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An Introduction to Particle Dark Matter

Lecture 5

Key ideas from last lecture

✓ **Galactic Center excess**: large systematics from 2D treatment, steady state assumption; key: **cosmic ray injection sources**

✓ Searching for DM with **colliders**: missing energy+something; top-down versus bottom-up; beware of EFT!

✓ **Axions**: likely exist in SM; mass/PQ-breaking scale unknown; if QCD axions, couple to photons (key for detection); cannot be produced thermally, non-thermal: misalignment, string decay

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

Simplest addition: set of ***n*** singlet fermions $\boldsymbol{N_a}$, gauge singlets

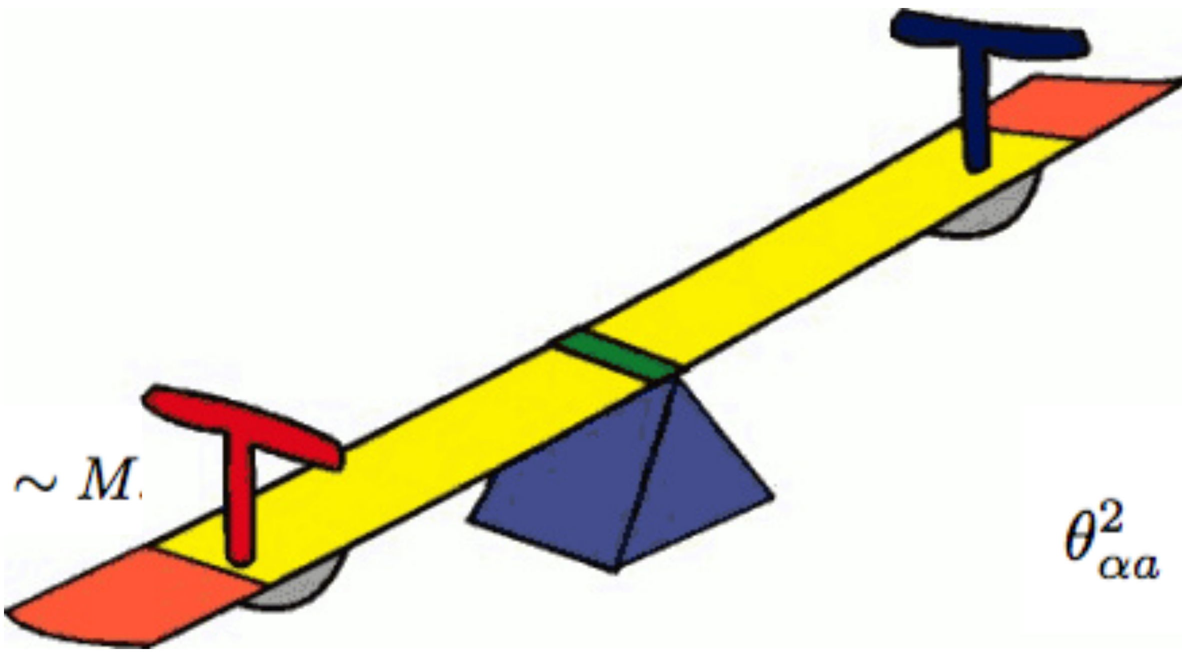
$$\mathcal{L} = \mathcal{L}_{\rm SM} + i\bar{N}_a \partial\!\!\!/ N_a - y_{\alpha a} H^\dagger \bar{L}_\alpha N_a - \frac{M_a}{2} \bar{N}_a^c N_a$$

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

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

"**See-saw**" mechanism!

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



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

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

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**?

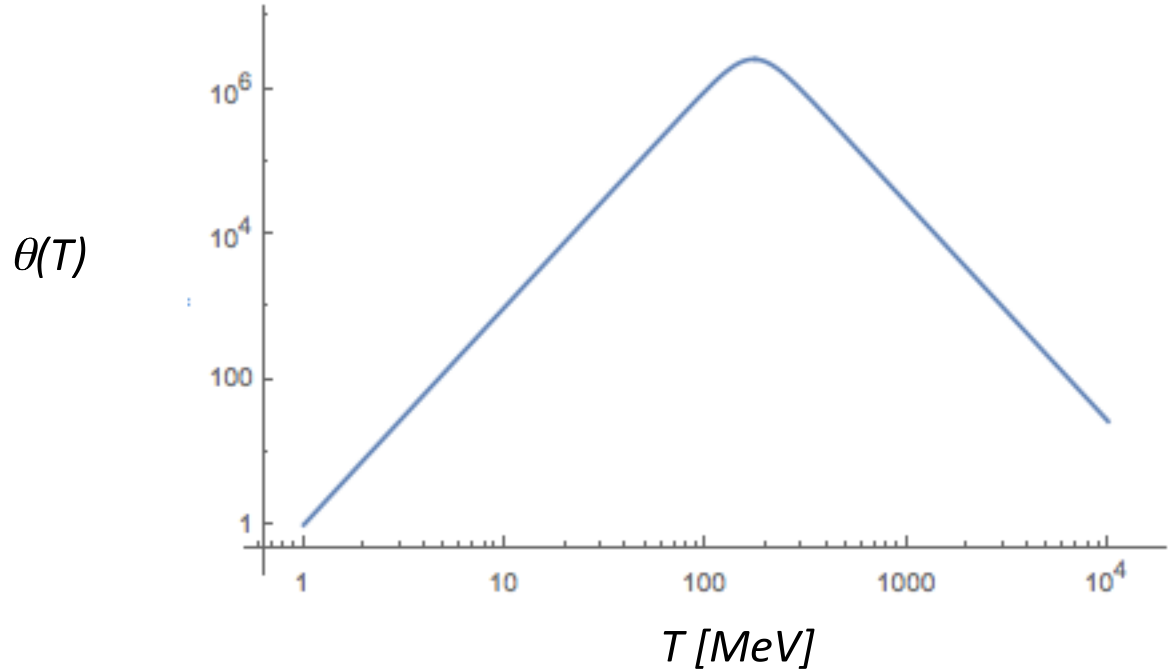
Basically, **freeze-in**: dump out-of-equilibrium sterile ν's through the universe history

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

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

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

$$S H^\dagger H \text{ and/or } S^2 H^\dagger H$$

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

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

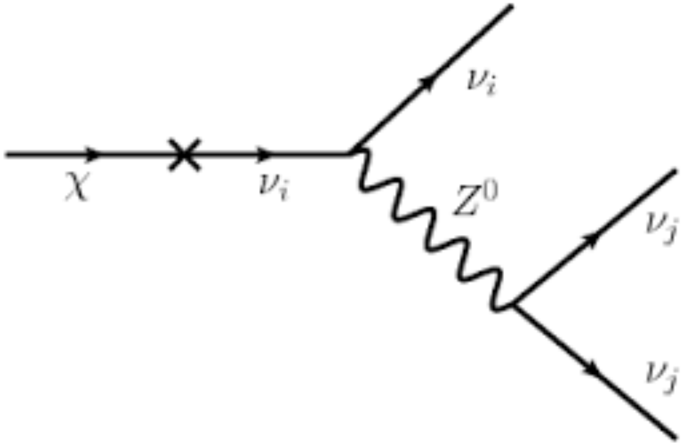
Sterile neutrino interesting from the standpoint of **structure formation** – remember

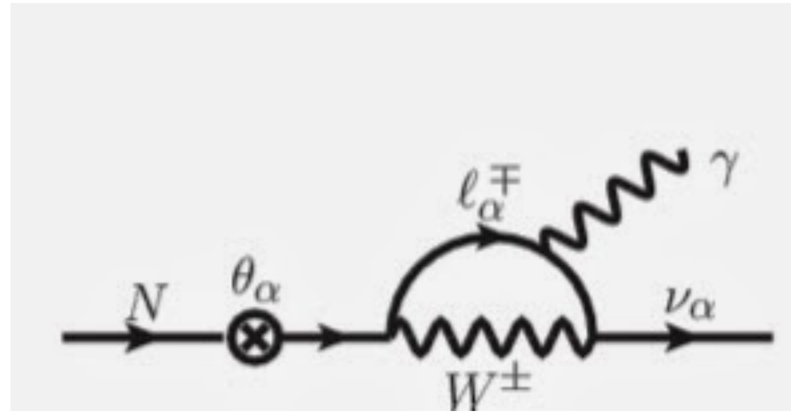
$$M_{\text{cutoff, hot}} \sim \left(\frac{1}{H(T=m_\nu)}\right)^3 \rho_\nu(T=m_\nu) \sim \left(\frac{M_P}{m_\nu^2}\right)^3 m_\nu \cdot m_\nu^3 = \frac{M_P^3}{m_\nu^2}$$

