Post-LHC Particle Dark matter

G. Bélanger

LAPTh, Annecy

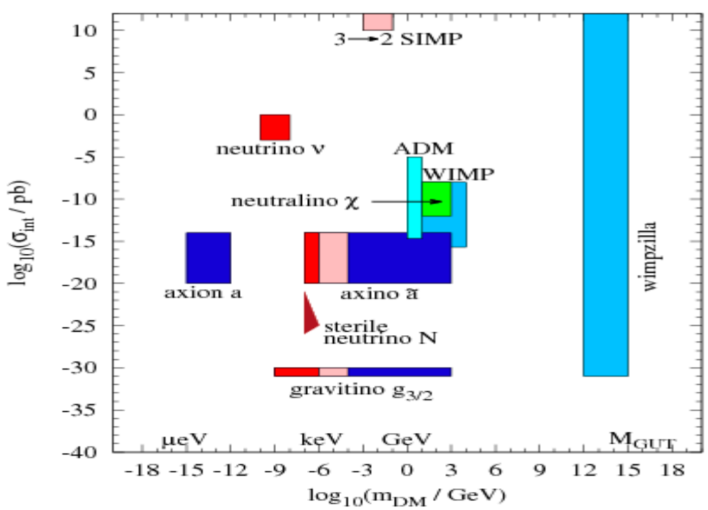
TUG - Annecy, 7/11/2024

Introduction

- Strong evidence for dark matter from many scales: galaxies, clusters, cosmological scales
- Relic density of DM known precisely (PLANCK)

$$\Omega_{\rm DM} h^2 = 0.1188 \pm 0.0010\,,$$

- Dark Matter a new particle? If so - cold, neutral (or very small charge), stable, non-baryonic, weak interactions with standard model (or feeble) – still lots of possibilities for DM of different mass and interaction strength



Baer et al, 1404.0071

Bertone, Tait, Nature 2018

- Well-motivated New Physics model has yet to be singled out
- 30 years ago, had a very good idea what would be this new DM particle : neutralino in SUSY – despite the large parameter space clear paths for DM searches (direct and indirect searches and production at colliders)
- With no sign of SUSY at LHC or of DM in direct/indirect searches – widespread conclusion that particle dark matter is disfavoured (or at least that WIMPs are disfavoured) – only partly true
- Reminder : LHC has failed to find new charged particles (up to m~1 TeV) and coloured particles (up to m~3TeV) – this puts new physics models such as TeV scale SUSY in trouble. Much less constraints on neutral particles
- In fact several possibilities for particle DM to have escaped detection
  - WIMPs (most challenging) - see examples
  - Other production mechanisms :
    - Freeze-in, SIMP, axions

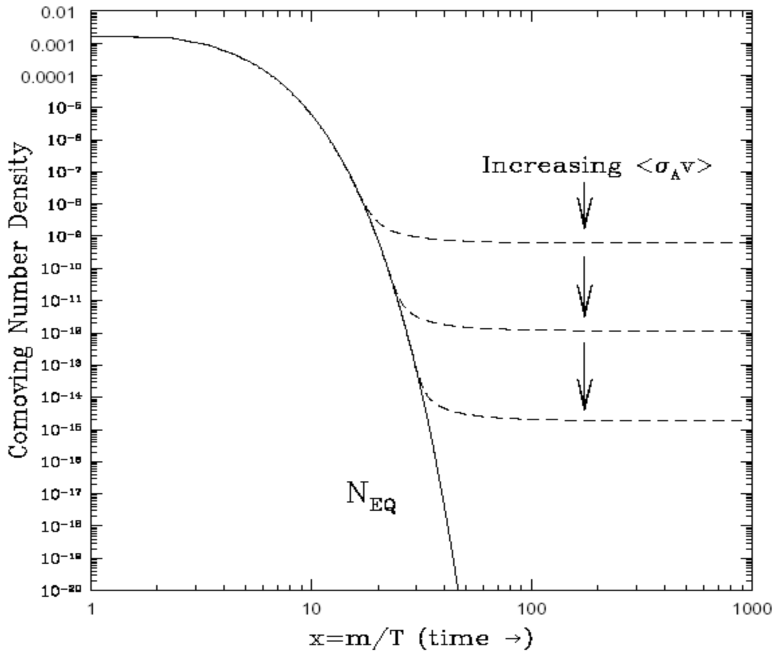
WIMP DM

- Most studied hypothesis: a new stable neutral weakly-interacting massive particle – WIMP – why are they good DM candidates?
- In thermal equilibrium in early Universe
- Equilibrium abundance maintained by processses $\chi\bar{\chi} \rightarrow e^+e^-, \mu^+\mu^-, \tau^+\tau^-, q\bar{q}, W^+W^-, ZZ$
- As Universe expands T drops below m_χ, n_{eq} drops exponentially,
- Eventually rate of annihilation drops below expansion rate $\Gamma < H$
- χ fall out of equilibrium and freeze-out
- Density depends only on expansion rate

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

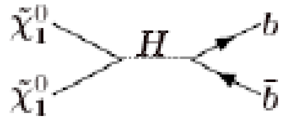
PLANCK

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



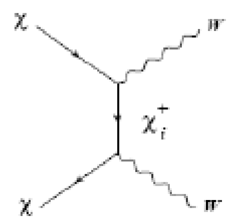
WIMP at EW scale has ‘typical’ annihilation cross section for $\Omega h^2 \sim 0.1$ -> miracle? Possible variations by orders of magnitude

- Relic density puts strong constraint on combination of mass/couplings
- Cases where couplings could be suppressed
- Resonance



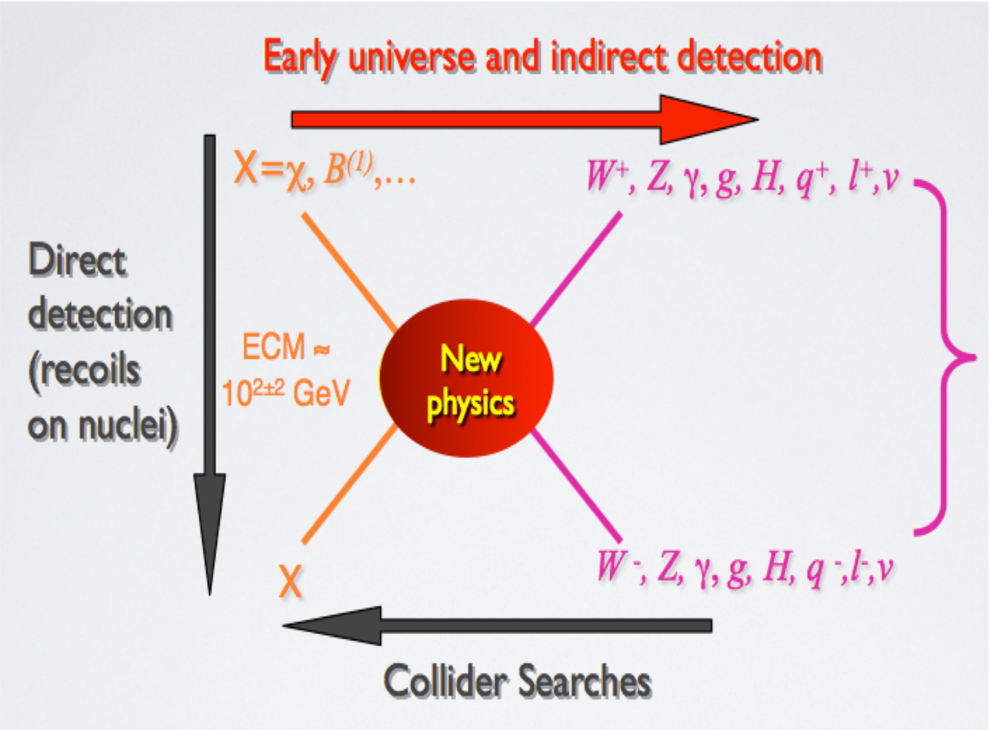
$$\sigma v \propto m_{\tilde{\chi}}^2/(4m_\chi^2 - m_H^2)^2$$

