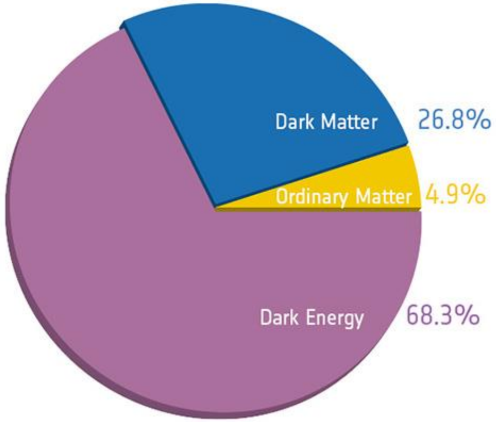
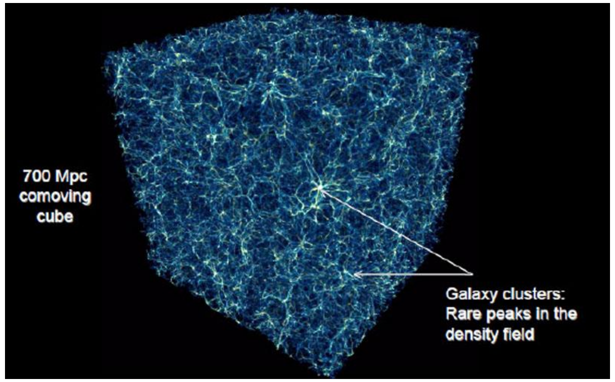
Constraining Particle Dark Matter with eROSITA Early Data

Chingam Fong, Kenny C. Y. Ng, Qishan Liu
The Chinese University of Hong Kong

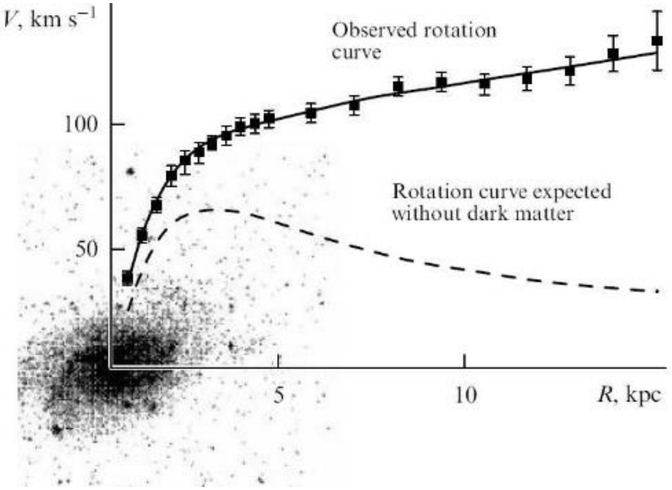
Dark Matter

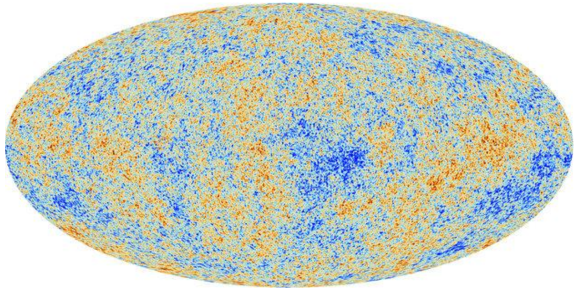
- Abundant everywhere in the universe
  - In Galaxy, density is described by Navrro-Frenk-White (NFW) profile
- *Astrophysical survey* can probe DM's nature through indirect detection
- Search for DM has covered the whole EM spectrum (and then some)





