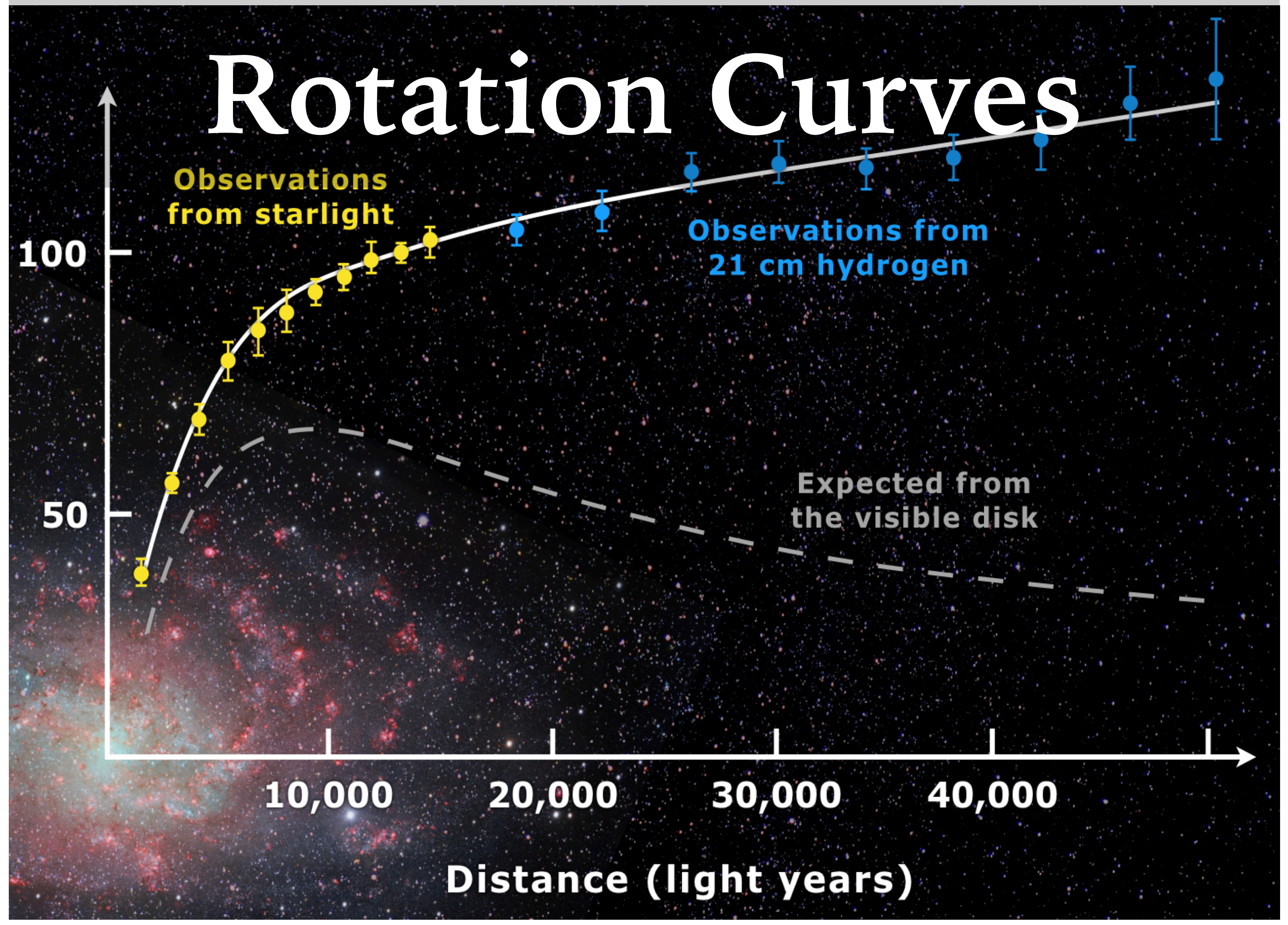
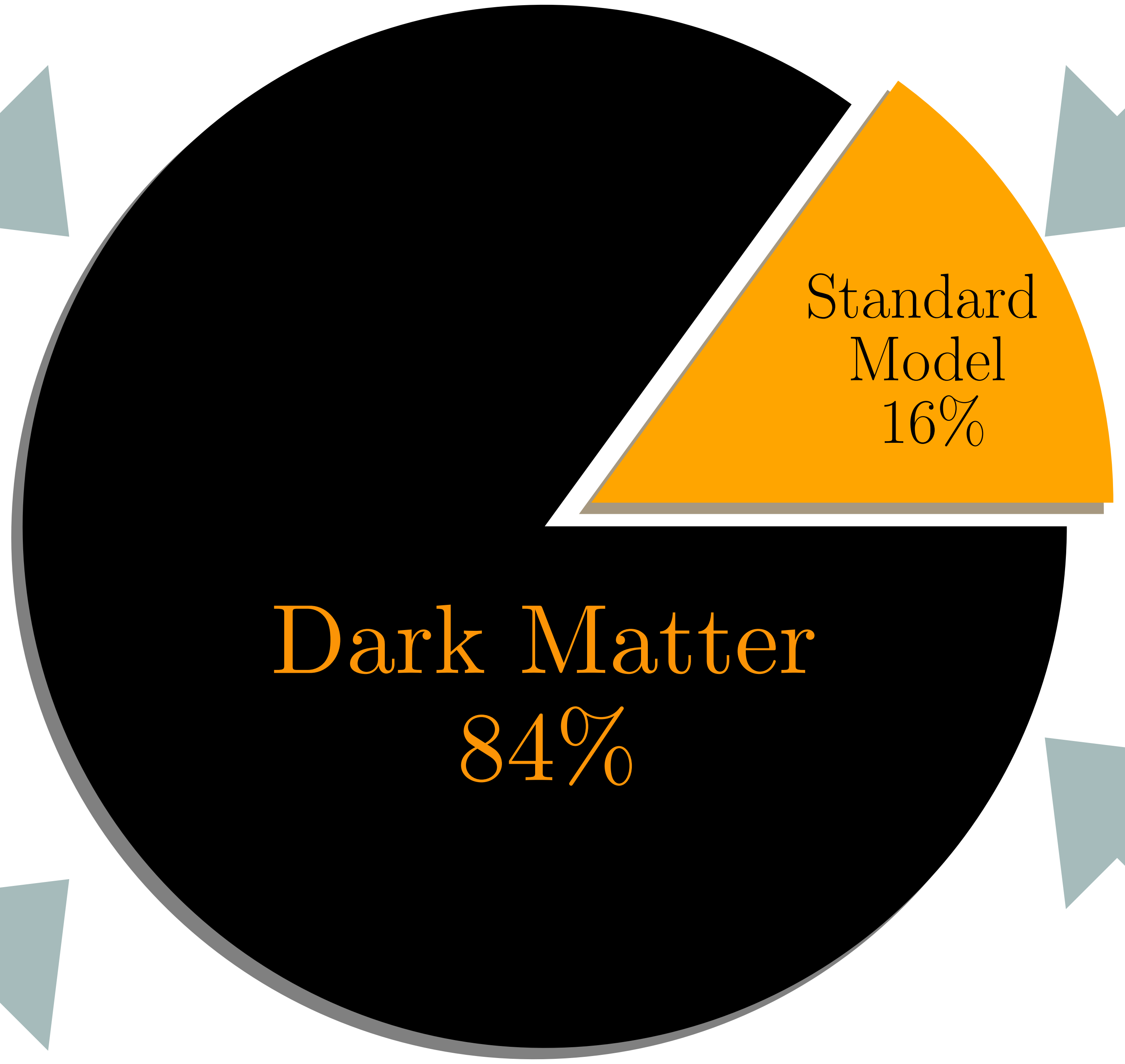
Massachusetts
Institute of
Technology

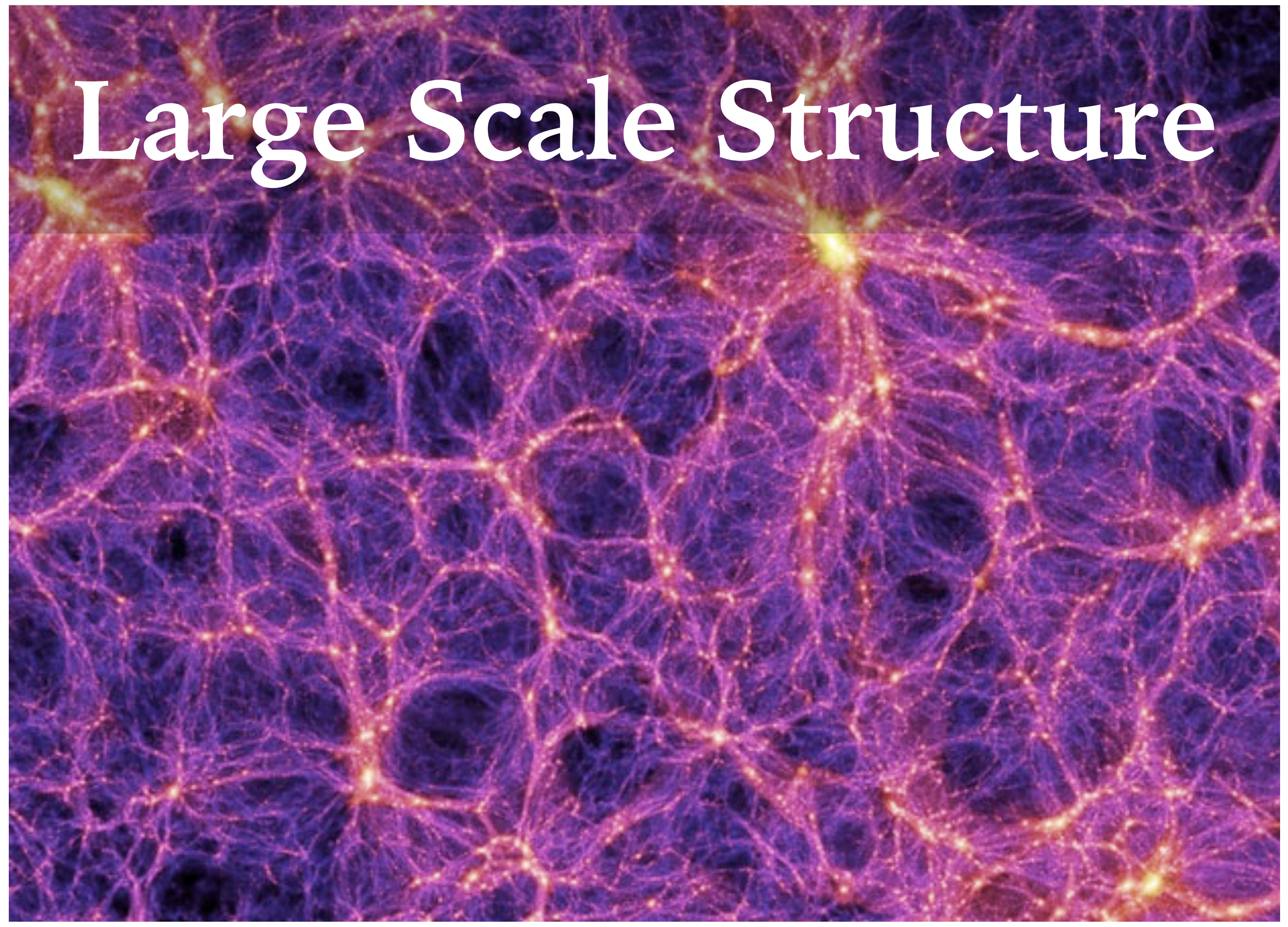
WAS THERE A 3.5 KEV LINE?

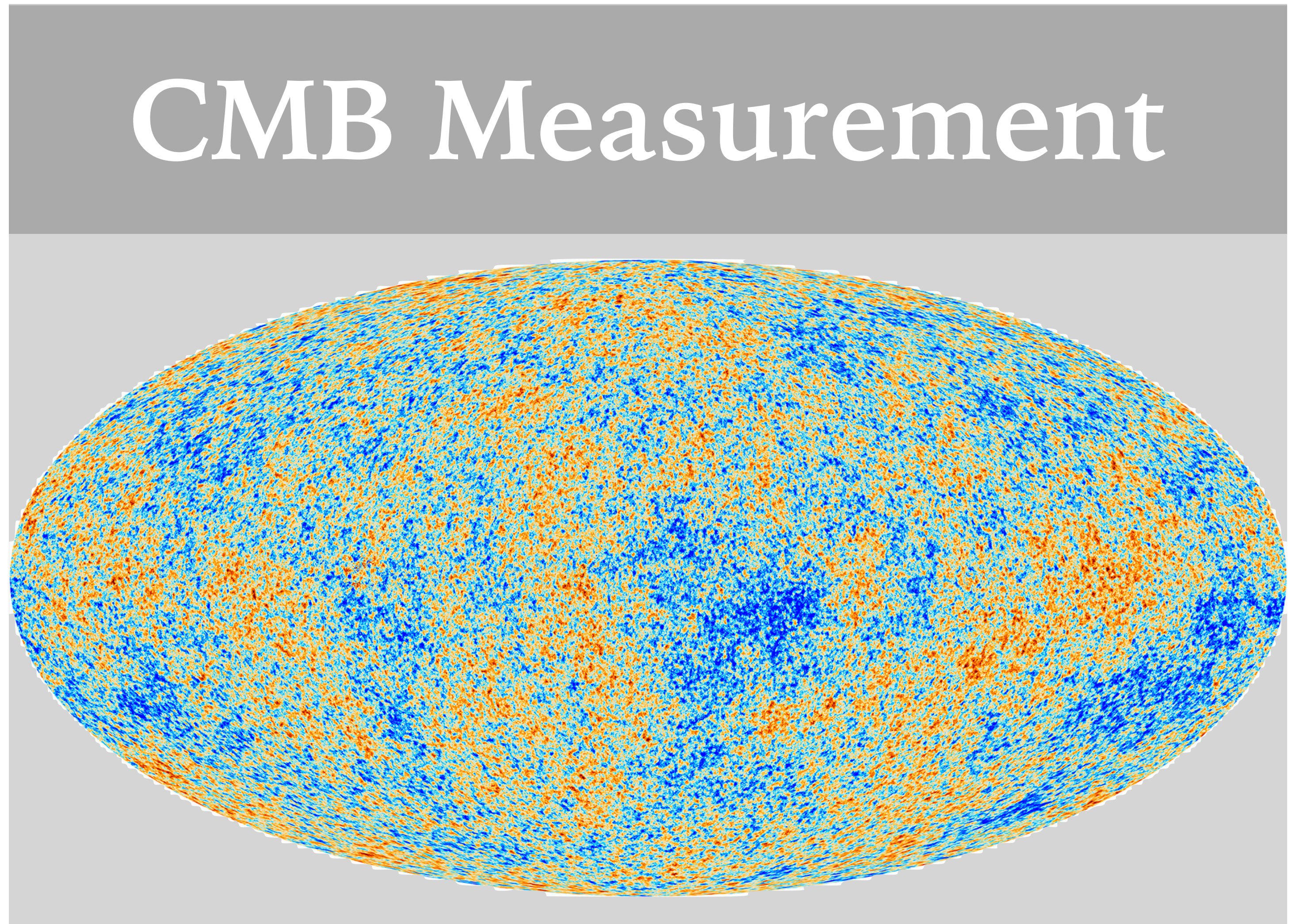
Joshua W. Foster

THE DARK MATTER MYSTERY



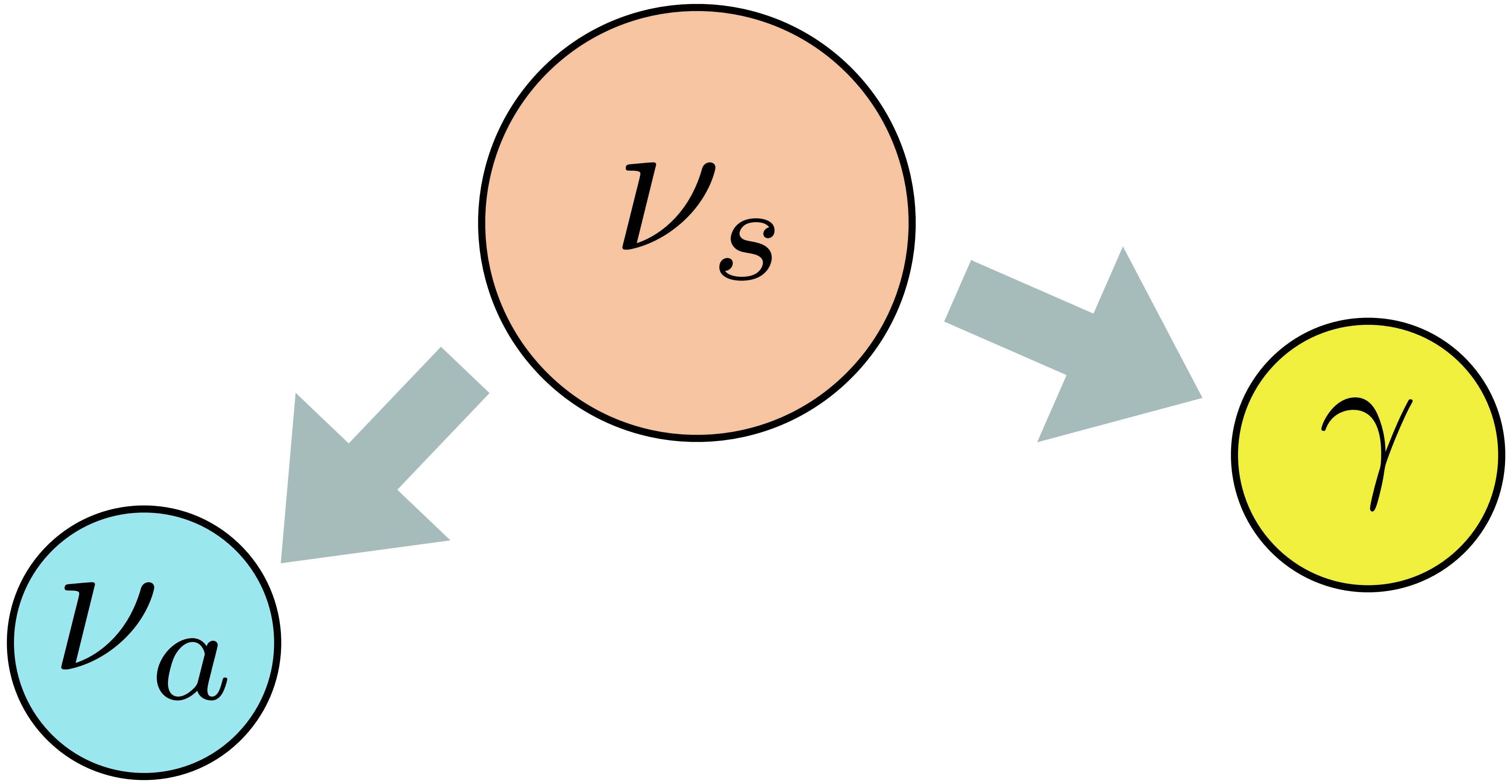






STERILE NEUTRINOS AS THE DARK MATTER

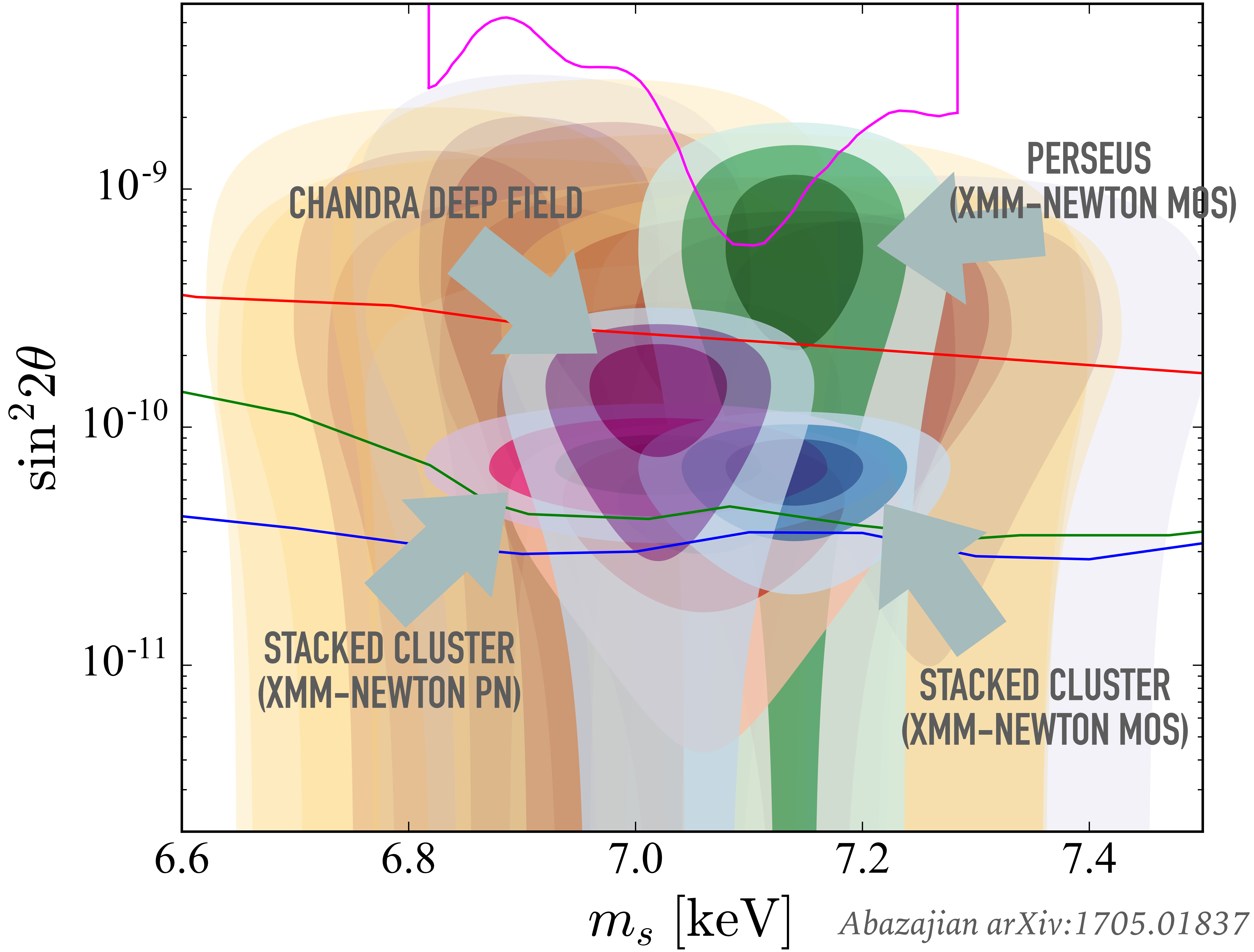
- Sterile neutrinos can provide a keV-scale relic that comprises the DM
  - Dodelson-Widrow, Shi-Fuller
- Radiative decay of sterile can produce detectable *X*-ray lines
- Other avenues of constraint
  - LSS/gravitational lensing
  - HUNTER experiment
- More generally, motivation for looking at keV-scale observables



$$\Phi \approx 0.26\,\mathrm{photons/cm^2/s/sr} \quad \times \left(\frac{m_\chi}{7.0\,\mathrm{keV}}\right)^4 \left(\frac{D}{10^{29}\,\mathrm{keV/cm^2}}\right) \left(\frac{\sin^2(2\theta)}{10^{-10}}\right)$$

SEARCHES FOR THE 3.5 KEV LINE CIRCA 2017

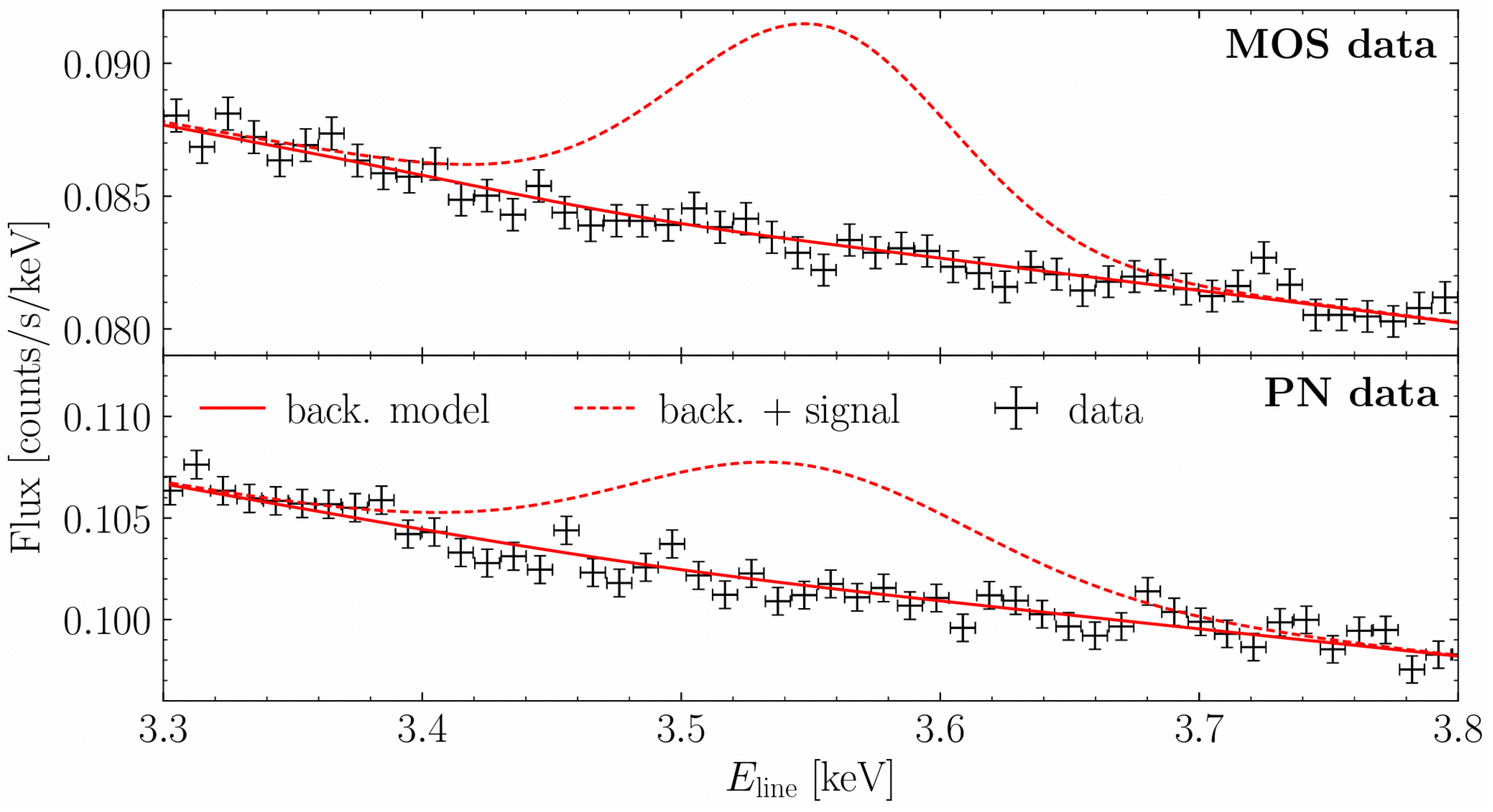
- Mixed evidence for 3.5 keV line
- Some high significance detections
  - Claimed 4.5σ evidence from galaxy clusters observed with XMM-Newton
  - Claimed 3.5σ evidence from Chandra Deep Field
- Marginal significance detection in Perseus with Suzaku
  - Potential tension with expected morphology
- No detection in stacked clusters analysis with Suzaku
- Tension with constraints from dwarf galaxies, M31