  - much weaker coupling required when $2m_\chi \sim m_H$
- t-channel : enhancement when small mass splitting



- Other processes can contribute to DM formation, eg coannihilation

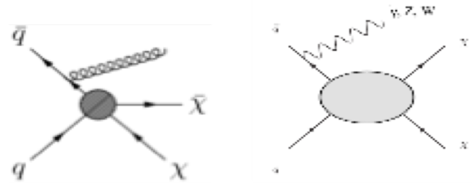
Searches for particle dark matter



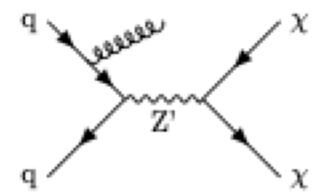
- All determined by interactions of WIMPS with Standard Model
- Not necessarily the same particles/process play dominant role, eg annihilation into dark sector can dominate relic – no effect on collider searches
- LHC searches for neutral particles (stable at colloder scale) and charged/coloured particles

DM@LHC search for neutral particle

Model independent approach (monoX) MET+ jet, γ,W,Z,h



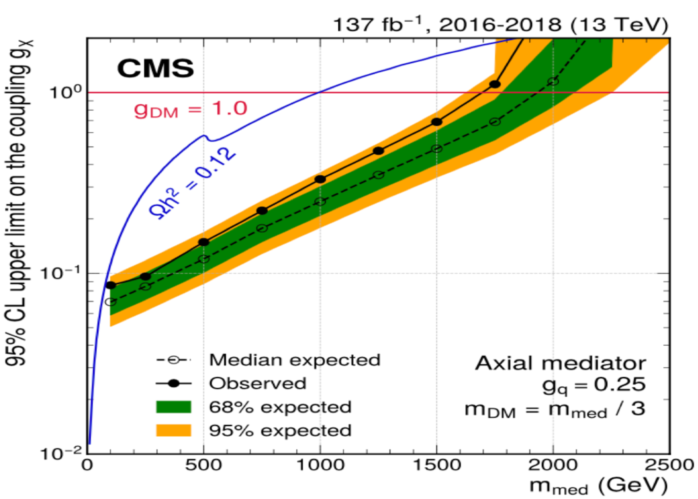
(a) $q\bar{q} \to \chi\chi + g$ (b) $q\bar{q} \to \chi\chi + \gamma, Z, W$

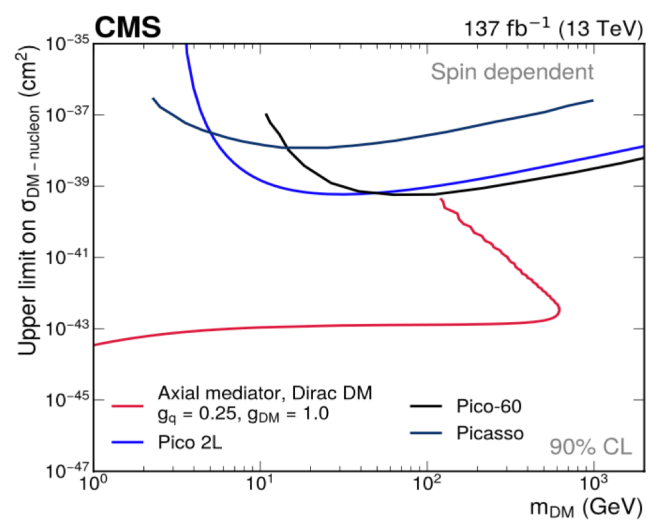


Also used for simplified model : mediator+DM

Can probe region compatible with relic in some cases

Axial vector mediator: probe DM below few hundred GeV's, and higher sensitivity than DD experiments (SD)

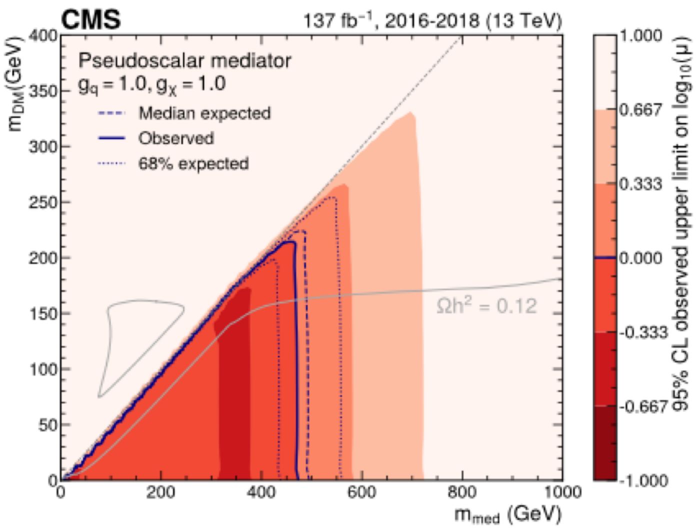


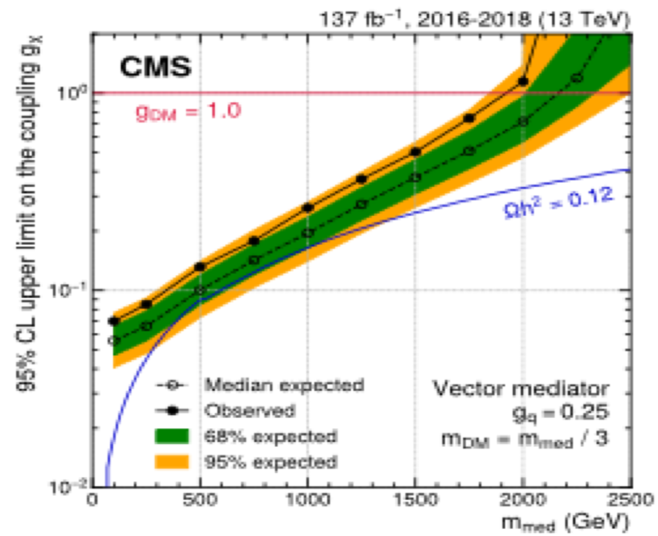


Monojet@LHC

Reach not as good for other mediators –

Some of parameter space compatible with relic ruled out for pseudoscalar mediators





CMS: 2107.13021

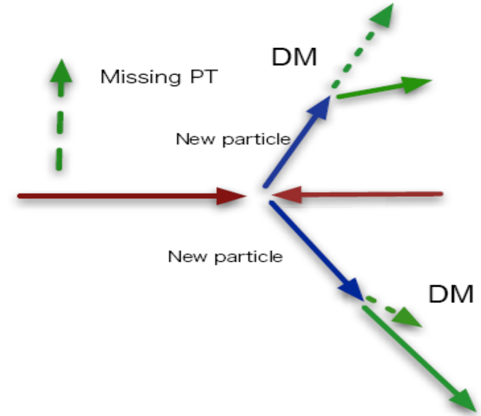
vector/scalar mediators – cannot probe the region favoured by relic but SI – DD powerful constraints except at low DM masses

