Enigmass
The enigma of mass

Hiding WIMPs?

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LAPTh, Annecy-le-Vieux

Sussex, May 20 2021

WIMP DM

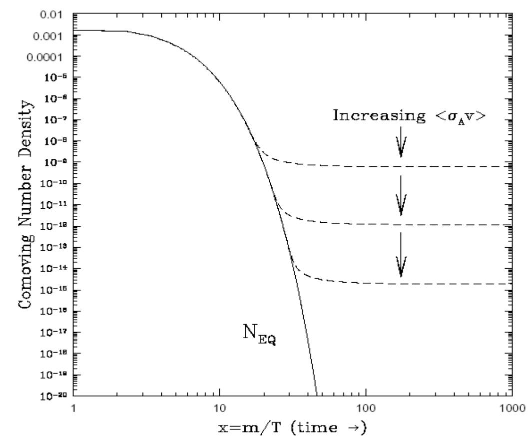
- DM a new stable WIMP is most studied candidate
- Despite strong experimental programs – no signs of WIMPs
- Well-motivated New Physics model has yet to be singled out
- Certainly important to consider other possibilities for DM formation and DM candidates – different scales and interaction strengths
- Does it mean we should give up on WIMPs?
- Will current and planned searches allow to close the argument?

Outline

- Motivation
- More mediators
- More dark matter
- Conclusions

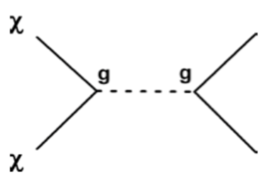
WIMP DM

- When rate of annihilation drops below expansion rate $\Gamma < H$ - > WIMPsfall out of equilibrium and freeze-out (at $T_{FO} \sim m/20$) density depends only on expansion rate



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

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

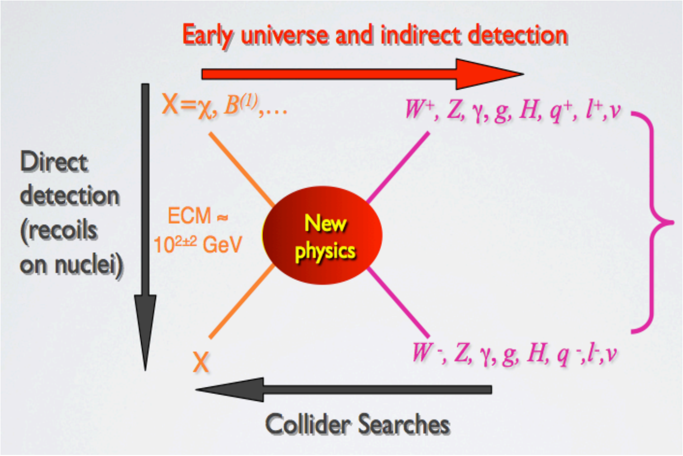


$$<\sigma v> \sim \frac{g^4}{32\pi m_{DM}^2}$$

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

- Weak couplings and weak masses -> $\Omega h^2 \sim 0.1$
- Simple estimate modified if 1) resonance 2) t-channel 3) co-annihilation 4)…

Probing the nature of dark matter



- All determined by interactions of WIMPS with Standard Model
- Strong connection relic/ID (only difference is v)
- Not necessarily the same particles/process play dominant role, eg annihilation into dark sector can dominate relic – no effect on collider searches

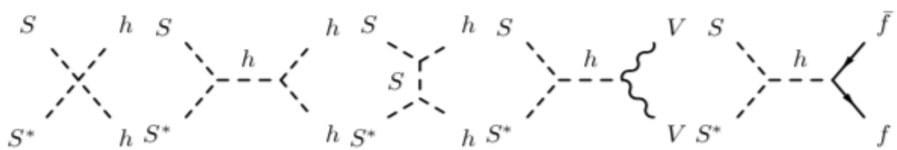
Singlet scalar

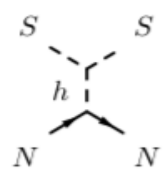
- Simplest SM extension : one singlet scalar + Z_2 symmetry
- Improves stability of Higgs sector
- Higgs portal : one coupling (to Higgs) drives all DM observables – relic,DD,ID

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

Direct detection

annihilation



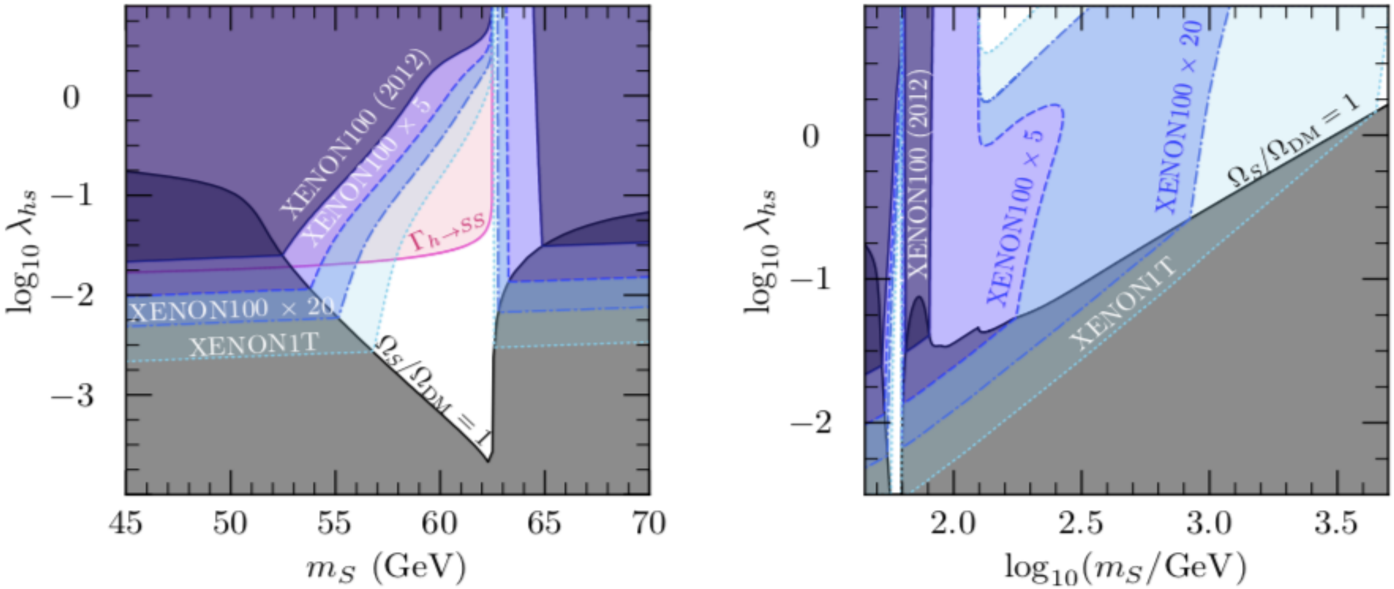


$m_s \gg m_i$	$\frac{\lambda_{SH}^2}{64\pi m_s^2}$	$\frac{\lambda_{SH}^2}{32\pi m_s^2}$	$\frac{\lambda_{SH}^2 m_f^2}{64\pi m_s^4}$
$m_s \ll m_h$			$\frac{\lambda_{SH}^2 m_f^2}{64\pi m_h^4}$

- Need large enough coupling for DM annihilation – but constraints from DD

Singlet scalar

Cline et al, 1306.4710



- 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, Lebedev, Mambrini, Quevillon, 1112.3299

- To relax constraints on WIMPs : uncorrelate relic density/ direct detection
- Several ways to do that (beyond exploiting resonance effect)
  - Pseudoscalar mediator(s)
  - New particles and new processes for relic (e.g. co-annihilation, semi-annihilation …)
  - More DM
- What about signatures, in particular LHC