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

...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 $\times 10^{18}$ GeV/cm^2

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

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

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

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

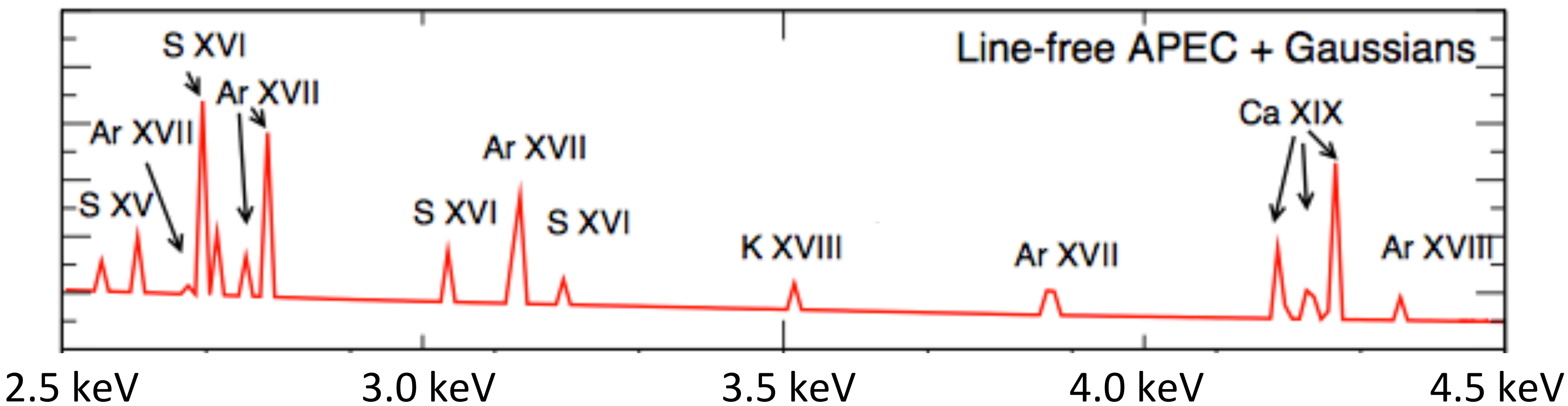
Have we **detected** it? **3.5 keV** line!

Bulbul+ (2014)
- Stacked clusters
- Perseus

Boyarsky+ (2014)
- M31 (Andromeda)
- Perseus

Jeltema+Profumo (2014)
- Galactic Center

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

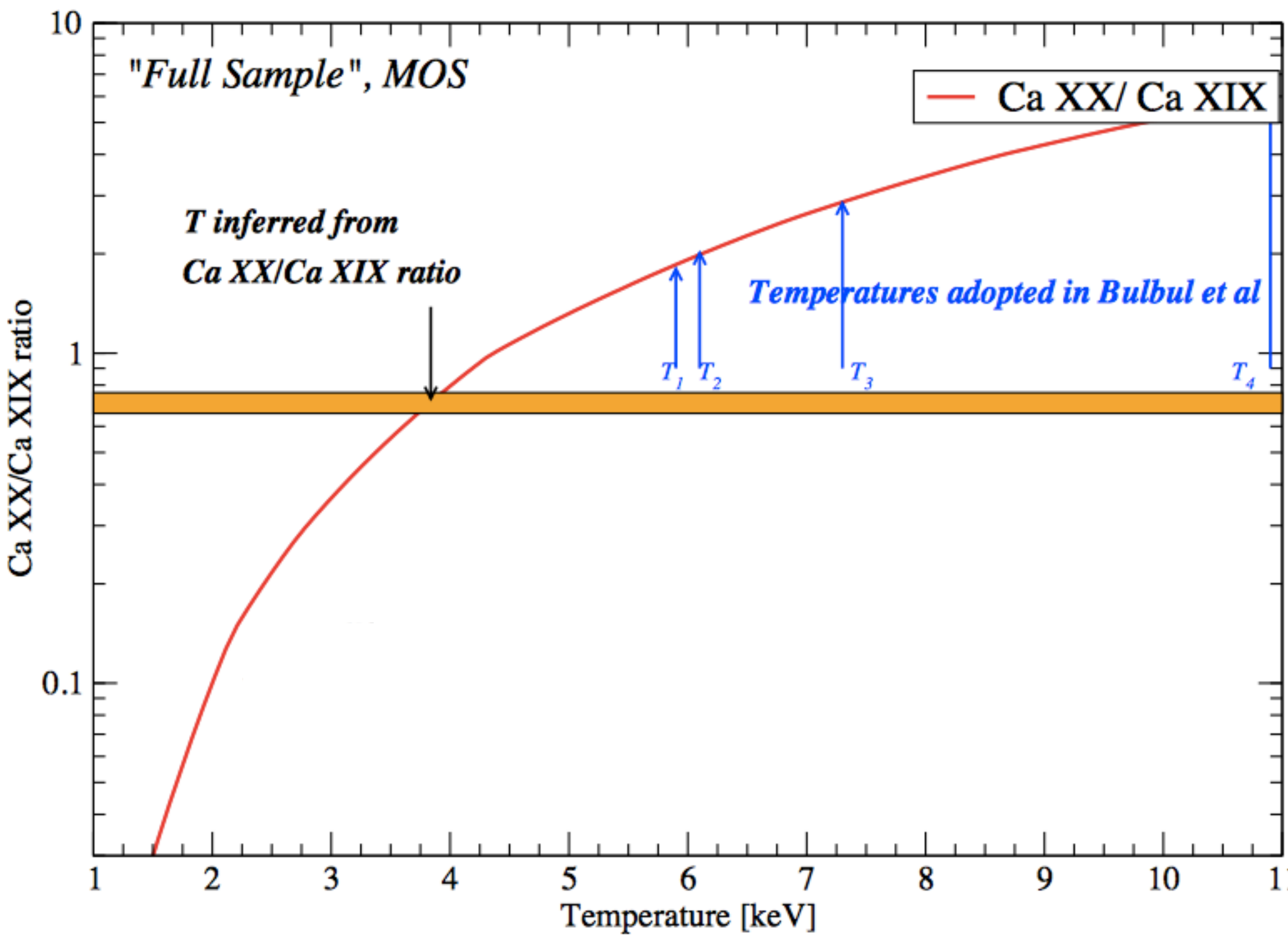
Bulbul+ argues against K XVIII since prediction for K 3.5 keV line too low (by factors ~20 for solar abundances)

…but this prediction makes two key mistakes:

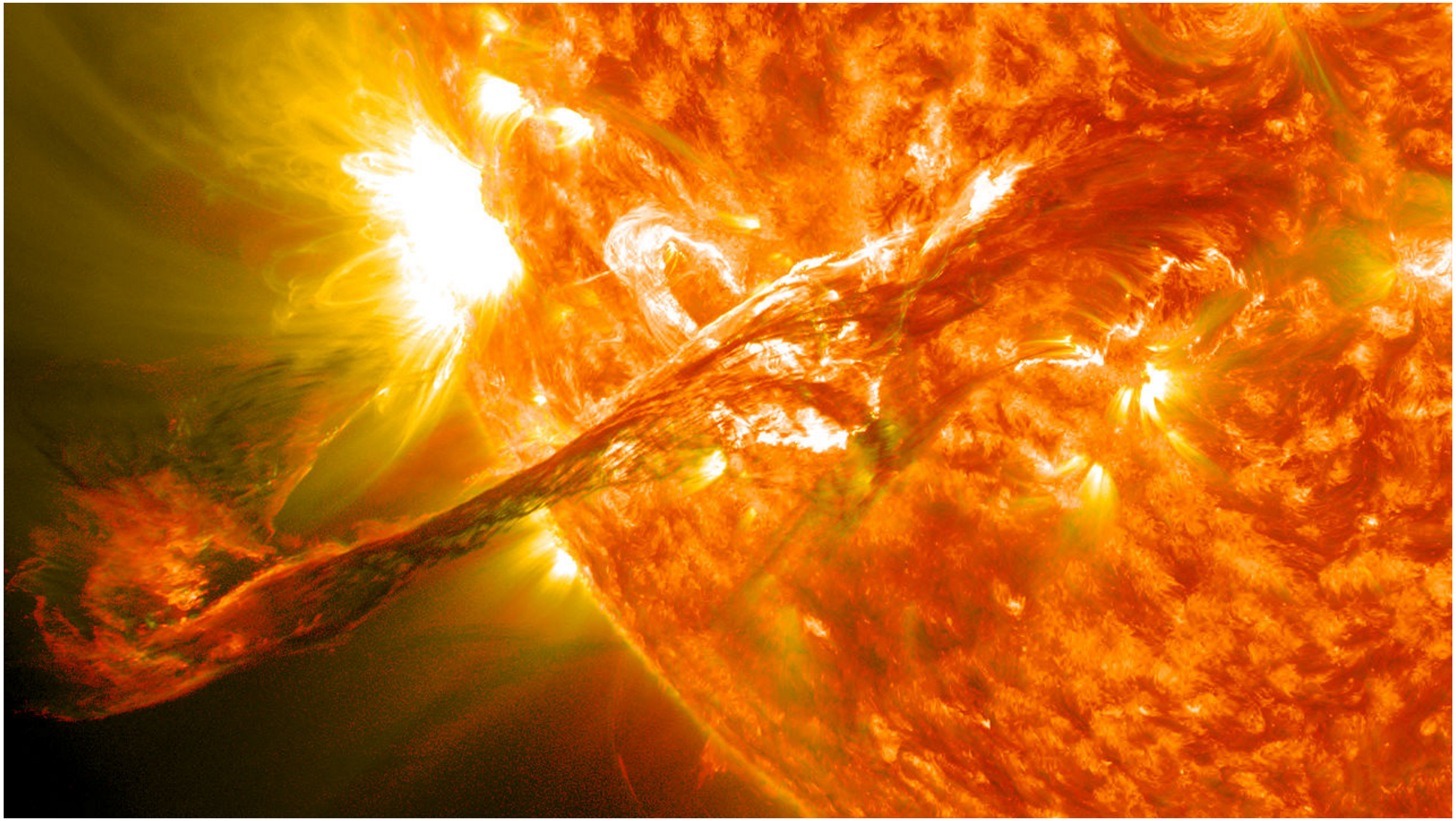
#1 Plasma Temperature

#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!

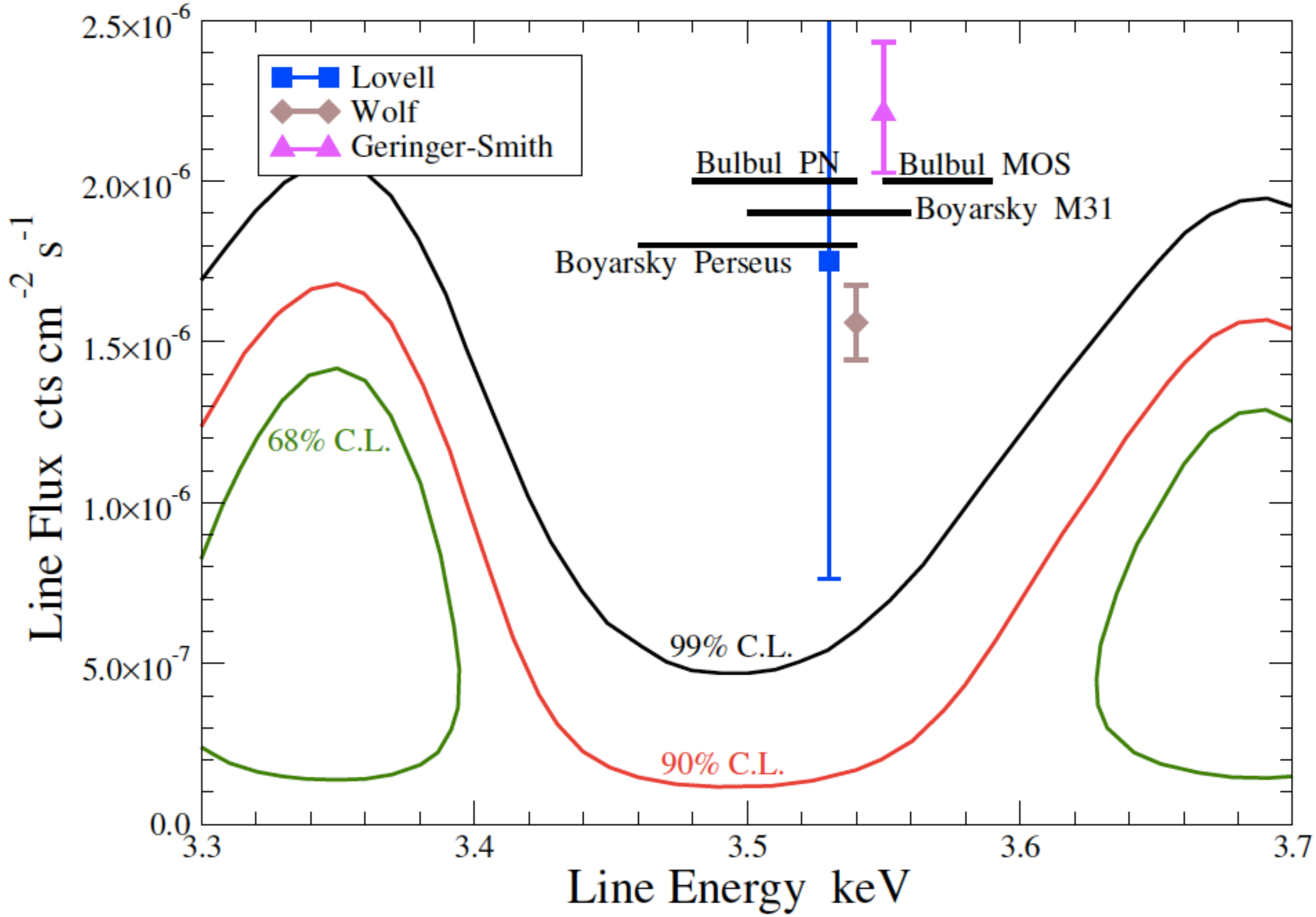
(2) use something different than spectrum!

