DMAstroLHC

Sneutrino dark matter

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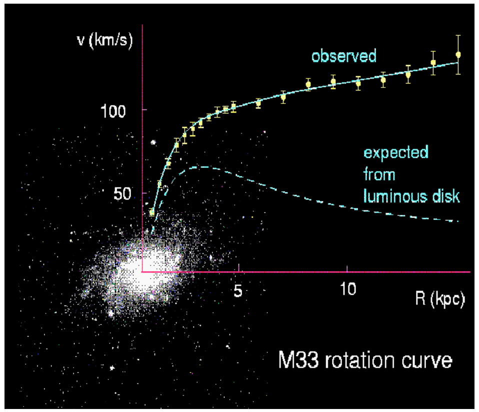
Introduction

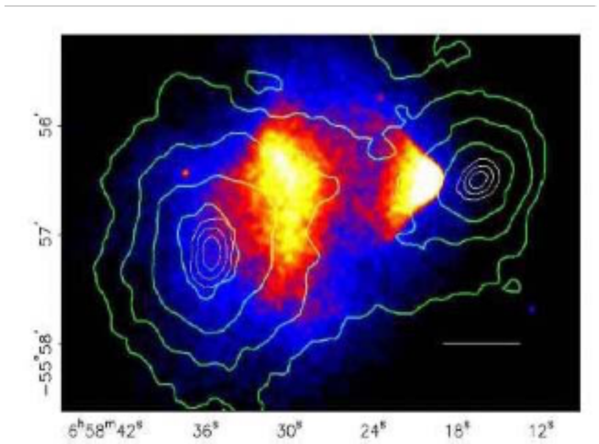
Strong evidence for dark matter from astrophysical and cosmological observations

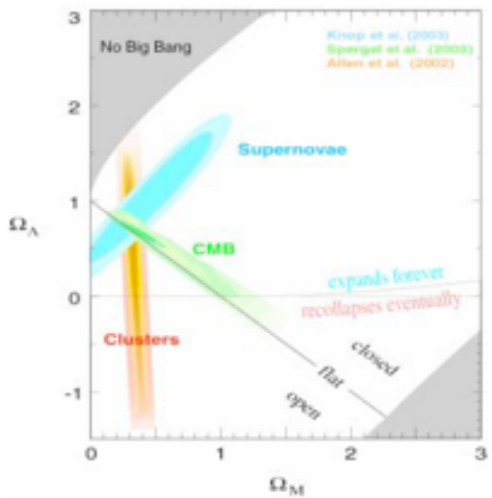
Motivation for new particles beyond standard model

