Dark Matter: From cosmos to collider

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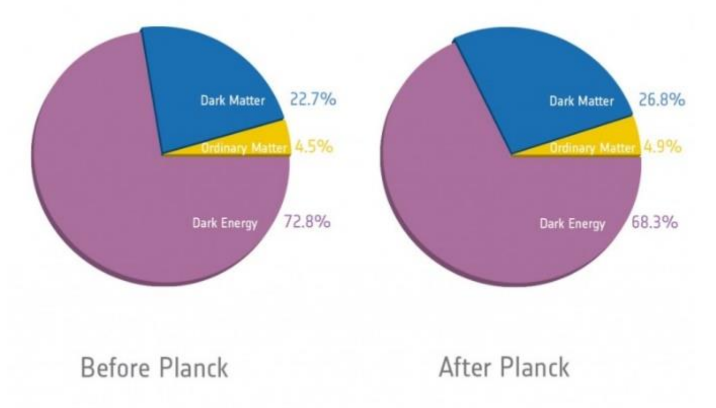
@Dept. of Physics, IIT Hyderabad, 21st October 2024

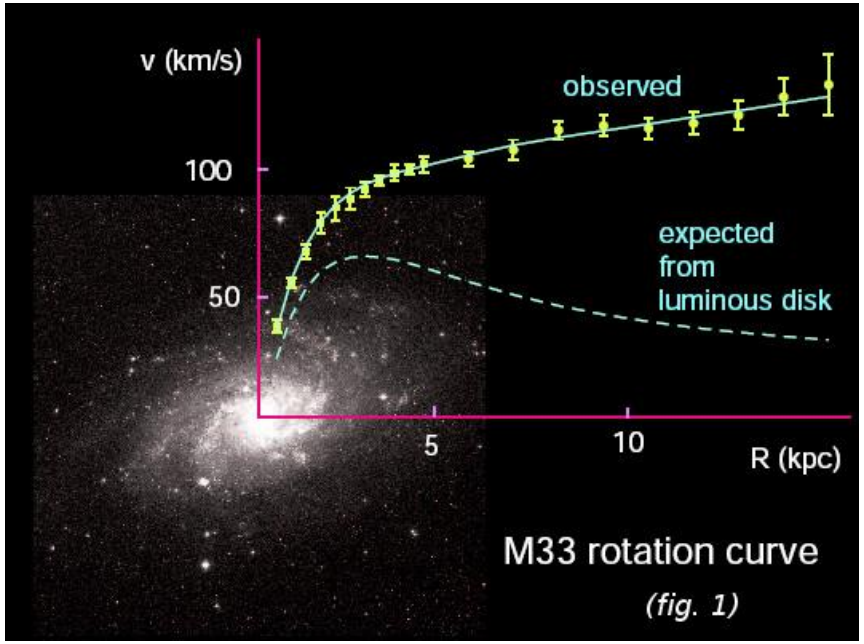
We don't know what precisely it is ?
But we know that it is certainly a form of matter whose existence in astrophysical environments has been observed via its gravitational interaction.
Therefore, we call this unknown form of matter as "dark matter (DM)".



What is Dark Matter ?

Evidence of DM from rotation curve

$$\frac{mv_r^2}{r} = \frac{GM_r m}{r^2}$$



$$v_r \sim \frac{1}{r^{1/2}} \quad \text{(Keplerian Decline)}$$

Missing mass ~ Non-baryonic

"Discovery" of Dark Matter – I
Jan Hendrik Oort (1932)

Jan Hendrik Oort (1900-1992)

11. It is found that the total density of matter near the sun is equal to 6·3.10⁻²⁴ g/cm³ or ·092 solar masses per cubic parsec. The observed total mass of the stars down to + 13·5 visual absolute magnitude is found to be ·038 solar masses per ps³ (Table 34). It is probable that this value would still be greatly increased if we could have taken the next 5 absolute magnitudes into account, so that the total mass of meteors and nebular material is probably small in comparison with that of the stars. There is an indication that the invisible mass is more strongly concentrated to the galactic plane than that of the visible stars (Table 33).

Integrating over a column perpendicular to the galactic plane I find that an average unit of photographic light corresponds to a mass of 1·8 (if both are expressed in the sun as unit), approximately agreeing with the proportion found in the central region of the Andromeda nebula, the only available case where a comparison is possible.

BULLETIN OF THE ASTRONOMICAL INSTITUTES OF THE NETHERLANDS.

1932 August 17 — Volume VI. — No. 238.

COMMUNICATION FROM THE OBSERVATORY AT LEIDEN.

The force exerted by the stellar system in the direction perpendicular to the galactic plane and some related problems, by *J. H. Oort.*

249

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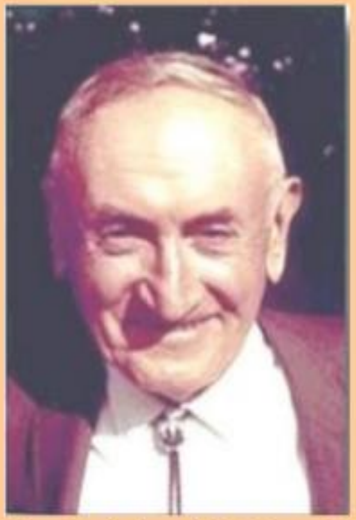
* Vertical velocities of stars too high – they should have escaped!

* Need "invisible" mass of density ~ 2 GeV / cc ! Modern value ~ 0.3 Gev / cc

Borrowed from Subir Sarkar

"Discovery" of Dark Matter – II
Fritz Zwicky (1933)



Fritz Zwicky (1898 - 1974)

F. Zwicky, "Die Rotverschiebung von extragalaktischen Nebeln", Helvetica Physica Acta 6: 110–127 (1933)

F. Zwicky, "On the Masses of Nebulae and of Clusters of Nebulae", Astrophysical Journal 86: 217 (1937)

Coma Cluster

$$N > 1000\,\text{galaxies}$$
$$D \sim 100\,\text{Mpc}$$
$$M \sim 10^{14} M_\odot$$

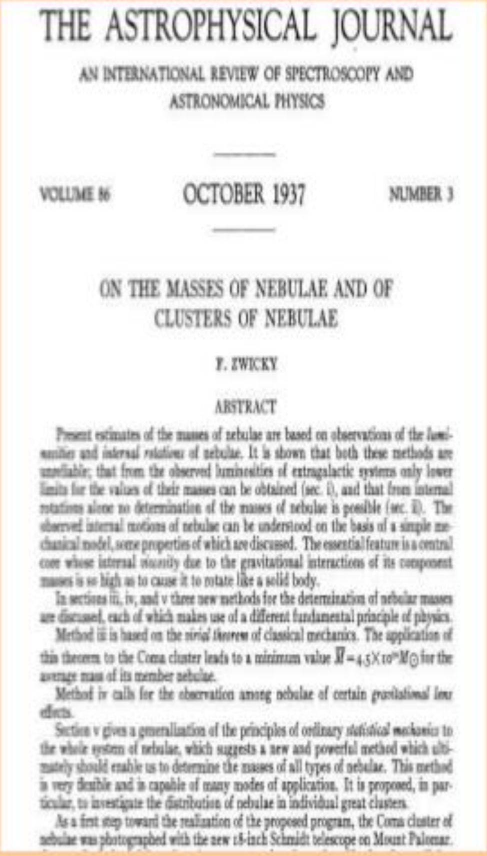
Virial Theorem $\Rightarrow \langle v^2 \rangle \sim \frac{1}{2}\frac{GM}{\langle r \rangle}$

Measured $\langle v^2 \rangle^{\frac{1}{2}} \sim 1000\,\text{km}\,\text{s}^{-1} \Rightarrow M \sim 400 M_{\text{visible}}$!!

— Radial velocities of galaxies in the Coma cluster are too large for the galaxies to be bound in the cluster with the known "visible" mass of the cluster.

Note: Zwicky used (wrong!) $H_0 = 558\,\text{km}\,\text{s}^{-1}\,\text{Mpc}^{-1}$ (as measured by Hubble!). Correct result

$$M_{\text{Coma cluster}} \sim 50 M_{\text{visible}}$$



THE ASTROPHYSICAL JOURNAL

AN INTERNATIONAL REVIEW OF SPECTROSCOPY AND ASTRONOMICAL PHYSICS

VOLUME 86 OCTOBER 1937 NUMBER 3

ON THE MASSES OF NEBULAE AND OF CLUSTERS OF NEBULAE

F. ZWICKY

ABSTRACT

Present estimates of the masses of nebulae are based on observations of the *luminosities* and *internal rotations* of nebulae. It is shown that both these methods are unreliable; that from the observed luminosities of extragalactic systems only lower limits for the values of their masses can be obtained (sec. i), and that from internal rotations alone no determination of the masses of nebulae is possible (sec. ii). The observed internal motions of nebulae can be understood on the basis of a simple mechanical model, some properties of which are discussed. The essential feature is a central core whose internal *viscosity* due to the gravitational interactions of its component masses is so high as to cause it to rotate like a solid body.

In sections iii, iv, and v three new methods for the determination of nebular masses are discussed, each of which makes use of a different fundamental principle of physics.

Method iii is based on the *virial theorem* of classical mechanics. The application of this theorem to the Coma cluster leads to a minimum value $\overline{M} = 4.5 \times 10^{10} M_\odot$ for the average mass of its member nebulae.

Method iv calls for the observation among nebulae of certain *gravitational lens* effects.

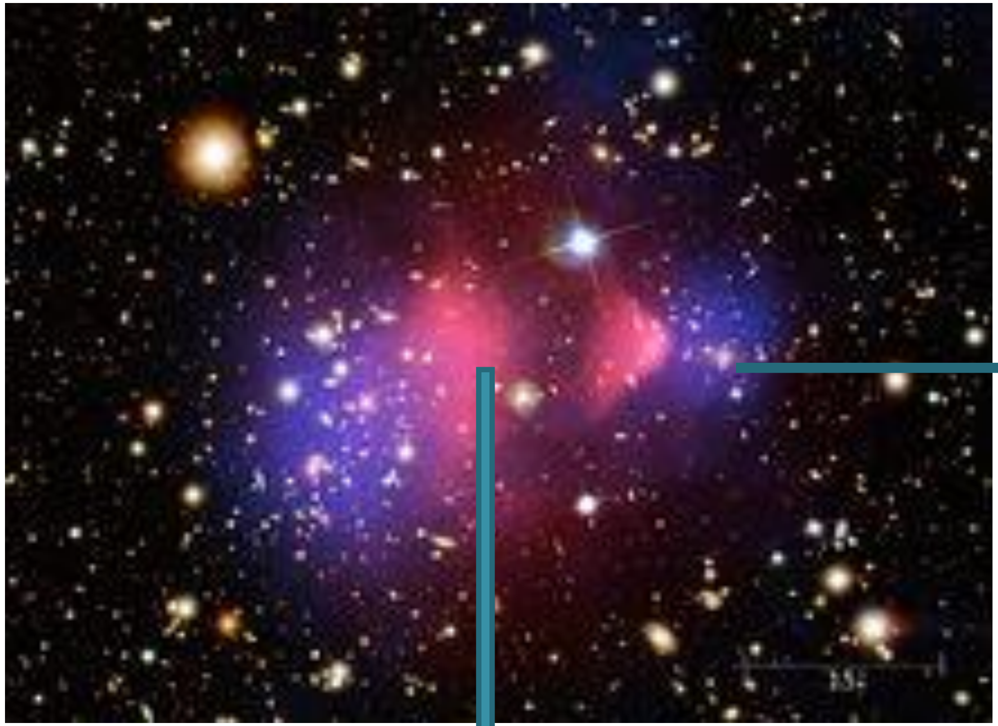
Section v gives a generalization of the principles of ordinary *statistical mechanics* to the whole system of nebulae, which suggests a new and powerful method which ultimately should enable us to determine the masses of all types of nebulae. This method is very flexible and is capable of many modes of application. It is proposed, in particular, to investigate the distribution of nebulae in individual great clusters.

As a first step toward the realization of the proposed program, the Coma cluster of nebulae was photographed with the new 18-inch Schmidt telescope on Mount Palomar.

Borrowed from Subir Sarkar

Evidence of DM in bullet cluster

(Collision of galaxies in Bullet cluster1E 0657-56)

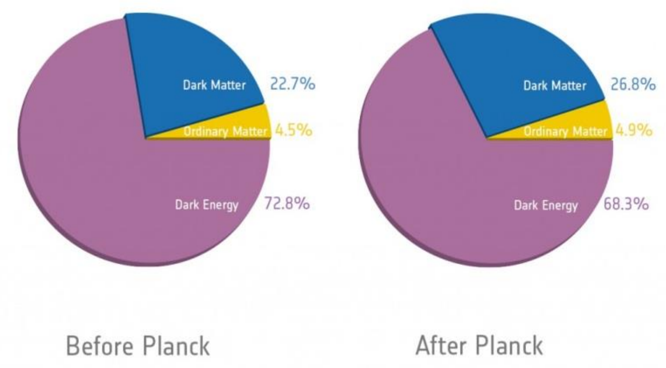


(Blue color) Dark matter seen through gravitational lensing and is found to be 7 times larger than baryonic mass.

Markevitch et.al, Astro Phy J, 2004

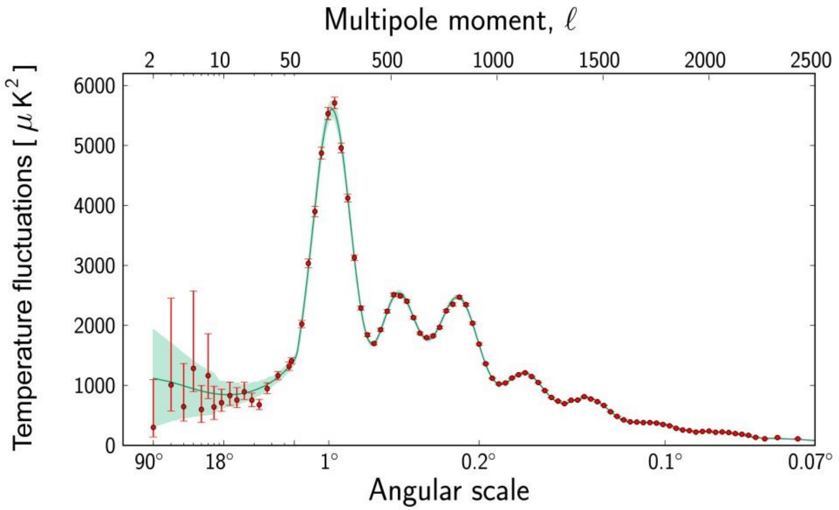
(Pink color) Hot gas seen through X-ray by Chandra X-ray observatory at the central part

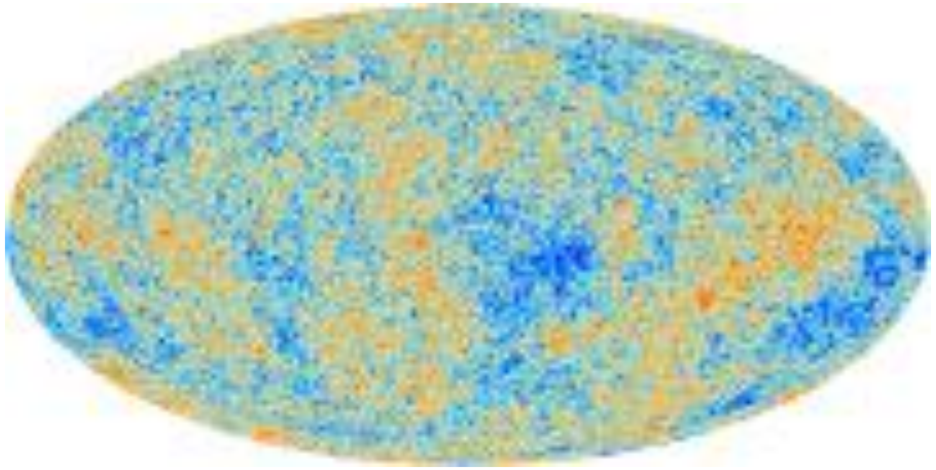
Evidence of DM in CMB



@WMAP(Wilkinson Microwave
Anisotropy Probe)

@ PLANCK 2013





Nature of Dark Matter…

From the astrophysical evidences of dark matter one infers that…

- ✓ DM should be a massive particle and hence interact gravitationally.
- ✓ It is electrically neutral and colorless. Therefore it could hide itself easily.
- ✓ It is stable on the cosmological time scale and therefore the large scale structure exists.

However,
We don't know …

Mass of DM= ?
Spin of DM= ?, Charge of DM= ?
Interaction apart from gravity ?
Relic abundance
(symmetric/asymmetric ?)

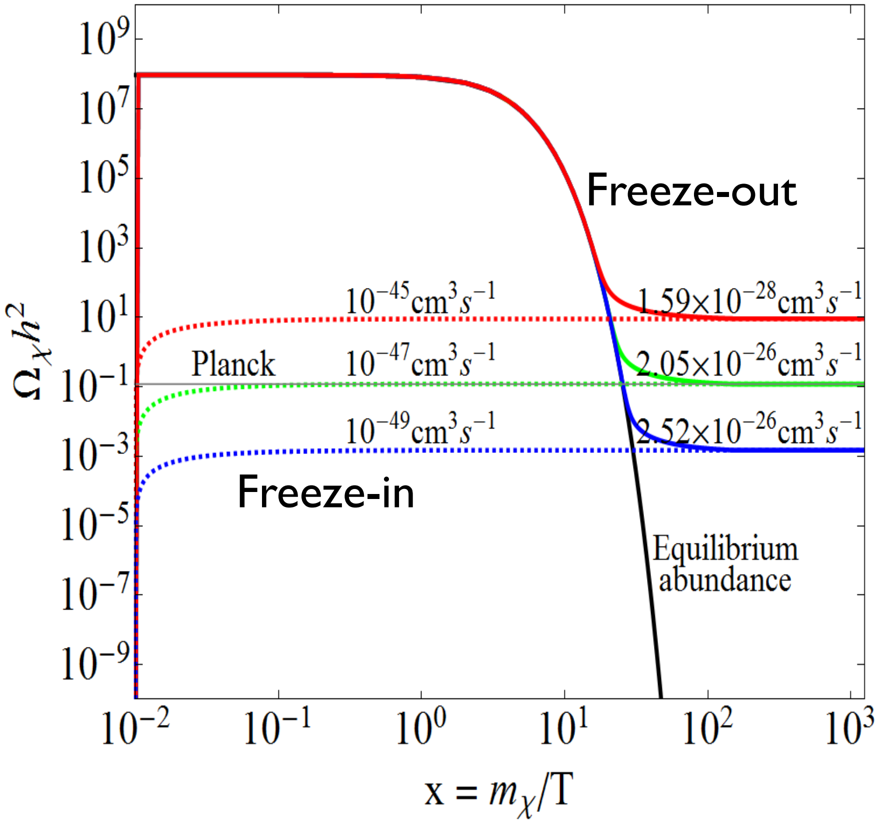
→ Many unanswered questions!

