A Fermionic Dark Matter Model

Ref: arXiv:1704.03417

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✧ ROTATIONAL VELOCITY OF SPIRAL GALAXY

- ✓ Virial theorem implies:

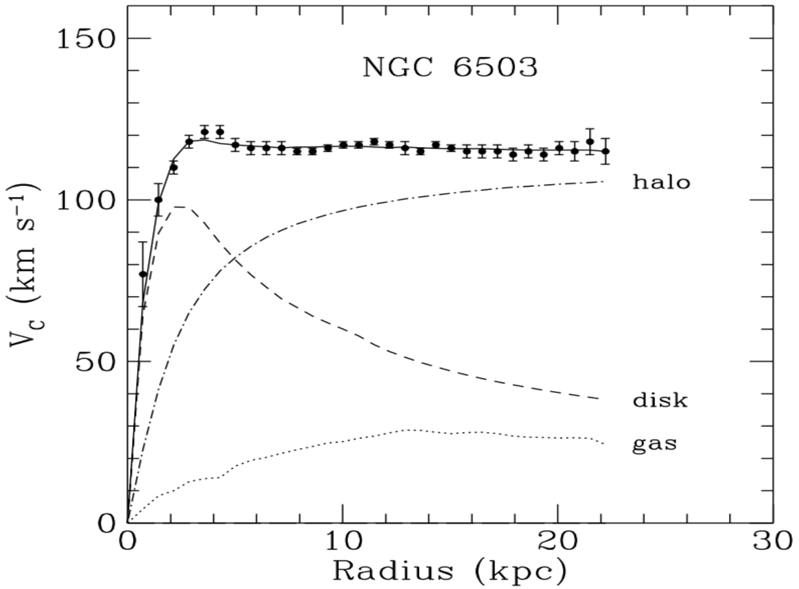
$$\langle K.E \rangle = -\frac{1}{2}\langle P.E \rangle$$

$$\langle v^2 \rangle = -\frac{GM}{R}$$

↓

Mass inferred >> Baryonic mass

MISSING MASS IS NON-BARYONIC



G. Jungman, M. Kamionkowski, and K. Griest 1996

Other Astrophysical Evidences

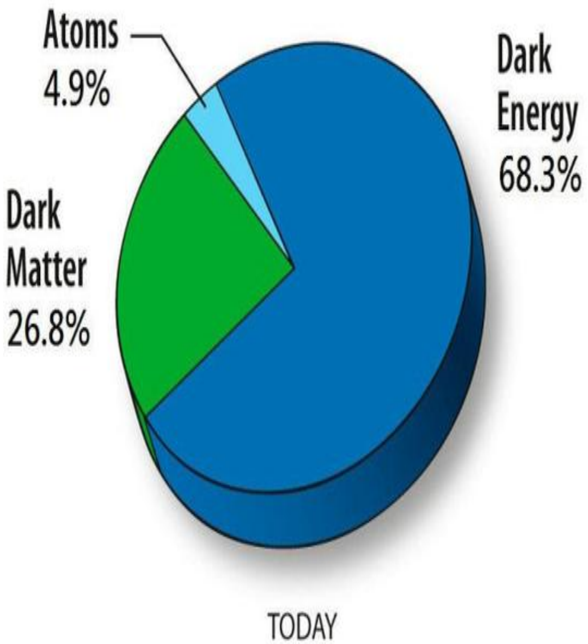
Collision of galaxies in Bullet Cluster

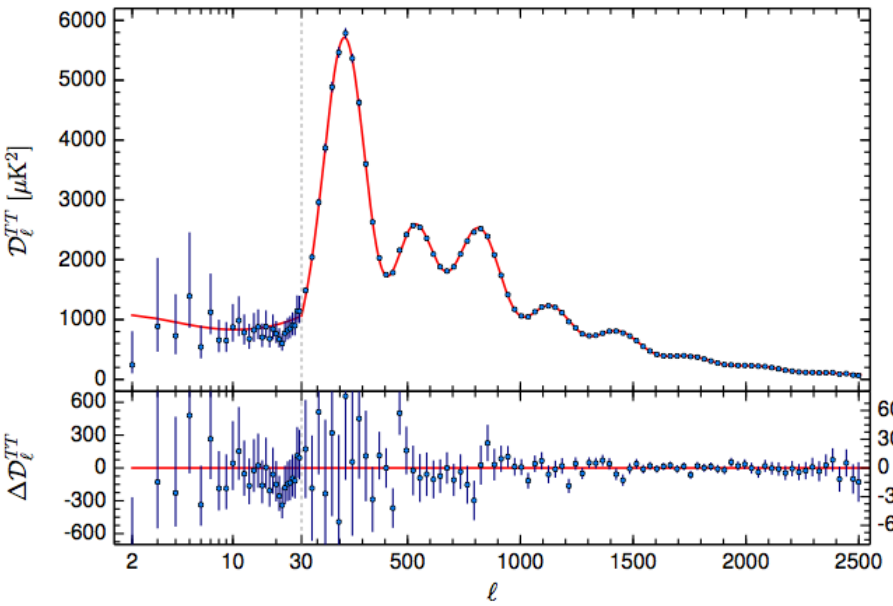
www.nasa.gov

Gravitational lensing effect due to presence of DM

Gravitational lensing observed by Hubble in Abel 1689 cluster

Evidence from Cosmic Microwave Data





PLANCK 2015

$$\Omega_{CDM}\, h^2 = 0.1199 \pm 0.0027$$

Vector Like Mixed Singlet-doublet Fermionic DM In Presence Of A Scalar Triplet

Particle contents of the model

$$N = \begin{pmatrix} N^0 \\ N^- \end{pmatrix} \equiv (1,2,-1), \chi^0 \equiv (1,1,0)$$

$$\Delta = \begin{pmatrix} \frac{\Delta^+}{\sqrt{2}} & \Delta^{++} \\ \Delta^0 & -\frac{\Delta^+}{\sqrt{2}} \end{pmatrix} (1,3,2)$$

The new Lagrangian apart from the SM is

$$-L_{NEW} = \bar{N} \not{D} N + \bar{\chi}^0 \not{\partial} \chi^0 + (D^\mu \Delta)^\dagger (D_\mu \Delta) + M_N \bar{N} N + M_\chi \overline{\chi^0} \chi^0 + L_{yuk} - V(\Delta, H)$$

where $$L_{yuk} = \frac{1}{\sqrt{2}} \left[(f_L)_{\alpha\beta} \overline{L^c_\alpha} i\tau_2 \Delta L_\beta + f_N \overline{N^c_\alpha} i\tau_2 \Delta N_\beta + h.c \right] + [Y \bar{N} \tilde{H} \chi^0 + h.c]$$

$$V(\Delta, H) = -M_H^2 H^\dagger H + \lambda_H (H^\dagger H)^2 + M_\Delta^2 \Delta^\dagger \Delta + \lambda_\Delta (\Delta^\dagger \Delta)^2$$

$$+ \lambda_{\Delta H} (H^\dagger H)(\Delta^\dagger \Delta) + \frac{1}{\sqrt{2}} \left[\mu \Delta^\dagger H H + h.c \right]$$

Hep-th/0501082, hep-ph/0510064, arXiv: 0705.4493, arXiv:0706.0918, arXiv:0804.4080, arXiv:1109.2604, arXiv:1311.5896, arXiv:1504.07892, arXiv:1505.03867

Neutrino Mass

$$(M_\nu)_{\alpha\beta} = \sqrt{2}(f_L)_{\alpha\beta}\langle u_\Delta\rangle \approx (f_L)_{\alpha\beta}\frac{-\mu v^2}{\sqrt{2}M_\Delta^2}$$

$\mu \approx M_\Delta = O(10^{14})\ GeV$

$f_L \approx 1$

→

$M_\nu \approx 0.1$ eV

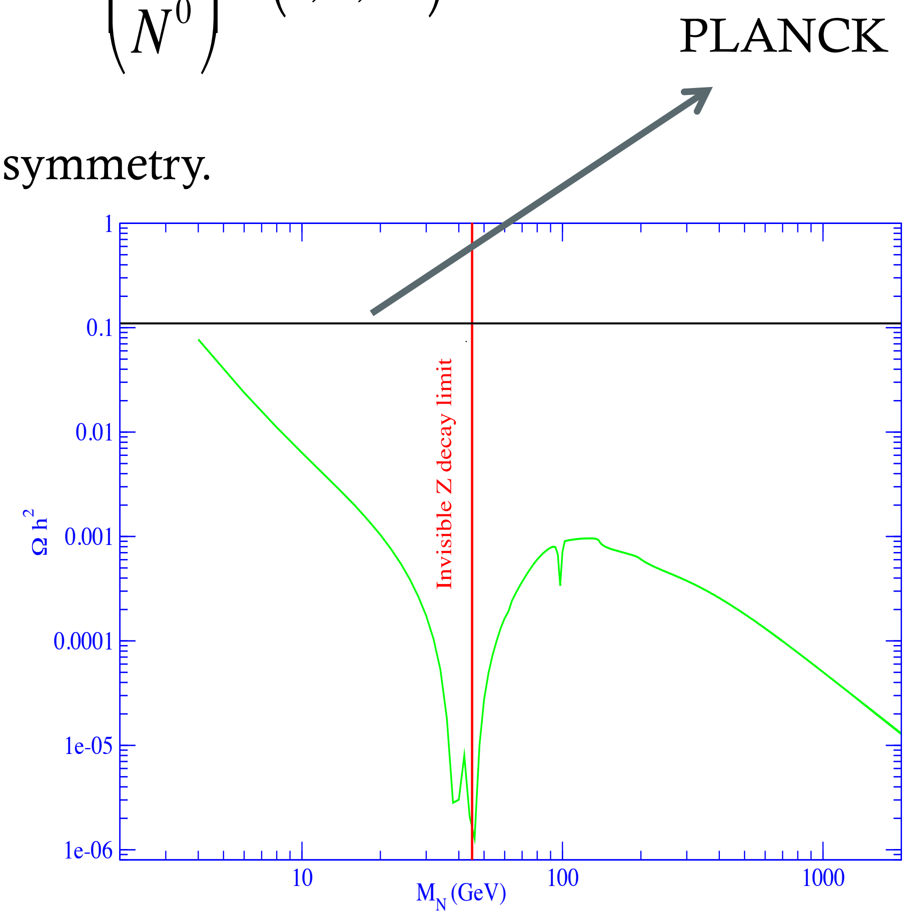
However mass of M_Δ can be in TeV scale
By choosing appropriate coupling

