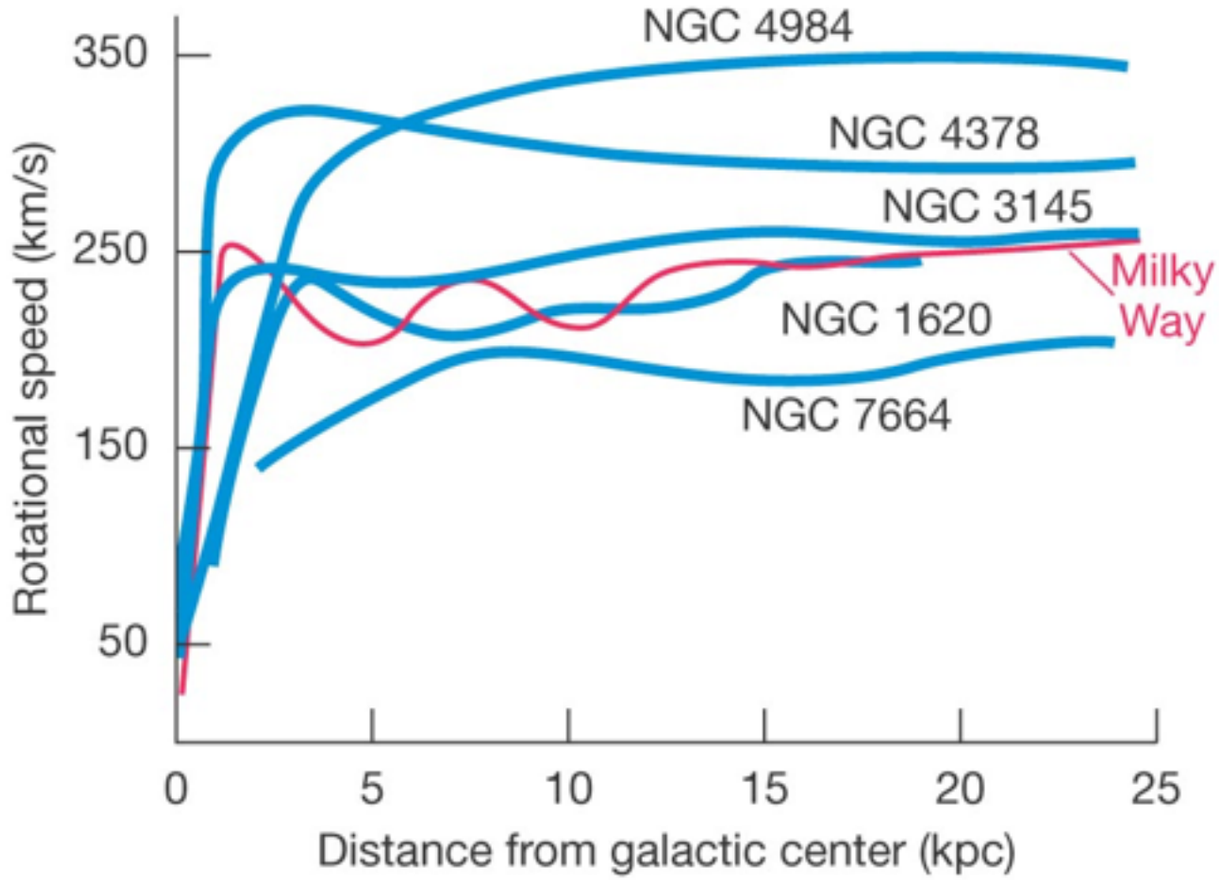
COLLIDING PIZZA SEMINAR

DARK MATTER @ LHC

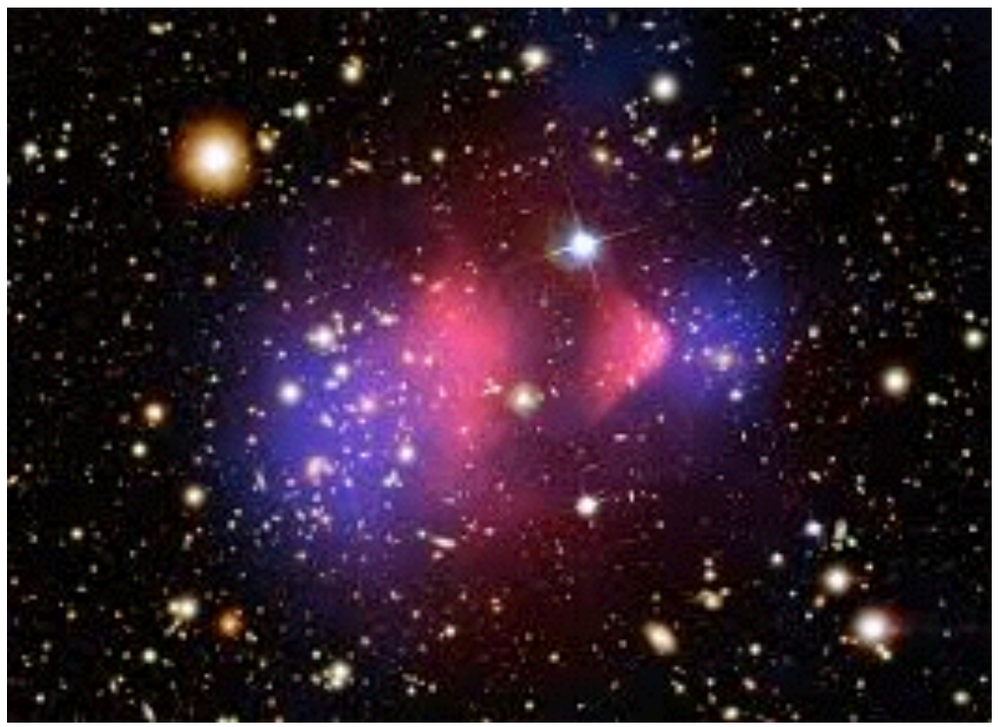
Nishita Desai

WHAT DO WE KNOW SO FAR?

HINTS FROM ASTROPHYSICS



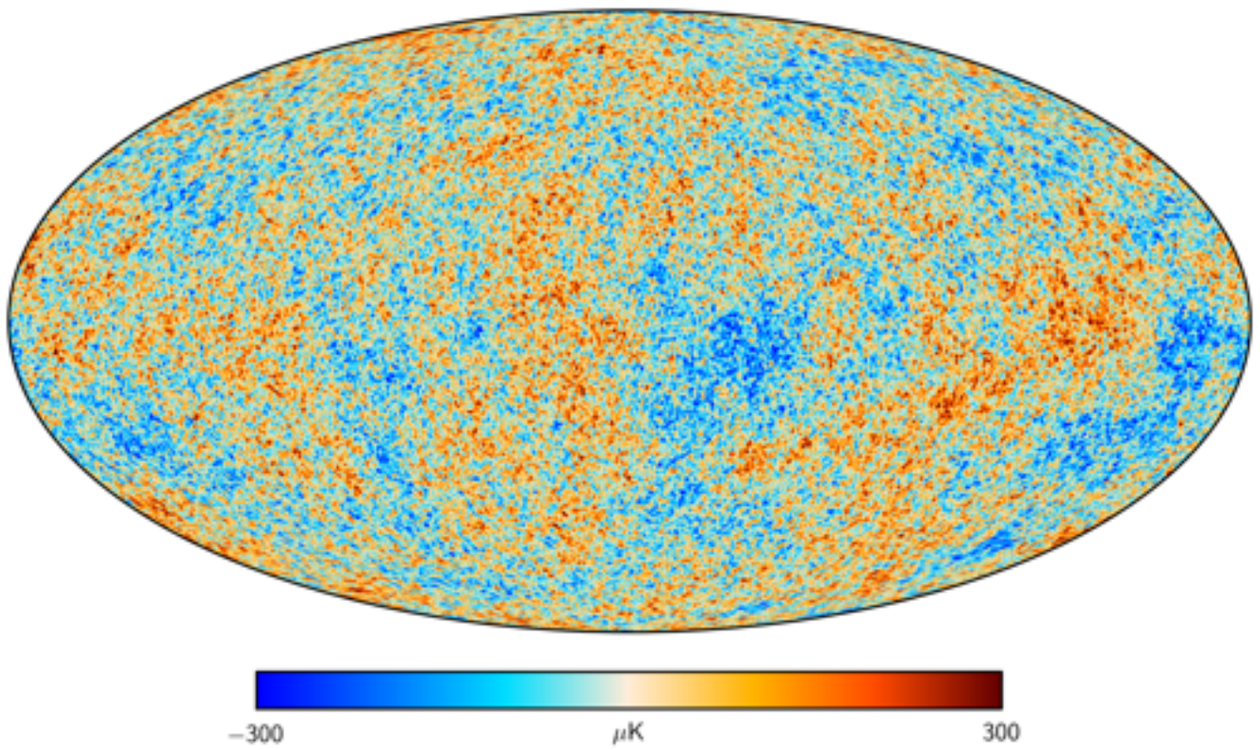
(b) Eric Chaisson, Steve McMillan



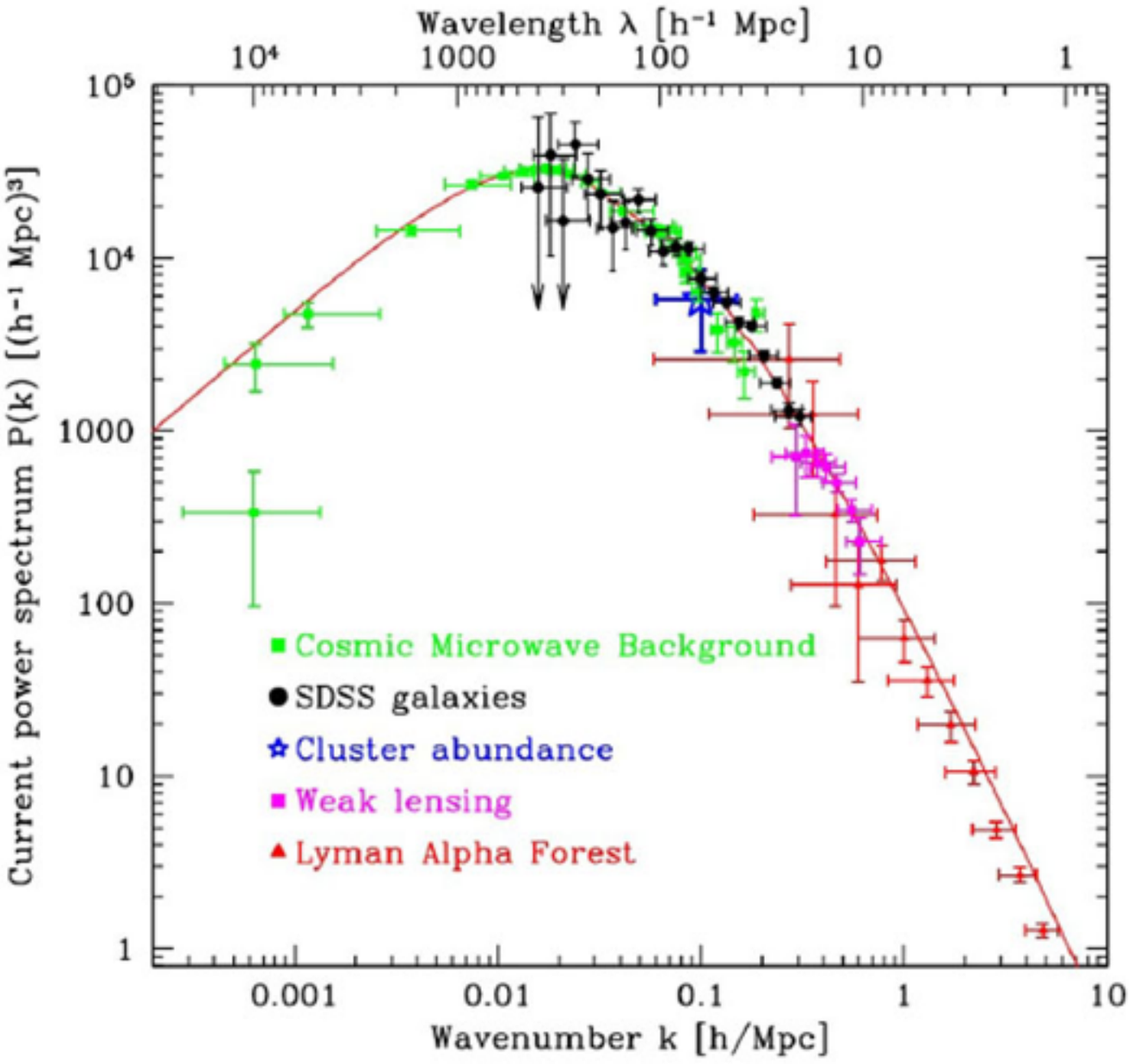
$$\Omega_m h^2 = 0.1415 \pm 0.0019$$

$$\Omega_b h^2 = 0.02226 \pm 0.00023$$

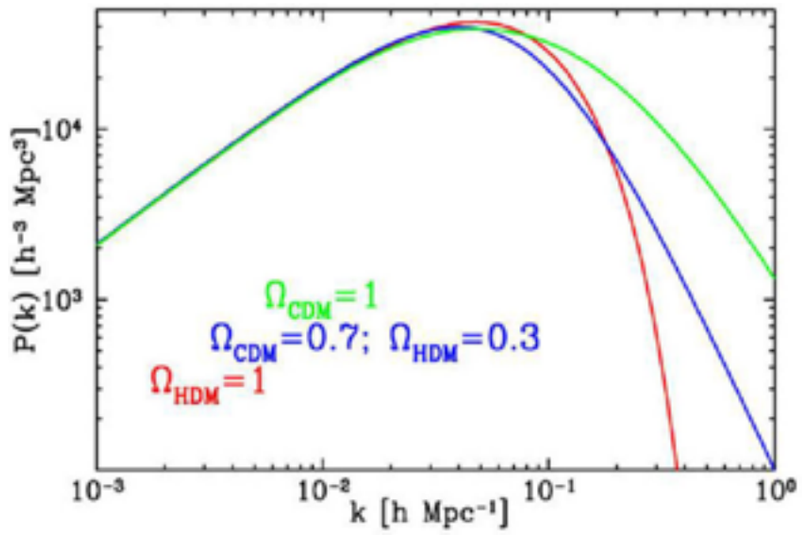
$$\Omega_c h^2 = 0.1186 \pm 0.0020$$



(DARK) MATTER POWER SPECTRUM



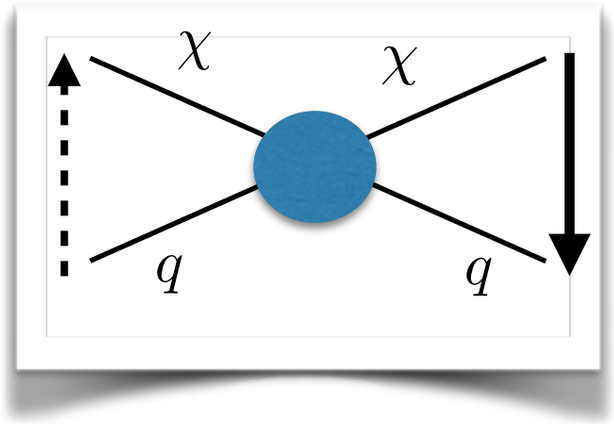
NASA/IPAC Extragalactic Database (NED)

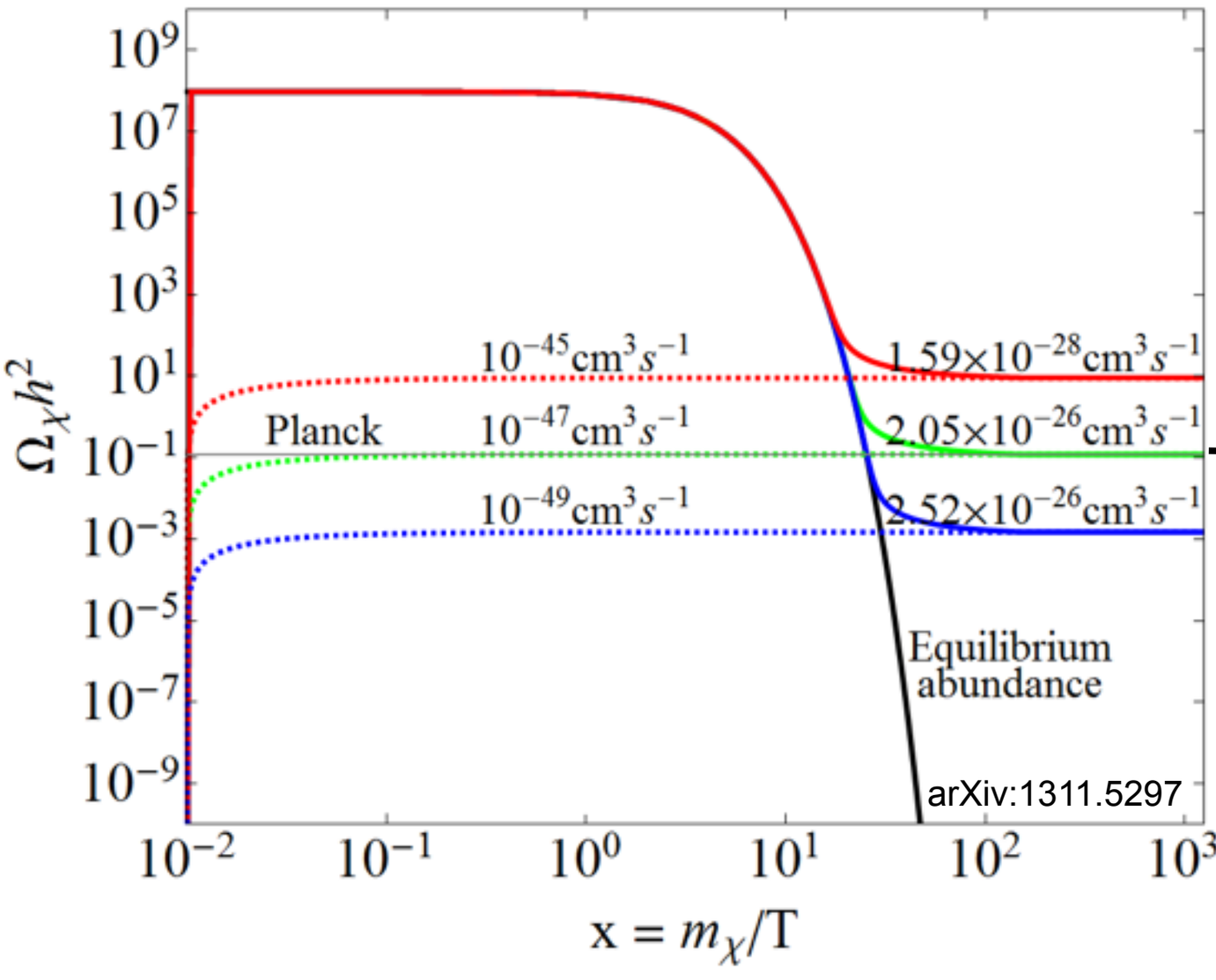


The assumption of CDM is essential to explain our Universe

HOW TO CALCULATE THE RELIC DENSITY?