Q. How to probe the DM, which is required for the existence of our Universe ?

Is DM a WIMP (Gravity+ weak) ?

The DM is assumed to be in equilibrium in the early Universe via the weak interaction processes. As the temperature, due to expansion of the Universe, falls below the mass scale of DM, the latter gets freeze-out from the thermal bath and gives the correct relic abundance.

Steigman and Turner, 1984



$$\frac{dY_\chi}{dx} = \frac{-x\langle\sigma|v|\rangle s}{H(m_\chi)}(Y_\chi{}^2 - Y_{eq}{}^2)$$

$$Y_\chi = \frac{n_\chi}{s}, x = \frac{m_\chi}{T}$$

$$\Omega_{DM} h^2 = \frac{1.1\times 10^9 \, GeV^{-1} x_F}{g_*^{1/2} M_{pl} \langle \sigma | v | \rangle_F} = 0.1198 \pm 0.0026$$

Analytical estimation of a WIMP relic density

The observed relic abundance of DM by WMAP and PLANCK

$$< \sigma | v | >|_F \approx 3\times 10^{-26} cm^3 / \sec \approx 2.6\times 10^{-9} GeV^{-2}$$

$$\approx O(10^{-36}) cm^2$$

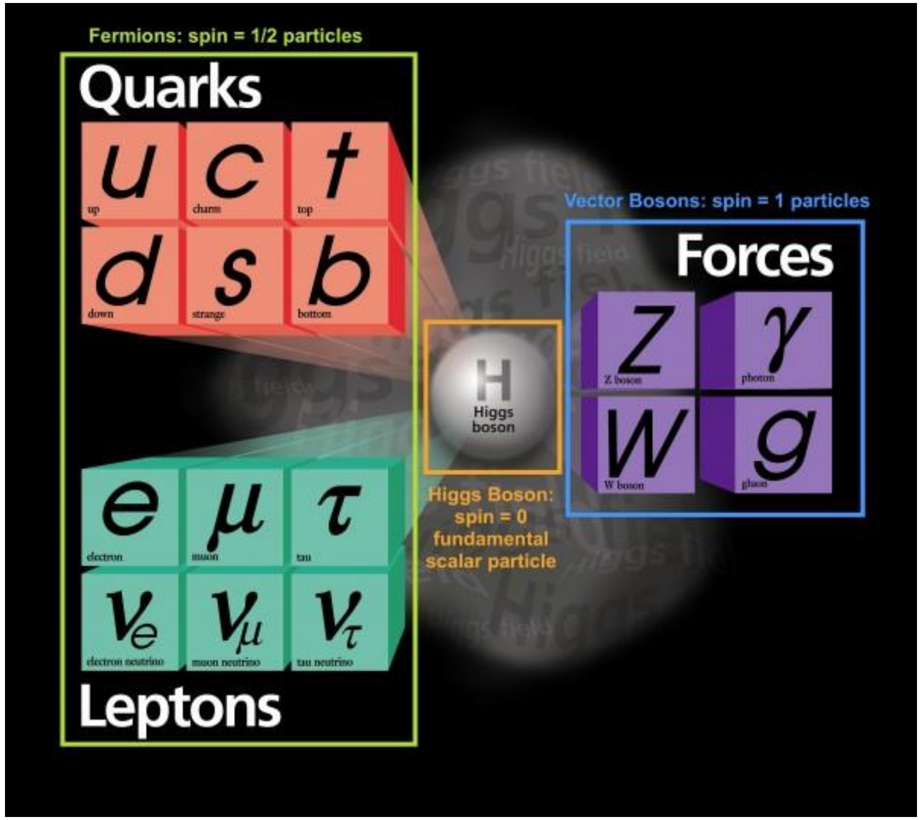
Which is typically a weak interaction cross-section.

WIMP Miracle

Therefore one believes that DM could be a WIMP.

Dark matter:
The Physics beyond the SM ?

DM: The physics beyond the SM



The only particles in SM which seem to satisfy some properties of DM are neutrinos:

$$\Omega_\nu h^2 = \frac{\sum m_\nu}{91.5eV} \approx 0.0024$$

$$<< \Omega_{DM} h^2$$

Cowsik and McClelland, PRL 1972

So, we need to look for a candidate of DM in the beyond standard model of particle physics, which is probably heavy (> a few GeV).

Lee and Weinberg, PRL 1977

General Strategy for DM physics

$$\mathcal{L}_{new} = \mathcal{L}_{SM} + \mathcal{L}_{DM} + \mathcal{L}_{DM\text{-}SM}$$

Constraints

(1) DM should satisfy the relic density constraint from WMAP and PLANCK
(2) DM must satisfy the direct detection constraint from latest expts like Xenon-1T and LZ and others
(3) DM should be stable in the cosmological time scale.

Look for predictions at indirect and collider search experiments without disturbing the SM physics.

Large number of possibilities, such as scalar, fermion and vectors… →Any stable particle with hypercharge, Y=0 can be a viable candidate of DM. For a particle with non-zero Y, one has to struggle to validate at DD experiments.

Dark Matter Zoo

Thermal Relics …

WIMP DM
FIMP DM
SIMP DM
Axion DM
Sterile neutrino DM
Self-Interacting DM
…..

Asymmetric DM

DM + Anti-DM

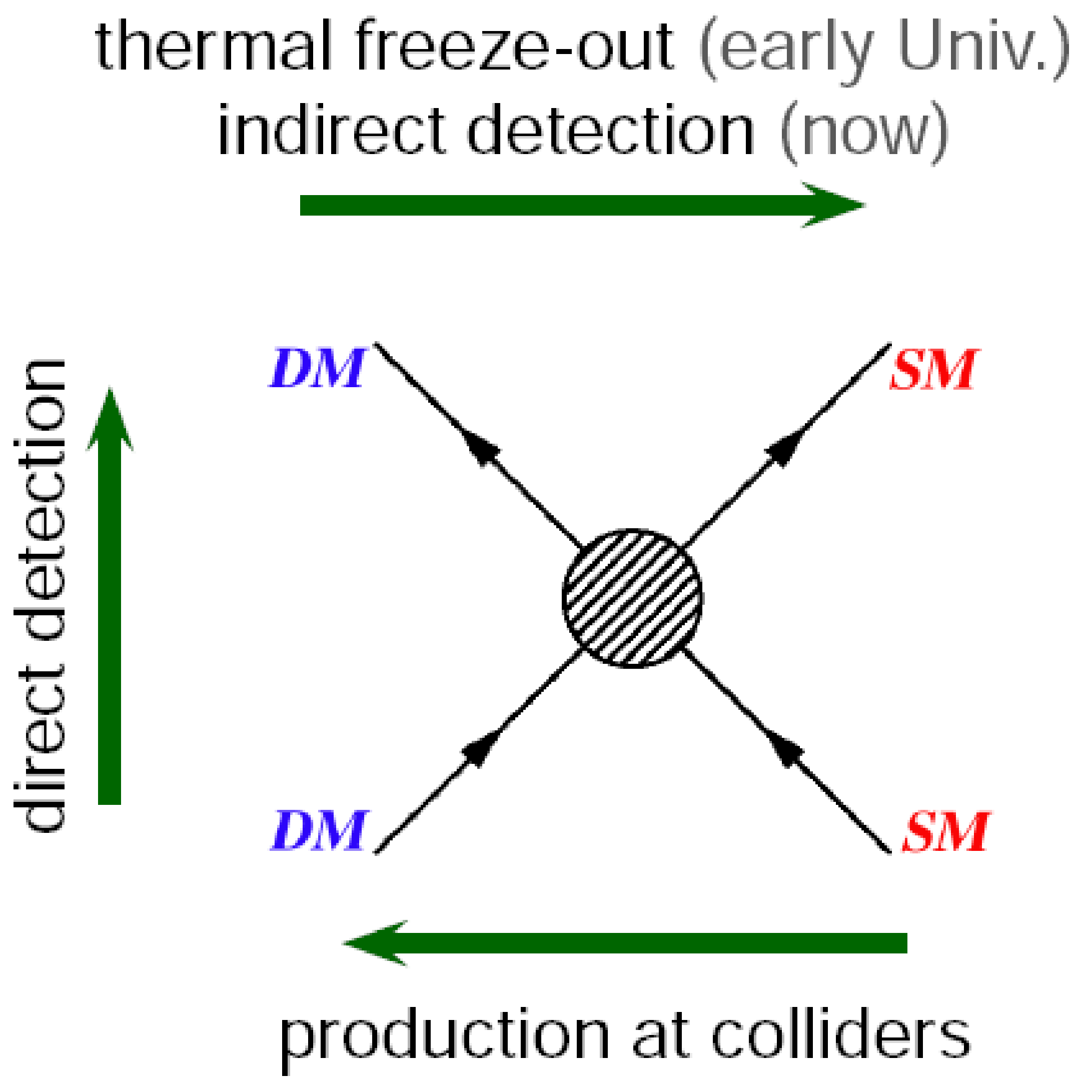
=

Energy

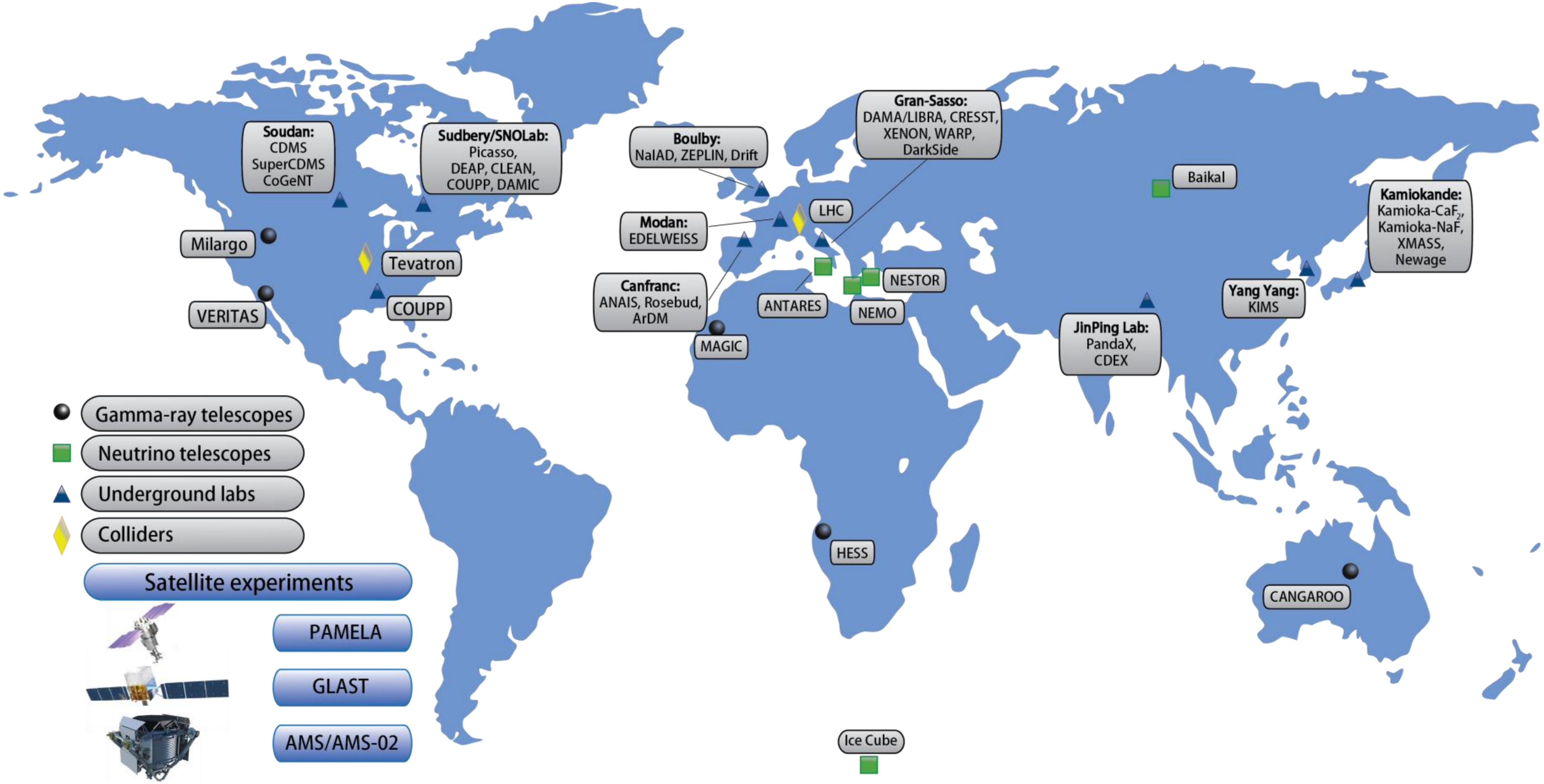
+

Net survival DM

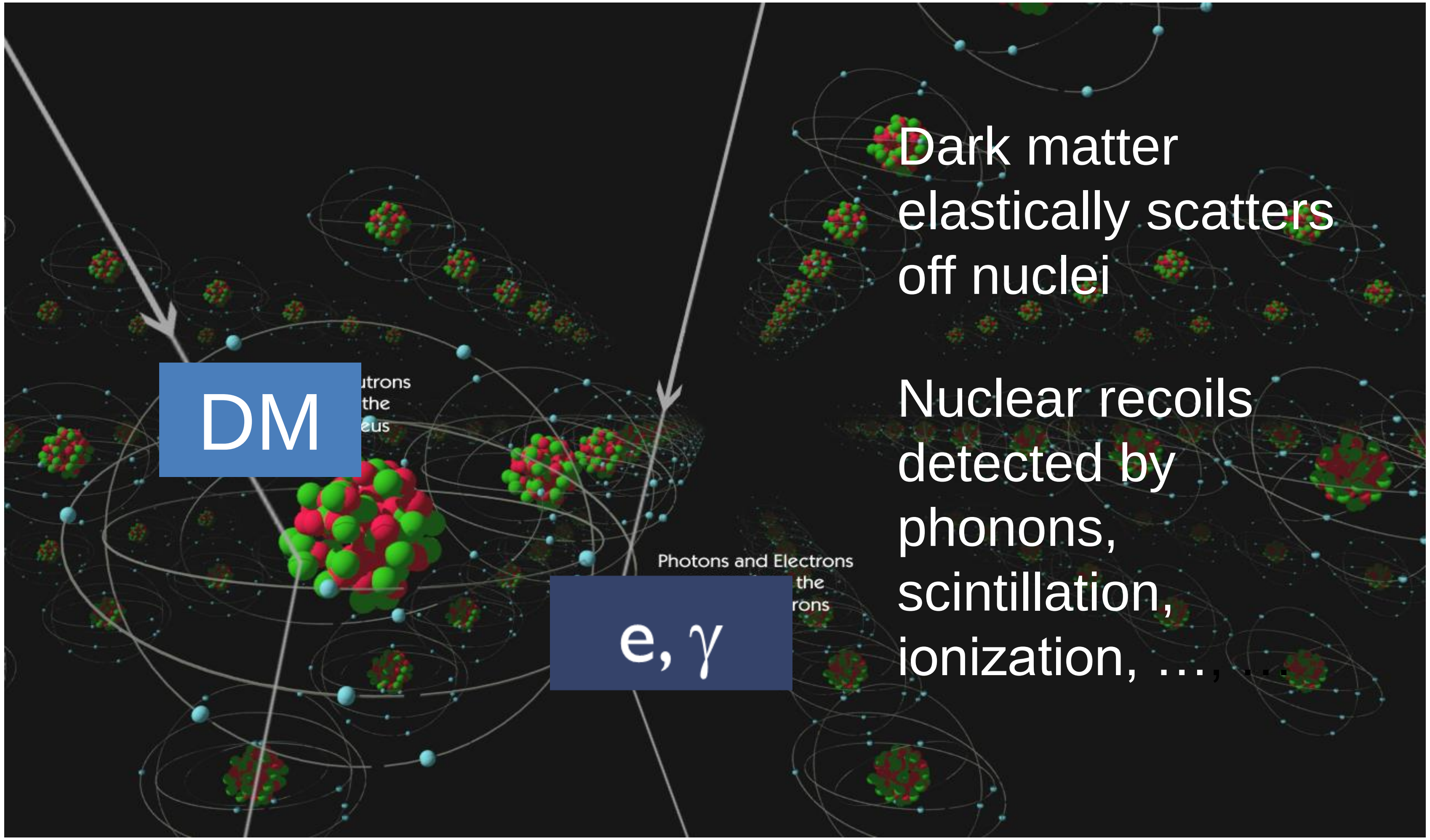
Testing a WIMP DM Hypothesis



DM search experiments in the world



Strategy for direct search of DM



Master formula for DM detection

The total number of dark matter particles detected in a terrestrial experiment

$$N = t\,(nv)(N_T\sigma) \qquad n = \frac{\rho}{m_\chi} \qquad N_T = \frac{M_T}{m_N}$$

M_T (Detector mass)

m_N (Nucleus mass)

Exposure time (t)

DM flux=number density of DM (n) x speed (v)

