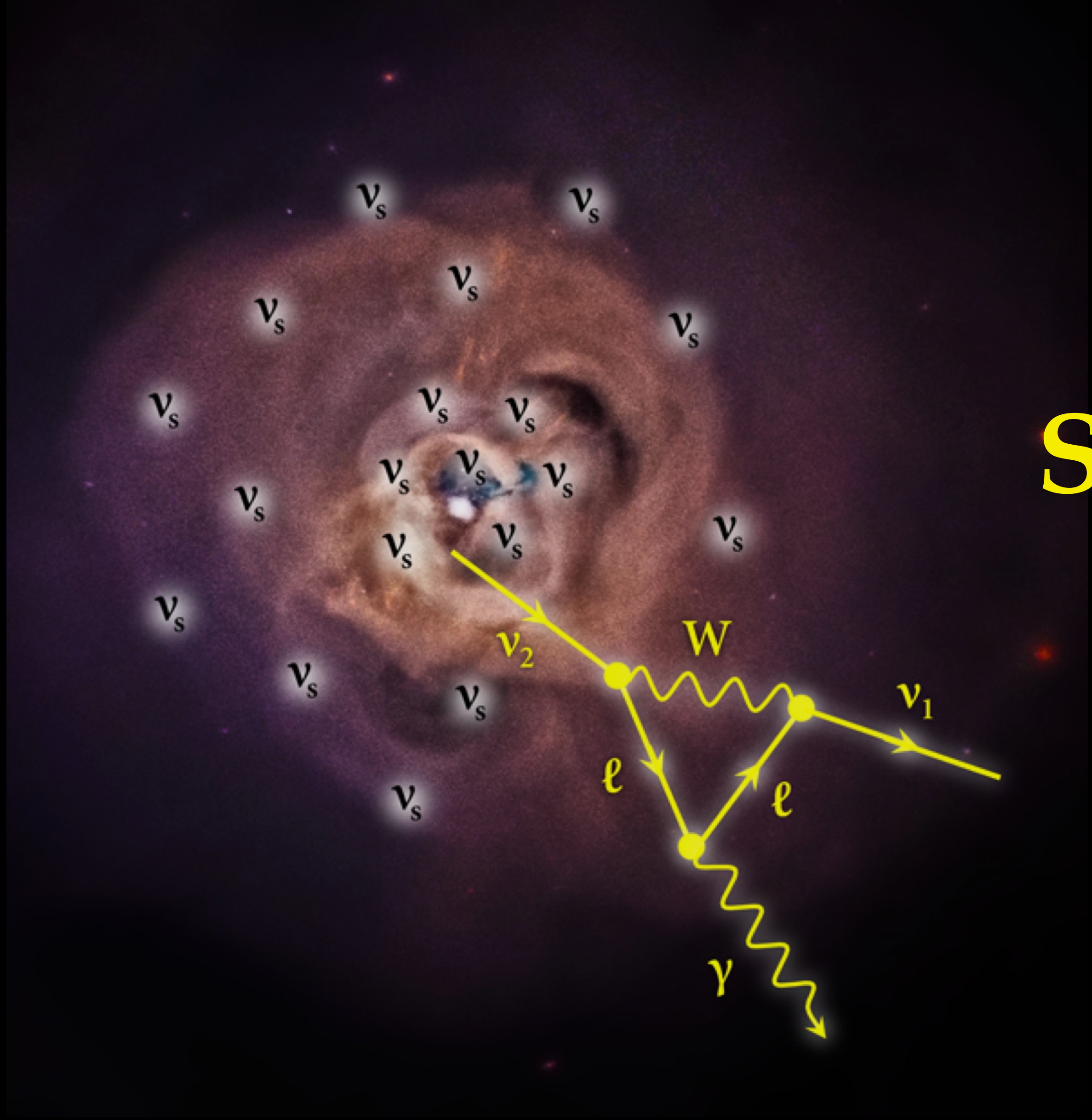


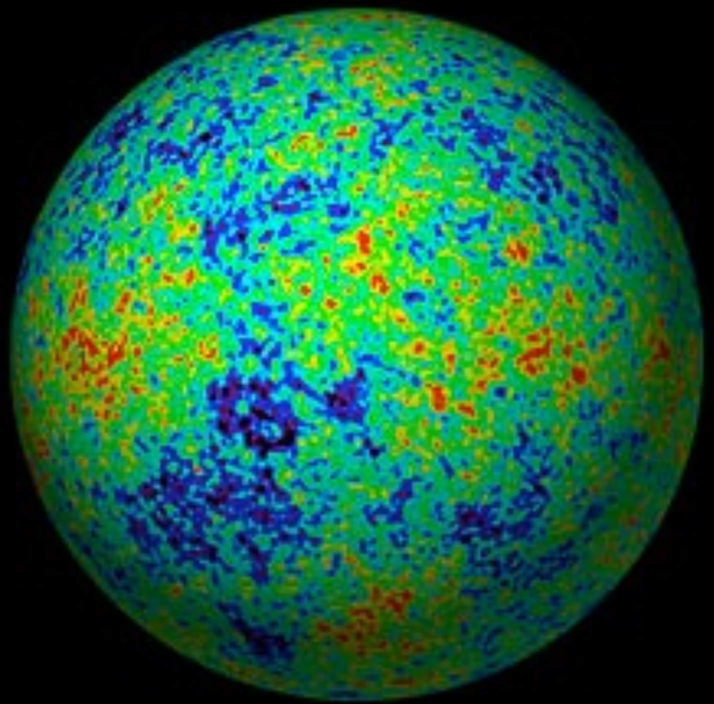

# Candidate Signals and Stringent Constraints from Dark Matter in the Sky

**Kevork Abazajian**
University of California, Irvine

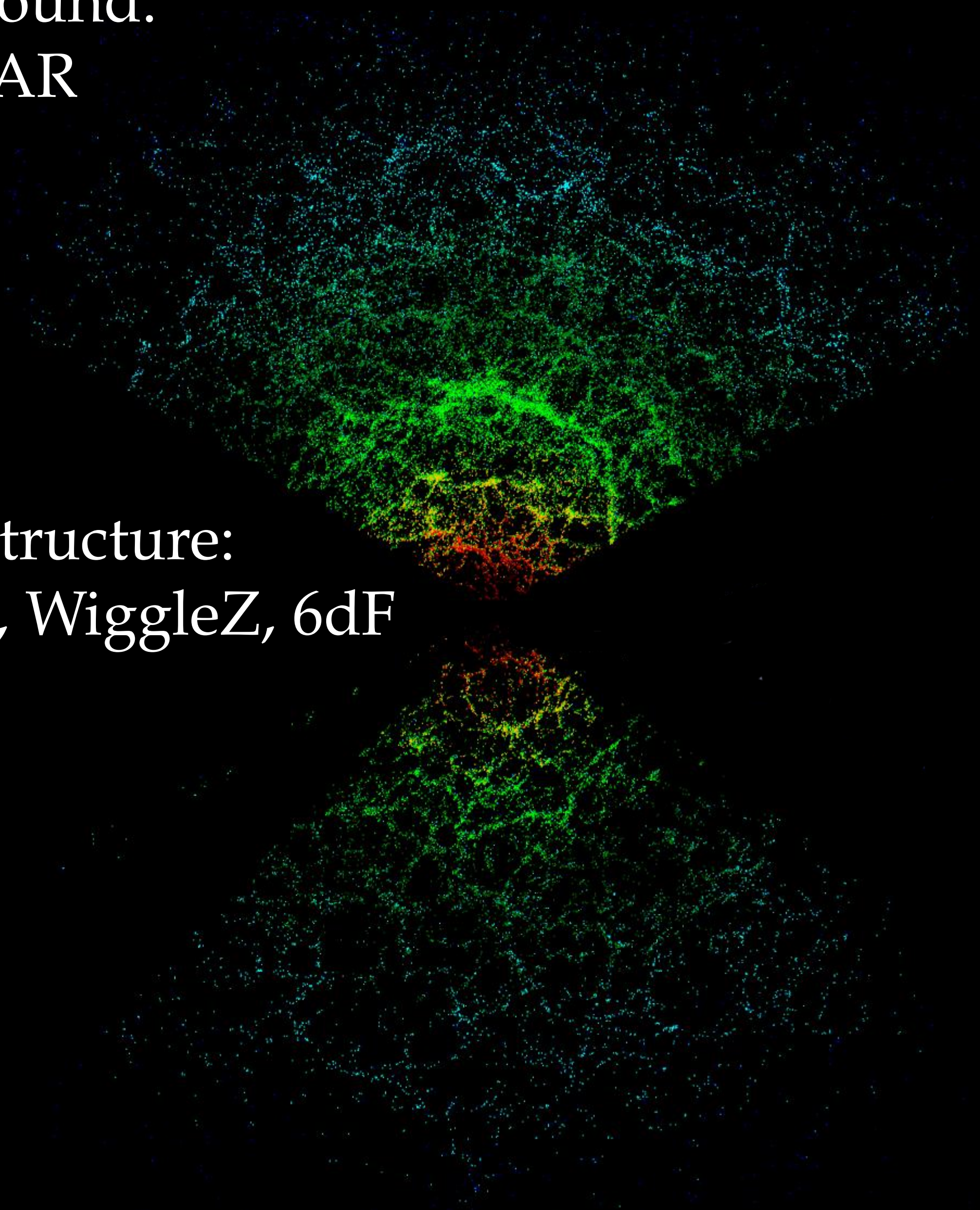
September 21

Lawrence Berkeley National Laboratory
Research Progress Meeting

# Dark Matter Today: from large scale cosmology



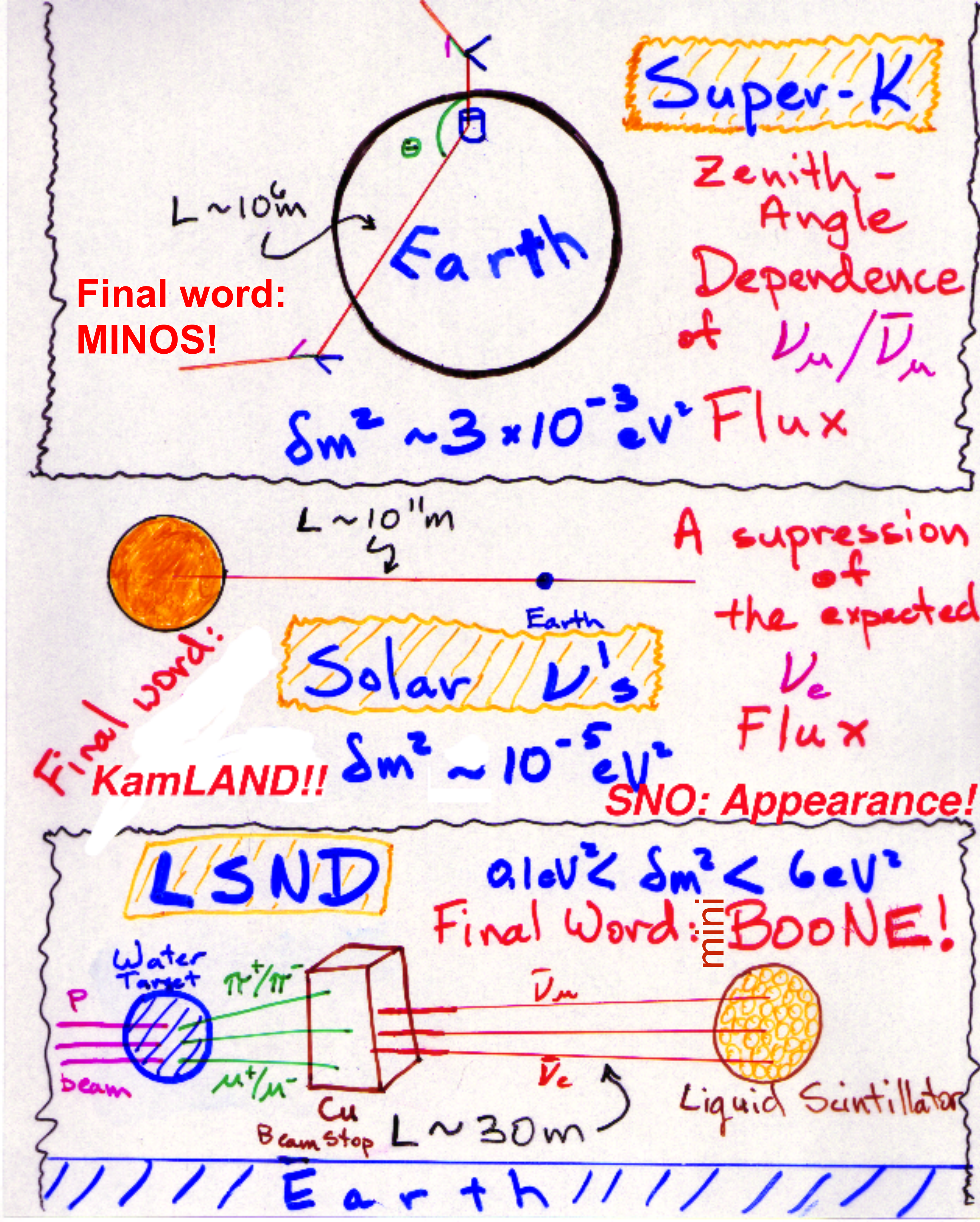
Cosmic Microwave Background:
Planck, SPT, ACT, PolarBEAR

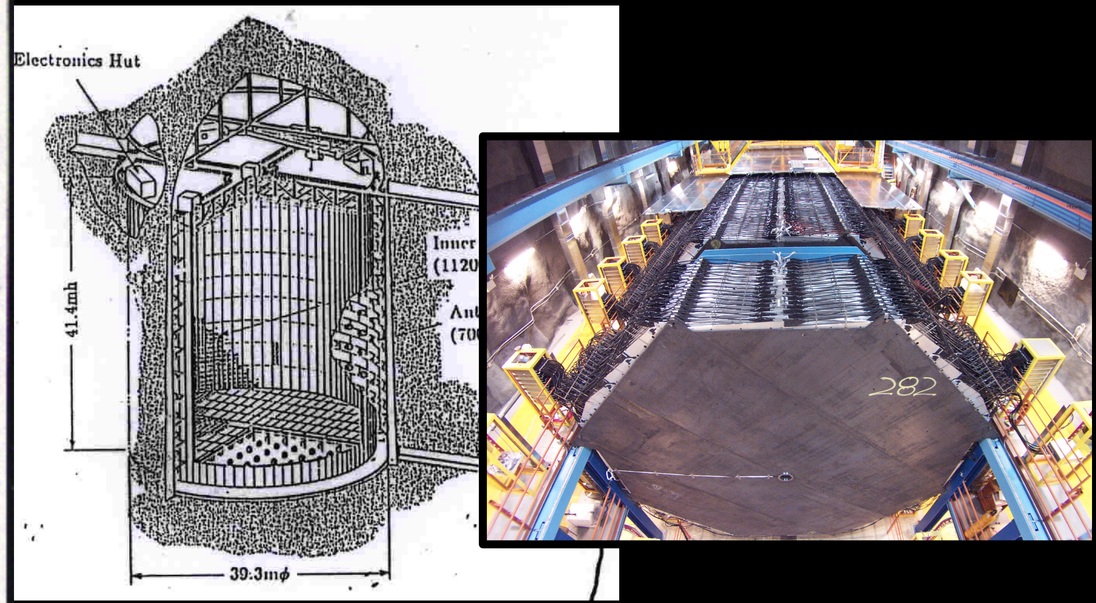


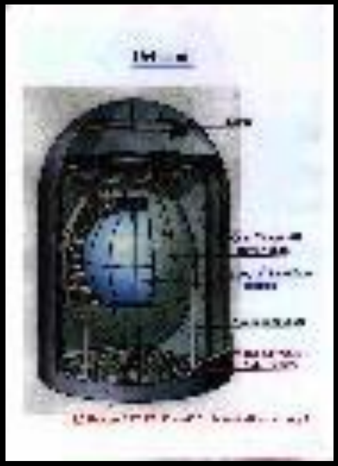
Large Scale Structure:
SDSS (BOSS), WiggleZ, 6dF

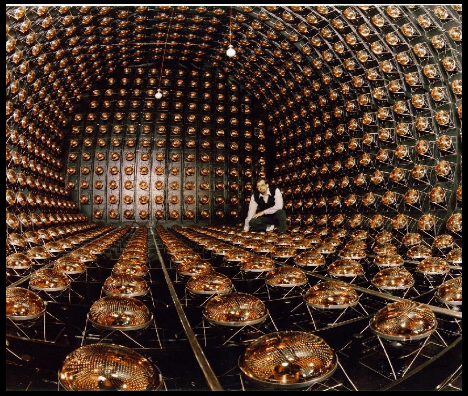
$$\Omega_{\mathrm{DM}} \equiv \frac{\rho_{\mathrm{DM}}}{\rho_{\mathrm{crit}}} = 0.259 \pm 0.002$$

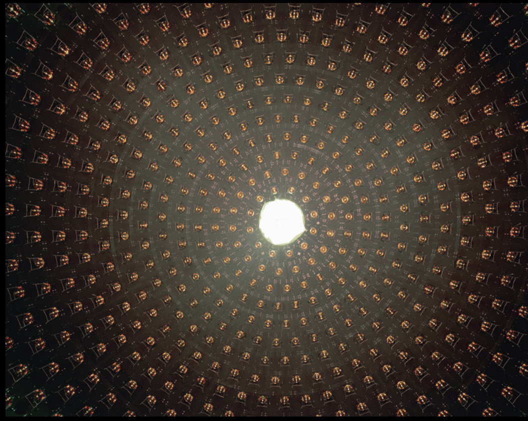
Planck 2015 + BAO + SNe + $H_0$
(Planck Collab. 2015)


Super-K
Zenith-Angle Dependence of $\nu_\mu/\bar{\nu}_\mu$ Flux
$L \sim 10^6$ m
Earth
Final word: MINOS!
$\delta m^2 \sim 3 \times 10^{-3}$ eV$^2$
$L \sim 10^{11}$ m
Earth
Solar $\nu$'s
A supression of the expected $\nu_e$ Flux
Final word: KamLAND!!
$\delta m^2 \sim 10^{-5}$ eV$^2$
SNO: Appearance!
LSND
$0.1$ eV$^2 < \delta m^2 < 6$ eV$^2$
Final Word: miniBOONE!
Water Target
p beam
$\pi^+/\pi^-$
$\mu^+/\mu^-$
Cu Beam Stop
$\bar{\nu}_\mu$
$\bar{\nu}_e$
$L \sim 30$ m
Liquid Scintillator
Earth


Electronics Hut
41.4mh
39.3m$\phi$
282







# Number of Neutrinos

## with Weak Interactions

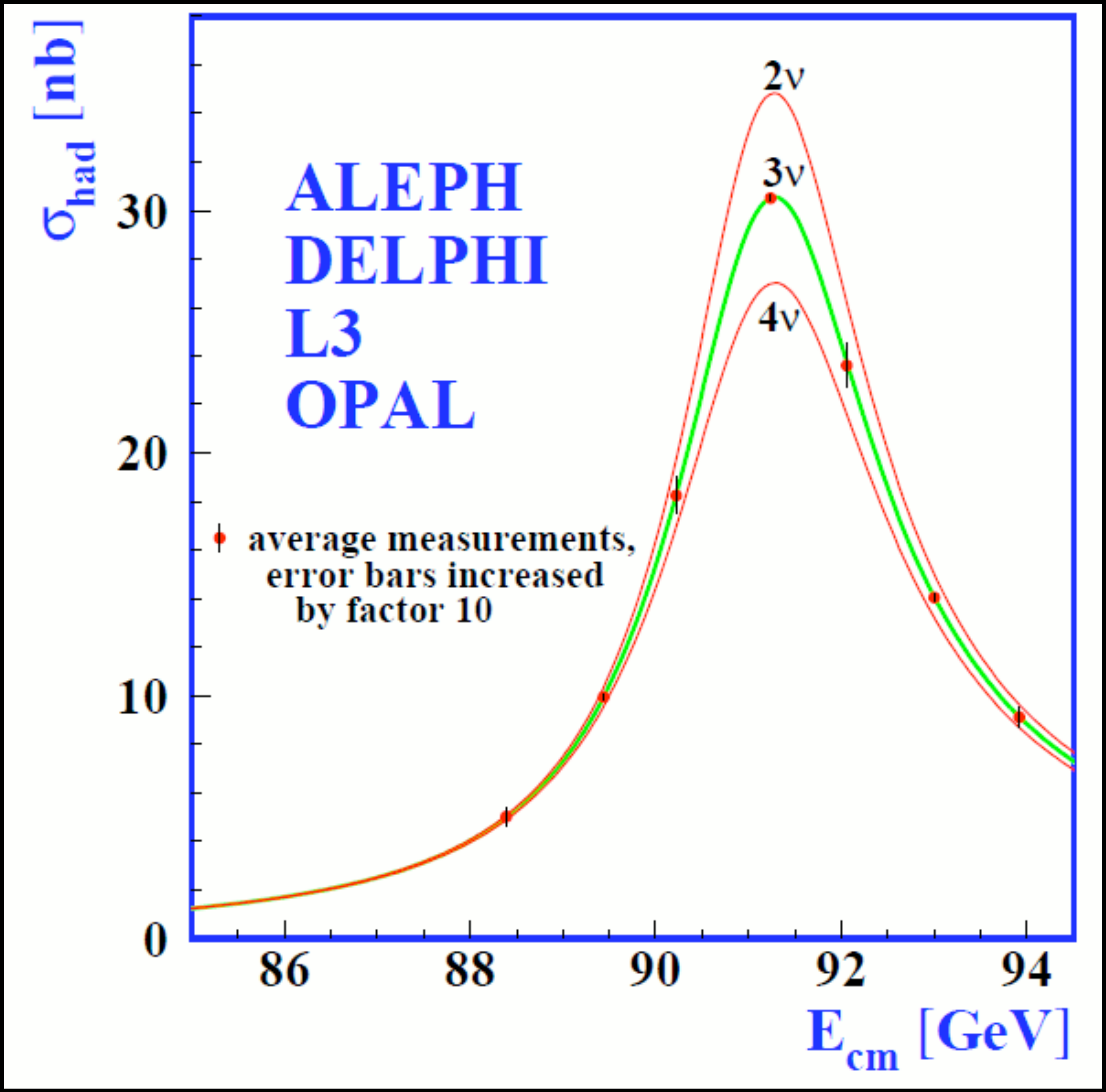
Invisible decays of $Z$ boson observed by LEP

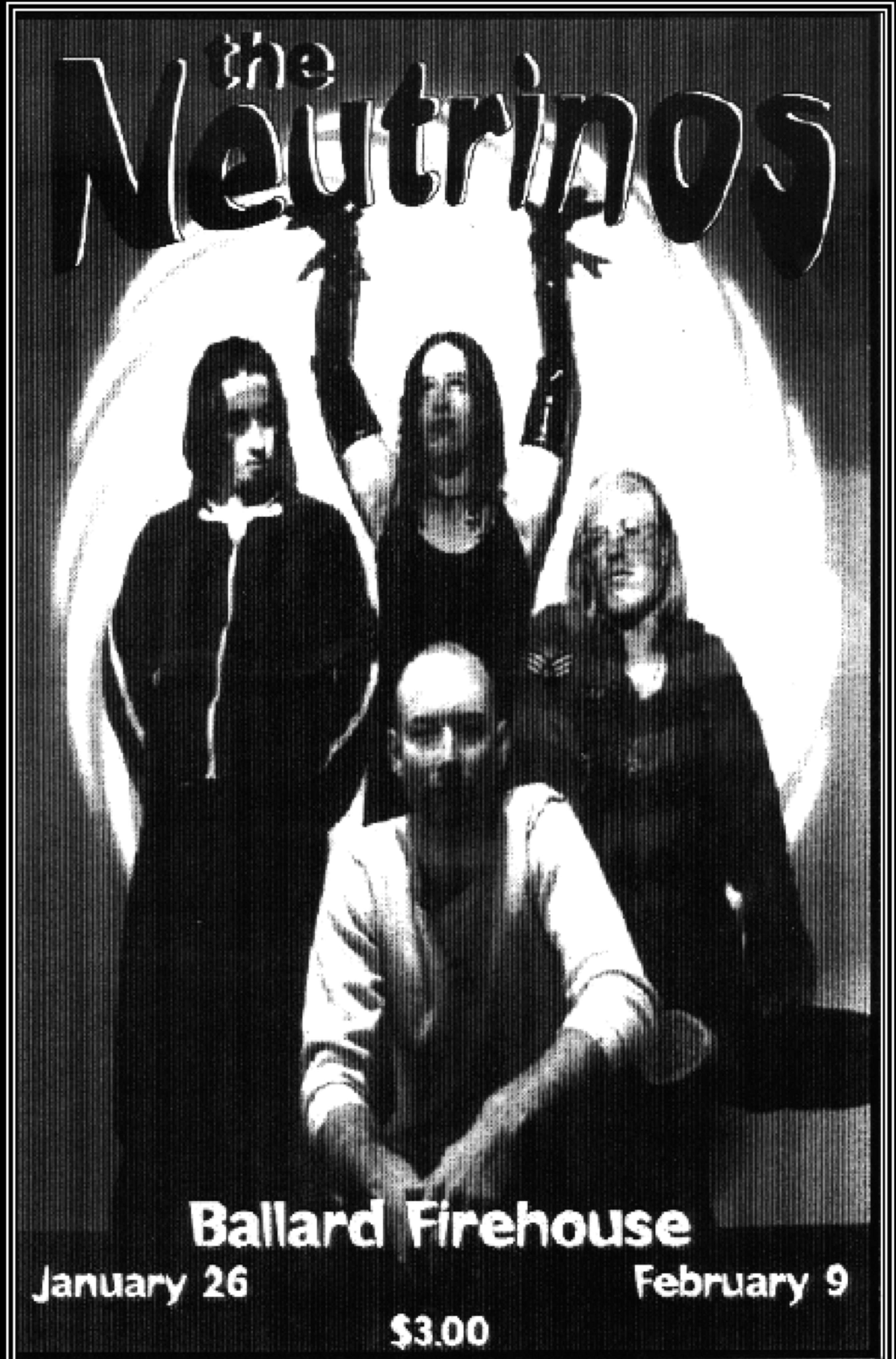
⇒Number of neutrinos

$N_\nu = 3.00 \pm 0.08$

***with weak interactions***

***any extra ν must be sterile***




the Neutrinos
Ballard Firehouse
January 26
February 9
$3.00

# Neutrino Mass & Sterile Neutrinos

## Beyond the Standard Model of Particle Physics

- Simplest models of neutrino mass introduce sterile neutrinos (See saw models)
- Phenomenological Insertion of Majorana & Dirac Mass Terms:

$$\mathcal{L} \supset -y_{\alpha i} L_\alpha N_i H - \frac{1}{2} M_{ij} N_i N_j + H.c.$$

