Dark matter searches

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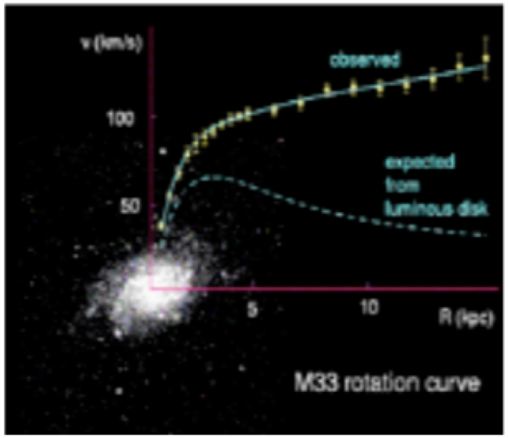
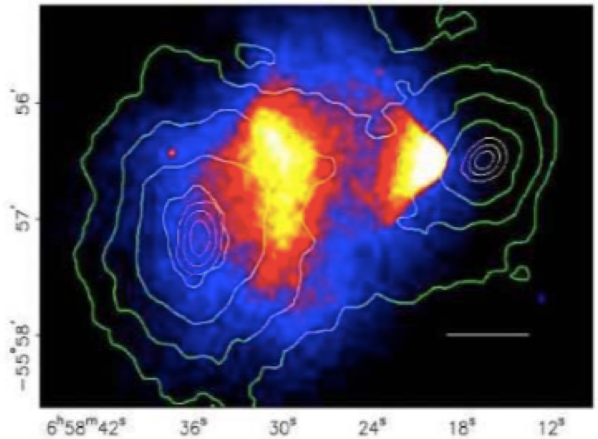
DM searches

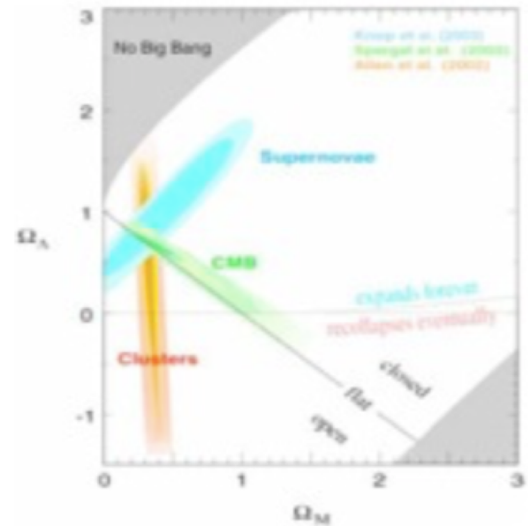
- Why dark matter a new particle– short recap
- Searching for DM underground
  - Direct detection
  - At colliders
- Searching for DM in the sky (see also lecture F. Calore)
- Searching for DM in the Universe

Mostly consider the hypothesis that DM is a weakly interacting massive particle (WIMP)

Introduction







- Strong evidence for dark matter from many scales
  - The galactic scale (rotation curves)
  - Scale of galaxy clusters: mass to light-ratio,gravitational lensing, Bullet cluster
  - Cosmological scales
    - DM required to amplify the small fluctuations in Cosmic microwave background to form the large scale structure in the universe today
- DM a new particle?

- In the last century, we had a very good idea what would be this new particle : neutralino in SUSY – despite the large parameter space clear paths for DM searches (direct and indirect searches and production at colliders)
- Same strategy applies for other WIMPs – a new stable neutral weakly interacting particle

- Now many more possibilities for dark matter, classified by:
  - Dark matter production mechanisms : in thermal equilibrium in early universe or not – interaction strengths (WIMPs, FIMPs, SIMPs, SIDM etc..) – mass…
  - Theoretically motivated beyond the standard model (e.g. naturalness)
  - Expt-motivated extension of the Standard model : neutrino, anomaly (B, g-2…); baryogenesis
  - Extension of SM with DM candidate (e.g. simplified model)

DM searches

- Underlying theoretical model allow to best exploit connections between search strategies – range masses, coupling strengths, spin of DM, nature of mediator(s)
- Mediator(s) : coupling between DM and SM – e.g. H, new particle

Bertone, Tait, Nature 2018

WIMP DM

- Most studied hypothesis: a new stable neutral weakly-interacting massive particle – WIMP – why are they good DM candidates?
- In thermal equilibrium when T of Universe much larger than its mass
- Equilibrium abundance maintained by processses

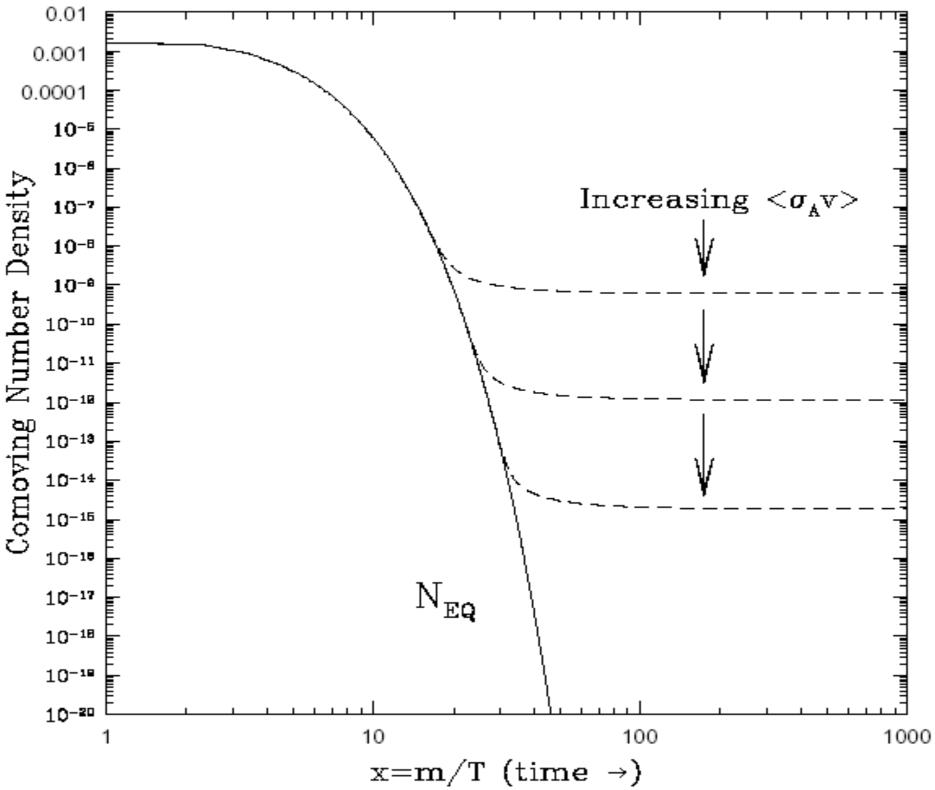
$$\chi\bar{\chi} \rightarrow e^+e^-, \mu^+\mu^-, \tau^+\tau^-, q\bar{q}, W^+W^-, ZZ$$

- As well as reverse processes, inverse reaction proceeds with equal rate
- As Universe expands T drops below m_χ, n_{eq} drops exponentially, production rate is suppressed (particles in plasma do not have sufficient thermal energy to produce $\chi\chi$) χ start to decouple – can only annihilate $dn/dt = \sigma v\ n^2$
- Eventually rate of annihilation drops below expansion rate $\Gamma < H$ – not enough χ for annihilation - > fall out of equilibrium and freeze-out (at $T_{FO} \sim m/20$), density depends only on expansion rate

$$\frac{dn}{dt} = -3Hn - <\sigma v> \left[n^2 - n_{eq}^2\right]$$

WIMP DM

- Why WIMP
- In thermal e… …ıan its mass
- Equilibrium … $\bar{q}, W^+W^-, ZZ$
- As well as r… …ith equal rate
- As Universe … …ıtially, production rate is suppr… …ent thermal energy to produce χ … …n/dt=σv n^2
- Eventually r… …e Γ< H – not enough χ fo… …reeze-out (at T_{FO}~m/20),



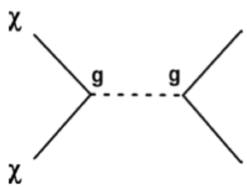
$$\frac{dn}{dt} = -3Hn - <\sigma v> \left[n^2 - n_{eq}^2\right]$$

Dark matter: a WIMP?

In standard scenario, relic abundance

$$\Omega_X h^2 \approx \frac{3 \times 10^{-27}\text{cm}^3\text{s}^{-1}}{\langle \sigma v \rangle} \quad .$$

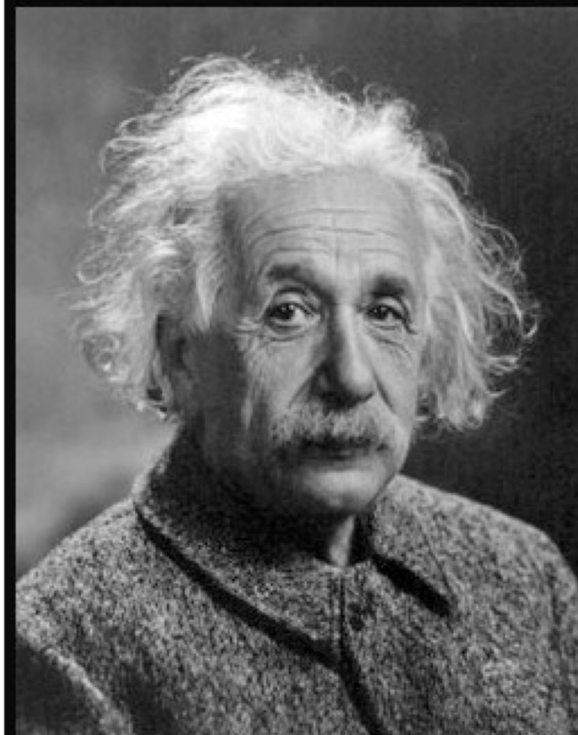
Depends only on effective annihilation cross section, a WIMP at EW scale has 'typical' annihilation cross section for $\Omega h^2 \sim 0.1$ (WMAP,PLANCK)



$< \sigma v > \sim \frac{g^4}{32\pi m_{DM}^2}$ $\sim 3\ 10^{-26}\ \text{cm}^3/\text{s}$ (or $\sigma \sim 1$pb)

Remarkable coincidence : particle physics independently predicts particles with the right density to be dark matter (WIMP miracle)

This is simple estimate – possible variations by orders of magnitude

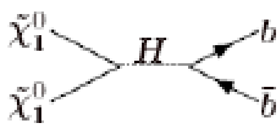


There are only two ways to live your life. One is as though nothing is a miracle. The other is as though everything is a miracle.

(Albert Einstein)

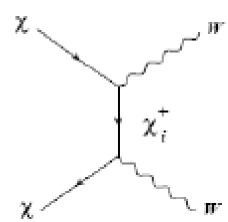
Miracle?

- Relic density puts strong constraint on combination of mass/couplings
- Will any weakly interacting particle lead to the 'miracle'?
- Resonance



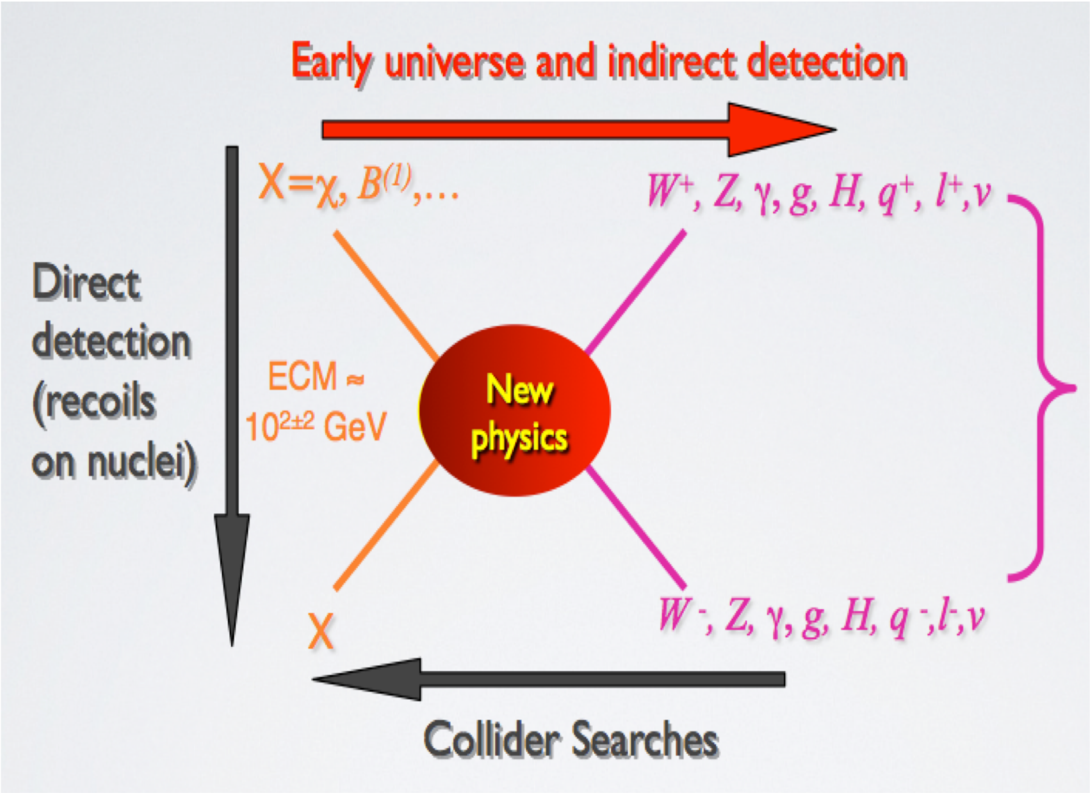
$$\sigma v \propto m_{\tilde{\chi}}^2/(4m_{\chi}^2 - m_H^2)^2$$

  - much weaker coupling required when $2m_\chi \sim m_H$
- New channels : increase of cross section if W/Z/h/t channels kinematically open, also larger cross sections for spin 1
- t-channel : enhancement when small mass splitting



- Coannihilation : when many 'dark' particles nearly degenerate

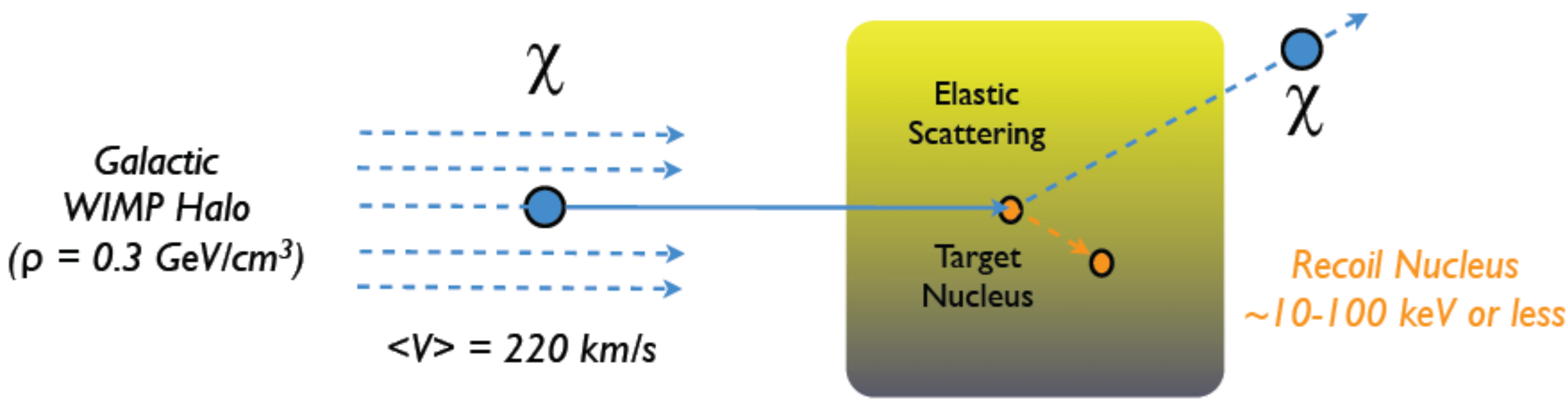
Probing the nature of dark matter



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

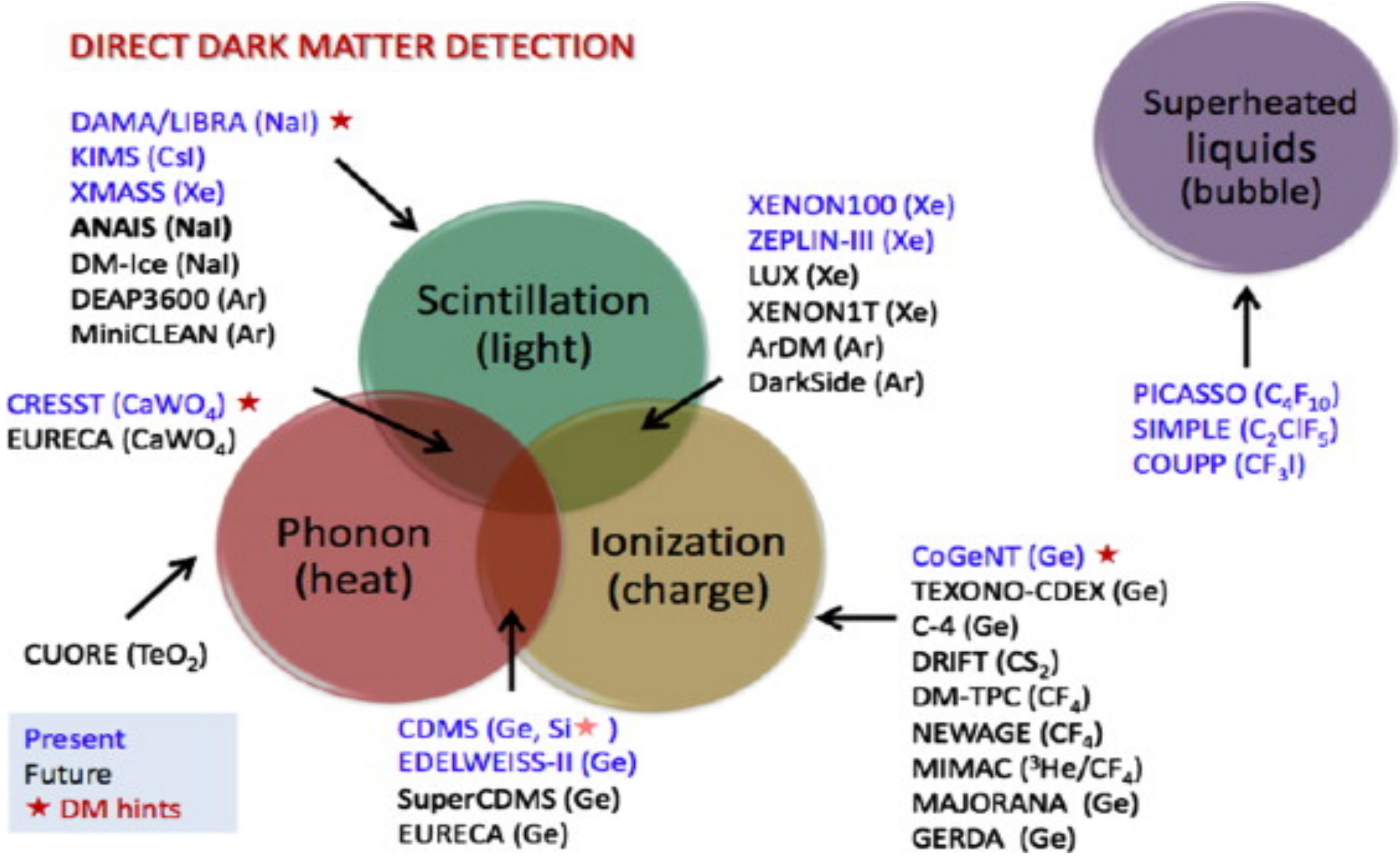
Direct detection

- Elastic scattering of WIMPs (weakly interacting massive particle) off nuclei in a large detector deep underground
- Measure nuclear recoil energy, E_R
- Best way to prove that WIMPs form DM



Direct detection

- Signals : production of heat (phonons in cristal), scintillation photons from de-excitation of target nucleus, ionization of target nucleus (usually one or two signals - depend on the detector technology)



