Unravelling the mysteries of dark matter

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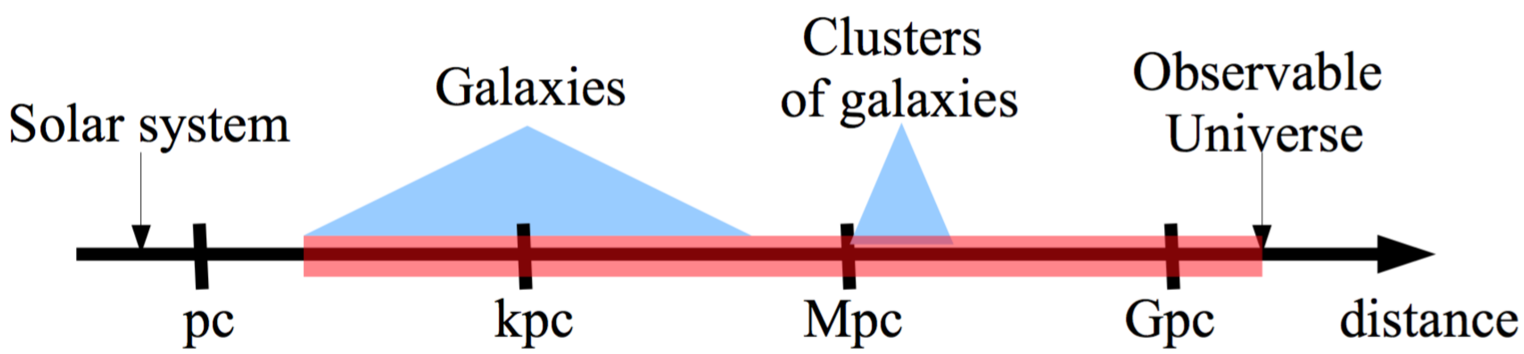
HEPHY
INSTITUT FÜR HOCHENERGIEPHYSIK

FWF
Der Wissenschaftsfonds.

ÖAW
ÖSTERREICHISCHE AKADEMIE DER WISSENSCHAFTEN

Dark Matter - evidence

- Strong evidence on all scales



- But apart from that…

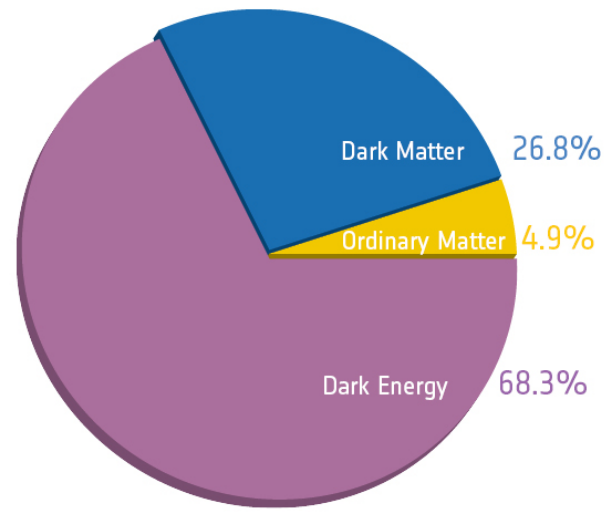
DARK MATTER

$J =$?

Mass $m =$?
Mean life $\tau =$?

DECAY MODES	Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
?	?	?	?

- Precise measurements of relic density



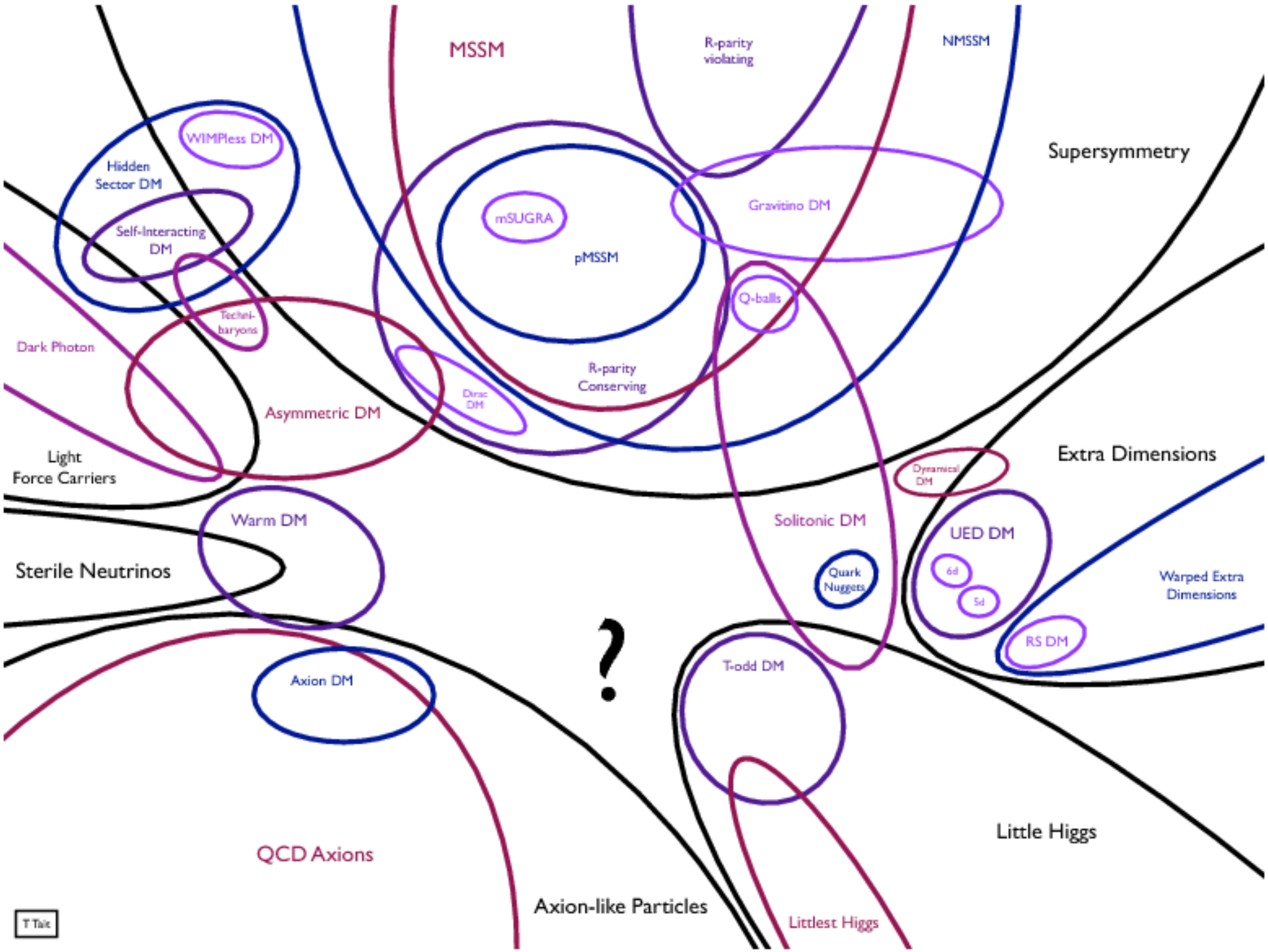
After Planck

Goal for 21st century: identify the properties of dark matter

~85% all matter in the Universe is dark matter

Slide inspired by A. Ibarra's talk

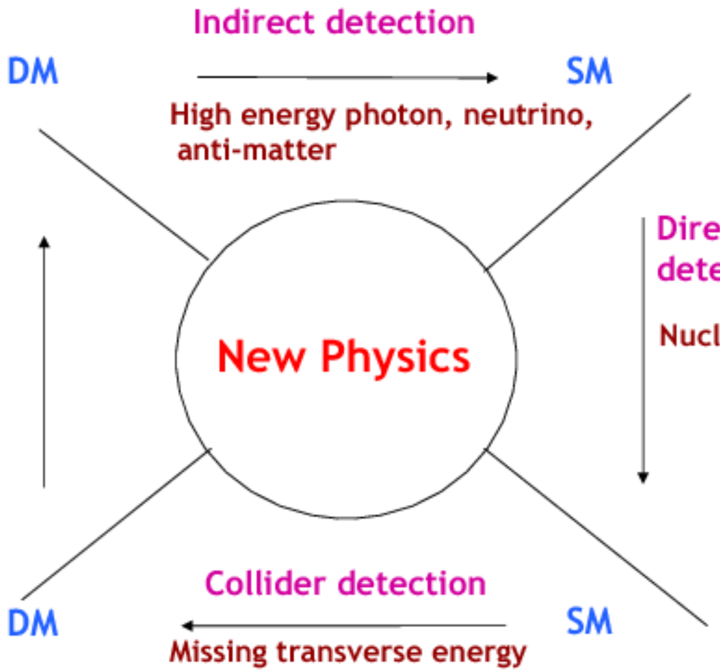
Theory development



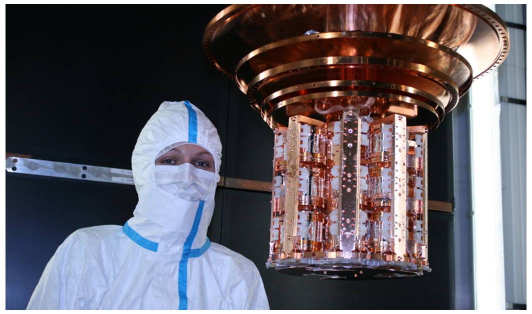
Avenues for progress

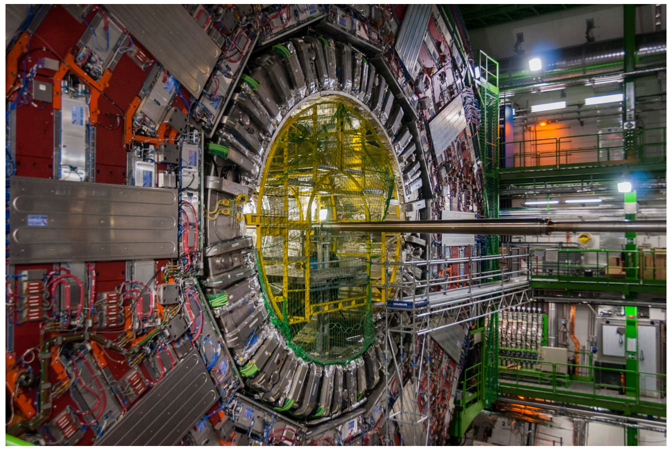
1. Potential signatures at multiple experiments
   - Cross-correlate signatures
2. Future experimental searches are in pipeline
   - Demonstrate their potential
3. Is there something we are missing?
   - Suggest new signatures

- Stay as model independent as possible



@HEPHY





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Cross-correlate signatures

LHC searches

LHC master formula for searches

$$N_{evts} = \mathcal{L} \times \mathcal{A} \times \epsilon \times \sigma \times \mathrm{BR}$$

LHC searches

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Final observable

LHC searches

LHC master formula for searches

$$N_{evts} = \mathcal{L} \times \mathcal{A} \times \epsilon \times \sigma \times \mathrm{BR}$$

Integrated luminosity

LHC searches

LHC master formula for searches

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Depends on the detector geometry

LHC searches

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$$N_{evts} = \mathcal{L} \times \mathcal{A} \times \epsilon \times \sigma \times \mathrm{BR}$$

Depends on the selection cuts

LHC searches

LHC master formula for searches

$$N_{evts} = \mathcal{L} \times \mathcal{A} \times \epsilon \times \sigma \times \mathrm{BR}$$

Theory prediction

LHC searches

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$$N_{evts} = \mathcal{L} \times \mathcal{A} \times \epsilon \times \sigma \times \mathrm{BR}$$

$$\begin{aligned} \sigma \times \mathrm{BR} &= 0.1\,\mathrm{fb} \\ \mathcal{L} &= 30\,\mathrm{fb}^{-1} \\ \mathcal{A} \times \epsilon &= 0.001 \\ \Rightarrow N_{evts} &= 0.003 \end{aligned}$$

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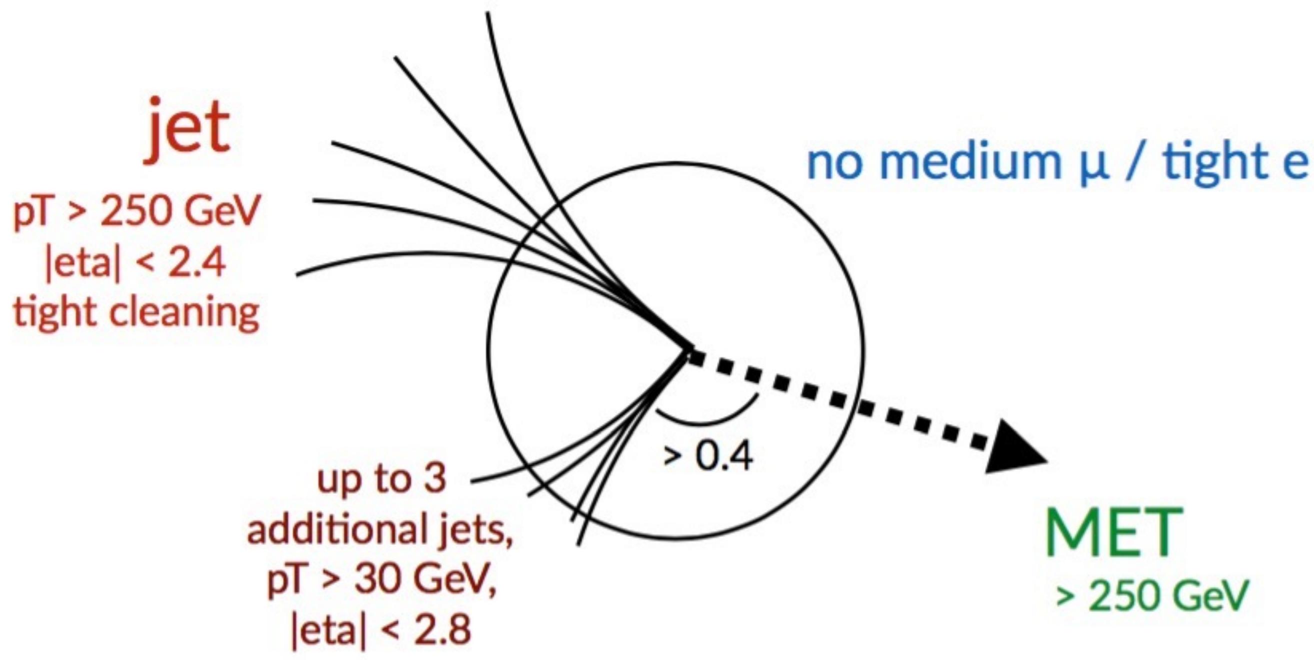
$\Rightarrow$

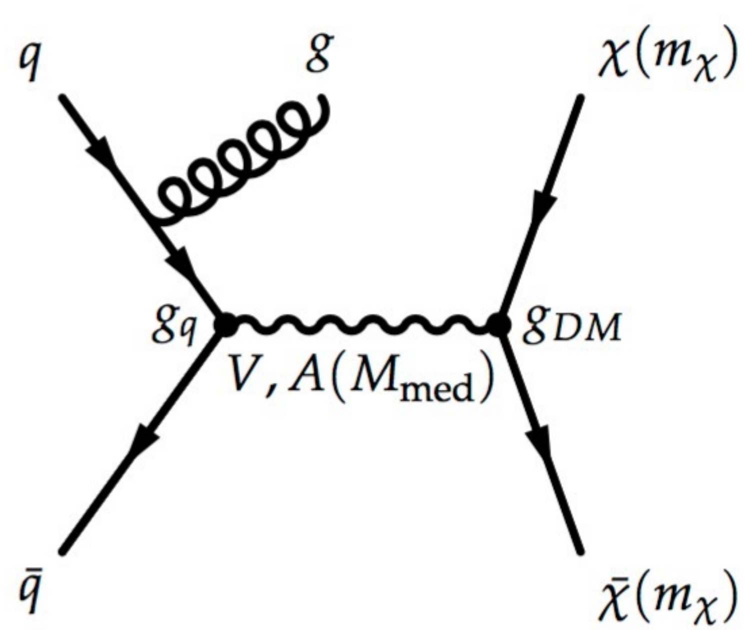
- For ideal detector there is some chance
- Hopeless to try to probe this cross section
- Situation better for higher luminosity

