Open problems in dark matter phenomenology

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LAPTH Annecy-le-Vieux

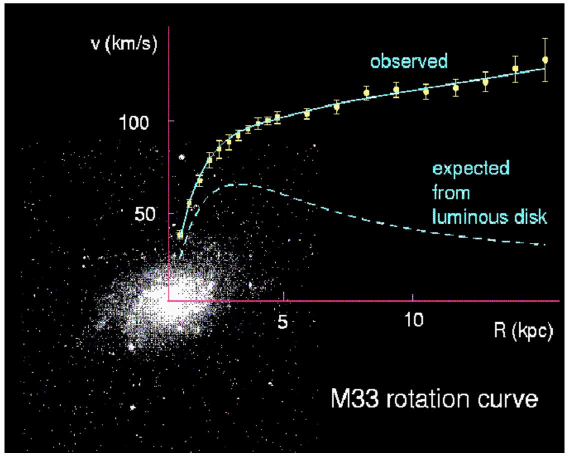
DMAstroLHC

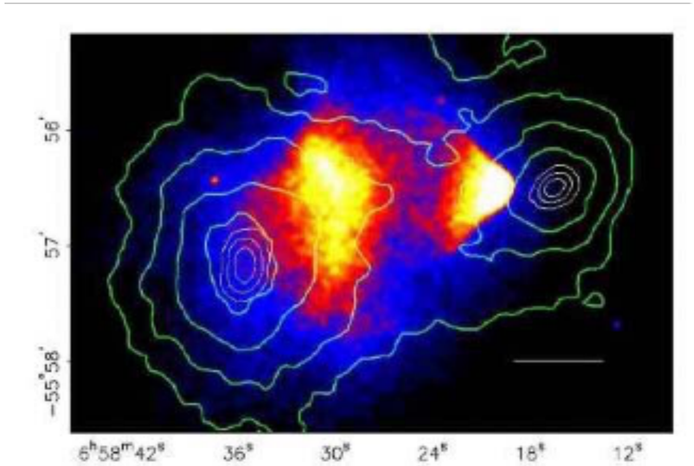
GGI, Firenze, 29 August 2017

What do we know about dark matter?

It has gravitational interactions (galaxies – rotation curves- galaxy clusters, - Xray, gravitational lensing)

No electromagnetic interactions



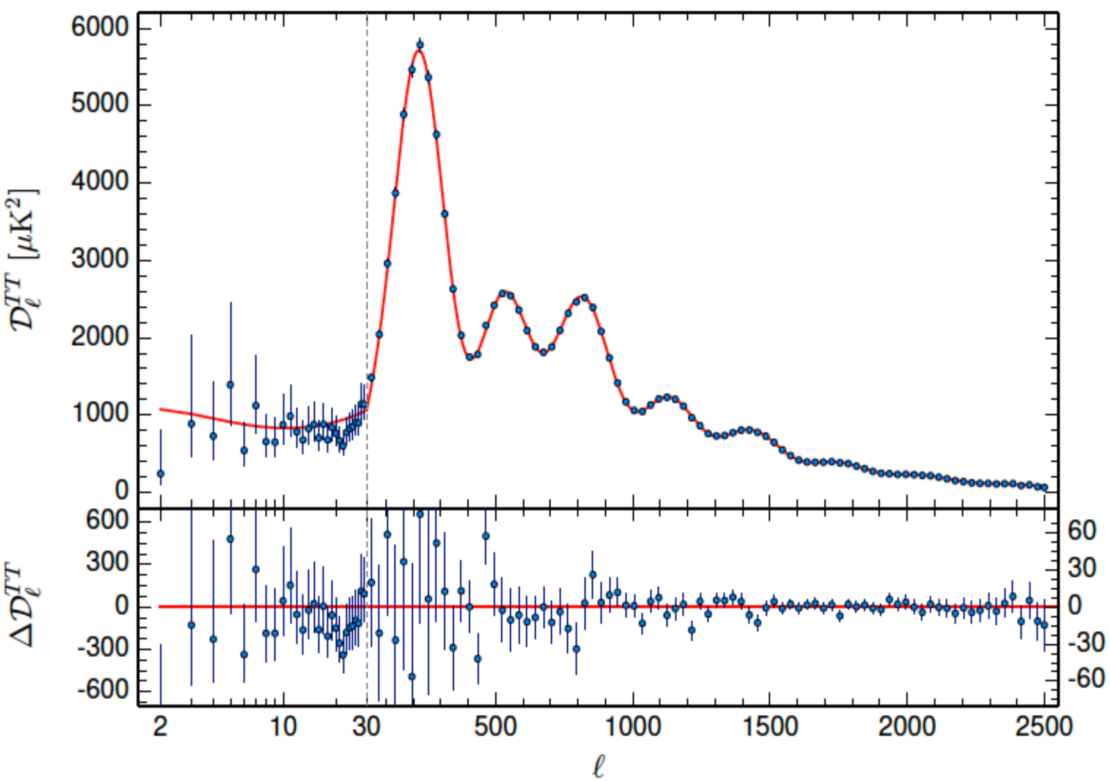


It is cold (or maybe warm) and collisionless

What do we know about dark matter?

Within ΛCDM model – precisely know its relic density

$\Omega_{cdm} h^2 = 0.1193 +/- 0.0014$ (PLANCK – 1502.01589)



That’s it !!

Leaves us with a lot of possibilities for dark matter

In particular from the particle physics point of view

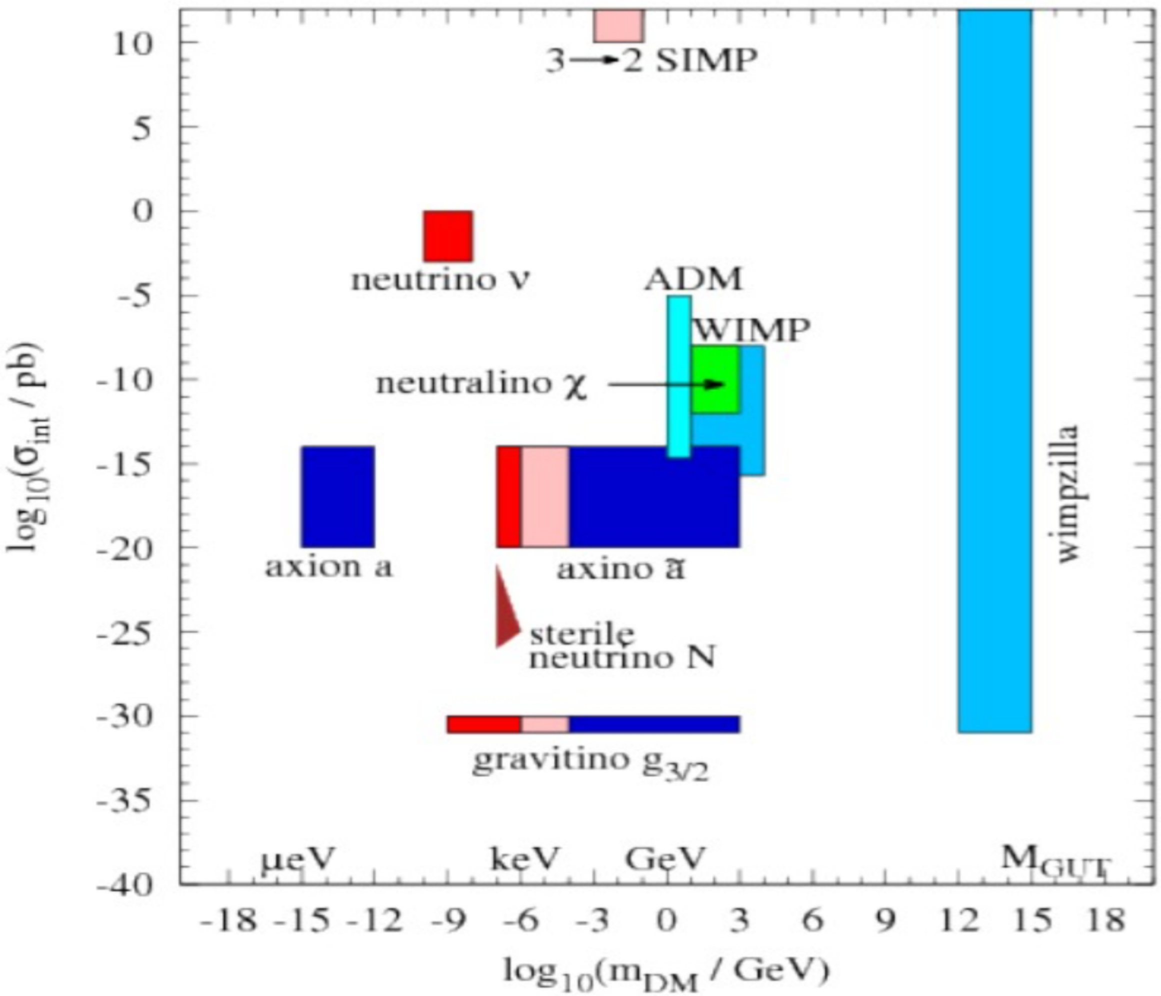
(Cannot be baryons, neutrinos (too hot))

Open problems

- Is DM a new particle : a fermion, a scalar, a vector? an elementary particle?
- DM mass and interaction strength?
- One or more dark matter particles?
- Large Self-interactions?
- DM/anti-DM asymmetry related to baryon asymmetry?
  - Density depends on initial asymmetry and freeze-out
- Primordial Black Hole?
  - Revived from LIGO grav.wave obs, I. Cholis et al, PRL116, 201301(2016)
  - Could make up all of the DM, Kuhmel, Freese, PRD95, 083508 (2017)

- What can we learn from collider -astroparticle experiments?

Mass scale/Interaction scale



- WIMPs
- FIMPs
- SIMPs
- GIMPs
- Asymmetric
- SIDM

L. Roszkowski

Progress in last 20 years

- 20 years ago we knew what DM was made of: neutralino in supersymmetry
- R parity needed to avoid proton decay predicts a stable LSP – WIMP
  - We knew how to look for it, Direct detection, indirect detection, LHC
  - Planned to measure its properties : use collider information and confront with signals from (in)direct detection
    - Baltz, Battaglia, Peskin, PRD74 (2006) 103521
    - Allanach, GB, Boudjema, Pukhov JHEP 0412(2004)020
  - Were expecting lots of new particles at TeV scale as soon as LHC turned on - but no excess!!

We know much less

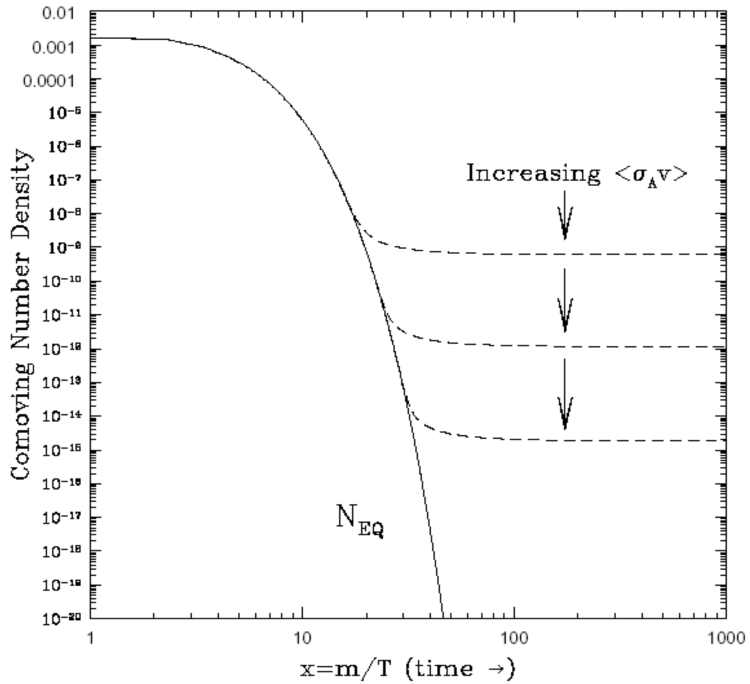
- No sign of DM in particle/astroparticle (a few hints)
- Strong constraints from colliders, (in)direct detection
- Much wider range of possibilities being considered

