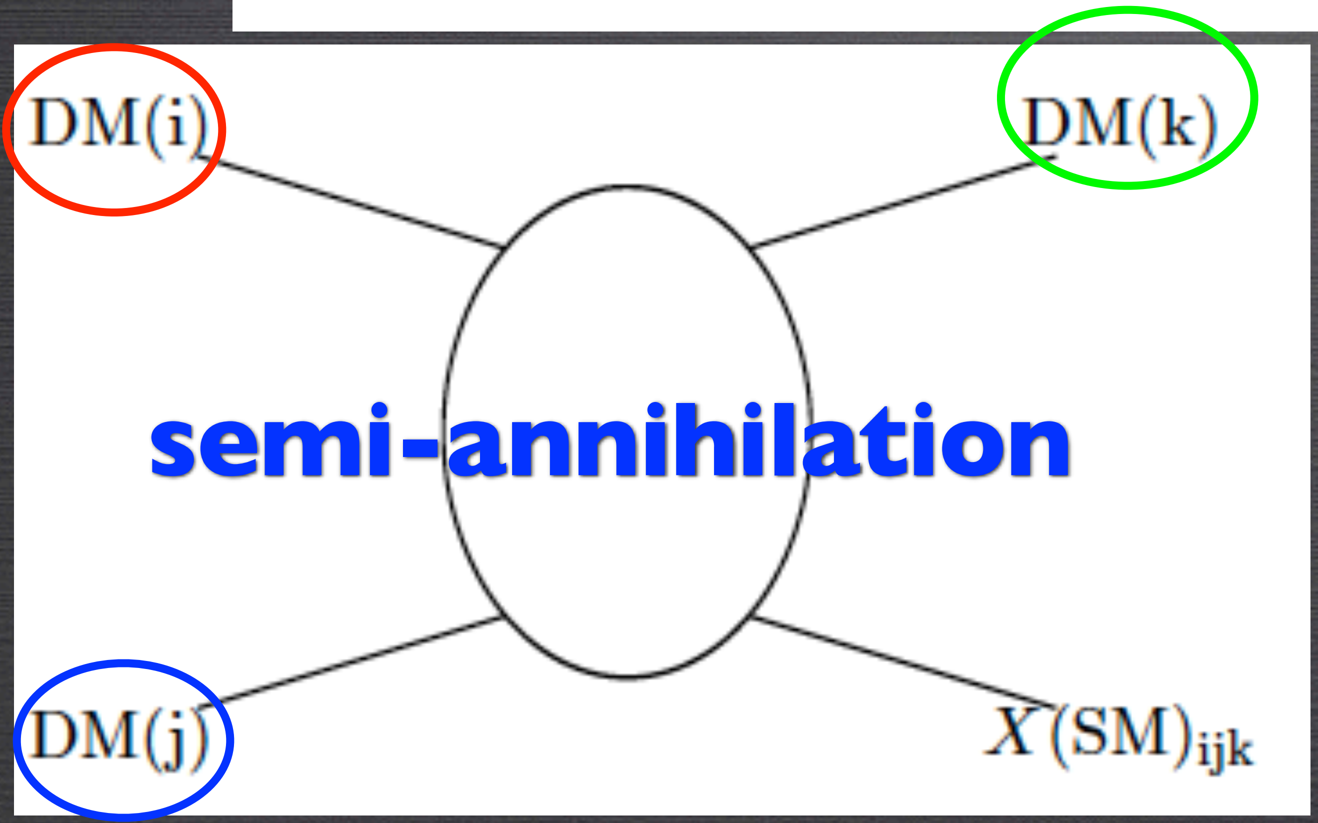
# of DMs=3: $(\eta,\ \chi,\ \phi)$ **or** $(N_R^c,\ \chi,\ \phi)$

# of DMs=2: $(\eta,\ \chi)$ **or** $(\chi,\ \phi)$ **etc**

Non-standard annihilations and relic abundance

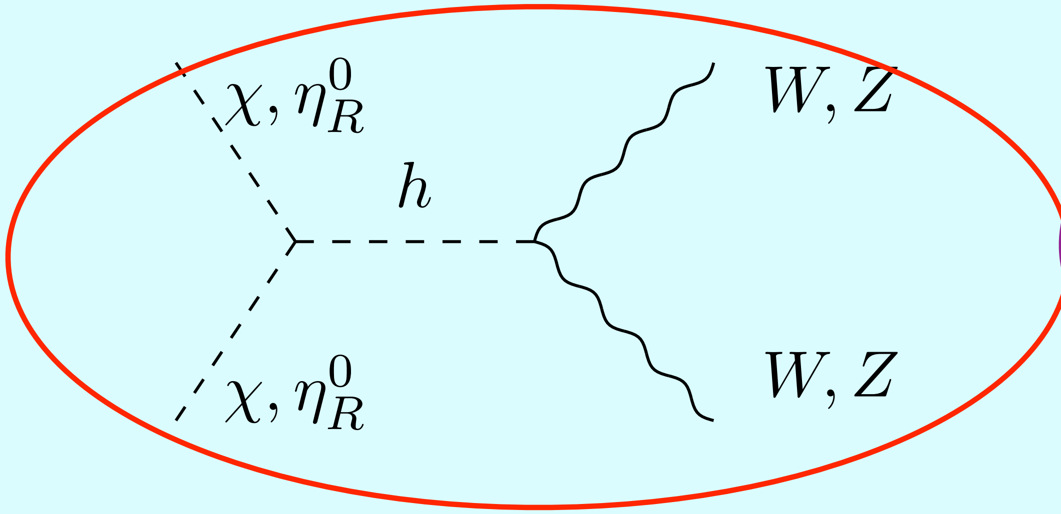


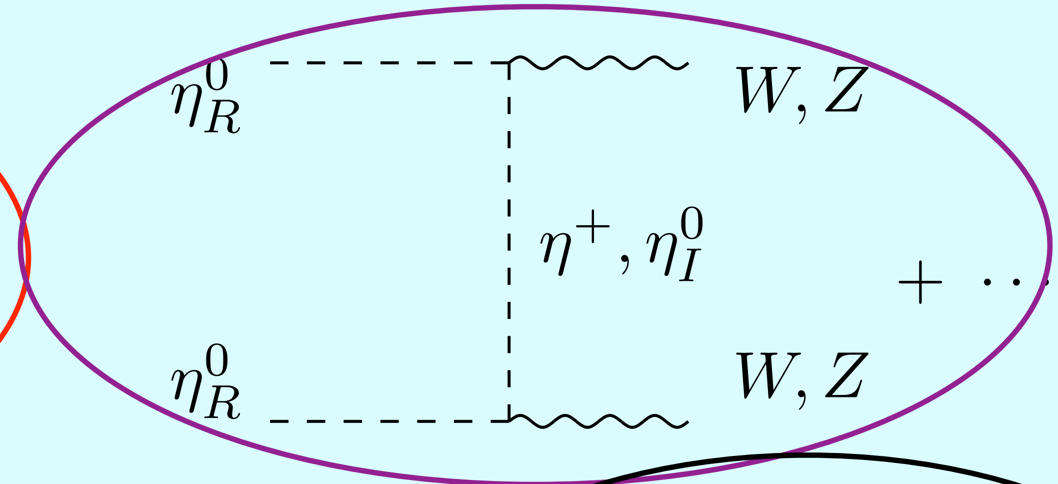




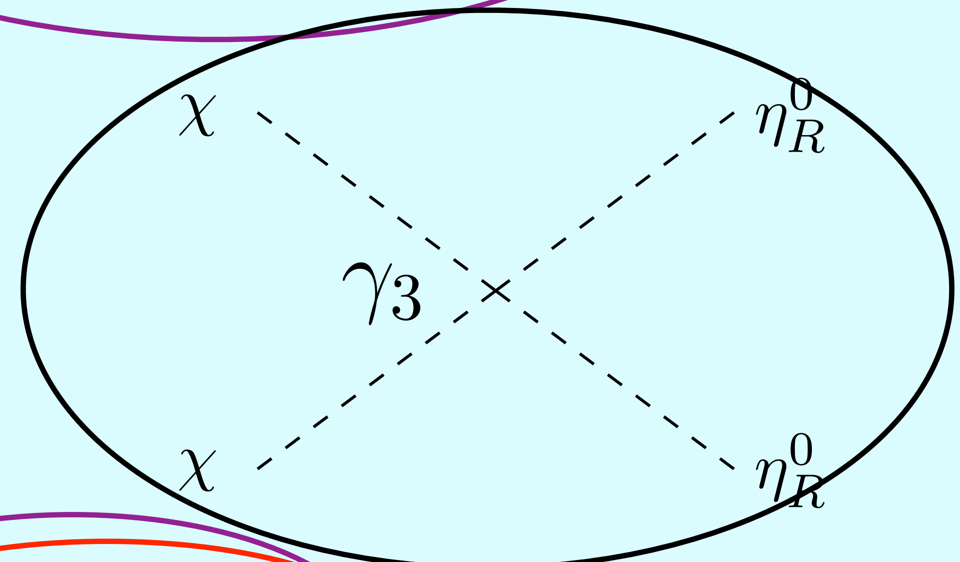
SEE FOR MORE DETAILS:
AOKI, DUERR, KUBO
+TAKANO,
ARXIV:1207.3318

η - χ DM system





$(2\gamma_2, \lambda_3)v_h$



Boltzmann eqs.

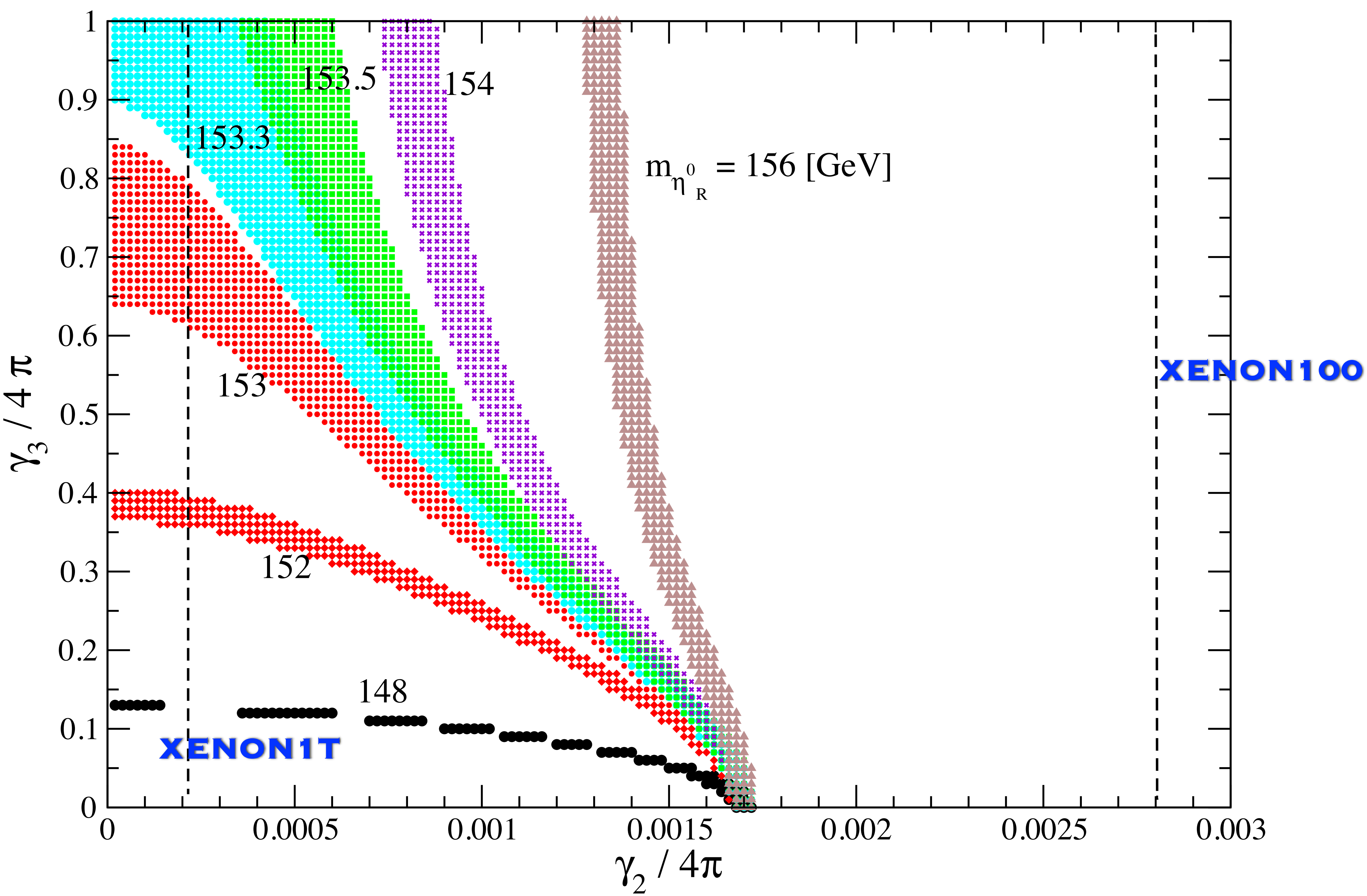
$$\frac{dY_{\eta_R^0}}{dx} = -0.264\ g_*^{1/2}\left[\frac{\mu M_{\rm PL}}{x^2}\right]\left\{ <\sigma(\eta_R^0\eta_R^0;{\rm SM})v> \left(Y_{\eta_R^0}Y_{\eta_R^0} - \bar{Y}_{\eta_R^0}\bar{Y}_{\eta_R^0}\right)\right.$$

