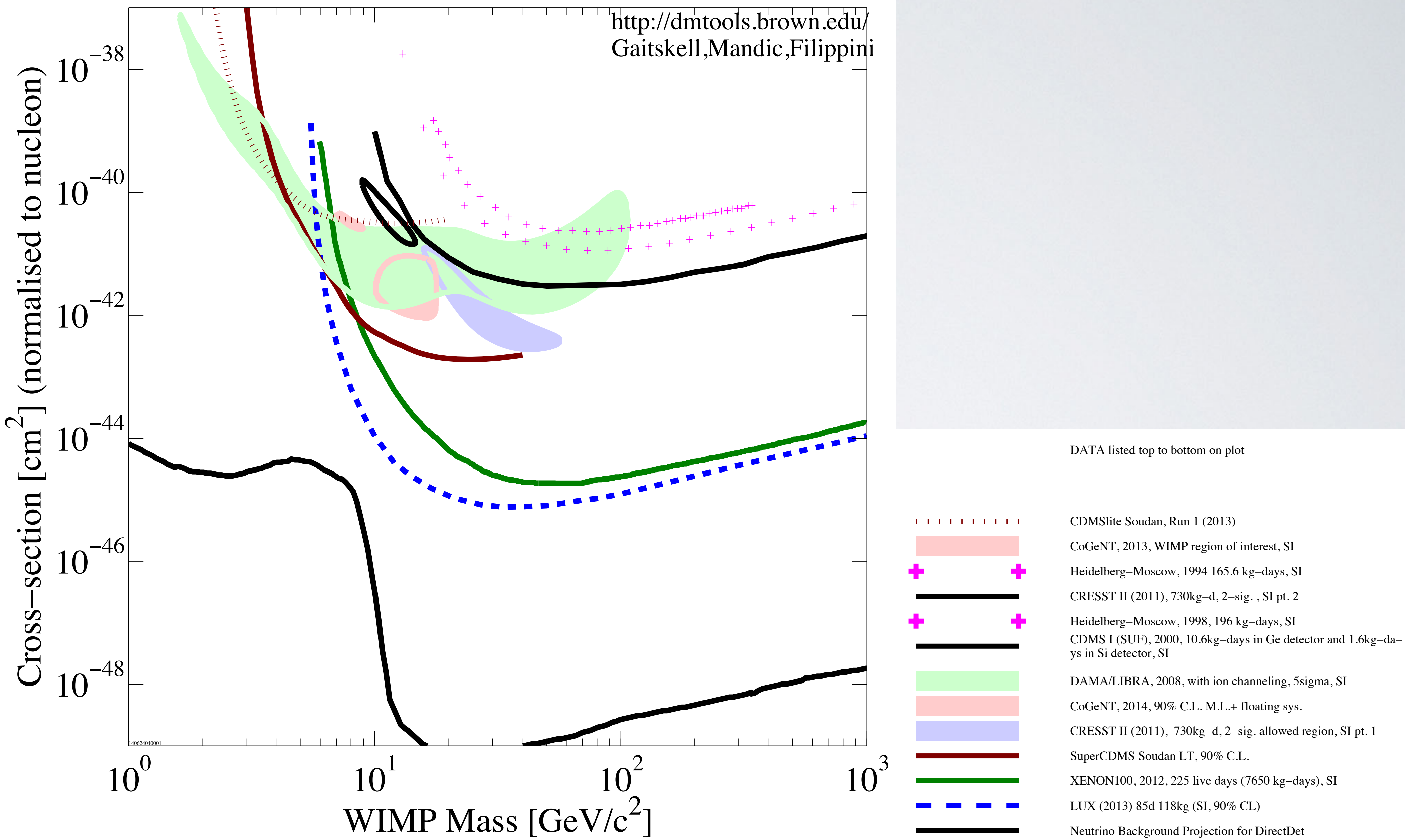
WIMPY AND NOT SO WIMPY WIMPS

Neal Weiner
CCPP-NYU

ICTP Workshop on Frontiers of New Physics
June 25, 2014

THE WIMP

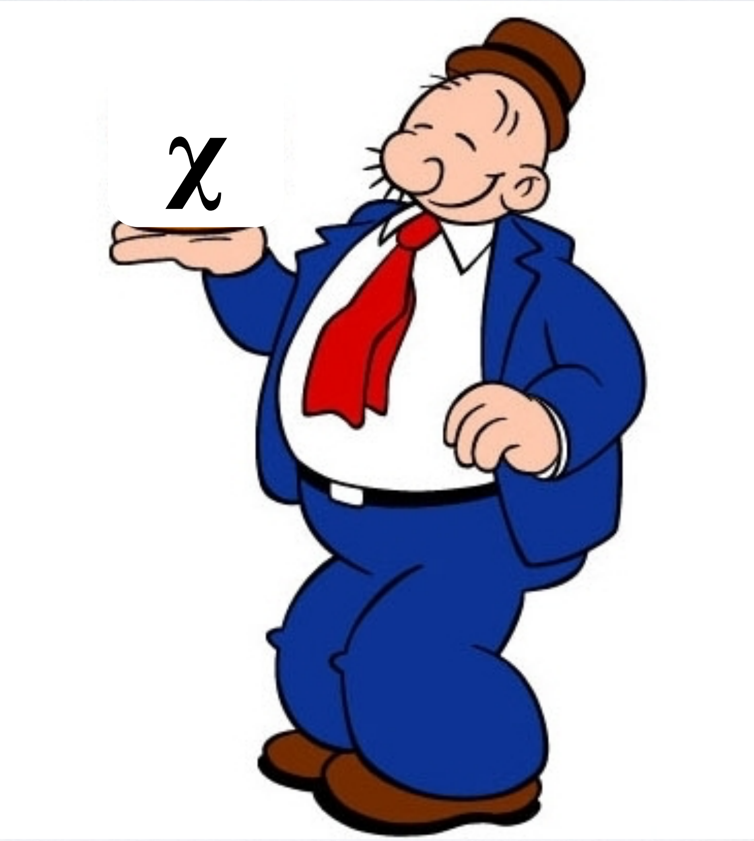


http://dmtools.brown.edu/
Gaitskell,Mandic,Filippini
Cross−section [cm^2] (normalised to nucleon)
10^{-38}
10^{-40}
10^{-42}
10^{-44}
10^{-46}
10^{-48}
10^{0}
10^{1}
10^{2}
10^{3}
WIMP Mass [GeV/c^2]
DATA listed top to bottom on plot
CDMSlite Soudan, Run 1 (2013)
CoGeNT, 2013, WIMP region of interest, 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−da−ys 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

THE SIGNALS

- Direct detection
- Indirect Detection
- Dark Force Searches
- Collider signals

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



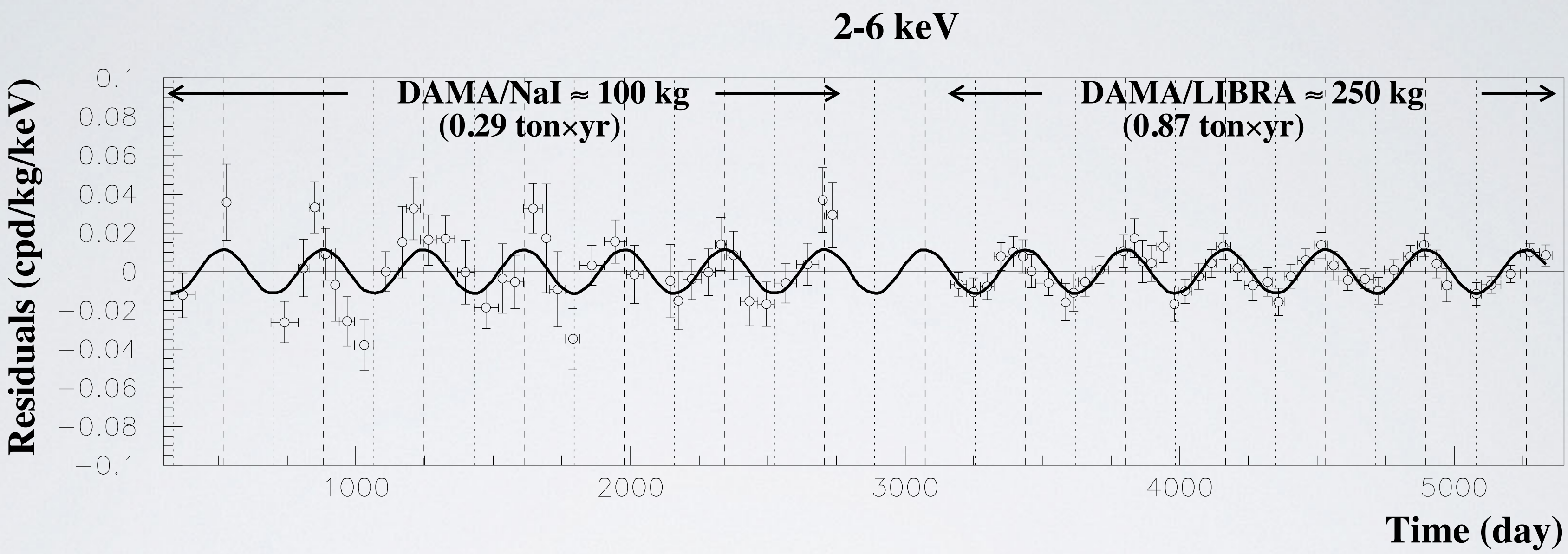
THE ANOMALIES

- DAMA modulation
- DAMA light WIMPs (& CoGeNT & CRESST & CDMS-Si)
- INTEGRAL 511 keV line
- PAMELA (& Fermi & AMS-2)
- The 130 GeV Line
- The GC Excessess
- (new!) the 3.55 keV X-ray line

ANOMALY FATIGUE

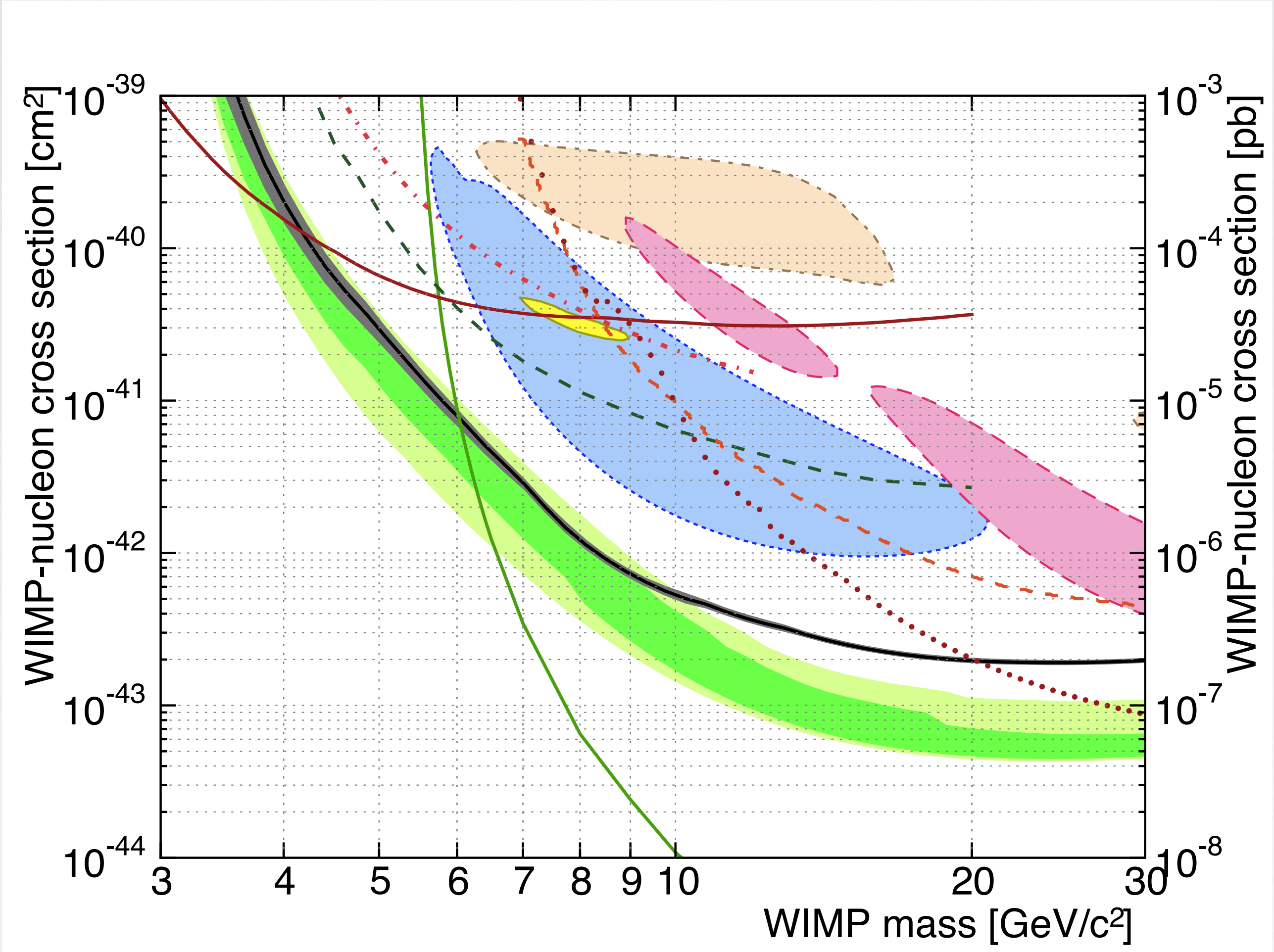
- Beware “anomaly stasis” or “anomaly fatigue”
- An anomaly that is not being updated or tested tends to be neglected for lack of good ideas
- This does not mean it is resolved

DAMA MODULATION

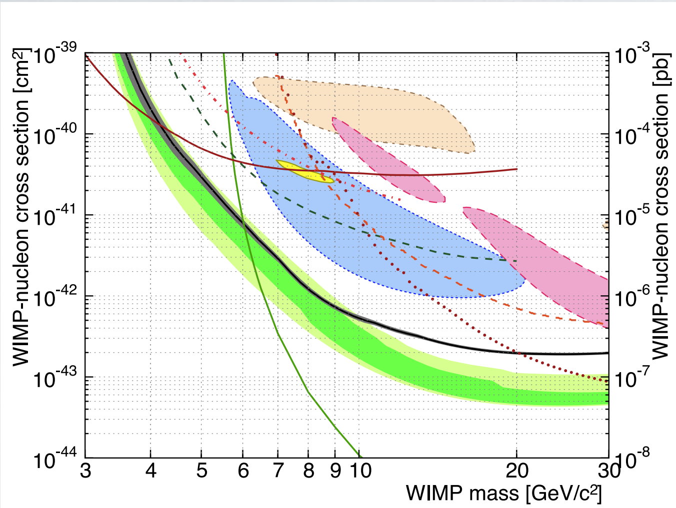


- Still there
- Explanations that I know must appeal to ignorance (e.g., MiDM with unknown magnetic form factors, Fitzpatrick et al general operator analysis w/o models)
- Modulation fraction must be large (>10—20%) [ask Itay]
- Non-WIMP explanations? (E.g., solar sources)

DAMA/LIGHT WIMPS



DAMA/LIGHT WIMPS



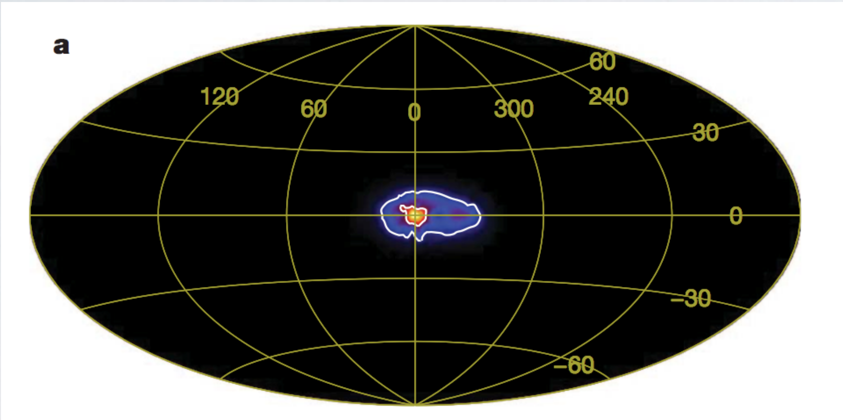
Looks bad

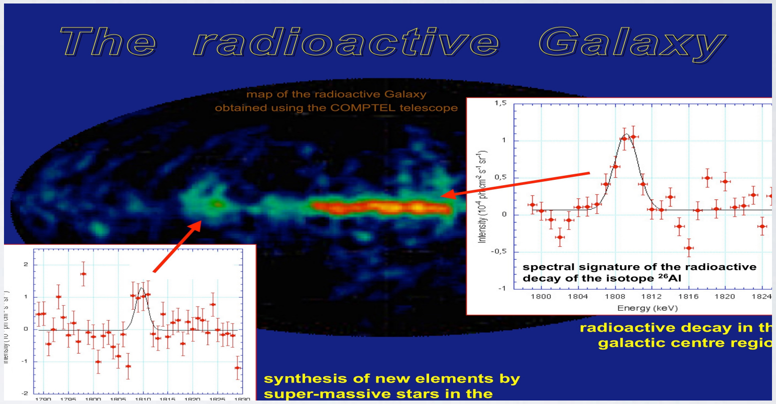
Even Xenonphobic/Germophobic models have trouble now

