Current Dark Matter Searches and the Neutrino Bound

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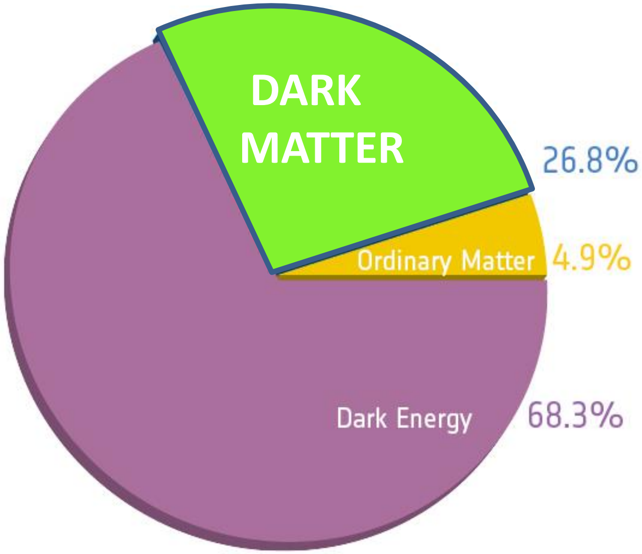
Dark Matter: One of the Biggest Problems in the Universe

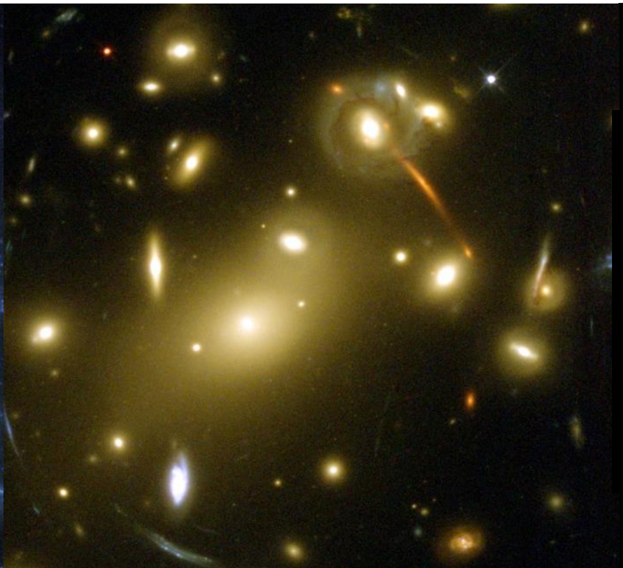
Huge amount of Evidence for Dark Matter

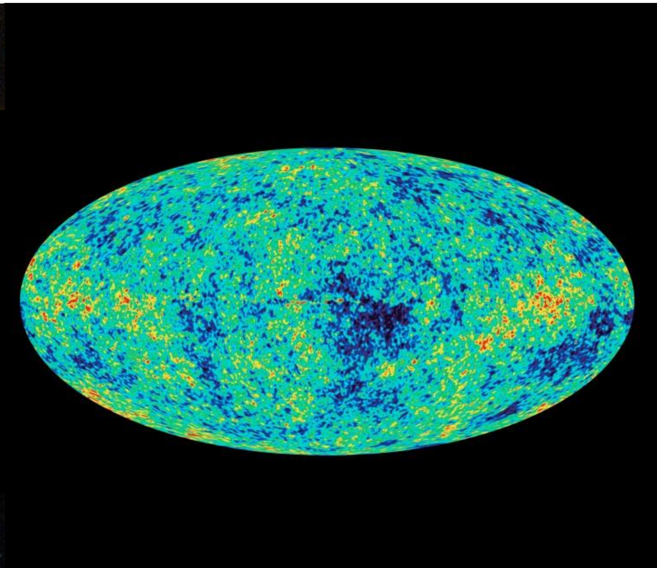
Galaxies, Clusters of Galaxies, Expansion of Universe, fluctuations in the CMB, etc

Thought to be an elusive particle not yet detected

New physics at the LHC energy scale can explain the dark matter in the Universe if it is a Weakly Interacting Massive Particle (WIMP) or similar







Thermal Relics Work !

(at least for the dark matter bit)

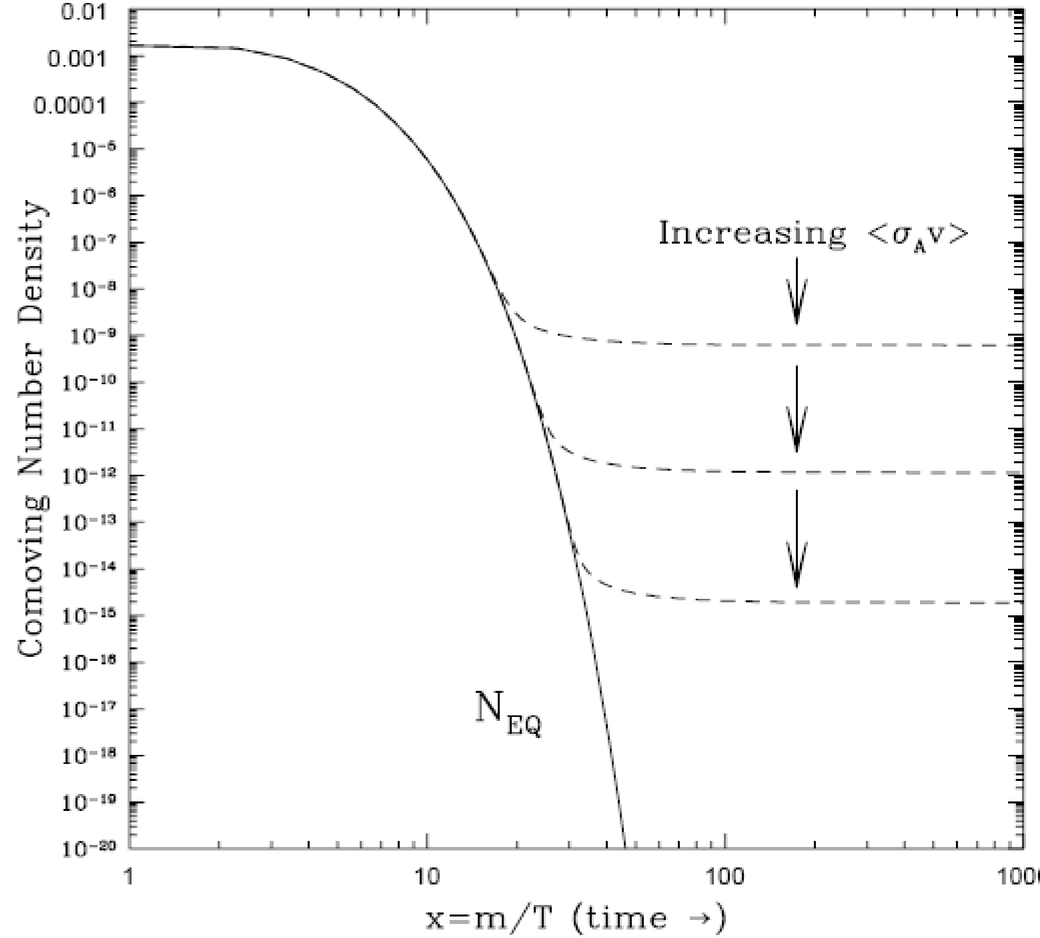
$$\sigma_{\rm weak} \simeq \frac{\alpha^2}{m_{\rm weak}^2}$$

$$\alpha \simeq \mathcal{O}(0.01)$$

+

$$m_{\rm weak} \simeq \mathcal{O}(100\,{\rm GeV})$$

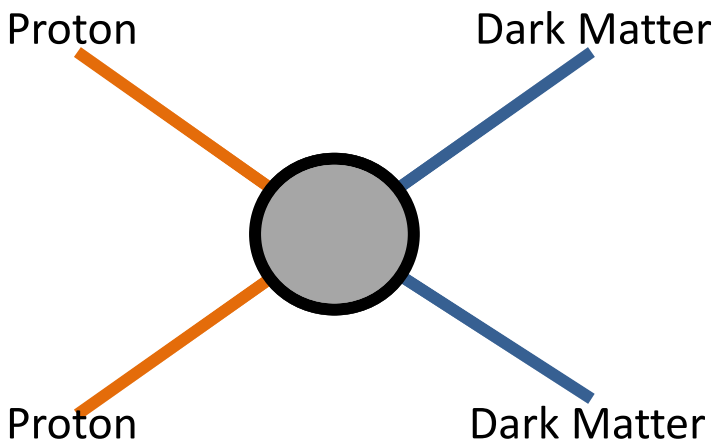
$$\Omega_\chi \sim 1$$



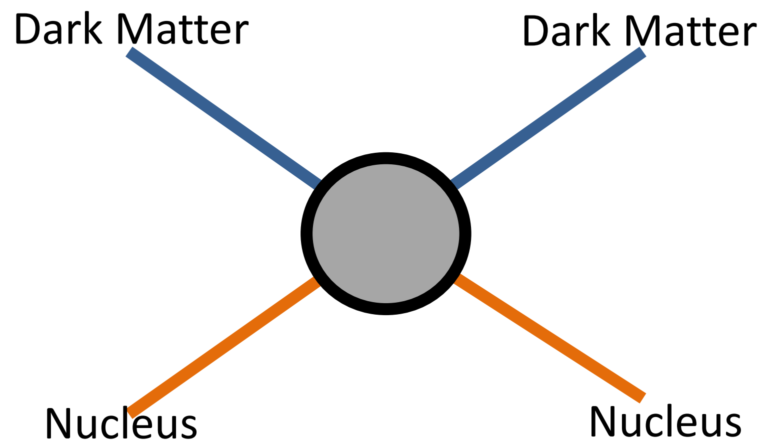
$$\frac{dn}{dt} = \langle \sigma v \rangle \left(\frac{\rho}{m_\chi} \right)^2$$

Right amount of dark matter if dark matter mass 100 MeV < M < 100 TeV

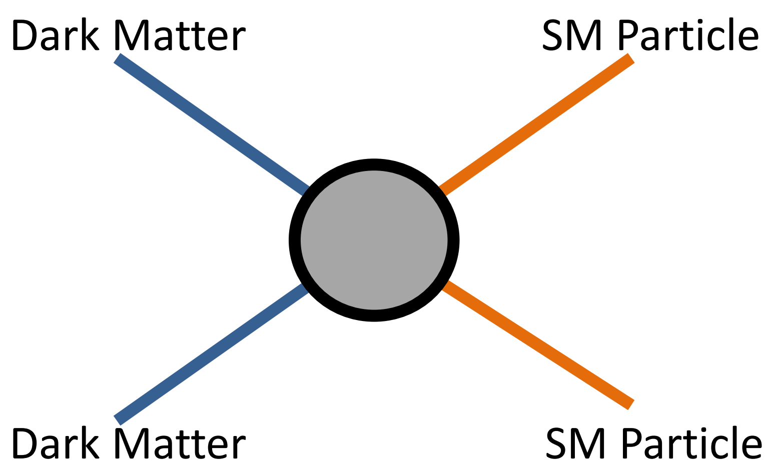
Ways to Detect Dark Matter – *Make, Shake and Break*



Make *– collider production*



Shake *– direct detection scattering*



Break *– indirect detection of annihilation*

Outline

- A word about SUSY
- Effective Lagrangians and Simplified Models of Dark Matter
- Problems with resonances in simplified models
- Using complementarity to probe these regions
- Future methods to cope with the neutrino bound

Based on:-
1305.3452 with Robert Hogan
1406.3288 with John Heal
1406.5047 with Philipp Grothaus and Jocelyn Monroe
1409.4075 with various

Constrained Minimal Supersymmetric Standard Model

Superfield		Bosons	Fermions
<u>Gauge</u>			
$\widehat{G}$		g	$\widetilde{g}$
$\widehat{V}^a$		W^a	$\widetilde{W}^a$
$\widehat{V}'$		B	$\widetilde{B}$
<u>Matter</u>			
$\widehat{L}$	leptons	$\widetilde{L} = (\widetilde{\nu}, \widetilde{e}^-)_L$	$(\nu, e^-)_L$
$\widehat{E}^c$	leptons	$\widetilde{E} = \widetilde{e}_R^+$	e_L^c
$\widehat{Q}$	quarks	$\widetilde{Q} = (\widetilde{u}_L, \widetilde{d}_L)$	$(u, d)_L$
$\widehat{U}^c$	quarks	$\widetilde{U}^c = \widetilde{u}_R^*$	u_L^c
$\widehat{D}^c$	quarks	$\widetilde{D}^c = \widetilde{d}_R^*$	d_L^c
$\widehat{H}_d$	Higgs	H_d^i	$(\widetilde{H}_d^0, \widetilde{H}_d^-)_L$
$\widehat{H}_u$	Higgs	H_u^i	$(\widetilde{H}_u^+, \widetilde{H}_u^0)_L$

All sfermion masses equal at GUT scale

All gaugino masses equal at GUT scale

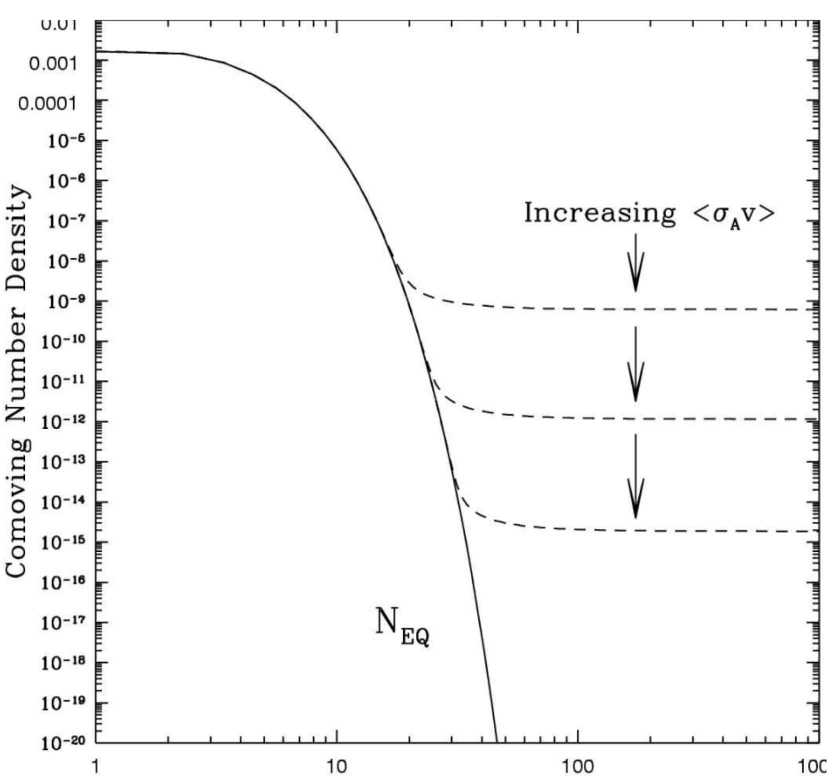
Reduced to 5 free parameters

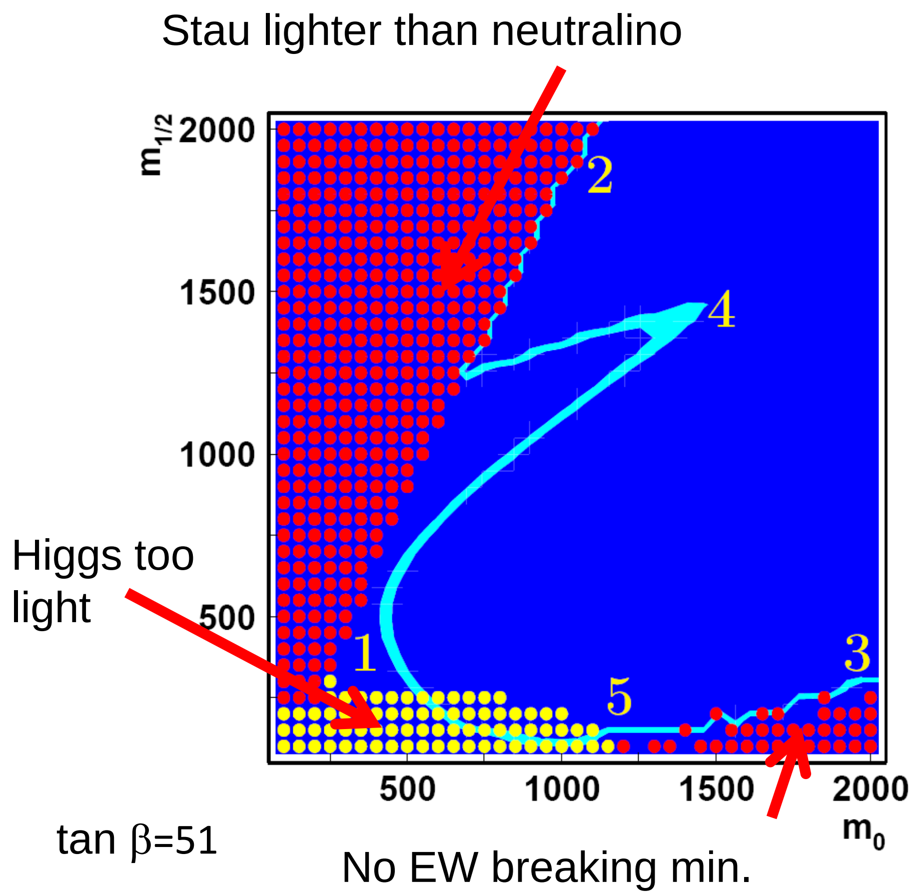
$$\mu,\ m_0,\ m_{1/2},\ A \text{ and } B \leftrightarrow \tan\beta = \frac{v_2}{v_1}$$

Is Neutralino Dark Matter Still OK?

Superpartners of neutral gauge and higgs bosons mix into four majorana *neutralinos* which make good WIMP candidate

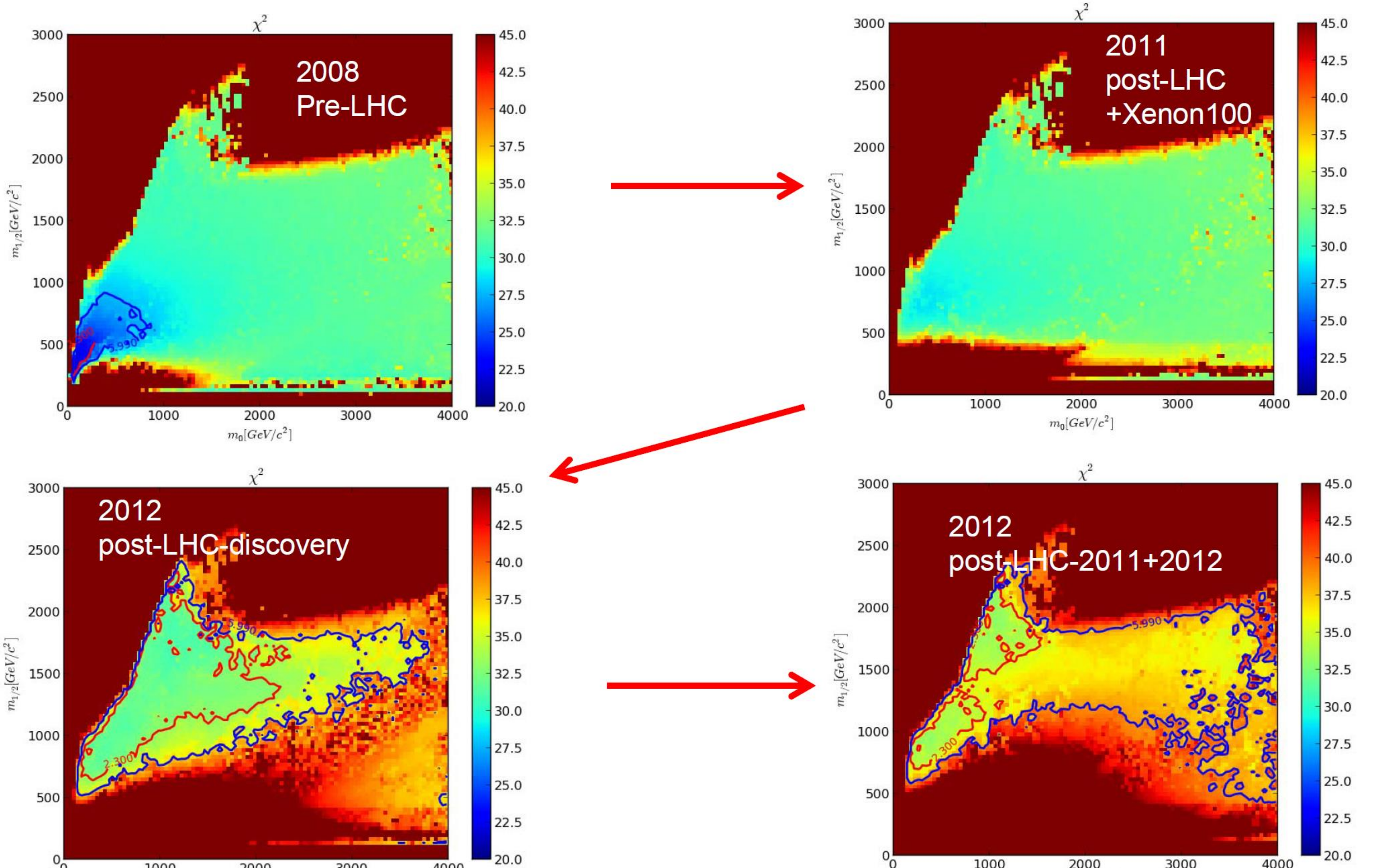
$$\chi = N_{11}\tilde{B} + N_{12}\tilde{W}_3 + N_{13}\tilde{H}_1^0 + N_{14}\tilde{H}_2^0$$





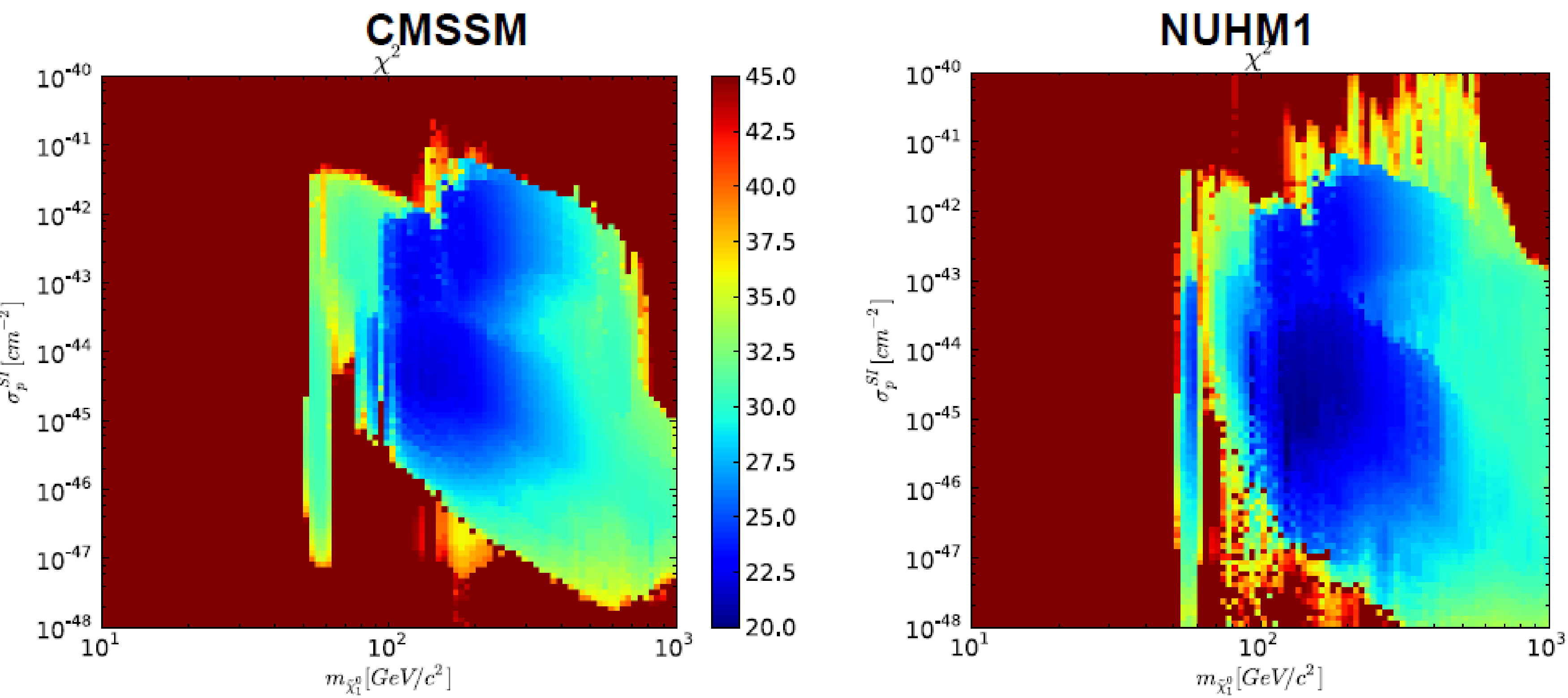
CMSSM: Evolution with time

Stolen from Oliver Buchmuller talk at Dark Attack



Changing Direct Detection Predictions

Pre-LHC 2008



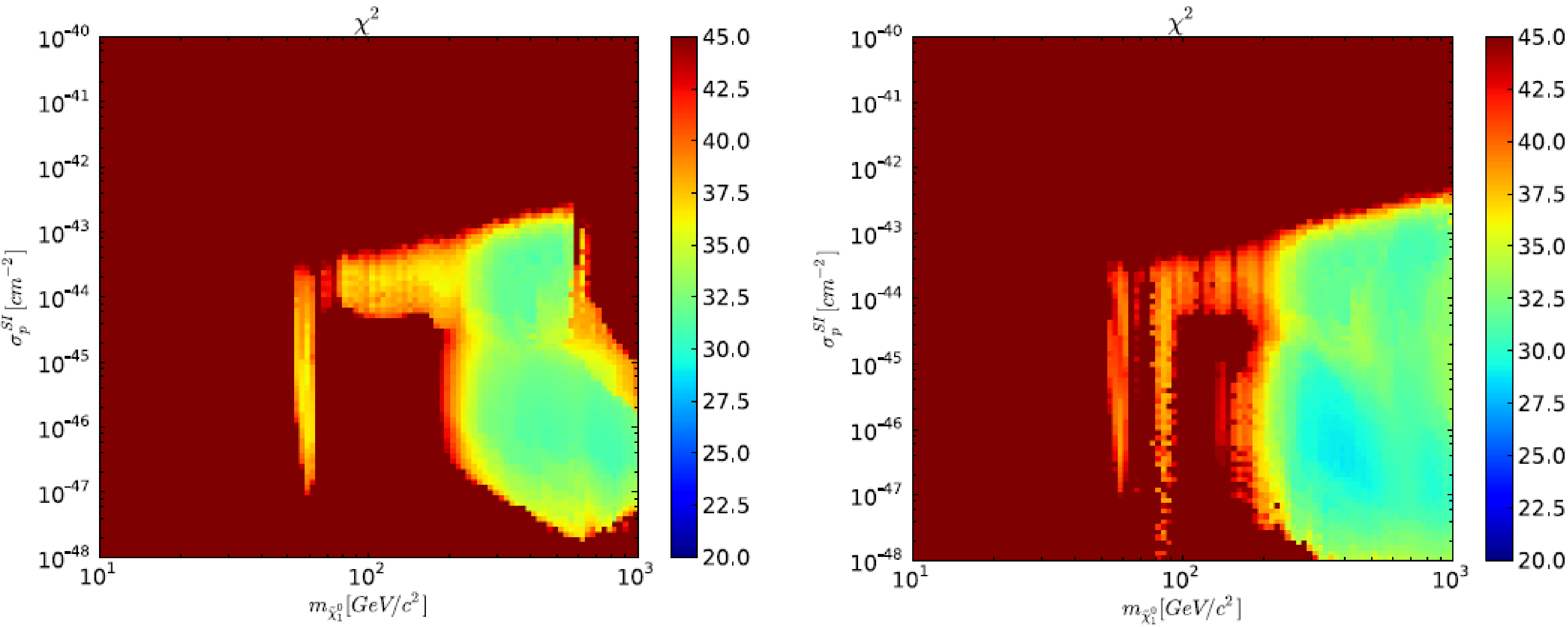
Stolen from Oliver Buchmuller talk at Dark Attack

