Neutrinos and Dark Matter

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We know very little about what the Dark Matter is

We do know it isn’t squirrels

One other thing we do know is that some of it is Standard Model neutrinos

How much?
SM neutrinos are thermal relics: their interaction rate $\Gamma$ once were much faster than the Hubble expansion rate $H$ …i.e., many more than one reaction per Hubble time, $\Gamma/H \gg 1$

However, the decline of $\Gamma$ with temperature was much faster than for $H$, so at some point neutrinos “decoupled” from the thermal bath.
Key idea of thermal decoupling:
if the reaction keeping a species in equilibrium is faster than the expansion rate of the universe, the reaction is in statistical equilibrium; if it is slower, the species decouples ("freeze-out")

$$\Gamma \ll H(T) \quad \Gamma(T_{\text{freeze-out}}) = H(T_{\text{freeze-out}})$$

the reaction rate (from definition of cross section!)

$$\Gamma = n \cdot \sigma \cdot v$$
(1) borrow **equilibrium number densities** from stat mech

\[
n_{\text{rel}} \sim T^3 \quad \text{for } m \ll T, \\
n_{\text{non-rel}} \sim (mT)^{3/2} \exp \left(-\frac{m}{T}\right) \quad \text{for } m \gg T.
\]

(2) borrow **Hubble rate** from general relativity

( FRW **solution** to Einstein's eq.)

\[
H^2 = \frac{8\pi G N}{3} \rho.
\]
\[ H^2 = \frac{8\pi G_N}{3} \rho. \]

GR+SM: **energy density** in radiation

\[ \rho \simeq \rho_{\text{rad}} = \frac{\pi^2}{30} \cdot g \cdot T^4 \quad \rightarrow \quad H \simeq T^2 \frac{\sqrt{\hbar c}}{M_P} \]

\[ M_P = \sqrt{\frac{\hbar c}{8\pi G}} \]
consider a **hot** thermal relic

/language definition: **hot** = relativistic at $T_{f.o}$  
**cold** = $v < c = 1$. (actually not by much, typically!)

calculate the abundance of **relic SM neutrinos** (cosmo $\nu$ background)

\[ \nu + \bar{\nu} \leftrightarrow f + \bar{f}, \]
\[ \nu + \bar{\nu} \leftrightarrow f + \bar{f}, \]

\[ n(T_\nu) \cdot \sigma(T_\nu) = H(T_\nu) \quad \sigma \sim G_F^2 T_\nu^2 \]

suppose this is a hot relic, \( T_\nu \gg m_\nu \ldots \quad n \sim T_\nu^3 \]

\[ T_\nu^3 G_F^2 T_\nu^2 = T_\nu^2 / M_P \]

\[ T_\nu = (G_F^2 M_P)^{-1/3} \approx (10^{-10} \times 10^{18})^{-1/3} \text{ GeV} \sim 1 \text{ MeV} \]
happy about two things in particular:

1. **hot** relic assumption works!

2. **Fermi** effective theory OK!

\[ T_{\nu} \gg m_{\nu} \]

\[ T_{\nu} \ll m_{W} \]

\[ T_{\nu} = (G_{F}^{2}M_{P})^{-1/3} \approx (10^{-10} \times 10^{18})^{-1/3} \text{ GeV} \sim 1 \text{ MeV} \]
now, how do we calculate the **relic** thermal **abundance** of this prototypical hot relic?

Introduce $Y = n/s$ (number and entropy **density**, $V = a^3$)

If universe is iso-entropic, $s \times a^3 = S$ is conserved

$Y \sim n a^3$ is thus $\sim$ **comoving number density**, and (without entropy injection)

$$Y_{\text{today}} = Y_{\text{freeze-out}} = Y(T_\nu)$$

$$Y_{\text{freeze-out}} = \frac{n(T_\nu)}{s(T_\nu)}$$
\[ Y_{\text{today}} = Y_{\text{freeze-out}} = Y(T_\nu) \]

\[ Y_{\text{freeze-out}} = \frac{n(T_\nu)}{s(T_\nu)} \]

\[ n_{\text{today}} = s_{\text{today}} \times Y_{\text{today}} = s_{\text{today}} \times Y_{\text{freeze-out}} \]

\[ \rho_{\nu, \text{today}} = m_\nu \times Y_{\text{freeze-out}} \times s_{\text{today}} \]

\[ \Omega_\nu h^2 = \frac{\rho_\nu}{\rho_{\text{crit}}} h^2 \simeq \frac{m_\nu}{91.5 \text{ eV}} \]

