

Ionizing feedback from super-Eddington compact objects in low-metallicity starbursts

Chatzis et al. 2026, Chatzis et al. in prep

Margaritis Chatzis

In collaboration with:

Lida Oskinova, Bret Lehmer,
Arjan Bik and many others!

NewAthena Rising: SWG4
ICE-CSIC, Barcelona



Deutsche
Forschungsgemeinschaft
German Research Foundation

Institute for Physics and Astronomy
University of Potsdam

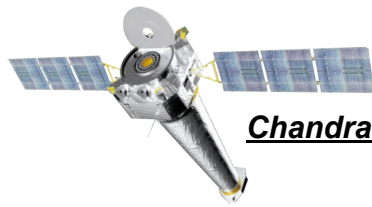


Outline

Goals

- ❖ Discover luminous HMXBs and hot gas in low-metallicity (sub-SMC) galaxies.
- ❖ Establish their nature. NS? BH? IMBH?
- ❖ Constrain ULX SED in the extreme-UV.
- ❖ Calculate Hell ionizing photon flux, addressing the Hell problem.

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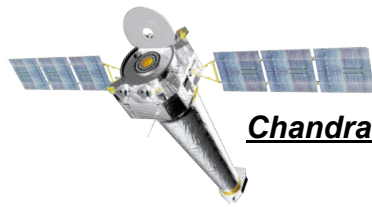


- ❖ Uniquely deconvolves ULX.
- ❖ Temporal variation search on the day timescale.

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Chandra

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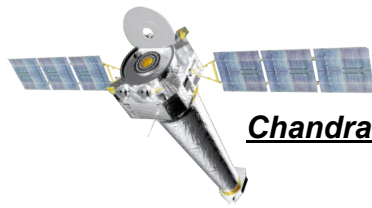
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XMM-Newton

- ❖ Reveals soft diffuse emission within and surrounding the galaxy.
- ❖ Jointly with Chandra constrains the SED in the X-ray range.
- ❖ Pulsation search.

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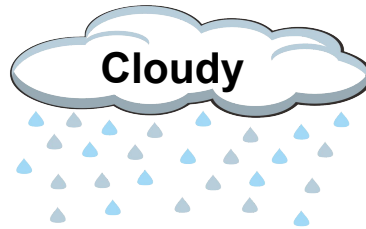
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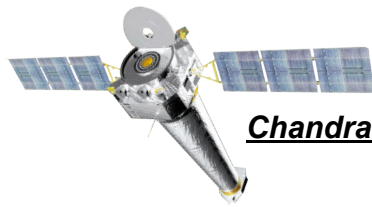


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- ❖ Derives nebular SED.
- ❖ Calculates strength of interesting emission lines.
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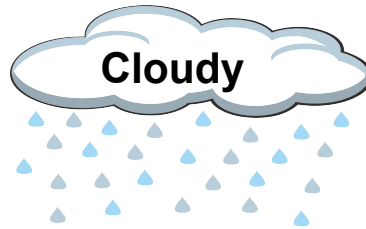
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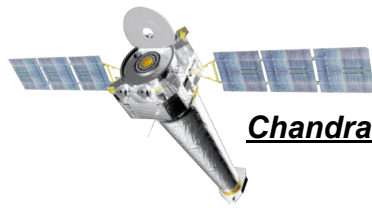


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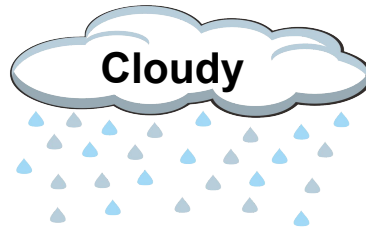
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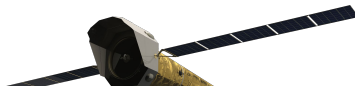
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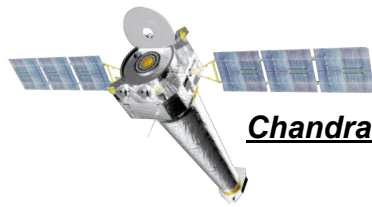
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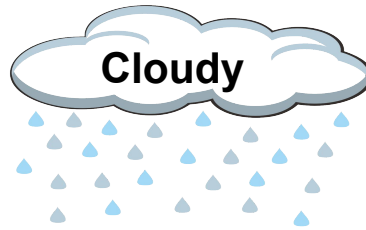
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- ❖ NewAthena's contribution to the ionizing feedback in low-metallicity starburst galaxies.