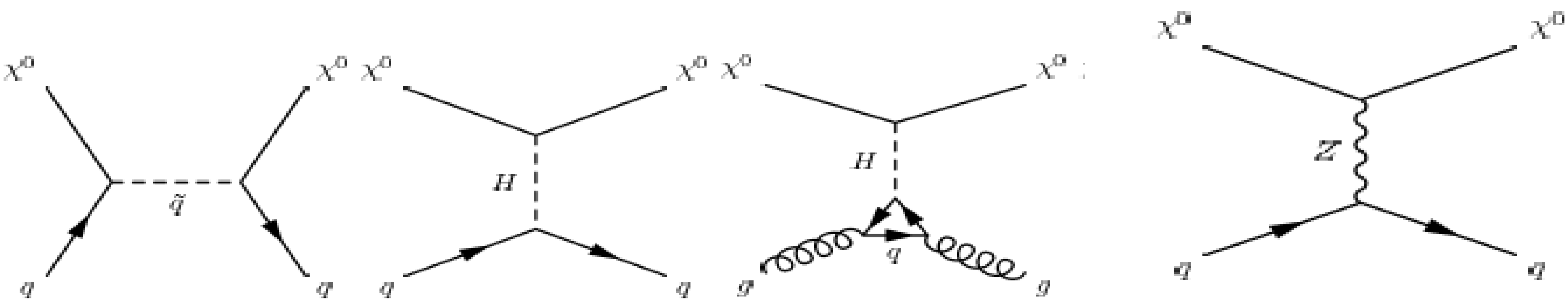
Direct detection

- Particle physics : effective Lagrangian for WIMP-nucleon and wimp-quark amplitude *at small momentum transfer* $\sim 2v\, m_\chi\, m_N/(m_\chi + m_N) \sim 100\text{MeV}$
- For Majorana fermion

$$\mathcal{L}_N = \lambda_N \overline{\chi}\chi\overline{N}N + \xi_N \overline{\chi}\gamma_\mu\gamma_5\chi\overline{N}\gamma^\mu\gamma_5 N$$

- For Dirac fermion

$$\mathcal{L}_F = \lambda_{N,e}\bar{\psi}_\chi\psi_\chi\bar{\psi}_N\psi_N + \lambda_{N,o}\bar{\psi}_\chi\gamma_\mu\psi_\chi\bar{\psi}_N\gamma^\mu\psi_N \quad \text{(for SI)}$$



For Dirac fermions Z exchange contributes to SI and SD

Spin dependent (fermion):

$$\xi_{N,e}\bar{\psi}_\chi\gamma_5\gamma_\mu\psi_\chi\bar{\psi}_N\gamma_5\gamma^\mu\psi_N - \frac{1}{2}\xi_{N,o}\bar{\psi}_\chi\sigma_{\mu\nu}\psi_\chi\bar{\psi}_N\sigma^{\mu\nu}\psi_N$$

WIMP-quark to WIMP-nucleon

- Coefficients for effective Lagrangian for WIMP – quark scattering – computed from fundamental Lagrangian, same as WIMP- nucleon : introduce coefficients relate WIMP-quark operators to WIMP nucleon operator (Scalar, vector…)
  - Extracted from experiments or computed from lattice
  - Recent progress in lattice –> reduce theoretical uncertainties
- Example : scalar coefficients, contribution of q to M_N(heavy quark contribution expressed in terms of gluonic content)

$$\langle N | m_q \overline{\psi}_q \psi_q | N \rangle = f_q^N M_N$$

$$\lambda_{N,p} = \sum_{q=1,6} f_q^N \lambda_{q,p} \qquad f_Q^N = \frac{2}{27}\left(1 - \sum_{q\leq 3} f_q^N\right)$$

Numerical values f_d^p=0.0191, f_u^p=0.0153, f_s^p=.0447, f_Q^p=0.07
Large contribution from heavy quarks

WIMP-nucleus

- Rates (SI and SD) depends on nuclear form factors and velocity distribution of WIMPs + local density

$$\frac{dN^{SI}}{dE} = \frac{2M_{det}t}{\pi}\frac{\rho_0}{M_\chi}F_A^2(q)\left(\lambda_p Z + \lambda_n(A-Z)\right)^2 I(E)$$

Nuclear form factors

Particle physics
+ quark content in nucleon

DM velocity distribution

$$I(E) = \int_{v_{min}(E)}^{\infty}\frac{f(v)}{v}dv$$

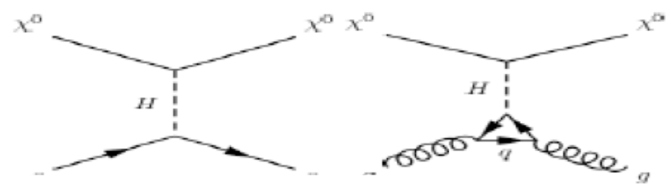
$$v_{min}(E) = \left(\frac{EM_A}{2\mu_\chi^2}\right)^{1/2}$$

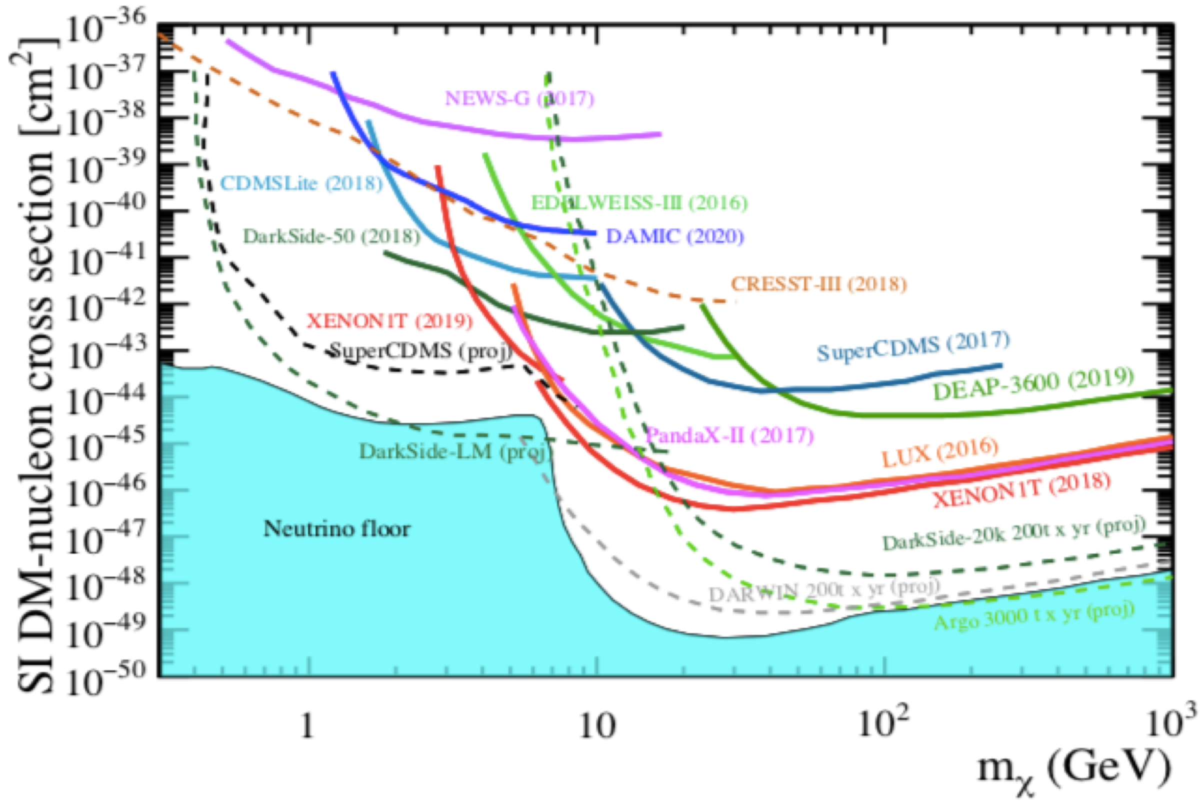
- For easy comparison between expt, assume $\lambda_p=\lambda_n$ and Maxwell Boltzmann velocity distribution with same parameters

$$\sigma_p^{SI} = \frac{4\mu_\chi^2}{\pi}\lambda_p$$

Spin independent

Elastic scattering of DM
off nucleons in a large detector





Best limit on SI for MDM=100 GeV~~few 10^{-11} pb (Xenon1T 1705.06655)

Spin independent

Elastic scattering of DM
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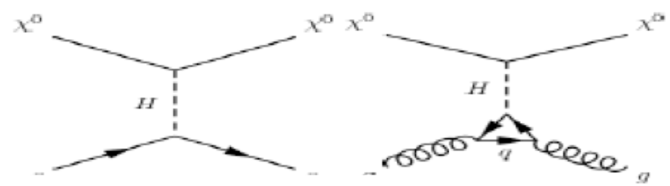
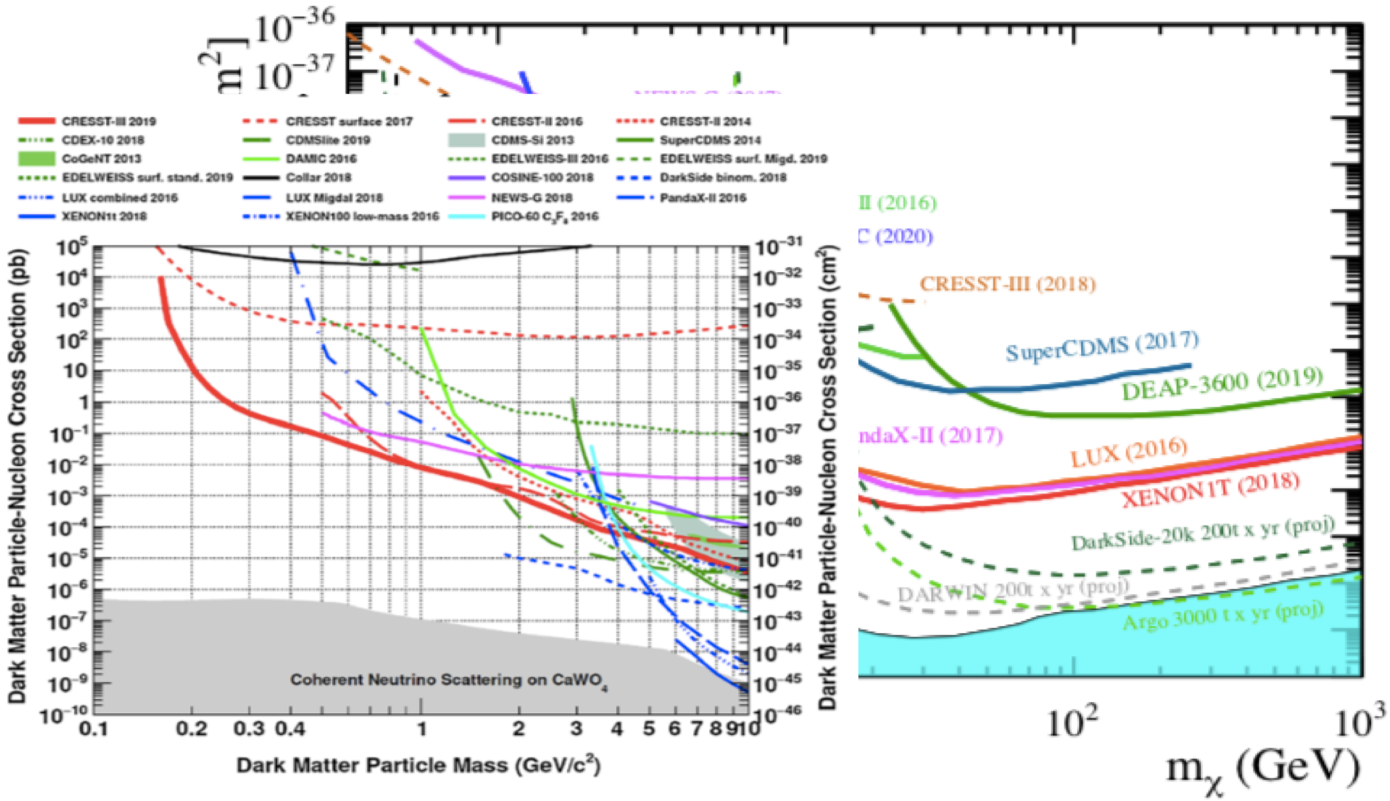
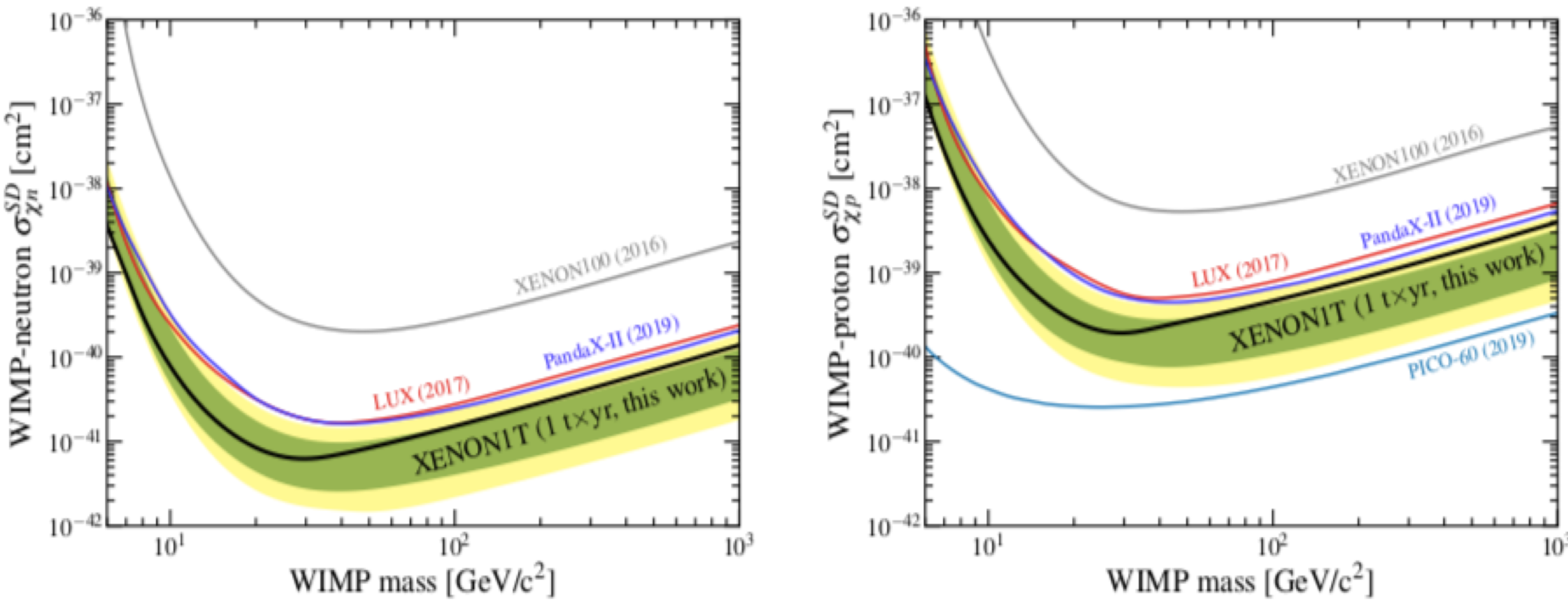




Best limit on SI cross section @MDM=100 GeV– Xenon1T (1705.06655)

Limits spin dependent

Aprile et al, 1902.03234



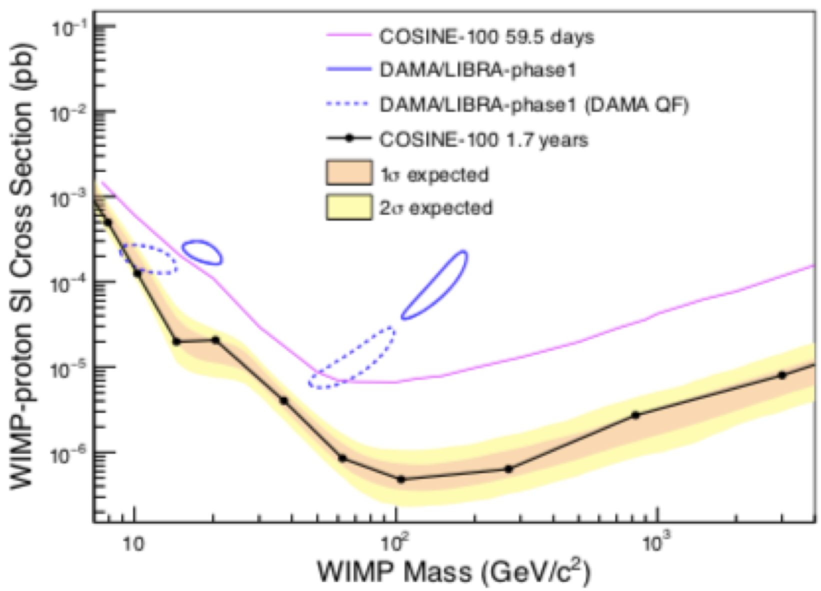
Cross sections probed are much larger than for SI
Just reaching the sensitivity to probe more popular DM model (MSSM)

Direct detection of dark matter

- In the last years direct detection experiments have put strong constraints on DM models both in SI and SD mode
- No confirmed signal
  - Does it mean that WIMPs are out? No – see examples
  - Goal for sensitivity : need to reach neutrino floor? Beyond? Yes
  - Directional detection : measurement of direction of nuclear recoil tracks could distinguish DM signal from background (CYGNUS project)
- Anomaly in annual modulation signal in DAMA for many years
- Excluded ?
- Excess in electron signal at low mass in XENON

Annual modulation -DAMA

- Anomaly in annual modulation signal in DAMA-NaI for many years – incompatible with other DD experiments (without modulation)
- COSINE-100 looked for annual modulation with NaI detectors –exclude DAMA assuming standard assumptions, all operators in EFT, as well as isospin violation



COSINE100-2104.03537

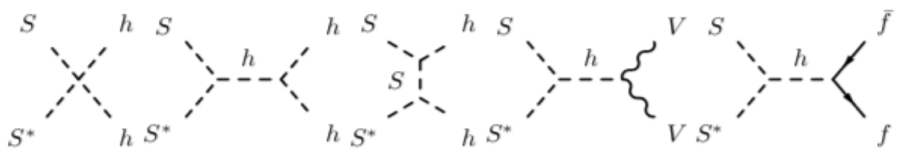
Higgs Portal : Singlet scalar

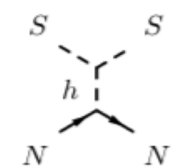
- Simplest SM extension : one singlet scalar + Z_2 symmetry
- Improves stability of Higgs sector
- One coupling (to Higgs) drives all DM observables – relic,DD,ID

$$V_{Z_2} = \mu_H^2|H|^2 + \lambda_H|H|^4 + \mu_S^2|S|^2 + \lambda_S|S|^4 + \lambda_{SH}|S|^2|H|^2$$

Direct detection

annihilation





$m_s \gg m_i$	$\frac{\lambda_{SH}^2}{64\pi m_s^2}$	$\frac{\lambda_{SH}^2}{32\pi m_s^2}$	$\frac{\lambda_{SH}^2 m_f^2}{64\pi m_s^4}$
$m_s \ll m_h$			$\frac{\lambda_{SH}^2 m_f^2}{64\pi m_h^4}$

- Need large enough coupling for DM annihilation – but constraints from DD
- For light DM – Higgs can decay invisibly

- For $m_S \gg m_{SM}$, annihilation in WW(½), ZZ (¼), HH (¼)
- DD directly related to annihilation cross-section

$$\langle \sigma v \rangle = 2 \frac{\lambda_{SH}^2}{32\pi m_s^2} \qquad \sigma_p^{SI} = \frac{\lambda_{SH}^2}{16\pi m_s^2} \left(\frac{m_p}{m_h}\right)^4 f_p^2$$

$$\sigma_p^{SI} = \langle \sigma v \rangle \left(\frac{m_p}{m_h}\right)^4 f_p^2 \approx 10^{-9}\text{pb} \quad \text{for} \quad f_p = 0.5, m_h = 125$$

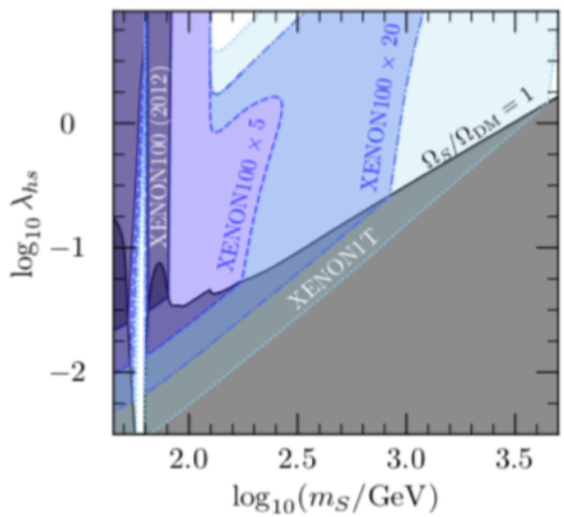
- Current DD limits exclude this model except 1) at very large masses where DD limit weakens and 2) near $m_h/2$
- Resonance in DM annihilation when $m_s \sim m_h/2$

