Dark matter candidates: status

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DMAstroLHC

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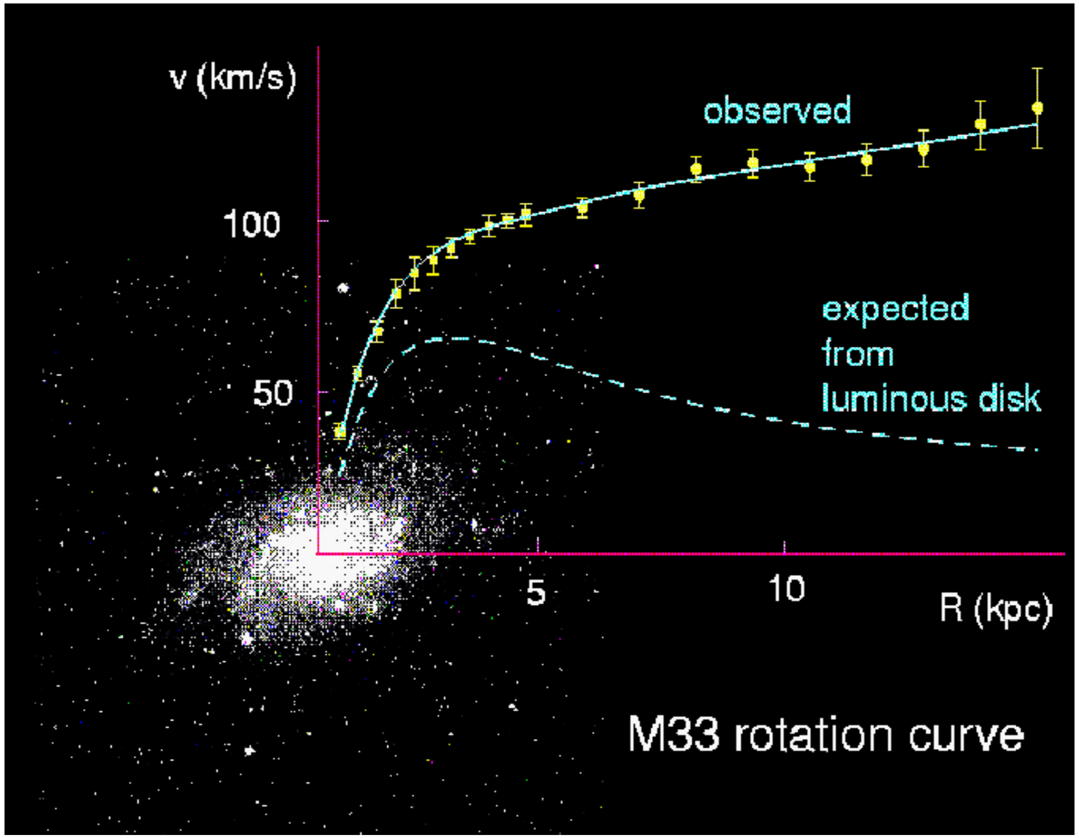
Outline

- Evidence and status of searches
- WIMP dark matter
- WIMP DM candidates
  - The special case of supersymmetry
  - Other wimps
- Non-wimp DM
- Conclusions

Dark matter : evidence

- In 1933 Fritz Zwicky measured velocity dispersion in COMA cluster to estimate the cluster mass and found orbital velocities about factor 10 larger than expected from the mass of galaxies in clusters. He postulated the existence of some kind of matter which does not emit light - > dark matter
- He was criticized and forgotten, BUT this result was later confirmed on many scales
  - The galactic scale (rotation curves)
  - Scale of galaxy clusters
  - Cosmological scales
    - Dark matter is required to amplify the small fluctuations in Cosmic microwave background to form the large scale structure in the universe today

Rotation curves of galaxies



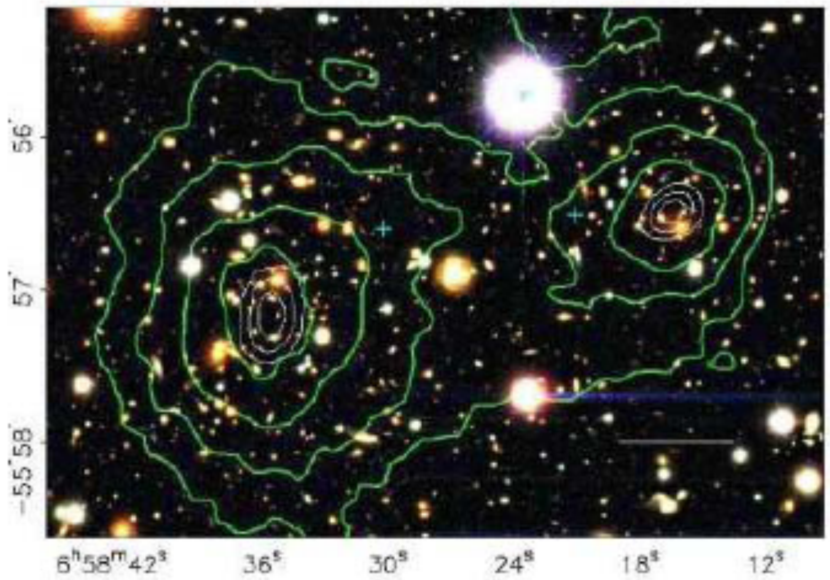
Explanation halo has a M ~ r   : a large part of the mass is in outer part of galaxy (dark matter halo) rather than in visible disk

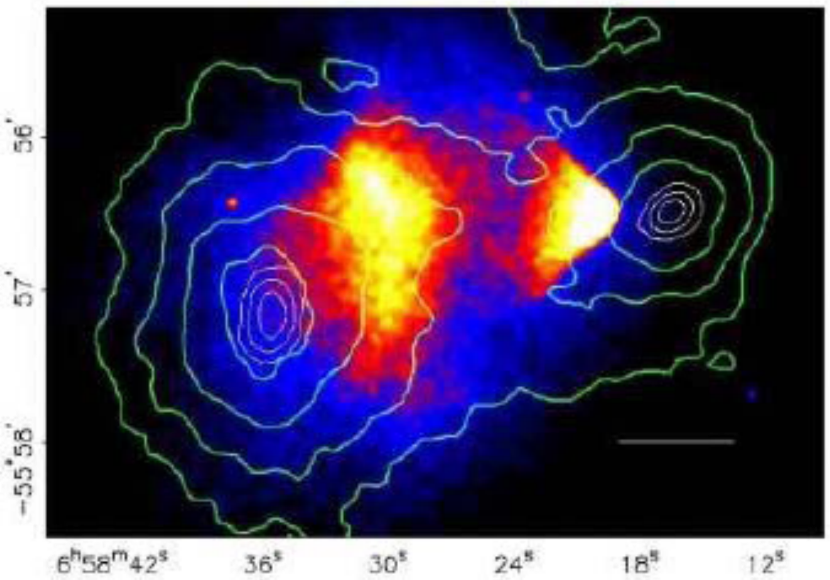
Bullet Cluster

- Collision of two clusters : direct evidence of dark matter
- Comparison of X-ray images of luminous matter with measurements of the cluster's total mass through gravitational lensing.
- Involves the observation of the distortion of light from background galaxies by the cluster's gravity -- the greater the distortion, the more massive the cluster (lensing).
- Two small clumps of luminous matter slowed down by the collision (interactions)
- Two large clumps of collisionless matter (not slowed down by the collision) – dark matter

Bullet cluster

- Total mass peak offset from X-ray peak (hot gas that forms most of baryonic mass) by 8 σ
- Most of mass in form of collisionless DM





Cosmic microwave background

and total amount of dark matter in the universe

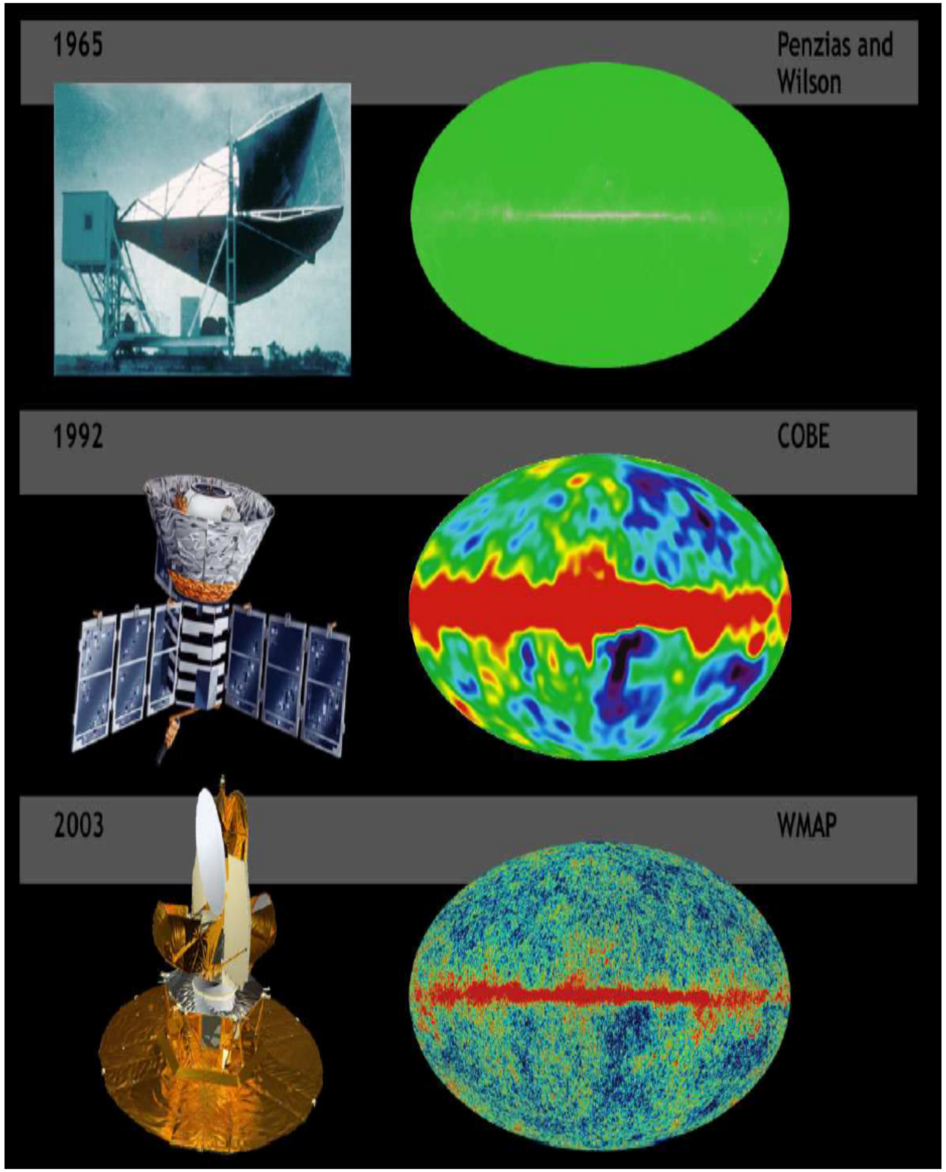
Background radiation originating from propagation of photons in early universe (once they decoupled from matter) predicted by Gamow in 1948

Discovered Penzias&Wilson 1965

CMB is isotropic at 10^{-5} level and follows spectrum of a blackbody with T=2.726K

Anisotropy to CMB tell the magnitude and distance scale of density fluctuation when universe was 1/1000 of present scale

Study of CMB anisotropies provide accurate testing of cosmological models, puts stringent constraints on cosmological parameters



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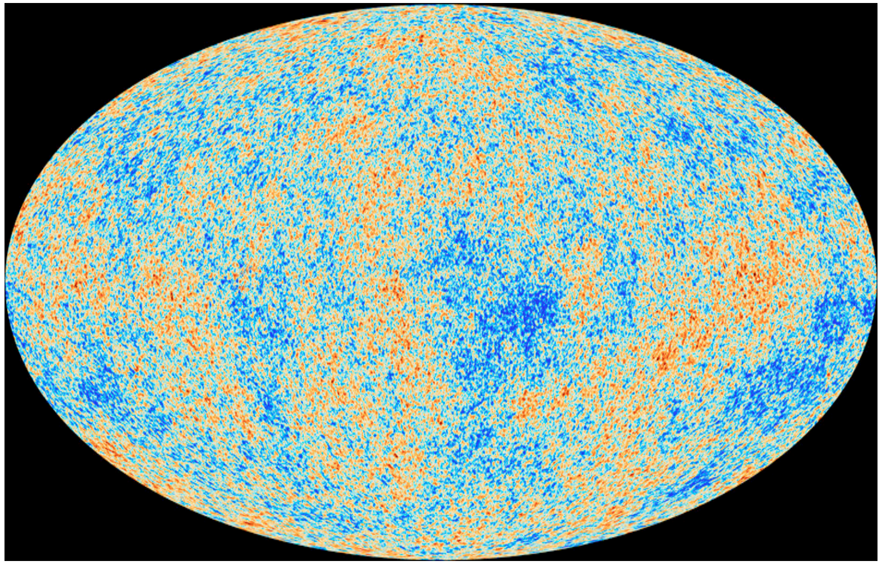
PLANCK



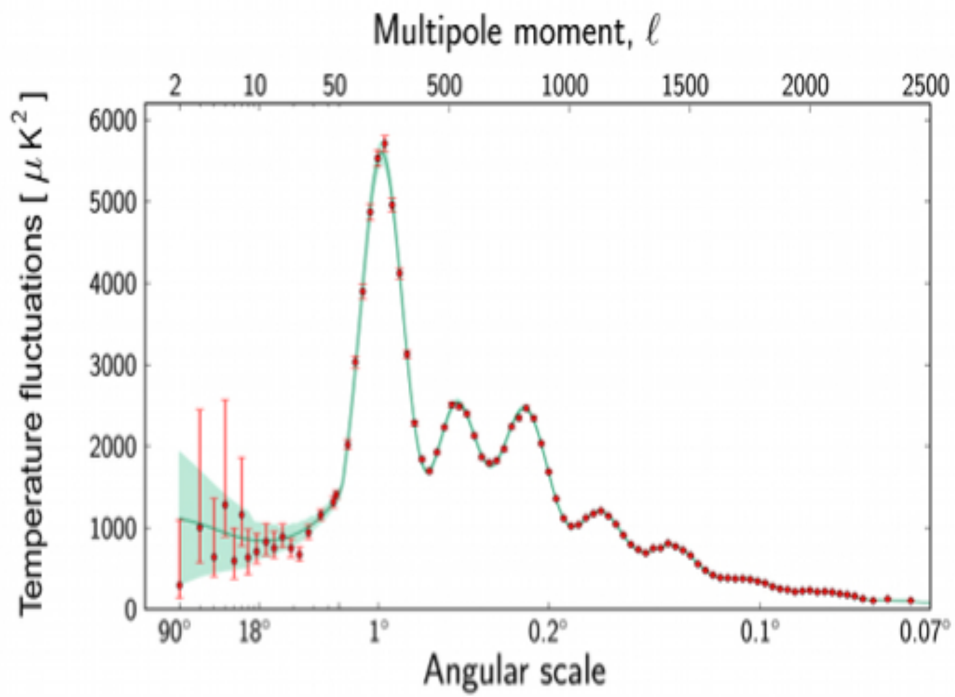
Density fluctuations

- Small anisotropy observed in sky
- All information contained in CMB maps can be compressed in power spectrum

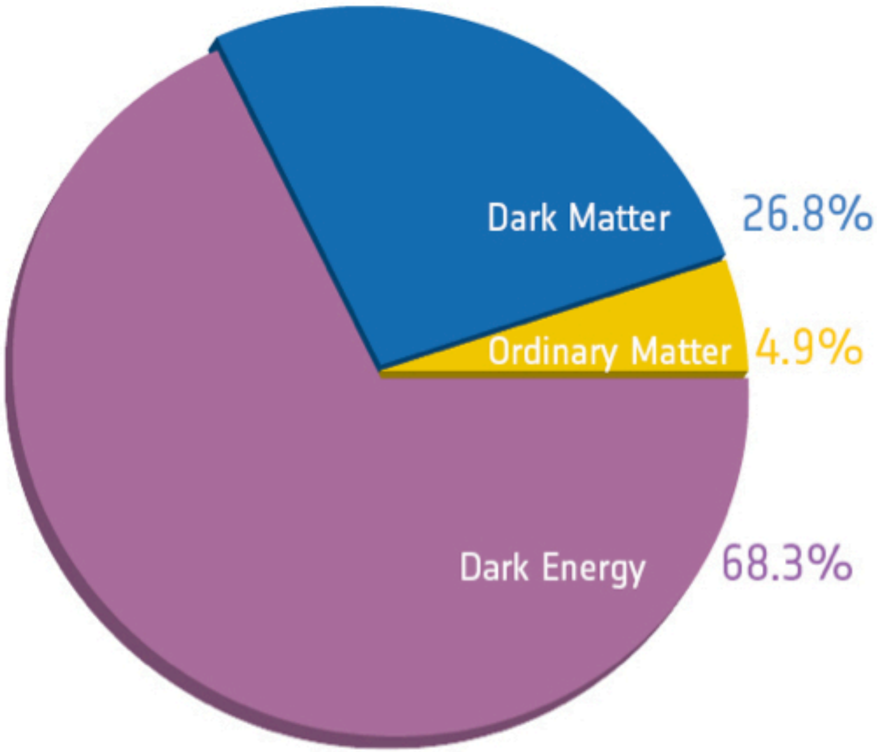
$$\frac{\delta T}{T}(\theta,\phi)=\sum_{\ell=2}^{+\infty}\sum_{m=-\ell}^{+\ell}a_{\ell m}Y_{\ell m}(\theta,\phi)$$

$$C_\ell \equiv < |a_{\ell m}|^2 > \equiv \frac{1}{2\ell+1}\sum_{m=-\ell}^{\ell}|a_{\ell m}|^2.$$

- CMB anisotropy maps contain inofrmation on cosmological model parameters (Ω_B, Ω_M, Ω_Λ ..) - best fit location and ehight of peaks



PLANCK 2013



Universe is made of 27% cold dark matter. Can it be a new particle?

*Cold: nonrelativistic during structure formation

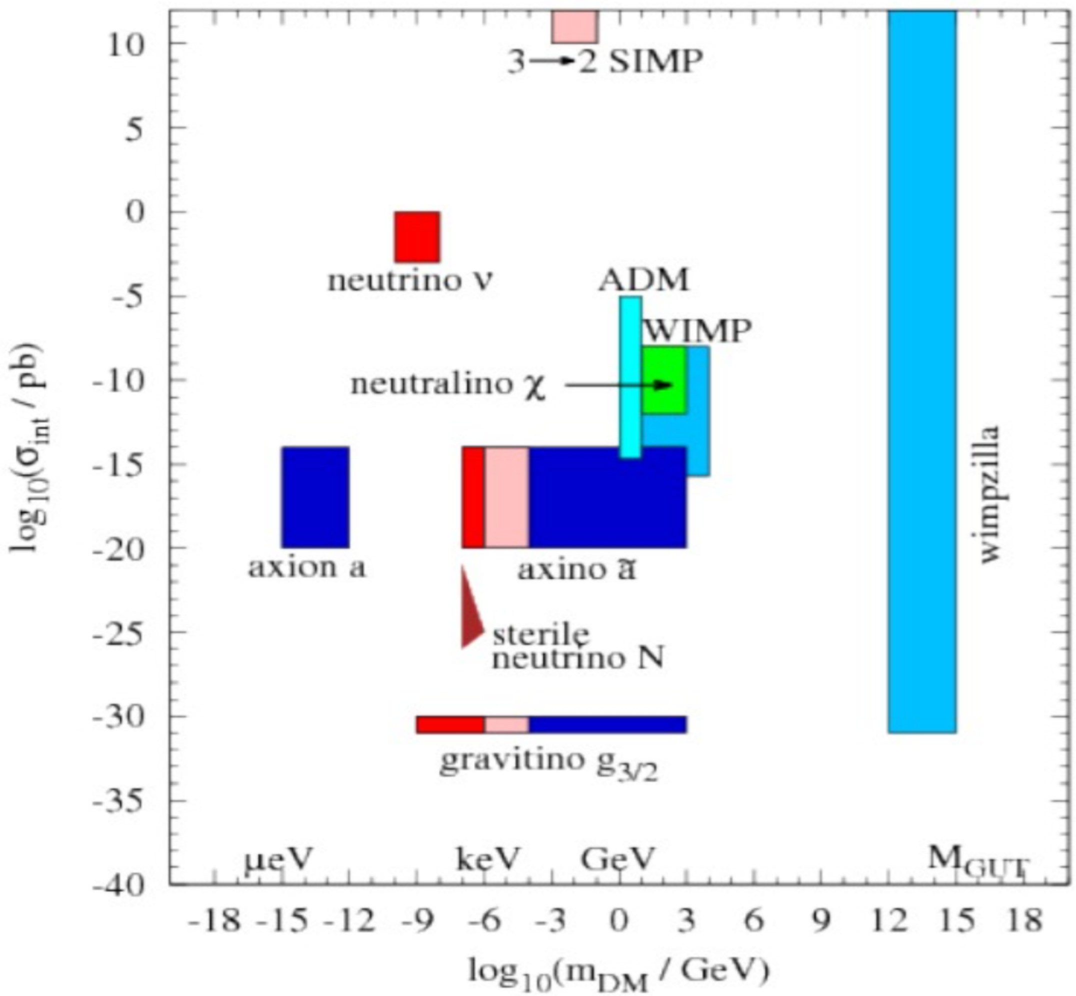
Hot (relavistic) dark matter excluded because smooths out structure

Relic density of dark matter

- CMB (WMAP then PLANCK) gives precise determination of amount of CDM (assuming standard cosmological model)
- $\Omega_{cdm}\, h^2 = 0.1196 +/- \ 0.0031$, $h = 0.674 +/- 0.014$

- What does that tell us about properties of a new stable particle that could form DM?

A wide variety of DM candidates



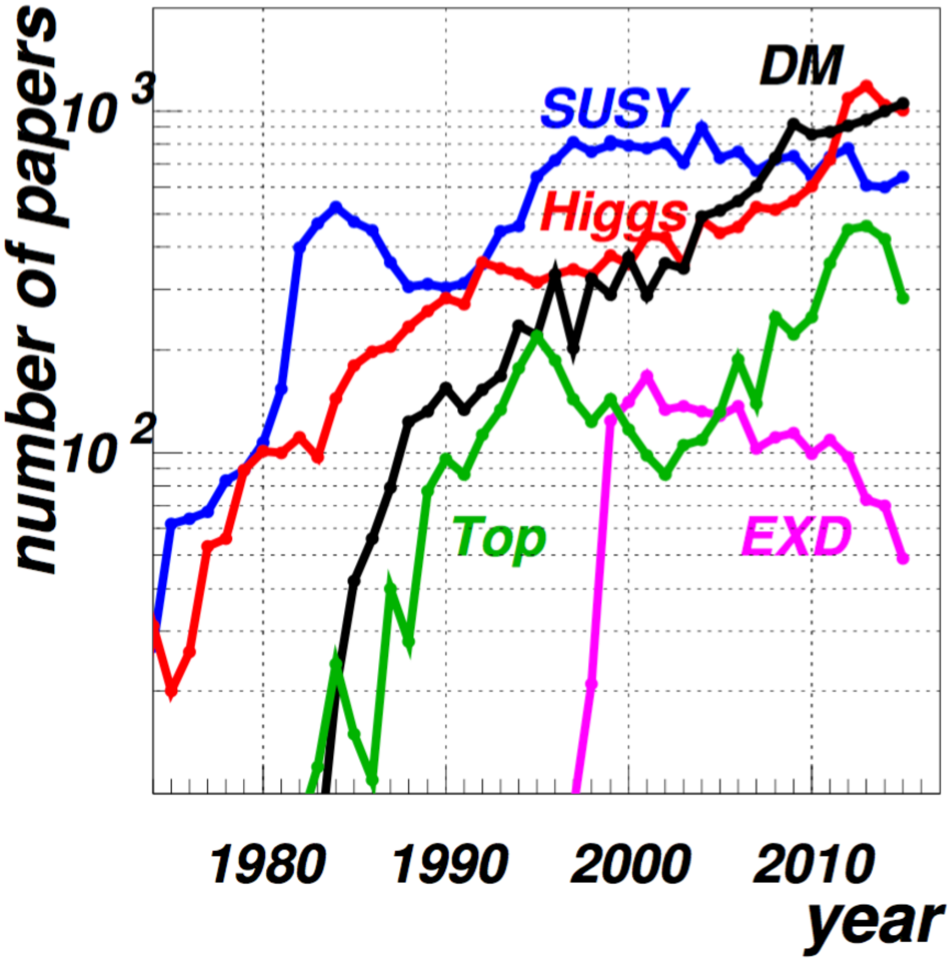
WIMPs

FIMPs

SIMPs

Asymmetric

… many publications



A. Belyaev

Because of strong evidence for DM, has become one of main motivation for BSM

Part 1 : WIMPs

Relic density of WIMPs

- Assume a new stable (very long-lived) neutral weakly-interacting particle
- Will be in thermal equilibrium when T of Universe much larger than its mass
- Equilibrium abundance maintained by processses

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

- As well as reverse processes, inverse reaction proceeds with equal rate

Boltzmann equation

- Describes interactions of wimp with photons and other relativistic particles in thermal bath before they decouple
- Number of part χ/unit volume -> creation – annihilation

$$\frac{1}{R^3}\frac{d\left(n_A R^3\right)}{dt} = \langle\sigma v\rangle_{B\to A} n_B^2 - \langle\sigma v\rangle_{A\to B} n_A^2$$

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

Depletion of χ due to annihilation

Creation of χ from inverse process

$$H = \dot{R}/R$$

H: Hubble expansion rate
R: scale factor of the Universe

Relic density of wimps

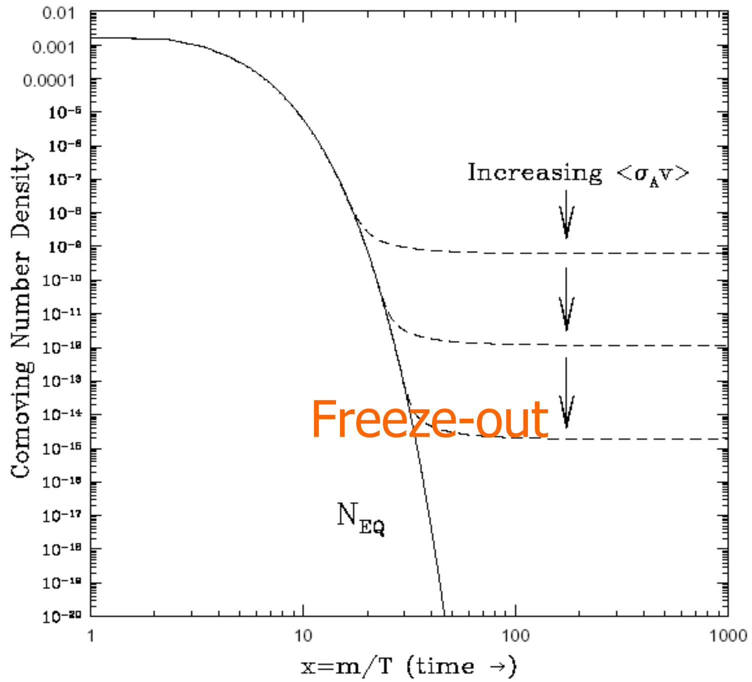
In early universe WIMPs are present in large number and they are in thermal equilibrium

As the universe expanded and cooled their density is reduced through pair annihilation

Eventually density is too low for annihilation process to keep up with expansion rate

Freeze-out temperature

LSP decouples from standard model particles, density depends only on expansion rate of the universe



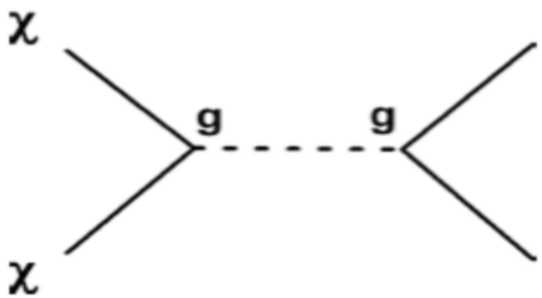
$$\frac{dn}{dt} = -3Hn - <\sigma v> \left[n^2 - n_{eq}^2\right]$$

Dark matter: a WIMP?

