Part 3

WIMPs are not the only viable DM candidates

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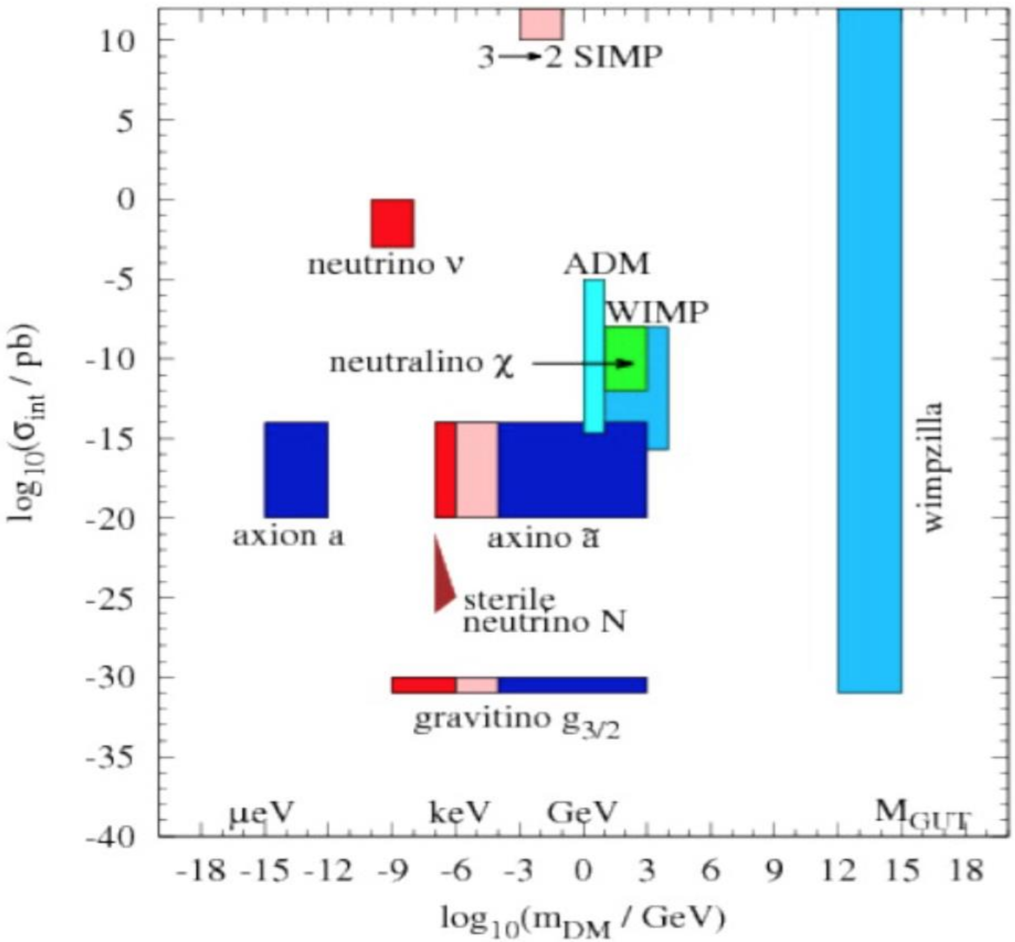
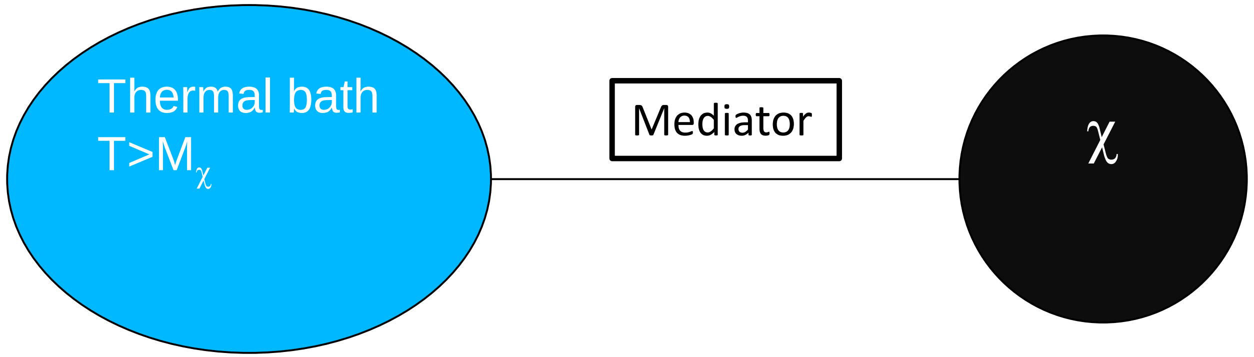


FIMPS (Feebly interacting MP)

