CENTER FOR ASTROPHYSICS
HARVARD & SMITHSONIAN

Shedding light on the dark matter paradigm with *Chandra*

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Outline

1. Introduction: The dark matter problem

❋ From Zwicky and Rubin to today

2. Shedding light on dark matter with *Chandra*

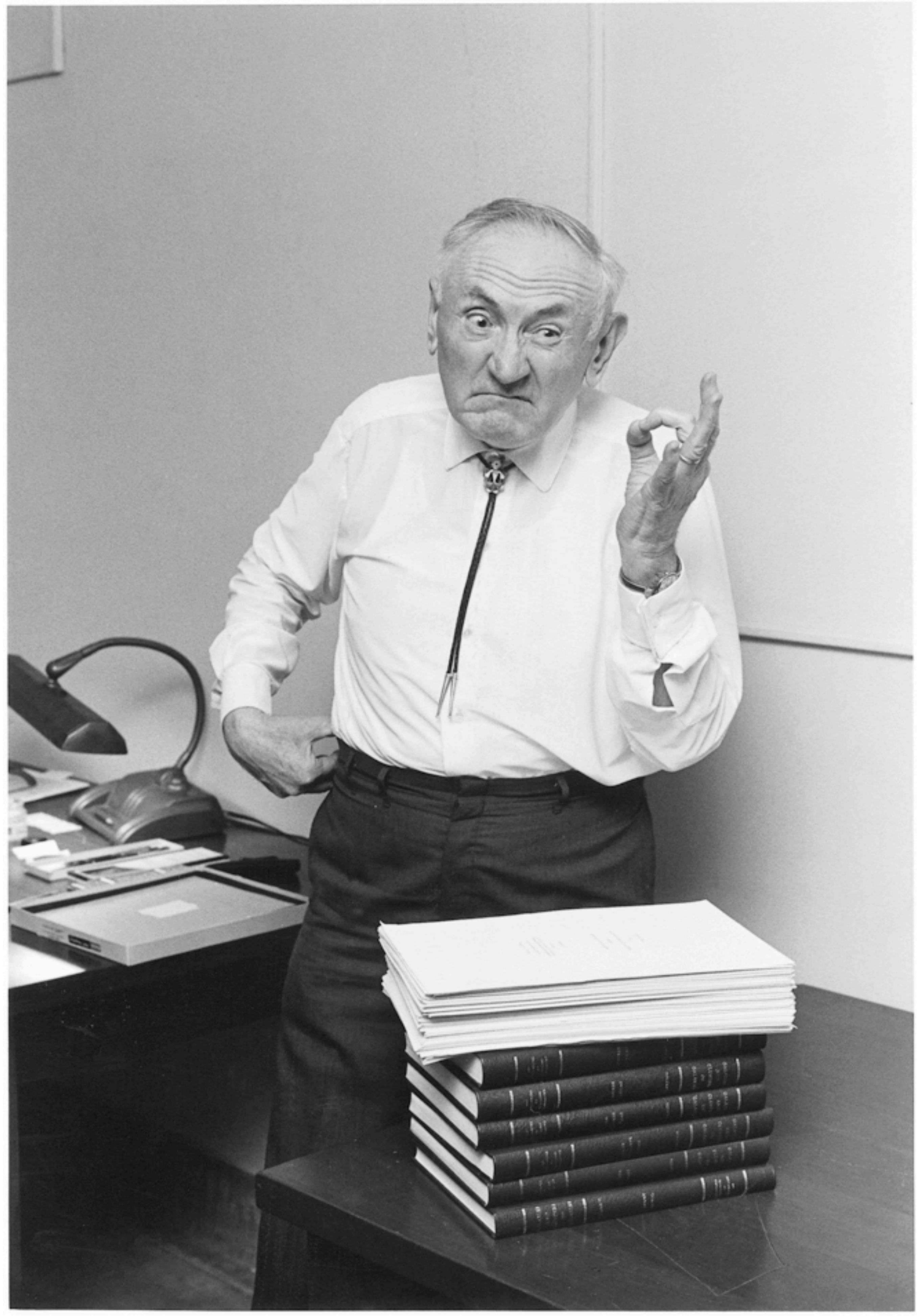
❋ (WIMPs) + sterile neutrinos + axions

3. What does the future hold?

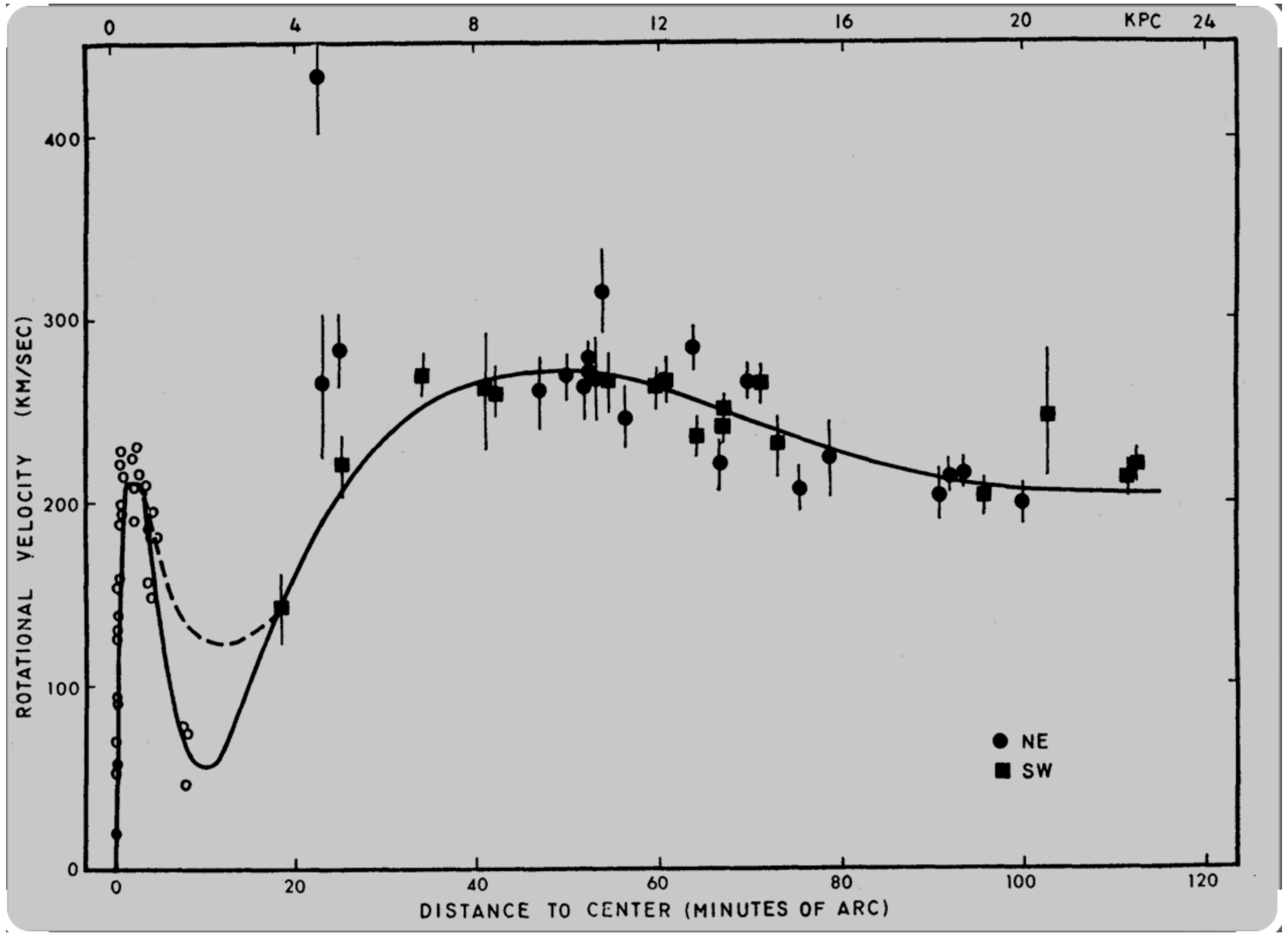
RAS Astronomy & Geophysics article, December 2024, now available!

The dark matter problem

- Clusters of galaxies
- Galaxy rotation curves



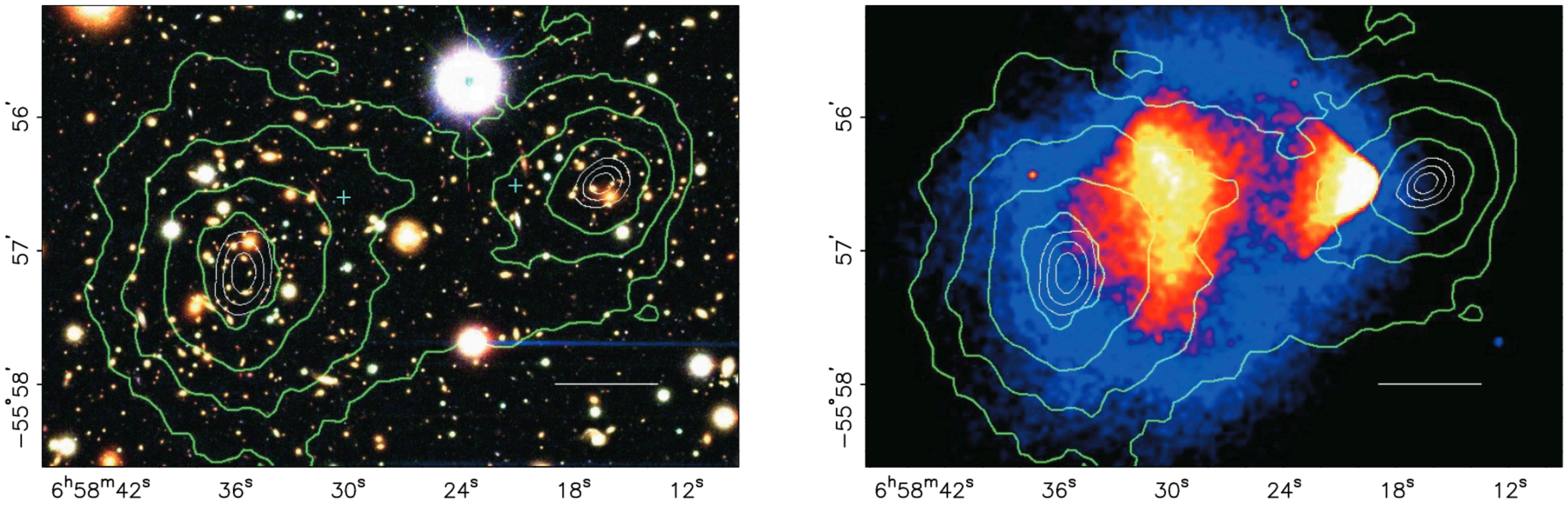
Fritz Zwicky



V. Rubin & K. Ford (1970), ApJ, 159, p. 173

The dark matter problem (II)

- Bullet cluster
- Gravitational lensing
- Cosmic microwave background



D. Clowe et al (2006), 648, L109-L113

Viable dark matter candidates...

Charge-free

Non-dissipative

Pressureless

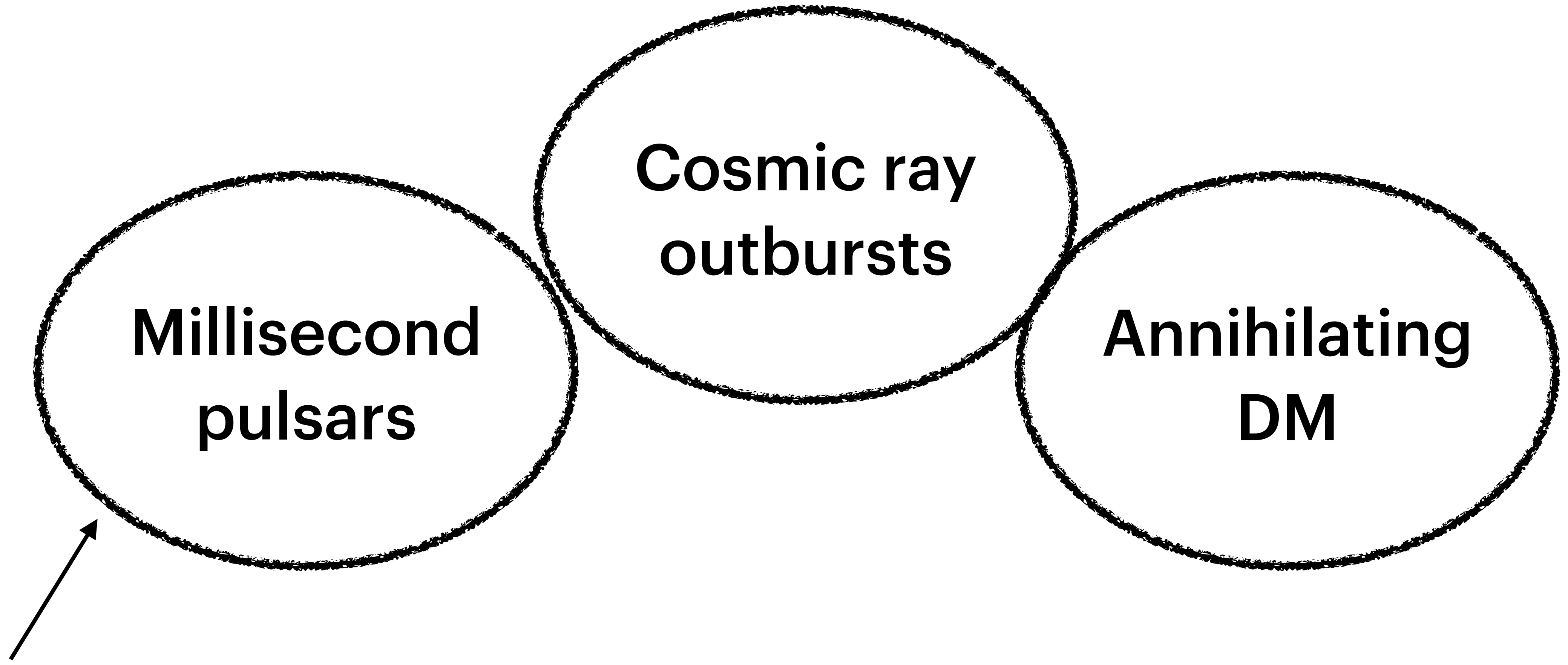
Solve other tensions

Quest for dark matter

The WIMP story

Advantages

- Produced thermally
- Cosmic abundance
- Predicted by SUSY

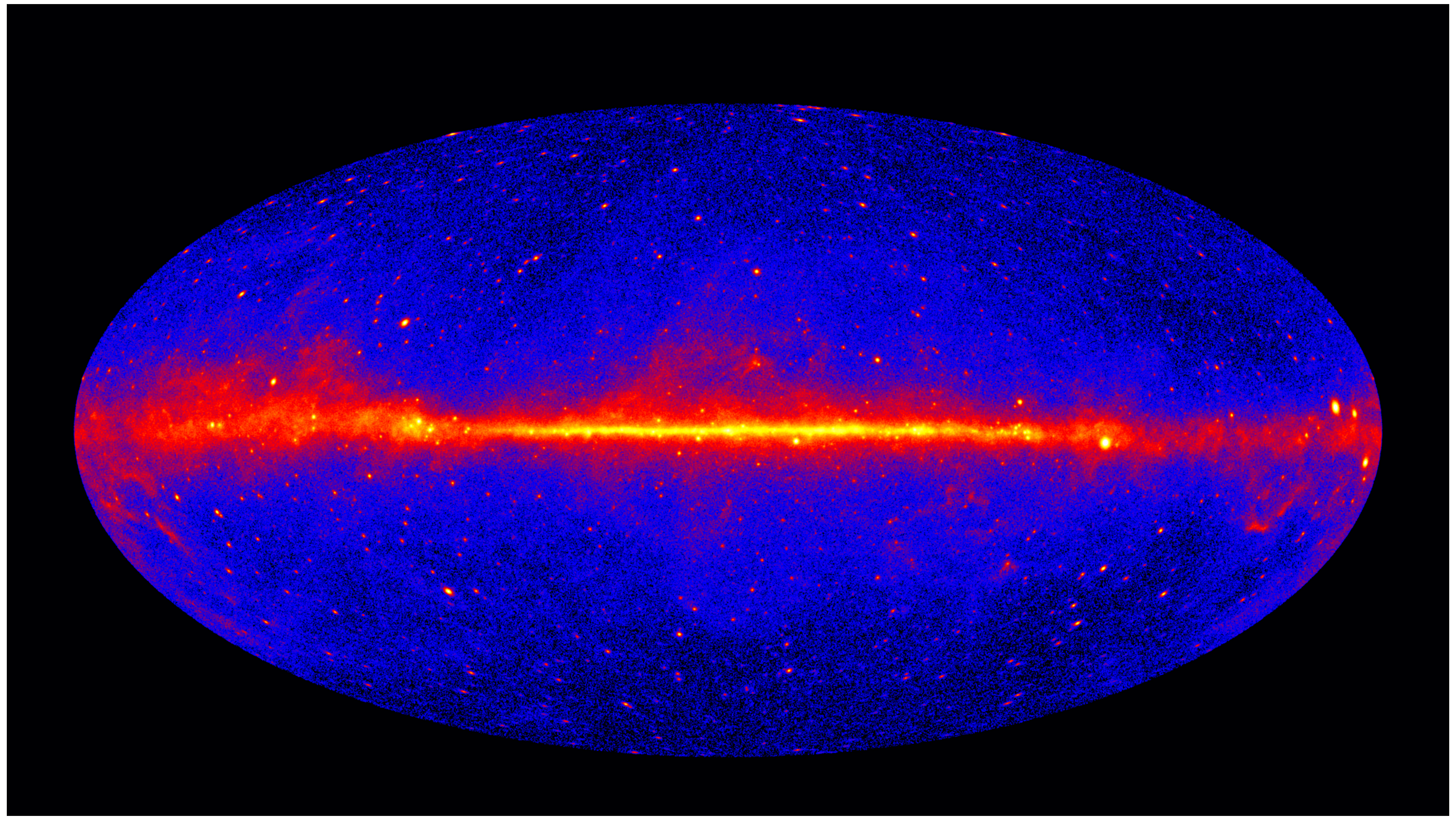


WIMP mass

Cross-section

$$\Omega_\chi \sim 1/(m_\chi \sigma_\chi) \qquad m_\chi \sim 100 \text{ GeV}$$

Fermi Galactic Center excess



Aalbers et al (2023), Phys. Rev. Lett. 131, 041002
[+ Papers by *R. Leane & T. Slayter*]

