Dark matter : SUSY and other BSM

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LAPTh Annecy-le-Vieux

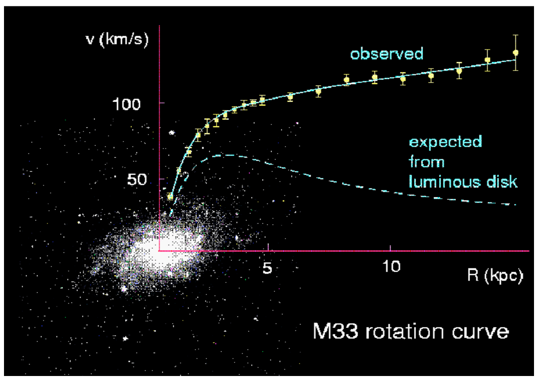
IMHEP2019, Bhubaneshwar, 17/01/19

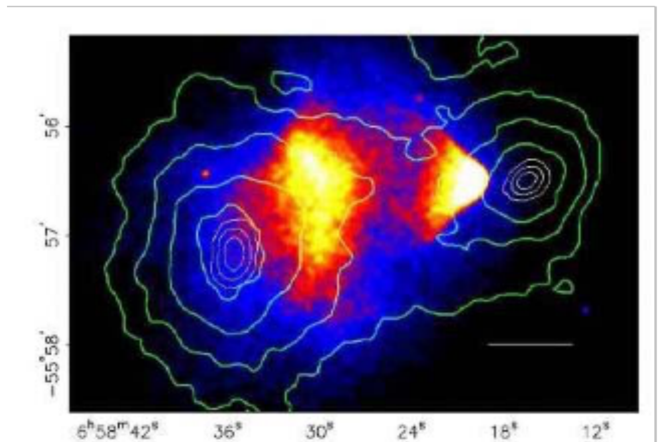
Dark matter postulated in 30’s (Zwicky) – 80 years later we know very little about DM

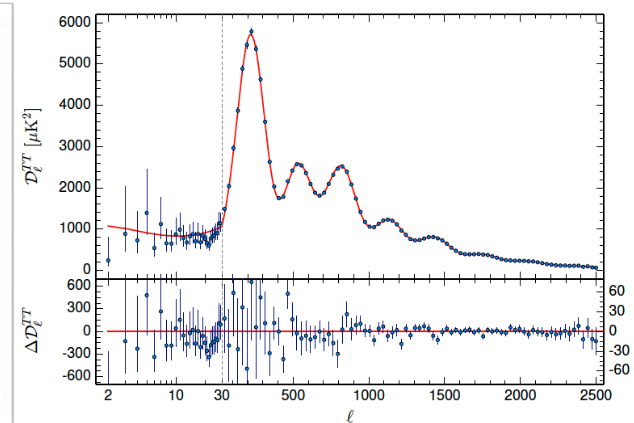
It has gravitational interactions (galaxies – rotation curves- galaxy clusters - Xray, gravitational lensing)

No electromagnetic interactions

It is cold (or maybe warm) and collisionless (or not)







Within ΛCDM model – precisely know DM relic density

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

Leaves us with a lot of possibilities for dark matter

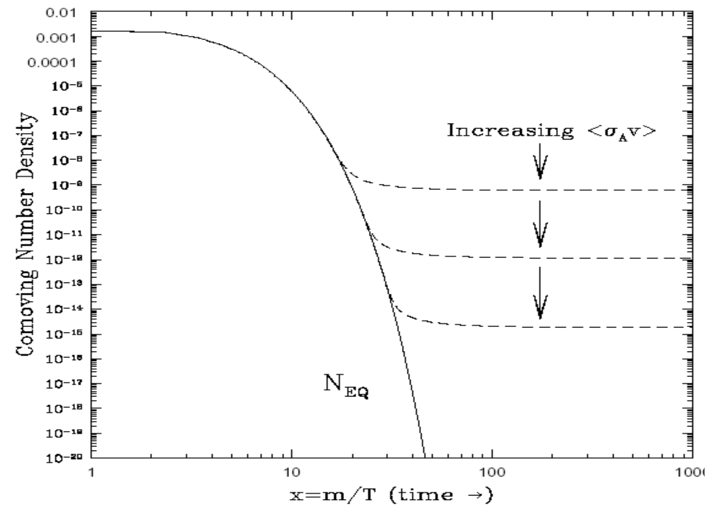
In particular from the particle physics point of view - Cannot be baryons, neutrinos (too hot)

- A new particle? Two DM? Mass scale? Interaction strength? large self-interactions? linked to baryon-antibaryon asymmetry?

- WIMPs – long time favourite : good theoretical motivation, typical annihilation cross-section leads to correct relic density
- WIMPs : elaborate search strategies from astroparticle/cosmo/colliders

WIMPs

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



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

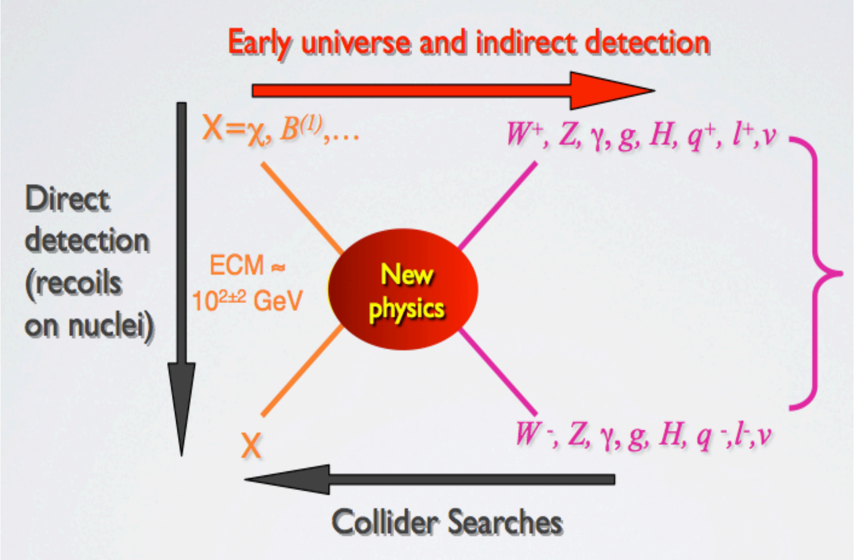
$$\Omega_\chi h^2 \approx \frac{3\times 10^{-27}\mathrm{cm}^3\mathrm{s}^{-1}}{\langle\sigma v\rangle}\ .$$

- Typical weak interaction -> $\Omega h^2 \sim 0.1$
- Also coannihilation when new particles nearly degenerate with DM - Boltzmann suppression exp(-Δm/T) can be compensated by larger cross sections

exp(- ΔM)/T

$$<\sigma v>= \frac{\sum_{i,j} g_i g_j \int_{(m_i+m_j)^2} ds\sqrt{s}K_1(\sqrt{s}/T)p_{ij}^2\sigma_{ij}(s)}{2T\left(\sum_i g_i m_i^2 K_2(m_i/T)\right)^2}$$

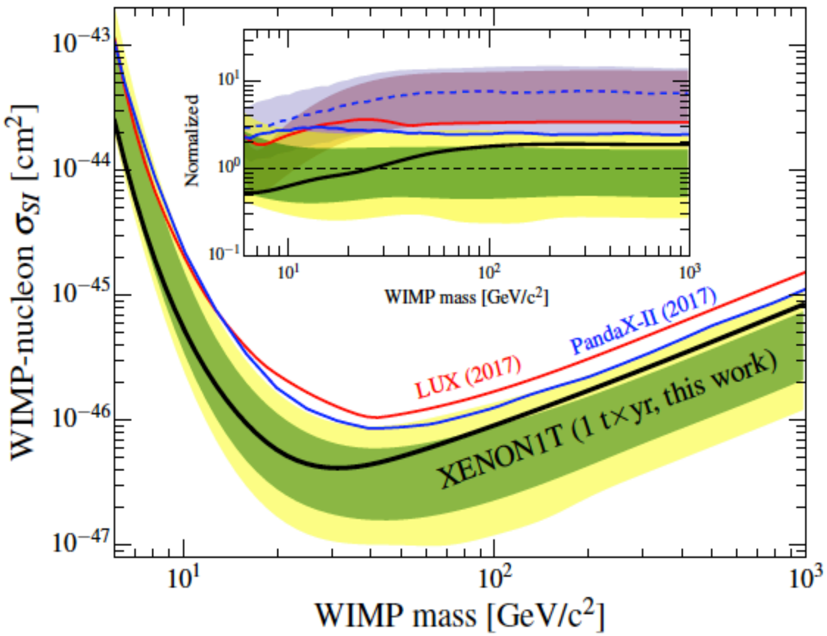
WIMP search strategies



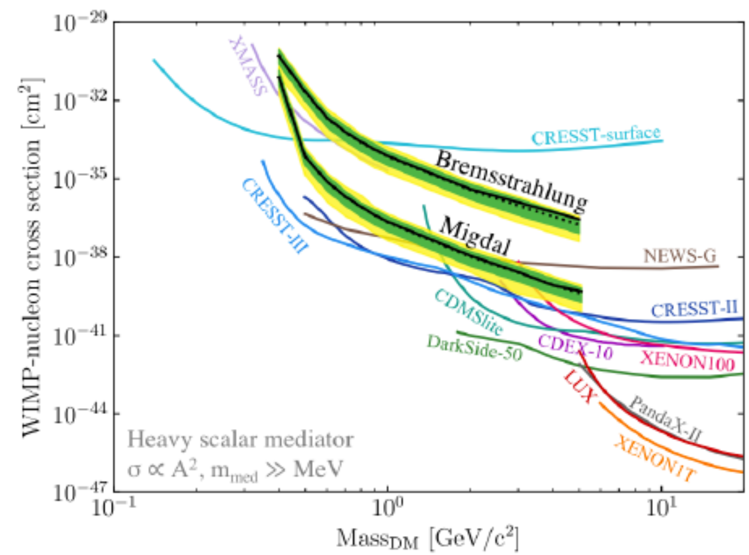
- All determined by interactions of WIMPs with standard model – specified by particle physics
- Several recent results :
  - LHC has finished Run2 – most analyses with fraction of total luminosity available
  - New limits from direct and Indirect detection

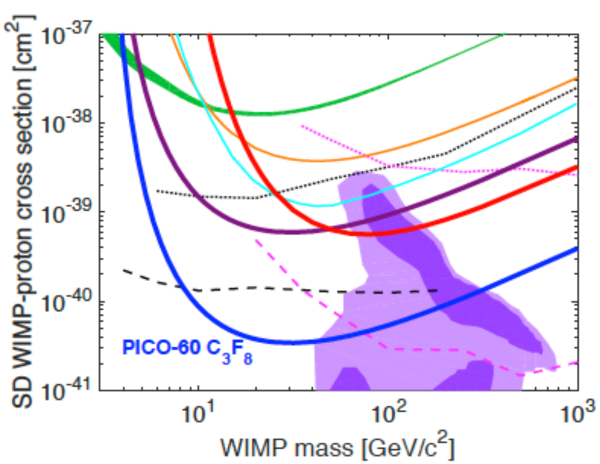
But no signatures of WIMPs

Xenon, Aprile et al, 1805.12562



LUX2013, Akerib et al , 1811.11241



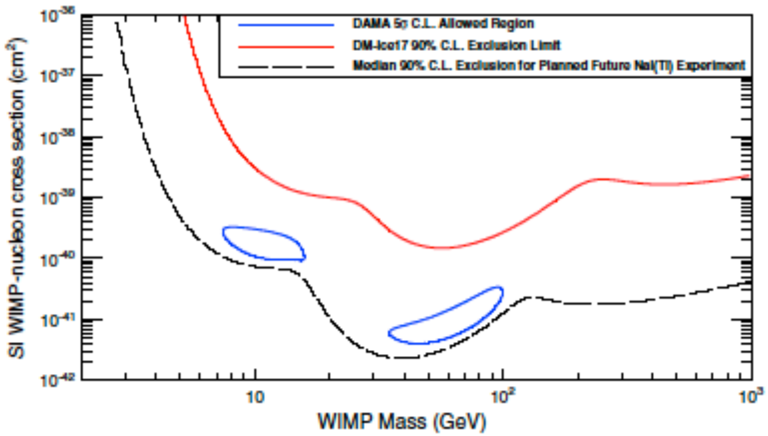


PICO, Amole et al, 1702.07666

- Improved limits in 2018 from direct detection (Xenon1T) and at low masses (DarkSide, CRESST, CDMSlite, LUX)
- Bremmstrahlung (Kouvaris, Pradler, 1607.01789) and Migdal effect (Ibe et al 1707.07258) extend reach at low mass

Annual modulation?

- Direct detection : DAMA long standing excess in annual modulation – incompatible with other direct searches — DM annual mod signal independent of location (seasonal variation opposite in phase)
- DM-Ice17 first run in South pole - no modulation observe



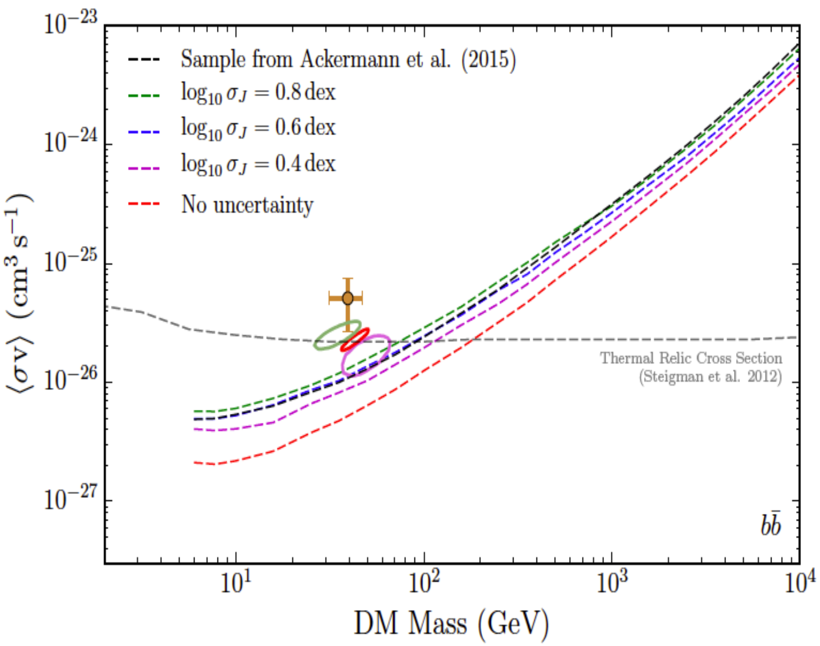
DM-Ice: Barbosa de Souza, PRD95 032006 (2017)

- Cosine100 published their first results recently, *Nature* **564**, 83–86 (2018) – exclude DAMA region – data taking is continuing.
- ANAIS, PICO-LON and SABRE all using NaI
- Will ignore this excess in the following

Indirect detection -photons

Continuum

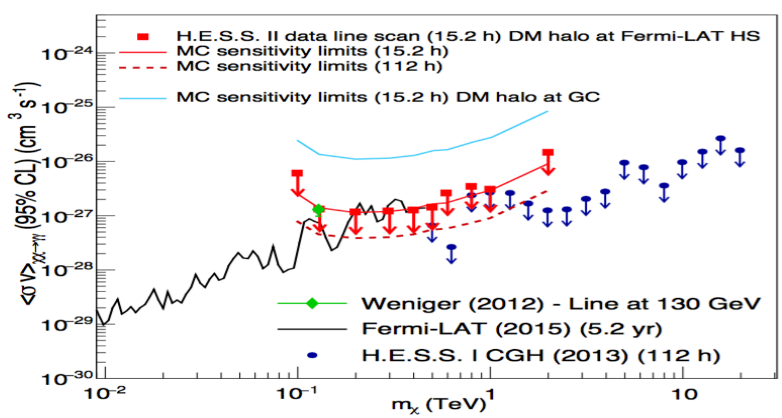
Fermi-LAT limit from dSPhs 1611.03184



$$\times \underbrace{\int_{\Delta\Omega}\int_{\text{l.o.s.}} \rho^2_{\text{DM}}(\boldsymbol{r}(l))\mathrm{d}l\mathrm{d}\Omega}_{\text{J-factor}},$$