Changing Direct Detection Predictions

(SUSY no-show, 125/6 GeV Higgs & XENON100)

Post Discovery!

assume m_H=125 +/- 1.5(theo) +/- 1.0 GeV



CMSSM **NUHM1**

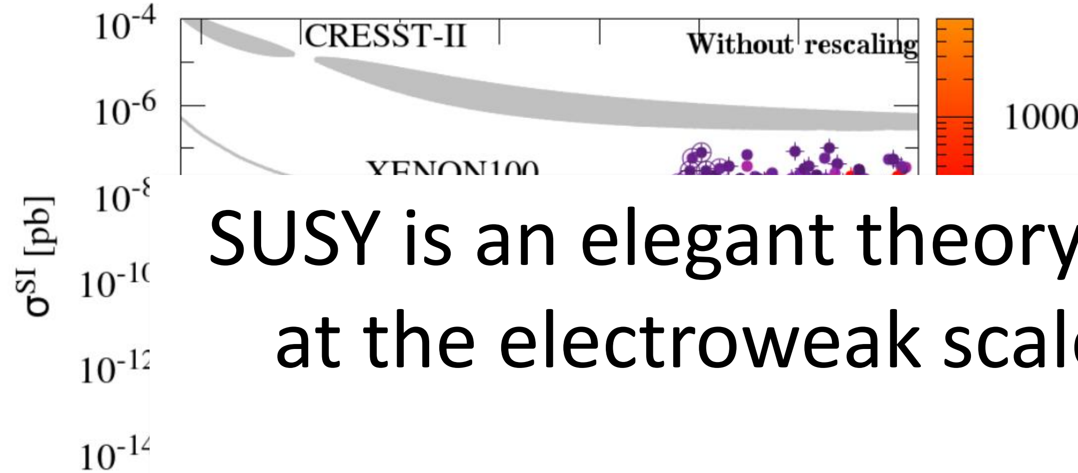
Stolen from Oliver Buchmuller talk at Dark Attack

Phenomenological Minimal Supersymmetric Standard Model PMSSM

Parameter	Description	Prior Range
$\tan\beta$	Ratio of the scalar doublet vevs	$[1, 60]$
μ	Higgs-Higgsino mass parameter	$[-3, 3]$ TeV
M_A	Pseudo-scalar Higgs mass	$[0.3, 3]$ TeV
M_1	Bino mass	$[-0.5, 0.5]$ TeV
M_2	Wino mass	$[-1, 1]$ TeV
M_3	Gluino mass	$[0.8, 3]$ TeV
$m_{\tilde{q}_L}$	First/second generation Q_L squark	$[0, 3]$ TeV
$m_{\tilde{u}_R}$	First/second generation U_R squark	$[0, 3]$ TeV
$m_{\tilde{d}_R}$	First/second generation D_R squark	$[0, 3]$ TeV
$m_{\tilde{\ell}_L}$	First/second generation L_L slepton	$[0, 3]$ TeV
$m_{\tilde{e}_R}$	First/second generation E_R slepton	$[0, 3]$ TeV
$m_{\tilde{Q}_{3L}}$	Third generation Q_L squark	$[0, 3]$ TeV
$m_{\tilde{t}_R}$	Third generation U_R squark	$[0, 3]$ TeV
$m_{\tilde{b}_R}$	Third generation D_R squark	$[0, 3]$ TeV
$m_{\tilde{L}_{3L}}$	Third generation L_L slepton	$[0, 3]$ TeV
$m_{\tilde{\tau}_R}$	Third generation E_R slepton	$[0, 3]$ TeV
A_t	Trilinear coupling for top quark	$[-10, 10]$ TeV
A_b	Trilinear coupling for bottom quark	$[-10, 10]$ TeV
A_τ	Trilinear coupling for τ-lepton	$[-10, 10]$ TeV

See e.g. Boehm, Dev, Mazumdar & Pukartas 2013

Fits in PMSSM



Fine tuning is sensitivity of

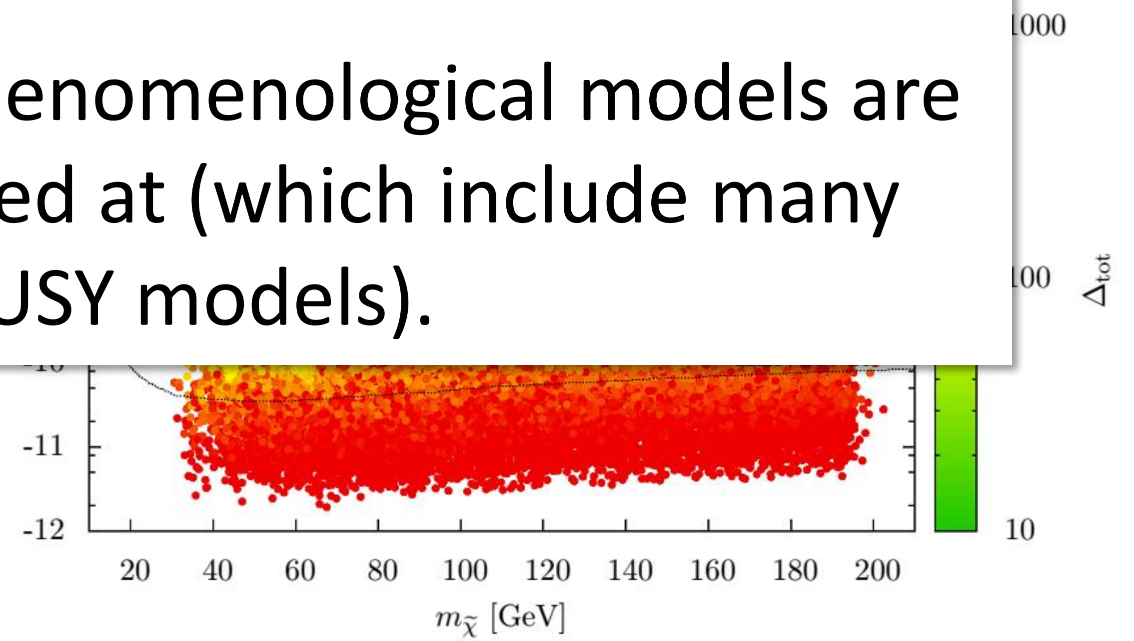
SUSY is an elegant theory which may appear at the electroweak scale or much higher.

Many searches are taking place at the LHC.

Simpler, more phenomenological models are also being looked at (which include many SUSY models).

Low
Boehr
Mazu
Pukar

Higher mass DM
Grothaus, Lindner and Yakanishi 2012



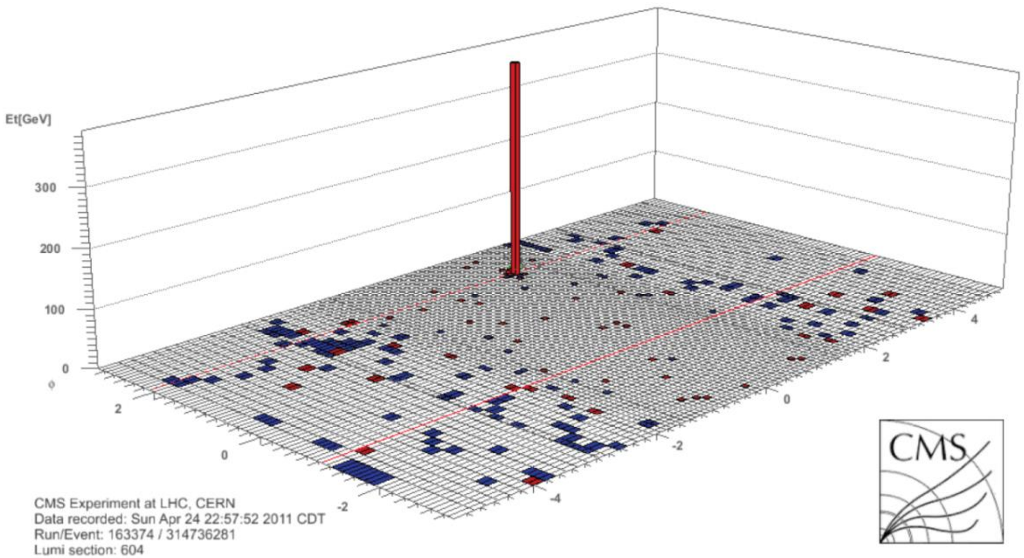
Effective Lagrangians for Dark Matter

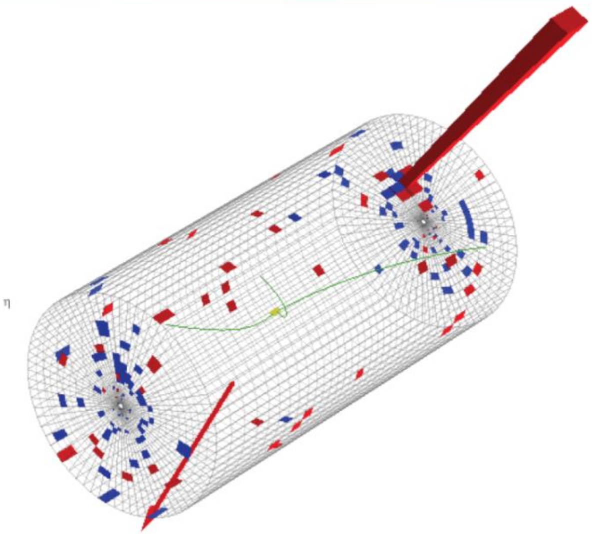
Imagine some purely phenomenological contact interactions for coupling between dark matter and standard model particles

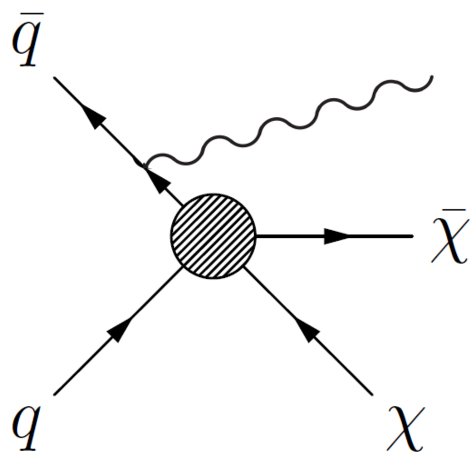
$$\begin{aligned}
\mathcal{O}_1 &= \frac{i\, g_\chi\, g_q}{q^2 - M^2} (\bar{q}q)(\bar{\chi}\chi) \ , \\
\mathcal{O}_2 &= \frac{i\, g_\chi\, g_q}{q^2 - M^2} (\bar{q}\gamma_\mu q)(\bar{\chi}\gamma^\mu\chi) \ , \\
\mathcal{O}_3 &= \frac{i\, g_\chi\, g_q}{q^2 - M^2} (\bar{q}\gamma_\mu\gamma_5 q)(\bar{\chi}\gamma^\mu\gamma_5\chi) \ , \\
\mathcal{O}_4 &= \frac{i\, g_\chi\, g_q}{q^2 - M^2} (\bar{q}\gamma_5 q)(\bar{\chi}\gamma_5\chi) \ ,
\end{aligned}$$

Bai, Fox and Harnik arXiv:10053797

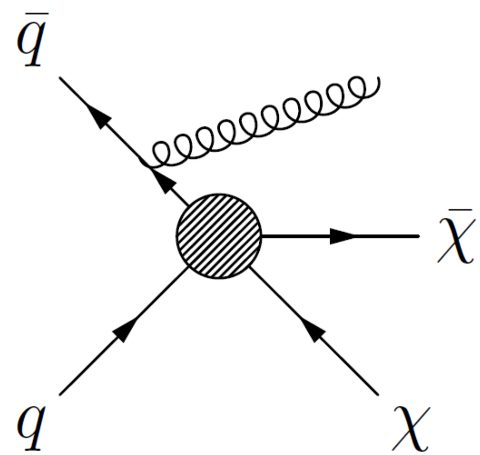
Monophoton – Event Display







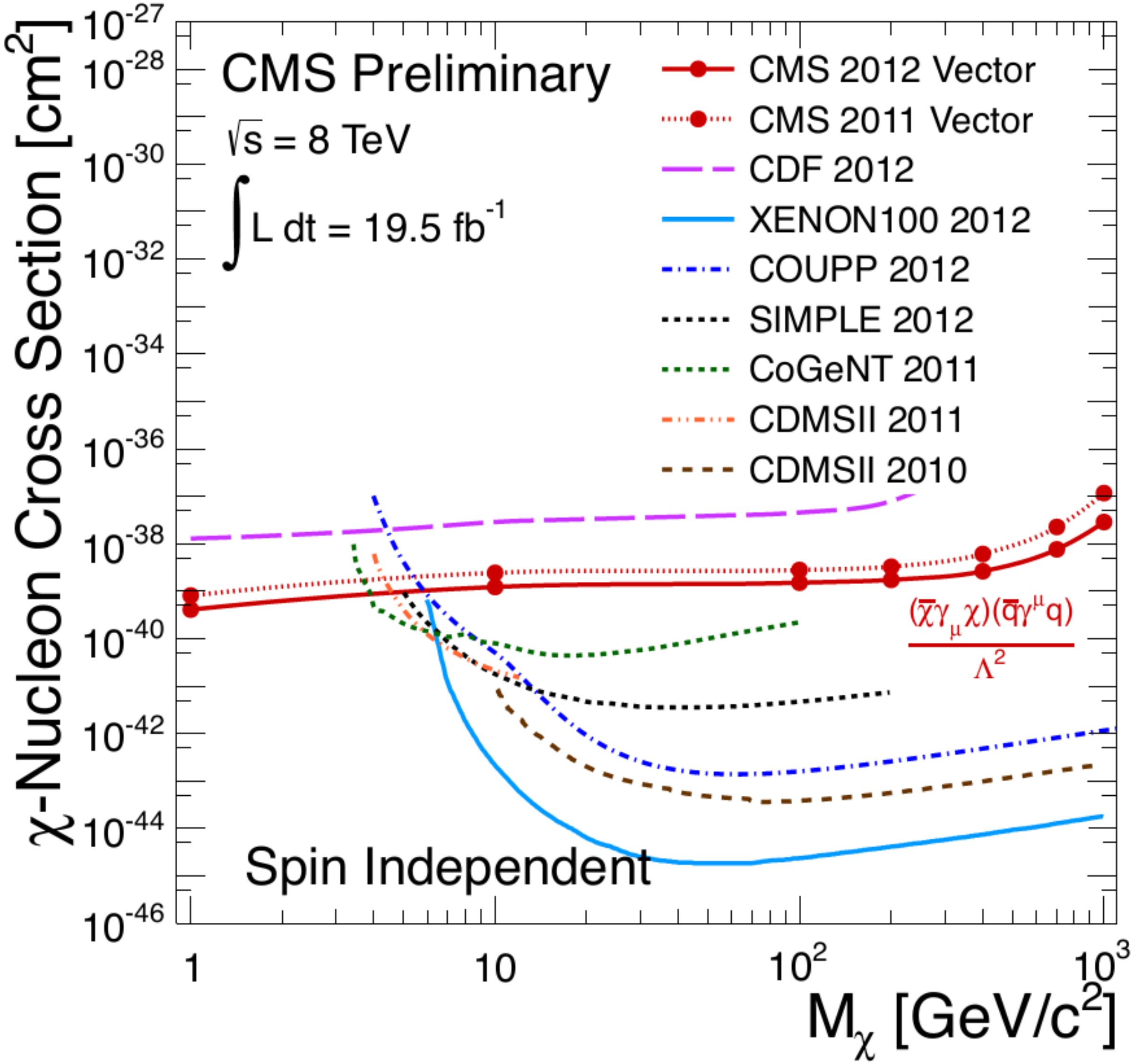
Monophoton + MET



Monojet + MET

Slide stolen from Steve Worm Oxford Presentation

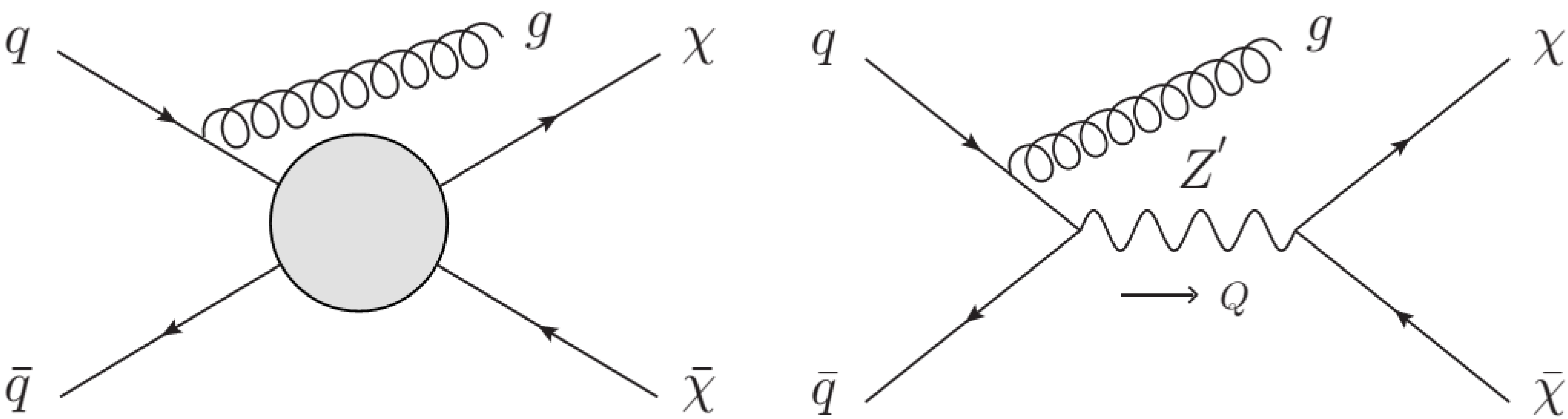
Monojet/Monophoton Constraints from colliders



CMS collaboration CMS-PAS-EXO-12-048

Precise constraints vary hugely depend upon assumed nature of interaction, Majorana vs Dirac etc…

How well can you trust this approach?



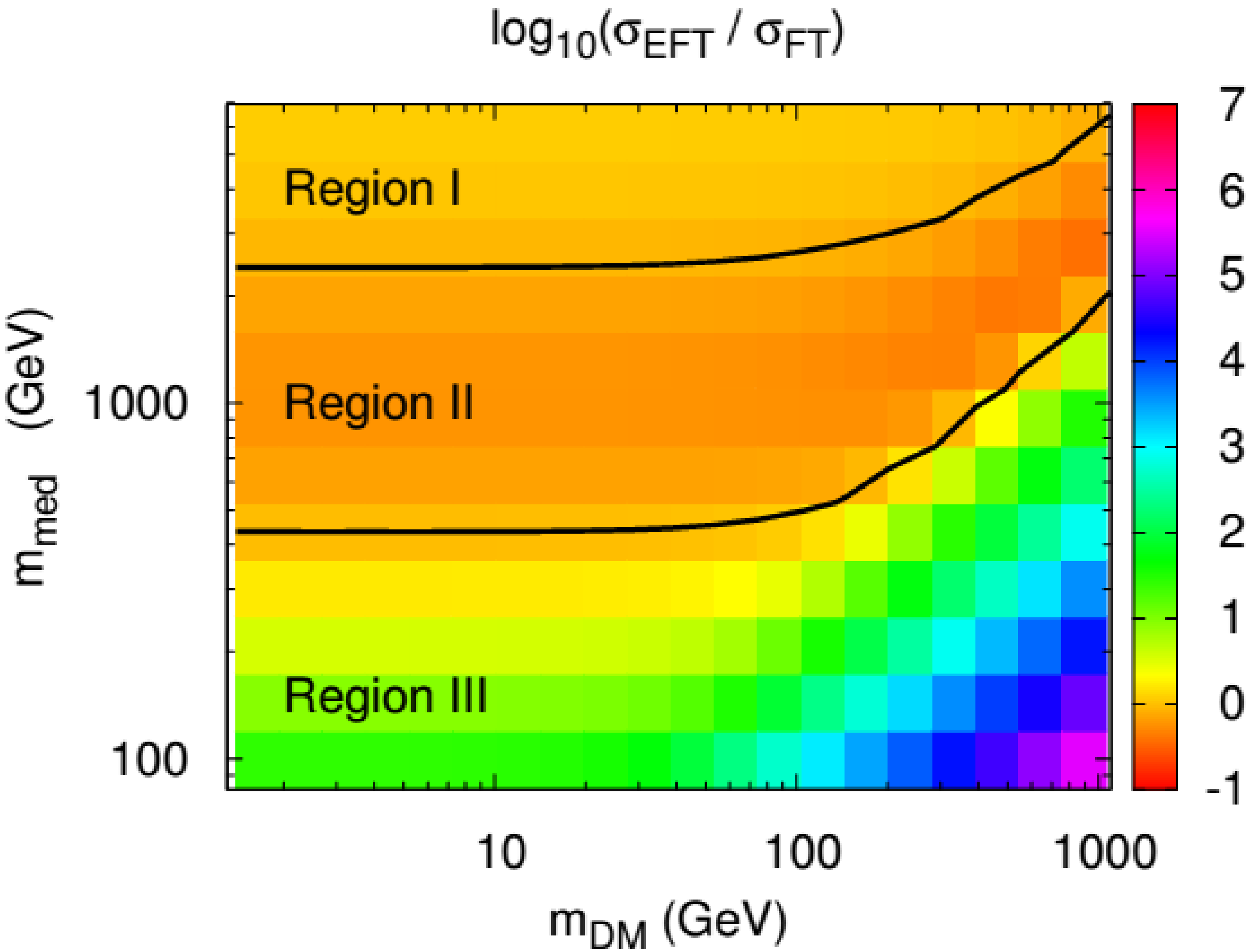
Compare Axial-Vector Effective contact theory with actual exchange of Vector

$$\Lambda \equiv \frac{m_{\text{med}}}{\sqrt{g_q\, g_\chi}}$$

Buchmuller, Dolan and McCabe, 2013

How well can you trust this approach?

- Region 1, both approaches in reasonable (20% agreement)
- Region 2, field theory cross section larger due to resonance in propagator
- Region 3, effective field theory overestimates the cross section relative to actual field theory



On the right, the high mass of DM means that Q^2 has to be large and the dynamics are set by the final state.

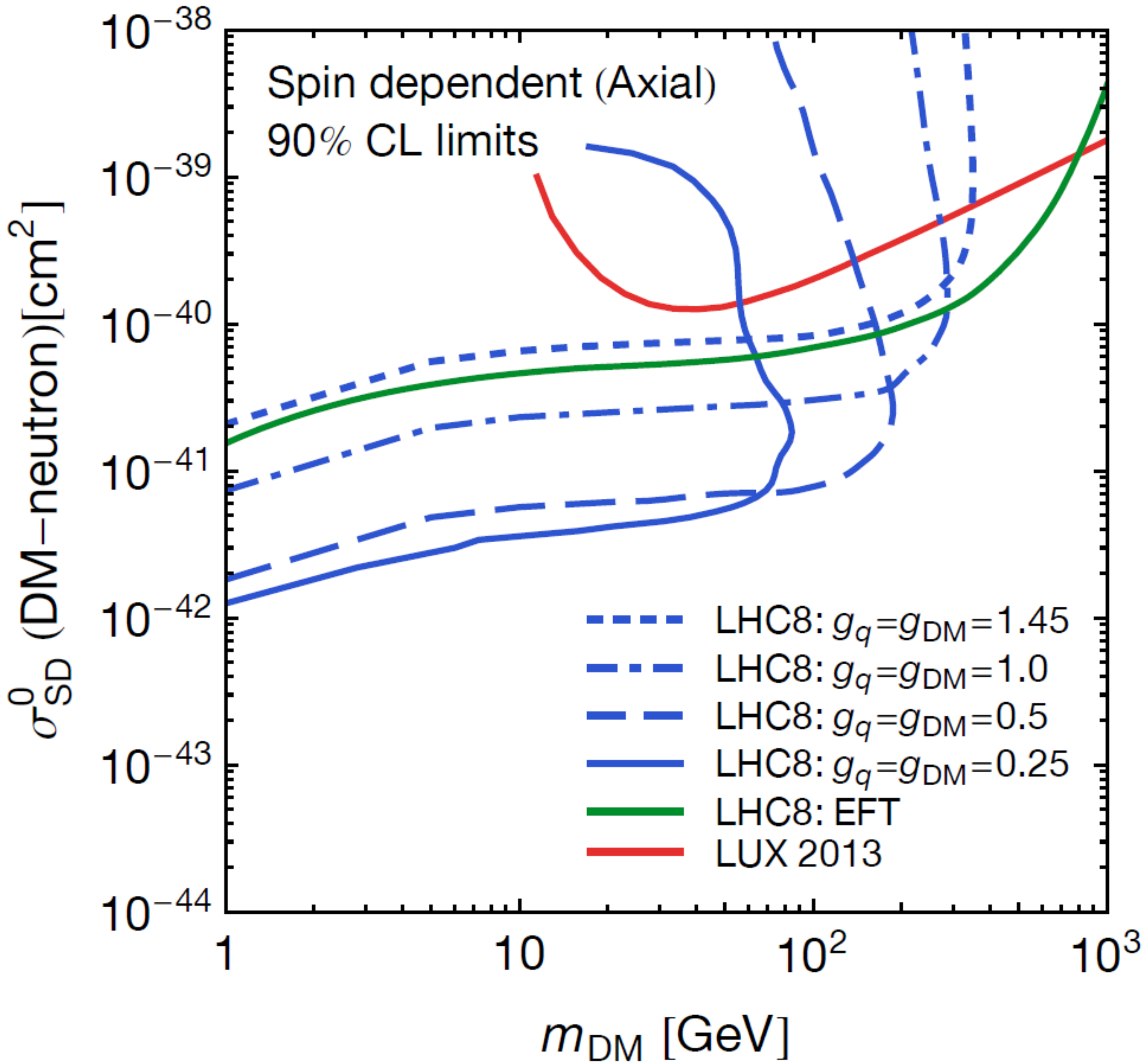
Buchmuller Dolan and McCabe, 2013

MSDM Minimal Simplified Model of Dark Matter
Simplified Model Lagrangian –
Vector coupling to DM and Quark sector

$$
\begin{aligned}
\Delta\mathscr{L} = & -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{1}{2}m_{A'}^2 A'_\mu A'^\mu \\
& + \bar{\chi}(i\gamma^\mu\partial_\mu - m_\chi)\chi + A'_\mu\bar{\chi}\gamma^\mu(g_{\chi V} - g_{\chi A}\gamma^5)\chi \\
& + A'_\mu\bar{q}\gamma^\mu(g_{qV} - g_{qA}\gamma^5)q
\end{aligned}
$$

arXiv:1409.4075

Simplified Model of Dark Matter – monojet constraints

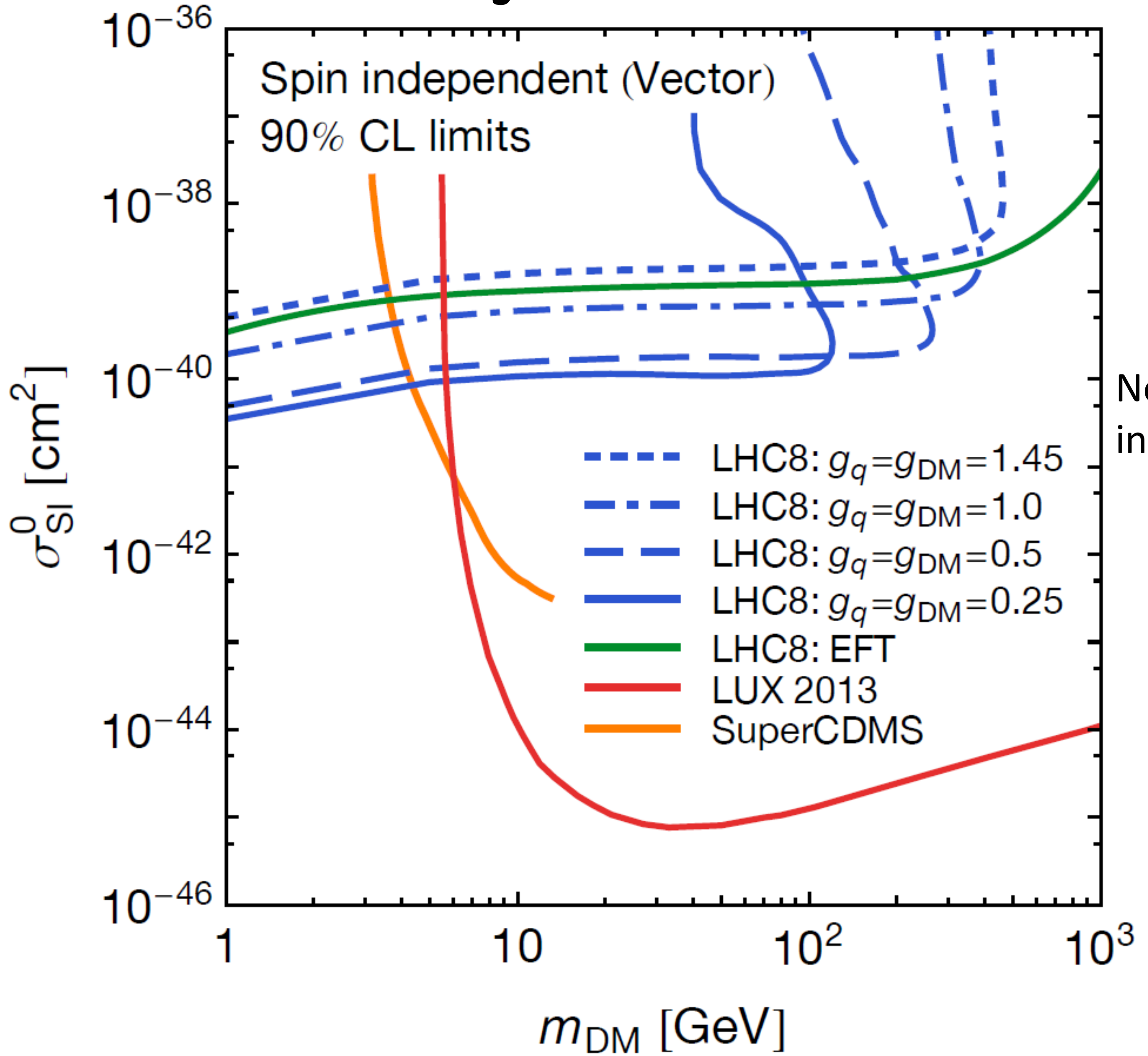


Test cases are for fixed arbitrary couplings.