Implication of precise determination of amount of CDM on DM particle properties

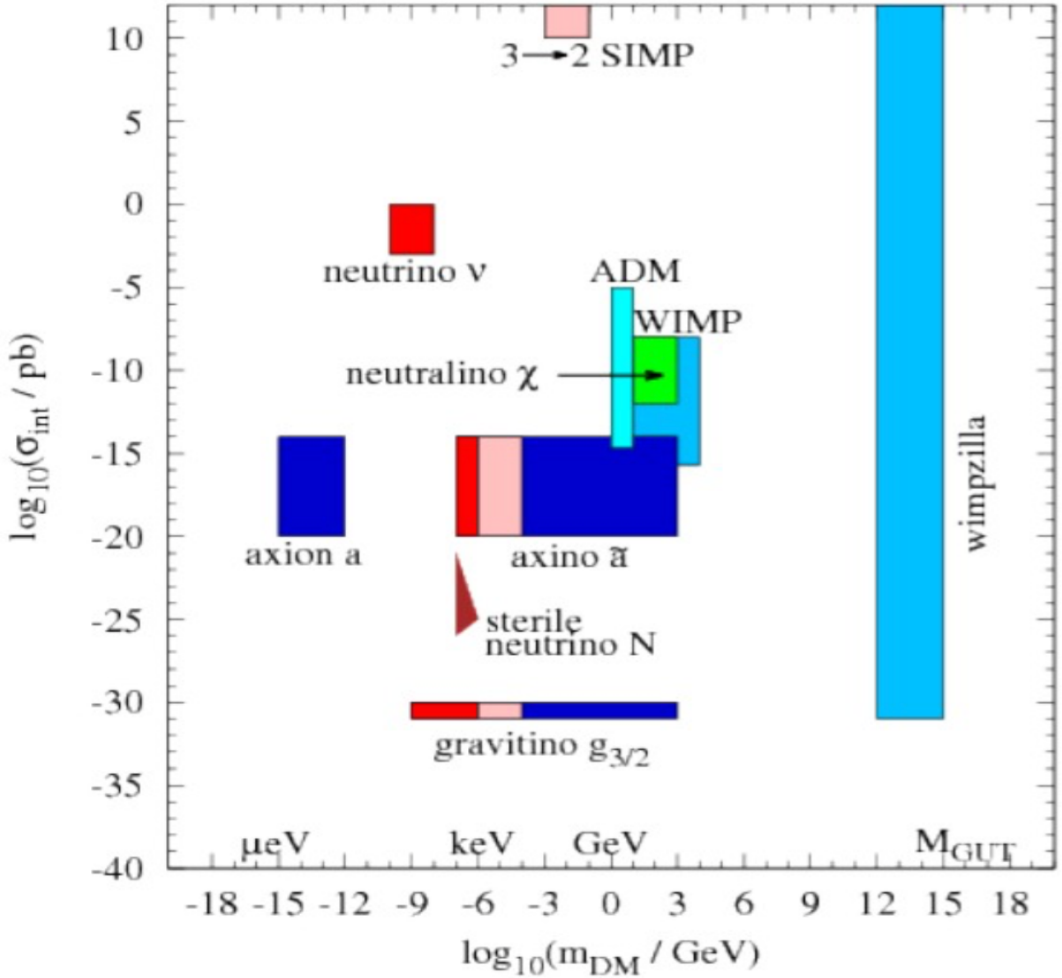
$\Omega_{cdm}\, h^2 = 0.1196 +/- 0.0031$