The sterile neutrinos story

Claimed detections

⁕ *XMM-Newton*

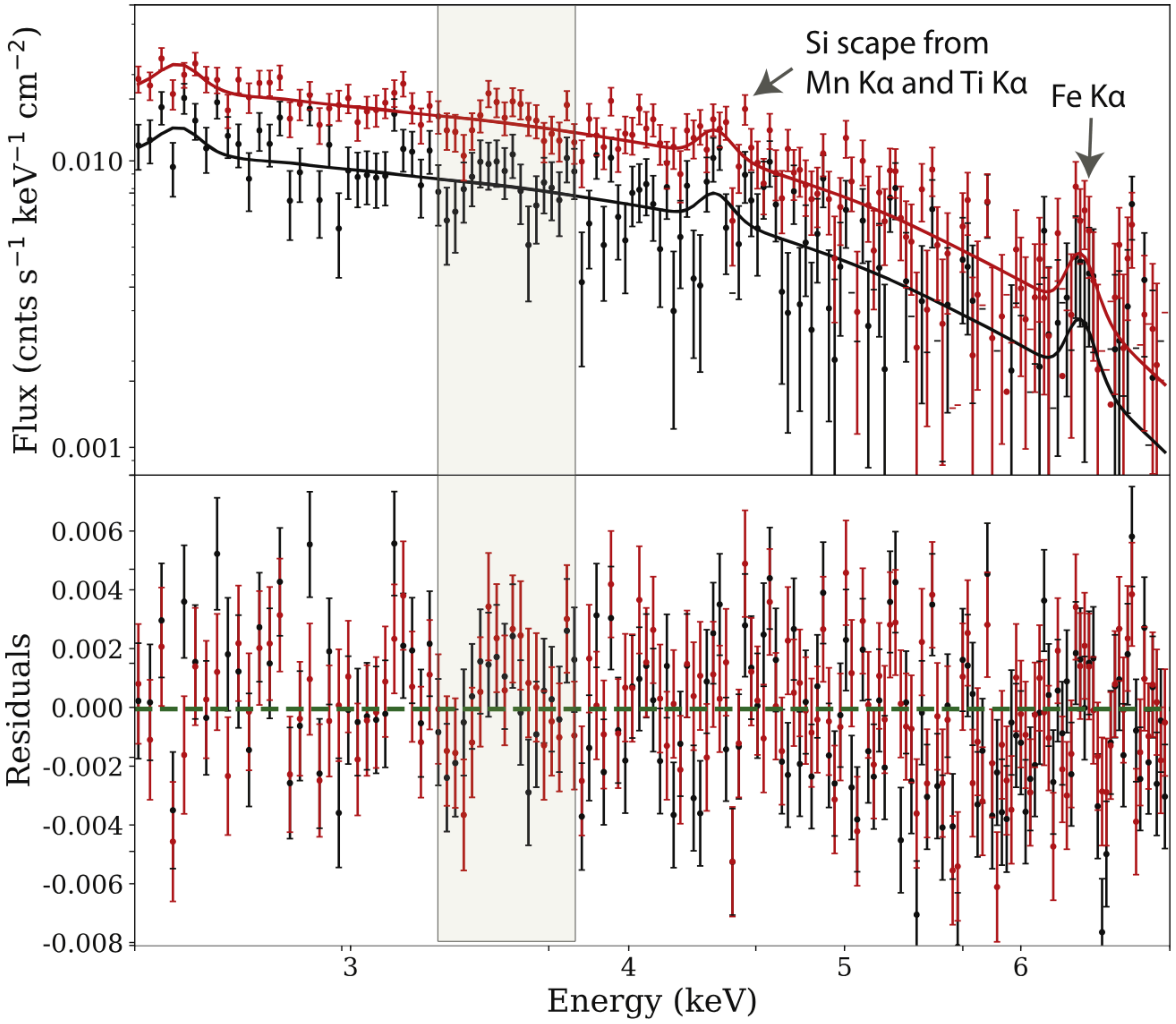
- Perseus (inc. cored)
- M31
- Stacked clusters

⁕ *Chandra*

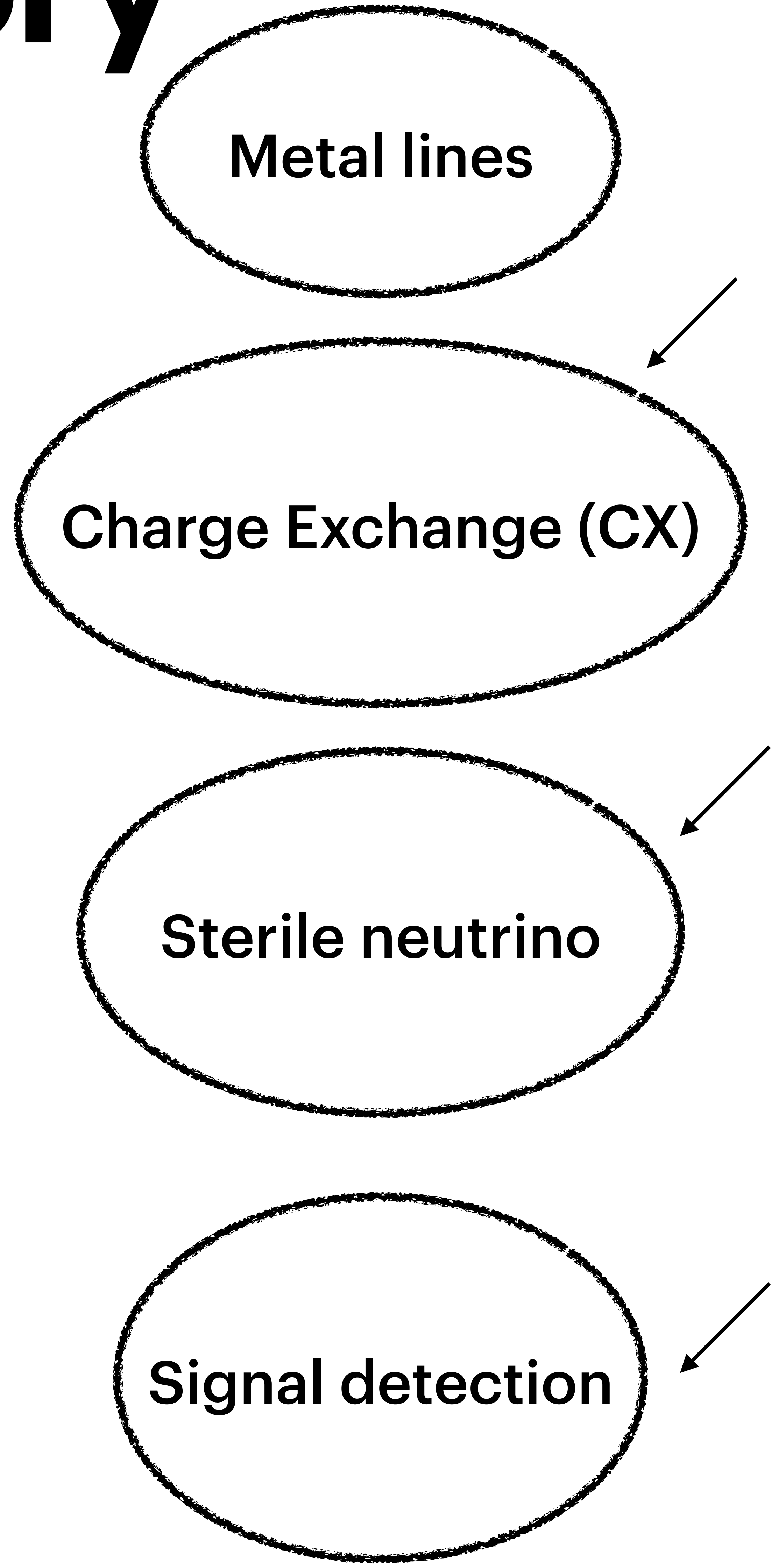
- Perseus (ACIS-S, ACIS-I)
- Deep Fields (ACIS-I)

⁕ *Hitomi & XRISM*

- (?) 3.44 - 3.47 keV CX?



Cappelluti et al. (2018), ApJ, 854, 2



Dessert et al. (2024), ApJ, 964, 2

The story with axions

Advantages

- Solve the strong charge-parity problem
- QCD axion: well-constrained

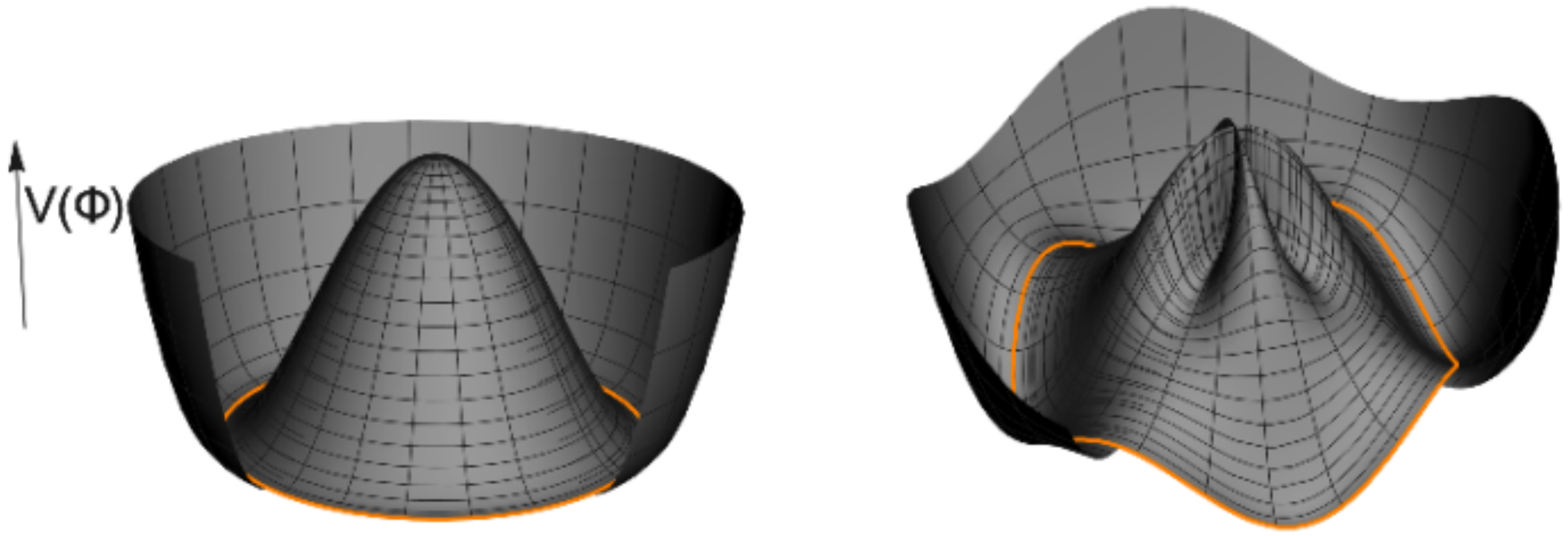
Global decay constant

$$m_{\rm a}\ f_{\rm a} \sim m_\pi\ f_\pi$$

Axion mass — Pion

$$f_{\rm a}[\mathrm{GeV}^{-1}] \approx 1/g_{{\rm a},i}[\mathrm{GeV}^{-1}]$$

Coupling constant with *i*



Chadha-Day et al. (2022), Sci. Adv, 8, 8

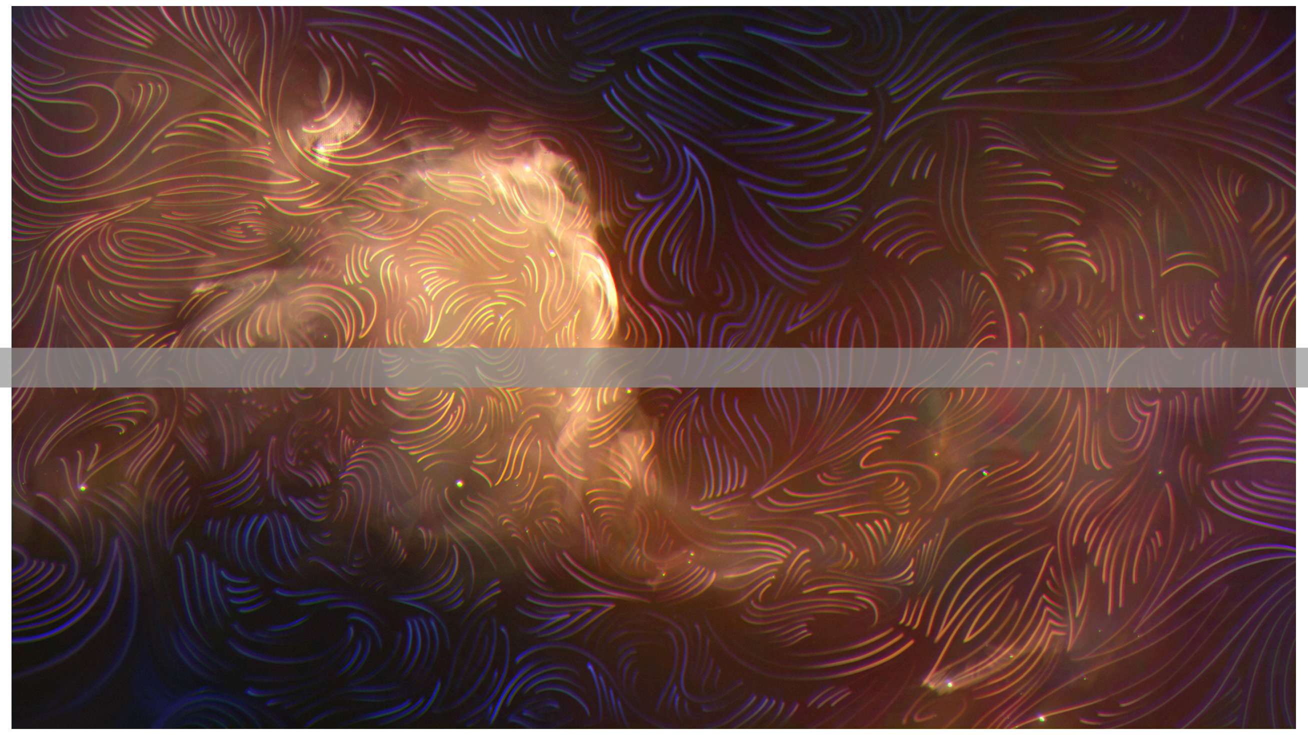
- Non-thermal axion production: Abbott & Sikivie (1983); Dine & Fischler (1983); Preskill et al. (1983)

Dark matter axions (II)

