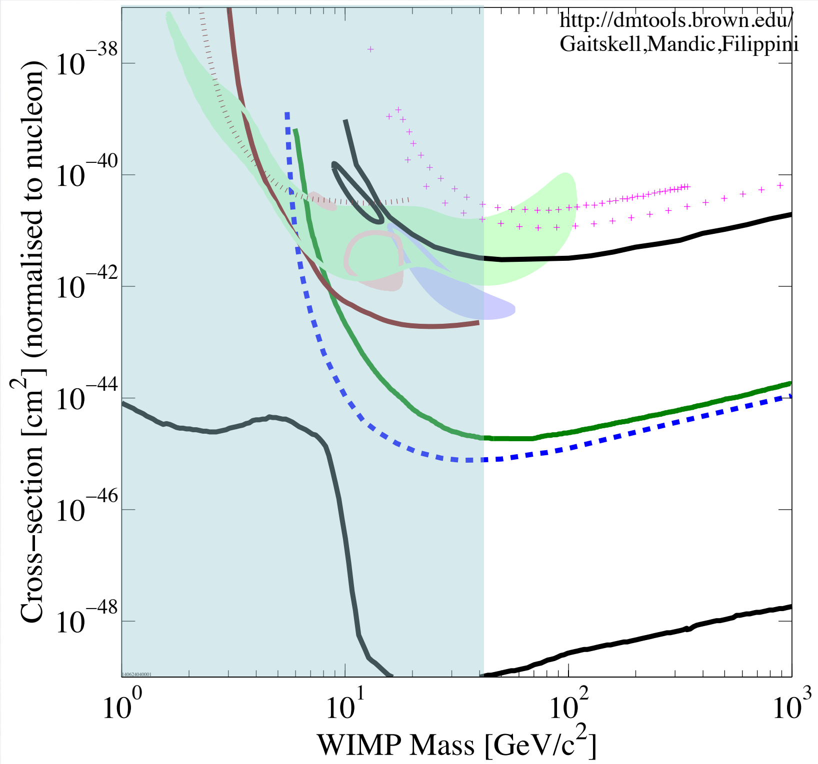
CURRENT DIRECTIONS IN DARK MATTER

Neal Weiner
CCPP NYU
Sept 25, 2014

DM LHC 2014

TOWARDS AN EFFECTIVE THEORY OF DARK MATTER

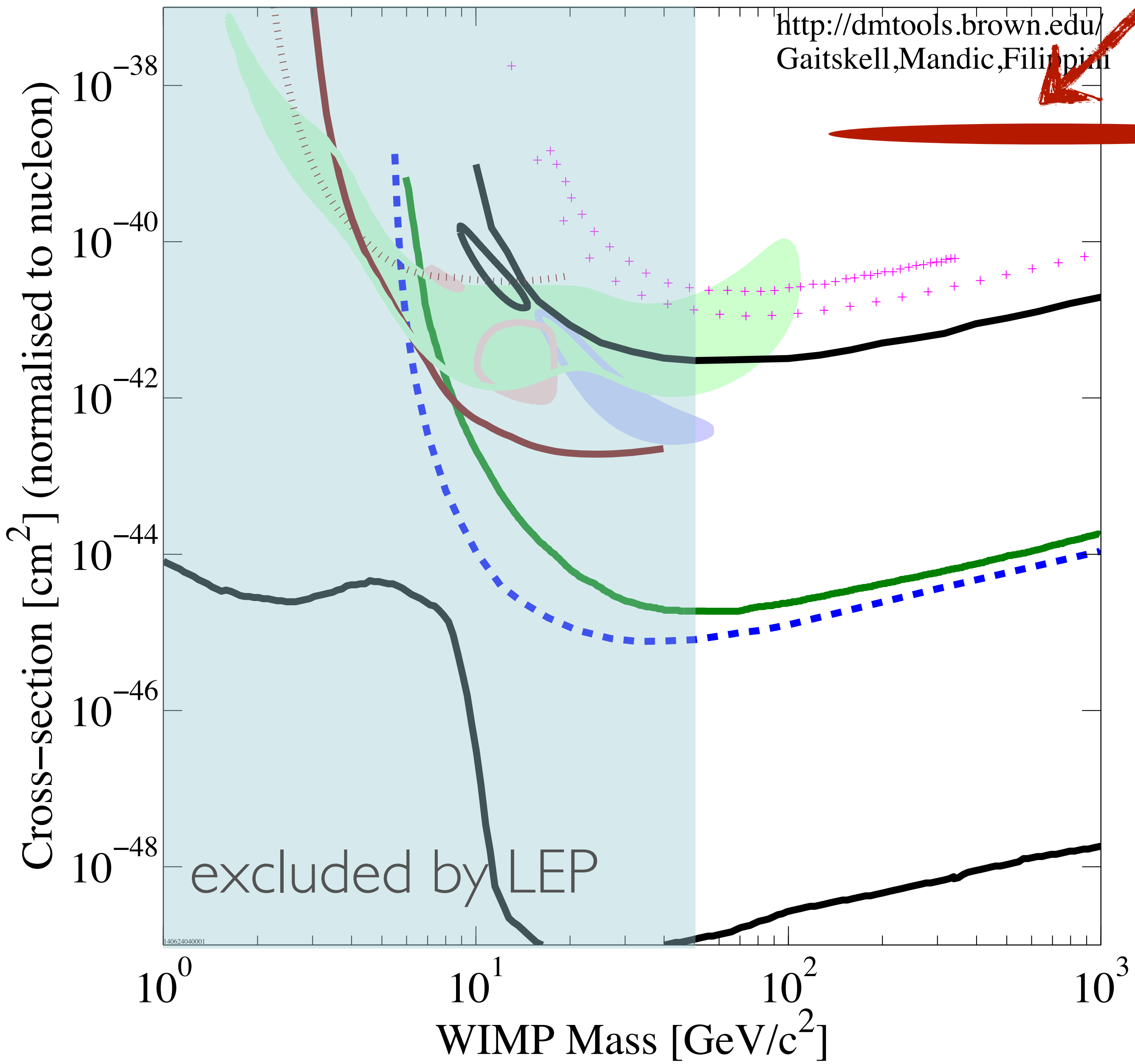
The problems in dark matter theory all begin with this plot



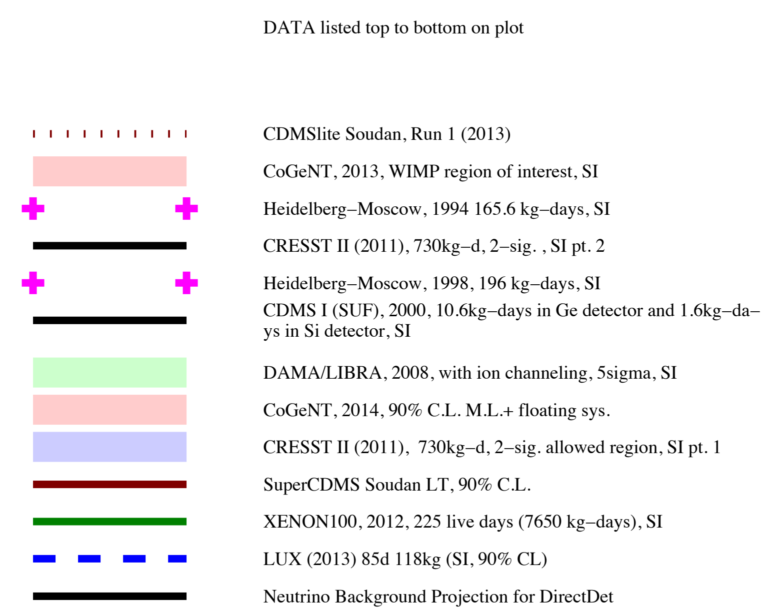
If it's not on this plot, it's "speculative". If it's on the wrong side of a line on this plot it's "excluded".

THE WIMP

SU(2) doublet (aka "Dirac Higgsino" "4th Gen Dirac Neutrino")



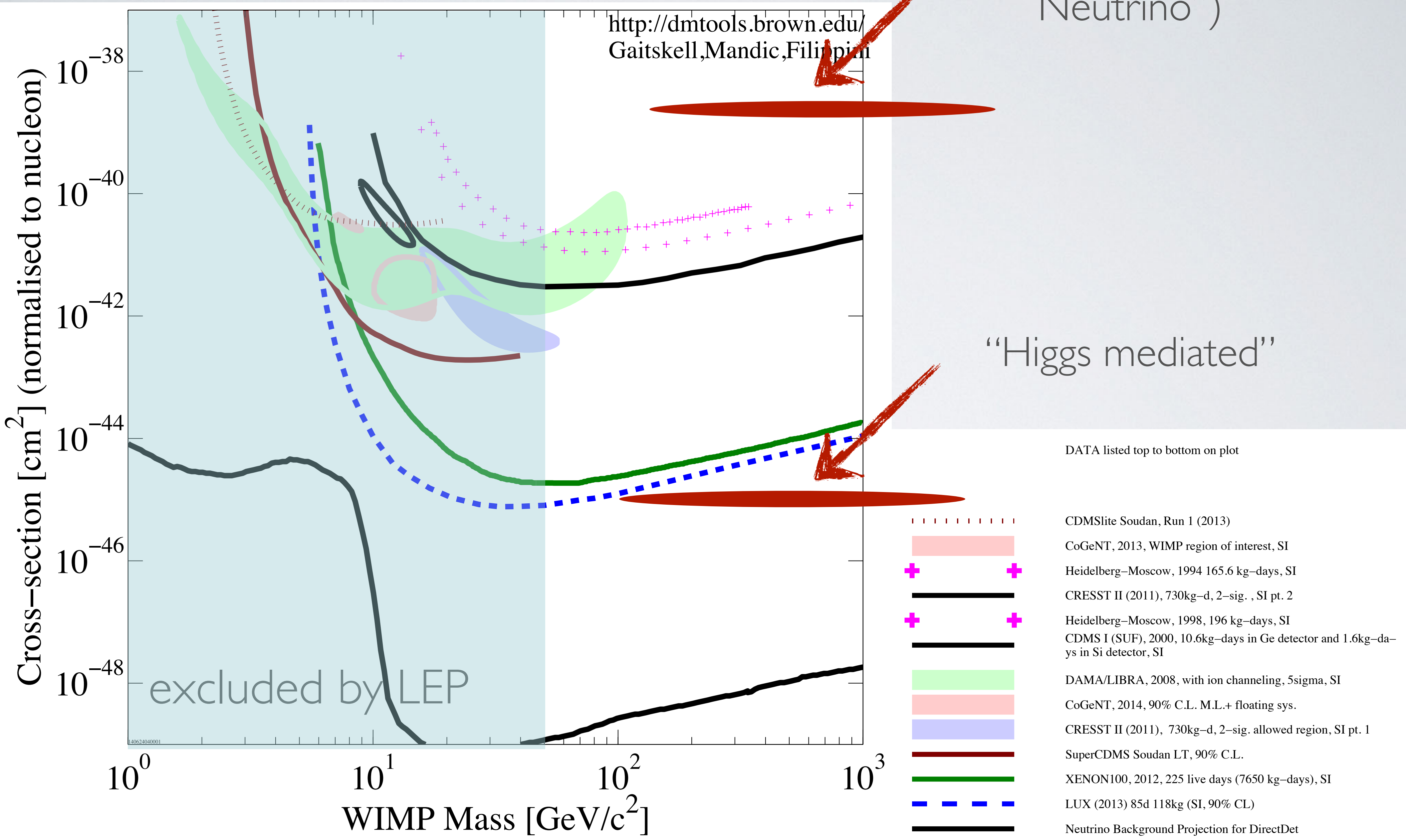
5/9 the way there!



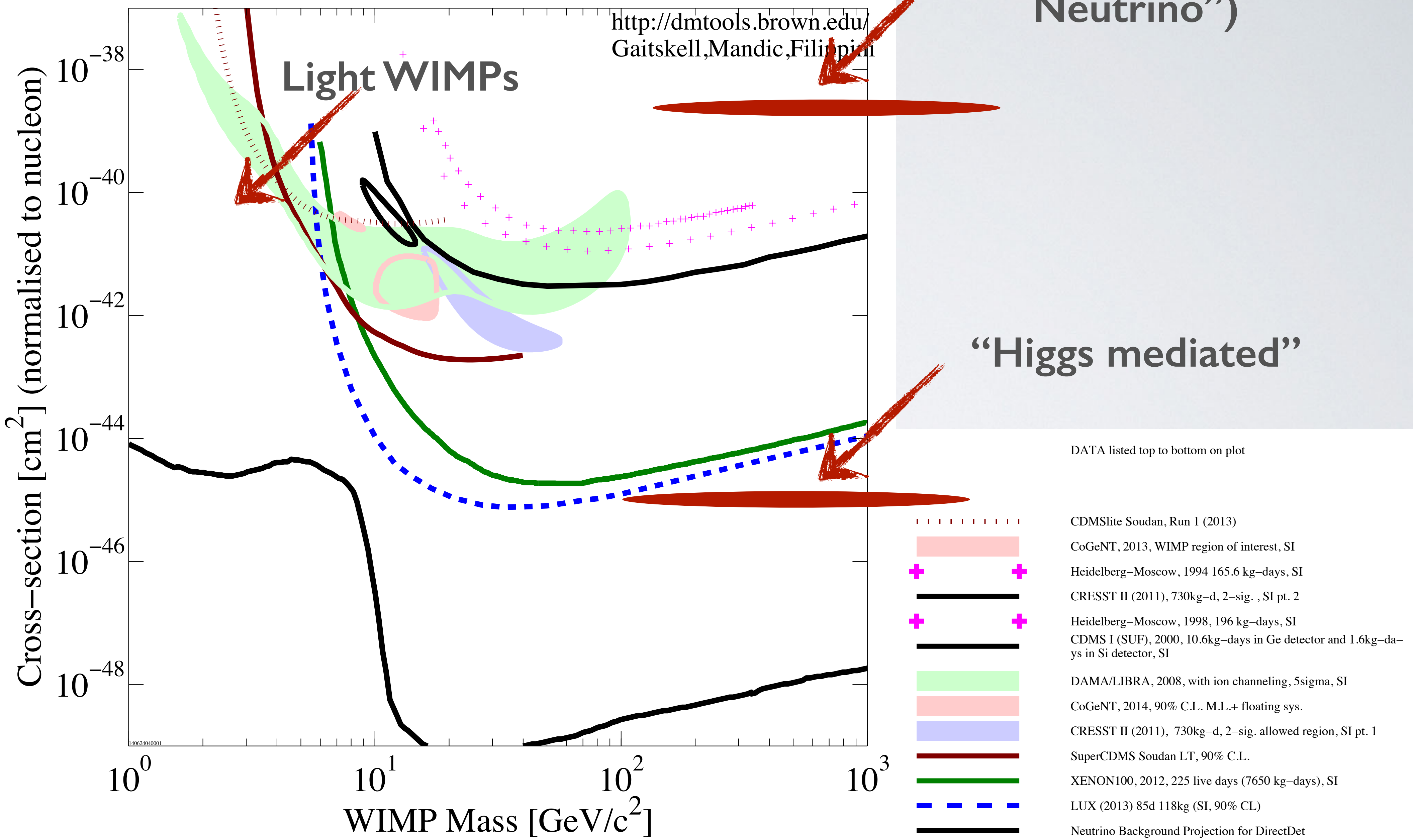
THE WIMP

SU(2) doublet (aka "Dirac Higgsino" "4th Gen Dirac Neutrino")

"Higgs mediated"



THE WIMP



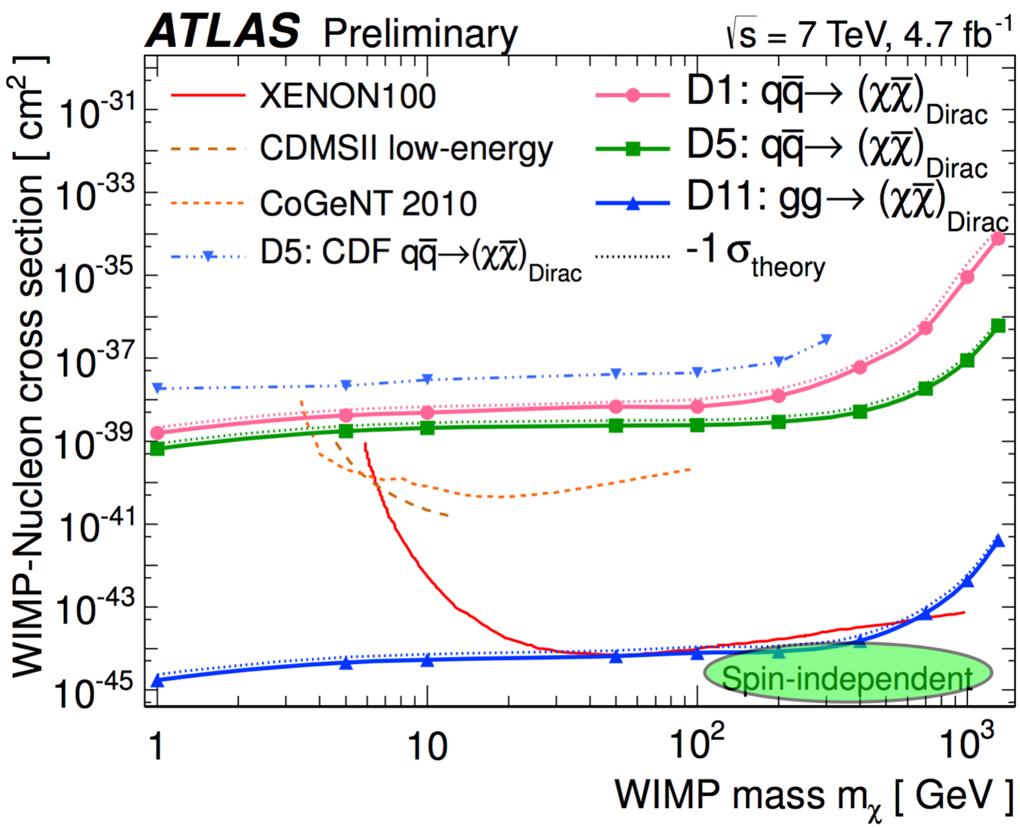
SU(2) doublet (aka "Dirac Higgsino" "4th Gen Dirac Neutrino")
Light WIMPs
"Higgs mediated"
http://dmtools.brown.edu/
Gaitskell,Mandic,Filippini
Cross−section [cm^2] (normalised to nucleon)
WIMP Mass [GeV/c^2]
DATA listed top to bottom on plot
CDMSlite Soudan, Run 1 (2013)
CoGeNT, 2013, WIMP region of 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
CDMS I (SUF), 2000, 10.6kg−days in Ge detector and 1.6kg−days in Si detector, SI
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

GETTING ON THE PLOT

Note: these plots are super useful except when they're not

Monojet

$$D1 = \bar{\chi}\chi\bar{q}q$$
$$D5 = \bar{\chi}\gamma^{\mu}\chi\gamma_{\mu}\bar{q}q$$
$$D11 = \bar{\chi}\chi G_{\mu\nu}G^{\mu\nu}$$



PJ Fox, Invisibles Conference '13

Note: these plots are totally misleading except when they convey important information

OUTLINE

- The zoology of DM
    - DAMA+direct anomalies
    - Galactic Center
    - 3.5 keV line
- New directions in missing energy

SO WHO IS TRYING TO GET ONTO THE PLOT?