Case 1 : pseudoscalar mediator(s)

- Fermion DM + 1 or 2 pseudoscalar mediators – relax DD constraint
  - Loop-induced contribution to DD much weaker, current experiments do not yet probe O(1) couplings -- Li, Wu , 1904.03407
- Simplified model (Banerjee, GB, Bhatia, Fuks, Raychaudhuri, 2110.15391)

$$\mathcal{L}^{(0)} \supset -\sum_q \left(\frac{i y_q g_q}{\sqrt{2}} \bar{q}\gamma_5 q \, P_1^0 \right) - i y_\chi \, \bar{\chi}\gamma_5\chi \, P_2^0 \,. \qquad \begin{pmatrix} P_1^0 \\ P_2^0 \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} P_1 \\ P_2 \end{pmatrix} .$$

$$\mathcal{L}_{\rm int,2} \supset A_{P_1} \, F_{\mu\nu}\widetilde{F}^{\mu\nu} P_1 + A_{P_2} \, F_{\mu\nu}\widetilde{F}^{\mu\nu} P_2 + G_{P_1} \, G_{a,\mu\nu}\widetilde{G}^{a,\mu\nu} P_1 + G_{P_2} \, G_{a,\mu\nu}\widetilde{G}^{a,\mu\nu} P_2 + m_{11} P_2 P_1 H + m_{22} H P_1 P_1 + m_{33} H P_2 P_2 .$$

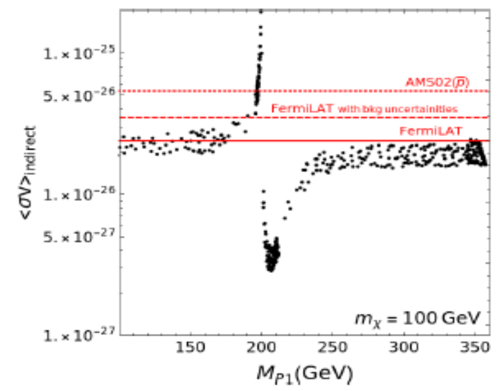
- m11, m22, m33 fixed to satisfy upper limit on Higgs decay + narrow width for $P_2 \to P_1 H$ + assume maximal mixing $\theta=\pi/4$
- Constraints: relic density, indirect detection, LHC

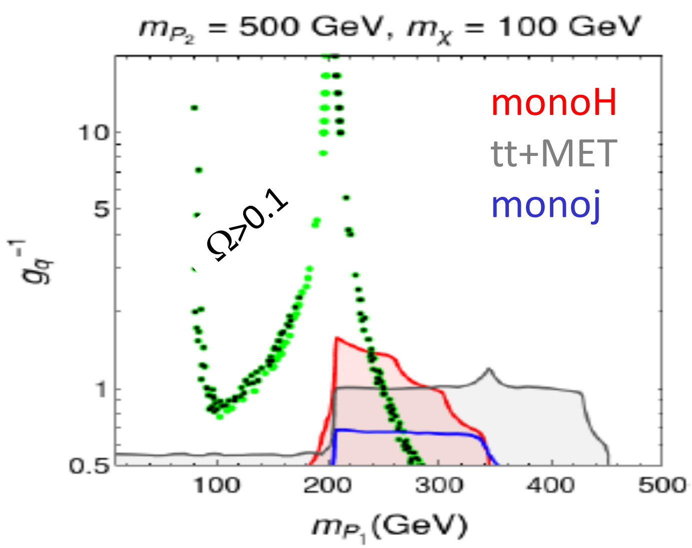
$$pp \to \chi\bar{\chi} j \quad \text{with } p_T(j) > 100 \text{ GeV} \,, \qquad pp \to \chi\bar{\chi} H \,, \qquad pp \to \chi\bar{\chi} t\bar{t} \,.$$

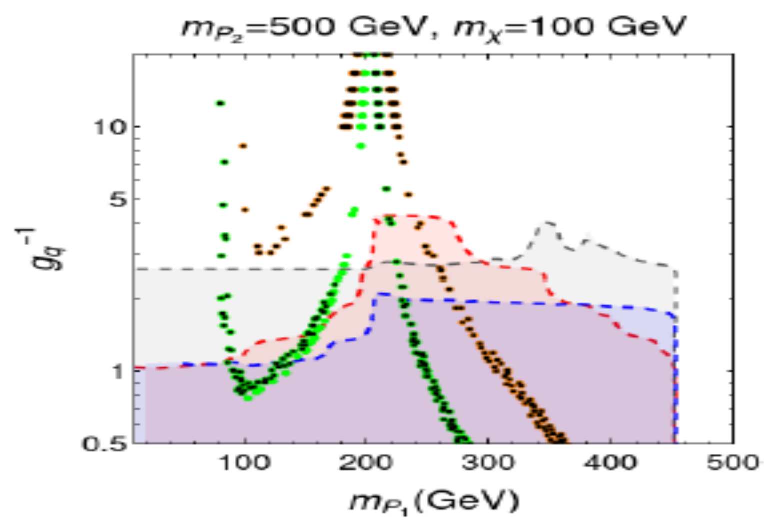
pp-> P_1H

$$pp \to P_2 \to P_1 H \to \bar{\chi}\chi H \,.$$

- For M_DM >100 GeV, model mostly escapes ID constraints
- Region compatible with relic barely probed by current monoX searches