A wide variety of DM candidates



L.Roszkowski

WIMPs

FIMPs

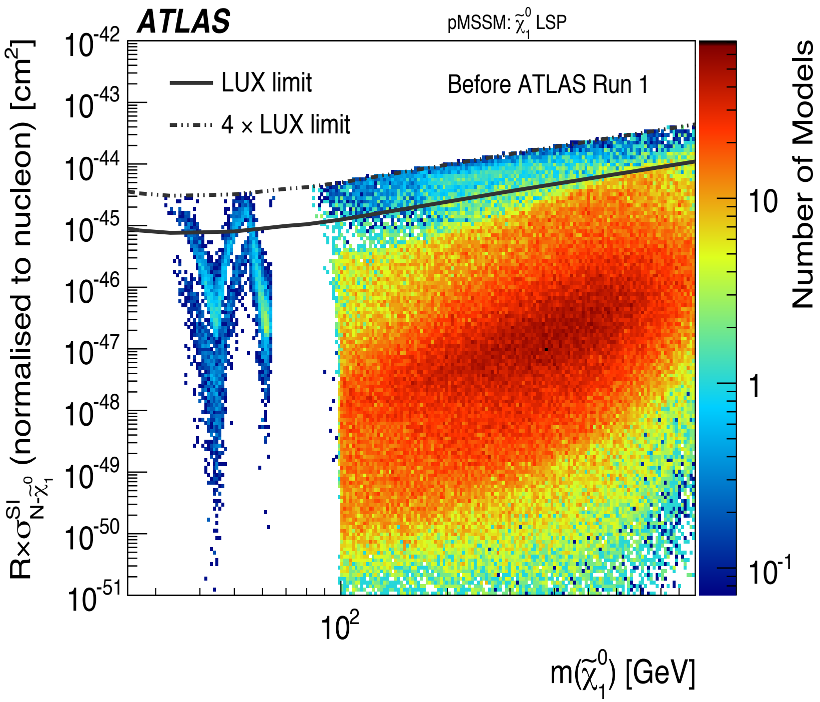
SIMPs

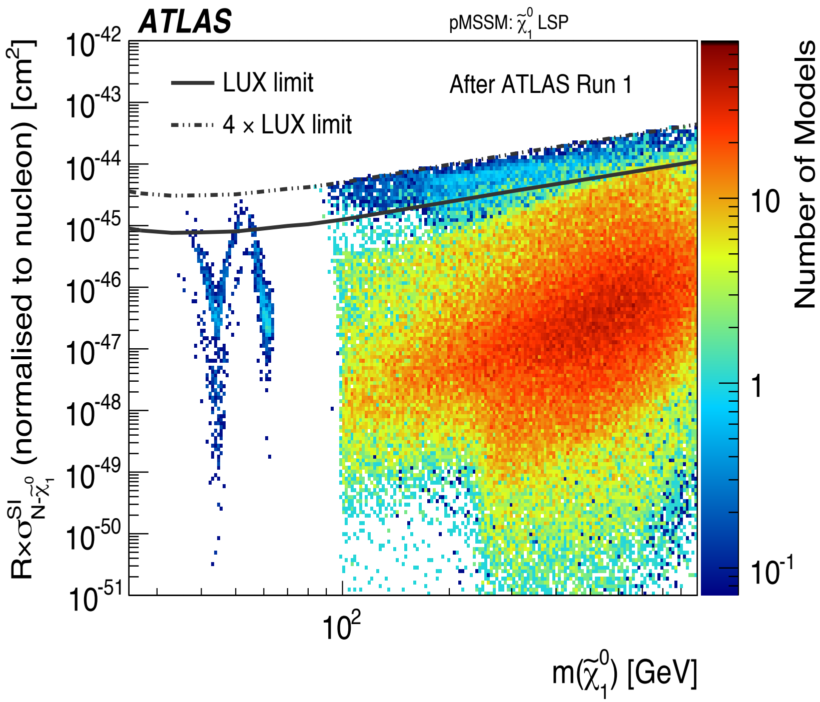
Asymmetric

- Supersymmetry one of best motivated extension of SM
- No sign at LHC → does that mean that most popular WIMP model (neutralino) is ruled out?
- Strong constraints from LHC + direct detection especially if below TeV scale
- Properties of neutralino DM : strong dependence on its nature : partner of gauge boson (B,W) or Higgs
  - SU(2) number: efficient annihilation into WW-> relic density prefers TeV scale (higgsino) or 2TeV (wino)
  - U(1) only : bino need light sfermions – LHC disfavoured
  - Mixed : satisfies relic density for any scale – mixed bino-higgsino strongly constrained from direct detection (bino-wino allowed)

What's left after LHC

ATLAS 1508.06608





Still large area of parameter space to be explored by LHC and (in)direct searches

What about other supersymmetry candidates?

Sneutrino DM

- Another neutral particle in SUSY : the 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)+ efficient annihilation
- Neutrino have masses – RH neutrino + supersymmetric partner well-motivated – if LSP then can be dark matter
- Thermalized?
  - Non-negligible L-R mixing - Arkani-Hamed et al PRD61 (2001), Borzumati, Namura PRD64 (2002) 053002
  - New interactions – Gauge : MSSM+U(1) (GB et al JCAP 1112:014) or scalar eg NMSSM (Cerdeno, Seto, JCAP0908:032)
  - Both cases are viable with respect to LHC constraints and feature new signatures – leptons (same-sign, monoleptons) (Arina, Cabrera, 1311.6549, Arina et al, 1503.02960, GB et al, 1505.06243)

Sneutrino DM

- Or not thermalized –
  - abundance from decay of other particles ‘next to lightest dark’ particle which has long lifetime,
  - NLSP freeze-out as usual then decays to feebly interacting sneutrino

MSSM+RH neutrino

- The framework : MSSM + three generations (ν_R + sneutrinoR).
- Assume pure Dirac neutrino masses
- Superpotential $W = y_\nu \hat{H}_u \cdot \hat{L}\, \hat{\nu}_R^c - y_e \hat{H}_d \cdot \hat{L}\, \hat{\ell}_R^c + \mu_H \hat{H}_d \cdot \hat{H}_u$
- Couplings of sneutrino proportional to neutrino mass
- Lower bound on neutrino mass from fits to solar, atmospheric, accelerator neutrino data

$$|\Delta m^2| = 2.43 \pm 0.06 \times 10^{-3} \mathrm{eV}^2 \quad \rightarrow m_\nu^H > 0.049 \mathrm{eV}$$

