The Nature of Dark matter

Oleg Ruchayskiy
on behalf of participants
of the proposal 76480 (AO-14)
PI: A. Boyarsky

Niels Bohr Institutet

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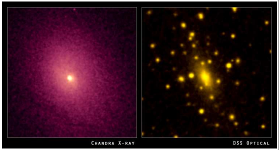
Dark matter in astrophysics and cosmology

One of the most firmly established evidence for new physics

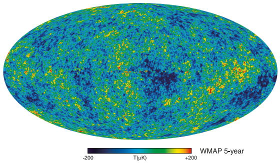
Dark matter in astrophysics

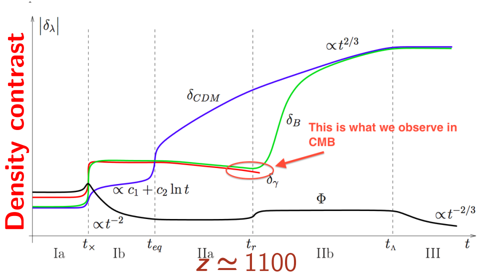
- Dynamics of stars in galaxies and gas in galaxies . . .
- Dynamics of galaxies in galaxy clusters . . .
- Hot X-ray emitting gas in galaxy clusters. . .
- Gravitational lensing . . .



Dark matter in cosmology

- The Universe is full of structures today
- ...but was very homogeneous in the past





- At recombination baryon density contrast $\delta_{\text{baryon}} \sim 10^{-5}$
- Small overdensities grow linear with redshift
- Without dark matter *today* $\delta_{\text{baryon}} \sim (1+z)10^{-5} \sim 10^{-2}$

Dark matter is the substance that was not coupled to photons and drove the formation of structures in the Universe

Neutrino dark matter

Cosmic neutrinos

- Neutrino seems to be a perfect dark matter candidate: neutral, stable, massive, abundantly produced in the early Universe
- We know how neutrinos interact and we can compute their primordial number density $n_\nu = 3 \times 112\,\mathrm{cm}^{-3}$
- To give correct dark matter abundance the sum of neutrino masses, $\sum m_\nu$, should be $\sum m_\nu \sim 11\,\mathrm{eV}$

Tremaine-Gunn bound (1979)

- Such light neutrinos **cannot form small galaxies** – one would have to put too many of them and violated Pauli exclusion principle
- Minimal mass for fermion dark matter $\sim 300 - 400\,\mathrm{eV}$
- If particles with such mass were **weakly interacting** (like neutrino) – they would oveclose the Universe ($\Omega \sim 3\,!$)

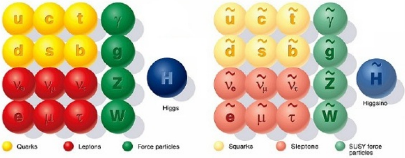
Beyond neutrino DM: weakly interacting particles

Dark matter cannot be both light and weakly interacting

Possible way out?

- Make dark matter particles **heavy** but **keep** interaction strength $\sim G_F$
- Number of such particles is Boltzmann-suppressed $n_{DM} \ll n_\nu$
- Particles should be **stable** – a **symmetry** should protect it from decay
- This class of dark matter candidates is known as **Weakly Interacting Massive Particles** (or **WIMP**s)

- A typical WIMP-predicting particle physics model:
- LHC is searching for these particles, but nothing has been found so far



No new physics at electroweak scale. Alternatives?


6-7 September 2016
CERN
Europe/Zurich timezone

Overview
Scientific Programme

Physics Beyond Colliders workshop

The aim of the workshop is to explore the opportunities offered by the CERN accelerator complex and infrastructure to get new insights into some of today's outstanding questions in particle physics through projects complementary to high-energy colliders and other initiatives in the world. The focus is on fundamental physics

Beyond neutrino DM: **super**-weakly interacting particles

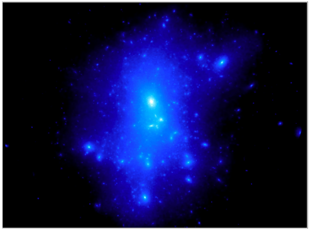
No traces of new weakly coupled particles – what are the alternatives?