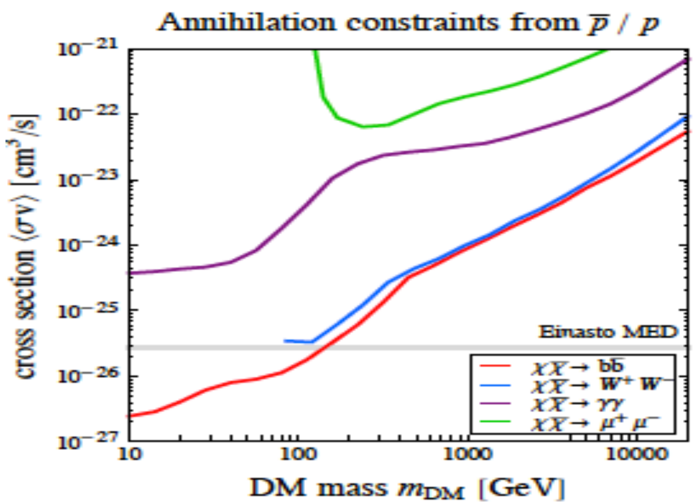
- FermiLAT (+DES) limits from Dwarf galaxies on DM
- Probe thermal cross-sections
- Excess from Galactic Center – could be due to DM or astro sources (millisec-pulsars, Abazajian, 1011.4275)
  - Gordon&Macias2013,Daylan et al 2016, Abazajian et al 2014, Calore et al, 2015.
- Limits on γ-ray lines

HESS, 1609.08091

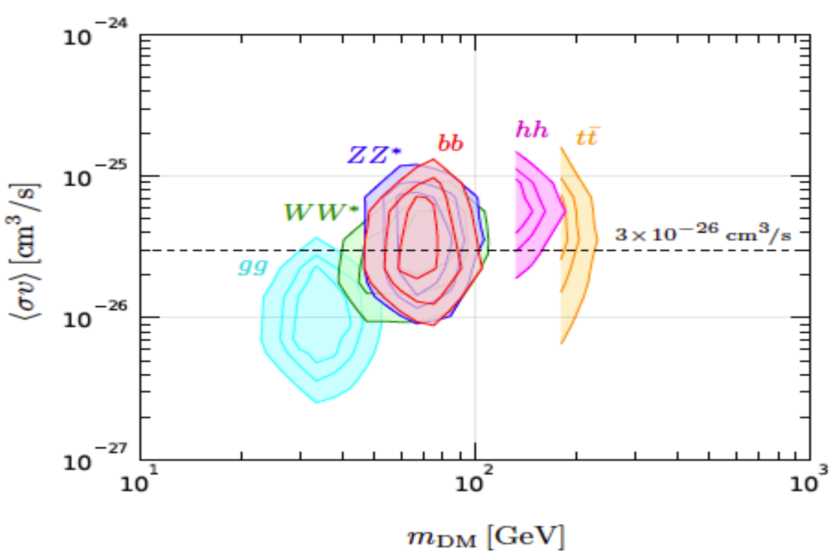


Indirect detection

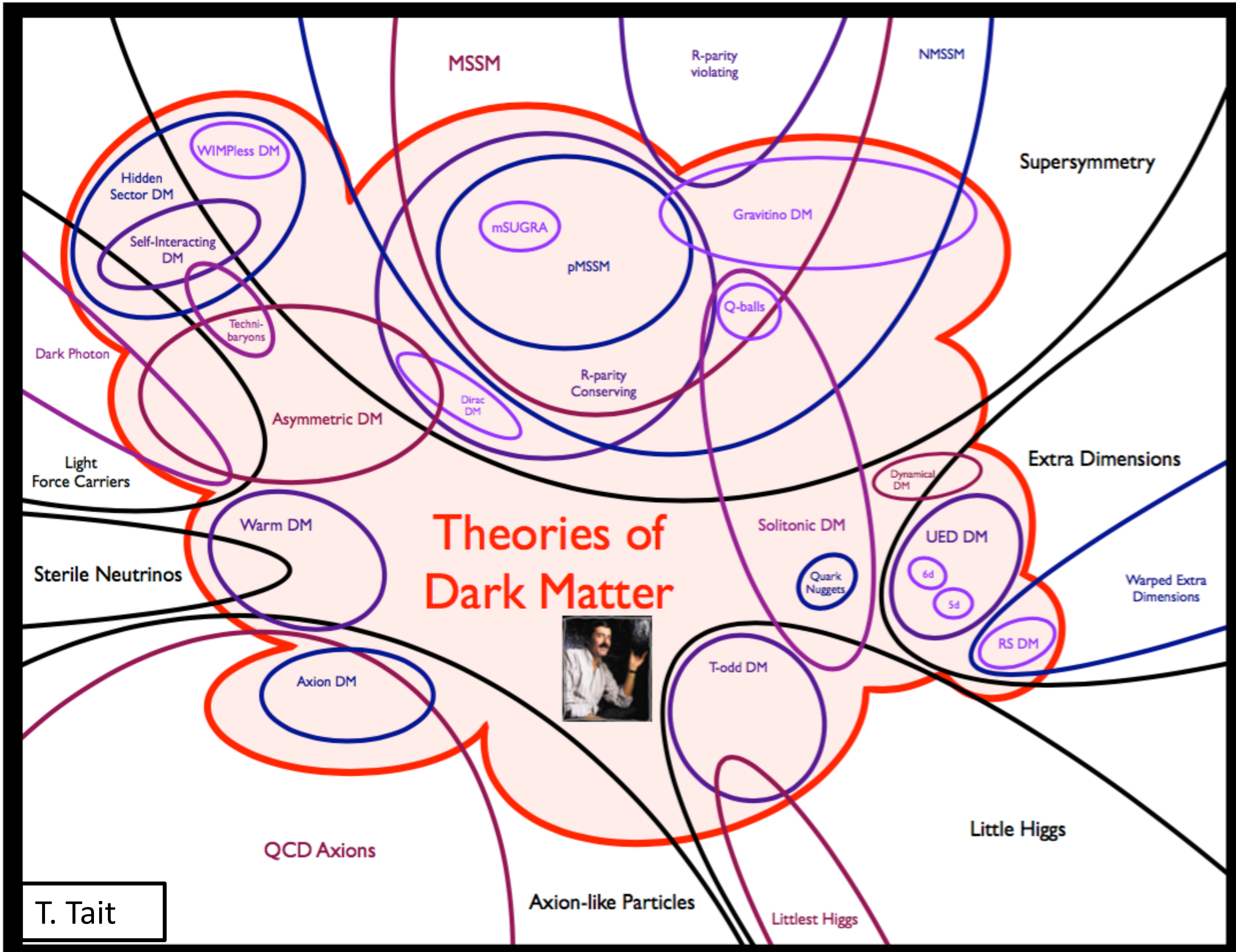
Giesen et al, 1504.04276



- Antiproton data from AMS02 - strong constraints on light DM – dependent on CR propagation model and parameter



- Some groups find improved fit with DM – simultaneous fit to CR propagation and DM – compatible with GC γ excess
  - Cuoco, Kraemer, Korsmaier 1610.03071
  - Cuoco, Heisig, Korsmaier, Kraemer, 1704.08258


MSSM
R-parity
violating
NMSSM
Supersymmetry
WIMPless DM
Hidden
Sector DM
Self-Interacting
DM
Techni-
baryons
mSUGRA
pMSSM
Gravitino DM
Q-balls
Dark Photon
Asymmetric DM
Dirac
DM
R-parity
Conserving
Light
Force Carriers
Dynamical
DM
Extra Dimensions
Warm DM
Theories of
Dark Matter
Solitonic DM
UED DM
Sterile Neutrinos
Quark
Nuggets
6d
5d
Warped Extra
Dimensions
RS DM
Axion DM
T-odd DM
Little Higgs
QCD Axions
Axion-like Particles
Littlest Higgs
T. Tait

Theory -> Pheno

- Many theoretical models for DM
- Based on non-observation of new coloured particles at LHC : can concentrate on simple ‘dark sectors’, phenomenologically all models – to rough approximation – boil down to nature of dark matter, spin, SU(2) properties

$SU(2)_L$	Majorana fermion	Dirac fermion	Scalar	Vector
Singlet	bino	singlet	Real singlet	U(1)’, SU(2)’, SU(N)’
Doublet	higgsino	doublet	Inert doublet	doublet
Triplet	wino	…	Scalar triplet	
Quintuplet	Minimal DM			

- + all possible mixed states (eg well-tempered neutralino)

Supersymmetric dark matter

- Leading candidate for WIMPs since 80's : neutralino Weinberg, PRL50 (1983) 387, Goldberg PRL50 (1983) 1419, Ellis et al, NPB238 (83) 453
- Strong theoretical motivation for supersymmetry: unification, hierarchy
- R parity needed to avoid proton decay predicts a stable LSP –if neutral then good WIMP candidate *«Dark matter comes for free »*
- Strategies to search for SUSY DM: colliders (LEP, Tevatron, LHC), direct detection, indirect detection - good for any WIMP
- Were expecting lots of new particles at TeV scale as soon as LHC turned on - but no excess!!
  - Can neutralino explain all DM? How to further probe?
  - Consider pMSSM without assumptions about underlying high scale model.
  - Generalise to extensions of MSSM and to other supersymmetric candidates

Neutralino : basics

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

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

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

Determine couplings of neutralino to vector bosons, scalars… hence annihilation properties, relic density etc..

When neutralino is mixed state : wide range of predictions each with preferred search strategy

Neutralino DM

Many free parameters in SUSY – only a few are directly connected with neutralino sector

μ, M_1, M_2 $\tan\beta$

To illustrate main constraints on neutralino DM first make simplifying assumption : keep only these 4 parameters, set all other SUSY parameters to 4TeV

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

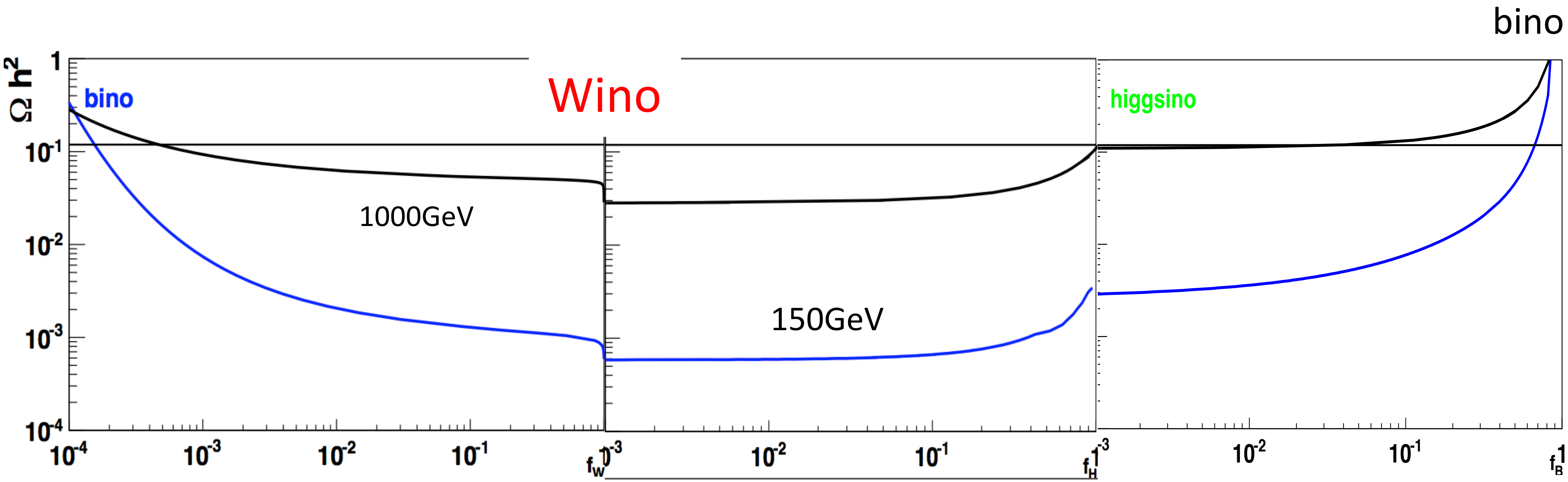
$$g_{h\chi\chi} = g(\mathcal{N}_{\chi 2} - t_W \mathcal{N}_{\chi 1})(\mathcal{N}_{\chi 3} \sin\alpha + \mathcal{N}_{\chi 4} \cos\alpha) .$$

gaugino Higgsino

- Coupling of bino (through U(1)) to sfermion-fermion
- Wino or higgsino efficient annihilation in WW

Neutralino DM

Vary μ, M_1, M_2 to change nature of LSP, tanβ = 10, all other SUSY parameters set to 4TeV



In general neutralino LSP can only be subdominant DM component unless TeV scale for higgsino and 2.8TeV for wino

Exception : bino overdominant

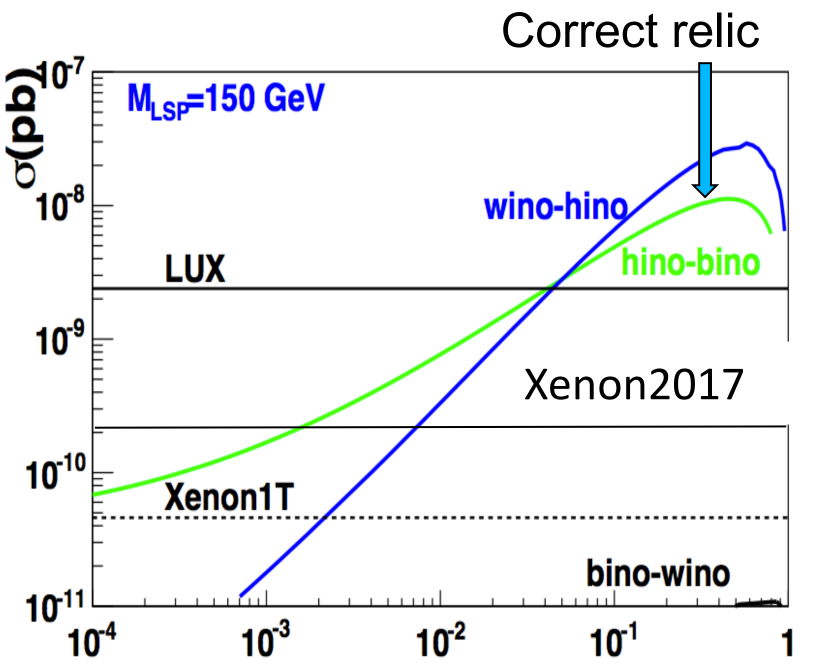
Higgsino and wino entail degenerate particles

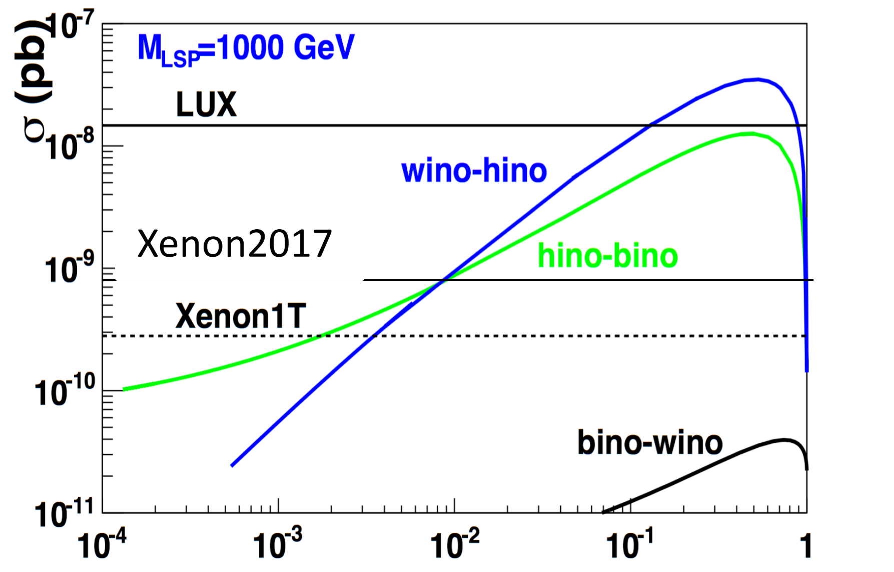
μ at TeV scale is not natural from Higgs points of view

