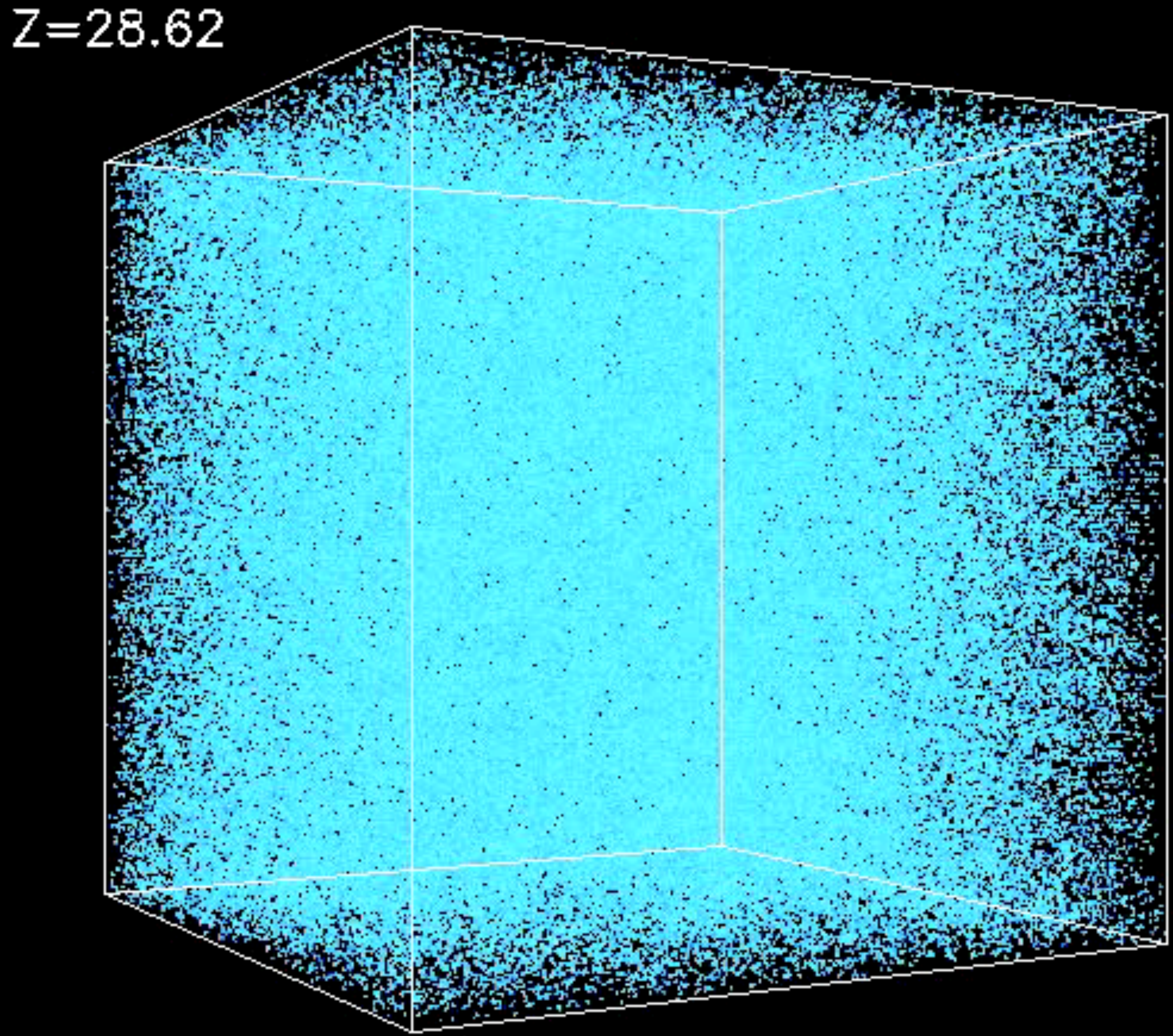
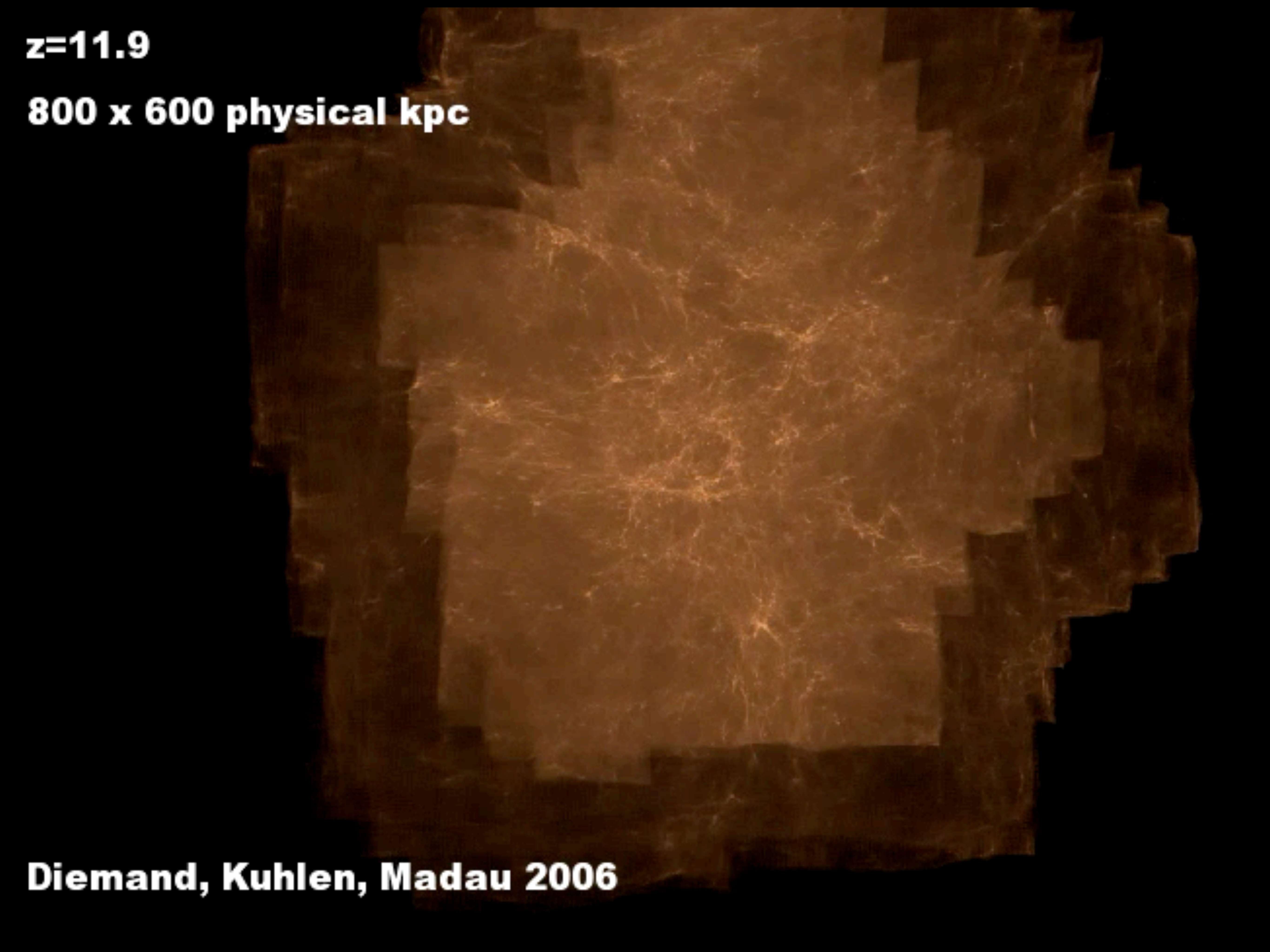
Arising and Demising Dark Matter Signals on the Sky & the Potential of Future Searches

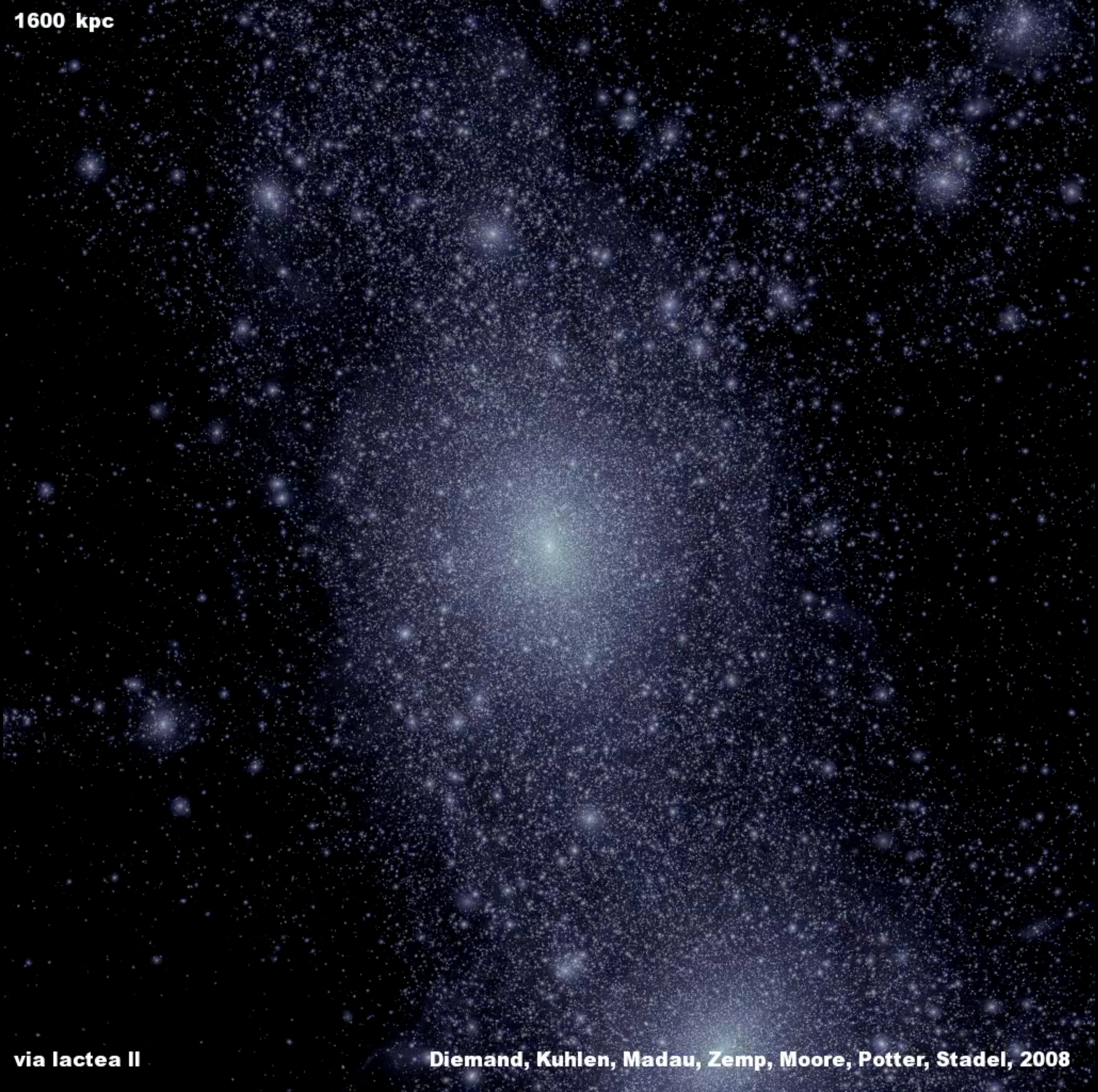
Kev Abazajian

UCI University of California, Irvine



Courtesy: Andrey Kravtsov

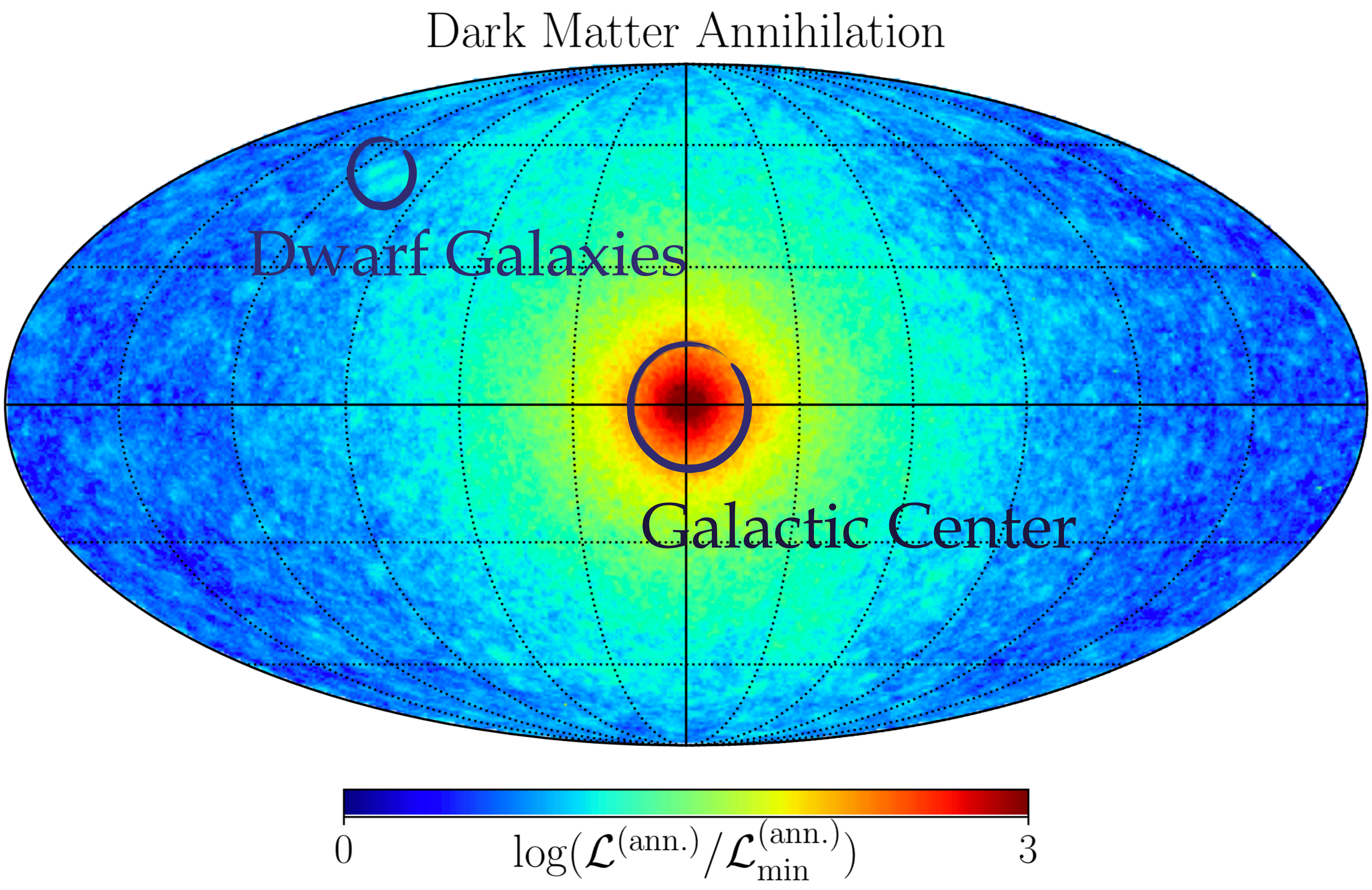

z=11.9
800 x 600 physical kpc
Diemand, Kuhlen, Madau 2006


1600 kpc
via lactea II
Diemand, Kuhlen, Madau, Zemp, Moore, Potter, Stadel, 2008

Small Scale Structure: for WIMPS, all of this should be annihilating today…

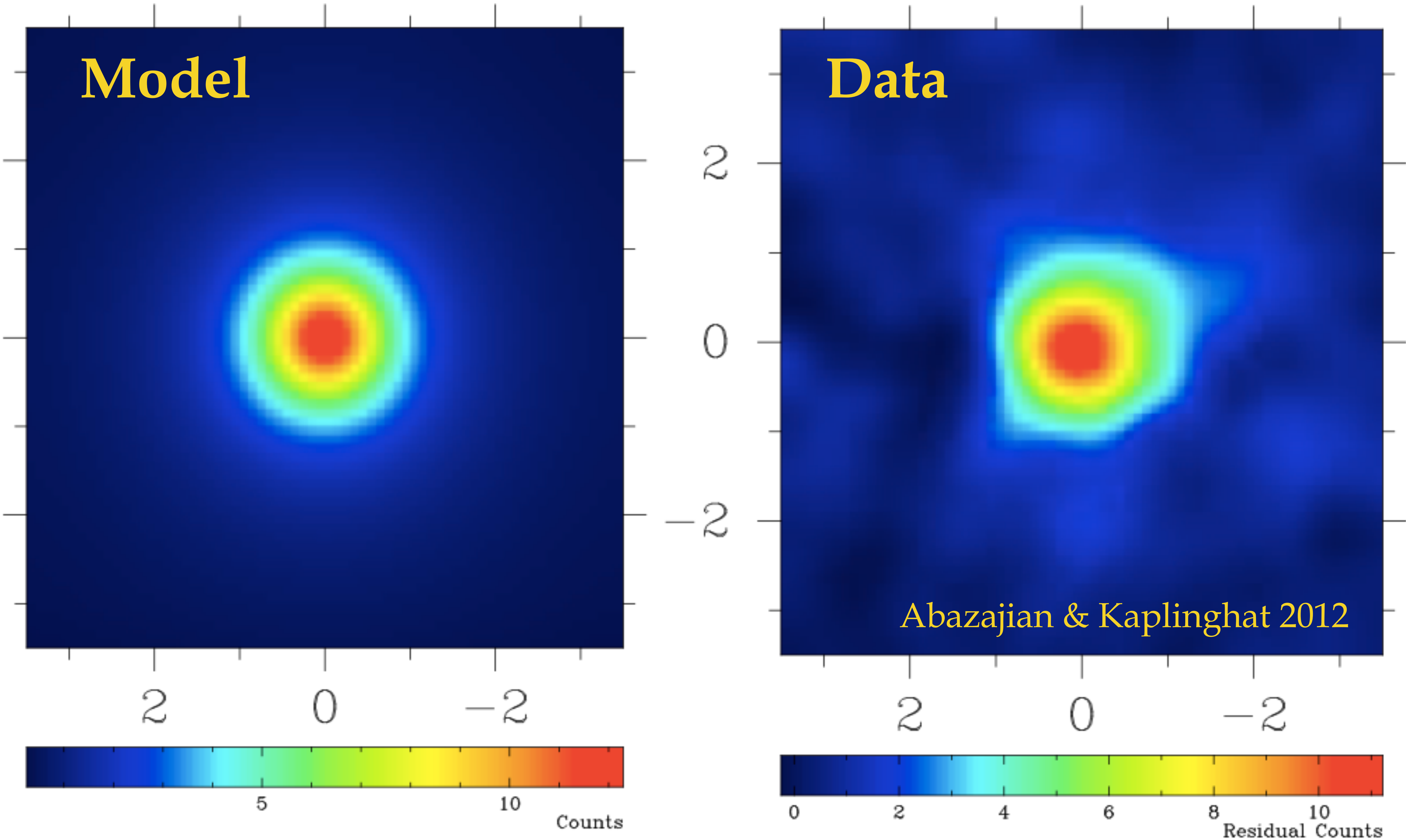
Need a line-of-sight integral through the dark matter…

The Signal Projected in Galactic Coordinates



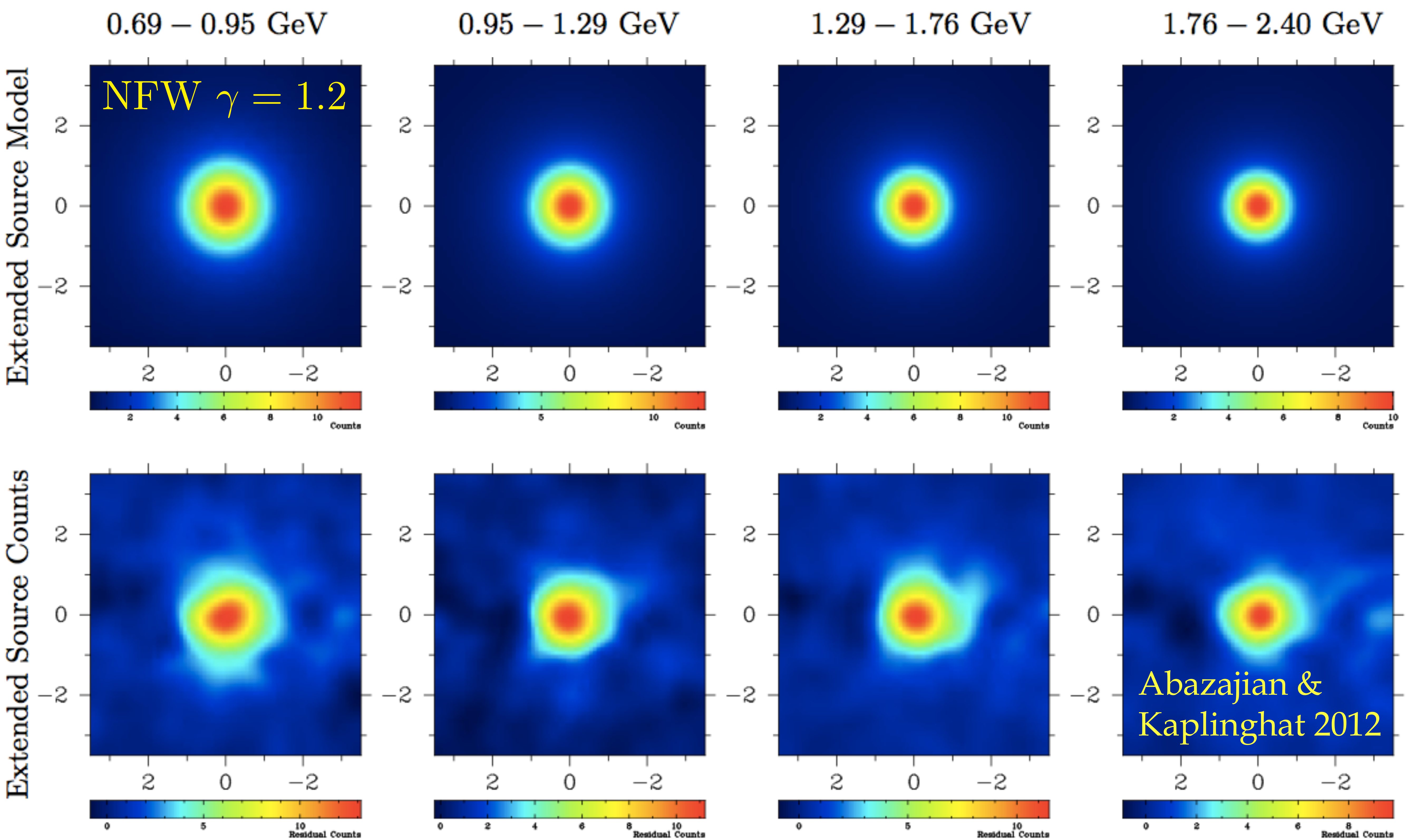
Zhong, Valli & Abazajian arXiv:2003.00148

Looks *so much* like dark matter...

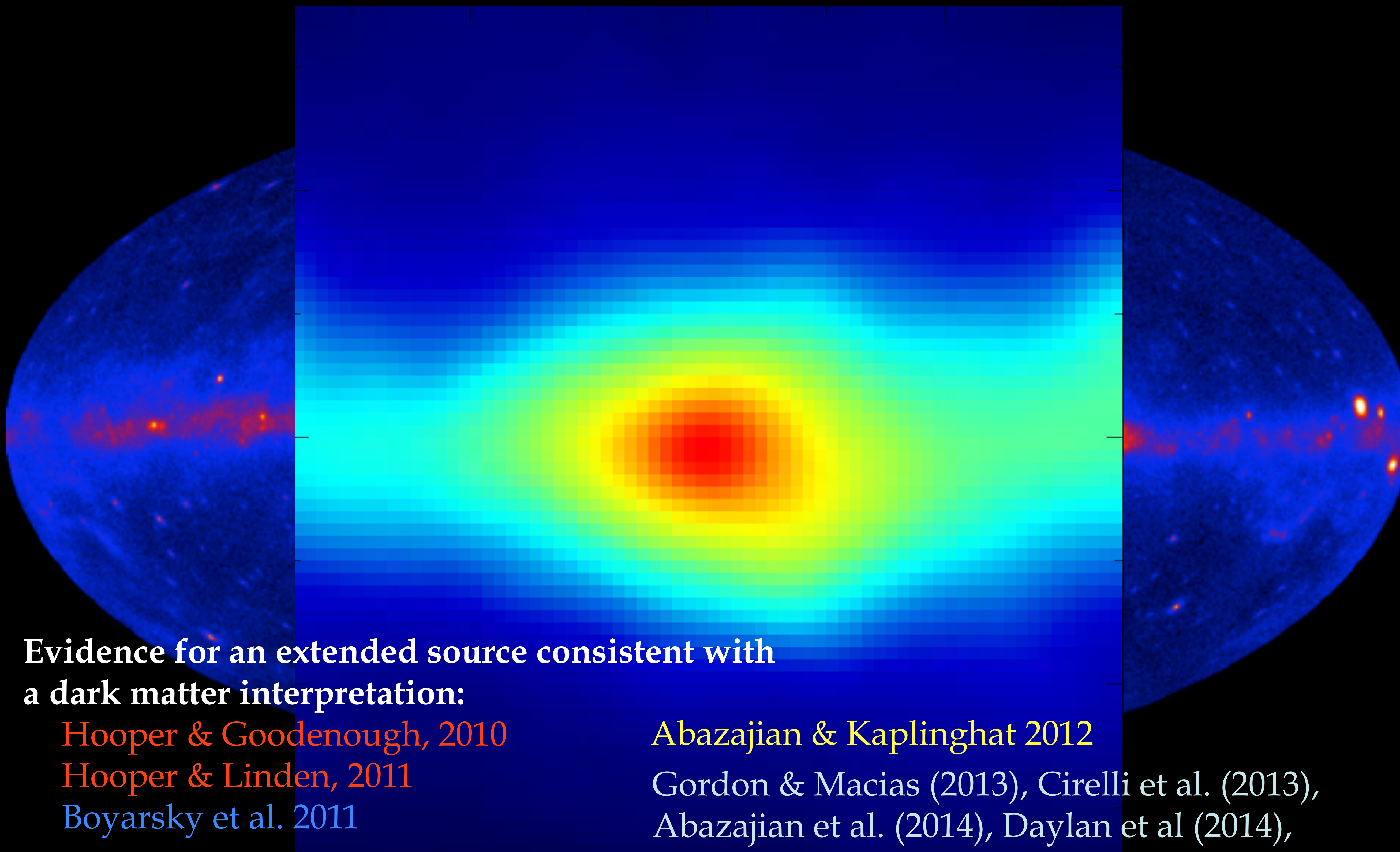


WIMP Dark Matter in the Galactic Center?!