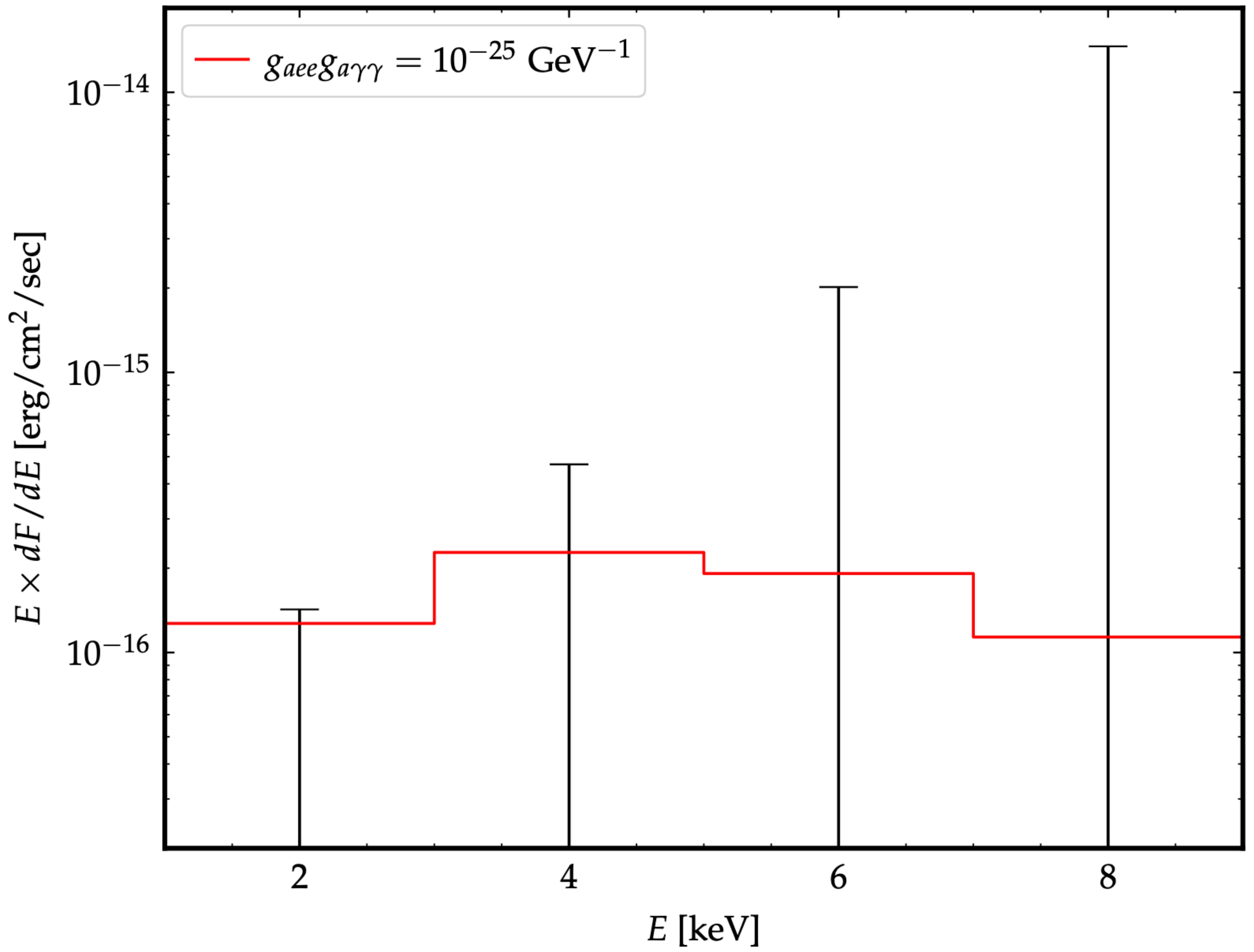
Photons + Leptons → Axion production e.g. stellar cores

CAST experiment at CERN
[+ Papers by G. Raffelt]

Cosmic magnetic fields

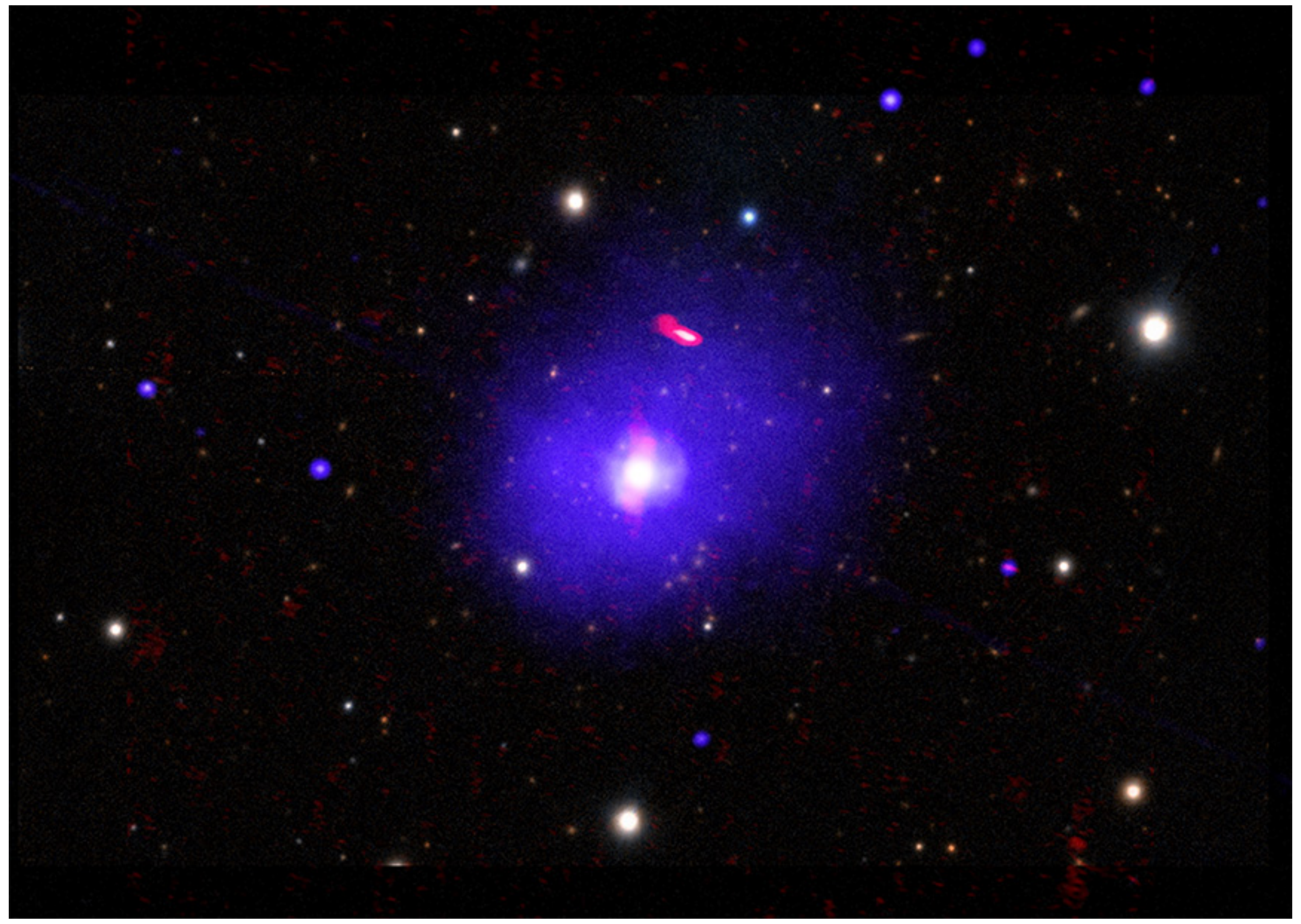


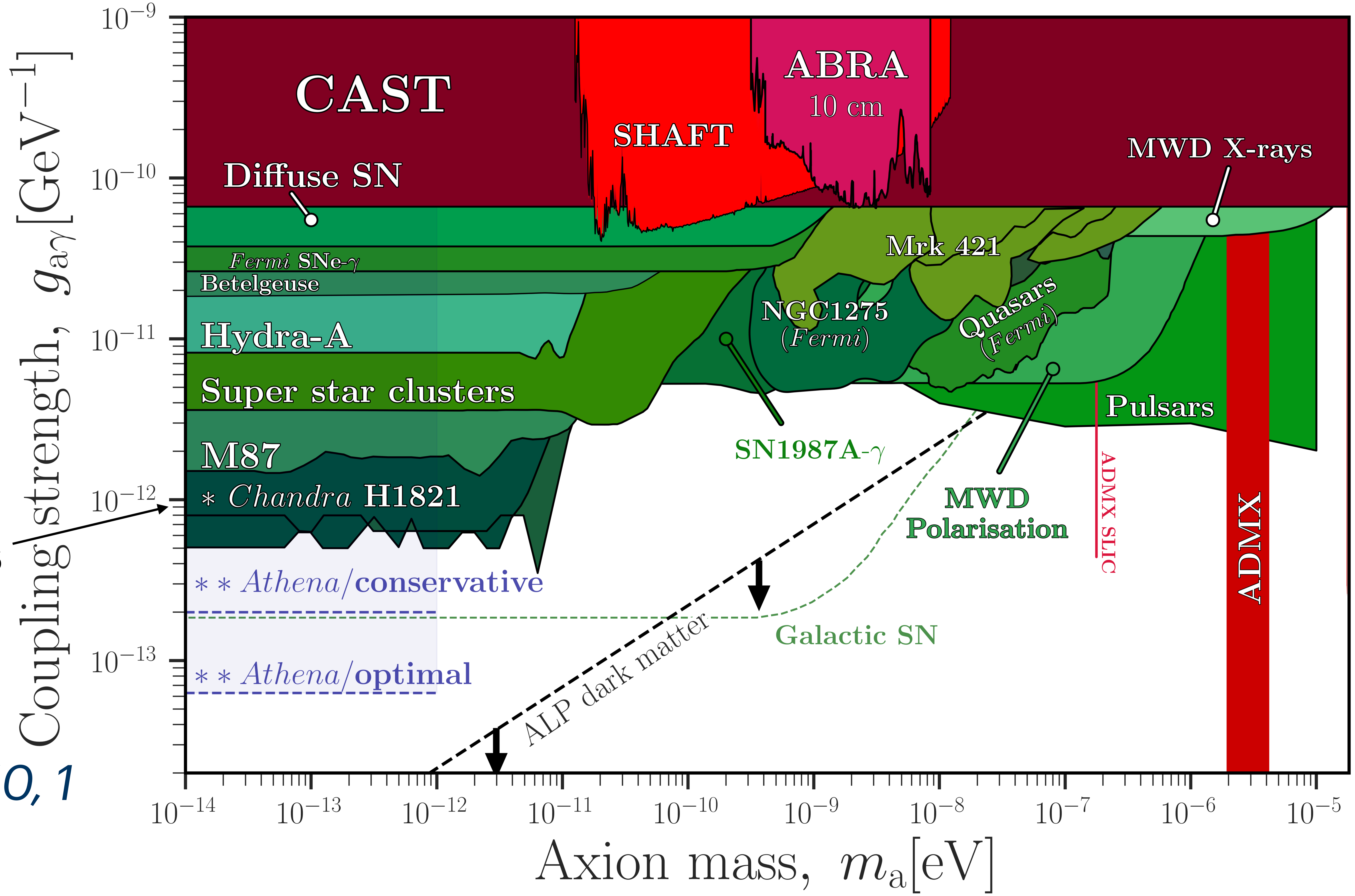
Photons → Spectral distortions e.g. AGN



Magnetized white dwarf
Dessert et al. (2022), PRL, 123, 7

Dark matter and stringy axions (III)





Adapted from *Axion Limits* (O'Hare Github)

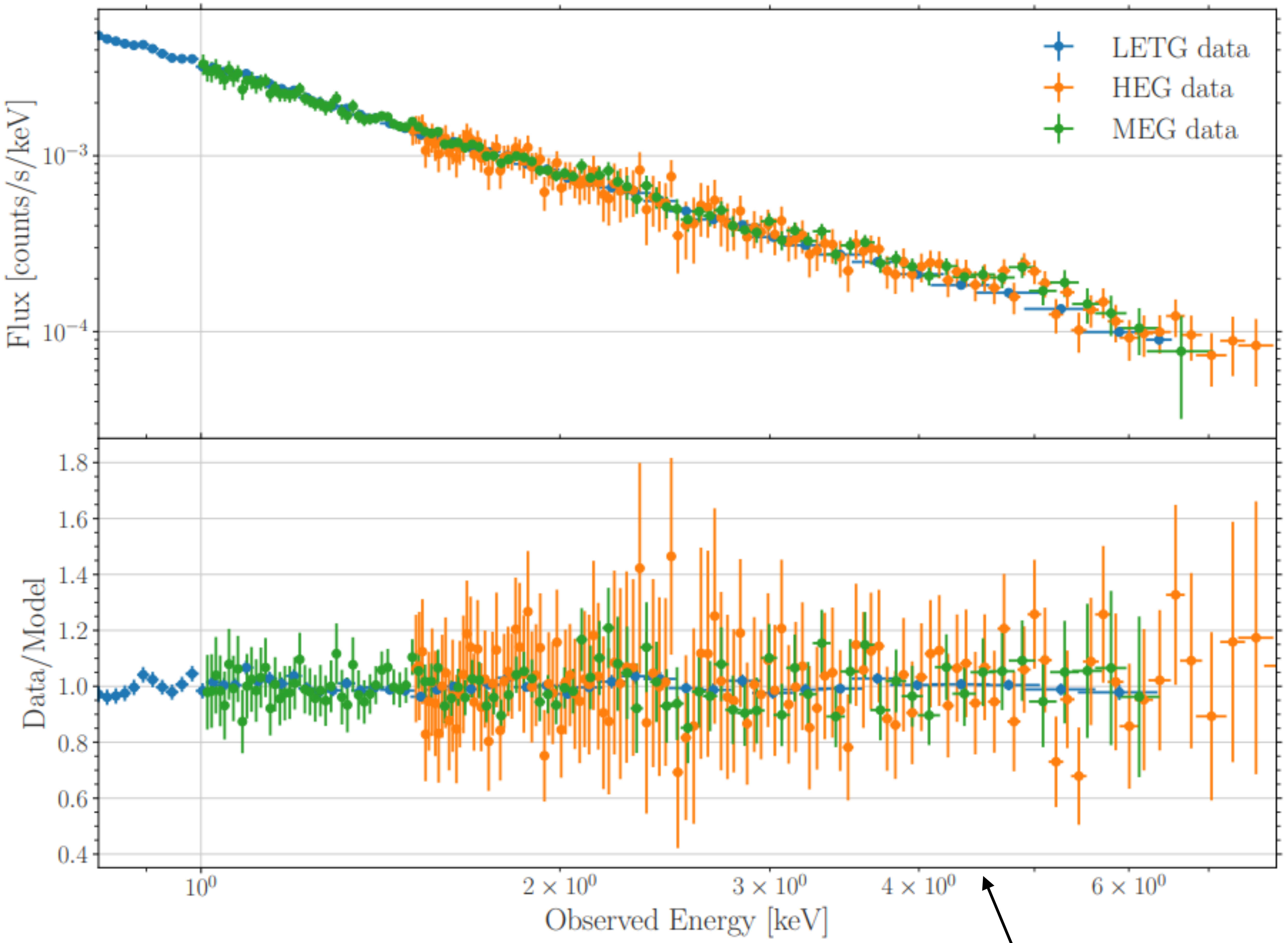
Leading bounds on light axions from *Chandra*/Grating observations of bright cluster-hosted AGN

> H1821+643 (H1821)
Sisk Reynes et al. (2022), MNRAS, 510, 1

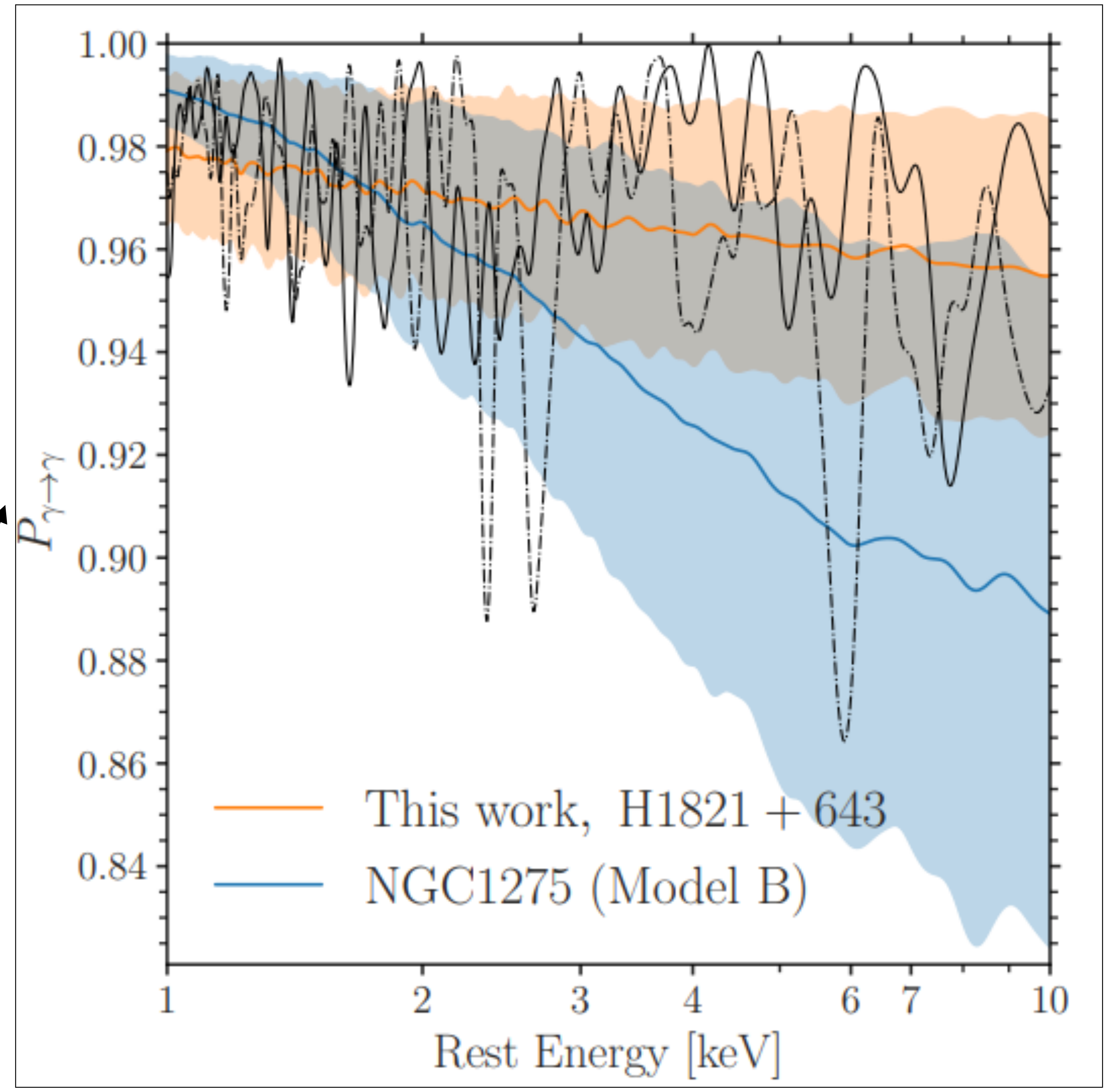
> NGC1275
Reynolds et al. (2020), ApJ, 890, 1

Axion distortions in the spectrum of H1821 (IV)

Best-fit model (typical of type-1 AGNs) + residuals



Mixing probability (different ICM *B*-field realizations)



$$F_{\rm obs}(E) = F_{\rm AGN}(E) \times P_{a\gamma}(E, g_{a\gamma}, B_{\rm ICM}, n_{\rm ICM})$$

Closing remarks

An exciting future ahead

CXC (NASA/J.Sanders/A.Fabian et al.)

