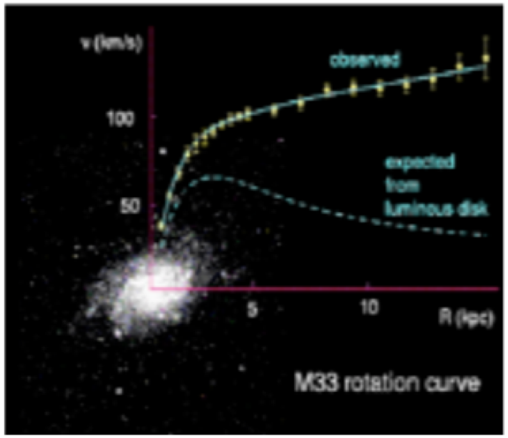
Dark matter models - status

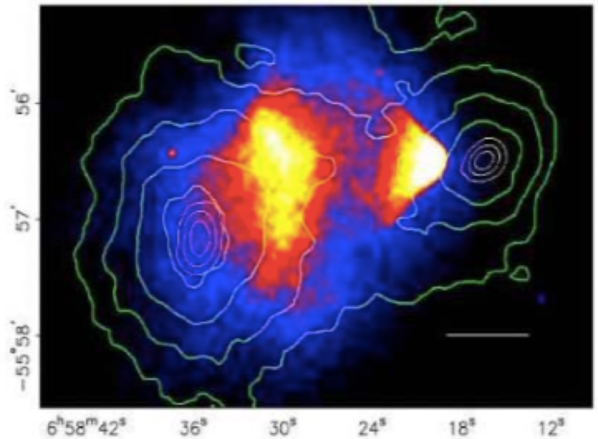
G. Bélanger

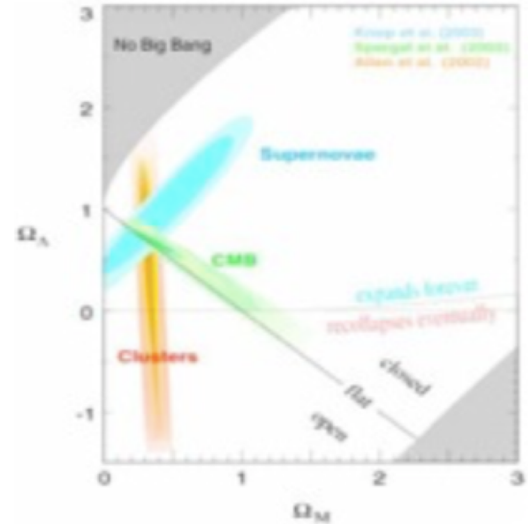
LAPTh, Annecy-le-Vieux

GDR-DeepUnderground,
June 1st 2021

Introduction



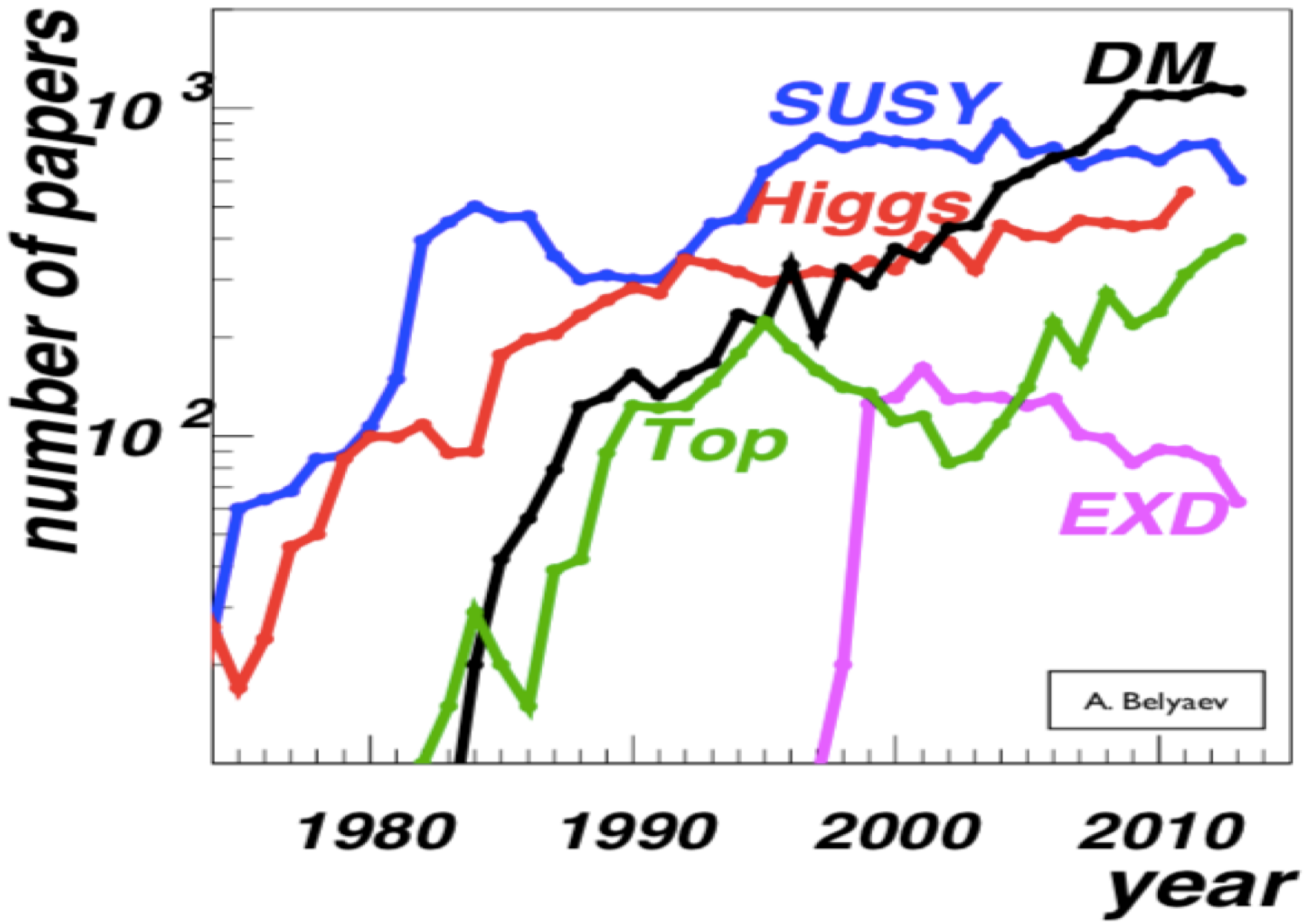




- Strong evidence for dark matter from many scales
  - The galactic scale (rotation curves)
  - Scale of galaxy clusters: mass to light-ratio,gravitational lensing, Bullet cluster
  - Cosmological scales
    - DM required to amplify the small fluctuations in Cosmic microwave background to form the large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