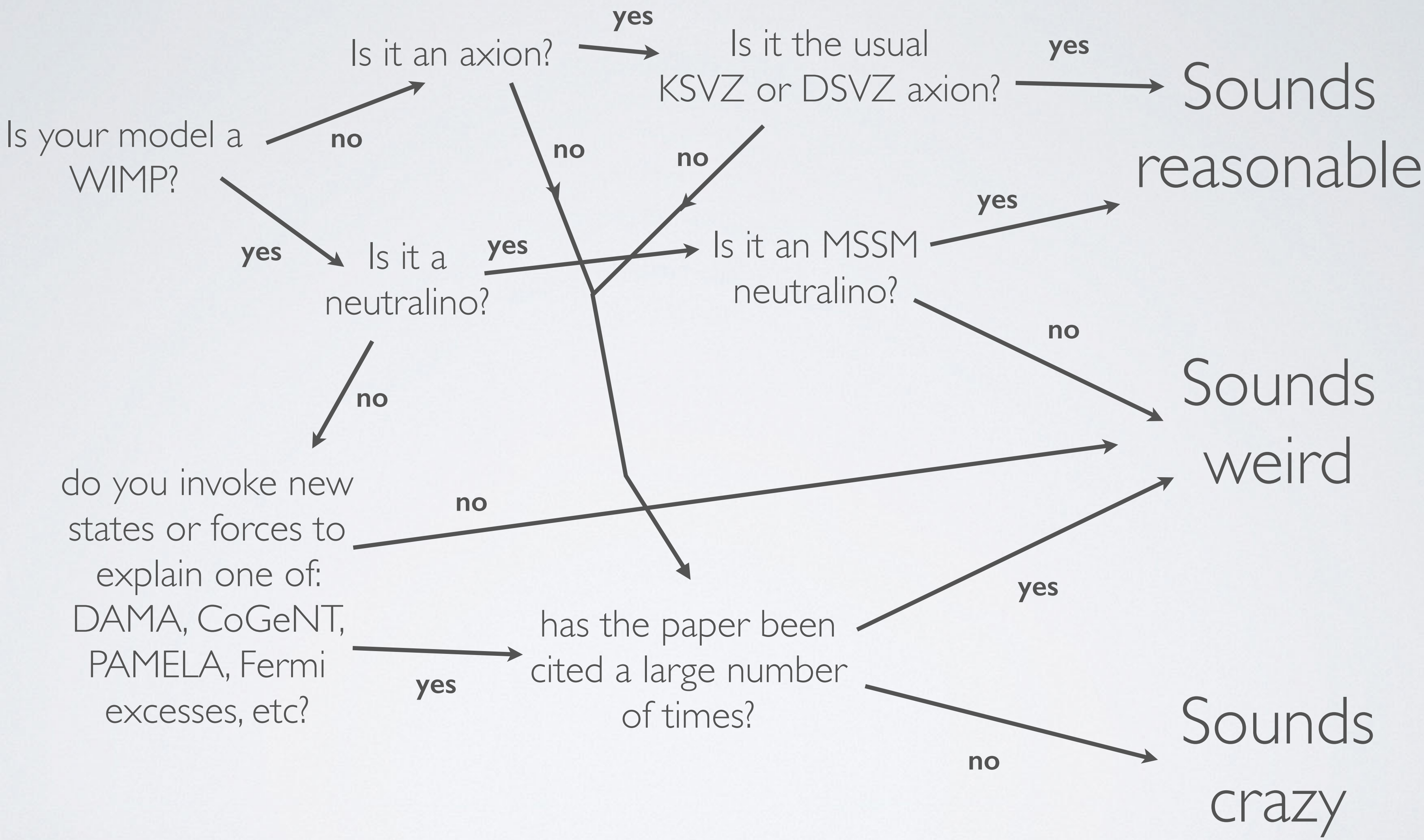
THE ZOOLOGY OF DARK MATTER

Three basic categories of dark matter:

Reasonable Weird Crazy

sometimes also called "normal"

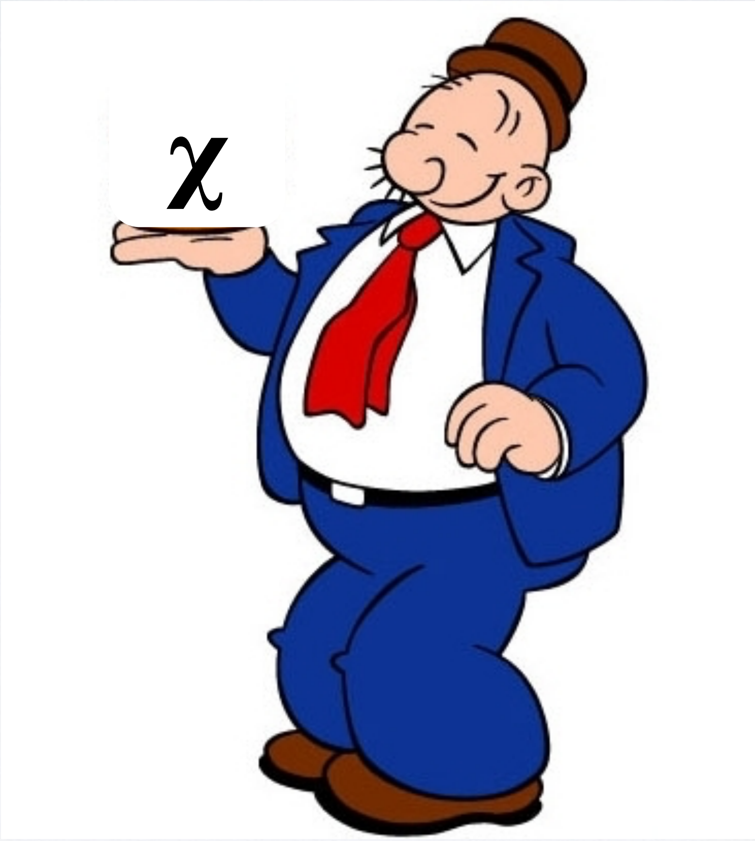
(also "wrong")


Is your model a WIMP?
no
yes
Is it an axion?
yes
no
Is it the usual KSVZ or DSVZ axion?
yes
no
Sounds reasonable
Is it a neutralino?
yes
no
Is it an MSSM neutralino?
yes
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

WHITHER DM CRAZINESS?

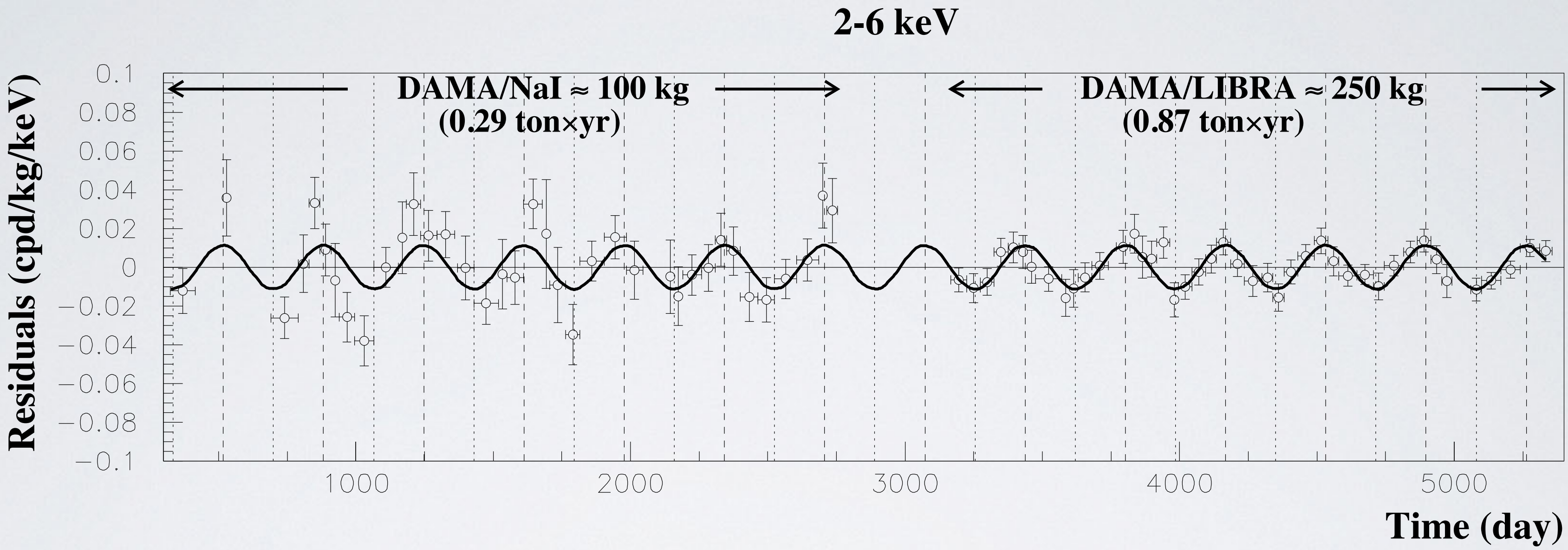
- it was a whirlwhind few years for DM
  - DAMA, CoGeNT, CRESST, CDMS-Si…
  - CDMS-Ge, XENON, LUX, CDMS-Lite…
  - PAMELA, INTEGRAL, AMS…
  - Pulsars, propagation
- And then it got quiet

“I will gladly build you a model Tuesday for an anomaly today”



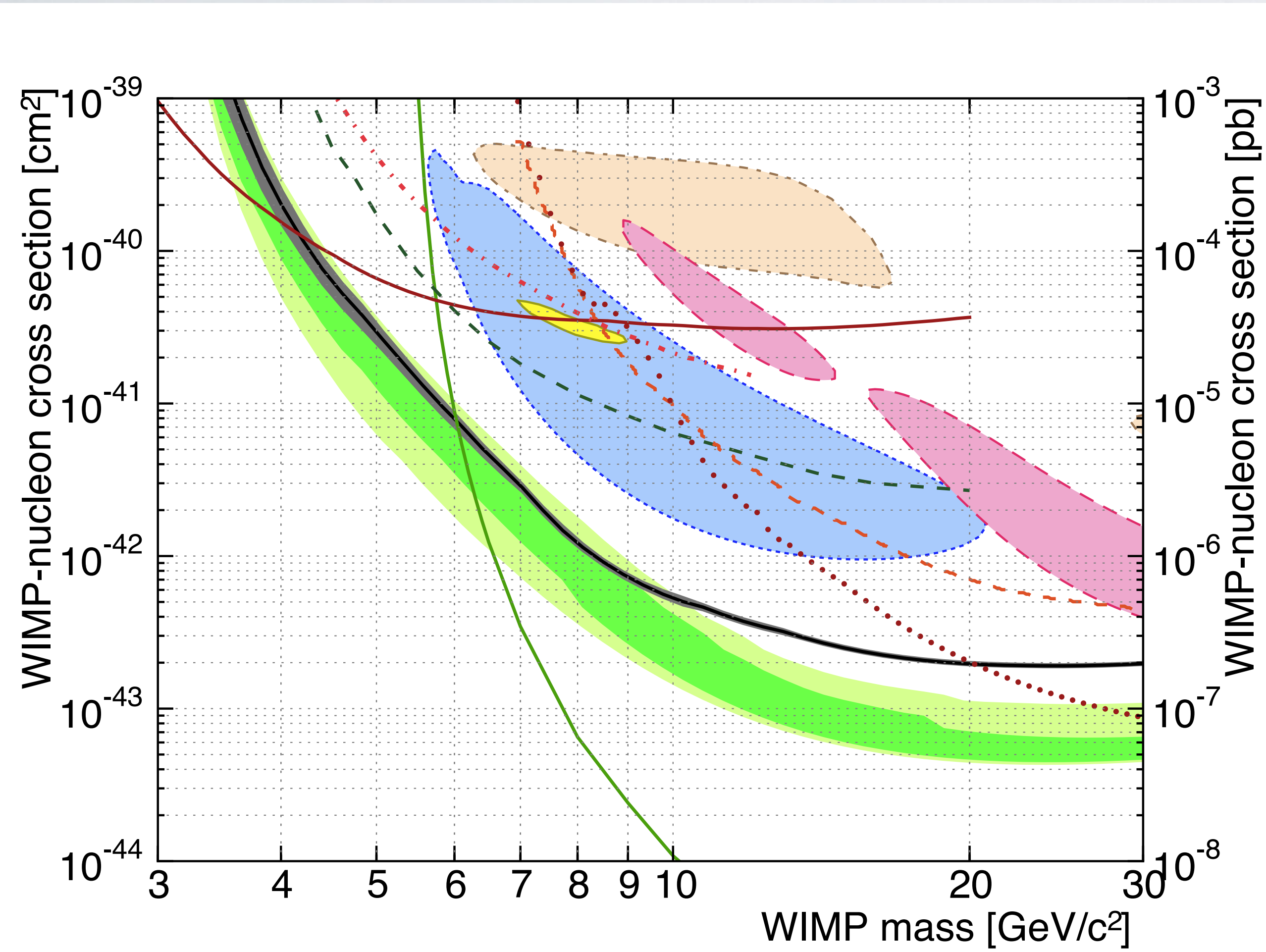
- There is still the modulating elephant in the room, so let’s start there

DAMA MODULATION



- Still there
- Explanations that I know must appeal to ignorance (e.g., MiDM with unknown magnetic form factors, Fitzpatrick et al general operator analysis w/o models)
- Modulation fraction must be large (>10—20%) [Pradler, Singh and Yavin] challenging other conventional models (i.e., pseudoscalar interactions)
- Non-WIMP explanations? (E.g., solar sources)

DAMA/LIGHT WIMPS

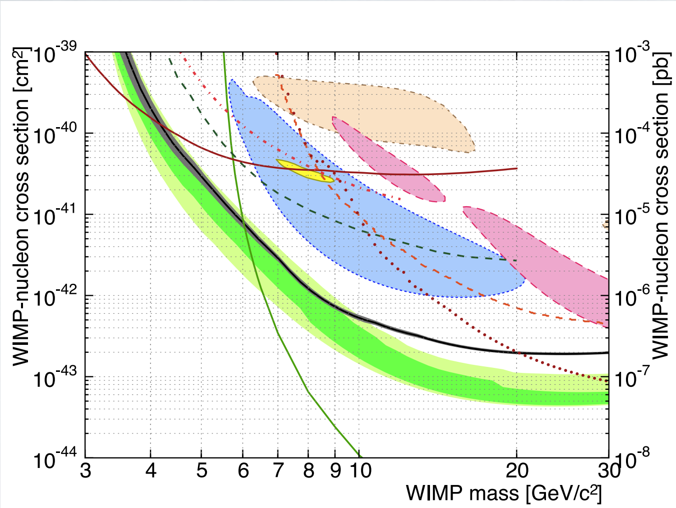


Various targets (Si, Ge, Xe)

Low thresholds

Improved understanding of LE Xe

DAMA/LIGHT WIMPS



Looks bad

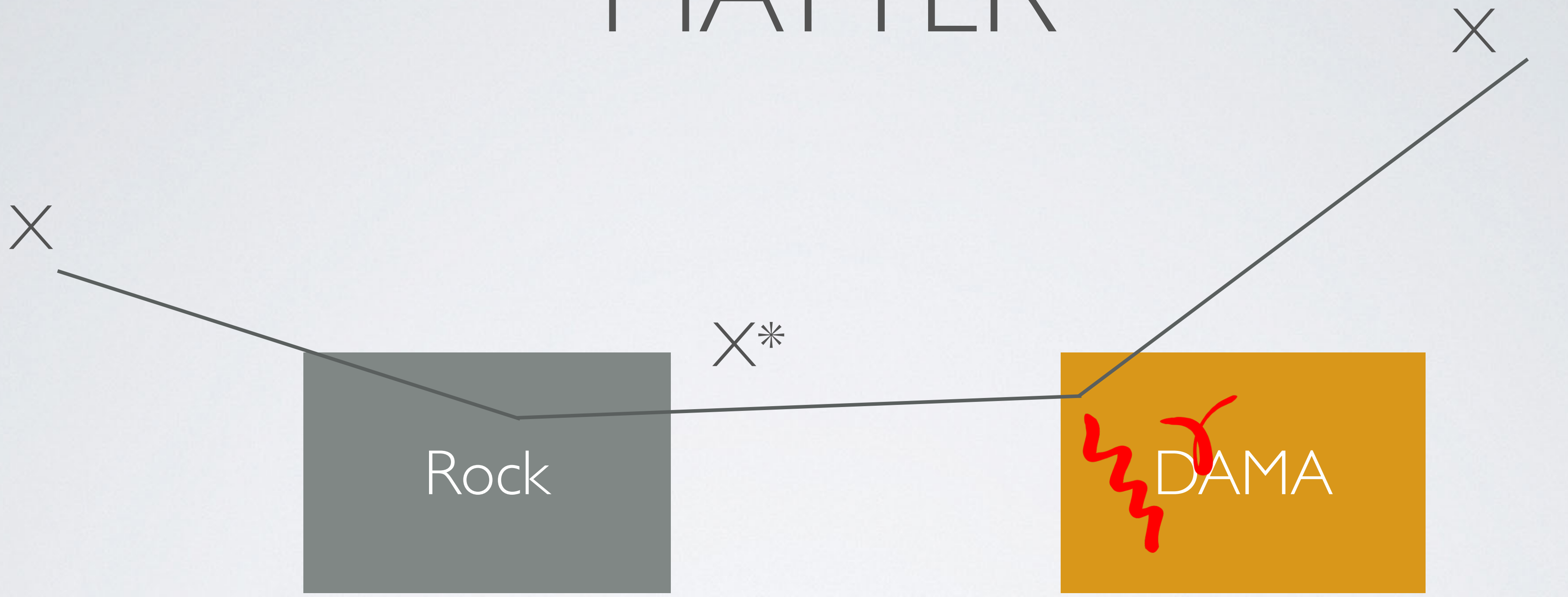
Even Xenonphobic/Germophobic models have trouble now

To the extent that these curves are mutually reinforcing, that is now gone.

Many people have thought a lot about this, but that doesn't mean something important hasn't been missed

EXAMPLE: LUMINOUS DARK MATTER

Feldstein, Graham, Rajendran '11



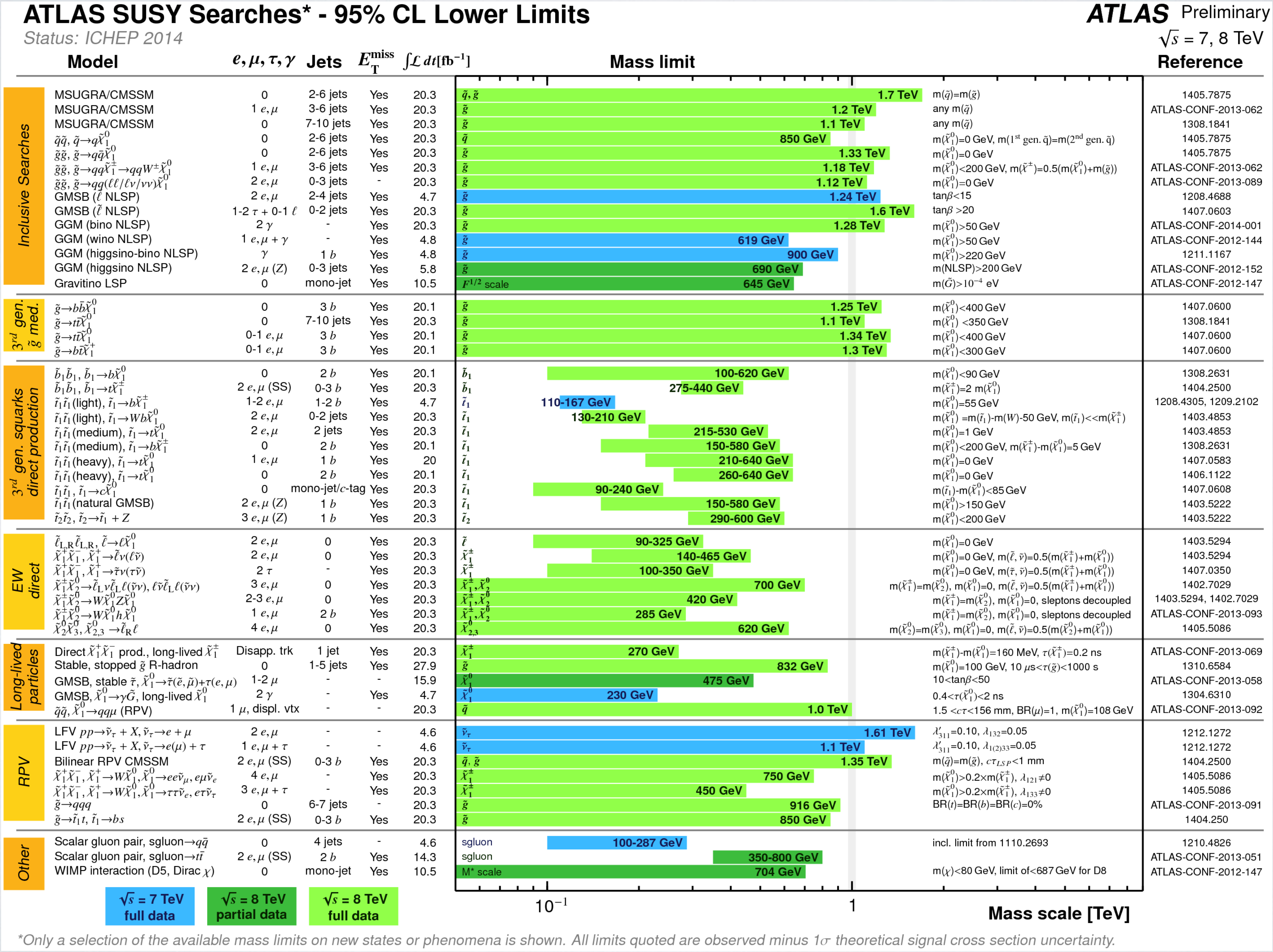
Well over a decade since DAMA first announced.