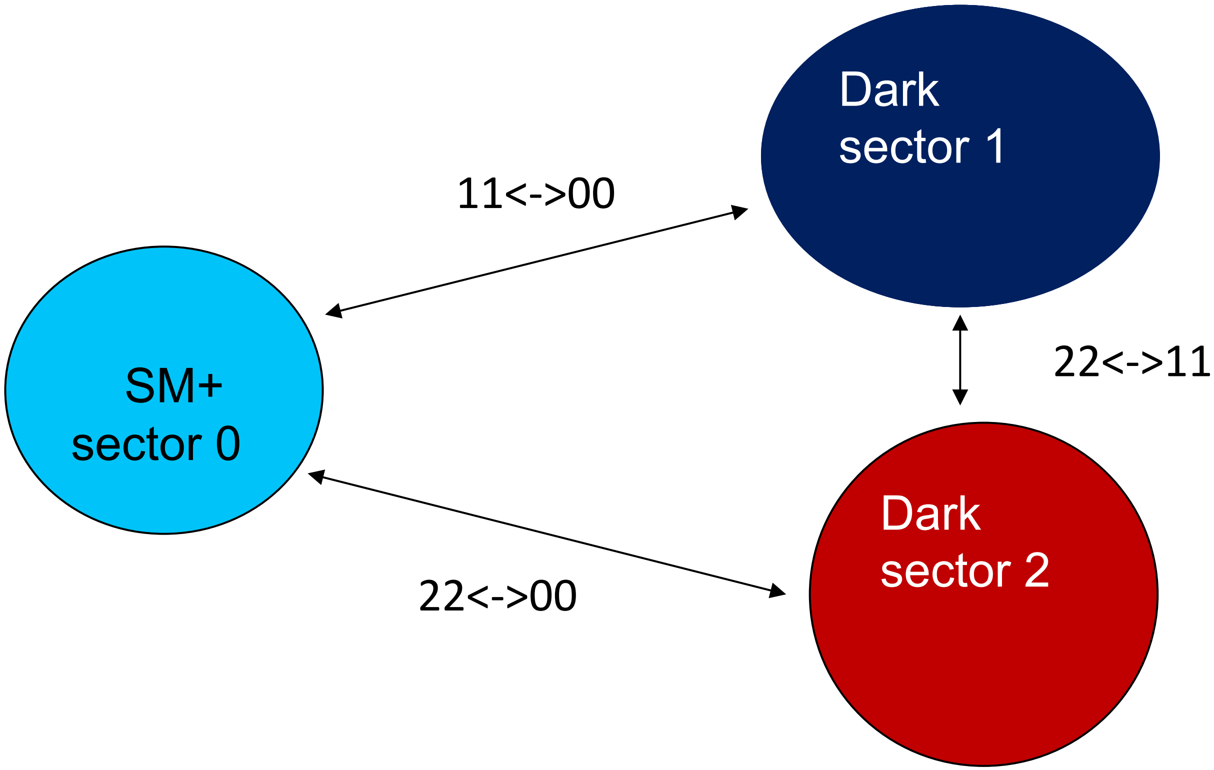






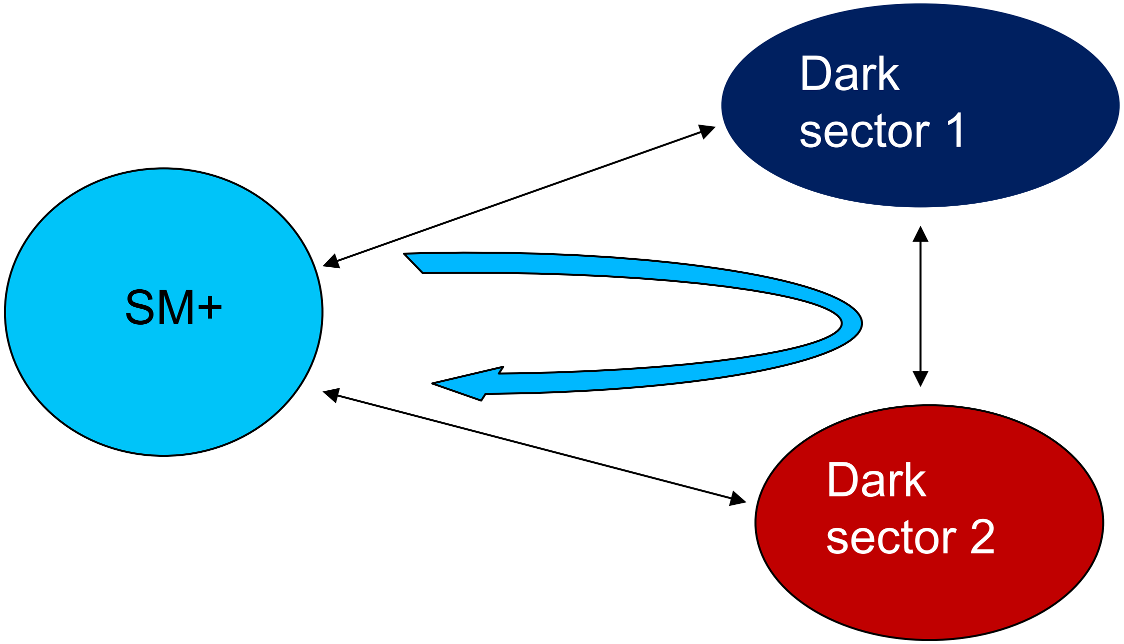
- Recast of Run2 ATLAS and CMS with MadGRAPH5_aMC@NLO+MadAnalysis5
- Mono-X searches at HL-LHC will probe part of the model – regions hard to probe: resonance and annihilation into mediators (no couplings of DM to SM required)

Case 2 : Two dark sectors



- Lightest particle of each dark sector is stable (transformation under a discrete symmetry determines the dark sector)
- If decoupled just two independent sectors
- In general : interactions involving 2 dark + SM sectors

Two dark sectors



- Assisted freeze-out : no interactions DS2-SM – interactions DS1-DS2 determine the abundance of DM2 (GB, JC Park, JCAP03 (2012) 038)
- DM conversion : include also DS2-SM
- Semi annihilation (Hambye, 0811.0172; D'Eramo, Thaler 1003.5912)
  - processes involving different number of dark particles 11-> 1*0 (Z_3) or 11->20 (Z_4)

Generalization Boltzmann equation

- Equations for number density

$$\frac{dn_1}{dt} = -\sigma_v^{1100}\left(n_1^2 - \bar{n}_1^2\right) - \sigma_v^{1120}\left(n_1^2 - \bar{n}_1^2\frac{n_2}{\bar{n}_2}\right) - \sigma_v^{1122}\left(n_1^2 - n_2^2\frac{\bar{n}_1^2}{\bar{n}_2^2}\right) - 3Hn_1$$

$$\frac{dn_2}{dt} = -\sigma_v^{2200}\left(n_2^2 - \bar{n}_2^2\right) + \frac{1}{2}\sigma_v^{1120}\left(n_1^2 - \bar{n}_1^2\frac{n_2}{\bar{n}_2}\right) - \frac{1}{2}\sigma_v^{1210}\left(n_1 n_2 - n_1\bar{n}_2\right)$$
$$-\sigma_v^{2211}\left(n_2^2 - n_1^2\frac{\bar{n}_2^2}{\bar{n}_1^2}\right) - 3Hn_2,$$

  - Details of model, masses couplings determine the importance of semi-annihilation, DM conversion ….
  - Can work both ways : increase or decrease abundance of each DM
  - Included in micrOMEGAs_4.1 and newer versions

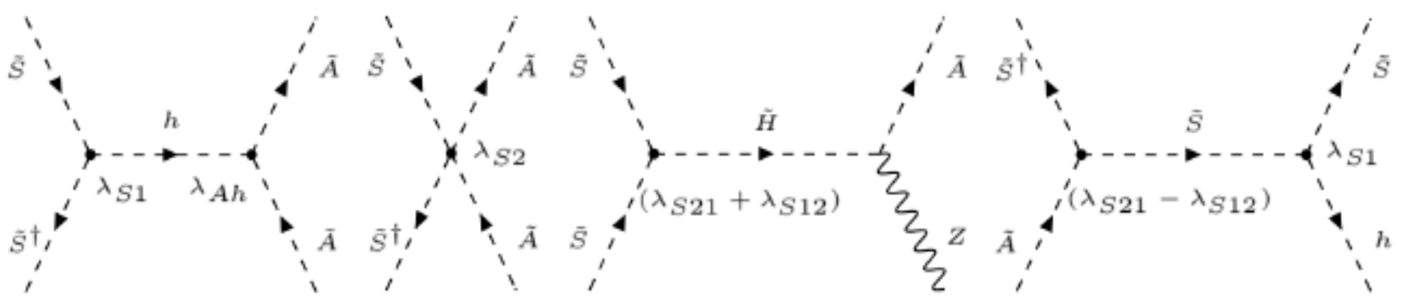
Example: Inert doublet+singlet

- Scalar sector with one extra doublet + singlet
- Z_4 symmetry : $X_S= 1$, $X_H=2$, S is first DM, lightest neutral component doublet (H or A) is second DM, stable only if $M_H<M_S/2$,

$$
\begin{aligned}
V_{Z4} \; = \; & \lambda_1 \left(|H|^2 - \frac{v^2}{2} \right)^2 + \mu_2^2 \, |H'^2| + \lambda_2 \, |H'|^4 + \mu_S^2 \, |S|^2 + \lambda_S \, |S|^4 + \frac{\lambda'_S}{2} \left(S^4 + S^{\dagger 4} \right) \\
& + \lambda_{S1} \, |S|^2 \, |H|^2 + \lambda_{S2} \, |S|^2 \, |H'|^2 \\
& + \lambda_3 \, |H|^2 \, |H'|^2 + \lambda_4 \left(H^\dagger H' \right) \left(H'^\dagger H \right) + \frac{\lambda_5}{2} \left[\left(H^\dagger H' \right)^2 + \left(H'^\dagger H \right)^2 \right] \\
& + \frac{\lambda_{S12}}{2} \left(S^2 H^\dagger H' + S^{\dagger 2} H'^\dagger H \right) + \frac{\lambda_{S21}}{2} \left(S^2 H'^\dagger H + S^{\dagger 2} H^\dagger H' \right)
\end{aligned}
$$