For Initiative II: Deep Observation of a Galaxy Cluster to Understand Key Physical Processes, the selected proposal is:

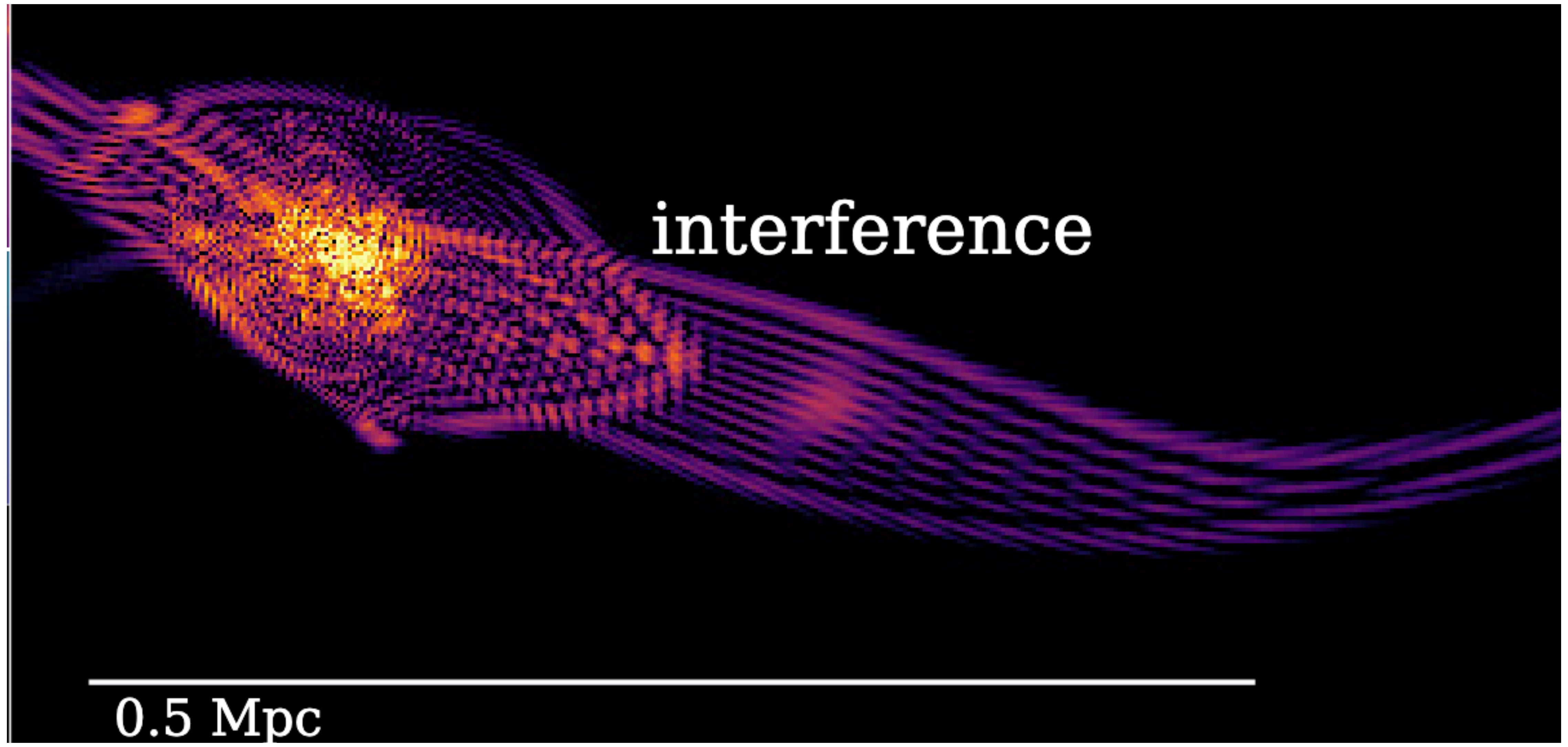
The Sounds of Feedback: Deep and Wide Imaging of the Cool Core of the Perseus Cluster

Additional 3 Ms ACIS-I observations of Perseus will open up a window to study:

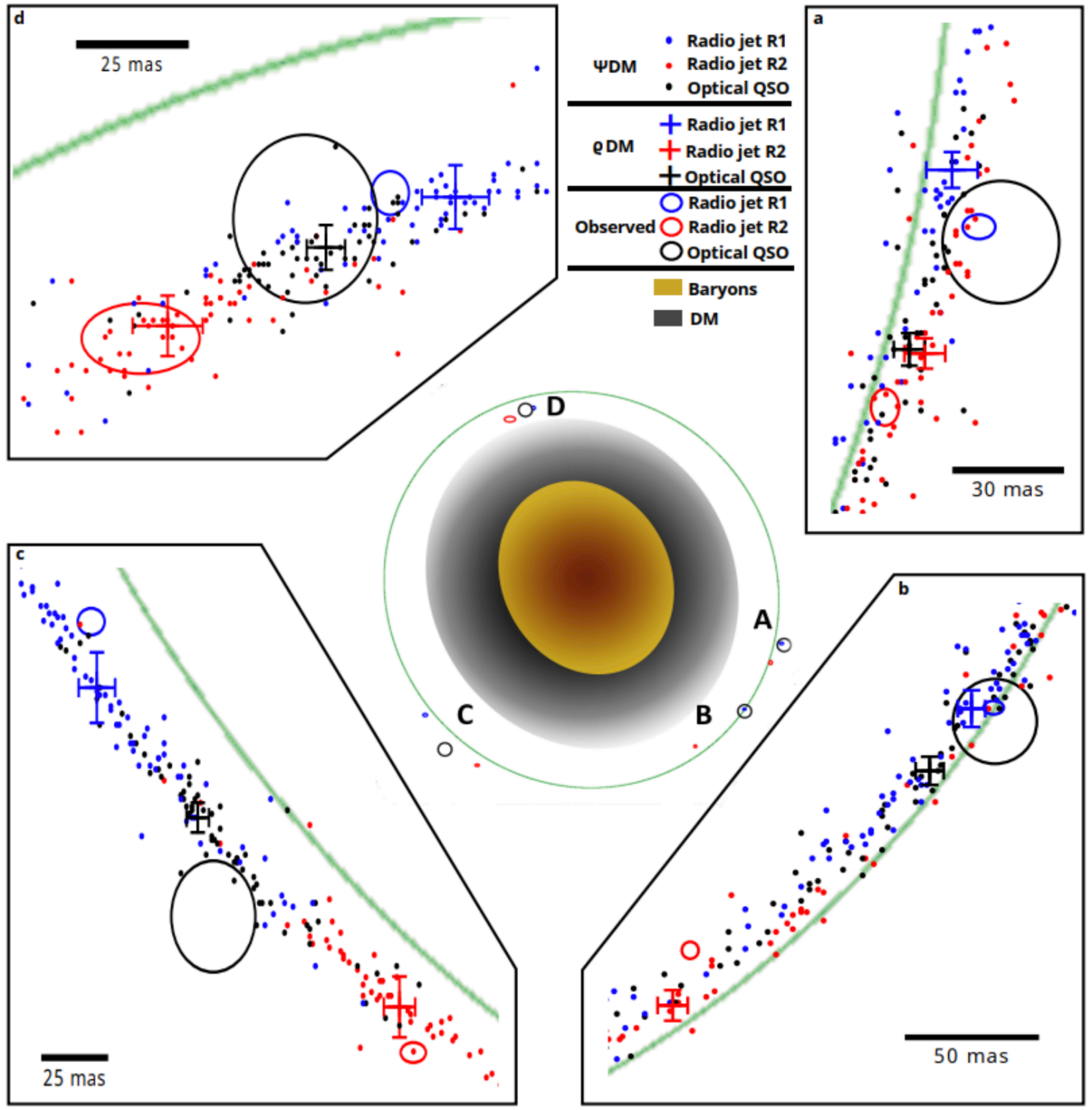
- Axions (intracluster *B*-field models)
- Sterile neutrinos (along with *XRISM*)
- *Chandra* Legacy Program (PI: Andy Fabian)
  Start: December 2024!

Fuzzy dark matter and strong lensing

- Induces substructure at ~kpc scales; $m_{\mathrm{a}} \sim 10^{-22}\ \mathrm{eV}$
- May solve the "cusp vs. core problem" in LCDM
- Is viable; plus dark matter may be a particle "cocktail"
- Could explain anomalous flux ratios + position offsets in lensed images of strongly lensed quasars



HS 0810+2554



Amruth et al. (2023), Nat Ast., 7

Conclusions

✷ The nature of dark matter remains unresolved

- Push towards searching for a *lighter* (sub-GeV) dark matter candidate
- Astrophysical searches play a key role in complementing laboratory DM searches
- Model-dependent, we must explore a wide range of parameters (masses, couplings)

✷ *Chandra* has played a key role in searching for:

- Sterile neutrinos (Perseus; Deep Fields)
- Axions (cluster-hosted AGN; magnetic white dwarfs)

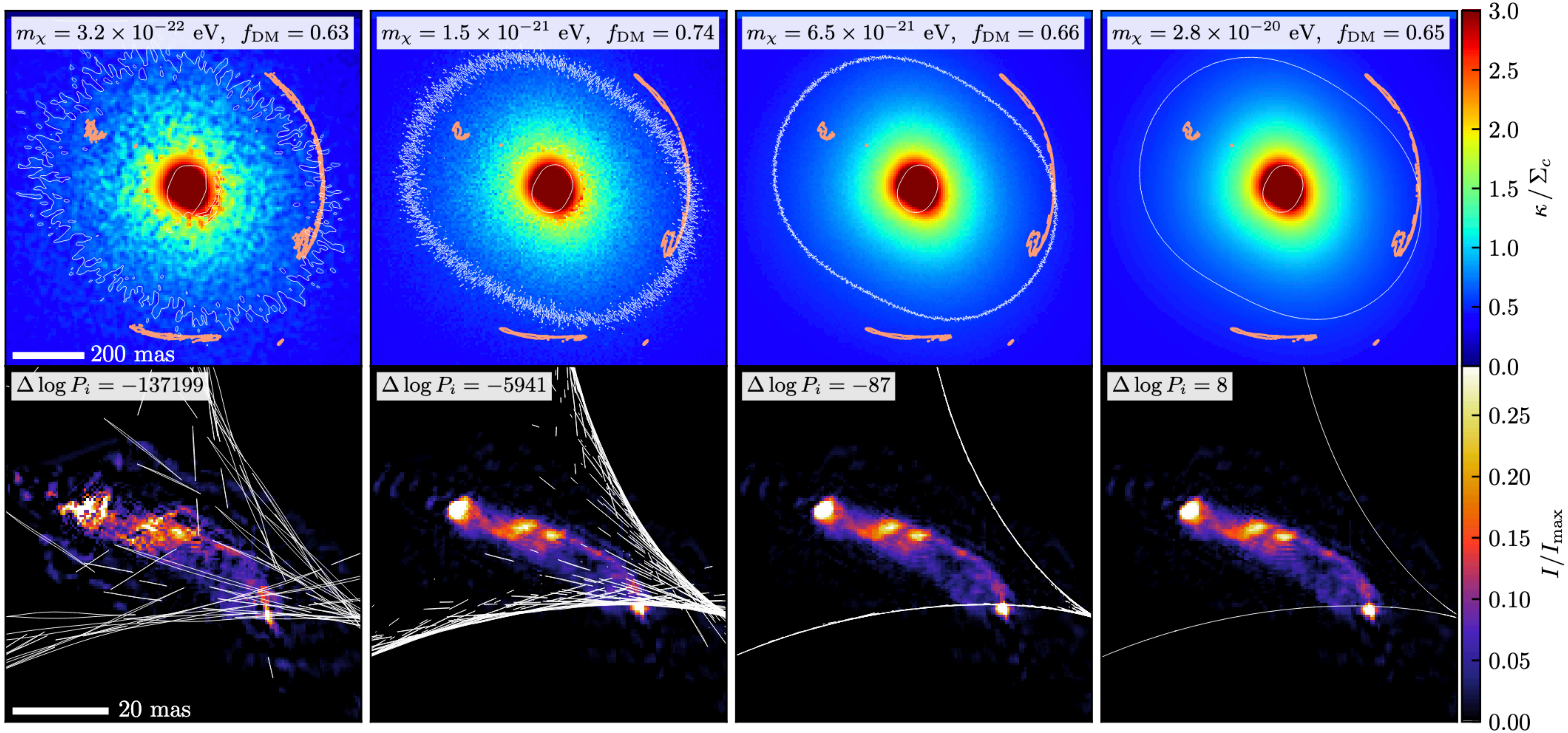
✷ Upcoming DM studies with *Chandra* have a promising agenda in view of:

- Perseus *Chandra* Legacy Program (PI Andy Fabian)
- Strongly lensed quasars > *Chandra* data (PI Dan Schwartz, + Anna Barnacka & Cristiana Spingola)