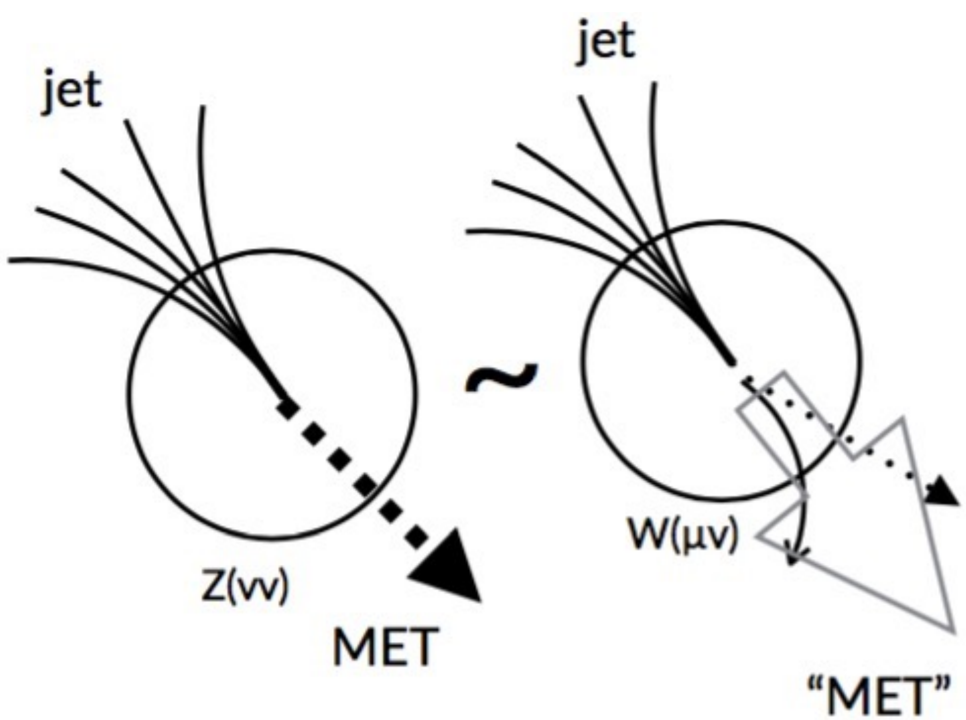
DM @ LHC

Figures curtesy A. Boveia's talk



- Signal regions with successively larger MET requirement



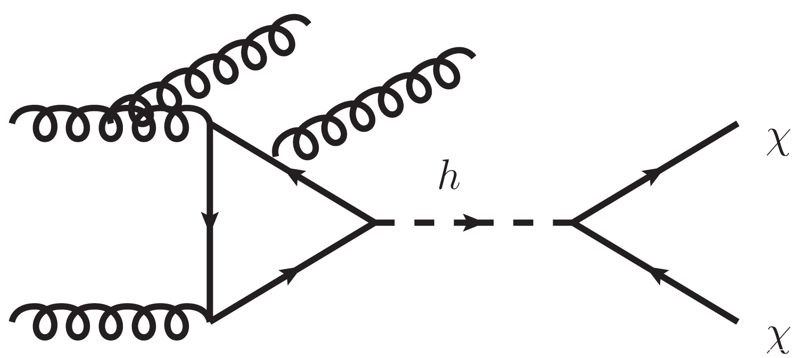


Theoretical motivation

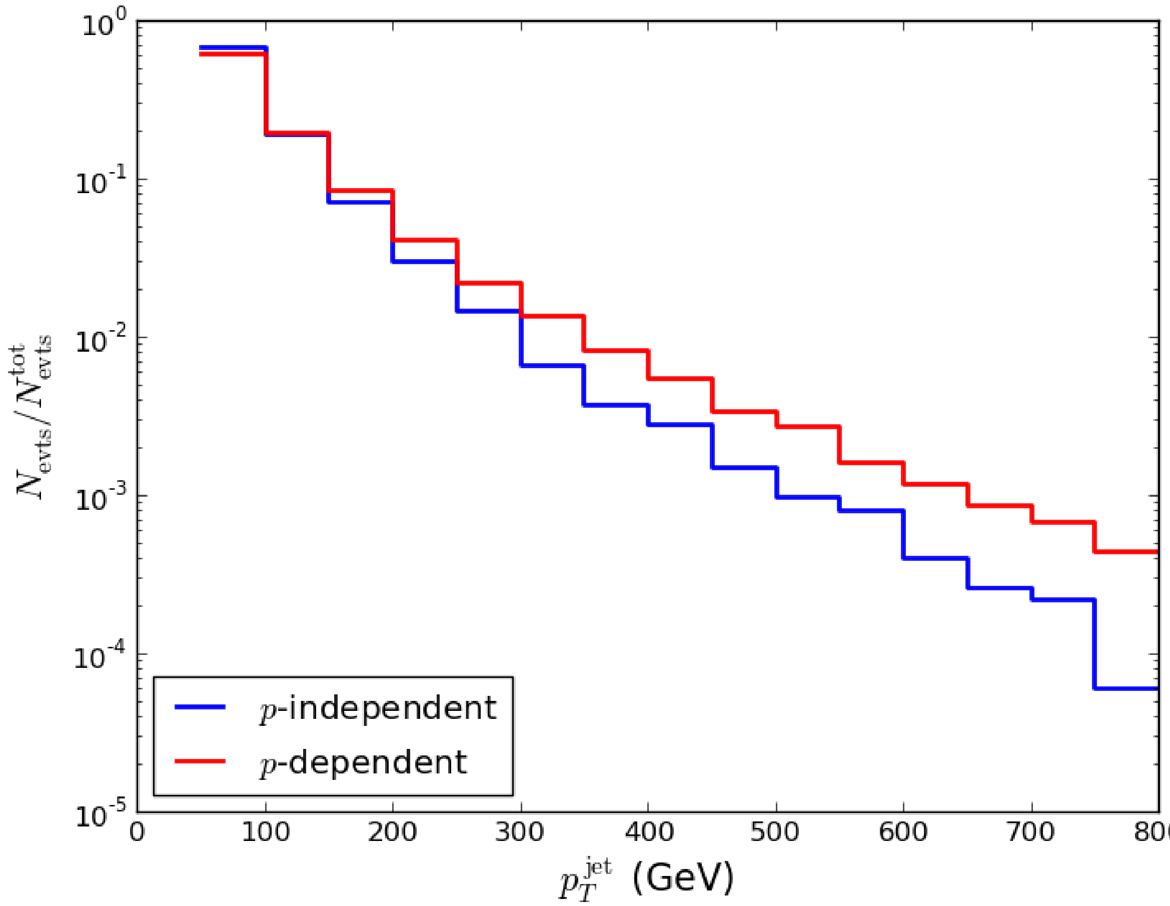
Kulkarni et al. JHEP 1701 (2017) 078

- Dark matter could be a pseudo Nambu Goldstone Boson appearing in the low energy theory as a result of the spontaneous breaking of a global symmetry by a new strong sector dynamics
- Strong sector dynamics can appear in the context of a new strongly-coupled sector above the TeV scale
- The analogy is the pion in QCD, the pions appear as Goldstone bosons of qqbar condensate breaking the chiral symmetry
- The shift symmetry of Goldstone bosons imply that their interactions are derivative (in the exact symmetry limit)
- What kind on phenomenological limits can be placed on such dark matter scenarios and what is the sensitivity of the LHC for these couplings?

Impact on monojets



$$ig_{h\eta\eta} = 2iv\left[\lambda_{\mathrm{mi}} + \frac{p_h^2}{f^2}\right]$$



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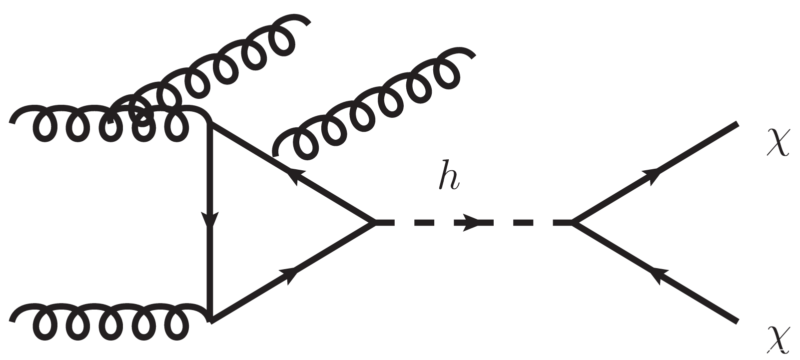

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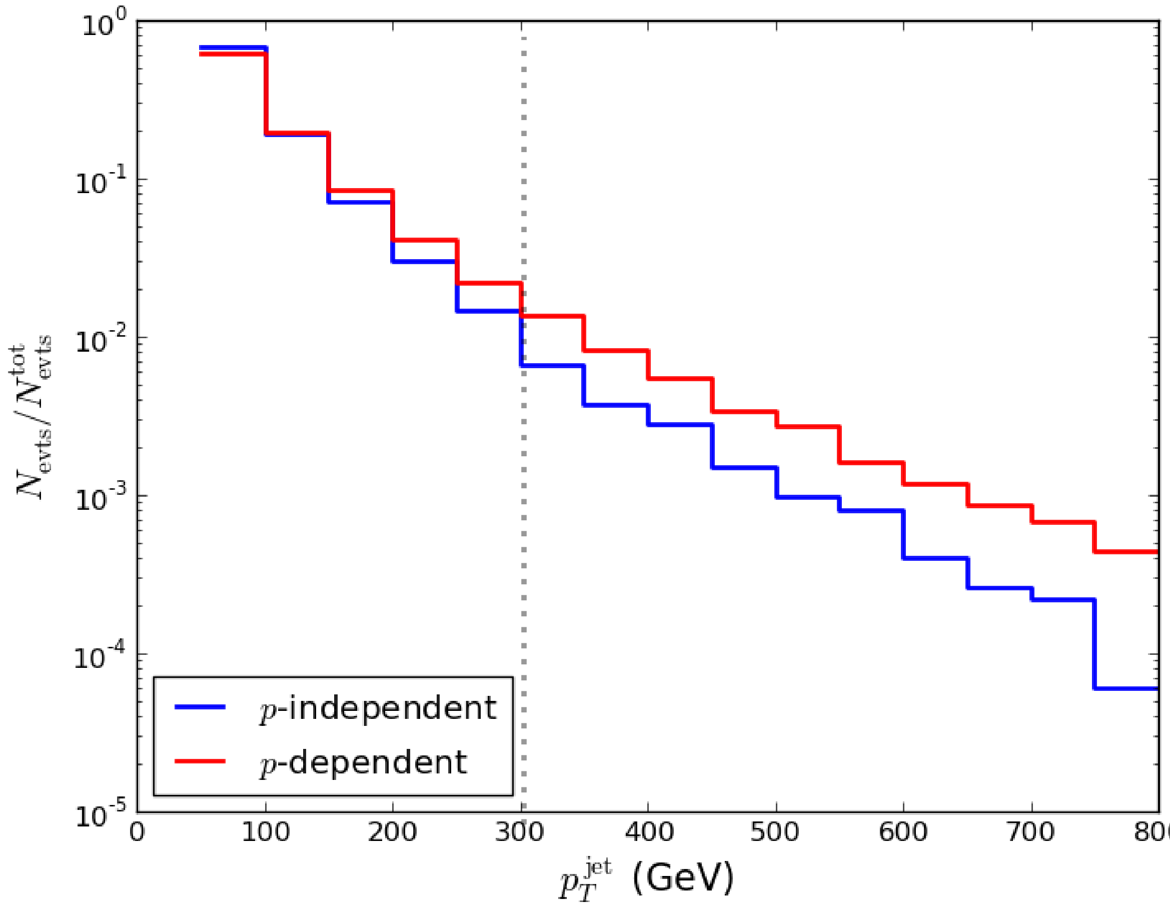

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Simple case

- Extension of the Standard Model by gauge singlet real scalar field

$$\mathcal{L}_\eta = \mathcal{L}_{SM} + \frac{1}{2}\partial_\mu\eta\partial^\mu\eta - \frac{1}{2}\mu_\eta^2\eta^2 - \frac{1}{4}\lambda_\eta\eta^4 - \frac{1}{2}\lambda\eta^2 H^\dagger H + \frac{1}{2f^2}(\partial_\mu\eta^2)\partial^\mu(H^\dagger H)$$

- After electroweak symmetry breaking

$$\mathcal{L}_\eta \supset -\frac{1}{4}(v+h)^2\left(\lambda\eta^2 + \frac{1}{f^2}\partial_\mu\partial^\mu\eta^2\right)$$

$$m_\eta^2 = \mu_\eta^2 + \lambda v^2/2$$

scale of spontaneous symmetry breaking

Momentum dependent coupling

For mono-Higgs signature study of similar model see e.g. arXiv:1312.2592, arXiv:1412.0258

Simple case

- Monojet production cross section

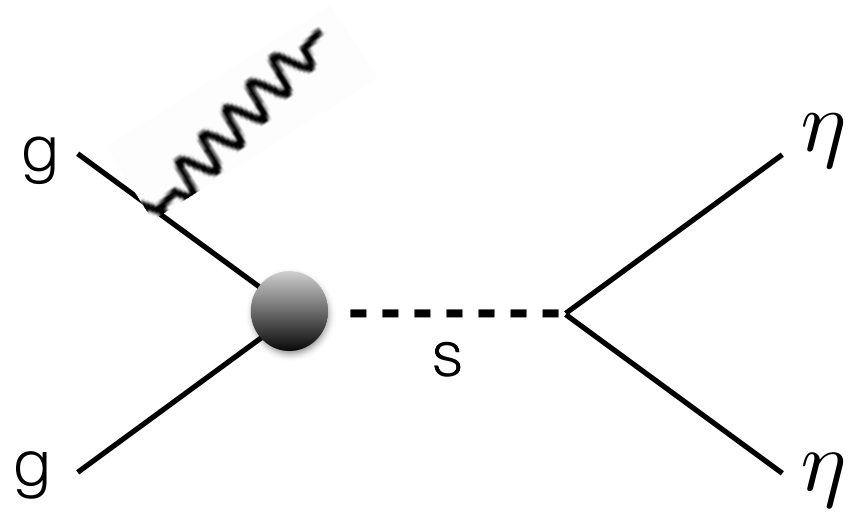
$$\hat{\sigma}(gg \to gh^* \to g\eta\eta) \propto \frac{\theta(p_h^2 - 4m_\eta^2)}{(p_h^2 - m_h^2)^2 + \Gamma_h^2 m_h^2} \left(\frac{p_h^2}{f^2} - \lambda\right)^2 \sqrt{1 - \frac{4m_\eta^2}{p_h^2}}$$

- For the onshell regime the momentum dependence vanishes
- Off-shell Higgs regime, leads to a very small cross section < 1 fb for momentum dependent and < 0.5 fb for momentum independent couplings
- Good measurements of Higgs production cross sections limit ggh couplings, decreasing the total cross section for monojet production

Model

- Z_2 odd real singlet scalar dark matter particle couplings to the Standard Model with Z_2 even scalar singlet

$$\mathcal{L}_{\eta,s} = \mathcal{L}_{\rm SM} + \frac{1}{2}\partial_\mu\eta\partial^\mu\eta - \frac{1}{2}m_\eta^2\eta\eta + \frac{1}{2}\partial_\mu s\partial^\mu s - \frac{1}{2}m_s^2 ss + \frac{c_{s\eta}f}{2}s\eta\eta + \frac{c_{\partial s\eta}}{f}(\partial_\mu s)(\partial^\mu\eta)\eta + \frac{\alpha_s}{16\pi}\frac{c_{sg}}{f}sG^a_{\mu\nu}G^{a\mu\nu}$$



For consistent model constructions and detailed dark matter phenomenology see arXiv:1501.05957

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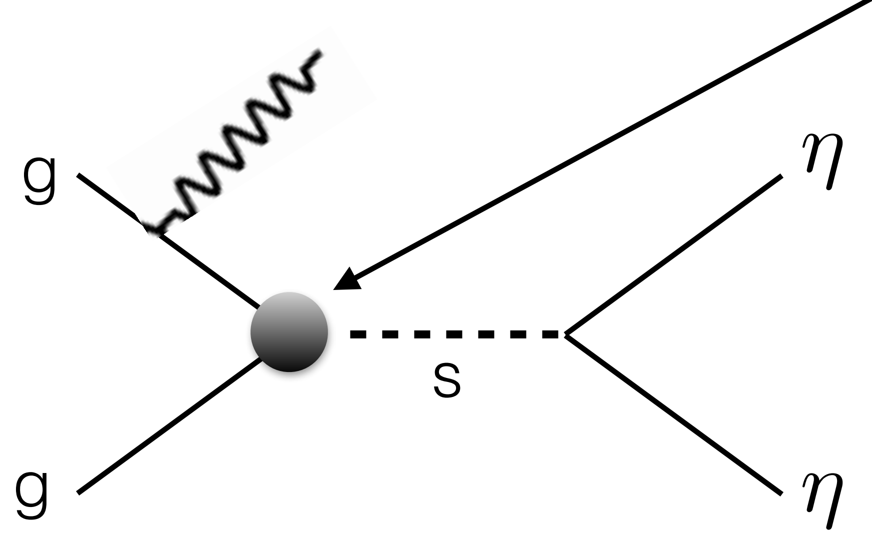

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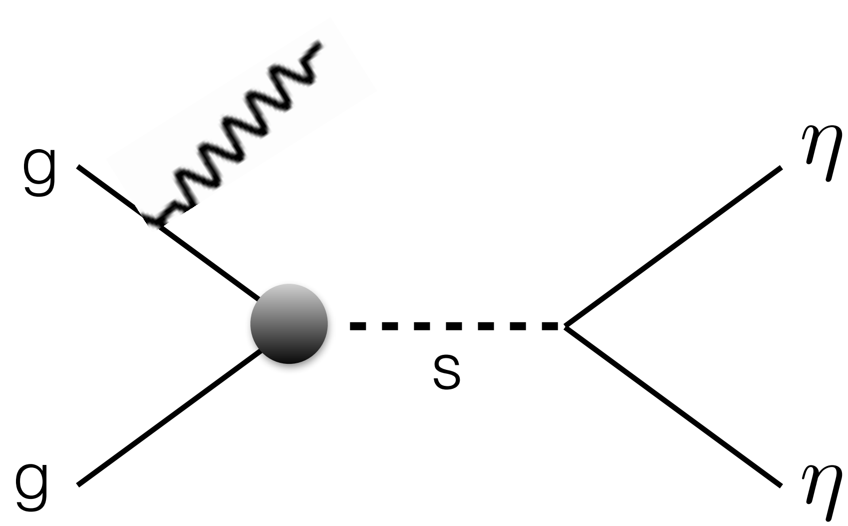

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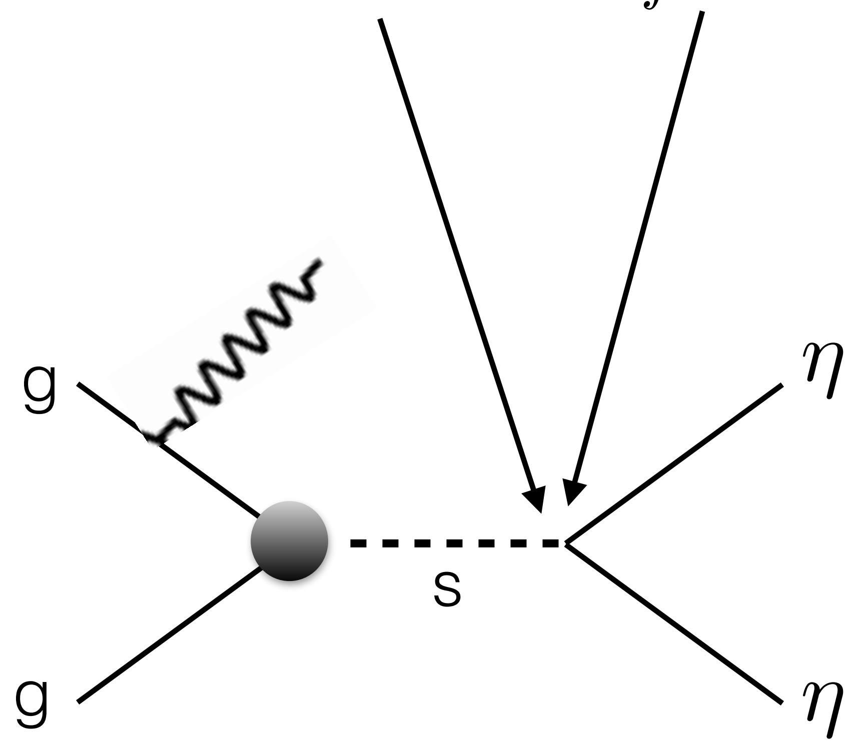

