SIGNALS AND THEORIES FOR DARK MATTER

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CERN-Fermilab School
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THE SEARCH FOR DARK MATTER IS A STORY OF LAMP POSTS

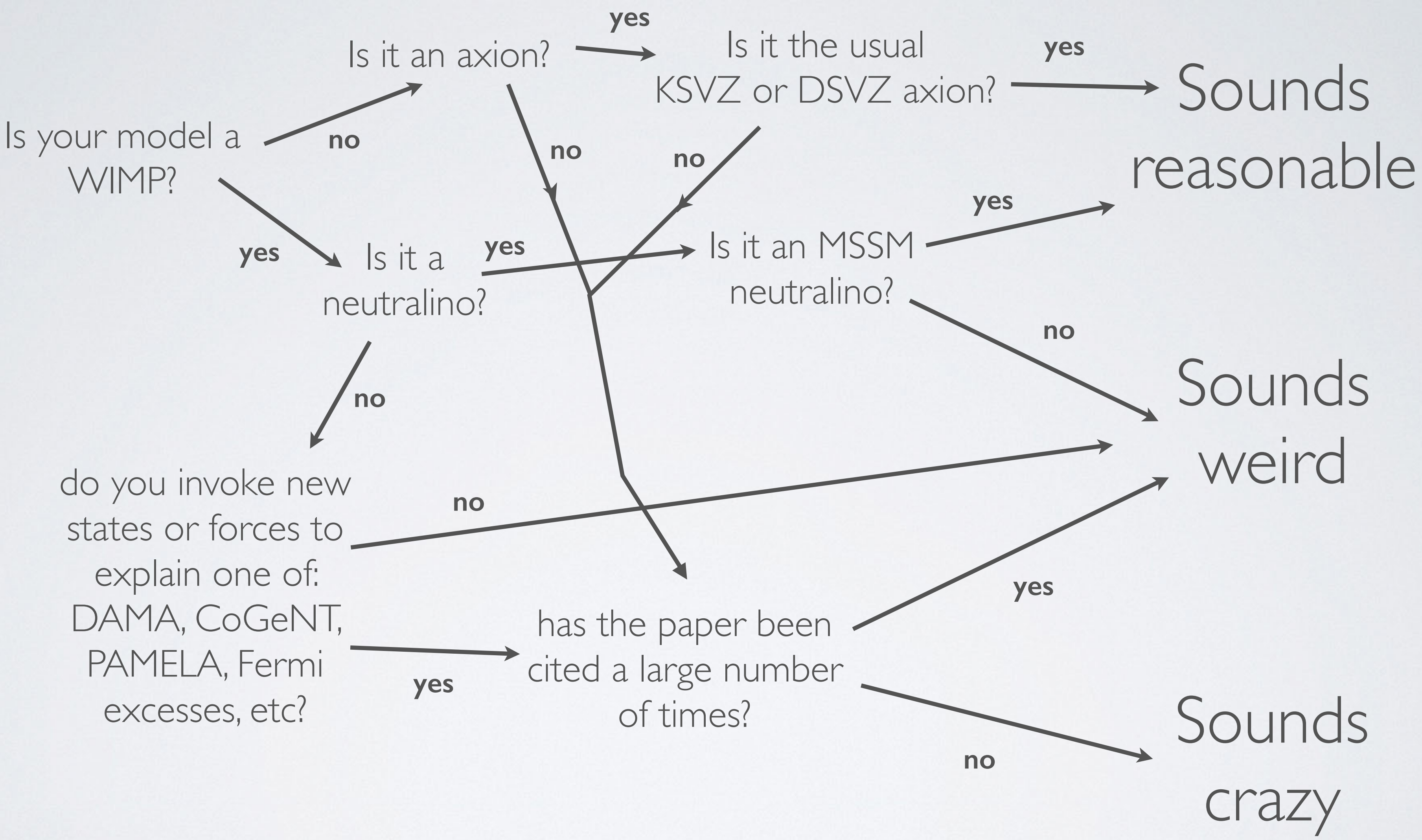
THE ZOOLOGY OF DARK MATTER

Three basic categories of dark matter:

Reasonable Weird Crazy

sometimes also
called "normal"

(also "obviously wrong")



Is your model a WIMP?

no

Is it an axion?

yes

Is it the usual KSVZ or DSVZ axion?

yes

Sounds reasonable

no

no

yes

Is it a neutralino?

yes

Is it an MSSM neutralino?

yes

no

no

Sounds weird

do you invoke new states or forces to explain one of: DAMA, CoGeNT, PAMELA, Fermi excesses, etc?

no

yes

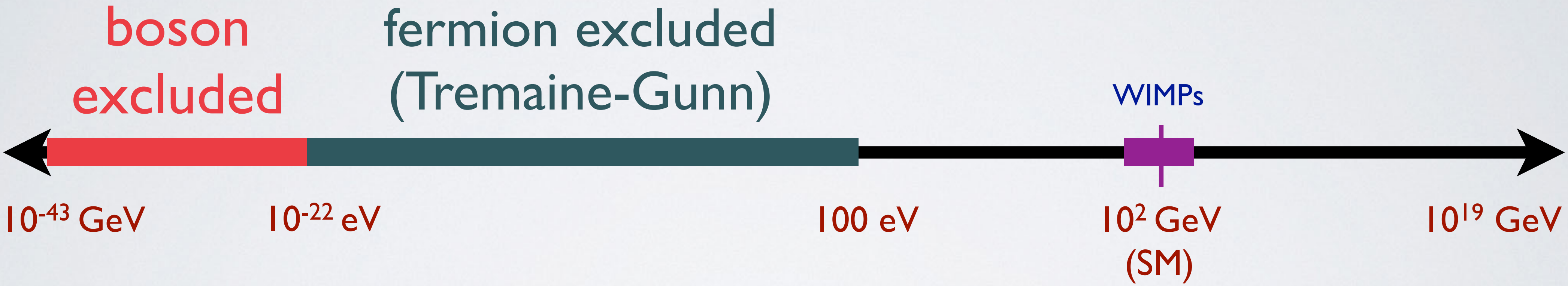
has the paper been cited a large number of times?

yes

no

Sounds crazy

THE SCALES OF DARK MATTER



boson excluded

fermion excluded (Tremaine-Gunn)

WIMPs

10^{-43} GeV

10^{-22} eV

100 eV

10^{2} GeV (SM)

10^{19} GeV

(courtesy S. Rajendran)

APPROACHING DARK MATTER THEORIES

- “Top down” - Begin with theory motivation (hierarchy problem, strong CP problem..) develop model (SUSY, axion) look for stable, neutral particle (LSP, axion)
- “Bottom up” - Motivated often by specific experimental anomalies, theories constructed. Implications for other experiments (and often SUSY)
- “Phenomenological” - Motivated by considering whether a viable and detectable model could exist of a certain type
- All give some hope of detection (almost by design)

OUTLINE

- Briefly on the axion
- A WIMP status update
- Dark forces and anomaly mediated dark matter: two cases

A STRONG CP PR0BLEM

$$\theta G_{\mu\nu} \tilde{G}^{\mu\nu}$$

leads to neutron EDM => less than 10-10

critical point 1: quark mass matrix phase contributes

critical point 2: this is a real problem for QFT

A STRONG CP PR0BLEM

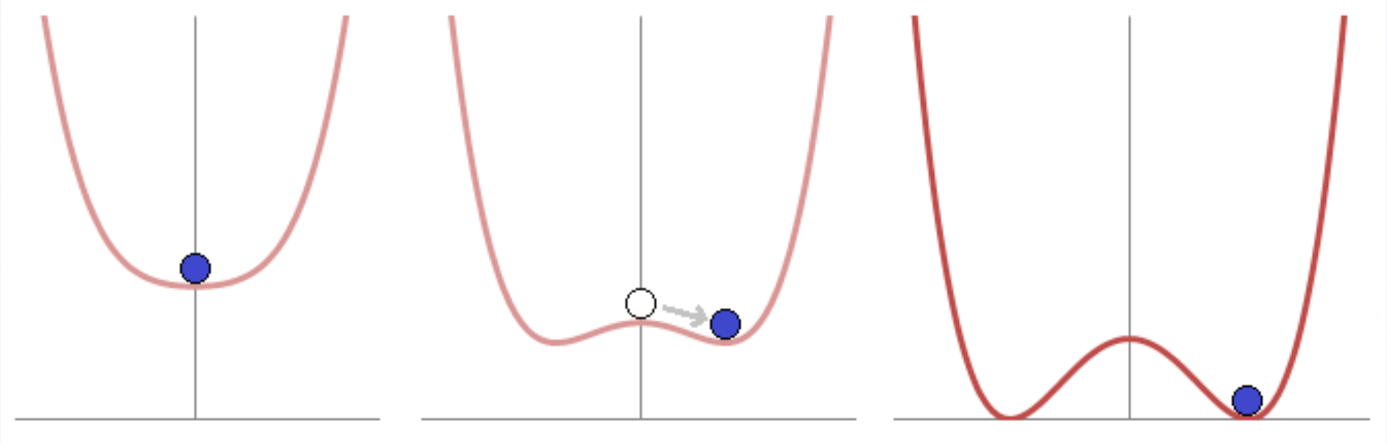
$$\theta G_{\mu\nu}\tilde{G}^{\mu\nu} \longrightarrow \frac{a}{f_a} G_{\mu\nu}\tilde{G}^{\mu\nu}$$

idea -> make θ a field

THE AXION

Peccei, Quinn; Weinberg, Wilczek

- Pseudo-goldstone boson arising from a global symmetry breaking



← higher temp lower temp →

- This symmetry breaking occurs at some scale f_a

THE AXION

Peccei, Quinn; Weinberg, Wilczek

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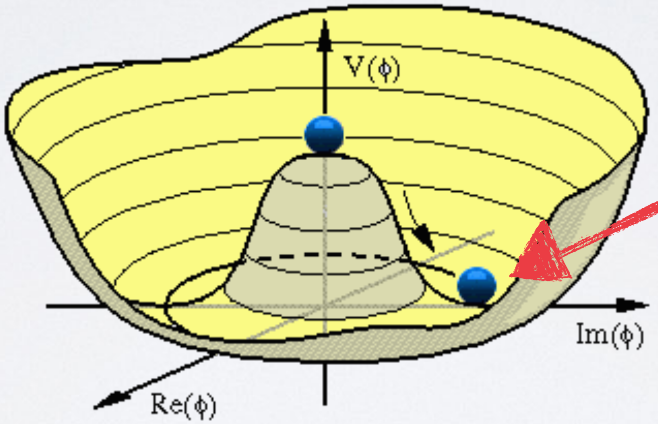


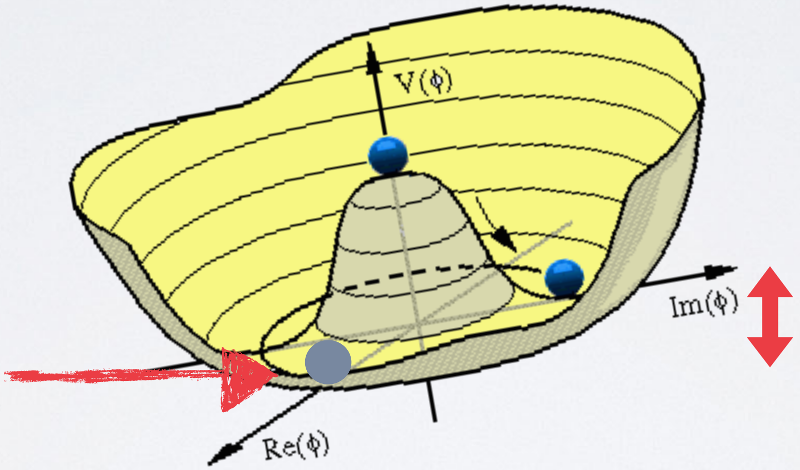
motions along valley correspond to massless particle

For the axion, this flat direction is identified with the QCD θ (or $\bar{\theta}$ parameter)

THE AXION

Peccei, Quinn; Weinberg, Wilczek

This symmetry is anomalous and QCD instanton effects "tilt" this potential at T~Λ_{QCD}, leading to a minimum at θ=0



potential minimum

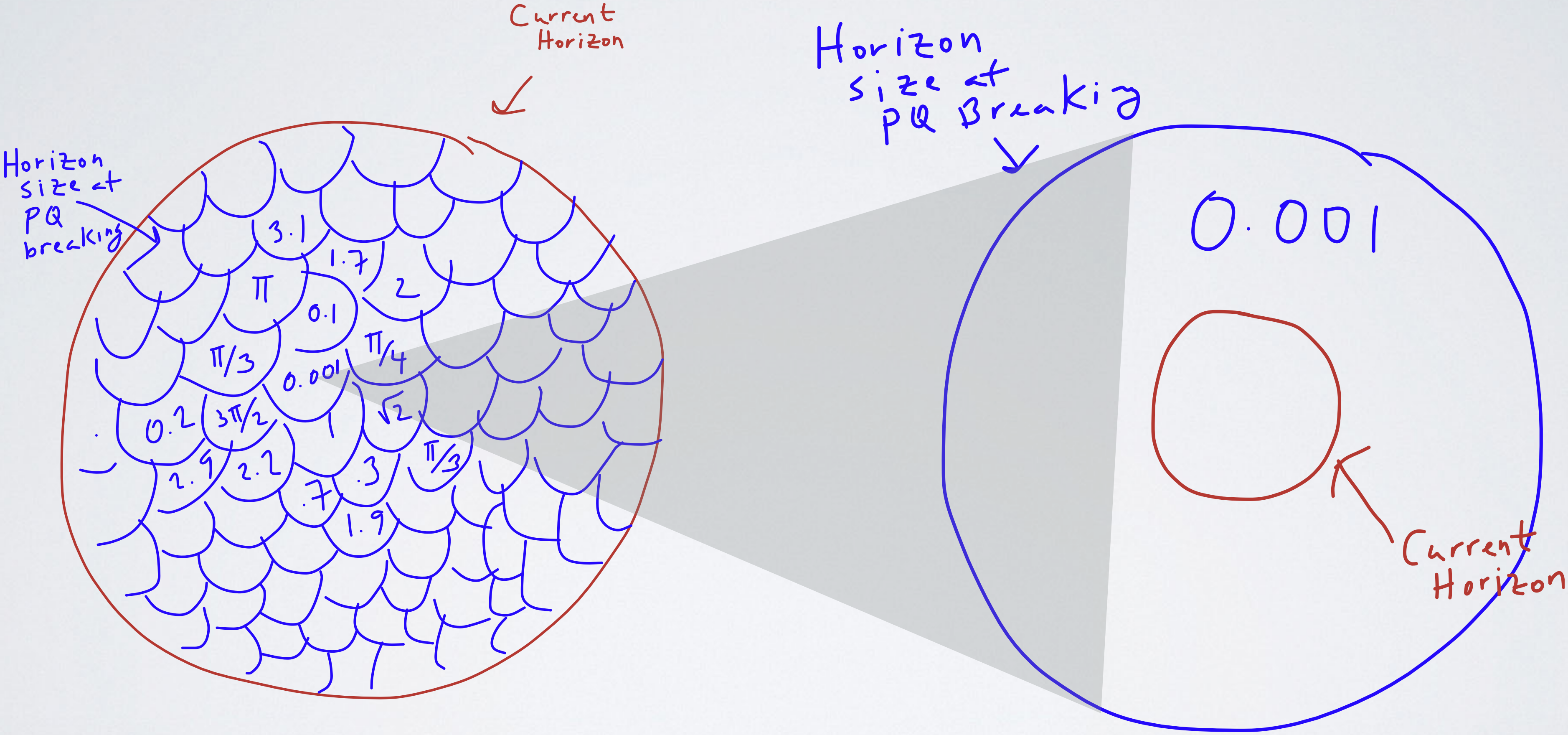
energy density in dark matter

The axion acquires a mass $\frac{m_\pi f_\pi}{f_a} \approx 0.6\mathrm{meV}\left(\frac{10^{10}\mathrm{GeV}}{f_a}\right)$

TWO HISTORIES

PQ Phase Transition
After Inflation

PQ Phase Transition
Before Inflation

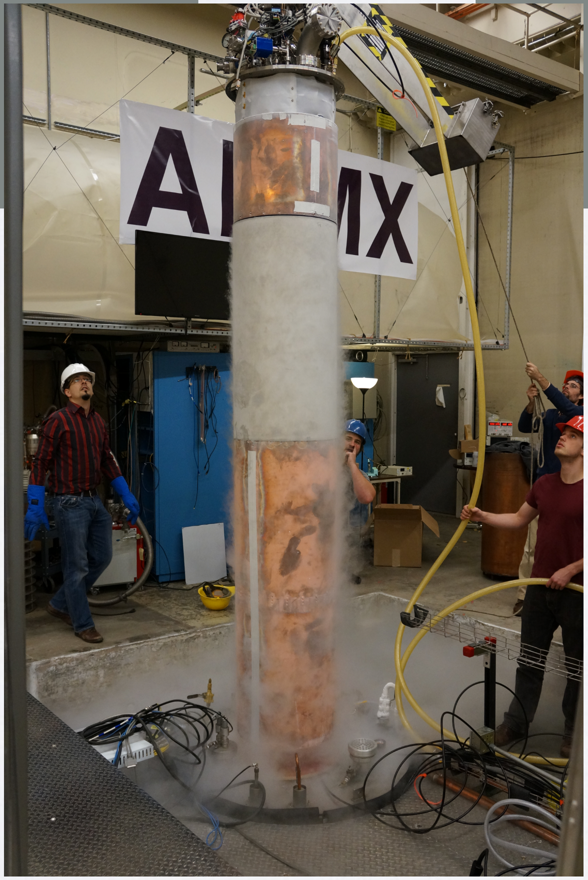


O(1) on average

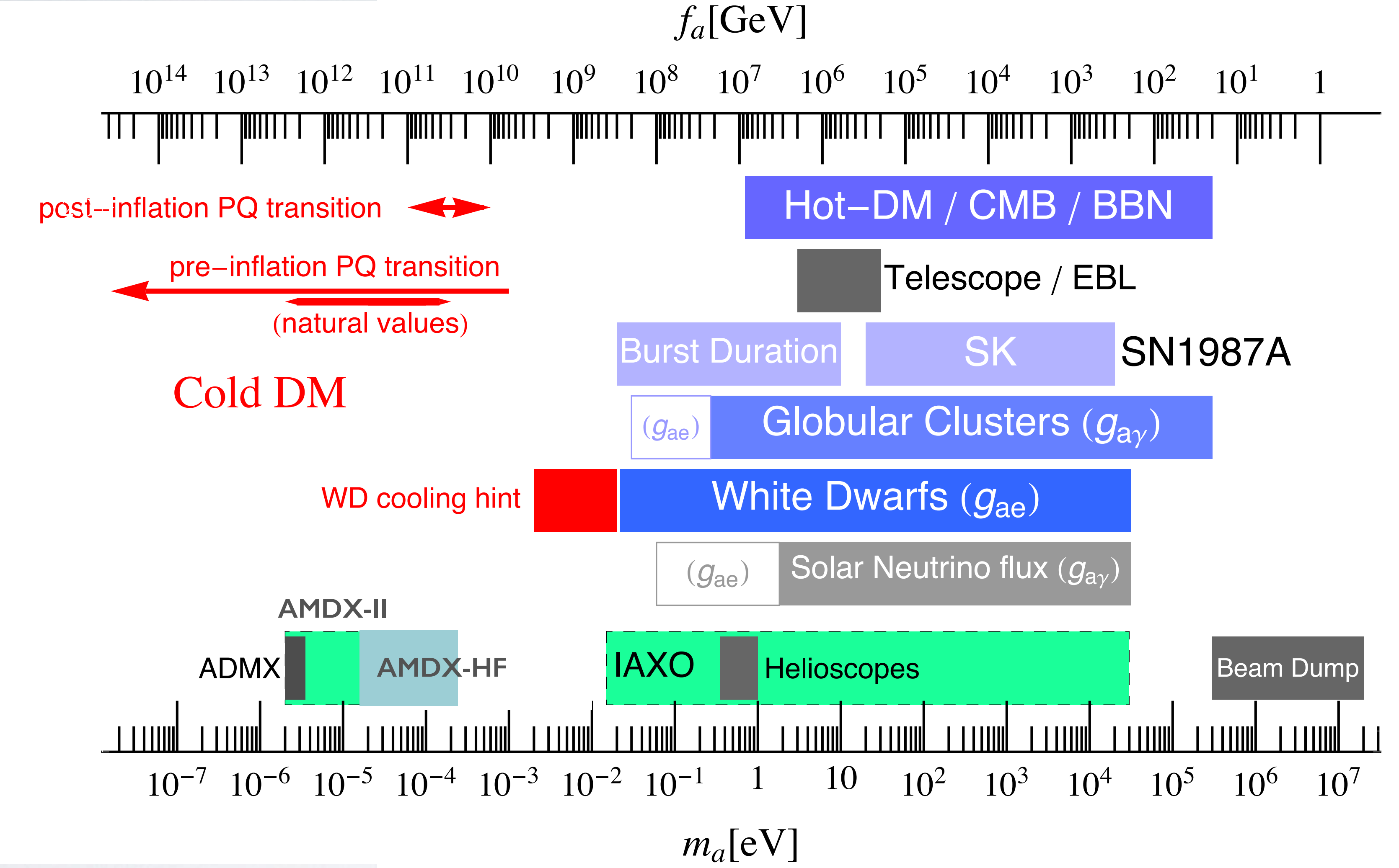
Could be anything -
anthropic arguments(?)

COUPLINGS TO OTHER MATTER

$$\frac{a}{f_a} G_{\mu\nu}\tilde{G}^{\mu\nu} \longrightarrow \frac{a}{f_a} F_{\mu\nu}\tilde{F}^{\mu\nu}$$



Axion parameters (adapted from Essig et al 1311.0029 via PDG)



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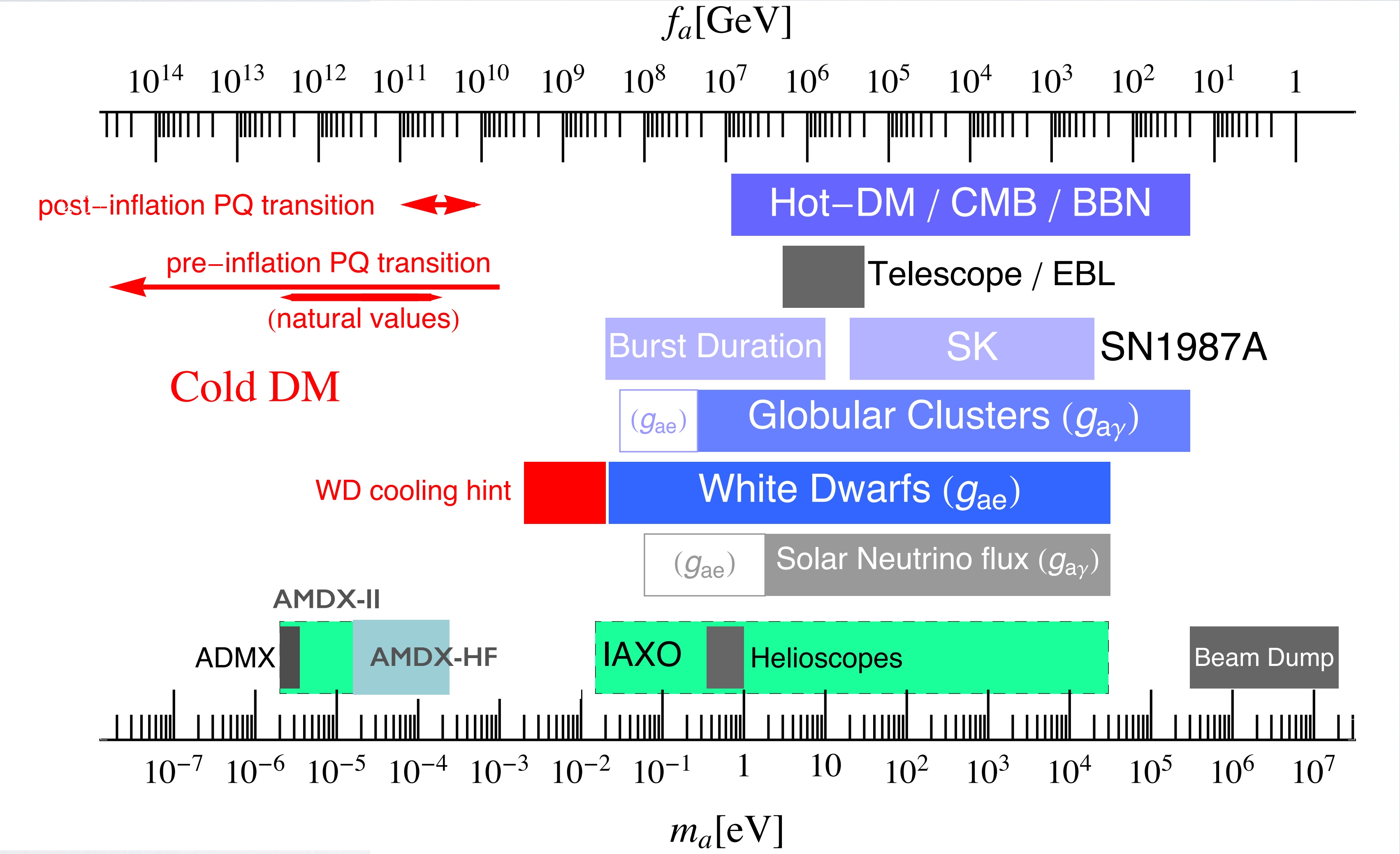
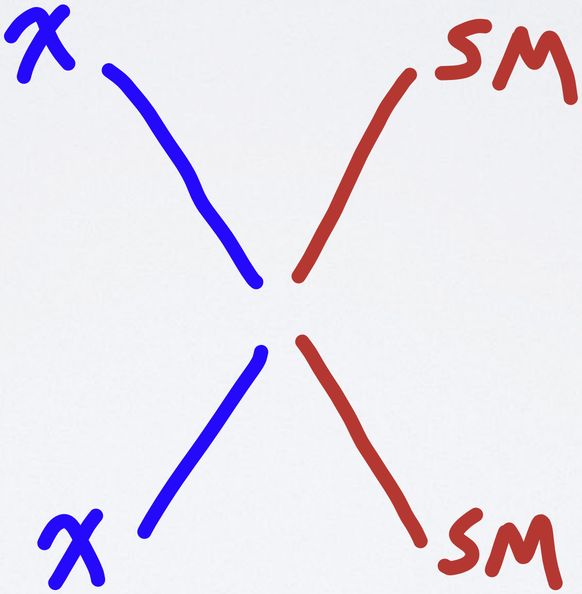


new ideas will be coming, e.g. CASPEr (exp) or new implications e.g., BH superradiance (th)

WIMPS AND WIMPY THINGS

A THERMAL RELIC

Assume dark matter is in thermal contact with the SM bath, and then at some temperature T (when DM is non-relativistic) it decouples



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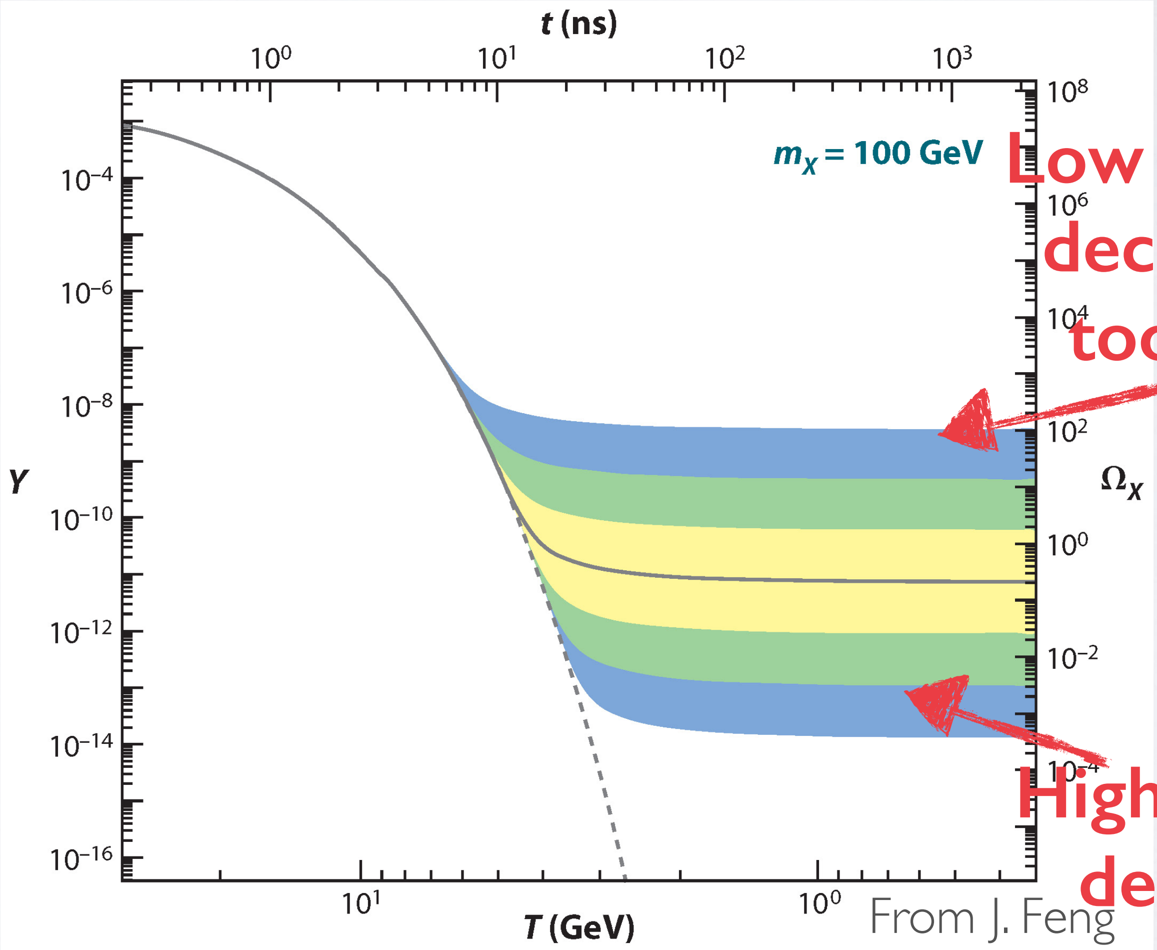
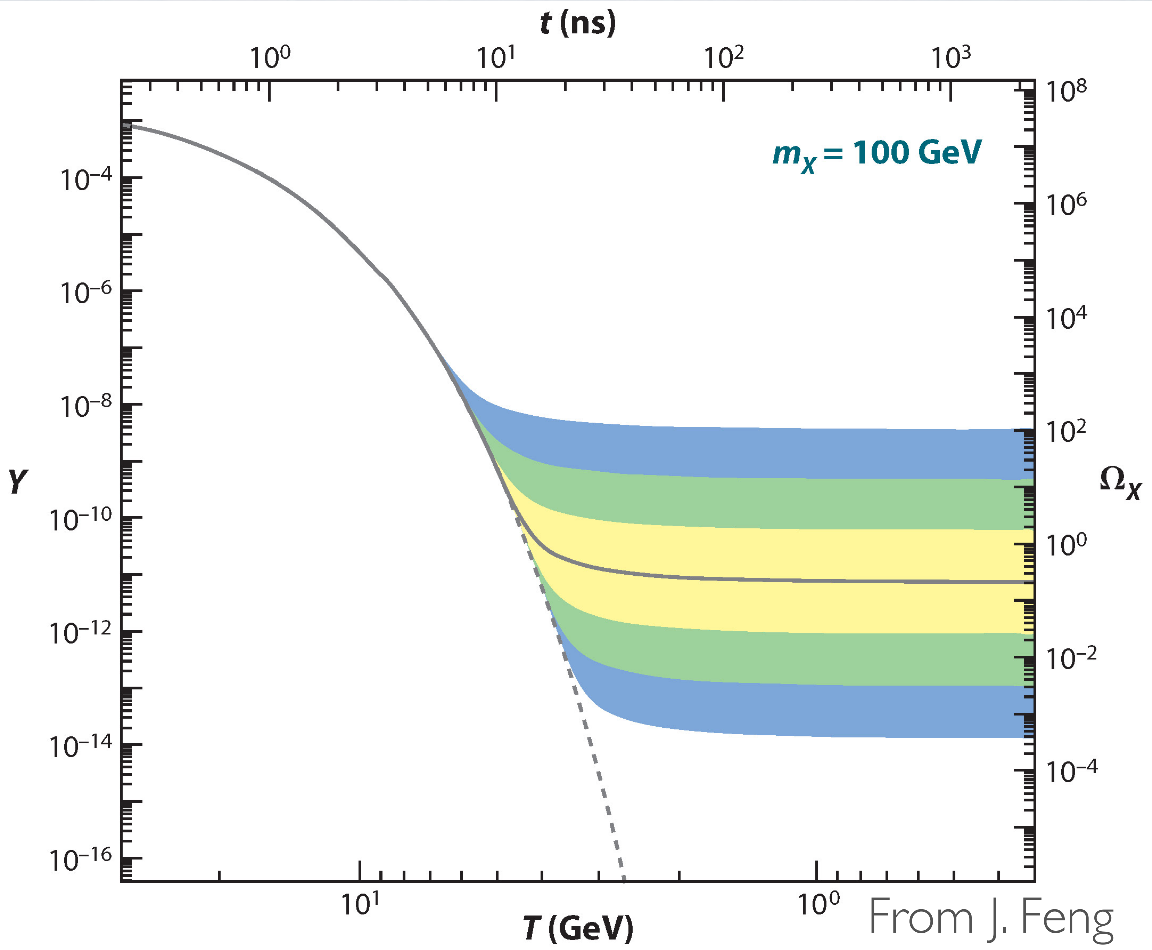