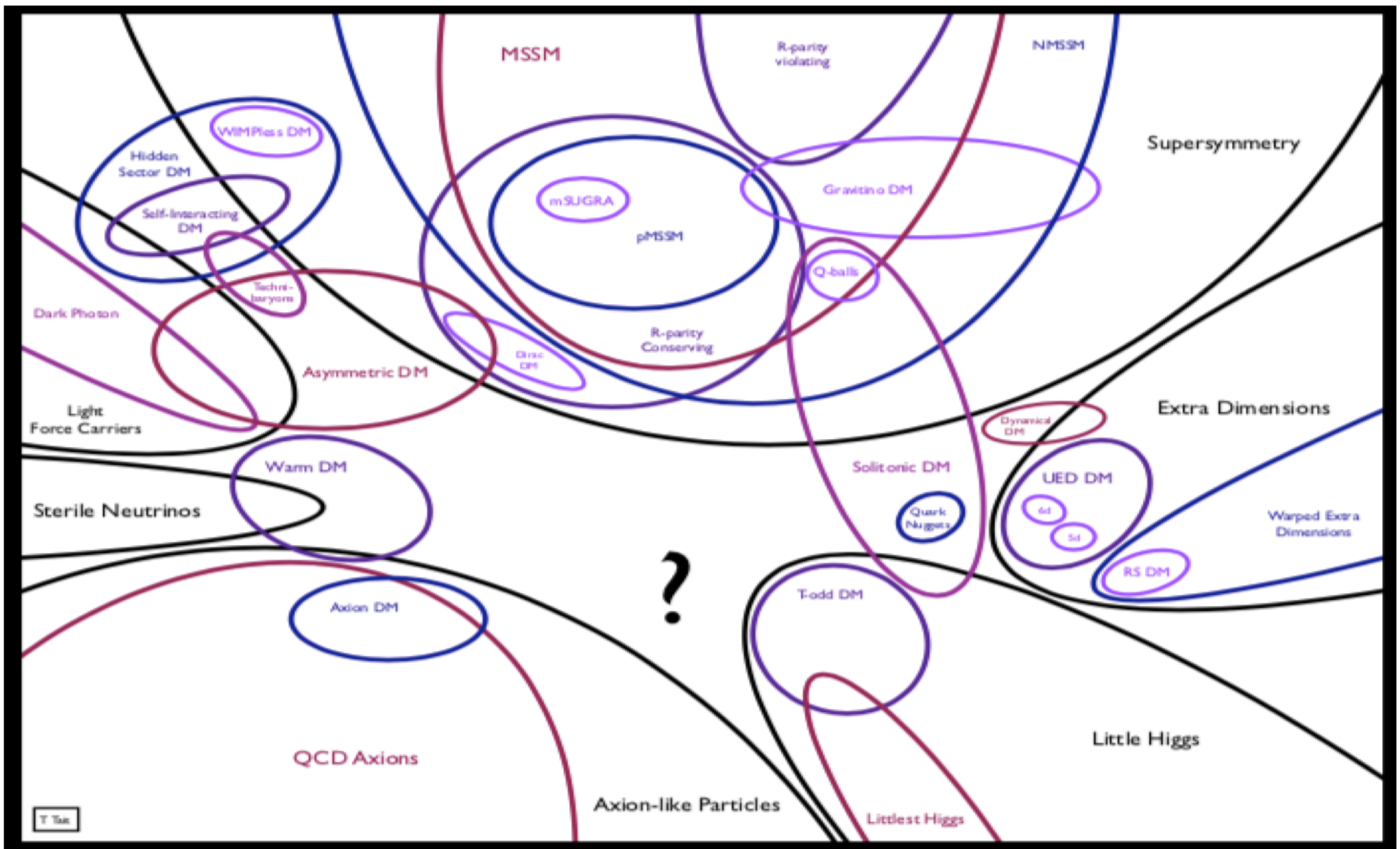
Many more possibilities for DM, strong motivation for BSM



- 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 for 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

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

- 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}~m/20), density depends only on expansion rate

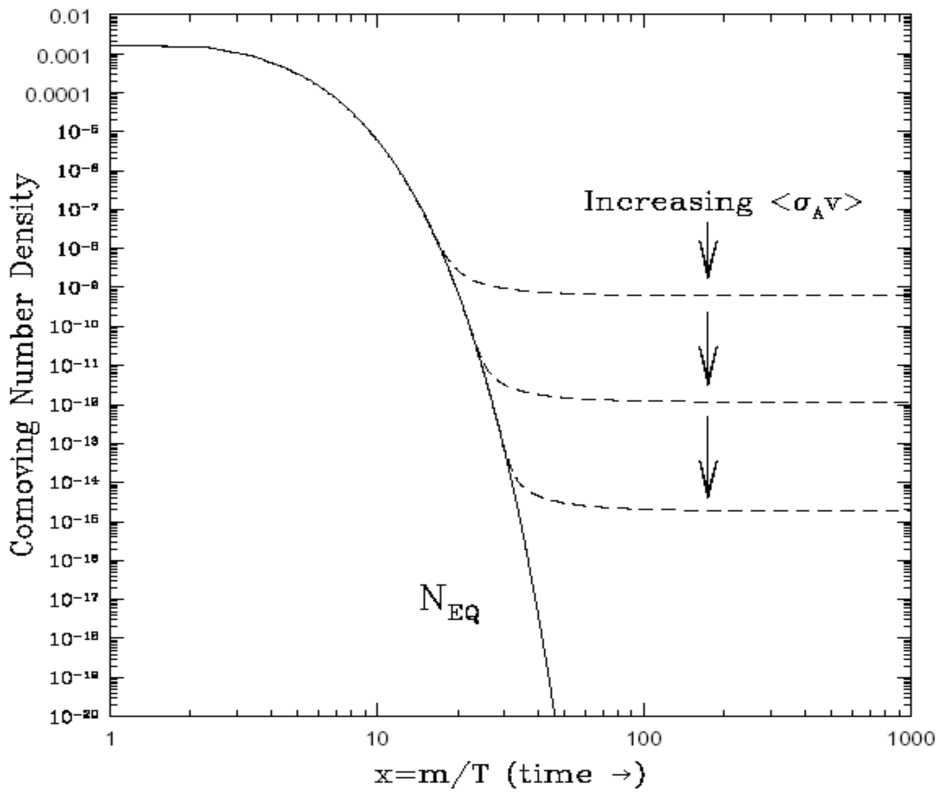
$$\frac{dn}{dt} = -3Hn - <\sigma v> \left[n^2 - n_{eq}^2\right]$$

WIMP DM

- Why WIMP
- In thermal e   ian its mass
- Equilibrium

  $\bar{q}, W^+W^-, ZZ$

- As well as r   ith equal rate
- As Universe   ntially, 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),

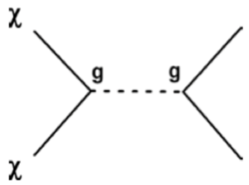


$$\frac{dn}{dt} = -3Hn - < \sigma v > \left[n^2 - n_{eq}^2\right]$$

Dark matter: a WIMP?

In standard scenario, relic abundance $$\Omega_X h^2 \approx \frac{3 \times 10^{-27} \mathrm{cm}^3 \mathrm{s}^{-1}}{\langle \sigma v \rangle} \, .$$

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)