(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*

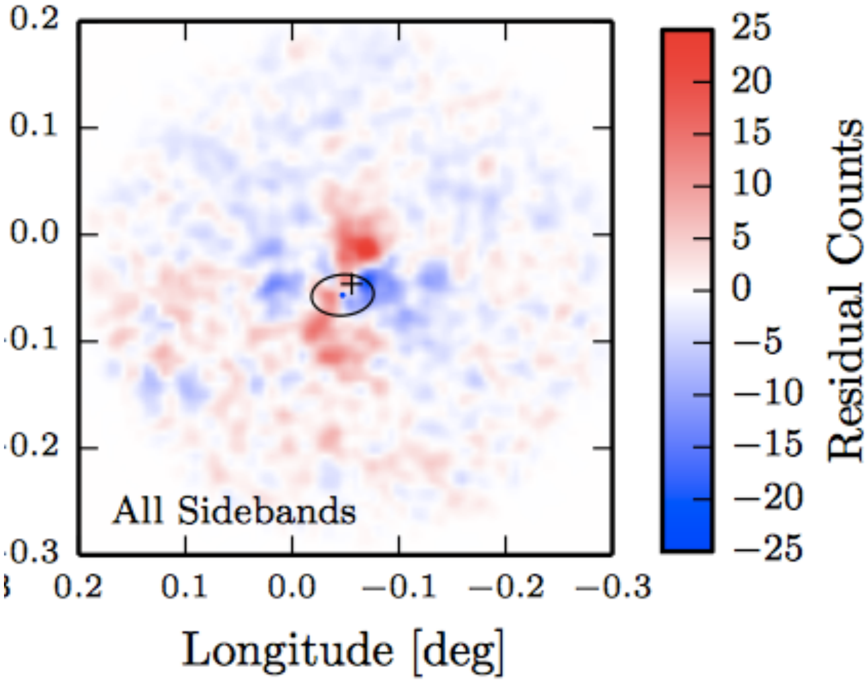


*** Jeltema and Profumo, MNRAS (2015)**

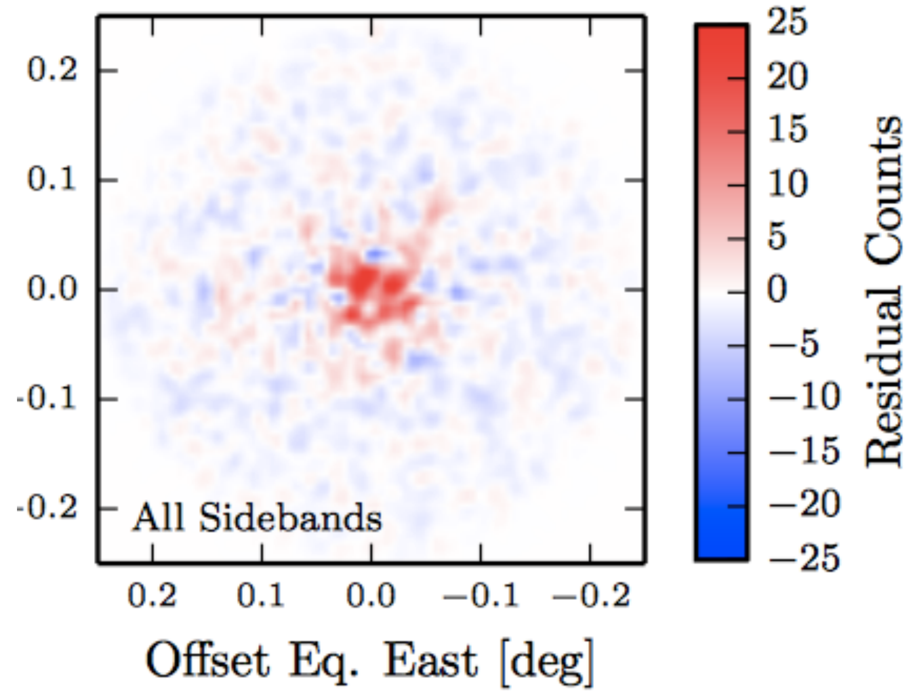
(2) use something
different than spectrum!

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

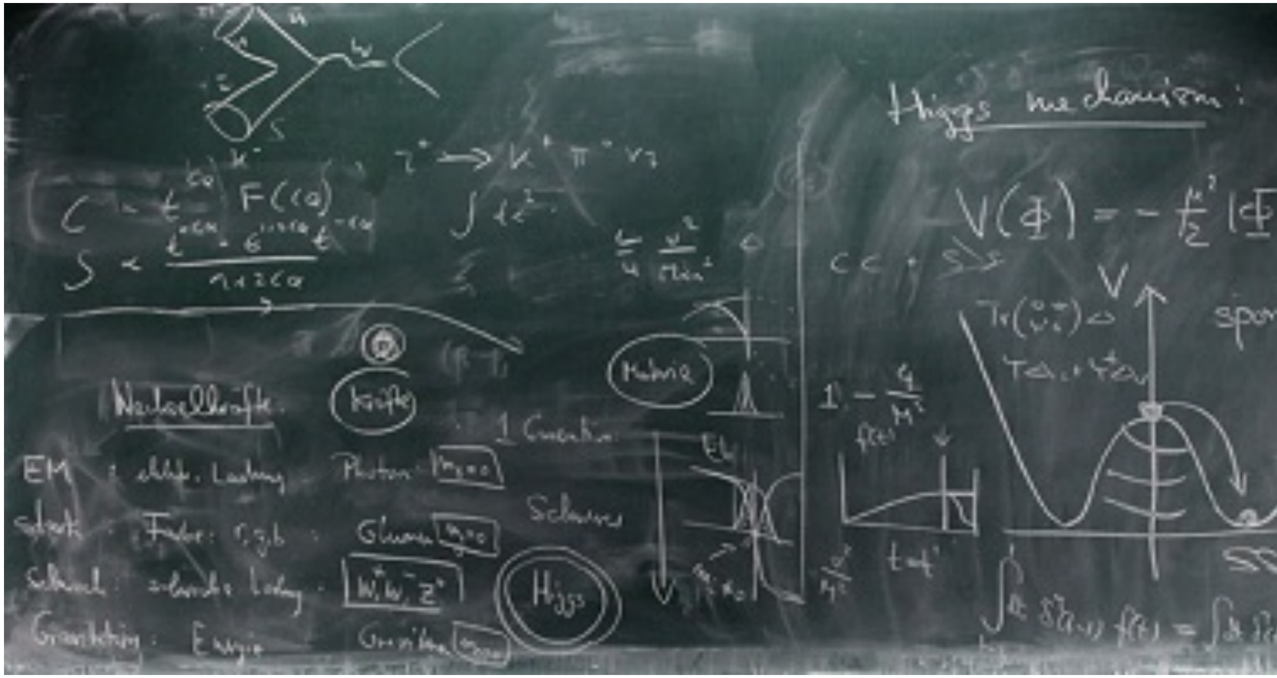
Recap!

	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

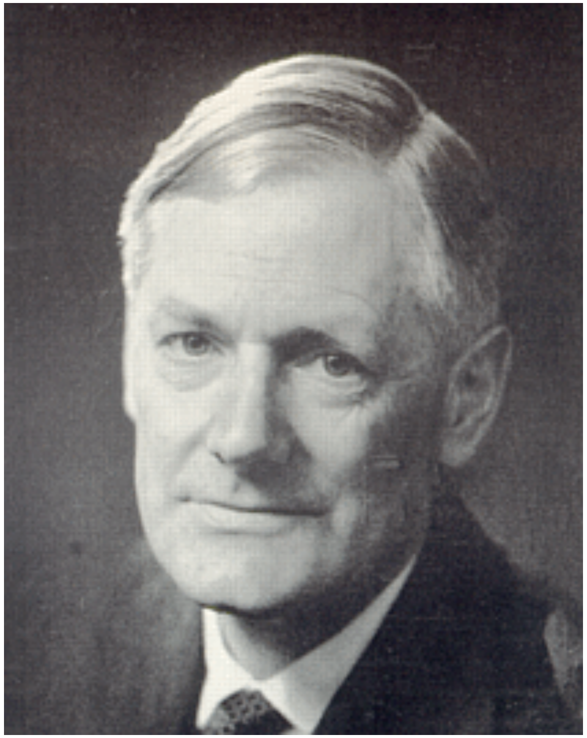
What if it is Dark Matter?

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" (*)

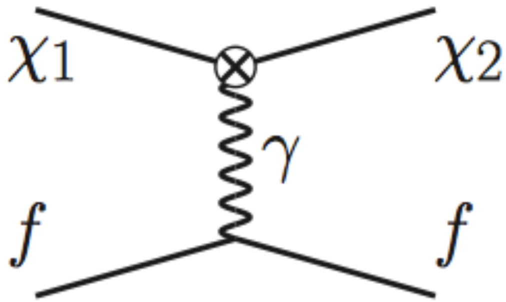


Roderick O. Redman (b. 1905, d. 1975) Professor of Astronomy at Cambridge University

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

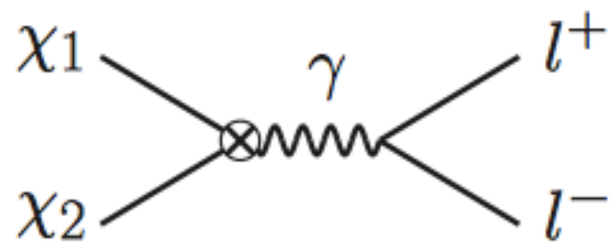
3.5 keV line …an excuse for an exciting, new mechanism for a signal from Dark Matter!