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 (e.g., Luminous dark matter)

INTEGRAL 511 KEV



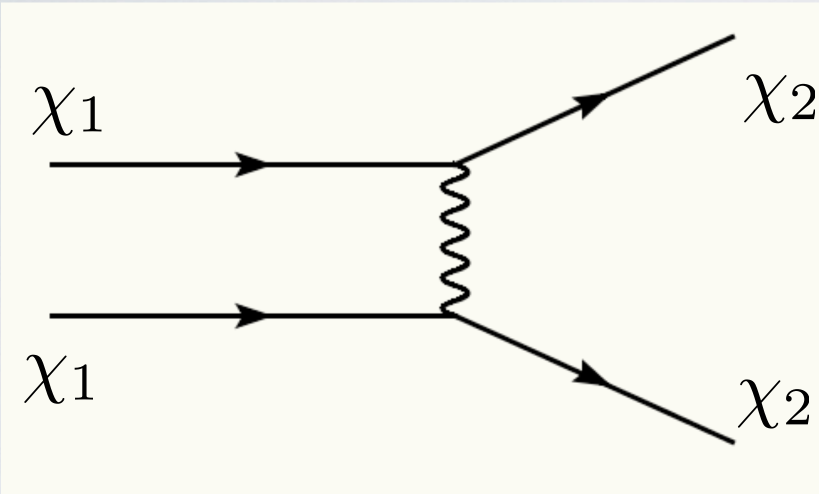


Large rate into e+e- at ~ MeV

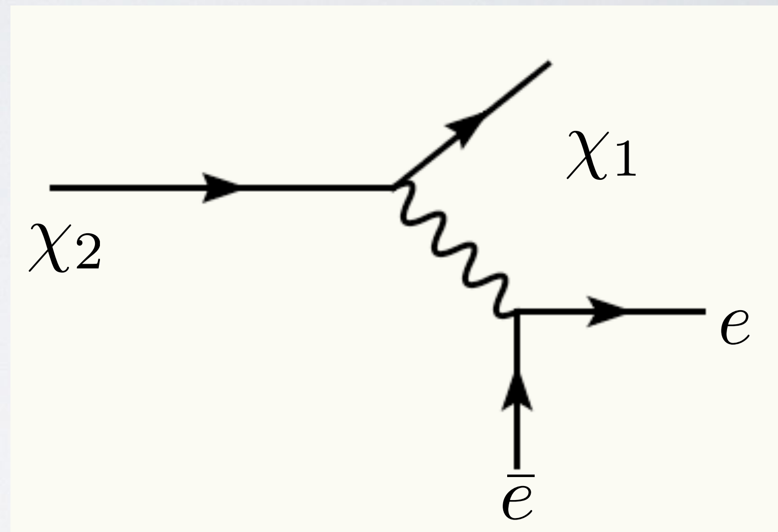
MeV dark matter seems borderline with CMB

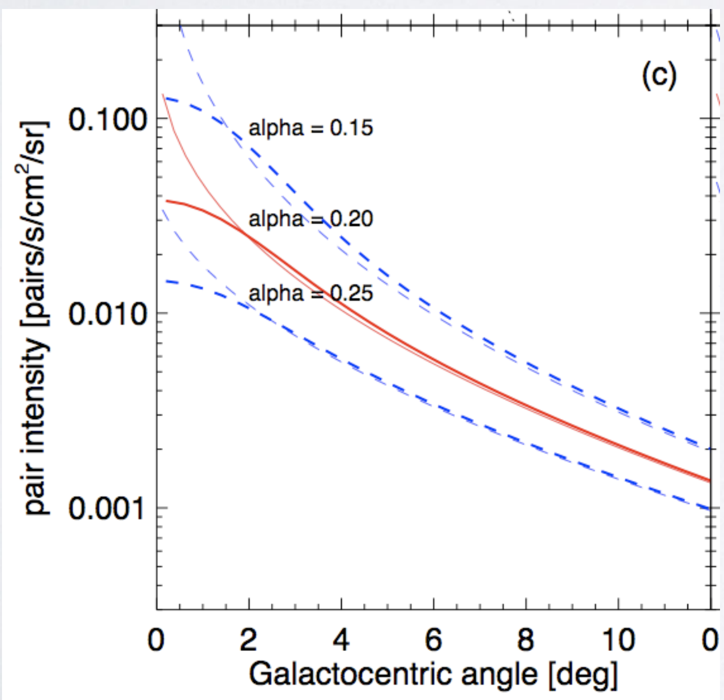
what about WIMPs?

EXCITED STATES AND INTEGRAL



if splittings ~ MeV, subsequent decays should produce e+e- pairs



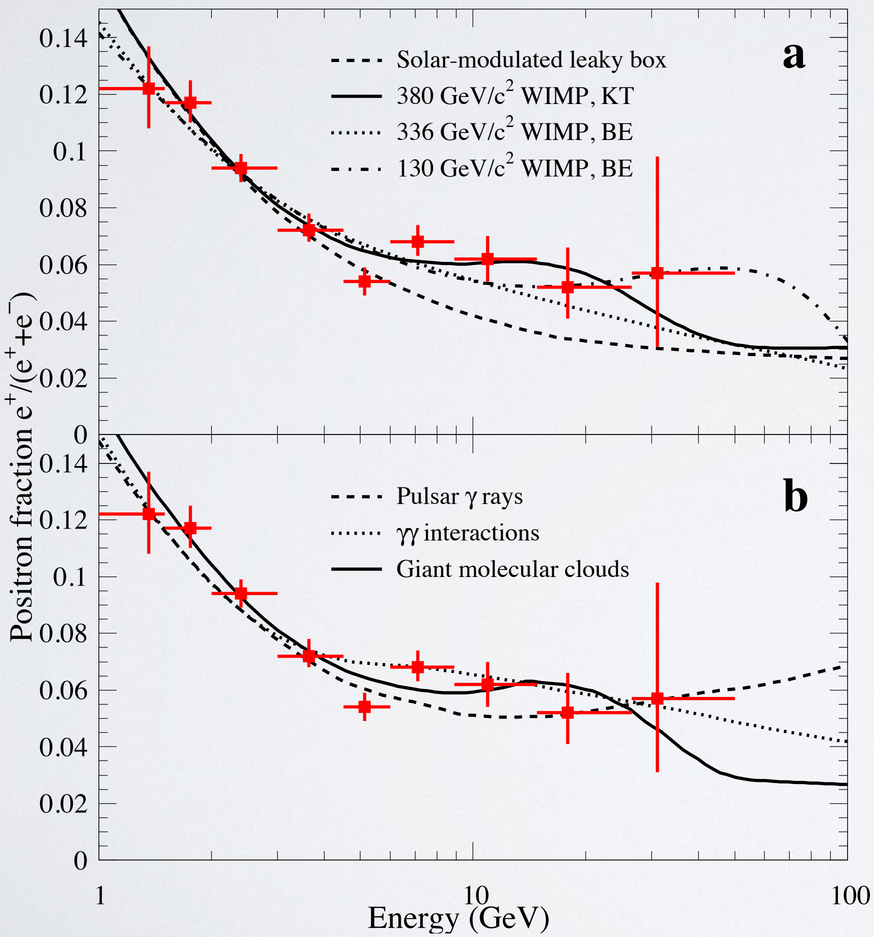


Possible origin for INTEGRAL positron excess - "eXciting DM"

D.Finkbeiner, NW, Phys.Rev.D76:083519,2007

POSITRONS!

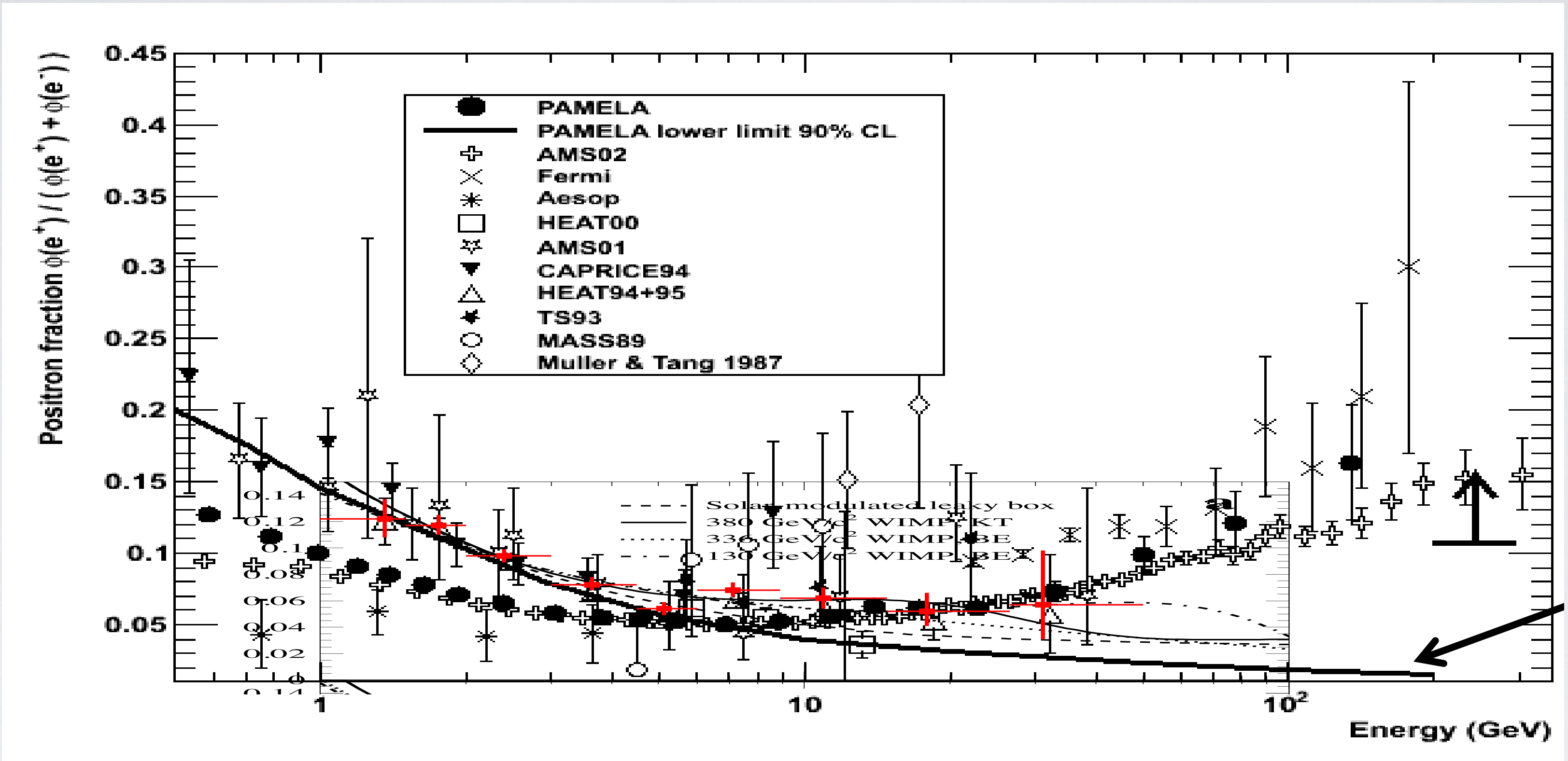
DM annihilation => positrons [antimatter]



Coutu et al, '99

1999 - HEAT results

NOW THAT'S A SIGNAL



PAMELA, Fermi and AMS

It's too great to be dark matter!

If DM:

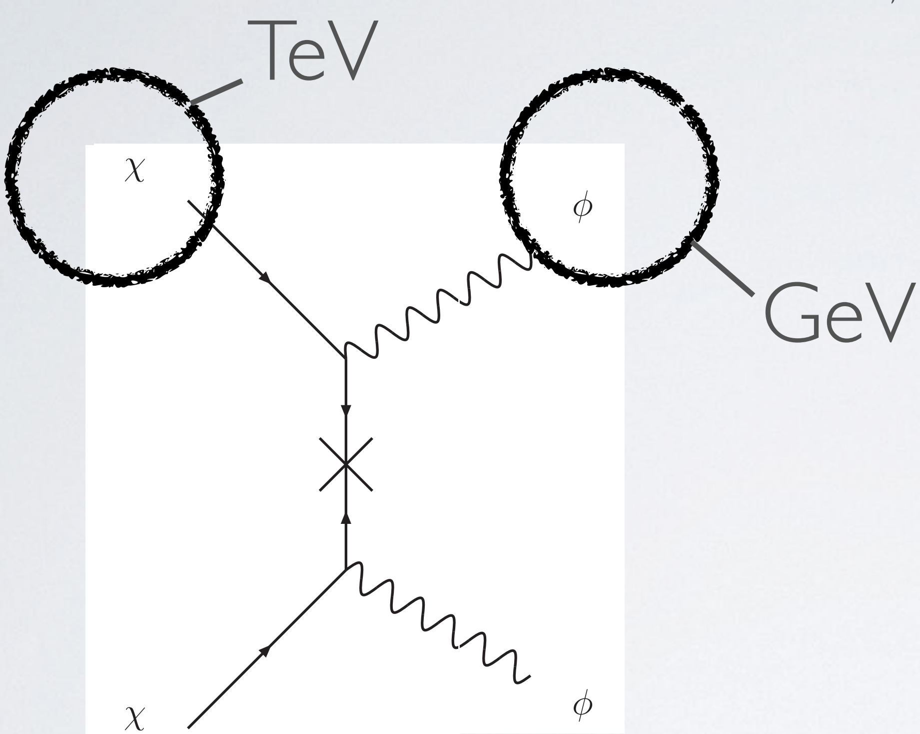
Need rate above expected.

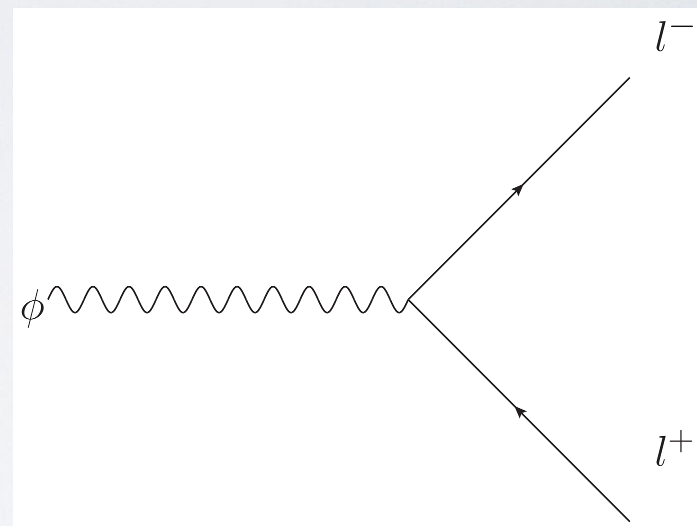
Need harder than expected positron spectrum.