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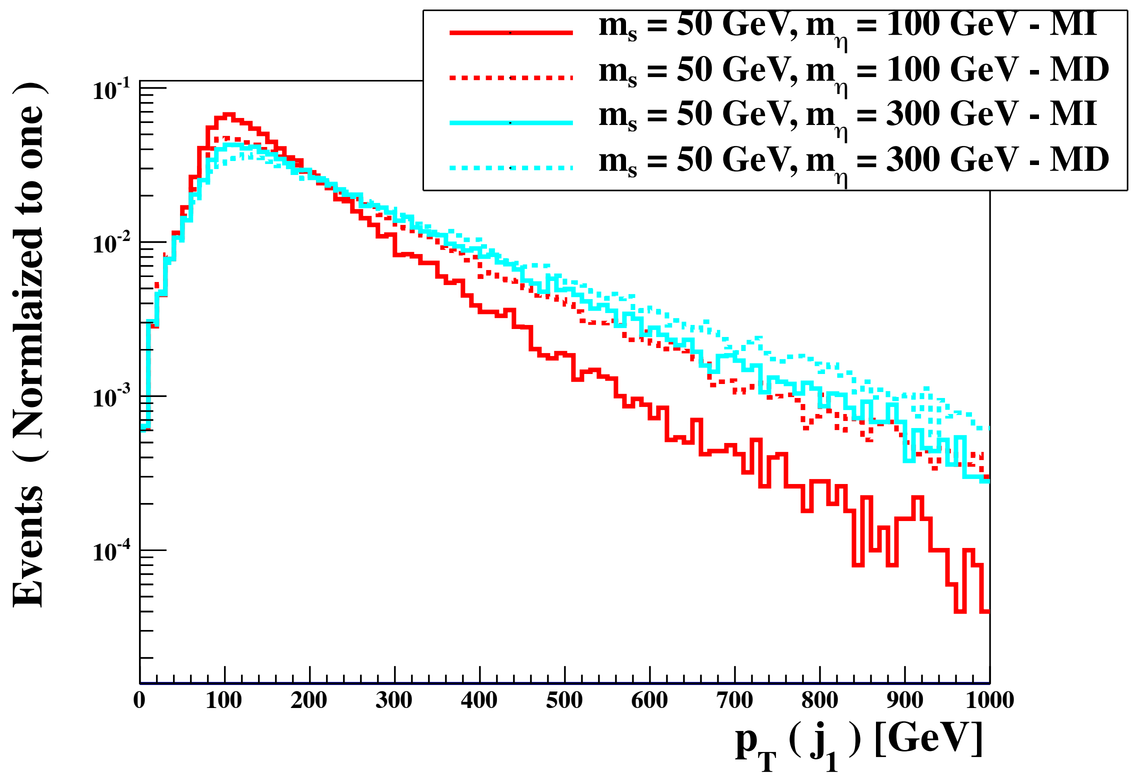
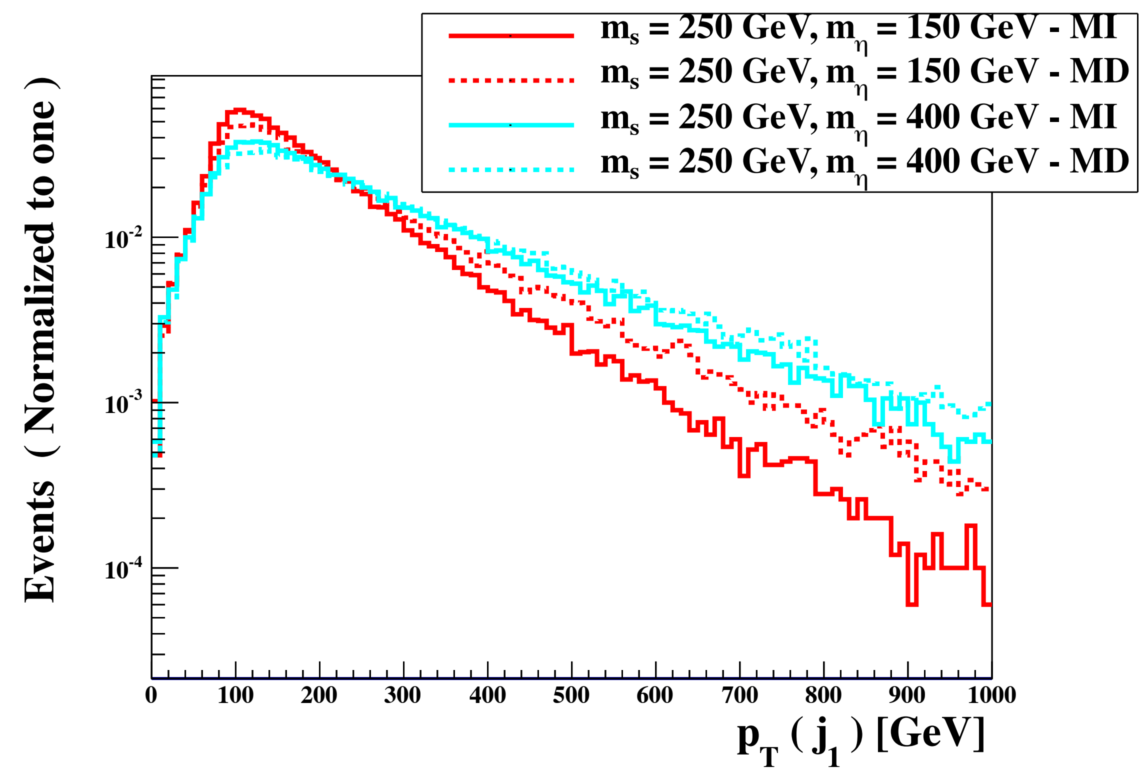
Momentum dependence





$$c_{gs} = 100 \quad f = 1\ \text{TeV} \quad c_{\partial s\eta} = 2.5 \quad c_{s\eta} = 0.5$$

Production cross section of 2.9 pb after generator cut of jet pT > 80 GeV

For $p_T > 300$ GeV,
Luminosity $300\ \text{fb}^{-1}$

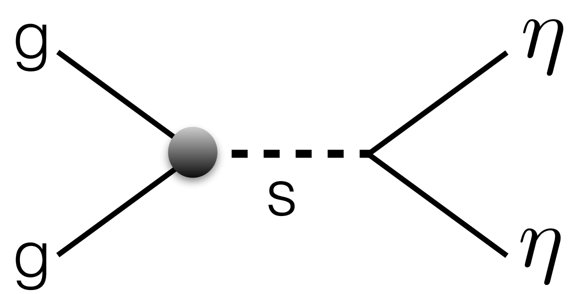
#events MI	#events MD
131300	196533

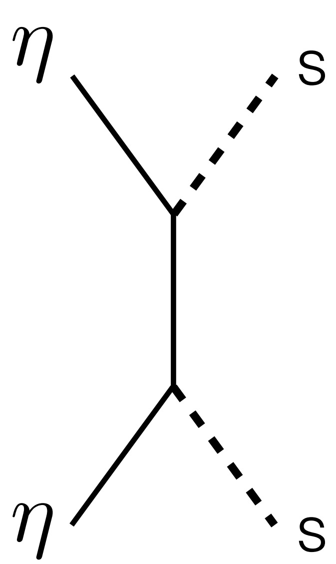
Momentum dependent expected to yield 50% better sensitivity

Relic density

- Unlike LHC constraints, relic density depends on the propagator mass
- Two annihilation channels

$$\langle \sigma v \rangle_{gg} \simeq \frac{\alpha_s^2 c_{sg}^2 \left(c_{s\eta} f^2 + 4 c_{\partial s\eta} m_s^2\right)^2}{256 \pi^3 f^4 \left(m_s^2 - 4 m_\eta^2\right)^2}$$





$$\langle \sigma v \rangle_{ss} \simeq \frac{\sqrt{1 - \frac{m_s^2}{m_\eta^2}} \left(c_{\partial s\eta} m_s^2 + c_{s\eta} f^2\right)^4}{16 \pi f^4 m_\eta^2 \left(m_s^2 - 2 m_\eta^2\right)^2}$$

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Mostly drives relic

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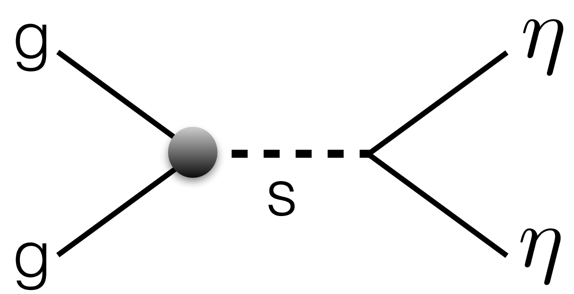

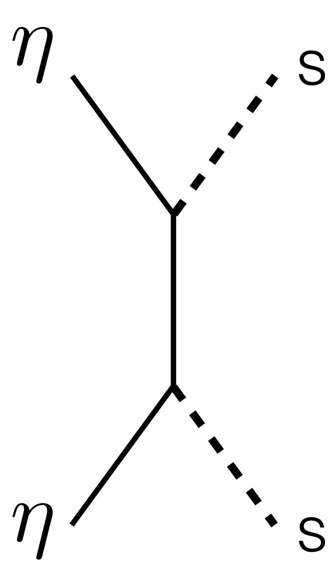

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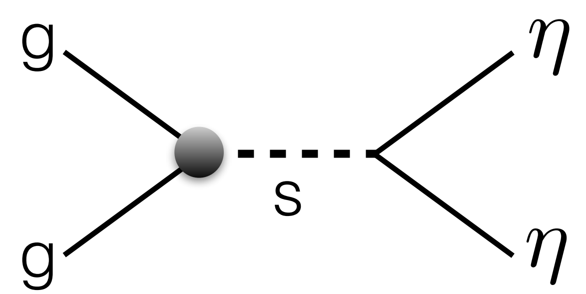
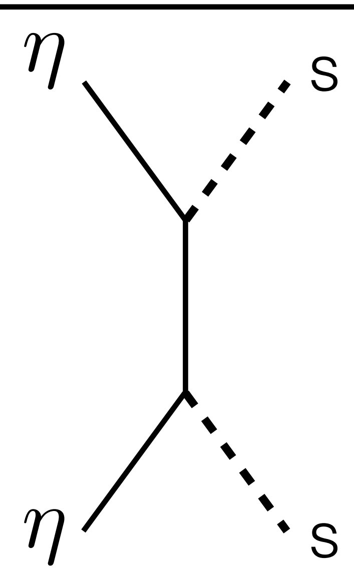


Contributes up to 15%



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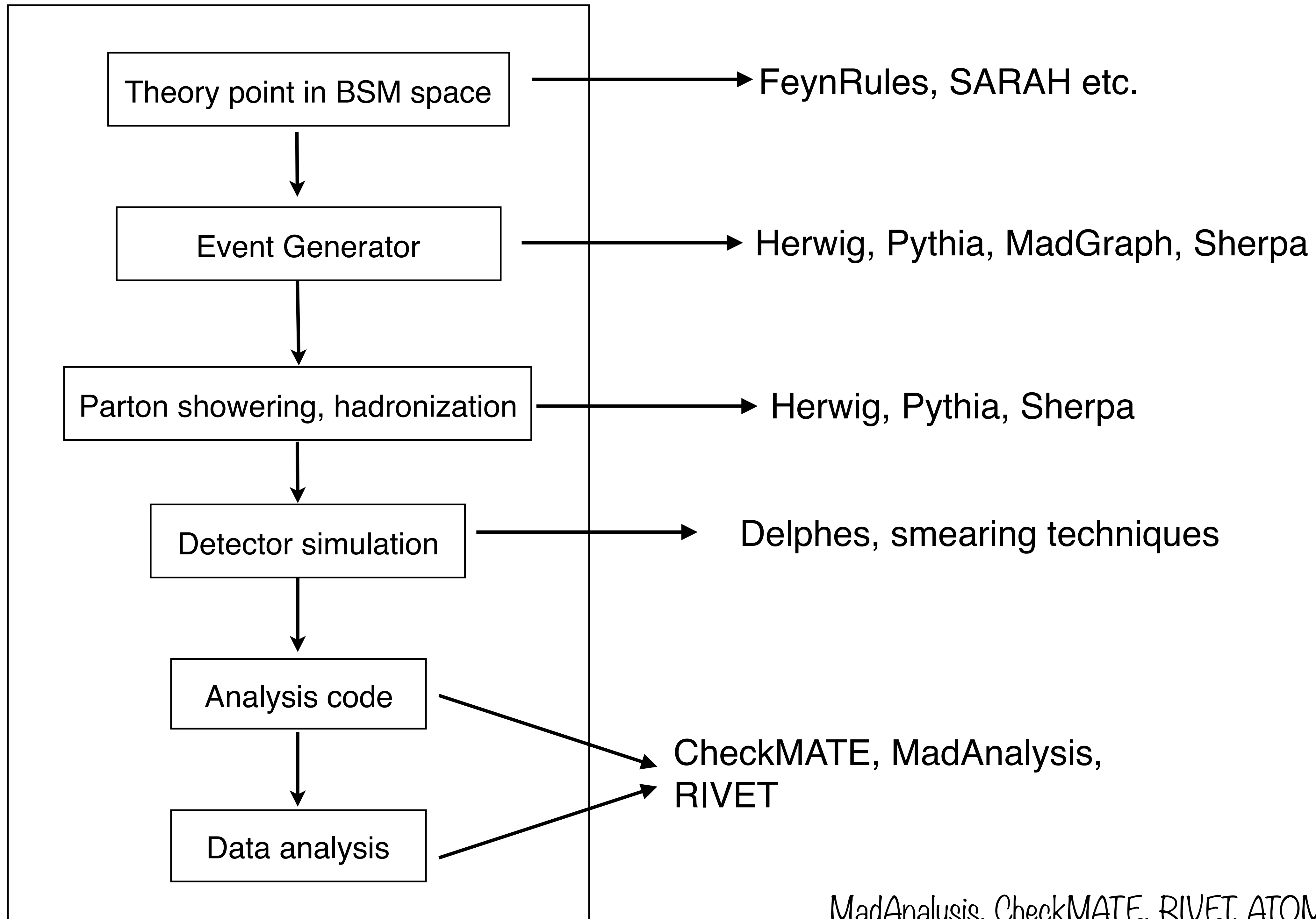
(

Analysis reinterpretation



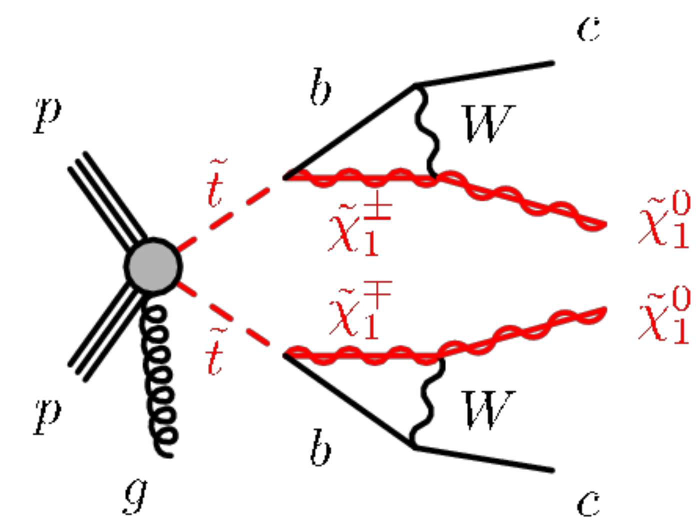
MadAnalysis, CheckMATE, RIVET, ATOM

MadAnalysis5

- Public framework for analysing Monte-Carlo events
- Has different levels of sophistication — partonic, hadronic, detector reconstructed
- Input formats: StdHEP, HepMC, LHE, LHCO, Delphes ROOT files
- Normal mode: Initiative commends typed in python interface
- Expert mode: C++/ROOT programmes

http://madanalysis.irmp.ucl.ac.be/,
Conte et al Eur. Phys. J. C74 (2014), no. 10 3103 ,
Dumont et al. Eur. Phys. J. C75 (2015), no. 2 56

ATLAS-SUSY-2013-21

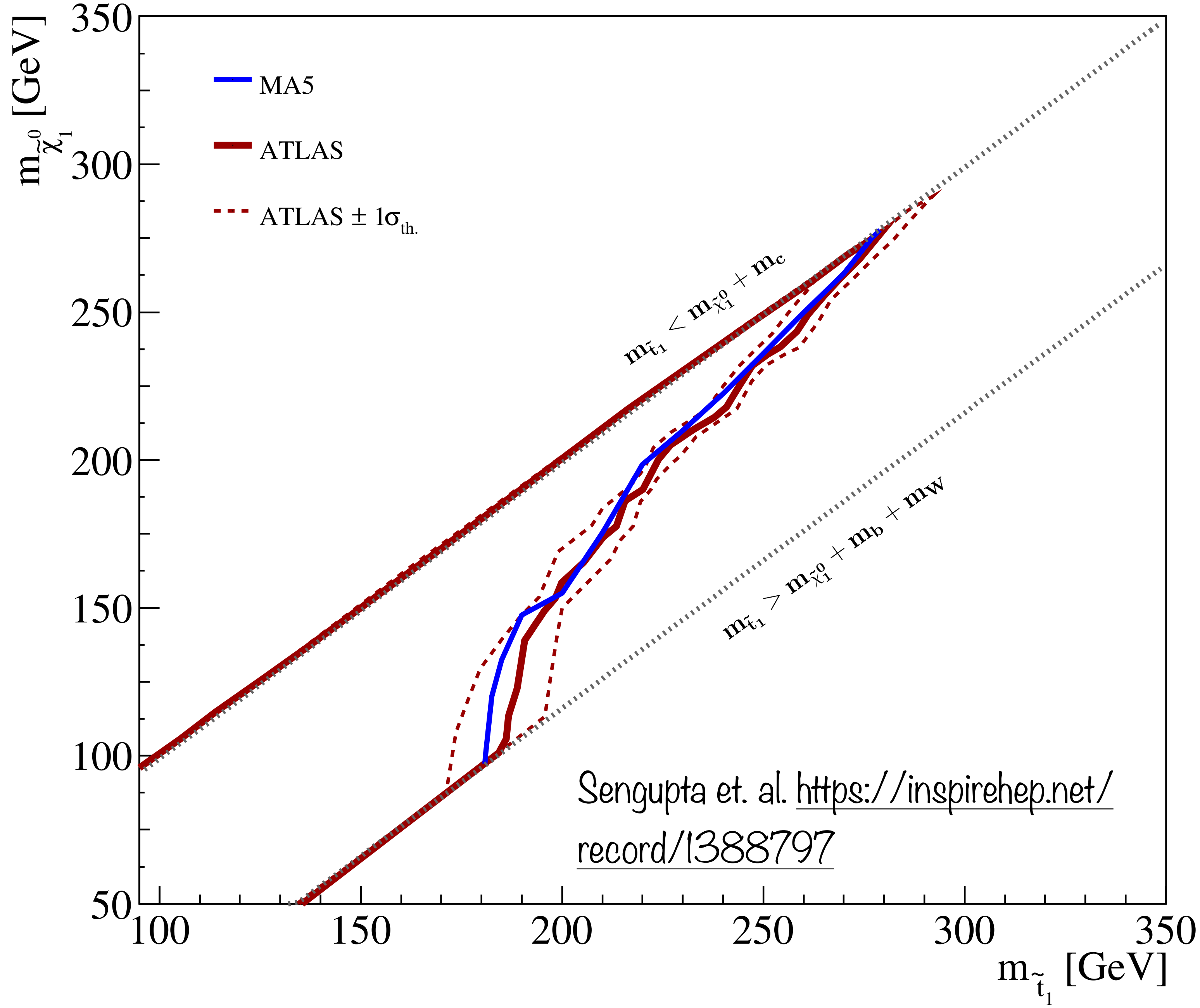


- Analysis designed to search for compressed stops
- Considers monojet (ISR) and c-tagging
- Only monojet analysis implemented in MA5
- Monojet analysis: three signal regions of different pT and missing ET ((pT, ET)= (280, 220), (340,340),(450,450))