Mediator mass varied until collider limit violated

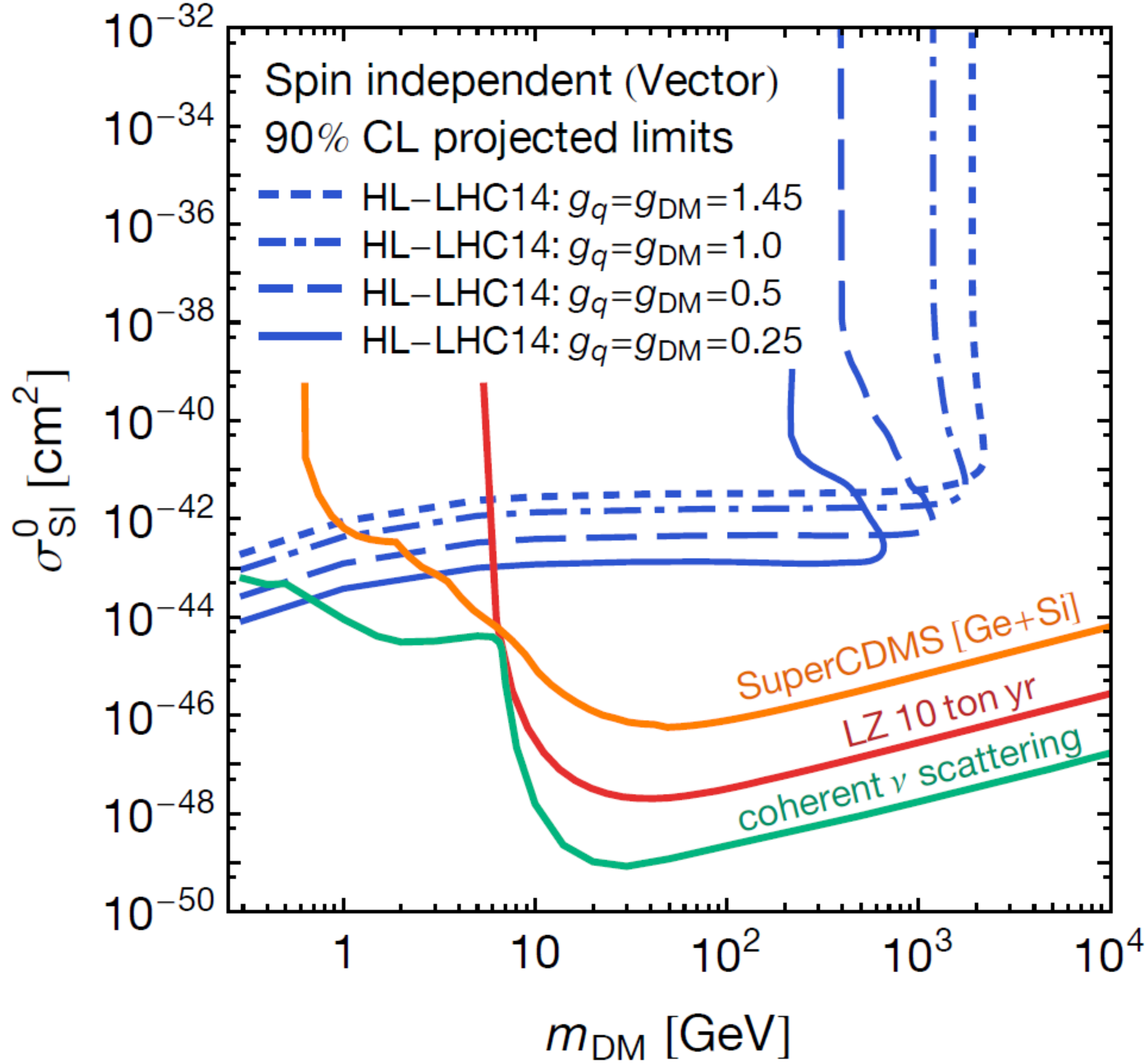
Corresponding direct detection cross section then calculated.

Simplified Model of Dark Matter – monojet constraints



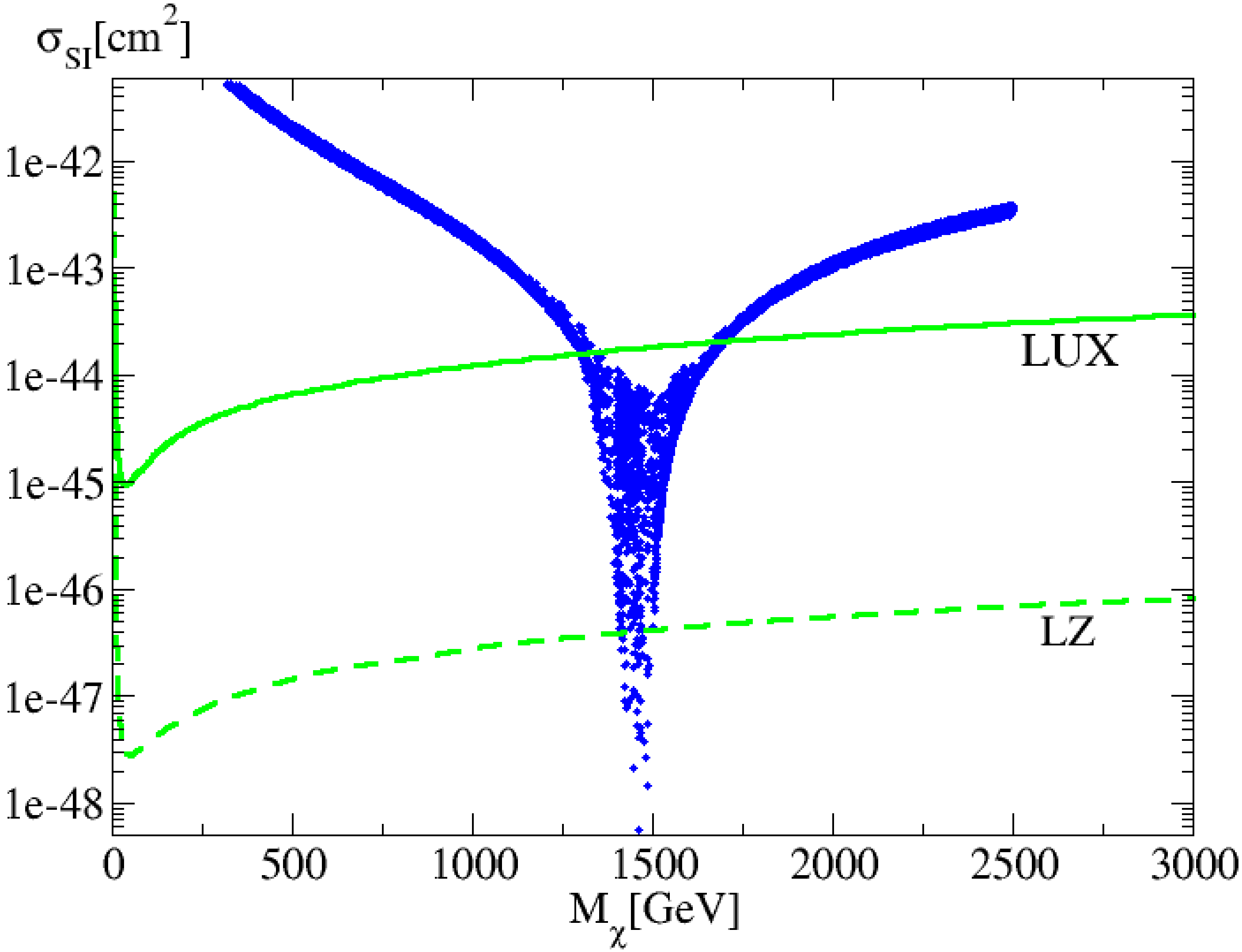
Not competitive for Spin independent cross sections

Simplified Model of Dark Matter – monojet constraints



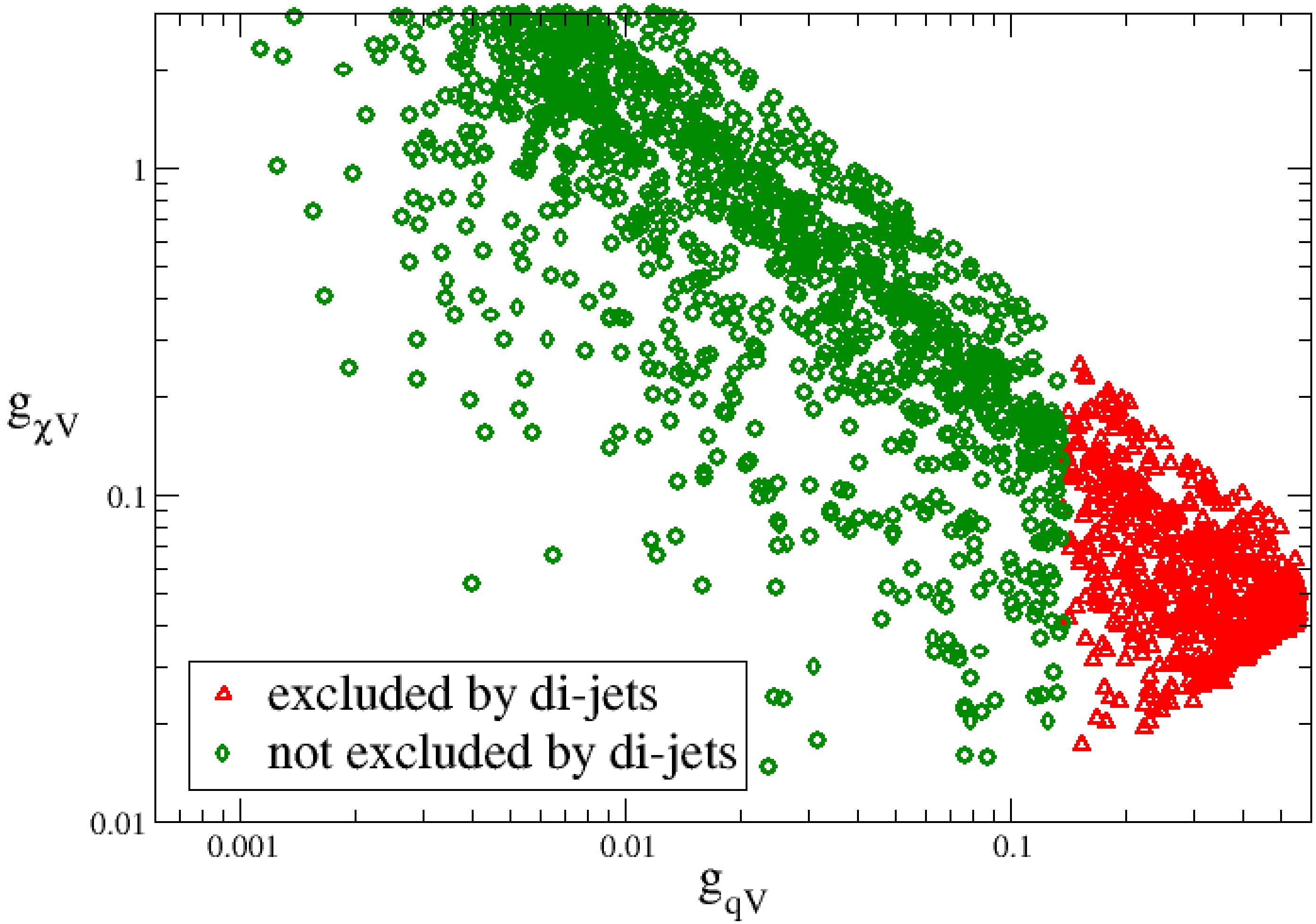
Projected limits with High Luminosity LHC at 14 TeV c.o.m.

Simplified Model of Dark Matter – dijet constraints



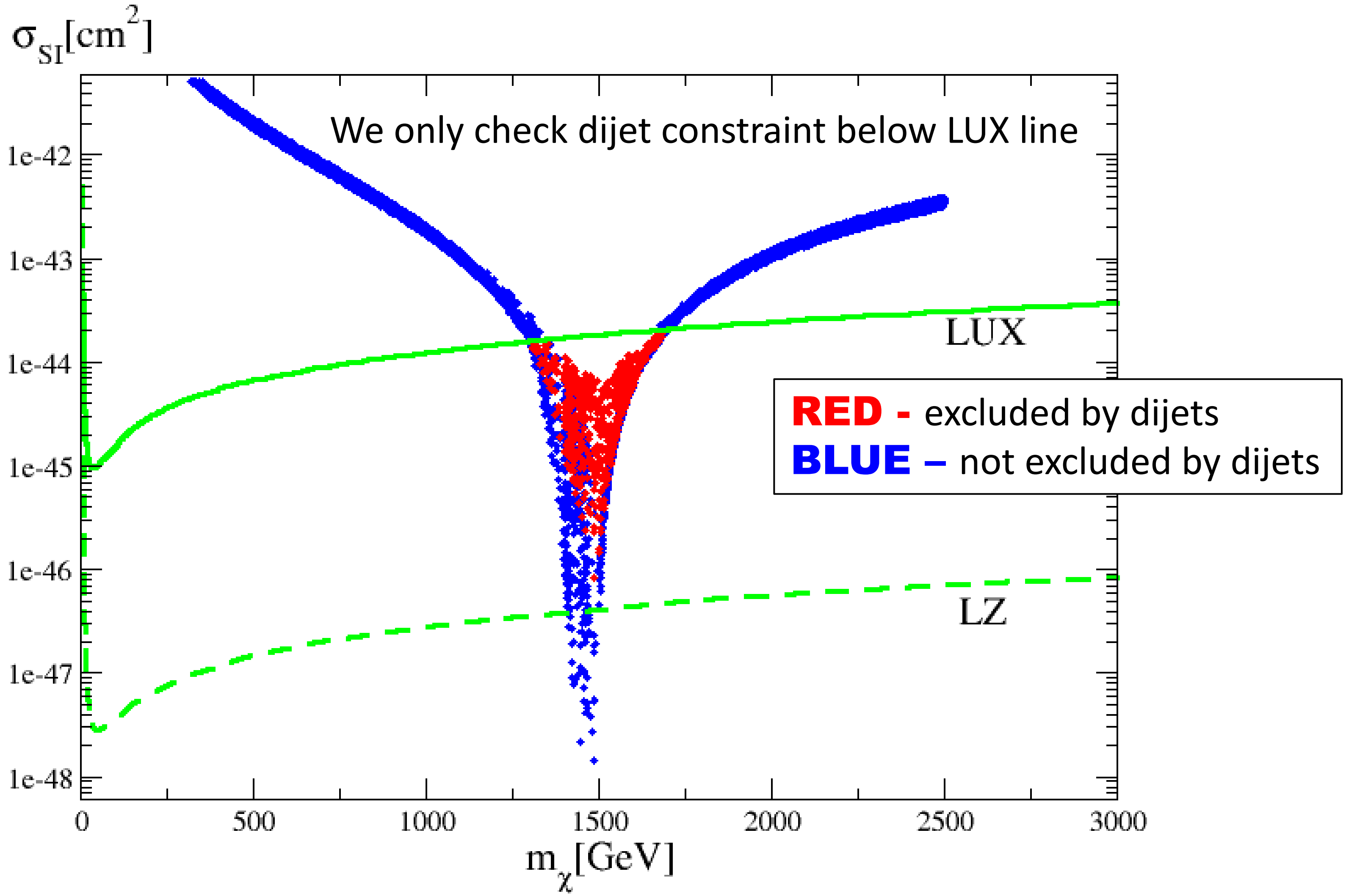
Which Points Are Excluded by Dijets?

$M_{mediator}$ = 3 TeV



All points here give same (naive) relic abundance – fairly simple pattern!

How well can dijets solve our resonance problem?

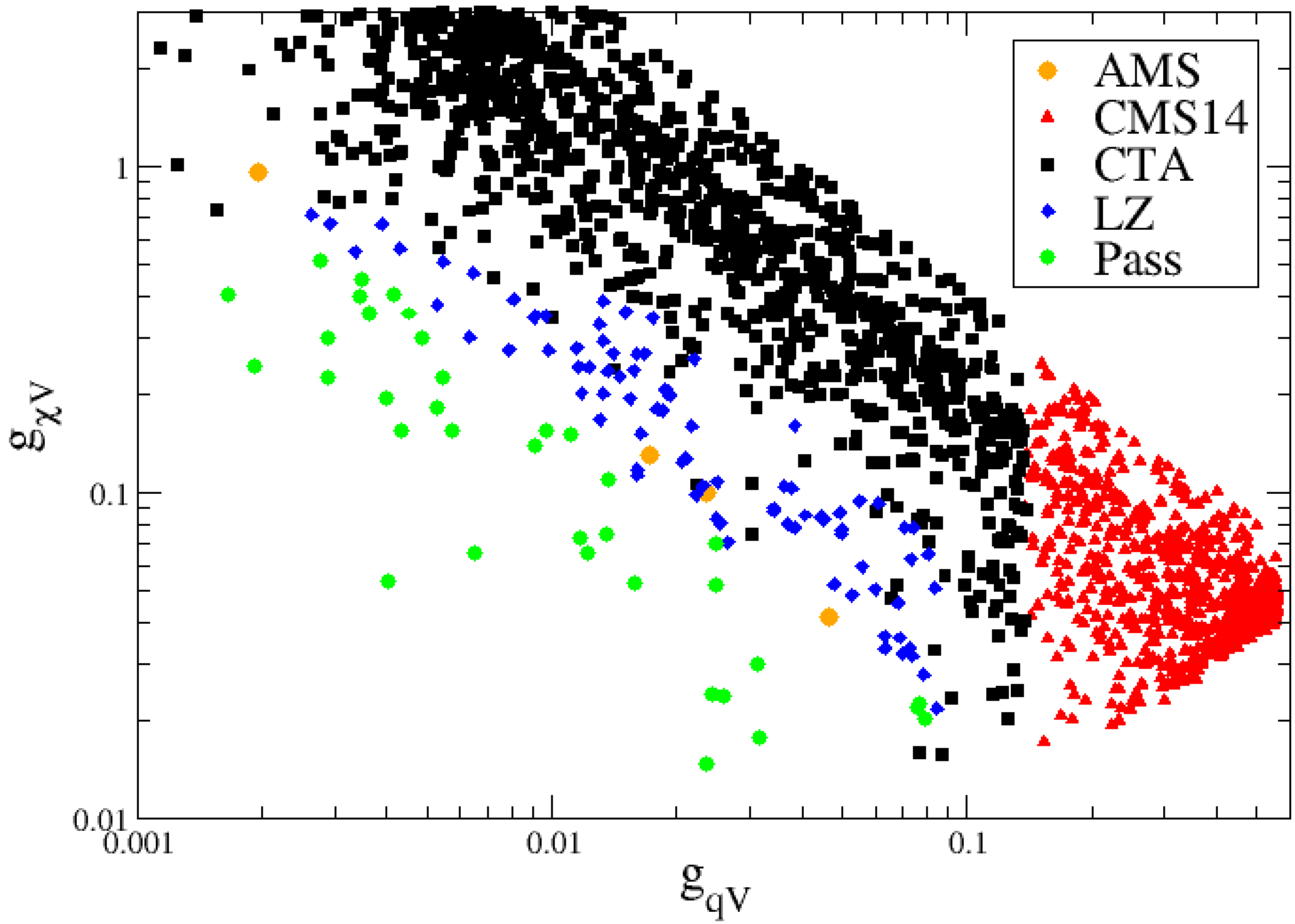


Large $g_{\chi V}$ small g_{qV} + resonance   abundance GOOD

Large $g_{\chi V}$ small g_{qV} direct detection BAD

What if we add other constraints?

$M_{mediator} = 3$ TeV



Cuts are performed in the order that they appear in the key

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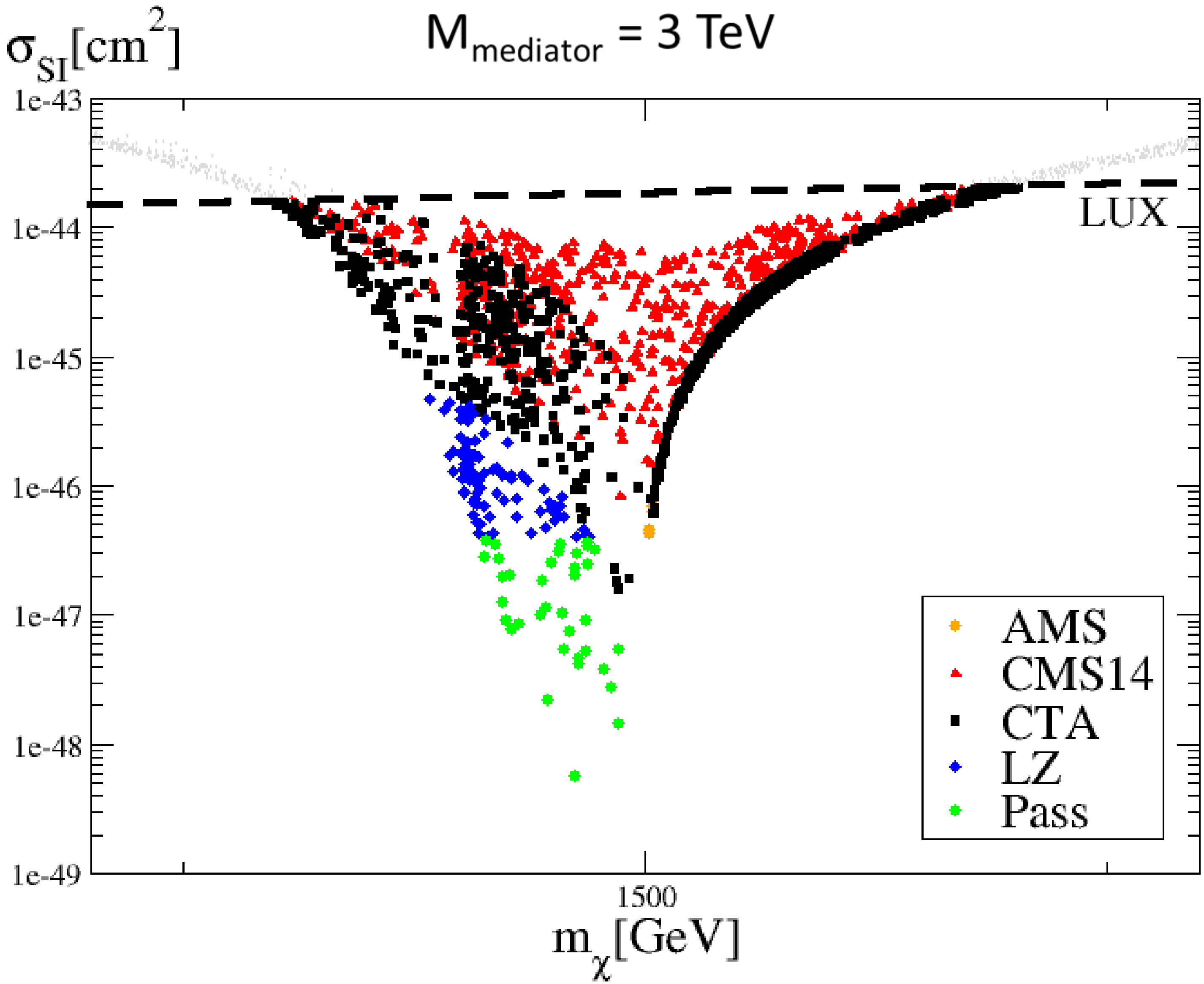

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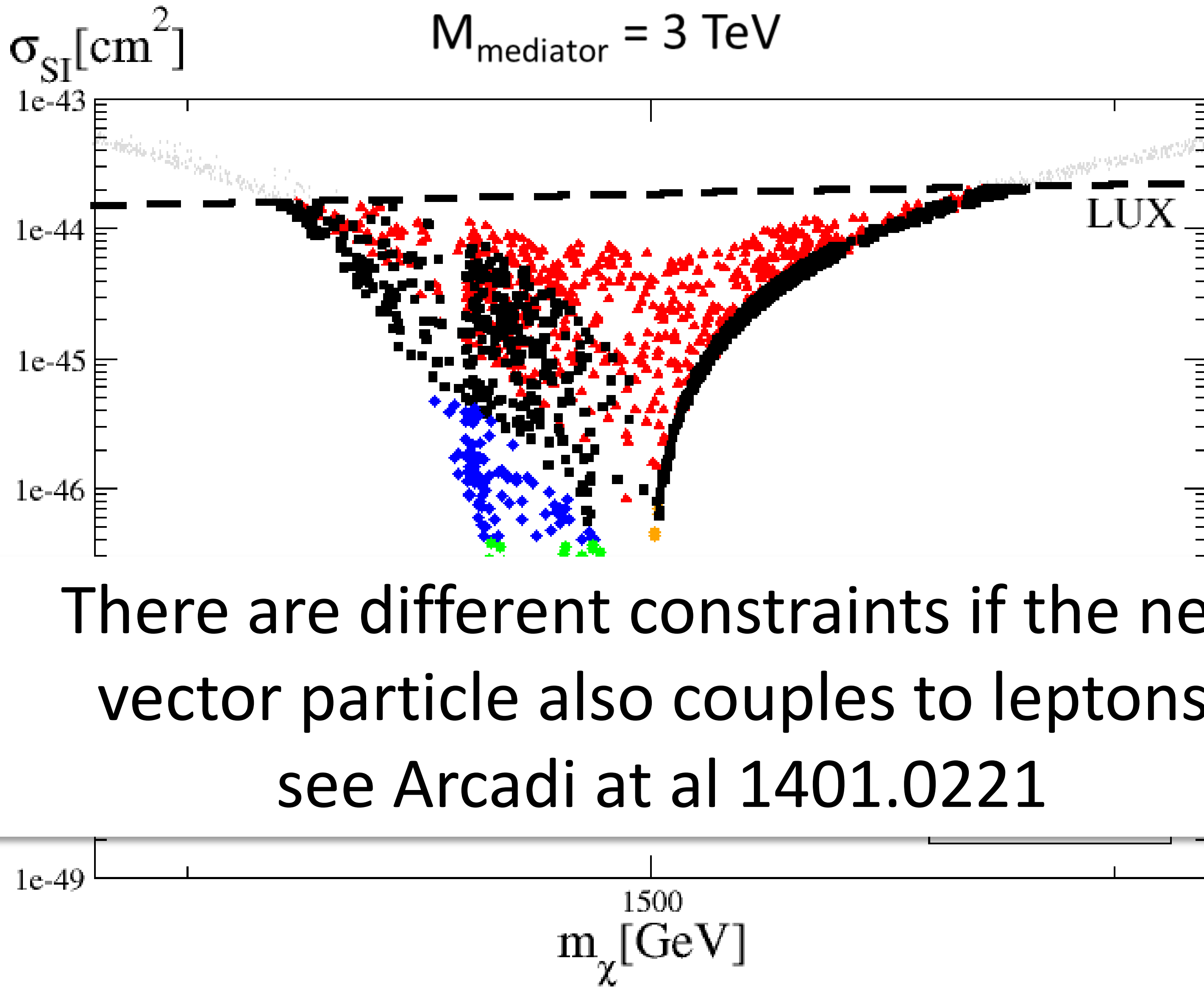