$$L_{DM} = \bar{N} i\gamma^{\mu} D_{\mu} N + M_N \bar{N} N \text{ where } N = \begin{pmatrix} N^- \\ N^0 \end{pmatrix} \equiv (1,2,-1)$$

- ♣ The neutral field N^0 can be stable by a Z_2 symmetry.
- ♣ Large annihillation cross-section

  Of process $\bar{N}^0 N^0 \to W^+ W^-$

  kills the relic density.



Hence N^0 can not alone be a DM candidate

After Electro-Weak Symmetry Breaking, the mass for vector like neutral fermions

$$\left(\overline{N^o}, \overline{\chi^0}\right)\begin{pmatrix} M_N & m_D \\ m_D & M_\chi \end{pmatrix}\begin{pmatrix} N^o \\ \chi^0 \end{pmatrix} \qquad m_D = Yv$$

✍ The new mass eigenstates are N_1 , N_2 and $N^{\pm}$:

$$N_1 = \cos\theta\chi^0 + \sin\theta N^0$$

$$N_2 = \cos\theta N^0 - \sin\theta\chi^0$$

$$N^{\pm}$$

$$M_1 = M_\chi - \frac{m_D^2}{M_N - M_\chi}$$

$$M_2 = M_N + \frac{m_D^2}{M_N - M_\chi}$$

$$M^{\pm} = M_1\sin^2\theta + M_2\cos^2\theta = M_N$$

✍ And mixing angle

$$\tan 2\theta = \frac{m_D}{M_N - M_\chi}$$

$$Y = \frac{\Delta M Sin 2\theta}{2v}$$

The lightest particle N_1 is the Dark Matter

Pseudo Dirac Nature of Dark Matter

After EW symmetry breaking ,when Δ gets an induced vev, a Majorana mass term is created for N_1.

$$m_1 = \sqrt{2} f_N \sin^2\theta \langle \Delta \rangle \approx f_N \sin^2\theta \frac{-\mu v^2}{\sqrt{2} M_\Delta^2}$$

Majorana mass splits Dirac state into two Majorana states (Ψ_1)^{a,b}

Mass Eigenvalues $M_1 \pm m_1$

Mass splitting $\delta m = 2m_1 = 2\sqrt{2} f_N \sin^2\theta \langle \Delta \rangle$

Small mass-splitting does not play any role
In relic abundance of DM, but plays important
role in direct detection of DM

Relic Abundance of Dark Matter

$$\Omega_{DM}h^2 = \frac{1.09\times 10^9}{g_*^{1/2}\left(M_{Pl}/GeV\right)}\frac{1}{J(x_f)}$$

$$J(x_f) = \int_{x_f}^{\infty}\frac{\langle \sigma |v| \rangle_{eff}}{x^2}dx$$

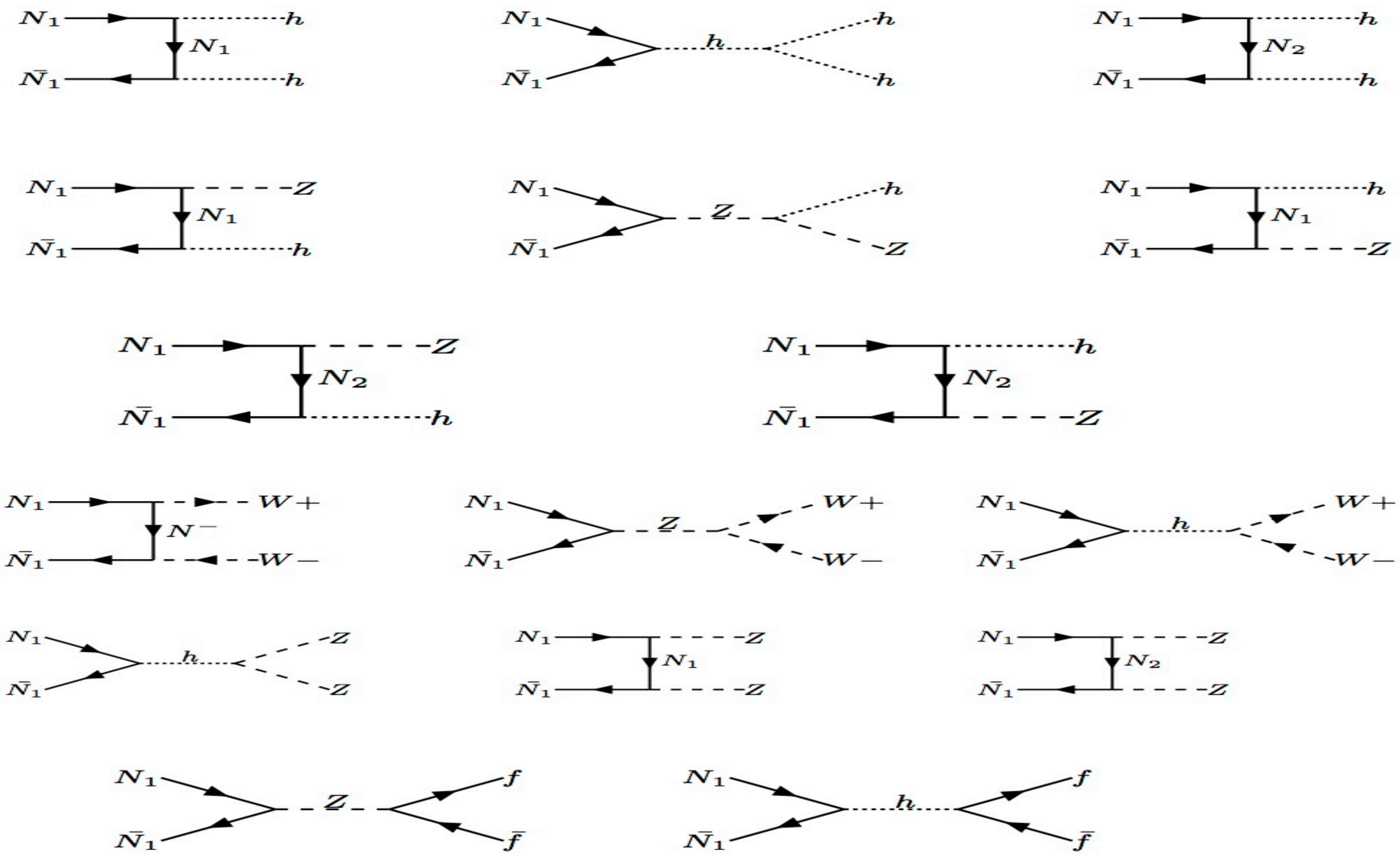
$$\langle \sigma |v| \rangle_{eff} = \sum_{i,j}^{3}(\sigma v)_{ij}\frac{g_i g_j}{g_{eff}^2}(1+\omega_i)^{3/2}(1+\omega_j)^{3/2}\exp[-x(\omega_i+\omega_j)]$$

