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SANTA CRUZ INSTITUTE FOR PARTICLE PHYSICS

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An Introduction to Particle Dark Matter

Lecture 4

3rd José Plínio Baptista School on Cosmology

25-30 September 2016

Pedra Azul, ES, Brazil

Key ideas from last lecture

✓ **Direct** detection: three layers of **EFT**

✓ Almost hitting the **neutrino floor**, strongly **constraining** models

✓ **Indirect detection**: very indirect, pretty indirect, not-so indirect

✓ **Charged cosmic rays**: diffusion vs energy loss time scales good approximation to diffusion equation

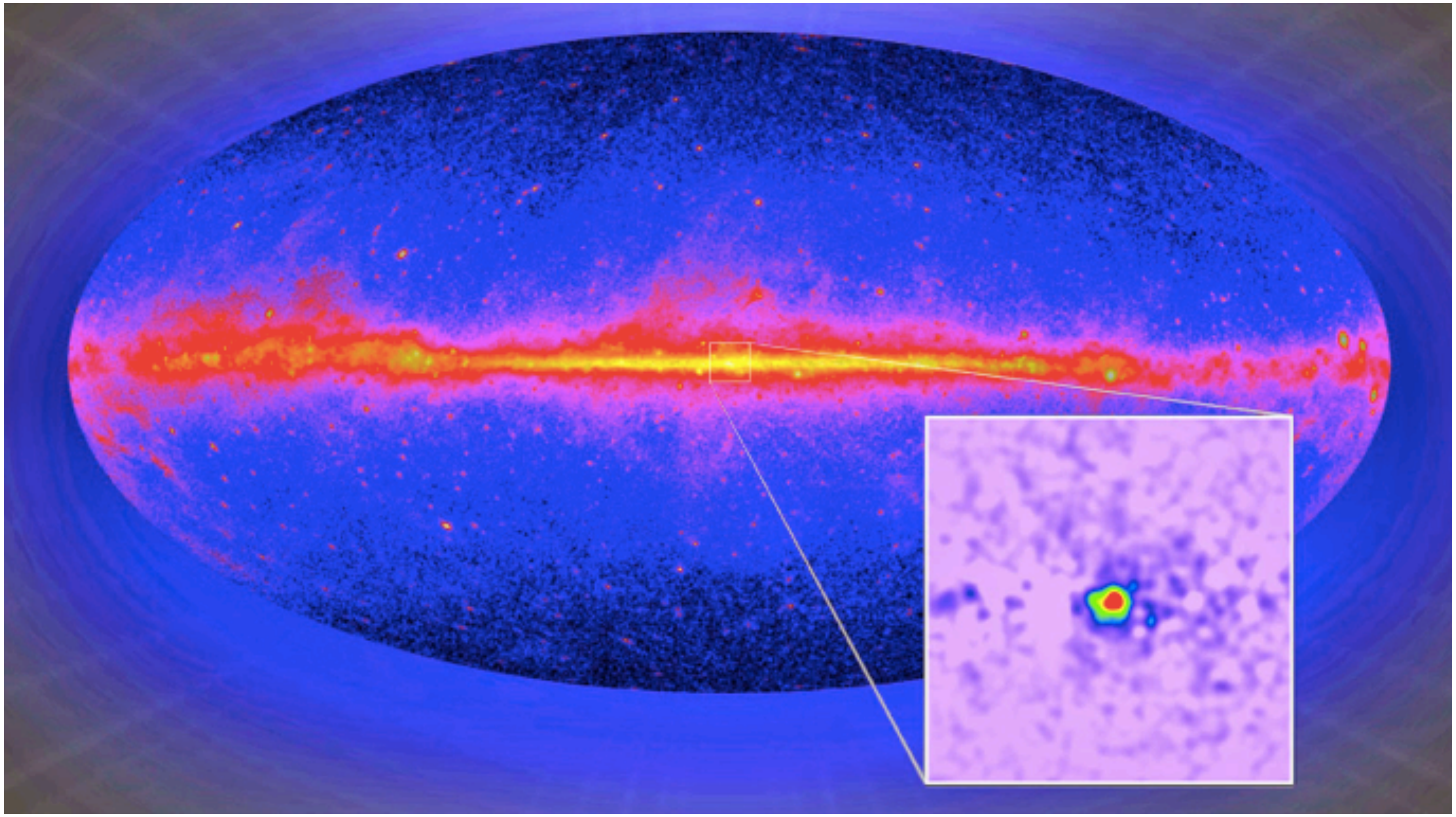
✓ **Positron anomaly**: estimate of point source age, distance; case for **dark matter** very **weak**…

✓ **Neutrinos from the Sun**: background-free, capture vs annihilation time scales

What is **left** on the **menu**

- ✓ Gamma-ray **Galactic Center Excess** and Diffuse Emission Models
- ✓ **Collider** searches for Dark Matter
- ✓ **Axions** and axion searches
- ✓ **Sterile neutrinos** and the 3.5 keV line puzzle
- ✓ **Bestiarium** of other dark matter candidates

After early reports (primarily by Hooper et al) **Galactic Center Excess** reported independently, and with a variety of different assumptions for background etc, by Daylan et al (Harvard+MIT+Fermilab); Abazijian et al (UCI); Macias and Gordon (NZ)



What produces the Galactic Center excess?

Fitting the excess with Dark Matter Annihilation not problematic

- ✓ Morphology ~OK
- ✓ Spectrum ~OK
- ✓ Constraints from dSph, radio, CMB ~sort of OK

What produces the Galactic Center excess?

Most obvious astrophysical counterpart (unresolved pulsars) does not work

- ✓ **Morphology NOT OK**
- ✓ **Spectrum NOT OK**
- ✓ **Not enough!**

What produces the Galactic Center excess?

WRONG QUESTION!

Rather: is the excess indeed there?

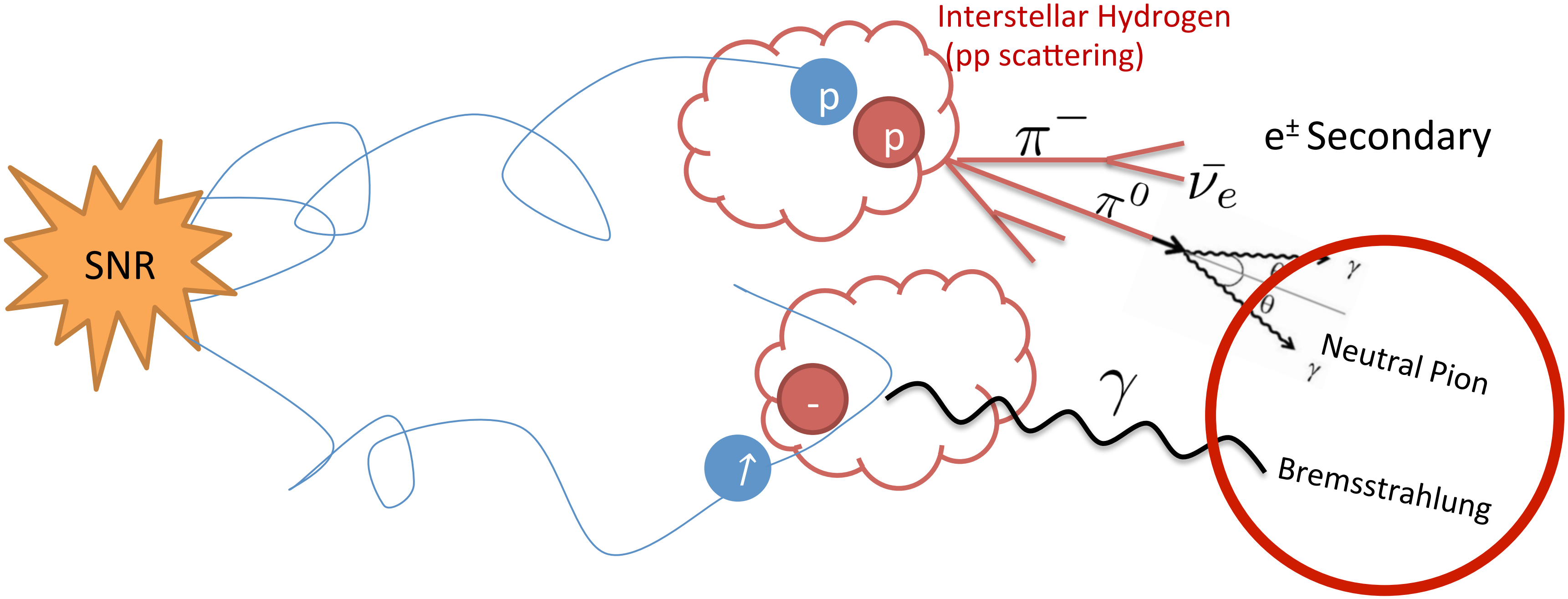
Are models of diffuse emission adequate to current data?

Ingredients of diffuse emission

Primary Source Injection

CR Transport

Gamma-Ray Generation



Gas x CR

All groups that find an excess assume:

1. 2-D Gas Density Distribution
2. 2-D Cosmic-Ray Propagation
3. Steady State
4. Simplistic Cosmic-ray source distribution

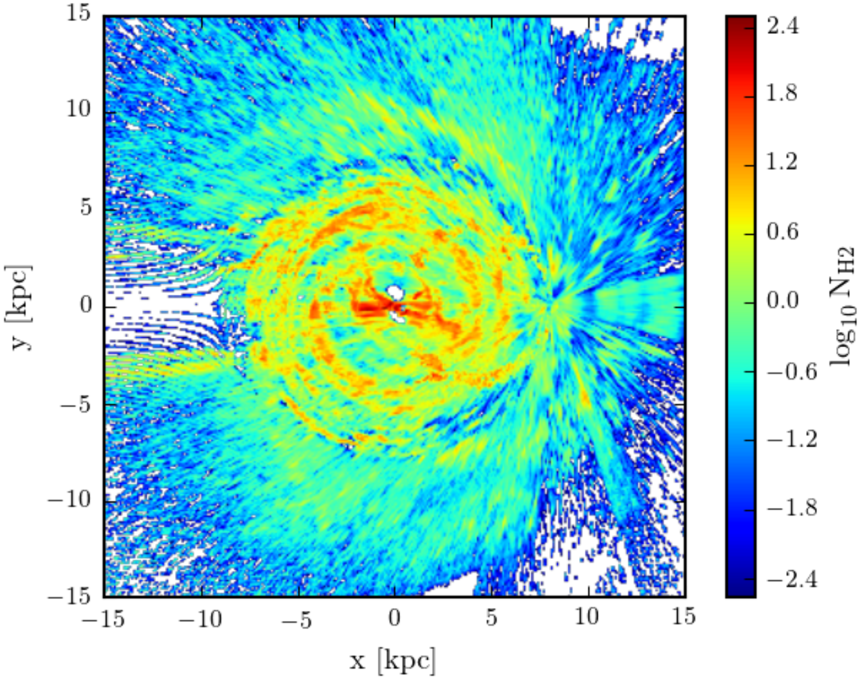
Every assumption costs a systematic effect of the same order as the excess (~ few %)!

Towards the next generation of diffuse gamma-ray models

1. 3-D Gas Density Distribution
2. 3-D Cosmic-Ray Propagation
3. Cosmic Ray Bursts/Transients
4. Physically motivated Cosmic-ray source distributions

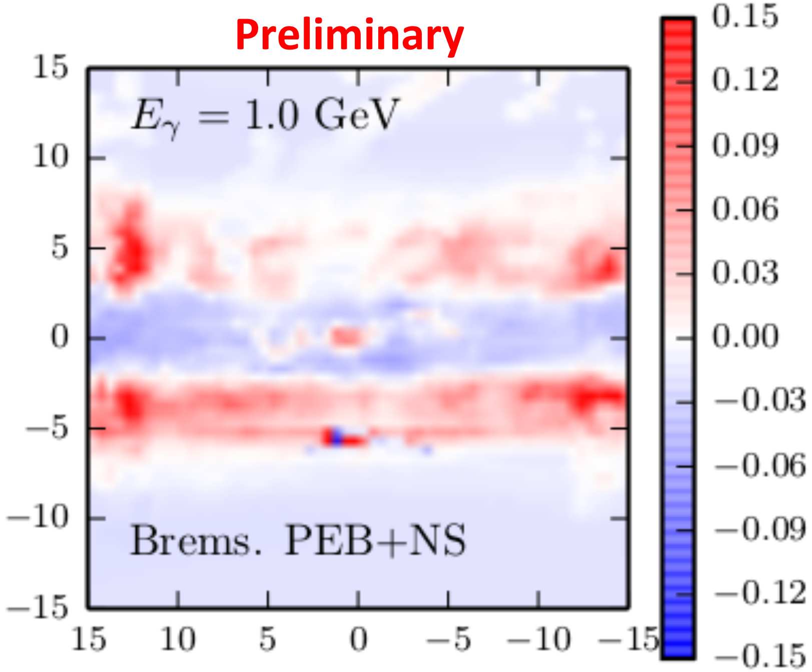
*** Carlson, Linden, Profumo 1510.04698 (Phys.Rev.Lett.), 1603.06584**

1. 3-D Gas Density Distribution



H2 column density

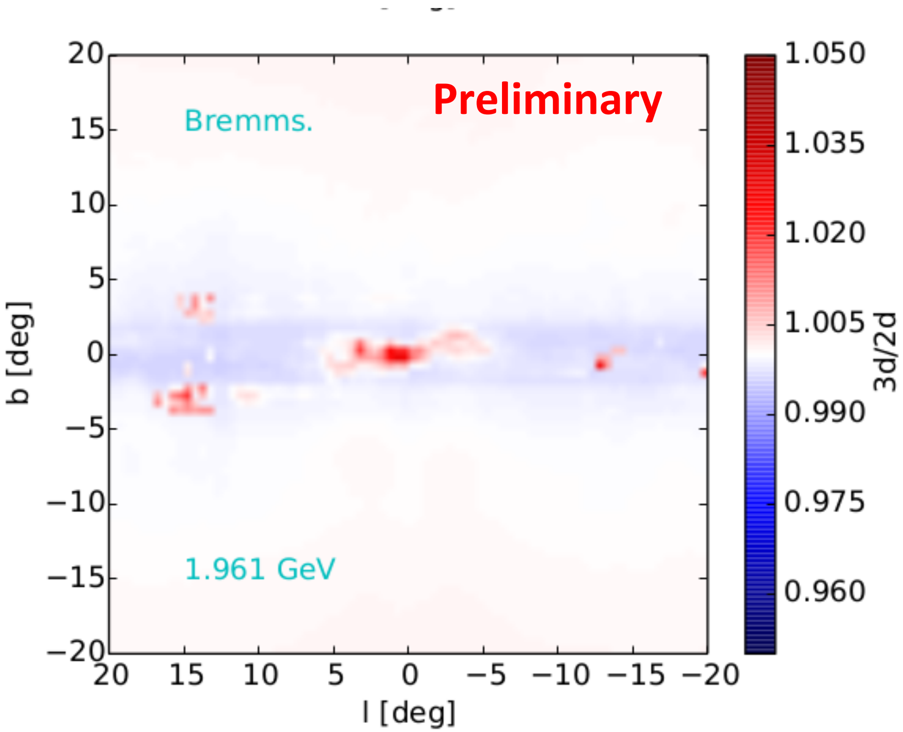
Preliminary



~3-10% effect

*** Carlson, Linden, Profumo 1510.04698 (Phys.Rev.Lett.), 1603.06584**

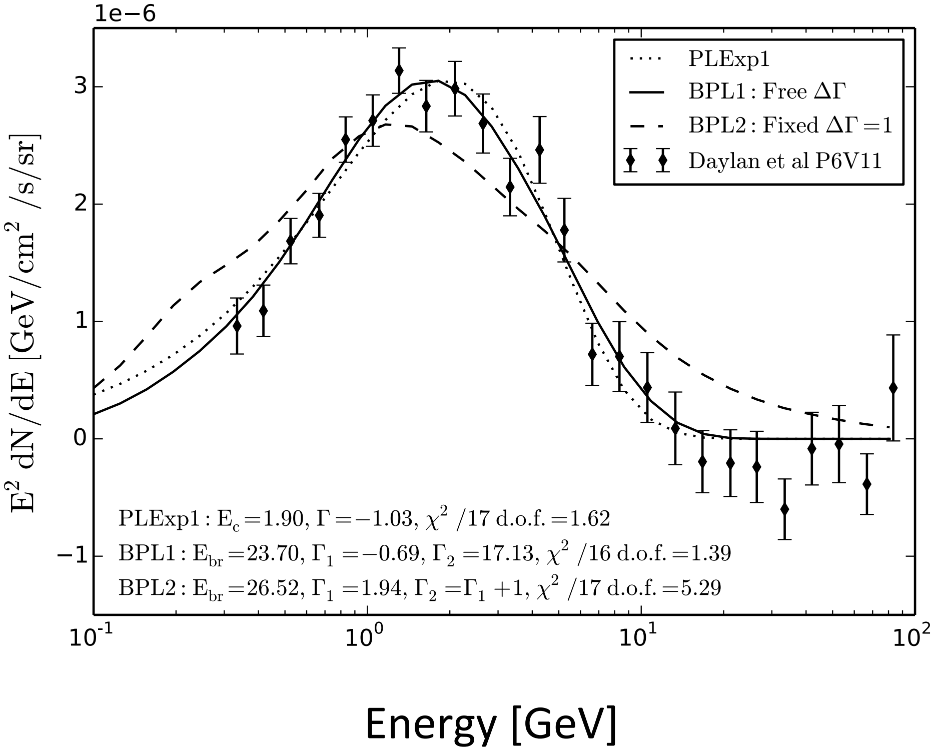
2. 3-D Cosmic-Ray Propagation



few % effect

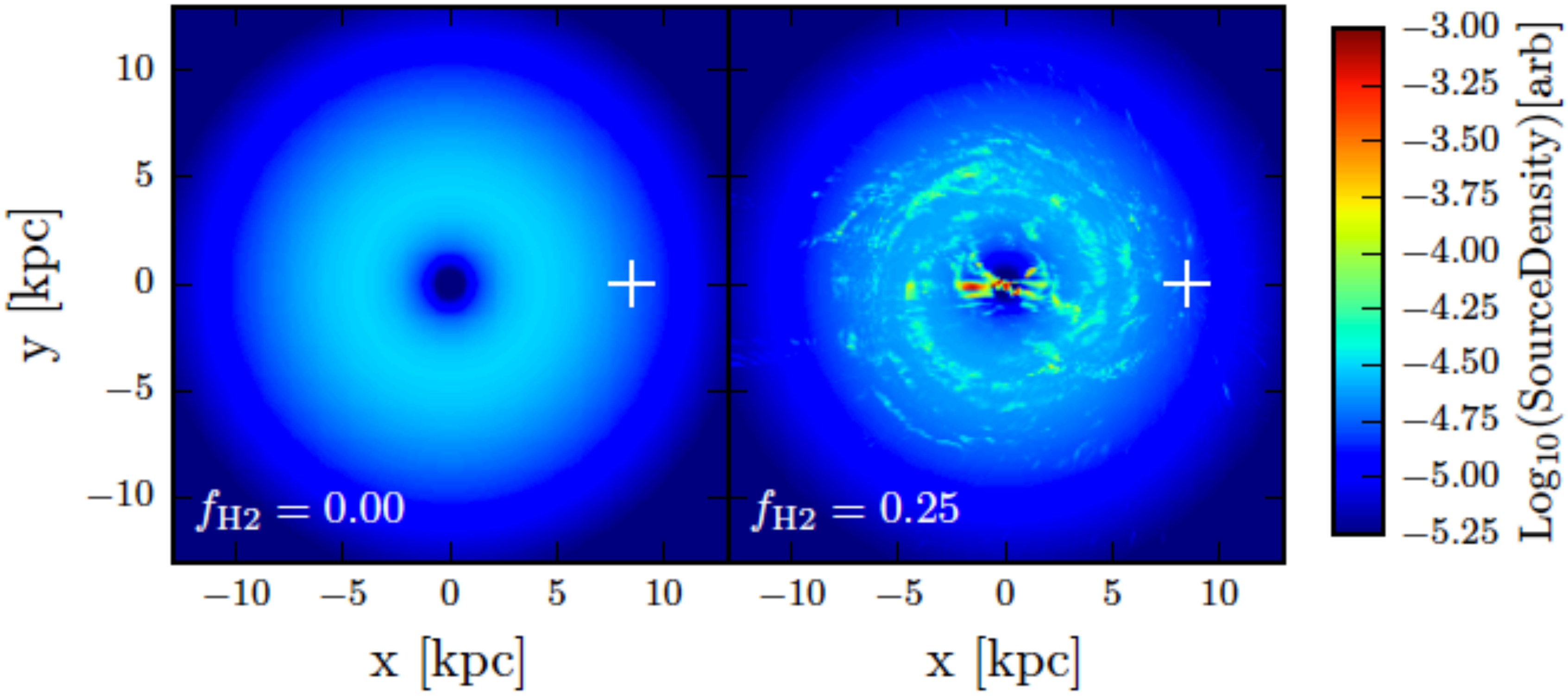
*** Carlson, Linden, Profumo 1510.04698 (Phys.Rev.Lett.), 1603.06584**