ATLAS-SUSY-2013-21

$\tilde{t} \to c\tilde{\chi}_1^0$ (200/125) cutflow

cut	# events (scaled to σ and $\mathcal{L}$)	relative change	# events (official)	relative change (official)
Initial number of events	376047.3	376047.3		
$E_T^{\text{miss}} > 80$ GeV Filter	192812.8	-48.7%	181902.0	181902.0
$E_T^{\text{miss}} > 100$ GeV	136257.1	-29.3%	97217.0	-46.6%
Trigger, Event cleaning...	-	-	82131.0	
Lepton veto	134894.2	-1.0%	81855.0	-15.8%
$N_{\text{jets}} \leq 3$	101653.7	-24.6%	59315.0	-27.5%
$\Delta\phi(E_T^{\text{miss}}, \text{jets}) > 0.4$	95568.8	-2.1%	54295.0	-8.5%
Leading jet $p_T > 150$ GeV	17282.8	-81.9%	14220.0	-73.8%
$E_T^{\text{miss}} > 150$ GeV	10987.8	-36.4%	9468.0	-33.4%
M1 Signal Region				
Leading jet $p_T > 280$ GeV	2031.2	-81.5%	1627.0	-82.8%
$E_T^{\text{miss}} > 220$ GeV	1517.6	-25.3%	1276.0	-21.6%
M2 Signal Region				
Leading jet $p_T > 340$ GeV	858.0	-92.2%	721.0	-92.4%
$E_T^{\text{miss}} > 340$ GeV	344.4	-59.9%	282.0	-60.9%
M3 Signal Region				
Leading jet $p_T > 450$ GeV	204.3	-98.1%	169.0	-98.2%
$E_T^{\text{miss}} > 450$ GeV	61.3	-70.0%	64.0	-62.1%


MA5
ATLAS
ATLAS ± 1σth.
$m_{\tilde{t}_1} < m_{\tilde{\chi}_1^0} + m_c$
$m_{\tilde{t}_1} > m_{\tilde{\chi}_1^0} + m_b + m_W$
Sengupta et. al. https://inspirehep.net/record/1388797
$m_{\tilde{\chi}_1^0}$ [GeV]
$m_{\tilde{t}_1}$ [GeV]

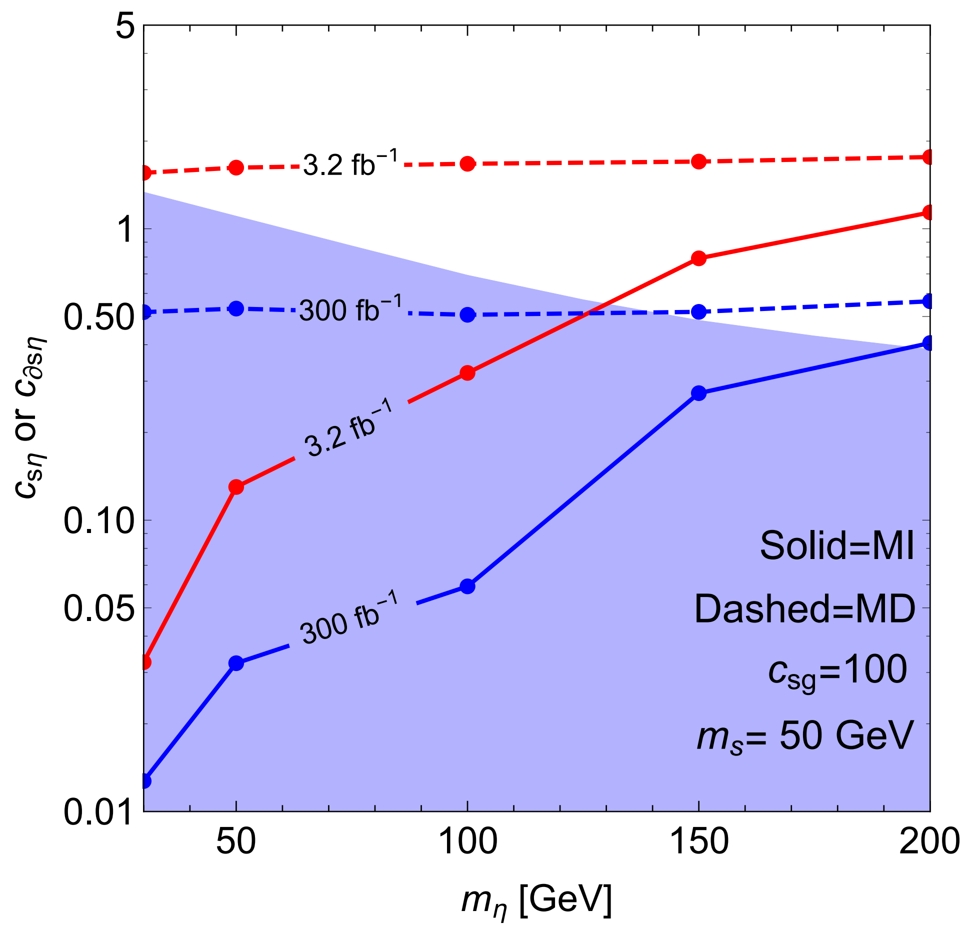
)

Melange des constraints

ATLAS monojet analysis at 13 TeV with 3.2 fb^{-1} data (arXiv:1604.07773)

Reimplemented using MadAnalysis 5 by D. Sengupta

Inspire id: 10.7484/INSPIREHEP.DATA.GTH3.RN26



- Current mono jet searches do not probe dark matter relic density
- For light dark matter, we have better prospects at high luminosity LHC

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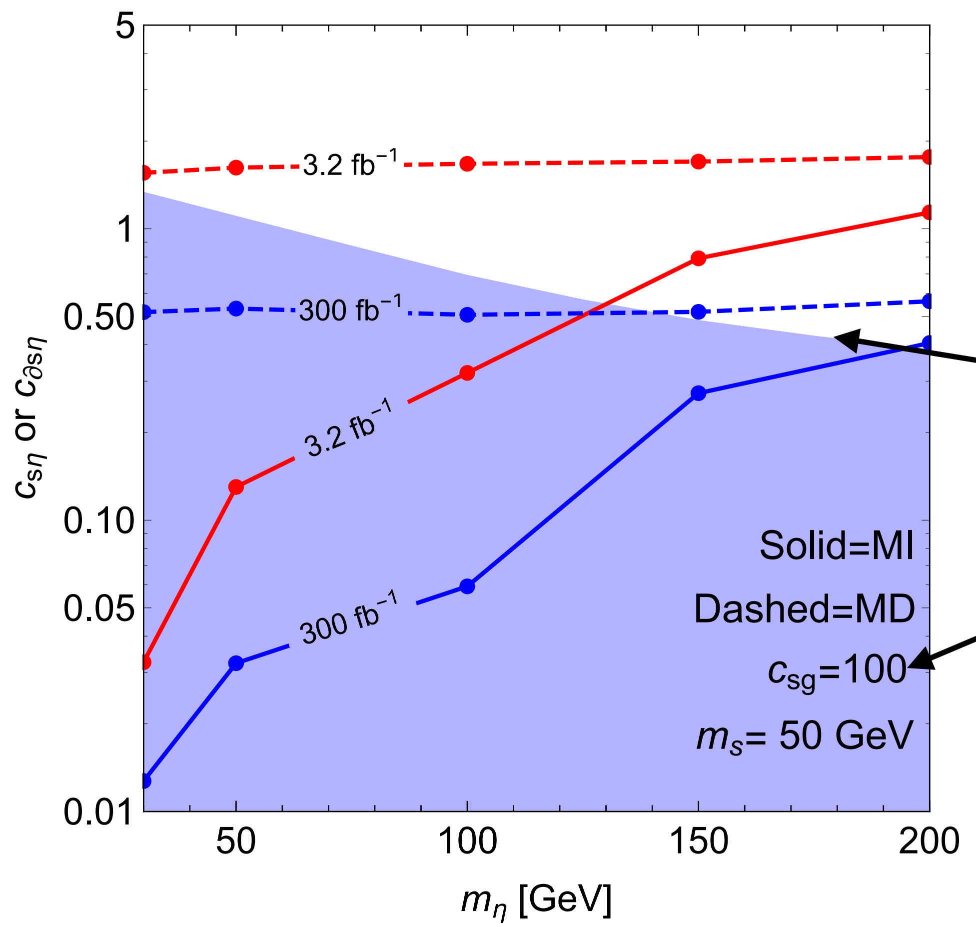

Low C_{sg} requires large $C_{\partial s\eta}$

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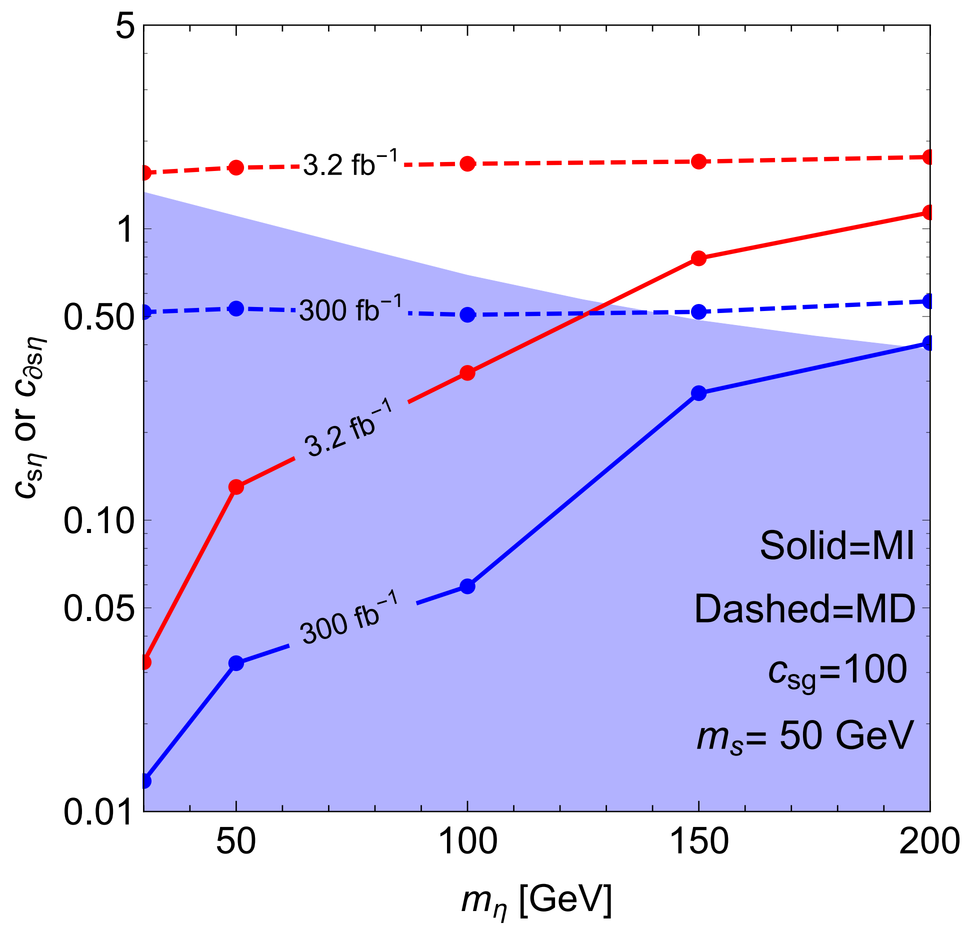

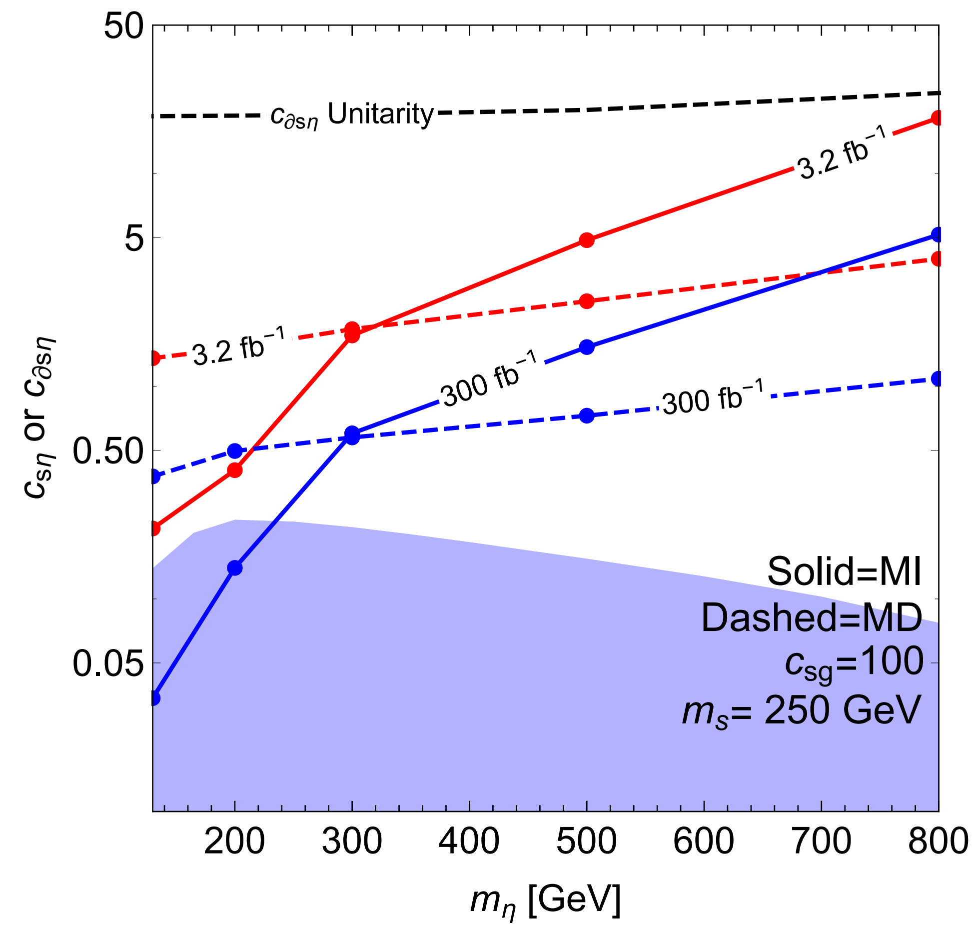

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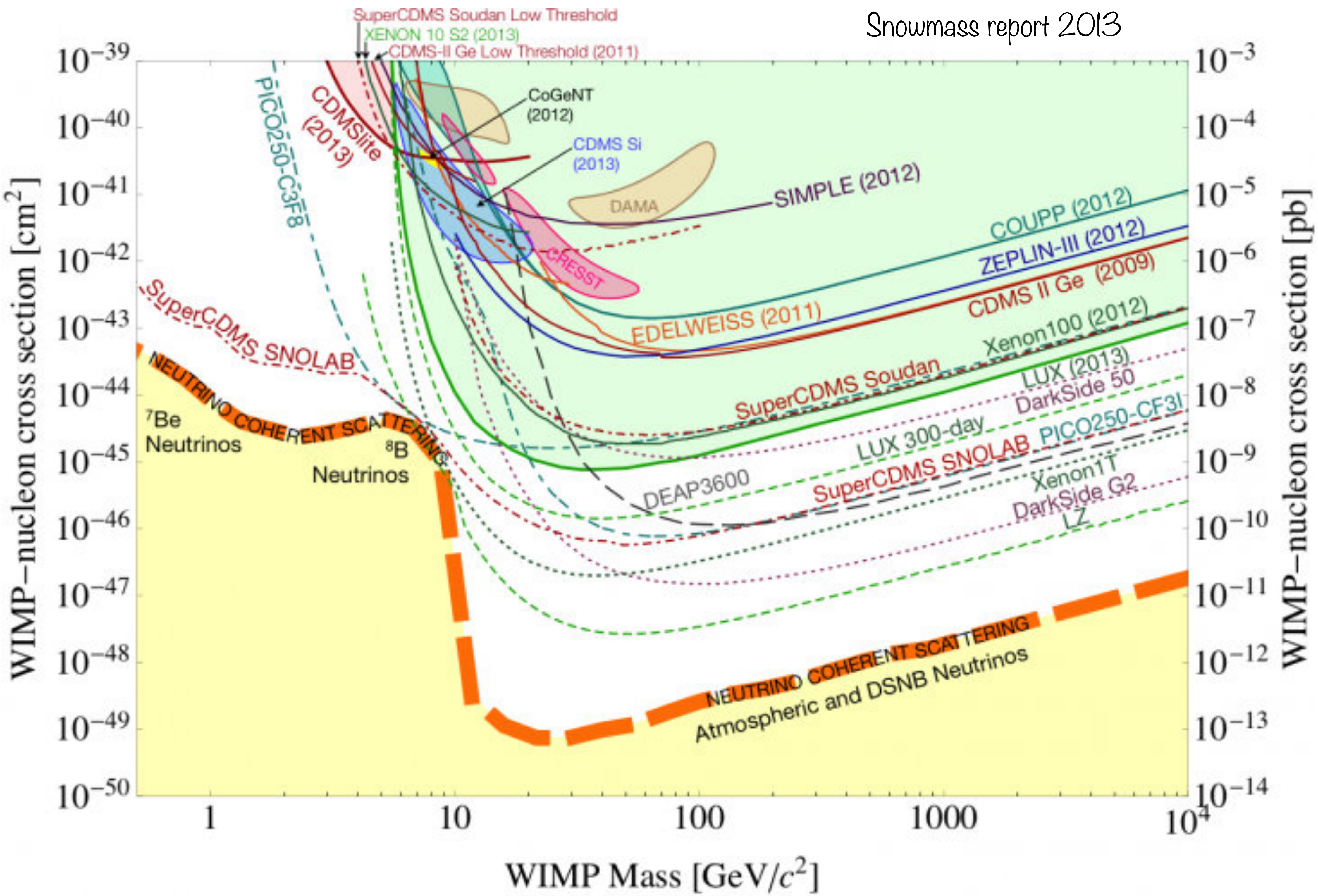
- For light dark matter, we have better prospects at high luminosity LHC
- For heavier dark matter, it is still difficult to probe relic density