(e.g. $\nu$SM de Gouvêa 2005; $\nu$MSM Asaka et al 2005)

- Two massive (>100 GeV) sterile neutrinos are required by atmospheric and solar neutrino mass scales

# Note:
# eV ≠ keV

short baseline ν ≠ dark matter ν

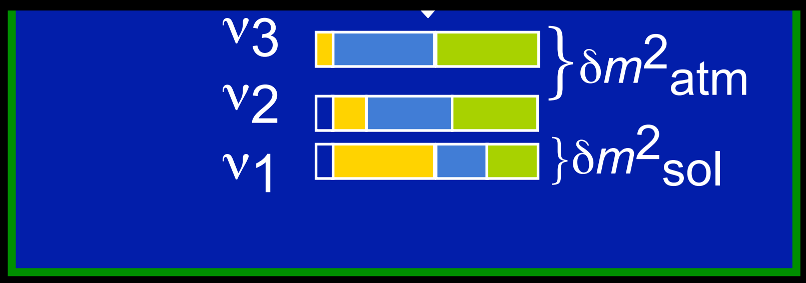
# Dark Matter Neutrinos

Sterile Neutrino Dark Matter $\nu_4$

$$\begin{aligned} |\nu_\alpha\rangle &= \cos\theta|\nu_a\rangle + \sin\theta|\nu_b\rangle \\ |\nu_s\rangle &= -\sin\theta|\nu_a\rangle + \cos\theta|\nu_b\rangle \end{aligned}$$

$\sim 1$ keV

$\sin^2 2\theta \lesssim 10^{-7}$




$\sim 0.01$ eV

# Sterile Neutrinos as Dark Matter: History

- "Super-weak" neutrinos ($G < G_F$) [Olive & Turner, 1982]: Earlier Decoupling, abundance set by standard dark matter production mechanism of decoupling temperature and degrees of freedom disappearance

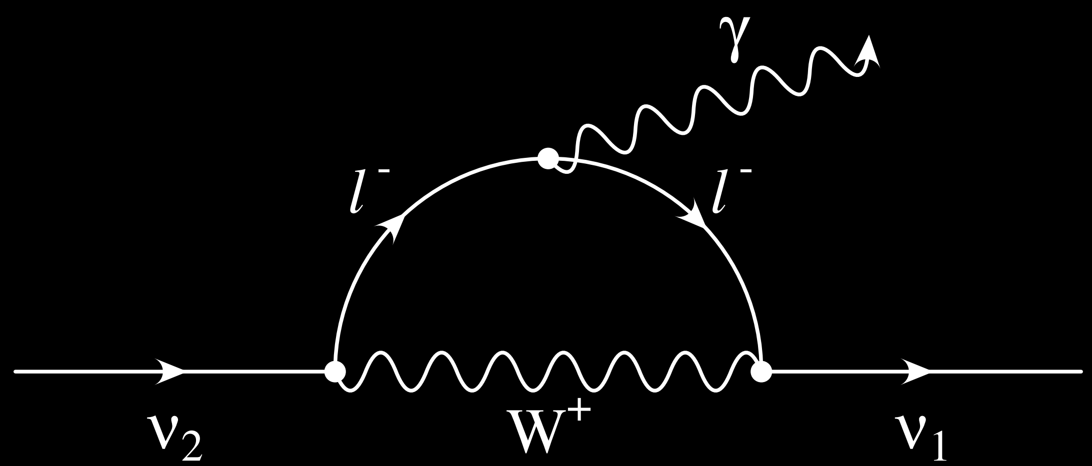
- "Sterile" neutrinos [Dodelson & Widrow, 1993]: No SM interactions beyond mass terms, inclusion of finite-temperature modifications to self-energy, lack of thermalization.  WDM.

- "Resonant" sterile neutrinos [Shi & Fuller, 1999]: Finite temperature production with non-zero lepton number resonant enhanced production. WDM to CDM. "Cool" Dark Matter.

- "Precision" Sterile Neutrino Dark Matter & **Proposal for X-ray Detection** [Abazajian, Fuller & Patel 2001; KA 2005]:  Full momentum-space production description with QCD transition corrections, resonant to non-resonant solutions as a continuum in lepton number.

# Observing the Sterile Neutrino in the X-ray:
# *Chandra & XMM-Newton X-ray Space Telescopes*

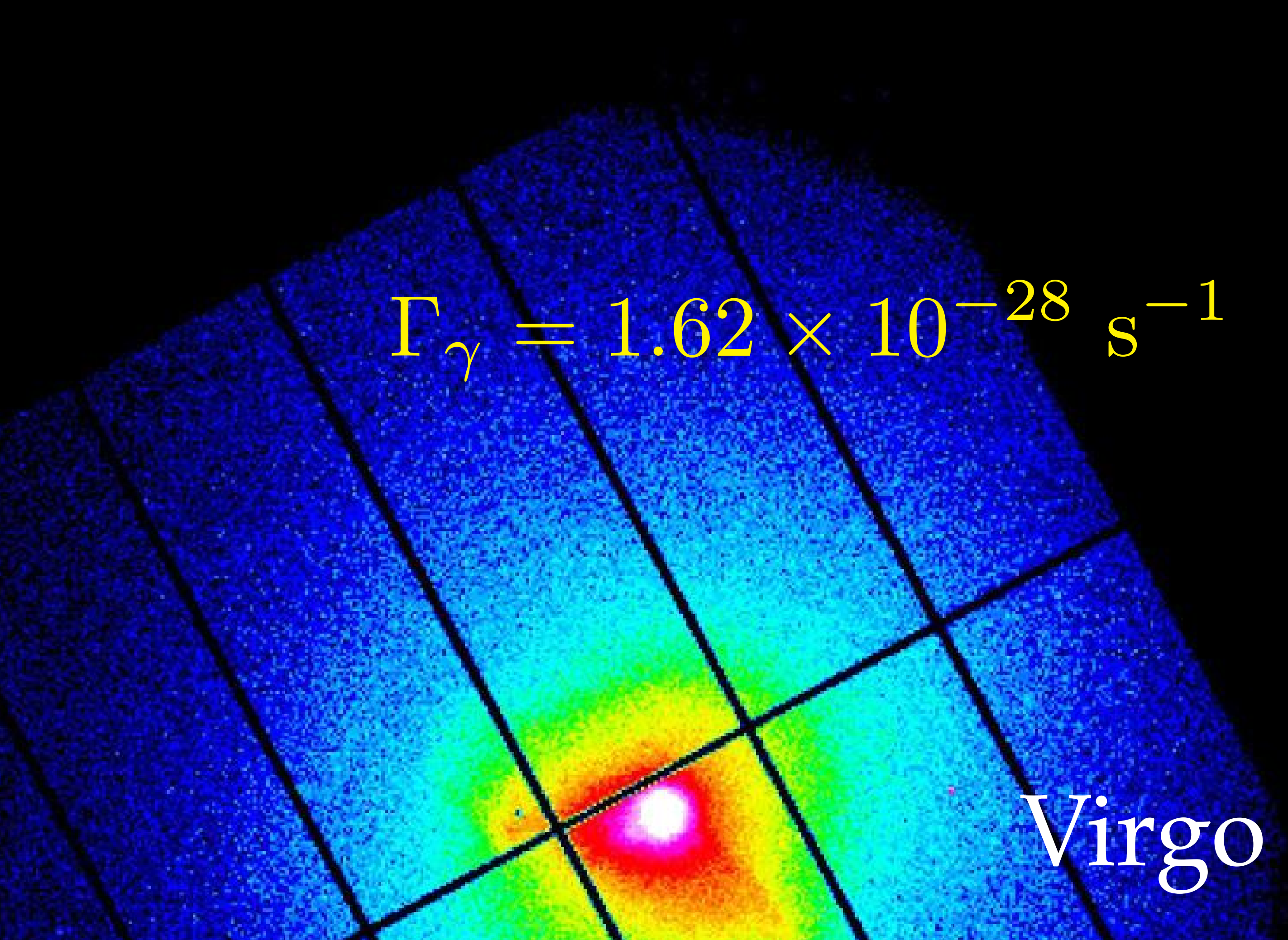
# Sterile ν WDM Radiative Decay in the X-ray




**Decay**: Shrock 1974; Pal & Wolfenstein 1981
**X-ray**: Abazajian, Fuller & Tucker 2001

$$\text{``}\nu_s\text{''} \rightarrow \text{``}\nu_\alpha\text{''} + \gamma$$

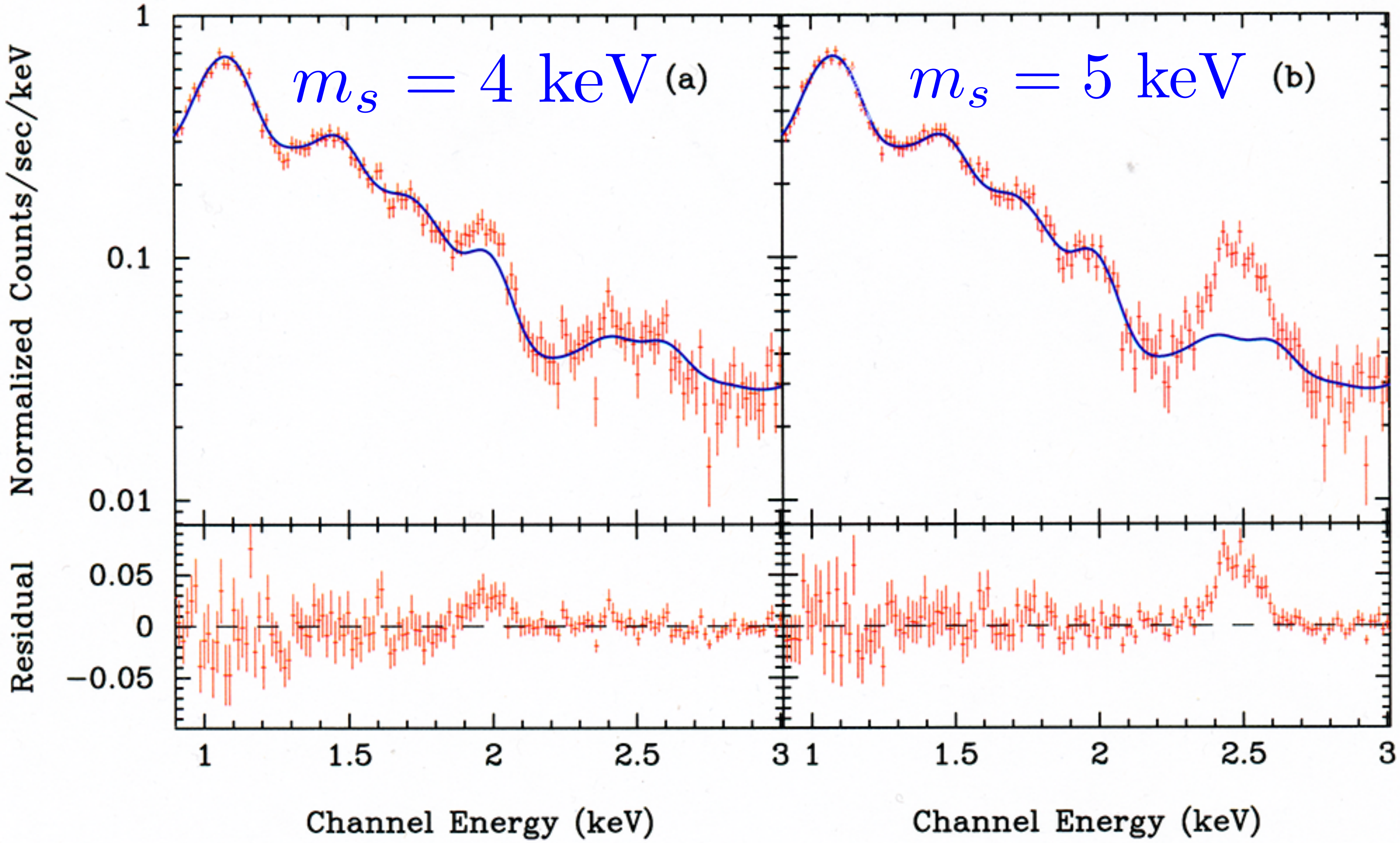
$$E_\gamma = \frac{m_s}{2} \sim 1 \text{ keV}$$



$$\Gamma_\gamma = 1.62 \times 10^{-28} \text{ s}^{-1} \left(\frac{\sin^2 2\theta}{7 \times 10^{-11}}\right) \left(\frac{m_s}{7 \text{ keV}}\right)^5$$

Virgo Cluster: $10^{78}$ DM particles

Slide from 2001

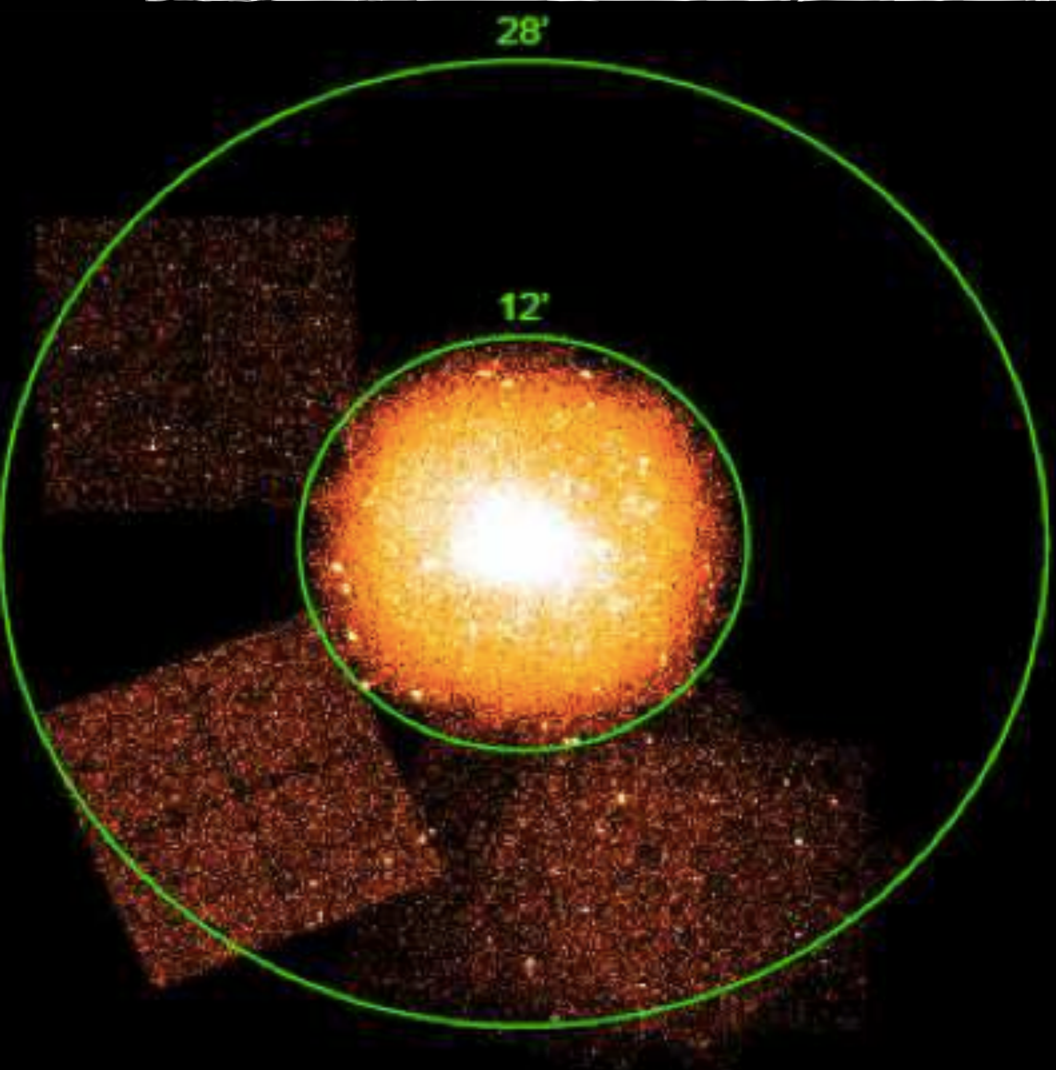


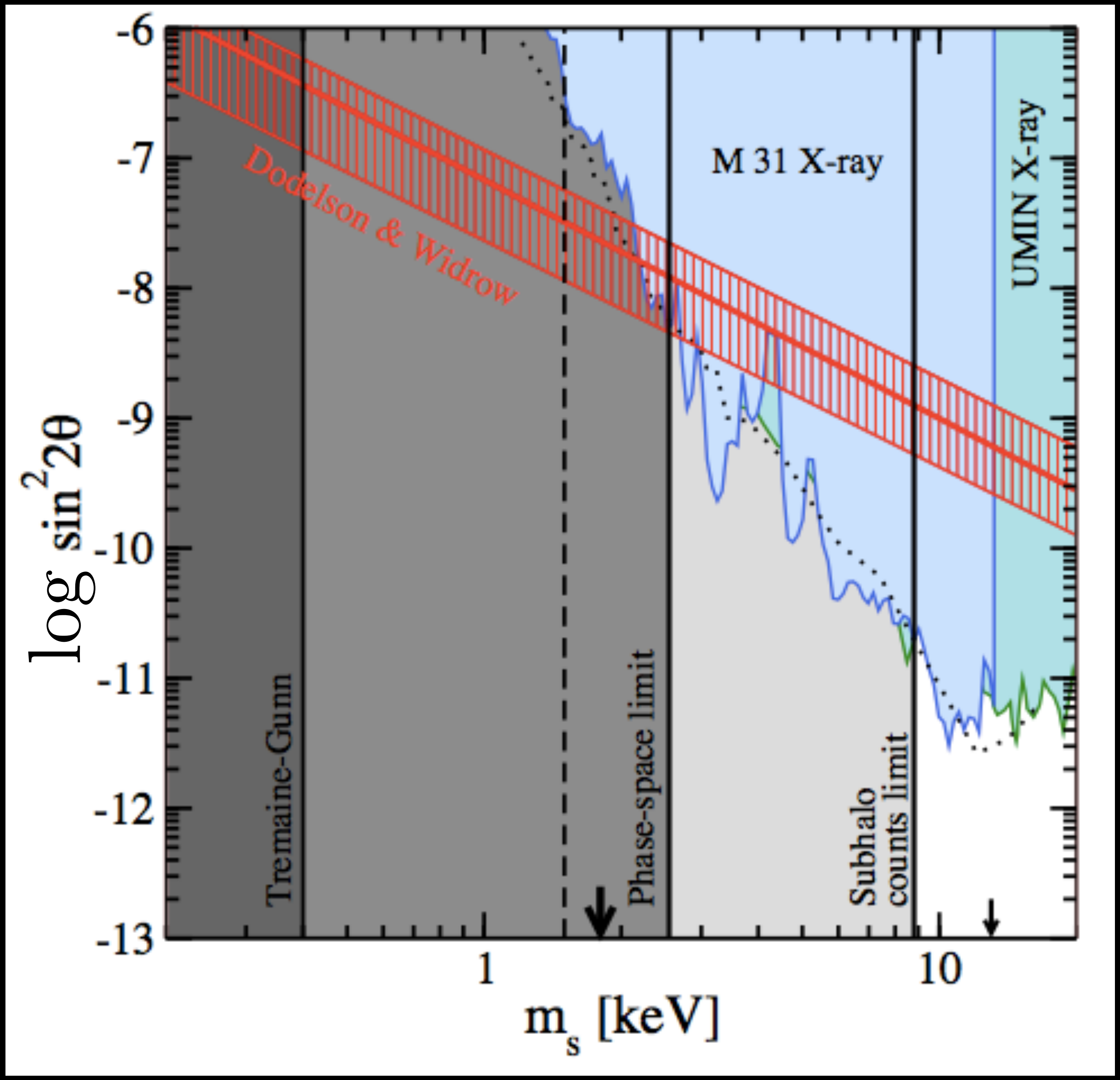

Current Limits

+

Future Detection?