- For hierarchical neutrino masses

$$(y_\nu^H \sin\beta)_{\mathrm{min}} \simeq 2.8 \times 10^{-13}$$

- Upper limit on Yukawa couplings from cosmological bound – Planck temperature and polarisation data, lensing, supernovae, BAO

$$\sum_{i=1}^{3} m_\mathrm{i} < 0.23 \text{ eV at } 95\% \text{ CL;} \qquad (y_\nu^H \sin\beta)_{\mathrm{max}} \simeq 4.4 \times 10^{-13}$$

(for quasi-degenerate neutrinos)

MSSM+RH neutrino

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

$$-\mathcal{L}_{soft} \supset M^2_{\tilde{\nu}_R}|\tilde{\nu}_R|^2 + (y_\nu A_\nu H_u \tilde{L}\,\tilde{\nu}^c_R + h.c.)$$

- Sneutrino mixing is very small – can be neglected

$$\tan 2\tilde{\Theta} = \frac{2y_\nu v \sin\beta|\cot\beta\mu - A_\nu|}{m^2_{\tilde{\nu}_L} - m^2_{\tilde{\nu}_R}}$$

- Assume mass of RH sneutrino is free parameter (even in sneu-CMSSM)
- Note that natural for sneutrinoR to be lightest particle as its mass does not evolve much with energy contrary to other sfermions.

- Sneutrino not thermalized in early universe – its interactions are too weak
- One possibility for DM is production through decays of sparticles
- Consider the case where stau is the NLSP (here assume CMSSM relations, for general MSSM Heisig et al 1310.2825) – neutralino NLSP no distinctive LHC signature
- Lifetime of stau (2 or 3-body decay) depends on mixing in sneutrino/stau sectors =- from a few seconds to 10^{11}s.

$$\Gamma_{\tilde{\tau}_1 \to \tilde{\nu}_R W} = \frac{g^2 \tilde{\Theta}^2}{32\pi} |U_{L1}^{(\tilde{\tau}_1)}|^2 \frac{m_{\tilde{\tau}_1}^3}{m_W^2} \left[1 - \frac{2(m_{\tilde{\nu}_R}^2 + m_W^2)}{m_{\tilde{\tau}_1}^2} + \frac{(m_{\tilde{\nu}_R}^2 - m_W^2)^2}{m_{\tilde{\tau}_1}^4}\right]^{3/2}$$

- Decay of NLSP (MSSM-LSP) after freeze-out
- Relic density obtained from that of the NLSP – can be charged

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

Model parameters and constraints

- CMSSM + RH neutrino
- Scan range

$$m_0 < 2500\,\mathrm{GeV}\ ; \quad m_{1/2} < 2500\,\mathrm{GeV}\ ; \quad |A_0| < 3000\,\mathrm{GeV}$$

  - and at elevtroweak scale

$$0 < m_{\tilde{\nu}_R} < m_{\tilde{\tau}_1}\ ; \quad 5 < \tan\beta < 40$$

- M_gluino > 1.8TeV
- Collider constraints – Higgs mass and couplings;
- Flavour constraints b-sγ, Bs-μμ,B-τυ;
- Susy searches (mostly not valid because stau is collider stable and charged);
- Charged stable stau m>340 GeV (from CMS Run 1 search)
- 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)allow 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
- At high T, weak interaction rates were in thermal equilibrium and n/p~1