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



Signal ~ ρ_{DM} x ρ_{gas}

Good Thermal Relic!



D'Eramo, Hambleton, Profumo and Stefaniak, 1603.04895, PRD

Why should you be excited by our model?

1. Brand new indirect detection channel!

2. Unmistakable signature, background free

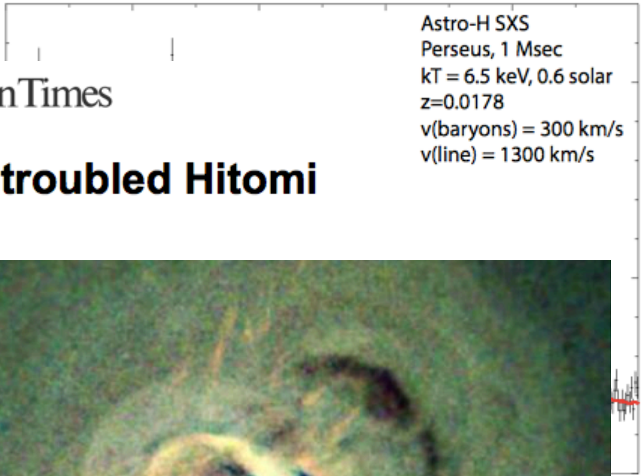
3. "Good" model: economical, natural UV completion, thermal relic DM

4. Bunch of cool physics!

D'Eramo, Hambleton, Profumo and Stefaniak, 1603.04895, PRD

A highly falsifiable scenario

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

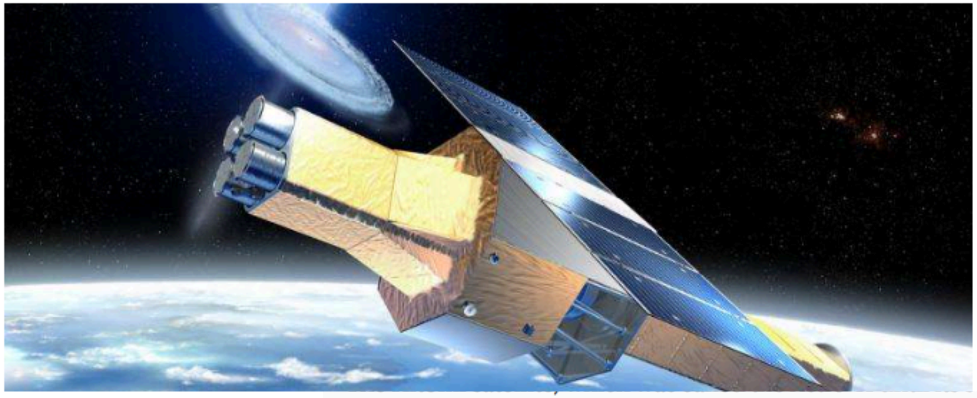


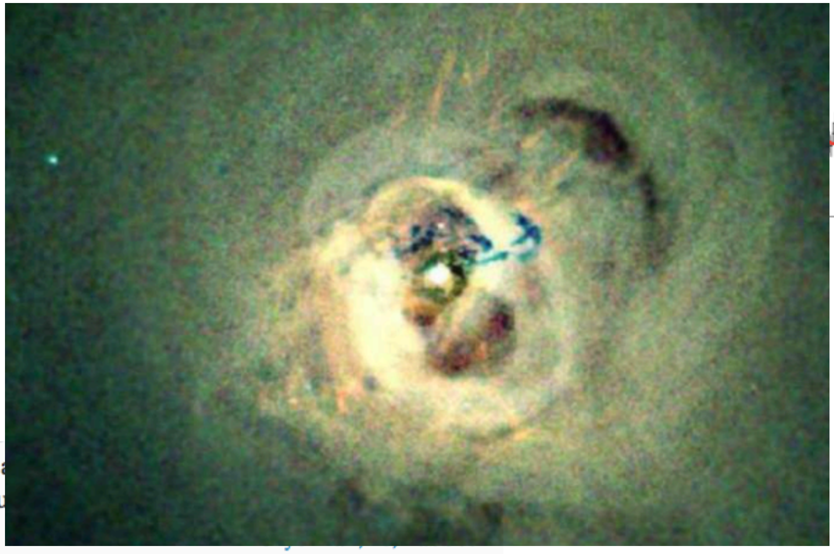
10°C LGT.RAIN

The Japan Times

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





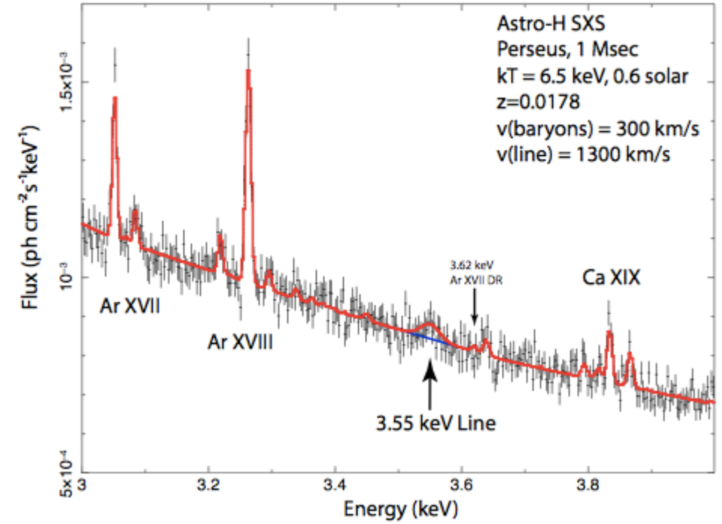
on a Japanese rocket in mid-February, could be experiencing
after an unexpected shift in its position may have rendered it u
solar power, it said.

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?

Bestiarium of other
notable DM candidates

- **Gravitinos** (and other depressing candidates)
- **WIMPzillas** (and other superheavy non-thermal particles)
- **Self-interacting** DM
- **Asymmetric** DM
- "**Minimal**" DM

Gravitinos – prototypical DM with Planck-suppressed interactions

$$\mathcal{L} = -\frac{1}{2}\varepsilon^{\mu\nu\rho\sigma}\bar{\Psi}_\mu\gamma_5\gamma_\nu\partial_\rho\Psi_\sigma - \frac{m_{3/2}}{4}\bar{\Psi}_\mu[\gamma^\mu,\gamma^\nu]\Psi_\nu + \frac{1}{2M_P}\bar{\Psi}_\mu S^\mu$$

$$\sigma(\tilde{G}\tilde{G}\to\gamma\gamma) = \frac{1}{576\pi}\frac{M_{\tilde{\gamma}}^2 s^2}{(m_{3/2}M_P)^4}$$

$$\sigma(\tilde{G}\tilde{G}\to\bar{f}f) = \frac{g_f}{720\pi}\frac{s^3}{(m_{3/2}M_P)^4}$$

$$T_{\mathrm{f.o.}} \sim \left(\frac{m_{3/2}^4 M_P^3}{M_{\tilde{\gamma}}^2}\right)^{1/5} \sim 450\ \mathrm{GeV}\ \left(\frac{m_{3/2}}{0.1\ \mathrm{eV}}\right)^{4/5}\left(\frac{100\ \mathrm{GeV}}{M_{\tilde{\gamma}}}\right)^{2/5}$$

Thermal gravitinos are **hot relics**
(in fact, first SUSY DM candidate ever proposed!)

$$\Omega_{3/2}h^2 = \frac{m_{3/2}n_{3/2}(T_0)}{\rho_c}h^2 \simeq \frac{m_{3/2}}{\mathrm{keV}}\left(\frac{100}{g_*(T_{\mathrm{f.o.}})}\right)$$