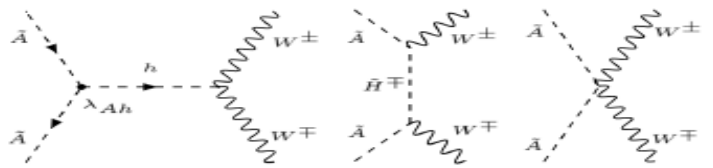
$$\lambda_{Ah} = \lambda_3 + \lambda_4 - \lambda_5$$

- Annihilation(λ_{S1},λ_{Ah}), assisted FO($\lambda_{S2,}$ $\lambda_{S1}\lambda_{Ah}$),semi-annihilation (λ_{S12},λ_{S21})

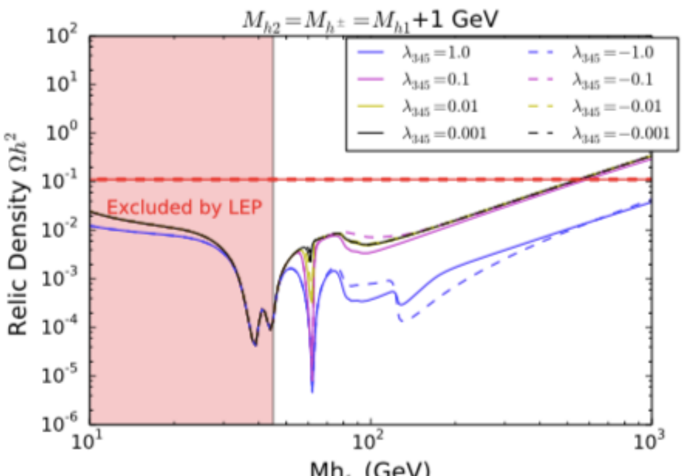


Features of Inert doublet

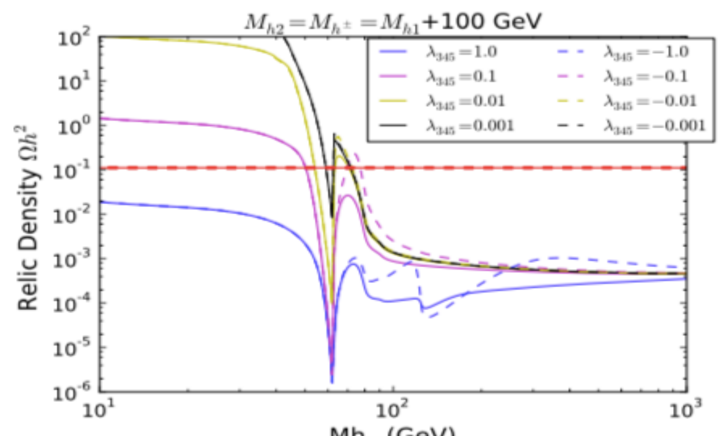
- Simple SM extension : one extra doublet + Z_2 symmetry
- Dark sector : Charged Higgs + Scalar + Pseudoscalar (either neutral is DM)
  - Deshpande, Ma, PRD18 (1978) 254; Barbieri, Hall, Rychkov, PRD74 (2006) 015007; Lopez-Honorez et al JCAP02 (2007) 028
  - Can help EW-baryogenesis



- No coupling of H_2 to fermions
- Most efficient annihilation into gauge bosons, also fermions and coannihilation
- relic density OK in three regions : m_H~55-60, m_H ~65-75GeV, m_H >500GeV



(a)

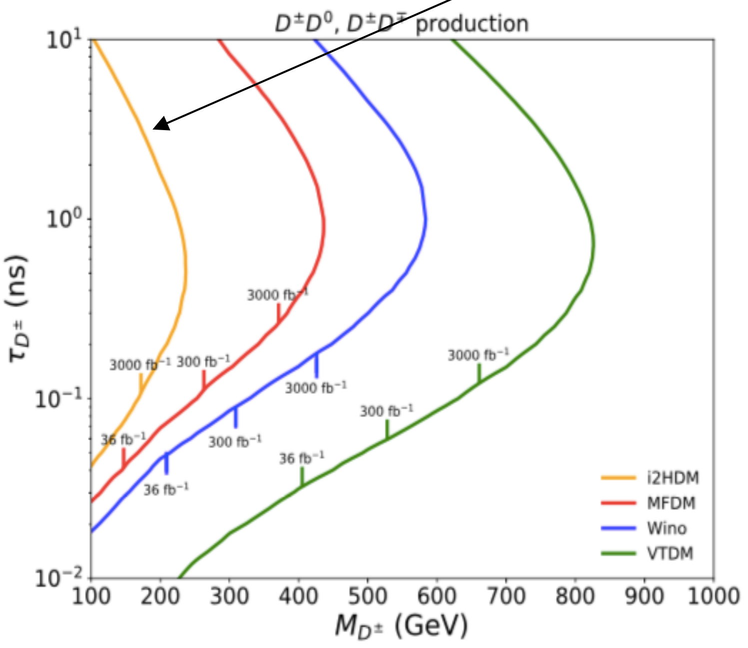


(b)

Belyaev et al, 1612.00511

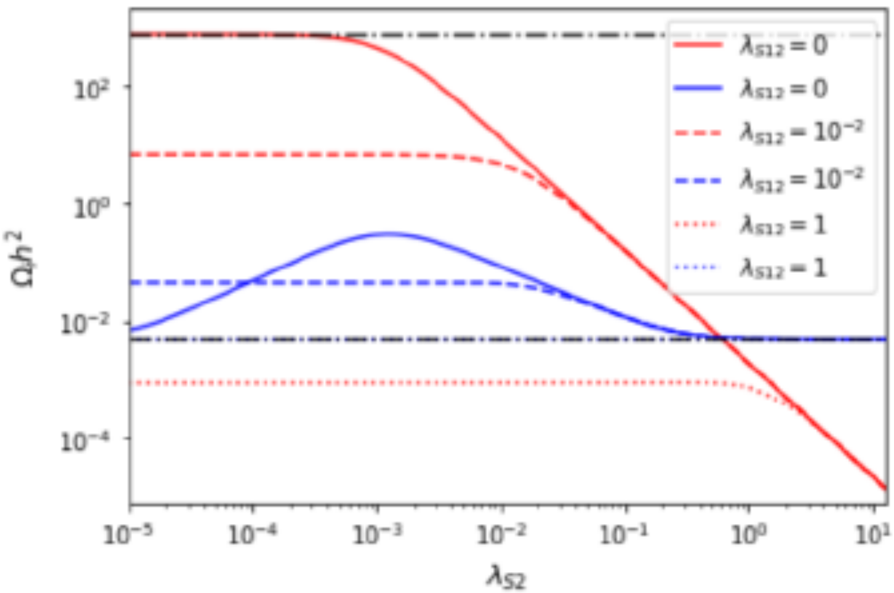
Signatures of Inert doublet

- Direct detection : From just allowed to very suppressed.
- Indirect detection : photons
- Constraints from LHC : dileptons (GB et al 1503.07367), trileptons (Miao, Su 1005.0090; Gustaffsson et al 1206.6316), monojet, mono-H, mono-Z, (Poulose, 1604.03045; Belyaev et al 1612.00511), HSCP, disappearing tracks (Belyaev et al, 2008.08581)



Z4-Inert doublet + singlet

- Interactions between Dark sectors (conversion)
  - GB,Kannike, Pukhov,Raidal, 1202.2962
- $M_S>M_H$ at $T_{FO}(S)$ SS->HH increases annihilation of S – decrease Ω_1, increase Ω_2. Vice versa if H is heavier.