M. L. Norman et al., 2007

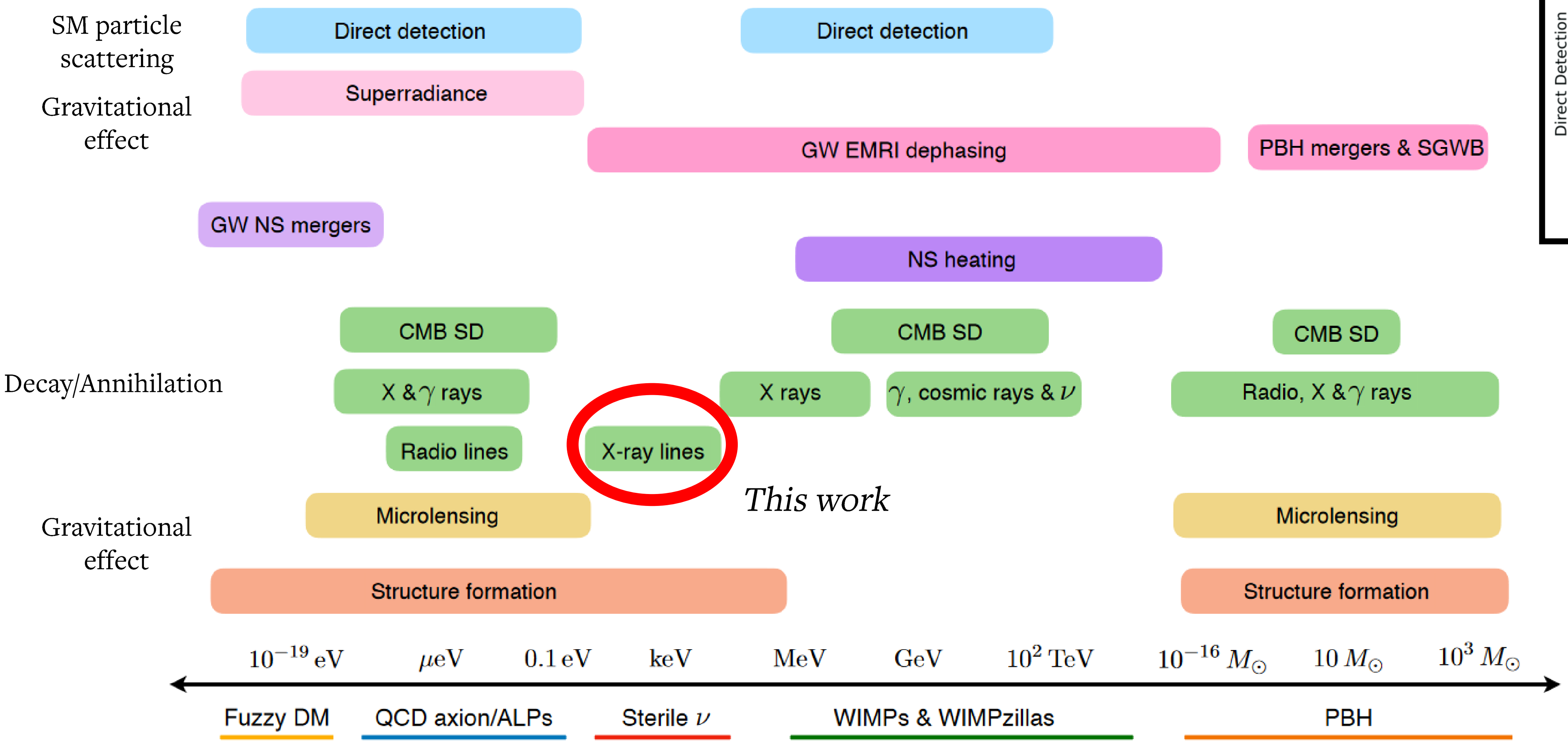


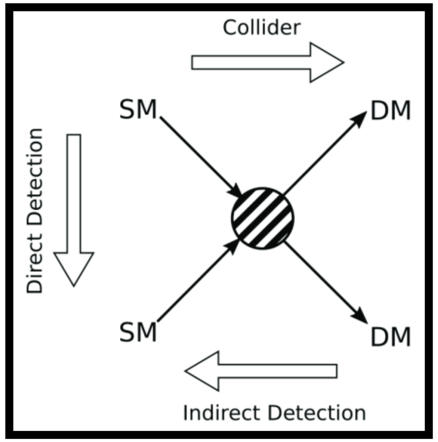


A.V. Zasov et al., 2017

R. Alves Batista et al., EuCAPT White Paper, arxiv: 2110.10074

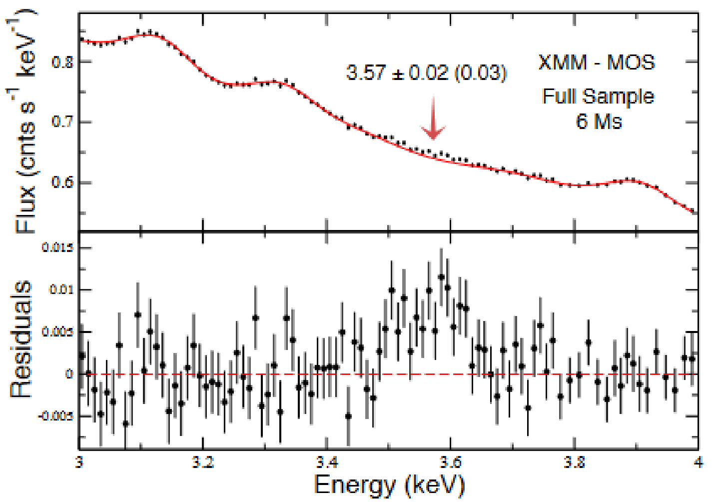
Acronyms: Extreme mass ratio inspirals (EMRI), stochastic GW background (SGWB), CMB spectral distortions (SD)



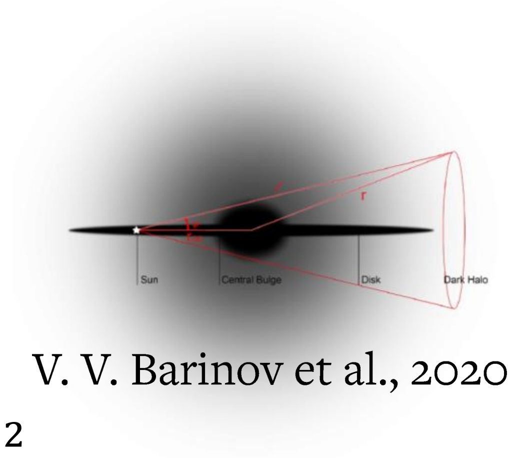


Decaying DM Search

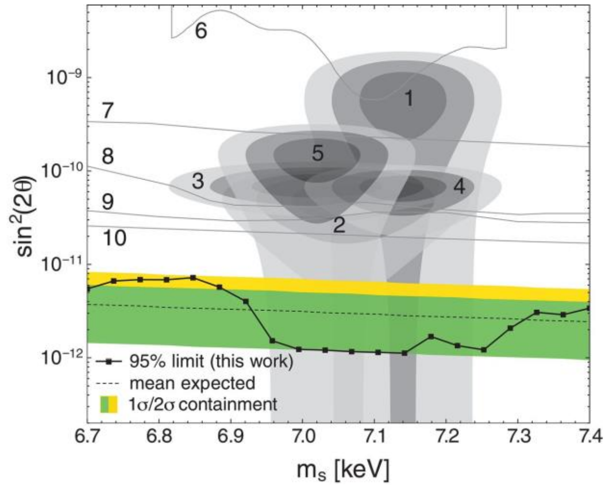
Galaxy cluster data
Bulbul et al., 2014



- Unexplained signature -> decay?
- Rate determined by particle physics & DM profile
  - $\Phi = \frac{\Gamma}{4\pi m_\chi} \Delta\Omega \frac{dN}{dE} \int \rho[r(l,\phi)]dl$
  - Sterile neutrino: (1 photon)
    - $\Gamma_{\nu_s} = 1.38 \cdot 10^{-29} s^{-1} \left[\frac{\sin^2(2\theta)}{10^{-7}}\right] \left(\frac{m_{\nu_s}}{1keV}\right)^5$
  - Axion-like particles: (2 photons)
    - $\Gamma_{a\gamma\gamma} = 5 \cdot 10^{-29} s^{-1} \left(\frac{m_a}{7keV}\right) \left(\frac{g_{a\gamma\gamma}}{1.74 \cdot 10^{-18} GeV^{-1}}\right)^2$
  - DM -> 1 or 2 equal energy photon(s)
    - $\frac{dN}{dE} = \delta(E - m_\chi/2)$