WIMPs

- One class of candidates : weakly-interacting massive particles
- Lead to roughly correct amount of DM
- Thermal equilibrium in early Universe

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

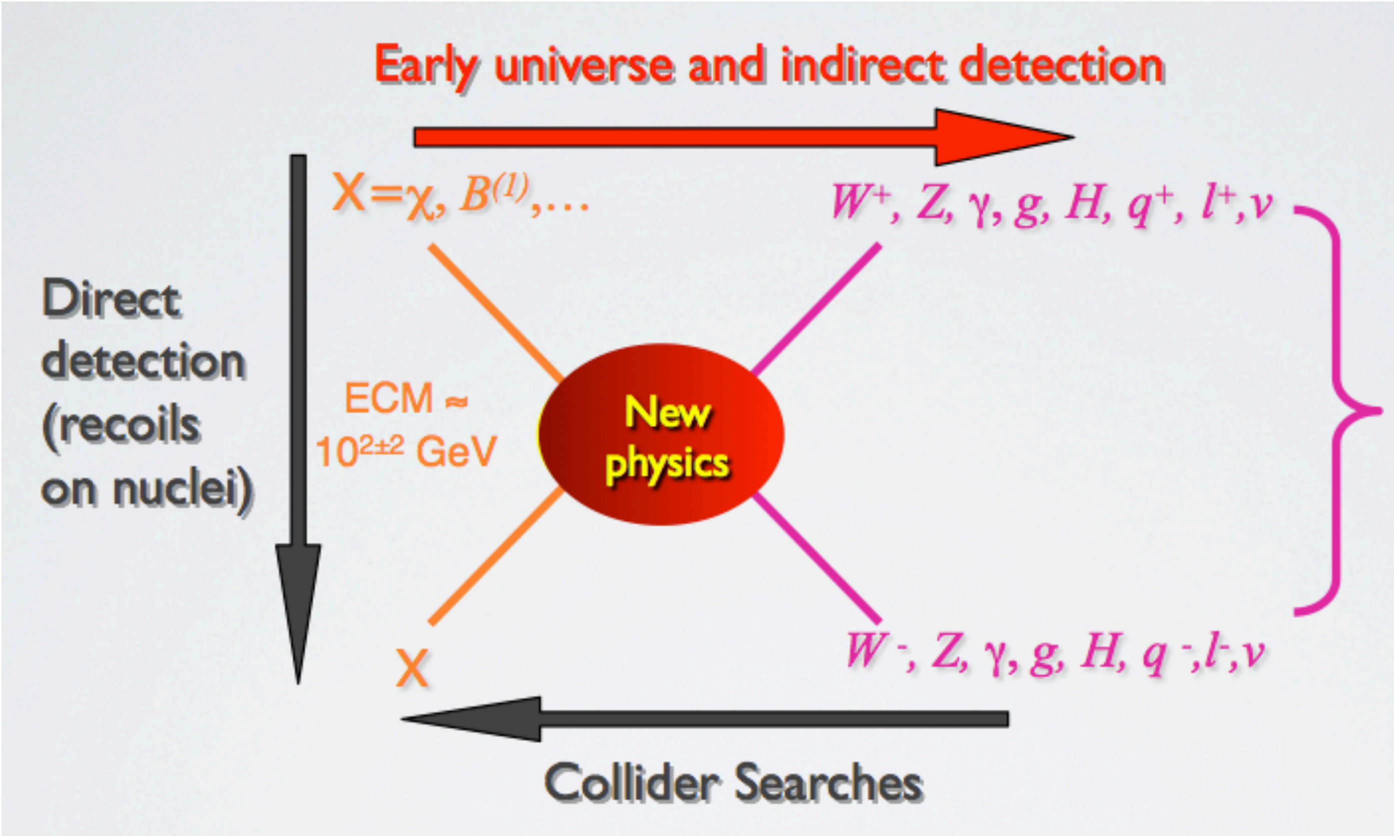
$$\Omega_\chi h^2 \approx \frac{3\times 10^{-27}\mathrm{cm}^3\mathrm{s}^{-1}}{\langle\sigma v\rangle} \ .$$



- Typical weak interaction -> $\Omega h^2 \sim 0.1$

- Also coannihilation when new particles nearly degenerate with DM - Boltzmann suppression $\exp(-\Delta m/T)$ can be compensated by larger cross sections

Probing the nature of dark matter



- All determined by interactions of WIMPS with Standard Model
- Specified within given particle physics model

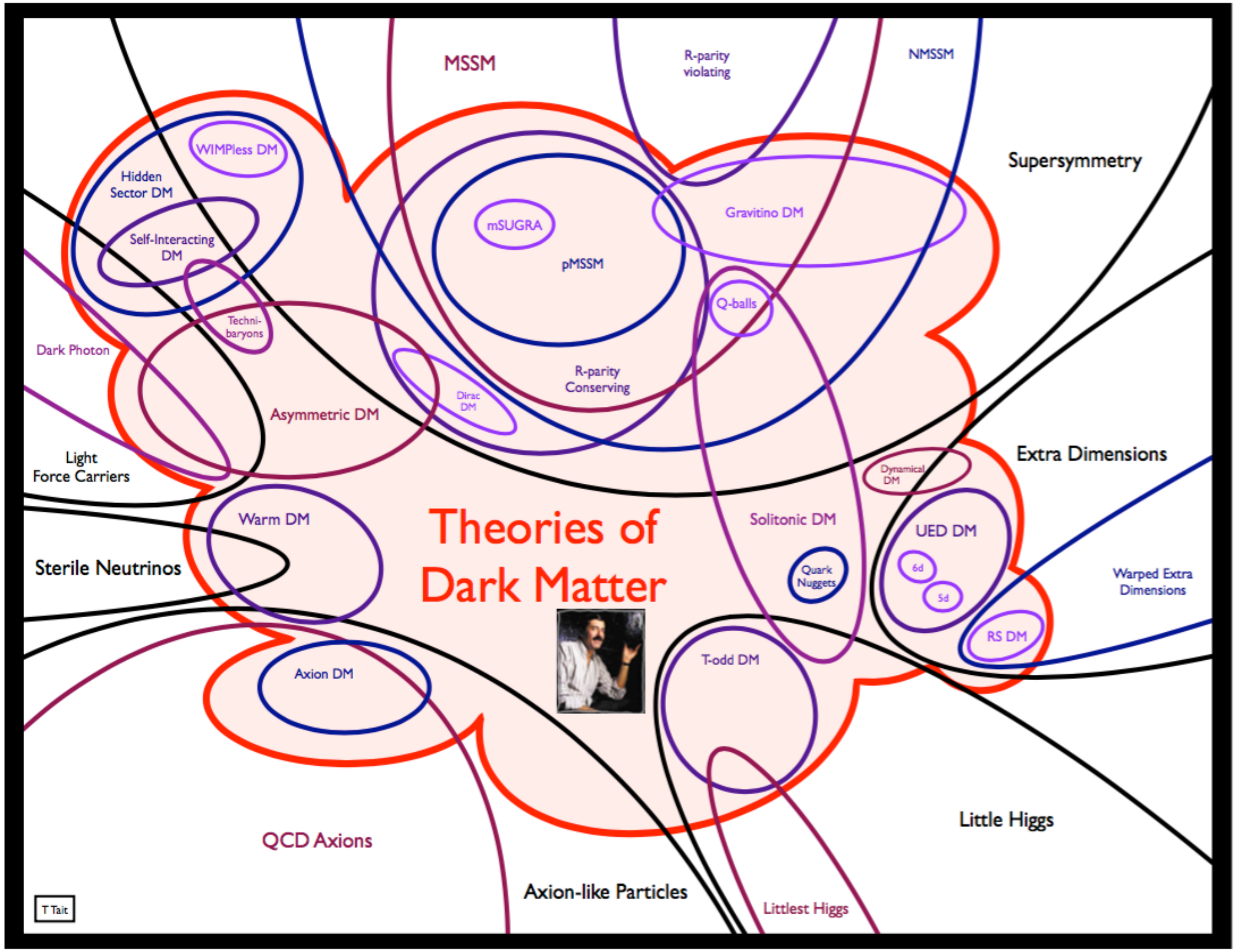

You're just going to keep looking under this light?
Well, I literally can't see anything in the dark, so yeah.
@redpenblackpen

Guidance from theory

- Is DM linked to some other problems in particle physics?
  - Symmetry-breaking/hierarchy (e.g. neutralino in SUSY)
  - Higgs (eg portals)
  - Unification
  - High-scale physics (unification or above)
  - Neutrinos (eg sneutrino)
  - Strong CP (eg axion)
  - Flavour
  - Matter-antimatter asymmetry (asymmetric DM)

- … or completely disconnected – dark sector

No shortage of DM models …



T. Tait

Guidance from experiments

- Indirect detection : gamma-ray from GC (Goodenough,Hooper,2009)
- Fermi-LAT confirms the GC excess, origin elusive: Fermi bubbles, interactions of CRs with sources near GC, undetected sources like millisecond pulsars or DM. DM-like excess in control region in galactic plane where no DM signal is expected - Ackermann et al 1704.03910
- DM interpretation of the GC excess cannot be robustly claimed.

- 3.5keV line in XMM-Newton Xray data from clusters of galaxies (Bulbul et al, APJ789, 13, 2014) or from GC (Jeltema,Profumo, MNRAS450, 2143, 2015) BUT no line found by XMM-Newton in Draco DSph – limit on line flux rules out at 99%CL DM decay as explanation (Jeltema, Profumo, 1512.01239)

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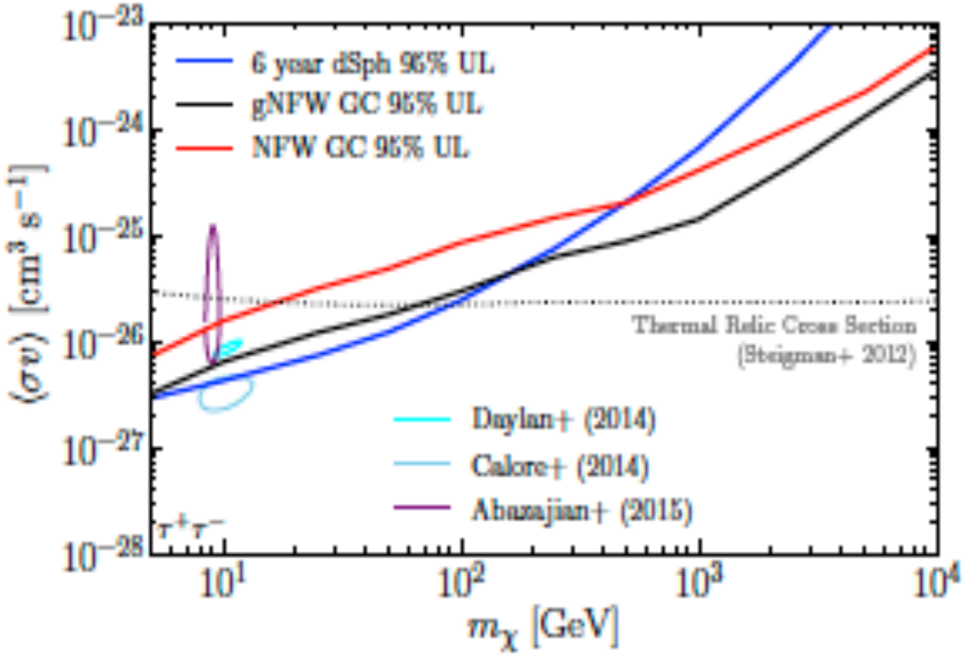

