Electroweak Multiplets for Dark Matter and the Higgs

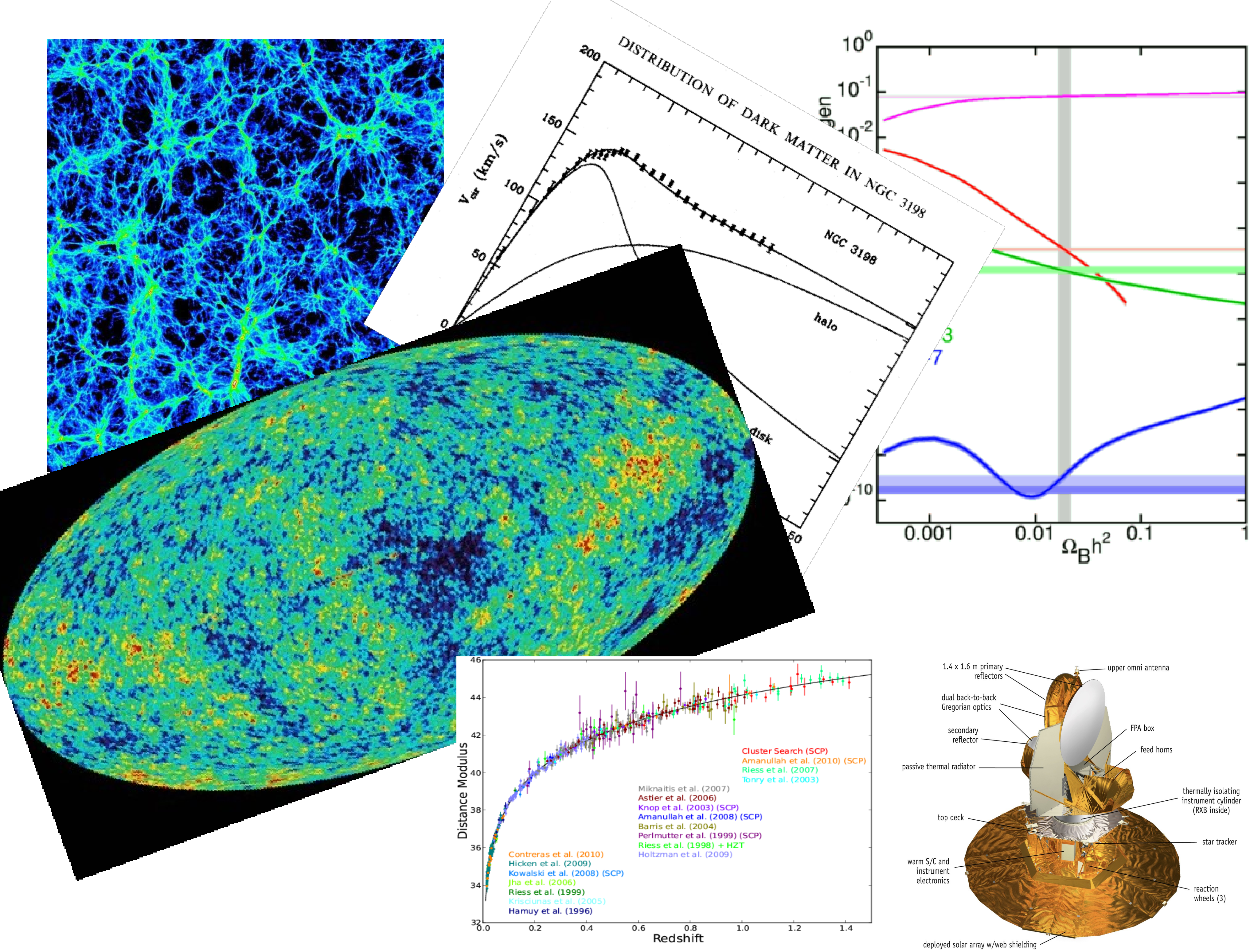
Reinard Primulando

Work with Joachim Kopp, Ethan Neil and Jure Zupan

Fermilab Seminar - 8/9/2012

Outline

- A tentative 130 GeV gamma ray line.
- Electroweak multiplet and the gamma ray line.
- Collider phenomenology.
- Effect to Higgs branching fraction.


DISTRIBUTION OF DARK MATTER IN NGC 3198
V_{cir} (km/s)
200
150
100
50
0
NGC 3198
halo
disk
50
10^{0}
10^{-1}
10^{-2}
10^{-10}
0.001
0.01
0.1
1
$\Omega_B h^2$
Distance Modulus
Redshift
46
44
42
40
38
36
34
32
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
Cluster Search (SCP)
Amanullah et al. (2010) (SCP)
Riess et al. (2007)
Tonry et al. (2003)
Miknaitis et al. (2007)
Astier et al. (2006)
Knop et al. (2003) (SCP)
Amanullah et al. (2008) (SCP)
Barris et al. (2004)
Perlmutter et al. (1999) (SCP)
Riess et al. (1998) + HZT
Holtzman et al. (2009)
Contreras et al. (2010)
Hicken et al. (2009)
Kowalski et al. (2008) (SCP)
Jha et al. (2006)
Riess et al. (1999)
Krisciunas et al. (2005)
Hamuy et al. (1996)
1.4 x 1.6 m primary reflectors
upper omni antenna
dual back-to-back Gregorian optics
secondary reflector
FPA box
feed horns
passive thermal radiator
thermally isolating instrument cylinder (RXB inside)
top deck
star tracker
warm S/C and instrument electronics
reaction wheels (3)
deployed solar array w/web shielding

The Universe in a ~~Nutshell~~ Cupcake

Figure 1: Contents of the Universe, as illustrated by a chocolate cupcake. Recipe available upon request.

Annika Peter, 1201.3942

The Universe in a ~~Nutshell~~ Cupcake

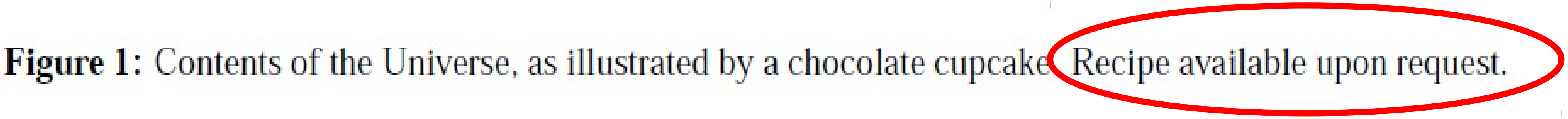


Figure 1: Contents of the Universe, as illustrated by a chocolate cupcake. Recipe available upon request.

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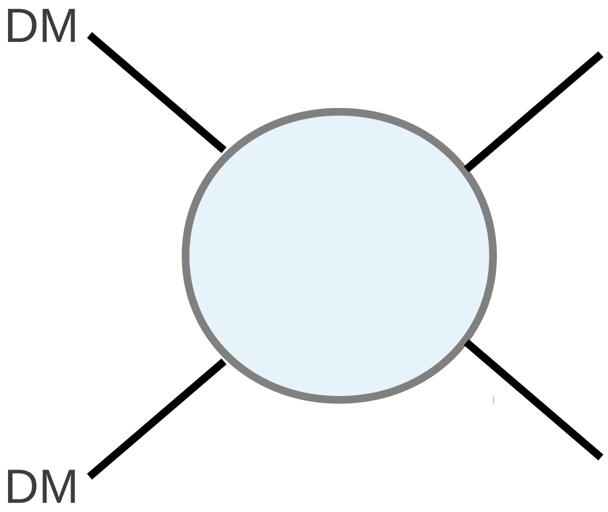
Indirect Detection of Dark Matter



SM → heavy nuclei, p, e, ν, γ

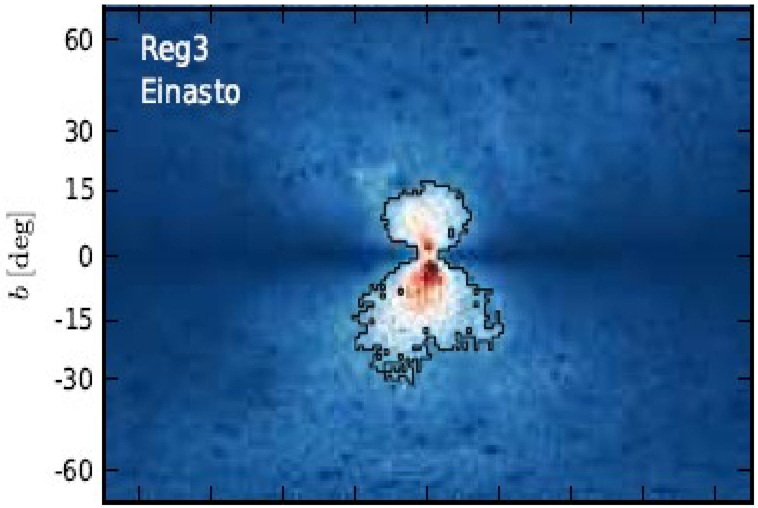
SM → heavy nuclei, p, e, ν, γ

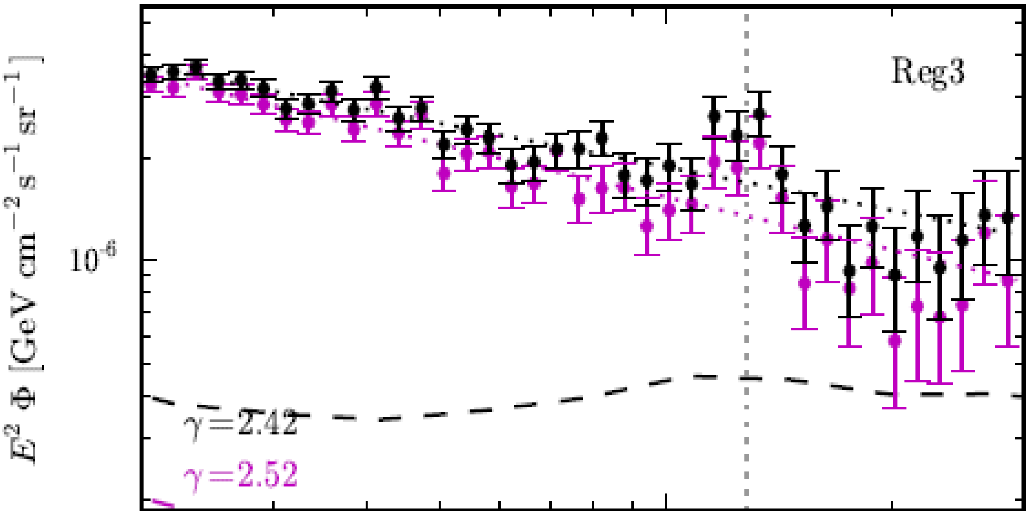
- Photons and neutrinos cosmic rays point to the source.
- Places to see DM: galactic center and dwarf galaxies

Gamma Rays from DM Annihilation

- **Continuous spectrum**
  - Decay products of heavier particles.
  - Usually hard to distinguish from astrophysical backgrounds.
- **Line spectrum**
  - Usually loop suppressed.
  - No astrophysical backgrounds.
  - Smoking gun.

Line Signal from the Galactic Center (?)

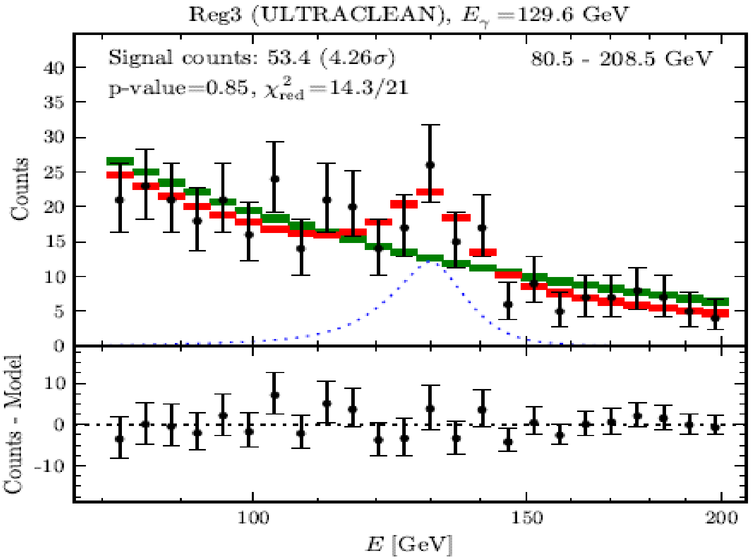




T. Bringmann, et.al., arXiv:1203.1312; C. Weniger, arXiv:1204.2797

- Four years of FERMI-LAT public data (Pass 7).
- Signal area is optimized to maximize SNR.
- Background fluxes are approximated by a single power law.