$$\left. + <\sigma(\eta_R^0\eta_R^0;\chi\chi)v> \left(Y_{\eta_R^0}Y_{\eta_R^0} - \frac{Y_\chi Y_\chi}{\bar{Y}_\chi\bar{Y}_\chi}\bar{Y}_{\eta_R^0}\bar{Y}_{\eta_R^0}\right)\right\} ,$$

$$\frac{dY_\chi}{dx} = -0.264\ g_*^{1/2}\left[\frac{\mu M_{\rm PL}}{x^2}\right]\left\{ <\sigma(\chi\chi;{\rm SM})v> \left(Y_\chi Y_\chi - \bar{Y}_\chi\bar{Y}_\chi\right)\right.$$

$$\left. - <\sigma(\eta_R^0\eta_R^0;\chi\chi)v> \left(Y_{\eta_R^0}Y_{\eta_R^0} - \frac{Y_\chi Y_\chi}{\bar{Y}_\chi\bar{Y}_\chi}\bar{Y}_{\eta_R^0}\bar{Y}_{\eta_R^0}\right)\right\} ,$$

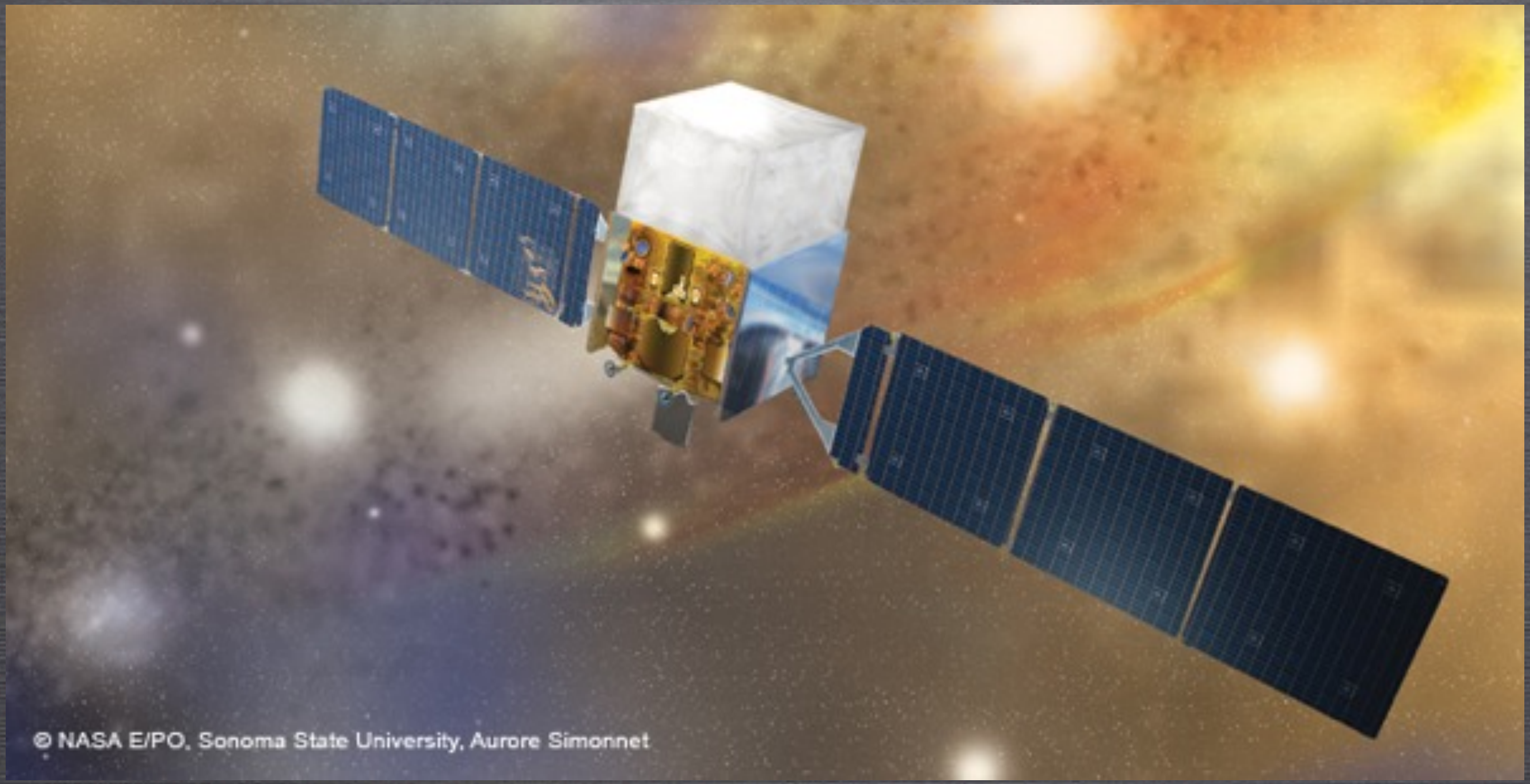
$\Omega_T h^2 (\simeq \Omega_\chi h^2) = 0.1157 \pm 0.0046 \ (2\sigma)$ **WITH** $m_\chi = 135$ **GeV**



$\lambda_1 = 0.129 \ , \ \lambda_3 = -1.26 \ , \ \lambda_4 = -0.0205$

III Bonus

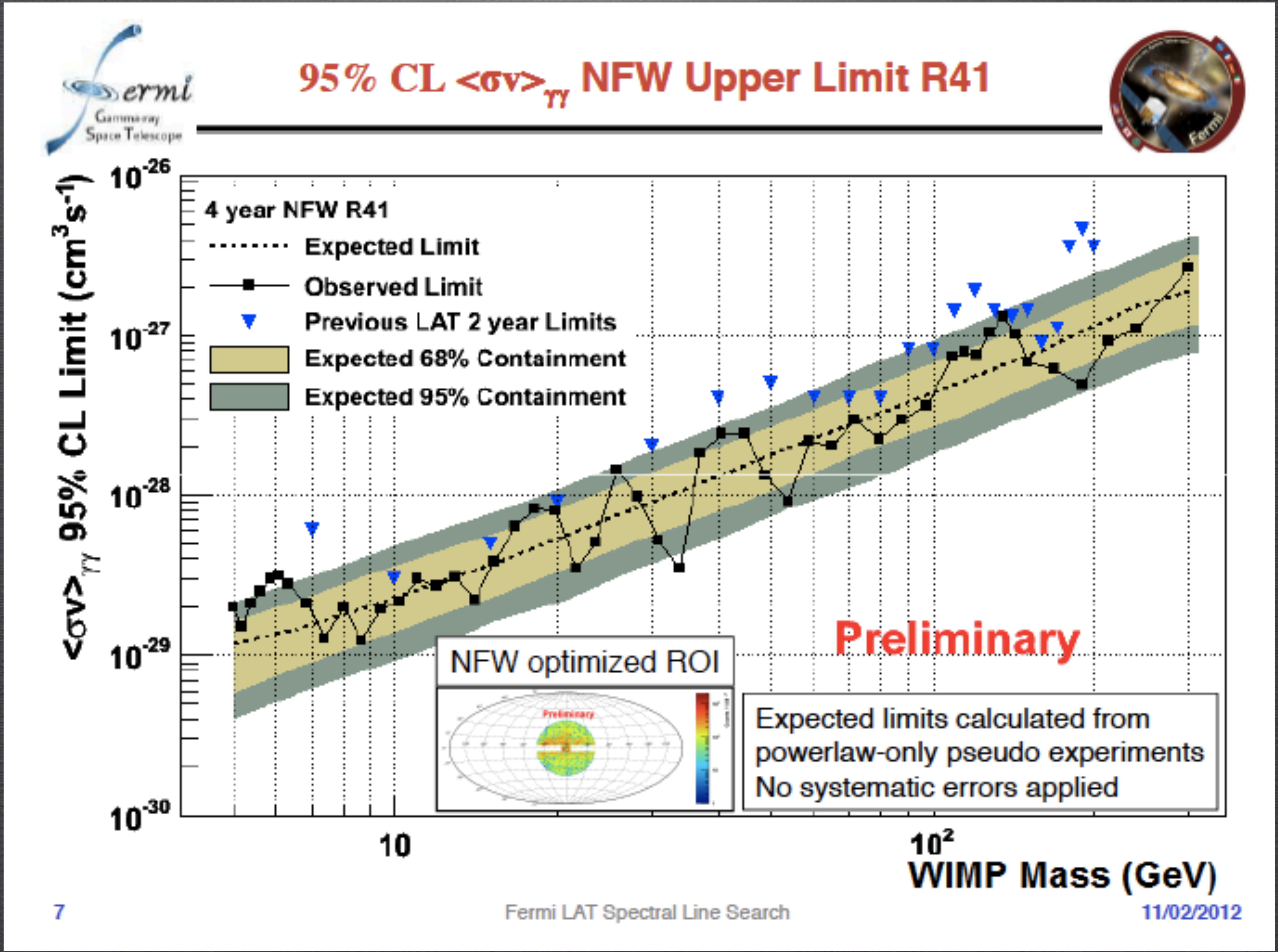
* The first bonus: Fermi-LAT 135 GeV gamma-ray line



Fermi-LAT is measuring gamma rays coming from the universe since 2008.