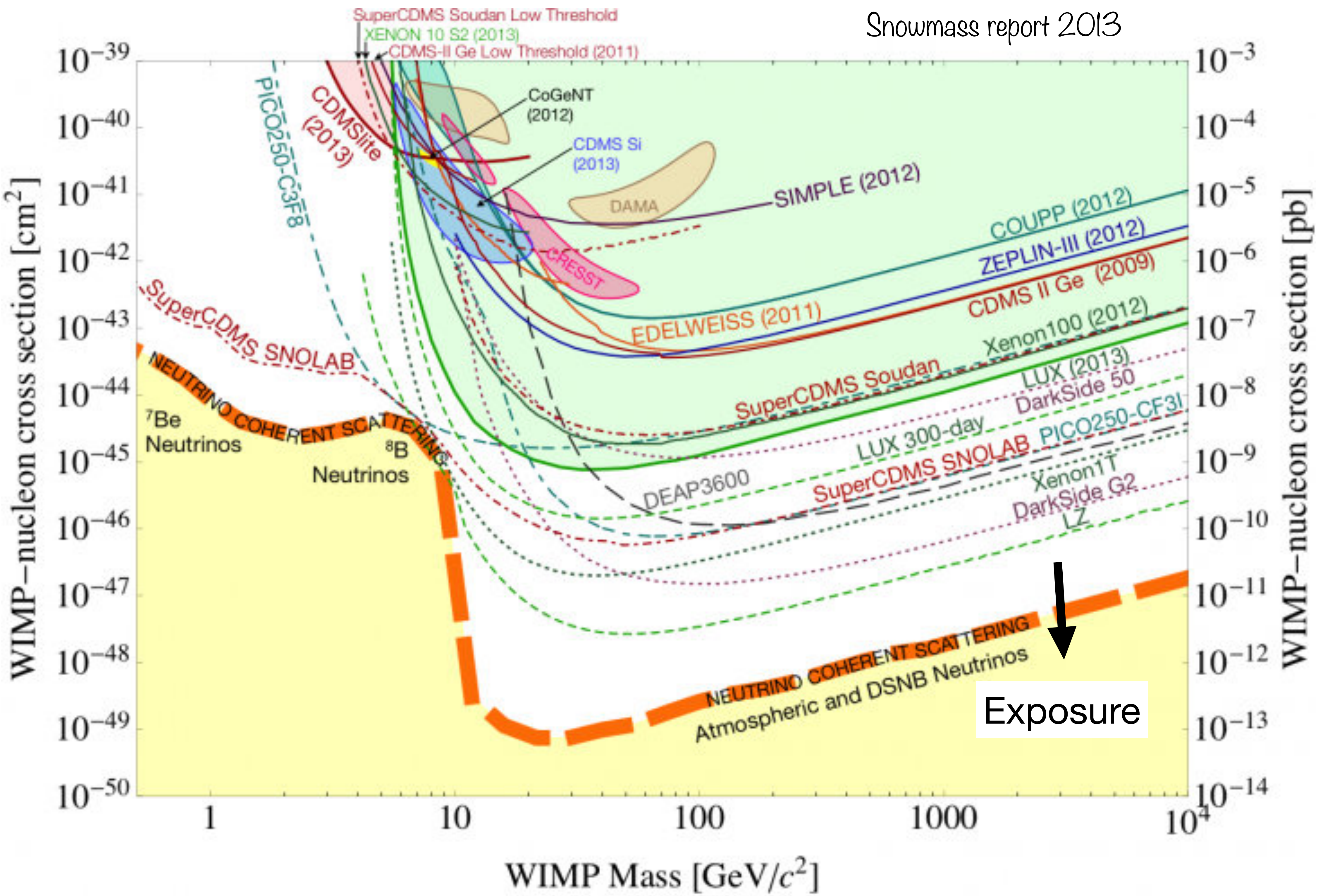
Potential of future searches

DM direct detection

Snowmass report 2013



DM direct detection



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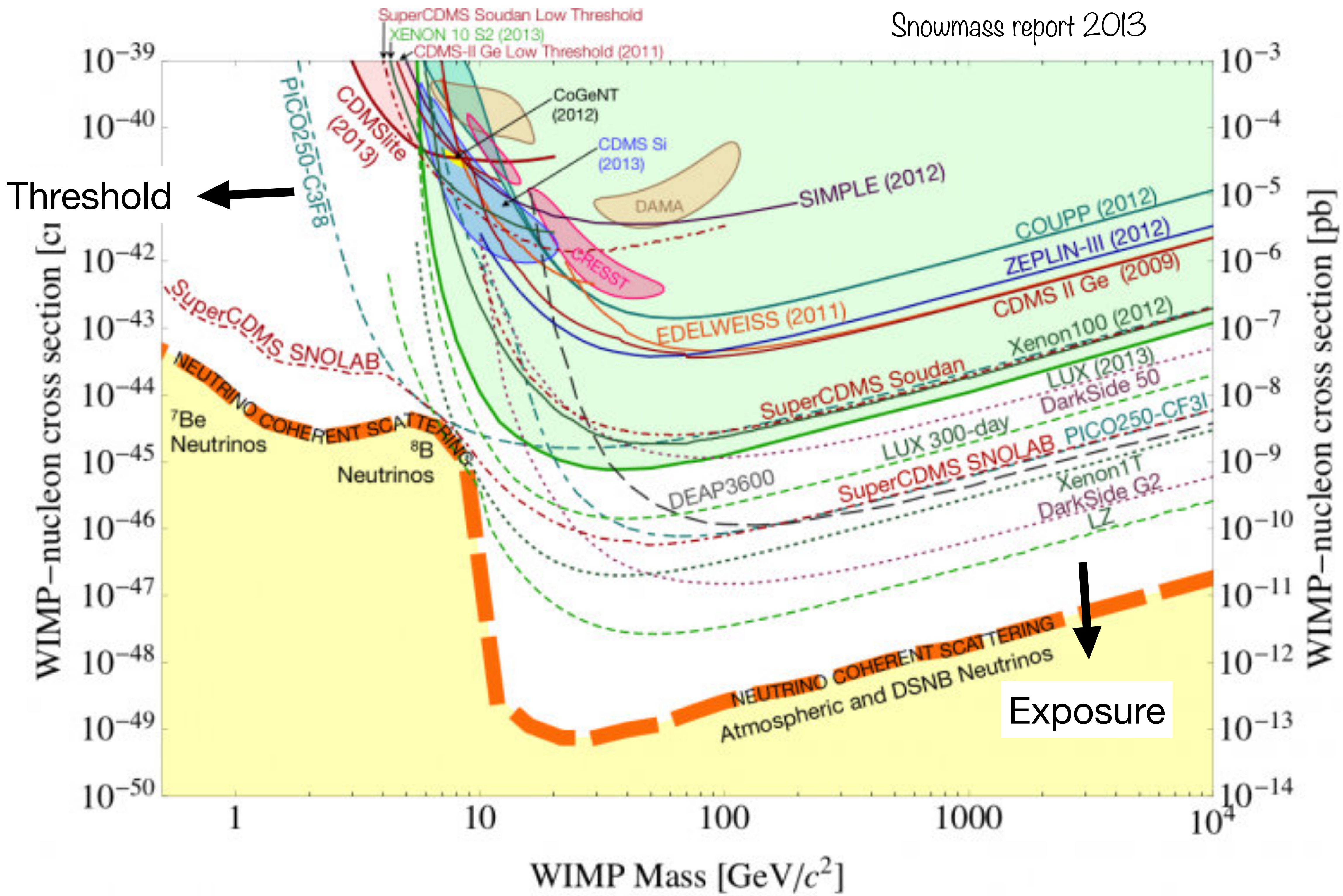

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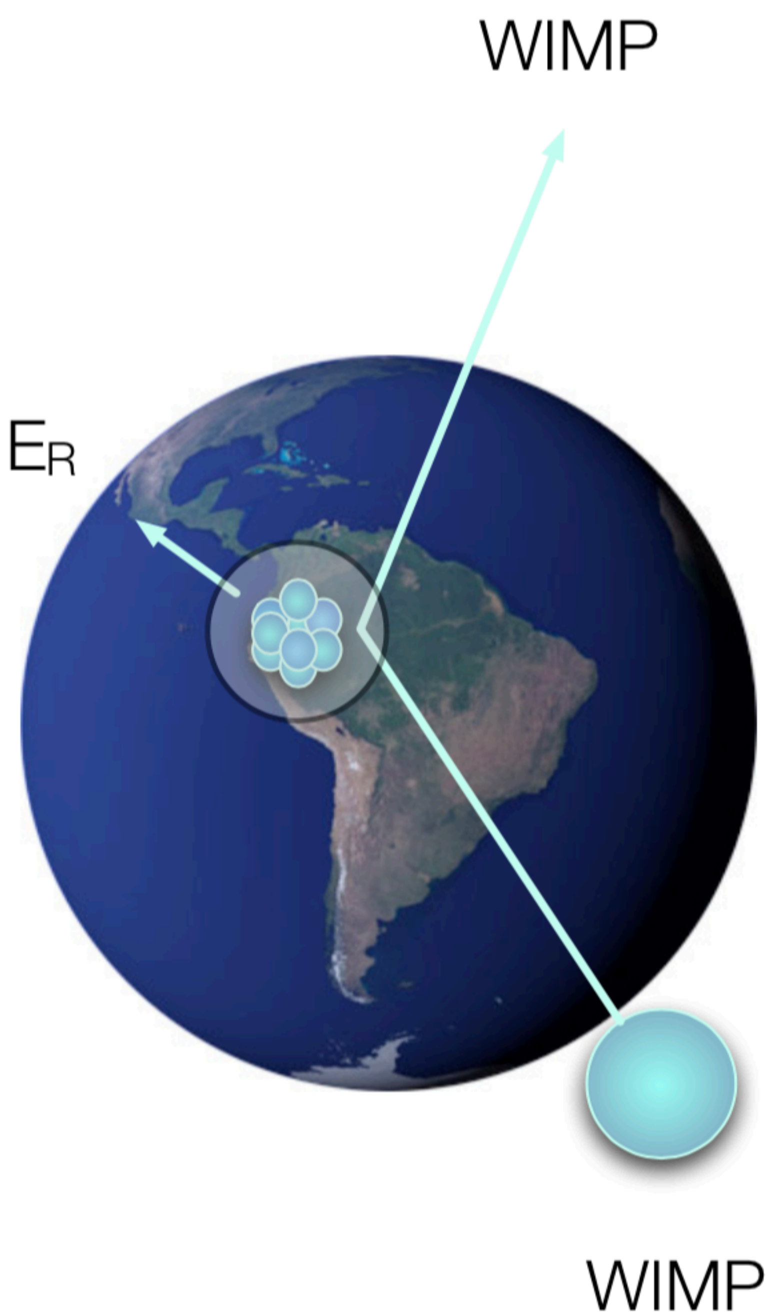


- Elastic collision between WIMPs and target nuclei

$$E_R = \frac{|\vec{q}|^2}{2m_N} = \frac{\mu^2 v^2}{m_N}(1 - \cos\theta)$$

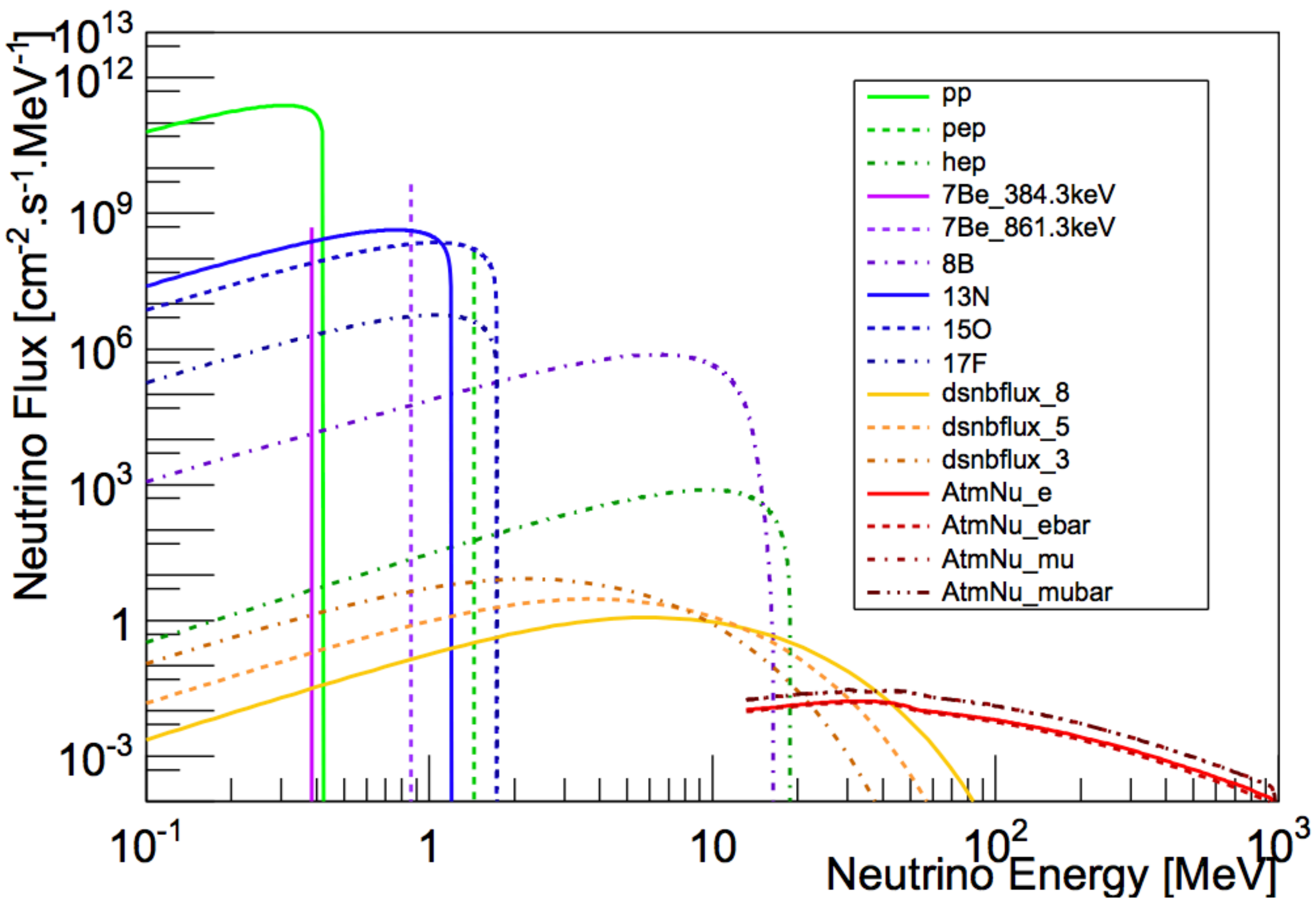
- Momentum transfer: q
- Reduced mass of nucleus: μ
- Mean WIMP velocity relative to target: v
- Scattering angle in center of mass system: θ

- WIMP recoils can be mimicked by neutrino recoils

The final frontier

- Neutrino fluxes are large, thankfully their cross sections are small
- Recoil energies peak at low threshold, more problem for light dark matter