Tentative Signal from the Galactic Center



- 3.3 σ after trial factor.
- $m_\chi = 129.8 \pm 2.4^{+7}_{-13}$ GeV
- $\langle\sigma v\rangle_{\chi\chi\to\gamma\gamma} = (1.27 \pm 0.32^{+0.18}_{-0.28}) \times 10^{-27}\ \mathrm{cm^3\ s^{-1}}$

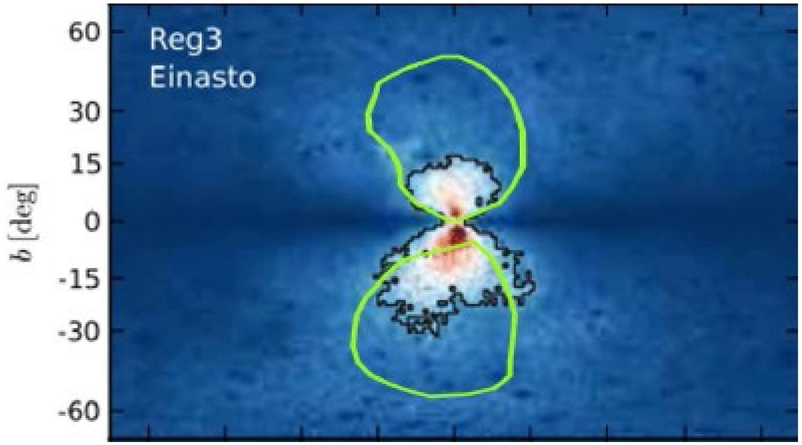
C. Weniger, arXiv:1204.2797

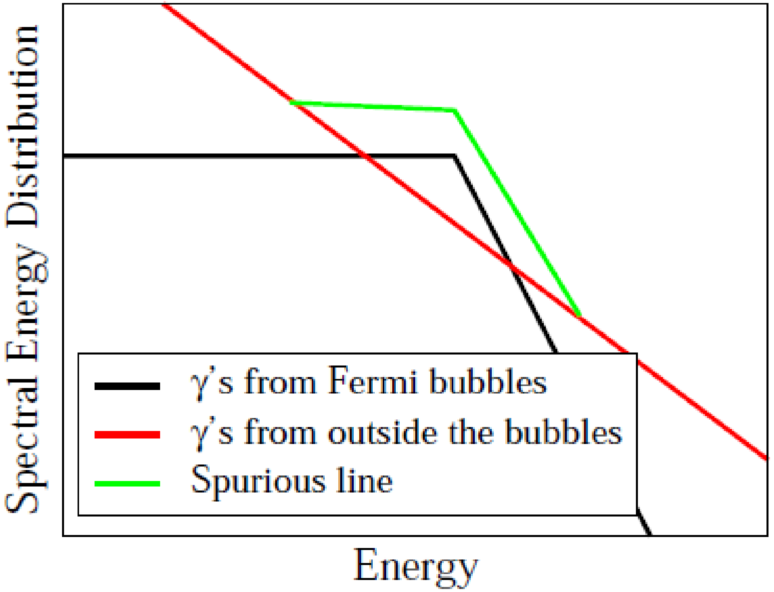
Astrophysics Backgrounds?

- Cold ultrarelativistic pulsar winds

F. Aharonian, D. Khangulyan, D. Malyshev, arXiv:1207.0458

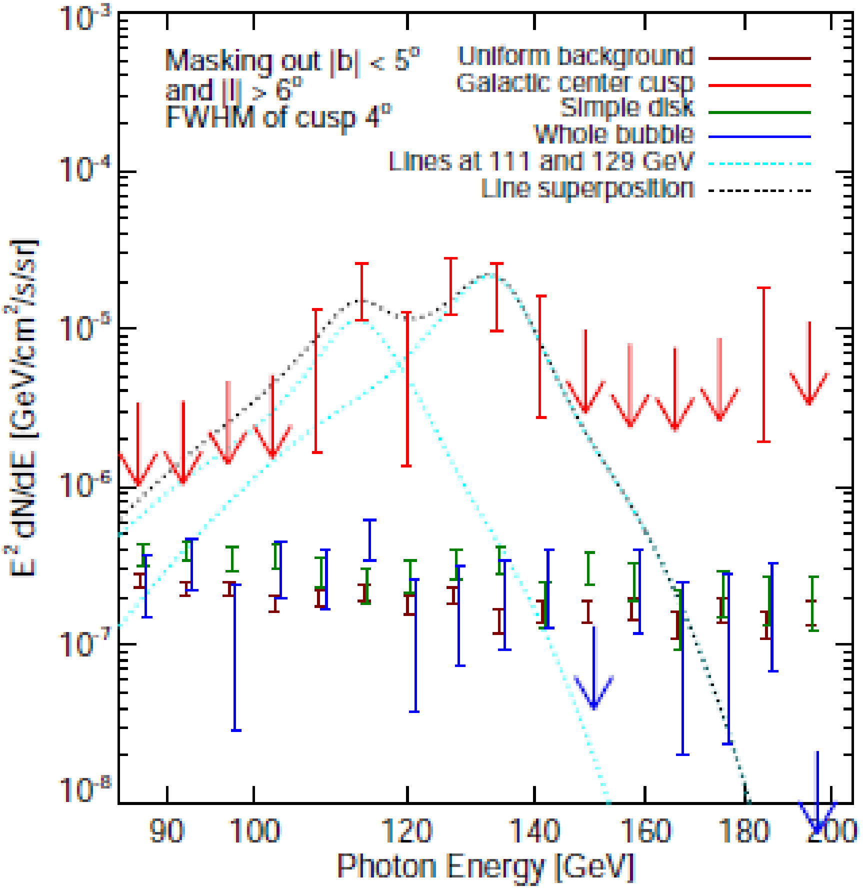
- Fermi Bubbles





S. Profumo, T. Linden, arXiv:1204.6047

Astrophysics Backgrounds?

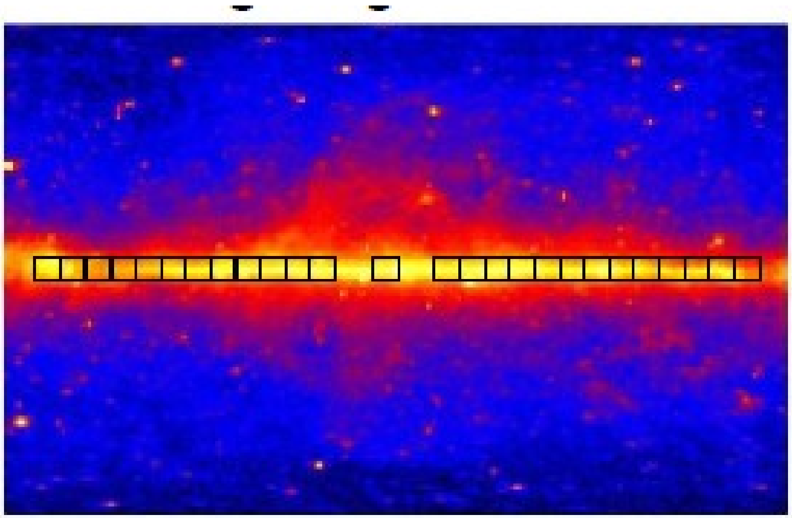


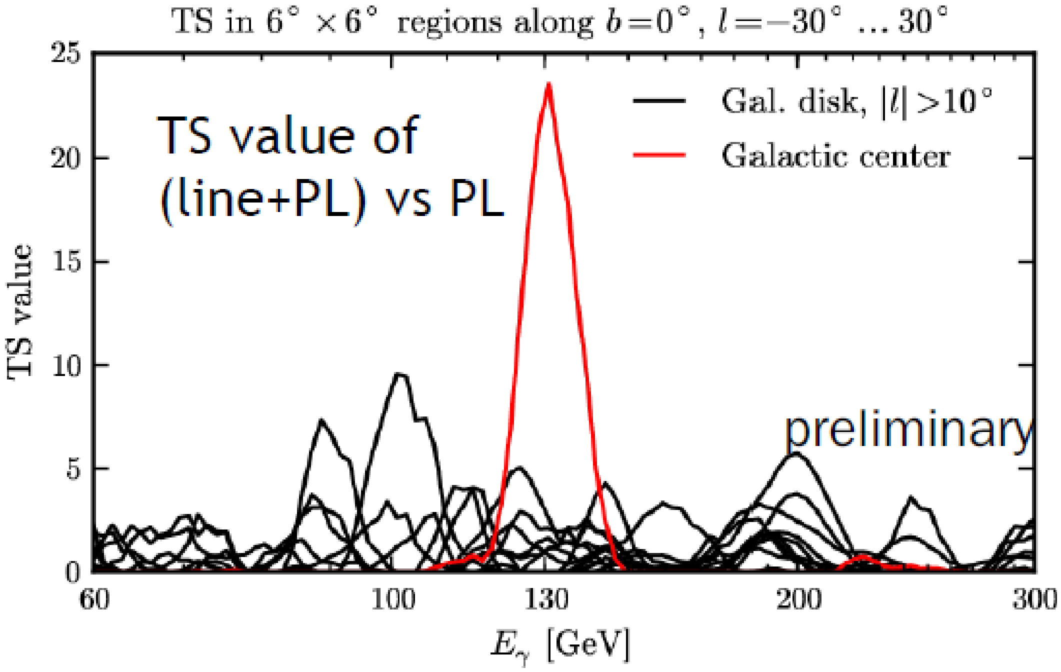
- Contributions from Fermi Bubbles are small.
- Also consistent with two lines at 111 GeV and 130 GeV.
- 5.1σ for one line, 5.5σ for two lines.

M. Su, D.P. Finkbeiner, arXiv:1206.1616

Validation Tests

Scan along the galactic disc:

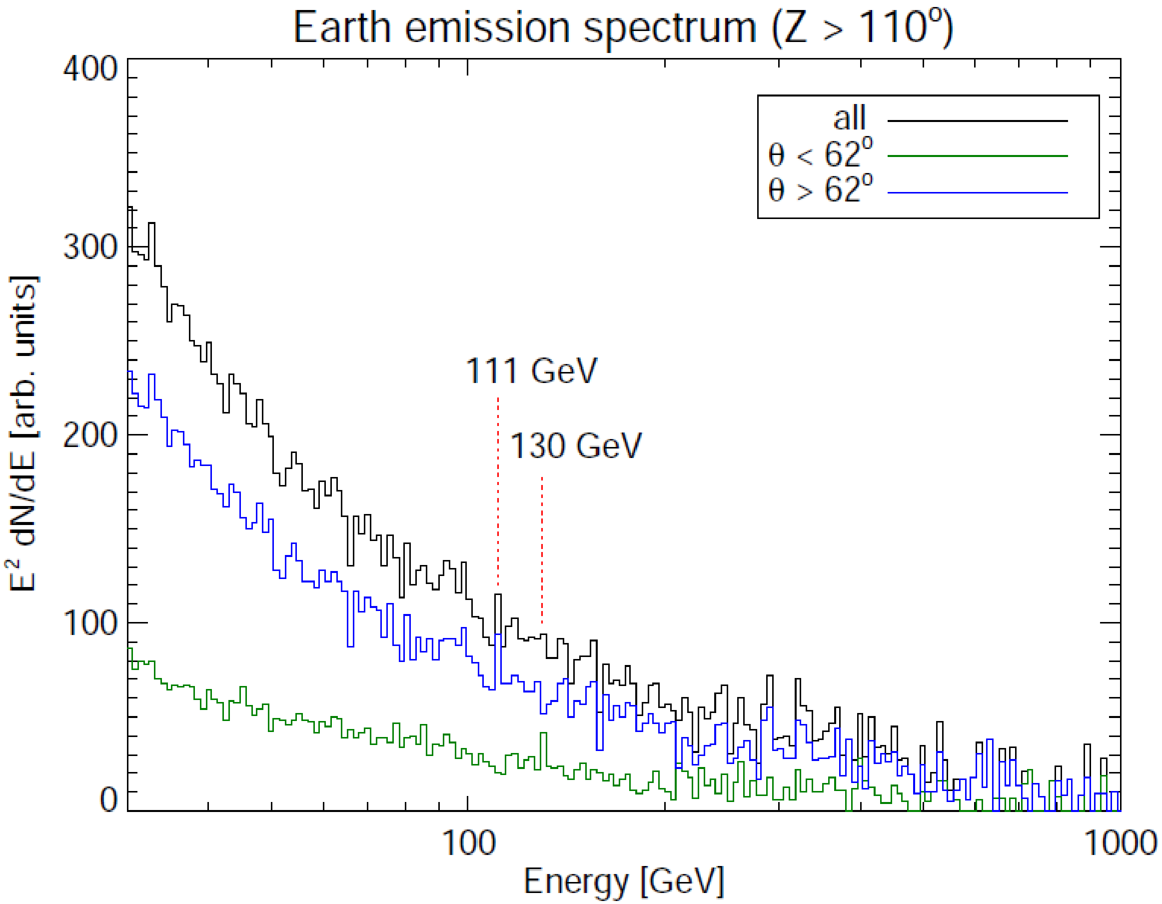




C. Weniger, IDM2012 talk

Validation Tests

Looking at the Earth limb:



- Cuts were used to maximize the line features.
- Need a trial factor.