Cowsik-Mc-Clelland limit
\[ \Omega_\nu h^2 = \frac{\rho_\nu}{\rho_{\text{crit}}} h^2 \approx \frac{m_\nu}{91.5 \text{ eV}} \]

...we know at least two neutrinos are massive

\[ \Delta m_{\text{sol}}^2 = (7.53 \pm 0.18) \times 10^{-5} \text{ eV}^2 \quad \Delta m_{\text{atm}}^2 = (2.44 \pm 0.06) \times 10^{-3} \text{ eV}^2 \]

...thus, at a minimum,

\[ \Omega_\nu h^2 > \frac{\Delta m_{\text{sun}} + \Delta m_{\text{atm}}}{91.5 \text{ eV}} \approx \frac{0.058 \text{ eV}}{91.5 \text{ eV}} \approx 0.00063 \]

\[ \frac{\Omega_\nu}{\Omega_{\text{DM}}} > 0.53\% \]
However, there is also an upper limit to how much Standard Model neutrinos can contribute to the Dark Matter!

Primarily this depends on the effects of neutrinos as Dark Matter on the formation of structure.

Gravitational collapse can only happen when the DM is non-relativistic, i.e. when $T < m_\nu$. 
Neutrinos decouple when $T >> m_\nu$

Structures can only collapse when $T \sim m_\nu$
(i.e. when things slow down enough for gravitational collapse!)

Structures are cutoff to the horizon size at that temperature

$$d_\nu \sim H^{-1}(T \sim m_\nu) \quad d_\nu \sim \frac{M_P}{m_\nu^2}$$

$$H \sim T^2/M_P$$
$$d_\nu \sim \frac{M_P}{m_\nu^2}$$

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

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

How does this compare with observations?
Observational constraints give

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

- Neutrinos cannot be all of the Dark Matter

- at best Dark Matter can be keV scale, if produced thermally
...a bit more quantitatively

*Frenk+White; **Viel et al
...a bit more quantitatively

*Wong
Massive neutrinos also affect **CMB** anisotropy power spectrum (see L. Knox’s lecture tomorrow!)

*Wong*
**CMB** by itself demands \[ \sum_j m_j \lesssim (0.3 - 1.3) \text{ eV}. \]

...adding **LSS** data \[ \sum_j m_j < 0.170 \text{ eV}, \quad 95\% \text{ CL.} \]

...putting the SM component of neutrinos as DM at

\[ \Omega_\nu h^2 < \frac{0.170 \text{ eV}}{91.5 \text{ eV}} \approx 0.0019 \]

\[ 0.5\% < \frac{\Omega_\nu}{\Omega_{DM}} < 1.6\% \]
Could that 99% ALSO be neutrinos?
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

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

$$
M^{(n+3)} = \begin{pmatrix}
0 & y_{\alpha a} \langle H \rangle \\
y_{\alpha a} \langle H \rangle & \text{diag}(M_1, \ldots, M_n)
\end{pmatrix}
$$
If the following holds \[ y_{\alpha a} \langle H \rangle \sim yv \ll M_a \sim M \]

“See-saw” mechanism!

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

\[ m(\nu_a) \sim M \]

\[ \theta_{\alpha a}^2 \sim \frac{y_{\alpha a}^2 v^2}{M^2} \]
Sterile neutrinos mix via explicit (but possibly very small) mixing with ordinary neutrinos

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

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

\[ \theta^{-2} \left( \frac{m}{\text{keV}} \right)^{-5} \gg 1 \]

Also, if these guys have anything to do with DM, \( m > 100 \text{ eV} \) (e.g. Tremaine-Gunn)
if the DM is a fermion – we know that the phase space density is bounded from above (Pauli blocking): $f = gh^{-3}$

Using observed density and velocity dispersion of dSph, Tremaine-Gunn limit (1979): observed phase space density cannot exceed upper bound! (Liouville theorem)

$$\sigma \sim 150 \text{ km/s}$$  \hspace{2cm} $$\rho \gtrsim 1 \text{ GeV/cm}^3$$

$$m^4 > \frac{\rho h^3}{[g(2\pi \sigma^2)^{3/2}]} \sim (25 \text{ eV})^4.$$  

...actual best limit around 0.1 keV
How can sterile neutrinos be produced?