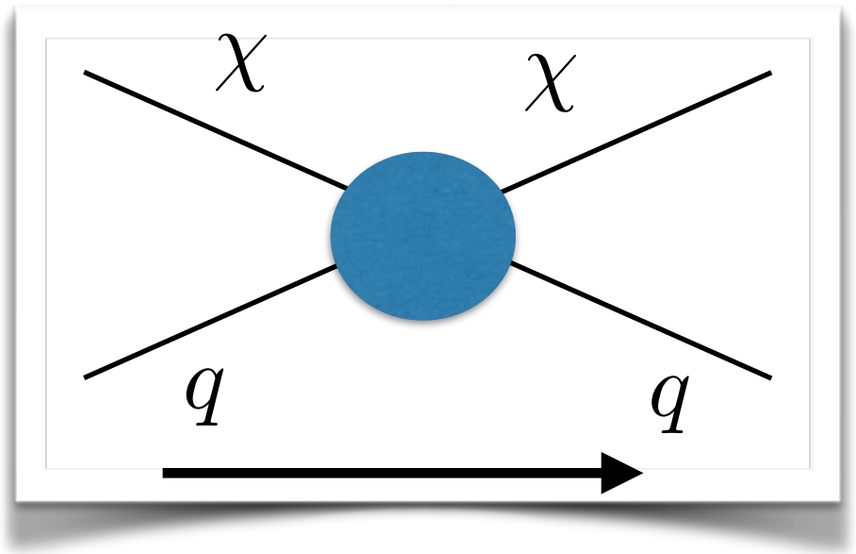
$$\frac{dn}{dt} + 3n\mathrm{H} = -\frac{1}{2}\langle\sigma \mathrm{v}\rangle \left(n^2 - (n^{eq})^2\right)$$

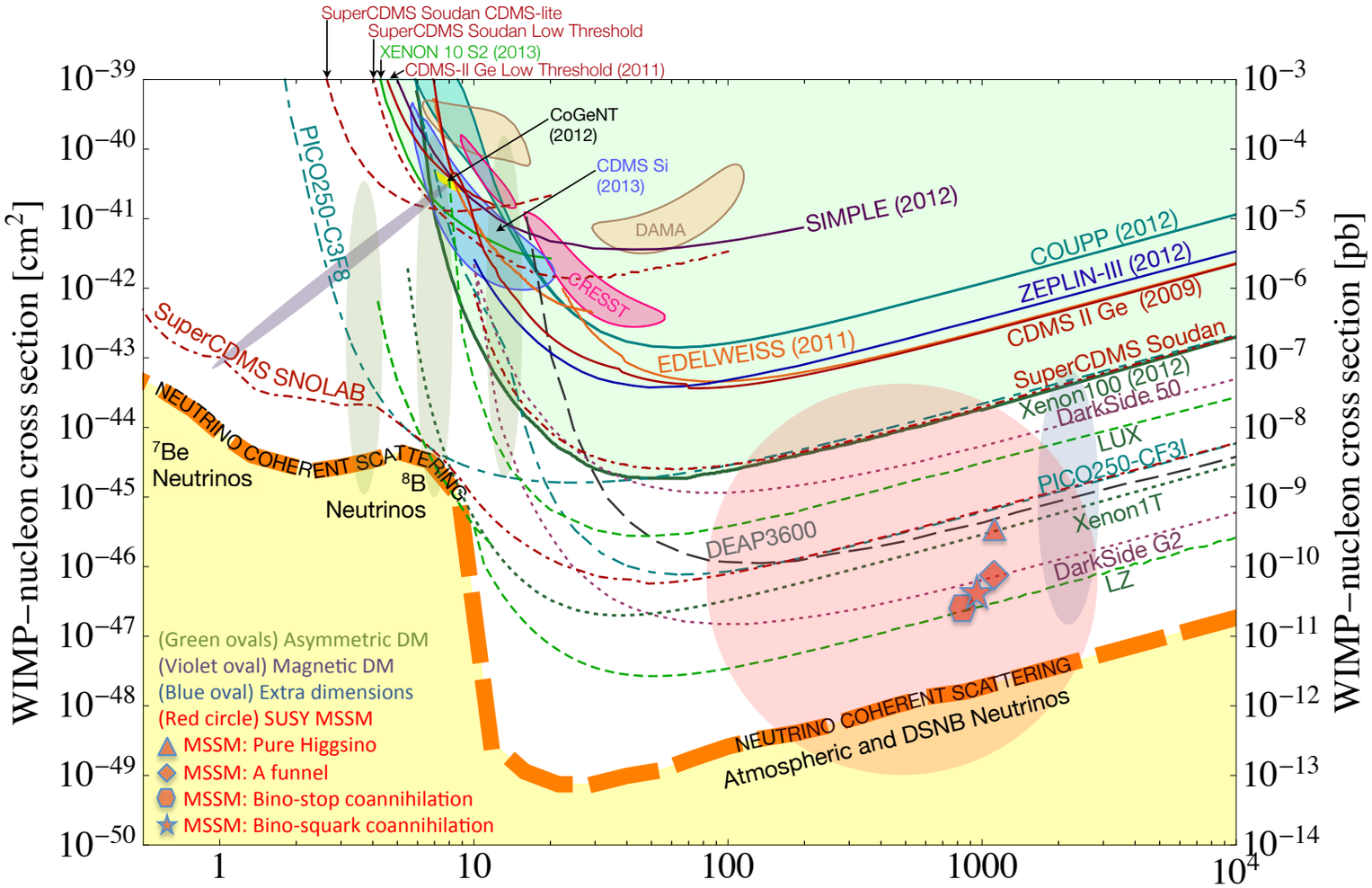


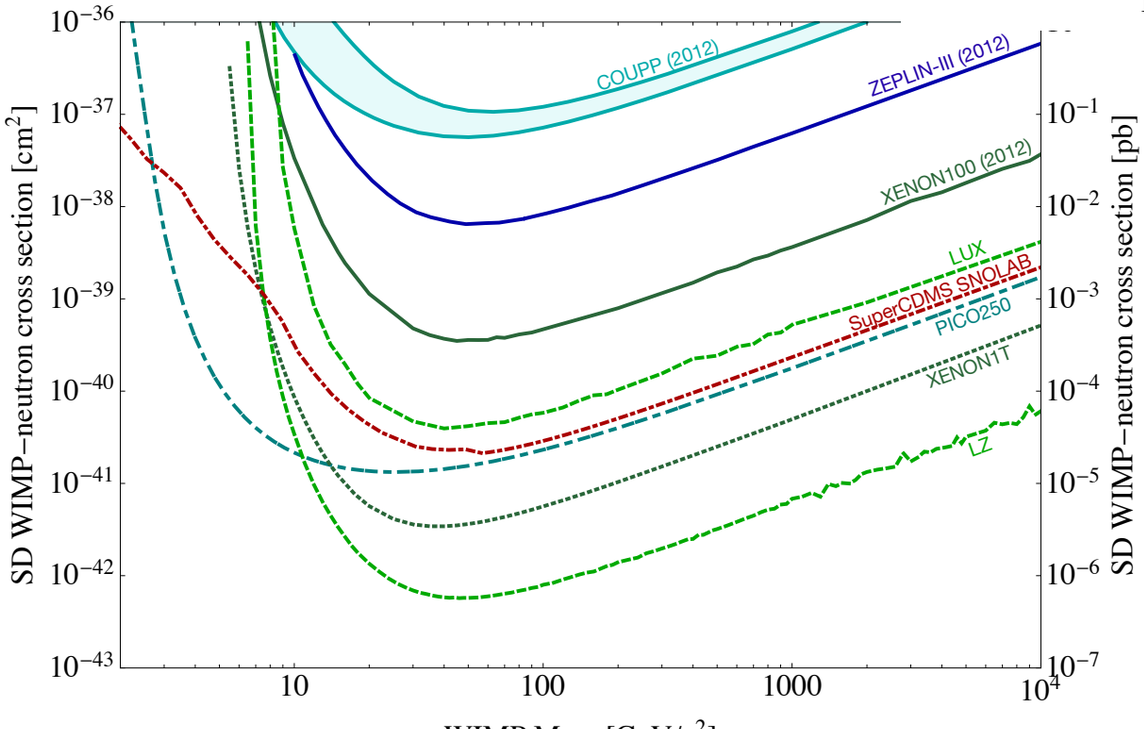


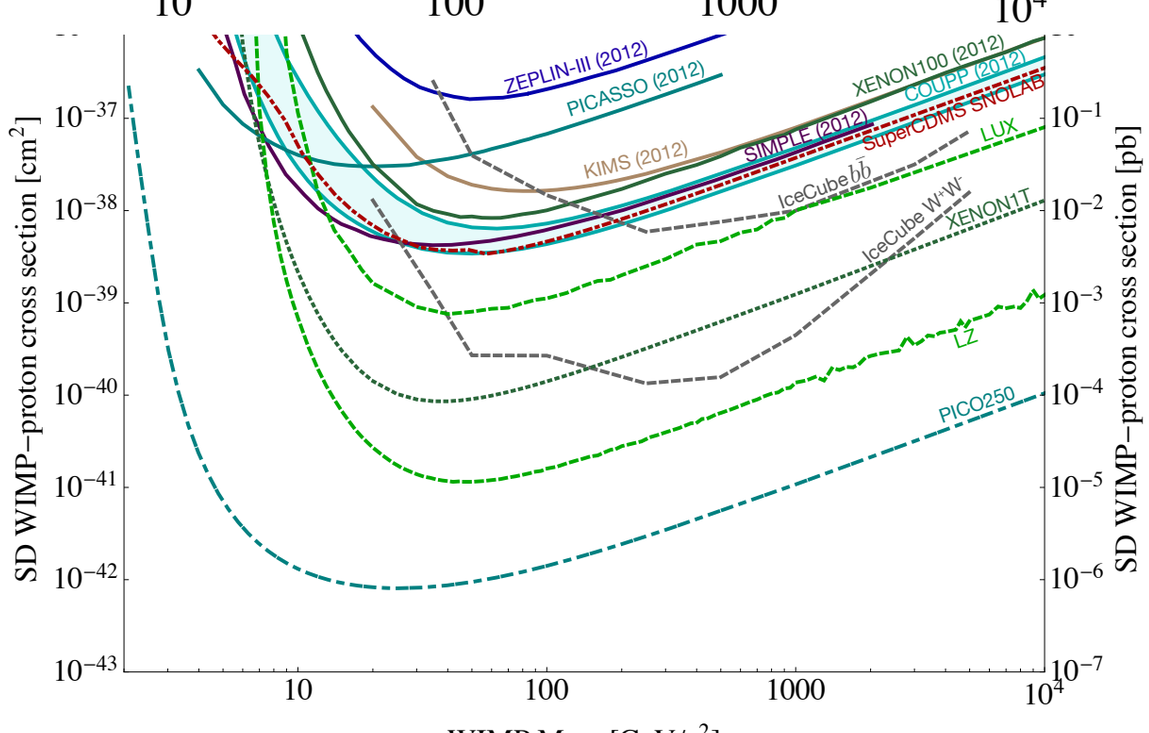
$$m_\chi \sim 100 \text{ GeV}$$
$$g \sim g_{EW}$$

LOOKING FOR DM WINDS: DIRECT DETECTION

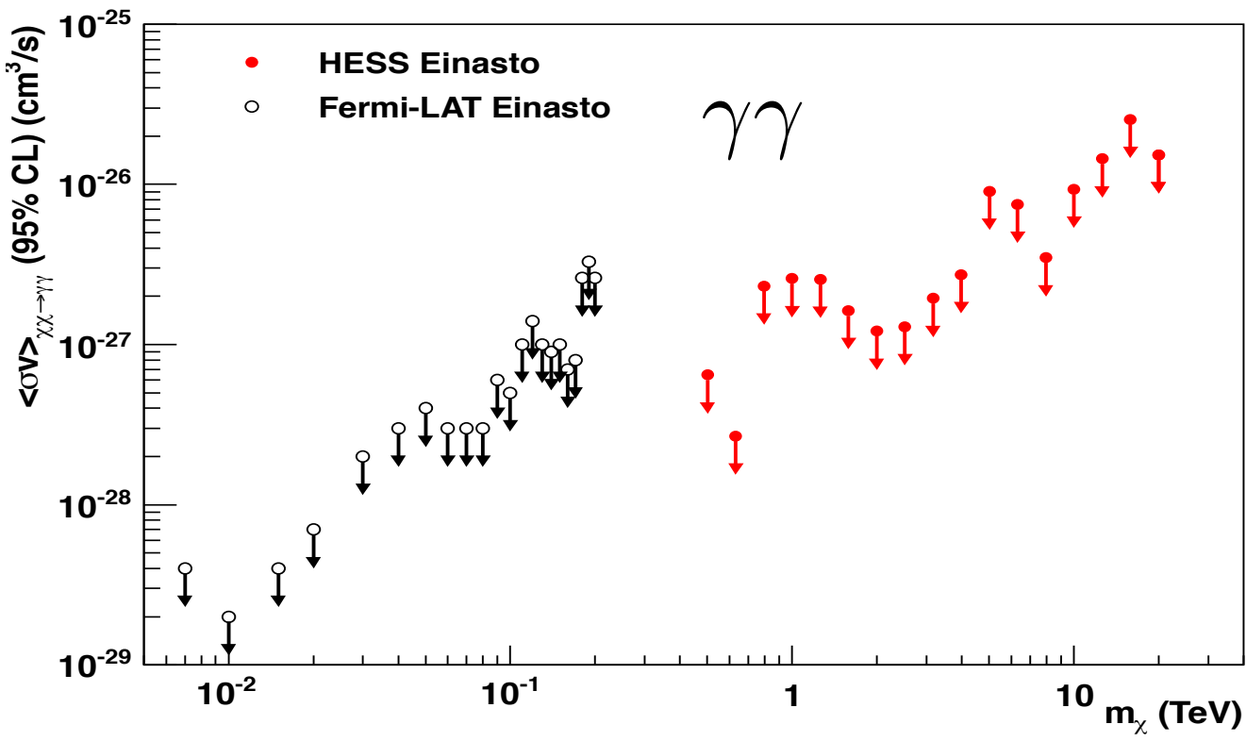




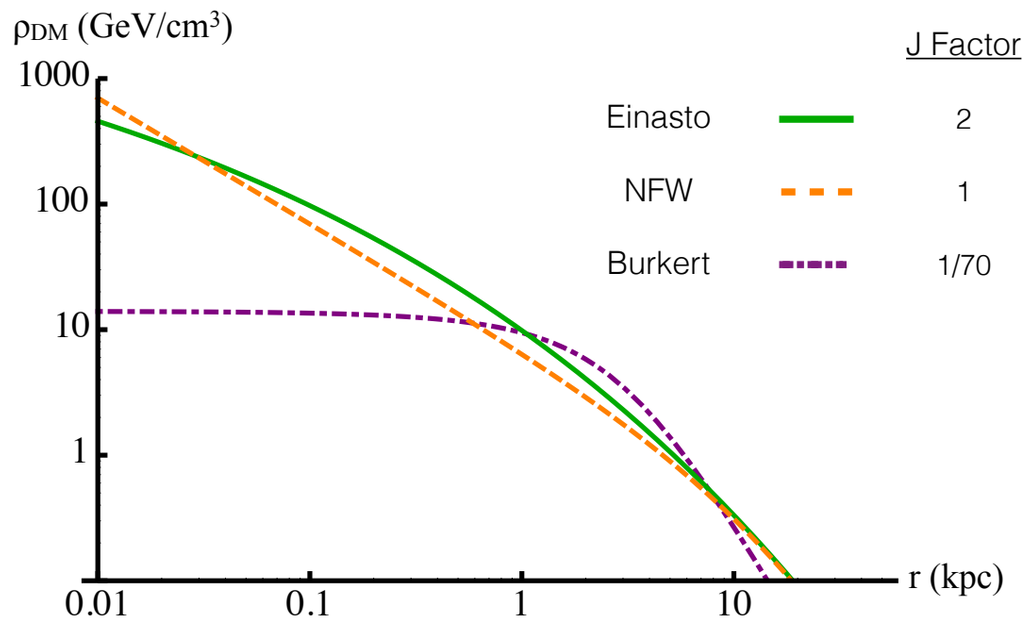


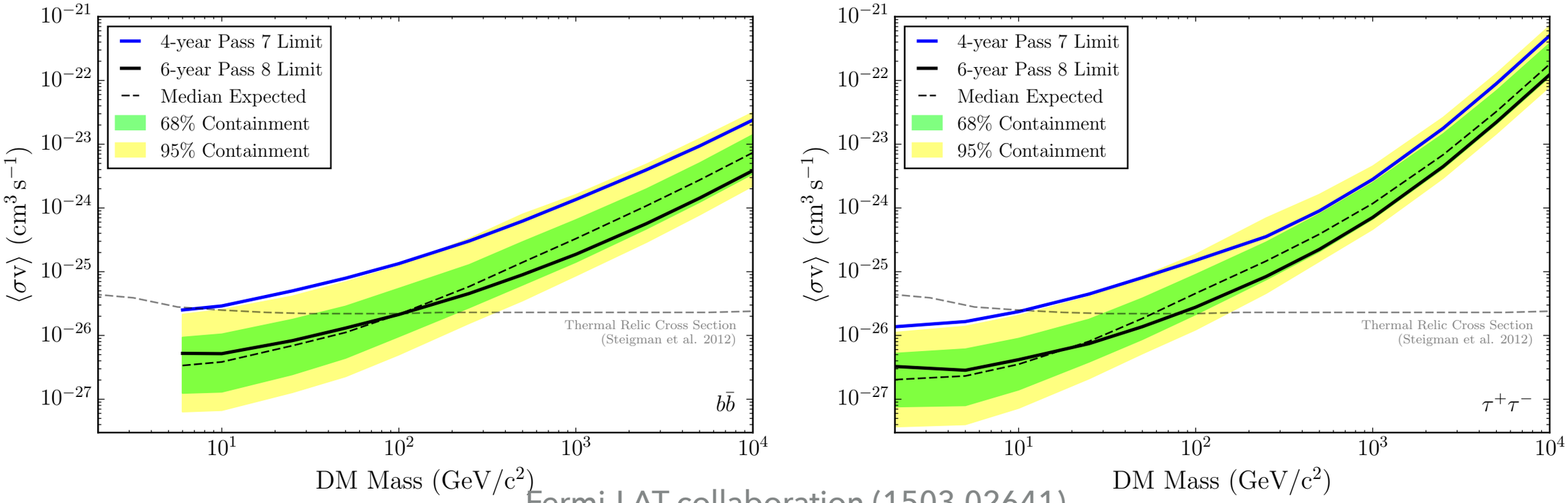


LOOKING FOR LINES IN THE SKY: INDIRECT DETECTION



$$\rho_{\rm NFW}(r) = \frac{\rho_\odot}{(r/R)\,(1+r/R)^2},\ \rho_{\rm Ein}(r) = \rho_\odot\ \exp\left[-\frac{2}{\alpha}\left(\left(\frac{r}{R}\right)^\alpha - 1\right)\right]$$





Fermi-LAT collaboration (1503.02641)

WHY USE COLLIDERS?

WE HAVE ONE, MIGHT AS WELL USE IT!