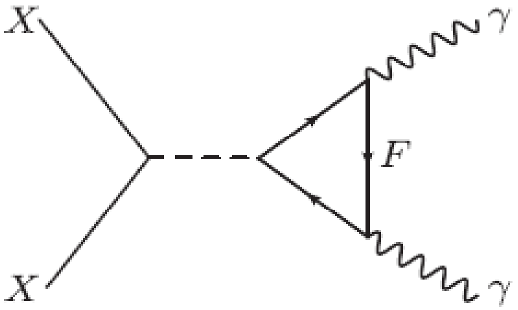
M. Su, D.P. Finkbeiner, arXiv:1206.1616

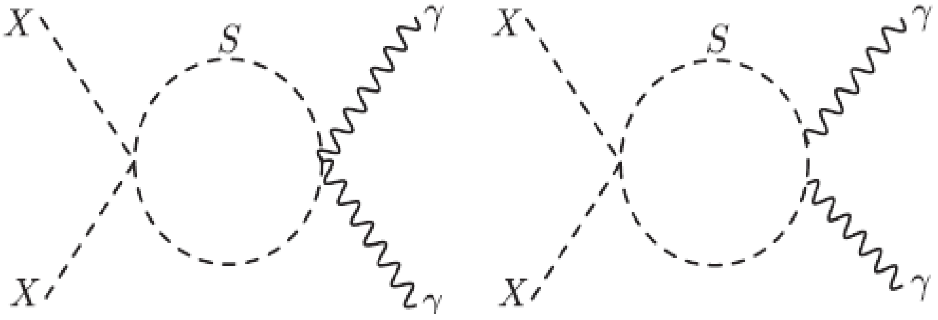
Everywhere else?

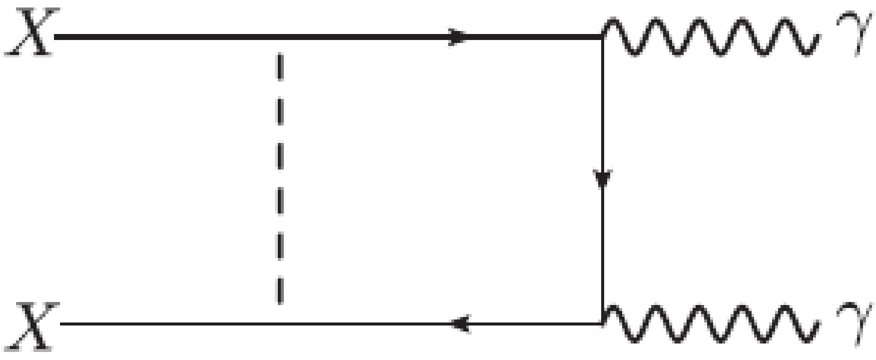
- Galaxy clusters (A. Hektor, M. Raidal, E. Tempel, arXiv:1207.4466).
- Unassociated Fermi-LAT source (M. Su, D. P. Finkbeiner, arXiv:1207.7060).

  However see D. Hooper, T. Linden, arXiv:1208.0828.

Models for the Lines



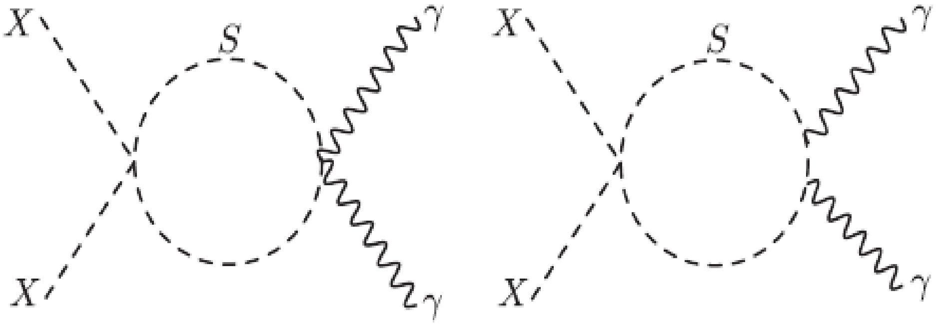




- Large DM-new particle couplings → Perturbativity.
- Charged particle masses are close to DM mass → Tuning.

M. Buckley, D. Hooper, arXiv:1205.6811

Models for the Lines



- Large DM-new particles couplings → Perturbativity.
- Charged particle masses are close to DM mass → Tuning.

$$m_S \to m_X$$
$$\lambda_X \sim 10$$

M. Buckley, D. Hooper, arXiv:1205.6811

Scalar Multiplet Model

- We consider a model with a scalar SU(2) multiplet.
- The components of the multiplet are multicharged.
- Presence of multicharged particles in the loop helps to alleviate the perturbativity constraints.

The Lagrangian

$$\mathcal{L} \supset |D_\mu \phi|^2 - \frac{1}{2} m_\phi^2 \phi^\dagger \phi - \lambda_{\phi H} \phi^\dagger \phi H^\dagger H - \lambda'_{\phi H} (\phi^\dagger T_N^a \phi)(H^\dagger \tau^a H) - \lambda_4 (\phi^\dagger \phi)^2$$

The Lagrangian

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$$\mathcal{L} \supset \frac{1}{2} \partial_\mu \chi \partial^\mu \chi - \frac{1}{2} m_\chi^2 \chi^2 - \lambda_{\chi H} \chi^2 H^\dagger H - \lambda_{\chi \phi} \chi^2 \phi^\dagger \phi.$$

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- Impose a Z_2 symmetry on χ.
- Accidental global U(1) symmetry on ϕ.

The Lagrangian

$$\mathcal{L} \supset |D_\mu \phi|^2 - \boxed{\frac{1}{2} m_\phi^2 \phi^\dagger \phi} - \boxed{\lambda_{\phi H} \phi^\dagger \phi H^\dagger H} - \boxed{\lambda'_{\phi H} (\phi^\dagger T_N^a \phi)(H^\dagger \tau^a H)} - \lambda_4 (\phi^\dagger \phi)^2$$

Multiplet masses

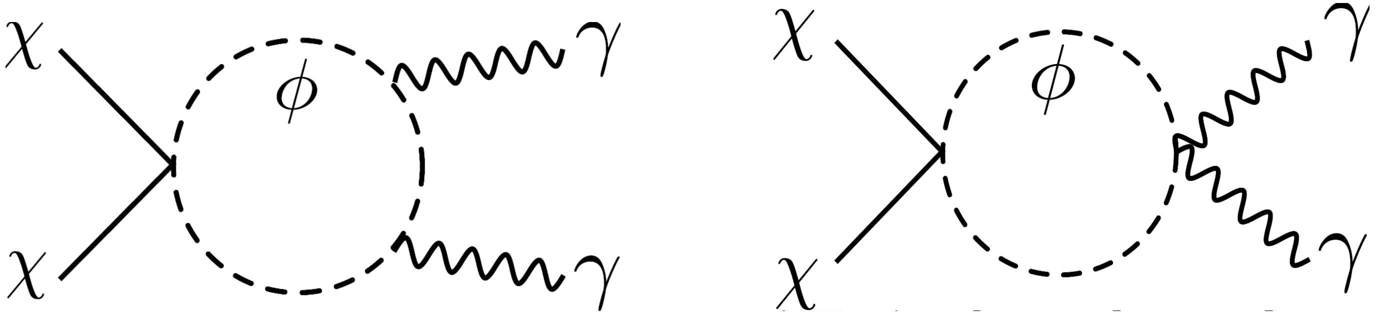
$$\mathcal{L} \supset \frac{1}{2} \partial_\mu \chi \partial^\mu \chi - \frac{1}{2} m_\chi^2 \chi^2 - \lambda_{\chi H} \chi^2 H^\dagger H - \lambda_{\chi \phi} \chi^2 \phi^\dagger \phi.$$

The Lagrangian

$$\mathcal{L} \supset \boxed{|D_\mu \phi|^2} - \frac{1}{2} m_\phi^2 \phi^\dagger \phi - \lambda_{\phi H} \phi^\dagger \phi H^\dagger H - \lambda'_{\phi H} (\phi^\dagger T_N^a \phi)(H^\dagger \tau^a H) - \lambda_4 (\phi^\dagger \phi)^2$$

DM annihilation into two photons

$$\mathcal{L} \supset \frac{1}{2} \partial_\mu \chi \partial^\mu \chi - \frac{1}{2} m_\chi^2 \chi^2 - \lambda_{\chi H} \chi^2 H^\dagger H - \boxed{\lambda_{\chi \phi} \chi^2 \phi^\dagger \phi.}$$



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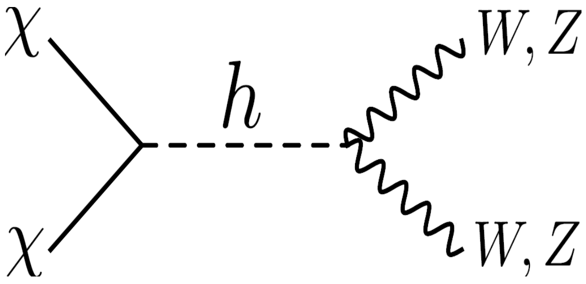
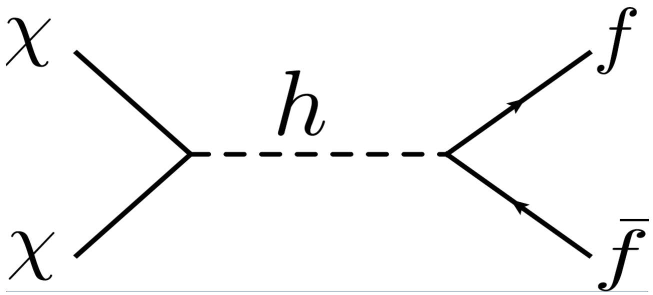
$$\mathcal{L} \supset |D_\mu\phi|^2 - \frac{1}{2}m_\phi^2\phi^\dagger\phi - \lambda_{\phi H}\phi^\dagger\phi H^\dagger H - \lambda'_{\phi H}(\phi^\dagger T_N^a\phi)(H^\dagger\tau^a H) - \lambda_4(\phi^\dagger\phi)^2$$

DM relic density

$$\mathcal{L} \supset \frac{1}{2}\partial_\mu\chi\partial^\mu\chi - \frac{1}{2}m_\chi^2\chi^2 - \boxed{\lambda_{\chi H}\chi^2 H^\dagger H} - \lambda_{\chi\phi}\chi^2\phi^\dagger\phi.$$





Multiplet Masses

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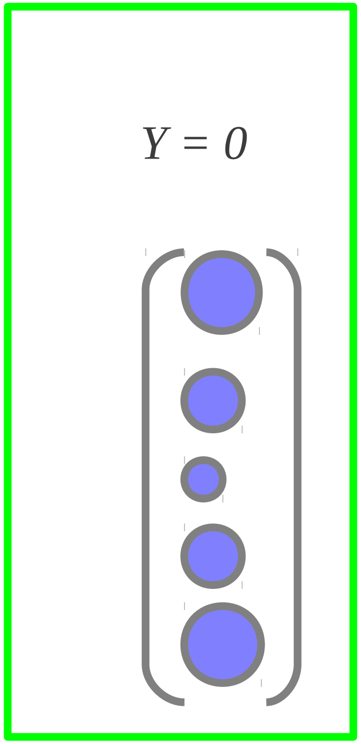
- The first two terms give an overall mass.
- For a (nearly) degenerate multiplet, the electroweak corrections gives mass splittings.
- The charged components get positive mass contributions.
- The corrections are in order of 100 MeV.



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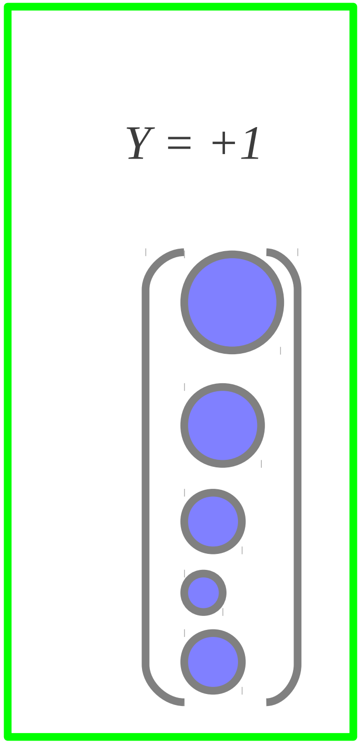

Multiplet Masses

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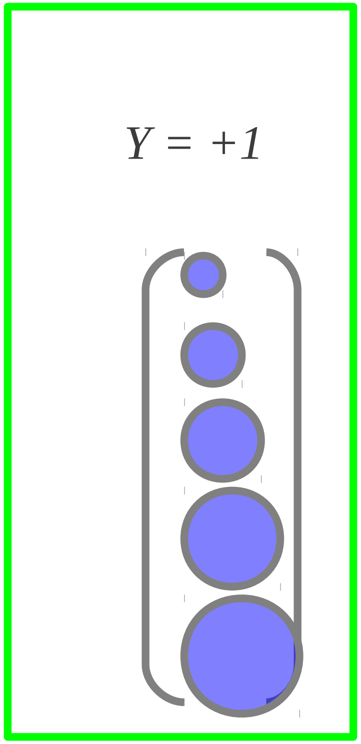
- Last term splits the masses between components.

$$-\lambda'_{\phi H}(\phi^\dagger T_N^a\phi)(H^\dagger\tau^a H) \rightarrow +\lambda'_{\phi H}v^2\phi^\dagger T_N^3\phi$$

- The top or bottom component of the multiplet becomes the lightest component.