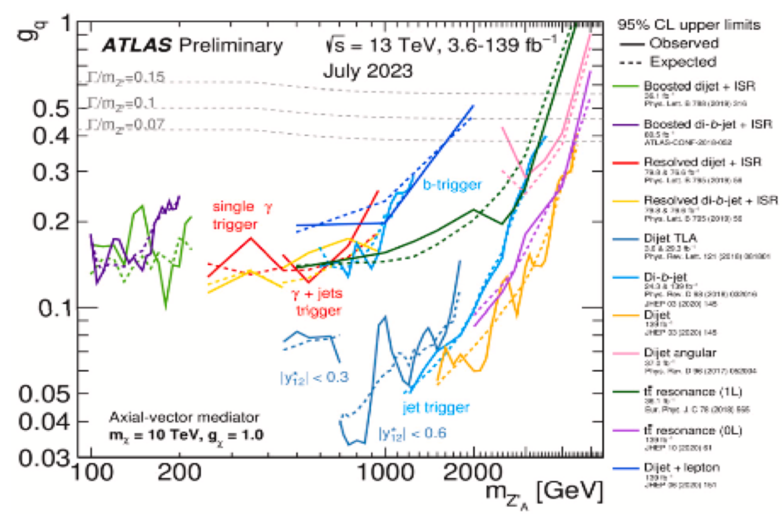
Model independent approach constrain some class of models – lots of parameter space left below the TeV scale in simplified models

DM@LHC

Model dependent approach:

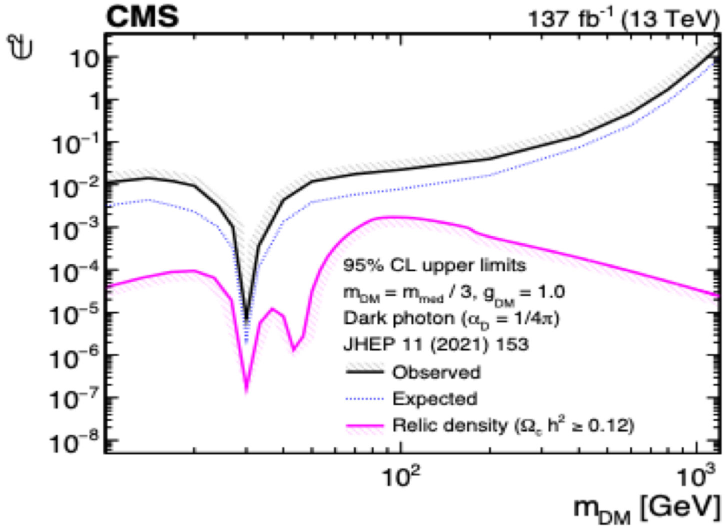
- Invisible decays of the Higgs
- Production of new particles that decay in DM, signature : MET + l, q,….
- Charged tracks/displaced vertices/Long-Lived particles
  - small mass splitting or very weak interactions
- DM in meson decays (LHCb)
- Searches for new particles in SM final state (e.g.mediator)
  - If coupling to quarks not too small – several probes of new mediators up and beyond the TeV scale
  - here assume no invisible decay of Z’
  - No connection to DM



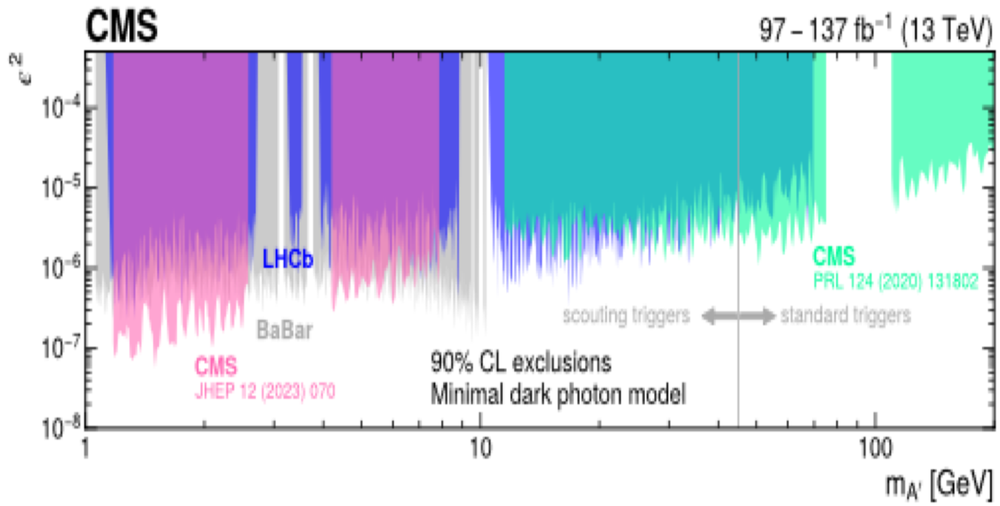


Vector portal : Z'/ dark photon

- Dark photon in monojet search

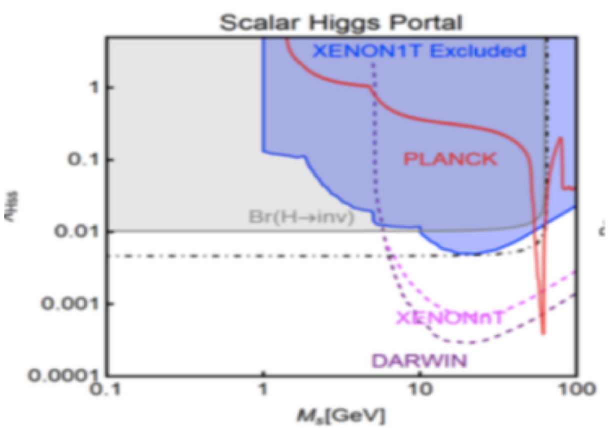


- Dark photon in di-muon search

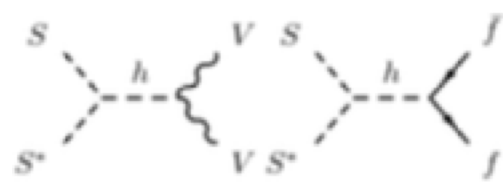


Higgs Portal (scalar mediator)

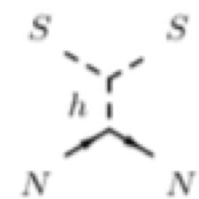
- DM couples to the SM Higgs
- Same coupling responsible for relic density – DM scattering on nucleons and Invisible decays of the Higgs (if $m_{DM}<m_h/2$)
- If coupling strong enough to have efficient annihilation -> incompatible with limit on H->invisible



Arcadi et al, 2101.02507



Relic density

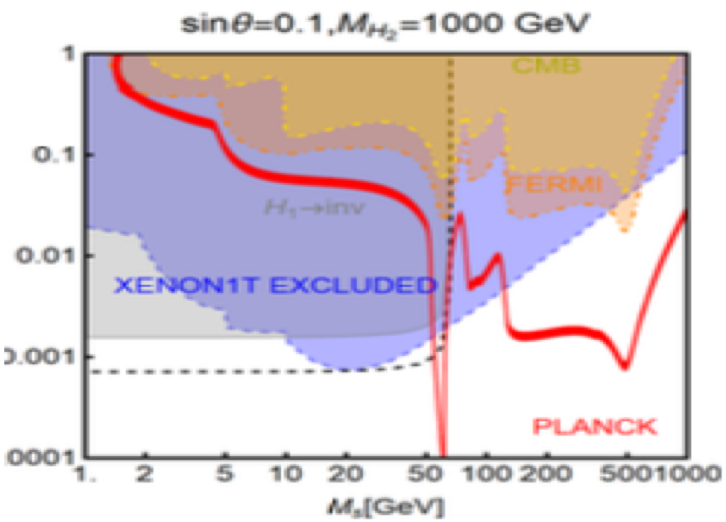


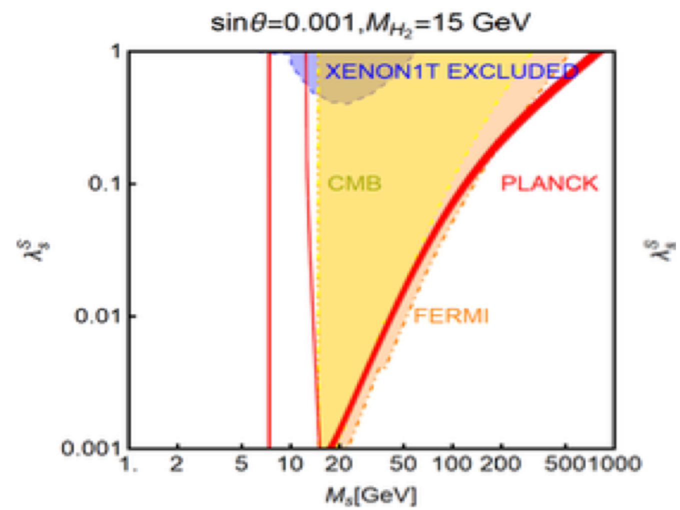
Direct detection

- Moreover for heavier DM masses (up to 1.2 TeV)– most of relic density compatible region incompatible with DD limits