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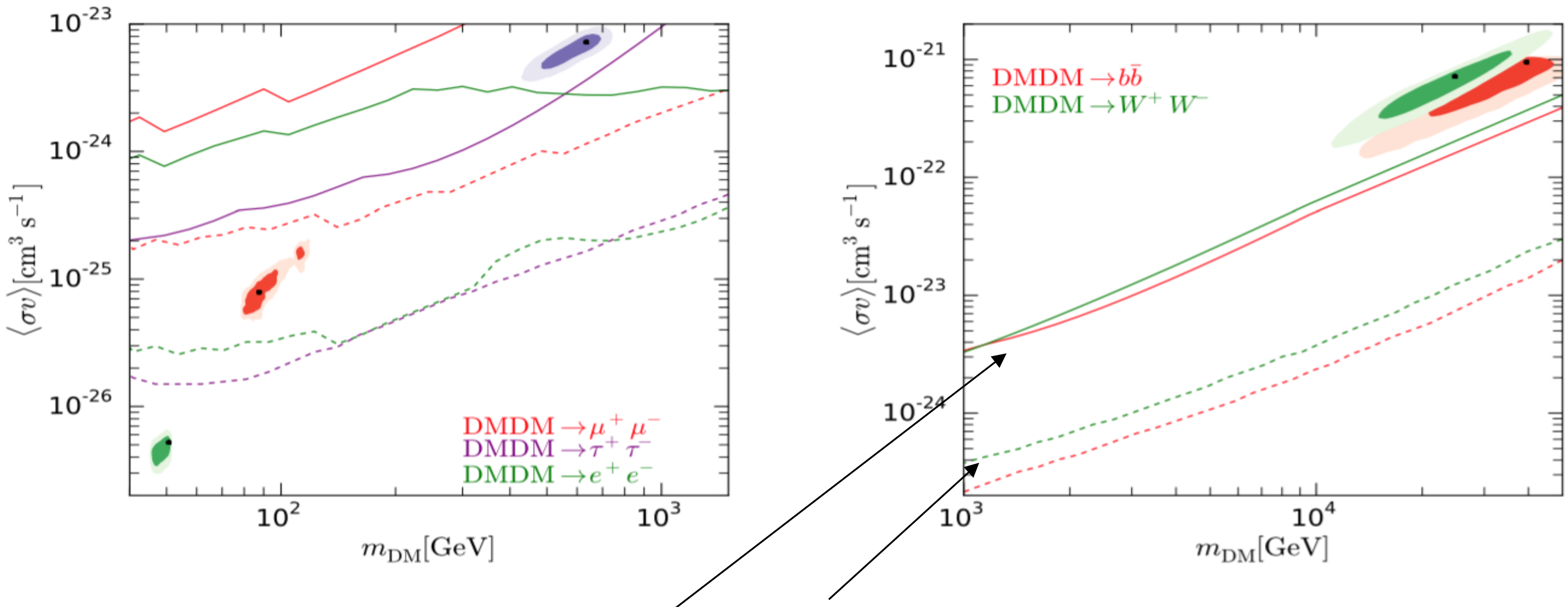
Guidance from experiments

- Positron excess : PAMELA, AMS
- Excess can be fitted with pulsars or DM (requires large cross-section – in tension with other constraints from gammas, antiprotons).
- Include pulsars+DM -> constraints on DM

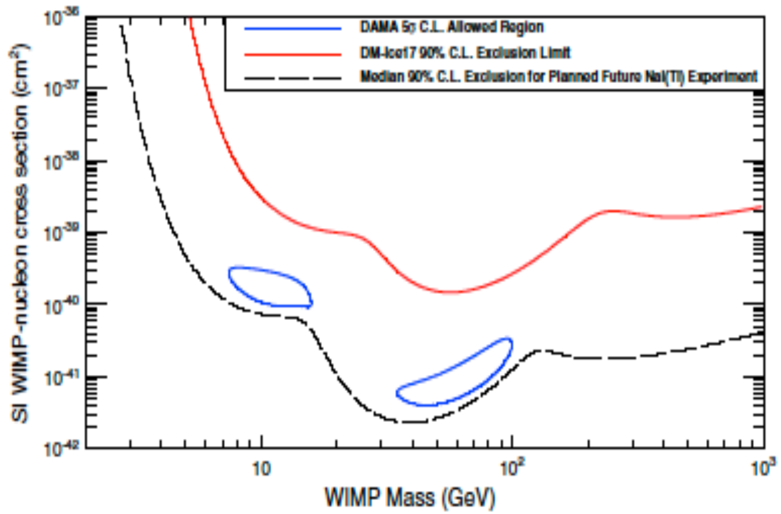


– FermiLAT (cons and optimistic)

Di Mauro et al, arXiv:1507.07001

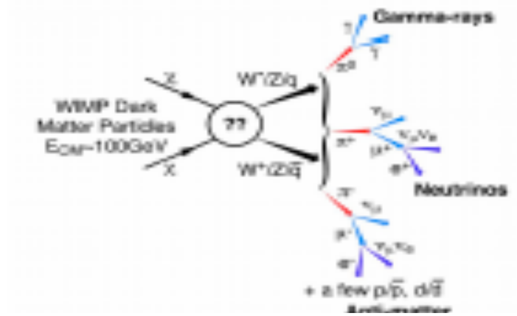
Guidance from experiments

- Direct detection : DAMA long standing signal in annual modulation – incompatible with other direct searches — DM annual mod signal independent of location (seasonal variation opposite in phase)
- DM-Ice17 first run in South pole - no modulation observe
- Cosine100 (expect DAMA sensitivity in 2 years), ANAIS, PICO-LON and SABRE all using NaI



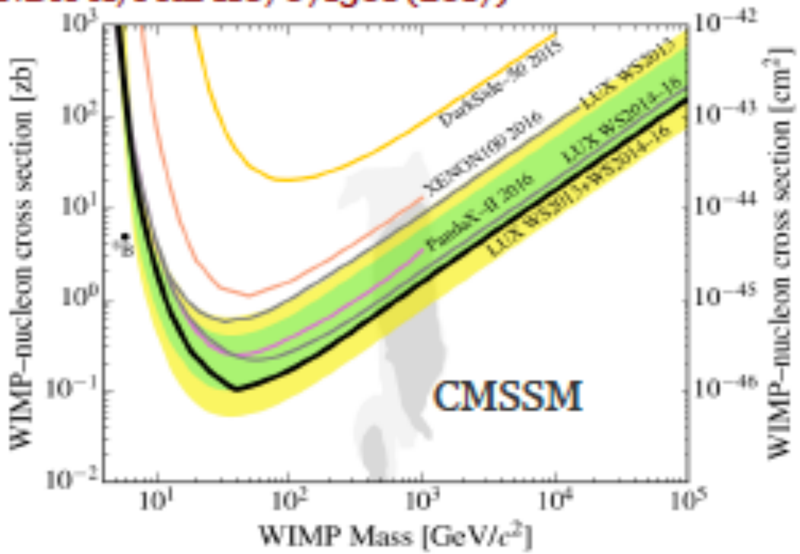
Barbosa de Souza, PRD95 032006 (2017)

Limits DM searches



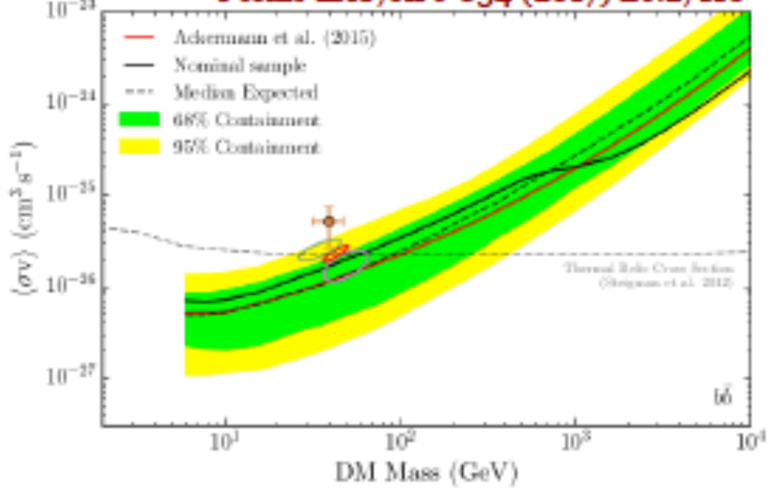
Continuum

LUX, PRL 118, 021303 (2017)
PANDA-X, PRL 118, 071301 (2017)



Fermi-LAT limit from dSPhs

Fermi-LAT, APJ 834 (2017) no.2, 110



Sensitive enough to probe DM models
Ongoing – Xenon1T
m<10GeV more challenging

Gamma rays from Dwarfs – robust limits
Probe generic annihilation cross section
for DM below ~70GeV

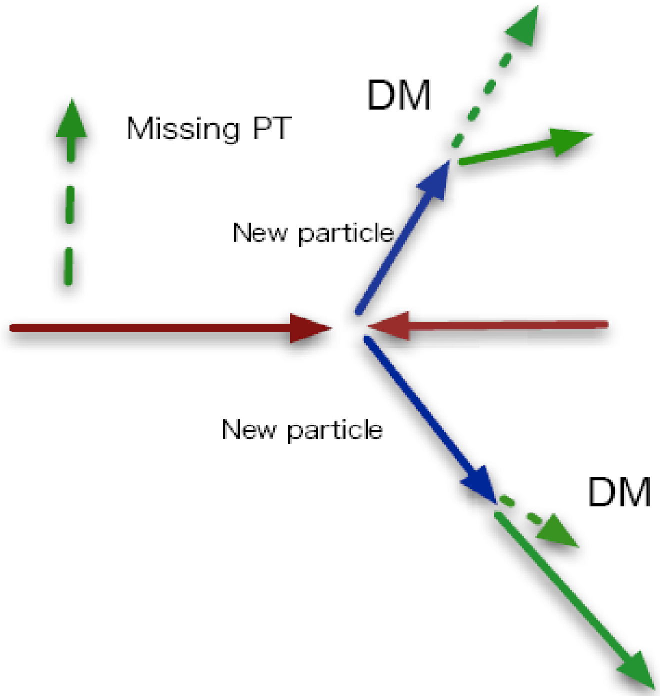
Searches for dark matter at the LHC
What have we learned?

Can only check for a stable particle at the colllider scale not cosmological scale

DM production at LHC

The traditional searches - DM in decay chain of new particles preferably coloured or charged, e.g. neutralino in SUSY

Signature : MET + jet, leptons… model dependent

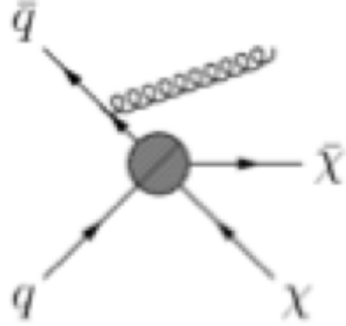


DM production at LHC

The model independent approach

Direct production of DM and Initial state radiation of gluon, photon.. serves as a trigger : monojet, monophoton, monoX

Signature : jet + large missing ET



(a) $q\bar{q} \to \chi\chi + g$

DM production at LHC

Exploiting the Higgs : search for invisible decays of the Higgs (relevant only if $m_{DM}<m_h/2$)

Charged tracks and displaced vertices - for long-lived–next-lightest dark sector particle : typically small mass splitting or very weak interactions

Search for new particle (mediator) in SM final states

Is DM supersymmetric?