Case I – Stable Multiplet

$$\mathcal{L} \supset |D_\mu\phi|^2 - \frac{1}{2}m_\phi^2\phi^\dagger\phi - \lambda_{\phi H}\phi^\dagger\phi H^\dagger H - \boxed{\lambda'_{\phi H}(\phi^\dagger T_N^a\phi)(H^\dagger\tau^a H)} - \lambda_4(\phi^\dagger\phi)^2$$

- We do not consider lightest charged component.
- The lightest component annihilates efficiently → small relic density.
- If $\lambda'_{\phi H}$ is sizable, the lightest component is the top or bottom of the multiplet → $Y = -(n-1)/2$.
- The nucleon-multiplet cross section is very large.

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Y = 0

Sizable $\lambda'_{\phi H}$

$$\begin{pmatrix} \boxed{+2} \\ +1 \\ 0 \\ -1 \\ -2 \end{pmatrix}$$

Case I – Stable Multiplet

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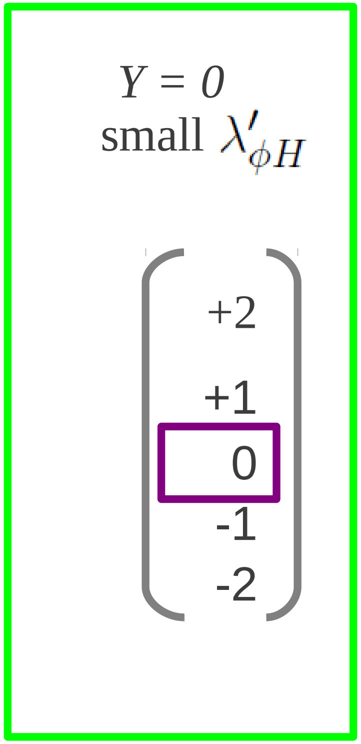
$Y = -2$

Sizable $\lambda'_{\phi H}$

$$\begin{pmatrix} \boxed{0} \\ -1 \\ -2 \\ -3 \\ -4 \end{pmatrix}$$

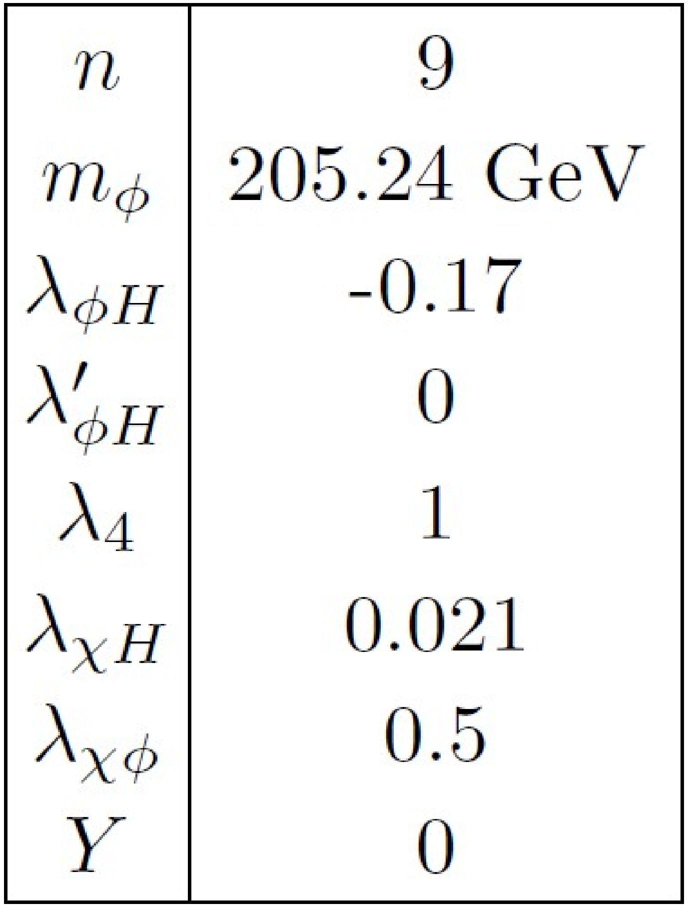
Case I – Stable Multiplet

- To avoid direct detection bound, we require $Y = 0$.
- In this case, $\lambda'_{\phi H}$ has to be small.
- The mass splitting comes mostly from the electroweak corrections.



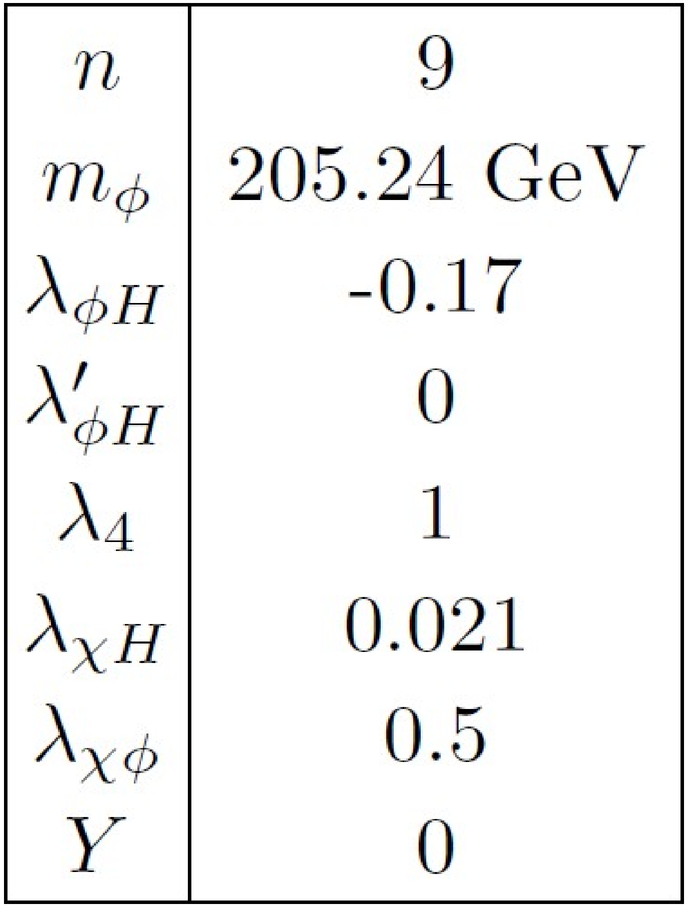
$Y = 0$
small $\lambda'_{\phi H}$

Case I – Benchmark Point



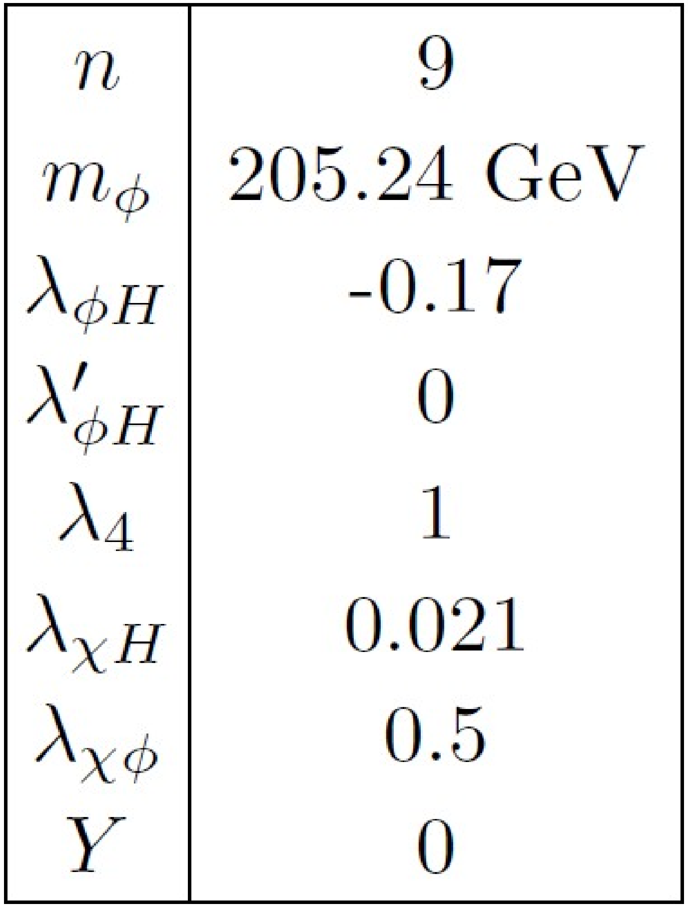
n	9
m_ϕ	205.24 GeV
$\lambda_{\phi H}$	-0.17
$\lambda'_{\phi H}$	0
λ_4	1
$\lambda_{\chi H}$	0.021
$\lambda_{\chi\phi}$	0.5
Y	0

Case I – Benchmark Point



n	9	dimension of representation
m_ϕ	205.24 GeV	
$\lambda_{\phi H}$	-0.17	multiplet-Higgs coupling
$\lambda'_{\phi H}$	0	mass splitting term
λ_4	1	
$\lambda_{\chi H}$	0.021	DM-Higgs coupling
$\lambda_{\chi\phi}$	0.5	DM-multiplet coupling
Y	0	hypercharge

Case I – Benchmark Point



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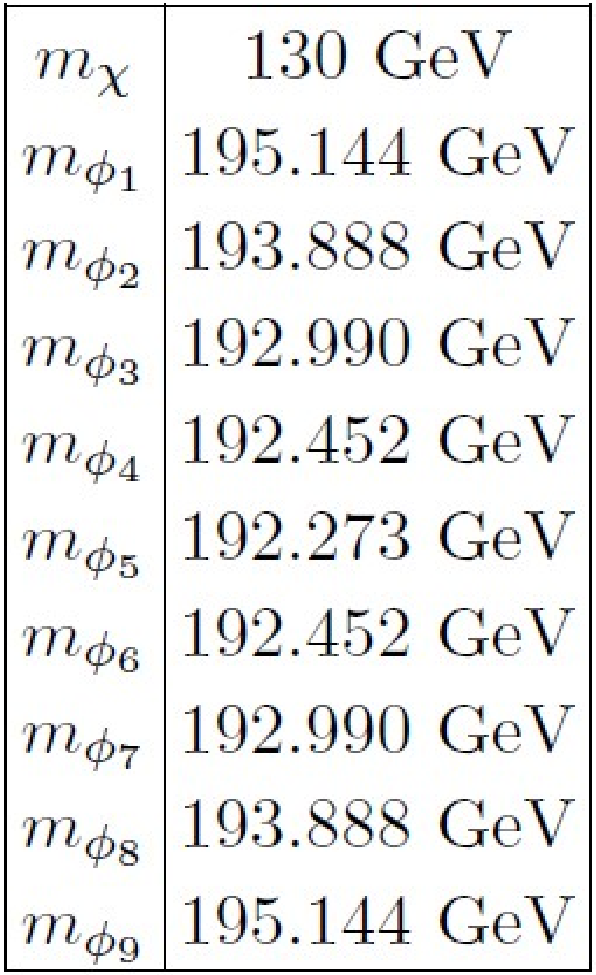

m_χ	130 GeV
m_{ϕ_1}	195.144 GeV
m_{ϕ_2}	193.888 GeV
m_{ϕ_3}	192.990 GeV
m_{ϕ_4}	192.452 GeV
m_{ϕ_5}	192.273 GeV
m_{ϕ_6}	192.452 GeV
m_{ϕ_7}	192.990 GeV
m_{ϕ_8}	193.888 GeV
m_{ϕ_9}	195.144 GeV

Case I – Benchmark Point

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$\lambda_{\chi H}$	0.021
$\lambda_{\chi\phi}$	0.5
Y	0

Perturbative

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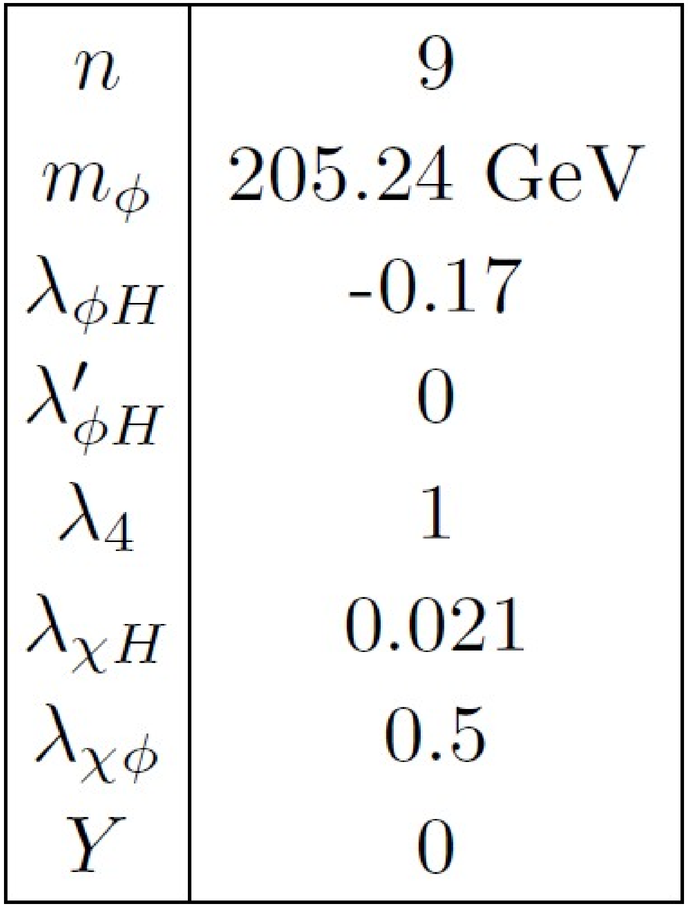
Case I – Benchmark Point