In standard scenario, relic abundance

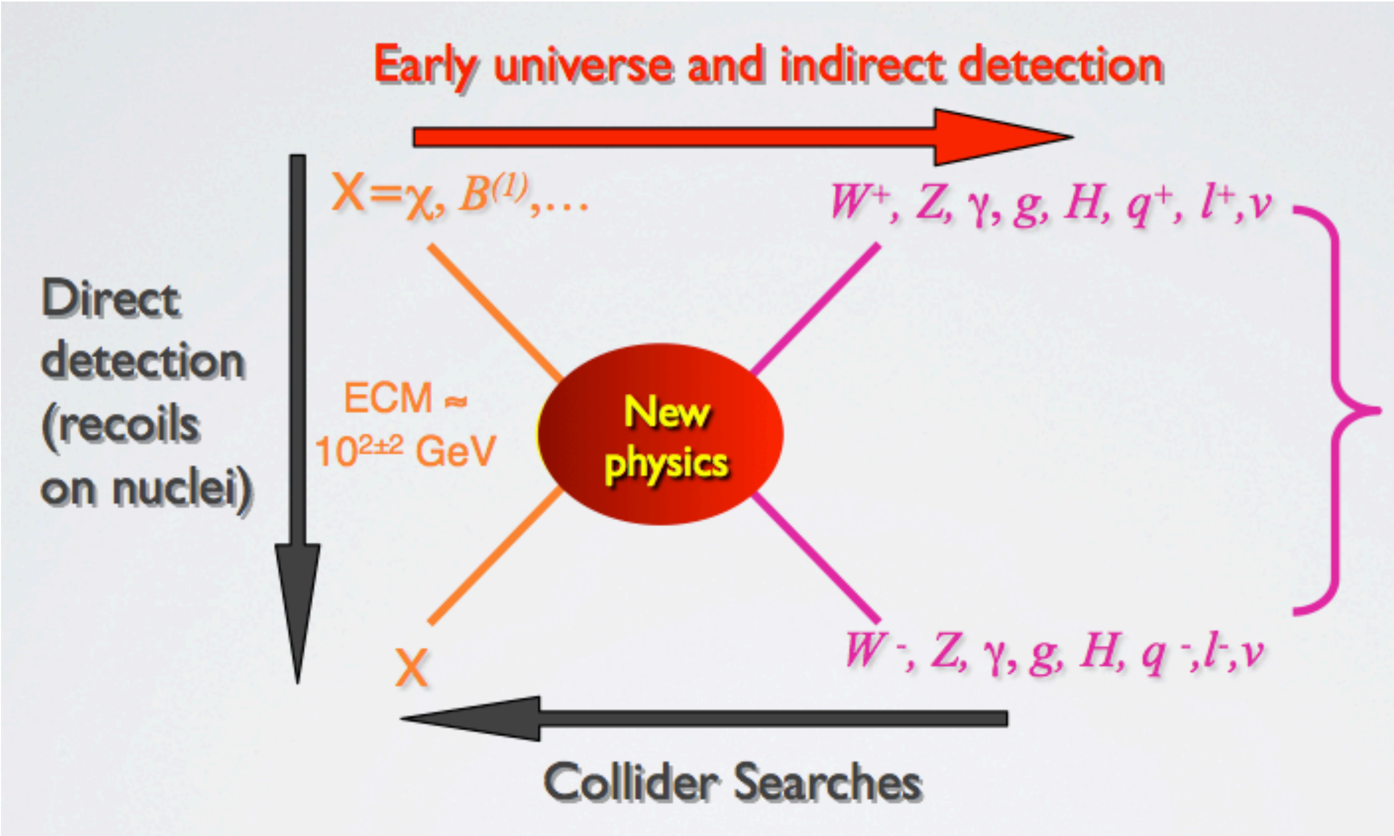
$$\Omega_X h^2 \approx \frac{3 \times 10^{-27}\mathrm{cm}^3\mathrm{s}^{-1}}{\langle \sigma v \rangle} \ .$$

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)



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

Probing the nature of dark matter



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

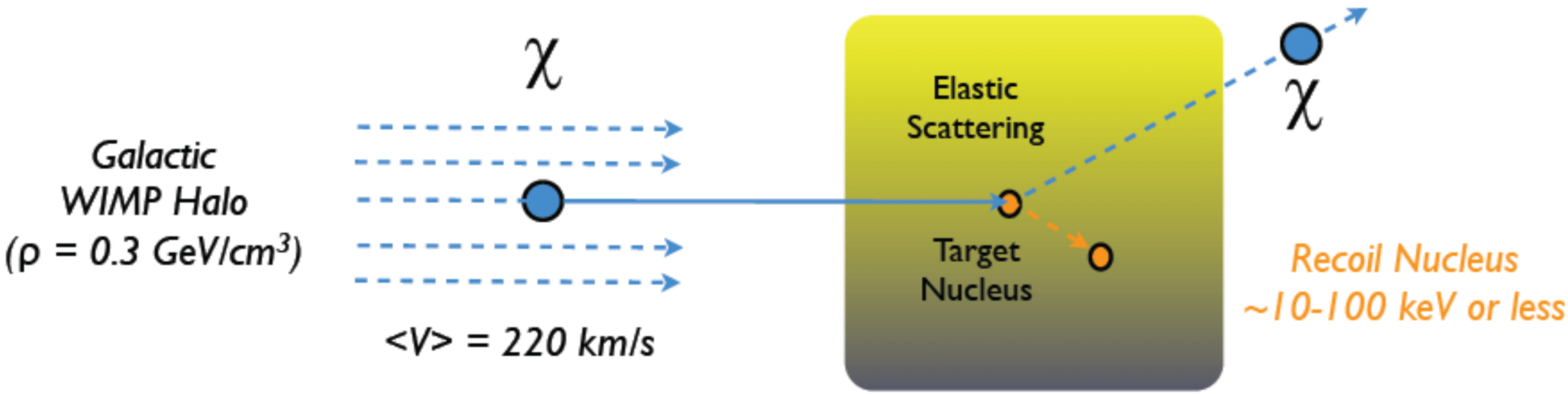
Constraints on WIMPs

- Reproduce the measured relic density assuming standard cosmological model
- Limits from astroparticle searches
  - Direct detection (LUX, CDMS, Xenon, Cresst, DAMIC, DAMA….)
  - Indirect detection (FermiLAT, HESS, Magic, AMS …) in particular with photons, positrons, antiprotons etc..
  - Neutrinos (IceCUbe)
- Hints in astroparticle searches
  - DAMA/CoGenT, CDMS-SI, Fermi-LAT Galactic Center, PAMELA, AMS02
- Collider constraints (model dependent – stability at collider scale only)

Direct detection

- Elastic scattering of WIMPs (weakly interacting massive particle) off nuclei in a large detector
- Measure nuclear recoil energy, E_R

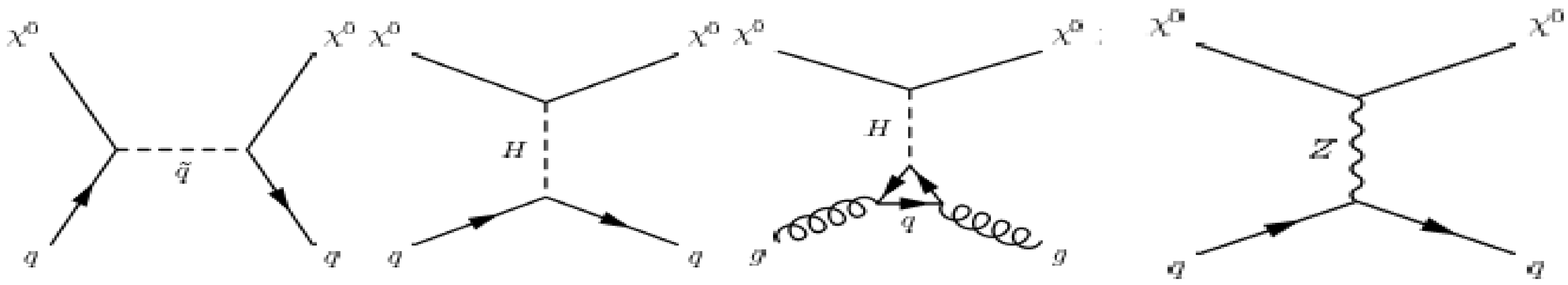
- Best way to prove that WIMPs form DM



Direct detection

- Particle physics : effective Lagrangian for WIMP-nucleon and wimp-quark amplitude *at small momentum transfer (~100MeV)*
- For spin independent (Majorana fermion)

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



For Dirac fermions Z exchange contributes to SI and SD

WIMP-nucleus

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

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

Nuclear form factors

Particle physics
+ quark content in nucleon

DM velocity distribution

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

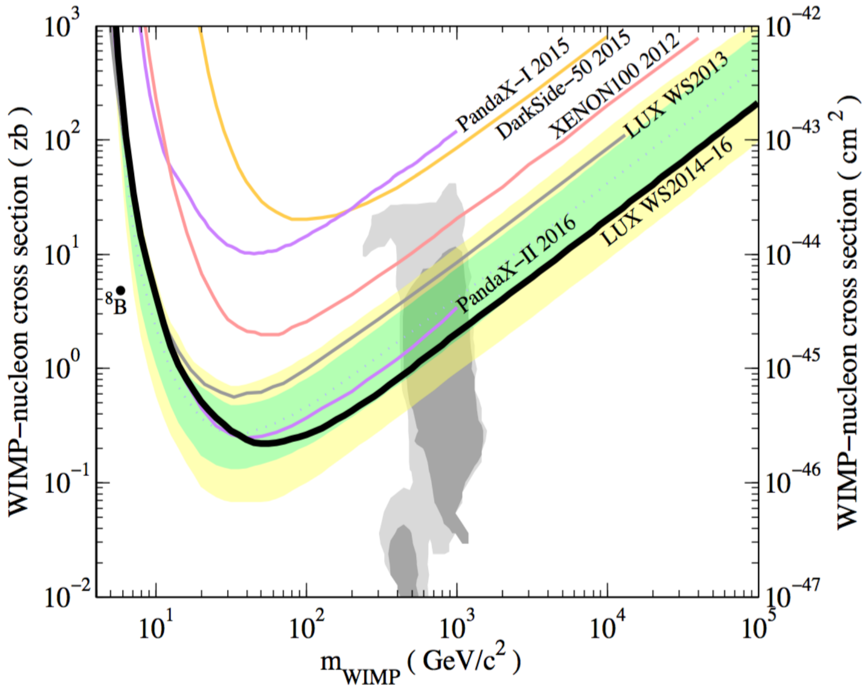
$$v_{min}(E) = \left(\frac{EM_A}{2\mu_\chi^2}\right)^{1/2}$$

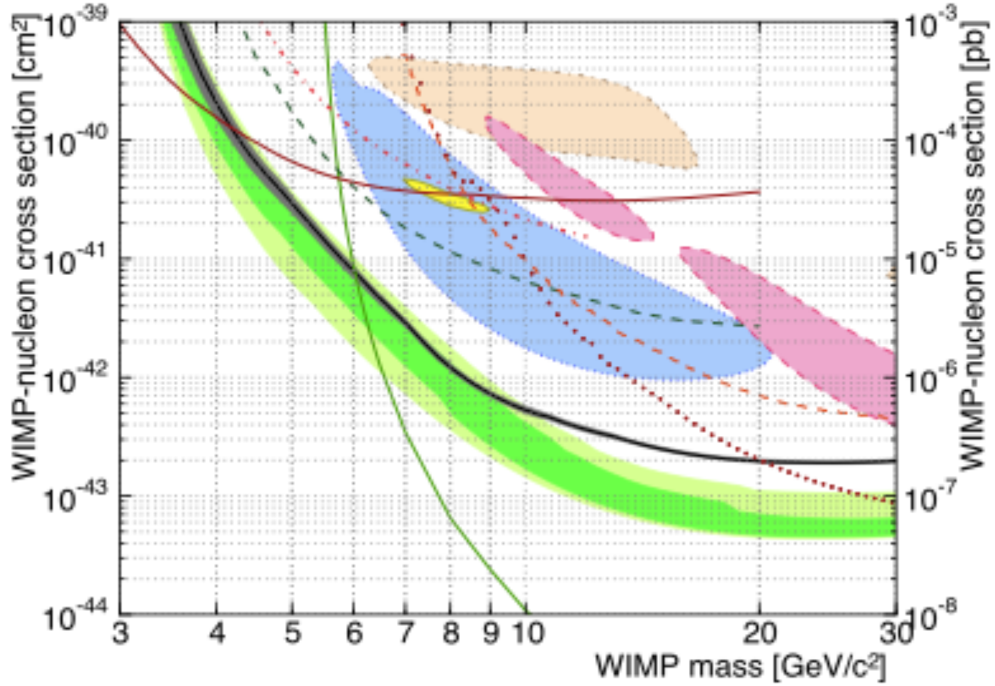
- For easy comparison between expt, assume $\lambda_p=\lambda_n$

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

Spin independent

Elastic scattering of DM
off nucleons in a large detector



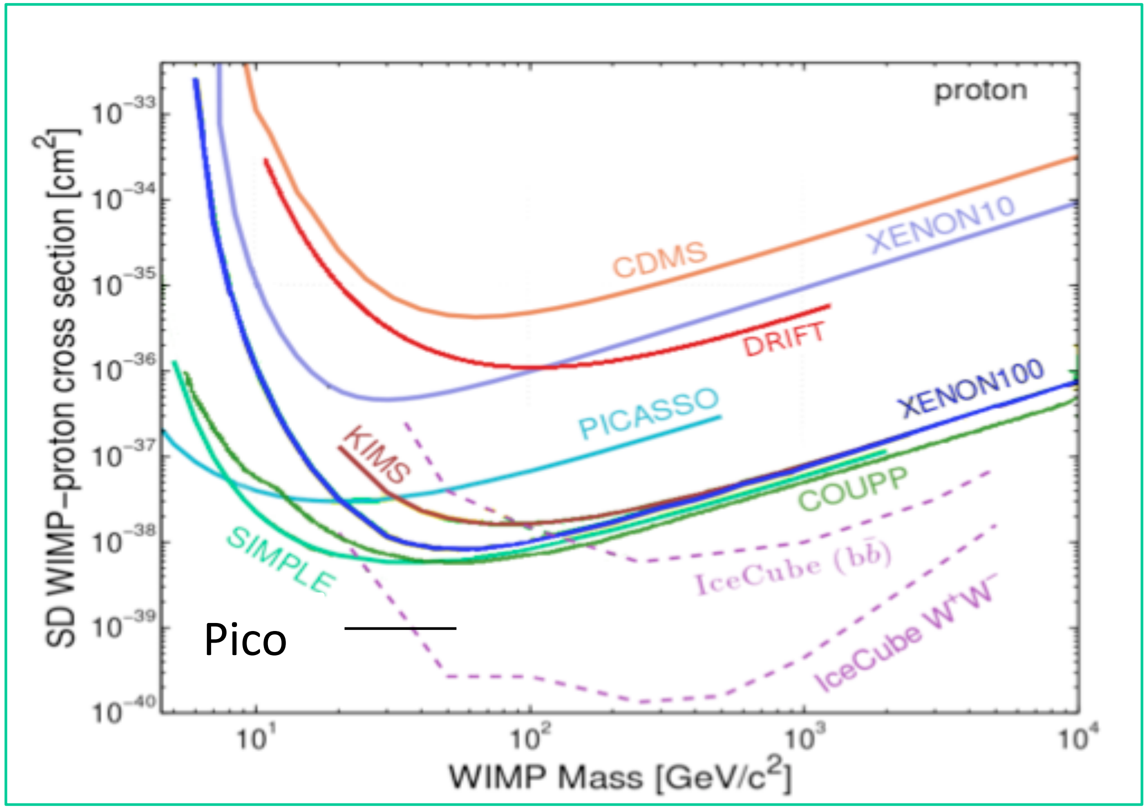


Much improved limit on SIcross section – PandaX and LUX (Akerib et al 1608.07648) also at low mass CDMS

Assuming f_p=f_n, rules out CDMS-Si, CoGENT, DAMA..

Limits spin dependent

Pico: 1503.00008

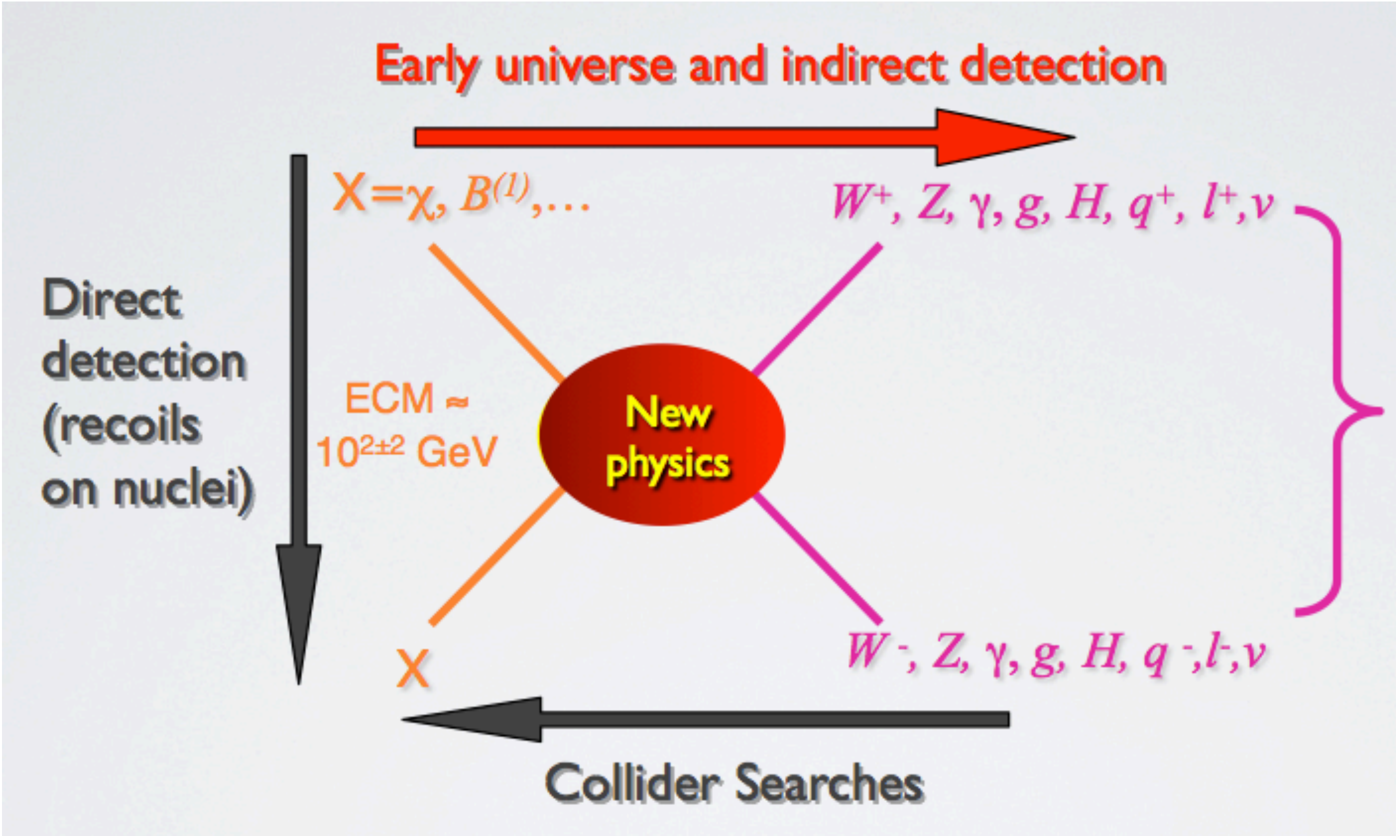


Cross sections probed are much larger than for SI

Just reaching the sensitivity to probe more popular DM model (MSSM)

Searching for dark matter at the LHC

Probing the nature of dark matter



- All determined by interactions of WIMPS with Standard Model
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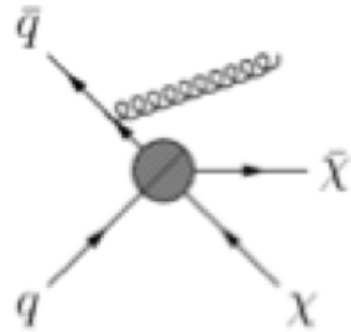
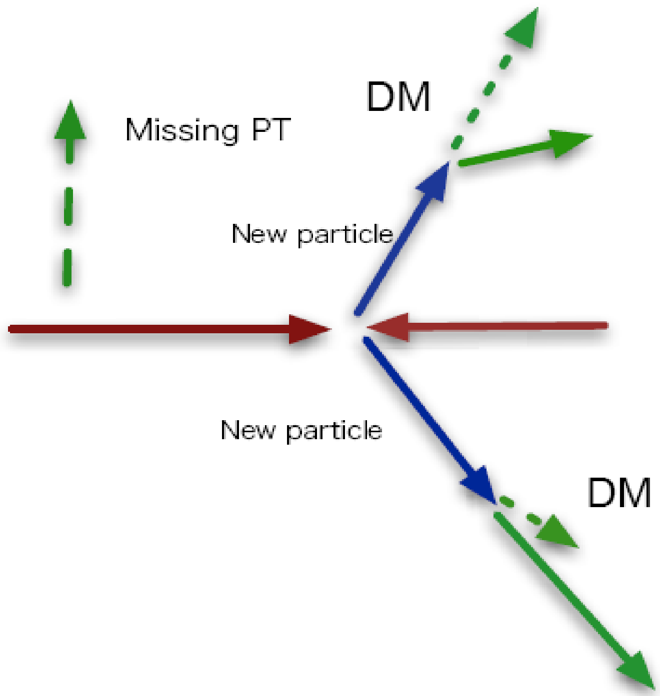
DM production at LHC

- pp collider 7-8TeV (Run 1) and 13TeV (Run2)
- DM direct production : missing energy (need additional particle to trigger) – monojet, monophoton, mono-X
- DM in Higgs decays
- Production of coloured particles: DM in decay chain (MET+..)
- Charged tracks and displaced vertices (for quasi stable NLDSP –next-lightest dark sector particle)
- Production of mediator (in standard channels)

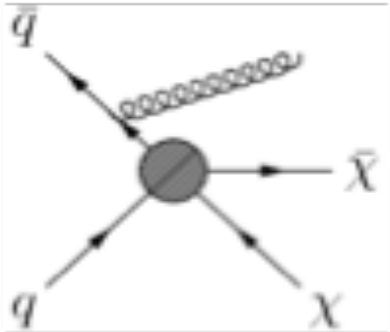


(a) $q\bar{q} \to \chi\chi + g$

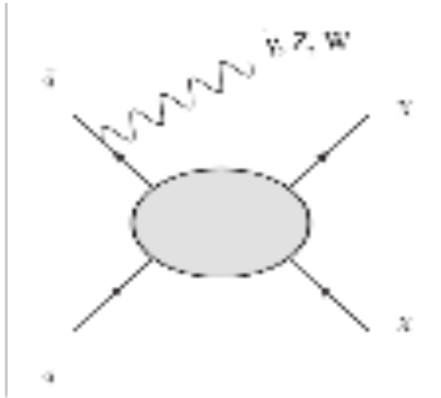


EFT/simplified model approach

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



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



(b) $q\bar{q} \rightarrow \chi\chi + \gamma, Z, W$

Effective interaction operators

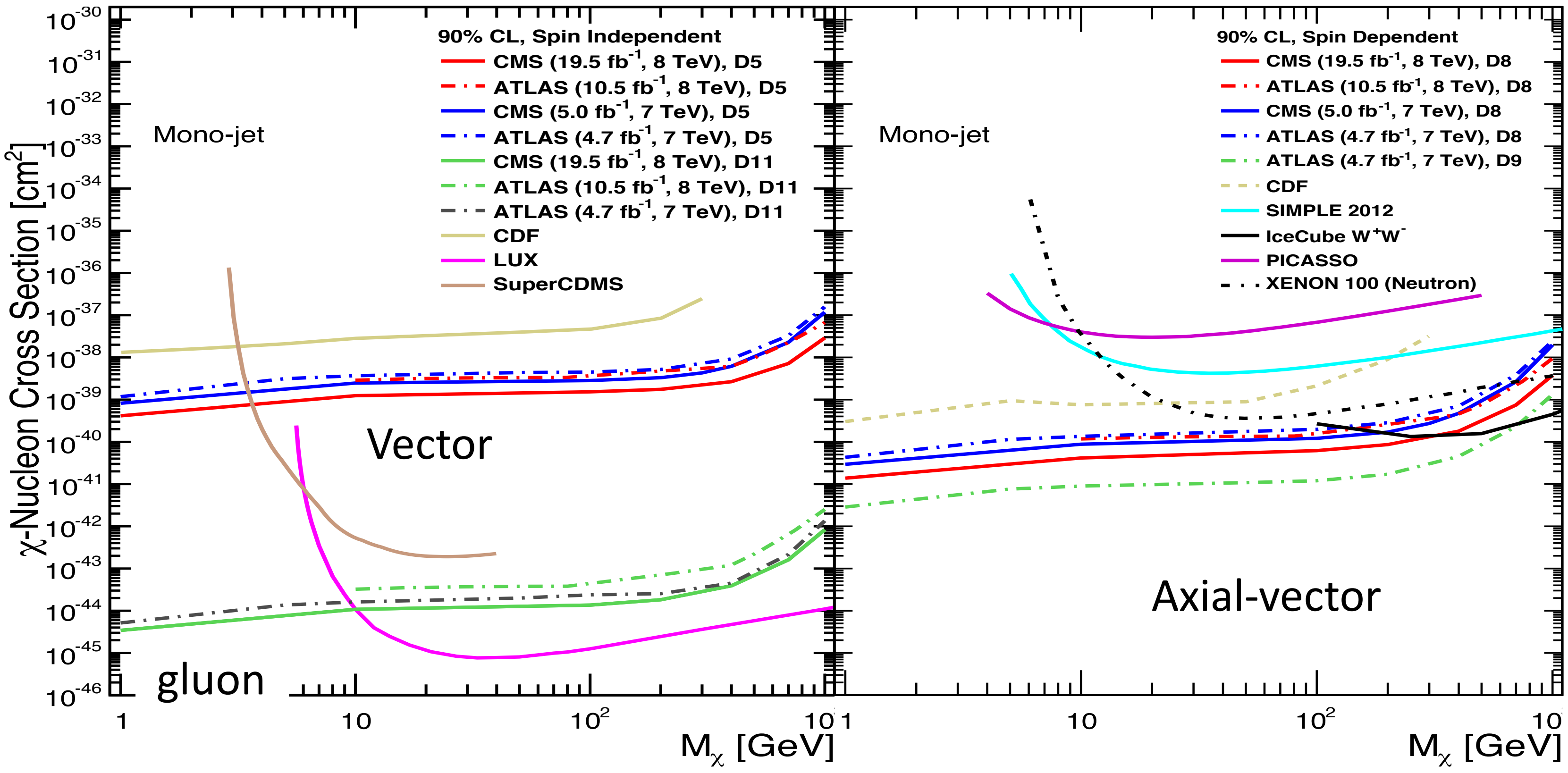
(a)Operators for Dirac fermion DM

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

For each operator : monojet limit --> limit on direct detection

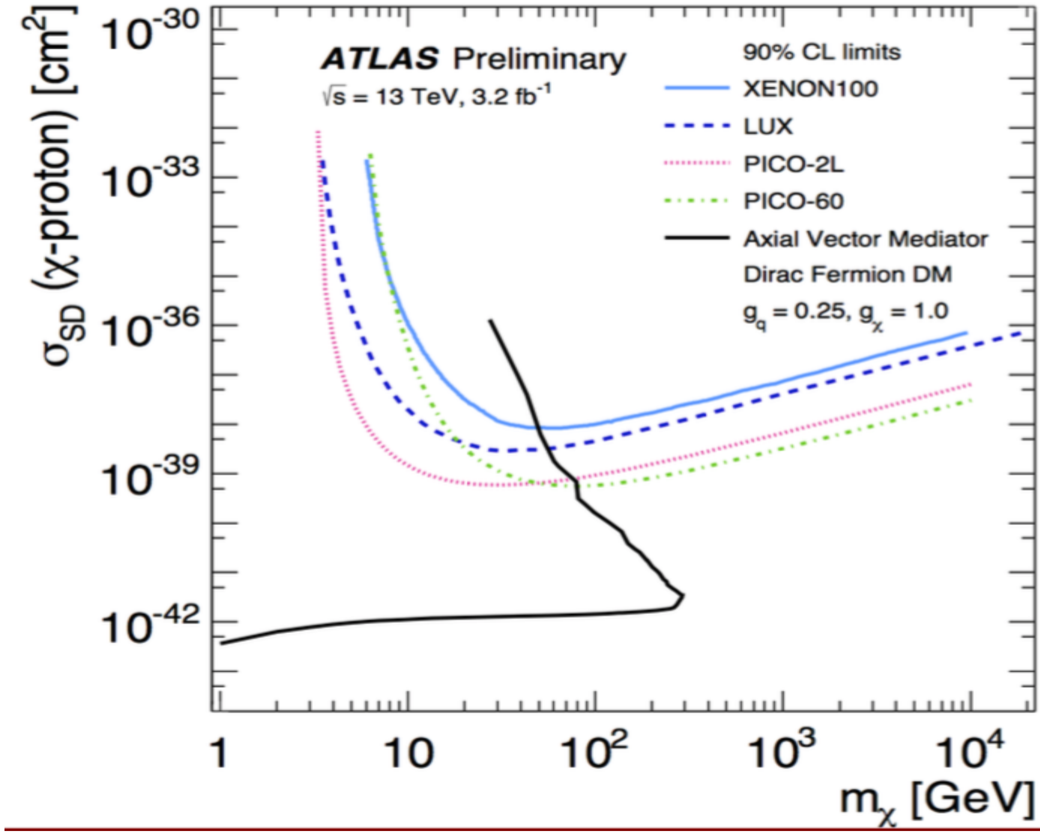
Caveats : monojet limit valid assuming scale NP large -> simplified models

– LHC not very sensitive to scalar operators with couplings proportional to mass



From EFT to simplified model

The case of axial vector mediator : for certain masses much improve sensitivity



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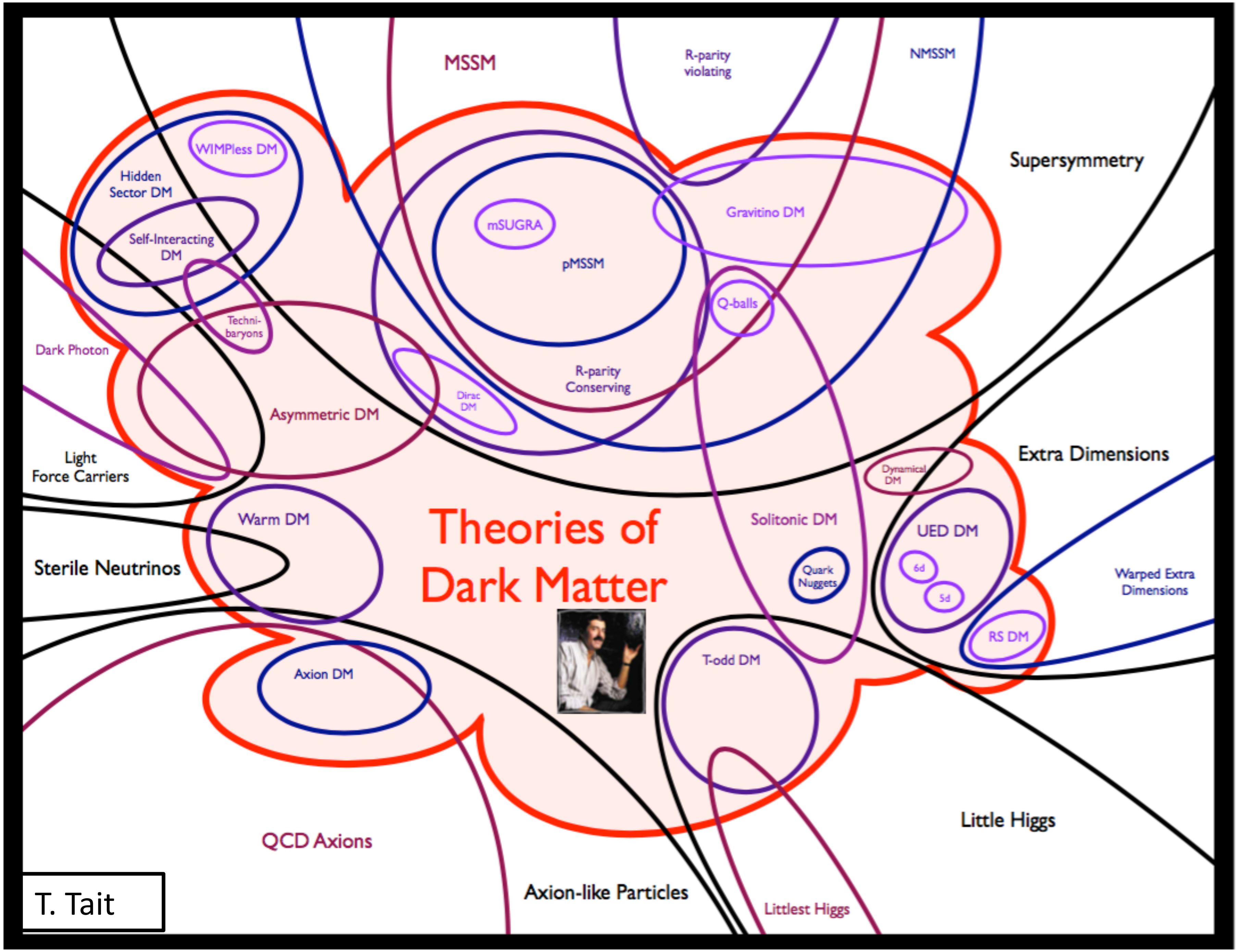
Other channels : mono-W, heavy flavour+DM –

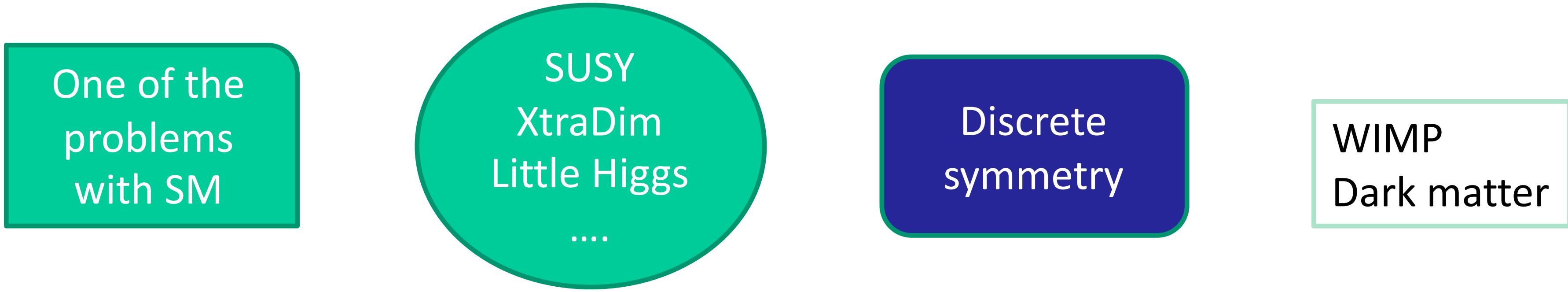
Wimp dark matter candidates


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

Beyond the standard model

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

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



Interplay Collider, dark matter searches, cosmology

Bottom-up approach

Start with stable neutral particle, and build from there (mediator, other dark particles) exploiting hints from data LHC or astroparticle searches