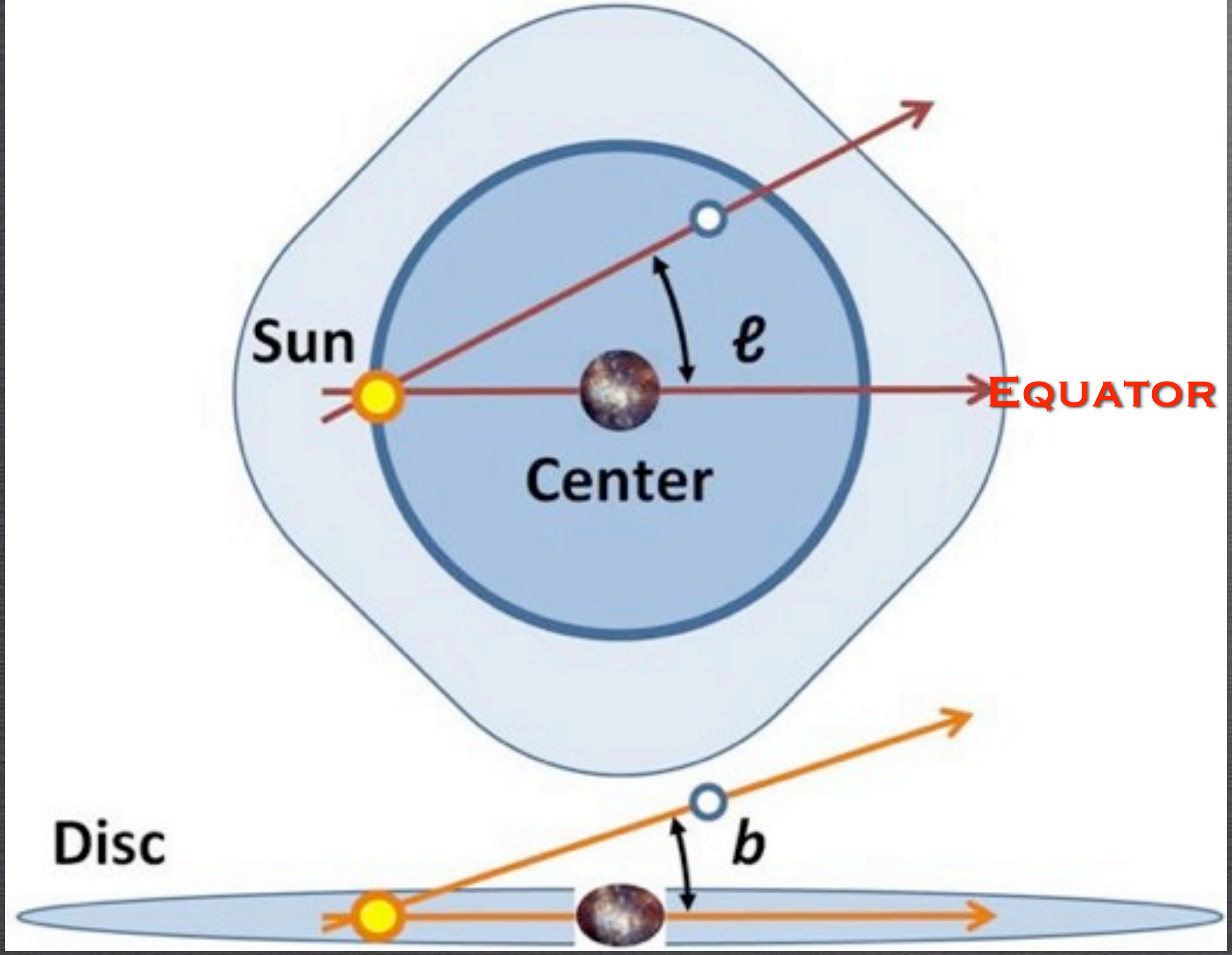
LAT Collaboration, arXiv:1205.2739; etc

If the data from the whole sky is included:



However , if you look at the center of the galaxy, something more interesting is going on.