# *Best constraints are from Horiuchi+ 2013*



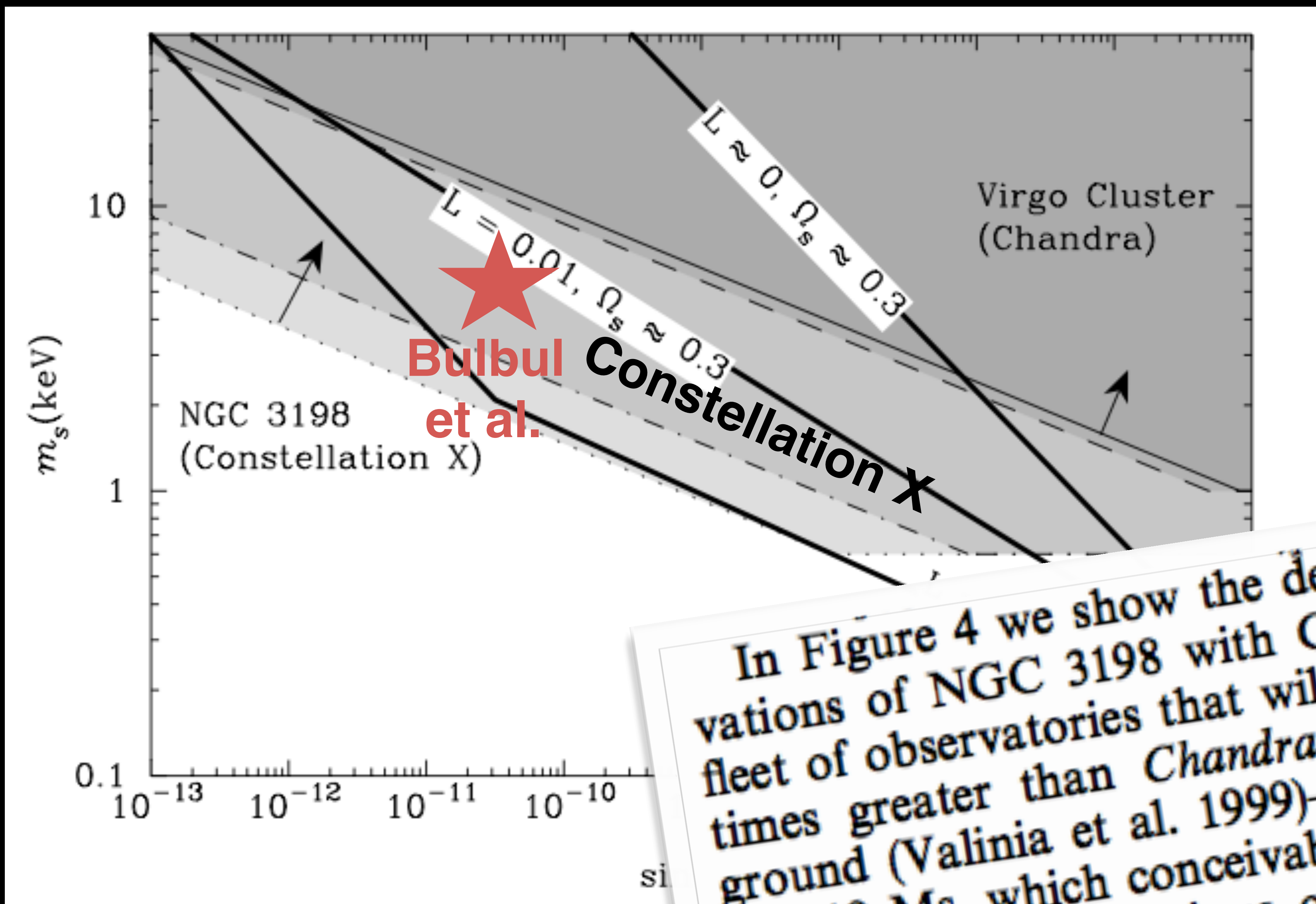



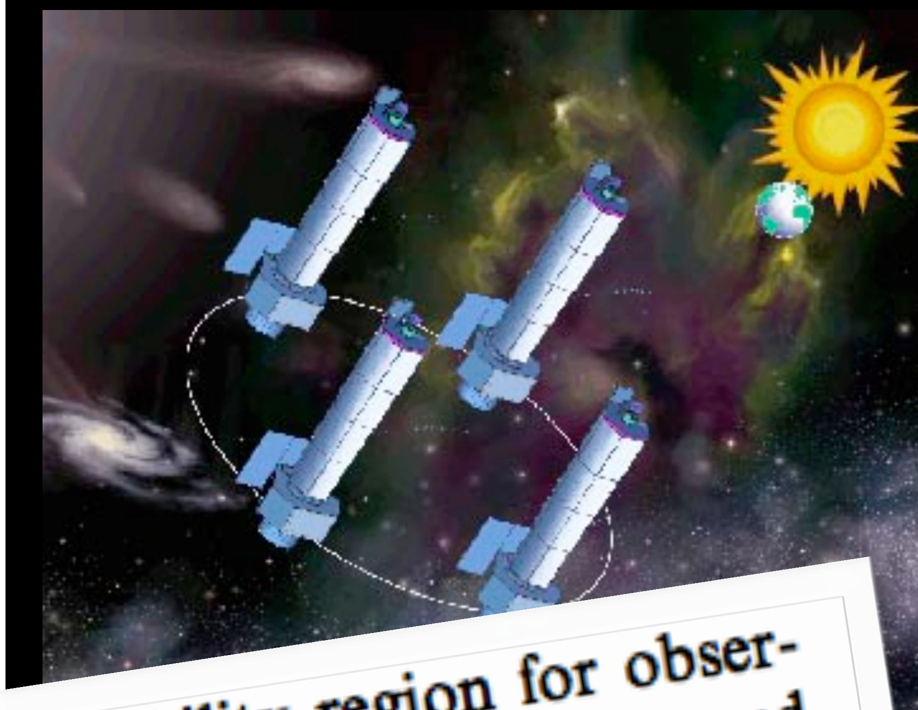

Combined subhalo and X-ray constraints: exclude standard DW dark matter $\nu_s$

Horiuchi, Humphrey, Abazajian & Kaplinghat, PRD arXiv:1311.0282

# Forecast X-ray Observation Sensitivity for *Constellation-X*

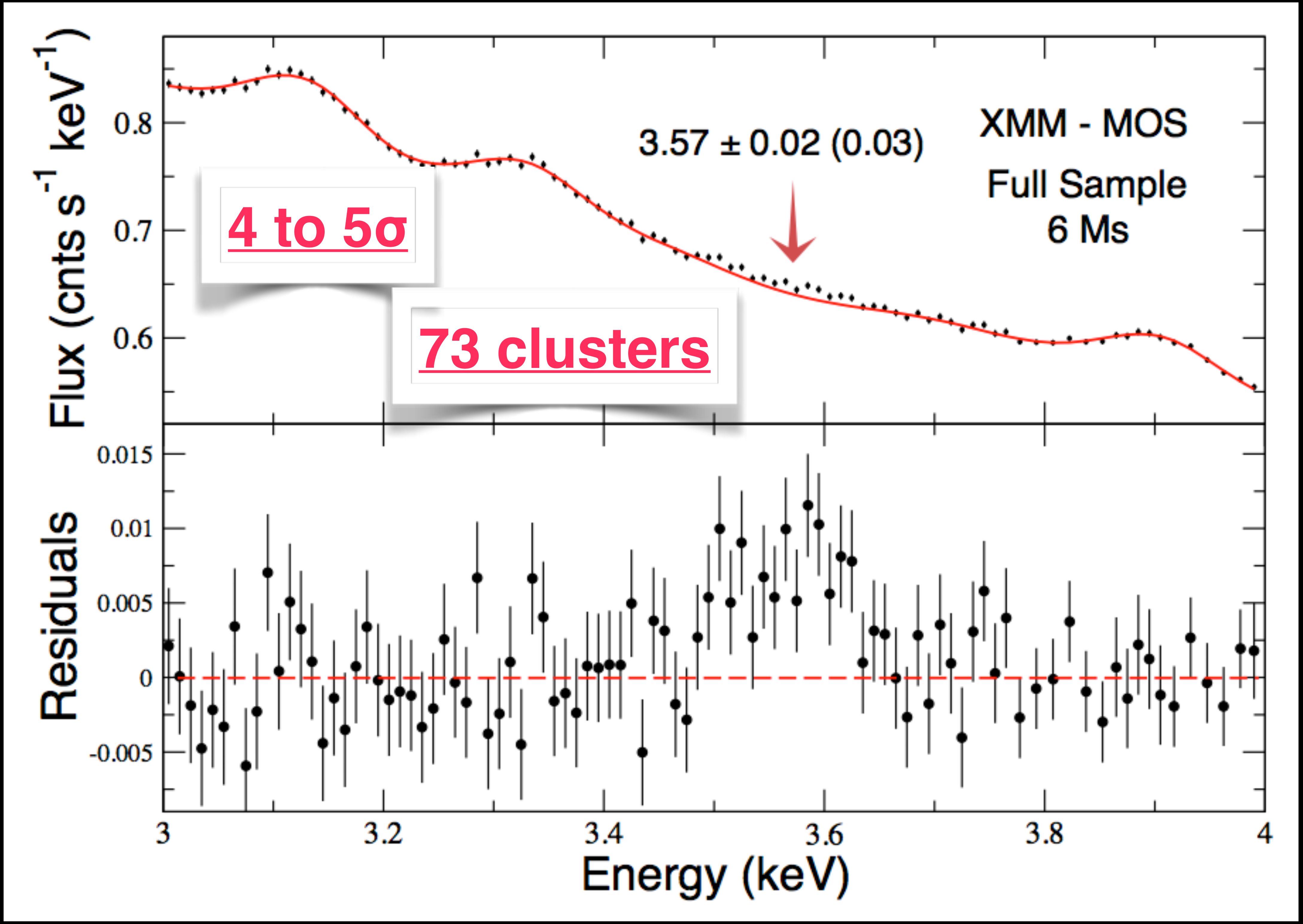
**Abazajian, Fuller & Tucker 2001**



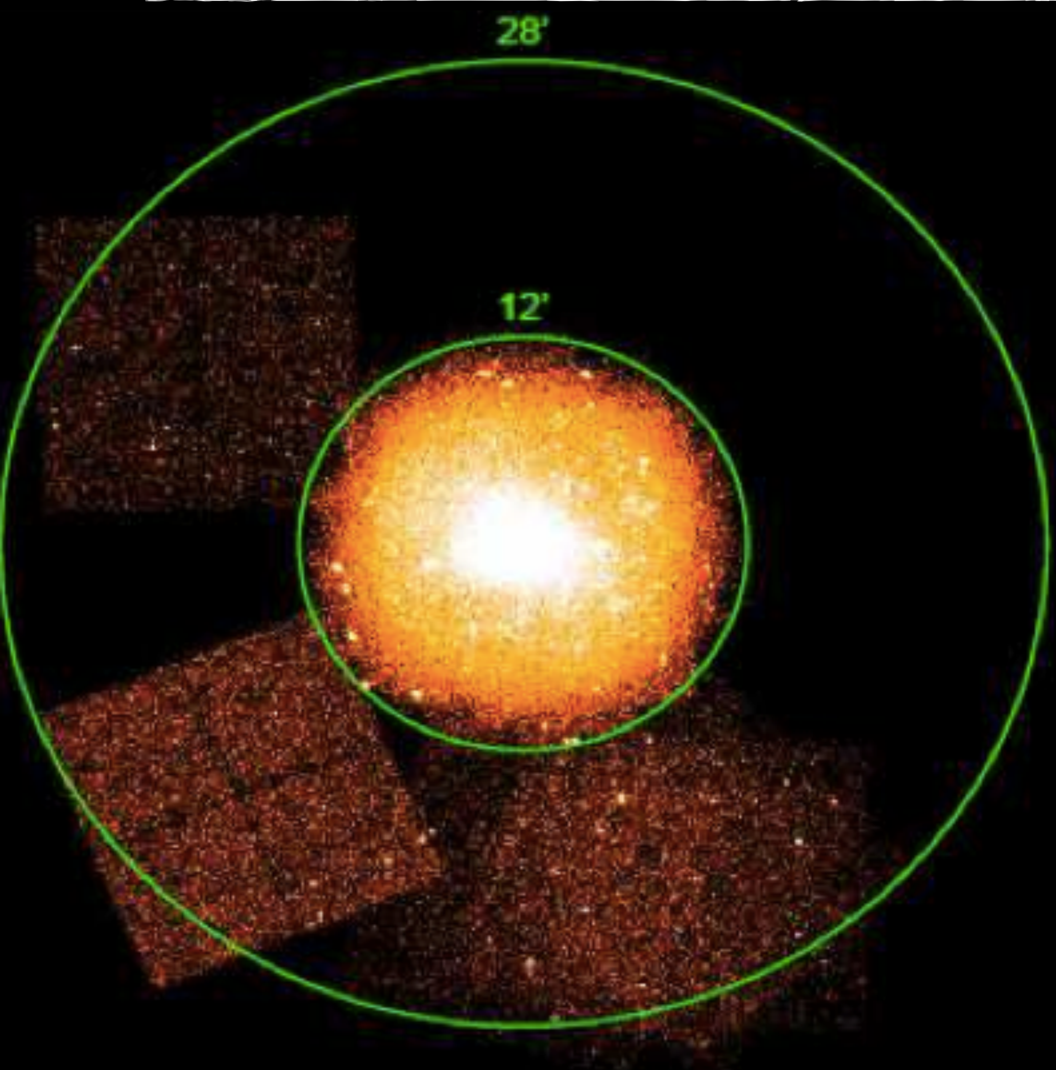
In Figure 4 we show the detectability region for observations of NGC 3198 with Constellation X—a proposed fleet of observatories that will have an effective area ~10 times greater than *Chandra* and no instrumental background (Valinia et al. 1999)—for two integration times, 1 and 10 Ms, which conceivably could be achieved through several long observations over a few years. An exposure equivalent to this could be obtained by a stacking analysis of the spectra of a number of similar clusters (see, e.g., Brandt et al. 2001; Tozzi et al. 2001). Constellation X, with very long integration times, holds out the prospect of covering nearly the entire WDM parameter space of interest for

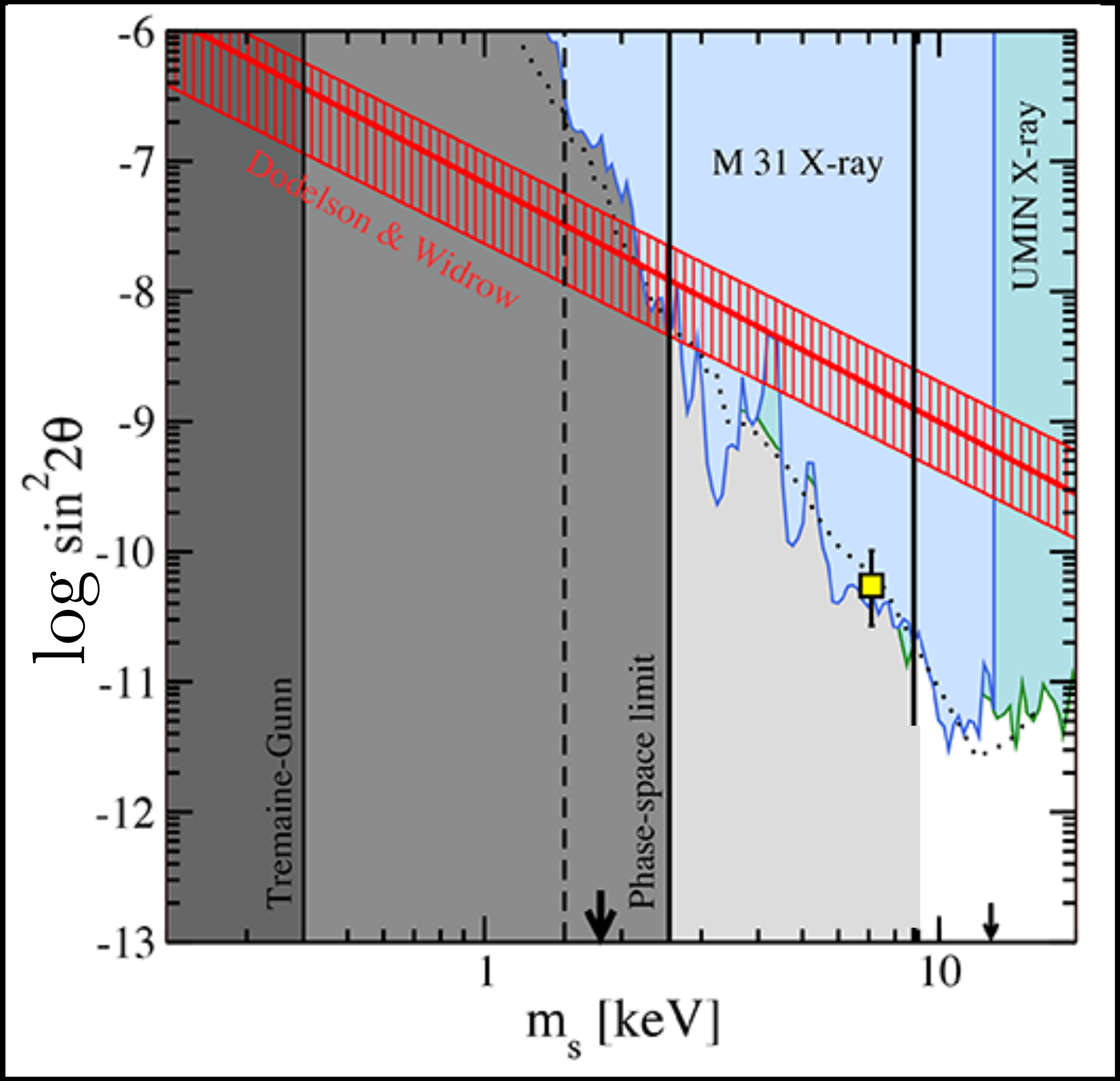
# The Detection of an Unidentified Line




Bulbul et al. ApJ arXiv:1402.2301

# *Chandra* X-ray M31 plus substructure constraints

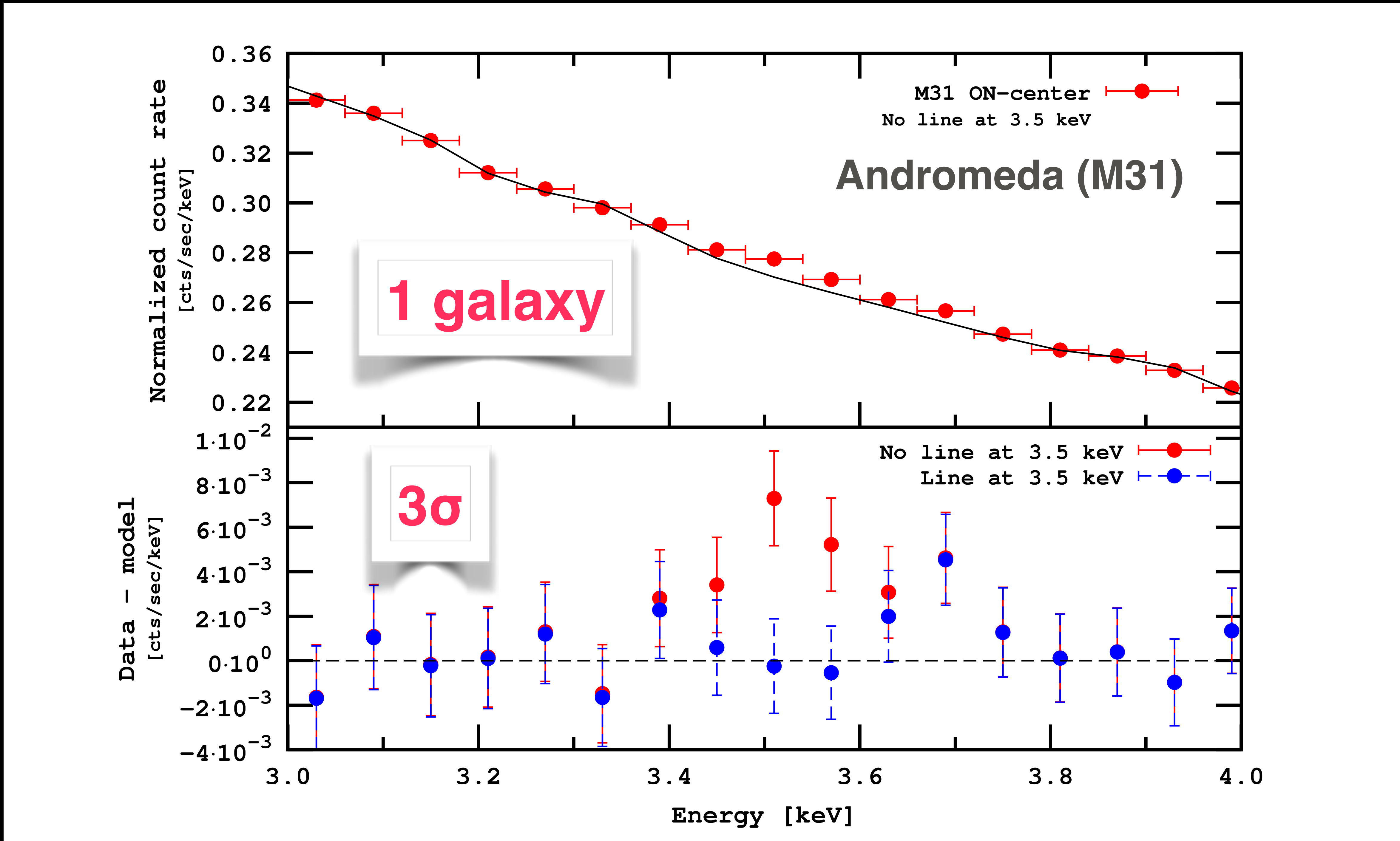



Combined subhalo and X-ray constraints: exclude standard $\nu_s$

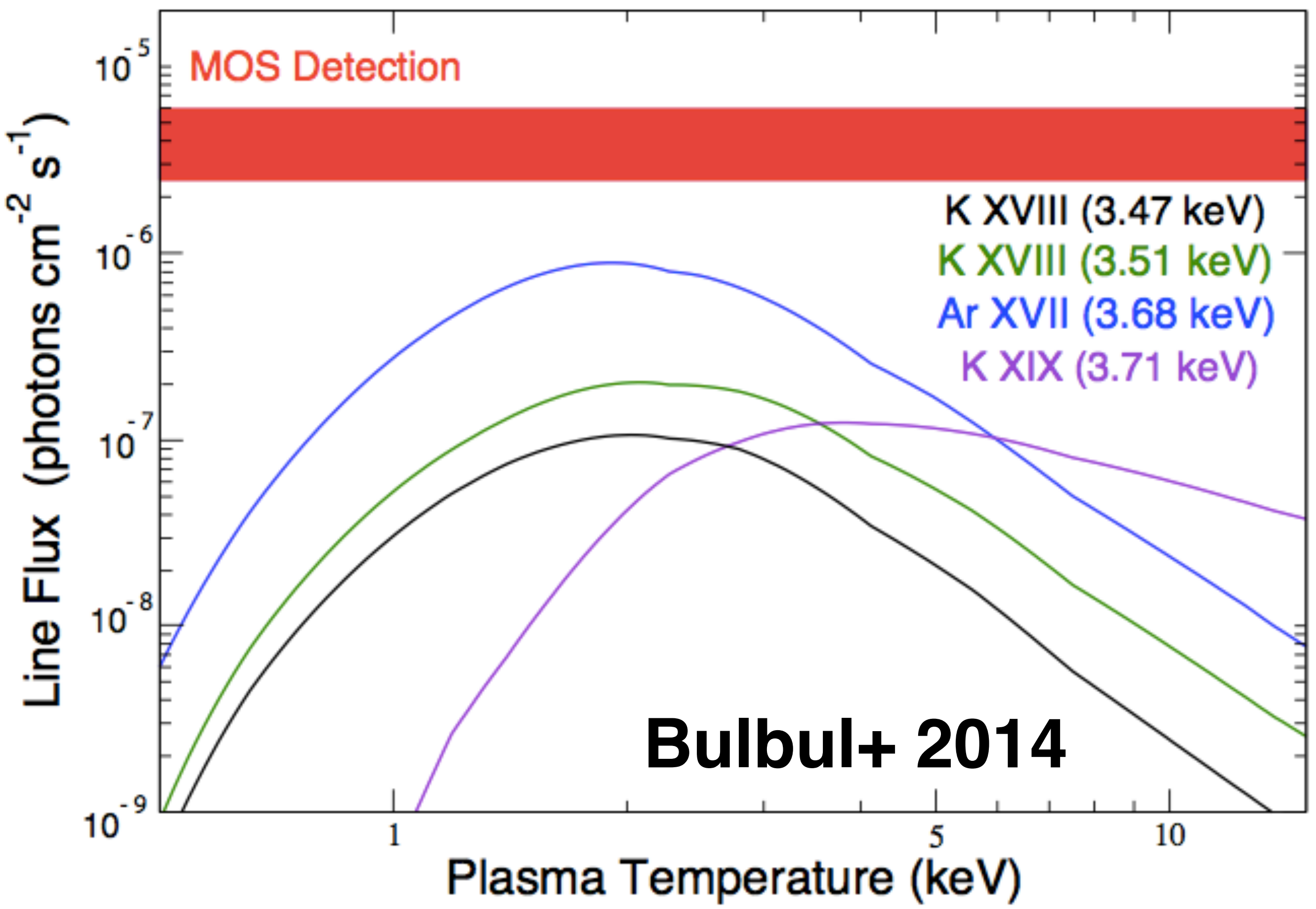
Horiuchi, Humphrey, Abazajian & Kaplinghat, PRD 2013

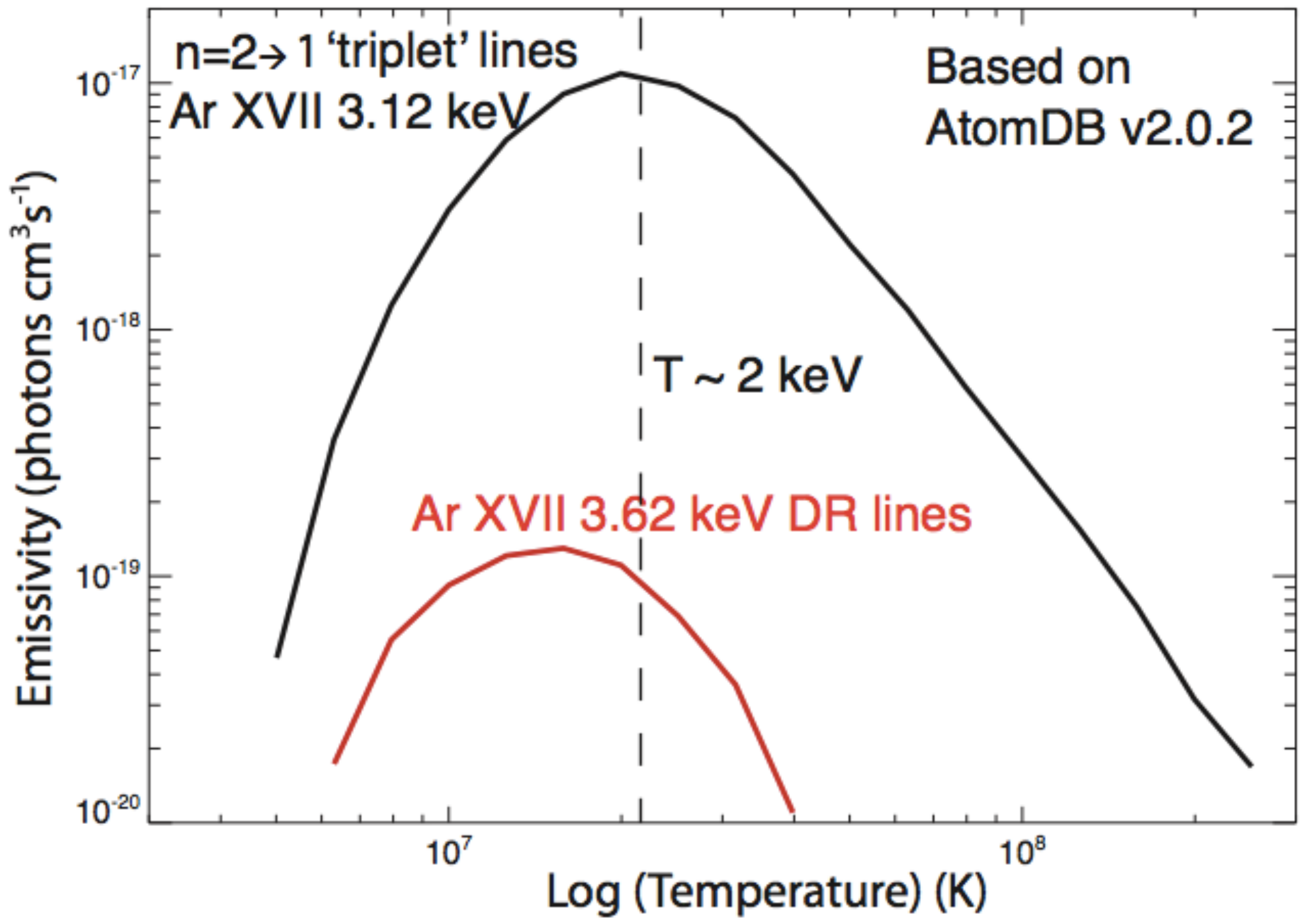
# The Detection of an Unidentified Line II