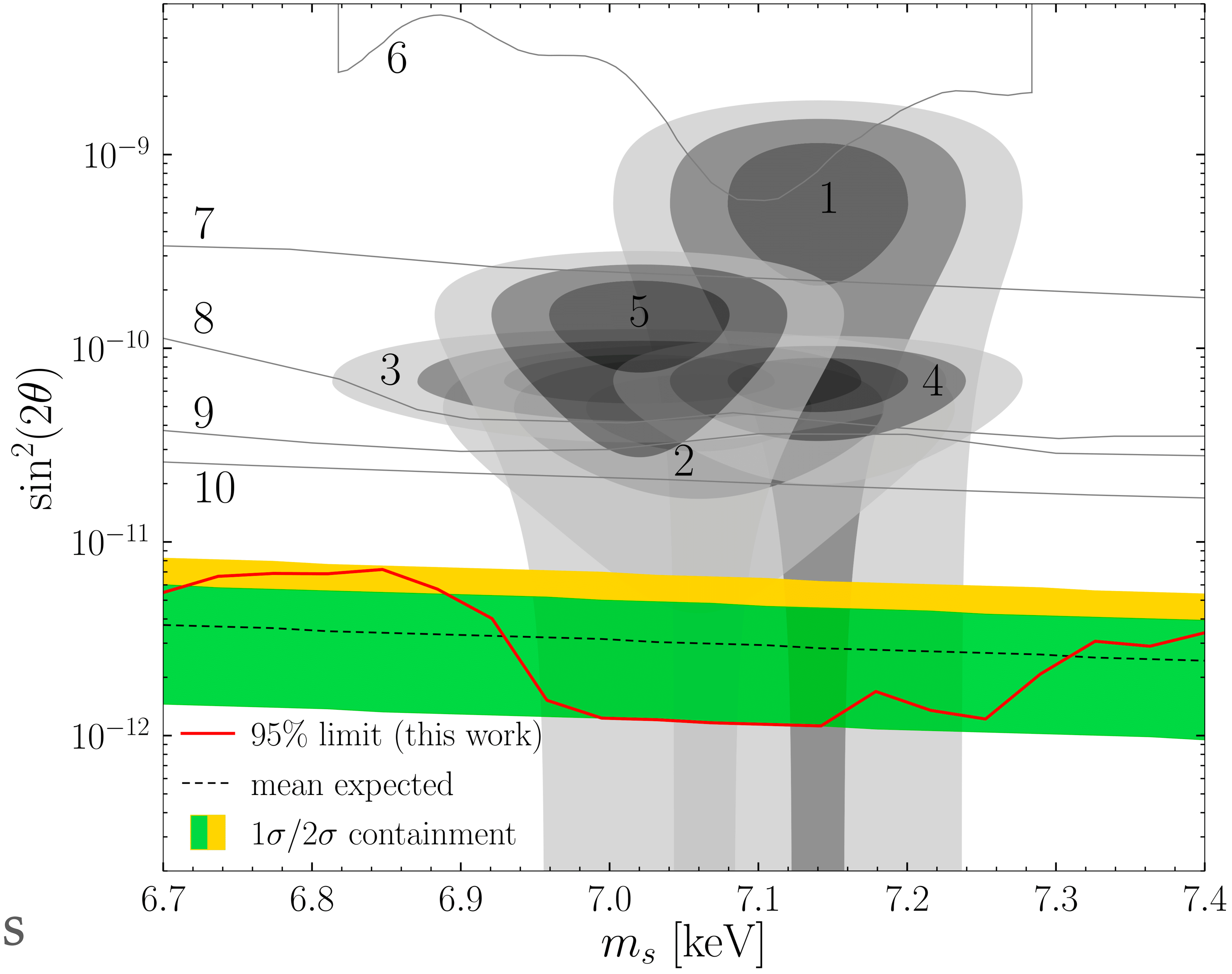


Abazajian arXiv:1705.01837

CONSTRAINING THE 3.5 KEV LINE WITH BLANK SKY DATA

C. Dessert+ Science 2018





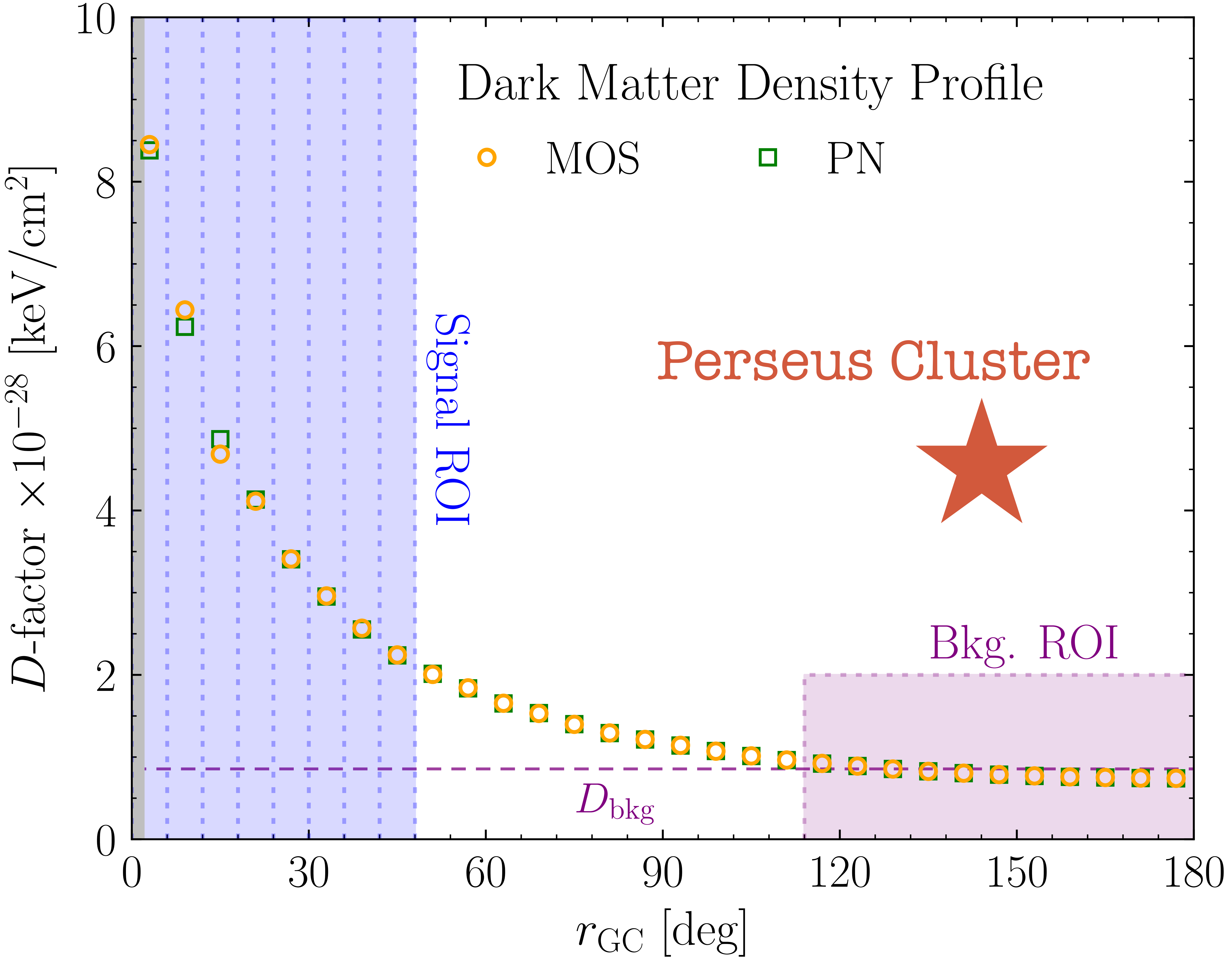
- Controversy generated by blank sky constraints
  - Technical responses: Boyarsky et al. 2004.06601, Abazajian 2004.06170, Dessert et al. 2006.03974
- **Complaints**: windowed analysis, background lines, continuum modeling, density profile, etc.

BLANK SKY SEARCHES WITH GAUSSIAN PROCESS MODELING

J.F. et al. 2102.02207 [astro-ph.CO]. PRL

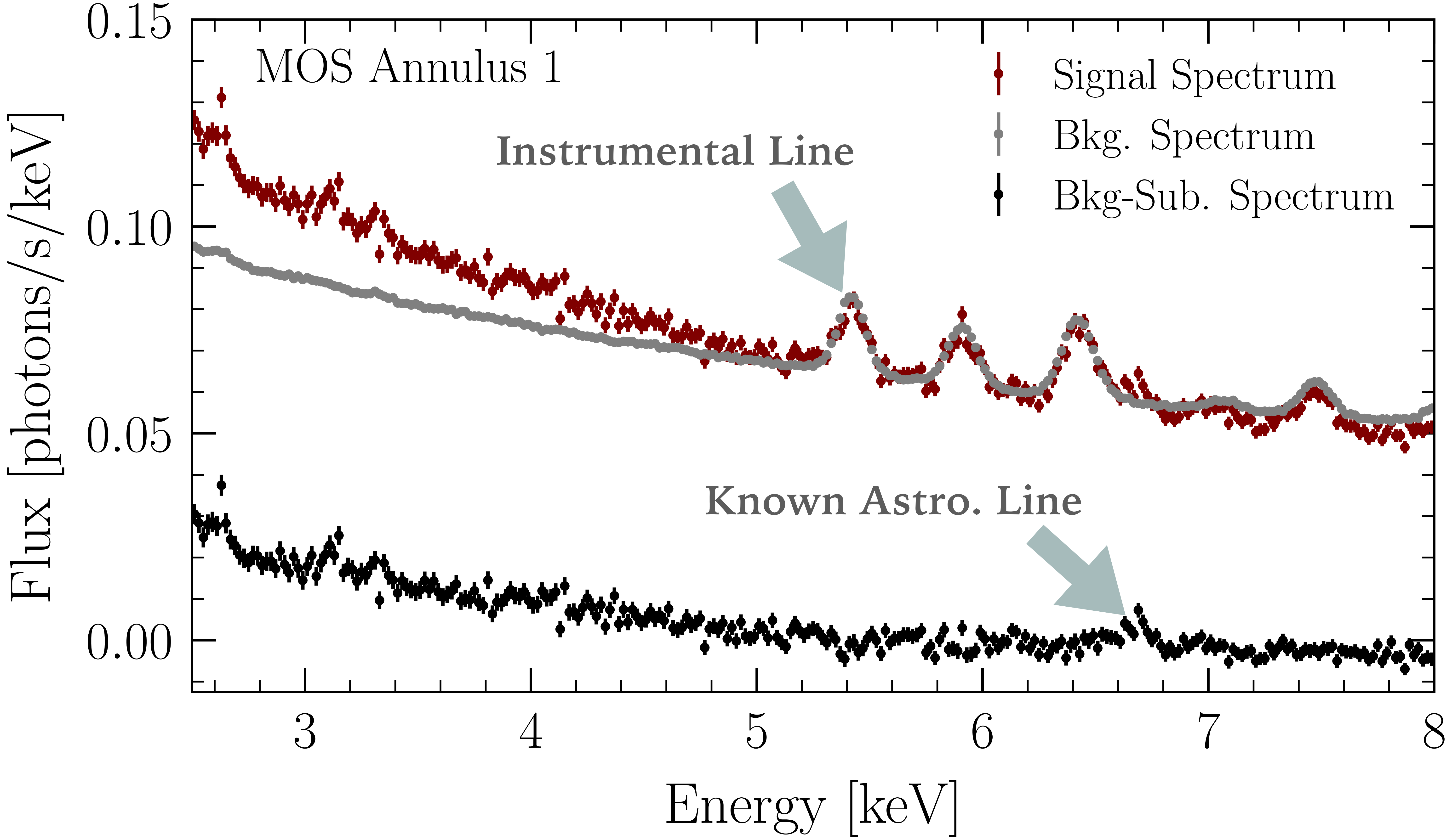
BLANK SKY SEARCHES FOR DECAYING DARK MATTER

- Milky Way halo bright in DM decay compared to Perseus cluster
  - Less but closer DM
- Cleaner backgrounds in blank sky data
  - 5000 seconds blank sky data ~ 300,000 seconds of Perseus cluster data
- Any observation could be a blank sky observation
- Motivates using all data collected by XMM-Newton
  - 20 years of data
  - Quality cuts, about 50% data acceptance

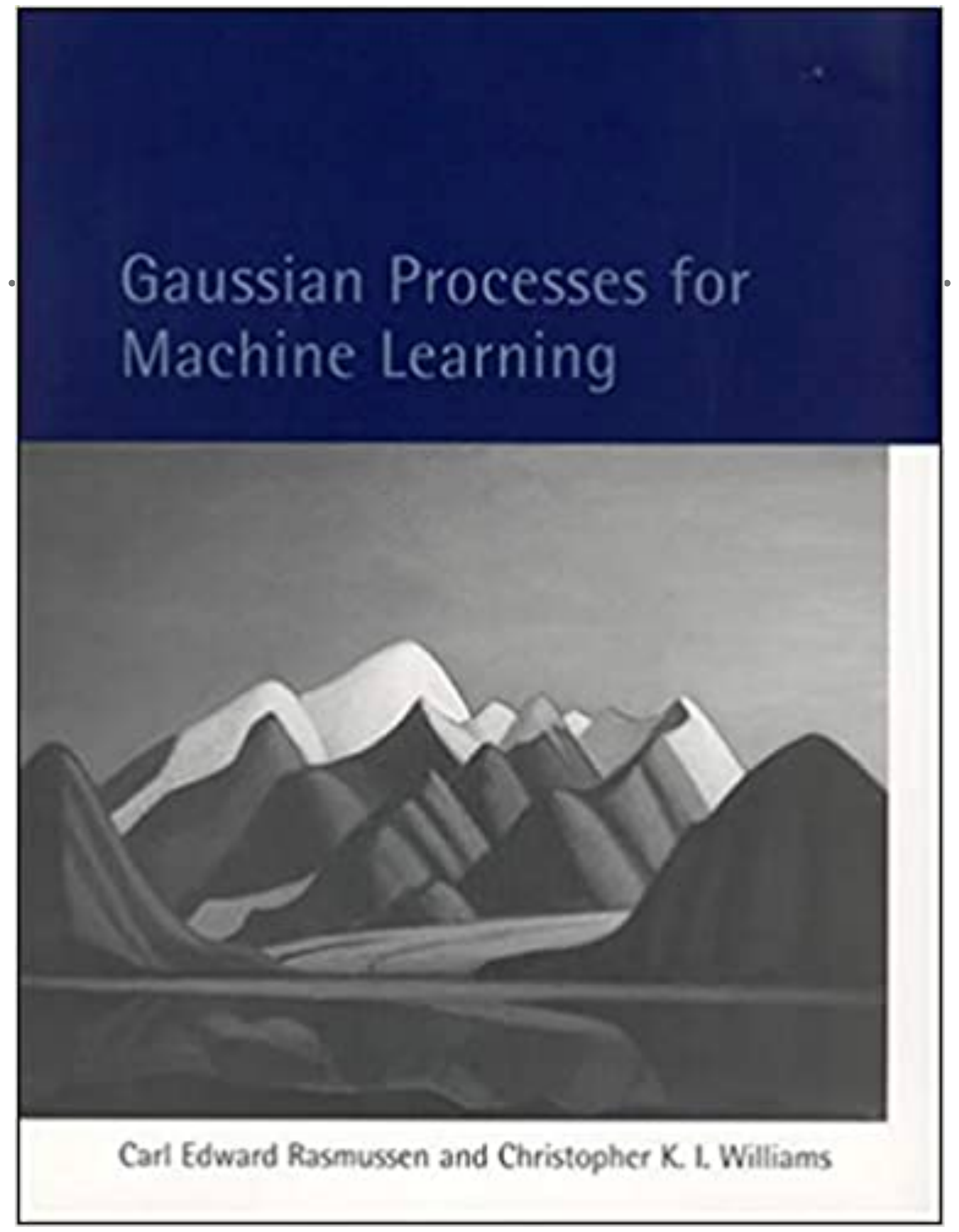


AN IMPROVED BLANK SKY ANALYSIS

- Large statistics, small errors
  - Good: more constraining power
  - Challenge: need high-performining background models
- Even the “background regions” of our analysis are messy
  - Instrumental lines
  - Spectral distortions, miscalibration
- Combine nonparametric GP with gaussian line models to model data



NONPARAMETRIC INFERENCE WITH GAUSSIAN PROCESSES



Gaussian Processes for Machine Learning

Carl Edward Rasmussen and Christopher K. I. Williams

- Start with a series of (gaussian) data

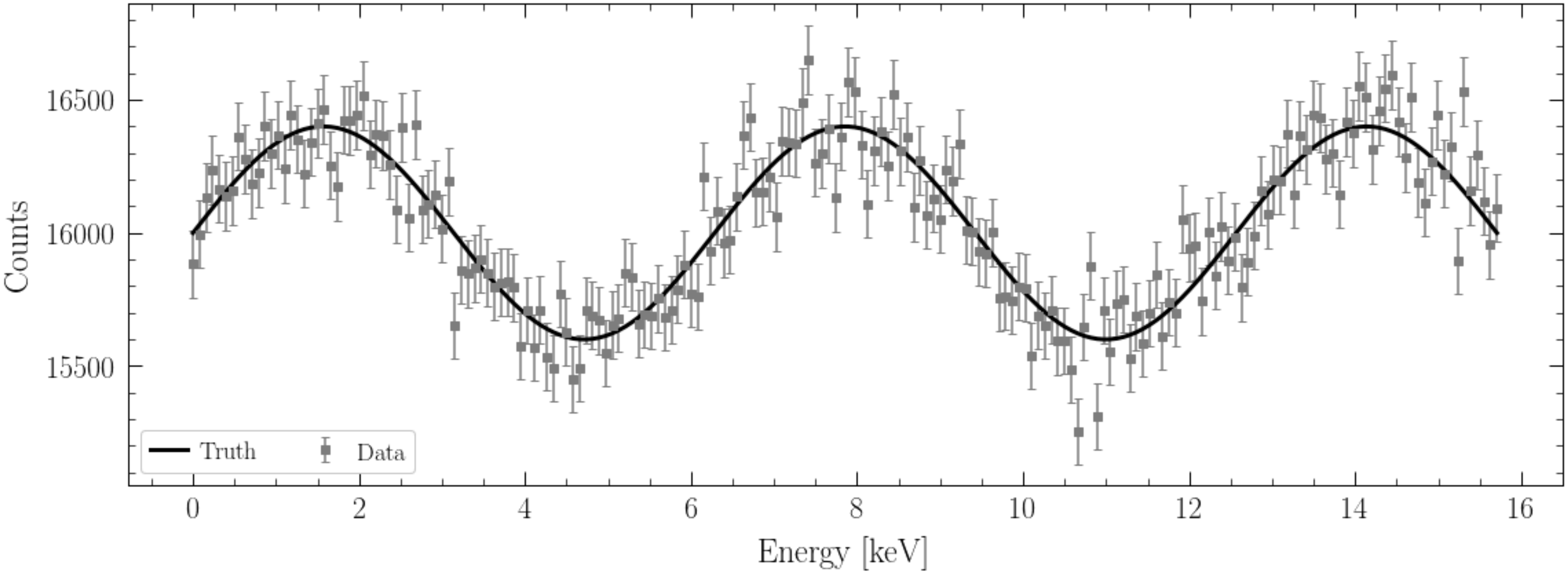
$$\{x_i, y_i\}$$

“Location"

“Value”

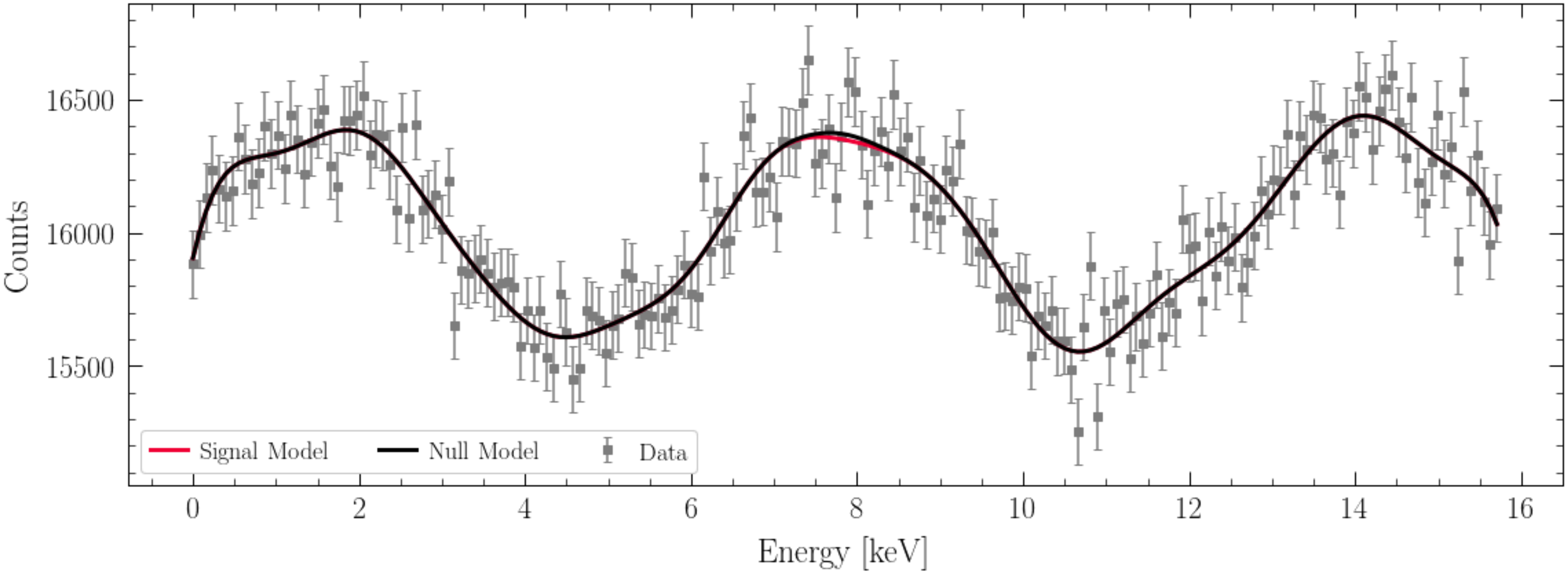
- Describe the data as a single realization of a multivariate Gaussian distribution
  - Specified by a mean (take to be zero for simplicity) and a covariance matrix
- Simplest case: covariance matrix is diagonal.
  - Each value is statistically independent
- Less trivial: endow the data with some covariance based on their “location”