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$\lambda'_{\phi H}$	0
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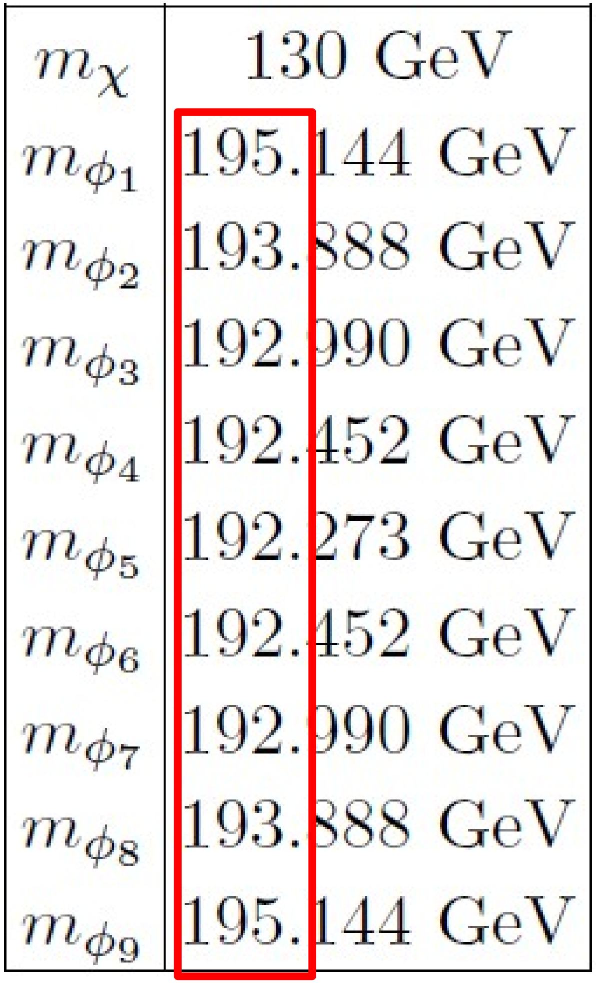
$\lambda_{\chi H}$	0.021
$\lambda_{\chi\phi}$	0.5
Y	0



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m_{ϕ_6}	192.452 GeV
m_{ϕ_7}	192.990 GeV
m_{ϕ_8}	193.888 GeV
m_{ϕ_9}	195.144 GeV

Not degenerate with DM

Case I – Benchmark Point

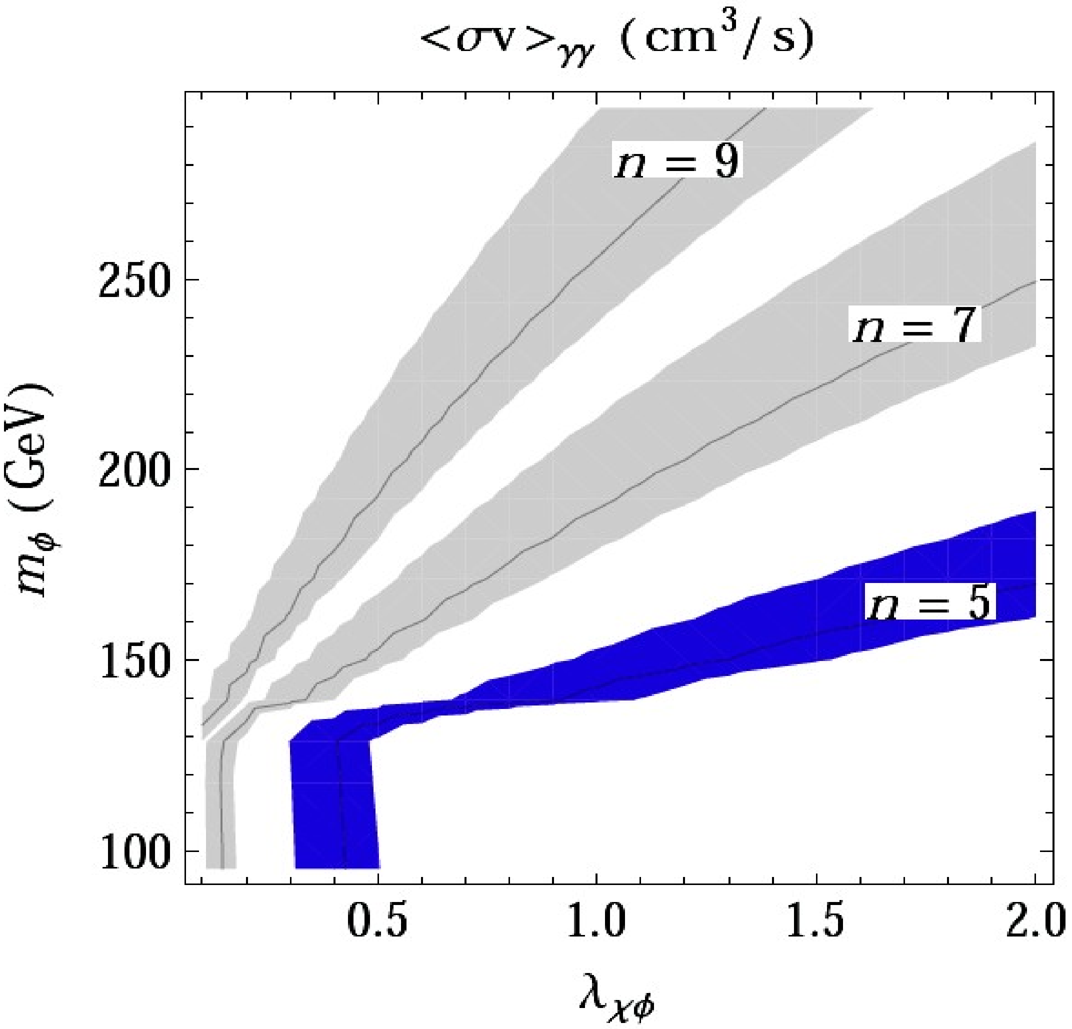
n	9
m_ϕ	205.24 GeV
$\lambda_{\phi H}$	-0.17
$\lambda'_{\phi H}$	0
λ_4	1
[illegible]	0.031
[illegible]	0

m_χ	130 GeV
m_{ϕ_1}	195.144 GeV
m_{ϕ_2}	193.888 GeV
m_{ϕ_3}	192.990 GeV
m_{ϕ_4}	192.452 GeV
m_{ϕ_5}	192.273 GeV
[illegible]	192.452 GeV
m_{ϕ_9}	195.144 GeV

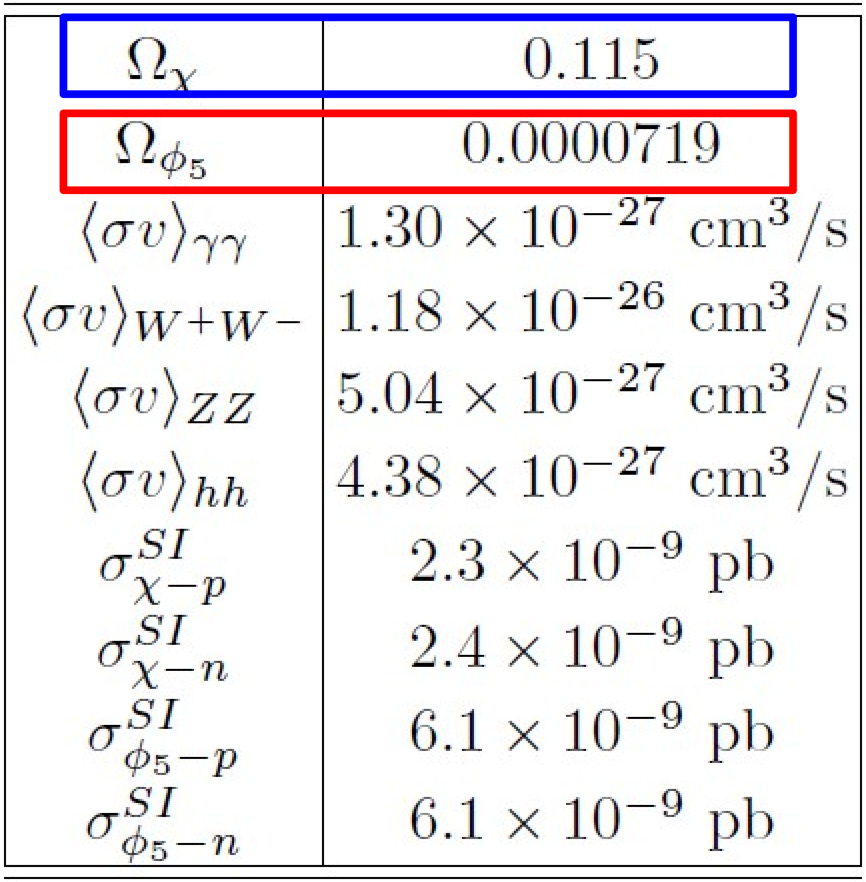
$$\langle \sigma v \rangle_{\gamma\gamma} \quad 1.30 \times 10^{-27}\ \mathrm{cm}^3/\mathrm{s}$$

Not degenerate with DM

Case I – Dependence on Multiplet



Astrophysical Bounds

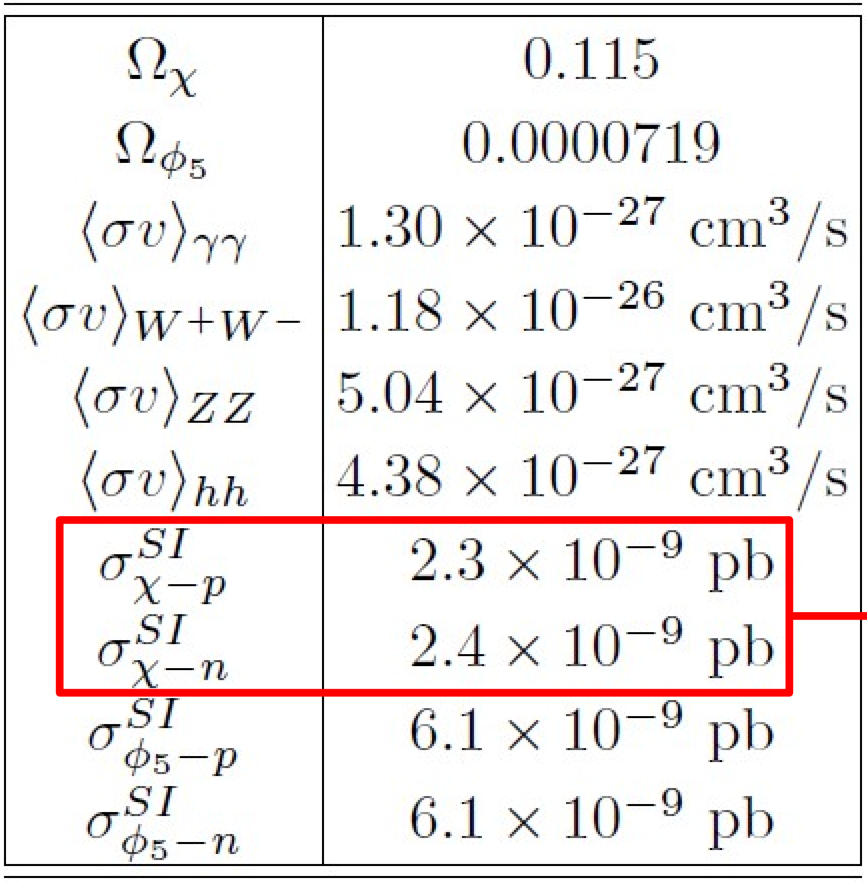


Ω_χ	0.115
Ω_{ϕ_5}	0.0000719
$\langle\sigma v\rangle_{\gamma\gamma}$	1.30×10^{-27} cm^3/s
$\langle\sigma v\rangle_{W+W-}$	1.18×10^{-26} cm^3/s
$\langle\sigma v\rangle_{ZZ}$	5.04×10^{-27} cm^3/s
$\langle\sigma v\rangle_{hh}$	4.38×10^{-27} cm^3/s
$\sigma^{SI}_{\chi-p}$	2.3×10^{-9} pb
$\sigma^{SI}_{\chi-n}$	2.4×10^{-9} pb
$\sigma^{SI}_{\phi_5-p}$	6.1×10^{-9} pb
$\sigma^{SI}_{\phi_5-n}$	6.1×10^{-9} pb