3. Steady State



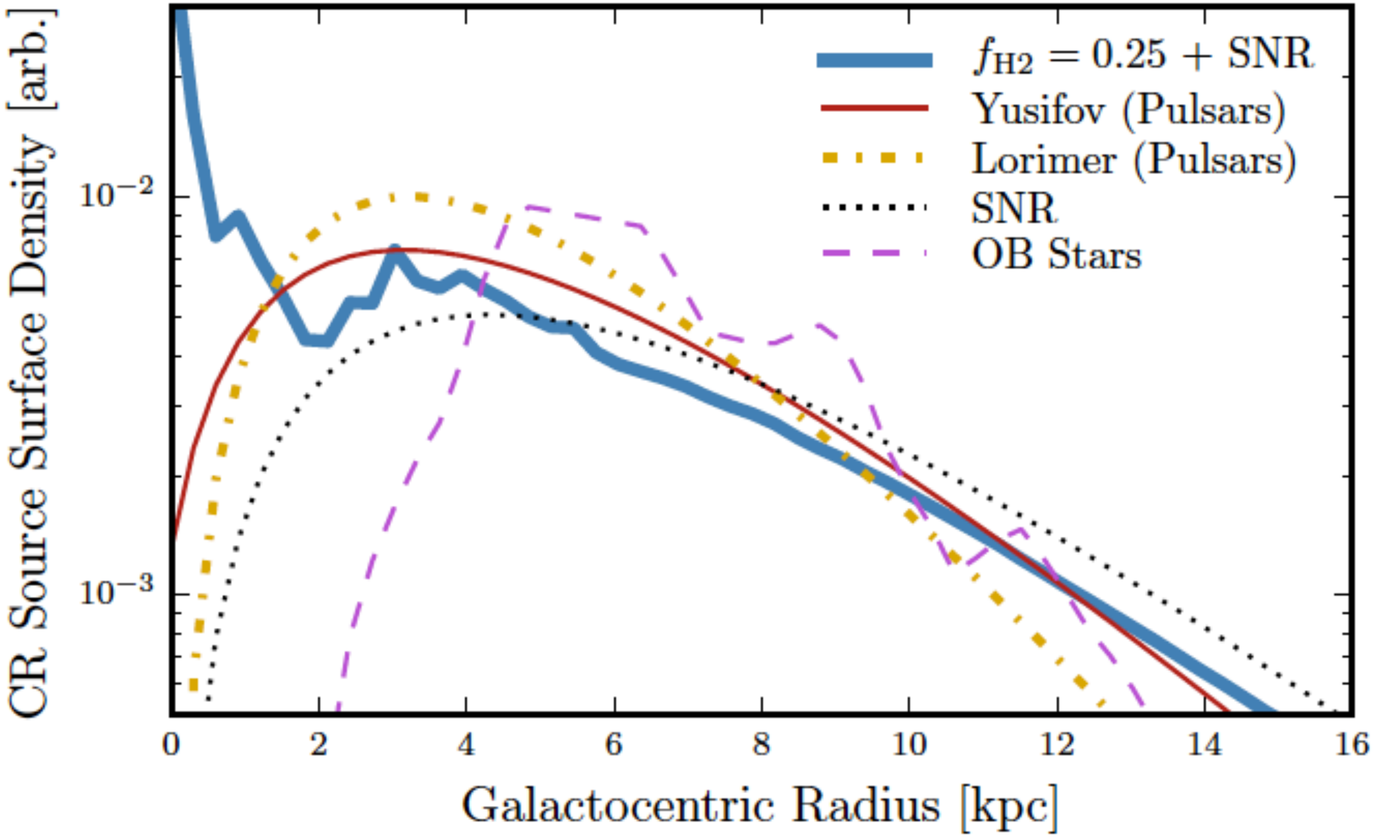
Carlson and Profumo, PRD 2014

4. Physically motivated, 3D Cosmic Ray source distributions



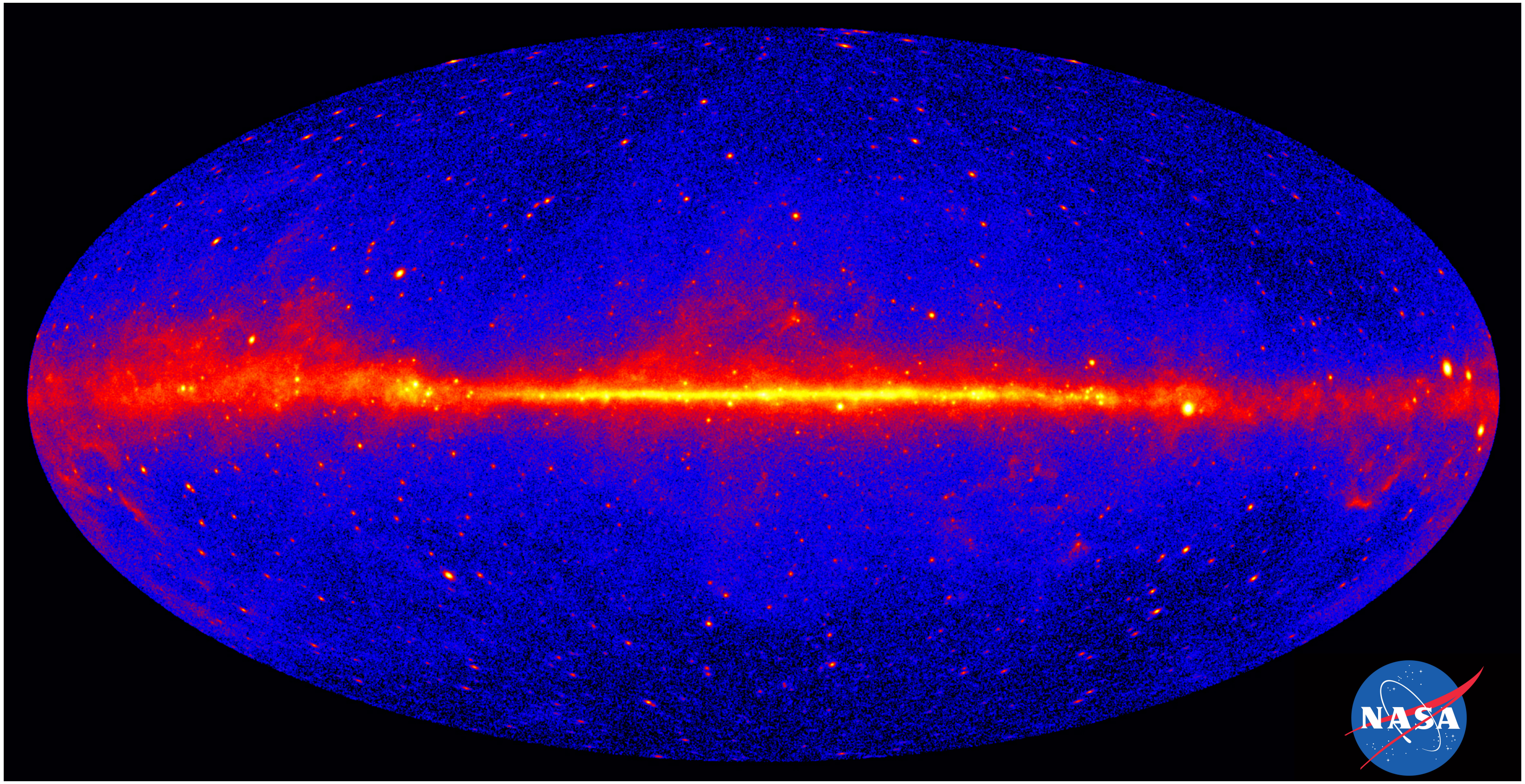
*** Carlson, Linden, Profumo 1510.04698 (Phys.Rev.Lett.), 1603.06584**

4. Physically motivated, 3D Cosmic Ray source distributions



* **Carlson, Linden, Profumo 1510.04698 (Phys.Rev.Lett.), 1603.06584**

Good to push the (theory) envelope.
But do you get a better or worse fit to data?



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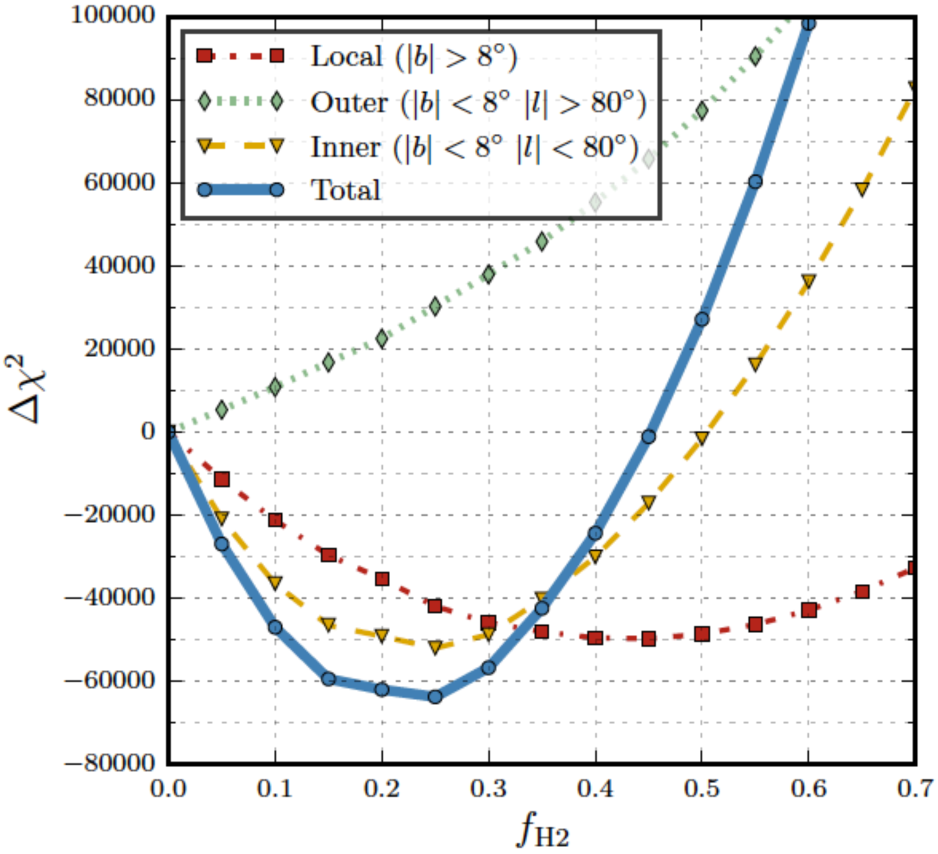
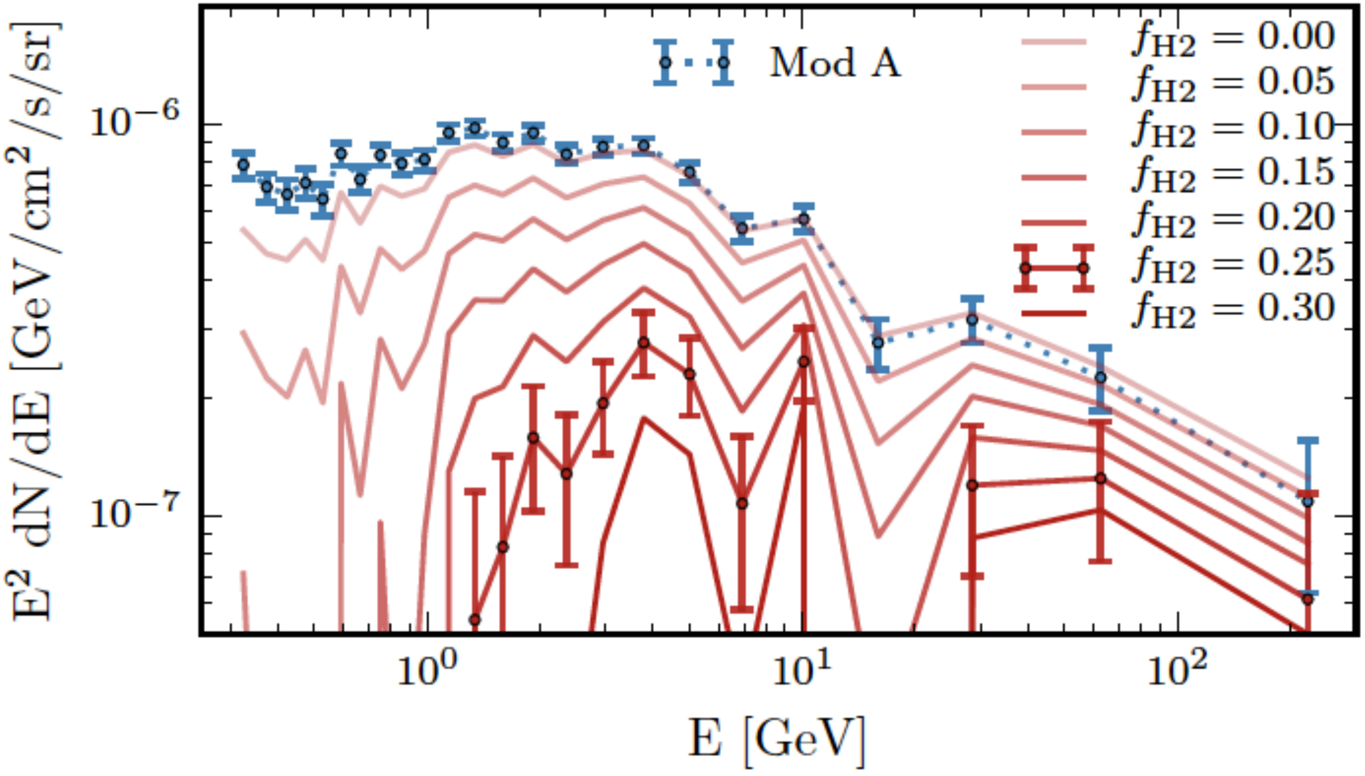


*** Carlson, Linden, Profumo 1510.04698, sub. to Phys.Rev.Lett.**

What do these **improved models** imply for the Galactic Center “**Excess**”?



*** Carlson, Linden, Profumo 1510.04698 (Phys.Rev.Lett.), 1603.06584**

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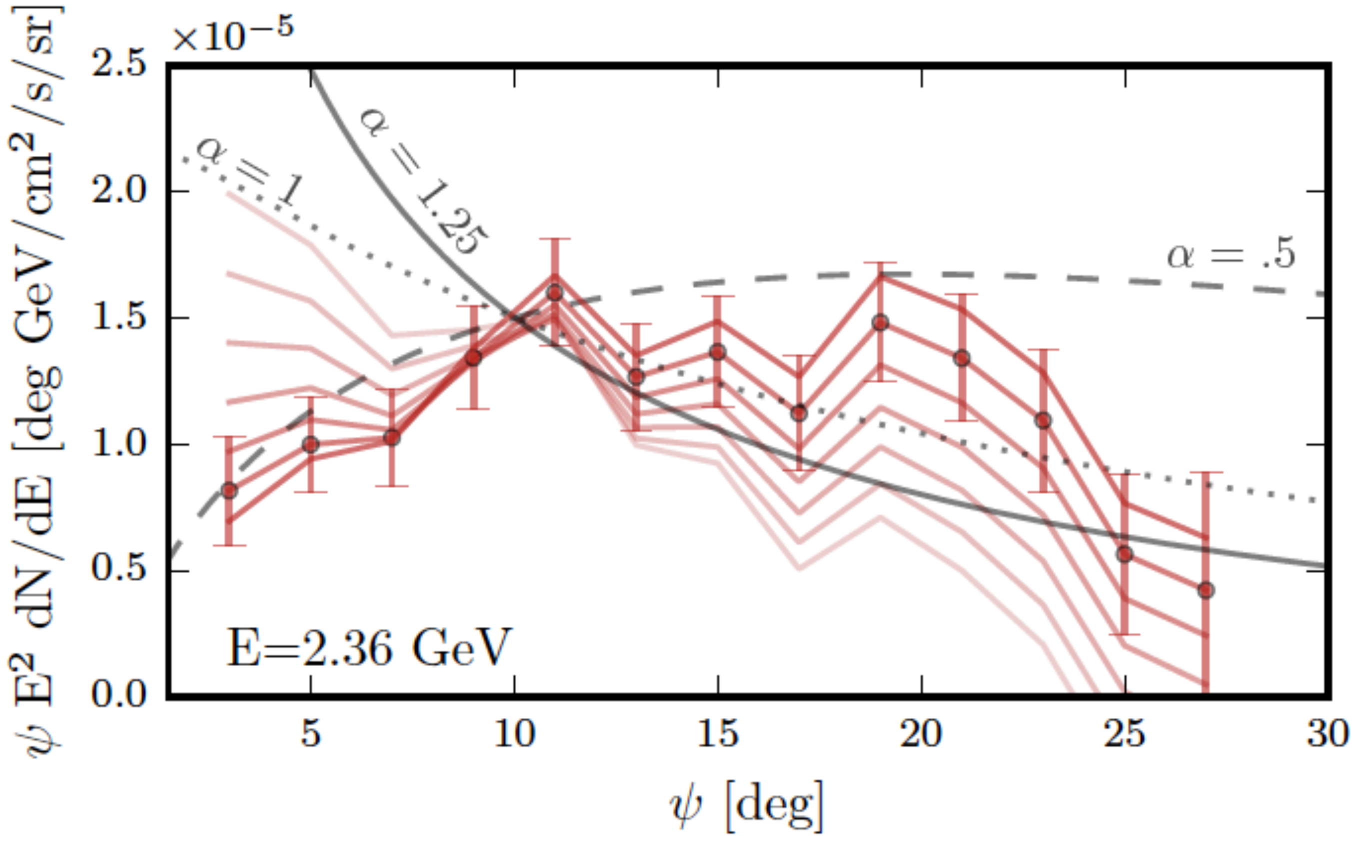

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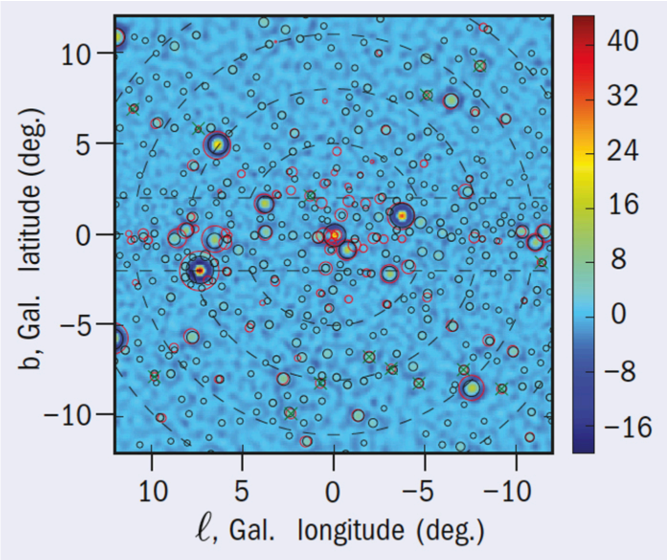
We are making significant progress towards understanding Galactic gamma rays

Cosmic-Ray injection and 3D models are key!