NONPARAMETRIC INFERENCE WITH GAUSSIAN PROCESSES



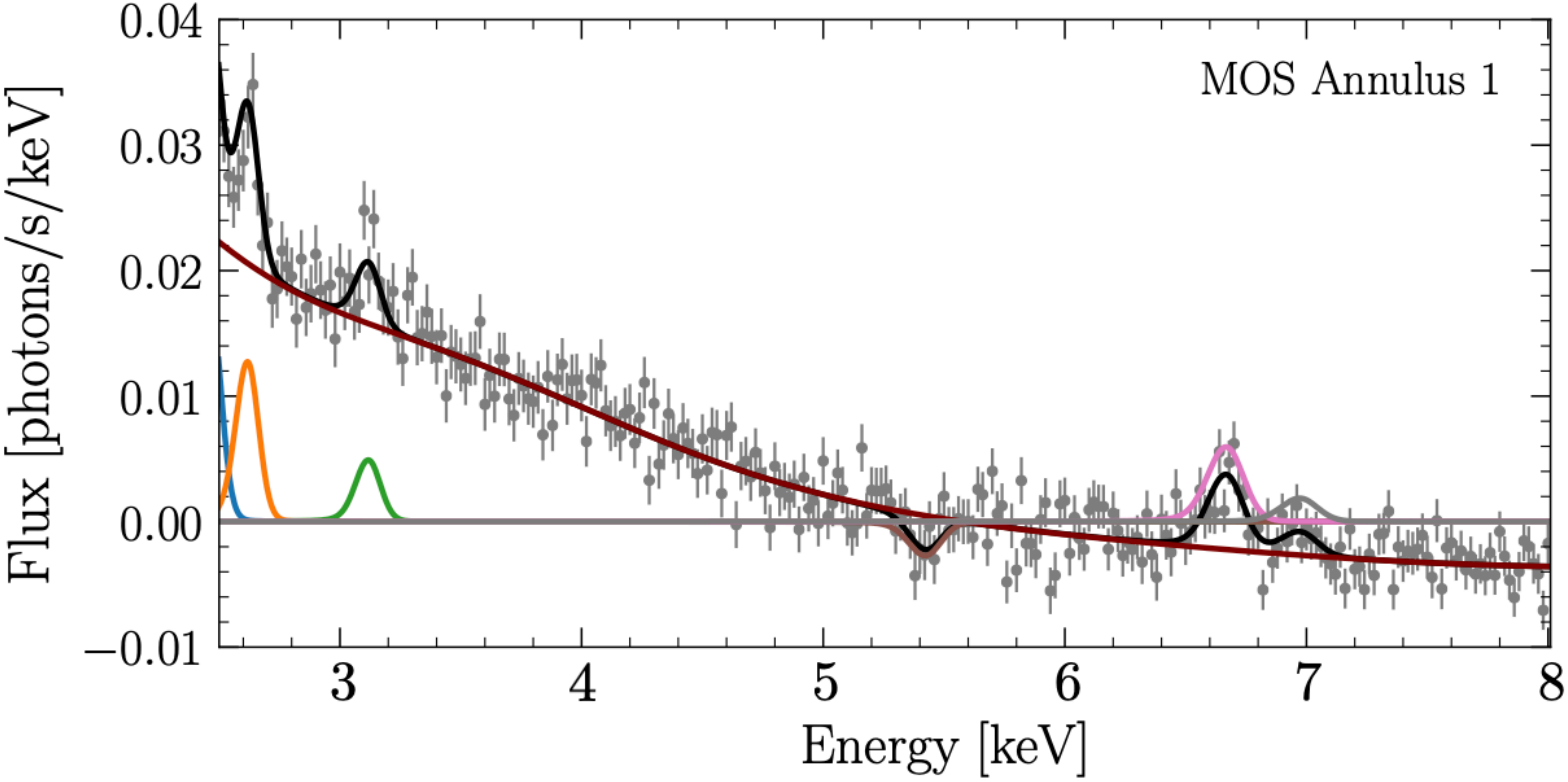
- Nontrivial covariance matrix allows for nontrivial fluctuations in the “model”
- Simplest kernel: double exponential kernel $\mathrm{Cov}(x_i, x_j) = -A_{GP}\mathrm{exp}\left[-\frac{x_i x_j}{2\sigma^2}\right]$

NONPARAMETRIC INFERENCE WITH GAUSSIAN PROCESSES

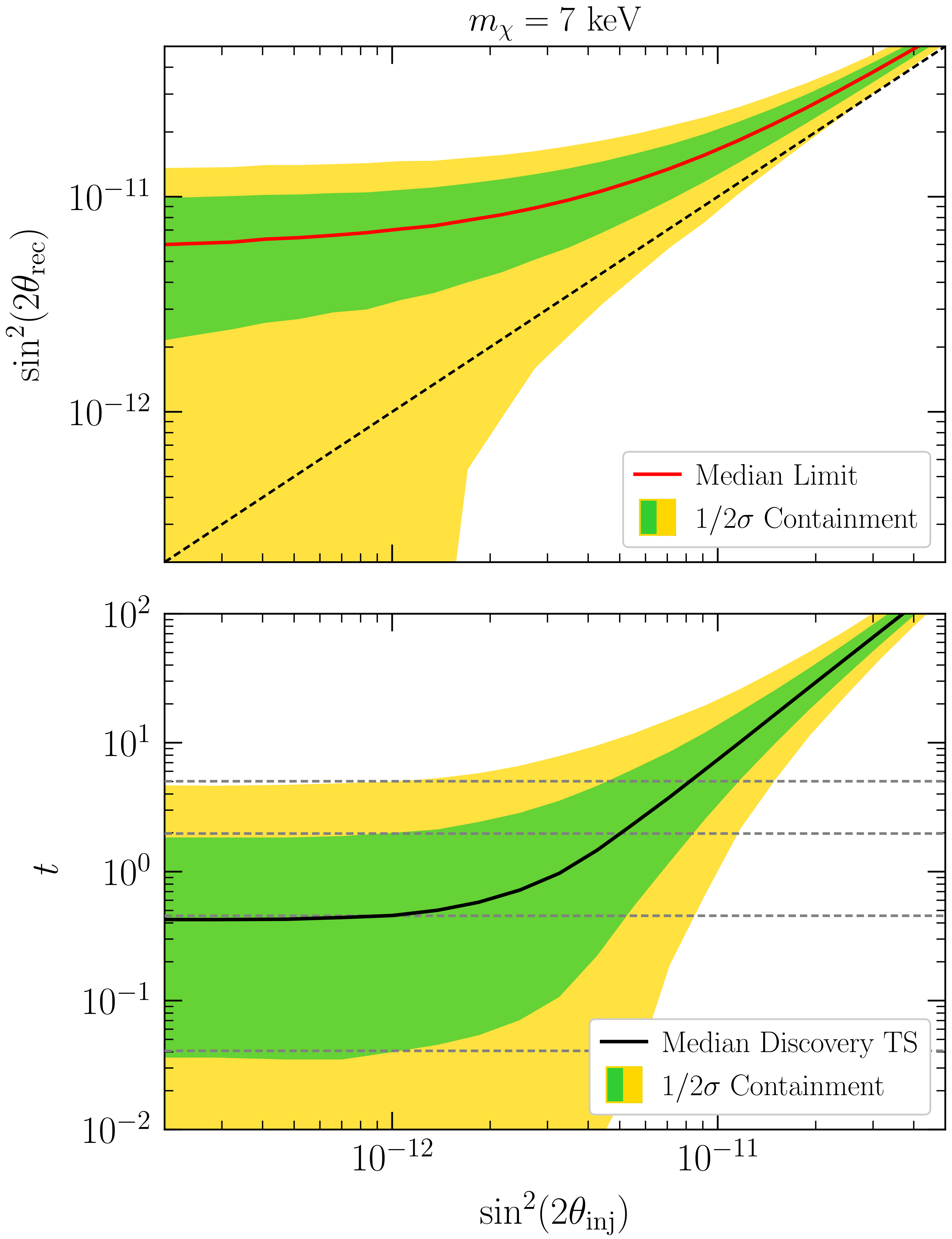


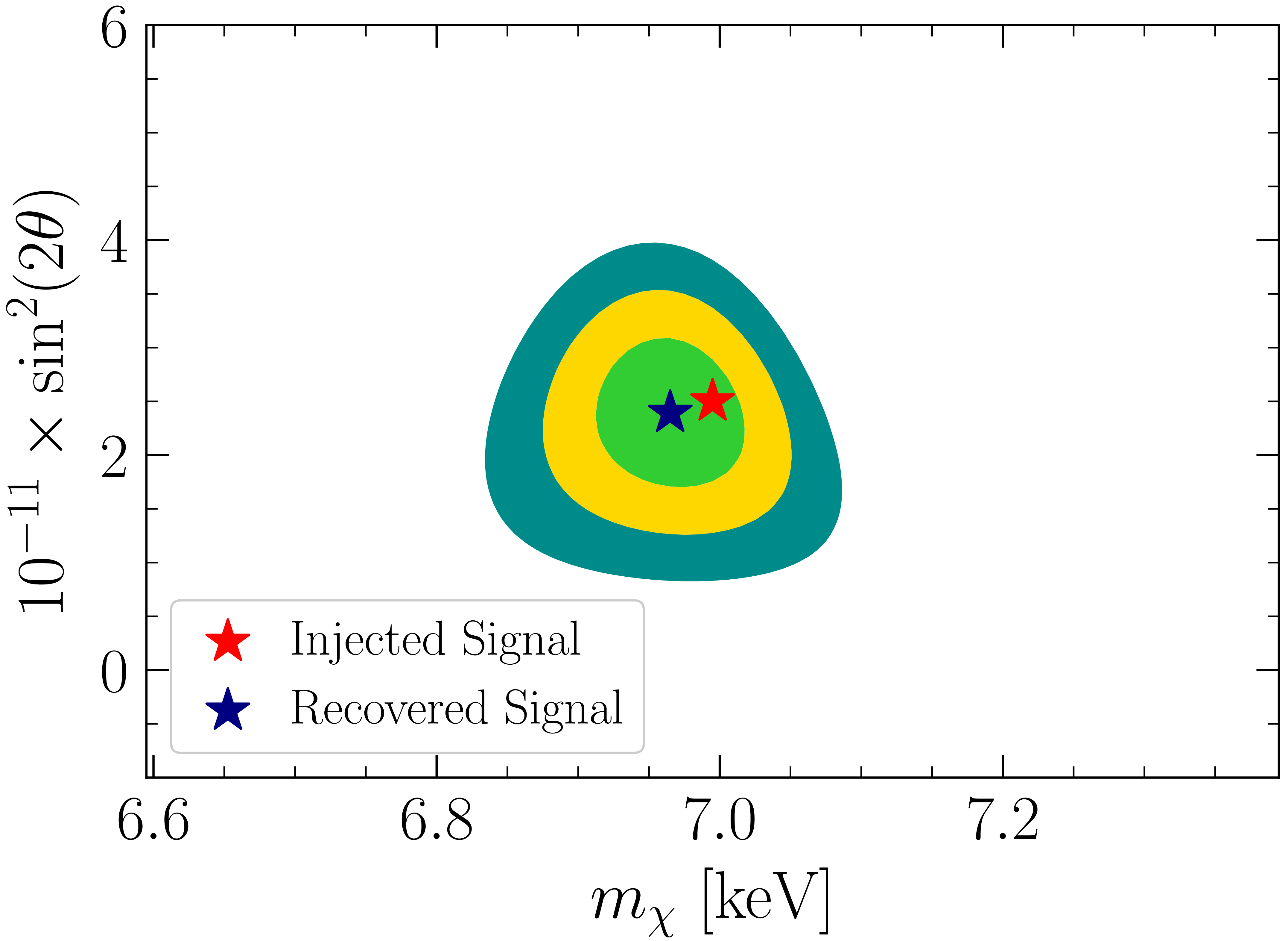
- Quality of fit depends on choice of kernel and hyperparameters
- Danger: small-scale kernel might reduce discovery power

ANALYZING THE BACKGROUND-SUBTRACTED BLANK SKY

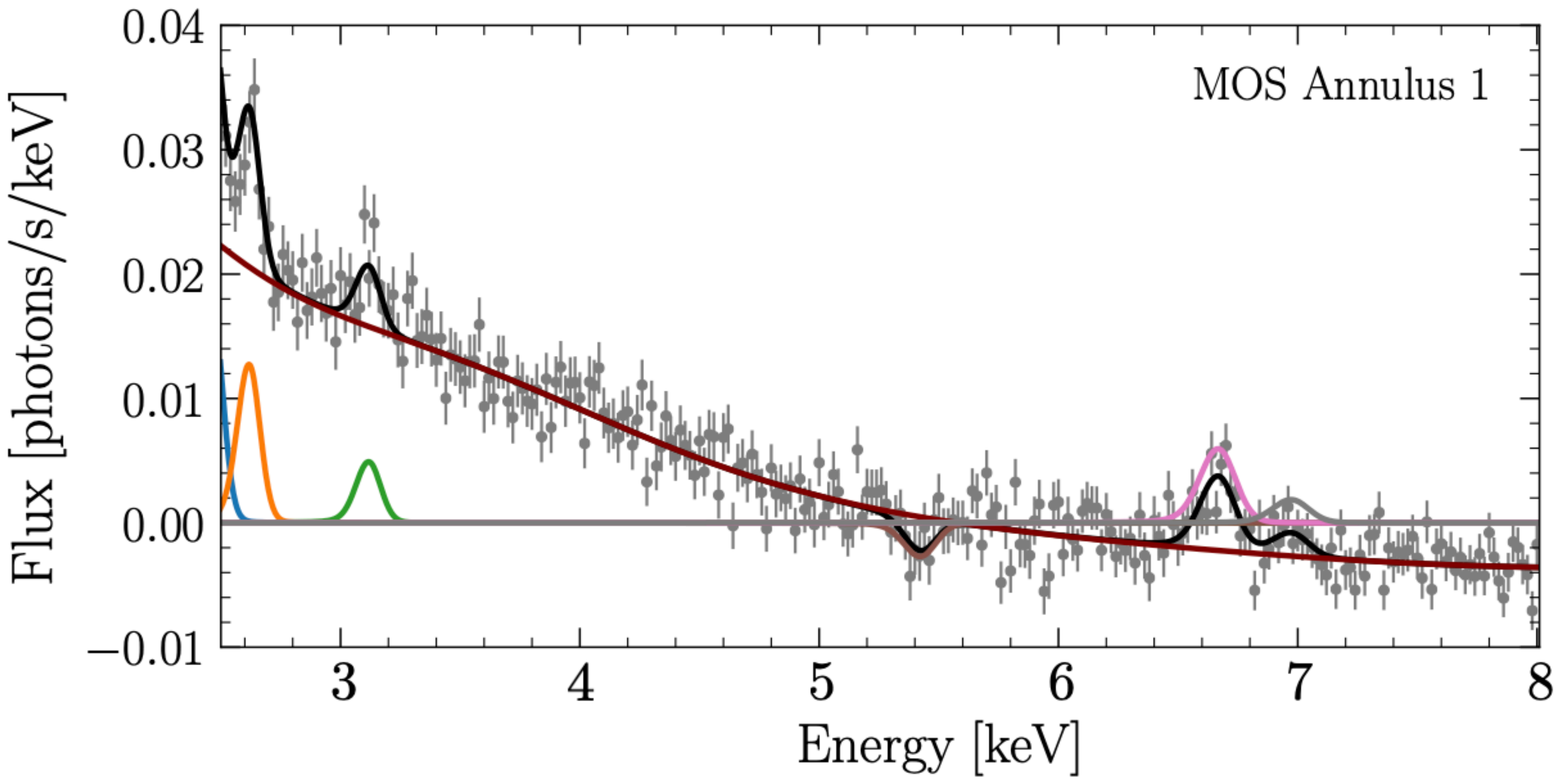


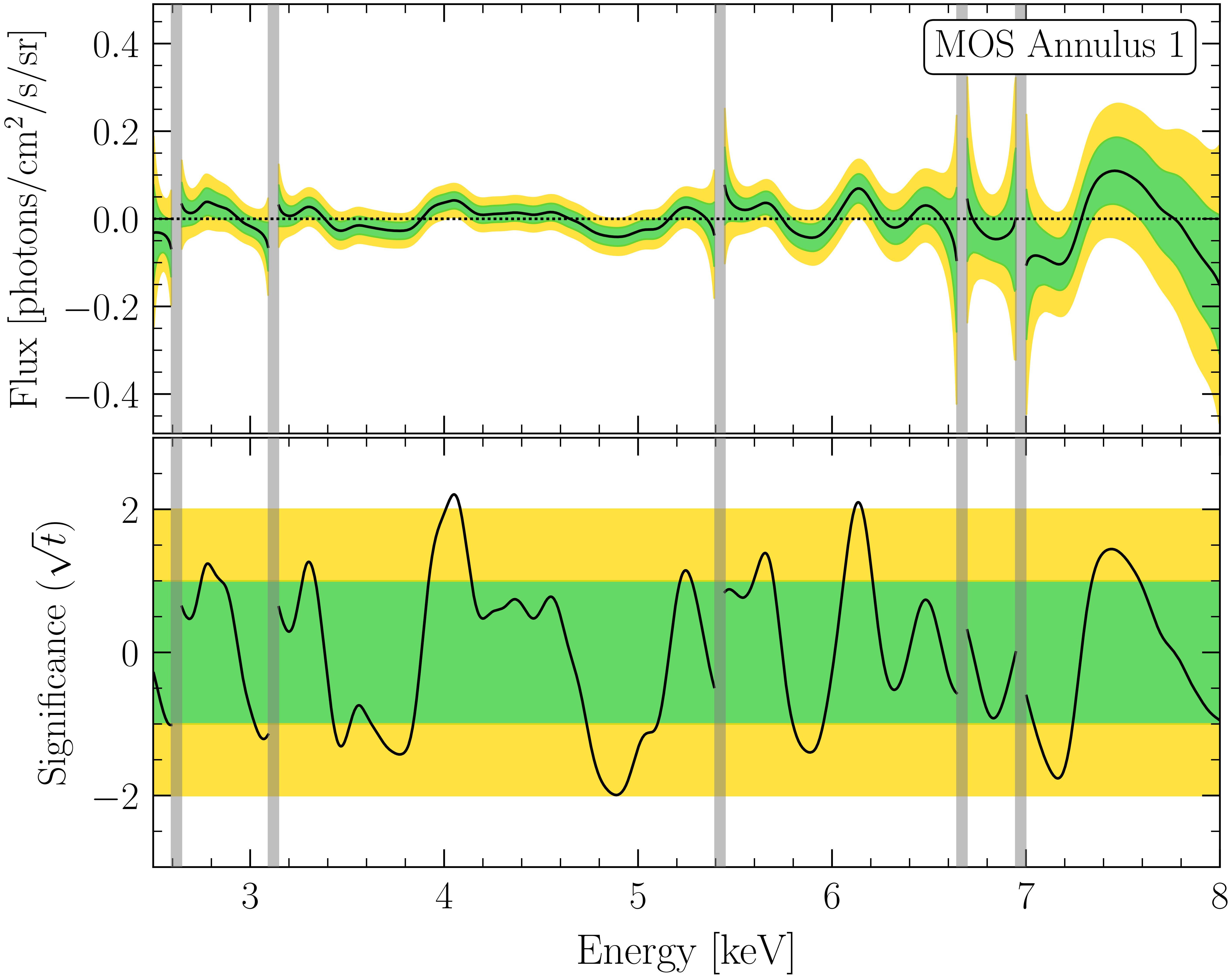
INJECTION TESTS





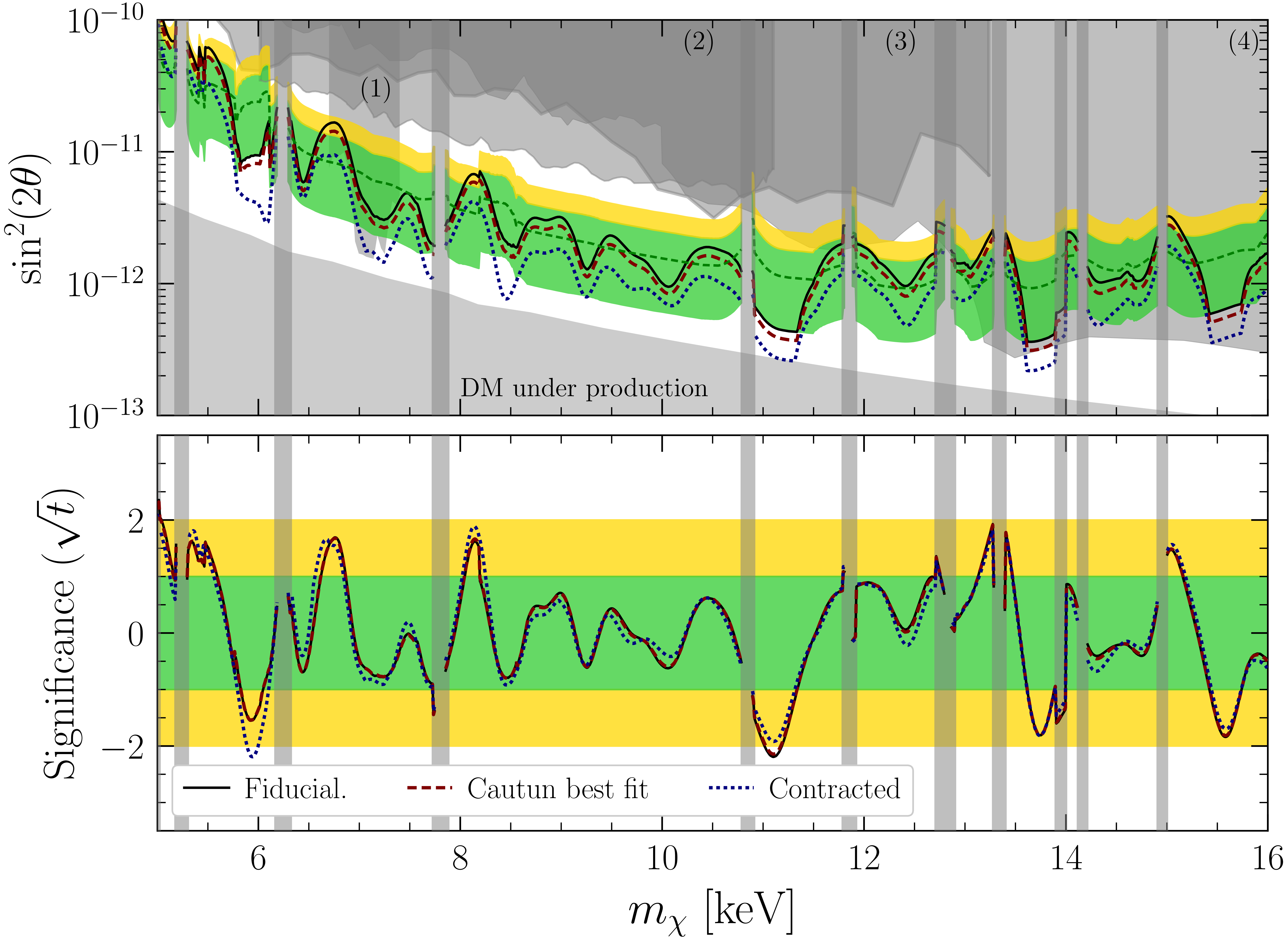
ANALYZING THE BACKGROUND-SUBTRACTED BLANK SKY



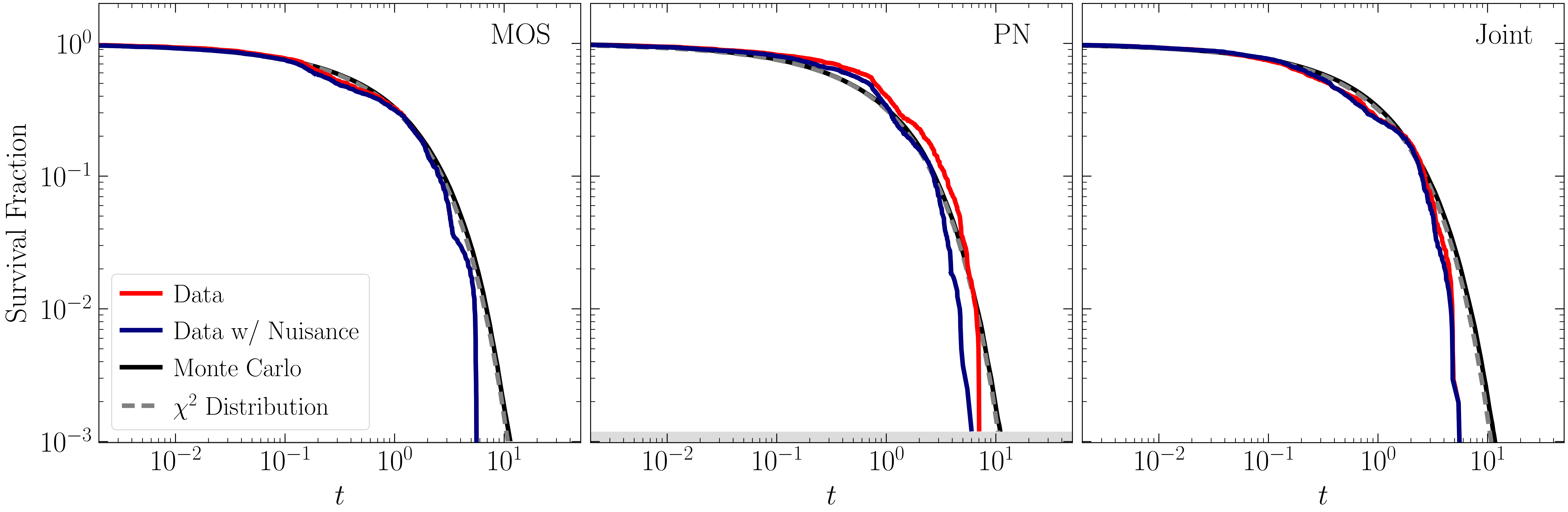


- Analyze each annulus in each instrumental independently
- Determine evidence/limits for a UXL at every energy

RESULTS


10^{-10}
10^{-11}
10^{-12}
10^{-13}
$\sin^2(2\theta)$
(1)
(2)
(3)
(4)
DM under production
Significance $(\sqrt{t})$
2
0
−2
Fiducial.
Cautun best fit
Contracted
6
8
10
12
14
16
m_χ [keV]

RESULTS



- Survival functions for each instrument (and joint) are consistent with null
- No evidence for decaying DM