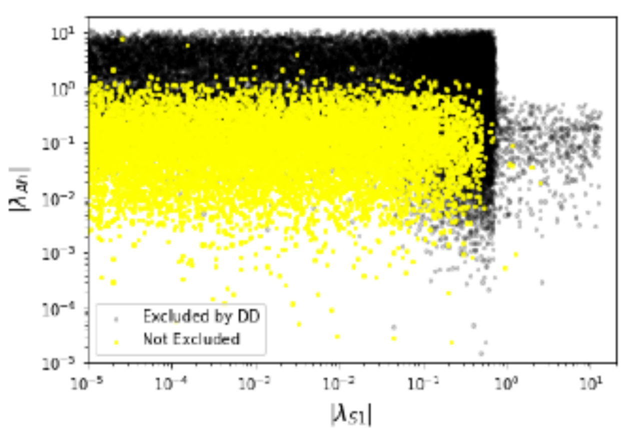


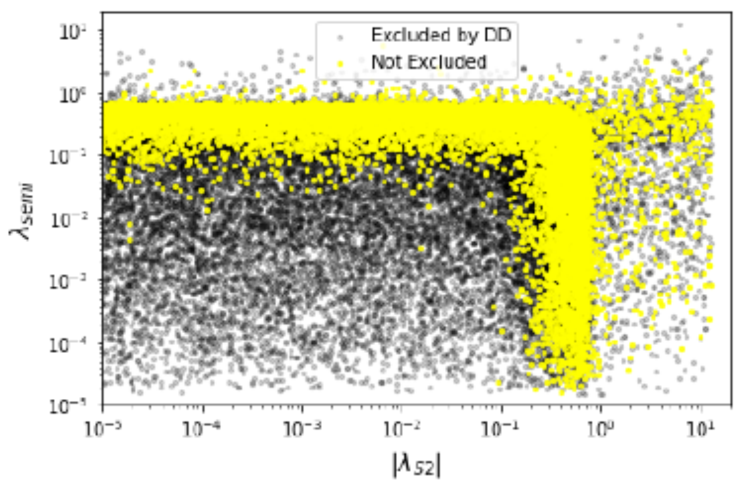
M_S=250 GeV, M_A=120GeV
M_H=M_{H+} =125GeV
λ_{S1}= 10^{-3}

- Semi-annihilation also typically reduces abundance of S

Z4-Inert doublet + singlet

- Scan over parameter space : m_S, m_A, m_{H+}, m_H, 8 couplings
- Theoretical constraints: perturbativity, unitarity, vacuum stability, EW precision, LEP(Z_{inv}), LEP(H+), H_{inv}, relic density, Xenon1T
- As expected λ_{S1} can be small but some DM conversion and/or semi-annihilation required





GB, Mjallal, Pukhov, 2108.08061

Z4-Inert doublet + singlet

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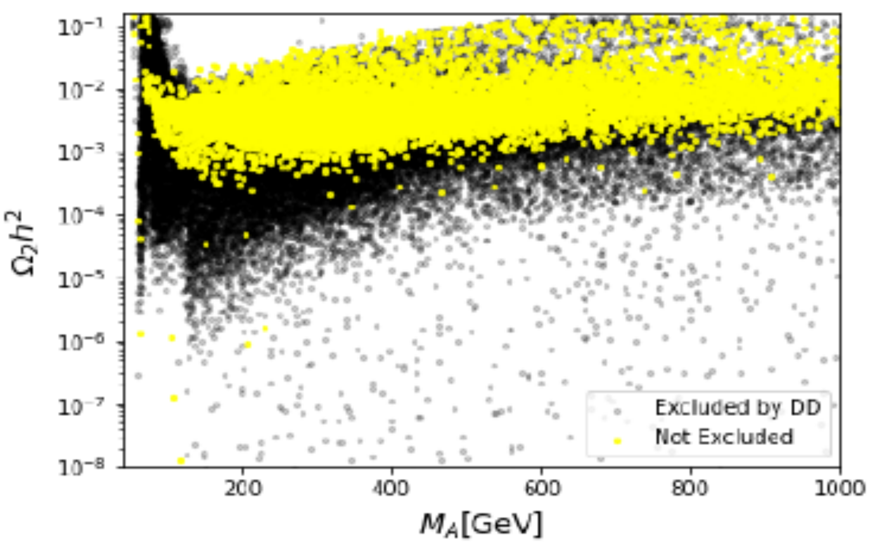
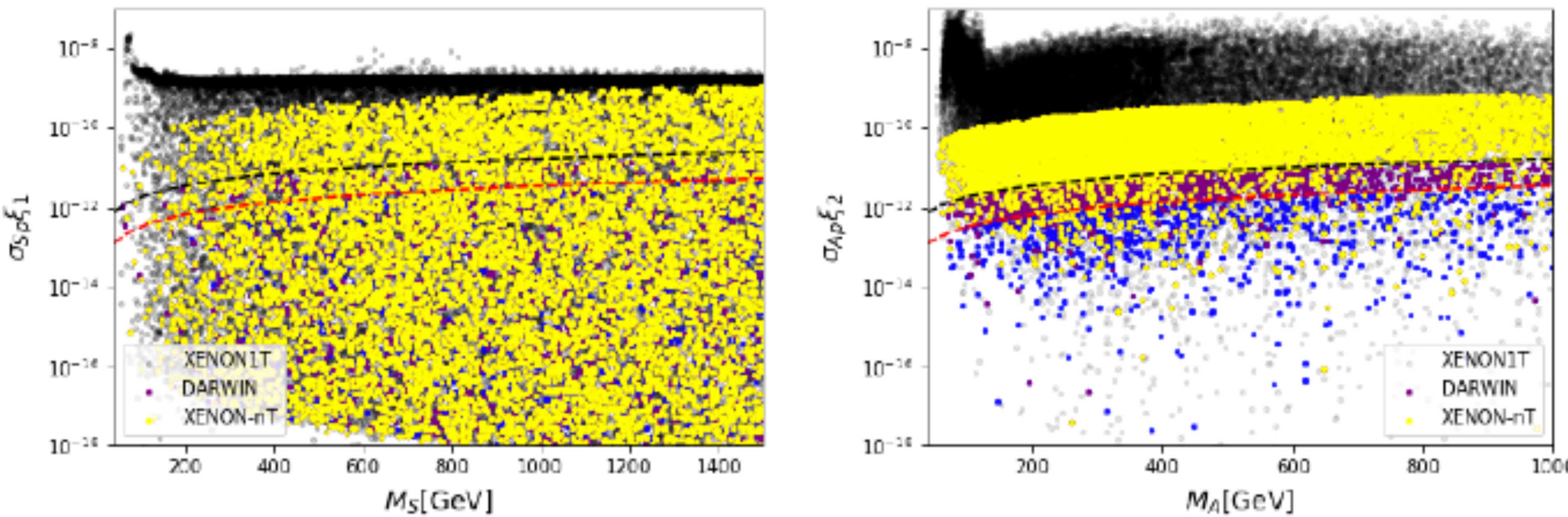
- Theoretical constraints: perturbativity, unitarity, vacuum stability, EW precision, LEP(Z_{inv}), LEP(H+), H_{inv}, relic density, Xenon1T
- Full range of masses is allowed for singlet and doublet, S is usually dominant