Higgs Portal (scalar mediator)

- To avoid strong constraints on DM coupling to Higgs - must uncorrelate process responsible for relic density from the one for DD - eg add new particles and new processes
- Example: add second Higgs mixing with SM Higgs (see Arcadi et al, arXiv:2101.02507)

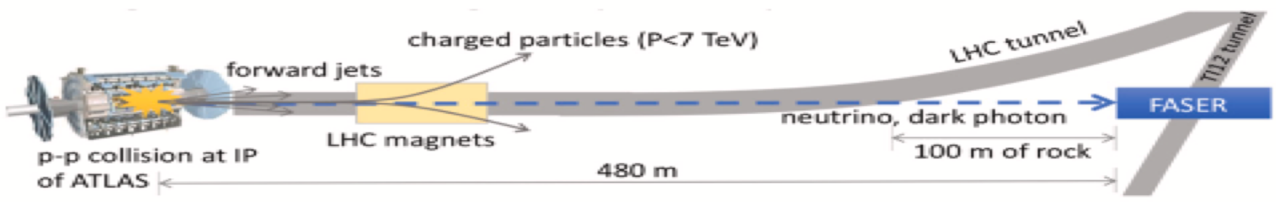




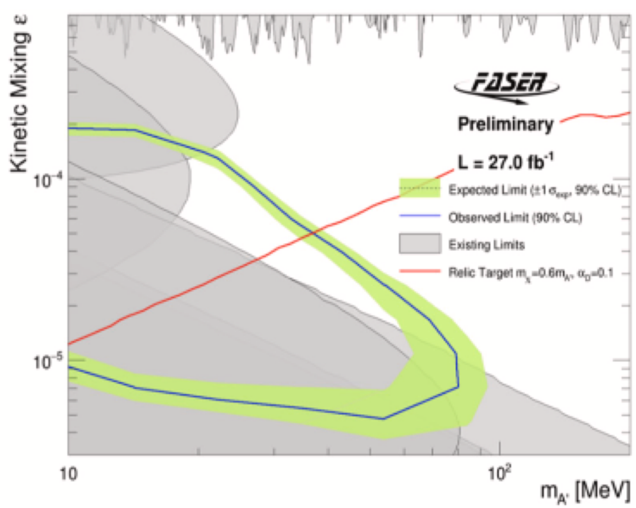
- Few additional probes (except H->h_1h_1 if light)
- Many other possibilities

LHC searches for LLP

- Production of light particle that decays into SM final state
- Example: dark photon decays into e+e- (relic density set by χχ->A'->ff)

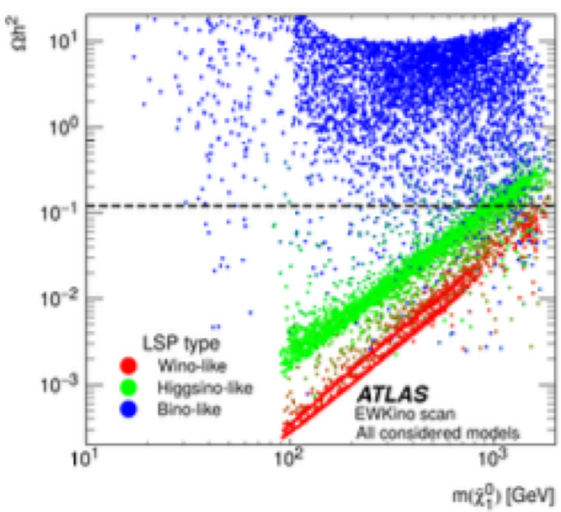


- Some parameter space compatible with relic density has been probed at FASER



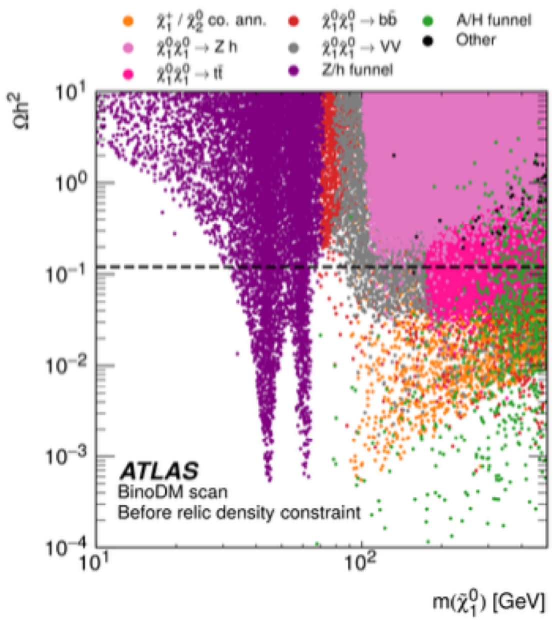
- Example of UV complete model with many new particles that decay into DM : supersymmetry (MSSM)
- DM is Majorana fermion can be singlet (bino), doublet (higgsino), triplet (wino) representation of SU(2)
  - To explain all DM (Omega=0.12) favoured scale depends on the representation – ~100 GeV for singlet, ~1 TeV for doublet , ~3 TeV for triplet
  - In minimal model (Cirelli et al) five-plet multi-TeV scale, etc…
- In LHC Run 1 : mainly excluded new coloured particles up to 1-2 TeV, in Run 2 better sensitivity to EW particles – increase on lower bound of electroweak-ino to TeV scale in specific channels - better test of the susy sector relevant for DM production