Effective area of target= Number of target nuclei x DM-nucleus cross-section

But the experiment detects the spectrum of DM recoils, i.e., Energy dependence of the number detected DM particles. So, the quantity of interest is

$$\frac{dN}{dE_R} = t\,n\,v\,N_T\,\frac{d\sigma}{dE_R}$$

The DM velocity is not unique in the vicinity of the detector. So need a distribution function to calculate the DM detection rate:

$$\frac{dN}{dE_R} = t\, n\, N_T \int_{v_{min}}^{v_{esc}} v\, \frac{d\sigma}{dE_R} f(\vec{v})\, d\vec{v}$$

$$\int_{v_{min}}^{v_{esc}} f(\vec{v}) d\vec{v} = 1$$

The minimum speed required to produce a DM recoil:

$$v_{min} = \sqrt{m_\chi E_R / 2\mu_{\chi N}^2}$$

$$\mu_{\chi N} = \frac{m_\chi m_N}{m_\chi + m_N}$$

If we define the experimental exposure: $\epsilon = t M_T$ then the DM detection rate can be expressed as

$$\frac{dN}{dE_R} = \epsilon \frac{\rho}{m_\chi\, m_N} \int_{v_{min}} v f(\vec{v})\, \frac{d\sigma}{dE_R}\, d\vec{v}$$

For light nuclei the DM particle sees the nucleus as a whole, while for bigger nucleus the DM sees the substructure, which can be taken into account by using a form factor. As a result the differential scattering cross-section becomes

$$\frac{d\sigma}{dE_R} = \frac{m_N}{2\mu_{\chi N}} \frac{\sigma_0}{v^2} F^2(E_R)$$

Finally we get a DM detection rate:

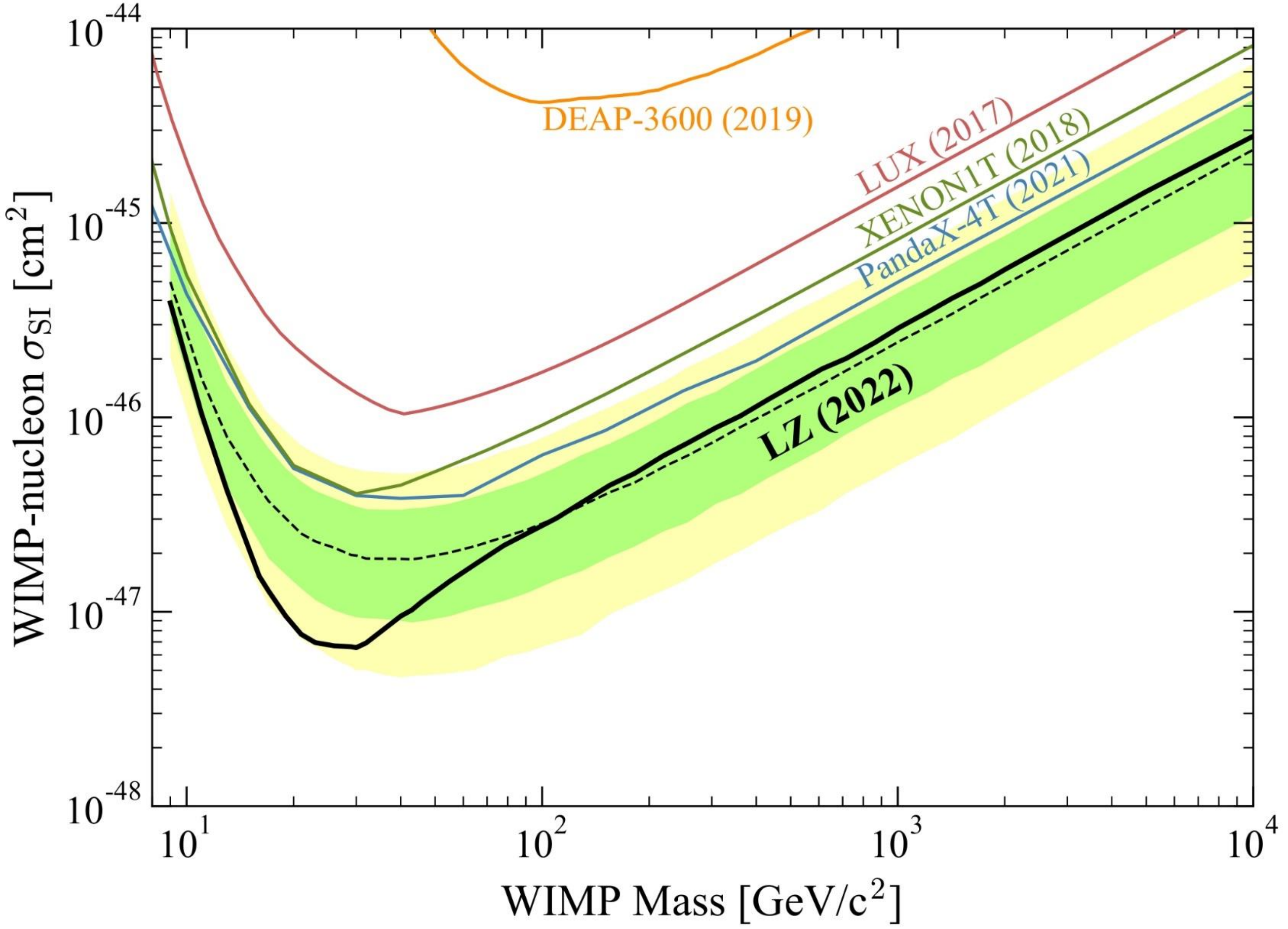
$$\frac{dN}{dE_R} = \epsilon \frac{\rho}{2\, m_\chi\, \mu_{\chi N}} \sigma_0\, F^2(E_R) \int_{v_{min}} \frac{f(\vec{v})}{v}\, d\vec{v}\,.$$

Similarly we will get background for each experiment: $\dfrac{dN_{bkg}}{dE_R}$

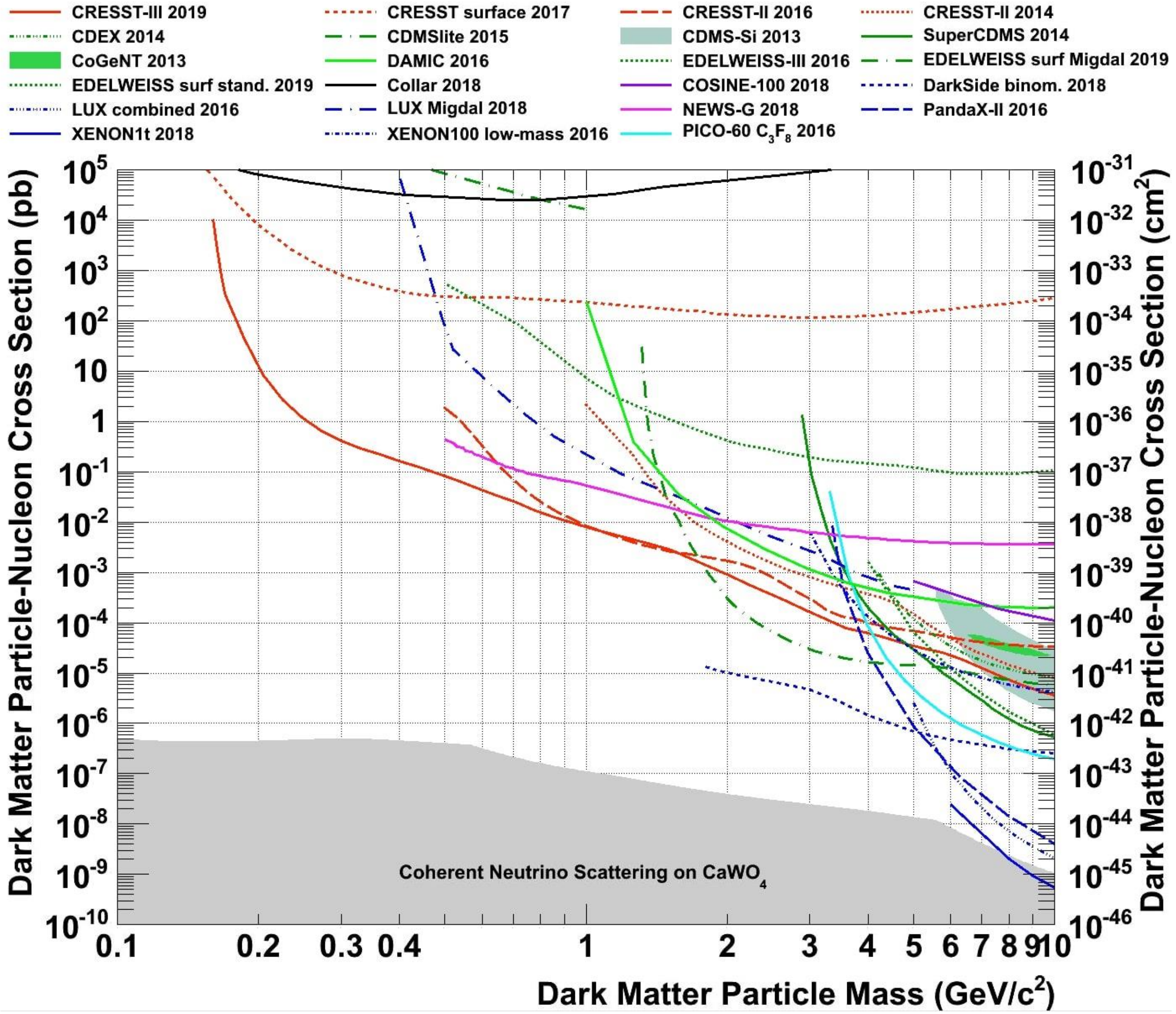
$$\frac{dN_{est}}{dE_R} = \frac{dN}{dE_R} + \frac{dN_{bkg}}{dE_R}$$

This has to be compared with the experimental result to give an exclusion plot in the plane of cross-section versus mass of dark matter.

Exclusion limits from direct search dark matter experiments (heavy mass particles)

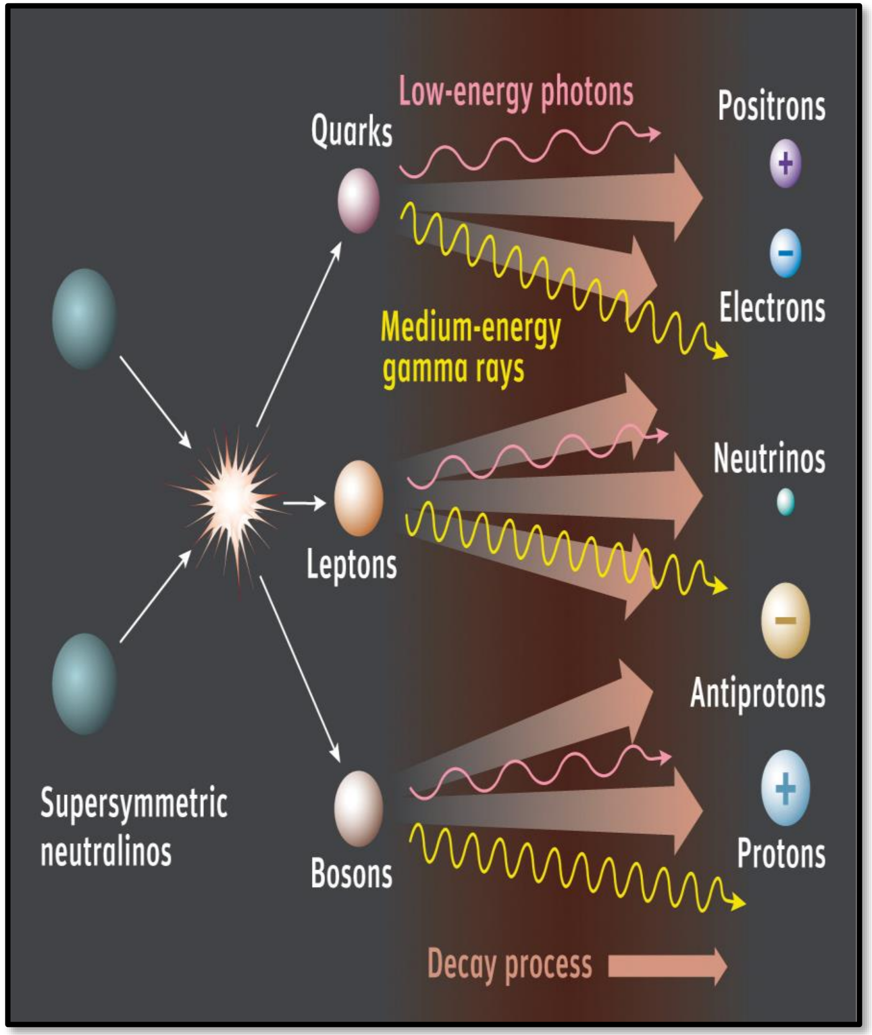


Exclusion limits from direct search dark matter experiments (light mass particles)



Strategy for Indirect search of DM

- Dark matter may pair annihilate in our galactic neighborhood to
  - Photons
  - Neutrinos
  - Positrons
  - Anti-protons
  - Anti-deuterons



- The relic density provides a target annihilation cross section

$\langle \sigma_A v \rangle \sim 3 \times 10^{-26}\ cm^3/s$

Example: Working formula for positron flux

Assume that the positrons are produced in the centre of galaxy and then propagates to us through the galactic magnetic field. The evolution of positron number density per unit energy $f(t, \vec{x}, E)$ obeys the diffusion equation:

$$\frac{\partial f}{\partial t} - K(E) \cdot \nabla^2 f - \frac{\partial}{\partial E}\left(b(E) f\right) = Q$$

Source term

Diffusion coefficient

Energy loss coefficient due to synchrotron radiation + inverse Compton scattering on CMB photon

Moskalenko & Strong, Astrophys, J493, 694, 1998(Galprop code)

The source tei

$$Q = \frac{1}{2}\left(\frac{\rho}{M_{\rm DM}}\right)^2 f_{\rm inj}, \qquad f_{\rm inj} = \sum_k \langle\sigma v\rangle_k \frac{dN^k_{e^+}}{dE}$$

Particle physics

In a steady state a semi-analytical formula for positron flux is given by:

$$\Phi_{e^+}(E, \vec{r}_\odot) = B \frac{v_{e^+}}{4\pi b(E)} \frac{1}{2} \left(\frac{\rho_\odot}{M_{\rm DM}} \right)^2 \int_E^{M_{\rm DM}} dE' \ f_{\rm inj}(E') \cdot I\left(\lambda_D(E, E')\right)$$

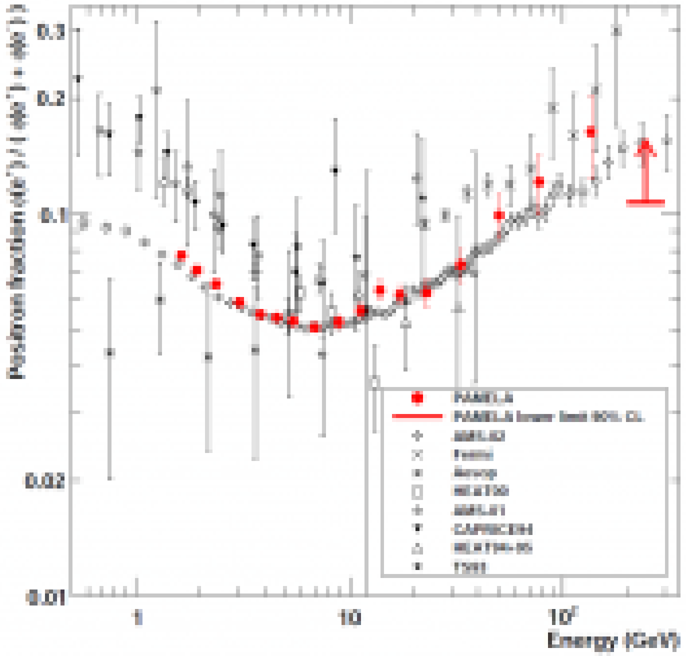
T. Delahaye et.al. (0712. 2312)
Hisano et.al. (hep-ph/0511118)

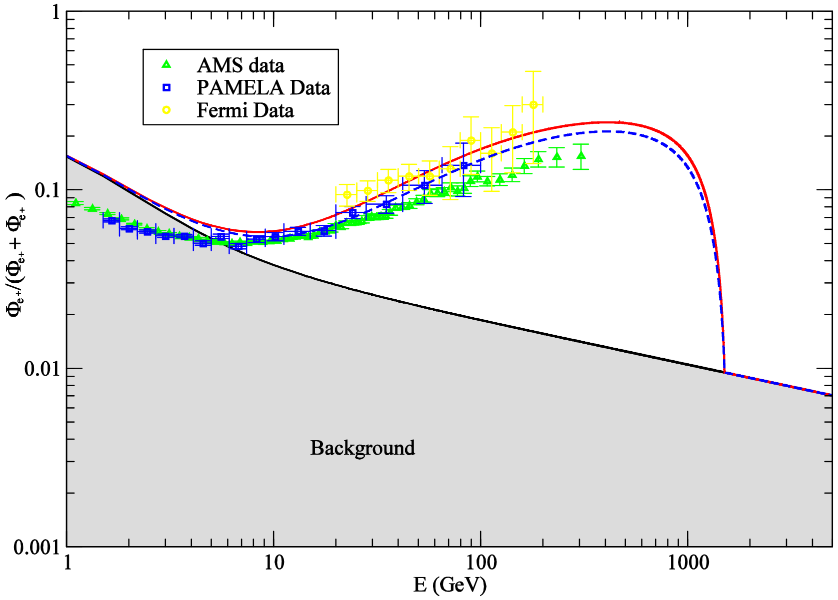
Particle Physics ($f_{\rm inj}$) — Astro physics (I)

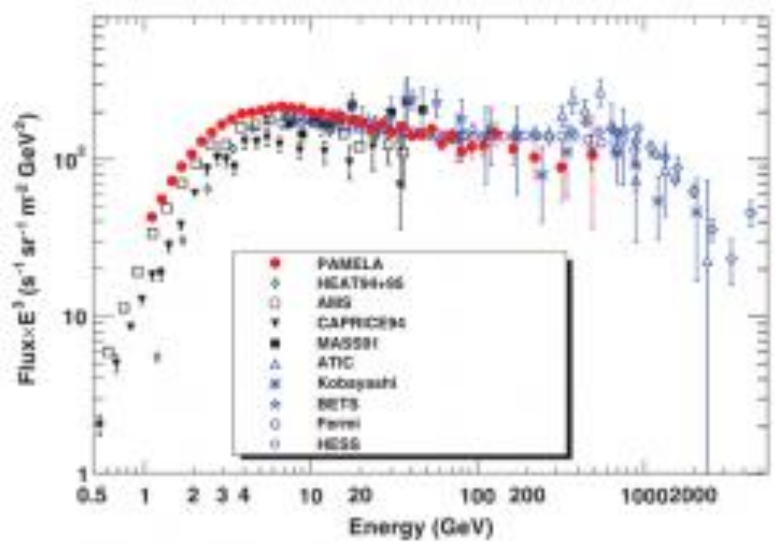
The astrophysics part can be reproduced with a fitting function:

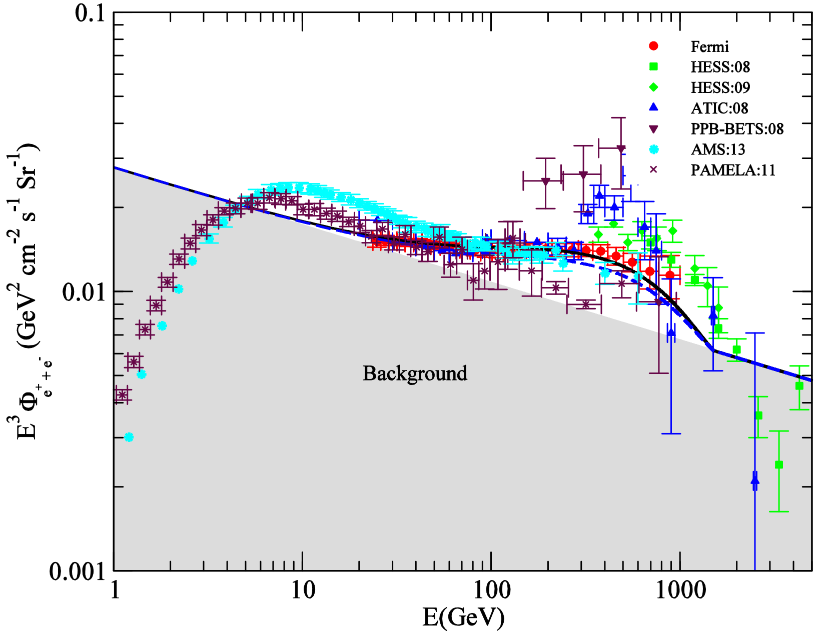
$$I(\lambda_D) = a_0 + a_1 \tanh\left(\frac{b_1 - \ell}{c_1} \right) \left[a_2 \exp\left(-\frac{(\ell - b_2)^2}{c_2} \right) + a_3 \right]$$

Marco Cirelli et.al. 0802.3378

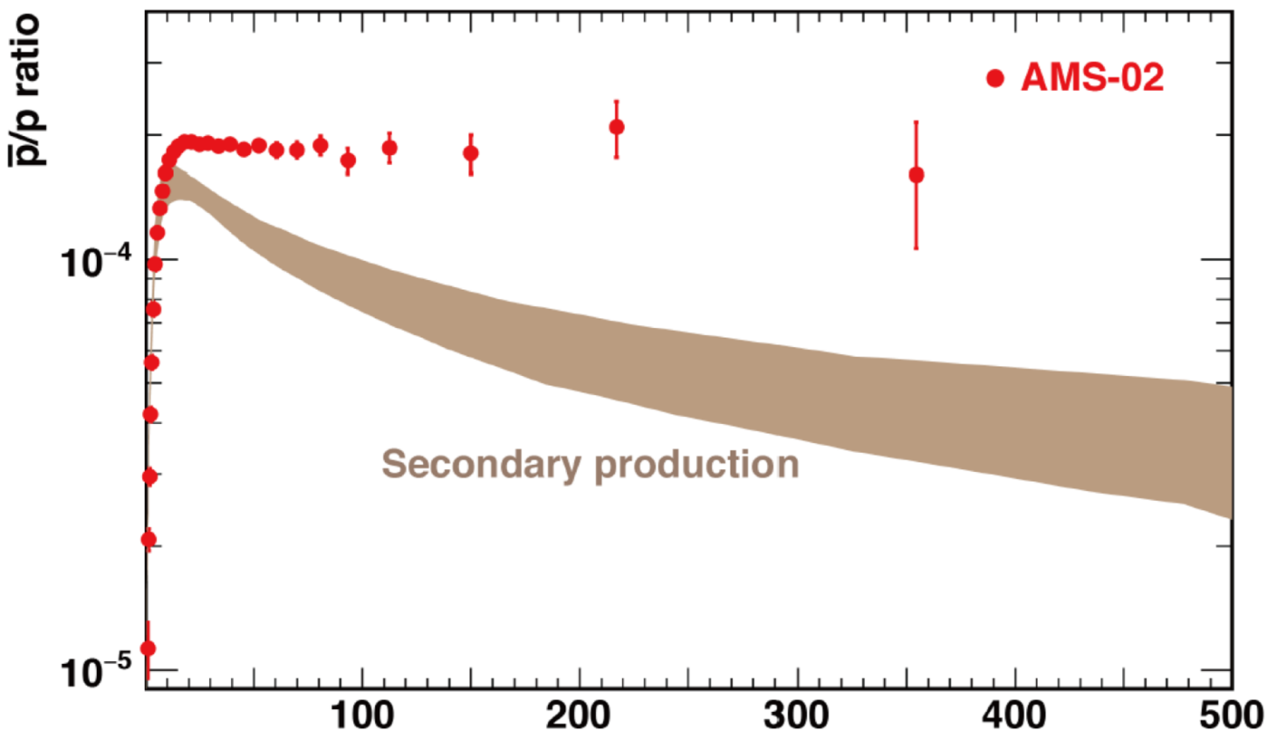

Positron fraction
Energy (GeV)
PAMELA
PAMELA lower limit 90% CL
Fermi
HEAT00
CAPRICE94
HEAT94+95


AMS data
PAMELA Data
Fermi Data
Background
E (GeV)


PAMELA
HEAT94+95
AMS
CAPRICE94
MASS91
ATIC
Kobayashi
BETS
Fermi
HESS
Energy (GeV)

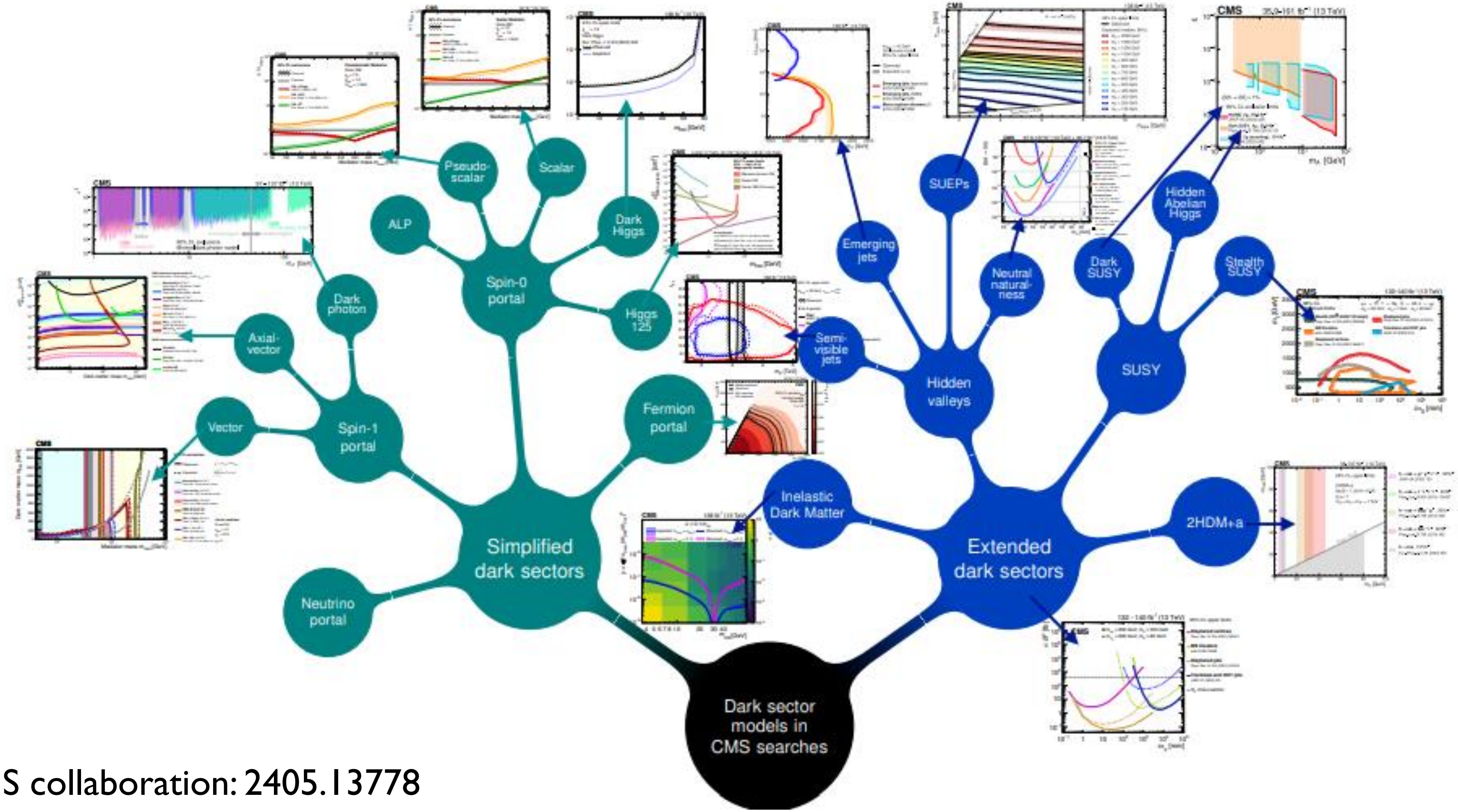

Fermi
HESS:08
HESS:09
ATIC:08
PPB-BETS:08
AMS:13
PAMELA:11
Background
E(GeV)

AMS-02, 2014



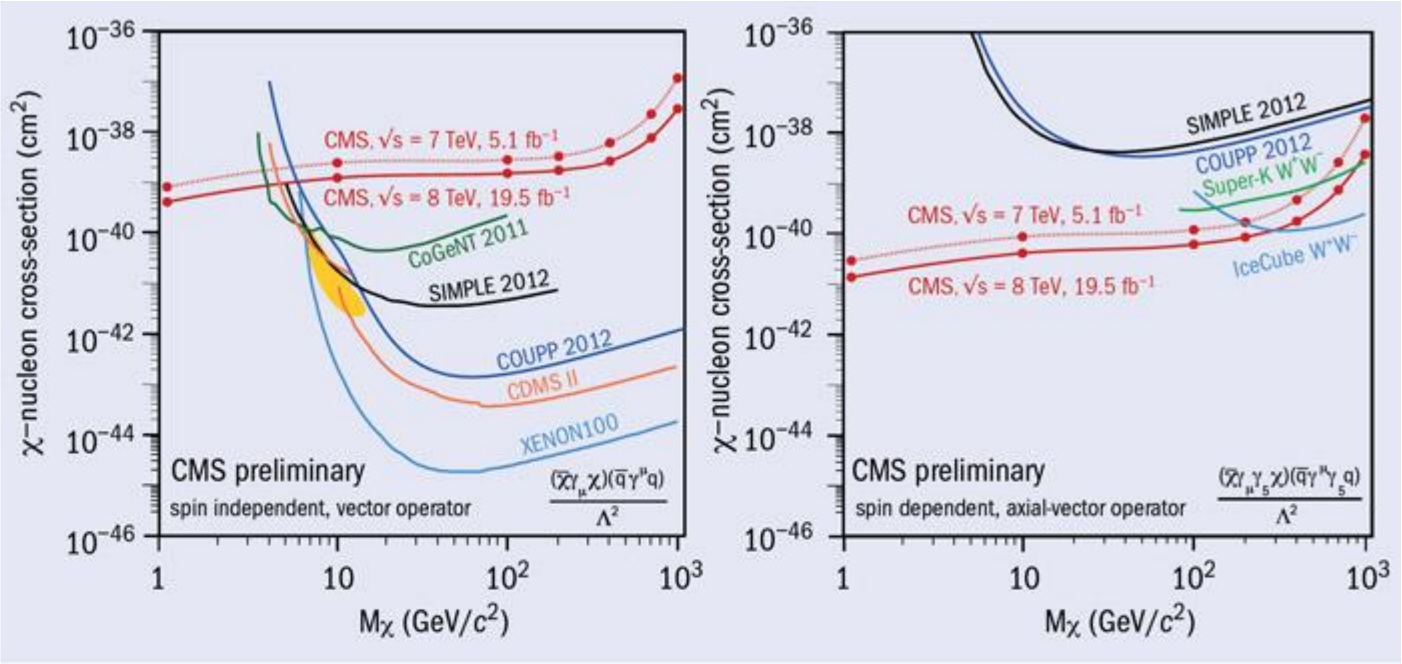
Hints for anti-proton excess ?

Collider search of dark matter



CMS collaboration: 2405.13778

CMS Search of DM at 7 TeV COM - Energy

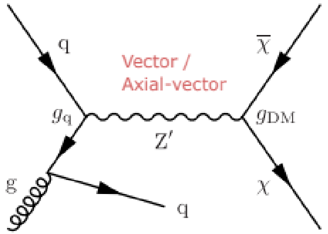


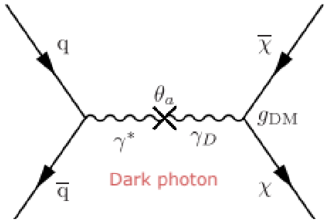
Note: Collider experiments constraint the DM mass more in the low energy region, where the direct detection experiments are not competitive.