- Keep dark matter **light** but **reduce** its interaction strength $\ll G_F$
- Number of such particles is low, $n_{DM} \ll n_\nu$, because they were never produced in the early Universe in large amounts
- The particles can be light (all the way down to Tremaine-Gunn bound)
- No need to stabilize them – low mass and feeble interaction cross-section can make them **cosmologically long-lived**
- Such particles **appear in many particle physics models** (sterile neutrino, gravitino, axino, . . .)

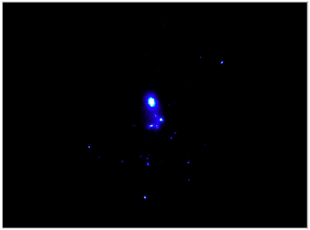
Light decaying dark matter

- Two-body decay into two massless particles ($\mathrm{DM} \to \gamma + \gamma$ or $\mathrm{DM} \to \gamma + \nu$)
- Monochromatic decay line $E_\gamma = \frac{1}{2} m_{\mathrm{DM}} c^2$
- The width of the decay line is determined by **Doppler broadening**:

$$\frac{\Delta E}{E_\gamma} \sim \frac{v_{\mathrm{vir}}}{c} \sim 10^{-4} \div 10^{-2}$$

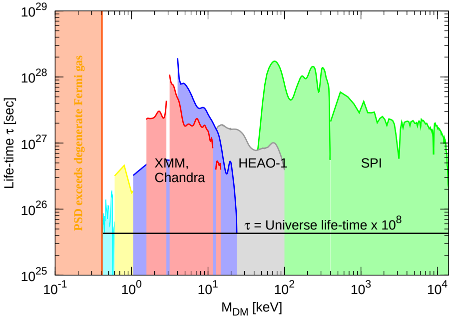


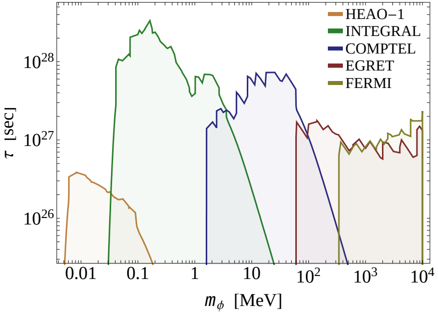
Decay signal $\propto \int \rho_{\mathrm{DM}}$



Annihilation signal $\propto \int \rho_{\mathrm{DM}}^2$

Searches for radiatively decaying dark matter





"Next decade of sterile neutrino studies" [1306.4954]

Essig et al.'13

Two groups reported a line-like feature in X-ray spectra of dark matter-dominated objects

DETECTION OF AN UNIDENTIFIED EMISSION LINE IN THE STACKED X-RAY SPECTRUM OF GALAXY CLUSTERS

Esra Bulbul[1,2], Maxim Markevitch[2], Adam Foster[1], Randall K. Smith[1] Michael Loewenstein[2], and Scott W. Randall[1]
[1] Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138.
[2] NASA Goddard Space Flight Center, Greenbelt, MD, USA.
Submitted to ApJ, 2014 February 10

ApJ (2014) [1402.2301]

An unidentified line in X-ray spectra of the Andromeda galaxy and Perseus galaxy cluster

A. Boyarsky[1], O. Ruchayskiy[2], D. Iakubovskyi[3,4] and J. Franse[1,5]
[1]Instituut-Lorentz for Theoretical Physics, Universiteit Leiden, Niels Bohrweg 2, Leiden, The Netherlands
[2]Ecole Polytechnique Fédérale de Lausanne, FSB/ITP/LPPC, BSP, CH-1015, Lausanne, Switzerland

PRL (2014) [1402.4119]

- **Energy:** 3.5 keV. Statistical error for line position $\sim 30 - 50$ eV.
- **Lifetime:** $\sim 10^{28}$ sec (uncertainty: factor ~ 0.3 dex)