$m_\chi = 30$ GeV $\quad \text{TS}_{\text{true}} = 2\Delta \ln \mathcal{L} = 824, \; 28.7\sigma, \; p = 4 \times 10^{-181}$



Let’s just go ahead and look…



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

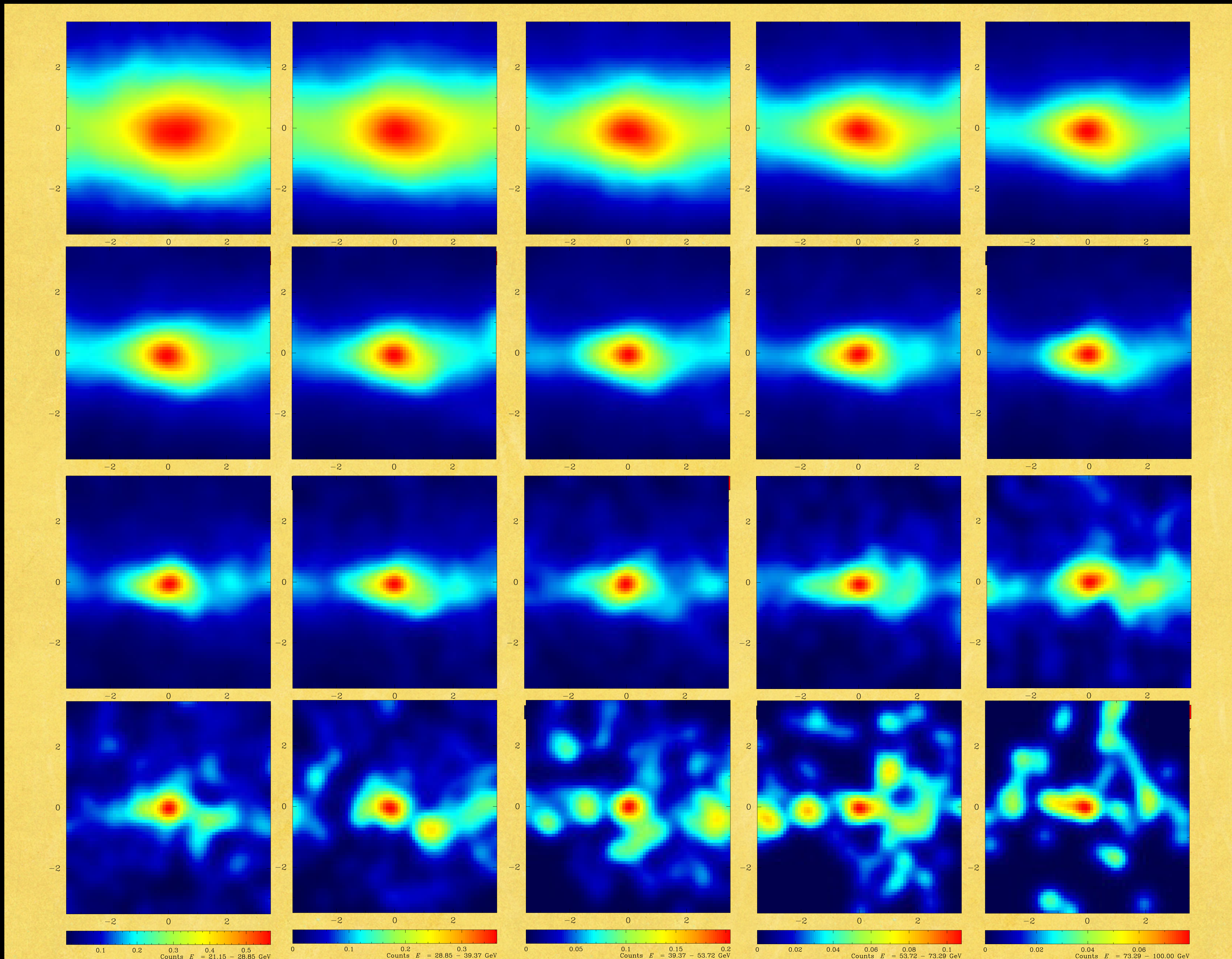
Hooper & Goodenough, 2010
Hooper & Linden, 2011
Boyarsky et al. 2011

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)

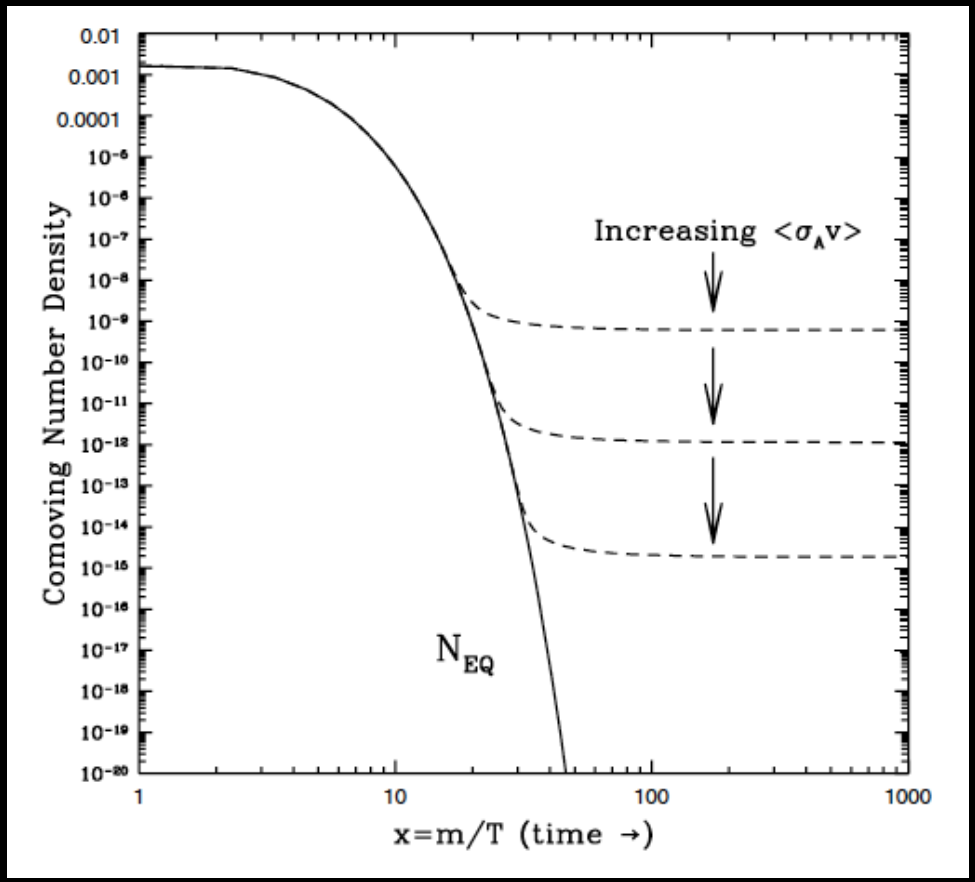
Sources in the Galactic Center: Spatial-Spectral Degeneracy

Abazajian & Kaplinghat, Phys. Rev. D, 2012



Canonical Weakly-Interacting Massive-Particle (WIMP) **Cold** Dark Matter

- Production proceeds from thermal equilibrium to freeze-out of pair-production/annihilation processes



$$\frac{dn_X}{dt} + 3Hn_X = -\langle \sigma_{XX} |v| \rangle \left(n_X^2 - n_{X,eq}^2 \right)$$

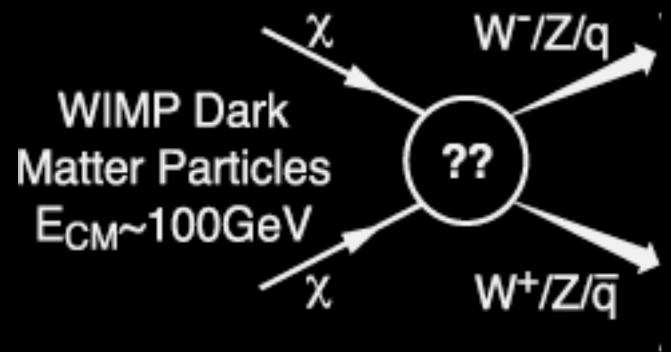
- The pair-production process is directly related to the annihilation rate in the present universe

$$XX \leftrightarrow \bar{Y}Y$$

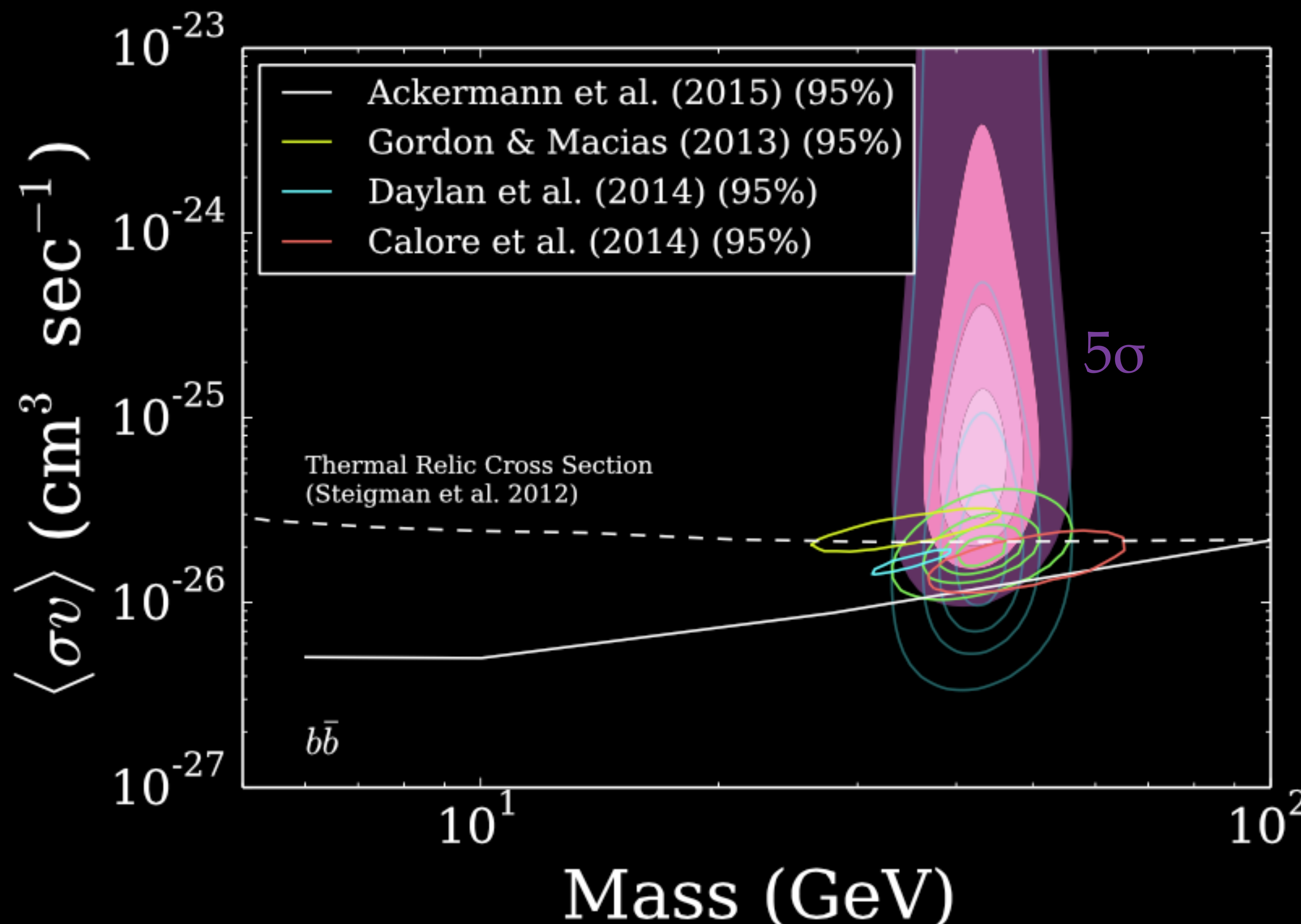
Predicted rate:

$$\langle \sigma_{XX} v \rangle \approx 3 \times 10^{-26}\ \mathrm{cm^3 s^{-1}}$$

- The predicted annihilation rate's associated primary and secondary photons are comparable to the detectable limit in gamma-ray observations



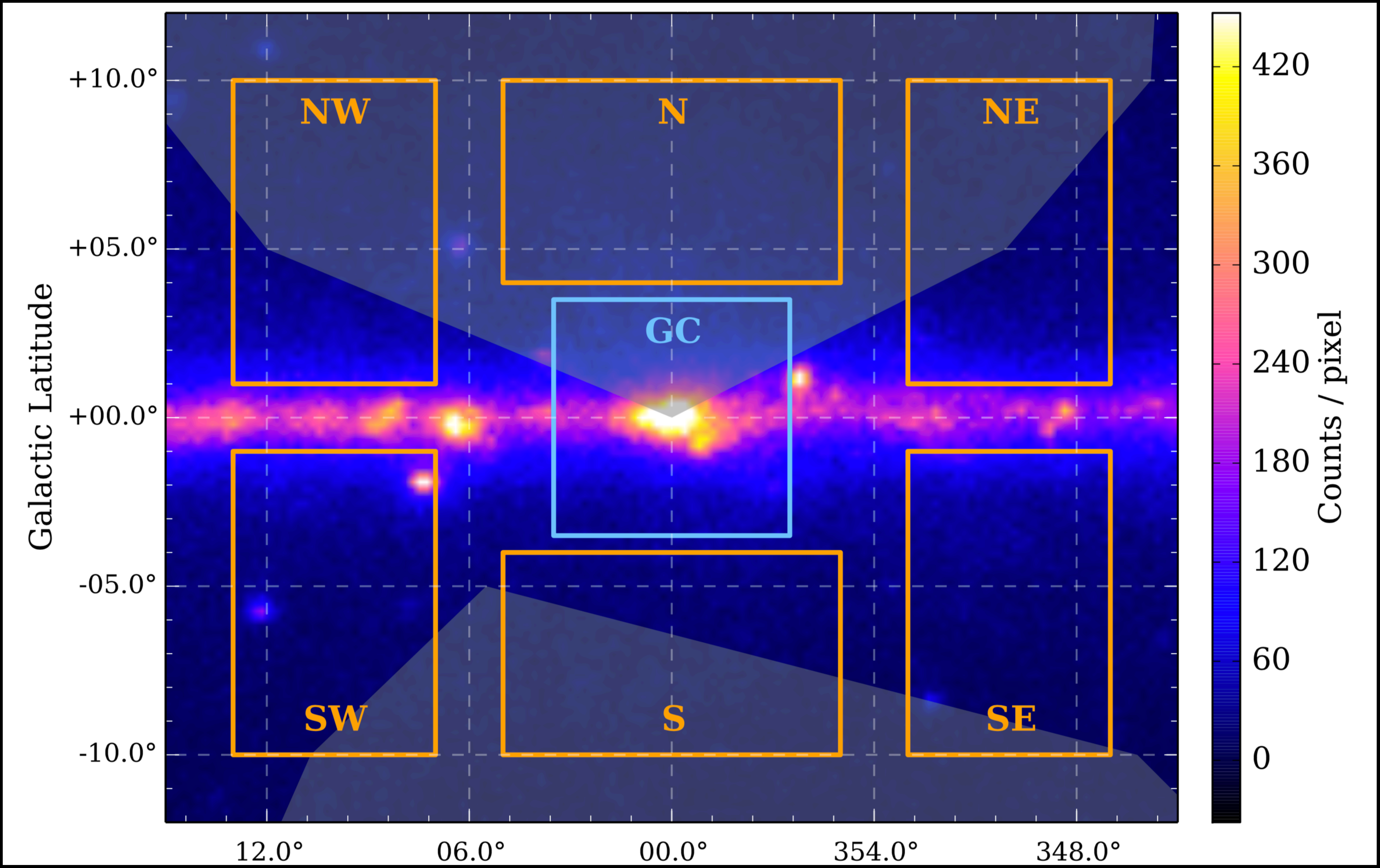
Thermal WIMP Dark Matter!



Abazajian & **Ryan Keeley** arXiv:1510.06424

Uniformity on Sky?

Kwa, Horiuchi & Kaplinghat (2016)



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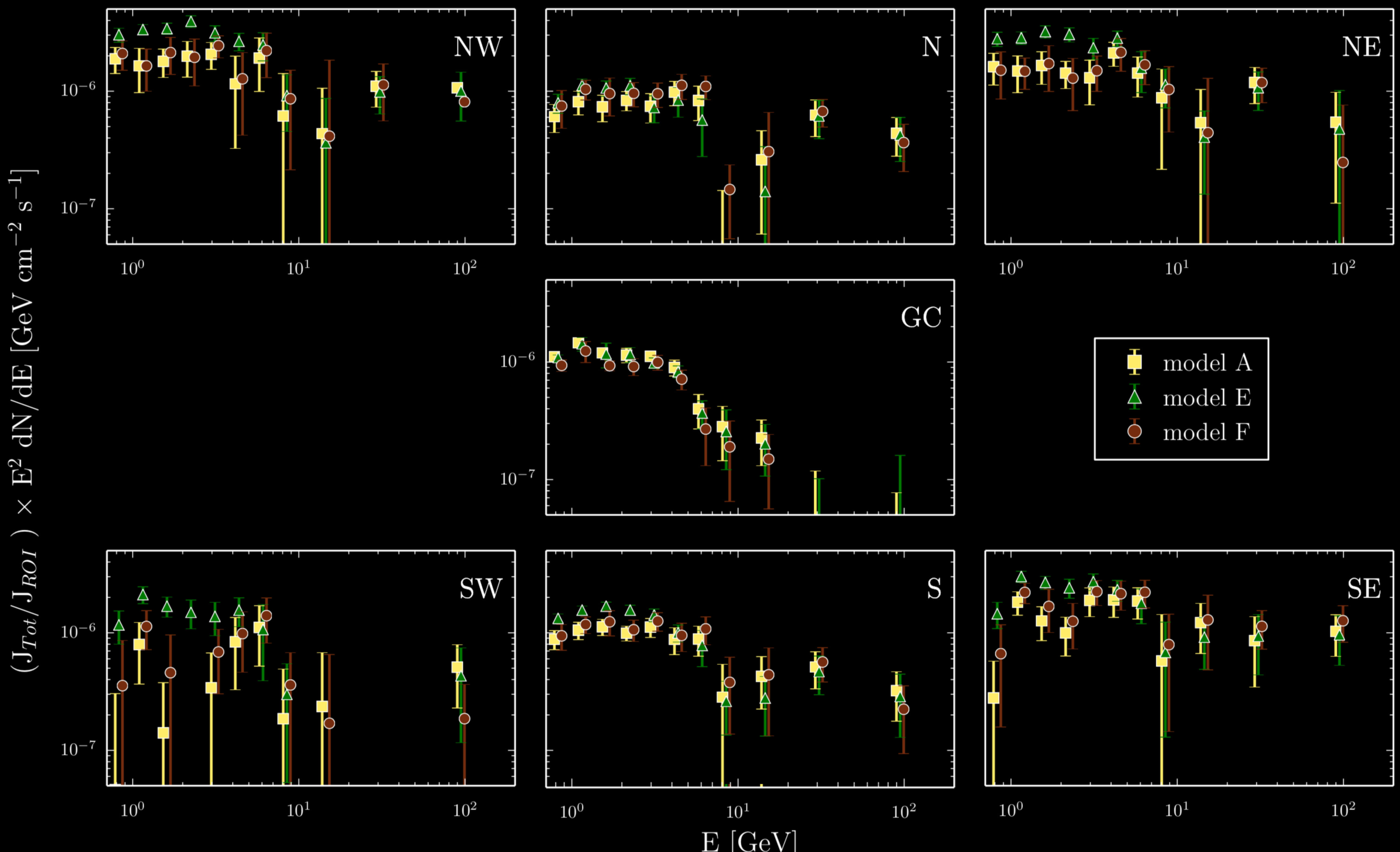
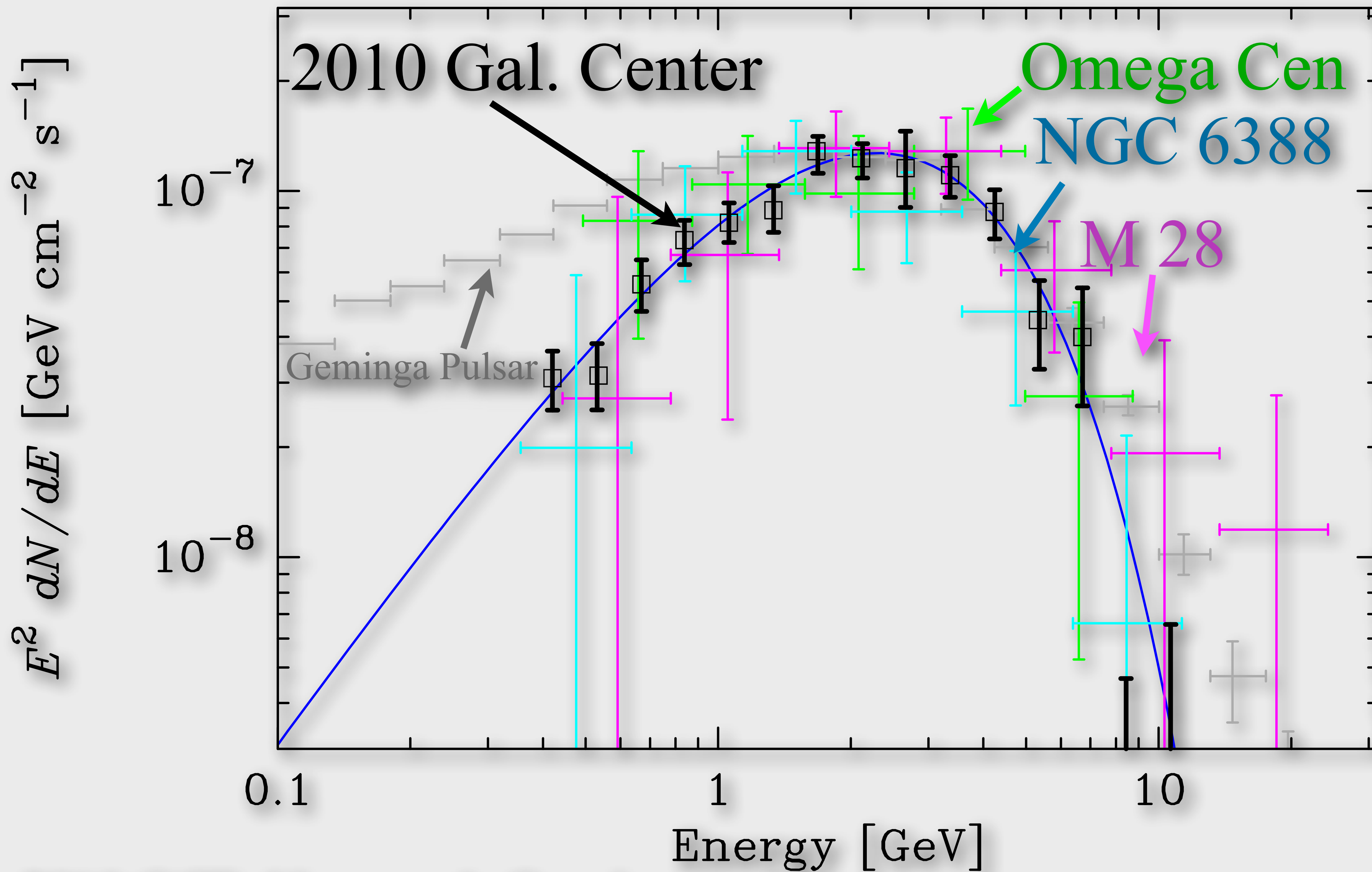