From J. Feng

Low cross section
decouples early
too much DM

High cross section
decouples late
too little DM



From J. Feng

For a thermal relic, you learn precisely one number, namely the annihilation cross section

$$< \sigma v >_{ann} \approx 3 \times 10^{-26} \mathrm{cm}^3 \mathrm{sec}^{-1}$$
$$\approx \frac{\alpha^2}{(200 \mathrm{GeV})^2}$$

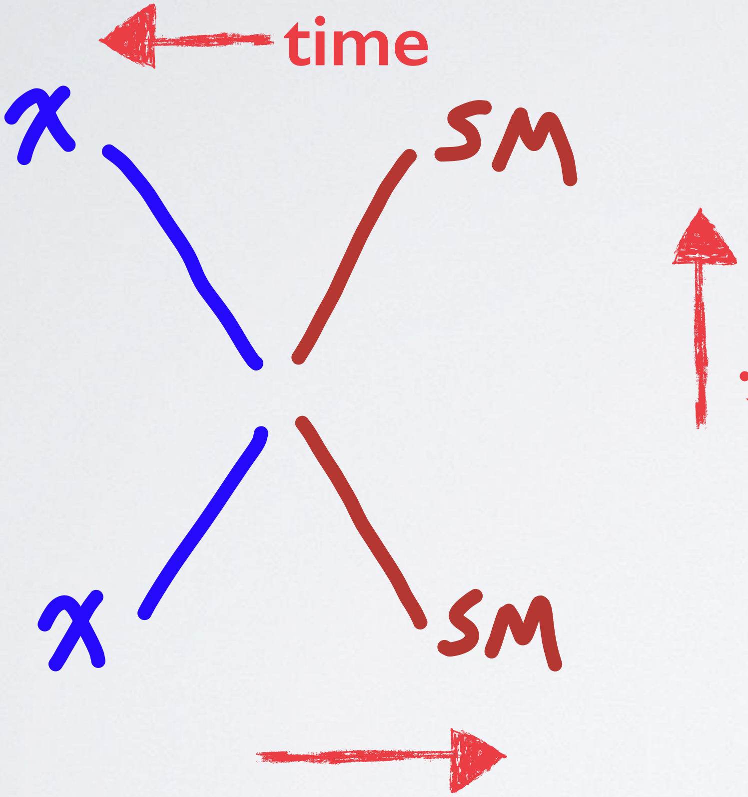
THE "WIMP MIRACLE"

$$
\begin{aligned}
<\sigma v>_{ann} &\approx 3 \times 10^{-26} \mathrm{cm}^3 \mathrm{sec}^{-1} \\
&\approx \frac{\alpha^2}{(200 \mathrm{GeV})^2}
\end{aligned}
$$

NB1: This is only a pretty good miracle O($10^{\pm 3}$)

THE "WIMP MIRACLE"

collider



time

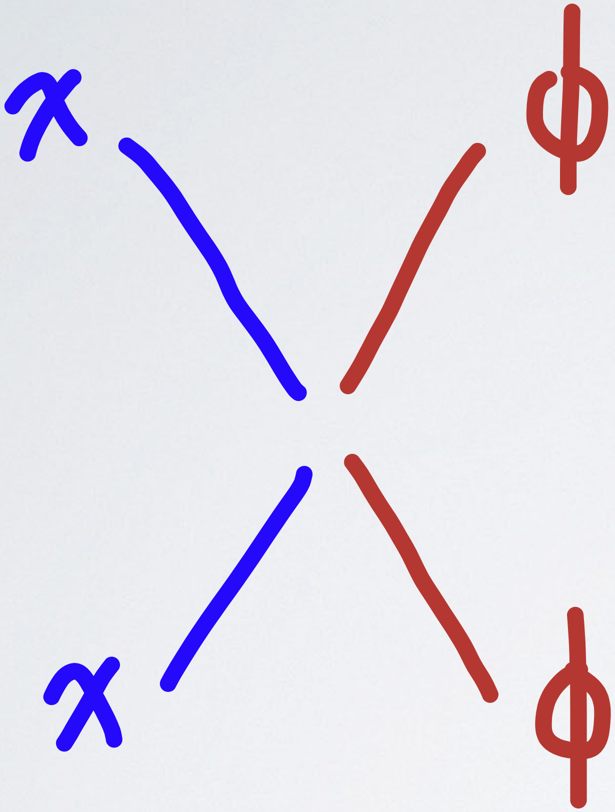
time

"direct"
scattering signals

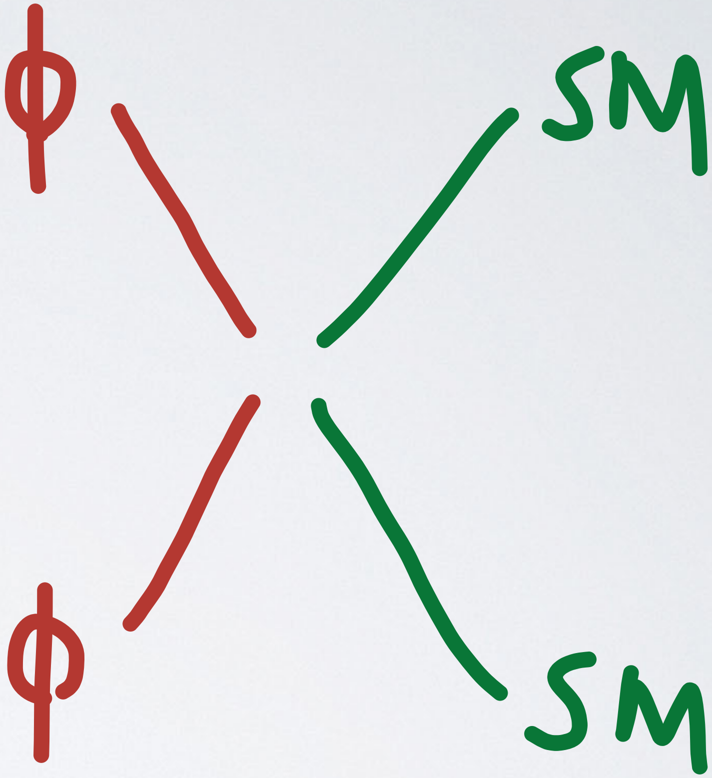
"indirect"
annihilation signals

NB: Direct and collider rely on SM= q or gluon (or direct mediator) [see seminars by Martin Schmaltz]

“DARK MEDIATORS”



DM in thermal
equilibrium with ϕ



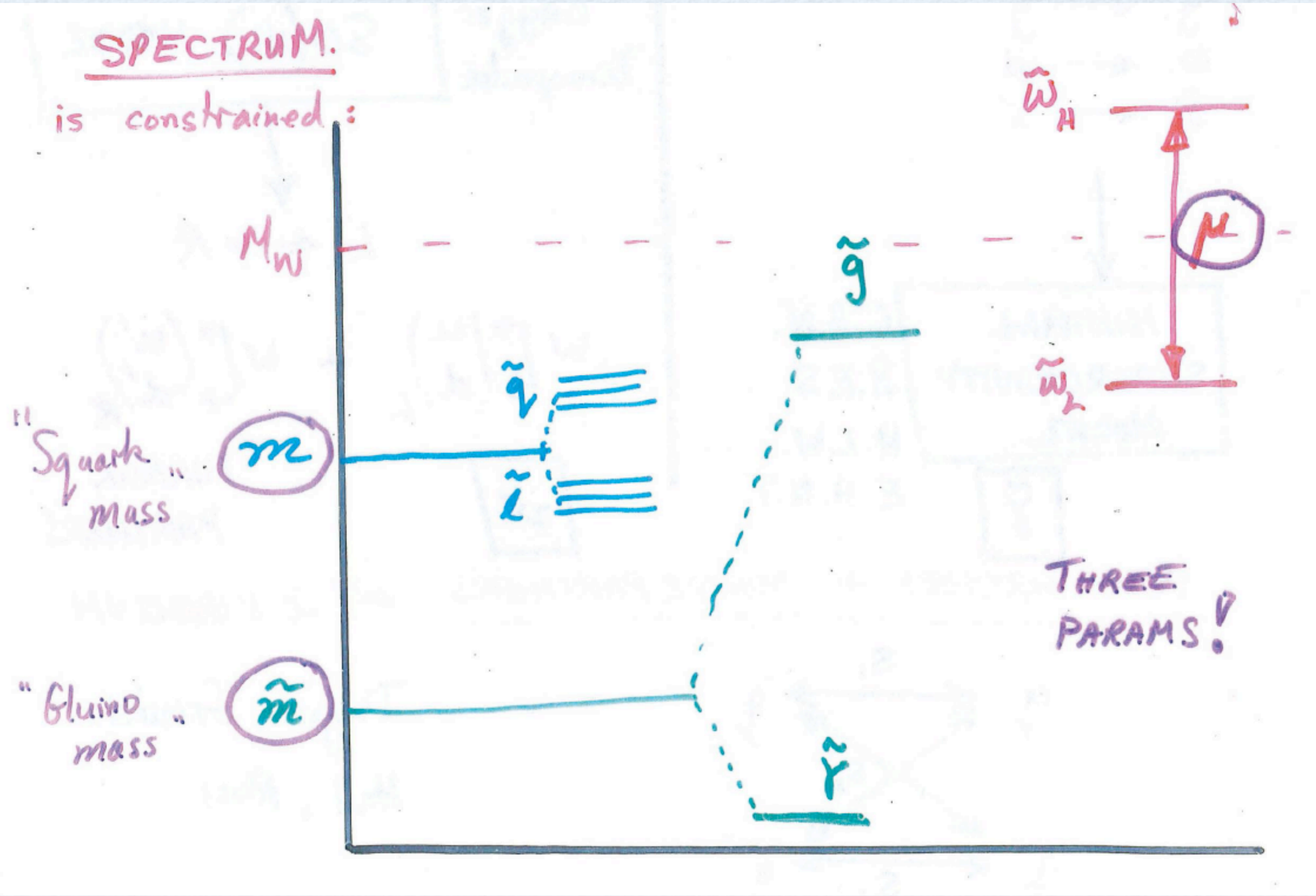
ϕ in thermal
equilibrium with SM

changes expectations dramatically of what signals can be

DIGRESSION: SOME COMMENTS ON SUSY

- The Lightest Super Partner (LSP) in SUSY is often an excellent DM candidate (typically neutralino)
- In general, a stable weak scale neutral particle also works.
- In general, any model can be made supersymmetric

SUSY Spectrum, 1984

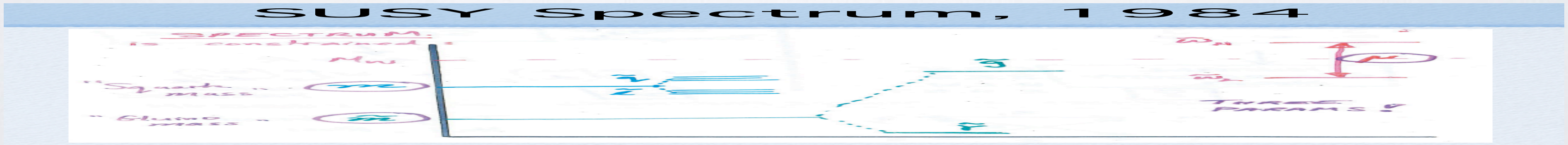


Lawrence Hall, Savasfest 2012

(cf Matt Reece talk LHCP2013)

gluino limits ~ 1400 GeV

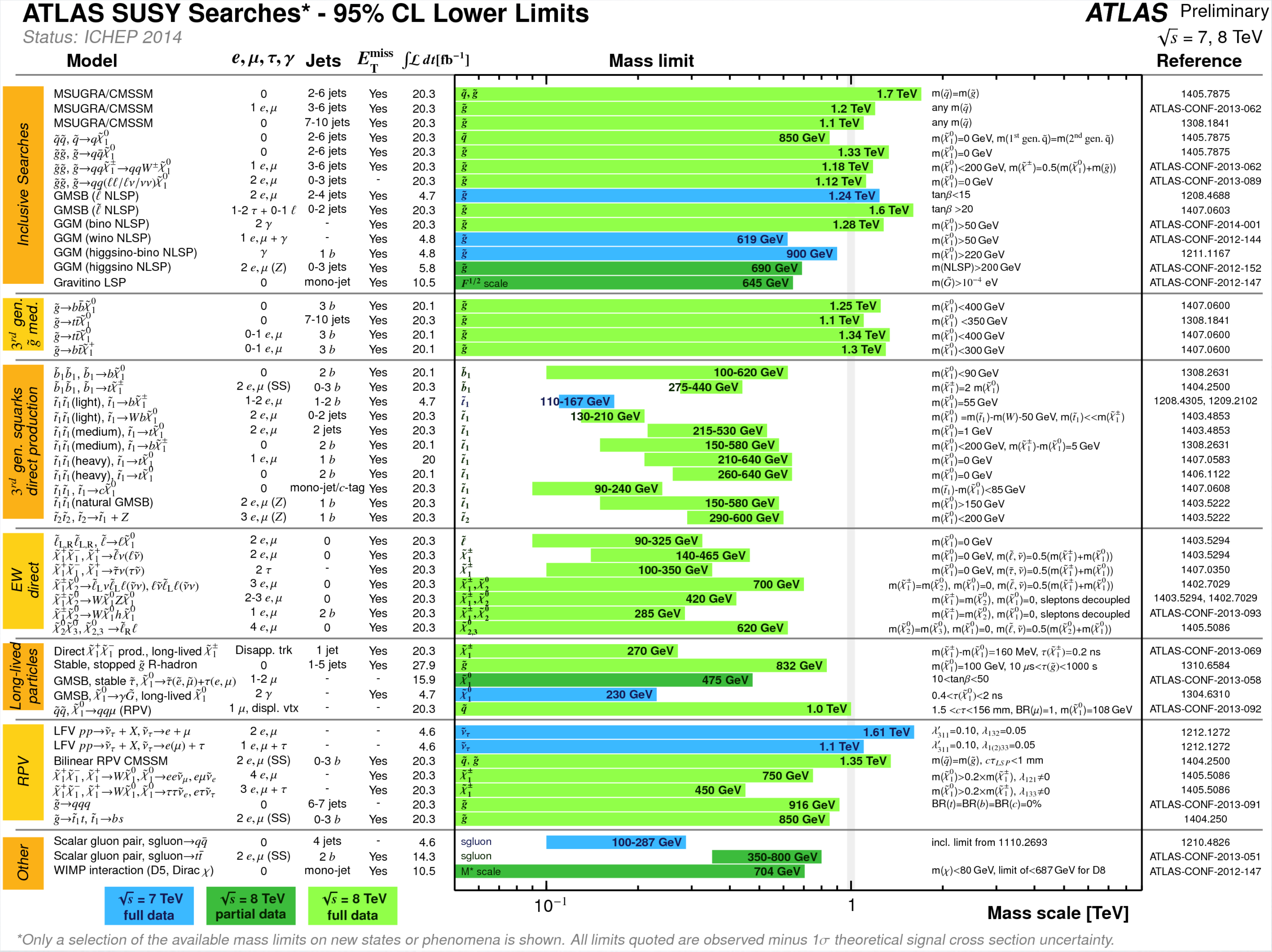
squark limits ~ 700 GeV



Lawrence Hall, Savasfest 2012

(cf Matt Reece talk LHCP2013)

- The WIMP miracle was supposed to be bi-directional



ATLAS SUSY Searches* - 95% CL Lower Limits

Status: ICHEP 2014

ATLAS Preliminary

$\sqrt{s}$ = 7, 8 TeV

	Model	e,μ,τ,γ	**Jets**	E_T^{miss}	$\int\mathcal{L}\,dt[\mathrm{fb}^{-1}]$	**Mass limit**			**Reference**
Inclusive Searches	MSUGRA/CMSSM	0	2-6 jets	Yes	20.3	$\tilde{q},\tilde{g}$	1.7 TeV	m($\tilde{q}$)=m($\tilde{g}$)	1405.7875
	MSUGRA/CMSSM	1 e,μ	3-6 jets	Yes	20.3	$\tilde{g}$	1.2 TeV	any m($\tilde{q}$)	ATLAS-CONF-2013-062
	MSUGRA/CMSSM	0	7-10 jets	Yes	20.3	$\tilde{g}$	1.1 TeV	any m($\tilde{q}$)	1308.1841
	$\tilde{q}\tilde{q}$, $\tilde{q}\rightarrow q\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{q}$	850 GeV	m($\tilde{\chi}_1^0$)=0 GeV, m(1^{st} gen. $\tilde{q}$)=m(2^{nd} gen. $\tilde{q}$)	1405.7875
	$\tilde{g}\tilde{g}$, $\tilde{g}\rightarrow q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{g}$	1.33 TeV	m($\tilde{\chi}_1^0$)=0 GeV	1405.7875
	$\tilde{g}\tilde{g}$, $\tilde{g}\rightarrow qq\tilde{\chi}_1^{\pm}\rightarrow qqW^{\pm}\tilde{\chi}_1^0$	1 e,μ	3-6 jets	Yes	20.3	$\tilde{g}$	1.18 TeV	m($\tilde{\chi}_1^0$)<200 GeV, m($\tilde{\chi}^{\pm}$)=0.5(m($\tilde{\chi}_1^0$)+m($\tilde{g}$))	ATLAS-CONF-2013-062
	$\tilde{g}\tilde{g}$, $\tilde{g}\rightarrow qq(\ell\ell/\ell\nu/\nu\nu)\tilde{\chi}_1^0$	2 e,μ	0-3 jets	-	20.3	$\tilde{g}$	1.12 TeV	m($\tilde{\chi}_1^0$)=0 GeV	ATLAS-CONF-2013-089
	GMSB ($\tilde{\ell}$ NLSP)	2 e,μ	2-4 jets	Yes	4.7	$\tilde{g}$	1.24 TeV	tanβ<15	1208.4688
	GMSB ($\tilde{\ell}$ NLSP)	1-2 τ + 0-1 ℓ	0-2 jets	Yes	20.3	$\tilde{g}$	1.6 TeV	tanβ >20	1407.0603
	GGM (bino NLSP)	2 γ	-	Yes	20.3	$\tilde{g}$	1.28 TeV	m($\tilde{\chi}_1^0$)>50 GeV	ATLAS-CONF-2014-001
	GGM (wino NLSP)	1 $e,\mu+\gamma$	-	Yes	4.8	$\tilde{g}$	619 GeV	m($\tilde{\chi}_1^0$)>50 GeV	ATLAS-CONF-2012-144
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	4.8	$\tilde{g}$	900 GeV	m($\tilde{\chi}_1^0$)>220 GeV	1211.1167
	GGM (higgsino NLSP)	2 e,μ (Z)	0-3 jets	Yes	5.8	$\tilde{g}$	690 GeV	m(NLSP)>200 GeV	ATLAS-CONF-2012-152
	Gravitino LSP	0	mono-jet	Yes	10.5	$F^{1/2}$ scale	645 GeV	m($\tilde{G}$)>10^{-4} eV	ATLAS-CONF-2012-147
3^{rd} gen. $\tilde{g}$ med.	$\tilde{g}\rightarrow b\bar{b}\tilde{\chi}_1^0$	0	3 b	Yes	20.1	$\tilde{g}$	1.25 TeV	m($\tilde{\chi}_1^0$)<400 GeV	1407.0600
	$\tilde{g}\rightarrow t\bar{t}\tilde{\chi}_1^0$	0	7-10 jets	Yes	20.3	$\tilde{g}$	1.1 TeV	m($\tilde{\chi}_1^0$) <350 GeV	1308.1841
	$\tilde{g}\rightarrow t\bar{t}\tilde{\chi}_1^0$	0-1 e,μ	3 b	Yes	20.1	$\tilde{g}$	1.34 TeV	m($\tilde{\chi}_1^0$)<400 GeV	1407.0600
	$\tilde{g}\rightarrow b\bar{t}\tilde{\chi}_1^+$	0-1 e,μ	3 b	Yes	20.1	$\tilde{g}$	1.3 TeV	m($\tilde{\chi}_1^0$)<300 GeV	1407.0600
3^{rd} gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\rightarrow b\tilde{\chi}_1^0$	0	2 b	Yes	20.1	$\tilde{b}_1$	100-620 GeV	m($\tilde{\chi}_1^0$)<90 GeV	1308.2631
	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\rightarrow t\tilde{\chi}_1^{\pm}$	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde{b}_1$	275-440 GeV	m($\tilde{\chi}_1^{\pm}$)=2 m($\tilde{\chi}_1^0$)	1404.2500
	$\tilde{t}_1\tilde{t}_1$(light), $\tilde{t}_1\rightarrow b\tilde{\chi}_1^{\pm}$	1-2 e,μ	1-2 b	Yes	4.7	$\tilde{t}_1$	110-167 GeV	m($\tilde{\chi}_1^0$)=55 GeV	1208.4305, 1209.2102
	$\tilde{t}_1\tilde{t}_1$(light), $\tilde{t}_1\rightarrow Wb\tilde{\chi}_1^0$	2 e,μ	0-2 jets	Yes	20.3	$\tilde{t}_1$	130-210 GeV	m($\tilde{\chi}_1^0$) =m($\tilde{t}_1$)-m(W)-50 GeV, m($\tilde{t}_1$)<<m($\tilde{\chi}_1^{\pm}$)	1403.4853
	$\tilde{t}_1\tilde{t}_1$(medium), $\tilde{t}_1\rightarrow t\tilde{\chi}_1^0$	2 e,μ	2 jets	Yes	20.3	$\tilde{t}_1$	215-530 GeV	m($\tilde{\chi}_1^0$)=1 GeV	1403.4853
	$\tilde{t}_1\tilde{t}_1$(medium), $\tilde{t}_1\rightarrow b\tilde{\chi}_1^{\pm}$	0	2 b	Yes	20.1	$\tilde{t}_1$	150-580 GeV	m($\tilde{\chi}_1^0$)<200 GeV, m($\tilde{\chi}_1^{\pm}$)-m($\tilde{\chi}_1^0$)=5 GeV	1308.2631
	$\tilde{t}_1\tilde{t}_1$(heavy), $\tilde{t}_1\rightarrow t\tilde{\chi}_1^0$	1 e,μ	1 b	Yes	20	$\tilde{t}_1$	210-640 GeV	m($\tilde{\chi}_1^0$)=0 GeV	1407.0583
	$\tilde{t}_1\tilde{t}_1$(heavy), $\tilde{t}_1\rightarrow t\tilde{\chi}_1^0$	0	2 b	Yes	20.1	$\tilde{t}_1$	260-640 GeV	m($\tilde{\chi}_1^0$)=0 GeV	1406.1122
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\rightarrow c\tilde{\chi}_1^0$	0	mono-jet/c-tag	Yes	20.3	$\tilde{t}_1$	90-240 GeV	m($\tilde{t}_1$)-m($\tilde{\chi}_1^0$)<85 GeV	1407.0608
	$\tilde{t}_1\tilde{t}_1$(natural GMSB)	2 e,μ (Z)	1 b	Yes	20.3	$\tilde{t}_1$	150-580 GeV	m($\tilde{\chi}_1^0$)>150 GeV	1403.5222
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\rightarrow\tilde{t}_1+Z$	3 e,μ (Z)	1 b	Yes	20.3	$\tilde{t}_2$	290-600 GeV	m($\tilde{\chi}_1^0$)<200 GeV	1403.5222
EW direct	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}$, $\tilde{\ell}\rightarrow\ell\tilde{\chi}_1^0$	2 e,μ	0	Yes	20.3	$\tilde{\ell}$	90-325 GeV	m($\tilde{\chi}_1^0$)=0 GeV	1403.5294
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\rightarrow\tilde{\ell}\nu(\ell\tilde{\nu})$	2 e,μ	0	Yes	20.3	$\tilde{\chi}_1^{\pm}$	140-465 GeV	m($\tilde{\chi}_1^0$)=0 GeV, m($\tilde{\ell},\tilde{\nu}$)=0.5(m($\tilde{\chi}_1^{\pm}$)+m($\tilde{\chi}_1^0$))	1403.5294
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\rightarrow\tilde{\tau}\nu(\tau\tilde{\nu})$	2 τ	-	Yes	20.3	$\tilde{\chi}_1^{\pm}$	100-350 GeV	m($\tilde{\chi}_1^0$)=0 GeV, m($\tilde{\tau},\tilde{\nu}$)=0.5(m($\tilde{\chi}_1^{\pm}$)+m($\tilde{\chi}_1^0$))	1407.0350
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\rightarrow\tilde{\ell}_L\nu\tilde{\ell}_L\ell(\tilde{\nu}\nu)$, $\ell\tilde{\nu}\tilde{\ell}_L\ell(\tilde{\nu}\nu)$	3 e,μ	0	Yes	20.3	$\tilde{\chi}_1^{\pm}$, $\tilde{\chi}_2^0$	700 GeV	m($\tilde{\chi}_1^{\pm}$)=m($\tilde{\chi}_2^0$), m($\tilde{\chi}_1^0$)=0, m($\tilde{\ell},\tilde{\nu}$)=0.5(m($\tilde{\chi}_1^{\pm}$)+m($\tilde{\chi}_1^0$))	1402.7029
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\rightarrow W\tilde{\chi}_1^0 Z\tilde{\chi}_1^0$	2-3 e,μ	0	Yes	20.3	$\tilde{\chi}_1^{\pm}$, $\tilde{\chi}_2^0$	420 GeV	m($\tilde{\chi}_1^{\pm}$)=m($\tilde{\chi}_2^0$), m($\tilde{\chi}_1^0$)=0, sleptons decoupled	1403.5294, 1402.7029
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\rightarrow W\tilde{\chi}_1^0 h\tilde{\chi}_1^0$	1 e,μ	2 b	Yes	20.3	$\tilde{\chi}_1^{\pm}$, $\tilde{\chi}_2^0$	285 GeV	m($\tilde{\chi}_1^{\pm}$)=m($\tilde{\chi}_2^0$), m($\tilde{\chi}_1^0$)=0, sleptons decoupled	ATLAS-CONF-2013-093
	$\tilde{\chi}_2^0\tilde{\chi}_3^0$, $\tilde{\chi}_{2,3}^0\rightarrow\tilde{\ell}_R\ell$	4 e,μ	0	Yes	20.3	$\tilde{\chi}_{2,3}^0$	620 GeV	m($\tilde{\chi}_2^0$)=m($\tilde{\chi}_3^0$), m($\tilde{\chi}_1^0$)=0, m($\tilde{\ell},\tilde{\nu}$)=0.5(m($\tilde{\chi}_2^0$)+m($\tilde{\chi}_1^0$))	1405.5086
Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^{\pm}$	Disapp. trk	1 jet	Yes	20.3	$\tilde{\chi}_1^{\pm}$	270 GeV	m($\tilde{\chi}_1^{\pm}$)-m($\tilde{\chi}_1^0$)=160 MeV, τ($\tilde{\chi}_1^{\pm}$)=0.2 ns	ATLAS-CONF-2013-069
	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	27.9	$\tilde{g}$	832 GeV	m($\tilde{\chi}_1^0$)=100 GeV, 10 μs<τ($\tilde{g}$)<1000 s	1310.6584
	GMSB, stable $\tilde{\tau}$, $\tilde{\chi}_1^0\rightarrow\tilde{\tau}(\tilde{e},\tilde{\mu})+\tau(e,\mu)$	1-2 μ	-	-	15.9	$\tilde{\chi}_1^0$	475 GeV	10<tanβ<50	ATLAS-CONF-2013-058
	GMSB, $\tilde{\chi}_1^0\rightarrow\gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$	2 γ	-	Yes	4.7	$\tilde{\chi}_1^0$	230 GeV	0.4<τ($\tilde{\chi}_1^0$)<2 ns	1304.6310
	$\tilde{q}\tilde{q}$, $\tilde{\chi}_1^0\rightarrow qq\mu$ (RPV)	1 μ, displ. vtx	-	-	20.3	$\tilde{q}$	1.0 TeV	1.5 <$c\tau$<156 mm, BR(μ)=1, m($\tilde{\chi}_1^0$)=108 GeV	ATLAS-CONF-2013-092
RPV	LFV $pp\rightarrow\tilde{\nu}_\tau+X$, $\tilde{\nu}_\tau\rightarrow e+\mu$	2 e,μ	-	-	4.6	$\tilde{\nu}_\tau$	1.61 TeV	λ'_{311}=0.10, λ_{132}=0.05	1212.1272
	LFV $pp\rightarrow\tilde{\nu}_\tau+X$, $\tilde{\nu}_\tau\rightarrow e(\mu)+\tau$	1 $e,\mu+\tau$	-	-	4.6	$\tilde{\nu}_\tau$	1.1 TeV	λ'_{311}=0.10, $\lambda_{1(2)33}$=0.05	1212.1272
	Bilinear RPV CMSSM	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde{q}$, $\tilde{g}$	1.35 TeV	m($\tilde{q}$)=m($\tilde{g}$), $c\tau_{LSP}$<1 mm	1404.2500
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\rightarrow W\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\rightarrow ee\tilde{\nu}_\mu, e\mu\tilde{\nu}_e$	4 e,μ	-	Yes	20.3	$\tilde{\chi}_1^{\pm}$	750 GeV	m($\tilde{\chi}_1^0$)>0.2×m($\tilde{\chi}_1^{\pm}$), $\lambda_{121}\neq0$	1405.5086
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\rightarrow W\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\rightarrow\tau\tau\tilde{\nu}_e, e\tau\tilde{\nu}_\tau$	3 $e,\mu+\tau$	-	Yes	20.3	$\tilde{\chi}_1^{\pm}$	450 GeV	m($\tilde{\chi}_1^0$)>0.2×m($\tilde{\chi}_1^{\pm}$), $\lambda_{133}\neq0$	1405.5086
	$\tilde{g}\rightarrow qqq$	0	6-7 jets	-	20.3	$\tilde{g}$	916 GeV	BR(t)=BR(b)=BR(c)=0%	ATLAS-CONF-2013-091
	$\tilde{g}\rightarrow\tilde{t}_1 t$, $\tilde{t}_1\rightarrow bs$	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde{g}$	850 GeV		1404.250
Other	Scalar gluon pair, sgluon$\rightarrow q\bar{q}$	0	4 jets	-	4.6	sgluon	100-287 GeV	incl. limit from 1110.2693	1210.4826
	Scalar gluon pair, sgluon$\rightarrow t\bar{t}$	2 e,μ (SS)	2 b	Yes	14.3	sgluon	350-800 GeV		ATLAS-CONF-2013-051
	WIMP interaction (D5, Dirac χ)	0	mono-jet	Yes	10.5	M* scale	704 GeV	m(χ)<80 GeV, limit of<687 GeV for D8	ATLAS-CONF-2012-147