However, this neglects **single-gravitino processes**
that keep dumping out of equilibrium gravitinos

$$V + \tilde{\lambda} \leftrightarrow V + \tilde{G}; \qquad V + V \leftrightarrow \tilde{\lambda} + \tilde{G}.$$

Generically, there is a **gravitino over-production problem**:
need to dilute them away!

$$\Omega_{3/2}h^2 \simeq 0.00167\, \frac{m_{3/2}}{1\ \mathrm{GeV}}\, \frac{T_{\mathrm{RH}}}{10^{10}\ \mathrm{GeV}}\, \frac{\gamma|_{T=T_{\mathrm{RH}}}}{T_{\mathrm{RH}}^6/\bar{M}_P^2}$$

gravitinos are also produced from **NLSP decays**,

$$\Omega_{3/2}h^2 = m_{3/2}\frac{\Omega_{\rm NLSP}h^2}{m_{\rm NLSP}}$$

Bottom line: light gravitinos ruled out, **heavier** gravitinos OK for combinations of **mass, T_{RH}**

Gravitinos might also be the next-to-lightest SUSY particles, with **long lifetimes**

$$\tau_{\tilde{G}} \sim M_P^2/m_{3/2}^3 \sim 10^{14}\ {\rm sec}\ \left(\frac{1\ {\rm GeV}}{m_{3/2}}\right)^3$$

Can we ever hope to **detect** gravitinos?

Clever ideas: use long-lived sleptons produced at LHC **trapping** them in water tanks, wait for decay to gravitinos

use **neutrino telescopes** to search for neutrino-induced long-lived sleptons

$$\nu + q \rightarrow \tilde{l} + \tilde{q}$$

Interesting class of models: **non-thermally**-produced super-heavy particles (**WIMPzillas**)

(i) the dark matter particle is *never* in thermal equilibrium whatsoever,

(ii) the particle mass is comparable to the inflaton mass M_ϕ, and that

(iii) the particle's lifetime is much longer than the age of the Universe.

$$\Omega_X h^2 \simeq 10^{-3} \Omega_R \frac{8\pi}{3} \left(\frac{T_{\rm RH}}{T_0}\right) \left(\frac{M_\phi}{M_P}\right)^2 \left(\frac{M_X}{M_\phi}\right)^{5/2} e^{-2M_X/M_\phi}$$

Detectable in UHECR detectors (e.g. Auger)

Other interesting super-heavy DM candidates: **strangelets**

macroscopic **clumps** of **quark matter**, 10 mm to 10 cm radius,

$$10^9 - 10^{18}\ \mathrm{g}$$

strangelets are possibly **connected** with **baryogenesis**!

Also, they could be detectable via **cosmic-ray** collisions,
or by **poking holes** in the Earth…

Exercise 160. Show that the rate of collision of strangelets with the Earth ranges between one per year (for small ones of 10 mm radius) and one per billion year (for the biggies of 10 cm radius).

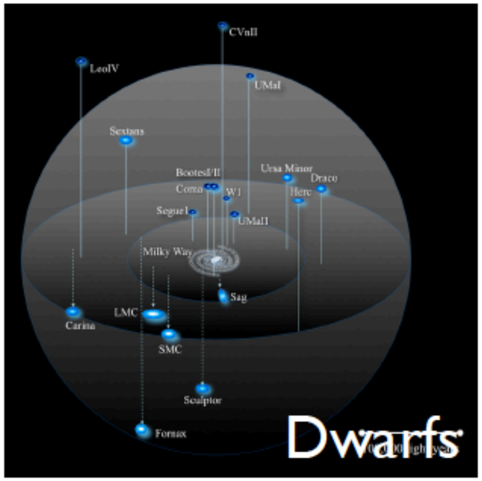
Self-interacting dark matter

$$\Gamma/H_0 = \frac{(\sigma_{\chi\chi}/m_\chi)\rho v}{H_0} \sim 1$$

$$\left(\frac{\sigma_{\chi\chi}}{m_\chi}\right) \sim 1.3\frac{\mathrm{cm}^2}{\mathrm{g}}\left(\frac{1\ \mathrm{GeV}/\mathrm{cm}^3}{\rho}\right)\left(\frac{10\ \mathrm{km/s}}{v}\right)$$

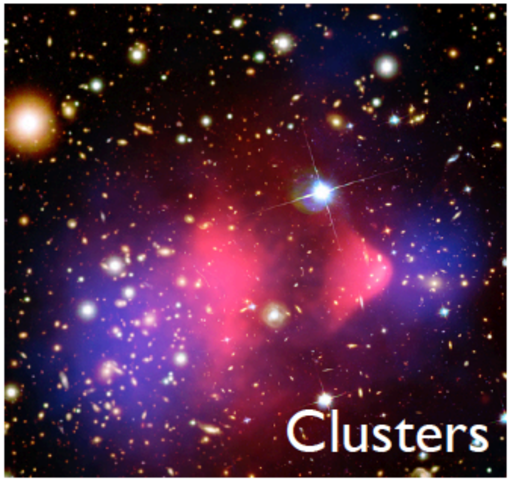
$$\left(\frac{\sigma_{\chi\chi}}{m_\chi}\right) \sim 1.3 \frac{\mathrm{cm}^2}{\mathrm{g}} \left(\frac{1\,\mathrm{GeV/cm}^3}{\rho}\right) \left(\frac{10\,\mathrm{km/s}}{v}\right)$$

- Dark matter halos are particle colliders (non-relativistic)



"B-factory" (v~30 km/s)

"LEP" (v~200 km/s)



"LHC" (v~1000 km/s)

Credit: Hai-bo Yu

which **particle physics model** could work?

e.g. a **dark QCD** with glueballs dark matter

$$\sigma(gb + gb \leftrightarrow gb + gb) \sim \frac{4\pi}{\Lambda^2}$$

$$\rho_{gb} \sim s_0 \Lambda (2(N^2 - 1)) \left(\frac{T_h}{T} |_{T\sim\Lambda} \right)^3$$

Other possibility: **dark atoms**!

Which relic density? Working on it...

other possibility: **light mediator**

$$(m_X v \ll m_\phi)$$

$$\sigma \sim 5 \times 10^{-23}\ \mathrm{cm}^2 \left(\frac{\alpha_X}{0.01}\right)^2 \left(\frac{m_X}{10\ \mathrm{GeV}}\right)^2 \left(\frac{10\ \mathrm{MeV}}{m_\phi}\right)^4$$

$$\sigma \sim \frac{\alpha_X^2}{m_X^2 v^4} \qquad (m_X v \gg m_\phi)$$

Effects **turn off** at **large** velocities,
but significant at small scales/low v…

assuming mediator has a small **coupling** ε to **SM** fermions...

Exercise 170. Show that the requirement that the lifetime of ϕ be shorter than ~ 1 second (the typical BBN time-scale) implies

$$\epsilon \gtrsim 10^{-10}\sqrt{10\ \mathrm{MeV}/m_\phi}.$$

Exercise 171. Show that the direct detection cross section

$$\frac{d\sigma}{dq^2} = \frac{4\pi\alpha_{\mathrm{EM}}\alpha_X\epsilon^2 Z^2}{(q^2+m_\phi^2)^2 v^2}.$$

Other interesting model: **complex scalar field**

$$\Phi = v + \frac{s + ia}{\sqrt{2}}$$

$$V(\Phi) = -\mu^2|\Phi|^2 + \frac{\lambda}{4}|\Phi|^4$$

$$\sigma(a + a \leftrightarrow a + a) = \frac{\lambda^2 m_a^2}{32\pi m_s^4}\left(1 - 4\frac{m_a^2}{m_s^2}\right)^{-2}$$

Set $m_s = 1$ MeV and $\lambda \simeq 0.5$

$$\frac{\sigma(a + a \leftrightarrow a + a)}{m_a} \sim 1\ \frac{\mathrm{cm}^2}{\mathrm{g}}$$

Asymmetric Dark Matter

(formerly known as "**Technocosmology**")

Idea: there's a **generalized baryon number**, with the DM lightest charged particle under B_D

$$B_{\rm conserved} = B_V - B_D; \qquad B_{\rm broken} = B_V + B_D.$$

These combinations are preserved/broken at some energy scale. At that high scale **produce** a net

$$\Delta B_{\rm broken} \qquad \Delta B_V = \Delta B_D = \Delta B_{\rm broken}/2$$

Otherwise, produce **asymmetry** in either sector, and transfer asymmetry

$$m_{\rm DM} = m_p \frac{\Omega_{\rm DM}}{\Omega_b} \frac{\eta(B_V)}{\eta(B_D)/q_{\rm DM}}.$$

charge-to-entropy ratio

$$m_{\rm DM} = q_{\rm DM} \times (1.6 - 5)\ {\rm GeV}.$$ for **baryon-symmetric** universes

$$\eta(B_D)/\eta(B_V) \sim \exp(-m_{\rm DM}/T_D).$$

if chemical decoupling of the two sectors happens when DM is **non-relativistic**

Minimality!