Wenider, arXiv:1204.2797;
Bringmann et al,arXiv:1203.1312; etc

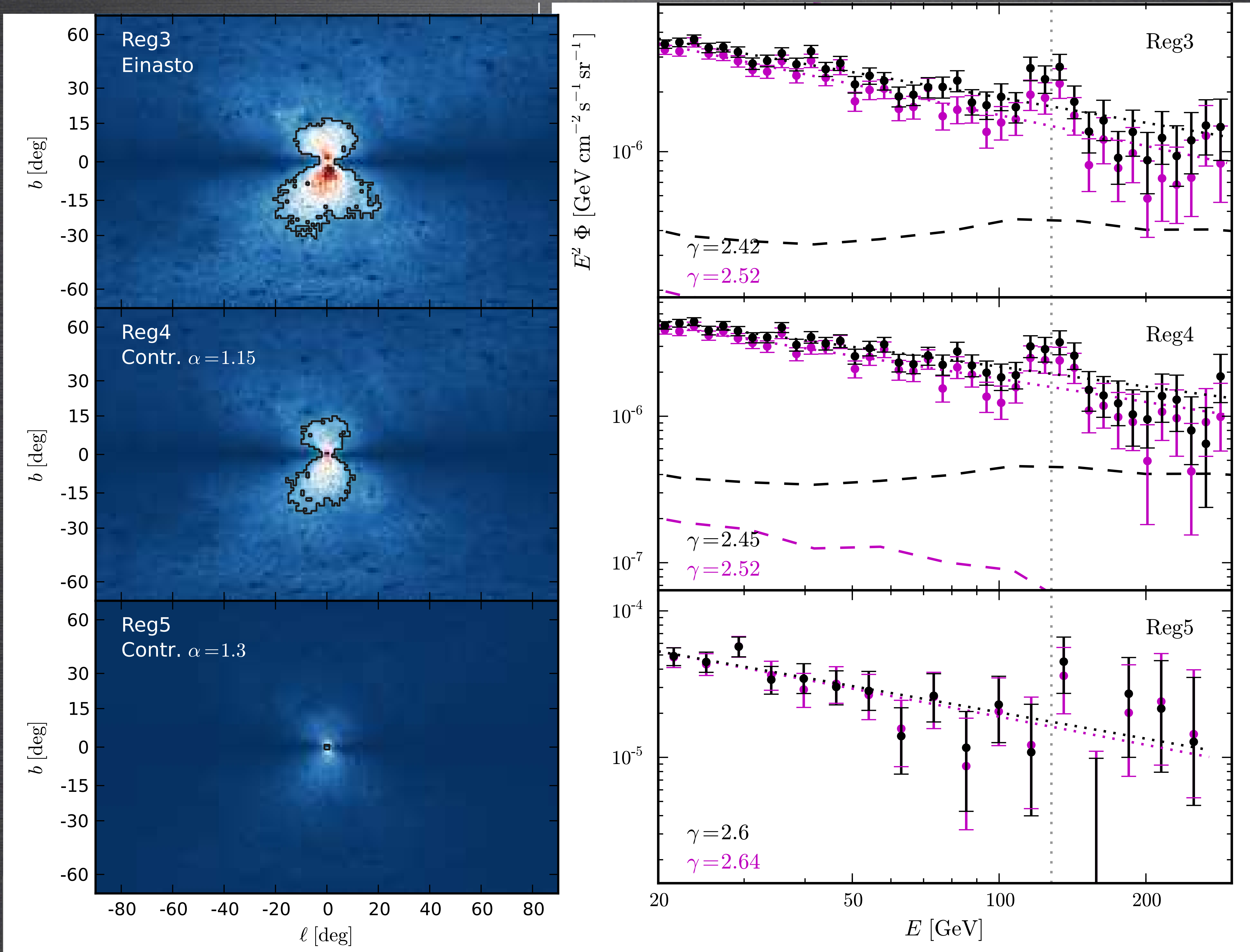


Galactic Coordinates

l: longitude

b: latitude

The center: l=b=0

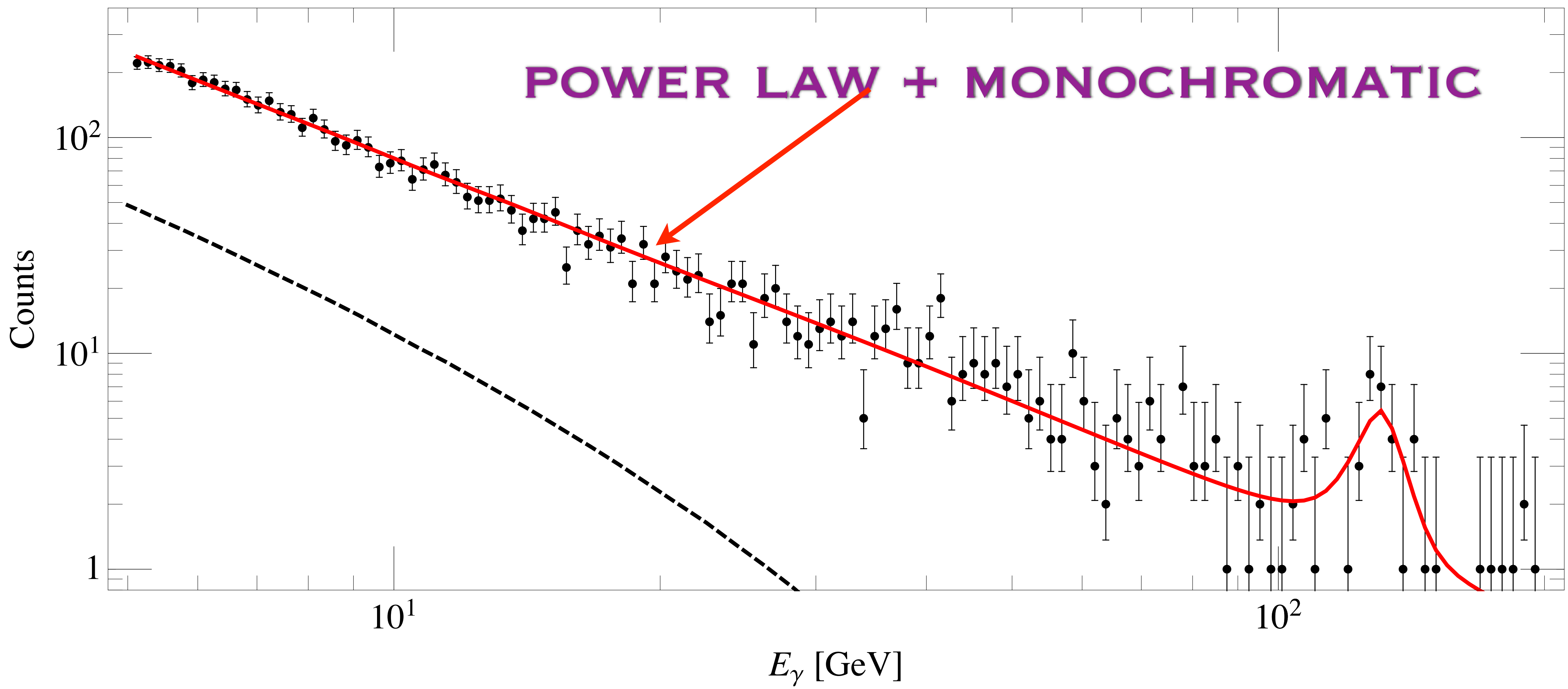


$$v\sigma_{\gamma\gamma} \simeq 10^{-27}\ \mathbf{cm^3 s^{-1}}$$

Weniger, JCAP 1208 (2012) 007

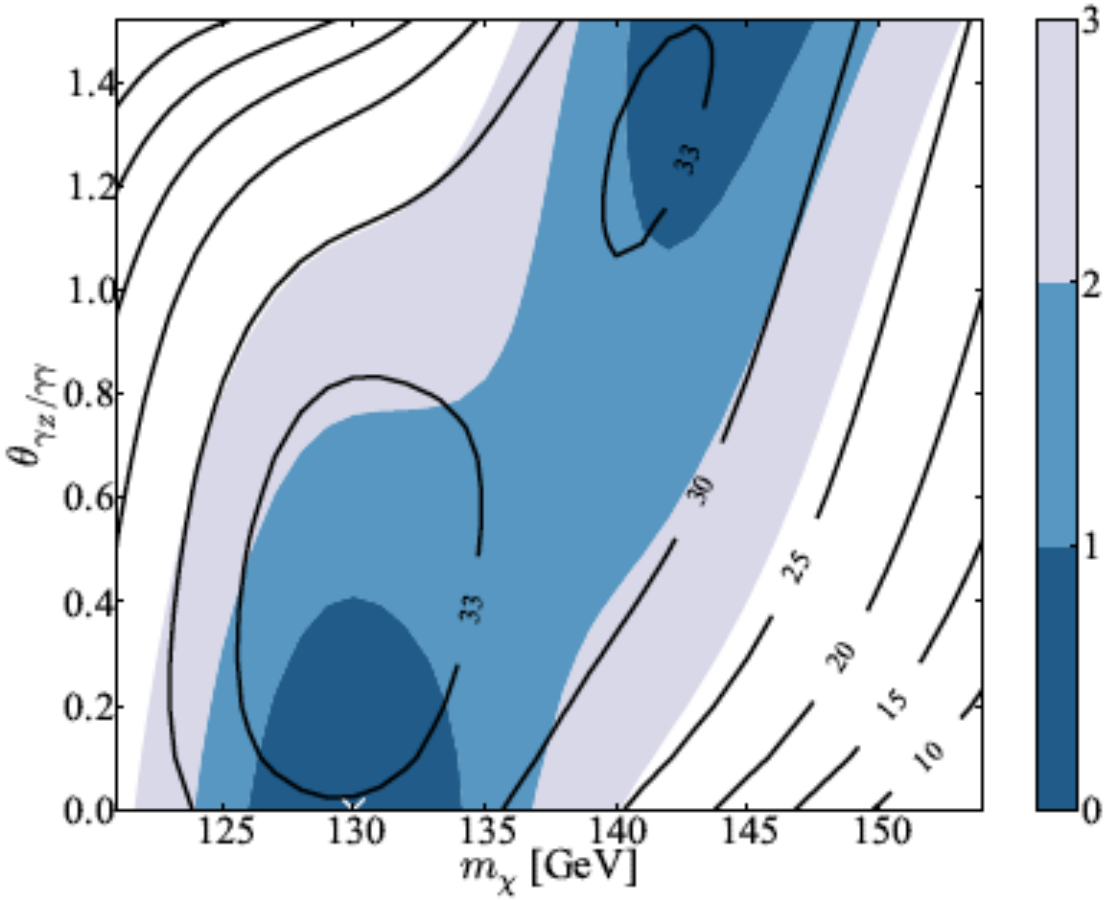
LOOKING AT THE CENTER MORE IN DETAIL. (INNER 3 DEGREE RADIUS AROUND THE CENTER)

COHEN ET AL, ARXIV:1207.0800

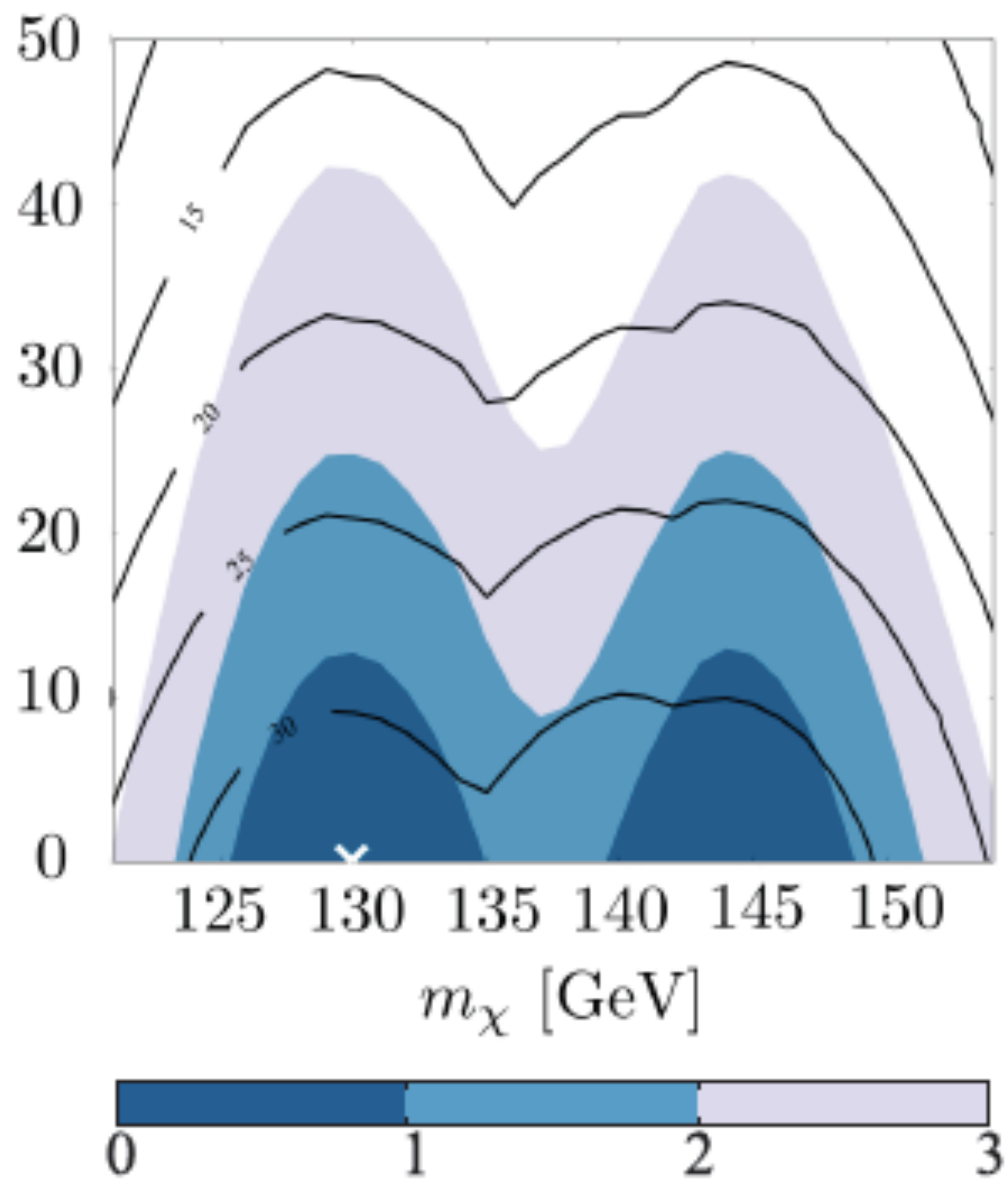


THE BEST FIT: NO ANNIHILATIONS INTO W^+W^- , ZZ , $Z\gamma$ ETC.

$\sigma_{\gamma Z}/\sigma_{\gamma\gamma}$



$\sigma_{W^+W^-}/(2\sigma_{\gamma\gamma} + \sigma_{\gamma Z})$



Cohen et al,
arXiv:1207.0800

Dilemma

* **Monochromatic gamma**

$$v\sigma_{\gamma\gamma} \simeq 10^{-27}\ \mathbf{cm^3 s^{-1}}$$ (loop effect)

* **Continuum gamma**

$$v\sigma(\mathbf{DMDM} \to \mathbf{SM}), i.e. v\sigma(\mathbf{DMDM} \to W^+W^-)\ \mathbf{etc}$$

$$\lesssim 10 \times v\sigma(\mathbf{DMDM} \to \gamma\gamma) \sim 10^{-26}\ \mathbf{cm^3 s^{-1}}$$ (tree level)

* **Observed relic density** $\Omega_T h^2 = 0.116$

$$v\sigma(\mathbf{DMDM}) \simeq 10^{-26}\ \mathbf{cm^3 s^{-1}}$$

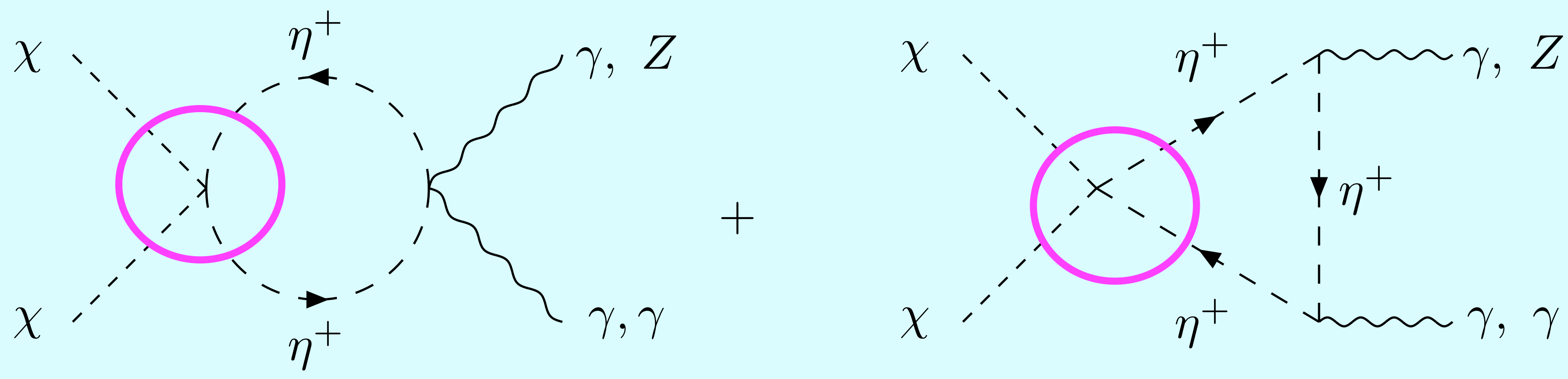
GOOD NEWS

ONE-LOOP ->

$$v\sigma(\mathbf{DMDM} \to \gamma\gamma) \sim \lambda^2 \frac{1}{\pi}\frac{1}{m_{DM}^2}\left(\frac{e^2}{16\pi^2}\right)^2 \simeq 1.2\left(\frac{\lambda}{4\pi}\right)^2 \times 10^{-26}\ \mathbf{cm^3 s^{-1}}$$

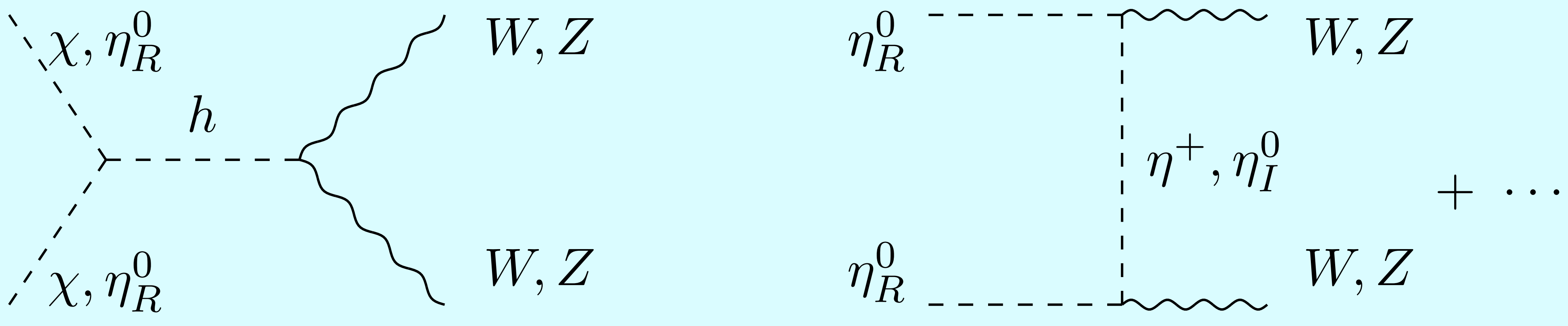
$$\textbf{for } m_{\rm DM} = 135\ \textbf{GeV}$$

In our model:



How to realize a large σ at the freeze out, while suppressing σ in the galaxy, i.e. at low temperature.