- Freeze-in (Hall et al 0911.1120, McDonald,j. hep-ph/0106249) relevant for FIMP
- In early Universe, χ so feebly interacting that χ is decoupled from plasma



- Interactions are feeble but lead to production of χ

Freeze-in

- DM particles are NOT in thermal equilibrium with SM
- Recall

$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle \sigma v \rangle \left((n_\chi)^2 - (n_\chi^{eq})^2 \right)$$

Depletion of χ due to annihilation

Creation of χ from inverse process

Freeze-in

- DM particles are NOT in thermal equilibrium with SM
- Recall

$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle\sigma v\rangle \left((n_\chi)^2 - (n_\chi^{eq})^2\right)$$

Depletion of χ due to annihilation

Creation of χ from inverse process

- Initial number of DM particles is very small

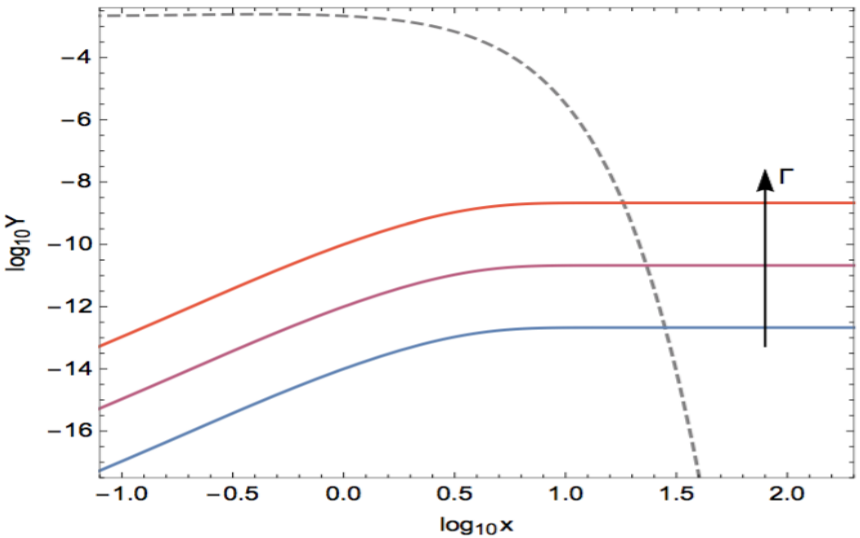
$$\dot{n}_\chi + 3Hn_\chi = \langle\sigma v\rangle_{X\bar{X}\to\chi\bar{\chi}}(T)n_{eq}^2(T) + n_{eq}(T)\Gamma_{Y\to\chi\chi}(T)$$

annihilation

Decay
(X,Y in Th.eq. With SM)

FIMPS (Feebly interacting MP)

- DM production from SM annihilation (or decay) until number density of SM becomes Boltzmann suppressed - n_χ constant 'freezes-in'
- T~ M, χ 'freezes-in' - yield increases with interaction strength,



x=m/T

- When decay possible, usually dominates

$$\dot{n}_\chi + 3Hn_\chi = n_Y \Gamma_{Y\to\chi\chi} = g_Y \Gamma_{Y\to\chi\chi} m_Y \int \frac{d^3p}{(2\pi)^3} \frac{1}{(e^{E/T}+s)} \frac{1}{E}$$

- Some possibilities for FIMPs:
  - 1) FIMP is DM pair production in annihilation of SM particles (or in decay of particle in thermal equilibrium)
  - 2) FIMP is dark matter - next to lightest ‘odd’ particle has long lifetime freeze-out as usual then decay to FIMP – typically l~10^{-12}
    - collider signature for production of stable charged particles (or displaced vertices)
    - Impact on BBN
  - 3) FIMP is not DM, freezes-in and then decay to DM

$$\Omega_{DM} = \frac{m_{DM}}{m_X} \Omega_X h^2$$

    - Relic abundance and DM annihilation cross section no longer related, freeze-in produces DM abundance, DM annihilation can be large – freeze-out abundance small – enhancement in indirect detection

- Examples of FIMPs:
  - In general a singlet under SM (to prevent reaching thermal equilibrium) - for example the singlet scalar model used for freeze-out but for a different choice of couplings
  - Any ‘dark sector’ particle feebly coupled to SM
  - Dirac neutrino mass + supersymmetry : RH sneutrino FIMP
  - Gravitino or axino
  - Asymmetric freeze-in (baryon asymmetry)