Dark sector searches with CMS experiment

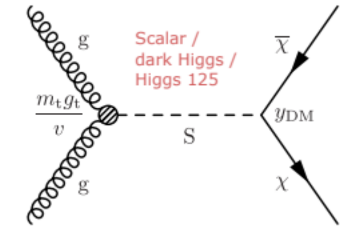
Simplified dark sectors

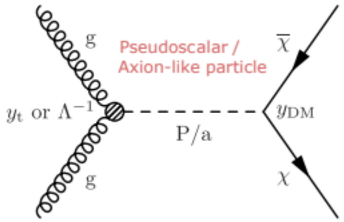
Spin-1 portal



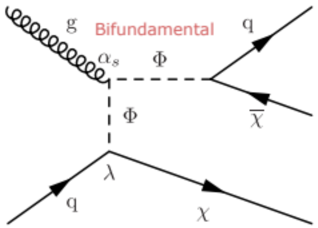


Spin-0 portal



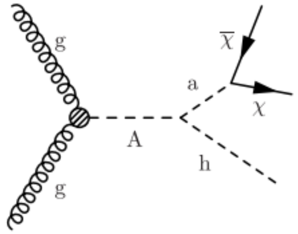


Fermion portal

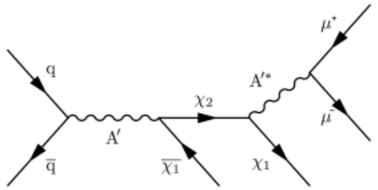


Extended dark sectors

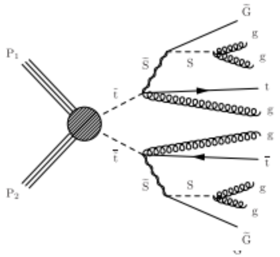
2HDM+a



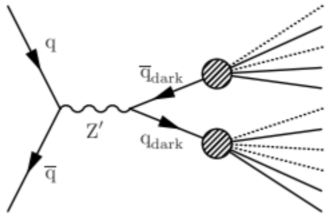
Inelastic Dark Matter

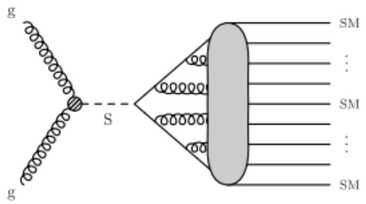


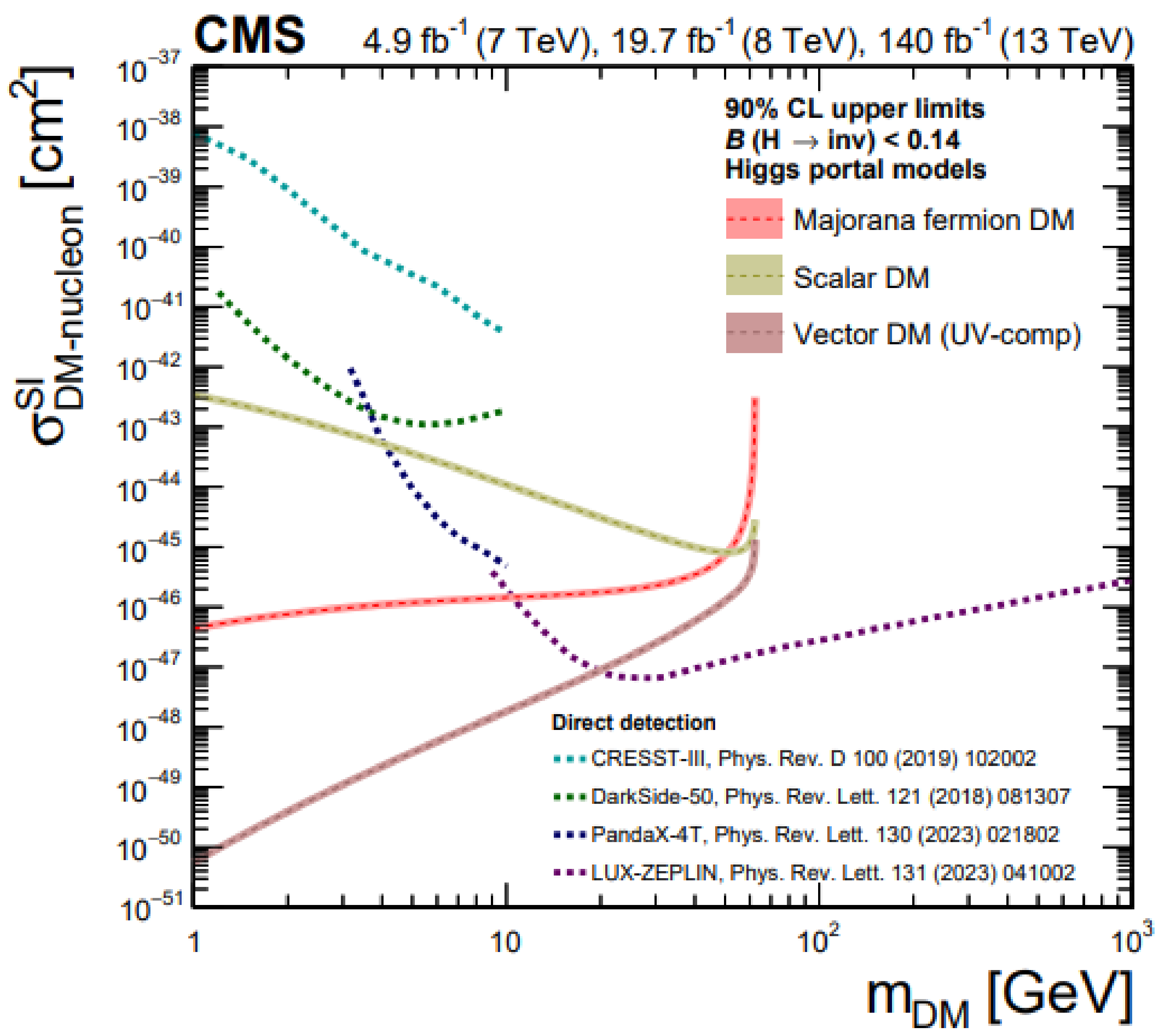
Stealth SUSY



Hidden valleys

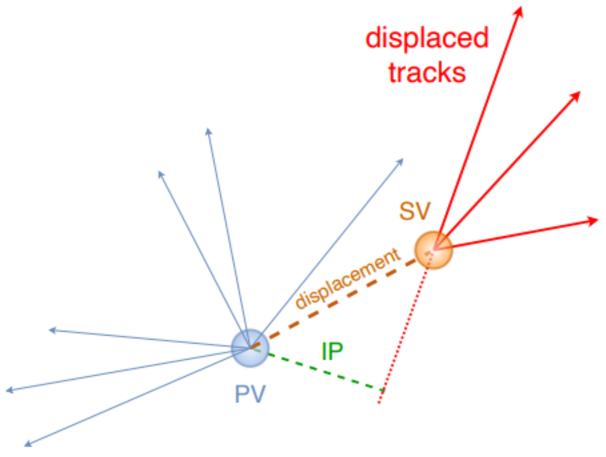


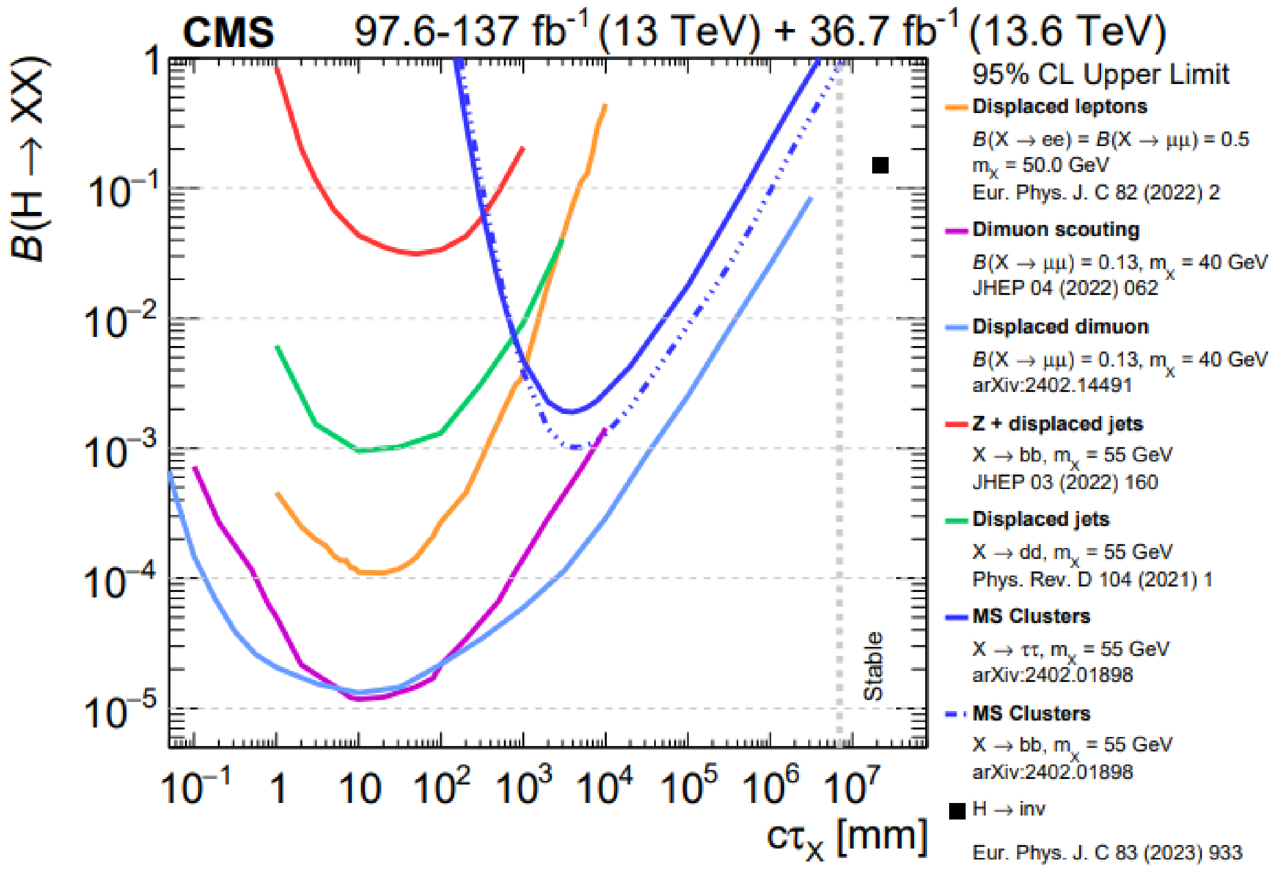




CMS
4.9 fb-1 (7 TeV), 19.7 fb-1 (8 TeV), 140 fb-1 (13 TeV)
90% CL upper limits
B (H → inv) < 0.14
Higgs portal models
Majorana fermion DM
Scalar DM
Vector DM (UV-comp)
Direct detection
CRESST-III, Phys. Rev. D 100 (2019) 102002
DarkSide-50, Phys. Rev. Lett. 121 (2018) 081307
PandaX-4T, Phys. Rev. Lett. 130 (2023) 021802
LUX-ZEPLIN, Phys. Rev. Lett. 131 (2023) 041002
σSI DM-nucleon [cm2]
mDM [GeV]

Long lived particle search through displaced vertex





Higgs decaying to long lived particle with mass varies between 40 – 55 GeV

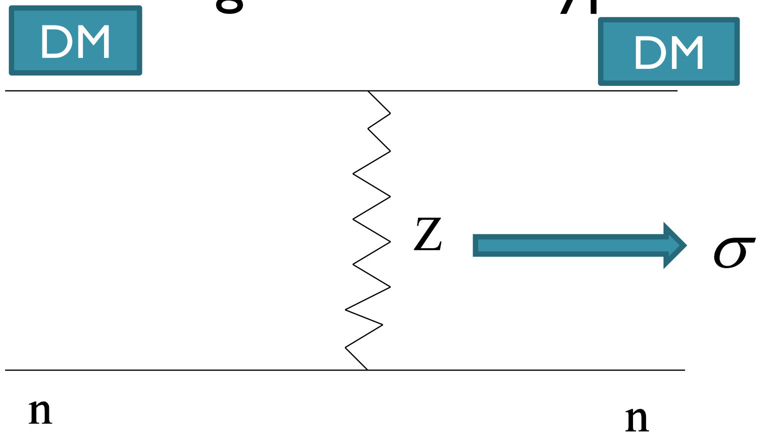
Theoretical modeling of dark matter….

Particle Physics Models

Aim: To find a viable particle physics model for DM content of the Universe…

The two important points that should be considered while building models of dark matter:

(1) The hyper charge $Y = 2(Q - T_3)$ of the additional field multiplet should be zero for elastic dark matter, so that large Z-boson mediated direct detection cross-section can be avoided. If $Y \neq 0$ then the large direct detection cross-section can be avoided by making it inelastic type.

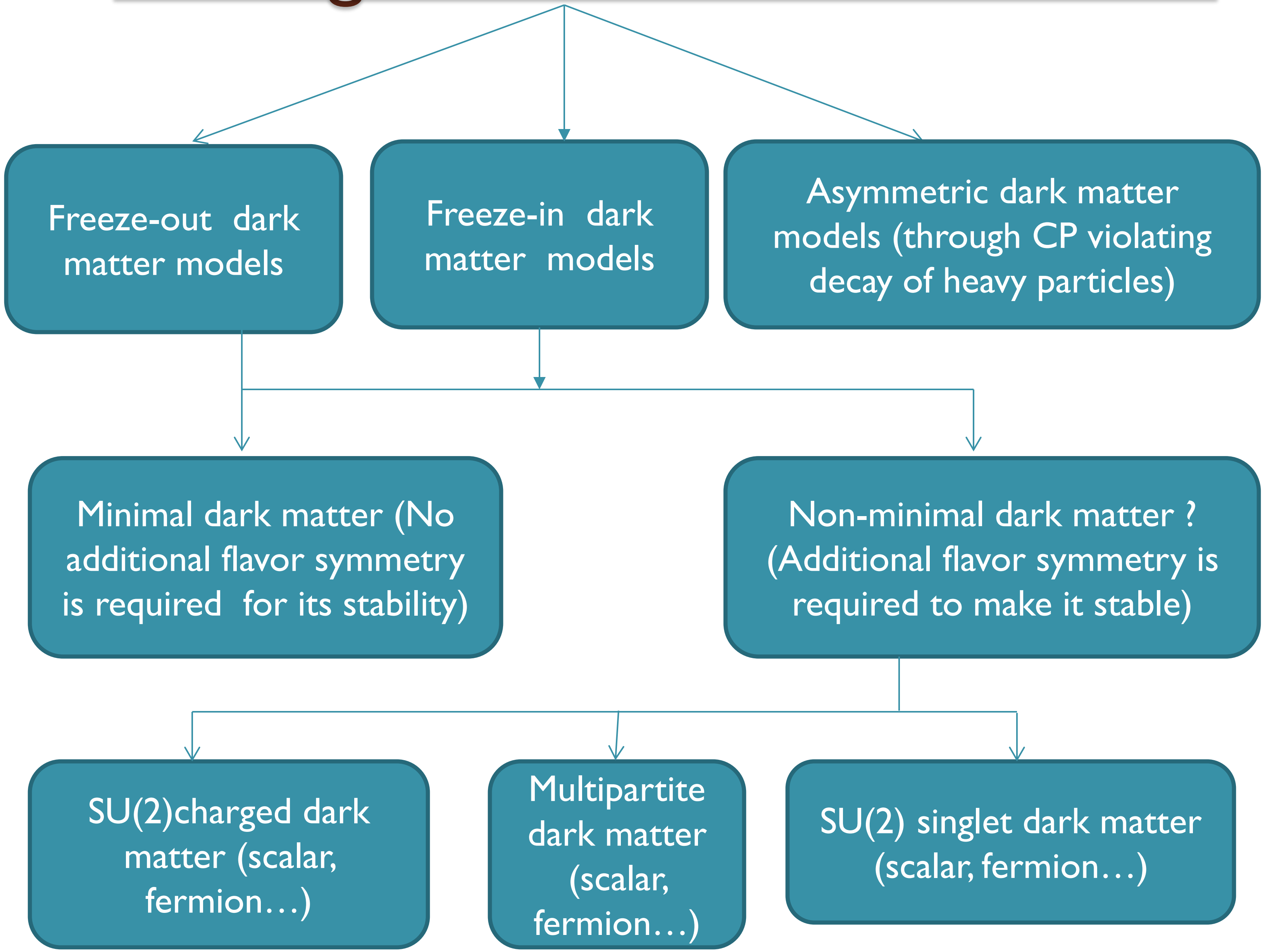


$\longrightarrow \quad \sigma \approx O(10^{-38})cm^2$

Excluded by DD

(2) The additional field should be stable by itself or should be made stable by adding additional flavor/gauge symmetry.

Catalogue of Dark matter models



Part-II (models of dark matter)

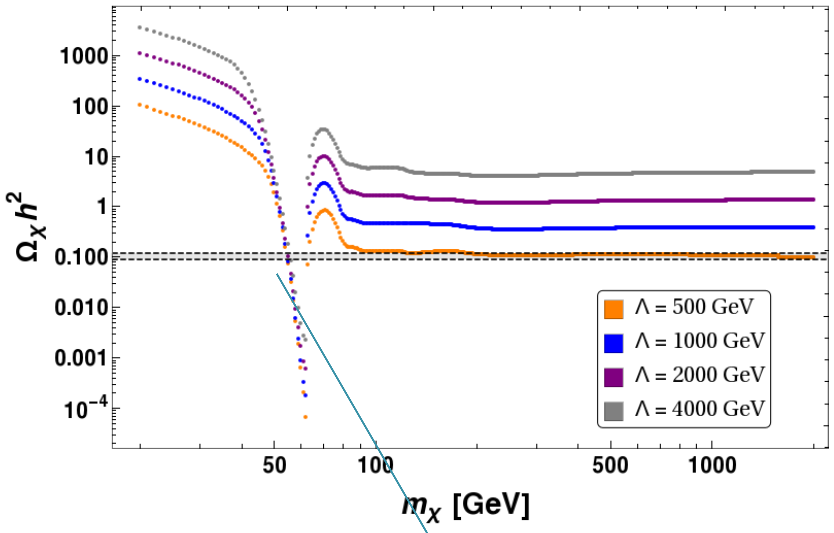
Examples of dark matter models…

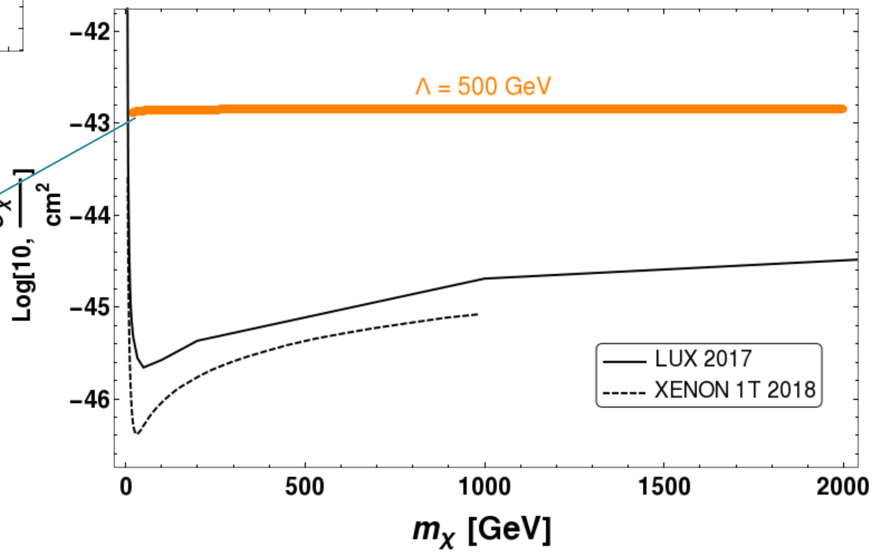
Weakly interacting vector-like lepton as dark matter

S. Bhattacharya, Nirakar Sahoo and **N. Sahu**, PRD93, 2016
S. Bhattacharya, S Patra, Nirakar Sahoo, **N.Sahu**, JCAP 1606, 2016
S. Bhattacharya, Nirakar Sahoo and **N. Sahu**, PRD96, 2017
S. Bhattacharya, Purusottam Ghosh, Nirakar Sahoo and **N. Sahu**, 1812.06505

Vector-like Singlet fermion DM

$$\mathcal{L}_{DM} = \bar{\chi}(i\gamma^{\mu}\partial_{\mu} - m_{\chi})\chi - \frac{1}{\Lambda}\left(H^{\dagger}H - \frac{v^2}{2}\right)\bar{\chi}\,\chi$$