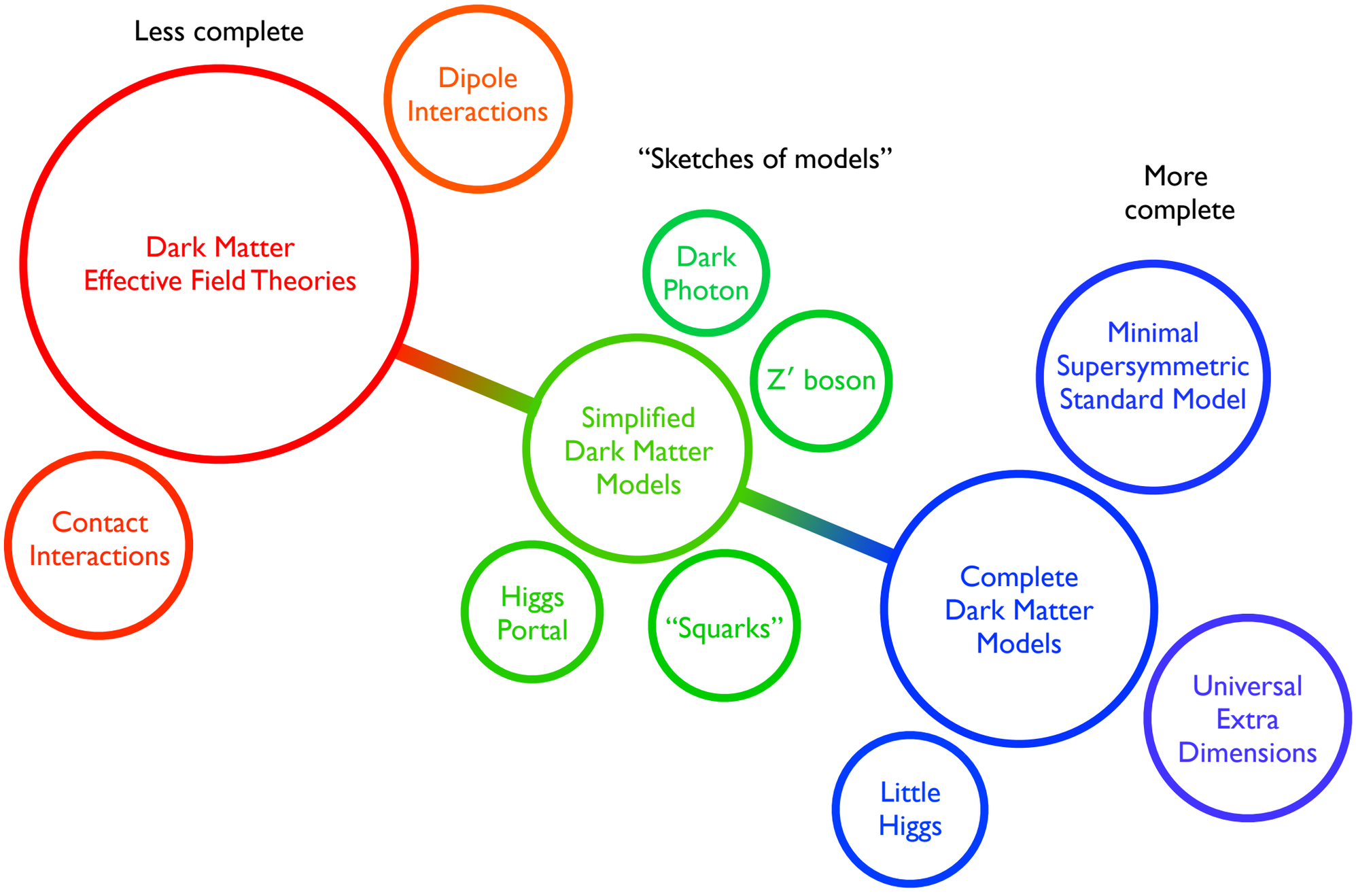
BUT ALSO . . .

IT TURNS OUT, COLLIDERS CAN DO THINGS OTHER EXPERIMENTS CAN'T — BETTER SPIN DEPENDENT SENSITIVITY + CONSTRAIN LOW RECOIL REGION + LOOK FOR ACCOMPANYING PARTICLES

TO MODEL DM WE NEED TO KNOW:

Does it couple directly to some SM particle?

If there is a mediator, how does the mediator couple to SM? to DM?



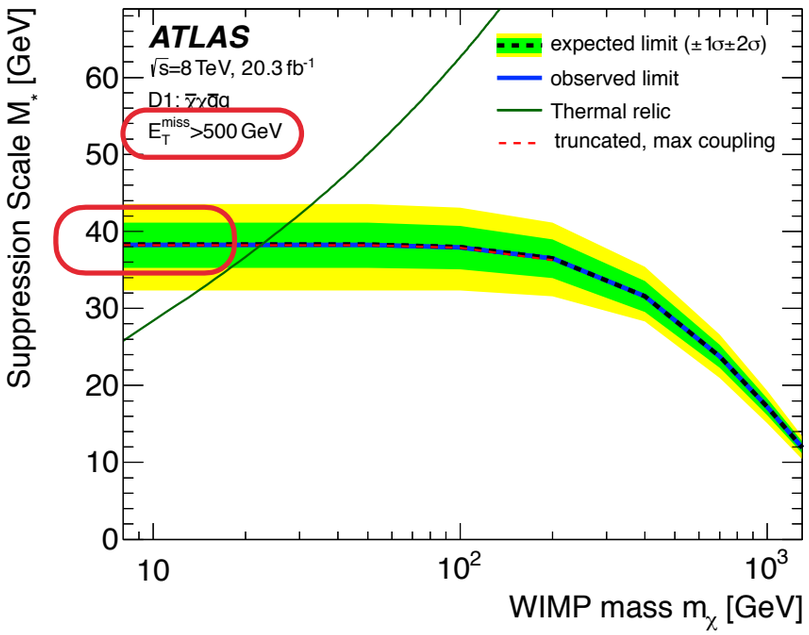
COLLIDER SEARCHES: A COMPLEMENTARY VIEW

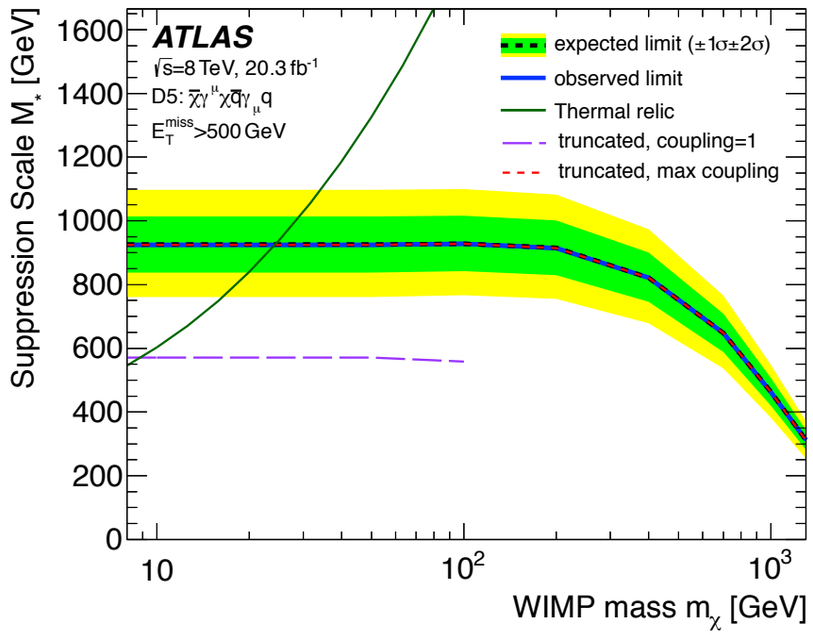
Goodman et al. (2010)

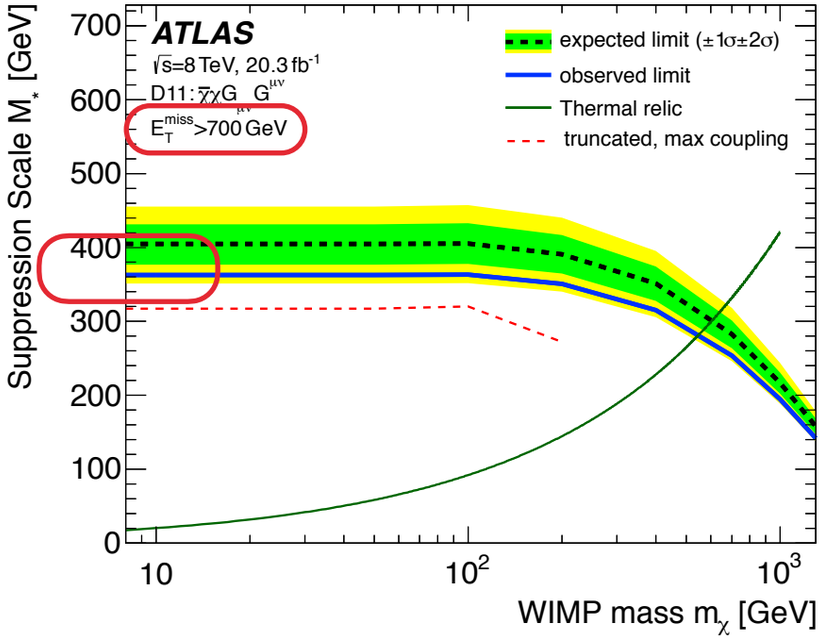
Name	Operator	Coefficient
D1	$\bar{\chi}\chi\bar{q}q$	m_q/M_*^3
D2	$\bar{\chi}\gamma^5\chi\bar{q}q$	im_q/M_*^3
D3	$\bar{\chi}\chi\bar{q}\gamma^5 q$	im_q/M_*^3
D4	$\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$	m_q/M_*^3
D5	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D6	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D7	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D8	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D9	$\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$	$1/M_*^2$
D10	$\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi\bar{q}\sigma_{\alpha\beta}q$	i/M_*^2
D11	$\bar{\chi}\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^3$
D12	$\bar{\chi}\gamma^5\chi G_{\mu\nu}G^{\mu\nu}$	$i\alpha_s/4M_*^3$
D13	$\bar{\chi}\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^3$
D14	$\bar{\chi}\gamma^5\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\alpha_s/4M_*^3$

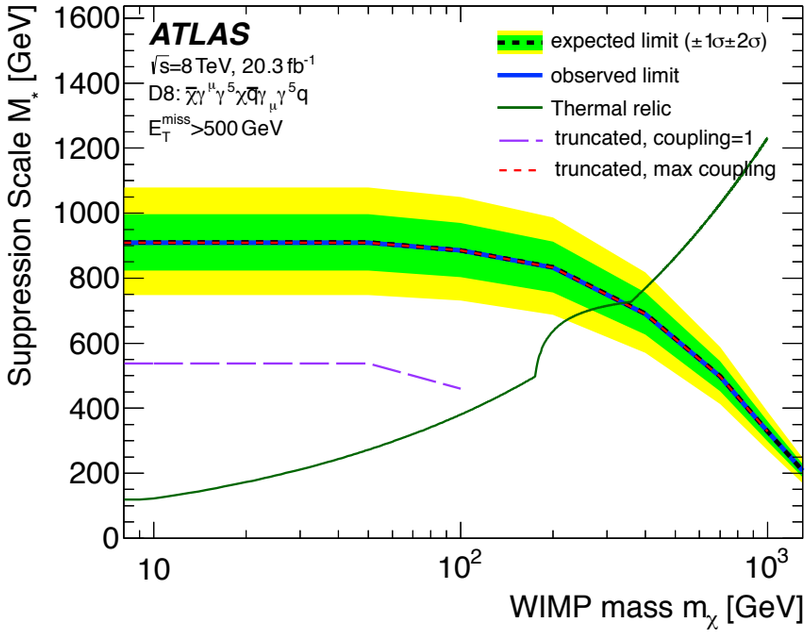
Name	Operator	Coefficient
C1	$\chi^\dagger\chi\bar{q}q$	m_q/M_*^2
C2	$\chi^\dagger\chi\bar{q}\gamma^5 q$	im_q/M_*^2
C3	$\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu q$	$1/M_*^2$
C4	$\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu\gamma^5 q$	$1/M_*^2$
C5	$\chi^\dagger\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^2$
C6	$\chi^\dagger\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^2$
R1	$\chi^2\bar{q}q$	$m_q/2M_*^2$
R2	$\chi^2\bar{q}\gamma^5 q$	$im_q/2M_*^2$
R3	$\chi^2 G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/8M_*^2$
R4	$\chi^2 G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/8M_*^2$

ATLAS LIMITS ON EFT OPERATORS

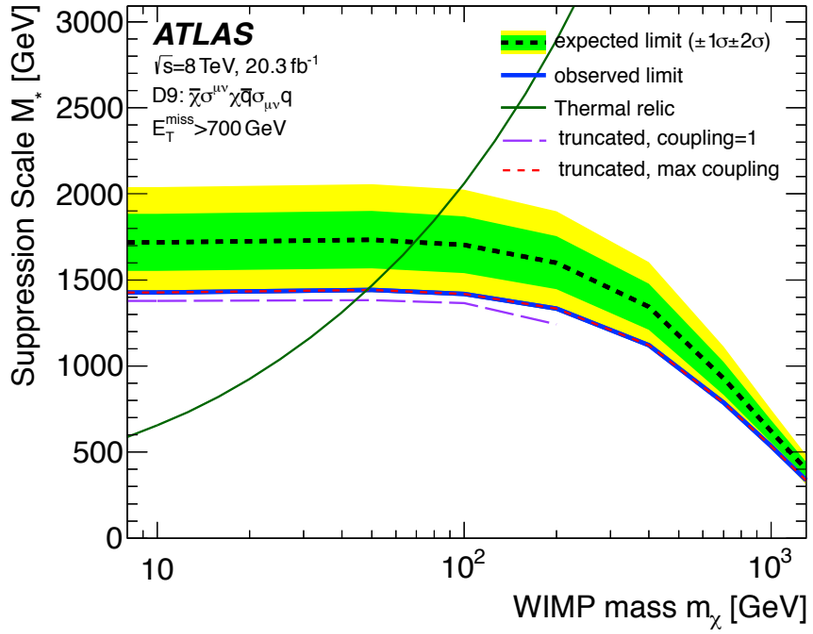




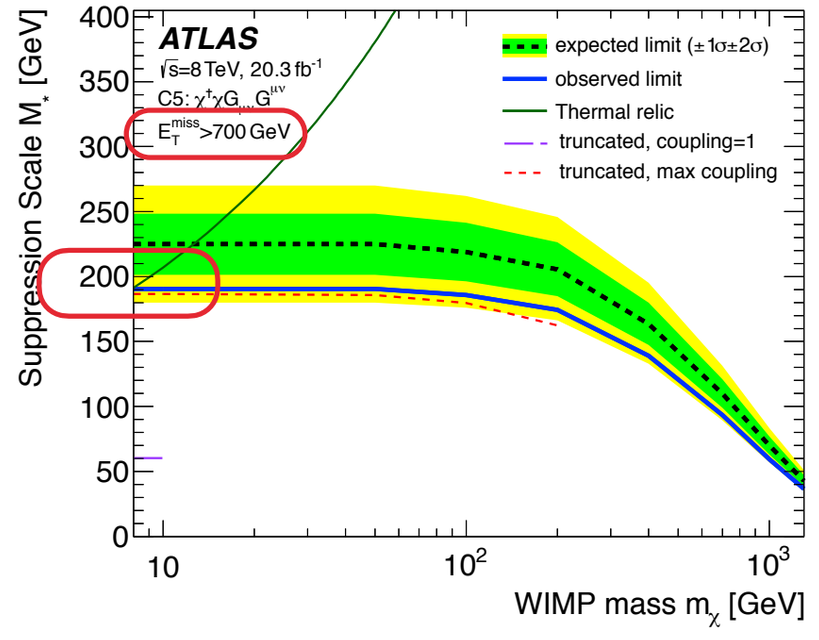




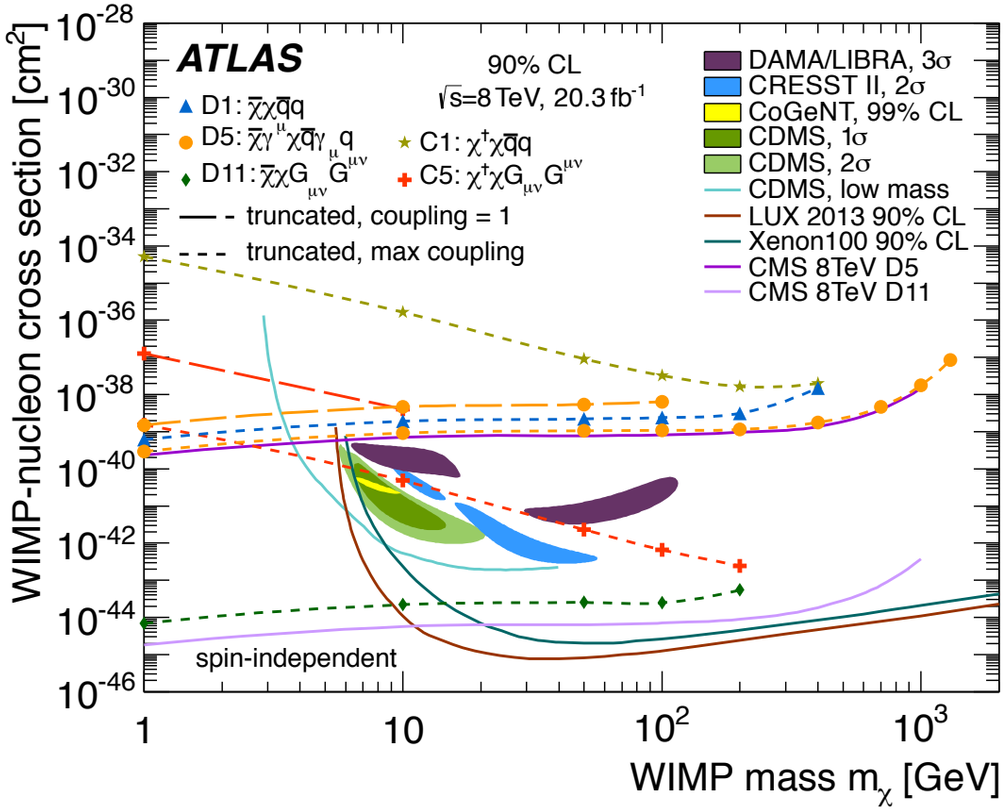
(c)



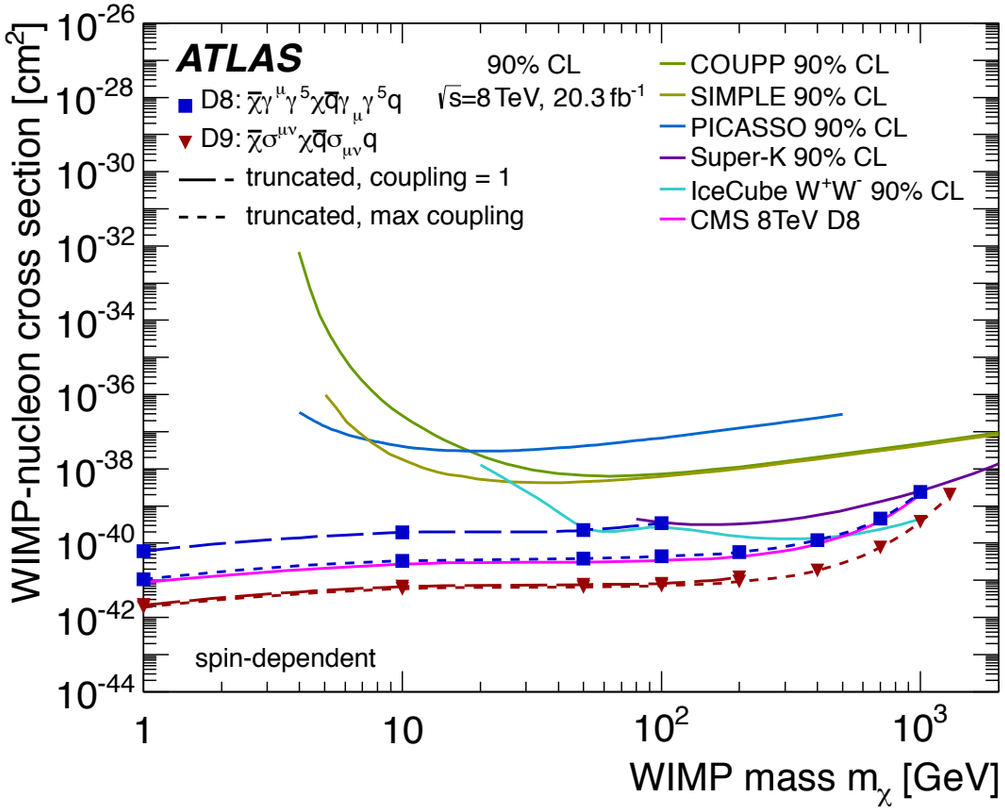
(d)