Direct detection

- Dominate by LSP coupling to Higgs (squarks are heavy/subdominant) - maximal for mixed gaugino/higgsino

Xenon1T probes large regions of parameter space

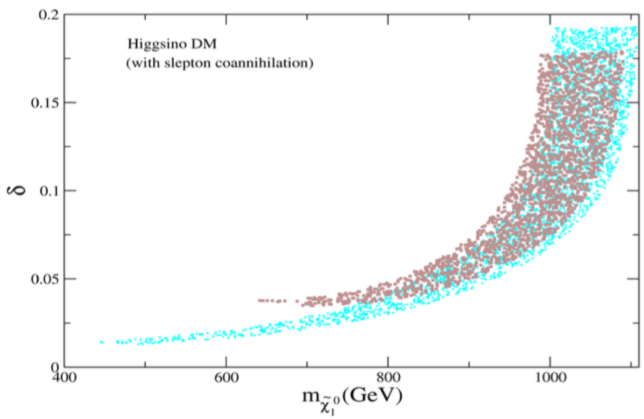




Strong constraints from on neutralinos (mixed higgsino-bino) that reproduce measured relic density
Bino-wino escape detection – also TeV scale DM

Planck+Direct detection

- Neutralino more likely subdominant DM unless TeV scale OR bino/wino
- Loopholes?
  - Enhanced annihilation via s-channel resonance, h,H (for $m\chi \sim m_{h,H}/2$)
  - Co-annihilation with nearly degenerate sparticle
    - Sfermion degeneracy: Decrease (bino) or increase Ωh^2 (higgsino/wino)



Lighter higgsino compatible PLANCK

M. Chakraborti et al, 1702.03954

  - Blind spots in direct detection : for $\mu < 0$, cancellation h,H (Cheung et al 1211.4873, Huang, Wagner, 1404.0392) occur also for $\mu > 0$ in generic extension of MSSM (GB, Delaunay,Goudelis, 1412.1833)
  - Cosmology: DM production in late time decay of some heavier specie (moduli, inflaton) or increase expansion rate of Universe before DM freeze-out

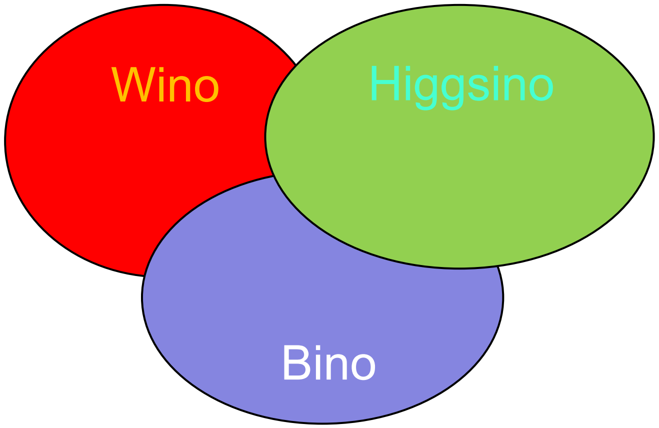
Neutralino DM after LHC and Xenon1T

Amazing results from LHC and from DD (PandaX,Xenon,Pico)
Coverage of neutralino DM scenario?

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

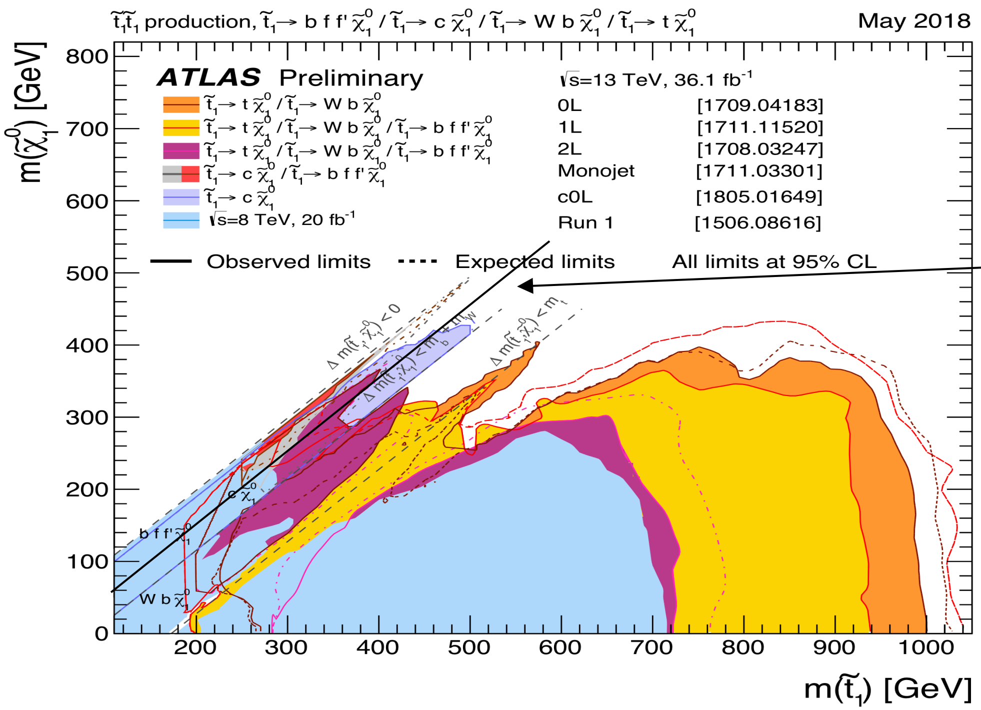
Neutralino DM at LHC

- Strong constraints on coloured sparticles ~2TeV means that must rely on searches through electroweakino production (production largest for wino)
- Other relevant searches
  - Search for invisible decays of the Higgs (relevant only if $m_\chi < m_h/2$)
  - Charged tracks and displaced vertices - for long-lived NLSP : typically small mass splitting (wino, higgsino)
  - Search for new particle in SM final states (heavy Higgs)
  - Monojet (not important for SUSY except compressed spectra)



Bino : coannihilation

- Stop important for DM if contribute to coannihilation - typical mass splitting ~40 GeV → mχ>~420GeV

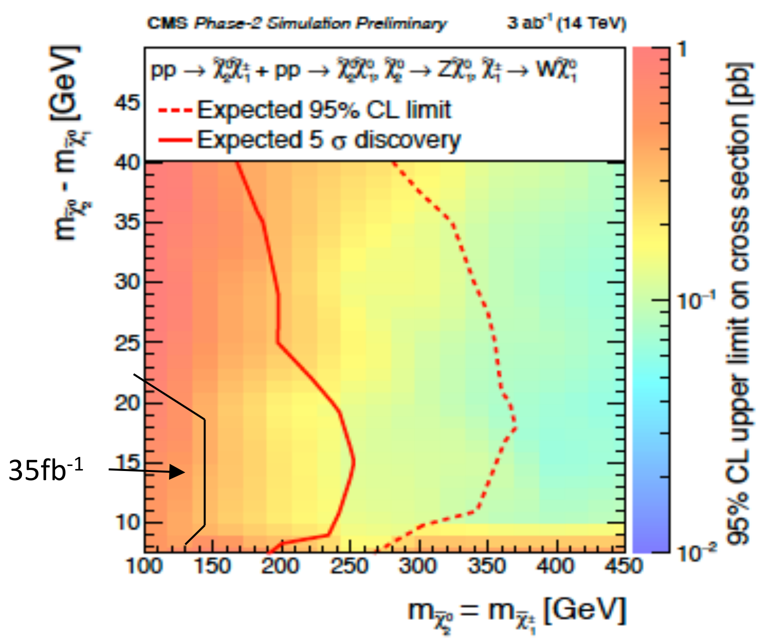


~Δm required
for correct relic
for bino+stop coann

- This exploits both stop decay into 4-body and flavour-changing decay

Doublet (Higgsino)

- Recall that relic requires TeV scale to explain DM
- pure higgsino : small mass splitting
  - ISR jet +low transverse momentum leptons (SFOS) + MET (smaller cross section than for wino)

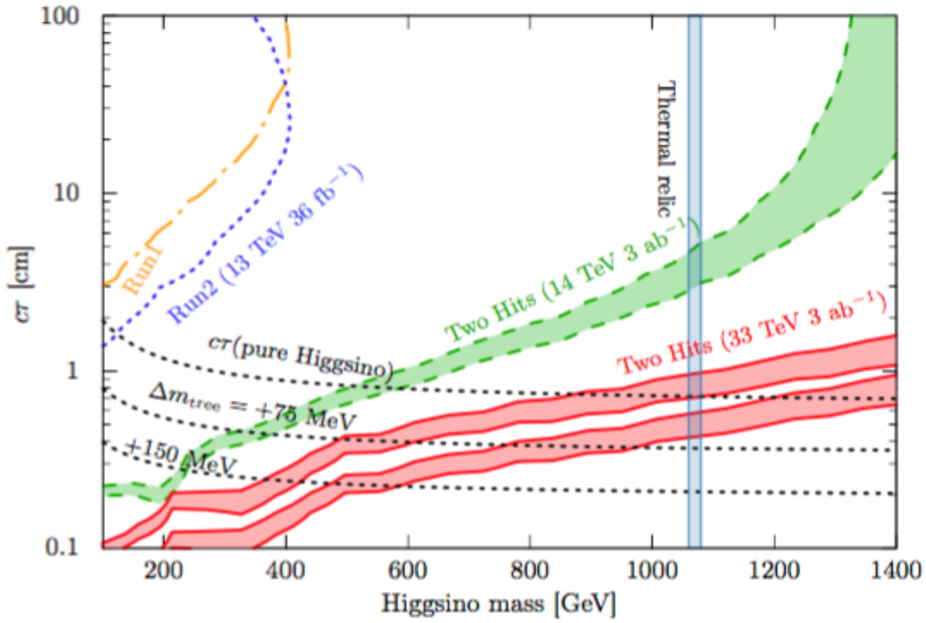


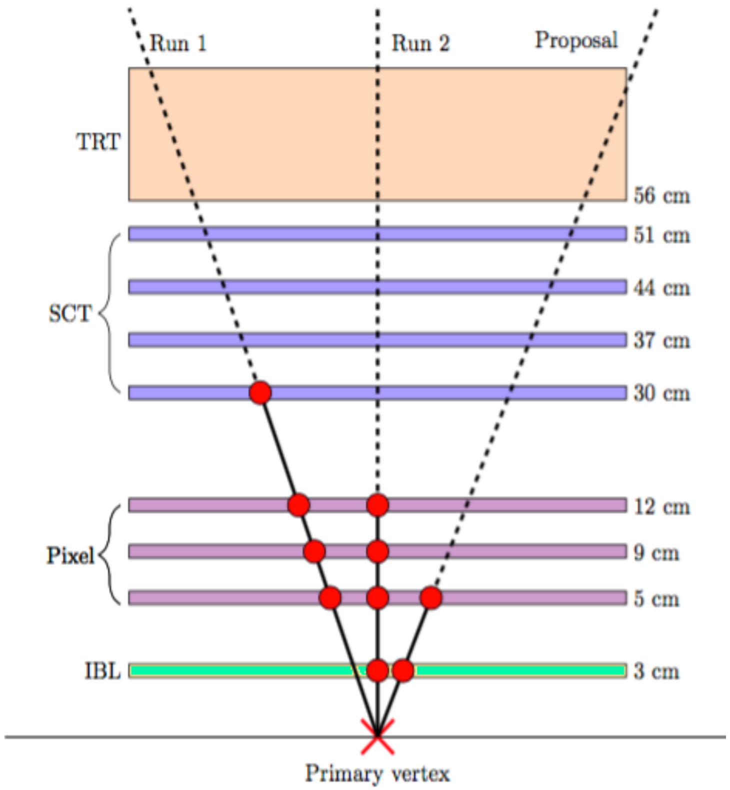
A long way from covering DM favoured region (Even allowing sfermion coannihilation) which requires m>600GeV

CMS PAS FTR 18001

Higgsino DM

- Suggestion : higgsino have decay length ~ 1cm, require only two-hits in pixel detector
- Significant increase in sensitivity – possibility to probe 1 TeV higgsino

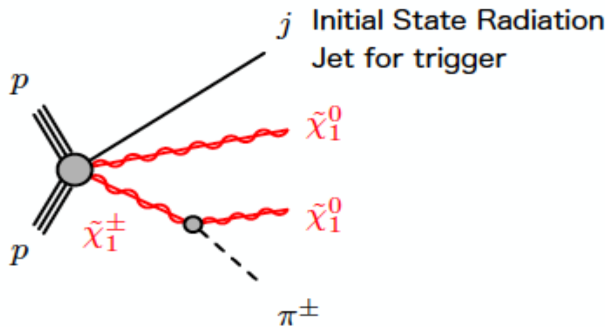


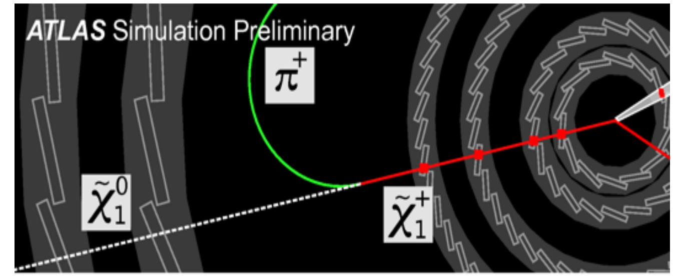


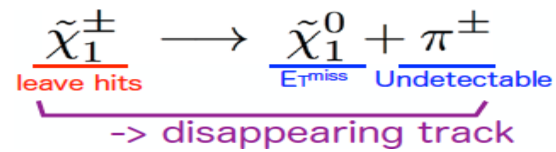
H. Fukuda et al 1703.09675

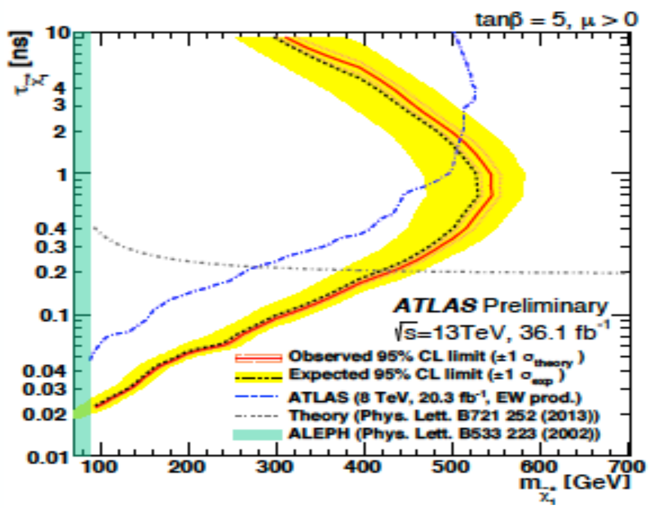
Triplet: wino case

- Long-lived (chargino lifetime .15-.25 ns)