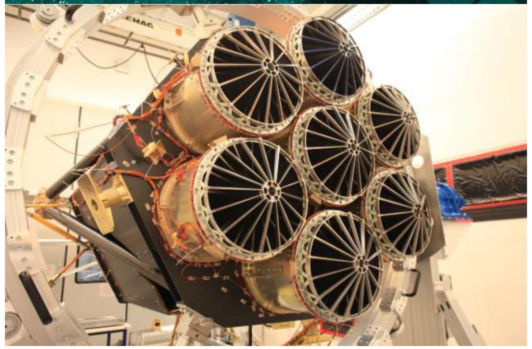
V. V. Barinov et al., 2020

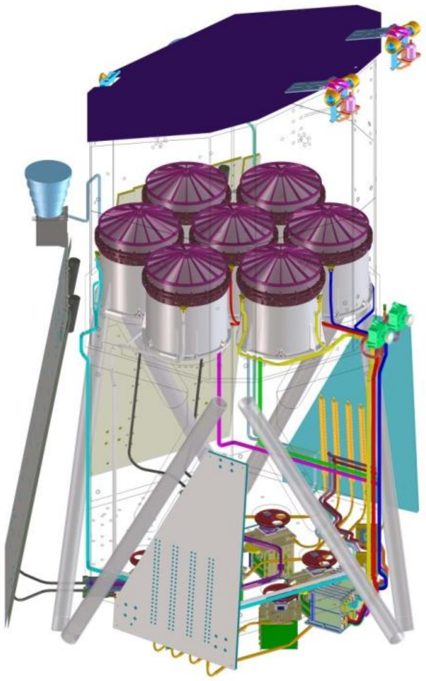


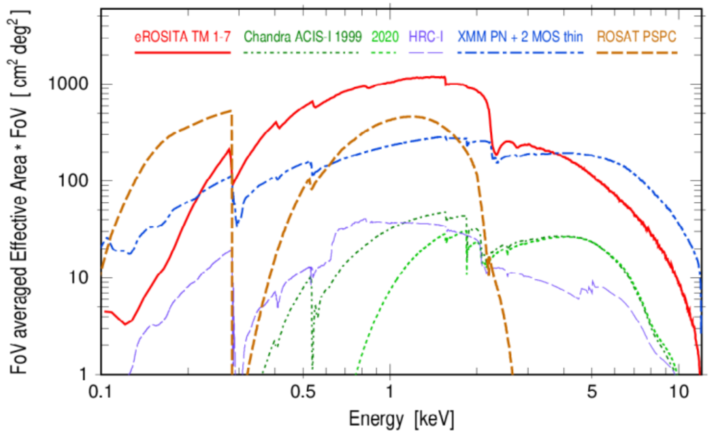
XMM Newton blank sky
C. Dessert, 2020

eROSITA Instrument & Mission

- On board Spectr-Roentegn-Gamma (SRG) mission
- Joint German-Russian operation launched in 2019
- Excellent angular and energy resolution
- Deepest all-sky X-ray survey after 4-year mission





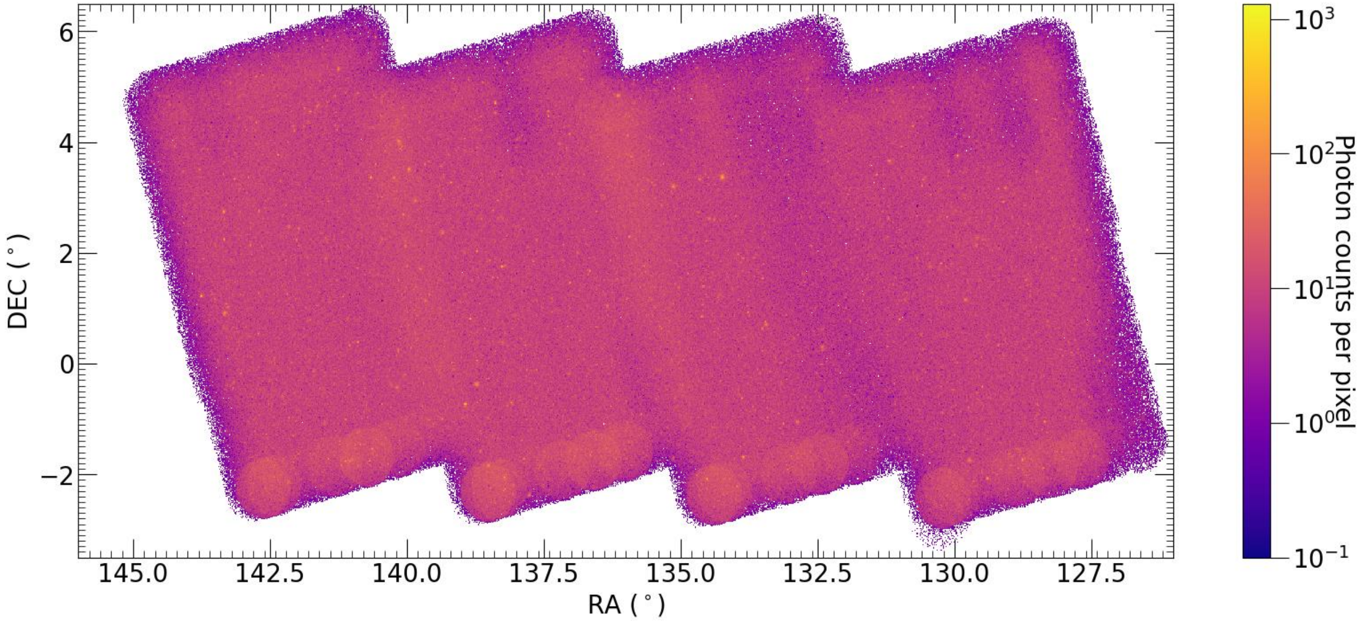


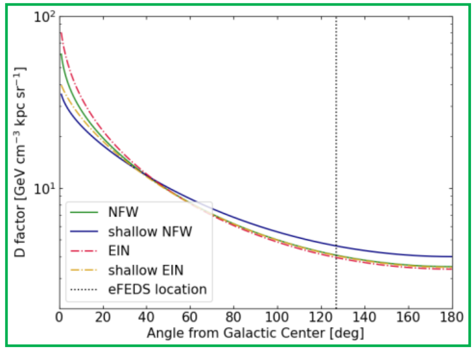
P. Predehl et al., 2021

eFEDS Data

	ObsID	Central R.A. [deg]	Central Dec [deg]	t_{exp} [s]	Start time [UTC]
I	300007	129.55	+1.5	89642	2019-11-03T02:25:50
II	300008	133.86	+1.5	89642	2019-11-04T04:05:52
III	300009	138.14	+1.5	89642	2019-11-05T05:45:54
IV	300010	142.45	+1.5	89642	2019-11-06T07:25:56