Here both approaches…

Supersymmetric dark matter
Status

Supersymmetry

Motivation: unifying matter (fermions) and interactions (mediated by bosons)

Symmetry that relates fermions and bosons

Prediction: new particles supersymmetric partners of all known fermions and bosons : differ spin 1/2

Not discovered yet

Hierarchy problem

SUSY particles (~TeV) to stabilize Higgs mass against radiative corrections →should be within reach of LHC

R-parity and dark matter

Minimal supersymmetric standard model

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

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

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

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

Susy features

New particles stabilize Higgs mass (~100GeV) against radiative corrections

If supersymmetry is exact each SM fermion contribution is cancelled by that of two scalar partners ($\lambda_S = \lambda_F^2$)

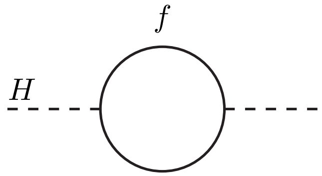
Quadratic divergences still cancelled if only soft susy breaking terms

SU(3), SU(2), U(1) coupling constants unification at high scale in MSSM but not in SM

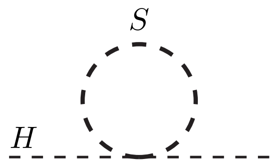
No susy particle found

$$-\lambda_f H\overline{f}f$$

$$-\lambda_S|H|^2|S|^2.$$



(a)



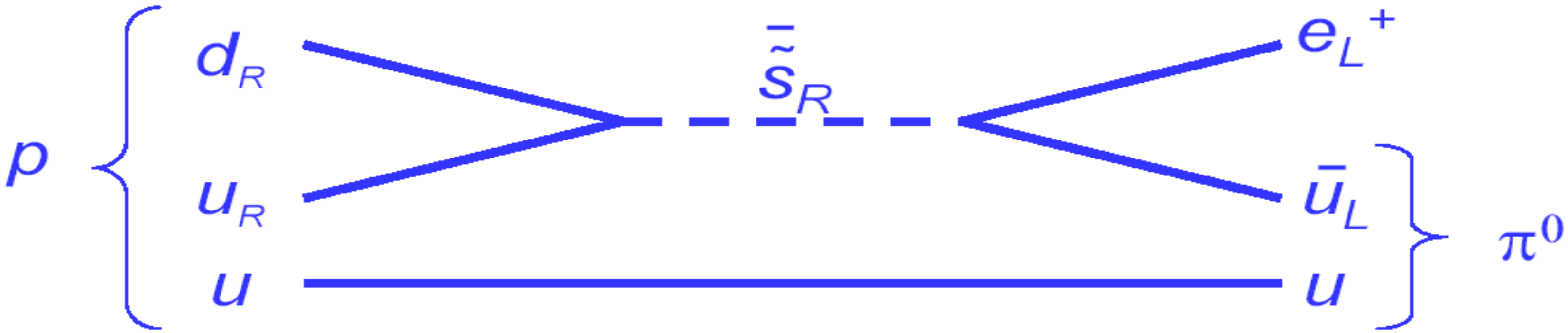
(b)

$$\Delta m_H^2 = -\frac{|\lambda_f|^2}{8\pi^2}\Lambda_{\mathrm{UV}}^2$$

$$\Delta m_H^2 = \frac{\lambda_S}{16\pi^2}\left[\Lambda_{\mathrm{UV}}^2\right.$$

Each increase quadratically with energy

R-parity



Proton decay

To prevent this introduce R parity

$R=(-1)^{3B-3L+2S}$; R=1: SM particles R=-1 SUSY

The LSP is stable : could be a suitable DM candidate if neutral

Minimal Supersymmetric Standard Model

MSSM – soft terms

Supersymmetry must be broken - many possibilities :
write most general Lagrangian which violate SUSY without disturbing cancellation of quadratic divergences in scalar mass (Grisaru and Girardelo 1982)

$$-\mathcal{L}_{\text{gaugino}} = \frac{1}{2}\left[M_1 \tilde{B}\tilde{B} + M_2 \sum_{a=1}^{3} \tilde{W}^a \tilde{W}_a + M_3 \sum_{a=1}^{8} \tilde{G}^a \tilde{G}_a\right.$$

$$-\mathcal{L}_{\text{sfermions}} = \sum_{i=gen} m^2_{\tilde{Q}_i} \tilde{Q}_i^\dagger \tilde{Q}_i + m^2_{\tilde{L}_i} \tilde{L}_i^\dagger \tilde{L}_i + m^2_{\tilde{u}_i} |\tilde{u}_{R_i}|^2 + m^2_{\tilde{d}_i} |\tilde{d}_{R_i}|^2 + m^2_{\tilde{\ell}_i} |\tilde{\ell}_{R_i}|^2$$

$$-\mathcal{L}_{\text{Higgs}} = m^2_{H_2} H_2^\dagger H_2 + m^2_{H_1} H_1^\dagger H_1 + B\mu (H_2 \cdot H_1 + \text{h.c.})$$

$$-\mathcal{L}_{\text{tril.}} = \sum_{i,j=gen} \left[A^u_{ij} Y^u_{ij} \tilde{u}^*_{R_i} H_2 \cdot \tilde{Q}_j + A^d_{ij} Y^d_{ij} \tilde{d}^*_{R_i} H_1 \cdot \tilde{Q}_j + A^l_{ij} Y^\ell_{ij} \tilde{\ell}^*_{R_i} H_1 \cdot \tilde{L}_j \ + \ \text{h.c.}\right]$$

Real parameters and no flavour structure : reduce from 105 to 22 parameters

Neutralino dark matter

- No theoretical prejudice
- Simplified discussion : consider only parameters relevant for neutralino sector – assume all sfermions are heavy
- Neutralino is mixed state – exact nature will determine its annihilation properties - wide range of predictions for DM interactions

The neutralino mass matrix

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

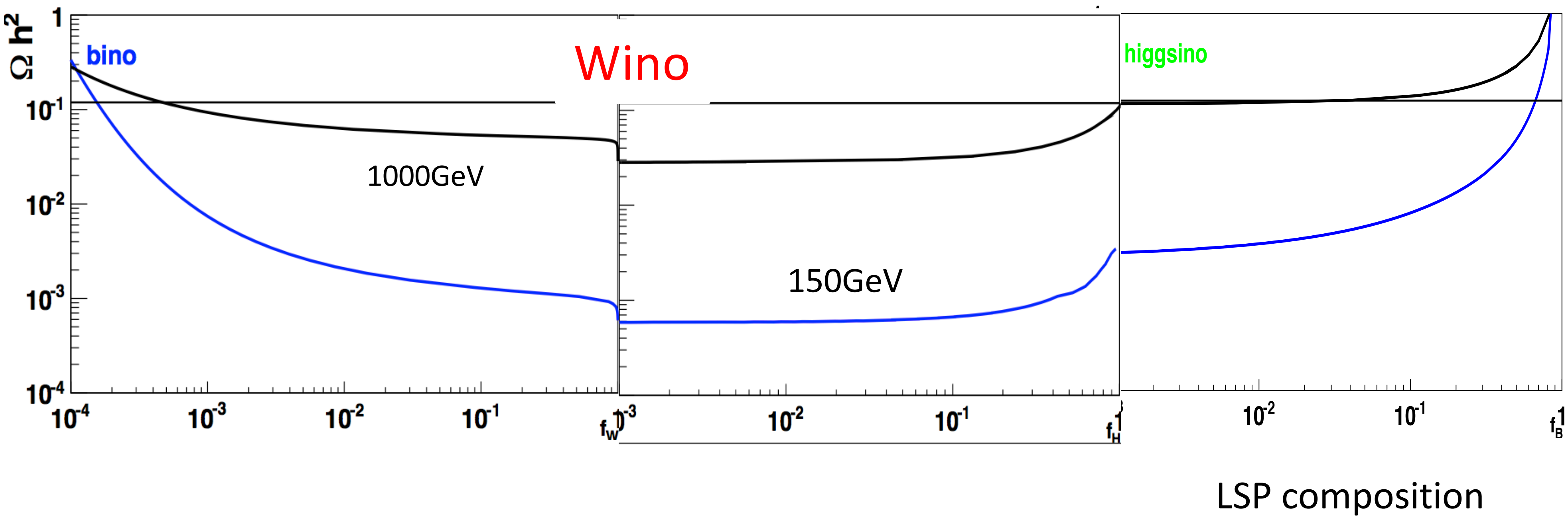
Mass and nature of neutralino LSP : determined by smallest mass parameter

- $M_1 < M_2, \mu$ 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…

In most studied SUSY model CMSSM the LSP is usually bino -> theoretical bias

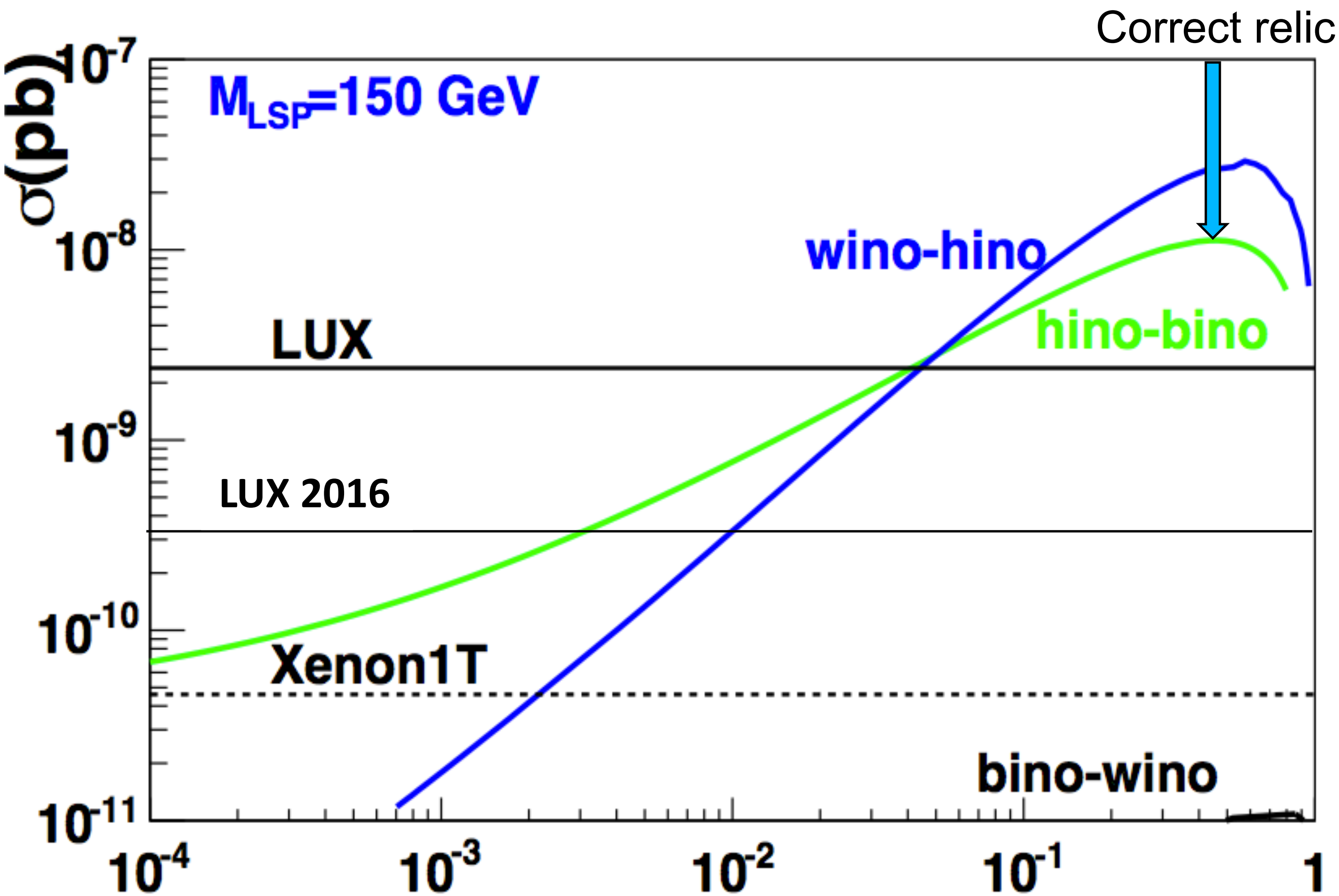
Relic density of neutralino



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
Exception : bino overdominant
Higgsino and wino mean degenerate particles-

Direct detection

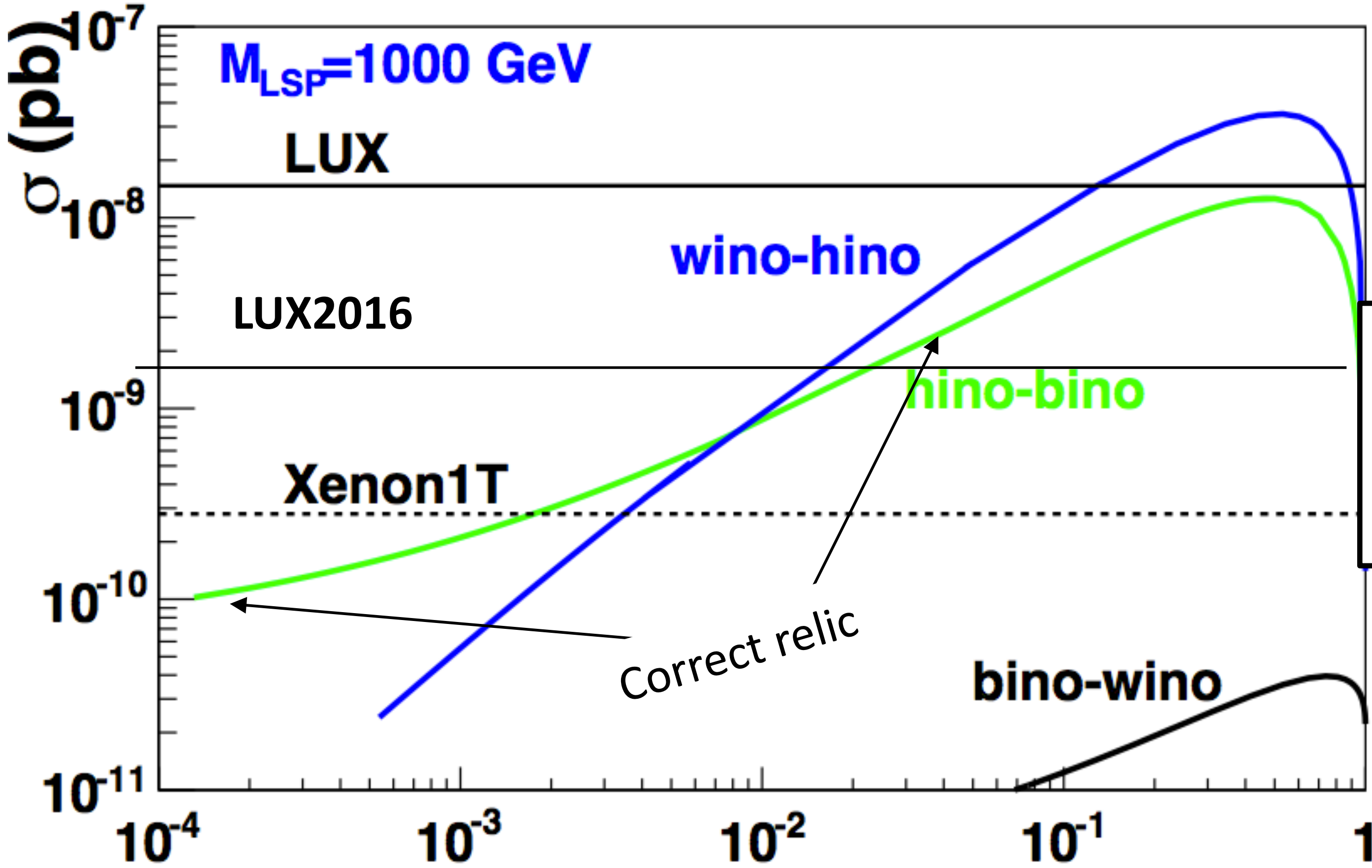


Constraints from DD (LUX) on neutralinos (mixed higgsino-bino) that naturally reproduce measured relic density
Bino-wino escape detection

Direct detection

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

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



1TeV Mixed higgsino/bino mostly compatible with relic+DD

Neutralino LSP

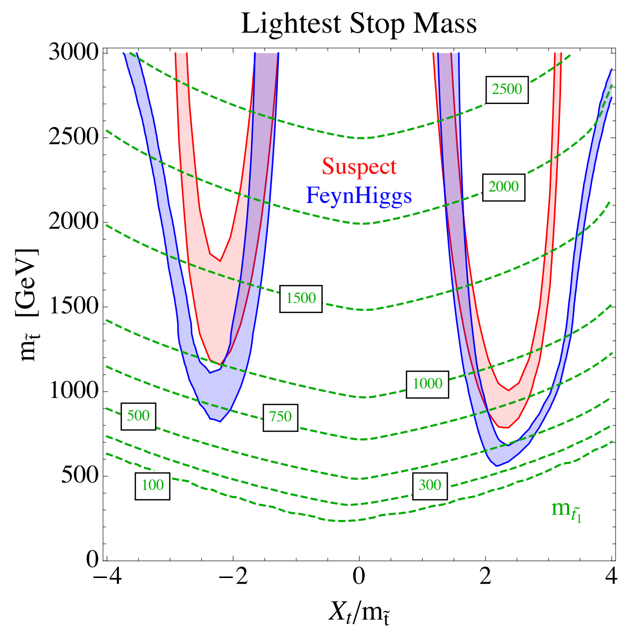
- Relic density constraint + exclusion by direct detection -> favours neutralino DM at TeV scale or mixed bino/wino or requires an additional DM candidate
- Way out?
  - Theoretical input: impose specific conditions on spectrum
  - For example : bino LSP with special mechanism to reduce relic density – coannihilation with sfermions or $m_{LSP} = m_H/2$ (resonant annihilation)

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

Light Higgs mass

Upper bound on Higgs mass

$$m_h < m_Z \cos 2\beta$$



- Mass at 125 GeV
  - need large radiative corrections

$$m_h^2 = M_Z^2 \cos^2 2\beta + \delta_t^2$$

  - δ_t~85 GeV (comparable to tree-level)
  - Large stop mixing

$$m_h^2 \approx m_Z^2 \cos^2 2\beta + \frac{3}{(4\pi)^2}\frac{m_t^4}{v^2}\left[\ln\frac{m_{\tilde{t}}^2}{m_t^2} + \frac{X_t^2}{m_{\tilde{t}}^2}\left(1 - \frac{X_t^2}{12 m_{\tilde{t}}^2}\right)\right]$$

$X_t = A_t - \mu/\tan\beta$

The MSSM case

Fine-tuning issue

$$M_Z^2 \simeq -2\mu^2 + \frac{2(m_{H_d}^2 - \tan^2\beta\, m_{H_u}^2)}{\tan^2\beta - 1}$$

Unless μ ~O(100)GeV (natural SUSY) need large cancellation

– implications for DM since μ determines the Higgsino component of the LSP

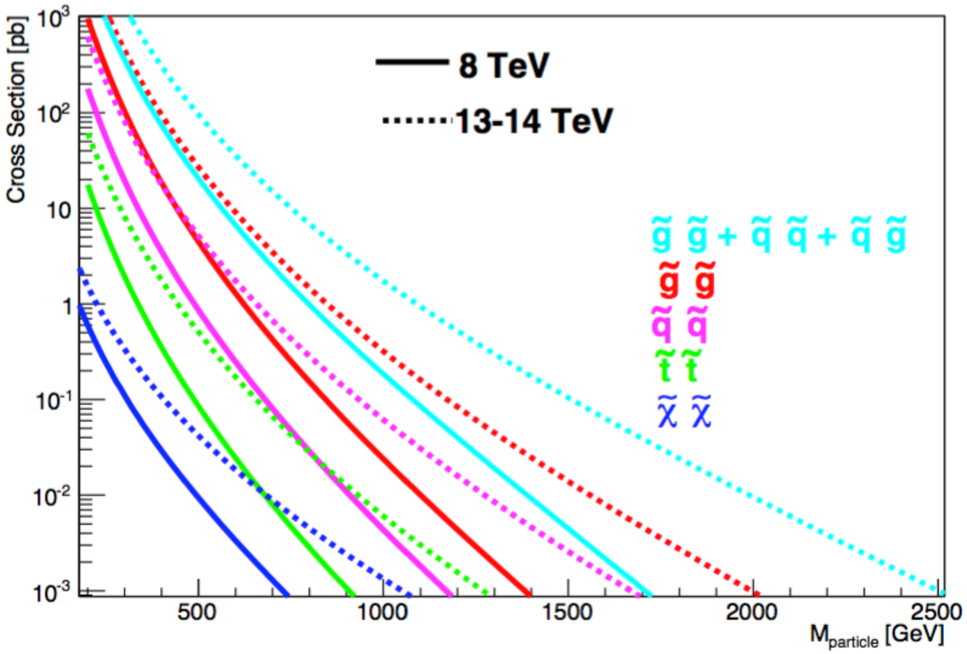
Fine-tuning also from radiative corrections – m_{Hu} strong dependence on parameters of stop sector

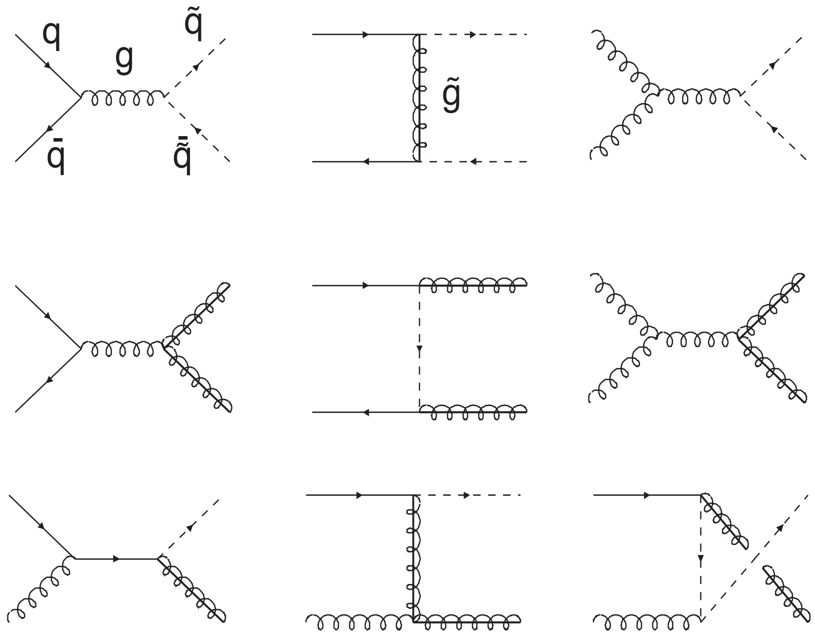
$$\delta m_{H_u}^2 = -\frac{3y_t^2}{8\pi^2}\left(m_{Q_3}^2 + m_{u_3}^2 + |A_t|^2\right)\ln\left(\frac{\Lambda}{m_{\tilde{t}}}\right)$$

What about LHC ?

SUSY production LHC

Standard susy searches : coloured particles

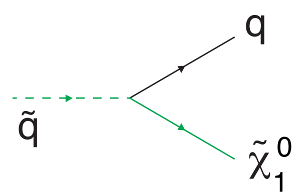


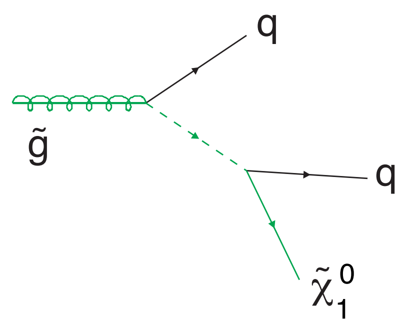


Cross section (13TeV/8TeV):
Gluino (1.4TeV) ~25
Stop/sbottom (750 GeV) ~10

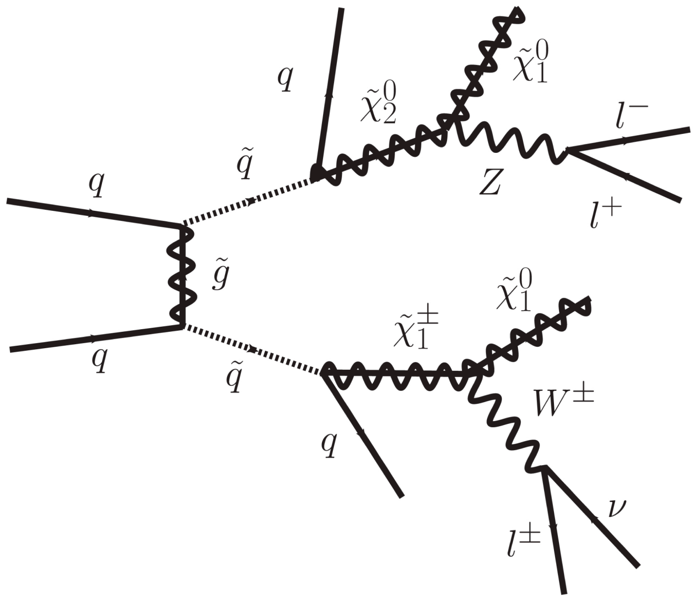
LHC – SUSY

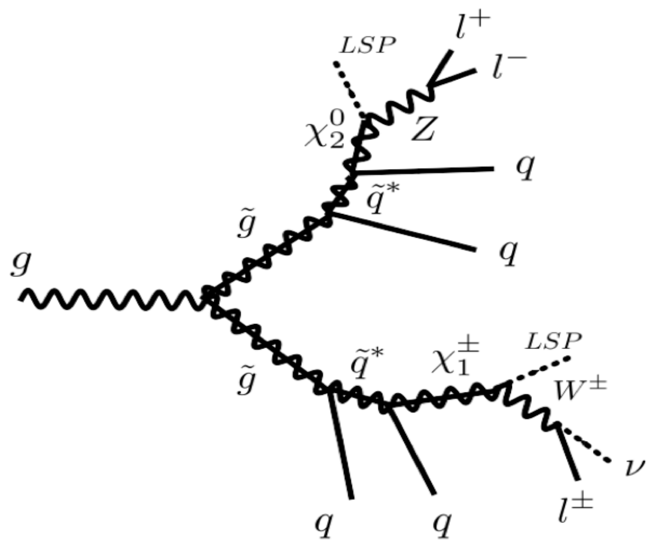
- Signatures of squarks and gluinos : jets+MET





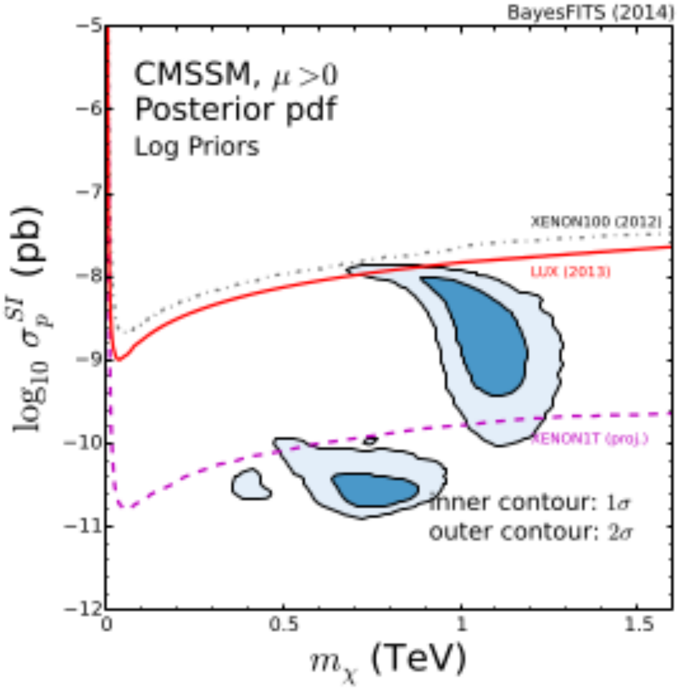
- Jets+MET +Leptons





A constrained model

- Traditionally predictions in context of CMSSM (scenario with parameters defined at unification scale) only handful of parameters
- Neutralino is generally bino U(1) or bino/higgsino
- Relations between masses of particles – e.g. $m_{gluino} \sim 6\ m_{LSP}$
- LHC has put strong constraints on this model – because m_h=125GeV with SM-like couplings, no squarks and/or gluino discovered , no evidence of SUSY in B physics
- What's left after fit to all observables
  - Relic, LUX, flavour LHC
  - L. Rozkowski, 1405.4289



SUSY search channels

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

SUSY search channels

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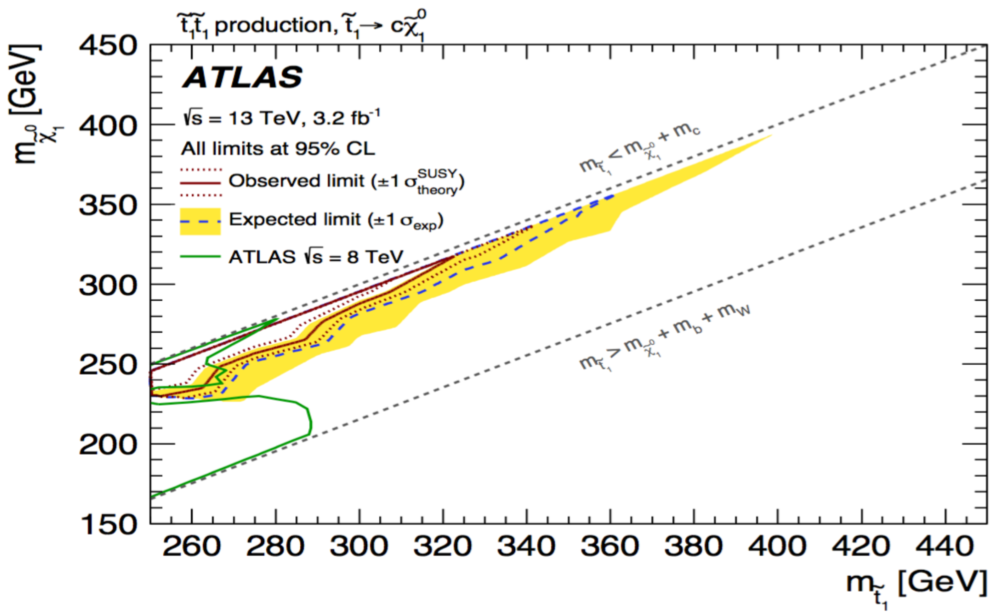
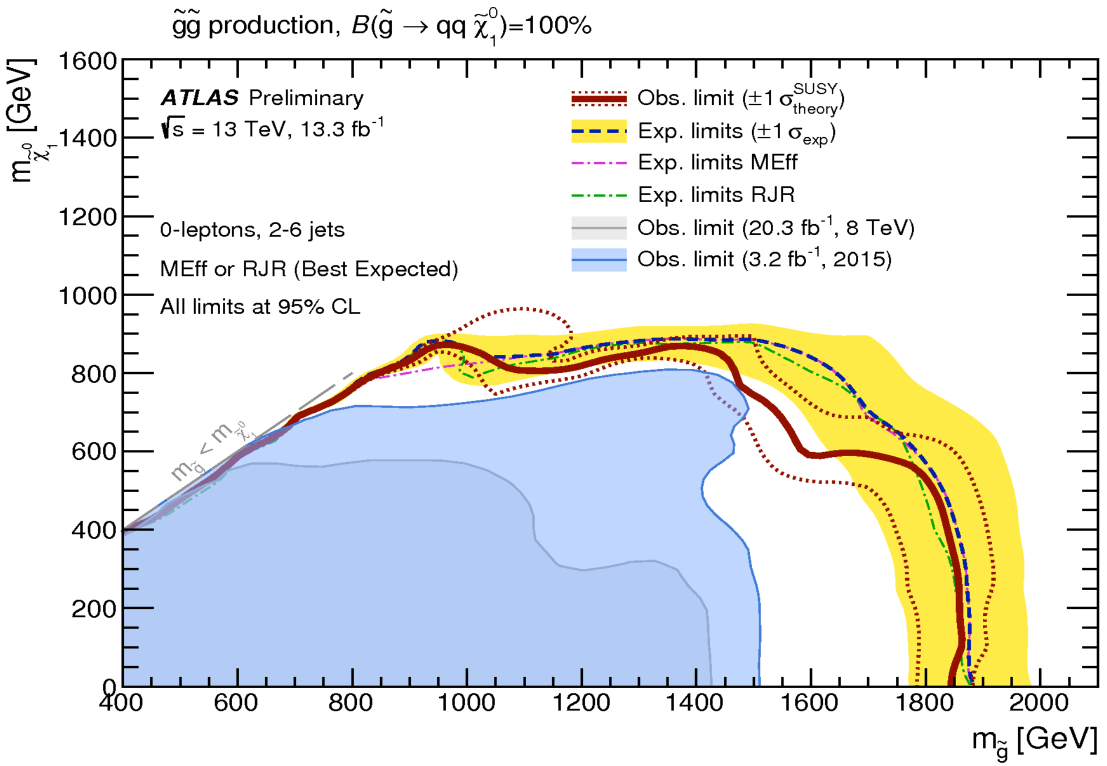
Monojet :
ATLAS Collab.
1604.07773