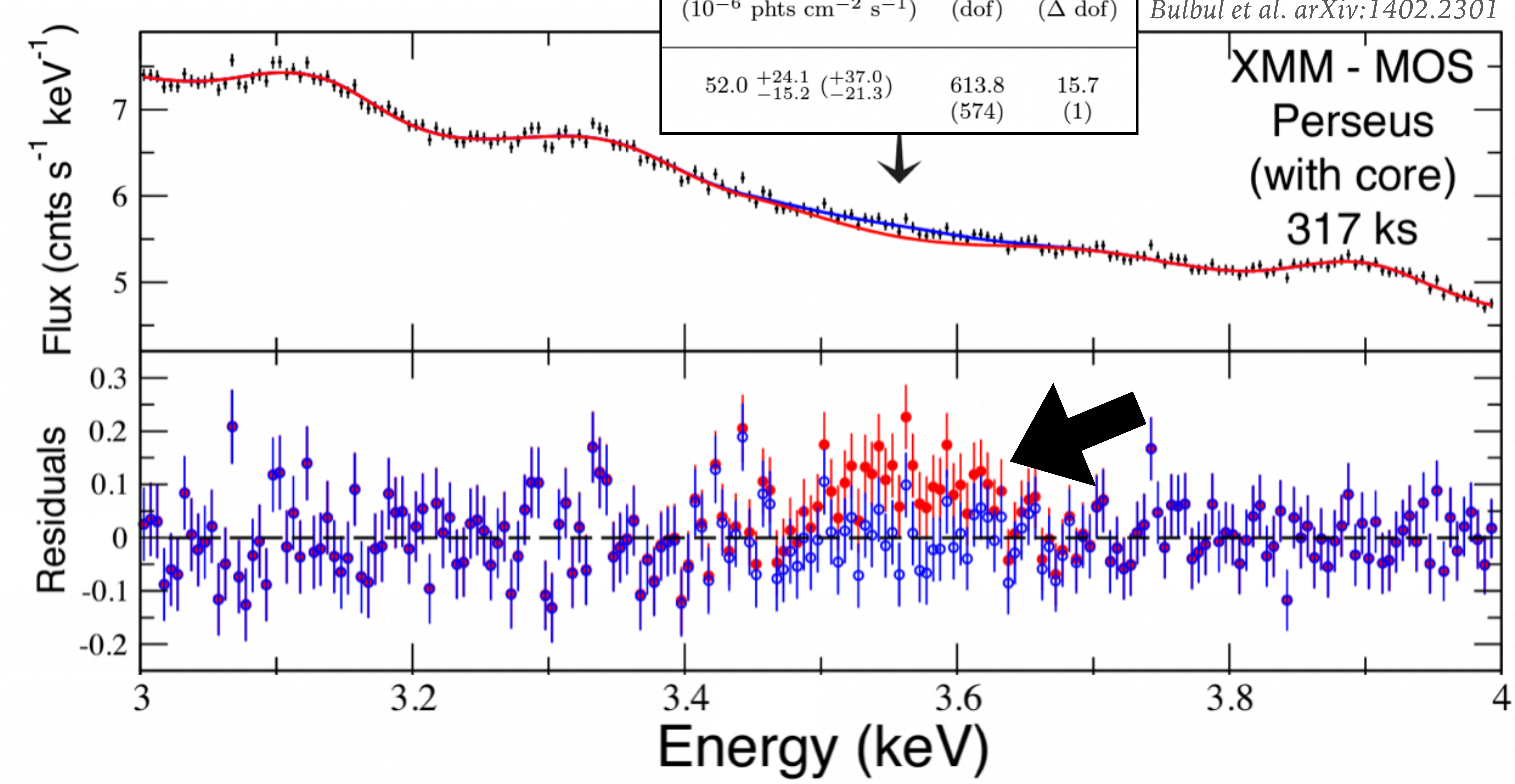
A RE-ANALYSIS OF 3.5 KEV DISCOVERY

(Finally) appearing with C. Dessert, Y. Park, and B. Safdi

A CLOSER LOOK AT CLAIMED DETECTIONS OF THE 3.5 KEV LINE

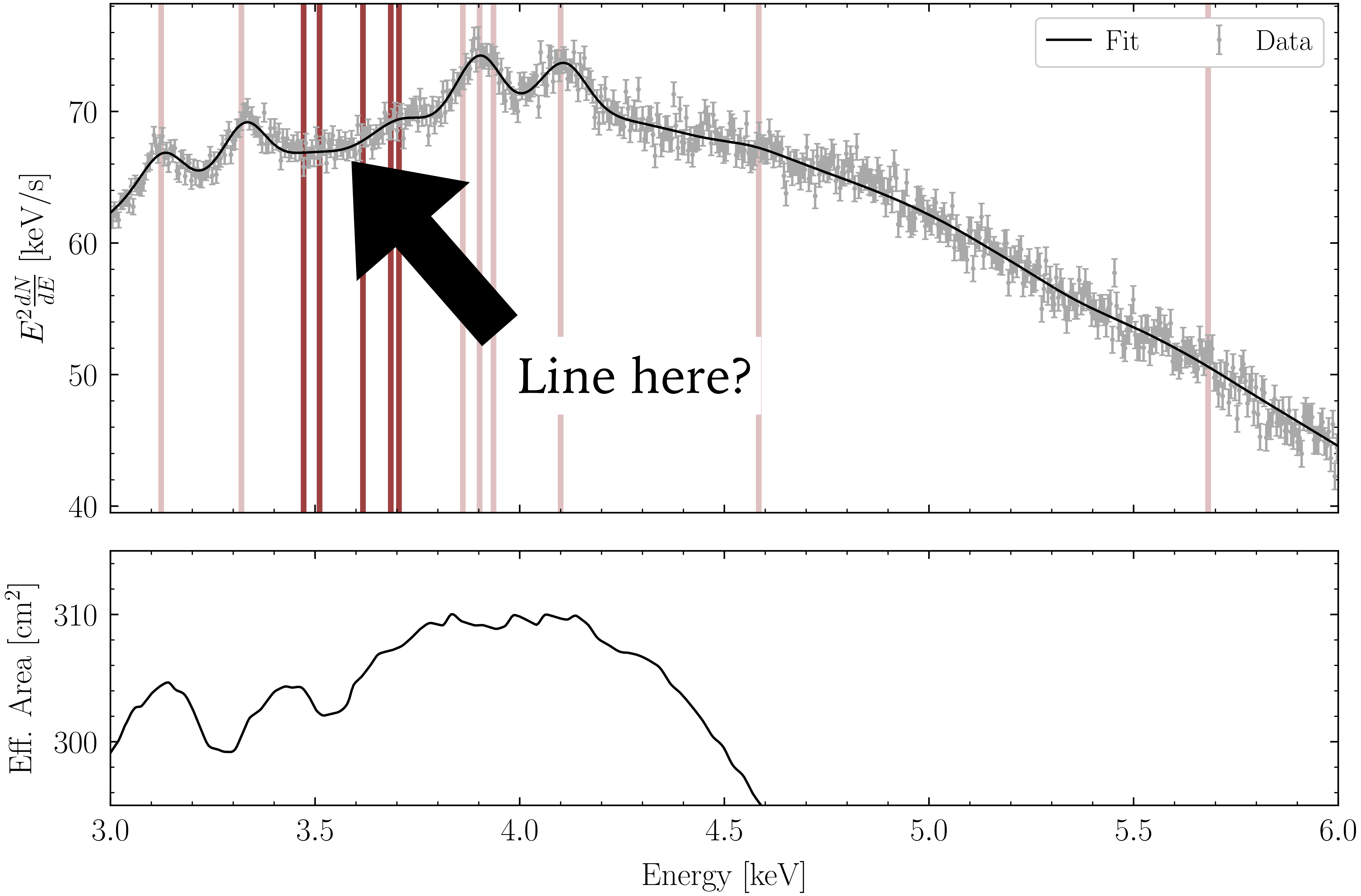
Flux (10^{-6} phts cm^{-2} s^{-1})	χ^2 (dof)	$\Delta\chi^2$ (Δ dof)
$52.0^{+24.1}_{-15.2}$ $(^{+37.0}_{-21.3})$	613.8 (574)	15.7 (1)

Bulbul et al. arXiv:1402.2301

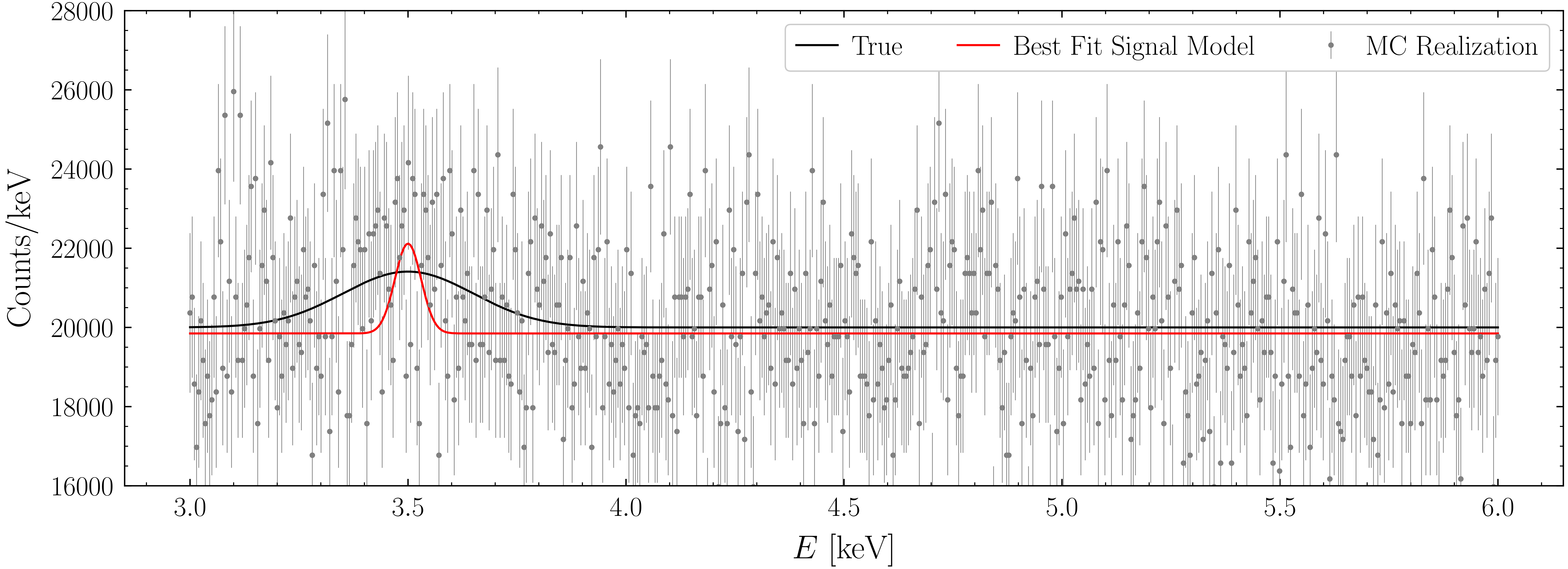


A CLOSER LOOK AT CLAIMED DETECTIONS OF THE 3.5 KEV LINE

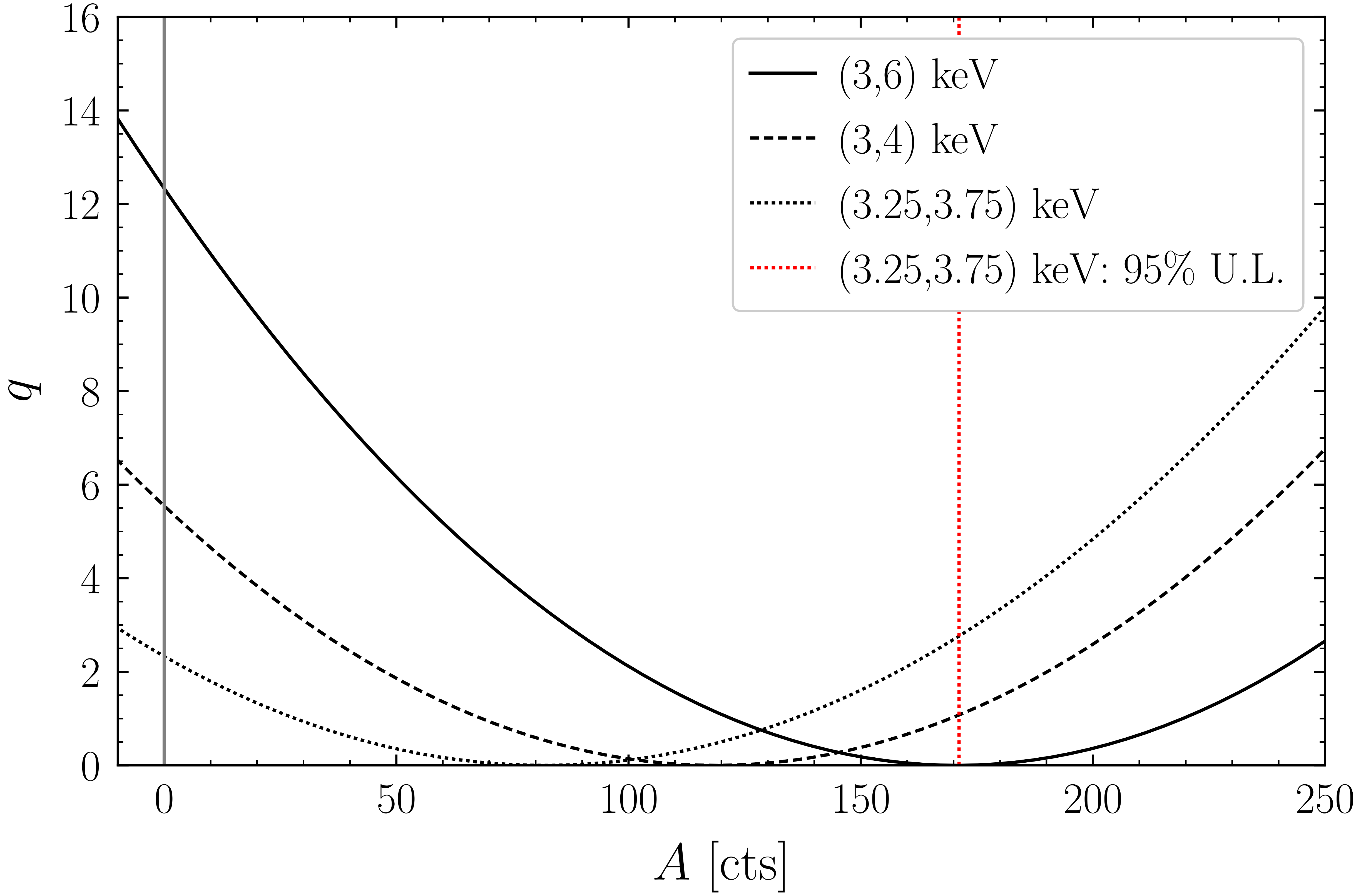
- Ambitious modeling of the background contributions
    - Instrumental+Cosmic+**Cluster**
    - 6 continuum model components, 15 parameters
    - 13 background line components, 39 model parameters
- Large analysis range, danger of systematics
    - Effective area/gain variations?
- Optimization challenges:
    - Local vs global minima
    - Discontinuous modeling, challenges for gradient-based minimization
    - Curse of dimensionality

