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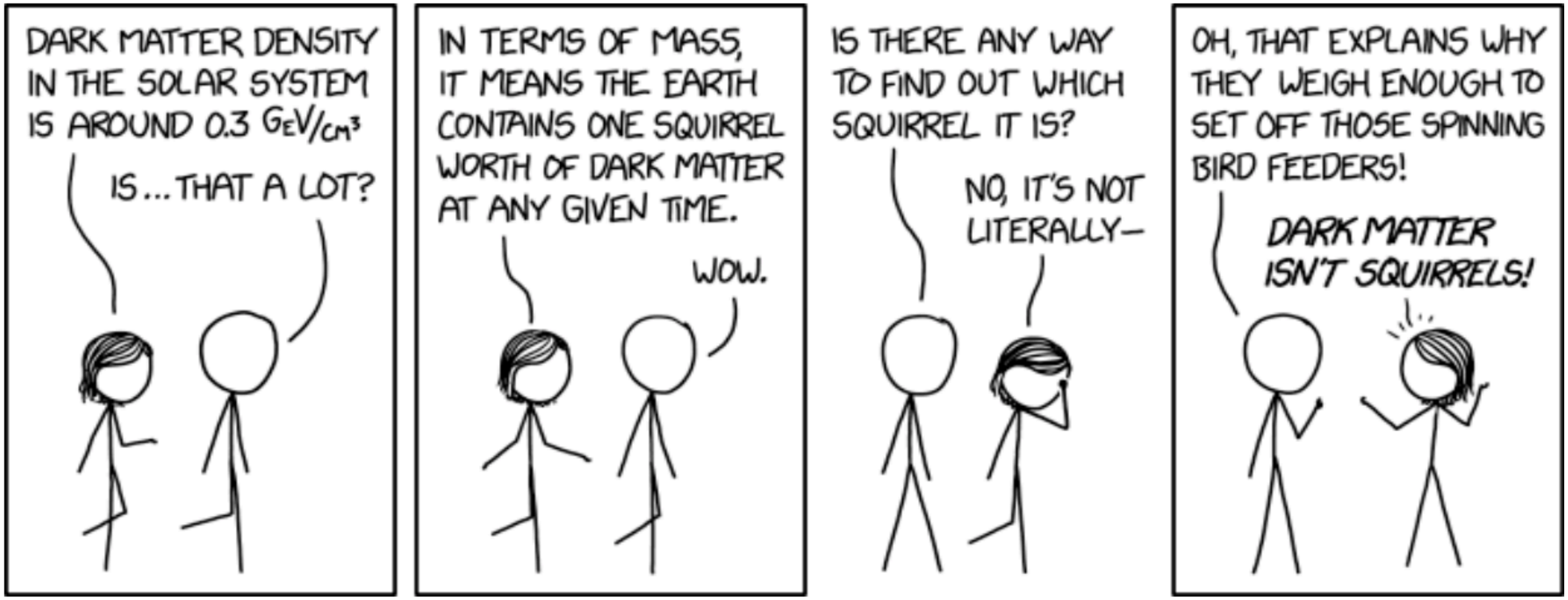
Neutrinos and Dark Matter



SSI 2019

SLAC, Thursday August 22, 2019

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 Γ once were much faster than the Hubble **expansion** rate *H*

…i.e., many more than one reaction per Hubble time,
Γ/H>>1

However, the decline of Γ 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")

$$\Gamma \ll H(T) \qquad \Gamma(T_{\mathrm{freeze-out}}) = H(T_{\mathrm{freeze-out}})$$

the **reaction rate** (from definition of cross section!)

$$\Gamma = n \cdot \sigma \cdot v$$

(1) borrow **equilibrium number densities** from stat mech

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

(2) borrow **Hubble rate** from general relativity
(FRW **solution** to Einstein's eq.)

$$H^2 = \frac{8\pi G_N}{3}\rho.$$

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

$$\rho \simeq \rho_{\mathrm{rad}} = \frac{\pi^2}{30} \cdot g \cdot T^4 \longrightarrow H \simeq T^2/M_P$$

$$M_{\mathrm{P}} = \sqrt{\frac{\hbar c}{8\pi G}}$$

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 ν background)

$$\nu + \bar{\nu} \leftrightarrow f + \bar{f},$$

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$$n(T_\nu) \cdot \sigma(T_\nu) = H(T_\nu) \qquad \sigma \sim G_F^2 T_\nu^2$$

suppose this is a **hot** relic, $T_\nu >> m_\nu$… ***$n \sim T_\nu^3$***

$$T_\nu^3 G_F^2 T_\nu^2 = T_\nu^2 / M_P$$

$$T_\nu = (G_F^2 M_P)^{-1/3} \simeq (10^{-10} \times 10^{18})^{-1/3} \text{ GeV} \sim 1 \text{ MeV}$$

happy about **two** things in particular:

1. **hot** relic assumption works! $T_\nu \gg m_\nu$

2. **Fermi** effective theory OK! $T_\nu \ll m_W$

$$T_\nu = (G_F^2 M_P)^{-1/3} \simeq (10^{-10} \times 10^{18})^{-1/3}\ \mathrm{GeV} \sim 1\ \mathrm{MeV}$$

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 ~ **comoving number density**, and (without entropy injection)

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

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

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

$$Y_{\rm freeze-out} = \frac{n(T_\nu)}{s(T_\nu)}$$

$$n_{\rm today} = s_{\rm today} \times Y_{\rm today} = s_{\rm today} \times Y_{\rm freeze-out}$$

$$\rho_{\nu,\rm today} = m_\nu \times Y_{\rm freeze-out} \times s_{\rm today}$$

$$\Omega_\nu h^2 = \frac{\rho_\nu}{\rho_{\rm crit}} h^2 \simeq \frac{m_\nu}{91.5\ \rm eV}$$

Cowsik-Mc-Clelland limit

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

…we know at least two neutrinos are **massive**

$$\Delta m^2_{\rm sol} = (7.53 \pm 0.18) \times 10^{-5} \text{ eV}^2 \qquad \Delta m^2_{\rm atm} = (2.44 \pm 0.06) \times 10^{-3} \text{ eV}^2$$

…thus, at a minimum,

$$\Omega_\nu h^2 > \frac{\Delta m_{\rm sun} + \Delta m_{\rm atm}}{91.5 \text{ eV}} \simeq \frac{0.058 \text{ eV}}{91.5 \text{ eV}} \simeq 0.00063$$

$$\frac{\Omega_\nu}{\Omega_{\rm DM}} > 0.53\%$$

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_ν**

Structures can only collapse when **T ~ m_ν**

(i.e. when things slow down enough for gravitational collapse!)

Structures are cutoff to the **horizon size** at that temperature

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

$$H \simeq T^2/M_P$$

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

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

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

How does this compare with **observations**?

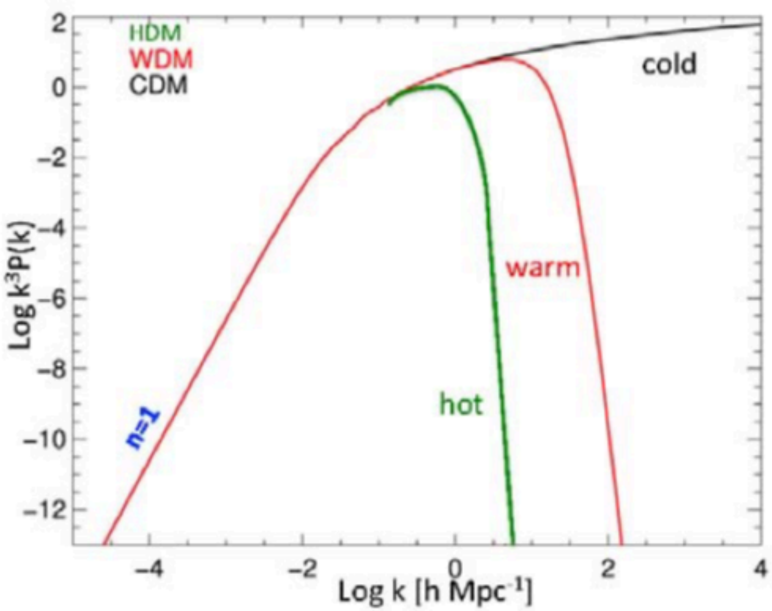
$$\frac{M_P^3}{m_\nu^2} \sim 10^{15}\, M_\odot \left(\frac{m_\nu}{30\ \mathrm{eV}}\right)^{-2} \sim 10^{12}\, M_\odot \left(\frac{m_\nu}{1\ \mathrm{keV}}\right)^{-2}$$

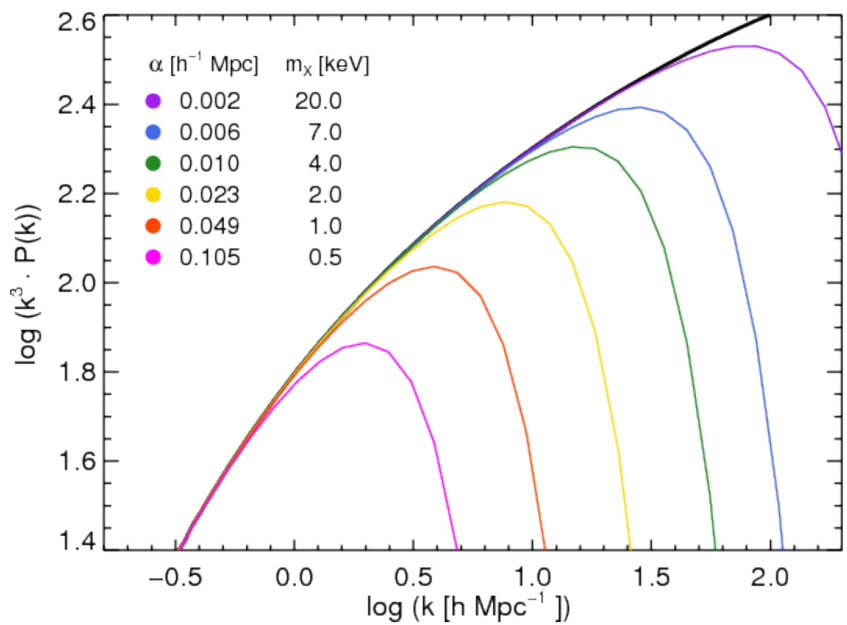
Observational **constraints** give

$$M_{\mathrm{cutoff}} \ll M_{\mathrm{Ly}-\alpha} \simeq 10^{10}\, M_\odot$$

- Neutrinos cannot be **all** of the Dark Matter
- at best Dark Matter can be **keV** scale, if produced thermally

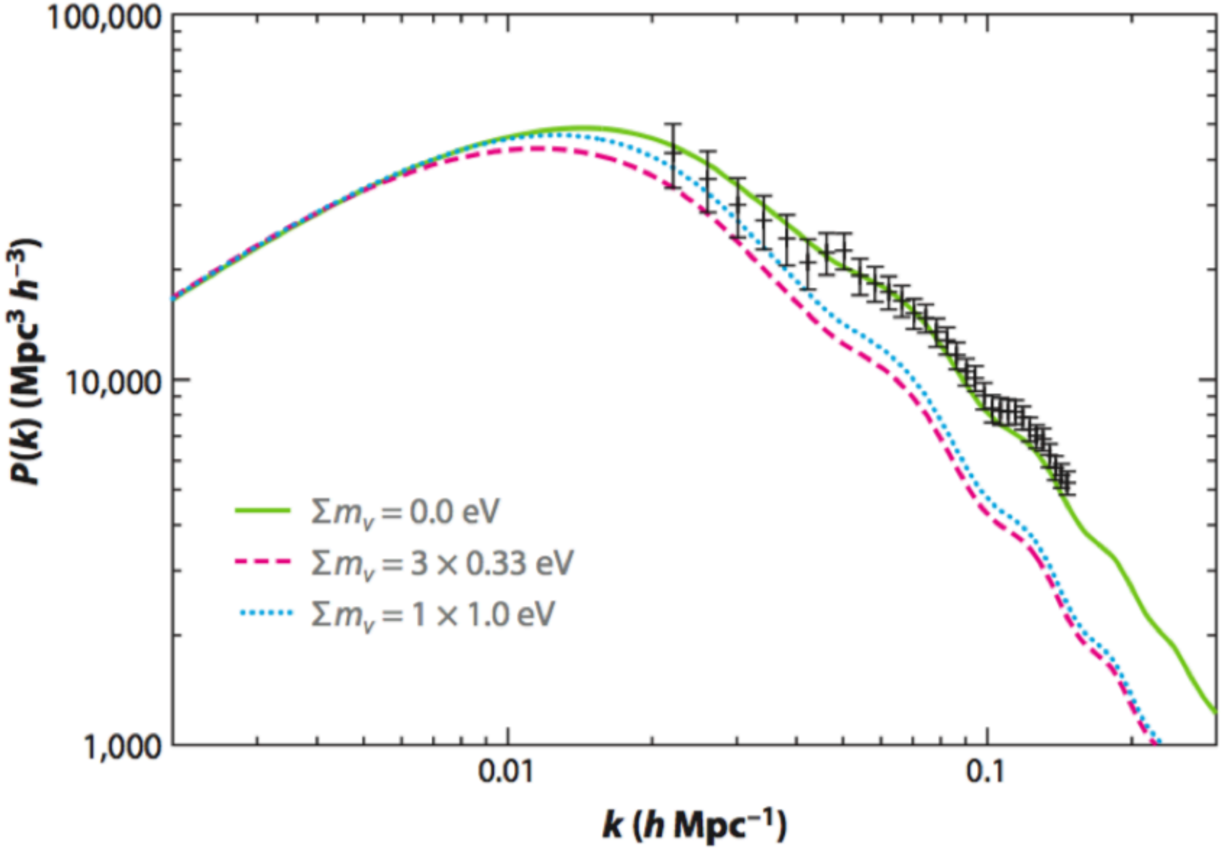
…a bit more quantitatively





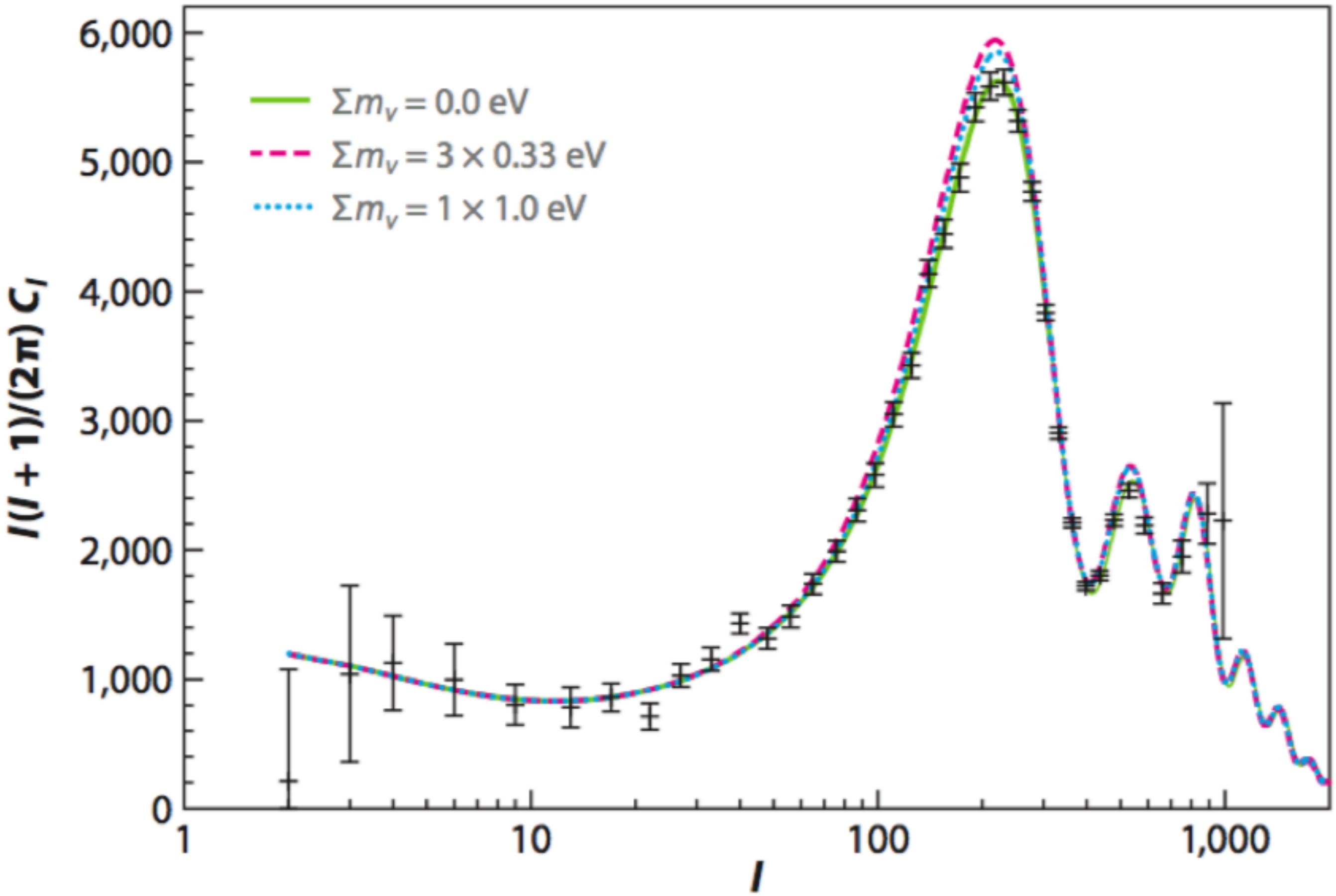
*Frenk+White; **Viel et al

…a bit more quantitatively



*Wong

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



*Wong

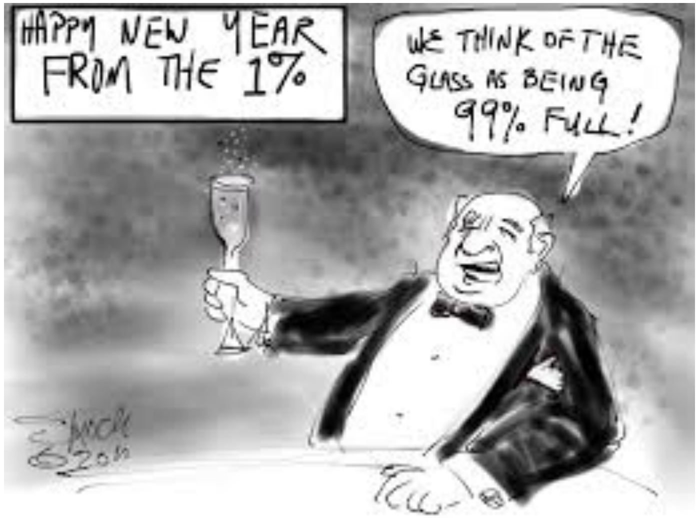
CMB by itself demands $\sum_j m_j \lesssim (0.3 - 1.3)$ eV