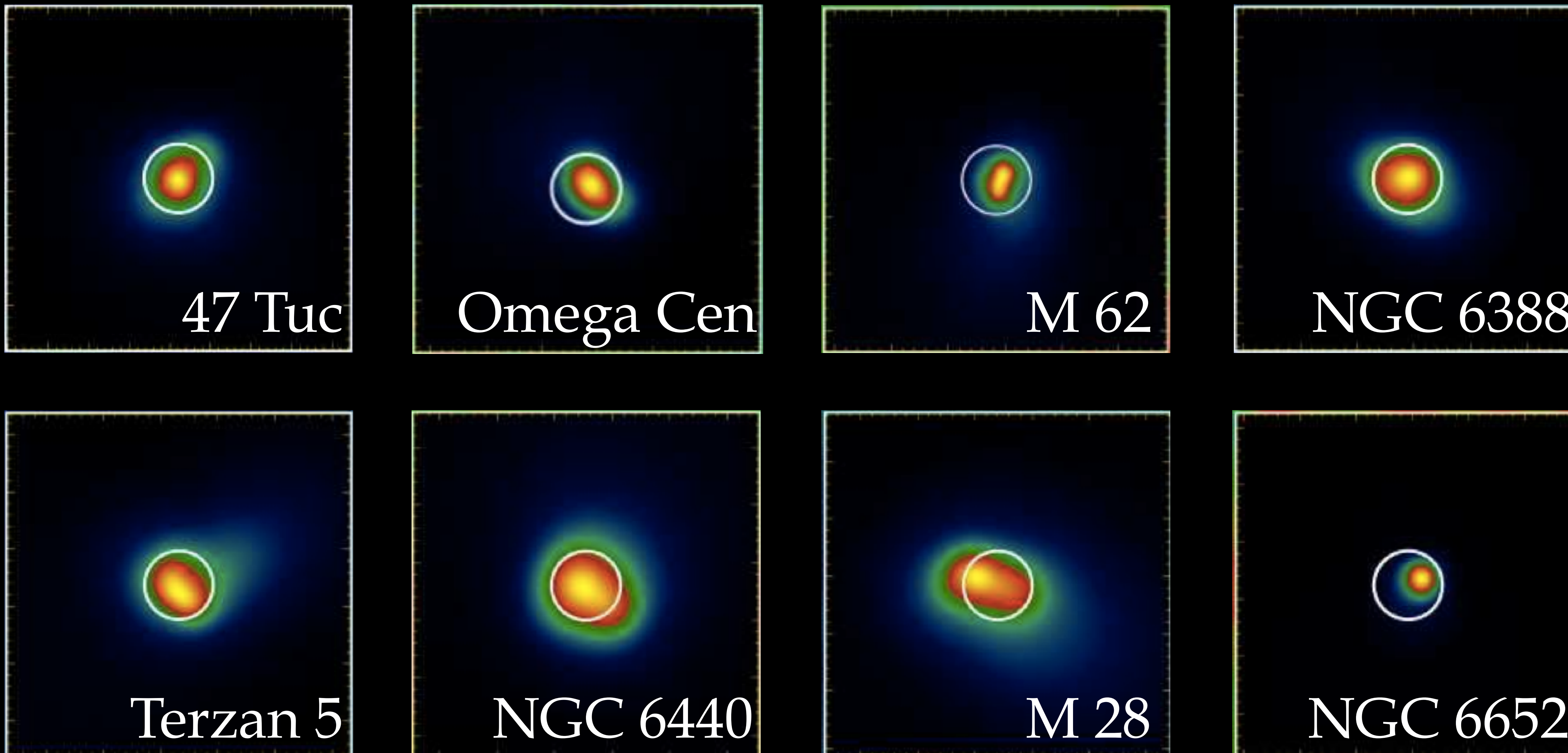
GCE as MSPs: Spectral Comparison



2010 GCE: Hooper & Goodenough

GCE-MSP Spectral Equivalence: Abazajian *2010*

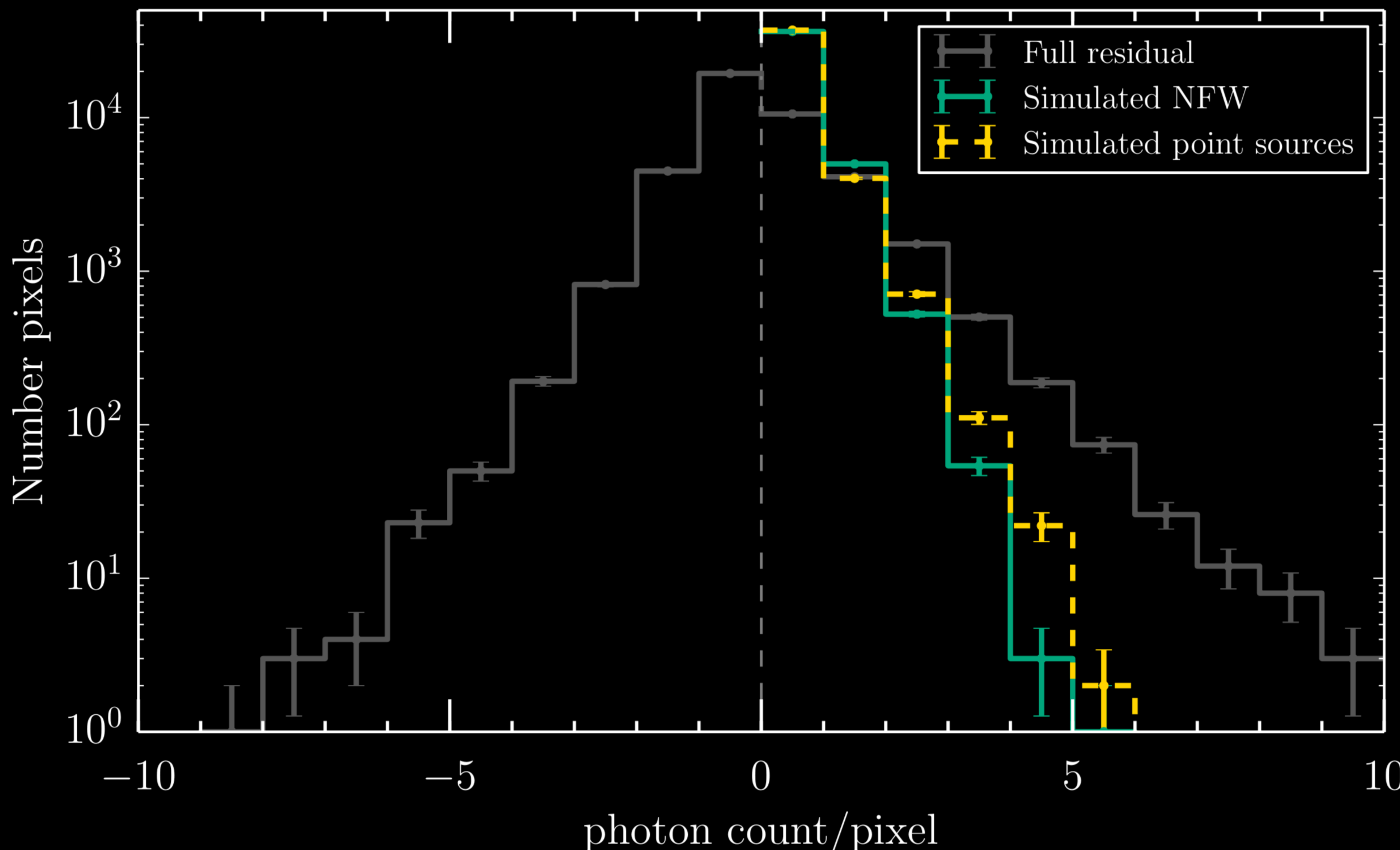
GCE is Consistent with MSPs (Abazajian 1011.4275)



- Requires the flux from the GC MSPs to be 200 times that in Omega Cen - reasonable stellar mass is 800 times
- Spectrum is consistent $\Gamma = 0.45 \pm 0.21$ and $E_c = 1.65 \pm 0.2$ 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)

The Trouble with Non-Poissonian Statistics…

Kwa, Horiuchi & Kaplinghat (2016)



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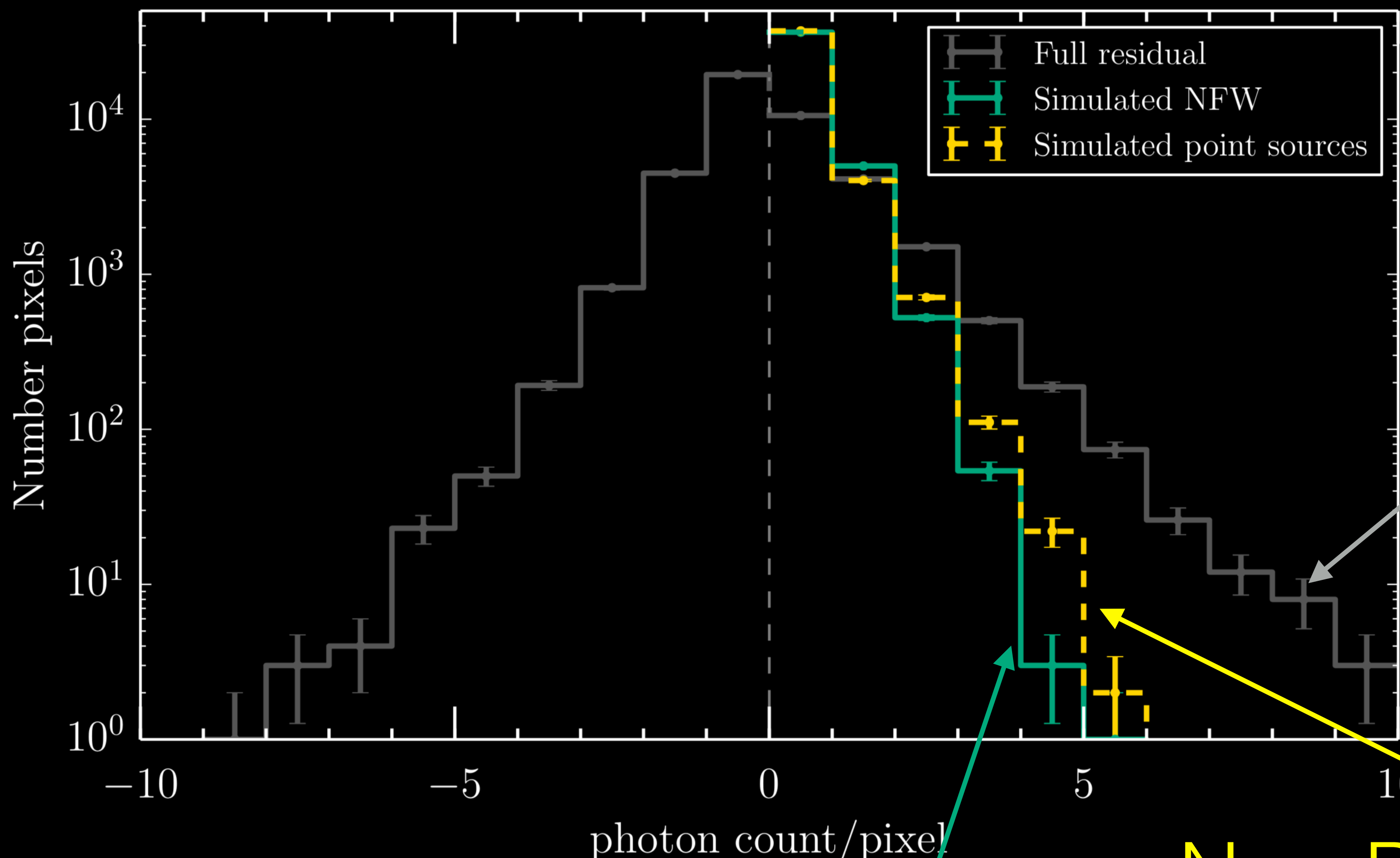


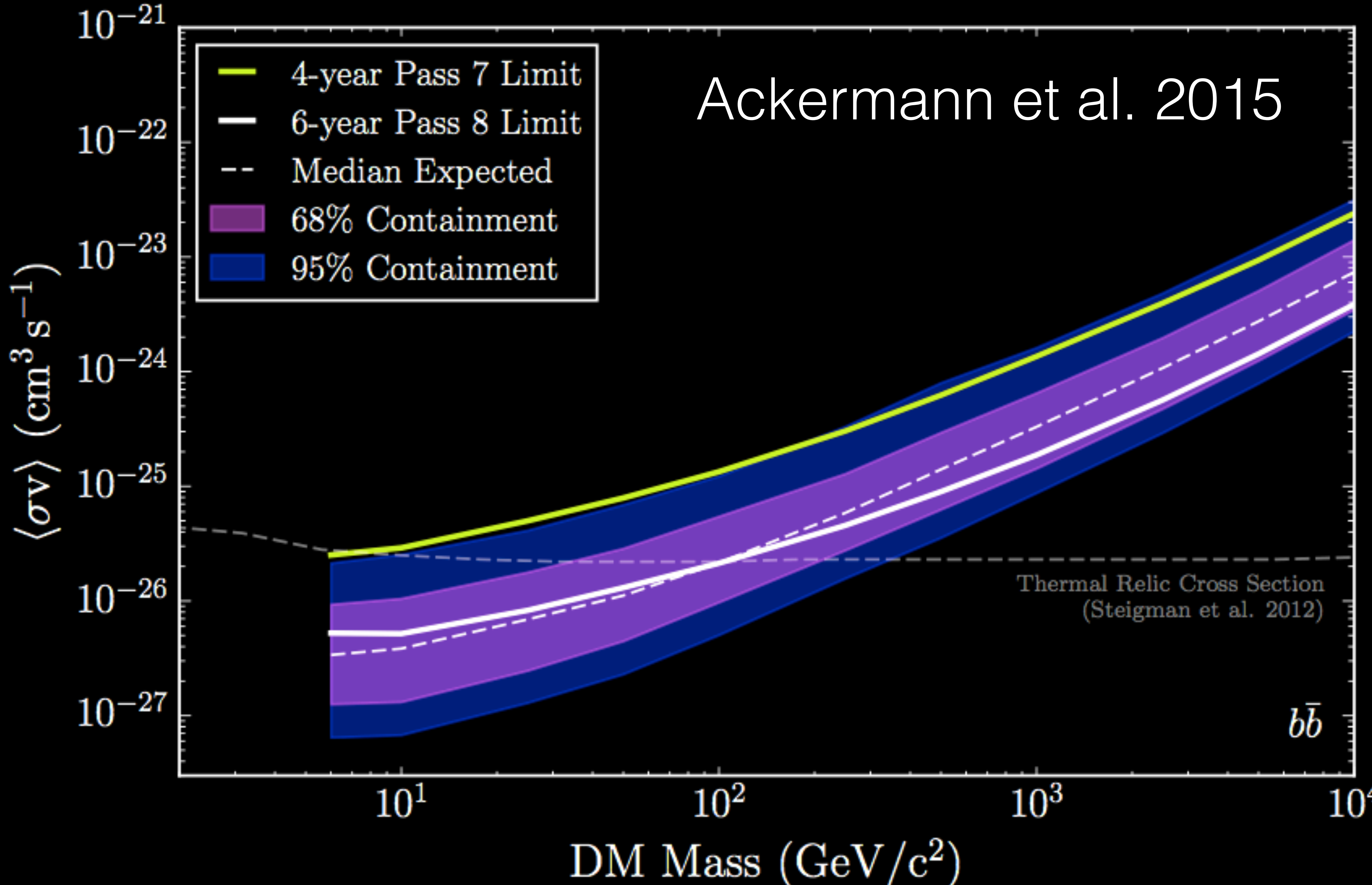
Modeling Residual

Non-Poissonian fluctuations consistent with point sources

Poissonian fluctuations consistent with smooth NFW

Similar conclusions: Leane & Slatyer (2019,2020)

Dwarf Galaxies Searches Remain Dark

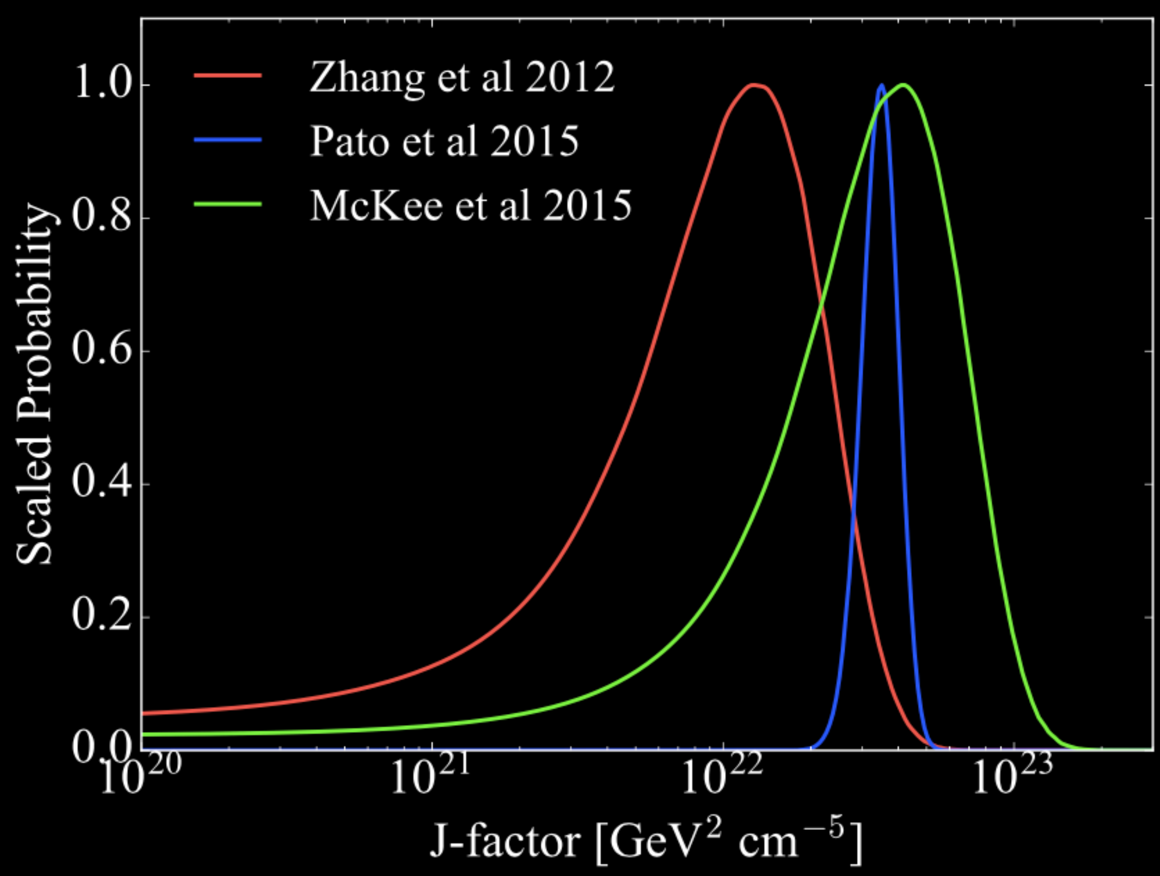


Bright GCE, Dim Dwarfs: *Tension?*

The inferred annihilation rate for the GCE is directly dependent on the DM profile of the Milky Way

$$\frac{d\Phi_\gamma}{dE} = \frac{\langle \sigma_A v \rangle}{2} \frac{\mathcal{J}_{\Delta\Omega}}{\mathrm{J}_0} \frac{1}{4\pi m_\chi^2} \frac{dN_\gamma}{dE}$$

$$\mathcal{J}(b,\ell) = \mathrm{J}_0 \int_{x_{\min}}^{x_{\max}} \rho^2 \left(r_{\rm gal}(b,\ell,x)\right) dx$$

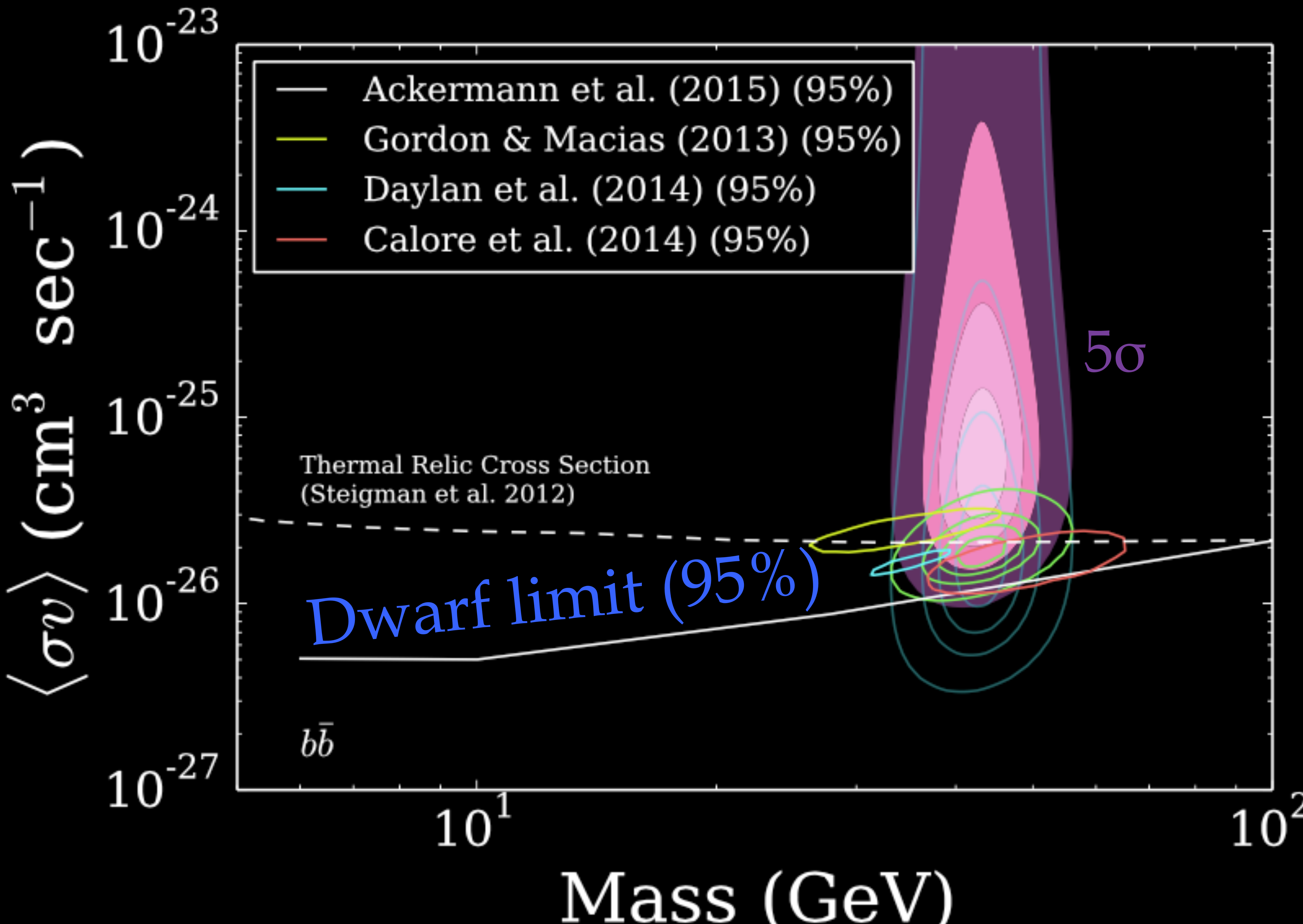


- Sample of 9000 K-dwarf stars from the Sloan Digital Sky Survey (SDSS) by Zhang et al. The velocity distribution ⇒ the local gravitational potential and, combined with stellar density constraints ⇒ $\rho_\odot = 0.28 \pm 0.08$ GeV cm^{-3}

- McKee et al. use star counts and find a significantly lower total stellar mass density than the dynamical stellar density profile measures. Combined with determinations of local total mass densities, they find a higher local dark matter density $\rho_\odot = 0.49 \pm 0.13$ GeV cm^{-3}.