Additional slides

Fuzzy dark matter and strong lensing

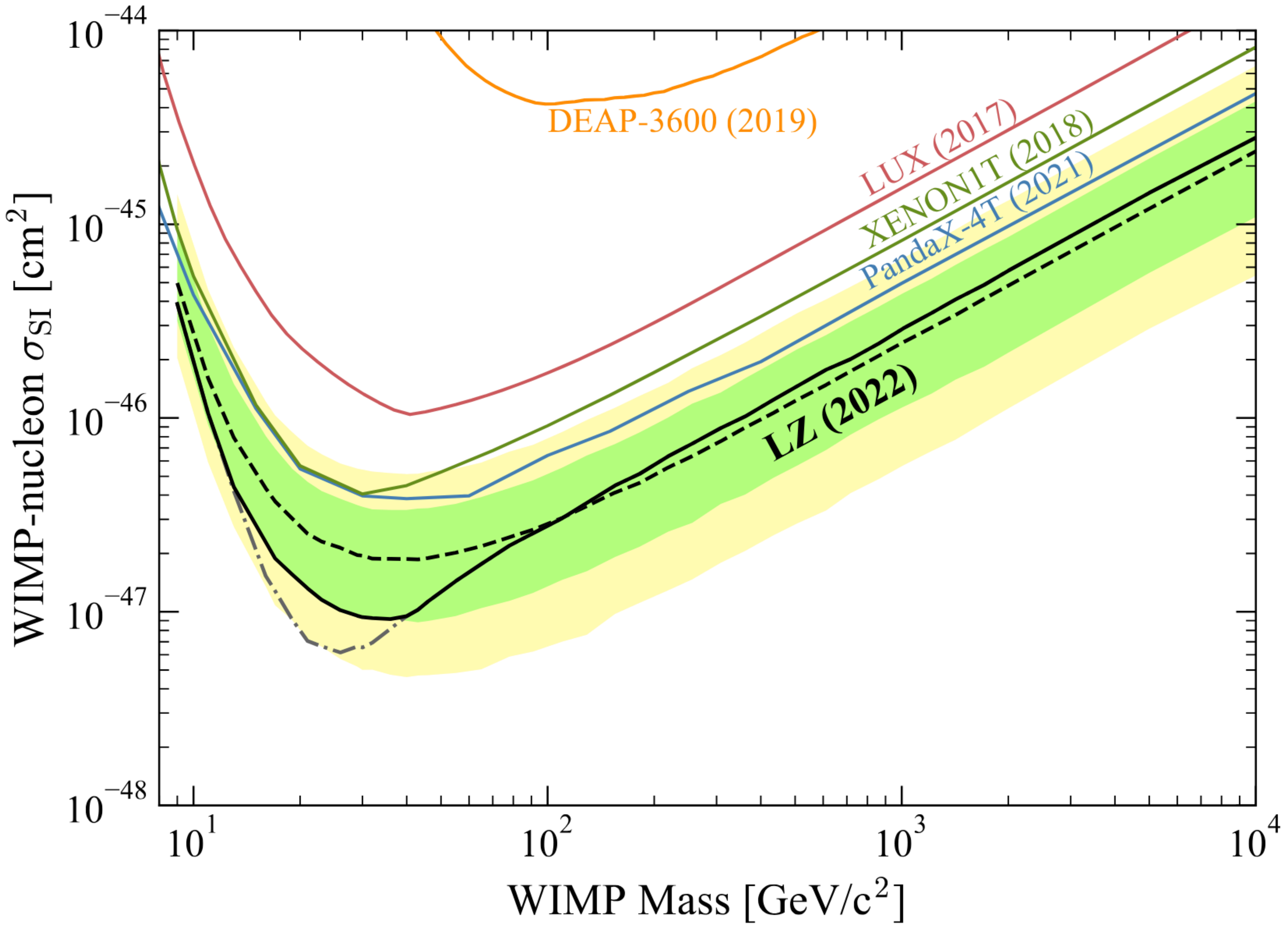
MG J0751+2716



Powell et al. (2023), MNRAS, 524, 1

The WIMP story

LUX-ZEPLIN exclusion



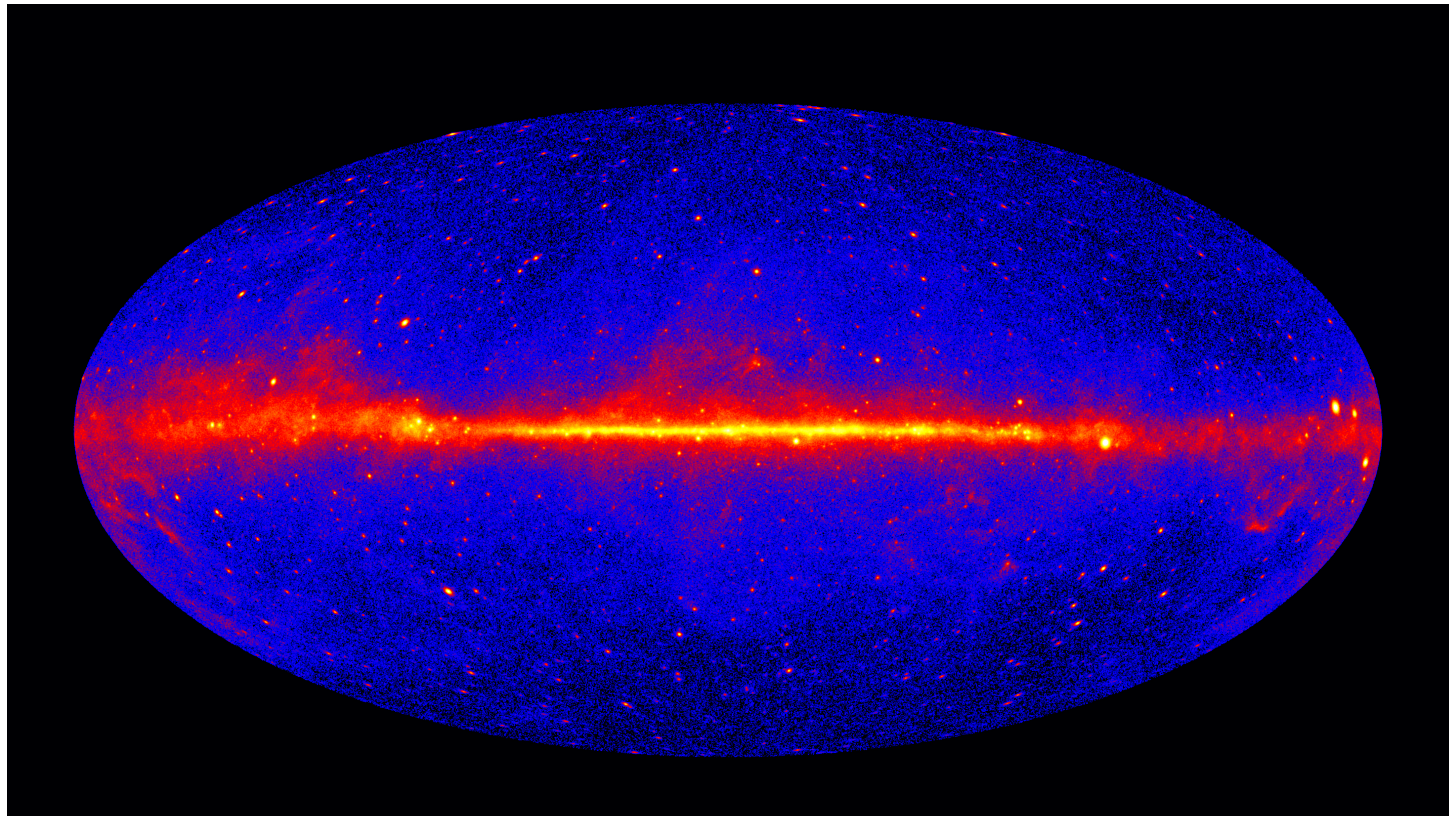
Aalbers et al (2023), Phys. Rev. Lett. 131, 041002
Spin-independent framework

Fermi Galactic Center excess

Millisecond pulsars

Cosmic ray outbursts

Annihilating DM



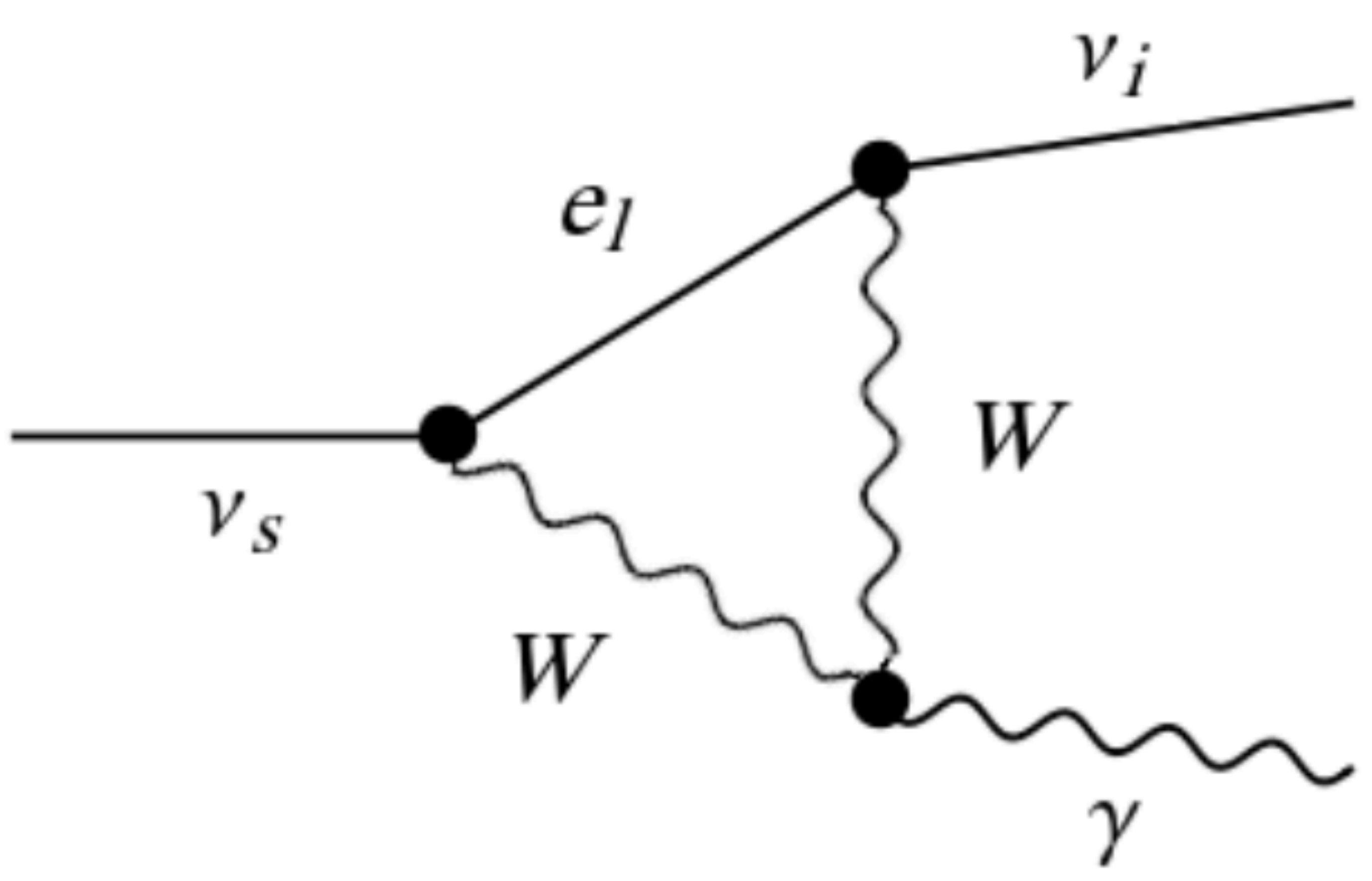
Aalbers et al (2023), Phys. Rev. Lett. 131, 041002

[+ Papers by *R. Leanne & T. Slayter*]

The sterile neutrino story

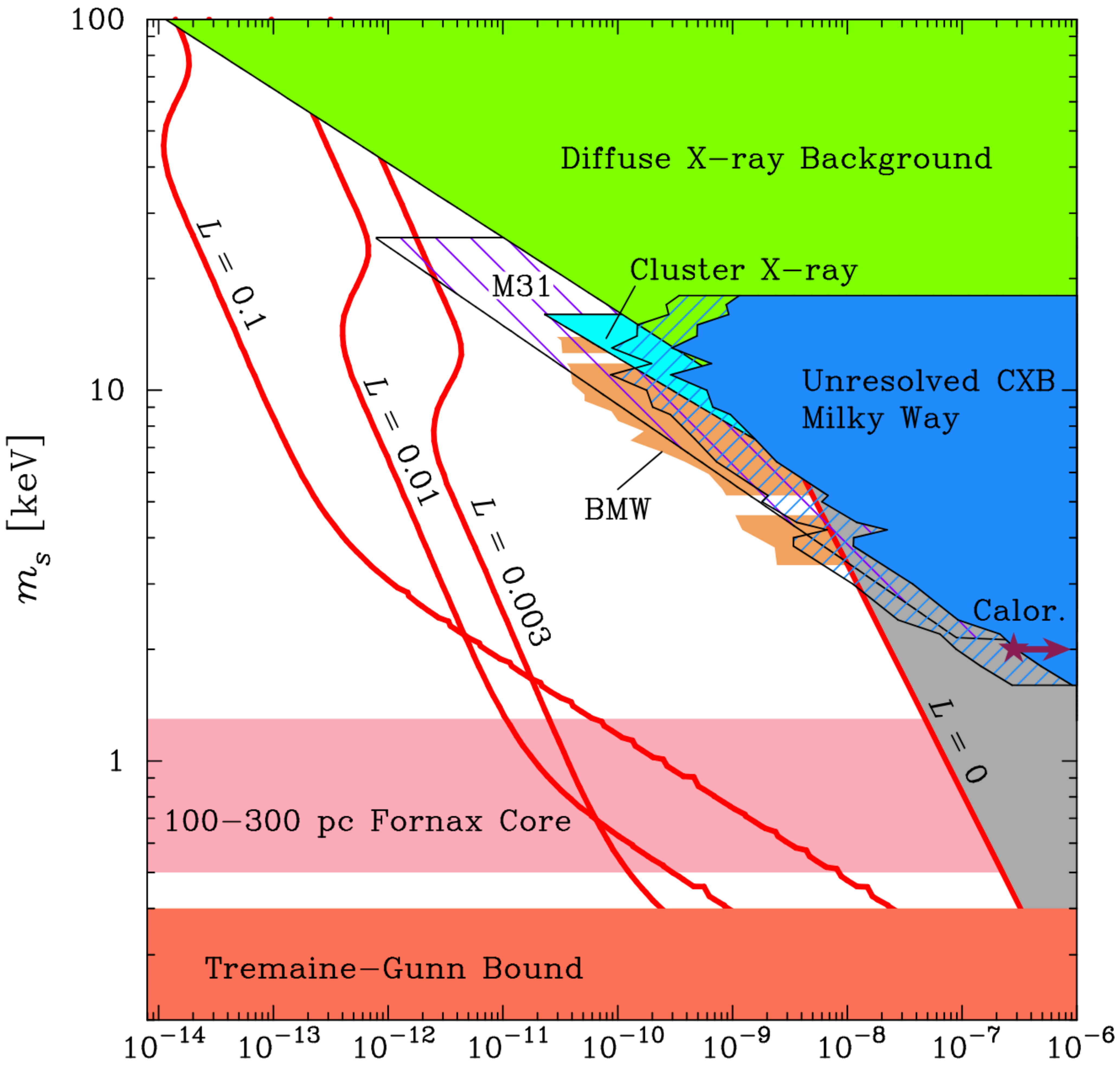
Advantages

- Explains sum of active neutrino masses
- Elusive, only gravity



$$\nu_s \rightarrow \gamma(E_\gamma) + \nu_\ell$$

$$E_\gamma = m_{\nu_s}/2$$



Mixing angle → $\sin^2 2\theta$

Abazajian et al (2007), Phys Rev D, 75, 6, 063511

Why do we need Physics BSM?

Dark matter

Dark energy

Strong CP problem

Astrophysics!

String compactifications

- Cosmic birefringence in CMB

Diego-Palazuelos et al. (2022), Phys. Rev. Lett, 128, 9
Minami and Komatsu, 2020, Phys. Rev. Lett, 125, 22

- TeV-scale transparency

De Angelis et al. (2011), Phys. Rev. D, 84, 10
Dessert et al. (2022), Phys. Rev. D, 105, 10

- Stellar cooling / Extra-galactic supernovae

Raffelt (1990), Phys. Rep., 198, 1-2
Meyer et al. (2020), Phys. Rev. Lett., 124, 23

- Foreground structure for lensed quasar

Amruth et al. (2023), Nat. Ast., 7

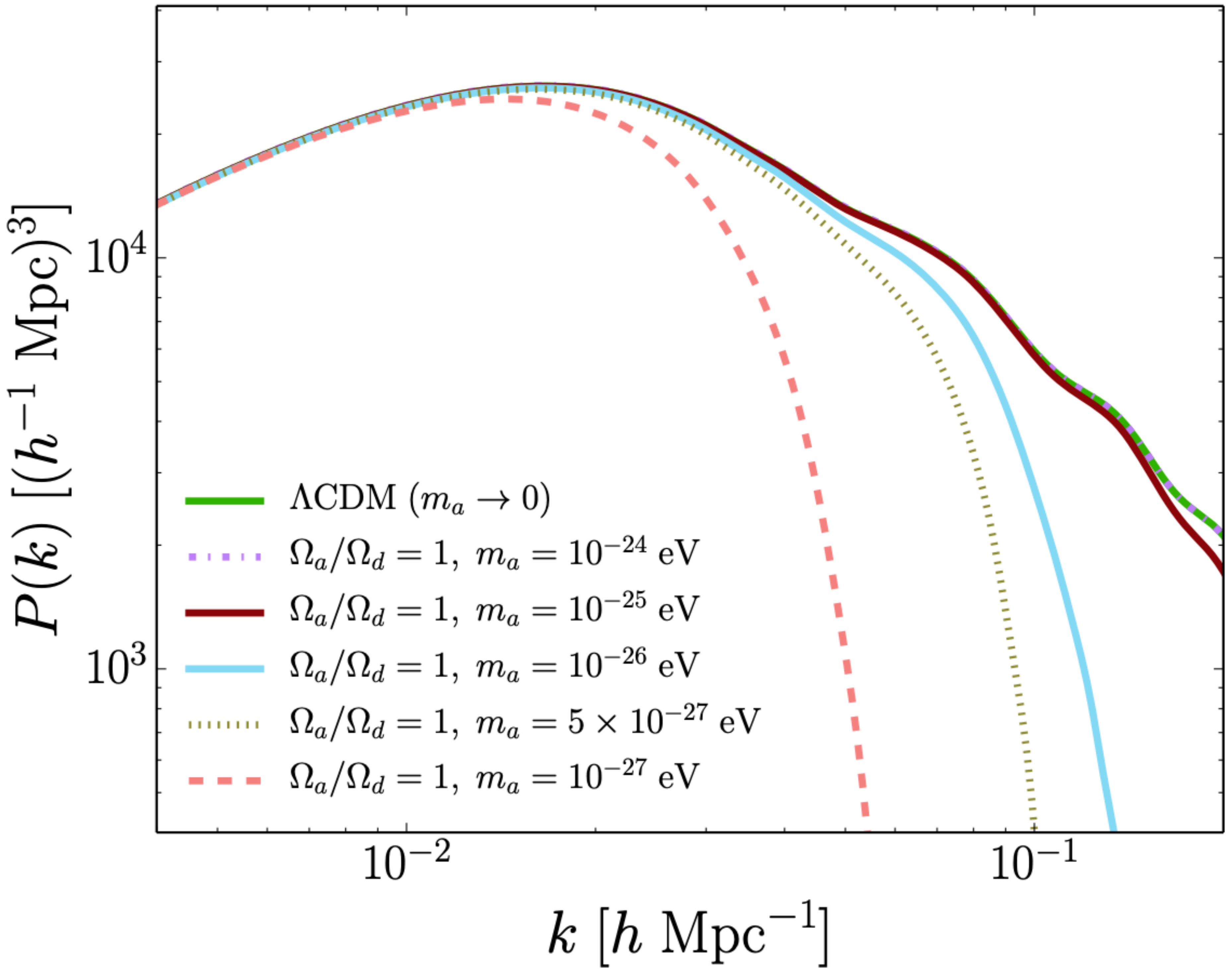
Axion dark matter and dark energy Constraints from the CMB