Basically, freeze-in: dump out-of-equilibrium sterile $\nu$'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

$$\theta \rightarrow \theta_M \sim \frac{\theta}{1 + 2.4 \left( \frac{T}{200 \text{ MeV}} \right)^6 \left( \frac{1 \text{ keV}}{m} \right)^2}$$

Sterile $\nu$ yield $Y=n/s$ scales as production rate times Hubble time $t_H=M_p/T^2$
Maximal yield in 100-200 MeV range $\rightarrow$ QCD phase transition effects

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

(Dodelson-Widrow)
Additional important effect from Mikheyev-Smirnov-Wolfenstein effect with large **lepton asymmetries**

**(Shi-Fuller** resonant production)

Other possibilities (1): **non-thermal production** from singlet scalar coupling

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

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

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

\[
\Omega_N \sim 0.2 \left( \frac{h}{10^{-8}} \right)^3 \frac{\langle S \rangle}{m_S}
\]
Other possibilities (2): **THERMAL** production in L-R models
e.g. in SO(10) GUTs, “sterile” neutrinos belong to the same 16-plet as
the rest of the SM matter fields

LHC implies $m_{WR} \gg 1$ TeV
Calculation is identical as for ordinary neutrinos, but with $m_W \rightarrow m_{WR}$

\[
\sigma \sim G_F^2 T^2 (m_W / m_{WR})^4 \quad \Gamma_N \sim G_F^2 T^5 (m_W / m_{WR})^4
\]

\[
T_f \sim g_s^{1/6} (T_f) \left( \frac{m_{WR}}{m_W} \right)^{4/3} \text{ MeV}
\]

\[
\frac{\Omega_N}{\Omega_{DM}} = \frac{1}{S} \left( \frac{10.75}{g_s(t_f)} \right) \left( \frac{M}{\text{keV}} \right) \times 100.
\]

* Nemevsek et al (2012)
So this doesn’t really work...

...unless we attach one or more epicycles...
Add many, many new particles that **magically vanish** between freeze-out and BBN

Invent **new interactions** that further deplete N's abundance

Inject **entropy**, maybe via decay of the next-to-lightest RH neutrino

\[
\frac{\Omega_N}{\Omega_{DM}} = \frac{1}{S} \left( \frac{10.75}{g_s(t_f)} \right) \left( \frac{M}{\text{keV}} \right) \times 100.
\]

\[
\Omega_{N_1} \approx 0.265 \left( \frac{M_1}{1\text{keV}} \right) \left( \frac{1.6\text{GeV}}{M_{N_2}} \right) \left( \frac{1\text{sec}}{\tau_{N_2}} \right)^{1/2} \frac{g_*(T_{f,2})}{g_*(T_{f,1})}
\]

* Nemevsek et al (2012)
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**!

...and could explain **baryon asymmetry** (MνSM)!!

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

*Kusenko et al * **Shaposhnikov et al*
\Gamma_{\nu_s \rightarrow \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_{\text{fov}} d\Omega \int_{\text{line of sight}} \rho_{\text{DM}} \frac{dr(\psi)}{m} = \frac{\Gamma_{\gamma \nu}}{8\pi m} J(\Delta \Omega, \psi)

\text{few } \times 10^{18} \text{ GeV/cm}^2
key background: diffuse cosmic X-ray background

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

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

\[ \left( \frac{\theta^2}{10^{-7}} \right) \left( \frac{m}{1 \text{ keV}} \right)^4 \lesssim 1 \]

Have we detected it?
Was sterile neutrino DM detected?

*Bulbul+ 14
Bulbul+ (2014)
- Stacked clusters
- Perseus

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

Jeltema+Profumo (2014)
- Galactic Center
Bulbul+ (2014)

- Stacked clusters
- Perseus
despite the **faint** signal (at most $3\sigma$), much **hype** ($\sim 600$ papers), much **press**
X-ray lines also from atomic transitions of highly-ionized $Z \sim 16-20$ atoms*

\[ E_z \sim 13.6 \, Z^2 \text{ eV} \Rightarrow Z \sim \left( \frac{3,500}{13.6} \right)^{1/2} \sim 16, \text{ but } Z_{\text{eff}} < Z \ldots \]
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 \(\sim 20\) for solar abundances)

...but this prediction has two key issues:

#1 Plasma Temperature

#2 Relative Elemental Abundances
#1: Bulbul+ uses very large T highly suppresses K emission!
#2: under-estimate $\sim 10$ of K abundance!