Motivation: unifying matter (fermions) and interactions (mediated by bosons)

Prediction: new particles supersymmetric partners of all known fermions and bosons : differ spin 1/2

Not discovered yet

Hierarchy problem

SUSY particles can stabilize Higgs mass against radiative corrections

Quadratic divergences in Higgs mass corrrections cancelled when SUSY broken softly, TeV scale →should be within reach of LHC

R-parity to prevent proton decay -> LSP stable ->dark matter

MSSM : Minimal field content : partner of SM particles and two higgs doublets (for fermion masses)

Neutralinos : neutral spin ½ partners of gauge bosons (bino,wino) and Higgs scalars (higgsinos)

$$\tilde{\chi}_1^0 = N_{11}\tilde{B} + N_{12}\tilde{W} + N_{13}\tilde{H}_1 + N_{14}\tilde{H}_2$$

The neutralino mass matrix

$$\mathcal{M}_{\tilde{\chi}} = \begin{pmatrix} M_1 & 0 & -M_Z\cos\beta\sin\theta_W & M_Z\sin\beta\sin\theta_W \\ 0 & M_2 & M_Z\cos\beta\cos\theta_W & -M_Z\sin\beta\cos\theta_W \\ -M_Z\cos\beta\sin\theta_W & M_Z\cos\beta\cos\theta_W & 0 & -\mu \\ M_Z\sin\beta\sin\theta_W & -M_Z\sin\beta\cos\theta_W & -\mu & 0 \end{pmatrix}$$

Mass and nature of neutralino LSP : determined by smallest mass parameter

$M_1 < M_2, \mu$ bino

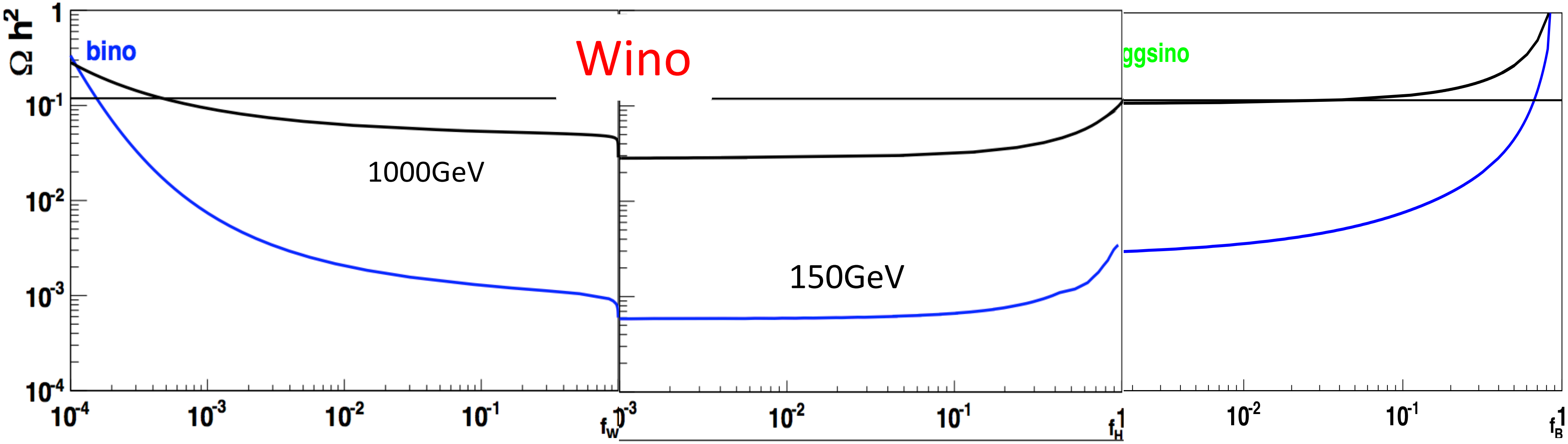
$\mu < M_1, M_2$ Higgsino (in this case $m\chi_1 \sim m\chi_2 \sim m\chi_+$)

$M_2 < \mu, M_1$ wino

Determine couplings of neutralino to vector bosons, scalars…

Neutralino DM

Neutralino is mixed state – exact nature will determine its annihilation properties
Vary μ, M_1, M_2 to change nature of LSP, $\tan\beta = 10$, all other SUSY parameters set to 4TeV



In general neutralino LSP can only be subdominant DM component unless TeV scale

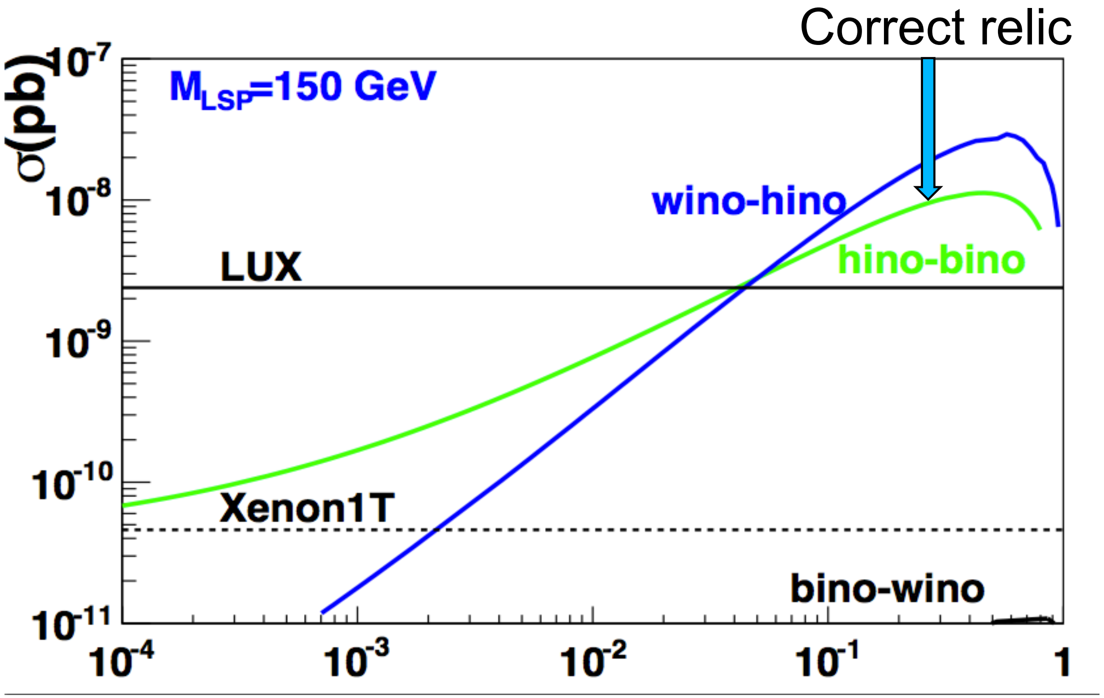
Exception : bino overdominant

Higgsino and wino mean degenerate particles

μ at TeV scale is not natural from Higgs points of view (low fine tuning leads upper bound on μ <700GeV – Casas et al, 1407.6966)

Direct detection

Xenon1T will probe large regions of parameter space



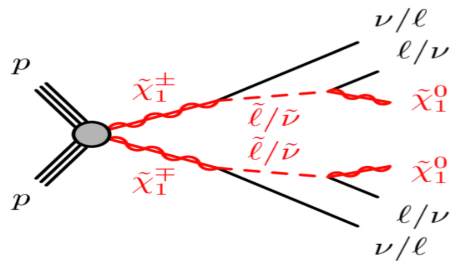
- Coupling of LSP to Higgs maximal for mixed gaugino/higgsino

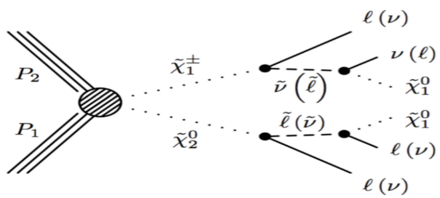
$$g_{h\chi\chi} = g(\mathcal{N}_{\chi 2} - t_W \mathcal{N}_{\chi 1})(\mathcal{N}_{\chi 3} \sin\alpha + \mathcal{N}_{\chi 4} \cos\alpha) .$$

Constraints from DD (LUX) on neutralinos (mixed higgsino-bino) that naturally reproduce measured relic density
Bino-wino escape detection – also TeV scale DM
Natural SUSY : μ small (higgsino content LSP)

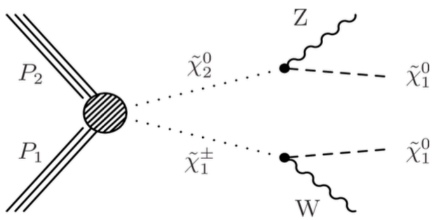
SUSY DM at LHC

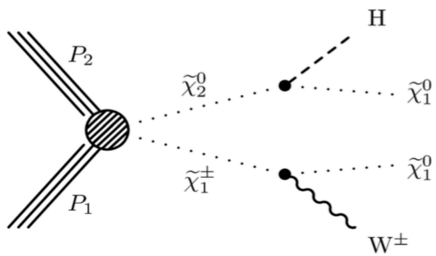
- Best limits on coloured particles ~2TeV (except compressed region)
- Direct connection with dark matter – electroweak inos
- Reach dependent on search channel (here simplified model)





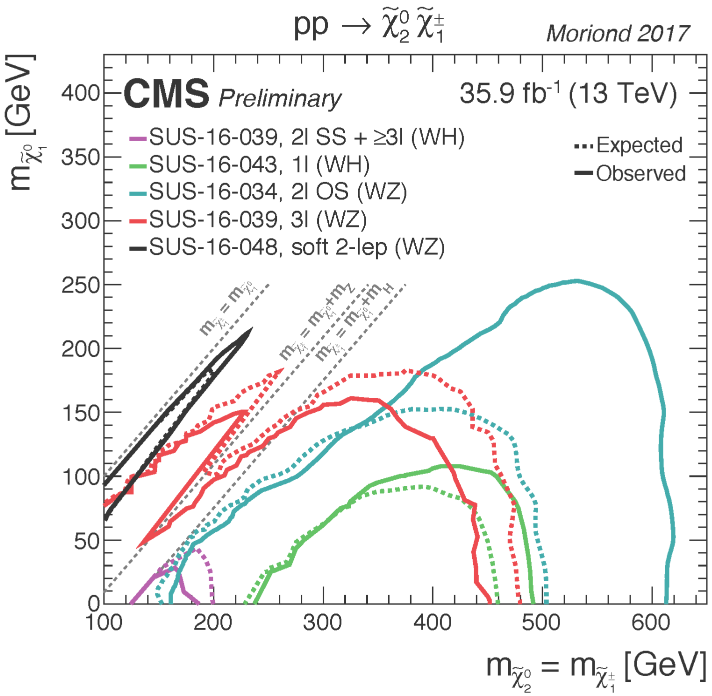
Chargino-neutralino production with
$\tilde{\chi}_1^{\pm} \rightarrow W^{\pm}\tilde{\chi}_1^0$ *and* $\tilde{\chi}_2^0 \rightarrow (Z/H)\tilde{\chi}_1^0$

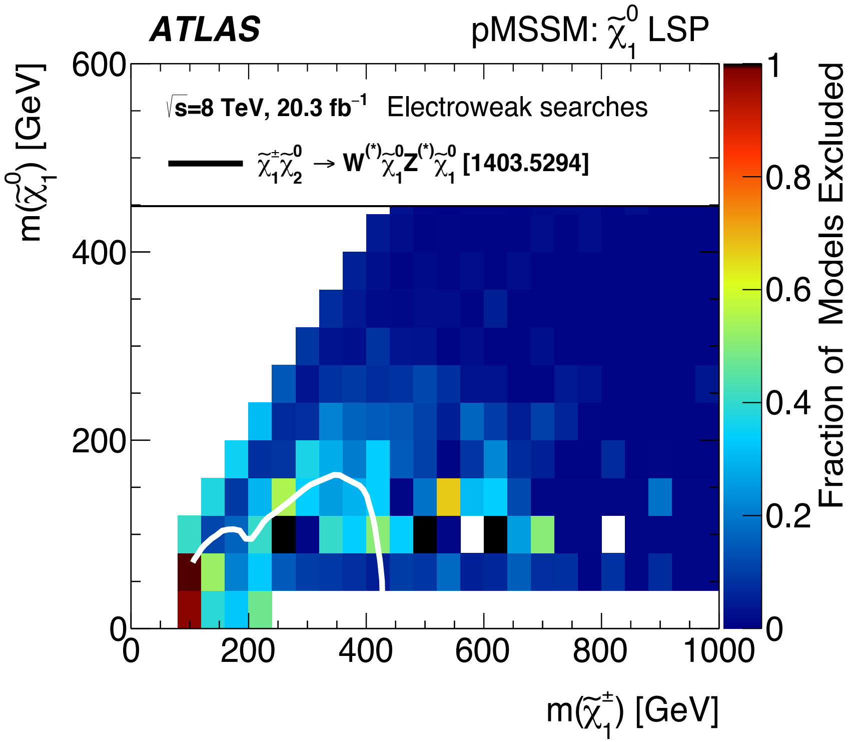




Electroweak-inos

- Weak constraints on charginos which decay into gauge bosons
- Even more so in the framework of full model (here pMSSM) – MSSM with 19 parameters