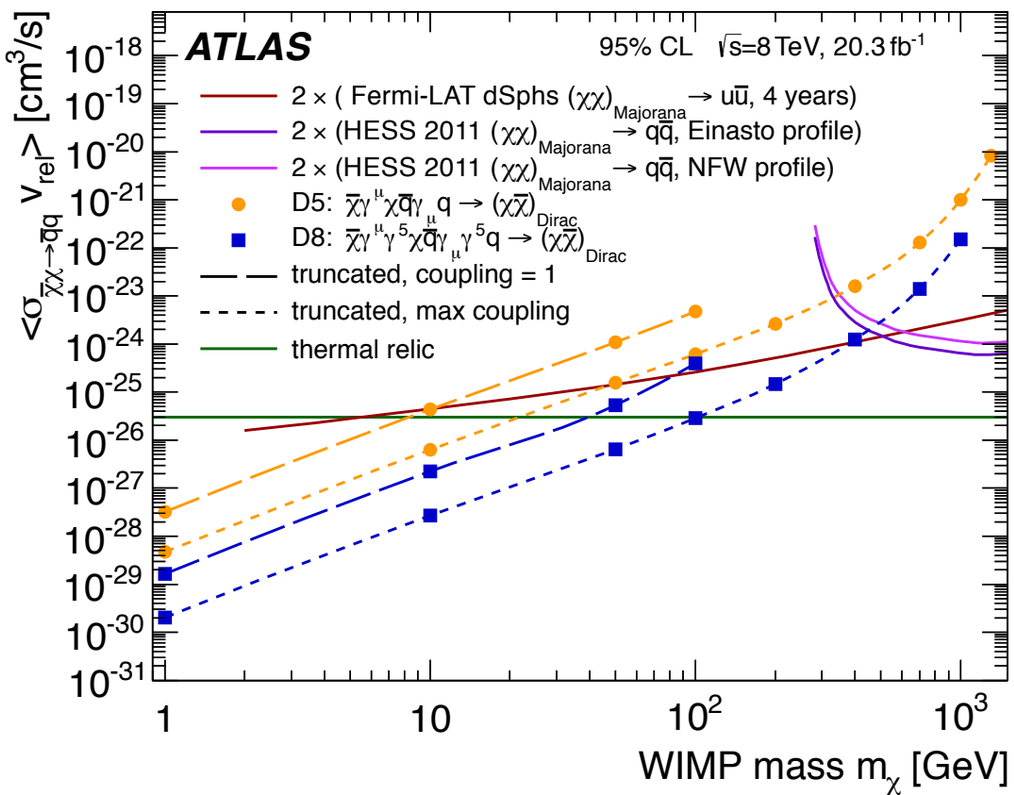
ATLAS LIMITS



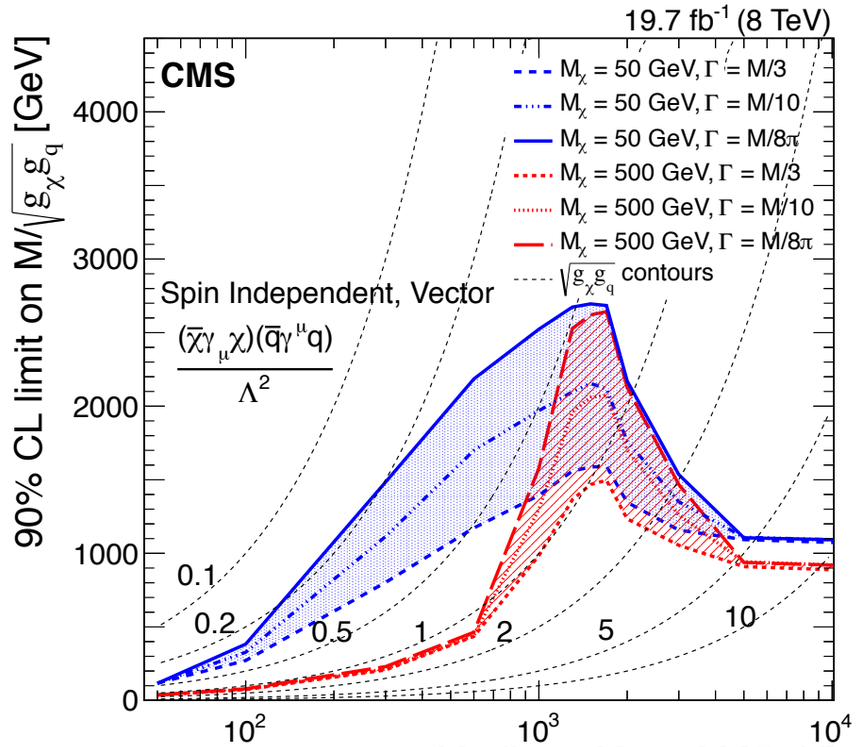
(a)

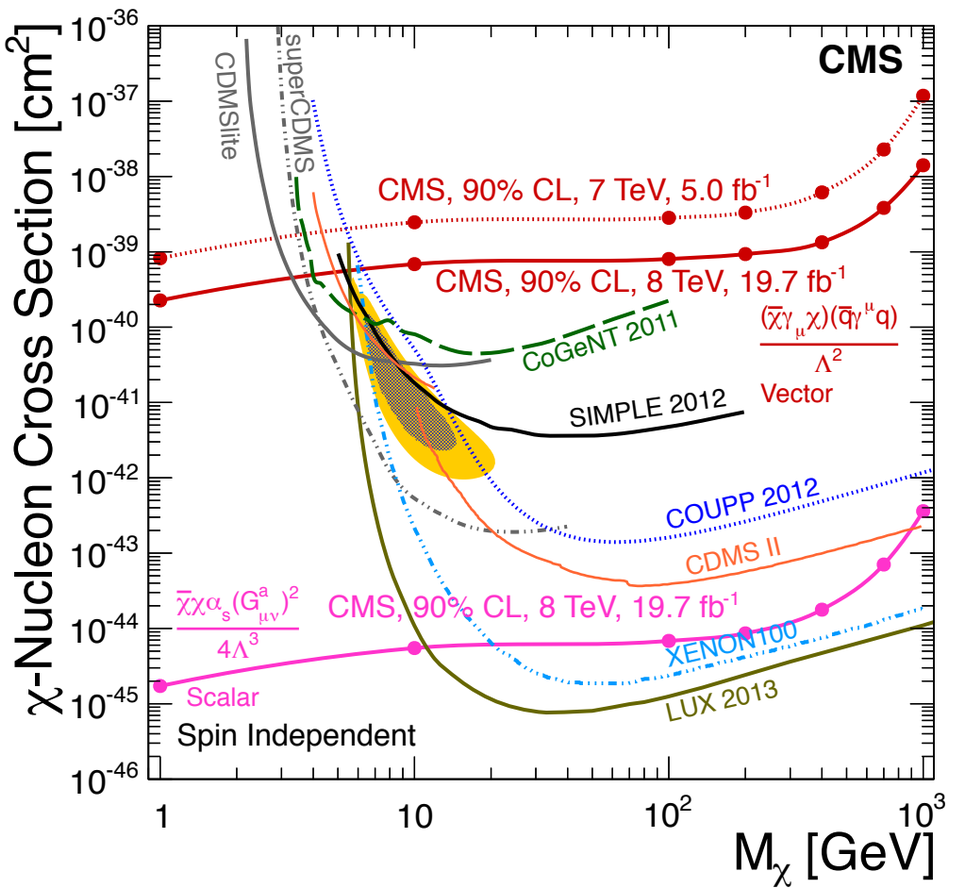


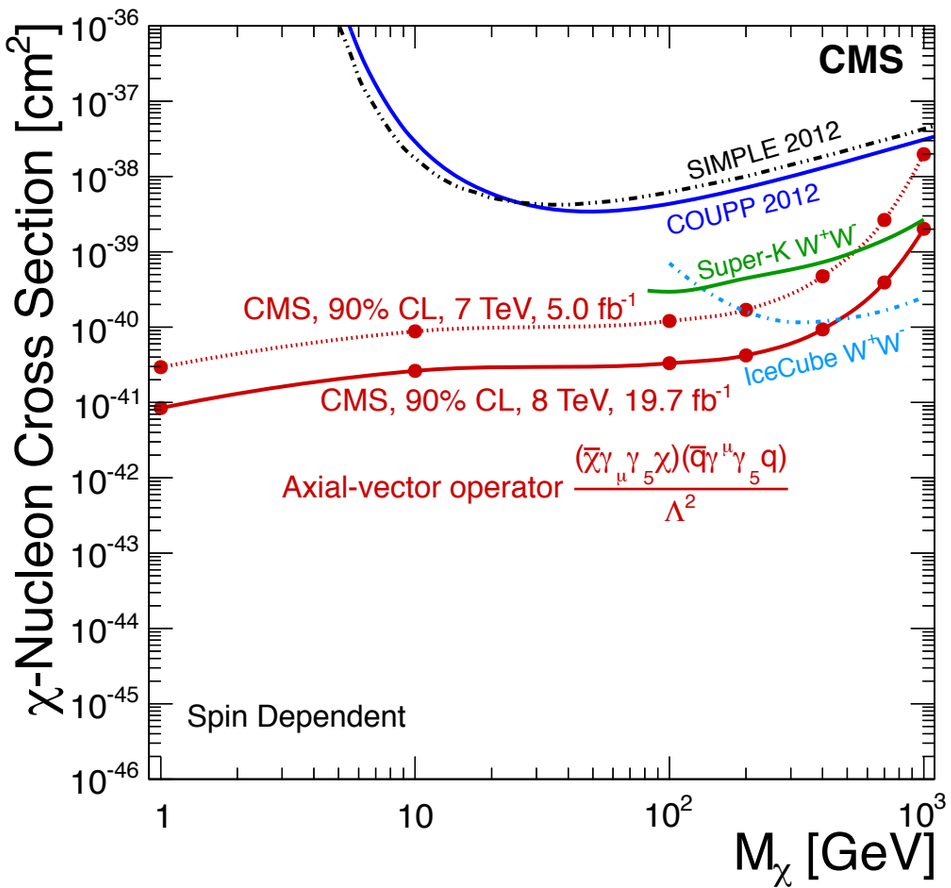
(b)



CMS LIMITS ON EFT OPERATORS



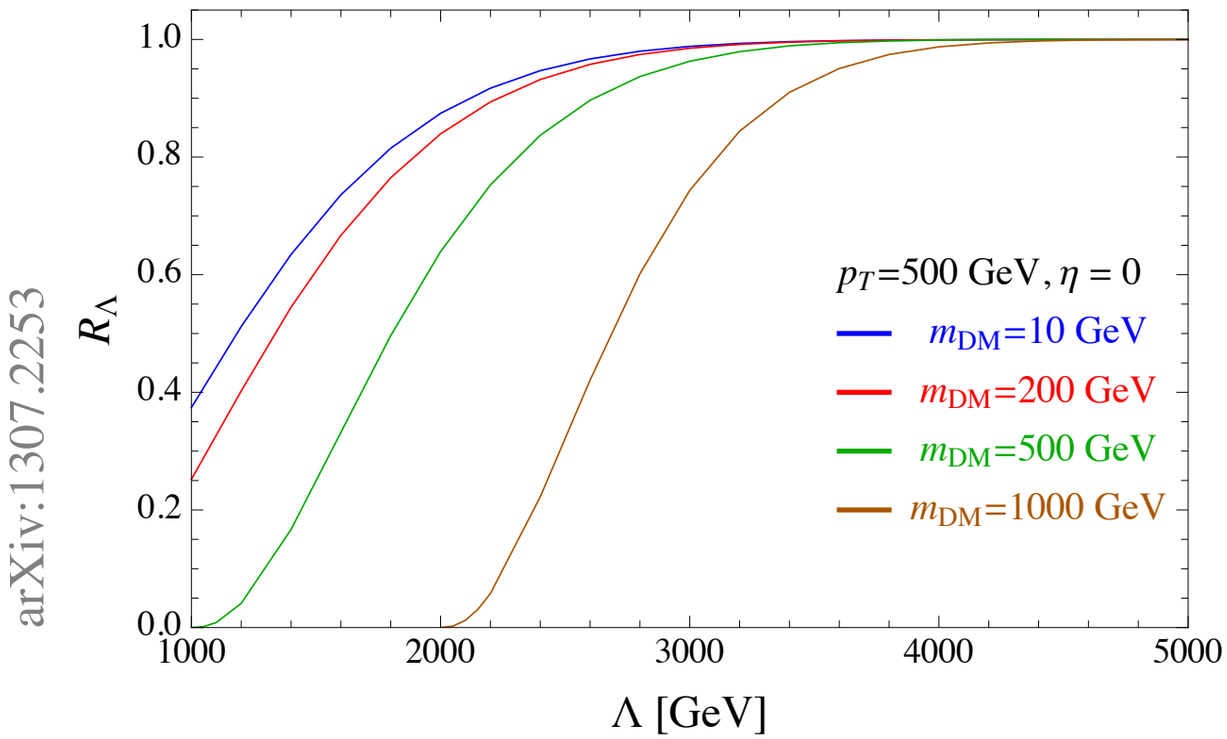


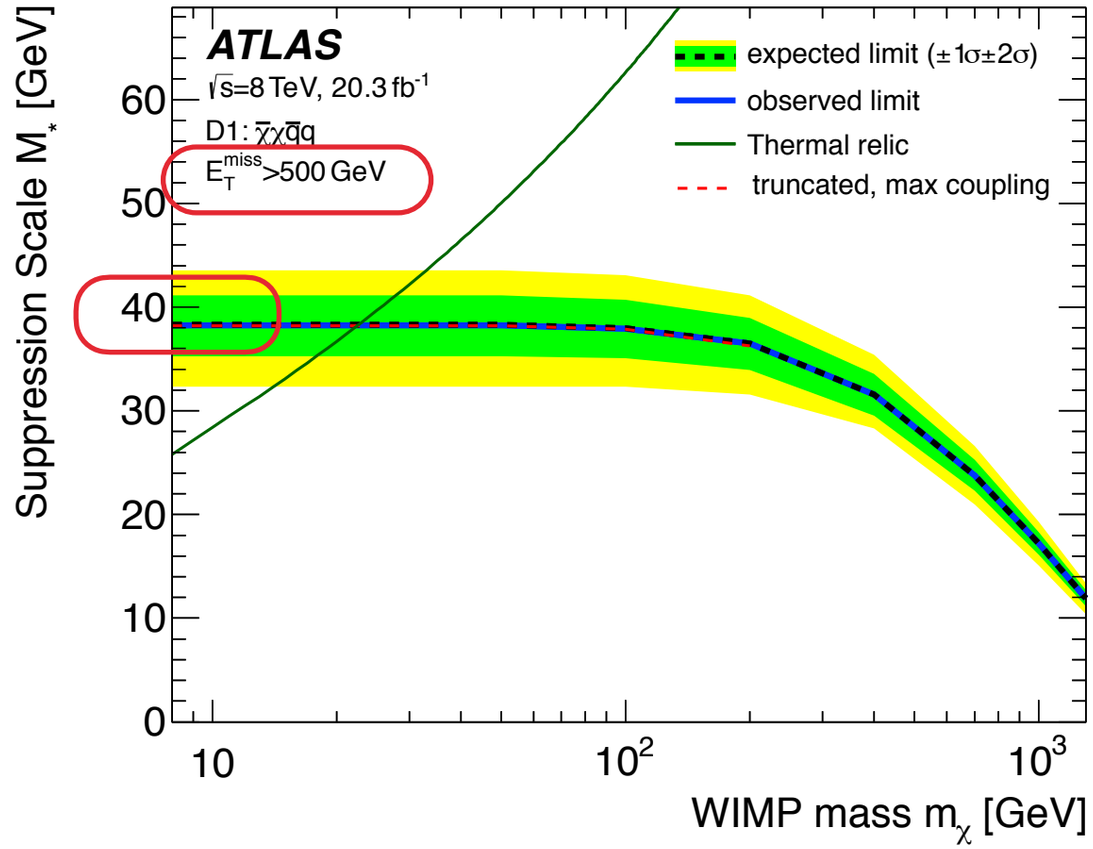


Original idea of "EFT":

$$\bar{q}q\frac{g}{p^2-M^2}\bar{\psi}\psi \quad \xrightarrow{M\gg p} \quad \frac{g}{M^2}\bar{q}q\bar{\psi}\psi$$

So how does one live with:

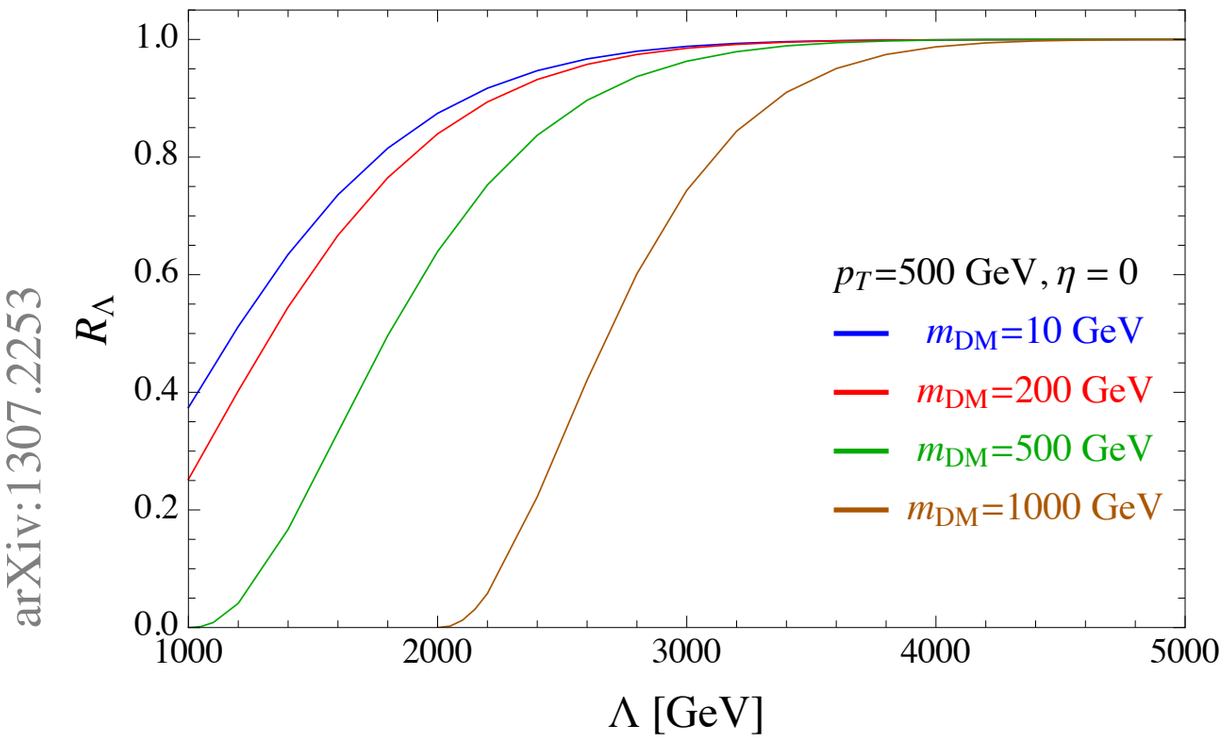


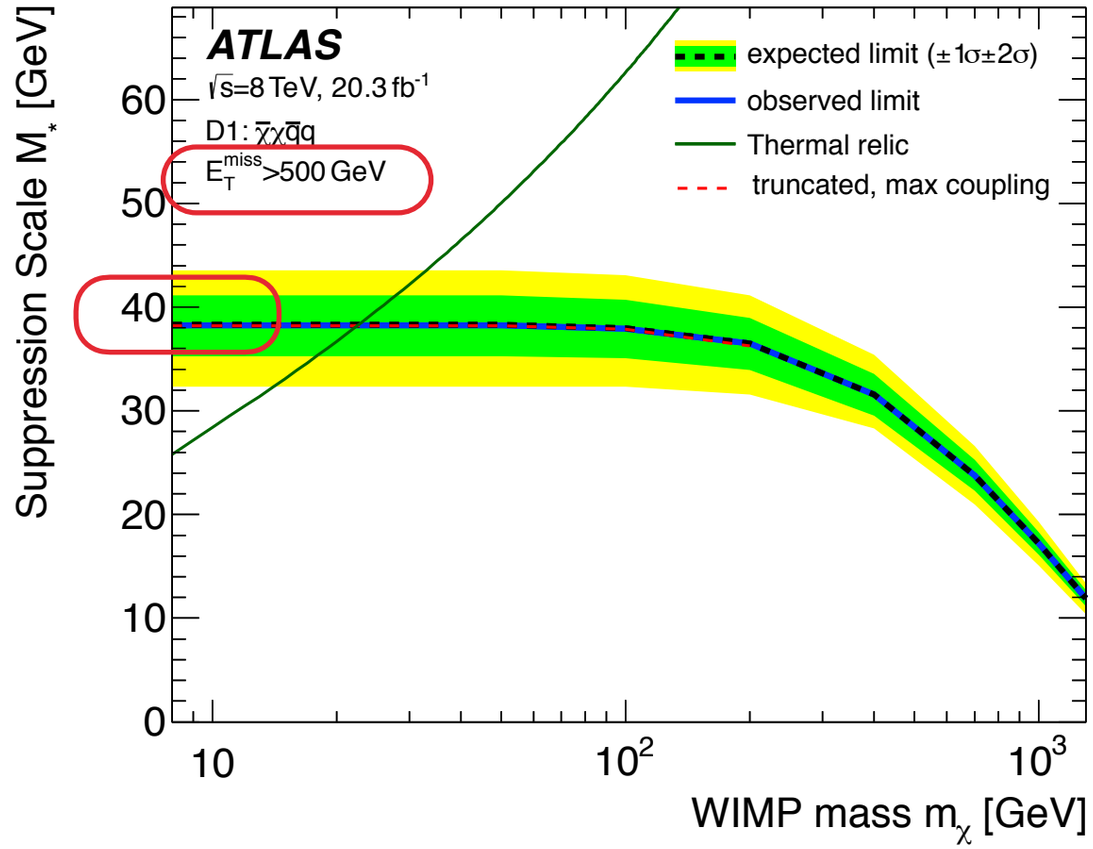


Original idea of "EFT":

$$\bar{q}q\frac{g}{p^2-M^2}\bar{\psi}\psi \xrightarrow{M\gg p} \frac{g}{M^2}\bar{q}q\bar{\psi}\psi$$