Datasets

Boyarsky, O.R. et al. PRL (2014) [1402.4119]

M31 galaxy	0.98 Msec	$\Delta\chi^2 = 13.0$	3.2σ for 2 d.o.f.
Perseus off-cluster (MOS)	0.63 Msec	$\Delta\chi^2 = 9.1$	2.5σ for 2 d.o.f.
Perseus off-cluster (PN)	0.22 Msec	$\Delta\chi^2 = 8.0$	2.4σ for 2 d.o.f.
Blank sky	15.7 Msec	No detection	
M31 + Perseus (MOS)		$\Delta\chi^2 = 25.9$	4.4σ for 3 d.o.f.

Global significance of detecting the same signal in 3 datasets: 4.8σ

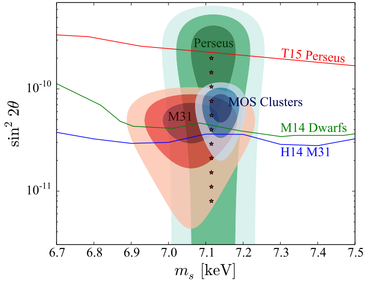
Bulbul et al. ApJ (2014) [1402.2301]

73 clusters (XMM, MOS)	6.78 Msec	$\Delta\chi^2 = 22.8$	4.3σ for 2 d.o.f
73 clusters (XMM, PN)	2.06 Msec	$\Delta\chi^2 = 13.9$	3.3σ for 2 d.o.f
69 distant clusters (XMM, MOS)	4.9 Msec	$\Delta\chi^2 = 16.5$	3.7σ for 2 d.o.f.
69 distant clusters (XMM, PN)	4.9 Msec	$\Delta\chi^2 = 16.5$	3.7σ for 2 d.o.f.
....			
Perseus center (XMM, MOS)	0.32 Msec	$\Delta\chi^2 = 12.8$	3.1σ for 2 d.o.f.
Perseus center (Chandra, ACIS-S)		$\Delta\chi^2 = 11.8$	3.0σ for 2 d.o.f.

Subsequent works

For overview see e.g. [1602.04816] "A White Paper on keV Sterile Neutrino Dark Matter"

- Subsequent works confirmed the presence of the 3.5 keV line in some of the objects
  Boyarsky O.R. et al., Iakubovskyi et al.; Franse et al.; Bulbul et al.; Urban et al.; Jeltema & Profumo
- challenged it existence in other objects
  Malyshev et al.; Anderson et al.; Tamura et al.; Sekiya et al.
- argued astrophysical origin of the line
  Gu et al.; Carlson et al.; Jeltema & Profumo; Riemer-Sørensen; Phillips et al.



[1507.06655]

A common explanation for every detection and non-detection?

- When comparing bounds from different objects one should be careful – uncertainty in the dark matter content in each of them results in large

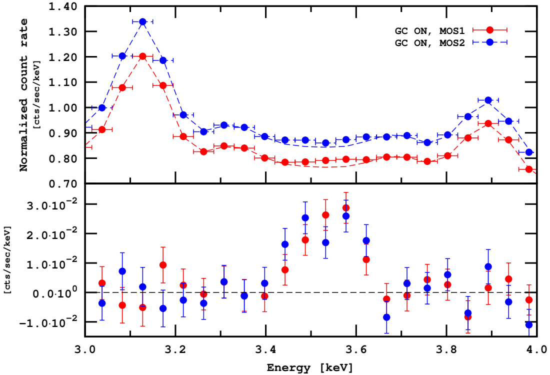
Dark matter is universal

Dark matter is a universal substance, present in every galaxy (spiral, elliptical, dwarf spheroidal) and every galaxy cluster

From the point of view of astrophysical processes these objects are very distinct!