$\sqrt{s}$ = 7 TeV full data

$\sqrt{s}$ = 8 TeV partial data

$\sqrt{s}$ = 8 TeV full data

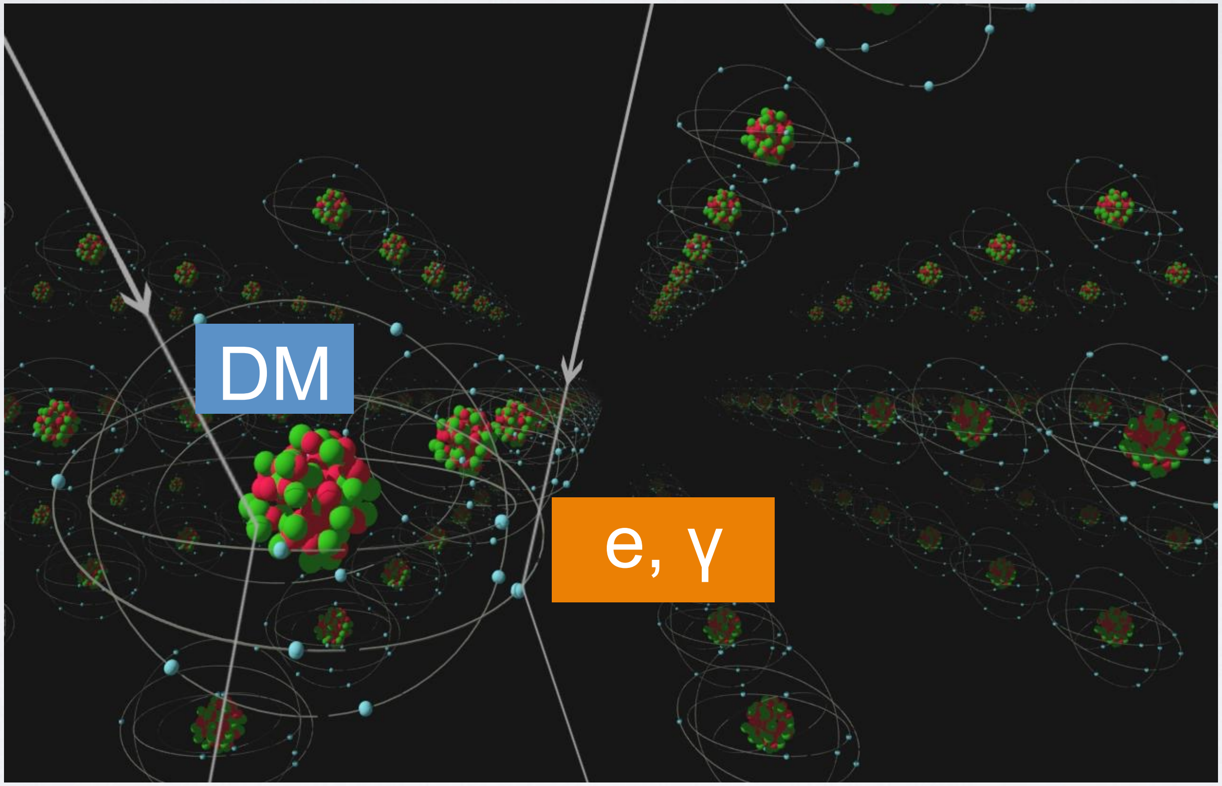
**Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.*

- IMHO good to think generally about DM models because conventional wisdom on the weak scale has not proven itself reliable
- So, even if it is a WIMP, it needn't look or act as we anticipated
- Light WIMPs, very heavy WIMPs, hidden sector DM…

SOME COMMENTS ON DIRECT DETECTION

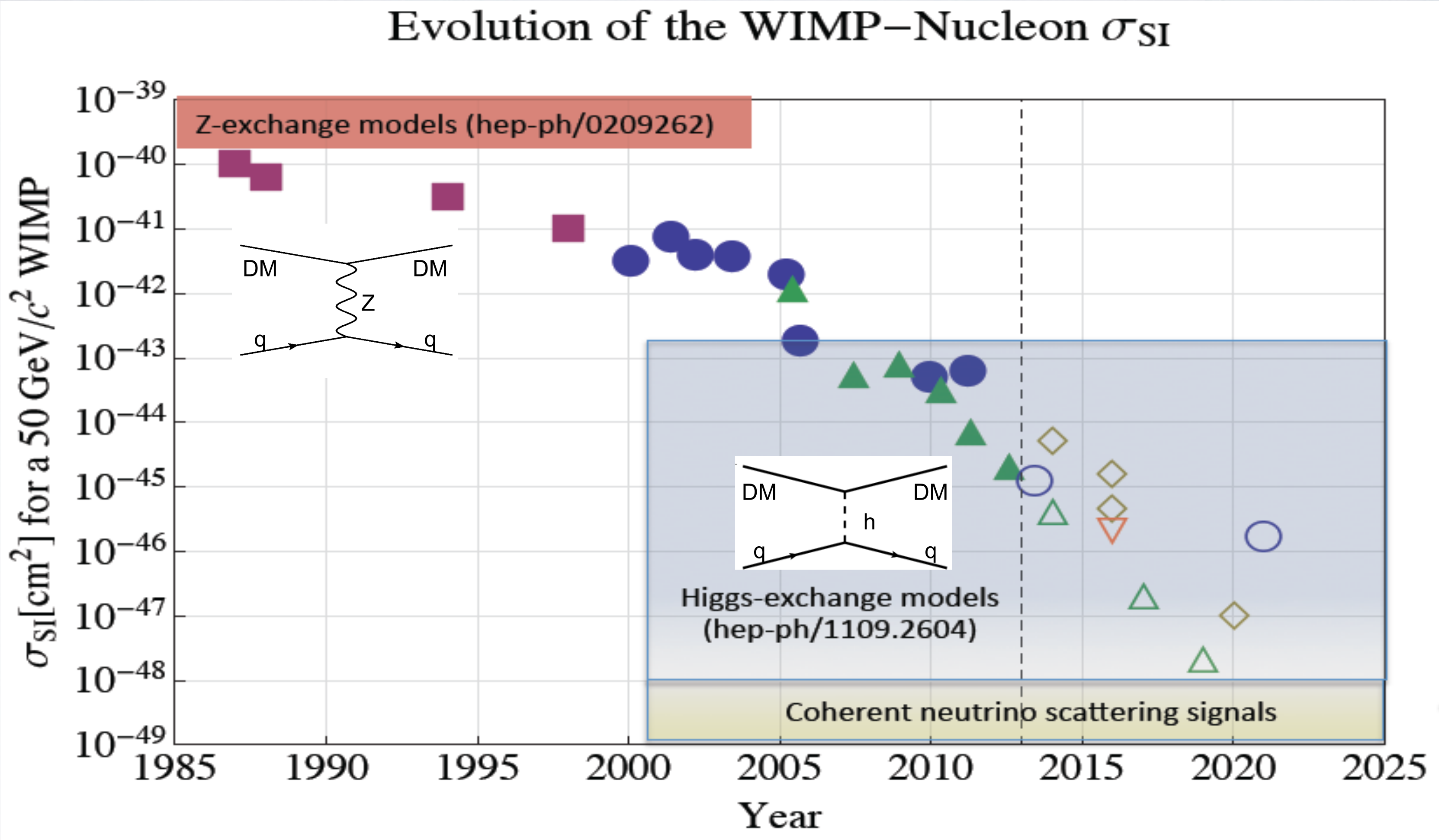
- We haven't seen a WIMP in direct detection yet. How worried should we be?

THE SEARCH FOR WIMPS



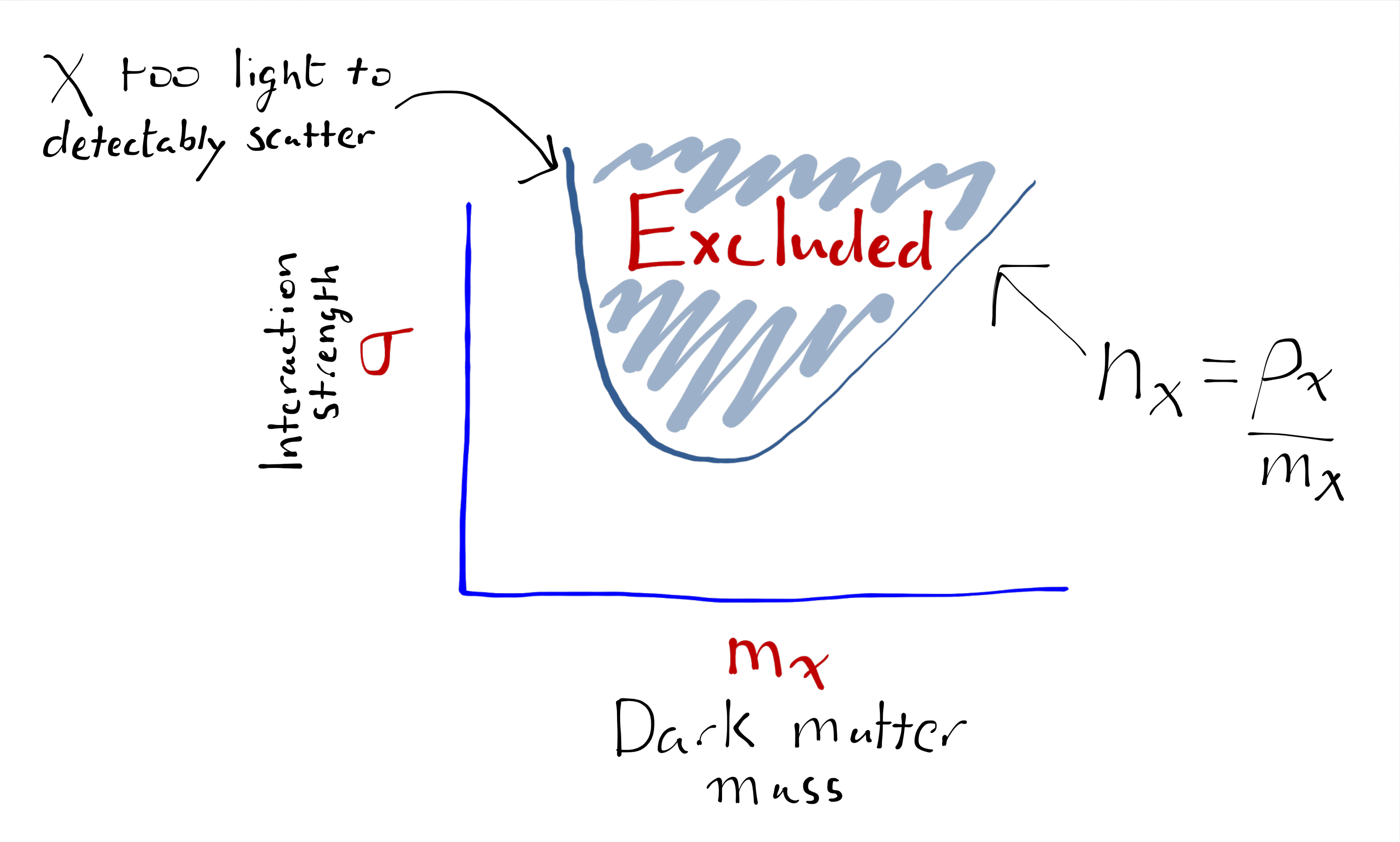
- Generic idea: look for nuclear recoils (Goodman + Witten ’85)

SO WHAT ABOUT THE SEARCH FOR WIMPS?

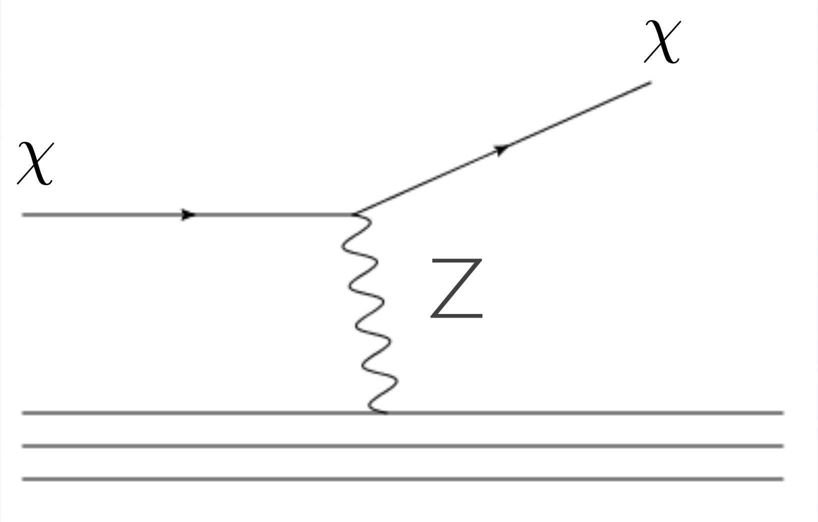


slide from J Feng

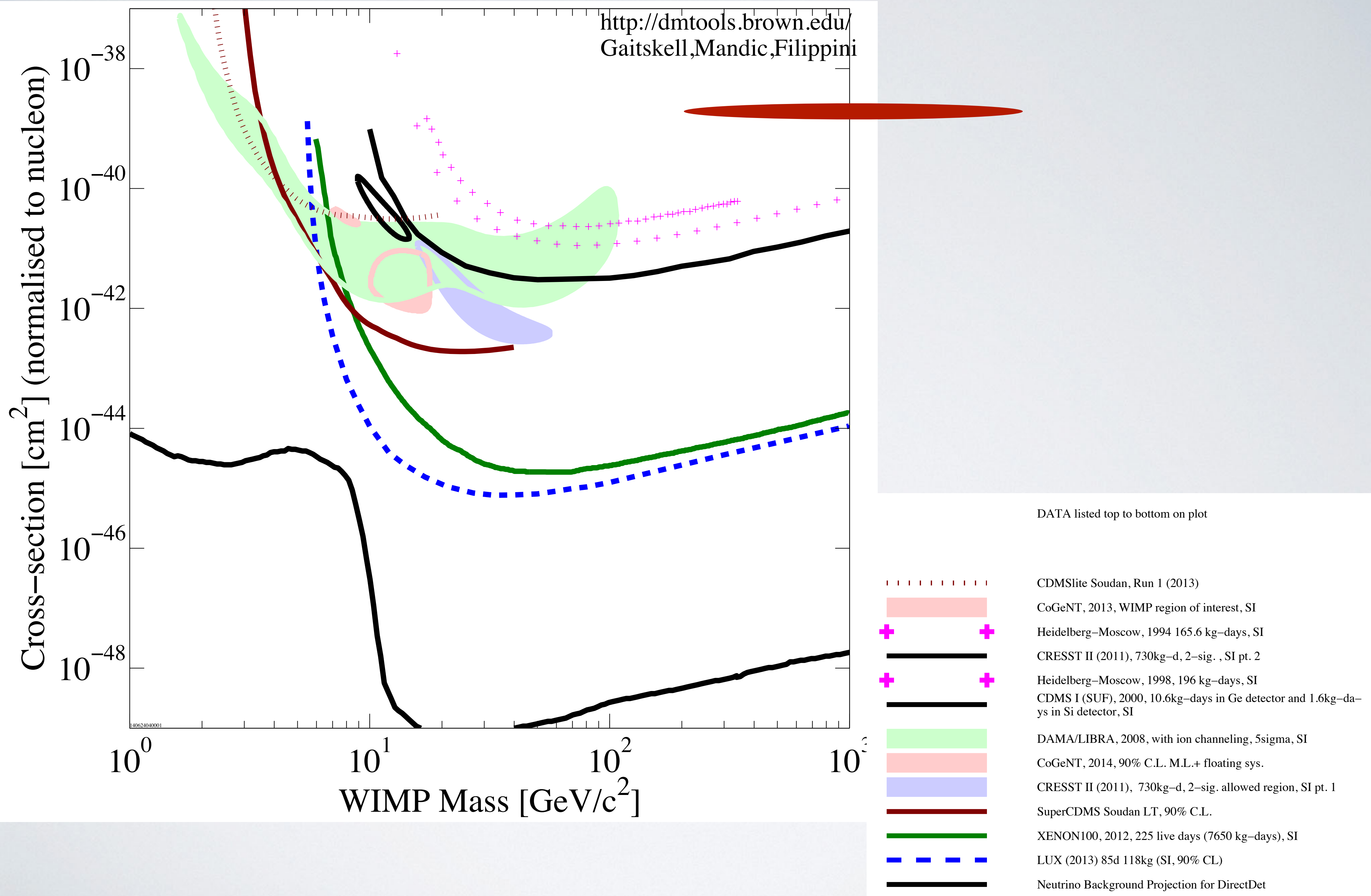
THE SEARCH FOR WIMPS



MODEL 1: HEAVY DIRAC "NEUTRINO"



$$\sigma_0 \approx \frac{G_f^2 \mu^2}{2\pi} \sim 10^{-39}\mathrm{cm}^2$$


http://dmtools.brown.edu/
Gaitskell,Mandic,Filippini
Cross-section [cm^2] (normalised to nucleon)
10^{-38}
10^{-40}
10^{-42}
10^{-44}
10^{-46}
10^{-48}
WIMP Mass [GeV/c^2]
10^0
10^1
10^2
10
140624040001
DATA listed top to bottom on plot
CDMSlite Soudan, Run 1 (2013)
CoGeNT, 2013, WIMP region of interest, SI
Heidelberg–Moscow, 1994 165.6 kg–days, SI
CRESST II (2011), 730kg–d, 2–sig. , SI pt. 2
Heidelberg–Moscow, 1998, 196 kg–days, SI
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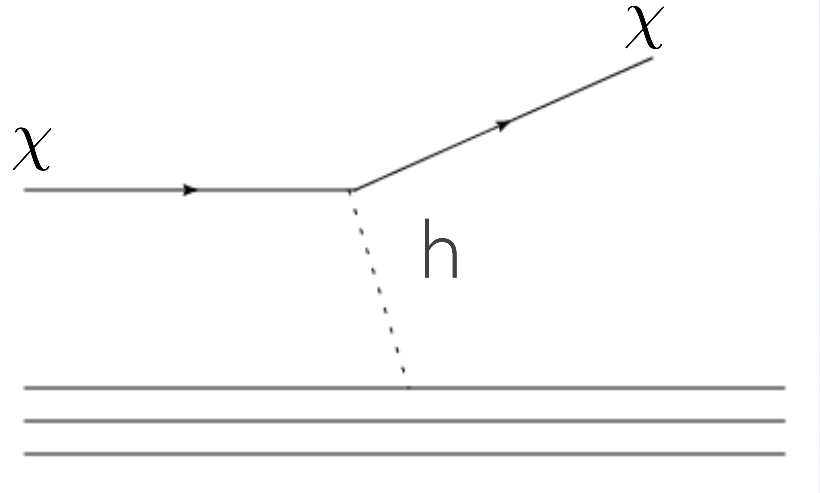
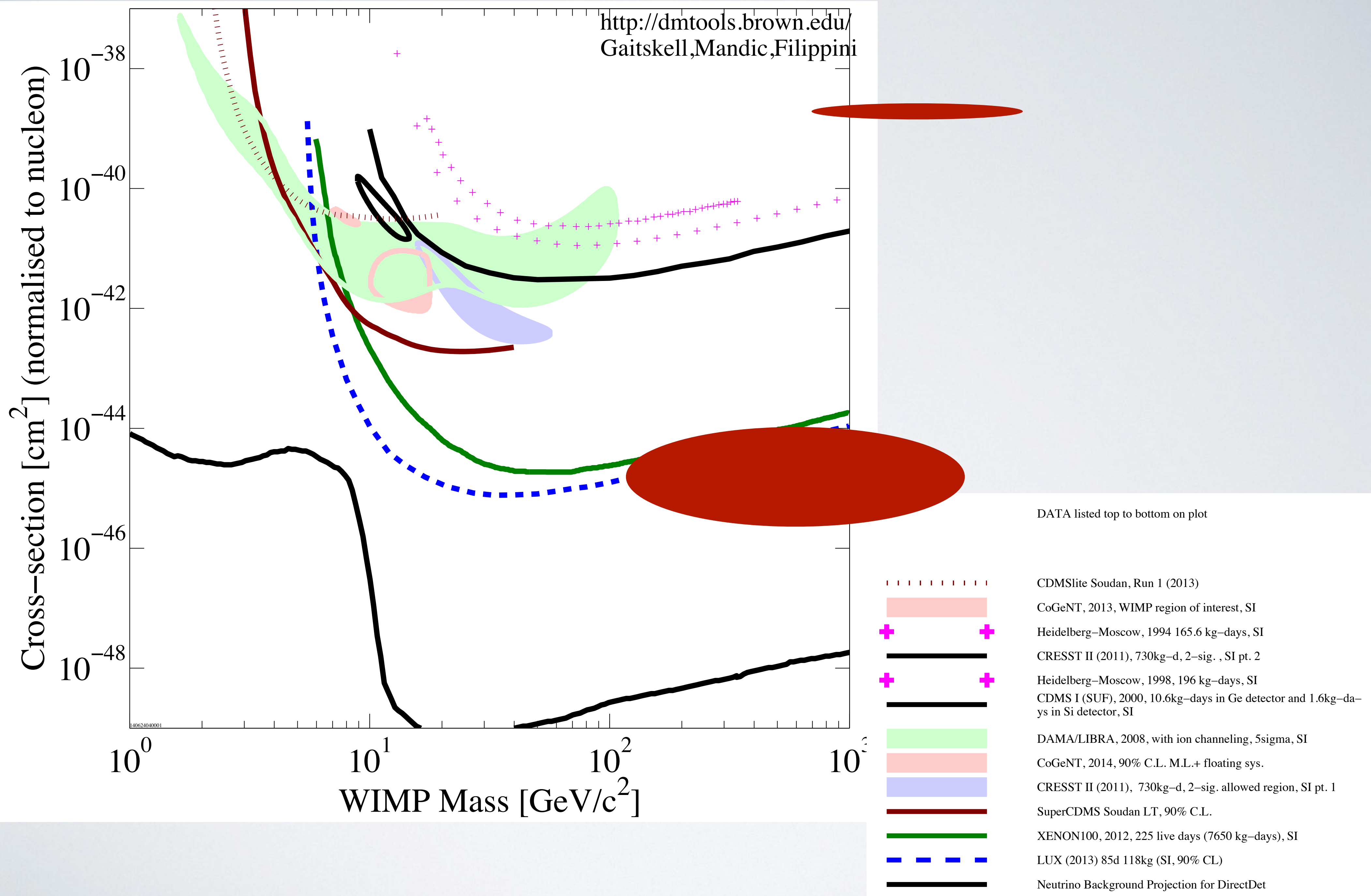
DAMA/LIBRA, 2008, with ion channeling, 5sigma, SI
CoGeNT, 2014, 90% C.L. M.L.+ floating sys.
CRESST II (2011), 730kg–d, 2–sig. allowed region, SI pt. 1
SuperCDMS Soudan LT, 90% C.L.
XENON100, 2012, 225 live days (7650 kg–days), SI
LUX (2013) 85d 118kg (SI, 90% CL)
Neutrino Background Projection for DirectDet

MAJORANA DOUBLET WIMP: HIGGS MEDIATED



$$g \sim 1 \Rightarrow y_p \sim \frac{1}{\text{few}} \frac{m_p}{v}$$

$$\sigma_0 \sim 10^{-39}\text{cm}^2 \times 10^{-6}$$
$$\sim 10^{-45}\text{cm}^2$$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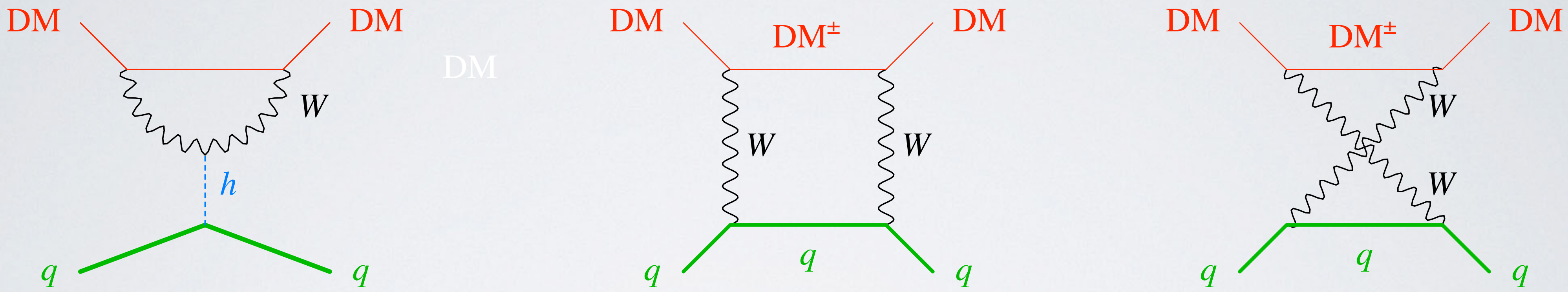
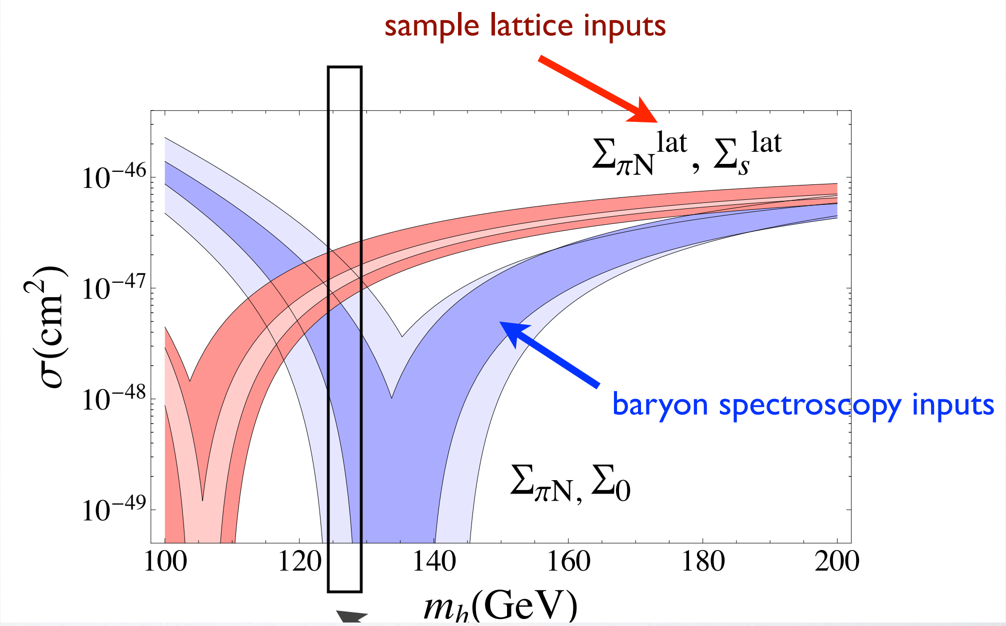
SuperCDMS Soudan LT, 90% C.L.
XENON100, 2012, 225 live days (7650 kg–days), SI
LUX (2013) 85d 118kg (SI, 90% CL)
Neutrino Background Projection for DirectDet