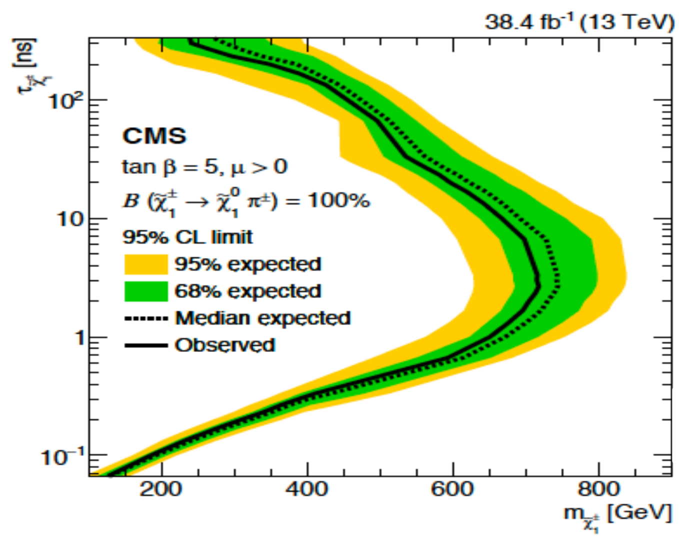








T. Kaji, Moriond 2017

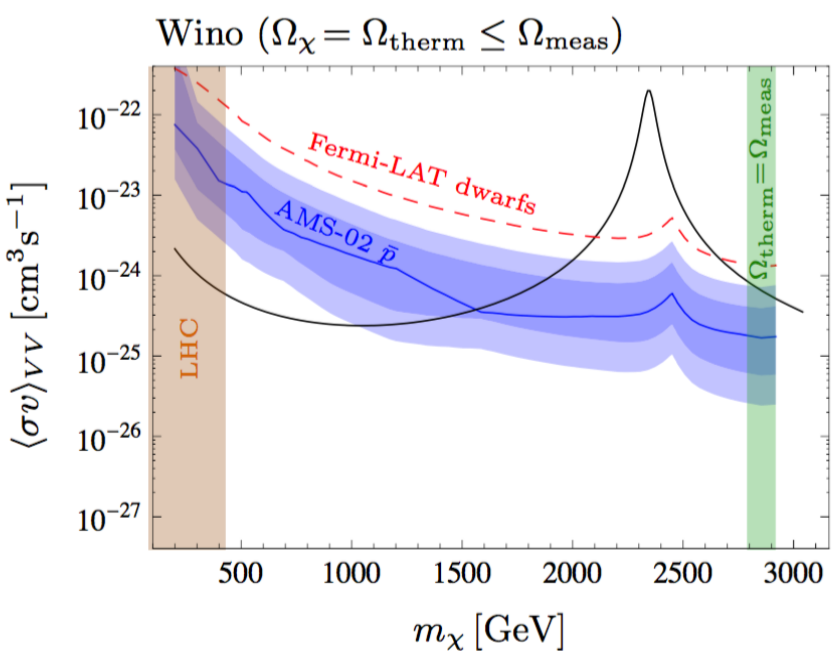


1804.07321

m>430GeV -> far from covering relevant DM region

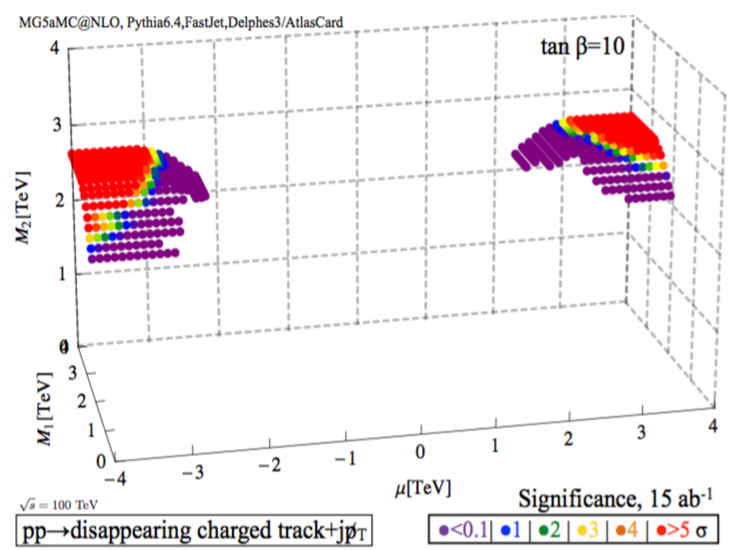
Triplet (wino)

- Indirect detection (AMS antiproton) constrain thermal wino - include Sommerfeld enhancement



Cuoco et al, 1711.05274

See also Beneke et al, 1611.00804

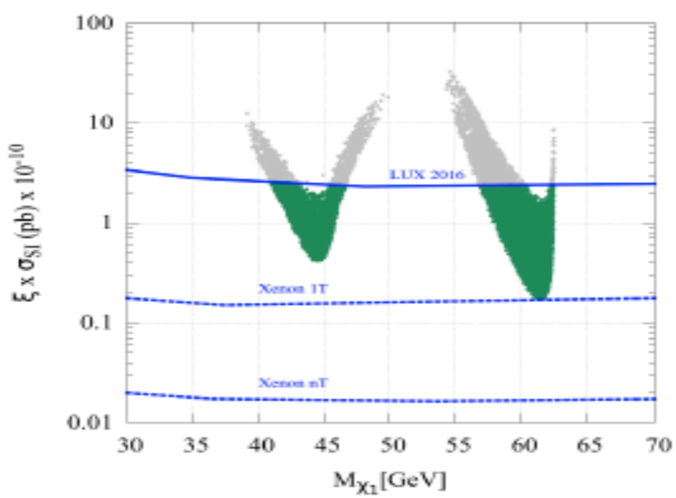


100TeV collider 15ab^{-1} cover most of wino DM

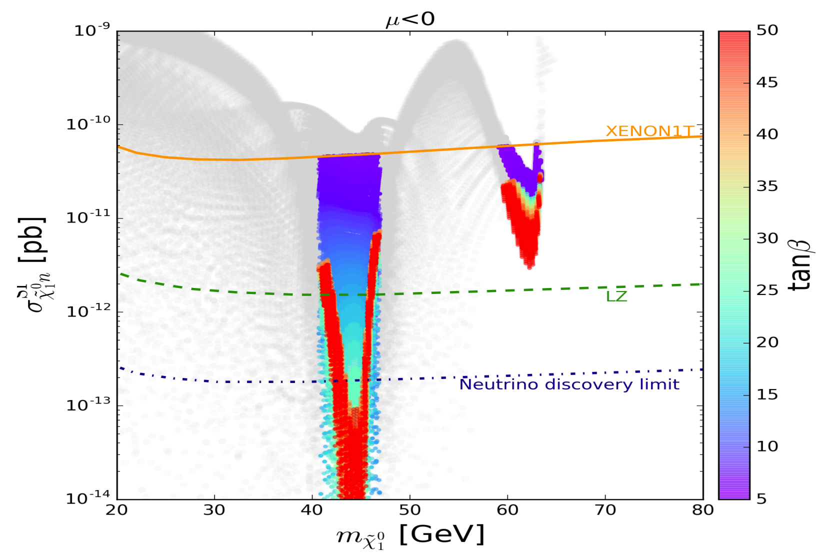
Bramante et al, 1510.03560

The light bino (+ higgsino)

- If neutralino DM light (<62GeV) – must be dominantly bino with some higgsino component (relic)→ contributes to invisible Higgs width
- After constraints from relic density (upper limit), Higgs (Brinv<24%), searches for chargino/neutralino, flavour +LEP : light bino (μ>0) will be completely probe in ongoing direct detection searches (Xenon1T) and almost completely by SD (μ<0)



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



Pozzo, Zhang, 1807.01476

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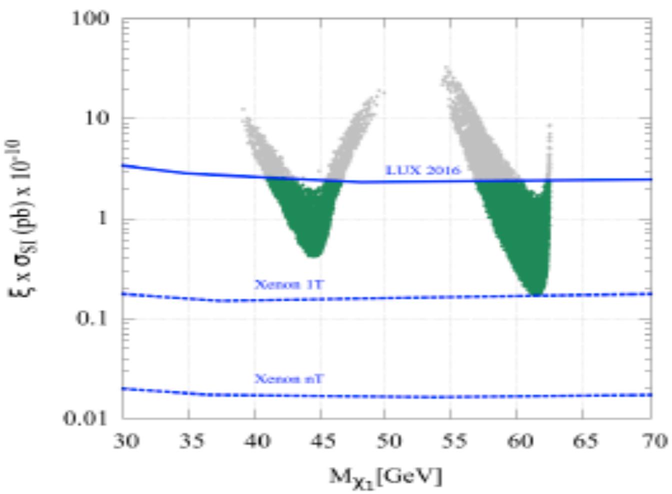
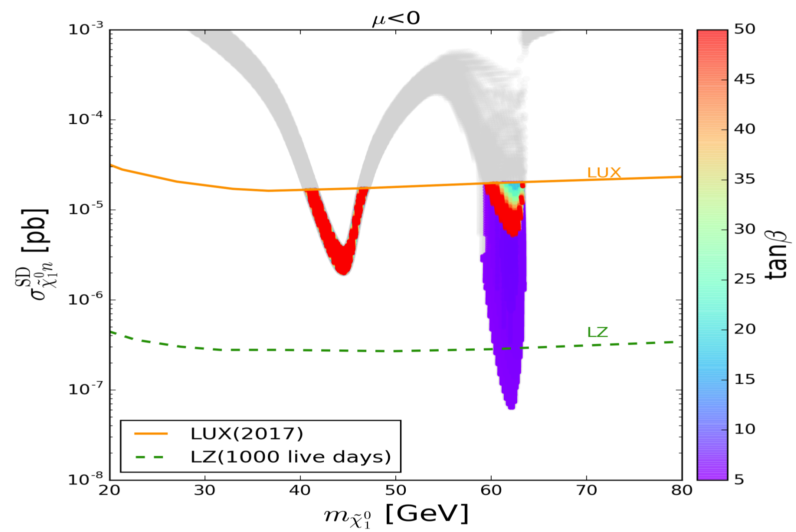




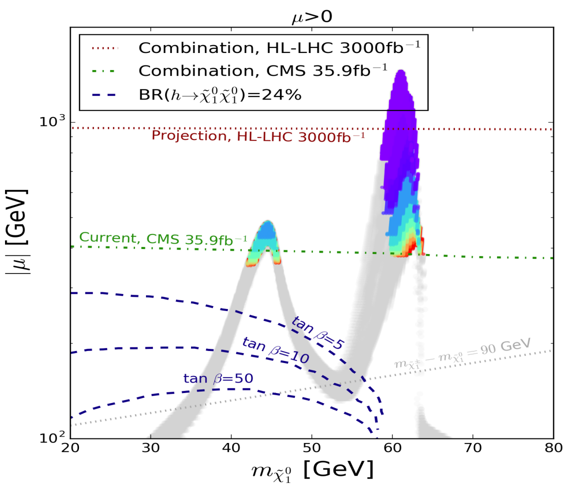
Barman, GB, Bhattacherjee, Godbole, Mendiratta, Sengupta, 1703.03838

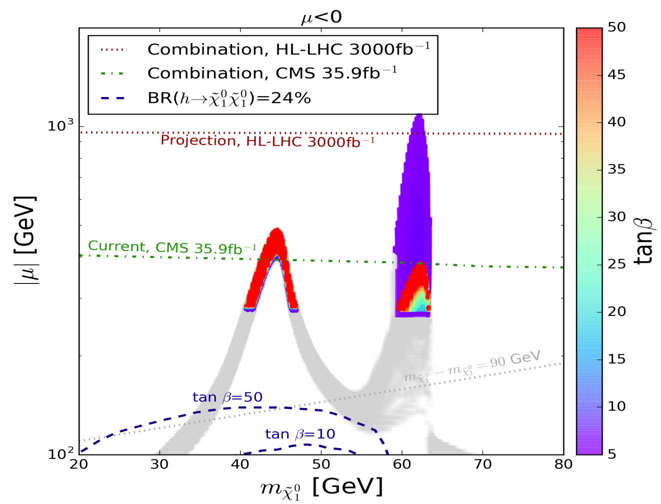
Pozzo, Zhang, 1807.01476

Complementarity with LHC

- Resonance region also probed by current electroweakino searches (36fb^{-1}) – see also Han et al, 1612.02387
  - 3leptons $pp \to \tilde{\chi}_1^{\pm}\tilde{\chi}_2^0 \to W^{\pm}Z\tilde{\chi}_1^0\tilde{\chi}_1^0 \to \ell\ell\nu\ell\tilde{\chi}_1^0\tilde{\chi}_1^0$
  - 2lep-on Z : (2OSSF reconstructing Z mass) + 2 non-b tagged jets+MET
    $$pp \to \tilde{\chi}_1^{\pm}\tilde{\chi}_2^0 \to ZW^{\pm}\tilde{\chi}_1^0\tilde{\chi}_1^0 \to \ell\ell jj\tilde{\chi}_1^0\tilde{\chi}_1^0$$
  - 1lep-2b : $pp \to \tilde{\chi}_1^{\pm}\tilde{\chi}_2^0 \to hW^{\pm}\tilde{\chi}_1^0\tilde{\chi}_1^0 \to b\bar{b}\nu\ell\tilde{\chi}_1^0\tilde{\chi}_1^0$

Pozzo,Zhang, 1807.01476

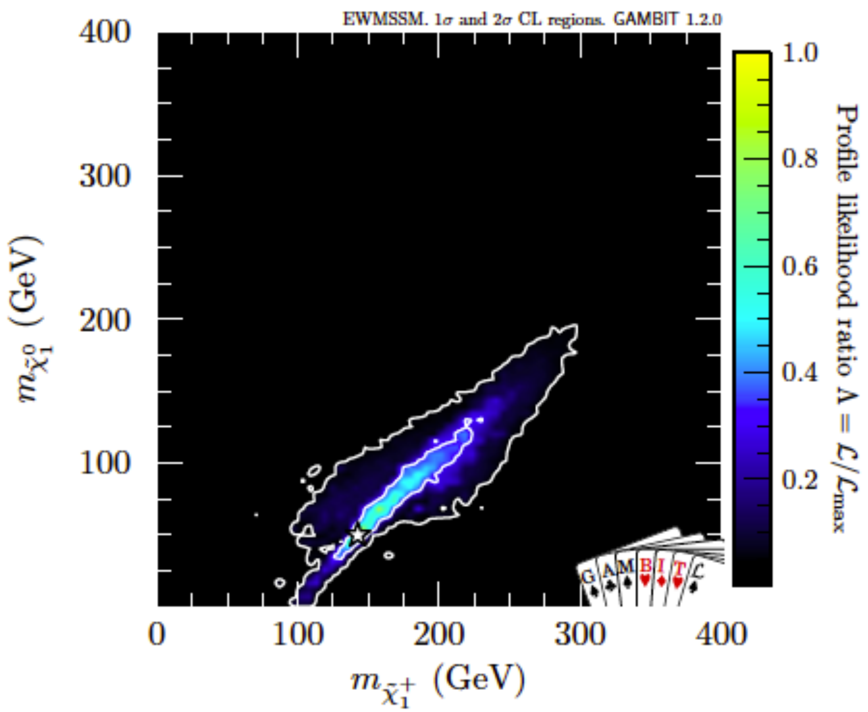




- Most Z funnel already probed – Higgs funnel largely within reach of HL-LHC

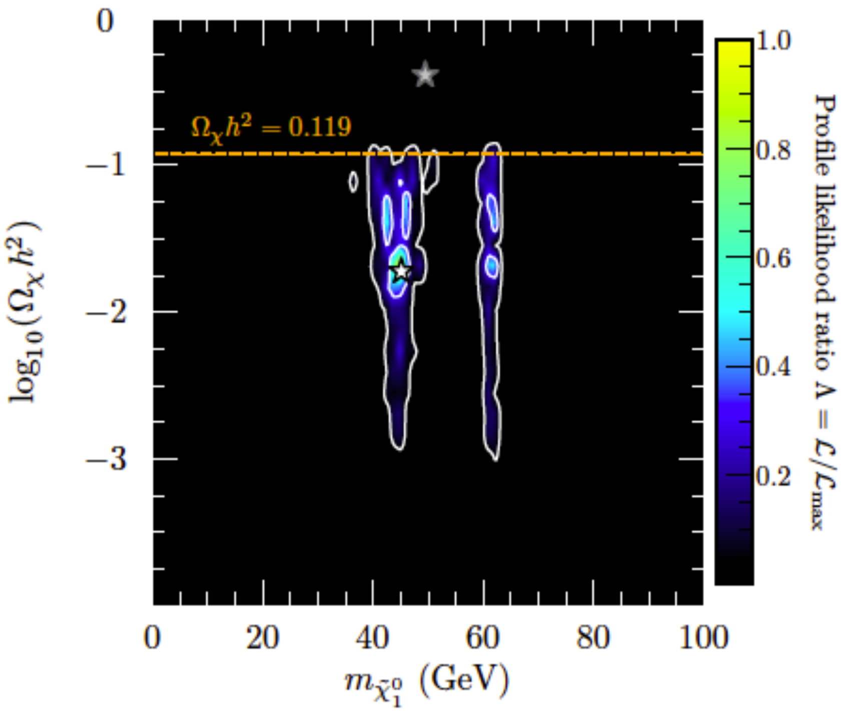
Excess?