Galactic center

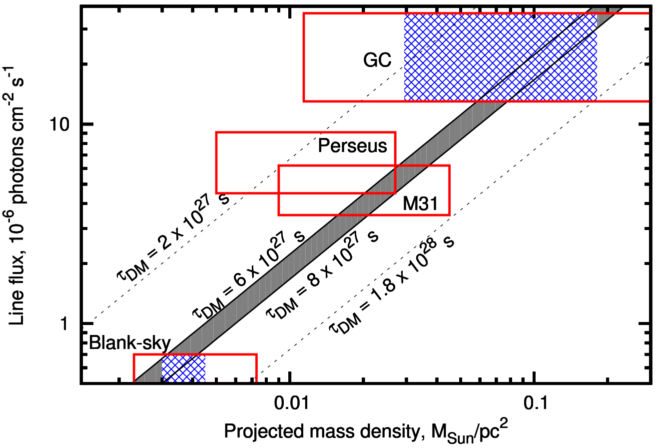
Boyarsky, O.R. et al. PRL 115, 161301



- MOS camera
- 1.82 Msec
- $4\sigma+$ statistical significance
- Also detected in S. Riemer-Sorensen [1405.7943]; T. Jeltema & S. Profumo [1408.1699]

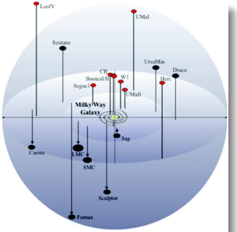
Non-trivial consistency check

Boyarsky, O.R. et al. PRL 115, 161301



Dwarf spheroidal galaxies – smallest DM-dominated objects known

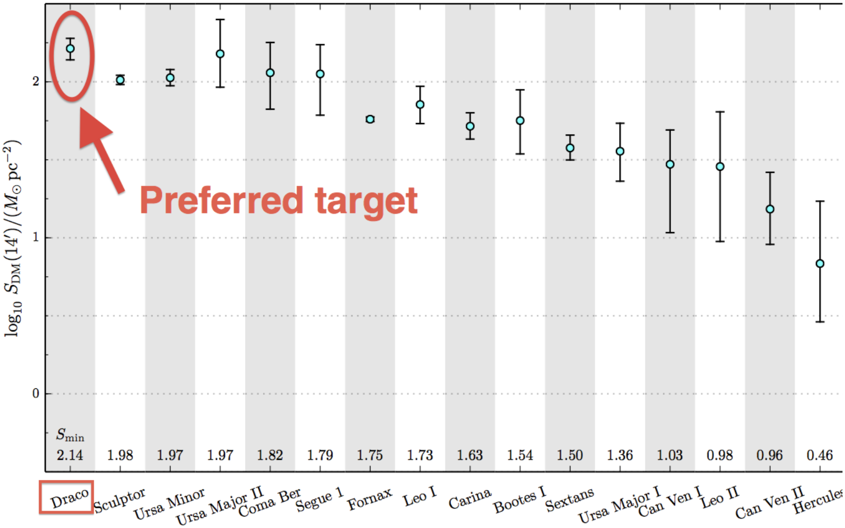
- Dwarf spheroidals are "*galaxies inside our Galaxy*"
- These are ancient galaxies "swallowed" by the Milky Way
- Perfect observational targets:
  - They are "dense"
  - They are "dark" ($M/L \sim 10^2 - 10^3$)
  - They are compact (typical sizes $5' - 30'$)
  - They are nearby (distances $30 - 100$ kpc)
- Dwarf spheroidal galaxies are **too light and compact** to confine X-ray emitting gas ($k_B T \sim G_N \frac{\text{Mass}}{\text{Size}}$)



- The best target for XMM – dwarf galaxy in the constellation of Draco – **Draco dSph galaxy**
- XMM-Newton's time allocation committee granted us 1.4 Mega-seconds in AO-14

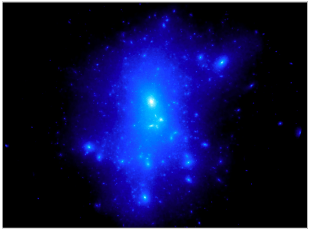
PI: A. Boyarsky

Choice of the target



Geringer-Sameth et al. (2014)

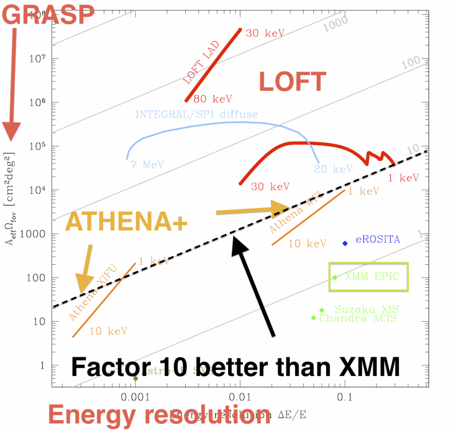
Why XMM?