ATLAS: 2402.01392

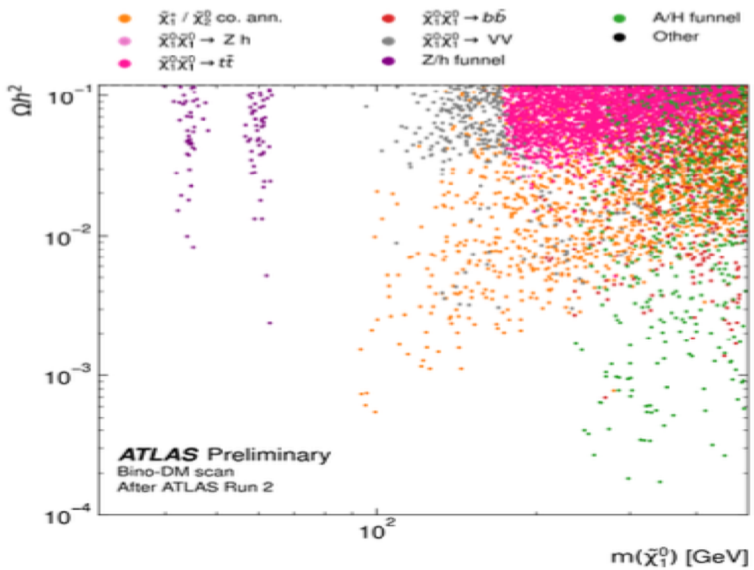


Status of SUSY after LHC and LZ

Searches for electroweakinos in RunII – more direct probe of DM sector



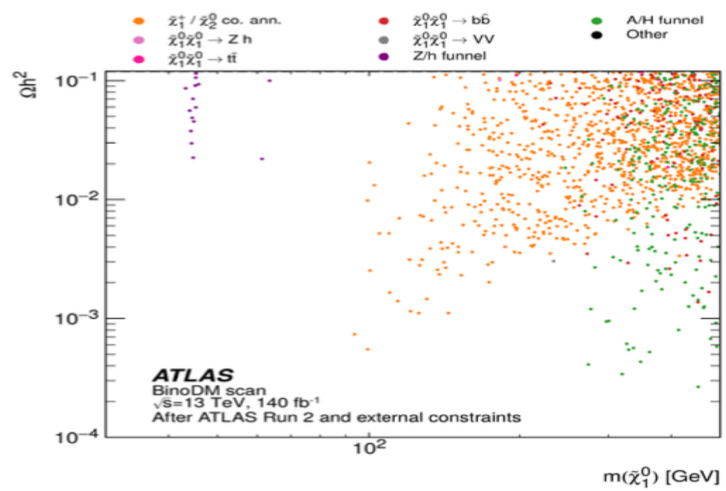
(b) BinoDM scan



(b) Models not excluded by ATLAS

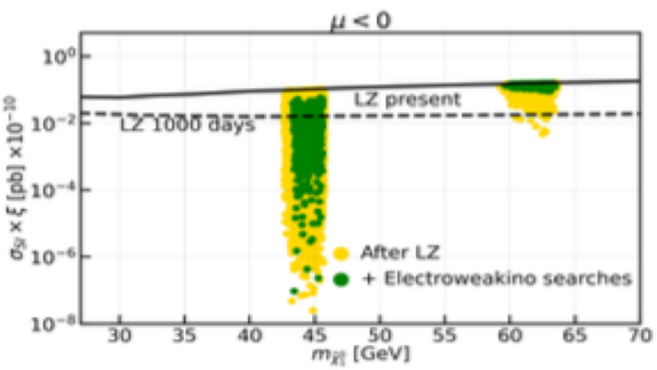
ATLAS-2402.01392

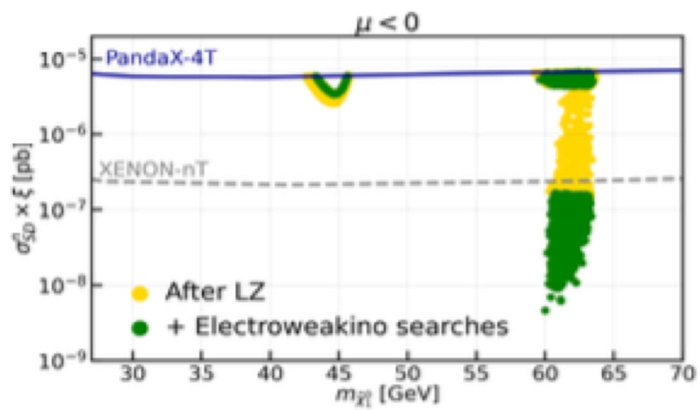
Little room for SUSY bino DM after Run2 and recent DM searches – mostly in funnels and if co-annihilation dominant



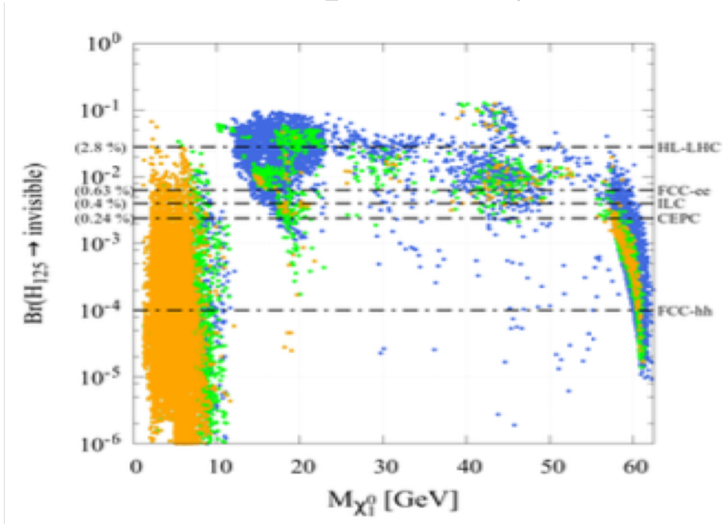
Light neutralinos ($<m_h/2$)

- A closer look at the funnels with dedicated scans: include important constraint from Higgs decay to invisible and electroweakino searches

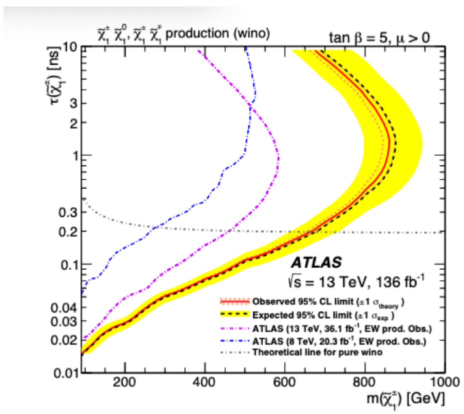


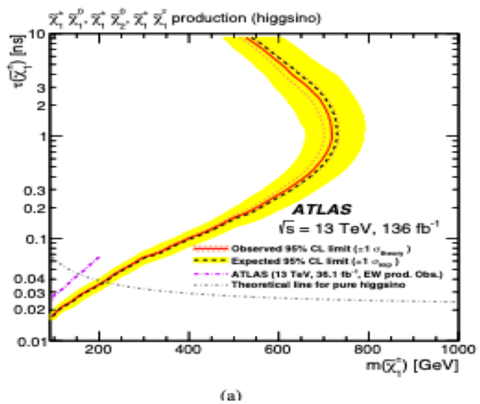


- Still room for 45-60 GeV neutralino DM in pMSSM – soon probed by DD
- Even more so in extensions (NMSSM)
- Presence of new light scalars
- DM near GeV allowed

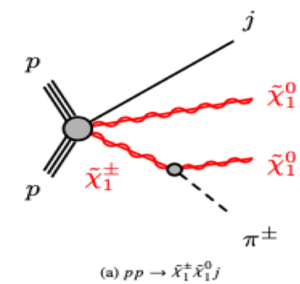


- Higgsino and Wino DM
- Small mass splitting between neutral and charged particles : searches dedicated to LLP's – disappearing tracks relevant





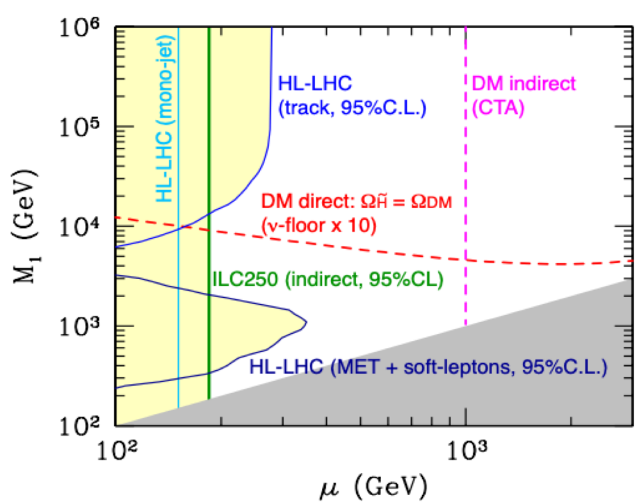
ATLAS: 2201.02472



- LHC (from $\chi^+\chi^-/\ \chi_2^0$ production in WZ,Wh+MET channels) +DD constrain scenarios below TeV scale where χ_1^0 subdominant DM