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

…putting the SM component of neutrinos as DM at

$$\Omega_\nu h^2 < \frac{0.170\ \text{eV}}{91.5\ \text{eV}} \simeq 0.0019$$

$$0.5\% < \frac{\Omega_\nu}{\Omega_{\text{DM}}} < 1.6\%$$



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

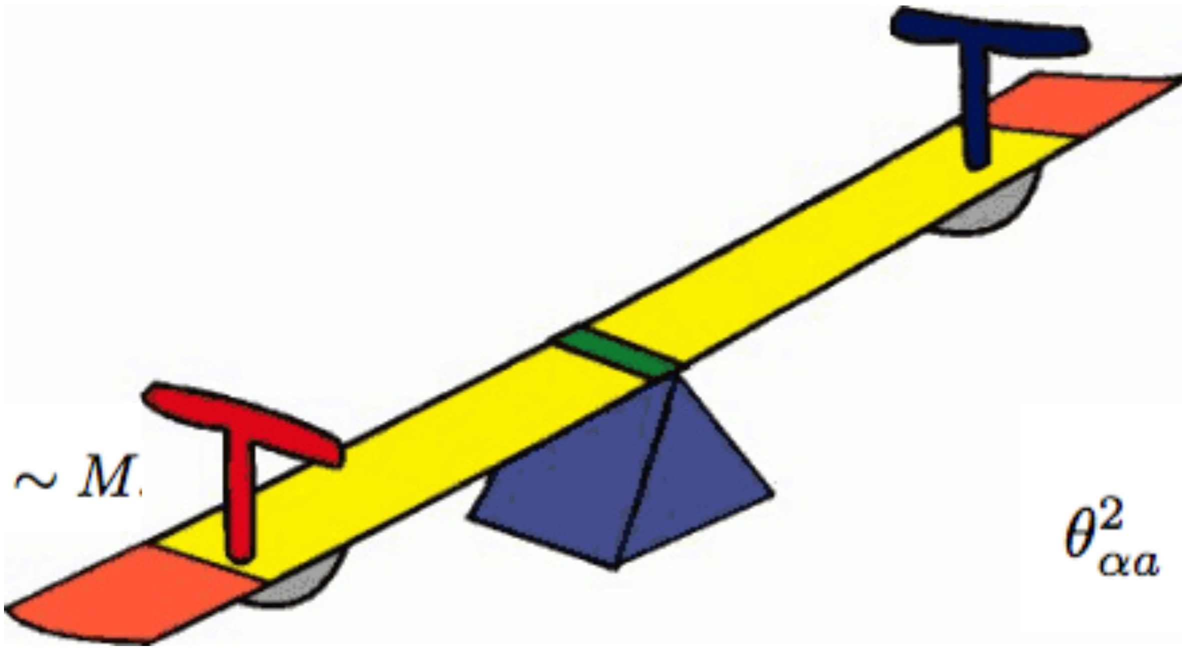
$$\mathcal{L} = \mathcal{L}_{\rm SM} + i\bar{N}_a \partial\!\!\!/ N_a - y_{\alpha a} H^\dagger \bar{L}_\alpha N_a - \frac{M_a}{2}\bar{N}_a^c N_a$$

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

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)

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

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

Also, if these guys have anything to do with DM, ***m > 100 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)

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

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

…actual best limit around **0.1 keV**

How can sterile neutrinos be **produced**?

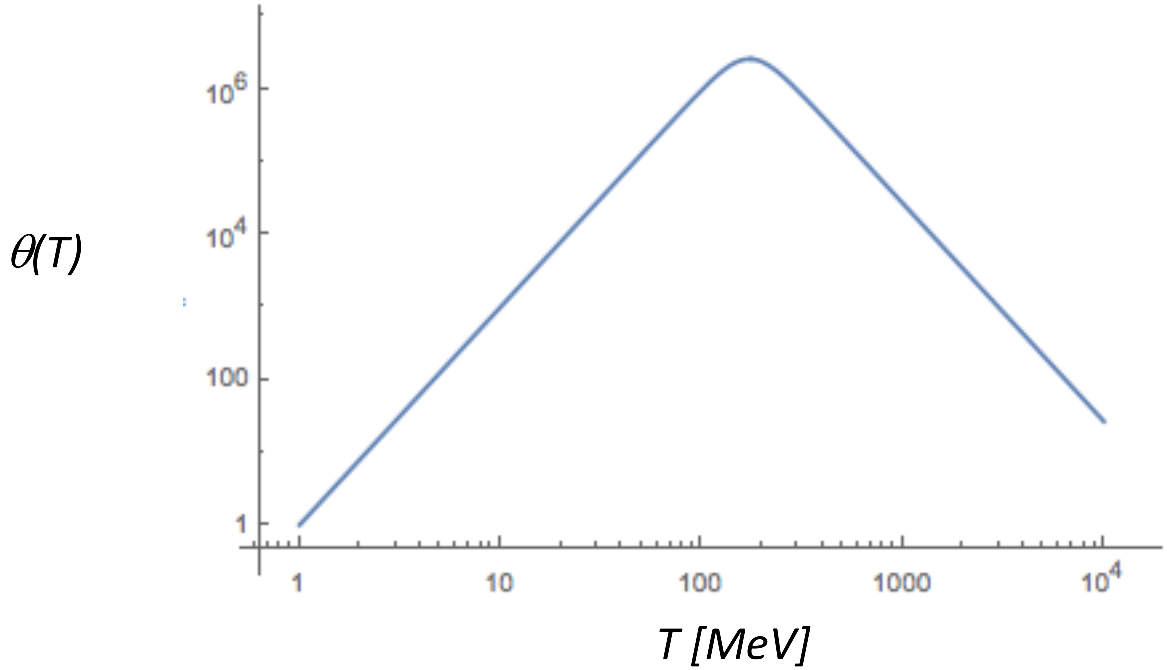
Basically, **freeze-in**: dump out-of-equilibrium sterile ν's through the universe history

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

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 ν 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 (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}>>1 TeV
Calculation is identical as for ordinary neutrinos, but with $m_W \rightarrow m_{WR}$

$$\sigma \sim G_F^2 T^2 (m_W/m_{W_R})^4 \qquad \Gamma_N \sim G_F^2 T^5 (m_W/m_{W_R})^4$$

$$T_f \sim g_*^{1/6}(T_f)\left(\frac{m_{W_R}}{m_W}\right)^{4/3} \mathrm{MeV}$$

$$\frac{\Omega_N}{\Omega_{\mathrm{DM}}} = \frac{1}{S}\left(\frac{10.75}{g_{*s}(t_f)}\right)\left(\frac{M}{\mathrm{keV}}\right) \times 100.$$

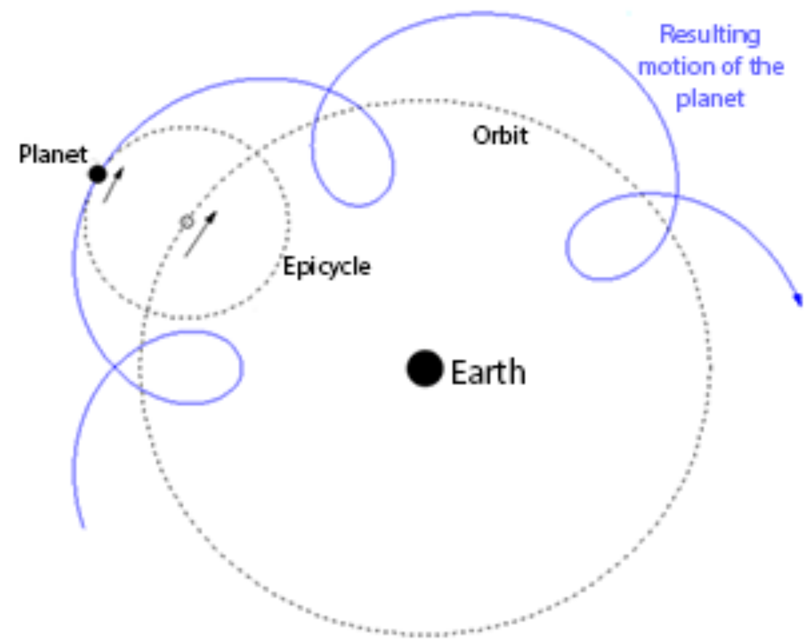
Possible entropy dilution effect

* Nemevsek et al (2012)

$$\frac{\Omega_N}{\Omega_{\rm DM}} = \frac{1}{S}\left(\frac{10.75}{g_{*s}(t_f)}\right)\left(\frac{M}{\rm keV}\right) \times 100.$$

So this doesn't really work...

...unless we attach one or more **epicycles**...



$$\frac{\Omega_N}{\Omega_{\rm DM}} = \frac{1}{S}\left(\frac{10.75}{g_{*s}(t_f)}\right)\left(\frac{M}{\rm keV}\right) \times 100.$$

- 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

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

* Nemevsek et al (2012)

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

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

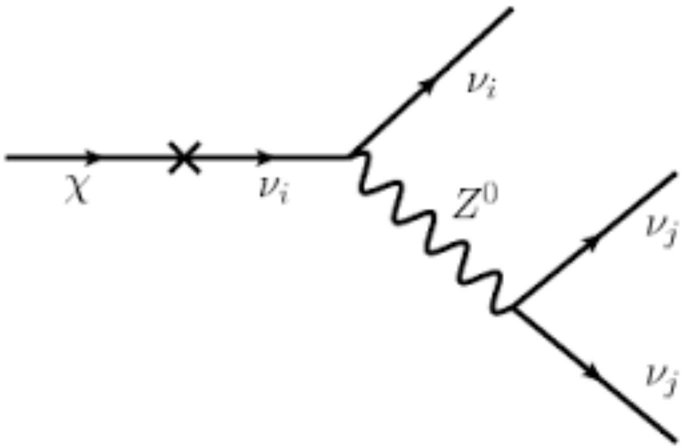
$$\frac{M_P^3}{m_\nu^2} \sim 10^{15}\ M_\odot \left(\frac{m_\nu}{30\ \rm eV}\right)^{-2} \sim 10^{12}\ M_\odot \left(\frac{m_\nu}{1\ \rm keV}\right)^{-2}$$

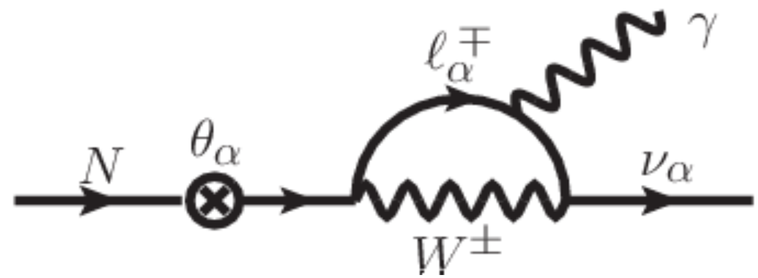
...and could explain high-velocity **pulsars**!

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

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

*Kusenko et al **Shaposhnikov et al





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

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

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

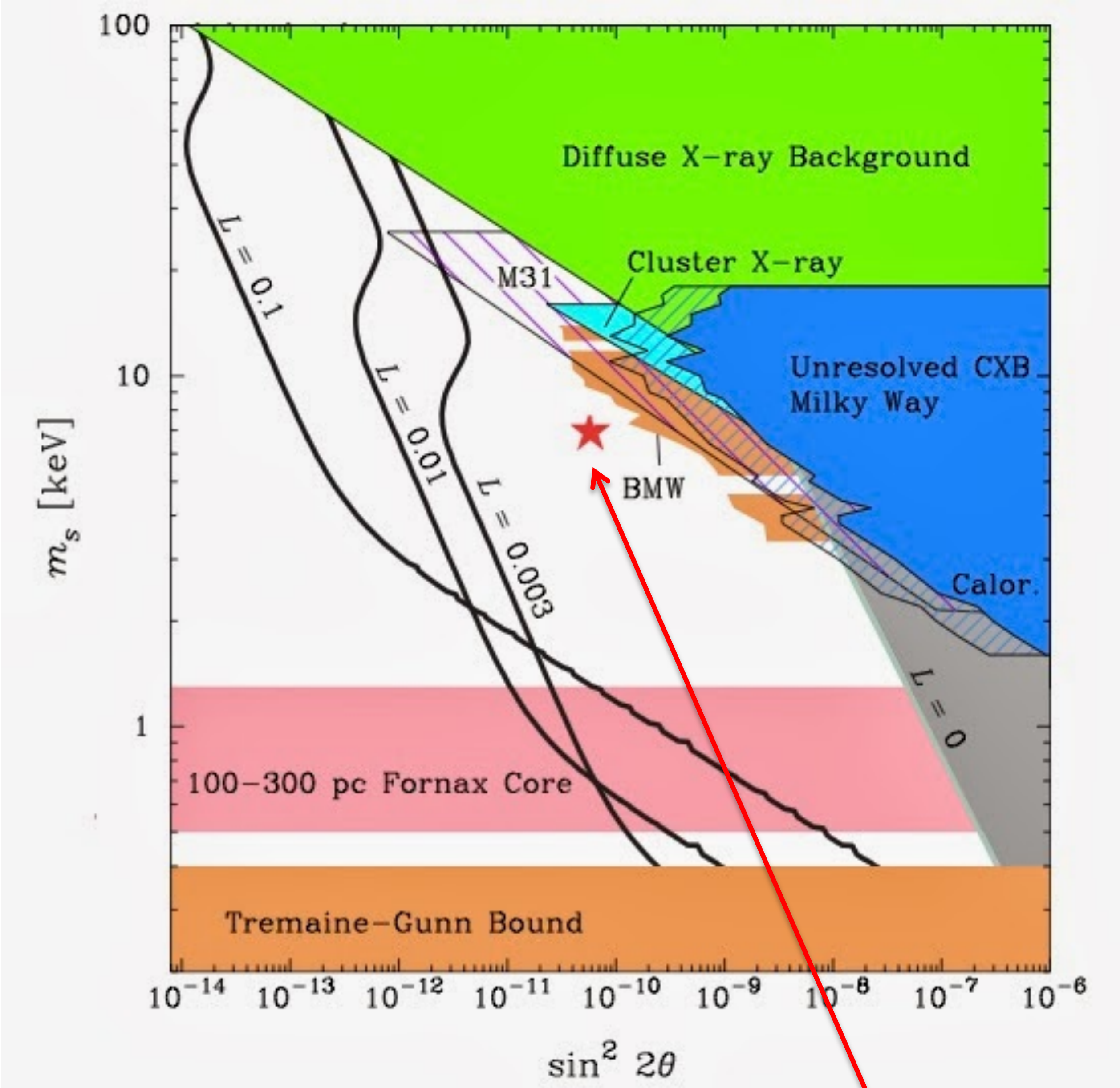
key background: diffuse **cosmic X-ray background**

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

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

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

Have we **detected** it?