with

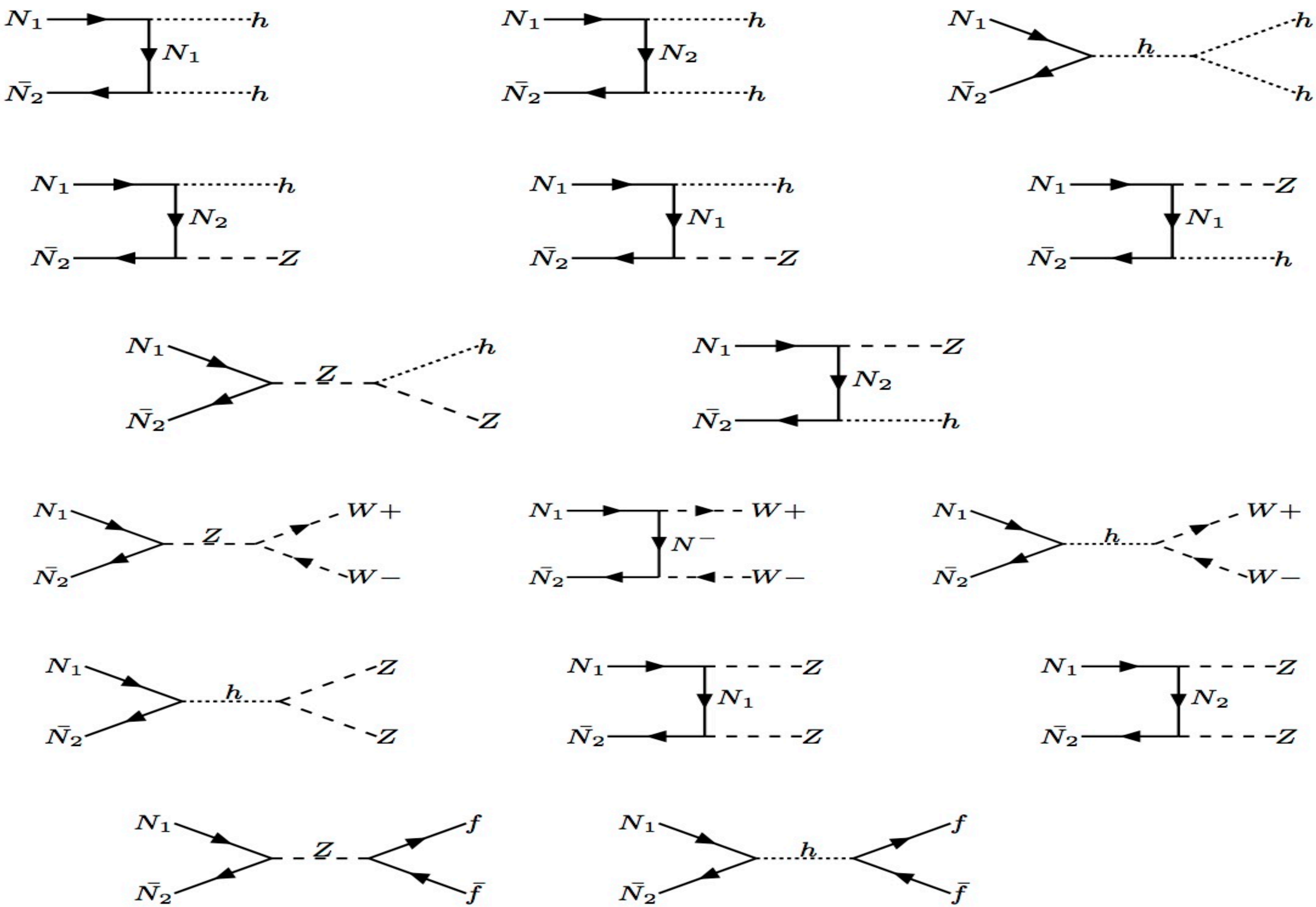
$$g_{eff} = \sum_{i=1}^{3} g_i(1+\omega_i)^{3/2}\exp(-x\omega_i) \qquad \omega_i = \frac{M_i - M_1}{M_1}$$