In our model:



$(2\gamma_2, \lambda_3)v_h$

To make the continuum gammas small:

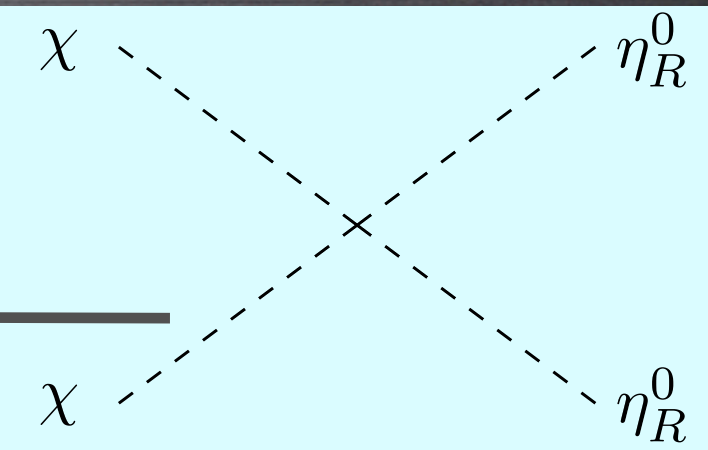
For chi DM: small γ_2

For eta DM: small Ω_η

TEMPERATURE DEPENDENT CROSS SECTION:

$$\frac{dY_\chi}{dx} = -0.264\ g_*^{1/2}\left[\frac{\mu M_{\rm PL}}{x^2}\right]\Big\{ <\sigma(\chi\chi;{\rm SM})v> \left(Y_\chi Y_\chi - \bar{Y}_\chi \bar{Y}_\chi\right)$$

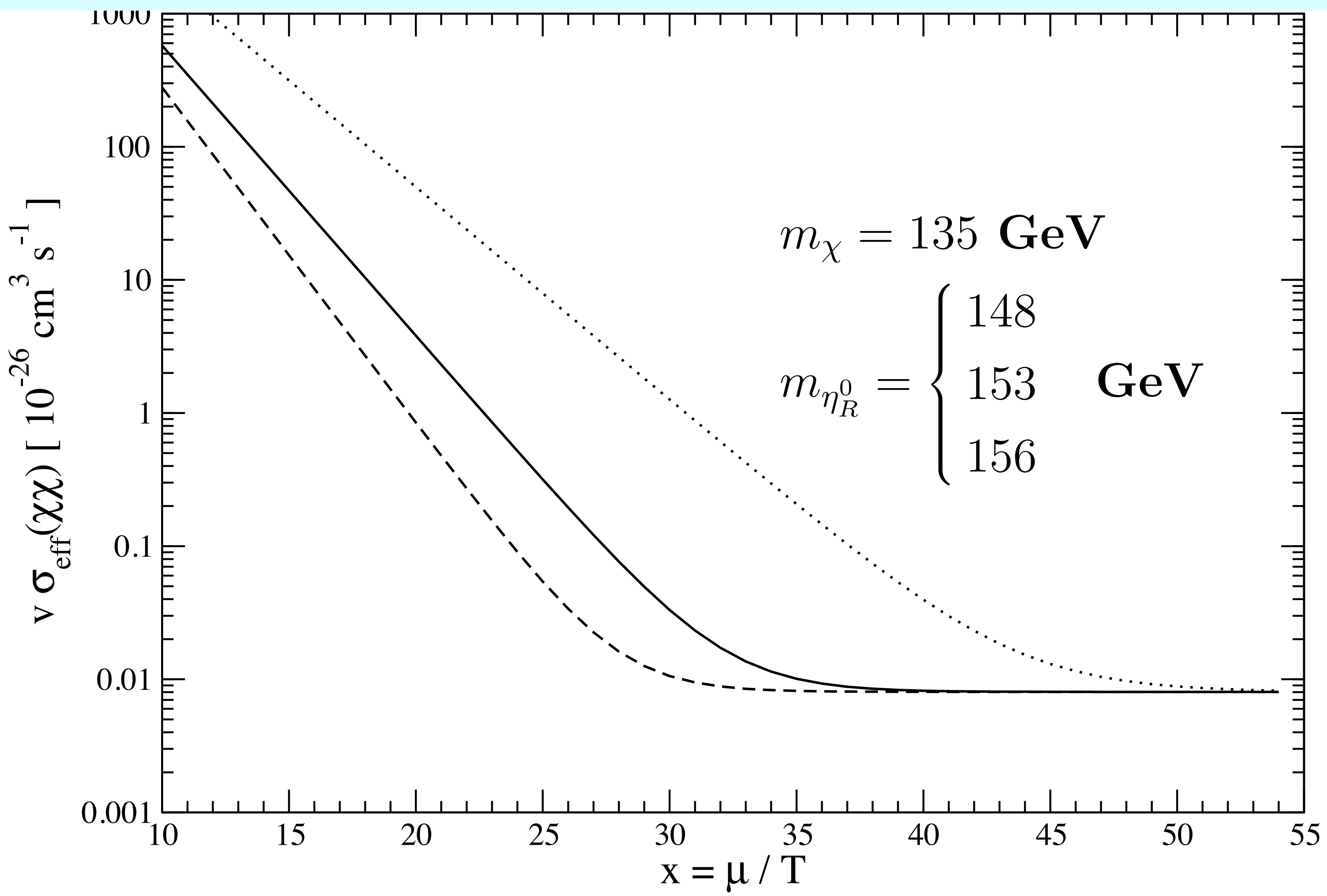
$$- <\sigma(\eta_R^0\eta_R^0;\chi\chi)v>\left(Y_{\eta_R^0}Y_{\eta_R^0} - \frac{Y_\chi Y_\chi}{\bar{Y}_\chi \bar{Y}_\chi}\bar{Y}_{\eta_R^0}\bar{Y}_{\eta_R^0}\right)\Big\},$$



σeff

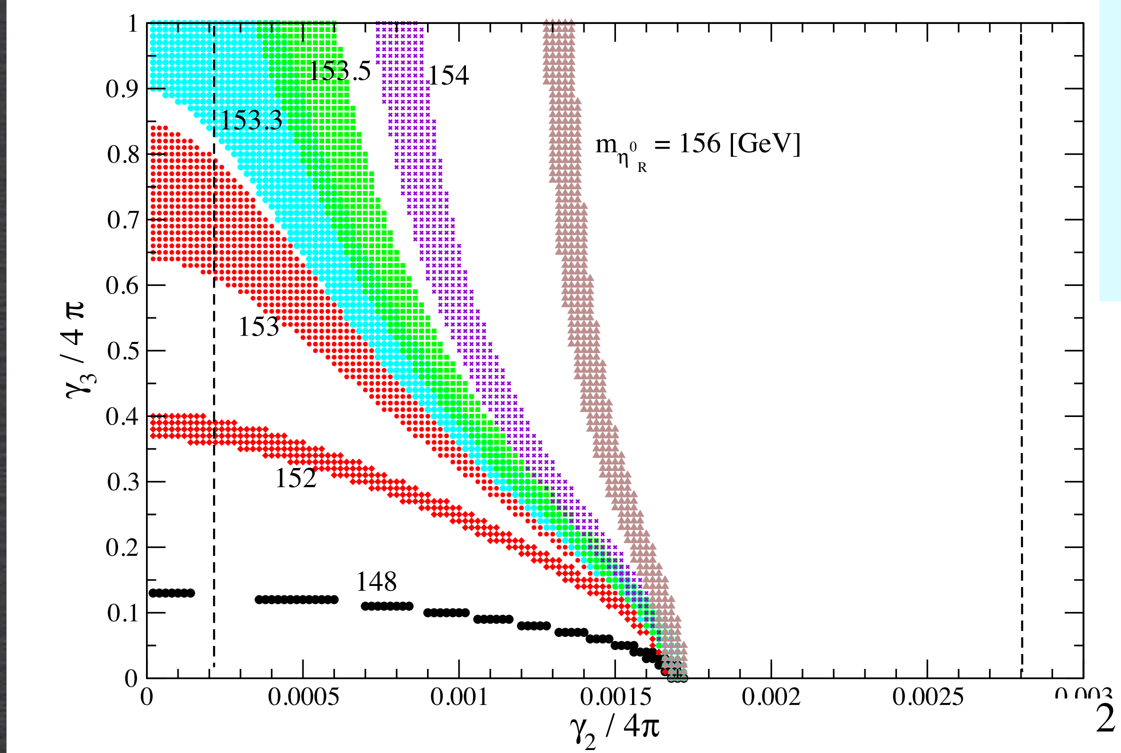
DM conversion

$$\left[<\sigma(\chi\chi;{\rm SM})v> + <\sigma(\eta_R^0\eta_R^0;\chi\chi)v>\ \frac{m_{\eta_R^0}^3}{m_\chi^3}\exp 2\left(\frac{m_\chi^2 - m_{\eta_R^0}^2}{m_\chi m_{\eta_R^0}}\right)x\right]\left(Y_\chi Y_\chi - \bar{Y}_\chi \bar{Y}_\chi\right)$$