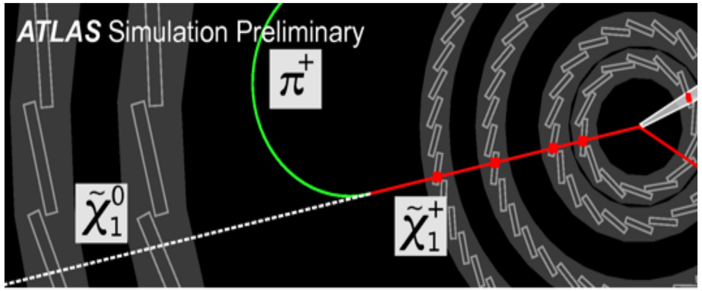
Long-lived charged particles

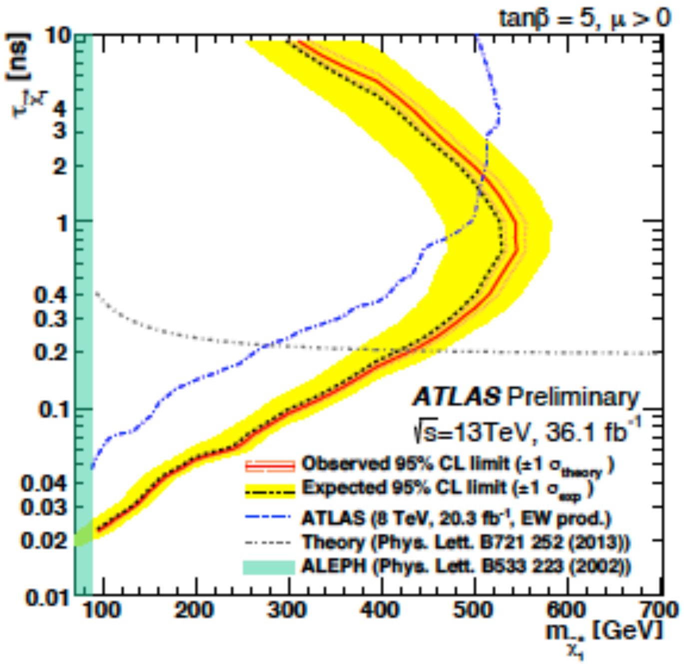
- Relevant for wino-LSP (chargino lifetime .15-.25 ns)

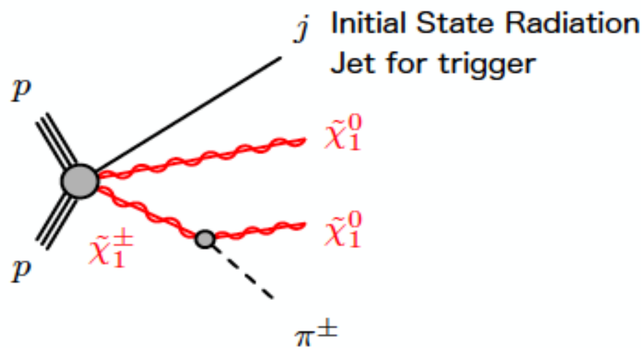
$$\tilde{\chi}_1^{\pm} \longrightarrow \tilde{\chi}_1^0 + \pi^{\pm}$$

leave hits | E_T^{miss} | Undetectable

-> disappearing track

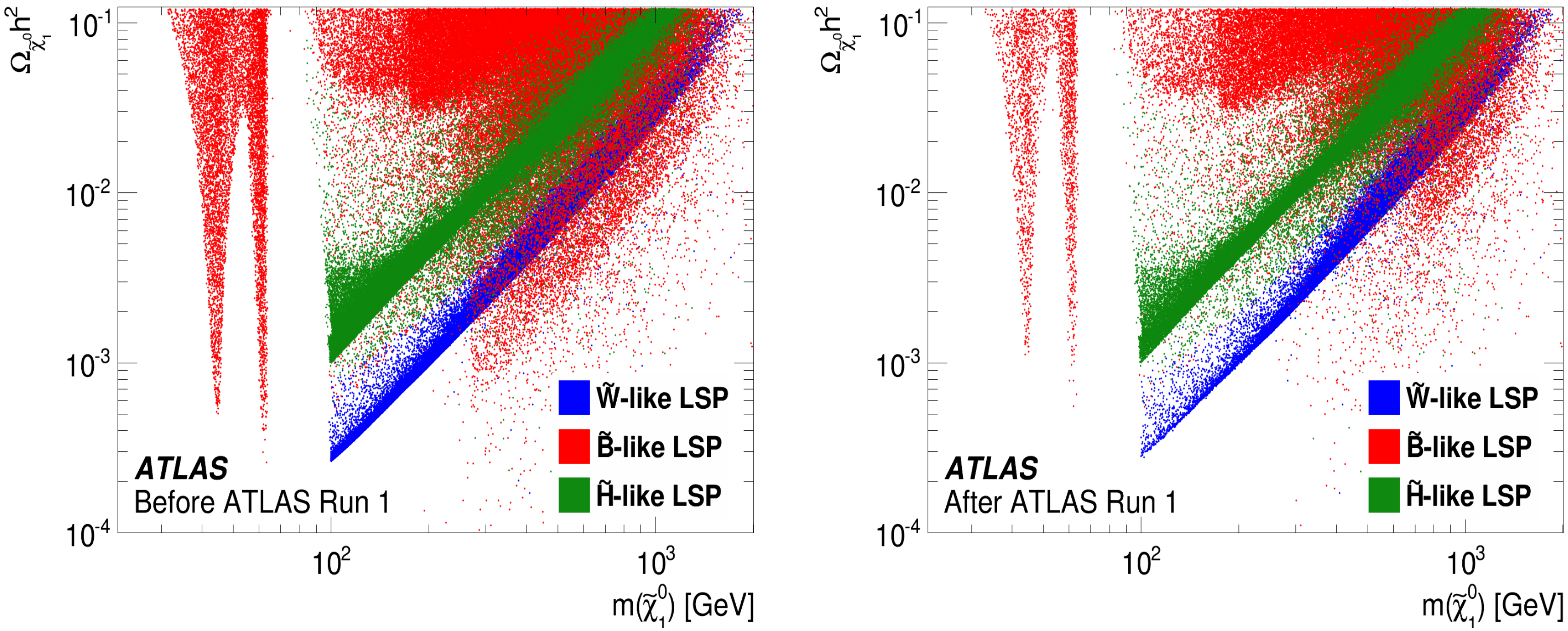






T. Kaji, Moriond 2017

What's left after LHC



(a) Before ATLAS Run 1

(b) After ATLAS Run 1

ATLAS 1508.06608

Still lot of parameter space to explore

Neutralino might only be one component of DM

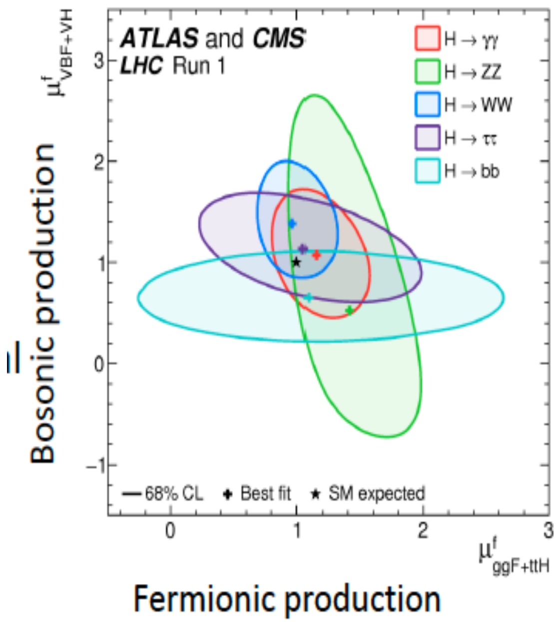
Higgs invisible

At LHC Measurement of Higgs in various production and decay modes

Global fit to Higgs couplings and comparison with SM →

Upper limit on invisible/not detected BR

Implications for any DM below 62GeV



Can be combined with direct searches for invisible Higgs

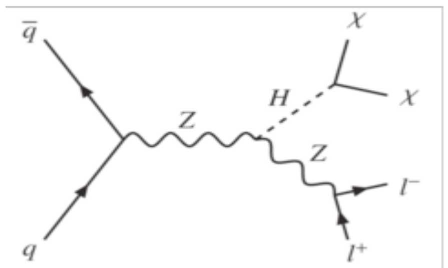
Current limits

Brinv < 28% (CMS)

Brinv < 24% (ATLAS)

Future LHC : with 3000fb^{-1} can reach 5%

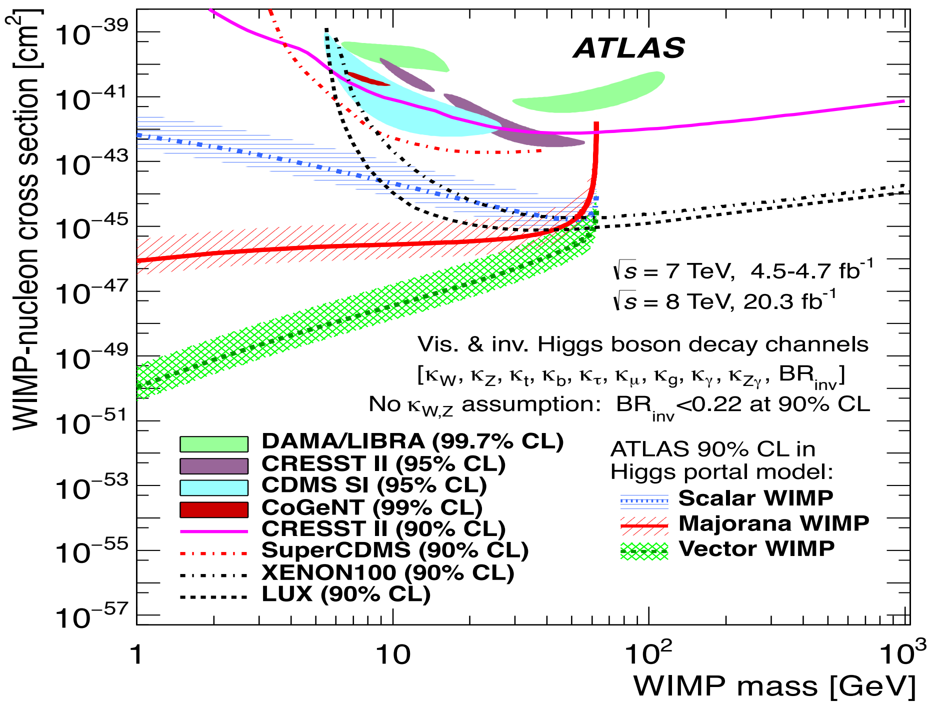
At ILC : reach 0.4%



- Generally in Higgs portal type model, both invisible width and SI cross section depend on h coupling to DM

$$\sigma_{SI} = \eta\mu_r^2 m_p^2 \frac{g^2}{M_W^2}\Gamma_{\rm inv}\left(\sum f_q^p\right)^2$$

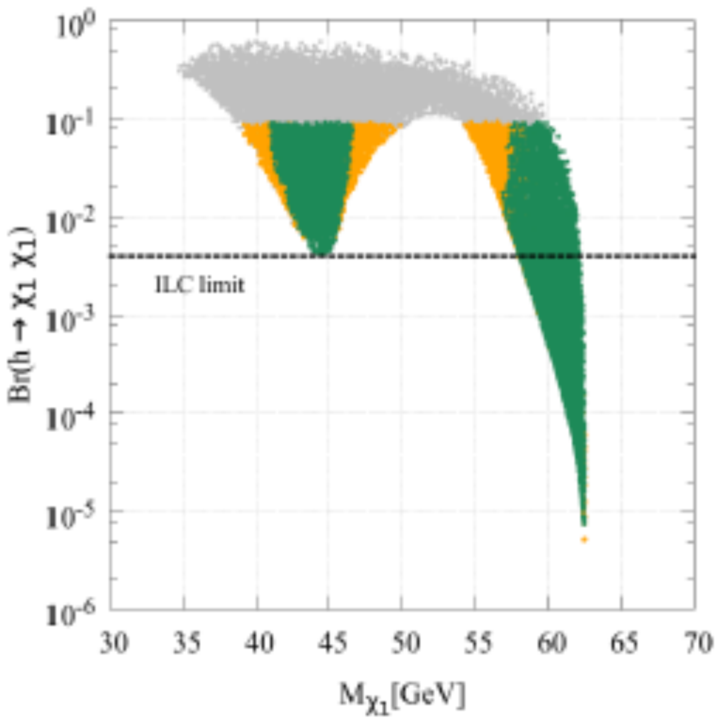
- Light DM model are constrained, Djouadi et al 1205.3169, DAMA region ruled out