There are different constraints if the new vector particle also couples to leptons, see Arcadi at al 1401.0221

Cuts are performed in the order that they appear in the key

Higgs Portal Dark Matter

Simply another particle which couples to the Standard model through the Higgs

$$\Delta\mathcal{L}_S = -\frac{1}{2}m_S^2 S^2 - \frac{1}{4}\lambda_S S^4 - \frac{1}{4}\lambda_{hSS} H^\dagger H S^2$$

Scalar dark matter

Standard model Higgs Field

V. Silveira, A. Zee, Phys. Lett. B161, 136 (1985);
J. McDonald, Phys. Rev. D50 (1994) 3637-3649;
C. P. Burgess, M. Pospelov, T. ter Veldhuis, Nucl. Phys. B619 (2001) 709-728;
L. L. Honorez, E. Nezri, J. Oliver, M.H.G. Tytgat, JCAP 0702 (2007) 028

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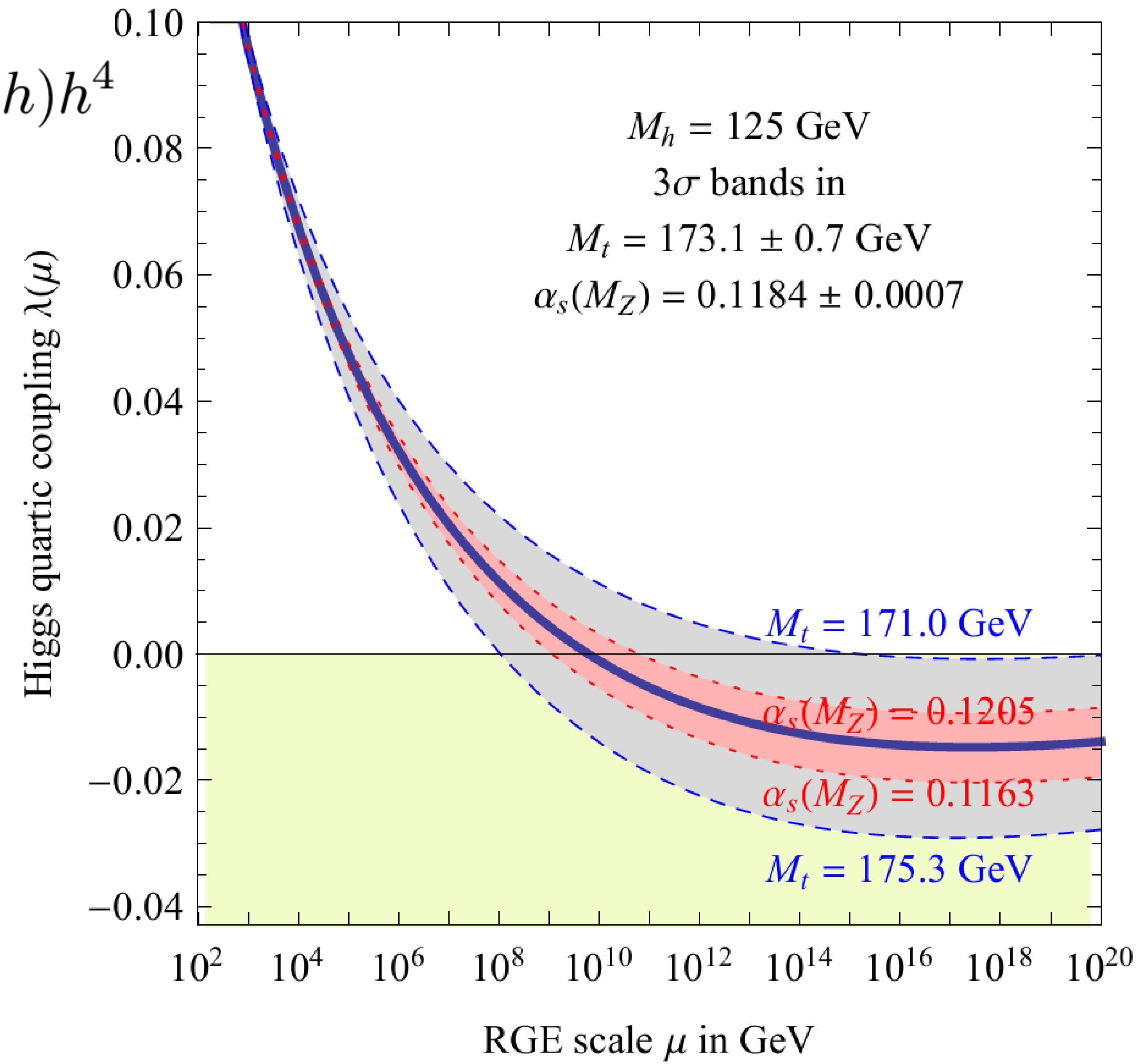
Scalars dramatically improve vacuum stability

V. Silveira, A. Zee, Phys. Lett. B161, 136 (1985);
J. McDonald, Phys. Rev. D50 (1994) 3637-3649;
C. P. Burgess, M. Pospelov, T. ter Veldhuis, Nucl. Phys. B619 (2001) 709-728 [hep-ph/0011335]

On the Stability of the Higgs Vacuum

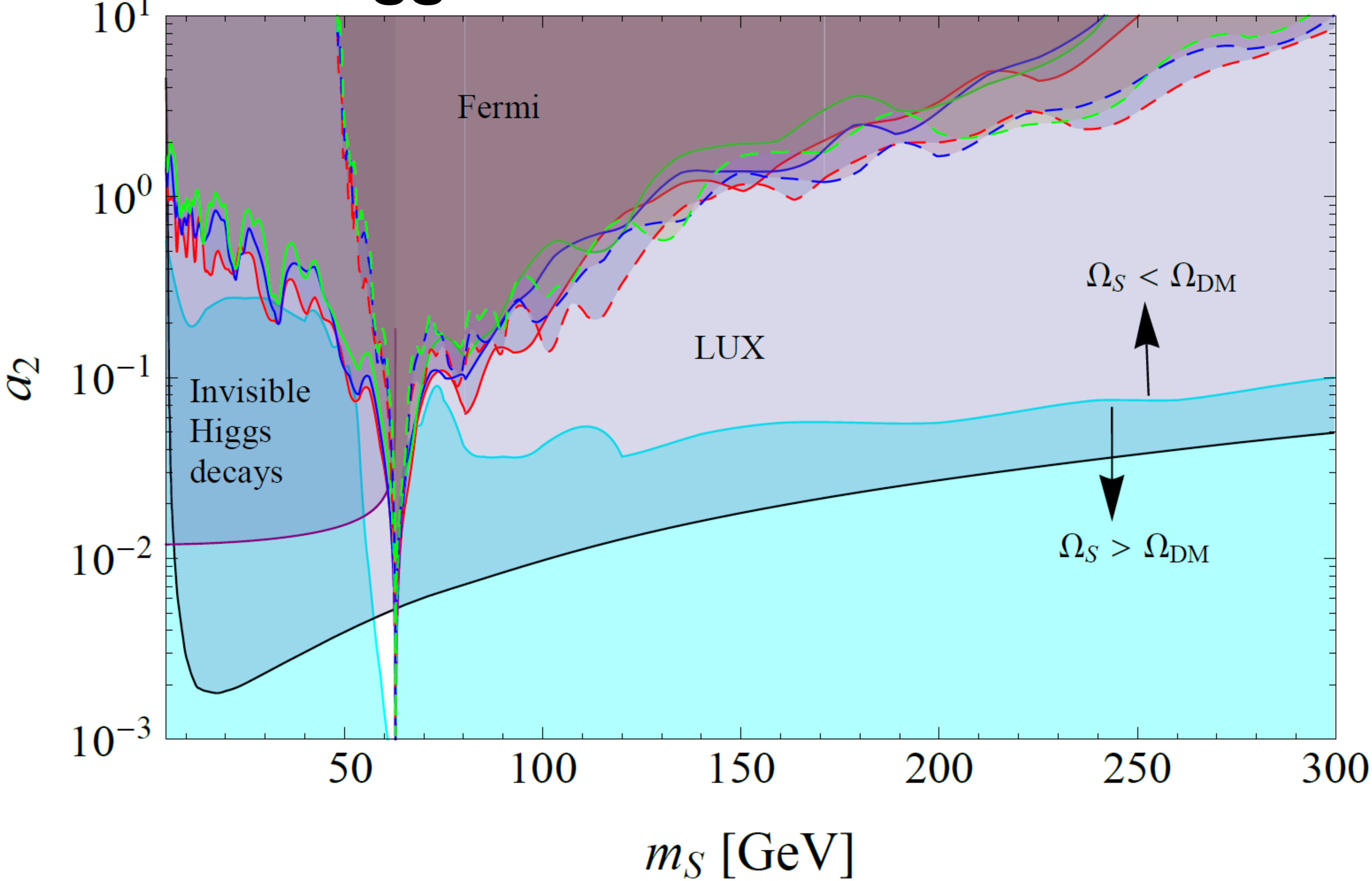
$$V_{\text{eff}}(h) = \frac{1}{4}\lambda_{\text{eff}}(h)h^4$$

Degrassi et al.



Higgs Portal Dark Matter

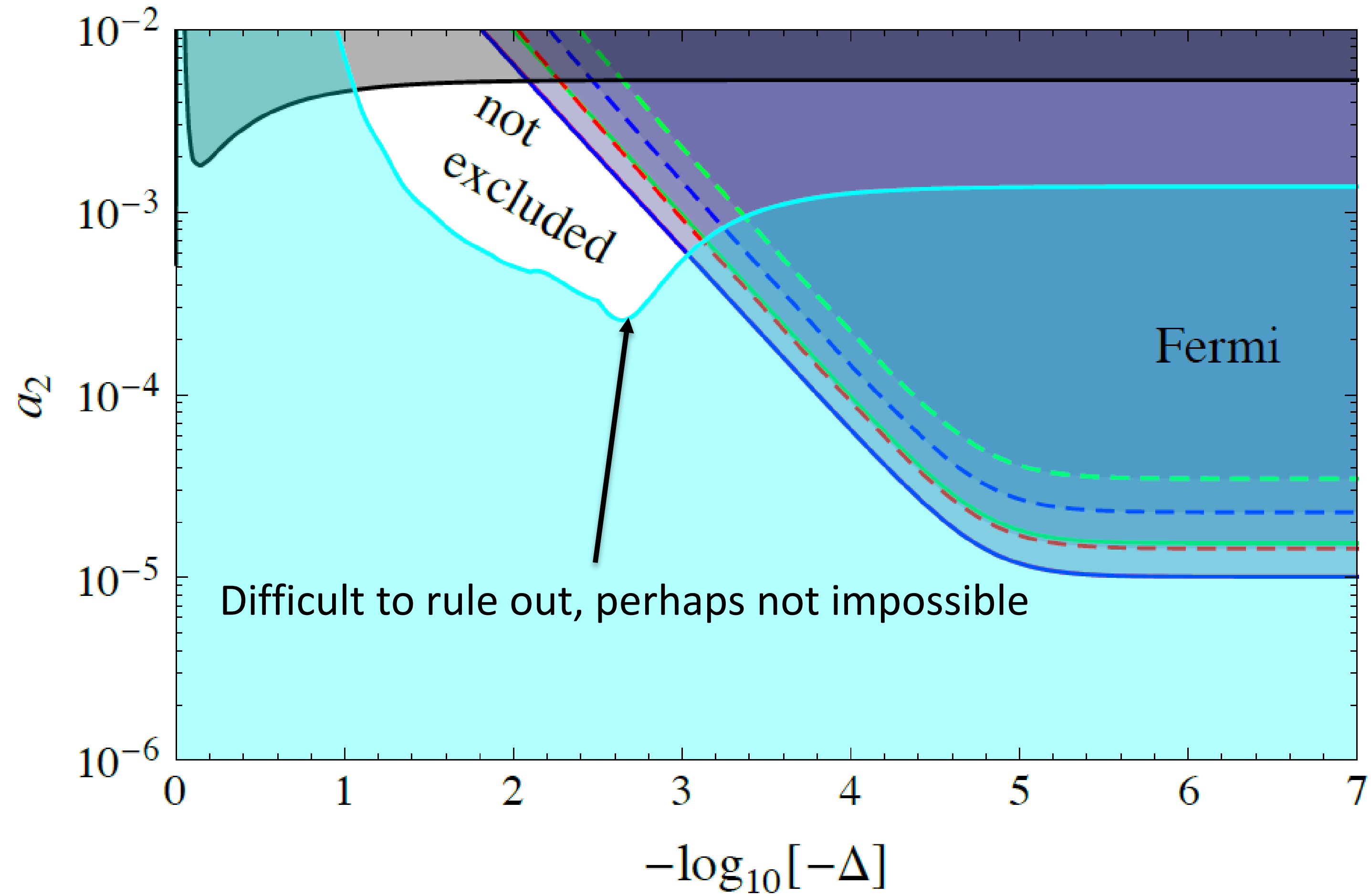
Feng et al. arXiv:1412.1105



$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{2}\partial_\mu S \partial^\mu S - \frac{b_2}{2}S^2 - \frac{b_4}{4}S^4 - a_2 S^2 H^\dagger H$$

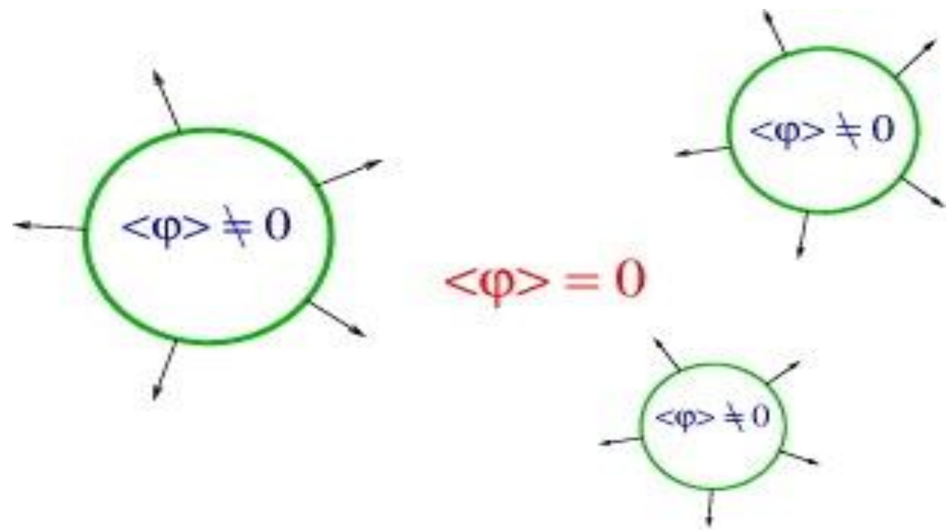
$a_2 S^2 H^\dagger H$ **Higgs Portal Dark Matter**

Feng et al. arXiv:1412.1105



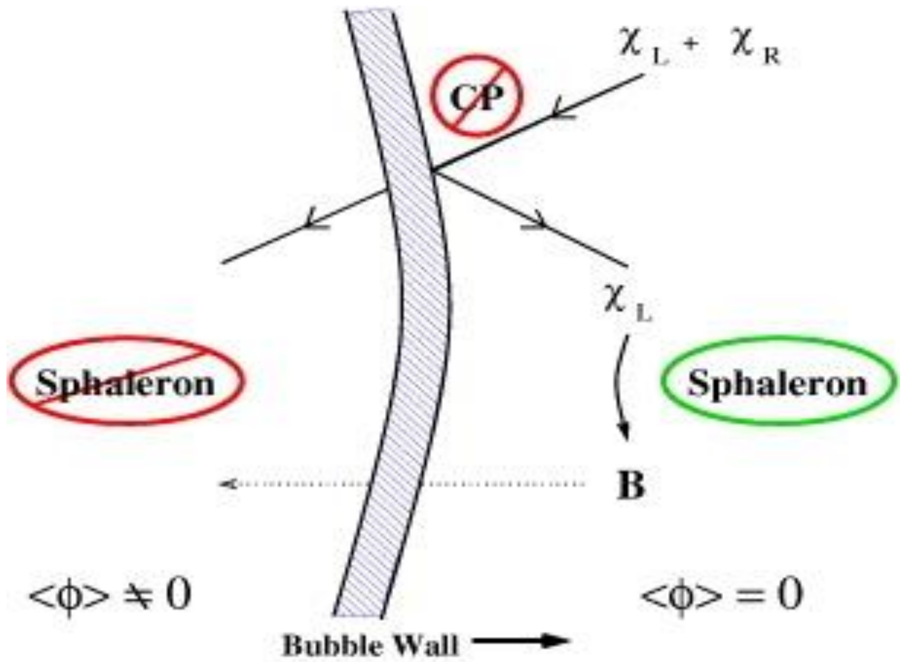
$\Delta \equiv \frac{2m_S - m_h}{m_h}$ $\qquad$ $56.6 \text{ GeV} < m_S < 62.8 \text{ GeV}$

Electroweak Baryogenesis



Figures from “Electroweak baryogenesis”
David E Morrissey and Michael J Ramsey-Musolf 2012 New J. Phys. 14

Electroweak Baryogenesis



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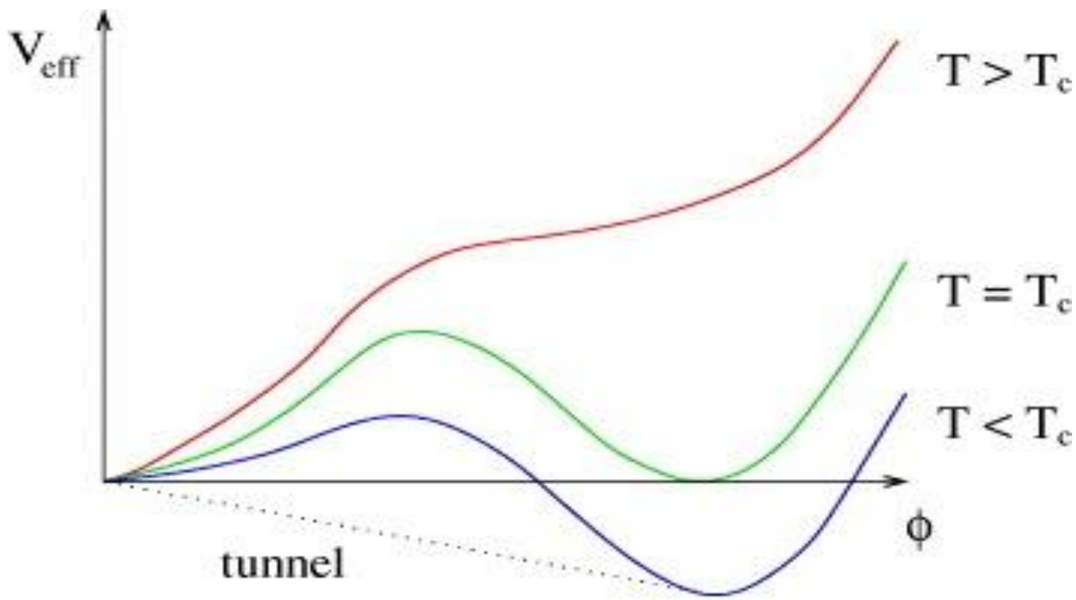
Electroweak Baryogenesis



Figures from “Electroweak baryogenesis”
David E Morrissey and Michael J Ramsey-Musolf 2012 New J. Phys. 14

Improved Electroweak Phase Transition with Subdominant Inert Doublet Dark Matter

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Kimmo Kainulainen†
Department of Physics, P.O.Box 35 (YFL), FIN-40014 University of Jyväskylä, Finland and Helsinki Institute of Physics, P.O. Box 64, FIN-00014 University of Helsinki, Finland

The inert doublet dark matter model has recently gained attention as a possible means of facilitating a strongly first order electroweak phase transition (EWPT), as needed for baryogenesis. We extend previous results by considering the regime where the DM is heavier than half the Higgs mass, and its relic density is determined by annihilation into W, Z and Higgs bosons. We find a large natural region of parameter space where the EWPT is strongly first order, while the lightest inert doublet state typically contributes only $0.1 - 3\%$ of the total dark matter. Despite this small density, its interactions with nucleons are strong enough to be directly detectable given a factor of 5 improvement over the current sensitivity of XENON100. A 10% decrease in the branching ratio for Higgs decays to two photons is predicted.

If we want dark matter and strong 1st order EW phase transition, we need something else

Example of Higgs Portal Model:- Singlet Fermionic Dark Matter

McDonald, (1994)
H. Davoudiasl, R. Kitano, T. Li, and H. Murayama, (2005)
Burgess, Pospelov, and ter Veldhuis,(2001)
Kim, Lee, and Shin,(2007/2008)
Qin, Wang, and Xiong, (2011)
Lopez-Honorez, Schwetz, and Zupan, (2012)
Baek, Ko, Park, and Senaha, (2012)

We heavily used
Espinosa, T. Konstandin, and F. Riva, (2012)

Remove symmetry of extra Scalar Field

$$V = -\frac{1}{2}u_h^2 h^2 + \frac{1}{4}\lambda_h h^4 + \frac{1}{2}u_s^2 s^2 + \frac{1}{4}\lambda_s s^4 + \frac{1}{4}\lambda_{hs} s^2 h^2$$

If you assume *s* = -*s* then *s* is a good dark matter candidate

However, you cannot get 1st order phase transition AND all the relic abundance (Cline et al 2012)

Remove symmetry of extra Scalar Field

$$V = -\frac{1}{2}u_h^2 h^2 + \frac{1}{4}\lambda_h h^4 + \frac{1}{2}u_s^2 s^2 + \frac{1}{4}\lambda_s s^4$$
$$+ \frac{1}{4}\lambda_{hs} s^2 h^2 + \mu_1^3 s + \frac{1}{3}\mu_3 s^3 + \frac{1}{4}\mu_m s h^2$$

These terms arise from not assuming field *s* = -*s*

then assume dark matter is a fermion that couples to s field

$$\mathcal{L}_{DM} = \bar{\psi}(i\partial\!\!\!/ - m)\psi + g_s s \bar{\psi}\psi$$

has global U(1) charge to prevent mixing with SM

The Phenomenology of the Extra Scalar Field

Two mass eigenstates:-

$$h_1 = \sin\alpha\ s + \cos\alpha\ h$$
$$h_2 = \cos\alpha\ s - \sin\alpha\ h$$

Effective branching ratio of $h_1 \to 2h_2,\ \bar{\psi}\psi$ needs to be calculated. Introduce parameter

$$\mu = \cos^2\alpha\left(1 - BR^1_{BSM}\right)\mu_{SM} = a'^2\mu_{SM}$$

Then current constraints are $a' > 0.9$

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and $b'^2 \lesssim 0.1$ for $\lesssim 400\ \mathrm{GeV}$, this latter constraint dropping rapidly as the mass increases

$$\tan\alpha = \frac{x}{1+\sqrt{1+x^2}}$$

$$x = \frac{2m^2_{sh}}{m_h^2 - m_s^2}$$

$$m^2_{sh} = \left.\frac{\partial^2 V}{\partial h \partial s}\right|_{(v,w)}$$

For LHC constraints,
Ellis and You 2013
Falkowski, Riva and Urbano 2013
CMS 1304.0213

Electroweak Phase Transition with h and s

Fairbairn and Hogan 2013

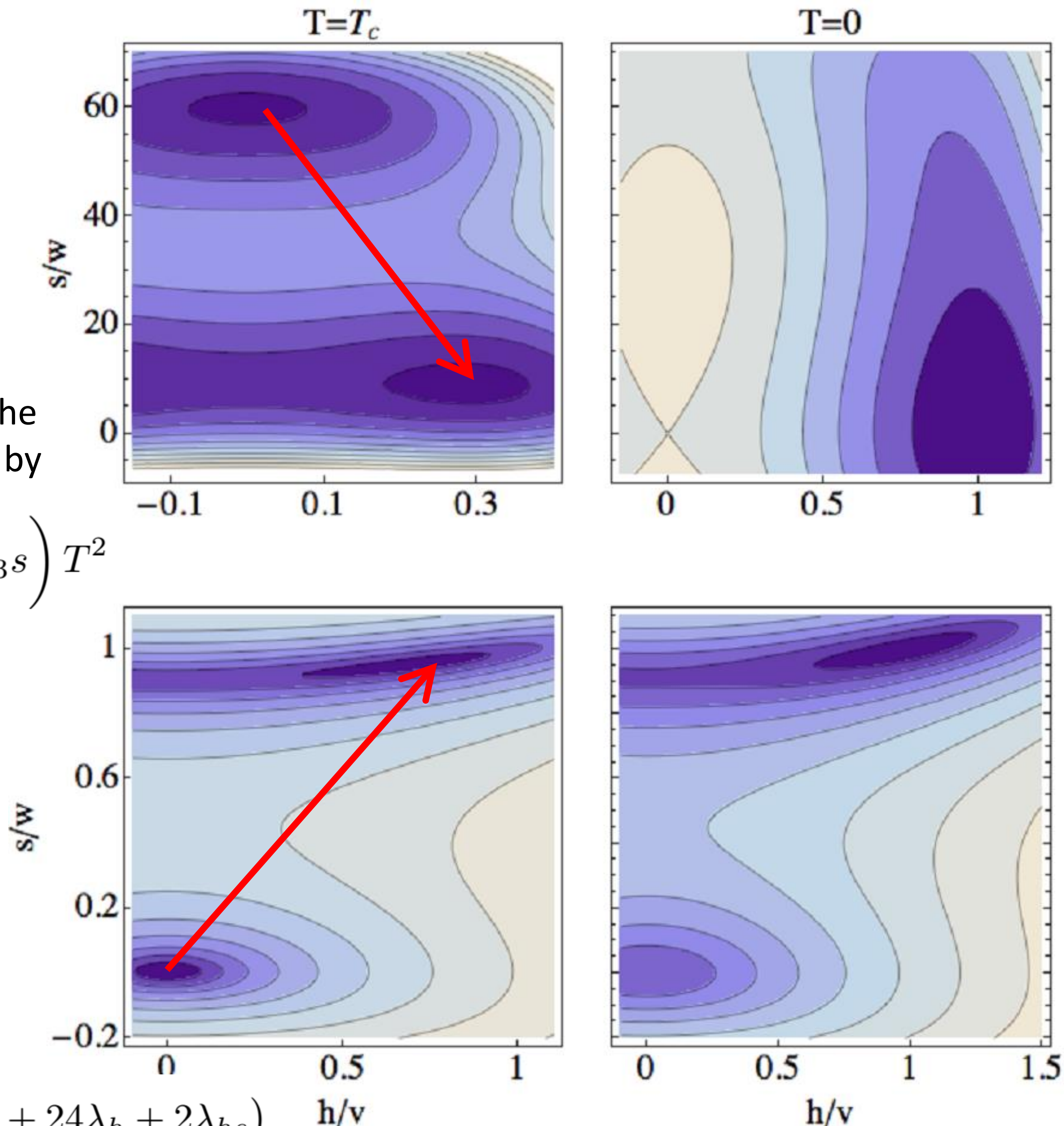
The thermal correction to the tree level potential is given by

$$V_T = \left(\frac{1}{2}c_h h^2 + \frac{1}{2}c_s s^2 + m_3 s\right) T^2$$

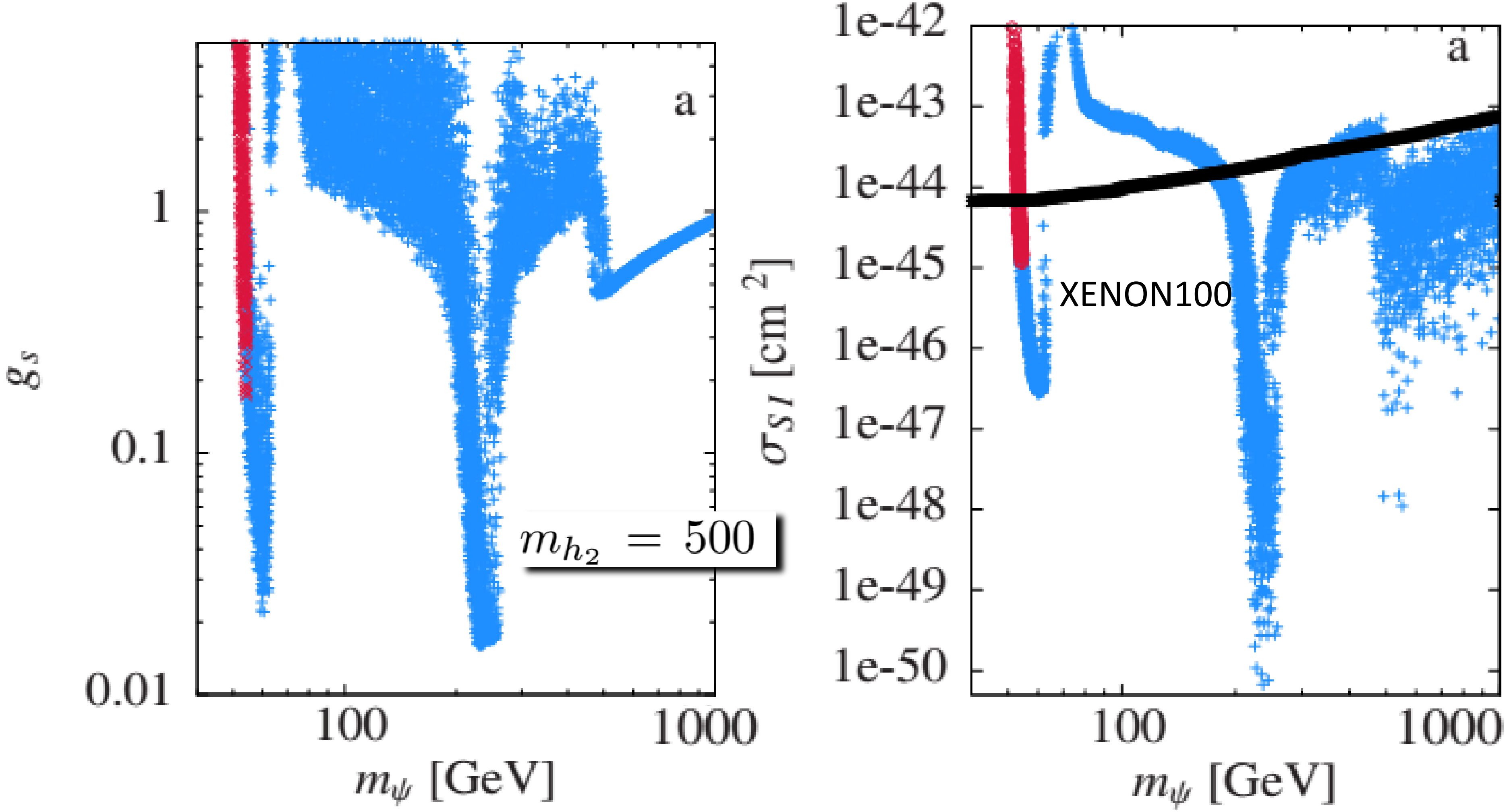
$$c_s = \frac{1}{12}\left(2\lambda_{hs} + 3\lambda_s + g_s^2\right)$$

$$m_3 = \frac{1}{12}\left(\mu_3 + \mu_m\right).$$

$$c_h = \frac{1}{48}\left(9g^2 + 3g'^2 + 12y_t^2 + 24\lambda_h + 2\lambda_{hs}\right)$$