Also: no significant anti-protons

DARK FORCE MODELS

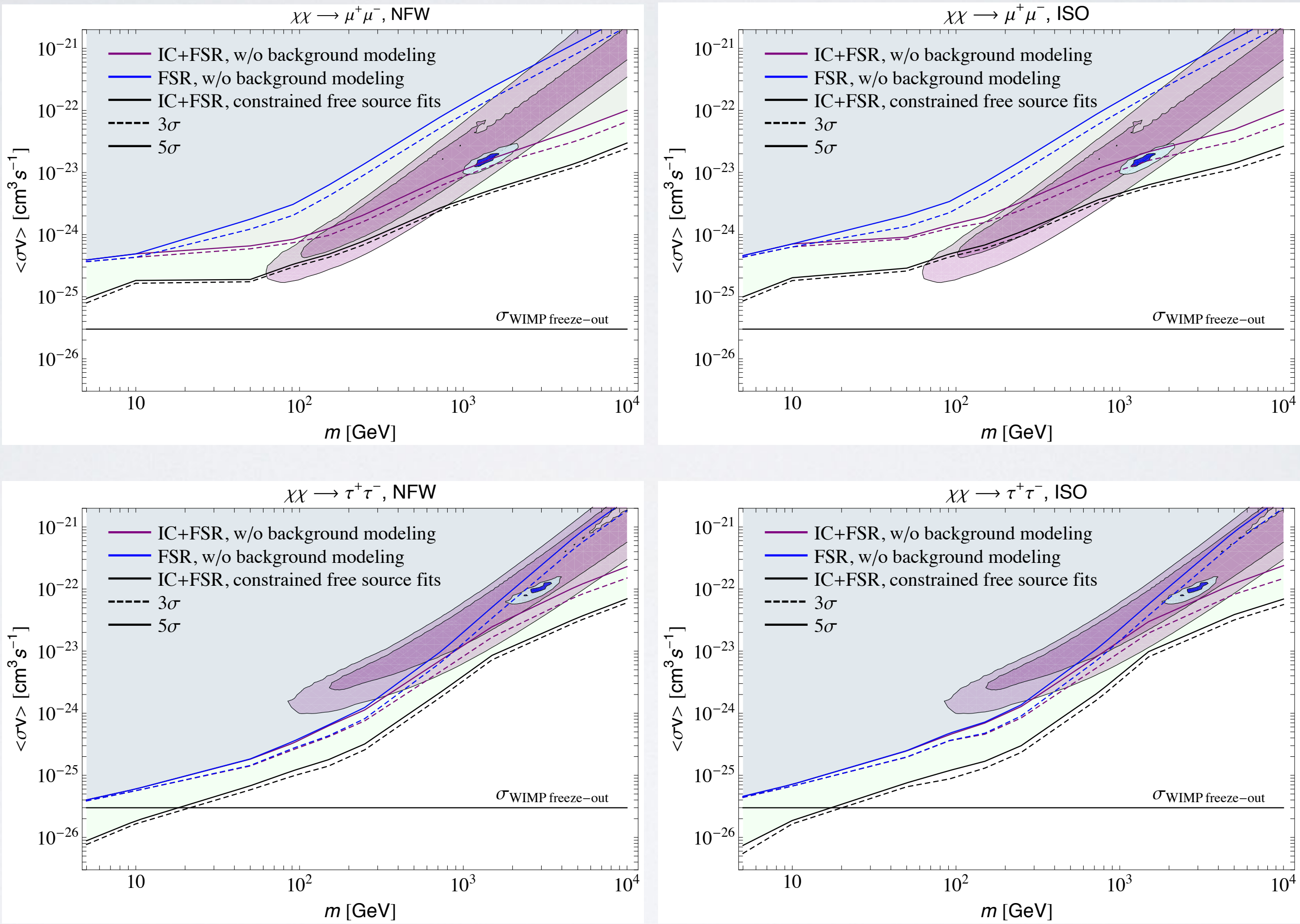
Finkbeiner+NW '07; Pospelov, Ritz, Voloshin '08; Arkani-Hamed, Finkbeiner, Slatyer, NW '09; Pospelov+Ritz '09; Nomura+Thaler '09…





generates hard leptons by annihilations into a light mediator, no anti-protons

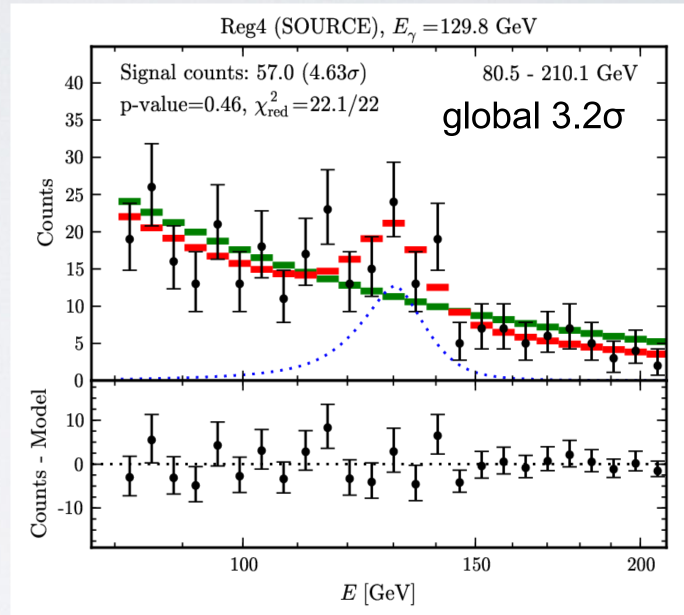
BEWARE: STRAWMAN CONSTRAINTS!



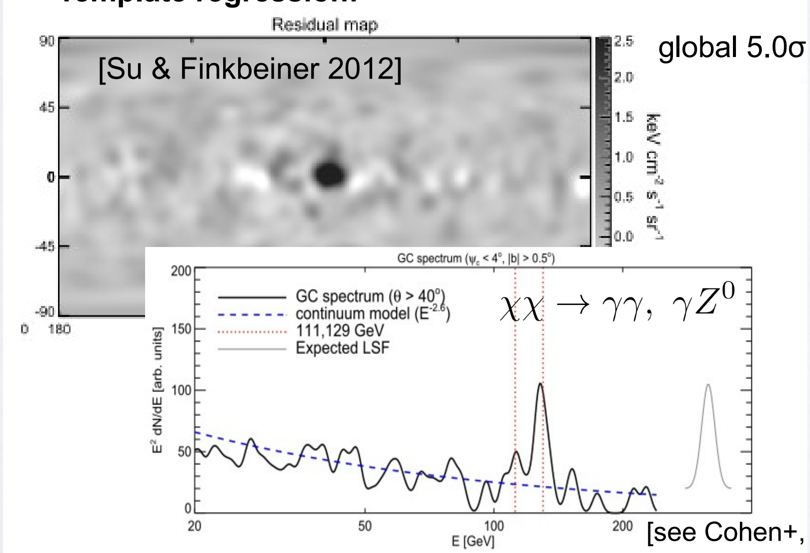
Rare are the constraints on dark photon scenarios…

130 GEV LINE

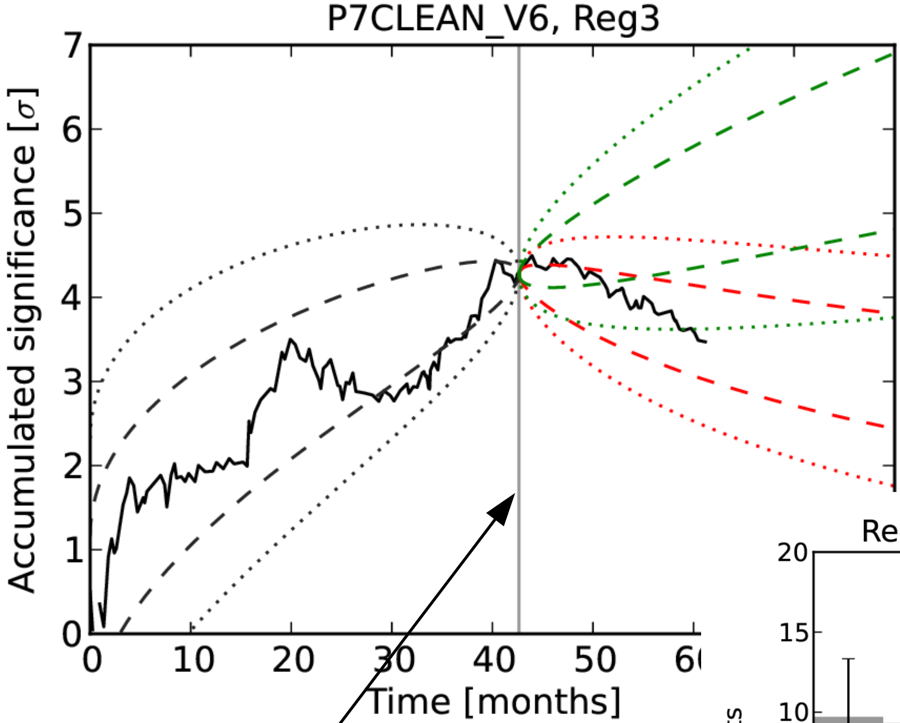
talk by Weniger May '14



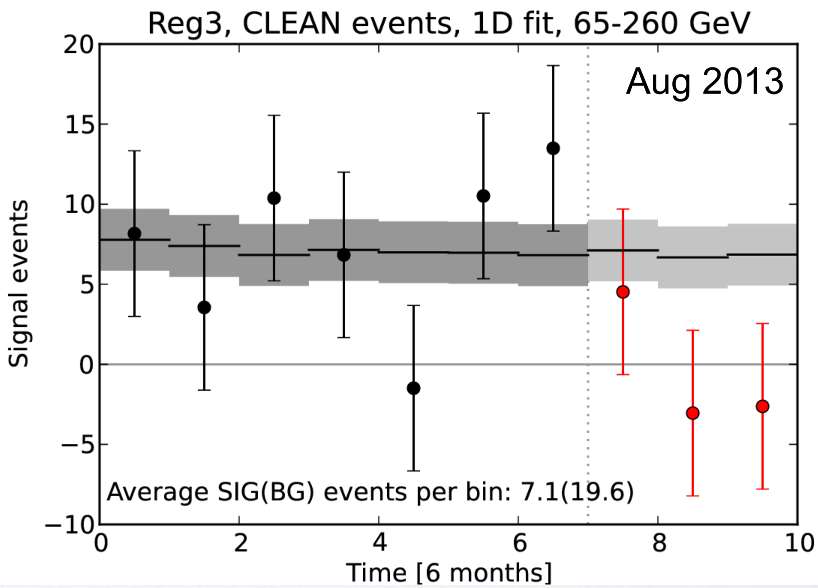
Template regression:



Time-evolution of significance

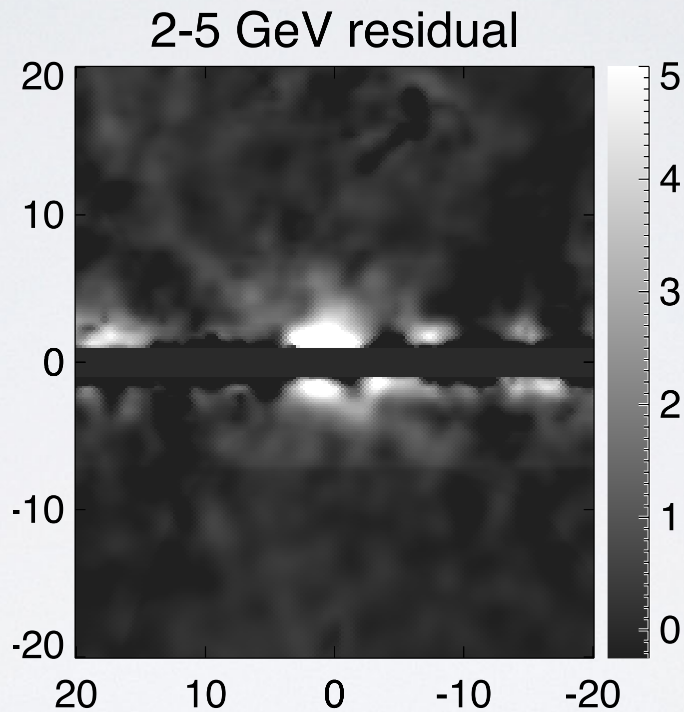


Dashed/dotted lines:
68% and 95% CL containment regions for **true signal** (green) and **statistical fluke** (red).

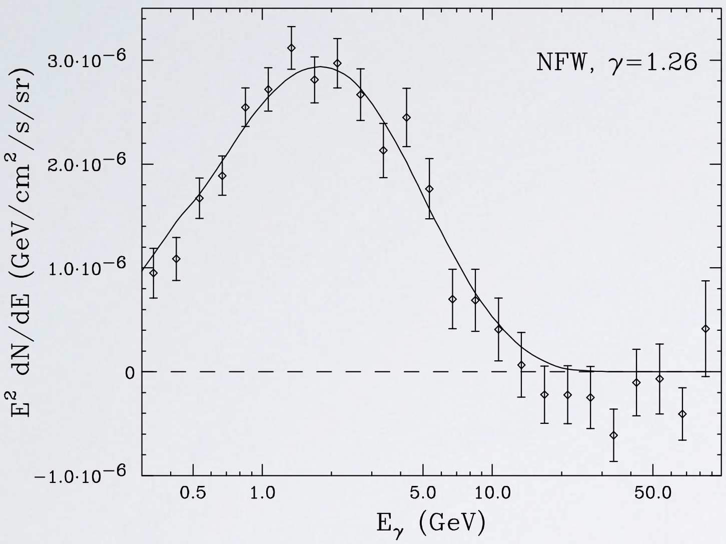


Bringmann+ 2012; CW 2012; Su & Finkbeiner 2012; Tempel+ 2012

A SIGNAL IN THE GC/IG

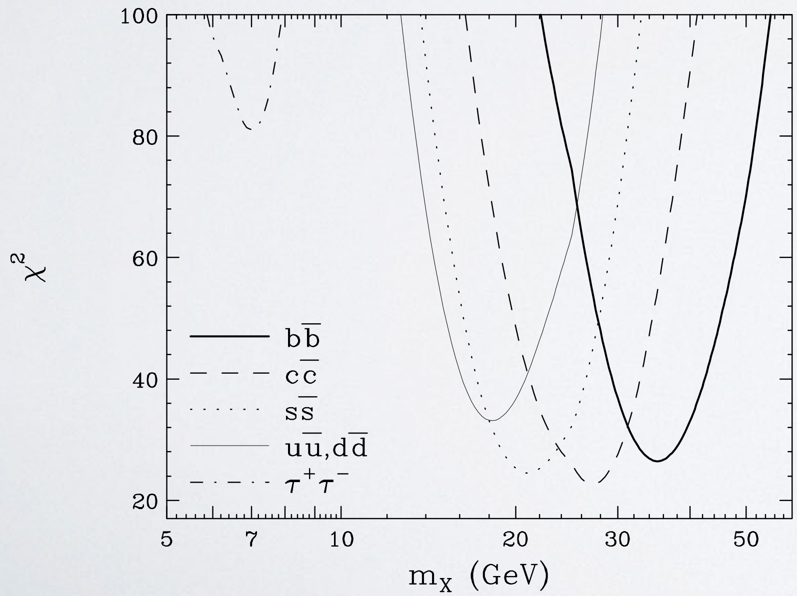


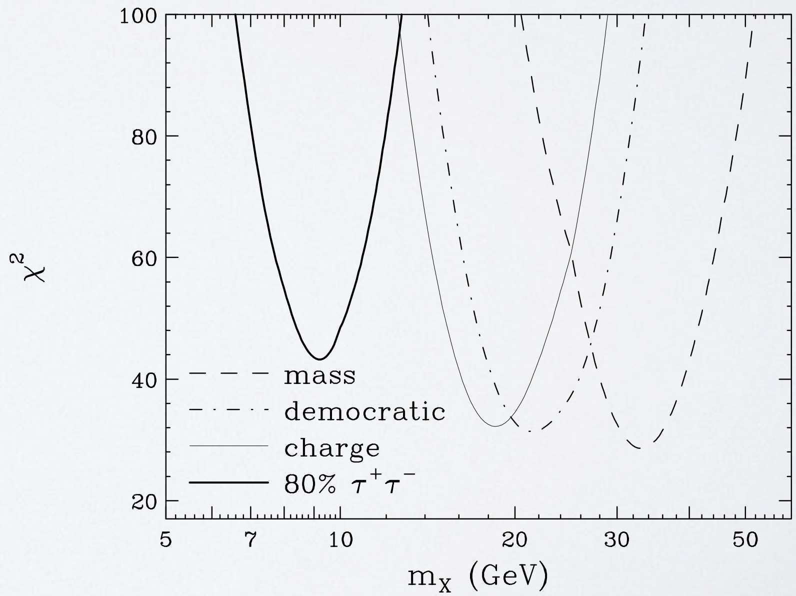
DARK ANNIHILATION TO BB?