Boyarsky et al. PRL arXiv:1402.4119

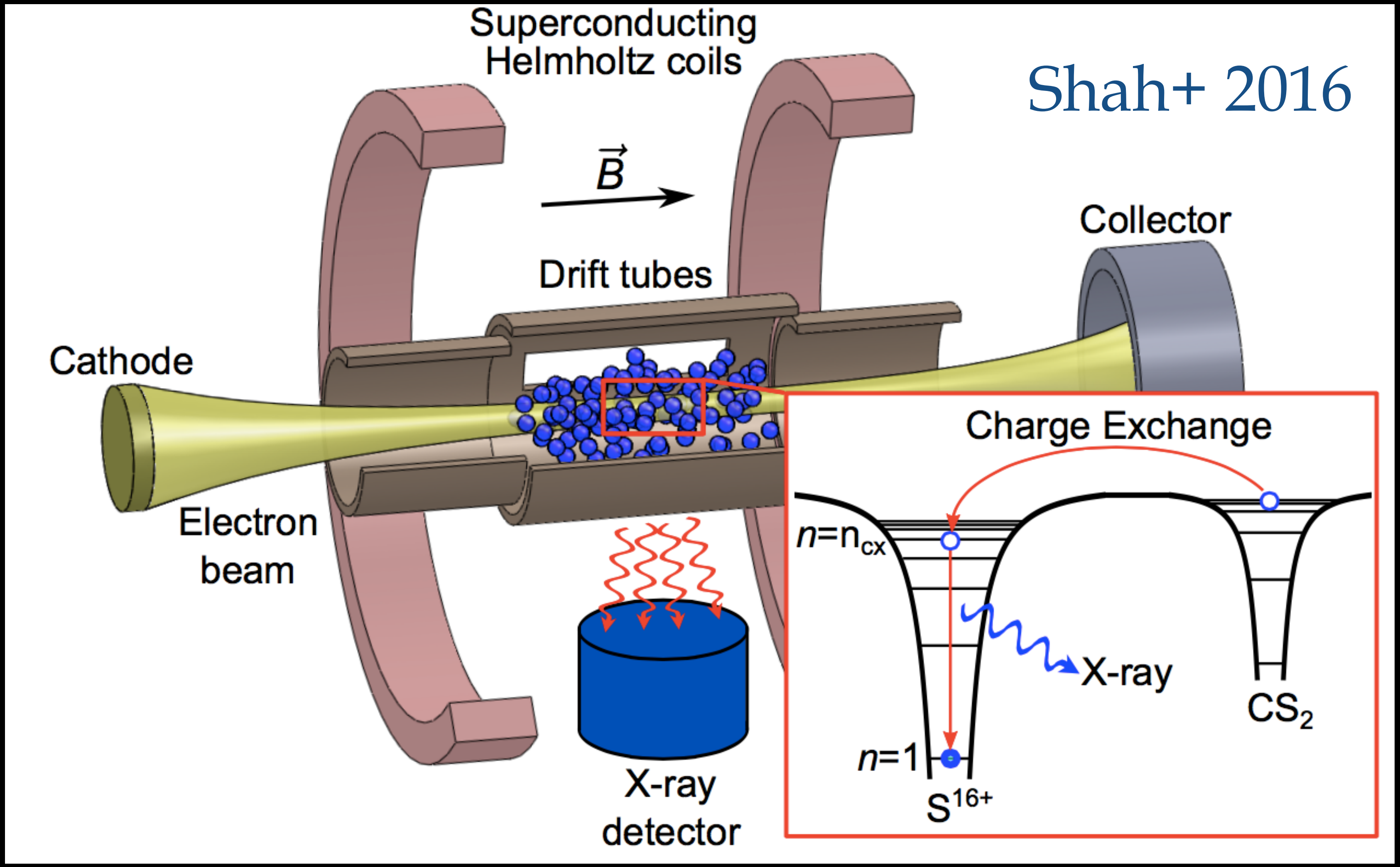
# Metal Lines in Clusters at 3.5 keV? *unlikely*




- Most lines at this energy are too low in flux for the typical plasma temperatures
- Those that could be close, Ar XVII DR, would have accompanying lines that make its flux a factor of 30 too low

# CX lines at ~3.5 keV?




Betancourt-Martinez+ 2014; Gu+ 2015; Shah+ arXiv:1608.04751

CX line(s) at 3.44 - 3.47 keV while unidentified line at
3.57±0.025 keV (Perseus)
3.57±0.02 keV (MOS stack)
3.51±0.03 keV (PN stack)

# Confirmation hope: Hitomi (Astro-H) X-ray Telescope

*Successful launch Feb. 17*

*Loss of satellite March 26*

*NASA Build-to-print SXS for XARM launch March 2021*

UK X-RAY ASTRO

**RAS X-ray 2017**
@UKXrayastro

Following

Richard Kelley: #Hitomi X-ray Astronomy Recovery Mission (#XARM) approved in Japan and USA! Launch ~03/2021. Remarkably quick turnround.

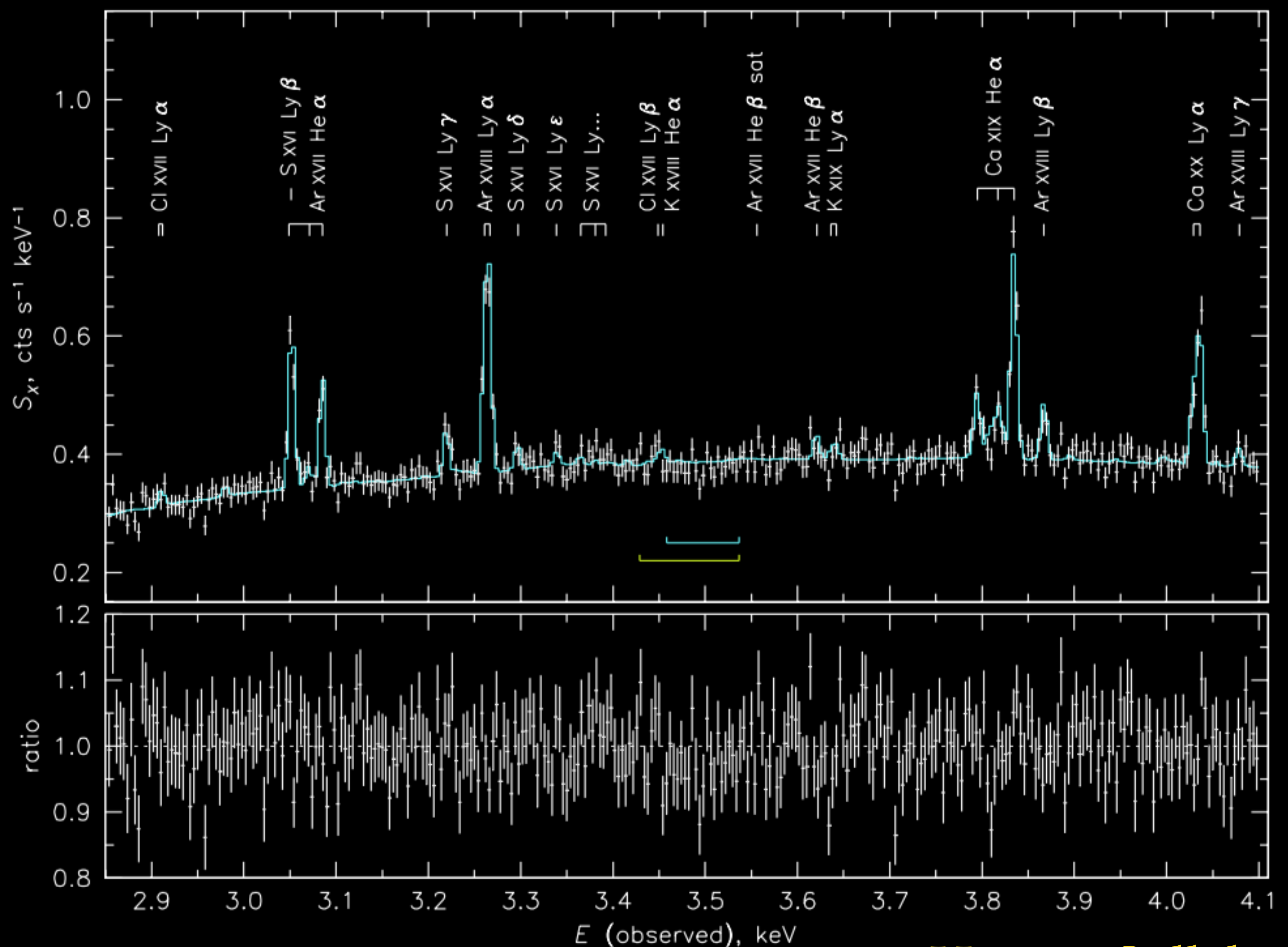
RETWEETS 7 LIKES 7

7:41 AM - 10 Feb 2017

1 7 7

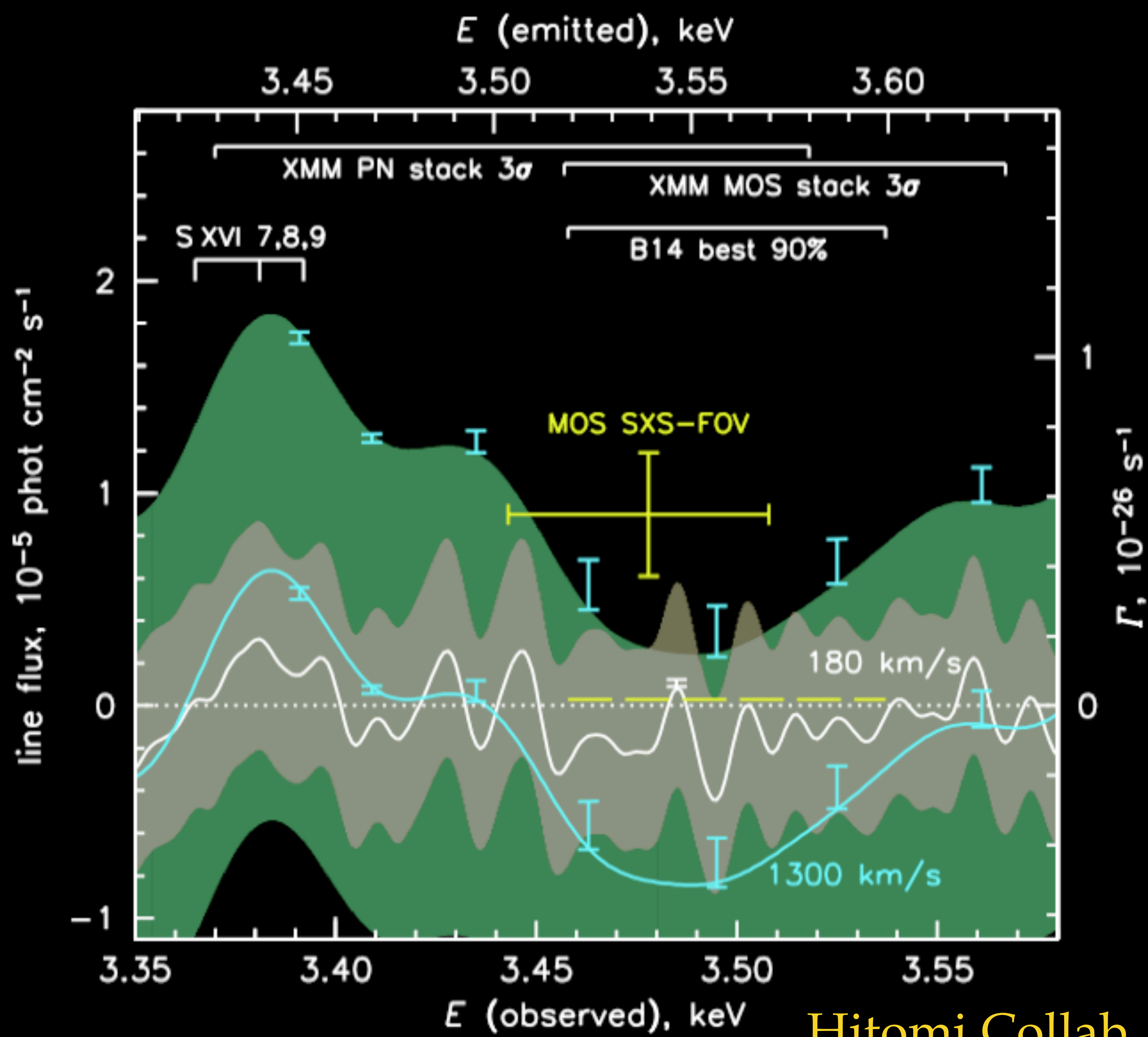
# Hitomi X-ray Telescope: Few Days of Data

Unprecedented energy resolution: factor ~50 higher



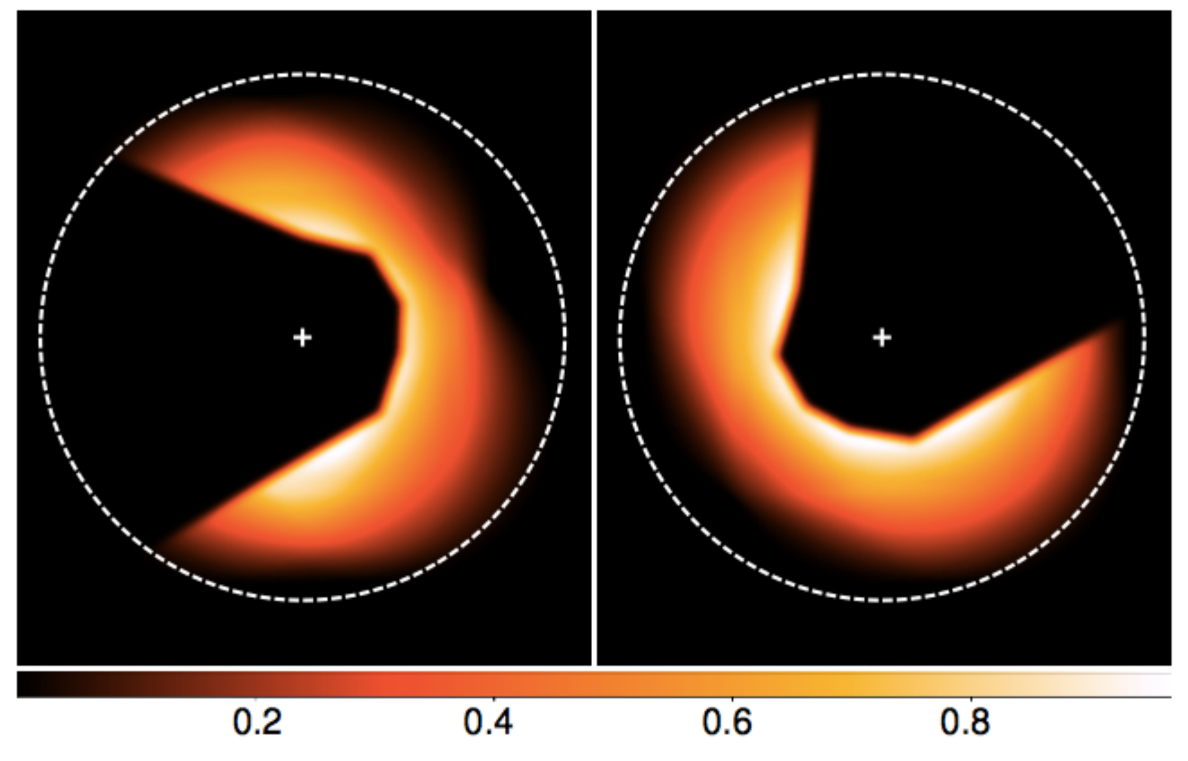

Hitomi Collab. 1607.07420

# *Hitomi X-ray Telescope: Expected line or not?*



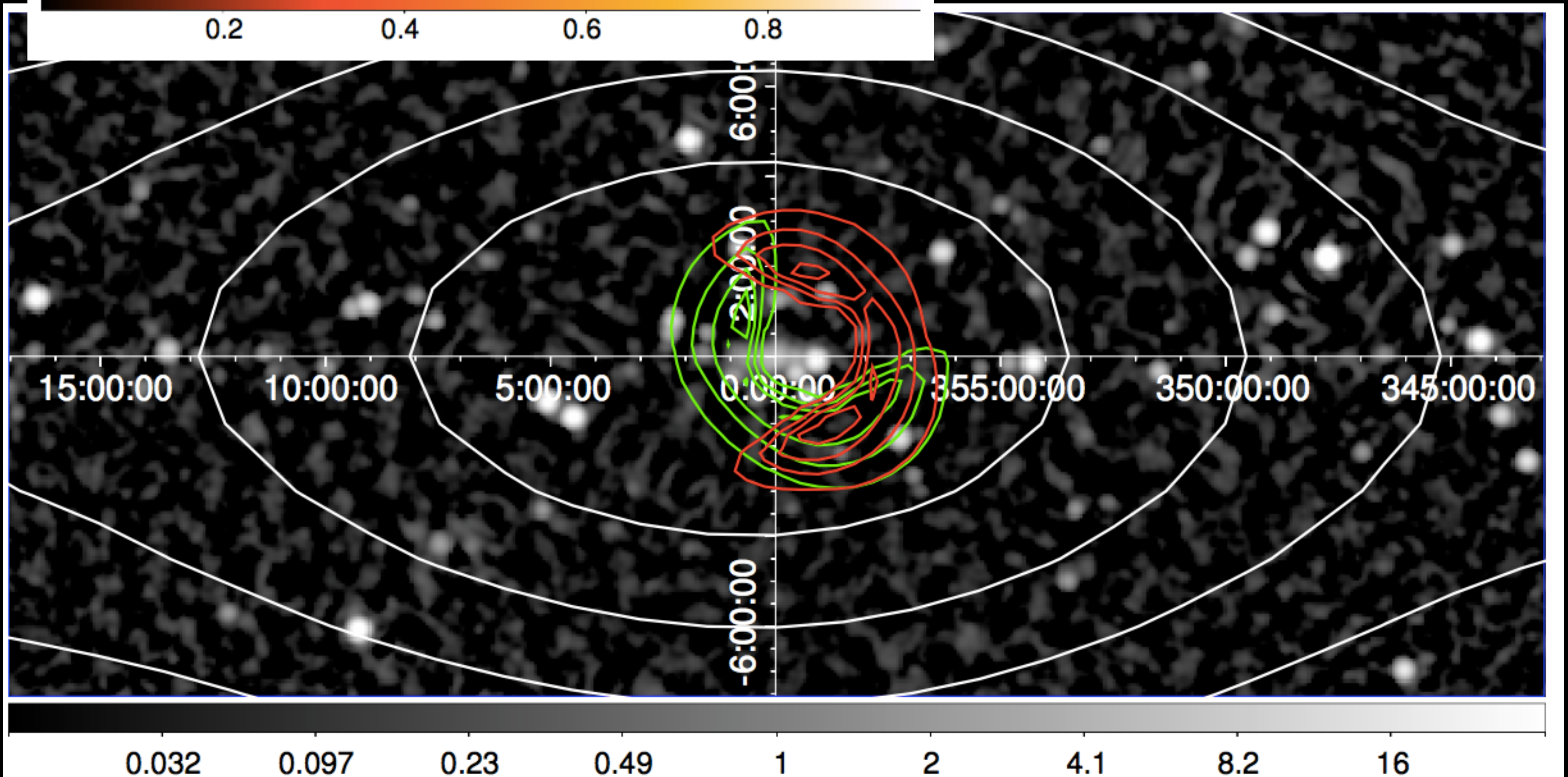

Hitomi Collab. 1607.07420

# *NuSTAR: the best current telescope?*

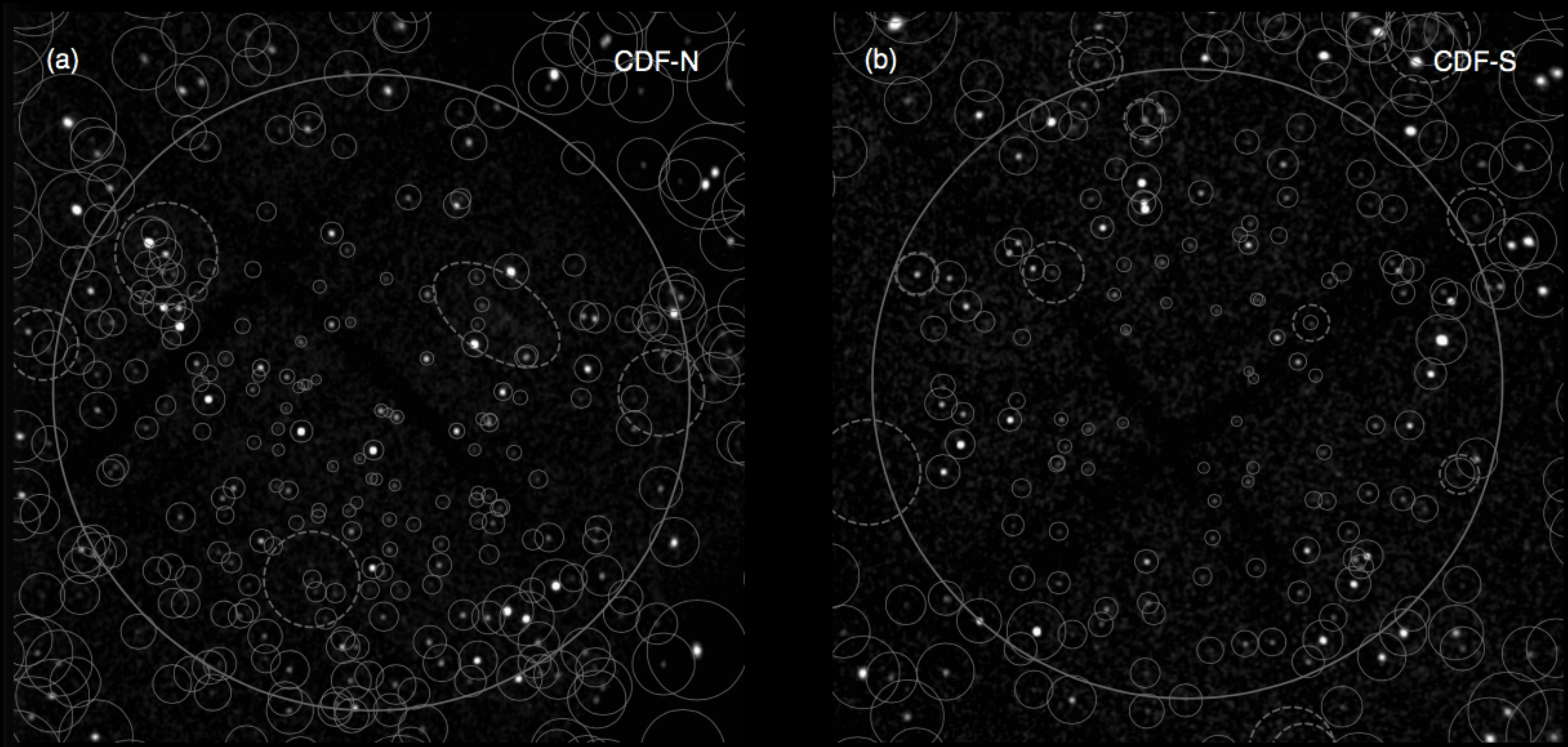



Shielding gap in telescope lets in 0 bounce photons. 37 deg$^2$ aperture!