Discrimination between unresolved point sources and diffuse emission*, also highly dependent on emission model!**

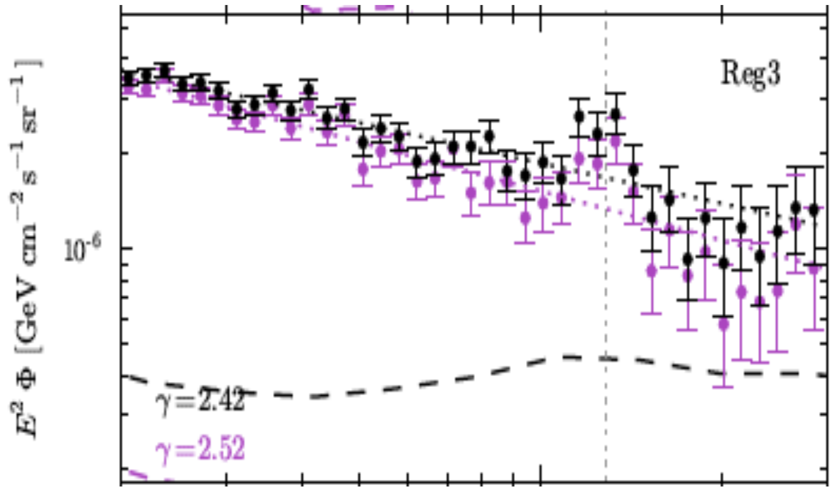
* Bartels et al, 2016, PRL 116 051102, ** Lee et al, 2016, PRL 116 051103

I remain skeptic about establishing a conclusive Dark Matter detection signal from the Galactic Center

Is DM detection with gamma rays possible at all? Yes.

A monochromatic gamma-ray line with a diffuse morphology has no astrophysical counterparts*

***Carlson, Linden, Profumo, JCAP 2013**



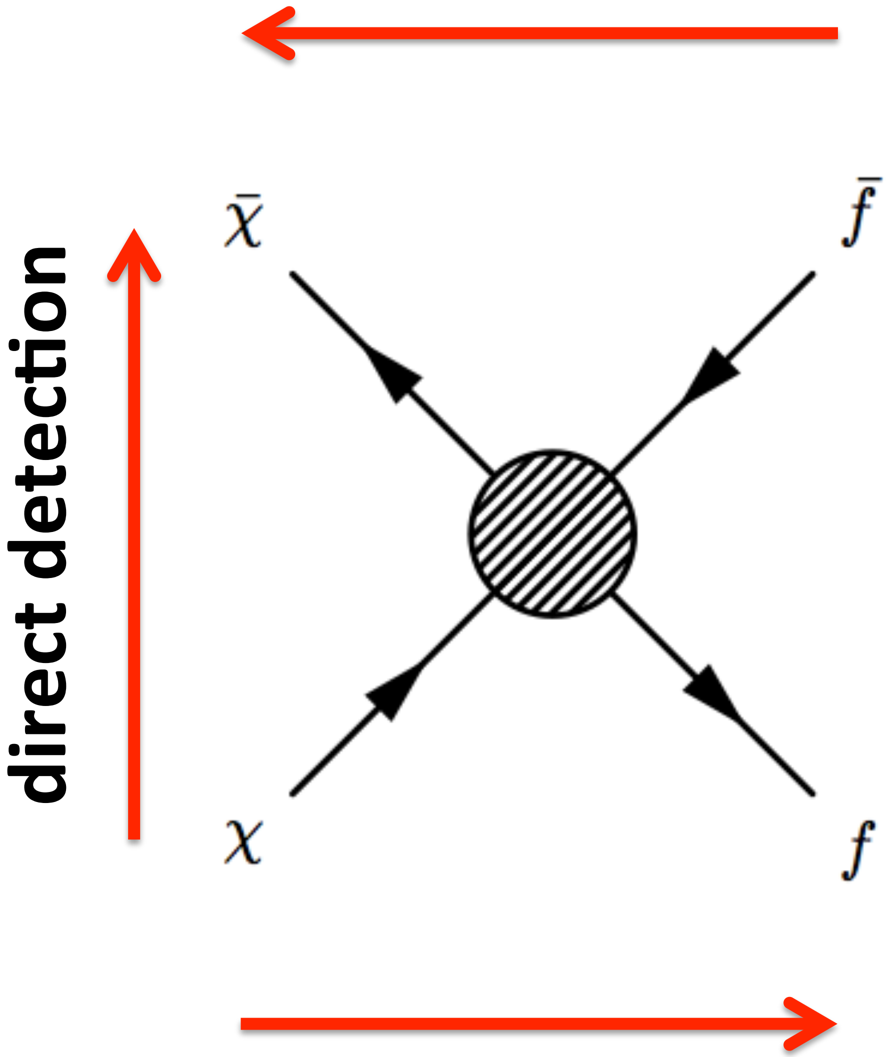
Unfortunately, the 130 GeV line was a statistical fluke

(sometimes happens to di-photon excesses…)

- too narrow right off the bat
- significance did not increase with time
- Pass 8 does not see any line

* Weniger 2012

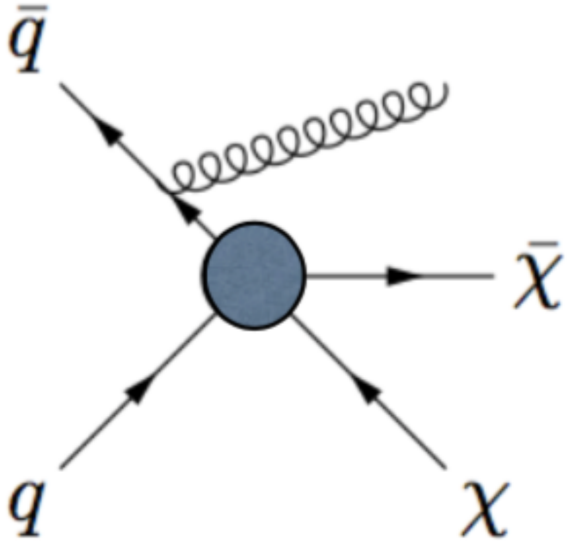
collider production



direct detection

thermal equilibrium ?
[pair annihilation]

DM particles can be produced at **colliders**, but at very **low rates** compared to Galactic DM fluxes... (see problem on next slide)



monojet +MET

Idea: look for **anomalous** events with missing energy and **SM particles** (e.g. monojets, monophotons, etc)

Exercise We want to compare the Galactic dark matter flux at Earth with the flux of dark matter that might be expected from collider production.
Assume $\rho_{\rm DM}(r_\oplus) = 0.3$ GeV/cm^3, $v = 220$ km/s. Assume that an LHC detector has an instantaneous luminosity $\dot{\mathcal{L}} = 5 \times 10^{33}$ cm^{-2}s^{-1}.

(i) Get an expression for the flux of dark matter particles produced at the LHC detector under consideration at a distance R, assuming isotropic production (discuss how realistic this assumption is), as a function of the total dark matter pair-production cross section $\sigma_{\rm LHC} = \sigma(pp \to \chi\chi + \text{anything})$.

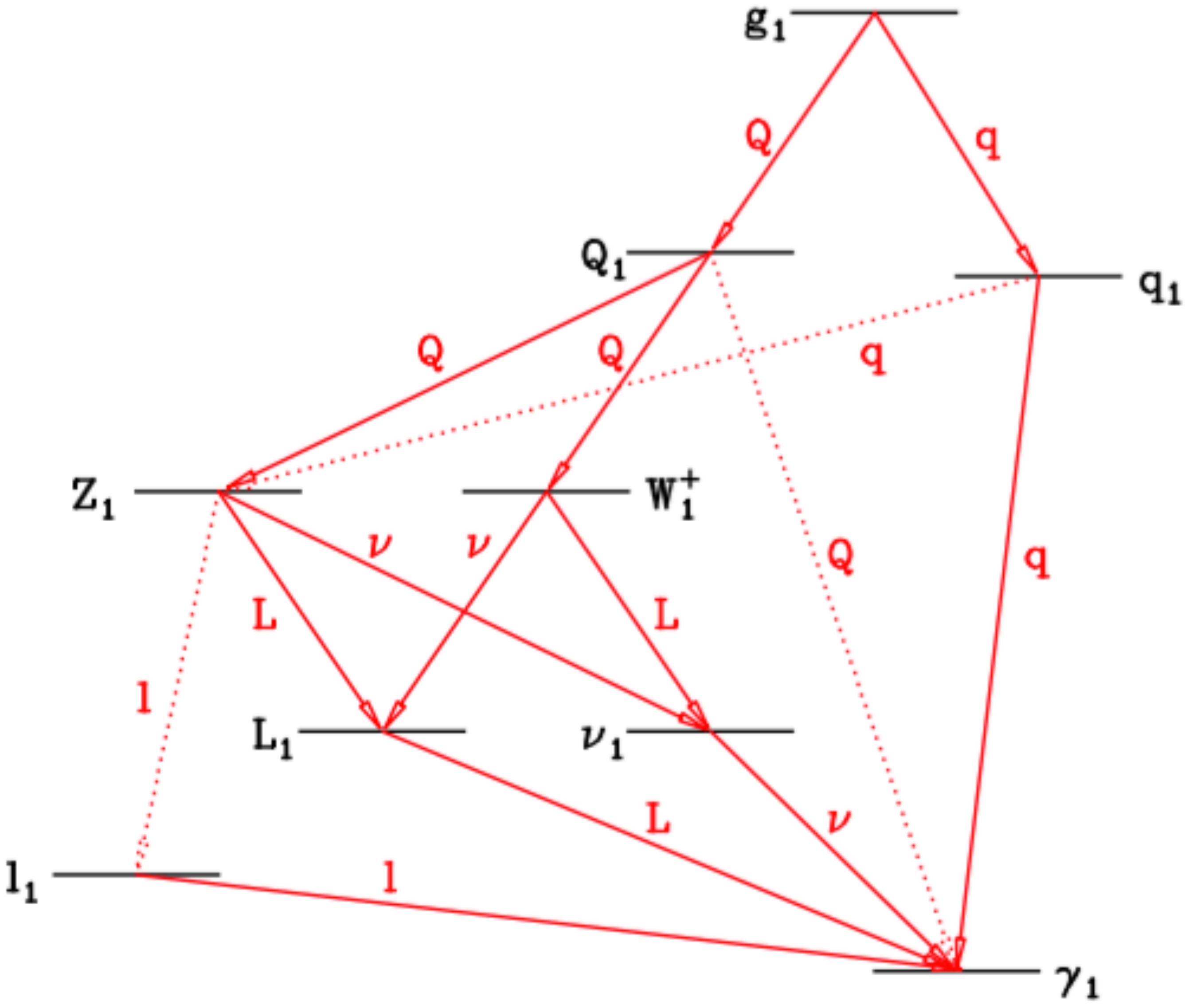
(ii) Assume $m_\chi = 100$ GeV, and a weak-interaction cross section $\sigma_{\rm LHC} = G_F^2 m_\chi^2$. Compare the flux from LHC production at $R = 10$ m with the Galactic flux.

(iii) For which $\sigma_{\rm LHC}$ are the two fluxes comparable?

Two possible **approaches**:

(i) **top-down**: pick a model, select best search strategies, optimize cuts, scan parameter space (e.g. SUSY, UED)

(ii) **bottom-up**: effective theory, or simplified model – sketch of how DM could manifest itself at colliders...


g_1
Q
q
Q_1
q_1
Q
Q
q
Z_1
W_1^+
ν
ν
Q
q
L
L
l
L_1
ν_1
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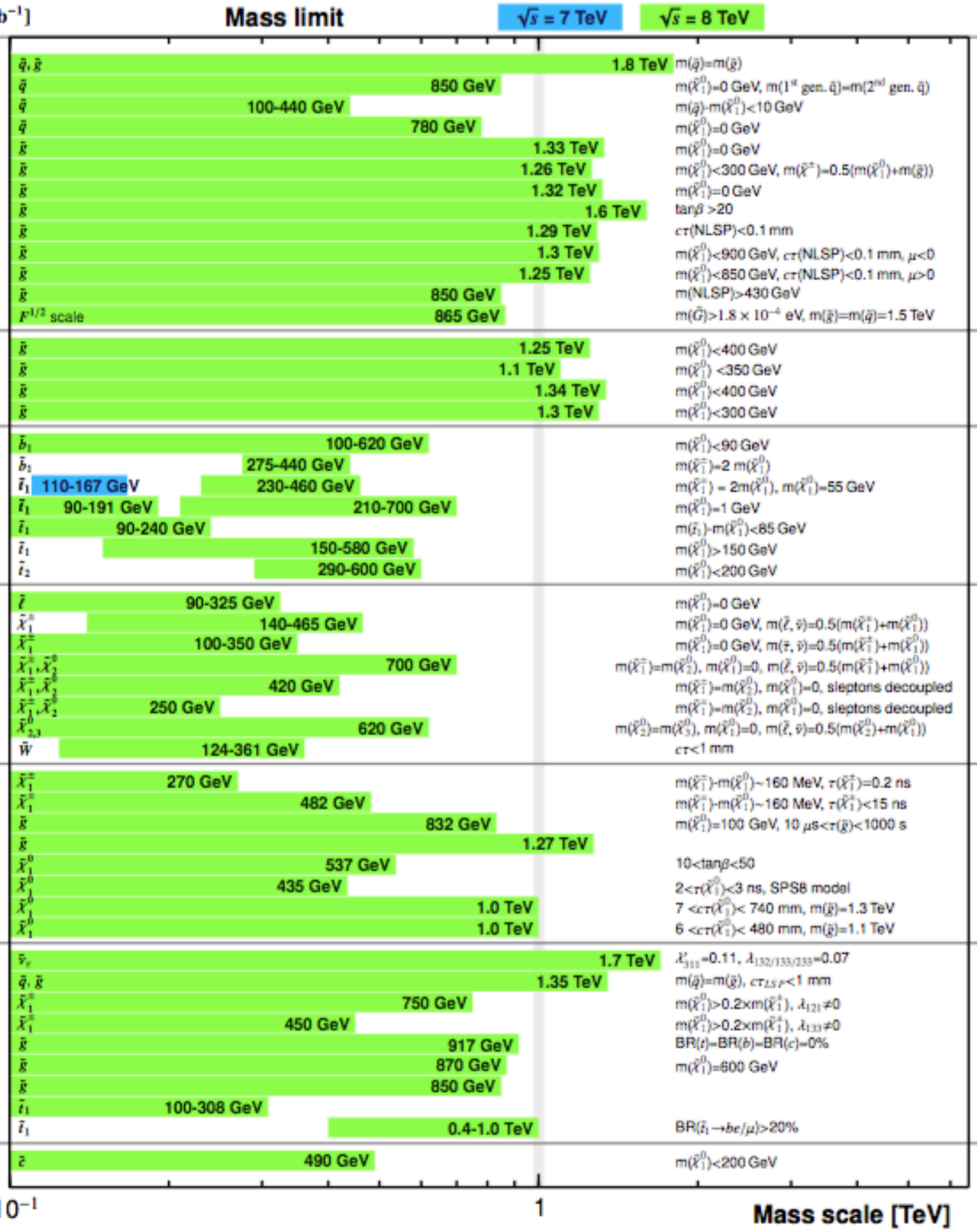
ν
l_1
l
γ_1

ATLAS SUSY Searches* - 95% CL Lower Limits

Status: July 2015

ATLAS Preliminary

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



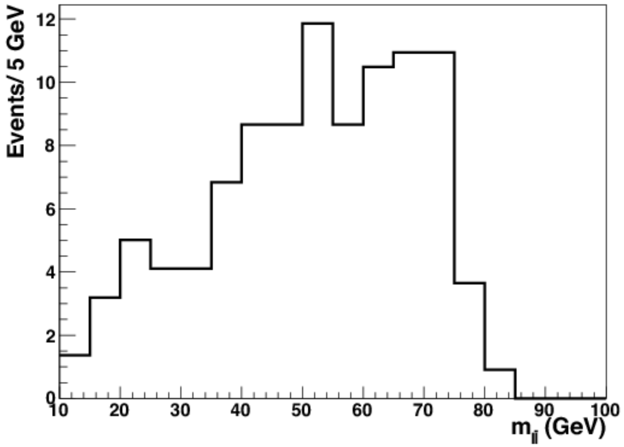
🟦 $\sqrt{s}$ = 7 TeV 🟩 $\sqrt{s}$ = 8 TeV