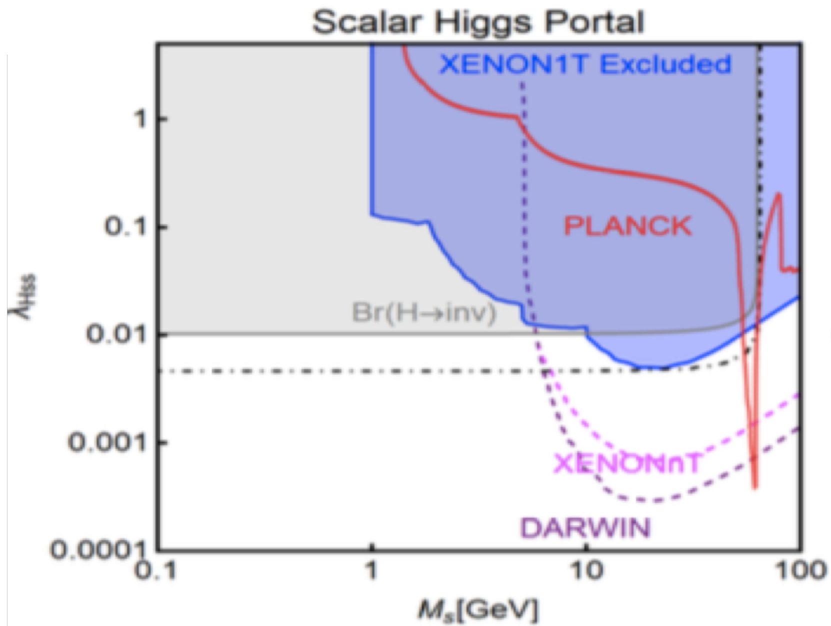
$$\langle \sigma v \rangle = \frac{\lambda_{SH}^2}{16\pi} \frac{m_f^2}{(4m_s^2 - m_h^2)^2}$$

- ->Much weaker couplings are required
- If $m_S < m_h/2$: Higgs invisible decay also constrain the model, Djouadi et al 1112.3299, Arcadi et al, 2101.02507

Singlet scalar

Cline et al, 1306.4710





Arcadi et al, 2101.02507

- If annihilation is efficient enough for relic density to be satisfied -> strong constraint from direct detection (unless DM mass >TeV, DM mass ~ mh/2)
- If $m_S<m_h/2$: Higgs invisible also constrain the model, Djouadi et al 1112.3299, Arcadi et al, 2101.02507
- Other analyses: P. Athron et al, 1808.10645

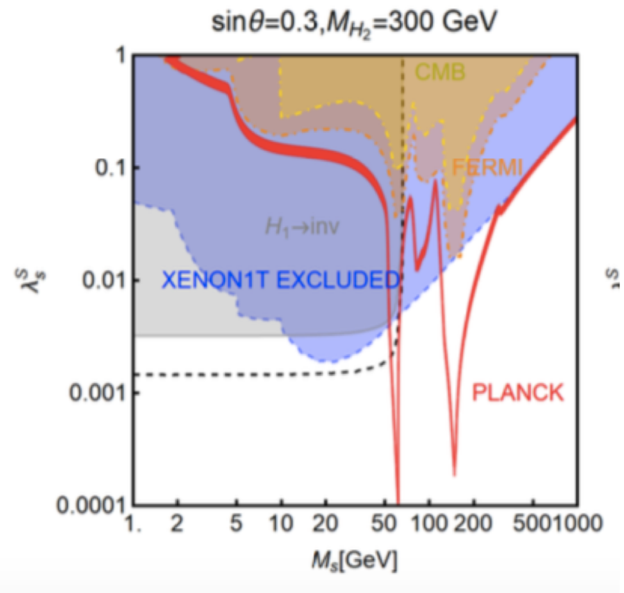
Direct detection of dark matter

- All DM models subject to strong constraints from DD?
- How to avoid DD constraints
  - Resonances (more scalars, vectors…)
  - Blind spots (Cancellation between SM Higgs and other)
  - Pseudoscalar mediator (contributes only at one-loop)
  - Dissociate interactions responsible for relic density from those responsible for DD

  - Goal for sensistivity : need to reach neutrino floor? Beyond? Lower masses?– see specific examples

Beyond minimal model

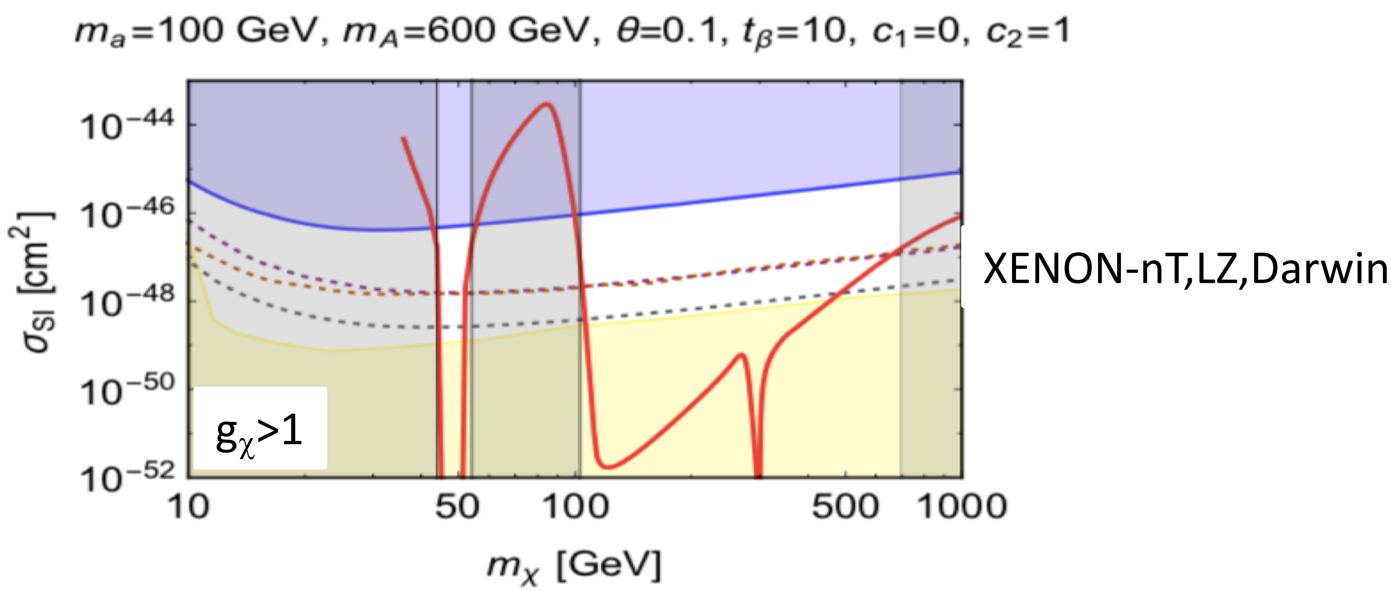
- Expanding the dark sector : other multiplets (inert doublet …) more singlets, new fermions etc…
- Relaxing DD constraints
  - New mediators – more resonances (2nd Higgs mixing with SM Higgs)



Arcadi et al, 2101.02507

  - interference (blind spot), e.g. cancellation between contributions of 2 Higgses (if fermion DM, SD not suppressed); isospin violation: cancellation between neutron and proton contribution in Xe (Feng et al, 1102.4331, GB et al 1311.0022)

- Relaxing DD constraints
  - Pseudoscalar mediator (DD only at one-loop – ID can be important)
  - Example: Singlet Majorana fermion, 2 scalar doublets + gauge singlet pseudoscalar (Abe et al, 2101.02507)
  - Loop contribution can be large enough to be probed in DD, generally much suppressed



Other WIMP DM production

- Other DM production: co-annihilation, semi-annihilation, multiple DM
- Co-annihilation : $\chi\chi'$ -> SM,SM

If M(NLSP)~M(LSP) then $\chi + X \rightarrow \chi' + Y$

maintains thermal equilibrium between NLSP-LSP even after new particles decouple from standard ones

Relic density then depends on rate for all processes

$$\chi\chi \rightarrow XY$$
$$\chi\chi' \rightarrow XY$$
$$\chi'\chi' \rightarrow XY$$

X,Y: SM particles

$$\frac{dn_i}{dt} = -3Hn_i - \sum_{i,j=1}^{N} \langle \sigma_{ij} v_{ij} \rangle \left(n_i n_j - n_i^{eq} n_j^{eq} \right)$$
$$- \sum_{j \neq i} \langle \sigma'_{Xij} v_{ij} \rangle \left(n_i n_X - n_i^{eq} n_X^{eq} \right) - \sigma'_{Xji} v_{ij} \rangle \left(n_j n_X - n_j^{eq} n_X^{eq} \right)$$

All particles eventually decay into LSP, calculation of relic density requires summing over all possible processes. important processes are those involving particles close in mass to LSP

$$\frac{n_i}{n} \approx \frac{n_i^{eq}}{n^{eq}}$$ ~exp(-Δm/T)

Coannihilation

Contribution of coannihilation processes strongly suppressed with increasing mass difference - for comparable cross sections : few percent mass split

When coan process more efficient than LSP annihilation → reduces the relic density (typically happens in most SUSY cases)

When coann process less efficient than LSP annihilation-> increases the relic density (typical for UED models)

If coannihilation is what gives the correct relic density -> since co-annihilation has no impact on DD – decorrelate predictions of relic from DD : can have much suppressed DD (and ID)

SUSY case

- Status of neutralino DM (gravitino is another DM candidate in SUSY)
- Fundamental scalar particles are unnatural – loop corrections to scalar mass requires fine-tuning. SUSY provides a solution if sparticles (in particular charged sparticles) are not too heavy - cancel contribution from SM fermions in loop contributions to the Higgs mass
- (electroweak) Naturalness implies μ not too large (μ is the higgsino parameter)

$$m_Z^2/2 = \frac{m_{H_d}^2 + \Sigma_d^d - (m_{H_u}^2 + \Sigma_u^u)\tan^2\beta}{\tan^2\beta - 1} - \mu^2$$

- R-parity is introduced to solve proton decay -> guarantees that the lightest particle is stable
- Strong bounds on coloured sparticles from colliders, harder to probe compressed spectra and susy electroweak partners at colliders (reach increase significantly with luminosity) – see later
- Still some parameter space for neutralino DM in constrained and general MSSM : if higgsino is all DM μ >1TeV, if Wino is all DM M_2 >2TeV-> μ, M_1 >2TeV

Minimal supersymmetric standard model

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

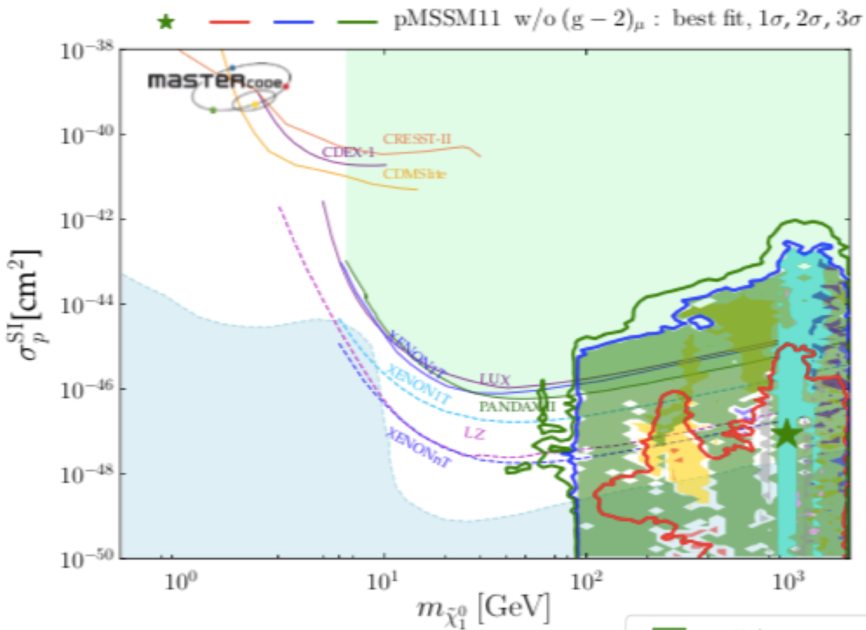
Neutralinos : neutral spin ½ partners of gauge bosons (bino,wino) and Higgs scalars (higgsinos)

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

The coupling of neutralino to Higgs requires higgsino/gaugino mixing

Standard Model particles and fields		Supersymmetric partners			
		Interaction eigenstates		Mass eigenstates	
Symbol	Name	Symbol	Name	Symbol	Name
$q = d, c, b, u, s, t$	quark	$\tilde{q}_L, \tilde{q}_R$	squark	$\tilde{q}_1, \tilde{q}_2$	squark
$l = e, \mu, \tau$	lepton	$\tilde{l}_L, \tilde{l}_R$	slepton	$\tilde{l}_1, \tilde{l}_2$	slepton
$\nu = \nu_e, \nu_\mu, \nu_\tau$	neutrino	$\tilde{\nu}$	sneutrino	$\tilde{\nu}$	sneutrino
g	gluon	$\tilde{g}$	gluino	$\tilde{g}$	gluino
$W^\pm$	W-boson	$\tilde{W}^\pm$	wino		
H^-	Higgs boson	$\tilde{H}_1^-$	higgsino	$\tilde{\chi}_{1,2}^\pm$	chargino
H^+	Higgs boson	$\tilde{H}_2^+$	higgsino		
B	B-field	$\tilde{B}$	bino		
W^3	W^3-field	$\tilde{W}^3$	wino		
H_1^0	Higgs boson			$\tilde{\chi}_{1,2,3,4}^0$	neutralino
H_2^0	Higgs boson	$\tilde{H}_1^0$	higgsino		
H_3^0	Higgs boson	$\tilde{H}_2^0$	higgsino		

MSSM



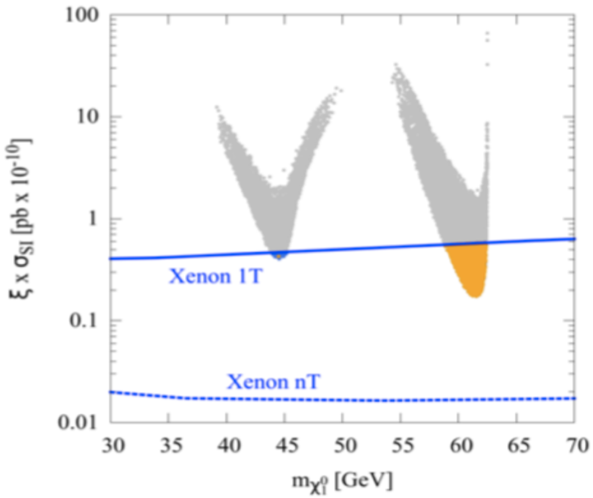
Baraschi et al (MasterCode), 1710.11091

- MSSM with 11 free parameters -global fit which includes LHC data + DM observables
- DM confined to special regions ‘coannihilation, funnel’
- DD detection can be much suppressed – below neutrino floor

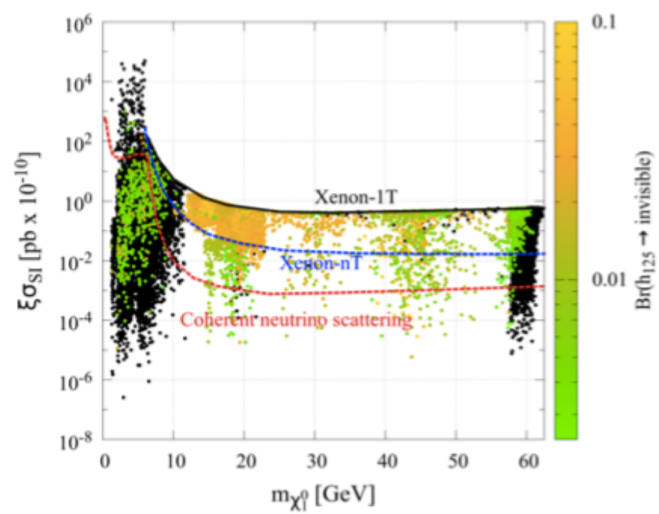
‘Light’ neutralino DM

- The case of light neutralino (below 10 GeV) : much more constrained – need coupling to Z or Higgs for efficient enough annihilation in early universe -> signals in Higgs invisible decay AND direct detection

Barman et al, 2010.11674



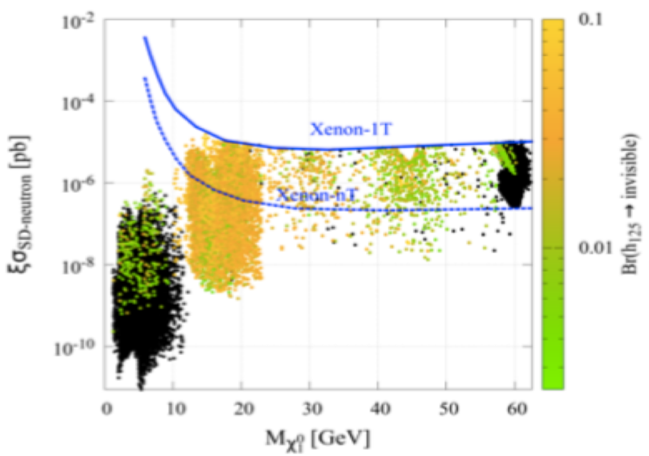
Barman et al 2006.07854

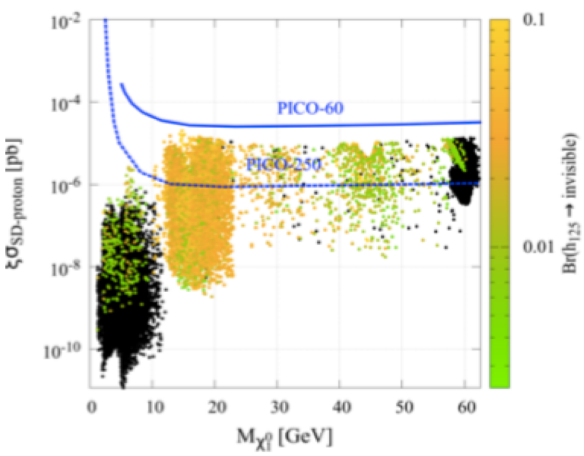


- Adding a singlet/singlino (NMSSM) opens up possibility for neutralino below 10 GeV – new mediators : (pseudo-)scalar singlet
- Important to increase sensitivity in the range below 10GeV

‘Light’ neutralino DM

- SD can offer complementary probes



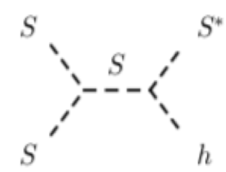


Barman et al 2006.07854

Semi-annihilation

- Semi-annihilation: processes involving different number of dark particles $\chi\chi \to \chi^* SM$ (Z_3)- Hambye, 0811.0172; D'Eramo, Thaler 1003.5912
- Singlet scalar model with Z3 symmetry

$$V_{Z_3} = \mu_H^2|H|^2 + \lambda_H|H|^4 + \mu_S^2|S|^2 + \lambda_S|S|^4 + \lambda_{SH}|S|^2|H|^2 + \frac{\mu_3}{2}(S^3 + S^{\dagger 3}),$$

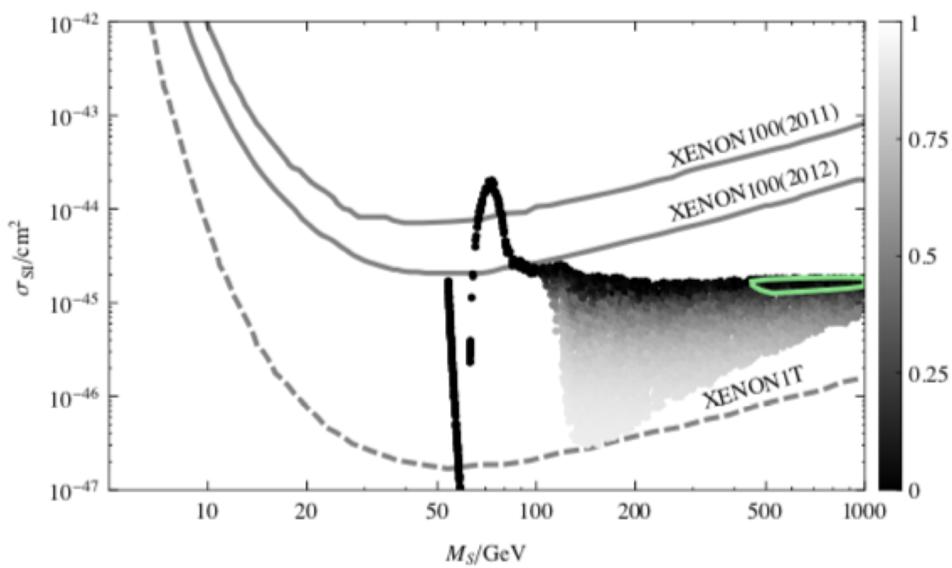


- As in singlet scalar+ new process

$$\frac{dn}{dt} = -v\sigma^{xx^* \to XX}\left(n^2 - \overline{n}^2\right) - \frac{1}{2}v\sigma^{xx \to x^* X}\left(n^2 - n\,\overline{n}\right) - 3Hn.$$