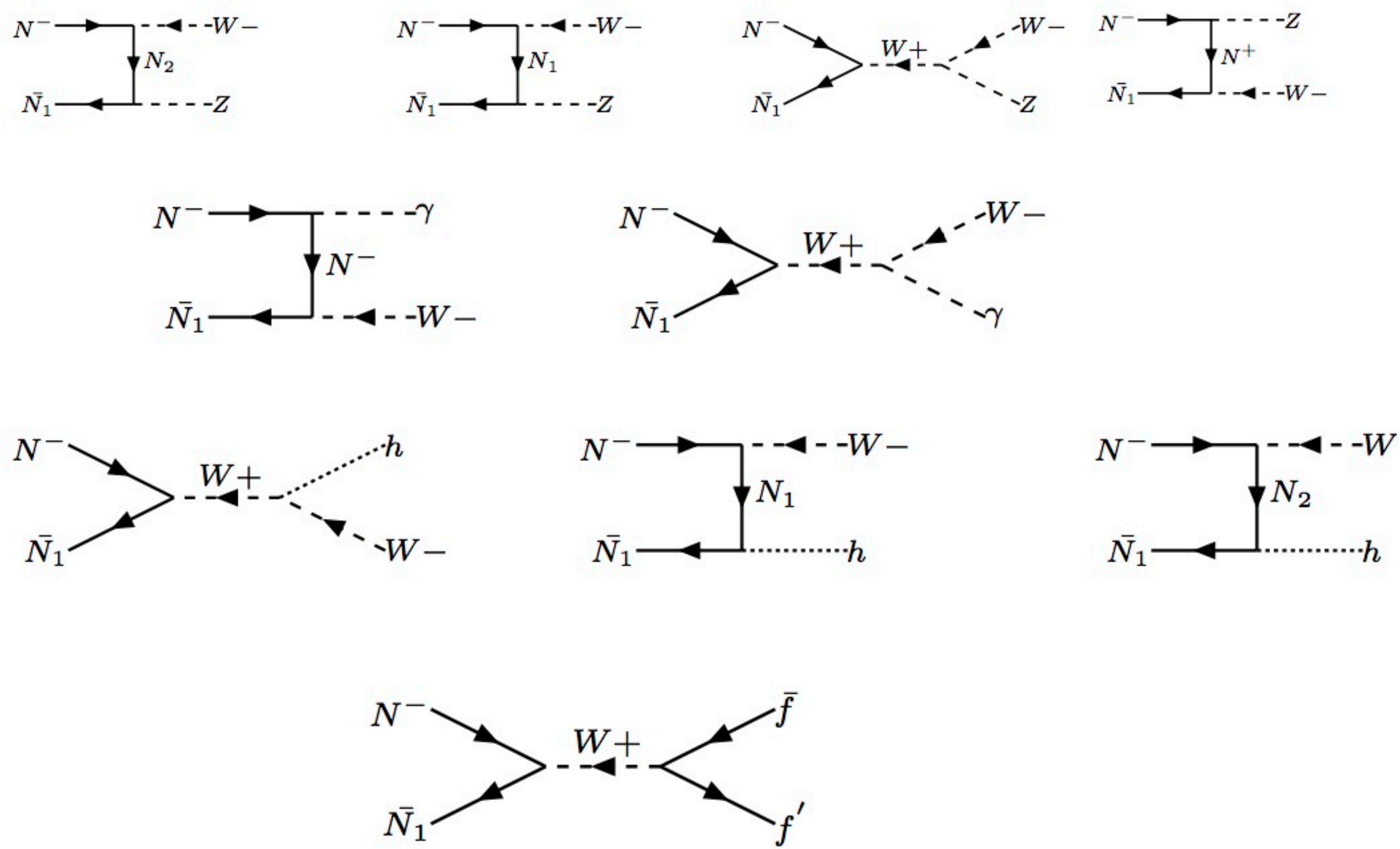
○ Griest and Seckel: PRD 1991

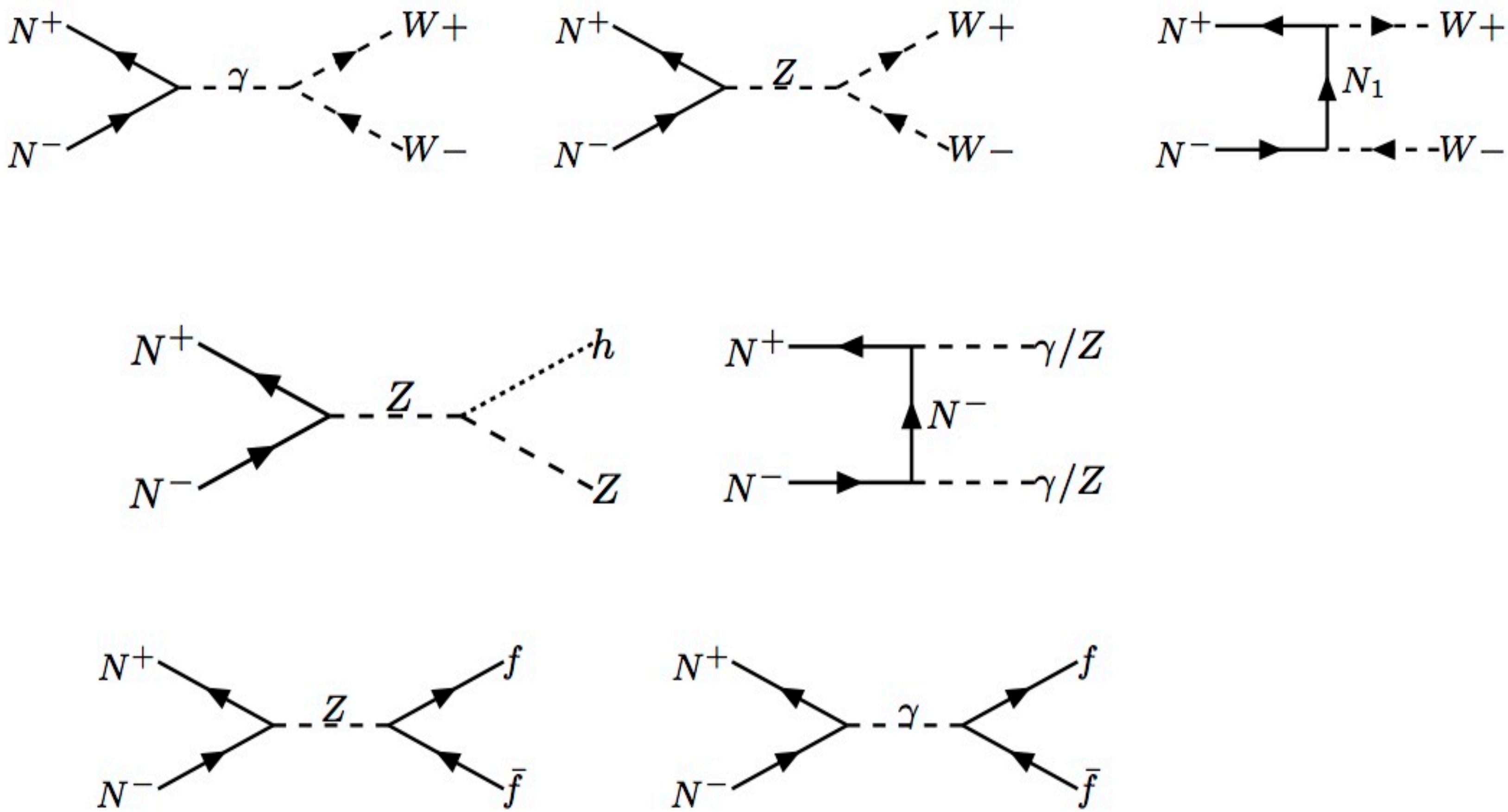
Annihilation processes



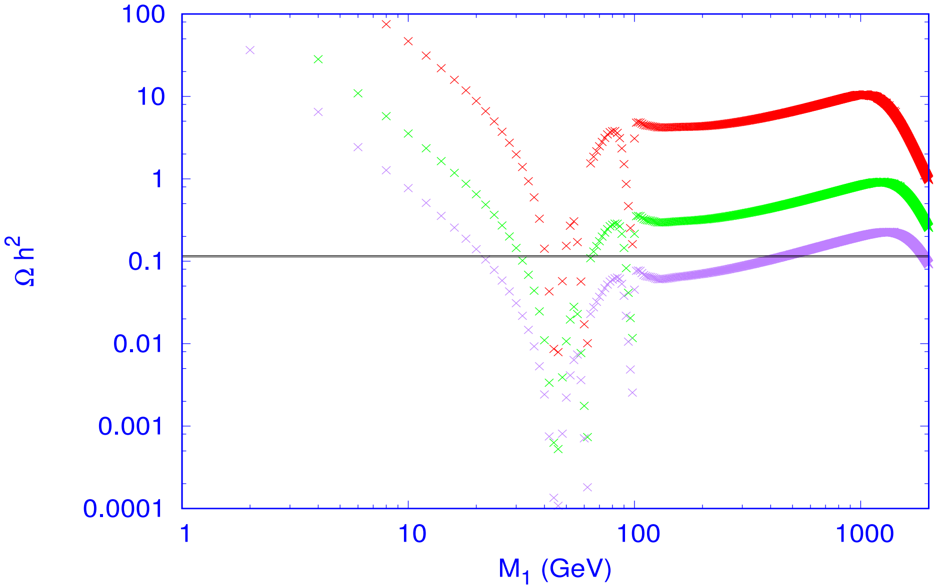
Dominant Co-annihilation processes

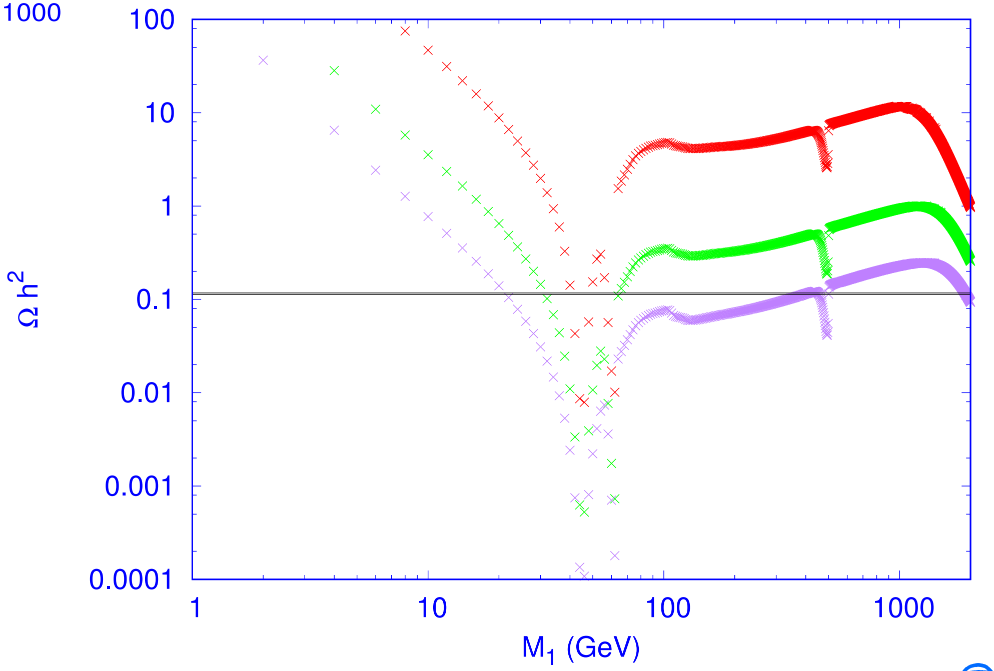



N^-
$W-$
N_2
$\bar{N}_1$
Z
N^-
$W-$
N_1
$\bar{N}_1$
Z
N^-
$W+$
$W-$
$\bar{N}_1$
Z
N^-
Z
N^+
$\bar{N}_1$
$W-$
N^-
γ
N^-
$\bar{N}_1$
$W-$
N^-
$W+$
$W-$
$\bar{N}_1$
γ
N^-
h
$W+$
$\bar{N}_1$
$W-$
N^-
$W-$
N_1
$\bar{N}_1$
h
N^-
W
N_2
$\bar{N}_1$
h
N^-
$W+$
$\bar{f}$
$\bar{N}_1$
f'