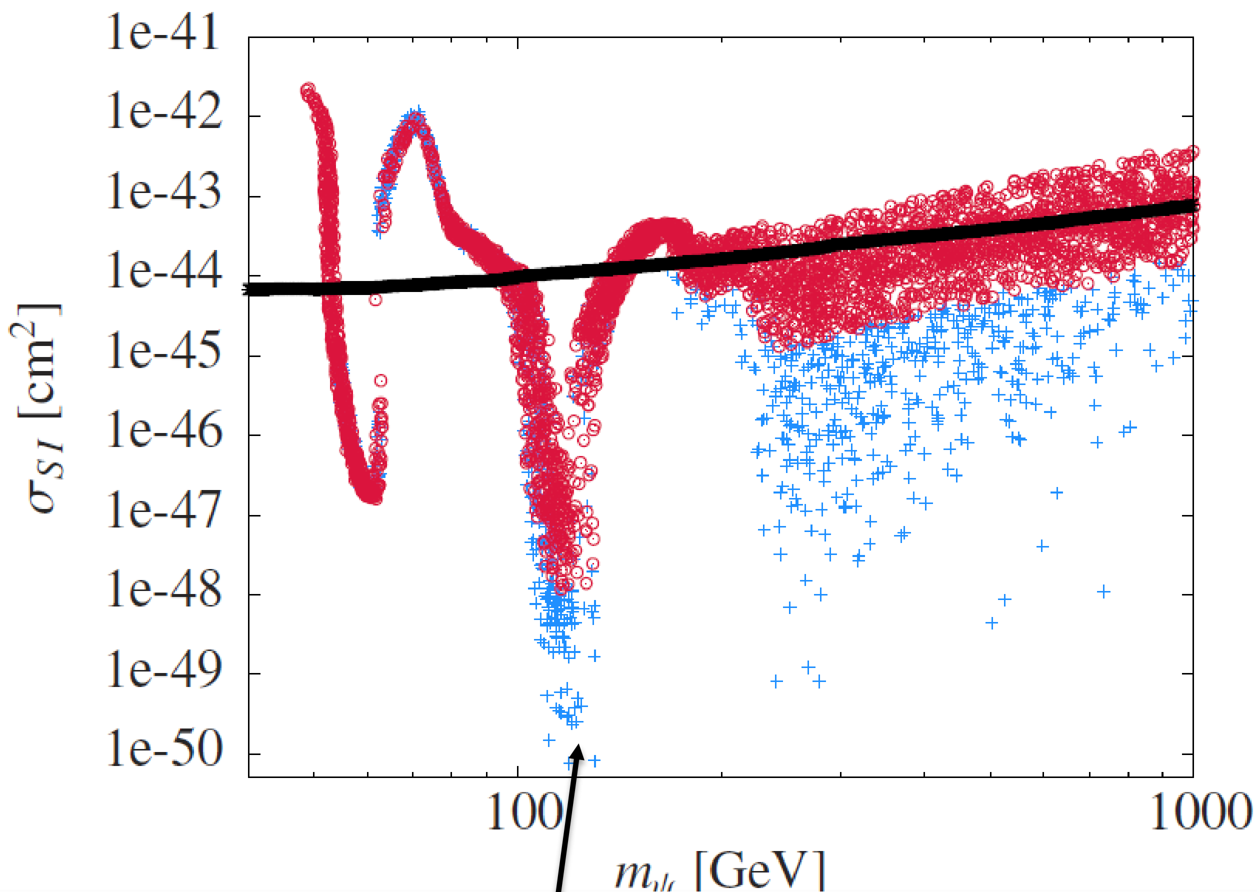


PROBLEM:- When $M_{DM} = M_{Mediator}$ relic abundance couplings and σ_{direct} drop



Higgs Portal model with additional scalar field coupled to dirac Fermion (Fairbairn and Hogan **1305.3452**)

Improvement in LHC exclusion if we move from 10% to 1% in branching ratio accuracy in next runs



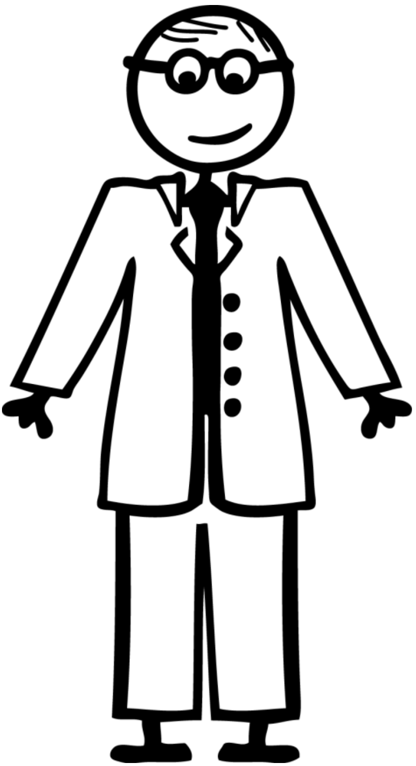
This is a generic problem in simple models, other mechanisms like cancellations and mixings can create the same problems in more complicated theories. Many potential effects in a theory such as pMSSM.

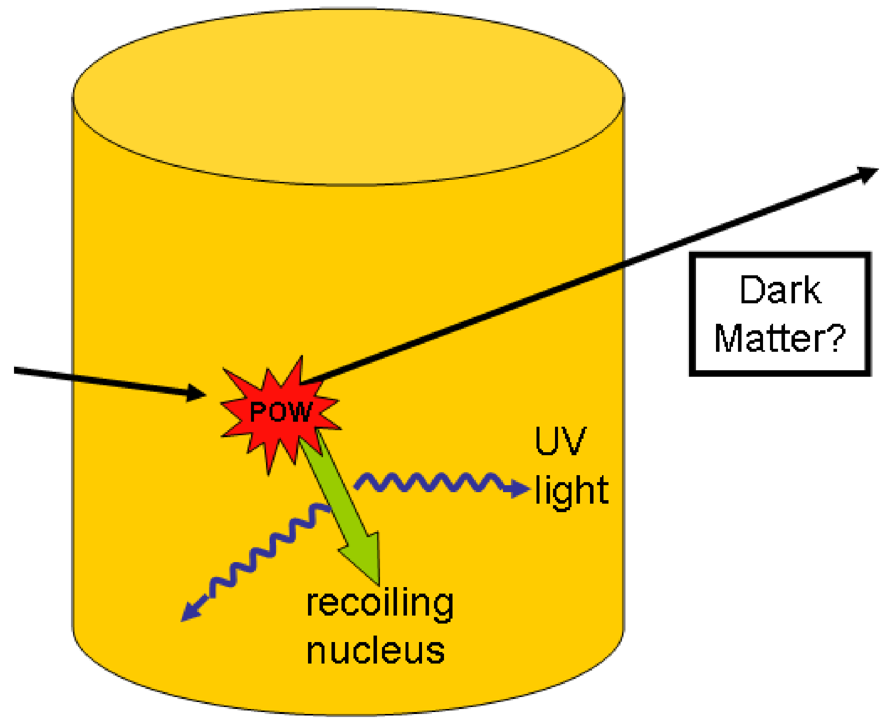
What does this tell us?

Despite our best efforts, some models will remain immune to many upcoming LHC and indirect detection search strategies.

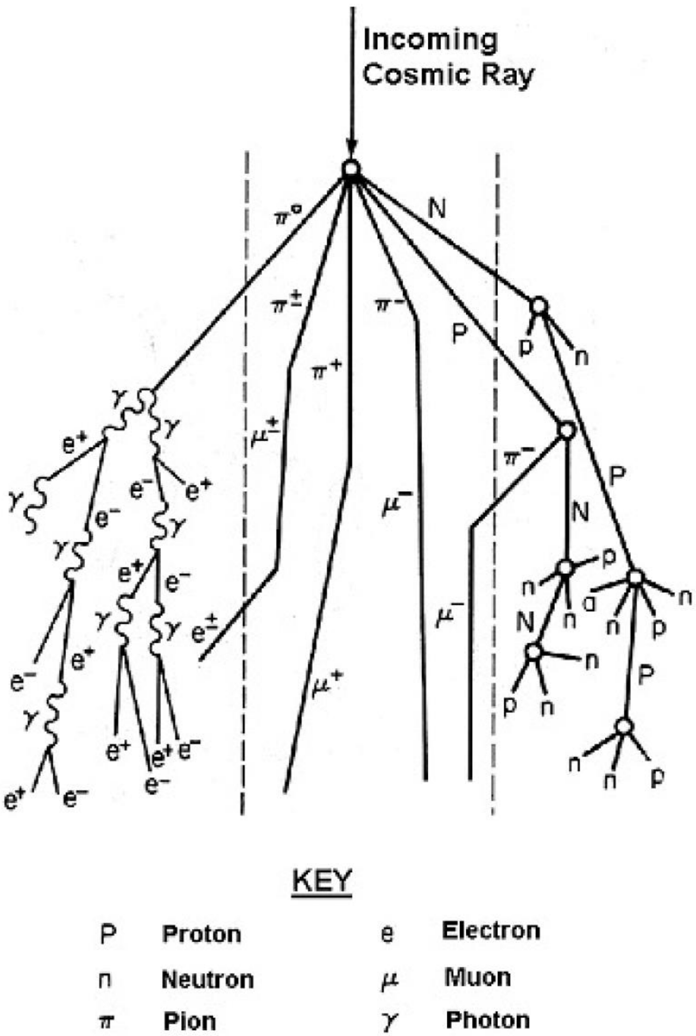
Direct detection is powerful for thermal relics but also cannot get all of them, even new upcoming state of the art detectors.

Surely just a problem of scale?

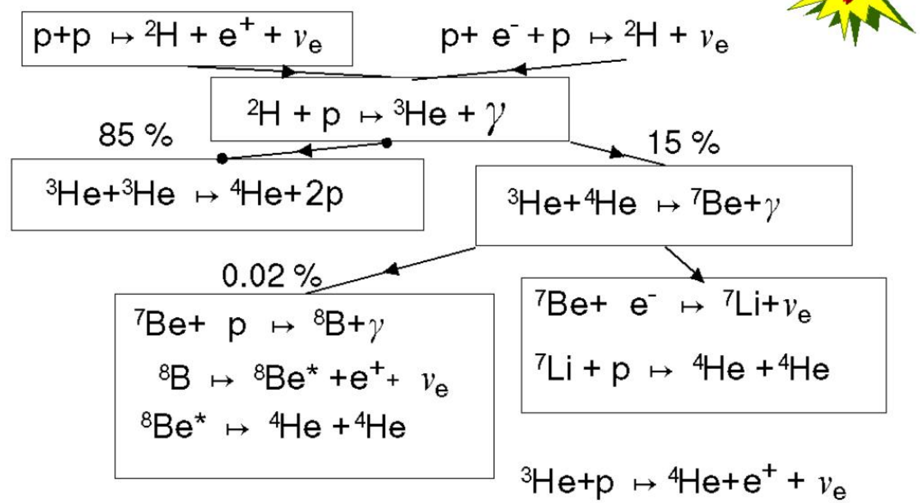


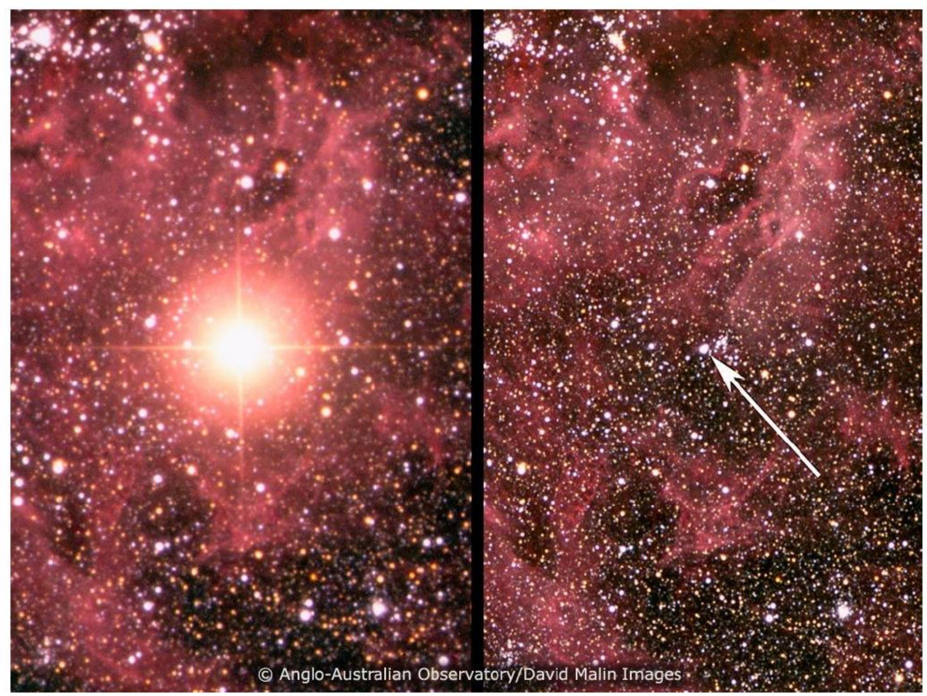


Astrophysical Neutrino Sources

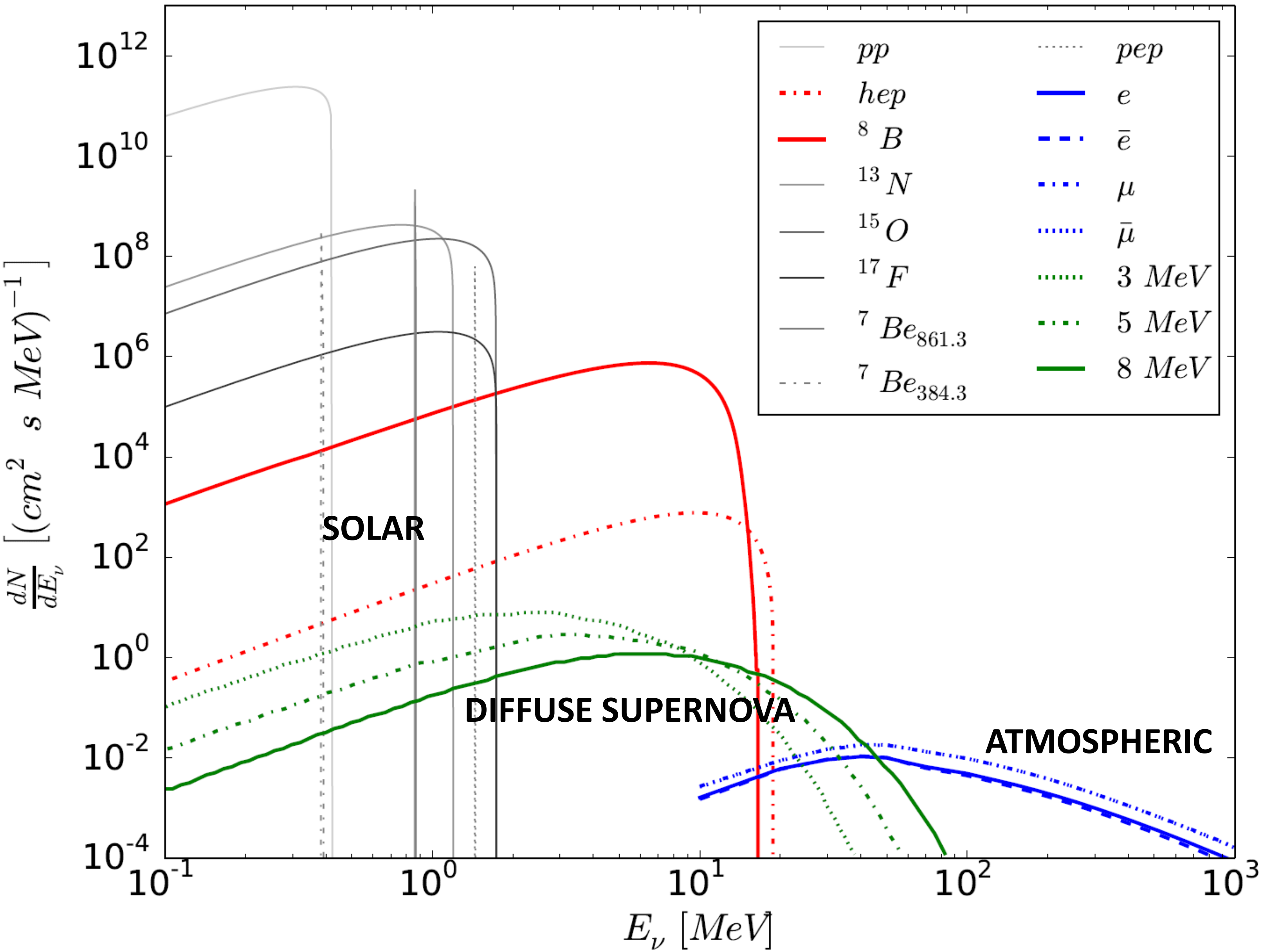


The nuclear reactions in the Sun generate a numerous amount of electron neutrinos. While the total number of neutrinos can be calculated very accurately, their energy spectrum contains more uncertainties. The following picture shows the principal energy producing reaction chains:





Neutrino Background



Coherent Neutrino-Nucleon Flux

$$\frac{d\sigma}{d(\cos\theta)} = \frac{G_F^2}{8\pi} Q_W^2 E_\nu^2 (1+\cos\theta) F(Q^2)^2$$

- Enhanced by factor N^2:

$$Q_W = N - (1 - 4\sin^2\theta_W)Z \approx N - 0.08 \times Z \approx N$$

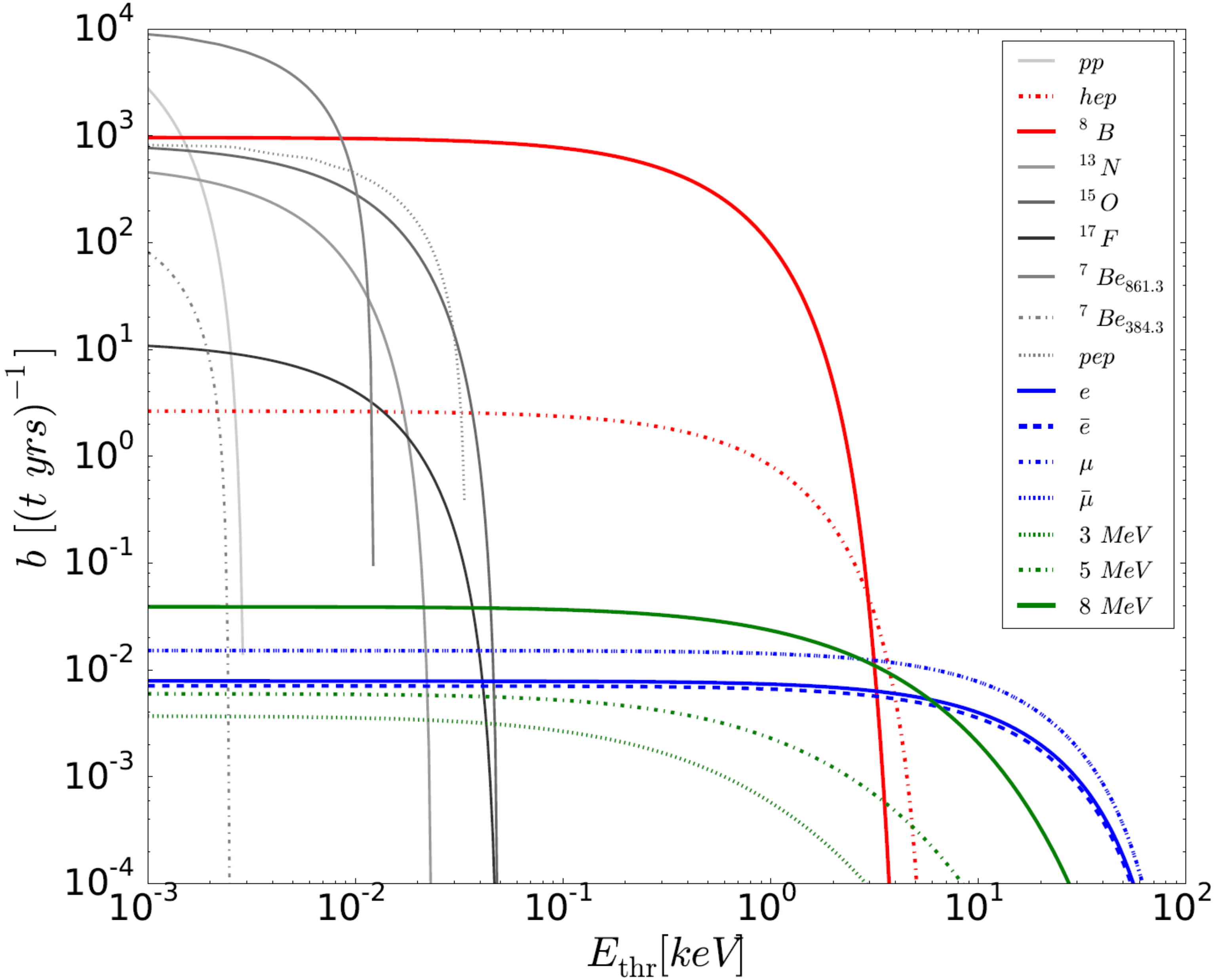
- $\cos\theta$: angle between in- and outgoing neutrino direction
- $2m_T E_r = q^2 = 2E_\nu^2(1-\cos\theta)$

$$\Rightarrow \frac{d\sigma}{dE_\mathrm{r}} = \frac{G_F^2}{4\pi} Q_W^2 m_T \left(1 - \frac{m_T E_\mathrm{r}}{2E_\nu^2}\right) F(Q^2)^2.$$