What else are we missing?

(NB I think this is probably already excluded)

CURRENT MOTIVATIONS FOR DARK MATTER

- The WIMP miracle was supposed to be bi-directional



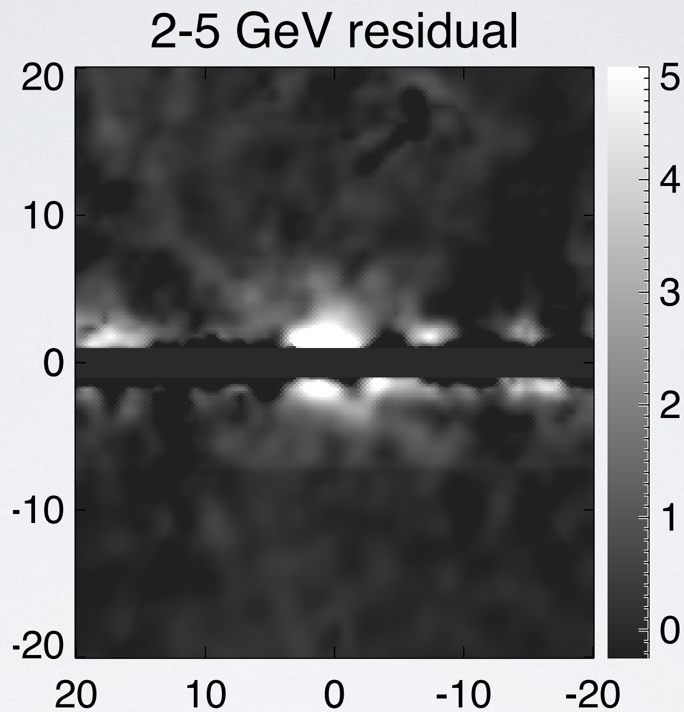
- The WIMP miracle was supposed to be bi-directional

"sashini"

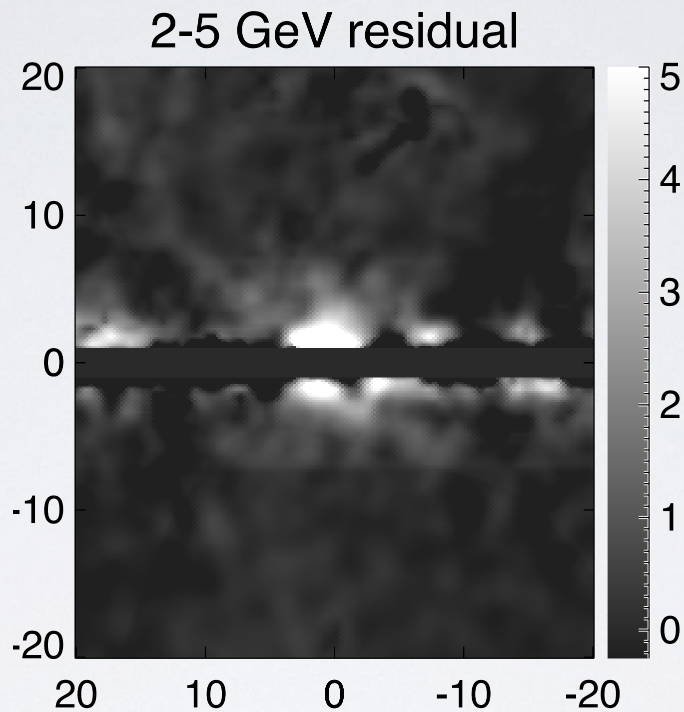
If we find SUSY, it appears it will look very different from how we expected it. Why trust our preconceptions about WIMPs?

Even absent experimental motivation, we should be getting out of our MSSM box by now..

A SIGNAL IN THE GC/IG



A SIGNAL IN THE GC/IG

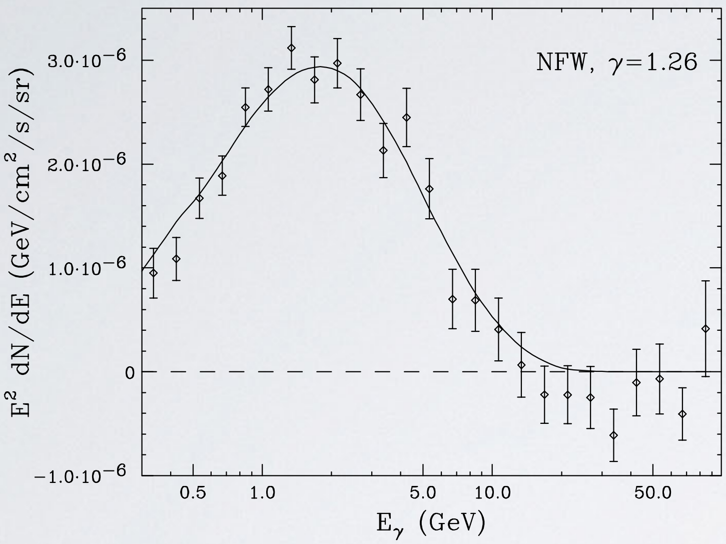


Personal opinion: from the literature and discussions, it is my impression that there is something there.

I don't know if it's dark matter, but it seems that it could be.

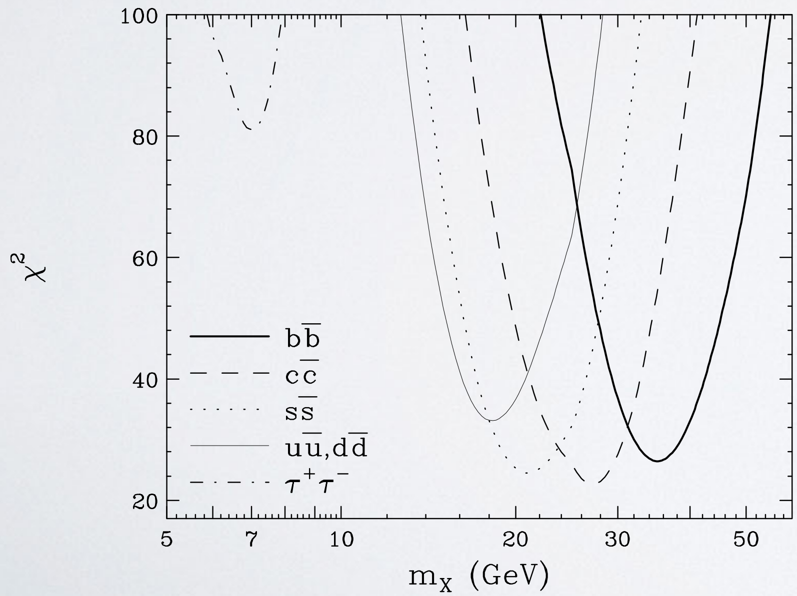
that said…

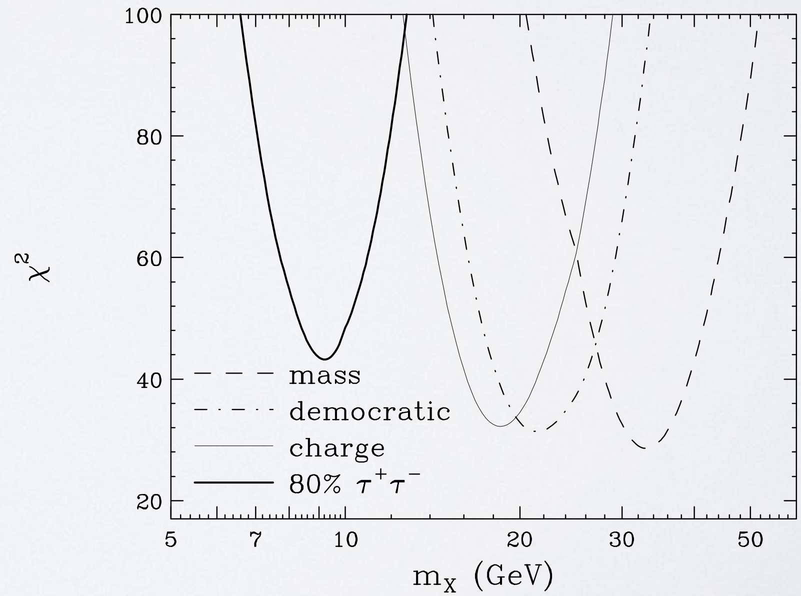
DARK ANNIHILATION TO BB?



not really chi-squared

methinks we are taking our data a little too seriously





WHY LOOK ELSEWHERE

- models to B-Bbar are not as easy as they sound
- Antiprotons are challenging (again)
- Sub-Z mass scale suggests alternative models

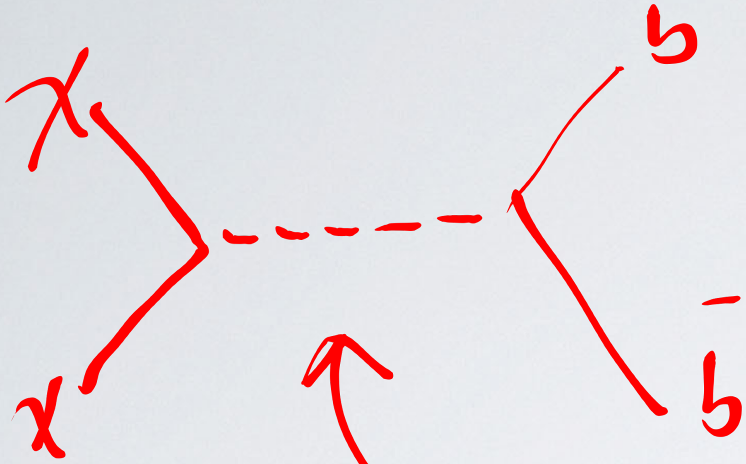
There are significant reasons to conclude, however, that the gamma-ray signal described in this paper is far more likely to be a detection of dark matter than any of the previously reported anomalies. Firstly, this signal

words

Thirdly, we once again note that the signal described in this study can be explained by a very simple dark matter candidate, without any baroque or otherwise unexpected features. After accounting for uncertainties in the overall

are required. Furthermore, it is not difficult to construct simple models in which a $\sim$30-40 GeV particle annihilates to quarks with the required cross section without violating constraints from direct detection experiments, colliders, or other indirect searches (for work related to particle physics models capable of accommodating this signal, see Refs. [62–74]).

not hard to make models $\neq$ not baroque annihilon



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

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

$$V_{\rm port} = i B a_0 H_1^\dagger H_2 + \text{h.c.}$$

pseudoscalar

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

Ipek, McKeen, Nelson '14

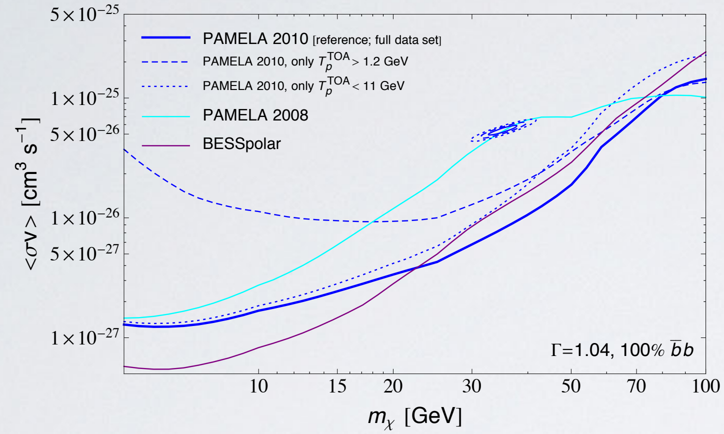
+ harder hierarchy problem + no sannihilon (scalar annihilon)

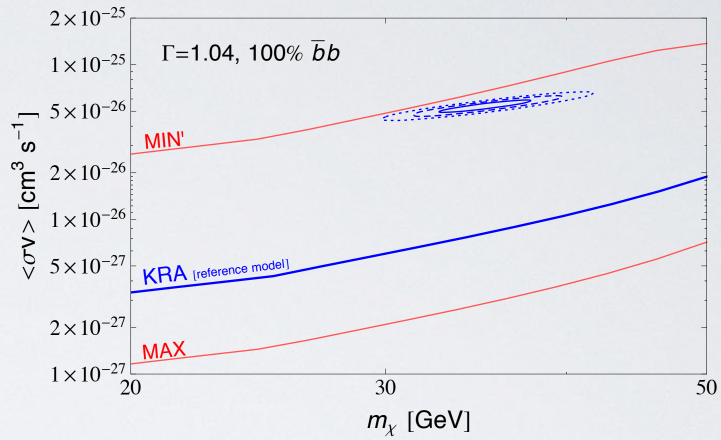
That said, I do not consider an anomaly more or less likely just because the models might require baroque or unexpected features (cough cough), so I think this one is still worth pursuing.

However, experimental issues might give me pause.

ALSO: ANTIPROTONS

Bringmann, Vollman, Weniger 1406.6027

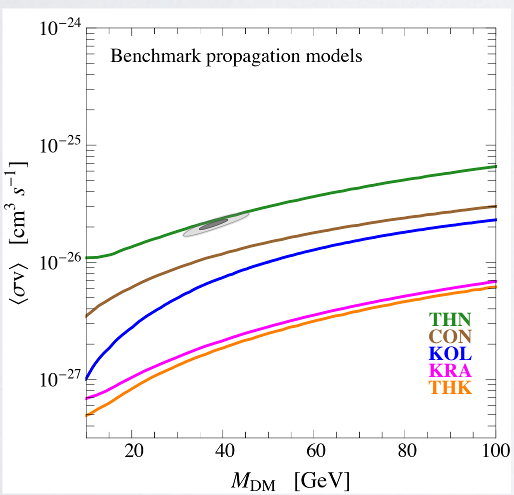


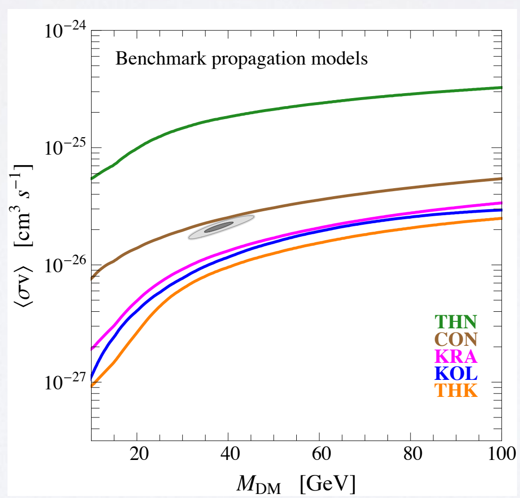


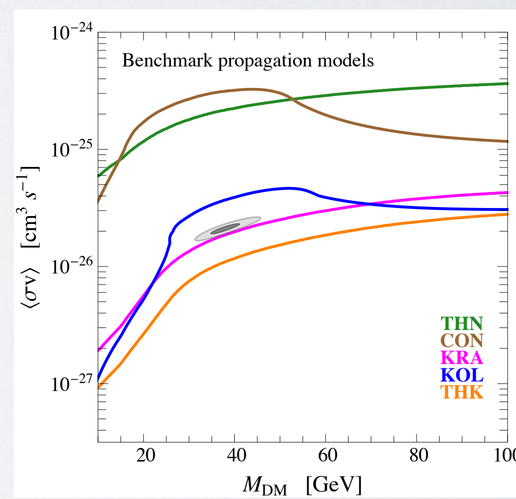
$\phi_F^{\bar{p}} = \phi_F^p$ fixed

$\phi_F^{\bar{p}} = \phi_F^p \pm 50\%$

$\phi_F^{\bar{p}} \in [0.1, 1.1]$ GV







Cirelli et al, 1407.2173

SIMPLE ALTERNATIVE MODELS?

GC SIGNALS OF LIGHT DARK FORCE MODELS

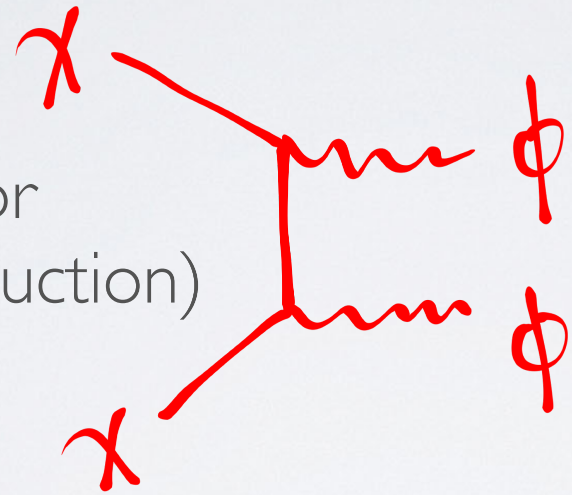
(cf PAMELA models)

Hooper, NW, Xue 1206.2929; Liu, NW, Xue in prep

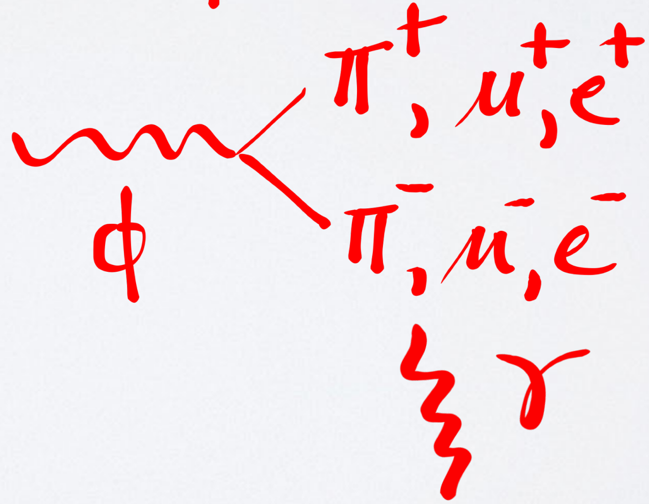
~5-10 GeV

~ 0.1 - 1 GeV

“light” mediator
(below proton production)