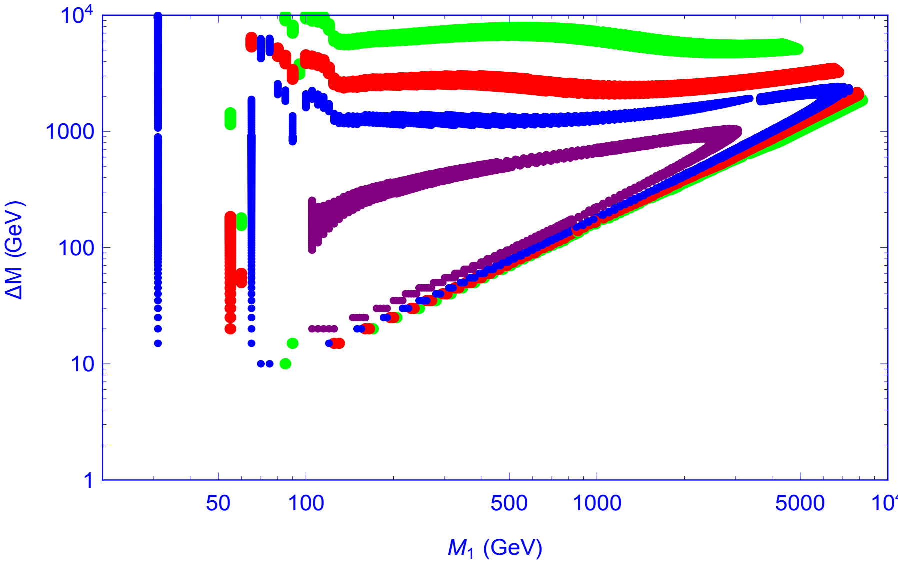
N+
N−
γ
W+
W−
Z
N1
h
γ/Z
f
f̄



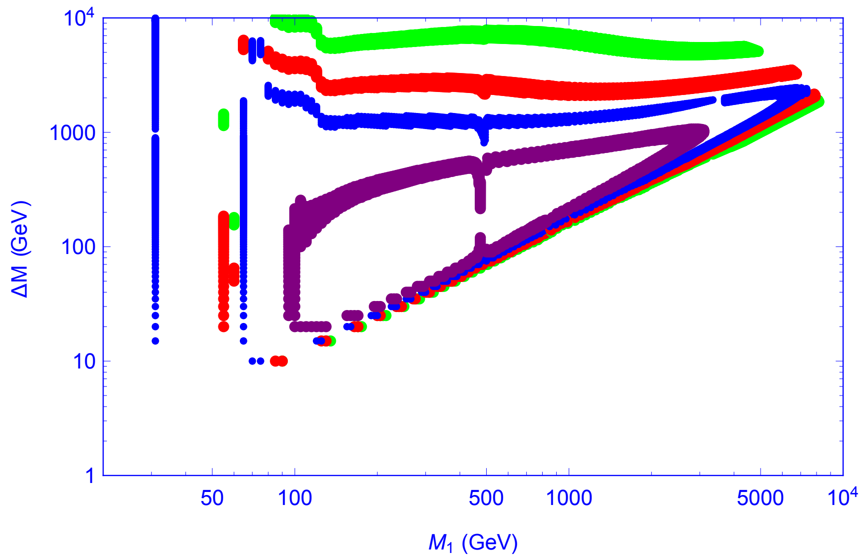


Sin θ =0.1 (Red)
Sin θ =0.2(Green)
Sin θ =0.3 (Purple)
f_L/f_N =0.001

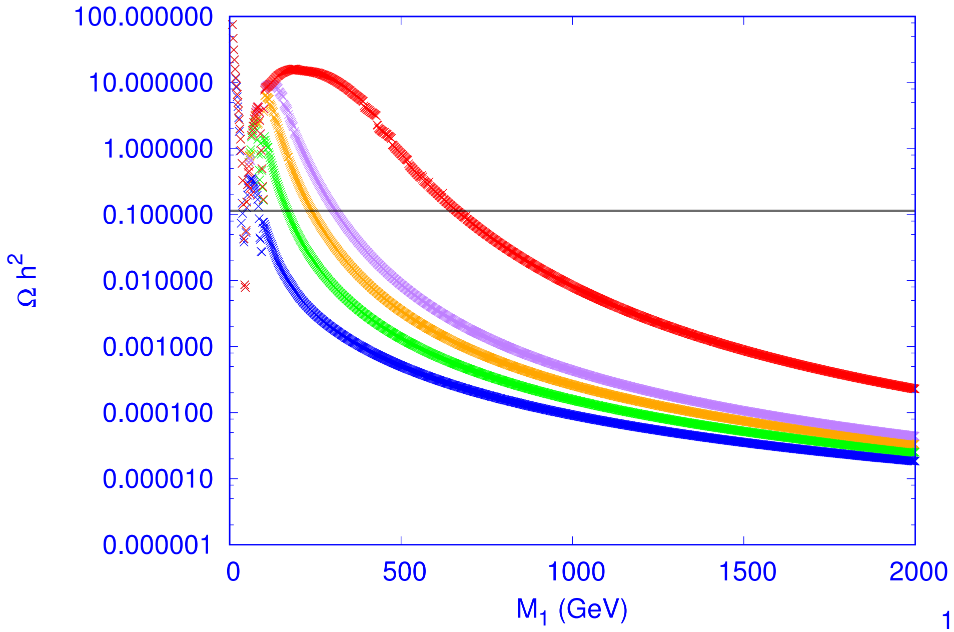
Sin θ =0.1 (Green)
Sin θ =0.1 5(Red)
Sin θ =0.2(Blue)
Sin θ =0.3 (Purple)



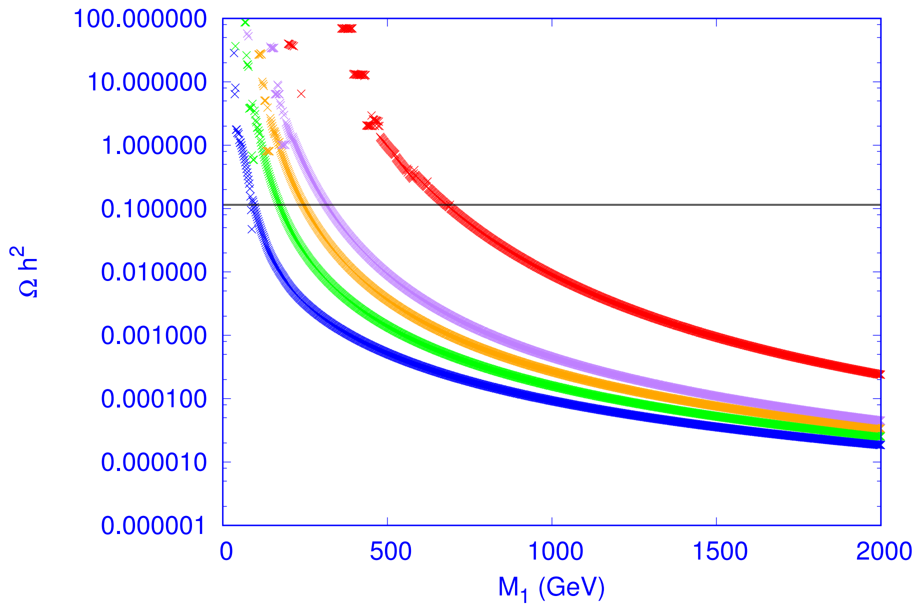
M_Δ =200 GeV



M_Δ =1000 GeV



$M_{\Delta} = 200$ GeV



$\Delta M = 10$ GeV(Blue)
$\Delta M = 20$ GeV(Green)
$\Delta M = 30$ GeV(Orange)
$\Delta M = 40$ GeV(Purple)
$\Delta M = 100$ GeV(Red)

Inelastic DM and its Direct Detection

The DM interaction Lagrangian with the nuclei through ***Z*** boson

$$L_{Z-DM} = \bar{N}_1 i(\gamma^\mu \partial_\mu + g_z \gamma^\mu Z_\mu) N_1$$

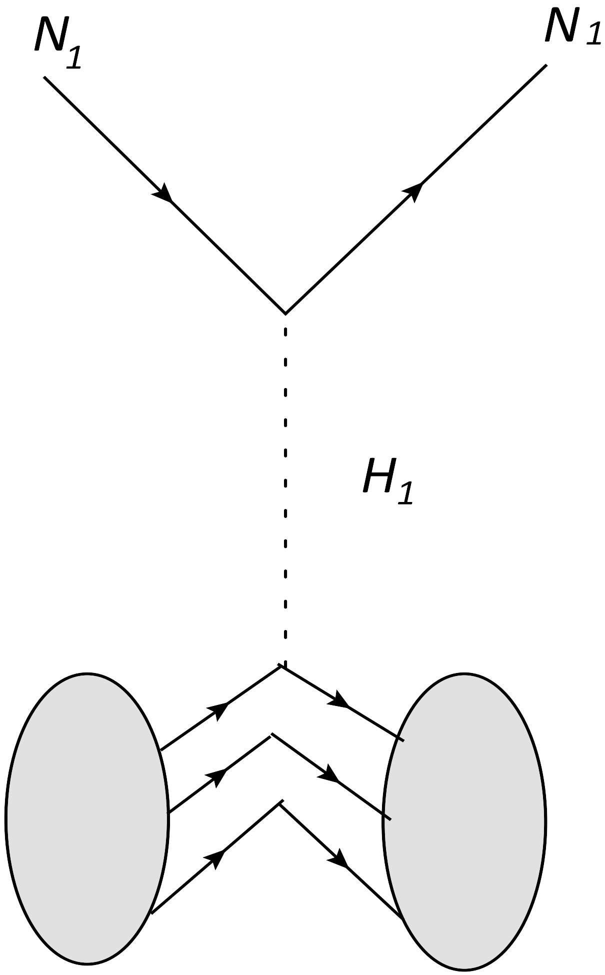
Where $$g_Z = \frac{g}{2Cos\theta_W} Sin^2\theta$$

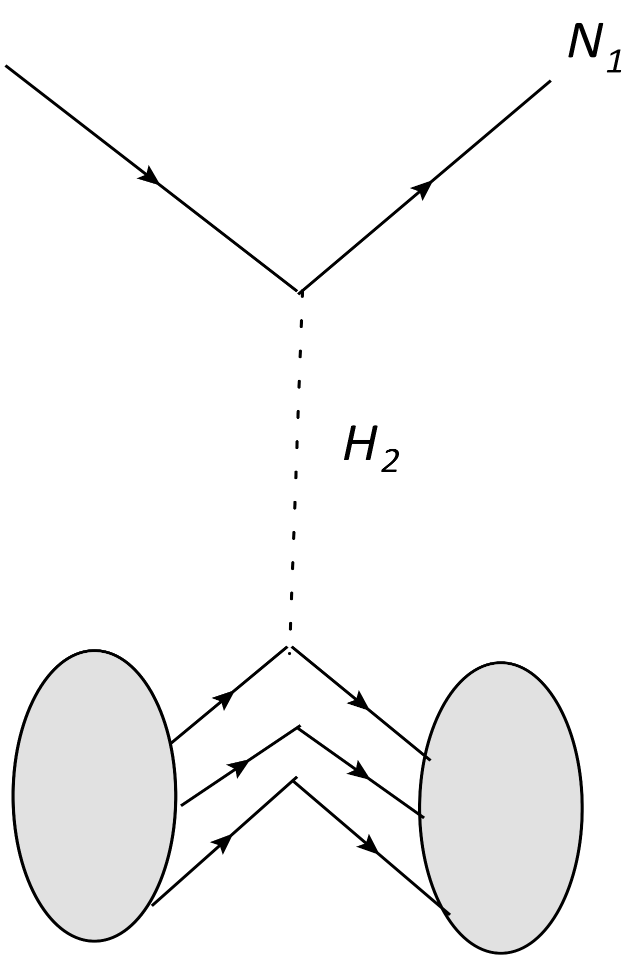
- ☞ Presence of Majorana mass splits the DM into two new states(Ψ_1)[a,b.]
- ☞ Mass splitting $\delta m = 2\sqrt{2} f_N \sin^2\theta \langle \Delta \rangle$
- ☞ Dominant ***Z*** interaction now off-diagonal $\bar{\psi}_1^a i g_z \gamma^\mu Z_\mu \psi_1^b$
- ☞ Minimum velocity required

$$v = c\sqrt{\frac{1}{2m_n E_R}} \left(\frac{m_n E_R}{\mu_R} + \delta M \right)$$