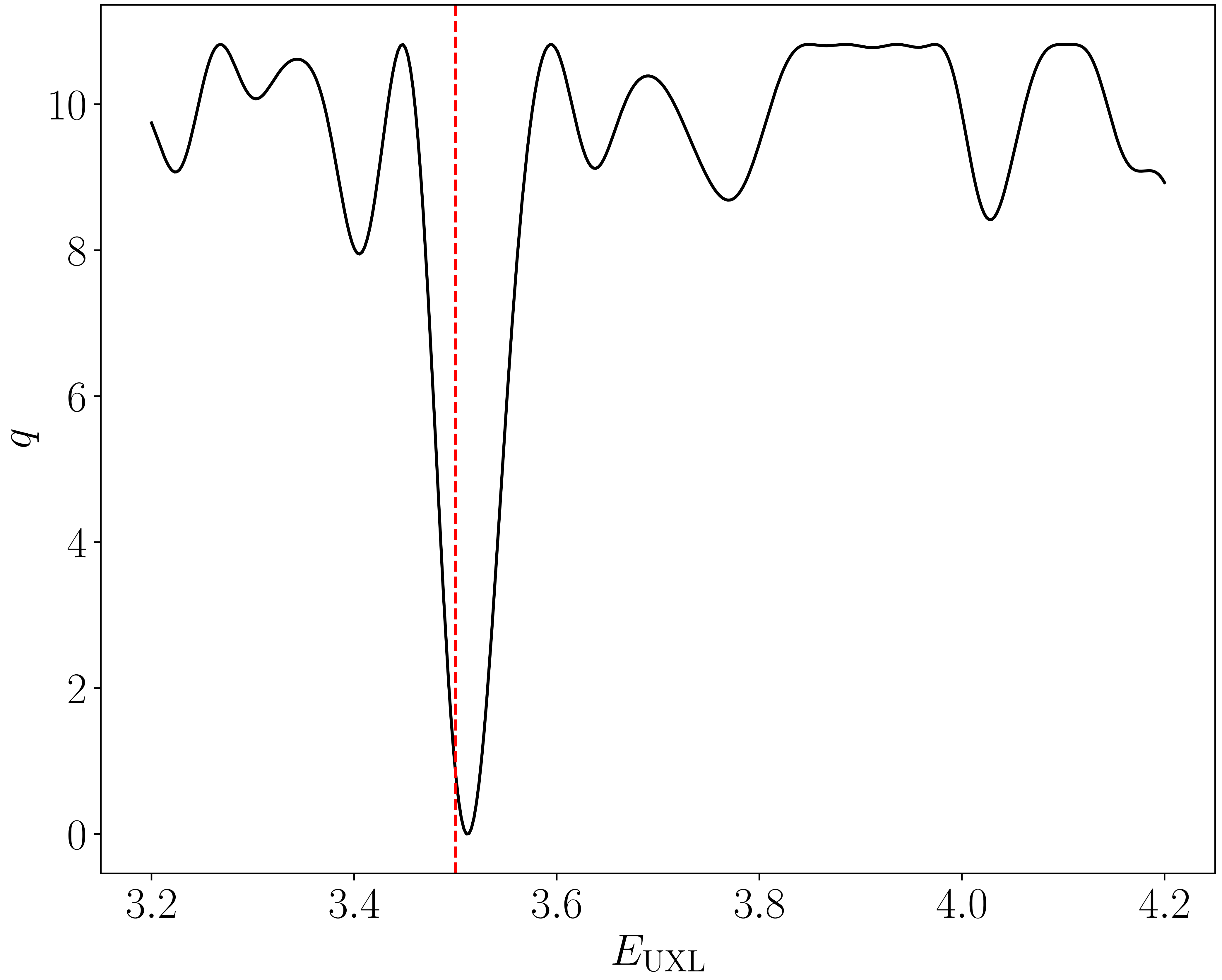


TOY MODELS FOR SYSTEMATIC MISMODELING



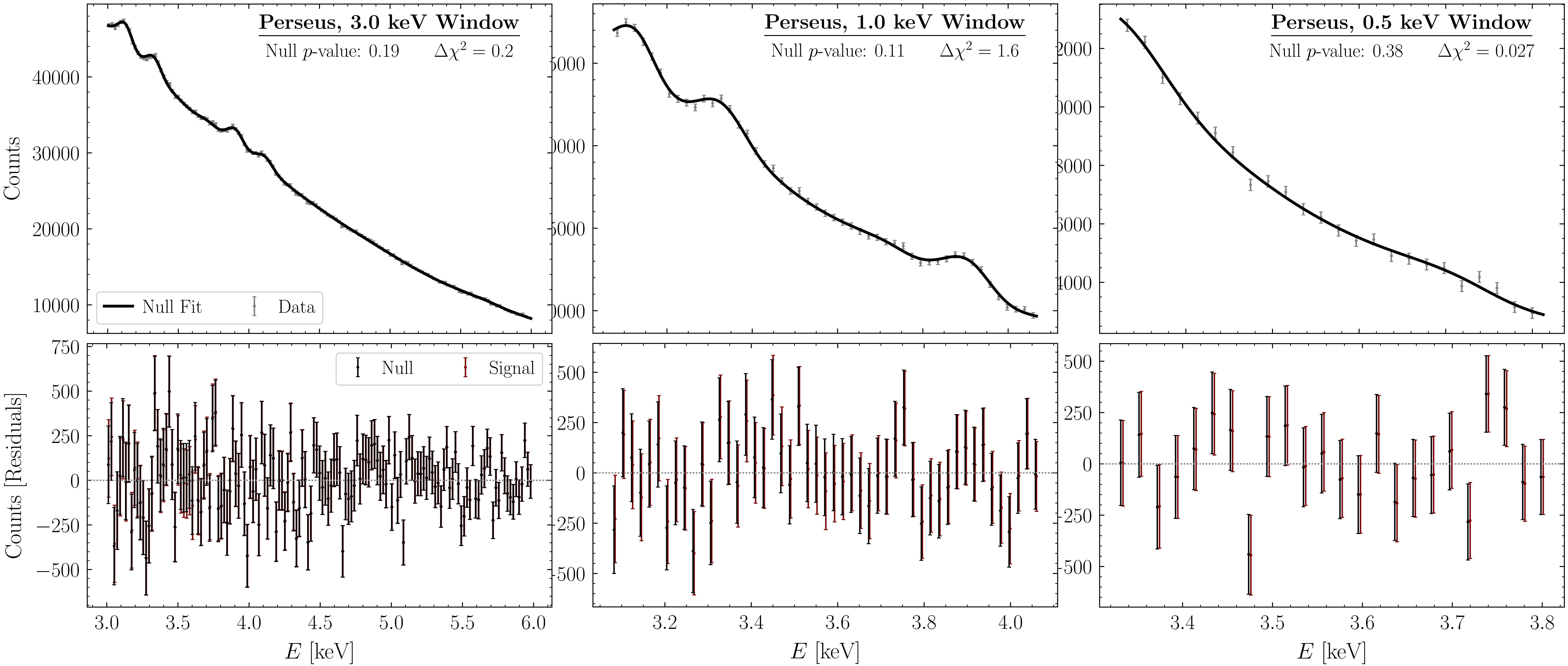
TOY MODELS FOR SYSTEMATIC MISMODELING





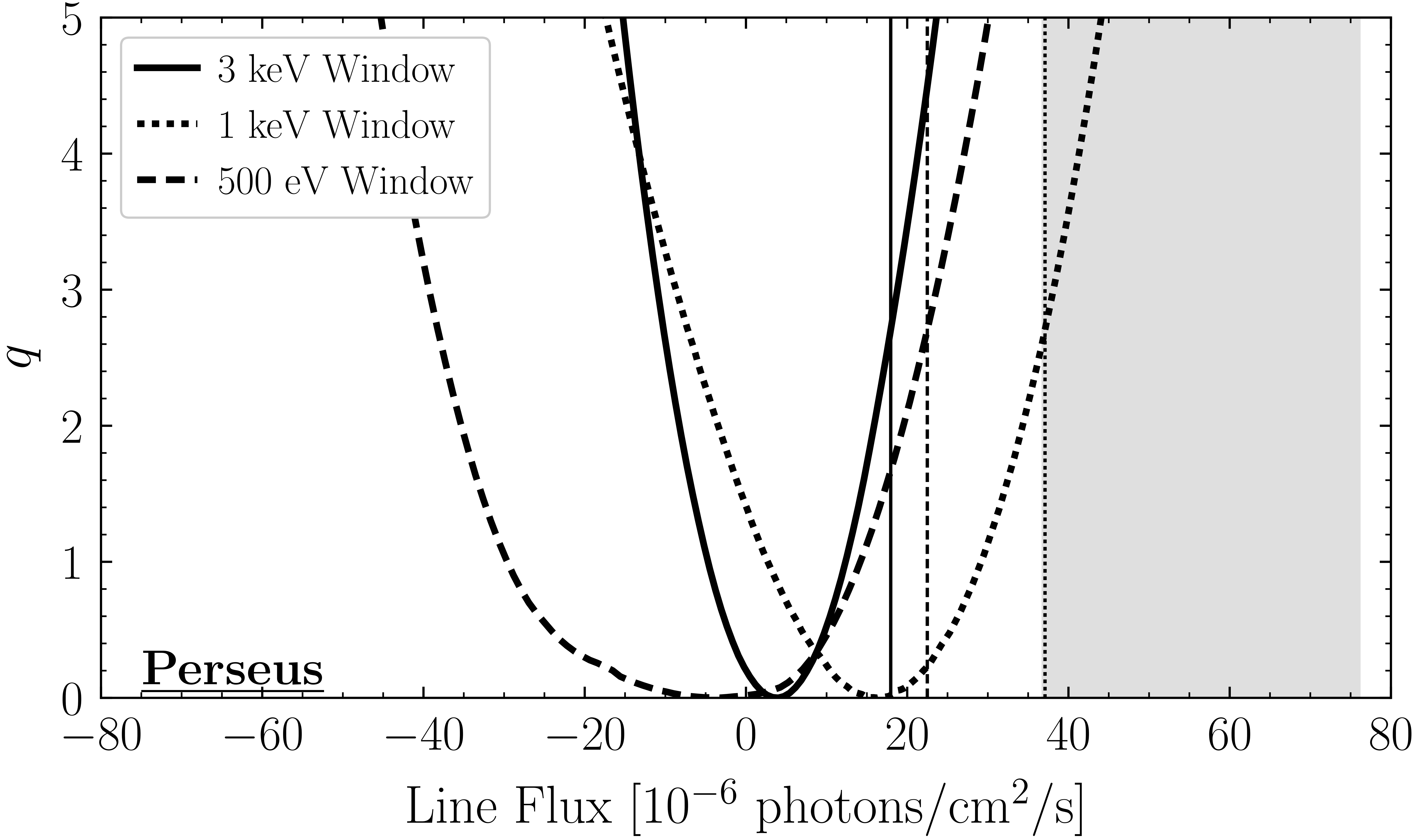
Bulbul et al. arXiv:1402.2301

THE PERSEUS CLUSTER

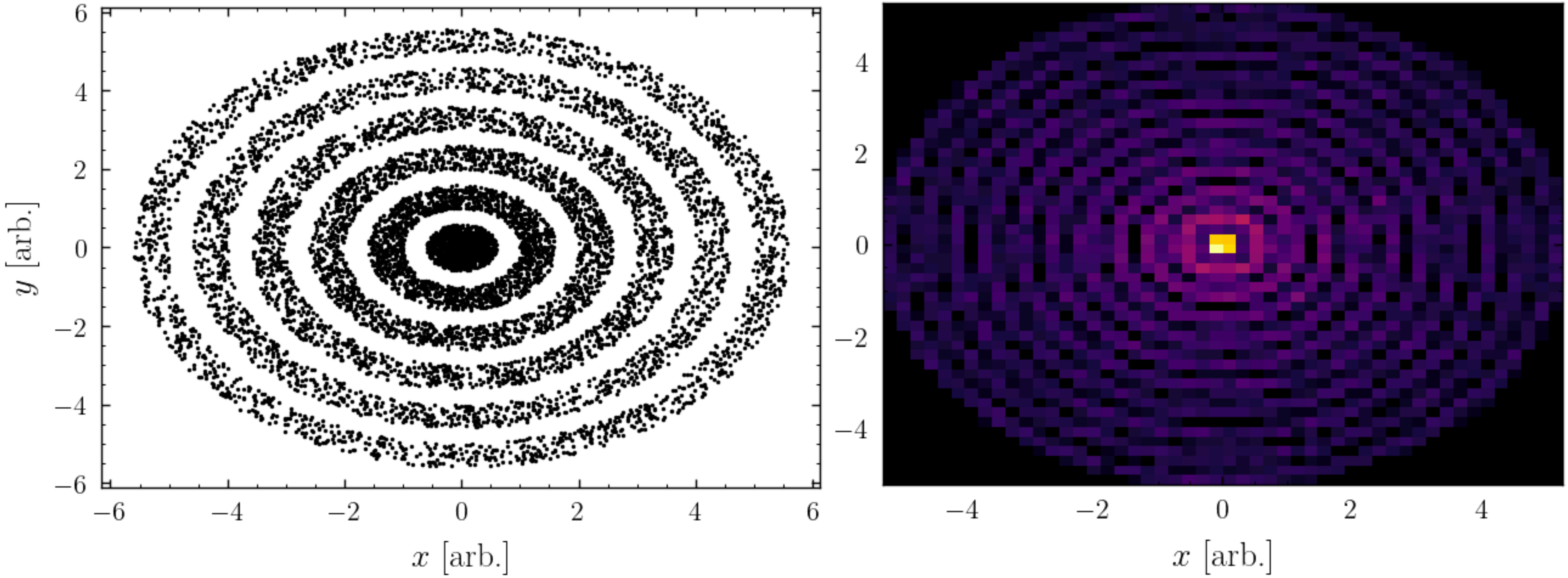


Bulbul et al. arXiv:1402.2301

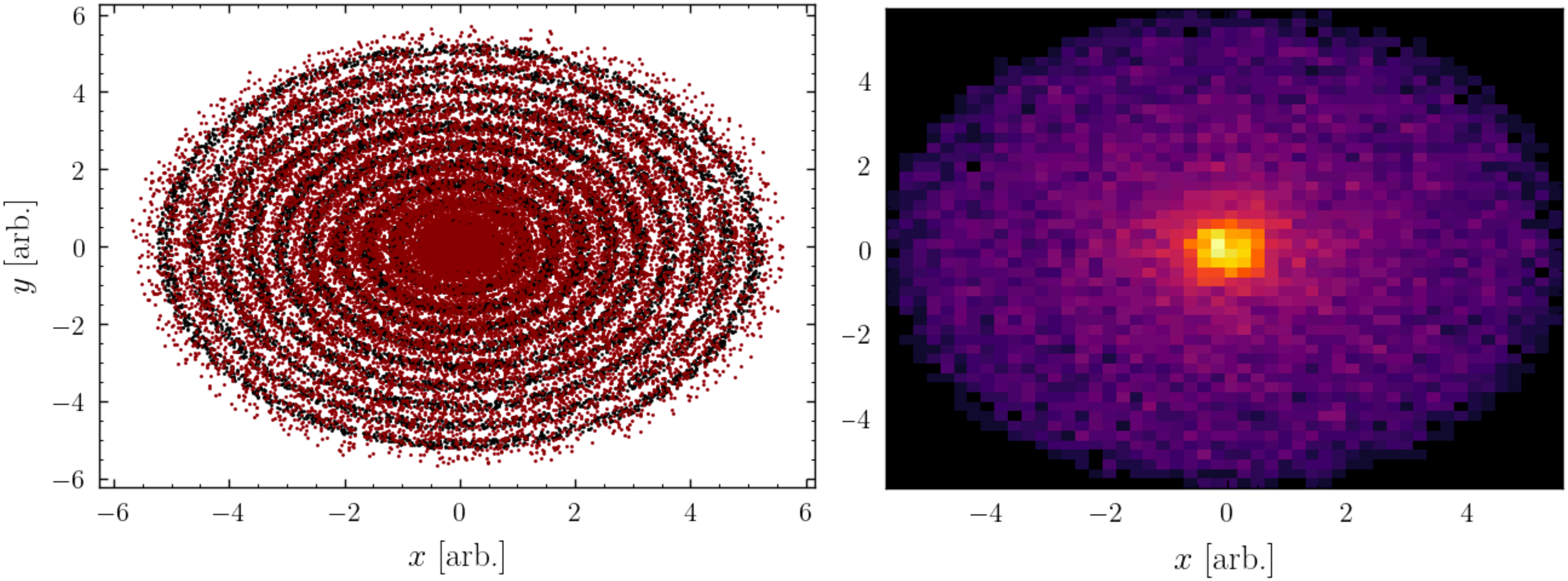
PERSEUS CLUSTER REANALYSIS



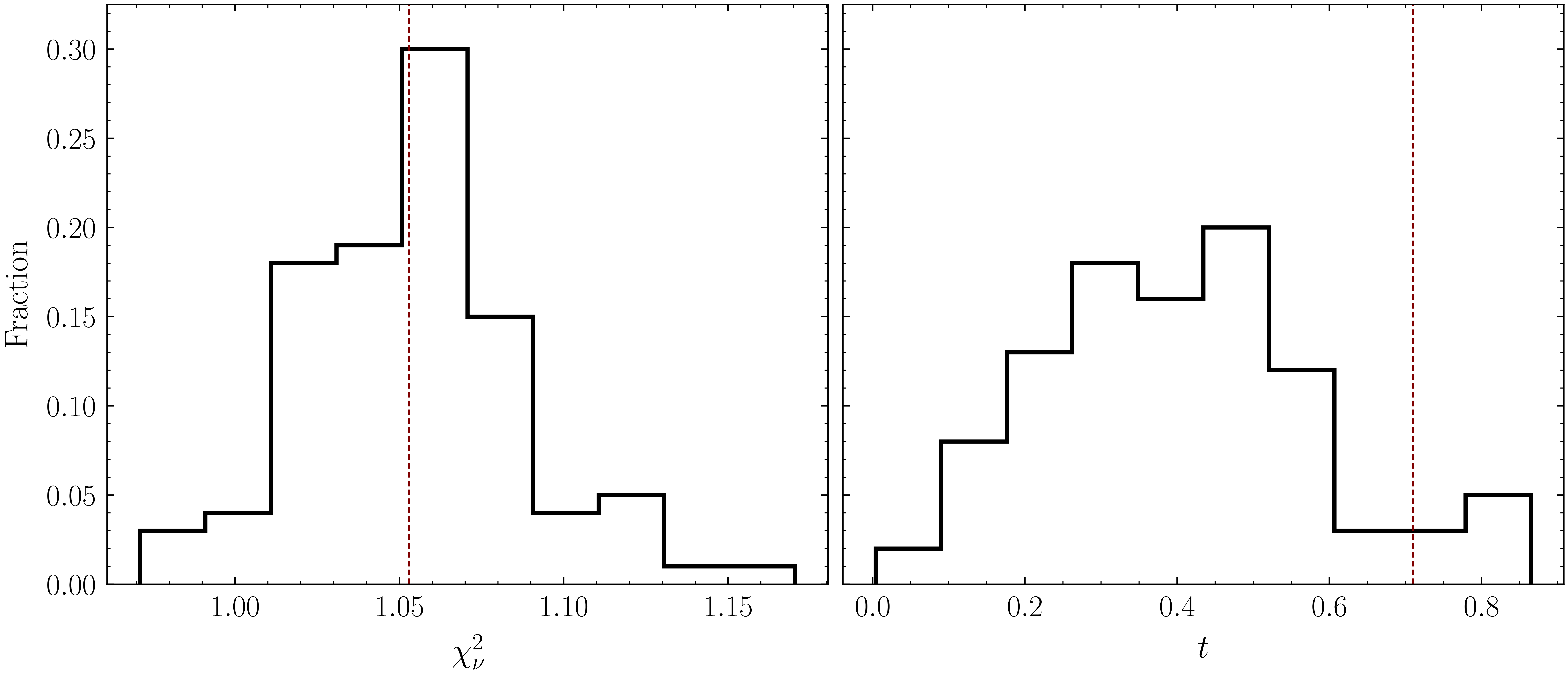
ARE YOU AN ASTRONOMER: A ROLE PLAYING GAME