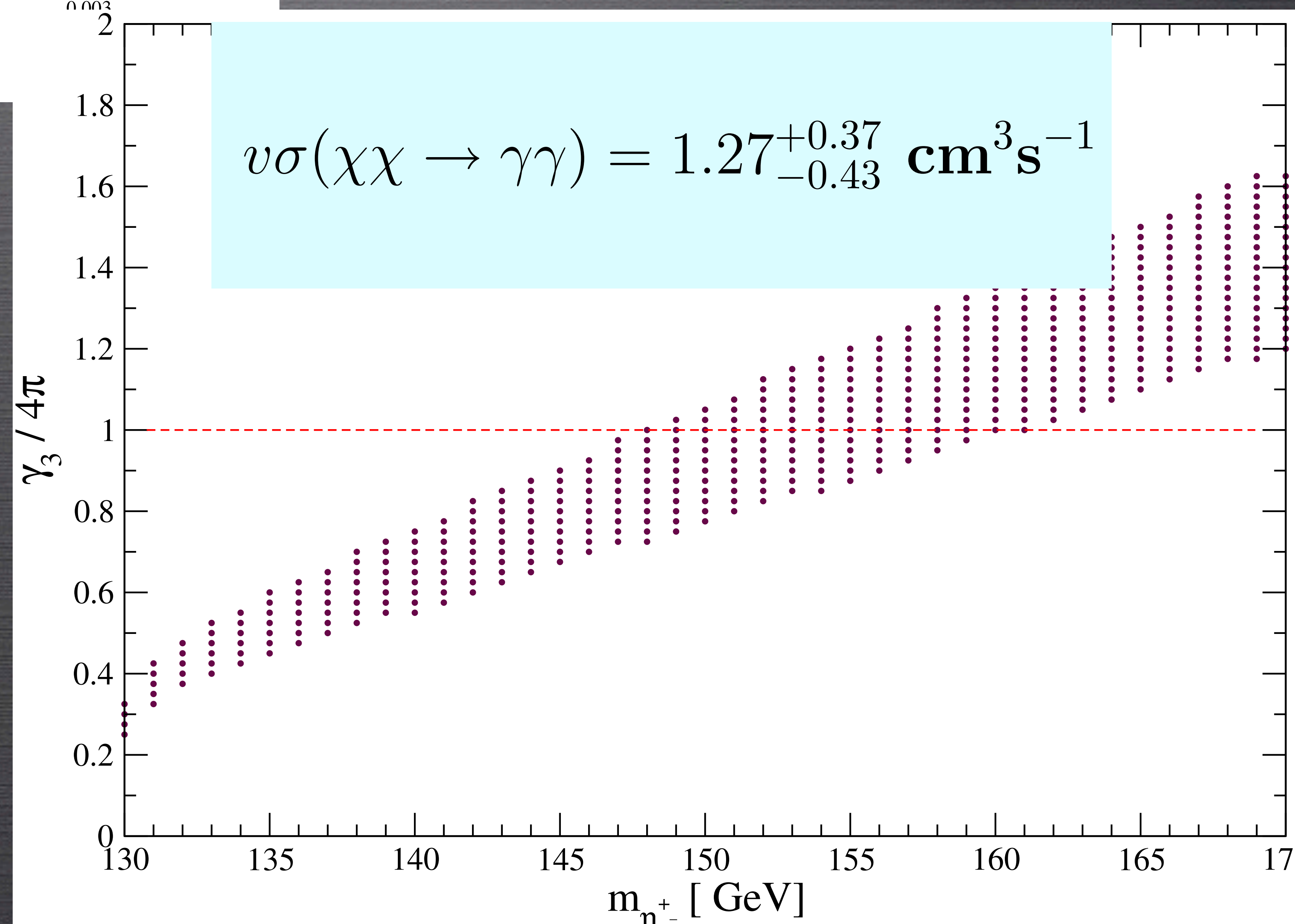


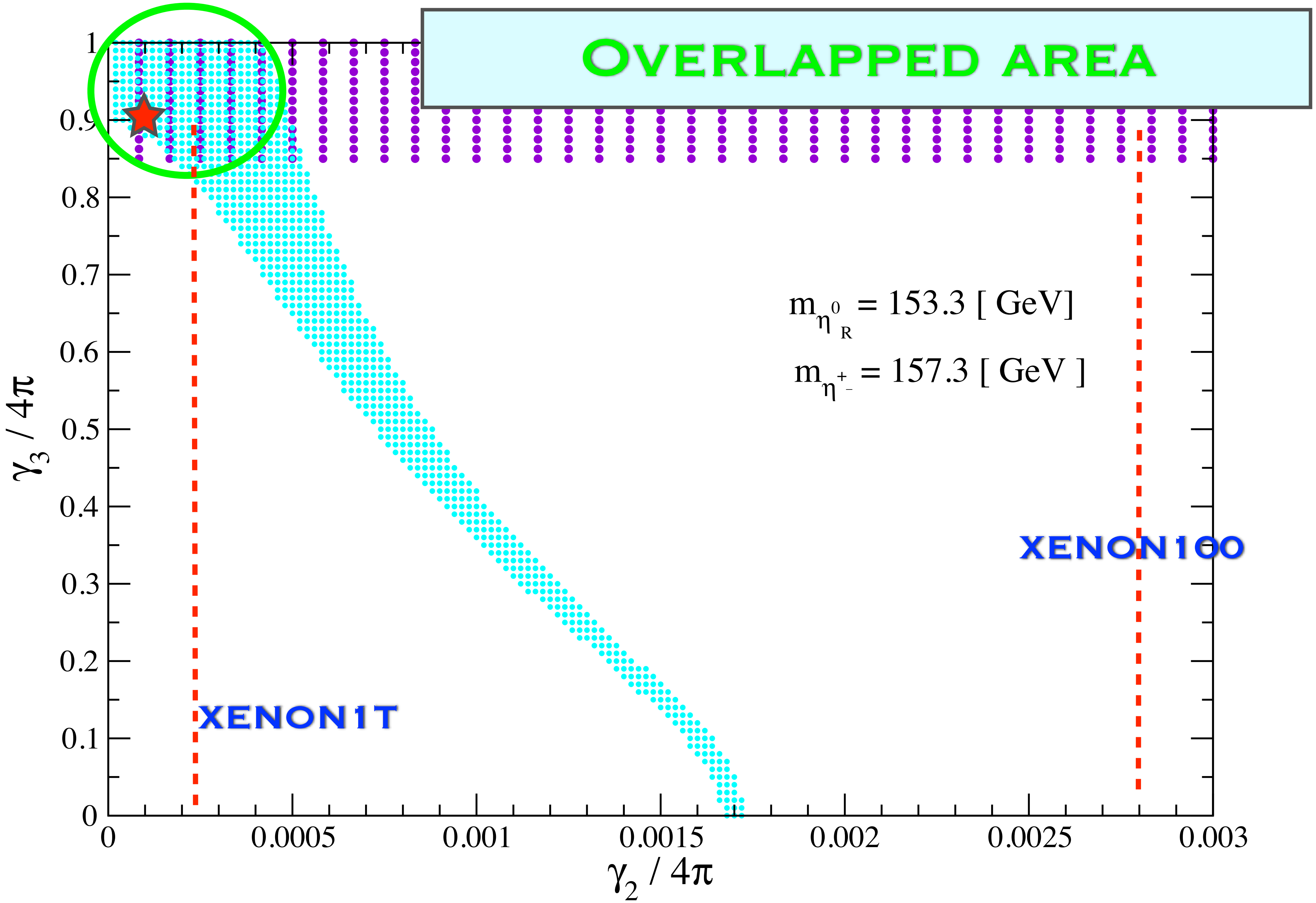
See also:
Baek, KO+Senaha, arXiv:1209.1685

$$\Omega_T = 0.1157 \pm 0.0046(2\sigma)$$



$$v\sigma(\chi\chi \to \gamma\gamma) = 1.27^{+0.37}_{-0.43}\ \mathbf{cm^3 s^{-1}}$$





$$v\sigma(\chi\chi \to \mathrm{SM}) \simeq 8.0 \times 10^{-29}\ \mathrm{cm^3 s^{-1}}$$

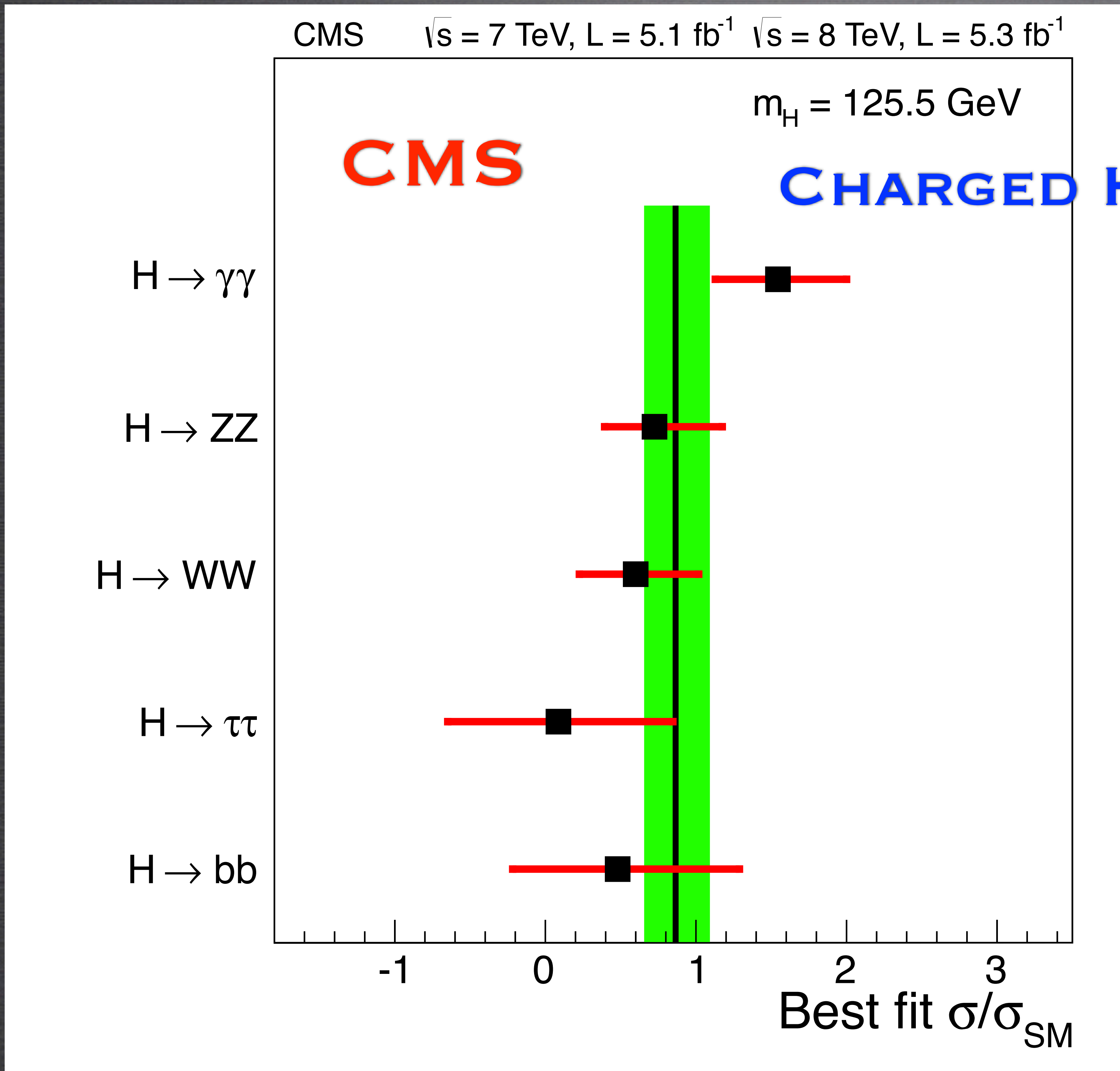
$$v\sigma(\chi\chi \to W^+W^-) \simeq 3.9 \times 10^{-29}\ \mathrm{cm^3 s^{-1}}$$

$$v\sigma(\chi\chi \to ZZ) \simeq 1.7 \times 10^{-29}\ \mathrm{cm^3 s^{-1}}$$

$$v\sigma(\chi\chi \to hh) \simeq 2.5 \times 10^{-29}\ \mathrm{cm^3 s^{-1}}$$

$$v\sigma(\chi\chi \to f\bar{f}) \simeq 1.1 \times 10^{-31}\ \mathrm{cm^3 s^{-1}}$$

* Yet another bonus:



Charged Higgs contributes:

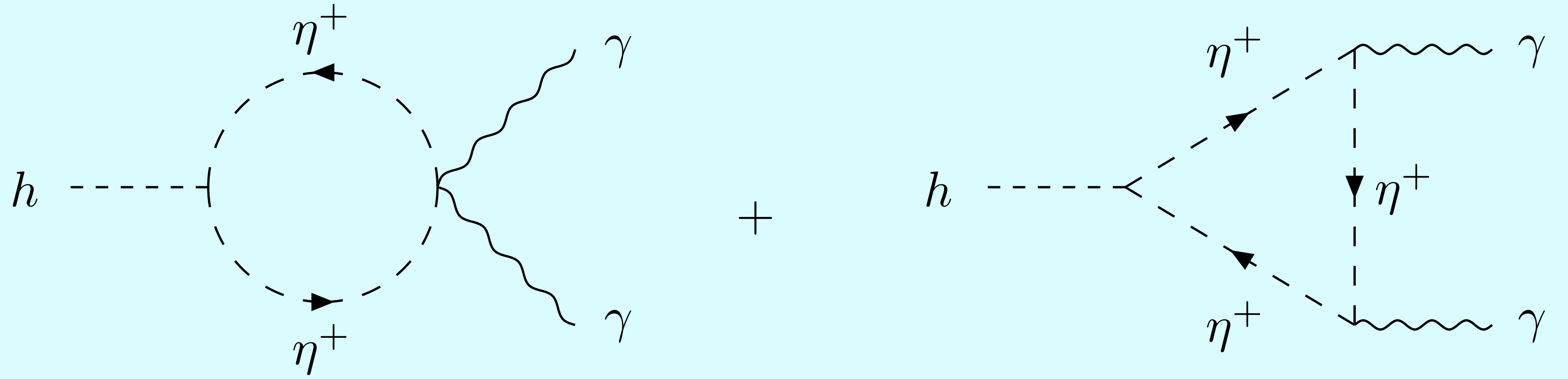
$$\sigma^{MCDM}/\sigma^{\rm SM} = 1.6 \pm 0.4$$