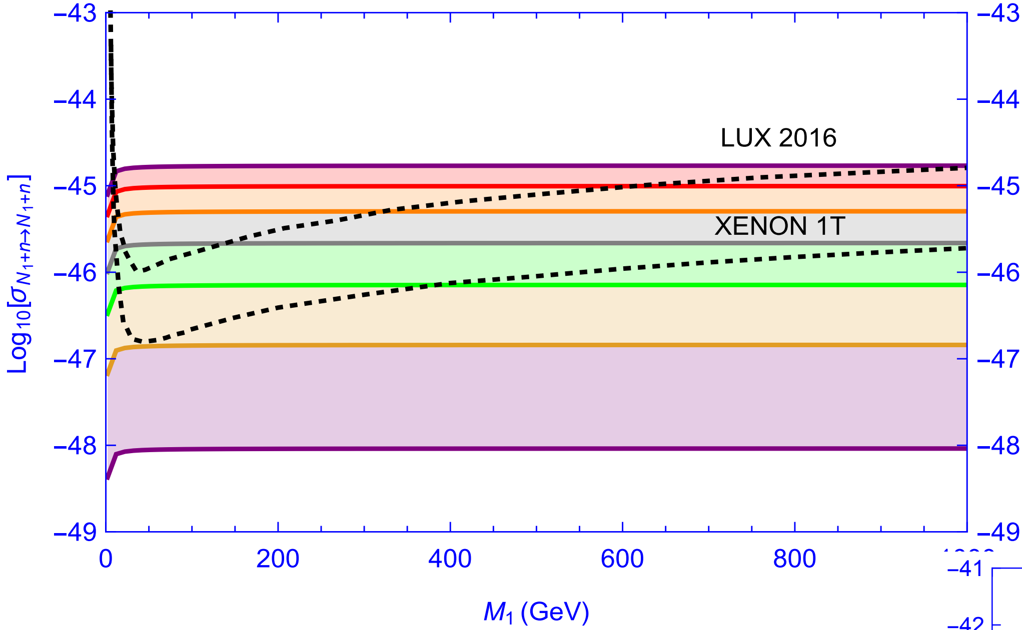
- ✓ m_n = nucleon mass
- ✓ E_R = Recoil Energy
- ✓ μ_R =Reduced mass

Elastic Scattering of DM with the nucleus



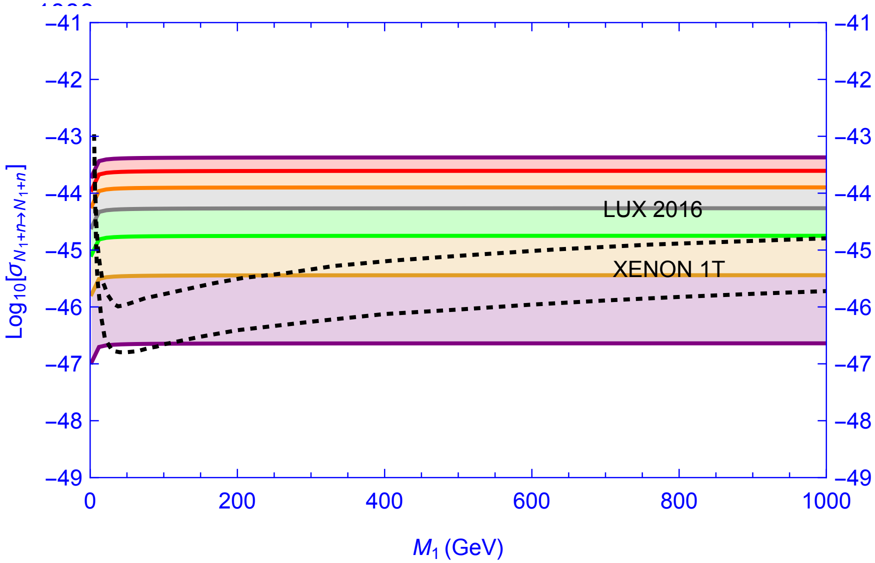


$\Delta M = 100$ GeV



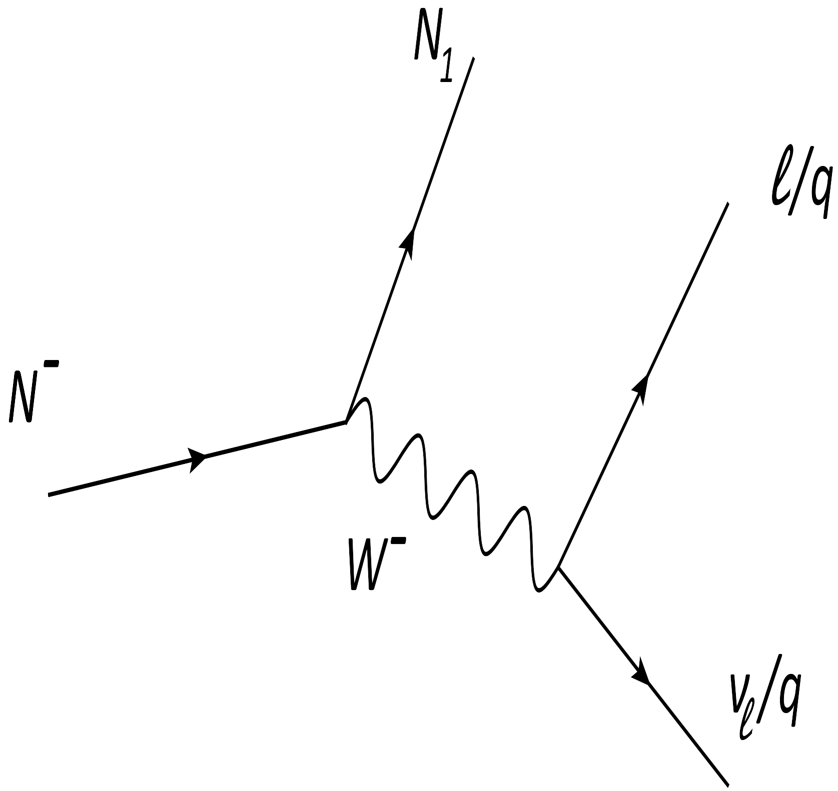
$M_\Delta = 200$ GeV

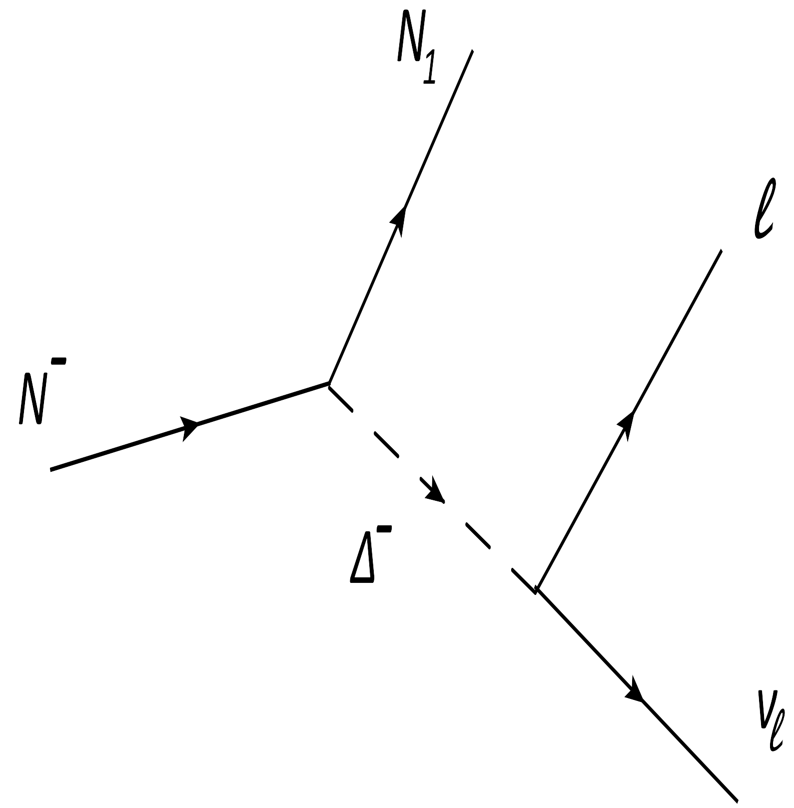
$\Delta M = 500$ GeV

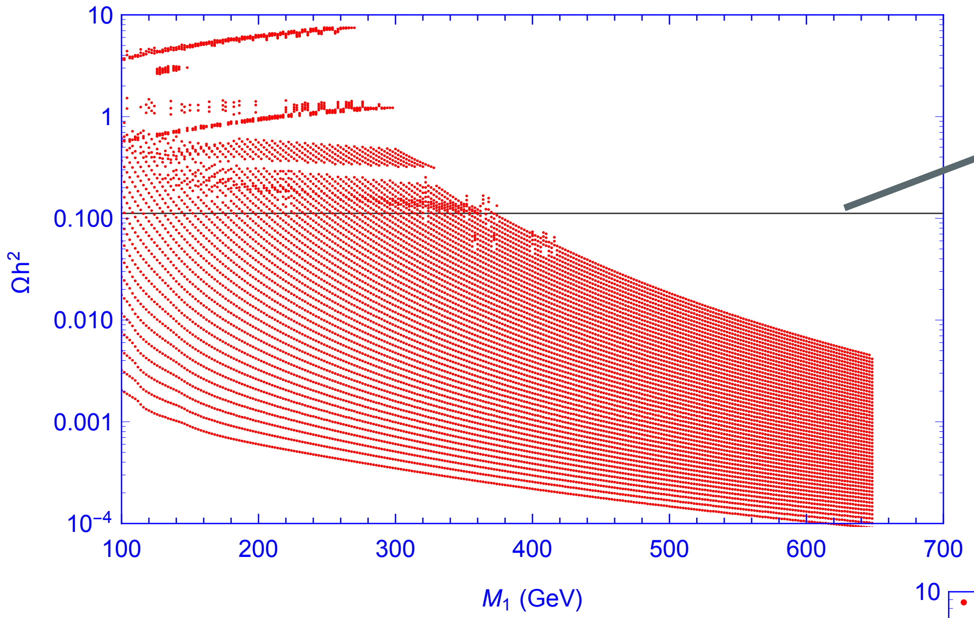


Sin θ =0.05-0.1 (Purple)
Sin θ =0.1-0.15 (Pitch)
Sin θ =0.15-0.2 (Green)
Sin θ =0.2-0.25 (Gray)
Sin θ =0.2-0.25 (Orange)
Sin θ =0.2-0.25 (Red)