Was sterile neutrino DM **detected**?

*Bulbul+ 14

Bulbul+ (2014)

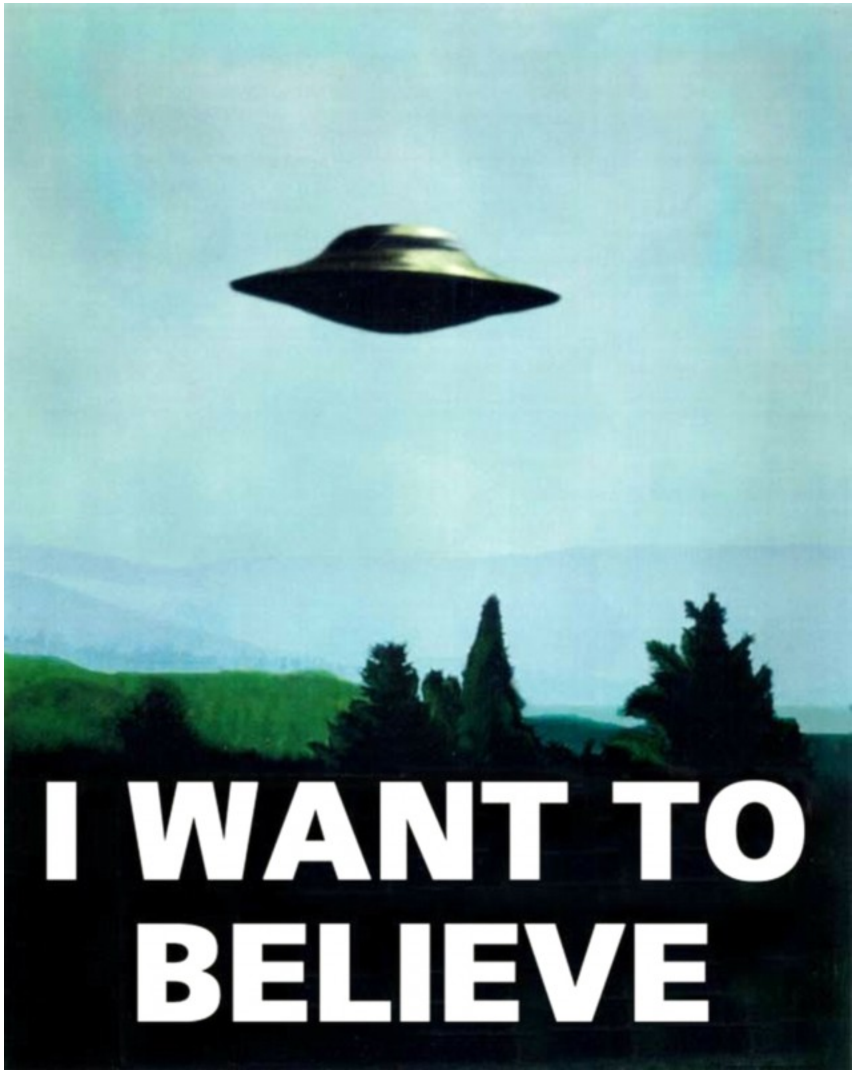
- Stacked clusters
- Perseus

Boyarsky+ (2014)

- M31 (Andromeda)
- Perseus

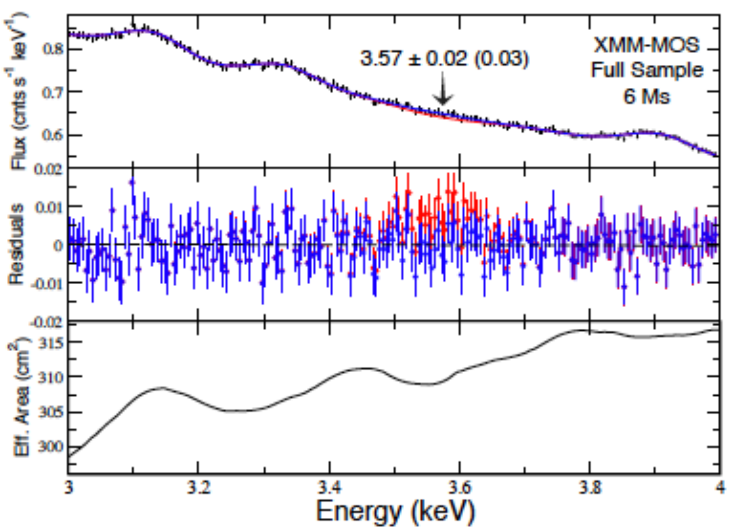
Jeltema+Profumo (2014)

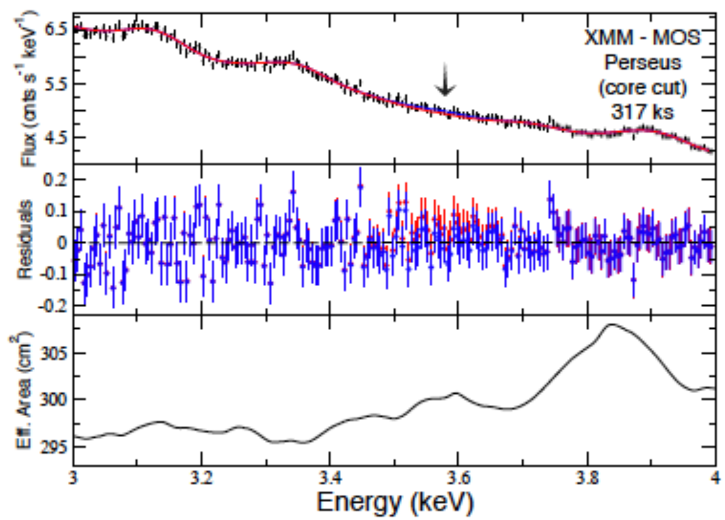
- Galactic Center


I WANT TO
BELIEVE

Bulbul+ (2014)

- Stacked clusters
- Perseus





despite the faint signal (at most 3σ), much hype (~600 papers), much press

SKY & TELESCOPE

Mysterious X-rays Might Hint at Dark Matter

By: **Monica Young** | July 8, 2014

The Register®

Biting the hand that feeds IT

Boffins say dark matter found with X-ray

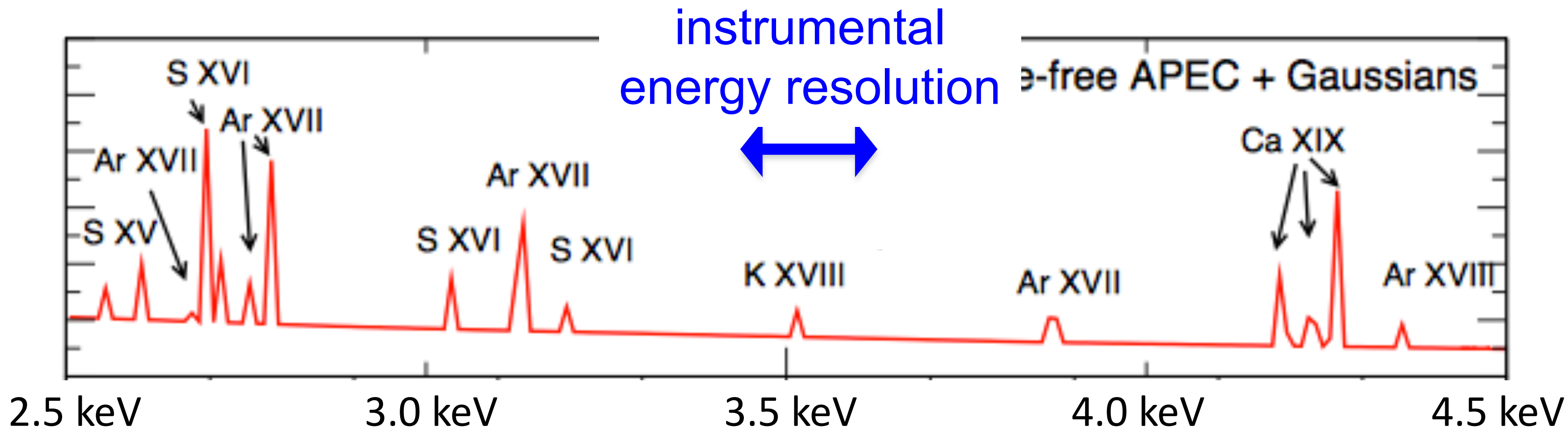
light on dark matter

gizmag

By Brian Dodson

March 10, 2014

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 → $Z \sim (3{,}500\ /\ 13.6)^{1/2} \sim 16$, 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

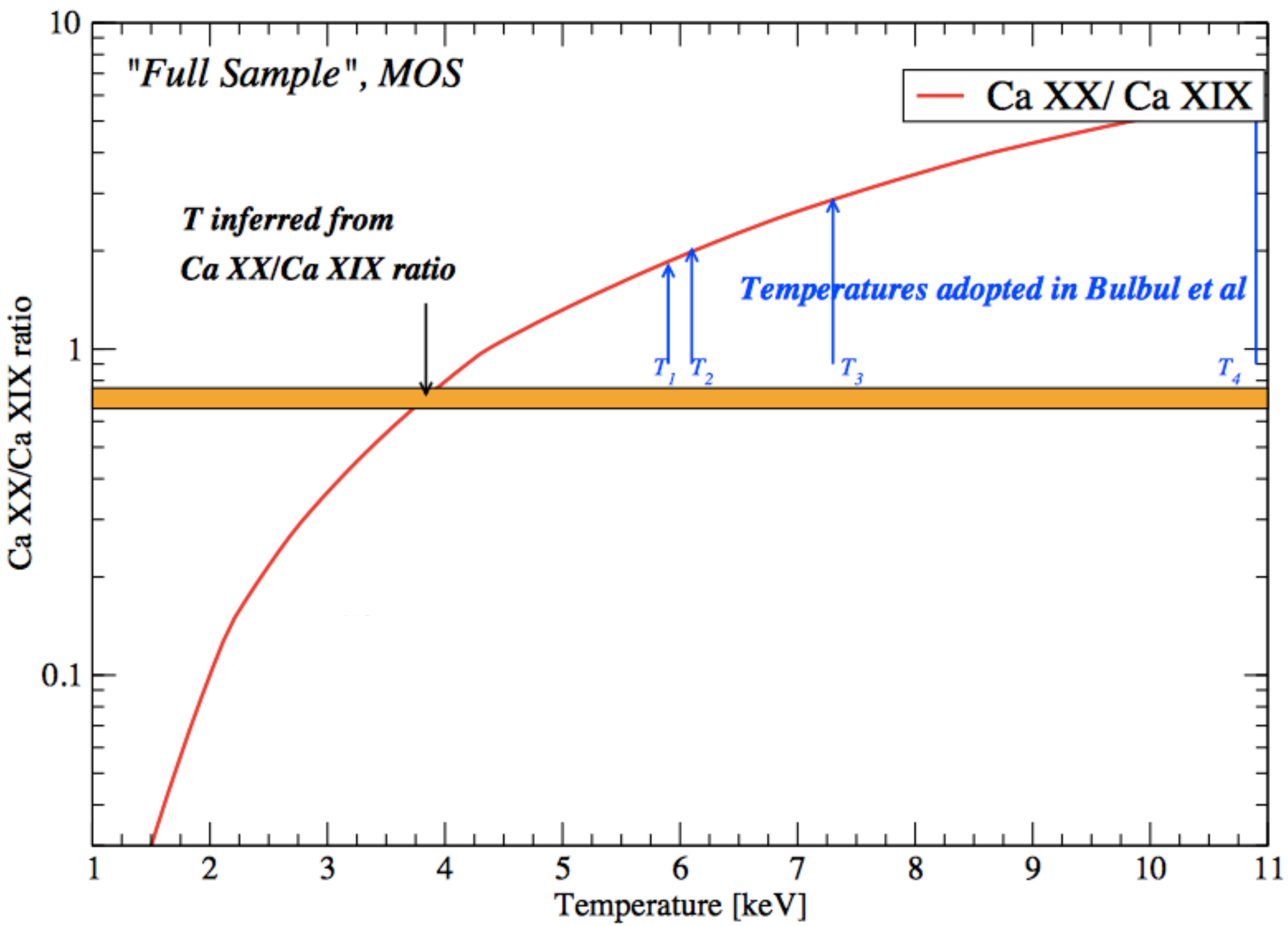
Bulbul+ argues against K XVIII since prediction for K 3.5 keV line too low (by factors ~20 for solar abundances)

…but this prediction has two key issues:

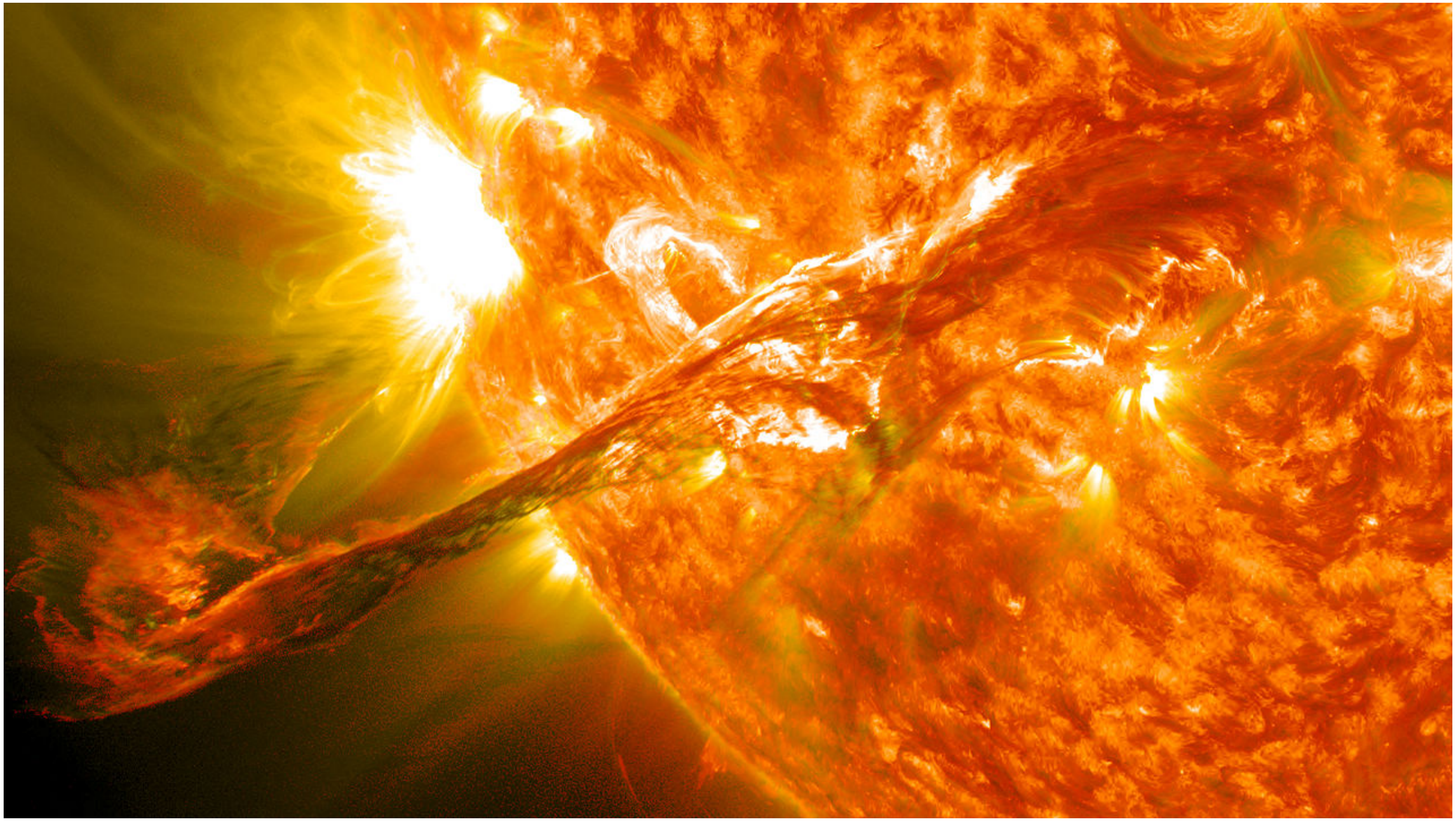
#1 Plasma Temperature

#2 Relative Elemental Abundances

#1: Bulbul+ uses very large T highly suppresses K emission!