New Extraction of the Cosmic Birefringence from the Planck 2018 Polarization Data

Yuto Minami*
High Energy Accelerator Research Organization, 1-1 Oho, Tsukuba, Ibaraki 305-0801, Japan

Eiichiro Komatsu†
Max Planck Institute for Astrophysics, Karl-Schwarzschild-Str. 1, D-85748 Garching, Germany and
Kavli Institute for the Physics and Mathematics of the Universe (Kavli IPMU, WPI),
Todai Institutes for Advanced Study, The University of Tokyo, Kashiwa 277-8583, Japan
(Dated: November 24, 2020)

Minami and Komatsu, 2020, Phys. Rev. Lett, 125, 22



Hlozek et al. (2015), Phys. Rev. D, 91, 10

- Cosmic birefringence in CMB

Parity-violating physics

- Effects on the matter power spectrum

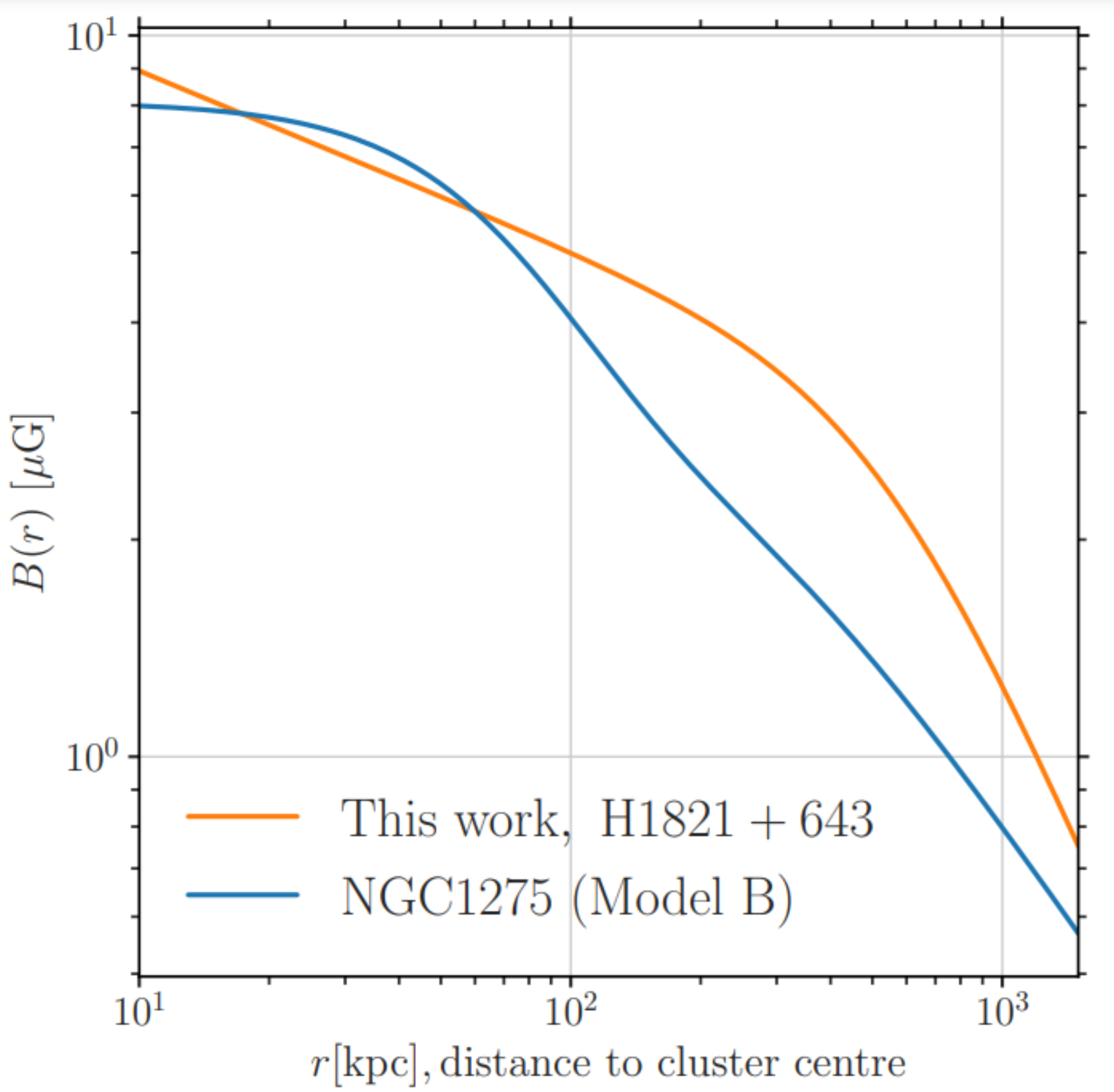
Dictated by the axion mass > λ_{dBg}

Modeling the ICM field: cell-based approach

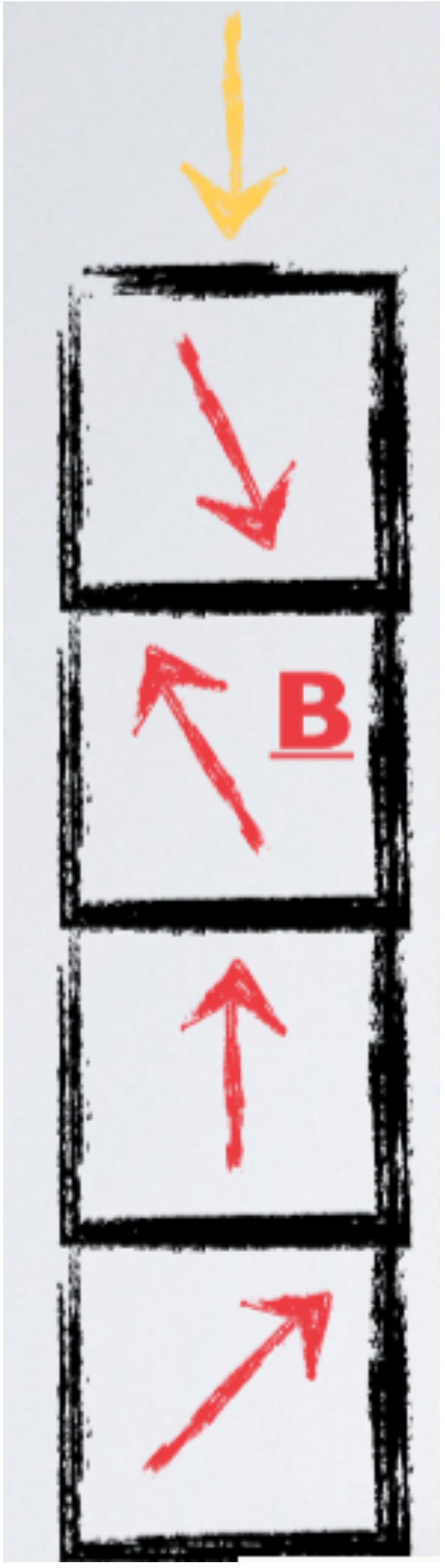
See Matthews et al. [inc. Sisk-Reynes] (2022), ApJ, 930, 1 for discussions

Field strength > drawn from assumption

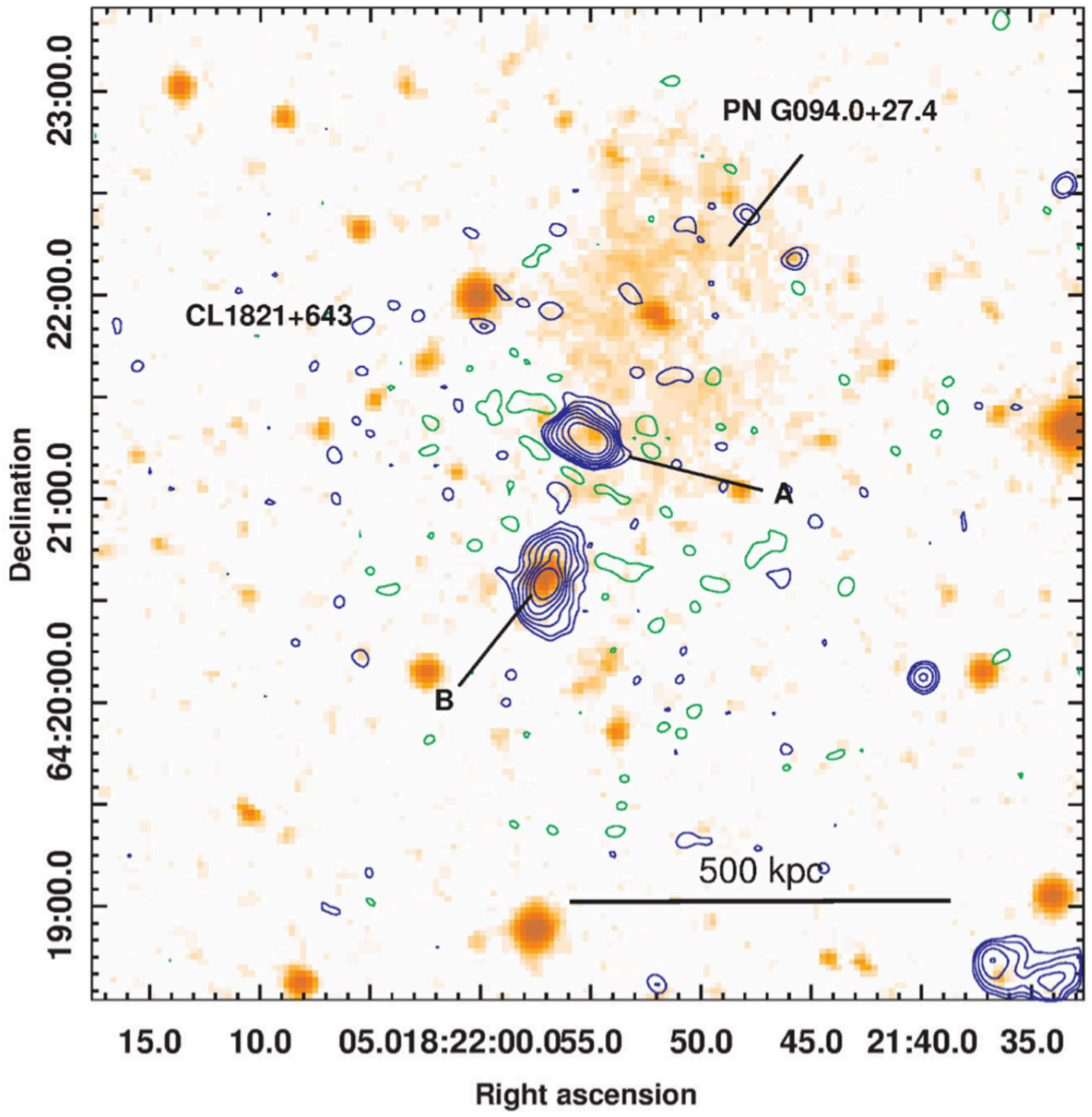
$$\beta_{\rm pl} = \frac{P_{\rm th}}{P_{\rm B}} \propto \frac{P_{\rm th}}{B^2} = 100$$