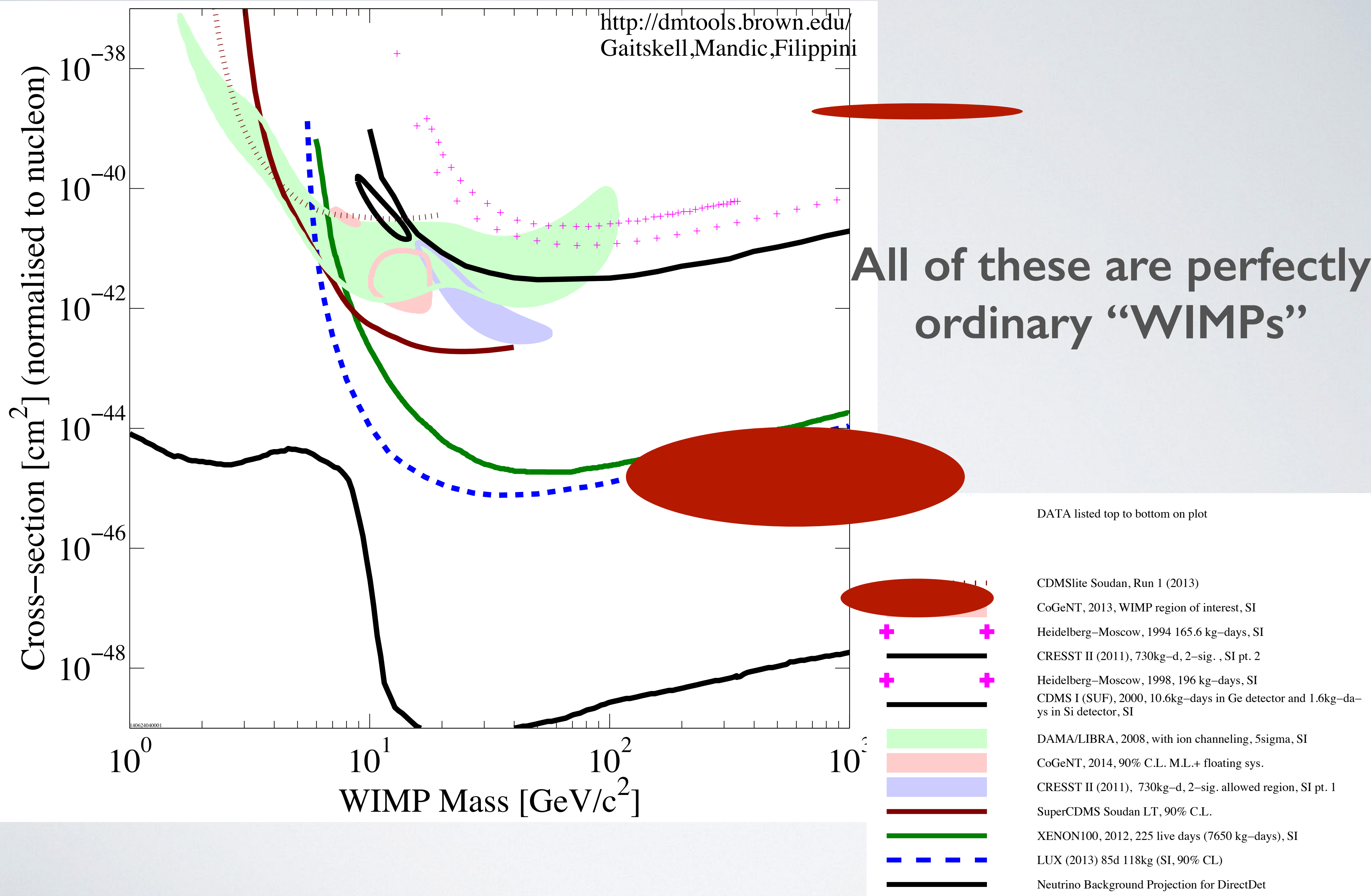
MAJORANA TRIPLET: LOOP MEDIATED




sample lattice inputs

baryon spectroscopy inputs

Hill + Solon ’13;
Hill + Solon ‘14



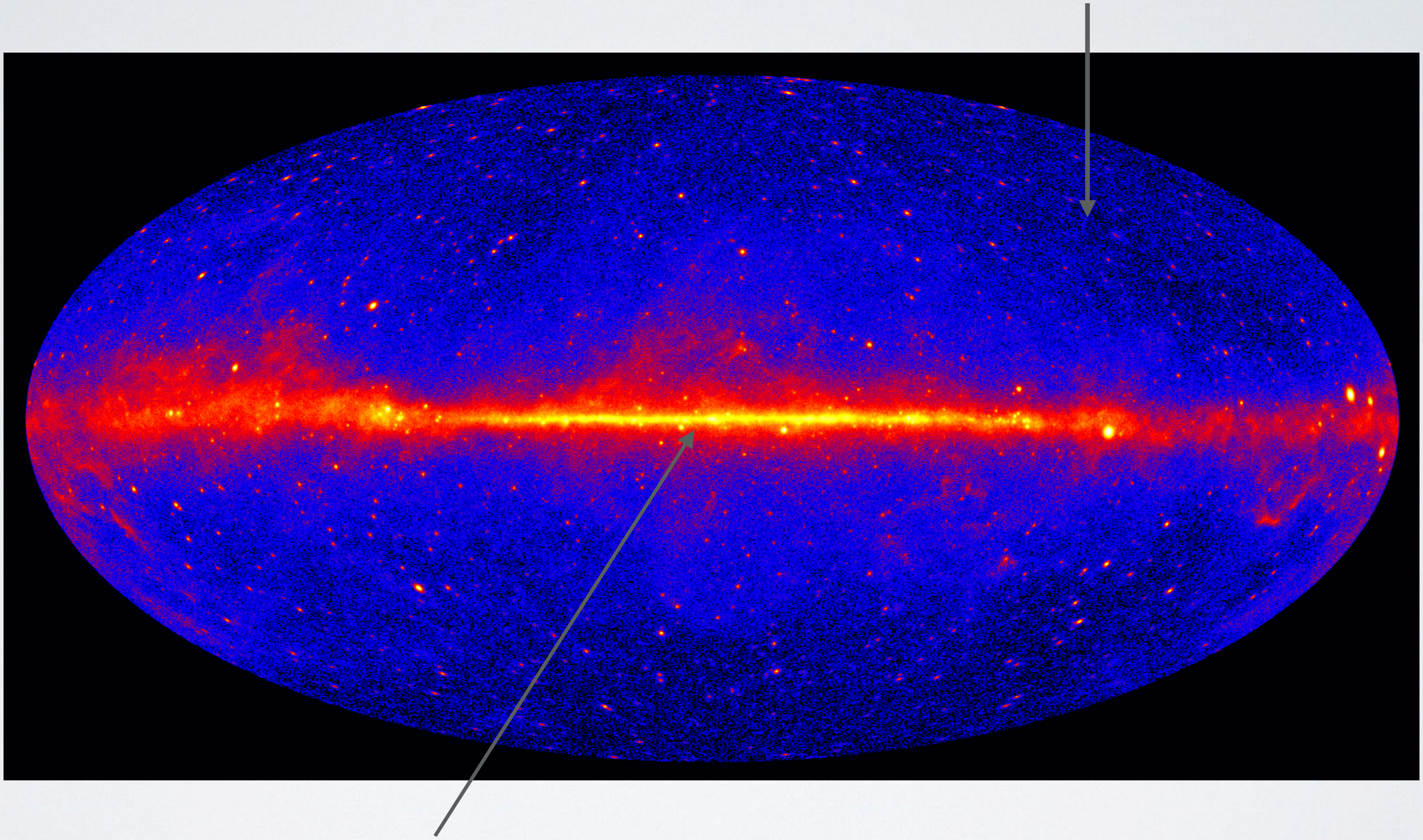
All of these are perfectly ordinary “WIMPs”

- This era will answer the question: does the dark matter couple at O(0.1-0.01) to the Higgs boson
- But perfectly plausible WIMPs can have *very* weak nucleon interactions

“INDIRECT” DETECTION

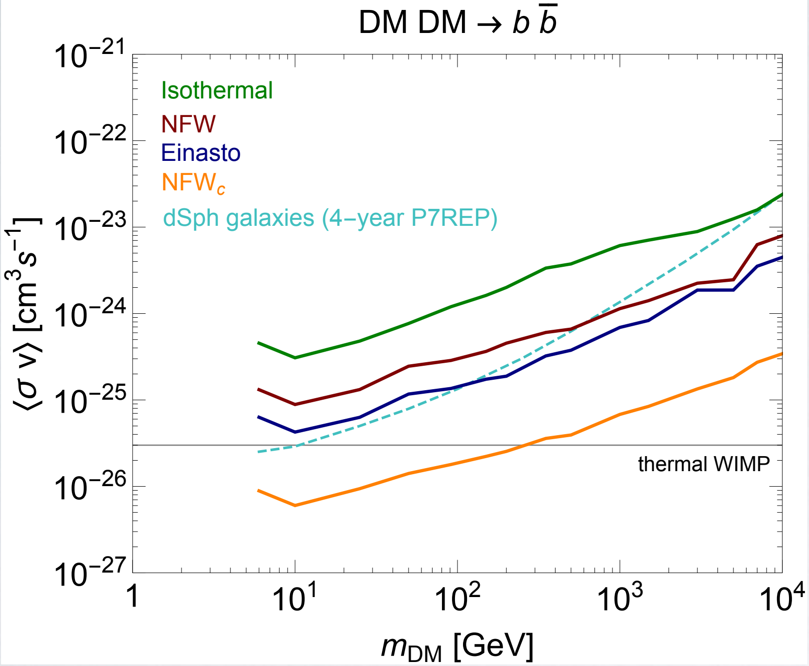
- Cosmic ray missions, WMAP, Planck all have been critical in constraining dark matter models
- Converts <σ v> into a signal (i.e., we observe the annihilation products)

MOST PROMINENT LIMITS



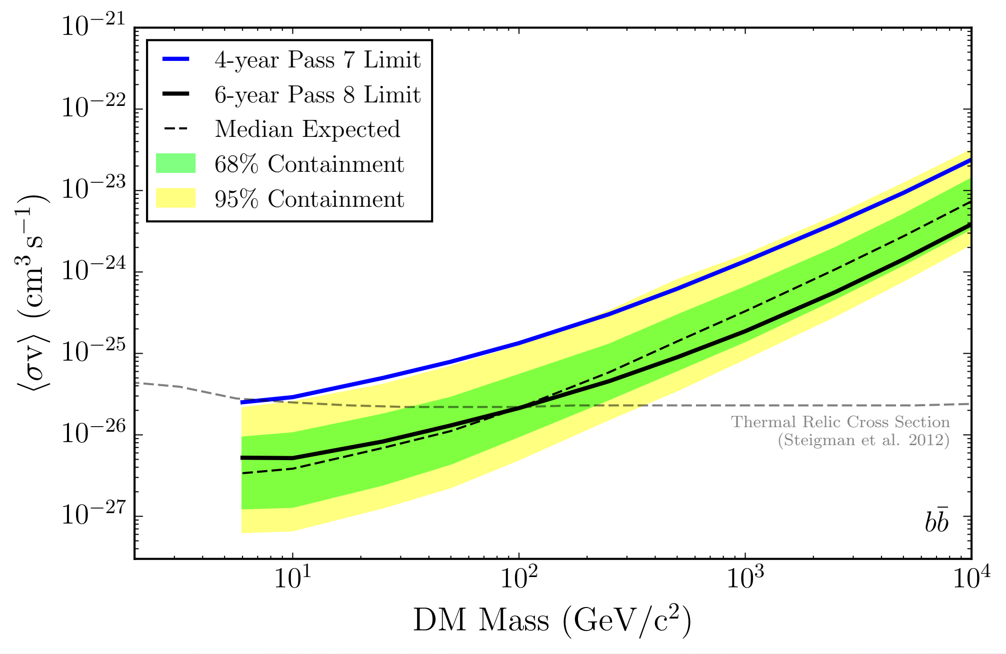
look here [dwarf galaxy]
(low background)

look here
(lots of DM)



“Conservative” limits

Massari et al 2015

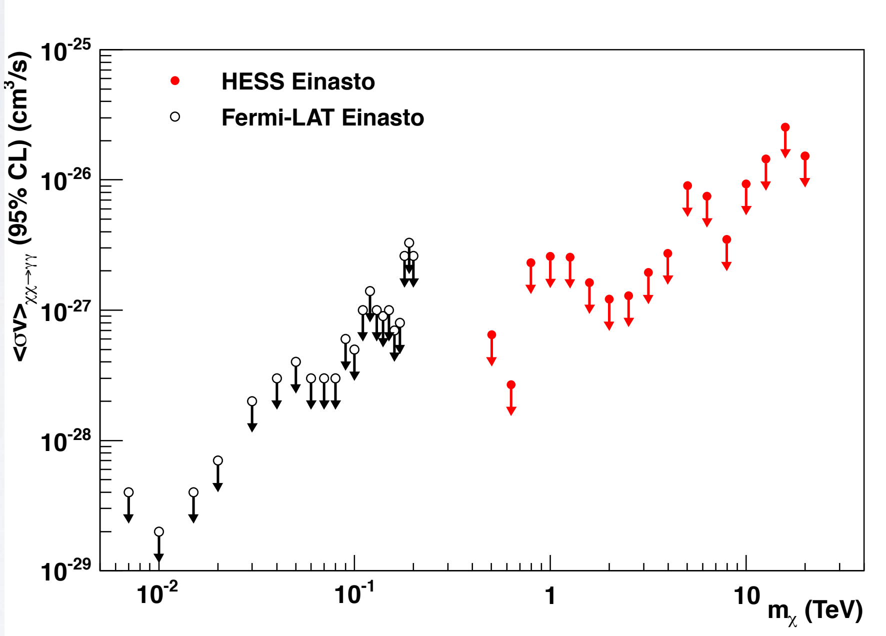


Dwarf limits

Fermi collab 2015

NB: The cross section needn’t be as large today!

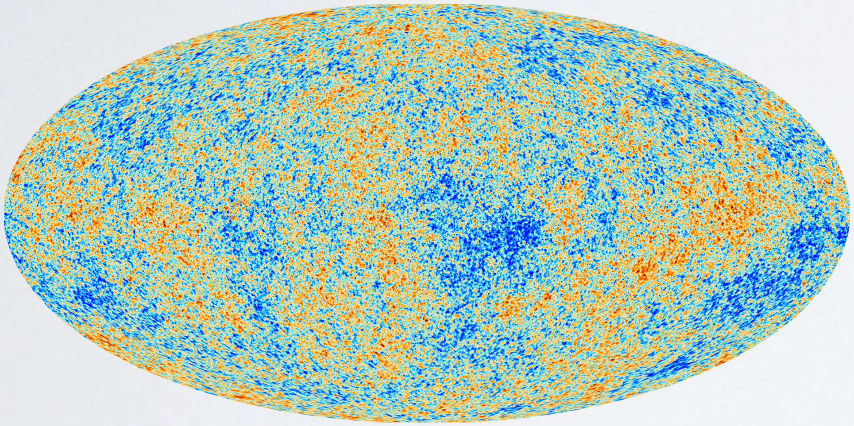
FOR HIGH ENERGY LINES: HESS

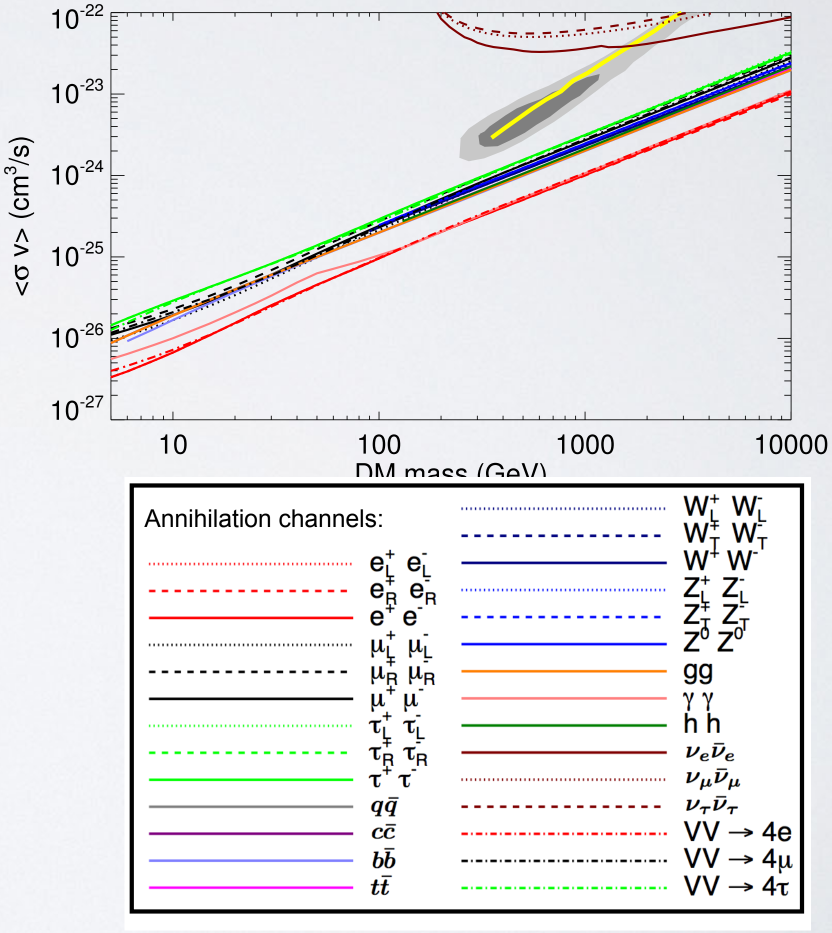


For heavier DM, this is often important

FOR EVERYONE: PLANCK

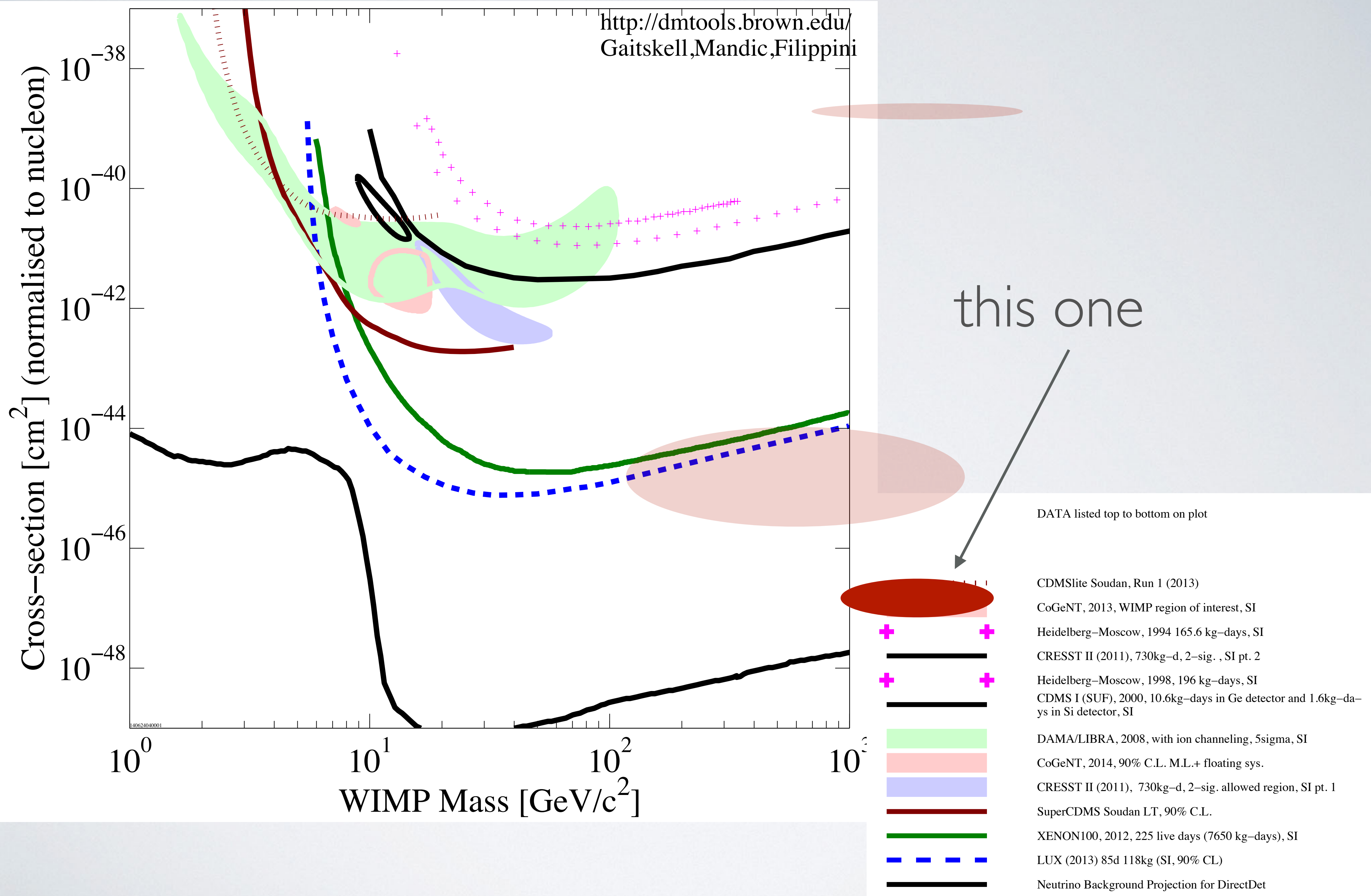
- Energy deposition during recombination affects CMB





Slatyer '15

WHAT ABOUT THAT HARD-TO-SEE CASE?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LUX (2013) 85d 118kg (SI, 90% CL)
Neutrino Background Projection for DirectDet

this one

WHAT ABOUT THAT HARD-TO-SEE CASE?

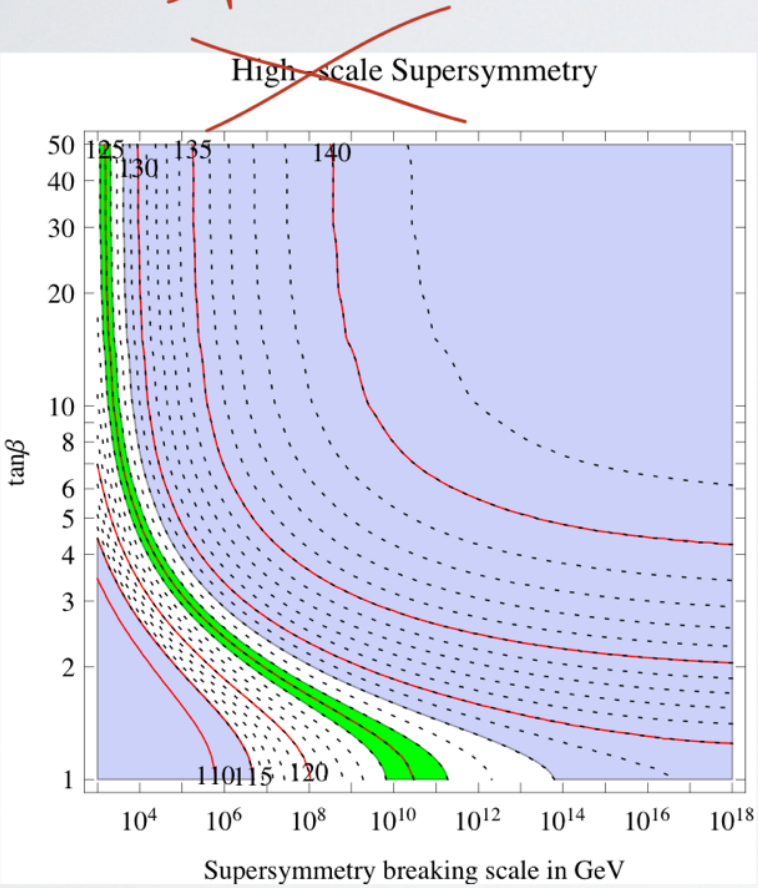
- It is not just another scenario, it is actually a critical point in parameter space

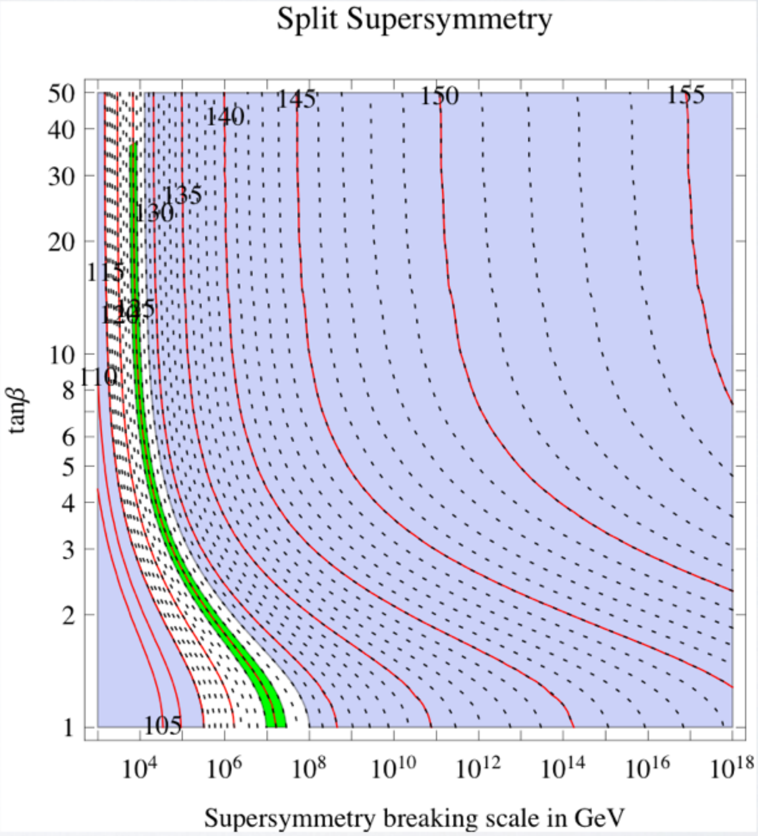
HEAVY DARK MATTER

- is the “Nightmare” scenario upon us?
- No sign at the LHC of new particles suggests that the scale of new physics may be very high

HIGGS AND SUSY SPECTRA

supersplit





Giudice + Strumia

MINI-SPLIT

Wells; Kane; Hall & Nomura; Arvanitaki et al; Arkani-Hamed et al

$M_{squark} \sim 100$ TeV

often inaccessible to colliders

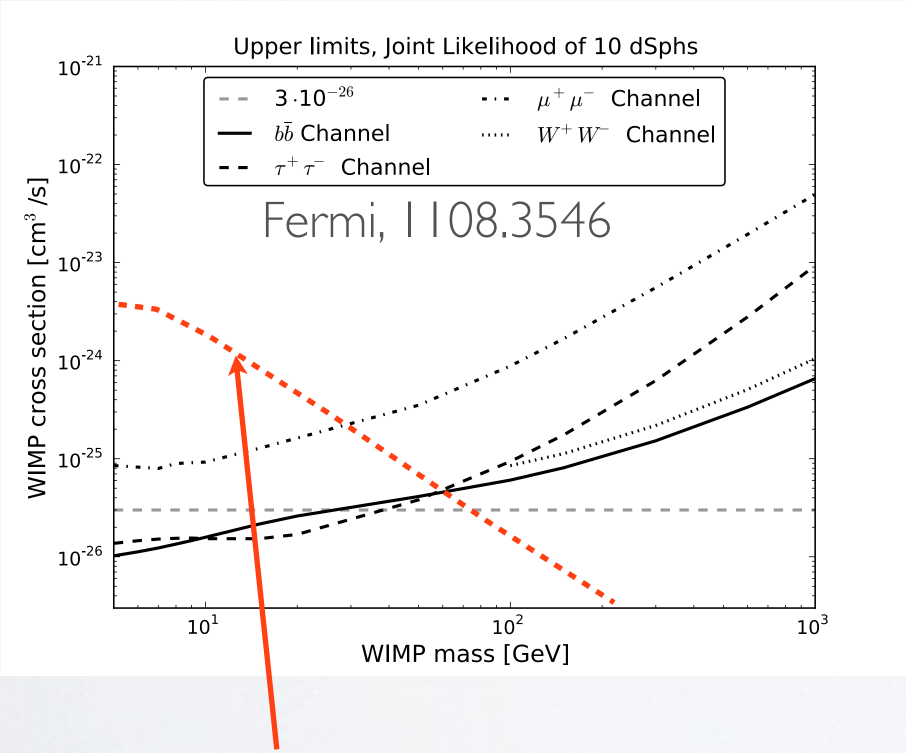
$M_{\chi} \sim M_{gauginos}$ few TeV

M_Z

WIMP is often (but not always) a Wino (masses from anomaly mediation)

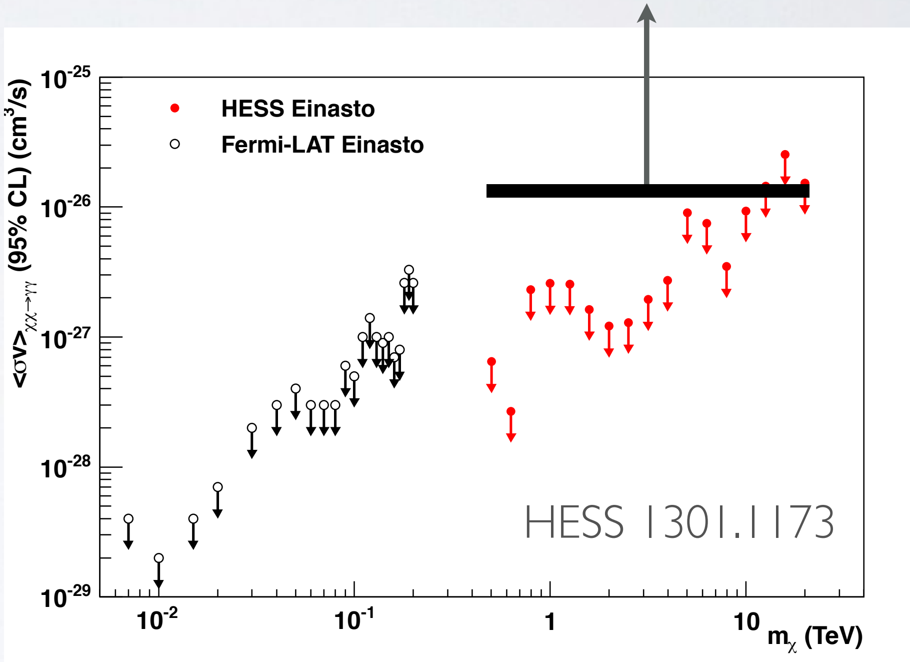
TESTS WITH COSMIC RAYS

fermi dwarf search



Wino cross section

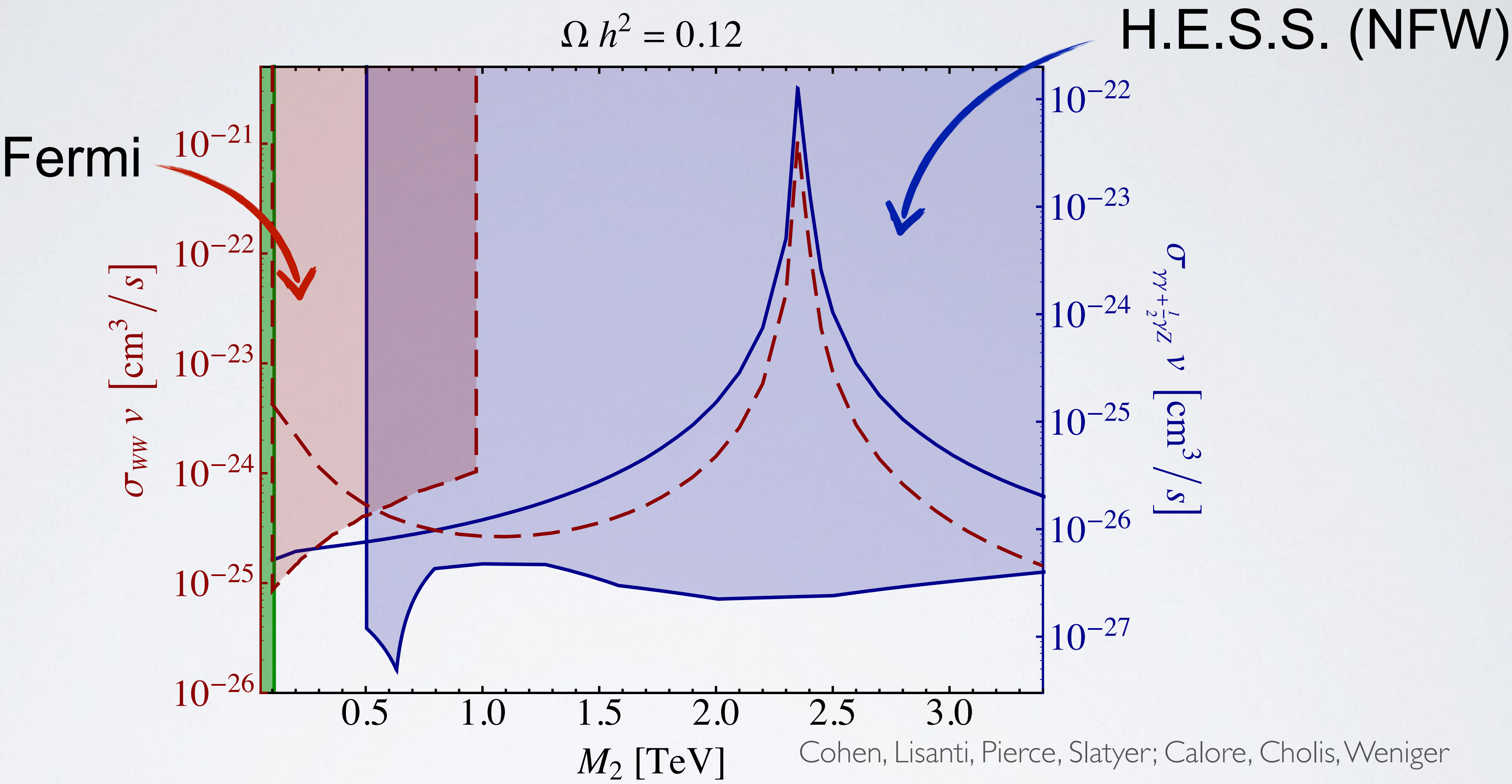
wino cross section



HESS gamma line search

Cohen, Lisanti, Pierce, Slatyer; Calore, Cholis, Weniger

Excluding Wino DM



Cohen, Lisanti, Pierce, Slatyer; Calore, Cholis, Weniger

- Plot assumes NFW (Einasto also constrained)
- If strong theory prior for Winos, very flat profiles allowed
- This is an important scenario that ***would not be tested by colliders or direct detection for the foreseeable future***