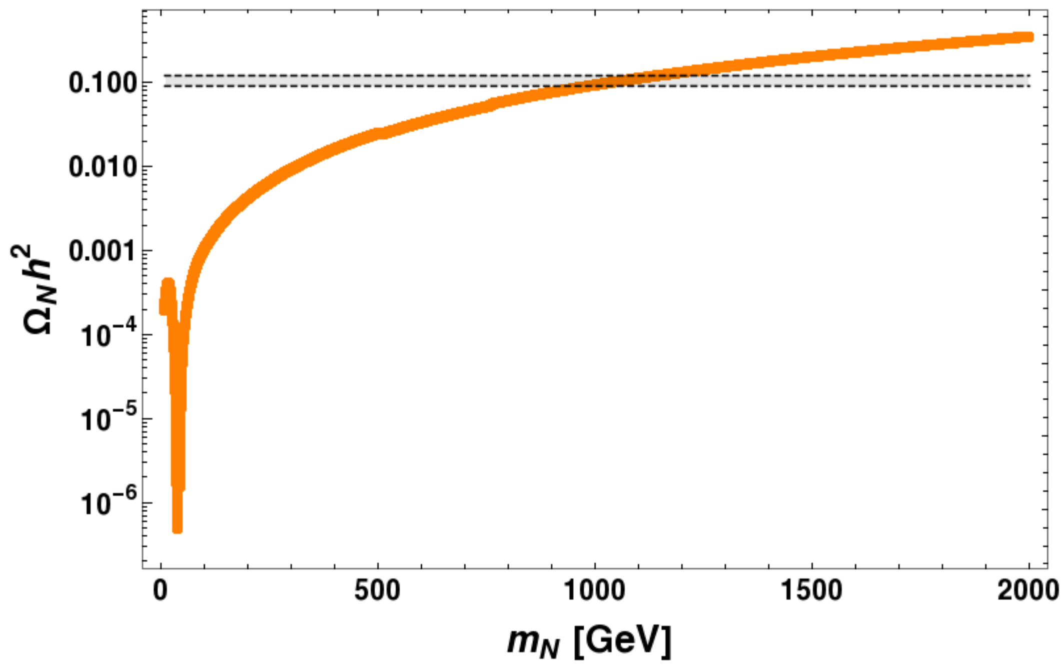


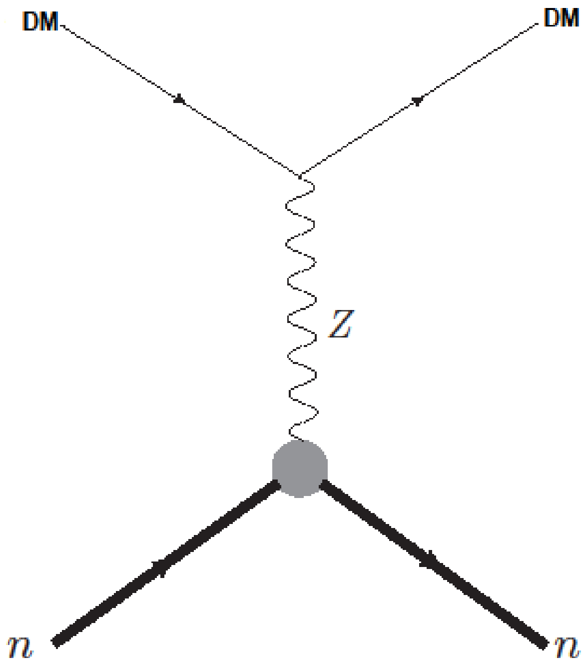


Allowed zone of valid DM

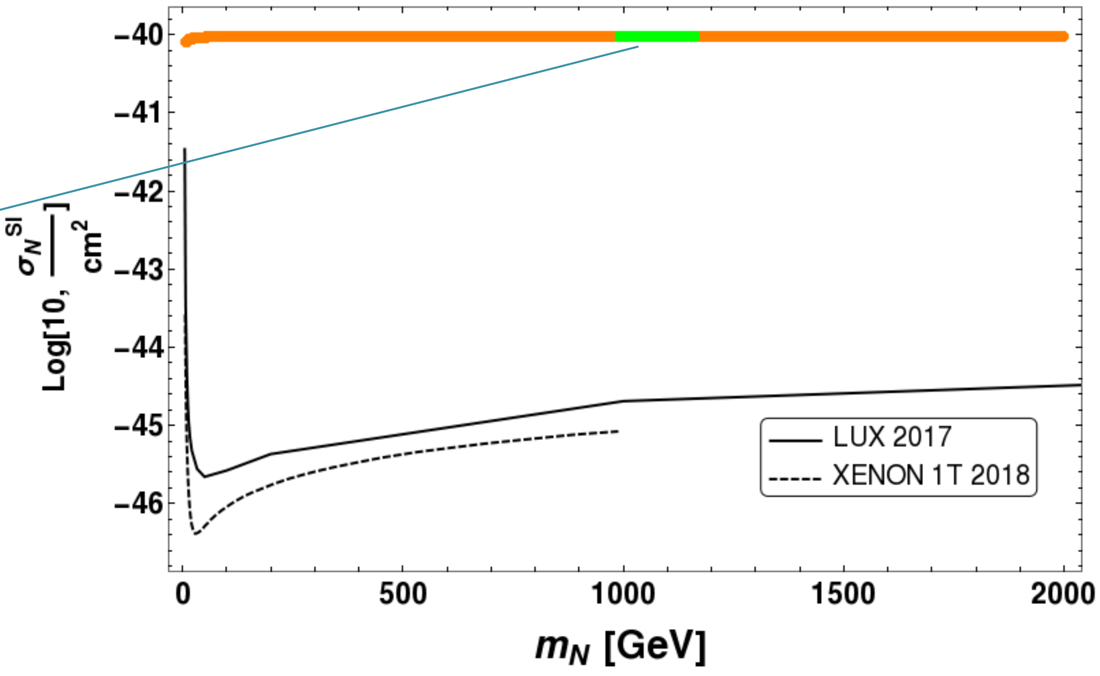
Vector-like Inert lepton doublet DM

$$\mathcal{L}_{DM} = \bar{N}(i\gamma^{\mu} D_{\mu} - m_N)\mathrm{N}$$





Inert lepton doublet DM alone is ruled out by direct search



Singlet-Doublet mixed Fermion DM

We overcome the problem of small relic abundance by introducing a vector-like singlet fermion χ^0, which mixes with the neutral component of the doublet fermion and decreases the annihilation cross-section. As a result we get the correct relic abundance.

$$\mathcal{L}_{DM} = M_N \overline{N} N + M_\chi \overline{\chi^0} \chi^0 + [Y \overline{N} \tilde{H} \chi^0 + h.c.]$$
$$+ \overline{N} i\gamma^\mu D_\mu N + \overline{\chi^0} i\gamma^\mu \partial_\mu \chi^0$$

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

Bhattacharya, Sahoo, Sahu, PRD 93, 2016, Bhattacharya, karmakar, Sahu, Sil, JHEP 2017, Bhattacharya, Sahoo and Sahu, PRD 96 (2017), Bhattacharya, Ghosh, Sahoo and Sahu, Front. In. Physics (2019), Dutta, Bhattacharya, Ghosh and Sahu, JCAP 03 (2021), Borah, Mahapatra and Sahu, PLB 831 (2022)

Singlet-Doublet mixed Fermion DM

Under Z_2 symmetry both χ^0 and N are odd. As a result the DM emerges as a mixture of singlet fermion χ^0 and the neutral component of the vector-like doublet fermion N.

After EW phase transition the mass matrix for neutral vector-like fermions is given by

$$\begin{pmatrix} \overline{N^0} & \overline{\chi^0} \end{pmatrix} \begin{pmatrix} M_N & m_D \\ m_D & M_\chi \end{pmatrix} \begin{pmatrix} N^0 \\ \chi^0 \end{pmatrix}$$

Where $m_D = Y < H >$

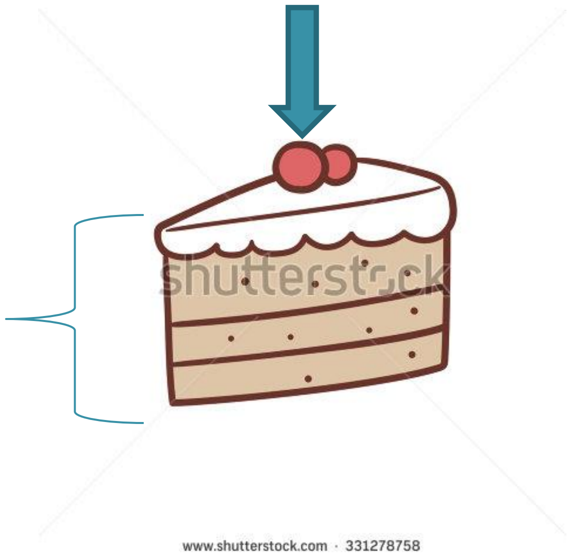
$$M_1 = M_\chi - \frac{m_D^2}{M_N - M_\chi}; N_1 = \cos\theta\chi^0 + \sin\theta N^0$$

$$M_2 = M_N + \frac{m_D^2}{M_N - M_\chi}; N_2 = \cos\theta N^0 - \sin\theta\chi^0$$

$$M^\pm = M_1 \sin^2\theta + M_2 \cos^2\theta = M_N; N^\pm$$

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

The lightest particle is the N_1, which is candidate of dark matter with appropriate mixing angle θ



$sin\theta \leq 0.1$ → From exclusion of direct detection of dark matter

$\sin\theta \geq O(10^{-5})$ → NLSP decay before the DM freezes out, so that no over production of dark matter

We will scan the parameter space within the given range of singlet-doublet mixing:

$$10^{-5} < \sin\theta < 0.1$$

Note: However, in case of Majorana singlet-doublet DM, the mixing angle can be as large as 0.5.

Dutta, Bhattacharya, Ghosh and Sahu, JCAP03, 008, 2021

Relic density of mixed Fermion DM

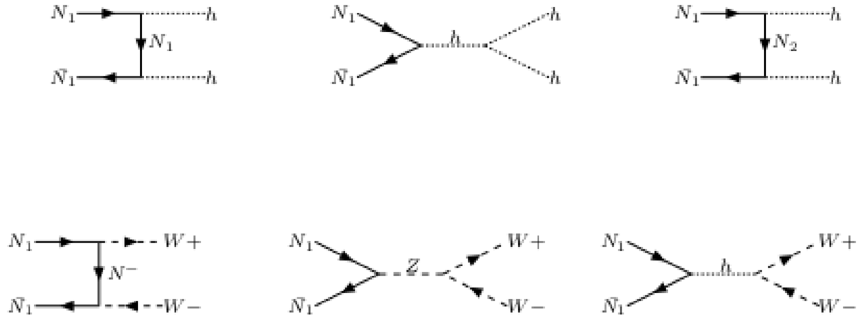
$$\Omega_{N_1} h^2 = \frac{1.09\times 10^9}{g_*^{1/2}(M_{pl}/GeV)}\frac{1}{J(x_f)}$$

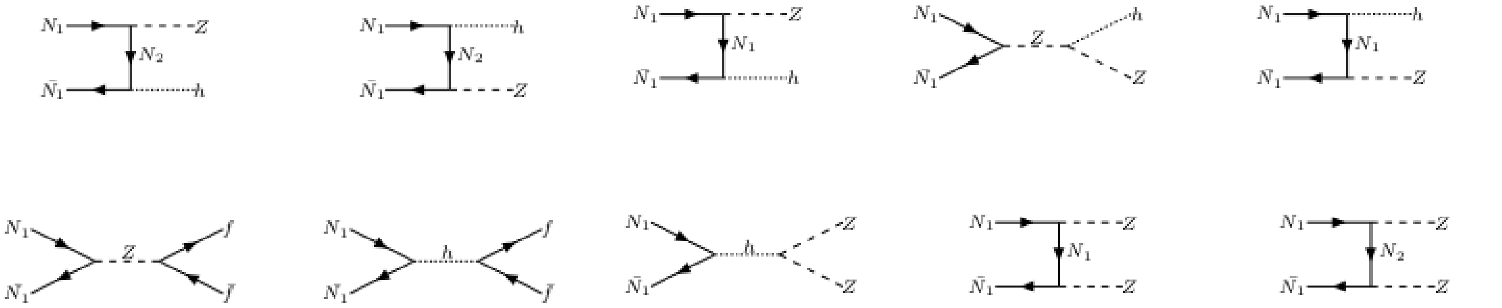
$$J(x_f) = \int_{x_f}^{\infty} \frac{\langle \sigma |v| \rangle_{eff}}{x^2} dx$$