	Model	e,μ,τ,γ	Jets	E_T^{miss}	$\int\mathcal{L}\,dt[\mathrm{fb}^{-1}]$		Mass limit		Reference
Inclusive Searches	MSUGRA/CMSSM	0-3 e,μ/1-2 τ	2-10 jets/3 b	Yes	20.3	$\tilde{q},\tilde{g}$	1.8 TeV	$m(\tilde{q})$=$m(\tilde{g})$	1507.05525
	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}^0_1$	0	2-6 jets	Yes	20.3	$\tilde{q}$	850 GeV	$m(\tilde{\chi}^0_1)$=0 GeV, m(1st gen. $\tilde{q}$)=m(2nd gen. $\tilde{q}$)	1405.7875
	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}^0_1$ (compressed)	mono-jet	1-3 jets	Yes	20.3	$\tilde{q}$	100-440 GeV	$m(\tilde{q})$-$m(\tilde{\chi}^0_1)$<10 GeV	1507.05525
	$\tilde{q}\tilde{q}$, $\tilde{q}\to q(\ell\ell/\ell\nu/\nu\nu)\tilde{\chi}^0_1$	2 e,μ (off-Z)	2 jets	Yes	20.3	$\tilde{q}$	780 GeV	$m(\tilde{\chi}^0_1)$=0 GeV	1503.03290
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}\tilde{\chi}^0_1$	0	2-6 jets	Yes	20.3	$\tilde{g}$	1.33 TeV	$m(\tilde{\chi}^0_1)$=0 GeV	1405.7875
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}^\pm_1\to qqW^\pm\tilde{\chi}^0_1$	0-1 e,μ	2-6 jets	Yes	20	$\tilde{g}$	1.26 TeV	$m(\tilde{\chi}^0_1)$<300 GeV, $m(\tilde{\chi}^\pm)$=0.5($m(\tilde{\chi}^0_1)$+$m(\tilde{g})$)	1507.05525
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq(\ell\ell/\ell\nu/\nu\nu)\tilde{\chi}^0_1$	2 e,μ	0-3 jets	-	20	$\tilde{g}$	1.32 TeV	$m(\tilde{\chi}^0_1)$=0 GeV	1501.03555
	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	$\tilde{g}$	1.29 TeV	$c\tau$(NLSP)<0.1 mm	1507.05493
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	20.3	$\tilde{g}$	1.3 TeV	$m(\tilde{\chi}^0_1)$<900 GeV, $c\tau$(NLSP)<0.1 mm, μ<0	1507.05493
	GGM (higgsino-bino NLSP)	γ	2 jets	Yes	20.3	$\tilde{g}$	1.25 TeV	$m(\tilde{\chi}^0_1)$<850 GeV, $c\tau$(NLSP)<0.1 mm, μ>0	1507.05493
	GGM (higgsino NLSP)	2 e,μ (Z)	2 jets	Yes	20.3	$\tilde{g}$	850 GeV	m(NLSP)>430 GeV	1503.03290
	Gravitino LSP	0	mono-jet	Yes	20.3	$F^{1/2}$ scale	865 GeV	$m(\tilde{G})$>1.8×10^{-4} eV, $m(\tilde{g})$=$m(\tilde{q})$=1.5 TeV	1502.01518
3rd gen. $\tilde{g}$ med.	$\tilde{g}\tilde{g}$, $\tilde{g}\to b\bar{b}\tilde{\chi}^0_1$	0	3 b	Yes	20.1	$\tilde{g}$	1.25 TeV	$m(\tilde{\chi}^0_1)$<400 GeV	1407.0600
	$\tilde{g}\tilde{g}$, $\tilde{g}\to t\bar{t}\tilde{\chi}^0_1$	0	7-10 jets	Yes	20.3	$\tilde{g}$	1.1 TeV	$m(\tilde{\chi}^0_1)$ <350 GeV	1308.1841
	$\tilde{g}\tilde{g}$, $\tilde{g}\to t\bar{t}\tilde{\chi}^0_1$	0-1 e,μ	3 b	Yes	20.1	$\tilde{g}$	1.34 TeV	$m(\tilde{\chi}^0_1)$<400 GeV	1407.0600
	$\tilde{g}\tilde{g}$, $\tilde{g}\to b\bar{t}\tilde{\chi}^+_1$	0-1 e,μ	3 b	Yes	20.1	$\tilde{g}$	1.3 TeV	$m(\tilde{\chi}^0_1)$<300 GeV	1407.0600
3rd gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to b\tilde{\chi}^0_1$	0	2 b	Yes	20.1	$\tilde{b}_1$	100-620 GeV	$m(\tilde{\chi}^0_1)$<90 GeV	1308.2631
	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to t\tilde{\chi}^\pm_1$	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde{b}_1$	275-440 GeV	$m(\tilde{\chi}^\pm_1)$=2 $m(\tilde{\chi}^0_1)$	1404.2500
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to b\tilde{\chi}^\pm_1$	1-2 e,μ	1-2 b	Yes	4.7/20.3	$\tilde{t}_1$	🟦 110-167 GeV 230-460 GeV	$m(\tilde{\chi}^\pm_1)$ = 2$m(\tilde{\chi}^0_1)$, $m(\tilde{\chi}^0_1)$=55 GeV	1209.2102, 1407.0583
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to Wb\tilde{\chi}^0_1$ or $t\tilde{\chi}^0_1$	0-2 e,μ	0-2 jets/1-2 b	Yes	20.3	$\tilde{t}_1$	90-191 GeV 210-700 GeV	$m(\tilde{\chi}^0_1)$=1 GeV	1506.08616
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to c\tilde{\chi}^0_1$	0	mono-jet/c-tag	Yes	20.3	$\tilde{t}_1$	90-240 GeV	$m(\tilde{t}_1)$-$m(\tilde{\chi}^0_1)$<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	$m(\tilde{\chi}^0_1)$>150 GeV	1403.5222
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\to\tilde{t}_1+Z$	3 e,μ (Z)	1 b	Yes	20.3	$\tilde{t}_2$	290-600 GeV	$m(\tilde{\chi}^0_1)$<200 GeV	1403.5222
EW direct	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}$, $\tilde{\ell}\to\ell\tilde{\chi}^0_1$	2 e,μ	0	Yes	20.3	$\tilde{\ell}$	90-325 GeV	$m(\tilde{\chi}^0_1)$=0 GeV	1403.5294
	$\tilde{\chi}^+_1\tilde{\chi}^-_1$, $\tilde{\chi}^+_1\to\tilde{\ell}\nu(\ell\tilde{\nu})$	2 e,μ	0	Yes	20.3	$\tilde{\chi}^\pm_1$	140-465 GeV	$m(\tilde{\chi}^0_1)$=0 GeV, $m(\tilde{\ell},\tilde{\nu})$=0.5($m(\tilde{\chi}^\pm_1)$+$m(\tilde{\chi}^0_1)$)	1403.5294
	$\tilde{\chi}^+_1\tilde{\chi}^-_1$, $\tilde{\chi}^+_1\to\tilde{\tau}\nu(\tau\tilde{\nu})$	2 τ	-	Yes	20.3	$\tilde{\chi}^\pm_1$	100-350 GeV	$m(\tilde{\chi}^0_1)$=0 GeV, $m(\tilde{\tau},\tilde{\nu})$=0.5($m(\tilde{\chi}^\pm_1)$+$m(\tilde{\chi}^0_1)$)	1407.0350
	$\tilde{\chi}^\pm_1\tilde{\chi}^0_2\to\tilde{\ell}_L\nu\tilde{\ell}_L\ell(\tilde{\nu}\nu)$, $\ell\tilde{\nu}\tilde{\ell}_L\ell(\tilde{\nu}\nu)$	3 e,μ	0	Yes	20.3	$\tilde{\chi}^\pm_1,\tilde{\chi}^0_2$	700 GeV	$m(\tilde{\chi}^\pm_1)$=$m(\tilde{\chi}^0_2)$, $m(\tilde{\chi}^0_1)$=0, $m(\tilde{\ell},\tilde{\nu})$=0.5($m(\tilde{\chi}^\pm_1)$+$m(\tilde{\chi}^0_1)$)	1402.7029
	$\tilde{\chi}^\pm_1\tilde{\chi}^0_2\to W\tilde{\chi}^0_1 Z\tilde{\chi}^0_1$	2-3 e,μ	0-2 jets	Yes	20.3	$\tilde{\chi}^\pm_1,\tilde{\chi}^0_2$	420 GeV	$m(\tilde{\chi}^\pm_1)$=$m(\tilde{\chi}^0_2)$, $m(\tilde{\chi}^0_1)$=0, sleptons decoupled	1403.5294, 1402.7029
	$\tilde{\chi}^\pm_1\tilde{\chi}^0_2\to W\tilde{\chi}^0_1 h\tilde{\chi}^0_1$, $h\to b\bar{b}/WW/\tau\tau/\gamma\gamma$	e,μ,γ	0-2 b	Yes	20.3	$\tilde{\chi}^\pm_1,\tilde{\chi}^0_2$	250 GeV	$m(\tilde{\chi}^\pm_1)$=$m(\tilde{\chi}^0_2)$, $m(\tilde{\chi}^0_1)$=0, sleptons decoupled	1501.07110
	$\tilde{\chi}^0_2\tilde{\chi}^0_3$, $\tilde{\chi}^0_{2,3}\to\tilde{\ell}_R\ell$	4 e,μ	0	Yes	20.3	$\tilde{\chi}^0_{2,3}$	620 GeV	$m(\tilde{\chi}^0_2)$=$m(\tilde{\chi}^0_3)$, $m(\tilde{\chi}^0_1)$=0, $m(\tilde{\ell},\tilde{\nu})$=0.5($m(\tilde{\chi}^0_2)$+$m(\tilde{\chi}^0_1)$)	1405.5086
	GGM (wino NLSP) weak prod.	1 e,μ + γ	-	Yes	20.3	$\tilde{W}$	124-361 GeV	$c\tau$<1 mm	1507.05493
Long-lived particles	Direct $\tilde{\chi}^+_1\tilde{\chi}^-_1$ prod., long-lived $\tilde{\chi}^\pm_1$	Disapp. trk	1 jet	Yes	20.3	$\tilde{\chi}^\pm_1$	270 GeV	$m(\tilde{\chi}^\pm_1)$-$m(\tilde{\chi}^0_1)$~160 MeV, $\tau(\tilde{\chi}^\pm_1)$=0.2 ns	1310.3675
	Direct $\tilde{\chi}^+_1\tilde{\chi}^-_1$ prod., long-lived $\tilde{\chi}^\pm_1$	dE/dx trk	-	Yes	18.4	$\tilde{\chi}^\pm_1$	482 GeV	$m(\tilde{\chi}^\pm_1)$-$m(\tilde{\chi}^0_1)$~160 MeV, $\tau(\tilde{\chi}^\pm_1)$<15 ns	1506.05332
	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	27.9	$\tilde{g}$	832 GeV	$m(\tilde{\chi}^0_1)$=100 GeV, 10 μs<$\tau(\tilde{g})$<1000 s	1310.6584
	Stable $\tilde{g}$ R-hadron	trk	-	-	19.1	$\tilde{g}$	1.27 TeV		1411.6795
	GMSB, stable $\tilde{\tau}$, $\tilde{\chi}^0_1\to\tilde{\tau}(\tilde{e},\tilde{\mu})+\tau(e,\mu)$	1-2 μ	-	-	19.1	$\tilde{\chi}^0_1$	537 GeV	10<tanβ<50	1411.6795
	GMSB, $\tilde{\chi}^0_1\to\gamma\tilde{G}$, long-lived $\tilde{\chi}^0_1$	2 γ	-	Yes	20.3	$\tilde{\chi}^0_1$	435 GeV	2<$\tau(\tilde{\chi}^0_1)$<3 ns, SPS8 model	1409.5542
	$\tilde{g}\tilde{g}$, $\tilde{\chi}^0_1\to ee\nu/e\mu\nu/\mu\mu\nu$	displ. $ee/e\mu/\mu\mu$	-	-	20.3	$\tilde{\chi}^0_1$	1.0 TeV	7 <$c\tau(\tilde{\chi}^0_1)$< 740 mm, $m(\tilde{g})$=1.3 TeV	1504.05162
	GGM $\tilde{g}\tilde{g}$, $\tilde{\chi}^0_1\to Z\tilde{G}$	displ. vtx + jets	-	-	20.3	$\tilde{\chi}^0_1$	1.0 TeV	6 <$c\tau(\tilde{\chi}^0_1)$< 480 mm, $m(\tilde{g})$=1.1 TeV	1504.05162
RPV	LFV $pp\to\tilde{\nu}_\tau+X$, $\tilde{\nu}_\tau\to e\mu/e\tau/\mu\tau$	$e\mu$,$e\tau$,$\mu\tau$	-	-	20.3	$\tilde{\nu}_\tau$	1.7 TeV	λ'_{311}=0.11, $\lambda_{132/133/233}$=0.07	1503.04430
	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
	$\tilde{\chi}^+_1\tilde{\chi}^-_1$, $\tilde{\chi}^+_1\to W\tilde{\chi}^0_1$, $\tilde{\chi}^0_1\to ee\tilde{\nu}_\mu, e\mu\tilde{\nu}_e$	4 e,μ	-	Yes	20.3	$\tilde{\chi}^\pm_1$	750 GeV	$m(\tilde{\chi}^0_1)$>0.2×$m(\tilde{\chi}^\pm_1)$, $\lambda_{121}\neq0$	1405.5086
	$\tilde{\chi}^+_1\tilde{\chi}^-_1$, $\tilde{\chi}^+_1\to W\tilde{\chi}^0_1$, $\tilde{\chi}^0_1\to\tau\tau\tilde{\nu}_e, e\tau\tilde{\nu}_\tau$	3 e,μ + τ	-	Yes	20.3	$\tilde{\chi}^\pm_1$	450 GeV	$m(\tilde{\chi}^0_1)$>0.2×$m(\tilde{\chi}^\pm_1)$, $\lambda_{133}\neq0$	1405.5086
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qqq$	0	6-7 jets	-	20.3	$\tilde{g}$	917 GeV	BR(t)=BR(b)=BR(c)=0%	1502.05686
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\tilde{\chi}^0_1$, $\tilde{\chi}^0_1\to qqq$	0	6-7 jets	-	20.3	$\tilde{g}$	870 GeV	$m(\tilde{\chi}^0_1)$=600 GeV	1502.05686
	$\tilde{g}\tilde{g}$, $\tilde{g}\to\tilde{t}_1 t$, $\tilde{t}_1\to bs$	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde{g}$	850 GeV		1404.250
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to bs$	0	2 jets + 2 b	-	20.3	$\tilde{t}_1$	100-308 GeV		ATLAS-CONF-2015-026
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to b\ell$	2 e,μ	2 b	-	20.3	$\tilde{t}_1$	0.4-1.0 TeV	BR($\tilde{t}_1\to be/\mu$)>20%	ATLAS-CONF-2015-015
Other	Scalar charm, $\tilde{c}\to c\tilde{\chi}^0_1$	0	2 c	Yes	20.3	$\tilde{c}$	490 GeV	$m(\tilde{\chi}^0_1)$<200 GeV	1501.01325

*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.

Particle properties can then be **reconstructed** using e.g. kinematic edges in invariant mass distributions:

$\tilde{\chi}_2^0 \to l\bar{l}\tilde{\chi}_1^0$ $m_{12} = \sqrt{p_1^2 + p_2^2}$ $m_{12} \leq m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0}$



$\tilde{\chi}_2^0 \to \tilde{l}\,\bar{l} \to l\,\tilde{\chi}_1^0\,\bar{l}.$

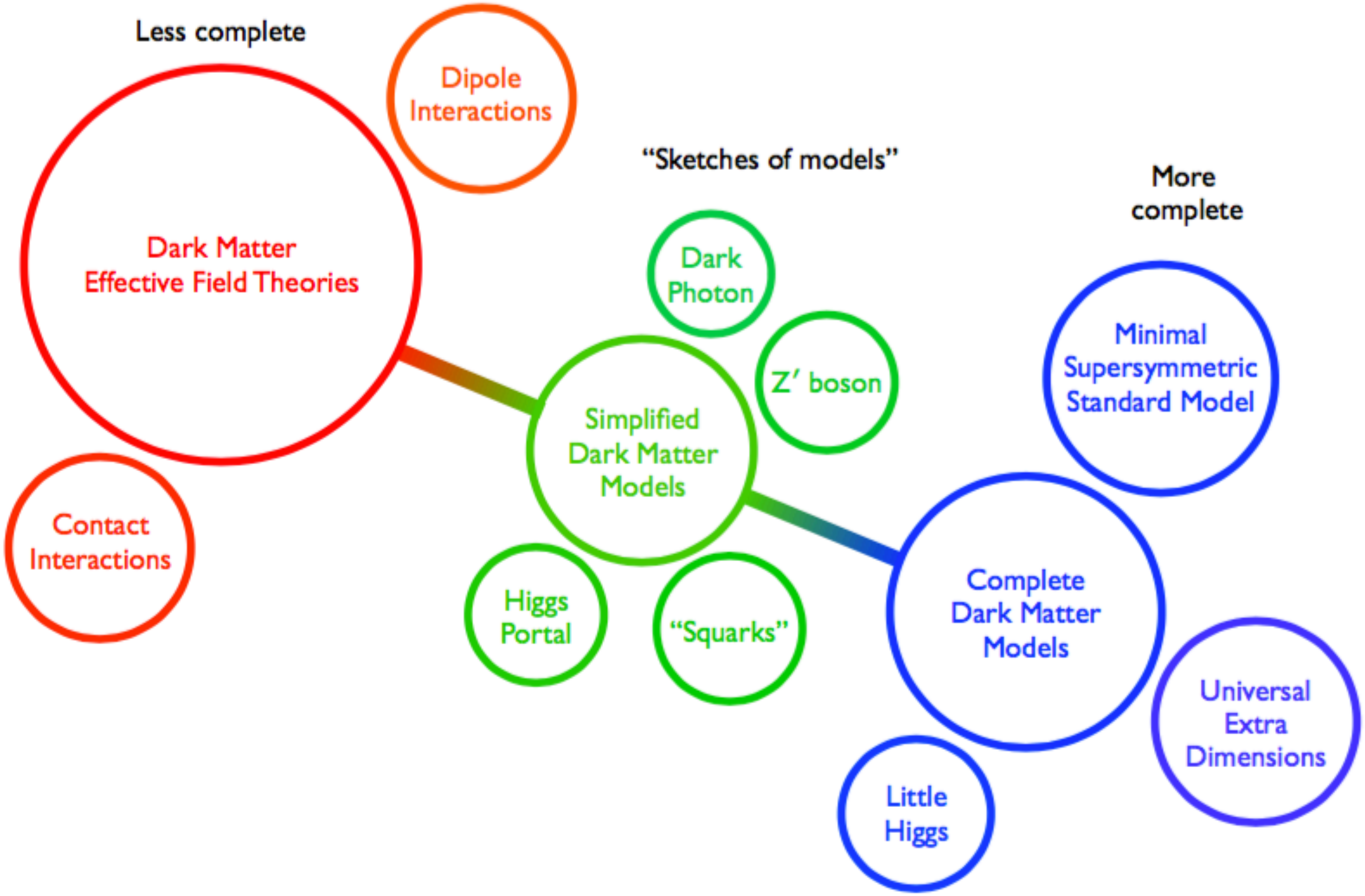
$$m_{12} < m_{\tilde{\chi}_1^0}\sqrt{1 - \frac{m_{\tilde{l}}}{m_{\tilde{\chi}_2^0}}}\sqrt{1 - \frac{m_{\tilde{\chi}_1^0}}{m_{\tilde{l}}}} \leq m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0}$$

Possible to construct **invariant mass** of multiple particles,

$$\tilde{q}_L \to q\tilde{\chi}_2^0 \to q\tilde{l}^{\pm}l^{\mp} \to ql^{\pm}l^{\mp}\tilde{\chi}_1^0$$

$$m(l\bar{l}q) \leq m_{\tilde{q}}\sqrt{1-\frac{m_{\tilde{\chi}_2^0}}{m_{\tilde{q}}}}\sqrt{1-\frac{m_{\tilde{\chi}_1^0}}{m_{\tilde{\chi}_2^0}}}.$$

Name of the game: devise **cuts**
(missing energy, number of jets, OS, SS leptons etc)
that **maximize S/N**



Less complete

Dipole Interactions

Dark Matter Effective Field Theories

Contact Interactions

"Sketches of models"

Dark Photon

Z′ boson

Simplified Dark Matter Models

Higgs Portal

"Squarks"