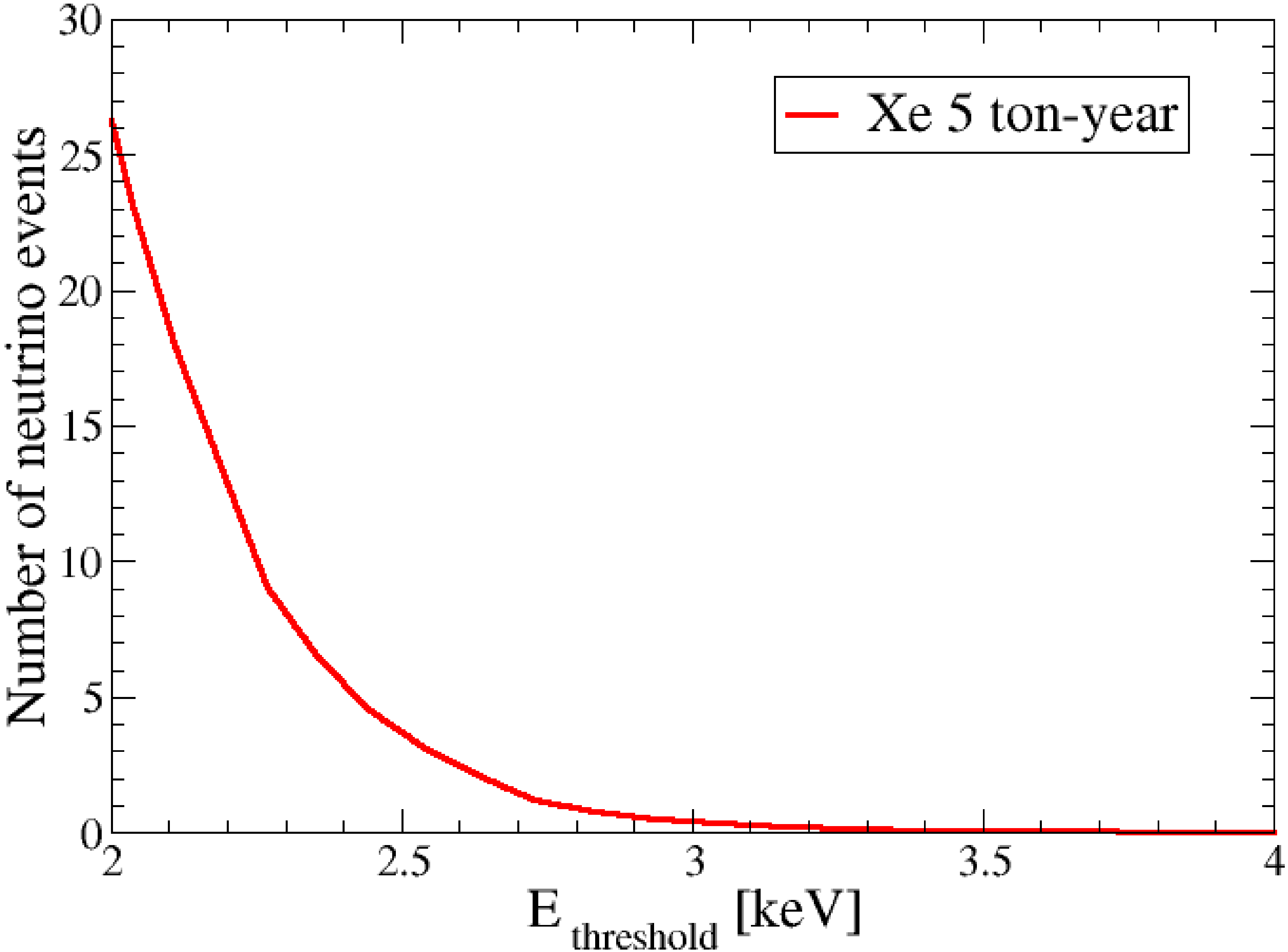
$$\frac{dR_\nu}{dE_r} = n_T \int_{t_0}^{t_1} \int_{E_\nu^\mathrm{min}}^{\infty} \frac{dN(t)}{dE_\nu} \frac{d\sigma(E_\nu, E_\mathrm{r})}{dE_\mathrm{r}} dE_\nu \, dt$$

$$R_\nu = \int_{E_\mathrm{thr}}^{E_\mathrm{up}} \frac{dR_\nu}{dE_r} dE_r$$

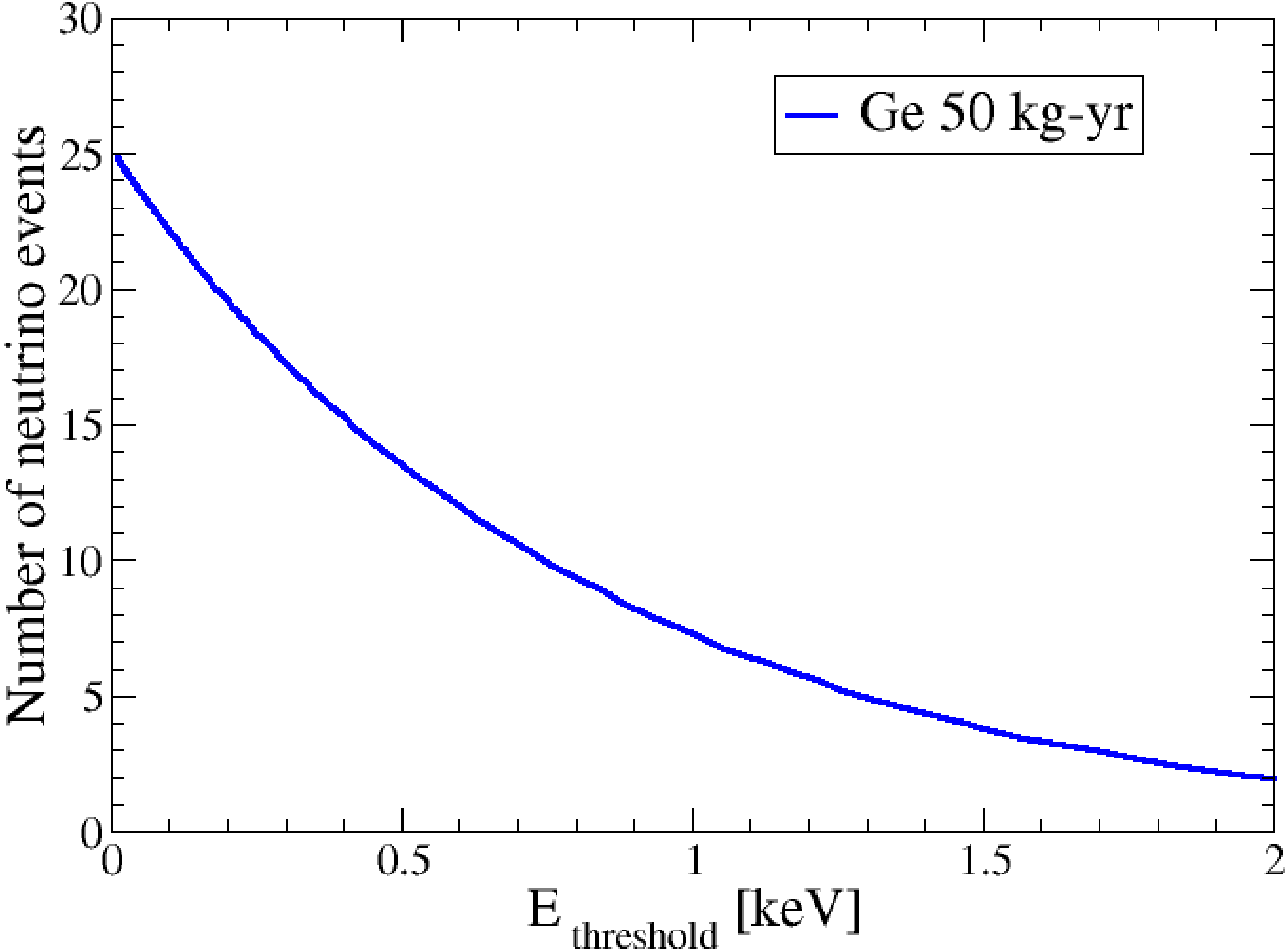
Integrated Event Rate in CF_4 detector above different Thresholds



Integrated Event Rate in Xe detector above different Thresholds

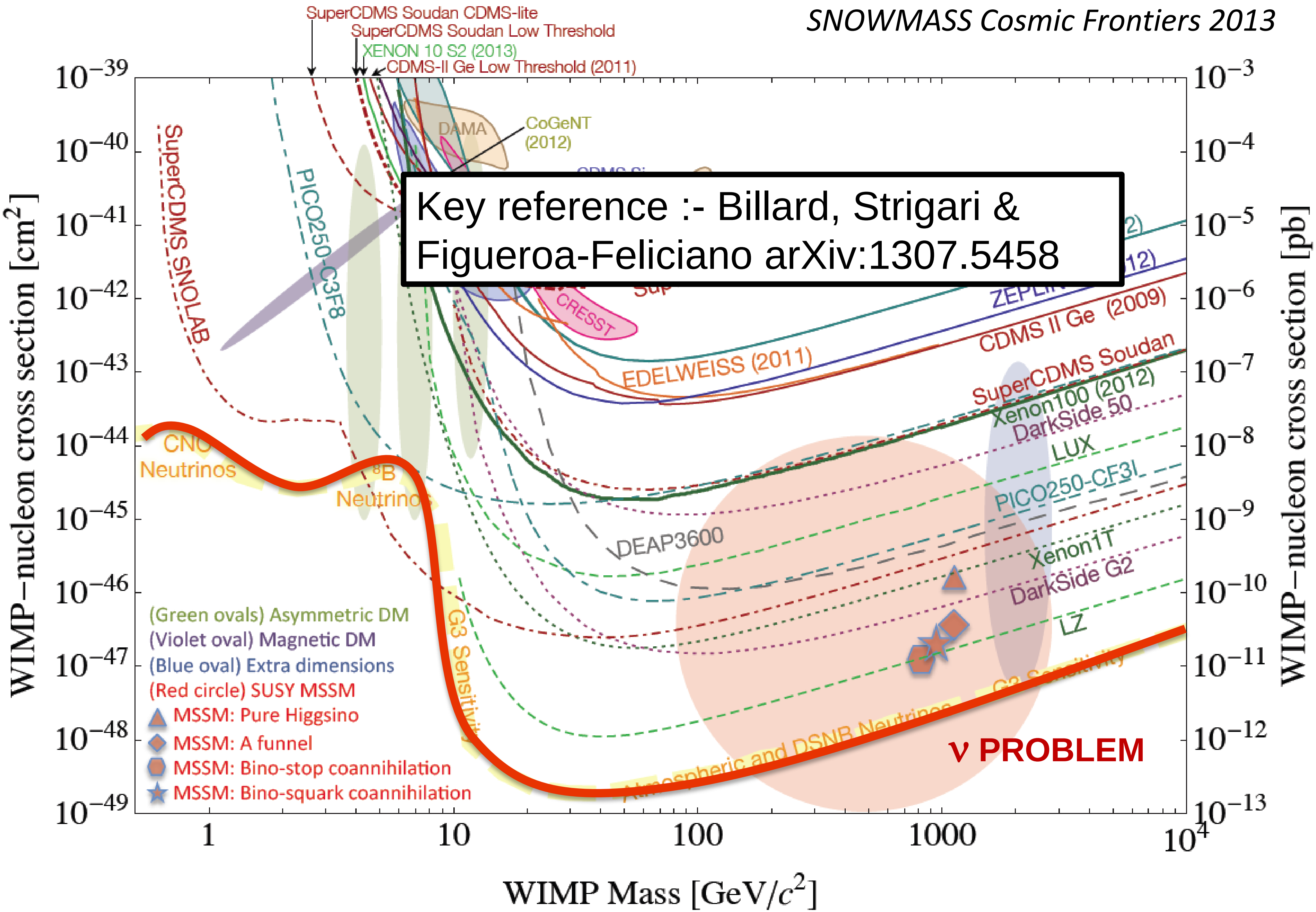


Integrated Event Rate in Ge detector above different Thresholds (just B8 and hep, good approx…)



This leads to this plot which is becoming famous.

SNOWMASS Cosmic Frontiers 2013



Key reference :- Billard, Strigari & Figueroa-Feliciano arXiv:1307.5458

Directional Dark Matter Detection Beyond the Neutrino Bound

Philipp Grothaus* and Malcolm Fairbairn
Department of Physics, Kings College London

Jocelyn Monroe
Department of Physics, Royal Holloway University of London
(Dated: June 20, 2014)

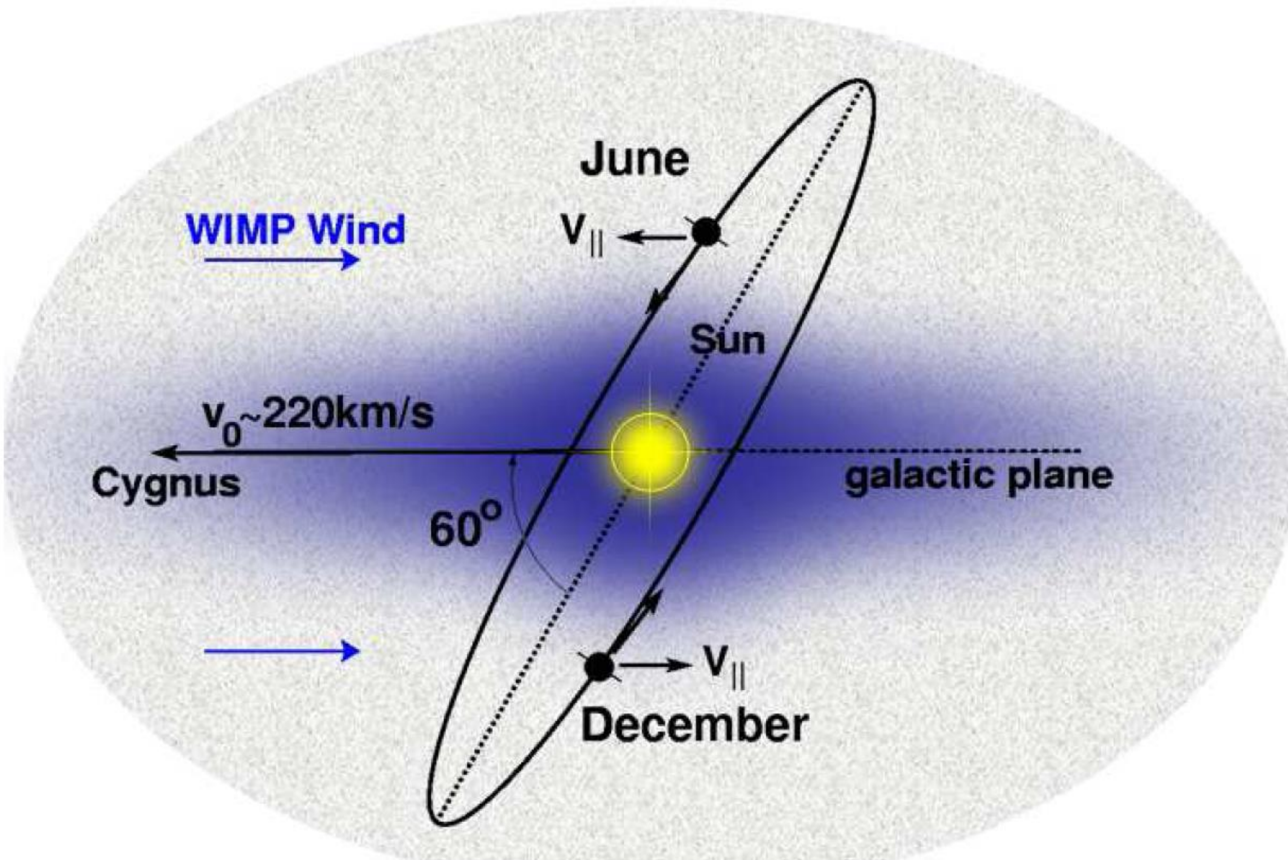
Here was our first attempt to look at the problem.
arXiv:1406.5047

Motion of Earth relative to sun

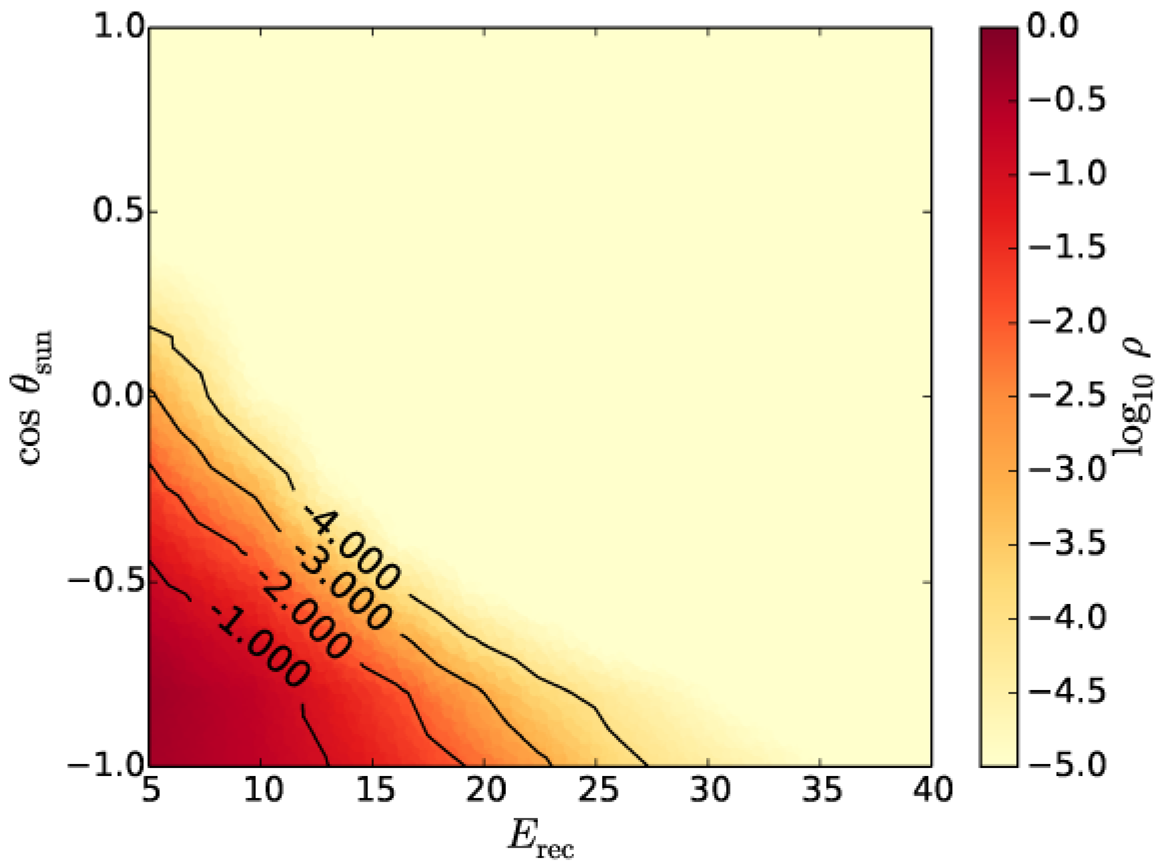
$$f_\oplus(\vec{v},t) = f_{\rm gal}(\vec{v}+\vec{v}_\odot+\vec{v}_\oplus(t))$$

sun velocity: $\vec{v}_\odot = (0,220,0)+(10,13,7)$ km/s

earth velocity: $\vec{v}_\oplus(t)$ with $v_\oplus \approx 30$ km/s

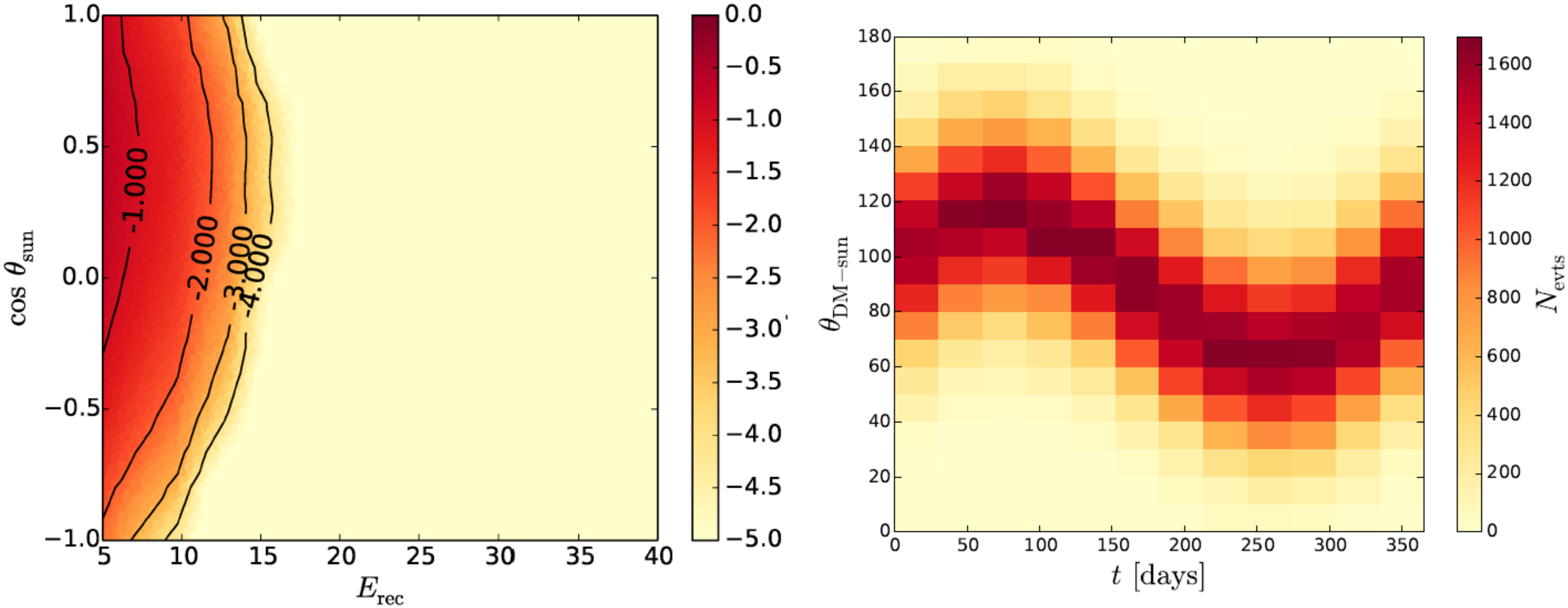


Relative angle between recoil from Solar neutrino and sun



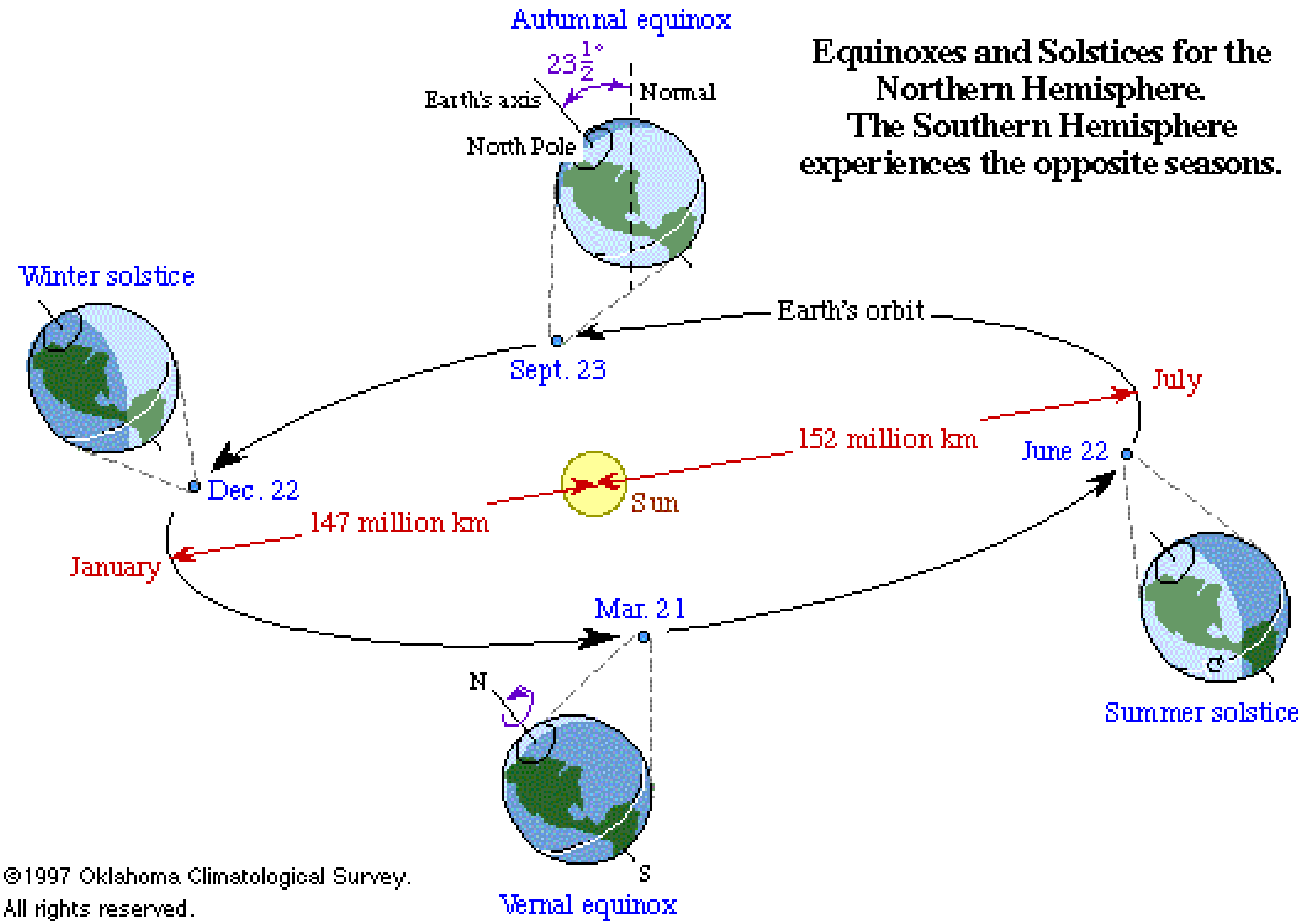
$$\cos\theta' = \frac{E_\nu + m_T}{E_\nu}\sqrt{\frac{E_{\rm r}}{2m_T}}$$

Relative angle between recoil from Dark Matter and sun



- Preferred arrival direction roughly from Cygnus A
- This changes during the year
- Lighter (heavier) dark matter more (less) directional above a given threshold

Also, distance between Earth and Sun changes throughout Year modulates neutrino flux



two event distributions in 3D parameter space
(3D = energy, time, scattering angle)

Distributions:- A) neutrino
B) neutrino + dark matter

can we separate background from signal plus background?