DM RELIES ON A COMBINATION OF SEARCHES

- Colliders, direct and indirect searches give very complementary searches for dark matter
- Direct and indirect especially useful as can probe parameter space totally inaccessible to colliders (and vice versa)

ANOMALY DRIVEN DARK MATTER

- DAMA
- INTEGRAL positrons (MeV scale)
- PAMELA/AMS positrons (100-1000 GeV scale)
- The galactic center gamma rays (few GeV scale)
- The 3.5 keV x-ray line (keV scale)

DISCLAIMER:
I THINK ANOMALIES, EVEN WRONG ONES ARE OFTEN GOOD THINGS

- Before we try to address an anomaly, conventional wisdom will tell you certain things are unlikely

- When pressed, many of these assumptions fall away (Sommerfeld enhancement, leptophilic models, light WIMPs, SIDM models…)

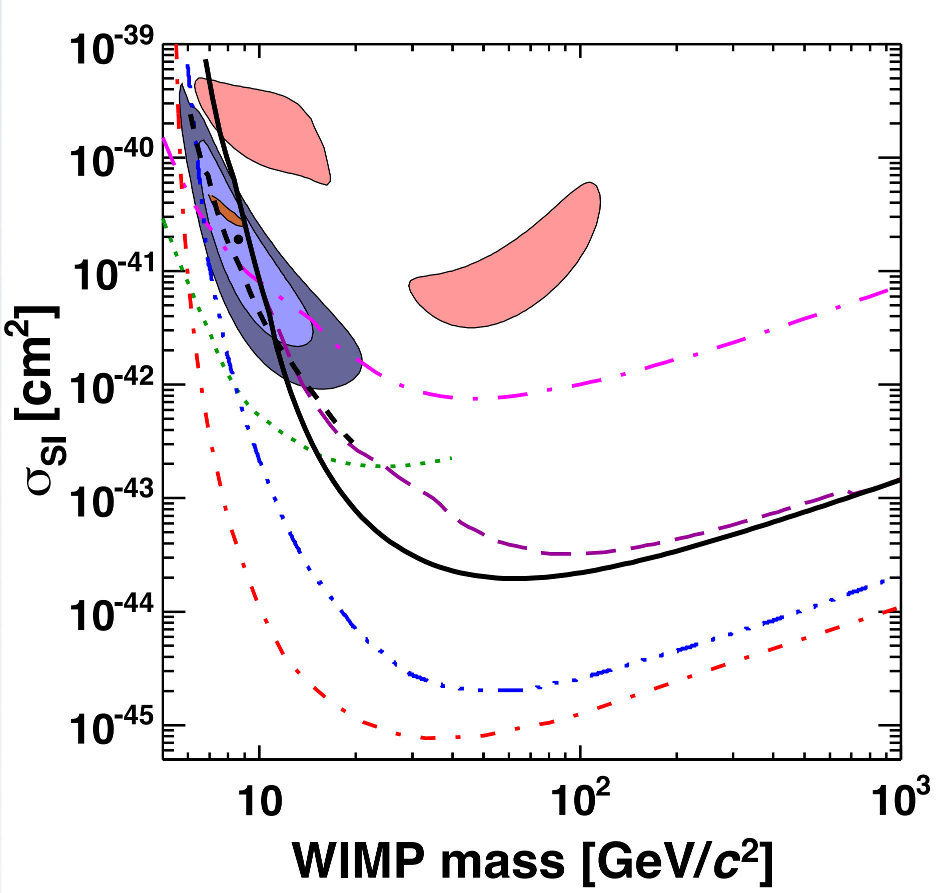
- Anomalies give a directed way to challenge CW ideas on dark matter

- My impression is that a lot of pushing in the boundaries of theory and experiment has come as a result of these

A MORE INTERESTING DARK SECTOR

- A major consequence of recent anomalies has been to consider dark matter with its own “dark sector”
- E.g., dark forces, multiple states of dark matter (akin to atomic states or neutron-proton), and multiple dark matter species are much better understood, and are fairly simple models to write down
- At this point, I think dark force scenarios are *more* theoretically motivated than an explanation of any particular anomaly

DIRECT ANOMALIES



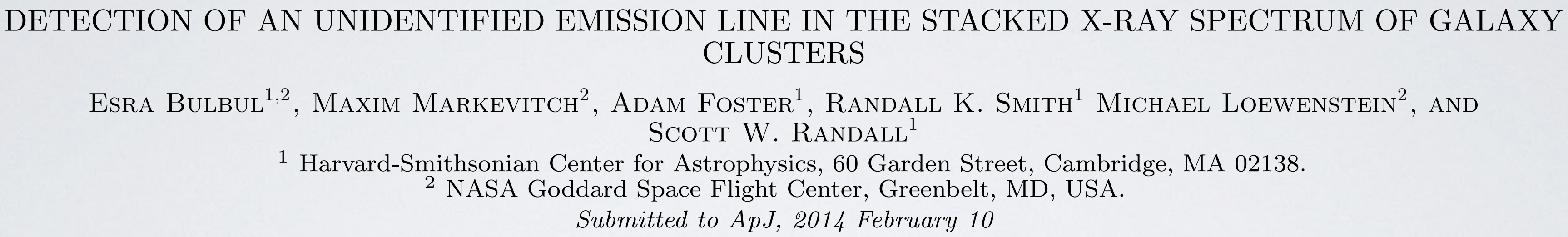
CDMS Collab '15

I think light WIMPs are *more* theoretically motivated than 10 years ago

but it appears converged that they are *not* the explanation of various direct detection anomalies

A TALE OF TWO ANOMALIES

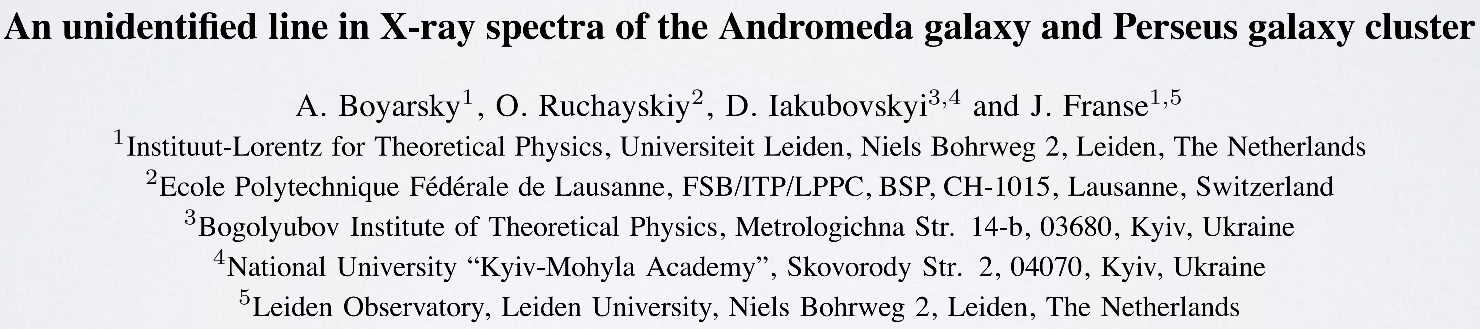
A LINE AT 3.55(ish) KeV



DETECTION OF AN UNIDENTIFIED EMISSION LINE IN THE STACKED X-RAY SPECTRUM OF GALAXY CLUSTERS

Esra Bulbul[1,2], Maxim Markevitch[2], Adam Foster[1], Randall K. Smith[1] Michael Loewenstein[2], and Scott W. Randall[1]
[1] Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138.
[2] NASA Goddard Space Flight Center, Greenbelt, MD, USA.

Submitted to ApJ, 2014 February 10



An unidentified line in X-ray spectra of the Andromeda galaxy and Perseus galaxy cluster

A. Boyarsky[1], O. Ruchayskiy[2], D. Iakubovskyi[3,4] and J. Franse[1,5]
[1]Instituut-Lorentz for Theoretical Physics, Universiteit Leiden, Niels Bohrweg 2, Leiden, The Netherlands
[2]Ecole Polytechnique Fédérale de Lausanne, FSB/ITP/LPPC, BSP, CH-1015, Lausanne, Switzerland
[3]Bogolyubov Institute of Theoretical Physics, Metrologichna Str. 14-b, 03680, Kyiv, Ukraine
[4]National University "Kyiv-Mohyla Academy", Skovorody Str. 2, 04070, Kyiv, Ukraine
[5]Leiden Observatory, Leiden University, Niels Bohrweg 2, Leiden, The Netherlands

Bulbul et al

73 Clusters, XMM, central,
to z=0.35
incl Coma, Perseus

Perseus Chandra, central

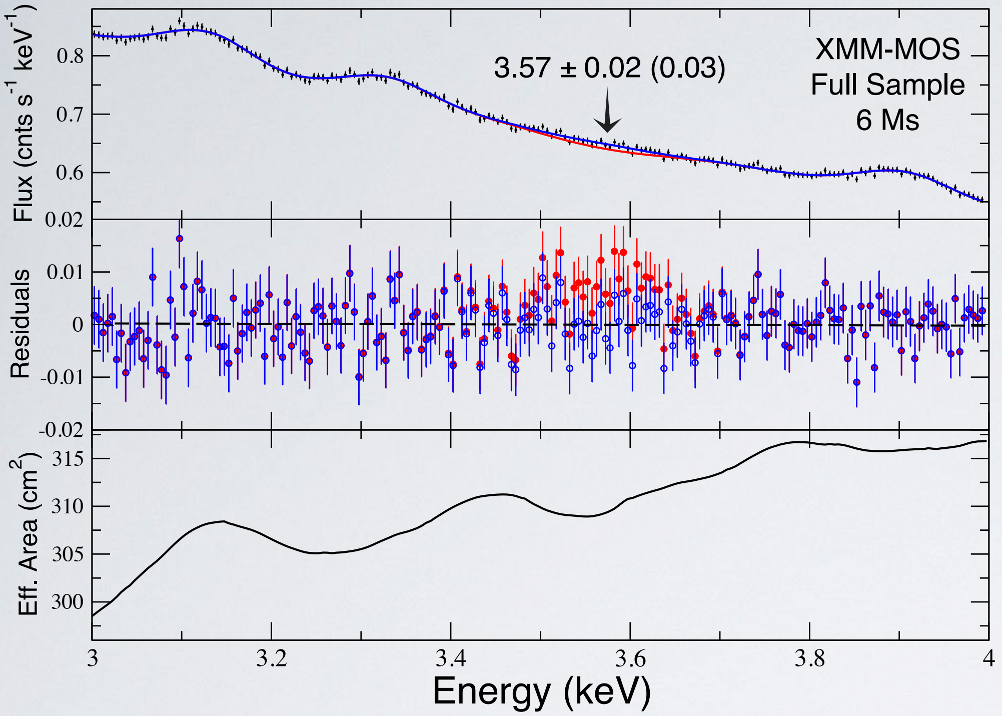
Virgo Chandra, central (not seen)

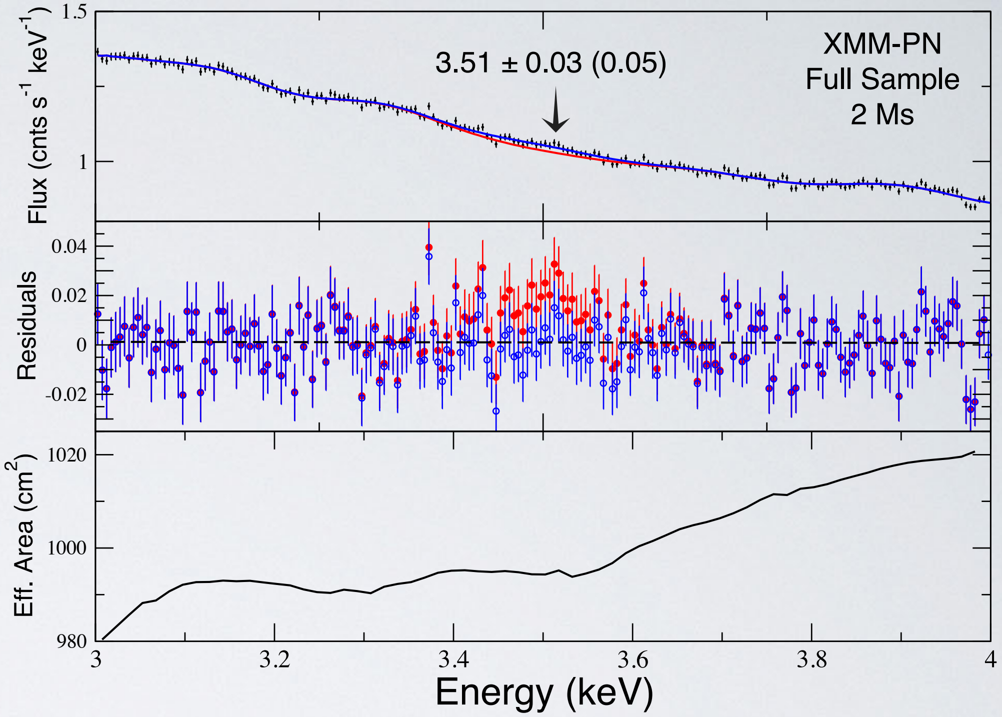
Boyarsky et al

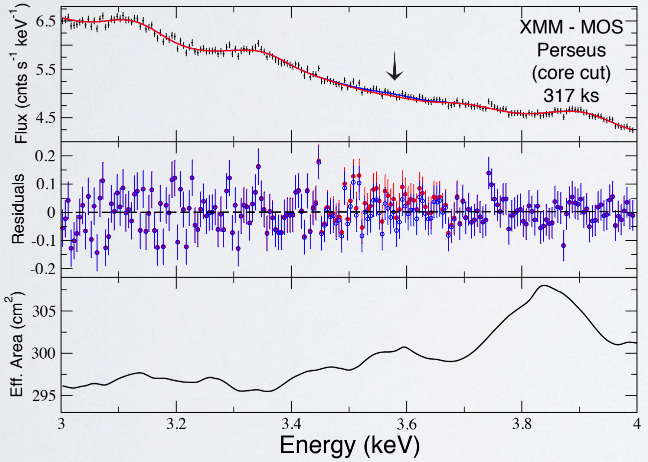
M31 XMM
central+non-central

Perseus XMM, non-central

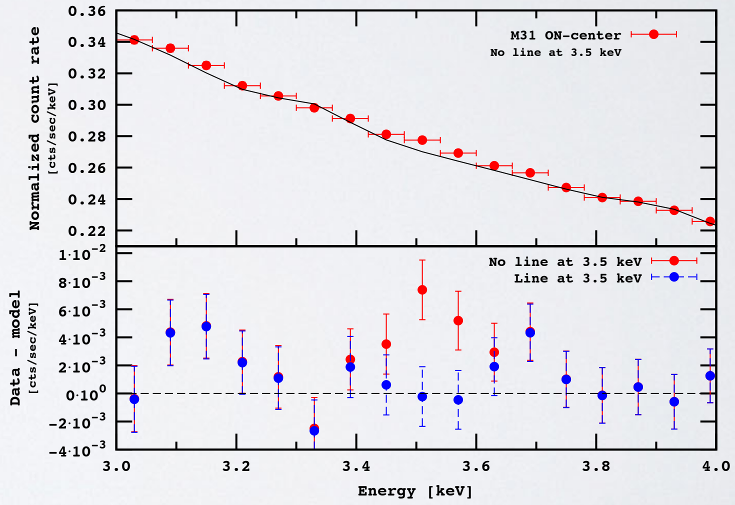
Bulbul et al





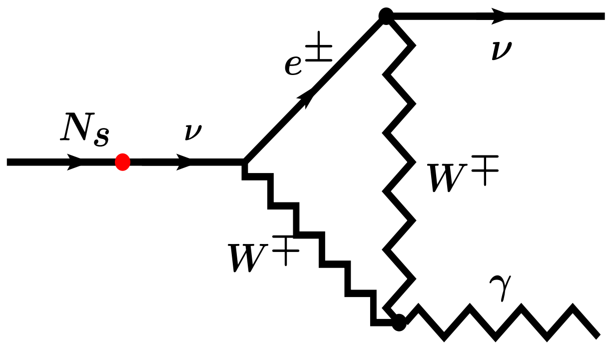


Boyarsky et al

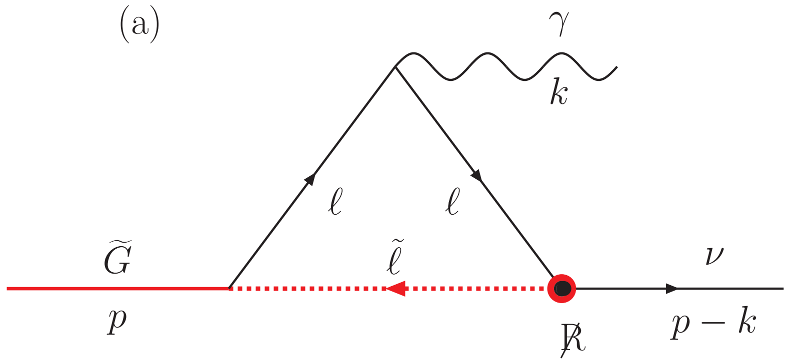


DECAYING DARK MATTER

- Sterile neutrino $N \to \nu + \gamma$



- R-parity violating gravitino $\tilde{g} \to \nu + \gamma$



- Also R-parity violating axino, . . .
- For bosonic DM axions (or axion-like particles) would decay $a \to \gamma\gamma$

from talk by Ruchayskiy, April 2014

A COMPLETE LIST OF RECENT CLAIMS

Positive

Bulbul et al - Perseus (XMM)
Bulbul et al - Perseus (Chandra)
Bulbul et al - Coma+Centaurus+Ophiocus (XMM)
Bulbul et al - Stacked Clusters (XMM)
Boyarsky et al - Perseus (XMM)
Boyarsky et al - M31 (XMM)
Boyarsky et al - Milky Way (XMM)

Negative

Horiuchi et al - M31 (XMM)
Tamura et al - Perseus (Suzaku)
Riemer-Sorensen - Milky Way (XMM)
Malyshev et al - Stacked dwarfs (XMM)
Anderson et al - Stacked Galaxies (XMM)
Anderson et al - Stacked Galaxies (Chandra)
Profumo et al - Milky Way
Urban et al - Coma, Centaurus, Ophiocus (Suzaku)

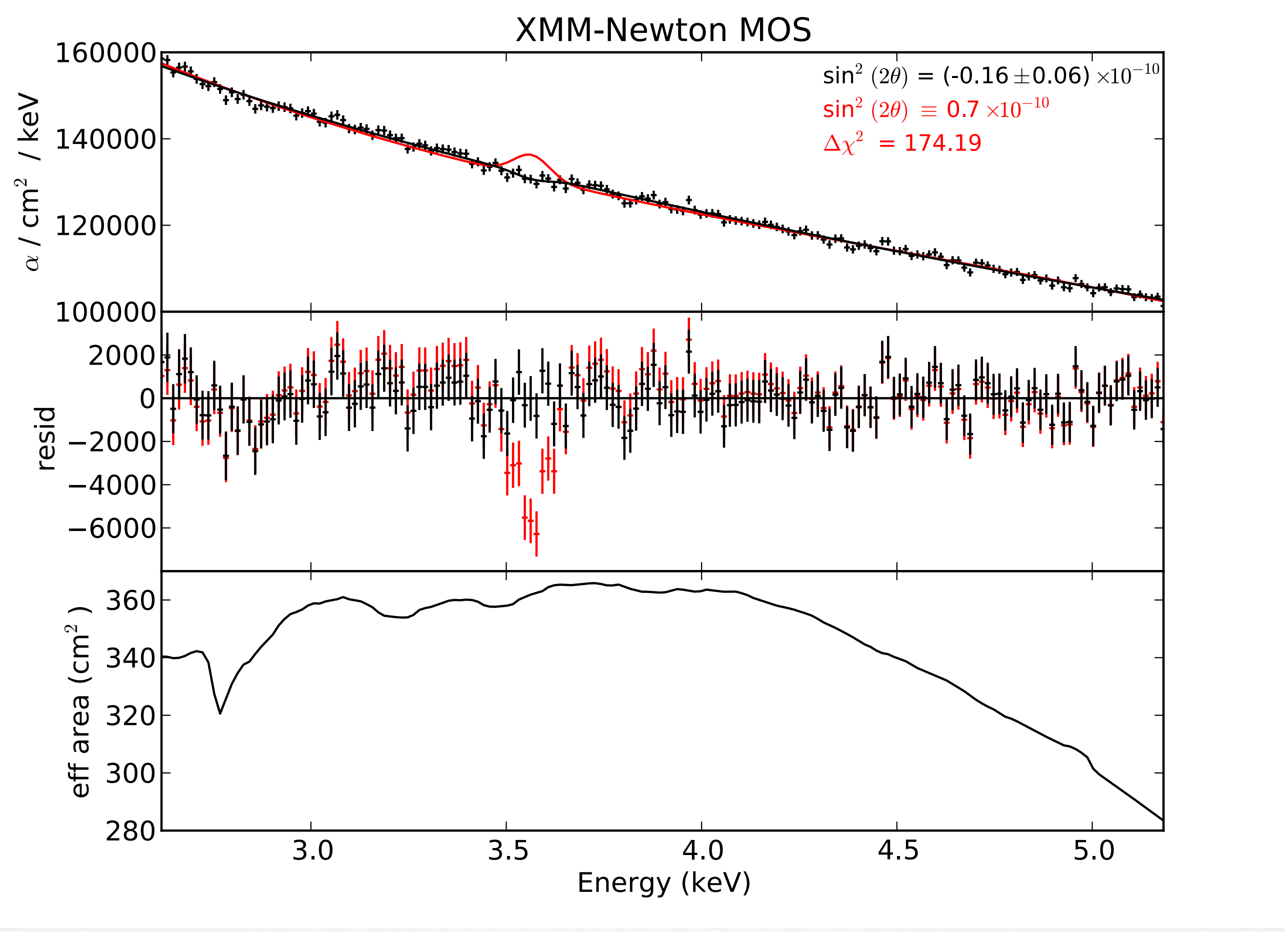
Yes, but

Urban et al - Perseus (Suzaku)
Profumo et al - Perseus

TENSIONS

- Signal seems very present in clusters (stacked) and Perseus (individually)
- Seems not in Virgo, not in dwarfs, and not in the outer parts of ordinary galaxies

STACKING OUTER PARTS OF GALAXIES



Anderson, Churazov, Bregman

1408.4115

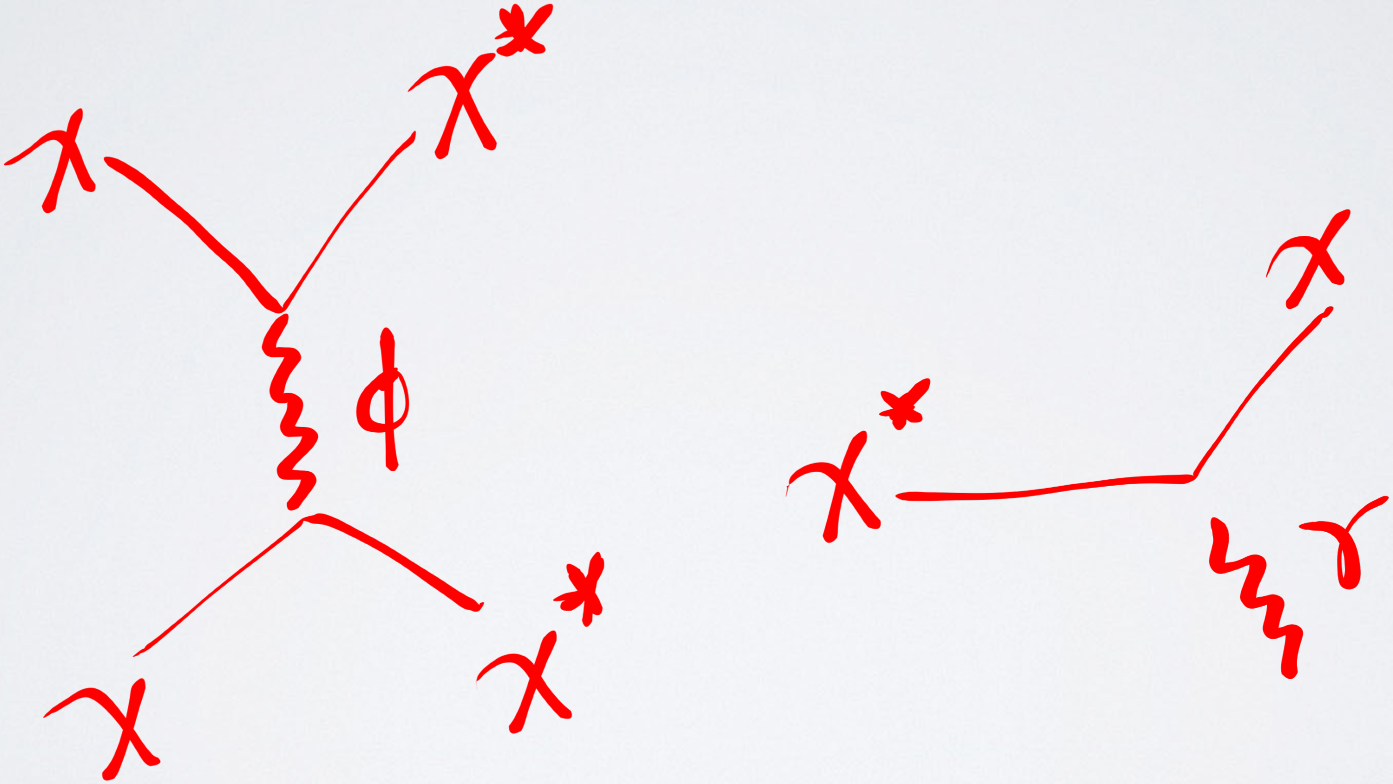
MODEL TESTS NOT ANOMALY TESTS

- The decaying interpretation of this is in trouble
- Alternative scenarios?

SCATTERING MODELS

Finkbeiner, NW 1402.6671

Convert *kinetic* energy to CR signal rather than *mass* energy



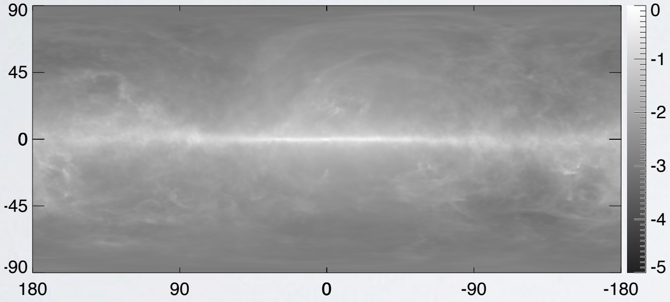
Just reapplication of older model for INTEGRAL

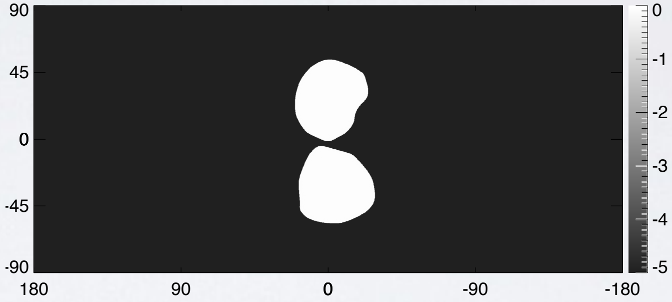
SCATTERING

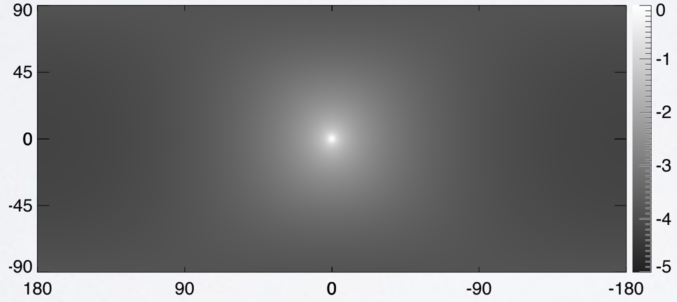
- Signal traces $\boldsymbol{\rho}^2$ not $\boldsymbol{\rho}$
- Turns off in low velocity systems
- Variations in NFW profiles give significant differences between e.g., Perseus and Virgo
- Astro-H and possible additional XMM time on Perseus could help distinguish scenarios
- Important to recognize that most tests are of individual models, not the excess itself

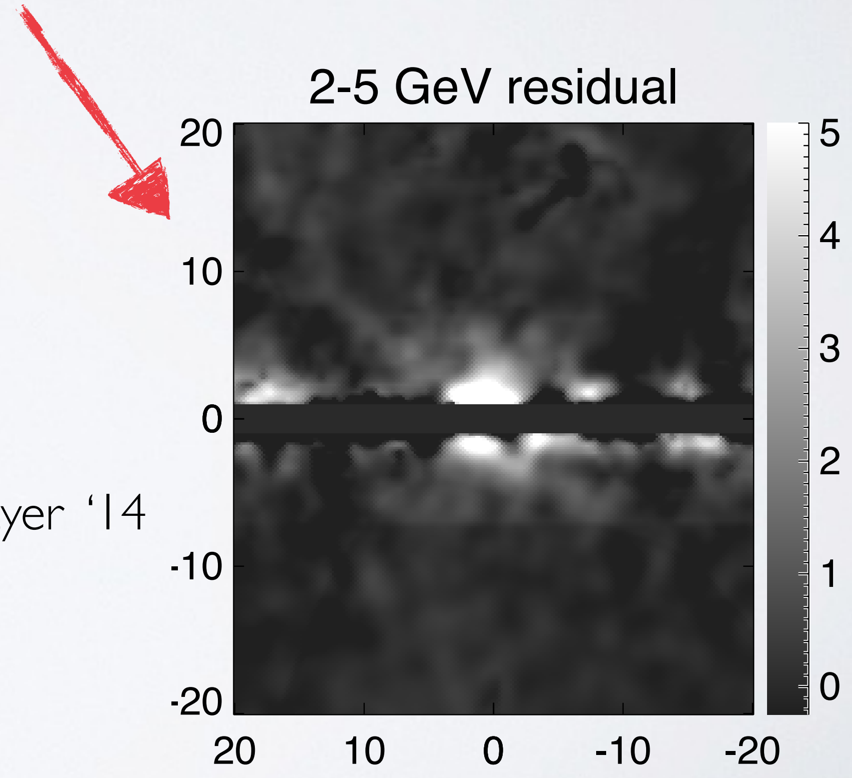
A SIGNAL IN THE GC?