(Photospheric versus Coronal)

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*

- Draco dSph observed for 1.66 Msec with XMM (19 days)
  - no expected plasma emission

- Spectrum well fit by simple power law background in 2.5-5 keV band

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

no signal from dedicated 1.4 Ms XMM observation of Draco dSph

An example of a zealous Referee:

“Finally, I would like to let you know that, after I was asked to referee this paper, I decided to download the data and examine the spectrum myself. I largely agree with your conclusions regarding the absence of a notable feature at ~3.5 keV, as well as your limits on the line flux in this region.”

(2) use something different than spectrum!

Morphology!

Look at where the 3.5 keV photons come from!
Where are the 3.55 keV photons? A Morphological study of the Galactic Center and of Perseus

Eric Carlson,\textsuperscript{a,b} Tesla Jeltema,\textsuperscript{a,b} Stefano Profumo\textsuperscript{a,b}

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1156 High St, Santa Cruz, CA 95064
\textsuperscript{b}Santa Cruz Institute for Particle Physics,
1156 High St, Santa Cruz, CA 95064

Carlson, Jeltema and Profumo, JCAP 2015
Morphology: looks like thermal line decaying DM strongly disfavored

Carlson, Jeltema and Profumo, JCAP 2015
The 3.5 keV emission is asymmetric with a distribution similar to nearby plasma lines.
Scanning Window Template

Perseus Cluster

Carlson, Jeltema and Profumo, JCAP 2015
The 3.5 keV morphology in GC (asymmetric) and Perseus (cool-core) follows astrophysical plasma not DM.

Limits inconsistent with DM decay origin of Bulbul line.
Are there plausible alternatives?

- Large systematic uncertainty in line predictions (Jeltema & Profumo 2015)
- Difficulty in modeling (Tamura et al. 2014)
- Charge-exchange sulfur lines (Gu et al. 2015, Gu et al. 2018)

3.47 keV line has no collisional only line!
Perseus observations with Hitomi

Reveals the challenges and opportunities of high spectral resolution...

- No 3.5 keV line detection (OK with KXVIII and DM interpr.)
- Hint of SXVI charge exchange? (1.6s)
- Differences seen between atomic codes point to need for improved modeling and laboratory measurements

* Hitomi Collaboration 2018
Summary of Current Constraints

1. Perseus (Boyarsky+ 14)
2. M31 (Boyarsky+ 14)
3. stacked clusters MOS (Bulbul+ 14)
4. stacked clusters PN (Bulbul+ 14)
5. Chandra deep fields (Cappelluti+ 18)
6. Hitomi (Aharonian+ 17)
7. Perseus Suzaku (Tamura+ 15)
8. stacked dwarfs (Malyshev+ 14)
9. M31 (Horiuchi+ 14)
10. stacked galaxies (Anderson+ 15)

Draco (Jeltema & Profumo 16)

XMM blank fields (Dessert+ 18)
New Cluster Analysis

Bhargava, Jeltema et al., in prep.

- Joint fitting of 144 clusters from the XMM Cluster Survey
- Bin by X-ray temperature with 20-30 clusters per bin

<table>
<thead>
<tr>
<th>$T_x$ bin (keV)</th>
<th>No. of clusters</th>
<th>$T_X$ average (keV)</th>
<th>$M_{500,DM}$ average ($10^{14} M_\odot$)</th>
<th>$M_{500,DM}/d_L^2$ average ($10^{10} M_\odot/\text{Mpc}^2$)</th>
<th>Total SNR (0.3 – 7.9 keV)</th>
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<tbody>
<tr>
<td>$\leq 3$</td>
<td>20</td>
<td>2.43</td>
<td>1.14</td>
<td>0.01</td>
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<tr>
<td>5 – 6</td>
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<td>5.44</td>
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<td>0.02</td>
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<tr>
<td>6 – 7</td>
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<td>$\geq 7$</td>
<td>31</td>
<td>9.50</td>
<td>12.4</td>
<td>0.18</td>
<td>3140</td>
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</tbody>
</table>
New Cluster Analysis

- Line near 3.5 keV significantly improves fit in lowest $T_X$ bin, 1-2 sigma in next two $T_X$ bins
- Other features of mild/moderate significance indicating imperfect line/continuum modeling

$T_X < 3 \text{ keV}$

Not significant

$4 \text{ keV} < T_X < 5 \text{ keV}$
New Cluster Analysis

6 keV < $T_X$ < 7 keV

T$_X$ > 7 keV

➢ No 3.5 keV line in the three highest $T_X$ bins!
Plasma or Dark Matter?