The final frontier



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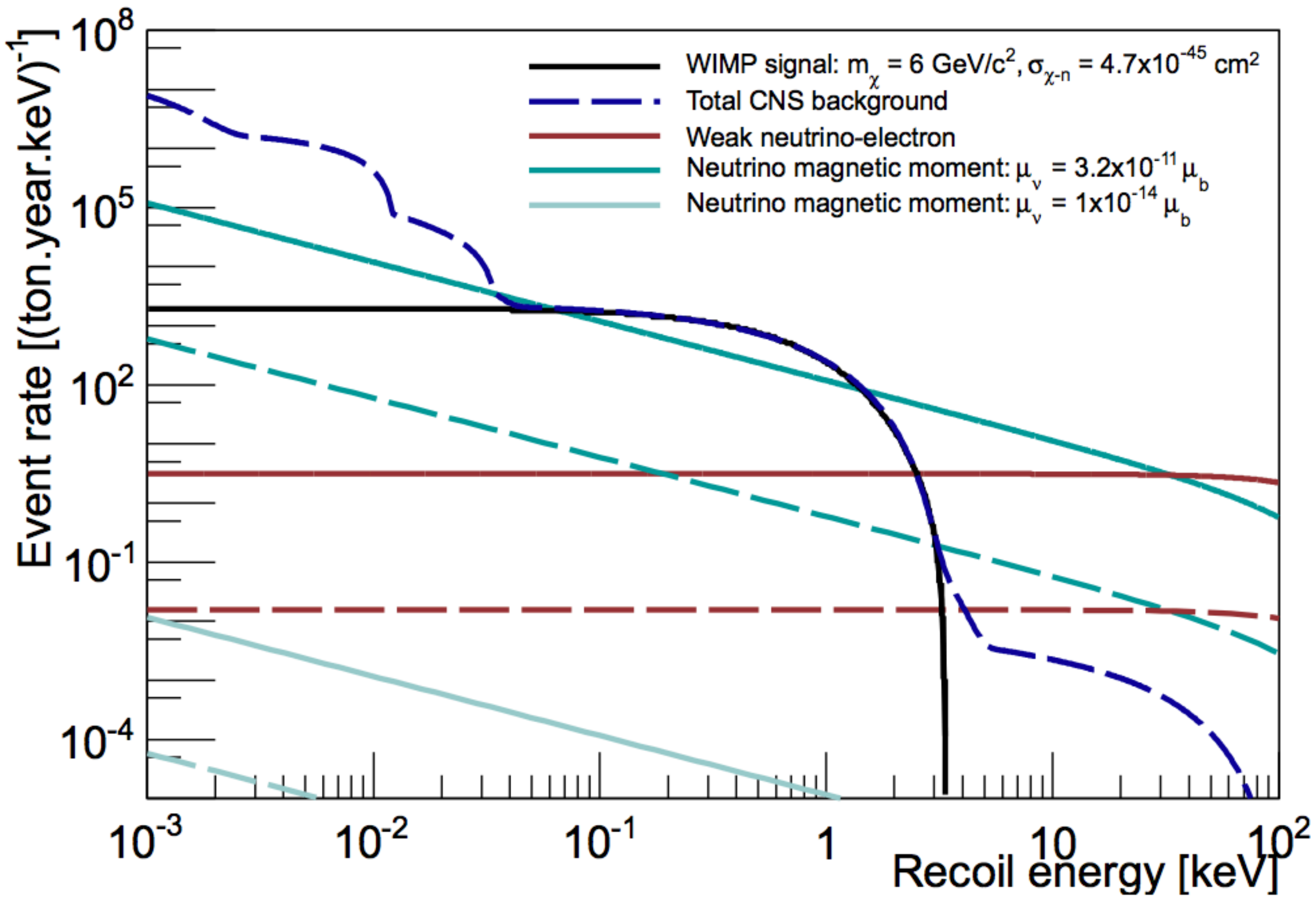
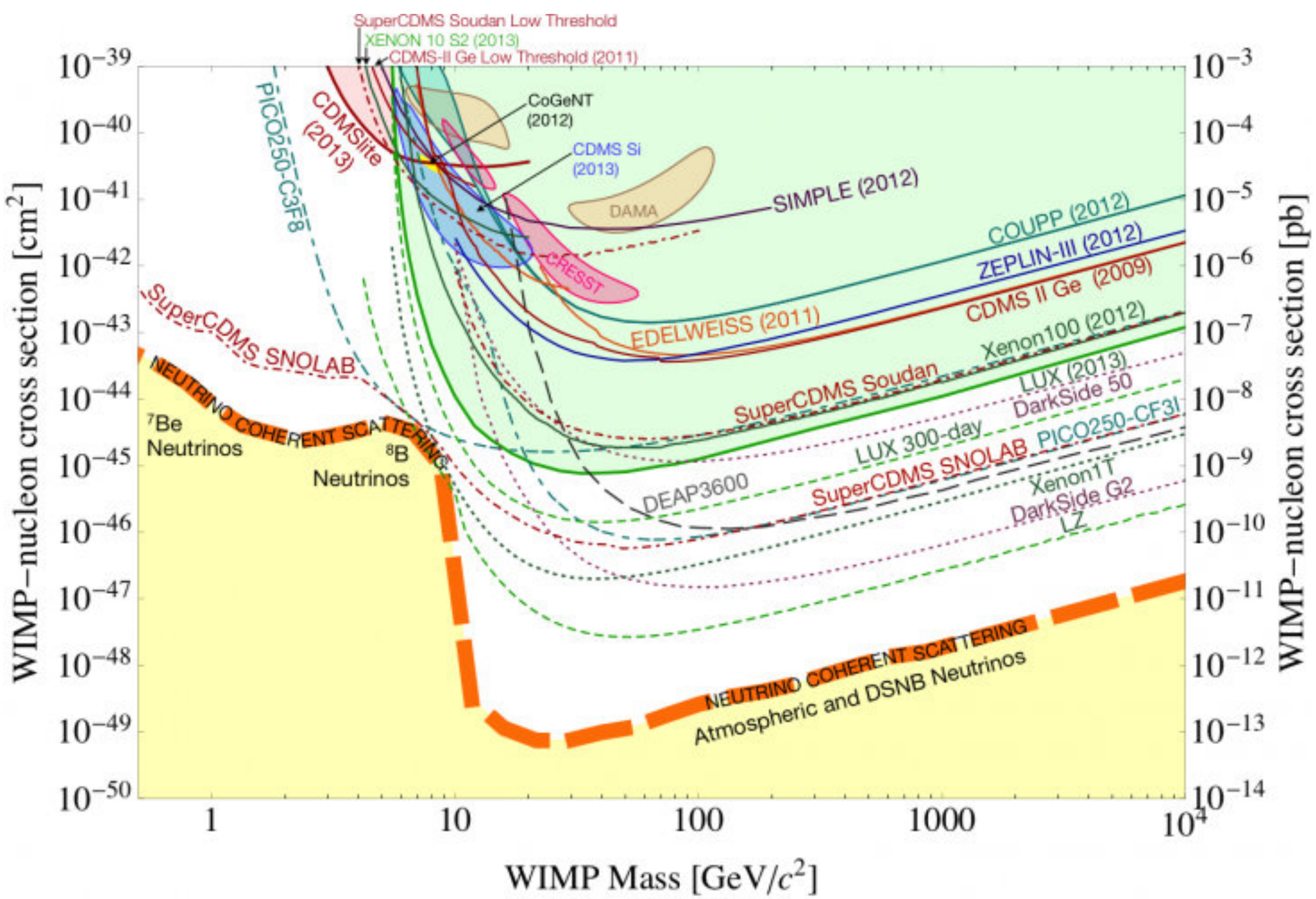


The final frontier



- Neutrino fluxes are large, thankfully their cross sections are small
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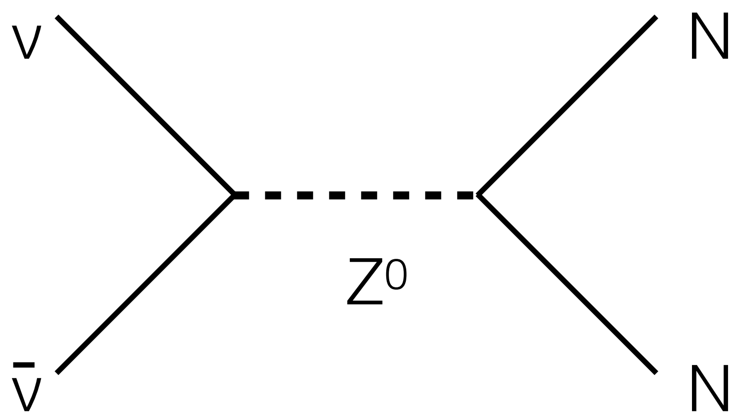
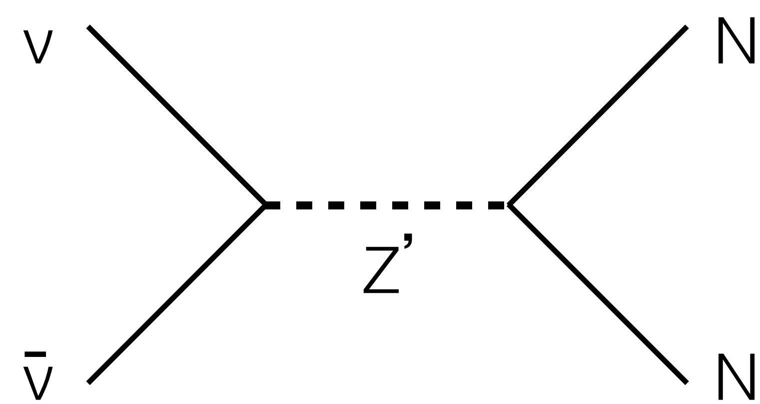
A toy model

Kulkarni et al. JHEP 1704 (2017) 073

- The coherent neutrino scattering at the direct detection is a coherent sum of the SM and new physics scattering diagrams



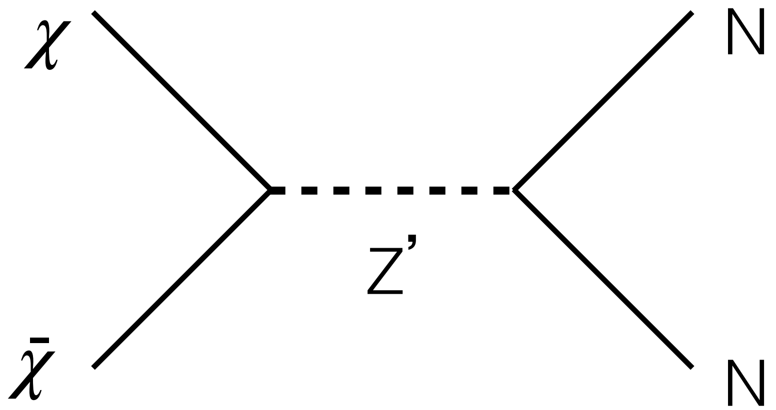


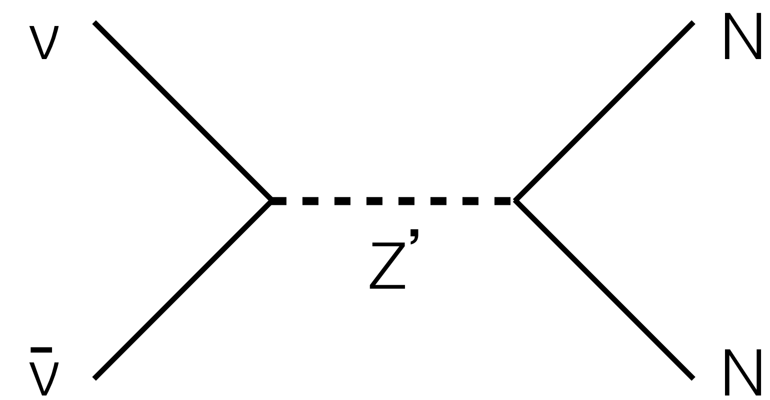
$$\left.\frac{d\sigma^{\nu}}{dE_R}\right|_V = \mathcal{G}_V \left.\frac{d\sigma^{\nu}}{dE_R}\right|_{SM}, \qquad \mathcal{G}_V = 1 + \left(\frac{\mathcal{Q}_V}{\mathcal{Q}_V^{SM}}\right)^2 \frac{4((g_V^{\nu})^2)}{G_F^2(q^2 - m_V^2)^2} - \frac{\mathcal{Q}_V}{\mathcal{Q}_V^{SM}} \frac{2\sqrt{2}(g_V^{\nu})}{G_F(q^2 - m_V^2)}$$

- Notice the possibility of destructive interference

A toy model

- The total signal is a sum of DM scattering and neutrino scattering rates



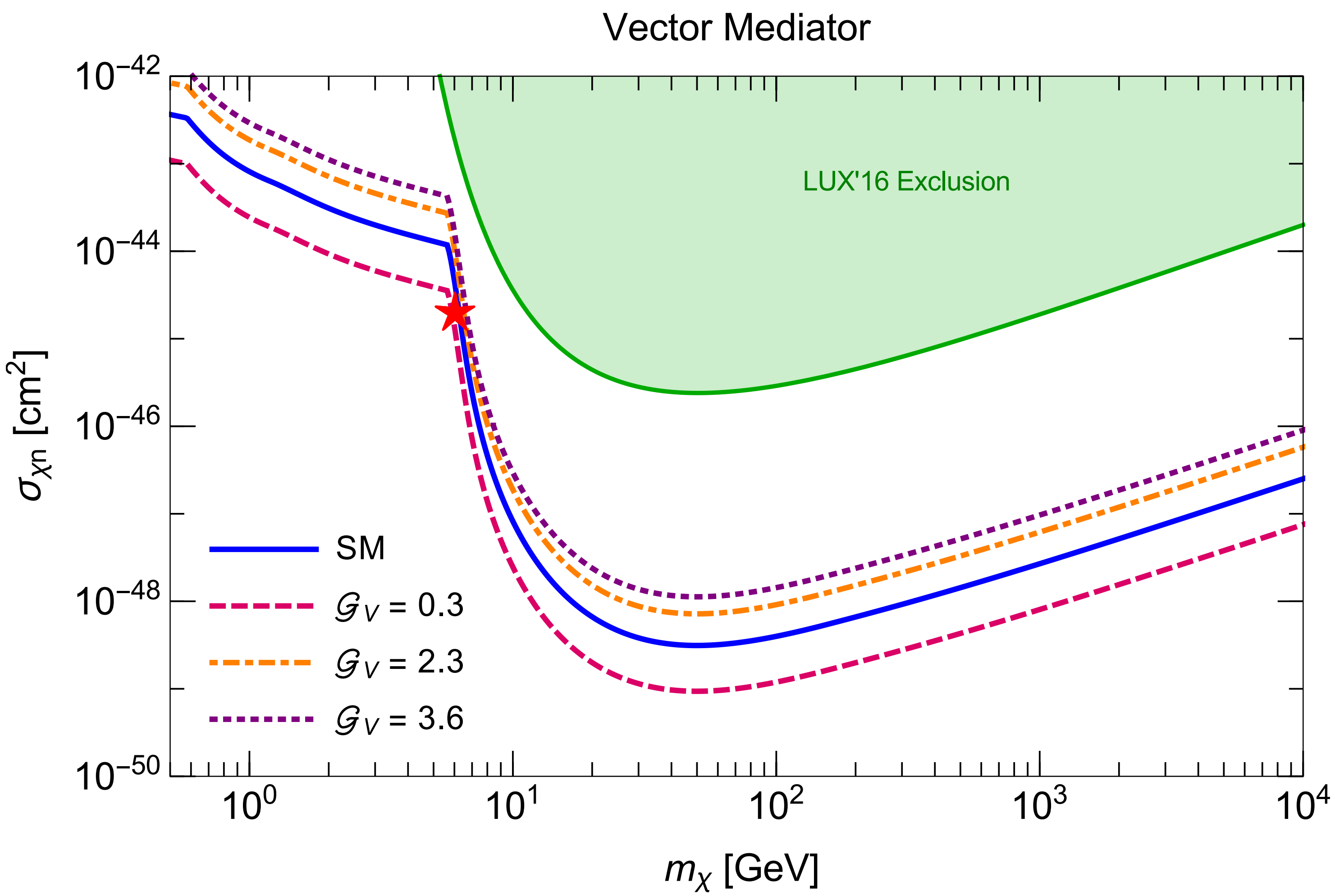


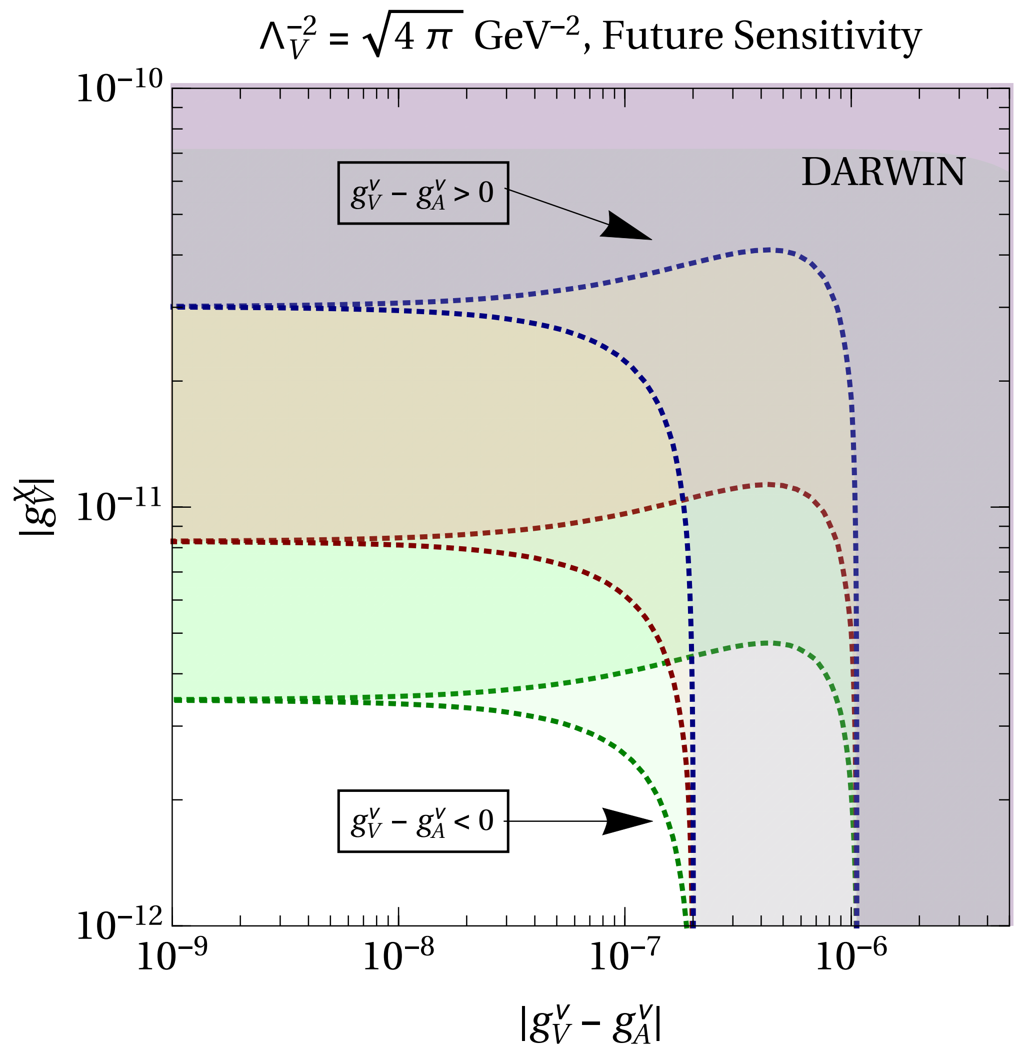
$$\left.\frac{dR}{dE_R}\right|_{\chi} = \mathcal{N} \frac{\rho_0}{m_N\, m_\chi} \int_{v_{\min}} v f(v) \frac{d\sigma^{\chi}_{SI}}{dE_R} d^3v \qquad \left.\frac{d\sigma^{\nu}}{dE_R}\right|_{V} = \mathcal{G}_V \left.\frac{d\sigma^{\nu}}{dE_R}\right|_{SM}$$