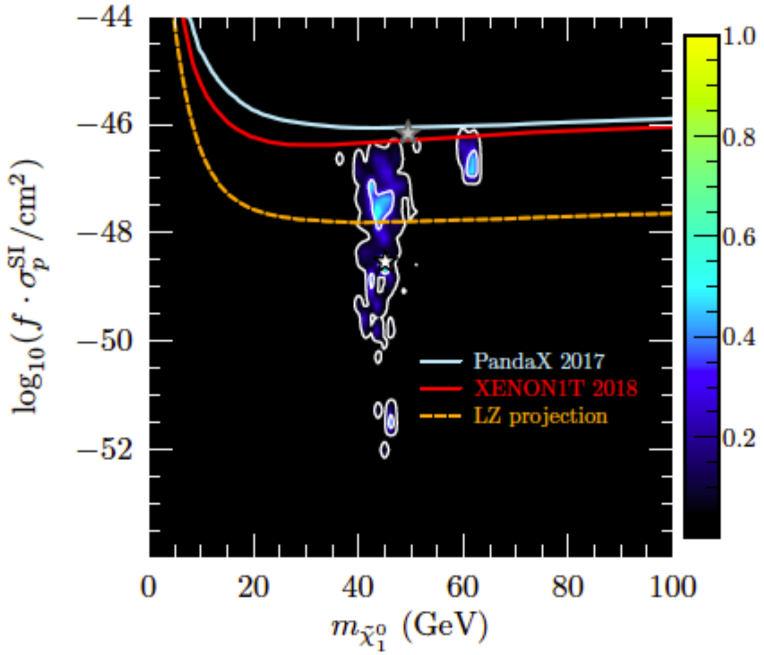
- Complete analysis of collider constraints (h,Z-inv, LEP + LHC electroweakino searches@13TeV) from Gambit collaboration shows a small excess in the combined likelihood corresponding to 'light' mostly bino LSP (Athron et al, 1809.02097) – some small higgsino or wino component



Excess?

- Combining with DM constraints (relic density + direct detection + FermiLAT) – model is viable (Z or Higgs funnel)

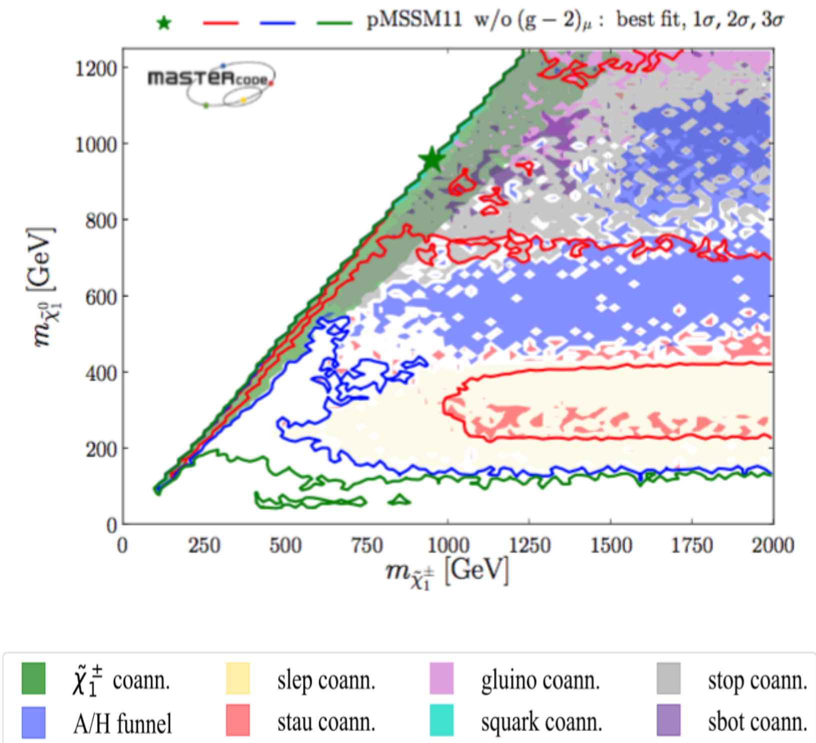


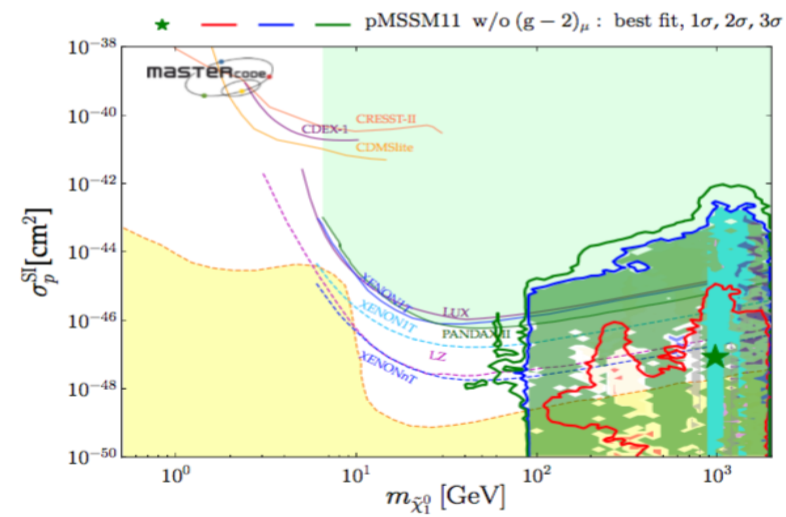


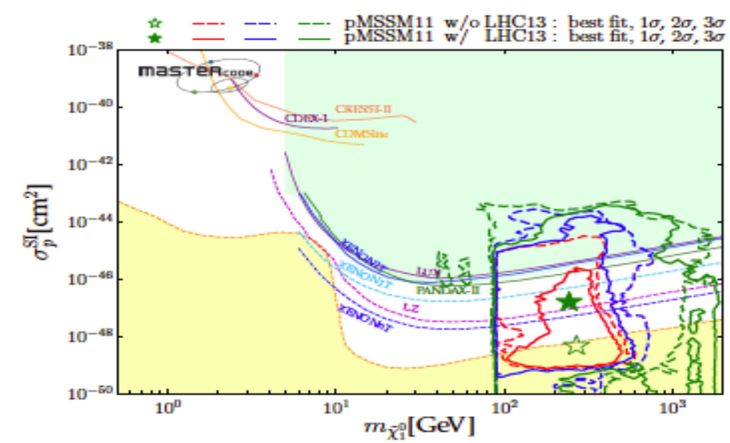
- Will be probed by future multi-ton DD experiments –further constraints on Z funnel from SD interactions???
- And of course with more LHC data

Global fit neutralino LSP, pMSSM11

Bagnashi et al, 1710.11091







Still lots of space for SUSY DM !!!

Beyond: Neutralino in NMSSM

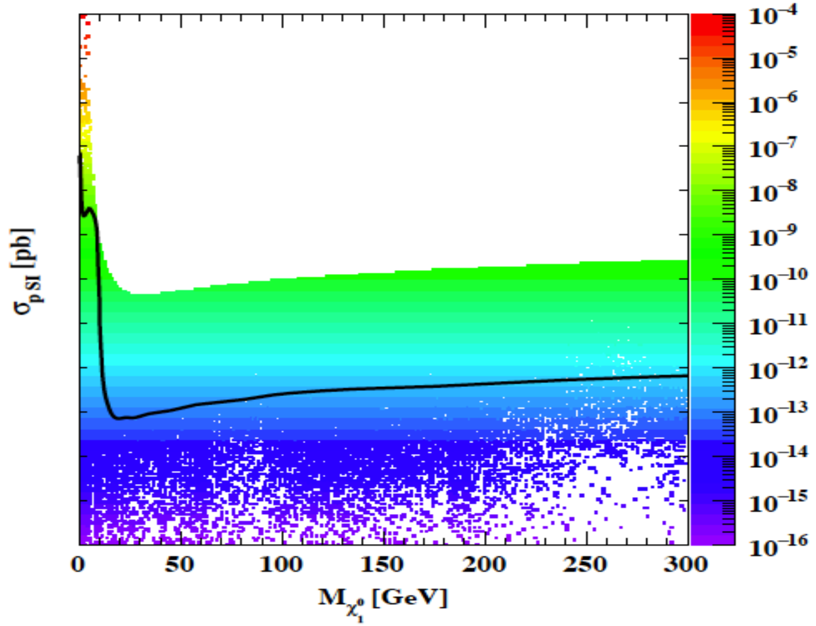
- MSSM+ singlet superfield (NMSSM)
- μ is related to singlet vev – naturally at EW scale $\mu=\lambda s$
- New tree-level contribution to Higgs mass – mh=125GeV
- New features: additional Higgses (singlet can be light) and additional neutralino (singlino)

$$\begin{pmatrix} M_1 & 0 & M_Z \sin\theta_W \sin\beta & -M_Z \sin\theta_W \cos\beta & 0 \\ 0 & M_2 & -M_Z \cos\theta_W \sin\beta & M_Z \cos\theta_W \cos\beta & 0 \\ M_Z \sin\theta_W \sin\beta & -M_Z \cos\theta_W \sin\beta & 0 & -\mu & -\lambda v \cos\beta \\ -M_Z \sin\theta_W \cos\beta & M_Z \cos\theta_W \cos\beta & -\mu & 0 & -\lambda v \sin\beta \\ 0 & 0 & -\lambda v \cos\beta & -\lambda v \sin\beta & 2\nu \end{pmatrix}$$

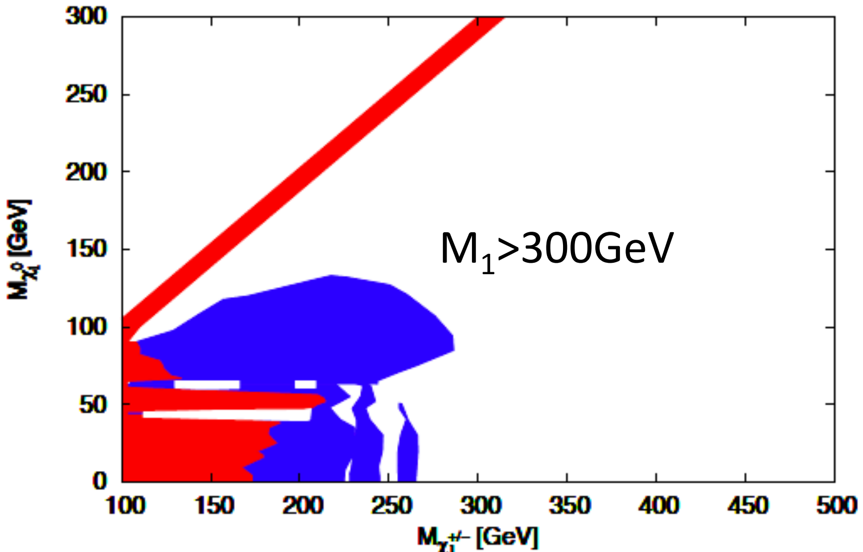
- DM : singlino LSP (can be light) annihilation not very efficient unless resonance (singlet Higgs), some higgsino component (GB et al 0509 (2005) 001)
- Higgsino LSP (with singlino component can be dominant DM even if light)

Singlino/Higgsino (singlet/doublet)

- Direct detection can be much below neutrino floor
  - Also H_1 and H_2 (SM-like) exchange interfere destructively – weaker cross section
- Relevant LHC searches : chargino – neutralino production in trilepton channel



- Region ruled out by trilepton
  - Ellwanger, Hugonie, 1806.09478
- Expect much better coverage with higher luminosity

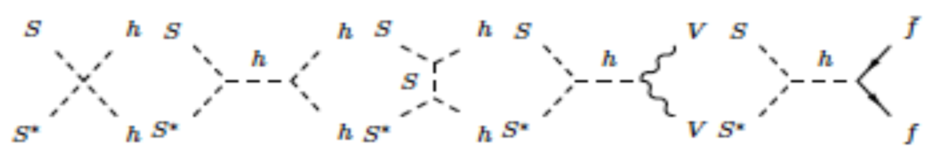


Scalar singlet

- Extended scalar are generic in BSM, minimal model: SM + singlet + Z_2
- Silveira, Zee (1985); J. McDonald PRD50(94) hep-ph/0702143, hep-ph/0106249; Burgess et al, hep-ph/0011335; Davoudiasl et al hep-ph/0405097; O'Connell et al, hep-ph/0611014; Barger et al. hep-ph/07064311; Yaguna, arXiv:0810.4267; Guo,Wu 1103.5606; Biswas, Majumdar 1102.3024, Asano,Kitano,1001.0486, Tytgat, arXiv:1012.0576, Cline et al 1306.4710 ....
- Stability of Higgs potential (quartic couplings gives positive contribution to β function preventing λ from running negative – stability at larger scale)
- Baryogenesis can work
- One coupling drives DM observables

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

annihilation



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

Scalar singlet

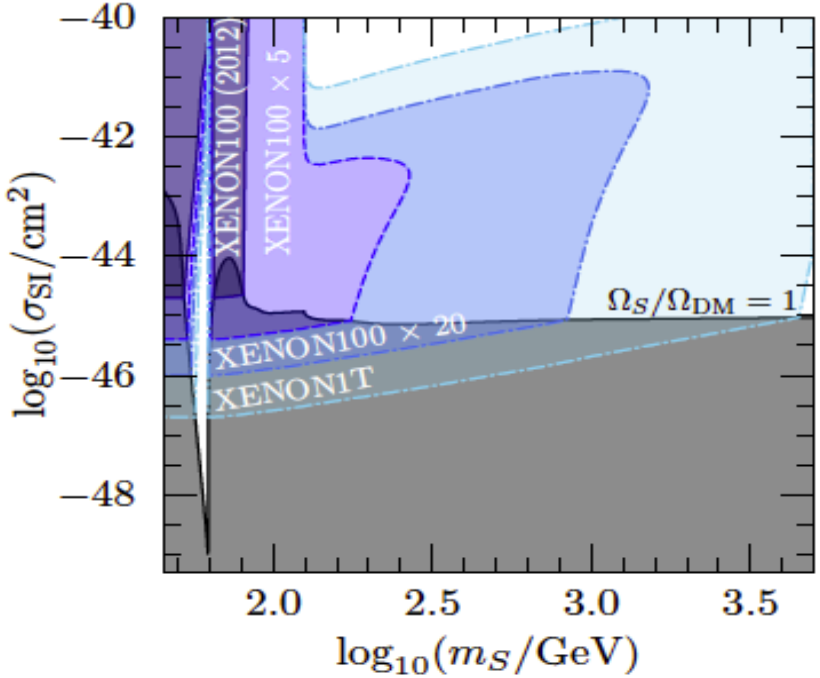
- Relic density determines λ_{HS}/m_S (for heay DM)
- Light DM – also Higgs resonance effect and W threshold
- The same coupling enters elastic scattering of DM on nucleus
- As in any Higgs portal model, both invisible width (if ms<mh/2) and SI cross-section depend on Higgs coupling to DM (Djouadi et al 1205.3169)

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

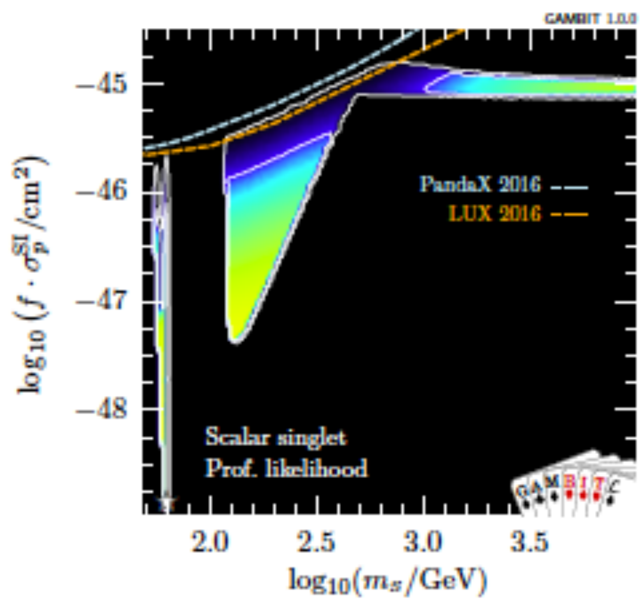
- In singlet scalar model, relic density requires coupling that leads to large invisible branching → ms>55GeV