#2: 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

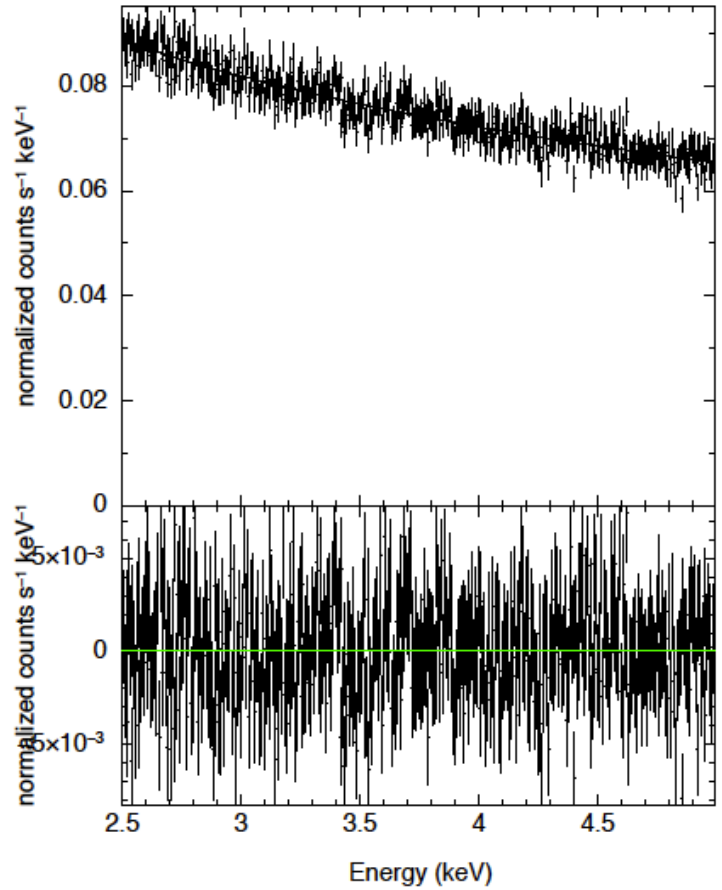
** Anderson et al 2014

*** Jeltema and Profumo 2014

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

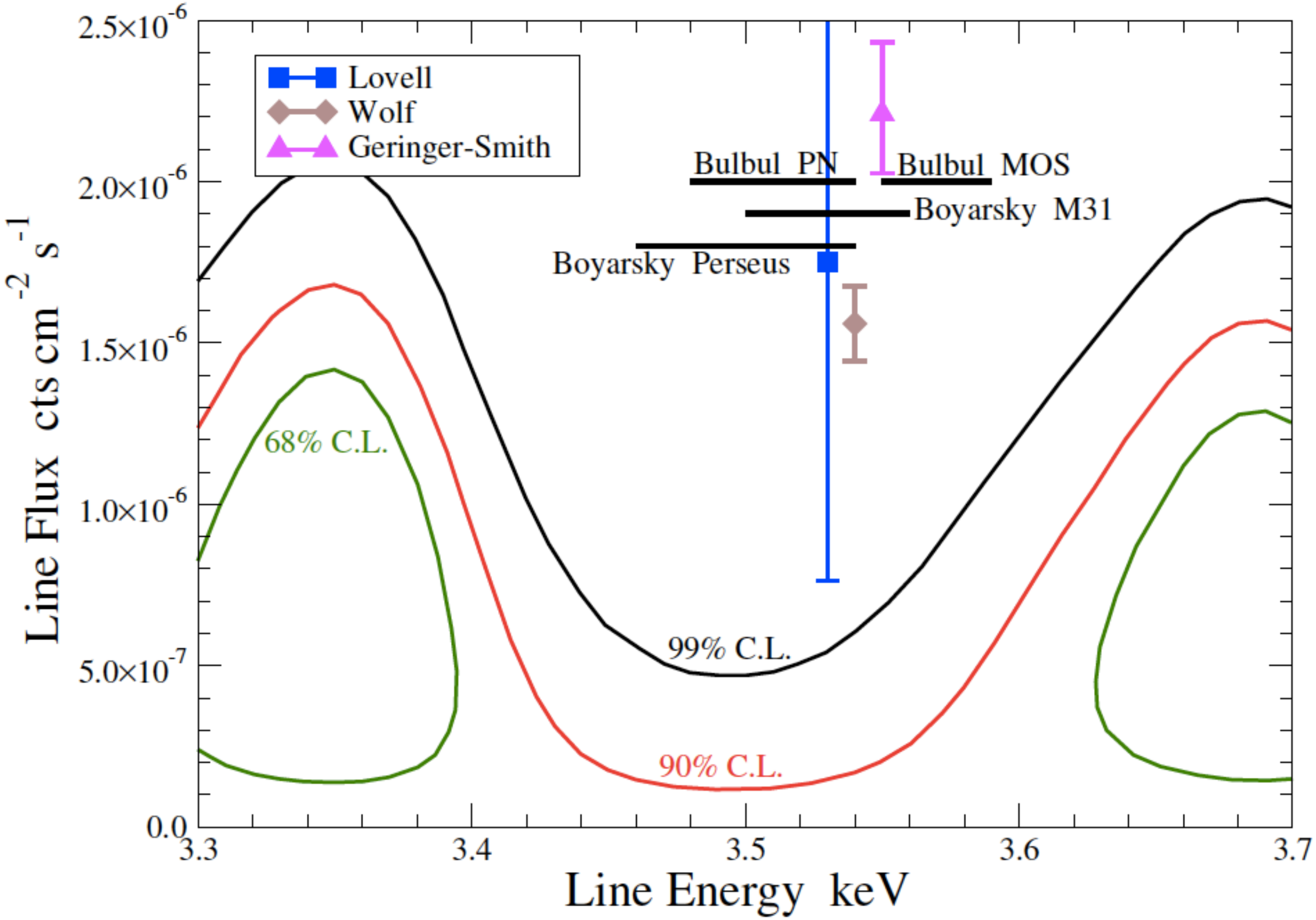
- Draco dSph observed for 1.66 Msec with XMM (19 days)
  – no expected plasma emission
- Spectrum well fit by simple power law background in 2.5-5 keV band

Stacked MOS Spectrum



* Jeltema and Profumo, MNRAS (2015)

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

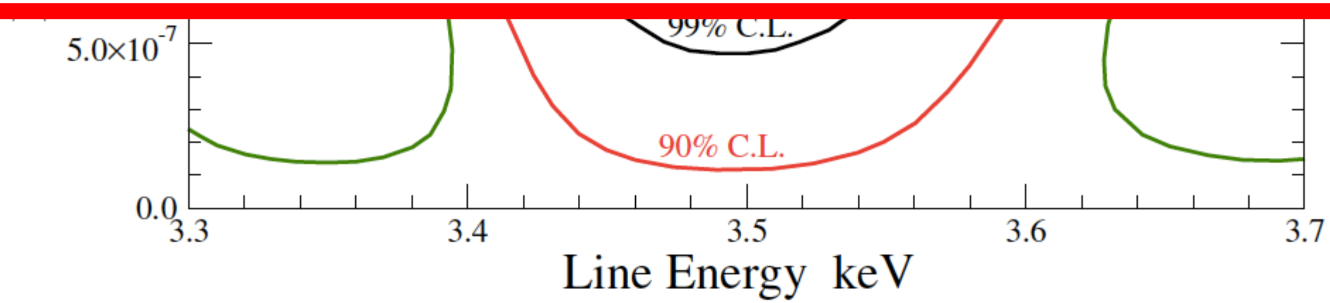


* Jeltema and Profumo, MNRAS (2015)

➢ 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."



* Jeltema and Profumo, MNRAS (2015)

(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,[a,b] **Tesla Jeltema,**[a,b] **Stefano Profumo**[a,b]

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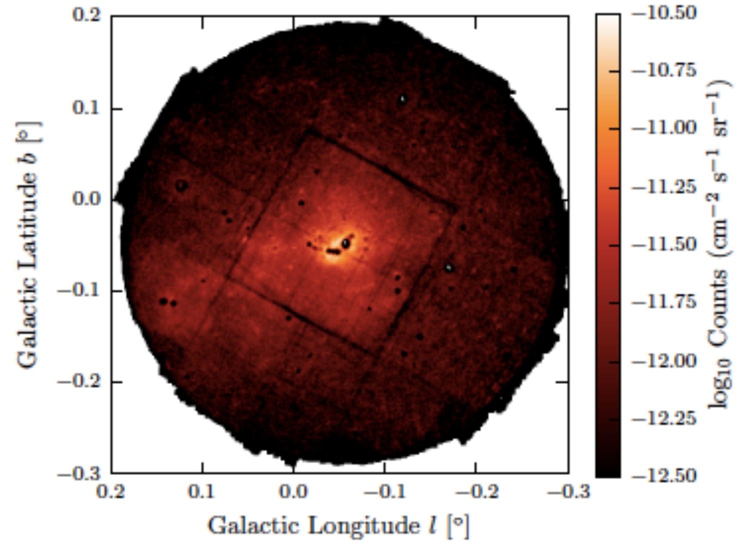
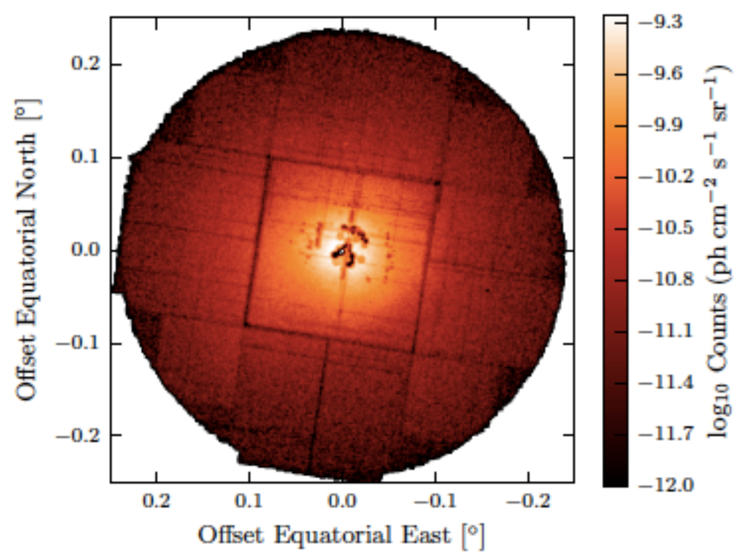
1156 High St, Santa Cruz, CA 95064
[b]Santa Cruz Institute for Particle Physics,
1156 High St, Santa Cruz, CA 95064