- Signal-to-noise ratio improves as

$$\frac{S}{N} = \int \rho_{DM} \sqrt{t_{exp} \cdot \Omega_{fov} \cdot A_{EFF} \cdot \Delta E}$$

- XMM is the best among today's missions, mainly due to its *Grasp*

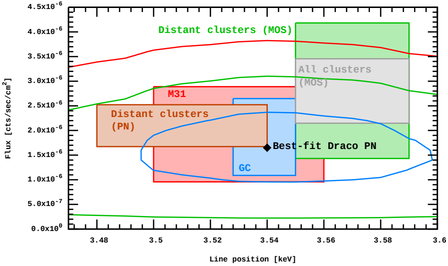


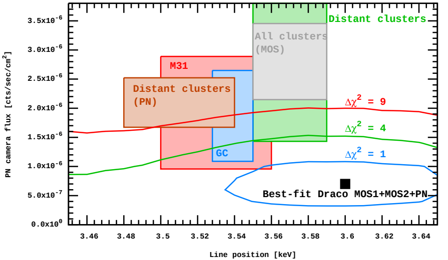
Adopted from
Boyarsky, den Herder et al.'2006;
Neronov, O.R. et al.'2014

Analysis of Draco dSph

Ruchayskiy et al. MNRAS (2016) [1512.07217]

- The line is detected in the spectrum of Draco dSph with low significance ($\Delta\chi^2 = 5.3$)
- Line flux/position are consistent with previous observations: $E = 3.54 \pm 0.06\,\mathrm{keV}$, $F = (1.65 \pm 0.7) \times 10^{-6}\,\mathrm{cts/sec/cm^2}$
- There is a shift in position ($\sim 1\sigma$) between MOS and PN
- The data is consistent with DM interpretation for lifetime $\tau_{\mathrm{DM}} > (7\text{–}9) \times 10^{27}\,\mathrm{sec}$





Summary

- The nature of dark matter is one of the main puzzles of modern physics
- We have no idea what is dark matter mass or what type of interactions it has
- A 3.5 keV spectral feature is consistent with a signal originating from dark matter decays
- Systematics? – Unlikely:
  - Correctly scales with redshift
  - signal not detected in some long-exposure datasets
- Astrophysics (e.g. K XVIII or S XVI charge exchange)? – Possible, but does not fit all observations!
- XMM observation of Draco Dwarf Spheroidal Galaxy is a critical test!
- The results from very large AO-14 observational programme support dark matter hypothesis
- Detecting a line from a dwarf galaxy at $\sim 3\sigma$ level would be crucial
- Requires another observation like this

Hitomi (Astro-H) spectrum of Perseus

- The line in the center of the Perseus cluster has flux $2.1^{+1.1}_{-1.0} \times 10^{-5}\,\mathrm{cts/sec/cm^2}$ (XMM, excluding central $1'$ circle)

  Bulbul et al. ApJ (2014) [1402.2301]

- The presence of the line is confirmed by Suzaku studies

  Urban et al. (2014); Franse et al. [1604.01759]

- Existing 200 ksec of Hitomi spectrum of Perseus galaxy cluster should see this line even with reduce sensitivity!

Information about the line in the Perseus center (its position, intensity, width) will be crucial in deciding on further strategy of searching for 3.5 keV line with XMM and other instruments

Outlook

If this **is** the dark matte signal. . .