- Part of eROSITA Early Data Release in 2021
- 360 ks, 140 deg² observation
- Pros:
  - Largest area
  - Longest exposure time
  - Very few point sources
- Cons:
  - pointing away from GC, constraint not as strong

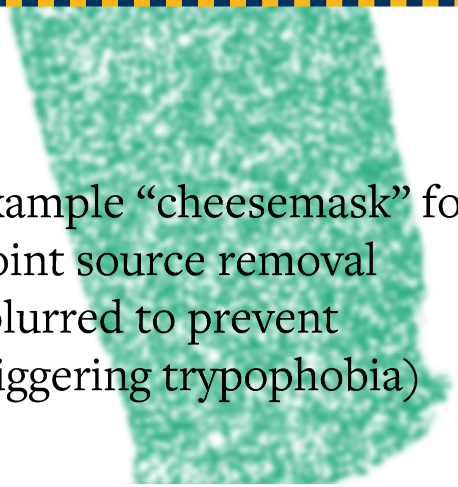




C. Fong, K. C. Y. Ng, Q. Liu, 2023 (in prep)

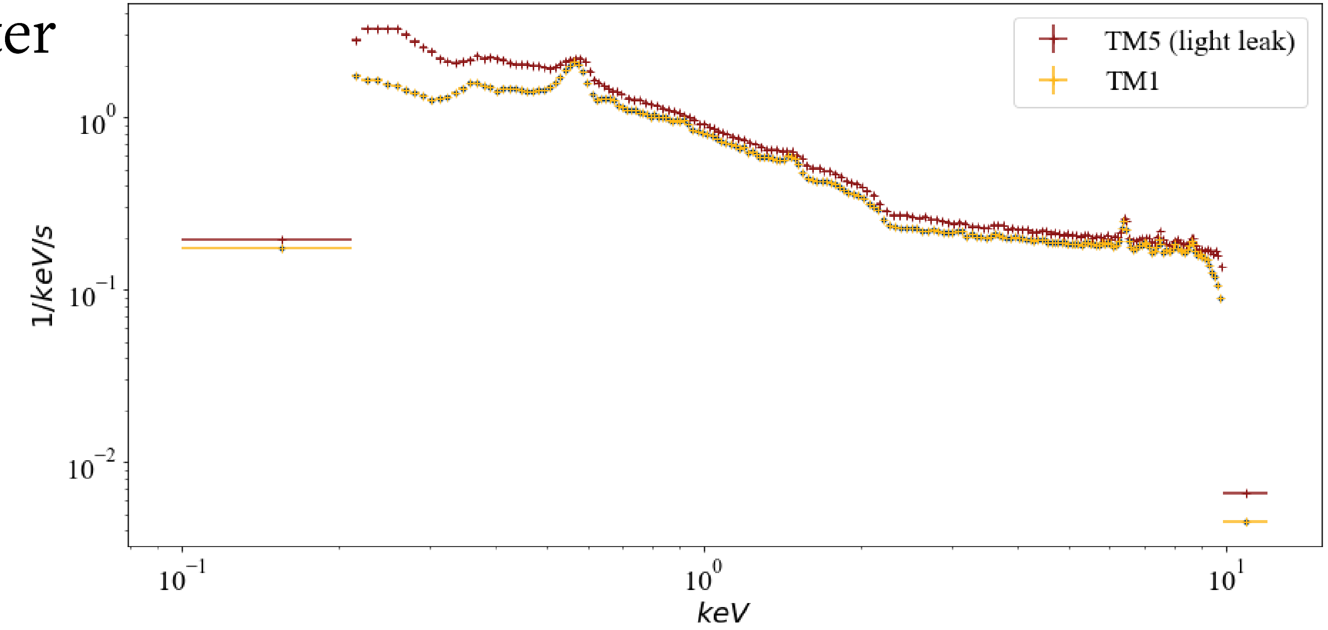
$$\Phi = \frac{\Gamma}{4\pi m_\chi} \Delta\Omega \frac{dN}{dE} \int \rho[r(l,\phi)]dl$$

eFEDS Data Shenanigans



example "cheesemask" for point source removal (blurred to prevent triggering trypophobia)

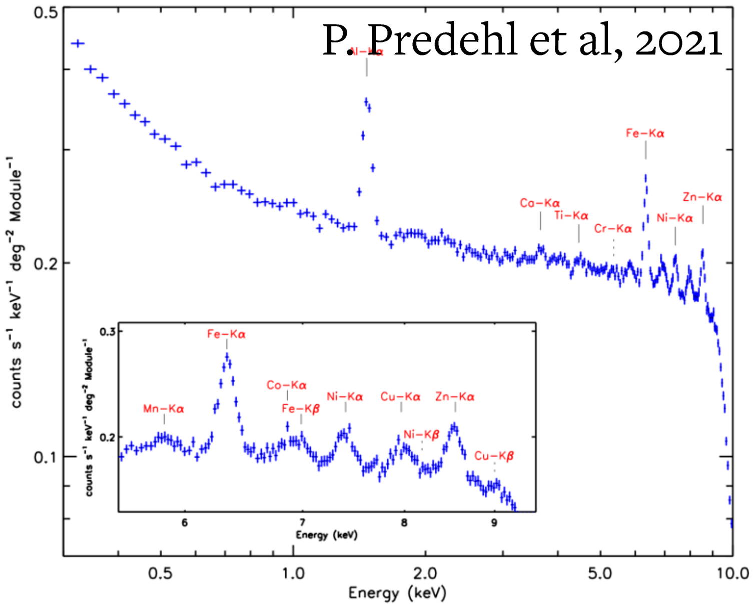
- Data extracted and processed with eSASS
  - Checked that point sources matter little, through "cheesemask"
  - eROSITA Science Analysis Software System removed flare, bad time interval
- Light leak
  - TM5 & TM7 light filter failed
  - We removed all energy range below 0.9 keV