Perez+: **GC no signal, limits** (1609.00667)
Neronov+: **Deep field sees 11.1σ 3.5 keV line consistent with DM decay** (1607.07328)

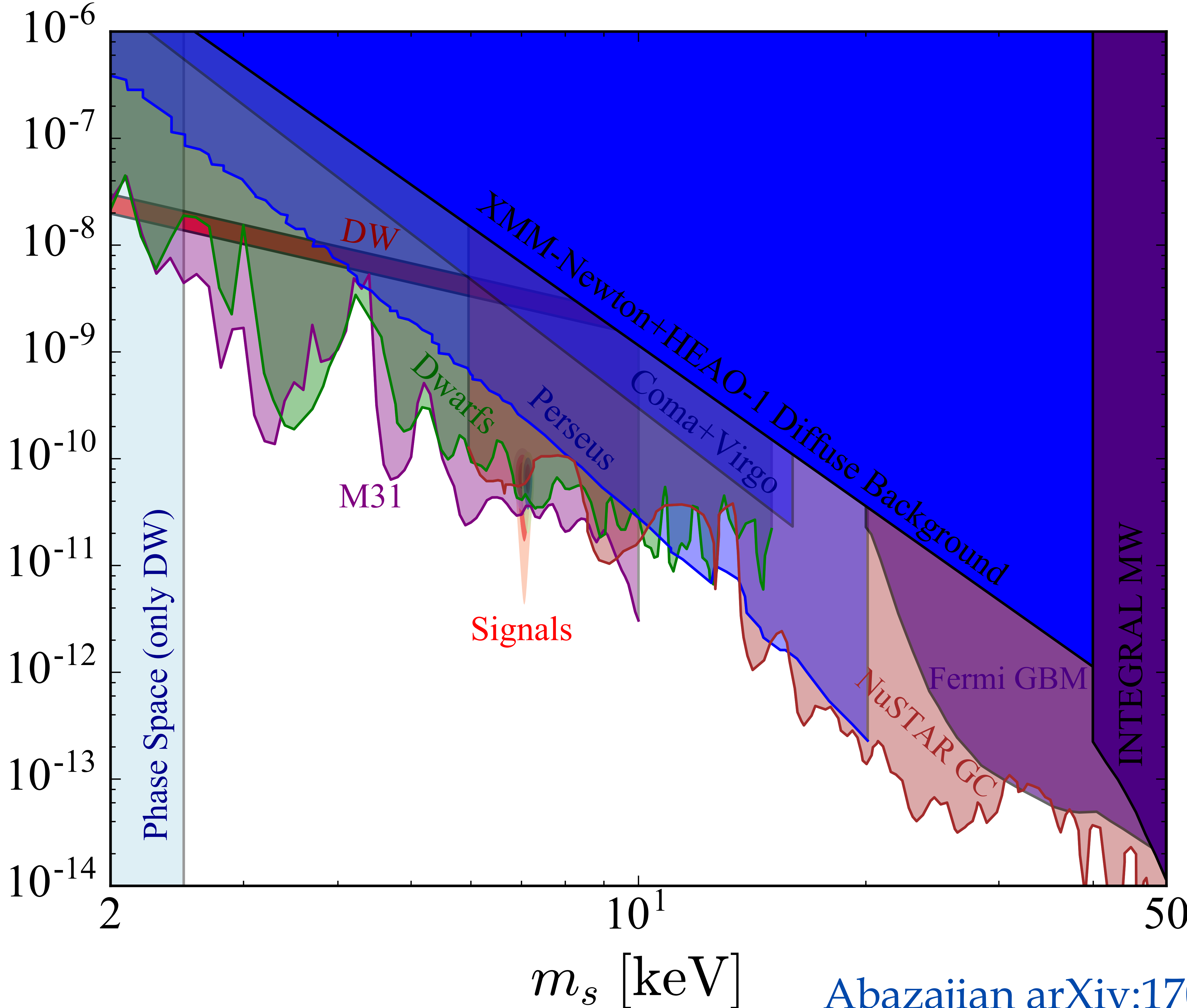


# *Chandra Deep Fields: 10 Ms of data*



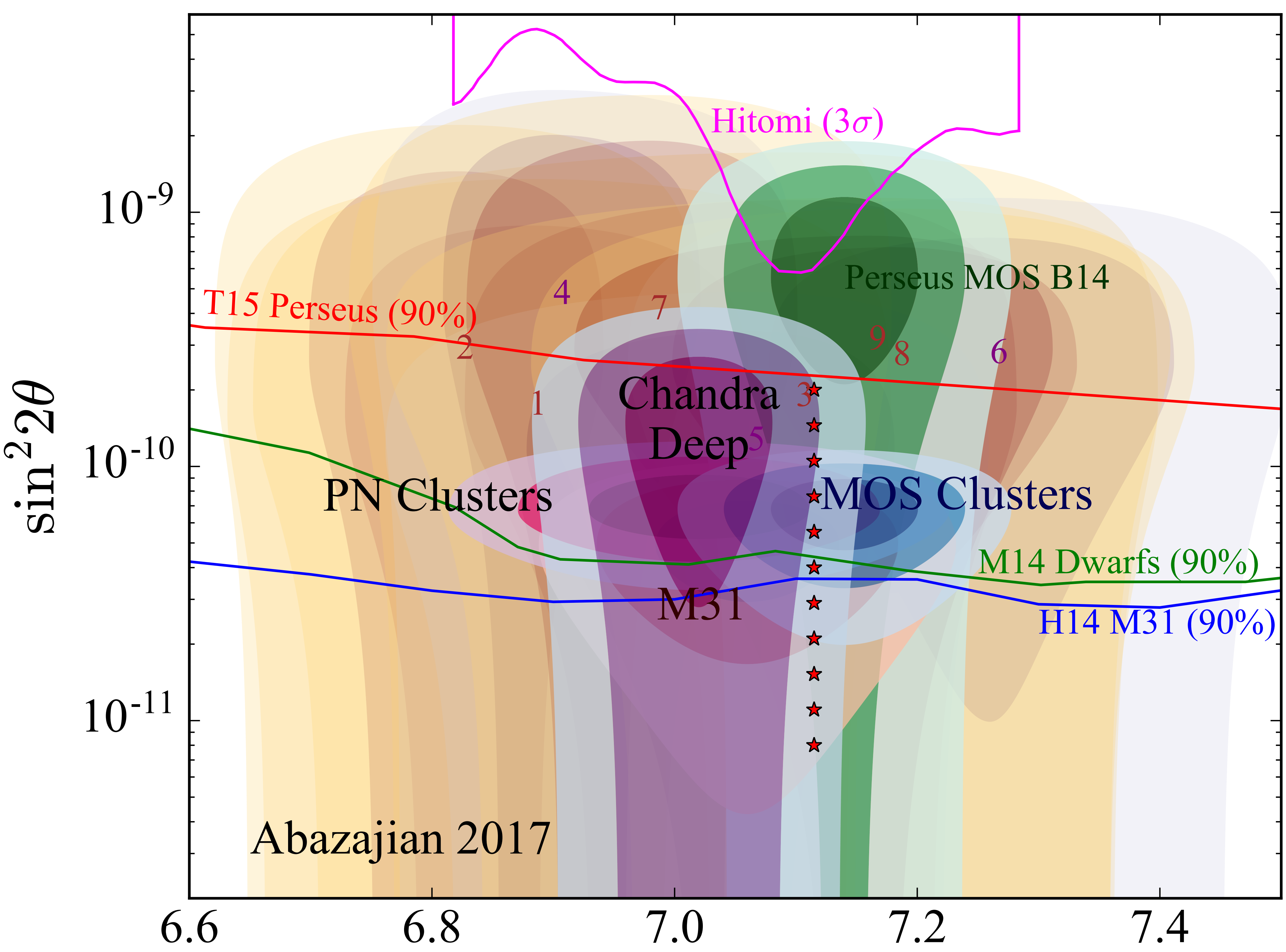

**Cappelluti+ 2017:** see the line at 3σ in ~10 Ms of COSMOS Legacy and Chandra Deep Field South observations,
Rule out instrumental feature based on detailed characterization of response,
Rule out CX & Ar lines due to lack of partner lines
(K shown to be incompatible in 2014) arXiv:1701.07932

# Sterile Neutrino Dark Matter: Parameter Space Summary




Abazajian arXiv:1705.01837

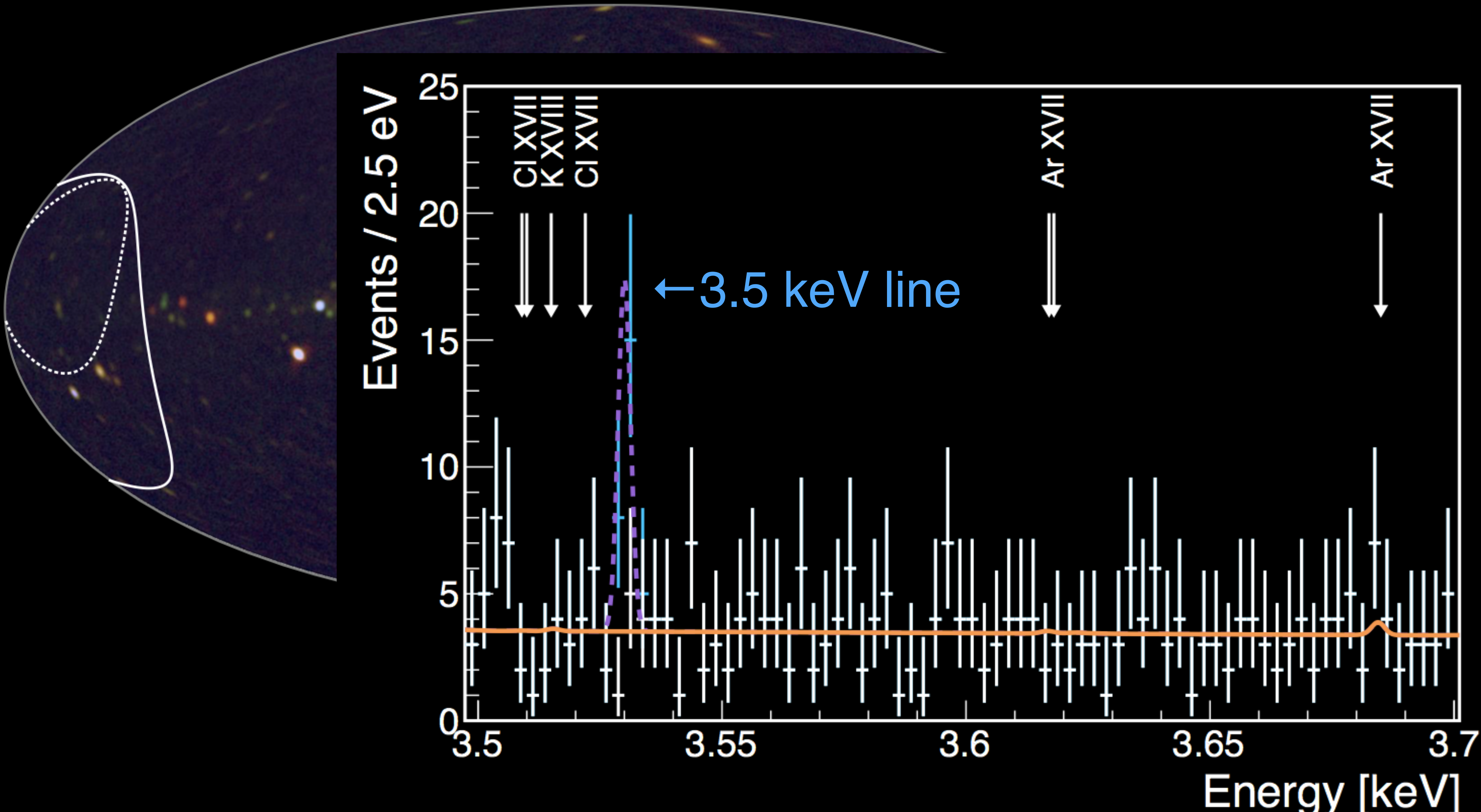
# The 7 keV Region Today




arXiv:1705.01837

Cluster search: Iakubovskyi+ 1508.05186

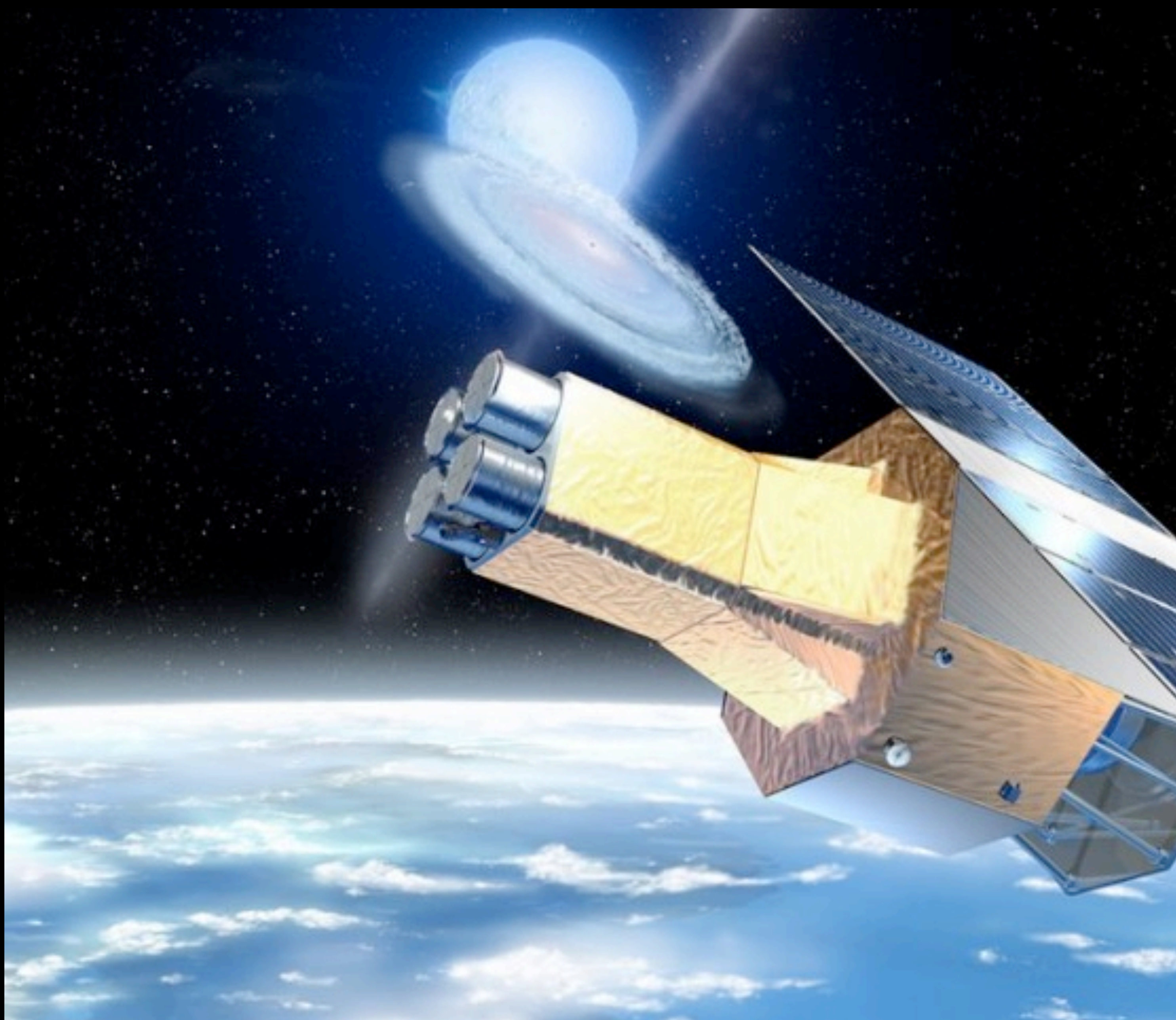
# *Confirmation? Sounding Rocket X-ray Observations: Micro-X & XQC*




Figueroa-Feliciano+ 1506.05519

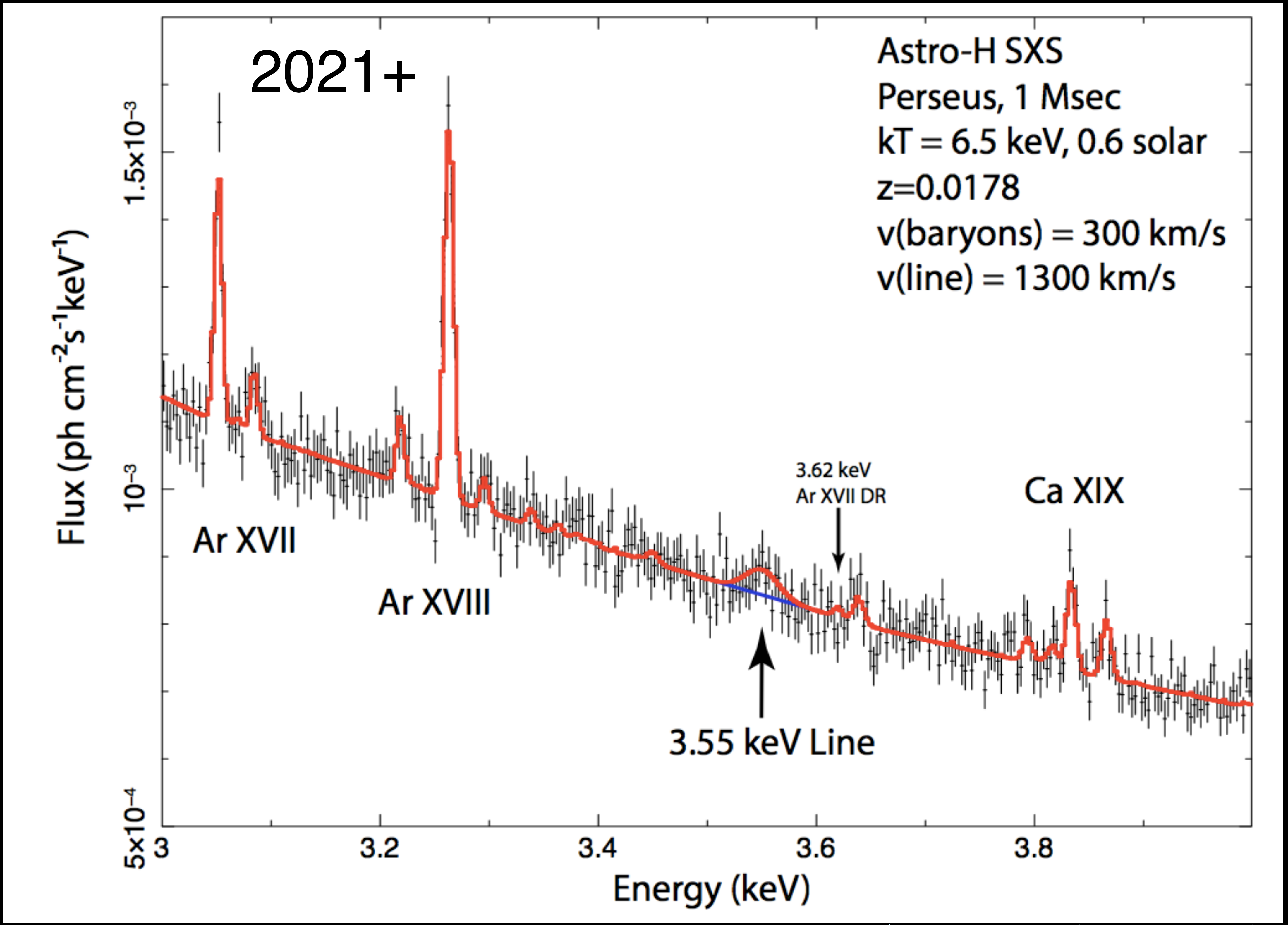
# *Next Space Mission in X-ray Astronomy*

## *X-ray Astronomy Recovery Mission (XARM)* ~2021



XARM will carry two instruments for studying the soft X-ray energy range: Build-to-print SXT-S (Soft X-ray Telescope for Spectrometer) & updated in energy resolution SXT-I (Soft X-ray Telescope for Imager).

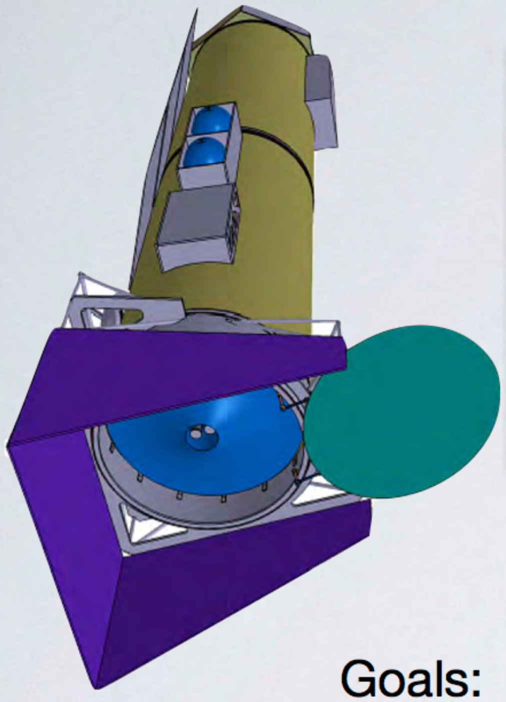
# *Confirmation? XARM*

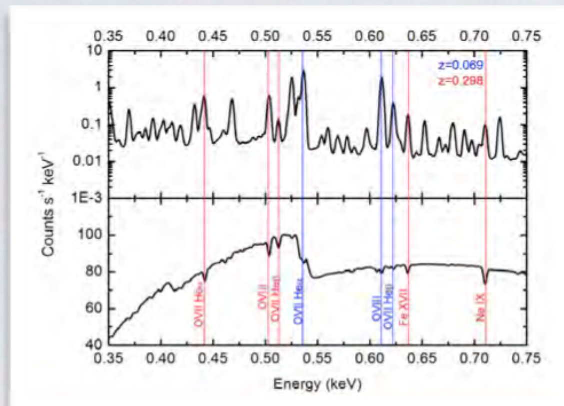



Bulbul et al. ApJ arXiv:1402.2301

# Future Space X-ray Astronomy

## Athena






**about 2028**

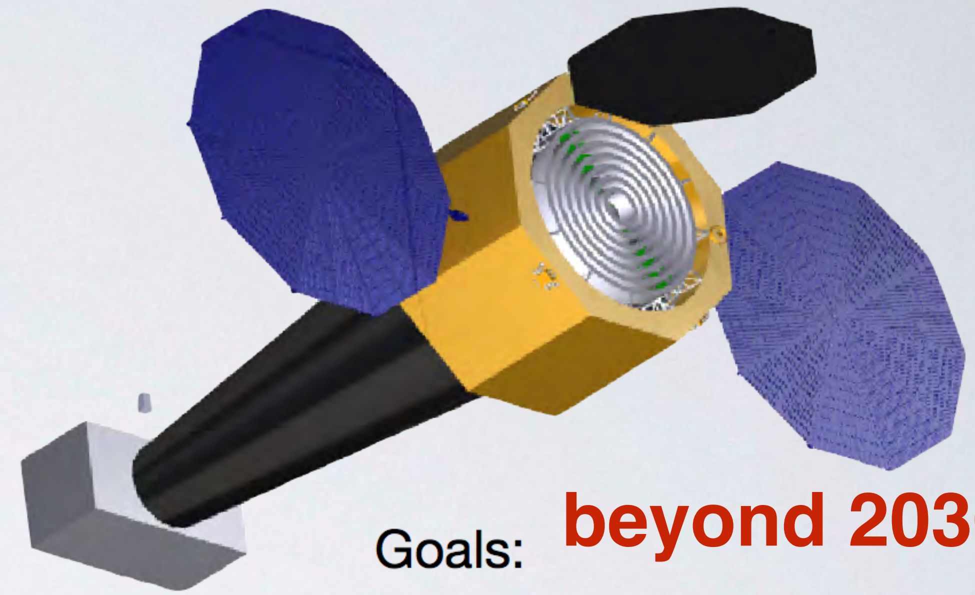
Goals:

- Microcalorimeter spectroscopy (R≈1000)
- Wide, medium-sensitivity surveys

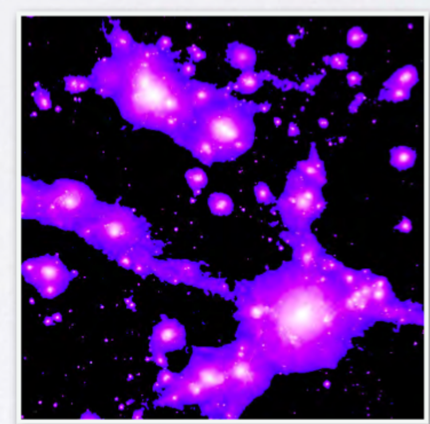
$$\left(R = \frac{\lambda}{\Delta\lambda}\right)$$

Area is built up at the expense of coarser angular resolution (10×) & sensitivity (5×)

## Lynx X-ray Surveyor



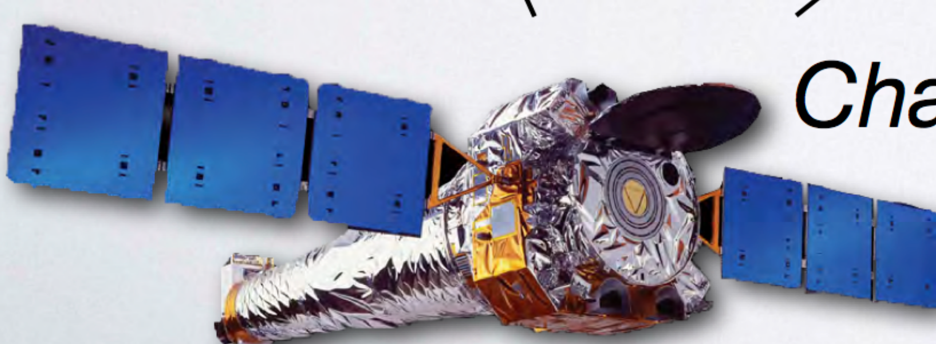
Goals: **beyond 2030**



- 50× sensitivity
- *R*≈1000 spectroscopy on 1″ scales adds 3rd dimension to the data
- *R*≈5000 spectroscopy for point sources

✓ Area is built up while preserving *Chandra* angular resolution (0.5″)