Griest and Secklel: PRD 1991

Annihilation processes

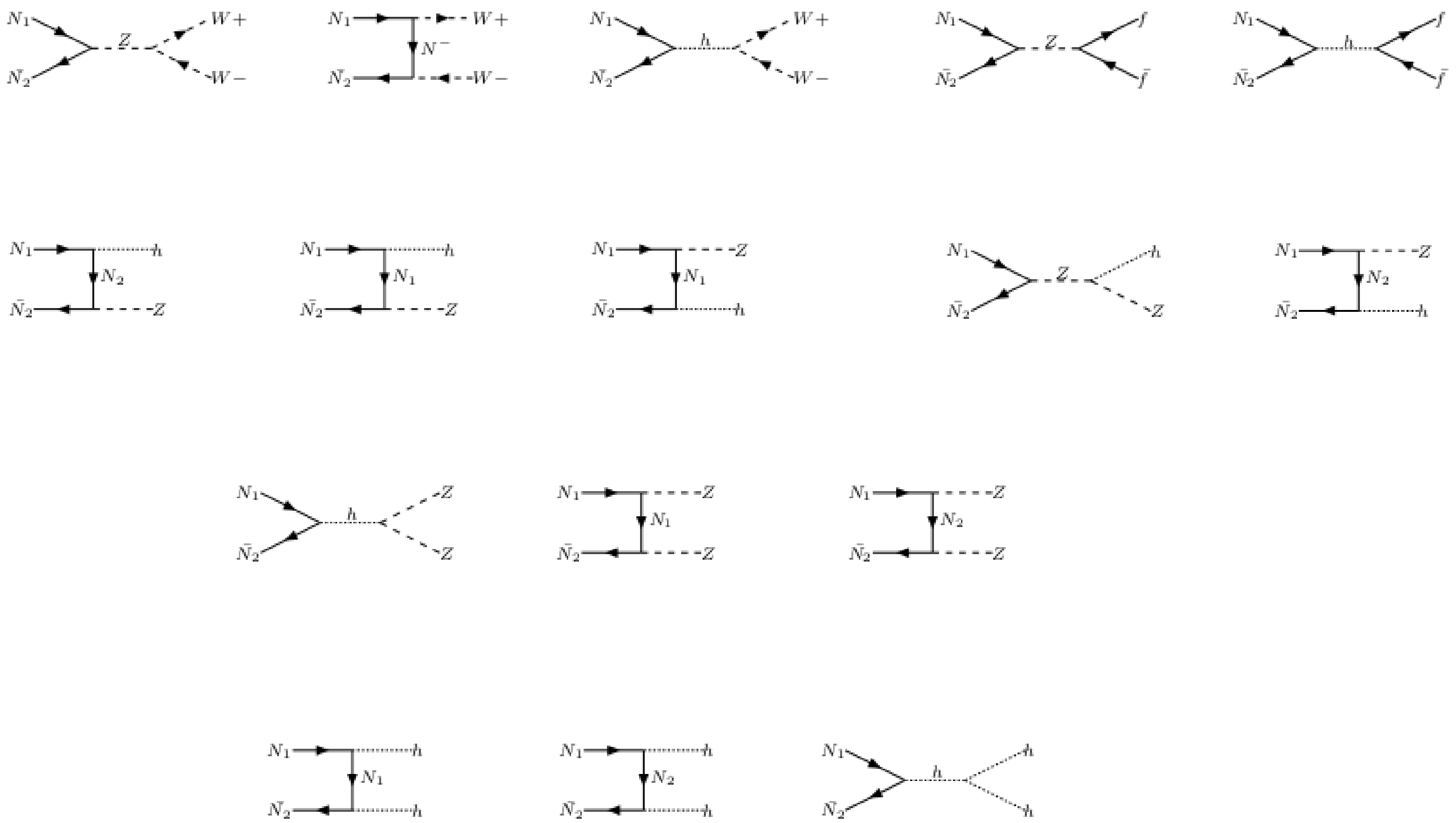
$$N_1 \overline{N_1} \rightarrow SM$$





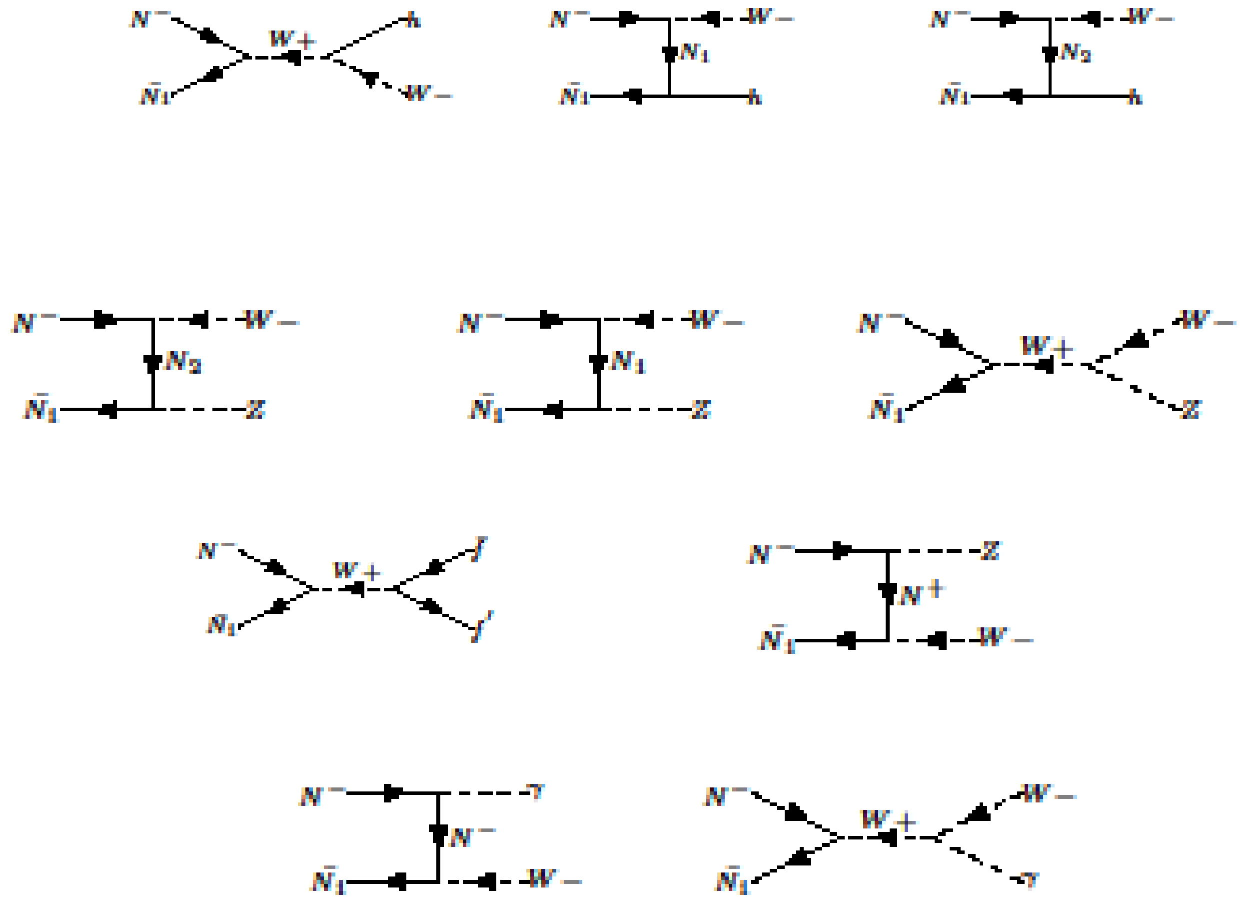
Co-annihilation process

$$N_1 N_2 \to SM$$



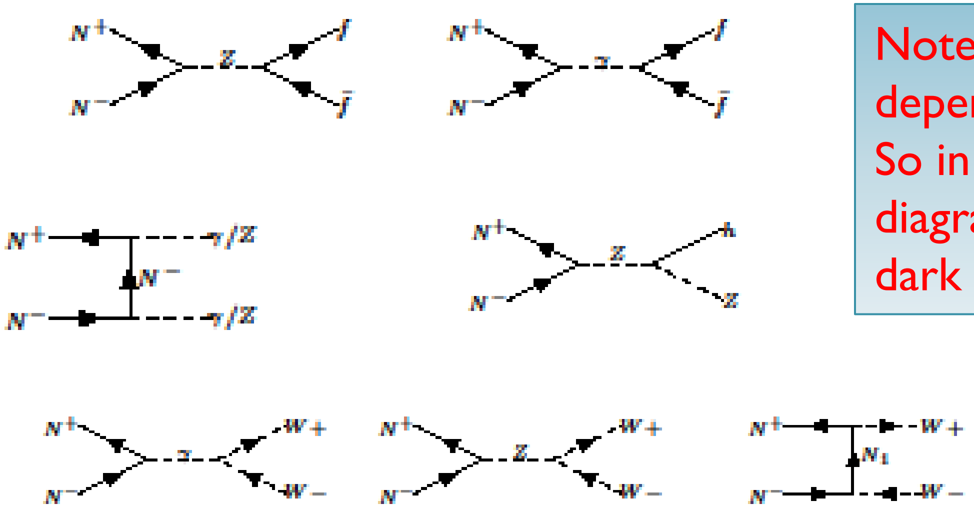
Co-annihilation process

$$N_1 N^- \rightarrow SM$$



Co-annihilation process

$$N^+N^- \to SM$$

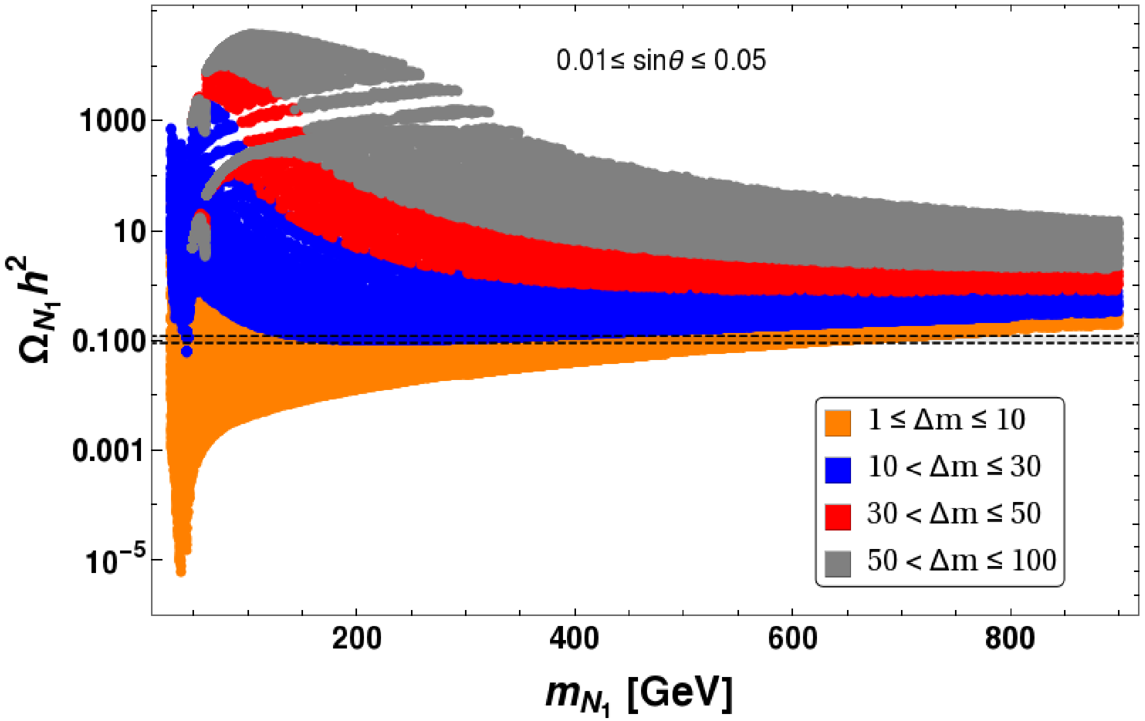


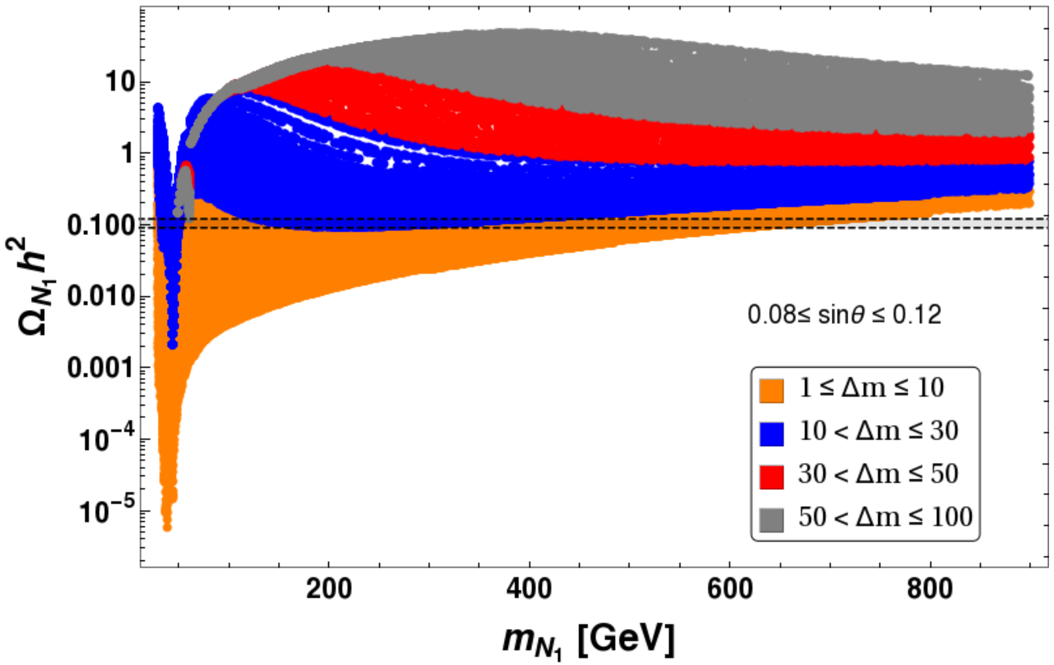
Note: These diagrams don't depend on singlet-doublet mixing. So in the small mixing limit these diagrams give relic abundance of dark matter.

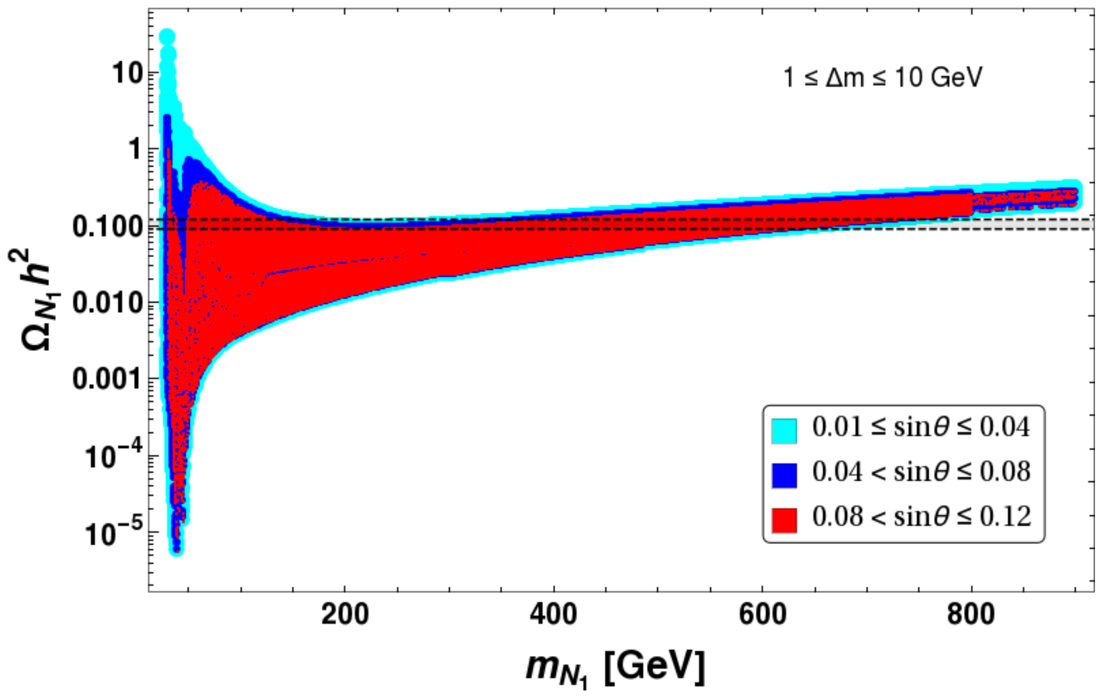
Note: There are many additional channels in presence of the scalar triplet, which we have not drawn here.

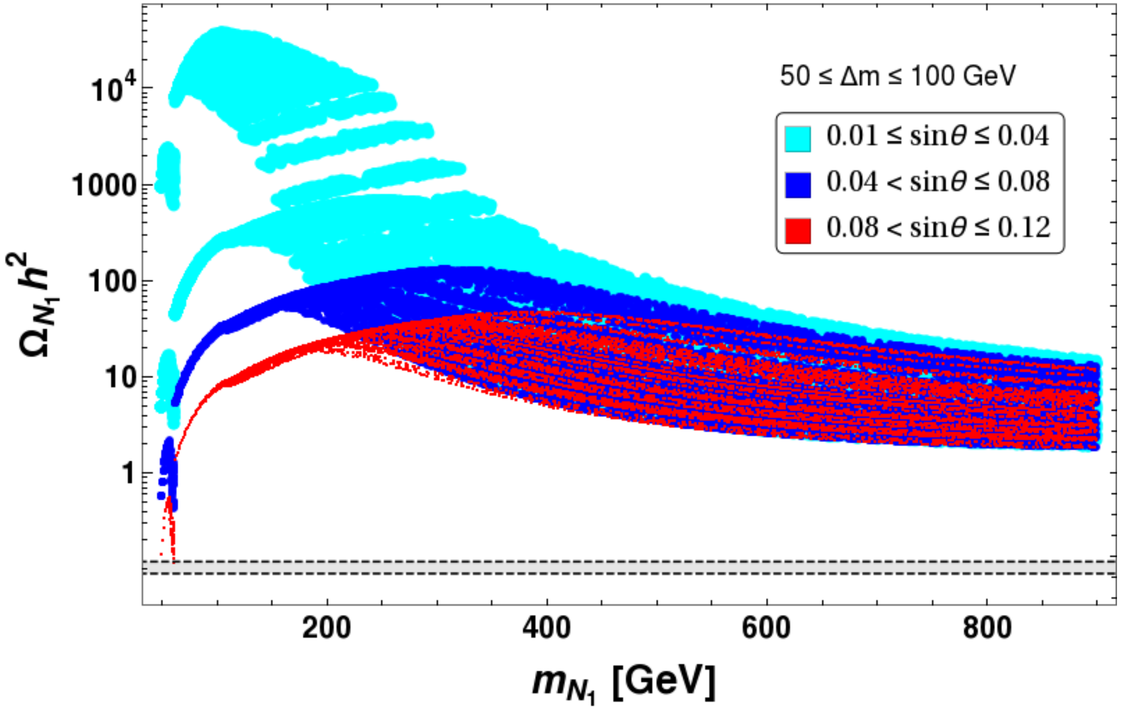
We look for the observed relic abundance in the parameter space spanned by

$$M_1, M_2 \approx M^{\pm}, \sin\theta \qquad Y = \frac{\Delta M \sin 2\theta}{2v}$$

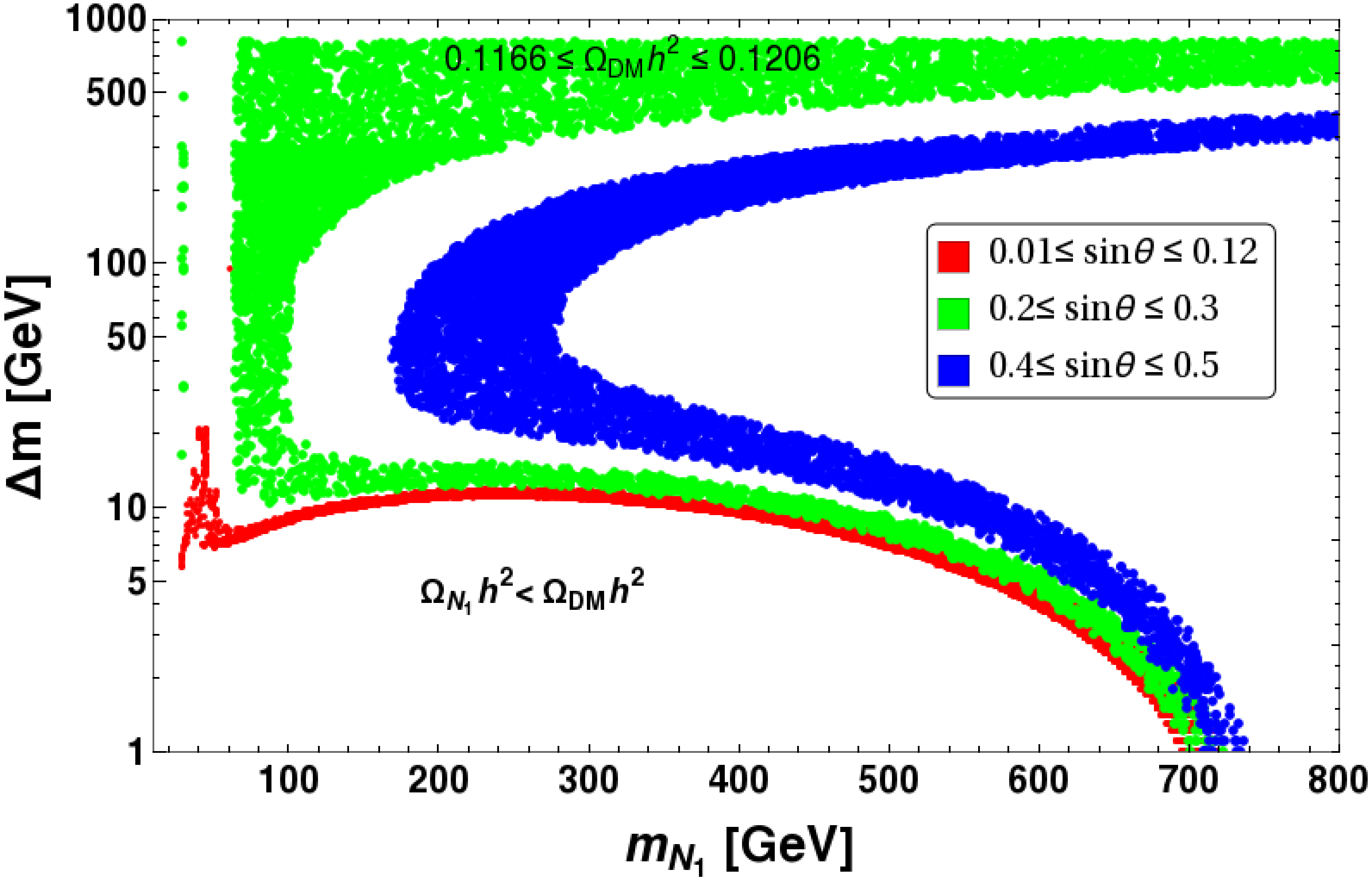

0.01≤ sinθ ≤ 0.05
$\Omega_{N_1} h^2$
m_{N_1} [GeV]
1 ≤ Δm ≤ 10
10 < Δm ≤ 30
30 < Δm ≤ 50
50 < Δm ≤ 100

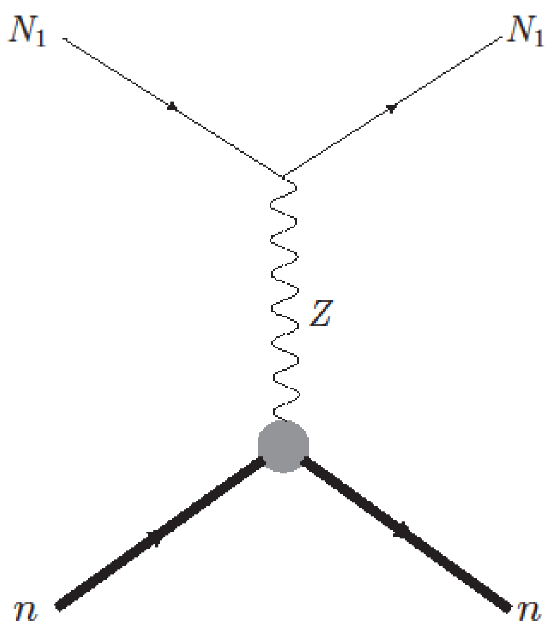

0.08≤ sinθ ≤ 0.12
$\Omega_{N_1} h^2$
m_{N_1} [GeV]
1 ≤ Δm ≤ 10
10 < Δm ≤ 30
30 < Δm ≤ 50
50 < Δm ≤ 100


1 ≤ Δm ≤ 10 GeV
0.01 ≤ sinθ ≤ 0.04
0.04 < sinθ ≤ 0.08
0.08 < sinθ ≤ 0.12
$\Omega_{N_1} h^2$
m_{N_1} [GeV]

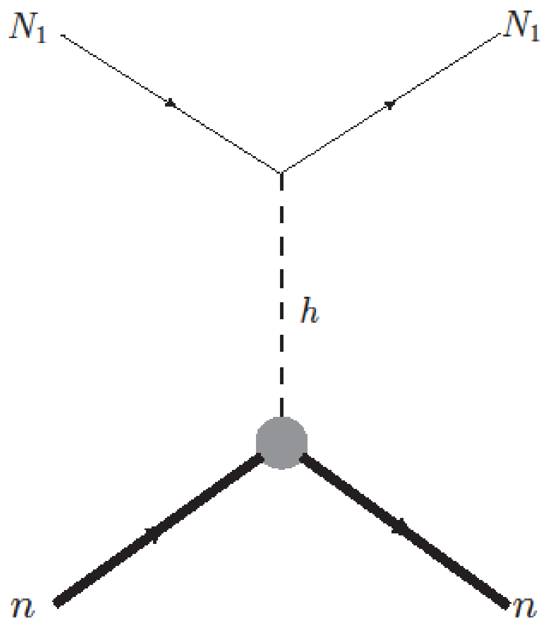

50 ≤ Δm ≤ 100 GeV
0.01 ≤ sinθ ≤ 0.04
0.04 < sinθ ≤ 0.08
0.08 < sinθ ≤ 0.12
$\Omega_{N_1} h^2$
m_{N_1} [GeV]