More complete

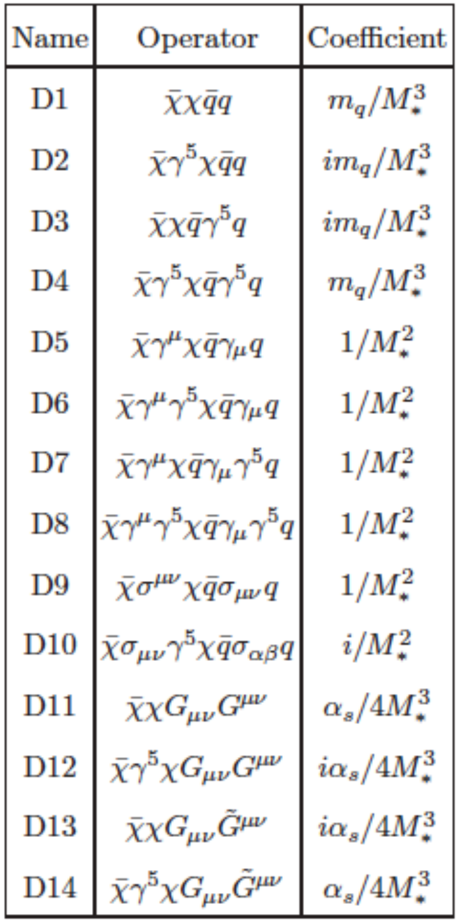
Minimal Supersymmetric Standard Model

Complete Dark Matter Models

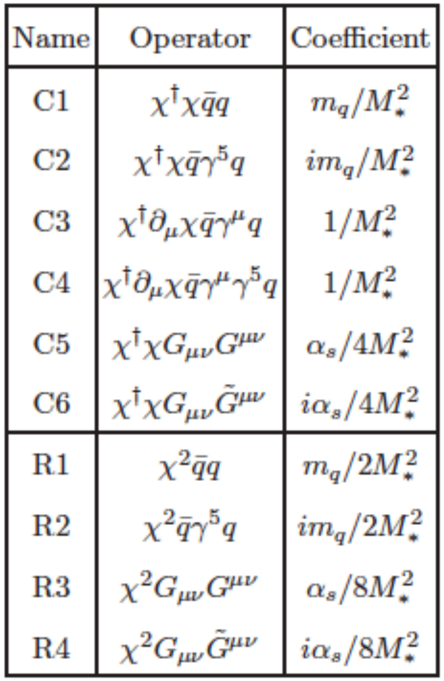
Universal Extra Dimensions

Little Higgs

EFT approach: assume some quantum numbers for DM (*m*,*J*), write down effective operators



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



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

arXiv:1008.1783 [hep-ph]

Algorithm is usual: calculate **production** cross section, **simulate** events, devise best possible set of **cuts**, compare **S/N**, set **limits** on effective operator scale

Issue: EFT has certain **range of validity**!
("cutoff") scale Λ corresponds to

$$\Lambda \sim M/\sqrt{g_1 g_2}.$$

Whether or not constraints make sense depends on whether the typical energy of the reaction (say momentum transfer P_{tr}) is smaller than, say, $4\pi\Lambda$

Good example of a **test**:

$$R(\Lambda) = \frac{\sigma(P_{\rm tr} < 4\pi\Lambda)}{\sigma(\text{any } P_{\rm tr})}$$

In practice, scales probed by LHC very **borderline** for EFT to make sense... cutoff scale close to P_{tr},
one would expect to produce new physics **on-shell**...

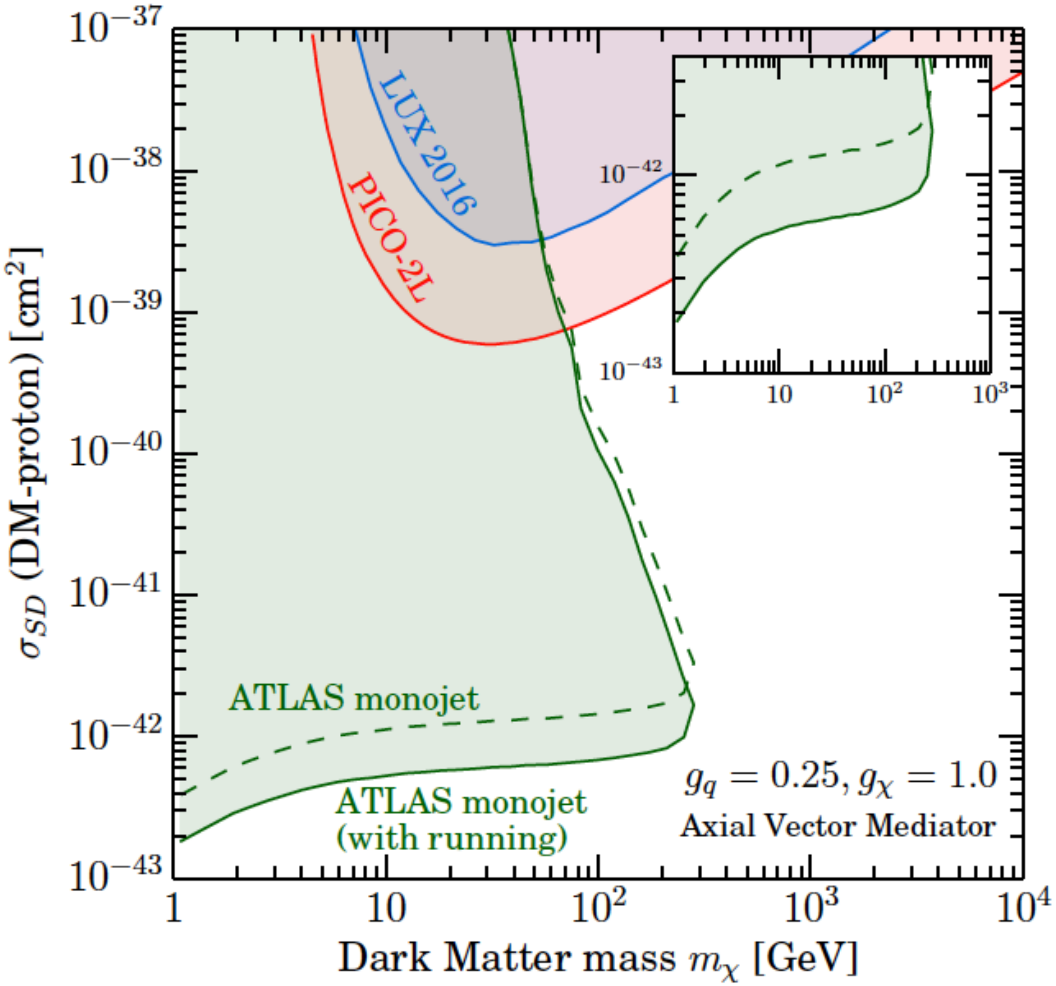
Alternate approach of **simplified models**, e.g.

$$\mathcal{L}_S \supset -\frac{1}{2}M_{\rm med}^2 S^2 - y_\chi S\bar{\chi}\chi - y_q^{ij} S\bar{q}_i q_j \ + \ \text{h.c.}$$

$$\mathcal{L}_V \supset -\frac{1}{2}M_{\rm med}^2 V_\mu V^\mu - g_\chi V_\mu \bar{\chi}\gamma^\mu \chi - g_q^{ij} V_\mu \bar{q}_i \gamma^\mu q_j \ + \ \text{h.c.}.$$

Set (meaningful) constraints on combinations of **mediator mass** and **couplings**, for given DM masses

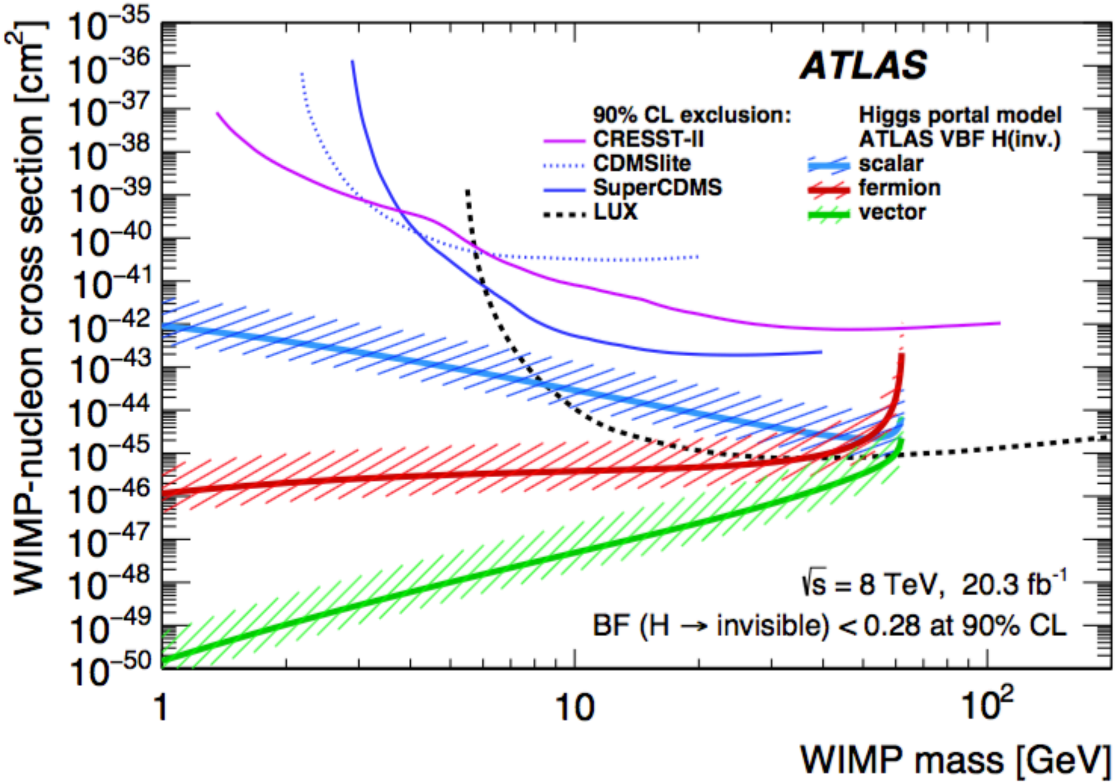
Can **compare** with **direct detection** results, but beware of RG effects in **matching scales**!!



10^{-37}
10^{-38}
10^{-39}
10^{-40}
10^{-41}
10^{-42}
10^{-43}
σ_{SD} (DM-proton) [cm^2]
1
10
10^2
10^3
10^4
Dark Matter mass m_χ [GeV]
LUX 2016
PICO-2L
ATLAS monojet
ATLAS monojet (with running)
$g_q = 0.25, g_\chi = 1.0$
Axial Vector Mediator
10^{-42}
10^{-43}
1
10
10^2
10^3

Additional probe: invisible **Higgs decay** to DM!

$$\lambda_{H\chi\chi}\,\bar{\chi}\chi|H|^2 \qquad\qquad \Gamma_H^{\rm inv} = \frac{{\rm BR}(H \to {\rm invisible})}{1 - {\rm BR}(H \to {\rm invisible})} \times \Gamma_H$$



What is **left** on the **menu**

- ✓ Gamma-ray **Galactic Center Excess** and Diffuse Emission Models
- ✓ **Collider** searches for Dark Matter
- ✓ **Axions** and axion searches

Axions and **ALP**s as dark matter candidates

$$\mathcal{L}_{\mathrm{QCD}} = -\frac{1}{4} G^a_{\mu\nu} G^{a\mu\nu} + \sum_{j=1}^{n} \left[\bar{q}_j \gamma^\mu i D_\mu q_j - \left(m_j q^\dagger_{\mathrm{L}j} q_{\mathrm{R}j} + \mathrm{h.c.} \right) \right] + \boxed{\frac{\theta g_s^2}{32\pi^2} G^a_{\mu\nu} \tilde{G}^{a\mu\nu}}$$

"theta" term innocuous **perturbatively** (total derivative), but entering pheno via **non-perturbative QCD effects**, producing large **neutron el. dipole moment**

$$d_n \simeq 5 \times 10^{-16} \bar{\theta} \;\; e \, \mathrm{cm} \qquad\qquad d_n < \mathrm{few} \times 10^{-26} \;\; e \, \mathrm{cm}$$

PQ: promote θ to **dynamical** variable,
driven to zero by its own **classical potential**

Postulate a global (quasi-)**symmetry** of the theory (broken by non-perturbative effects) $U(1)_{PQ}$;
Symmetry spontaneously **broken** at a scale f_a.
Axion is the (pseudo-)Nambu-Goldstone boson associated with $U(1)_{PQ}$

Axion **mass** is $$m_a \sim \frac{\Lambda^2_{\mathrm{QCD}}}{f_a} \sim 0.6\ \mathrm{eV} \left(\frac{10^7\ \mathrm{GeV}}{f_a}\right)$$

QCD effects produce effective (slightly model-dependent) **couplings** to **fermions** and **photons**, which drive phenomenology

$$\mathcal{L}_{a\bar{f}f} = i g_f \frac{m_f}{(f_a/N)} a \bar{f} \gamma_5 f$$

$$\mathcal{L}_{a\gamma\gamma} = -g_\gamma \frac{\alpha}{\pi} \frac{a}{f_a} \vec{E} \cdot \vec{B}.$$

Similar setup for axion-like particles (**ALP**s): new global U(1) symmetry spontaneously broken by a **hidden Higgs-type mechanism** at a scale v_h

Recast Higgs field as

$$H_h(x) = \frac{1}{\sqrt{2}}\left(v_h + h_h(x)\right) e^{ia(x)/v_h}$$

The potential for the ALP field ***a(x)*** is flat, and depending on the model realization one generates **couplings** to SM particles

$$\mathcal{L}_{ALP} = \frac{1}{2}\partial_\mu a \partial^\mu a - \frac{\alpha_s}{8\pi} C_{ag} \frac{a}{f_a} G^a_{\mu\nu} \tilde{G}^{a\mu\nu} - \frac{\alpha}{8\pi} C_{a\gamma} \frac{a}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu} + \frac{1}{2} \frac{C_{af}}{f_a} \partial_\mu a \bar{f} \gamma^\mu \gamma^5 f$$

Because of coupling to SM particles, esp. to photons, axions **decay** to **two photons**,

$$\tau_{a\to\gamma\gamma} \sim \frac{16\pi^2}{\alpha^2}\frac{\Lambda_{\rm QCD}^4}{m_a^5} \simeq 10^{24}\,\mathrm{s}\left(\frac{1\,\mathrm{eV}}{m_a}\right)^5 .$$

To have a **sufficiently long-lived axion** we must demand

$$\tau_U \sim 10^{10}\times(\pi 10^7)\,\mathrm{s} \lesssim 10^{24}\,\mathrm{s}\left(\frac{1\,\mathrm{eV}}{m_a}\right)^5 \Rightarrow m_a \lesssim 25\,\mathrm{eV},\quad f_a \gtrsim 4\times 10^6\,\mathrm{GeV}$$

Axions can have dramatic **impact** on **stars**:
Compton-like and brems-like processes

$$\gamma + e \to a + e \qquad e + Z \to a + e + Z.$$

produce an **axion luminosity**, e.g. for the Sun, of

$$L_a \sim 6 \times 10^{-4} \left(\frac{m_a}{1\ \mathrm{eV}}\right)^2 L_\odot$$

Since solar luminosity is whatever it is, axion emission would require **enhanced nuclear energy production**, thus larger **neutrino** flux!
Limits are around 1 eV...

Axions would also **cool supernovae**, $L_a \sim 10^{59}\text{ergs/s}\left(\frac{m_a}{1\text{ eV}}\right)^2$

$L_\nu \sim 10^{53}$ ergs/s $L_a \gg L_\nu$ for $m_a \gg 10^{-3}$ eV.

If axions are **too massive**, they get **trapped** and they don't contribute to SN luminosity efficiently

$$10^{-3} \lesssim m_a/(1\text{ eV}) \lesssim 2.$$

How can axions be **produced**? **Thermally**?

$a+g \leftrightarrow \bar{q}+q$ or $g+g$, or $a+q(\bar{q}) \leftrightarrow g+q(\bar{q})$

$$\frac{\alpha_s}{8\pi}\frac{a}{f_a}G\tilde{G} \qquad \sigma_{q,g} \sim \frac{\alpha_s^3}{\pi^2 f_a^2}$$

$$\frac{\Gamma}{H} \sim 1 \quad \Rightarrow \quad N_c N_f T^3 \sigma_{q,g} \sim \frac{T^2}{M_P}$$

$$T_{\rm th.ax.} \simeq {\rm few} \times 10^{11}\ {\rm GeV} \left(\frac{f_a}{10^{12}\ {\rm GeV}}\right)$$

However, at **lower temperatures** (below QCD phase transition)

$$\pi + \pi \leftrightarrow \pi + a. \qquad \sigma_\pi \sim 1/f_a^2$$

$$\frac{n_\pi \sigma_\pi}{H} \sim \frac{m_\pi M_P}{f_a^2} \gtrsim 1 \quad \Rightarrow f_a \lesssim 5 \times 10^8 \text{ GeV}.$$

$$\Omega_{\text{th.ax.}} \sim \frac{m_a}{130 \text{ eV}}$$

...but we know this doesn't work! **Hot DM** not good! Also, other constraints on axion mass... how about **non-thermal production**?

mis-alignment mechanism and **axion strings**

$$\Omega_{\rm mis} h^2 \simeq 0.4 \left(\frac{m_a}{10\ \mu{\rm eV}} \right)^{-1.18} \left(\frac{\bar{\theta}_1}{\pi} \right)^2$$

$$(\bar{\theta}_1)_{\rm RMS} \equiv \left(\int_{-\pi}^{\pi} {\rm d}\bar{\theta}_1 \frac{\bar{\theta}_1^2}{2\pi} \right)^{1/2} = \frac{\pi}{\sqrt{3}}$$

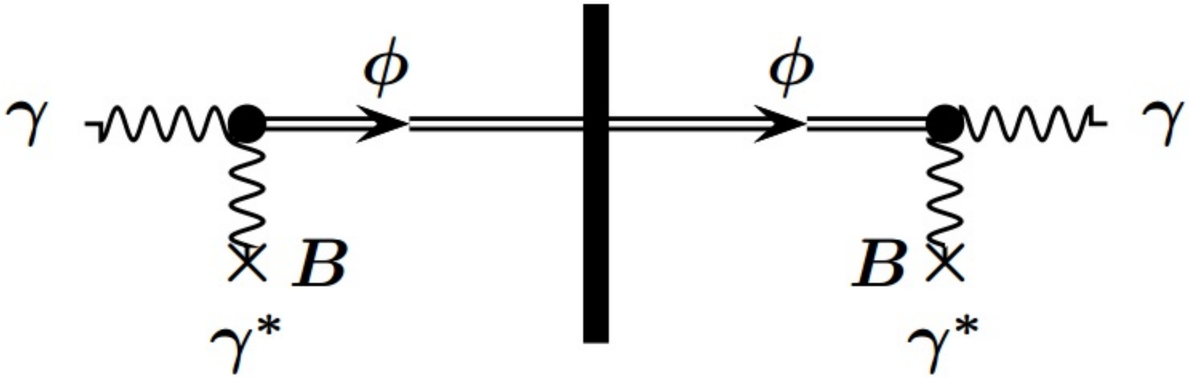
$$\Omega_{\rm mis,RMS} h^2 \sim 0.13 \left(\frac{m_a}{10\ \mu{\rm eV}} \right)^{-1.18}$$

$$\Omega_{\rm strings+domain\ walls} h^2 = (3.5 \pm 1.7) \left(\frac{m_a}{10\ \mu{\rm eV}} \right)^{-1.18}$$