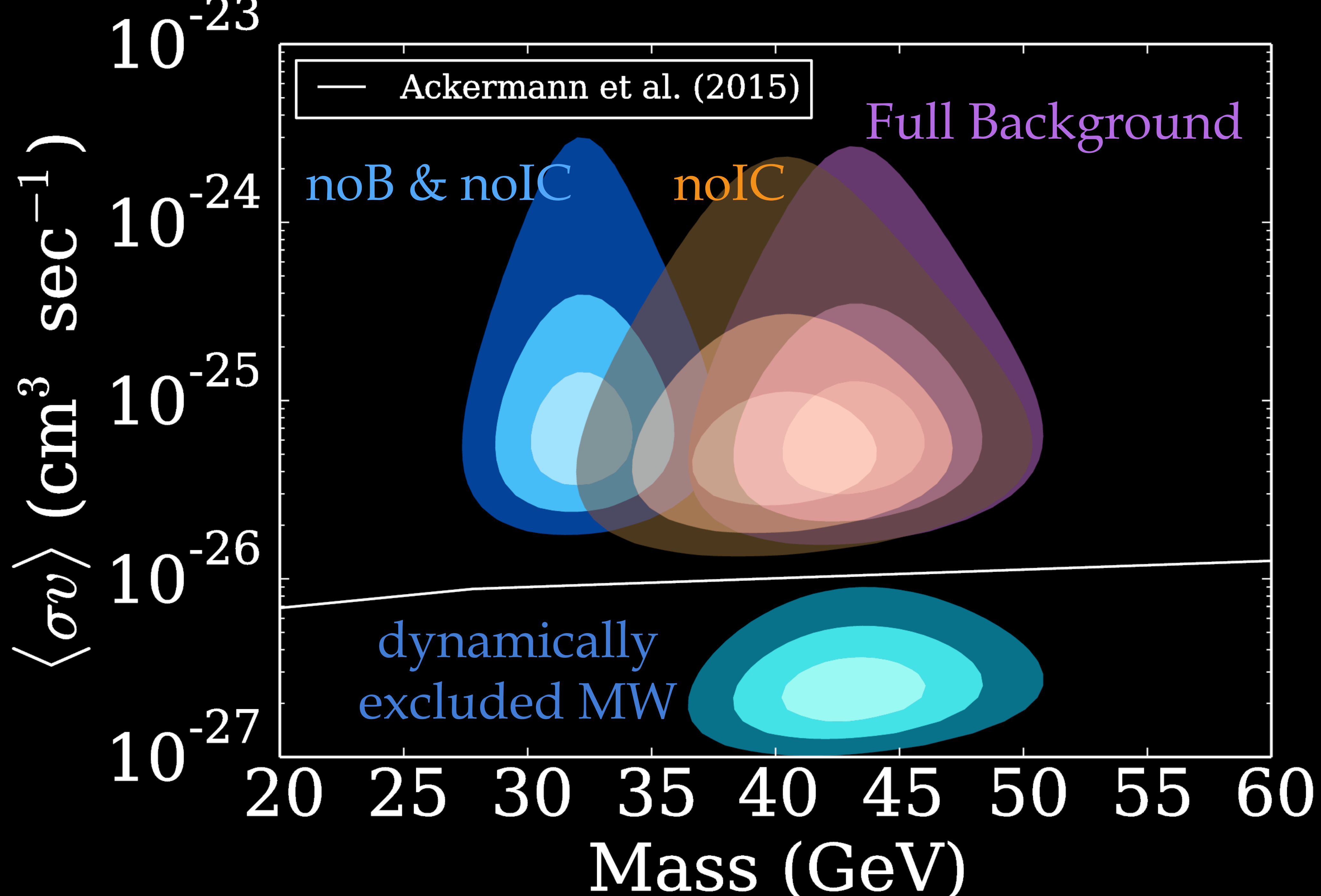
- Pato et al. use measures of gas kinematics from neutral hydrogen terminal velocities and thickness, carbon monoxide terminal velocities, ionized hydrogen regions, and giant molecular clouds, as well as stellar and maser kinematics: $\rho_\odot = 0.420{+}0.011 \pm 0.025$ GeV cm^{-3}.

Bright GCE, Dim Dwarfs: *Strong Tension!*



Abazajian & **Ryan Keeley** arXiv:1510.06424

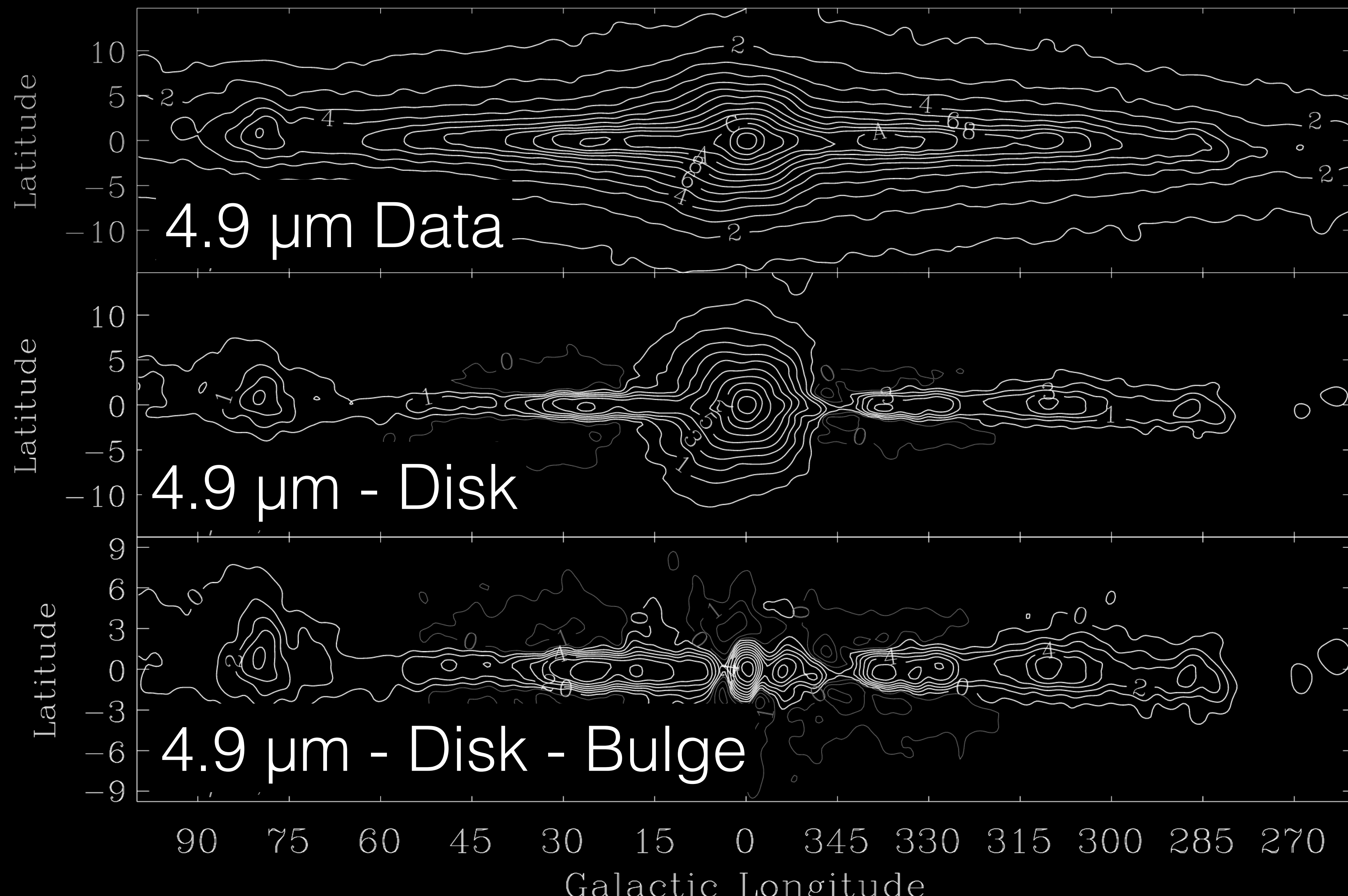
Dependence on Diffuse Emission Models… and tension remains…



Abazajian & **Ryan Keeley** arXiv:1510.06424

Keeley, Abazajian, Kwa, Rodd & Safdi arXiv:1710.03215

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

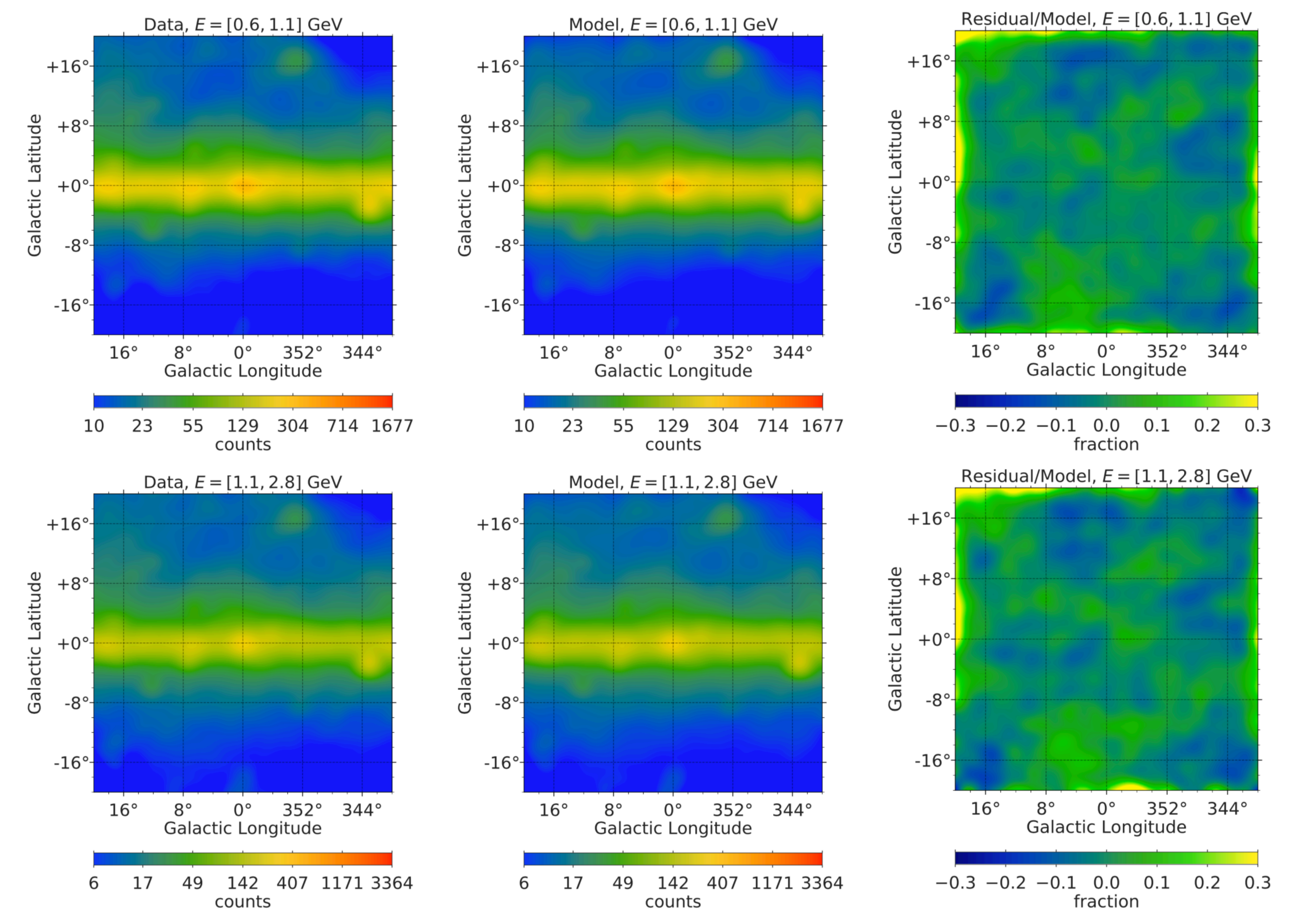


GCE match with WISE IR X-map & even better with COBE/DIRBE Boxy Bulge Map: Macias+ arXiv:1611.06644, Luminosity function consistency: Ploeg+ arXiv:1705.00806

Oscar Macias Visits Irvine: April 18, 2017

How much better are stellar maps than DM?

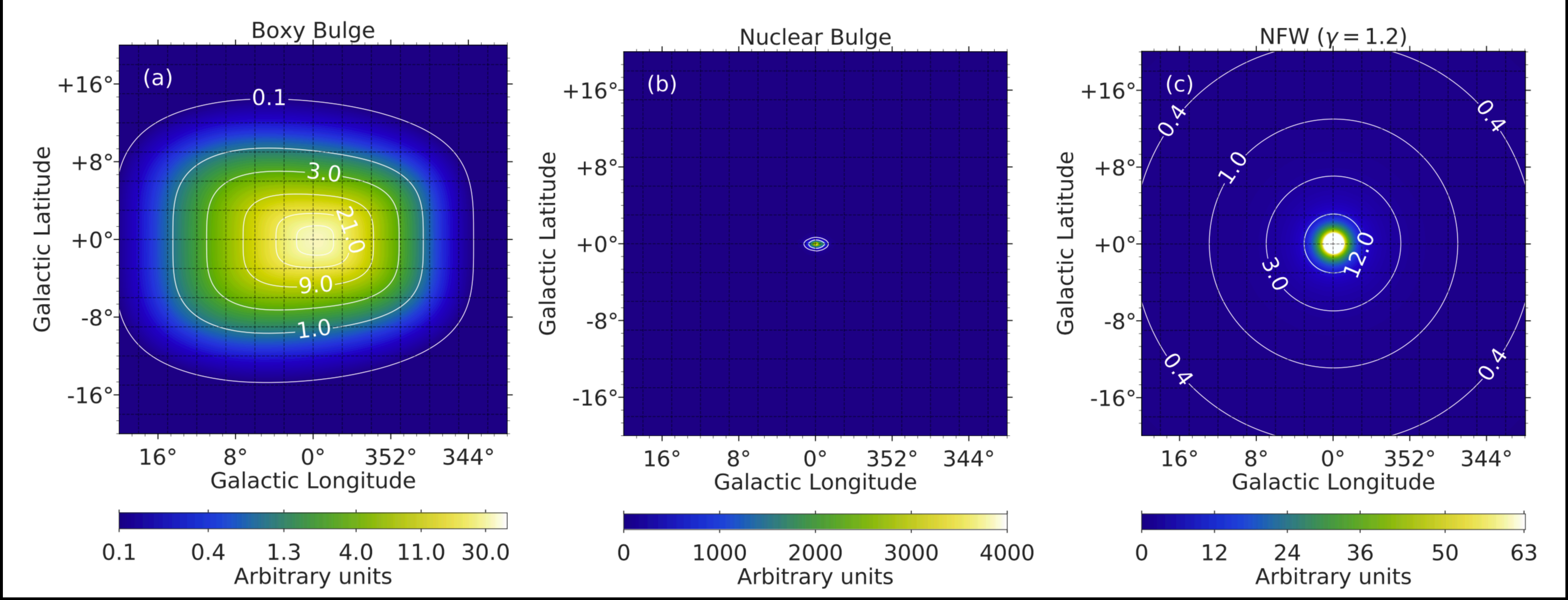
Bulge Maps are ***> 10σ Better Fit:*** Macias+ 1901.03822



How much room can be left for dark matter?

Not much!

Abazajian, Horiuchi, Kaplinghat, **Keeley, Macias** 2003.10416



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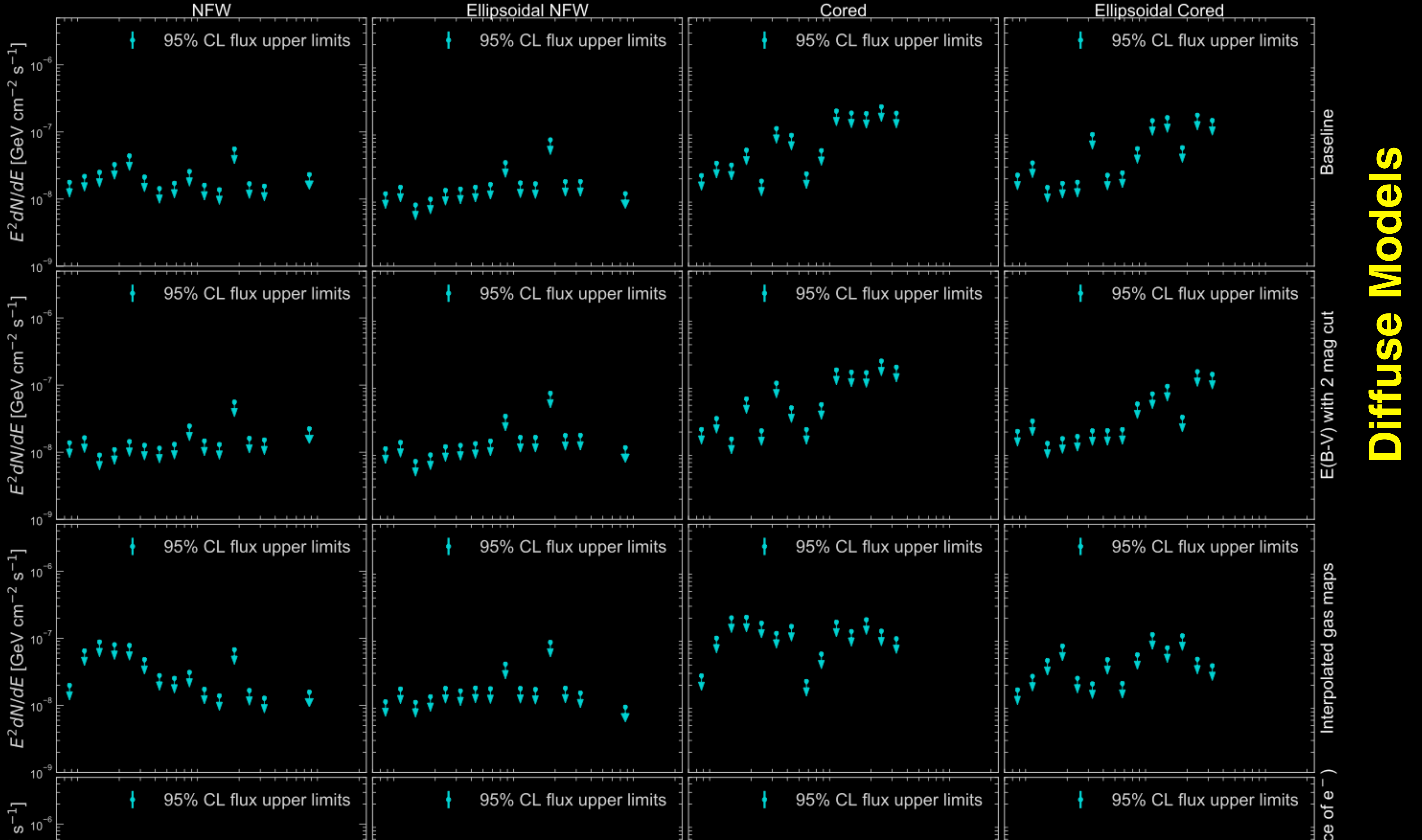

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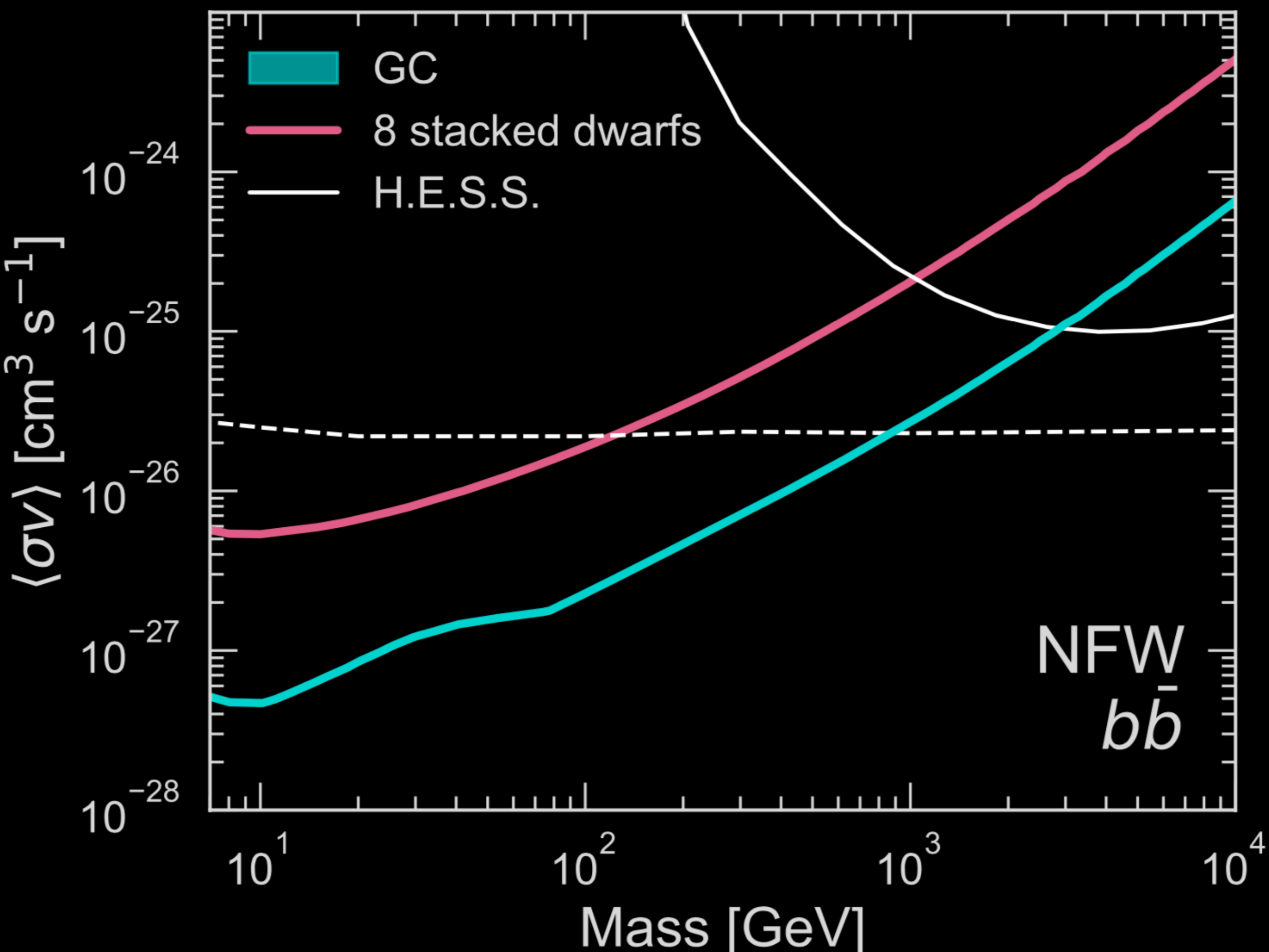
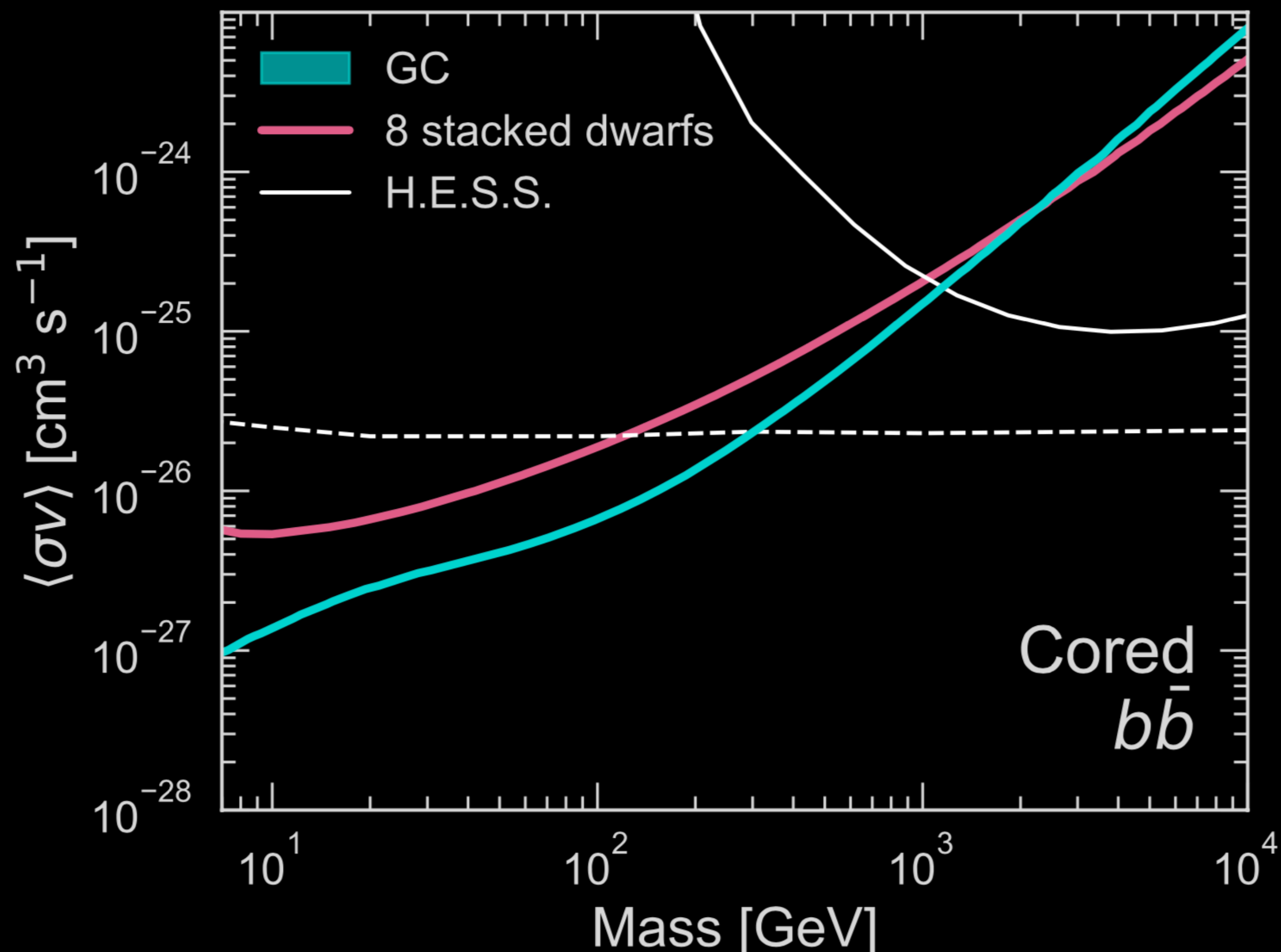
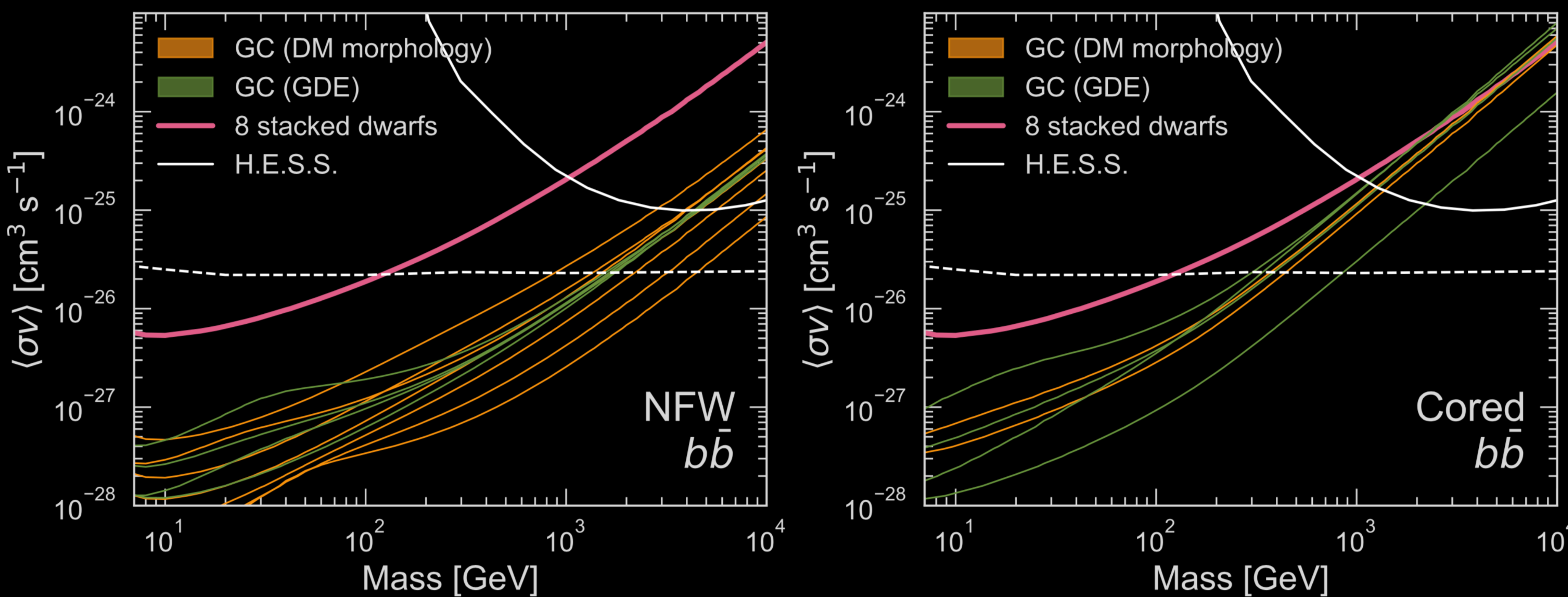