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

- At lower T : weak interactions fall out of equilibrium
- Freeze-out when interaction rate $\Gamma_{weak} < H$, 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

$$p + n \rightarrow D + \gamma$$

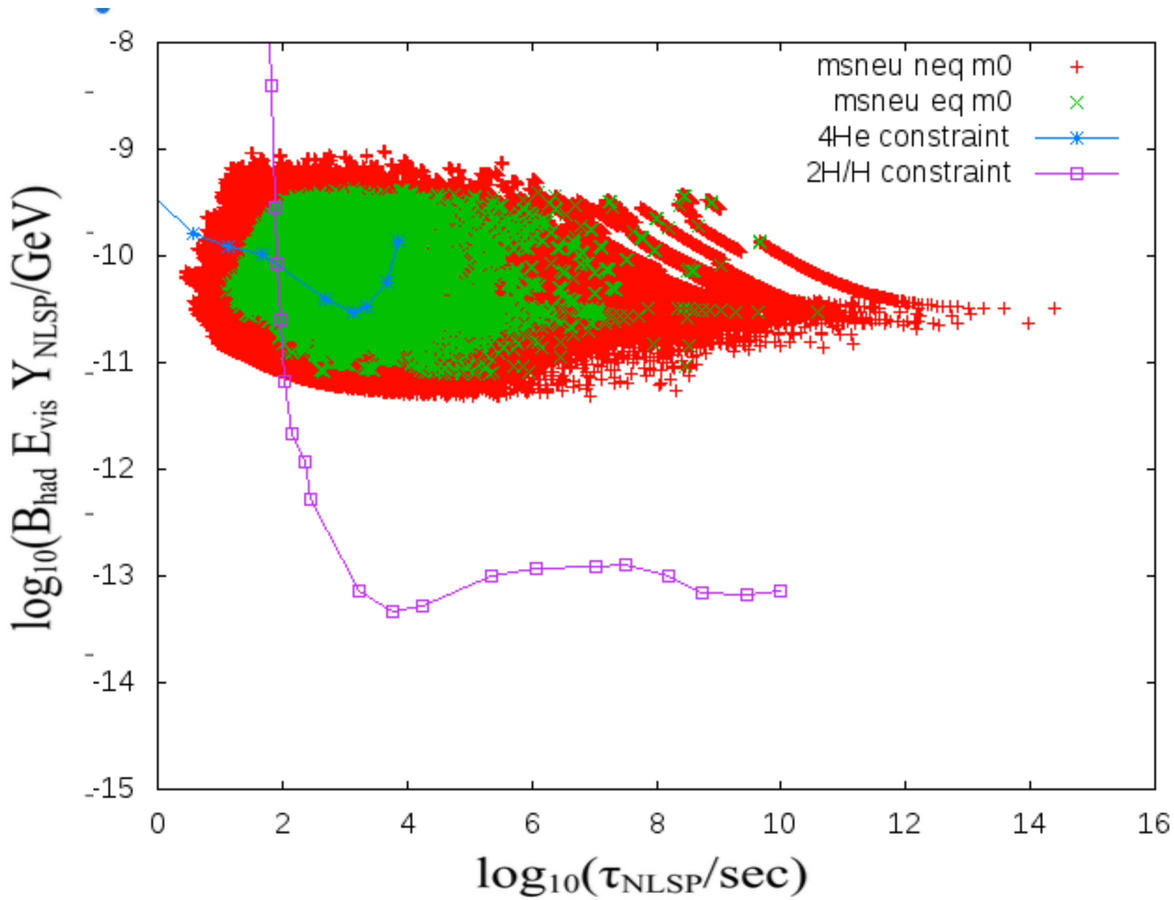
- … and the chain continues with production of heavier elements
- Relationship between expansion rate of Universe (relate to total matter density) and density of p and n (baryonic matter density) determine abundance of light elements

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

- Main product of BBN ^{4}He
- Other elements produced in lesser amounts D, ^{3}He, ^{7}Li