$r = 10$ kpc



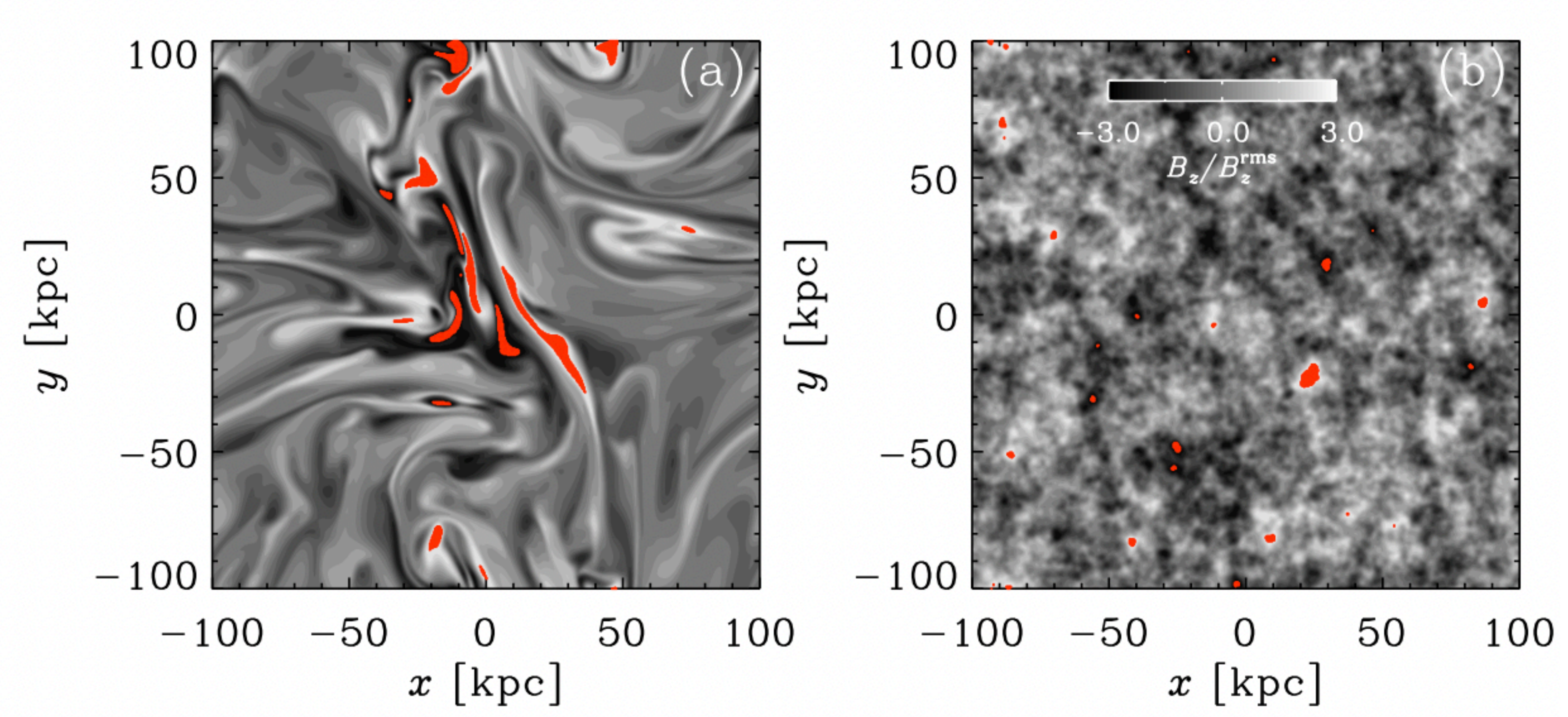
$r_{\rm max} = 1.5$ Mpc

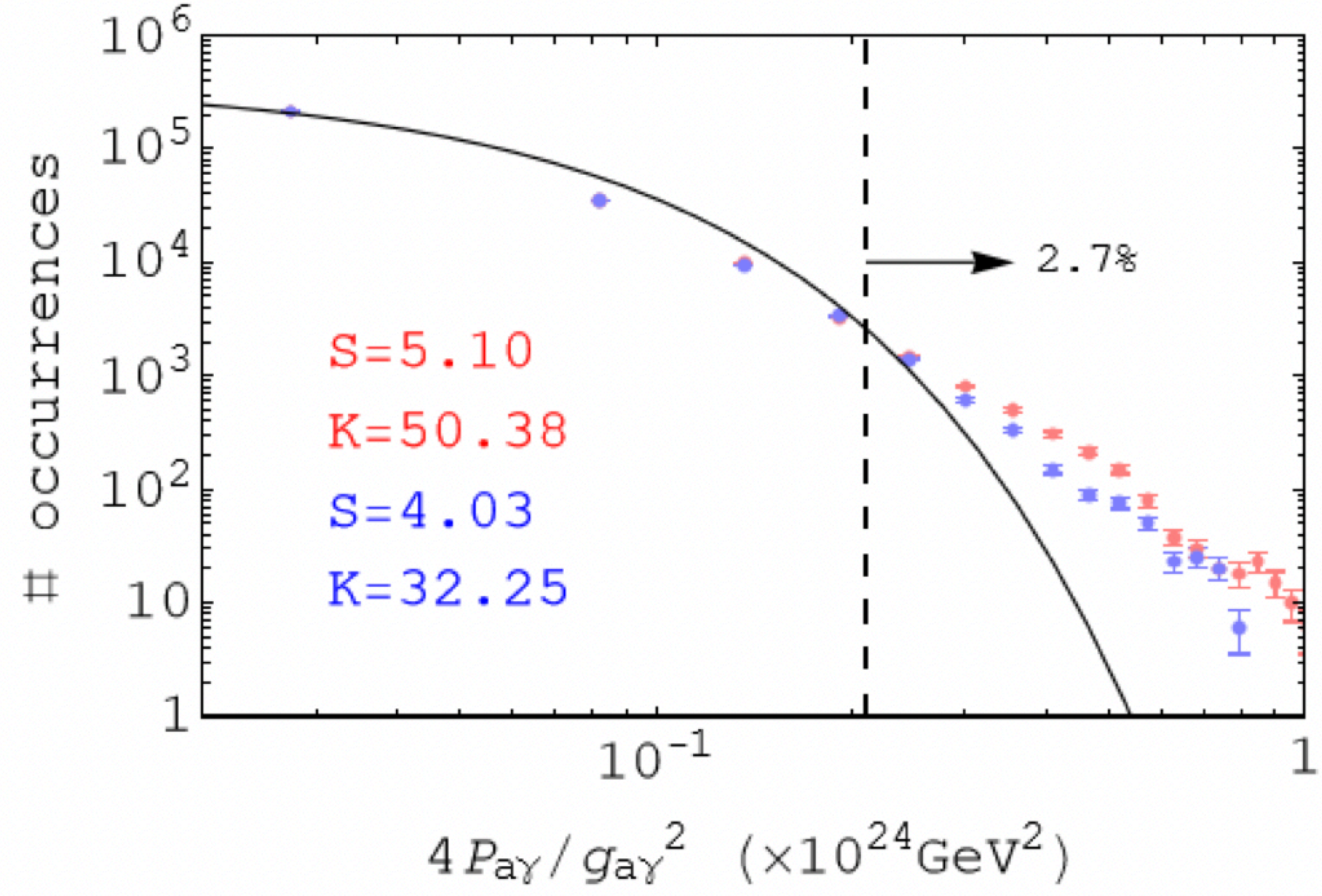


Kale and Parekh, 2016, MNRAS, 469, 3

Photon-axion mixing predictions with MHD simulations

- MHD simulation of an ICM-like environment
- Externally-driven turbulence in a box of L = 200 kpc
- MHD induces excess mixing in the hard band!



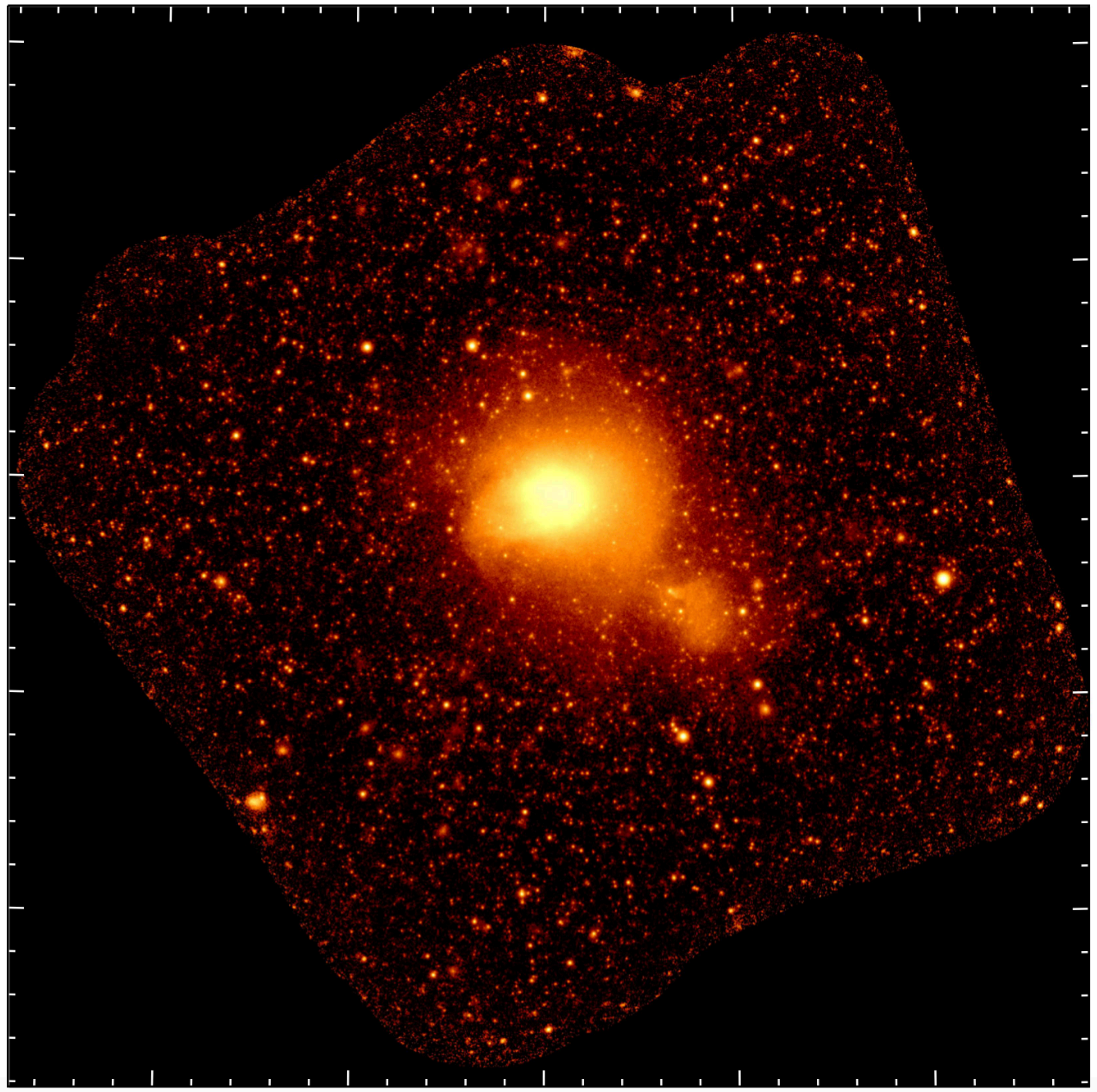


Carenza et al. (2023), Phys. Rev. D, 108, 10

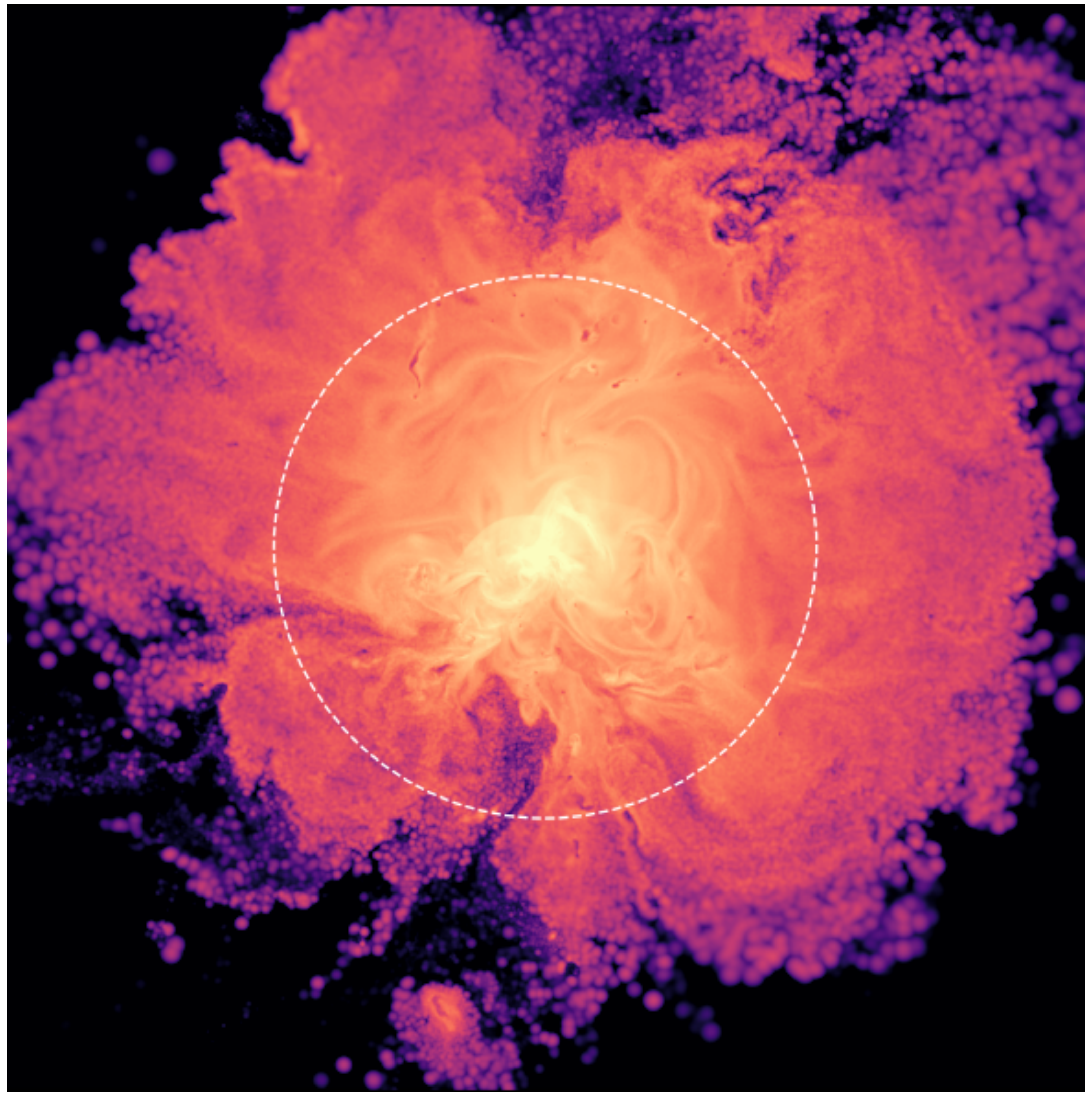
Mapping axion signals to *B*-fields in a Coma-like cluster

$$P_{a\gamma}(\eta_a) = \frac{{g_{a\gamma}}^2}{4} \left|\tilde{B}(\eta_a)\right|^2$$

Hard tails are induced by non-Gaussianity > large coherence lengths + field strengths



Churazov et al. (2021), A&A, 651, A41

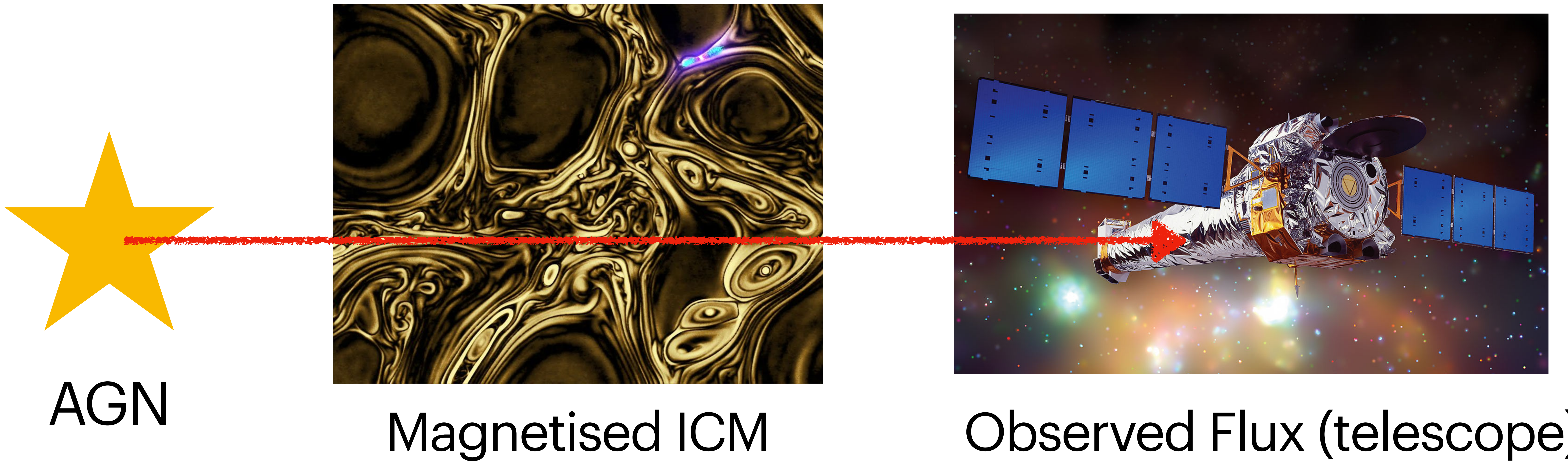


Steinwandel et al. (2022), ApJ, 933, 131

Probing axions with the ICM magnetic field

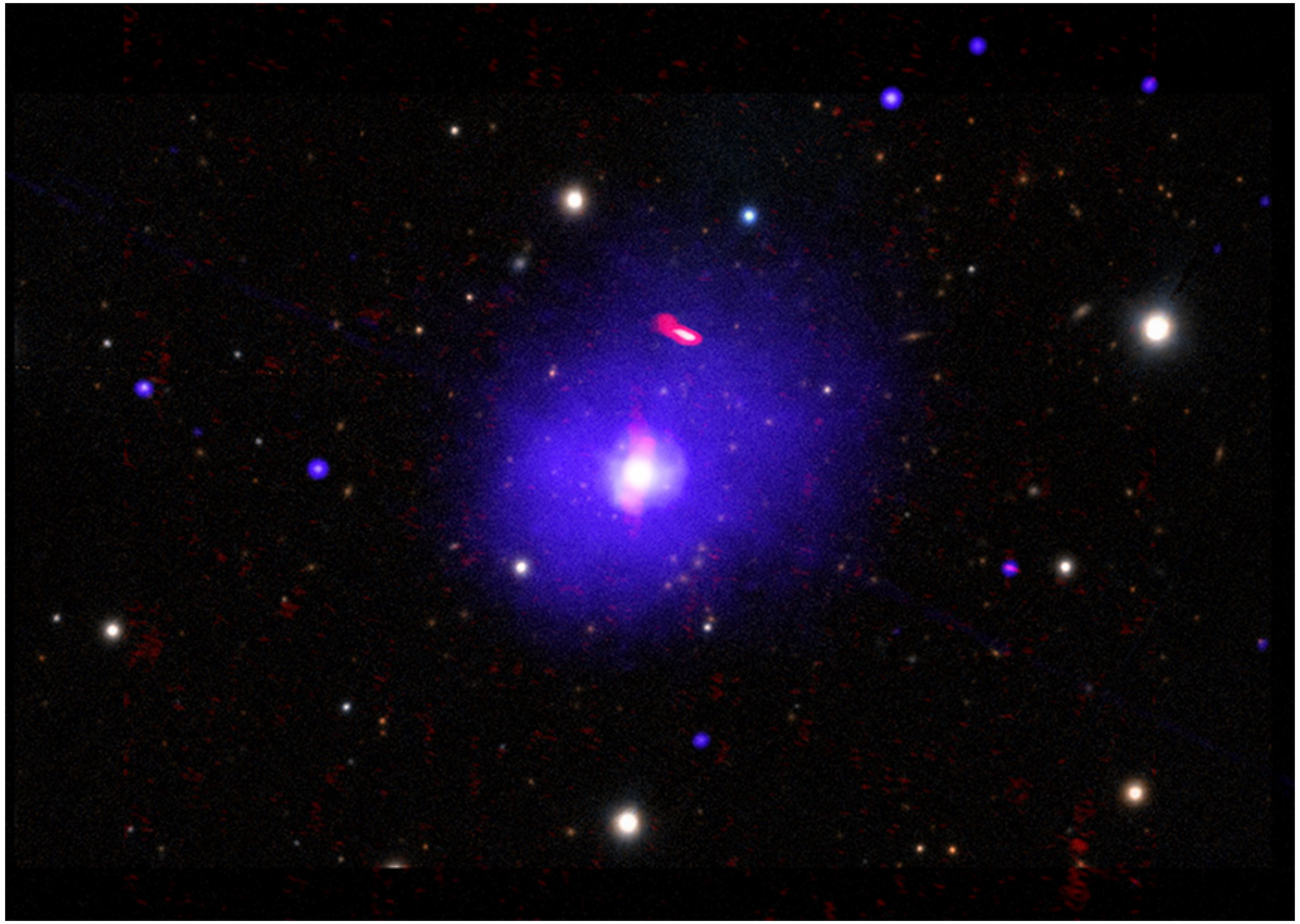
$$P_{a\gamma} \sim (g_{a\gamma}\ B\ L_{\rm coh})^2 \qquad B_{\rm ICM} \sim \mathcal{O}(1 - 10\ \mu{\rm G})$$

$$m_{\rm a} < \omega_{\rm ICM} \qquad L_{\rm coh} \sim \mathcal{O}(1 - 100\ {\rm kpc})$$



Observed X-ray flux > $F_{\rm obs}(E) = F_{\rm AGN}(E) \times P_{a\gamma}(E, g_{a\gamma}, B_{\rm ICM}, n_{\rm ICM})$

Leading constraints on axions from H 1821+643



A multi-wavelength view of H 1821 from a *Chandra* Press Release based on Sisk-Reynes et al. (2022), MNRAS, 514, 2. Credit: R.Smith/H.Russell.