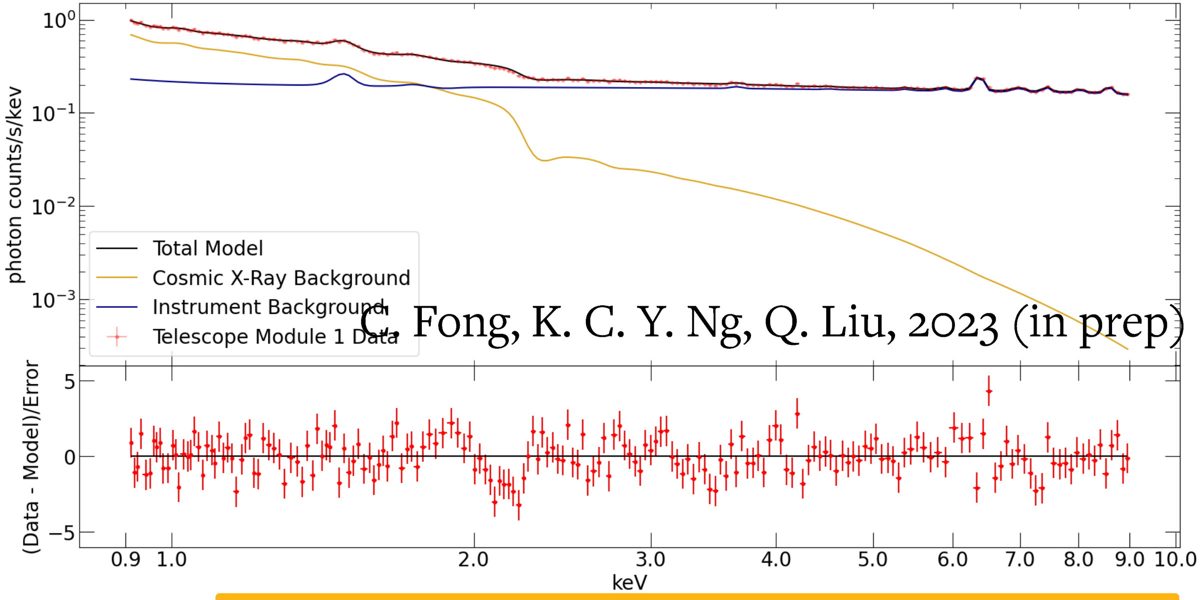


Construct Blank Sky Spectrum

- 2 categories
- Instrumental background
  - Induced by high energy particles interacting with internal elements
  - Modeled by continuum + 14 gaussian lines, based on closed camera obs
- Astrophysical background
  - Absorbed **apec** - local group
    - **apec** = model of ionized diffused gas
  - Absorbed **powerlaw** - diffuse sources
- Fitting done with **xspec**