So how does one live with:



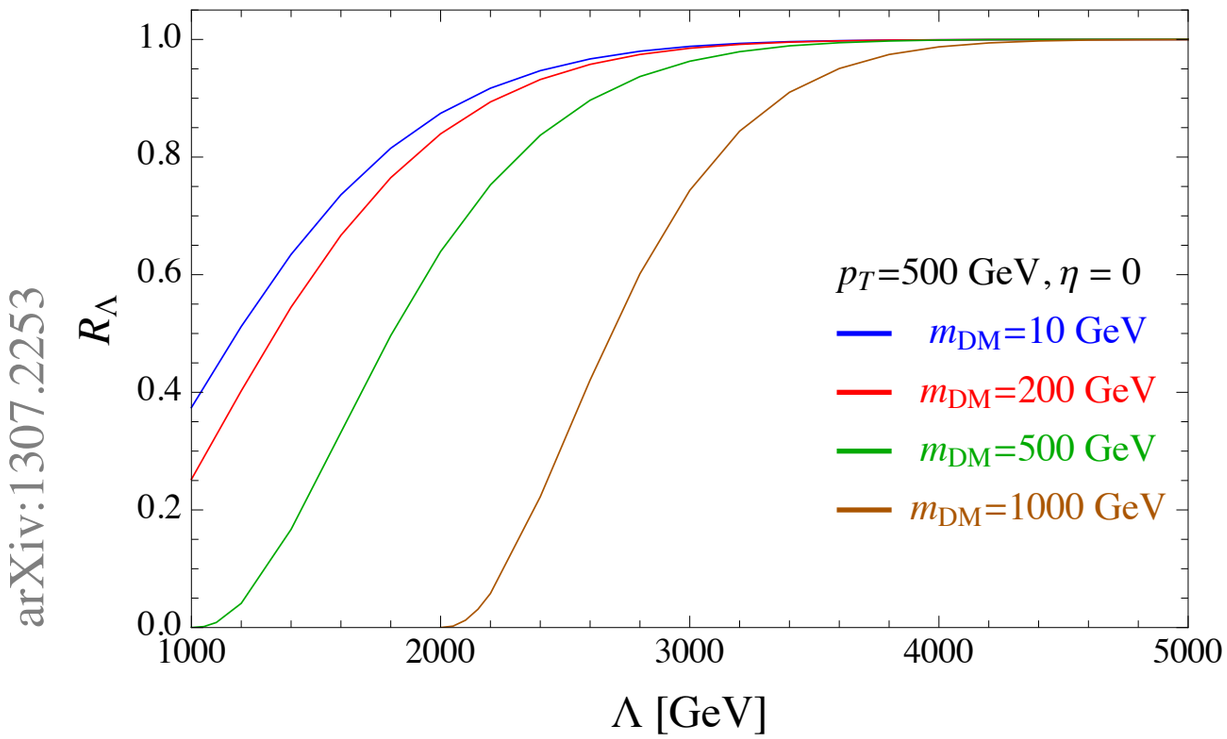


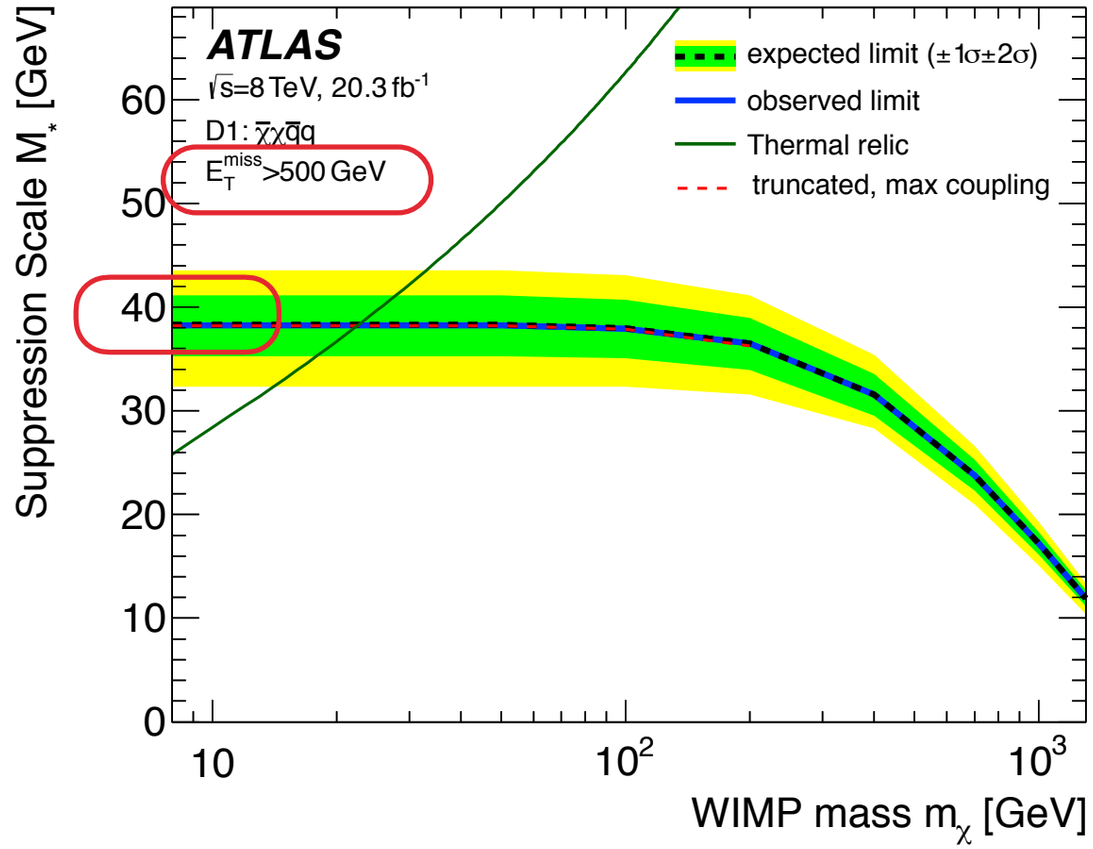
Option 1: Use only those events with p << Lambda

Original idea of "EFT":

$$\bar{q}q\frac{g}{p^2-M^2}\bar{\psi}\psi \quad \xrightarrow{M\gg p} \quad \frac{g}{M^2}\bar{q}q\bar{\psi}\psi$$

So how does one live with:

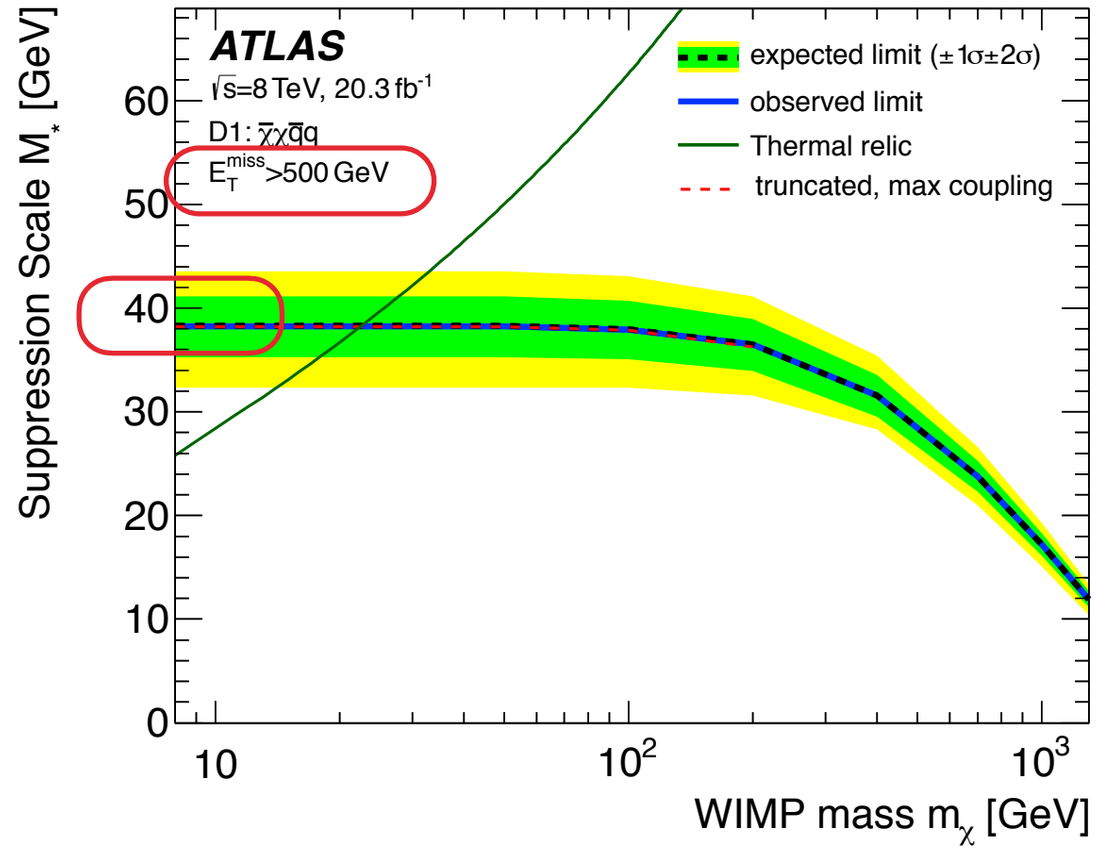




Original idea of "EFT":

$$\bar{q}q\frac{g}{p^2-M^2}\bar{\psi}\psi \xrightarrow{M\gg p} \frac{g}{M^2}\bar{q}q\bar{\psi}\psi$$

So how does one live with:



Option 2: Treat the EFT as simply a basis of operators and not as a result of integrating out massive particles.

FERMIONIC

SPIN-1

SPIN-0

DIRAC

MAJORANA

DM

2

3

4

5

2'

1

1'

Mediator

SPIN-1

SPIN-0

HOW TO WRITE A SIMPLIFIED MODEL?

1

$$\mathcal{L}_S = \frac{1}{2}\partial_\mu S \partial^\mu S - m_S^2 S^2 + \sum g_{s\chi\bar{\chi}}\bar{\chi}\chi S + \sum g_{sq\bar{q}}\bar{q}qS + \bar{\chi}(i\partial_\mu\gamma^\mu - m_\chi)\chi$$

$$\mathcal{L}_P = \frac{1}{2}\partial_\mu P \partial^\mu P - m_P^2 P^2 + \sum g_{s\chi\bar{\chi}}\bar{\chi}\gamma^5\chi P + \sum g_{sq\bar{q}}\bar{q}\gamma^5 qP + \bar{\chi}(i\partial_\mu\gamma^\mu - m_\chi)\chi$$

$$\begin{aligned}\mathcal{L}_T &= \frac{1}{2}D_\mu T D^\mu T - m_T^2 T^2 + \sum g_{T\chi\bar{\chi}}(\bar{\chi}qT^* + \text{c.c.}) \\ &\quad + \bar{\chi}(i\partial_\mu\gamma^\mu - m_\chi)\chi\end{aligned}$$

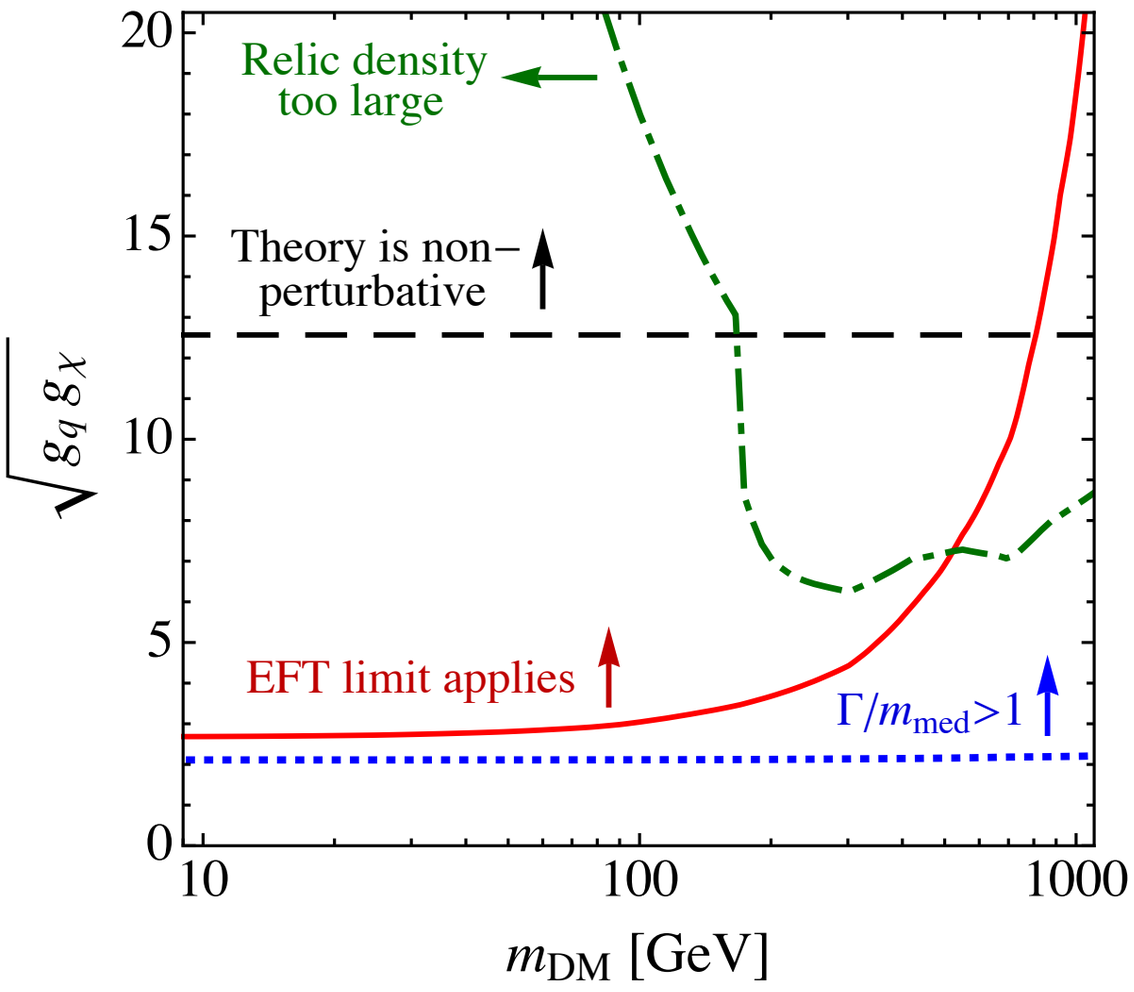
2

$$\begin{aligned}\mathcal{L}_{Z'} &= \sum g_{Z'\chi\bar{\chi}}\bar{\chi}\gamma^\mu\chi Z'^\mu + \sum g_{Z'q\bar{q}}\ \bar{q}\gamma^\mu q Z'^\mu \\ &\quad + \bar{\chi}(i\partial_\mu\gamma^\mu - m_\chi)\chi + \text{gaugeterms}\end{aligned}$$

$$\begin{aligned}\mathcal{L}_{A'} &= \sum g_{A'\chi\bar{\chi}}\bar{\chi}\gamma^\mu\gamma^5\chi A'^\mu + \sum g_{A'q\bar{q}}\ \bar{q}\gamma^\mu\gamma^5 q A'^\mu \\ &\quad + \bar{\chi}(i\partial_\mu\gamma^\mu - m_\chi)\chi + \text{gaugeterms}\end{aligned}$$

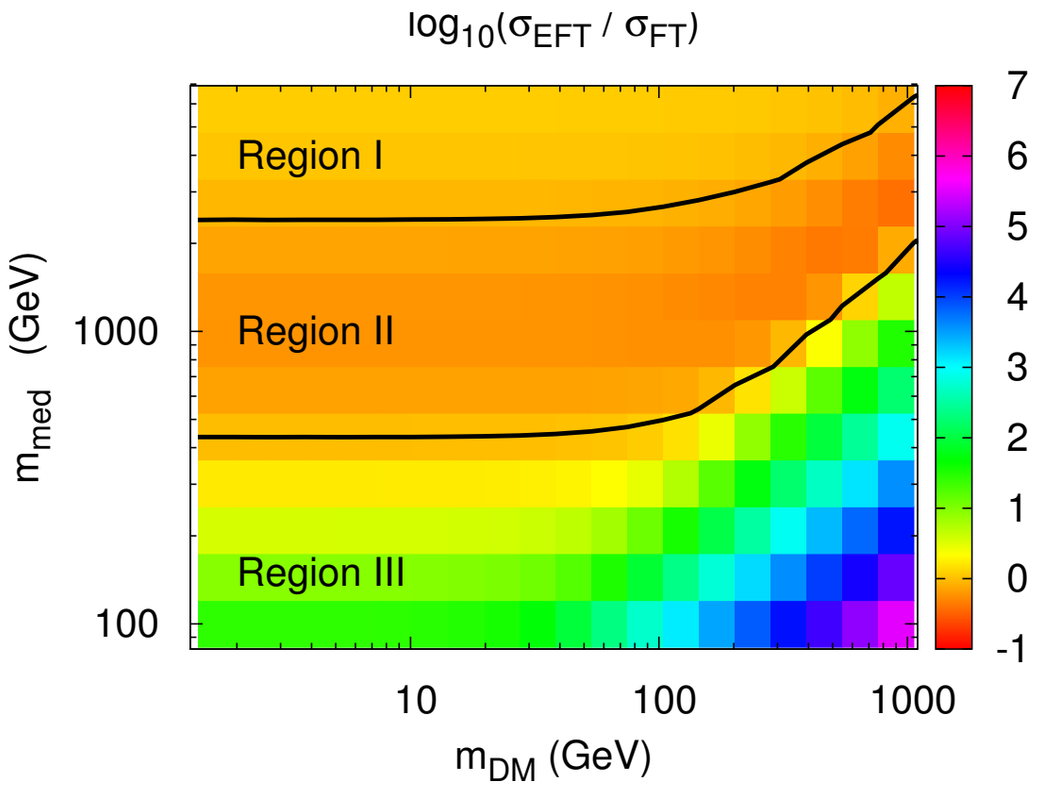
EXAMINING THE EFT-SIMP LINK MORE CLOSELY