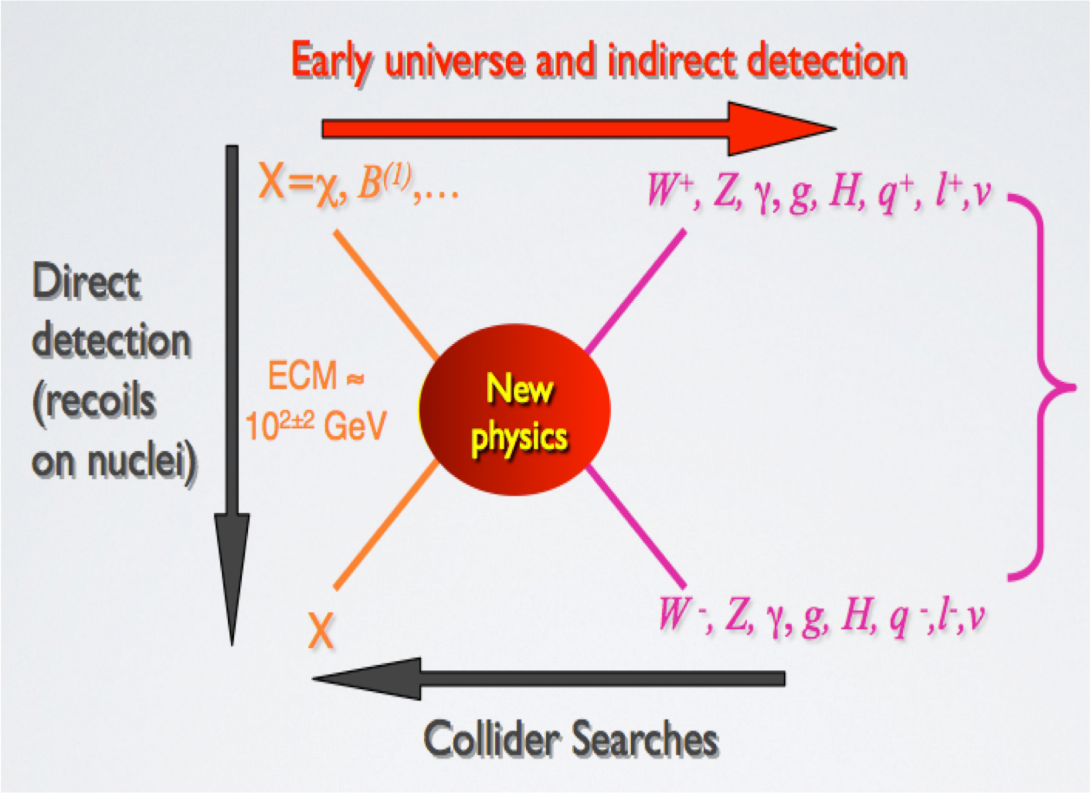
$$< \sigma v > \sim \frac{g^4}{32\pi m_{DM}^2}$$ $\sim 3\ 10^{-26}\ \mathrm{cm}^3/\mathrm{s}$ (or $\sigma \sim 1\mathrm{pb}$)

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

- resonance
- new DM production processes in early Universe: co-annihilation, semi-annihilation, DM conversion when more than one dark sector
- departure from chemical equilibrium (not in this talk)