- Notice the possibility of destructive interference

Preparing for the end game

See also: Boehm et al. arXiv:1809.06385

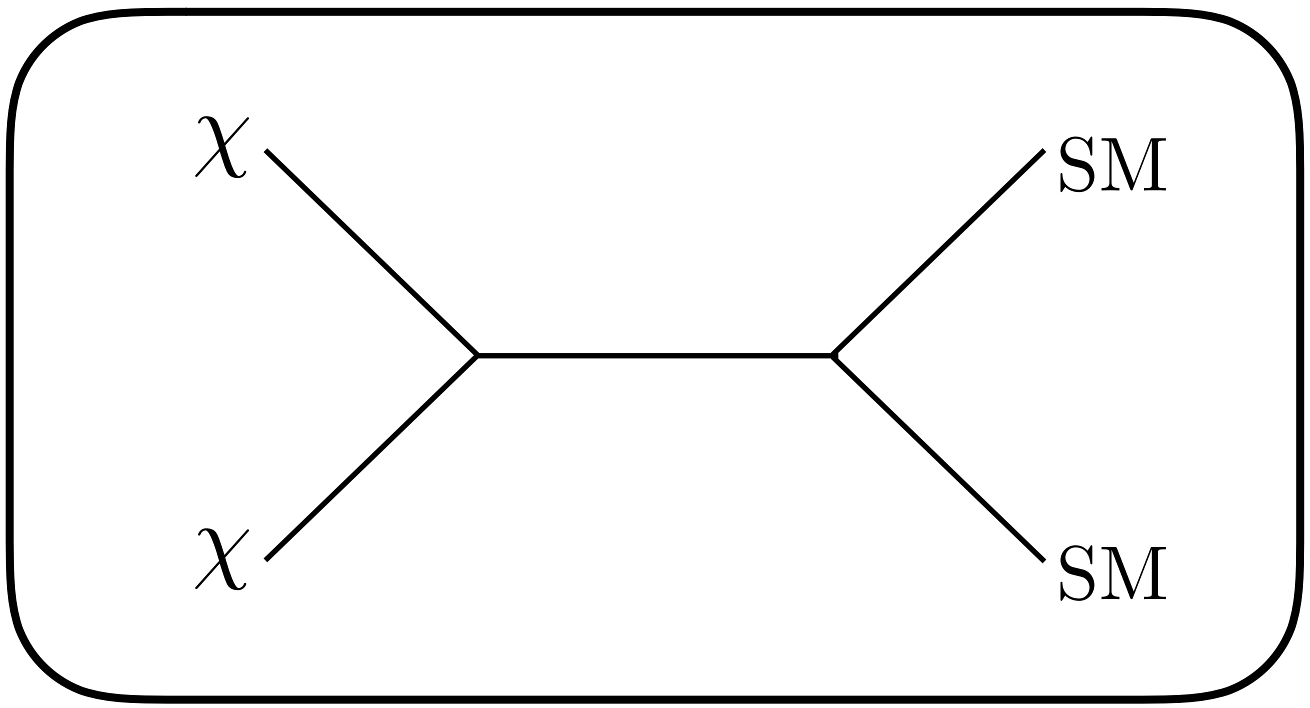




- Exotic neutrino interaction can lead to measurable effects at the direct detection experiments
- Next generation direct detection experiments can put constraints on combined DM - SM and neutrino SM interactions

Light mediators

- Previous analysis very much valid in effective theory limit, no longer the case if DM - SM interactions are mediated by light mediators



Kulkarni et. al. JCAP 1711 (2017) no.11, 016

Future prospects for direct detection

- Dark matter event rate at direct detection experiment for heavy mediators

$$\frac{\mathrm{d}R_T}{\mathrm{d}E_\mathrm{R}} = \frac{\rho_0}{m_\mathrm{DM}}\,\eta(v_\mathrm{min}(E_\mathrm{R}))\,\frac{g^2\,F_T^2(E_\mathrm{R})}{2\pi\,m_\mathrm{med}^4}$$

- Dark matter event rate at direct detection experiment for light mediators

$$\frac{\mathrm{d}R_T}{\mathrm{d}E_\mathrm{R}} = \frac{\rho_0\,\xi_T}{2\pi\,m_\mathrm{DM}}\,\frac{g^2\,F_T^2(E_\mathrm{R})}{\left(2\,m_T\,E_\mathrm{R}+m_\mathrm{med}^2\right)^2}\,\eta(v_\mathrm{min}(E_\mathrm{R}))$$

- Shape of differential event rate changes as soon as mediator mass is comparable to momentum transfer
- This sensitivity might be greatly altered by experimental and astrophysical uncertainties e.g. background fluctuations and DM velocity distributions

Light mediators at direct detection

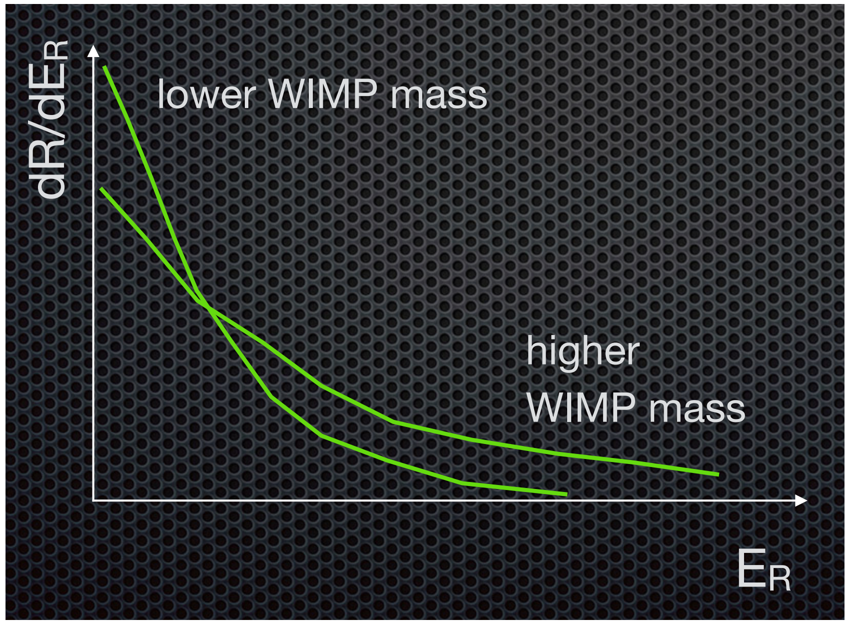
- Sharply falling recoil spectrum: need of very low threshold

See An et al. arxiv: 1412.8378 (PLB)

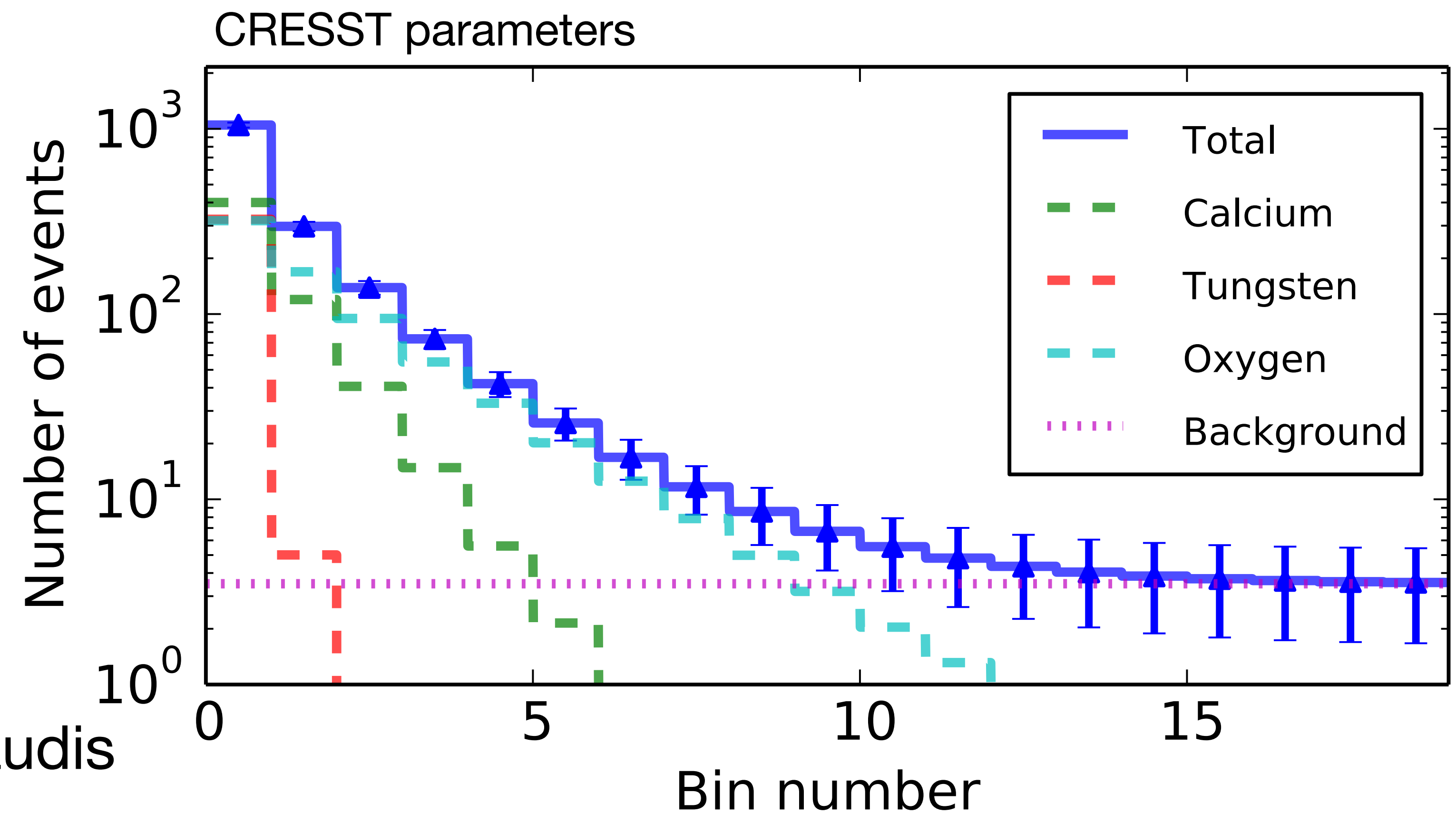
- Recoil spectrum shape important: need good energy resolution

See Gelmini et al. arxiv:1612.09137

- Cryogenic detectors are ideal for this!



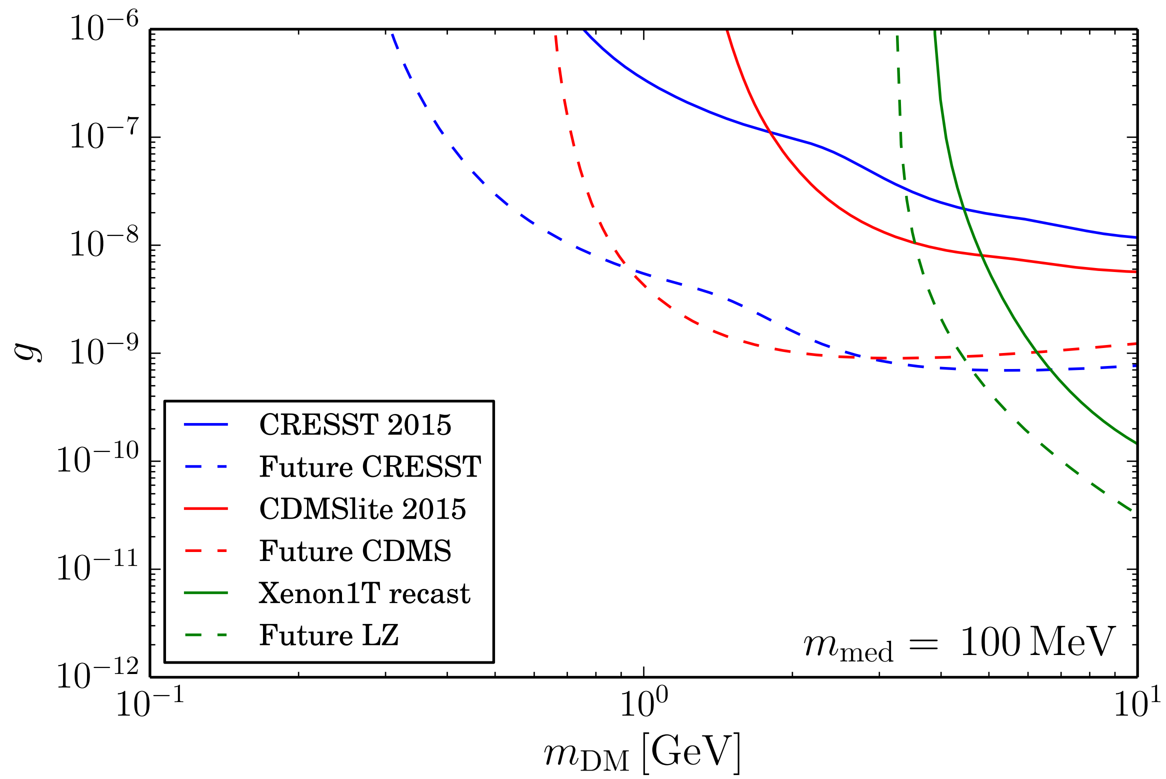
Shamelessly stolen from talk by L. Baudis



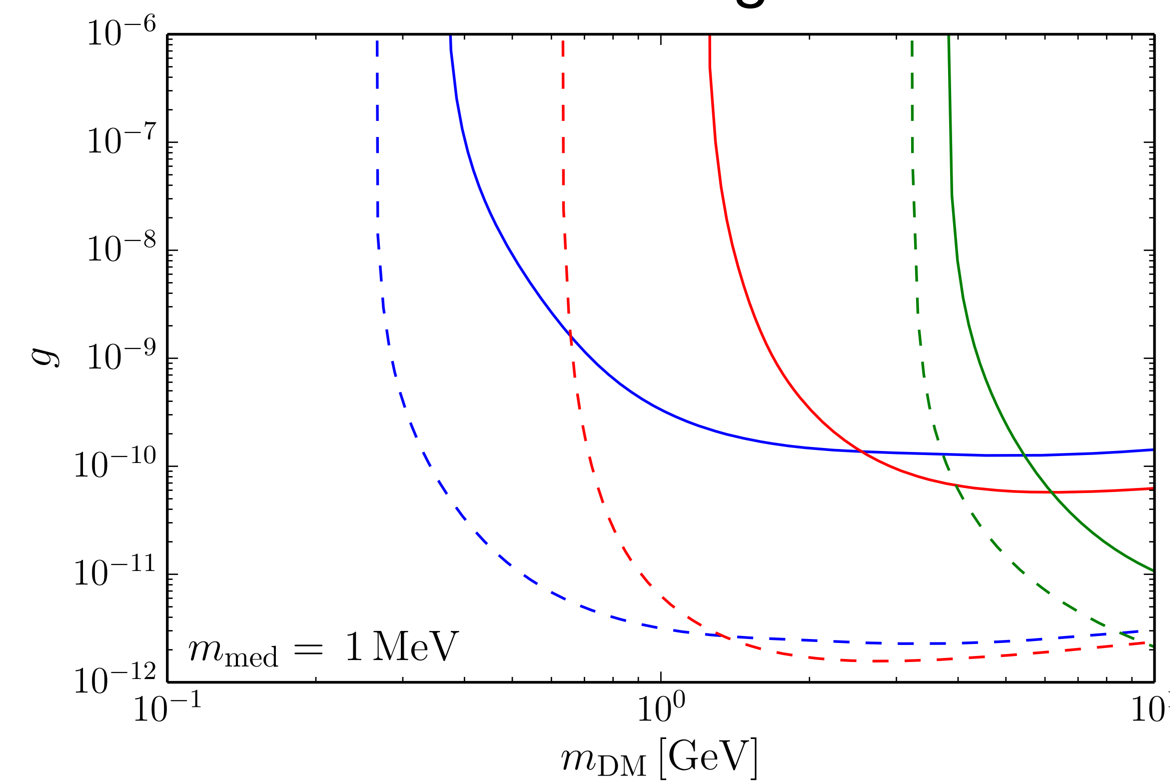
Contact interactions vs. light mediators

Kulkarni et. al. JCAP 1711 (2017) no.11, 016

Traditional limits on DM space



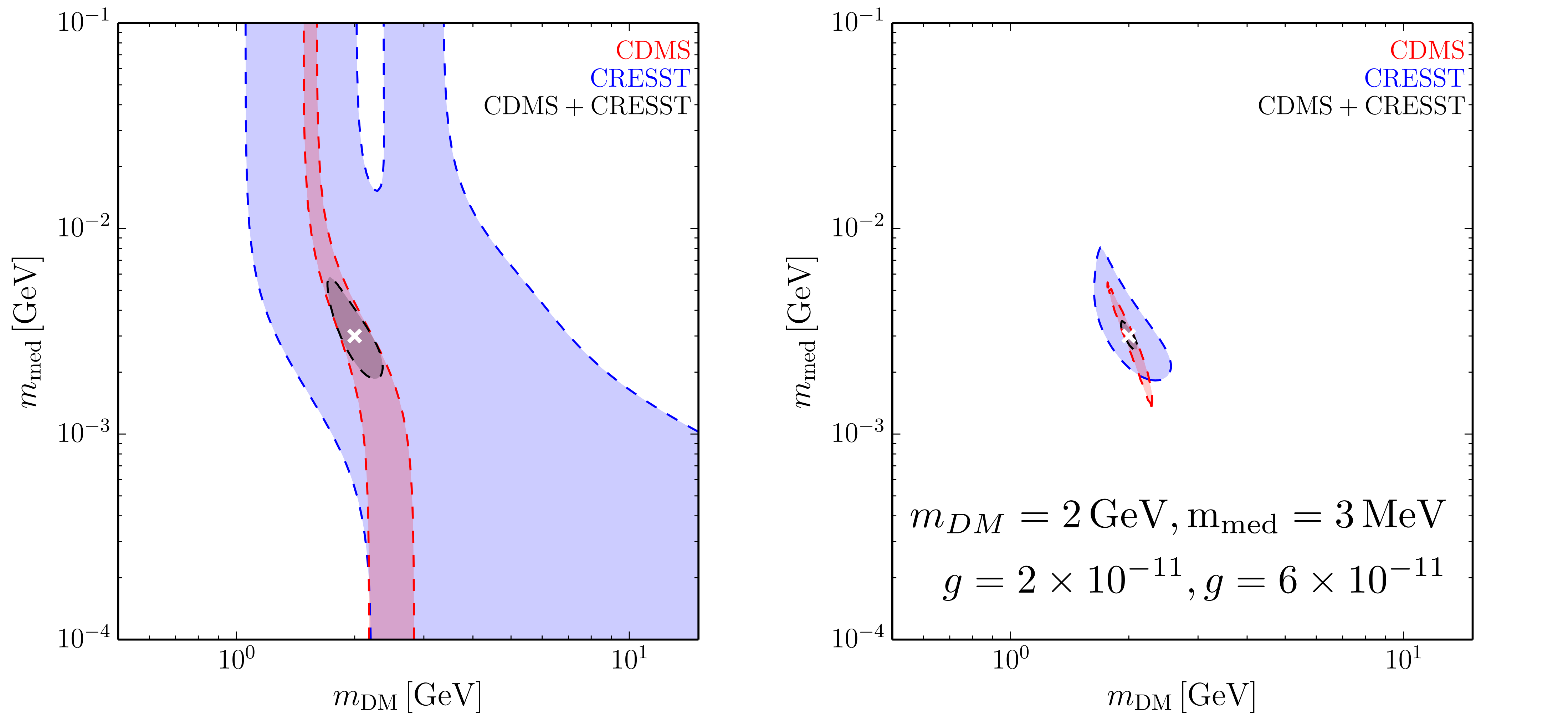
Limits on models with light mediators



- g = product of SM - mediator and DM - mediator coupling
- Best sensitivity of cryogenic experiments for DM masses with light mediators ~ 10 GeV
- Two orders of magnitude improvement for effective coupling g, corresponds to up to four orders of magnitude in terms of the scattering rate.
- Thousands of events can be observed!!