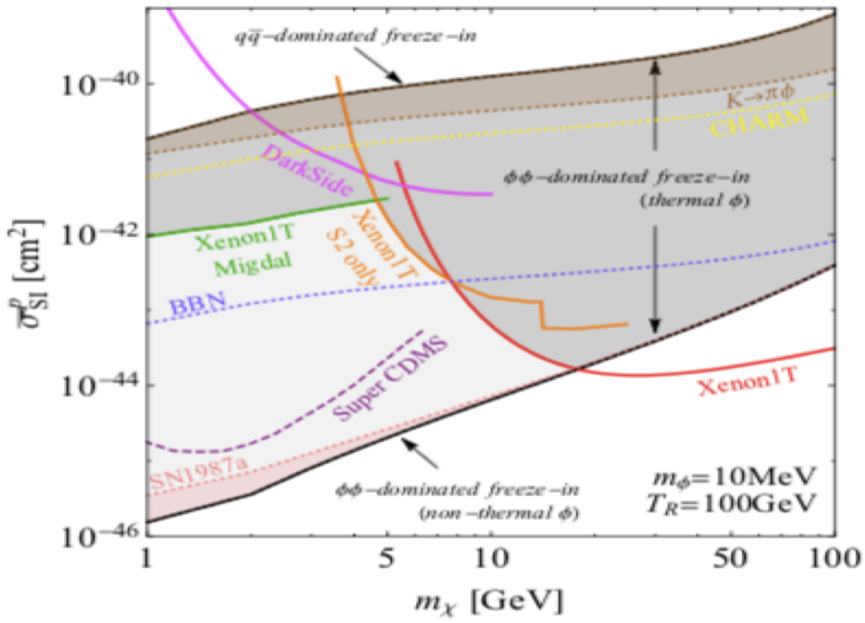
- Increase DM annihilation
- Relaxes DD constraint

GB et al, 1211.1014



GeV scale

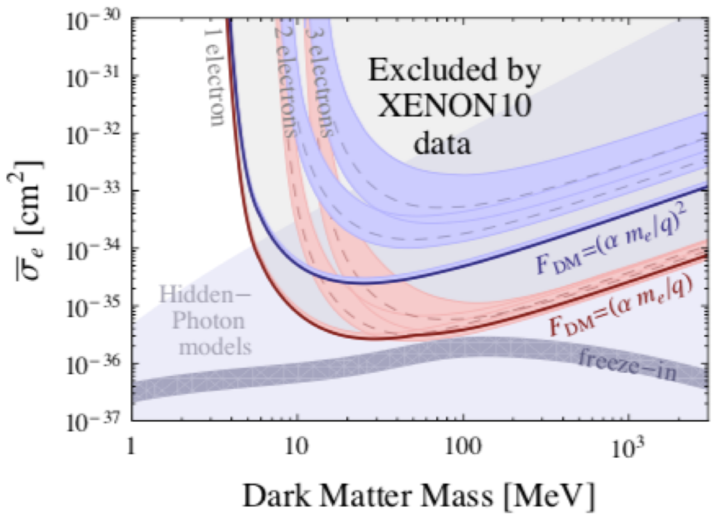
- DM at the GeV scale in model with freeze-in (DM that couples to quark + light scalar mediator)
- Presence of a light mediator can bring DD prediction within testable range (recall that cross-section ~ $1/(m_S^4)$ for $m_S >> q^2$)



GB et al 2005.06294

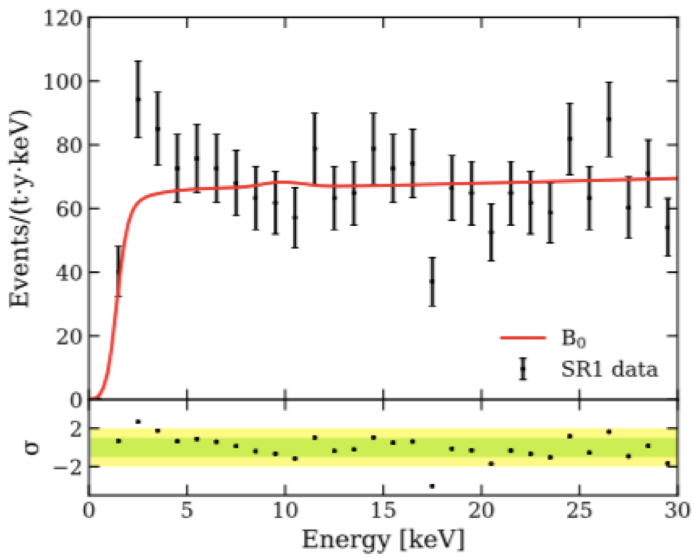
Direct detection – electrons

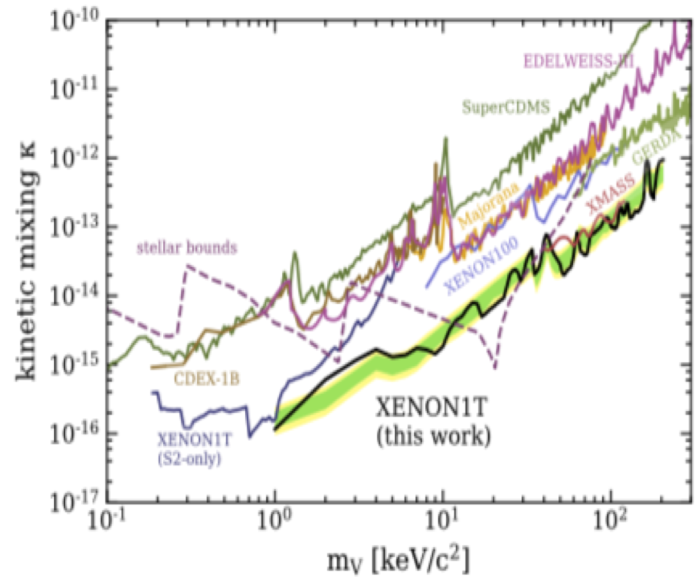
- DM can scatter off electrons – scattering ionize atoms in target leading to single electron signal, recoiling electron can also ionize other atoms if has sufficient energy – lead to few electron signals
- Allow to extend the sensitivity of DM detector below m~GeV where typical nuclear recoil energy is below threshold. $E_{nr} \sim m_{DM}^2 v^2/2m_N$
- Energy available, $E_{kin} = m_{DM}/2\ v^2$
- First limits from Xenon10 (Essig et al 1206.2644)



Direct detection – electrons

- Excess electron recoil events in XENON1T E~2keV, Aprile et al 2006.09721





- Possible interpretation : tritium, axions, neutrino magnetic moment, light vector DM, inelastic DM, decaying DM and more

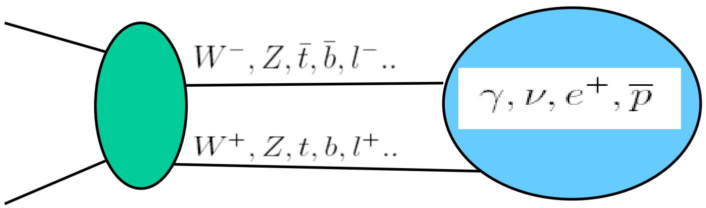
Summary

- Direct detection experiments strongly constraints WIMP models
- Many possibilities to weaken the constraints in a variety of DM models
- Spin dependent interaction although less sensitive can offer complementary probes
- To cover all possibilities, need to reach below the GeV scale
- Direct detection form elastic scattering on electrons offers the possibility to probe MeV region
- In some cases, DD can probe feebly-interacting particles

Some remarks on indirect detection

Indirect detection

Annihilation of pairs of DM particles into SM : decay products observed



Searches for DM in 4 channels

- Antiprotons and Positrons from galactic halo
- Photons from GC/Dwarfs
- Neutrinos from Sun/GC

Rate for production of e^+,p,γ

- Dependence on the DM distribution (ρ) – not well known in center of galaxy
- Dependence on propagation

$$Q(x, \mathbf{E}) = \frac{<\sigma v>}{2} \left(\frac{\rho(\mathbf{x})}{m_\chi} \right)^2 \frac{dN}{dE}$$

Typical annihilation cross section $<\sigma v> = 3 \times 10^{-26} \mathrm{cm}^3/\mathrm{sec}$

Indirect Detection

In galaxy where v->0.001c , σv can be different than at "freeze-out"

$$\sigma v = a + b v^2$$

σv(0) < σv(FO) if b dominates (e.g. neutralinos into fermions)

	s-channel mediator				*t*-channel mediator			
	$\bar{f}f$	$\bar{f}\gamma^5 f$	$\bar{f}\gamma^\mu f$	$\bar{f}\gamma^\mu\gamma^5 f$	$\bar{f}f$	$\bar{f}\gamma^5 f$	$\bar{f}\gamma^\mu f$	$\bar{f}\gamma^\mu\gamma^5 f$
Dirac fermion	v^2	v^0	v^0	v^0	v^0	v^0	v^0	v^0
Majorana fermion	v^2	v^0	0	v^0	v^0	v^0	v^0	v^0
real/complex scalar	v^0	v^0	$0/v^2$	$0/v^2$				

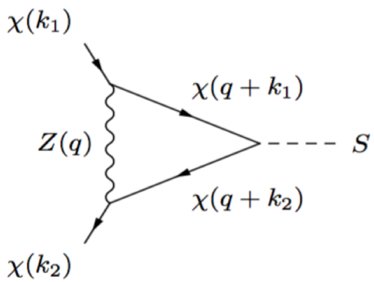
Also suppressed cross section if coannihilation dominant

Indirect Detection

Increased cross section at small v (Sommerfeld effect):

Example: Annihilation of 2 fermions into scalar at small v

Loop correction ~1/v in the limit of massless gauge

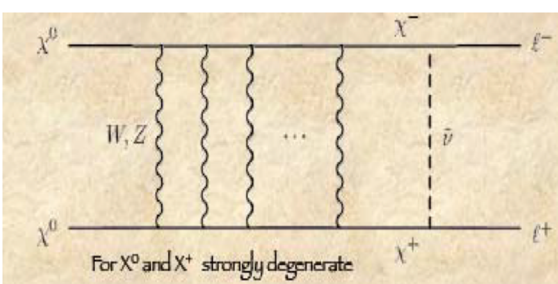


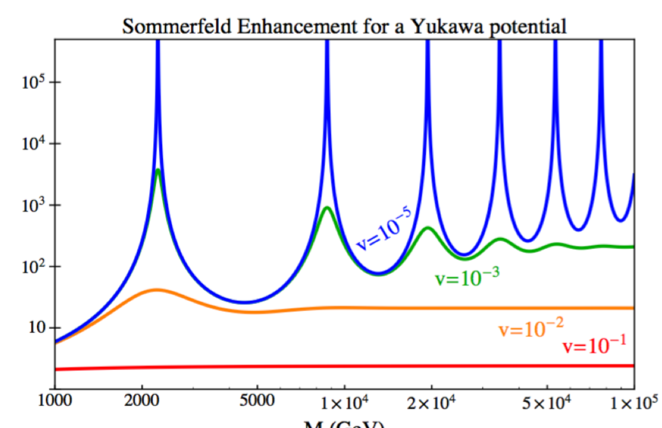
Non-relativistic QM effect – scattering of particles in potential

Exchange of light particles long range potential V= -α/r

Distorts DM wave function leads to enhancement factor as v->0

Example: long range Coulomb Arkani-Hamed et al 0818.0713





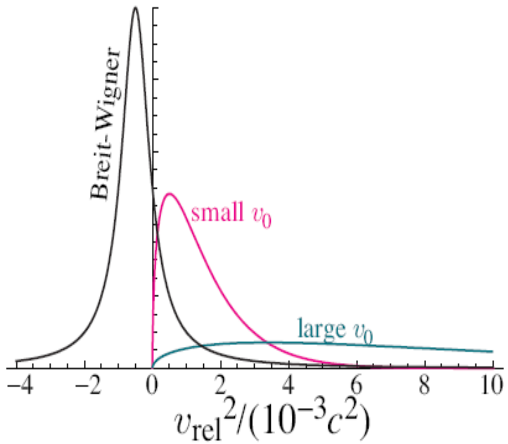
Indirect Detection

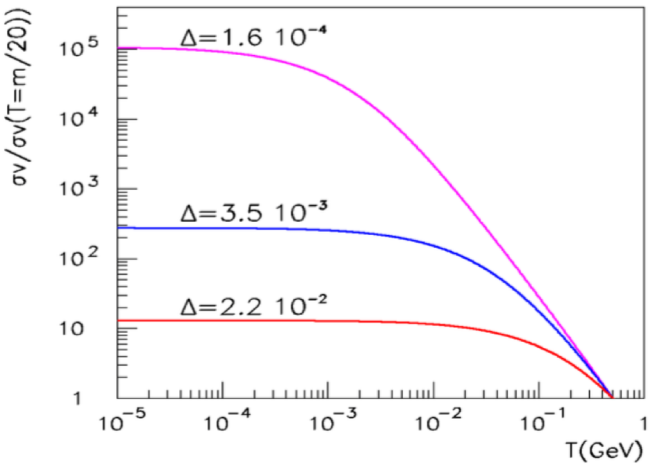
Near resonance annihilation

$$v\sigma(v) \propto \frac{1}{(s-m_A^2)^2+\Gamma_A^2 m_A^2} = \frac{1}{16m_\chi^4}\frac{1}{(v^2/4+\Delta)^2+\Gamma_A^2(1-\Delta)/4m_\chi^2}$$

$\Delta = 1 - m_A^2/4m_\chi^2$

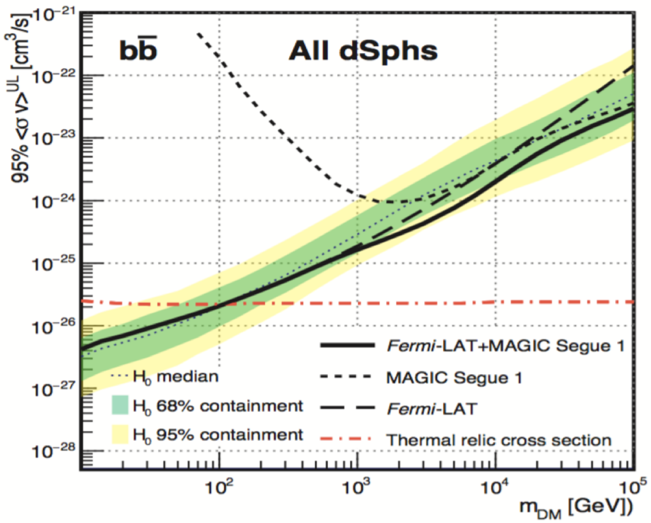
For $m_\chi \sim m_A/2$ and narrow width– at small v can have full resonance enhancement while in early universe (non relativistic but thermal average) mostly above the resonance



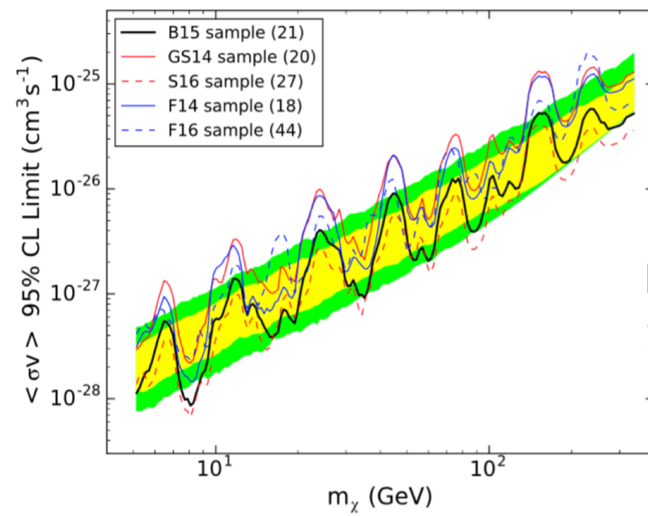


Results - photons

Ahnen et al, 1601.06590
Fermi+MAGIC



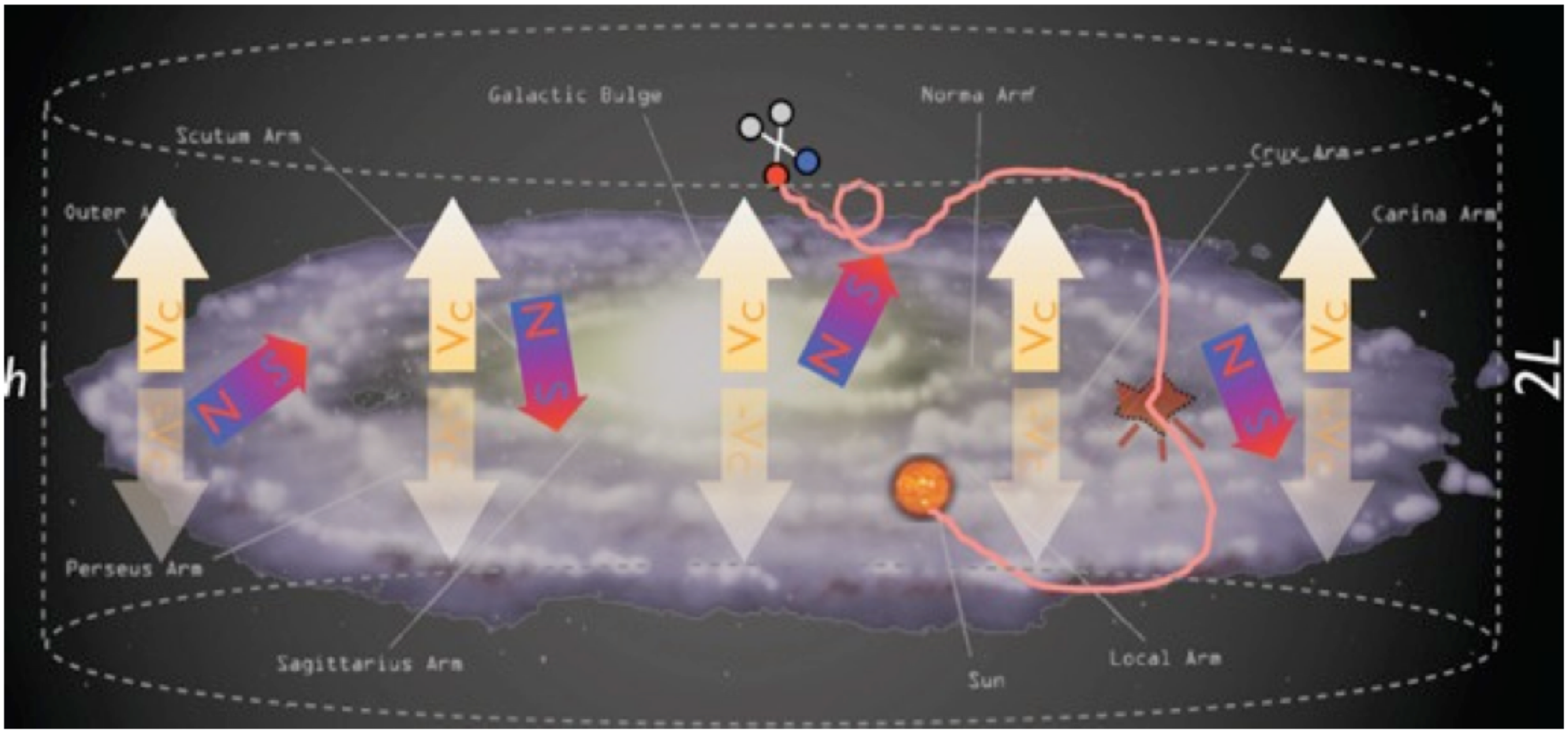
γ–ray lines from DM annihilation in diphoton or γZ - loop induced



Liang et al, 1608.07184

- For light dark matter FermiLAT probes cross sections expected of a thermal relic with photons from Dwarf galaxies
- Also searches in Galactic center : strong dependence on profile
- Excess (see other lectures)