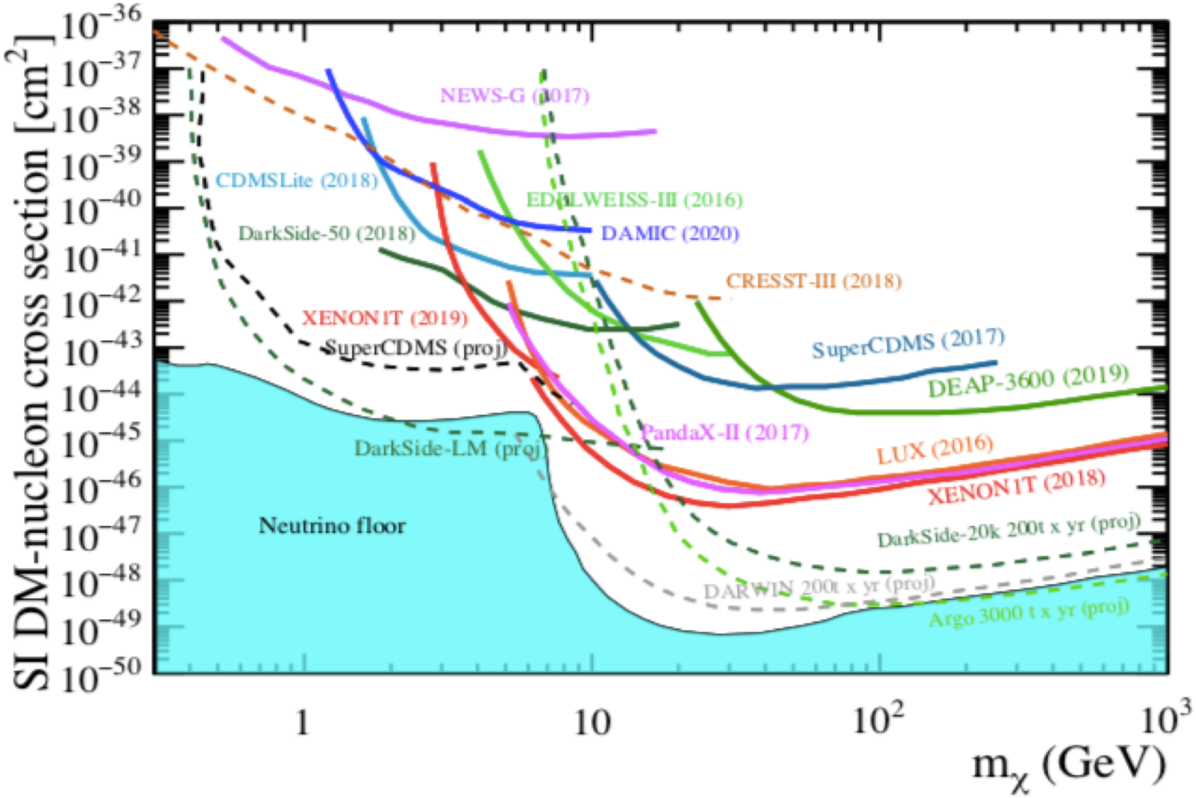
Probing the nature of dark matter



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

Direct detection - status

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



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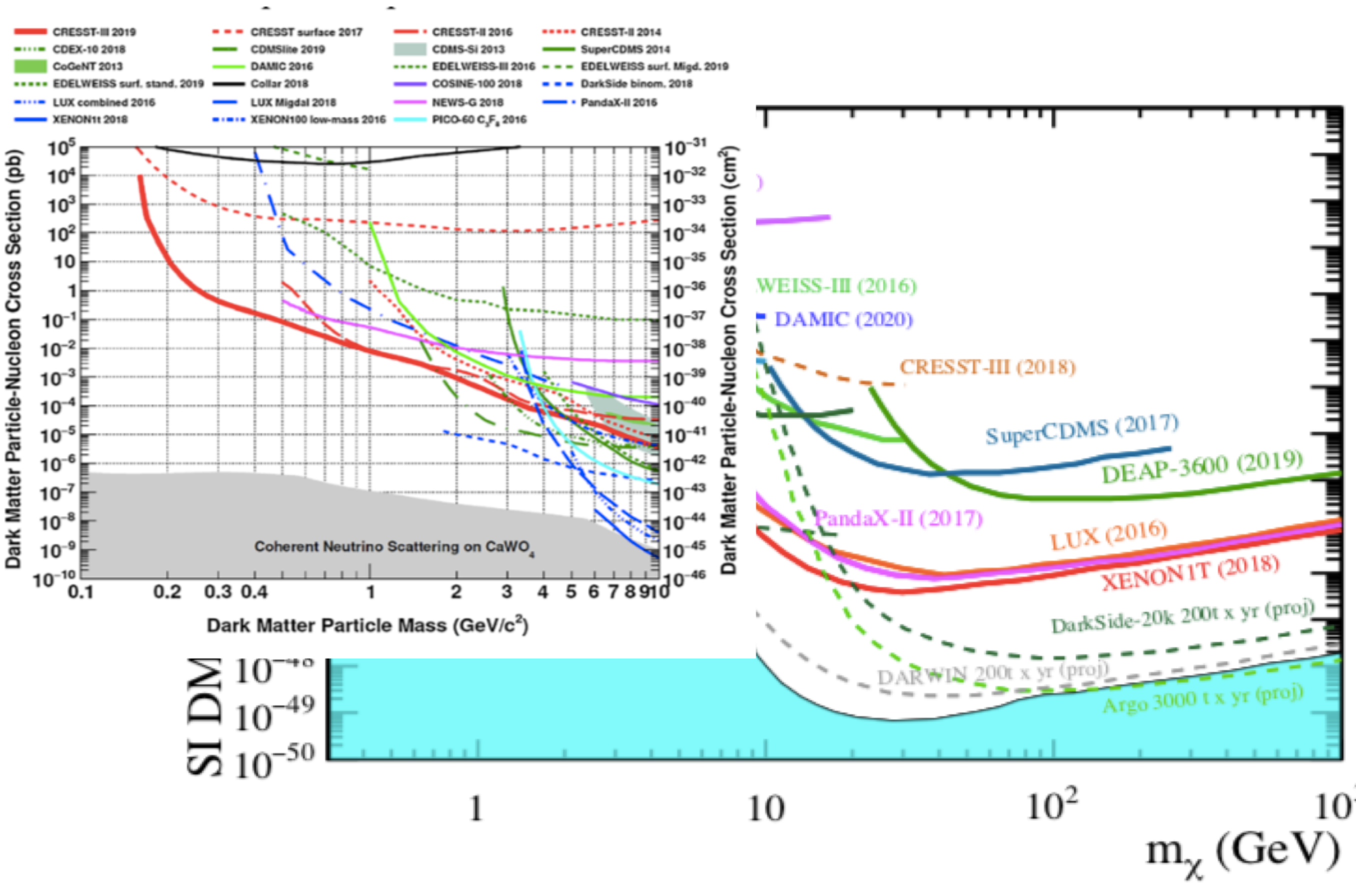
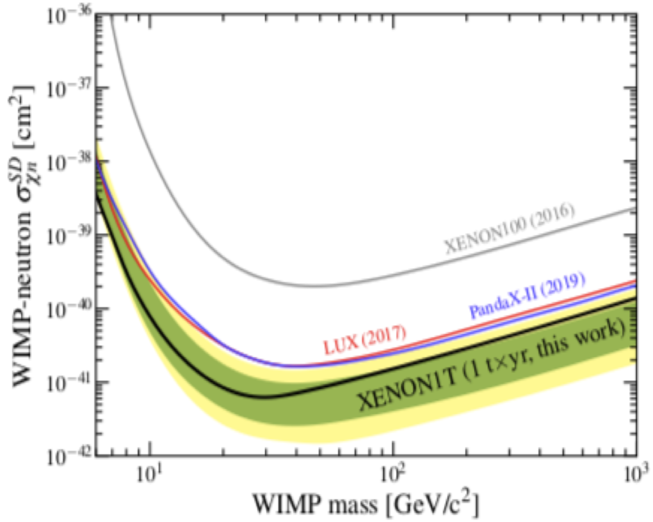
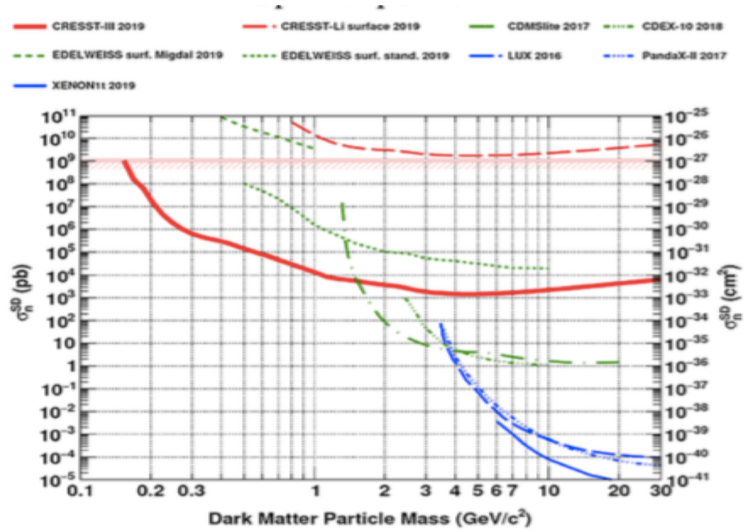


- Spin Dependent on neutrons



E. Aprile et al, XENON1T, 1902.03234



M. Mancuso, CRESST 2020

WIMP DM

- Higgs portal : singlet scalar
- Beyond minimal : more mediators, new processes
- The SUSY case

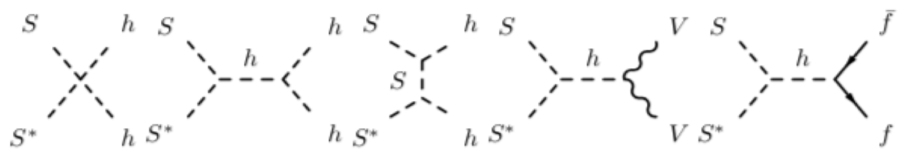
Higgs Portal : Singlet scalar

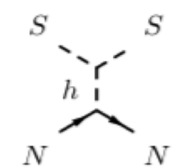
- Simplest SM extension : one singlet scalar + Z_2 symmetry
- Improves stability of Higgs sector
- One coupling (to Higgs) drives all DM observables –relic,DD,ID

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

Direct detection

annihilation



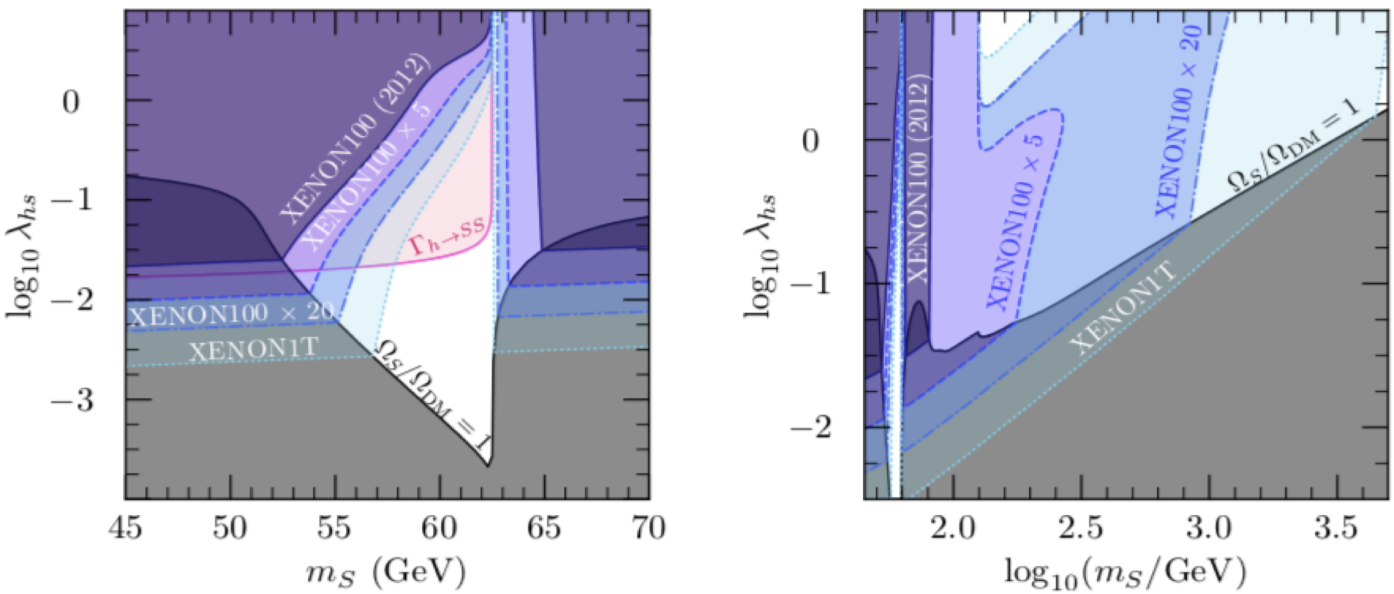


$m_s \gg m_i$	$\frac{\lambda_{SH}^2}{64\pi m_s^2}$	$\frac{\lambda_{SH}^2}{32\pi m_s^2}$	$\frac{\lambda_{SH}^2 m_f^2}{64\pi m_s^4}$
$m_s \ll m_h$			$\frac{\lambda_{SH}^2 m_f^2}{64\pi m_h^4}$

- Need large enough coupling for DM annihilation – but constraints from DD
- For light DM – Higgs invisible bound sets lower limit.