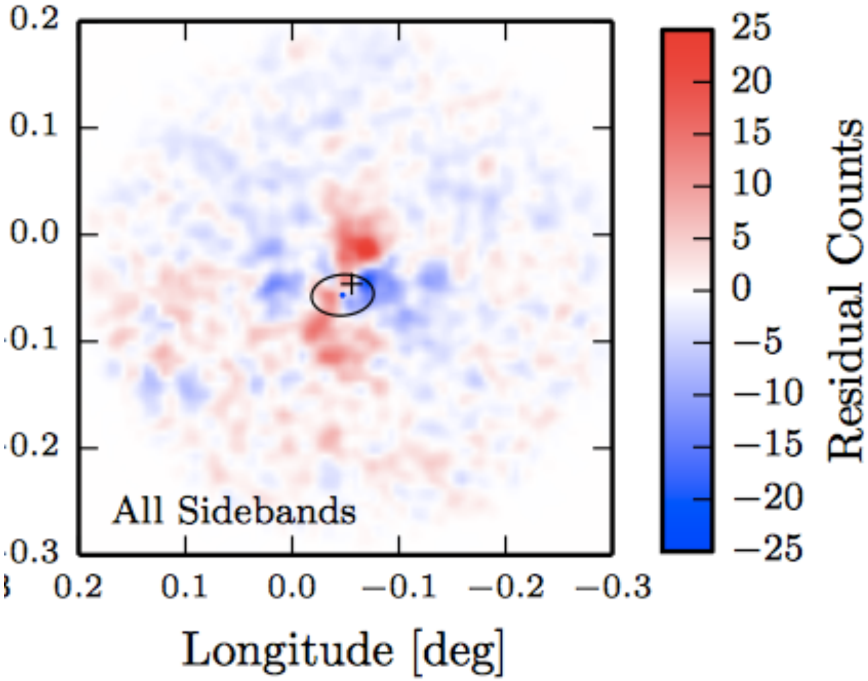


(a) Galactic Center

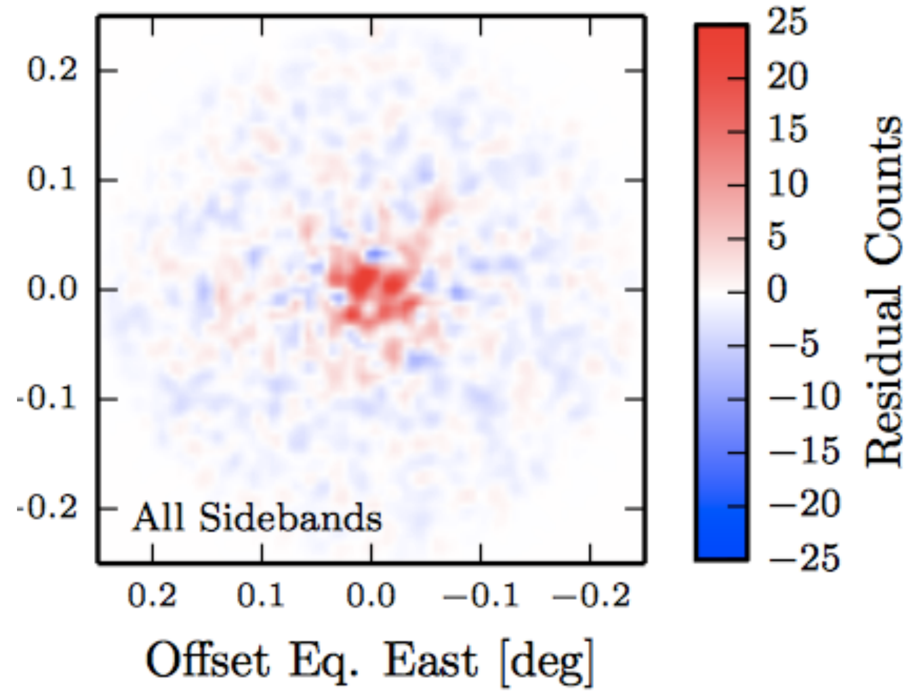


(b) Perseus Cluster

Carlson, Jeltema and Profumo, JCAP 2015



Milky Way



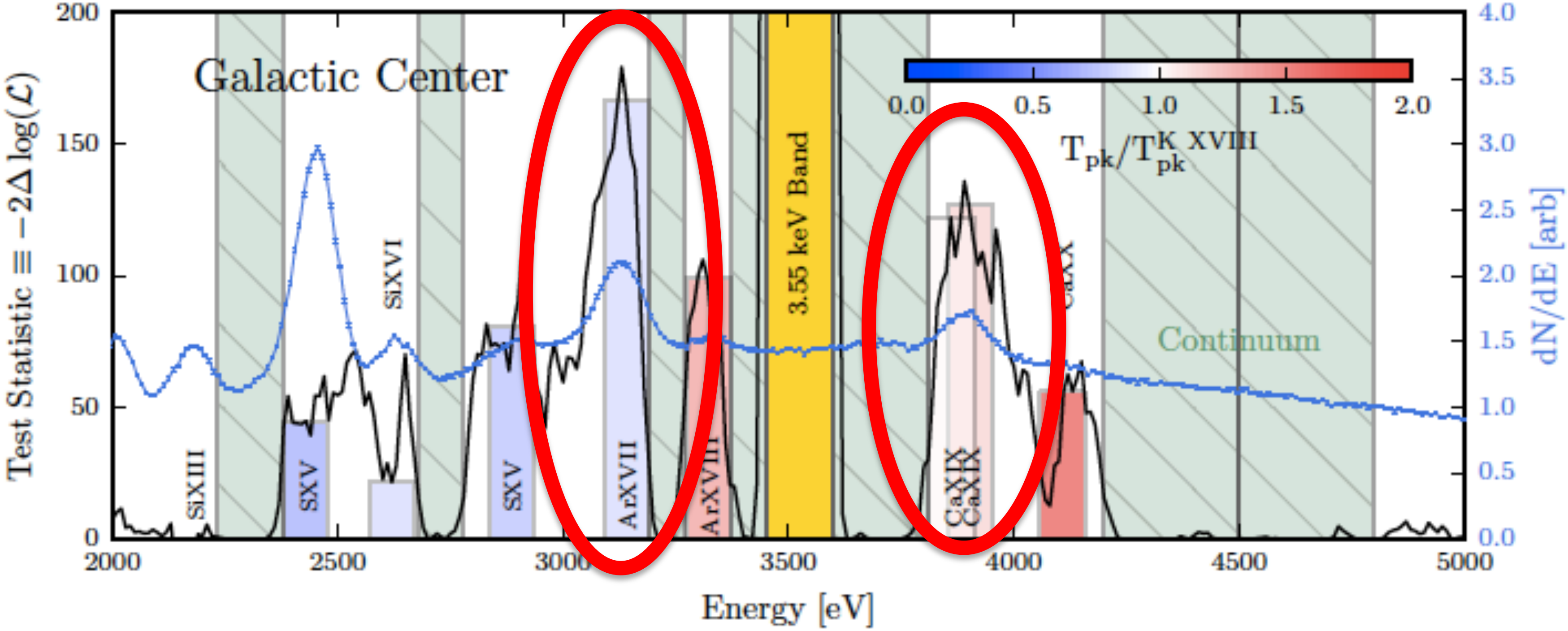
Perseus

Morphology: looks like thermal line
decaying DM strongly disfavored

Carlson, Jeltema and Profumo, JCAP 2015

Scanning Window Template

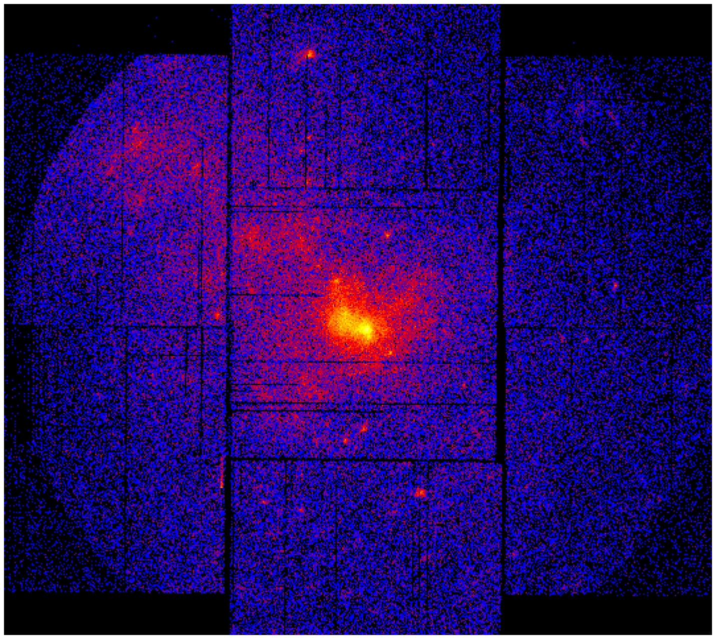
Galactic Center



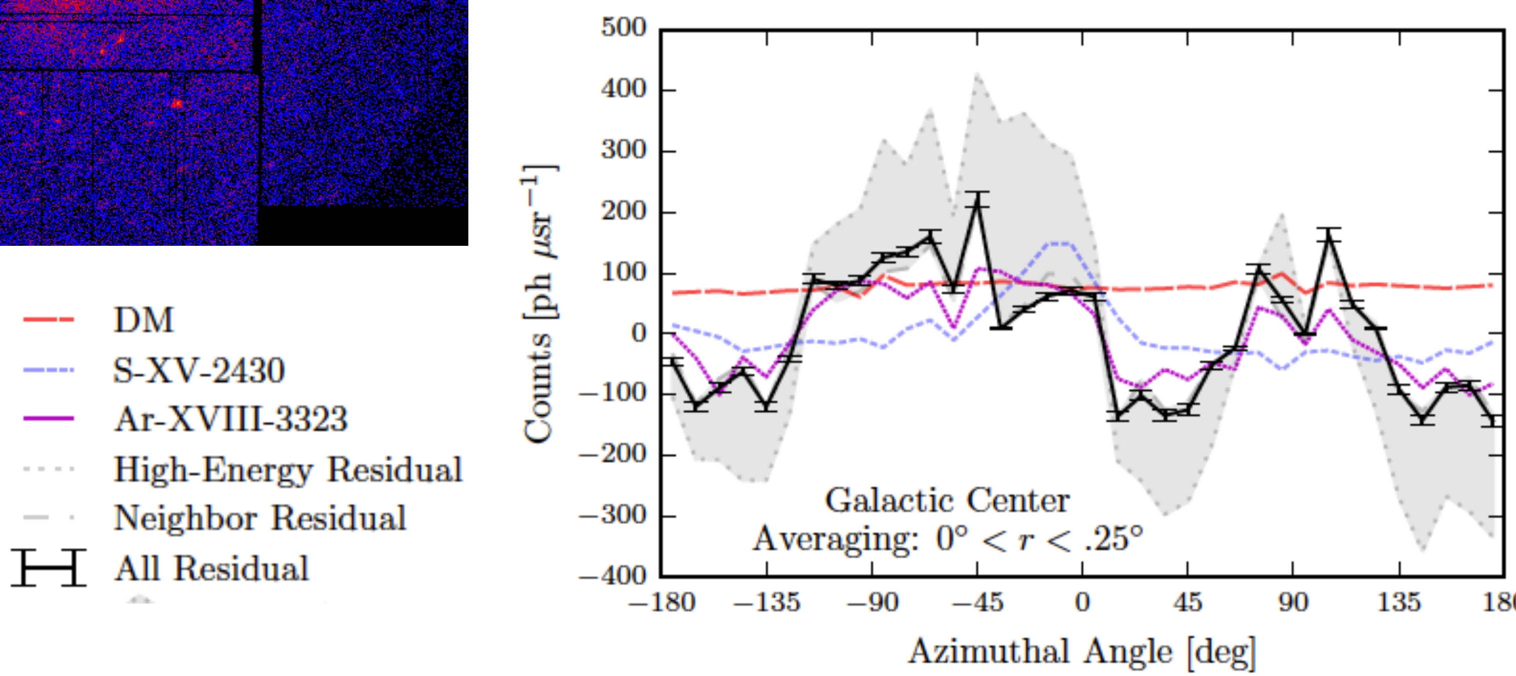
Carlson, Jeltema and Profumo, JCAP 2015

Scanning Window Template

Galactic Center

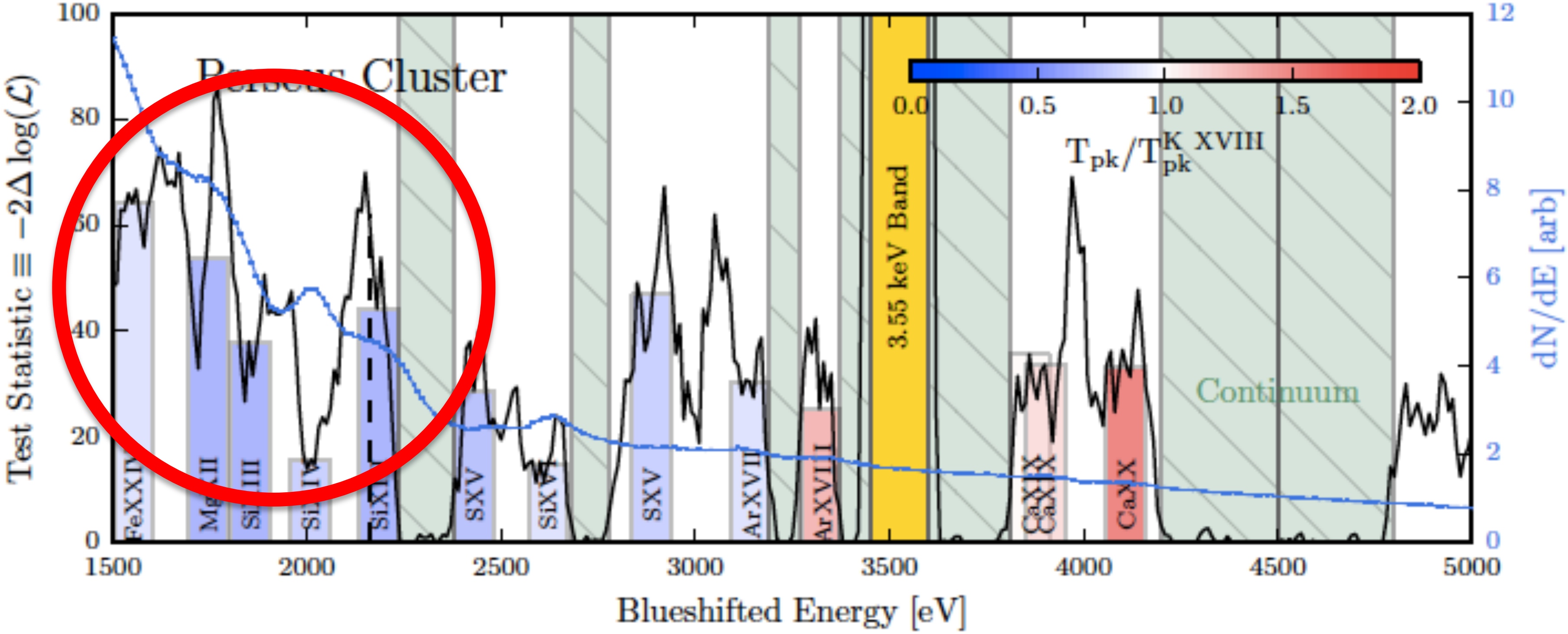


- The 3.5 keV emission is asymmetric with a distribution similar to nearby plasma lines



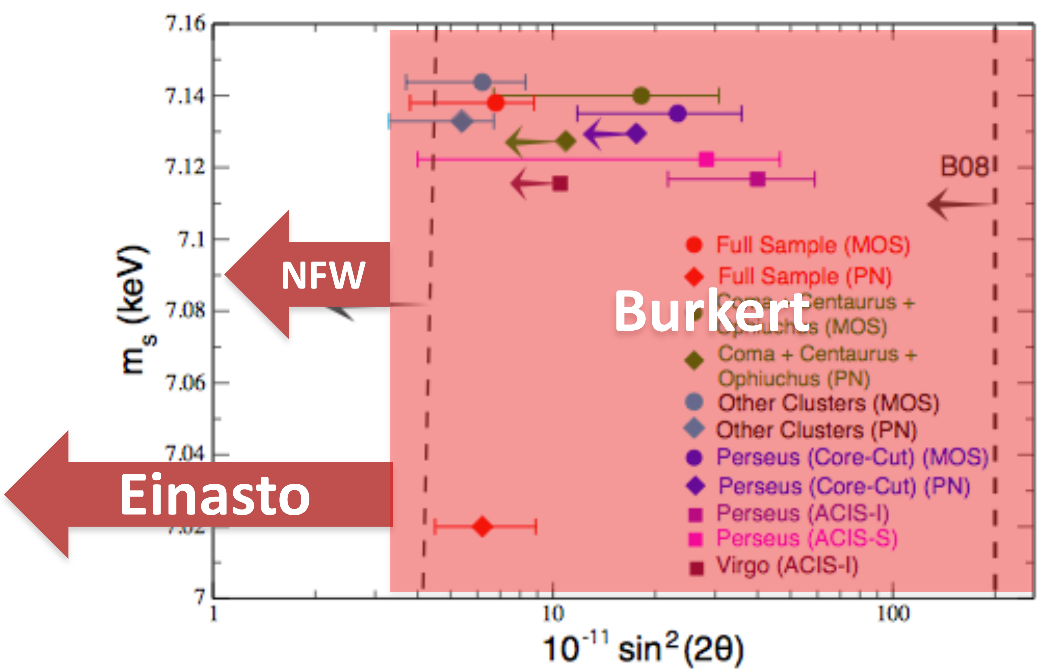
Carlson, Jeltema and Profumo, JCAP 2015

Scanning Window Template
Perseus Cluster



Carlson, Jeltema and Profumo, JCAP 2015

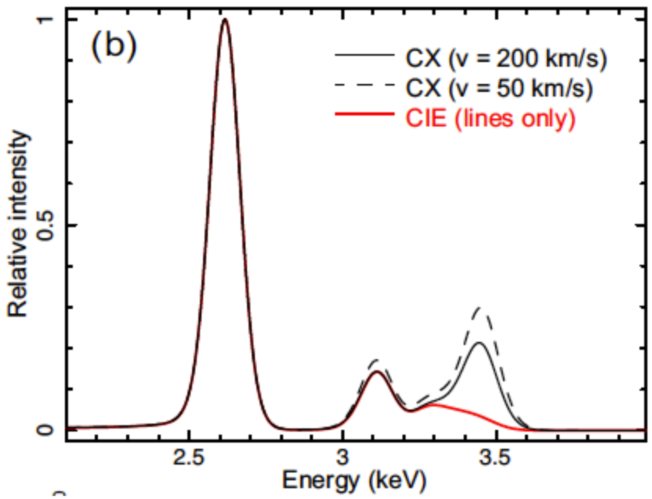
- The 3.5 keV morphology in GC (asymmetric) and Perseus (cool-core) follows astrophysical plasma not DM
- Limits inconsistent with DM decay origin of Bulbul line



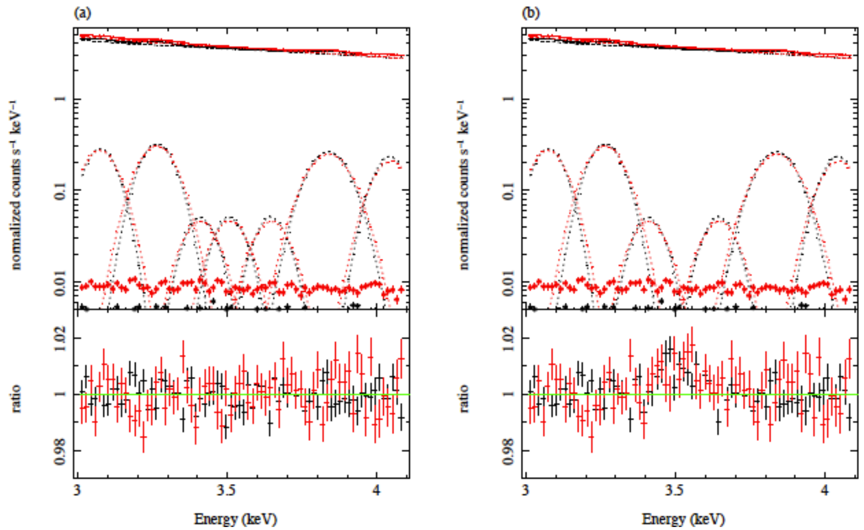
Carlson, Jeltema and Profumo, JCAP 2015

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)**



3.47 keV line has no collisional only line!

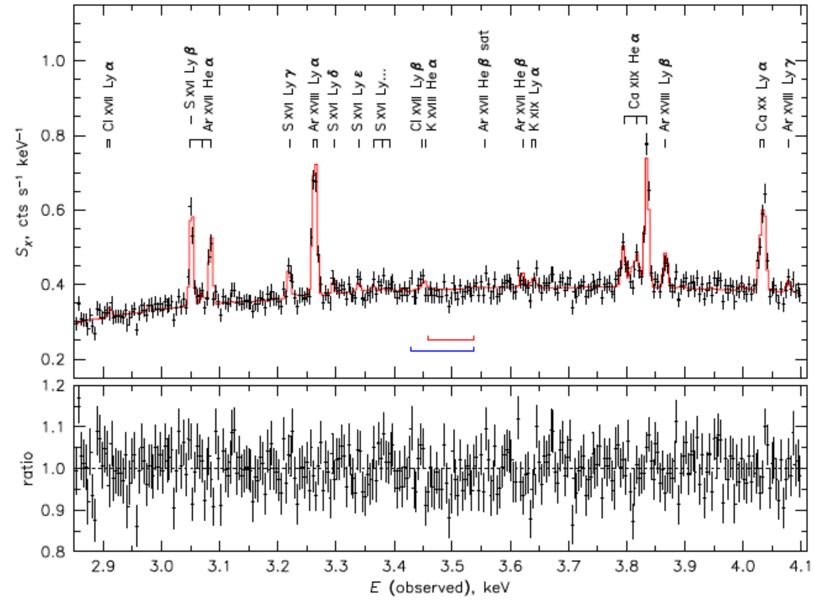


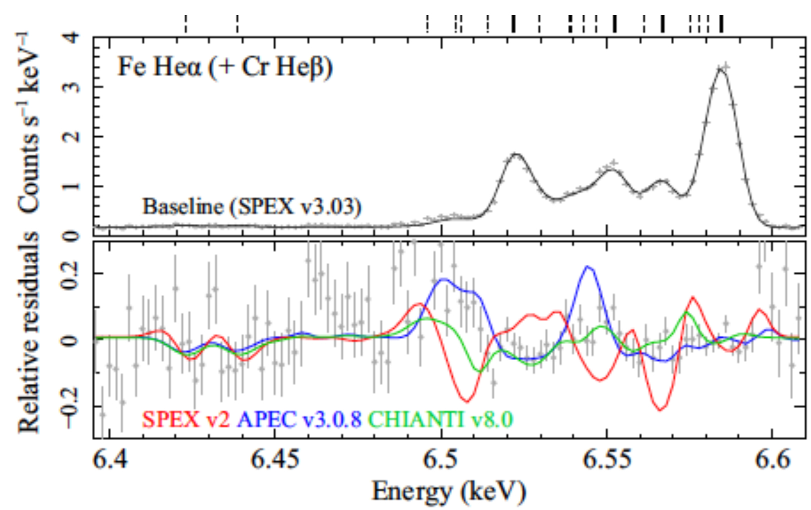
over-subtracting lines leads to introducing fake features!