Minimal FIMP models

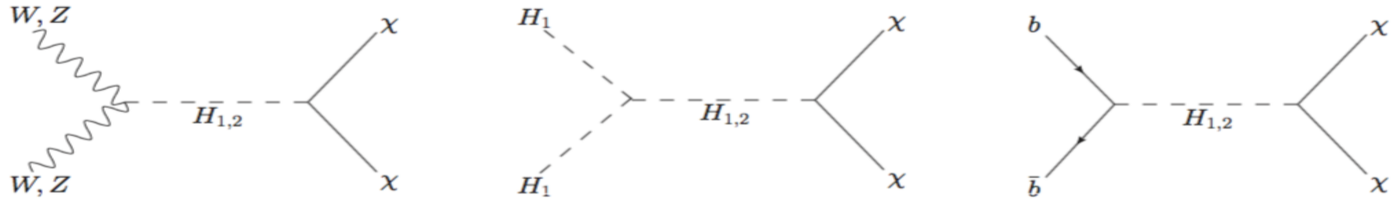
- SM+ majorana fermion (DM) + real scalar + Z_2 symmetry (Klasen, Yaguna, 1309.2777) - 'simplified model'

$$\mathcal{L}_\chi = -\frac{1}{2}M_\chi\bar{\chi}\chi + g_s\phi\bar{\chi}\chi + ig_p\phi\bar{\chi}\gamma_5\chi,$$

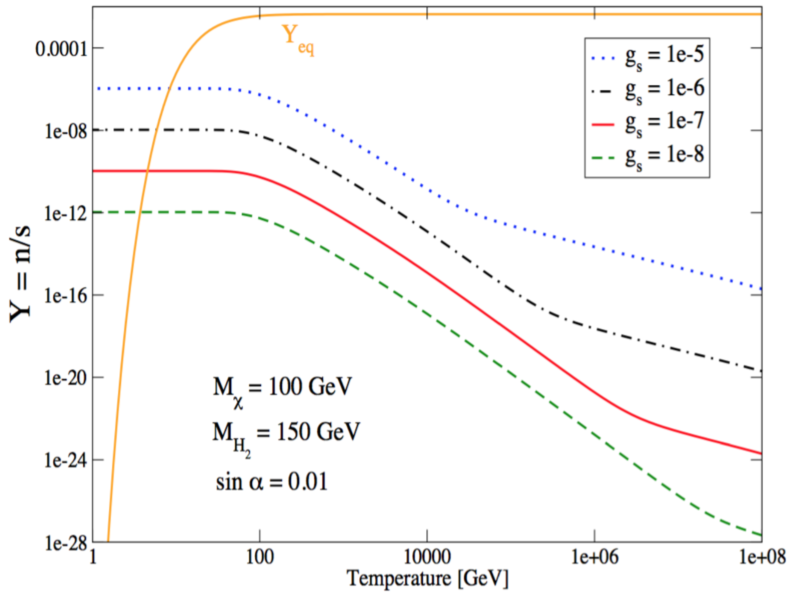
$$V(\phi, H) = -\mu_H^2 H^\dagger H + \lambda_H (H^\dagger H)^2 - \frac{\mu_\phi^2}{2}\phi^2 + \frac{\lambda_\phi}{4}\phi^4 + \frac{\lambda_4}{2}\phi^2 H^\dagger H + \mu_1^3\phi + \frac{\mu_3}{3}\phi^3 + \mu\,\phi(H^\dagger H),$$

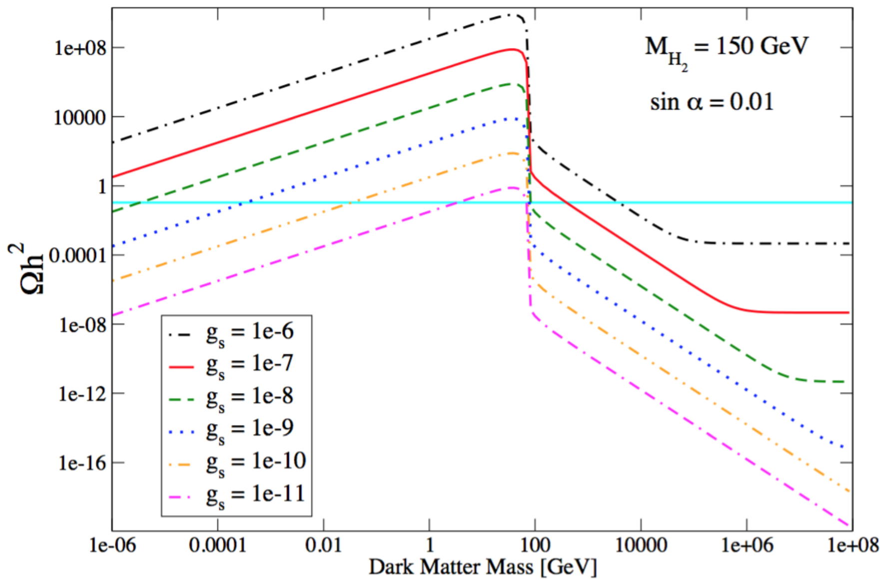
- The scalar mixes with the Higgs $H_1 = h\cos\alpha + \phi\sin\alpha,$
- Parameters $M_\chi, M_{H_2}, g_s, \sin\alpha, \lambda_4, \mu_3.$