GB, Mjallal, Pukhov, in preparation

Direct detection probes

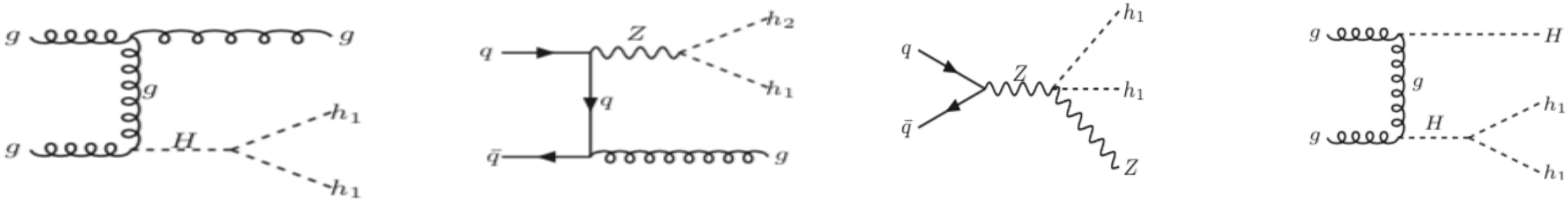
- Best probe of the model
- For XENON-1T : recoil energy spectrum includes the sum of S and A
- XENONnT & DARWIN can probe both singlet and doublet components
- Incomplete coverage



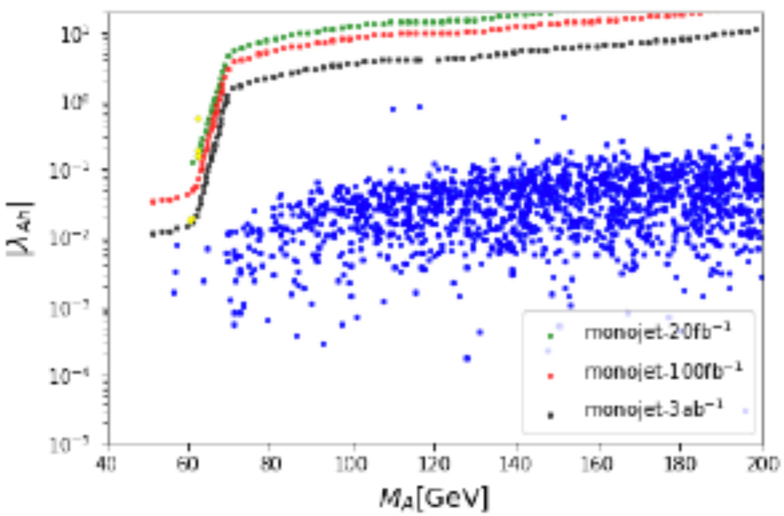
GB, Mjallal, Pukhov, 2108.08061

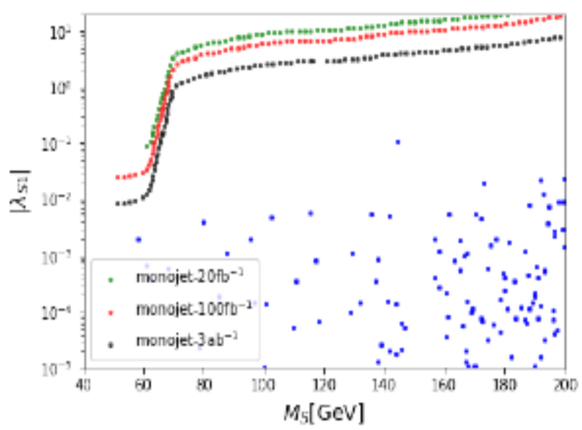
MonoX signatures

- Collider signatures: monojet, monoZ, monoH in the IDM



- Sensitive mainly to large couplings λ_{Ah} (or λ_{S1} for S)- no useful constraint

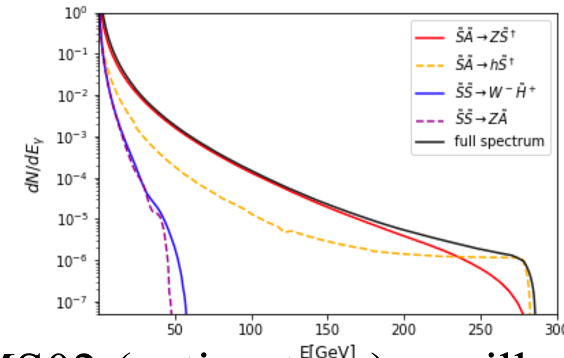




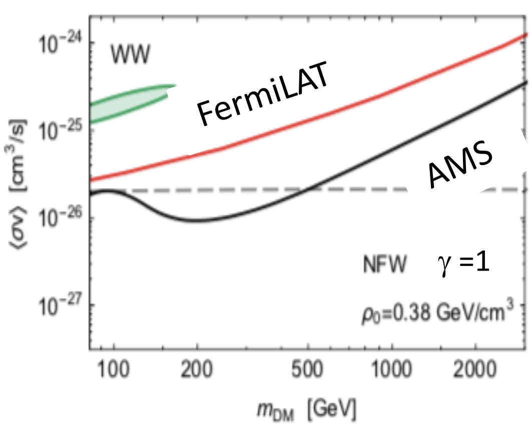
Using recast from Belyaev et al, 1612.00511

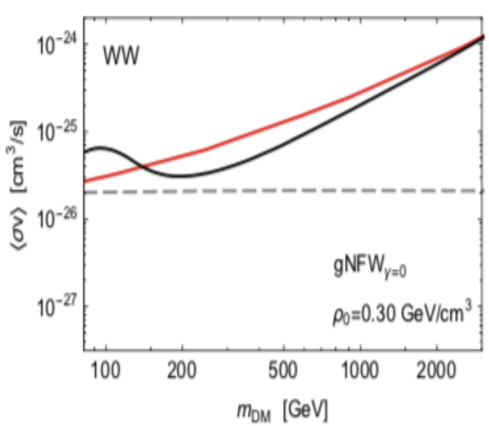
Indirect detection

- Annihilation channels with large cross-sections, WW/ZZ (as for IDM) also new channels : SS->H^+W^-, SS-> H^+H^-,SA-> ZS



- Can be probed by FermiLAT (Dwarfs) and by AMS02 (antiprotons) – will use only WW, ZZ
- Antiprotons: dependence on DM profile and on cosmic rays propagation parameters – fit to B/C measured by AMS





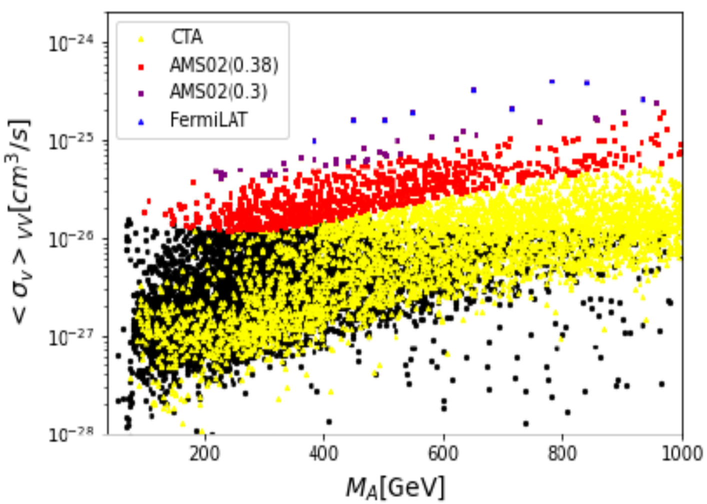
$$\rho_{DM} = \rho_0 \left(\frac{R_0}{r}\right)^\gamma \left(\frac{R_0 + r_s}{r + r_s}\right)^{3-\gamma},$$