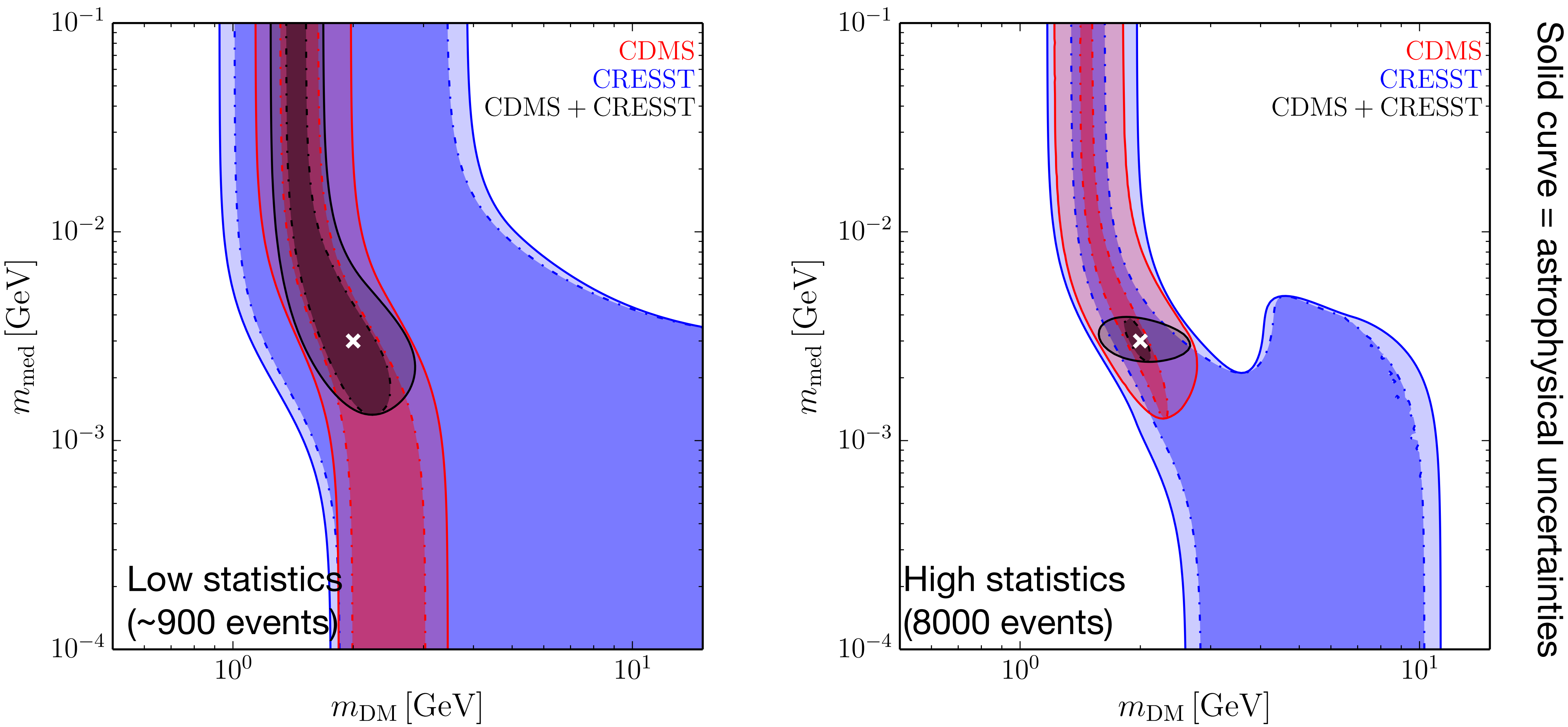
Optimistic scenario

Low statistics (~900 events) High statistics (8000 events total)



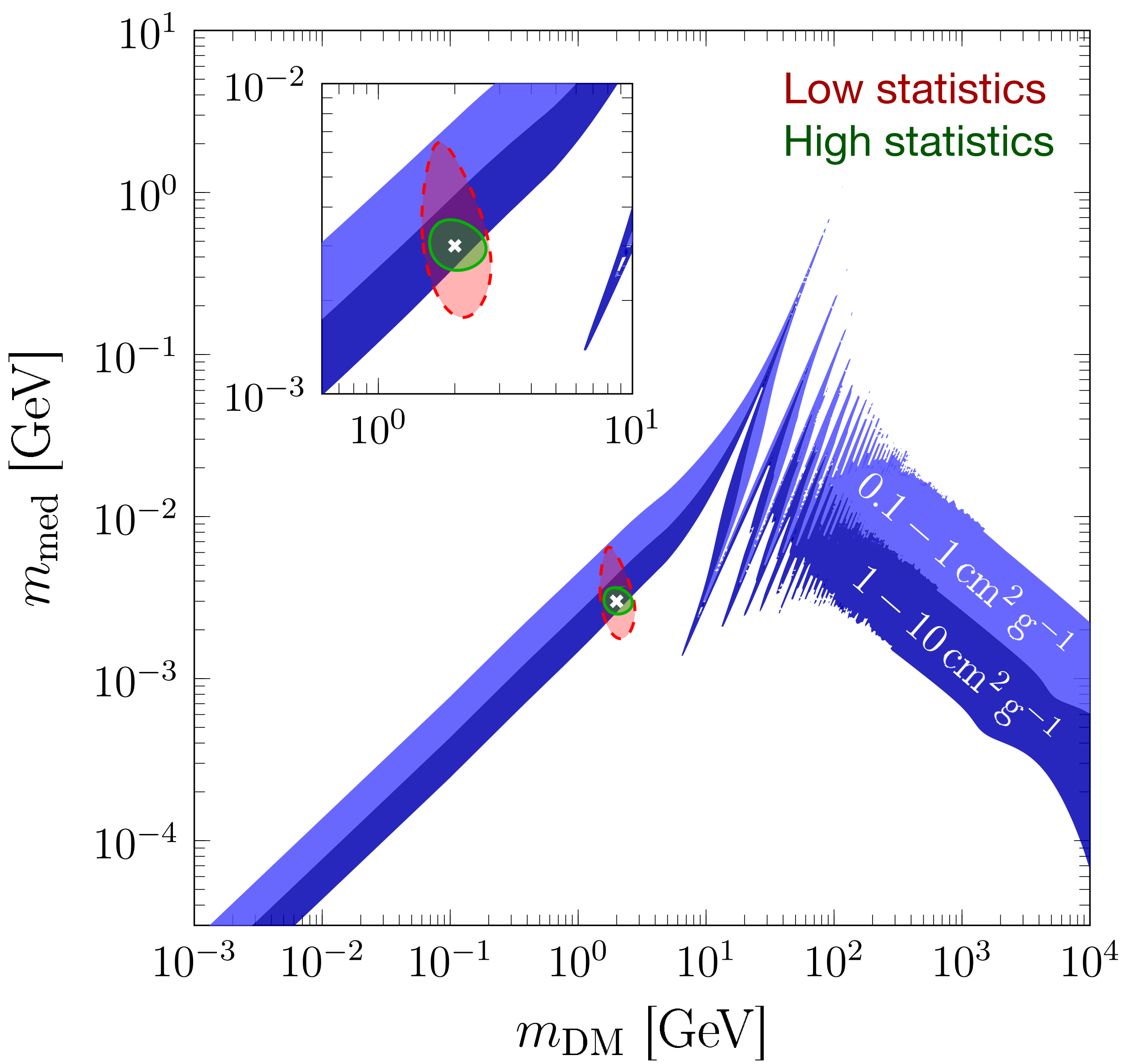
- Let us assume, we know the backgrounds, there are no astrophysical uncertainties, also let's assume DM couples to protons only
- Realistic treatment including detector resolution and background events
- Coupling g a nuisance parameter for reconstruction (fixed at max likelihood)

Realistic scenario



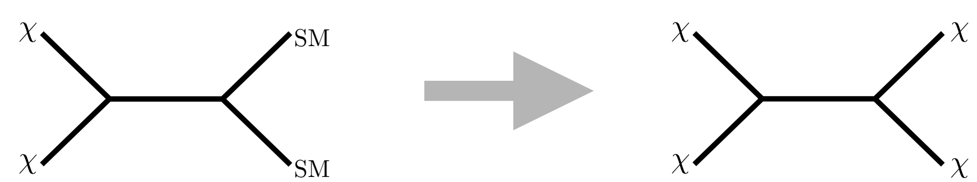
- Even with astrophysical uncertainties, it is possible to reconstruct particle physics parameters
- Combination of data from different experiments better than single experiment

Self-interacting DM



See also
Vogelsberger et al. arXiv:1211.1377
Chen et al. arXiv:1505.03781
Del Nobile et al. arXiv:1507.04007

For plot:
Tulin et. al. arXiv:1302.3898



- Within **specific model** (not a general conclusion)
- Fermionic DM, scalar mediator
  - Relic via dark sector freeze out and mediator decay via Higgs mixing

Conclusions

- Investigating particle nature of dark matter is a crucial avenue for fundamental physics
- Plenty of new ideas for dark matter theories and a plethora of experimental searches ongoing
- Experiments and theory are no longer two separate fields but have to make progress hand in hand
- Multiple possibilities for progress however each possibility should be realistically evaluated
- Example 1: monojet is a powerful search for dark matter at the LHC, however the interpretation of these searches depends on the underlying theory scenario. The limits get stronger shall there be momentum dependence in DM - SM couplings
- Example 2: Direct detection experiments perfectly complement this quest at the LHC. While preparing for the end game at direct detection experiments, it will be important to consider complete BSM models rather than just one interaction
- Example 3: Having two direct detection low threshold experiments is better than having one for reconstructing parameters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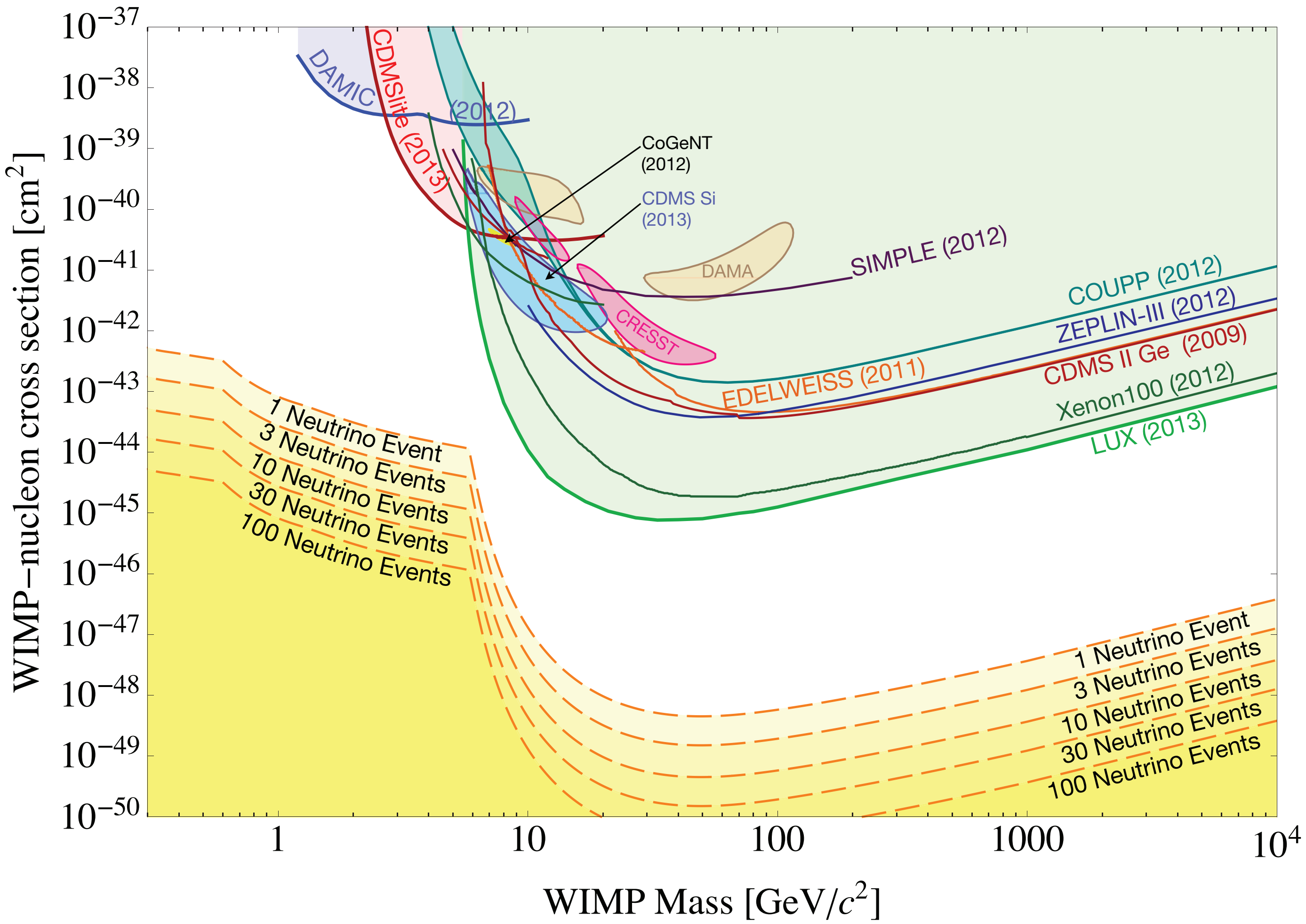
DM + neutrinos setup

- Two different setups: current and future LUX experiment
- Target Xenon
- <u>Current setup</u>
  - Take into account the efficiencies of the LUX experiment as given in LUXCalc
  - Exposure: 1.4 X 10^4 kg day (2013 results)
  - Number of observed events: 2, estimated background: 1.9 per ton year
- <u>Future setup:</u> similar to LZ
  - Keep the efficiencies the same
  - Exposure: 15 ton - year
  - background: 0.64 (including SM contribution)

DM calculating neutrino floor



$$\mathscr{L}(\sigma_{\chi-n}, \vec{\phi}) = \frac{e^{-(\mu_\chi + \sum_{j=1}^{n_\nu} \mu_\nu^j)}}{\mathrm{N}!} \times \prod_{i=1}^{\mathrm{N}} \left[\mu_\chi f_\chi(E_{r_i}) + \sum_{j=1}^{n_\nu} \mu_\nu^j f_\nu^j(E_{r_i}) \right] \times \prod_{i=1}^{n_\nu} \mathscr{L}_i(\phi_i),$$

$$\lambda(0) = \frac{\mathscr{L}(\sigma_{\chi-n} = 0, \hat{\hat{\vec{\phi}}})}{\mathscr{L}(\hat{\sigma}_{\chi-n}, \hat{\vec{\phi}})}$$

- For a given target, consider one threshold, adjust exposure to attain N neutrino events
- Test the discrimination power between neutrino only and dark matter plus neutrino hypothesis by means of hypothesis testing

DM light mediators set up

- CRESST III

  See CRESST arXiv:1503.08065.

  - Molecular experiment: target $CaWO_4$, exposure: 1000 kg days
  - Energy threshold: 100 eV
  - Background level: 3.5×10^{-2} keV^{-1} kg^{-1} day^{-1} = 3.5 events each bin
  - Flat efficiency and Gaussian energy resolution of 20 eV

- SuperCDMS

  See SuperCDM arXiv:1610.00006

  - High voltage Germanium, exposure 1.6×10^4 kg days
  - Energy threshold 100 eV (conservative)
  - Background level: 10 keV^{-1} kg^{-1} $year^{-1}$
  - Flat signal efficiency, energy resolution of 10 eV

DM light mediators technical details

- Generate mock data and attempt reconstruction
- Likelihood function

Particle physics parameters

Nuisance parameters

$$-2\log\mathcal{L}^{\alpha}(\mathbf{x},\mathbf{y}) = 2\sum_i\left[R_i^{\alpha}(\mathbf{x},\mathbf{y}) + B_i^{\alpha}(\mathbf{y}) - N_i^{\alpha} + N_i^{\alpha}\log\frac{N_i^{\alpha}}{R_i^{\alpha}(\mathbf{x},\mathbf{y}) + B_i^{\alpha}(\mathbf{y})}\right]$$

Predicted signal events

Predicted background events

Observed events

- Construct likelihood ratio (R), log likelihood follows a chi-square
- Exclude parameters, for two free parameter model if:

$$-2\log\mathcal{R} < 5.99$$