Cosmic rays - Propagation



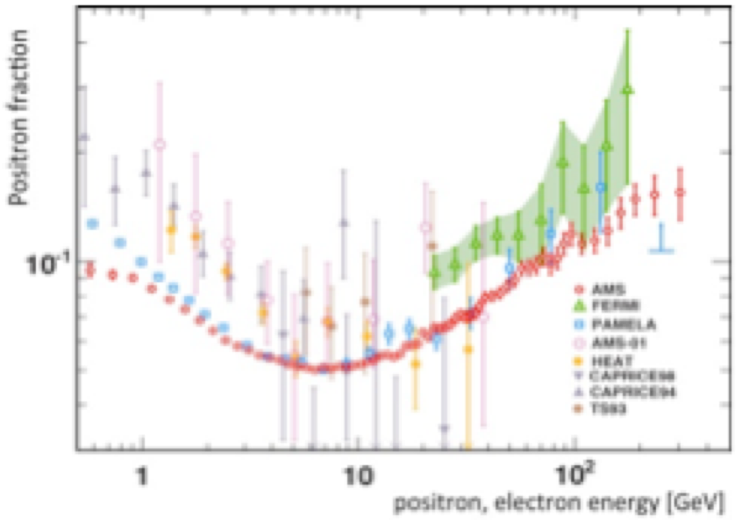
$$\frac{\partial N}{\partial t} - \nabla \cdot [K(\mathbf{x}, E) \nabla N] - \frac{\partial}{\partial E} [b(E) N] = q(\mathbf{x}, E)$$

Source

Positrons

- Large excess in positron fraction (from PAMELA and AMS)
- No excess in antiprotons (PAMELA) and AMS compatible with background

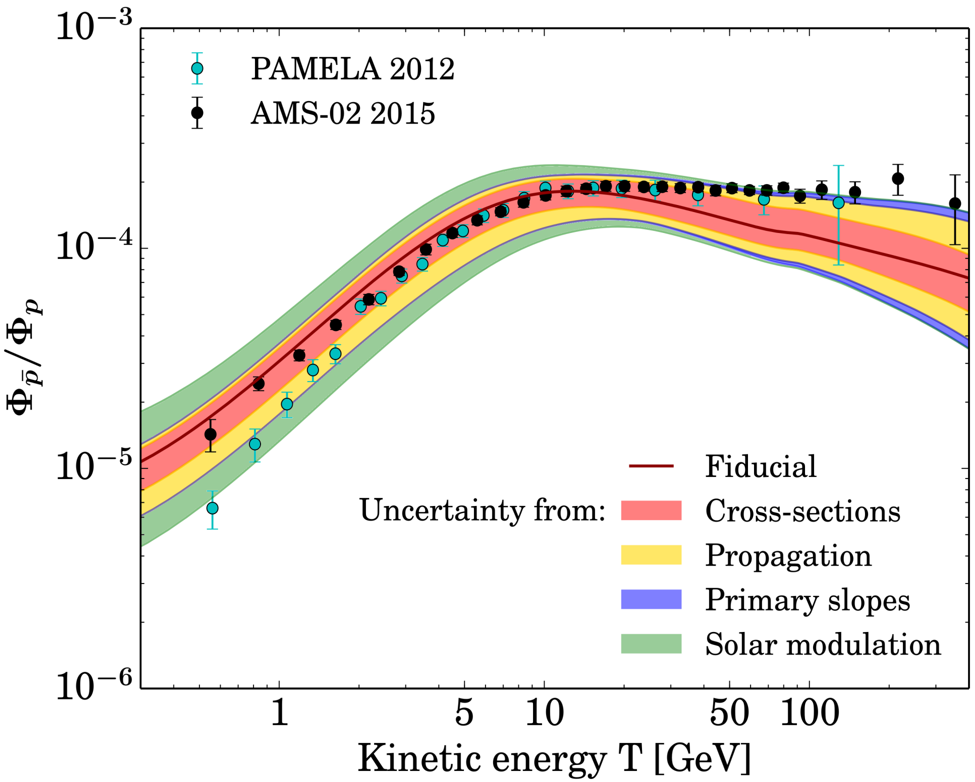
  - Can this be DM? Leptophilic?
  - Model-independent approach but required cross-section very large (M. Boudaud et al, 1410.3799) : in tension with results from photon (Abramowski et al, 1410.2589) antiproton, IceCube, CMB(Cline, Scott, 2013)
  - More likely due to astro source – pulsar could explain positron excess -> difficult to see DM



AMS, PRL113.121101

Antiprotons

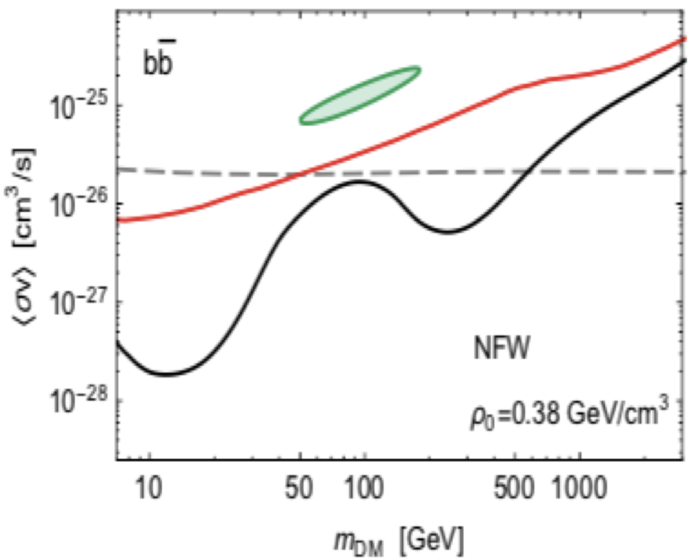
- Using AMS' updated proton and helium fluxes, secondary pbar/p with uncertainties was reevaluated
- No significant excess observed

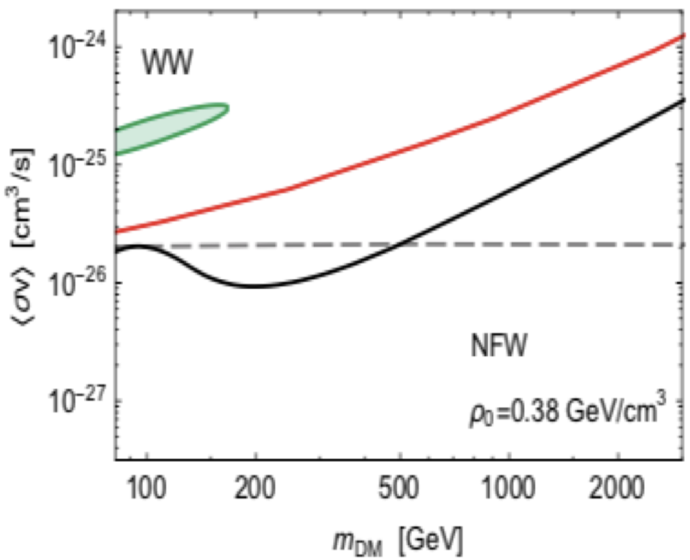


G.Gliesen et al, 1504.04276

Results - Antiprotons

- AMS02 measurements of B/C lead to refined constraints on propagation parameters (Genolini et al, 2103.04108)
- Model independent analysis of DM constraint – including DM +B/C fit
- Strong constraints on DM annihilation especially in bbar channel

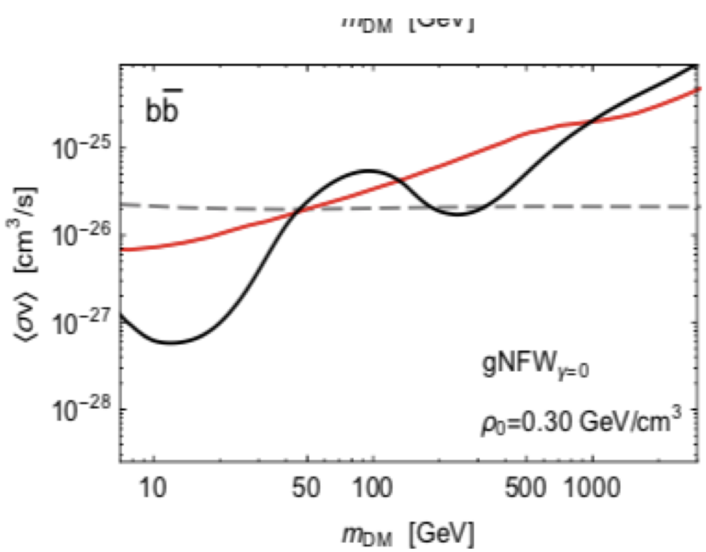




Reinert, Winkler, 1712.00002

Results - Antiprotons

- AMS02 measurements of B/C lead to refined constraints on propagation parameters (Genolini et al, 2103.04108)
- Model independent analysis of DM constraint – including DM +B/C fit
- Strong constraints on DM annihilation especially in bbar channel – dependence on propagation and DM profile



$$\rho_{\rm DM} = \rho_0 \left(\frac{R_0}{r}\right)^{\gamma} \left(\frac{R_0 + r_s}{r + r_s}\right)^{3-\gamma}$$

NFW: γ=1 r_s=18.6kpc R_0=8.2kpc
gNFW: γ=0 r_s=12.3kpc R_0=8.2kpc

Reinert, Winkler, 1712.00002

Indirect detection - Summary

- Constraints on DM with canonical cross-section below ~100GeV both from photons and antiprotons
- Possibility of enhanced cross-sections (Sommerfeld)
- Anomalies are still there : due to dark matter or astro sources?

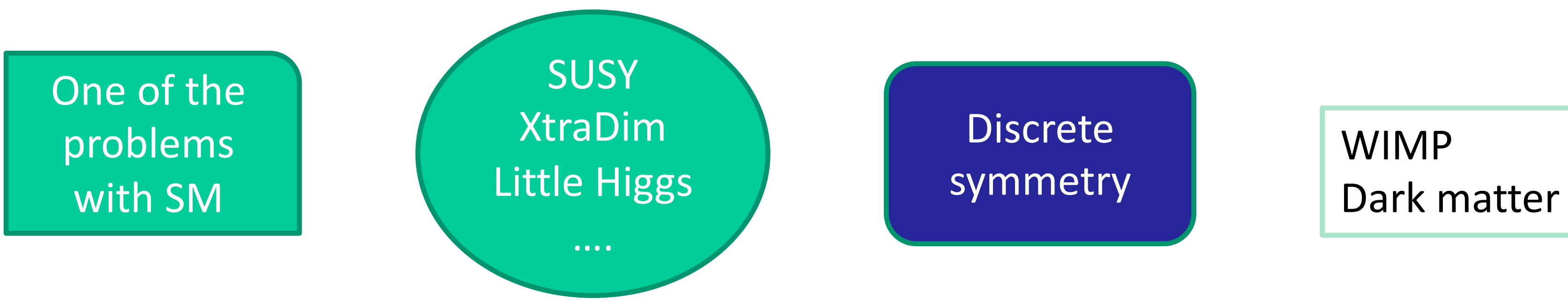
Searches for dark matter at colliders

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

Beyond the standard model

For many years – clear direction on how to explore BSM/DM

Start with problems with SM: symmetry breaking, Higgs, unification, fermion masses …



Interplay Collider, (in-)direct DM searches, cosmology

But there are a lot more possibilities for WIMPs and for DM

Start with stable neutral particle, and build from there (mediator, other dark particles)

DM searches at LHC

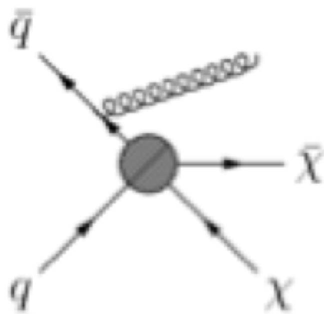
- LHC pp colliders at 8-13-14TeV,   largest production cross-section for coloured particles and charged particles
- Neutral particles leave no signature : missing transverse energy (MET)
- Variety of processes for probing DM
  - Monojet
  - MonoX (W,Z,H)
  - MET + stuff (dijets, di-leptons, b jets, tops, multileptons…)
  - Invisible decays of the Higgs
  - Charged tracks and displaced vertices : for long-lived next-to-lightest dark sector particle: small mass splitting or very weak interactions
  - Searches for new particle (mediator) in SM final states

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

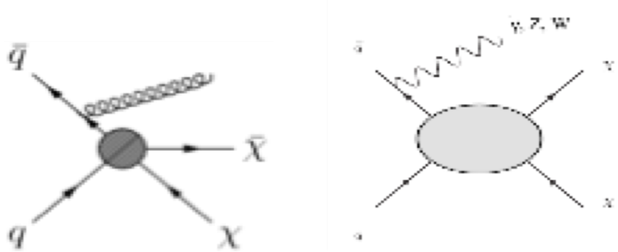
Signature : jet + large missing ET



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

EFT approach

Direct production of pairs of DM + radiation : high E_T miss + single jet/photon/boson



(a) $q\bar{q} \to \chi\chi + g$ (b) $q\bar{q} \to \chi\chi + \gamma, Z, W$

Effective interaction operators

(a)Operators for Dirac fermion DM

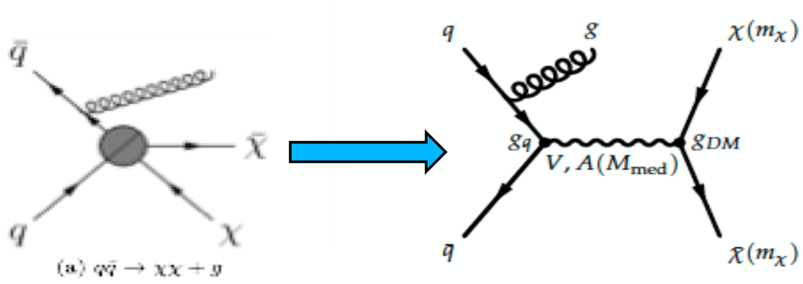
Name	Operator	Dimension	SI/SD
D1	$\frac{m_q}{\Lambda^3}\bar{\chi}\chi\bar{q}q$	7	SI
D5	$\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	6	SI
D8	$\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$	6	SD
D9	$\frac{1}{\Lambda^2}\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$	6	SD
D11	$\frac{\alpha_s}{\Lambda^3}\bar{\chi}\chi G^{\mu\nu}G_{\mu\nu}$	7	SI

For each operator : monojet limit compared to limit from direct detection

Caveats : monojet limit valid assuming scale NP large, may not be valid at LHC energies-> simplified models

Simplified models

- Capture essential features with small number of parameters/assumptions
- SM + mediator +DM + some Z_2 symmetry



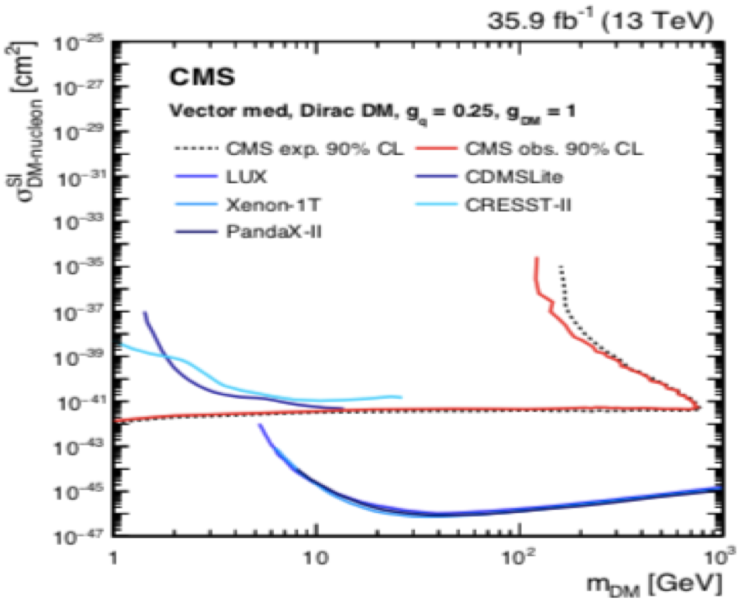
- 4 parameters : g_q, g_{DM}, M_M, M_{DM}

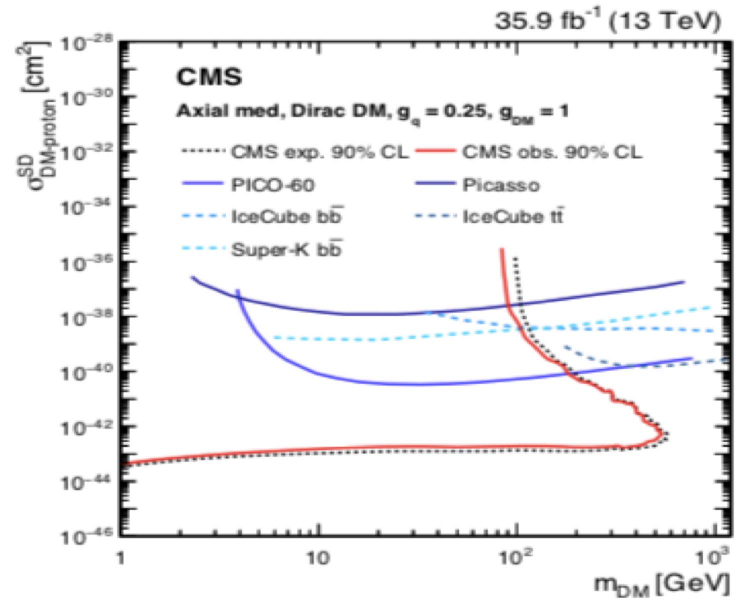
Looking for monojet within large SM background –less background at large missing E_T

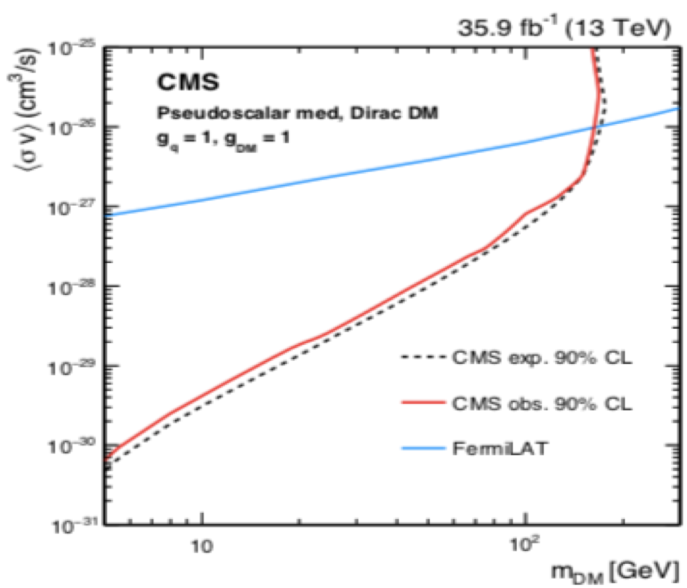
No excess –> constraint on DM model

Constraints from monojet vs (in)direct detection

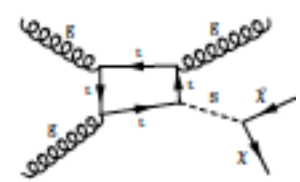
CMS 1712.02345





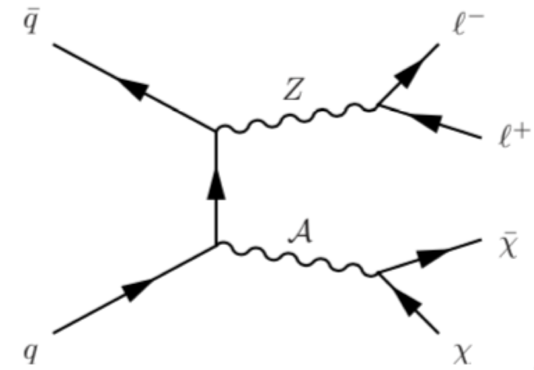


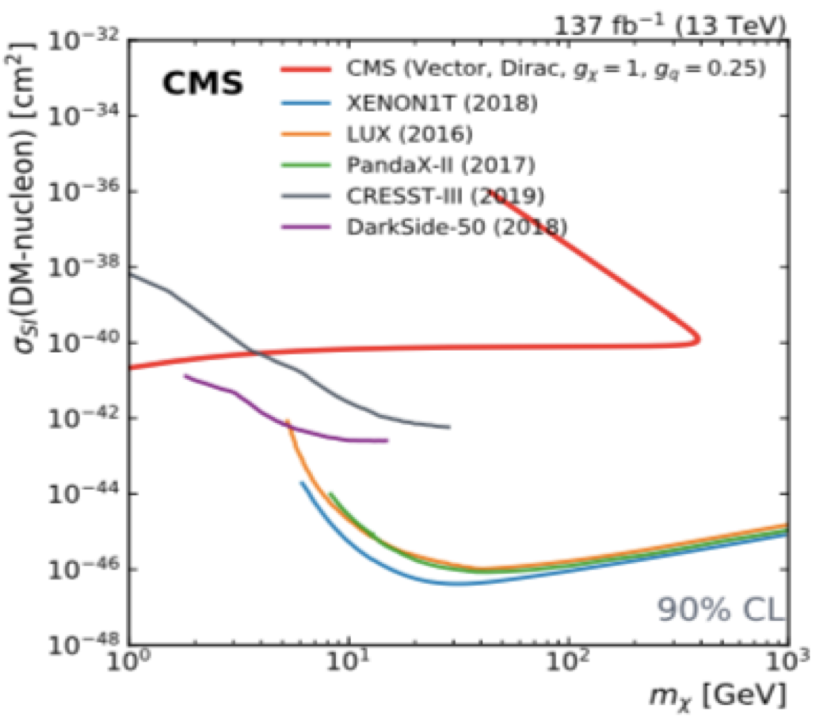
Assume $M_{DM} < M_{med}/2$

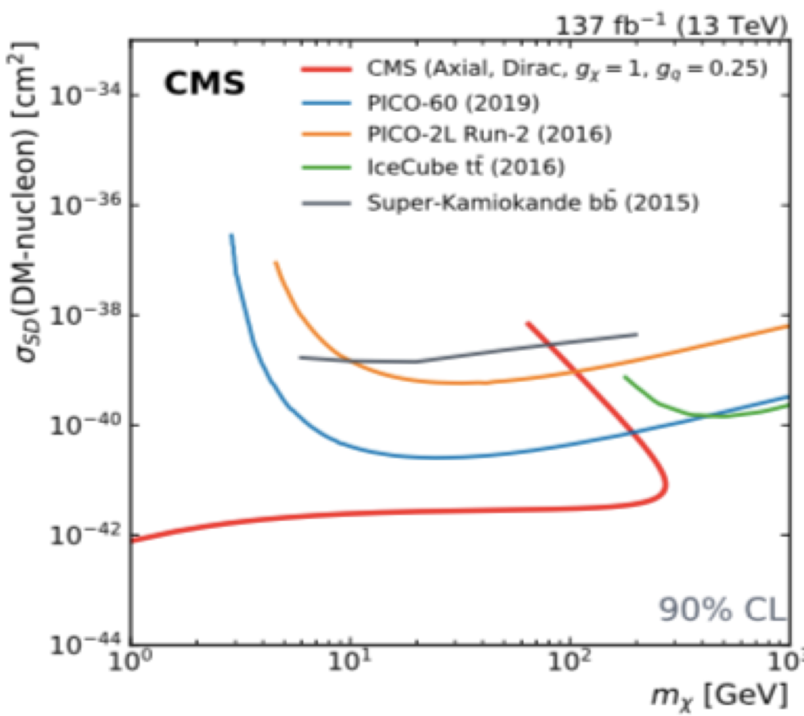


Mono-W/Z

- The case of Vector/axial-vector mediator
  - About one order of magnitude weaker than monojet (despite higher lumi)