not really chi-squared

methinks we are taking our data a little too seriously





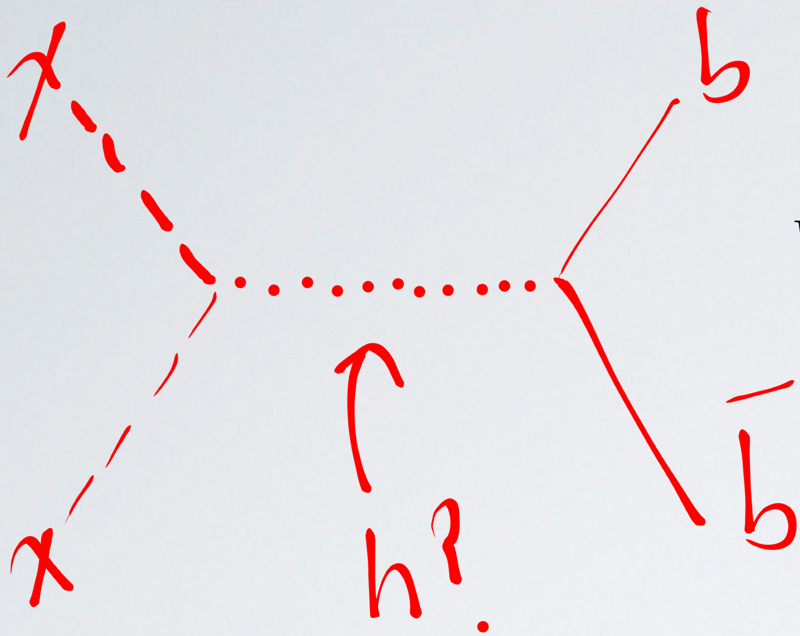
words

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

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

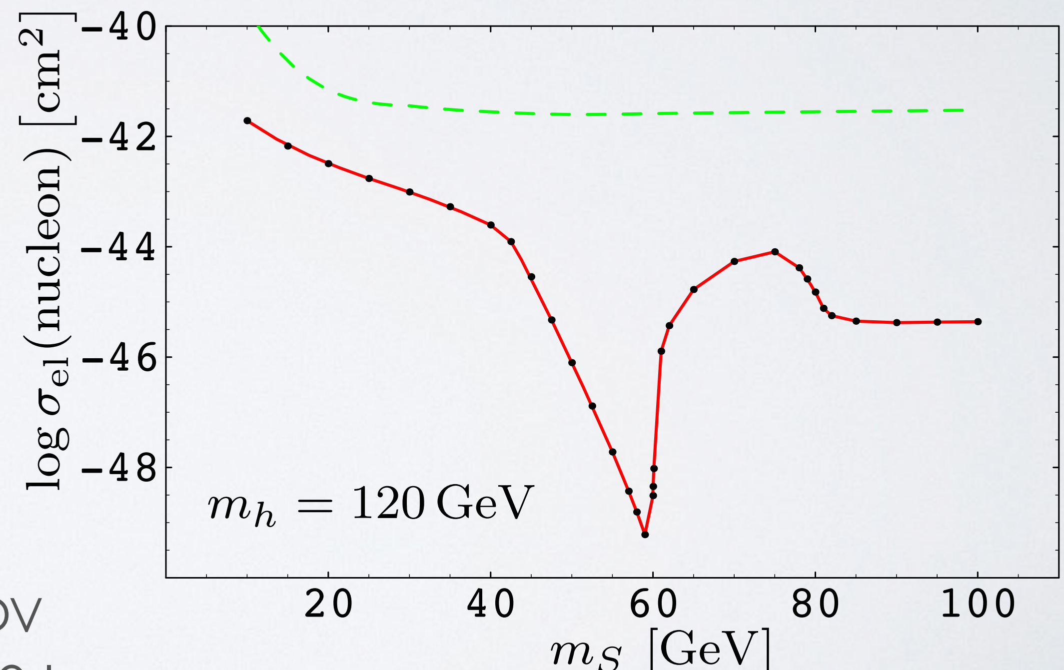
are required. Furthermore, it is not difficult to construct simple models in which a $\sim$30-40 GeV particle annihilates to quarks with the required cross section without violating constraints from direct detection experiments, colliders, or other indirect searches (for work related to particle physics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

not hard to make models ≠ not baroque



$$V = \frac{m_0^2}{2}\,S^2 + \frac{\lambda}{2}\,S^2 h^2 + \frac{\lambda_S}{4}\,S^4 + \frac{\lambda_h}{4}\left(h^2 - v_{EW}^2\right)^2$$

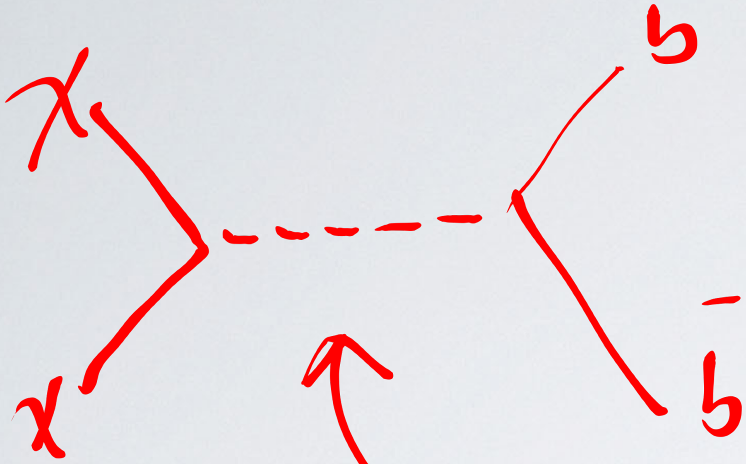
LUX limits ~ 10^{-45}cm^2



Burgess, Pospelov
and ter Veldhuis ‘01

annihilon

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



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

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

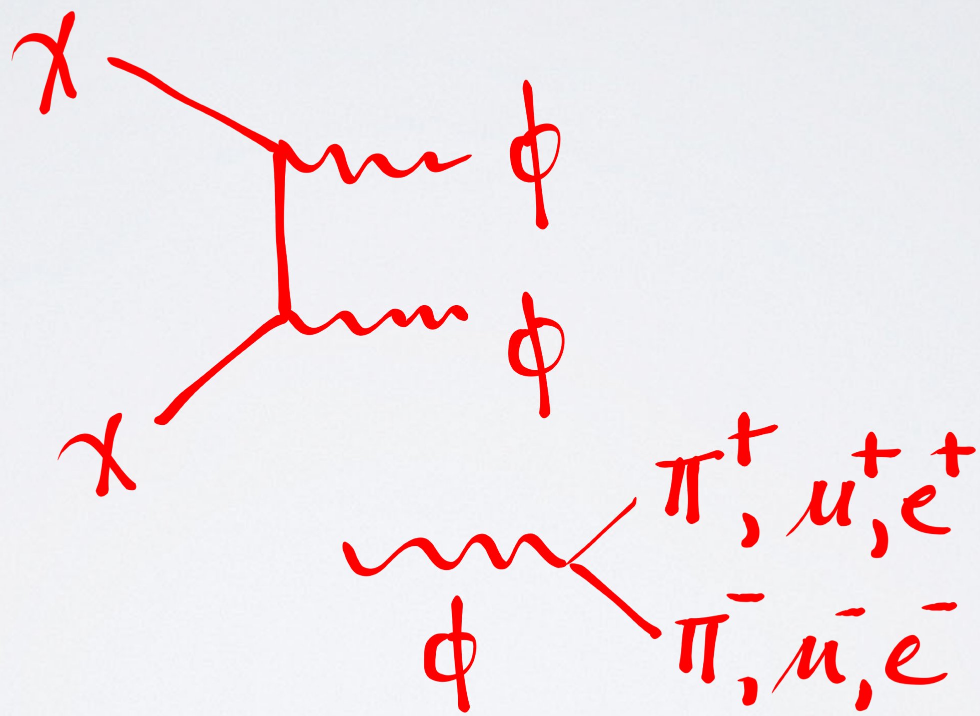
pseudoscalar

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

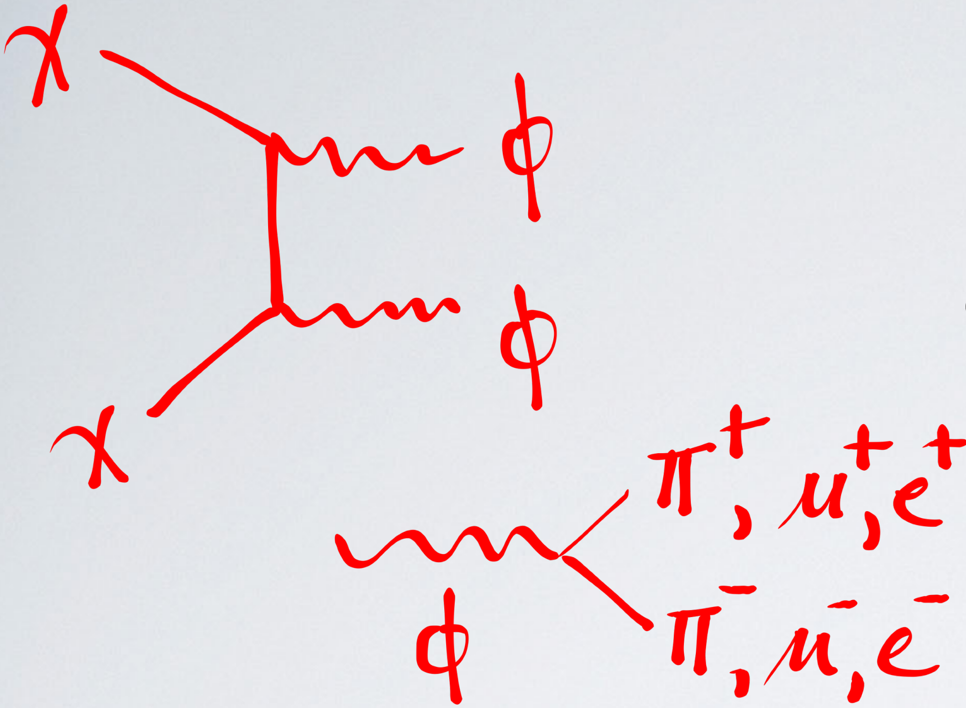
Ipek, McKeen, Nelson '14

+ harder hierarchy problem + no sannihilon (scalar annihilon)

GC SIGNALS OF XDM MODELS

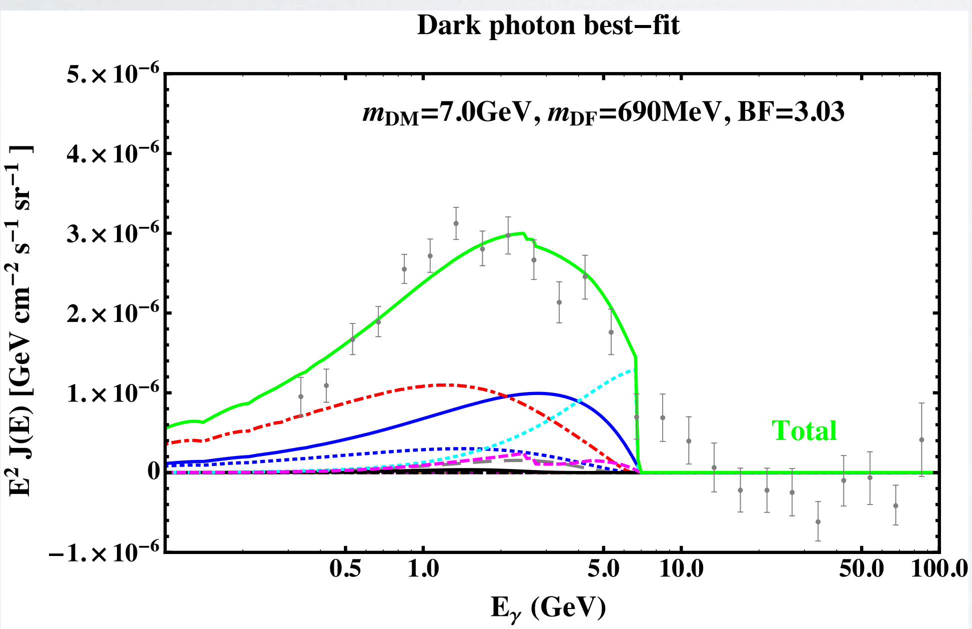


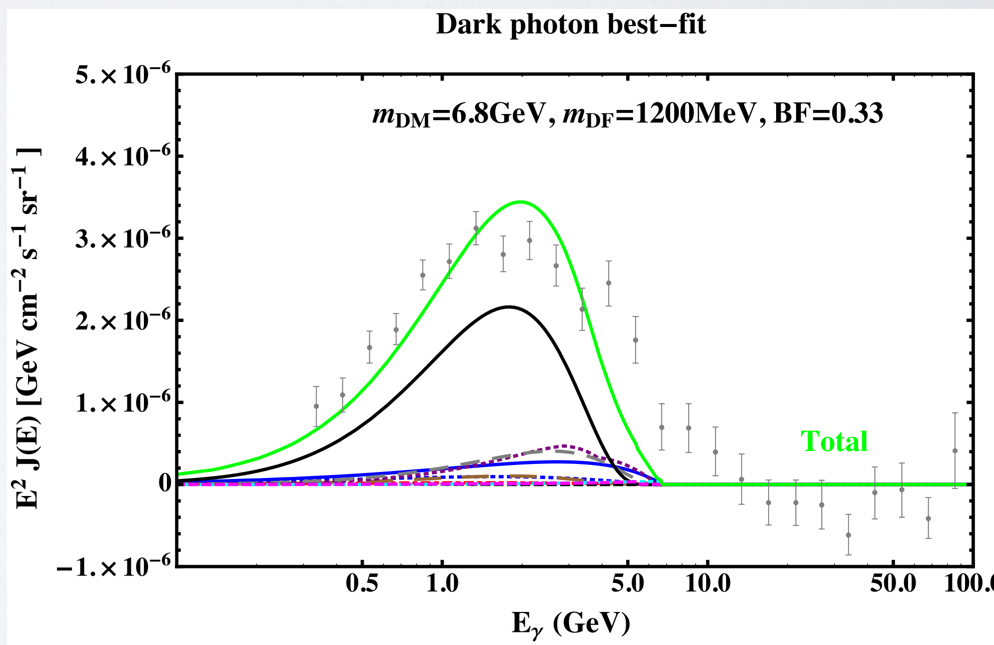
Liu, NW, Xue in prep



Easy to write down

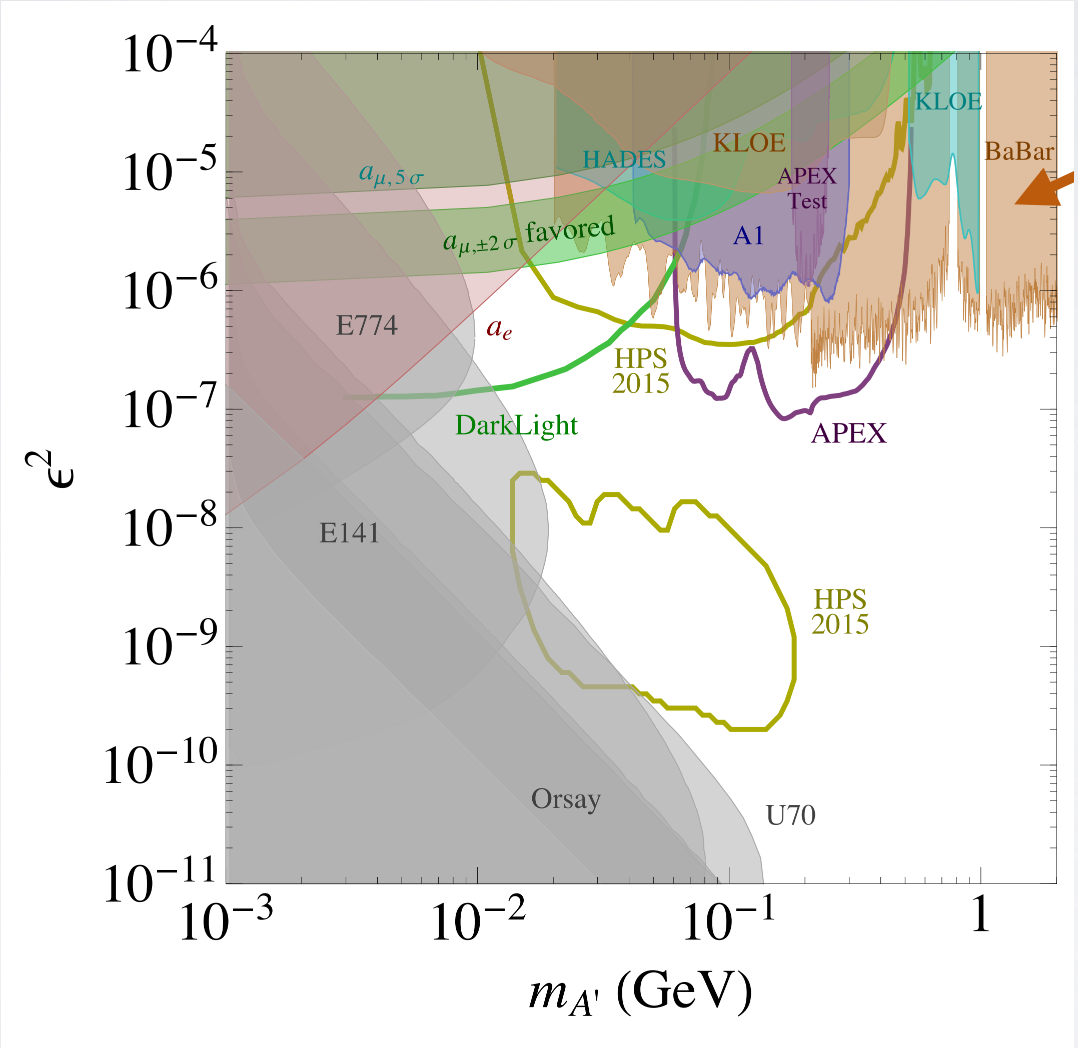
determination of baroquocity left to the reader





Liu, NW, Xue in prep

SEARCHES FOR DARK PHOTONS



interesting to $\epsilon\sim10^{-8}$

just at the start

talk by Rouven Essig

THE GC

- Signal => wait and see
- Models: bbar seems not as simple as it sounds
- 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