- Some diagrams that contribute to DM annihilation



Minimal FIMP model





- Can reproduce relic density for DM with any mass
- From Higgs precision measurements : limit on the mixing with the scalar
- Few other direct or indirect signatures

Another example : Sneutrino

- Partner of LH neutrino NOT a good DM candidate
  - Very large contribution to direct detection- through Z exchange (Falk,Olive, Srednicki, PLB354 (1995) 99)
- Neutrino have masses – RH neutrino + supersymmetric partner well-motivated – if LSP then can be dark matter
  - Thermalized?
    - Non-negligible L-R mixing (Arina et al, 1503.02960)
    - New gauge interactions MSSM+U(1) (GB, DaSilva, Laa, Pukhov 1505.06243)
    - Both cases are viable with respect to LHC constraints and feature new signatures
  - Or not – abundance from decay of other particles

MSSM+RH (s)neutrino

- The framework : MSSM + three generations (ν_R + sneutrinoR).
- Assume pure Dirac neutrino mass
- Superpotential $W = y_\nu \hat{H}_u \cdot \hat{L}\, \hat{\nu}_R^c - y_e \hat{H}_d \cdot \hat{L}\, \hat{\ell}_R^c + \mu_H \hat{H}_d \cdot \hat{H}_u$
- Small Yukawa couplings O(10^{-13}) depending on assumption : neutrino mass saturates atmospheric neutrino or cosmological bound with degenerate neutrino

$$y_\nu \sin\beta \simeq 3.0 \times 10^{-13} \times \left(\frac{m_\nu^2}{2.8 \times 10^{-3}\ \mathrm{eV}^2} \right)^{1/2}$$

- Sneutrino mass same order as other sfermions – can be LSP

$$- \mathcal{L}_{\mathrm{soft}} \supset \tilde{M}_L^2 |\tilde{L}|^2 + \tilde{M}_{\nu_R}^2 |\tilde{\nu}_R|^2 + \left(\tilde{A}_\nu H_u \cdot \tilde{L}\, \tilde{\nu}_R^c - \tilde{A}_e H_d \cdot \tilde{L}\, \tilde{\ell}_R^c + h.c. \right)$$

- Sneutrino mixing $$\tan 2\Theta = \frac{2 m_\nu |\cot\beta\, \mu_H - A_\nu^*|}{m_{\tilde{\nu}_L}^2 - m_{\tilde{\nu}_R}^2},$$

- Sneutrino not thermalized in early universe – its interactions are too weak
- One possibility for DM is production through decays of sparticles
- Consider decay of MSSM-LSP after freeze-out (lifetime of NLSP is quite long)
- Relic density obtained from that of the NLSP (or MSSM-LSP) – can be charged

$$\Omega^{\rm FO}_{\tilde{\nu}_R} = \frac{m_{\tilde{\nu}_R}}{m_{\rm MSSM\text{-}LSP}} \Omega_{\rm MSSM\text{-}LSP}$$

- Consider the case where stau is the NLSP (and for simplicity assume SUGRA relations)
- Collider constraints – Higgs; flavour constraints; susy searches (mostly not valid because stau is collider stable and charged); charged stable particles
- Constraints from BBN : lifetime of stau can be long enough for decay around or after BBN→ impact on abundance of light elements

Big Bang Nucleosynthesis

- BBN (T~MeV-10keV, t~0.1-10^4s) allows to predict abundances of light elements $D, He^3, He^4, {}^7Li.$
- Depends on photon to baryon ratio
- In early Universe, energy density dominated by radiation (γ e)
- At high T, weak interaction rates were in thermal equilibrium

$$n + e^+ \rightarrow p + \nu$$
$$n + \nu \rightarrow p + e^-$$

- Reverse process proceed at same rate and n/p~1
- At lower T : weak interactions fall out of equilibrium
- Freeze-out when interaction rate Γ_{weak}< H, species decouple
- When T approaches freeze-out (around 0.8MeV)

$$n/p \approx exp^{-\Delta m/T} \approx 1/6$$

- Nucleosynthesis begins with formation of Deuterium
- Number of photons>> number of nucleons the reverse process occurs much faster, deuterium production is delayed, starts only at T~0.1MeV