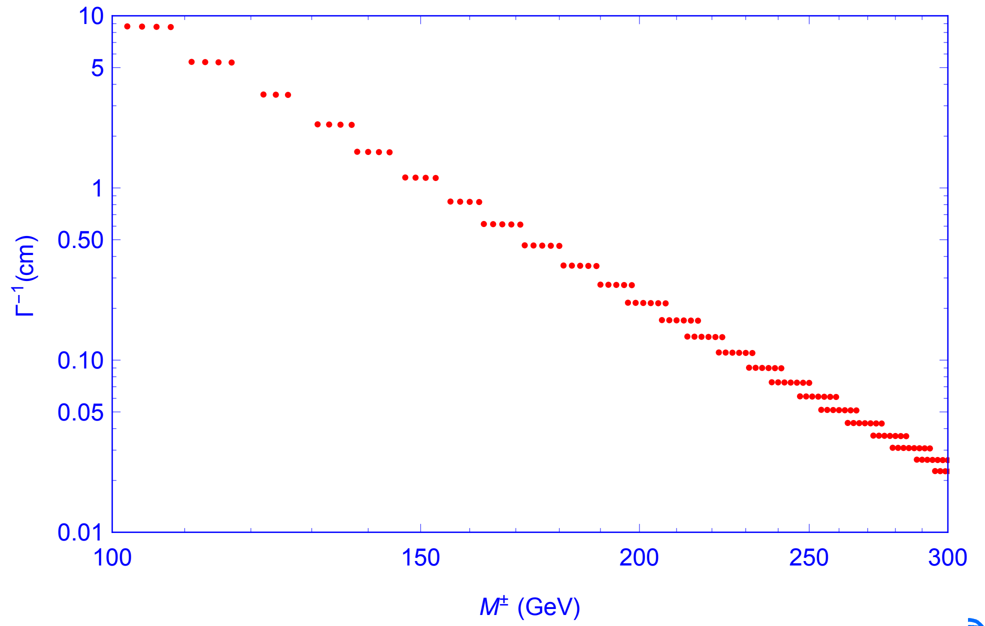
Decay Of N^- And Displaced Vertex Signature



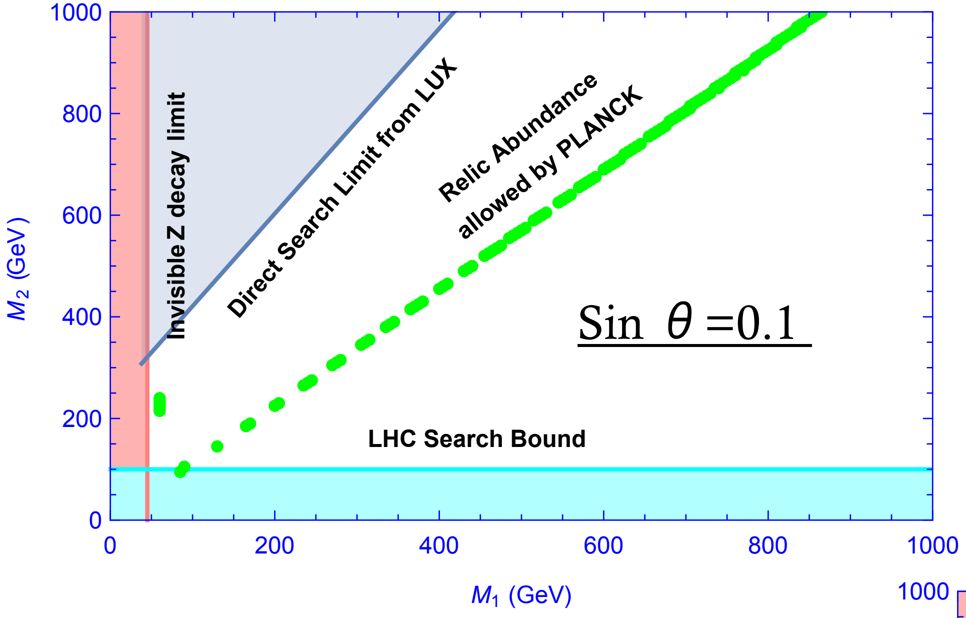


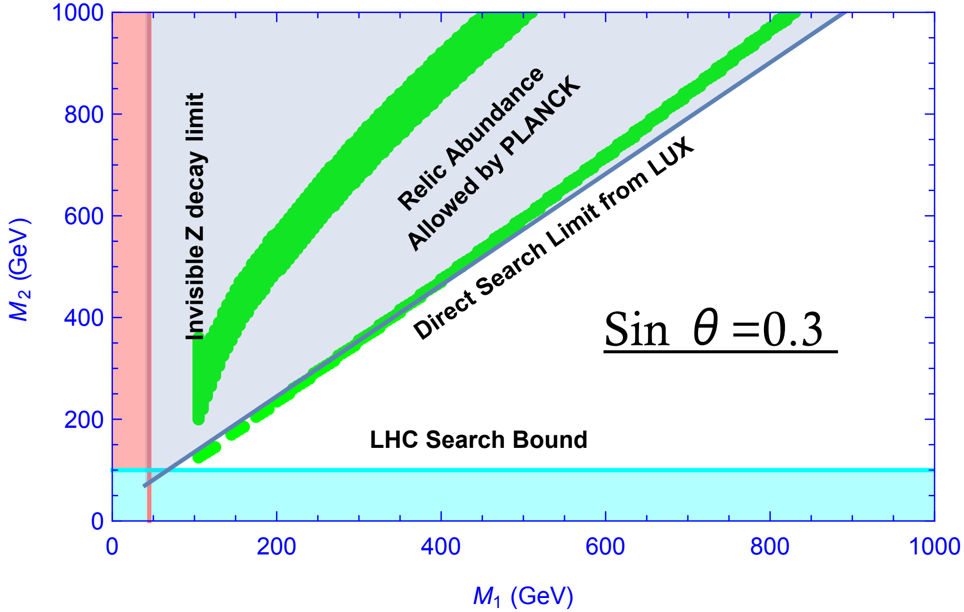


PLANCK



$\Delta M < 50$ GeV
Sin θ =0.0003


1000
800
600
400
200
0
M_2 (GeV)
0
200
400
600
800
1000
M_1 (GeV)
Invisible Z decay limit
Direct Search Limit from LUX
Relic Abundance
allowed by PLANCK
Sin θ =0.1
LHC Search Bound


1000
800
600
400
200
0
M_2 (GeV)
0
200
400
600
800
1000
M_1 (GeV)
Invisible Z decay limit
Relic Abundance
Allowed by PLANCK
Direct Search Limit from LUX
Sin θ =0.3
LHC Search Bound

Conclusion

- ☆ We have studied the case of a vector like DM model where the DM is a mixed state of doublet and singlet fermion
- ☆ Relic abundance is satisfied in large parameter space of the model
- ☆ The relic abundance of DM largely dependent on annihilation and coannihilation of DM to the SM gauge bosons.
- ☆ The scalar triplet does not contribute to the relic density except for few points near resonance
- ☆ The scalar triplet after EW symmetry breaking gives a small Majorana mass to the DM as well as to the SM neutrinos.
- ☆ The Majorana mass splits DM into two Majorana mass states with a mass-splitting of sub GeV order. As a result the DM can scatter inelastically from the nucleus through Z mediation.
- ☆ But the elastic scattering is still be possible through scalar mediation.
- ☆ The charged companion of DM decay via 3 body decay process and can show a displaced vertex.