✓ 10× field of view with fine imaging

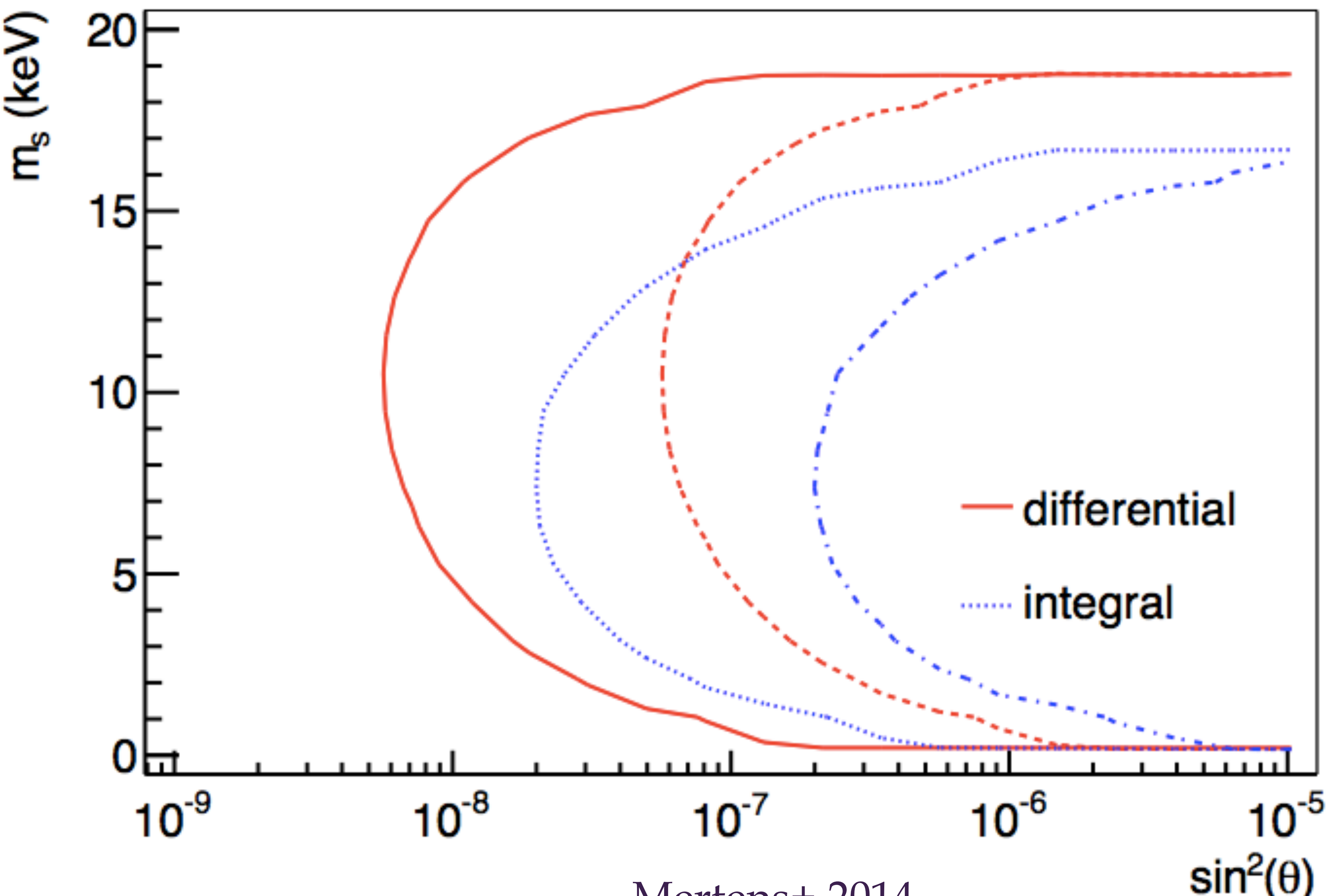


*Chandra*

**[Courtesy Alexey Vikhlinin]**

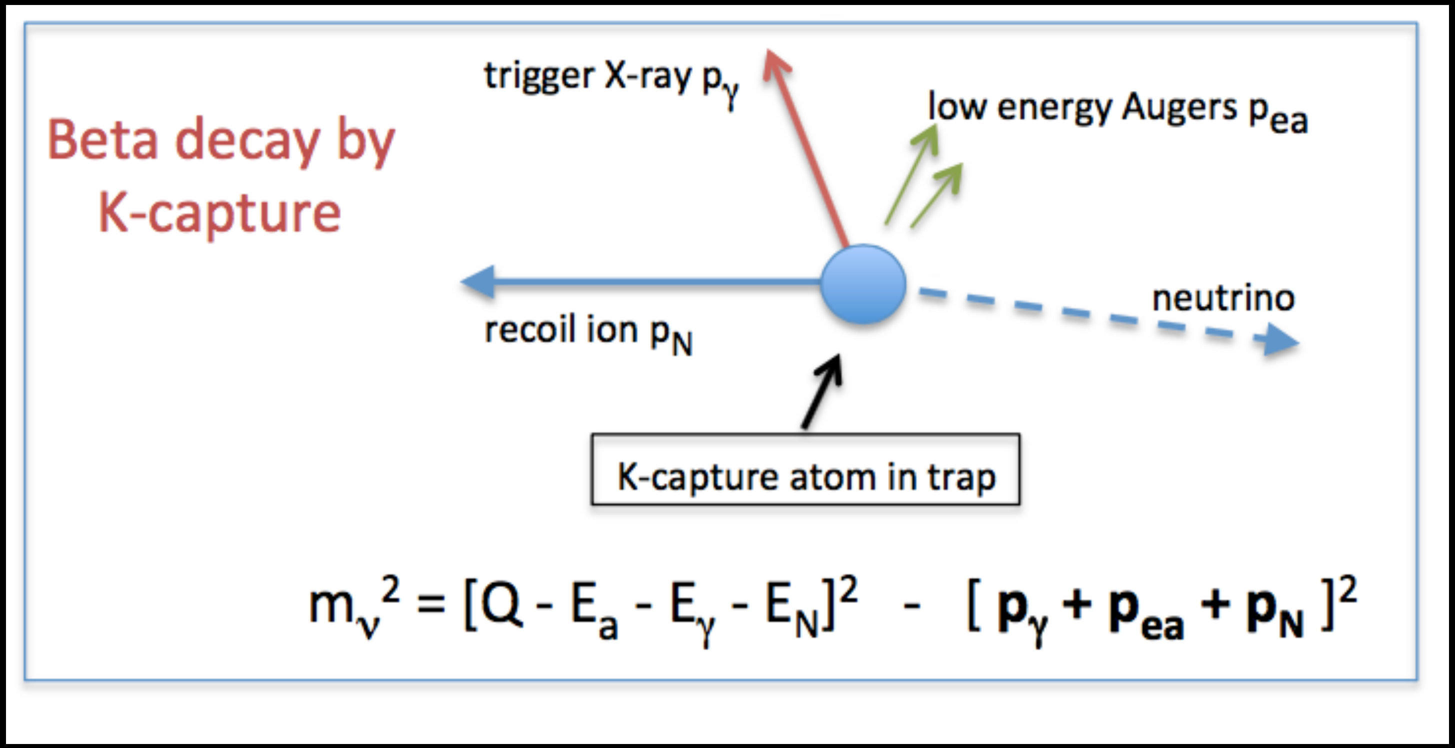
# *Confirmation? kinematic searches in nuclear $\beta$-decay*

# Confirmation? kinematic searches in nuclear $\beta$-decay




Mertens+ 2014

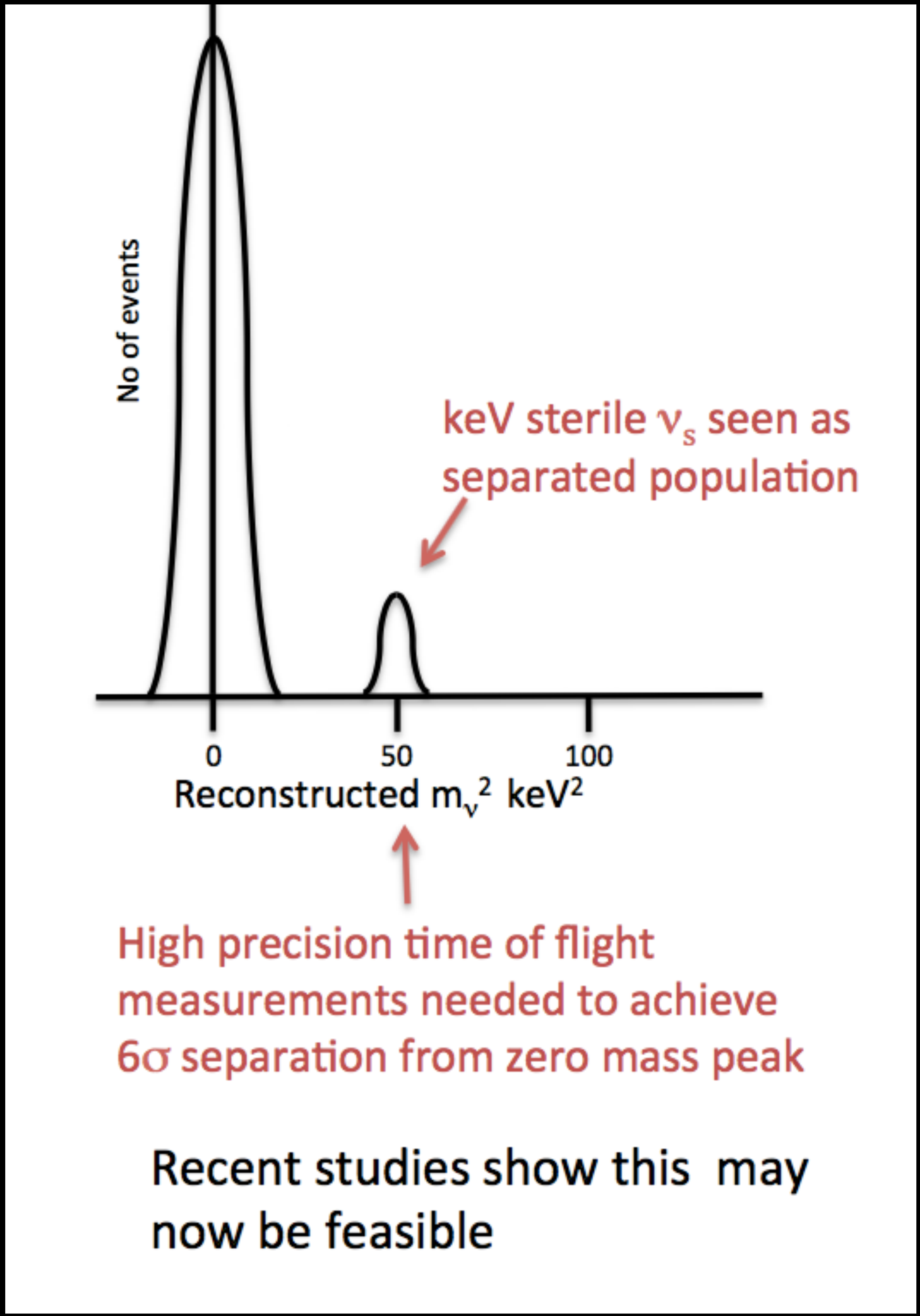
# *Confirmation Method #4: full kinematic reconstruction of K-capture nuclear decay*



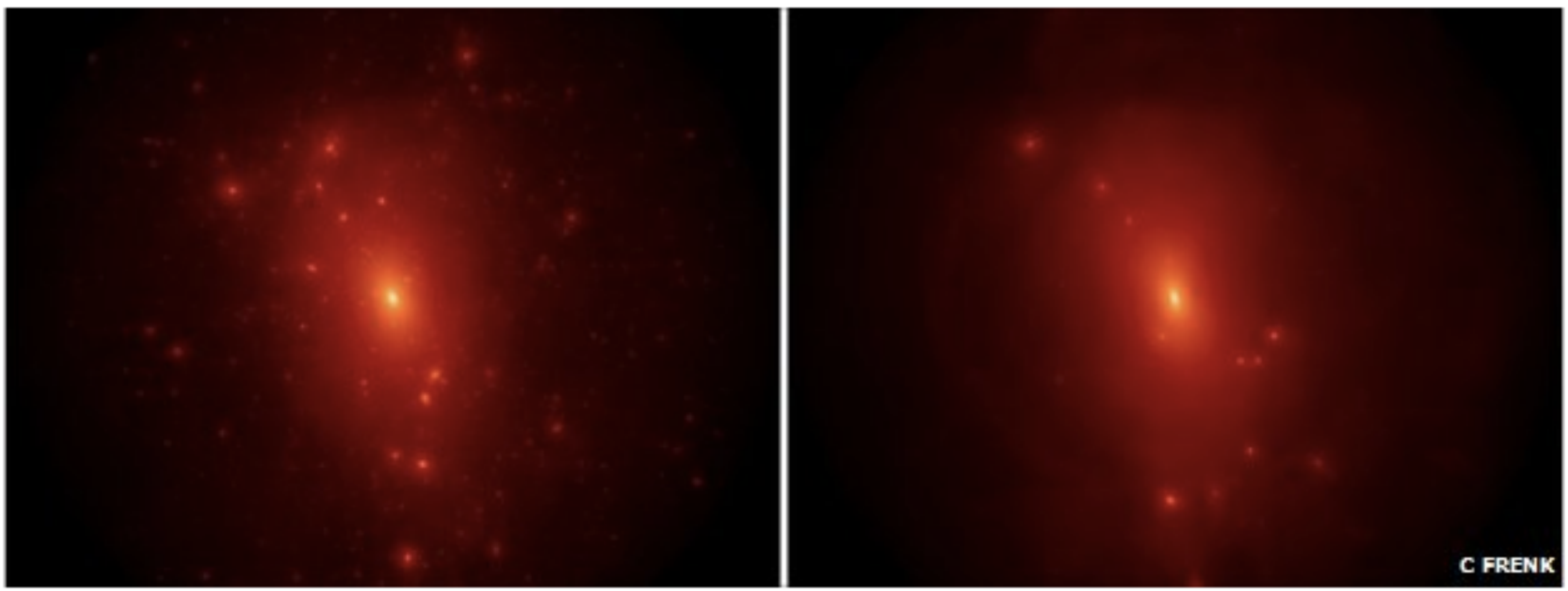

Original studies: Finocchiaro & Schrock 1992

CACHE (Cesium Atomic-electron Capture with Heavy neutrino Emission)

$^{131}$Cs Ion trap proposal:
Peter Smith+ arXiv:1705.06876

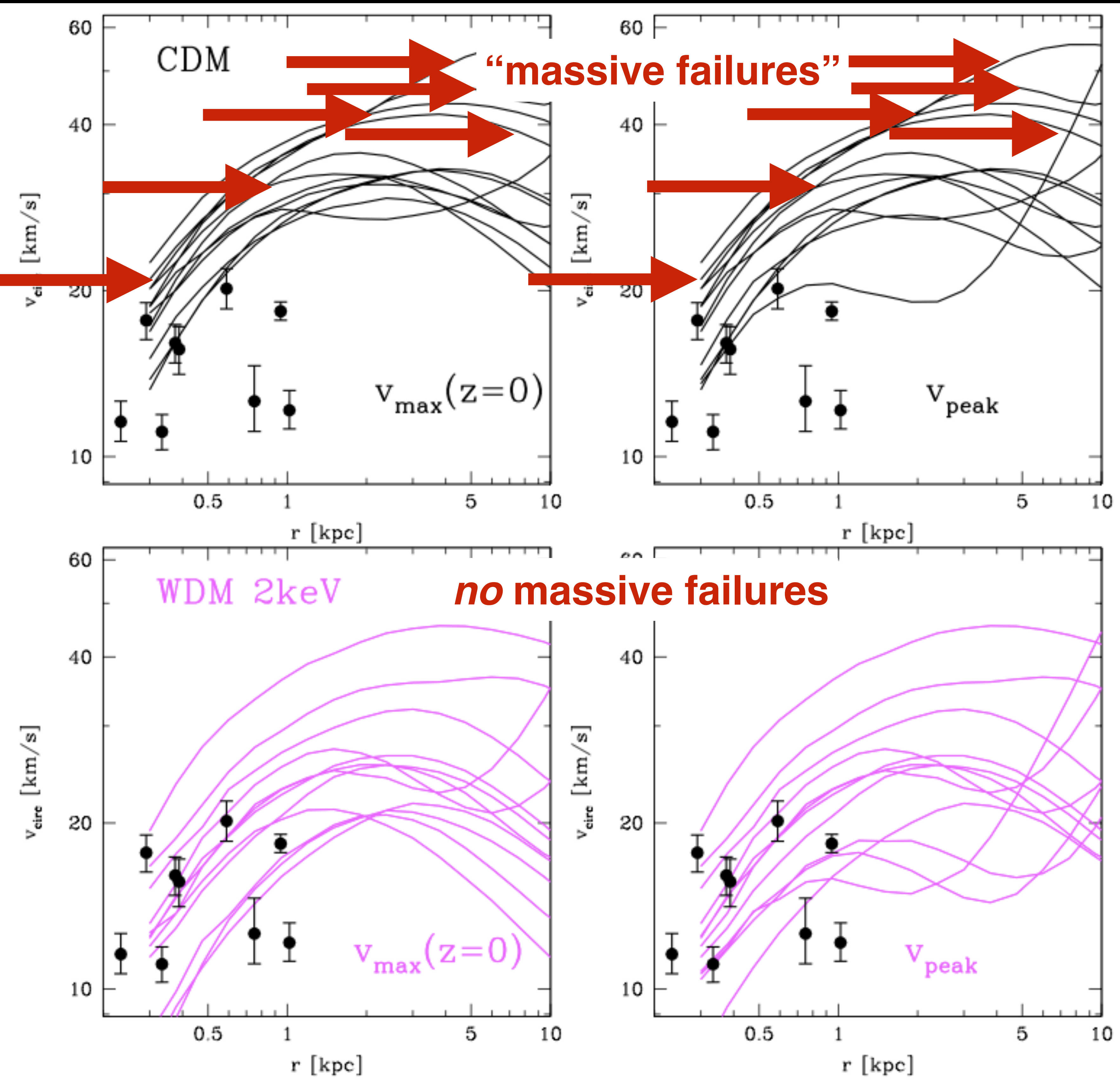


# Issues in Cosmological Small-scale Structure?



Dwarf galaxies around the Milky Way are less dense than they should be if they held cold dark matter

# WDM Solution to All Local Group Galaxy Properties?




Anderhalden et al. arXiv:1212.2967

*"It seems that only the pure WDM model with a 2 keV [thermal] particle is able to match the all observations" of the Milky Way Satellites: "the total satellite abundance, their radial distribution and their mass profile" (or TBTF)*

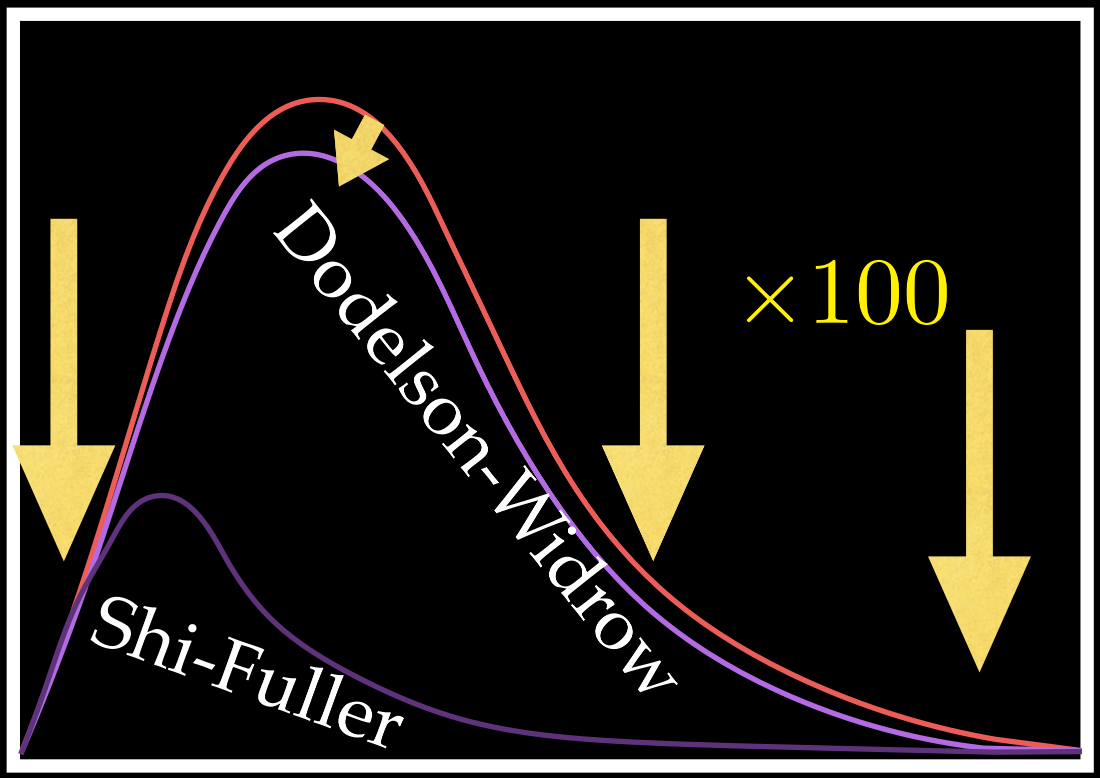
# What is the relationship between particle mass and warm dark matter effects?

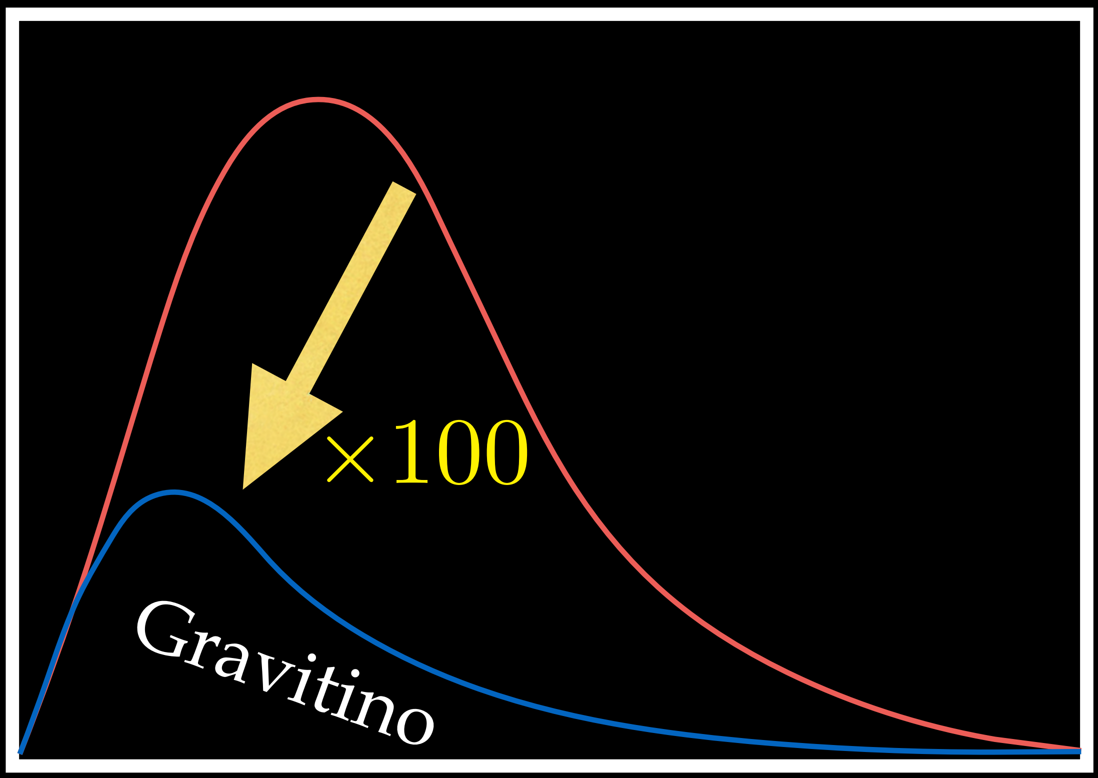
*"It seems that only the pure WDM model with a 2 keV [thermal] particle is able to match the all observations" of the Milky Way Satellites: "the total satellite abundance, their radial distribution and their mass profile" (or TBTF)*

$$\lambda_{\mathrm{FS}} = \int_0^{\mathrm{EQ}} \frac{v(t)dt}{a(t)} \approx 40\,\mathrm{Mpc}\left(\frac{30\,\mathrm{eV}}{m_\nu}\right)\left(\frac{\langle p/T\rangle}{3.15}\right)$$

$$\text{Cowsik-McClelland/Gershtein-Zeldovich bound: } \Omega = \frac{M}{94.1h^2\,\mathrm{eV}} < 1$$