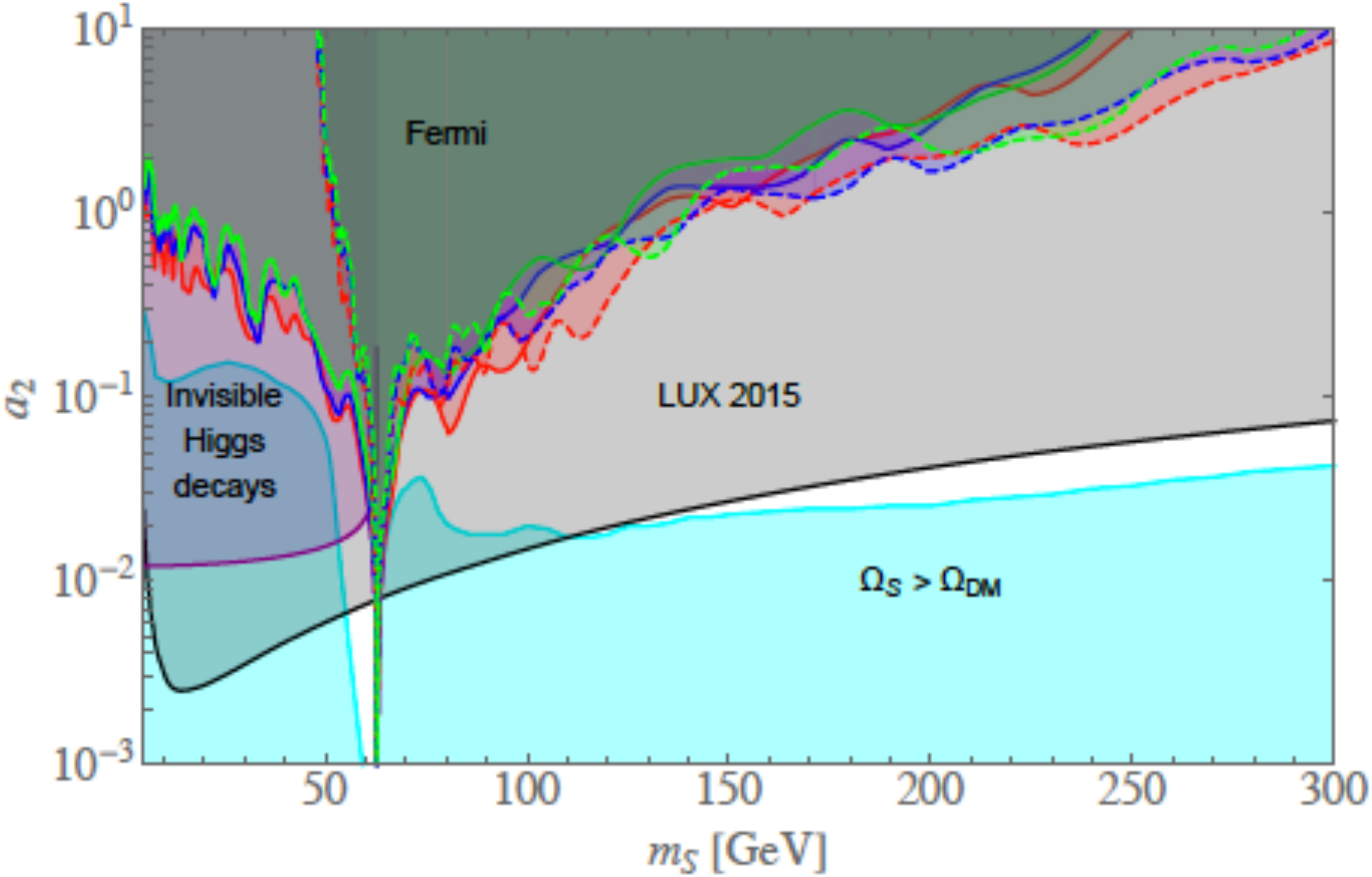
What does it mean? minimal number of **new parameters**?
Minimal number of new **field content**???

minimal number of ingredients: **heavy neutrinos**.
But death by direct detection unless suppressed coupling to the ***Z***...

Minimal number of new fields: **real scalar singlet**

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{(\partial_\mu S)^2}{2} - \frac{b_2}{2} S^2 - \frac{a_2}{2} H^\dagger H S^2 - \frac{b_4}{4} S^4$$

$$\langle S \rangle = 0 \qquad\qquad \sigma_{\rm SI} = \frac{a_2^2 m_N^4 f^2}{\pi m_s^2 m_h^4}$$



Profumo et al, 2014

The "Original" **Minimal Dark Matter model**:
SU(2)$_L$ multiplet, given spin and mass

$$\mathcal{L} = \bar{\chi}(i\not{D} + M)\chi \qquad \text{fermion}$$

$$\mathcal{L} = |D_\mu\chi|^2 - M^2|\chi|^2 \qquad \text{scalar.}$$

need zero **hypercharge**, **electric charge** $Q = T_3 + Y$

no operators that could mediate **decay** (e.g. $\chi e H$ $\chi \to eh$

for *n=2, Y=1/2*

very constrained set of possibilities: ***n=5 M=9.4* TeV** spin **½** fermion....

such heavy *SU(2)* particles have important **Sommerfeld** enhancement effects, affecting indirect DM constraints...

Other minimal possibility: **inert doublet model**: new *SU(2)* Higgs doublet, with Z_2 symmetry

Lightest Z_2-odd particle is stable, and a good **WIMP**!

One more I like: **dark photons**! with kinetic mixing term

$$-\frac{\varepsilon}{2\cos\theta_W} B_{\mu\nu} F'^{\mu\nu}. \qquad \varepsilon e A'_\mu J^\mu_{EM}$$

$m_{A'} \ll 2m_e$: can be **long-lived** enough!