0lepton+jets+MET

- Wide ranging sensitivity to strong particle production with squark-> q+LSP and gluino-> qq+LSP + various cascade decays

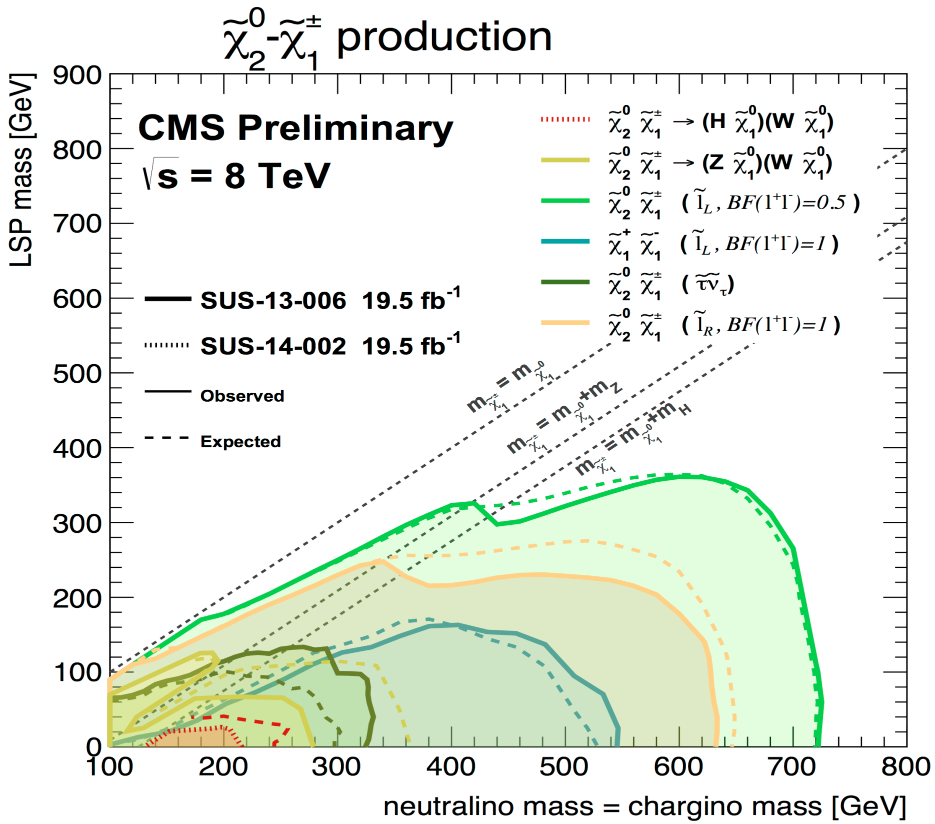


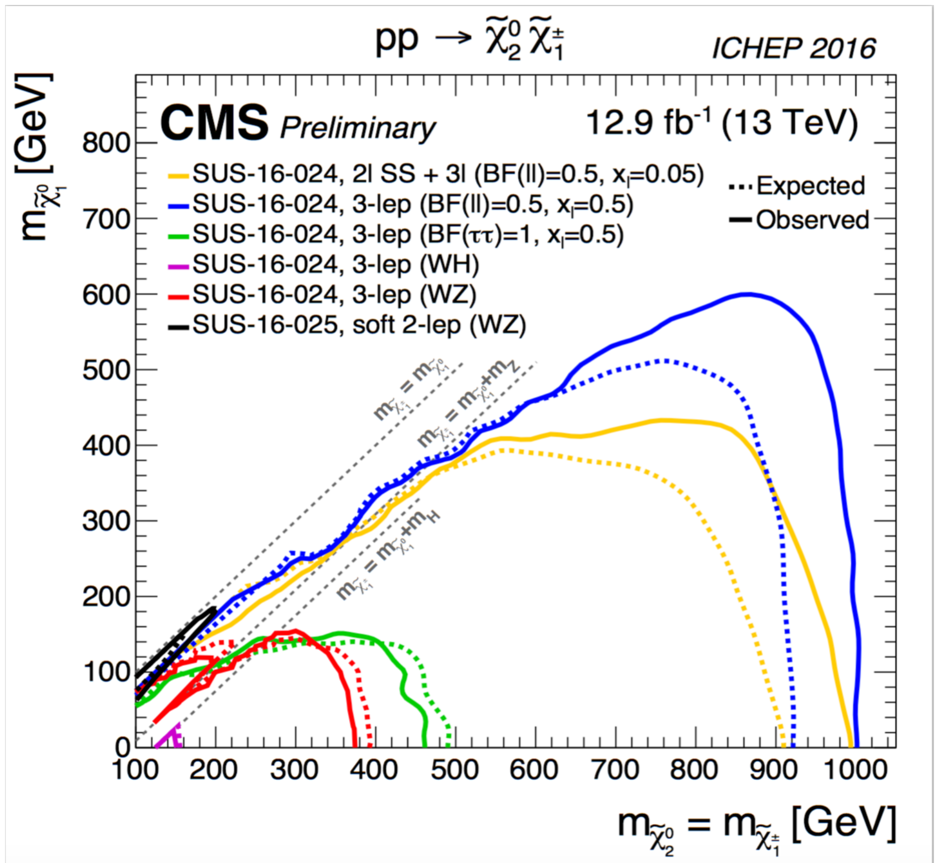
13 TeV

mgluino>1850 GeV

Electroweak-inos

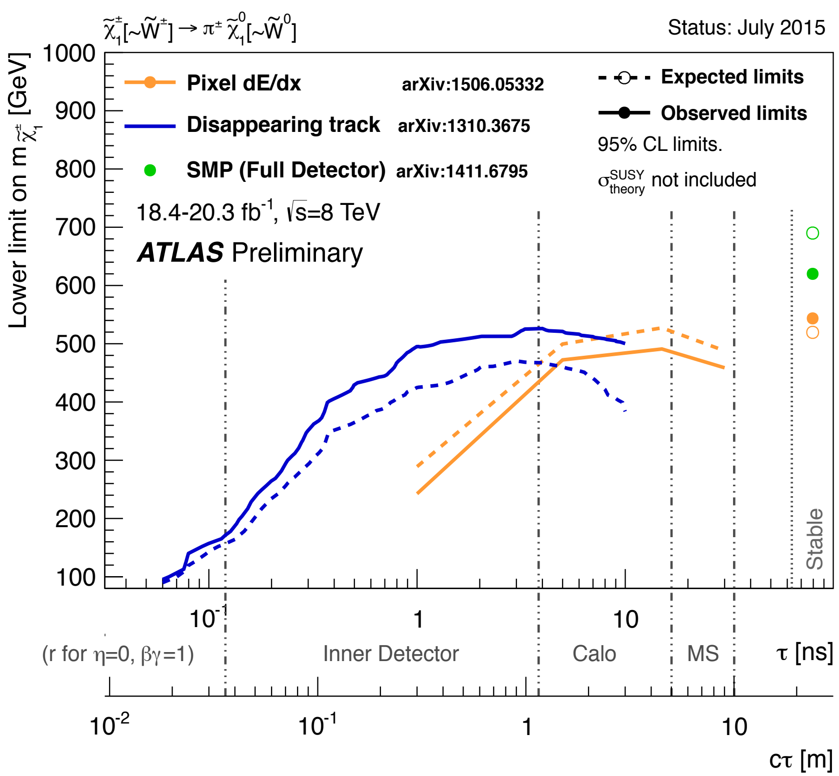
- Direct connection with dark matter (neutralino sector)
- Reach dependent on search channel (here simplified model)
- Weak constraints on charginos which decay into gauge bosons



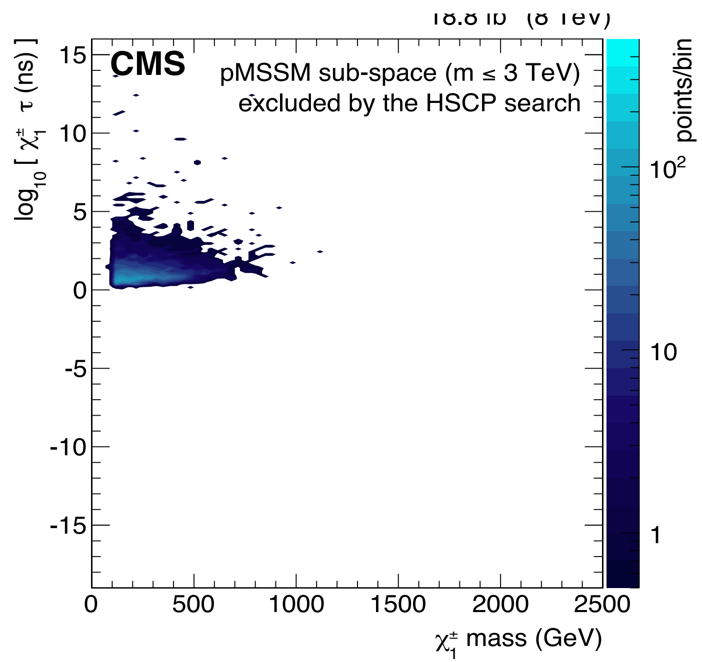


Long-lived particles

- In SUSY, charged/neutral winos have very small mass splitting (<3GeV) -> displaced vertex, disappearing tracks, slow moving particles
- Recall : cannot explain all DM



ATLAS 1506.05332



CMS 1502.02522

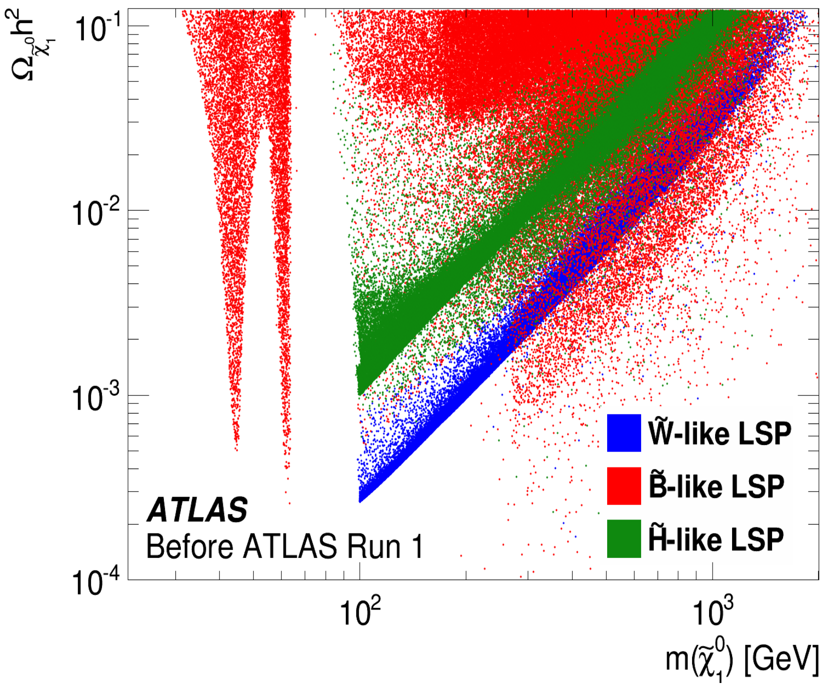
What's left after LHC (only Run 1)

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

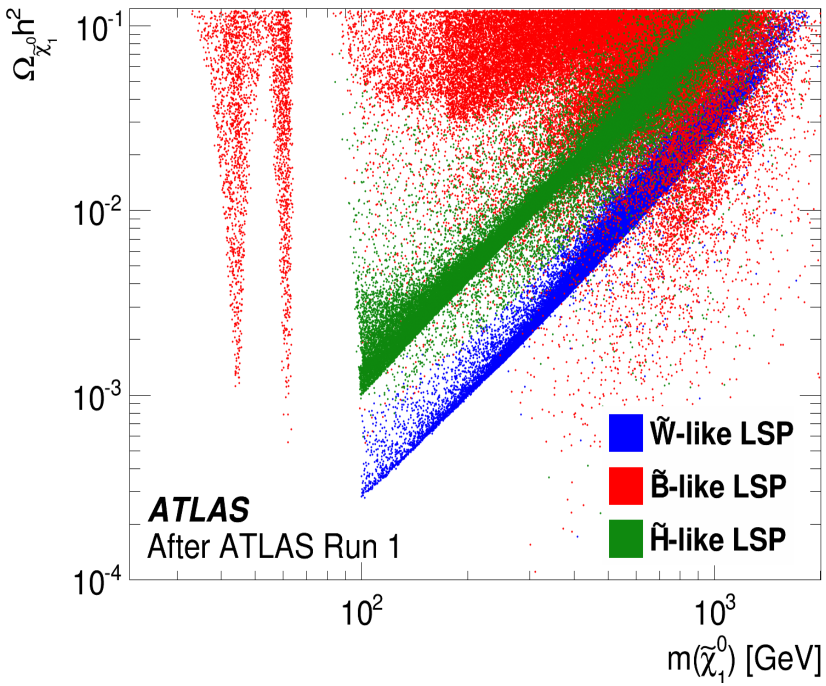
Analysis	All LSPs	Bino-like	Wino-like	Higgsino-like
0-lepton + 2–6 jets + E_T^{miss}	32.1%	35.8%	29.7%	33.5%
0-lepton + 7–10 jets + E_T^{miss}	7.8%	5.5%	7.6%	8.0%
0/1-lepton + 3b-jets + E_T^{miss}	8.8%	5.4%	7.1%	10.1%
1-lepton + jets + E_T^{miss}	8.0%	5.4%	7.5%	8.4%
Monojet	9.9%	16.7%	9.1%	10.1%
SS/3-leptons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

ATLAS 1508.06608

What's left after LHC



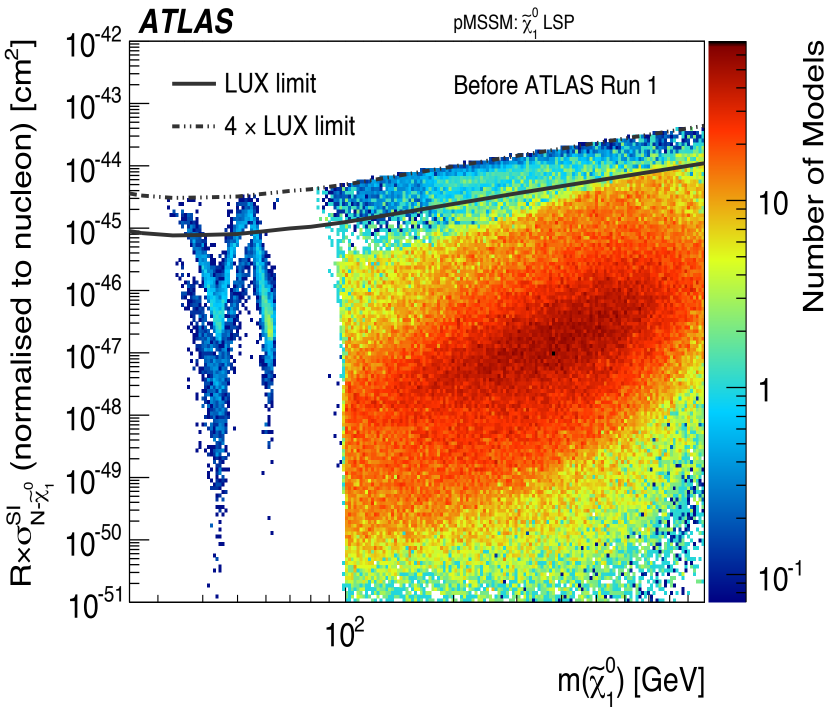
(a) Before ATLAS Run 1

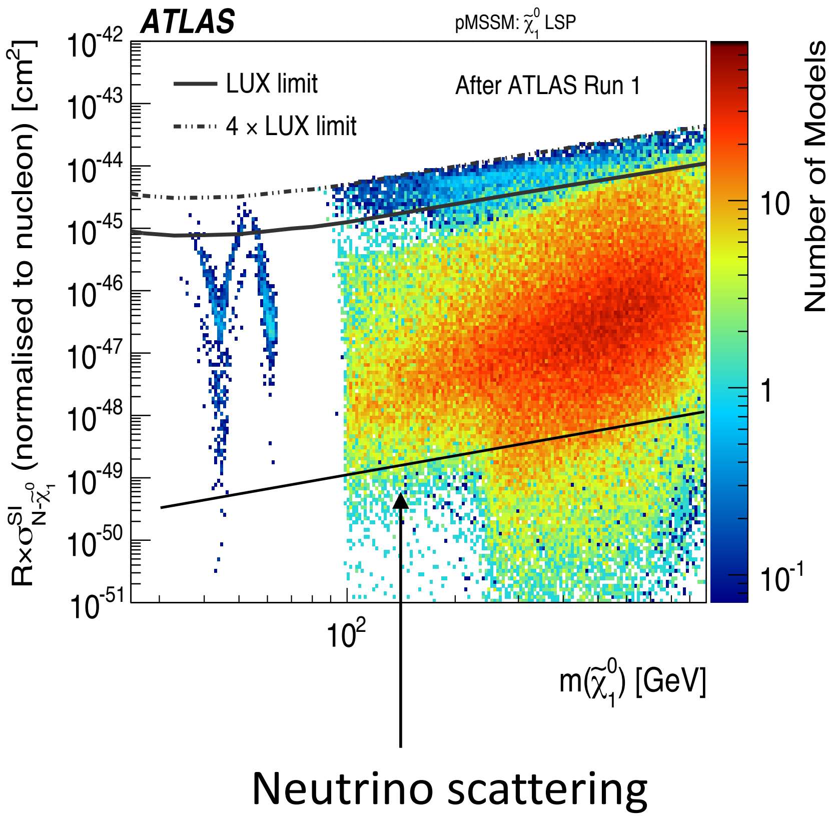


(b) After ATLAS Run 1

ATLAS 1508.06608

What's left after LHC



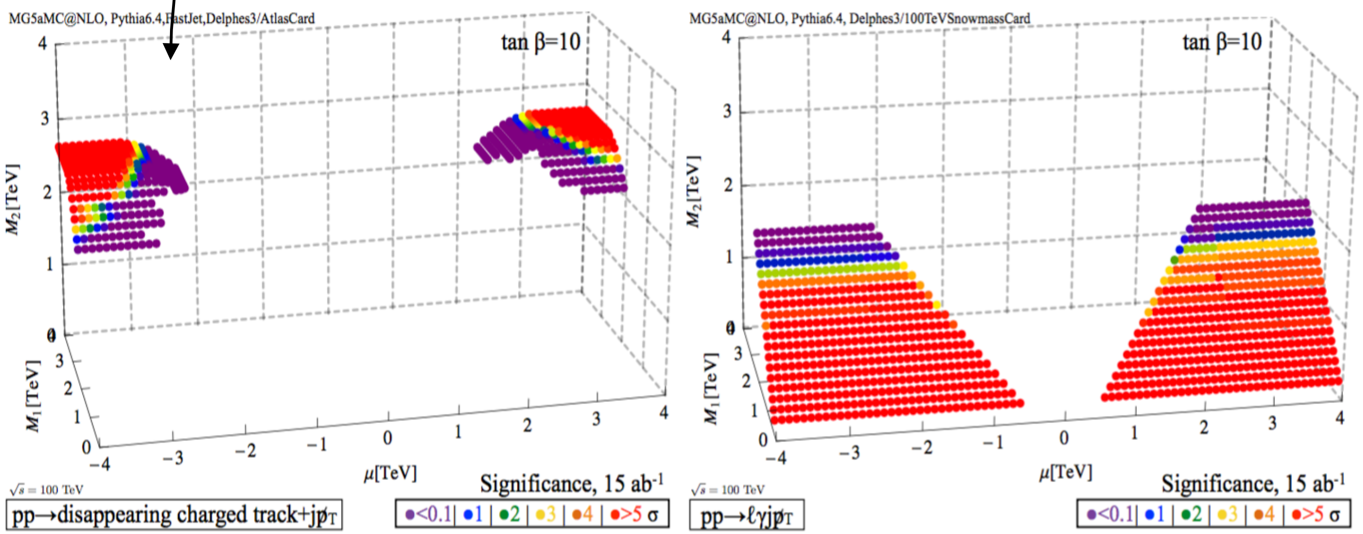


ATLAS 1508.06608

Remarks

- bino - wino : fairly unconstrained – direct detection insensitive
  - If nearly pure wino : mass splitting small, chargino long lifetime ->charged tracks
  - If mixed : compressed spectra , electroweakino production

$$pp \to (\tilde{\chi}_2^0 \to \gamma\tilde{\chi}_1^0)\,(\tilde{\chi}_1^\pm \to \ell^\pm\nu_\ell\tilde{\chi}_1^0)j \to \tilde{\chi}_1^0\tilde{\chi}_1^0\ell^\pm\nu_\ell\gamma j$$



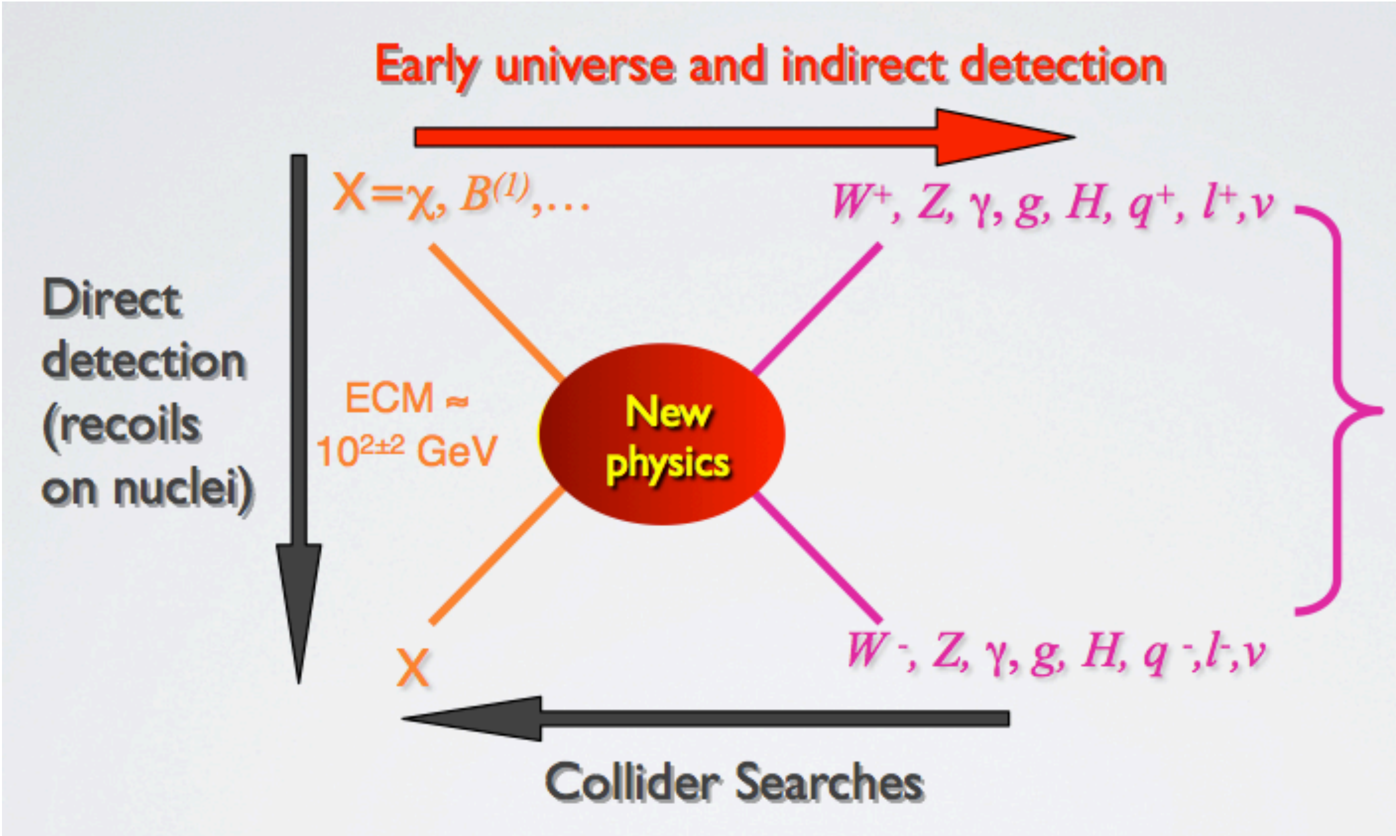
100TeV collider 15ab^{-1},

Bramante et al, 1510.03460

Summary MSSM+DM

- Higgs mass → fine-tuning issue with MSSM, heavily mixed stops
- Coloured sector under pressure by LHC if below TeV unless small mass difference with LSP
- Electroweak sector still quite open
- Higgs decays -> constrain light LSP
- Flavour physics : constrain large tanbeta
- Neutralino as a single DM component under pressure
  - Bino : constrain by Higgs + direct search
  - Mixed higgsino/gaugino : constrain by LUX
  - Pure higgsino or pure wino : not enough relic + long-lived particles
  - Mixed bino-wino : mostly for higher energy collider

Probing the nature of dark matter

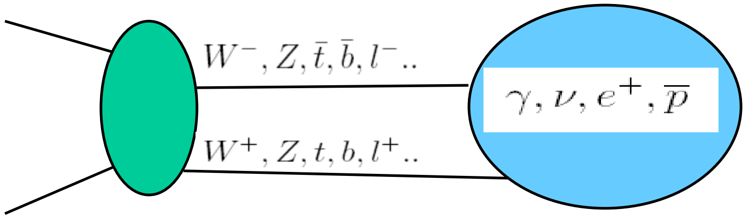


- All determined by interactions of WIMPS with Standard Model
- Specified within given particle physics model

Some remarks on indirect detection

Indirect detection

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



Searches for DM in 4 channels

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

Rate for production of e^+,p,γ

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

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

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

Indirect Detection

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

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

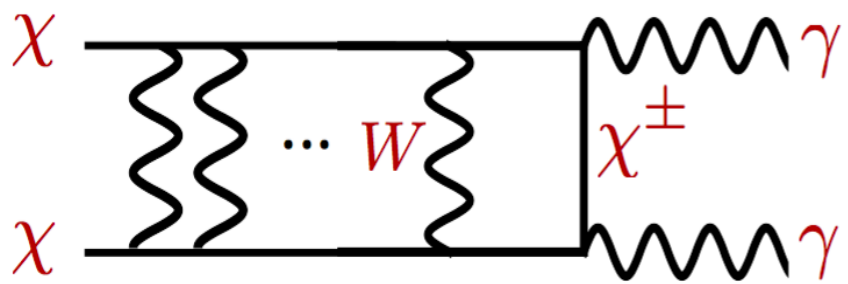
σv(0) < σv(FO) if b dominates (e.g. in MSSM)

Also suppressed cross section if coannihilation dominant

Increased cross section at small v:

Sommerfeld enhancement (1/v term)

– long range force

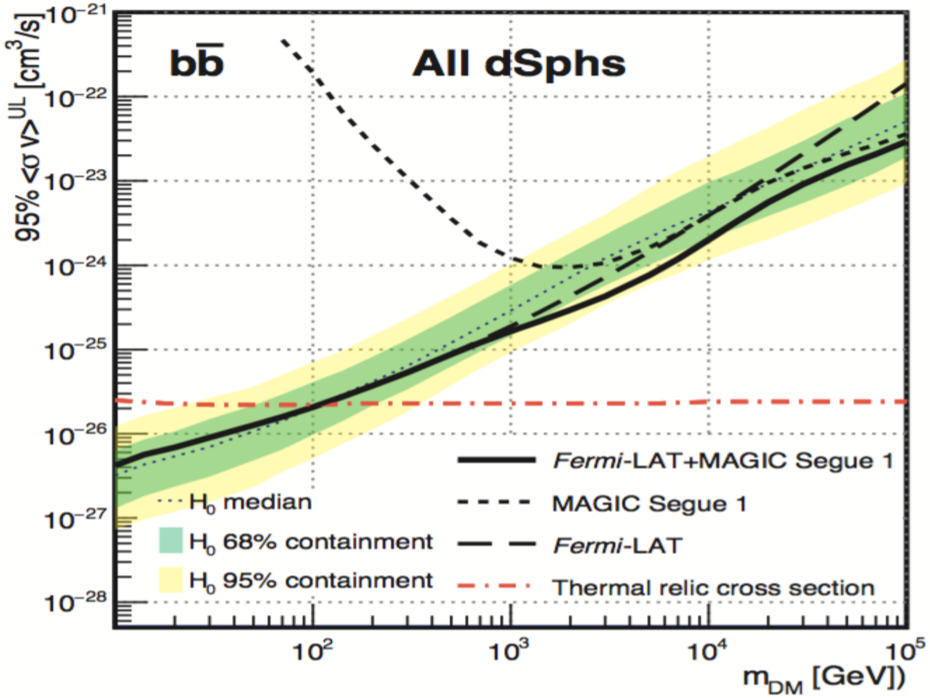


Near resonance annihilation

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

Results - photons

• For light dark matter FermiLAT probes cross sections expected of a thermal relic with photons from dwarf galaxies