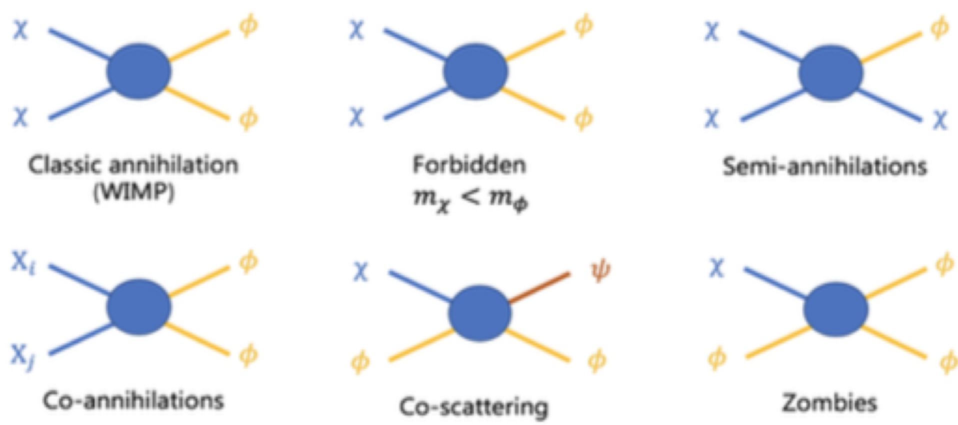
Higgsino LSP: future prospect (in a next few decades)

T. Moroi



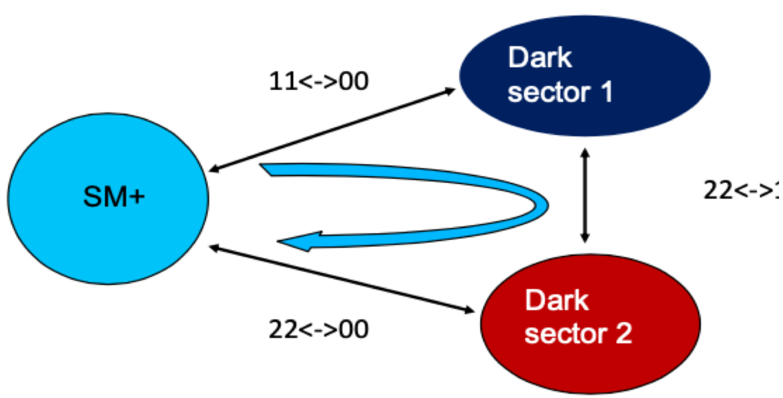
Several other WIMP models with dedicated collider searches involving either MET, SM processes, LLPs – similar conclusions

- Other processes for WIMPs:



Hochberg, Les Houches
SciPost Phys. Lect. 2022

- Multi-component

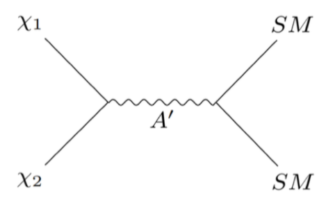


Same Strategy of direct/indirect/collider searches to probe WIMPs – possibility to construct WIMP models to avoid certain constraints

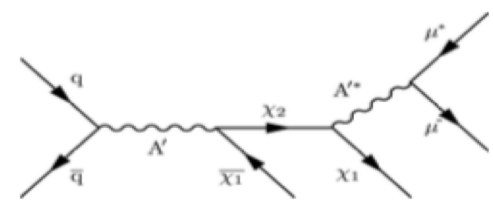
Zurek 0811.4429; Bhattacharya 1607.08461; Lu Wu Zhou, 1101.4148; GB, Mjallal, Pukhov, 2108.08061; Beneito, et al, 2207.02874

Inelastic DM

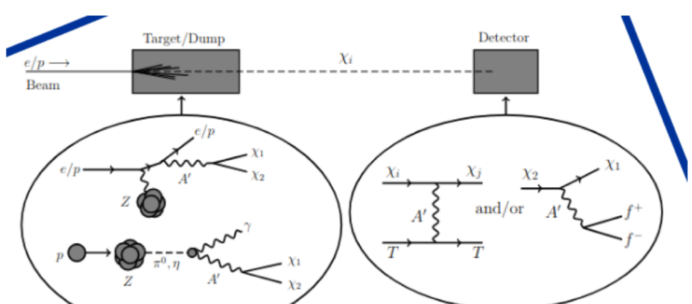
- Two dark sector states with mass nearly degenerate
  - Tucker-Smith, Weiner, PRD64 (2001) 043502



- DM coupling to mediator suppressed, dominant coupling with other dark particle with small mass splitting-> co-annihilation responsible for relic density (DD constraints weaker)
- Collider: search in monoX and displaced signatures

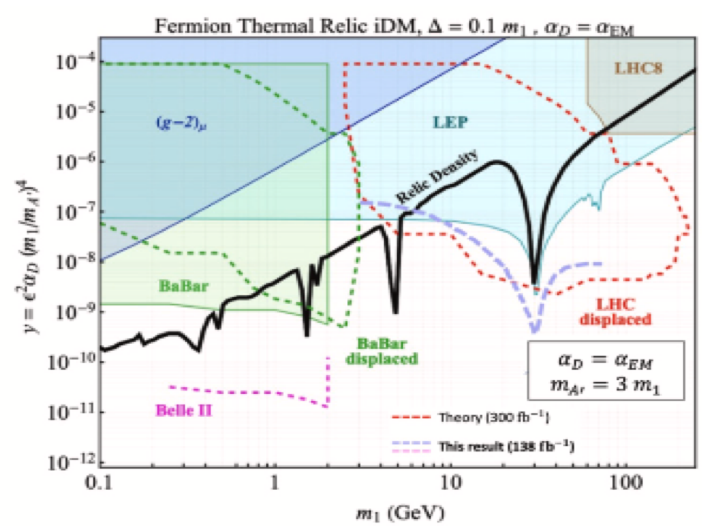


- Beam dumps (probe mass below 1 GeV)



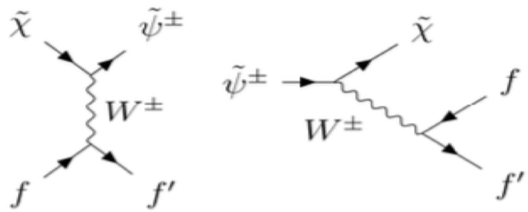
[Izaguirre et.al. '19]

CMS: 2405.13778

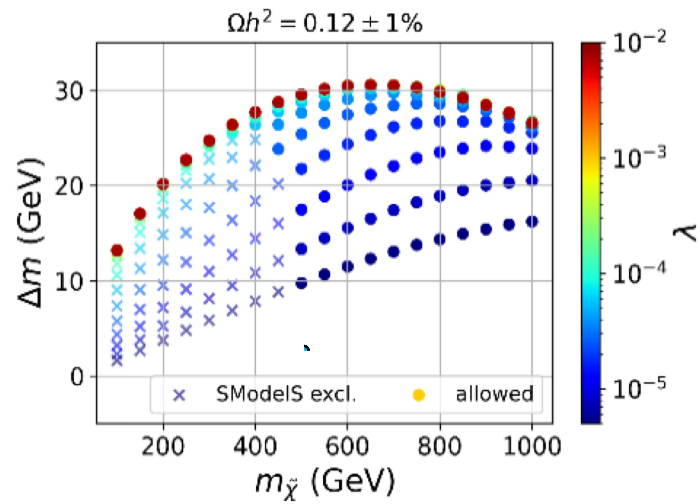


Co-scattering

- Transitions involving DS particles and bath particles are responsible for DM formation when DM self-annihilation inefficient



- Example with Singlet/Triplet fermions (SUSY-like)
- Constraints from LHC : reinterpretation of chargino searches, disappearing tracks typical decay length ~10cm
- Smaller couplings excluded