ARE YOU AN ASTRONOMER: A ROLE PLAYING GAME

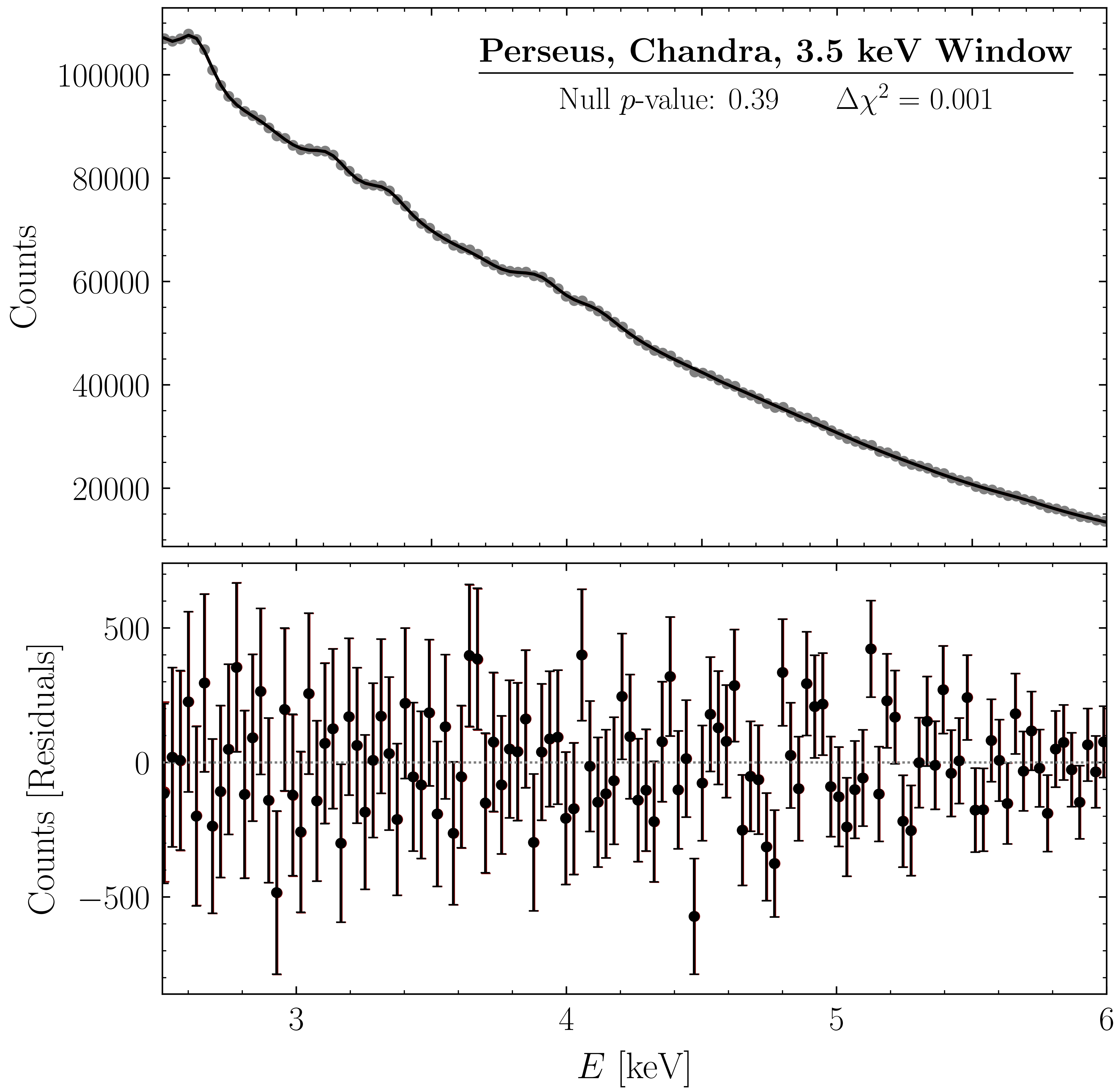


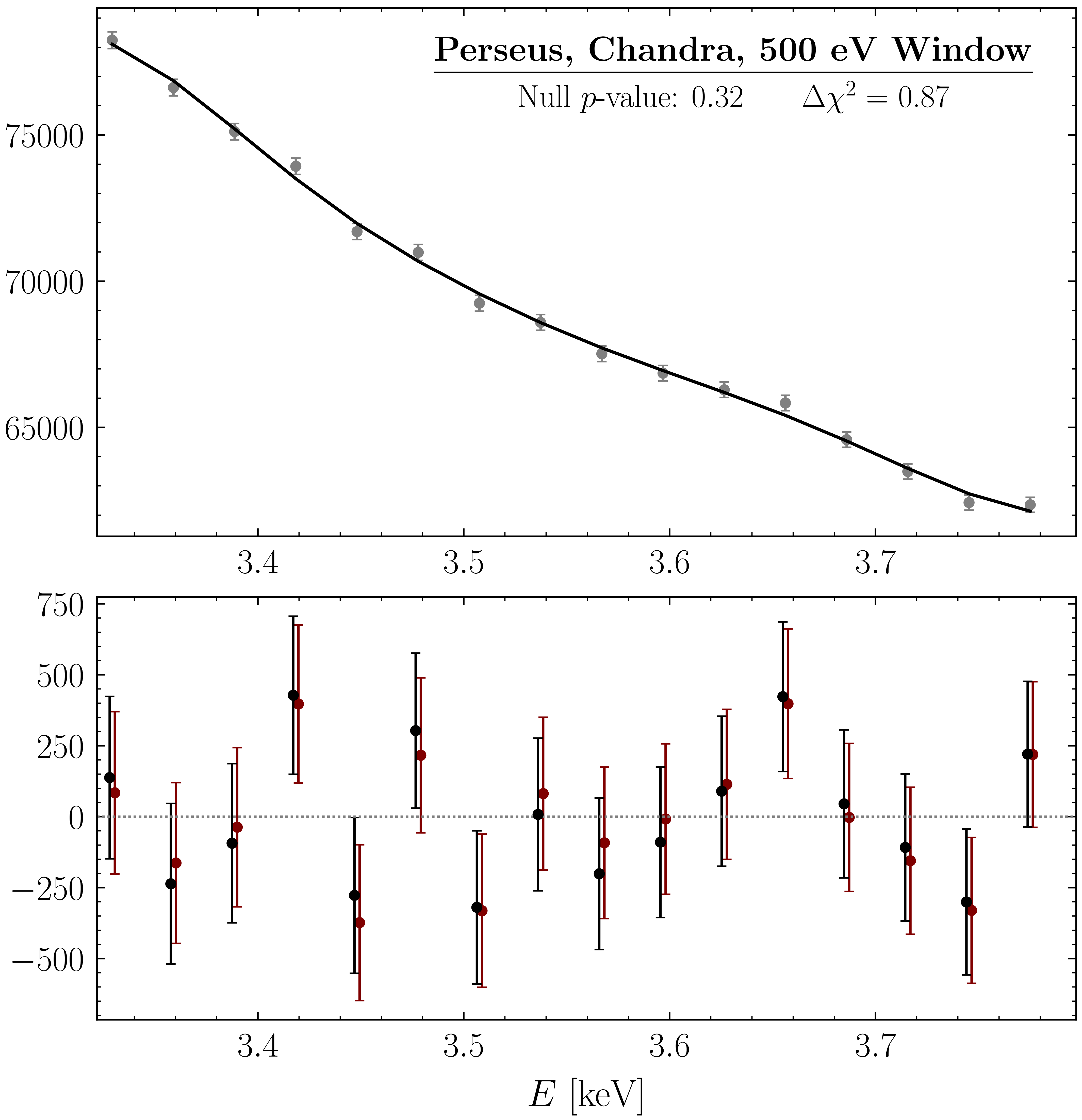
RANDOMIZATION ERROR IN XMM-NEWTON DATA



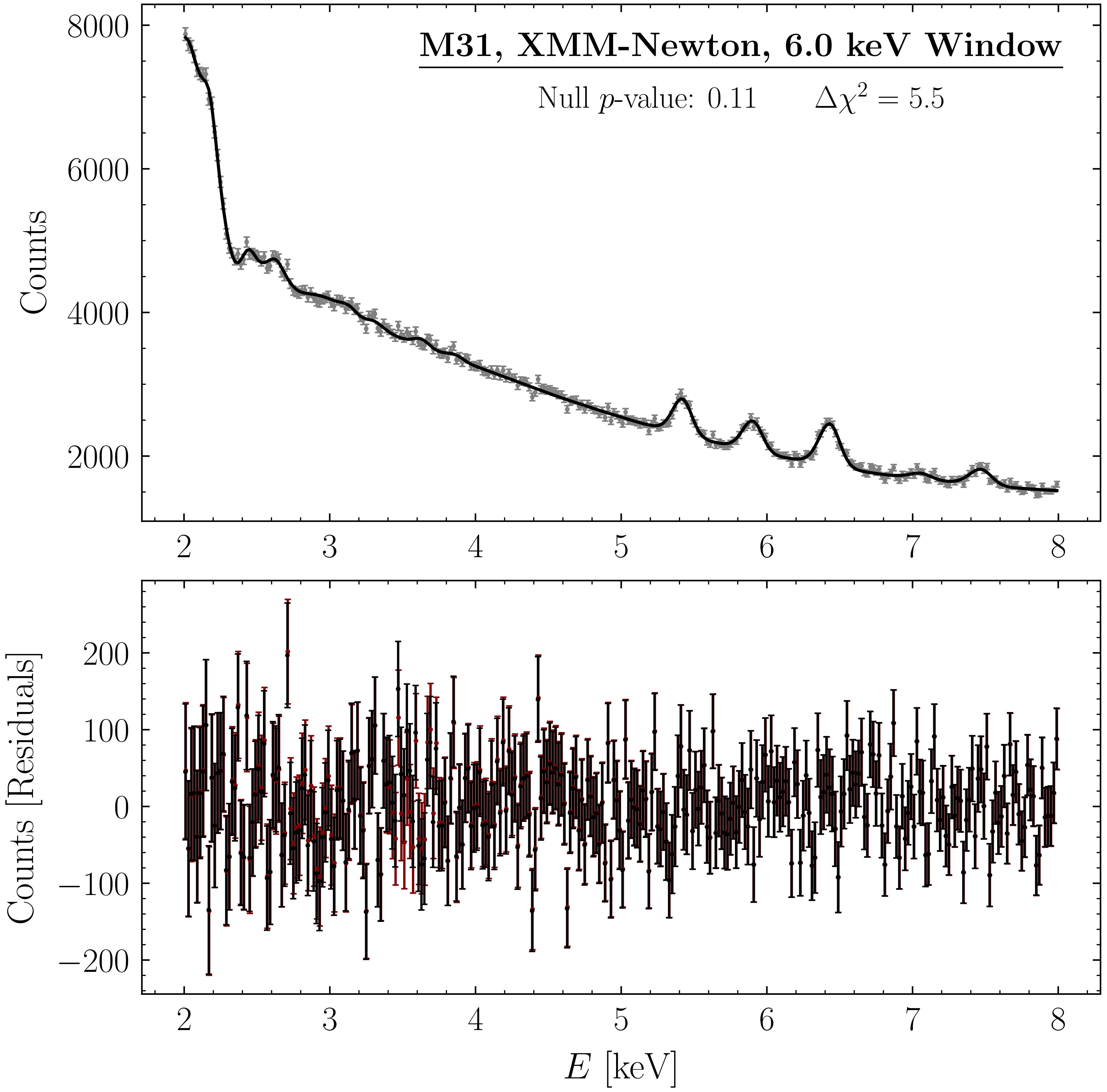
Bulbul et al. arXiv:1402.2301

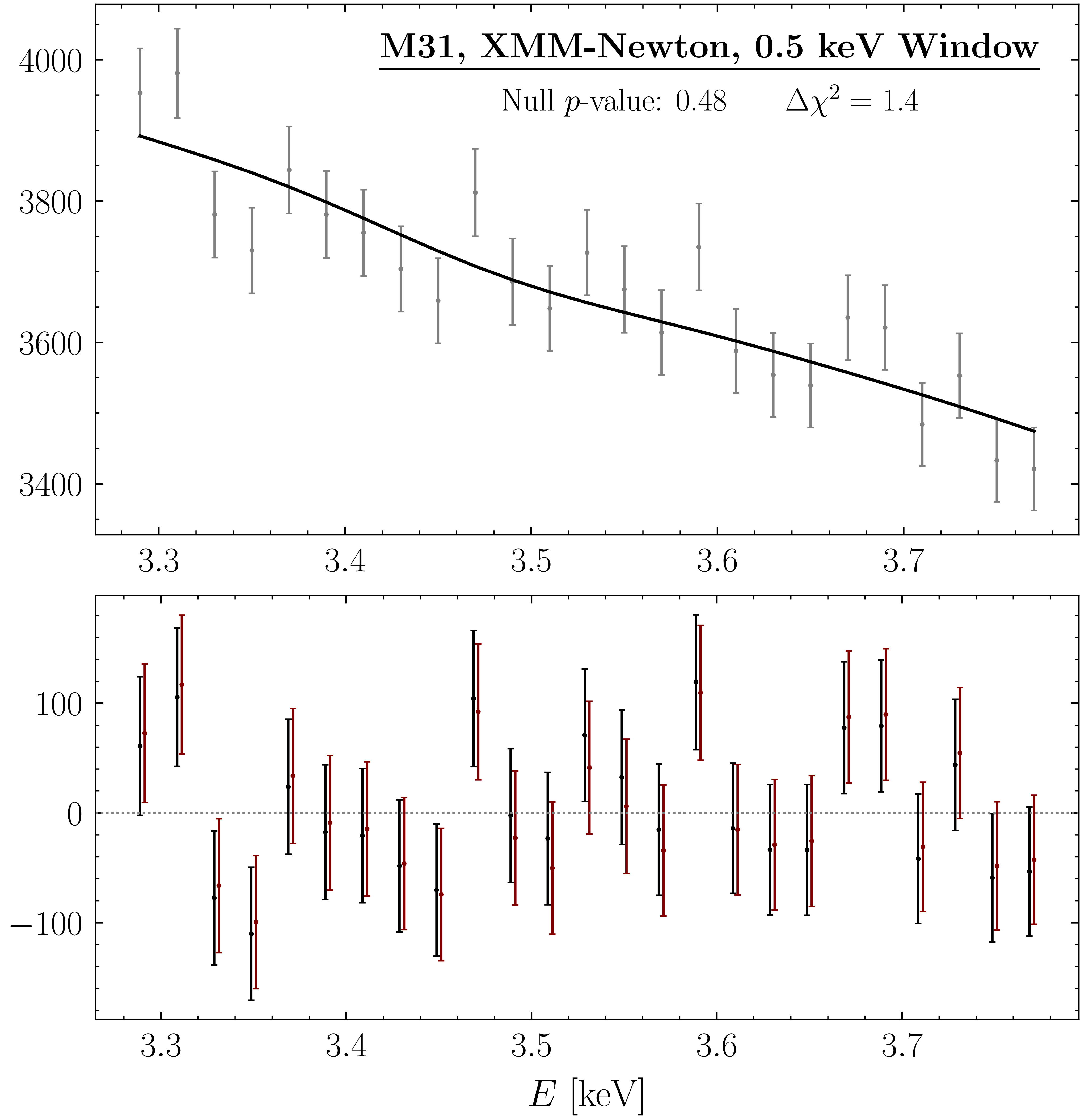
CHANDRA PERSEUS



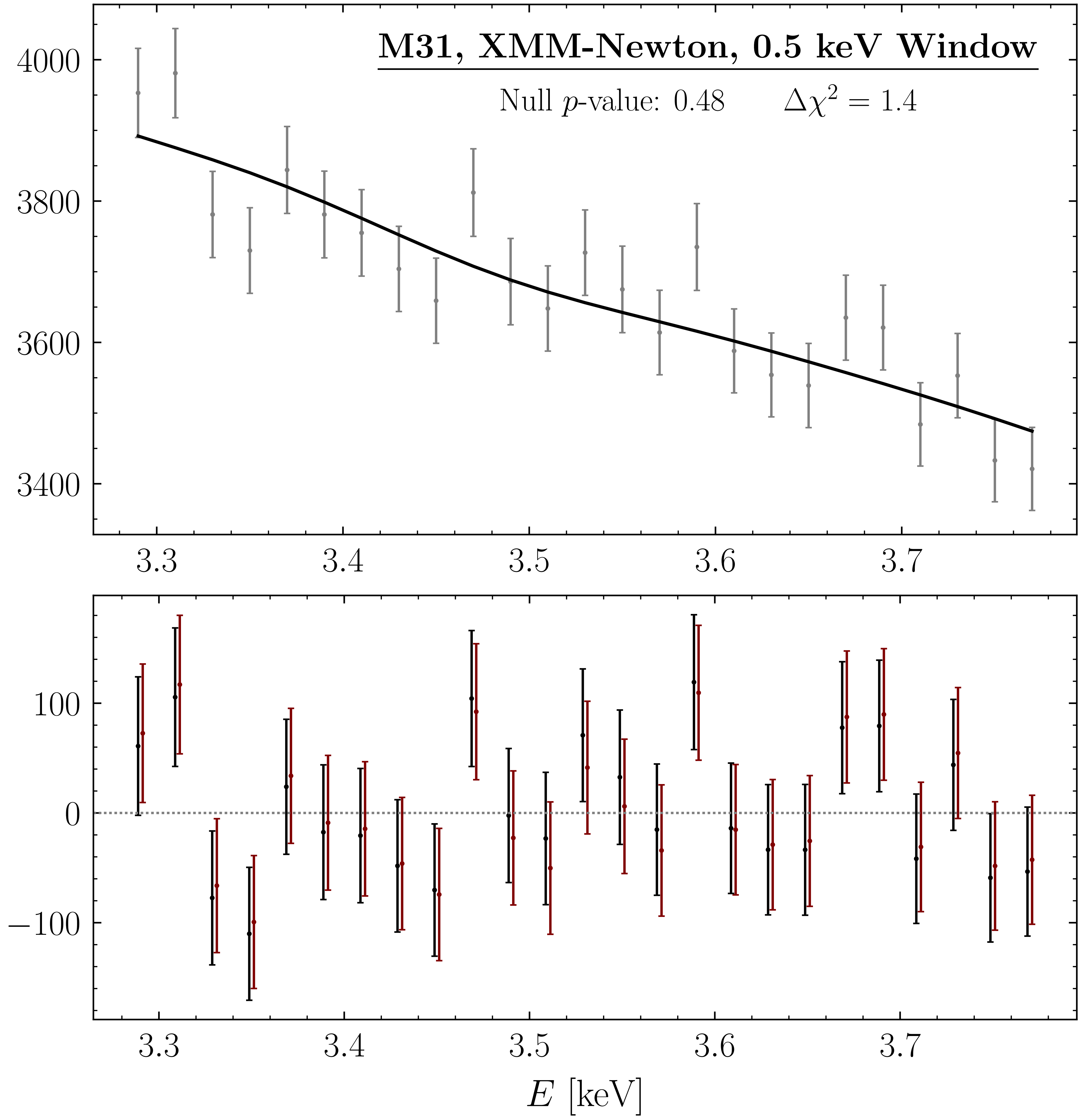


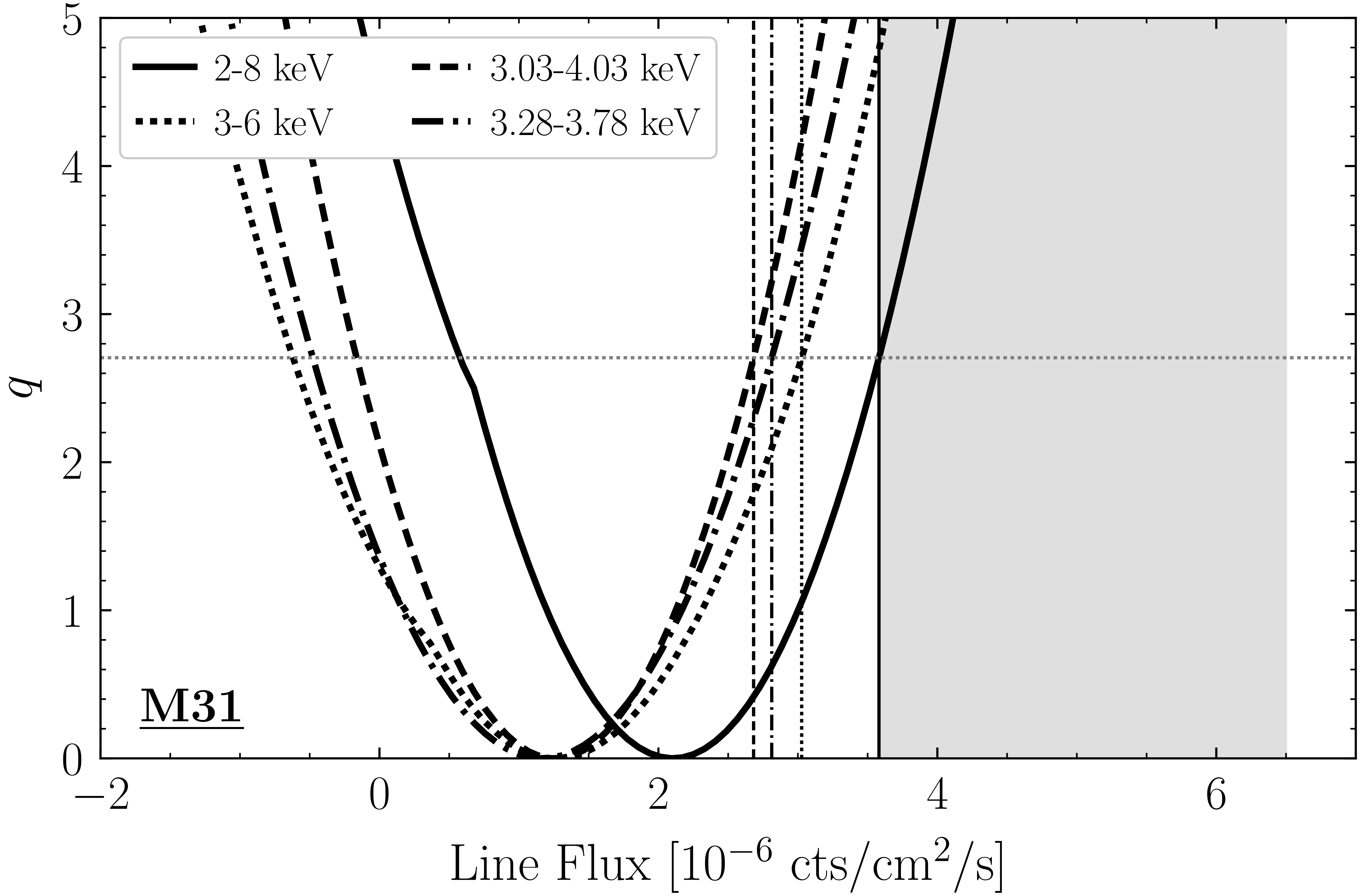
M31


M31, XMM-Newton, 6.0 keV Window
Null p-value: 0.11 $\Delta\chi^2 = 5.5$
Counts
8000
6000
4000
2000
Counts [Residuals]
200
100
0
−100
−200
2
3
4
5
6
7
8
E [keV]

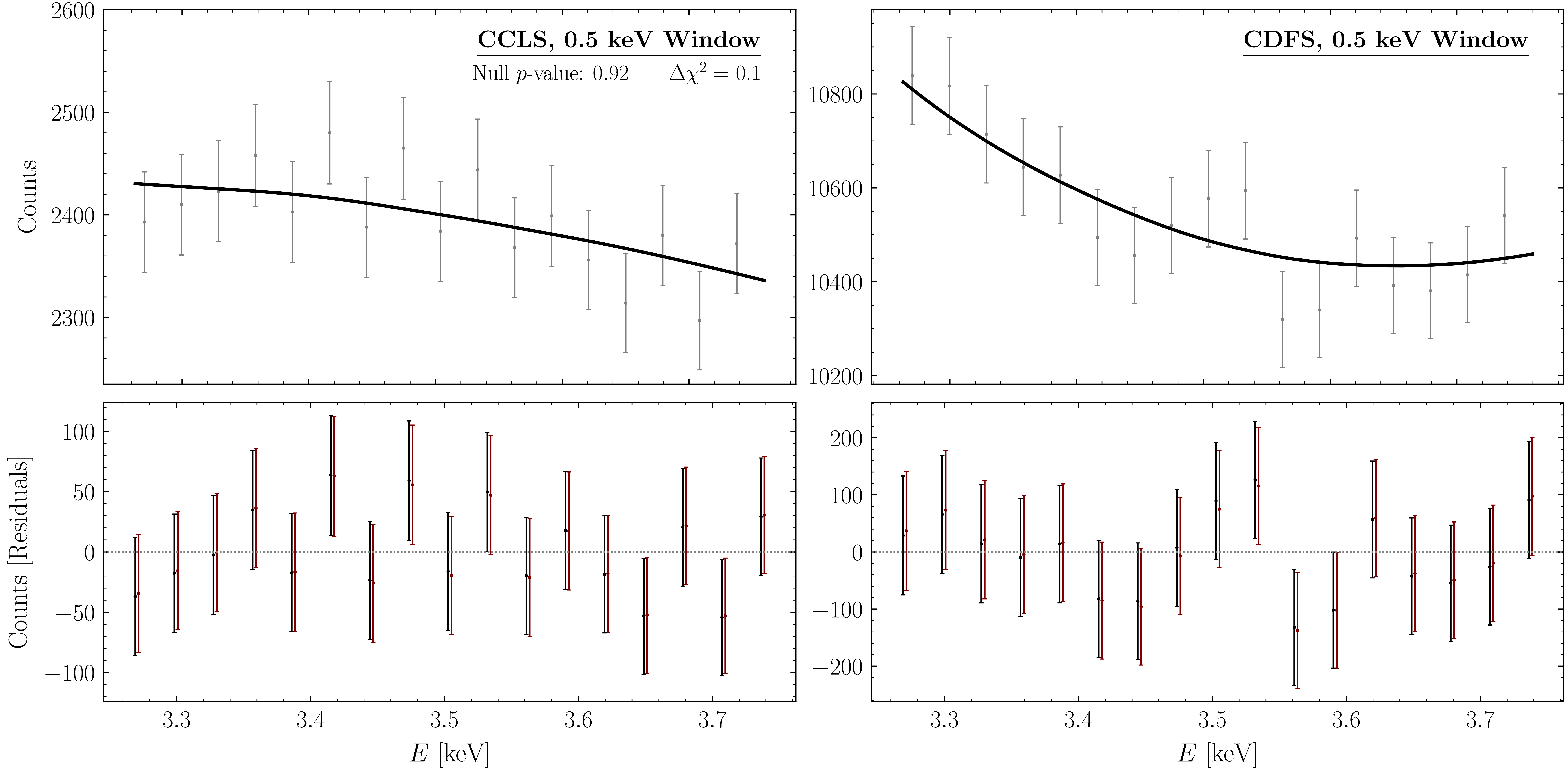

M31, XMM-Newton, 0.5 keV Window
Null p-value: 0.48 $\Delta\chi^2 = 1.4$
4000
3800
3600
3400
100
0
−100
3.3
3.4
3.5
3.6
3.7
E [keV]

M31


M31, XMM-Newton, 0.5 keV Window
Null p-value: 0.48
$\Delta\chi^2 = 1.4$
4000
3800
3600
3400
3.3
3.4
3.5
3.6
3.7
100
0
−100
E [keV]

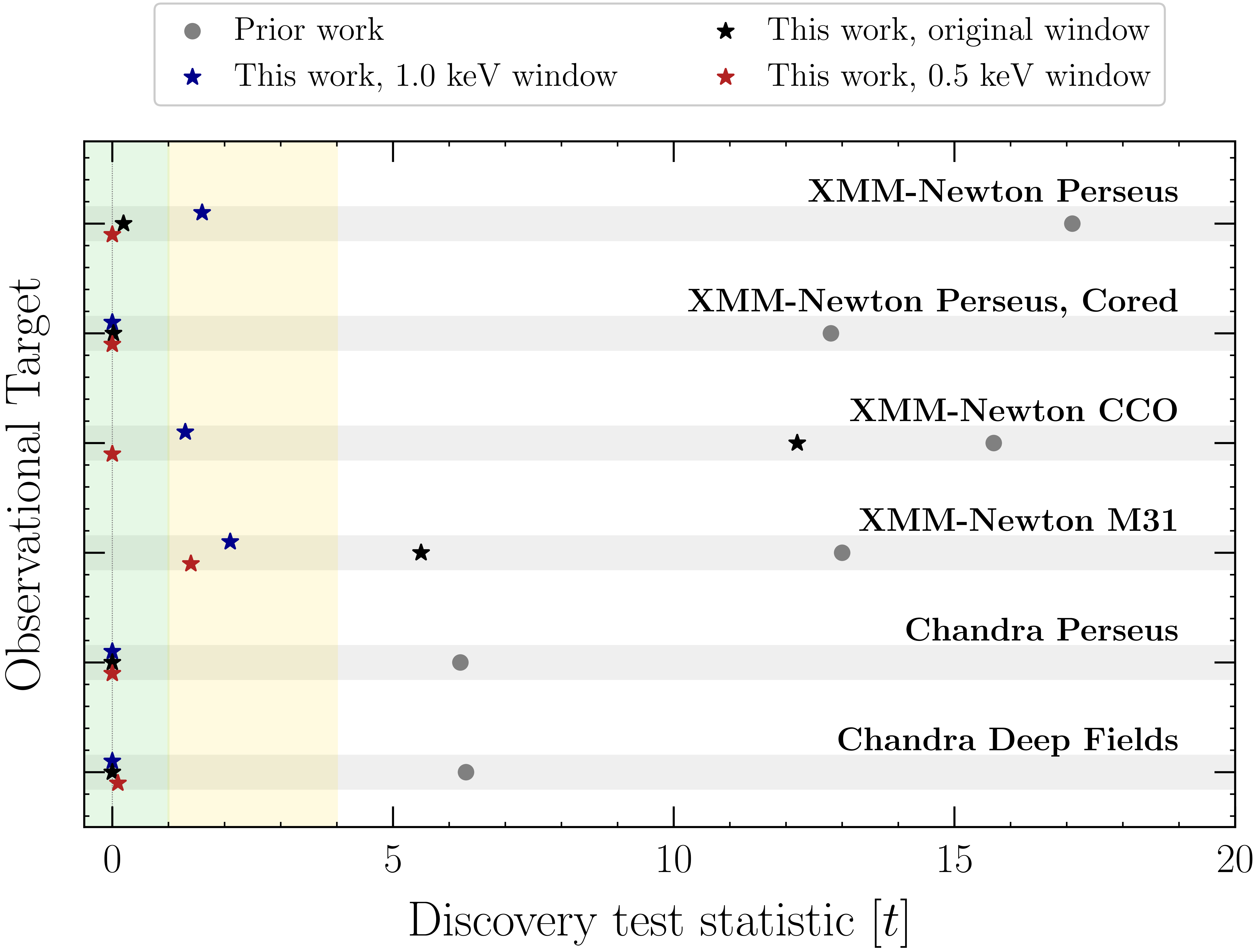

2-8 keV
3-6 keV
3.03-4.03 keV
3.28-3.78 keV
M31
q
0
1
2
3
4
5
−2
0
2
4
6
Line Flux [10^{-6} cts/cm^2/s]

CHANDRA DEEP FIELDS



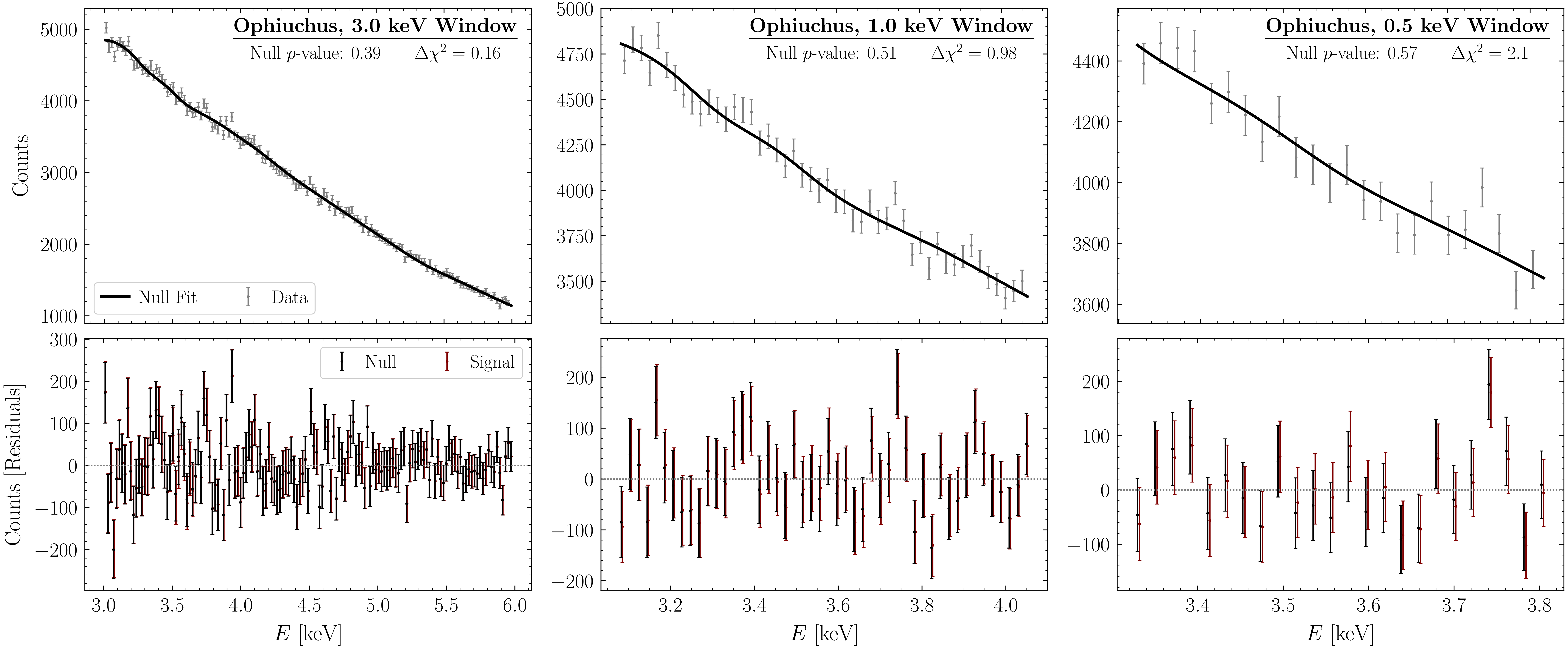
SUMMARIZING

- No single explanation for why 3.5 keV line was "discovered"
- Future X-ray telescopes will help
  - Improved effective area
  - Improved spectral resolution
- Still need optimal observation and analysis strategies