Hooper + Goodenough '09; Hooper + Linden '11; Abazajian+Kaplinghat '12; Hooper+Slatyer '13





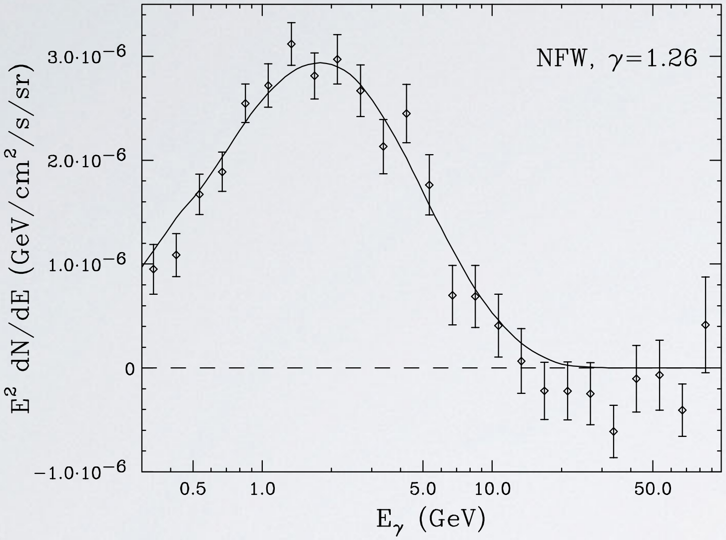




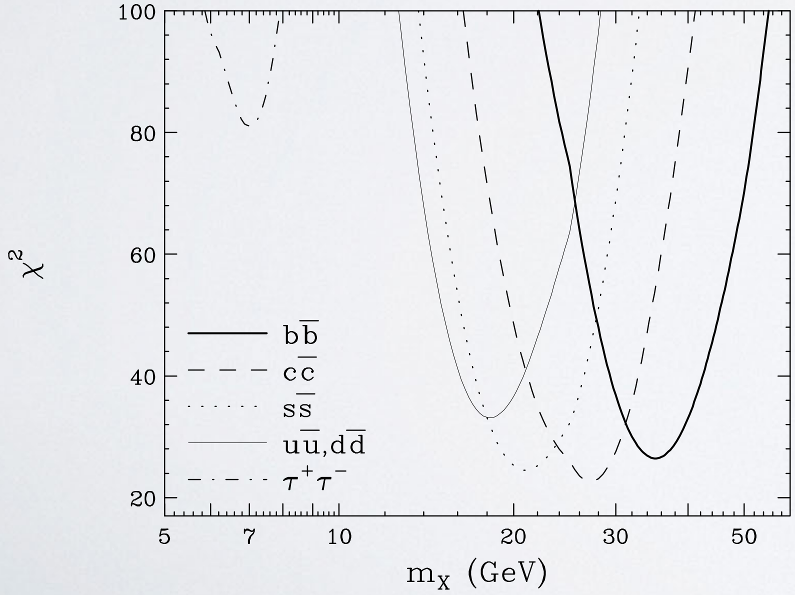
Daylan, Finkbeiner, Hooper, Linden, Portillo, Rodd + Slatyer '14

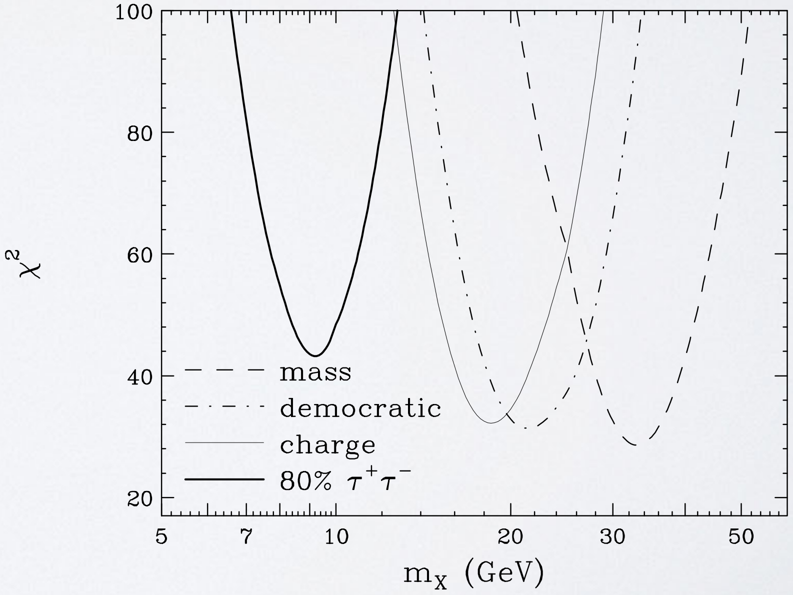
See talk tomorrow by T. Slatyer

DARK ANNIHILATION TO BB?

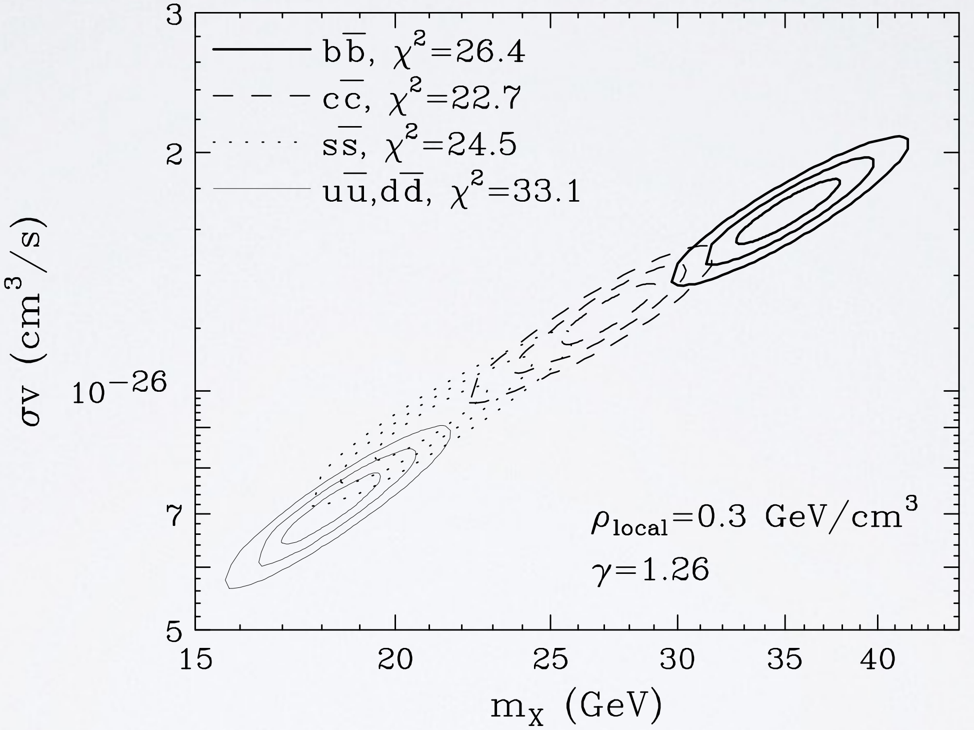


not really chi-squared





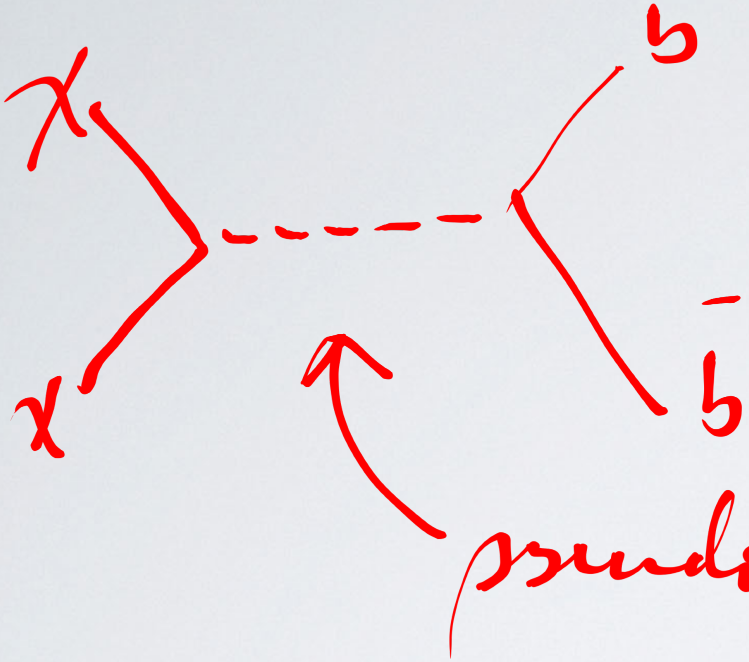
ANNIHILATIONS



BEWARE OF THEORISTS BEARING MODELS

- NB: “DM annihilating into bb, what could be simpler?” ≠ actual model

- In general requires a decent amount of machinery at ~ 100 GeV. Can evade constraints, but not at all trivial



annihilon

$$\mathcal{L}_{\text{dark}} = y_\chi a_0 \bar{\chi} i \gamma^5 \chi$$

$$V = V_{\text{2HDM}} + \frac{1}{2} m_{a_0}^2 a_0^2 + \frac{\lambda_a}{4} a_0^4 + V_{\text{port}}$$

$$V_{\text{port}} = iBa_0 H_1^\dagger H_2 + \text{h.c.}$$

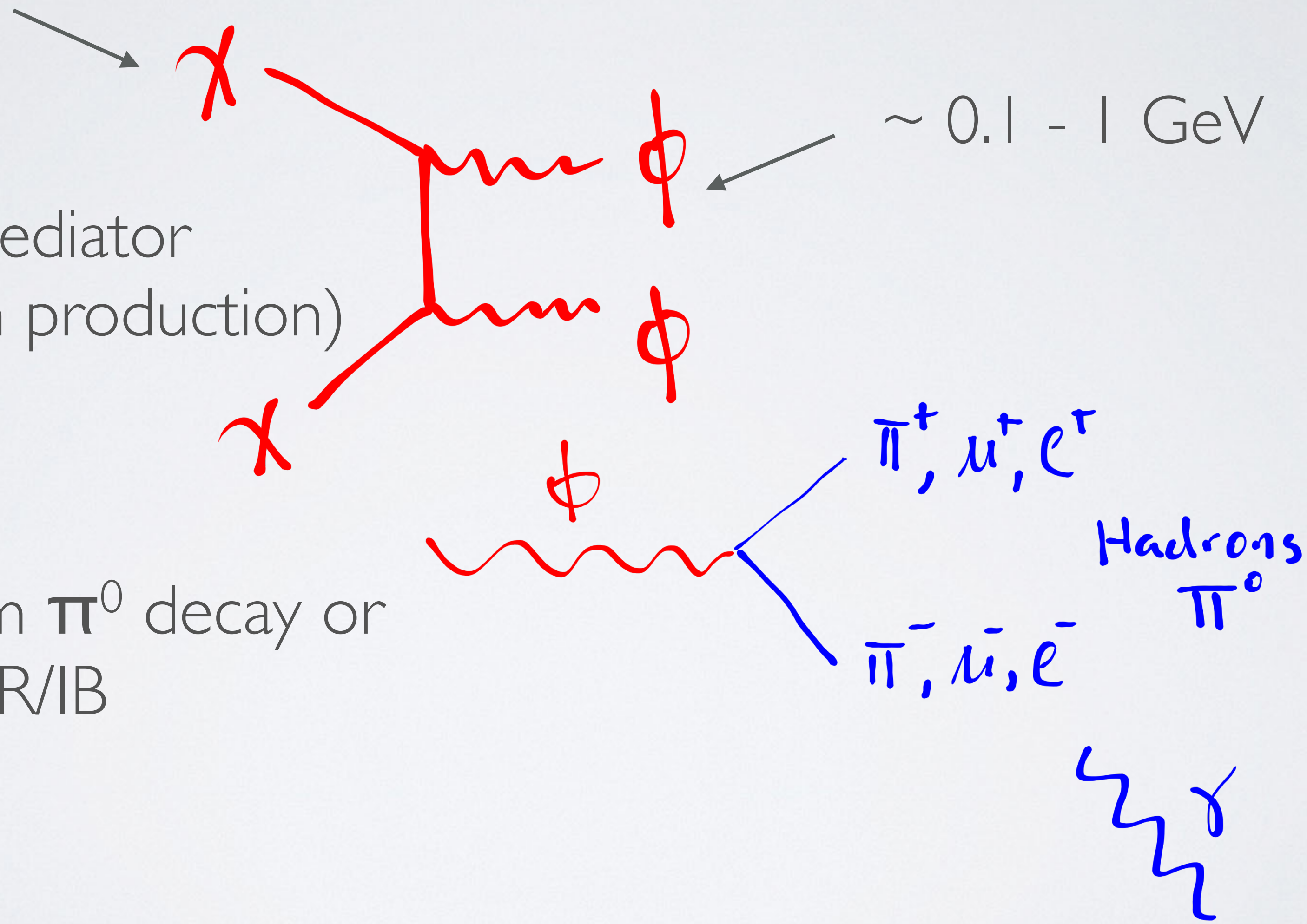
$$\begin{aligned} V_{\text{2HDM}} &= \lambda_1 \left(H_1^\dagger H_1 - \frac{v_1^2}{2} \right)^2 + \lambda_2 \left(H_2^\dagger H_2 - \frac{v_2^2}{2} \right)^2 \\ &+ \lambda_3 \left[\left(H_1^\dagger H_1 - \frac{v_1^2}{2} \right) + \left(H_2^\dagger H_2 - \frac{v_2^2}{2} \right) \right]^2 \\ &+ \lambda_4 \left[\left(H_1^\dagger H_1 \right) \left(H_2^\dagger H_2 \right) - \left(H_1^\dagger H_2 \right) \left(H_2^\dagger H_1 \right) \right] \\ &+ \lambda_5 \left[\text{Re} \left(H_1^\dagger H_2 \right) - \frac{v_1 v_2}{2} \right]^2 + \lambda_6 \left[\text{Im} \left(H_1^\dagger H_2 \right) \right]^2 \end{aligned}$$

Ipek, McKeen, Nelson '14

+ *harder hierarchy problem* + *no sannihilon (scalar annihilon)*

GC SIGNALS OF LIGHT DARK FORCE MODELS

(cf PAMELA models)



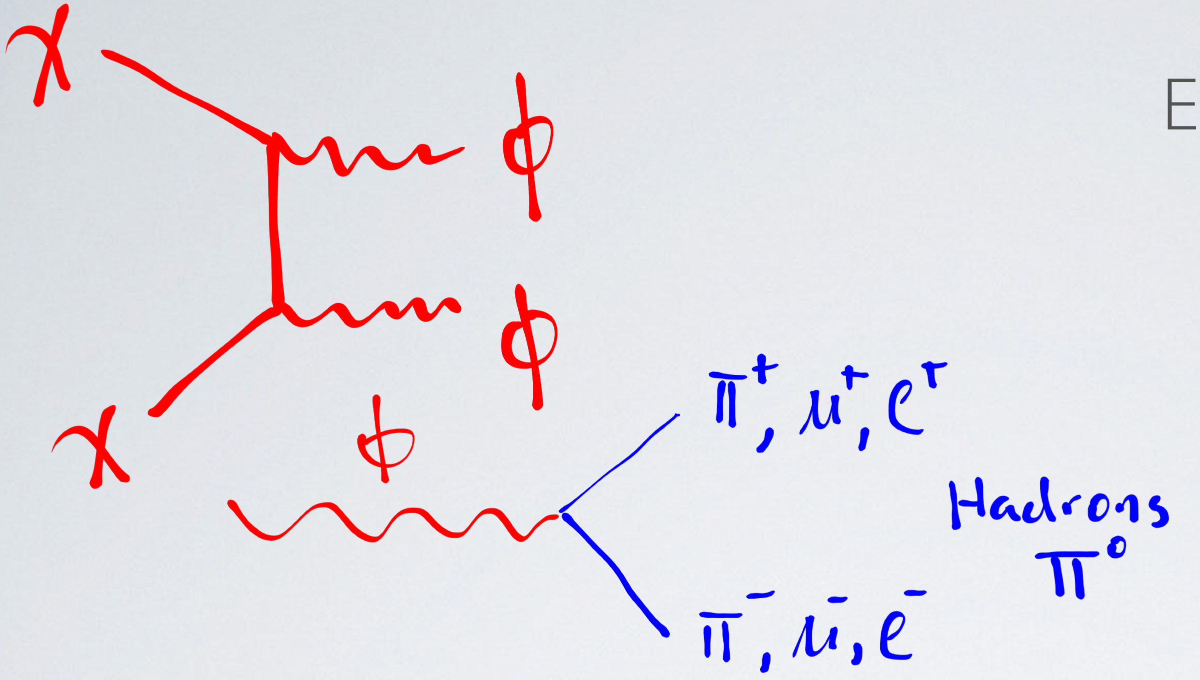
~5-10 GeV

~ 0.1 - 1 GeV

“light” mediator
(below proton production)

photons from π^0 decay or
FSR/IB

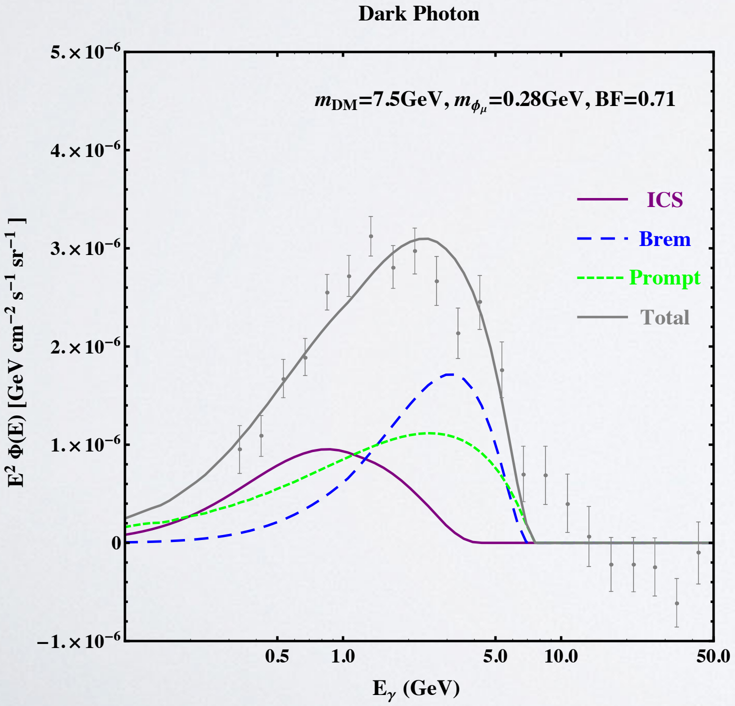
(Hooper, NW, Xue 1206.2929; Martin, Shelton, Unwin 1405.0272; Berlin, Gratia, Hooper, McDermott 1405.5204; Liu, NW, Xue 1412.1485; Elor, Rodd, Slatyer 1503.01773)

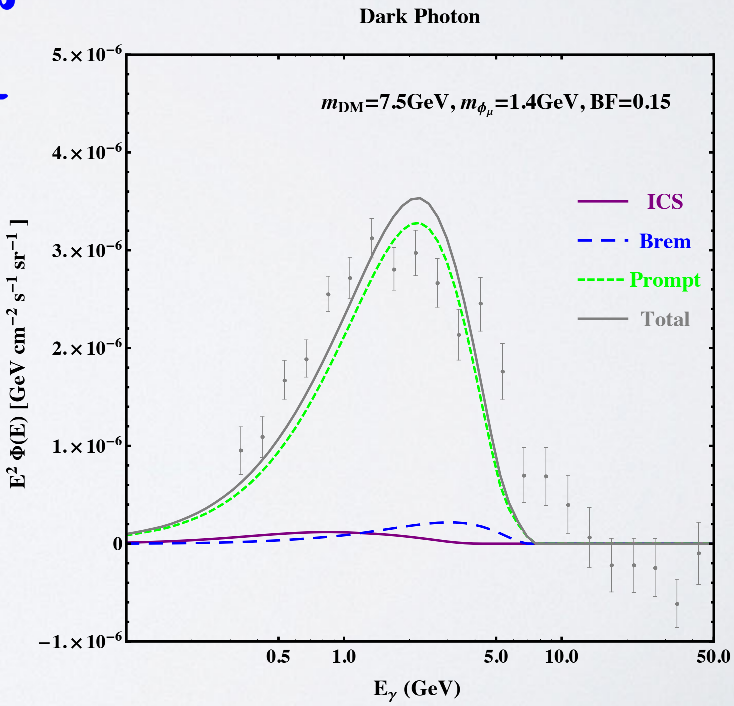


Easy to write down

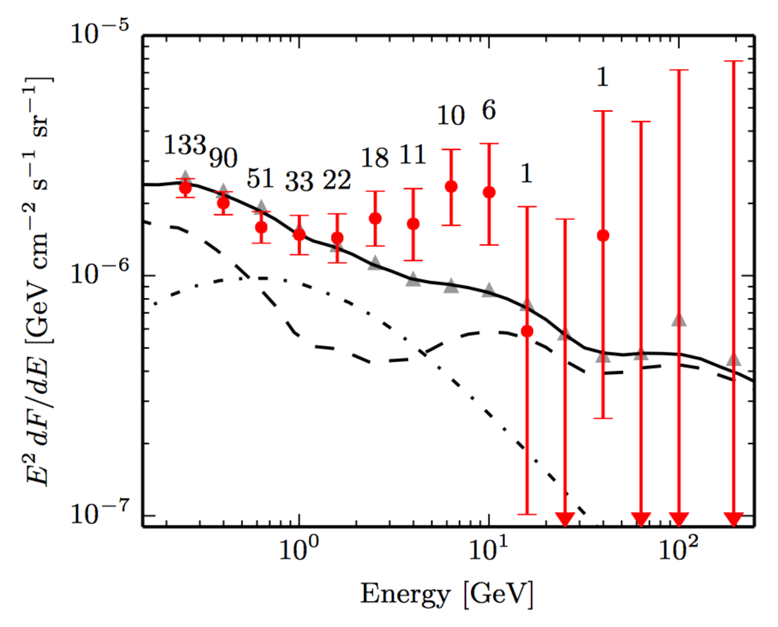
simple freezeout

no antiprotons

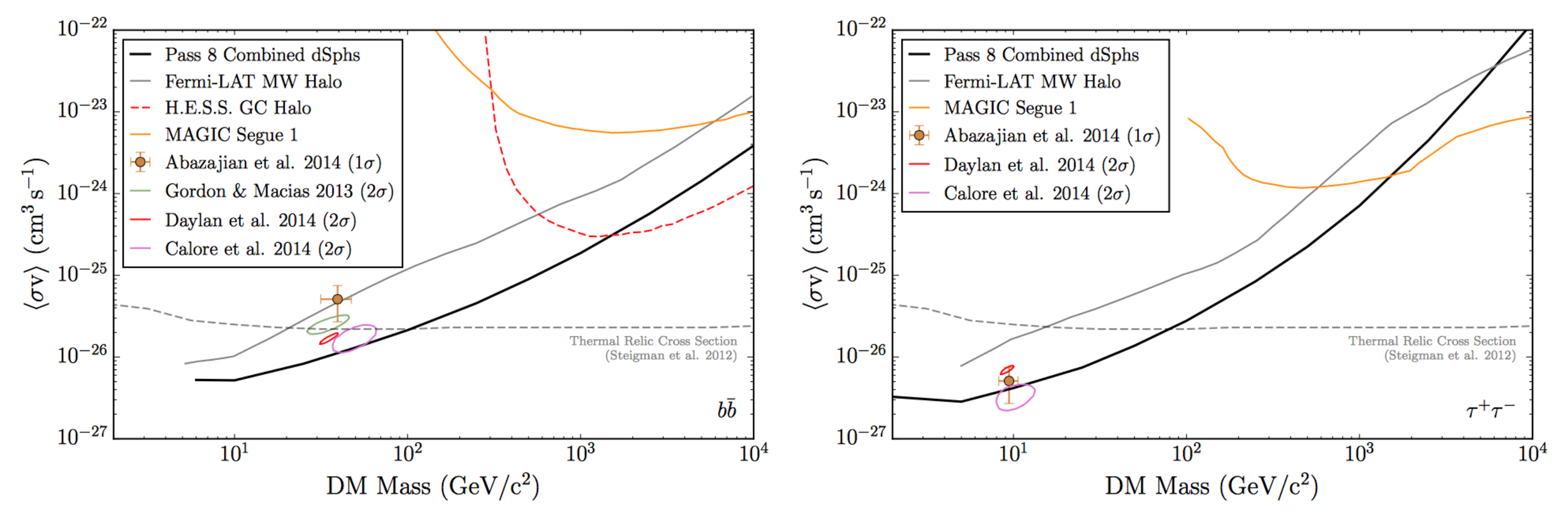




DWARF GALAXIES

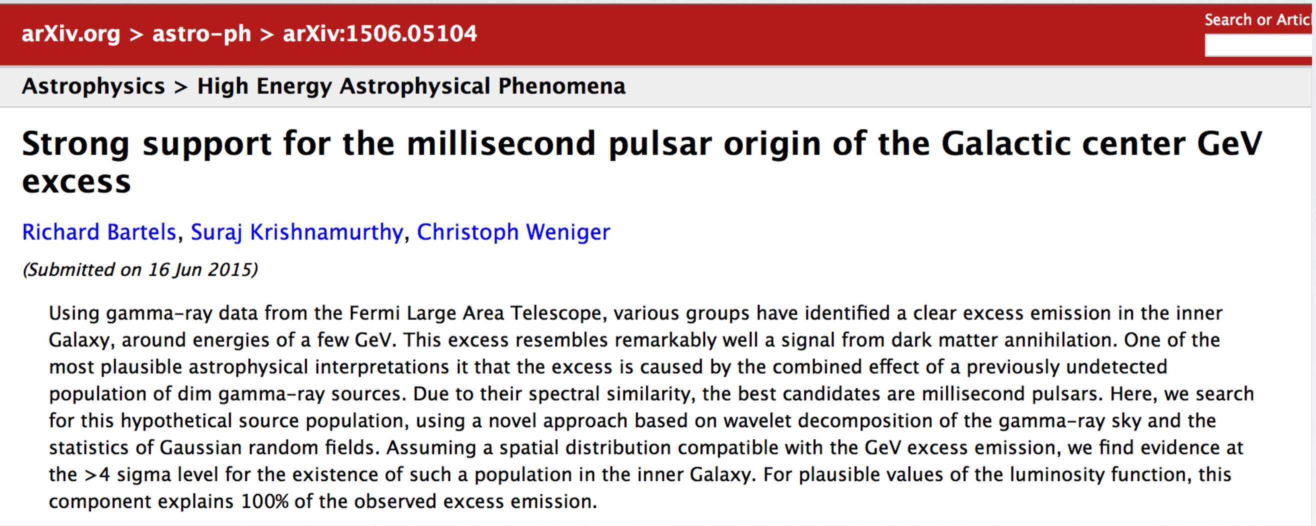


Garinger-Sameth et al ‘15



Fermi Collaboration ‘15

LIES, DAMN LIES AND STATISTICS



arXiv.org > astro-ph > arXiv:1506.05104

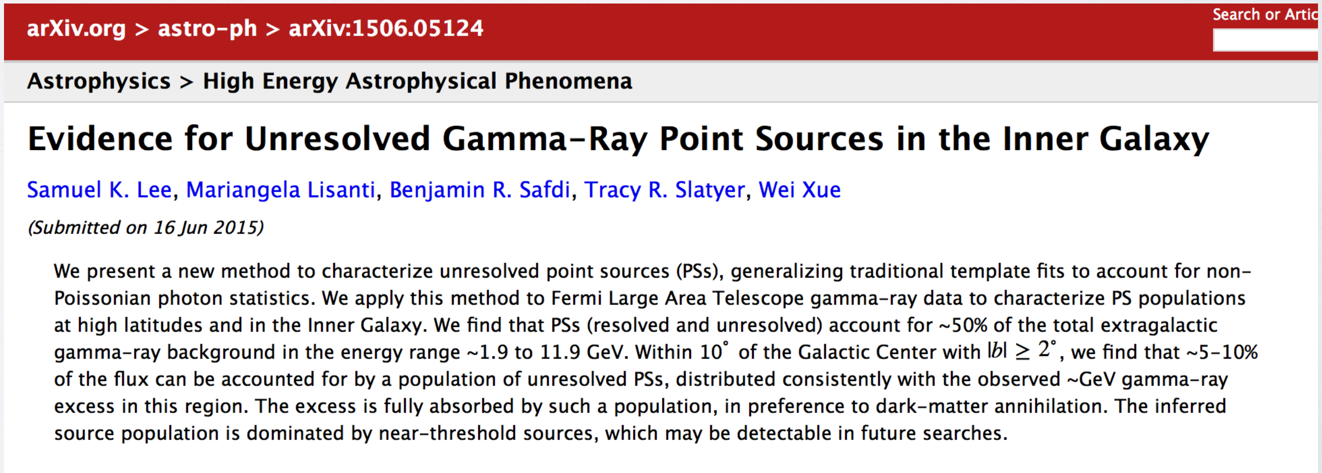
Astrophysics > High Energy Astrophysical Phenomena

Strong support for the millisecond pulsar origin of the Galactic center GeV excess

Richard Bartels, Suraj Krishnamurthy, Christoph Weniger

(Submitted on 16 Jun 2015)

Using gamma-ray data from the Fermi Large Area Telescope, various groups have identified a clear excess emission in the inner Galaxy, around energies of a few GeV. This excess resembles remarkably well a signal from dark matter annihilation. One of the most plausible astrophysical interpretations it that the excess is caused by the combined effect of a previously undetected population of dim gamma-ray sources. Due to their spectral similarity, the best candidates are millisecond pulsars. Here, we search for this hypothetical source population, using a novel approach based on wavelet decomposition of the gamma-ray sky and the statistics of Gaussian random fields. Assuming a spatial distribution compatible with the GeV excess emission, we find evidence at the >4 sigma level for the existence of such a population in the inner Galaxy. For plausible values of the luminosity function, this component explains 100% of the observed excess emission.



arXiv.org > astro-ph > arXiv:1506.05124

Astrophysics > High Energy Astrophysical Phenomena

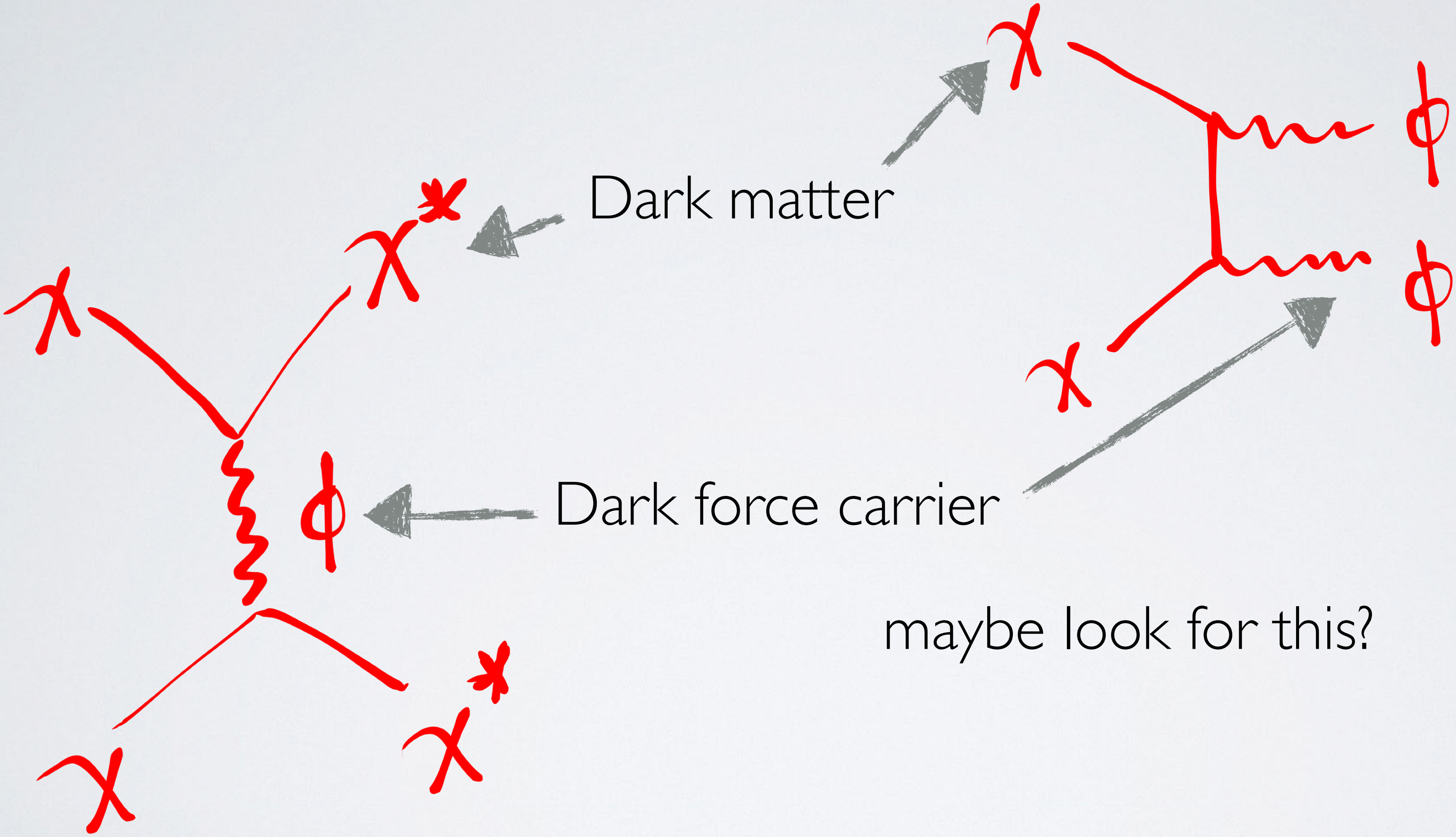
Evidence for Unresolved Gamma-Ray Point Sources in the Inner Galaxy

Samuel K. Lee, Mariangela Lisanti, Benjamin R. Safdi, Tracy R. Slatyer, Wei Xue

(Submitted on 16 Jun 2015)

We present a new method to characterize unresolved point sources (PSs), generalizing traditional template fits to account for non-Poissonian photon statistics. We apply this method to Fermi Large Area Telescope gamma-ray data to characterize PS populations at high latitudes and in the Inner Galaxy. We find that PSs (resolved and unresolved) account for ~50% of the total extragalactic gamma-ray background in the energy range ~1.9 to 11.9 GeV. Within 10° of the Galactic Center with $|b| \geq 2^\circ$, we find that ~5-10% of the flux can be accounted for by a population of unresolved PSs, distributed consistently with the observed ~GeV gamma-ray excess in this region. The excess is fully absorbed by such a population, in preference to dark-matter annihilation. The inferred source population is dominated by near-threshold sources, which may be detectable in future searches.