Scalar singlet

- DD excludes most of the model (except near mh/2 and ms>1 TeV) – larger area allowed if include all uncertainties



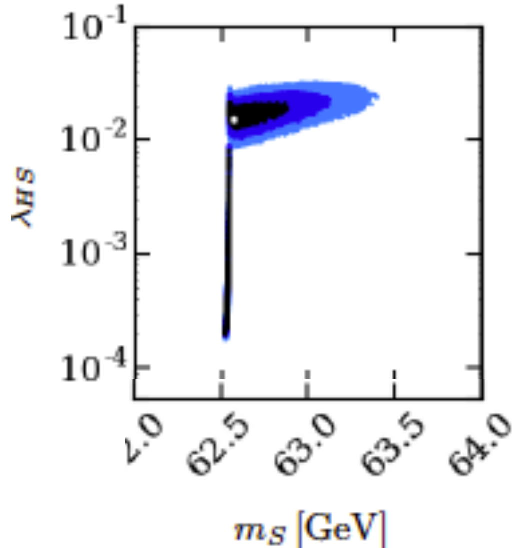
Cline et al 1306.4710



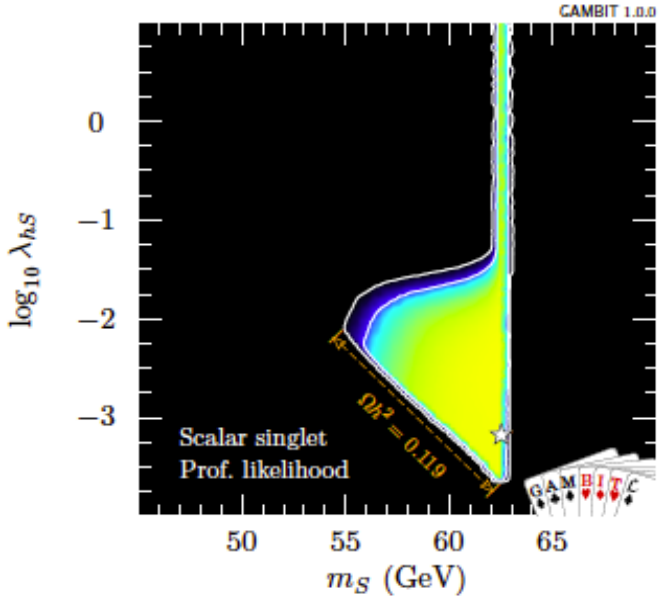
GAMBIT, 1705.07931

Scalar singlet

- DD excludes most of the model (except near mh/2 and ms>1 TeV) – larger area allowed if include all uncertainties
- Compatible with AMS and GC excess



Cuoco, 1704.08258



GAMBIT, 1705.07931

Inert doublet

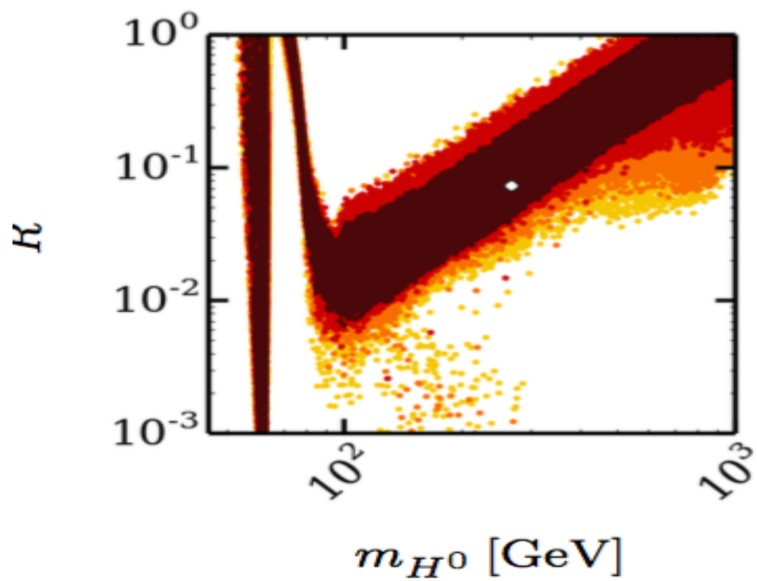
- Two-Higgs doublet model with Z_2 symmetry
  - Deshpande, Ma, PRD18(1978) 2574; Barbieri, Hall, Rychkov, PRD74 (2006) 015007
  - Although suggested as alternative to light Higgs model (natural to have mh >>100 GeV) compatible with light Higgs and provide alternative to neutralino dark matter
  - Lopez Honorez, Nezri,Oliver, Tytgat, JCAP 0702(2007) 028; Arina et al (2009); Hambye et al, 0903.4010; Lopez Honorez ,Yaguna (2011); Goudelis et al, 1303.3010
  - odd under Z_2 --> H or A stable
  - no coupling of H_2 to fermions

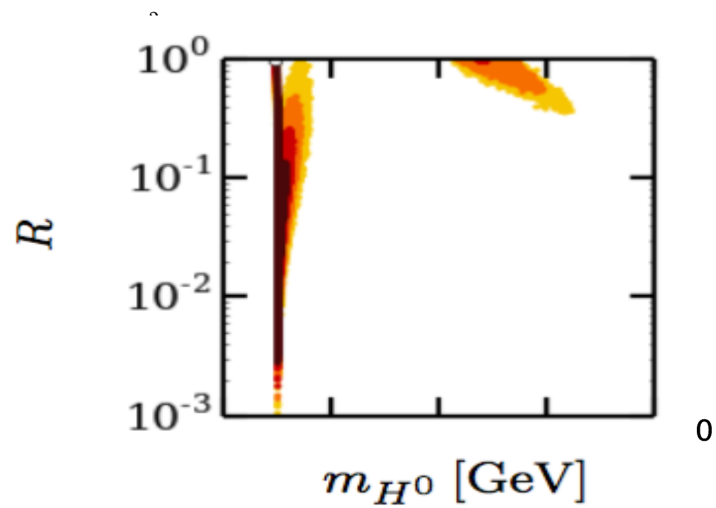
$$V = \mu_1^2|H_1|^2 + \mu_2^2|H_2^2| + \lambda_1|H_1|^4 + \lambda_2|H_2|^4 + \lambda_3|H_1|^2|H_2|^2 + \lambda_4|H_1^\dagger H_2|^2 + \frac{\lambda_5}{2}\left[(H_1^\dagger H_2)^2 + \text{h.c.}\right] ,$$

parameters : m_h, m_H, m_A, m_{H+}, λ_2, $\lambda_3+\lambda_4+\lambda_5 = \lambda_L$

Inert doublet DM

- Efficient annihilation into gauge bosons SU(2)





Eitenauer et al 1705.01458

Fit GC excess

IDM at LHC

- Constraints from electroweak precision : corrections to gauge bosons self energies

$$S = 0.06 \pm 0.09, \quad T = 0.10 \pm 0.08.$$

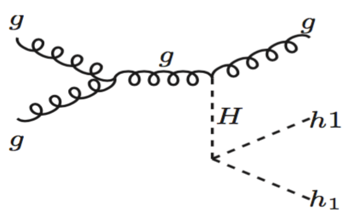
- Higgs invisible width, Higgs-two-photon
- At LHC8 TeV : recast some SUSY searches
  - dileptons + missing E_T (GB et al, 2015)
  - Trileptons+MET Miao, Su, Thomas, 2010
  - multileptons - Gustafsson et al 2012

$$q\bar{q} \to Z \to A^0 H^0 \to Z^{(*)} H^0 H^0 \to \ell^+ \ell^- H^0 H^0,$$

$$pp \to AH^{\pm}, A \to Z^{(*)}_{\rm lep} H, H^{\pm} \to W^{\pm}_{\rm lep} H.$$

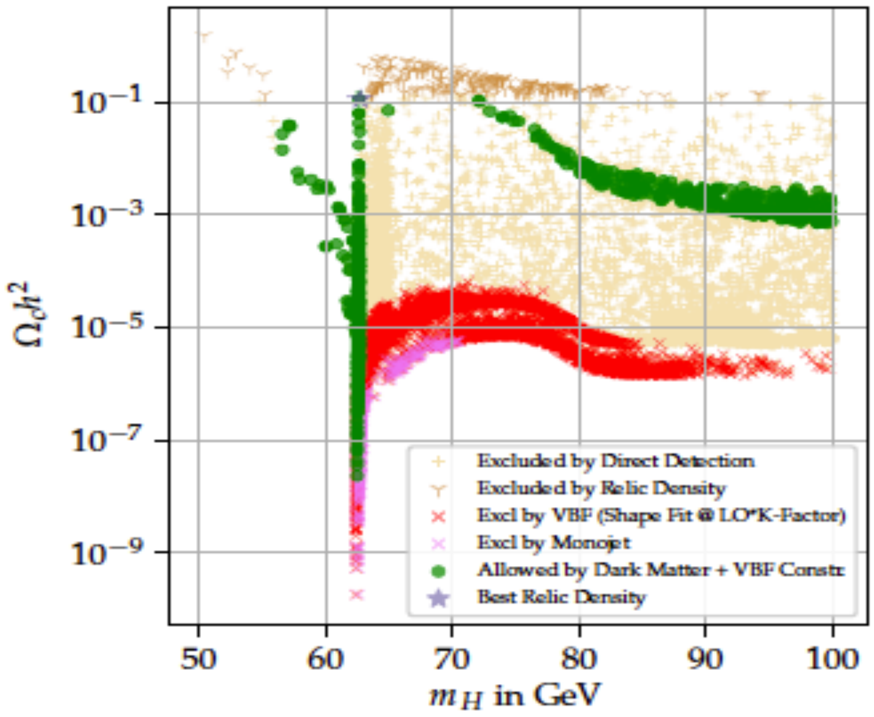
- At LHC13 : most powerful constraints from
  - VBF (Poulose et al 1604.03045, Dercks, Robens, 1812.07913)
  - Monojet (Belyaev et al, 1612.00511, 1809.00933)

$$pp \to h^* jj \to HHjj$$



Scalar doublet (Inert)

- Both VBF and monojet at 13TeV probe the ‘Higgs funnel’



Dercks and Robens, 1812.07913

VBF based on recast of CMS invisible Higgs, 13TeV 35.9fb^{-1}, 1809.05937

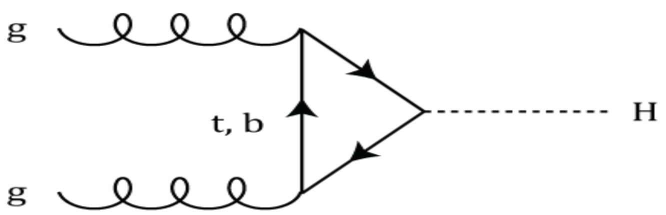
Dirac fermion

- Simplified model : Capture essential features with small number of parameters/assumptions
- Pseudoscalar mediator (evade direct detection constraints), fermion DM, also assume couplings proportional to Yukawas-> 3rd generation

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

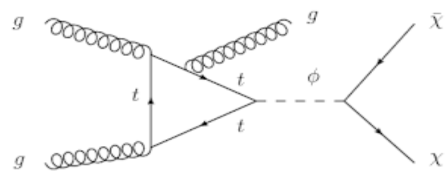
$$\mathcal{L}_{\rm f} = i\sum_{f_u} c_u \frac{m_{f_u}}{v} A \bar{f}_u \gamma^5 f_u + i\sum_{f_d} c_d \frac{m_{f_d}}{v} A \bar{f}_d \gamma^5 f_d$$

- Loop coupling to two-gluons and two-photons

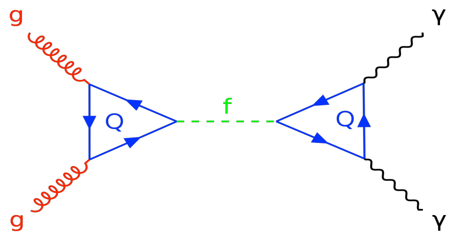


At the LHC

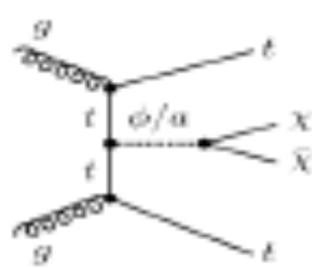
- Several probes :
  - monojet



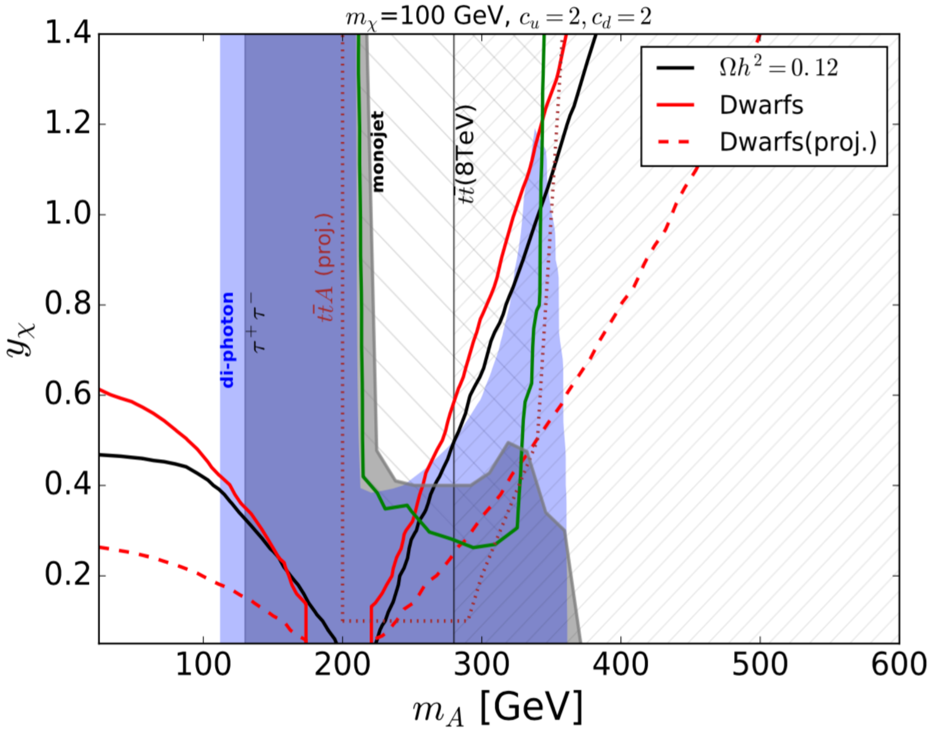
  - searches for mediator in visible (γγ,ττ,tt) or invisible decays,

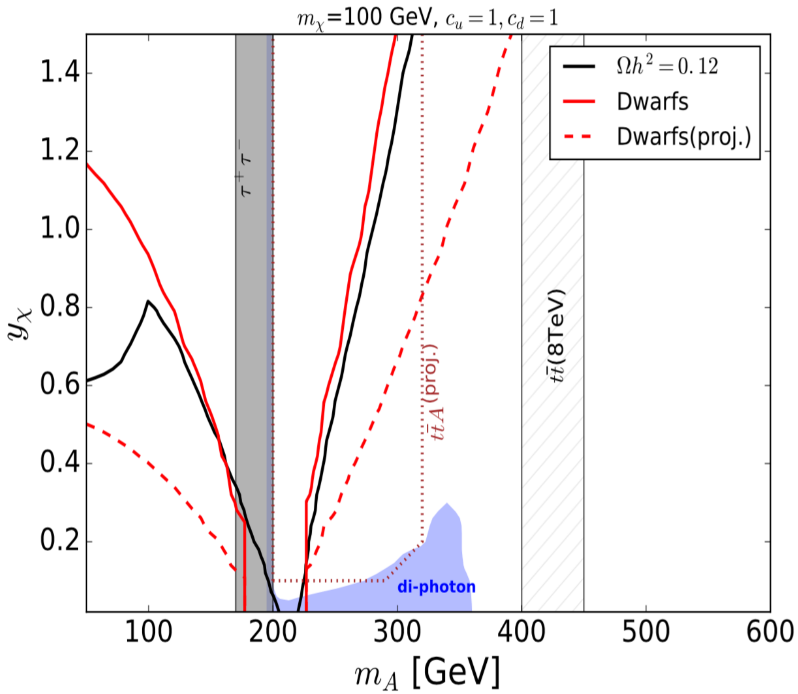


  - contribution of mediator to di-top cross section,
  - associated production of mediator, ttA, bbA