Thank You

Back-Up

Singlet Fermion as WIMP

$$L_{DM} = \bar{\chi} i\gamma^{\mu}\partial_{\mu}\chi + M\bar{\chi}\chi + \frac{\bar{\chi}\chi HH}{\Lambda}$$

$$\Omega h^2 = F(M_{\chi}, \Lambda)$$

$$\sigma_{SI} = \sigma(M_{\chi}, \Lambda)$$

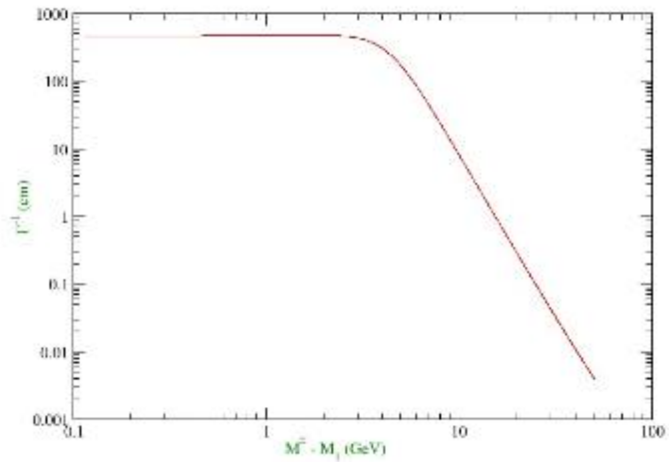
- Relic abundance is large for apart from the Higgs funnel.
- We can not do any further prediction about our weak interaction assumption of dark matter

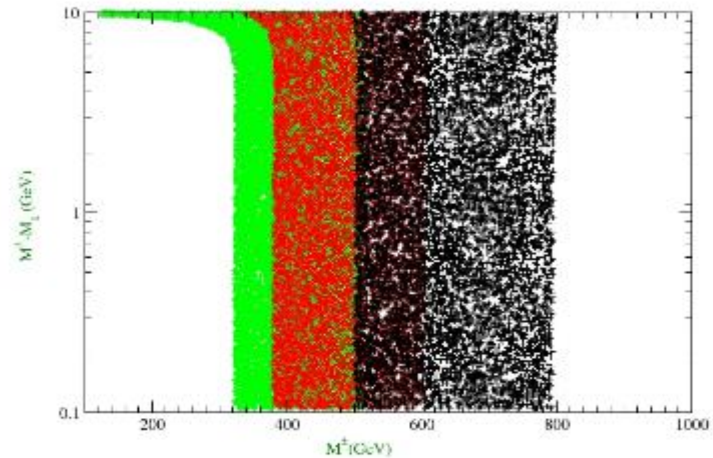
- Where Λ is the scale of new physics
- H is the standard model Higgs
- A Z_2 symmetry ensures the stability of DM

COLLIDER SEARCH

- Displaced vertex signature of $N^{\pm}$

$$N^{\pm} \rightarrow N_1 + l^{\pm} + \nu_l$$



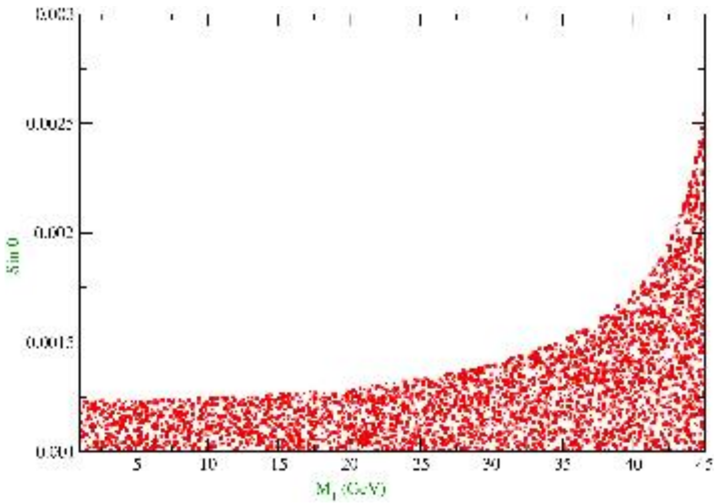


$$M^{\pm} = 150 GeV$$
$$\sin\theta = 3\times 10^{-4}$$
$$m_l = 105 MeV$$

Sin θ=3×10^{-4} (Green)
Sin θ=2×10^{-4} (Red)
Sin θ=10^{-4} (Black)

For a small mass difference we expect a large displaced vertex for the charge companion of DM

CONSTRAINT FROM INVISIBLE HIGGS AND Z DECAY

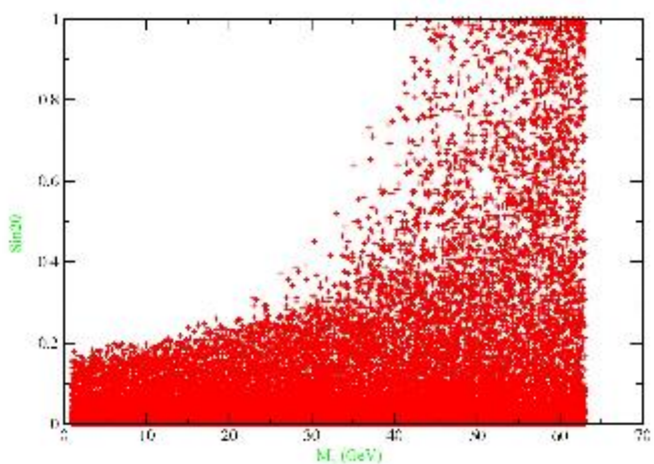


Constraint from Invisible Z Decay : LEP

$M_1 < M_Z/2 = 45$ GeV
$M_2 = 45$ GeV

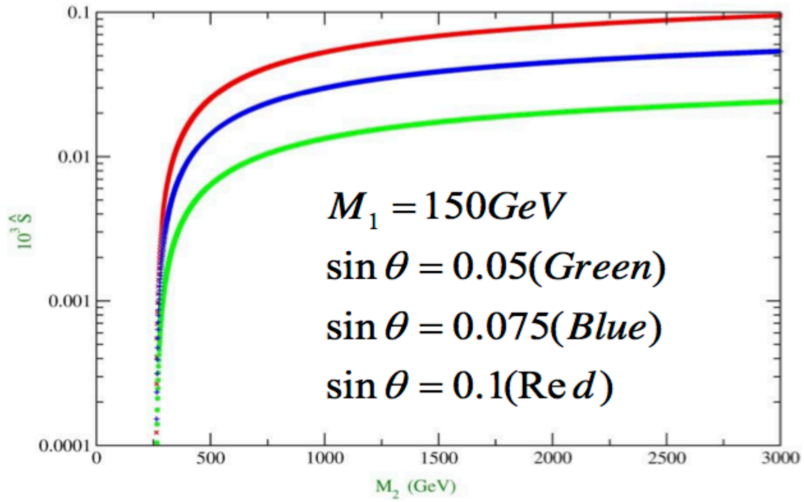
Constraint from Invisible Higgs Decay
All possible values of M_2 is used that opens the decay channel

$$Br_{inv} = \frac{\Gamma_h^{inv}}{\Gamma_h^{SM} + \Gamma_h^{inv}} < 0.3$$



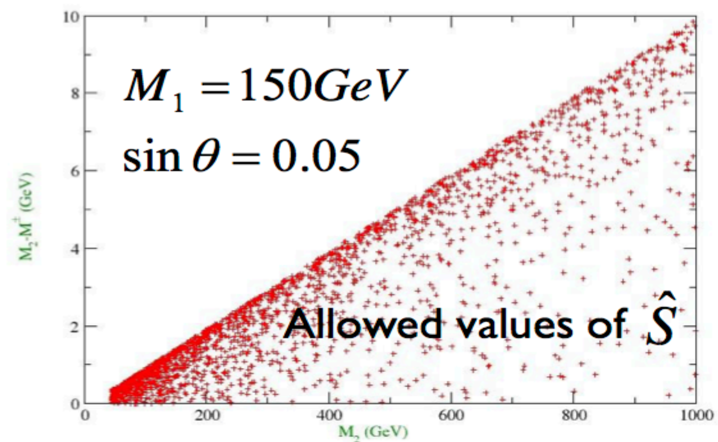
- ATLAS COLLABORATION , 1508.07869 arXiv

S parameter

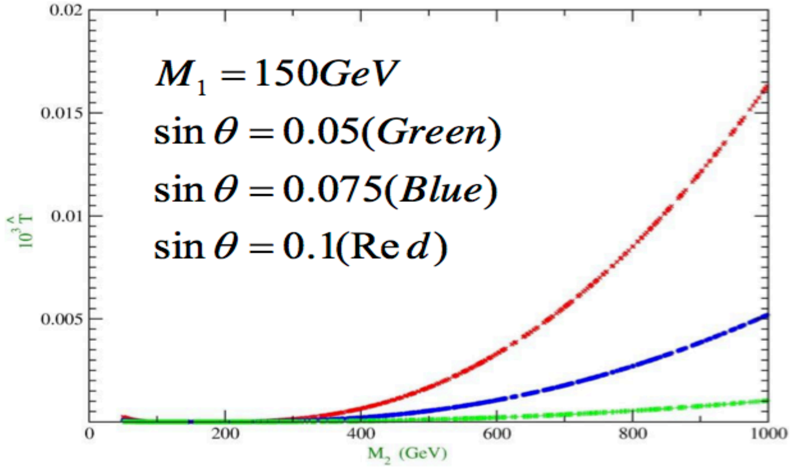


$$\hat{S} = \frac{\alpha S}{4\sin^2\theta_w}$$

$$1000\hat{S} = 0.0 \pm 1.3$$



T parameter



$$\hat{T} = \alpha T$$

$$1000\hat{T} = 0.1 \pm 0.9$$