➜We use very conservative local density determinations, marginalize over them, as well as physical, conservative DM profiles

Limits are close to that expected from GC by Fermi-LAT Collaboration (Charles+ arXiv:1605.02016)

But what about Diffuse Model Uncertainties??



We took all diffuse models used in GCE analyses into account…

some much better fits than others…

still report ***most conservative*** limit

Abazajian, Horiuchi, Kaplinghat, **Keeley, Macias** 2003.10416

Is an extra neutrino the dark matter?

Sterile Neutrino Dark Matter

Neutrino Mass Generation: An Original Hidden Sector Theory

- Simplest models of neutrino mass introduce sterile neutrinos that generate small active neutrino mass scales from very massive sterile neutrinos (Seesaw 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. νSM de Gouvêa 2005; νMSM Asaka et al 2005; L_e-L_μ-L_τ Lindner+ 2010)

- Two massive (≳100 GeV) sterile neutrinos are required by atmospheric and solar neutrino mass scales. *Only hidden sector model with evidence for its existence!*
- 3rd sterile neutrino has complete freedom. In simplest formulations, since lowest mass light ν is unbounded from below, so is the mixing of the lightest sterile neutrinos with the active ν.

$$\theta \sim \sqrt{\frac{m_\alpha}{M}}$$

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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

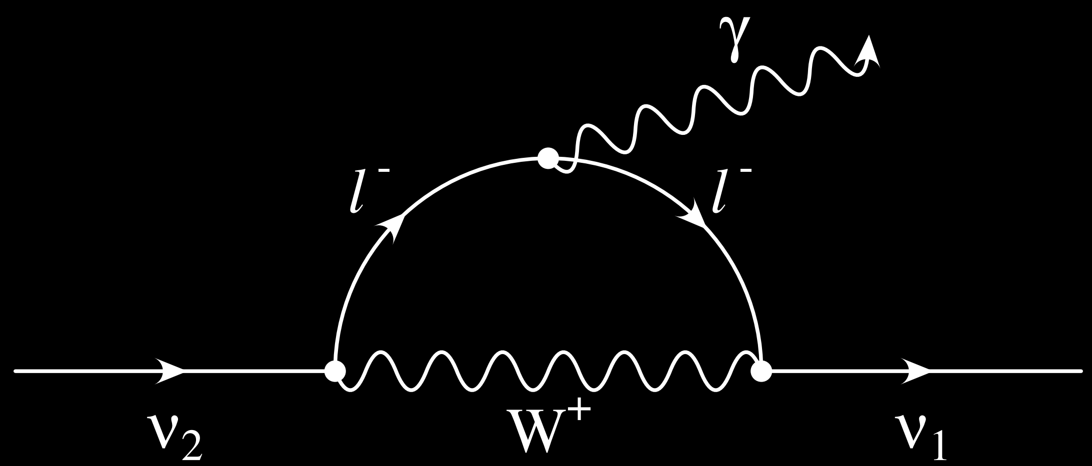
- "Sterile" neutrinos [Dodelson & Widrow, 1993]: No SM interactions beyond mass terms, inclusion of finite-temperature modifications to self-energy, lack of thermalization. WDM.

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

- "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 Sterile Neutrinos in the X-ray: *Chandra* & *XMM-Newton X-ray Space Telescopes*

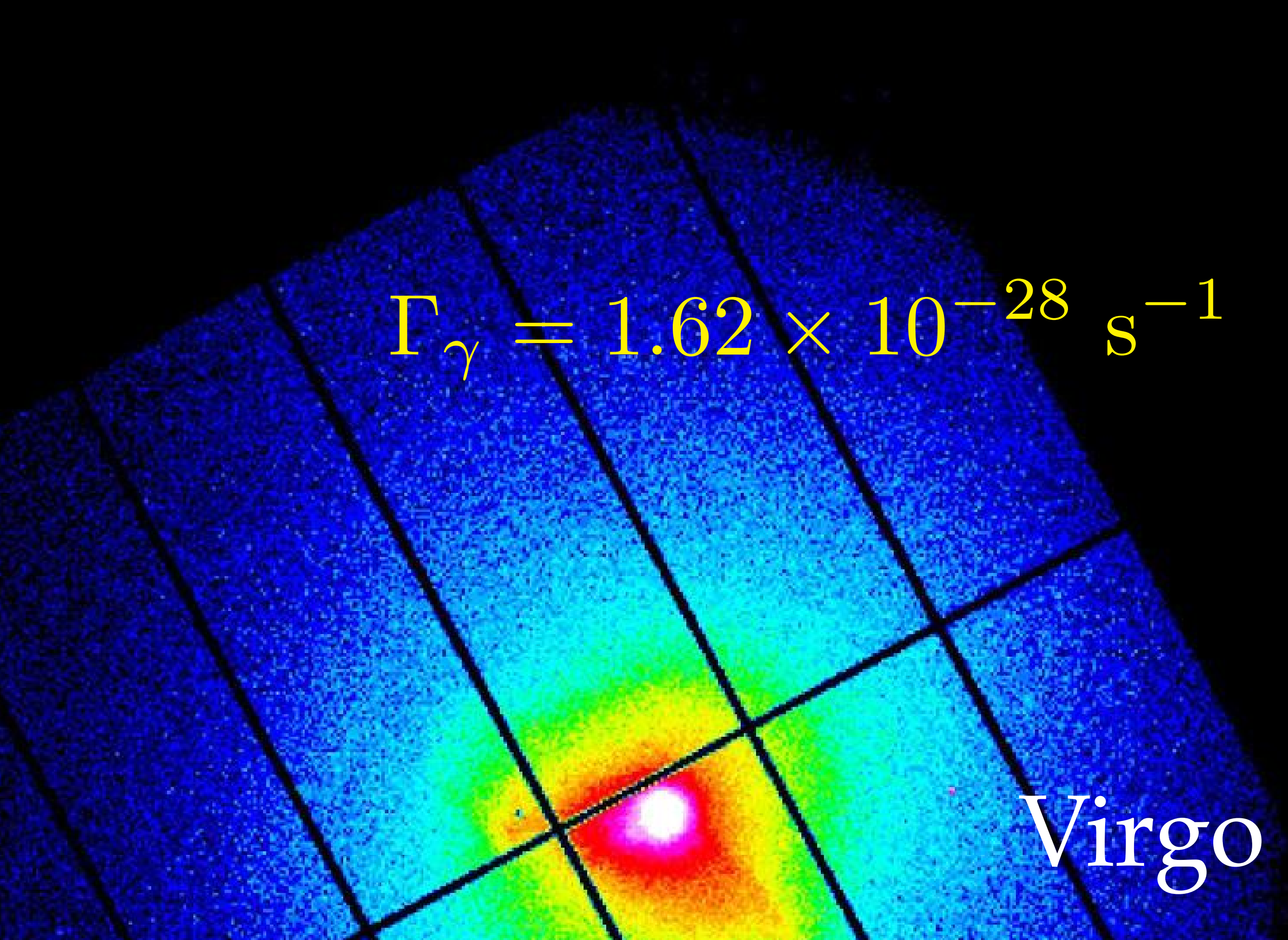
Sterile Neutrino WDM Radiative Decay in the X-ray



Decay: Shrock 1974; Pal & Wolfenstein 1981; Barger, Philips & Sarkar 1995
X-ray: Abazajian, Fuller & Tucker 2001

$$\text{“}\nu_s\text{”} \rightarrow \text{“}\nu_\alpha\text{”} + \gamma$$

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

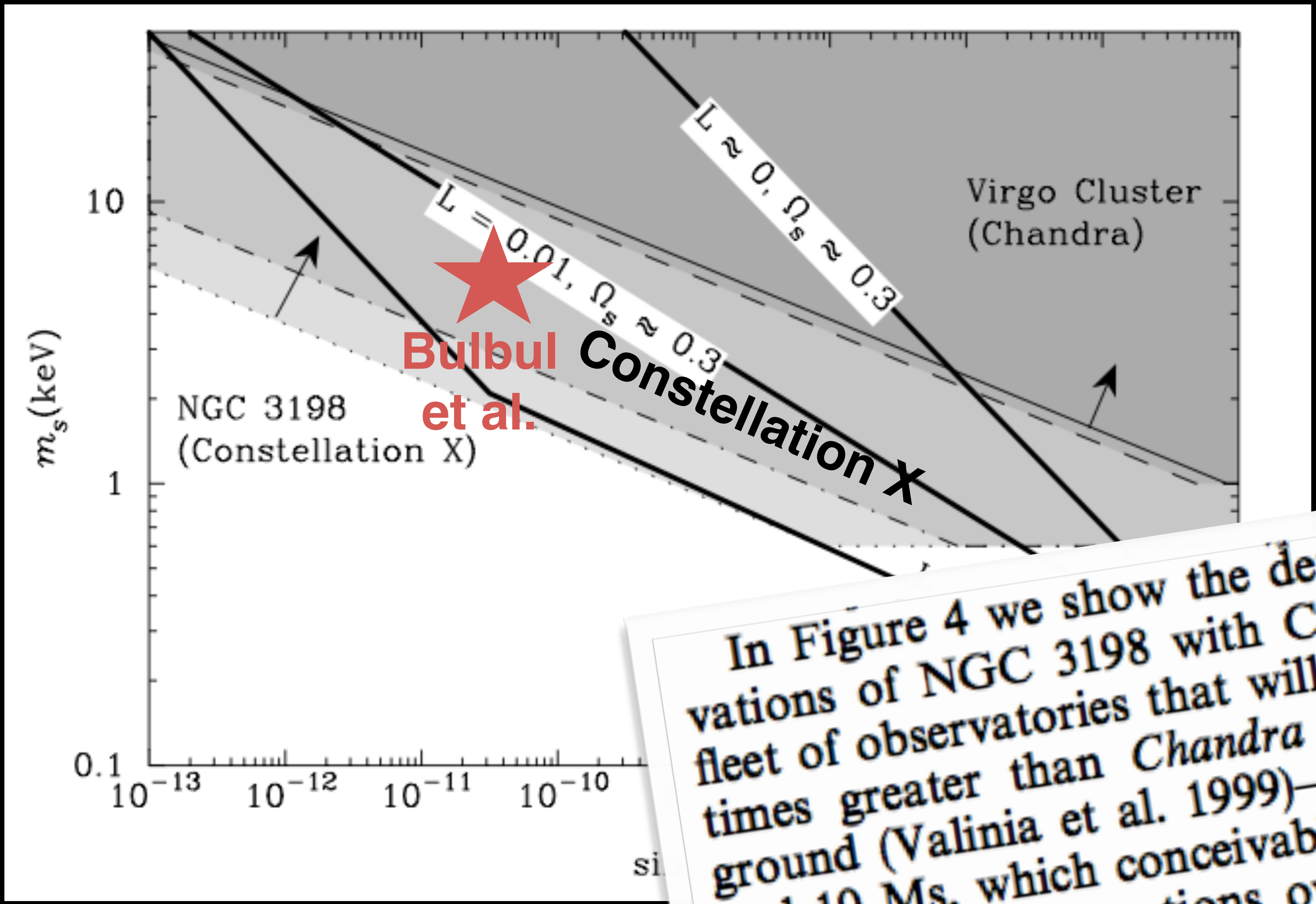


$$\Gamma_\gamma = 1.62 \times 10^{-28}\ \text{s}^{-1} \left(\frac{\sin^2 2\theta}{7 \times 10^{-11}}\right)\left(\frac{m_s}{7\ \text{keV}}\right)^5$$

Virgo Cluster: 10^{78} DM particles

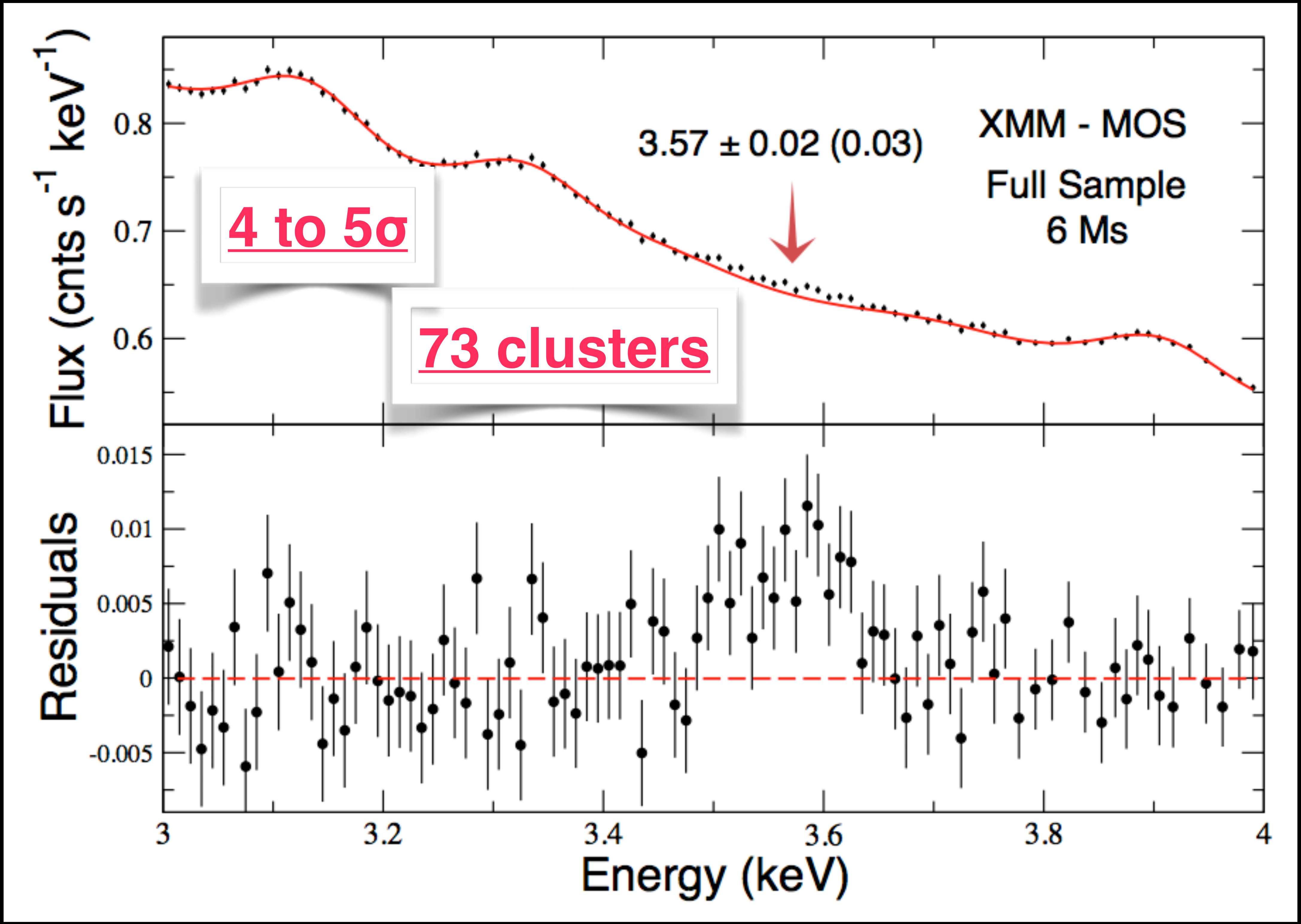
Forecast X-ray Observation Sensitivity for *Constellation-X*

Abazajian, Fuller & Tucker 2001



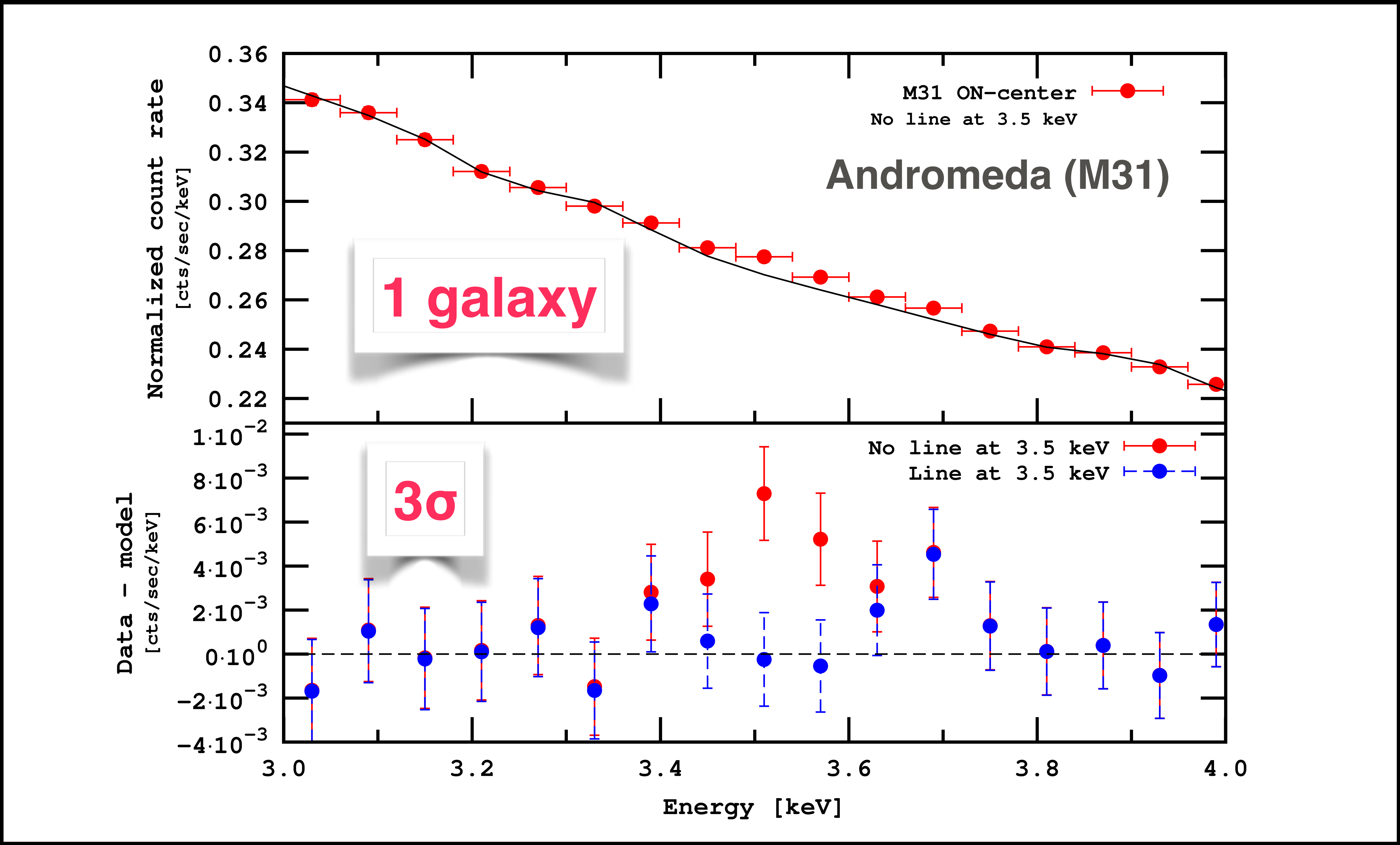
In Figure 4 we show the detectability region for observations of NGC 3198 with Constellation X—a proposed fleet of observatories that will have an effective area ~10 times greater than *Chandra* and no instrumental background (Valinia et al. 1999)—for two integration times, 1 and 10 Ms, which conceivably 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