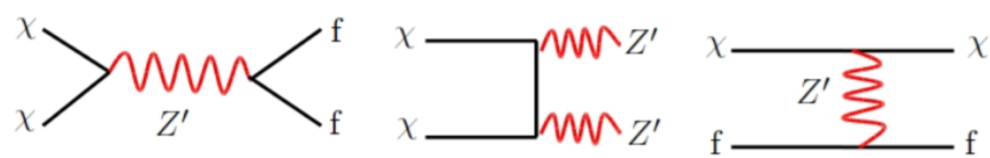
CMS collaboration, 2008.04735

DM and SM signatures

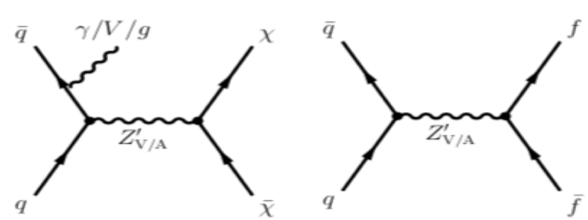
- Z' portal : well motivated extension of SM, e.g. in GUT
  SU(3)XSU(2)XU(1)XU(1)
- Discrete symmetry
- Dark matter: neutral fermion or scalar in dark sector
- Many constructions possible (popular simplified model)

$$\mathcal{L} \supset Z'_{\mu} \left[\bar{\chi}\gamma^{\mu}\left(g_{\chi \mathrm{v}} + g_{\chi a}\gamma^{5}\right)\chi + \sum_{f \in \mathrm{SM}} \bar{f}\gamma^{\mu}\left(g_{f\mathrm{v}} + g_{fa}\gamma^{5}\right) f\right]$$

- Dark matter observables :

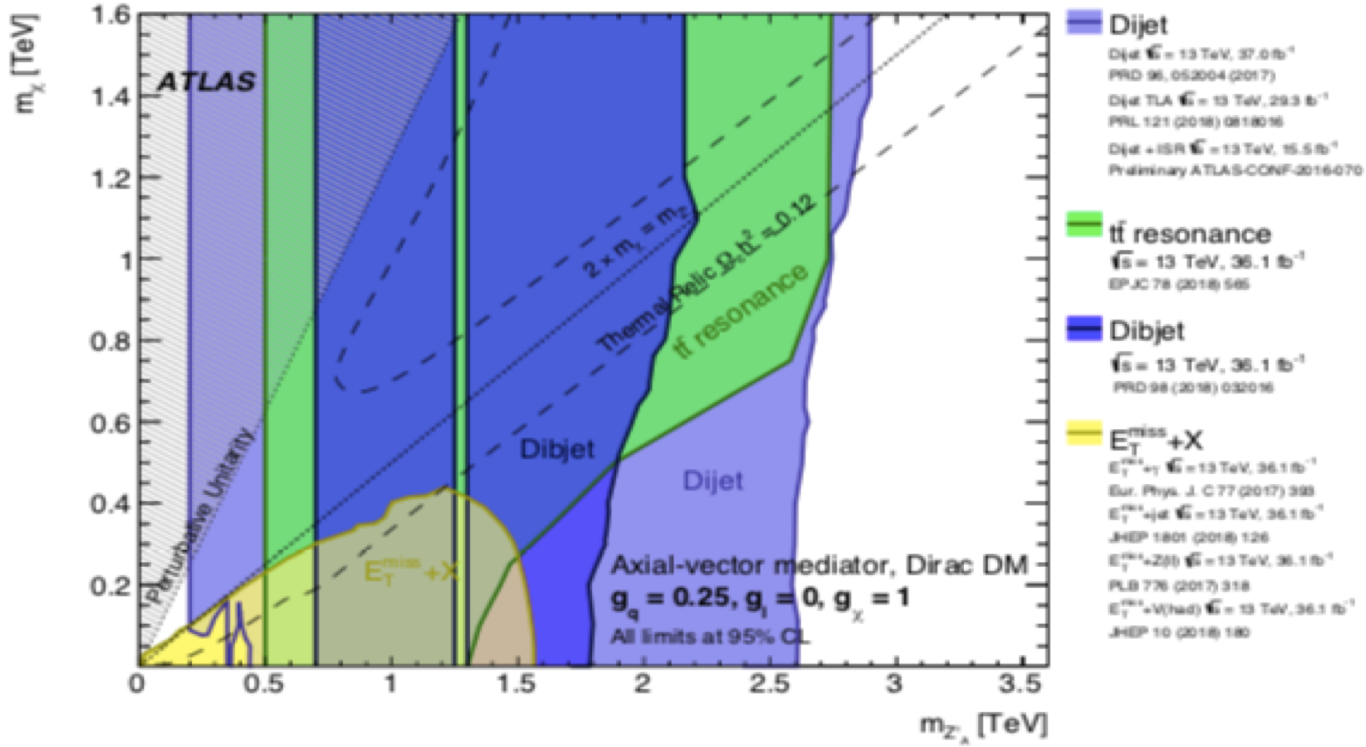


- Coupling to quarks and leptons +dark matter → dijet and dilepton limits



Z’ portal at LHC

ATLAS, 1903.01400



For g_q<< g_{DM} dijet limit shrinks

DM properties (relic) also sensitive to other particles in spectrum

Could relax limits on Z’->SM with Z’ -> invisible but too large coupling to DM

-> Direct detection limit, Arcadi et al, 1402.0221

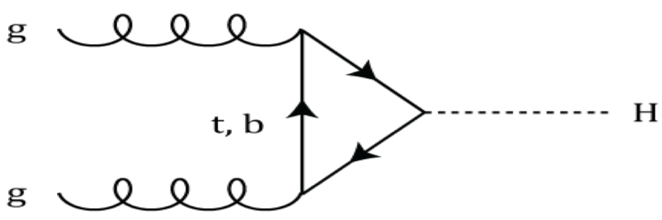
Pseudoscalar mediator

- Specific example : pseudoscalar mediator, fermion DM, also assume couplings proportional to Yukawas-> 3rd generation

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

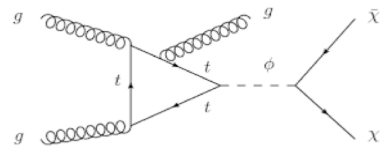
$$\mathcal{L}_{\rm f} = i\sum_{f_u} c_u \frac{m_{f_u}}{v} A \bar{f}_u \gamma^5 f_u + i\sum_{f_d} c_d \frac{m_{f_d}}{v} A \bar{f}_d \gamma^5 f_d$$

- Loop coupling to two-gluons and two-photons

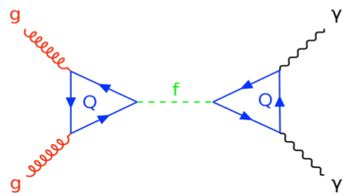


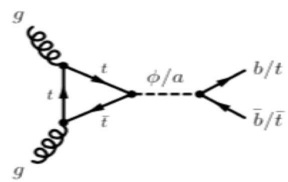
- Coupling of mediator to quark important for LHC constraints

- Several probes at the LHC:
  - monojet

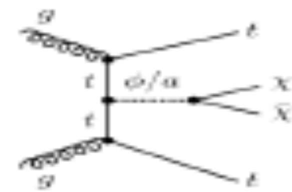


  - searches for mediator in visible (γγ,ττ,tt) or invisible decays, ditop

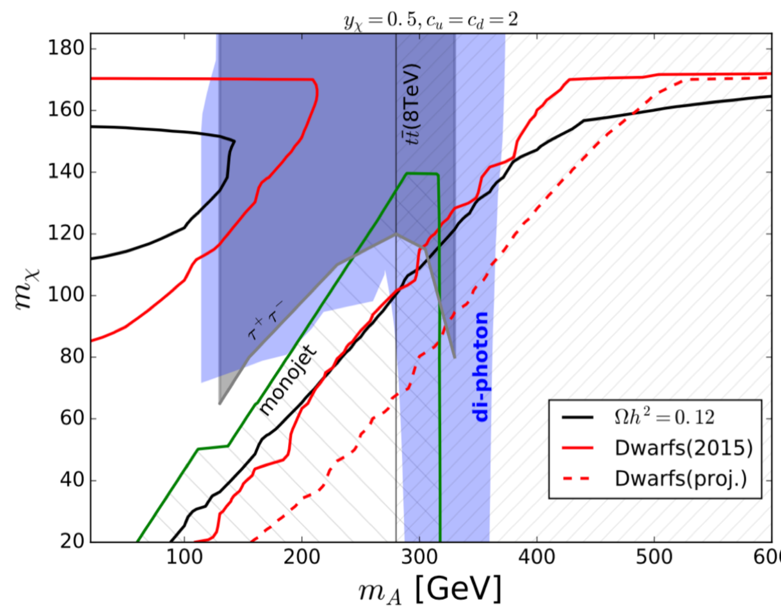




  - associated production of mediator, ttA, bbA



Banerjee et al, 1705.02327



DM searches at LHC

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- Variety of processes for probing DM
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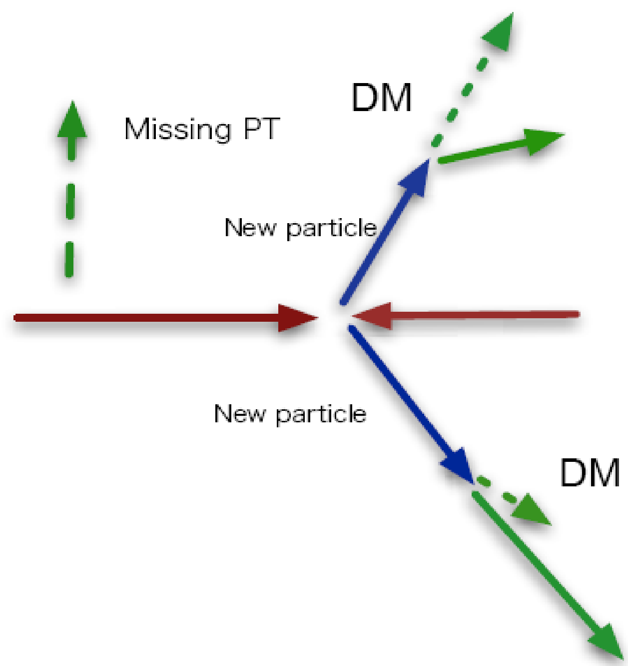
  - Searches for new particle (mediator) in SM final states

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 – in the framework of a BSM model, usually have all signatures

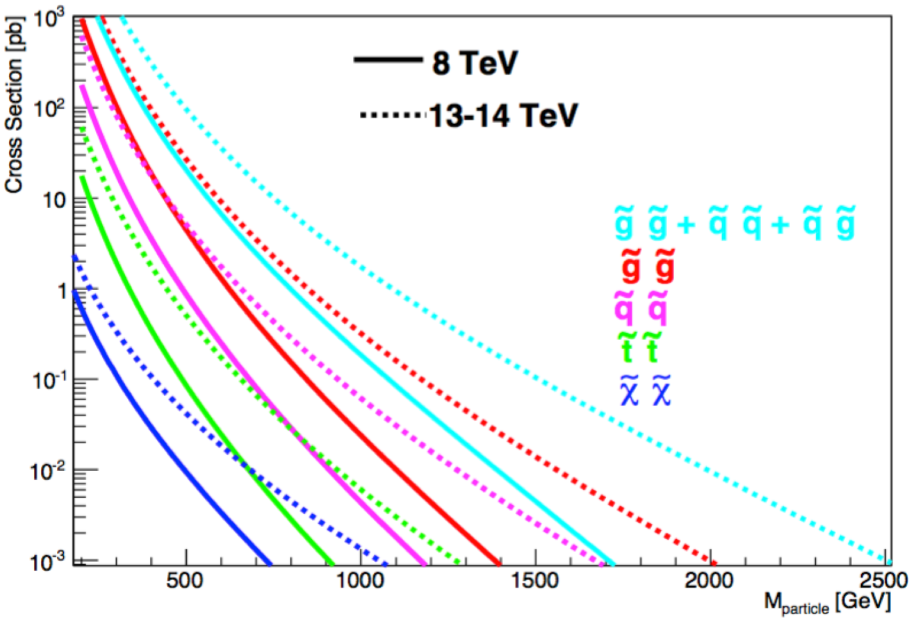


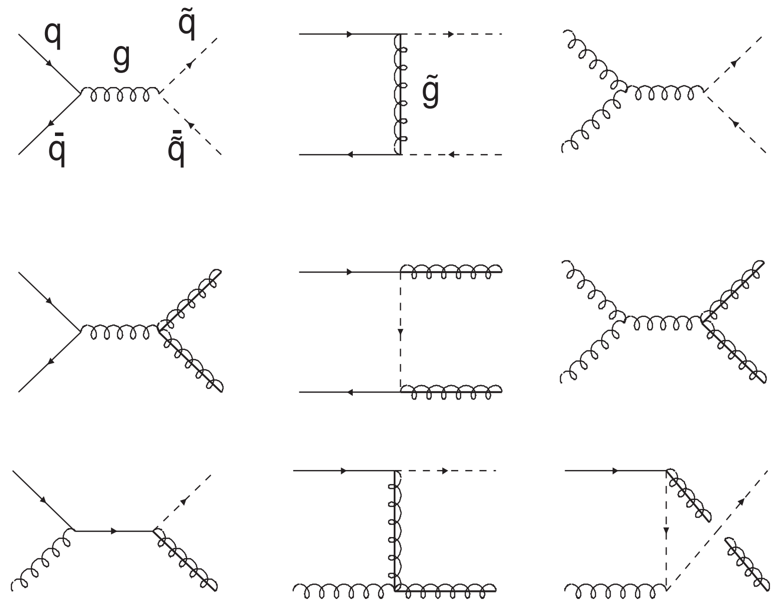
Neutralino DM in SUSY

- For general SUSY model (or pMSSM) must exploit a variety of new physics searches (not just MET)
  - x-lepton + jets + MET
  - Third generation
  - Monojet (most powerful for compressed spectra with production of NLSP,NLSP+jet)
  - Disappearing or charged tracks

SUSY production LHC

Standard susy searches : coloured particles

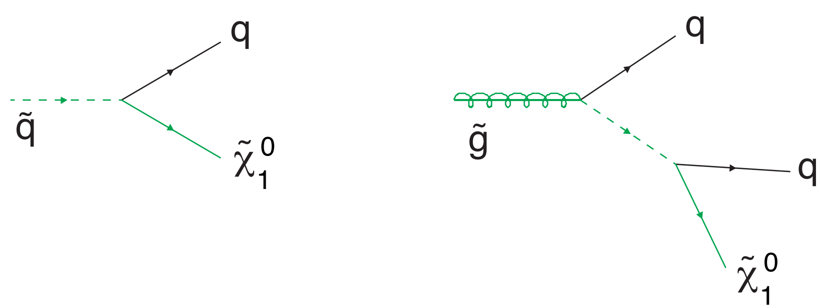




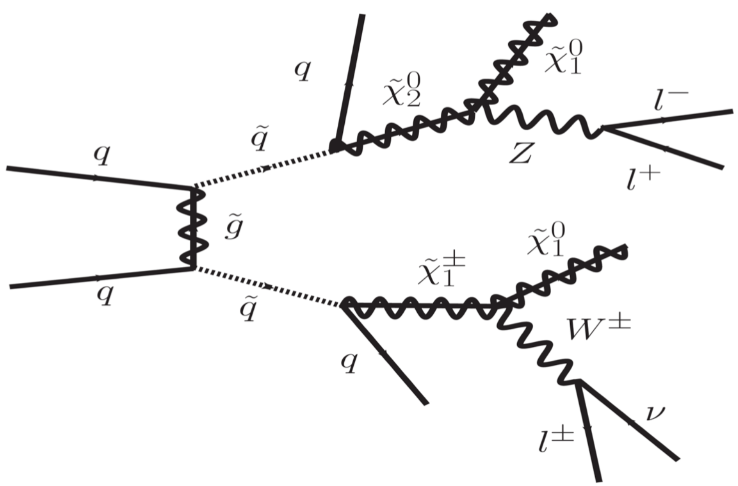
Cross section (13TeV/8TeV):
Gluino (1.4TeV) ~25
Stop/sbottom (750 GeV) ~10

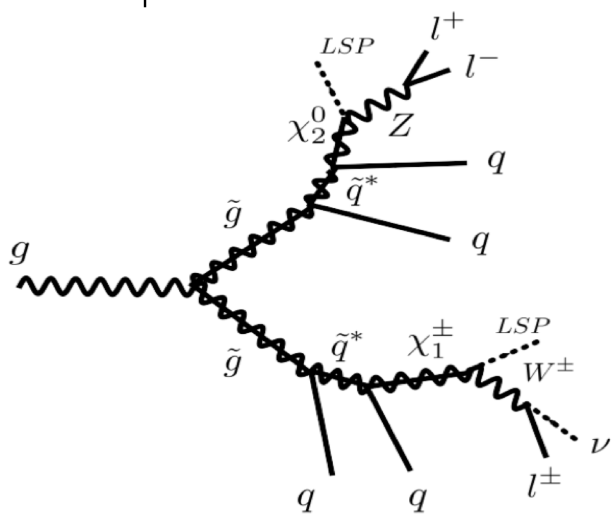
LHC – SUSY

- Signatures of squarks and gluinos : jets+MET; wide ranging sensitivity to strong particle production