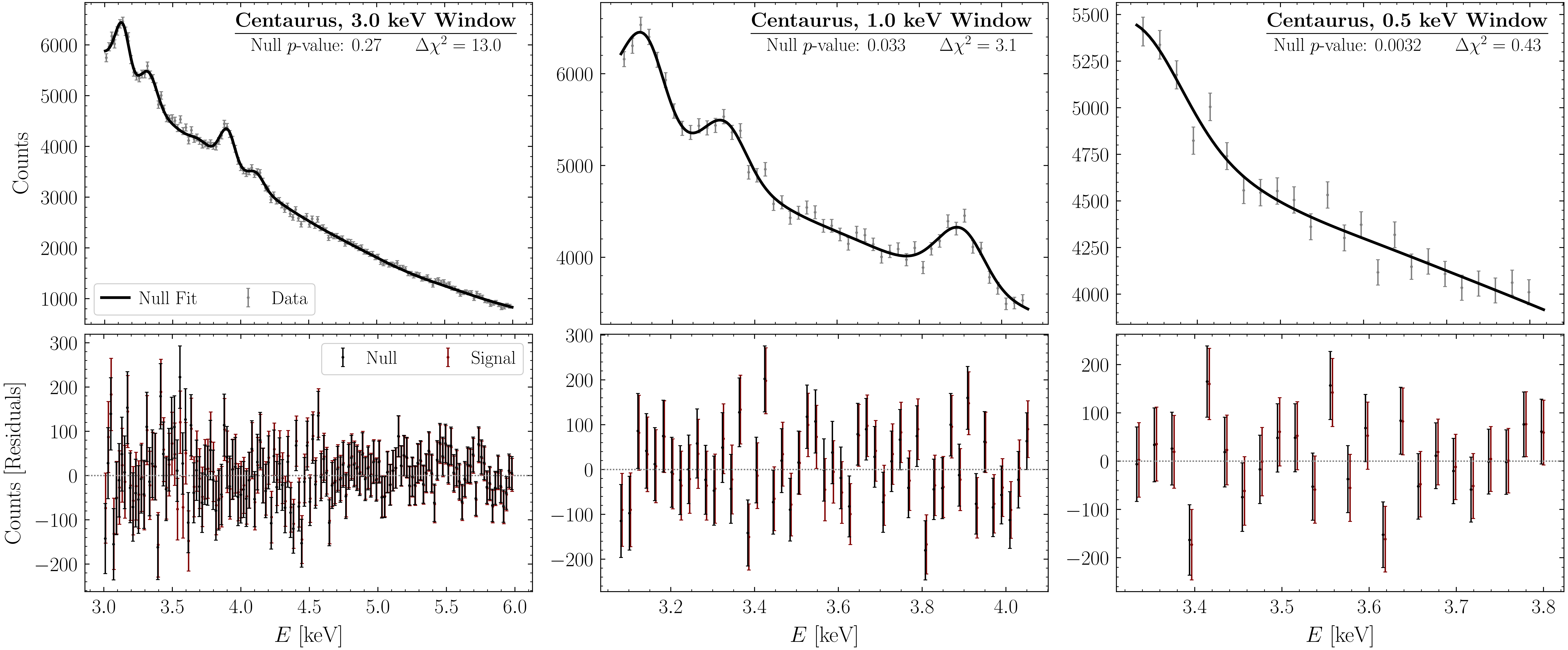
BACKUP SLIDES

OTHER BRIGHT CLUSTERS



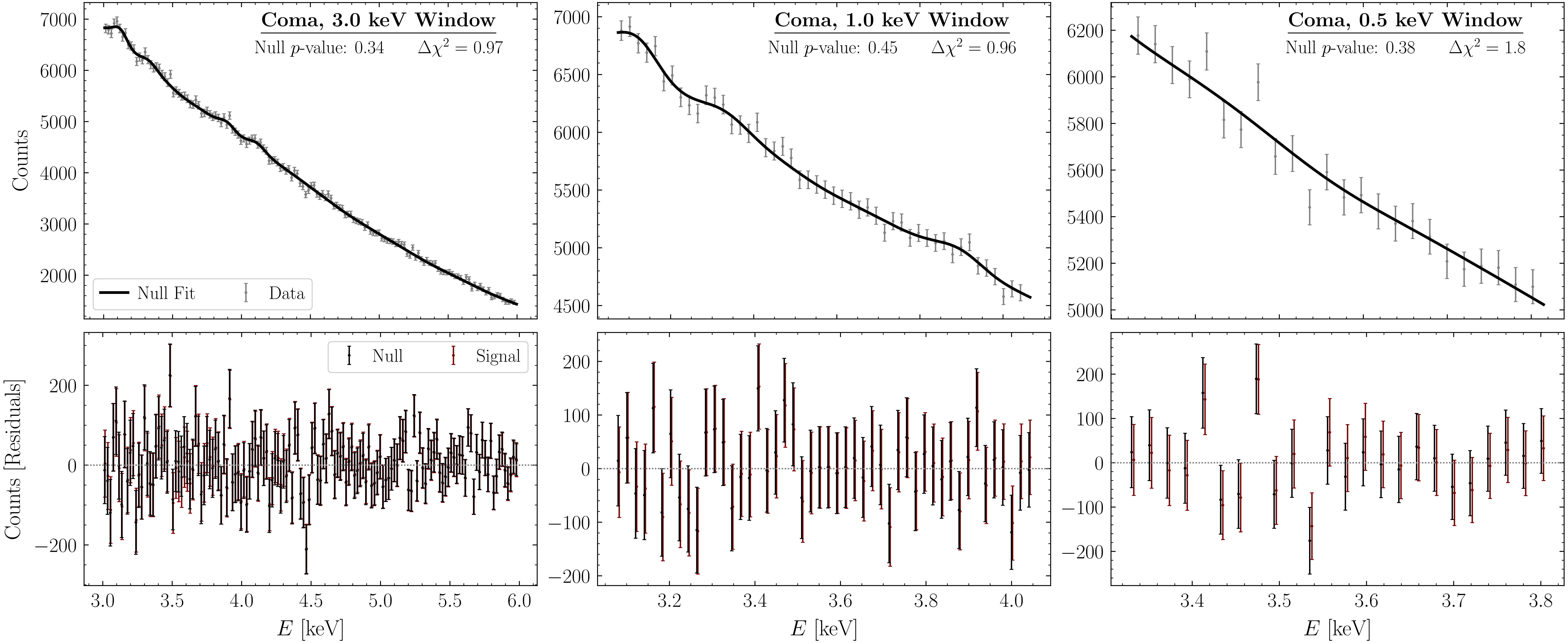
Bulbul et al. arXiv:1402.2301

OTHER BRIGHT CLUSTERS

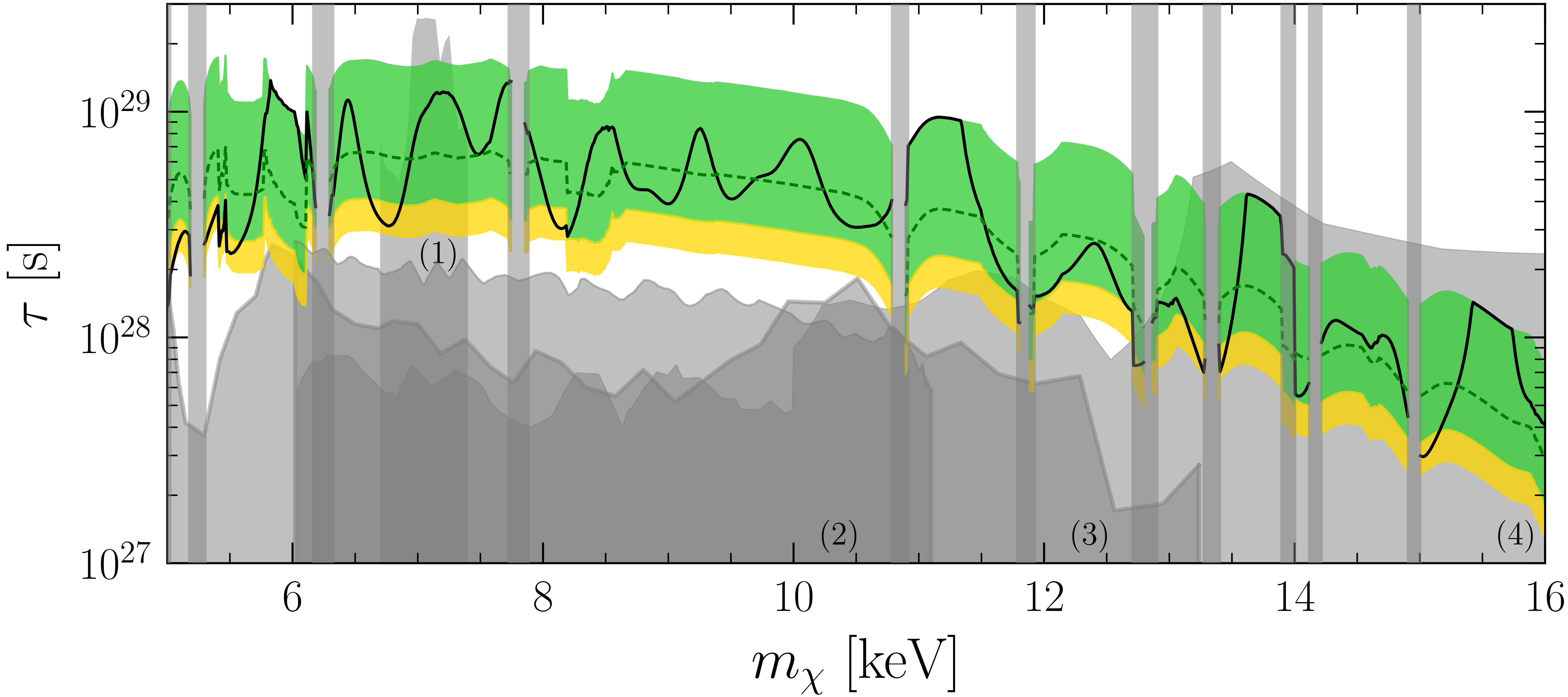


Bulbul et al. arXiv:1402.2301

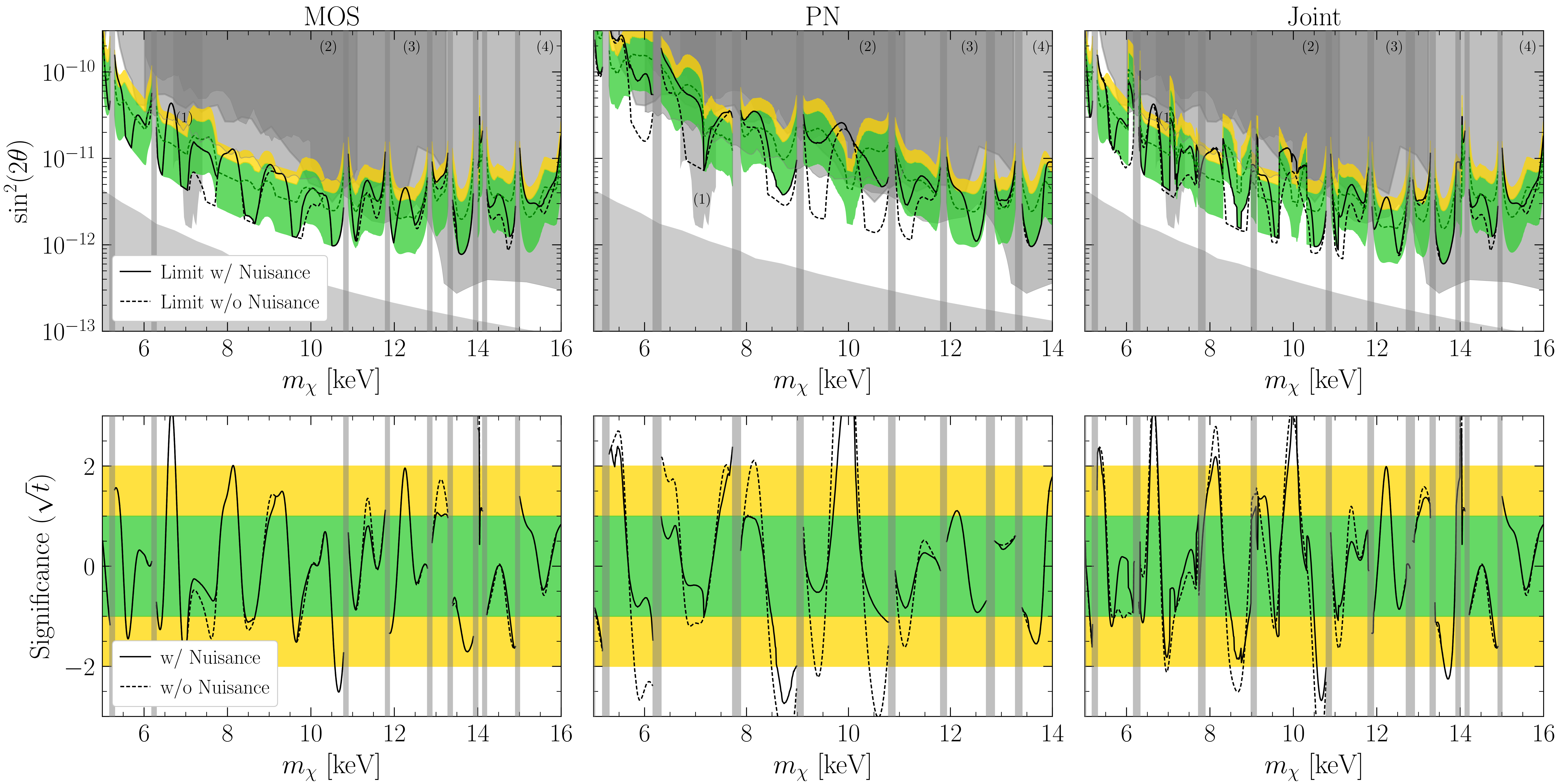
OTHER BRIGHT CLUSTERS



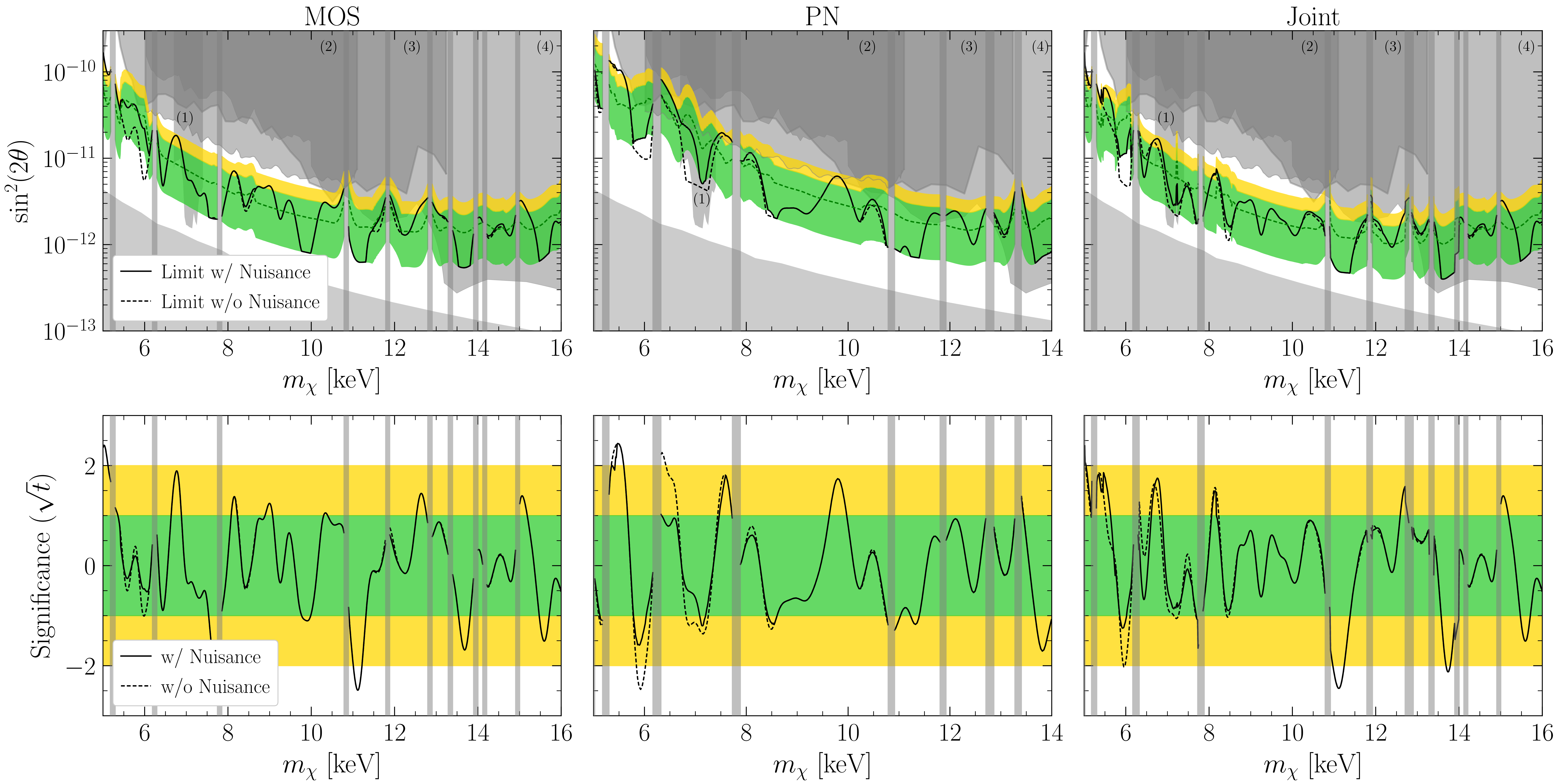
DM LIFETIME LIMITS



UNSUBTRACTED ANALYSIS



ALTERNATE GP KERNEL: STATIONARY KERNEL AT 1KEV



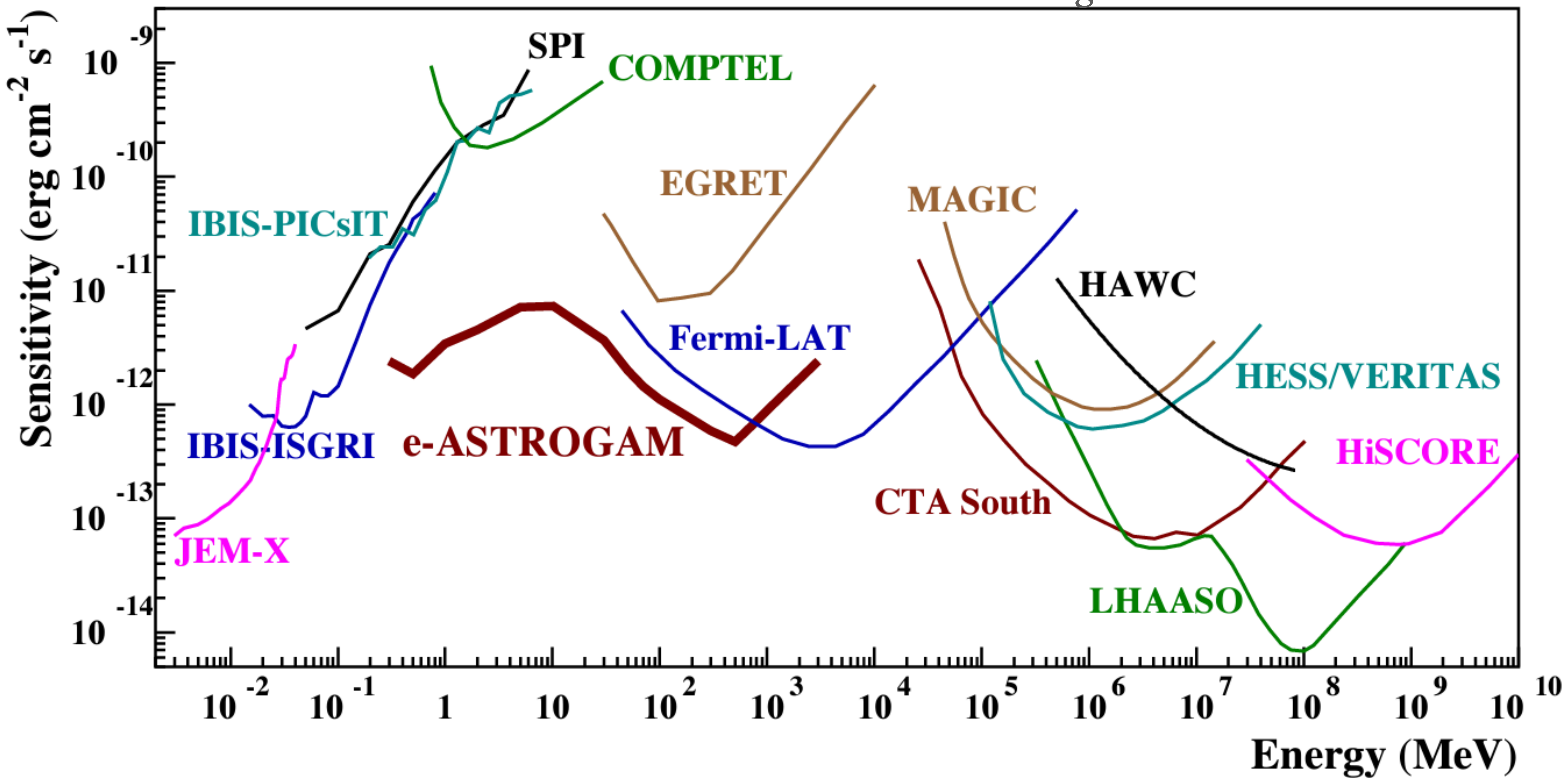
PROSPECTS AND MODELS FOR KEV/MEV DM

To appear with S. Kumar, B. Safdi, and Y. Soreq

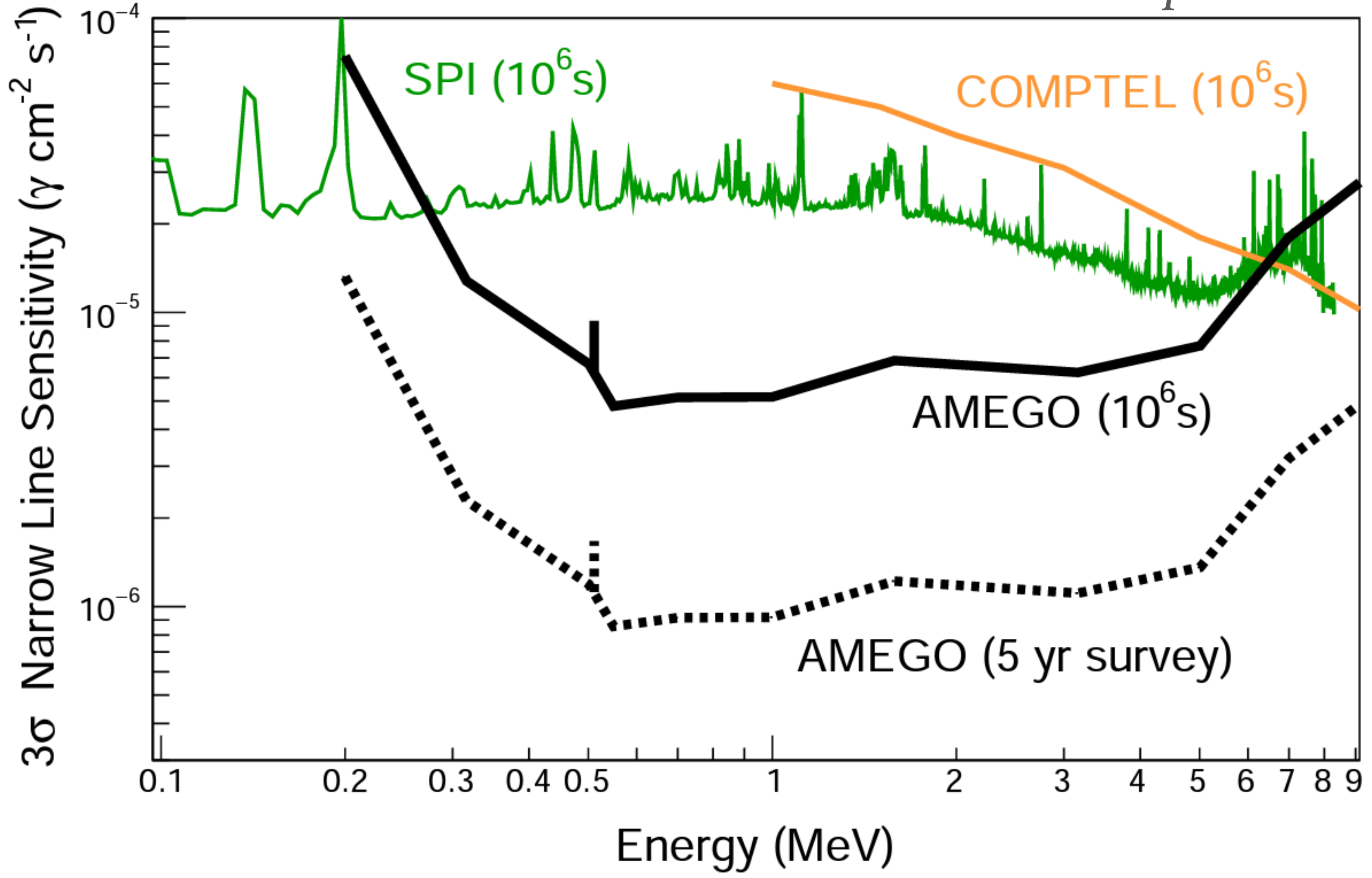
FUTURE PROSPECTS FOR INDIRECT DETECTION

- Workhorse telescopes are aging
  - XMM-Newton (Hard X-Ray): 22 years
  - Nustar (Very Hard X-Ray): 10 years
  - Comptel (Soft Gamma Ray): 10 years
  - Integral (Soft Gamma Ray): 20 years
  - Fermi LAT (Gamma Ray): 14 years
- Other operational challenges
- Upcoming and proposed telescopes
  - **XRISM (Hard X-Ray): 2023**
  - **Cherenkov Telescope (Gamma Ray): 2026**
  - **HERD (Gamma Ray): 2027**
  - ATHENA (Hard X-Ray): 2030s
  - AMEGO/e-Astrogram (Very Hard X-Ray, Soft Gamma Ray): 2030s

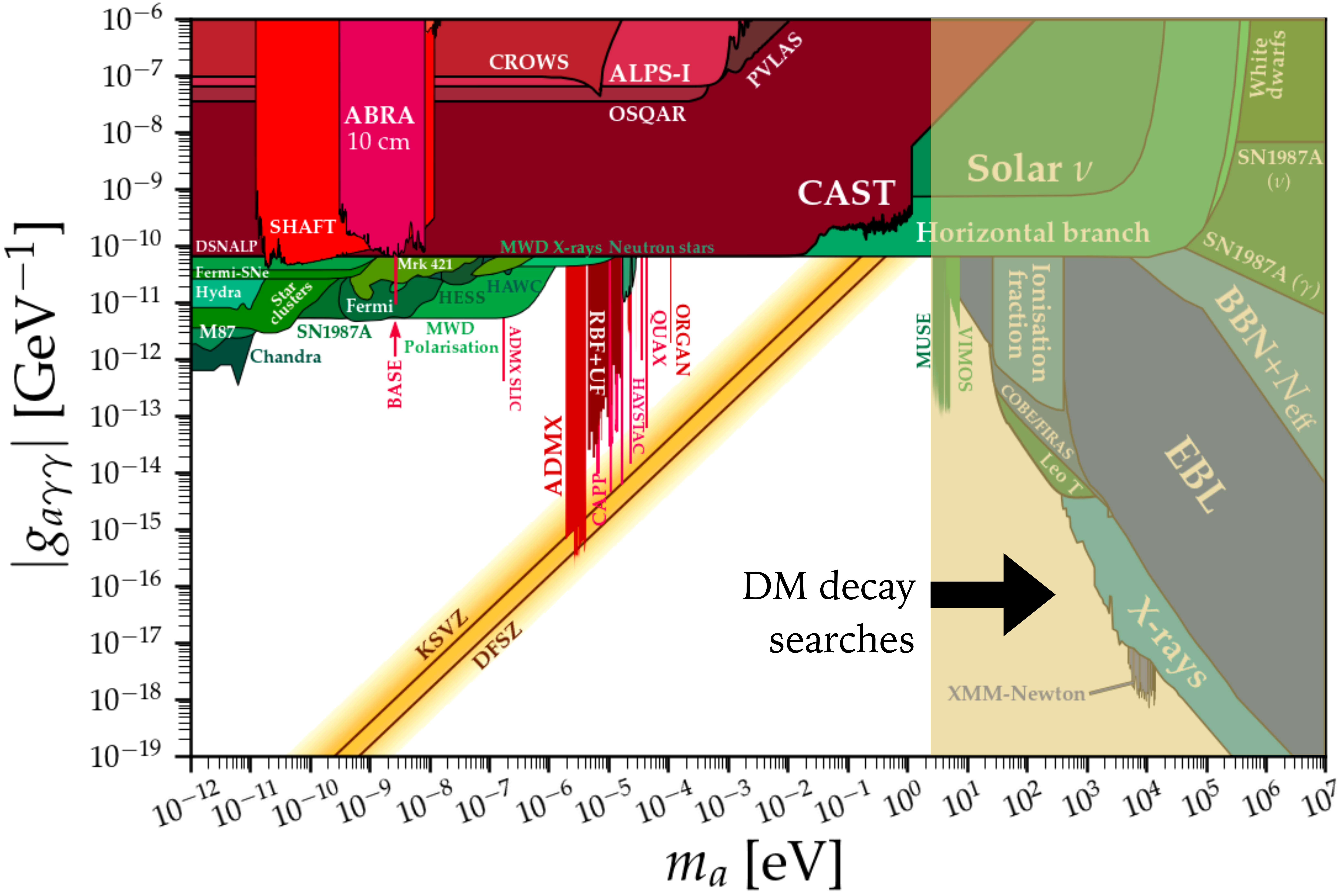
Science with e-Astrogram. arXiv: 1711.01265



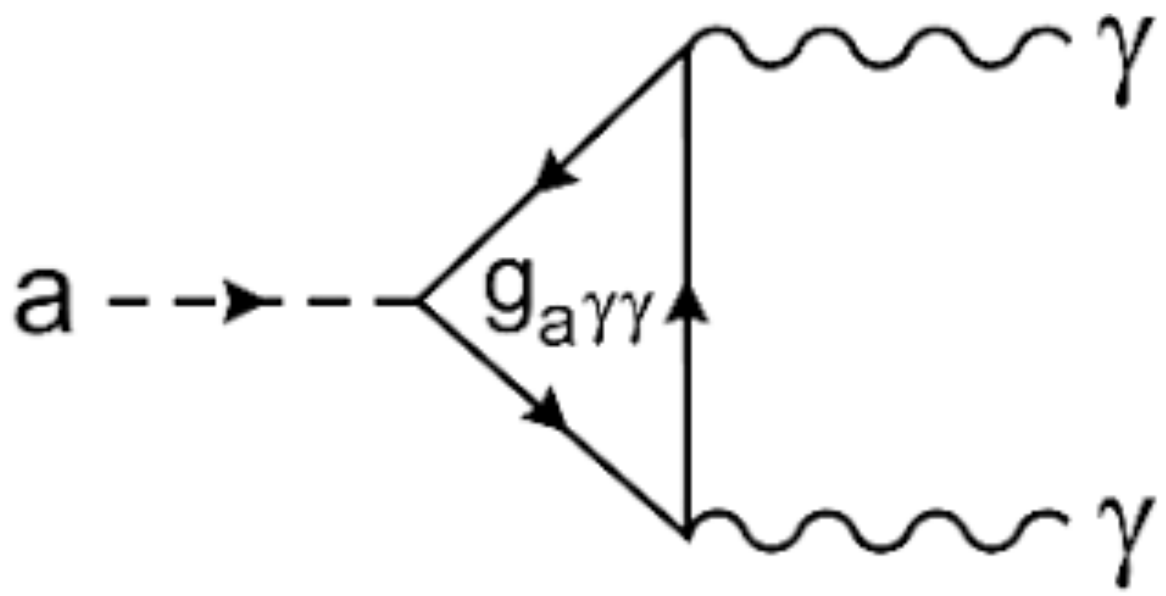
AMEGO White Paper. arXiv: 1907.07558



AXIONS AS DECAYING DARK MATTER



DM decay searches



$$\Gamma_a = \frac{m_a^3 g_{a\gamma\gamma}^2}{64\pi}$$

HEAVY AXIONS FROM DARK NONABELIAN GAUGES

$$\mathcal{L} = \frac{a}{8\pi f_a}\left[\alpha_D C_{aDD}\mathrm{Tr}(G_D\tilde{G}_D) + \alpha_{\mathrm{EM}} C_{a\gamma\gamma} F\tilde{F}\right]$$