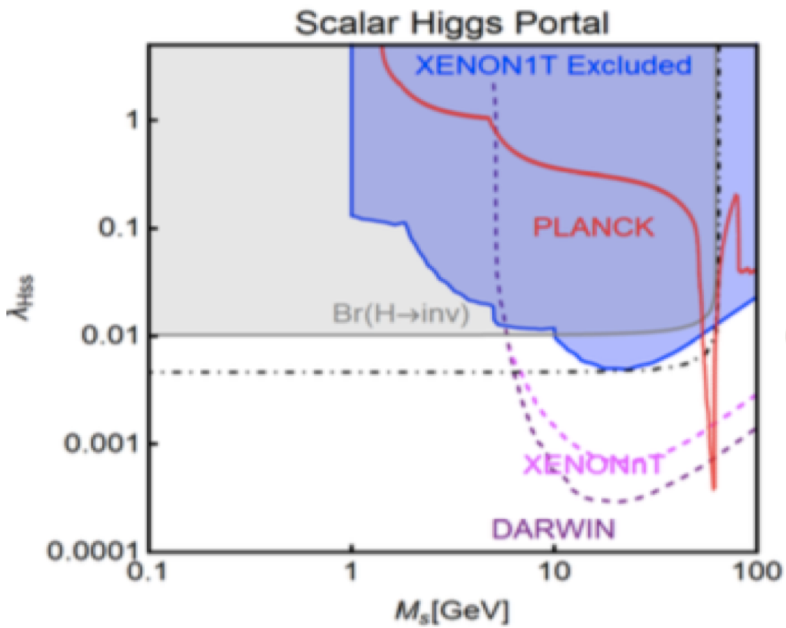
Singlet scalar

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 et al 1112.3299
- Other analyses: P. Athron et al, 1808.10645

Singlet scalar



Arcadi et al, 2101.02507

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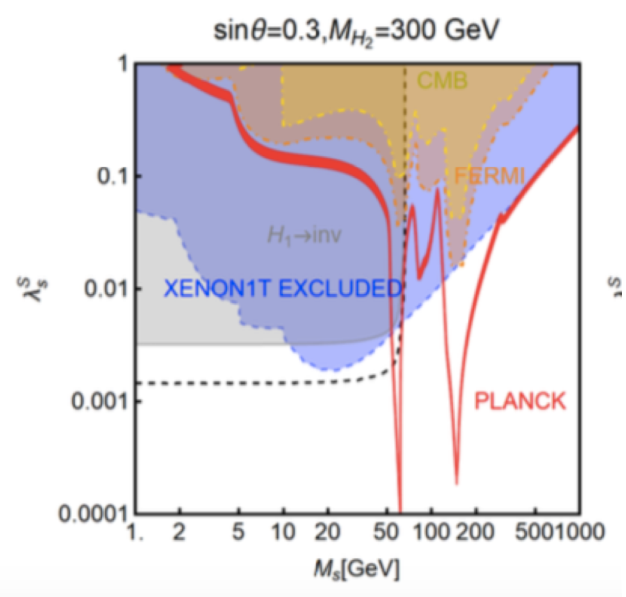
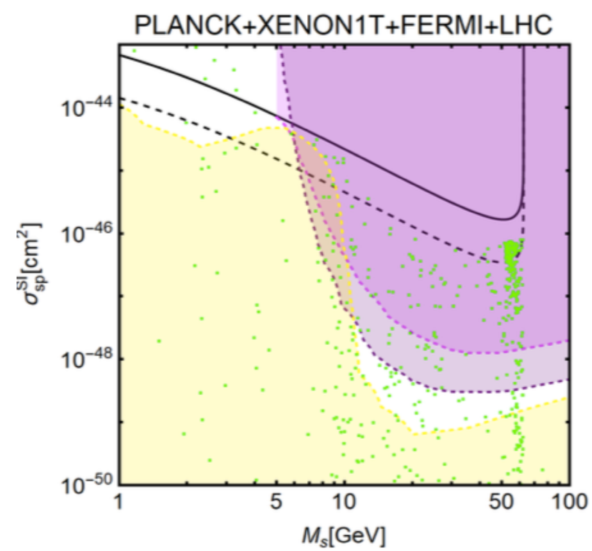
Beyond minimal model

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



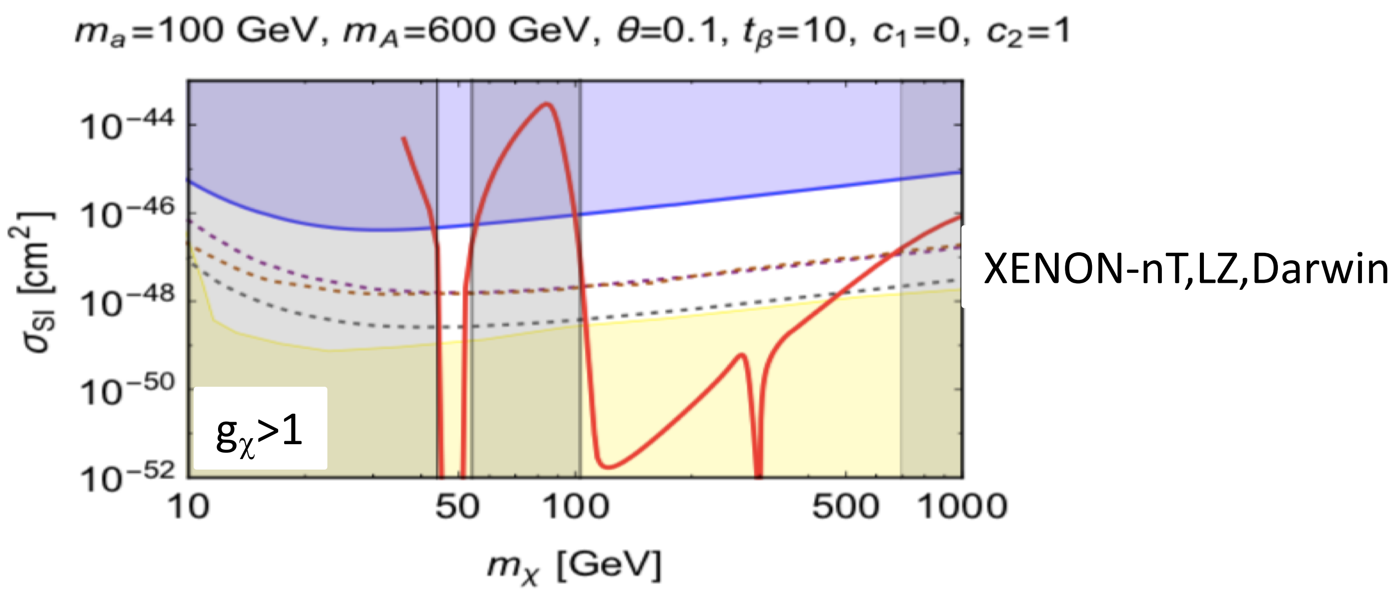


Arcadi et al, 2101.02507

  - 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)