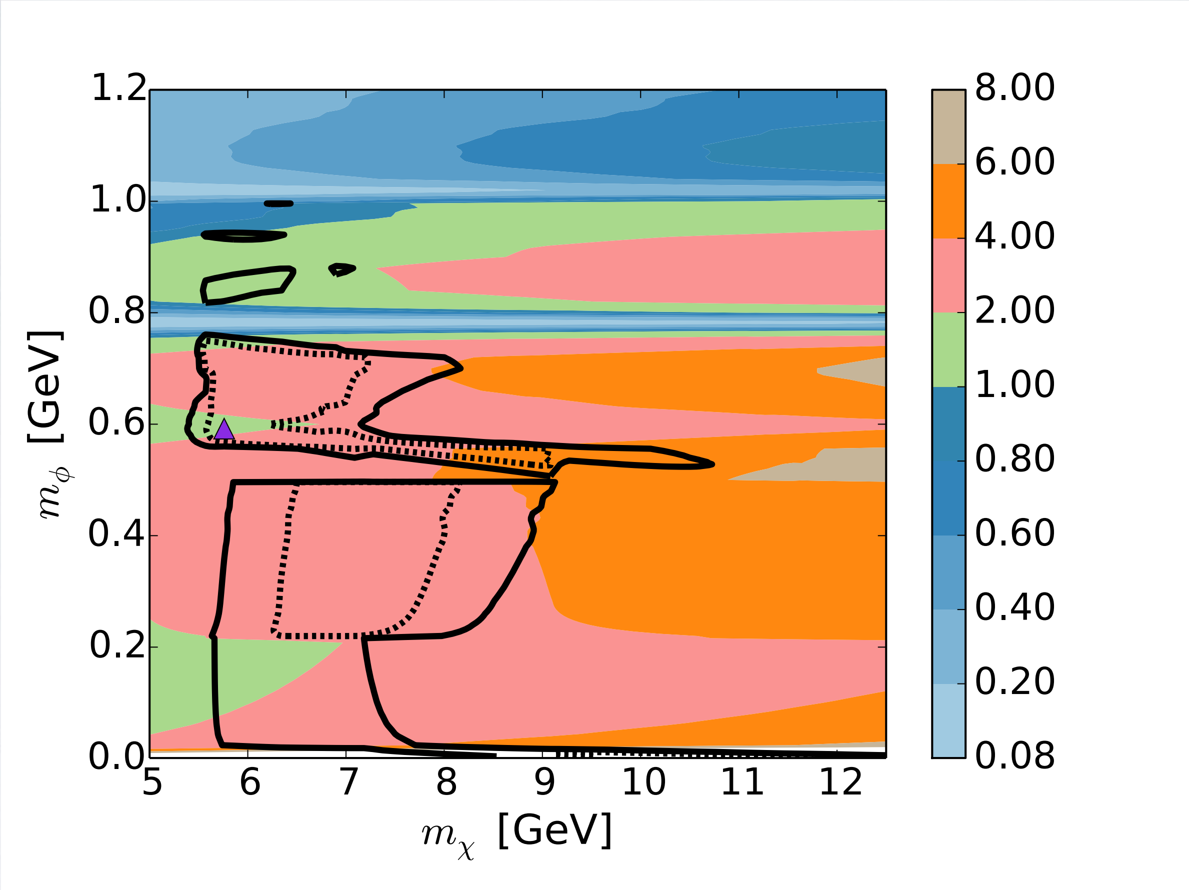


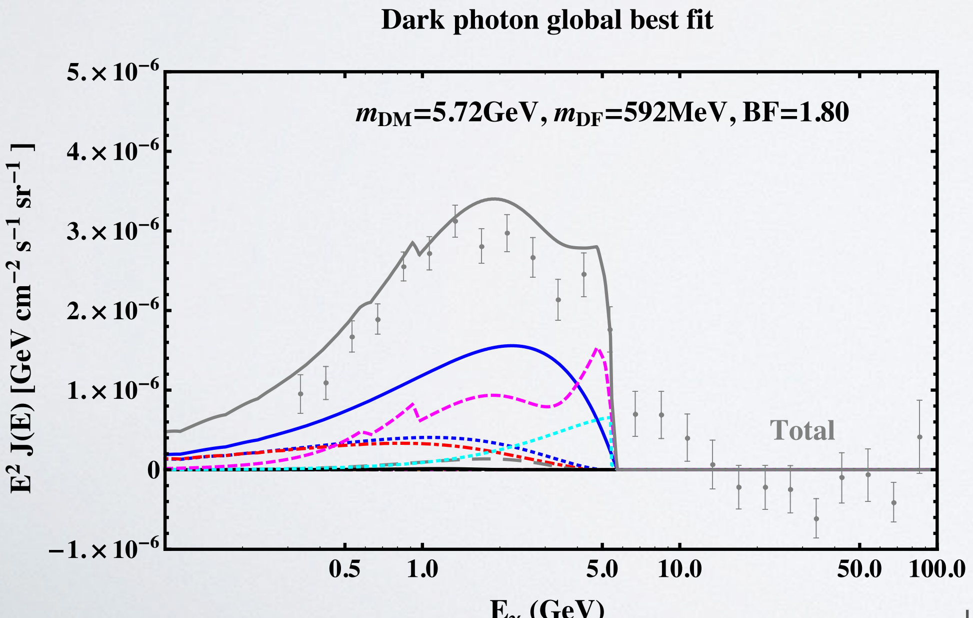
photons from π^0 decay or
FSR/IB

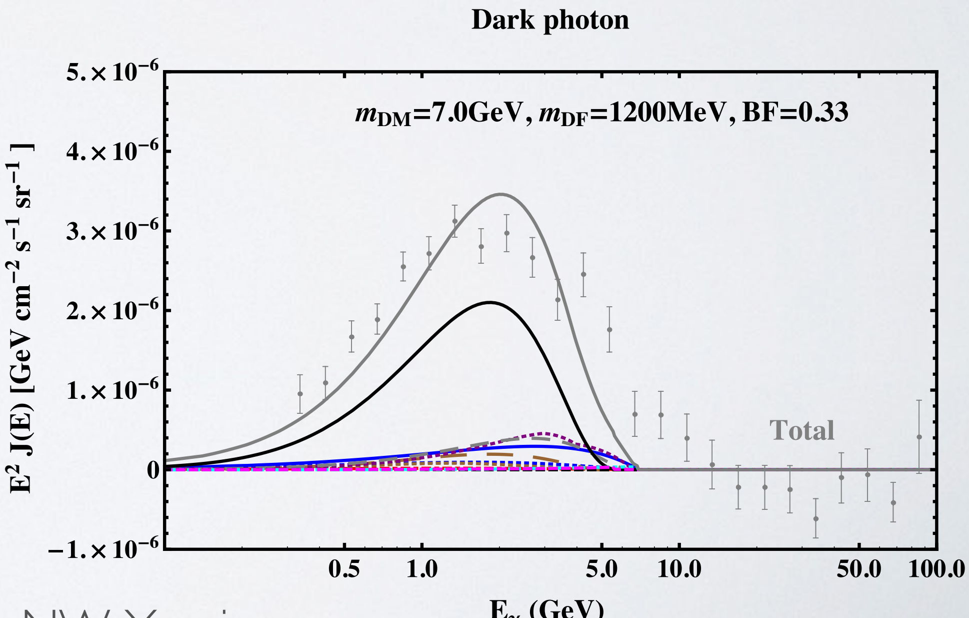


(See Martin, Shelton, Unwin 1405.0272; Berlin, Gratia, Hooper, McDermott 1405.5204 for heavier mediators; Talk by A. Berlin)

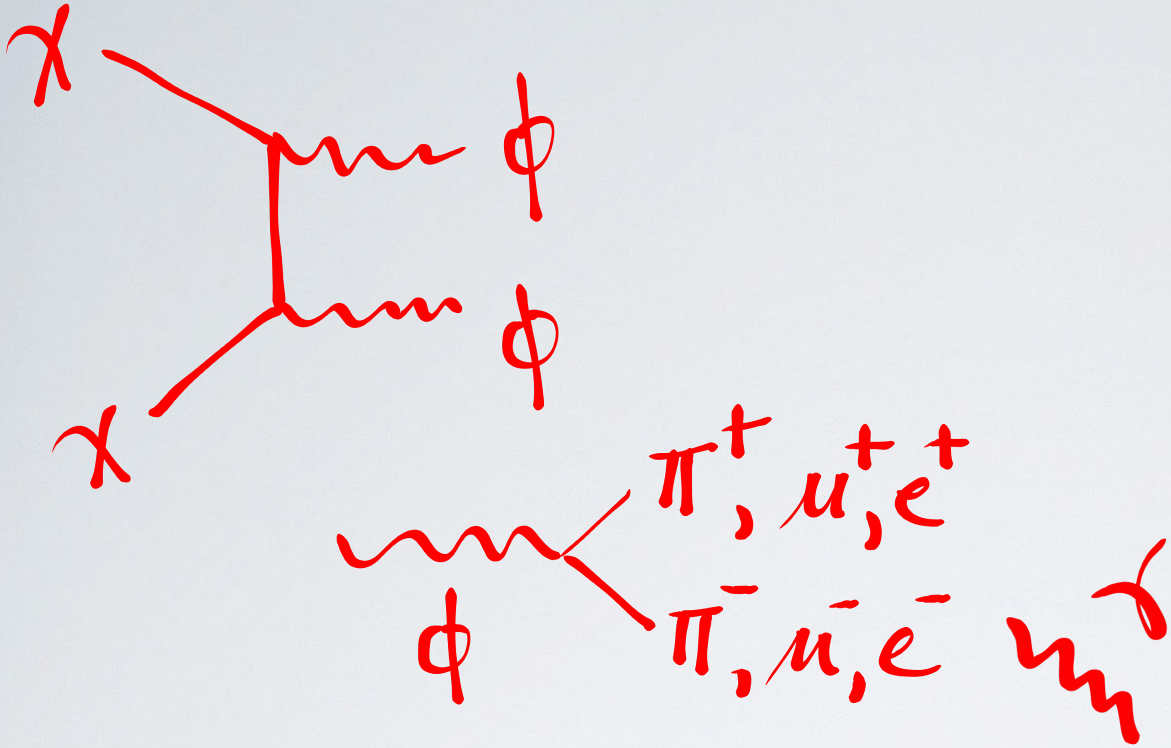
Liu, NW, Xue in prep







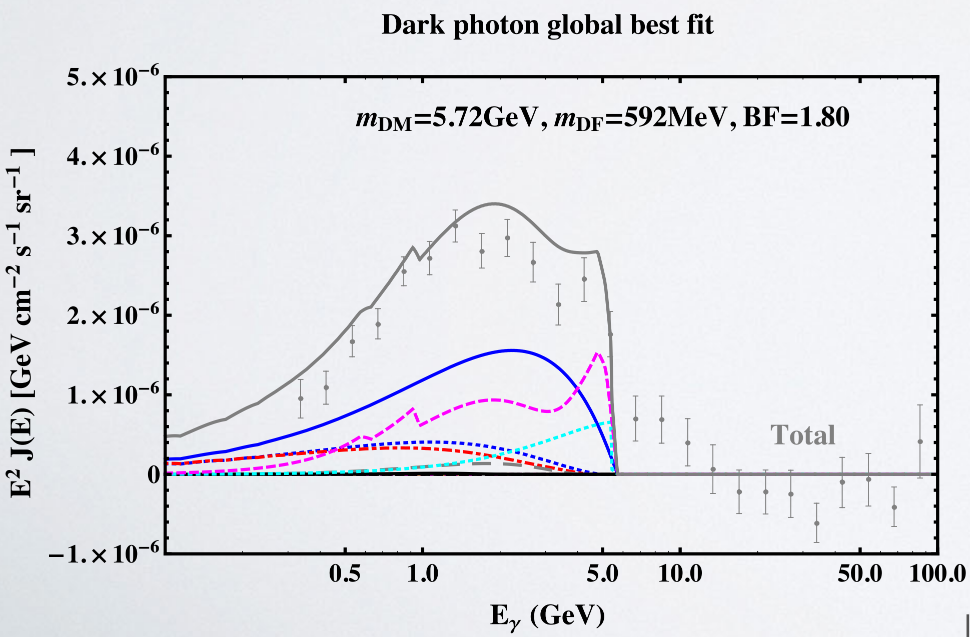
Liu, NW, Xue in prep

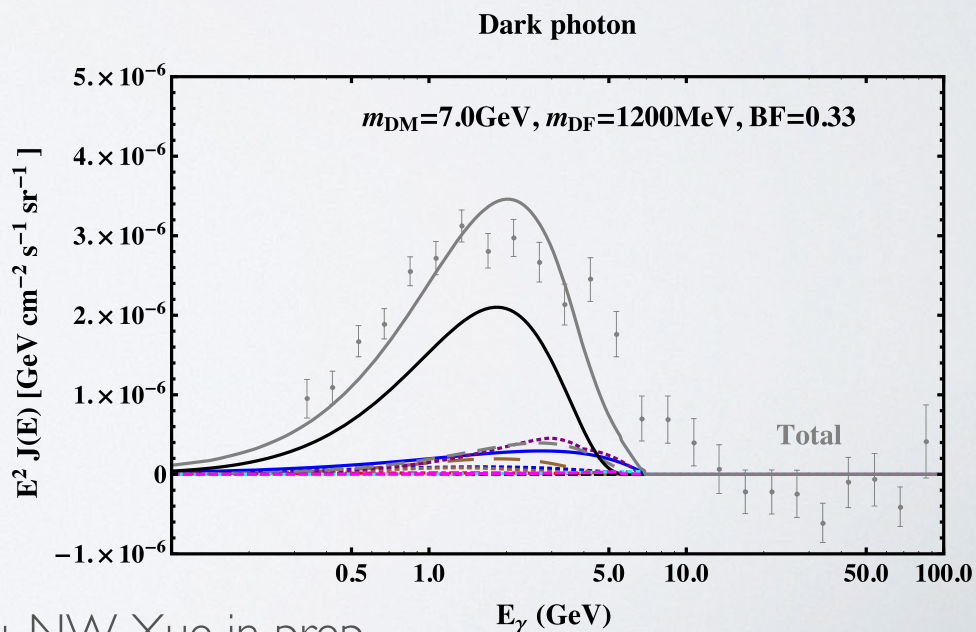


Easy to write down

simple freezeout

no antiprotons





Liu, NW, Xue in prep

THE GC

- Signal => wait and see, but interesting
- Models: bbar seems not as simple as it sounds
- Effective theories are super useful, but also sweep important issues under the rug
- Dark forces: I know when you have a dark hammer, everything looks like a dark nail, but still these look like nice explanations to me

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

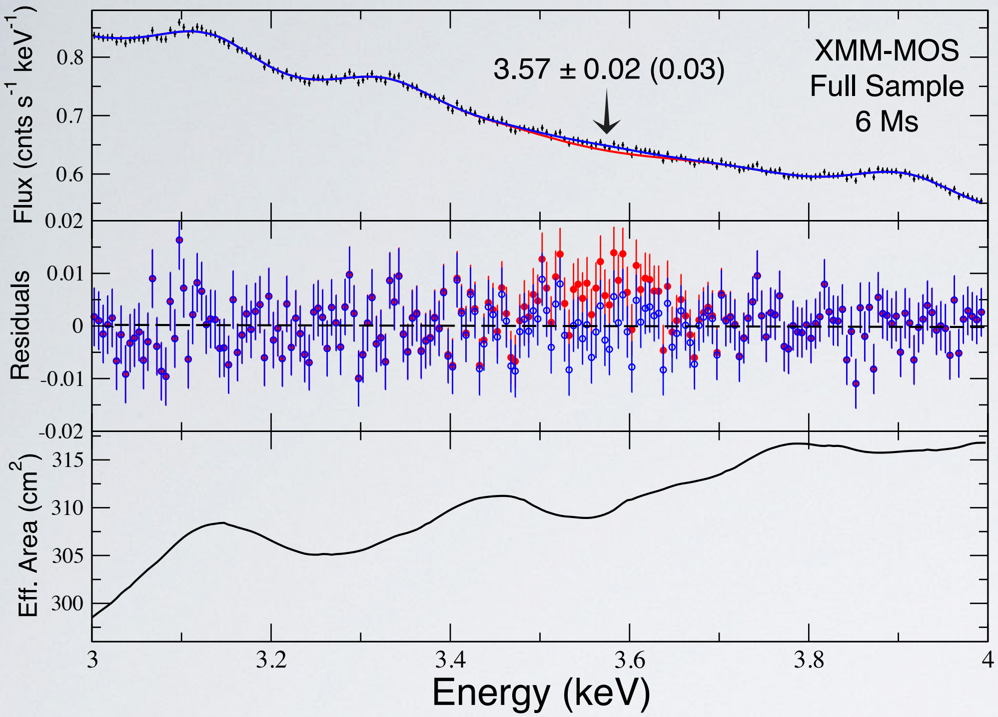
Virgo Chandra, central (not seen)