Statistics

$$\tilde{Q} = \frac{\frac{e^{-(s+b)}(s+b)^n}{n!}}{\frac{e^{-b}b^n}{n!}} \frac{\prod_{j=1}^{n} \frac{sS_t(t_j)+bB_t(t_j)}{s+b} \frac{sS_{\theta,E}(\theta_j,E_j)+bB_{\theta,E}(\theta_j,E_j)}{s+b}}{\prod_{j=1}^{n} B_t(t_j)\ B_{\theta,E}(\theta_j,E_j)}$$

$$Q = -2\log\tilde{Q}$$

1. Calculate expected number of ν events then generate n_1 events using Poisson
2. Choose dark matter mass and cross section and generate n_2 dark matter events
3. Generate Q_B for n1 ν events and Q_{SB} for n_1+n_2 ν+DM events, then

$$\beta_{SB} = \int_{-\infty}^{q} P_{Q_{SB}}(Q_{SB})\ dQ_{SB}$$

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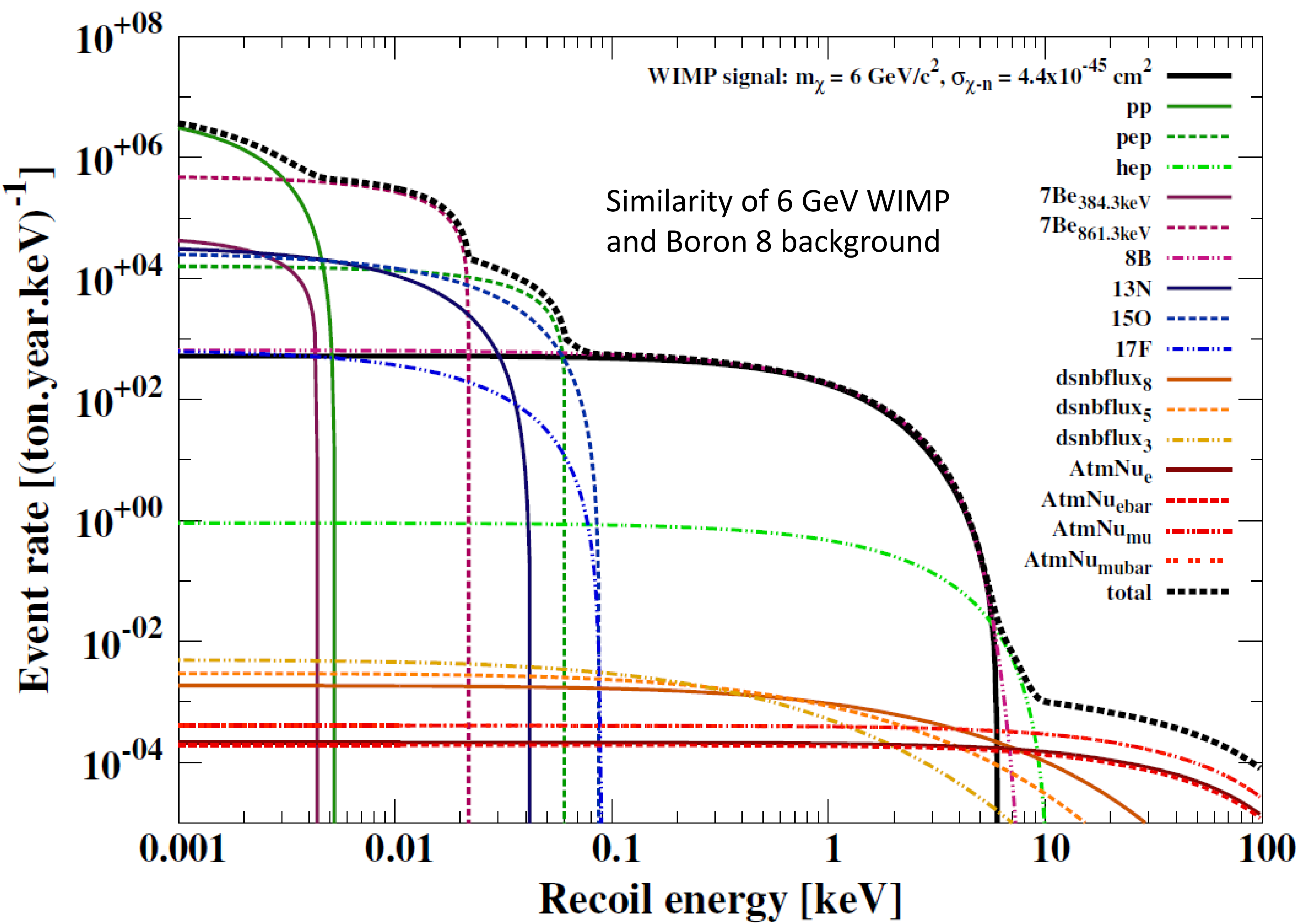
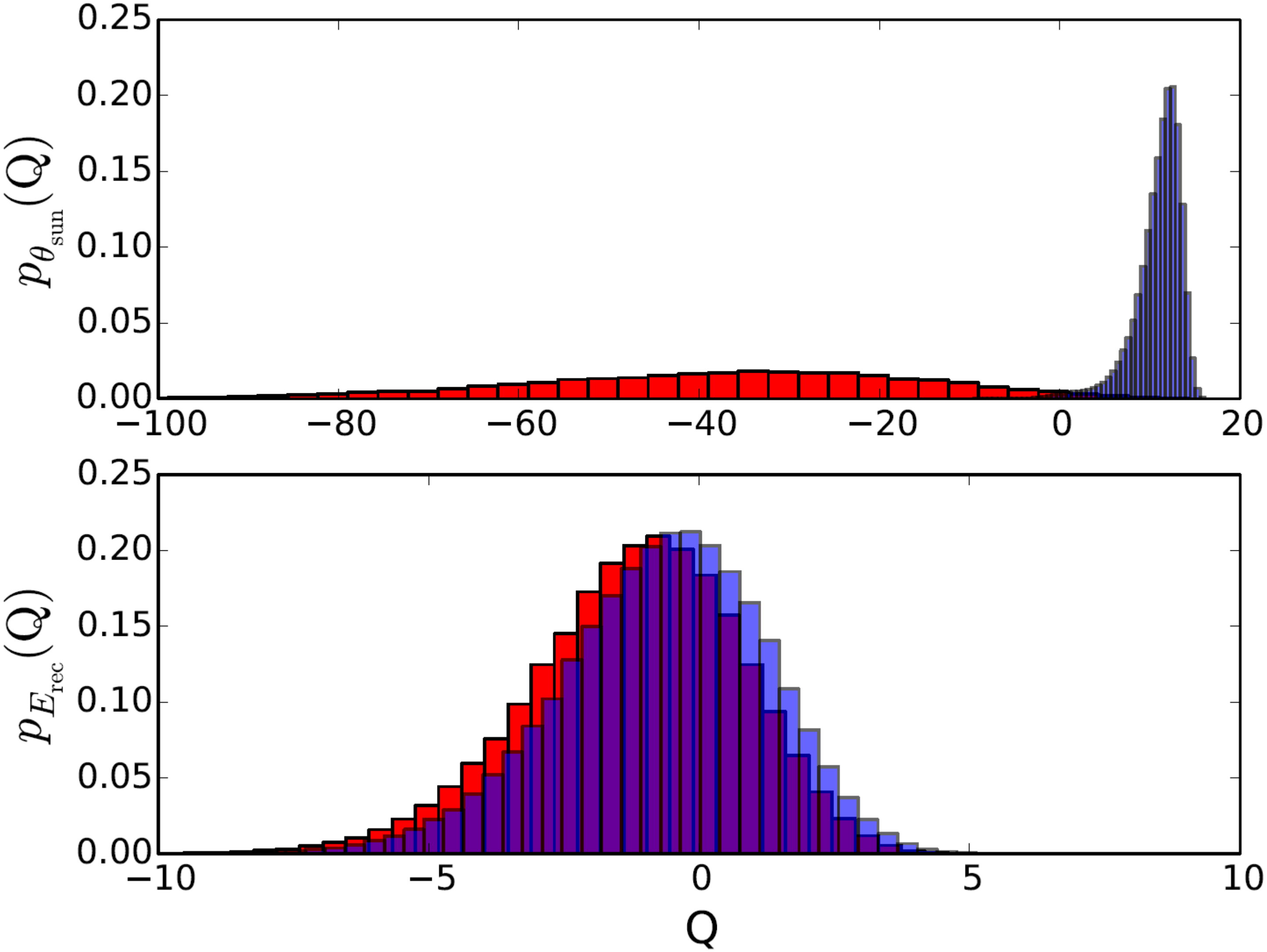
4. Choose integral limit *q* such that $1 - \beta_{SB} = \beta_B = \alpha$

where α is your desired exclusion probability.



Similarity of 6 GeV WIMP and Boron 8 background

Ruppin et al 1408.3581

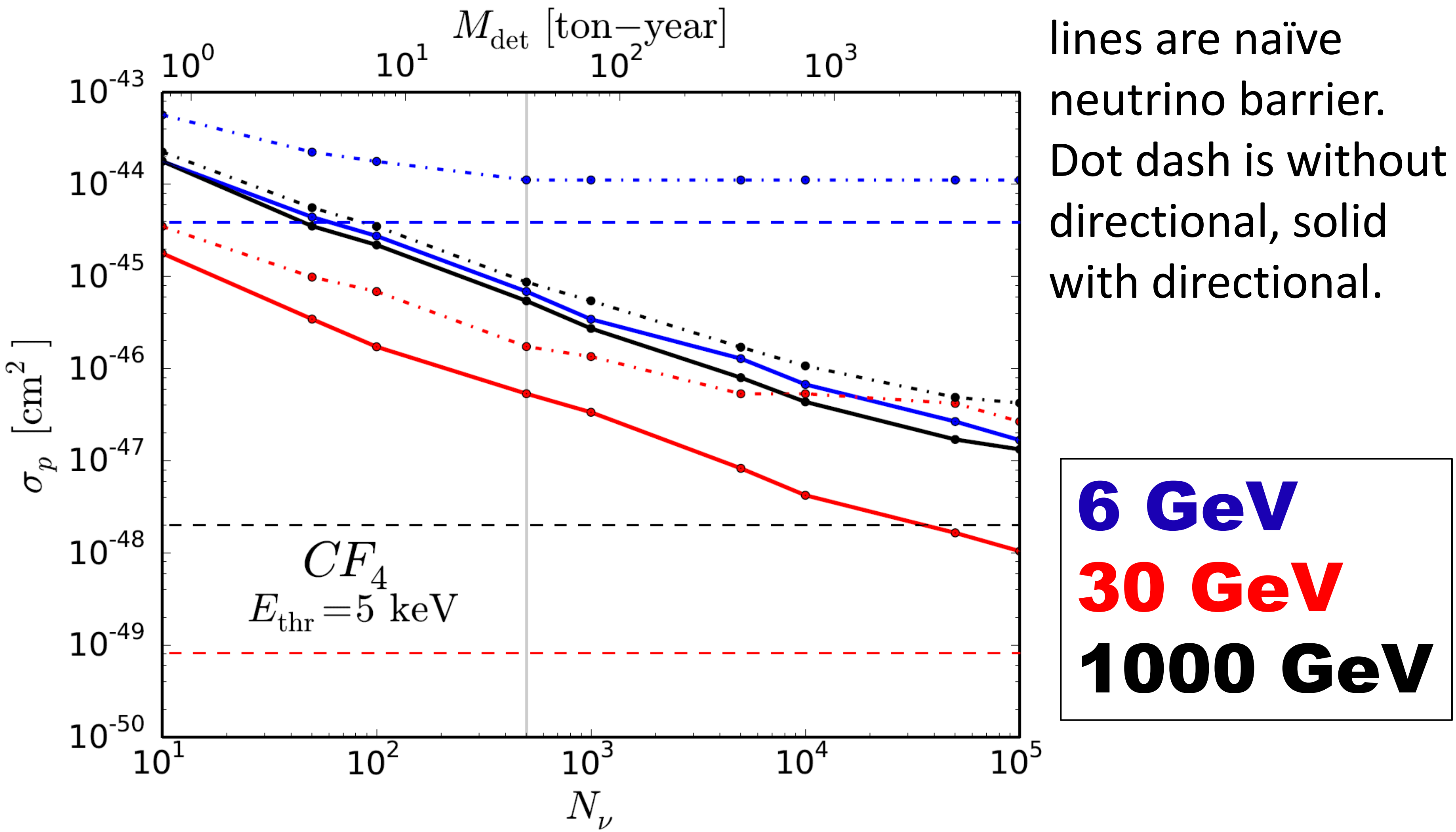


The normalised background only distribution $p_B(Q_B)$ (blue) and signal plus background distribution $p_{SB}(Q_{SB})$ (red) including angular information (top) and excluding angular information (bottom) for s=10 and b=500 for a 6 GeV dark matter particle in a CF_4 detector.

Various Effects, some of which compete with each other:-

- For Low mass DM, only fastest moving particles will give a signal, so that points right back to Cygnus, easy to discriminate from the Sun
- High mass DM can give a signal for DM coming from all directions so directionality less important, but it has an energy spectrum quite different from solar neutrinos
- Higher energy recoil tracks have a much better directional angle reconstruction

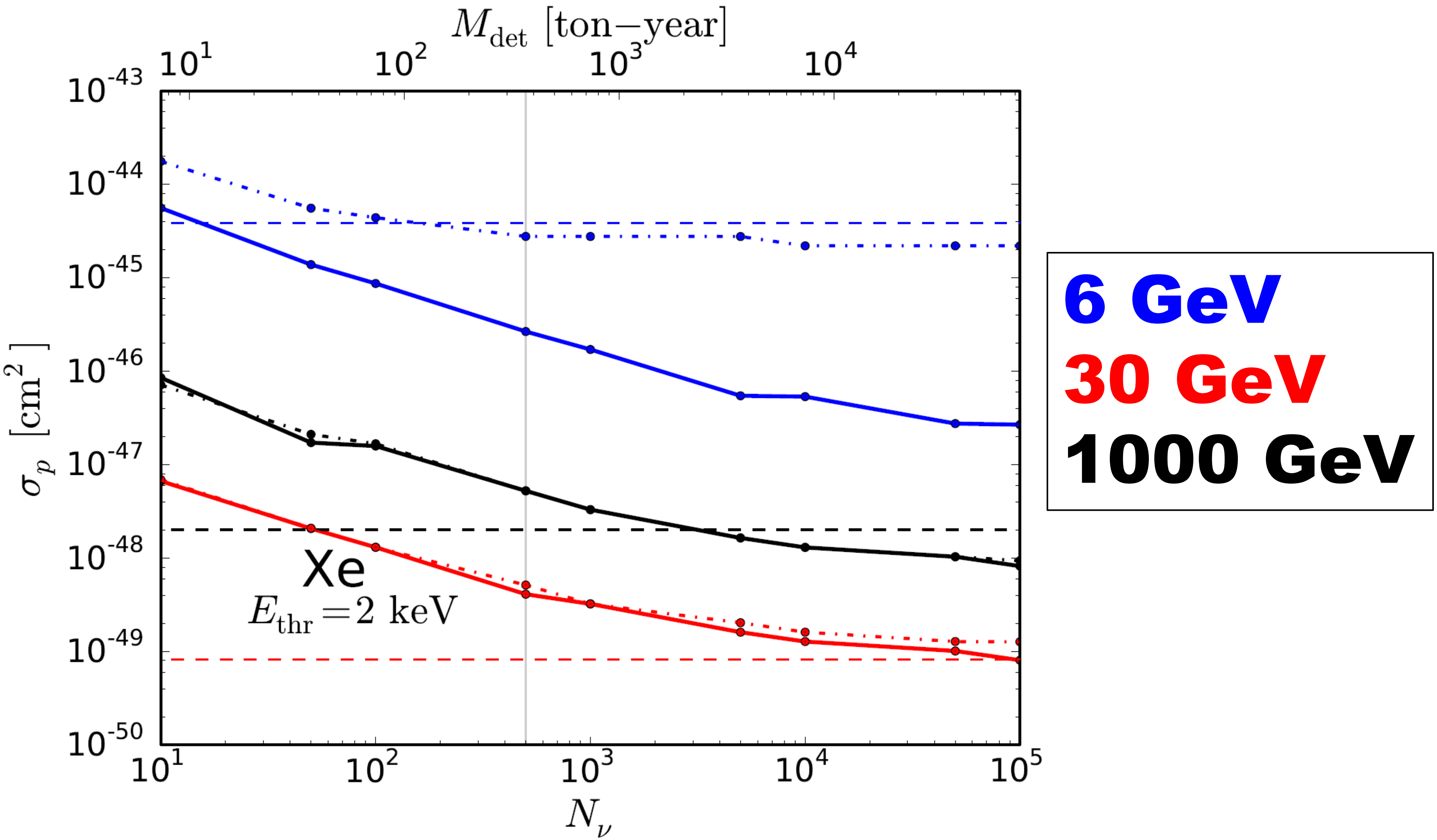
How far can we push things?



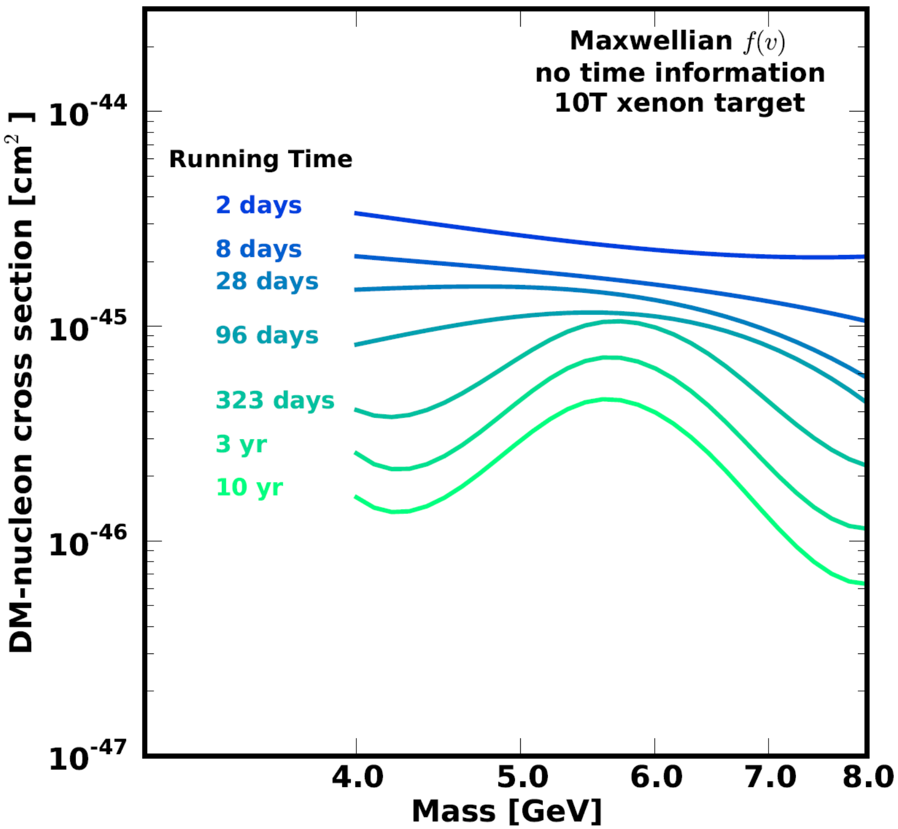
Horizontal Dashed lines are naïve neutrino barrier. Dot dash is without directional, solid with directional.

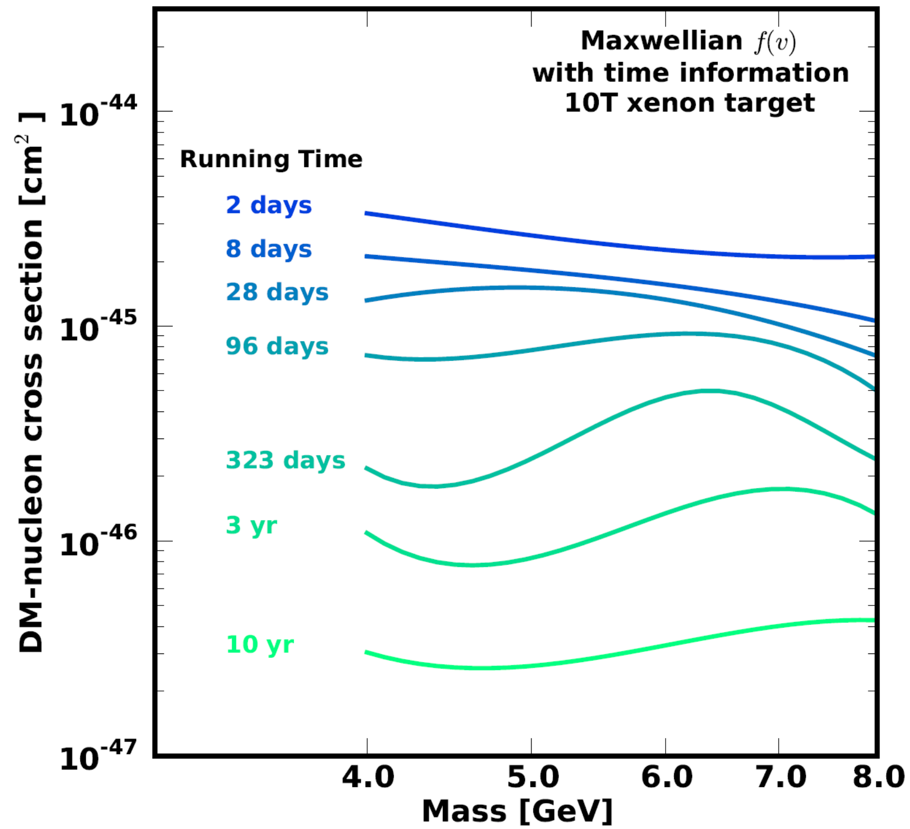
Ultimately, this depends on how well we know the neutrino background

Same thing for imaginary Xenon Directional Detector



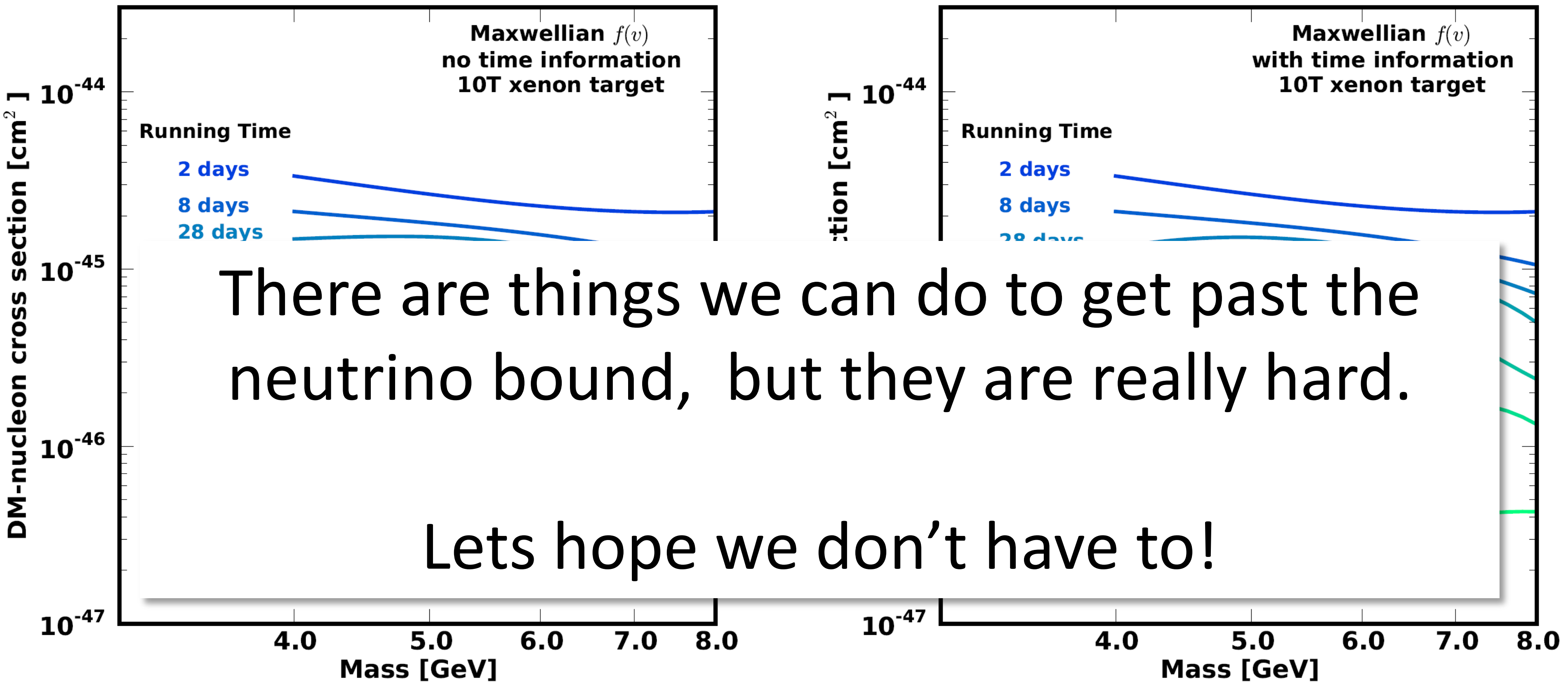
Effect of Time resolution on the 6 GeV case





Davis arXiv:412.1475

Effect of Time resolution on the 6 GeV case

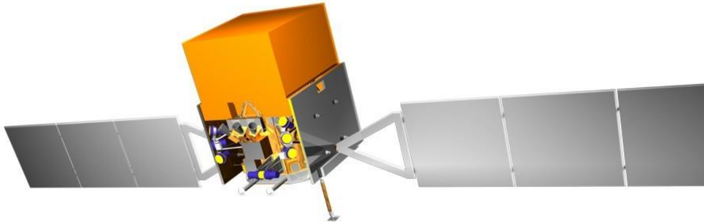


There are things we can do to get past the neutrino bound, but they are really hard.

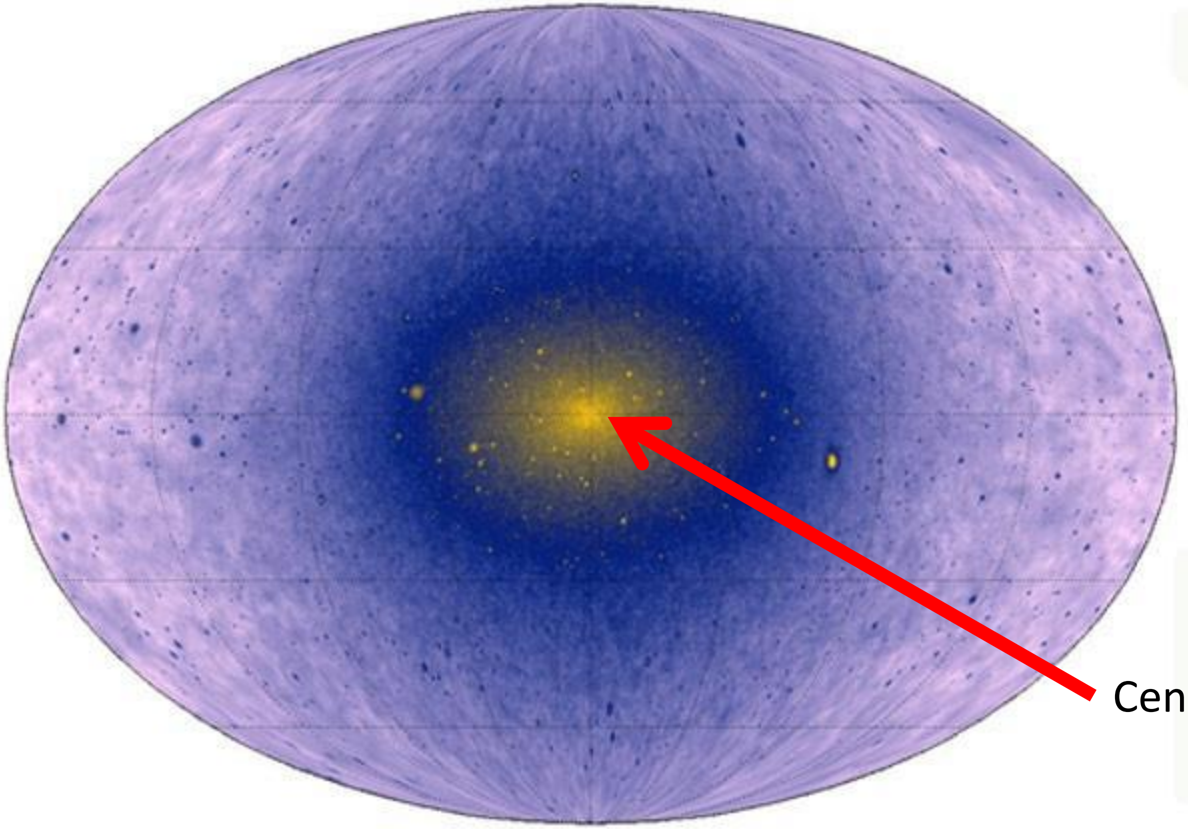
Lets hope we don't have to!

Davis arXiv:412.1475

Can try to detect annihilation of dark matter with itself at Galactic Centre

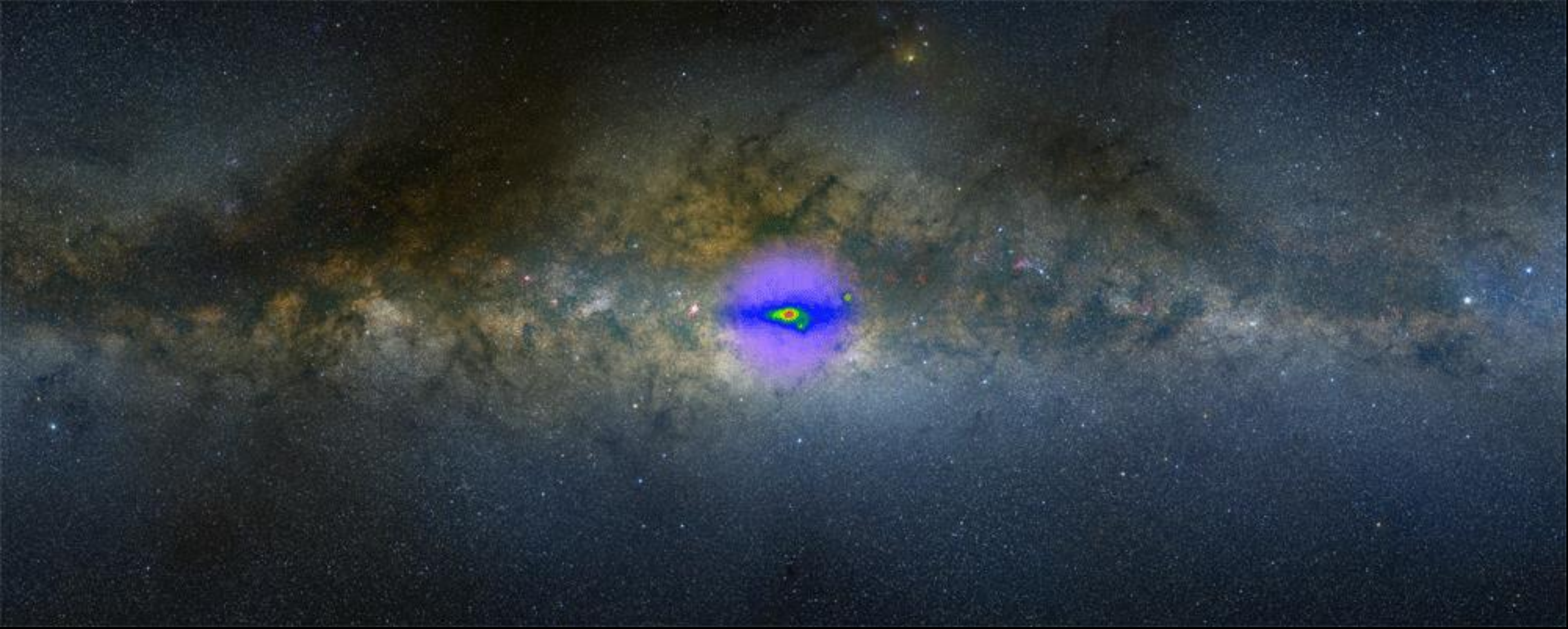


FERMI – gamma ray telescope
Launched!