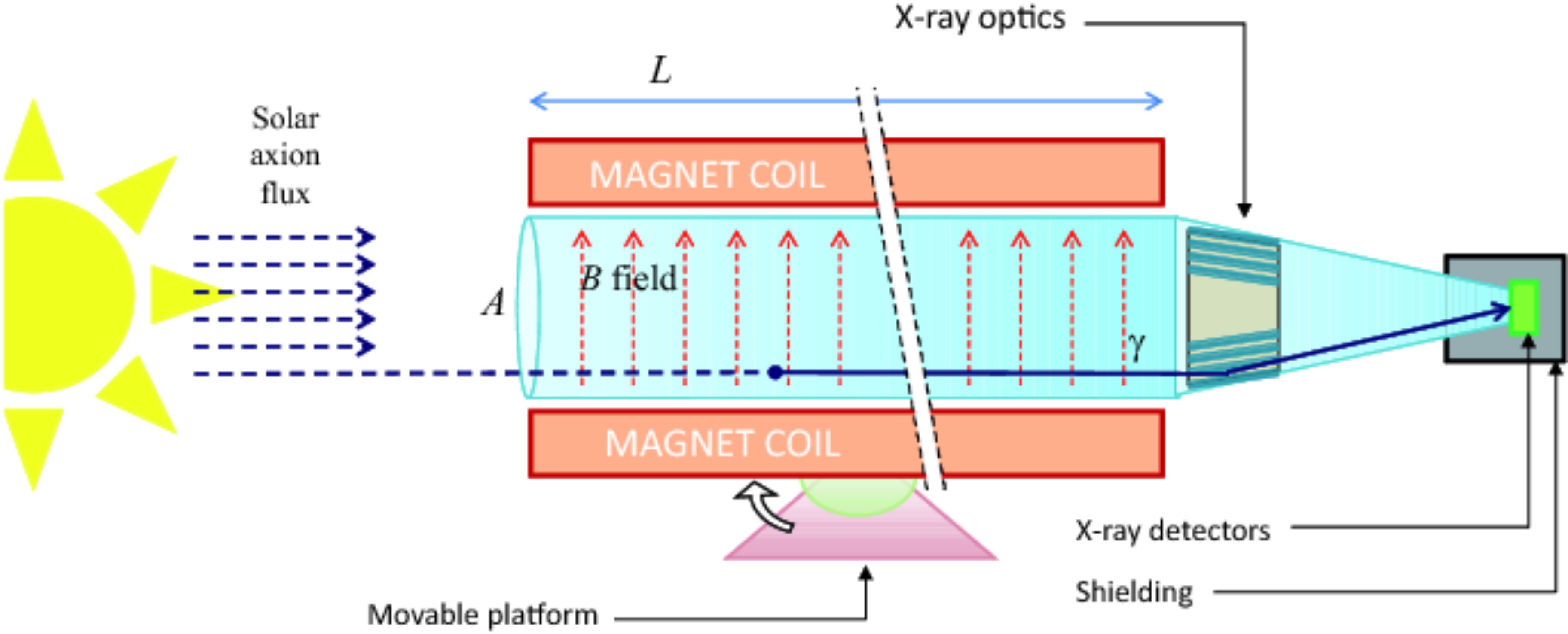
$$\Omega_{\rm strings+domain\ walls} h^2 \sim 0.4 \left(\frac{m_a}{10\ \mu{\rm eV}} \right)^{-1.18}$$

Axion laboratory searches based on **light-shining-through-wall** experiments

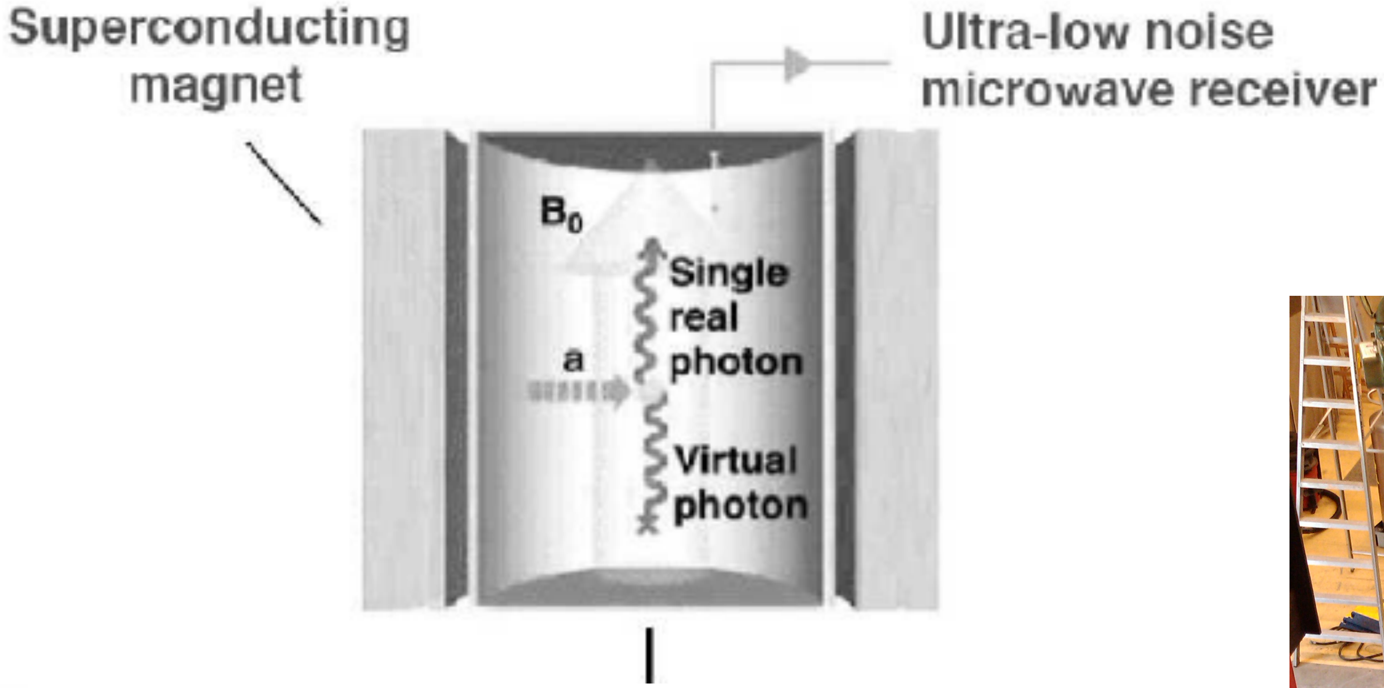
$$\gamma + Ze \leftrightarrow Ze + a$$

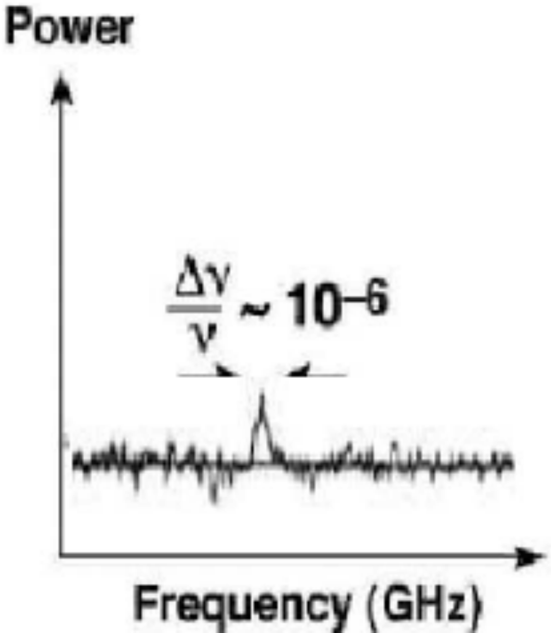


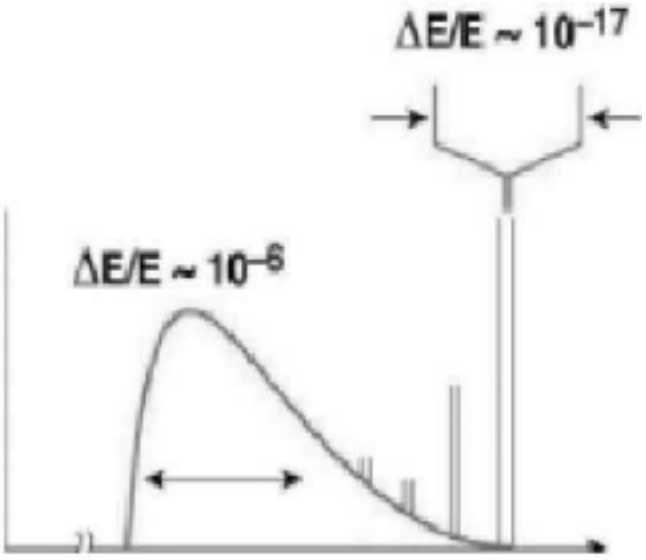
microwave cavities, and "**helioscopes**"

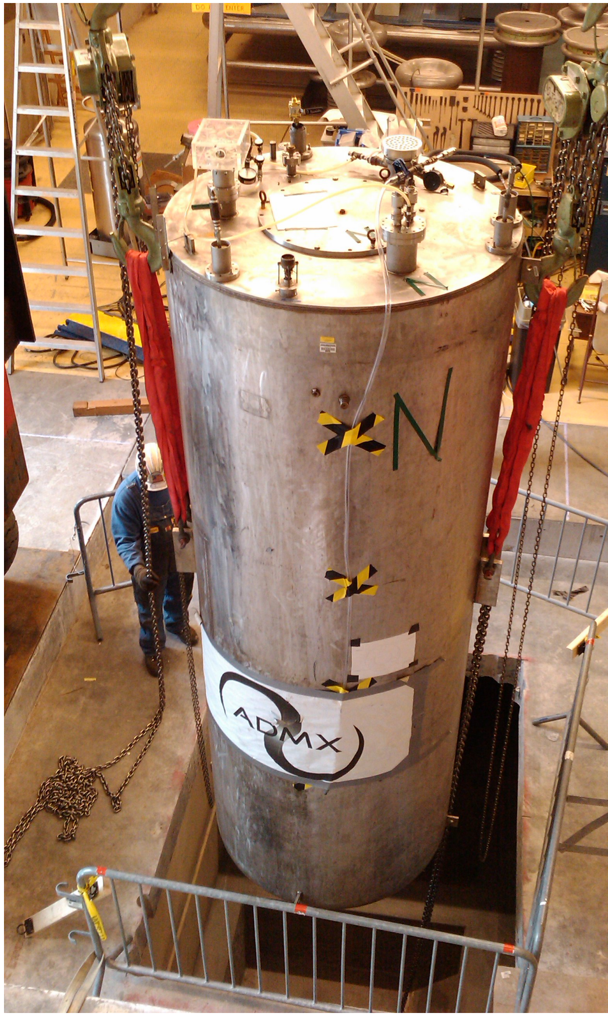


microwave cavities, and "**helioscopes**"


Superconducting magnet
Ultra-low noise microwave receiver
B_0
a
Single real photon
Virtual photon


Power
$\frac{\Delta\nu}{\nu} \sim 10^{-6}$
Frequency (GHz)


$\Delta E/E \sim 10^{-17}$
$\Delta E/E \sim 10^{-6}$


ADMX
N

What is **left** on the **menu**

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- ✓ **Sterile neutrinos** and the 3.5 keV line puzzle

Sterile neutrino: killing two (or three) birds with one stone

“prendere due (o tre) piccioni con una fava”

SM Neutrinos are strictly **massless**;
however, they are not observed to be!

Simplest addition: set of ***n*** singlet fermions ***N**$_a$*, gauge singlets

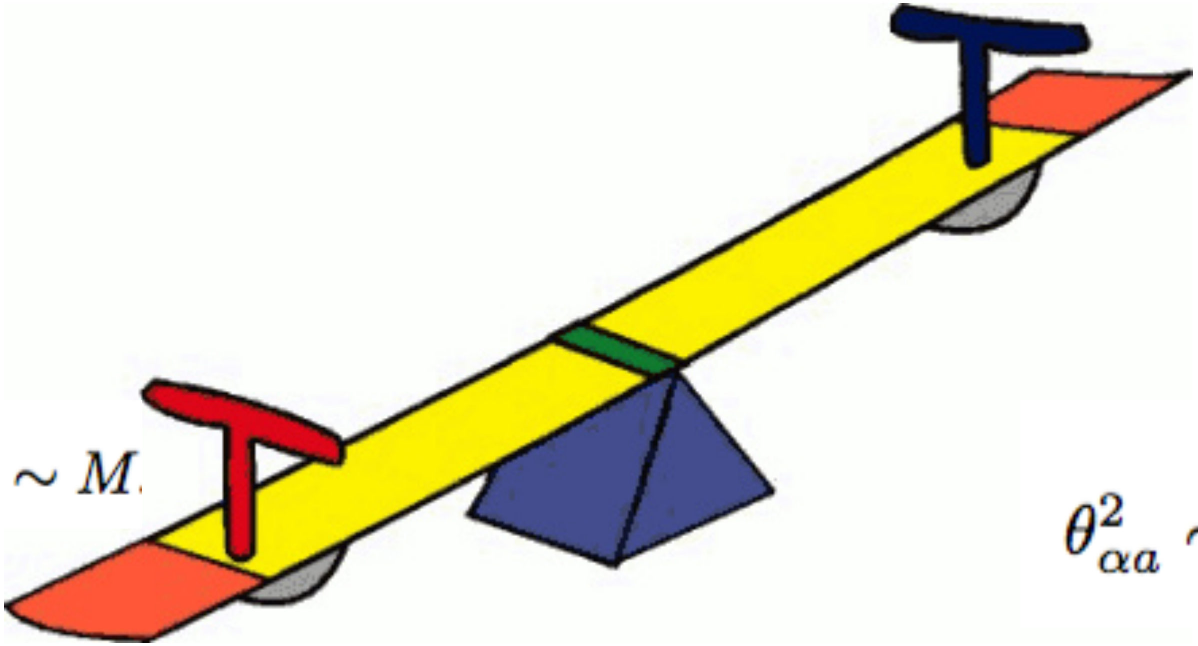
$$\mathcal{L} = \mathcal{L}_{\rm SM} + i\bar{N}_a \partial\!\!\!/ N_a - y_{\alpha a} H^\dagger \bar{L}_\alpha N_a - \frac{M_a}{2}\bar{N}_a^c N_a$$

$$M^{(n+3)} = \begin{pmatrix} 0 & y_{\alpha a}\langle H\rangle \\ y_{\alpha a}\langle H\rangle & \mathrm{diag}(M_1, ..., M_n) \end{pmatrix}$$

If the following holds $y_{\alpha a}\langle H\rangle \sim yv \ll M_a \sim M$

"**See-saw**" mechanism!

$$M(\nu_{1,2,3}) \sim \frac{y^2v^2}{M}$$



$$m(\nu_a) \sim M$$

$$\theta^2_{\alpha a} \sim \frac{y^2_{\alpha a}v^2}{M^2}$$

Sterile neutrinos mix via explicit (but possibly very small) **mixing** with ordinary neutrinos

...as such, they **decay** (into 3 SM neutrinos)

$$\Gamma \sim \theta^2 G_F^2 m^5 \sim \theta^2 \left(\frac{m}{\mathrm{keV}}\right)^5 10^{-40}\ \mathrm{GeV} \Rightarrow \tau \sim 10^{16}\mathrm{s}\ \theta^{-2} \left(\frac{m}{\mathrm{keV}}\right)^{-5}$$

$$\theta^{-2} \left(\frac{m}{\mathrm{keV}}\right)^{-5} \gg 1$$

Being fermions, ***m > keV*** (e.g. Tremaine-Gunn)

How can sterile neutrinos be **produced**?

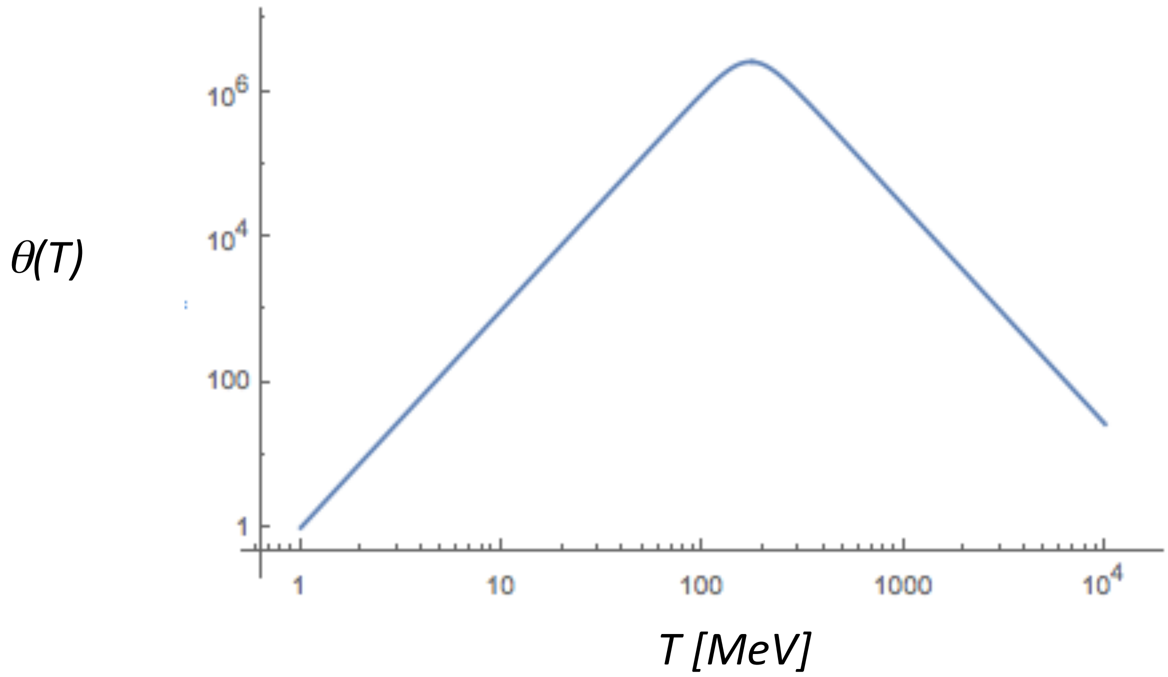
Basically, **freeze-in**: dump out-of-equilibrium sterile ν's through the universe history

$$\Gamma_{\nu_s} \sim (G_F^2 T^5)\theta^2(T)$$

Subtlety is **matter effects**, inducing ***T*-dependence** in the mixing angle

$$\theta \to \theta_M \simeq \frac{\theta}{1+2.4\left(\frac{T}{200\ \mathrm{MeV}}\right)^6\left(\frac{1\ \mathrm{keV}}{m}\right)^2}$$

Sterile n yield **$Y=n/s$** scales as production rate times Hubble time **$t_H=M_P/T^2$**



Maximal yield in **100-200 MeV** range → QCD phase transition effects

$$\Omega_{\nu_s} h^2 \sim 0.1 \left(\frac{\theta^2}{3 \times 10^{-9}} \right) \left(\frac{m_s}{3\,\mathrm{keV}} \right)^{1.8}$$

(**Dodelson**-Widrow)