$$p+n \to D+\gamma$$

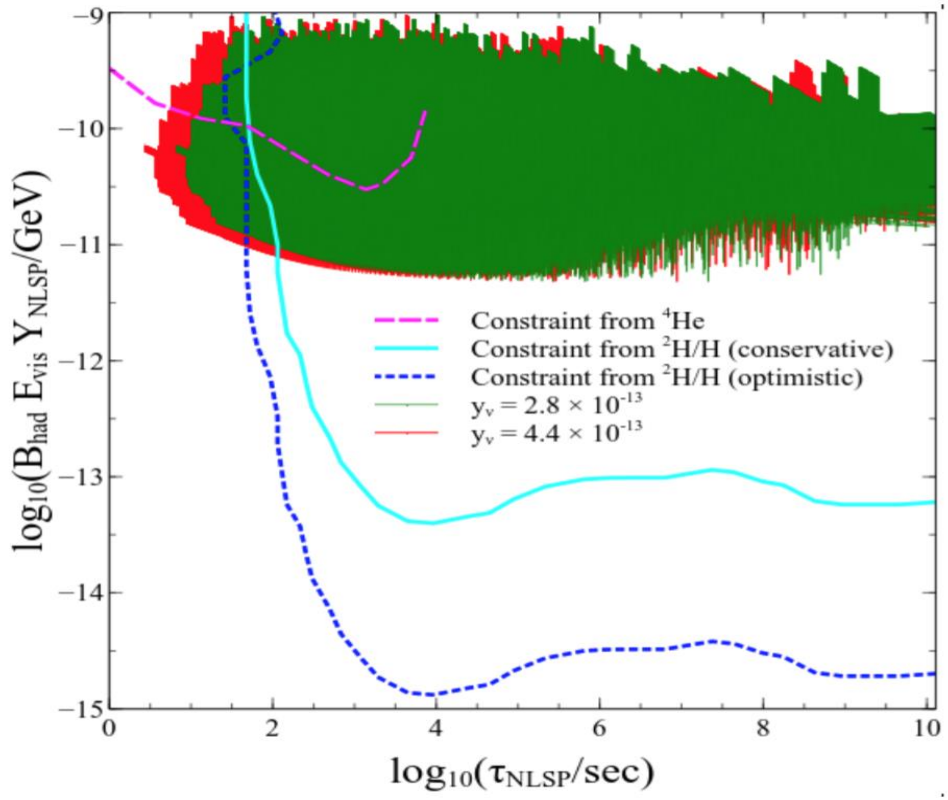
- … and the chain continues with production of heavier elements
- Relationship between expansion rate of Universe (relate to total matter density) and density of p and n (baryonic matter density) determine abundance of light elements
- Main product of BBN ^4He

$$Y \approx \frac{2n/p}{1+n/p} \approx 0.25$$

- Other elements produced in lesser amounts D, ^3He, ^7Li

- If particle with lifetime > 0.1s decays can cause non-thermal nuclear reaction during or after BBN – spoiling predictions – in particular if new particle has hadronic decay modes
    - Kawasaki, Kohri, Moroi, PRD71, 083502 (2005)
- Alteration of n/p ratio - for example . $\pi^- + p \longrightarrow \pi^0 + n$
  - -> overproduction He^4
- Hadrodissociation of He^4 causes overproduction of D
  - $n + He^4$ -> $He^3 + D$, $2D + n$, $D + p + n$

- Key elements :
  - Bhad : hadronic BR of stau (nuR+W)
  - Evis : net energy carried away by hadrons
  - Ystau : yield