Production from **oscillation**, or from processes like

$$\gamma + e^\pm \to A' + e^\pm, \qquad e^+ + e^- \to A' + \gamma$$

...or from dark photon **condensate** (~axion misalignment!)

$$\Omega_{A'} \sim 0.3 \sqrt{\frac{m_{A'}}{1\ \mathrm{keV}}} \left(\frac{H_{\mathrm{inf}}}{10^{12}\ \mathrm{GeV}}\right)$$

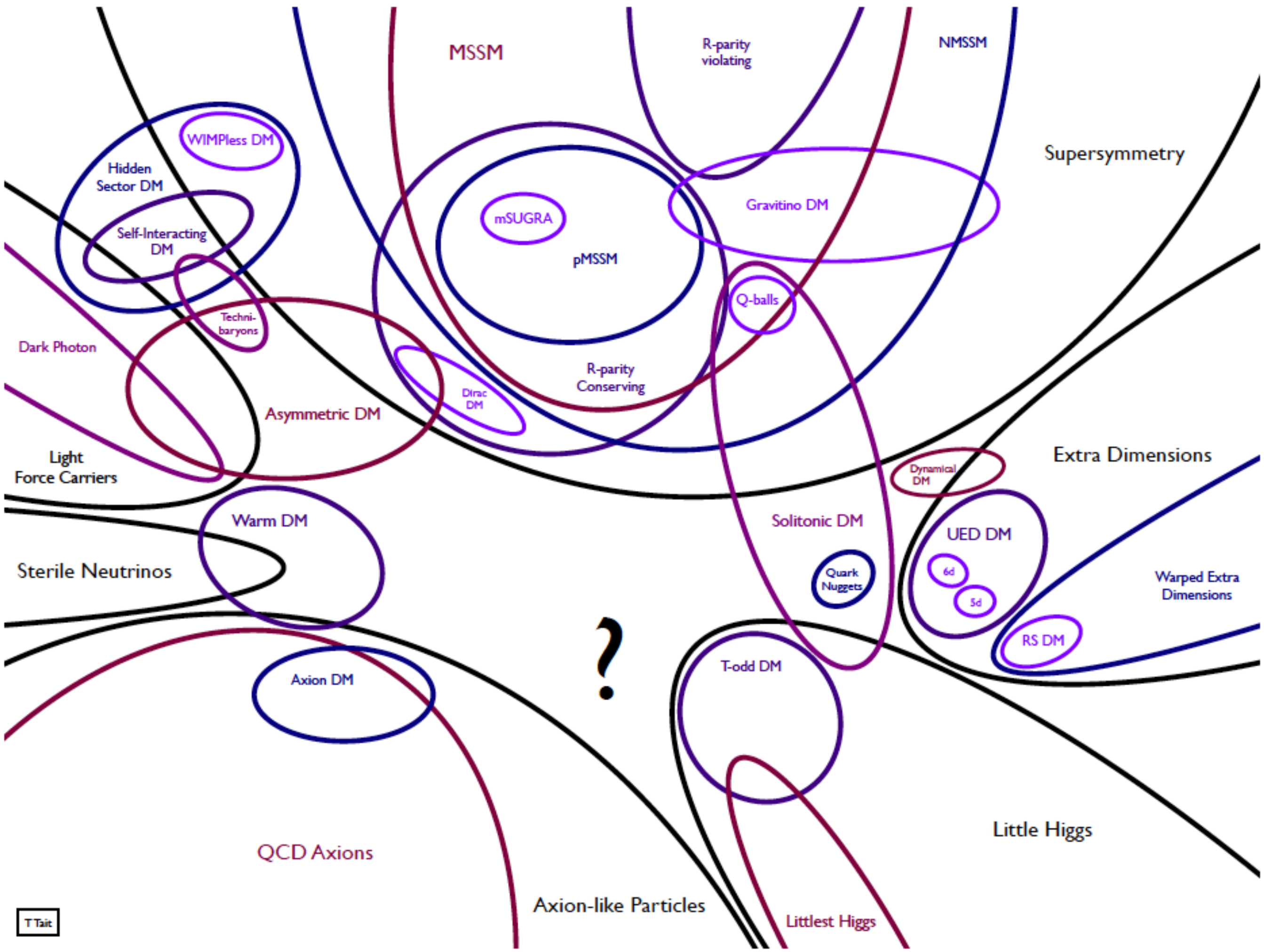
If new dark photons are charged under a **non-Abelian** symmetry group, kinetic mixing term is automatically **prohibited**, and particle is stable! e.g.

$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{1}{4}F'^{\mu\nu} \cdot F'_{\mu\nu} + (D_\mu \phi)^\dagger((D^\mu \phi)) - \lambda|\phi|^2|H^2| - \mu_\phi^2|\phi|^2 - \lambda_\phi|\phi|^4$$

interesting **phenomenology**: e.g. for SU(3) semi-annihilation, and **bright** gamma-ray **lines** (~α instead of ~α^2)

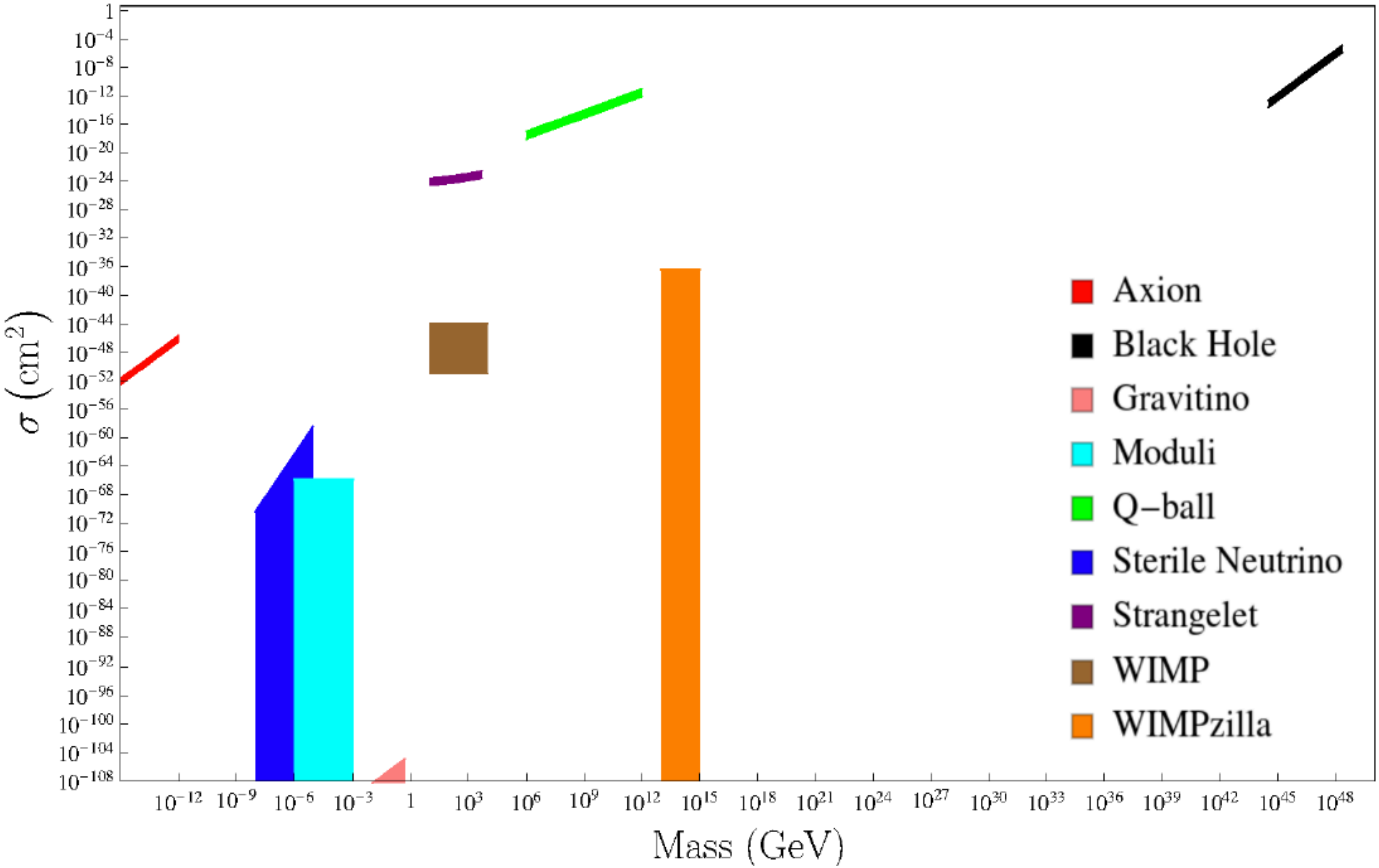
$$\psi_i \psi_j \to \psi_k \gamma$$

Theoretical **landscape** is quite large...



Credit: Tim Tait

Landscape of possible **particle candidates** very broad too..



Many other interesting **possibilities**...

The pages on the **particle** nature of **dark matter** in the great book of physics are yet to be written – a field full of **opportunities**, which will reward creativity and critical thinking!

Make sure to **learn lessons** from recent **successes** and **failures**, and the **bag of tricks** that comes with those lessons!