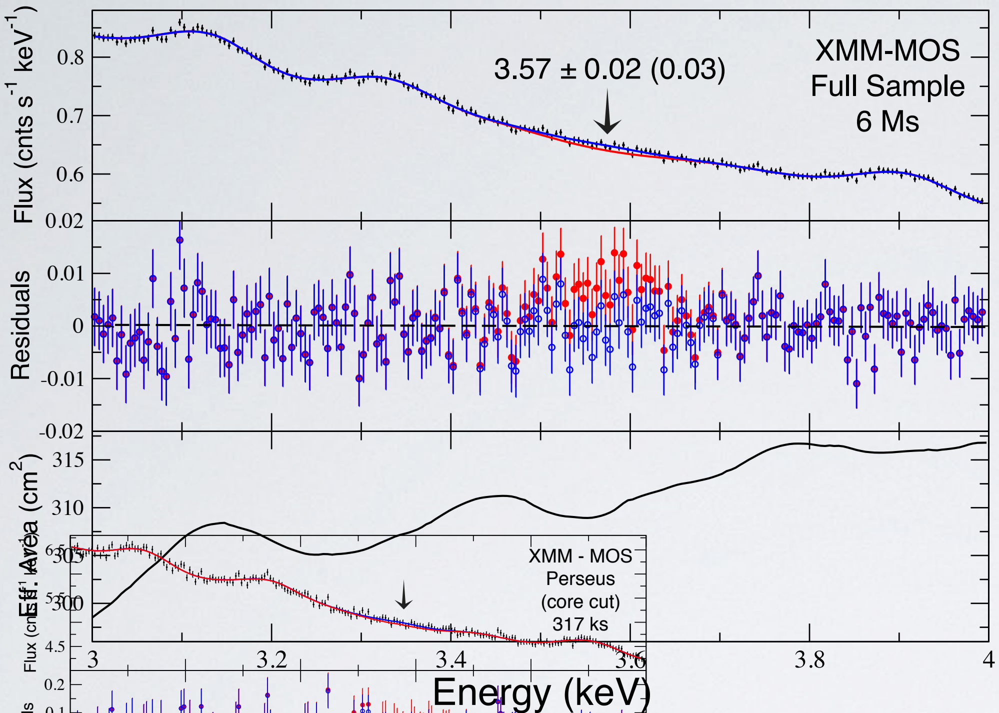
Perseus Chandra, central

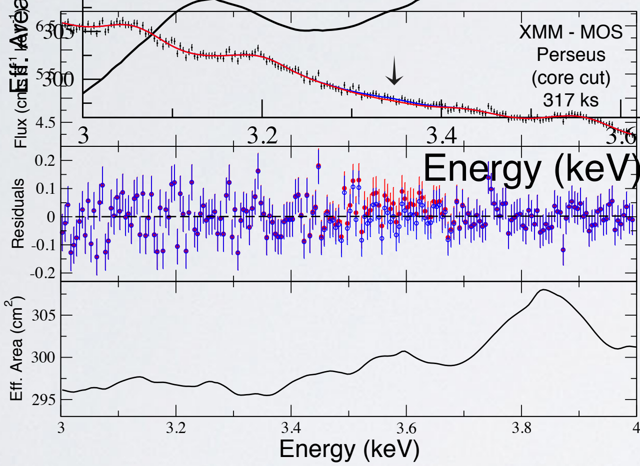
Virgo Chandra, central (not seen)

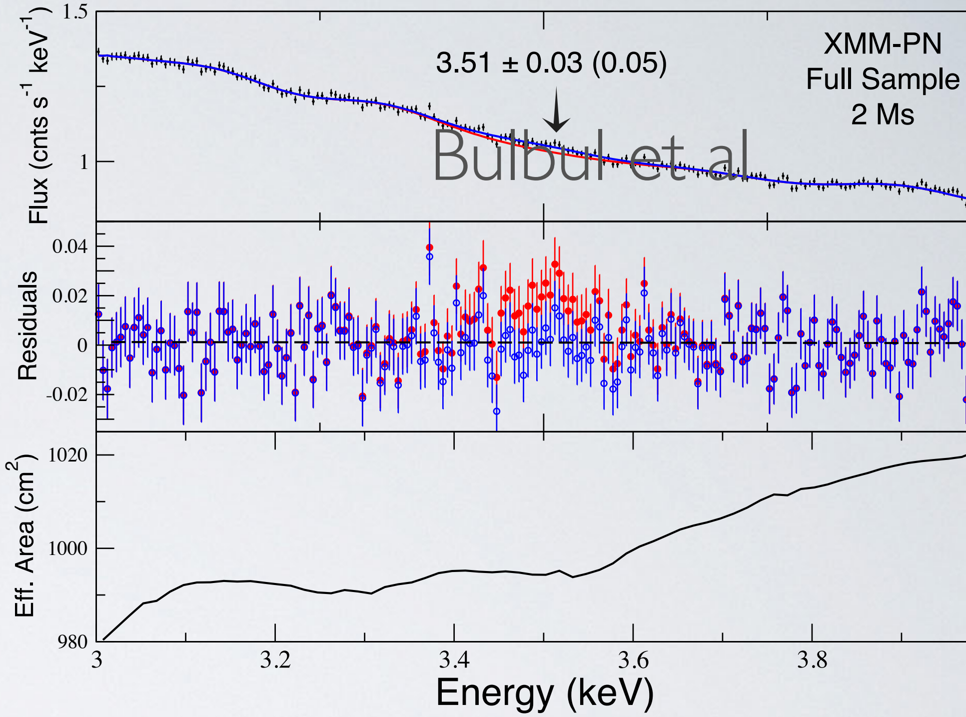
Boyarsky et al

M31 XMM
central+non-central

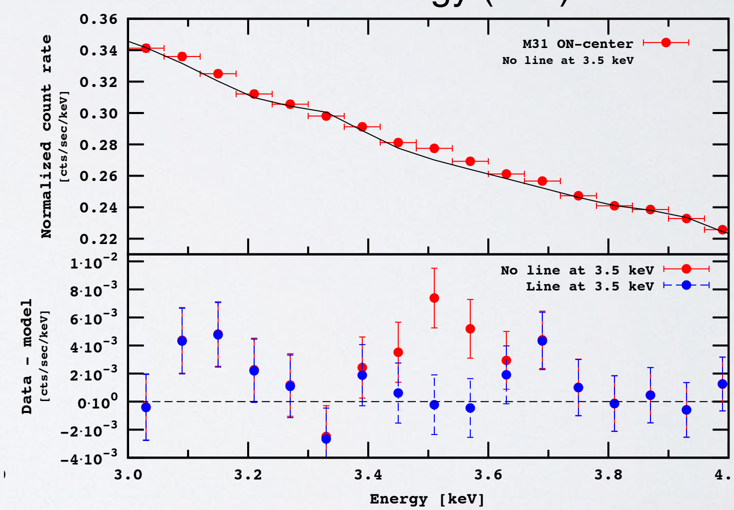
Perseus XMM, non-central







Bulbul et al



Boyarsky et al

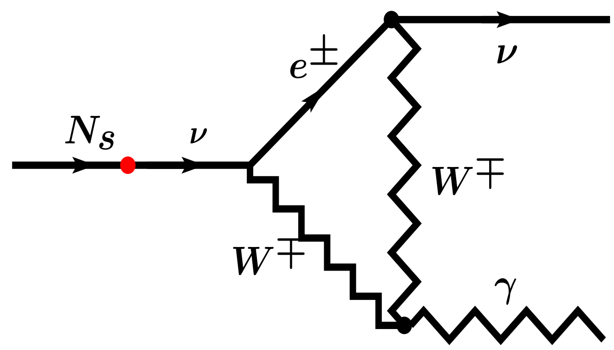
Passes the Toro test…

BUT WHAT IS IT?

assuming it's BSM physics, that is

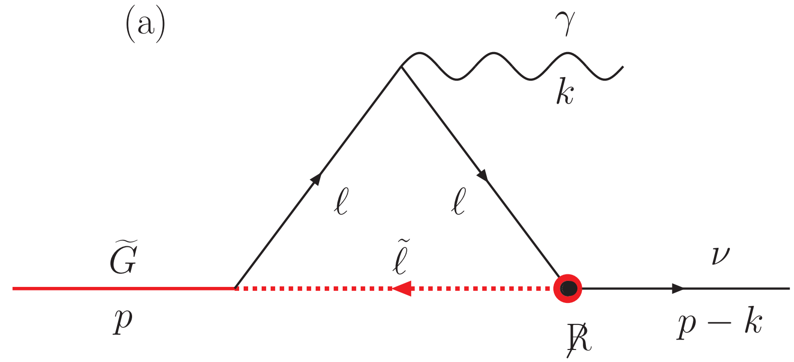
DECAYING DARK MATTER

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



(a)

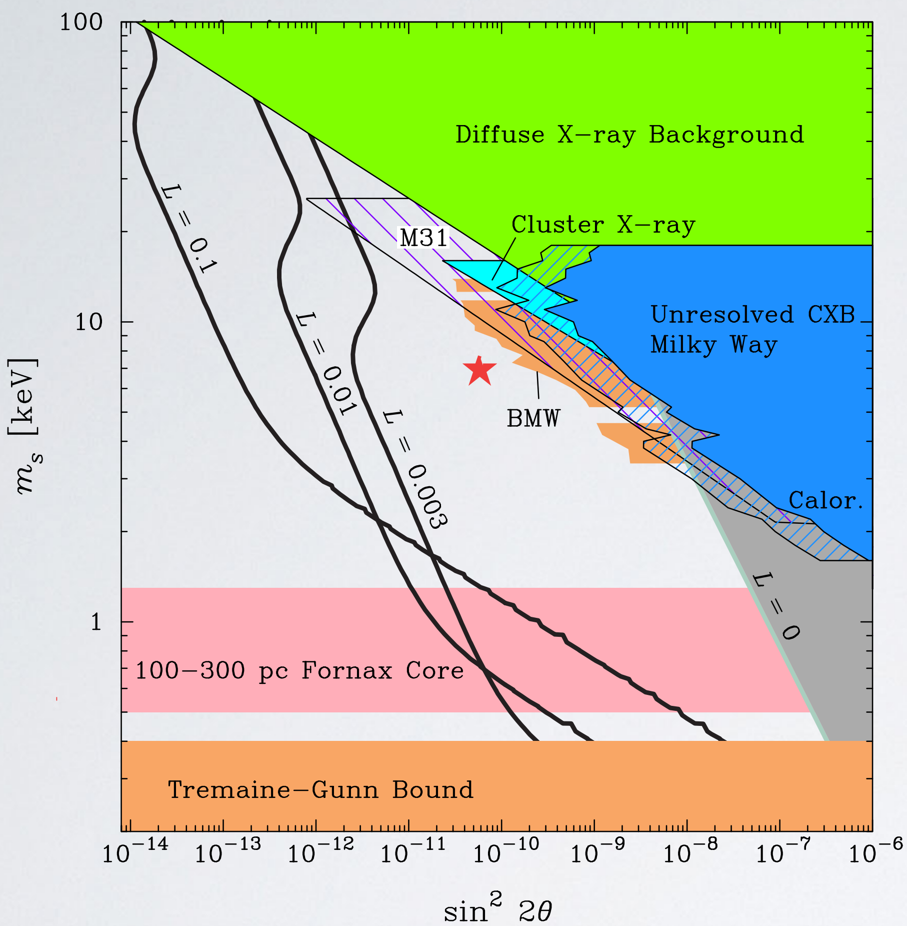
- R-parity violating gravitino
$\tilde{g} \to \nu + \gamma$



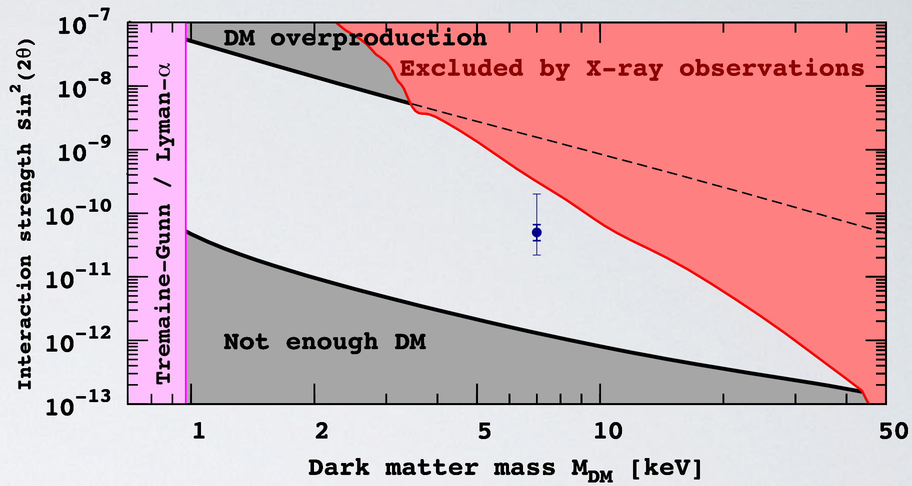
- Also R-parity violating axino, . . .

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

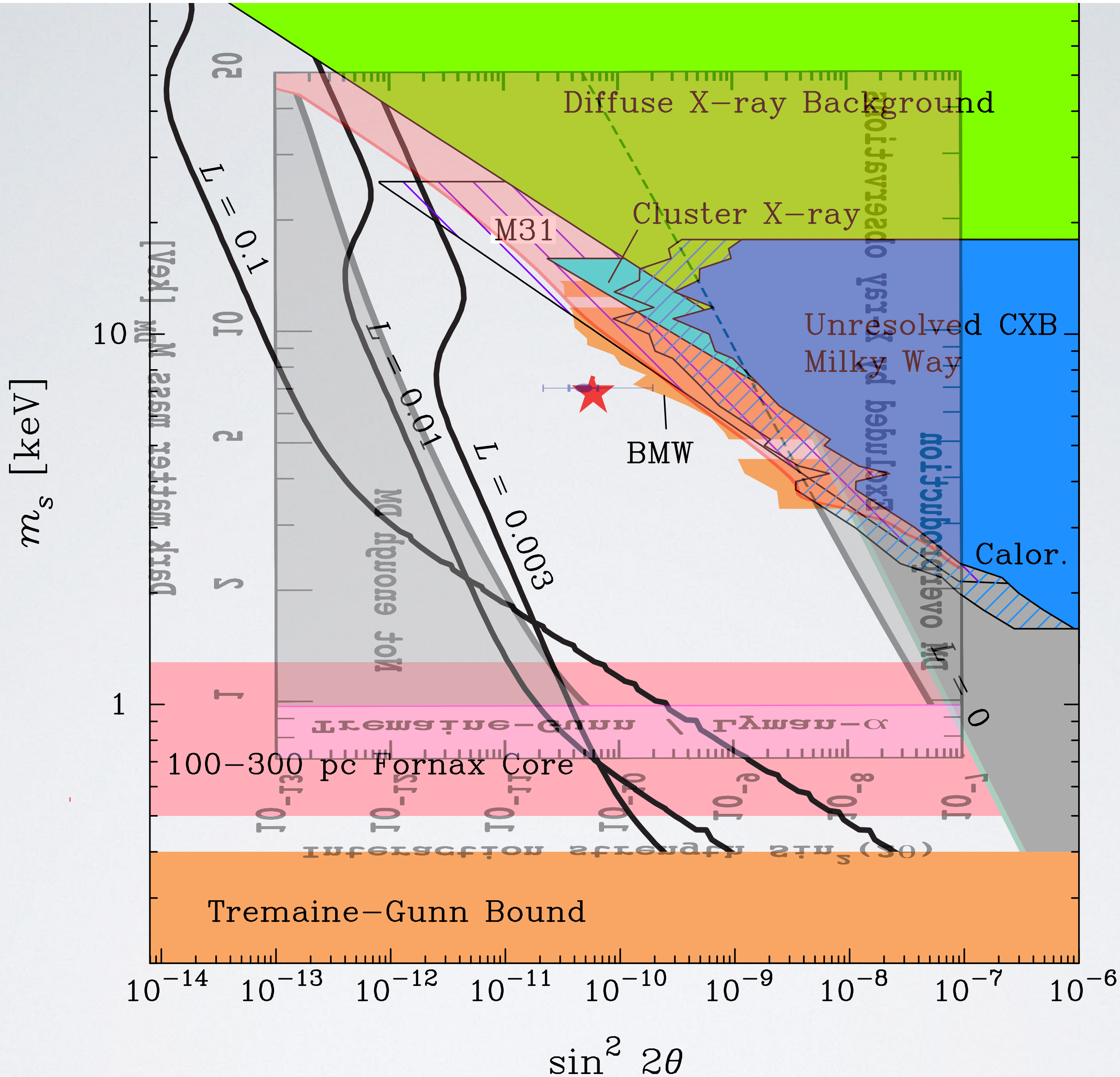
shamelessly stolen from talk by Ruchayskiy, April 2014