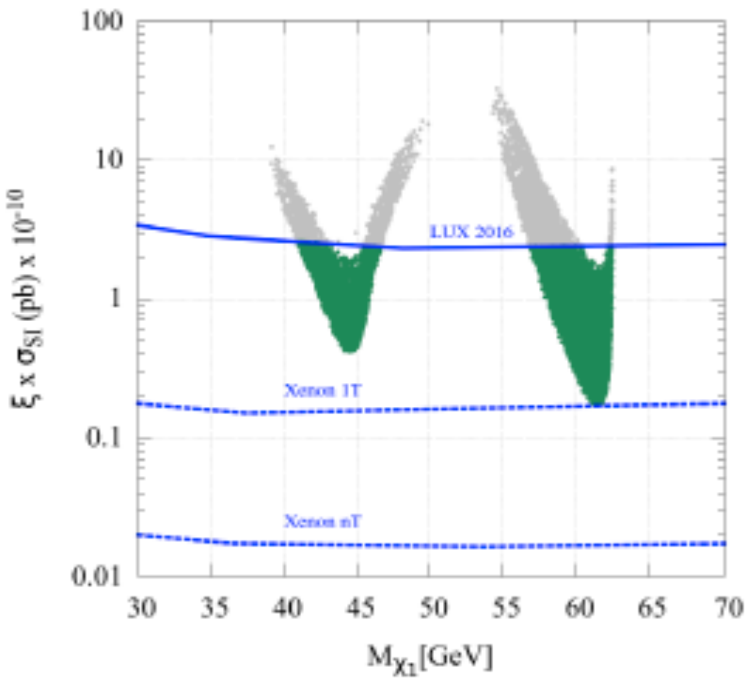


ATLAS Collaboration, arXiv:1509.00672

Invisible Higgs - future

- If neutralino DM is light (<62GeV) – contributes to invisible Higgs width
- After applying constraints from relic density (upper limit), Higgs at LHC, searches for chargino/neutralino, flavour +LEP
- Will be completely probe in ongoing direct detection searches (Xenon1T)

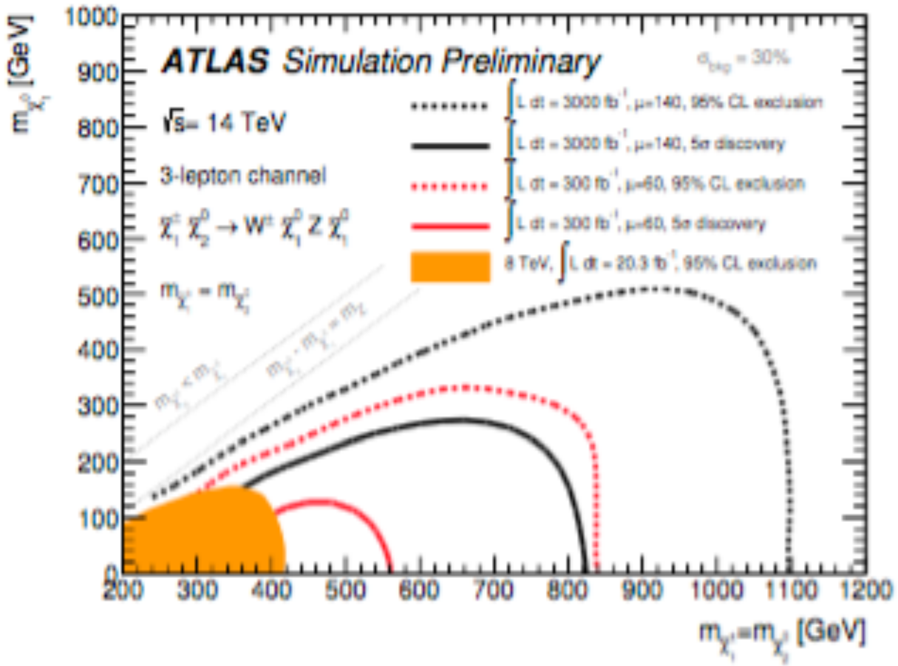


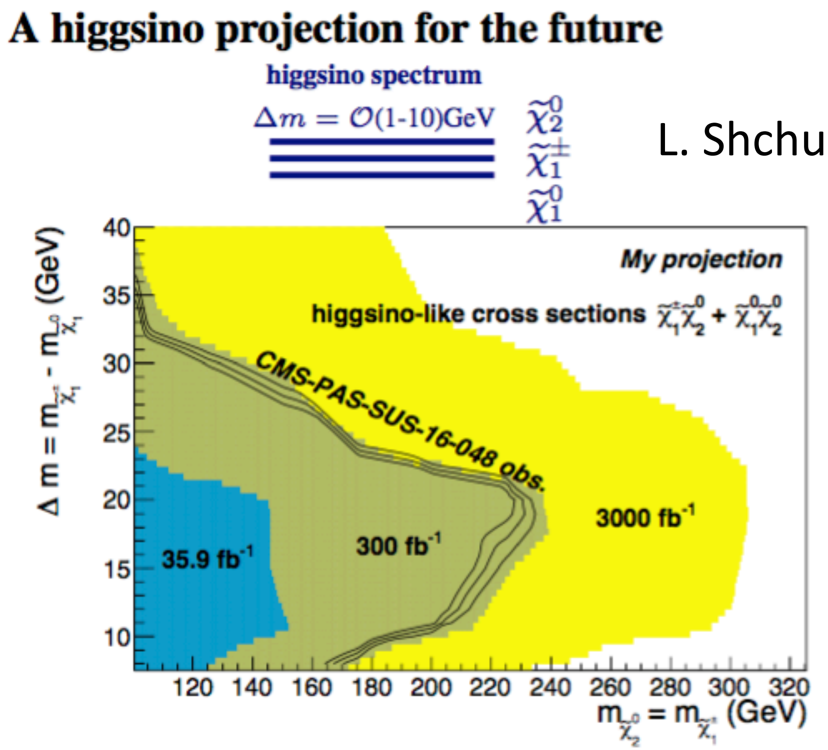


Barman, GB, Bhattacherjee, Godbole, Mendiratta, Sengupta, 1703.03838

Projections

- Much to gain with higher luminosity – since small cross section for electroweakinos





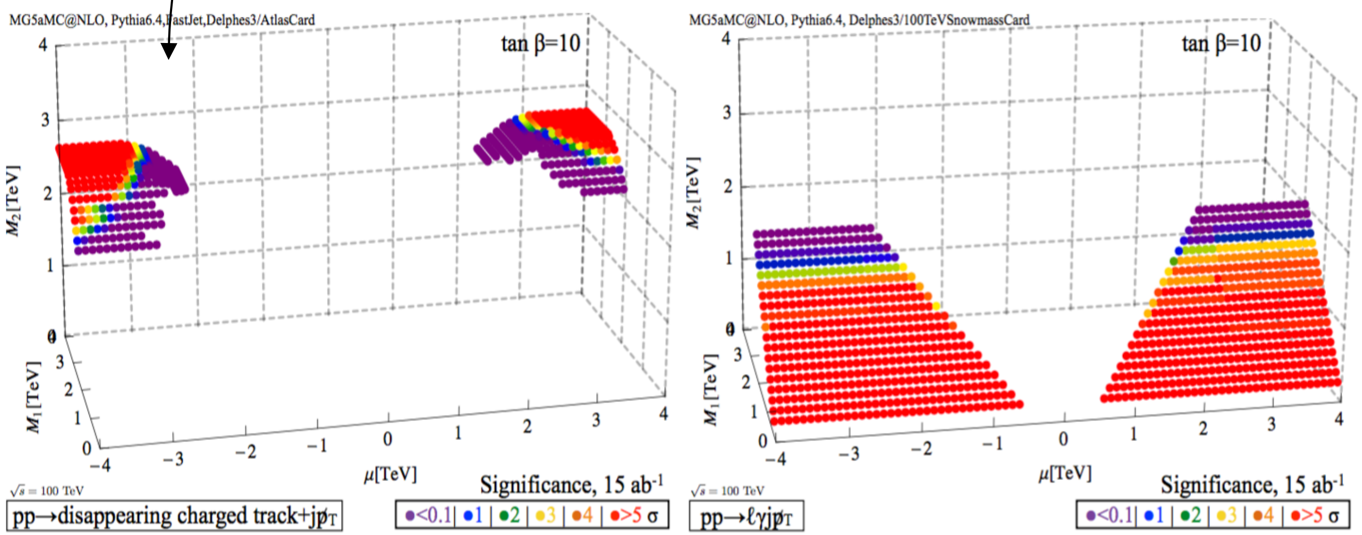
L. Shchutska

- Far from covering the DM preferred region (TeV for higgsino)

Projections

- bino - wino : fairly unconstrained – direct detection insensitive
  - If nearly pure wino : mass splitting small, chargino long lifetime ->charged tracks –@100TeVcould probe 2TeV wino (DM favoured)
  - If mixed : compressed spectra , electroweakino production

$$pp \to (\tilde{\chi}_2^0 \to \gamma \tilde{\chi}_1^0)\,(\tilde{\chi}_1^\pm \to \ell^\pm \nu_\ell \tilde{\chi}_1^0) j \to \tilde{\chi}_1^0 \tilde{\chi}_1^0 \ell^\pm \nu_\ell \gamma j$$



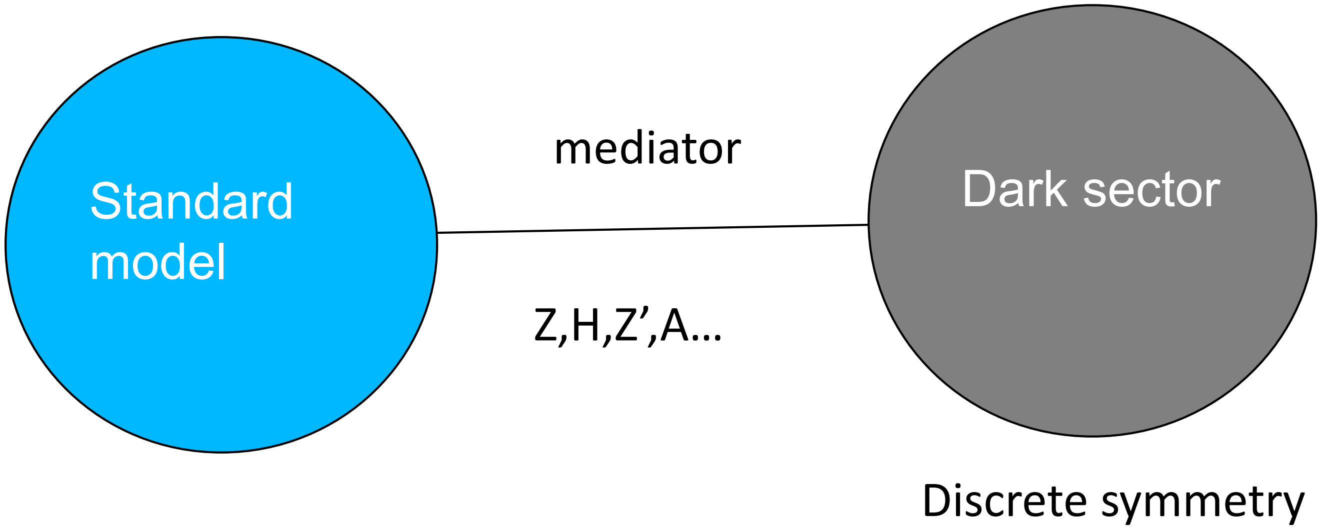
100TeV collider 15ab^{-1},

Bramante et al, 1510.03460

Other WIMPs

- Still plenty of room for neutralino DM, altough as a single DM component somewhat under pressure by relic + direct search unless TeV scale
- Other susy candidates possible : gravitino, sneutrino, axino…
- SUSY just one of many alternatives
- Extra dimensions – extended scalar, extended gauge etc…
- Extended scalar : good example of a Higgs portal, improve stablity of Higgs potential, harder to probe at LHC – only new scalars
- In general strong constraint from Direct Detection on DM that couples to Higgs

•Rather easy to construct a DM model, SM + mediator +DM + some Z_2 symmetry



•DM and the Higgs portal : Bertolami,Rosenfeld, 0708.1794; March-Russell et al, 0801.3440; J. Mcdonald, Sahu, 0802.3847, 0905.1312; Tytgat, 0906.1100; Aoki et al, 0912.5536; Andreas et al, 1003.3295; Arina et al, 1004.3953; Cheug,Nomura 1008.5153; Djouadi et al, 1112.3299 ..