At the LHC





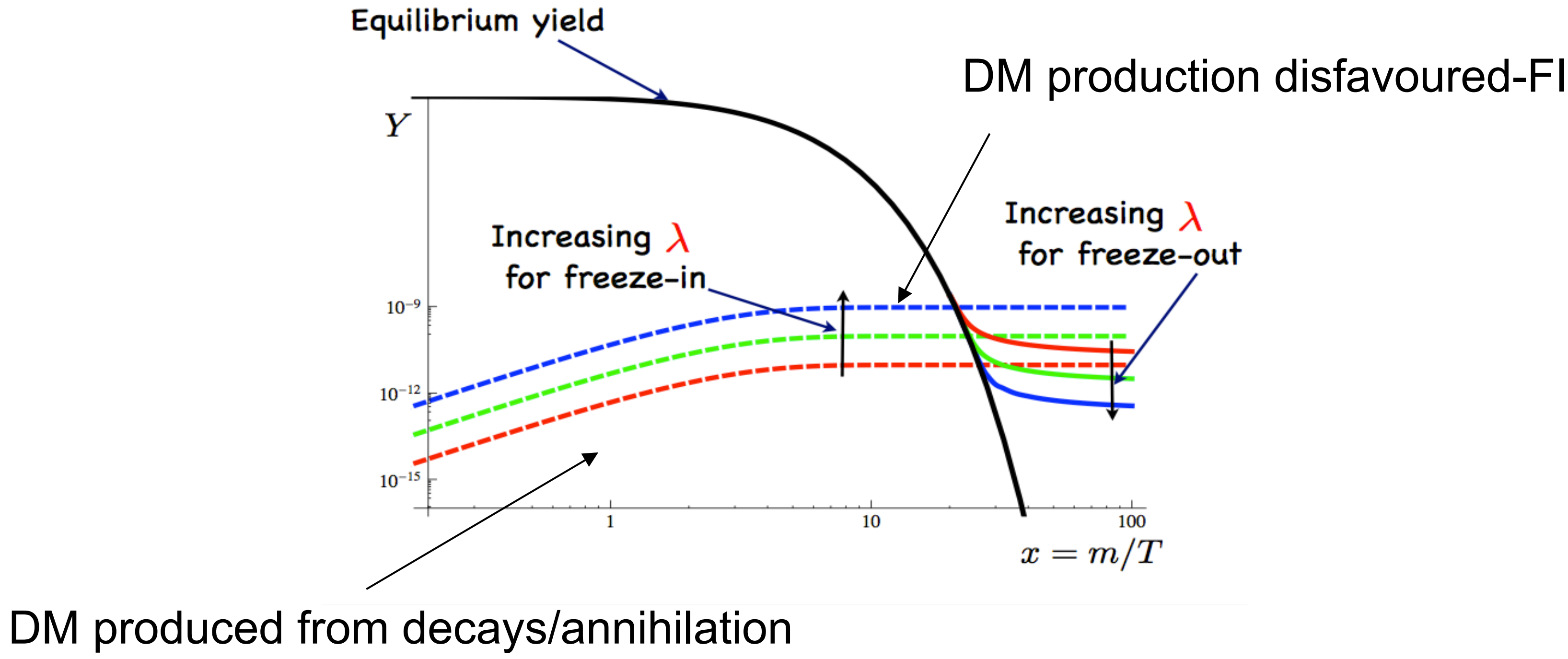
- LHC constraints strongly depend on mediator couplings to quarks
- Independent of coupling to DM in visible channels – allow to cover the region m_{DM}~$m_A/2$ with very small coupling hard for indirect detection
- Narrow range of couplings allowed by PLANCK+dwarfs
- Similar conclusions for spin 1 (ATLAS)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

Other DM candidates (beyond WIMPs)

- FIMPS, Sneutrino, gravitino, axino…
- Forget about WIMP miracle
- Consider much weaker interaction strength and maybe mass scale

FIMPS (Feebly interacting MP)

- Freeze-in (McDonald, PRL88, 091304 (2002); Hall et al, 0911.1120): in early Universe, DM so feebly interacting that never reach thermal equilibrium
- Assume that after inflation abundance DM very small, interactions are very weak but lead to production of DM
- T~M, DM 'freezes-in' - yield increase with interaction strength



Freeze-in

- DM particles are 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)

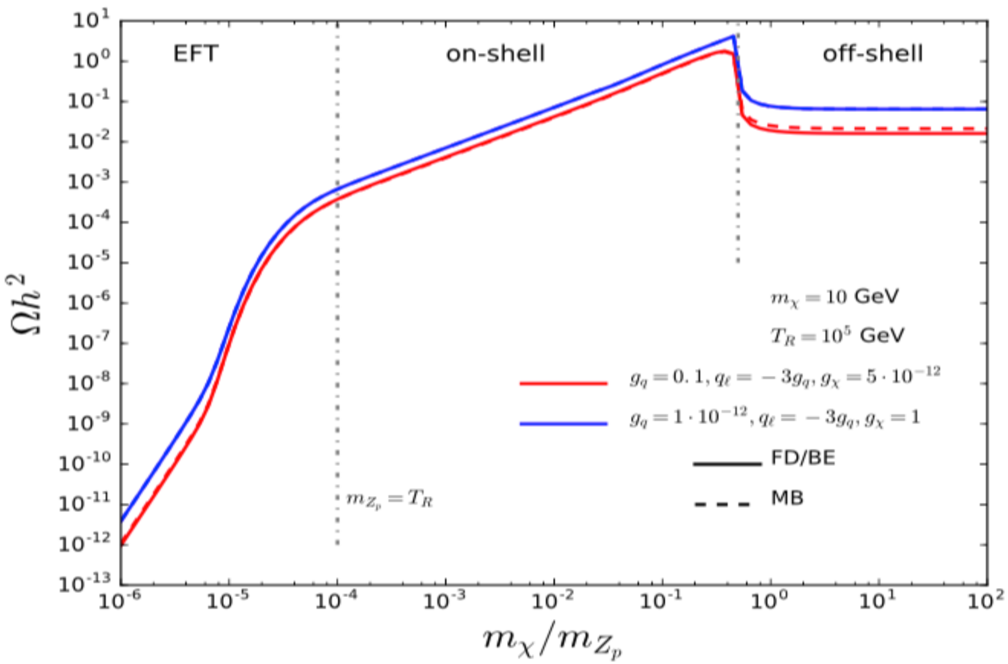
$$n = \int \frac{d^3p}{(2\pi)^3} f(p)$$

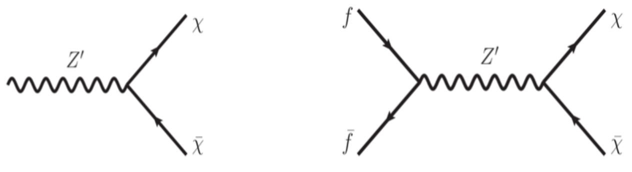
Simple example : vector portal

- Z' portal with vector couplings to fermion DM and SM

$$\mathcal{L}_{\text{int}} = -g_\chi Z'_\mu \bar{\chi}\gamma^\mu \chi - \sum_q g_q Z'_\mu \bar{q}\gamma^\mu q$$

- 3 regimes





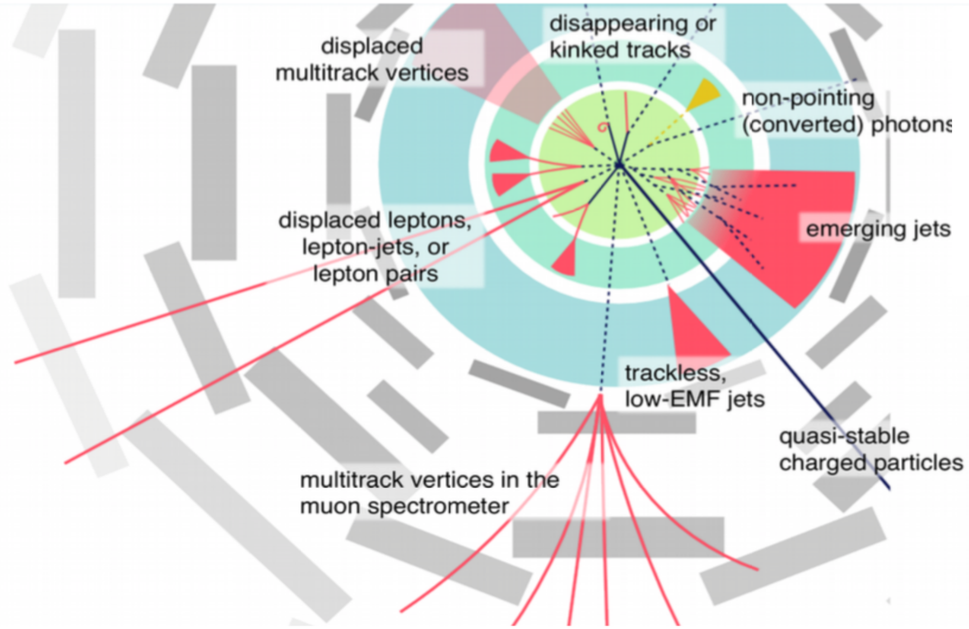
$g_q\, g_\chi \sim 10^{-10} - 10^{-12}$

Typically get expected relic density both in off-shell ($m_\chi \sim m_{Med}$) and on-shell regime ($m_\chi << m_{Med}$) - DM can be very light

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

- Heavy stable charged particles (HSCP)
- Disappearing tracks
- Displaced leptons
- Displaced vertices

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

Relic density

- DM mainly produced from decay of F (F-> f s) e.g. consider lepton
- DM yield (assuming Maxwell-Boltzmann statistics)

$$Y_s \approx \frac{45\,\xi\,M_{\rm Pl}}{8\pi^4 \cdot 1.66}\frac{g_F}{m_F^2}\Gamma \int_{m_F/T_R}^{m_F/T_0} dx\; x^3 \frac{K_1(x)}{g_*^s(m_F/x)\sqrt{g_*(m_F/x)}},$$

- Γ : partial width to DM , depends on y_s^f
- DM abundance

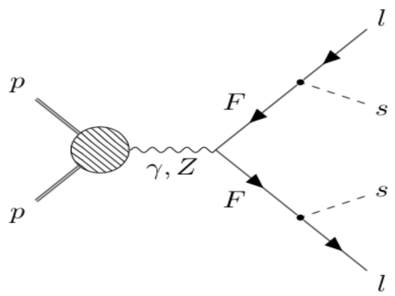
$$\Omega_s h^2 \approx \frac{m_s Y_s}{3.6 \times 10^{-9}\ \mathrm{GeV}}$$

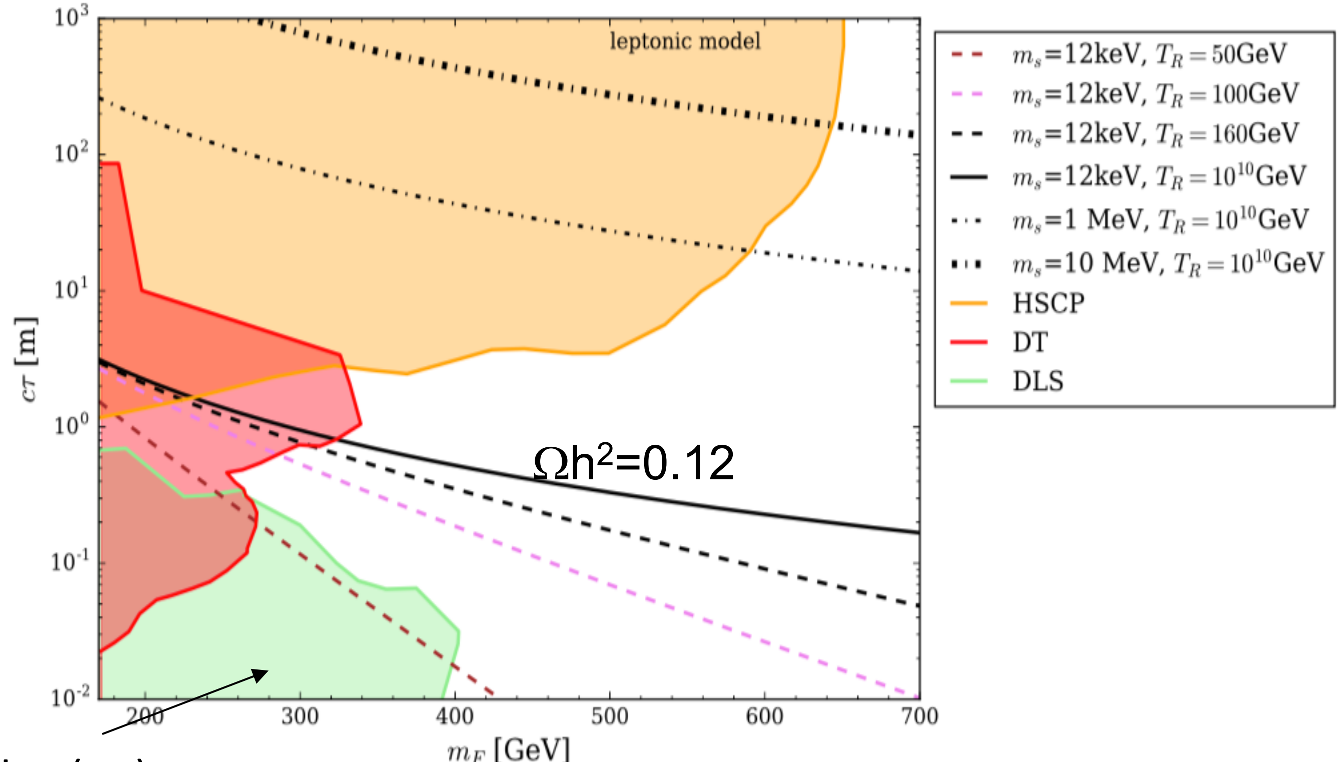
- F lifetime

$$c\tau[\mathrm{m}] \approx\ 4.5\ \xi\ g_F\ \left(\frac{0.12}{\Omega_s h^2}\right)\left(\frac{m_s}{100\ \mathrm{keV}}\right)\left(\frac{200\ \mathrm{GeV}}{m_F}\right)^2$$

- Lowering reheating temperature - > shorter lifetime
- Lower bound on ms from from Lyman-α forest observation (m_S>12keV)
  - Wash-out of small and intermediate scale structures if DM has non-negligible velocity dispersion
- FI naturally leads to Long-lived particles (from cm to many meters)

LHC constraints (lepton)





Disappearing track

Displaced lepton searches(eμ)

- As DM becomes heavier – only HSCP searches relevant
- Lower T_R : expect signatures for smaller $c\tau$

FI beyond simplified models

- FI can also occur in some of the common BSM models, e.g. in supersymmetry with RH sneutrino, gravitino, axino etc..
  - Cheung et al, 1103.4394; Hall et al, 1010.0245; Co et al 1611.05028…
- An example MSSM+RH sneutrino
  - Asaka et al, hep-ph/0612211, Banerjee et al, 1603.08834
- Neutrino have masses – RH neutrino + Susy partner well-motivated – if LSP then can be DM
- Example MSSM+3 RH neutrinos with pure Dirac neutrino mass
- Superpotential

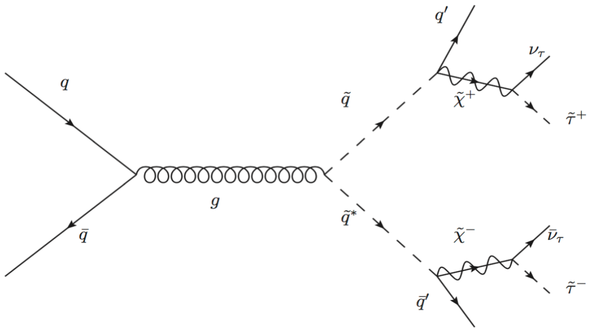
$$W = y_\nu \hat{H}_u \cdot \hat{L}\, \hat{\nu}_R^c - y_e \hat{H}_d \cdot \hat{L}\, \hat{\ell}_R^c + \mu_H \hat{H}_d \cdot \hat{H}_u$$