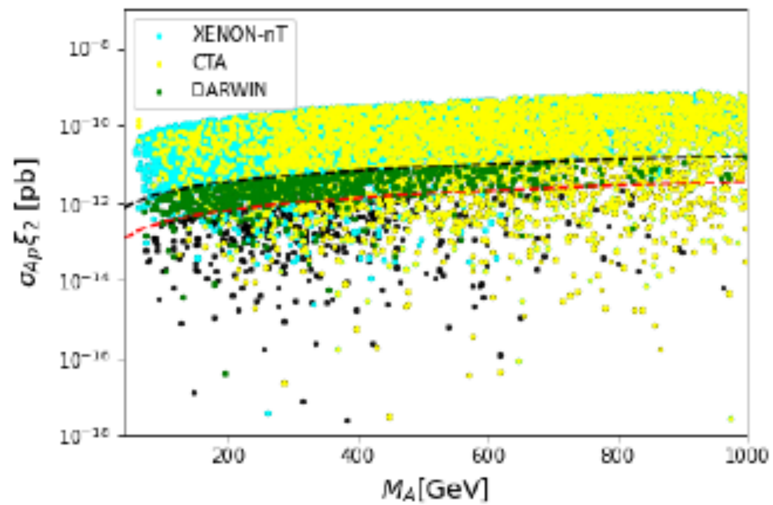
Reinert, Winkler, JCAP01 (2018) 055

Indirect detection

- Also within reach of CTA (photons) – include all channels, A. Acharya et al, JCAP01(2021) 057

$$Q_a(E) = \frac{1}{2}\langle\sigma v\rangle\left(\frac{\rho}{m_A}\right)^2\left(\xi_A + \frac{m_A}{m_S}\xi_S\right)^2\frac{dN_a}{dE}$$

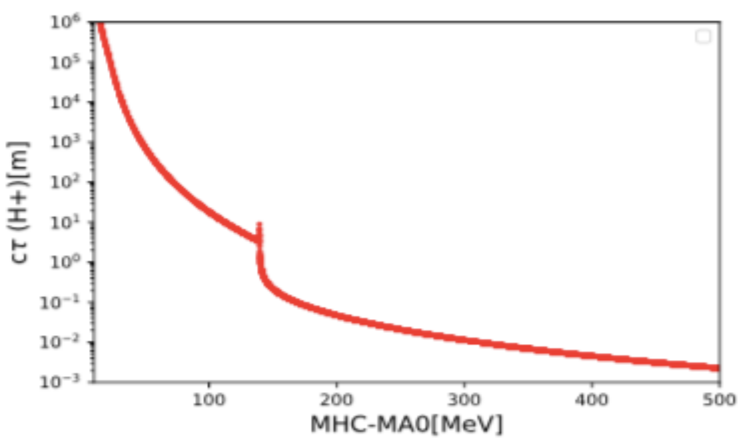


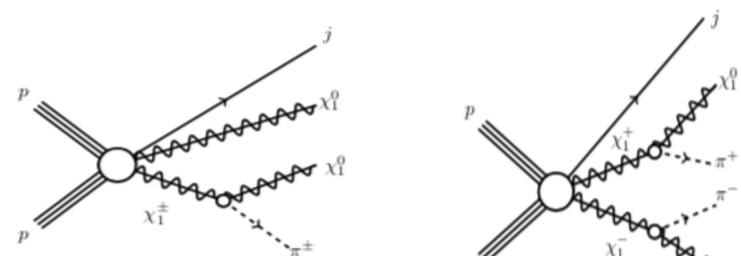


- *Large fraction of the parameter space is within reach of CTA and/or XENON-nT*
- *Beyond reach : doublet DM O(100)GeV+*

Special case : nearly degenerate doublet

- Refined analysis of the region with very compressed spectrum
- Note that even in completely degenerate case : loop corrections will partially lift degeneracy
- Charged Higgs can be probe at LHC -> heavy stable charged particle or disappearing track $H^+ \to \pi^+$ +DM
- Smodels_2.0 to implement HSCP (Ambrogi et al 1811.10624) and disappearing tracks constraints – compatible with Belyaev et al 2008.08581



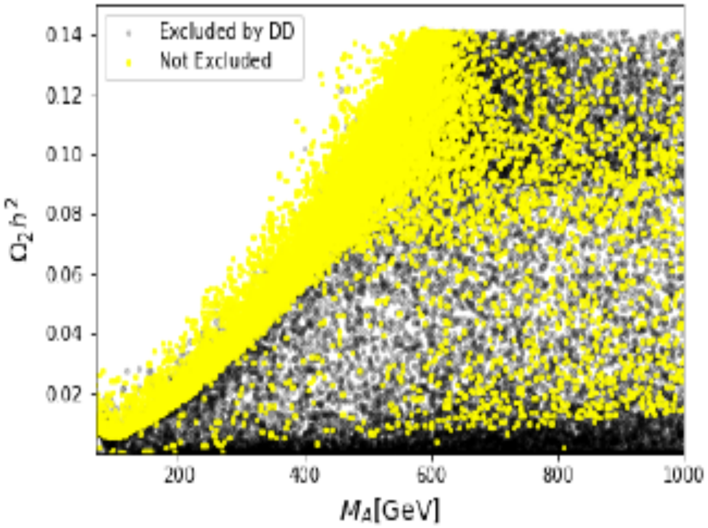


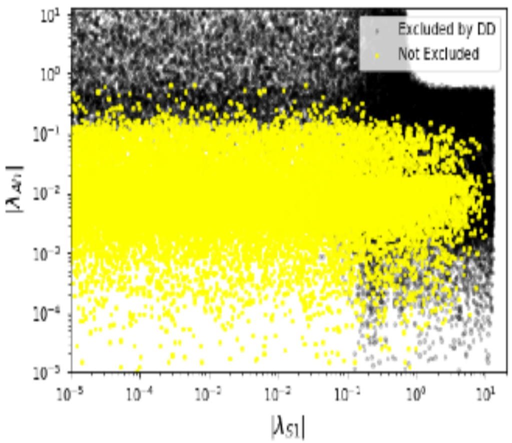
(a) $pp \to \chi_1^\pm \chi_1^0 j$

(b) $pp \to \chi_1^\pm \chi_1^\mp j$

Special case : nearly degenerate doublet

- Dedicated scan in the region where $M_H = M_A + 200\text{keV}$, $M_{H+} - M_A$: 1-500MeV
- Three neutral stable particles H,A (about same relic) and S
- Here the doublet ($\Omega_2 = \Omega_H + \Omega_A$) can be dominant