Beyond minimal model

- 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

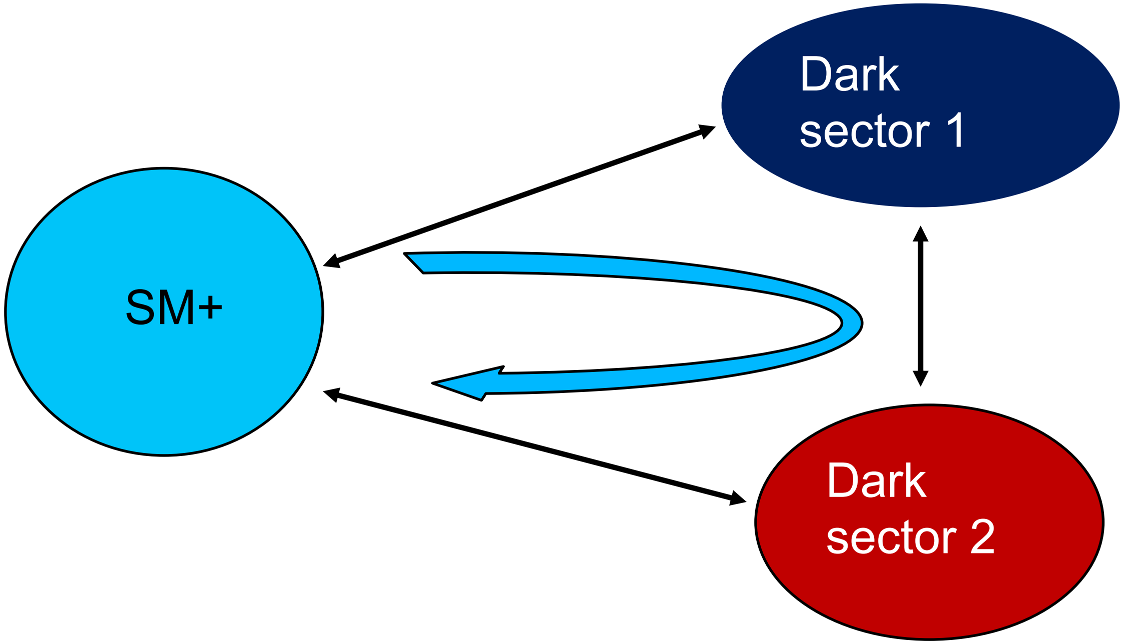


New WIMP DM production

- Other DM production: co-annihilation, semi-annihilation, multiple DM
- Co-annihilation : $\chi\chi'$ -> SM,SM
  - When process more efficient than $\chi\chi$ -> SM,SM increase annihilation -> decrease relic, since co-annihilation has no impact on DD – decorrelate predictions of relic from DD : can have much suppressed DD
- Semi annihilation : processes involving different number of dark particles $\chi\chi$-> χ^* SM (Z_3)
  - Hambye, 0811.0172; D'Eramo, Thaler 1003.5912
  - increase DM annihilation-> decrease relic density

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

Two dark sectors



- In general, interactions between different sectors affect relic
  - 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 : processes involving different number of dark particles 11-> 1*0 (Z_3) or 11->20 (Z_4)

Generalization Boltzmann equation

- Equations for number density

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

$$\frac{dn_2}{dt} = -\sigma_v^{2200}\left(n_2^2-\bar{n}_2^2\right)+\frac{1}{2}\sigma_v^{1120}\left(n_1^2-\bar{n}_1^2\frac{n_2}{\bar{n}_2}\right)-\frac{1}{2}\sigma_v^{1210}\left(n_1n_2-n_1\bar{n}_2\right)$$

$$-\sigma_v^{2211}\left(n_2^2-n_1^2\frac{\bar{n}_2^2}{\bar{n}_1^2}\right)-3Hn_2,$$

  - Details of model, masses couplings determine the importance of semi-annihilation, DM conversion ….
  - Can work both ways : increase or decrease abundance of each DM

Two singlets and Z_5

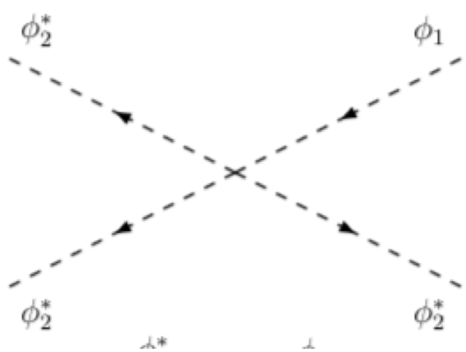
- SM + two complex singlets +Z5 symmetry (GB, Pukhov, Yaguna, Zapata, 2006.14922)

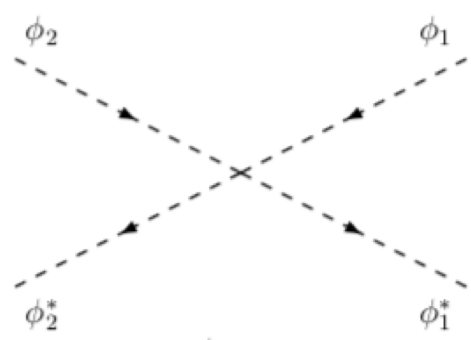
$$\phi_1 \sim \omega_5, \;\; \phi_2 \sim \omega_5^2; \qquad \omega_5 = \exp(i2\pi/5).$$

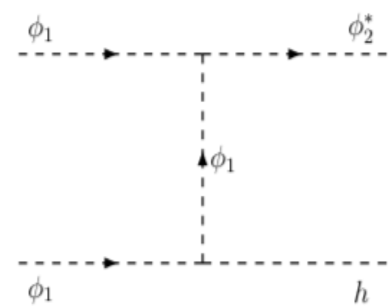
- Potential

$$\mathcal{V} = -\mu_H^2|H|^2 + \lambda_H|H|^4 + \mu_1^2|\phi_1|^2 + \lambda_{41}|\phi_1|^4 + \lambda_{S1}|H|^2|\phi_1|^2 + \mu_2^2|\phi_2|^2 + \lambda_{42}|\phi_2|^4 + \lambda_{S2}|H|^2|\phi_2|^2$$
$$+ \lambda_{412}|\phi_1|^2|\phi_2|^2 + \frac{1}{2}\left[\mu_{S1}\phi_1^2\phi_2^* + \mu_{S2}\phi_2^2\phi_1 + \lambda_{31}\phi_1^3\phi_2 + \lambda_{32}\phi_1\phi_2^{*3} + \text{H.c.}\right], \qquad (2)$$

- With only first line : two separate sectors which couple to SM through Higgs only – similar issues as for singlet scalar model
- DM conversion and semi-annihilation