Perseus observations with Hitomi

Reveals the challenges and opportunities of high spectral resolution…

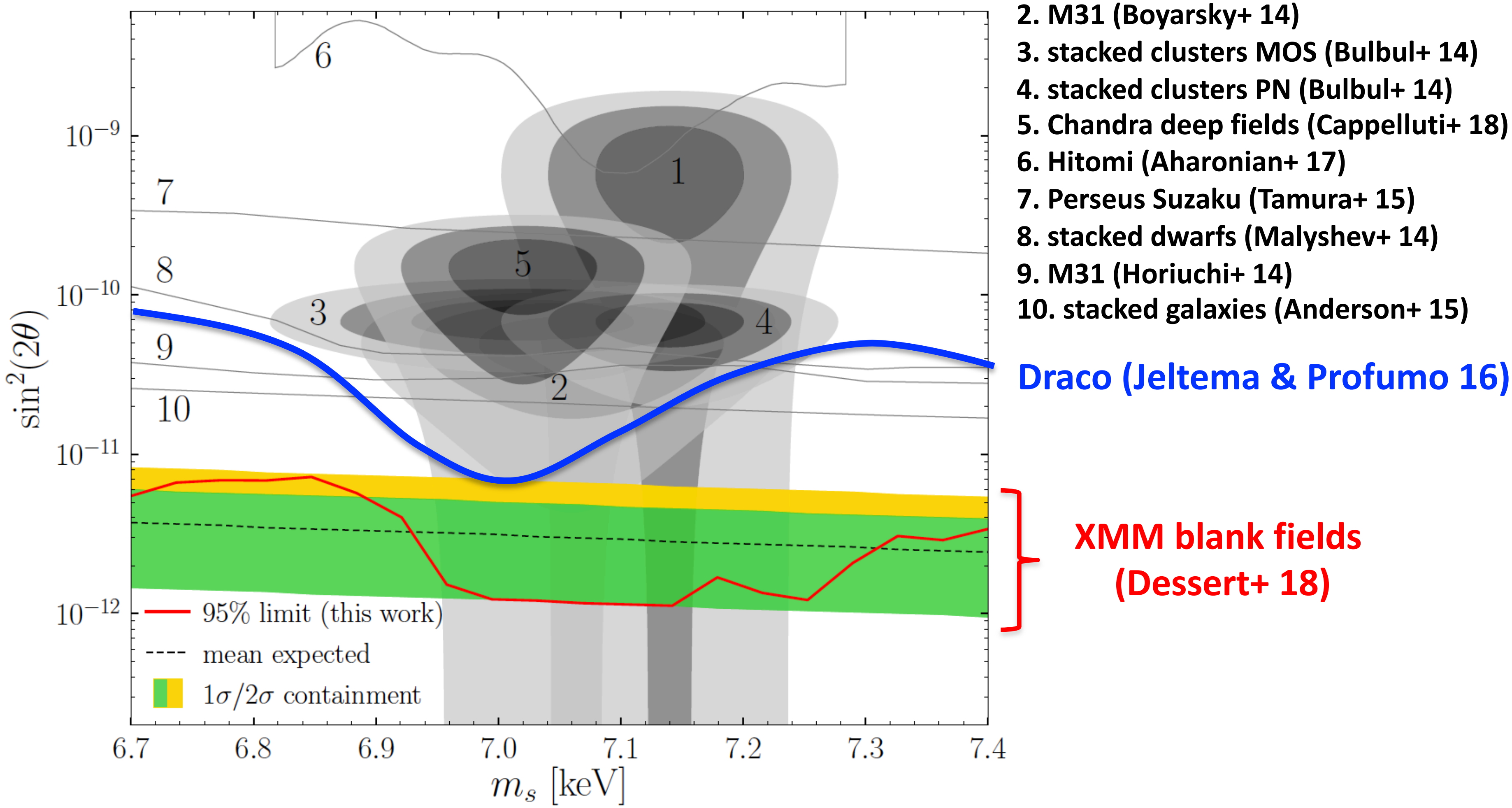
- No 3.5 keV line detection (OK with KXVIII and DM interpr.)
- Hint of SXVI charge exchange? (1.6s)
- Differences seen between atomic codes point to need for improved modeling and laboratory measurements





* 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)

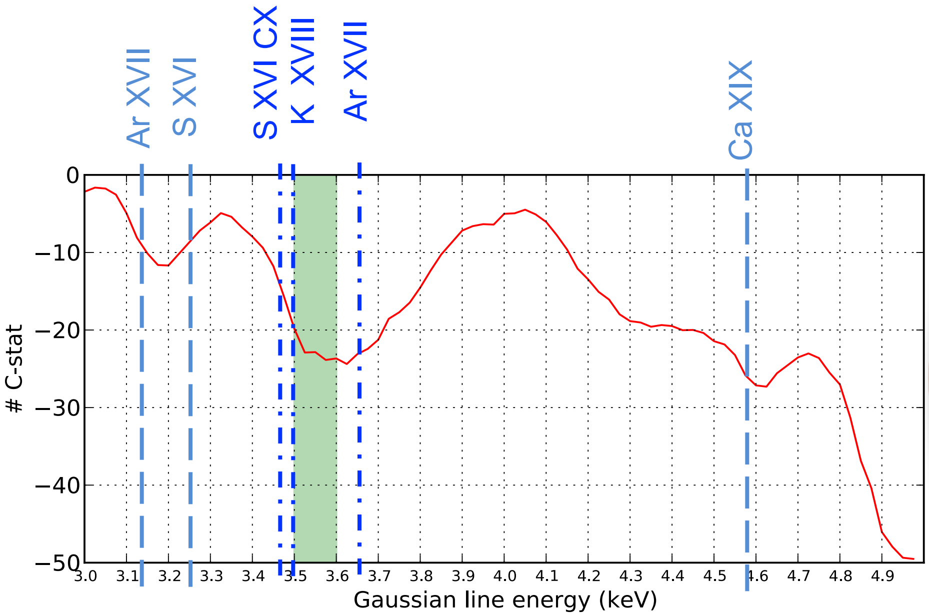
New Cluster Analysis

Bhargava, Jeltema et al., in prep.

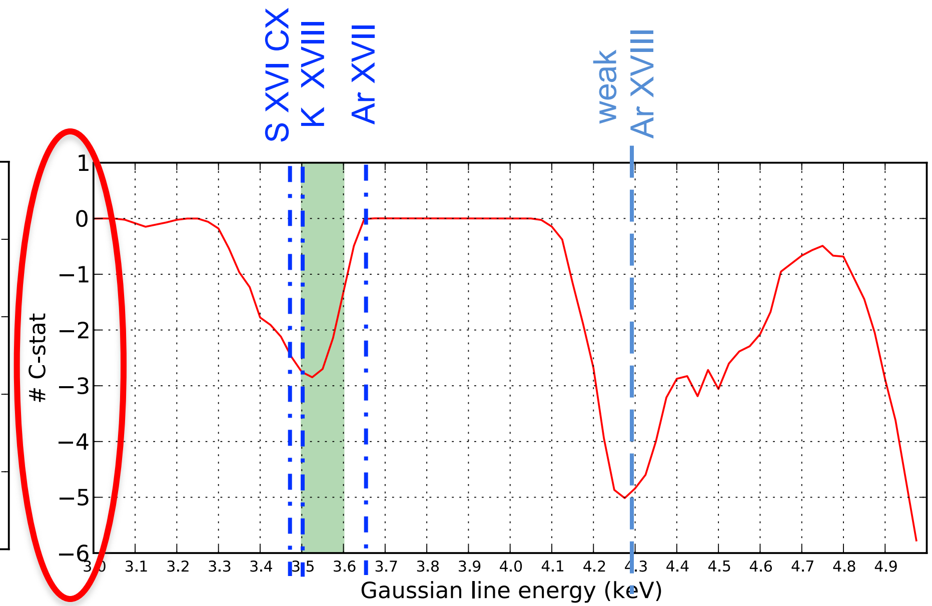
- Joint fitting of 144 clusters from the XMM Cluster Survey
- Bin by X-ray temperature with 20-30 clusters per bin

T_x bin (keV)	No. of clusters	T_X average (keV)	$M_{500,DM}$ average (10^{14} $M_\odot$)	$M_{500,DM}/d_L^2$ average (10^{10} $M_\odot$/Mpc^2)	Total SNR (0.3 – 7.9 keV)
≤ 3	20	2.43	1.14	0.01	1254
$3-4$	29	3.50	2.11	0.03	2435
$4-5$	23	4.63	3.31	0.04	2389
$5-6$	22	5.44	4.23	0.02	2339
$6-7$	19	6.57	5.95	0.04	2856
≥ 7	31	9.50	12.4	0.18	3140

New Cluster Analysis



$T_X < 3$ keV

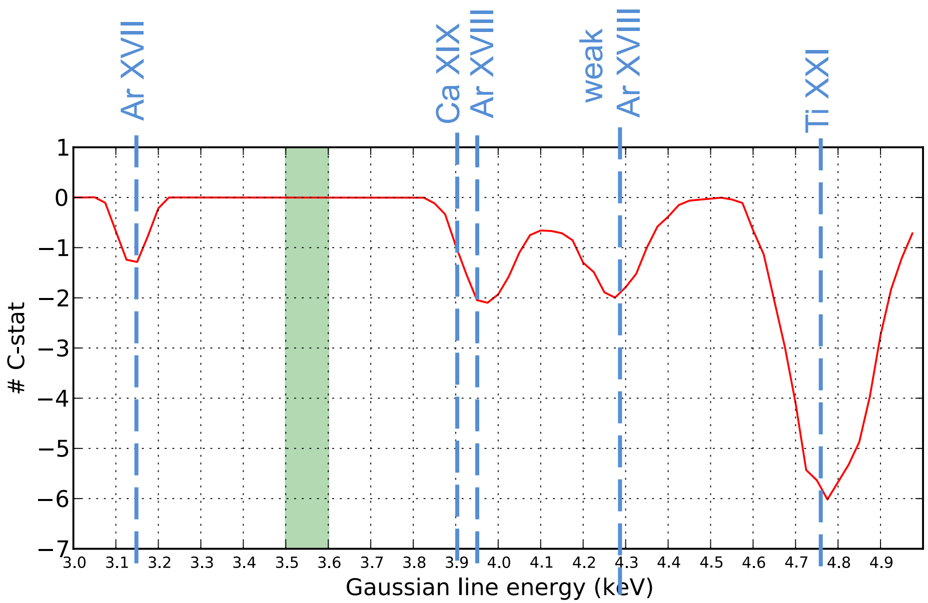


Not significant

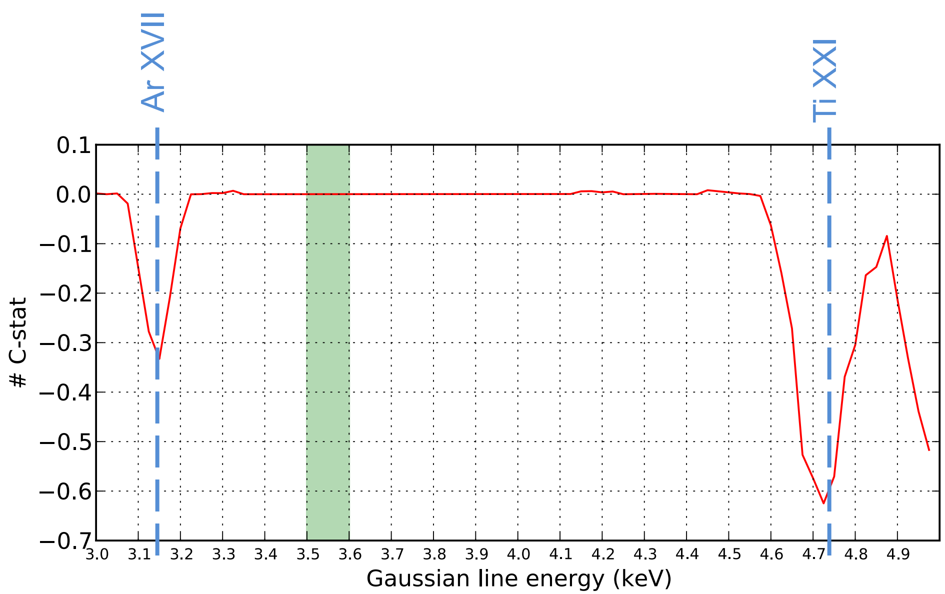
4 keV $< T_X <$ 5 keV

- **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**

New Cluster Analysis



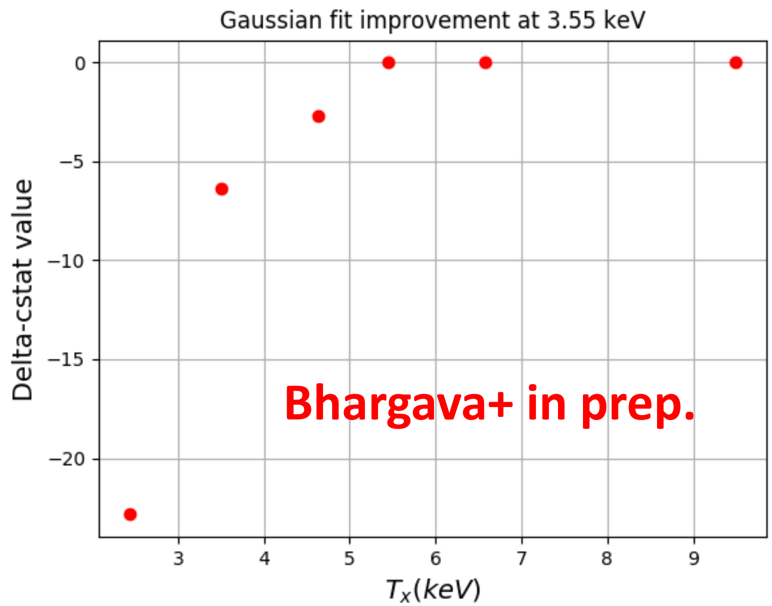
6 keV < T_X < 7 keV



T_X > 7 keV

- **No 3.5 keV line in the three highest T_X bins!**

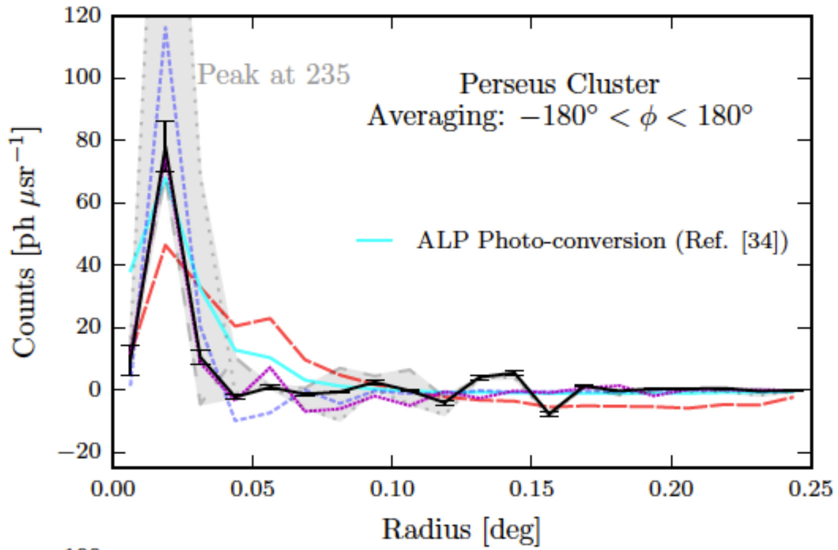
Plasma or Dark Matter?