DM abundance

Stable component abundance

Astrophysical Bounds



Ω_χ	0.115
Ω_{ϕ_5}	0.0000719
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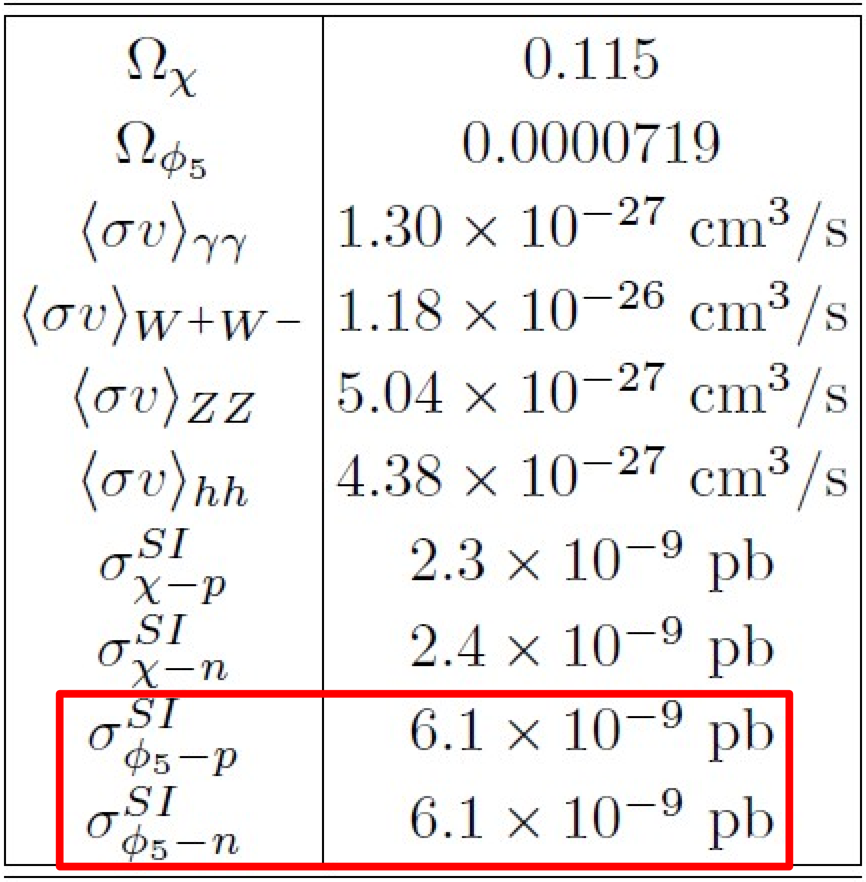
$\sigma^{SI}_{\phi_5-p}$	$6.1 \times 10^{-9}\ \mathrm{pb}$
$\sigma^{SI}_{\phi_5-n}$	$6.1 \times 10^{-9}\ \mathrm{pb}$

DM-nucleon cross section.
Close to the current XENON-100 exclusion,
arXiv:1207.5988

Astrophysical Bounds



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$\sigma^{SI}_{\phi_5-n}$	$6.1 \times 10^{-9}\ \mathrm{pb}$

Stable multiplet component-nucleon cross section

Case II – Unstable Multiplet

$$\mathcal{L} \supset |D_\mu\phi|^2 - \frac{1}{2}m_\phi^2\phi^\dagger\phi - \lambda_{\phi H}\phi^\dagger\phi H^\dagger H - \boxed{\lambda'_{\phi H}(\phi^\dagger T^a_N\phi)(H^\dagger\tau^a H)} - \lambda_4(\phi^\dagger\phi)^2$$

- If we want a sizable $\lambda'_{\phi H}$, the lightest multiplet has to decay.
- It can decay to SM particles by higher dimension operators.

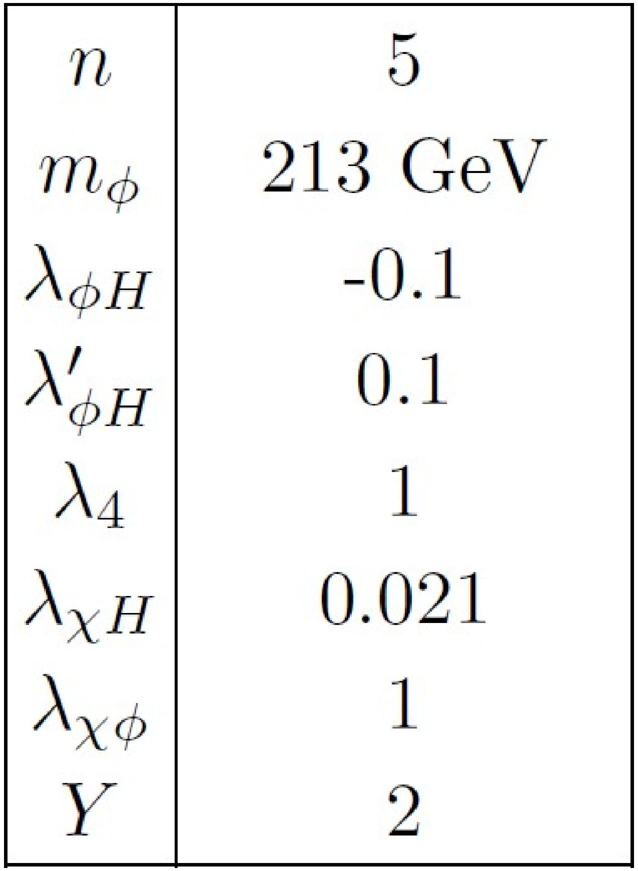
$$\mathcal{L}_5 \supset \frac{c_\phi}{\Lambda}\phi(H^\dagger)^4$$

Y = 2

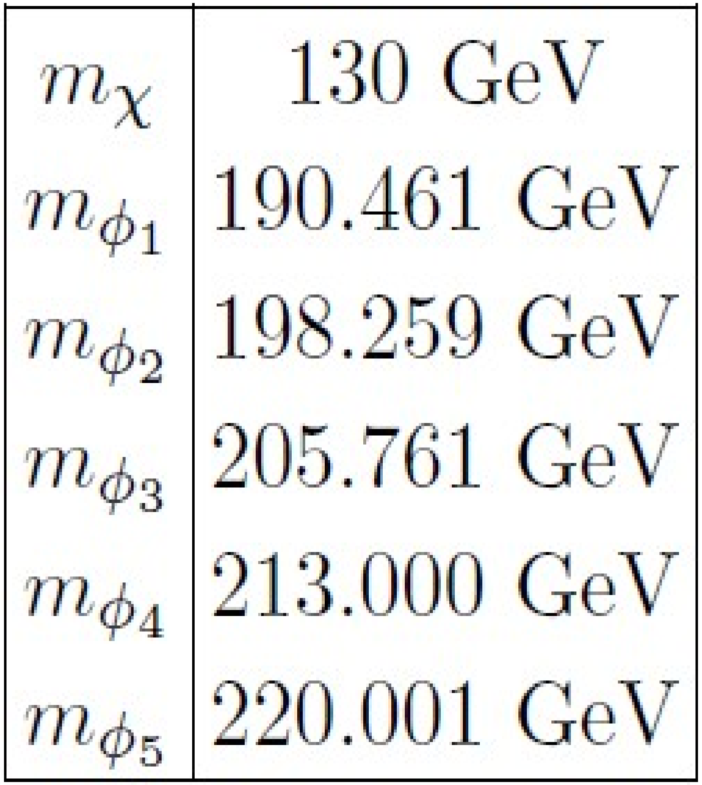
Sizable $\lambda'_{\phi H}$

$$\begin{pmatrix} \boxed{+2} \\ +1 \\ 0 \\ -1 \\ -2 \end{pmatrix}$$

Case II – Benchmark Point

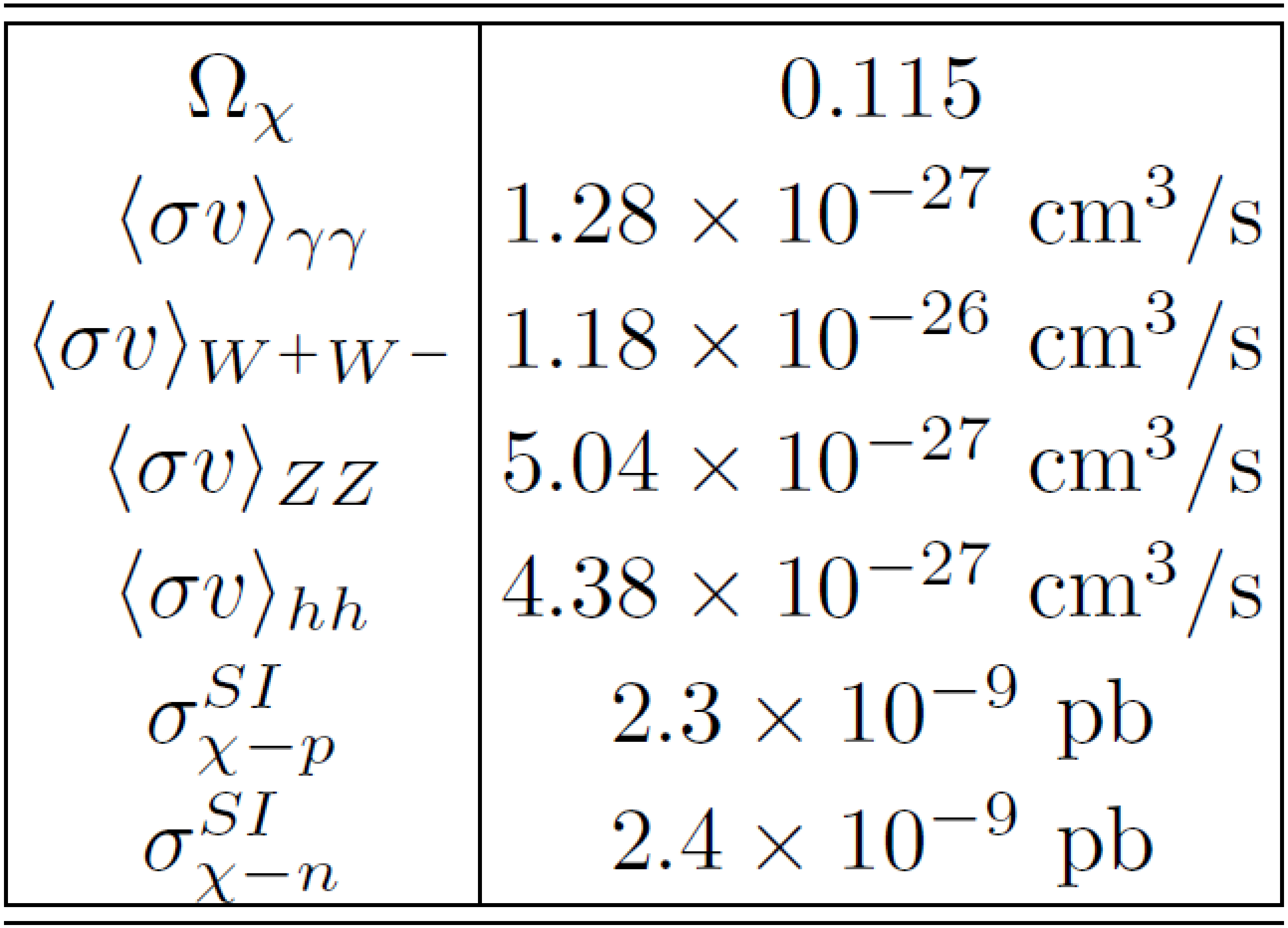


n	5
m_ϕ	213 GeV
$\lambda_{\phi H}$	-0.1
$\lambda'_{\phi H}$	0.1
λ_4	1
$\lambda_{\chi H}$	0.021
$\lambda_{\chi\phi}$	1
Y	2



m_χ	130 GeV
m_{ϕ_1}	190.461 GeV
m_{ϕ_2}	198.259 GeV
m_{ϕ_3}	205.761 GeV
m_{ϕ_4}	213.000 GeV
m_{ϕ_5}	220.001 GeV