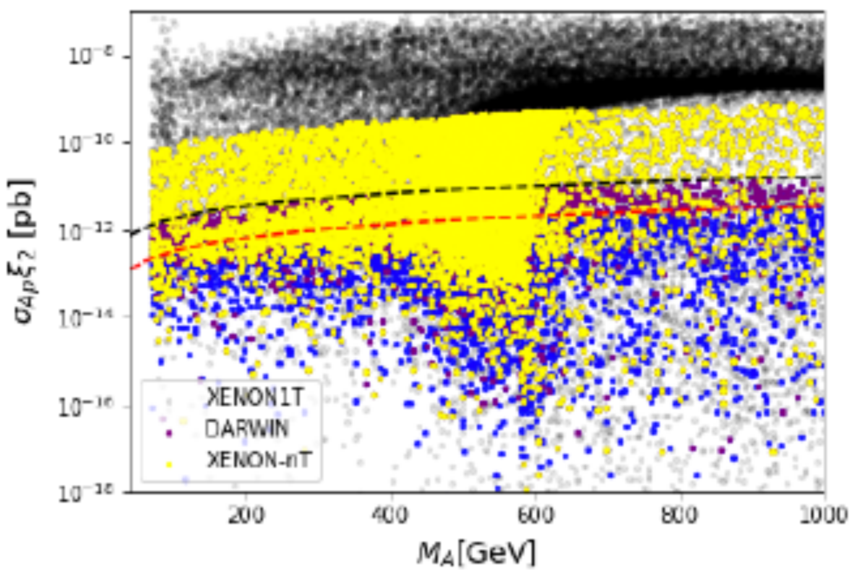


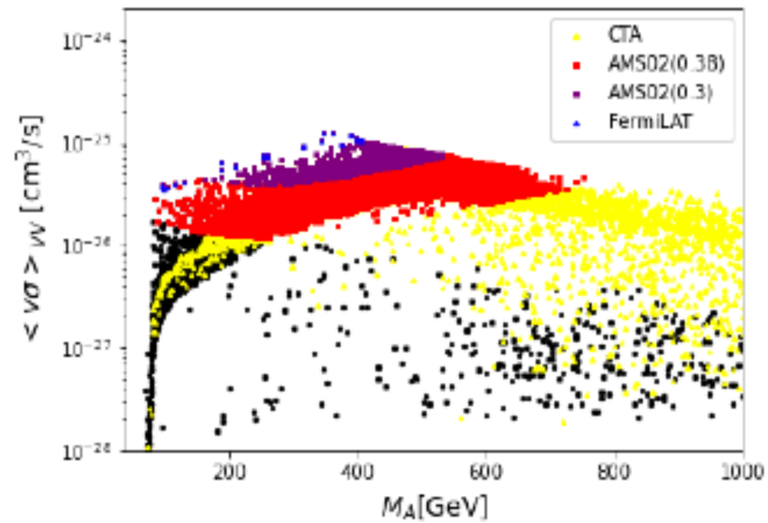


GB, Mjallal, Pukhov, 2108.08061

Direct/indirect

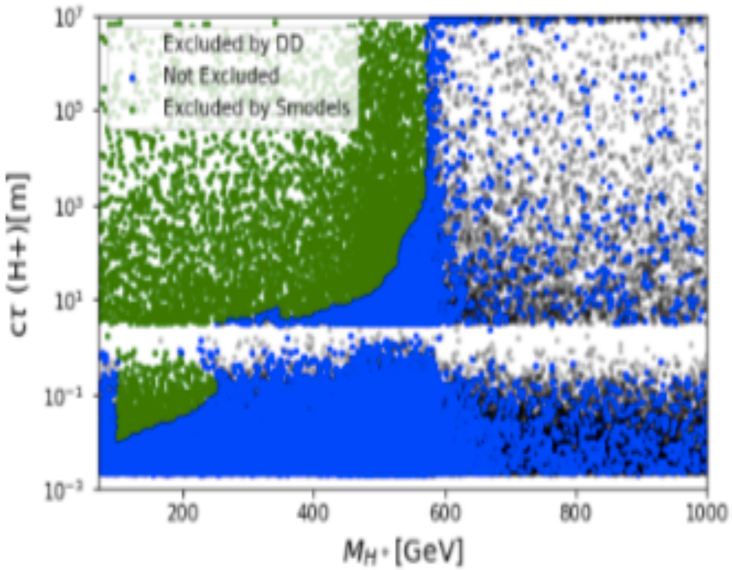
- Both S and A can be within reach of XENONnT
- Constraints from FermiLAT, AMS and prospects for CTA





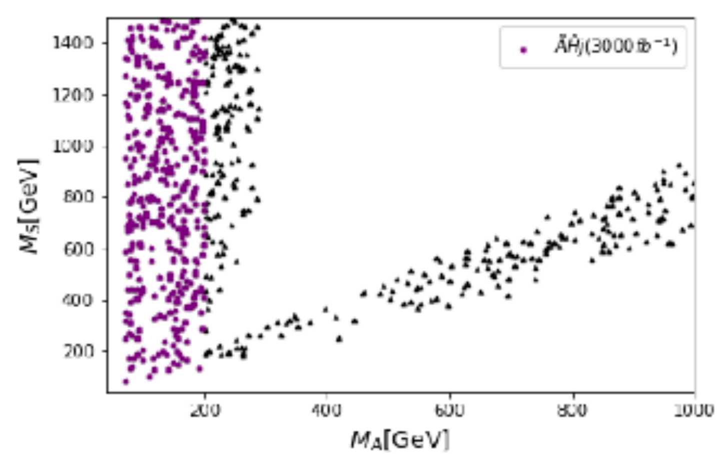
- What about LHC?

- Strong constraints from LHC – both HSCP and disappearing tracks
- Other LHC signatures challenging (soft decay products) and λ_{Ahh} coupling small– to be investigated
- Monojet @ HL-LHC : pp->AHj could constrain DM masses up to 200 GeV for any λ_{AH} (Belyaev et al 1809.00933)



Current LHC constraints –
GB, Mjallal, Pukhov, 2108.08061

Monojet,HL-LHC



Here only points out of reach
of future Darwin &CTA

Complementarity DD/ID/HL-LHC

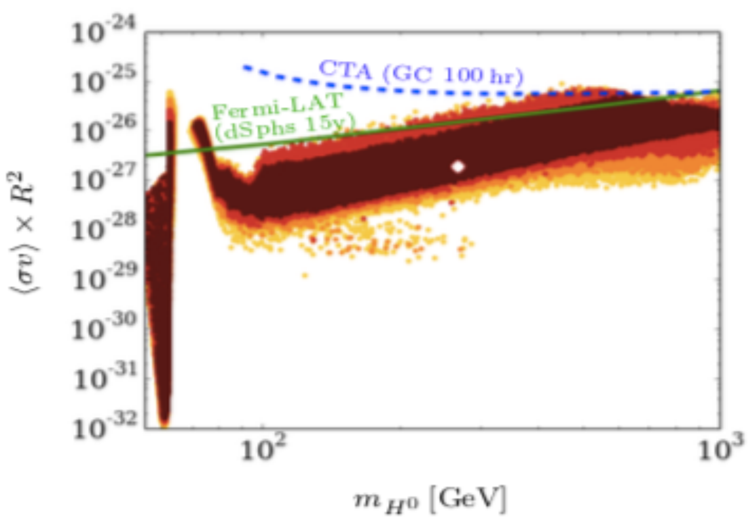
Can full parameter space be probed in other channels or with HE-LHC or e+e- (for prospects in IDM see T. Robens 1908.10809)

Conclusion

- Although classical WIMP models are severely contrained from relic/LHC/direct detection/indirect detection – WIMPs are not dead
- WIMP models can be constructed to avoid certain constraints, but strategy of direct/indirect/collider searches offer powerful probes of WIMPs
- Collider searches relevant also for case where WIMP is subdominant
- It will become more and more difficult to hide WIMPs
- Note : if one of the DM is a FIMP easier to make all signals disappear

Signatures of Inert doublet

- Direct detection : From just allowed to very suppressed.
- Indirect detection : photons
- Constraints from LHC : dileptons (GB et al 1503.07367), trileptons (Miao, Su 1005.0090; Gustaffsson et al 1206.6316), monojet, mono-H, mono-Z, (Poulose, 1604.03045; Belyaev et al 1612.00511), HSCP, disappearing tracks (Belyaev et al, 2008.08581)



Eitenauer, Goudelis, Heisig, 1705.01458