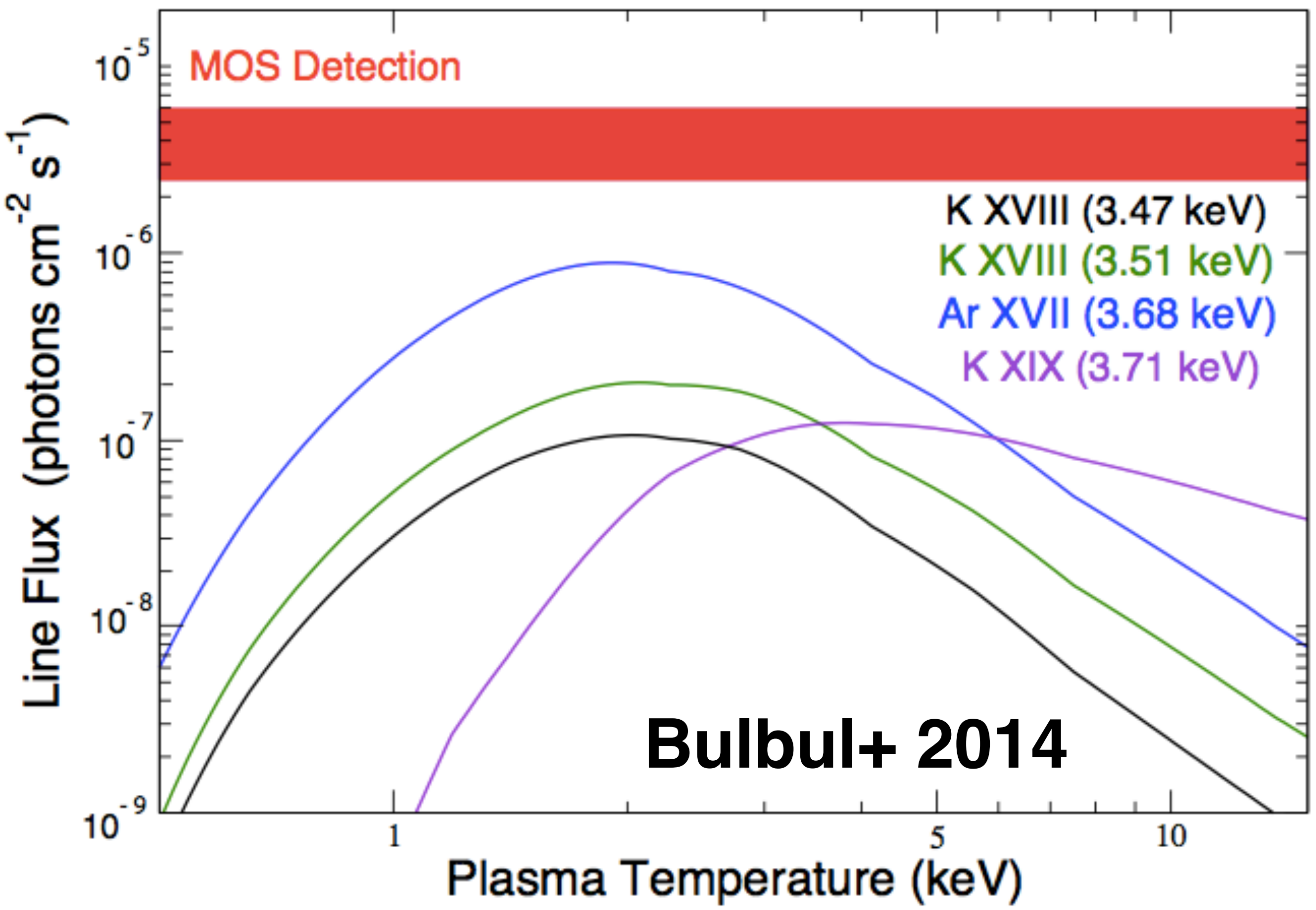
Bulbul et al. ApJ 2014

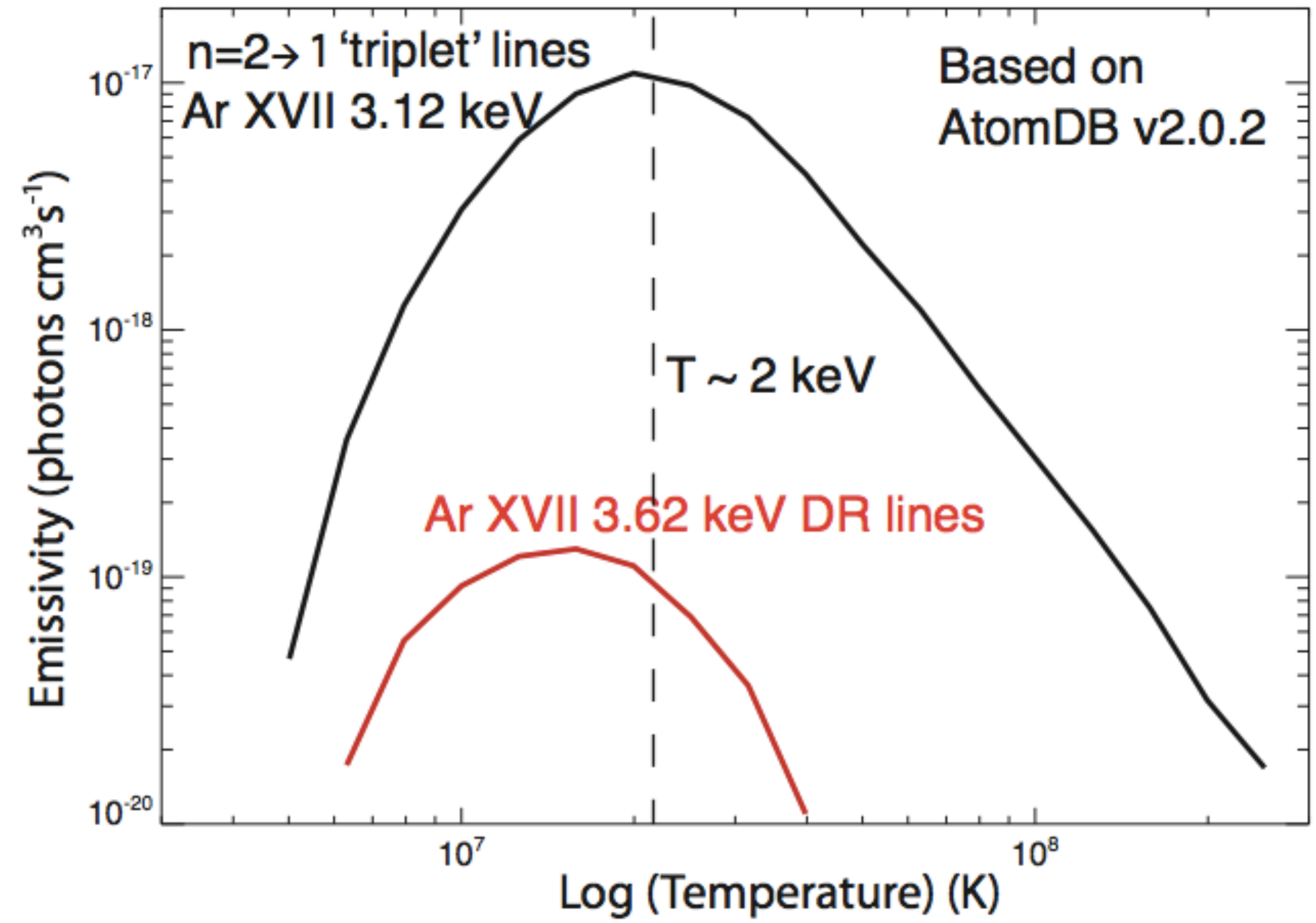
The Detection of an Unidentified Line II



Boyarsky et al. PRL 2014

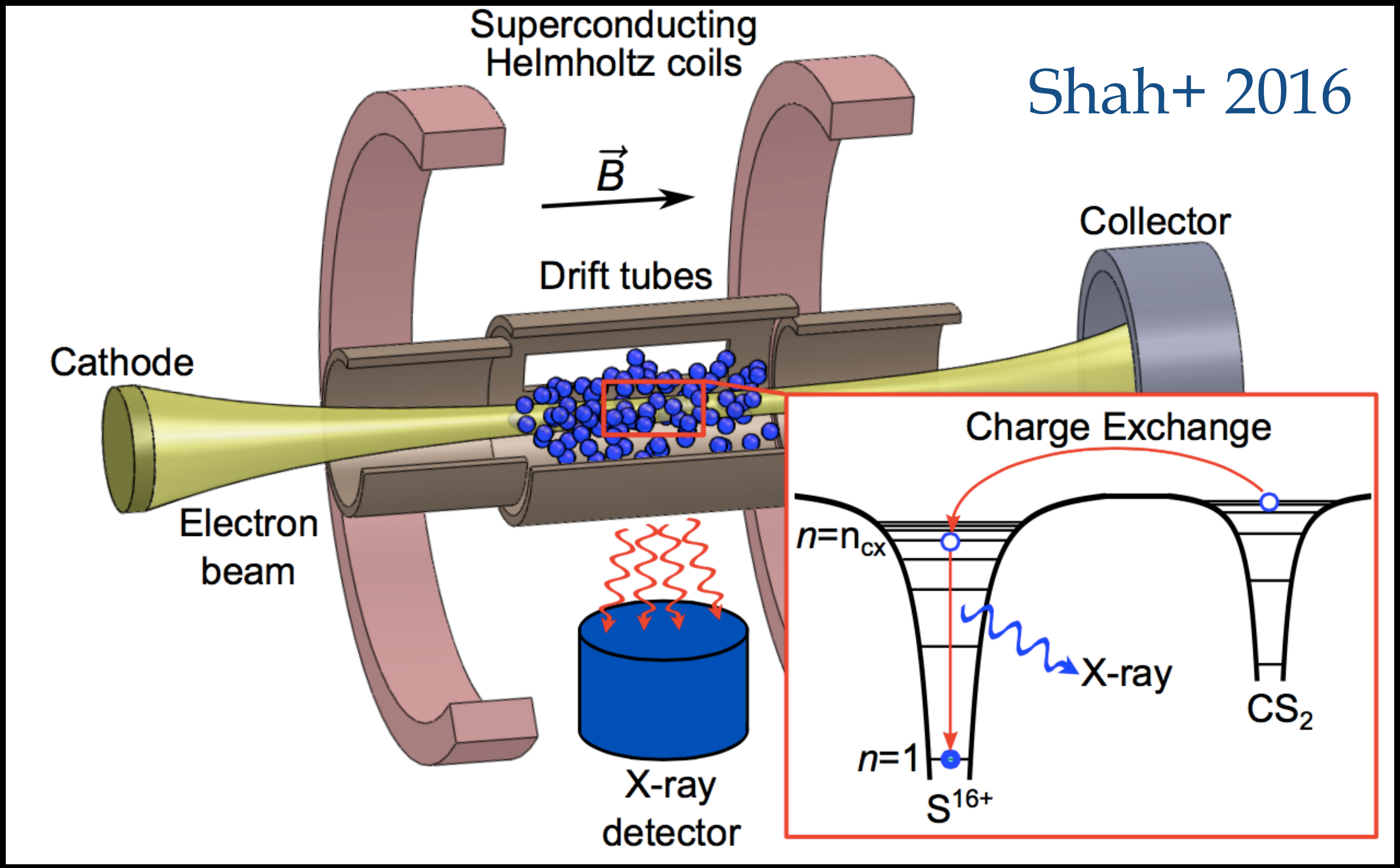
Metal Lines in Clusters at 3.5 keV? *unlikely*





- 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?



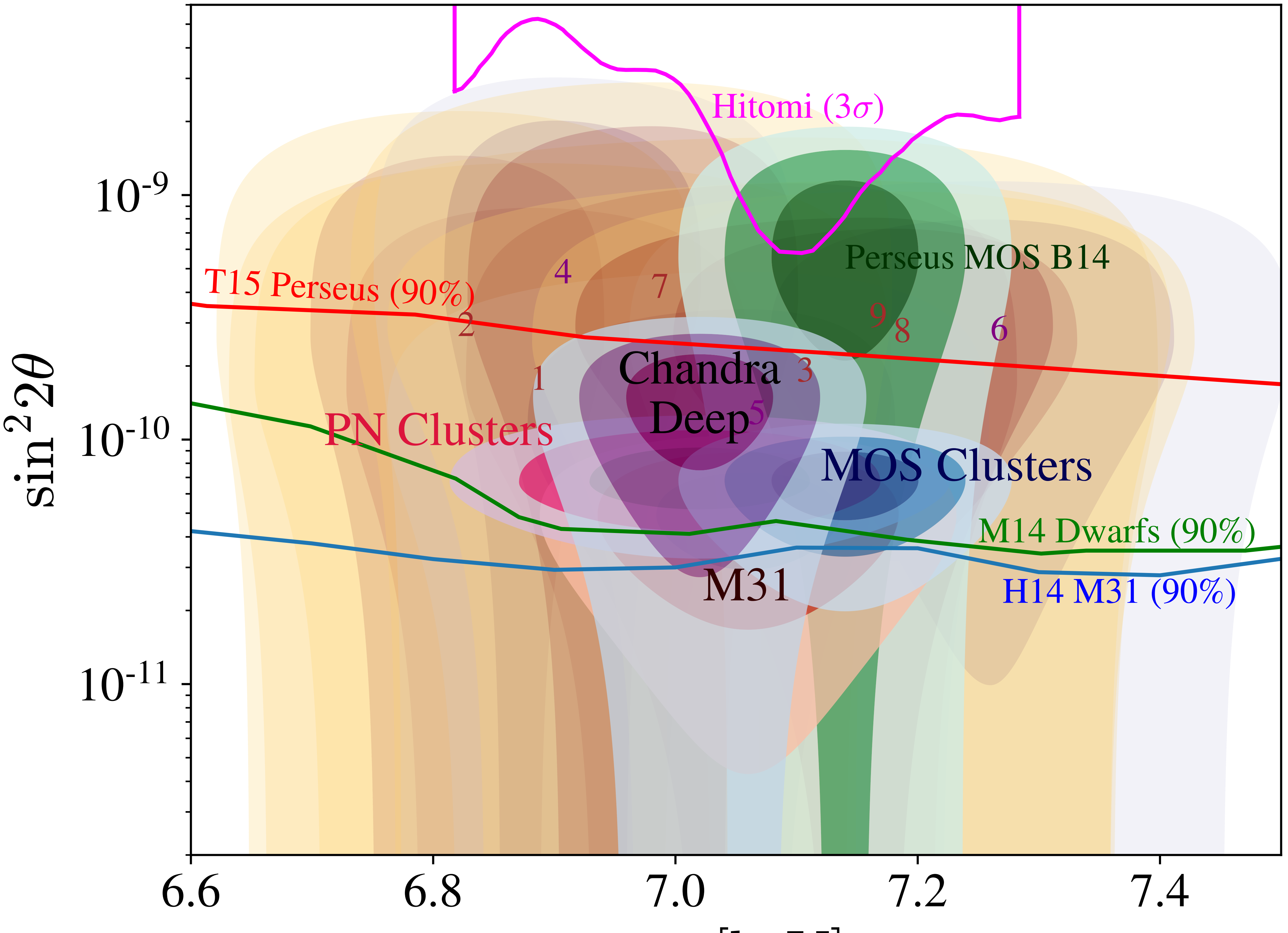
Betancourt-Martinez+ 2014; Gu+ 2015; Shah+ 2016

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)

3.55 keV line consistent with DM in field of view seen

- in Andromeda (M31) with *XMM-Newton* (Boyarsky+ 2014)
- Perseus with *XMM-Newton, Chandra and Suzaku* $\gtrsim 3\sigma$ (Bulbul+ 2014, Boyarsky+ 2014, Urban+ 2014)
- in 8 more clusters at > 2σ significance (*XMM-Newton*) (Iakubovskyi+ 2015)
- Milky Way Galactic Center out to > 10° (*XMM-Newton*) (Boyarsky+ 2014, 2018)
- Milky Way Galactic Center at 1.5° at Galactic Bulge limiting window (*Chandra*) (Hofmann & Wegg 2019)
- *NuSTAR* observations of Deep Fields at **11.1σ** and Galactic Center (Neronov+ 2016, Perez+ 2016)
- *Chandra* Deep Fields at 3σ (Cappelluti+ 2017): rule out CX, Ar or instrumental

The 7 keV Region Today



Updated from Abazajian 2017 arXiv:1705.01837

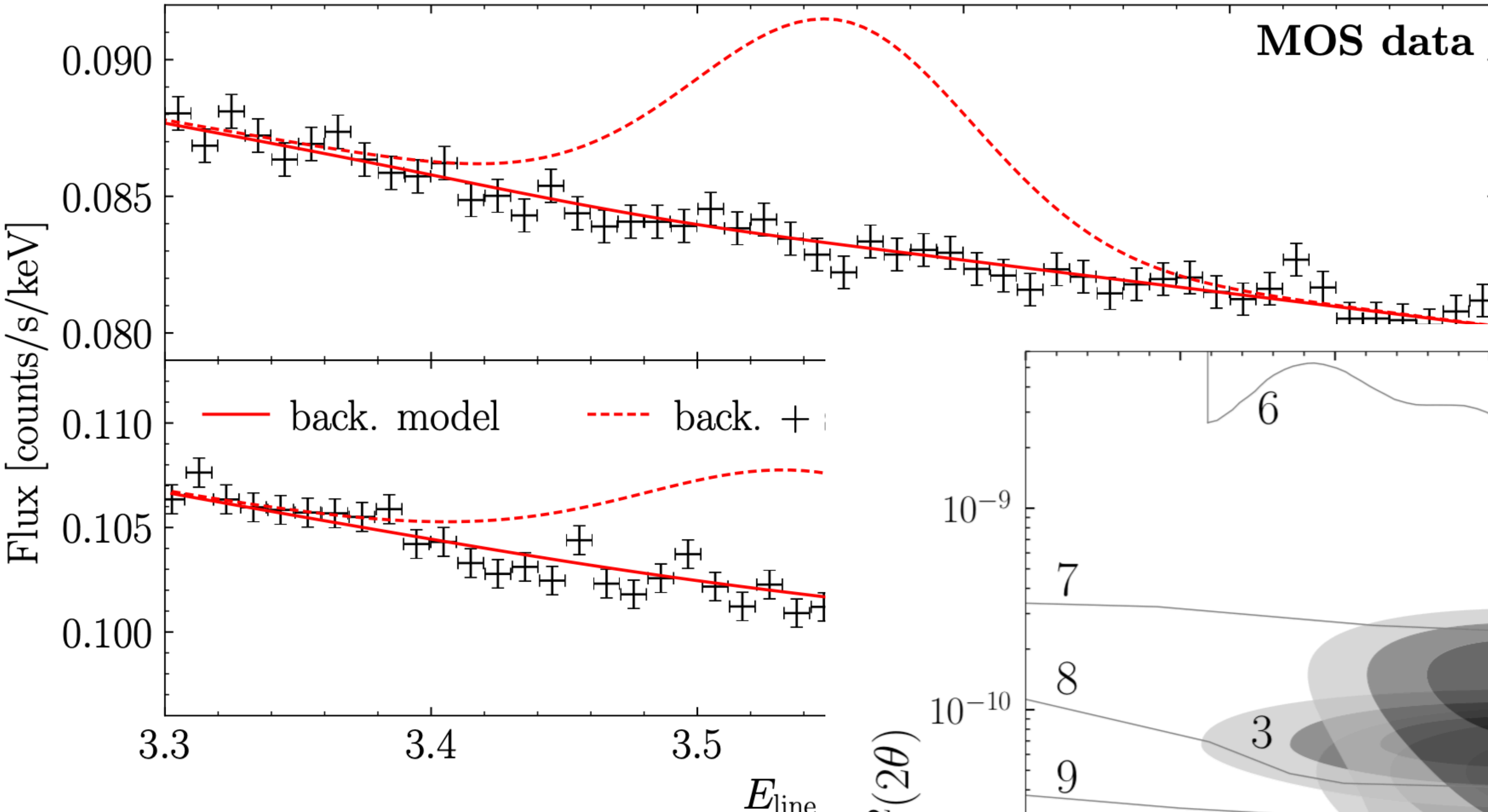
3 places it may have been expected

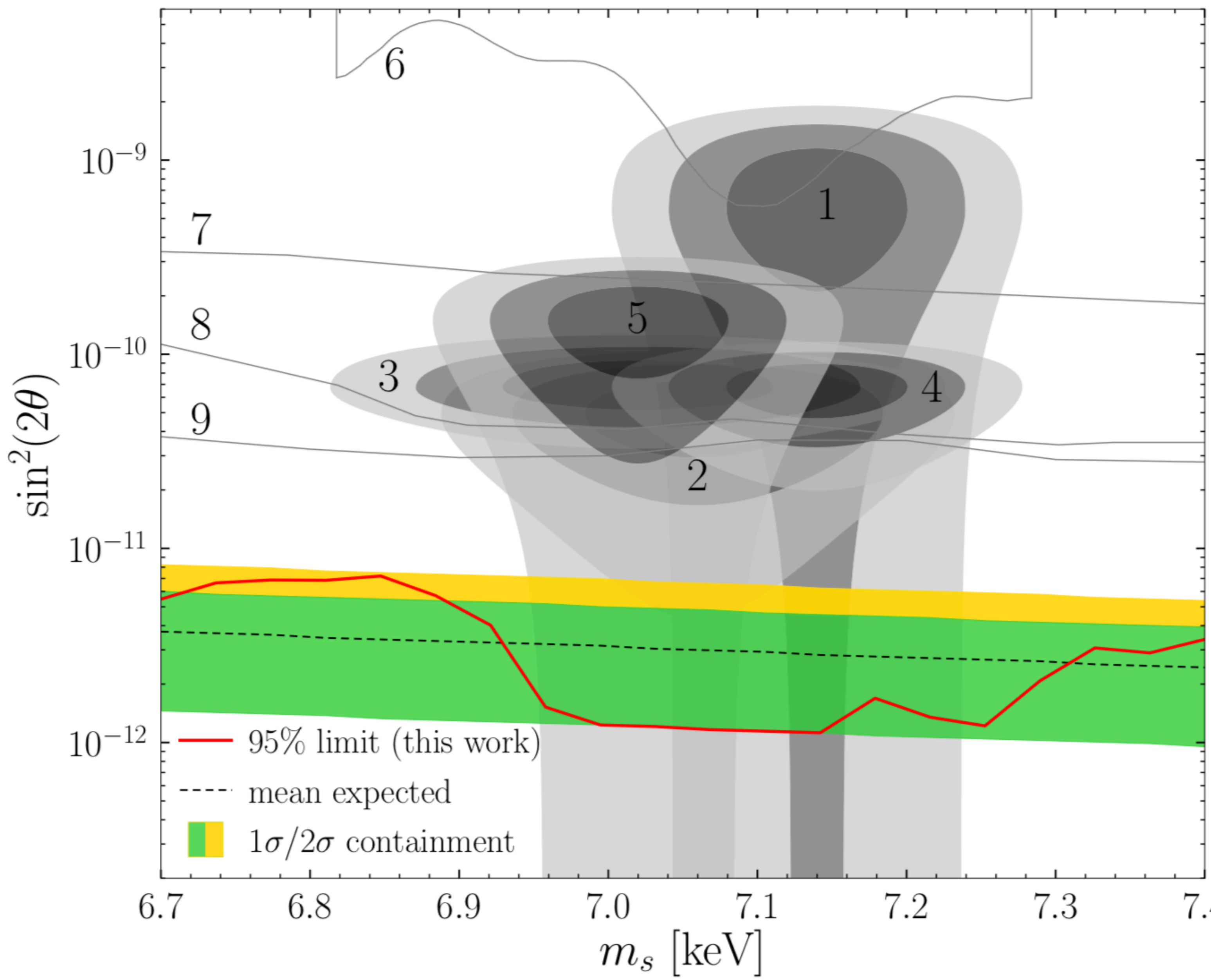
- **Draco 1 Ms exposure:** not seen in MOS detectors, at lower than expected flux in PN. But, ***"We conclude that this Draco observation does not exclude the dark matter interpretation of the 3.5 keV line in those objects."*** Boyarsky+ arXiv:1512.07217

- **Stacked galaxies:** 81 with Chandra and 89 with *XMM-Newton*, using outskirts of the galaxies:
Anderson, Churazov & Bregman arXiv:1408.4115.
➥***Systematic continuum errors are of order the uncertainties on detected*** $\sin^2 2\theta$

- **Stacked blank sky:** 30 Ms *XMM-Newton* data, 0.5 keV energy window analysis.
Dessert, Rodd & Safdi arXiv:1812.06976 (journal *Science*, 2020)

Joint Multi-Pointing observations…





"Our analysis rules out the decaying DM interpretation of the previously observed 3.5-keV UXL because our results exclude the required decay rate by more than an order of magnitude."