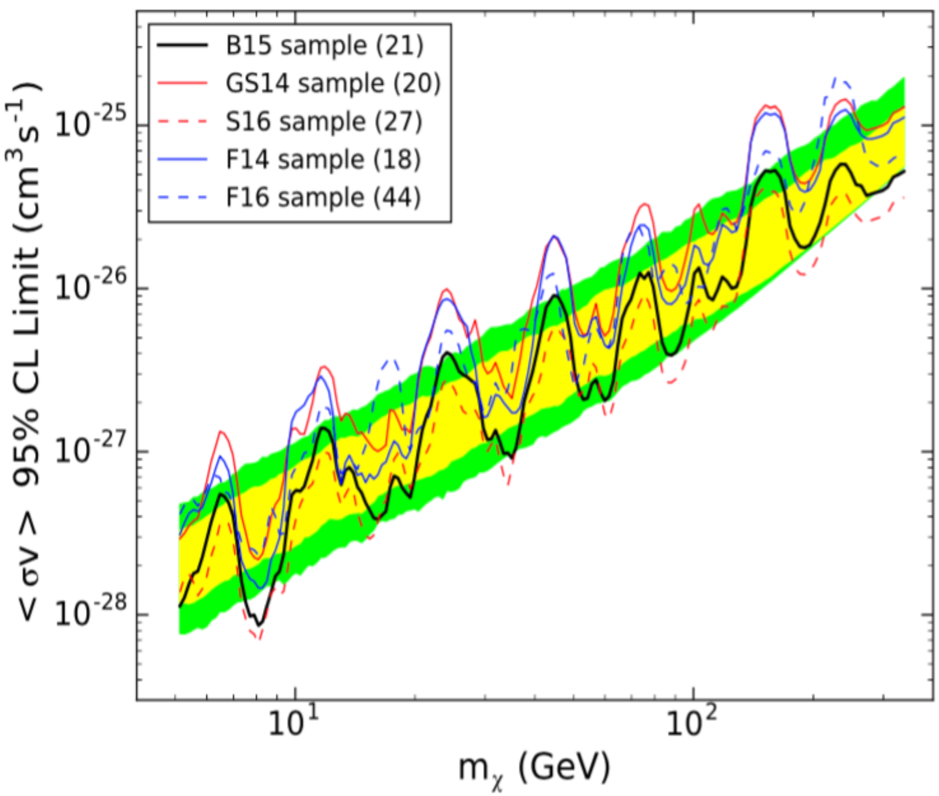
Ahnen et al, 1601.06590
Fermi+MAGIC

•Also searches in Galactic center : strong dependence on profile

Searches for γ–ray lines

From DM annihilation in diphoton or γZ

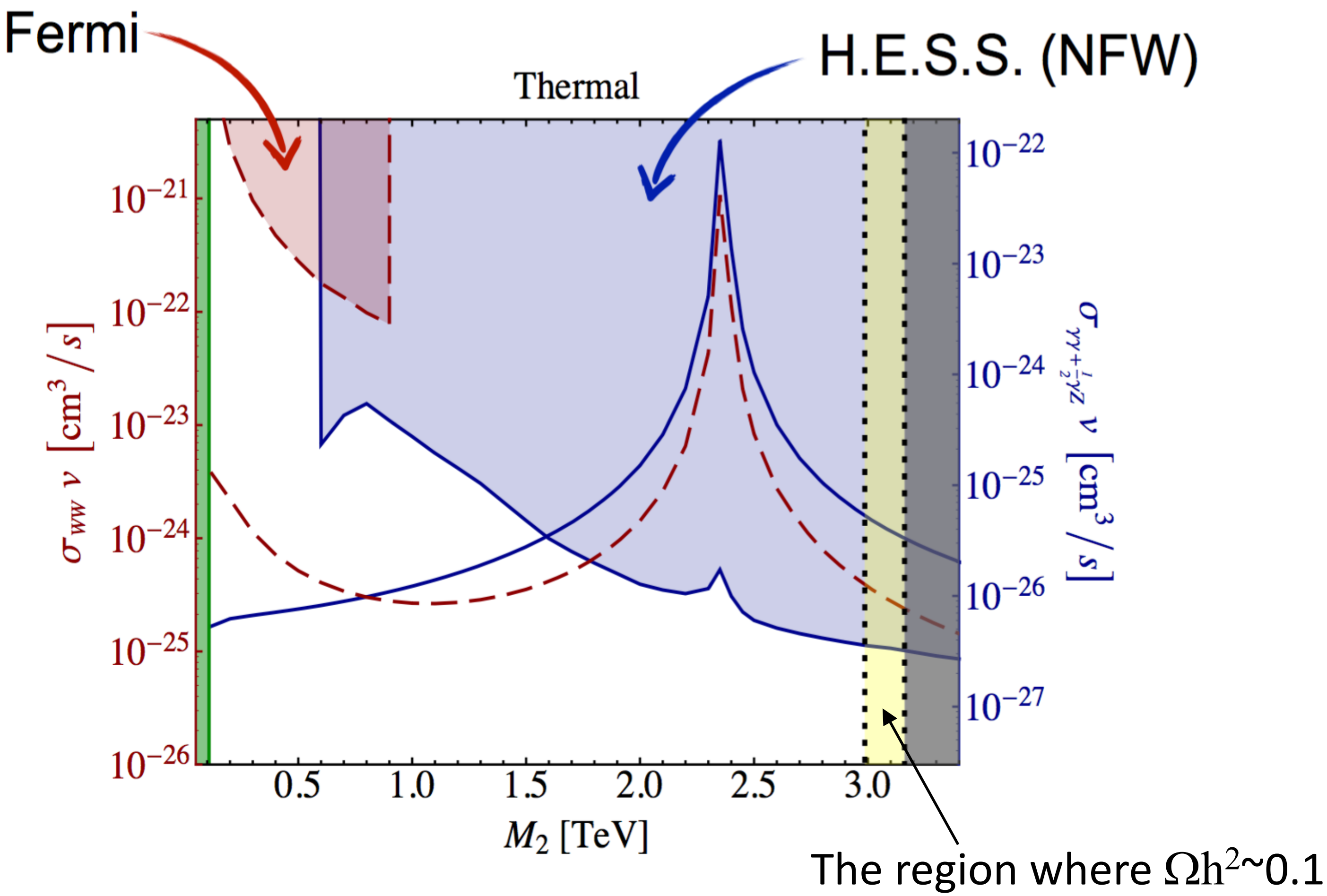
- loop induced



using Fermi-LAT Pass8 data

Liang et al, 1608.07184

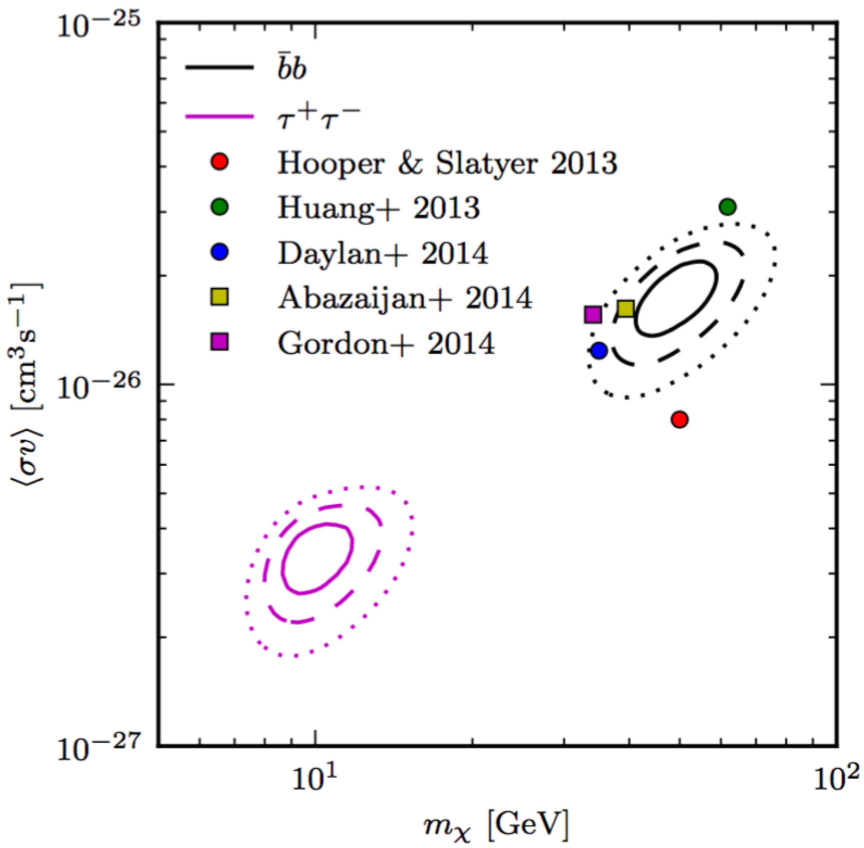
Limits on winos (or SU(2) triplet) - photons



Cohen et al 1307.4082

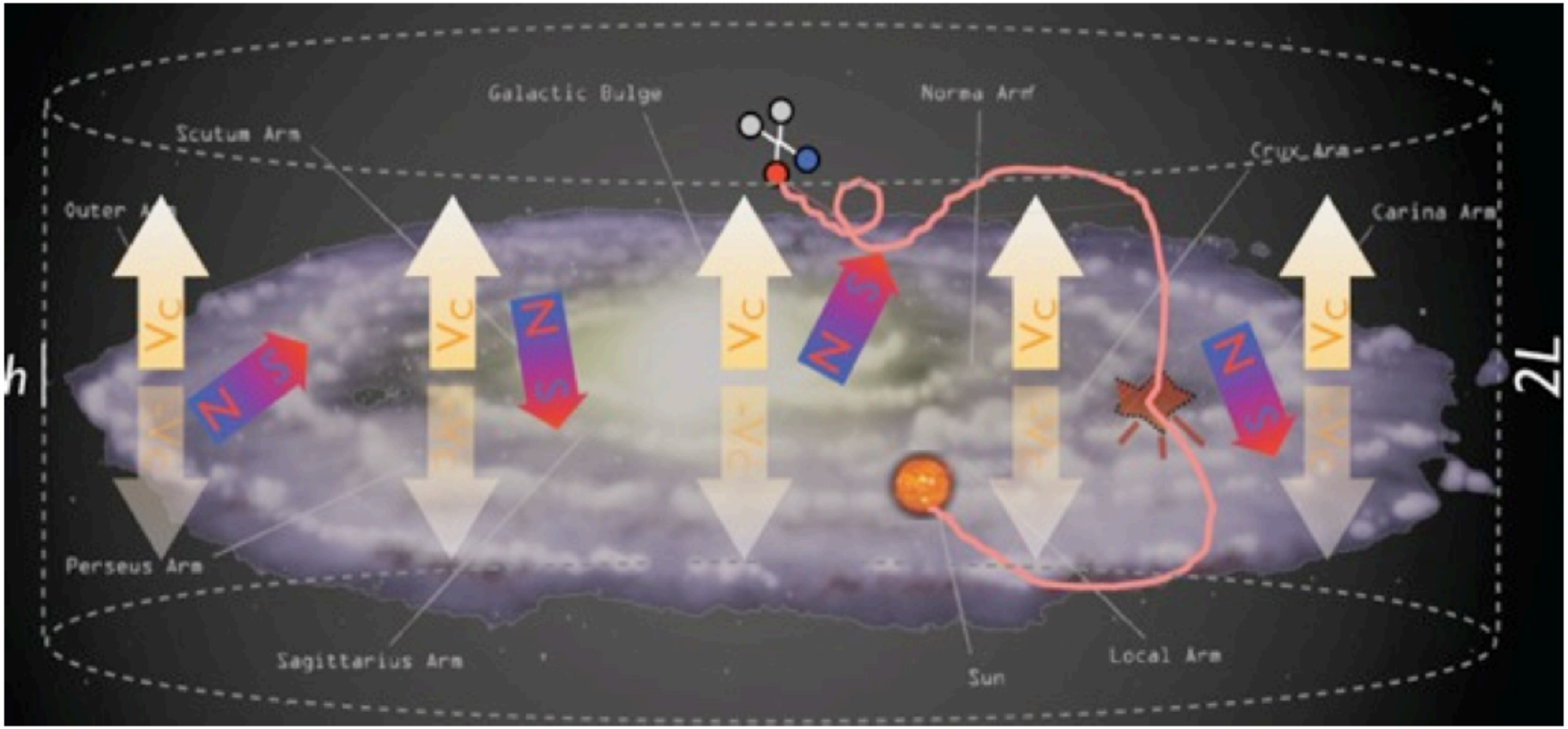
Results - photons

- Excess gamma-ray from 10°X10° region around the GC
- High statistical significance
- Energy spectrum well fit by DM
  - Hooper,Goodenough, PLB697(2011)
  - Easily explain with pseudoscalar + Dirac fermion, Boehm et al 1401.6458
- millisecond pulsars could mimick DM signal
  - O'Leary et al 1601.05797



Calore, Cholis, & Weniger [1409.0042]

Cosmic rays - Propagation

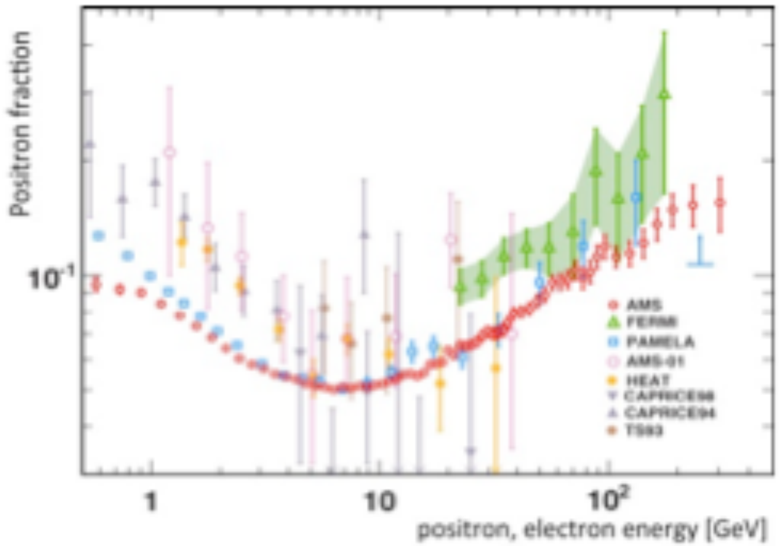


$$\frac{\partial N}{\partial t} - \nabla \cdot [K(\mathbf{x}, E) \nabla N] - \frac{\partial}{\partial E}[b(E) N] = q(\mathbf{x}, E)$$

Source

Results

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

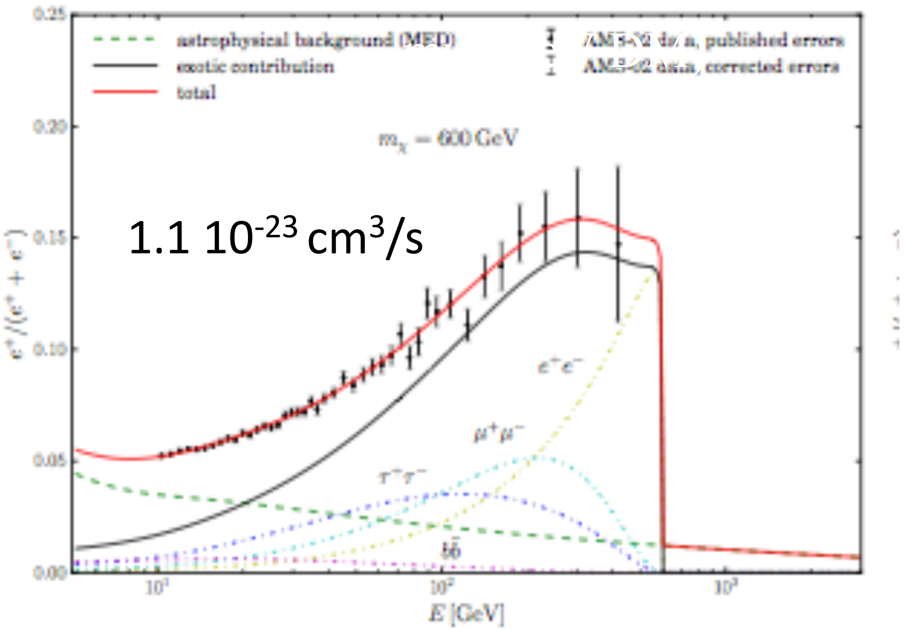


AMS, PRL113.121101

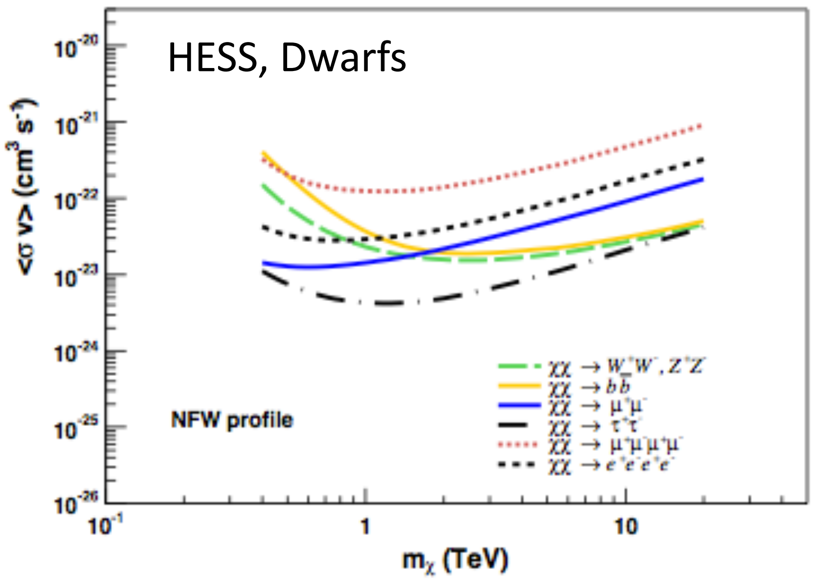
- Can this be DM? Leptophilic?
- Model-independent approach

Positron fraction excess

- With better measured total lepton flux from AMS02 – not possible to obtain good fit for pure leptophilic DM
- Mixed channels : good fit for any mass 0.5-40TeV
- Cross sections are very large (up to 10^{-21} for multiTeV DM) - excluded by indirect searches with photons
- Also challenged by IceCube, antiprotons unless DM multiTeV, and by CMB (Cline, Scott, 2013)



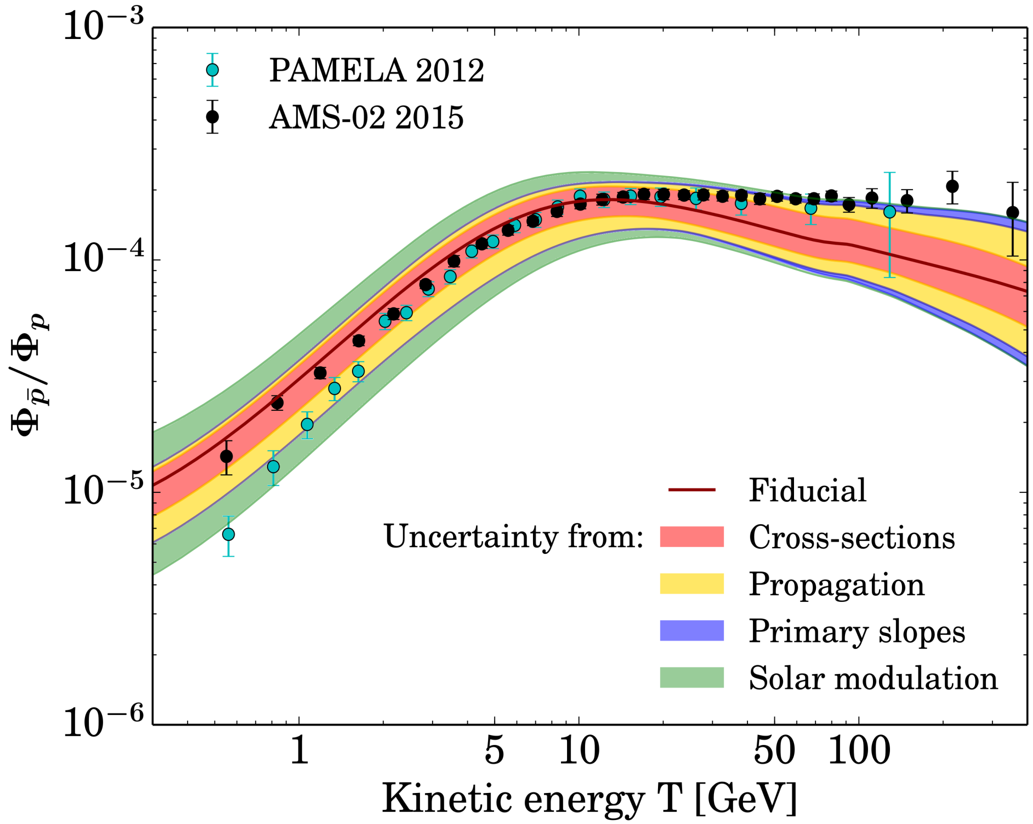
M.Boudaud et al, 1410.3799



Abramowski et al, 1410.2589

Antiprotons

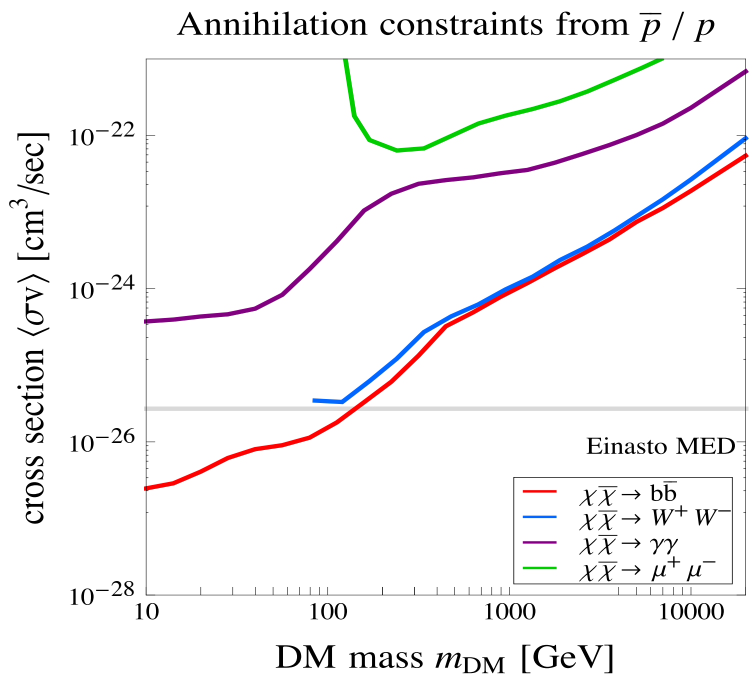
- Using AMS' updated proton and helium fluxes, secondary pbar/p with uncertainties was reevaluated
- No significant excess observed

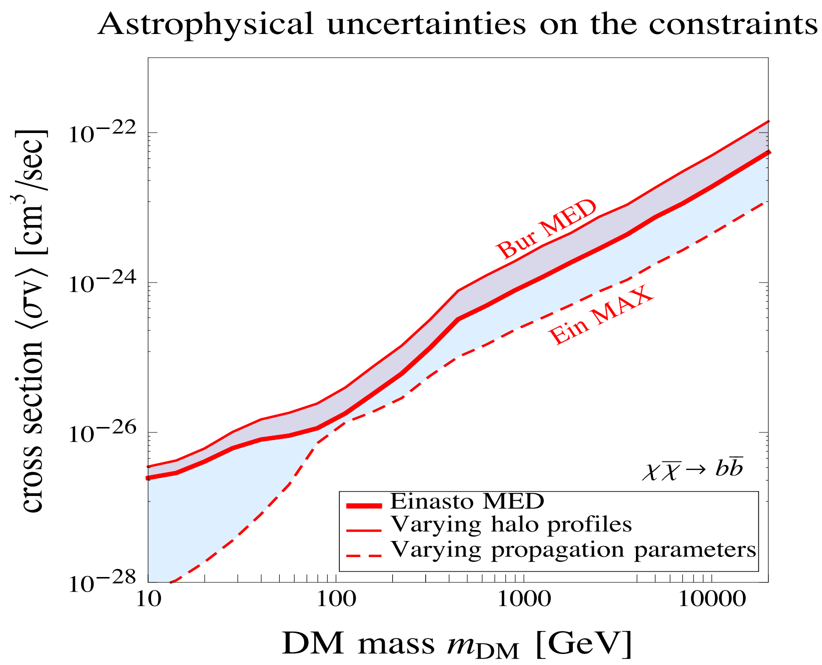


G.Gliesen et al, 1504.04276

Antiprotons

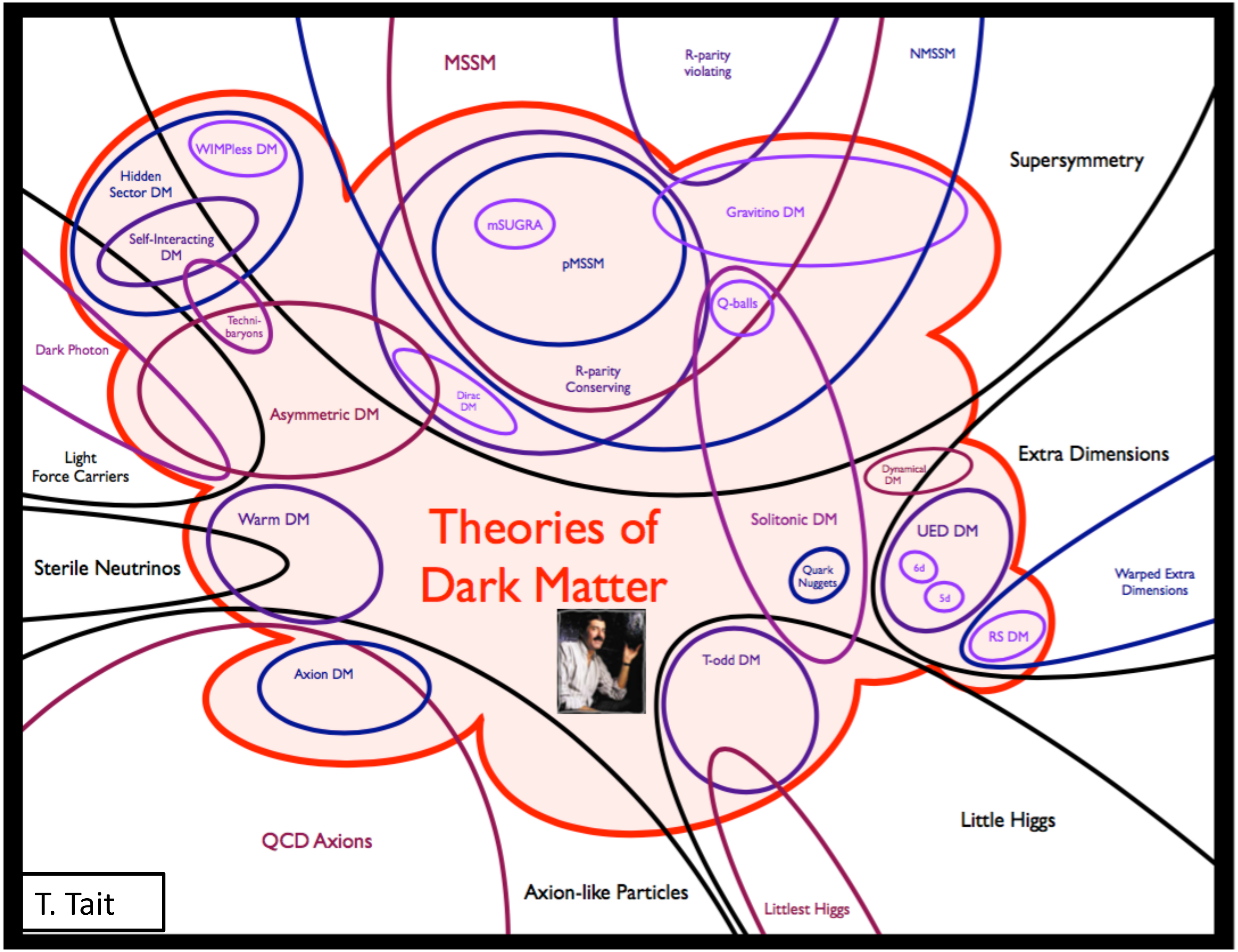
- Upper bound on annihilating dark matter





G.Gliesen et al, 1504.04276

Pulsar could explain the positron excess –> difficult to see DM signal



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

Dark Matter in UED

- Consistent theory of quantum gravity and unification of all interactions

- Xtra dim models solve the hierarchy problem either with compactified dim on circles of radius R effectively lowering the Planck scale near EW scale or introducing large curvature (warped)

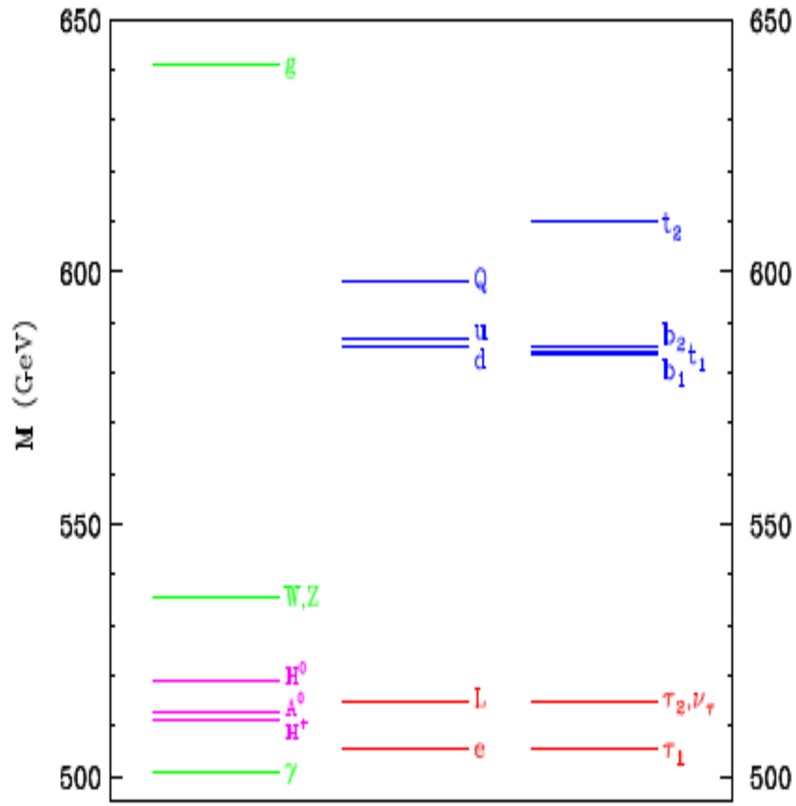
- UED: flat Xdim , all fields propagate in the "bulk", flat compact dim of size 10^{-18} m.
- Minimal UED : one extra dim size R compactified on circle
- Higgs mass free parameter
- After compactification : only chiral SM – low-energy effective theory
- Each SM particle has infinite number of partner particles
- KK particles have same spin as their SM counterpart