- Jets+MET +Leptons

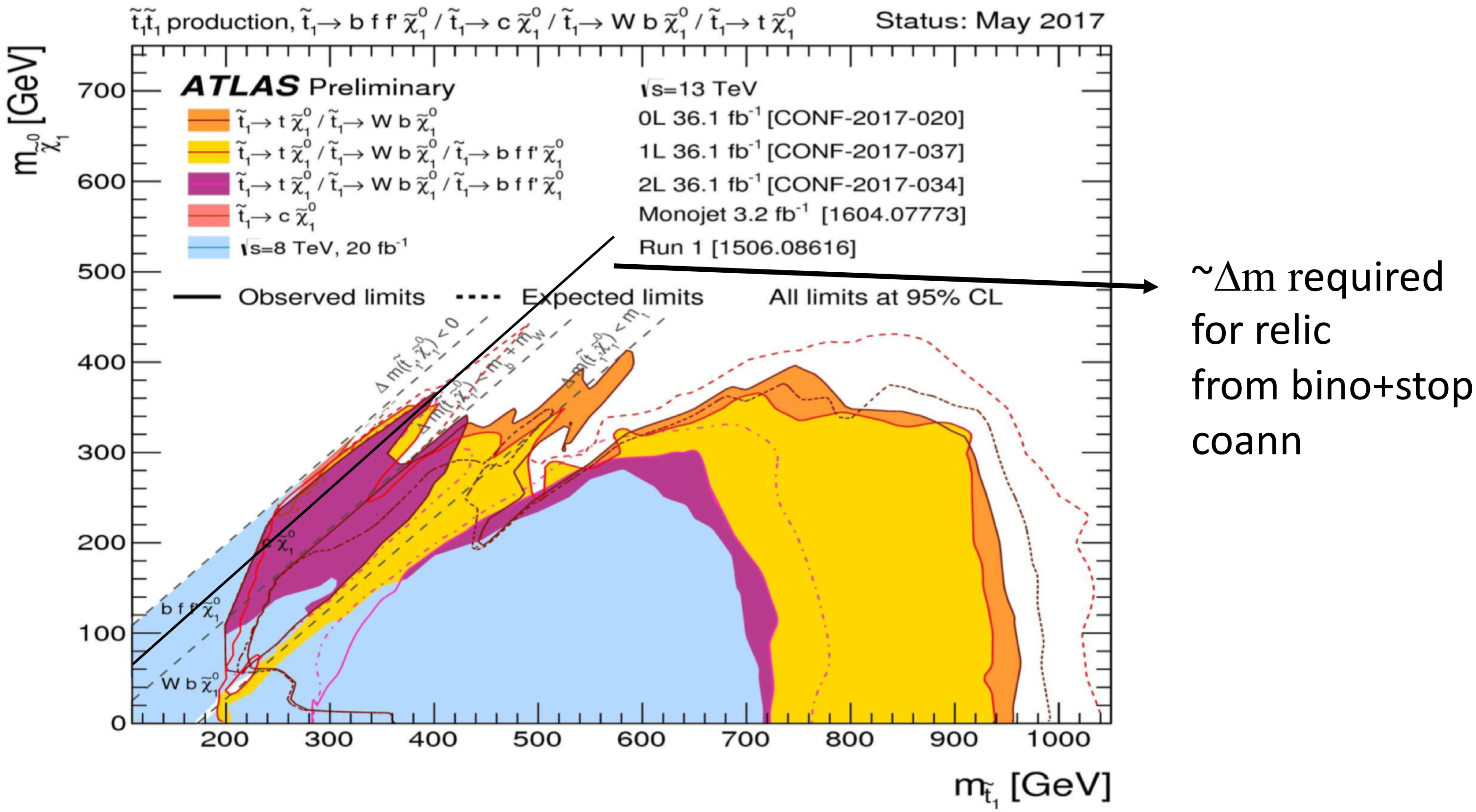




- Limits on squarks and gluinos ~2TeV, not as good for 3rd generation and/or compressed spectra.

Stop- Relevance for DM

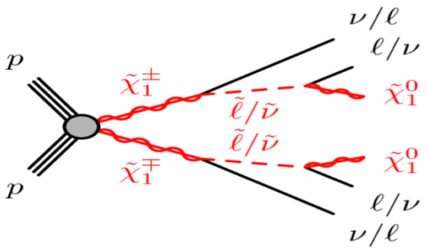
- Stop important for DM is contribute to coannihilation – typical mass splitting 40GeV, covered for m_{DM}<340 GeV

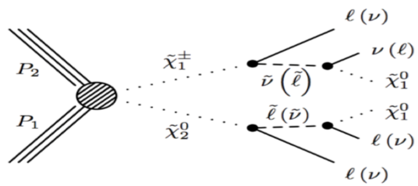


ATLAS,1604.07773

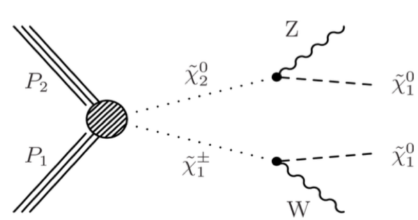
Electroweak-inos

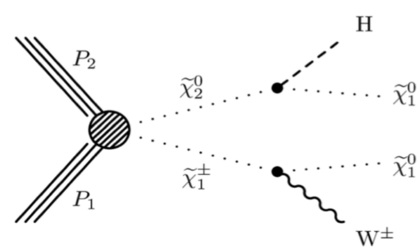
- Direct connection with dark matter (neutralino sector)
- Reach dependent on search channel (here simplified model)





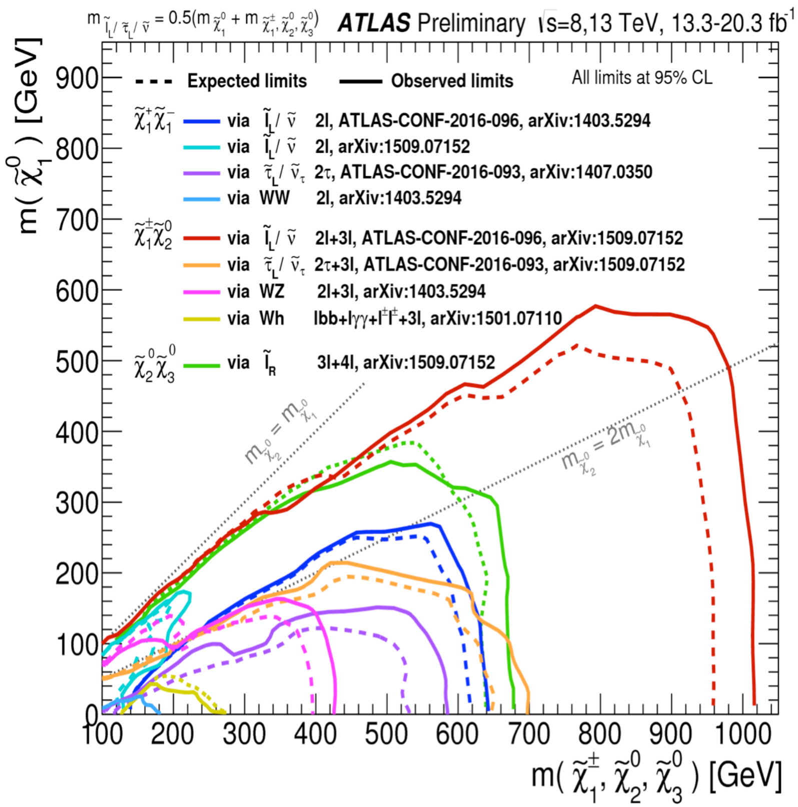
Chargino-neutralino production with
$\tilde{\chi}_1^{\pm} \rightarrow W^{\pm}\tilde{\chi}_1^0$ *and* $\tilde{\chi}_2^0 \rightarrow (Z/H)\tilde{\chi}_1^0$

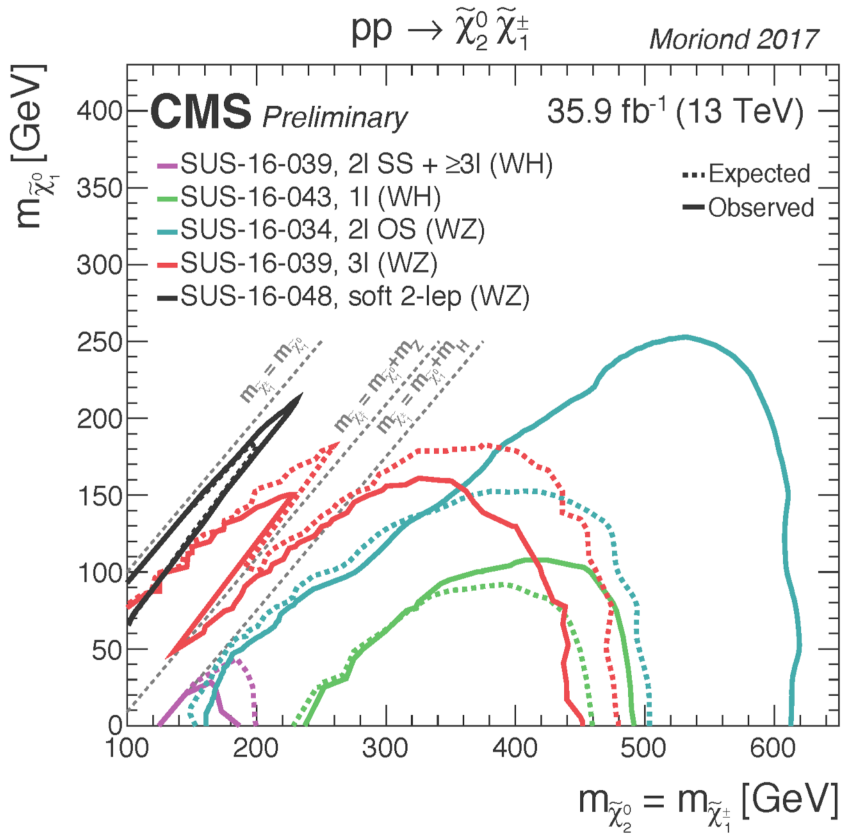




Electroweak-inos

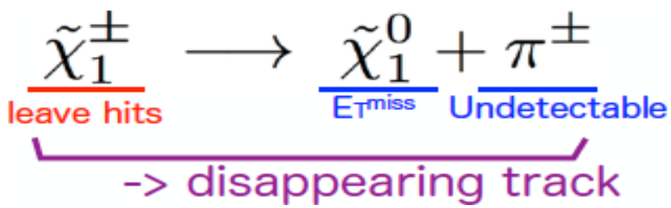
- Weak constraints on charginos which decay into gauge bosons

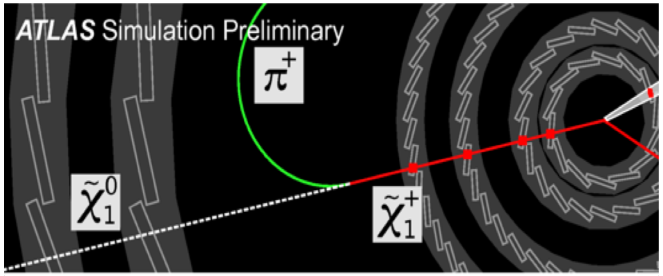


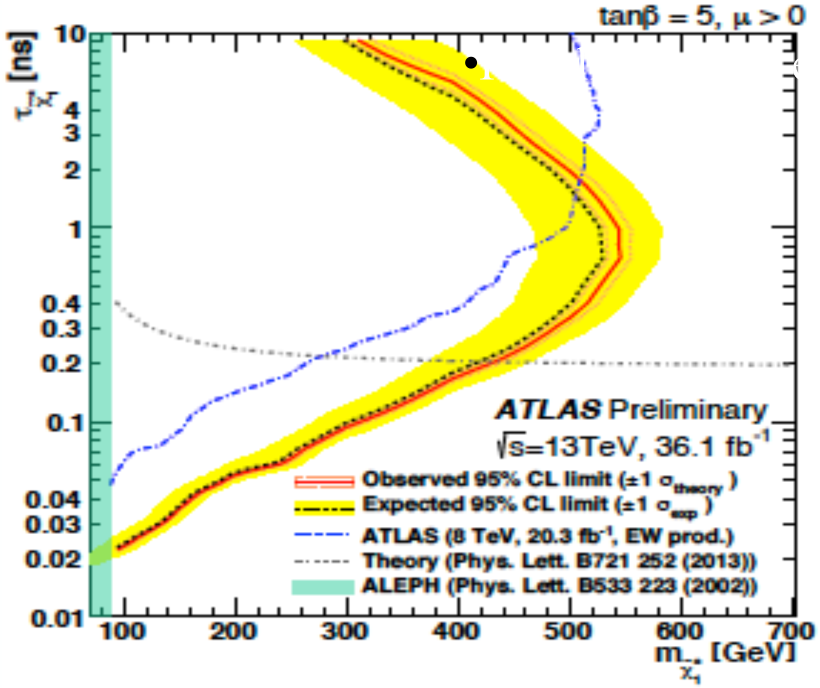


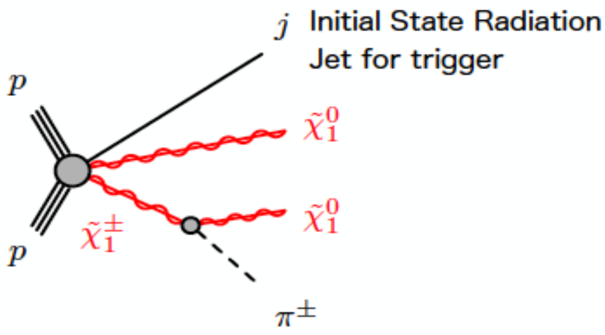
Long-lived charged particles

- Relevant for wino-LSP with small mass splitting (<3 GeV, chargino lifetime .15-.25 ns)







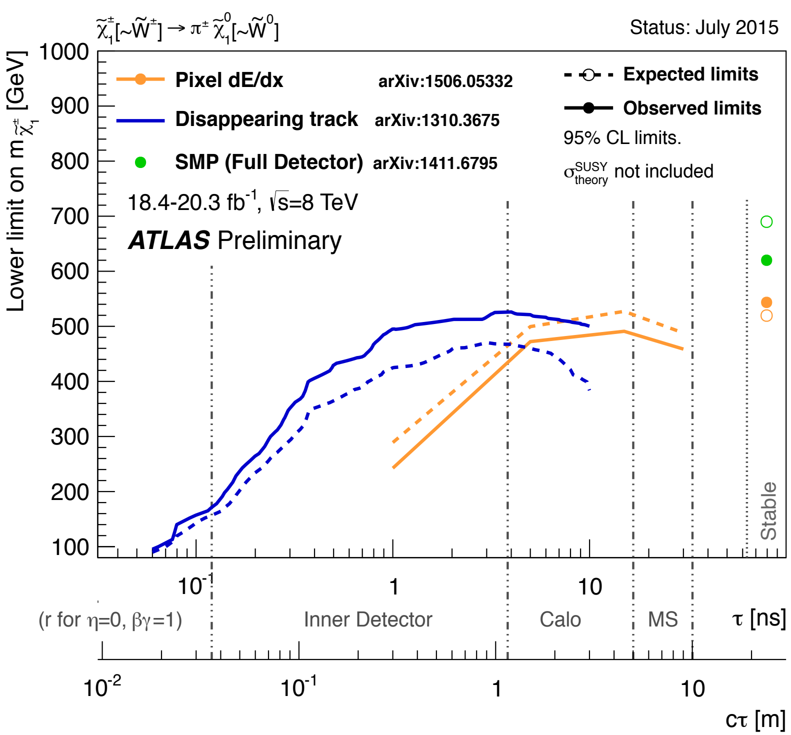


Recall cannot explain all DM

T. Kaji, Moriond 2017

Heavy stable charged particles

LLPs expected to be slow-> specific ionisation higher than any SM particle at high momenta. ATLAS can measure the velocity of charged particles; measures the ionisation energy loss (dE/dx) with pixel detector while calorimeters and the muon spectrometer provide direct measurement of TOF



ATLAS 1506.05332

What's left after LHC (only Run 1)

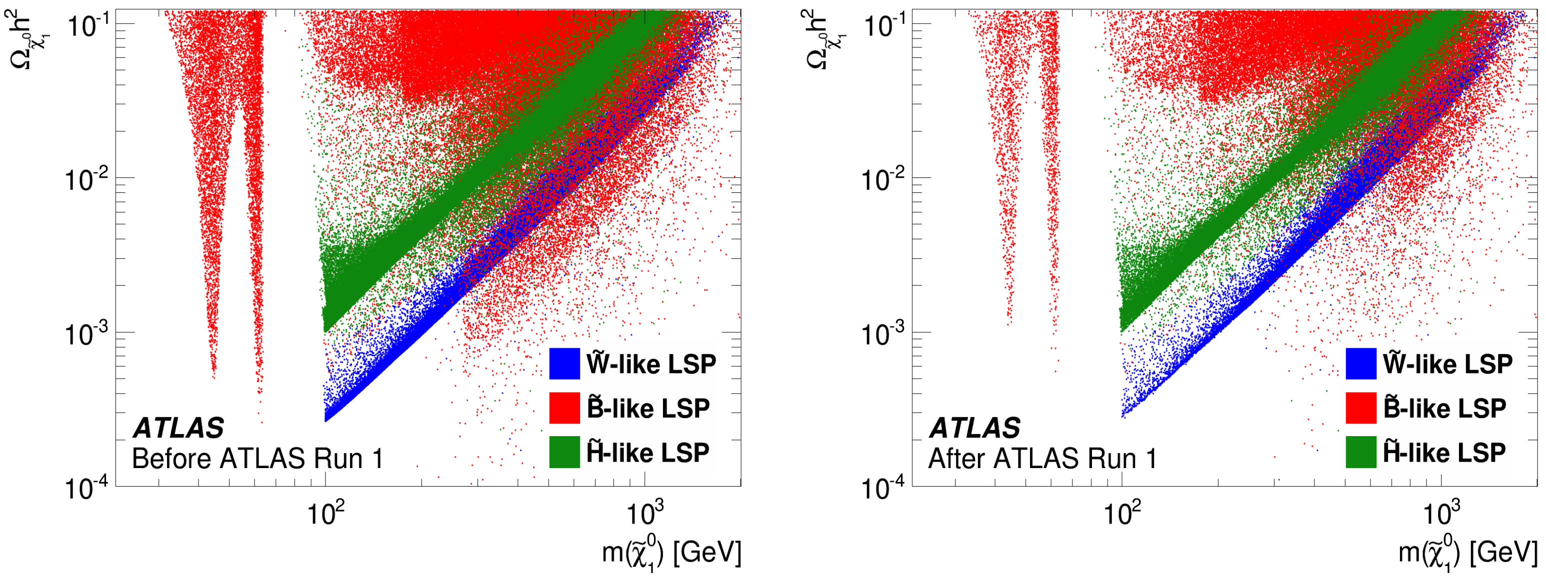
production of DM + jet from ISR and/or compressed spectra

Analysis	All LSPs	Bino-like	Wino-like	Higgsino-like
0-lepton + 2–6 jets + E_T^{miss}	32.1%	35.8%	29.7%	33.5% ⇐
0-lepton + 7–10 jets + E_T^{miss}	7.8%	5.5%	7.6%	8.0%
0/1-lepton + 3b-jets + E_T^{miss}	8.8%	5.4%	7.1%	10.1%
1-lepton + jets + E_T^{miss}	8.0%	5.4%	7.5%	8.4%
Monojet	9.9%	16.7%	9.1%	10.1% ⇐
SS/3-leptons + jets + E_T^{miss}	2.4%	1.6%	2.4%	2.5%
$\tau(\tau/\ell)$ + jets + E_T^{miss}	3.0%	1.3%	2.9%	3.1%
0-lepton stop	9.4%	7.8%	8.2%	10.2% ⇐
1-lepton stop	6.2%	2.9%	5.4%	6.8%
2b-jets + E_T^{miss}	3.1%	3.3%	2.3%	3.6%
2-leptons stop	0.8%	1.1%	0.8%	0.7%
Monojet stop	3.5%	11.3%	2.8%	3.6%
Stop with Z boson	0.4%	1.0%	0.4%	0.5%
tb+E_T^{miss}, stop	4.2%	1.9%	3.1%	5.0%
ℓh, electroweak	0	0	0	0
2-leptons, electroweak	1.3%	2.2%	0.7%	1.6%
2-τ, electroweak	0.2%	0.3%	0.2%	0.2%
3-leptons, electroweak	0.8%	3.8%	1.1%	0.6%
4-leptons	0.5%	1.1%	0.6%	0.5%
Disappearing Track	11.4%	0.4%	29.9%	0.1% ⇐
Long-lived particle	0.1%	0.1%	0.0%	0.1%
$H/A \to \tau^+\tau^-$	1.8%	2.2%	0.9%	2.4%
Total	40.9%	40.2%	45.4%	38.1%

ATLAS 1508.06608

What's left after LHC

ATLAS 1508.06608



(a) Before ATLAS Run 1 (b) After ATLAS Run 1

- Strong constraints on the model but almost full mass range for neutralino DM remains possible
- Recall : for light neutralino, limits on invisible Higgs decays (from global fit to Higgs properties or direct search of inv. Higgs, e.g. in WH or ZH) also restricts model parameter space