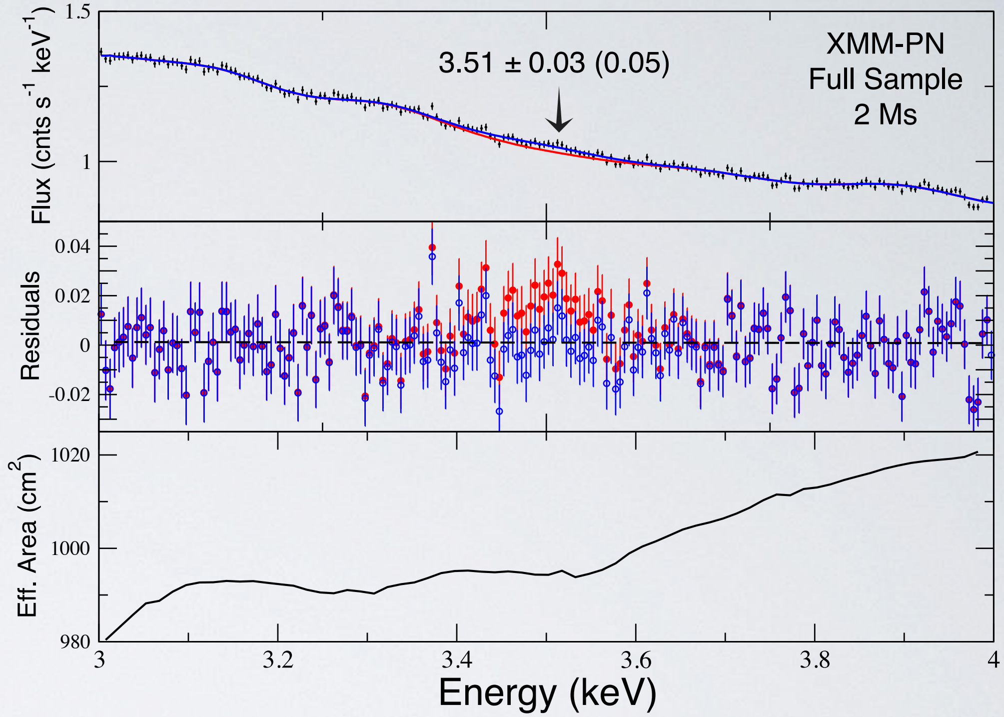
Boyarsky et al

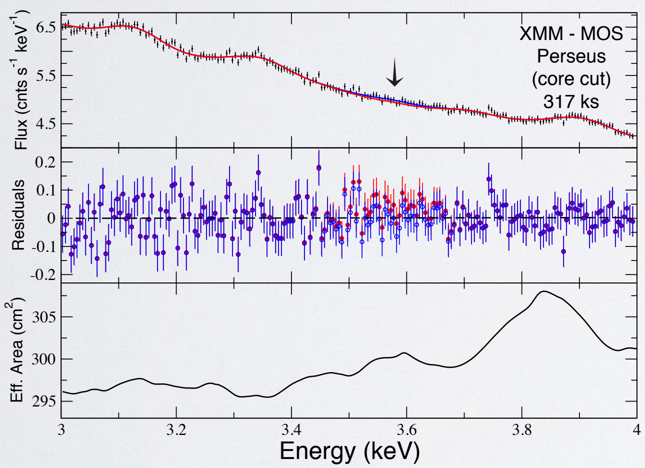
M31 XMM
central+non-central

Perseus XMM, non-central

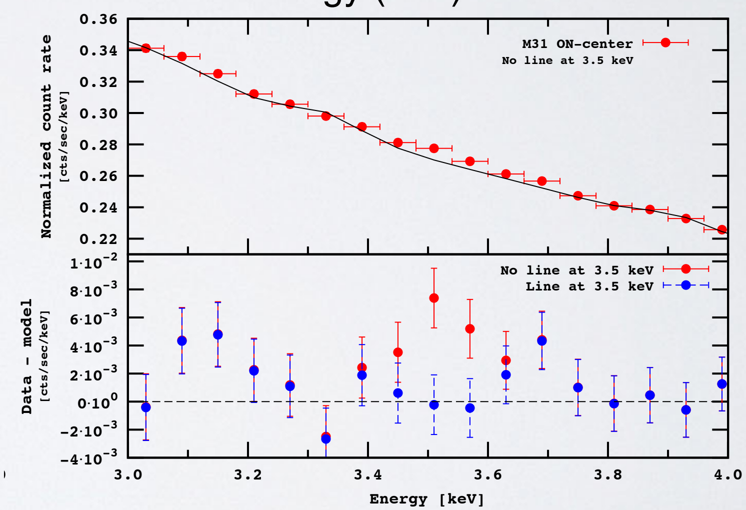
Bulbul et al







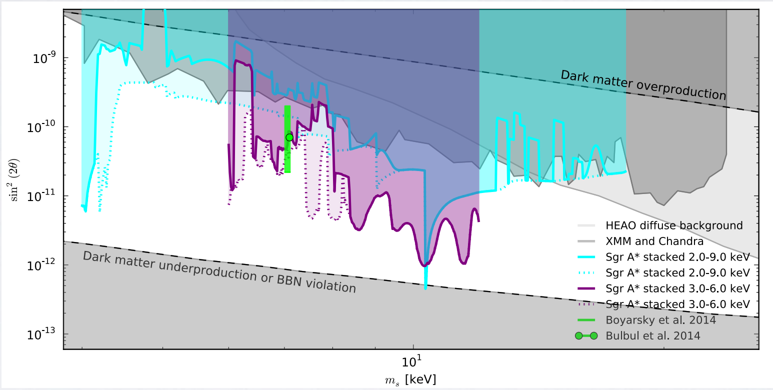
Boyarsky et al

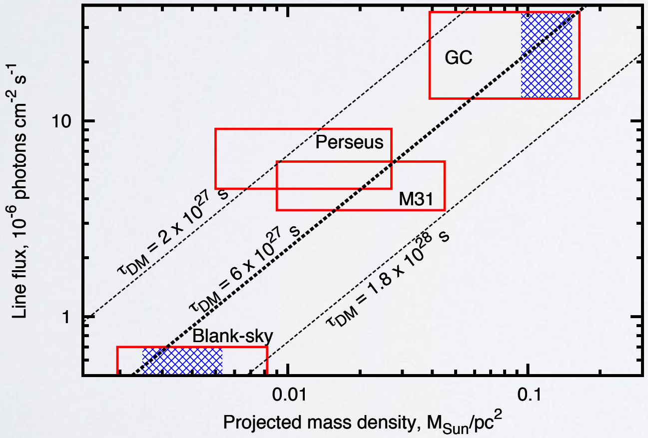


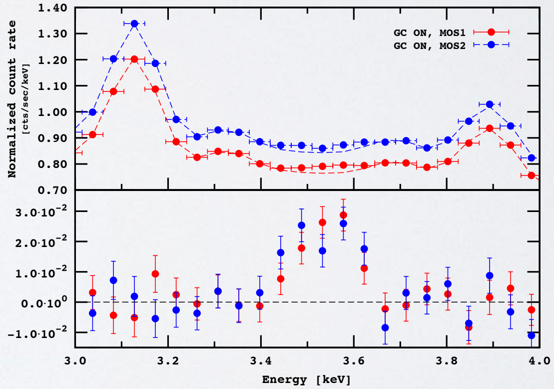
Passes the Toro test…

THE MILKY WAY

Riemer-Sorensen



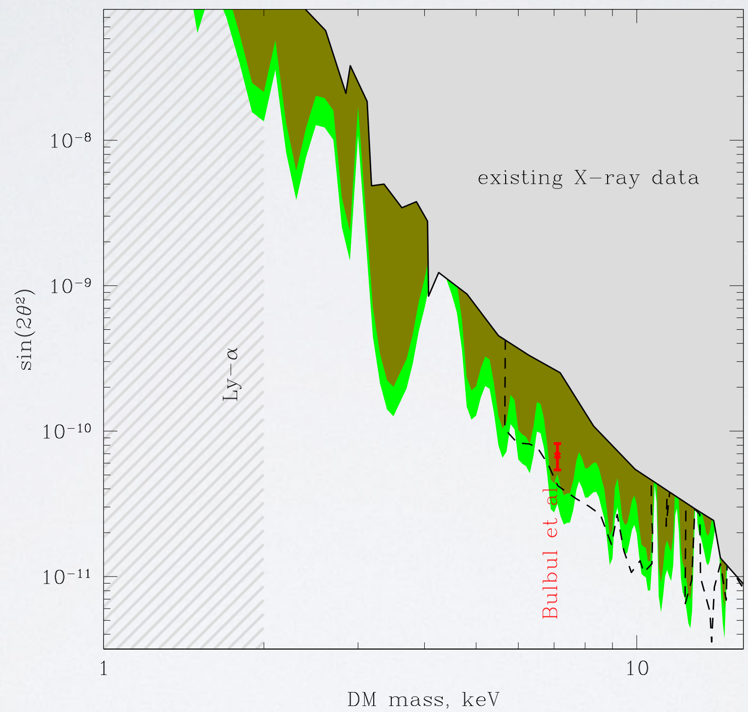




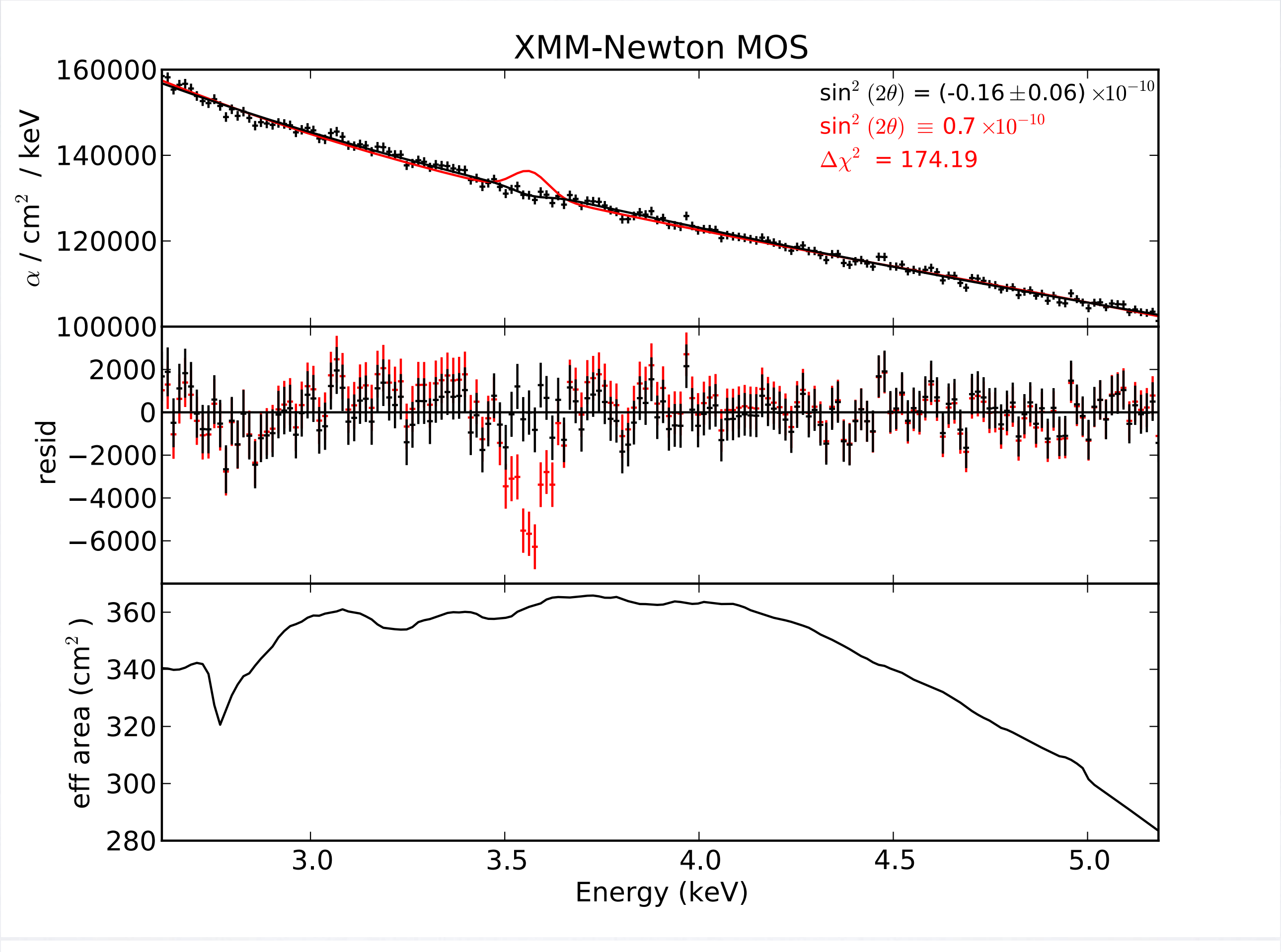
Boyarsky, et al

DWARFS

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



STACKED GALAXIES



Anderson, Churazov, Bregman

1408.4115

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
- Cl can explain clusters

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)

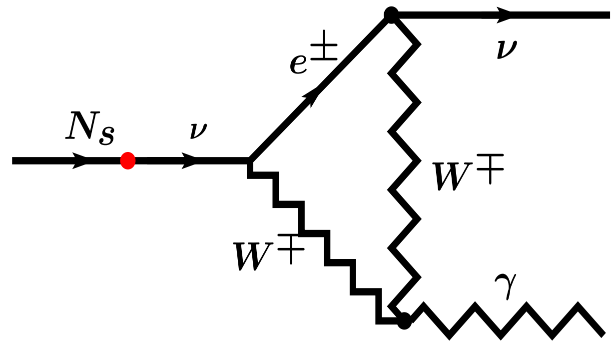
- JP used wrong atomic line data
- Flux from Cl is negligible
- Most conservative K assumptions still yield 4 sigma detection

BUT WHAT IS IT?

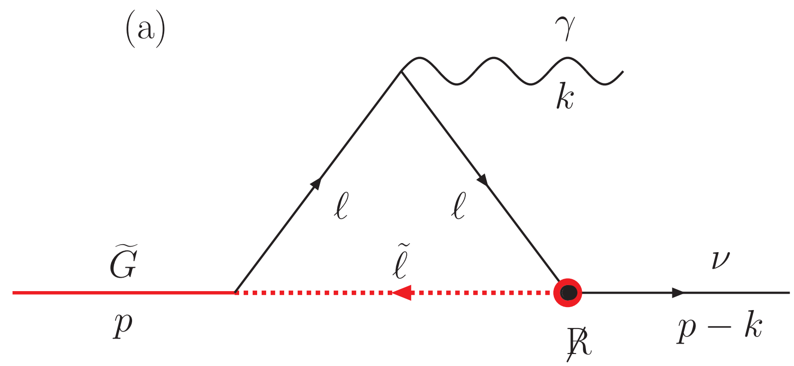
assuming it's BSM physics, that is

DECAYING DARK MATTER

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



(a)

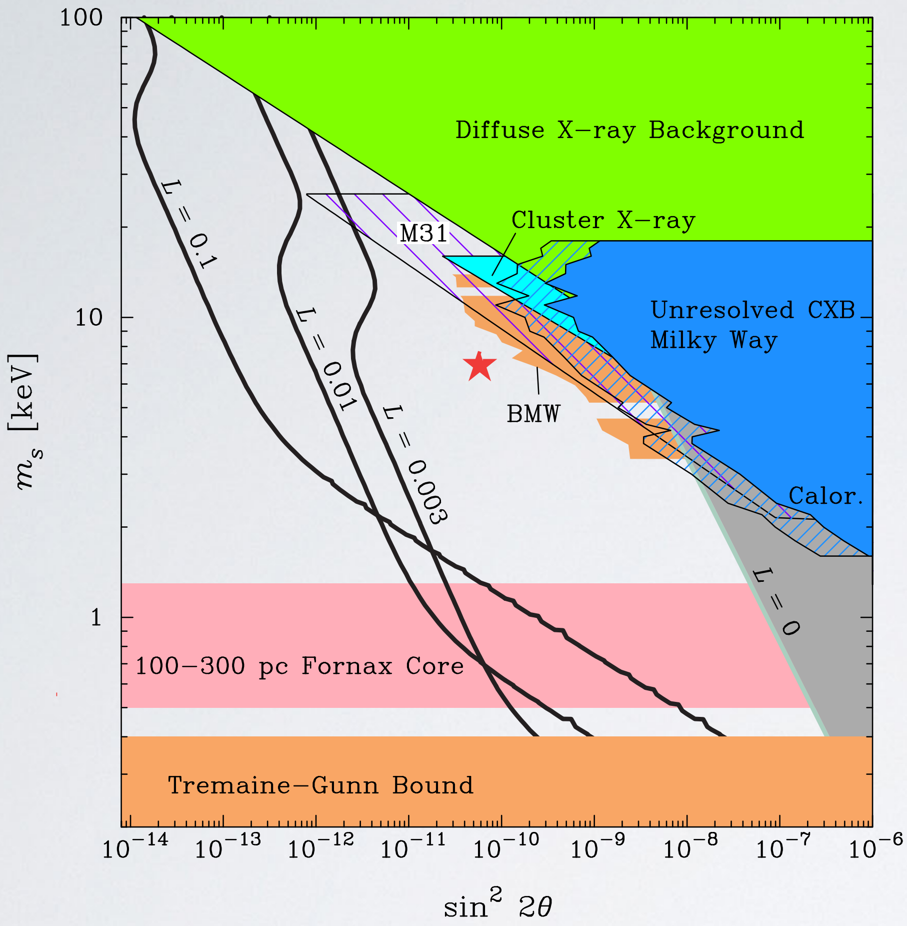


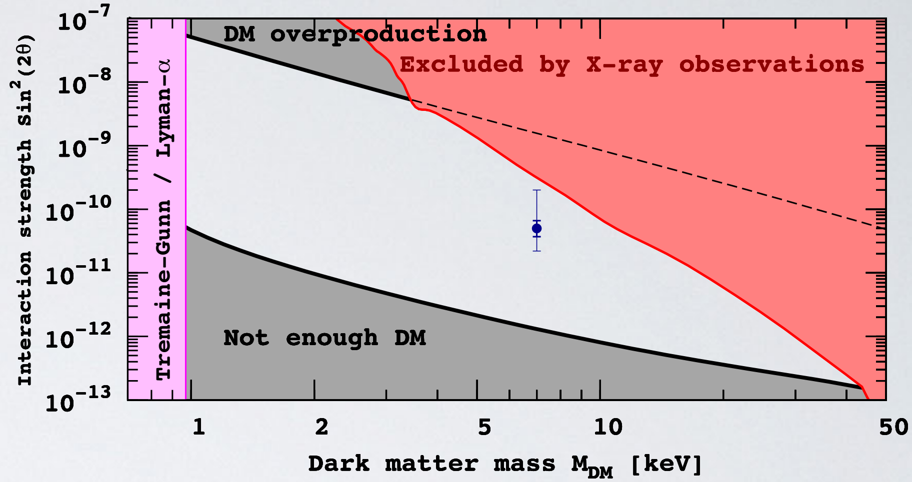
- R-parity violating gravitino
  $\tilde{g} \to \nu + \gamma$

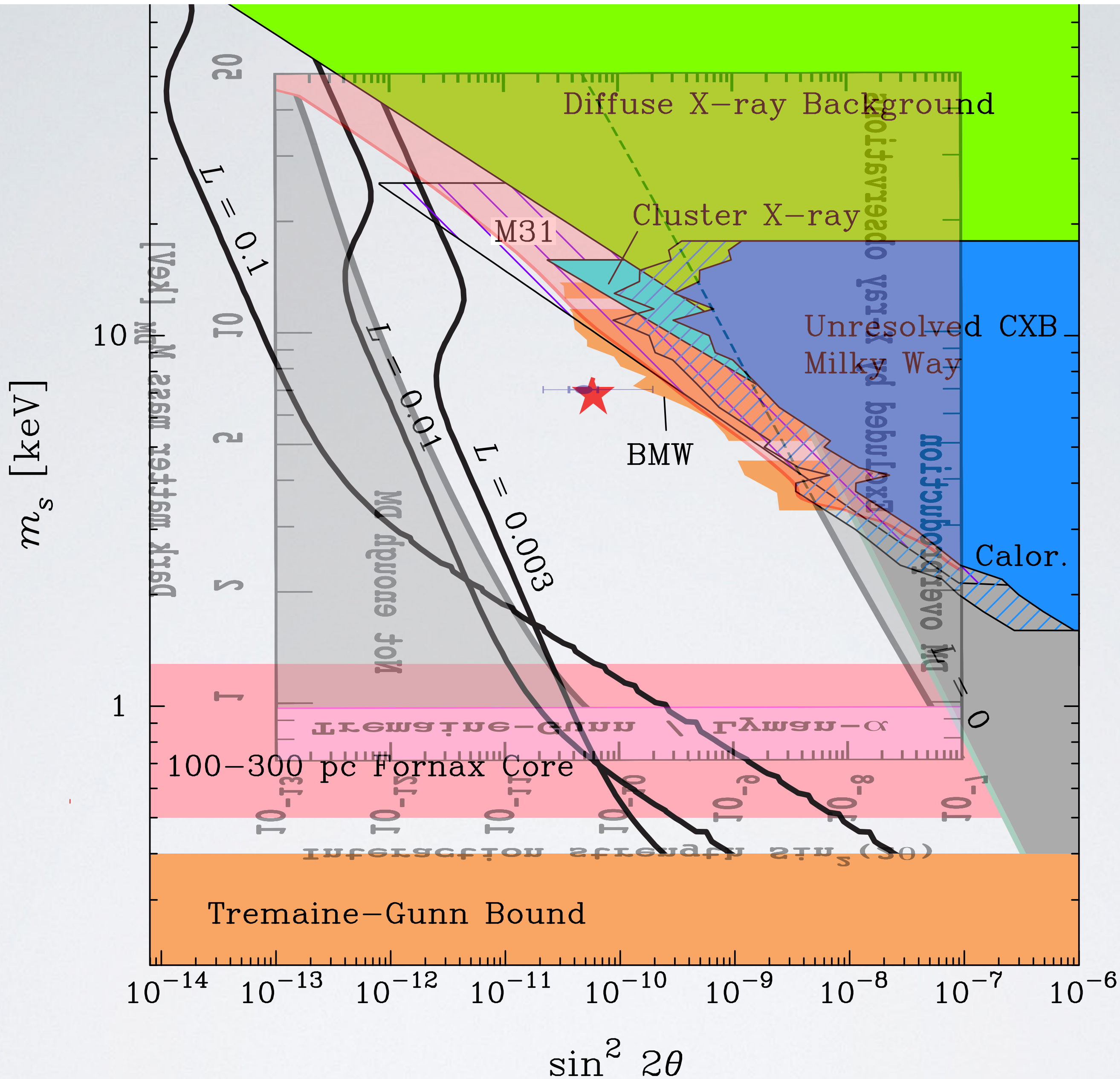
- Also R-parity violating axino, . . .