Case II – Astrophysics Bounds



Ω_χ	0.115
$\langle \sigma v \rangle_{\gamma\gamma}$	$1.28 \times 10^{-27}\ \mathrm{cm}^3/\mathrm{s}$
$\langle \sigma v \rangle_{W+W-}$	$1.18 \times 10^{-26}\ \mathrm{cm}^3/\mathrm{s}$
$\langle \sigma v \rangle_{ZZ}$	$5.04 \times 10^{-27}\ \mathrm{cm}^3/\mathrm{s}$
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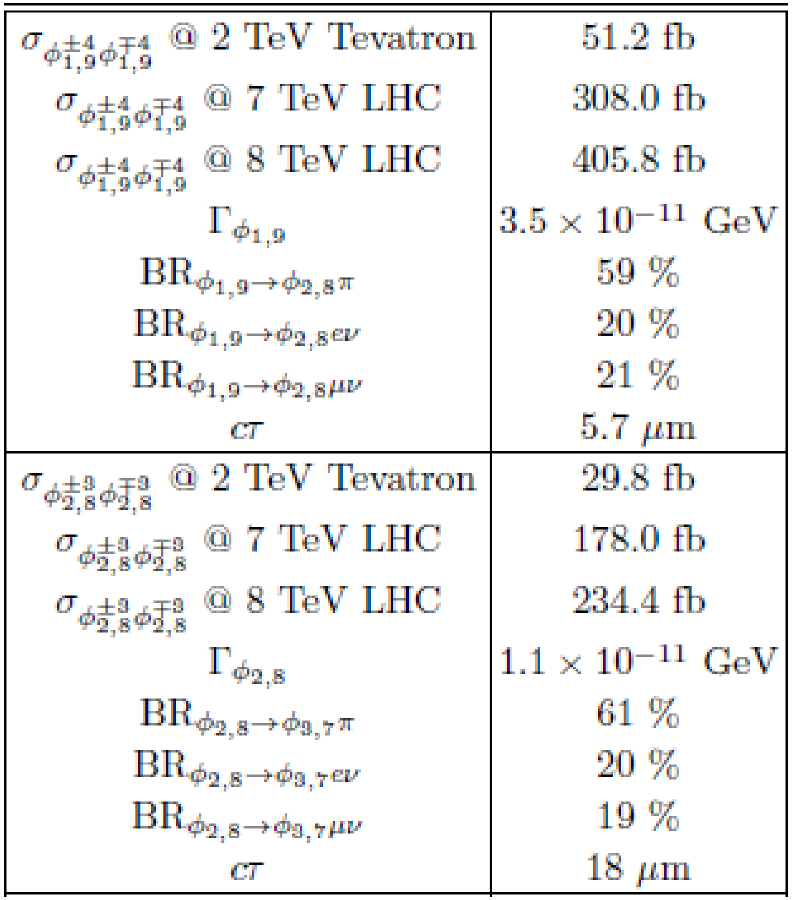
$\sigma^{SI}_{\chi-p}$	$2.3 \times 10^{-9}\ \mathrm{pb}$
$\sigma^{SI}_{\chi-n}$	$2.4 \times 10^{-9}\ \mathrm{pb}$

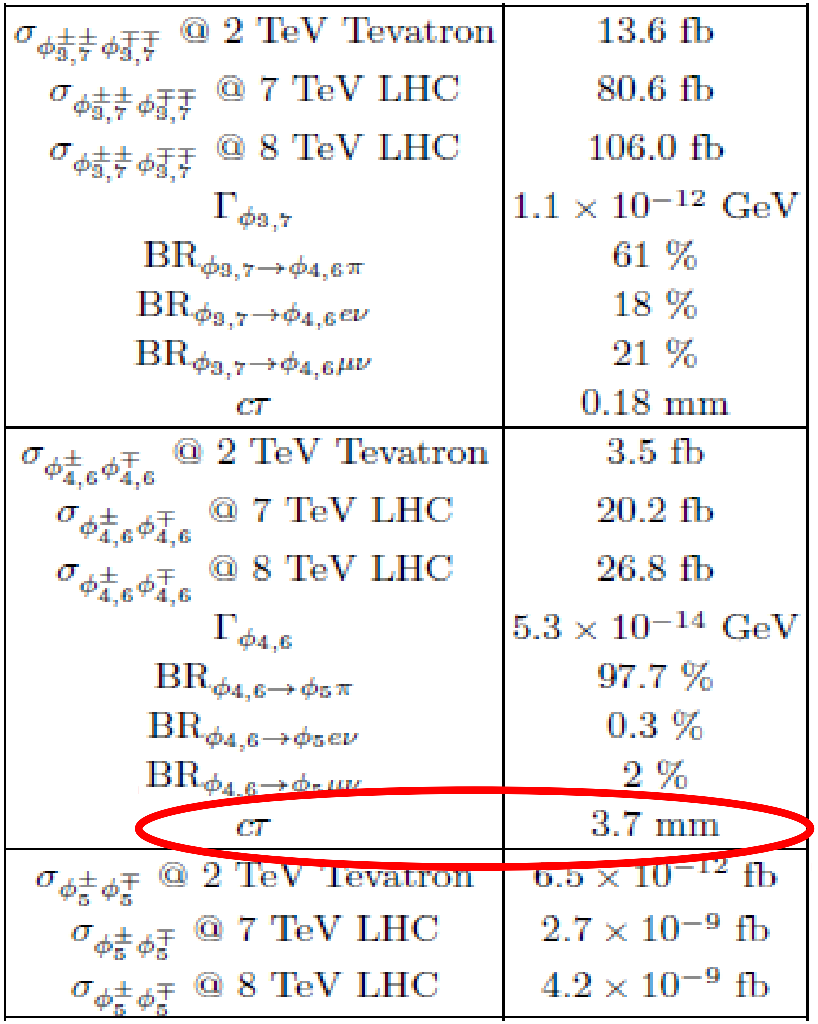
Collider Phenomenology

- For case I, the mass splitting is small.
- It is possible that the charged multiplets has long lifetime.
- For case II, heavier multiplets decay into lower multiplet and soft jets/leptons.

Collider Phenomenology



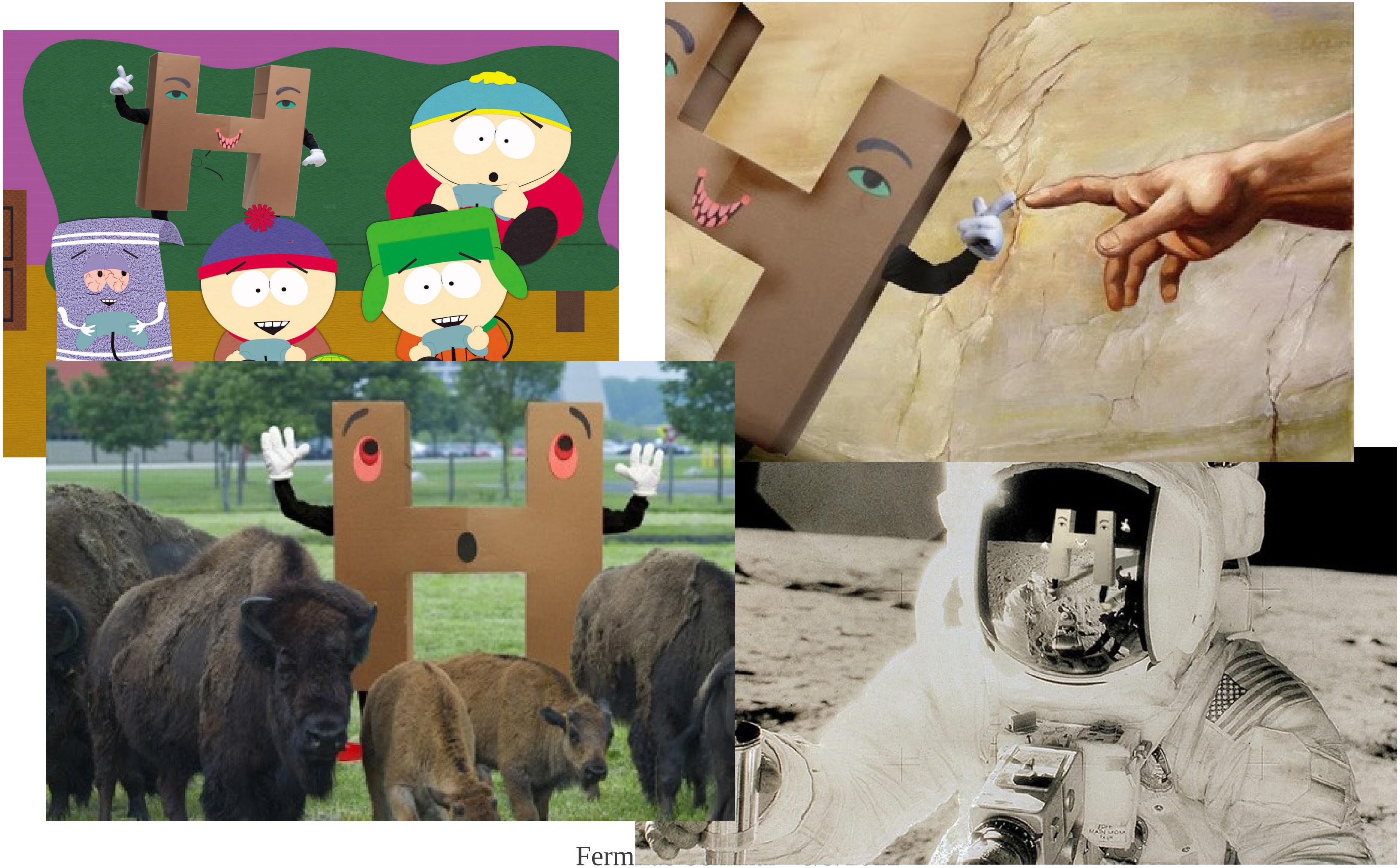
$\sigma_{\phi^{\pm 4}_{1,9}\phi^{\mp 4}_{1,9}}$ @ 2 TeV Tevatron	51.2 fb
$\sigma_{\phi^{\pm 4}_{1,9}\phi^{\mp 4}_{1,9}}$ @ 7 TeV LHC	308.0 fb
$\sigma_{\phi^{\pm 4}_{1,9}\phi^{\mp 4}_{1,9}}$ @ 8 TeV LHC	405.8 fb
$\Gamma_{\phi_{1,9}}$	3.5×10^{-11} GeV
$\mathrm{BR}_{\phi_{1,9}\to\phi_{2,8}\pi}$	59 %
$\mathrm{BR}_{\phi_{1,9}\to\phi_{2,8}e\nu}$	20 %
$\mathrm{BR}_{\phi_{1,9}\to\phi_{2,8}\mu\nu}$	21 %
$c\tau$	5.7 μm
$\sigma_{\phi^{\pm 3}_{2,8}\phi^{\mp 3}_{2,8}}$ @ 2 TeV Tevatron	29.8 fb
$\sigma_{\phi^{\pm 3}_{2,8}\phi^{\mp 3}_{2,8}}$ @ 7 TeV LHC	178.0 fb
$\sigma_{\phi^{\pm 3}_{2,8}\phi^{\mp 3}_{2,8}}$ @ 8 TeV LHC	234.4 fb
$\Gamma_{\phi_{2,8}}$	1.1×10^{-11} GeV
$\mathrm{BR}_{\phi_{2,8}\to\phi_{3,7}\pi}$	61 %
$\mathrm{BR}_{\phi_{2,8}\to\phi_{3,7}e\nu}$	20 %
$\mathrm{BR}_{\phi_{2,8}\to\phi_{3,7}\mu\nu}$	19 %
$c\tau$	18 μm



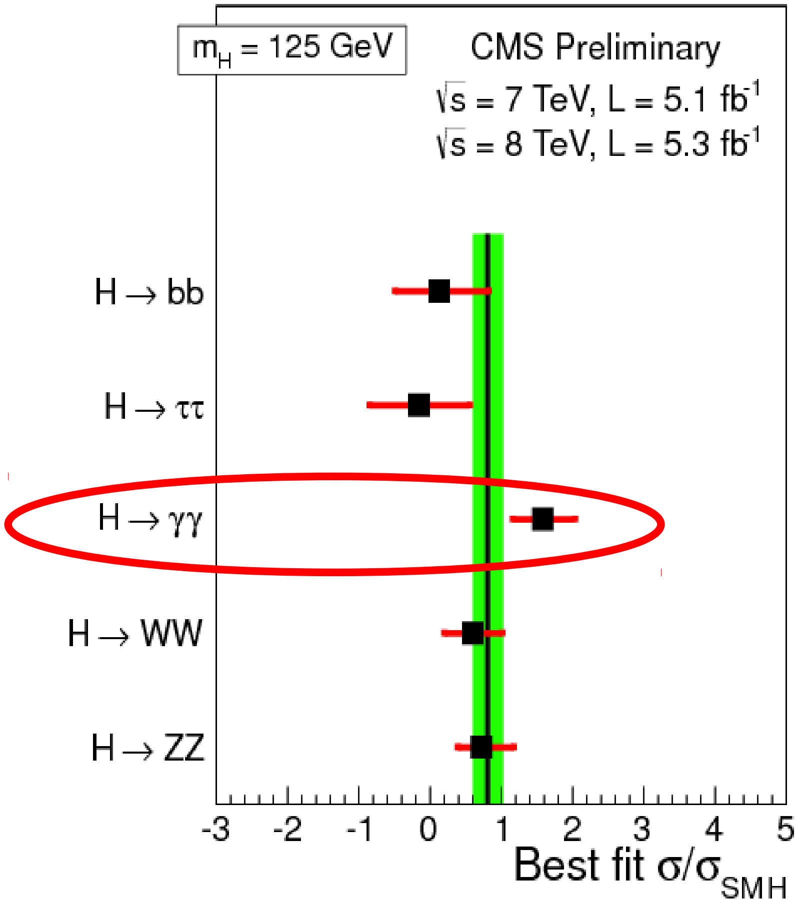
$\sigma_{\phi^{\pm\pm}_{3,7}\phi^{\mp\mp}_{3,7}}$ @ 2 TeV Tevatron	13.6 fb
$\sigma_{\phi^{\pm\pm}_{3,7}\phi^{\mp\mp}_{3,7}}$ @ 7 TeV LHC	80.6 fb
$\sigma_{\phi^{\pm\pm}_{3,7}\phi^{\mp\mp}_{3,7}}$ @ 8 TeV LHC	106.0 fb
$\Gamma_{\phi_{3,7}}$	1.1×10^{-12} GeV
$\mathrm{BR}_{\phi_{3,7}\to\phi_{4,6}\pi}$	61 %
$\mathrm{BR}_{\phi_{3,7}\to\phi_{4,6}e\nu}$	18 %
$\mathrm{BR}_{\phi_{3,7}\to\phi_{4,6}\mu\nu}$	21 %
$c\tau$	0.18 mm
$\sigma_{\phi^{\pm}_{4,6}\phi^{\mp}_{4,6}}$ @ 2 TeV Tevatron	3.5 fb
$\sigma_{\phi^{\pm}_{4,6}\phi^{\mp}_{4,6}}$ @ 7 TeV LHC	20.2 fb
$\sigma_{\phi^{\pm}_{4,6}\phi^{\mp}_{4,6}}$ @ 8 TeV LHC	26.8 fb
$\Gamma_{\phi_{4,6}}$	5.3×10^{-14} GeV
$\mathrm{BR}_{\phi_{4,6}\to\phi_{5}\pi}$	97.7 %
$\mathrm{BR}_{\phi_{4,6}\to\phi_{5}e\nu}$	0.3 %
$\mathrm{BR}_{\phi_{4,6}\to\phi_{5}\mu\nu}$	2 %
$c\tau$	3.7 mm
$\sigma_{\phi^{\pm}_{5}\phi^{\mp}_{5}}$ @ 2 TeV Tevatron	6.5×10^{-12} fb
$\sigma_{\phi^{\pm}_{5}\phi^{\mp}_{5}}$ @ 7 TeV LHC	2.7×10^{-9} fb
$\sigma_{\phi^{\pm}_{5}\phi^{\mp}_{5}}$ @ 8 TeV LHC	4.2×10^{-9} fb