Vector boson DM – UED

- Conserved momentum in 5^{th} dimension leads to conserved KK number
- KK parity implies lightest KK particle is stable $KK=(-1)^n$
- At tree level masses at each KK level are degenerate

$$m^2_{X^{(n)}} = \frac{n^2}{R^2} + m^2_{X^{(0)}},$$

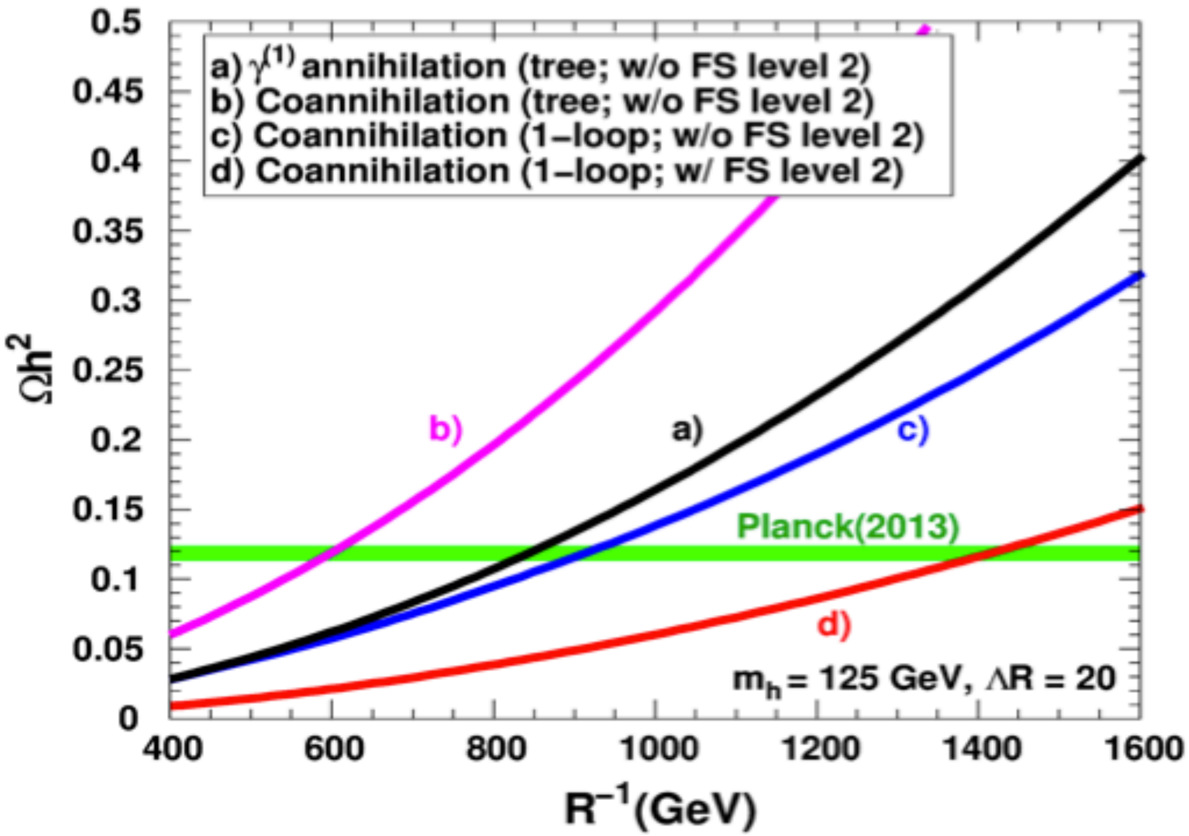
- Radiative corrections are crucial in determining exact mass splitting and LKP
- Minimal UED: LKP is $B^{(1)}$, partner of hypercharge gauge boson (spin 1)
- s-channel annihilation of LKP (gauge boson) efficient –> TeV scale DM
- Significant annihilation into leptons
- Many degenerate particles -> coannihilations and annihilation enhancement by resonances natural

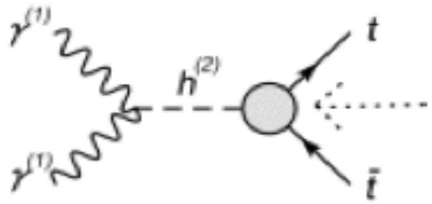


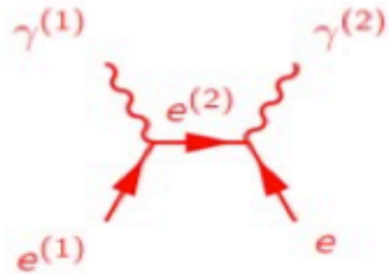
Parameters : cut-off scale Λ, R-1, m_h

Scale for UED DM

Relic density strongly depends on coannihilation and contribution of level 2 particles in s-channel and in final state (since decay into SM particles)





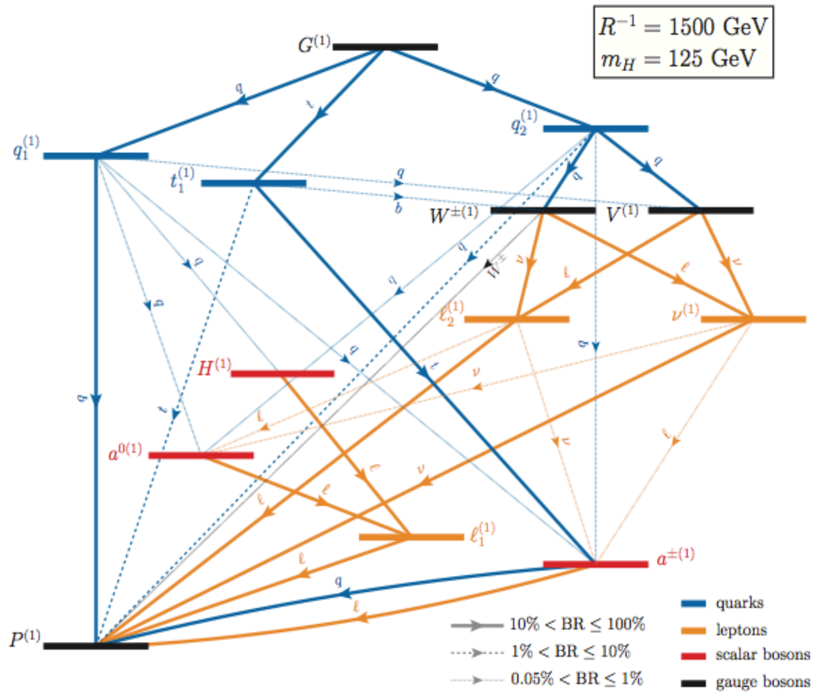


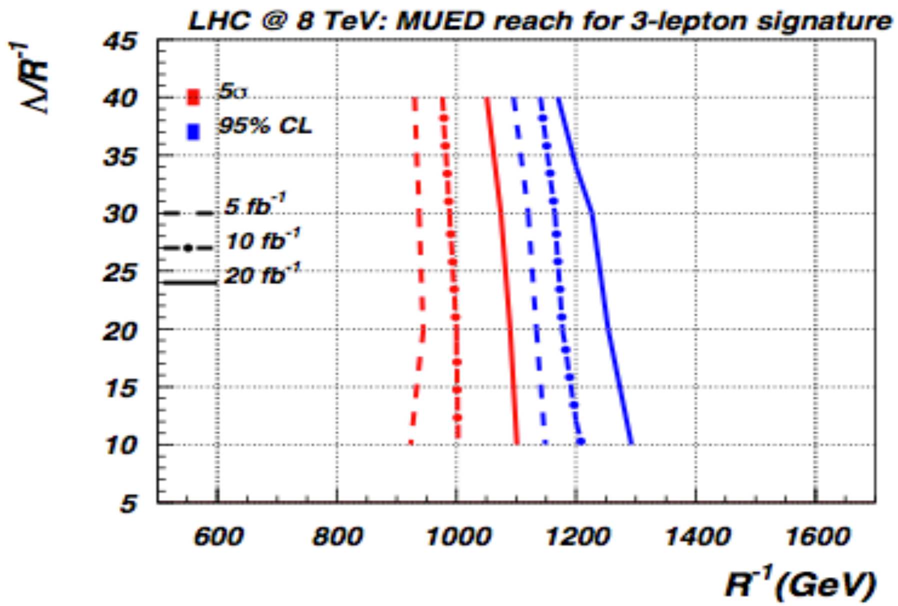
M. Kakizaki
GB, Kakizaki, Pukhov JCAP(2011)

UED at the LHC

- KK quarks+ISR : $R^{-1} > 825$GeV
- KK quark decays - high lepton multiplicity
- Trilepton reach 8TeV - $R^{-1} > 1.2$TeV

  Belyaev et al 1212.4858
- Contribution to H partial width--> $R^{-1} > 600$GeV
  - GB et al, 1207.0798
- Production of level 2 resonances
  - Yu, Snowmass white paper
  - Rey, Raychaudury 1410.1463

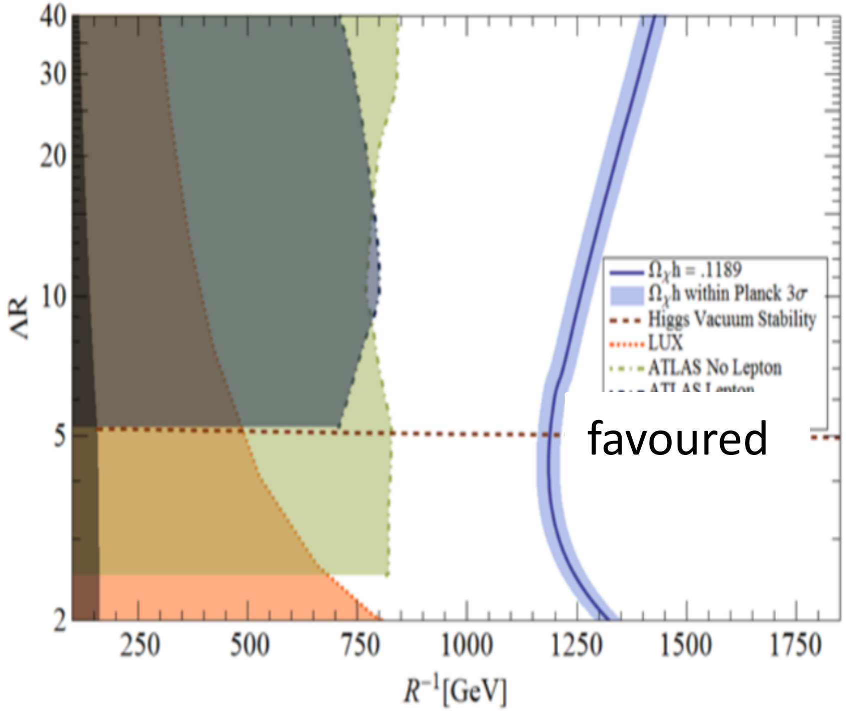


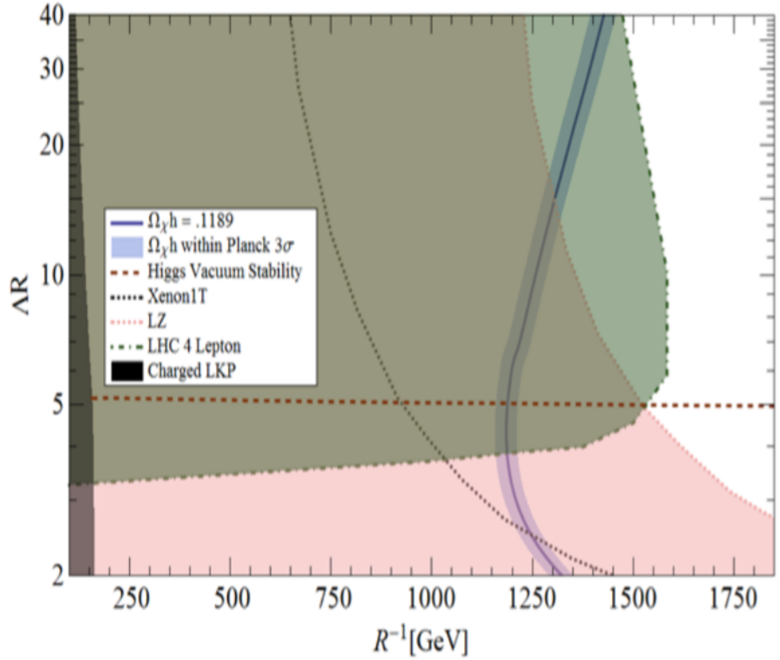


DM searches

Direct detection – rather weak

Projection





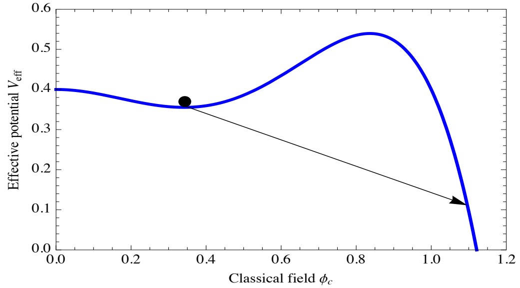
Cornell et al, 1401.7050

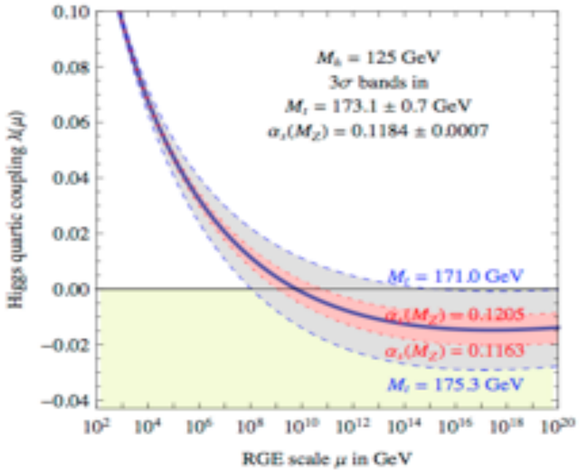
Extended scalar sector

- Generic in extensions of the SM
- Much studied from Higgs point of view (e.g. two-Higgs doublet model) compatible with all Higgs data as long as 125GeV is SM-like (in particular HWW couplings)
- To also provide DM candidate – impose discrete symmetry to guarantee stability of lightest particle in the 'dark' sector
- Usually a Z_2 symmetry (R-parity in SUSY or KK parity)
- Improves stability of Higgs potential

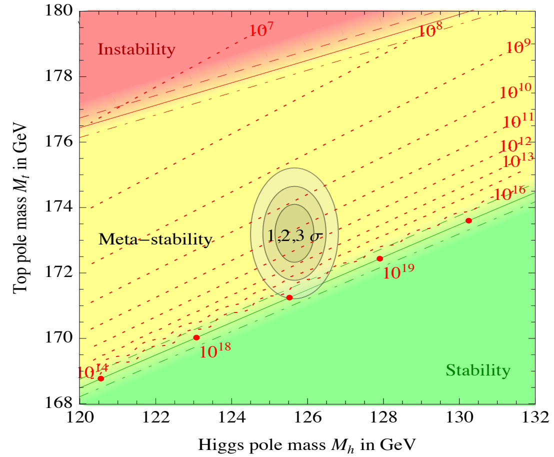
SM Higgs potential

V ~ λφ[4]





NNLO



Buttazzo et al 1307.3536

$$\beta_\lambda = \frac{1}{16\pi^2}\left(4\lambda^2 - 36y_t^4 + 12\lambda y_t^2 + ...\right)$$

- At some scale λ can run negative leading to new minimum- lose stability
- Due to large negative top quark contribution to β_λ

- Improved with additional couplings, positive contribution to β function, prevents λ from running negative -> stability at large scale, eg. SM + singlet

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

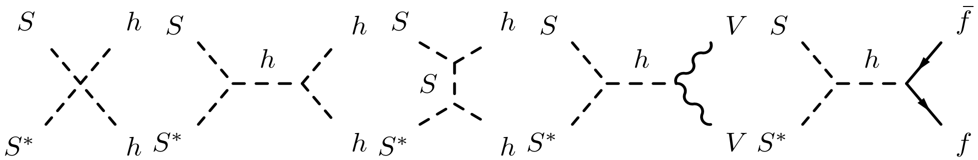
$$\beta_\lambda = \frac{1}{16\pi^2}\left(4\lambda_H^2 + 12\lambda_{SH}^2 - 36y_t^4 + 12\lambda_H y_t^2 + ...\right)$$

Scalar DM

- Minimal case : SM + one singlet +Z_2 symmetry
  - 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 ....
- A simple model, one coupling drives DM observable

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

annihilation



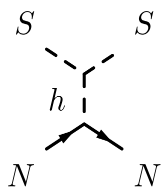
$m_s \gg m_i$ $\quad \dfrac{\lambda_{SH}^2}{64\pi m_s^2} \quad \dfrac{\lambda_{SH}^2}{32\pi m_s^2} \quad \dfrac{\lambda_{SH}^2 m_f^2}{64\pi m_s^4}$

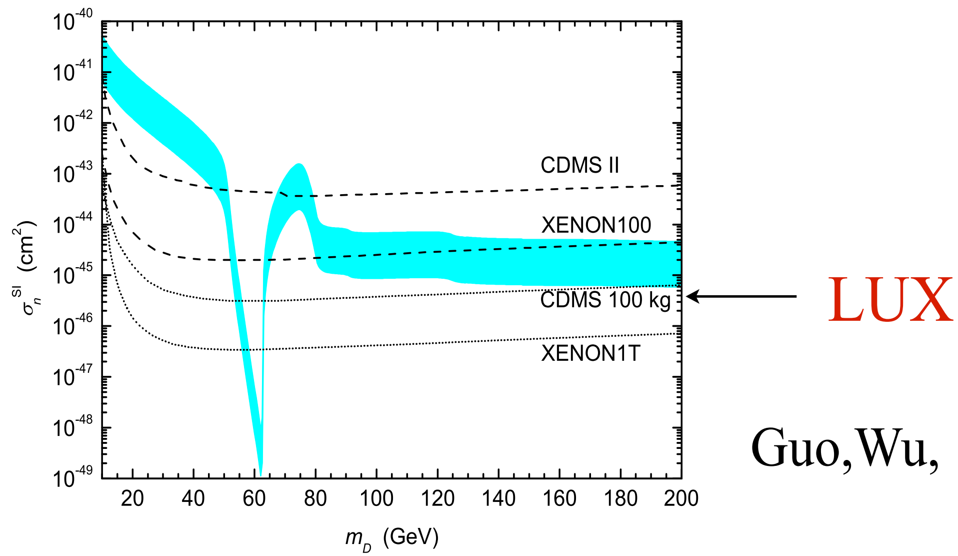
$m_s \ll m_h$ $\quad \dfrac{\lambda_{SH}^2 m_f^2}{64\pi m_h^4}$

Relic density Ωh^2 =0.1199 determines λ_{SH}/m_S (for heavy DM)

The same coupling enters amplitude for elastic scattering on nuclei

Direct detection





Guo,Wu, 1103.5606

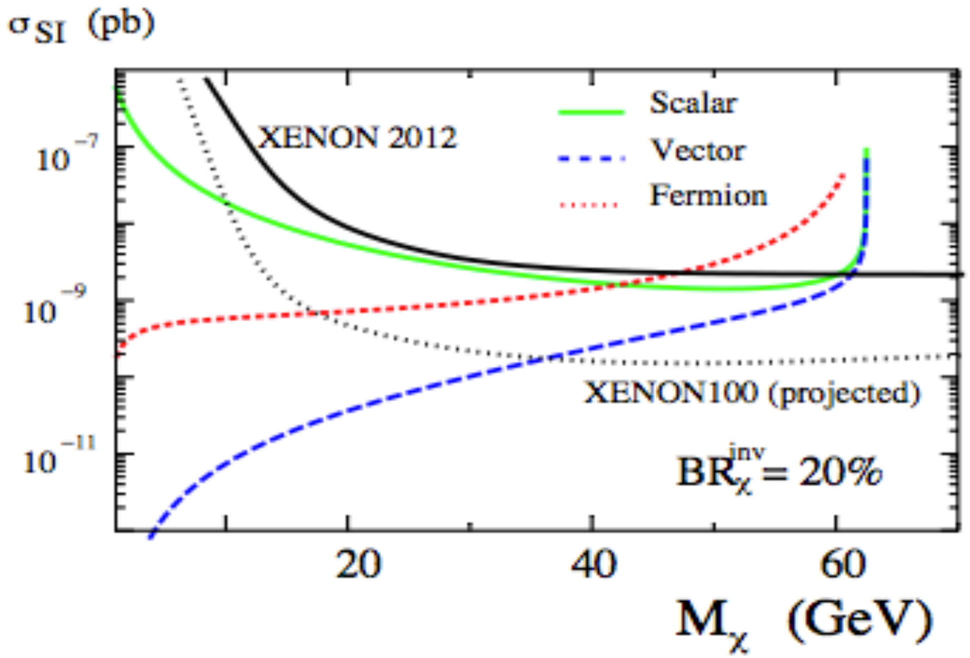
Light scalars : also W threshold and Higgs resonance effects

Light scalars --> contribution to Higgs invisible width (depends on λ_{SH})

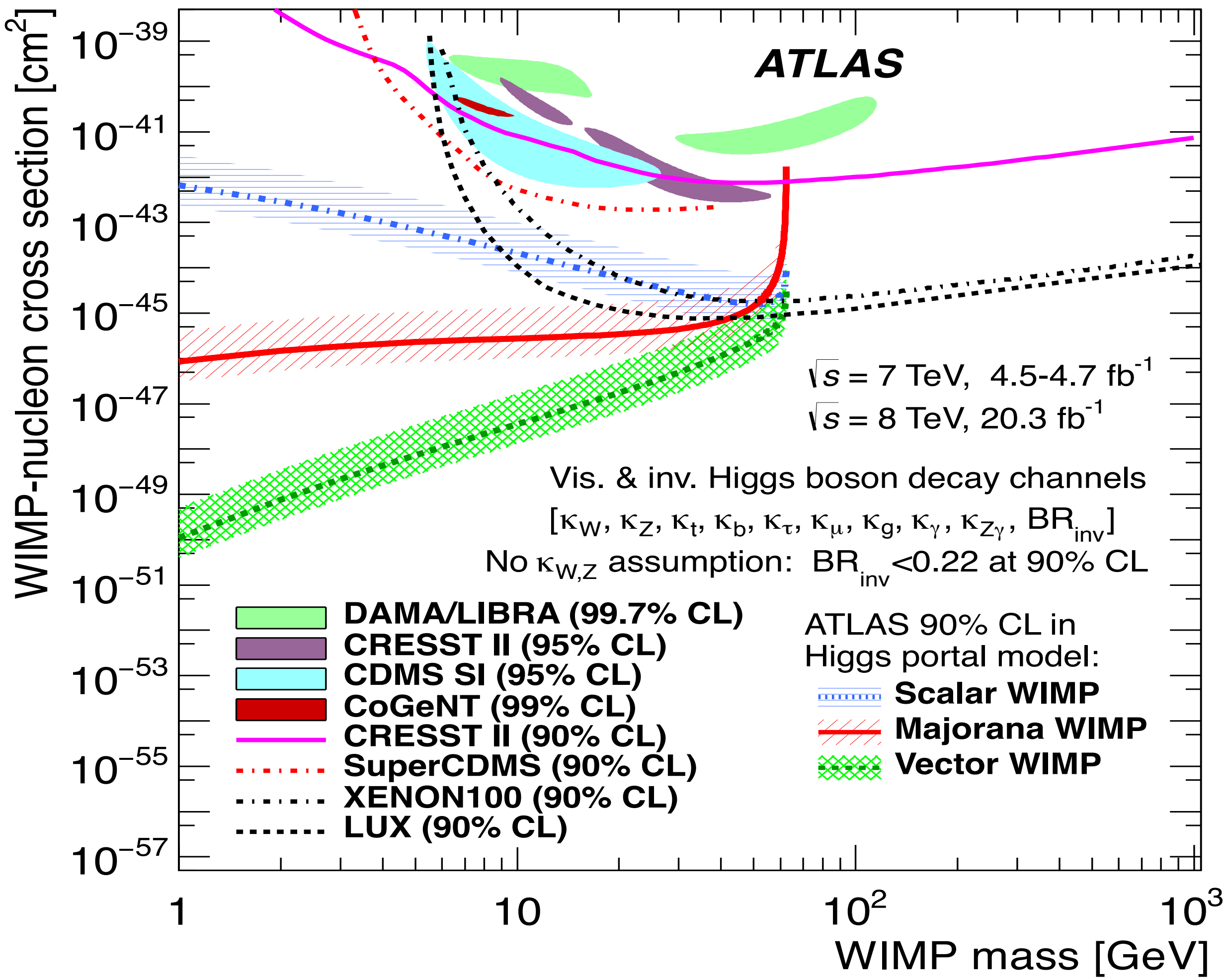
- LHC has discovered a Higgs boson with couplings close to SM,
    - invisible width of the Higgs <23 % of total width – combination of direct search in VBF and fits of couplings of 125GeV Higgs – ATLAS 1509.00672
    - In singlet scalar DM model, relic density requires coupling that leads to large invisible branching → ms>55GeV
- Generally in Higgs portal type model, both invisible width and SI cross section depend on h coupling to DM

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

- Light DM model are constrained
- Djouadi et al 1205.3169



Invisible Higgs and light DM



ATLAS Collaboration, arXiv:1509.00672

Inert doublet

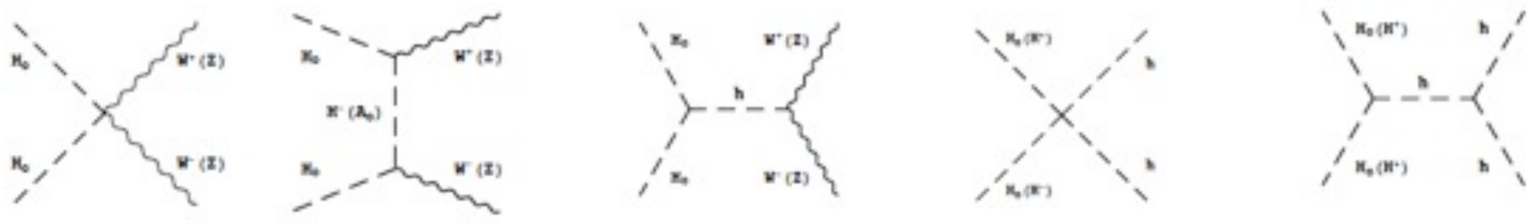
- Two-Higgs doublet model with Z_2 symmetry
  - Deshpande, Ma, PRD18(1978) 2574; Barbieri, Hall, Rychkov, PRD74 (2006) 015007
  - Although suggested as alternative to light Higgs model (natural to have mh >>100 GeV) compatible with light Higgs and provide alternative to neutralino dark matter
  - Lopez 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

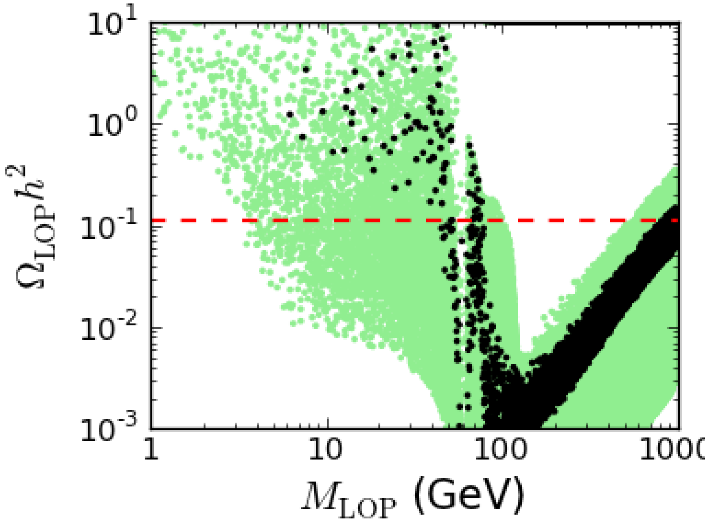
$$V = \mu_1^2|H_1|^2 + \mu_2^2|H_2^2| + \lambda_1|H_1|^4 + \lambda_2|H_2|^4 + \lambda_3|H_1|^2|H_2|^2 + \lambda_4|H_1^\dagger H_2|^2 + \frac{\lambda_5}{2}\left[(H_1^\dagger H_2)^2 + \mathrm{h.c.}\right] ,$$

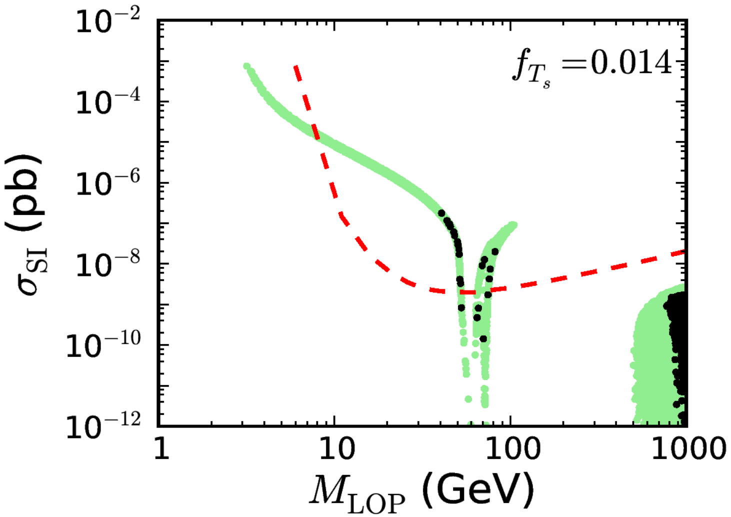
parameters : m_h, m_H, m_A, m_{H+}, λ_2, $\lambda_3+\lambda_4+\lambda_5 = \lambda_L$

Inert doublet DM

- Efficient annihilation into gauge bosons SU(2)







Goudelis, Herrmann, Stal 1303.3010

IDM at LHC

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

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

- LHC : Higgs pair production – cross sections are small
- At LHC8 TeV : some constraints from
  - dileptons + missing E_T
  - trileptons Miao, Su, Thomas, 2010
  - multileptons - Gustafsson et al 2012
- Dominant process AH, only depends on masses

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

$$q\bar{q} \to Z \to H^\pm H^\mp \to W^{\pm(*)} H^0 W^{\mp(*)} H^0$$
$$\to \nu l^+ H^0 \nu l^- H^0$$

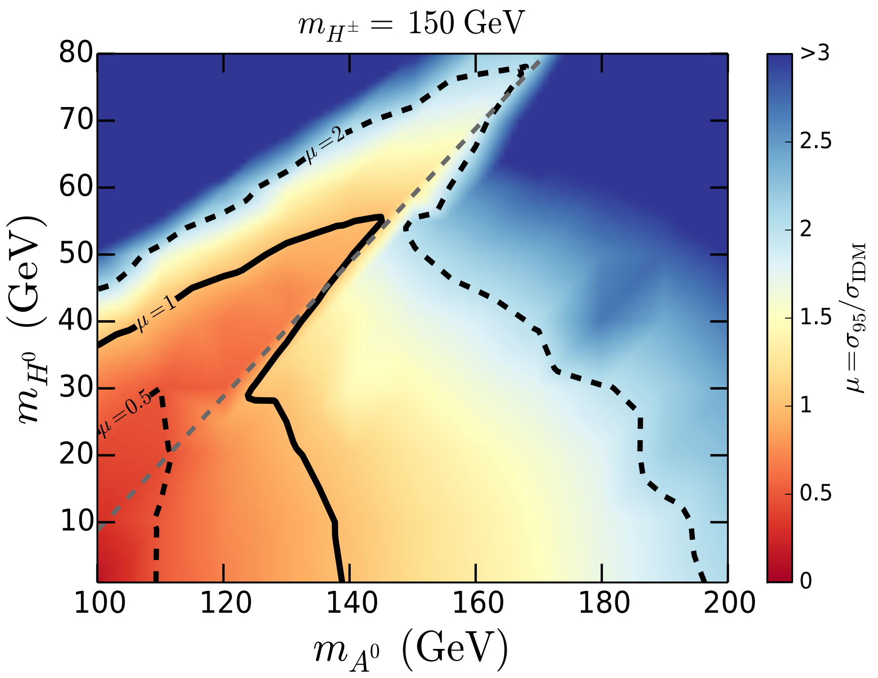
$$q\bar{q} \to Z \to Z h^{(*)} \to l^+ l^- H^0 H^0$$

$$q\bar{q} \to Z \to Z H^0 H^0 \to l^+ l^- H^0 H^0.$$

- Only process that depends on λ_L, already constrained by Higgs invisible with

LHC8TeV constraints

- Reinterpretation of SUSY searches + Higgs results
  - GB, Dumont, Goudelis, Herrmann, Kraml, Sengupta