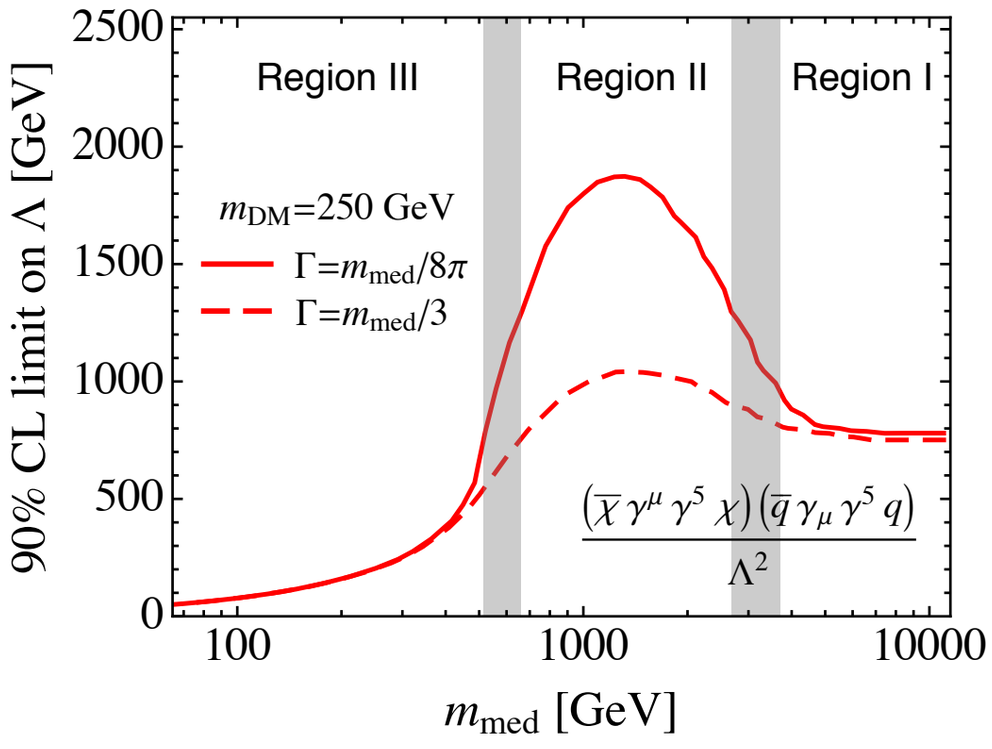
arXiv:1308.6799 Buchmueller et al.



$$\frac{\Gamma}{m_{\rm med}} = \frac{N_C\, g_f^2}{12\pi}\left(1-\frac{4m_f^2}{m_{\rm med}^2}\right)^{3/2}$$

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





LOOKING FOR THE MEDIATOR

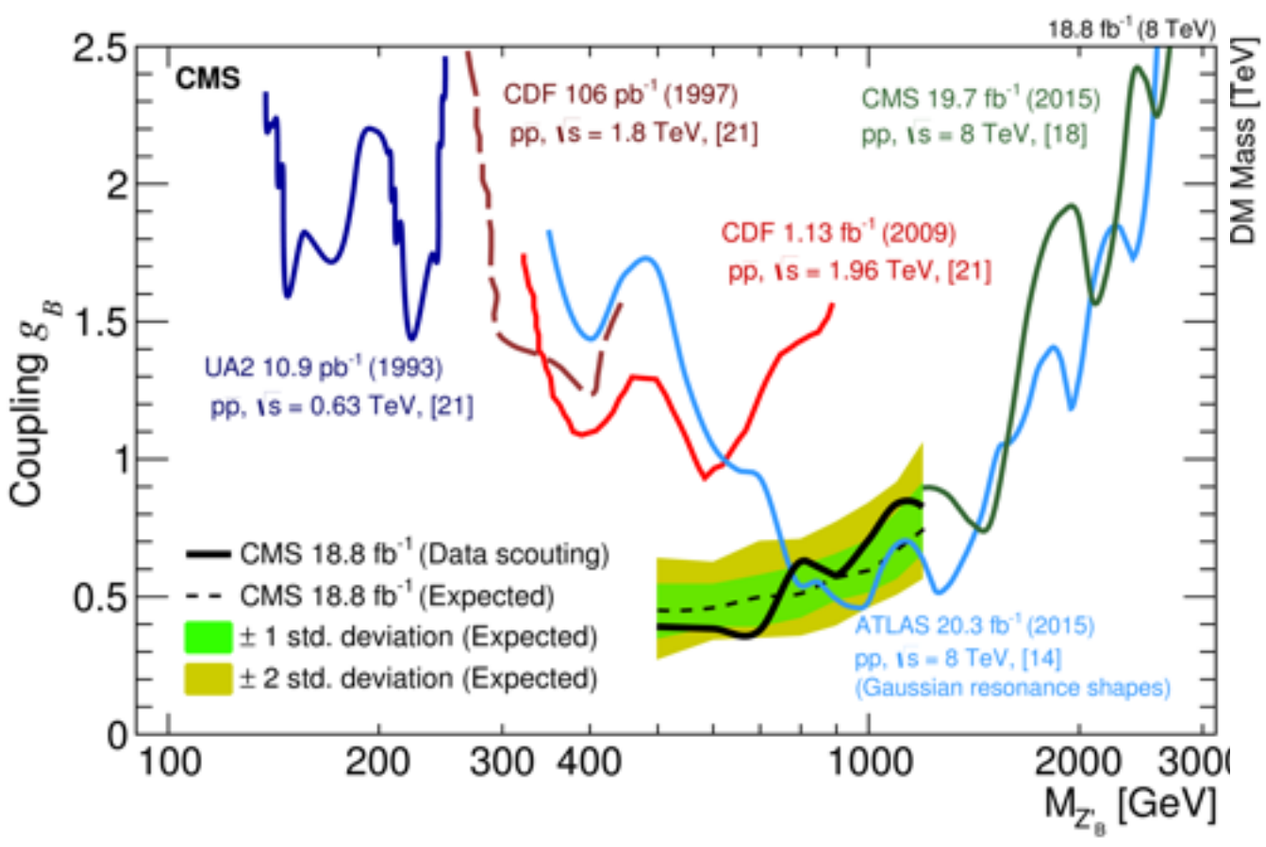
ATLAS Exotics Searches* - 95% CL Exclusion

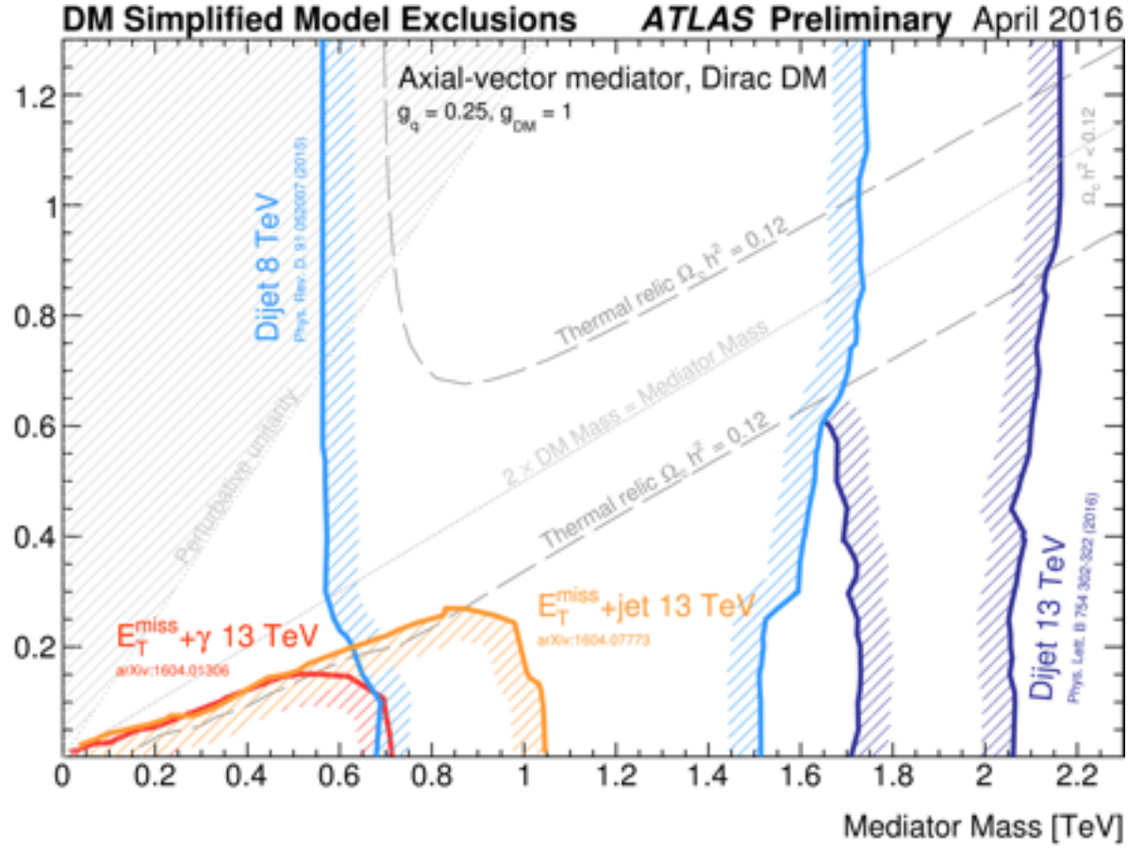
Status: March 2016

ATLAS Preliminary

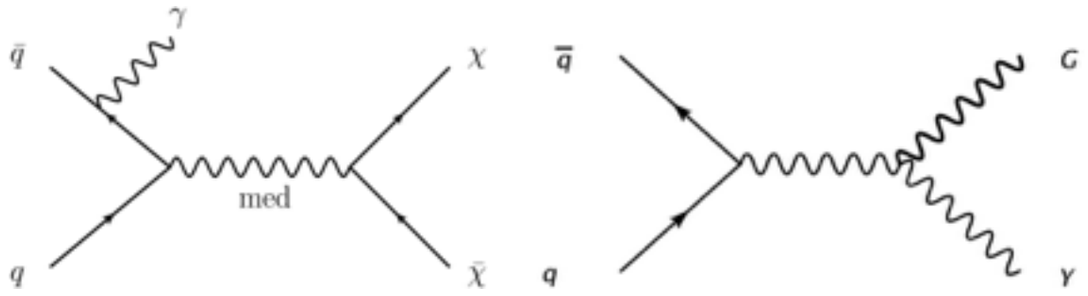
$\int \mathcal{L}\, dt$ = (3.2 - 20.3) fb^{-1} $\sqrt{s}$ = 8, 13 TeV

Gauge bosons	SSM $Z' \to \ell\ell$	2 e,μ	–	–	3.2	Z' mass	3.4 TeV		ATLAS-CONF-2015-070
	SSM $Z' \to \tau\tau$	2 τ	–	–	19.5	Z' mass	2.02 TeV		1502.07177
	Leptophobic $Z' \to bb$	–	2 b	–	3.2	Z' mass	1.5 TeV		Preliminary
	SSM $W' \to \ell\nu$	1 e,μ	–	Yes	3.2	W' mass	4.07 TeV		ATLAS-CONF-2015-063
	HVT $W' \to WZ \to qq\nu\nu$ model A	0 e,μ	1 J	Yes	3.2	W' mass	1.6 TeV	$g_V = 1$	ATLAS-CONF-2015-068
	HVT $W' \to WZ \to qqqq$ model A	–	2 J	–	3.2	W' mass	1.38-1.6 TeV	$g_V = 1$	ATLAS-CONF-2015-073
	HVT $W' \to WH \to \ell\nu bb$ model B	1 e,μ	1-2 b, 1-0 j	Yes	3.2	W' mass	1.62 TeV	$g_V = 3$	ATLAS-CONF-2015-074
	HVT $Z' \to ZH \to \nu\nu bb$ model B	0 e,μ	1-2 b, 1-0 j	Yes	3.2	Z' mass	1.76 TeV	$g_V = 3$	ATLAS-CONF-2015-074
	LRSM $W'_R \to tb$	1 e,μ	2 b, 0-1 j	Yes	20.3	W' mass	1.92 TeV		1410.4103
	LRSM $W'_R \to tb$	0 e,μ	≥ 1 b, 1 J	–	20.3	W' mass	1.76 TeV		1408.0886



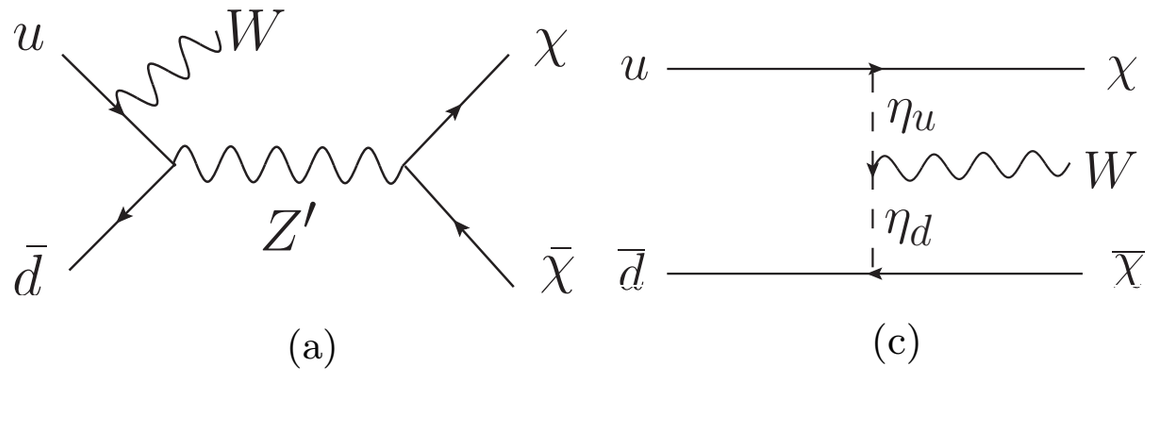


MONO-PHOTON



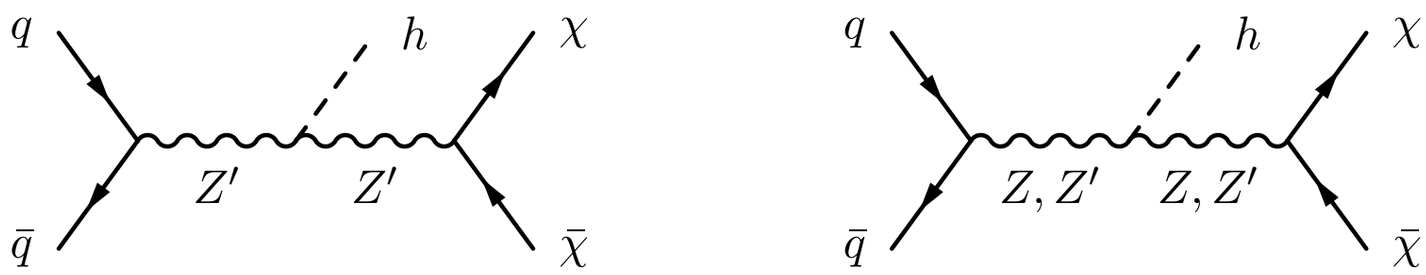
MONO-W

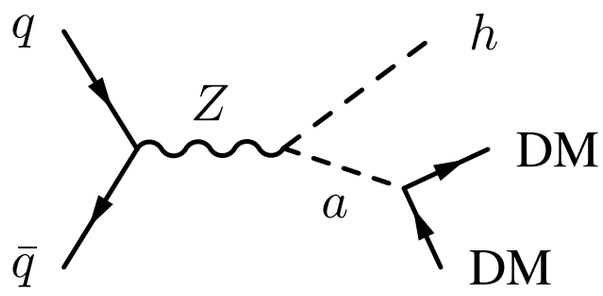
arXiv:1512.00476

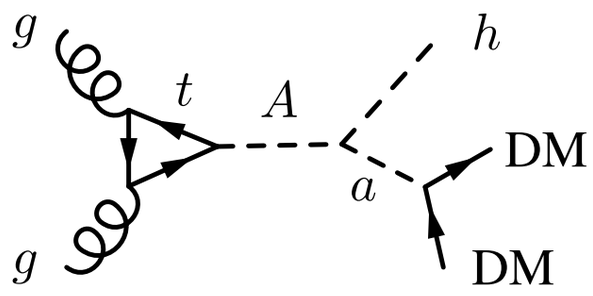


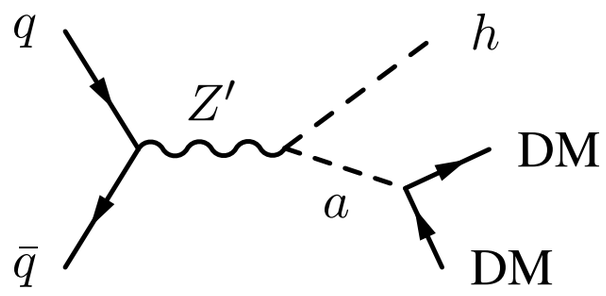
MONO-H

Carpenter et al. (2013)





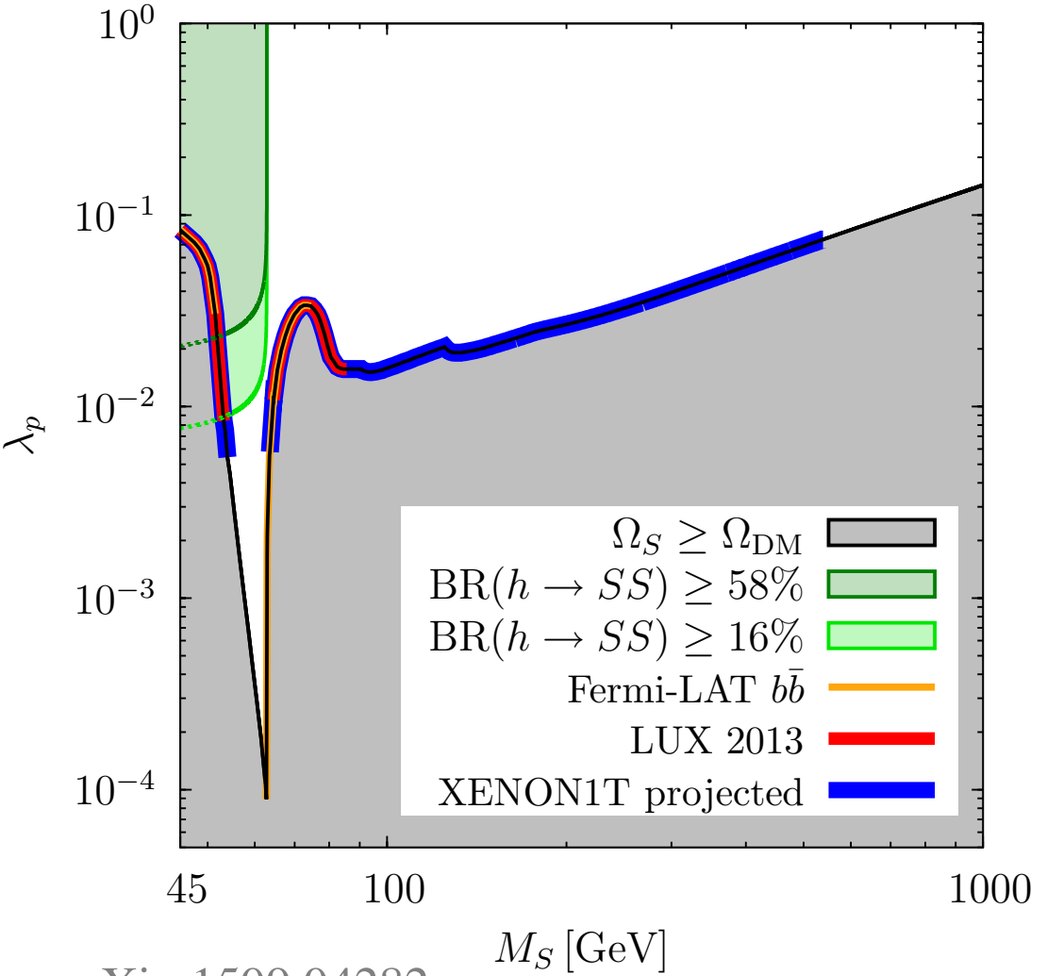




HIGGS PORTAL DM

$$\mathcal{L}_{\text{scalar},H} \supset -\lambda_\chi \chi^4 - \lambda_p \chi^2 |H|^2 \,,$$

$$\Gamma(h \to \chi\chi) = \frac{\lambda_p^2 v^2}{2\pi m_h} \left(1 - \frac{4m_\chi^2}{m_h^2}\right)^{1/2}$$