- For bosonic DM axions (or axion-like particles) would decay $a \to \gamma\gamma$

shamelessly stolen from talk by Ruchayskiy, April 2014


Diffuse X−ray Background
Cluster X−ray
M31
Unresolved CXB
Milky Way
BMW
Calor.
L = 0.1
L = 0.01
L = 0.003
L = 0
100−300 pc Fornax Core
Tremaine−Gunn Bound
m_s [keV]
$\sin^2 2\theta$
100
10
1
10^{-14} 10^{-13} 10^{-12} 10^{-11} 10^{-10} 10^{-9} 10^{-8} 10^{-7} 10^{-6}


DM overproduction
Excluded by X-ray observations
Not enough DM
Tremaine-Gunn / Lyman-α
Interaction strength $\sin^2(2\theta)$
Dark matter mass M_{DM} [keV]
10^{-7} 10^{-8} 10^{-9} 10^{-10} 10^{-11} 10^{-12} 10^{-13}
1 2 5 10 50



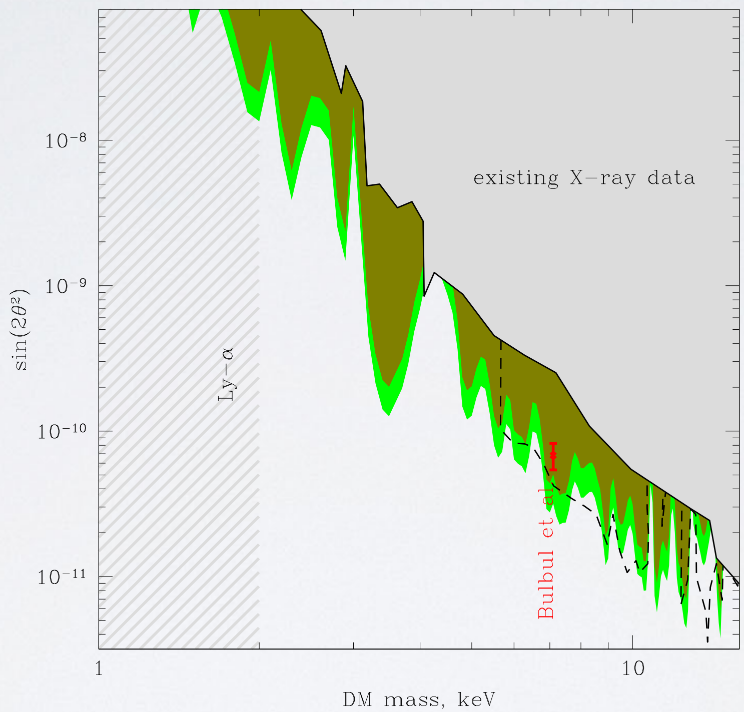
benchmark model is sterile neutrino, BUT decaying models seem to be excluded

CONSIDERING ALTERNATIVES

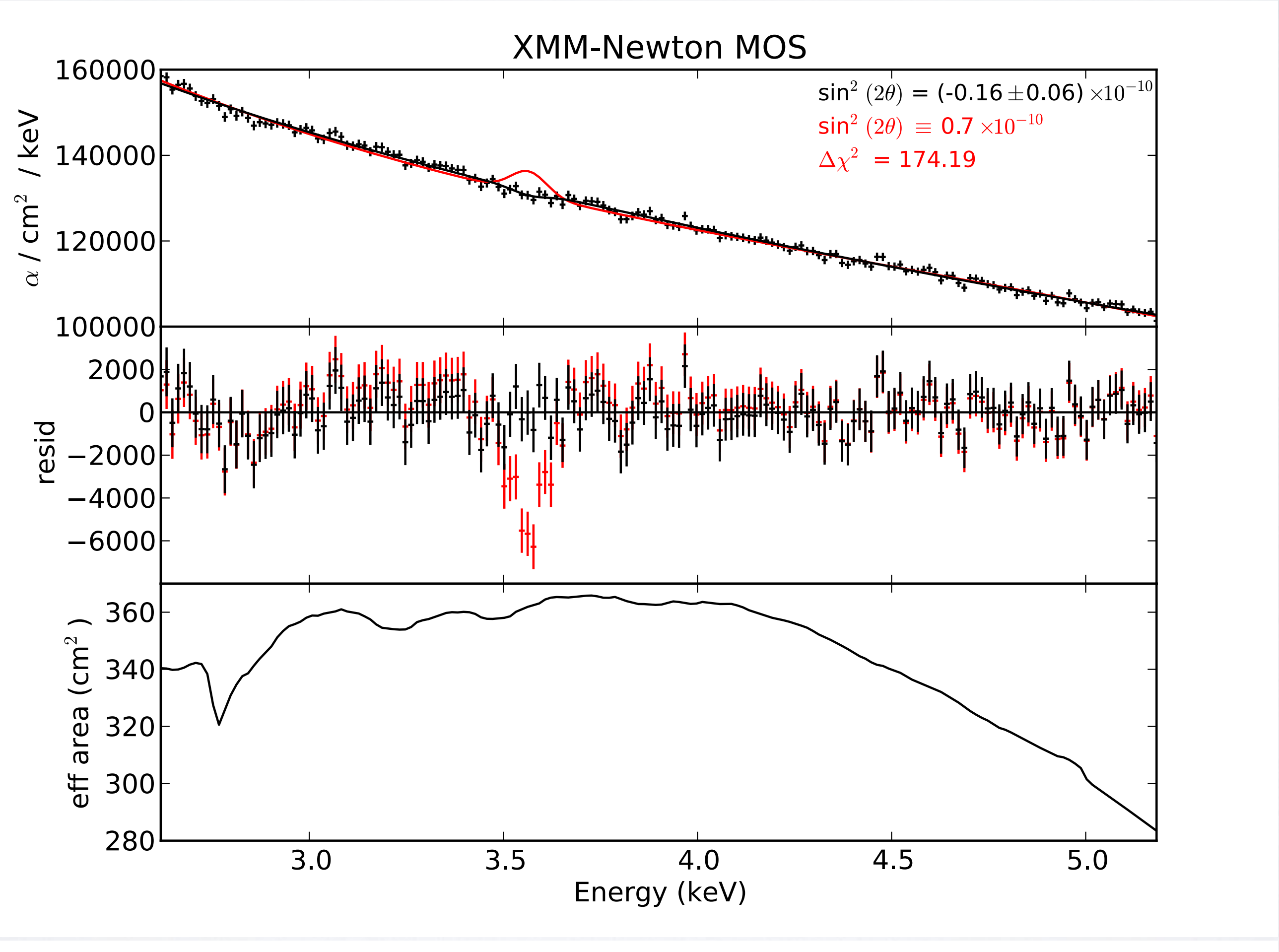
- Important to have alternatives just to ask what to test
- Other observations may motivate other scales of DM (e.g., the GeV excess in the GC)
- ?

DWARFS

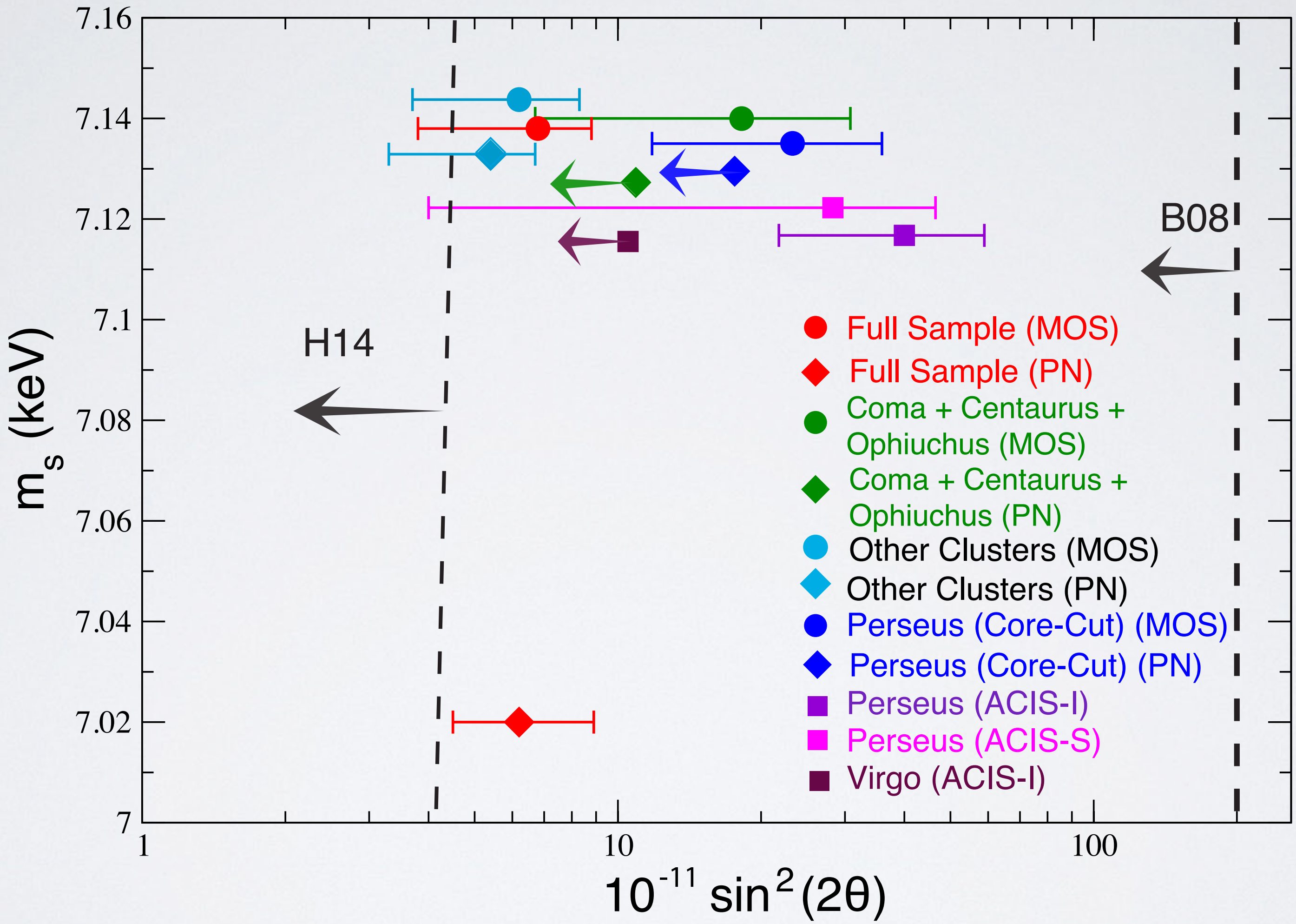
No sign in stacked MW dwarfs (Malyshev, Neroonov, Eckert)



OTHER GALAXIES



VIRGO VS PERSEUS



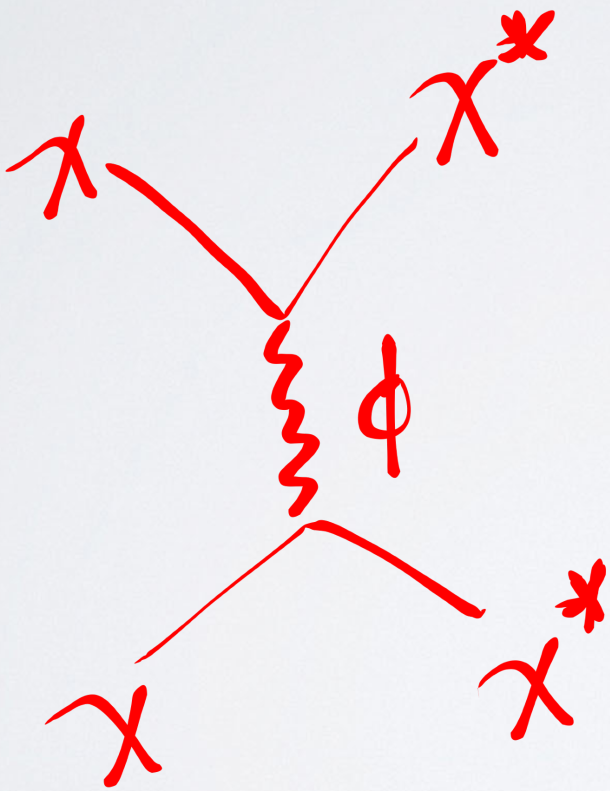
VIRGO VS PERSEUS

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

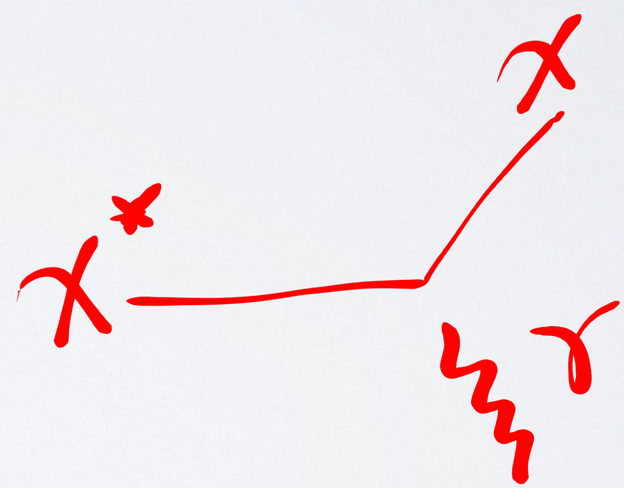
$d_{virgo} \sim 15$ Mpc $d_{perseus} \sim 75$ Mpc

PROPOSAL: SCATTERING VS DECAY

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



Finkbeiner, NW 1402.6671

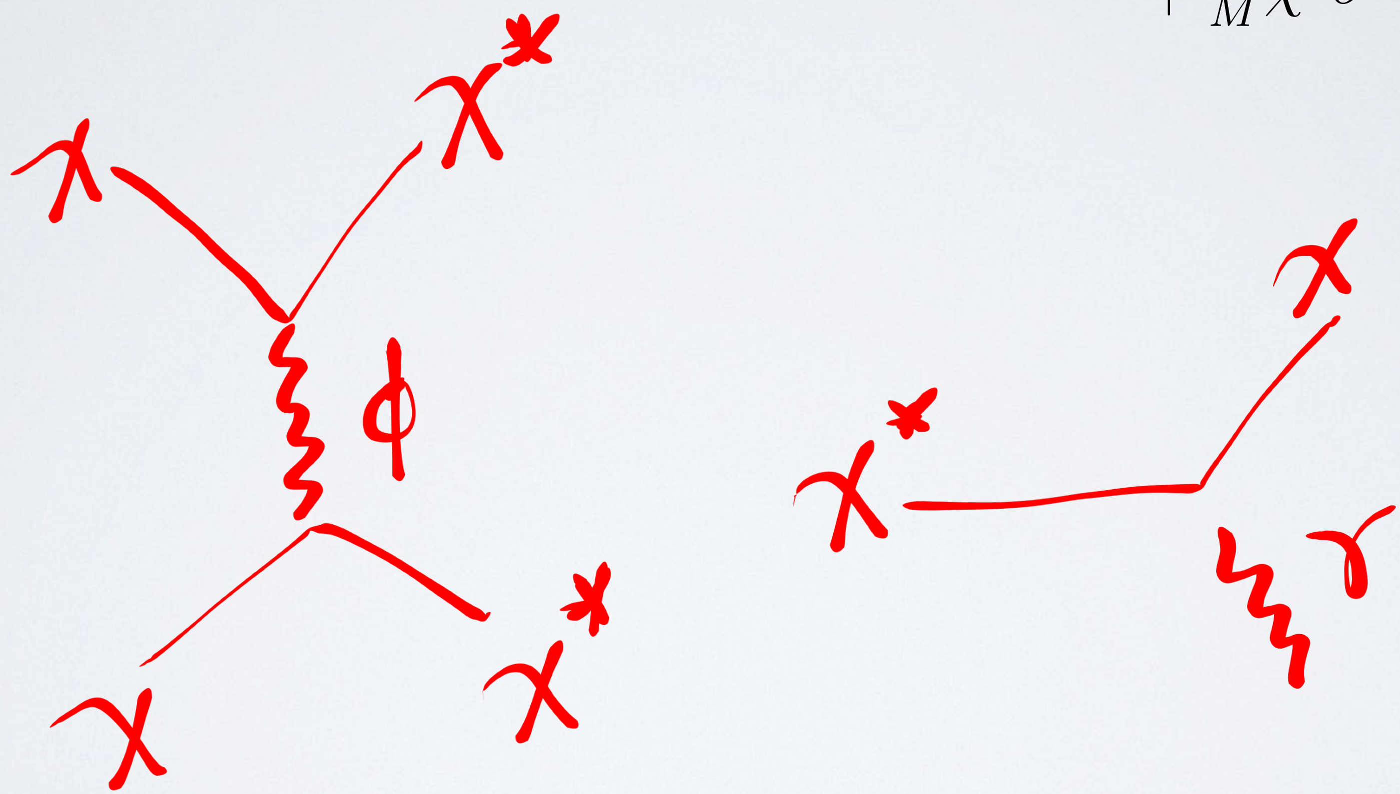


Just reapplication of older XDM model

Finkbeiner NW '07

THE MODEL

$$\mathcal{L} = \bar{\chi}_i \not{D} \chi_i + \frac{1}{4} F^d_{\mu\nu} F^{d\mu\nu} + \epsilon F_{\mu\nu} F^{d\mu\nu} + m^2 \phi_\mu \phi^\mu + M_i \bar{\chi}_i \chi_i + \delta_i \chi_i \chi_i$$
$$+ \tfrac{1}{M} \chi^* \sigma^{\mu\nu} \chi F_{\mu\nu}$$



THE SIGNAL

(Perseus)

$$\begin{aligned}\mathcal{L} &= \int_0^{R_{200}} 4\pi r^2 \left(\frac{\rho(r)}{m_\chi}\right)^2 \langle \sigma_{scatt} v\rangle \\ &= 1.9 \times 10^{49} \text{photons/sec} \times \left(\frac{\langle \sigma_{scatt} v\rangle}{10^{-19}\text{cm}^3\text{sec}^{-1}}\right)\left(\frac{10\text{GeV}}{m_\chi}\right)^2\end{aligned}$$

$$\Phi = 2.6 \times 10^{-5} \left(\frac{\langle \sigma v\rangle}{10^{-19}\text{cm}^3\text{sec}^{-1}}\right)\left(\frac{10\text{GeV}}{m_\chi}\right)^2 \text{photons cm}^{-2}\,\text{sec}^{-1}$$

THE SIGNAL

$$\langle \sigma_{scatt} v \rangle = \sigma_{mr} \sqrt{v^2 - v^2_{thresh}}$$

$$\sigma_{mr} = 10^{-28}\mathrm{cm}^2 \quad \gamma = (0.7, 1, 1.3)$$

$$F_{perseus} = (0.12, 0.29, 1.1) \times 10^{-5}$$

$$F_{virgo} = (0.47, 2.0, 13.0) \times 10^{-5}$$

$$F_{M31} = (0.29, 1.3, 9.6) \times 10^{-5}$$

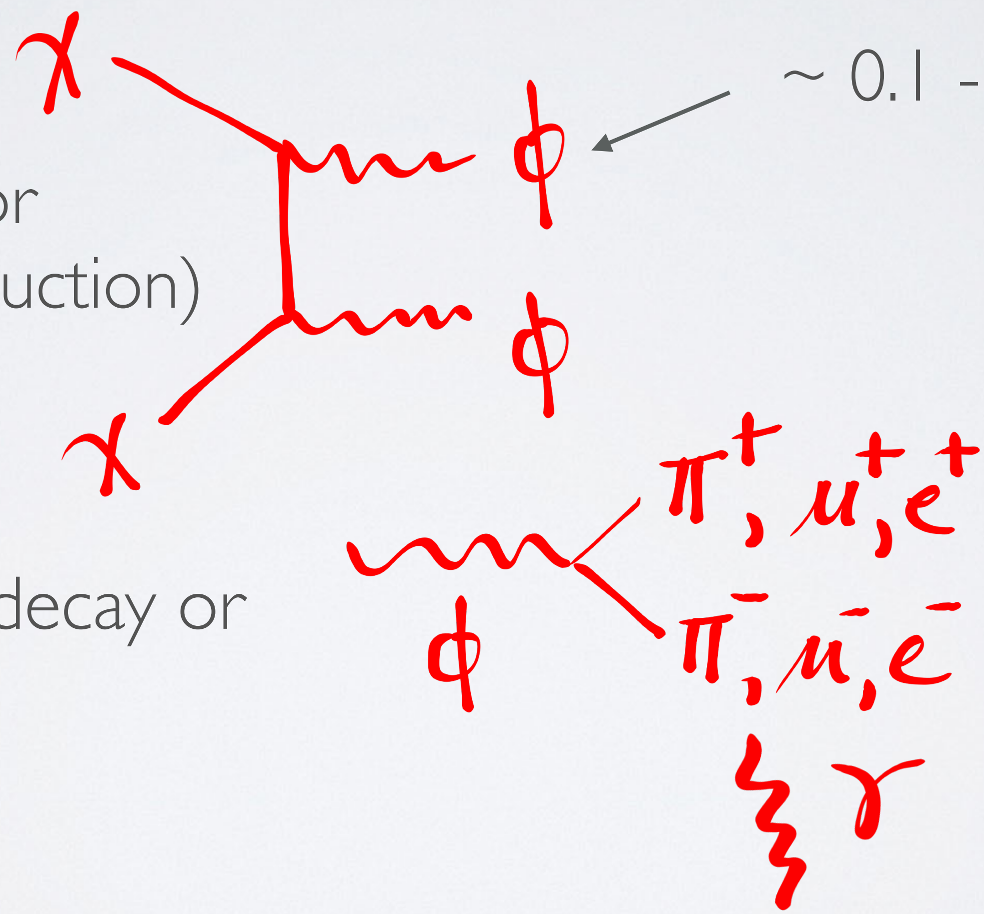
(think 10^{-5} for Perseus, limit of 10^{-5} for Virgo, few x 10^{-6} for M31)

RE-PRODUCES LIGHT DF MODELS FOR THE GC SIGNAL

~5-10 GeV

~ 0.1 - 1 GeV

"light" mediator
(below proton production)



photons from π^0 decay or FSR/IB

X-RAY SIGNALS OF SCATTERING

- while the sterile neutrino is the default BSM explanation of this line, it is worth looking elsewhere
- scattering signals, in particular, seem an interesting direction where the energy scale is the fine structure of the theory
- motivated as: non-observation in dwarfs, Perseus vs Virgo
- Can simultaneously explain GC excess