- 3.5 keV feature only at lowest $T_X$
- Not seen in bins with largest expected DM flux

- 3.5 keV feature also correlates with cool core in Perseus cluster
- Likely associated to plasma

Bhargava+ in prep.

Carlson+ 2015
3.5 keV Line Summary

- A simple DM decay origin is inconsistent with:
  - non-detection in Draco and blank fields
  - GC morphology
  - scaling with cluster mass/temperature

- The signal correlates with plasma physics
  - Present for low $T_X$ clusters not high $T_X$ clusters
  - Present in systems with hot plasma (clusters, GC) and not in systems without (Draco, M31)
Around **1%** of the DM is **Standard Model Neutrinos**

- Theory work needed to control systematics in non-linear matter power spectrum calculation (L. Knox’s lecture tomorrow)
- New observations can pinpoint exactly how much of the DM is SM neutrinos – and how much neutrinos weigh! (L. Knox’s lecture tomorrow)

**Sterile neutrinos** are fine DM candidates, detectable with **X-ray observations**

- We (very probably) haven’t detected DM at 7.1 keV
- XRISM (successor to Hitomi) slated to launch in 2021 (then Lynx, Athena+)
<table>
<thead>
<tr>
<th></th>
<th>Signal?</th>
<th>Morphology?</th>
<th>K XVIII</th>
</tr>
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<tbody>
<tr>
<td>Clusters [Perseus]</td>
<td></td>
<td>~Cool core</td>
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<tr>
<td>Galactic Center</td>
<td></td>
<td>~Quadrupolar</td>
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<tr>
<td>dSph [Draco]</td>
<td>X</td>
<td>N/A</td>
<td>N/A</td>
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</table>
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” (*)

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

Roderick O. Redman (b. 1905, d. 1975) Professor of Astronomy at Cambridge University
3.5 keV line ...an excuse for an exciting, new mechanism for a signal from Dark Matter!

Signal $\sim \rho_{DM} \times \rho_{gas}$

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)

*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
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?
Examining the 3.5 keV Line

Discovery of a 3.5 keV line in the Galactic Center and a Critical Look at the Origin of the Line Across Astronomical Targets

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Deep XMM Observations of Draco rule out at the 99% Confidence Level a Dark Matter Decay Origin for the 3.5 keV Line

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\textsuperscript{1}Department of Physics and Santa Cruz Institute for Particle Physics University of California, Santa Cruz, CA 95064, USA

Where do the 3.5 keV photons come from? A morphological study of the Galactic Center and of Perseus

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New: Joint fitting of 144 clusters as a function of temperature - Bhargava et al., in prep.

→ spectral analysis of the Galactic Center (and reanalysis of M31)

→ spectral analysis of very deep Draco data

→ morphology of 3.5 keV emission in the GC and Perseus
Analysis of XMM Galactic Center data

=> There is a line at 3.5 keV

Line is compatible with an atomic emission;
Line is also compatible with DM interpretation

Jeltema & Profumo 2015
The 3.5 keV Line in M31

Re-analysis of XMM M31 data

=> No significant line found

Jeltema & Profumo 2015
Are there plausible alternatives?

- Large systematic uncertainty in line predictions (Jeltema & Profumo 2015)
- Difficulty in modeling (Tamura et al. 2014)
- Charge-exchange sulfur lines (Gu et al. 2015, Gu et al. 2018)
The 3.5 keV emission is asymmetric with a distribution similar to nearby plasma lines.
The 3.5 keV morphology in GC (asymmetric) and Perseus (cool-core) follows astrophysical plasma not DM.

Limits inconsistent with DM decay origin of Bulbul line

Carlson, Jeltema and Profumo 2015
Deep Observations of Draco

- Draco dSph observed for 1.66 Msec with XMM (19 days)
  - no expected plasma emission

- Spectrum well fit by simple power law background in 2.5-5 keV band

Jeltema & Profumo 2016
Deep Observations of Draco

- Non-detection inconsistent with flux observed from clusters and GC for DM decay origin
- Dark matter decay excluded at > 99%

Jeltema & Profumo 2016
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** ($\nu$MSM)
- Would **decay** via mixing with active neutrinos

3.5 keV lines (roughly) **compatible** with this!
Plasma or Dark Matter?

- 3.5 keV feature only at lowest $T_X$
- Not seen in bins with largest expected DM flux

- Likely associated to plasma

Imperfections in modeling of relative line intensities at low T? Charge exchange?