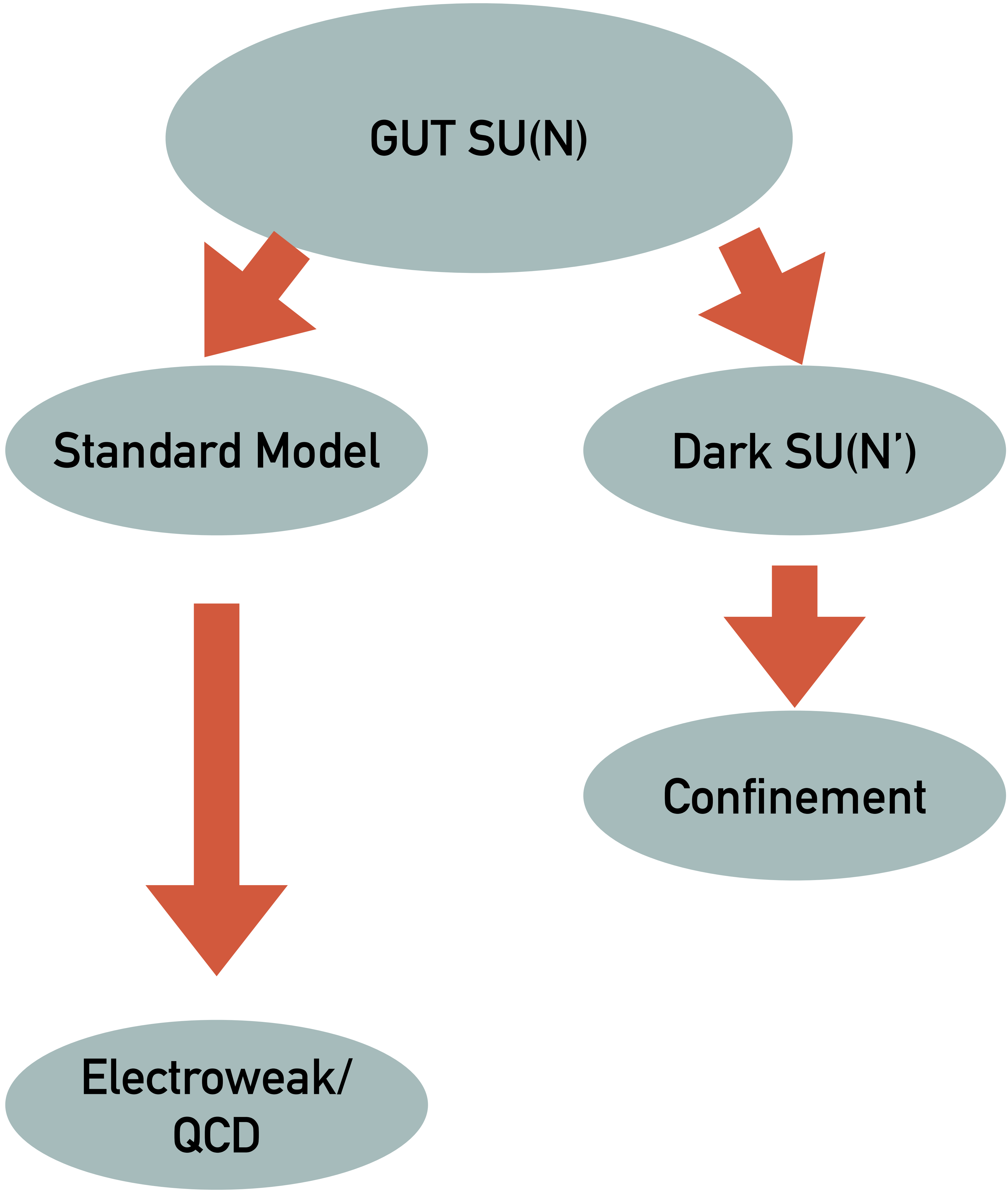
- Axion coupled to dark non-abelian gauge G and E&M

$$\Lambda_D = \Lambda_{\mathrm{UV}} \exp\left[-18\pi/33\alpha_{\mathrm{UV}} C_2\right]$$

- Dark gauge confines at low energies, axion acquires a mass from confinement

$$m_a \approx \frac{\Lambda_D^2}{f_a} \approx 1\ \mathrm{MeV}\left(\frac{\Lambda_D}{10^6\ \mathrm{GeV}}\right)^2\left(\frac{10^{15}\ \mathrm{GeV}}{f_a}\right)$$

- Model benchmarks: Dark SU(2) at the GUT scale leads to ~10 PeV confinement scale, ~10-100 keV axion mass



GUT SU(N)

Standard Model

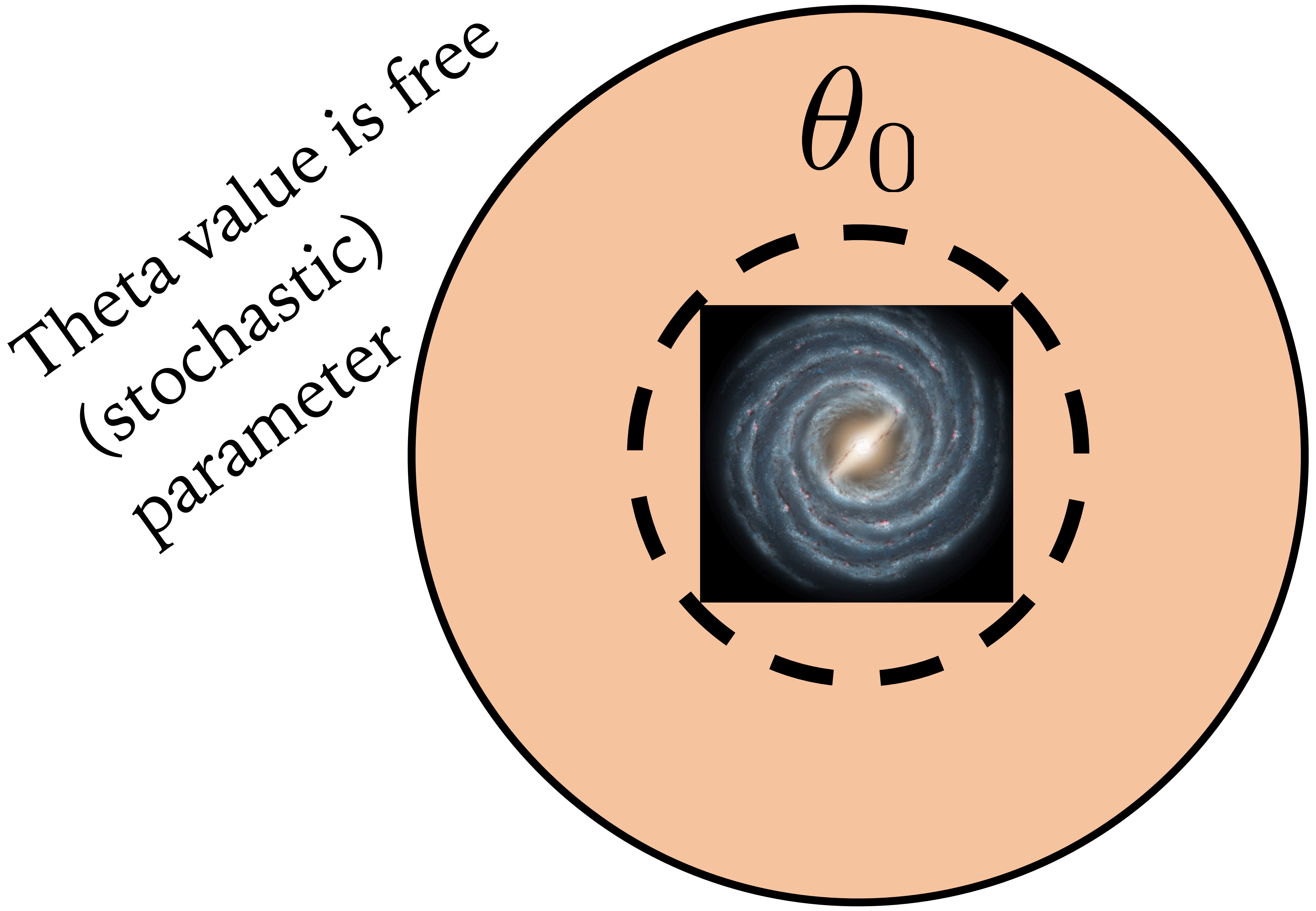
Dark SU(N')

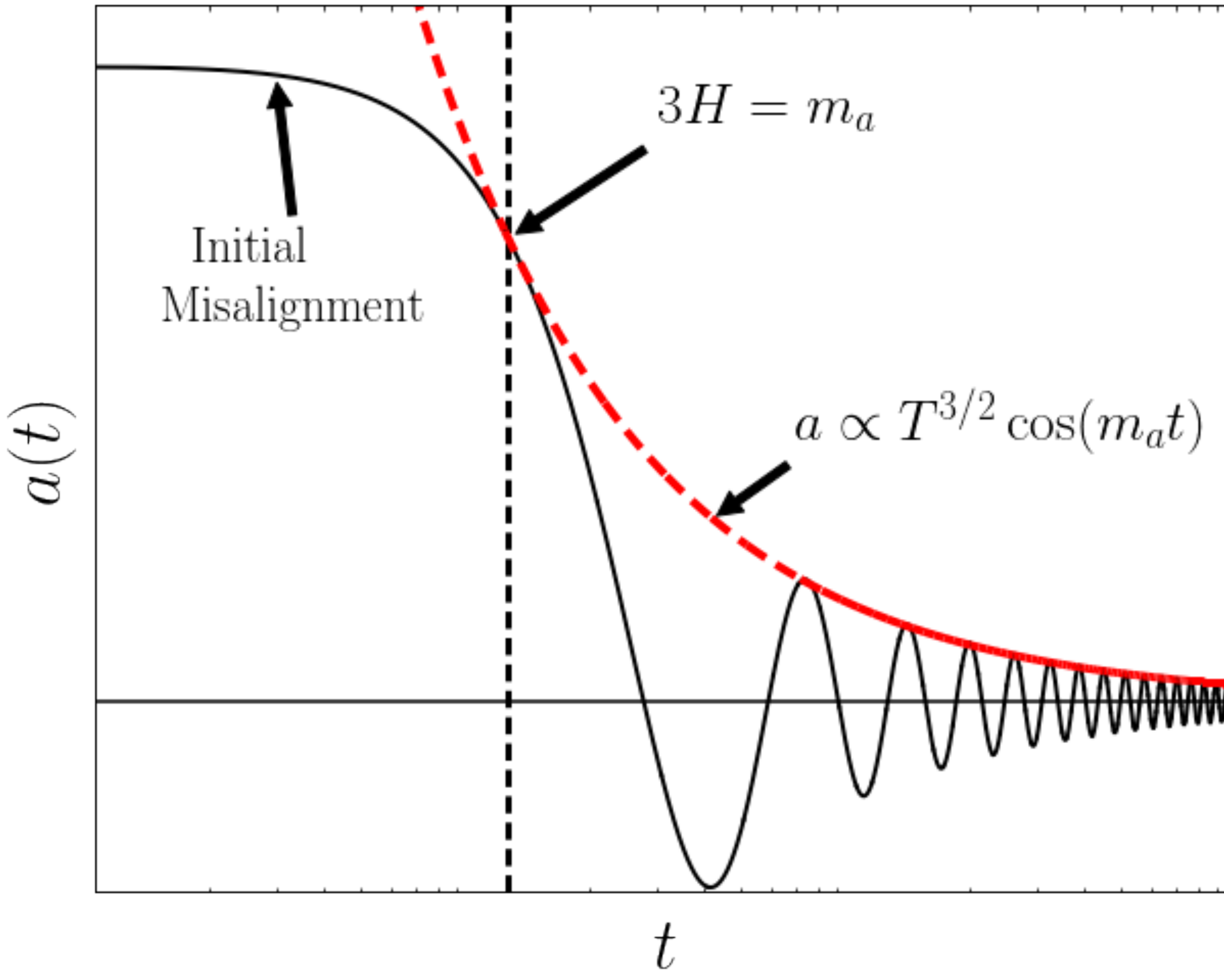
Confinement

Electroweak/
QCD

MISALIGNMENT IN A RADIATION DOMINATED COSMOLOGY

- Axion produced before inflation, homogeneous initial conditions





$$\Omega_a h^2|_{\mathrm{RD}} \approx 0.12 \left(\frac{\theta_i f_a}{2\times 10^{13}\ \mathrm{GeV}}\right)^2 \times \left(\frac{m_a}{1\ \mu\mathrm{eV}}\right)^{\frac{1}{2}} \left(\frac{90}{g_{S*}(T_{\mathrm{osc}})}\right)^{\frac{1}{4}}$$

Huge DM overproduction in benchmark scenario

MISALIGNMENT WITH AN EARLY MATTER DOMINATED ERA

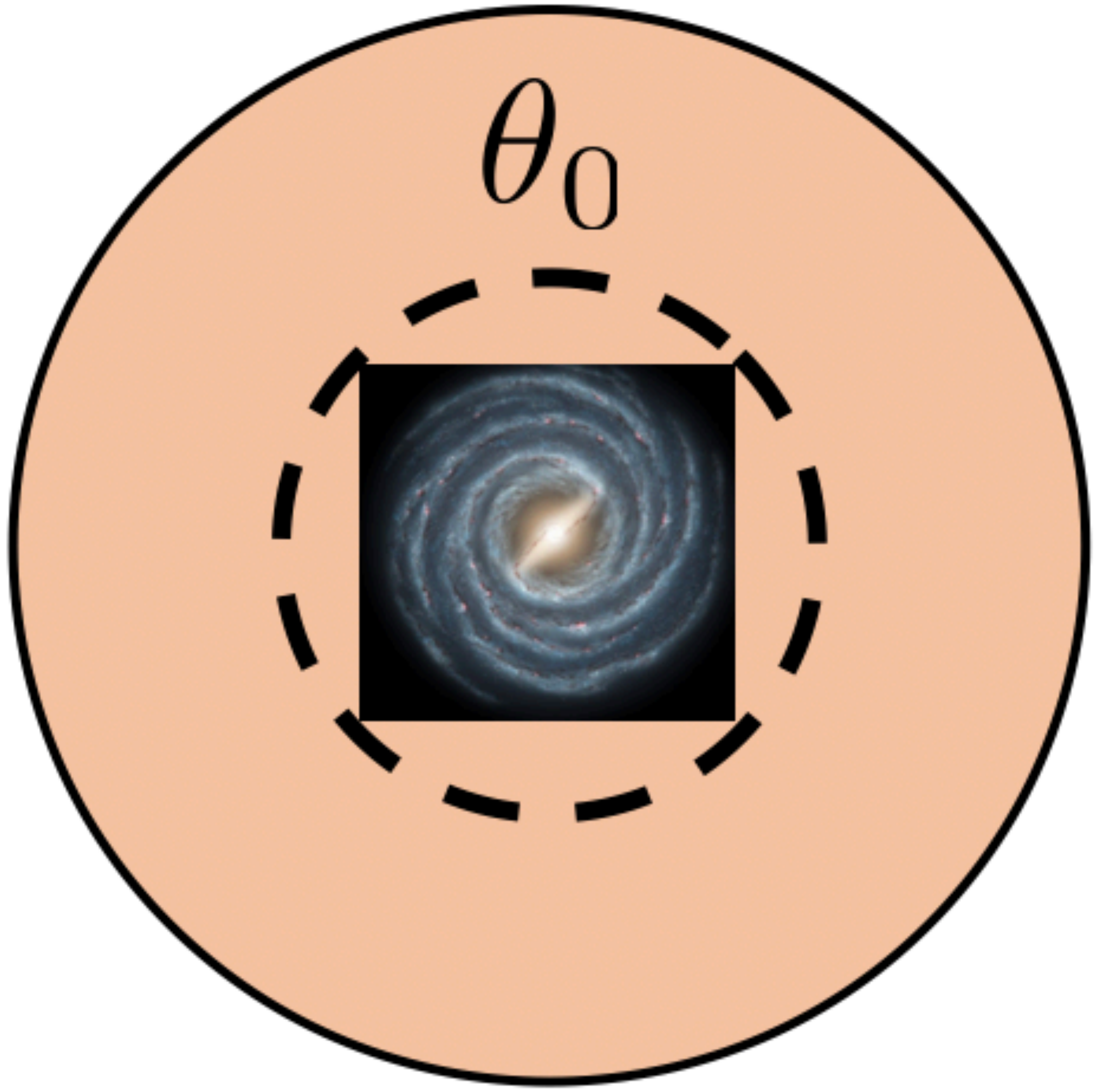
$$\Omega_a = \frac{1}{2}\frac{m_a^2 f_a^2 \theta_i^2}{\rho_c}\left(\frac{R_{\rm osc}}{R_{\rm RH}}\right)^3\left(\frac{T_0}{T_{\rm RH}}\right)^3\frac{g_{*S}(T_0)}{g_{*S}(T_{\rm RH})}$$

Constant axion mass,

Oscillations beginning during EMDE

Instantaneous reheating and RD onset

$$\Omega_a h^2\big|_{\rm EMD} \approx 0.12\left(\frac{\theta_i f_a}{10^{15}\ {\rm GeV}}\right)^2\left(\frac{T_{\rm RH}}{10\ {\rm MeV}}\right)$$



Blinov et al. arXiv: 1905.06952

AXION PRODUCTION THROUGH MISALIGNMENT WITH A GLUEBALL EMDE

- Confinement gives me glueballs, use these to generate EMDE

$$\mathcal{L} \supset \frac{c_6 \alpha_D}{4\pi} G^{a}_{d\,\mu\nu} G^{\mu\nu}_{d\,a} \frac{H^\dagger H}{\Lambda^2}$$

- Need glueballs to decay, couple to SM Higgs

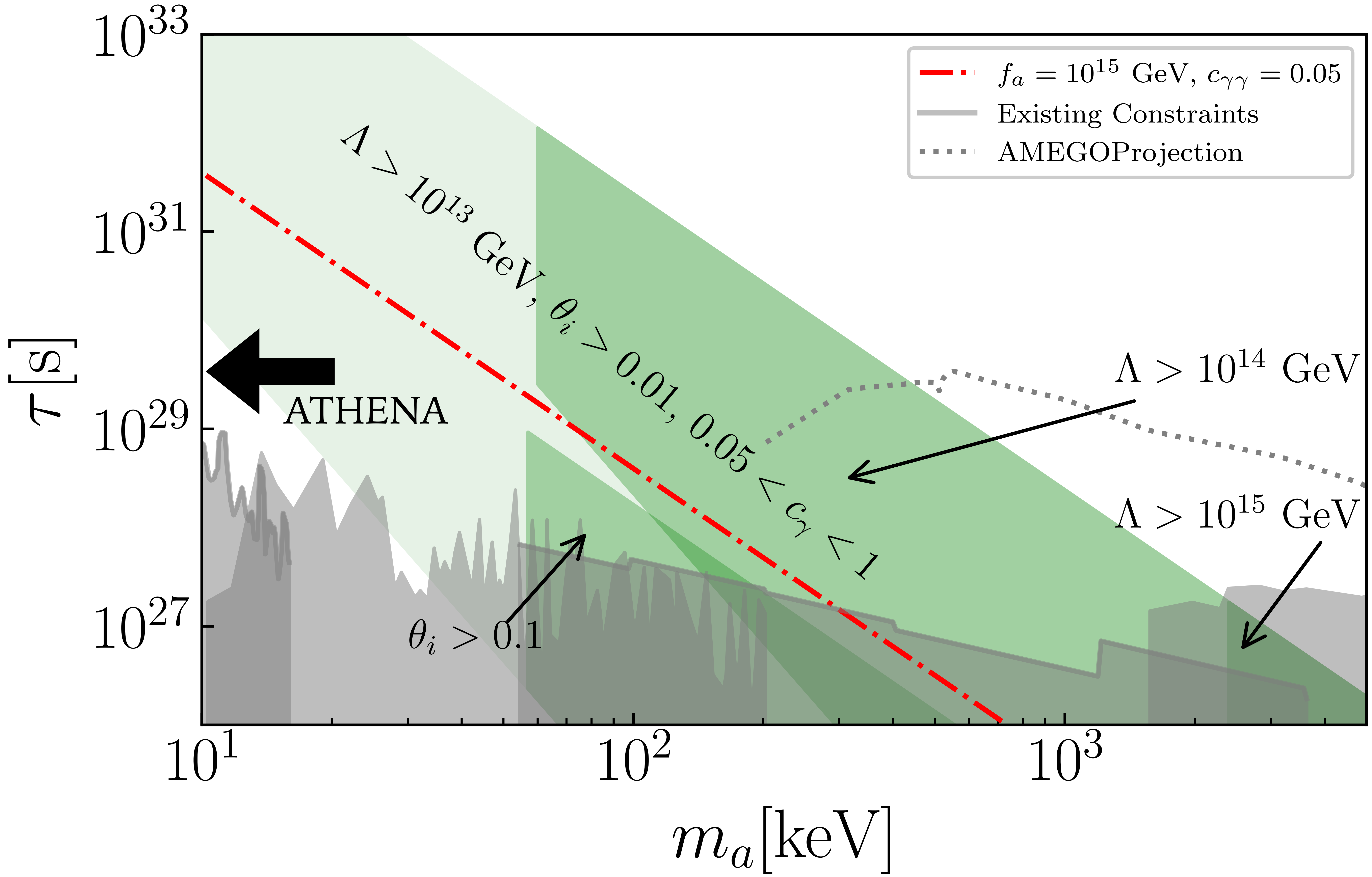
$$\Gamma_{0^{++}\to \mathrm{SM}} \approx 9 \times 10^{-2}\ \mathrm{s}^{-1} c_6^2 \left(\frac{m_{0^+}}{10^7\ \mathrm{GeV}}\right)^5 \times \left(\frac{10^{14}\ \mathrm{GeV}}{\Lambda}\right)^4$$

- Glueball decays reheat universe, must be compatible with BBN

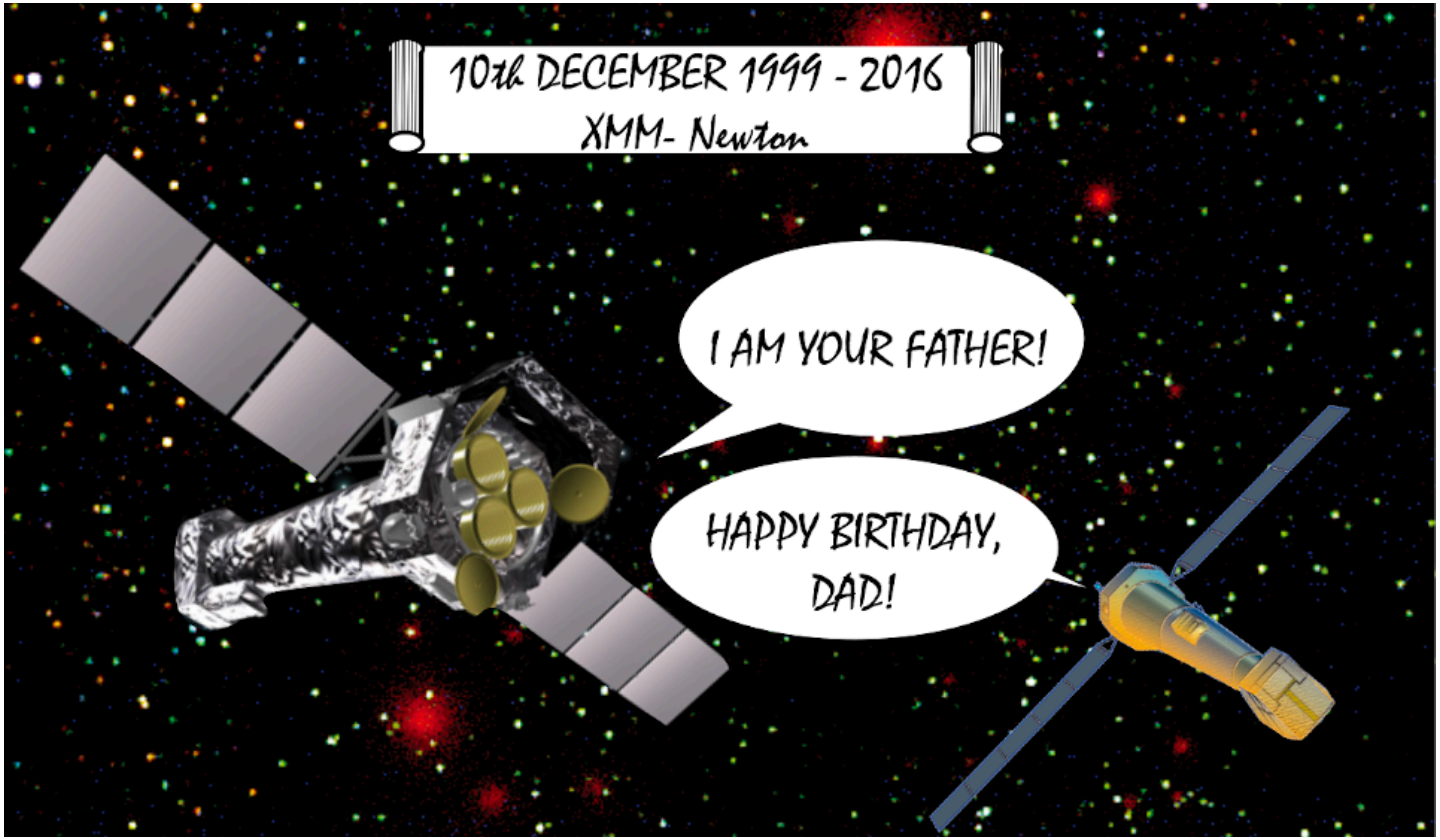
$$T_{\mathrm{RH}} \approx 5\ \mathrm{MeV} \left(\frac{10.8}{g_*(T_{\mathrm{RH}})}\right)^{1/4} c_6 \times \left(\frac{m_{0^+}}{3.1 \times 10^7\ \mathrm{GeV}}\right)^{5/2} \left(\frac{10^{14}\ \mathrm{GeV}}{\Lambda}\right)^2 .$$

See also T .Slatyer et al. 2203.15813 for application to thermal squeezeout dark matter

HEAVY ALP PARAMETER SPACE



CONCLUSION



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