A lot of exciting science

- Dark matter tomography becomes possible!
- We will be able to see 3D structures in the Universe —
    - visualized cosmic web
    - histories of major mergers
    - tidal streams
    - 3D structures of galaxy clusters
    - . . .
- X-ray astronomy becomes major cosmological tool of next decades

And a major challenge for particle physics

. . . to detect a particle that is **73** times lighter than electron and interacts **10 orders of magnitude weaker** than neutrino!

XMM-Newton is (and will remain for a long time**) the best instrument to discover light decaying dark matter**

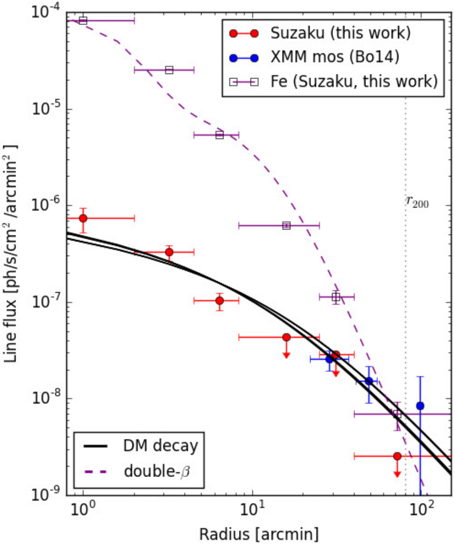
XMM-Newton is (and will remain for a long time**) the best instrument to discover light decaying dark matter**

Thank you for your attention!

Backup slides

Perseus cluster with Suzaku [1604.01759]

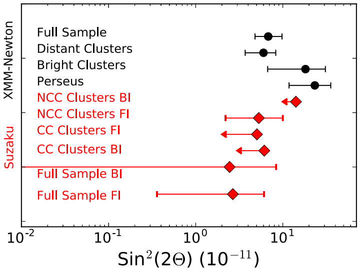
Jeroen Franse et al. *"Radial Profile of the 3.55 keV line out to R200 in the Perseus Cluster"*



- Confirms the line's presence in the Perseus cluster's core (c.f. Bulbul et al.; Urban et al. in contrast with Tamura et al.)
- Not sensitive enough to probe off-center surface brightness profile
- Upper bound consistent with XMM results of (Boyarsky et al.'14)

Stacked galaxy clusters with Suzaku

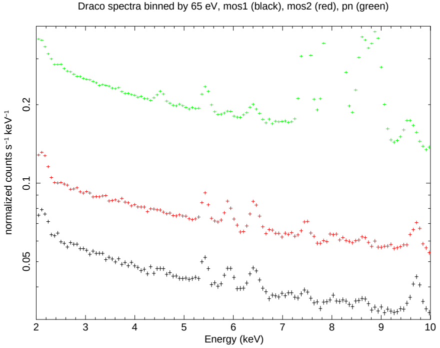
Bulbul et al. [1605.02034]



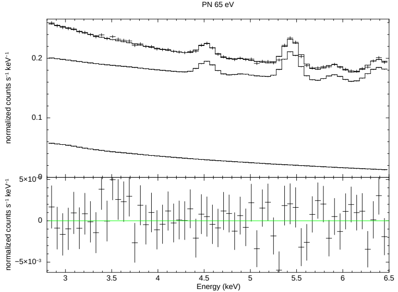
Sample	Inst.	Energy (keV)	Flux (10^{-6} phts cm^{-2} s^{-1})	χ^2 (dof)	$\Delta\chi^2$ (dof)
Full Sample	FI	3.54	$1.0^{+0.5}_{-0.5}$ $(^{+1.3}_{-0.9})$	1028.1 (1068)	4.11 (1)
	BI	3.54	$0.9^{+0.2}_{-0.7}$ $(^{+0.2}_{-0.9})$	1109.9 (1077)	1.46 (1)
Cool-Core Clusters	FI	3.54	<1.4	1131.7 (1069)	1.68 (1)
	BI	3.54	<2.1	1143.0 (1072)	0.15 (1)
Non-Cool Core Clusters	FI	3.54	$2.0^{+1.0}_{-0.7}$ $(^{+1.9}_{-1.2})$	1034.7 (1075)	6.56 (1)
	BI	3.54	<5.4	1159.9 (1072)	0.51 (1)