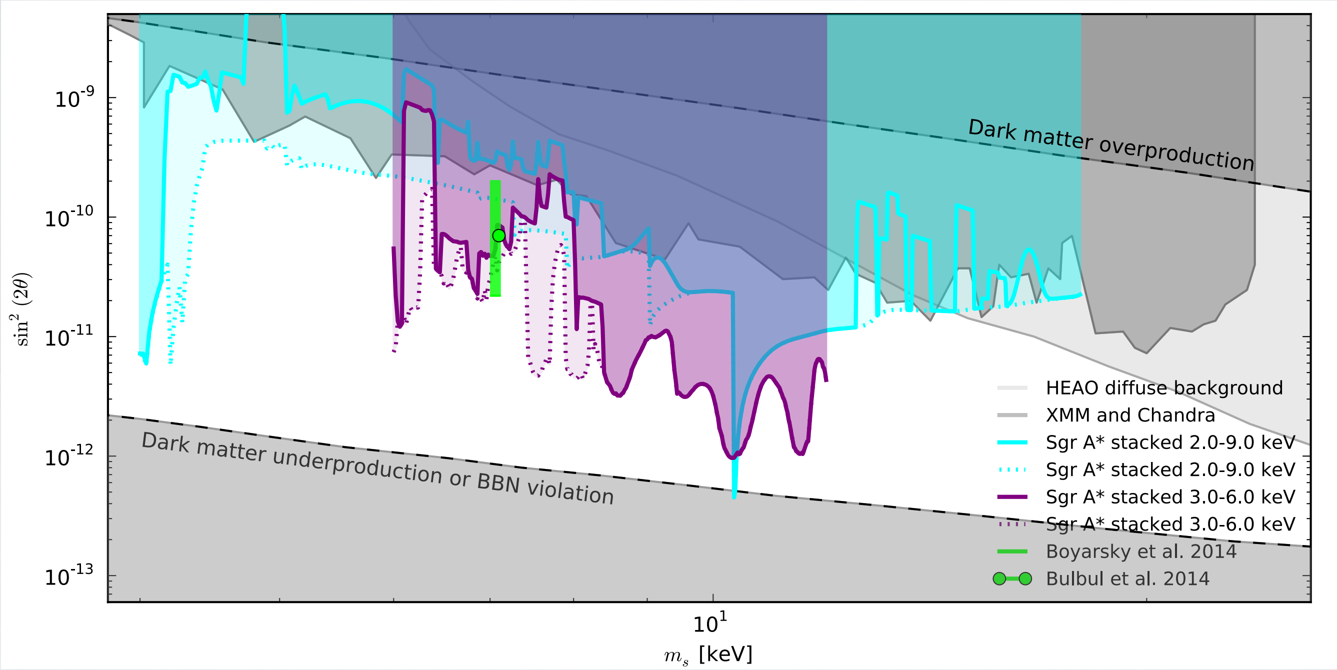
Diffuse X−ray Background
Cluster X−ray
M31
Unresolved CXB
Milky Way
BMW
Calor.
L = 0.1
L = 0.01
L = 0.003
L = 0
100−300 pc Fornax Core
Tremaine−Gunn Bound
m_s [keV]
$\sin^2 2\theta$

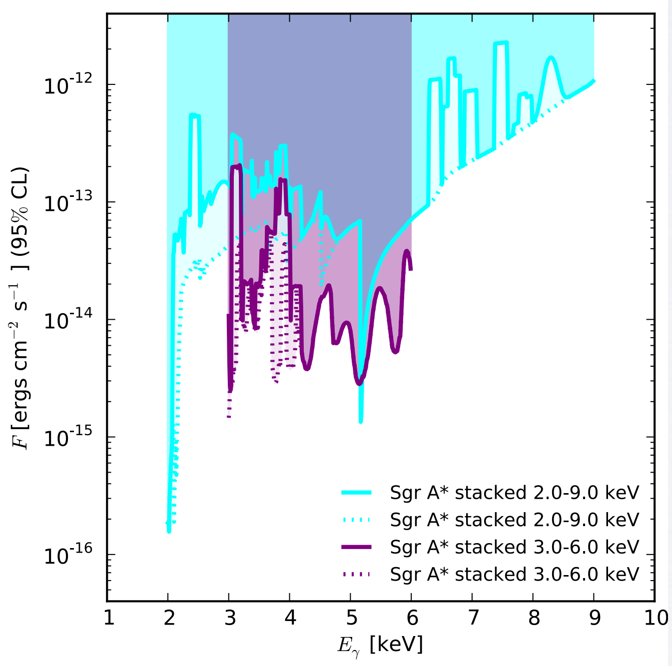


DM overproduction
Excluded by X-ray observations
Not enough DM
Tremaine-Gunn / Lyman-α
Interaction strength $\sin^2(2\theta)$
Dark matter mass M_{DM} [keV]



the model we should compare all models to is the sterile neutrino…
(cf Davoudiasl et al hep-ph/0405097)





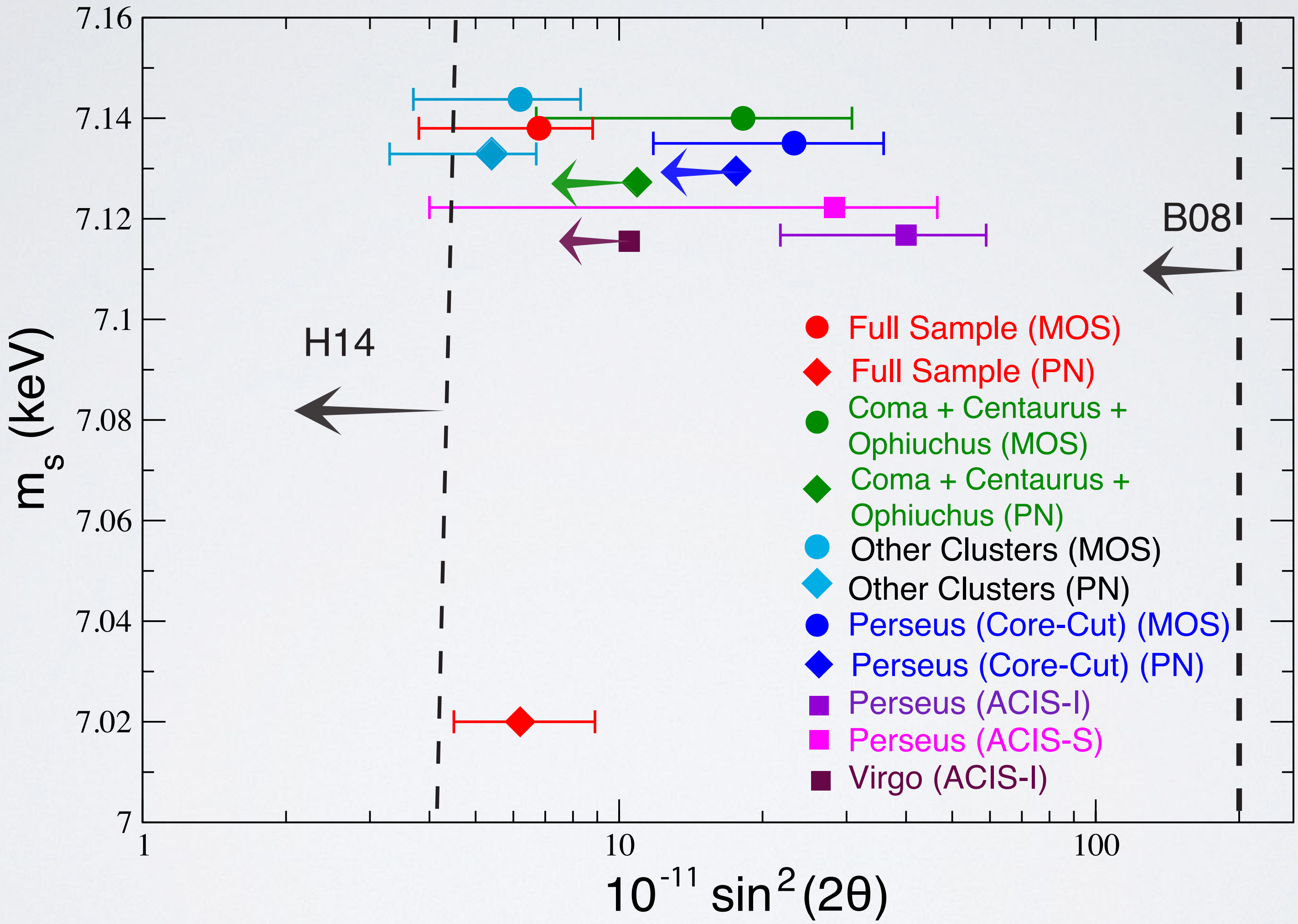
Looking in the MW center

S. Riemer-Sørensen

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)
- ?

VIRGO VS PERSEUS



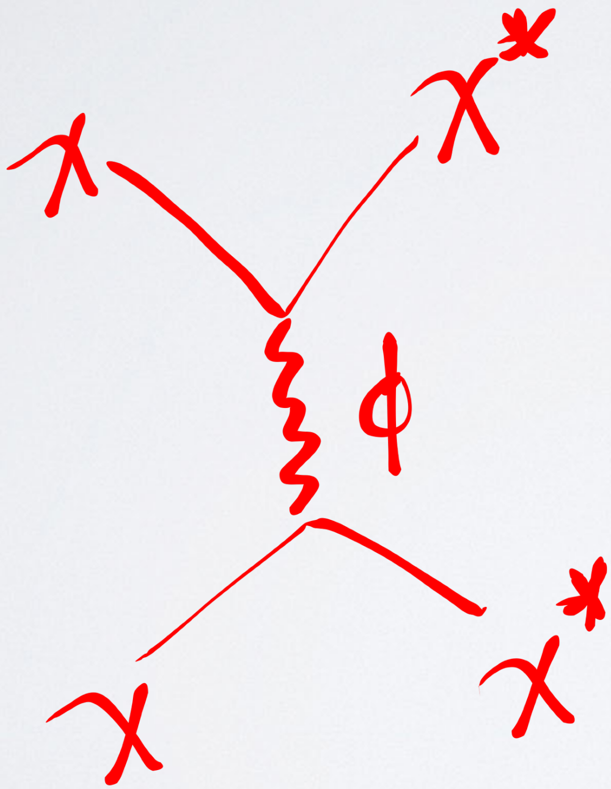
VIRGO VS PERSEUS

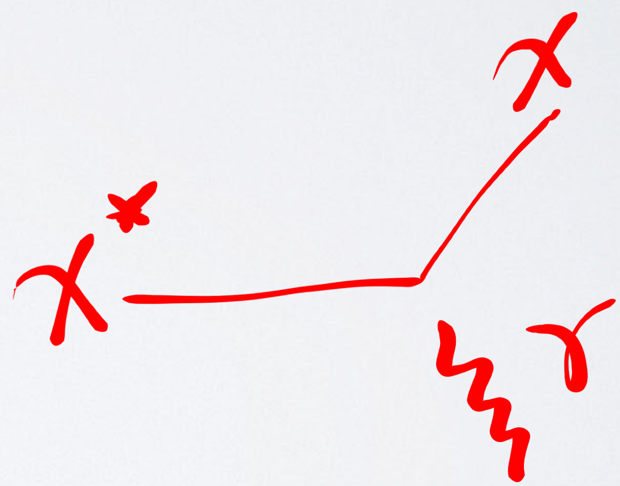
$m_{virgo} \sim$ few $10^{14}\ M_\odot$ $m_{perseus} \sim$ few $10^{14}\ M_\odot$

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

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

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

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

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

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

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

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

THE SIGNAL

$$\frac{1}{M}\chi^{*}\sigma^{\mu\nu}\chi F_{\mu\nu}$$

$$\tau = 10^{-2}\,\text{sec} \times \left(\frac{M_{\text{slip}}}{\text{TeV}}\right)^{2} \times \left(\frac{3.5\ \text{KeV}}{\delta}\right)^{3}$$

Signal could look like $\boldsymbol{\rho}^2$, could look like $\boldsymbol{\rho}$

END ANOMALIES

NEXT: COMMENTS ON COLLIDERS

KNOW YOUR LSP

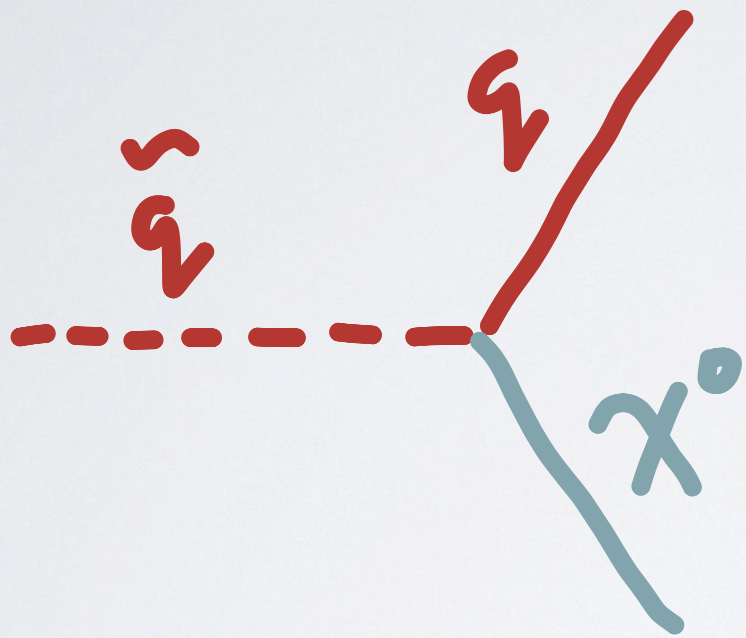
or

How the details of your dark matter can effect your limits

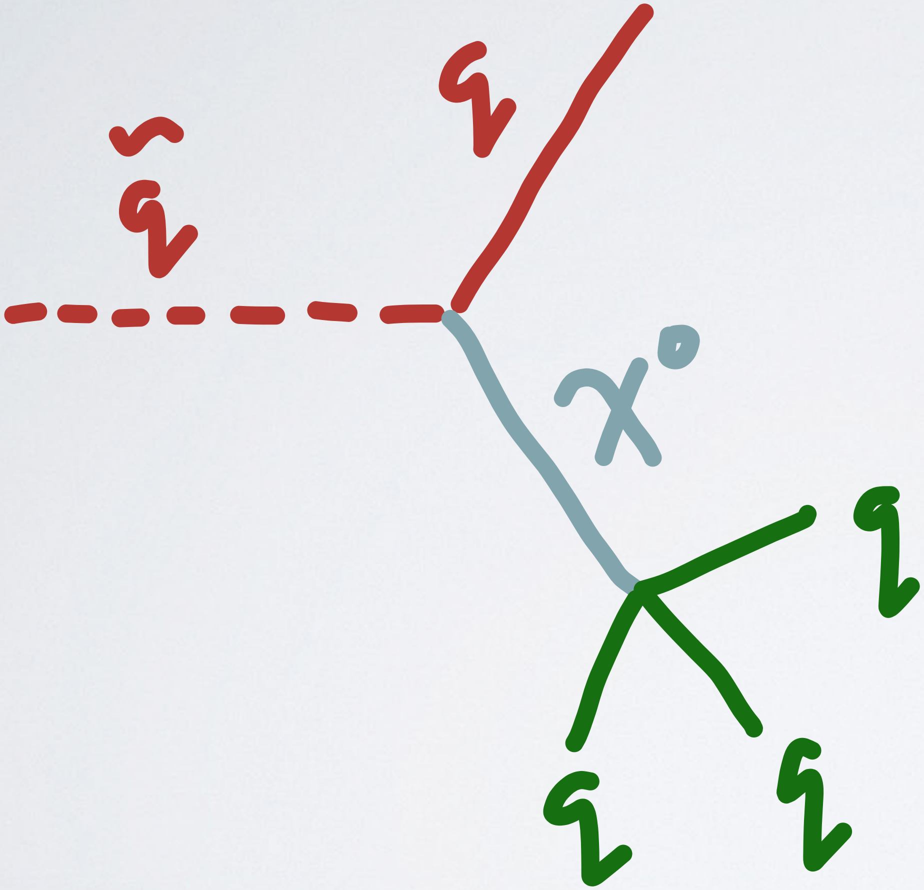
WHAT IS THE THING TO BE LOOKING FOR?

Jets + MET

HIDING SUSY



HIDING SUSY: RPV



Pro: Hides SUSY!