Additional important effect from Mikheyev-Smirnov-Wolfenstein effect with large **lepton asymmetries**
(**Shi-Fuller** resonant production)

Other possibilities: **non-thermal production** from singlet scalar coupling

$$\frac{h_a}{2} S \bar{N}_a^c N_a$$

$SH^\dagger H$ and/or $S^2 H^\dagger H$

$$\frac{n_N}{s} \sim \frac{n_S}{s} \tau \Gamma \sim \frac{M_P}{M_S^2} \frac{h^2}{16\pi} M_S$$

$$\Omega_N \sim 0.2 \left(\frac{h}{10^{-8}} \right)^3 \frac{\langle S \rangle}{m_S}$$

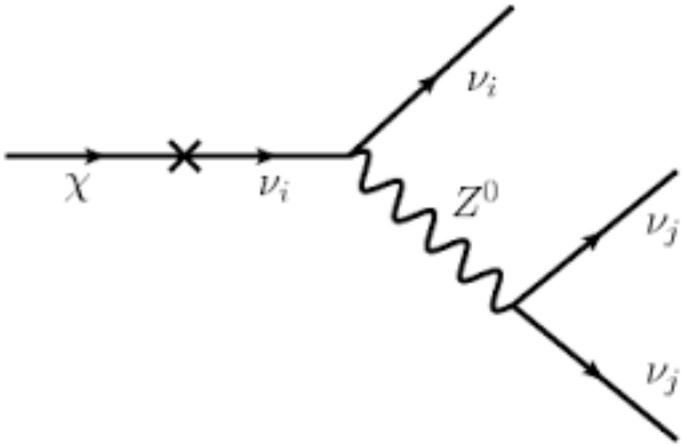
Sterile neutrino interesting from the standpoint of **structure formation** – remember

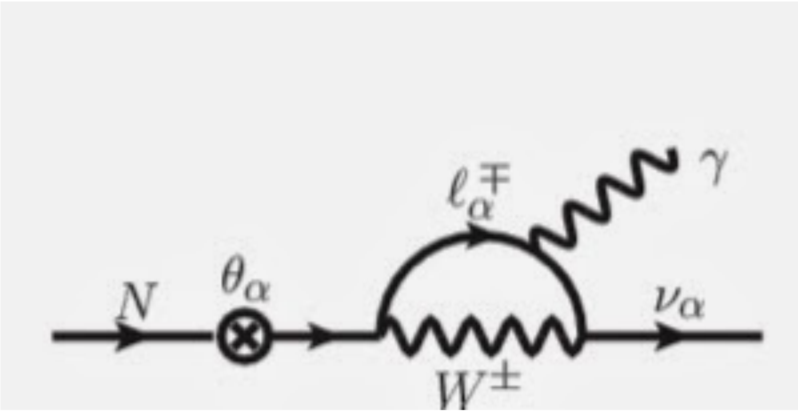
$$M_{\text{cutoff, hot}} \sim \left(\frac{1}{H(T=m_\nu)}\right)^3 \rho_\nu(T=m_\nu) \sim \left(\frac{M_P}{m_\nu^2}\right)^3 m_\nu \cdot m_\nu^3 = \frac{M_P^3}{m_\nu^2}$$

$$\frac{M_P^3}{m_\nu^2} \sim 10^{15}\, M_\odot \left(\frac{m_\nu}{30\ \text{eV}}\right)^{-2} \sim 10^{12}\, M_\odot \left(\frac{m_\nu}{1\ \text{keV}}\right)^{-2}$$

...and could explain high-velocity **pulsars**!

How would we **detect** sterile neutrino dark matter?





$$\Gamma_{\nu_s \to \gamma \nu_a} \approx \frac{\alpha}{16\pi^2} \theta^2 G_F^2 m^5$$

$$\phi_\gamma = \frac{\Gamma_{\gamma\nu}}{4\pi} \frac{E_\gamma}{m} \int_{fov} d\Omega \int_{\text{line of sight}} \frac{\rho_{\rm DM}}{m} dr(\psi) = \frac{\Gamma_{\gamma\nu}}{8\pi m} J(\Delta\Omega, \psi)$$

few ×10^{18} GeV/cm^2

key background: diffuse **cosmic X-ray background**

$$\phi_{\rm CXB} \sim 9.2 \times 10^{-7} \left(\frac{E}{1\ \rm keV}\right)^{-0.4} \rm cm^{-2}\, s^{-1}\, arcmin^{-2} \quad \rightarrow \quad \sim 10^{-4}\, cm^{-2}\, s^{-1}$$

$$\phi_\gamma = \frac{\Gamma_{\gamma\nu}}{8\pi}\frac{J}{m} \sim 10^{-4}\ \rm cm^{-2}\, s^{-1} \left(\frac{\theta^2}{10^{-7}}\right)\left(\frac{m}{1\ \rm keV}\right)^4 \left(\frac{J}{10^{18}\ \rm GeV/cm^2}\right)$$

$$\left(\frac{\theta^2}{10^{-7}}\right)\left(\frac{m}{1\ \rm keV}\right)^4 \lesssim 1$$

Have we **detected** it?

Bulbul+ (2014)

- Stacked clusters
- Perseus

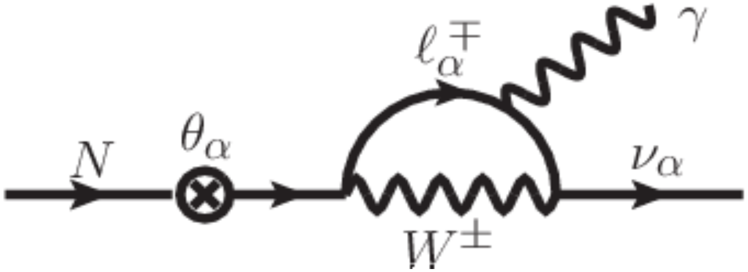
Boyarsky+ (2014)

- M31 (Andromeda)
- Perseus

Jeltema+Profumo (2014)

- Galactic Center

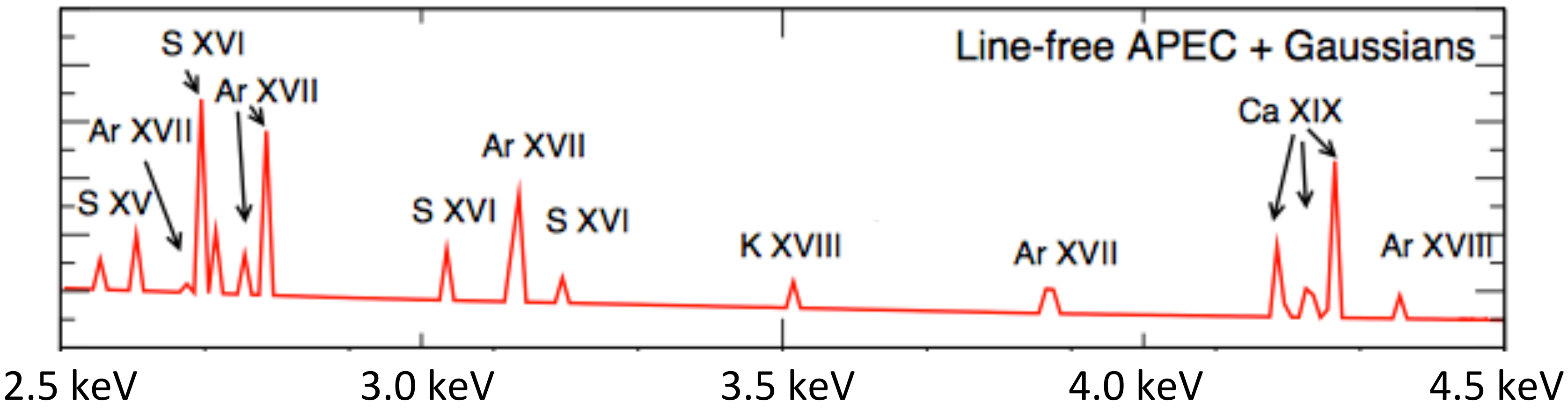
X-ray lines predicted from sterile neutrinos



- SU(2)$_L$ gauge singlet, but (small) mixing angle with active neutrinos
- Viable DM candidates (Dodelson-Woodrow production; "warm" DM)
- Possibly connected with baryogenesis (νMSM)
- Would decay via mixing with active neutrinos

3.5 keV lines (roughly) compatible with this!

X-ray lines also from atomic transitions of highly-ionized Z ~ 16-20 atoms*



K XVIII has (two) lines near 3.5 keV

[K (Z=19) ion with 18-1 electrons missing, i.e. “He-like”]

* $E_z \sim 13.6\ Z^2$ eV$\rightarrow$ $Z \sim (3{,}500 / 13.6)^{1/2} \sim 16$, but $Z_{eff} < Z$…

How do we tell K apart from sterile ν or other exotica??

Try to predict K XVIII line brightness using other elemental lines

two key complications:

#1 Plasma Temperature

#2 Relative Elemental Abundances

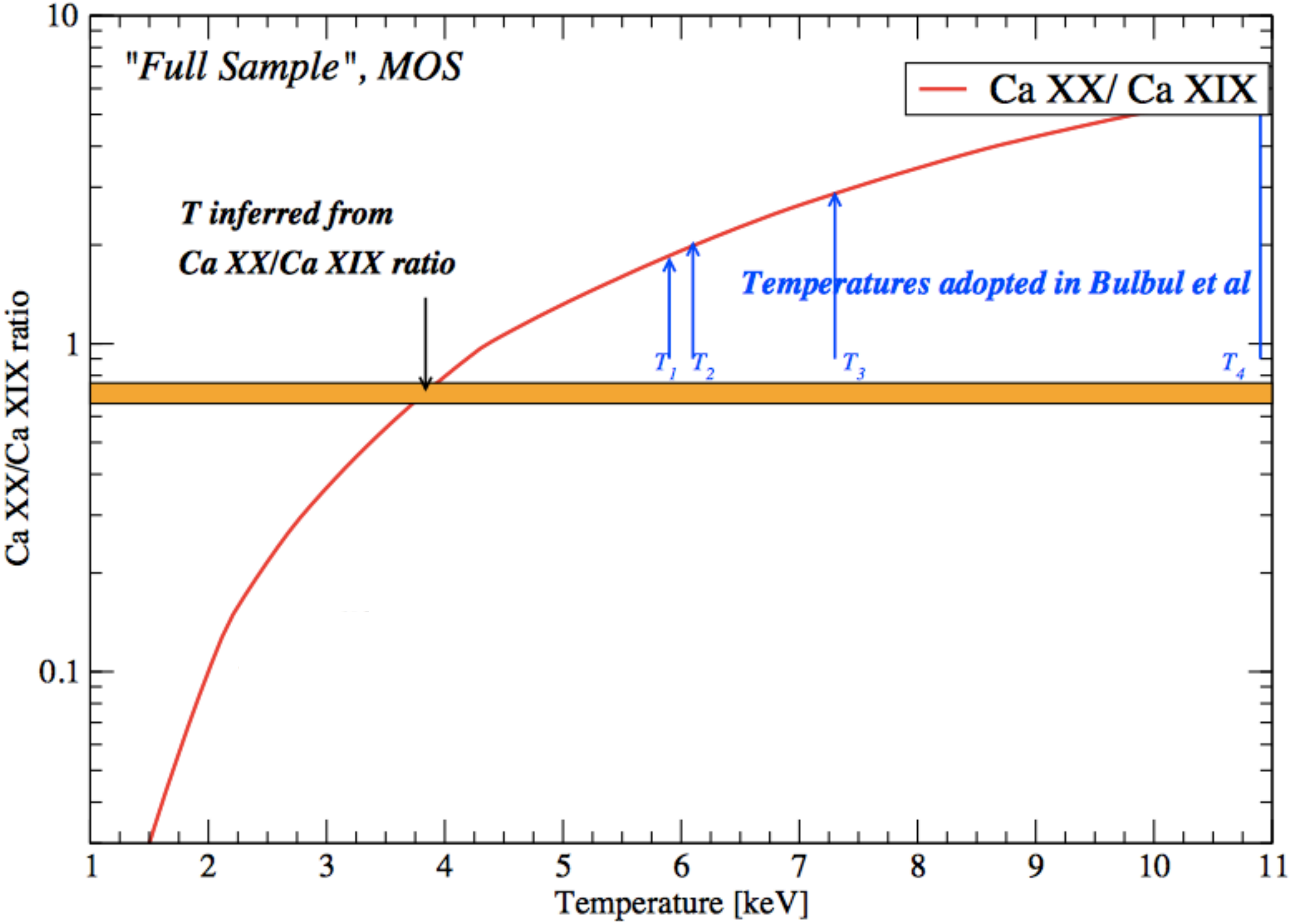
Bulbul+ argues against K XVIII
since prediction for K 3.5 keV line too low
(by factors ~20 for solar abundances)

…but this prediction makes two
key mistakes:

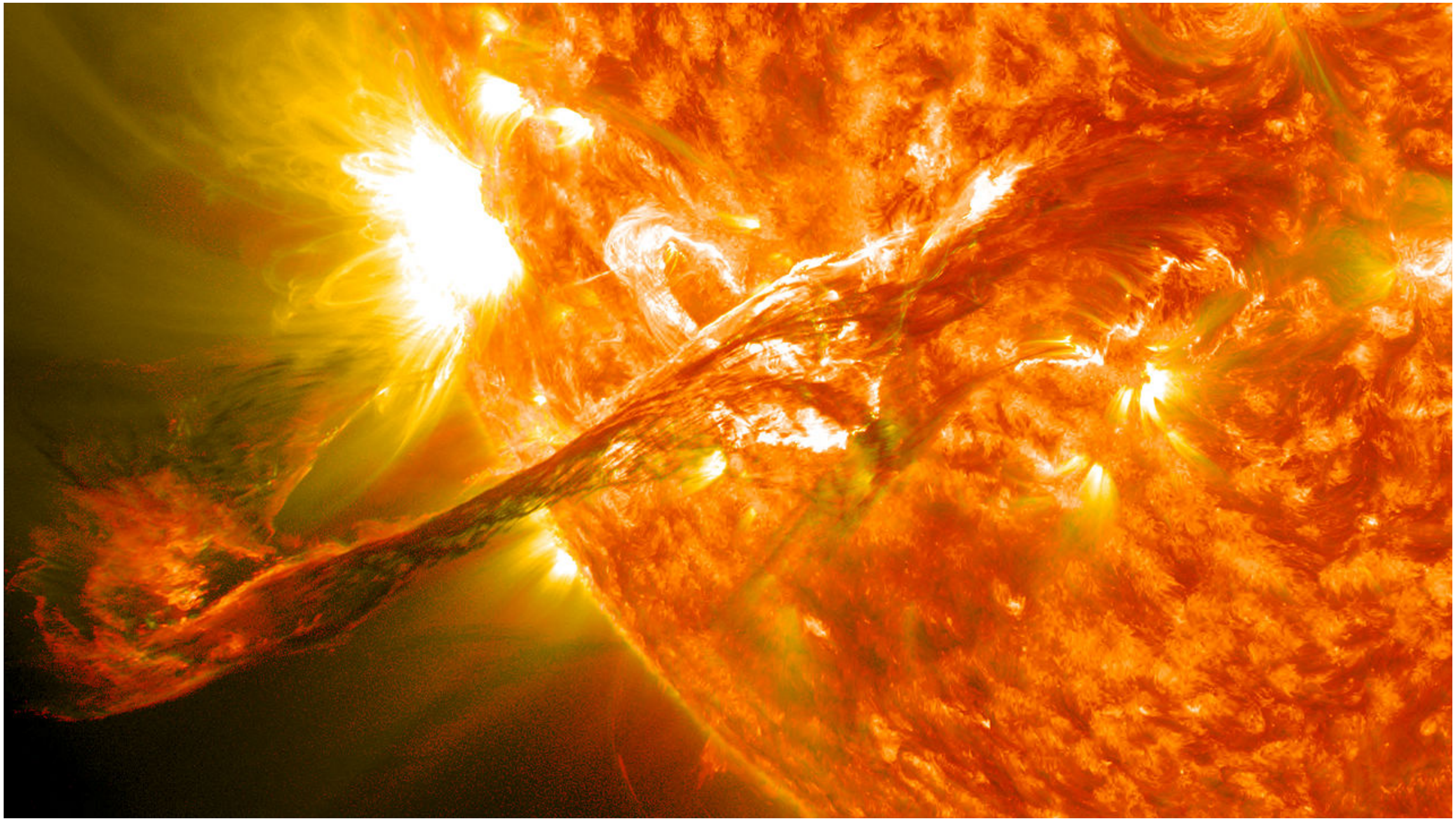
#1 Plasma Temperature

#2 Relative Elemental Abundances

Bulbul+ uses very large T highly suppresses K emission!



also, under-estimate ~10 of K abundance! (Photospheric versus Coronal)



* Phillips et al, ApJ 2015, RESIK crystal spectrometer

Jeltema+Profumo (2014) showed that
for clusters, and for our Galaxy
KXVIII could explain the 3.5 keV line

Other tests?

(1) look elsewhere!

(2) use something different than spectrum!