P. Predehl et al, 2021



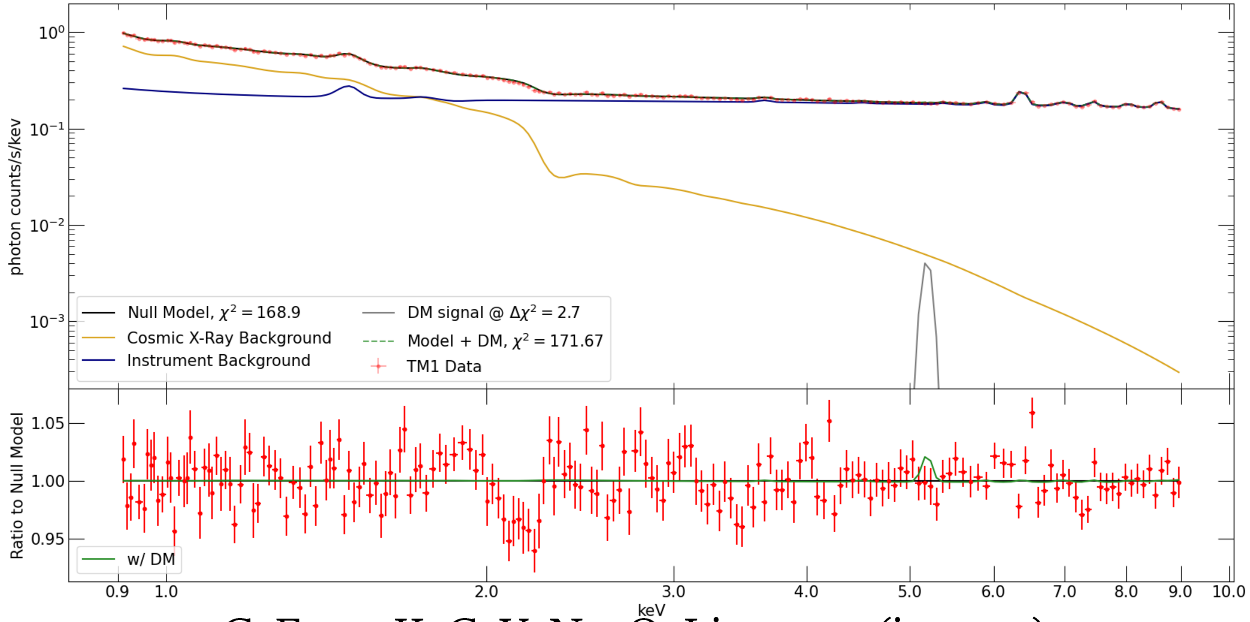


C. Fong, K. C. Y. Ng, Q. Liu, 2023 (in prep)

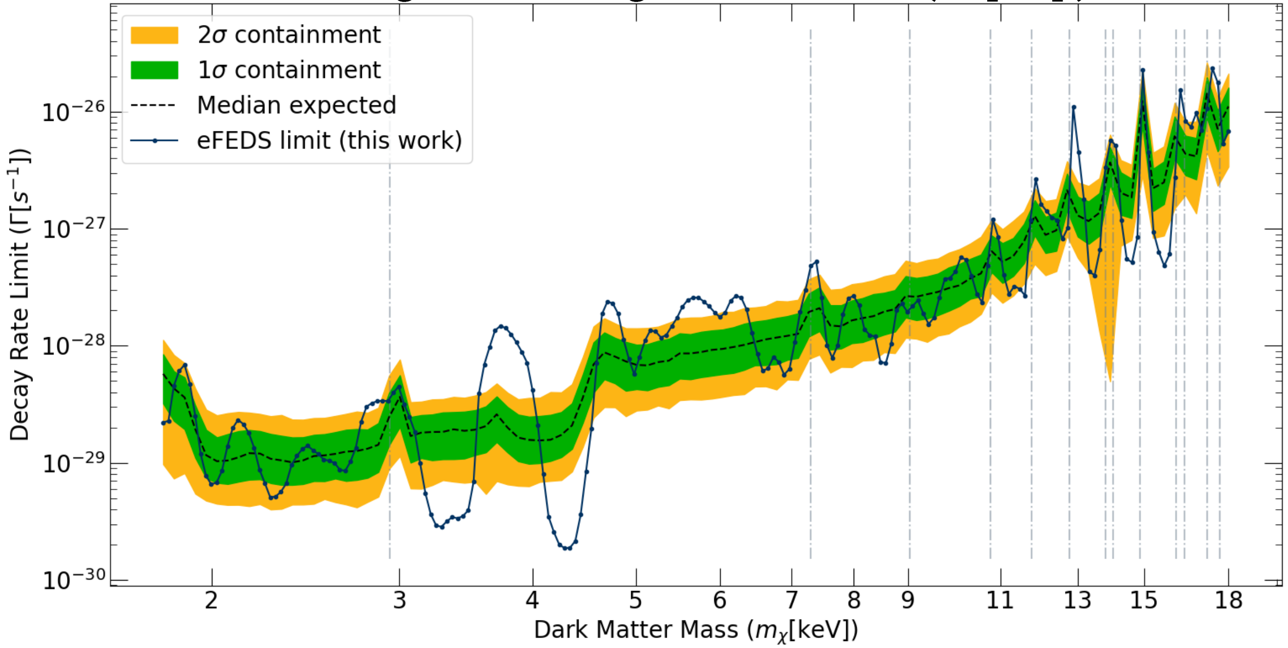
Takeaway: $\chi^2/d.f. \approx 1$, *a good fit.*

Dark Matter Test

- Mock signal + Null model $\Sigma\chi^2(\Gamma) - \Sigma\chi_0^2 = 2.71$, 1 sided 95% upper limit
- Increase confidence by doing 1,000 Monte Carlo runs
  - Most limit falls within 2σ band
  - Out of bounds regions are either Gaussian line, or feature in response function



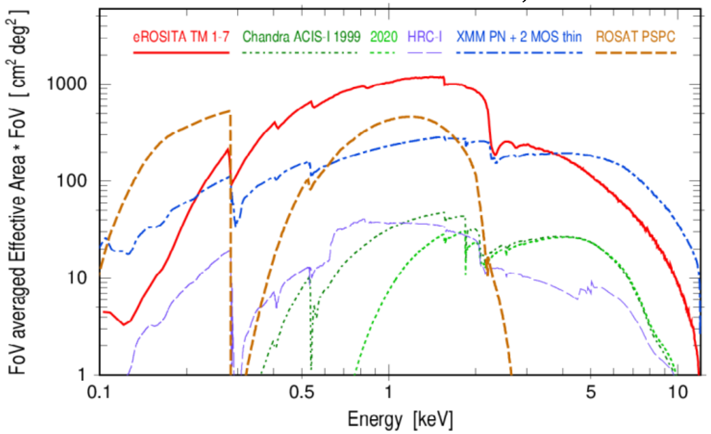
C. Fong, K. C. Y. Ng, Q. Liu, 2023 (in prep)



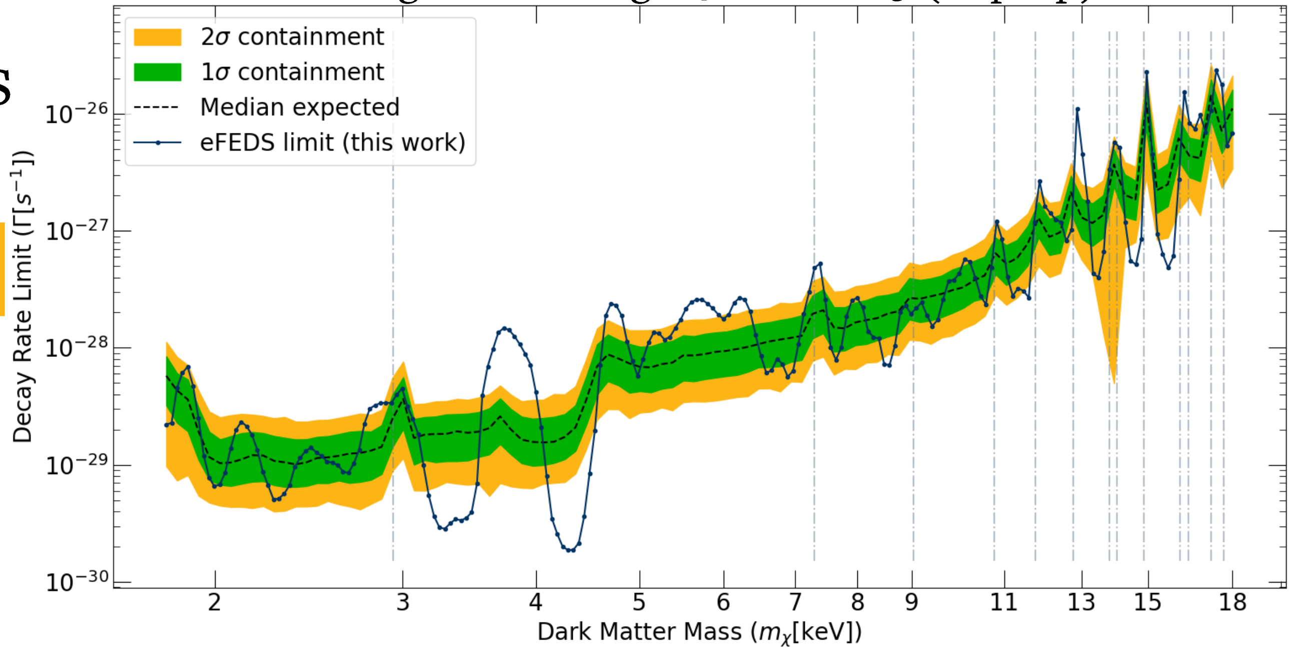
"Wiggles" at 4-6 keV

- At 2-3 keV eROSITA effective area drops significantly
  - Measured from calibration
  - Decay product of 4-6 keV DM
- Correspondingly, the model fits poorly at this range
- DM detection? *Most likely NO*
  - It's a "wiggle", not a "bump"
- As eROSITA effective area model improves, our limits will be more reasonable