Dessert, Rodd & Safdi
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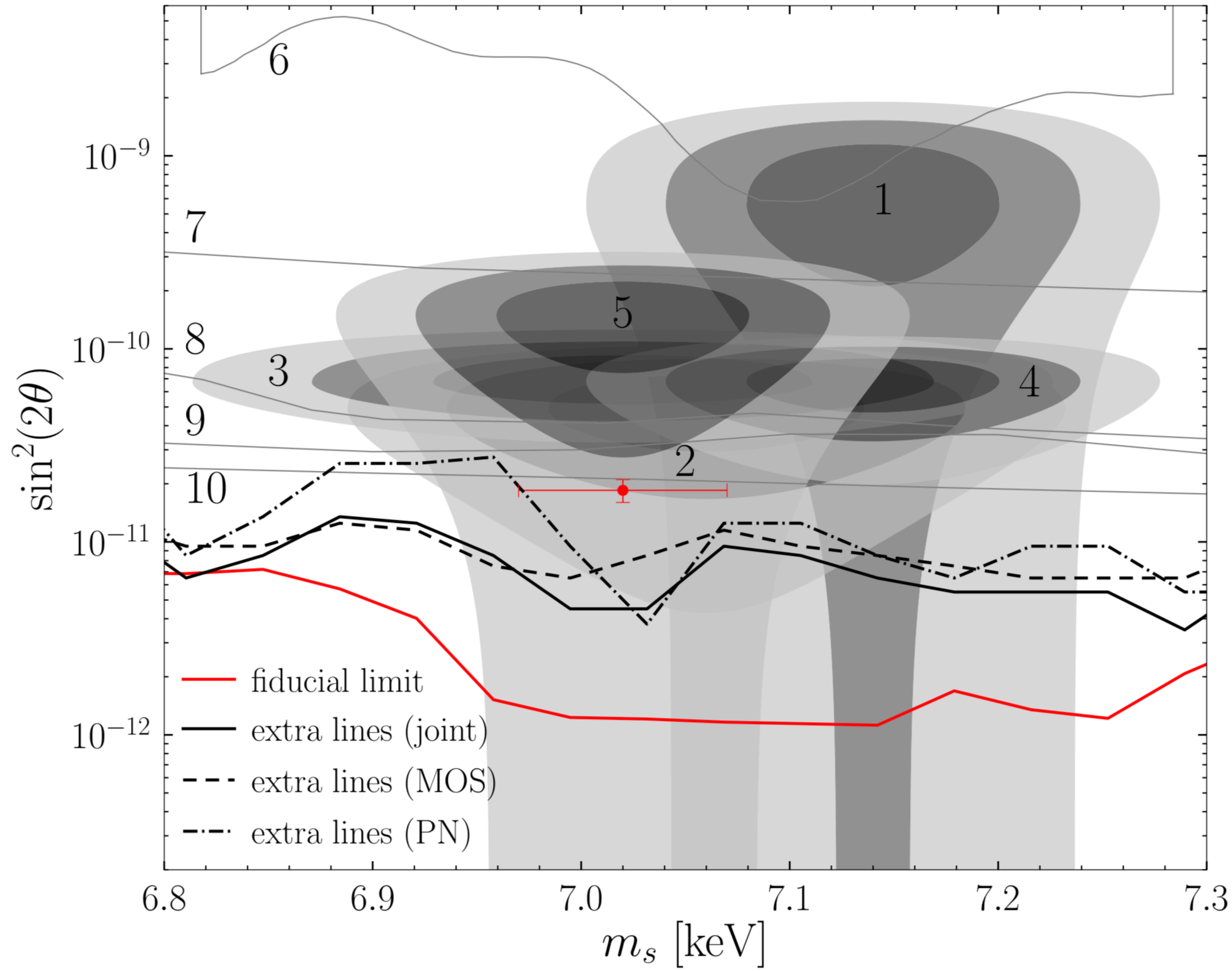

Relaxation of DM density profile gives factor of ~3 relaxation of limit

Adding other known lines gives another factor of ~8 relaxation of limit

[3.3: AR XVIII, S XVI and of K Kα instrumental line]
[3.7: AR XVII complex and instrumental Ca Kα line]

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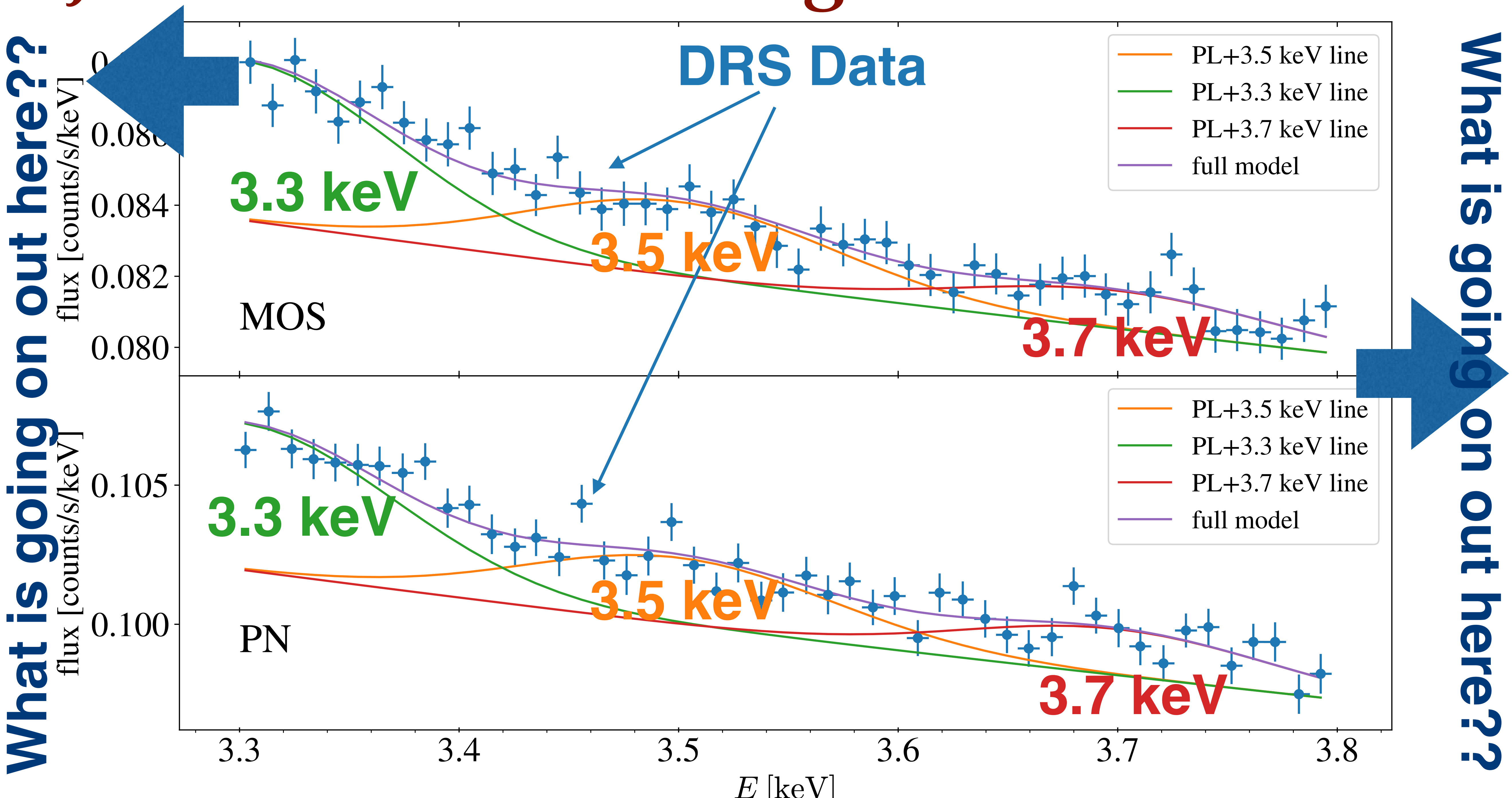
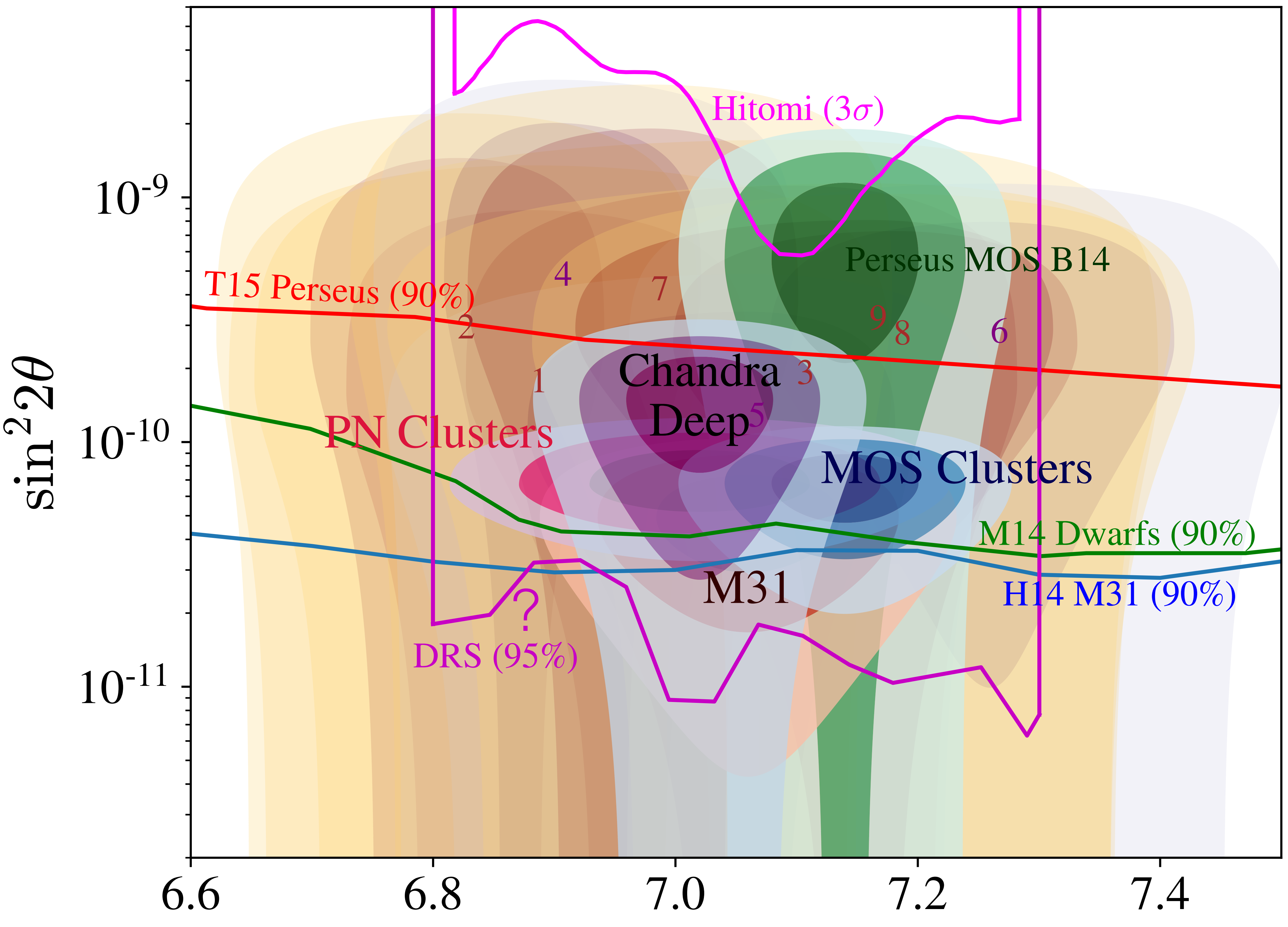


➜ extra 3.3 & 3.7 keV lines preferred by DRS data at 4.3(3.5)σ & 2.8(1.6)σ, for the PN (MOS) cases

➜ plenty of room left for 3.5 keV line (shown at 95% upper limit) [3.3 & 3.7 keV also left out of Draco by Jeltema & Profumo (2016)]

The 7 keV Region Today

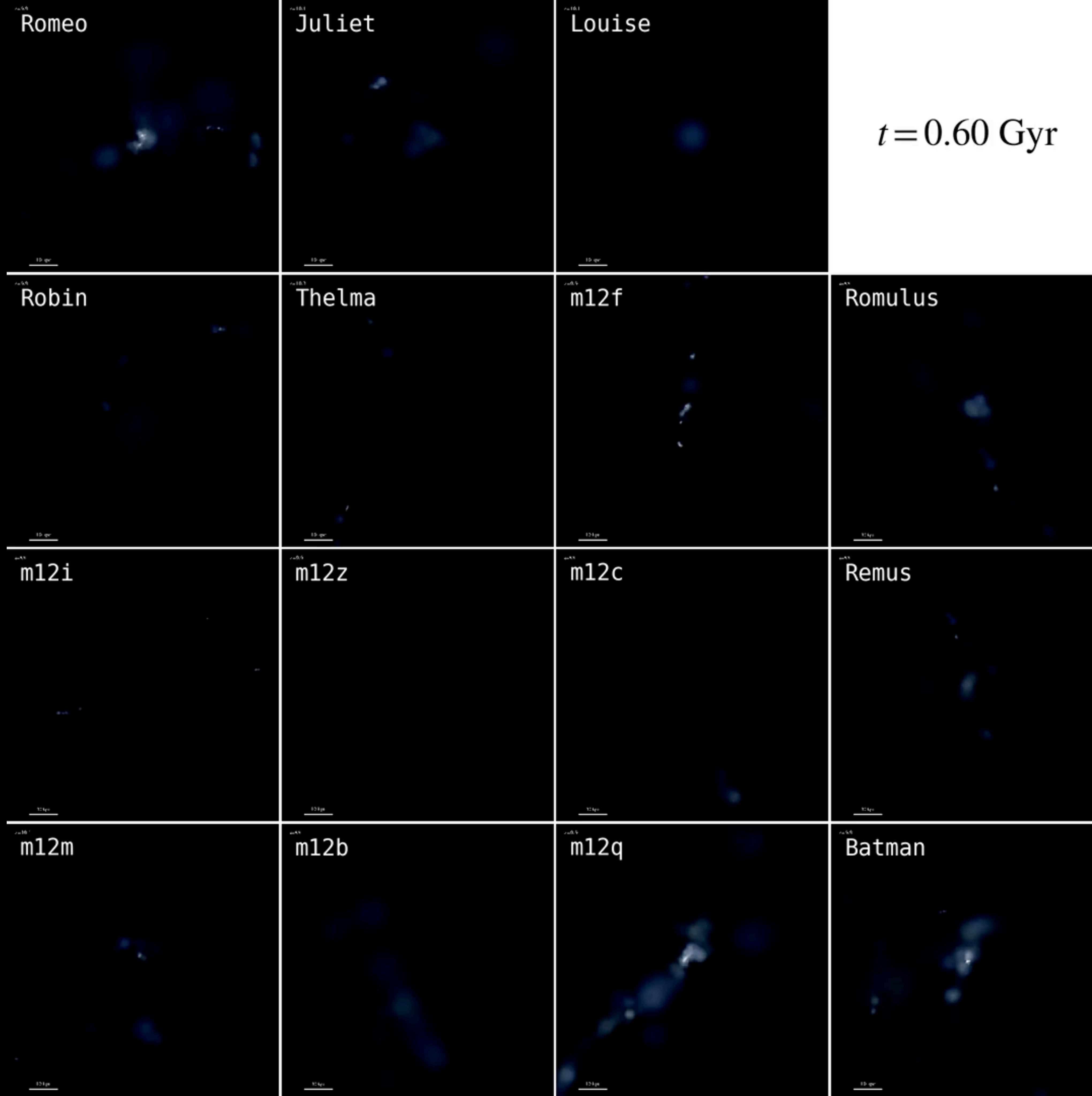


Updated from Abazajian 2017 arXiv:1705.01837

What if we do really see dark matter emission on the sky?

FIRE Simulations of Local Group

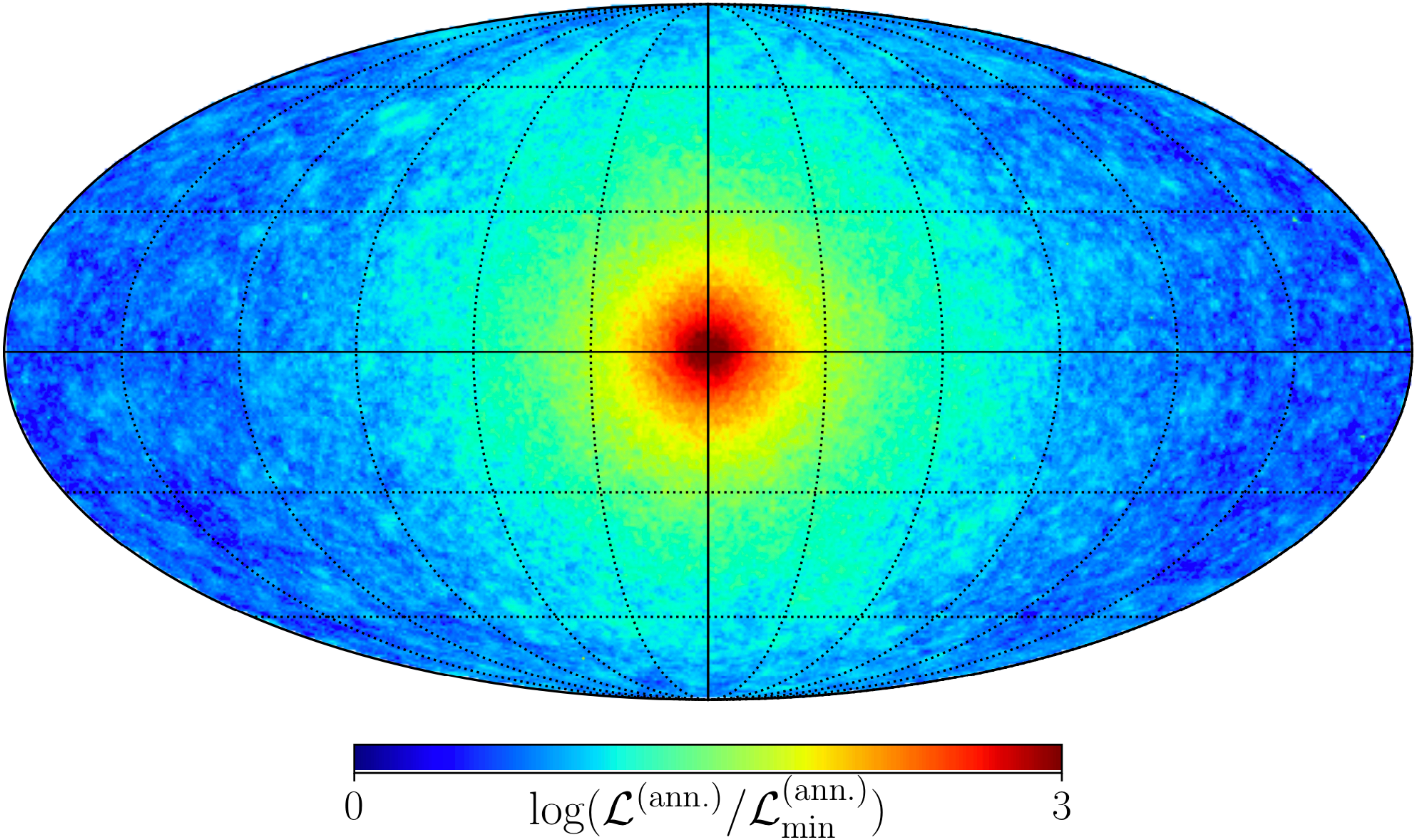
[Latte suite of FIRE-2 Simulations
Hopkins+ (2018)]



The Era of Dark Matter Astronomy?