SIMILAR PLAY, NEW PLAYERS UNKNOWN CONCLUSION

- Searches for DM continue to march forward, covering huge swaths of the conventional model parameter space
- The failure to find NP are colliders so far suggests we should at least be open minded about what might appear as dark matter
- Anomalies continue to appear, even as some old ones linger without clear resolution (DAMA, PAMELA->AMS)
- New models seem to ubiquitously have new, light states => tread carefully with effective theories

SIMILAR PLAY, NEW PLAYERS UNKNOWN CONCLUSION

- Default models for current anomalies (bbar annihilation for GC and sterile nu for 3.5 keV) hit some immediate concerns
  - antiprotons (GC)
  - dwarfs/Virgo v Perseus (3.5 keV)
- The toolbox developed especially since 2007 (DAMA, INTEGRAL, PAMELA) of dark forces and excited states provide useful model structures for current anomalies
- These may or may not be the explanation, but point is these secondary issues are *model dependent*
- Keep an open mind - the data, not our gut reaction, will be the decider

END ANOMALIES
NEXT: COMMENTS ON COLLIDERS

KNOW YOUR LSP

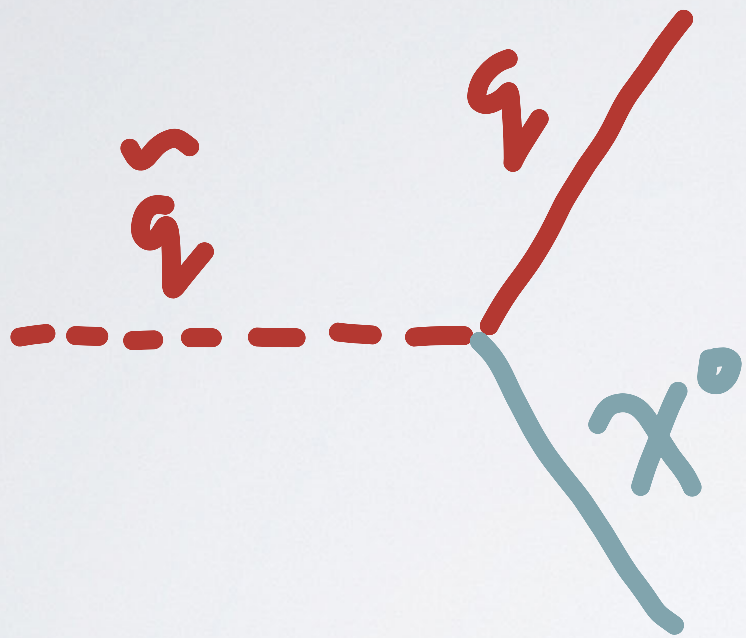
or

How the details of your dark
matter can effect your limits

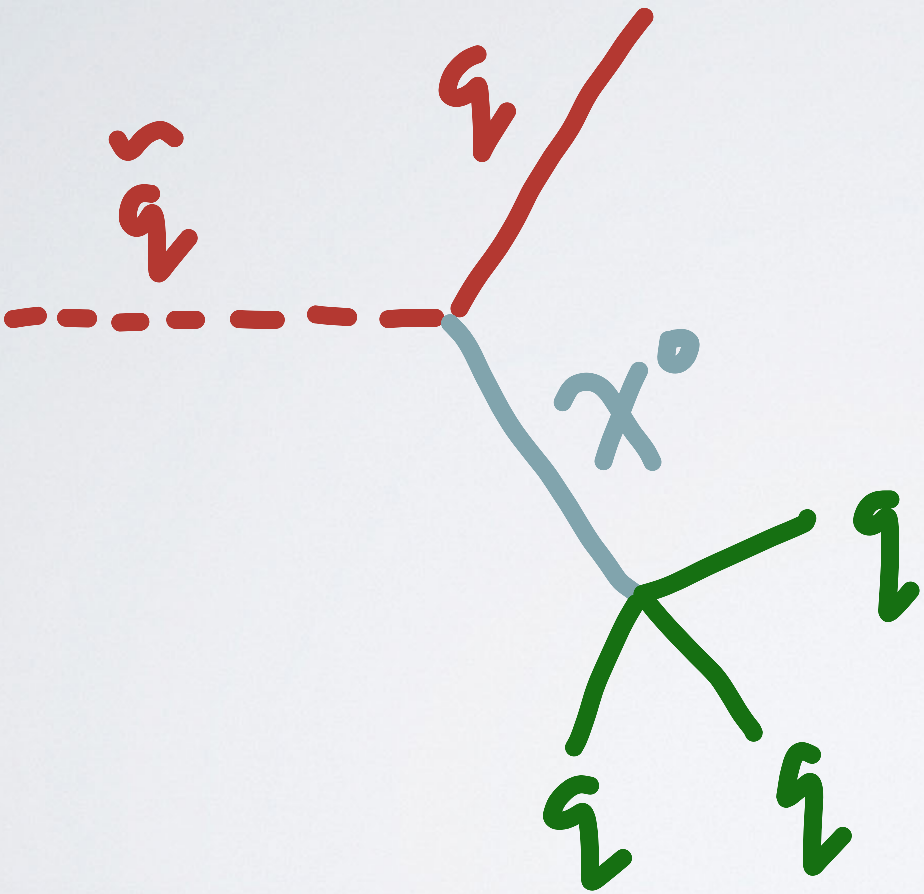
WHAT IS THE THING TO BE LOOKING FOR?

Jets + MET

HIDING SUSY



HIDING SUSY: RPV



Pro: Hides SUSY!

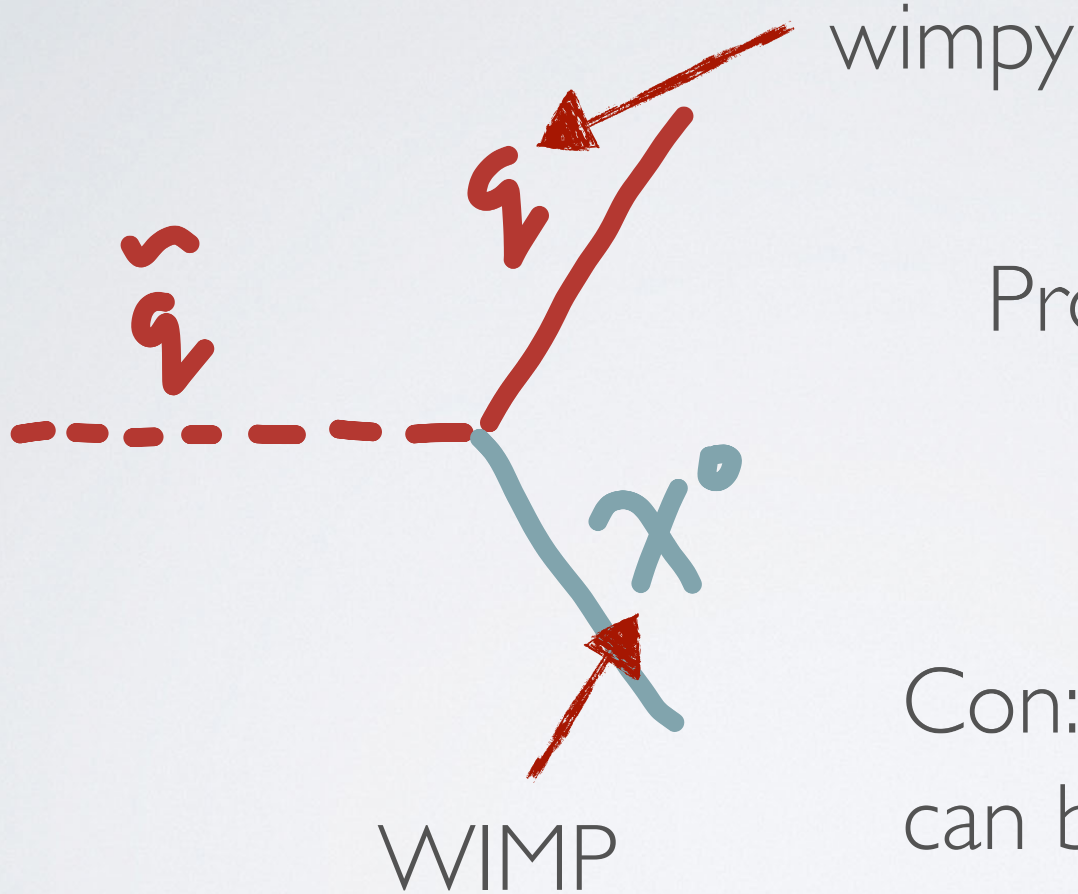
Con: Maybe not (multijets)

Flavor constraints

Baryon # violation

Dark Matter

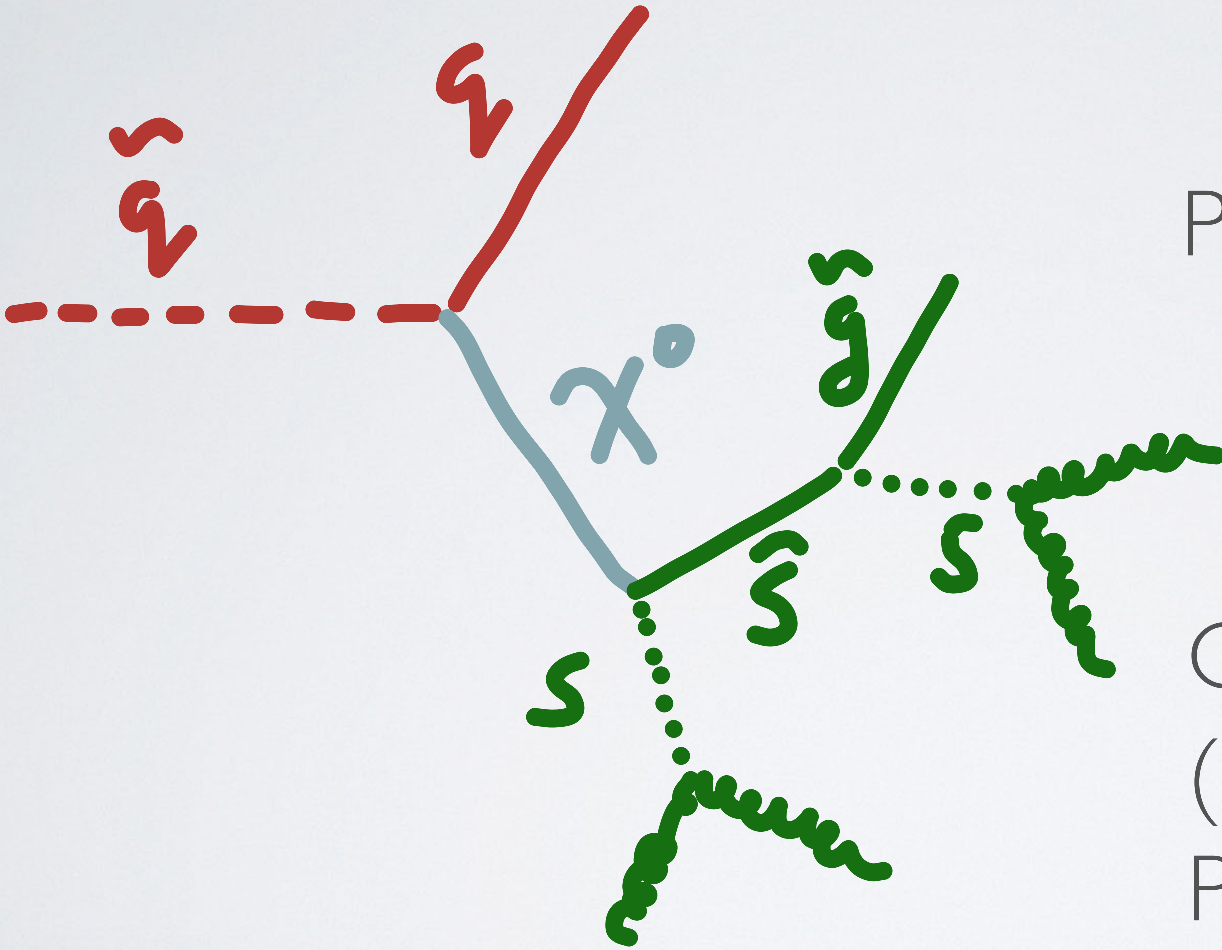
HIDING SUSY: SQUEEZING



Pro: Hides SUSY!

Con: Really just 1 particle can be pretty tuned

HIDING SUSY: STEALTH



Pro: Hides SUSY!

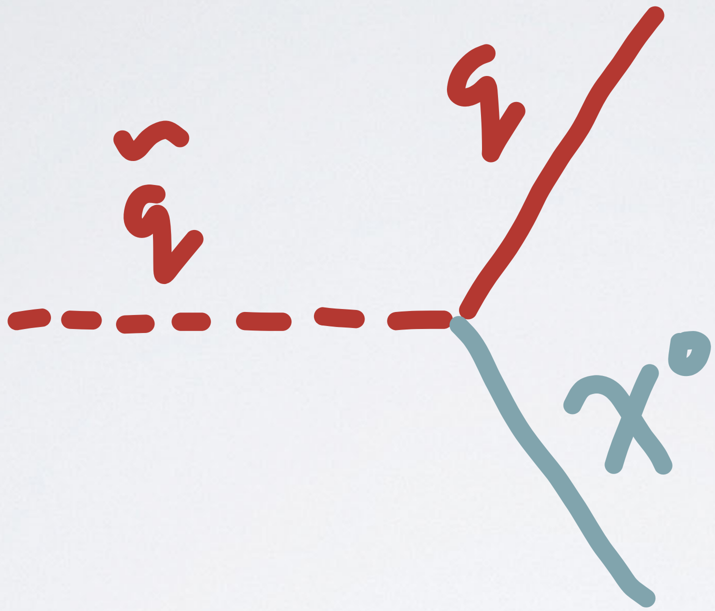
Con: Maybe not
(specific searches)
Particular model setup

A CRAZY IDEA

(D. Alves, J. Liu, NW '13)

- Hard jets and MET for searches
- Try *adding* missing energy to the event

A SIMPLIFIED MODEL



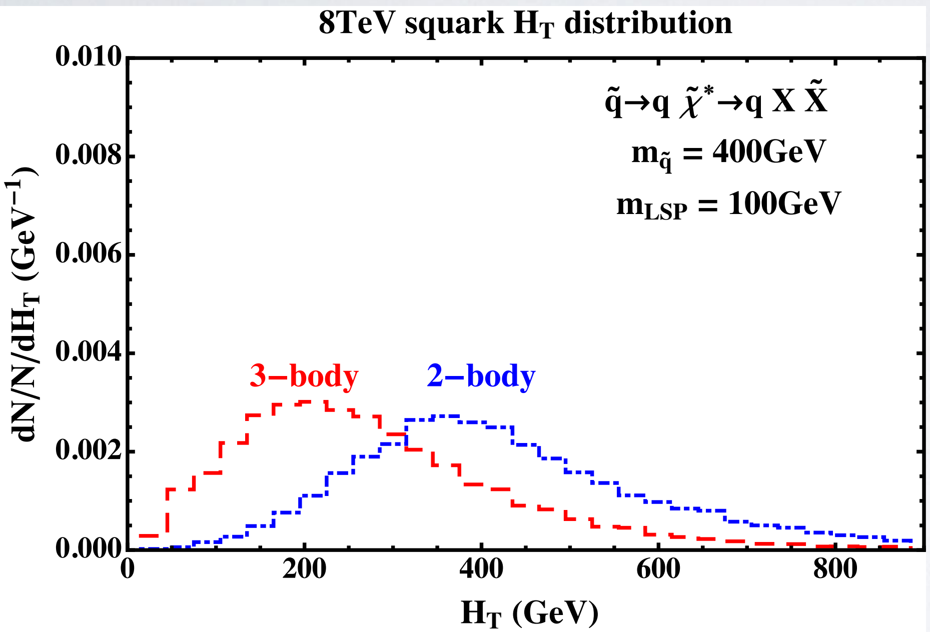
A SIMPLIFIED MODEL

"doubly invisible"
SUSY

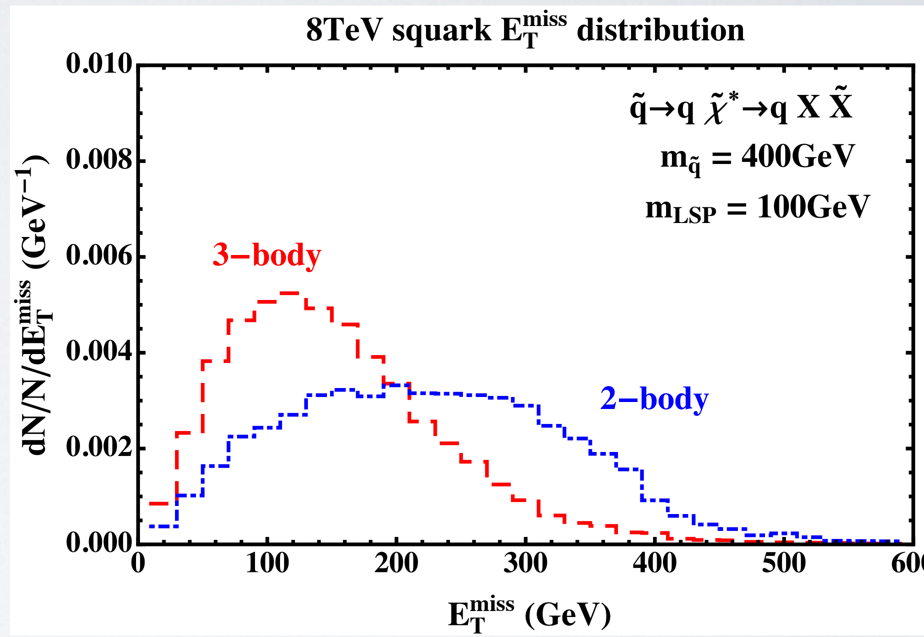
A SIMPLIFIED MODEL

"doubly invisible"
SUSY

More (scalar sum) missing energy
Less (vector sum) missing energy



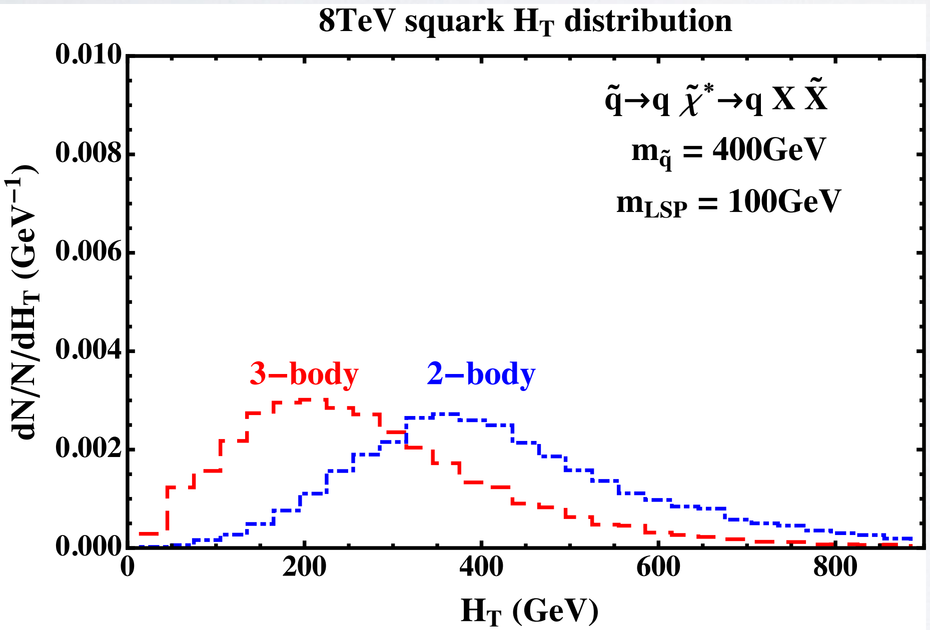
8TeV squark H_T distribution
$\tilde{q} \to q\ \tilde{\chi}^* \to q\ X\ \tilde{X}$
$m_{\tilde{q}}$ = 400GeV
m_{LSP} = 100GeV
3−body
2−body
dN/N/dH_T (GeV^{-1})
0.010
0.008
0.006
0.004
0.002
0.000
0
200
400
600
800
H_T (GeV)