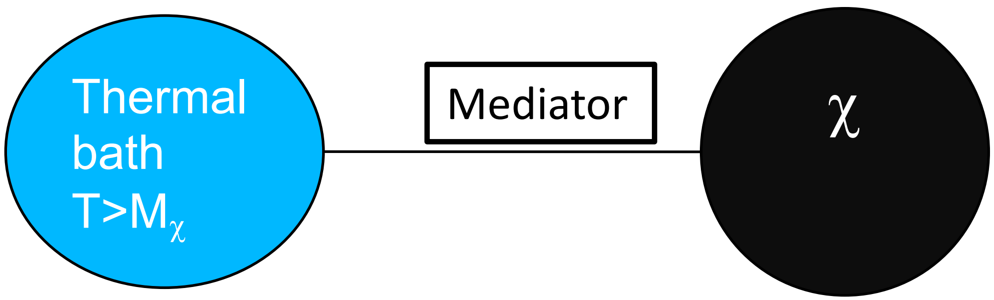
Alguero, GB, Kraml Pukhov

Summary for WIMPs

- WIMPs are under close scrutiny LHC+DD+ID
- Mainly viable below TeV scale if : resonance annihilation or co-annihilation (UV complete model, inelasticDM) or small couplings to quarks or subGeV or less simple dark sector
- Much remains to be probed to completely rule out single WIMPs model
- To avoid strongest constraints: can move away from this paradigm and requirement of thermal equilibrium and/or modify cosmology (eg low reheating temperature), in particular
  - FIMPs
  - Axions – well motivated theoretically to solve the strong CP problem, or more generally axion-like particles (ALPs) a pseudoscalar that does not necessarily couples to gluons – best probe in astrophysics (see also talk of Sylvia Manconi yesterday) also searches of ALPs in PbPb collisions ($\gamma\gamma \to a \to \gamma\gamma$)

FIMPS (Feebly interacting MP)

- Freeze-in mechanism (Hall et al 0911.1120, McDonald,J. hep-ph/0106249)
- In early Universe, χ so feebly interacting that χ decoupled from plasma - initial nb density of DM is low



- Interactions are feeble but lead to production of χ
- Review : Bernal et al, 1706.07442; GB, Chakraborti, Pukhov, 2309.00491

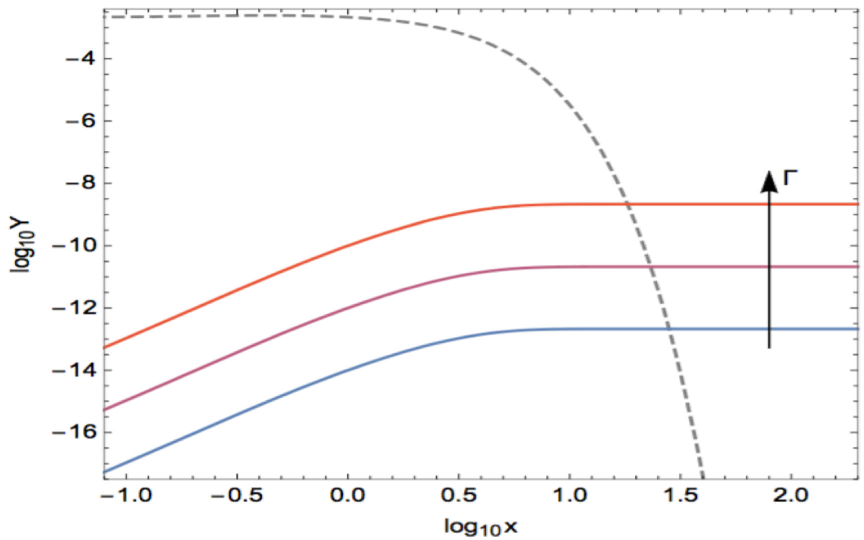
$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle\sigma v\rangle \left((n_\chi)^2 - (n_\chi^{eq})^2\right)$$

Depletion of χ due to annihilation

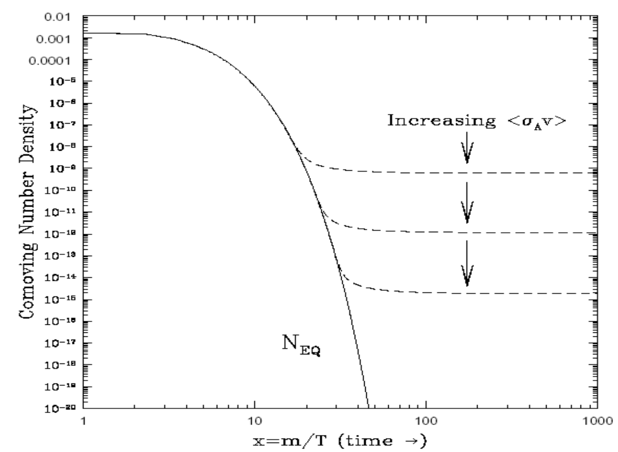
Creation of χ from inverse process (also from decay

FIMPS (Feebly interacting MP)

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



x=m/T



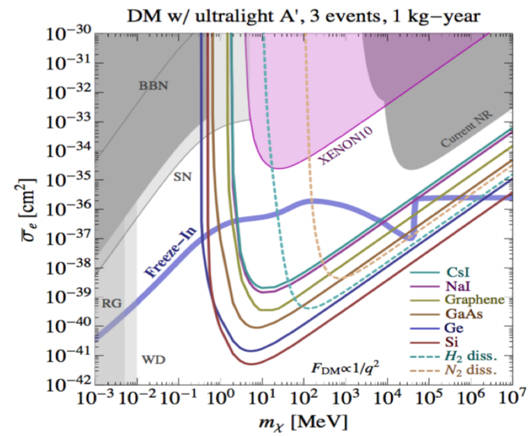
Comparison with WIMPs

- When decay possible, usually dominates
- Typical interaction strength : $10^{-12} – 10^{-10}$
- Mass range : from very light to above TeV scale

- Some possibilities for FIMPs:
  - FIMP is DM : pair production in annihilation of SM particles (or in decay of particle in thermal equilibrium)
  - FIMP is DM, next to lightest ‘odd’ particle has long lifetime freeze-out as usual then decay to FIMP – typically $\lambda \sim 10^{-12}$
    - a new long-lived particle with signature at collider (LLP) and/or also affect BBN or CMB depending on lifetime
  - FIMP can also be part of multi-component DM – if the WIMP is only a small fraction of DM its DD and ID signals are suppressed.
  - FIMP is not DM, freezes-in and then decay to WIMP DM increasing abundance of WIMP
    - Relic abundance and DM annihilation cross section no longer related, freeze-in produces DM abundance, DM annihilation can be large – freeze-out abundance small
    - Hard to identify the presence of the FIMP, but mismatch between properties of measured WIMP with value of relic density
    - Possible boost in indirect detection signals ($\sigma v > 3\ 10^{-26}\ cm^2/s$)

Probes of FIMPs

- FIMP in general a singlet under SM (to prevent reaching thermal equilibrium)
- Probes not as generic as for WIMPs
- Direct detection on nucleons (if mediator is light) or on electron
- Colliders
    - need some other particle in dark sector with at least weak couplings, preferably charged : typical search for Heavy Stable Charged Particle and/or displaced signatures (especially for small reheating temperature)
    - most of standard DM searches at colliders useless, host of additional probes in ATLAS/CMS/LHCb,
    - If mass scale is low : in fixed targets, mesons decays (e.g at BESIII and KLOE) and e^+e^- collisions
    - Decays outside detector (MATHUSLA, FASER etc..)
- Indirect detection – relevant if LLP decays now
- Cosmology : BBN, energy injection ….