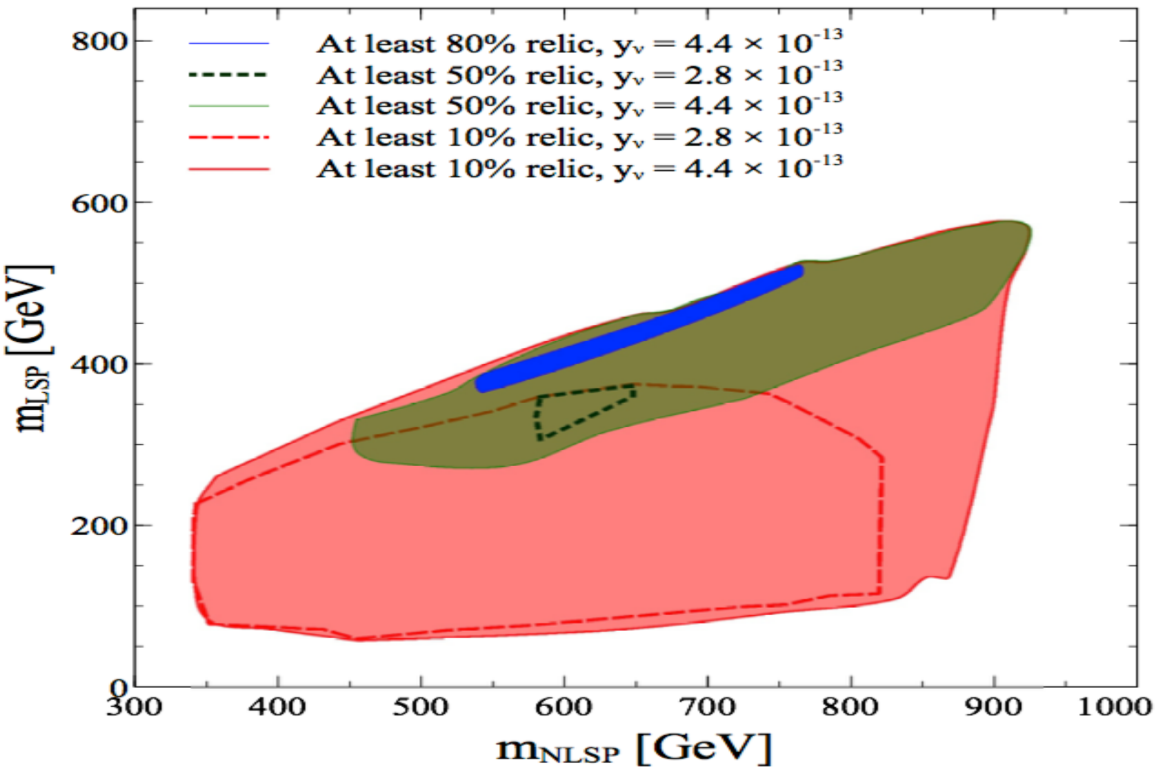
- If particle with lifetime > 0.1s decays can cause non-thermal nuclear reaction during or after BBN – spoiling predictions – in particular if new particle has hadronic decay modes
    - Kawasaki, Kohri, Moroi, PRD71, 083502 (2005)
- Alteration of n/p ratio - for example . $\pi^- + p \rightarrow \pi^0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



Allowed region

- After all constraints – room for sneutrinoR DM (even in CMSSM)
- Can constitute dominant dark matter component



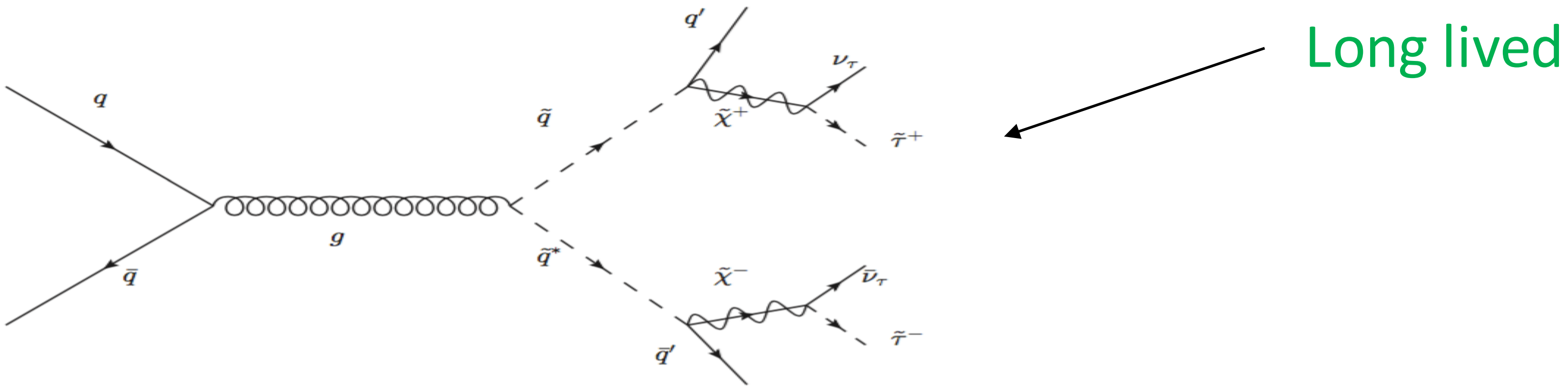
Banerjee, GB, Mukhopadyhyay, Serpico, 1603.08834