The light or the feeble

- When DM particles are feebly interacting 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

The light or the feeble

- When DM particles are feebly interacting 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

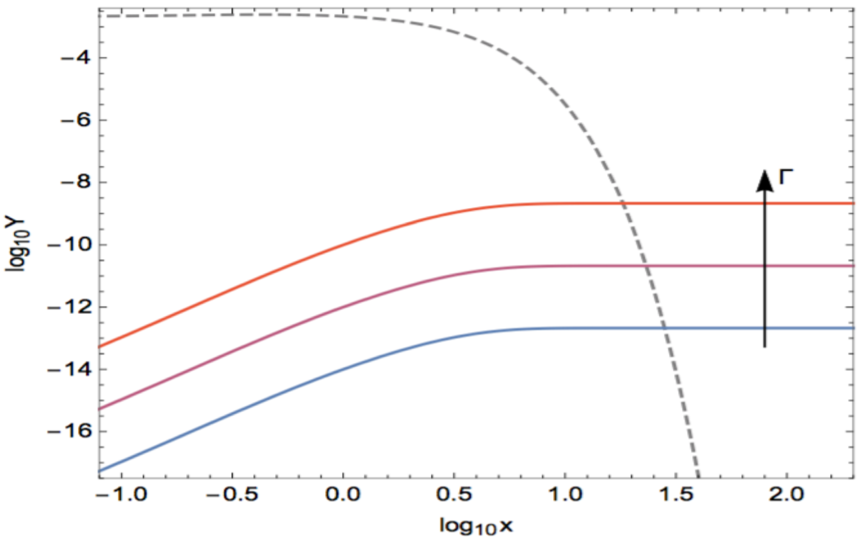
$$\dot{n}_\chi + 3Hn_\chi = \langle\sigma v\rangle_{X\bar{X}\to\chi\bar{\chi}}(T)n_{eq}^2(T) + n_{eq}(T)\Gamma_{Y\to\chi\chi}(T)$$

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, c 'freezes-in' - yield increases with interaction strength, Y~l



x=m/T

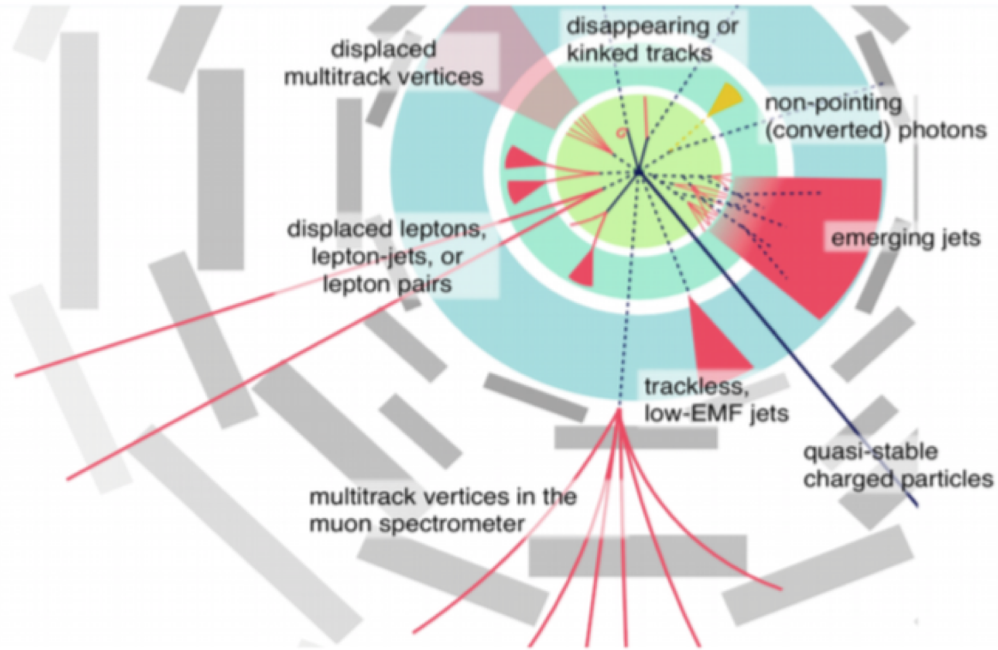
- When decay possible, usually dominates

$$\dot{n}_\chi + 3Hn_\chi = n_Y\Gamma_{Y\to\chi\chi} = g_Y\Gamma_{Y\to\chi\chi}m_YT^2S_{BMF}(m/T,s)$$

FIMPs at colliders

- Despite small couplings could lead to some interesting LHC phenomenology
- Most relevant for colliders : DM is produced from the decay of a heavier particle (Y) in thermal equilibrium with thermal bath (eg Y is a WIMP but DM is FIMP)
- Y copiously produced, but small coupling→ long-lived
- Long-lived particles (either collider stable or displaced vertices)

The "LLP zoo"



H. Russell, LHC LLP workshop

Few examples of displaced vertices in FI:
Co, d'Eramo, Hall, Pappadopoulo, 1506.07532
Evans, Shelton 1601.01326
Hessler, Ibarra, Molinaro, Vogl, 1611.09540

Minimal Freeze-in model

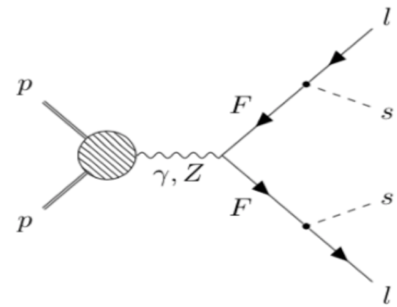
- Only one FIMP : DM, discrete Z_2 symmetry → stable DM
- DM is a SM gauge singlet – no thermalization in the early universe
- Minimality: smallest number of exotic fields (Y) but require some collider signature
  - Higgs portal y $H^2 \chi^2$, DM production depends on y - no observable signature
- Y : Z_2 odd otherwise mostly coupled to SM suppressed decay to DM pairs
- Consider F vector-like fermion SU(2) singlet, DM : scalar singlet

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \partial_\mu s\, \partial^\mu s - \frac{\mu_s^2}{2} s^2 + \frac{\lambda_s}{4} s^4 + \lambda_{sh} s^2 \left(H^\dagger H\right)$$
$$+ \bar{F}\left(i\not{D}\right) F - m_F \bar{F} F - \sum_f y_s^f \left(s\bar{F}\left(\frac{1+\gamma^5}{2}\right) f + \text{h.c.}\right)$$

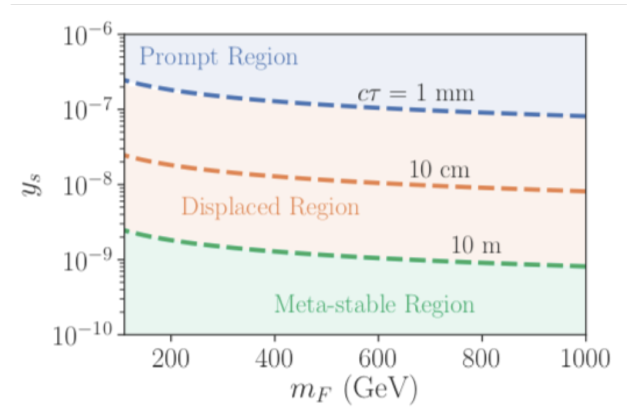
- Free parameters : m_s, m_F, y_s^f (assume λ_s, λ_{sh} <<1)
- Model also considered for FO, Giacchino et al 1511.04452, Colucci et al, 1804.05068, 1805.10173

- DM produced from decay of F (F->f s) where F lepton or quark

Production at LHC



- DM yield depend on partial width of F
- FI naturally leads to long-lived particle or at low reheating temperature to displaced vertices
- Lifetime varies from cm to many meters
- Signatures
  - Heavy stable charged particles
  - Disappearing tracks
  - Displaced vertices



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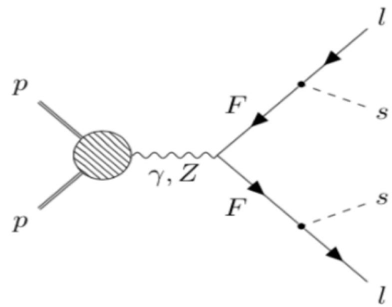

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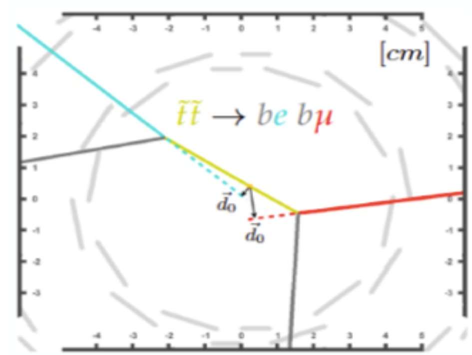
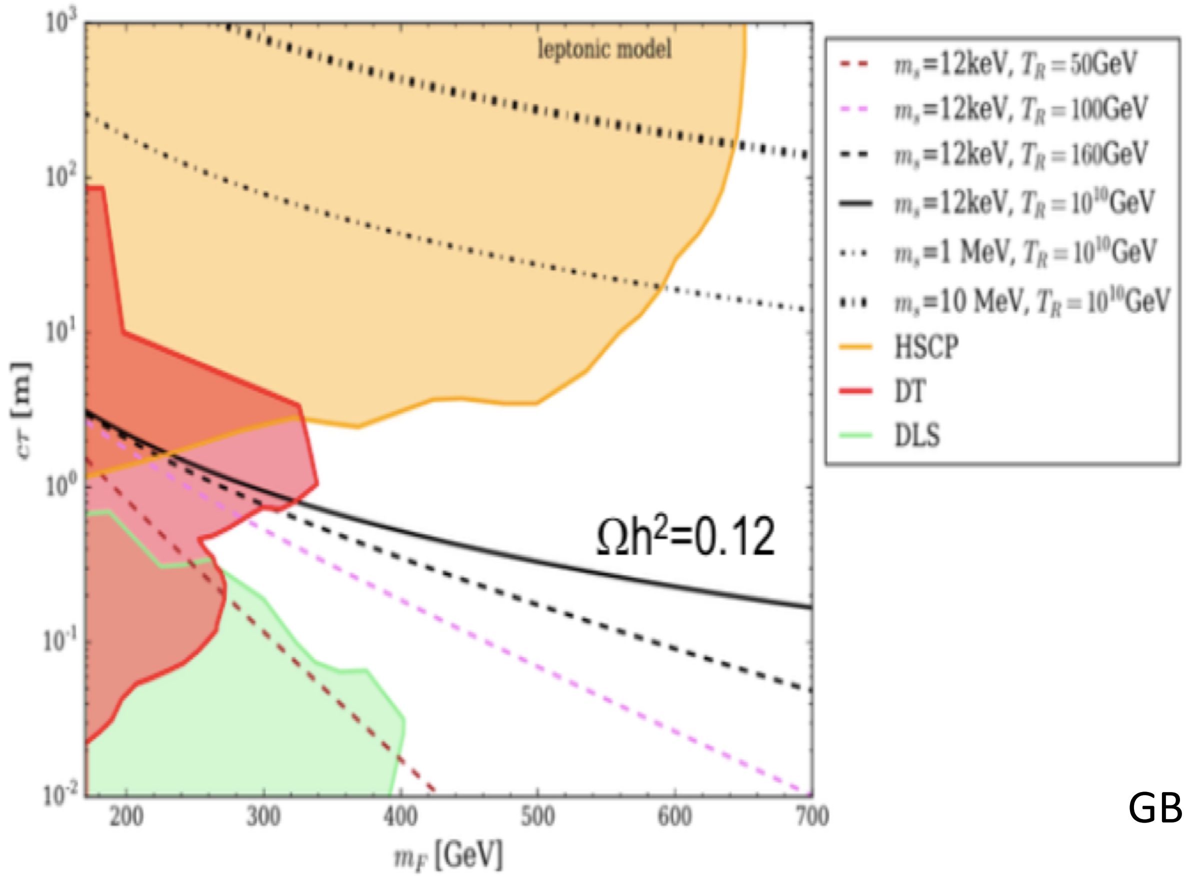
- Lepton transverse impact parameter - closest distance between beam axis and lepton track in transverse plane



cds.cern.ch/record/2205146?ln=en

LHC constraints (leptons)



GB et al, 1811.05478

- As DM becomes heavier only HSCP becomes relevant

Light DM

- Light feeble DM can naturally satisfy relic density (often via freeze-in) in this case most standard collider searches useless, host of additional probes in ATLAS/CMS/LHCb, new displaced detectors, in fixed targets, mesons decays (e.g at BESIII and KLOE) and e^+e^- collisions
- To compare potential of various searches use dark photon model where a new vector boson kinetically mix with U(1)

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm DS} + \frac{1}{2}m_X^2 X^\mu X_\mu - g_X j_\mu^X X^\mu - \frac{\epsilon}{2\cos\theta_{\rm W}} B_{\mu\nu} X^{\mu\nu}.$$

- Dark sector can be a fermion(or scalar) with fermion/mediator coupling α_D

$$\mathcal{L}_{DS} \supset \bar{\chi}(i\not{D} - m_\chi)\chi,$$

- Can also contain extra fermion almost degenerate with DM

$$\mathcal{L}_{DS} \supset i\alpha_D X_\mu \bar{\chi}_1 \gamma^\mu \chi_2,$$

Searches

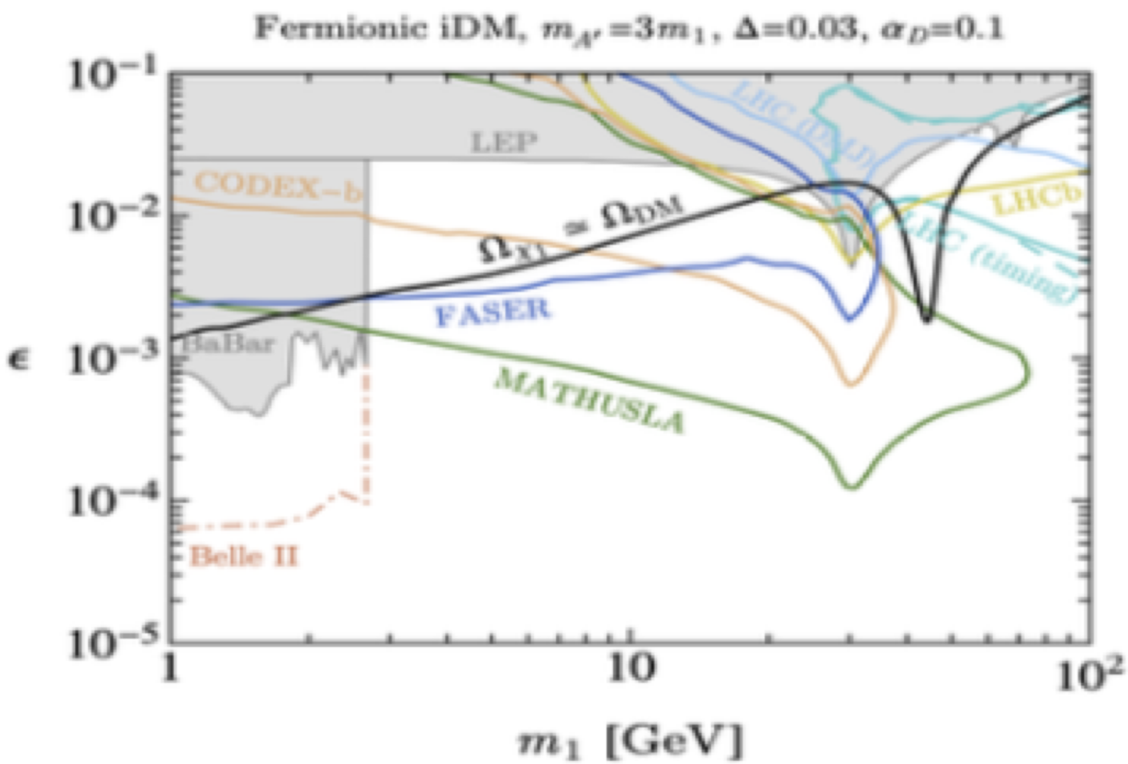
- A few sample searches:
  - NA64(CERN) & MAGIX(Mainz): high energy eN and μN scattering, A'mixing with bremstrahlung A (A'→ invisible)
  - NA62 (CERN): search for $K^+ \to \pi^+ \pi^0 \to A' + g$ (with A' invisible)
- At LHC: new displaced detectors

Experiment	$\sqrt{s}$	η **- range**	IP-distance	decay volume
FASER	14 TeV	>9	480 m	0.06 m^3
CODEX-b	14 TeV	0.13 - 0.54	25 m	1k m^3
MATHUSLA	14 TeV	0.9 - 1.5	$\approx$ 150 m	800k m^3
SHiP	0.028 TeV	–	70 m	10k m^3

- Note these detectors (eg MATHUSLA) are also sensitive to heavy LLP's
- Fixed target at electron colliders (LDMX)

Exclusions and projections

- A few comparisons (FIPS Workshop, 2102.12143)
- Production of χ_2 with long lifetime decay into χ_1



Exclusions and projections

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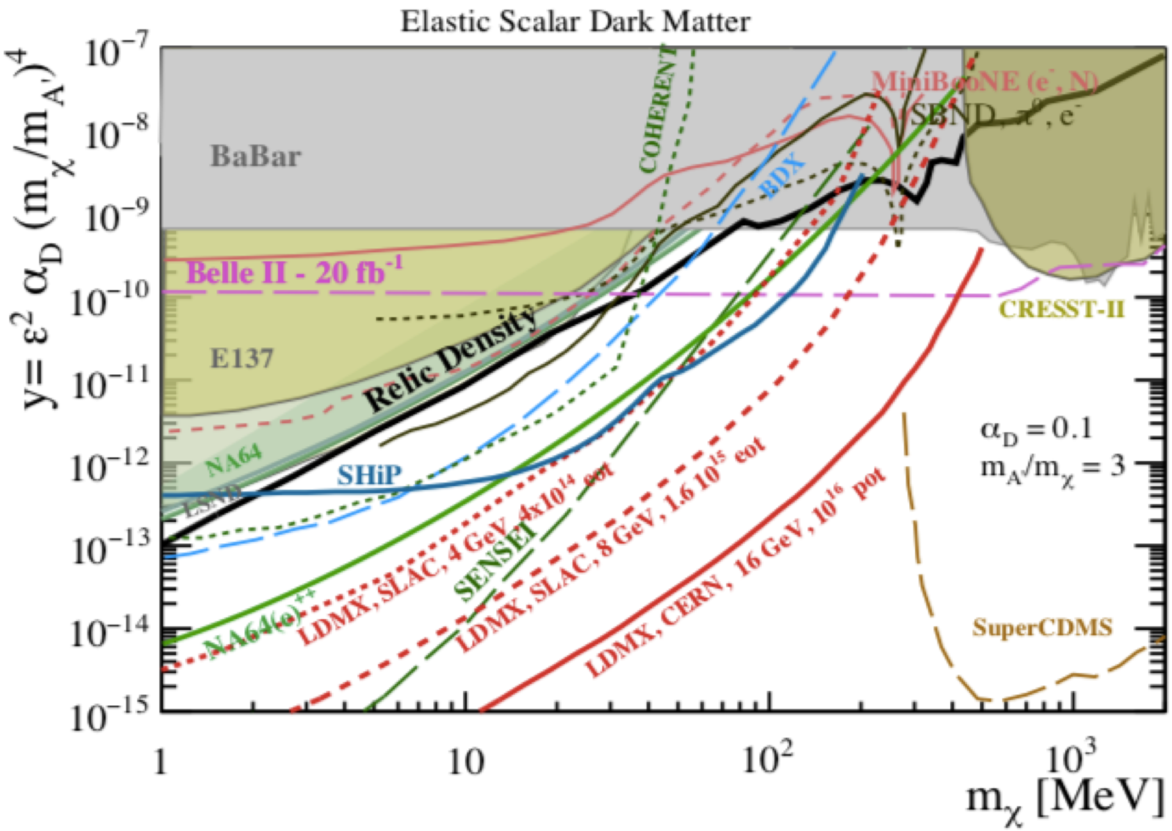

- Parameter space consistent with relic density will soon be probed

Conclusions

- DM searches is very active field, lots of experiments running and many plans for the future, DM candidates are being probed
- Content of dark sector determines the relevant search(es)
- Astro searches best hope for a signal for DM while colliders allow to identify DM (properties)
- In WIMP case : complementarity between in(direct) searches and collider searches
- WIMPs are not the only possibility, DM can be much lighter and feebly interacting – various searches ongoing/planned
- Need to improve sensitivity of (in)direct searches to light DM
- Cosmological probes of DM also important (not in this talk)