A NEW FORCE



Dark matter

Dark force carrier

maybe look for this?

HIDDEN SECTOR MODELS

- models with new interactions are now a part of the standard toolbox (i.e., Dark matter χ and dark force ϕ, A', Z_D…)
- depending on how those mediators interact with us, radically different search strategies appear

DARK SECTORS

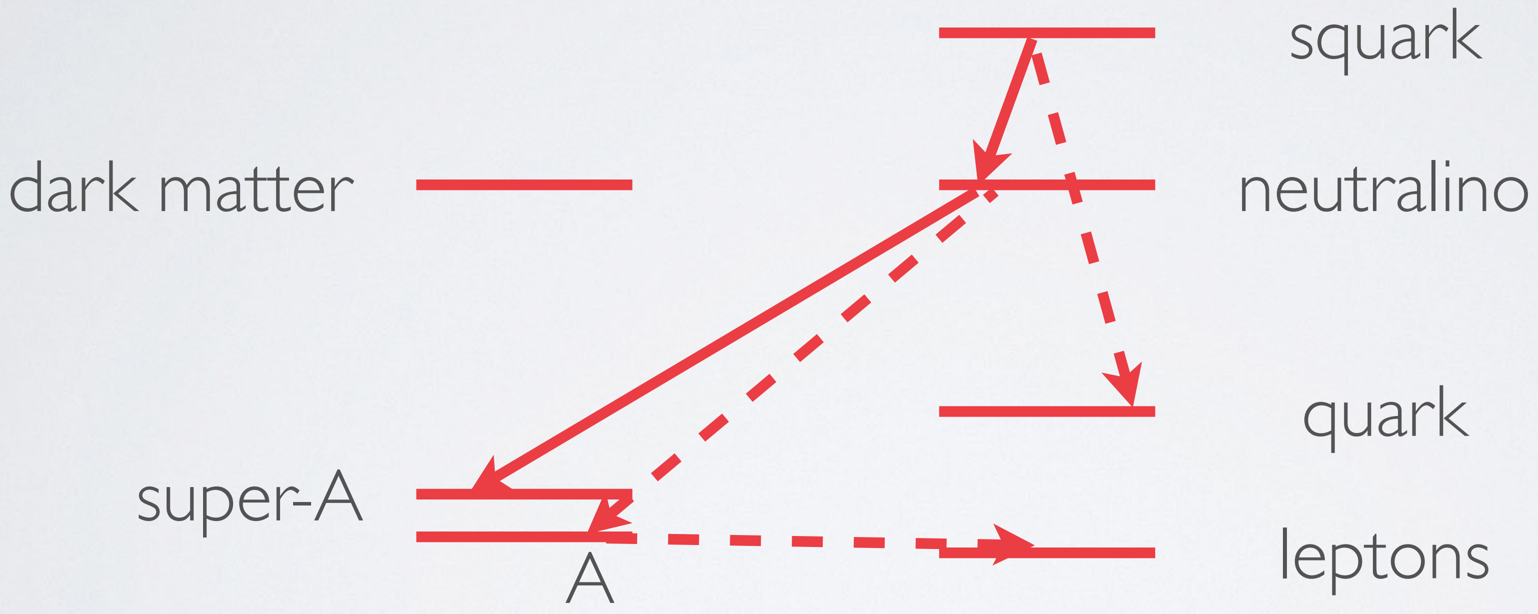
Standard model can connect to hidden sectors through “portals”

vector or kinetic mixing	$\epsilon_Y F^Y_{\mu\nu} F_d^{\mu\nu}$	dark photon couples like photon or hypercharge
Higgs	$\epsilon_h h^\dagger h \phi^* \phi$	dark scalar couples like Higgs
neutrino	$\epsilon_\nu (LH) n$	dark fermion couples like neutrino

Backgrounds make even O(.1-.001) difficult to see depending on mass

LHC?

- What happens if these states are produced at the LHC?



squark

dark matter

neutralino

quark

super-A

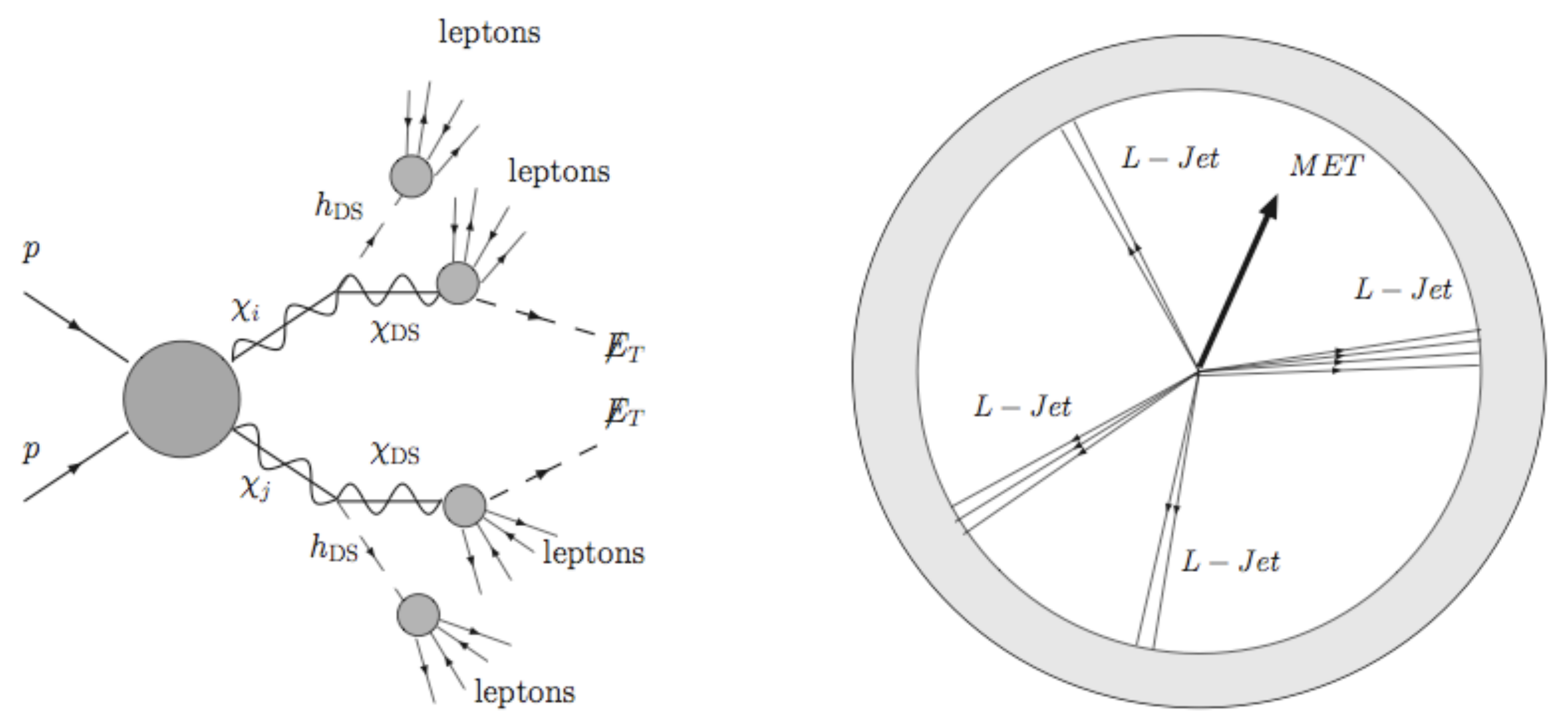
A

leptons

invariant mass ~GeV

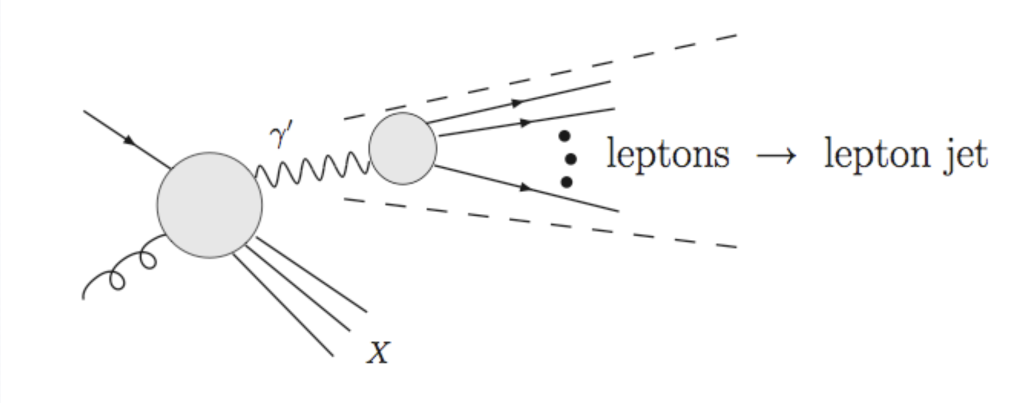
$$\tau \sim (\alpha\epsilon^2 m_{Z_{Dark}} N_{decaychannels})^{-1} \sim (\frac{10^{-7}}{\epsilon})^2 cm$$

N.Arkani-Hamed, NW, arXiv:0810.0714



Baumgart, Cheung, Ruderman, Wang, Yavin, ' 09

for light mass range,
yields "lepton jets"



At low energy accelerators:

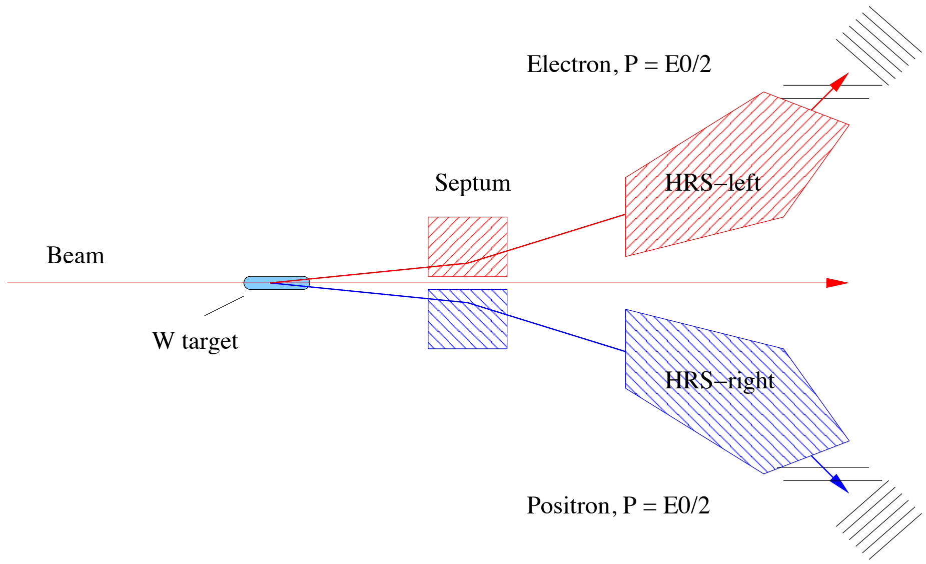
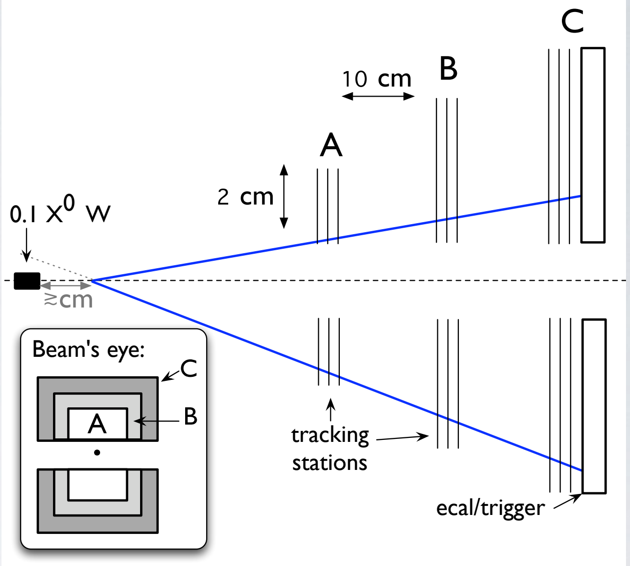
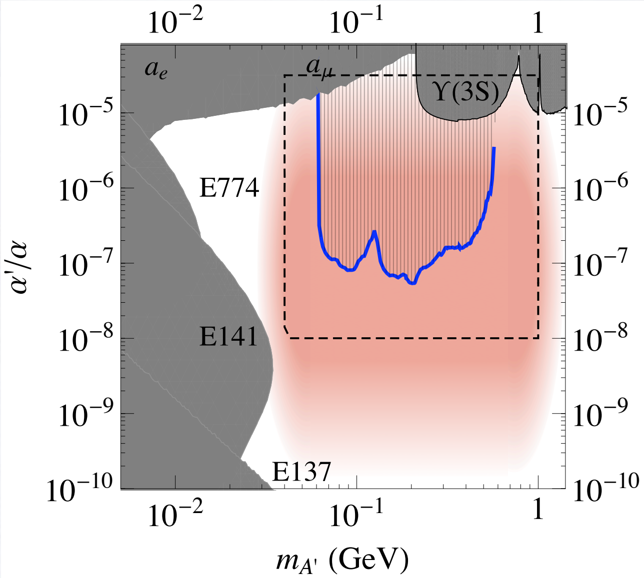


FIG. 5: The layout of the experimental setup — see text for details.

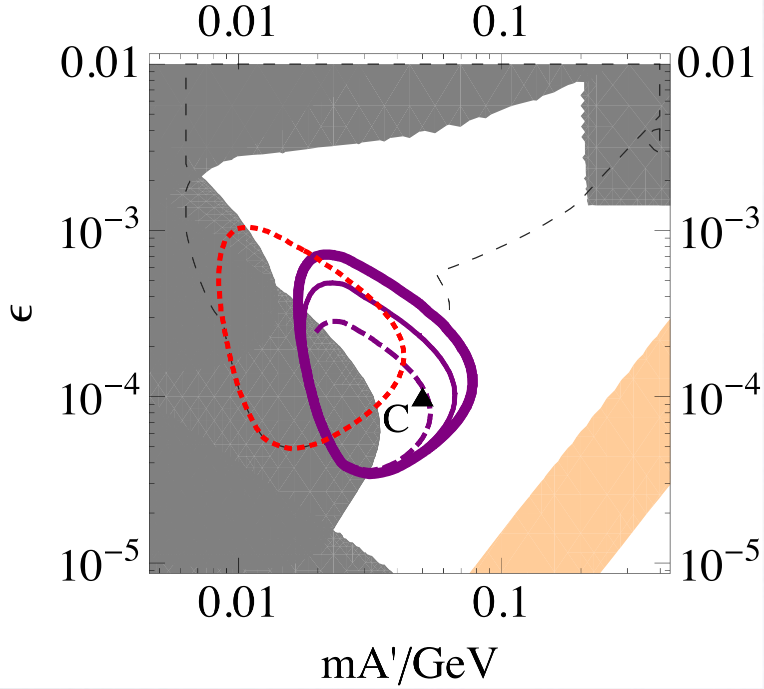




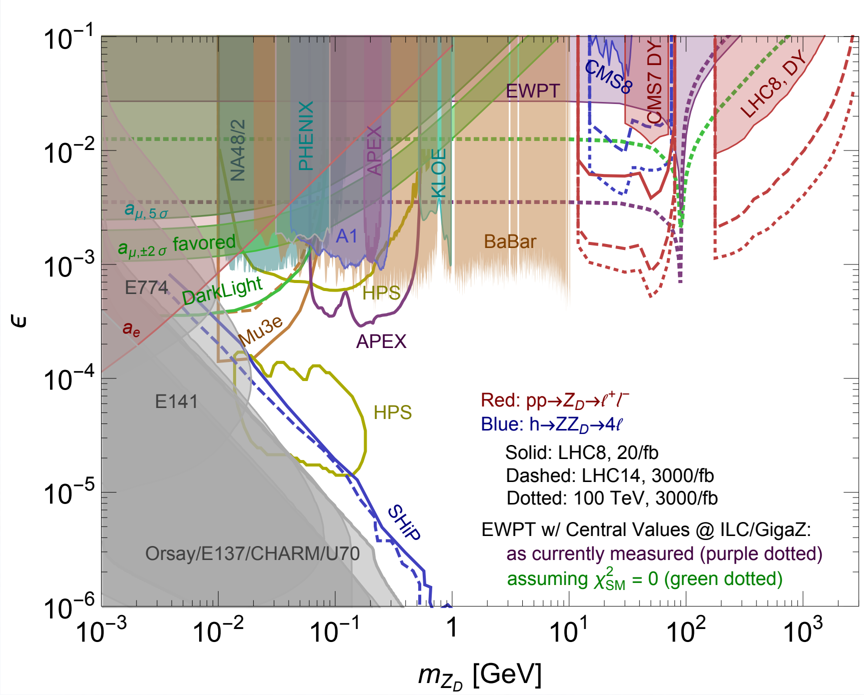
Bjorken, Essig, Schuster, Toro

APEX, HPS, Darklight... - searches for new physics at the **<GeV** scale

SEARCHES FOR DARK FORCES

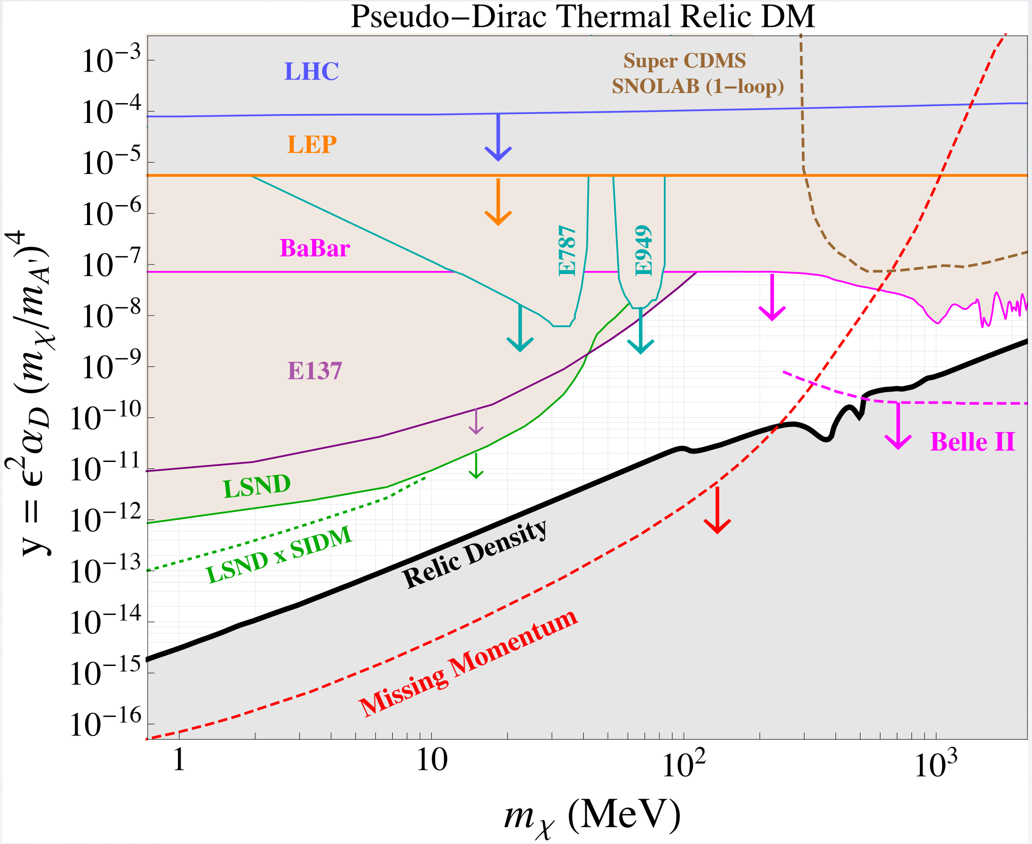


Bjorken, Essig, Schuster, Toro '08



Curtin, Essig, Gori, Shelton '14

LIGHT HIDDEN SECTOR DM



Izaguirre, Krnjaic, Schuster + Toro, '15
c.f. Boehm + Fayet '04

CONCLUSIONS:
THE SEARCH FOR DARK MATTER IS MESSY

- Axions, WIMPs, hidden sector models and other are all well motivated.

- As WIMP searches mature, absent a discovery, expect increasing development of theory in alternate directions (esp axions, dark sectors)

- Top-down motivations (e.g., SUSY) are critical, but we must be careful in applying the conventional wisdom gleaned from them

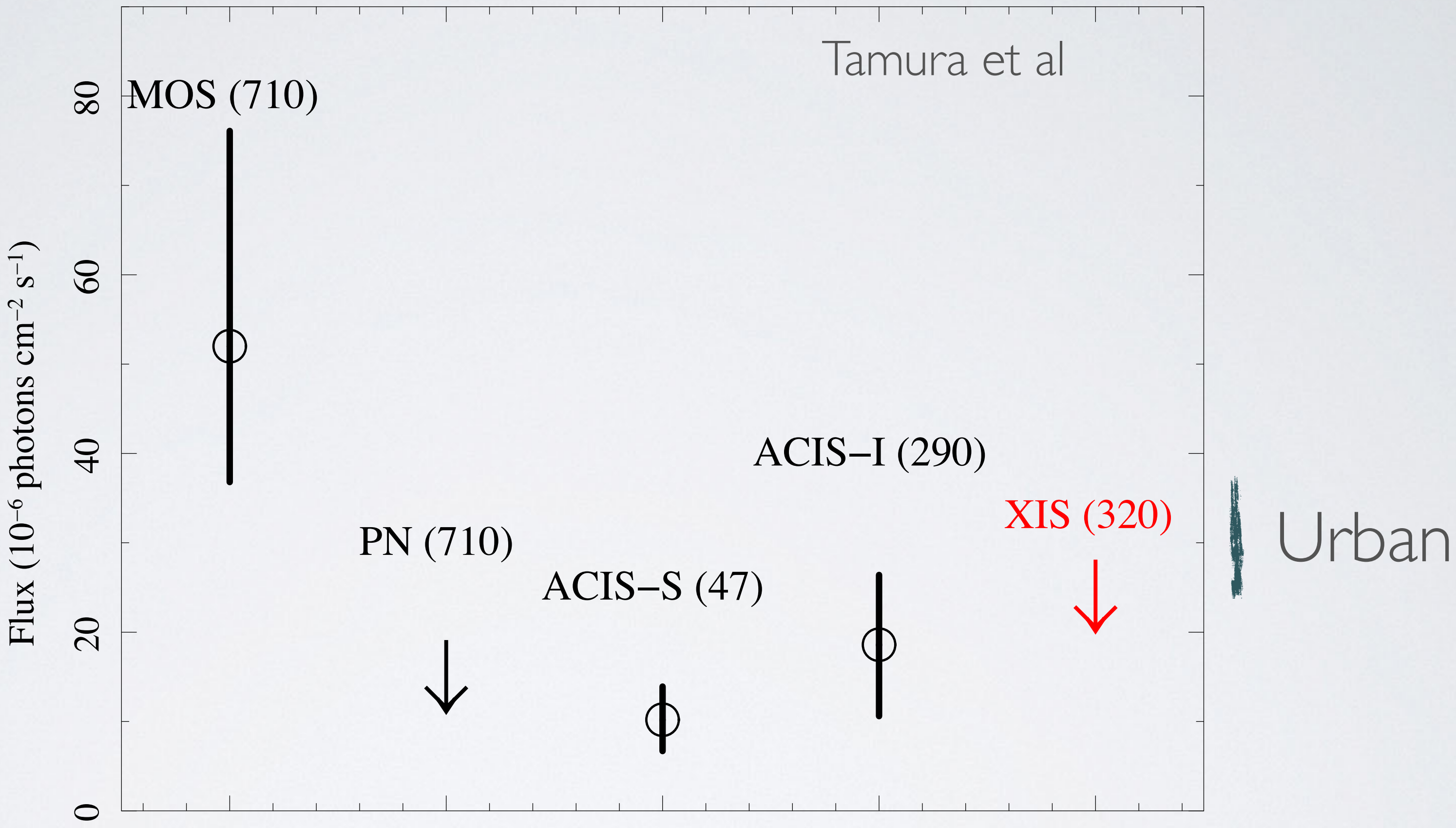
- Anomalies have proven an important in the development of our toolbox for DM from the bottom up *even when the anomalies ended up not being DM*

- Theory-experiment interplay richer than ever. Exciting times ahead!

THANK YOU VERY MUCH!