- ➢ 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**



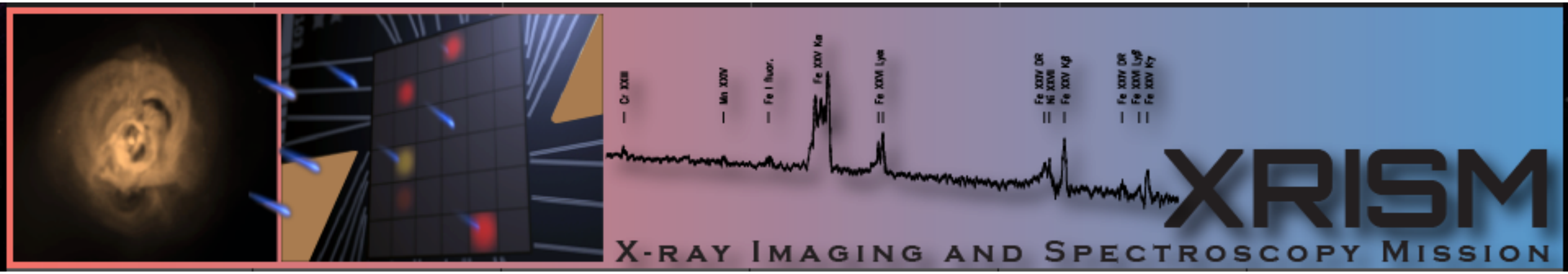
Carlson+ 2015

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+)



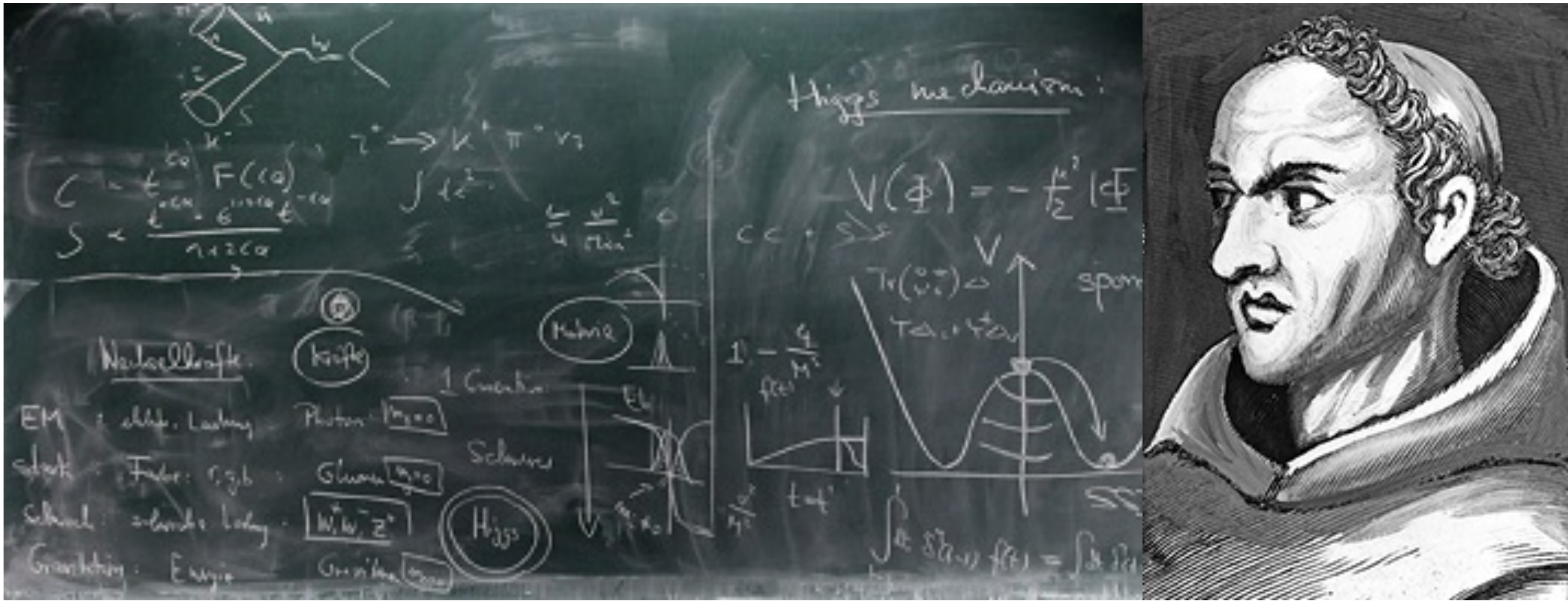
Recap!

	Signal?	Morphology?	K XVIII
Clusters [Perseus]		~Cool core	
Galactic Center		~Quadrupolar	
dSph [Draco]	X	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

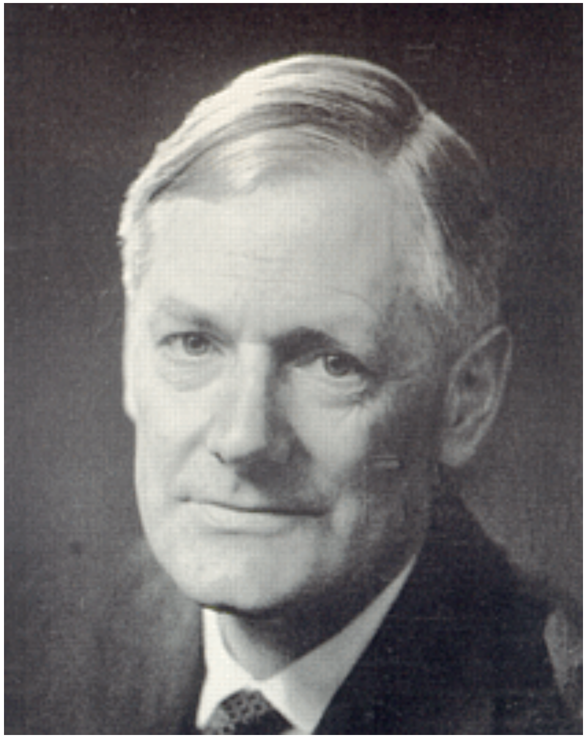
What if it is Dark Matter?

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" (*)

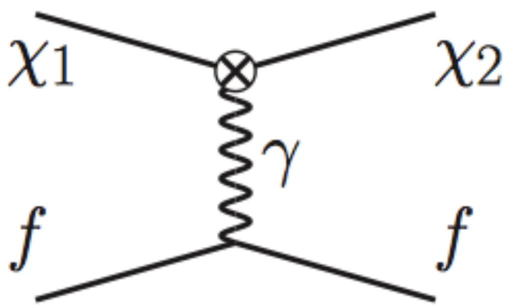


Roderick O. Redman
(b. 1905, d. 1975)
Professor of Astronomy at Cambridge University

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

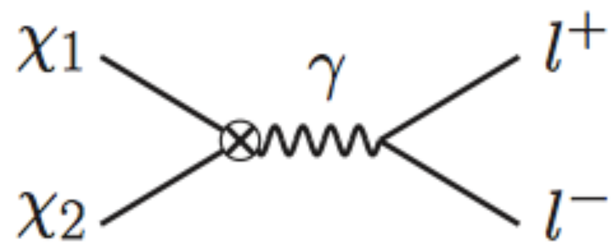
3.5 keV line …an excuse for an exciting, new mechanism for a signal from Dark Matter!

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



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

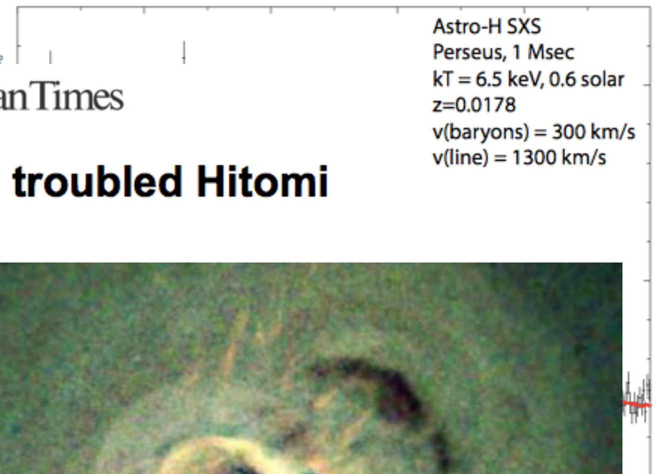
3. "Good" model: economical, natural UV completion, thermal relic DM

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)

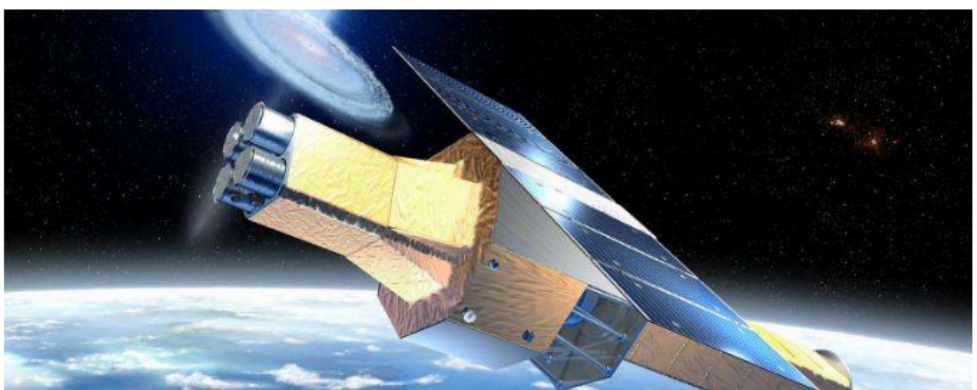


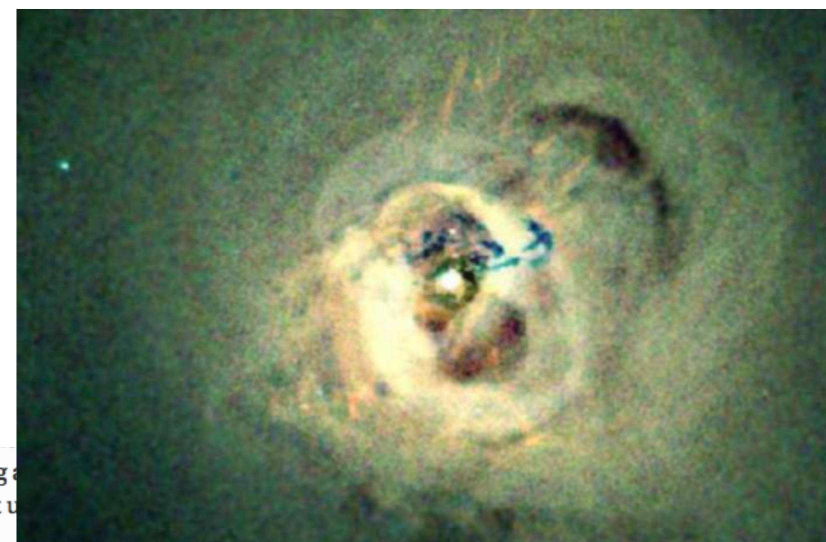
10°C LGT.RAIN

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





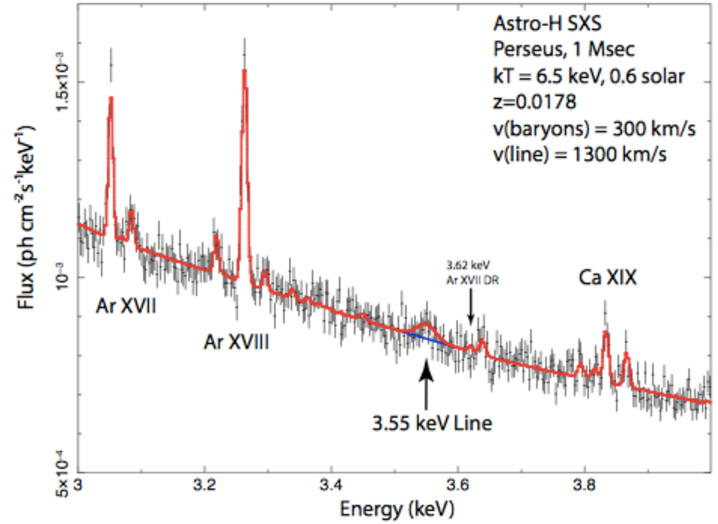
on a Japanese rocket in mid-February, could be experiencing
after an unexpected shift in its position may have rendered it u
solar power, it said.

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?

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

Tesla Jeltema[1]* and Stefano Profumo[1]†
[1] *Department of Physics and Santa Cruz Institute for Particle Physics University of California, Santa Cruz, CA 95064, USA*

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

spectral analysis of very deep Draco data →

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

Tesla Jeltema[1]* and Stefano Profumo[1]†
[1] *Department of Physics and Santa Cruz Institute for Particle Physics University of California, Santa Cruz, CA 95064, USA*

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

Eric Carlson,[a,b] Tesla Jeltema,[a,b] Stefano Profumo[a,b]