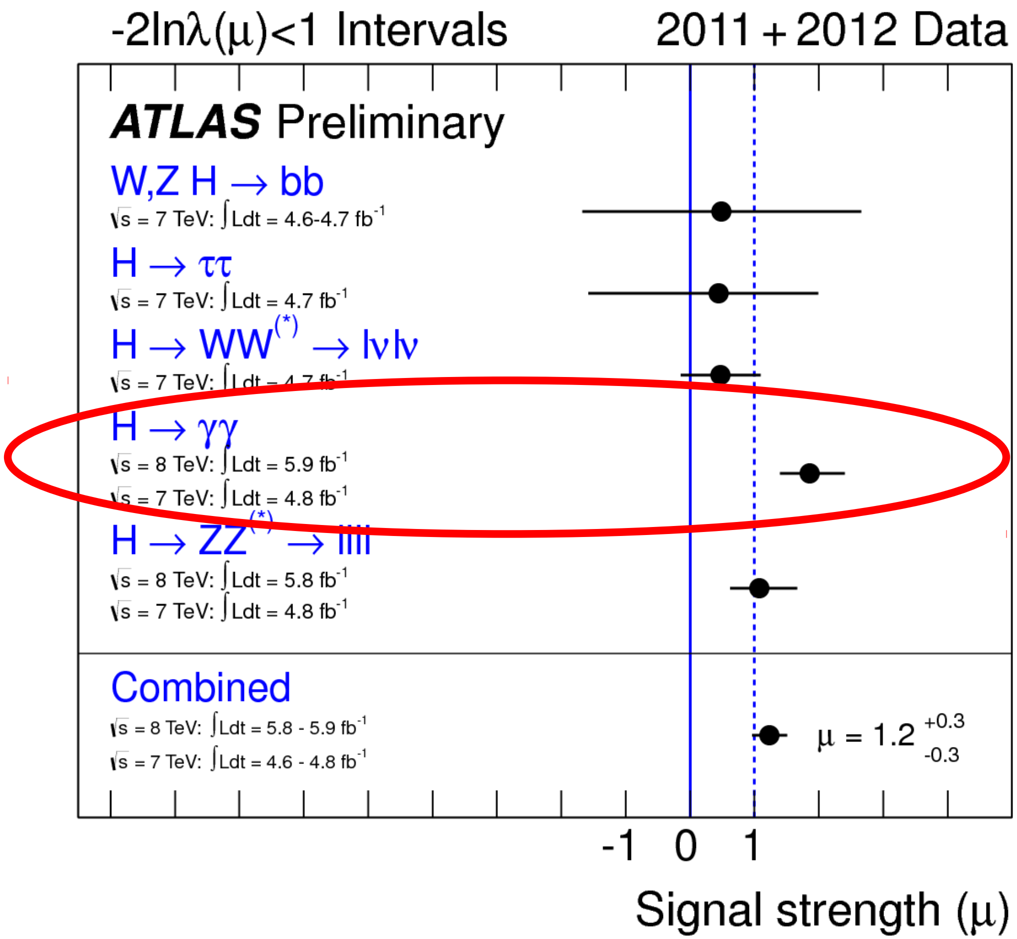
Case I

What About the Higgs?



Higgs Branching Fractions

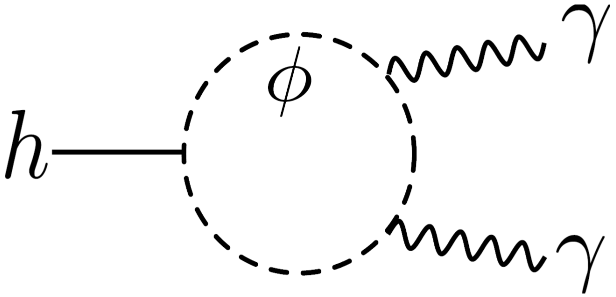


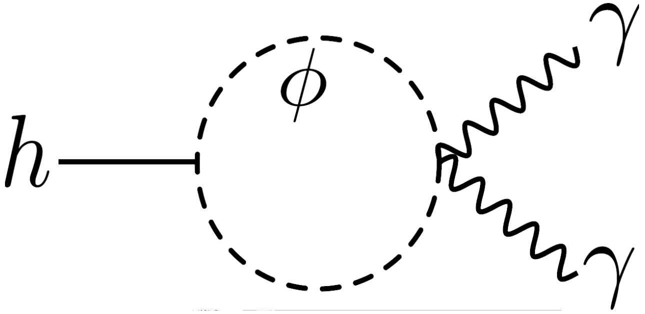


$h \rightarrow \gamma\gamma$ in the Model

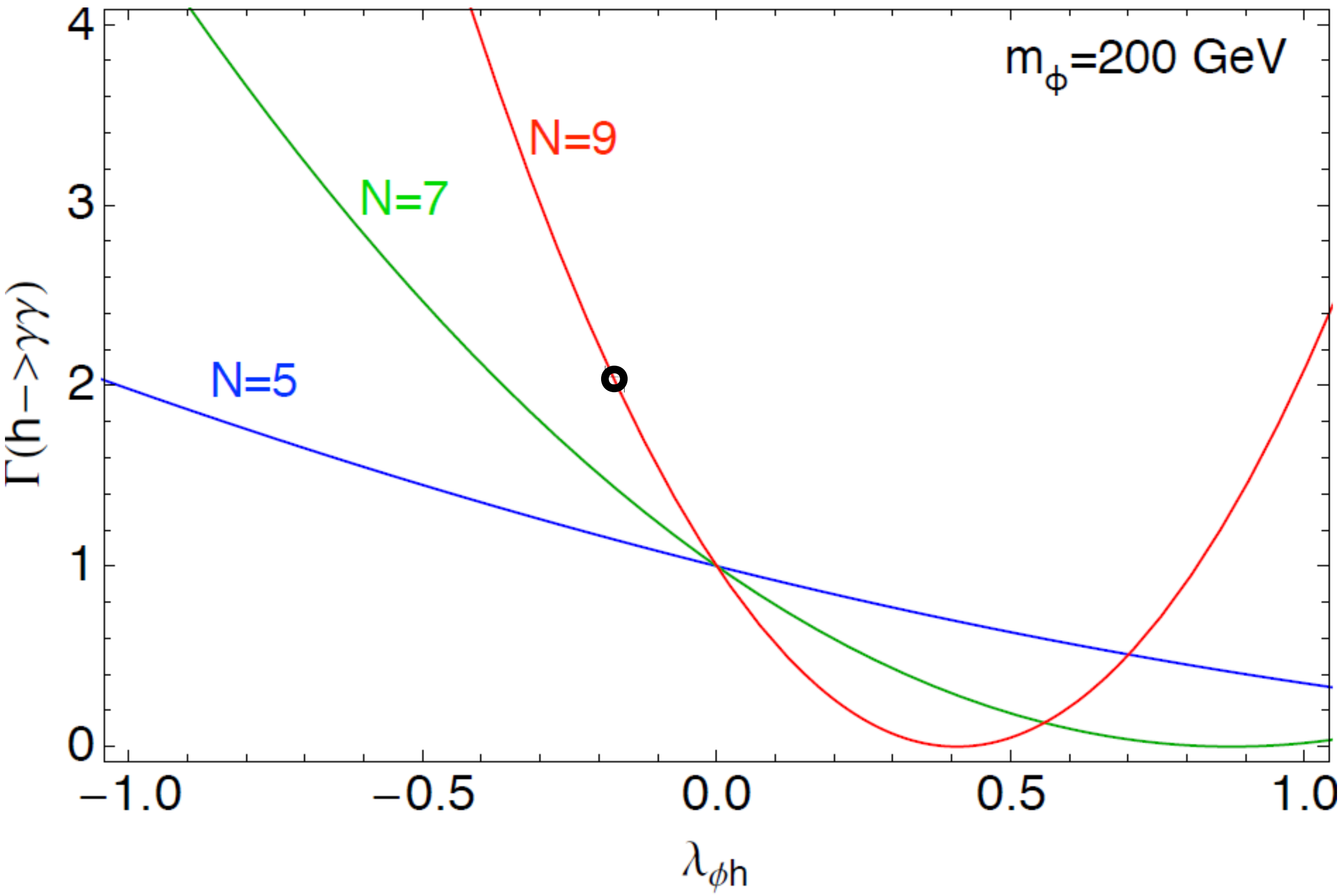
$$\mathcal{L} \supset \boxed{|D_\mu \phi|^2} - \frac{1}{2} m_\phi^2 \phi^\dagger \phi - \boxed{\lambda_{\phi H} \phi^\dagger \phi H^\dagger H} - \lambda'_{\phi H} (\phi^\dagger T_N^a \phi)(H^\dagger \tau^a H) - \lambda_4 (\phi^\dagger \phi)^2$$

enhance $h \rightarrow \gamma\gamma$





$h \to \gamma\gamma$ in the Model



- No modification for $h \to WW$ and $h \to ZZ$

Conclusion

- A possible line feature has been found in FERMI-LAT data.
- A model with a multiplet electroweak scalar can explain the line without having problems with perturbativity.
- Interesting collider phenomenology.
- The model can also explain enhancement of $h \to \gamma\gamma$

THANK YOU

BACKUP SLIDES

Oblique Parameters Bounds

$$
\begin{aligned}
\alpha S &\equiv 4e^2[\Pi'_{33}(0) - \Pi'_{3Q}(0)], \\
\alpha T &\equiv \frac{e^2}{s^2c^2m_Z^2}[\Pi_{11}(0) - \Pi_{33}(0)], \\
\alpha U &\equiv 4e^2[\Pi'_{11}(0) - \Pi'_{33}(0)].
\end{aligned}
$$

Oblique Parameters Bounds

$$\boxed{\begin{aligned}
\alpha S &\equiv 4e^2[\Pi'_{33}(0) - \Pi'_{3Q}(0)], \\
\alpha T &\equiv \frac{e^2}{s^2c^2m_Z^2}[\Pi_{11}(0) - \Pi_{33}(0)], \\
\alpha U &\equiv 4e^2[\Pi'_{11}(0) - \Pi'_{33}(0)].
\end{aligned}}$$

$$S \propto \Pi'_{33}(0) - (\Pi'_{33}(0) + \Pi'_{3Y}(0)) \to \Pi'_{3Y}(0).$$

S is proportional to $\mathrm{tr}(T^3)$

Oblique Parameters Bounds

$$\boxed{\begin{aligned} \alpha S &\equiv 4e^2[\Pi'_{33}(0) - \Pi'_{3Q}(0)], \\ \alpha T &\equiv \frac{e^2}{s^2c^2m_Z^2}[\Pi_{11}(0) - \Pi_{33}(0)], \\ \alpha U &\equiv 4e^2[\Pi'_{11}(0) - \Pi'_{33}(0)]. \end{aligned}}$$

$$T \propto \mathrm{tr}(T^1T^1) - \mathrm{tr}(T^3T^3) = C(\mathbf{N})(\delta^{11} - \delta^{33}) = 0.$$