# Sterile WDM vs. Thermal WDM



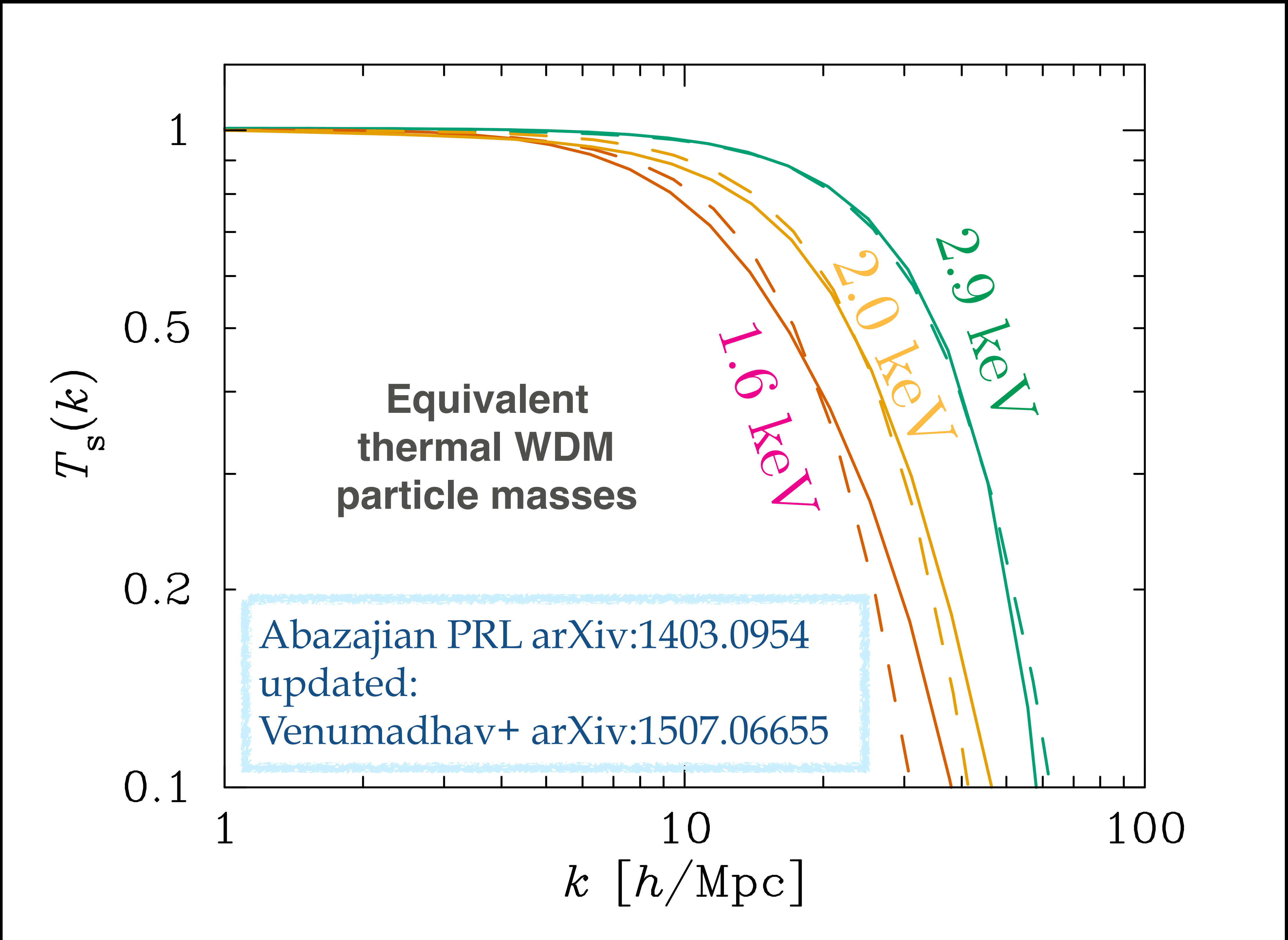

$$m_s\big|_{\text{Dodelson-Widrow,ideal}} \approx 4.46\,\text{keV}\left(\frac{m_{\text{thermal}}}{1\,\text{keV}}\right)^{4/3}$$

$$m_s\big|_{\text{Shi-Fuller}} < m_s\big|_{\text{Dodelson-Widrow}}$$

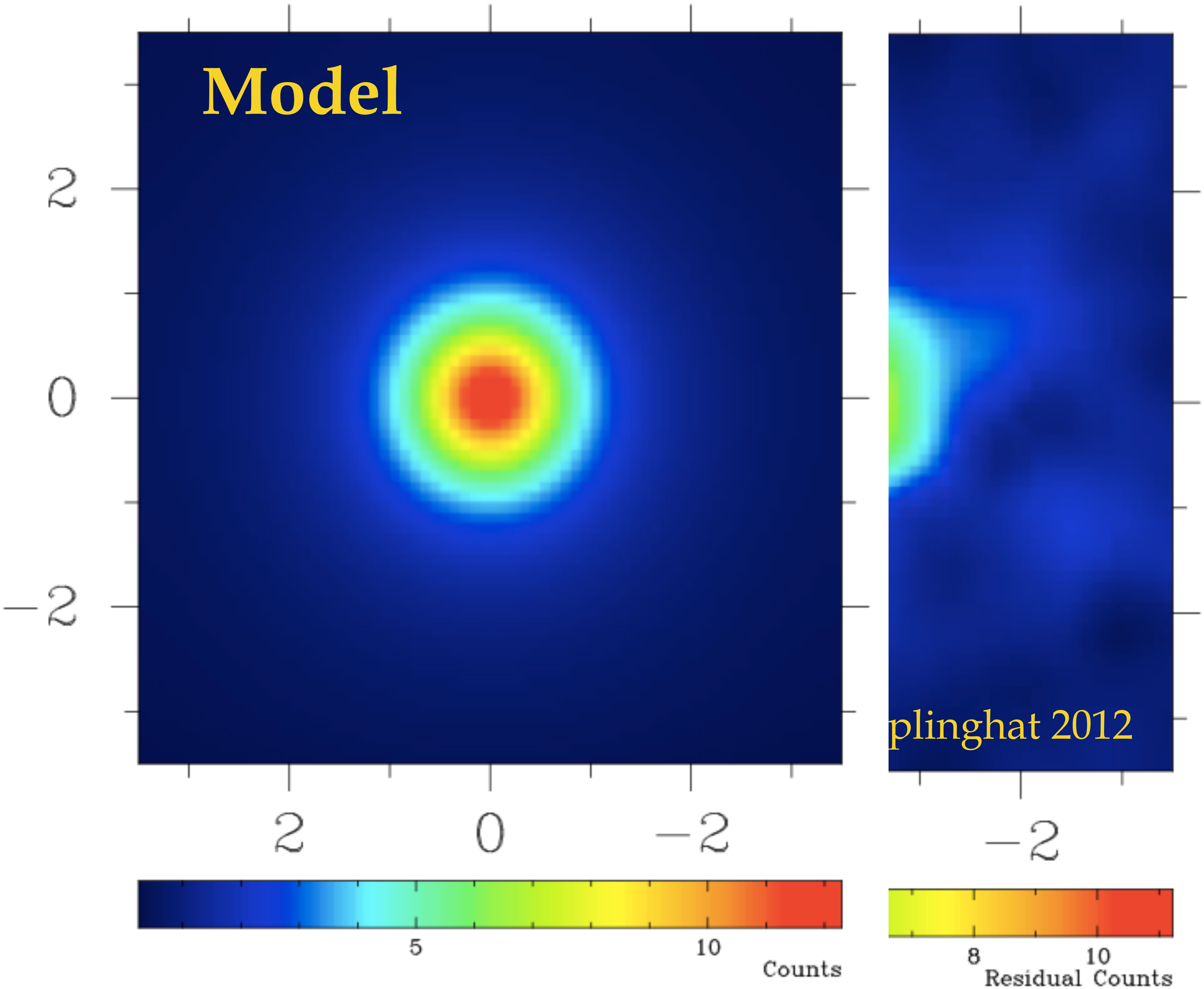
$$m_{\text{thermal}} = 2\,\text{keV} \Rightarrow m_s\big|_{\text{DW,ideal}} \approx 11\,\text{keV} \Rightarrow m_s\big|_{\text{Shi-Fuller}} \approx 7\,\text{keV}$$

Colombi, Dodelson & Widrow astro-ph/9505029;
Abazajian astro-ph/0511630, astro-ph/0512631, arXiv:1705.01837

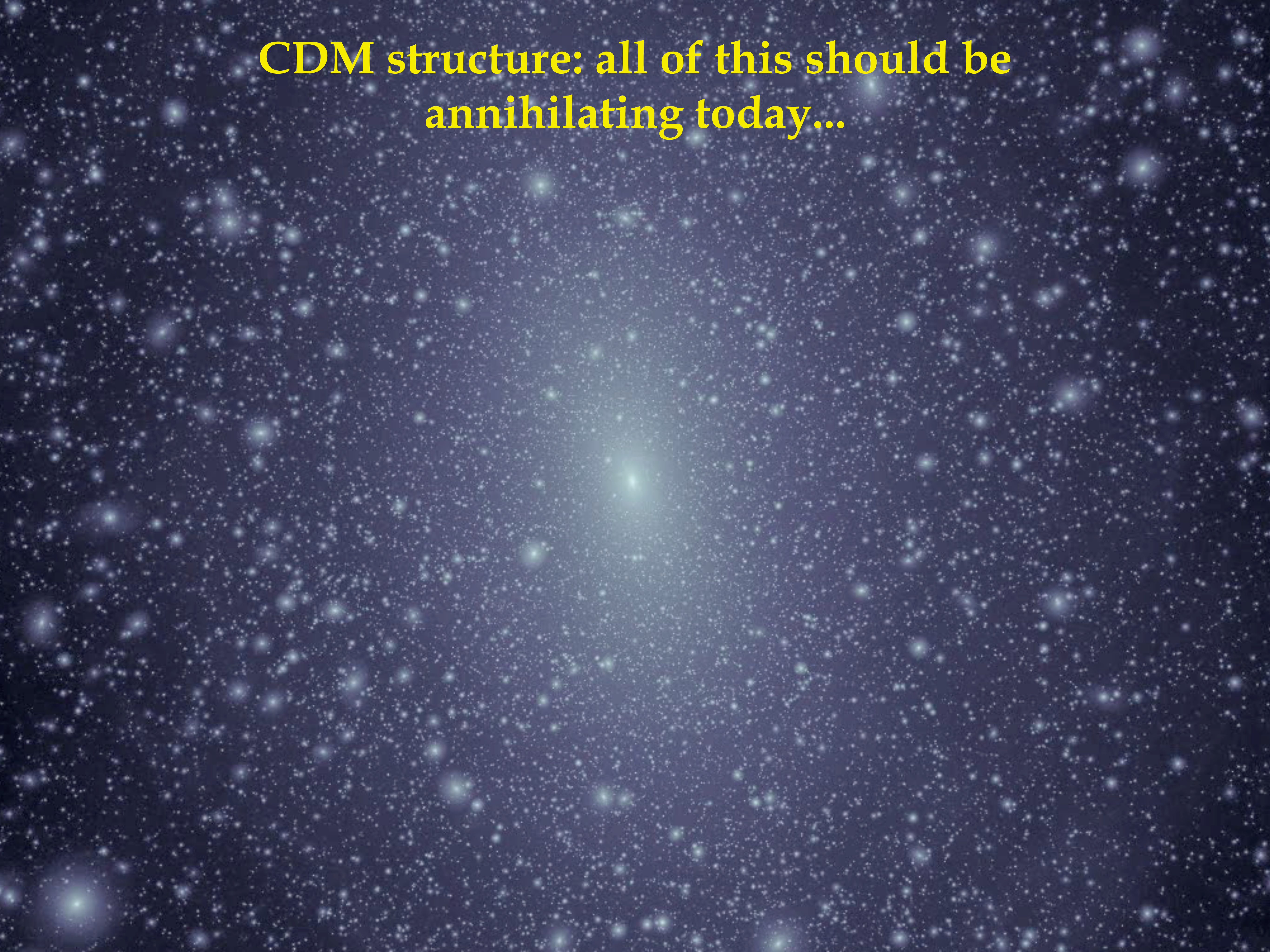
*7 keV Resonant Sterile Neutrino:*
*Free streaming cutoff is very different, even for the same particle mass*



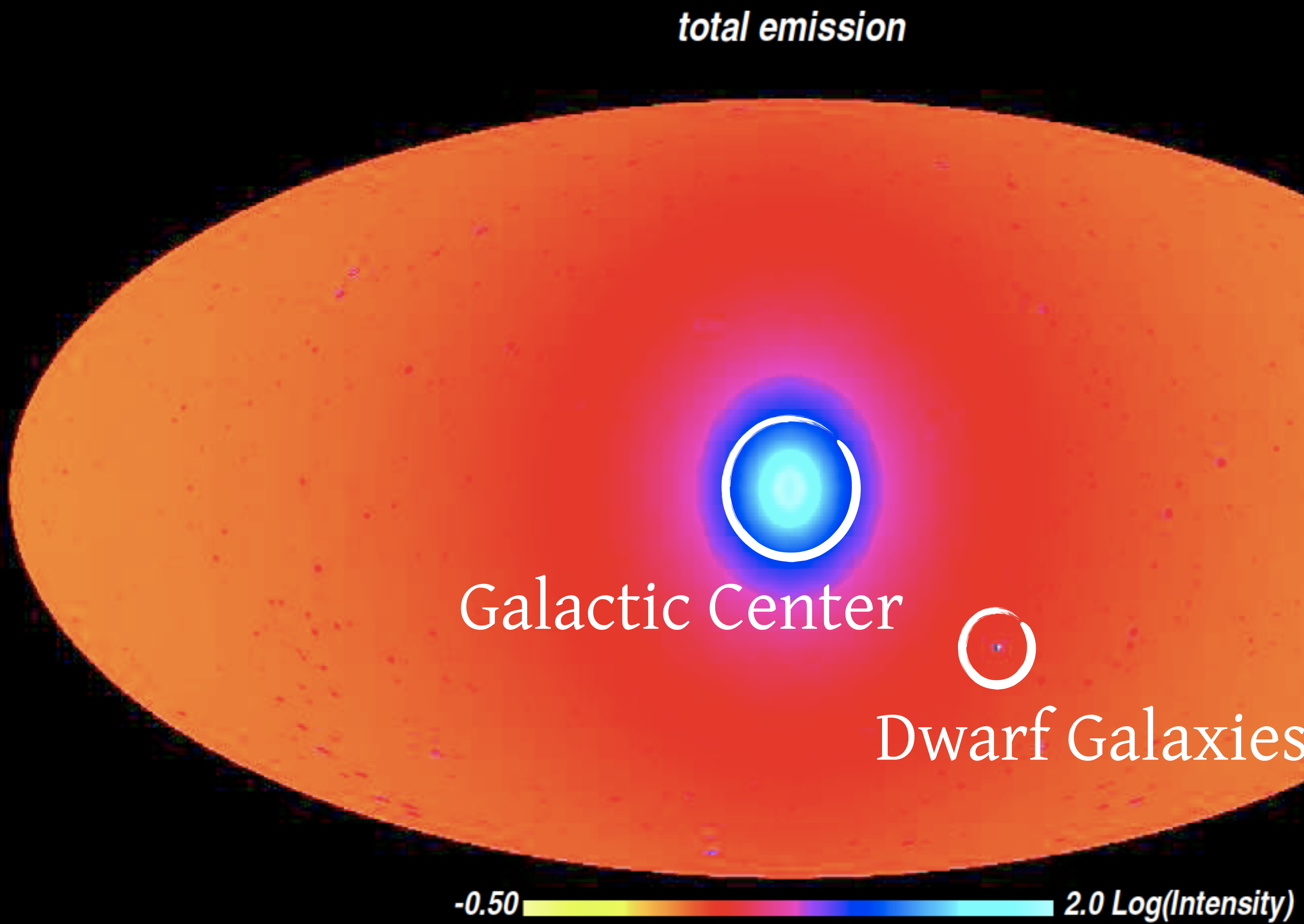
# WIMP Annihilation gamma rays in the Galactic Center?



# CDM structure: all of this should be annihilating today...

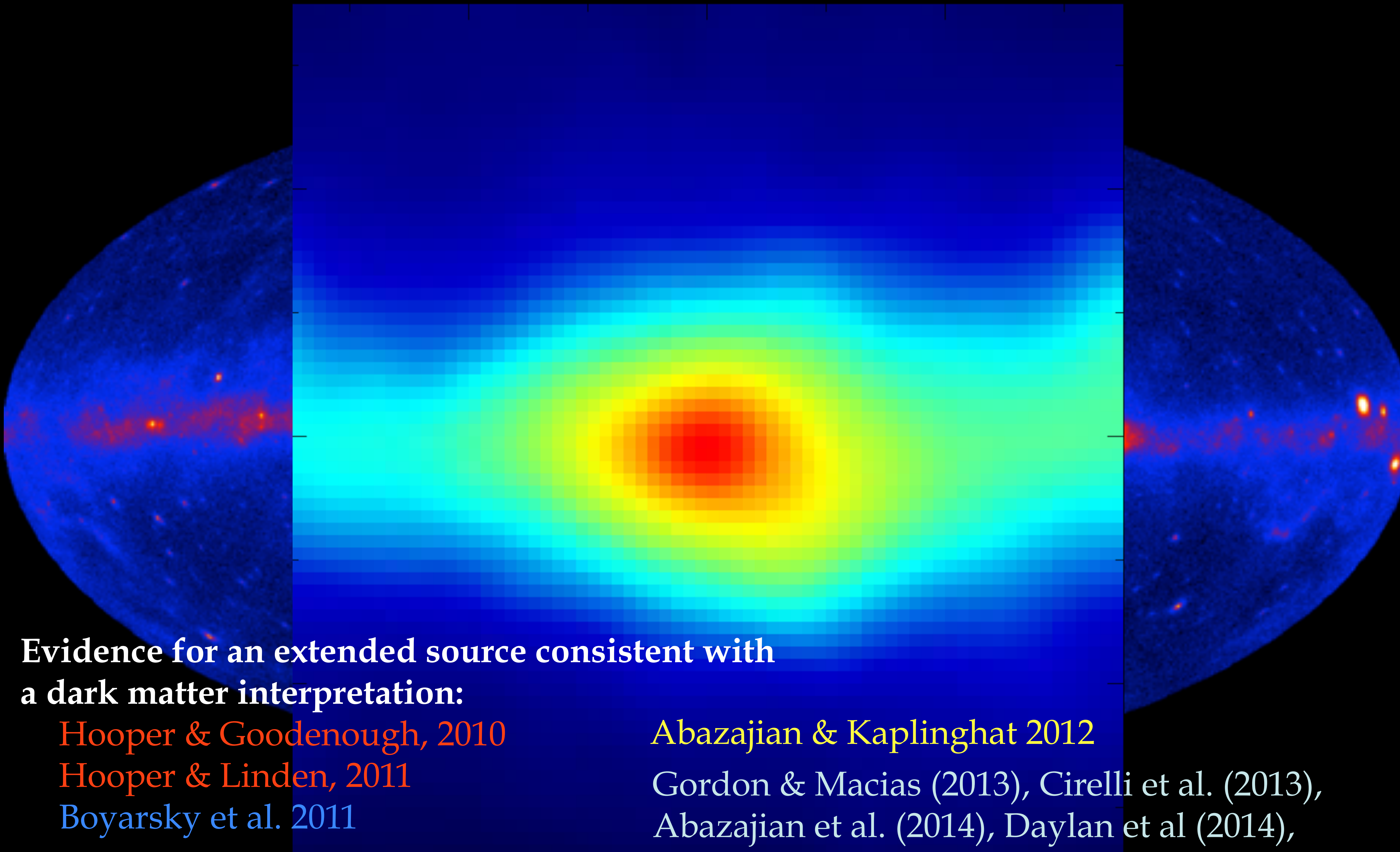


# The Signal Projected in Galactic Coordinates




Springel et al 2008

# Let's just go ahead and look...



**Evidence for an extended source consistent with a dark matter interpretation:**

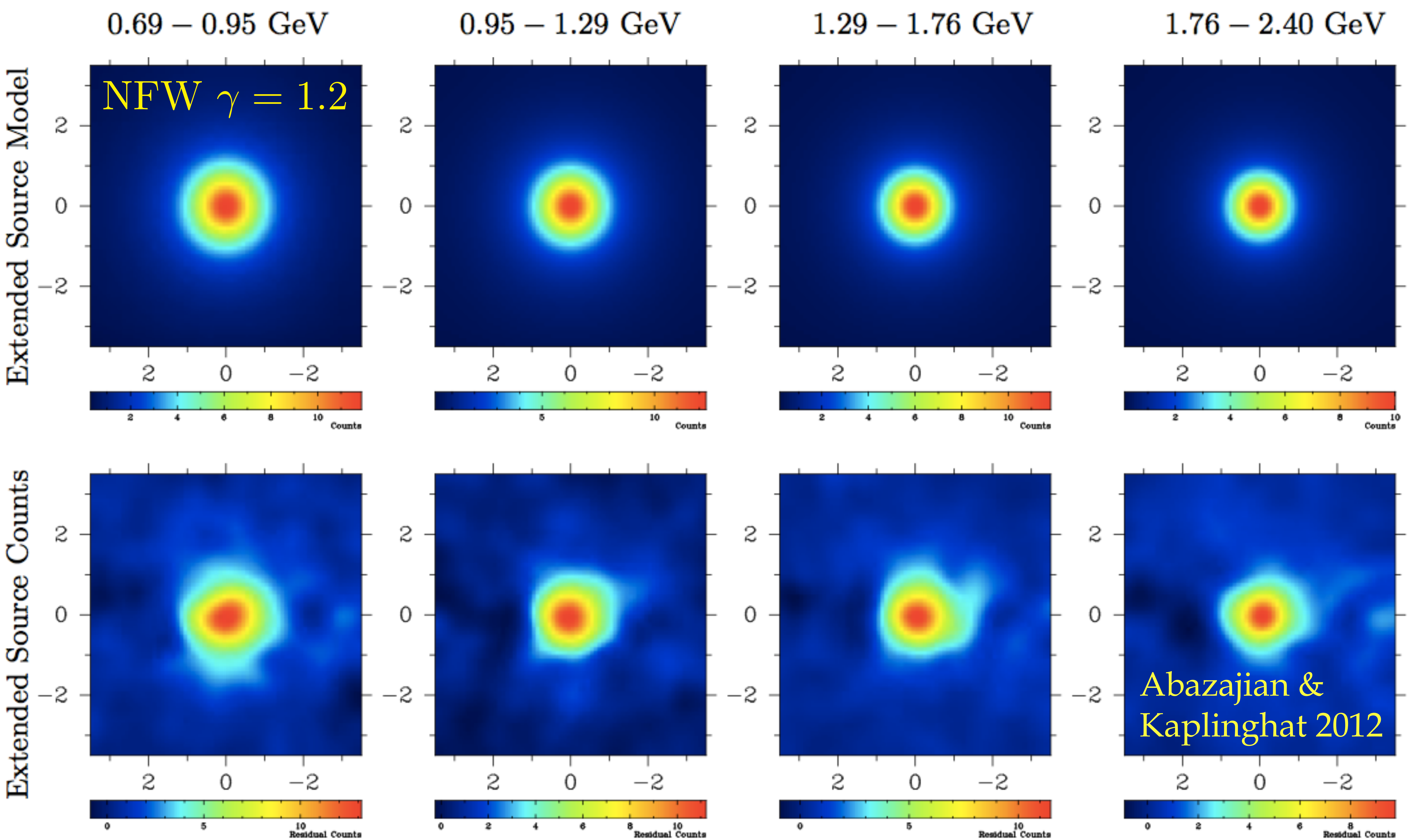
- Hooper & Goodenough, 2010
- Hooper & Linden, 2011
- Boyarsky et al. 2011

Abazajian & Kaplinghat 2012

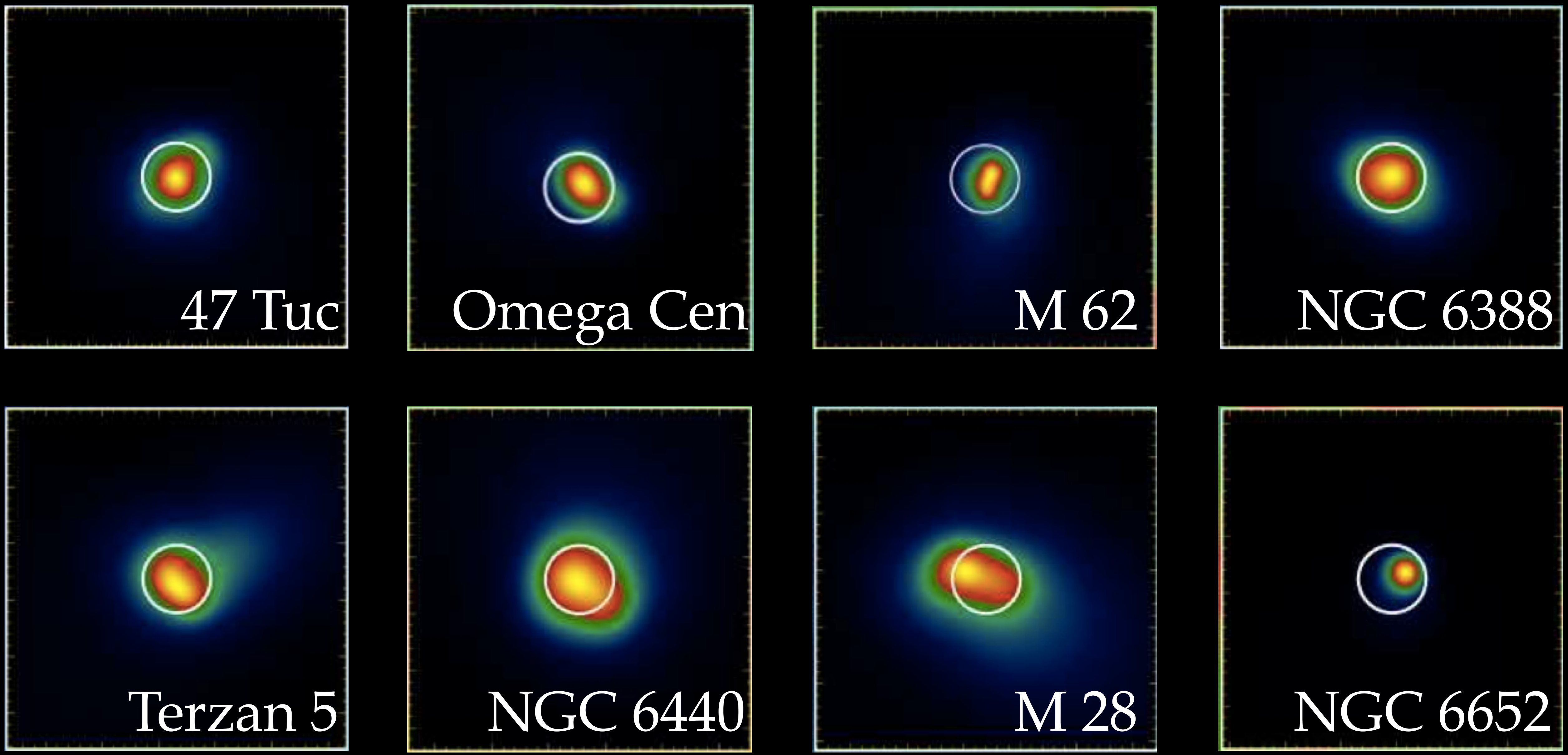
Gordon & Macias (2013), Cirelli et al. (2013), Abazajian et al. (2014), Daylan et al (2014), Calore et al. (2014), Abazajian et al (2015), Ackermann et al (2015)

# WIMP Dark Matter in the Galactic Center?!

$m_\chi = 30$ GeV  $\mathrm{TS_{true}} = 2\Delta \ln \mathcal{L} = 824,\ 28.7\sigma,\ p = 4\times 10^{-181}$