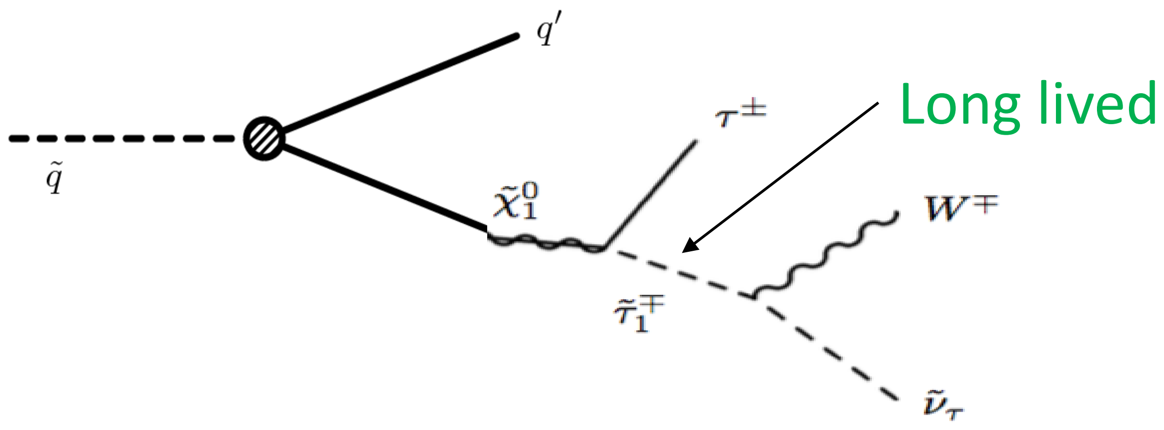


LHC signatures

- Characteristic signature : stable charged particle NOT MET
- Staus live from sec to min : decay outside detector
- Searches
  - Cascades : coloured sparticles decay into jets + SUSY→ N jets + stau
  - Pair production of two stable staus
  - Passive search for stable particles
- Stable stau behaves like « slow » muons $\beta = p/E < 1$
  - Use ionisation properties and time of flight measurement to distinguish from muon
  - kinematic distribution

Banerjee, GB, Mukhopadyhyay, Serpico, 1603.08834

Charged tracks from cascades

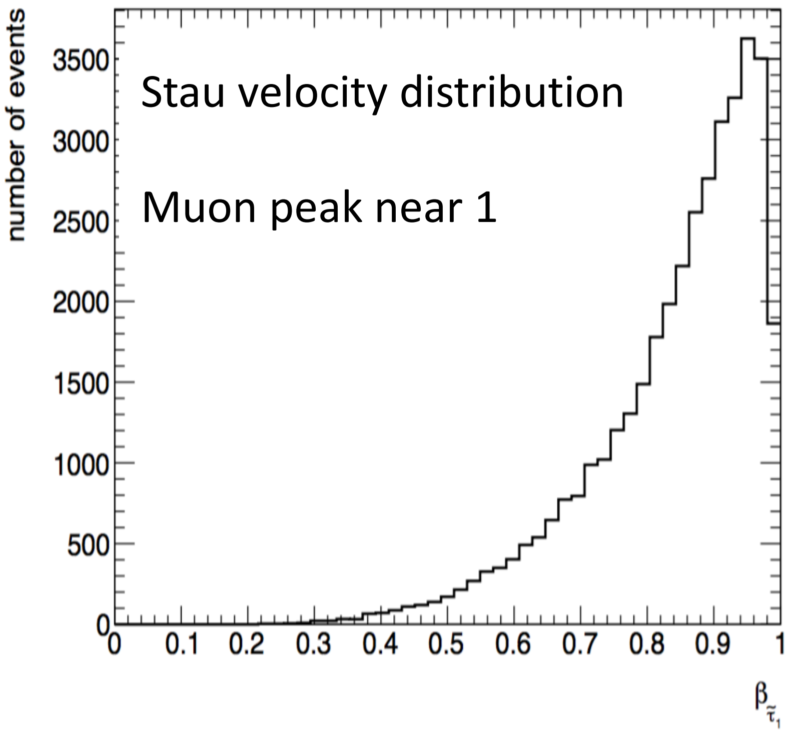


- Dominant contribution from squark pairs (heavy gluinos)
- Can probe mass ~600 GeV but depends on squark mass – recall that some limits coming from signatures with MET do not apply

Banerjee, GB, Mukhopadyhyay, Serpico, 1603.08834

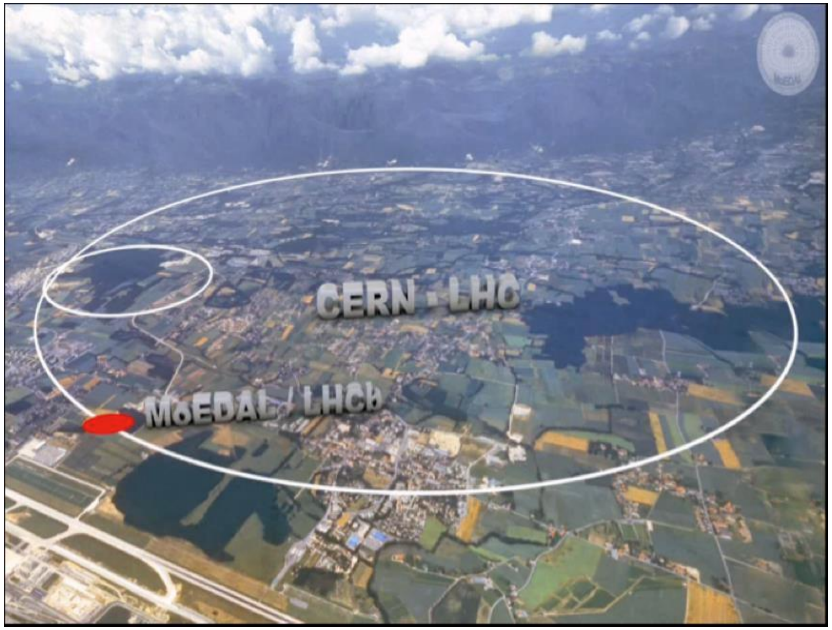
Pair production

- Pair production : no model dependence but EW cross section -> lower reach
- Staus look like ‘slow’ muons
- Main background muon pairs