•DM and the Z' or A' portal : Alves et al, 1610.7282,Arcadi et al 1708.00890, Lebedev,Mambrini, 1403.0837

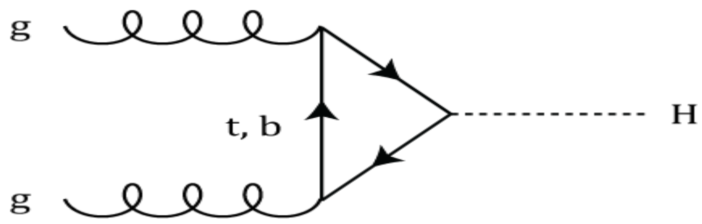
An example

- Simplified model : Capture essential features with small number of parameters/assumptions
- Specific example : pseudoscalar mediator, fermion DM, also assume couplings proportional to Yukawas-> 3rd generation

$$\mathcal{L}_{\rm DS} = \frac{1}{2}(\partial^\mu A)^2 - \frac{m_A^2}{2}A^2 + \frac{1}{2}\bar{\chi}\left(i\partial\!\!\!/ - m_\chi\right)\chi - i\frac{y_\chi}{2}A\bar{\chi}\gamma^5\chi\,.$$

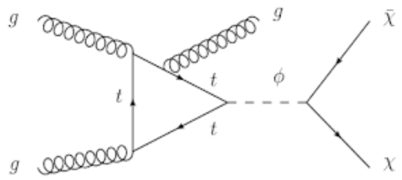
$$\mathcal{L}_{\rm f} = i\sum_{f_u} c_u \frac{m_{f_u}}{v} A \bar{f}_u \gamma^5 f_u + i\sum_{f_d} c_d \frac{m_{f_d}}{v} A \bar{f}_d \gamma^5 f_d$$

- Loop coupling to two-gluons and two-photons

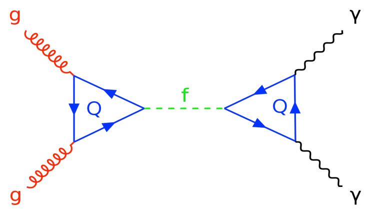


At the LHC

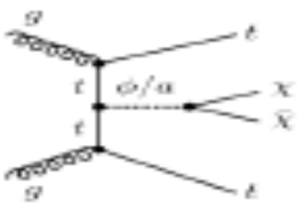
- Several probes :
  - monojet



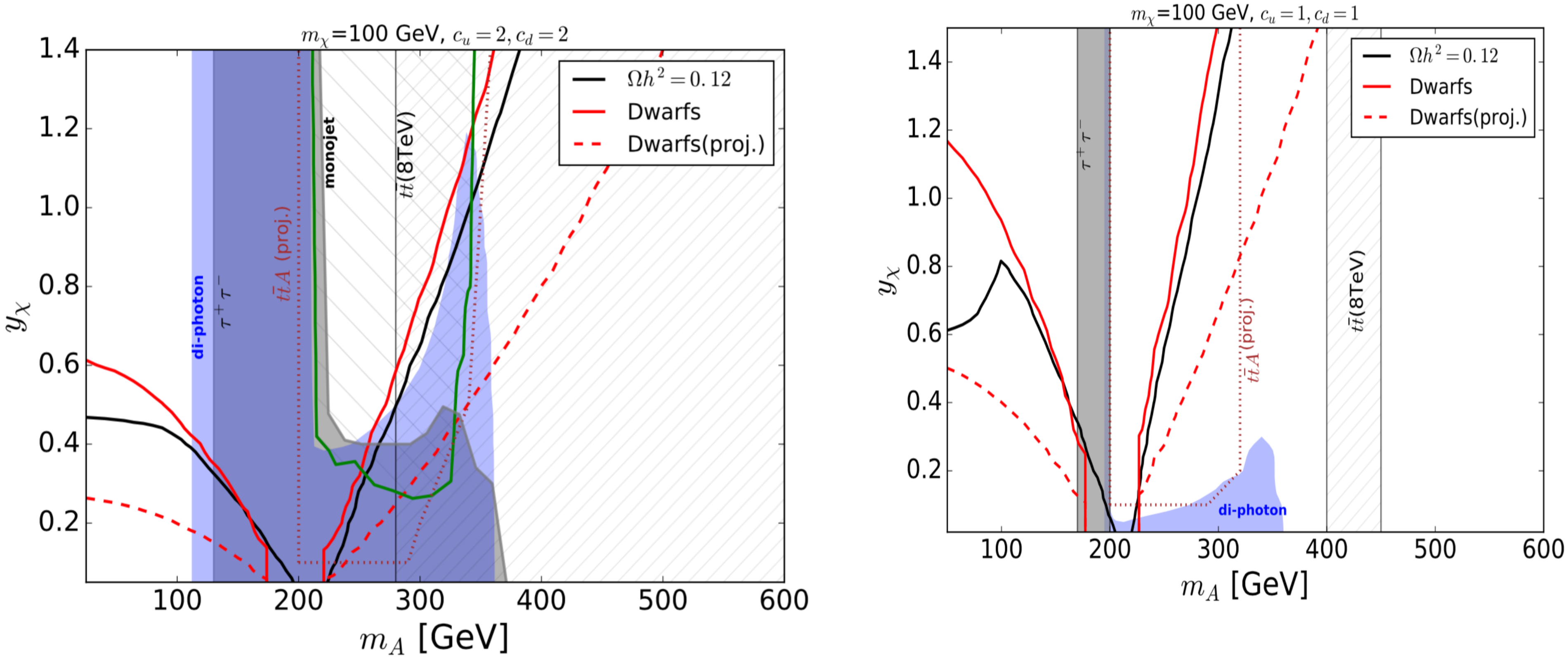
  - searches for mediator in visible (γγ,ττ,tt)or invisible decays,



  - contribution of mediator to di-top cross section,
  - associated production of mediator, ttA, bbA



At the LHC



- LHC constraints strongly depend on mediator couplings to quarks
- Independent of coupling to DM in visible channels – allow to cover the region $m_{DM} \sim m_A/2$ with very small coupling hard for indirect detection
- Narrow range of couplings allowed by PLANCK+dwarfs
- Similar conclusions for spin 1 (ATLAS) and 2 (Kraml et al 1701.07008)

Should we give up on WIMPs?

Should we give up on WIMPs?
Let Xenon … and LHC look more closely

Consider alternatives

Open problems

- Small objects collapse under self-gravity, merge to form larger and larger objects (hierarchical growth of structure)
- Predictions of ΛCDM cosmological model : successful for describing large scale structure of Universe
- BUT some challenges at small scales (~10's kpc)
- Core cusp : observed core of DM dominated galaxies less dense and less cuspy than prediced in ΛCDM (simulation prefer NFW-like profile)
- Missing satellite : Number of small galaxies and dwarf galaxies in Local group far below the predicted number (by at least an order of magnitude)

Open problems

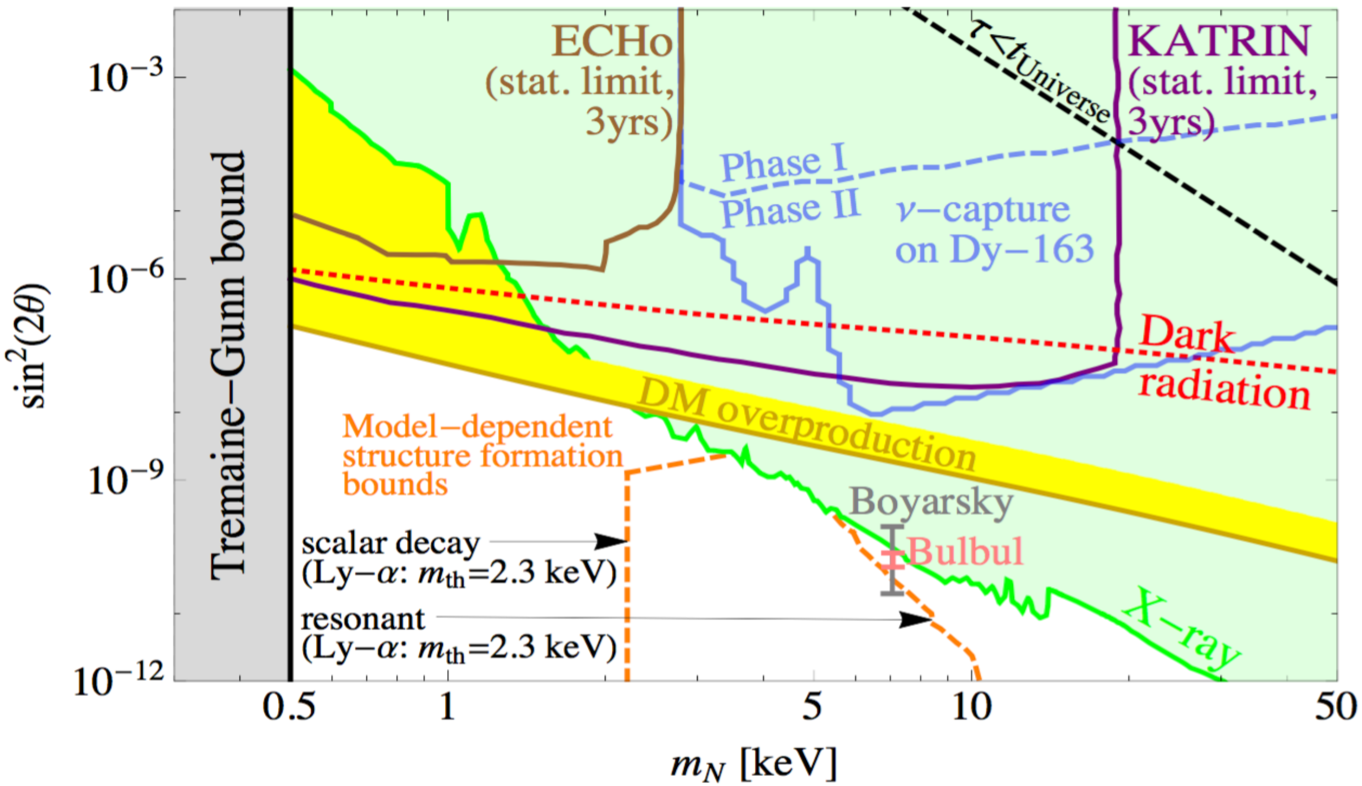
- Maybe large and dense galaxies exist but are invisible due to suppression of star formation – no mechanism known for this suppression – 'Too big to fail' producing stars

- Possible solutions :
  - Inclusion of baryons : can flatten cusp - ongoing
  - Astrophysics feedback effects
  - Warm DM (or mixture of cold and warm) – larger free-streaming length affect structure formation- could reduce the built-up of small objects
  - Self-interactions? Solve both problems, need very large $\sigma \gg \sigma_{weak}$

Sterile neutrinos

- Neutrinos have mass – natural to add RH neutrino
- Mass scale? Astro constraints favour keV mass scale – consistent with ν_s DM produced from mixing with ν
- Small mixing with active neutrino – DM decay, $\nu_s \to \nu\gamma$
  - Not observed in Xray -> m <10's keV (or 7keV)
- Particle velocity not cold – but warm DM : help small scale structure problems
- keV scale not very natural from theory – sterile neutrino with Majorana mass – expected to be heavy
  - Either use loop effect to increase mass of massless neutrino or mechanim to suppress naturally large mass
  - Need to split flavours

Sterile neutrinos



M Drewes et al 1602.04816

Self-interactions

Enough self-interaction to solve small scale structure problem

DM self interactions cannot be too large since Bullet cluster show DM is collisionless -> $\sigma/m < 1cm^2/g$

Self interactions - > DM particles transfer energy, change velocity of DM, more isotropic velocity distribution -> more spherical halos