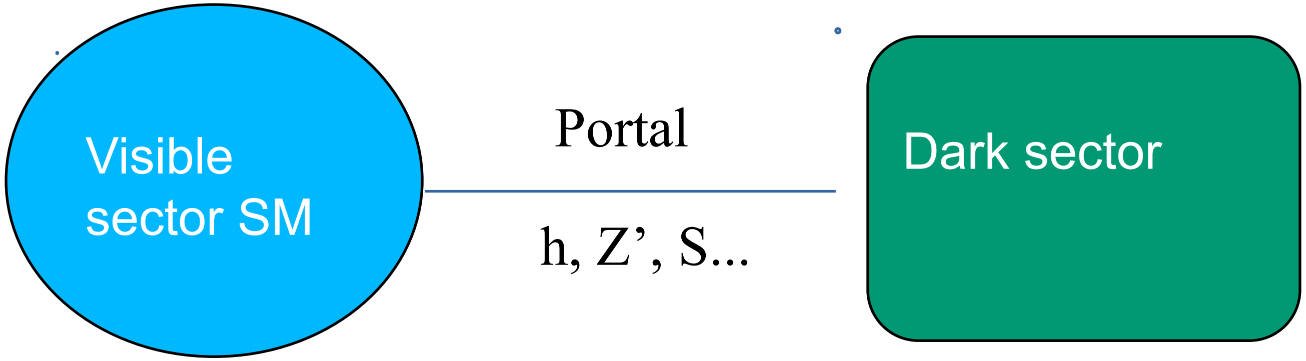


- Constraints generic (no dependence on λ_L)
- LHC exclusions of region also excluded by DD + relic – more at 13TeV

Dark sector

- Many more possibilities for dark sector : more singlets, doublet (Deshpande, Ma 1978), doublet+ singlet, more doublets, triplet (Fileviez Perez 2012), triplet+ singlet (Wang, Han, 2012, Fisher, Van der Bij 2013) ….
- Or alternate discrete symmetry – lead to semi-annihilation, possibility of two dark matter (Hambye 0811.0172, Adulpravitchai et al 1103.3053, Boucenna et al, 1101.2874, GB et al, 1211.1014, Esch, Klasen,Yaguna 1406.0617…)
- Or fermion dark matter, new Z' ….
- Some with peculiar DM properties : isospin violation
- Signatures at LHC : Higgs searches, Z' searches, new fermions …
- Some inspired by excess (diphoton)

Portals – dark sector



Higgs-field portal into hidden sectors
Patt, Wilczek 0605188

- DM and the Higgs portal
  - Bertolami,Rosenfeld, 0708.1794; March-Russell et al, 0801.3440; J. Mcdonald, Sahu, 0802.3847, 0905.1312; Tytgat, 0906.1100; Aoki et al, 0912.5536; Andreas et al, 1003.3295; Arina et al, 1004.3953; Cheug,Nomura (singlet)1008.5153; Djouadi et al, 1112.3299 ..
- DM and the Z' portal
  - Krokilowski, 0712.0505; Chu et al, 1112.0493; Dudas et al, 0904.1745….; Arcadi et al 1402.0221

Z' portal

- Well motivated extension of SM, e.g. in GUT

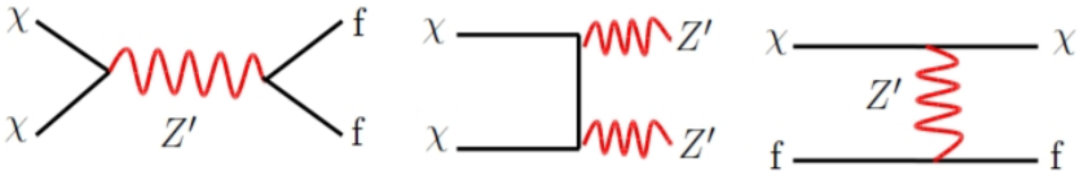
  SU(3)XSU(2)XU(1)XU(1)

- Discrete symmetry

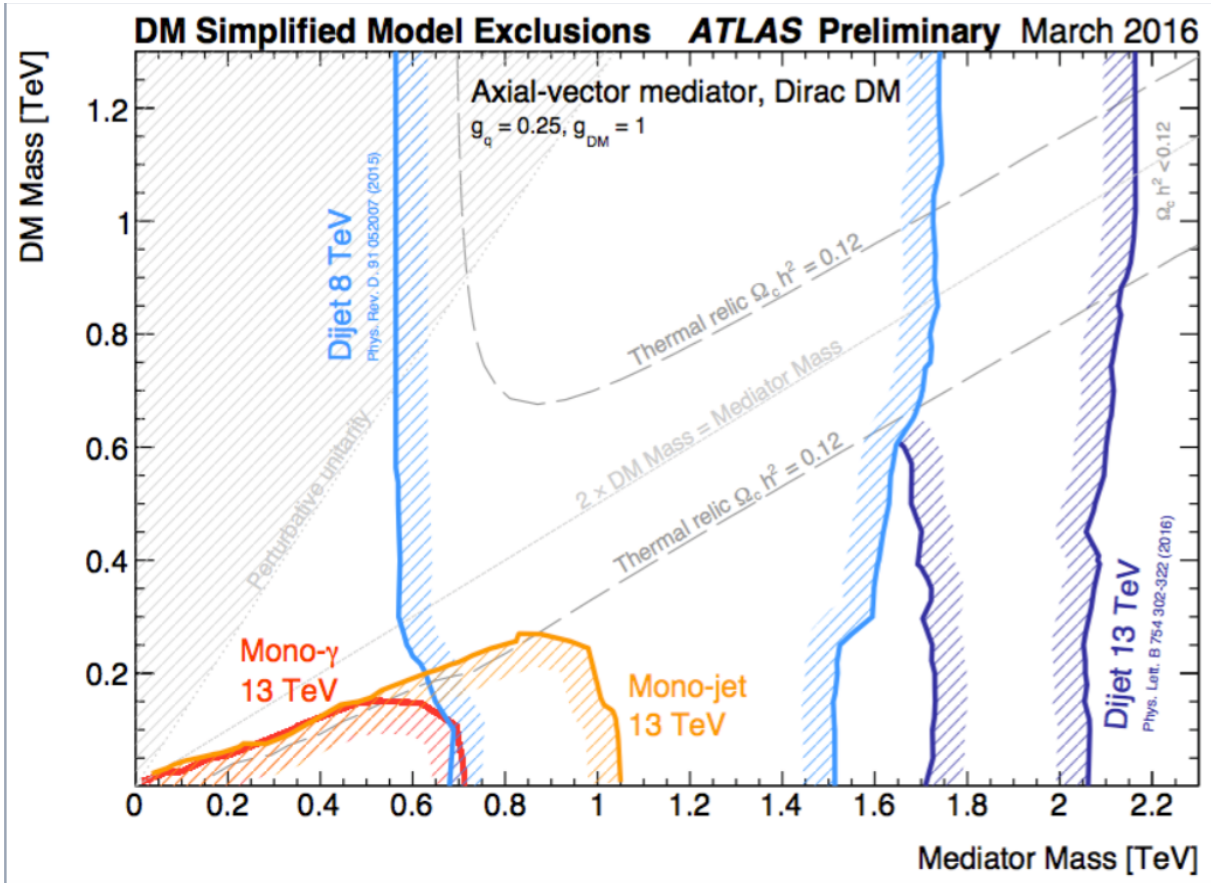
- Dark matter: neutral fermion or scalar in dark sector
- Many constructions possible (popular simplified model)

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

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



Z' portal at LHC



For $g_q << g_{DM}$ dijet limit shrinks

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

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

-> Direct detection limit, Arcadi et al, 1402.0221

Beyond simplified models, one example : Isospin violation

Direct detection limits are extracted assuming $\lambda_n=\lambda_p$

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

Quantity used for comparisons

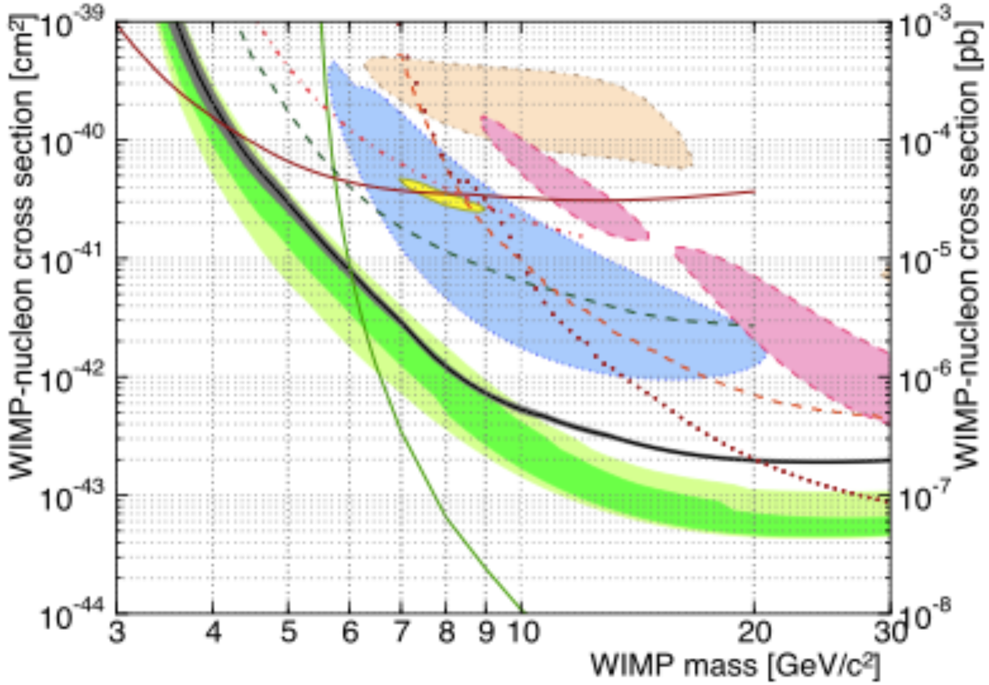
$$\sigma_p^{SI} = \frac{4\mu_\chi^2}{\pi}\lambda_p$$

In general does not have to be the case, in particular if $\lambda_n= - 0.7\ \lambda_p$ direct detection rate on Xenon (54,132) much suppressed

Chang et al, 1004.0697; Feng et al 1102.4331; Frandsen et al, 1304.6066

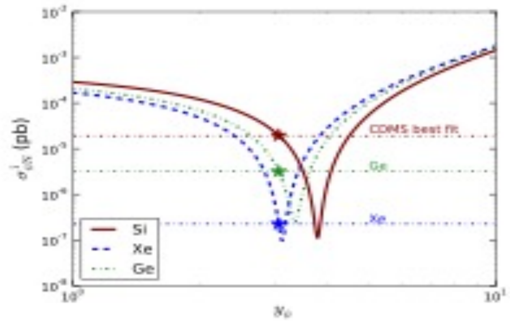
Spin independent

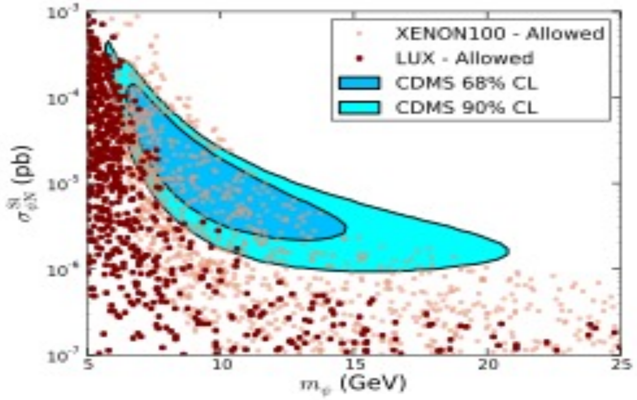
Possible to reconcile strong limits obtained with Xe with excesses from Si, Ge, NaI?



H+Z' portal

- SM+U(1)x
- Hidden sector : Dirac fermion + Scalar
- Possibility of isospin violating interactions - reconcile CDMS/LUX



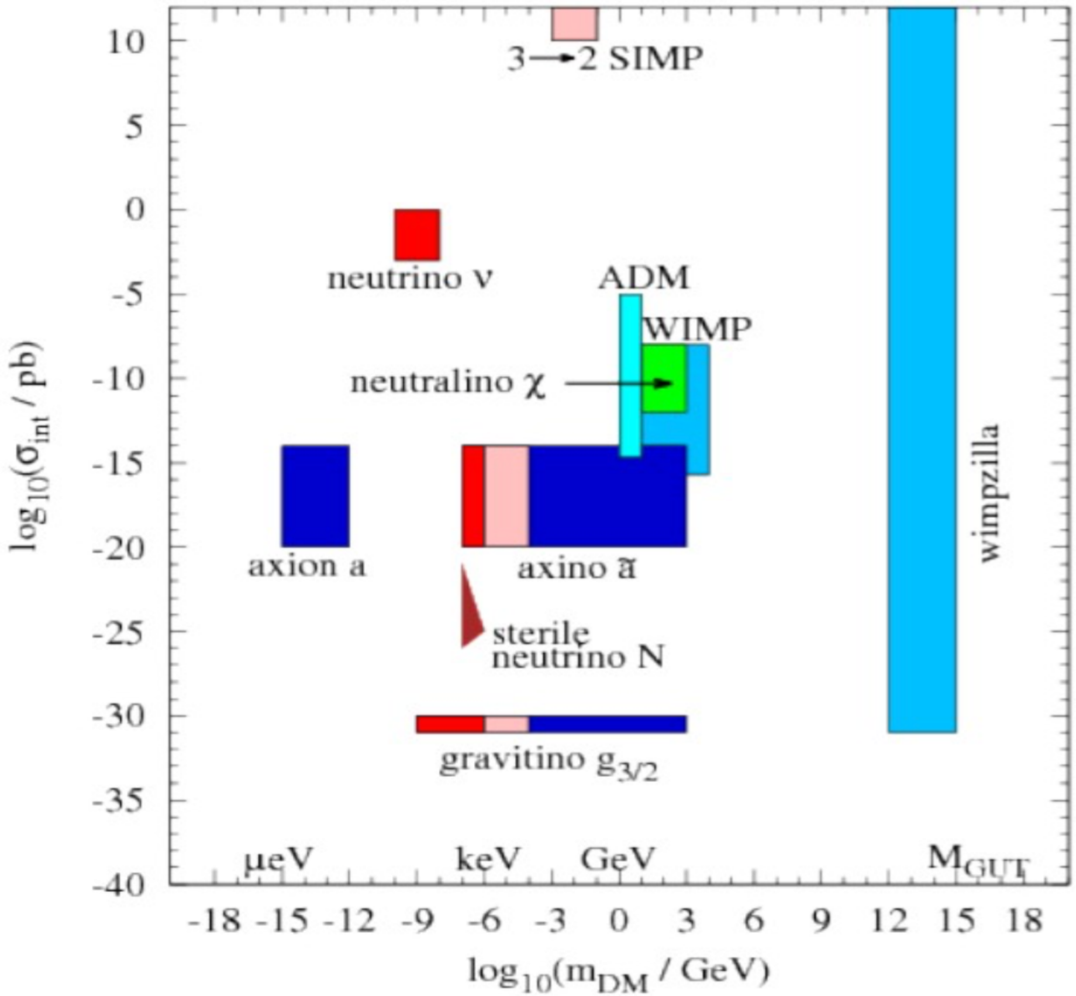


G.B, Goudelis, Park (2013)

Not possible to reconcile DAMA with Xenon
New limits from LUX probably close the allowed parameter space

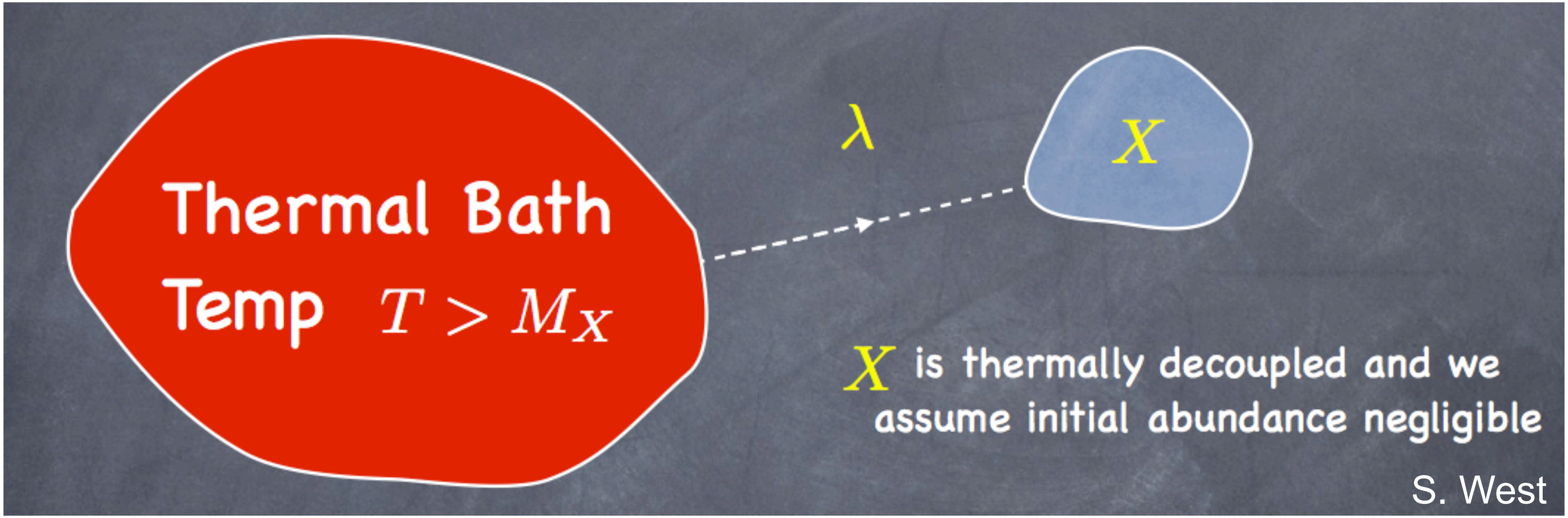
WIMPs are not the only viable DM candidates

WIMPs are not the only viable DM candidates



FIMPS (Feebly interacting MP)

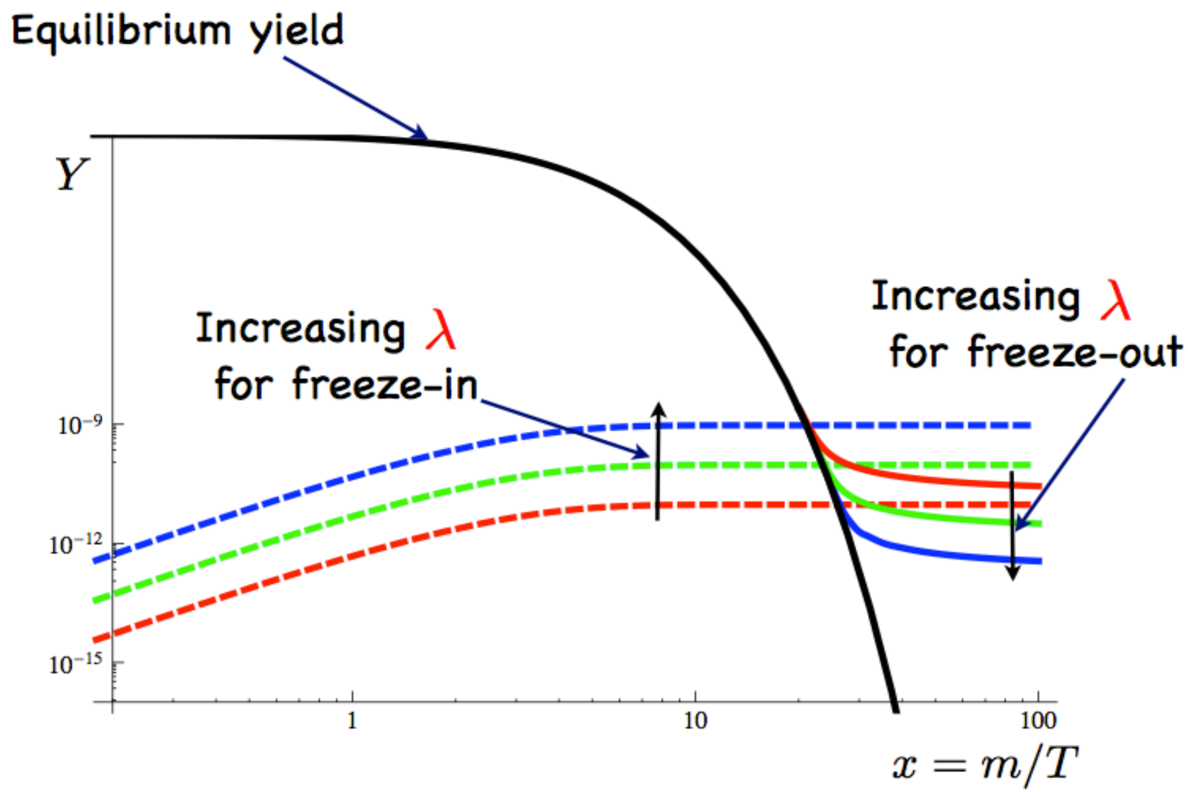
- Freeze-in (Hall et al 0911.1120) relevant for FIMP
- In early Universe, X so feebly interacting that X is decoupled from plasma



- Interactions are feeble but lead to production of X

FIMPS (Feebly interacting MP)

- Assume that after inflation abundance X very small
- Interactions with SM -> X production
- T~M, X 'freezes-in' - yield increase with interaction strength, Y~λ



- Some possibilities for FIMPs:
  - 1) FIMP is DM pair production in annihilation of SM particles
  - 2) FIMP is dark matter - next to lightest ‘odd’ particle has long lifetime freeze-out as usual then decay to FIMP – typically $\lambda \sim 10^{-12}$
    - collider signature for production of stable charged particles (or displaced vertices)
    - Impact on BBN
  - 3) FIMP (X) is not DM, freezes-in and then decay to DM

$$\Omega_{DM} = \frac{m_{DM}}{m_X} \Omega_X h^2$$

- X can have very long lifetime : late decay impact on BBN, indirect dark matter detection
  - Indirect detection from X decay into DM+SM particles → boost factor
  - Relic abundance and DM annihilation cross section no longer related, freeze-in produce DM abundance, DM annihilation can be large – freeze-out abundance small
- Examples of FIMPs:
  - Any 'dark sector' particle feebly coupled to SM or to MSSM
  - Dirac neutrino mass + supersymmetry : RH sneutrino FIMP
  - Gravitino

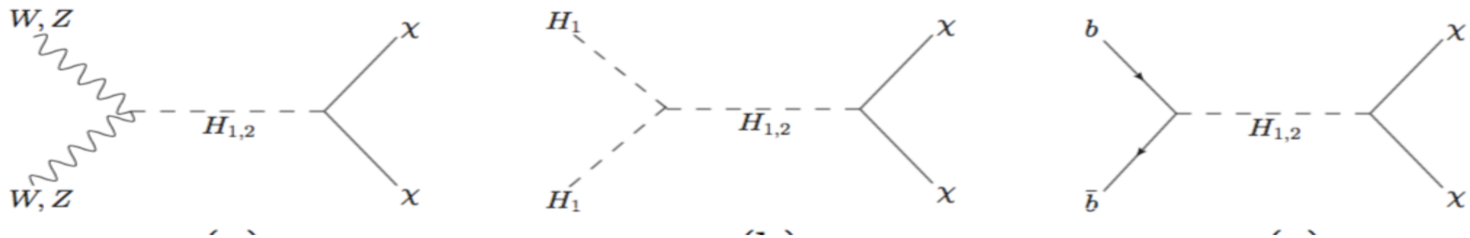
Minimal FIMP model

- SM+ majorana fermion (DM) + real scalar + Z_2 symmetry (Klasen, Yaguna, 1309.2777)

$$\mathcal{L}_\chi = -\frac{1}{2} M_\chi \bar{\chi}\chi + g_s \phi \bar{\chi}\chi + i g_p \phi \bar{\chi}\gamma_5 \chi,$$

$$V(\phi, H) = -\mu_H^2 H^\dagger H + \lambda_H (H^\dagger H)^2 - \frac{\mu_\phi^2}{2}\phi^2 + \frac{\lambda_\phi}{4}\phi^4 + \frac{\lambda_4}{2}\phi^2 H^\dagger H + \mu_1^3 \phi + \frac{\mu_3}{3}\phi^3 + \mu\,\phi(H^\dagger H),$$

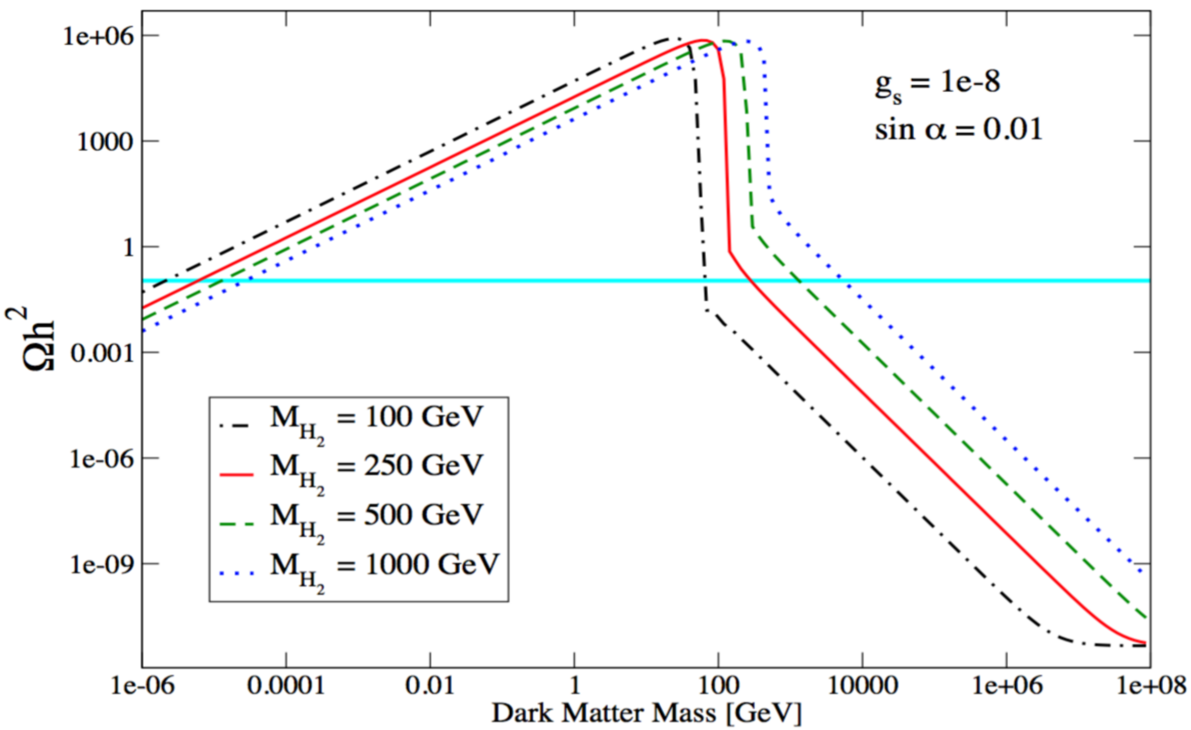
- Some diagrams that contribute to DM annihilation



- Can reproduce relic density for DM with any mass

Minimal FIMP model

- SM+ majorana fermion (DM) + real scalar + Z_2 symmetry (Klasen, Yaguna, 1309.2777)
- Can reproduce relic density for DM with any mass



Example : RH Sneutrino

- Partner of LH neutrino NOT a good DM candidate
  - Very large contribution to direct detection- through Z exchange (Falk,Olive, Srednicki, PLB354 (1995) 99)
- Neutrino have masses – RH neutrino + supersymmetric partner well-motivated – if LSP then can be dark matter
  - Thermalized?
    - Non-negligible L-R mixing (Arina et al, 1503.02960)
    - New gauge interactions MSSM+U(1) (GB, DaSilva, Laa, Pukhov 1505.06243)
    - Both cases are viable with respect to LHC constraints and feature new signatures
  - Or not – abundance from decay of other particles

MSSM+RH (s)neutrino

- The framework : MSSM + three generations (ν_R + sneutrinoR).
- Assume 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}) depending on assumption : neutrino mass saturates atmospheric neutrino or cosmological bound with degenerate neutrino

$$y_\nu \sin\beta \simeq 3.0 \times 10^{-13} \times \left(\frac{m_\nu^2}{2.8 \times 10^{-3}\ \mathrm{eV}^2}\right)^{1/2}$$

- Sneutrino mass same order as other sfermions – can be LSP

$$-\mathcal{L}_{\rm soft} \supset \tilde{M}_L^2 |\tilde{L}|^2 + \tilde{M}_{\nu_R}^2 |\tilde{\nu}_R|^2 + \left(\tilde{A}_\nu H_u \cdot \tilde{L}\,\tilde{\nu}_R^c - \tilde{A}_e H_d \cdot \tilde{L}\,\tilde{\ell}_R^c + h.c.\right)$$

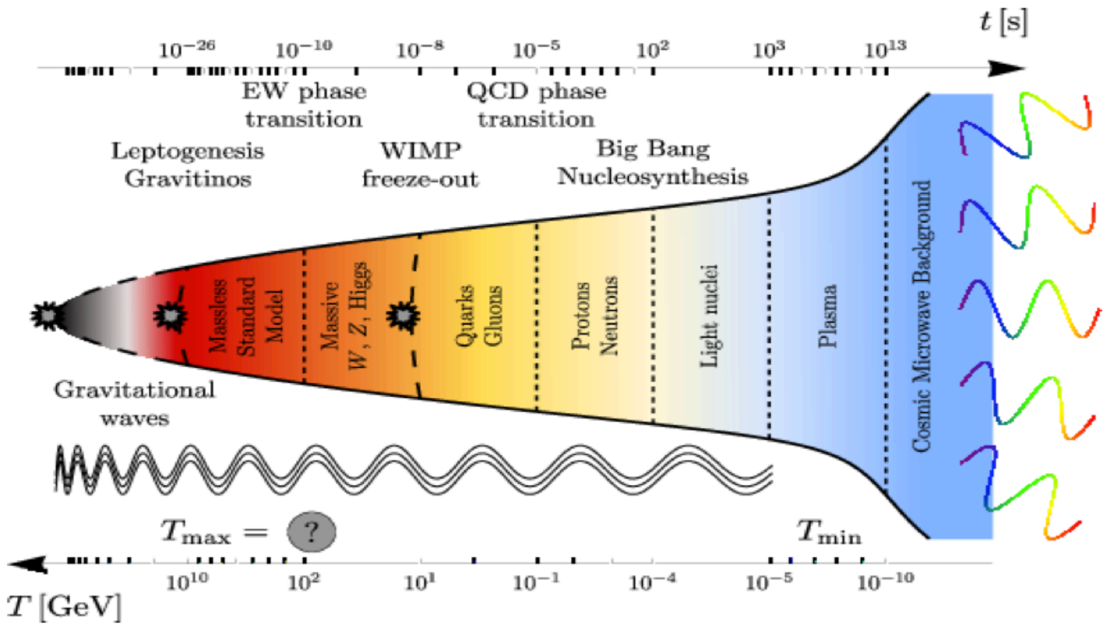
- Sneutrino mixing $$\tan 2\Theta = \frac{2m_\nu |\cot\beta\,\mu_H - A_\nu^*|}{m_{\tilde{\nu}_L}^2 - m_{\tilde{\nu}_R}^2},$$

- Sneutrino not thermalized in early universe – its interactions are too weak
- One possibility for DM is production through decays of sparticles
- Consider decay of MSSM-LSP after freeze-out (lifetime of NLSP is quite long)
- Relic density obtained from that of the NLSP (or MSSM-LSP) – can be charged

$$\Omega^{\rm FO}_{\tilde{\nu}_R} = \frac{m_{\tilde{\nu}_R}}{m_{\rm MSSM\text{-}LSP}} \Omega_{\rm MSSM\text{-}LSP}$$

- Consider the case where stau is the NLSP (and for simplicity assume SUGRA relations)
- Collider constraints – Higgs; flavour constraints; susy searches (mostly not valid because stau is collider stable and charged); charged stable particles
- Constraints from BBN : lifetime of stau can be long enough for decay around or after BBN→ impact on abundance of light elements