P. Predehl et al., 2021

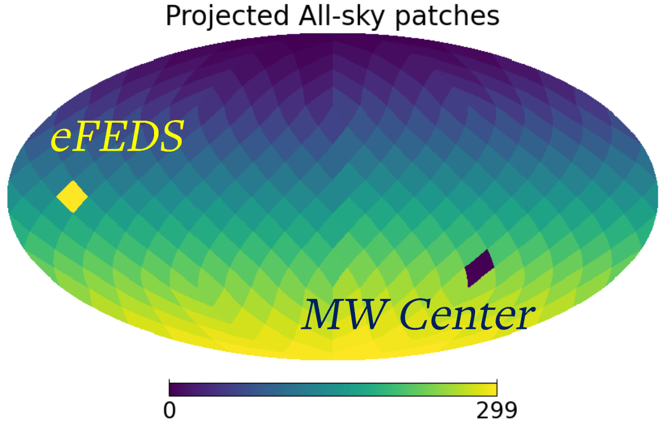


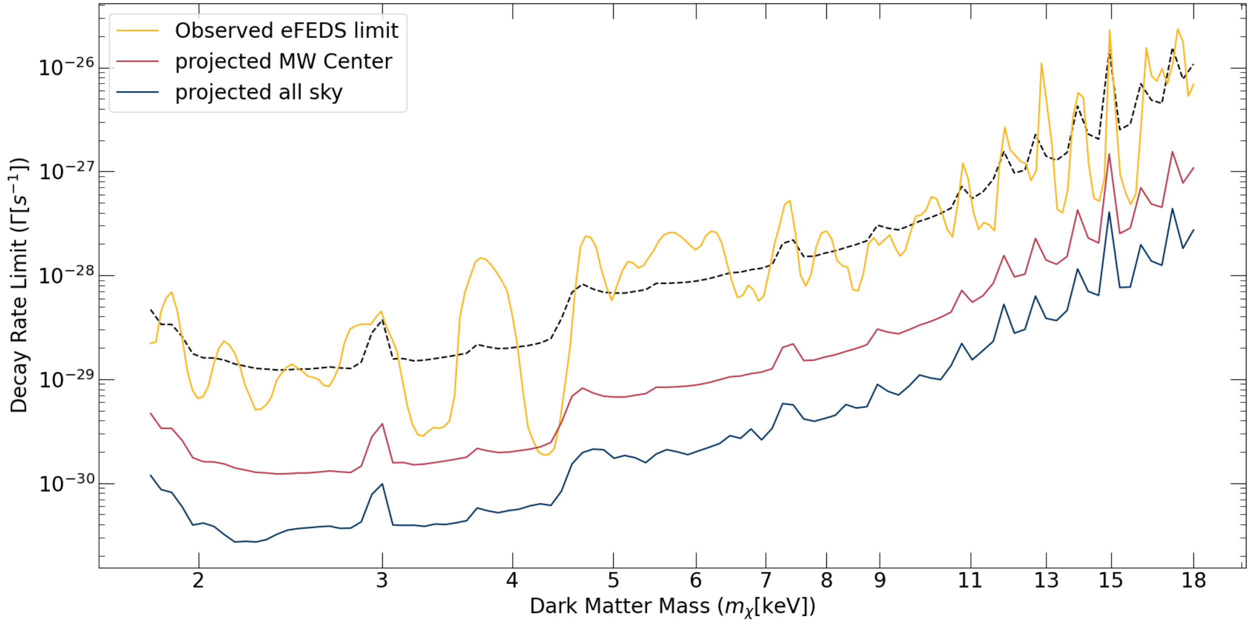
C. Fong, K. C. Y. Ng, Q. Liu, 2023 (in prep)



All sky projection

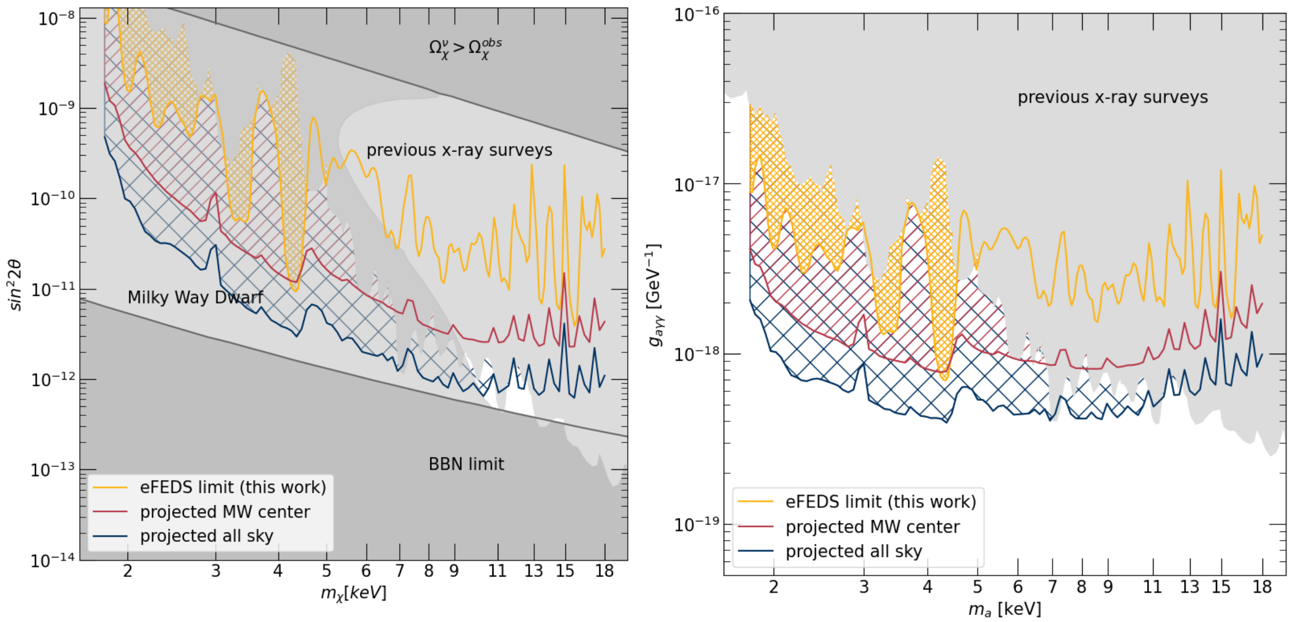
- 1 mock data set, perfect model assumed (Asimov procedure)
- `Healpy` generated 300 patches of sky, same area as eFEDS
- Estimated the limit obtainable from each patch, from its DM column density (D-factor)