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)
- Signal computed with Spheno+ Madgraph5aMC@NLO + Pythia+Delphes3+prospino k-factors
- Background : tt,μμ+jets, WW,WZ strongly suppressed with cuts
- Use approach suggested in Gupta et al PRD75075007 (2007)

Banerjee, GB, Mukhopadyhyay, Serpico, 1603.08834

Charged tracks from cascades (2)

- Luminosity required for 5sigma
- Fairly easy to discover if mass stau < 400 GeV
- Luminosity 1ab^{-1} can probe mass ~580GeV
- Dependence on mass of squarks

Benchmark point	$\mathcal{L}$ for 5σ [fb^{-1}]	N_S	N_B	N_S/N_B
357 GeV	9.1	25	0.35	72
400 GeV	2.5	25	0.09	265
442 GeV	68.5	27	2.7	10
600 GeV	1100	48	43	1.1

Pair production

- No model dependence – only mass of stau
- Smaller cross section (EW only)
- Background : muon pairs
- Best cuts – close to current ATLAS analysis -JHEP1501 (2015) 068
- Lower reach than previous channel

$\mathcal{L} = 3000\ \text{fb}^{-1}$

Cut	Benchmark	N_S	N_B	N_S/N_B	$\mathcal{S}$
$\Delta R(\mu\mu) > 0.4$	357 GeV	1543		0.44	21.8
$\beta < 0.95$	400 GeV	1014	3481	0.29	15.1
$p_T^{\mu_{1,2}} > 70\text{GeV}$	442 GeV	715		0.21	11.0
$\lvert y(\mu_{1,2})\rvert < 2.5$	600 GeV	211		0.06	3.5

Banerjee, GB, Mukhopadyhyay, Serpico, 1603.08834

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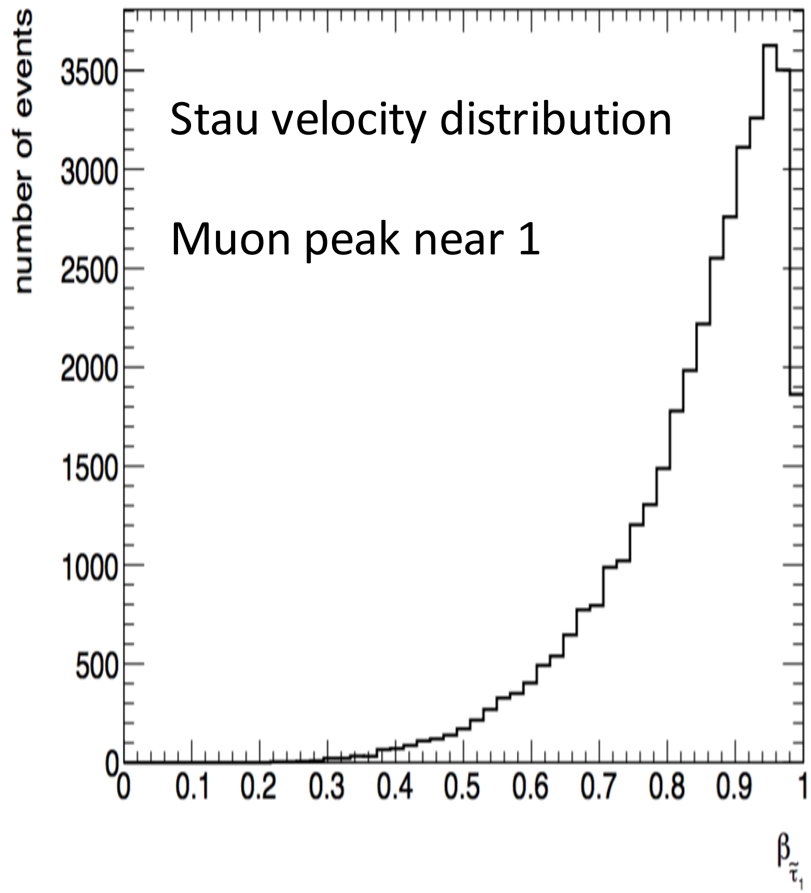