Banerjee, GB, Mukhopadyhyay, Serpico, 1603.08834

MoEDAL detector



- Passive detector
- Array of nuclear track detector stacks
- Surrounds intersection region point 8
- Sensitive to highly ionising particles
- Does not require trigger, one detected event is enough
- Major condition : ionizing particle has velocity β<0.2

B. Acharya et al, 1405.7662

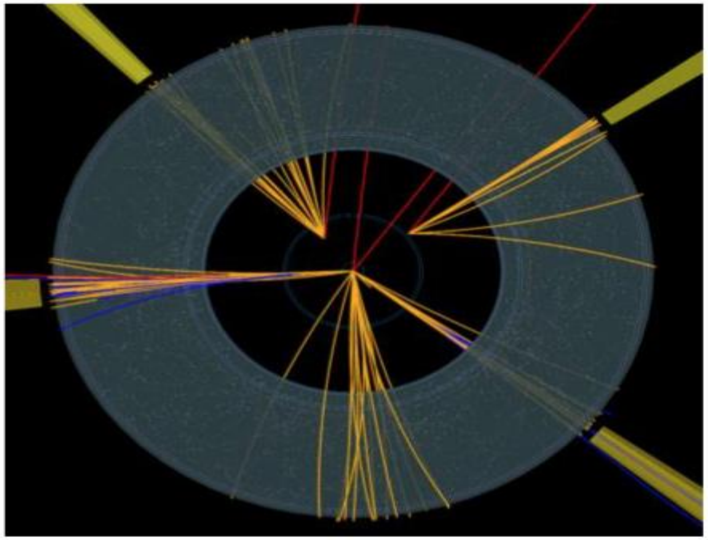
Benchmark point	Cascade	Pair
357 GeV	45	2.5
400 GeV	296	1.5
442 GeV	24	1.1
600 GeV	6	0.5

Banerjee, et al, 1603.08834

Number of $\tilde{\tau}_1$'s with $\beta \leq 0.2$ with $\mathcal{L} = 3000\,\text{fb}^{-1}$

Other possible signatures

- LHC :
  - Some models lead to displaced vertices or disappearing tracks



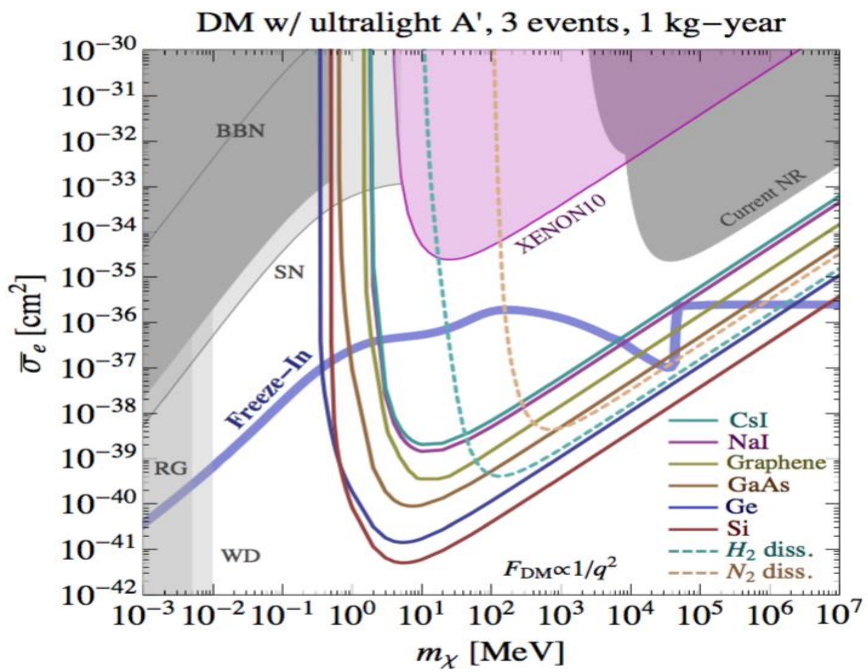
  - searches for mediator (if coupling of mediator to SM is not suppressed

Other possible signatures

- When DM is light (well below GeV) : limits from invisible meson decays, electron fixed targets..
- Indirect detection : Models with feeble couplings can lead to very long lifetime, if FIMP is not DM but decays into it. DM annihilation can be large - > boost factor for indirect detection
- Various cosmological constraints (dark sector sensitive to primordial initial conditions in freeze-in)