(1) look elsewhere: depressing

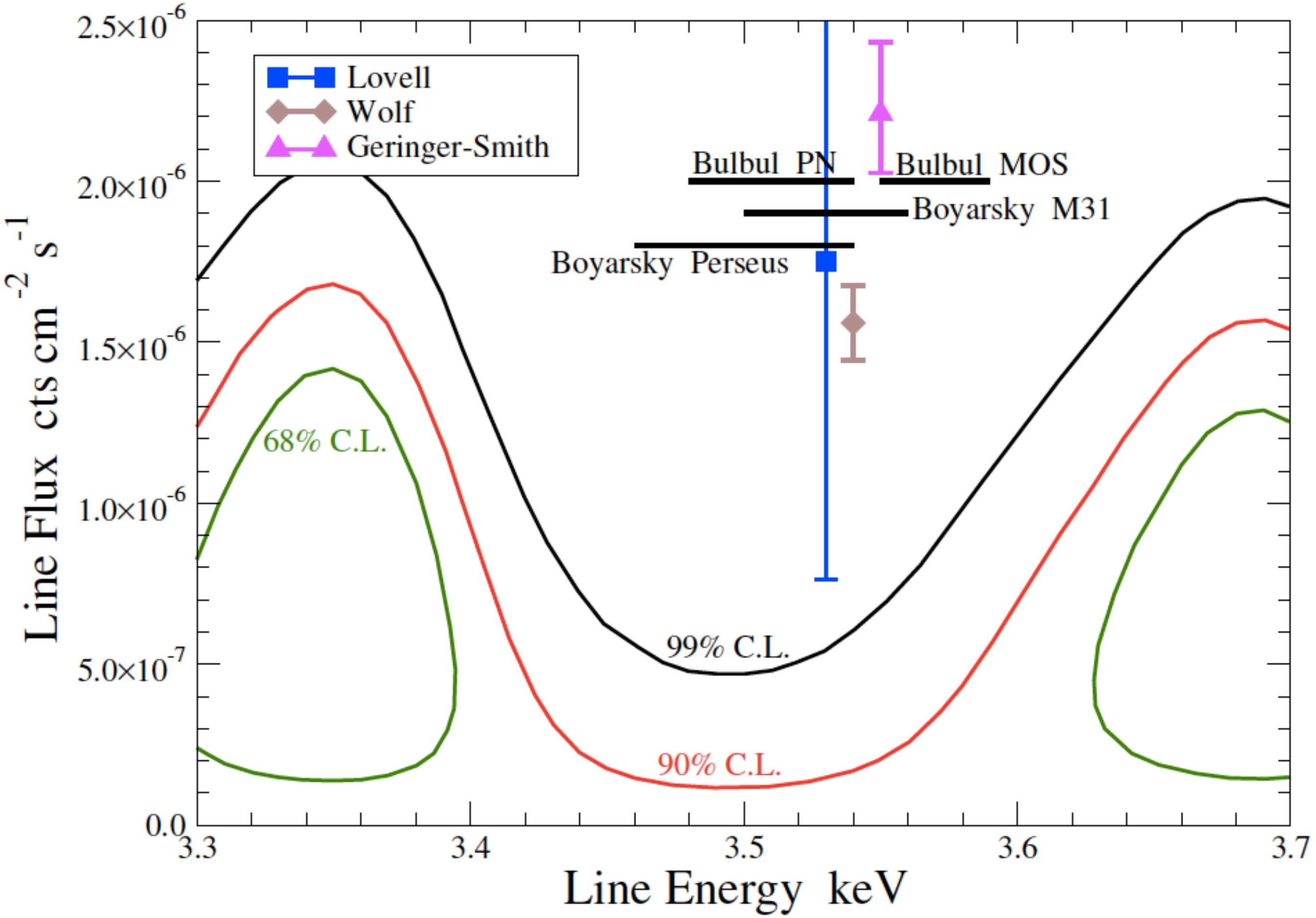
- no signal from dSph*
- no signal from stacked galaxies and groups, low-T plasma**
- no signal from M31***

*Malyshev et al 2014

** Anderson et al 2014

*** Jeltema and Profumo 2014

- **no signal from dedicated 1.4 Ms XMM observation of Draco dSph***

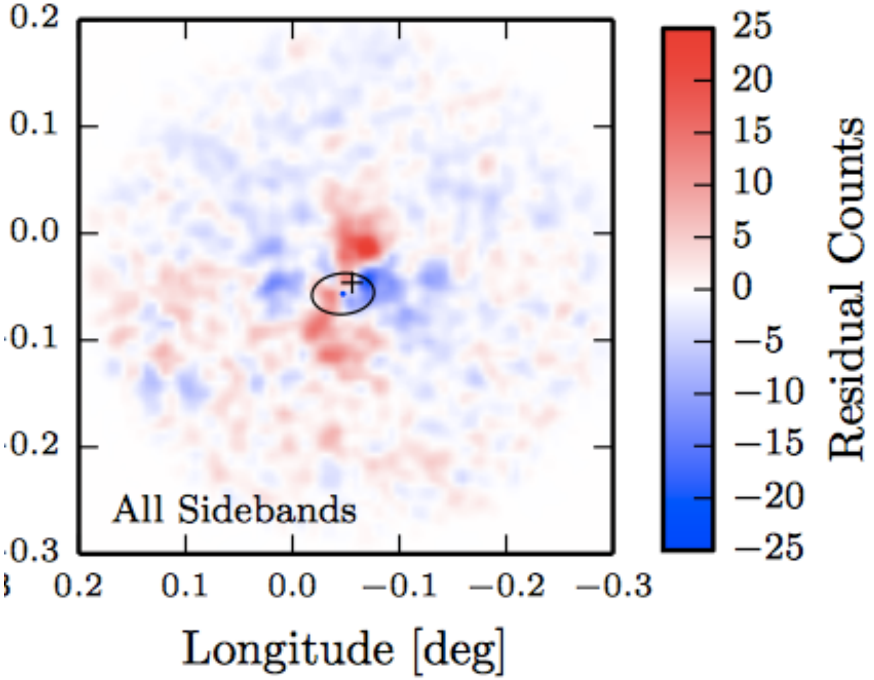


* Jeltema and Profumo, MNRAS (2015)

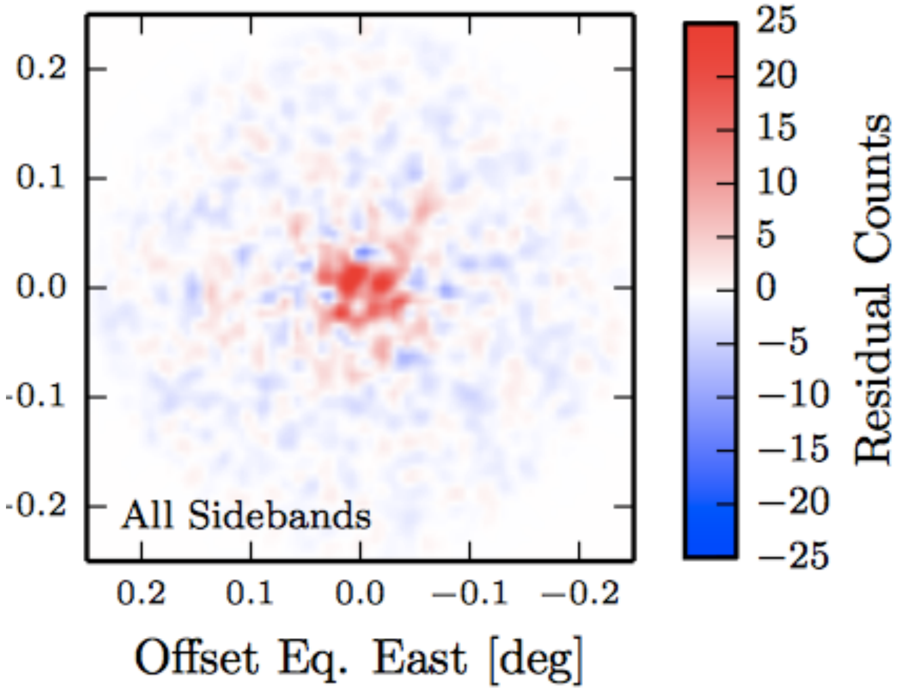
(2) use something
different than spectrum!

Morphology!

Look at where the
3.5 keV photons come from!



Milky Way



Perseus

Morphology: looks like thermal line
decaying DM strongly disfavored

Carlson, Jeltema and Profumo, JCAP 2015

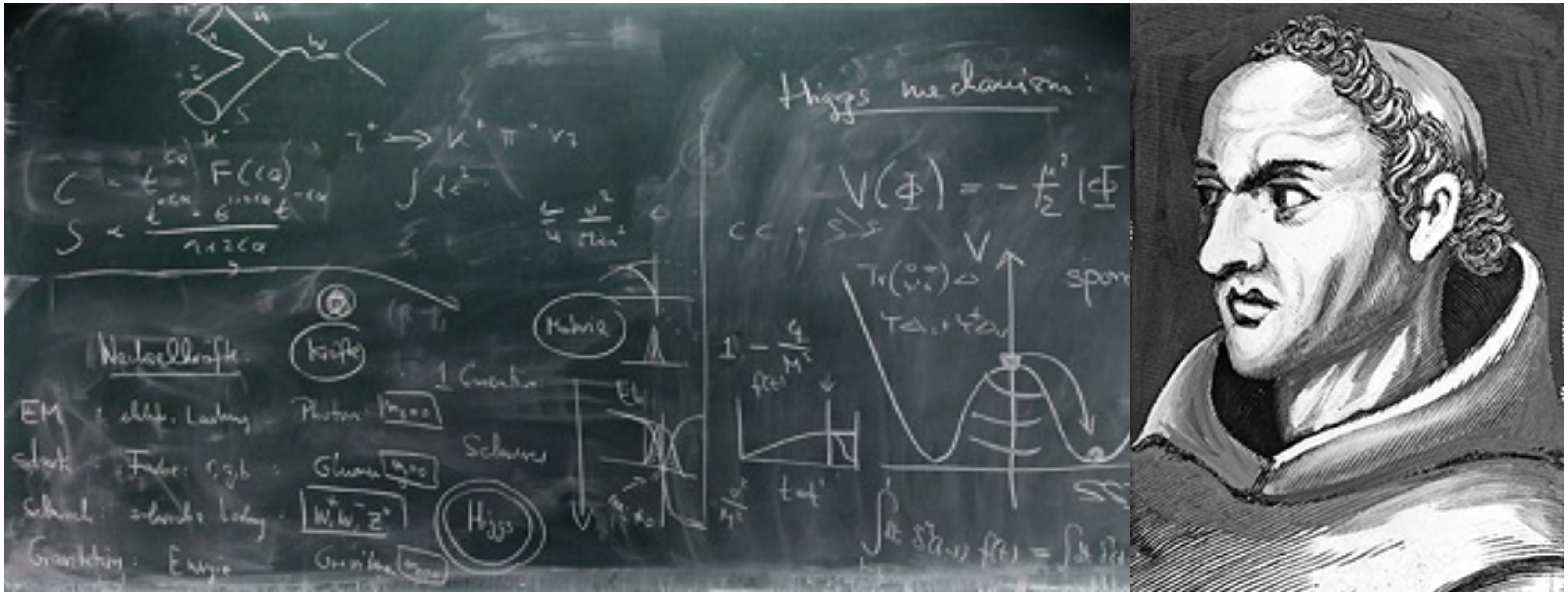
Recap!

	Signal?	Morphology?	K XVIII
Clusters [Perseus]	✔	~Cool core	✔
Galactic Center	✔	~Quadrupolar	✔
dSph [Draco]	✗	N/A	N/A

Dark Matter, or Potassium?

Entia non sunt multiplicanda praeter necessitatem

(William of Occam, c. 1286-1347)



Rare picture of William of Occam, perplexed by XXI century particle theorists working on dark matter

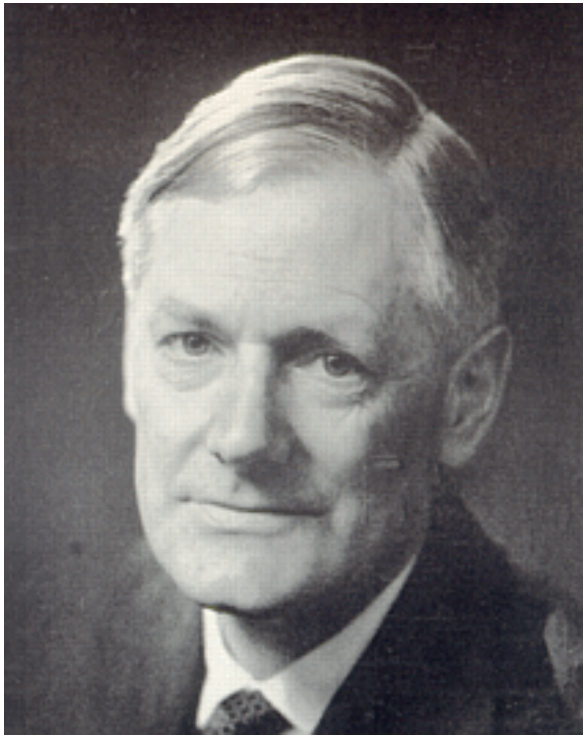
What if it is Dark Matter?

simplest models (sterile neutrino) don’t work

every challenge is an opportunity…
…interesting riddle for theorists!

Redman's Theorem

"Any competent theoretician can fit any given theory to any given set of facts" (*)

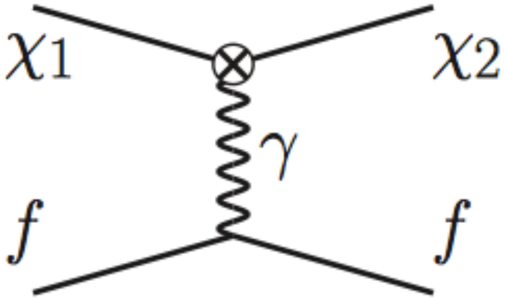


Roderick O. Redman
(b. 1905, d. 1975)
Professor of Astronomy
at Cambridge University

(*) Quoted in M. Longair's "High Energy Astrophysics", sec 2.5.1 "The psychology of astronomers and astrophysicists"

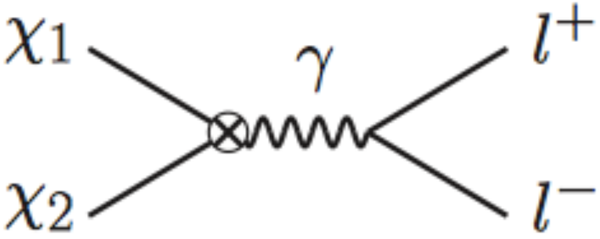
3.5 keV line …an excuse for an exciting, new mechanism for a signal from Dark Matter!

$$\chi_1 f \to \chi_2 f \longrightarrow \chi_2 \to \chi_1 \gamma$$



Signal ~ ρ_{DM} x ρ_{gas}

Good Thermal Relic!



D'Eramo, Hambleton, Profumo and Stefaniak, 1603.04895

Why should you be excited by our model?

1. Brand new indirect detection channel!

2. Unmistakable signature, background free

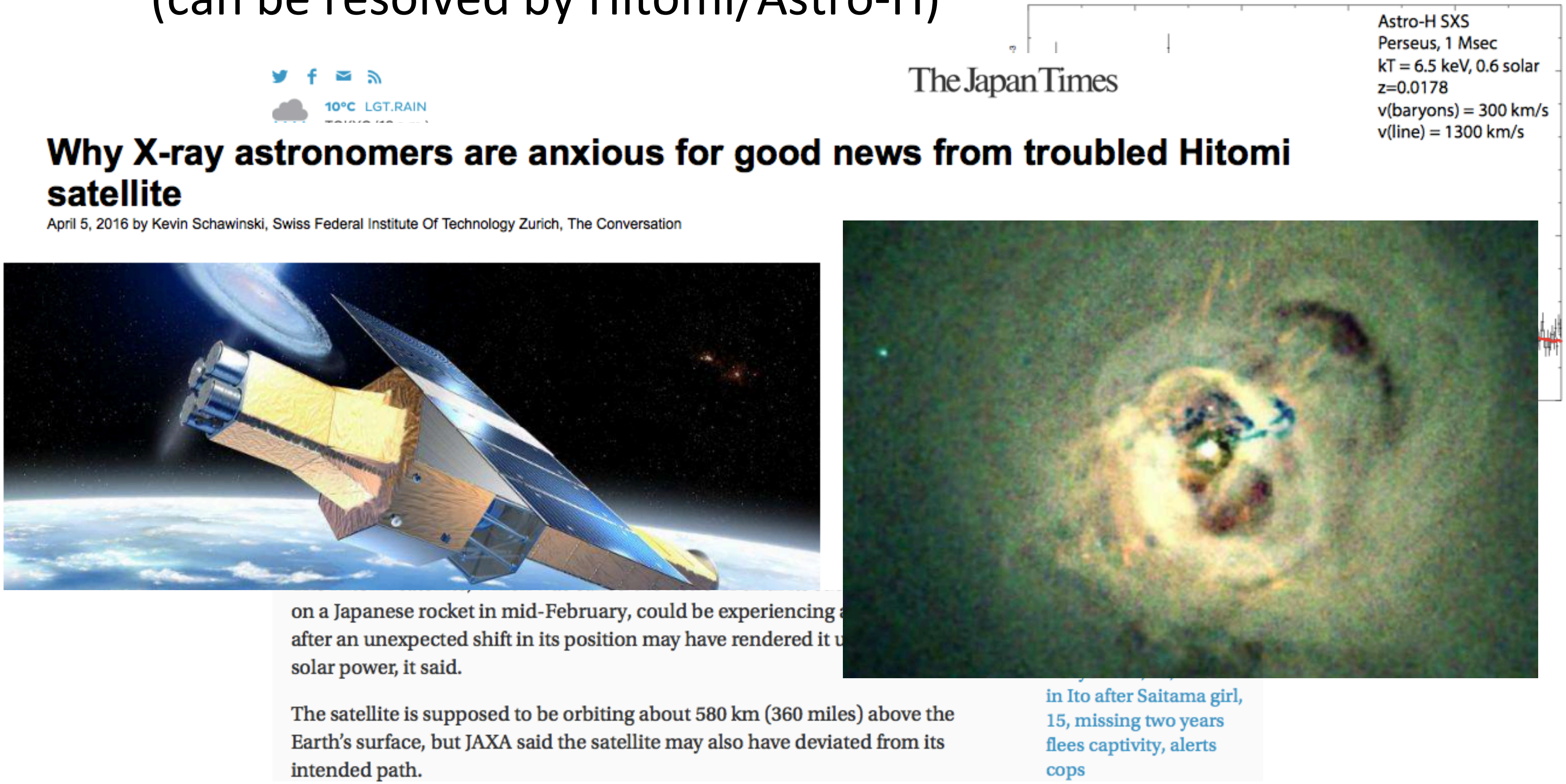
3. "Good" model: economical, natural UV completion, thermal relic DM

4. Bunch of cool physics!

D'Eramo, Hambleton, Profumo and Stefaniak, 1603.04895

A highly falsifiable scenario

- Line **Shape** – geometric average of thermal, DM velocities (can be resolved by Hitomi/Astro-H)



The Japan Times

Astro-H SXS
Perseus, 1 Msec
kT = 6.5 keV, 0.6 solar
z=0.0178
v(baryons) = 300 km/s
v(line) = 1300 km/s

Why X-ray astronomers are anxious for good news from troubled Hitomi satellite

April 5, 2016 by Kevin Schawinski, Swiss Federal Institute Of Technology Zurich, The Conversation

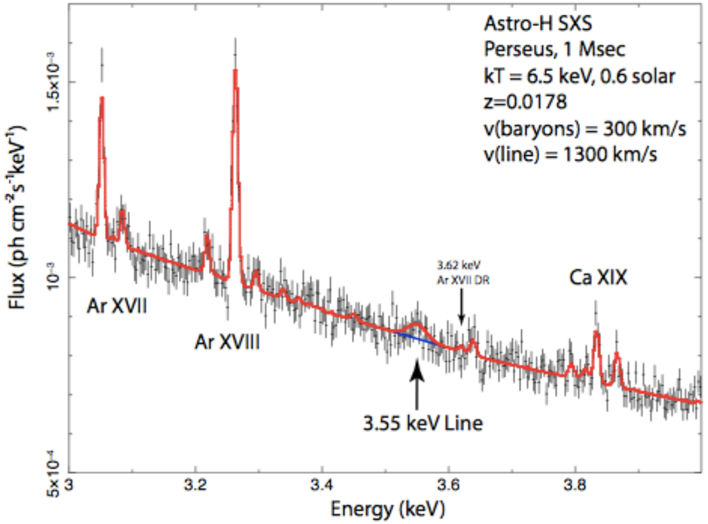
on a Japanese rocket in mid-February, could be experiencing
after an unexpected shift in its position may have rendered it
solar power, it said.

The satellite is supposed to be orbiting about 580 km (360 miles) above the Earth's surface, but JAXA said the satellite may also have deviated from its intended path.

in Ito after Saitama girl, 15, missing two years flees captivity, alerts cops

A highly **falsifiable** scenario

- Line **Shape** – geometric average of thermal, DM velocities (can be resolved by Hitomi/Astro-H)



- Unique **morphology**

- Unique **target**-dependence

- **Lines** could appear **anywhere** from eV (**visible**) to **UV**, to **X-ray**

K XVIII remains Occam's razor's fav. option

Plasma-excited DM:
New mechanism to detect DM

Lines anywhere eV…keV

Unique obs. predictions, background "free"

Structure formation? Small-scale structure?