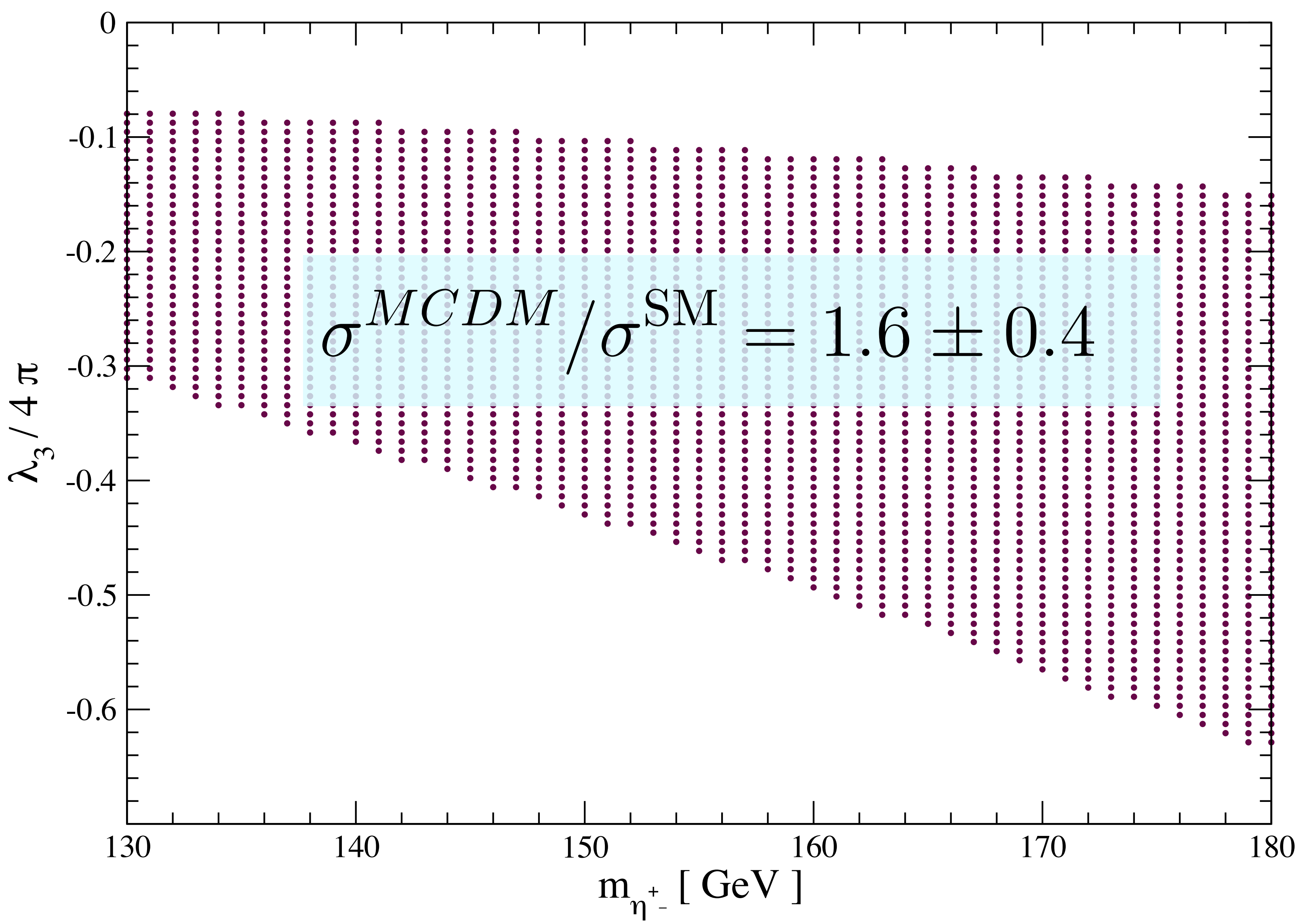
CMS

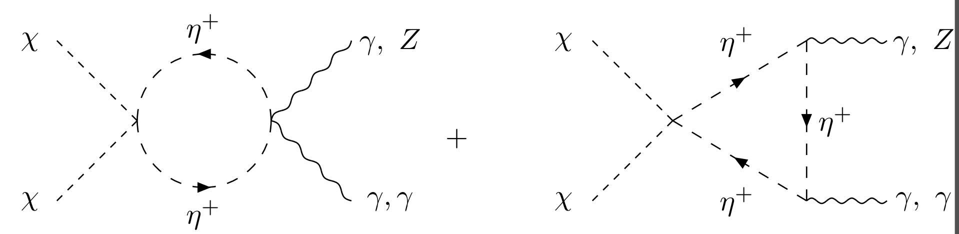
CMS Collaboration, arXiv:1207.7235

ATLAS Collaboration arXiv:1207.7214

Higgs decay into two gammas







DM annihilation

Gunion, Haber, Kane +Dawson;
Akeroyd, Diaz + River;
Arhrib, Benbrik + Gaur;
Swiezewska + Krawczyk; etc

IV Conclusion

1 A Two-loop seesaw model is proposed;

* L is softly violated by a dim. 2 operator,
* Z_2 x Z_2 is the unbroken symmetry, and
* the Higgs sector is minimal.

2 With η_R^0 **and** χ as DM the model has a potential to explain:

* 135 GeV gamma-ray line observed at the Fermi LAT and
* enhancement of $h \to \gamma\gamma$ observed at LHC.

Tank you very much!

$$B(\mu \to e\gamma) = \frac{3\alpha}{64\pi(G_F m_{\eta^\pm}^2)^2} \left| \sum_k Y_{\mu k}^\nu Y_{ek}^\nu F_2\left(\frac{M_k^2}{m_{\eta^\pm}^2}\right) \right|^2 \lesssim 2.4 \times 10^{-12}$$

$$F_2(x) = \frac{1}{6(1-x)^4}(1 - 6x + 3x^2 + 2x^3 - 6x^2 \ln x) \ ,$$

$$\delta a_\mu \ = \ \frac{m_\mu^2}{16\pi^2 m_{\eta^\pm}^2} \sum_k Y_{\mu k}^\nu Y_{\mu k}^\nu F_2\left(\frac{M_k^2}{m_{\eta^\pm}^2}\right)$$

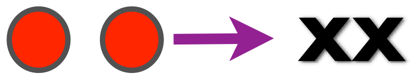
$$|\delta a_\mu| \ \simeq \ 2.2 \times 10^{-5} B(\mu \to e\gamma) \lesssim 3.4 \times 10^{-11}$$

$$\Delta T \ \simeq \ 0.54 \left(\frac{m_{\eta^\pm} - m_{\eta_R^0}}{v}\right)\left(\frac{m_{\eta^\pm} - m_{\eta_I^0}}{v}\right) = 0.02^{+0.11}_{-0.12}$$

$$(\mathcal{M}_\nu)_{ij} \ = \ \left(\frac{1}{16\pi^2}\right)^2 \frac{\kappa^2 v_h^2}{8} \sum_k Y_{ik}^\nu Y_{jk}^\nu \ \int_0^\infty dx\{ \ B_0(-x, m_\chi, m_{\phi_R}) - B_0(-x, m_\chi, m_{\phi_I}) \ \}$$
$$\times \frac{x}{(x + m_\eta^2)^2 (x + M_k^2)} \ \ \text{for } m_\eta = m_{\eta_R^0} \simeq m_{\eta_I^0}$$
$$\sim \ -\lambda_5^{\text{eff}} v_h^2 \sum_k \frac{Y_{ik}^\nu Y_{jk}^\nu}{16\pi^2 M_k} \left(ln\left(\frac{m_{\eta_R^0}}{M_k}\right)^2 + 1 \right) \text{for } m_\eta << M_k \ ,$$

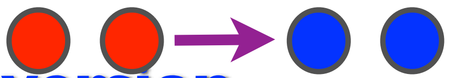
Coupled Boltzmann eqs.

D'Eramo+Thaler, 11, Belanger, Kannike, Pukov+Raidal, 12; Aoki, Duerr, Kubo+Takano, 12.



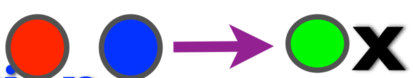
standard

$$\frac{dY_i}{dx} = -0.264\ g_*^{1/2}\left[\frac{\mu M_{\rm PL}}{x^2}\right]\Big\{\ <\sigma(ii;X_iX_i')v>\left(Y_iY_i - \bar{Y}_i\bar{Y}_i\right)$$



conversion

$$+\sum_{i>j}<\sigma(ii;jj)v>\left(Y_iY_i - \frac{Y_jY_j}{\bar{Y}_j\bar{Y}_j}\bar{Y}_i\bar{Y}_i\right) - \sum_{j>i}<\sigma(jj;ii)v>\left(Y_jY_j - \frac{Y_iY_i}{\bar{Y}_i\bar{Y}_i}\bar{Y}_j\bar{Y}_j\right)$$



semi-annihilation

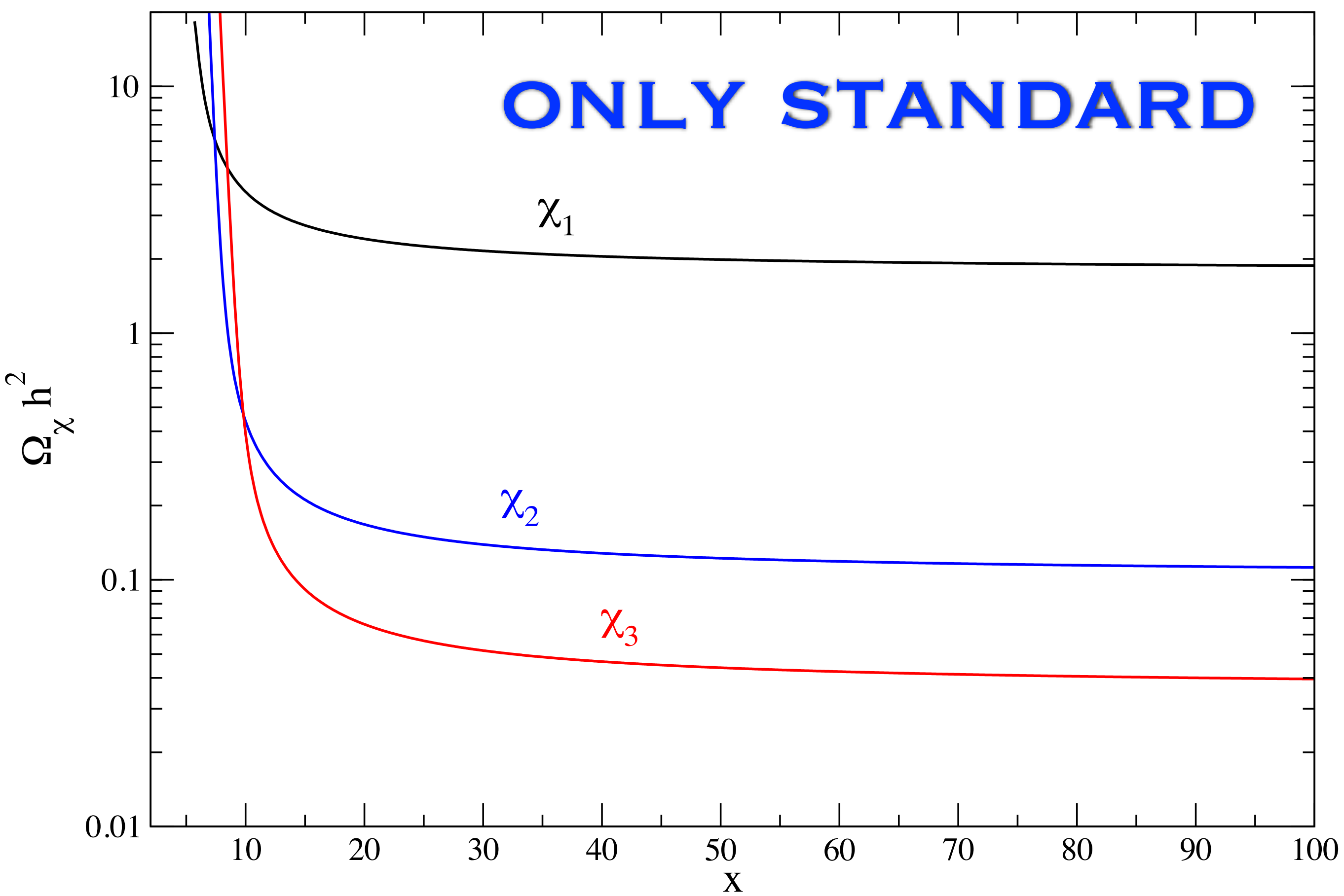
$$+\sum_{j,k}<\sigma(ij;kX_{ijk})v>\left(Y_iY_j - \frac{Y_k}{\bar{Y}_k}\bar{Y}_i\bar{Y}_j\right) - \sum_{j,k}<\sigma(jk;iX_{jki})v>\left(Y_jY_k - \frac{Y_i}{\bar{Y}_i}\bar{Y}_j\bar{Y}_k\right)\Big\}$$