Cut	Benchmark	
$\Delta R(\mu\mu) > 0.4$	357 GeV	1
$\beta < 0.95$	400 GeV	1
$p_T^{\mu_{1,2}} > 70\text{GeV}$	442 GeV	
$\lvert y(\mu_{1,2})\rvert < 2.5$	600 GeV	

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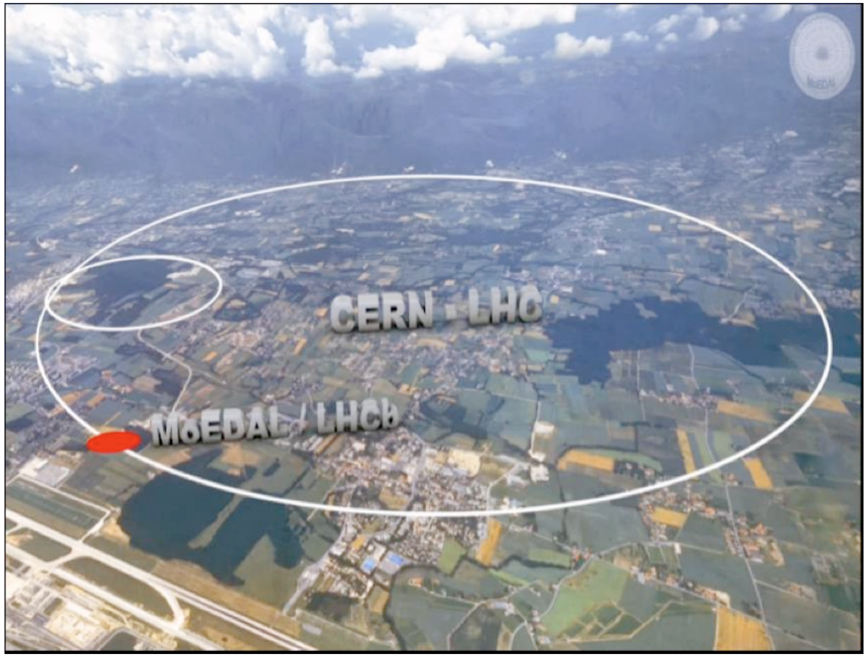
MoEDAL detector



- 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 $\beta<0.2$

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 $\mathcal{L} = 3000\,\text{fb}^{-1}$

CONCLUSION

Sneutrino viable very weakly interacting DM candidate in supersymmetry

LHC has unique potential to probe a whole class of DM models that predict heavy stable charged particles

BBN constraints are important

Class of model with few signatures in astroparticle searches

Charged tracks from cascades (2)

- $p_T^{\mu_{1,2}} > 200$ GeV, $|y(\mu_{1,2})| < 2.4$,
- $p_T^{j_{1,2}} > 200$ GeV, $|\eta(j_{1,2})| < 5.0$,
- $\sum |p_T^{vis.}| > 1000$ GeV,
- $\Delta R(\mu_1, \mu_2) > 0.2$,
- $\Delta R(j, j) > 0.4$,
- $\Delta R(\mu, j) > 0.4$,
- $M_{\mu_1,\mu_2} > 1000$ GeV,