Direct detection – light DM

- FIMPS can be very light - new projects to search for very light DM with different materials, eg. superconductors– exploit DM-e scattering



DM with strong interactions

- Strong interactions with itself – SIDM
- Strong interactions with SM – SIMP

Strongly Interacting MP

Strong interactions of DM with SM particles (SIMP)

If thermal freeze-out : can only be subdominant DM component

Otherwise : some non-thermal mechanism or asymmetric

Constraints: DM captured and accreted at core of Earth, annihilating SIMP source of heat -> measurements of heat flow set strong constraints unless DM asymmetric

Here simplified model with vector or scalar mediator, e.g

$$-\tilde{g}_\chi \phi_\mu \, \bar{\chi}\gamma^\mu \chi - \tilde{g}_q \phi_\mu \, \bar{q}\gamma^\mu q$$

Astrophysics constraints on Strong interaction with DM

At collider probe interaction with ordinary matter

Searches SIMP

Direct detection : large cross sections SIMP stopped in earth atmosphere – no sensitivity in underground detectors,

High altitude detectors search for SIMP above atmosphere (e.g. RSS-balloon based)

If cross section not too large -> stringent constraints from undergound detectors

Interactions of DM with baryons also constrained from CMB and large scale structure (Dvorkin et al, 1311.2937) affect dynamics of linear density perturbation in early universe: a baryon in halo of galaxy does not scatter from DM particles during age of galaxy

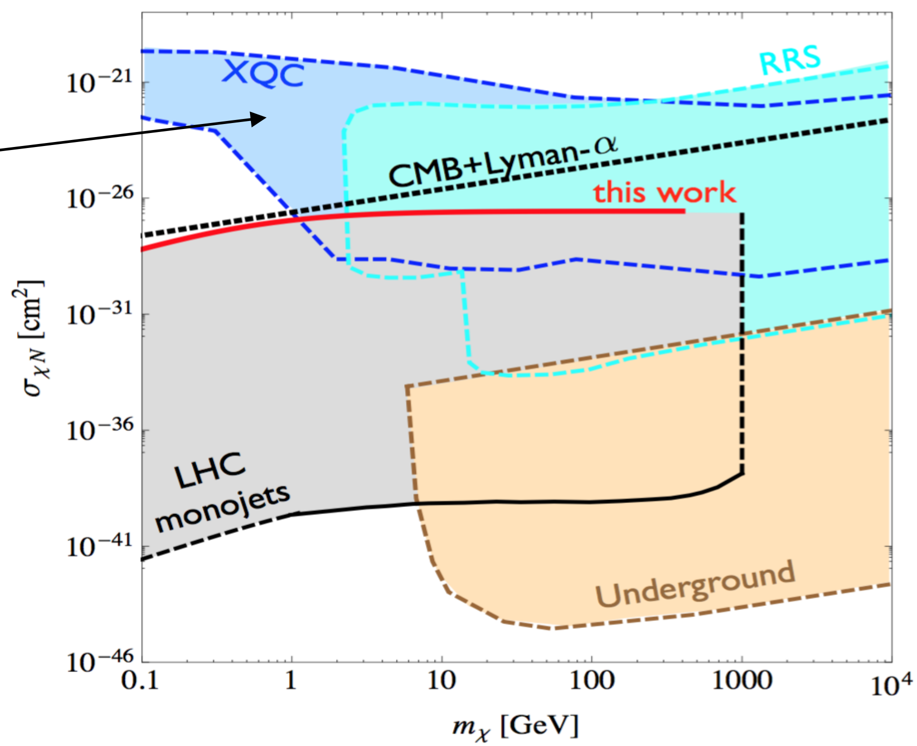
SIMP - Collider signature

SIMP produced in pairs – strong interations with ordinary matter can behave like neutrons – deposit energy or stop in hadronic calorimeter – depends on inelastic scattering of SIMP with hadrons

'trackless jets' DM jets zero tracks and less electromagnetic activity in Ecalorimeter than QCD jets - smaller charged energy fraction $\sum_i p_{\mathrm{T,i}}/p_{\mathrm{T,jet}}$

If all DM energy deposit in detector (2 back-to-back jets no MET)

For SIMP all DM



Assume vector mediator m=1GeV

$$\sigma_{\chi N}/\sigma_{\mathrm{QCD}} = 1$$

LHC8 20fb^{-1}

Daci et al, 1503.05505

and many more DM models…

Conclusion

- Strong evidence on dark matter
- List of possible dark matter candidates and models has grown rapidly in last few years and covers a wide range of masses and interaction strengths
- WIMP hypothesis is being probed by LHC in a variety of signatures(not only MET), direct and indirect detection
- Still no clear picture although parameter space of popular models is shrinking - next few years will be crucial
- Dark matter might be much different than expected