Particle Constraints

- Neutrino Minimal SM (νMSM) parameters heavily constrained
  - BBN limit, milky way dwarf galaxy count, previous x-ray tests
- Major improvement to existing limits in lower energy range
- We project eROSITA all-sky can (nearly) close out νMSM



C. Fong, K. C. Y. Ng, Q. Liu, 2023 (in prep)

Takeaway: even only with early data, eROSITA is already probing into uncharted territories!

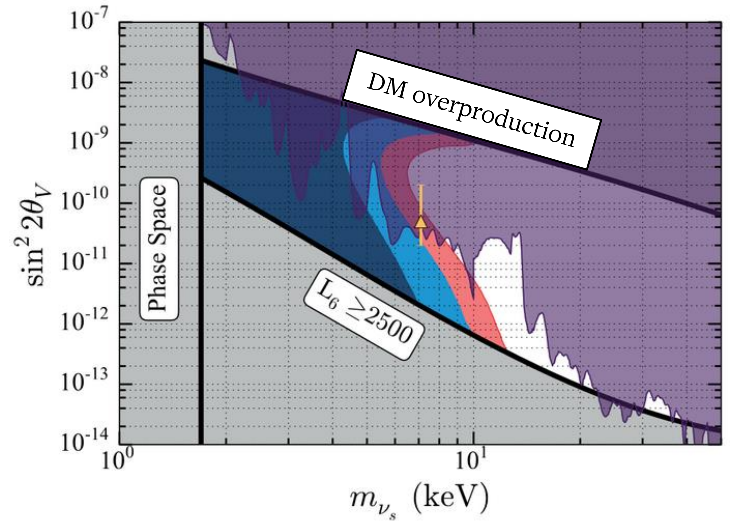
Conclusion & Outlook

- We demonstrated the ***potential of eROSITA*** in astrophysical DM searches by using its early data to produce ***one of the best limits on keV DM lifetime***
- By converting the limit into a few DM particle models, we ***ruled out new parameter space***
- With eROSITA planned (German) ***data release*** coming up in ***September 2023***, we could produce even ***stronger limits***, nearly rule out minimal neutrino standard model DM
- ***New approaches and strategies*** could easily be adapted to our eROSITA DM search. E.g.: DM annihilation, use dense dwarf galaxy

Questions?

Sterile Neutrino DM – Other Constraints

- Galaxy satellite counts & phase space constraints
  - Warm DM will suppress small scale structure -> less sub halo -> less satellite “missing satellite problem” (Dwarf galaxy count constraint)
  - Structure: DM is “cold enough” -> sterile neutrino > 1.7 keV (Phase space)
- BBN limit
  - Sterile neutrinos resonantly produced during BBN, limited by lepton asymmetry measured from Helium abundance (Shi-Fuller mechanism)
    - Non-resonant production in 0 lepton asymmetry (Dodelson-Widrow mechanism)



J. F. Cherry & S. Horiuchi 2017

- Rebinning
  - Equal width bins in log space
  - Narrower than 1 photon energy ($FWHM$) resolution but wider than many photon energy resolution ($FWHM/\sqrt{N}$)

	TM1	TM2	TM3	TM4	TM5	TM6	TM7
HEW Al-Kα at 1.49 keV	16.0 ± 0.2	15.5 ± 0.2	16.5 ± 0.2	15.9 ± 0.2	15.5 ± 0.2	15.6 ± 0.2	17.0 ± 0.2
FWHM Al-Kα at 1.49 keV	~9.3	~7.0	~7.9	~7.6	~8.5	~7.9	~9.2
HEW Cu-Kα at 8.04 keV	14.5 ± 0.2	15.1 ± 0.2	15.6 ± 0.2	16.3 ± 0.2	15.1 ± 0.2	16.2 ± 0.2	14.7 ± 0.2
FWHM Cu-Kα at 8.04 keV	~7.9	~7.5	~6.5	~7.6	~6.6	~7.8	~5.7
Eff. Area at Al-Kα at 1.49 keV	391 ± 22	393 ± 16	388 ± 19	369 ± 25	378 ± 19	392 ± 25	392 ± 16
Eff. Area at Cu-Kα at 8.04 keV	24.9 ± 1.1	25.1 ± 1.2	24.1 ± 0.6	23.8 ± 0.9	25.1 ± 1.1	25.0 ± 0.9	24.8 ± 0.8

Extra Topic: the Case for Delta Line

- DM decay line signal can be redshifted either cosmologically in Extra Galactic (EG) DM signal, or by velocity dispersion in galactic DM
- EG DM would have been shifted into a continuum.
  - We didn't consider EG DM due to it will be degenerate with other continuum. In practice although the flux is high compared to galactic, EG flux doesn't improve the fitting result.
- Galactic flux red shift should be smaller than eROSITA energy resolution, such that the delta line assumption is still valid:
  - $\frac{\Delta f}{f} = \frac{v}{c} < \frac{\Delta E}{E} \approx 0.1\%$
  - $v = 3e5\ km/s$ galactic DM definitely doesn't have this much dispersion

Extra Topic: ALP DM 101

- ALP
  - Unlike QCD Axion DON'T solve strong CP problem
  - Couples to EM field and converts to photon
  - Can decay into 2 photons

Extra Topic: Dark Photon and Limits

- Can decays into 3 photons
- Already constrained by other means, such as direct detection
- In astrophysics side, can use lifetime of horizontal branch star and solar lifetimes
- Comparing to astrophysical ones, eROSITA isn't competitive.