- Small Yukawa couplings $O(10^{-13})$ (from neutrino oscillation and Planck+lensing +BAO)

- Sneutrino not thermalized in early universe - produced from decay of MSSM-LSP before or after freeze-out

$$\Omega_{\tilde{\nu}_R}^{\rm FO} = \frac{m_{\tilde{\nu}_R}}{m_{\rm MSSM\text{-}LSP}} \Omega_{\rm MSSM\text{-}LSP} \qquad \Omega_{\tilde{\nu}_R}^{FI} h^2 \simeq \frac{1.09 \times 10^{27}}{g^{*\,3/2}} m_{\tilde{\nu}_R} \sum_i \frac{g_i \Gamma_i}{m_i^2}$$

- Consider stau as the NLSP - live from sec to min : decay outside detector
- Constraints from BBN : lifetime of stau can be long enough for decay around or after BBN→ impact on abundance of light elements
- LHC signature : stable charged particle NOT MET
- Cascades : jets+stable stau (slow muon)
  - with 1ab^{-1} could probe mass ~580GeV
  - Banerjee et al, 1603.08834



- Pair production of two stable staus (HSCP)
- Passive search for stable particles (eg Moedal)
  - Array of nuclear track detector stacks that surround intersection region point 8
  - Sensitive to highly ionising particles with velocity β<0.5

Conclusions

- Combination of LHC, direct, indirect searches put strong constraints on neutralino DM – depending on nature of neutralino lower limit vary from 45GeV, ~200GeV, ~400GeV, 1TeV, 2.8TeV
- Still lots of possibilities to explore DM both in MSSM, its extensions and other BSM – diversity of collider signatures
- High expectations from Direct and indirect detection experiments (hints confirmed?)
- Current search strategies can also be powerful probes of FIMPs
- Need to look beyond WIMP paradigm

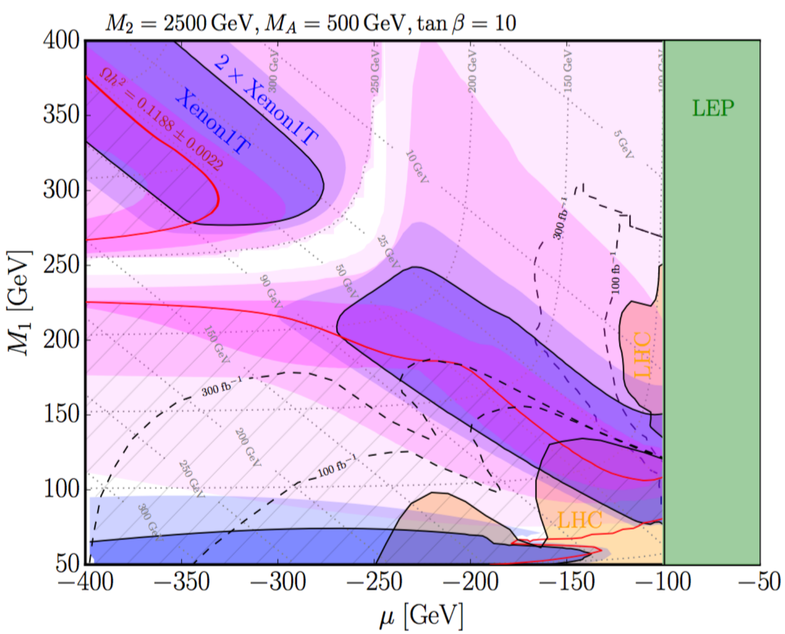
- *Dark matter was proposed by Zwicky in 1933 still to be « discovered »*

Are we searching at the right place?

Extra Slides

Bino/Higgsino

- Relaxing strong direct detection constraint μ<0
- Heavy Higgs not too heavy



Profumo et al 1706.08537

Xenon1T will cover part of parameter space
+
LHC searches for Higgsino also
+
Indirect detection through gamma-rays (assuming factor 10,100,1000 improvement over FermiLAT current limits) could cover all relevant region

Note SD searches (including IceCube) can also probe this scenario as well as heavy Higgs searches
(P. Huang et al 1701.02737)

Gravitino

- Considered early as DM candidate in SUSY (Phut, PLB69 (1977) 55; Pagels, Primack PLB 48 (1982) 223)
- Superpartner of the graviton – couplings Planck scale suppressed couplings – no signature direct/indirect detection (unless unstable)
- Two production mechanisms : 1) from scattering of SUSY particles in thermal bath (especially gluinos) 2) from decay of NLSP after freeze-out

$$\Omega^{th}_{\tilde{G}}\, h^2 = 0.83\, \frac{T_{RH}}{10^9\,\mathrm{GeV}} \left(\frac{m_{3/2}}{1\,\mathrm{GeV}}\right)^{-1} \sum_{i=1}^{3} \gamma_i(T_{RH}) \left(\frac{M_i}{300\,\mathrm{GeV}}\right)^2$$

$$\Omega^{SW}_{\tilde{G}}\, h^2 = \left(\frac{m_{3/2}}{M_\chi}\right) \Omega_\chi\, h^2$$

- BBN constraint -> lifetime of NLSP < 100s and upper bound on hadronic energy injected
- If NLSP charged– signature stable charged particle
- If NLSP neutral :– collider signatures as for neutralino LSP – alter relation with relic density – revival of bino LSP
- LHC14 with $300\mathrm{fb}^{-1}$ can probe significant parameter space

Gravitino

- Considered early as DM candidate in SUSY (Phut, PLB69 (1977) 55; Pagels, Primack PLB 48 (1982) 223)
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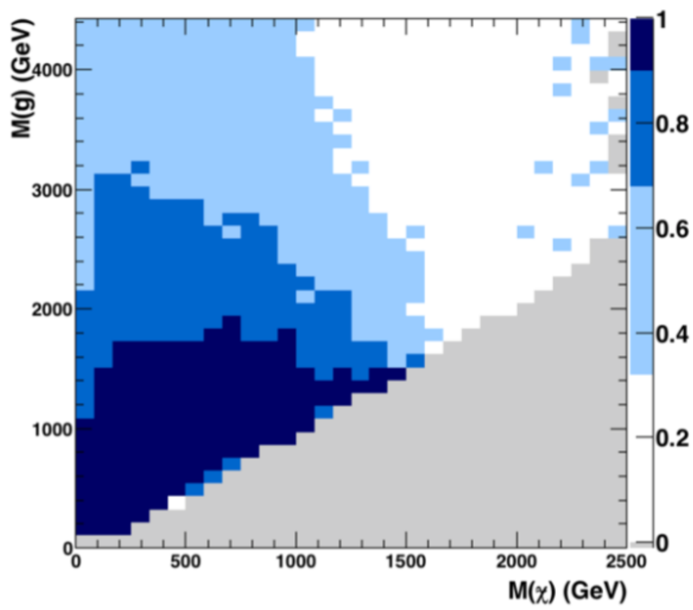
$$\Omega^{th}_{\tilde{G}}\, h^2 = 0.83\, \frac{T_{RH}}{10^9\,\mathrm{GeV}} \;($$

$$\Omega^{SW}_{\tilde{G}}\, h^2 = \left(\frac{m_{3/2}}{M_\chi}\right) \Omega_\chi\, h^2$$



- BBN constraint... upper bound on hadronic energy injected...
- If NLSP charge... e
- If NLSP neutra... ralino LSP – alter relation with relic densi...
- LHC14 with $300 fb^{-1}$ can probe significant parameter space, Arbey et al, 1505.04595

NMSSM

- New decays for the Higgs , for example in a light DM scenario (Barducci et al 1510.00246, De Florian et al 1610.07922)
- h_{SM}->A_sA_s

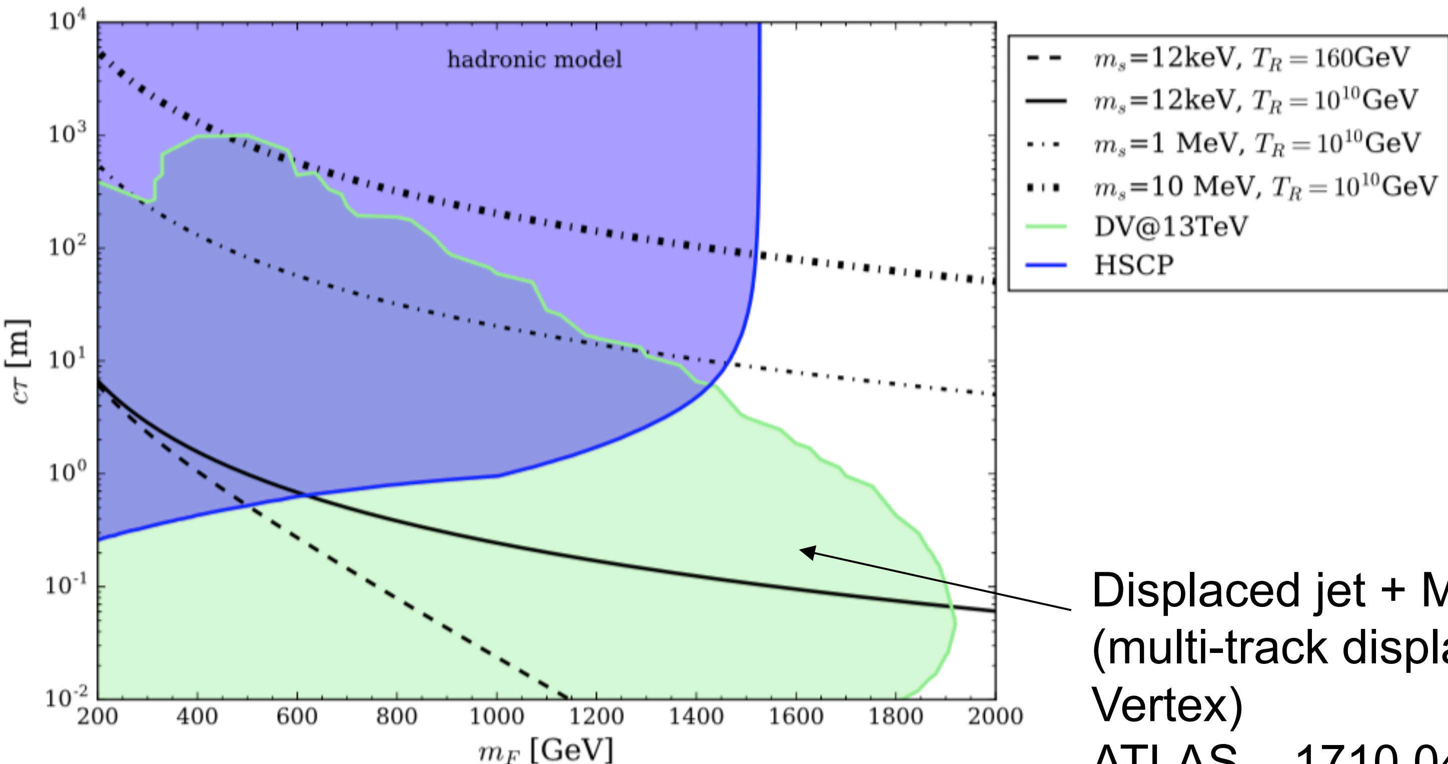
$$BR(A_S \to \tilde{\chi}_1^0\tilde{\chi}_1^0) \approx 73\%, BR(A_S \to \tau^+\tau^-) \approx 25\%$$

- If singlino light also impact on susy searches, eg in singlino DM scenario (Han et al 1504.05085)

$$\begin{aligned} \mathrm{pp} \to \tilde{\chi}^0{}_{2,3} + \tilde{\chi}_1^\pm &\to A_S + \tilde{\chi}_1^0 + \mathrm{W}^\pm + \tilde{\chi}_1^0 \\ &\to \mu^+\mu^- + \tilde{\chi}_1^0 + \ell^\pm + \nu_l + \tilde{\chi}_1^0: \end{aligned}$$

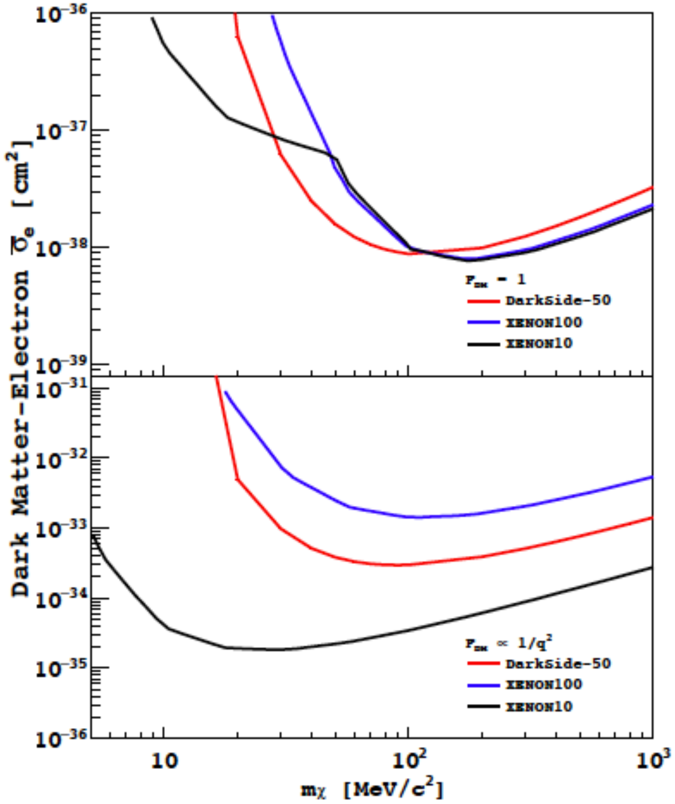
- Significance via A_s much larger than standard trilepton search but only when decay into SM-like H or Z forbidden

LHC constraints (quark)



Displaced jet + MET(>250GeV)
(multi-track displaced
Vertex)
ATLAS – 1710.04901

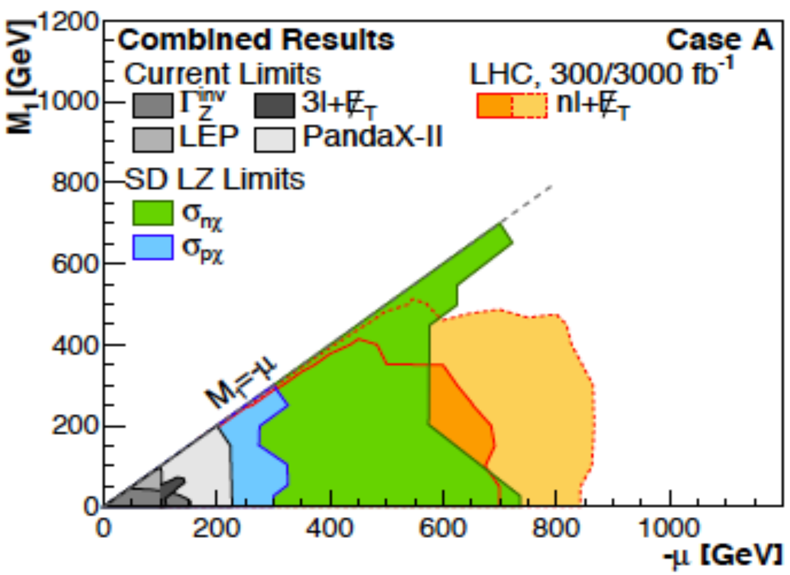
- Region m_F< 1.5TeV fully covered
- Lower T_R : expect signatures for smaller $c\tau$



Darkside: Agnes et al 1802.06998

Complementarity DD/LHC

- When couplings of LSP to Z or Higgs vanish -> much suppressed SD or SI occurs e.g. when $\mu<0$
- Si and SD are complementary (usually cannot suppress both couplings)
- Searches for electroweakino extend reach, e.g. Bino/higgsino LSP (also assume coan with stau for right relic)



Han et al 1612.02387