Big Bang nucleosynthesis



- BBN success in predicting abundances of light elements, D, He^3, He^4, ^7Li
- Depends on photon to baryon ratio
- In early Universe, energy density dominated by radiation (γ e) conditions for synthesis of light elements at T~ 1MeV
- At these T, weak interaction rates were in thermal equilibrium

$$n + e^+ \rightarrow p + \nu \qquad\qquad n \rightarrow p + e^- + \nu_e$$
$$n + \nu \rightarrow p + e^-$$

- Reverse process proceed at same rate and n/p~1
- At lower temperatures : weak interactions fall out of equilibrium

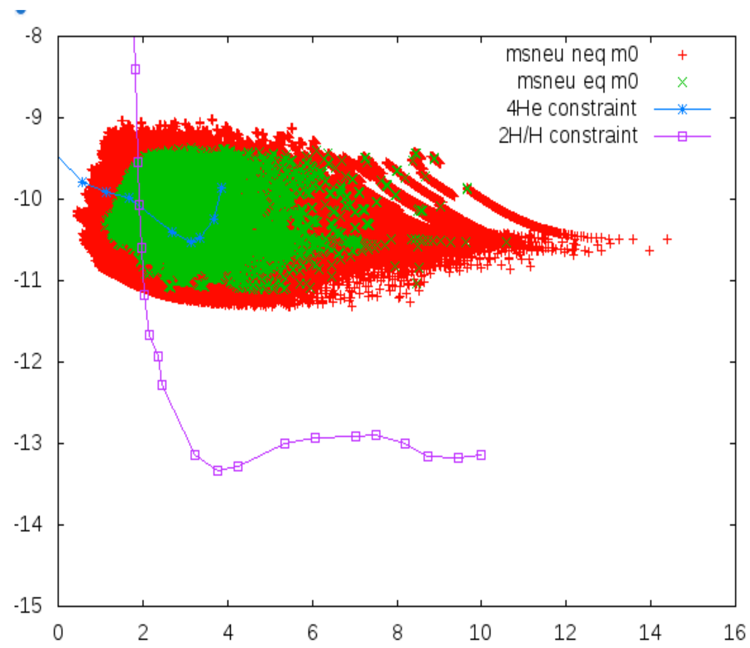
- Relationship between expansion rate of Universe (relate to total matter density) and density of p and n (baryonic matter density) determine abundance of light elements

$$Y \approx \frac{2n/p}{1+n/p} \approx 0.25$$

- Main product of BBN ^4He
- Other elements produced in lesser amounts D, $^3He \sim 10^{-5}$, $^7Li \sim 10^{-10}$
- Decay of particle with lifetime > 0.1s can cause non-thermal nuclear reaction during or after BBN – spoiling predictions – in particular if new particle has hadronic decay modes
  - Kawasaki, Kohri, Moroi, PRD71, 083502 (2005)

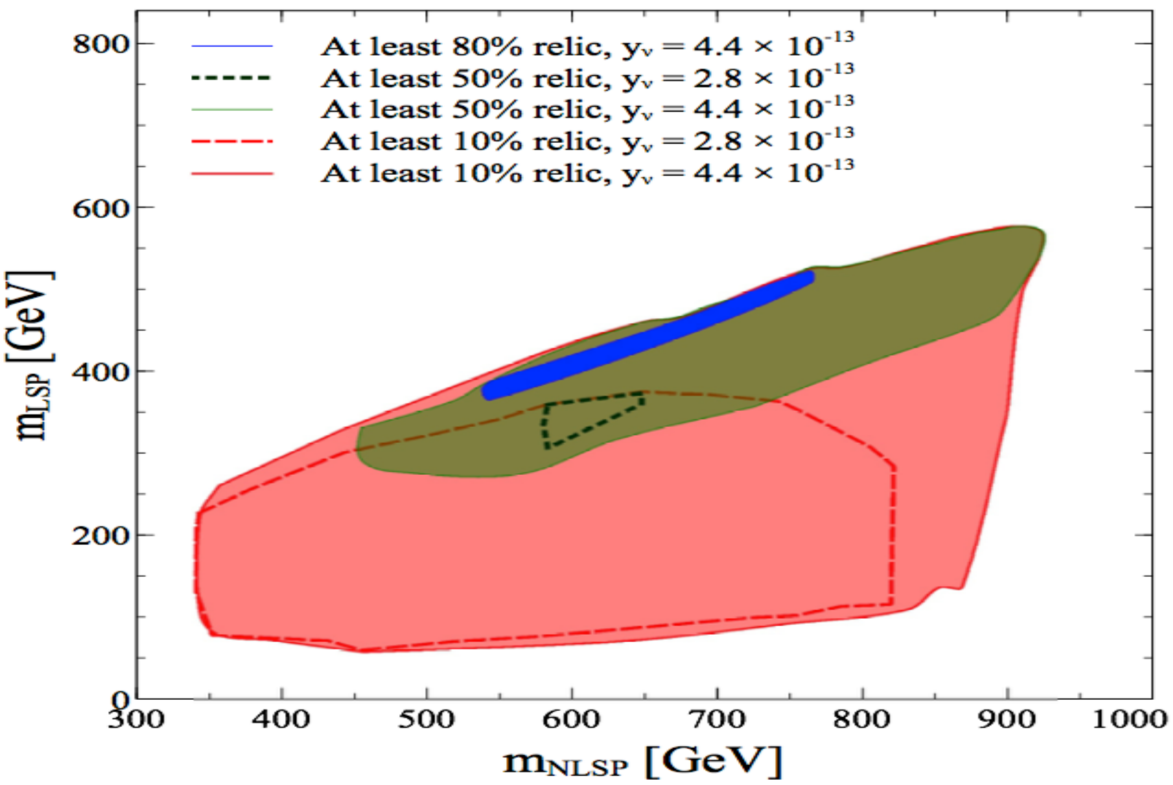
- Hadrodissociation of He^4 - overproduction D
  - $n+He^4$ -> He^3+D, 2D+n, D+p+n

- Key elements : B_{had}, E_{vis} (net energy carried away by hadrons), Y_{NLSP} : yield



Allowed region

- After all constraints – room for sneutrinoR DM (even in CMSSM)
- Can constitute dominant dark matter component



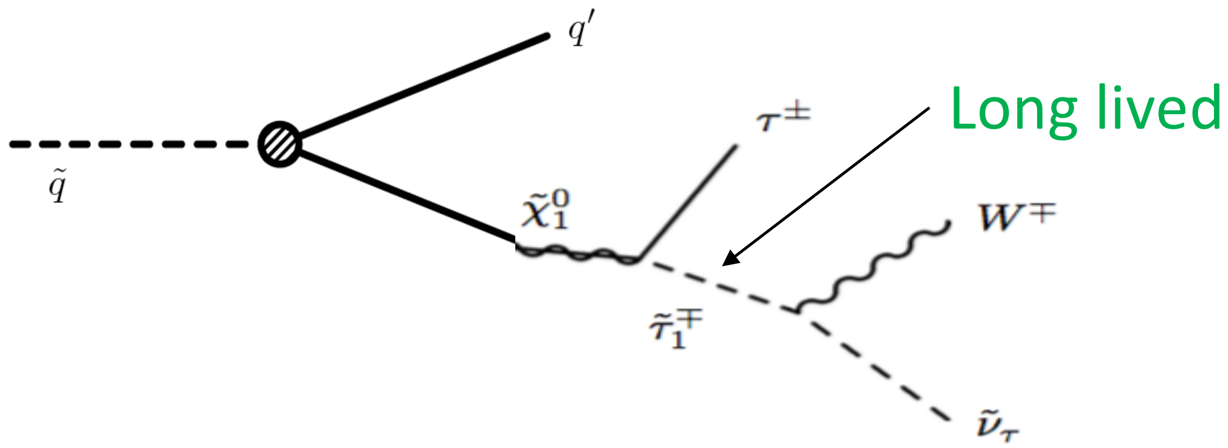
Banerjee, GB, Mukhopadyhyay, Serpico, 1603.08834

LHC signatures

- Characteristic signature : stable charged particle NOT MET
- Staus live from sec to min : decay outside detector
- Searches
  - Cascades : coloured sparticles decay into jets + SUSY→ N jets + stau
  - Pair production of two stable staus
  - Passive search for stable particles
- Stable stau behaves like « slow » muons $\beta = p/E < 1$
  - Use ionisation properties and time of flight measurement to distinguish from muon
  - kinematic distribution

Banerjee, GB, Mukhopadyhyay, Serpico, 1603.08834

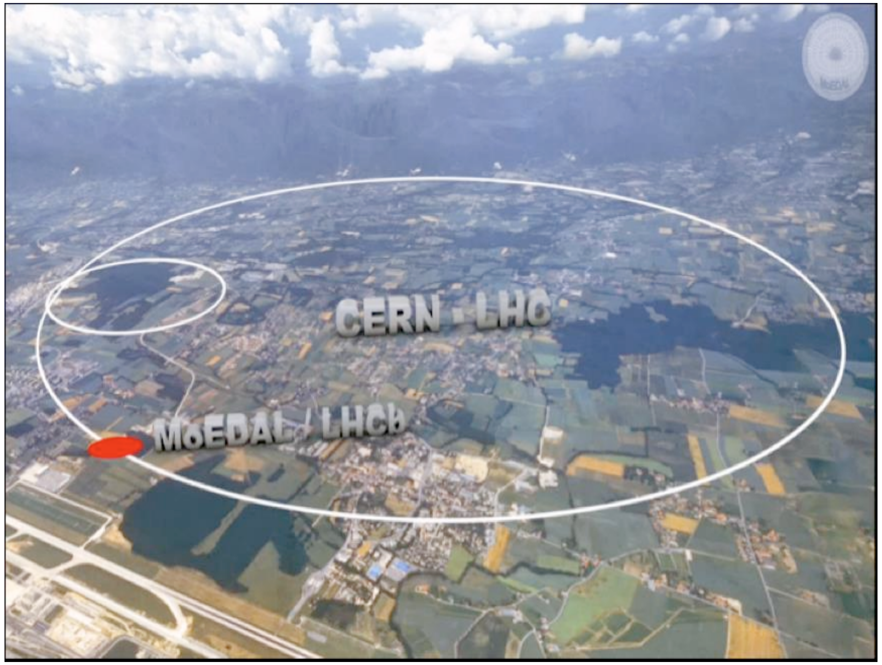
Charged tracks from cascades



- Dominant contribution from squark pairs (heavy gluinos)
- Can probe mass ~600 GeV but depends on squark mass
- Pair production : no model dependence but EW cross section -> lower reach

Banerjee, GB, Mukhopadyhyay, Serpico, 1603.08834

MoEDAL detector



- Passive detector
- Array of nuclear track detector stacks
- Surrounds intersection region point 8
- Sensitive to highly ionising particles
- Does not require trigger, one detected event is enough
- Major condition : ionizing particle has velocity $\beta<0.2$

B. Acharya et al, 1405.7662

Benchmark point	Cascade	Pair
357 GeV	45	2.5
400 GeV	296	1.5
442 GeV	24	1.1
600 GeV	6	0.5

Banerjee, et al, 1603.08834

Number of $\tilde{\tau}_1$'s with $\beta \leq 0.2$ with $\mathcal{L} = 3000\,\mathrm{fb}^{-1}$

DM with strong interactions

- Strong interactions with itself – SIDM
- Strong interactions with SM – SIMP

Self-interactions : motivation

- Collisionless CDM works well at large scale however discrepancies between Nbody simulations in ΛCDM and astrophysical observations on galactic or galaxy cluster scales

Cusp-core problem : simulations of CDM predict dense core of DM (cusp) but central regions of dwarf galaxies : cored profile

Missing satellites problem : simulations predict how many galaxies should be for different masses in particular how many satellite galaxies and how massive they are

- Milky Way is big galaxy with an expect 500 satellites while observe only 11 dwarf galaxies

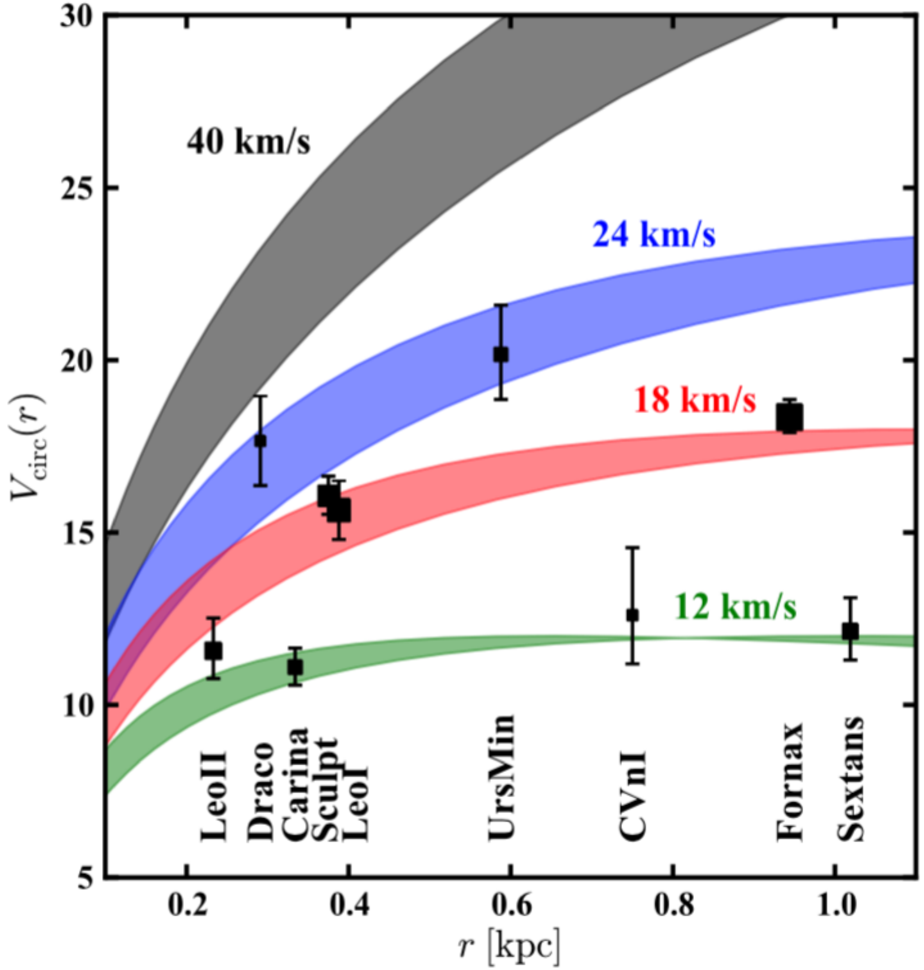
- Could be that small halos exist but are not visible because they were not able to attract enough baryonic matter to create visible dwarf galaxy

- OR galaxies get stripped of their stars and gas by interacting with host galaxy

Self-interactions

Too big to fail : (related to missing satellites) some of predicted galaxies are so massive that there's no way they would not have visible stars

Massive galaxies are not observed



Boylan-Kolchin, Bullock, Kaplinghat, 1111.2048

Self-interacting DM

DM self interactions could help solve these problems :

DM interactions with SM are weak but large self-interactions (when they collect in core of galaxies, they scatter, heat up the core so their pressure extends it and reduce central density)

DM self interactions cannot be too large since Bullet cluster show DM is collisionless -> $\sigma/m < 1\text{cm}^2/\text{g} \sim 2$ barns/GeV

orders of magnitude above weak interactions ~1pb !!

Distinctive astro signature : separation between DM halo and stars in a galaxy moving through region of large DM density (observed in Abell3827, Massey et al 1504.03388)

If DM interactions are strong would naturally lead to negligible relic density

Need mechanism where self-interactions are enhanced today as compared with annihilation in early Universe

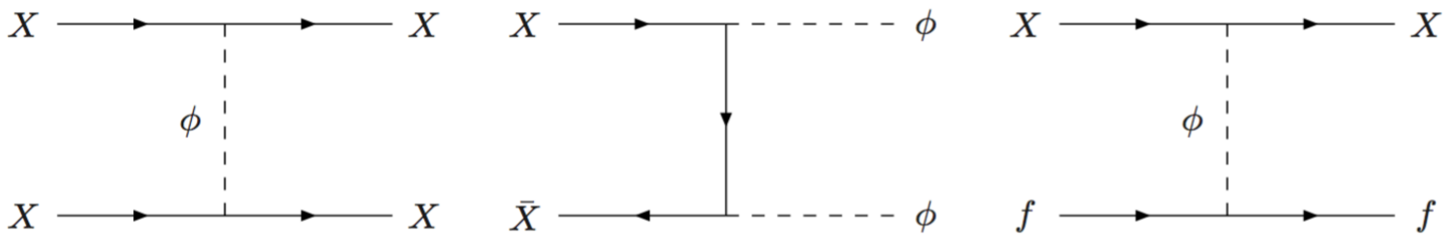
2 possibilities: - light mediators (Sommerfeld-type enhancement)

- freeze-out from 3->2 processes

SIDM : an example

- Dirac fermion DM, mediator : gauge boson U(1) (ϕ) mass below GeV
- Self interactions $V(r) = \pm \frac{\alpha_X}{r} e^{-m_\phi r}$
- DM couples to SM through kinetic mixing $\epsilon_\gamma \, \phi_{\mu\nu} F^{\mu\nu}$ induces coupling to SM fermions

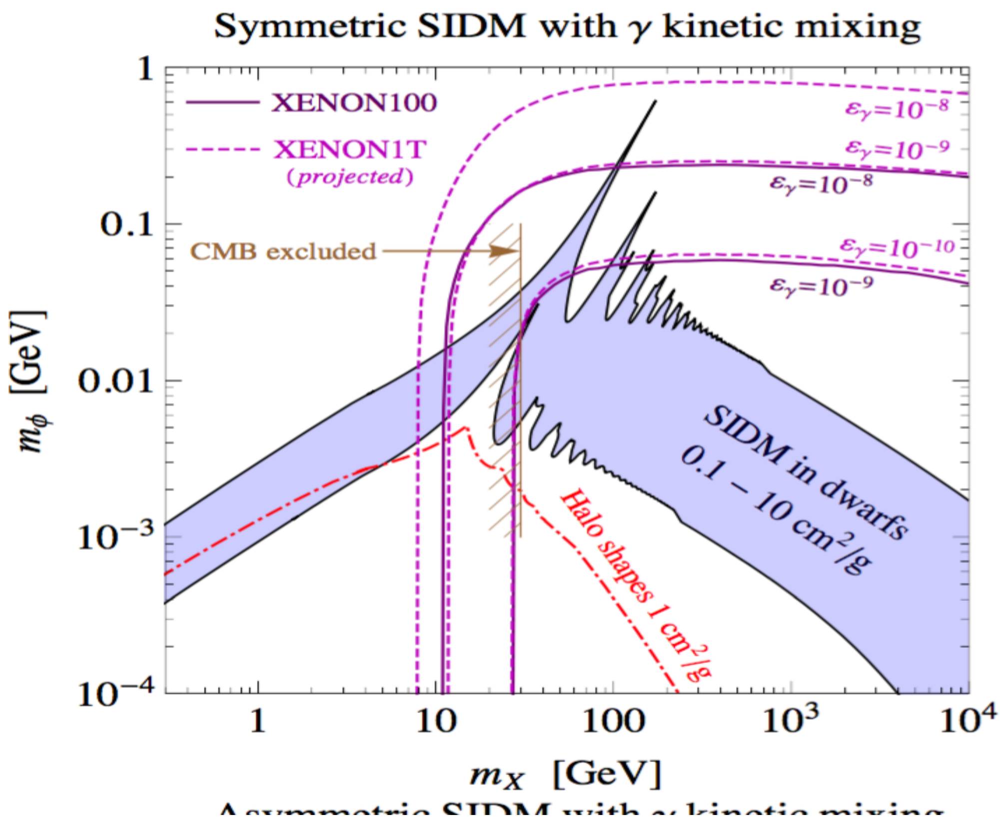
$$\epsilon_\gamma e \sum_f Q_f \bar{f} \gamma^\mu f \phi_\mu$$



DM self-interactions DM annihilation Direct detection

SIDM : an example

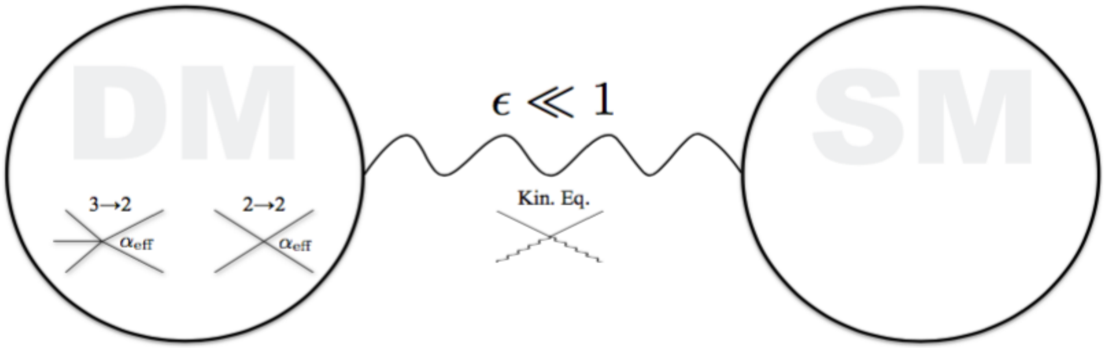
- Relic density : freeze-out $\sigma v \sim \pi\, \alpha_X^2/m_X^2$
- $\Omega\, h^2 \sim .1$ for weak scale DM
- Direct detection : small mediator mass enhances cross section compensates for small coupling
- ϕ must decay with lifetime ~1sec otherwise dominates energy of Universe
- Lower limit on SM coupling



Kaplingat, Tulin, Yu, 1310.7945

SIDM : another case

- Freeze-out via processes 3->2, because phase-space suppression, relic abundance not too small
  - Carlson, Machacek, Hall, Astrophys.J. 398 (1992)
  - Hochberg et al , 1402.5143; Bernal et al, 1510.08063



- Coupling required close to non-perturbative…

Strongly Interacting MP

Strong interactions of DM with SM particles (SIMP)

If thermal freeze-out : can only be subdominant DM component

Otherwise : some non-thermal mechanism or asymmetric

Constraints: DM captured and accreted at core of Earth, annihilating SIMP source of heat -> measurements of heat flow set strong constraints unless DM asymmetric

Here simplified model with vector or scalar mediator, e.g

$$-\tilde{g}_\chi \phi_\mu \, \bar{\chi}\gamma^\mu \chi - \tilde{g}_q \phi_\mu \, \bar{q}\gamma^\mu q$$

Astrophysics constraints on Strong interaction with SM

At collider probe interaction with ordinary matter

Searches SIMP

Direct detection : large cross sections SIMP stopped in earth atmosphere – no sensitivity in underground detectors,

High altitude detectors search for SIMP above atmosphere (e.g. RSS-balloon based)

If cross section not too large -> stringent constraints from undergound detectors

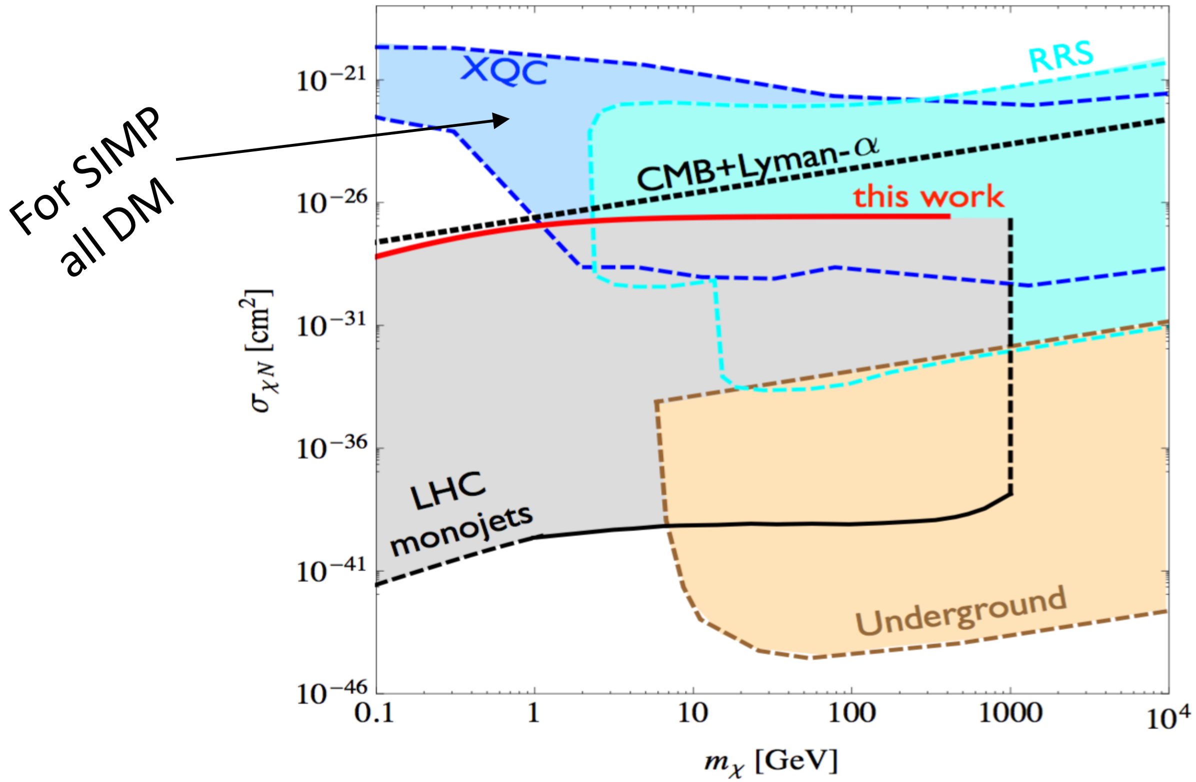
Interactions of DM with baryons also constrained from CMB and large scale structure (Dvorkin et al, 1311.2937) affect dynamics of linear density perturbation in early universe: a baryon in halo of galaxy does not scatter from DM particles during age of galaxy

SIMP - Collider signature

SIMP produced in pairs – strong interations with ordinary matter can behave like neutrons – deposit energy or stop in hadronic calorimeter – depends on inelastic scattering of SIMP with hadrons

Dark matter jets have zero tracks and less electromagnetic activity in Ecalorimeter than QCD jets - smaller charged energy fraction $\sum_i p_{\mathrm{T,i}}/p_{\mathrm{T,jet}}$

If all DM energy deposit in detector (2 back-to-back jets no MET)



Assume vector mediator m=1GeV

$\sigma_{\chi N}/\sigma_{\mathrm{QCD}} = 1$

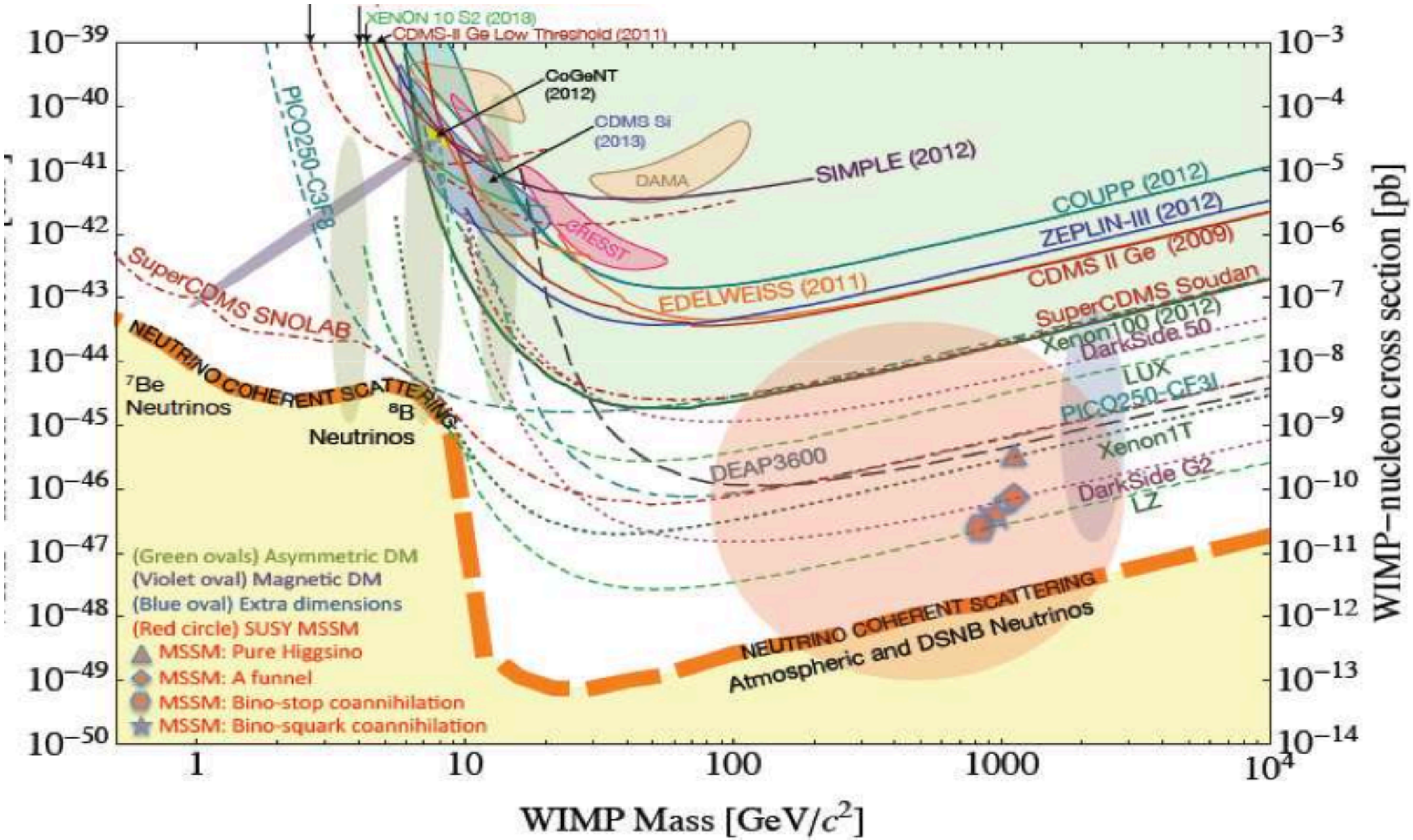
LHC8 20fb^{-1}

Daci et al, 1503.05505

and many more DM models…

Conclusion

- Strong evidence on dark matter
- List of possible dark matter candidates and models has grown rapidly in last few years
- WIMP hypothesis is being probed by LHC (not only MET), direct and indirect detection
- Still no clear picture although parameter space of popular model is shrinking - next few years will be crucial
- Non-WIMP candidates also interesting possibility
- Dark matter might be much different than expected



XENON 10 S2 (2013)
CDMS-II Ge Low Threshold (2011)
CoGeNT (2012)
CDMS Si (2013)
DAMA
SIMPLE (2012)
COUPP (2012)
ZEPLIN-III (2012)
CDMS II Ge (2009)
CRESST
EDELWEISS (2011)
SuperCDMS Soudan
Xenon100 (2012)
DarkSide 50
LUX
PICO250-CF3I
Xenon1T
DarkSide G2
LZ
DEAP3600
PICO250-C3F8
SuperCDMS SNOLAB
NEUTRINO COHERENT SCATTERING
^{7}Be Neutrinos
^{8}B Neutrinos
NEUTRINO COHERENT SCATTERING
Atmospheric and DSNB Neutrinos
(Green ovals) Asymmetric DM
(Violet oval) Magnetic DM
(Blue oval) Extra dimensions
(Red circle) SUSY MSSM
MSSM: Pure Higgsino
MSSM: A funnel
MSSM: Bino-stop coannihilation
MSSM: Bino-squark coannihilation
10^{-39}
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1
10
100
1000
10^{4}
WIMP Mass [GeV/c^2]
WIMP–nucleon cross section [pb]