Centre of the milky way

Simulated map of gamma rays from dark matter annihilation seen by GLAST telescope



- Galactic Centre Excess detected by Fermi Gamma Ray Telescope
- Consistent with 30 GeV DM annihilating into b quarks
- Approximately right density profile, annihilation cross section
- May also be consistent with Millisecond pulsars
- Next Fermi data release may clarify the situation
- May require instrument with better angular resolution (Pangu?)

4 large elliptical Galaxies at the centre of Cluster Abell 4827

Mass appears displaced from galaxy

Could be a signal of dark matter self interaction – dark matter pressure…

Conclusions

Ongoing Searches for dark matter.

No completely convincing evidence so far.

Devices are in place and running / will start in the next years, LHC, LUX, SuperCDMS, Xenon 1T, LZ, Fermi, CTA - critical next period.

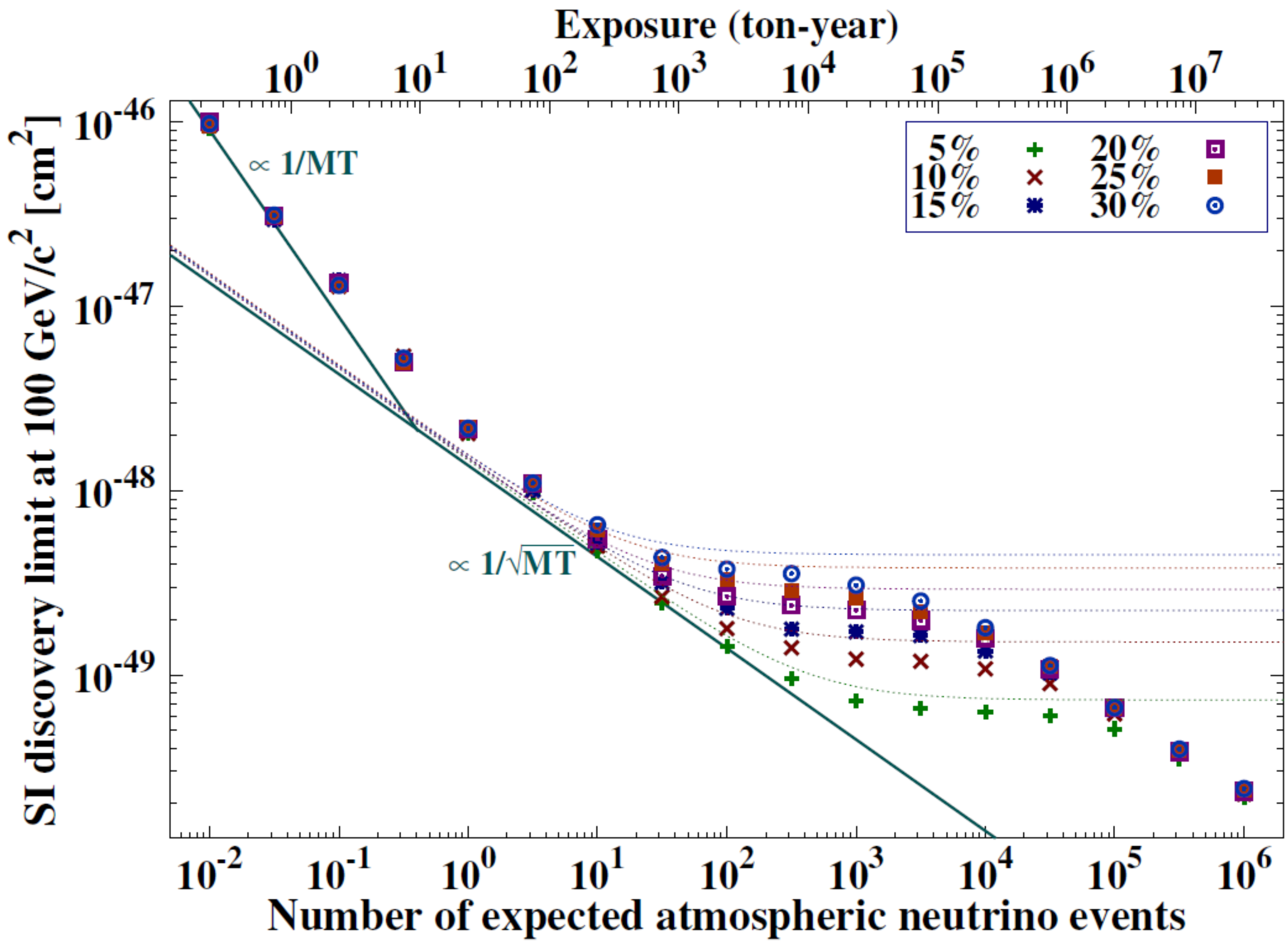
Neutrino bound will shape future of direct detection.

ADDITIONAL MATERIAL

Future Prospects for understanding background

- Solar flux in our range of interest dominated by B-8 and He-p neutrinos – depends sensitively upon iron abundance in core of Sun, abundance problem
- SNO+ will measure B-8 and Be-7 neutrinos which will hopefully tie this down.
- Longer term Hyperkamiokande would detect hundreds of B-8 neutrinos per day and test for time variation!
- Possible upgrade of Superkamiokande with Gadolinium will increase discrimination and should make it capable of detecting the Diffuse supernova and atmospheric neutrinos
- A supernova might go off! Would be very useful. Please lobby your local deity.
- Studies of geomagnetic field, solar wind and nuclear propagation models will all reduce uncertainties in atmospheric neutrinos.

For example, this is the effect of reducing error on Atmospheric neutrino flux



Ruppin et al 1408.3581

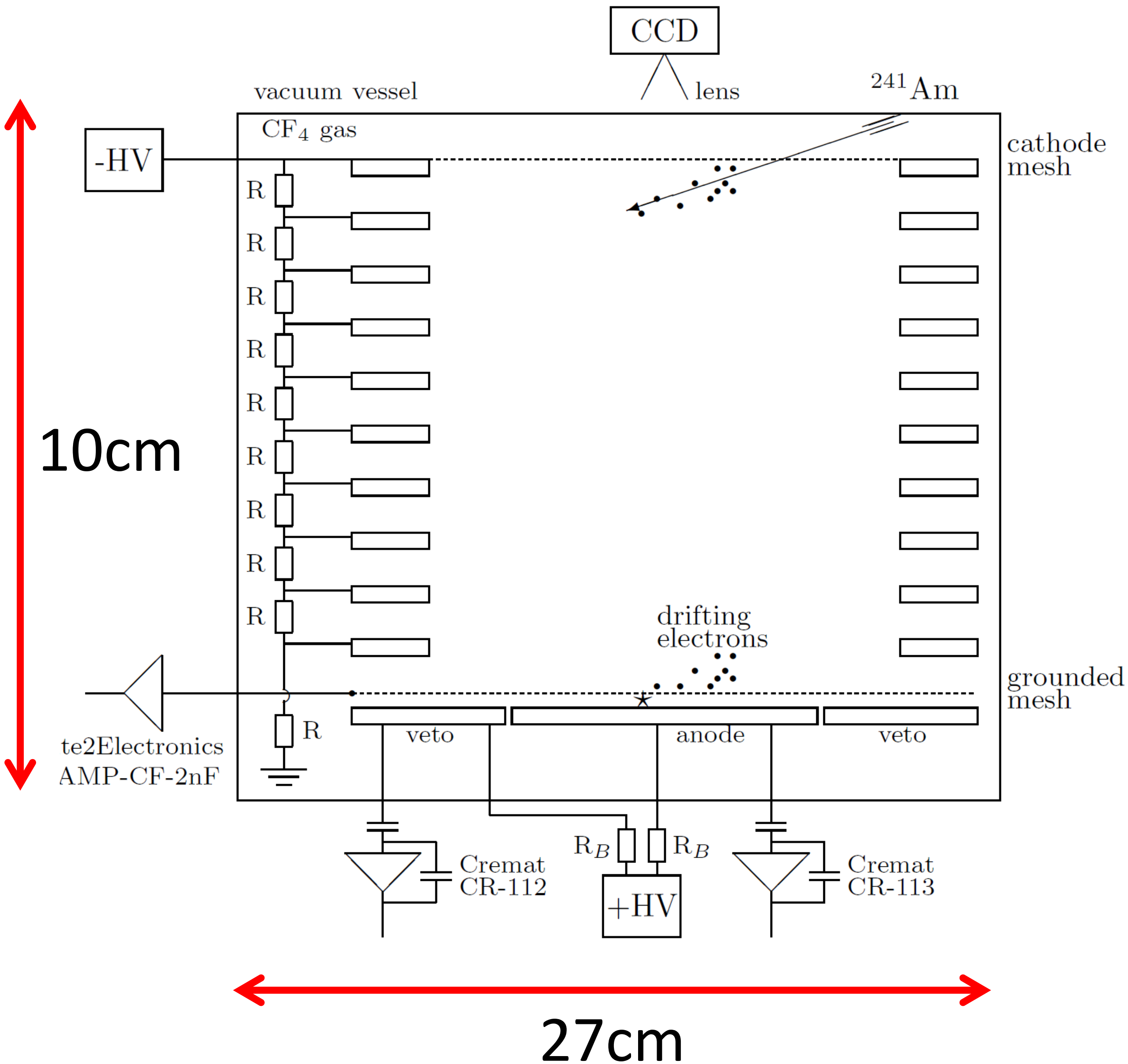
Current Experimental Status of Directional Detection

Essentially still in R & D phase, detectors with directional sensitivity not yet competitive

Small prototypes have demonstrated energy thresh-olds of a few keV

at higher thresholds (50 keV-100keV) have demonstrated angular resolution of 30-55 degrees

Current Experimental Status of Direct Detection



DMTPC experiment
(for example)

50 Torr pressure CF_4

Camera images tracks

Electronics veto electrons

See e.g. arXiv:1301.5685

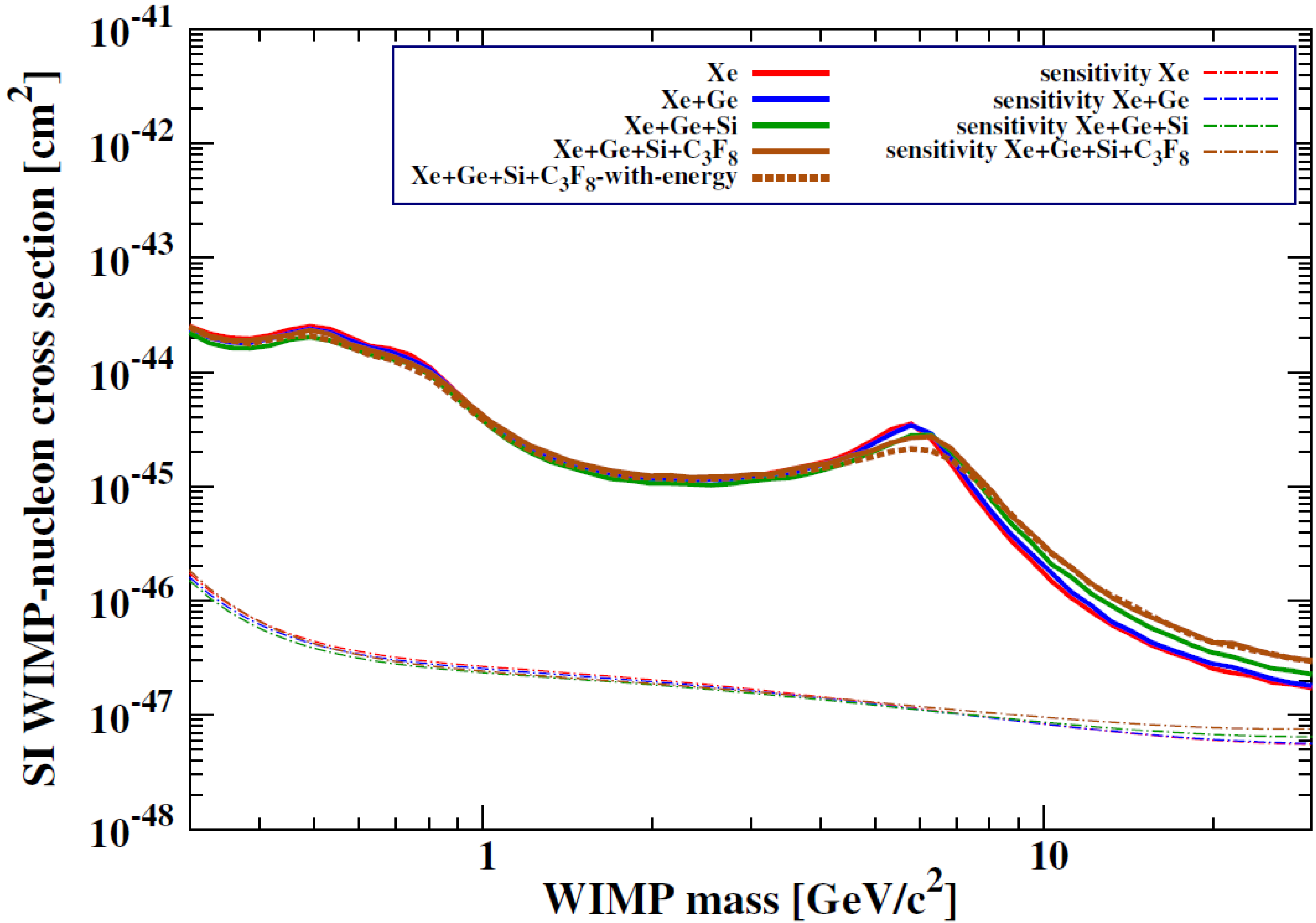
TINY experiment,
Only a few grams for now!

Simplified Model Lagrangian – Dijet analysis

1. Choose mass close to resonance and some couplings
2. Obtain relic abundance (using full expression not velocity expansion)
3. Test for relic abundance, see if its within Planck errors (if not goto 1)
4. Use Madgraph and Pythia to generate events with at least 2 jets with $p_T > 30$ GeV and $|\eta| < 2.5$
5. Use Fastjet to form outgoing jets using trigger parameters from CMS analysis $m_{jj} > 890$ GeV and $|\eta_{jj}| < 1.3$
6. Look for constraints based upon 300 fb^{-1} at 14 TeV assuming similar signal to background ratio to run 1

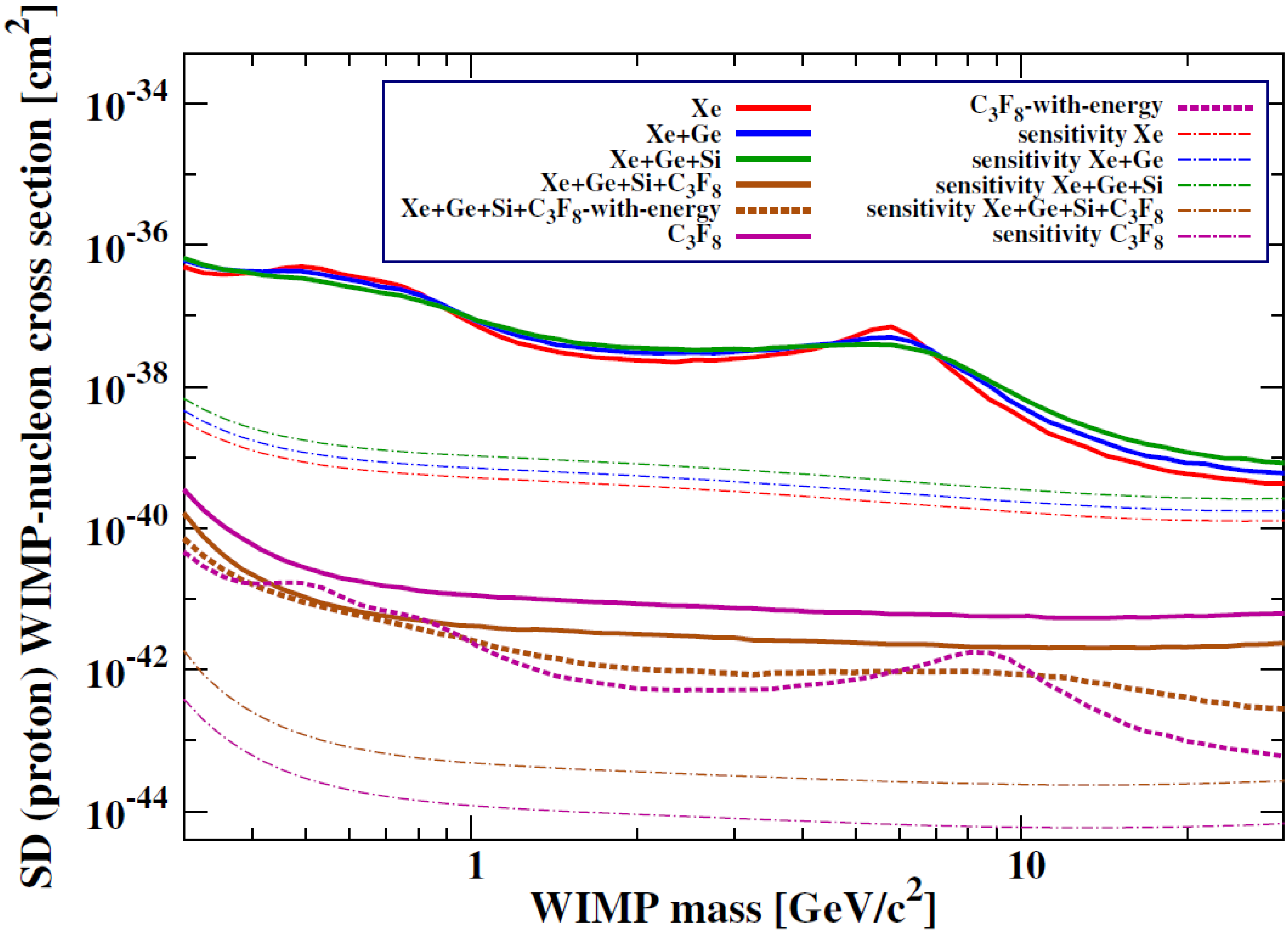
We respect $\Gamma_{A'} < 0.15\ m_{A'}$ to allow events to be studied in context of CMS narrow dijet search :- CMS-PAS-EXO-12-059

Combining different targets not particularly effective for Spin Independent Searches…



Ruppin et al 1408.3581

…but more interesting for Spin Dependent Searches



Ruppin et al 1408.3581

The Phenomenology of the Extra Scalar Field

Two mass eigenstates:-

$$h_1 = \sin\alpha\ s + \cos\alpha\ h$$
$$h_2 = \cos\alpha\ s - \sin\alpha\ h$$

Effective branching ratio of $h_1 \to 2h_2,\ \bar{\psi}\psi$ needs to be calculated. Introduce parameter

$$\mu = \cos^2\alpha\left(1 - BR^1_{BSM}\right)\mu_{SM} = a'^2\mu_{SM}$$

Then current constraints are $a' > 0.9$

Likewise can look at coupling of h_2 to the standard model. Signal strength is

$$\mu = \sin^2\alpha(1 - BR^2_{BSM})\mu_{SM} = b'^2\mu_{SM}$$

and $b'^2 \lesssim 0.1$ for $\lesssim 400\ \mathrm{GeV}$, this latter constraint dropping rapidly as the mass increases

$$\tan\alpha = \frac{x}{1+\sqrt{1+x^2}}$$

$$x = \frac{2m^2_{sh}}{m^2_h - m^2_s}$$

$$m^2_{sh} = \left.\frac{\partial^2 V}{\partial h \partial s}\right|_{(v,w)}$$

For LHC constraints,
Ellis and You 2013
Falkowski, Riva and Urbano 2013
CMS 1304.0213

Statistics

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$$Q = -2\log\tilde{Q}$$

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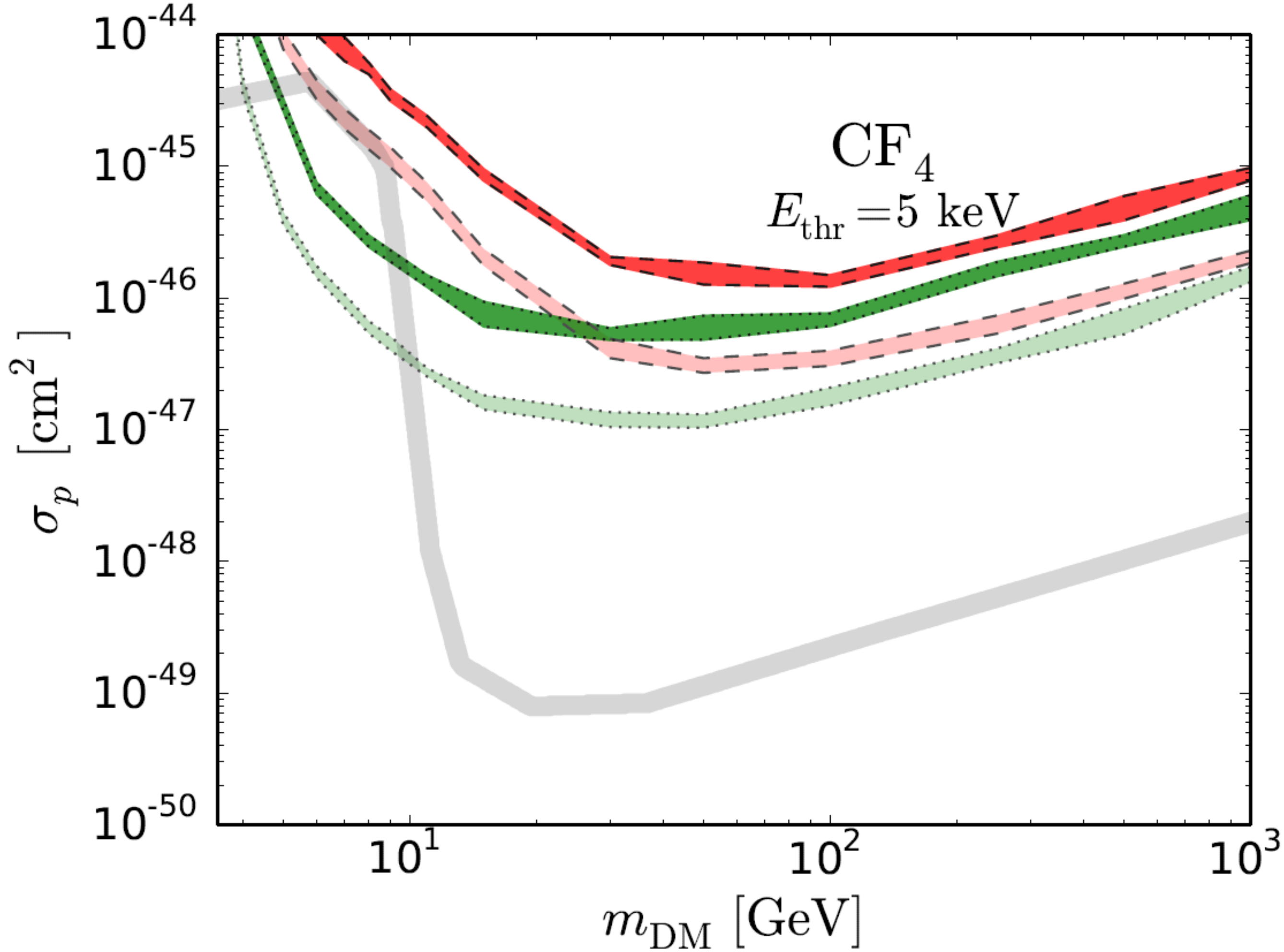
4. Choose integral limit *q* such that $1 - \beta_{SB} = \beta_B = \alpha$

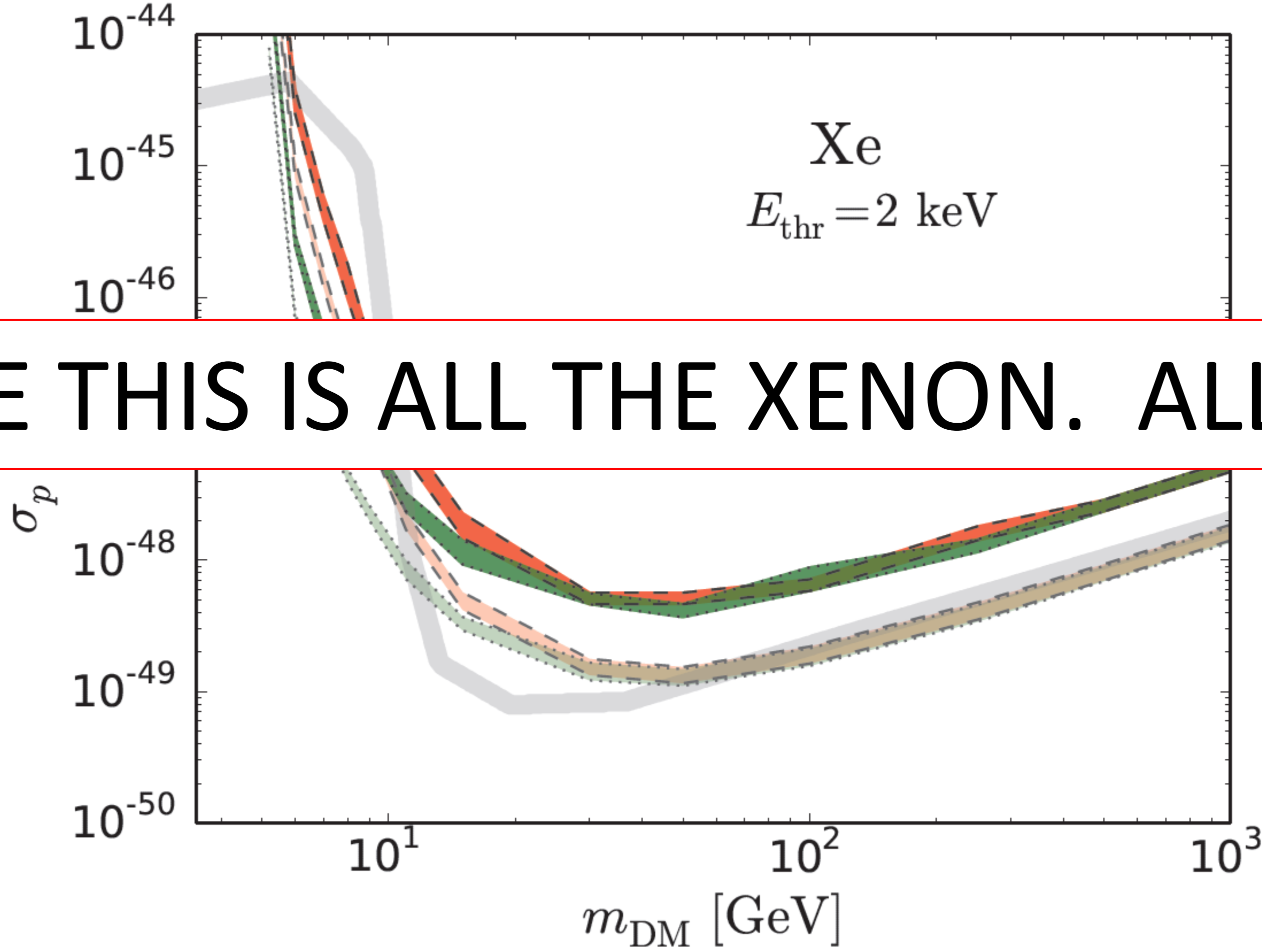
where α is your desired exclusion probability.

Results (in comic sans)



36 ton years of CF4 (500 neutrino events)
Energy threshold = 5 keV
Green is with directional dependence, red without.

Results



NOTE THIS IS ALL THE XENON. ALL OF IT.

367 ton years of Xe (500 neutrino events)
Energy threshold = 2 keV
Green is with directional dependence, red without.

Some fun facts about Xenon (mostly from Wikipedia)

- Makes up 0.1 ppm of air - 10^{12} tons in total
- Costs about $3 per gram
- Only about 36 tons obtained per year
- Increased demand might actually lower the cost (that was the one that didn't come from wikipedia)
- Xenon is used as a general anaesthetic
- Ultraviolet laser
- Fluoresces with same colour as noon day sun
- Photographic Flash Tube
- Protects against brain and cardio damage when blood supply compromised
- Couldn't tell from Wikipedia if it gets you high

Philosophy

- Understand and quantify problem of neutrino background
- Estimate the size of detectors required to fight the problem
- Throw ideas around
- Can we come up with ideas for viable detectors? (not yet)

YES

OK, should we build them?

NO

OK, end of direct detection.