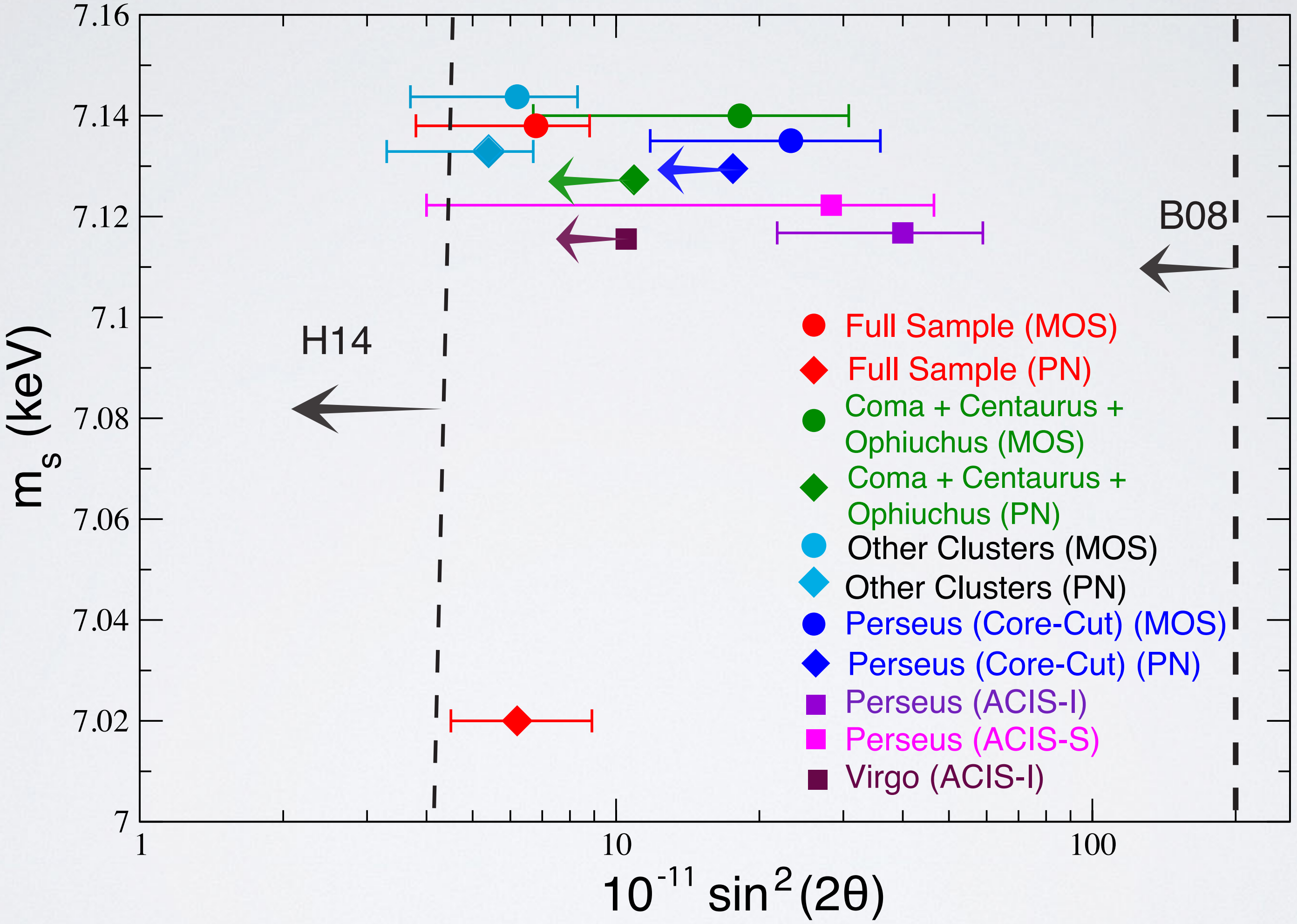
BACKUP

PERSEUS + SUZAKU



Urban says: too concentrated in Perseus

VIRGO VS PERSEUS



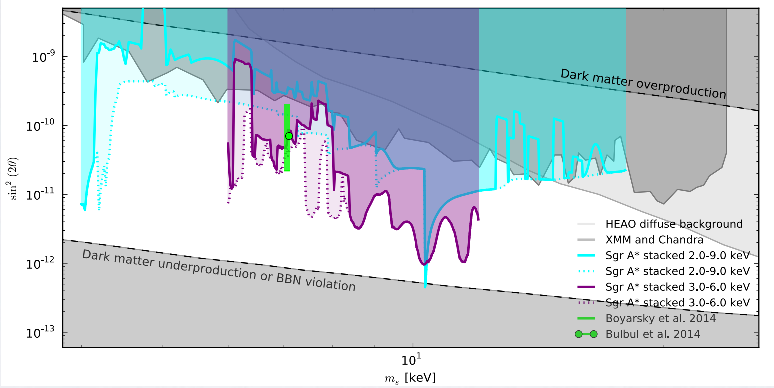
VIRGO VS PERSEUS

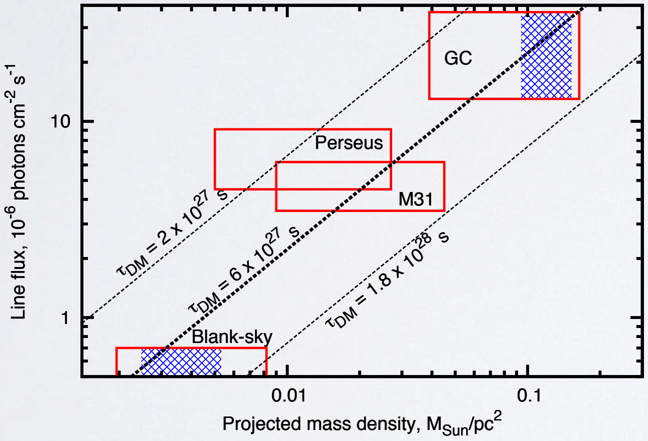
$m_{virgo} \sim$ few $10^{14}\ M_\odot$ $m_{perseus} \sim$ few $10^{14}\ M_\odot$

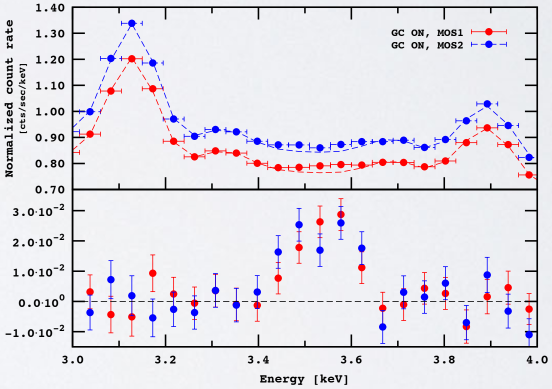
$d_{virgo} \sim 15$ Mpc $d_{perseus} \sim 75$ Mpc

THE MILKY WAY

Riemer-Sorensen





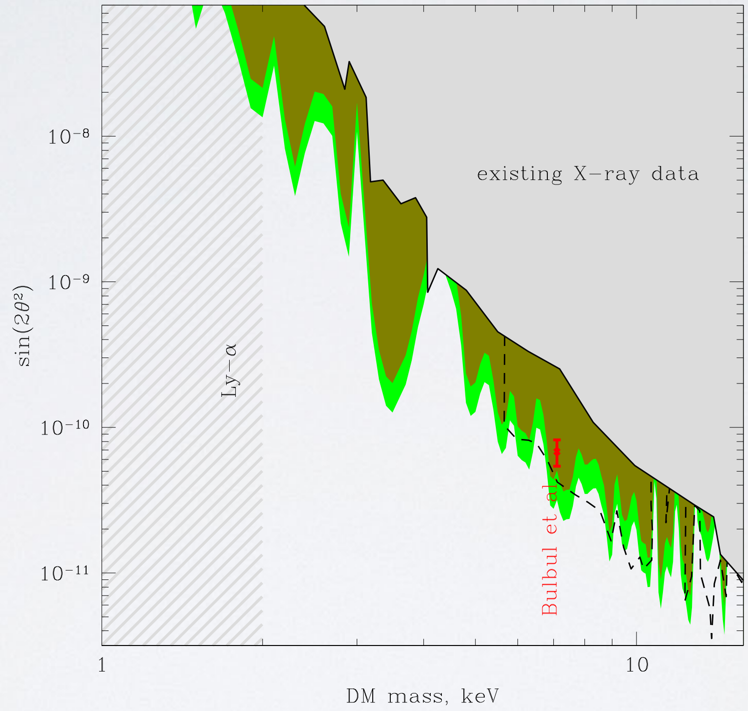


Boyarsky, et al

Morphology?

DWARFS

No sign in stacked MW dwarfs (Malyshev, Neroonov, Eckert)



THE DEBATE

Jeltema and Profumo (1408.1699)

Dark matter searches going bananas:
the contribution of Potassium (and Chlorine) to the 3.5 keV line

Tesla Jeltema[1]* and Stefano Profumo[1]†
[1]Department of Physics and Santa Cruz Institute for Particle Physics University of California, Santa Cruz, CA 95064, USA

- K line can explain M31
- K+Cl can explain clusters

Jeltema and Profumo (1411.1759)

- Different line data not significant
- Temperature fitting shows important systematics

Boyarsky et al (1408.4388)

- (M31) Need to study over range larger than 3-4 keV
- K requires super-solar ratio to Ar, Ca lines

Bulbul et al (1409.4143)

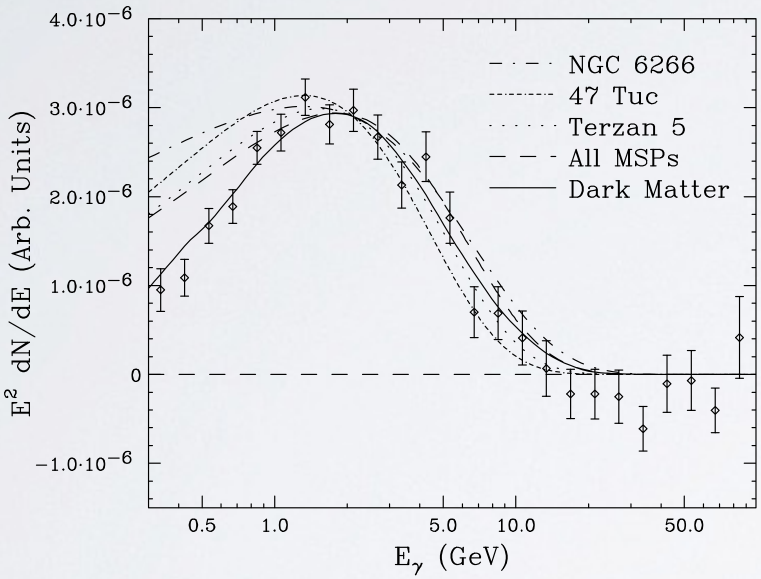
- JP used wrong atomic line data
- Flux from Cl is negligible
- Most conservative K assumptions still yield 4 sigma detection

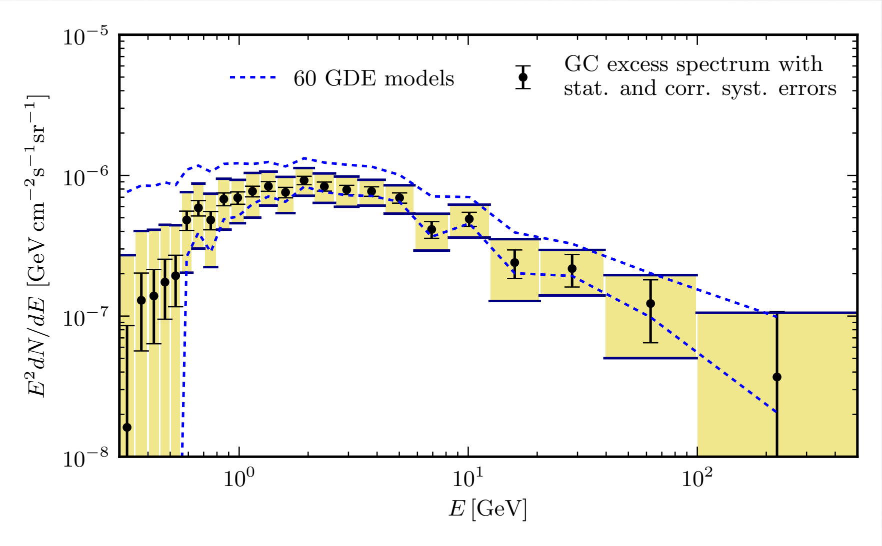
…

SUMMARY

- Seems probably there in Perseus, but too concentrated
- Also in stacked clusters
- M31 maybe weaker
- MW maybe weaker, and morphology is off
- Missing in dwarfs
- Very missing in outer parts of galaxies

WHY NOT PULSARS?



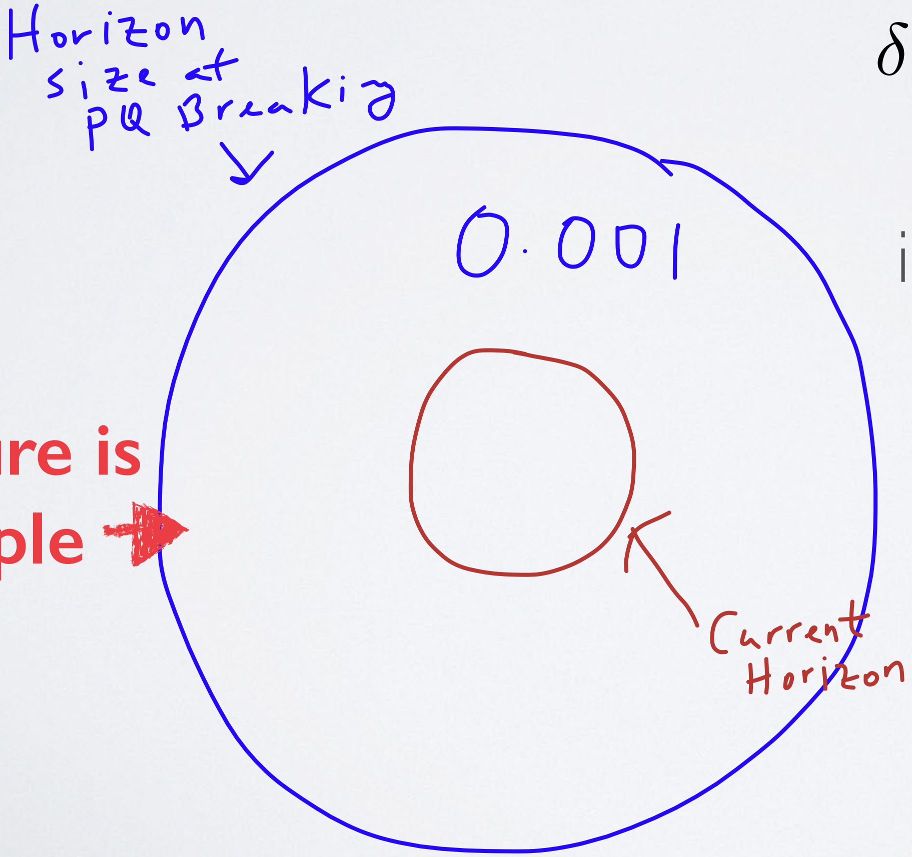


- Spectrum
- 6 INTEGRAL LMXBs in inner 5deg

  =>Estimate MSPs in same region. Need 100.
- LMXBs trace stellar population, not DM like
- Luminosity function for MSPs would suggest Fermi should have resolved bright point sources

B-MODES AND AXIONS

- If inflationary B-modes are discovered, the scale of inflation is ~ 10^{16} GeV
- The axion field fluctuates during inflation



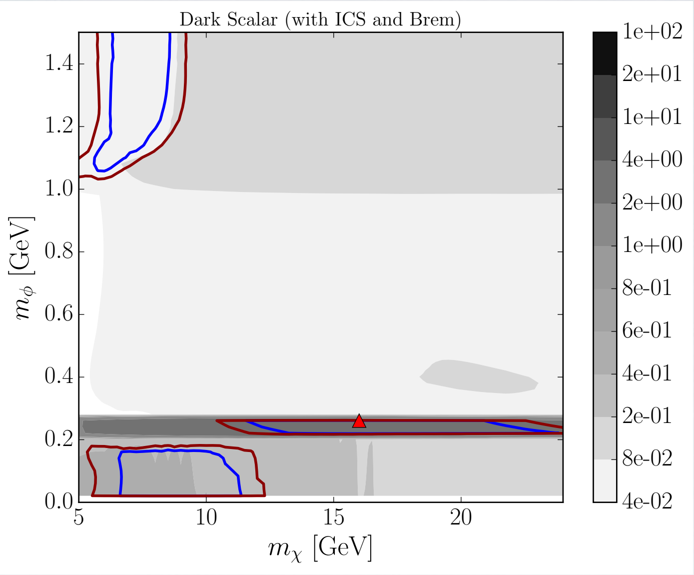
This picture is too simple

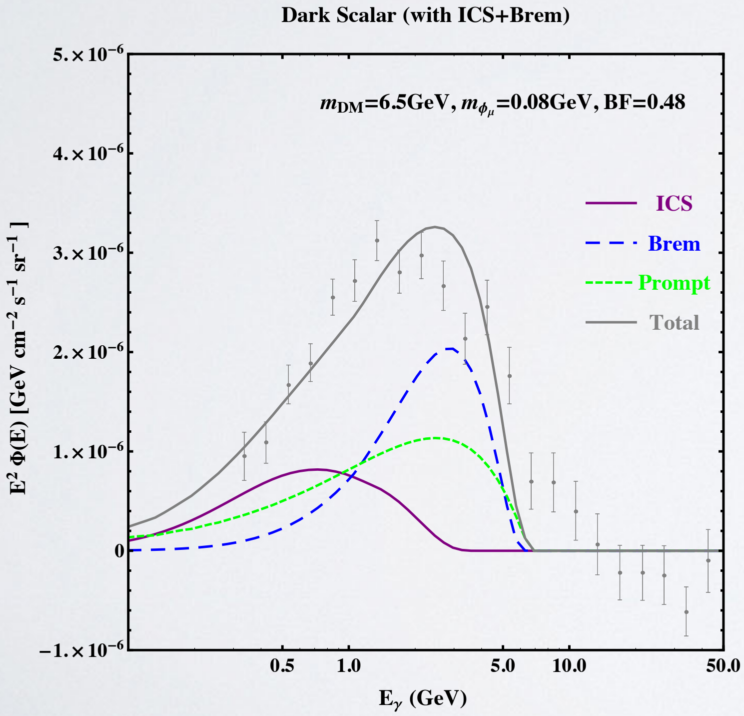
$$\delta a \approx H \sim 10^{14}\text{GeV}$$

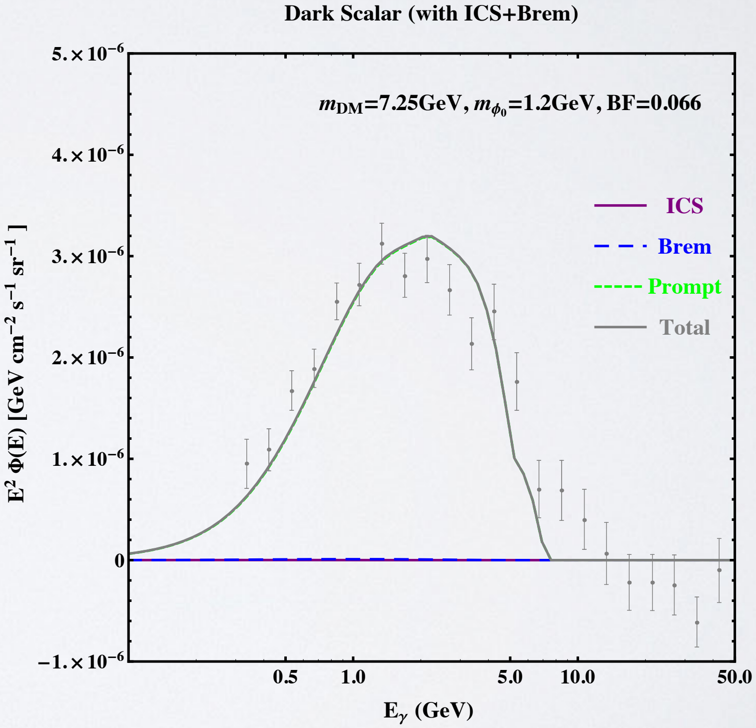
These fluctuations are isocurvature and constrained (Fox, Pierce, Thomas '04)

Hence seeing B-modes would strongly constrain pre-inflationary PQ breaking

Dark scalar

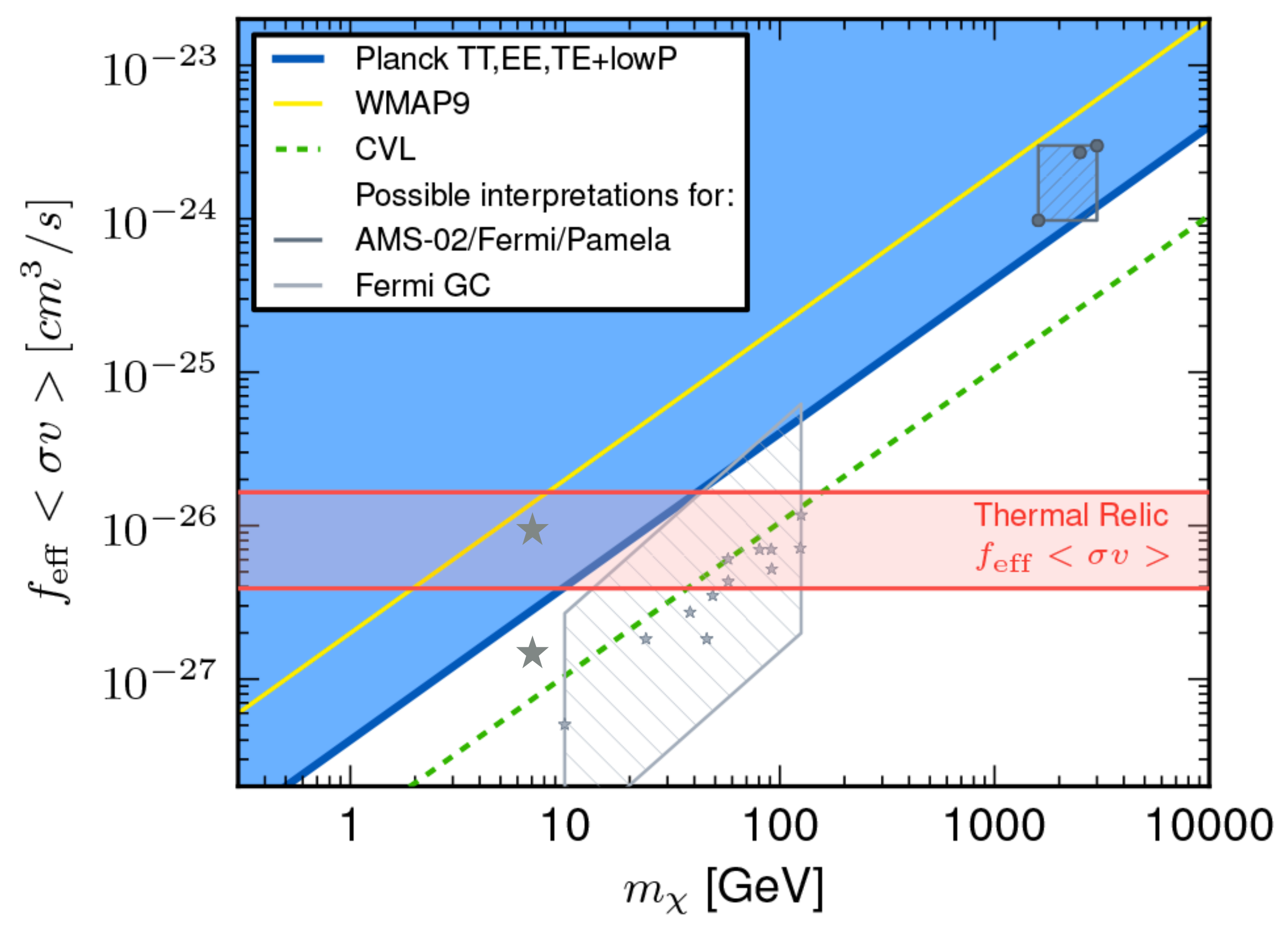






In the presence of dark scalar, even small part can be important

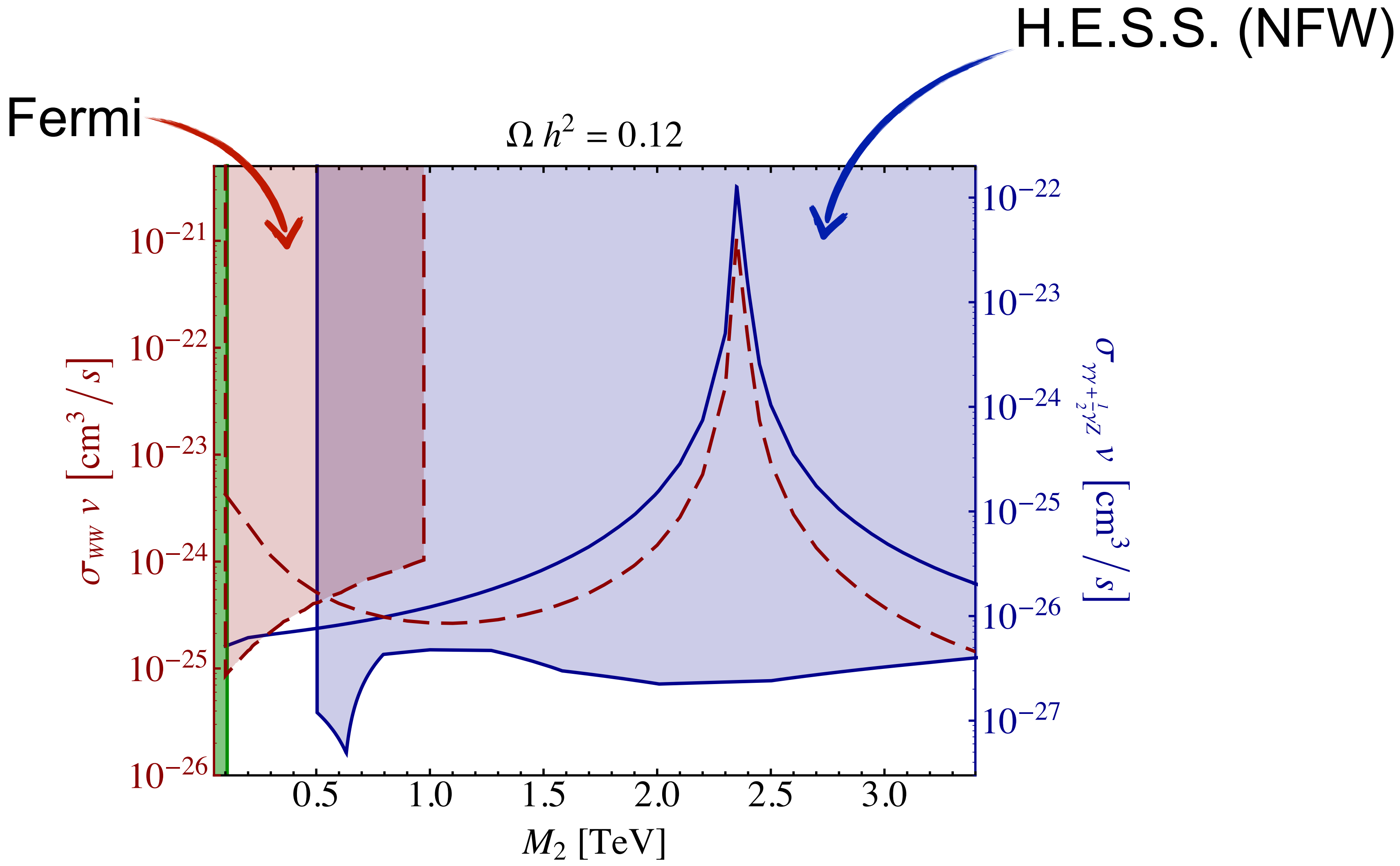
CMB LIMITS



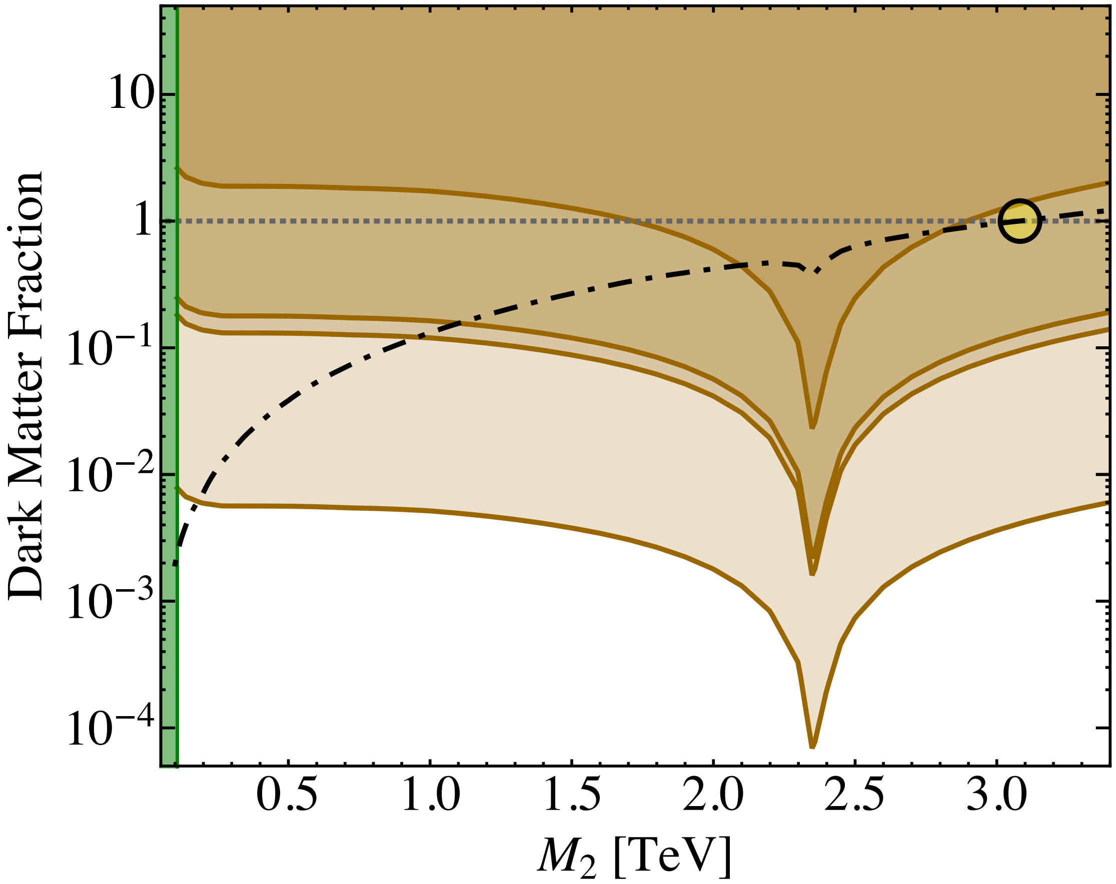
Planck collaboration

Channel	DM Mass (GeV)	$f_{\rm eff}$	$f_{\rm eff,new}$
Electrons	1	0.85	0.45
$\chi\chi \to e^+e^-$	10	0.77	0.67
	100	0.60	0.46
	700	0.58	0.45
	1000	0.58	0.45
Muons	1	0.30	0.21
$\chi\chi \to \mu^+\mu^-$	10	0.29	0.23
	100	0.23	0.18
	250	0.21	0.16
	1000	0.20	0.16
	1500	0.20	0.16
Taus	200	0.19	0.15
$\chi\chi \to \tau^+\tau^-$	1000	0.19	0.15
XDM electrons	1	0.85	0.52
$\chi\chi \to \phi\phi$	10	0.81	0.67
followed by	100	0.64	0.49
$\phi \to e^+e^-$	150	0.61	0.47
	1000	0.58	0.45
XDM muons	10	0.30	0.21
$\chi\chi \to \phi\phi$	100	0.24	0.19
followed by	400	0.21	0.17
$\phi \to \mu^+\mu^-$	1000	0.20	0.16
	2500	0.20	0.16
XDM taus	200	0.19	0.15
$\chi\chi \to \phi\phi, \phi \to \tau^+\tau^-$	1000	0.18	0.14
XDM pions	100	0.20	0.16
$\chi\chi \to \phi\phi$	200	0.18	0.14
followed by	1000	0.16	0.13
$\phi \to \pi^+\pi^-$	1500	0.16	0.13
	2500	0.16	0.13
W bosons	200	0.26	0.19
$\chi\chi \to W^+W^-$	300	0.25	0.19
	1000	0.24	0.19
Z bosons	200	0.24	0.18
$\chi\chi \to ZZ$	1000	0.23	0.18
Higgs bosons	200	0.30	0.22
$\chi\chi \to h\bar{h}$	1000	0.28	0.22
b quarks	200	0.31	0.23
$\chi\chi \to b\bar{b}$	1000	0.28	0.22
Light quarks	200	0.29	0.22
$\chi\chi \to u\bar{u}, d\bar{d}$ (50% each)	1000	0.28	0.21

Non-Thermal Wino



CTA



Dark Matter Fraction
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0.5
1.0
1.5
2.0
2.5
3.0
M_2 [TeV]