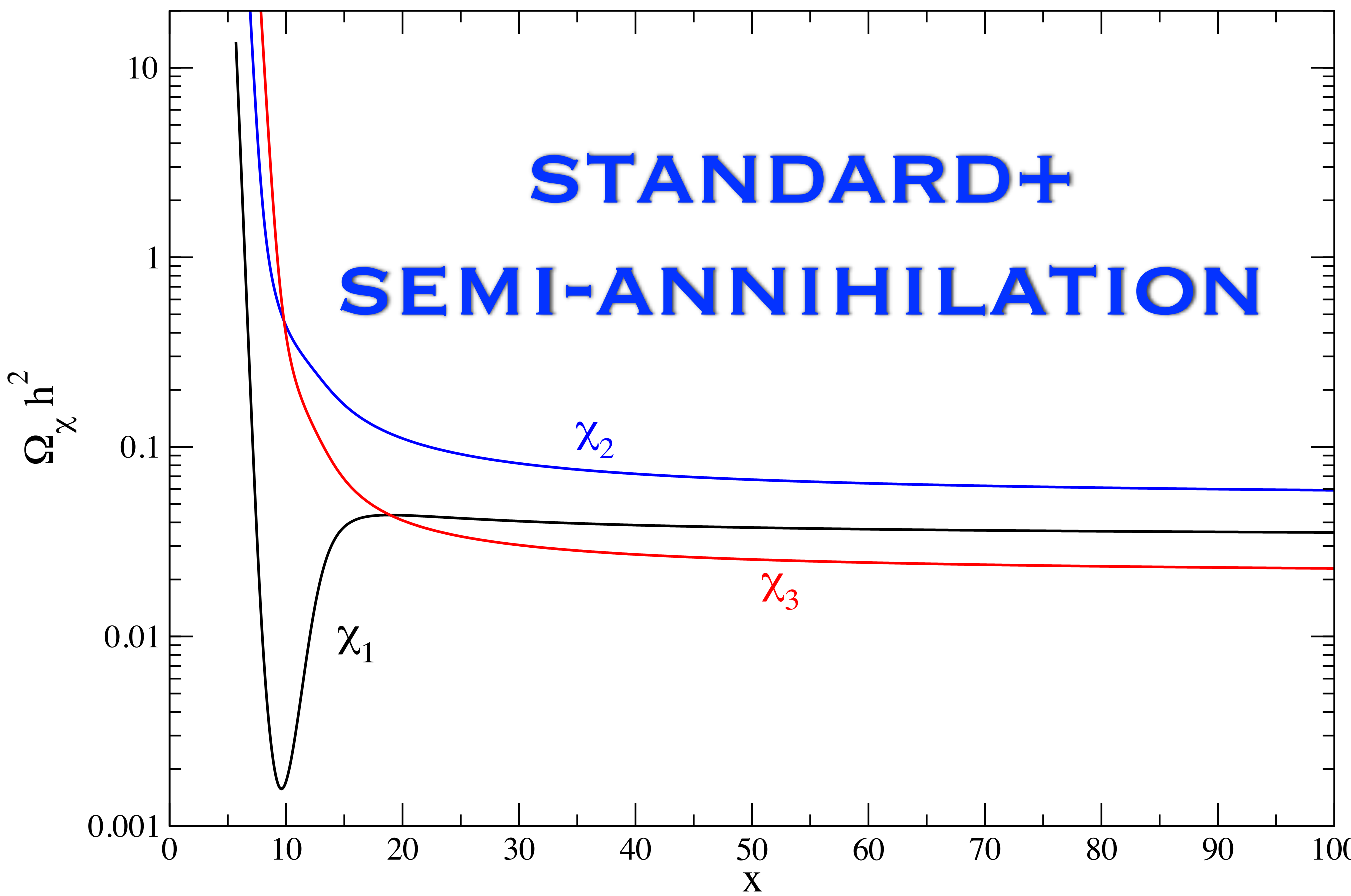
$$Y_i = n_i/s \qquad \mu = \left(\textstyle\sum_i m_i^{-1}\right)^{-1}$$

$$m_1 = 200 \text{ GeV} , \ m_2 = 160 \text{ GeV} , \ m_3 = 140 \text{ GeV}$$

STANDARD: $\sigma_{0,1} = 0.1 , \ \sigma_{0,2} = 2 , \ \sigma_{0,3} = 6$

Temperature evolution

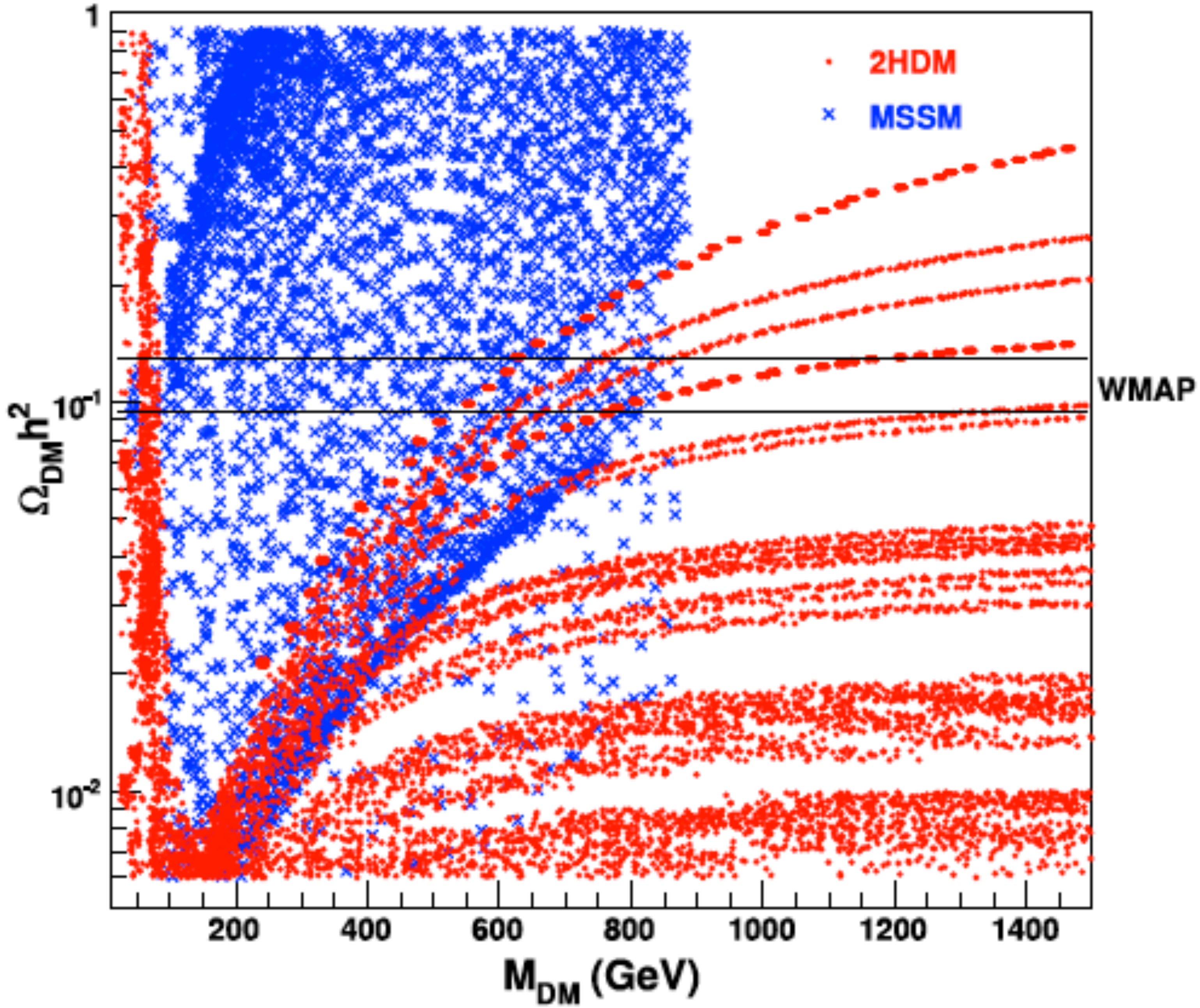




Aoki, Duerr, Kubo+Takano, 2012

$$\sigma_{0,123} = \sigma_{0,312} = \sigma_{0,231} = 5.1$$

Relic abundance



Lopez, Oliver and Tytgat,'06

Only low mass and higher mass regimes are allowed.

SUSY

Higgsino:

$$\sigma_{\gamma\gamma} v \simeq 1.1 \times 10^{-28}\ \mathrm{cm}^3/\mathrm{s}$$
$$\sigma_{\gamma Z} v \simeq 3.7 \times 10^{-28}\ \mathrm{cm}^3/\mathrm{s}$$
$$\sigma_{\mathrm{ann}} v \simeq \sigma_{WW} v + \sigma_{ZZ} v \simeq 4.2 \times 10^{-25}\ \mathrm{cm}^3/\mathrm{s}$$

Wino:

$$\sigma_{\gamma\gamma} v \simeq 2.5 \times 10^{-27}\ \mathrm{cm}^3/\mathrm{s}$$
$$\sigma_{\gamma Z} v \simeq 1.4 \times 10^{-26}\ \mathrm{cm}^3/\mathrm{s}$$
$$\sigma_{\mathrm{ann}} v \simeq \sigma_{WW} v \simeq 4.0 \times 10^{-24}\ \mathrm{cm}^3/\mathrm{s}$$

Bino:

$$\sigma_{\gamma\gamma} v \simeq \mathrm{few} \times 10^{-30}\ \mathrm{cm}^3/\mathrm{s};$$
$$\sigma_{\gamma Z} v \simeq \mathrm{few} \times 10^{-31}\ \mathrm{cm}^3/\mathrm{s};$$
$$\sigma_{\mathrm{ann}} v \simeq \sigma_{\ell\bar{\ell}} v \simeq \mathrm{few} \times 10^{-27}\ \mathrm{cm}^3/\mathrm{s}.$$

Neutralino DM can not explain the 130 gamma ray line.

Buchmüller+Garny, JCAP 1208 (2012)035;
Cohen et al, arXiv:1207.0800

Belanger et al, arXiv:1208.5009