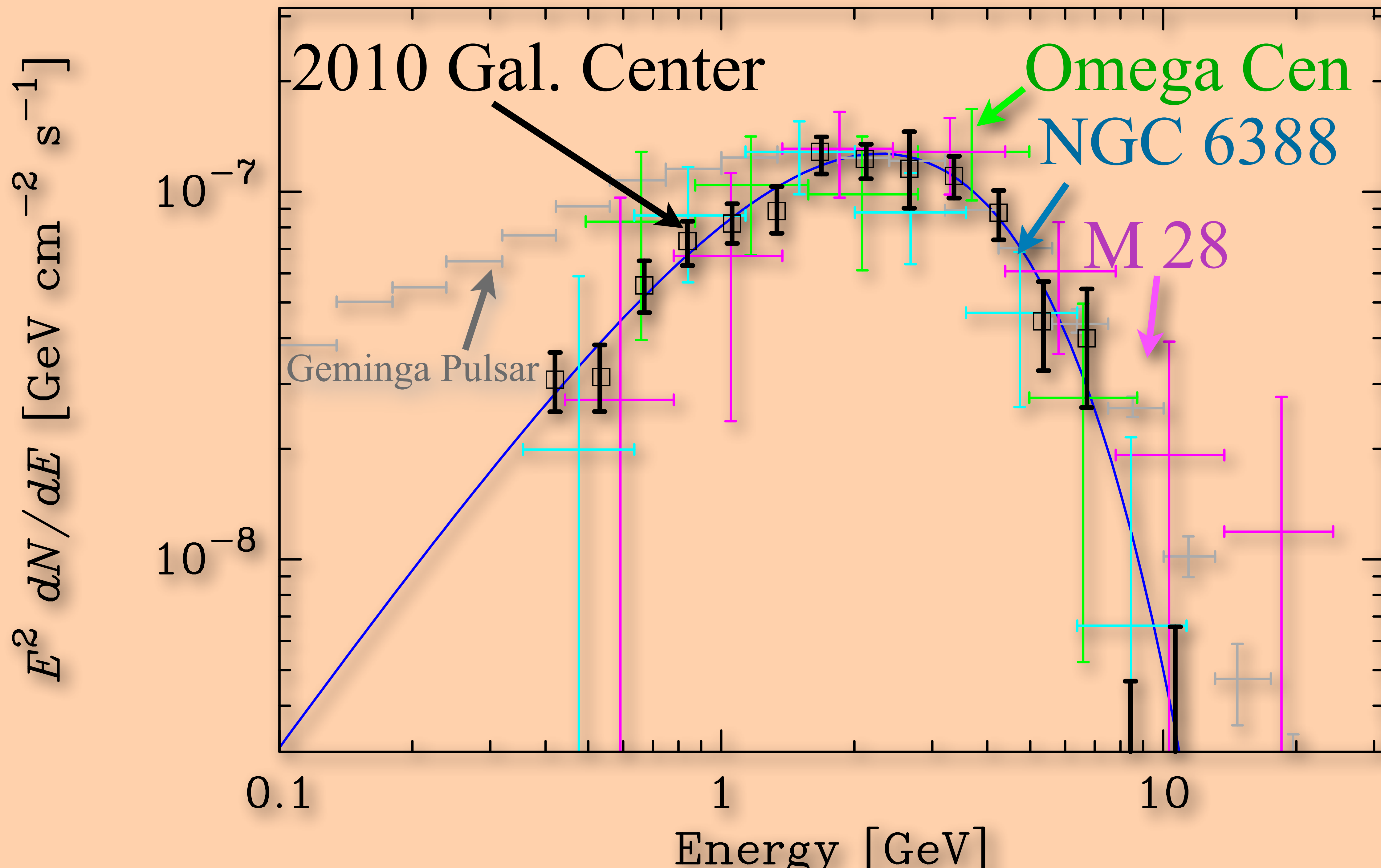


# GCE is Consistent with MSPs (Abazajian 1011.4275)




- Requires the flux from the GC MSPs to be 200 times that in Omega Cen - reasonable stellar mass is 800 times
- Spectrum is consistent $\Gamma$=0.45 ± 0.21 and $E_c$ = 1.65 ± 0.2 GeV
- Requires a centrally concentrated density profile $n \sim r^{-2.6}$, which is seen for the central density distribution of LMXBs in M31
- Point source consistent with non-Poisson statistics (Lee+ 2015; Bartels+ 2015)

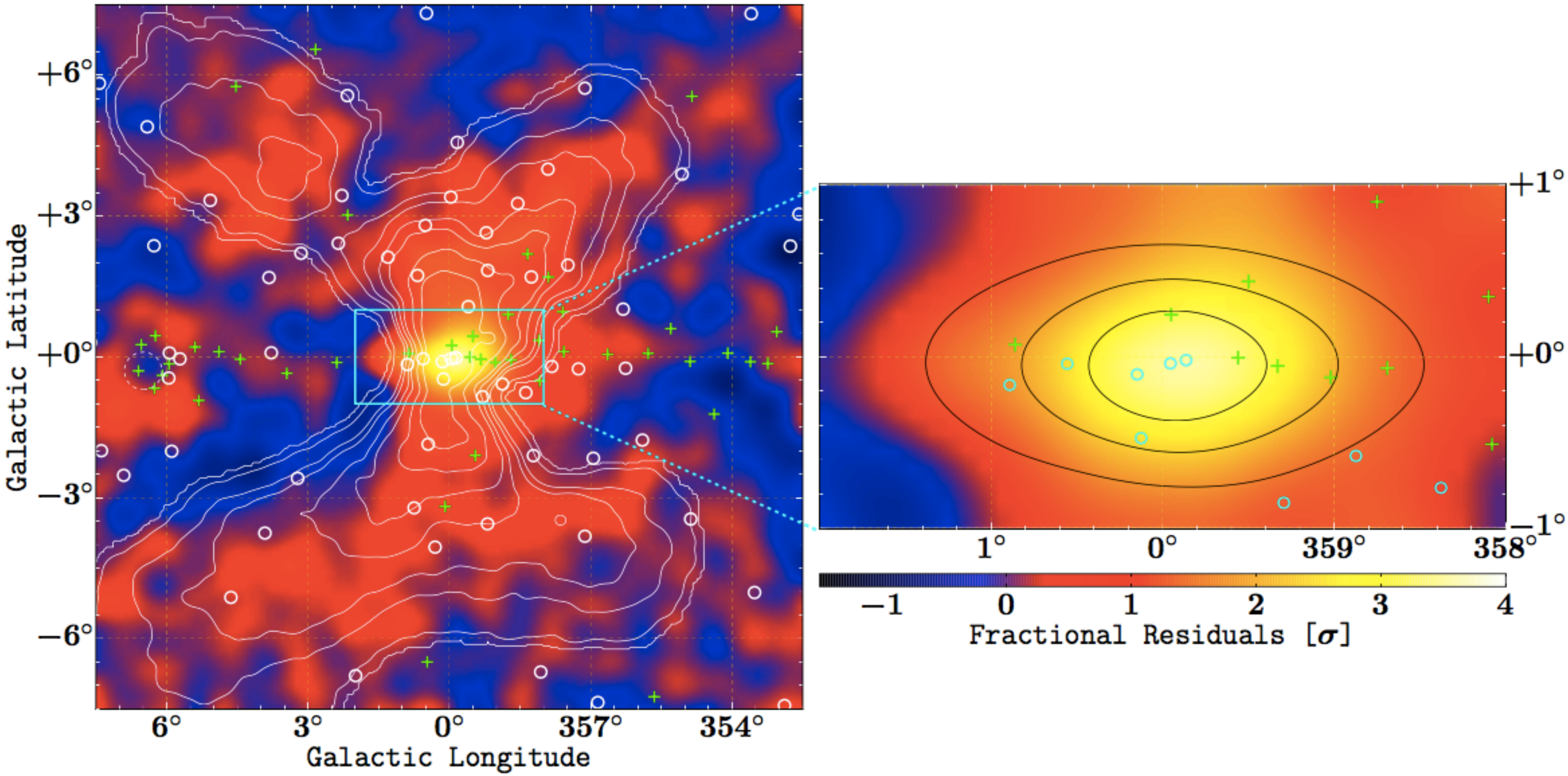
# GCE as MSPs: Spectral Comparison




2010 GCE: Hooper & Goodenough

GCE-MSP Spectral Equivalence: Abazajian ***2010***

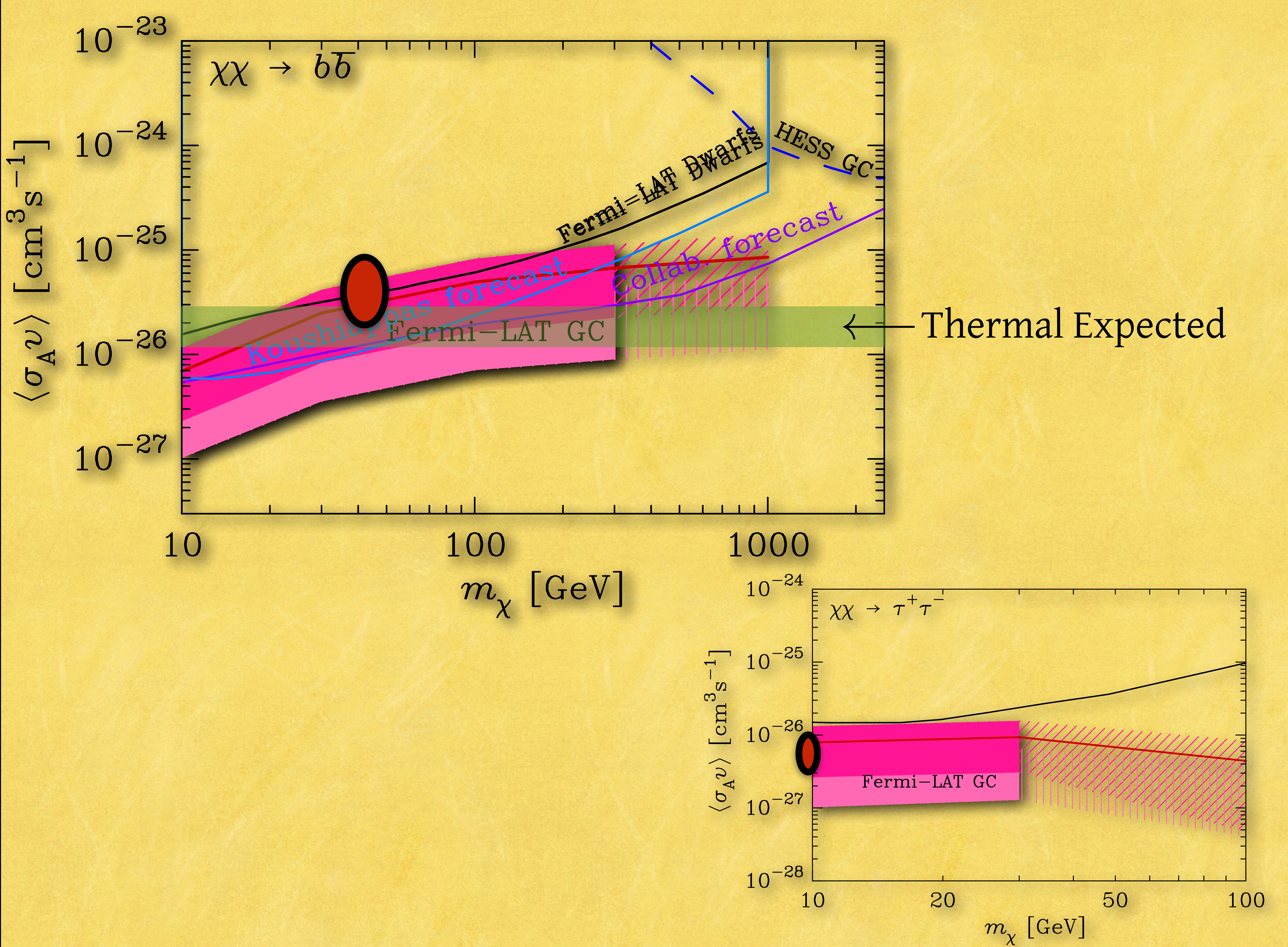
# End of GCE and start of Stellar Bulge Gamma-rays?



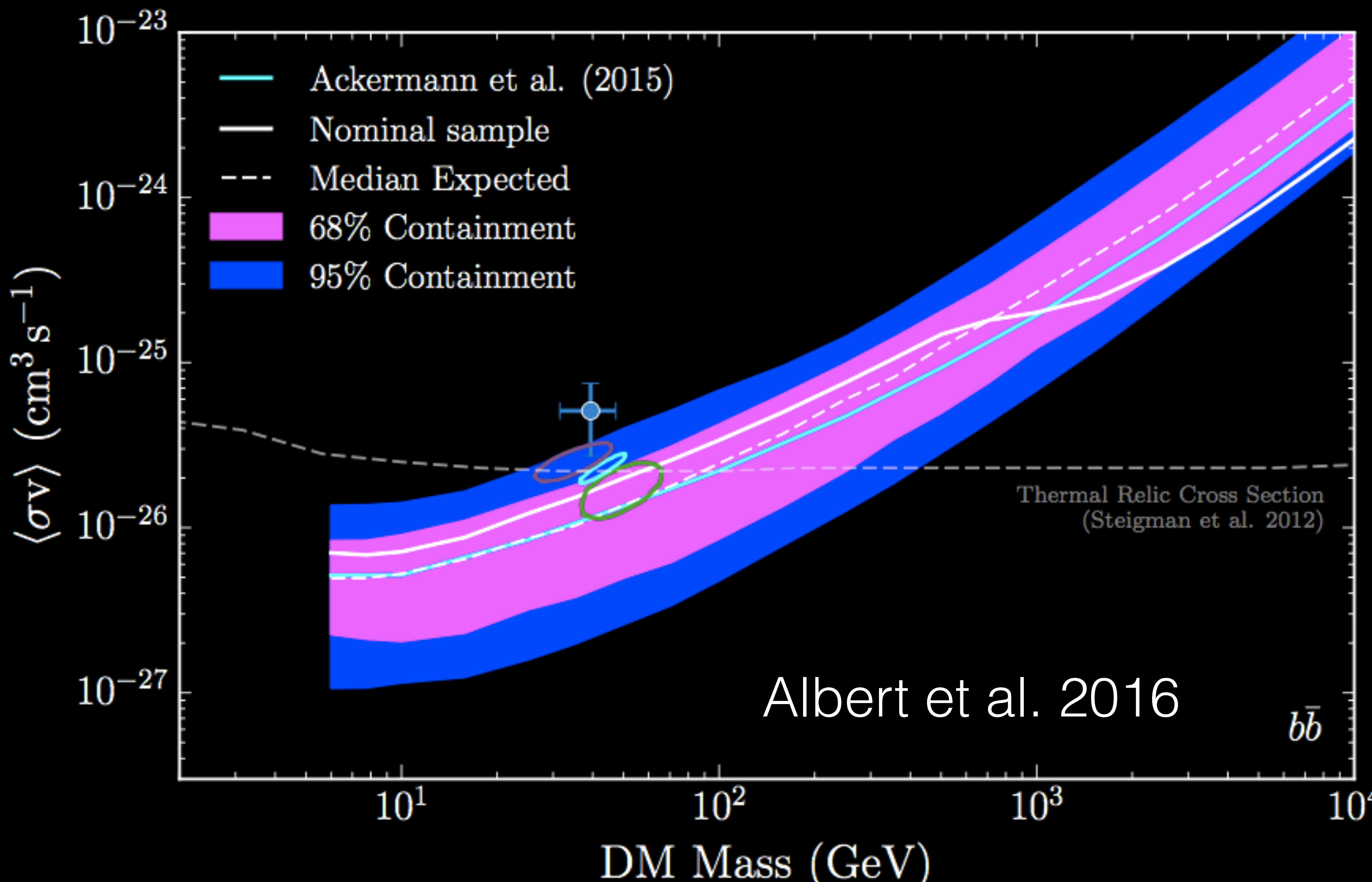

GCE match with WISE IR X-map: Macias+ arXiv:1611.06644

Luminosity function consistency: Ploeg+ arXiv:1705.00806

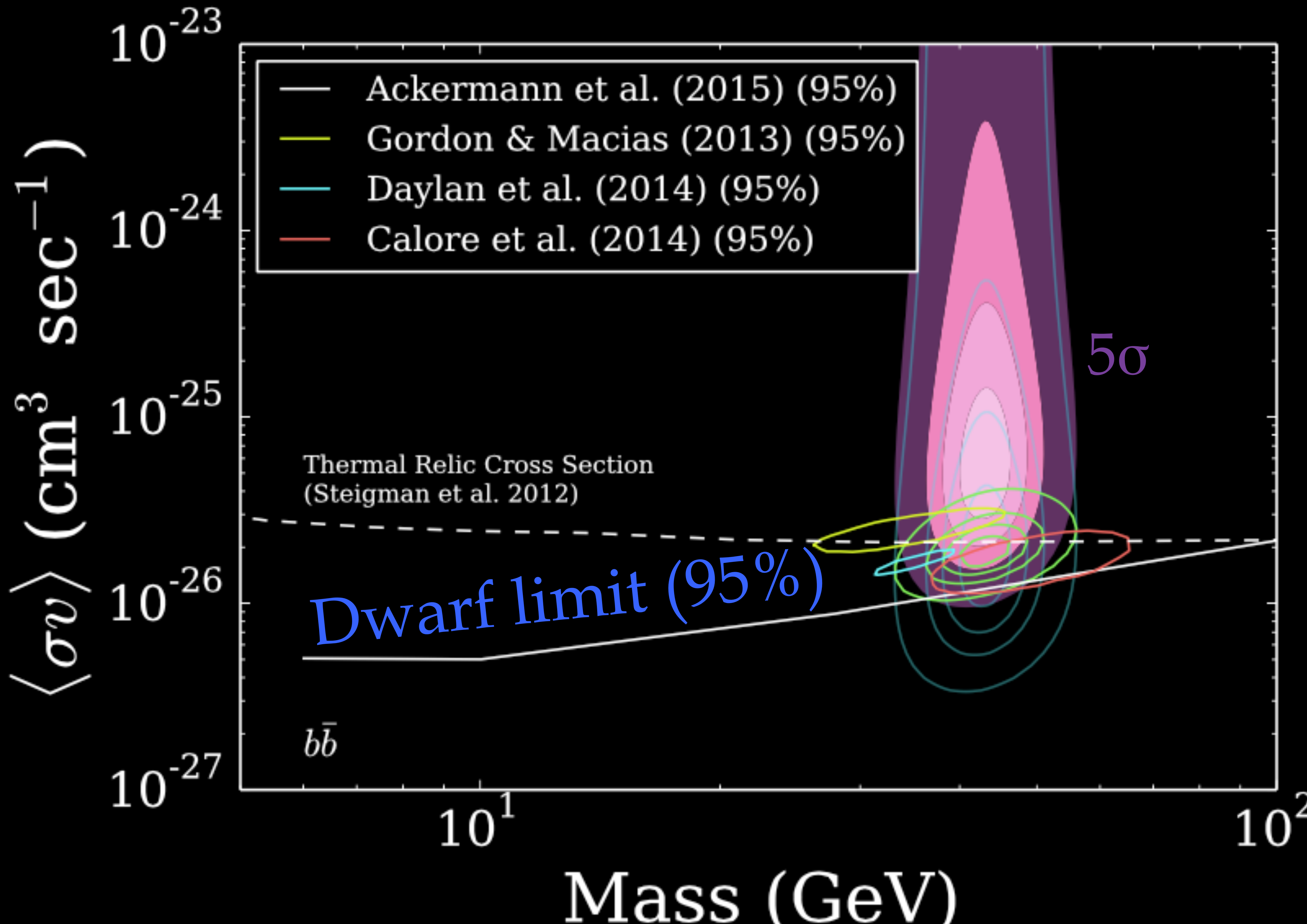
# Signal Parameters: forecasts for dwarf galaxy sensitivities ***in 2013***



# Dwarf Galaxies Searches Remain *Mostly* Dark

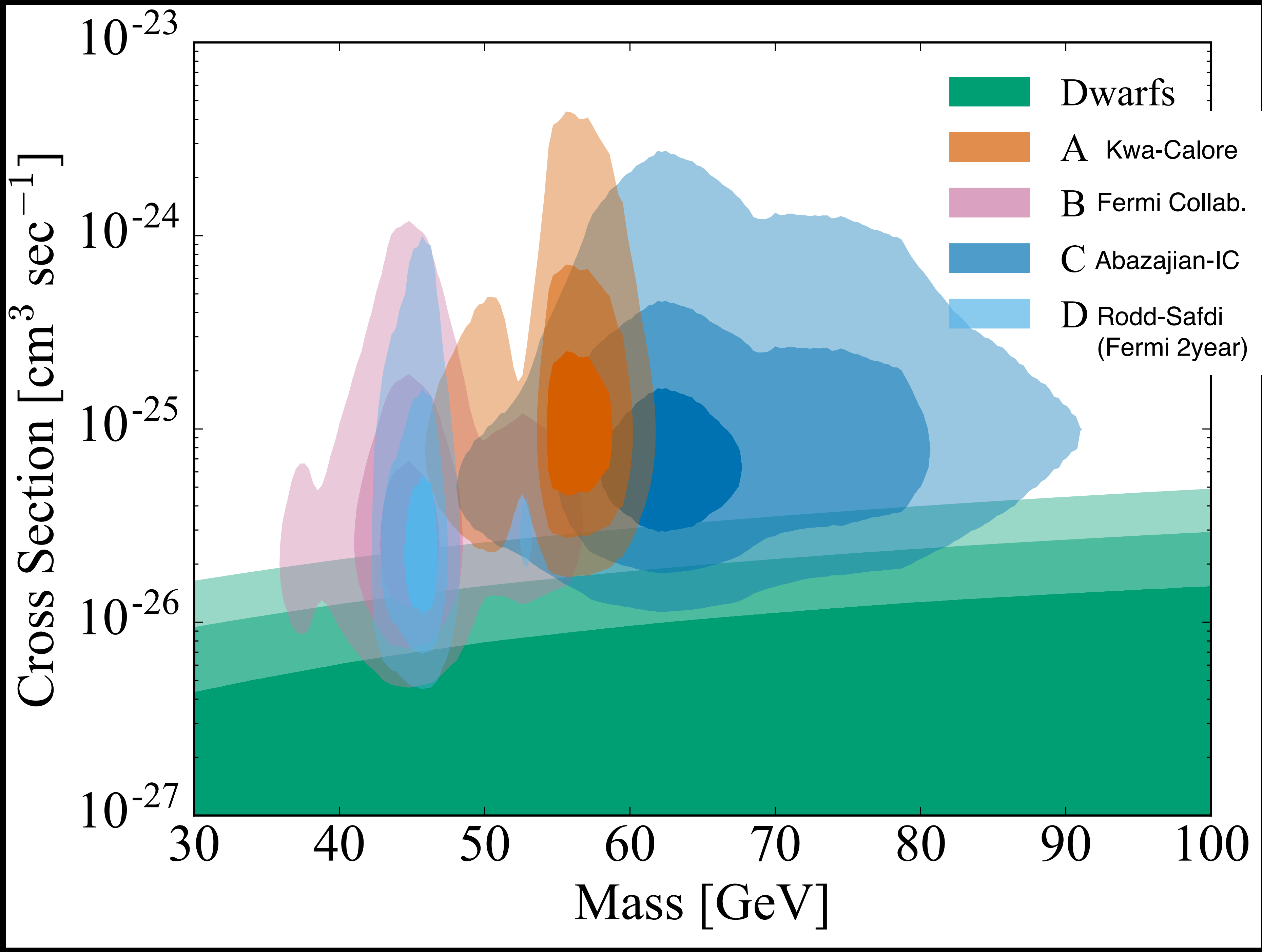


# Bright GCE, Dim Dwarfs: *Strong Tension!*




Abazajian & **Ryan Keeley** arXiv:1510.06424

# Where is the dark matter signa?
# Dwarf/GCE Tension & Tool-building




Keeley, Abazajian, Kwa, Rodd, Safdi (in preparation)

# Summary

- Sterile Neutrino Dark Matter has been investigated for 24+ years; indirect detection via cluster & field galaxy searches proposed by yours truly in 2001.
- An unidentified line has been detected at 4σ to 5σ in two independent samples of stacked X-ray clusters with *XMM-Newton*. It was seen by the same group in the *Perseus* Cluster with *Chandra* data. (Bulbul et al. ApJ 2014). An independent group reported a line at the same energy toward Andromeda (M31) and *Perseus* with *XMM-Newton* (Boyarsky et al. PRL 2014).
- Also seen:
    - in our Milky Way Galactic Center (*XMM-Newton*)
    - with *SUZAKU* X-ray Space Telescope data toward Perseus,
    - in 8 more clusters at > 2σ significance.
    - Seen in *Chandra* deep fields (Galactic Halo)
- **No consistent astrophysical interpretation exists.**

# Summary

- The simplest model for the signal is resonant sterile neutrino production with a cosmological $L$. The signal crosses a transition region from "cold" dark matter to "warm" dark matter, particularly at a small-scale structure cutoff scale of great interest in galaxy formation of the local group of galaxies, ~2 keV thermal WDM.
- Future Follow up observations:
  - 2017-2018: Micro-X, XQC
  - 2021: XARM
  - 2028+: ATHENA
  - 2030+: X-Ray Surveyor
- "Space will not be conquered by missiles… but by the impregnation of all of space with human sensibility."
  — Yves Klein (1962)

# Summary

- The $\gamma$-ray excess in the Galactic Center is a whopping signal (~13$\sigma$) that is *in itself* consistent with dark matter annihilation of ~40 GeV WIMPS to $\boldsymbol{b}$-quarks or ~10 GeV to $\boldsymbol{\tau}$-leptons.
- Since 2010, we have known of an astrophysical interpretation of the $\gamma$-ray excess in the GC: a standard population of millisecond pulsars. Spectrum, flux and morphology are consistent with MSPs, most closely following stellar X-bulge. Luminosity function is also consistent.
- DM interpretation in > 5$\sigma$ tension with dwarf galaxies in most measures of local DM density
  [Abazajian & Keeley 2016, Keeley+ 2017]
- DM models that discriminate between GC and dwarf galaxies can survive constraints, e.g. SIDM models. Abazajian & Keeley 2016, Keeley+ 2017 releasing tools to test your favorite model.