- 570-ks (archival *Chandra*/Gratings)
- No cluster contamination or pileup
- Extremely luminous quasar in a rich cluster/BCG!

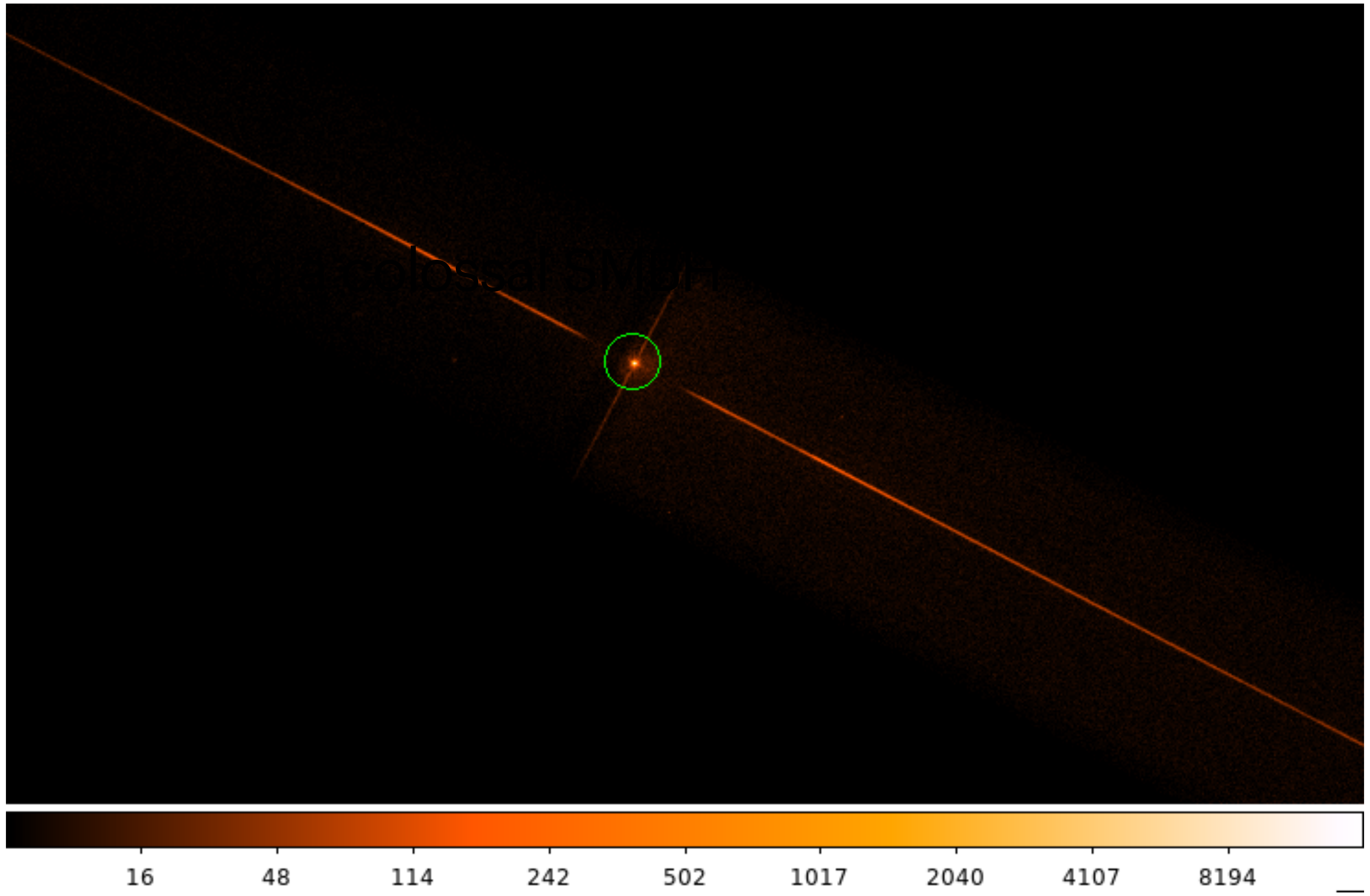
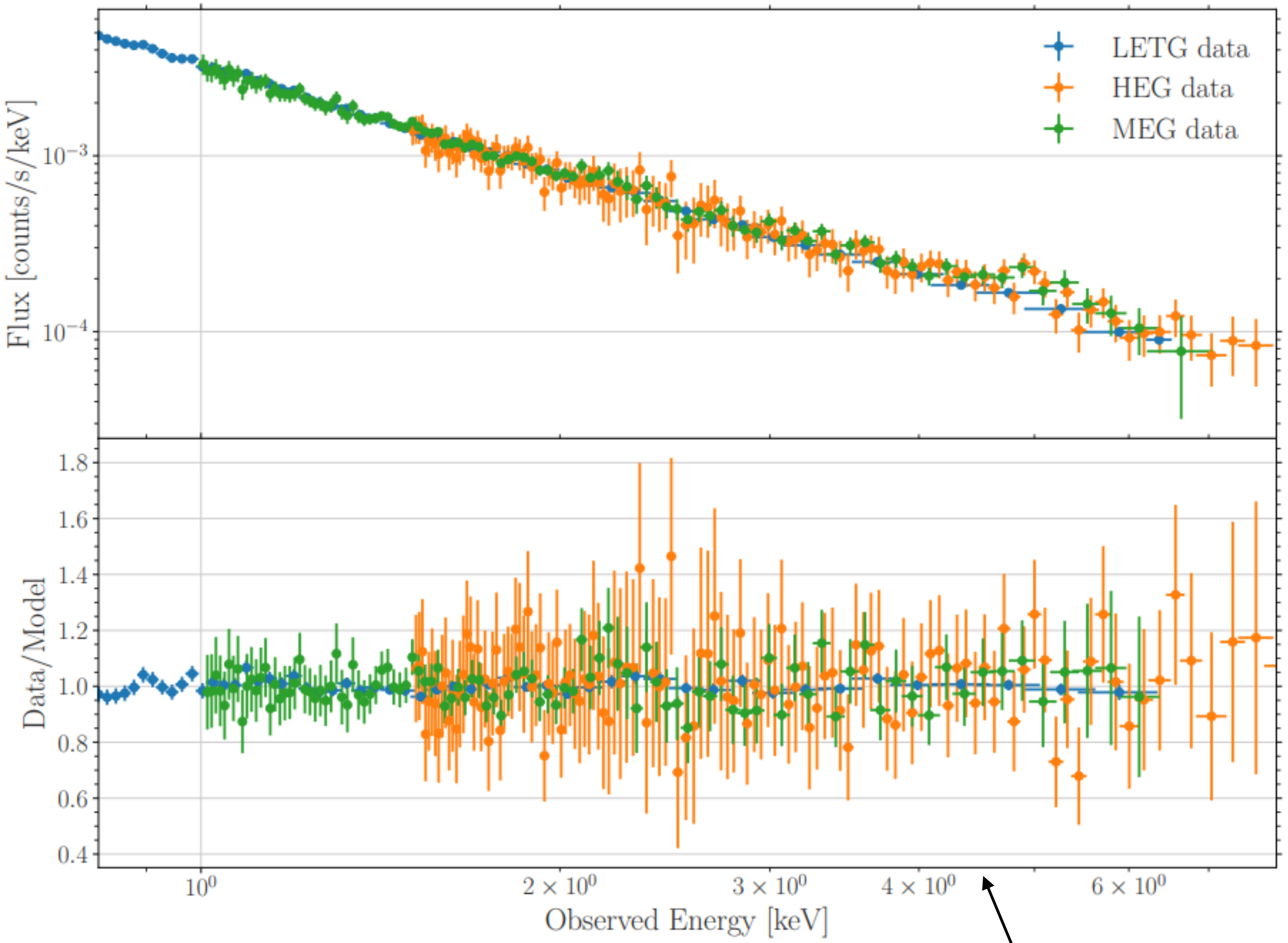


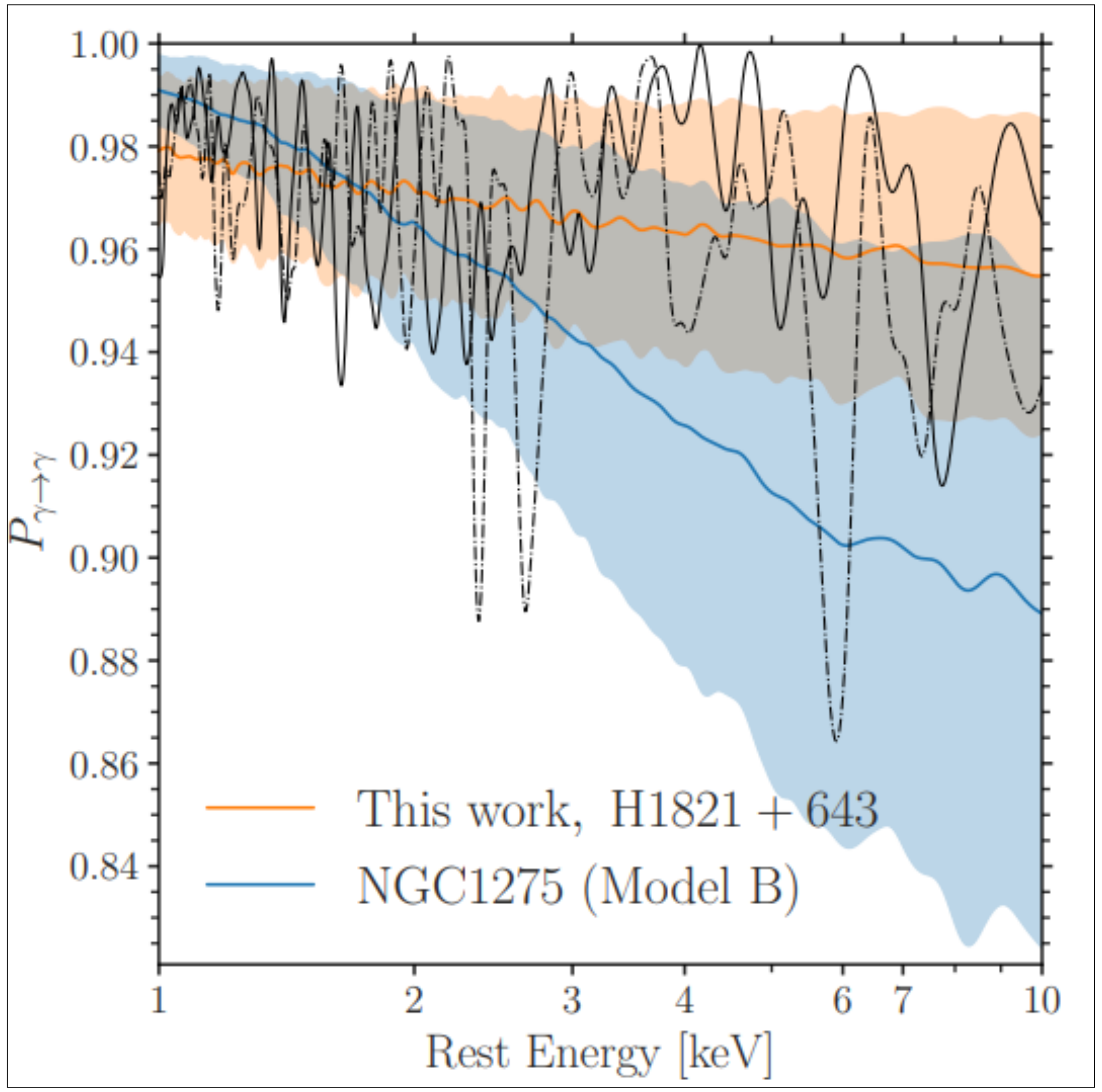
Image of a *Chandra*/LETG observation (167 ks) used in our analysis.

Are axion-induced distortions present in the spectrum of H 1821?

Best-fit model (typical of type-1 AGNs) and residuals

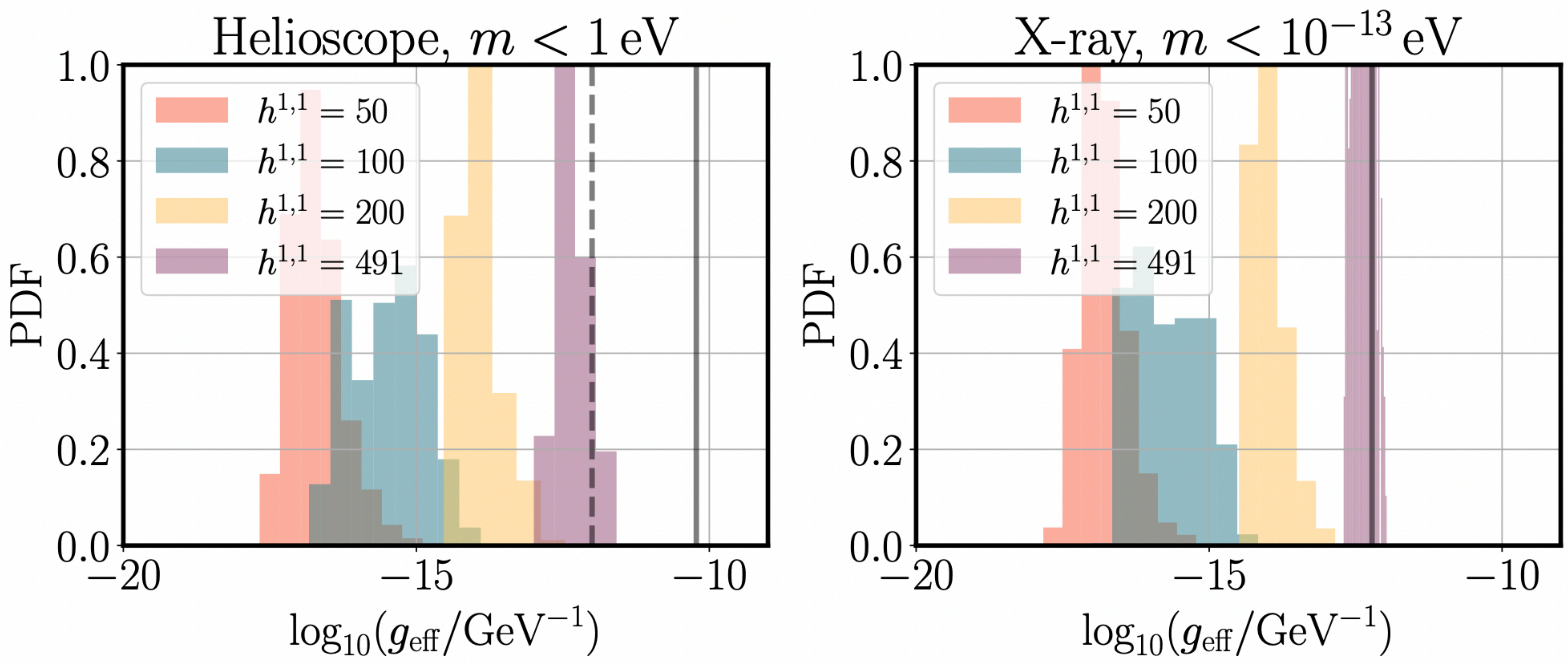


Survival probability (different ICM field models)



$$F_{\rm obs}(E) = F_{\rm AGN}(E) \times P_{\rm a\gamma}(E, g_{\rm a\gamma}, B_{\rm ICM}, n_{\rm ICM})$$

Implications for string theories



Gendler et al. (2023), 2309.13145