→ morphology of 3.5 keV emission in the GC and Perseus

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

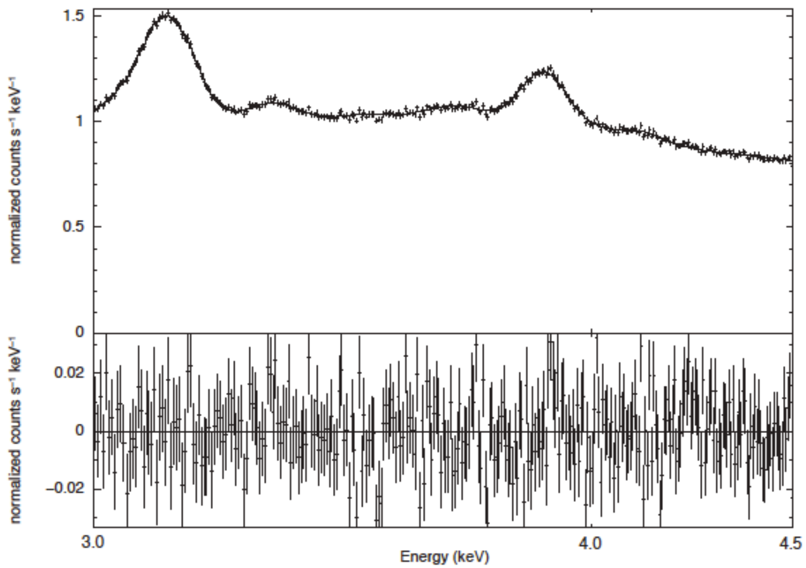
Galactic Center Spectrum

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

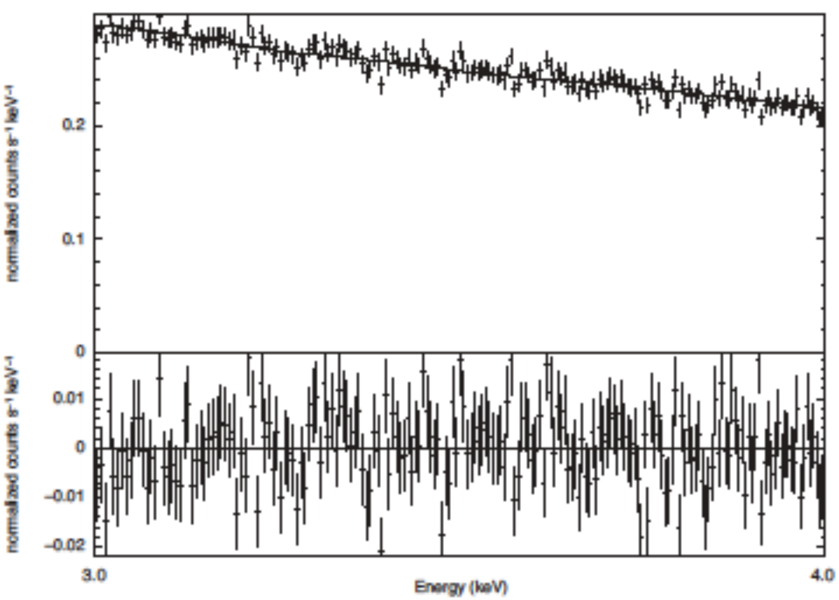


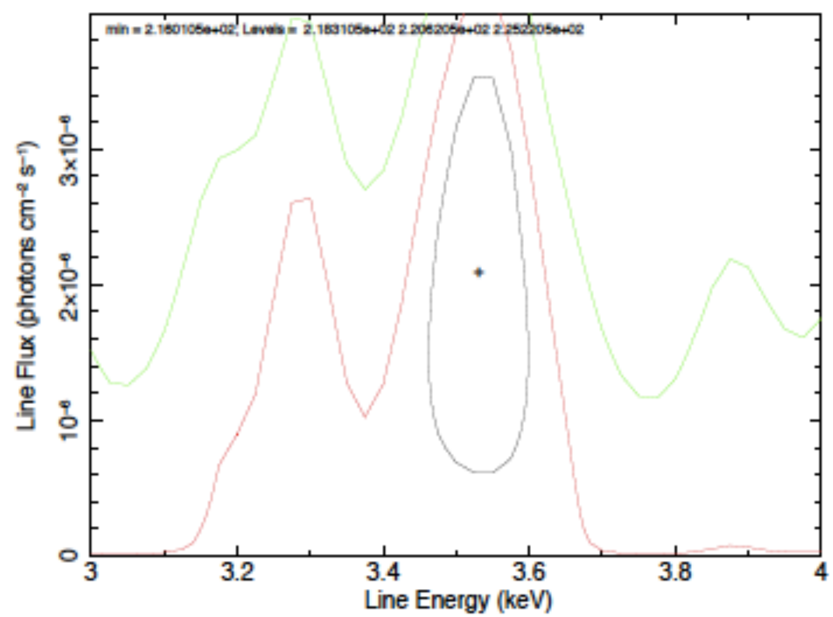
Jeltema & Profumo 2015

The 3.5 keV Line in M31

Re-analysis of XMM M31 data

=> No significant line found





Jeltema & Profumo 2015

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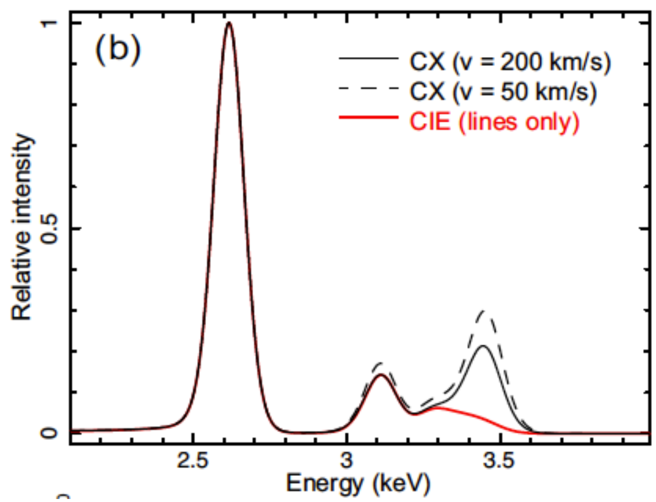
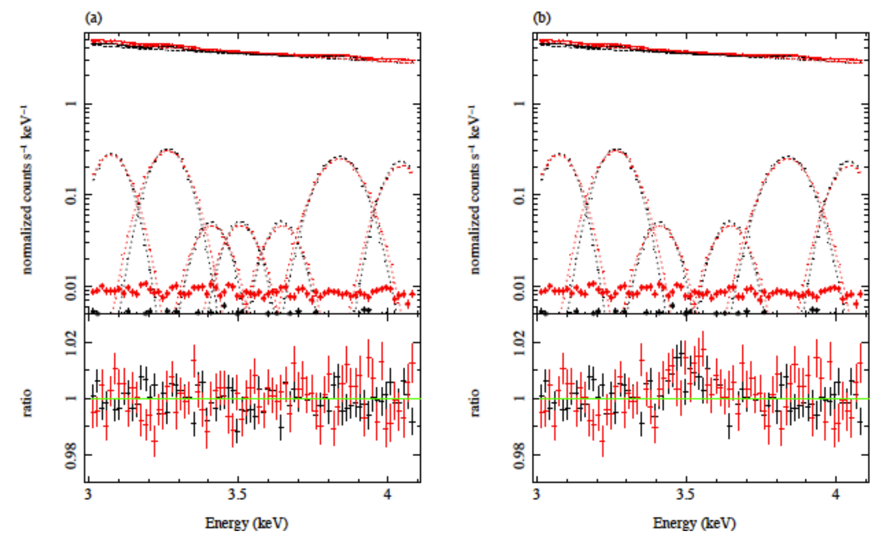
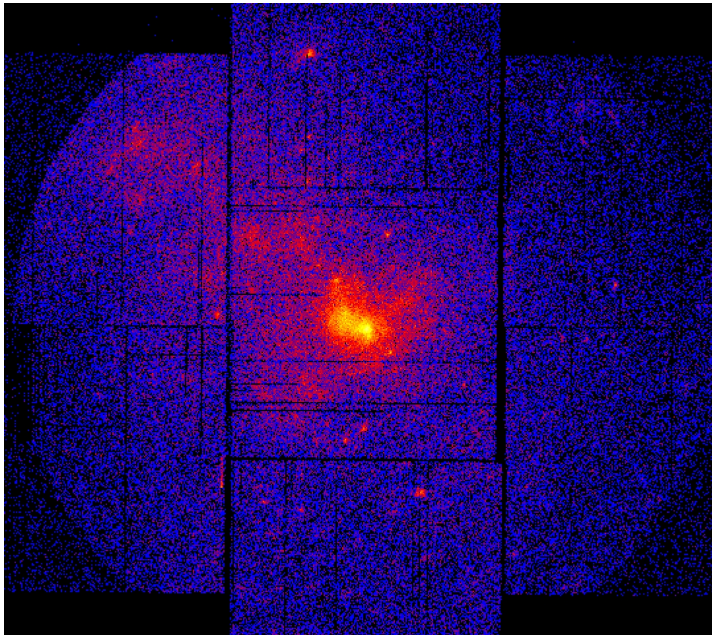




Galactic Center Morphology



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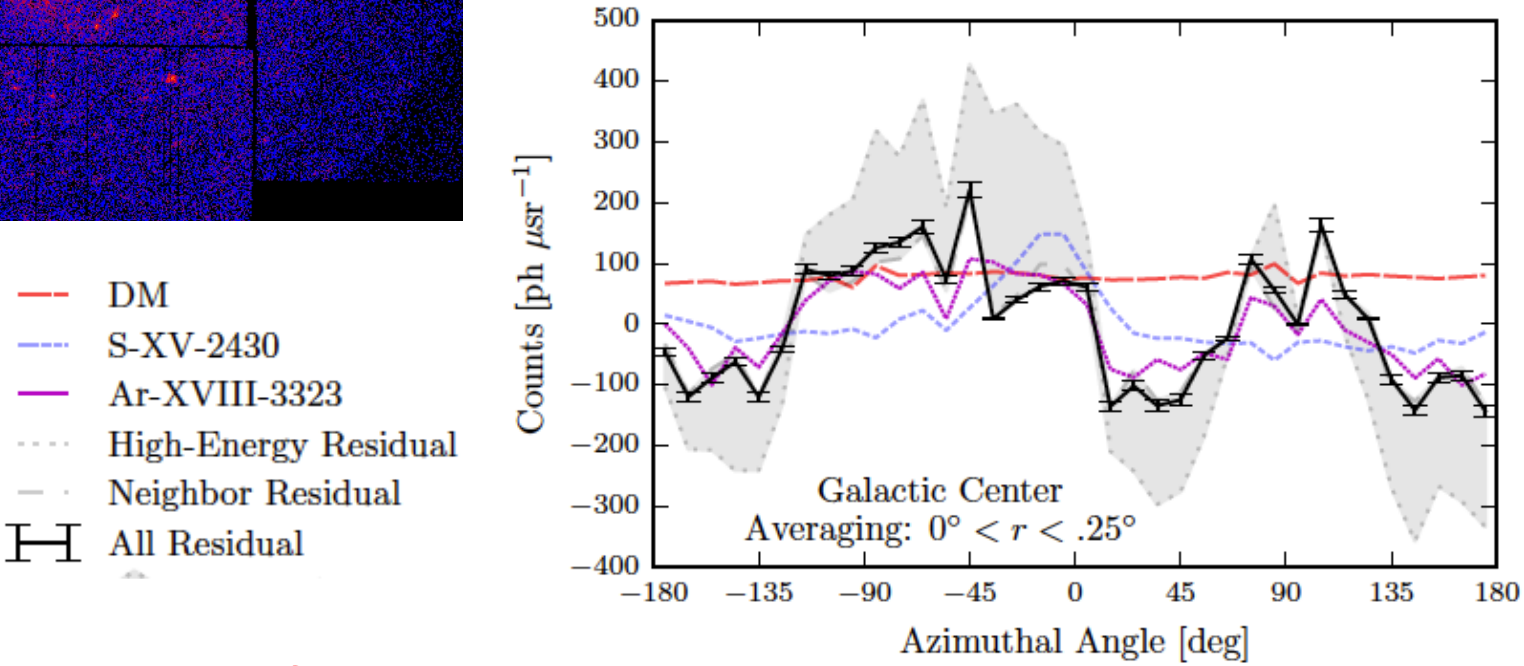

Carlson, Jeltema and Profumo 2015

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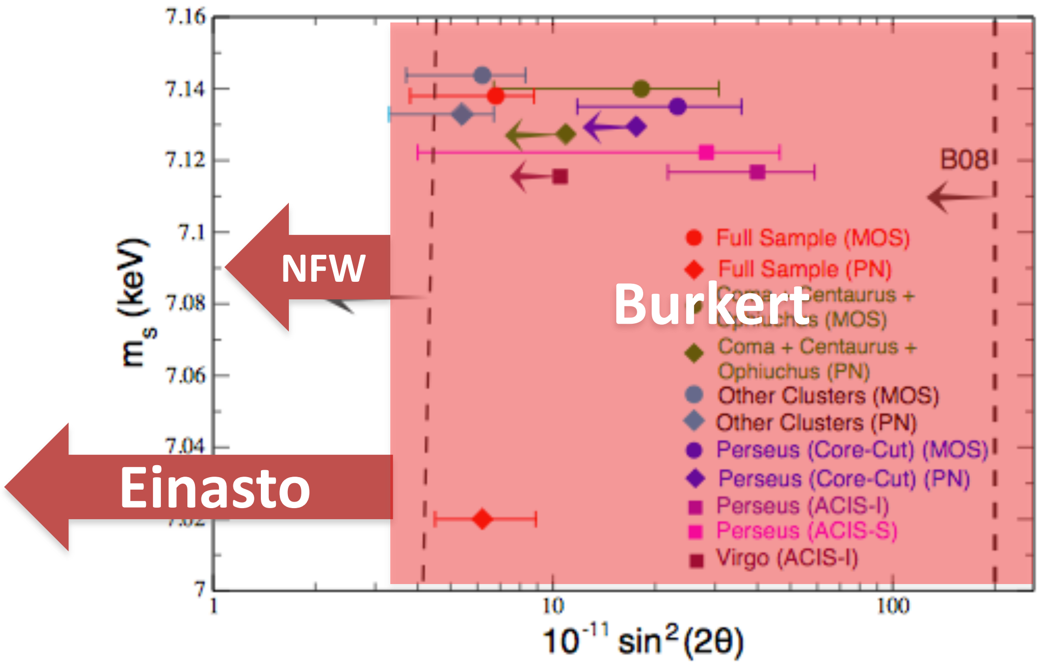
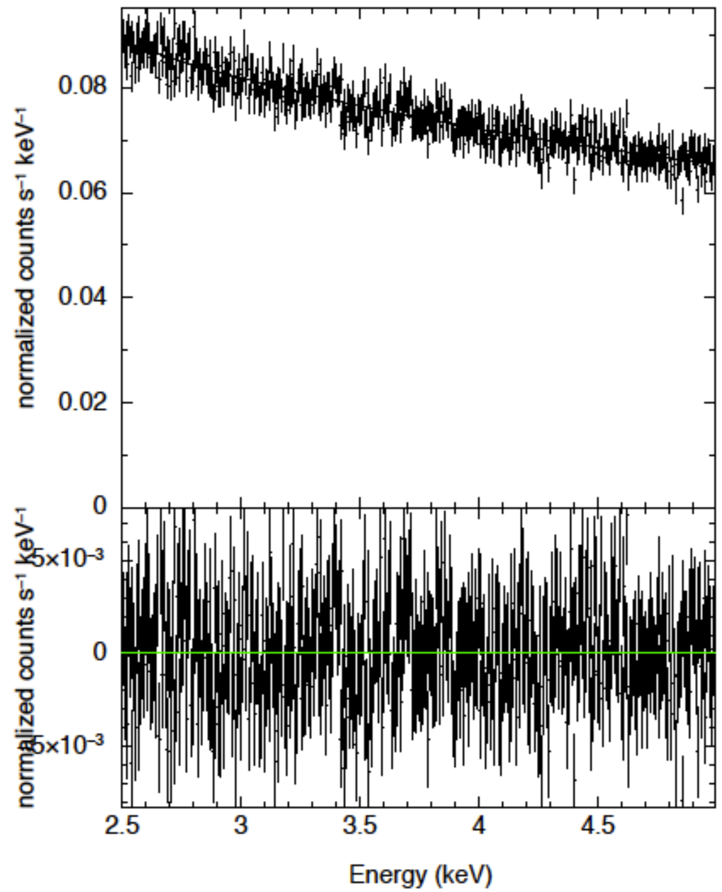


Carlson, Jeltema and Profumo 2015

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

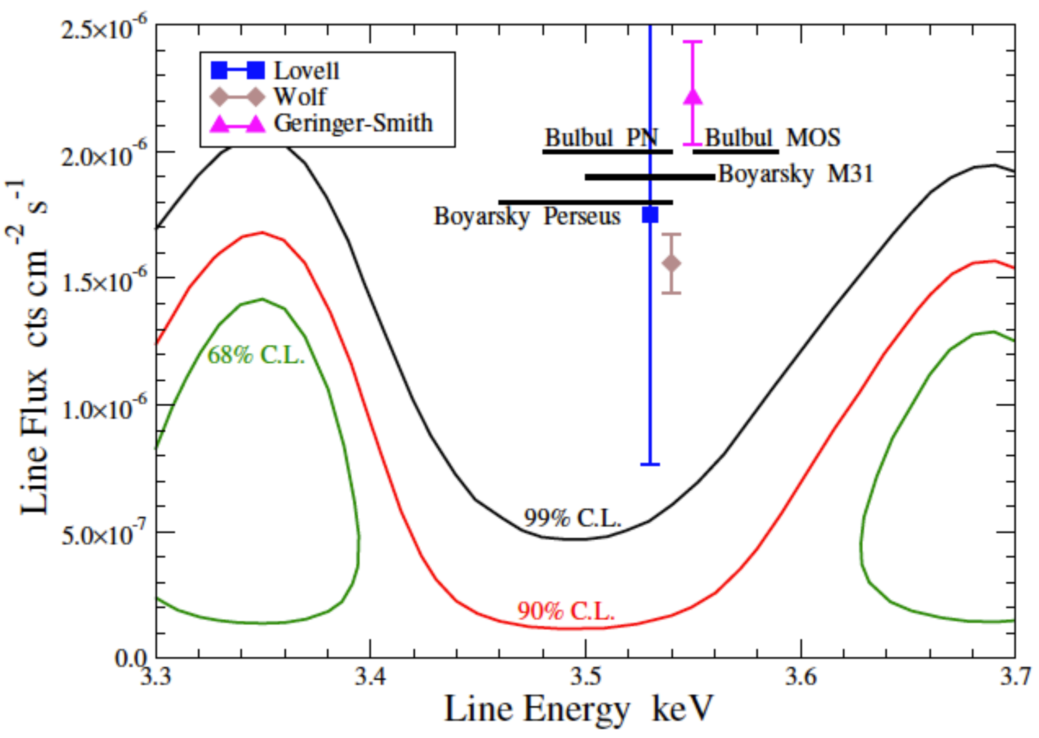
Stacked MOS Spectrum



Jeltema & Profumo 2016

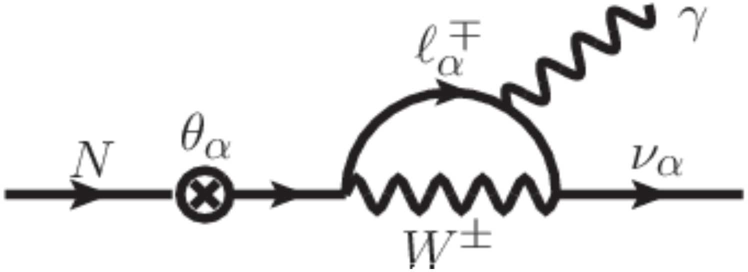
Deep Observations of Draco

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



Jeltema & Profumo 2016

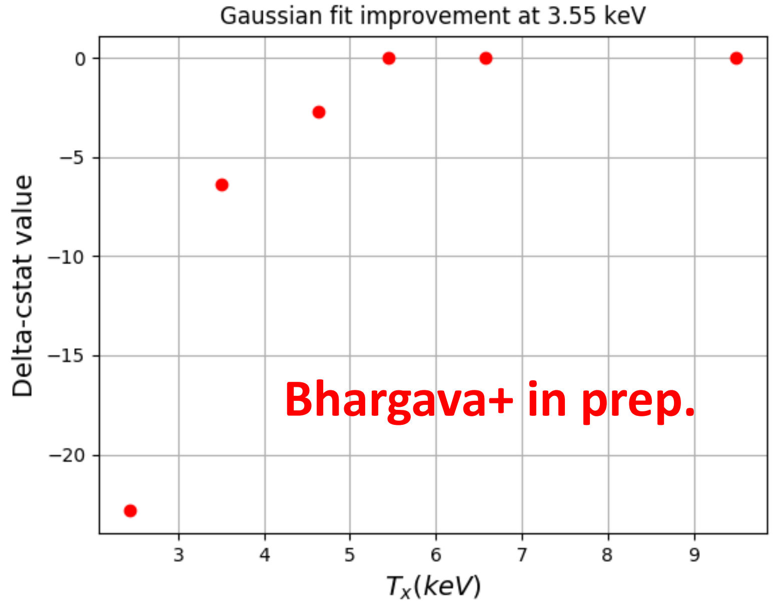
X-ray lines predicted from sterile neutrinos



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