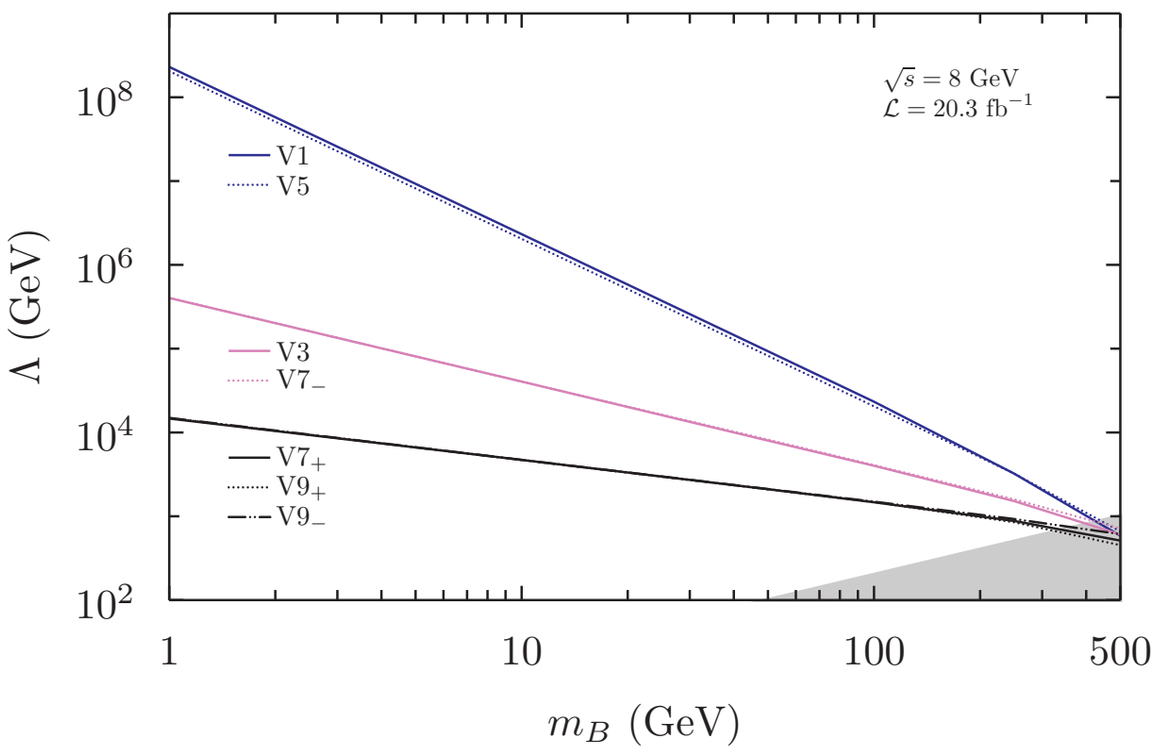


arXiv:1509.04282

VECTOR DM

Operator	Structure	Dim D
V1	$(1/\Lambda) B_\mu^\dagger B^\mu \bar{q} q$	5
V2	$(1/\Lambda) \imath B_\mu^\dagger B^\mu \bar{q} \gamma^5 q$	5

arXiv:1508.04466



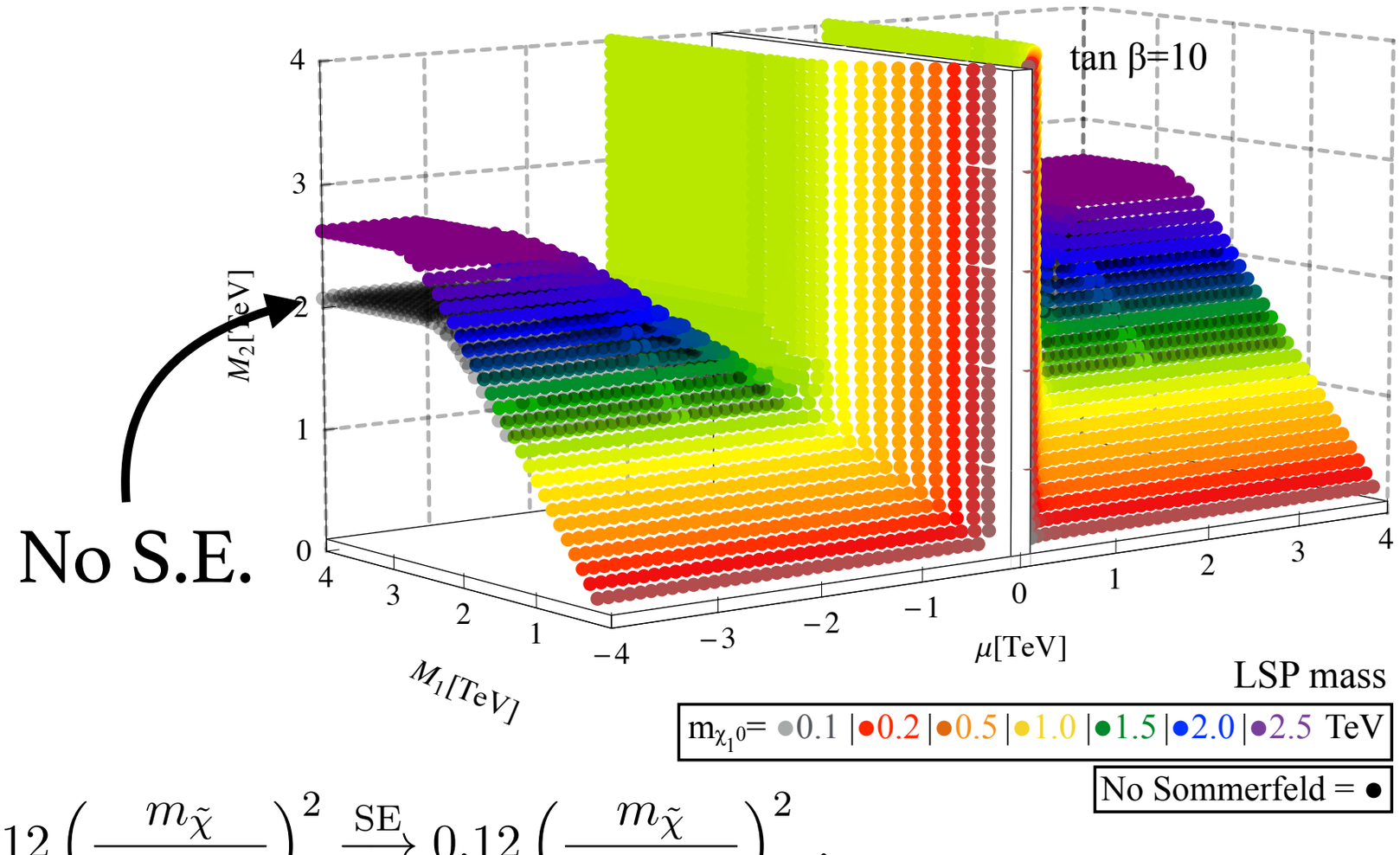
EXAMPLE OF A UV-COMPLETE MODEL: SUSY

- What kinds of interactions?
- Co-annihilation
- Sommerfeld enhancement
- Direct detection constraints
- Indirect detection constraints

$$g_{Z\tilde{\chi}_1^0\tilde{\chi}_1^0} = \frac{g}{2\cos\theta_w}\left(|N_{13}|^2 - |N_{14}|^2\right)$$

$$g_{h\tilde{\chi}_1^0\tilde{\chi}_1^0} = \left(gN_{11} - g'N_{12}\right)\left(\sin\alpha\, N_{13} + \cos\alpha\, N_{14}\right)$$

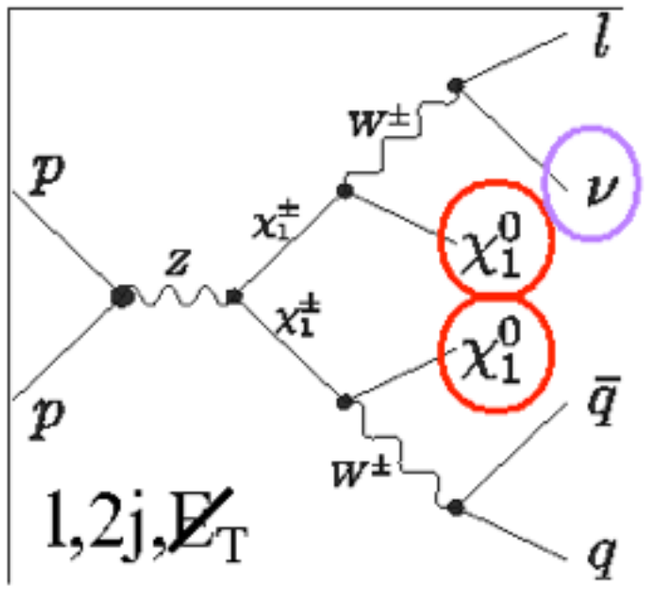
$$g_{W\tilde{\chi}_1^0\tilde{\chi}_1^+} = \frac{g\sin\theta_w}{\sqrt{2}\cos\theta_w}\left(N_{14}V_{12}^* - \sqrt{2}N_{12}V_{11}^*\right) ,$$

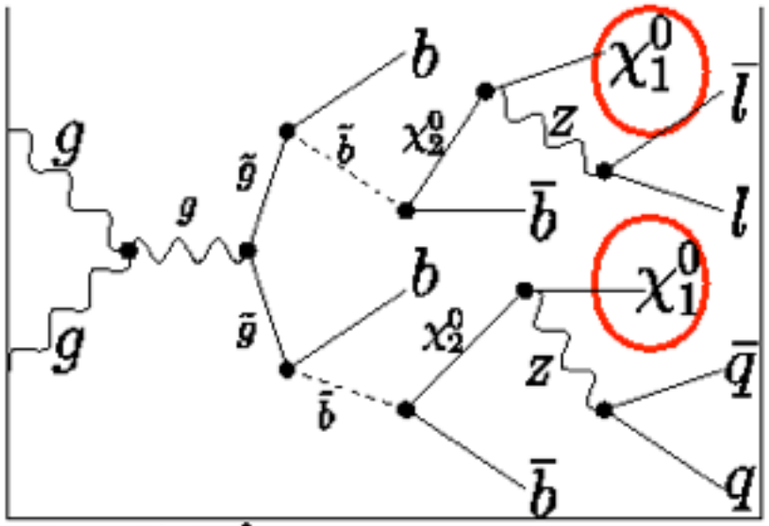


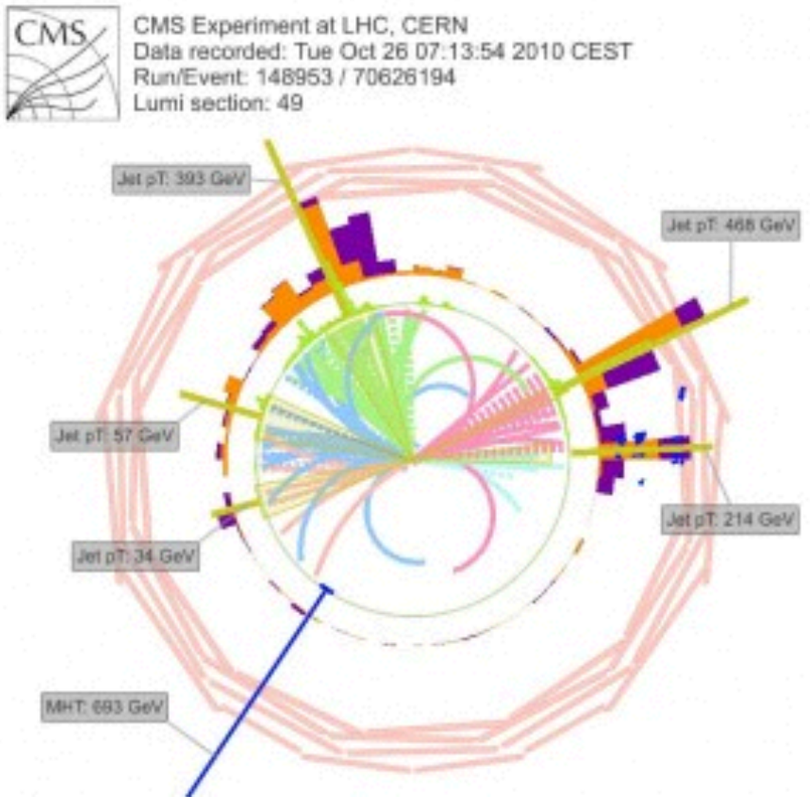
$$\Omega_{\tilde{W}}h^2 \simeq 0.12\left(\frac{m_{\tilde{\chi}}}{2.1\ \text{TeV}}\right)^2 \xrightarrow{\text{SE}} 0.12\left(\frac{m_{\tilde{\chi}}}{2.6\ \text{TeV}}\right)^2 .$$

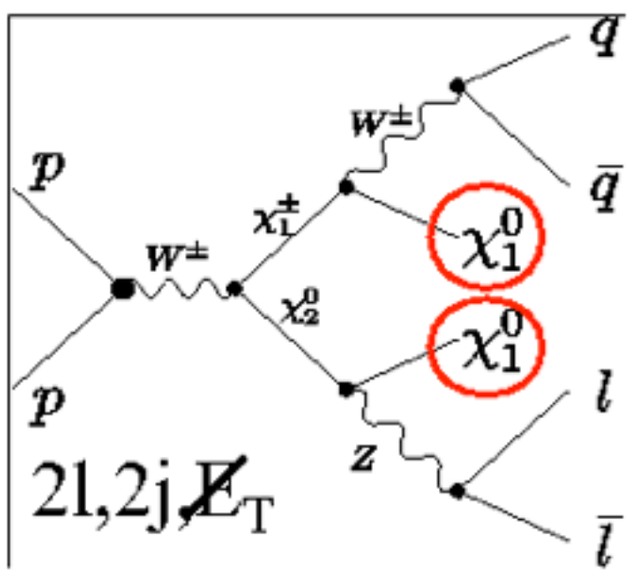
$$\Omega_{\tilde{H}}h^2 \simeq 0.12\left(\frac{m_{\tilde{\chi}}}{1.13\ \text{TeV}}\right)^2 \xrightarrow{\text{SE}} 0.12\left(\frac{m_{\tilde{\chi}}}{1.14\ \text{TeV}}\right)^2 .$$

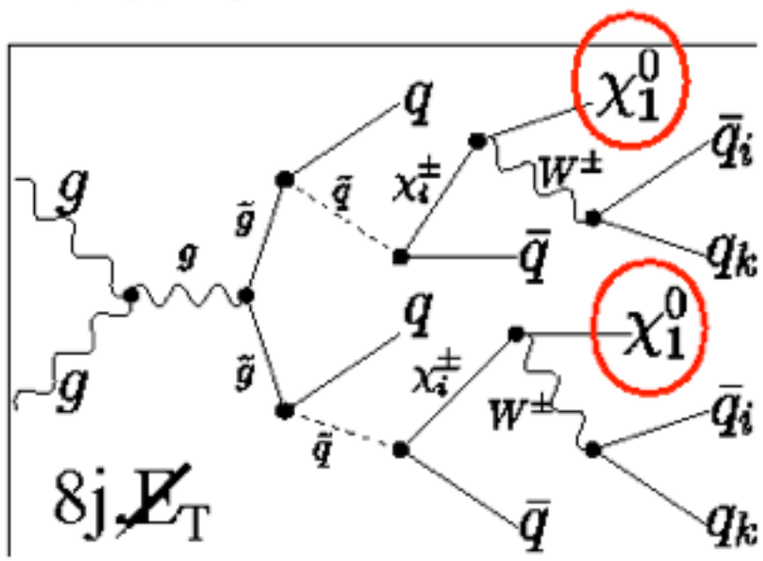
OBSERVING LSP PRODUCTION AT THE LHC: JETS + MET