Distinctive astro signature : separation between DM halo and stars in galaxy moving through region of large DM density (obs. in Abell3827, Massey et al 1504.03388)

If self-interaction dominate

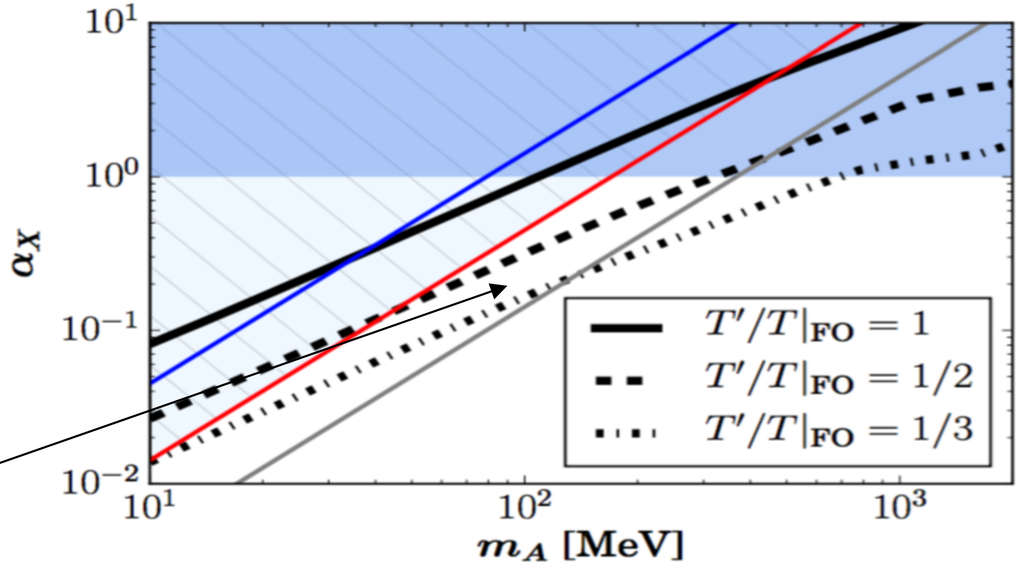
– DM nb changing interactions 3->2

Example: hidden vector model SU(2)

Bernal et al, 1510.08063

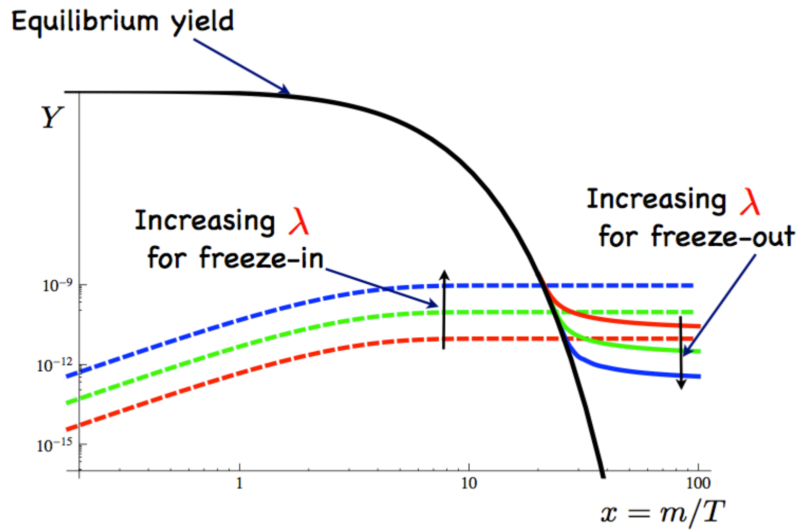
solve small scale structure +

correct relic



FIMPS (Feebly interacting MP)

- Freeze-in (Hall et al 0911.1120): in early Universe, DM so feebly interacting that decoupled from plasma
- Assume that after inflation abundance DM very small, interactions are very weak but lead to production of DM
- T~M, DM 'freezes-in' - yield increase with interaction strength



- Several possibilities for FIMP DM
  - Production by annihilation
  - or by decay
  - Freeze-in talk by A. Goudelis

- Signatures: indirect detection from X decay into DM+SM particles ->boost factor. Relic abundance and DM annihilation cross section no longer related

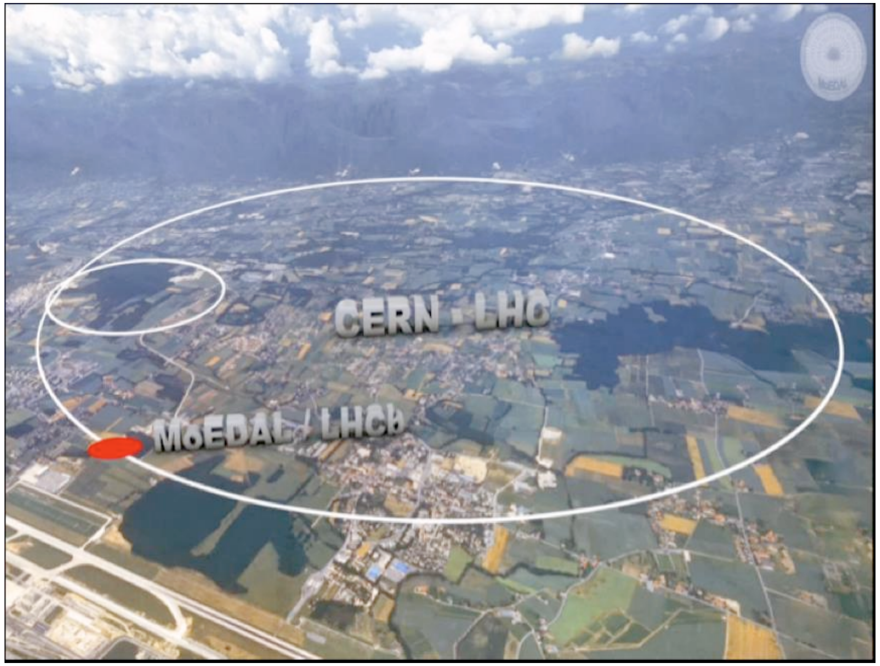
FIMP from decay

- Case where FIMP is DM, next to lightest ‘odd’ particle has long lifetime freeze-out as usual then decay to FIMP
- e.g. in SUSY : gravitino or RH sneutrino
- Neutrino have masses – RH neutrino + Susy partner well-motivated – if LSP then can be DM
- Example MSSM+3 RH neutrinos with 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})
- Sneutrino not thermalized in early universe - produced from decay of MSSM-LSP after freeze-out
- Relic density obtained from that of the NLSP – can be charged

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

- Consider stau as the NLSP - live from sec to min : decay outside detector
- LHC signature : stable charged particle NOT MET
- Constraints from BBN : lifetime of stau can be long enough for decay around or after BBN→ impact on abundance of light elements
- Decay of particle with lifetime > 0.1s 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)
- LHC Searches
  - Cascades : coloured sparticles decay into jets + SUSY→ N jets + stau
  - Pair production of two stable staus (model independent but lower cross section)
  - 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

MoEDAL detector



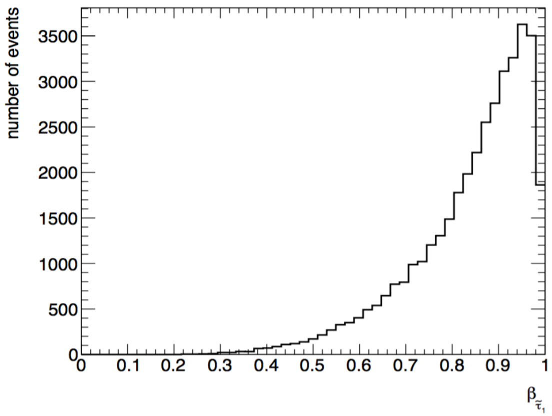
- Passive detector
- Array of nuclear track detector stacks
- Surrounds intersection region point 8
- Sensitive to highly ionising particles
- Does not require trigger, one detected event is enough
- Major condition : ionizing particle has velocity β<0.2

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

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

Stau velocity distribution



Long-lived particles

- LLP occur in many DM models (WIMPs, FIMPs …) : SUSY, Hidden Valley....
- Can be charged or neutral
- Variety of signatures : charged tracks, displaced vertices, exotic Higgs decays, new proposals to search for them
- MATHUSLA : large volume tracking detector – at the surface above CMS or ATLAS – empty barn with top equipped with charged particle tracking to detect LLP decay (can detect neutral LLP)
  - If pair produced in Higgs decays can measure its mass and decay mode

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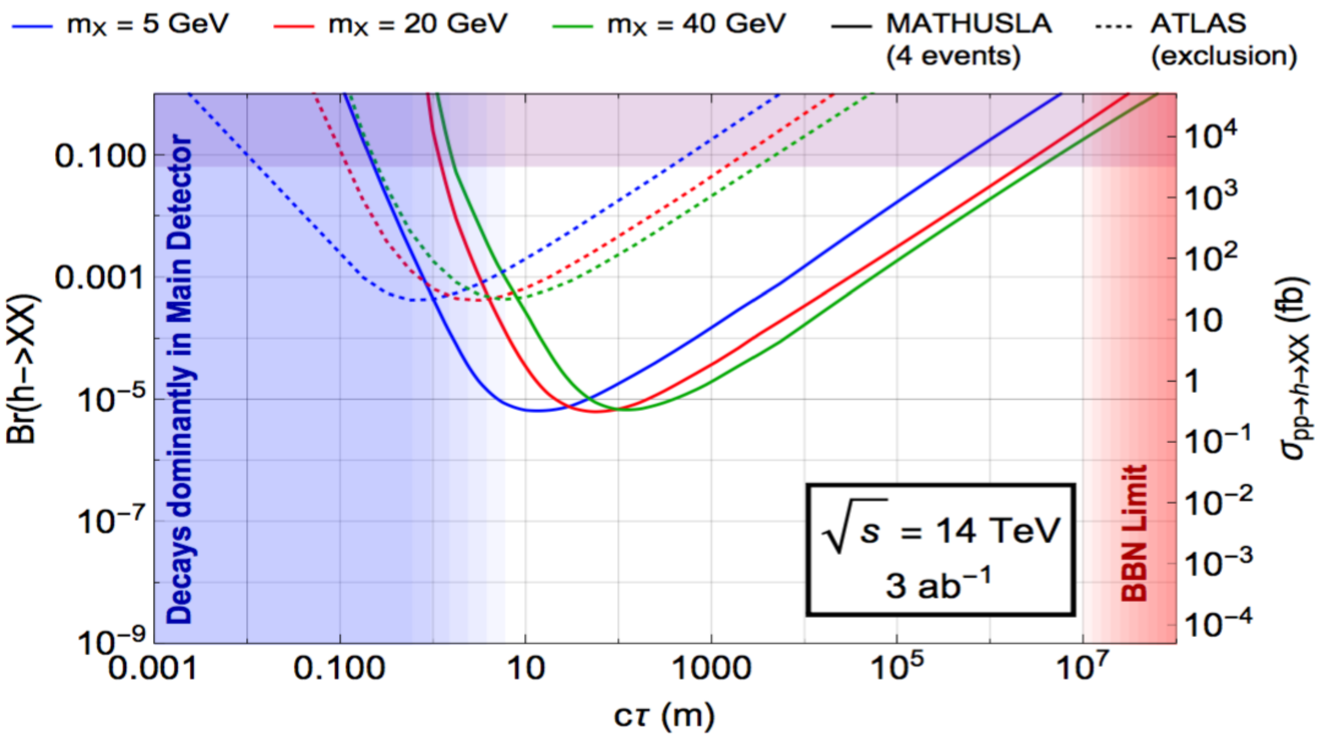
  - If … ay mode



Curtin, Peskin 1705.06327

Conclusion

- What is the nature of dark matter?
- Made enormous progress in searching for DM with direct/indirect and collider searches
- With searches for long-lived and ‘collider-stable’ particles – signatures from whole classes of DM candidates/models
- Need to look beyond the WIMP paradigm

The Higgs was proposed in 1964 and discovered in 2012 – but we knew where to look for it

Dark matter was proposed by Zwicky in 1933 still to be « discovered »

Are we searching at the right place?