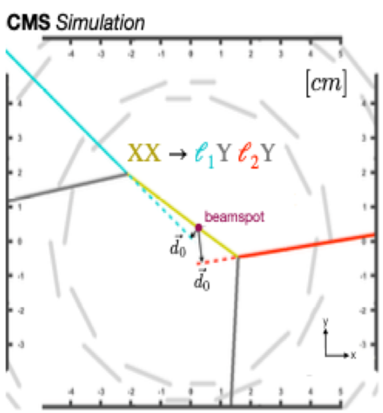


FIPS 2020 report : 2102.12143

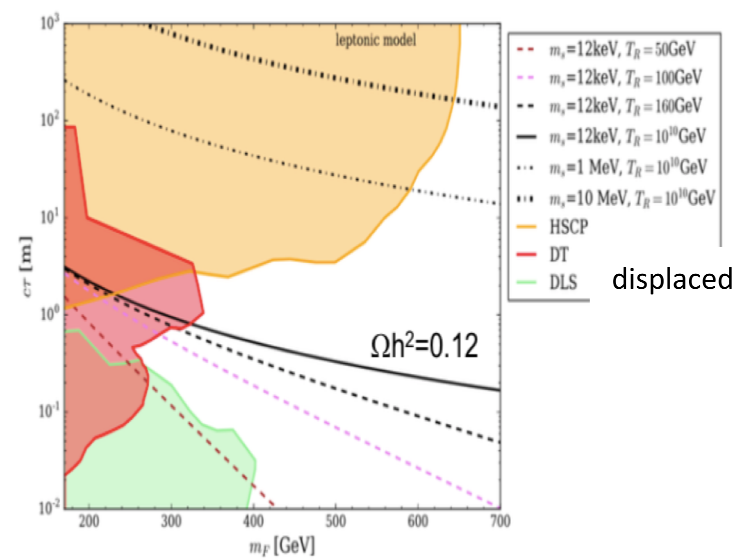
FIMPs at LHC

•DM is produced from the decay of heavier particle (F) whose interactions allow copious production at LHC

•F decays in FIMP+SM with very small coupling -> LLP (either colllider stable or displaced signatures : disappearing tracks, displaced leptons….)



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



GB et al, 1811.05478

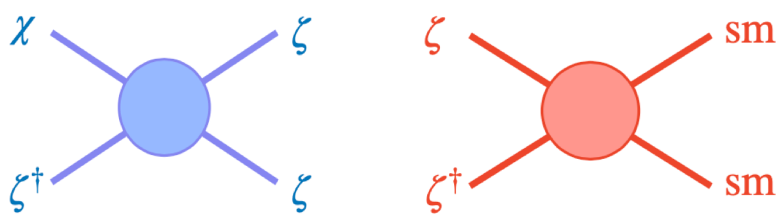
•As FIMP becomes heavier only heavy stable charged particle becomes relevant

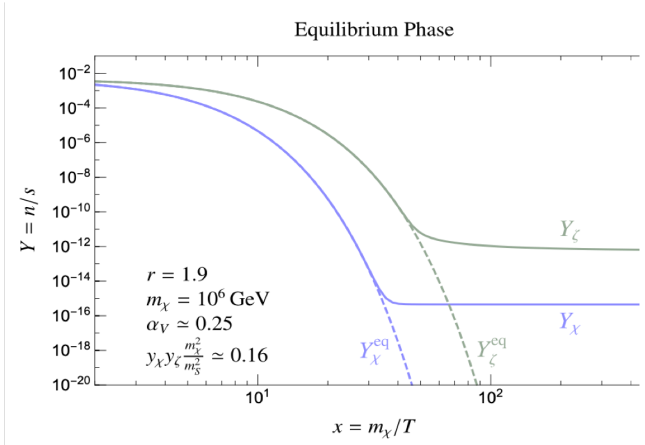
Conclusion

- Several processes can contribute to DM production – gives rise to a variety of DM models not necessarily tied to the electroweak scale or to weak interactions
- Although classical WIMP models are severely constrained from relic/LHC/direct detection/indirect detection – WIMPs are far from being ruled out
- Recent effort in improving probes for light DM (e.g. DD or intensity frontier) or LLPs (colliders, cosmo)
- *After so many years, still in the dark about the nature of dark matter*

- General properties of thermal DM
- No naturalness -> mass scale extends from 10 MeV->100TeV
  - For FO mechanism from $\chi\chi$->SM SM
    - rate of DM annihilation $\Gamma = n\langle\sigma v\rangle$, unitarity imposes upper limit on $\langle\sigma v\rangle$-> lower bound on n at FO ($\Gamma \sim H$)
    - $\Omega h^2 \sim m_\chi\, n$ -> upper bound on m_χ
    - Or if DM is heavier than upper bound it will be overabundant
    - Remark : if DM is > few TeV : hard for LHC and for ID (CTA can reach high masses) but signal scales as $n^2 \sim \rho^2/m^2$
  - Note : with zombie can relax this constraint -> almost to Planck scale

- Note : with zombie can relax this constraint -> almost to Planck scale
- Kramer et al, 2003.04900 (assumes that $\chi\chi$->$\zeta\zeta$ or SM SM small)



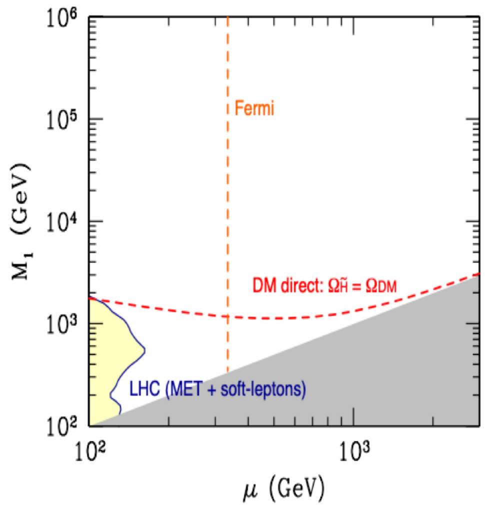


- DM is χ; $m_\zeta < m\chi < 3\ m_\zeta$ (to prevent χ–> $\zeta\zeta\zeta$ decay)
- If ζ remains in equilibrium, at FO of χ, n_ζ large

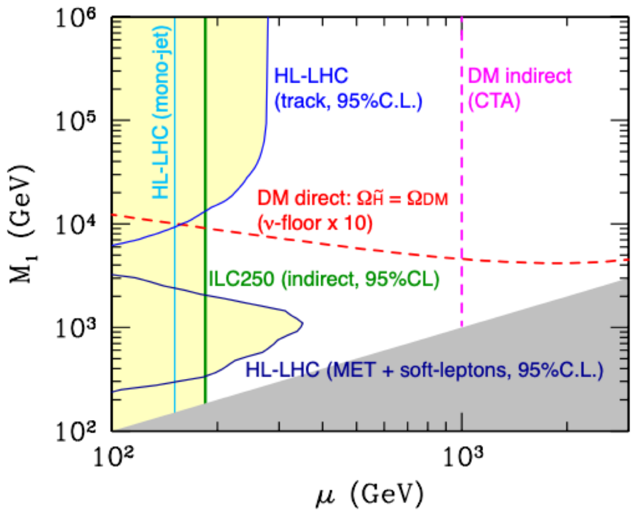
$$\dot{n}_\chi + 3Hn_\chi = -n_\zeta^{\rm eq}\langle\sigma_{\chi\zeta\to\zeta\zeta}v\rangle\left(n_\chi - n_\chi^{\rm eq}\right) \ .$$

- Relaxes upper bound on $m\chi$
- Also if DM at weak scale - much smaller interaction rates than standard WIMPs

- Higgsino DM
- Challenge for next generation



Higgsino LSP: future prospect (in a next few decades)



T. Moroi

- Several other WIMP models with dedicated collider searches involving either MET, SM processes, LLPs – similar conclusions
    - Extended scalar sector (2HDM+a, inert Doublet model …)
    - Hidden Valleys – specific signatures : emerging jets…