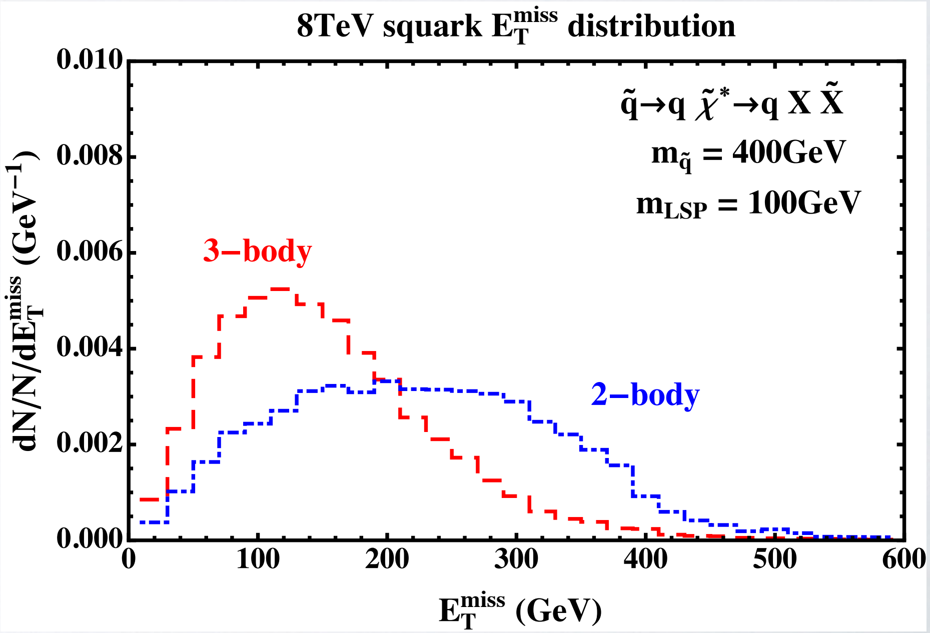


8TeV squark E_T^{miss} distribution
$\tilde{q} \to q\ \tilde{\chi}^* \to q\ X\ \tilde{X}$
$m_{\tilde{q}}$ = 400GeV
m_{LSP} = 100GeV
3−body
2−body
dN/N/dE_T^{miss} (GeV^{-1})
0.010
0.008
0.006
0.004
0.002
0.000
0
100
200
300
400
500
600
E_T^{miss} (GeV)

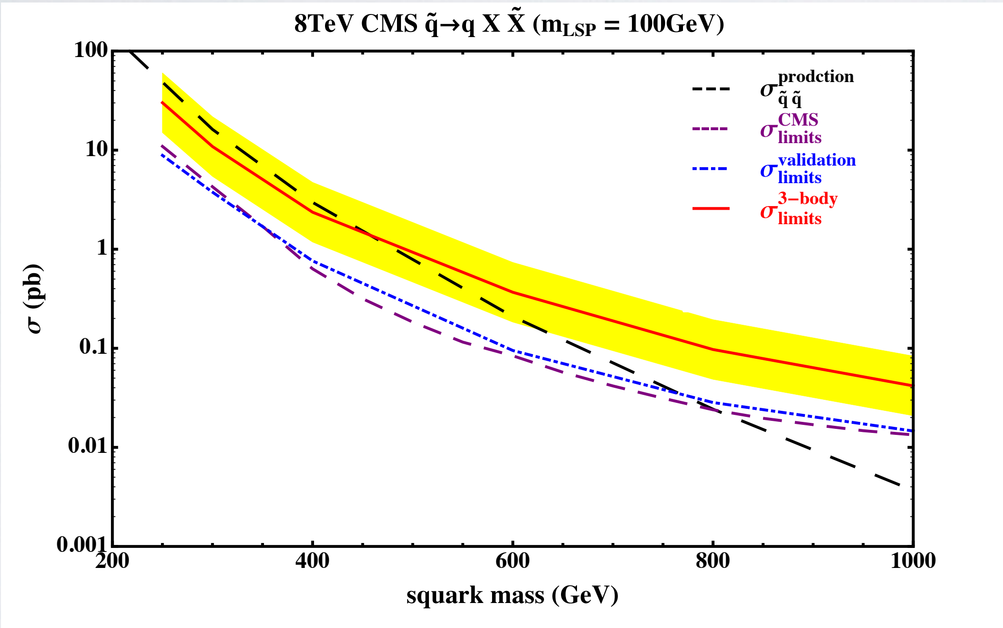
CMS SEARCHES

N_{jets}	Selection H_{T}	$\not{H}_{\mathrm{T}}$	$Z \to \nu\bar{\nu}$ from γ+jets	$t\bar{t}$/W $\to$ e, μ+X	$t\bar{t}$/W $\to \tau_{\mathrm{h}}$+X	QCD	Total background	Obs. data
3-5	500-800	200-300	1821.3±326.5	2210.7±447.8	1683.7±171.4	307.4±219.4	6023.1±620.2	6159
3-5	500-800	300-450	993.6±177.9	660.1±133.3	591.9± 62.5	34.5± 23.8	2280.0±232.1	2305
3-5	500-800	450-600	273.2± 51.1	77.3± 17.9	67.6± 9.5	1.3± 1.5	419.5± 55.0	454
3-5	500-800	> 600	42.0± 8.7	9.5± 4.0	6.0± 1.9	0.1± 0.3	57.6± 9.7	62
3-5	800-1000	200-300	215.8± 40.0	277.5± 62.4	191.6± 23.2	91.7± 65.5	776.7±101.6	808
3-5	800-1000	300-450	124.1± 23.7	112.8± 26.9	83.3± 11.2	9.9± 7.4	330.1± 38.3	305
3-5	800-1000	450-600	46.9± 9.8	36.1± 9.9	23.6± 3.9	0.8± 1.3	107.5± 14.5	124
3-5	800-1000	> 600	35.3± 7.5	9.0± 3.7	11.4± 3.2	0.1± 0.4	55.8± 9.0	52
3-5	1000-1250	200-300	76.3± 14.8	103.5± 25.9	66.8± 10.0	59.0± 24.7	305.6± 40.1	335
3-5	1000-1250	300-450	39.3± 8.2	52.4± 13.6	35.7± 6.2	5.1± 2.7	132.6± 17.3	129
3-5	1000-1250	450-600	18.1± 4.4	6.9± 3.2	6.6± 2.1	0.5± 0.7	32.1± 5.9	34
3-5	1000-1250	> 600	17.8± 4.3	2.4± 1.8	2.5± 1.0	0.1± 0.3	22.8± 4.7	32
3-5	1250-1500	200-300	25.3± 5.5	31.0± 9.5	22.2± 3.9	31.2± 13.1	109.7± 17.5	98
3-5	1250-1500	300-450	16.7± 4.0	10.1± 4.4	11.1± 3.6	2.3± 1.6	40.2± 7.1	38
3-5	1250-1500	> 450	12.3± 3.2	2.3± 1.7	2.8± 1.5	0.2± 0.5	17.6± 4.0	23
3-5	>1500	200-300	10.5± 2.8	16.7± 6.2	15.2± 3.4	35.1± 14.1	77.6± 16.1	94
3-5	>1500	> 300	10.9± 2.9	9.7± 4.3	6.5± 2.0	2.4± 2.0	29.6± 5.8	39

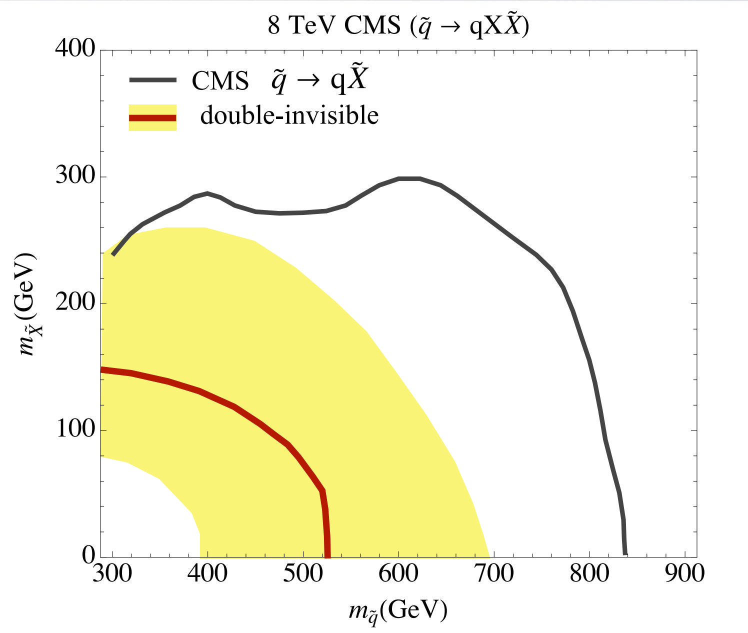




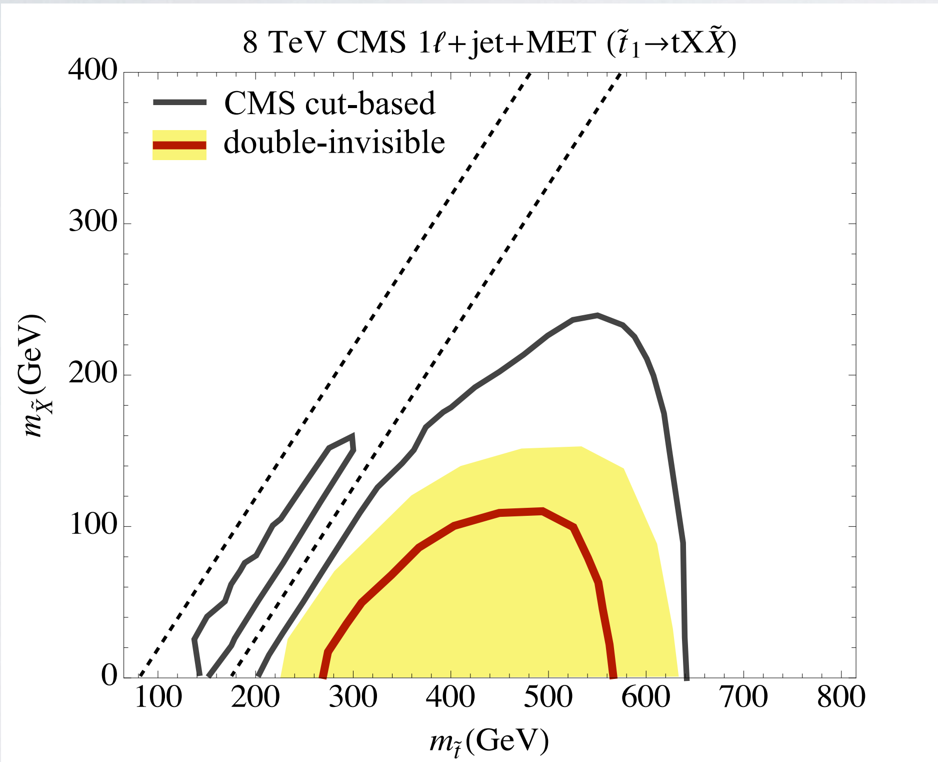
RECASTING



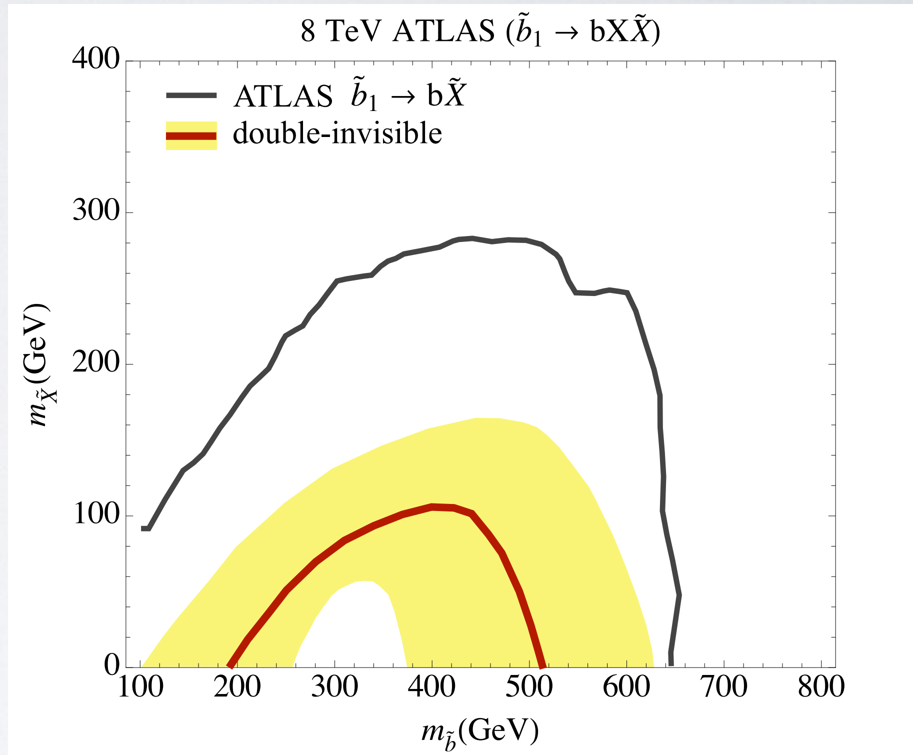
8TeV CMS q̃→q X X̃ (m_LSP = 100GeV)
σ (pb)
squark mass (GeV)
σ prodction q̃ q̃
σ CMS limits
σ validation limits
σ 3−body limits
100
10
1
0.1
0.01
0.001
200
400
600
800
1000



8 TeV CMS (q̃ → qXX̃)
CMS q̃ → qX̃
double-invisible
m_X̃(GeV)
m_q̃(GeV)
400
300
200
100
0
300
400
500
600
700
800
900

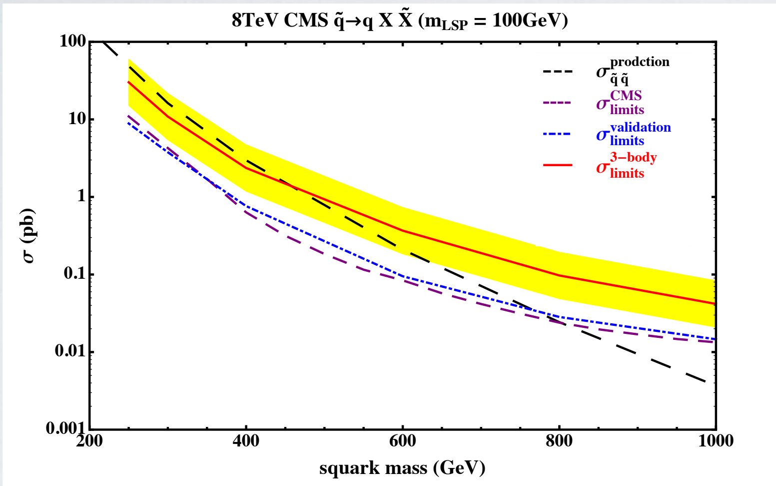


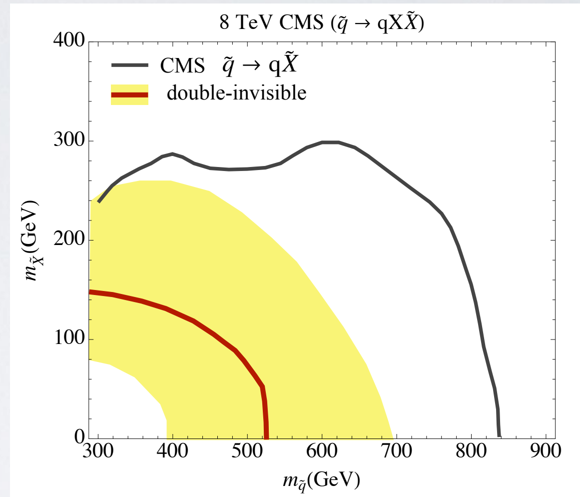
8 TeV CMS 1ℓ+jet+MET ($\tilde{t}_1 \to tX\tilde{X}$)
CMS cut-based
double-invisible
$m_{\tilde{X}}$(GeV)
$m_{\tilde{t}}$(GeV)

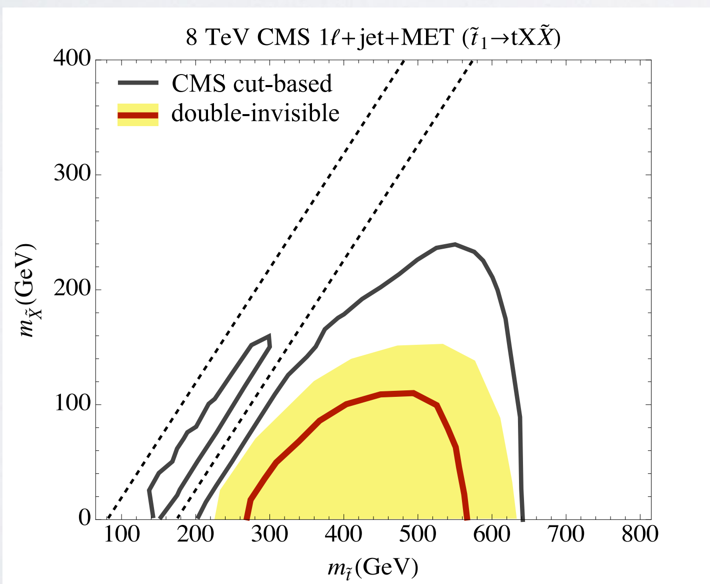


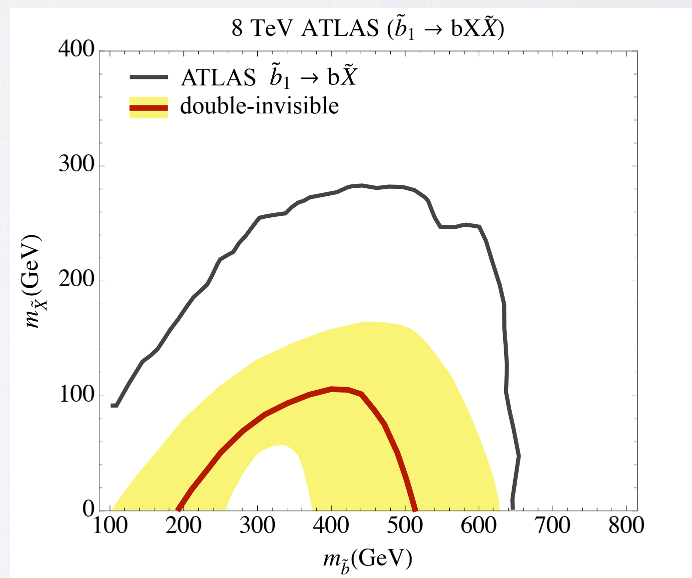
8 TeV ATLAS ($\tilde{b}_1 \to bX\tilde{X}$)
ATLAS $\tilde{b}_1 \to b\tilde{X}$
double-invisible
$m_{\tilde{X}}$(GeV)
$m_{\tilde{b}}$(GeV)

RECASTING









NB: Need proper limits (LHC8 and LHC13)

MISSING MISSING ENERGY

- Doubly invisible SUSY has suppressed HT and MET because of the increase in energy in invisible particles
- Limits seem weakened - what are the limits?
- Opportunities for more natural SUSY models
- Simple simplified model - easy to implement

ACTUAL MODELS

- Yes there are actual models

ANOMALY CONCLUSION

- DAMA: Not dead, but "light WIMPs" in bad shape, no good, complete model (that I know of)
- PAMELA, INTEGRAL: Probably astrophysics? But how will we know? CMB?
- GC ~ GeV excess - seems interesting. Dark matter? What's the test?
- IMHO: models that sound nice for various things are often not nice
- IMHO: dark photon toolbox seems interesting as general approach
- A new signal at 3.55 keV - just getting started!

CONCLUSIONS

- Accessible WIMP parameter space is precisely 5/9 covered => this program is running strong
- A good time to consider alternatives
- A range of anomalies have motivated DM model building
- 3 body decays (due to an LSP symmetry) can dramatically change squark/sbottom/stop limits. Pretty dumb simplified model - should be studied.
- Beware plots. People take them seriously and they circumscribe discussion.
- Not sure: is "more plots" the solution to "plots"?

THANK YOU!