Con: Maybe not (multijets)

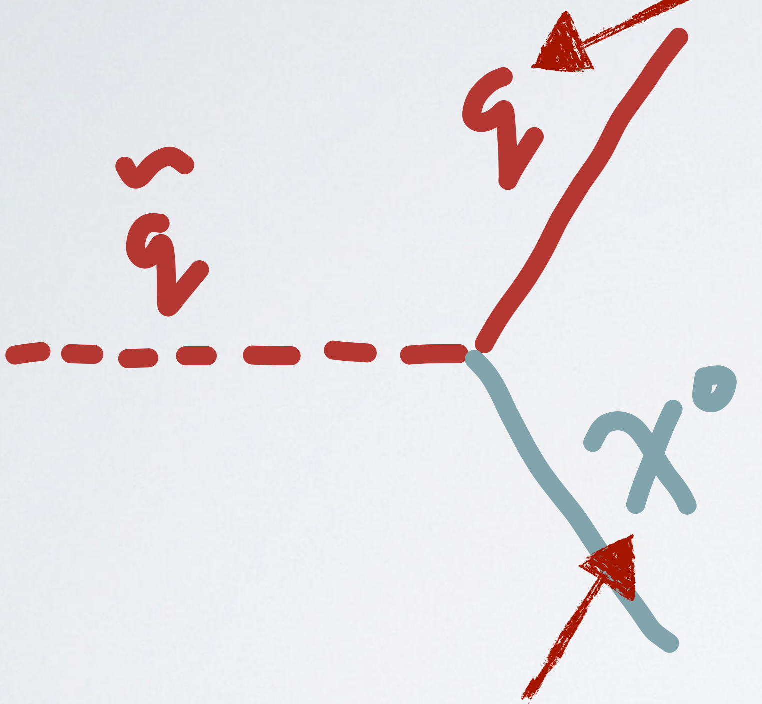
Flavor constraints

Baryon # violation

Dark Matter

HIDING SUSY: SQUEEZING

wimpy

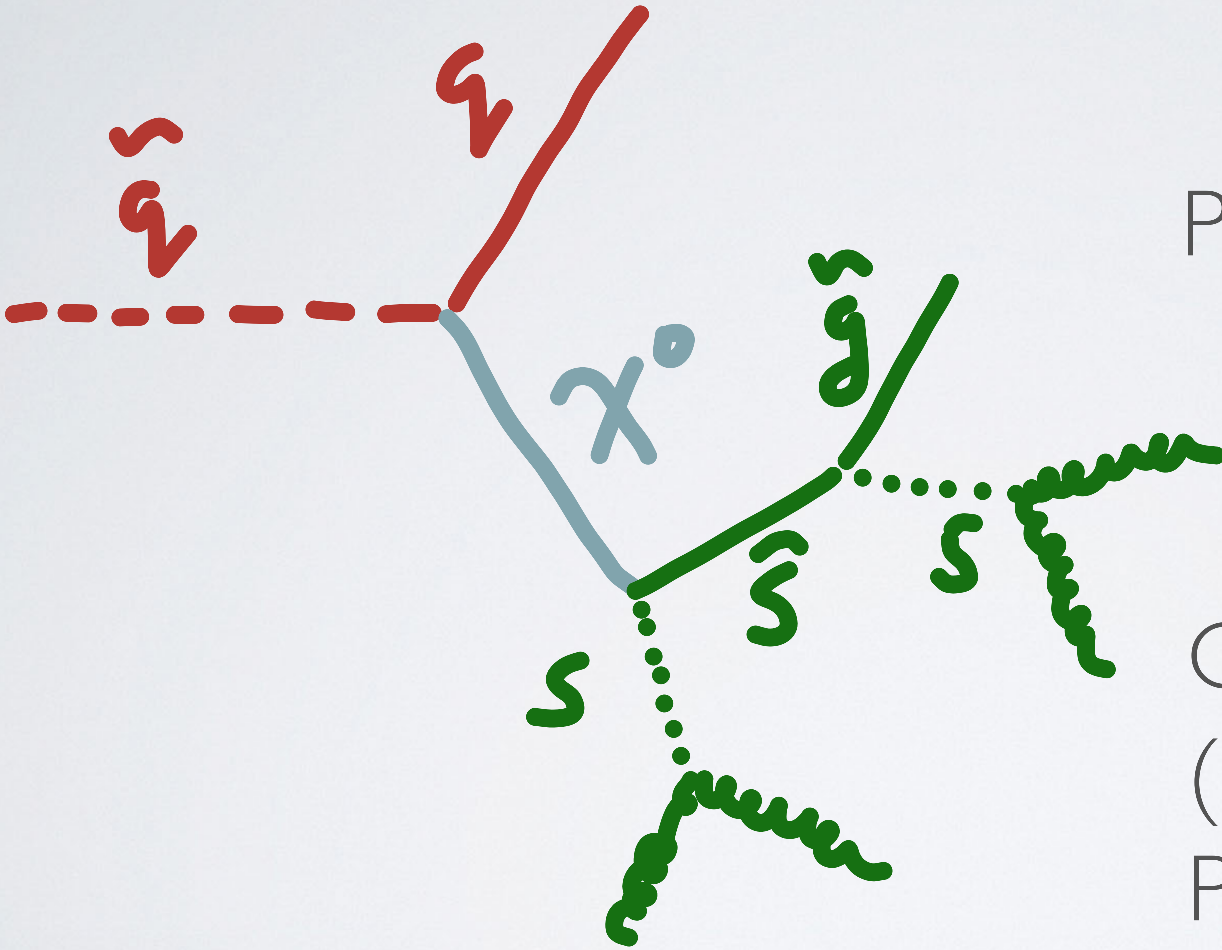


WIMP

Pro: Hides SUSY!

Con: Really just 1 particle can be pretty tuned

HIDING SUSY: STEALTH



Pro: Hides SUSY!

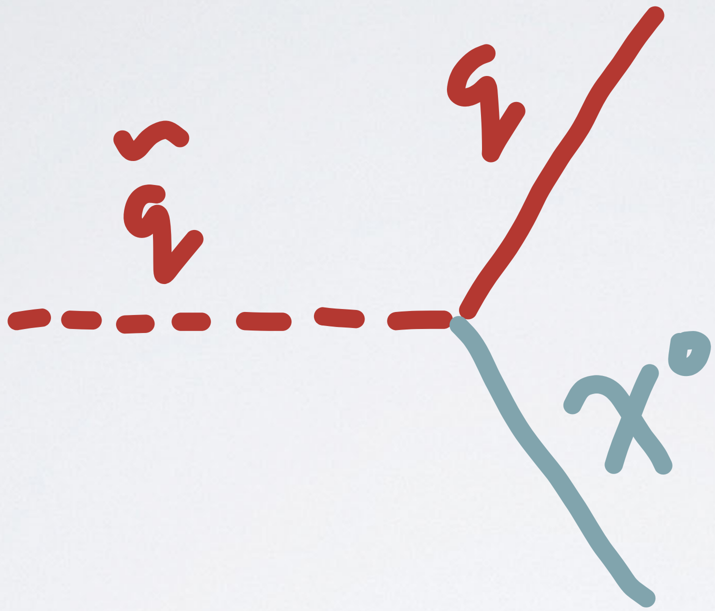
Con: Maybe not
(specific searches)
Particular model setup

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



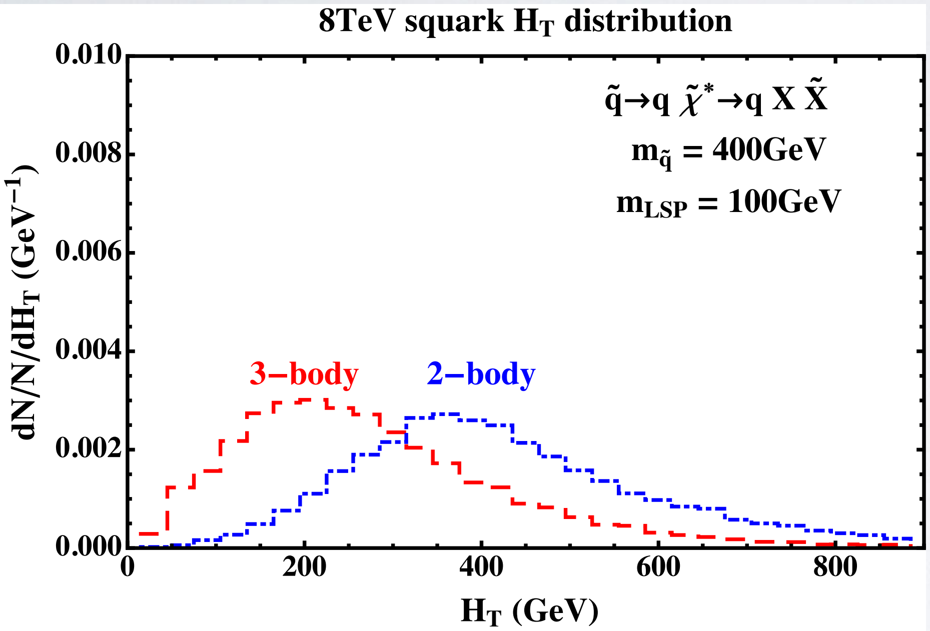
A SIMPLIFIED MODEL

“doubly invisible”
SUSY

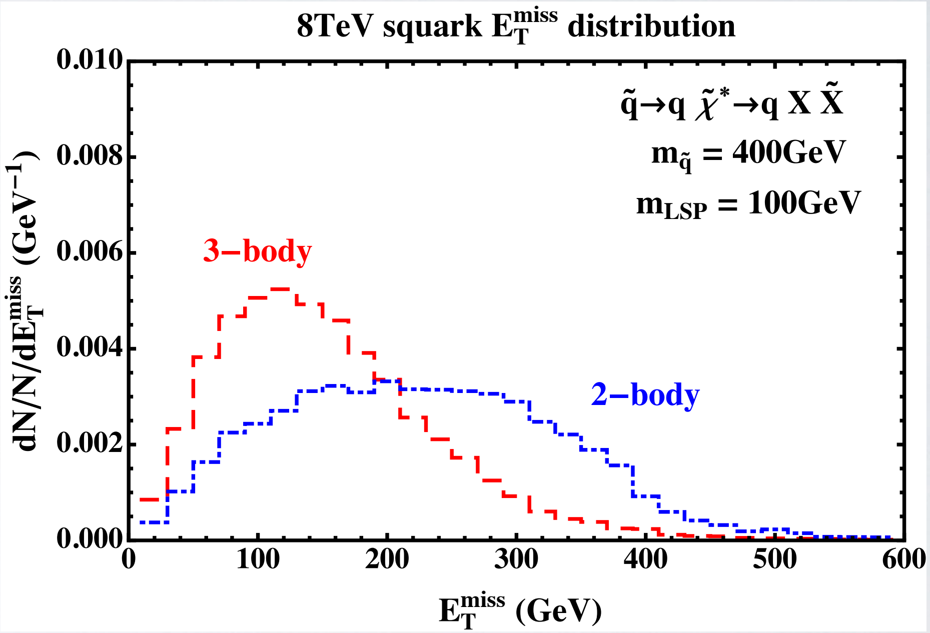
A SIMPLIFIED MODEL

"doubly invisible"
SUSY

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



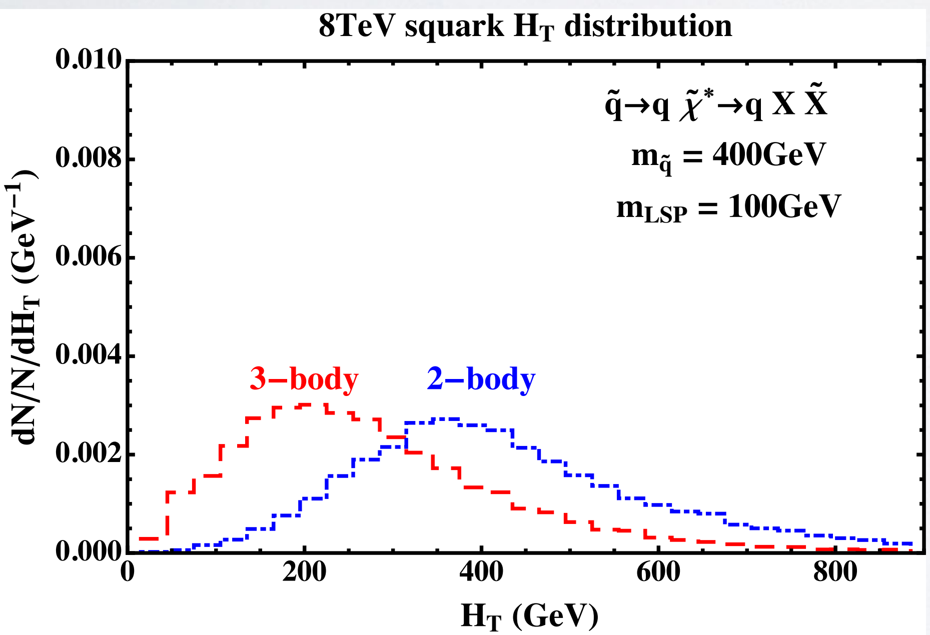
8TeV squark H_T distribution
$\tilde{q} \to q\ \tilde{\chi}^* \to q\ X\ \tilde{X}$
$m_{\tilde{q}} = 400$GeV
$m_{LSP} = 100$GeV
3−body
2−body
$dN/N/dH_T$ (GeV^{-1})
H_T (GeV)
0.000
0.002
0.004
0.006
0.008
0.010
0
200
400
600
800

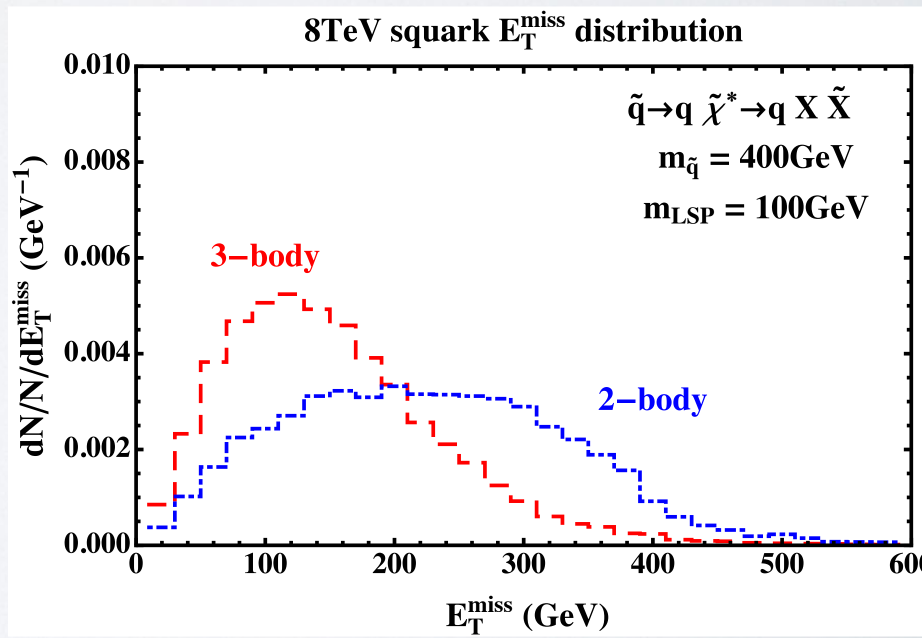


8TeV squark E_T^{miss} distribution
$\tilde{q} \to q\ \tilde{\chi}^* \to q\ X\ \tilde{X}$
$m_{\tilde{q}} = 400$GeV
$m_{LSP} = 100$GeV
3−body
2−body
$dN/N/dE_T^{miss}$ (GeV^{-1})
E_T^{miss} (GeV)
0.000
0.002
0.004
0.006
0.008
0.010
0
100
200
300
400
500
600

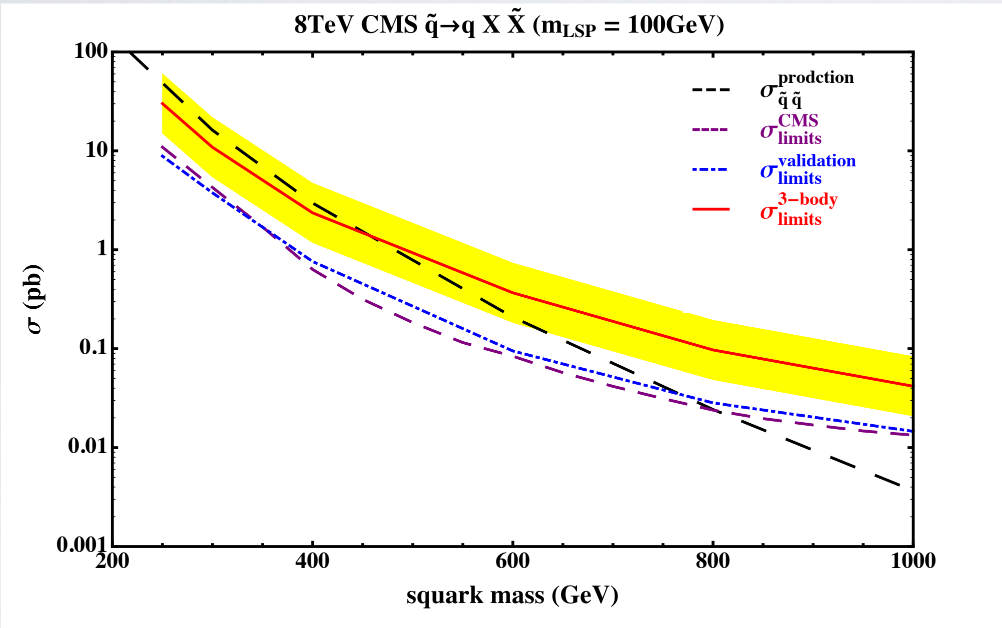
CMS SEARCHES

$N_{\rm jets}$	Selection $H_{\rm T}$	$\not{H}_{\rm T}$	$Z \to \nu\bar{\nu}$ from γ+jets	$t\bar{t}/W$ $\to e, \mu$+X	$t\bar{t}/W$ $\to \tau_h$+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