Draco dSph 2015 observations

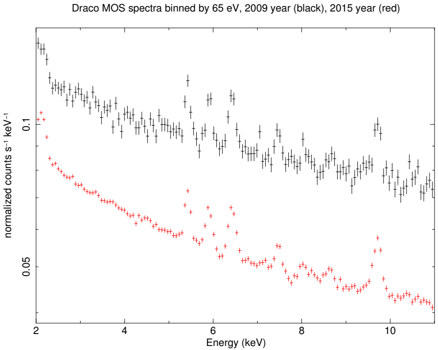
[1512.07217]

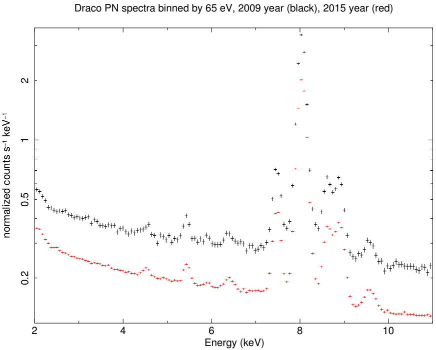


	Raw/Cleaned [Msec]	FoV [arcmin^2]
MOS1	1.43 / 0.97	318.9
MOS2	1.44 / 1.02	573.5
PN	1.29 / 0.65	543.9



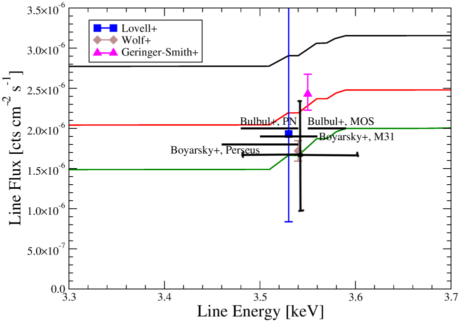
Draco dSph in 2009 vs. 2015



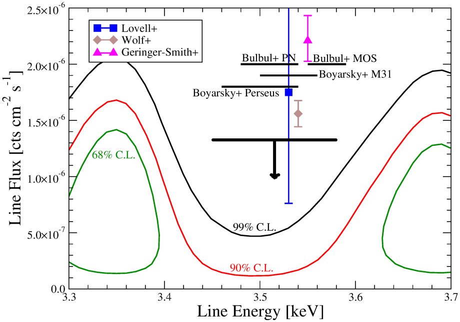


Jeltema & Profumo (2015)- I

- Independent analysis of the 2009+2015 Draco observations was done in [1512.01239]
- No line detected even in PN camera
- Much stronger upper limits on flux



Black cross: detection of Ruchayskiy et al. [1512.07217]



Black down arrow: 2σ upper limit from Ruchayskiy et al. [1512.07217]

Jeltema & Profumo (2015)- II

- JP15 [1512.07217] is a very succinct paper. No details of data analysis. Trying to reproduce the results we made a number of modifications of our procedure

PN dataset/data processing	Flux, 10^{-6} ph/cm^2/s	$\Delta\chi^2$
2015 year dataset (26 obs.) used in R15		
65 eV bin, 2.3-11 keV, NXB+CXB	$1.65^{+0.67}_{-0.70}$	5.3
65 eV bin, 2.3-11 keV, NXB+CXB no OOT corr.	$1.57^{+0.74}_{-0.74}$	4.3
5 eV bin, 2.3-11 keV, NXB+CXB	$1.50^{+0.67}_{-0.71}$	4.4
5 eV bin, 2.5-5 keV, NXB+CXB	$1.56^{+0.71}_{-0.76}$	3.9
5 eV bin, 2.5-5 keV, NXB	$1.18^{+0.71}_{-0.70}$	2.8
2009+2015 years dataset (31 obs.) used in JP15		
65 eV bin, 2.3-11 keV, NXB+CXB	$1.47^{+0.72}_{-0.74}$	4.2
5 eV bin, 2.5-5 keV, NXB	$1.04^{+0.66}_{-0.70}$	2.2