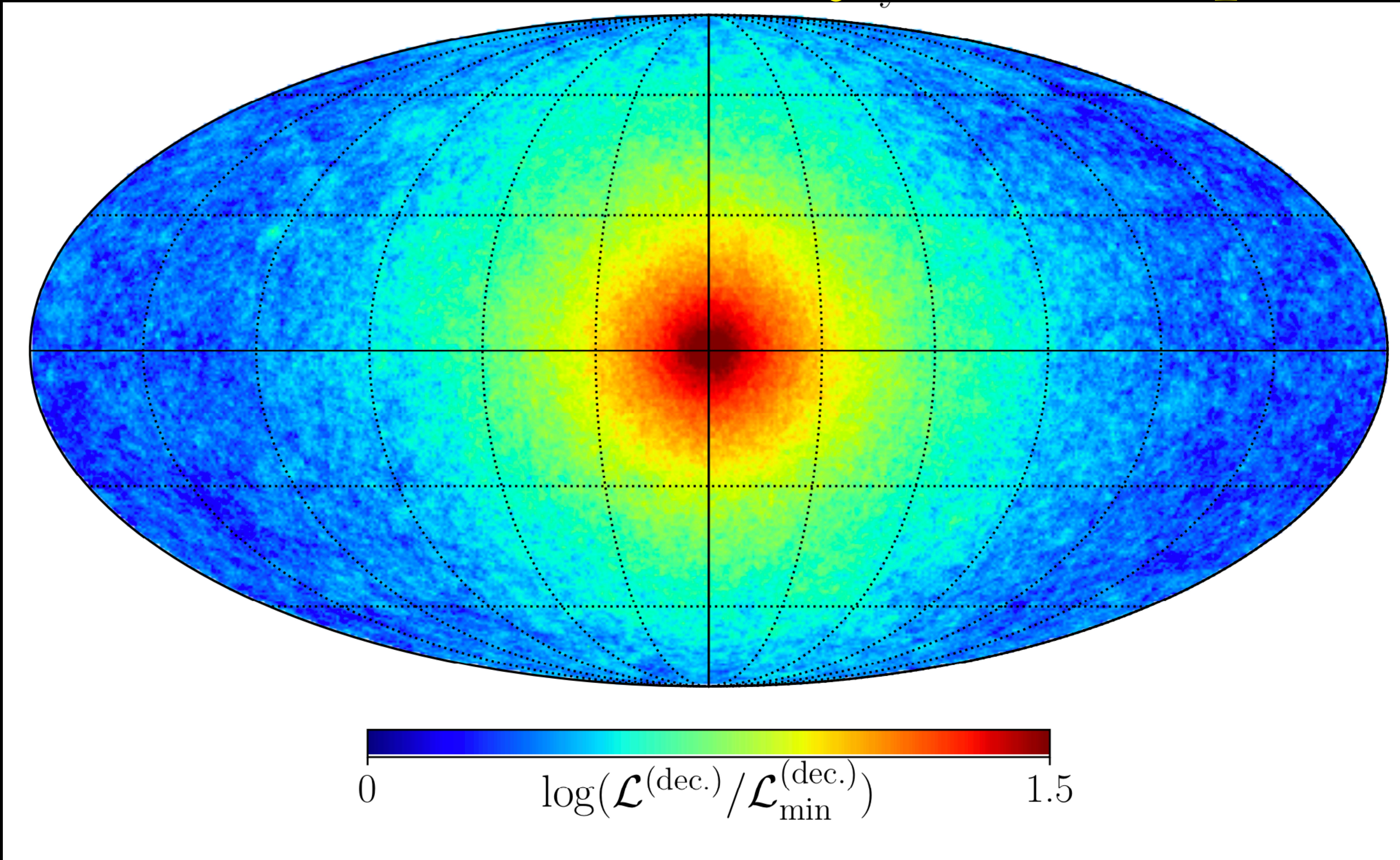
Zhong, Valli, Abazajian 2003.00148

Dark Matter Annihilation Flux Map



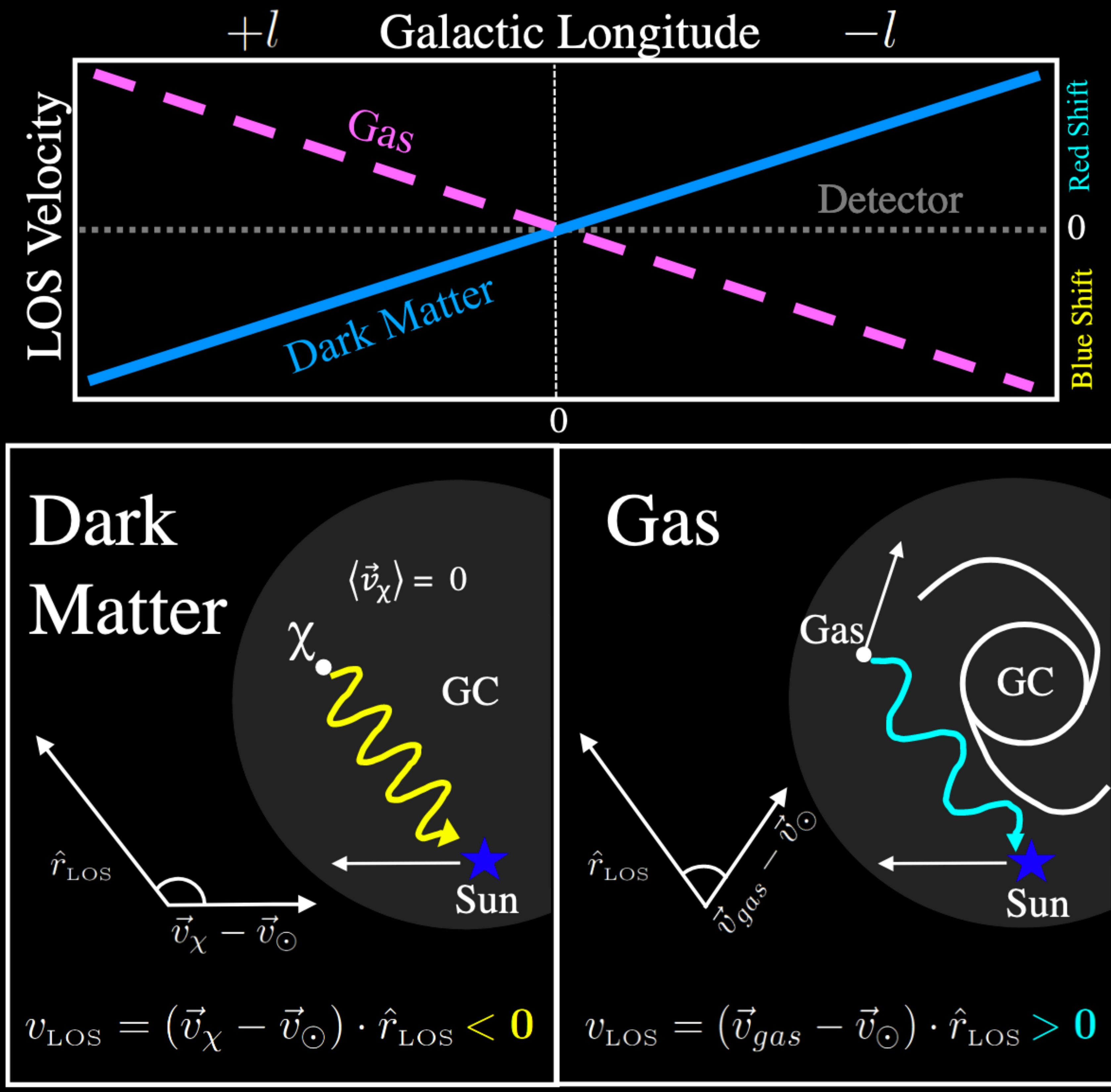
Zhong, Valli, Abazajian 2003.00148

Dark Matter Decay Flux Map



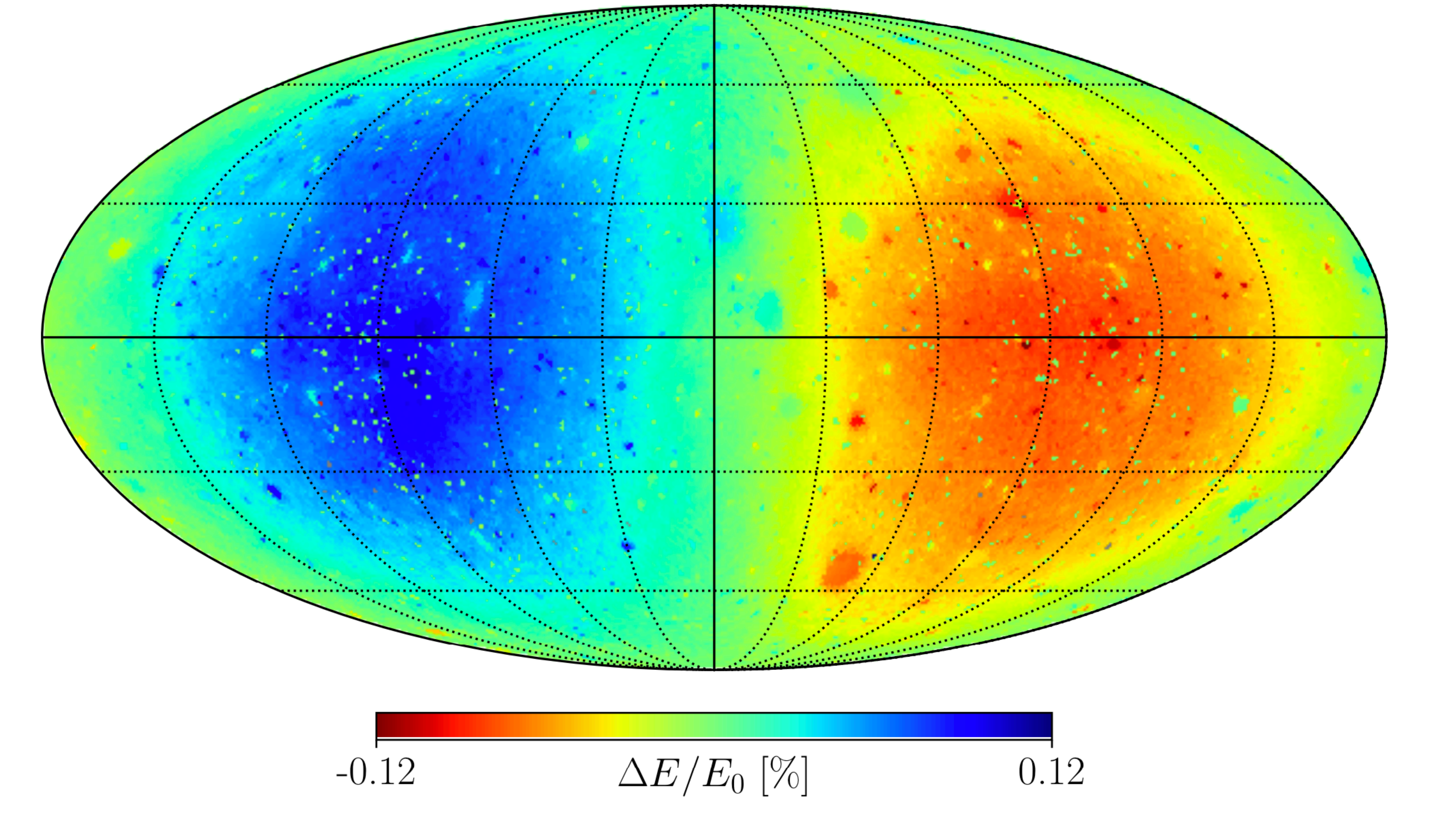
Zhong, Valli, Abazajian 2003.00148

Much More Information Is Available…



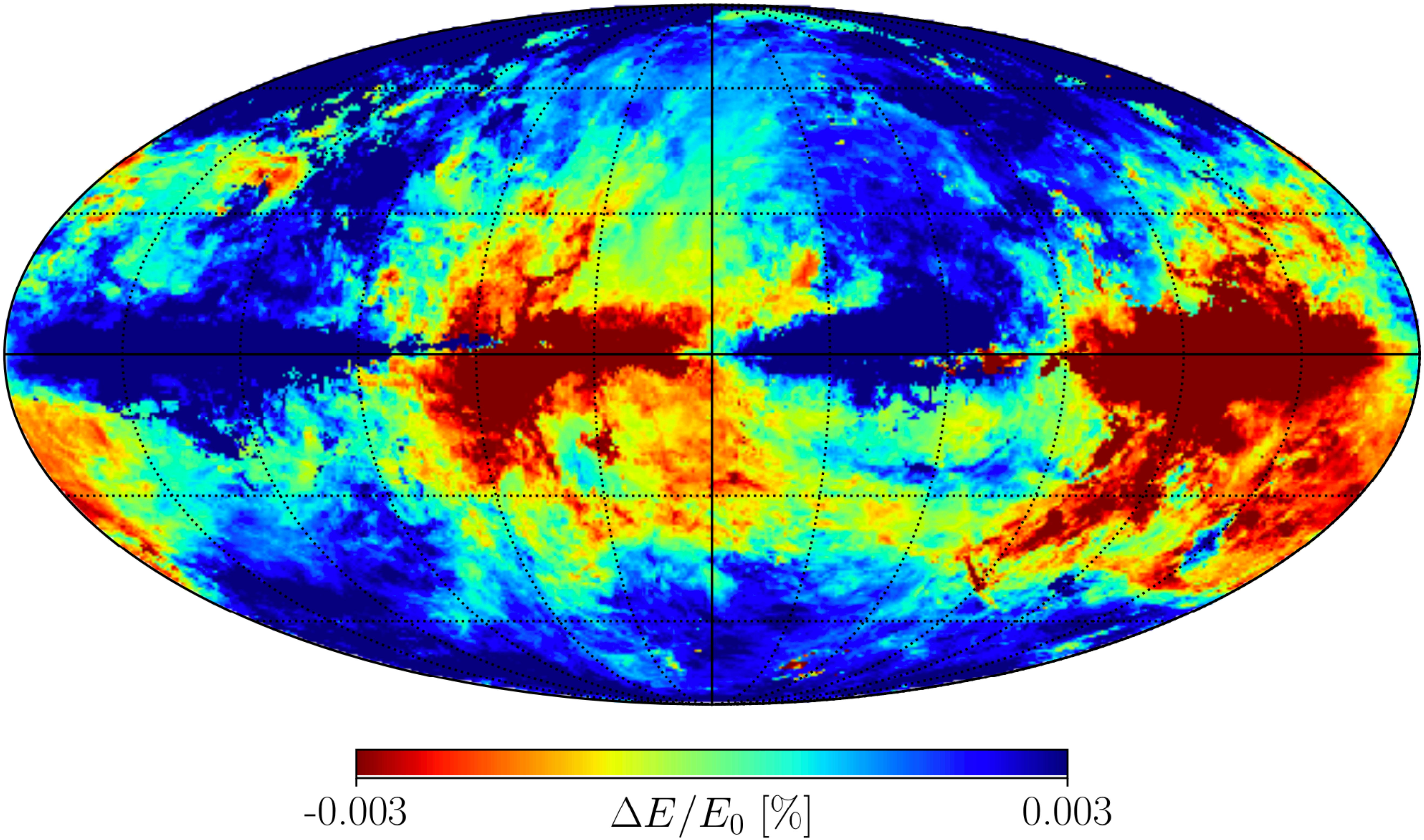
Speckhard+ 1507.04744

Dark Matter Doppler Energy Shift



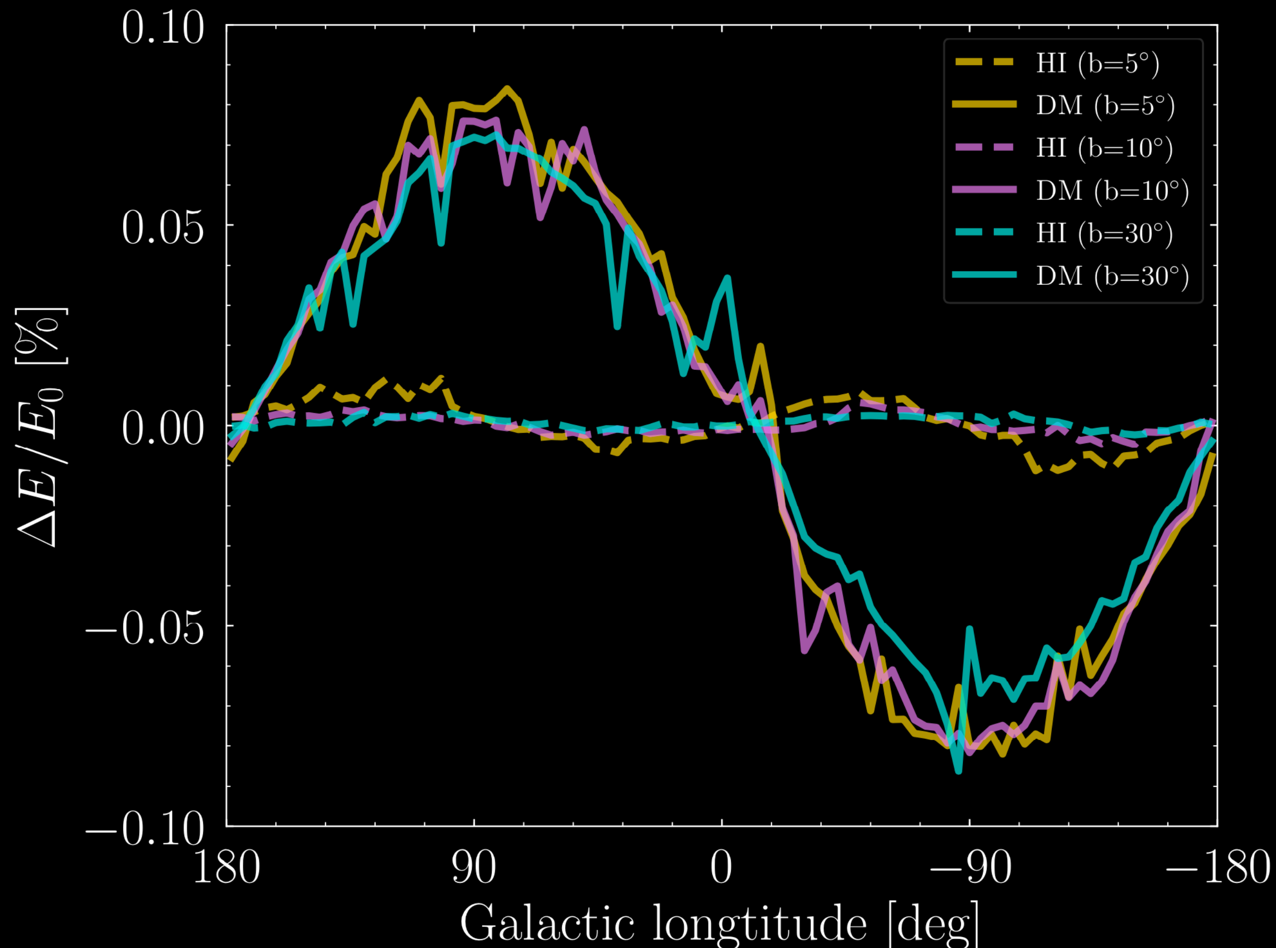
Zhong, Valli, Abazajian 2003.00148

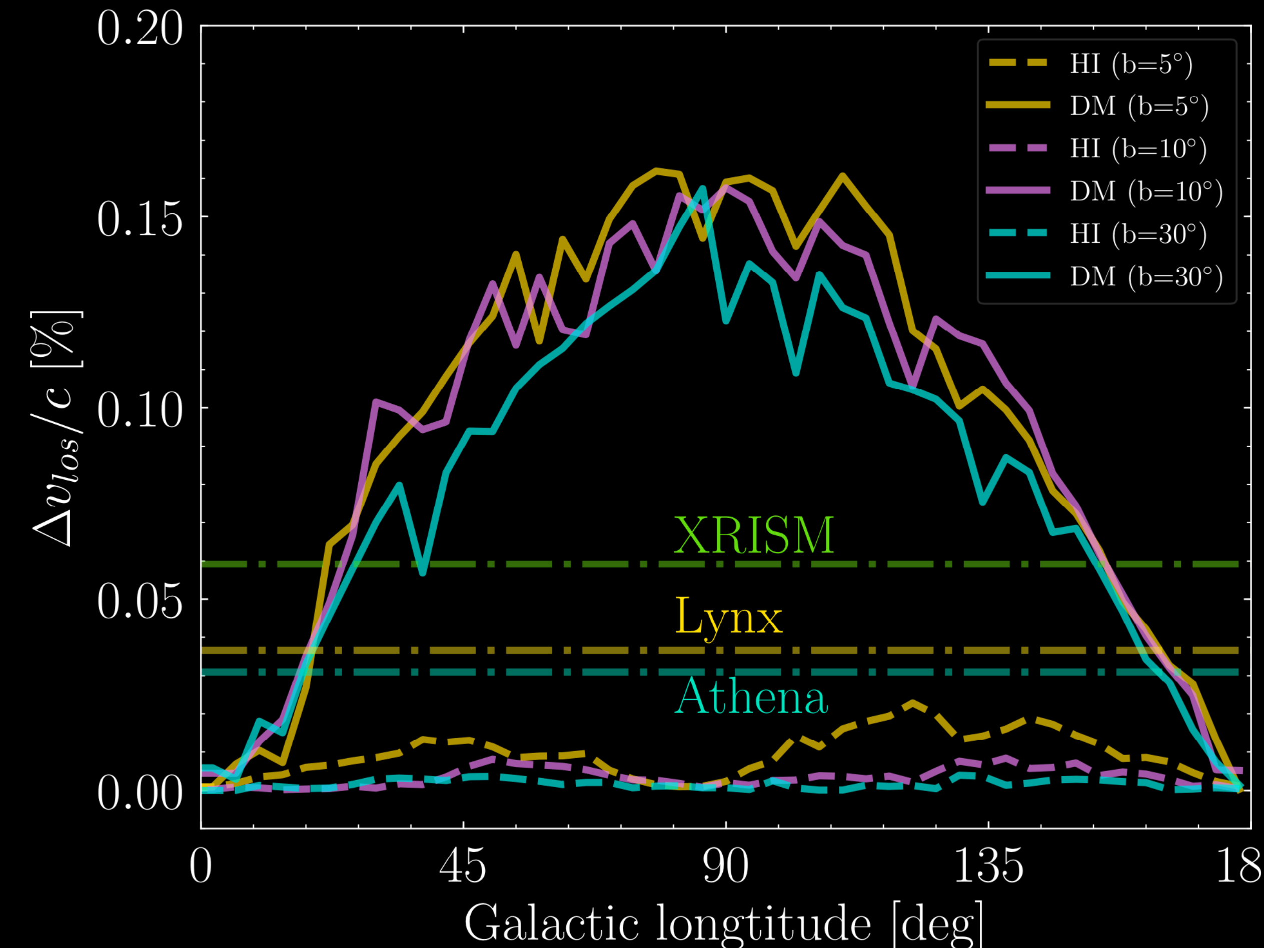
HI Gas Velocity Map from HI4PI Survey



Zhong, Valli, Abazajian 2003.00148

Dark Matter Velocity Spectroscopy: Differentiating Dark Matter from Gas Lines/Features





Similar to previous result, more contrast with gas

Can be enhanced with stacking in longitudinal symmetry

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Dark Matter Velocity Spectroscopy: Differentiating Dark Matter from Gas Lines/Features

X-ray Mission	**Lynx**	**Athena**	**XRISM**
Energy Resolution [eV] (FWHM)	3	2.5	5
Effective Area [cm^2] (@ 3.5 keV)	4000	6000	250
Exposures for $\boldsymbol{5\sigma}$ *detection*			
Low X-ray background case	23 ks	10 ks	3.9 Ms
High X-ray background case	110 ks	52 ks	15 Ms

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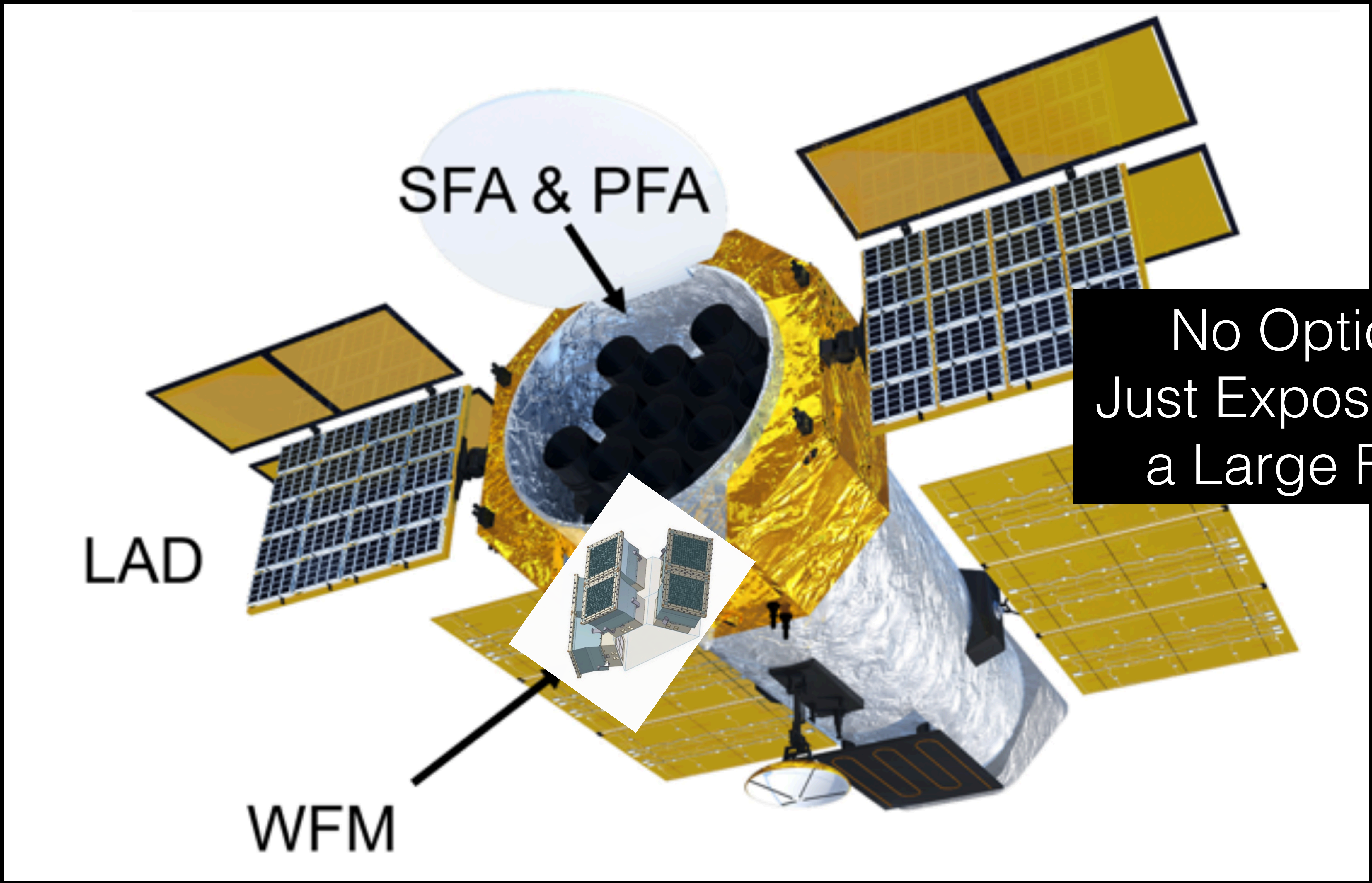
The Power of Pure Counts:
The Wide Field Monitor aboard the Enhanced X-ray Timing Explorer



No Optics,
Just Exposure to
a Large FOV

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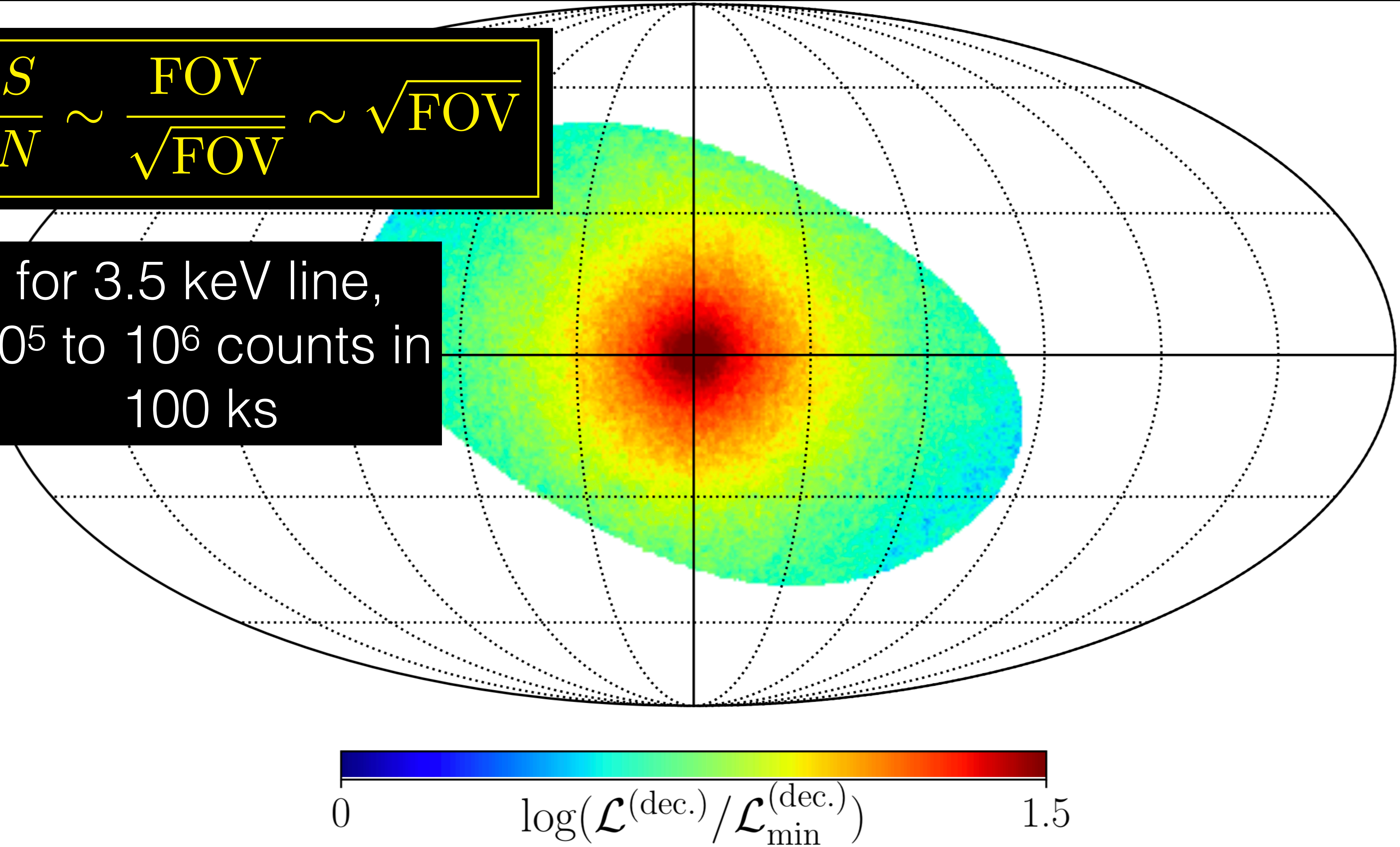
The Power of Pure Counts: WFM Field of View

$$\frac{S}{N} \sim \frac{\text{FOV}}{\sqrt{\text{FOV}}} \sim \sqrt{\text{FOV}}$$

for 3.5 keV line, 10^5 to 10^6 counts in 100 ks



Zhong, Valli, Abazajian 2003.00148

Summary: Gamma Ray Searches

- The gamma-ray excess in the Galactic Center (GCE) is a whopping signal (>13σ) that is <u>***consistent with dark matter annihilation***</u> of ~40 GeV WIMPS to ***b***-quarks or ~10 GeV to ***τ***-leptons.

- Since 2010, we have known of an astrophysical interpretation of the GCE: a standard population of millisecond pulsars. Spectrum, flux and morphology are consistent with MSPs, most closely following stellar bulge. Luminosity function is also consistent.

- Non-Poissonian statistical methods are of interest, but are likely dominated by mis-modeling.

- Stellar Bulge templates are > 10σ better fits to the GCE than dark matter templates

- Including the stellar bulge allows placing the strongest limits yet on WIMP Dark Matter from the sky with Fermi-LAT data, independent of diffuse modeling uncertainties.

Summary: X-ray Searches

- ***Sterile neutrino dark matter*** has been investigated for 26+ years; indirect detection via cluster & field galaxy searches proposed in 2001.
- An unidentified line at ~3.55 keV has been detected at 4σ to 5σ in two independent samples of stacked X-ray clusters with *XMM-Newton*. It has been seen in several followup observations.
- ***There is tension*** in the line not being seen in blank sky, Draco & M31 observations. Claims of a factor of >10 “rule out” of 3.5 keV line are overstated.
- ***Velocity spectroscopy*** of differentiating line from gas is promising, but even more promising is ***pure counts***.
- Future follow up observations:
  - 2020: *eROSITA*
  - 2021: *Micro-X, XQC,* X-ray CubeSAT
  - 2022: *XRISM*
  - 2027*: eXTP*
  - 2030+: *ATHENA*, *Lynx*