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

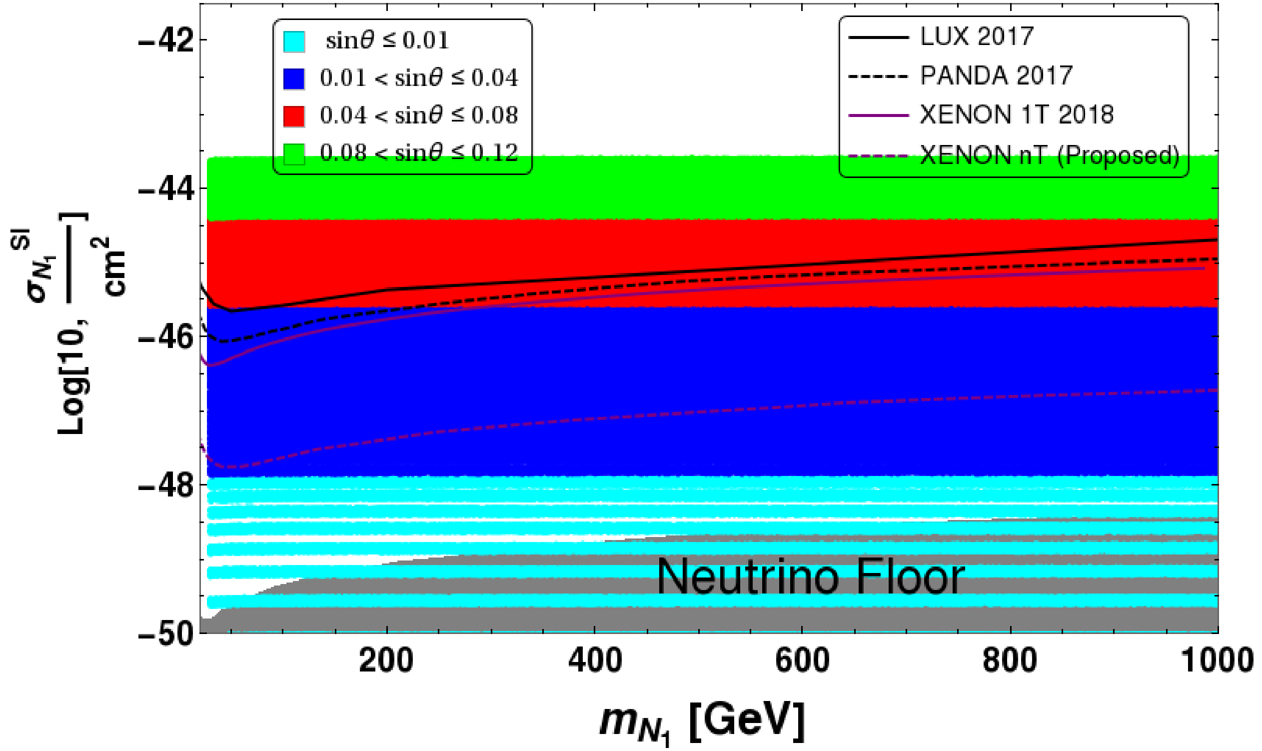




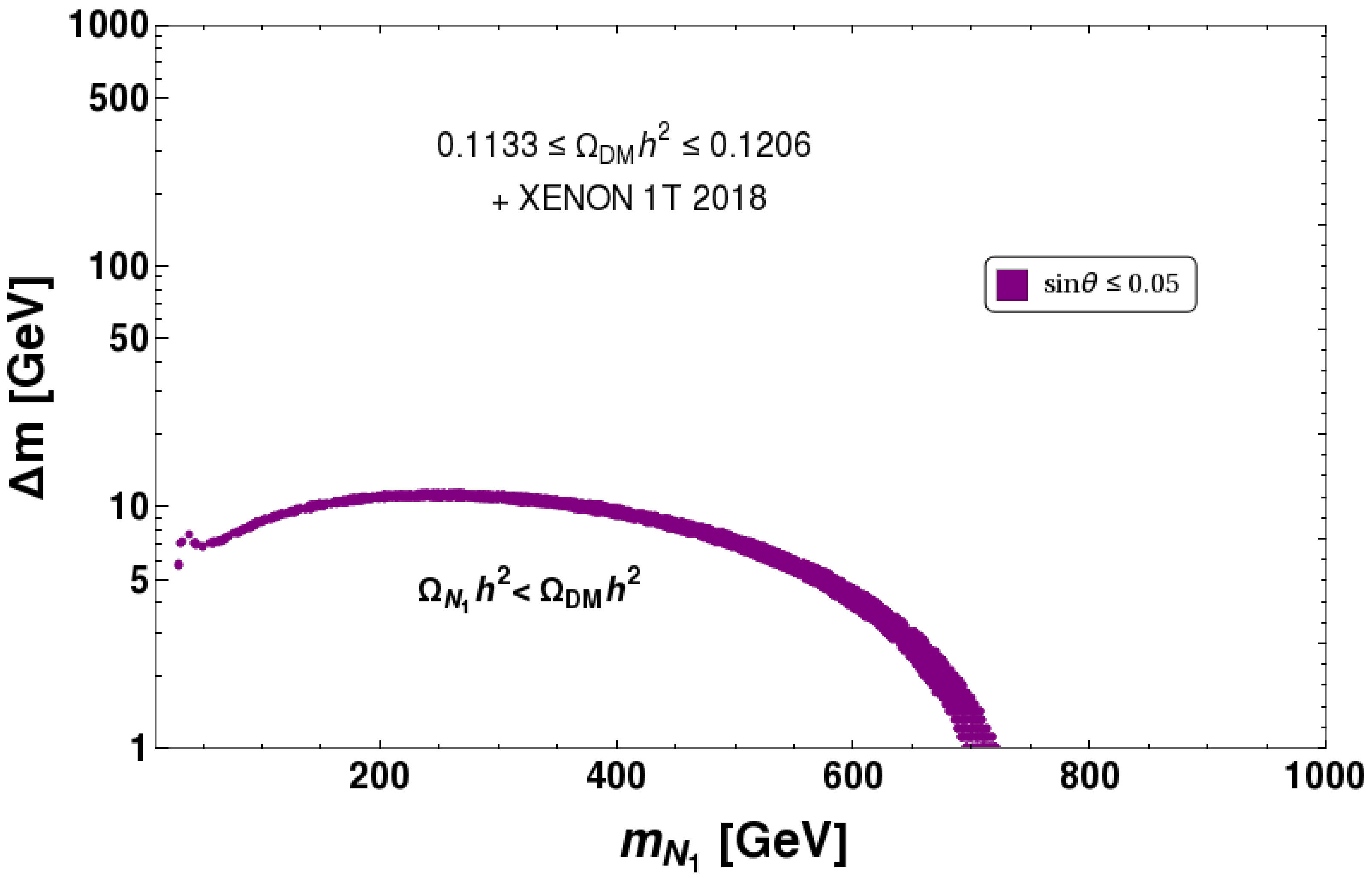
N_1
N_1
Z
n
n



N_1
N_1
h
n
n



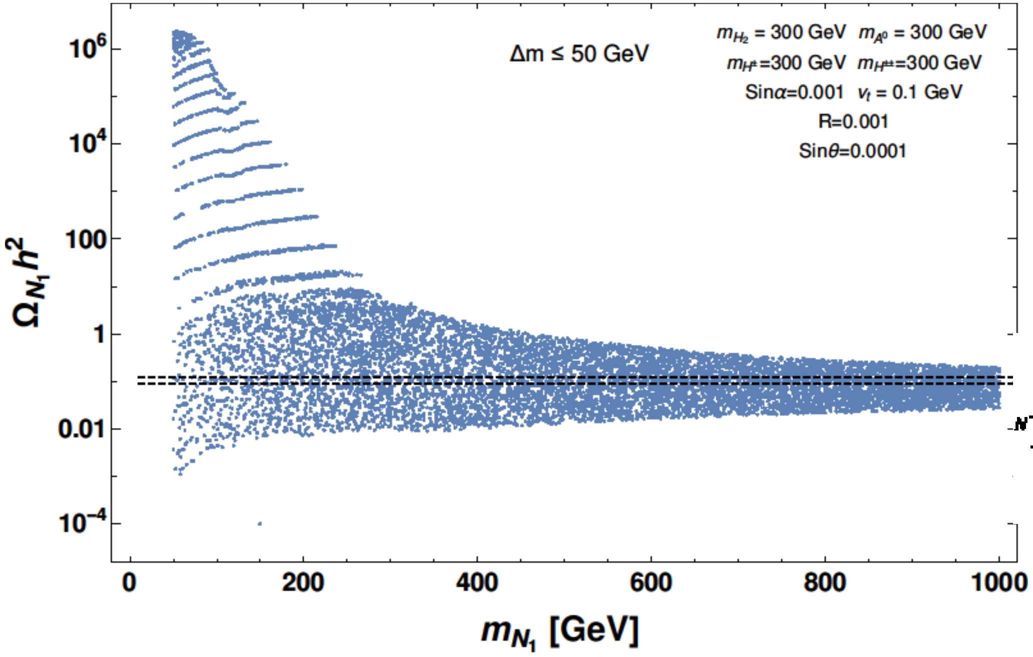
sinθ ≤ 0.01
0.01 < sinθ ≤ 0.04
0.04 < sinθ ≤ 0.08
0.08 < sinθ ≤ 0.12
LUX 2017
PANDA 2017
XENON 1T 2018
XENON nT (Proposed)
Neutrino Floor
−42
−44
−46
−48
−50
200
400
600
800
1000
$\mathrm{Log}[10, \frac{\sigma_{N_1}^{SI}}{cm^2}]$
m_{N_1} [GeV]



0.1133 ≤ $\Omega_{DM}h^2$ ≤ 0.1206
+ XENON 1T 2018
sinθ ≤ 0.05
$\Omega_{N_1}h^2 < \Omega_{DM}h^2$
Δm [GeV]
m_{N_1} [GeV]
1000
500
100
50
10
5
1
200
400
600
800
1000

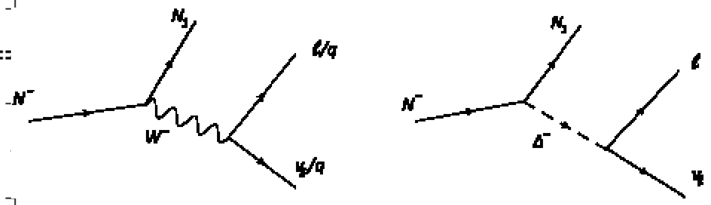
Small singlet-doublet mixing

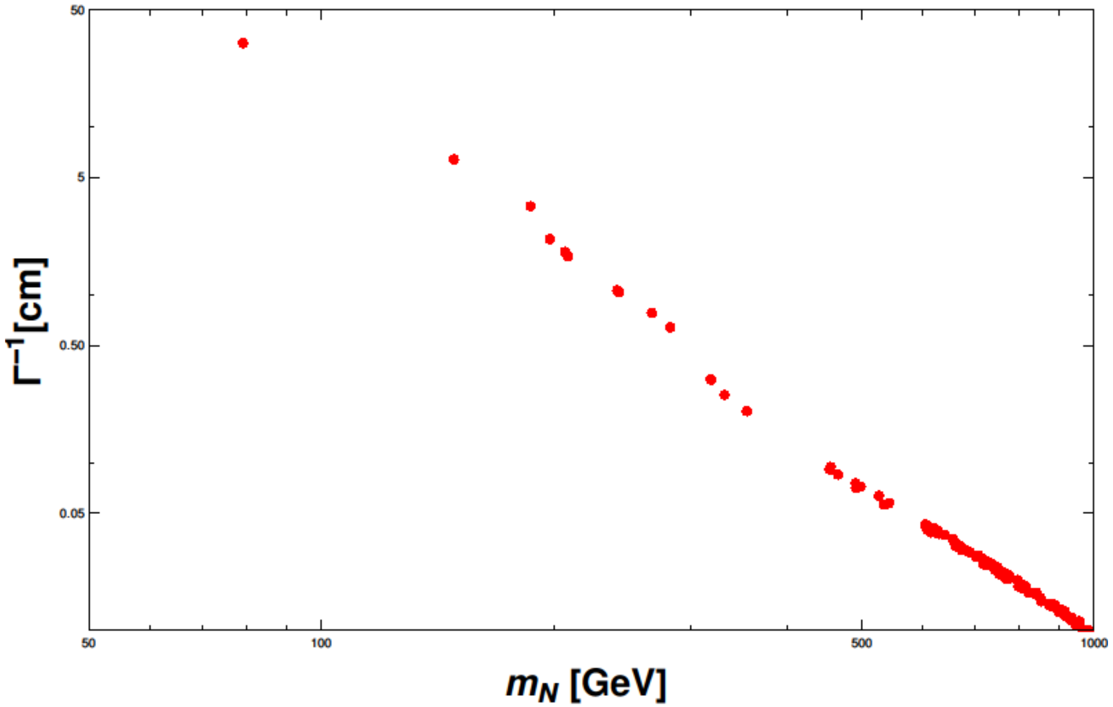
Testing the Hypothesis at collider via displaced vertex signature…



Displaced vertex signature of for small mixing angle:

$$N^{\pm} \rightarrow N_1 + \ell^{\pm} + \nu_{\ell}$$





Thus for a small mass difference we expect a large displaced vertex signature of charged partner of the dark matter.

Conclusions

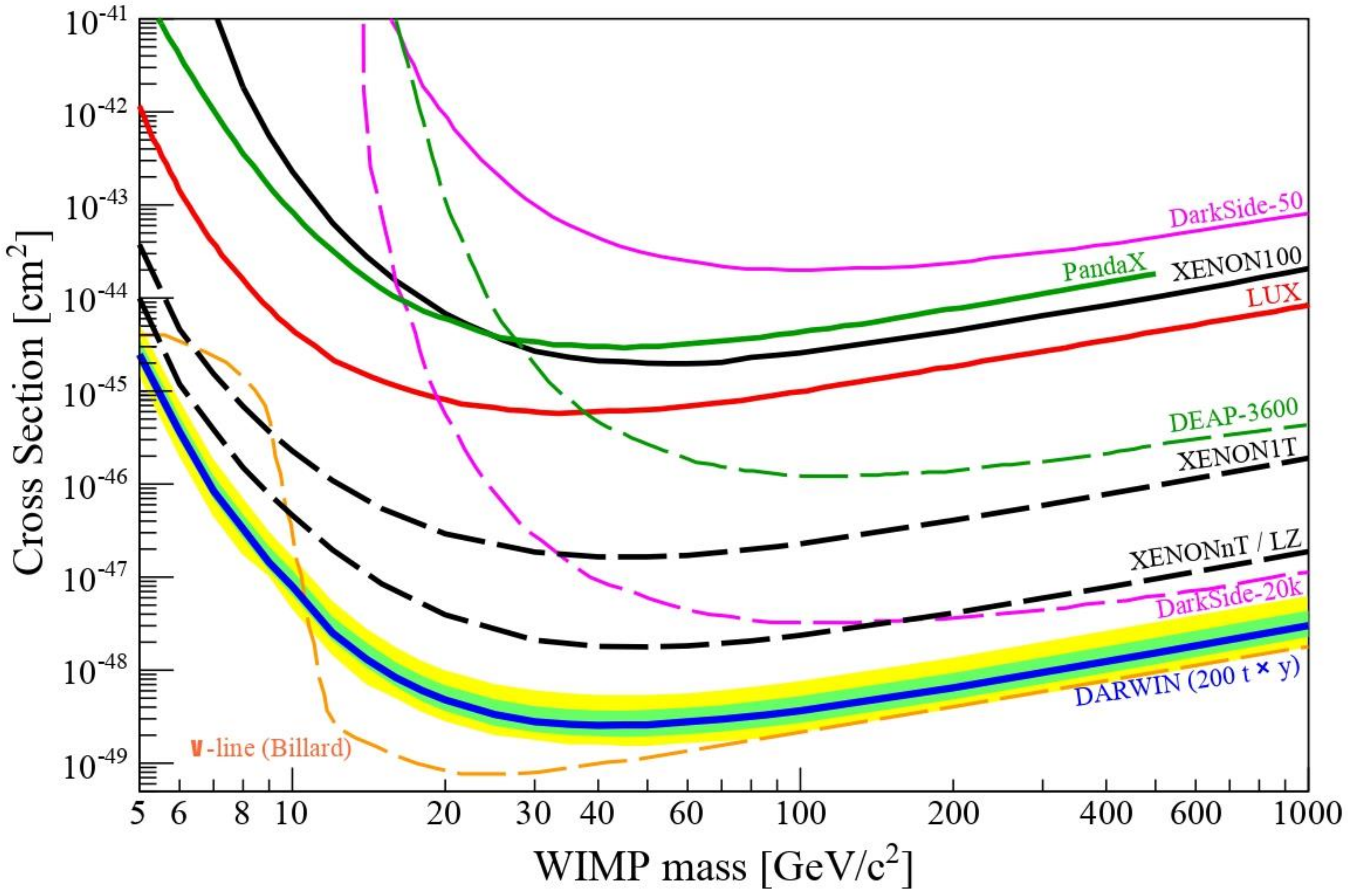
(1) The observed relic abundance of DM implies that its freeze-out cross-section (~0.1pb) is typically a weak interaction cross-section. So it is largely believed that the DM is a WIMP.

(2) We studied the case of a mixed (singlet+doublet) leptonic DM which satisfies the relic abundance in a large parameter space.

(3) The spin independent direct detection cross-section is within the reach of Xenon-nT.

(4) The displaced vertex signature of the charged partner looks promising.

Thank you



Cross Section [cm^2]
10^{-41}
10^{-42}
10^{-43}
10^{-44}
10^{-45}
10^{-46}
10^{-47}
10^{-48}
10^{-49}
DarkSide-50
PandaX
XENON100
LUX
DEAP-3600
XENON1T
XENONnT / LZ
DarkSide-20k
DARWIN (200 t × y)
ν-line (Billard)
5 6 8 10 20 30 40 60 100 200 400 600 1000
WIMP mass [GeV/c^2]