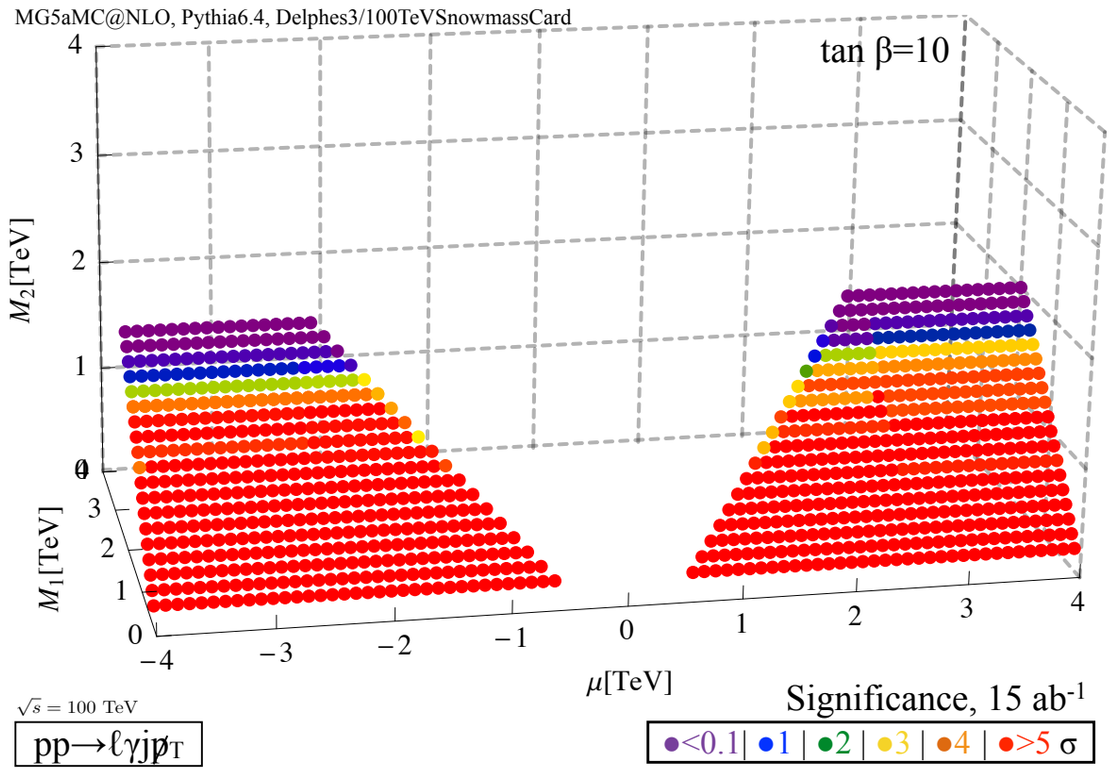


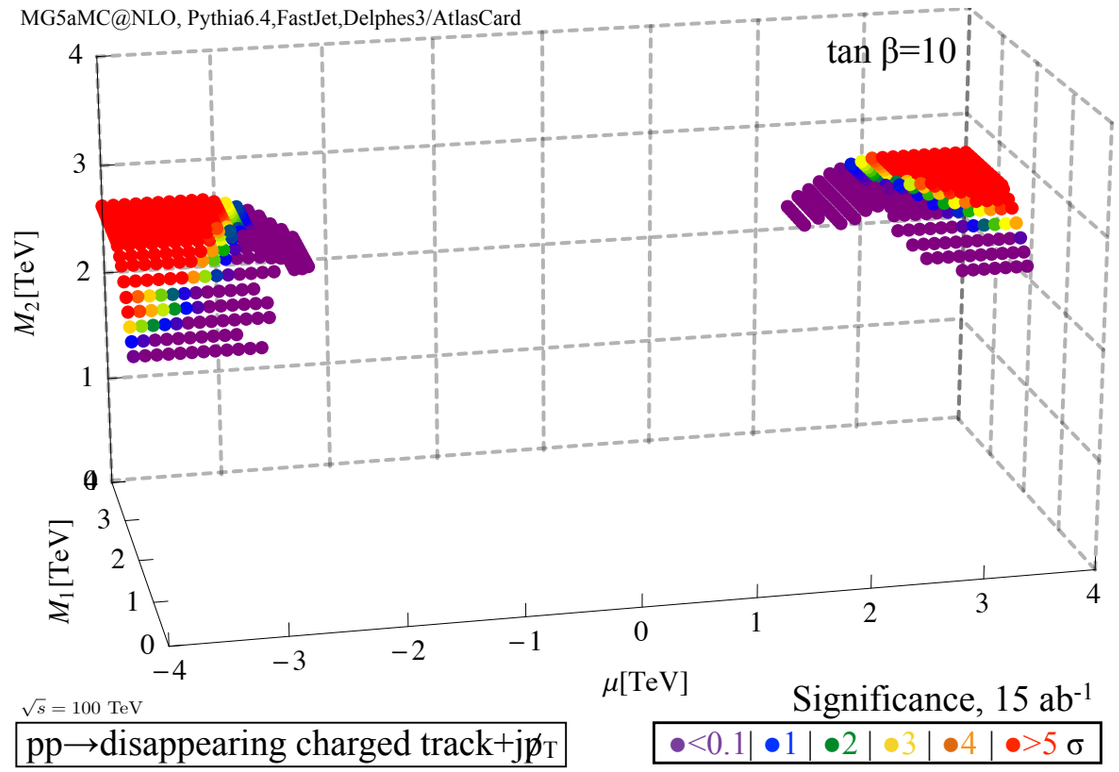




(POTENTIAL) COLLIDER SEARCHES

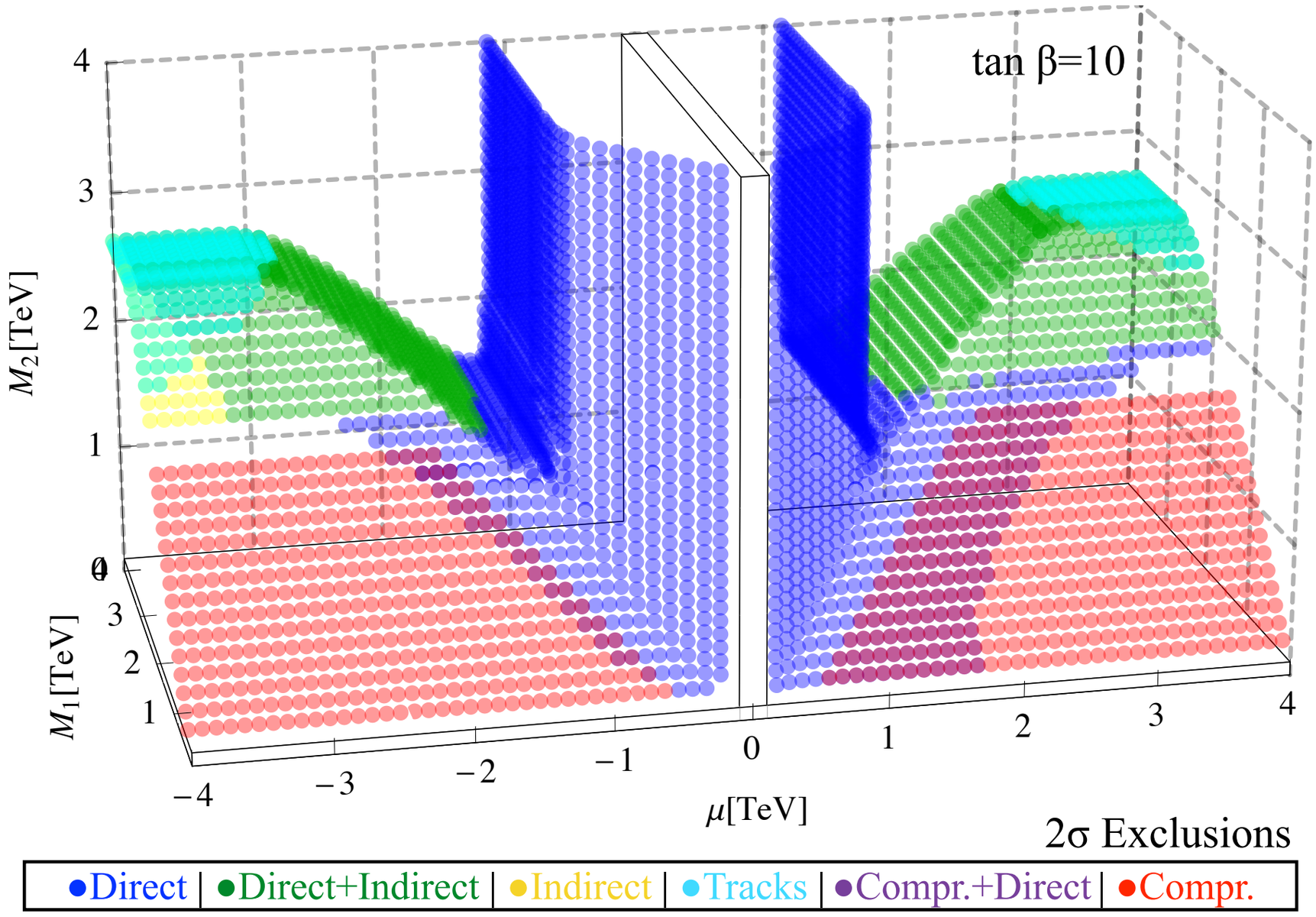
$$pp \to (\tilde{\chi}_2^0 \to \gamma\tilde{\chi}_1^0)\,(\tilde{\chi}_1^\pm \to \ell^\pm\nu_\ell\tilde{\chi}_1^0)j \to \tilde{\chi}_1^0\tilde{\chi}_1^0\ell^\pm\nu_\ell\gamma j\ ,$$



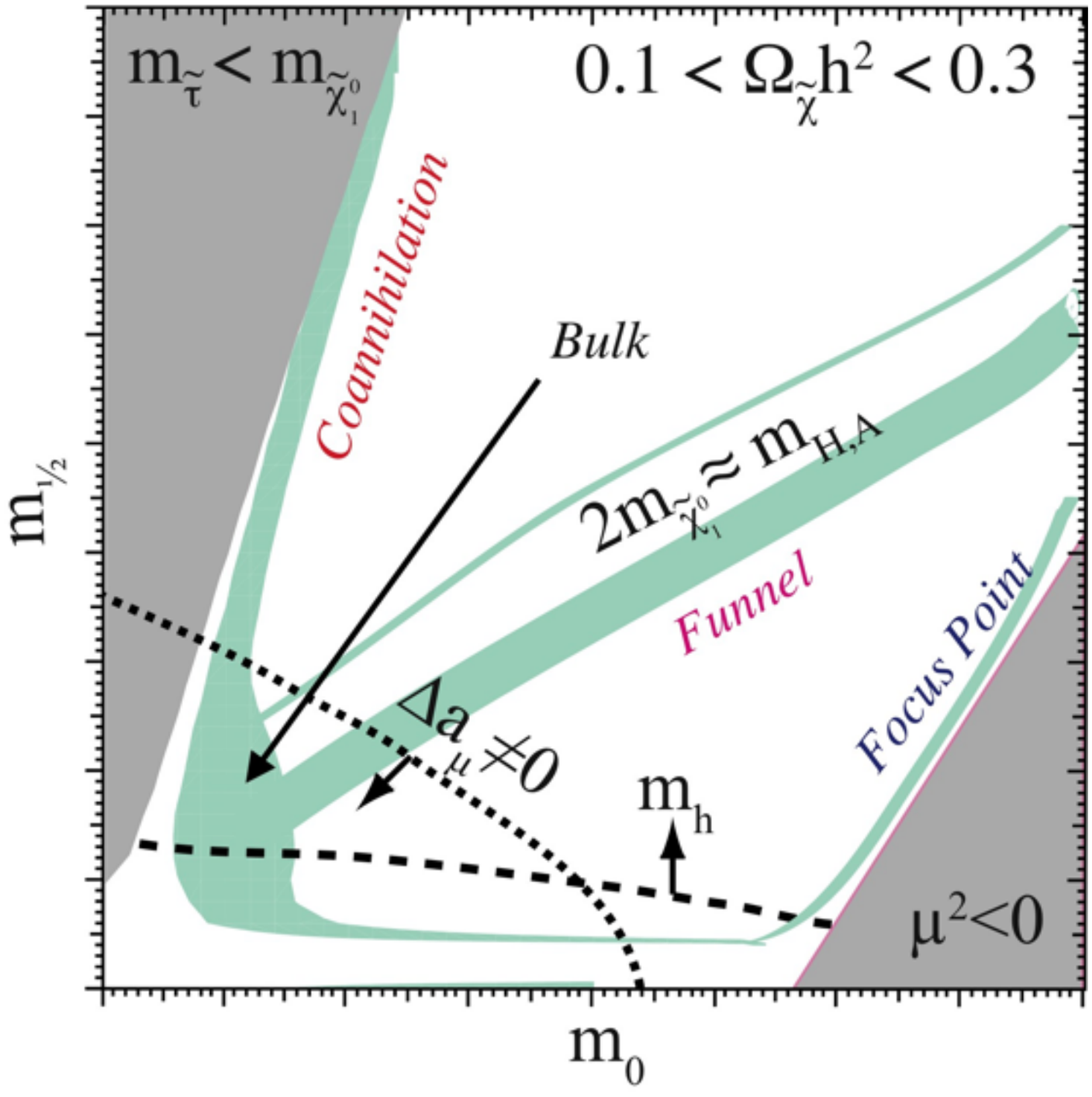


$$pp \to \chi_1^+\chi_1^-,\ \chi_1^0\chi_1^+$$

PUTTING IT ALL TOGETHER



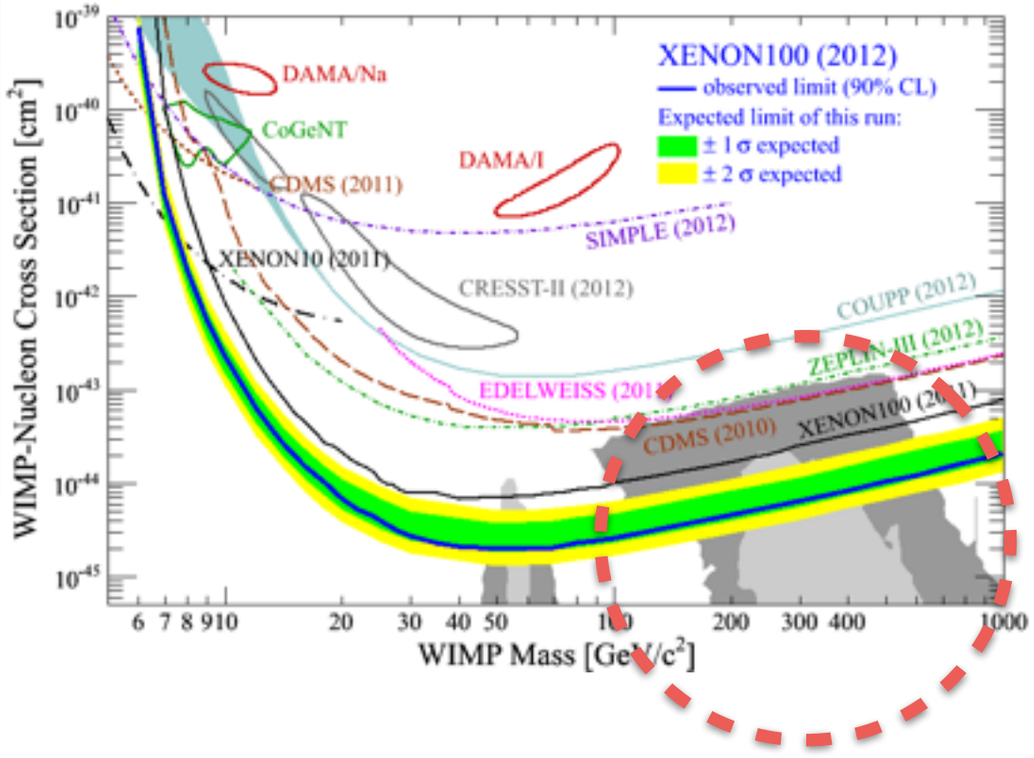
COANNIHILATION WITH SFERMIONS (STAUS)



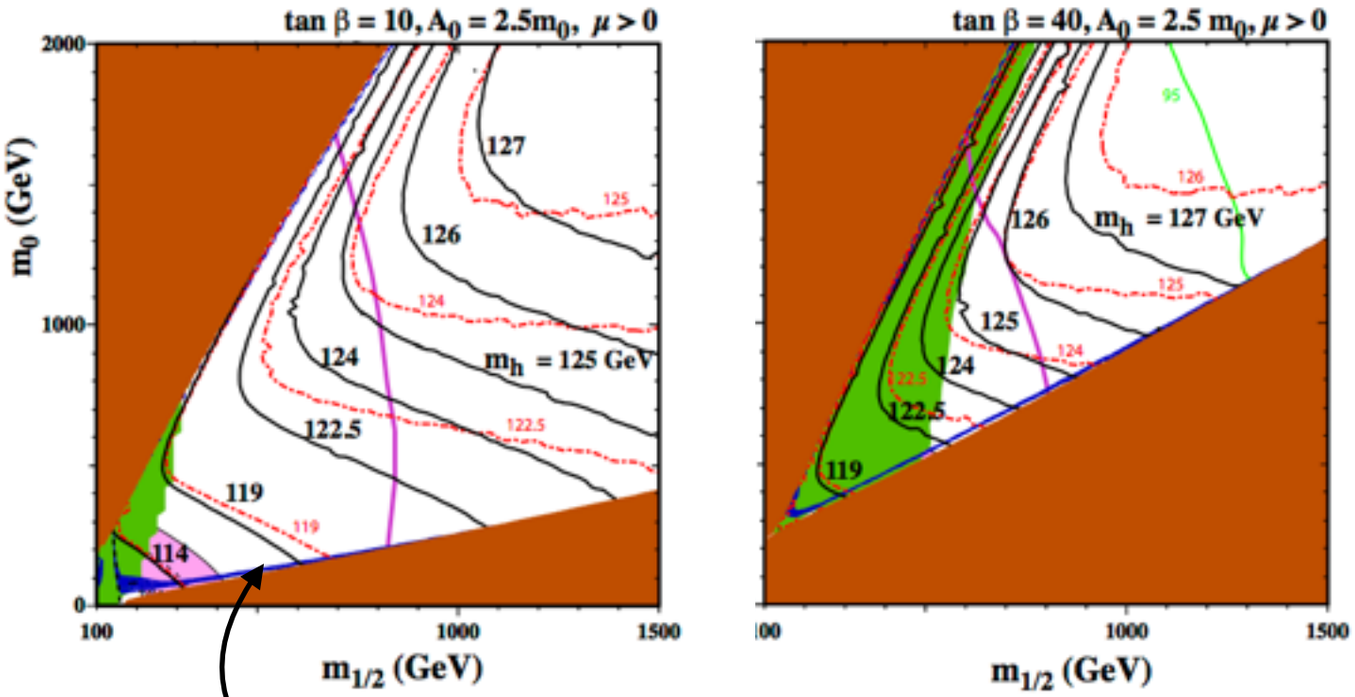
http://www.nevis.columbia.edu/~mcooke/susy_page/susy.html

we use:

$$0.115 < \Omega_\chi h^2 < 0.125$$

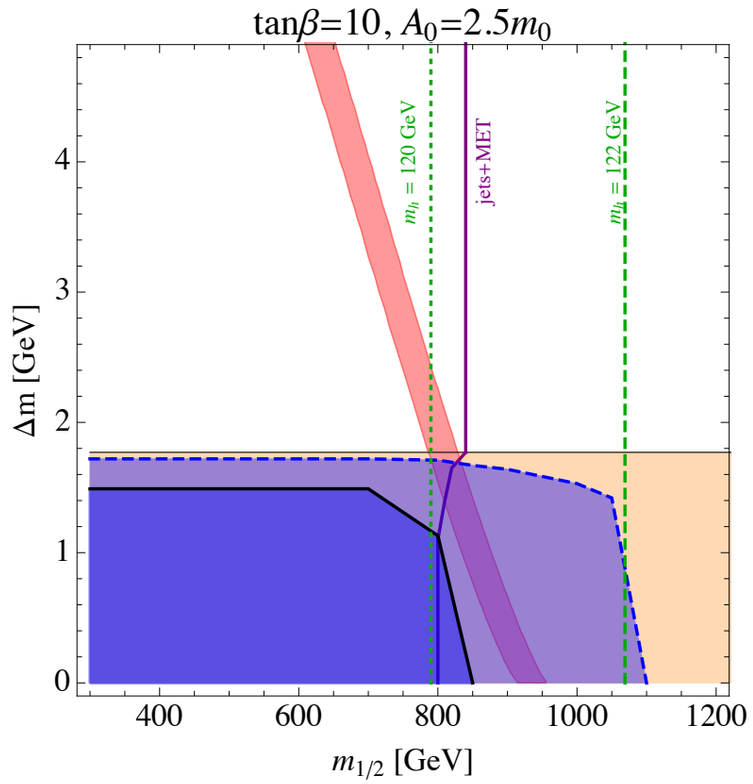


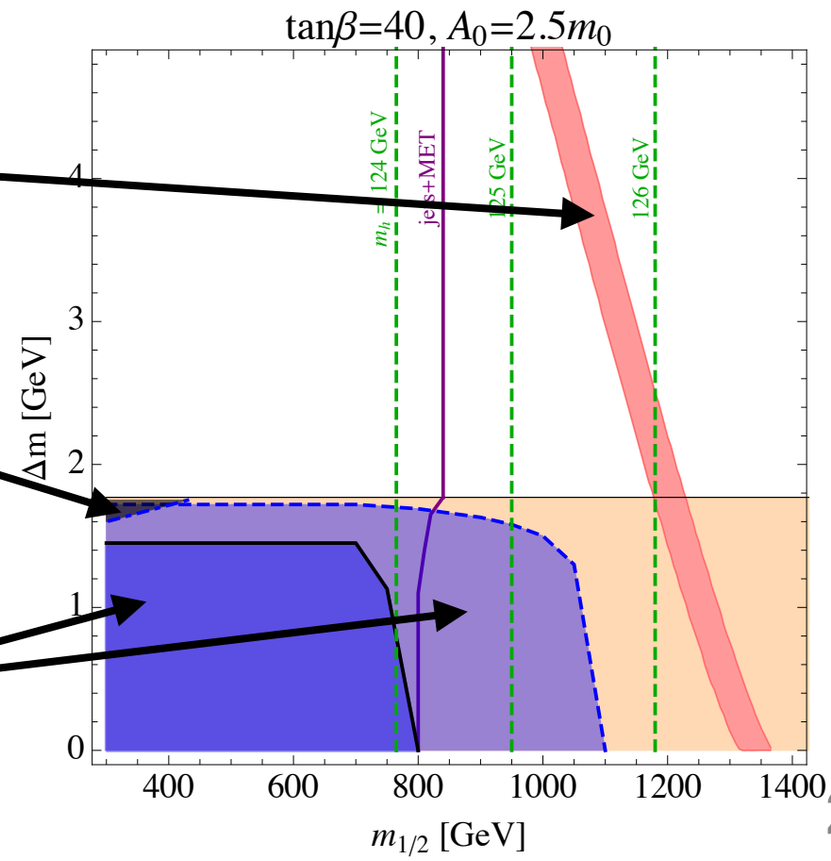
LIMITS FOR THE STAU-COANNIHILATION REGION



$m_\tau > \Delta m$

= Long-lived or stable staus





Disappearing tracks

Charged tracks

IN SUMMARY

- You can (and should) look for DM at the LHC
- EFT approach simple but not wholly unambiguous, tread with care.
- Simplified models are useful as a first strike, but also quite simplistic.
- Real UV complete theories may have more particles in the Dark Sector that one can probe.
- Much more to come in future …