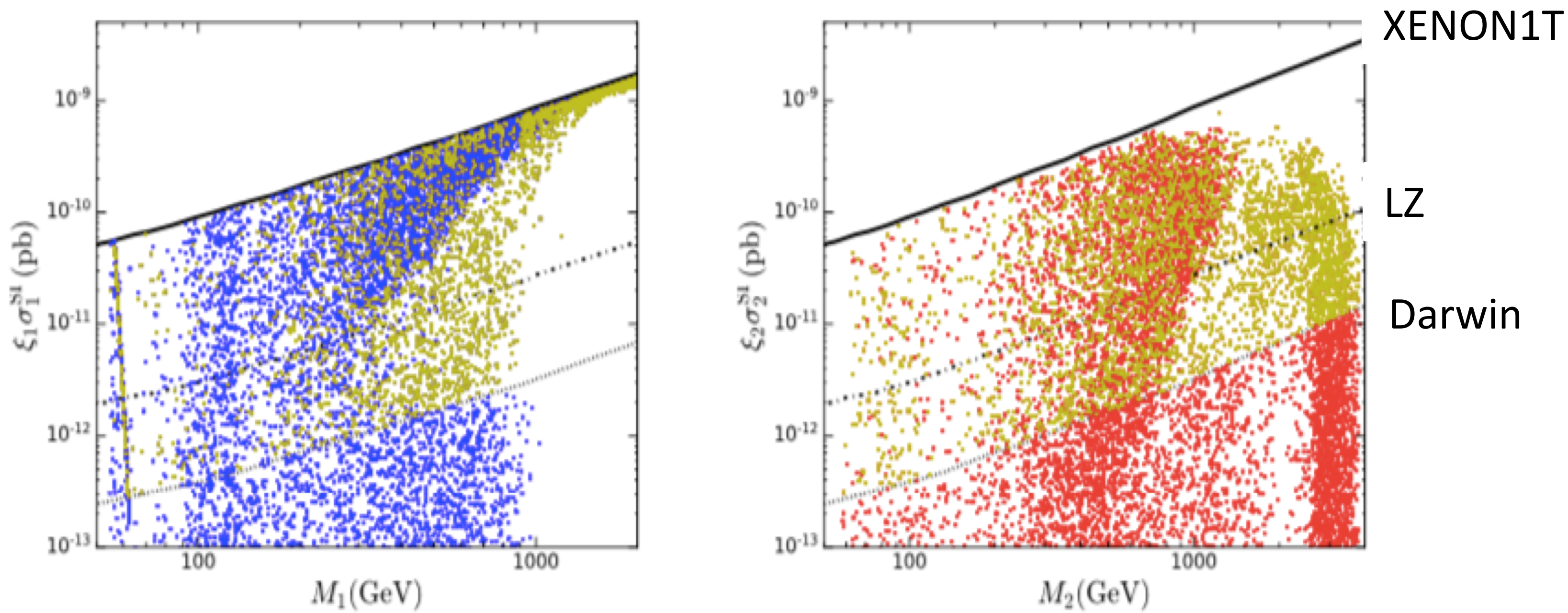






Direct detection

- Rescale sigma SI – with fraction of relic density $\xi_i = \frac{\Omega_i}{\Omega_{DM}} \quad (i = 1, 2),$



- Yellow : both are within reach of future large detectors – even subdominant component (here generally DM2)

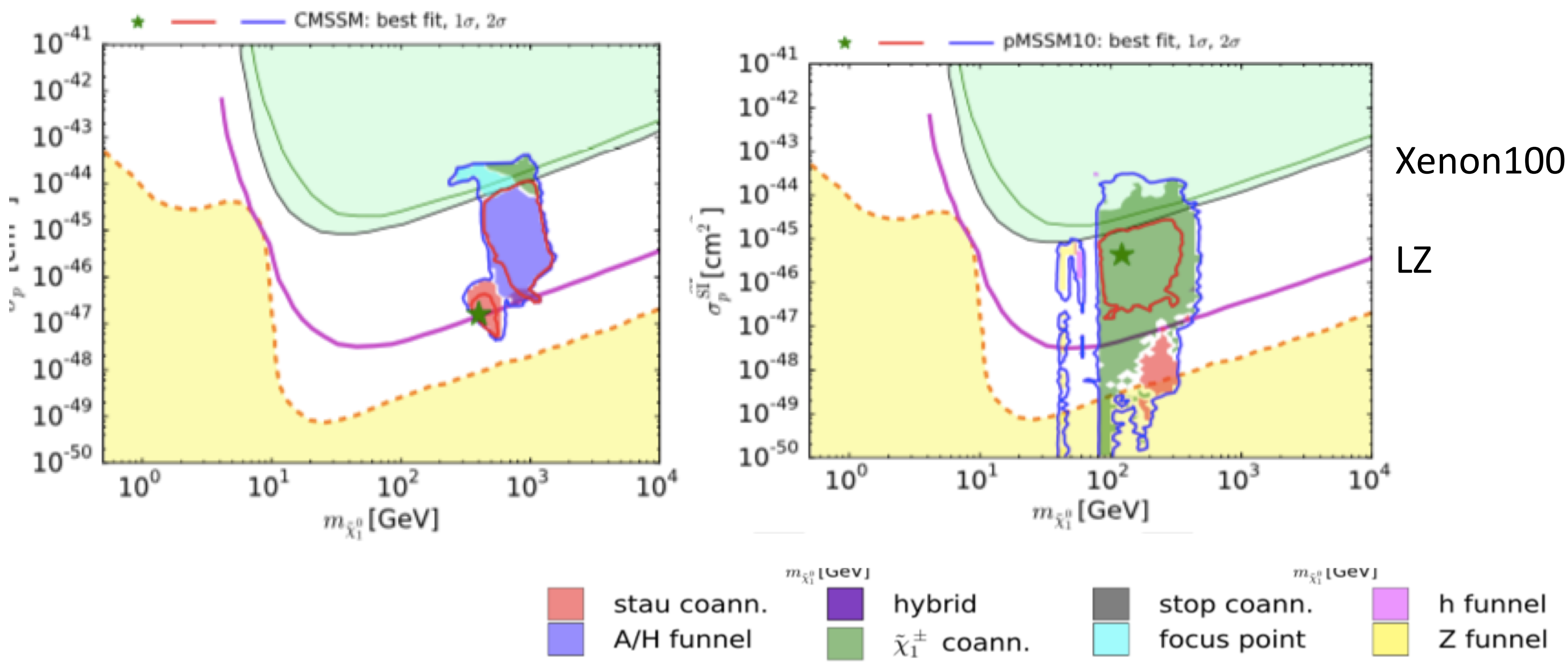
SUSY case

- 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)
- Still some parameter space for neutralino DM in constrained and general MSSM – but what about naturalness/hierarchy : if higgsino is all DM μ >1TeV, if Wino is all DM M_2 >2TeV-> μ, M_1 >2TeV

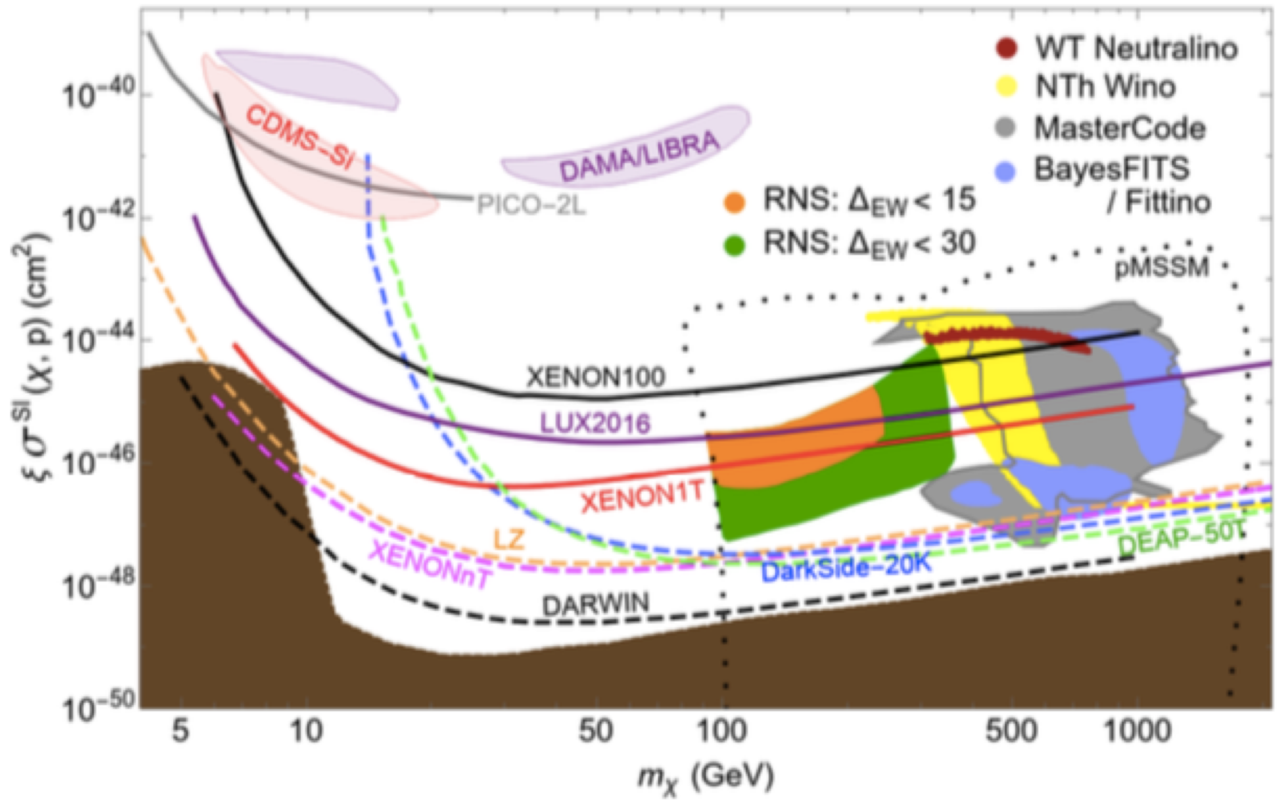
- CMSSM (5 parameters) and pMSSM (10 parameters) after LHCRun1 – MasterCode arXiv: 1508.01173