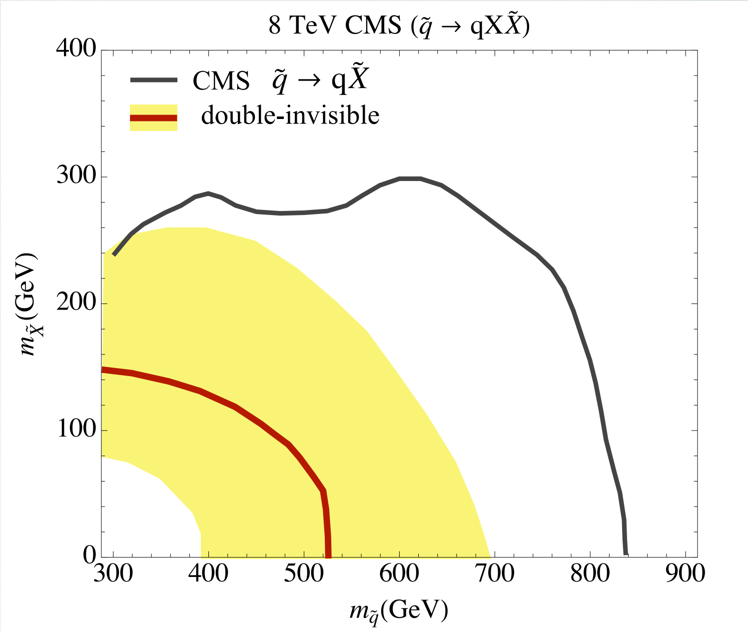




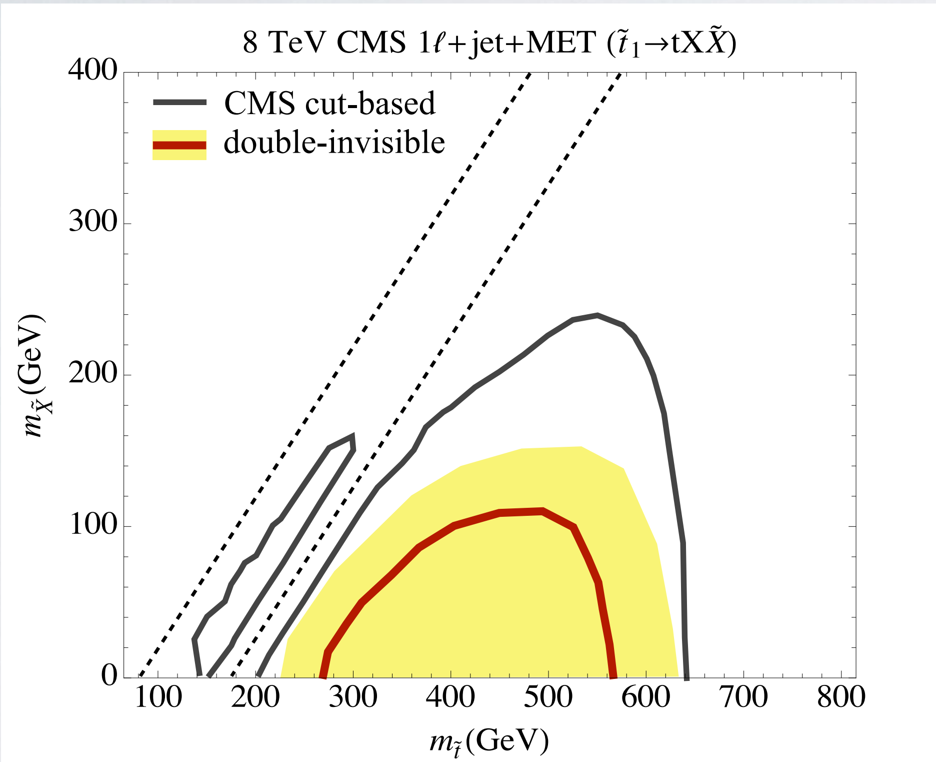
RECASTING



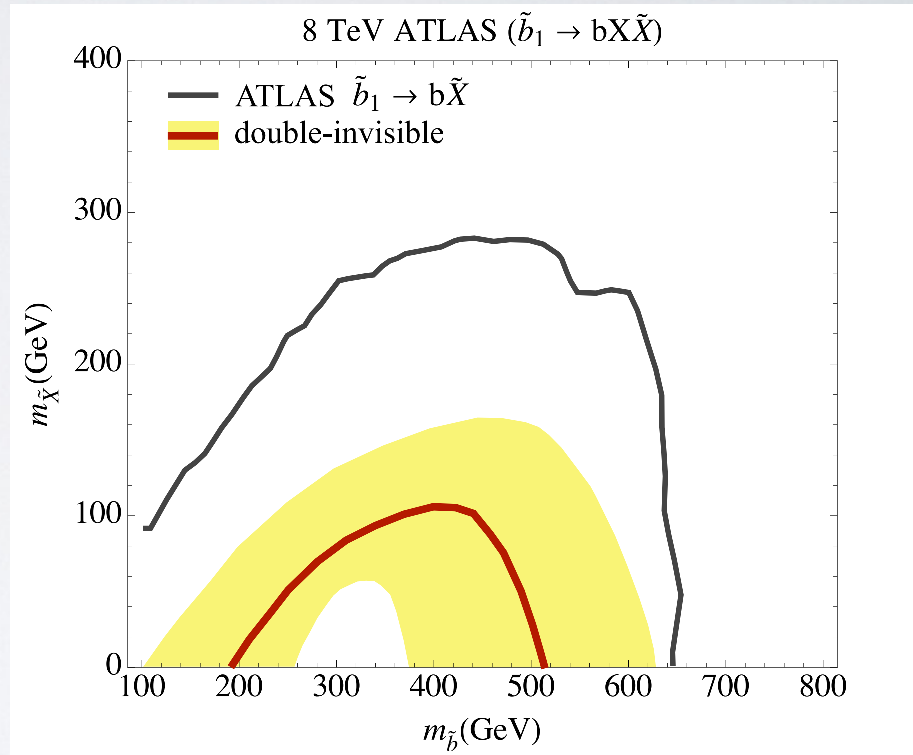
8TeV CMS $\tilde{q} \to q\, X\, \tilde{X}$ (m_{LSP} = 100GeV)
$\sigma^{\text{prodction}}_{\tilde{q}\,\tilde{q}}$
$\sigma^{\text{CMS}}_{\text{limits}}$
$\sigma^{\text{validation}}_{\text{limits}}$
$\sigma^{\text{3-body}}_{\text{limits}}$
100
10
1
0.1
0.01
0.001
200
400
600
800
1000
σ (pb)
squark mass (GeV)



8 TeV CMS ($\tilde{q} \to qX\tilde{X}$)
CMS $\tilde{q} \to q\tilde{X}$
double-invisible
400
300
200
100
0
300
400
500
600
700
800
900
$m_{\tilde{X}}$(GeV)
$m_{\tilde{q}}$(GeV)

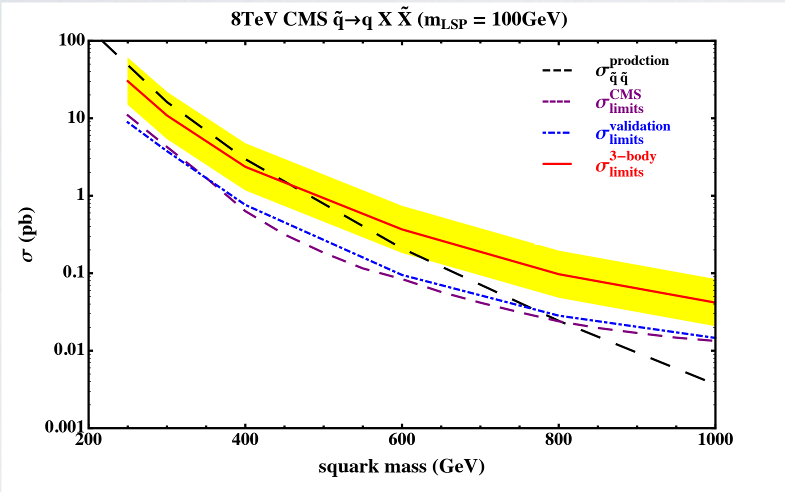


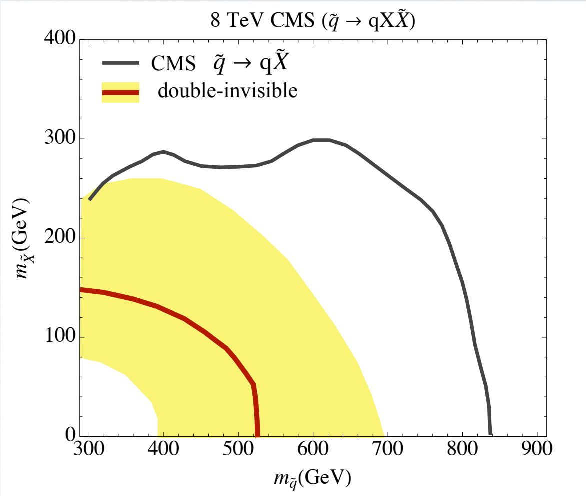
8 TeV CMS 1ℓ+jet+MET ($\tilde{t}_1 \to tX\tilde{X}$)
CMS cut-based
double-invisible
$m_{\tilde{X}}$(GeV)
$m_{\tilde{t}}$(GeV)
0
100
200
300
400
500
600
700
800

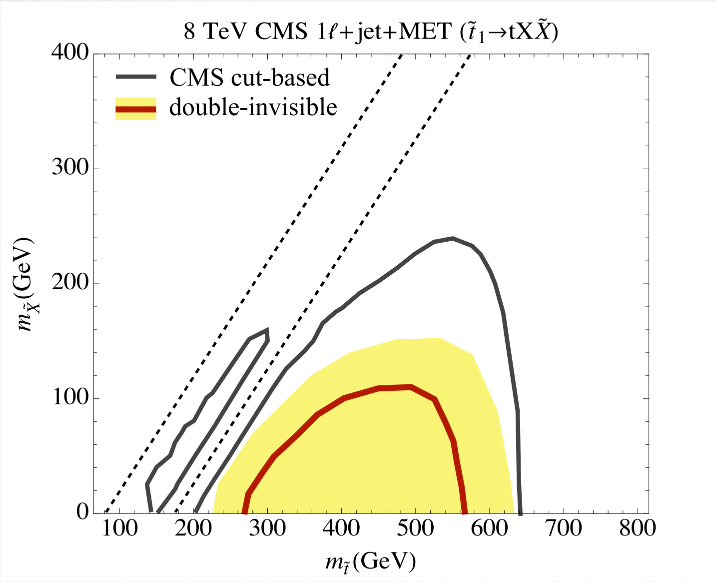


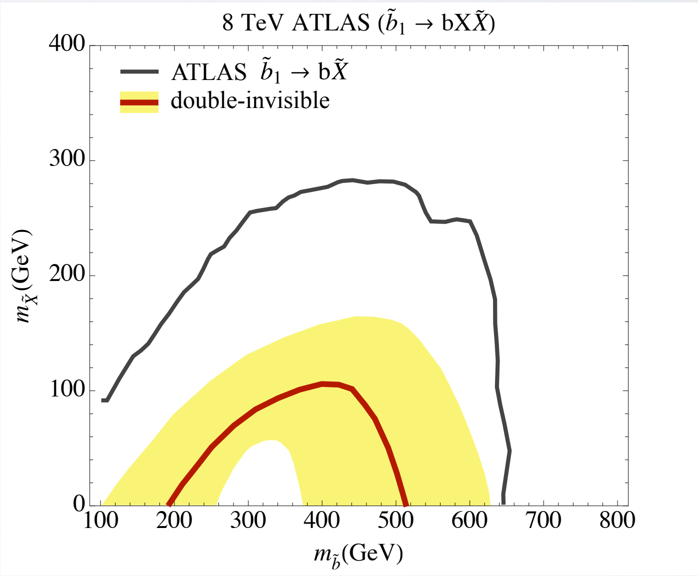
8 TeV ATLAS ($\tilde{b}_1 \to bX\tilde{X}$)
ATLAS $\tilde{b}_1 \to b\tilde{X}$
double-invisible
$m_{\tilde{X}}$(GeV)
$m_{\tilde{b}}$(GeV)
0
100
200
300
400
500
600
700
800

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

ACTUAL MODELS

- Yes there are actual models

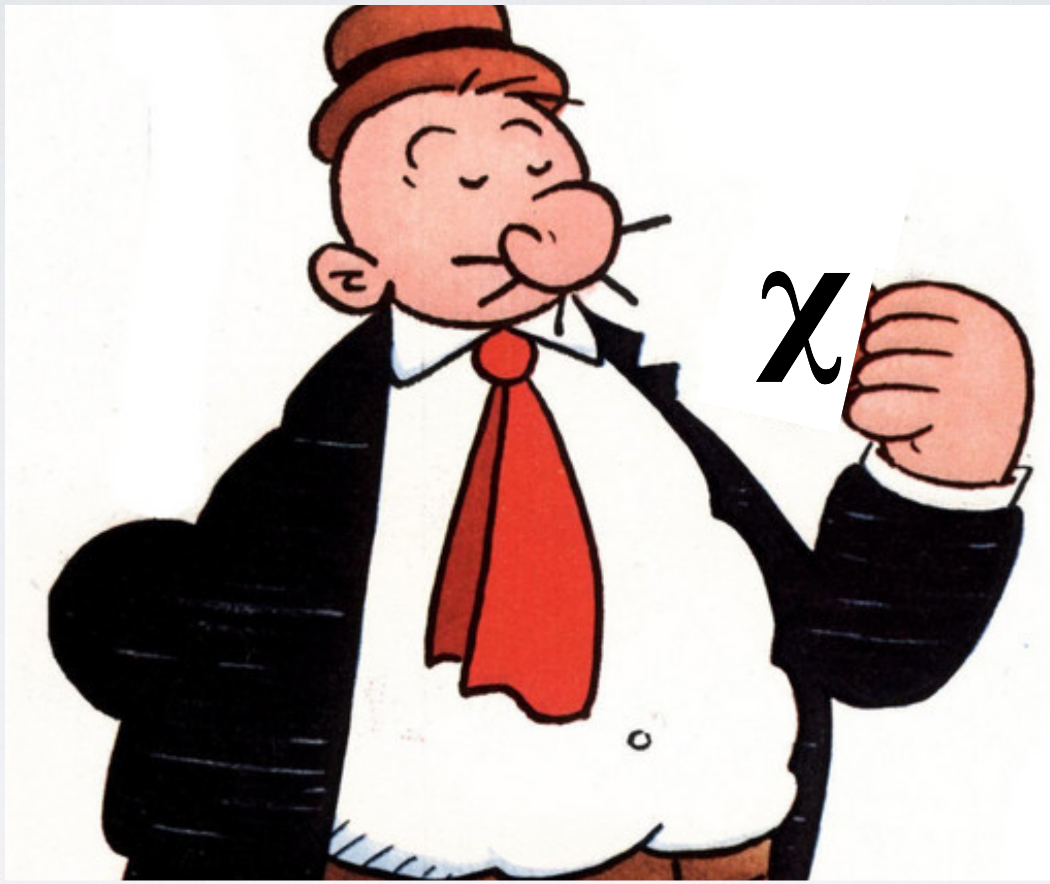
ANOMALY CONCLUSION

- 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.

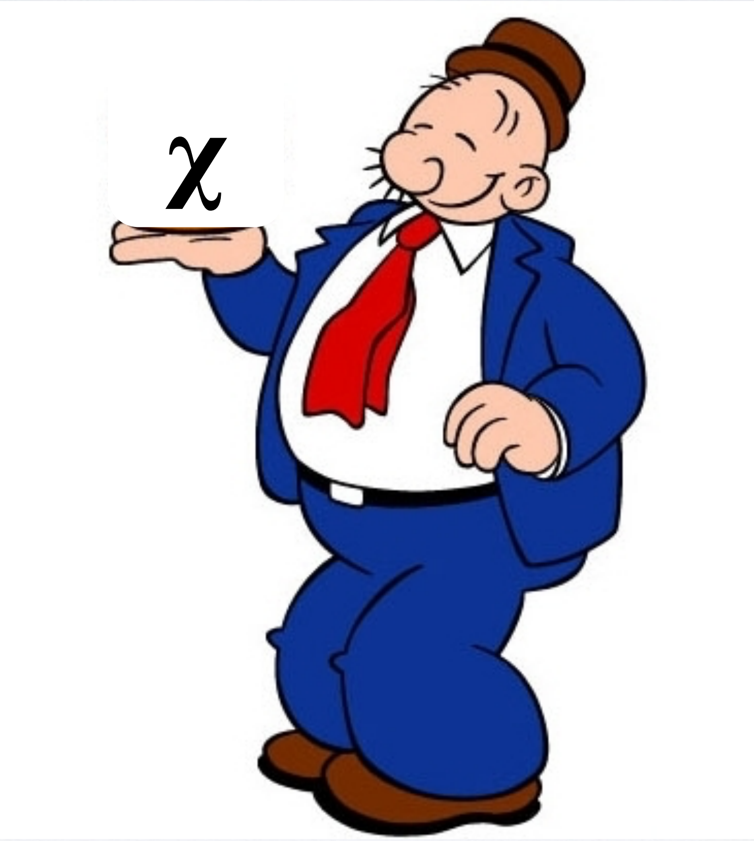
GRAZIE MILLE!



χ^0 carries only R-parity

$\tilde{\nu}$ carries R-parity and lepton #

$\Rightarrow$ final state needs ν to cancel lepton #


χ

LSPS WITH A QUANTUM NUMBER

in MSSM only neutral LSP with quantum number is sneutrino

More generally - could have symmetry group G and consider lightest G-sector particle(s)