- DM confined to special regions ‘coannihilation, funnel’

SUSY case

- After Run2, Baer et al 2002.03013

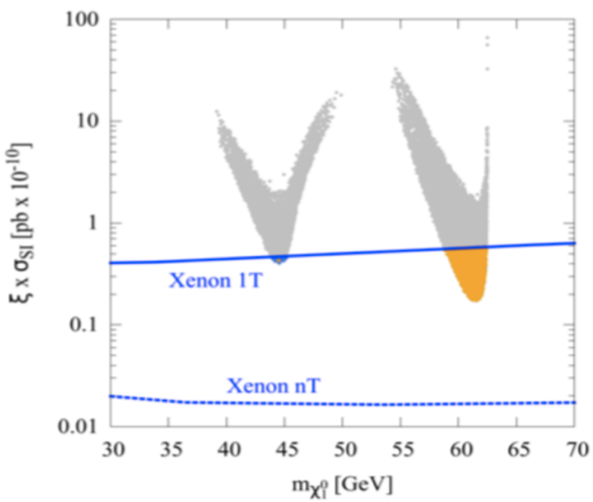


- Mixed bino/higgsino/wino ruled out – CMSSM pushed to higher masses,
- Models with less fine-tuning will be probed by XENON-nT

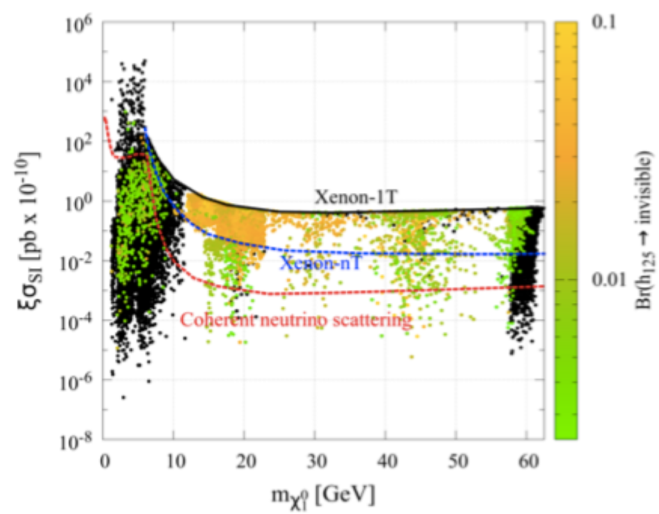
‘Light’ neutralino DM

- 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



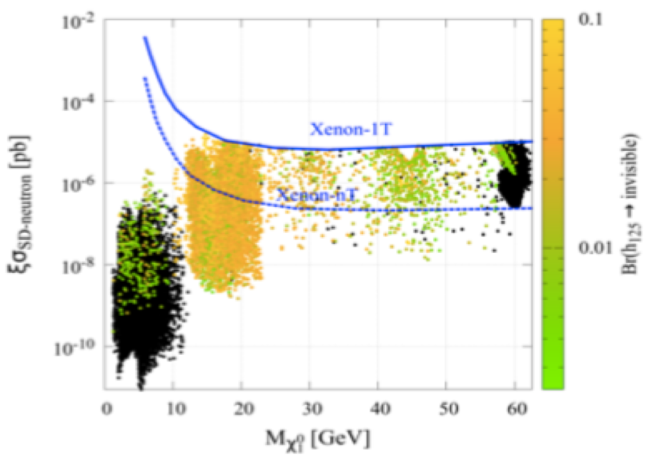
Barman et al 2006.07854

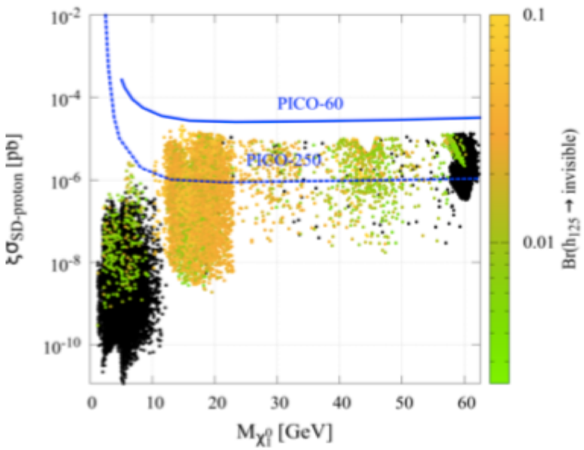


- Adding a singlet/singlino (NMSSM) opens up possibility for neutralino below 10 GeV – new mediators : (pseudo-)scalar singlet

‘Light’ neutralino DM

- SD can offer complementary probes



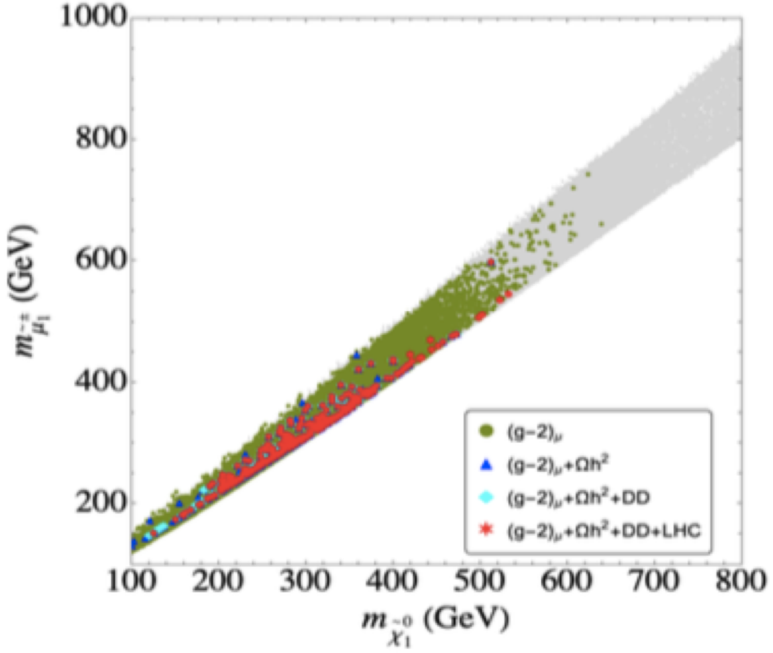


Barman et al 2006.07854

- Can also have a singlet sneutrino as DM as well as axino, gravitino (usually not WIMP)

DM and muon (g-2)

- In general no direct correlation between new physics in g-2 and DM
- In MSSM, compatibility with DM, DD, LHC, g-2, provided sparticles not too heavy – e.g. bino with slepton coannihilation scenario



Chakraborti et al, 2104.03287

Conclusions

- Number of viable DM models is large (even within WIMP paradigm) – not only models motivated by problems with the SM
- The standard neutralino in MSSM still a viable candidate – can be probed to a large extent by DD as well as other WIMP models
- Possible to have WIMPs below 10 GeV - important to cover the low mass region
- WIMPs are not the only possibility … (Talk by Andreas Goudelis)