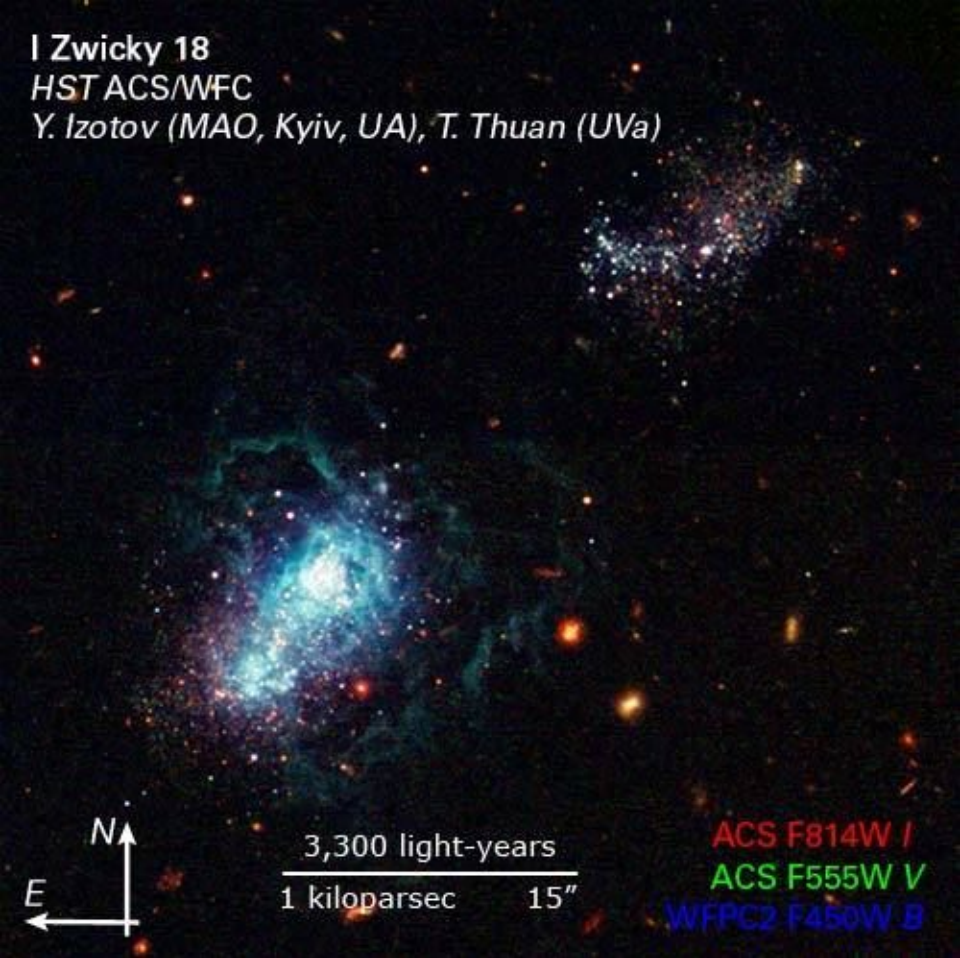
The Hell problem

- ❖ He II $\lambda 4686\text{\AA}$ (optical) traces extremely hard ionizing radiation (He II I.P. >54.4 eV).
- ❖ Strong He II emission is observed in many low-metallicity and high-redshift galaxies.
- ❖ Nearby template galaxies exhibit the same behaviour.
- ❖ Not limited only to Helium!
E.g., [NeV] $\lambda 14.32$ μm (infrared)
(NeV I.P. >97.12 eV)
- ❖ Normal stellar population models underpredict the observed He II strength. We need one or more of the following:
 - A. Very massive or weird stars
 - B. ULX
 - C. Diffuse X-ray emission

I Zwicky 18

HST ACS/WFC

Y. Izotov (MAO, Kyiv, UA), T. Thuan (UVa)



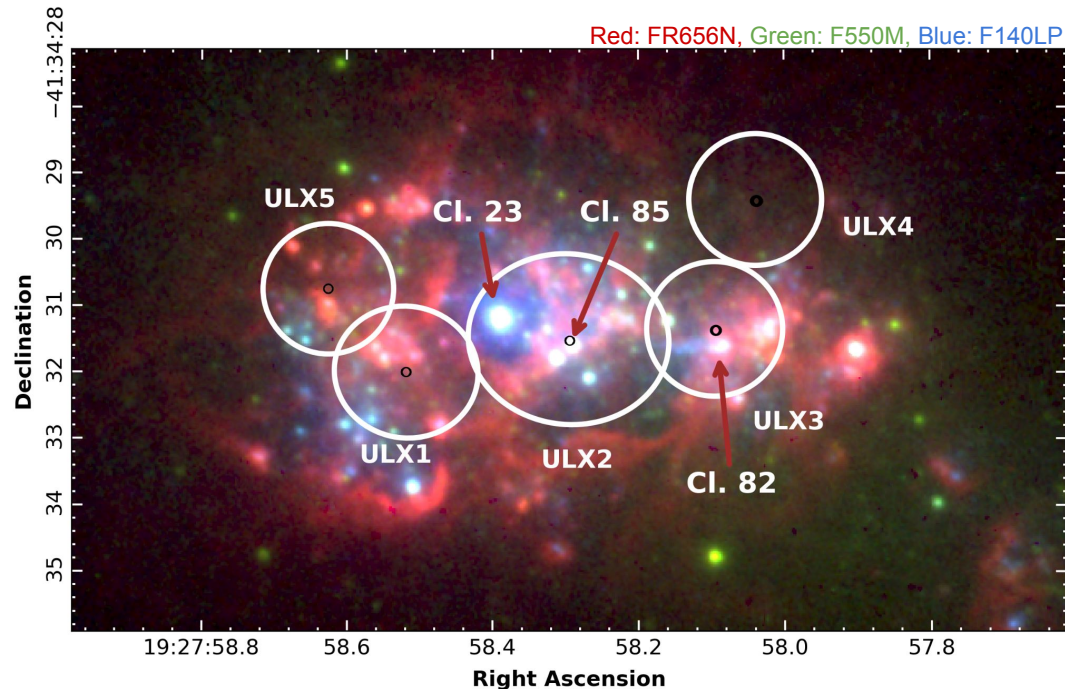
Credit: NASA

ESO 338-4 | Template Dwarf Galaxy with HST

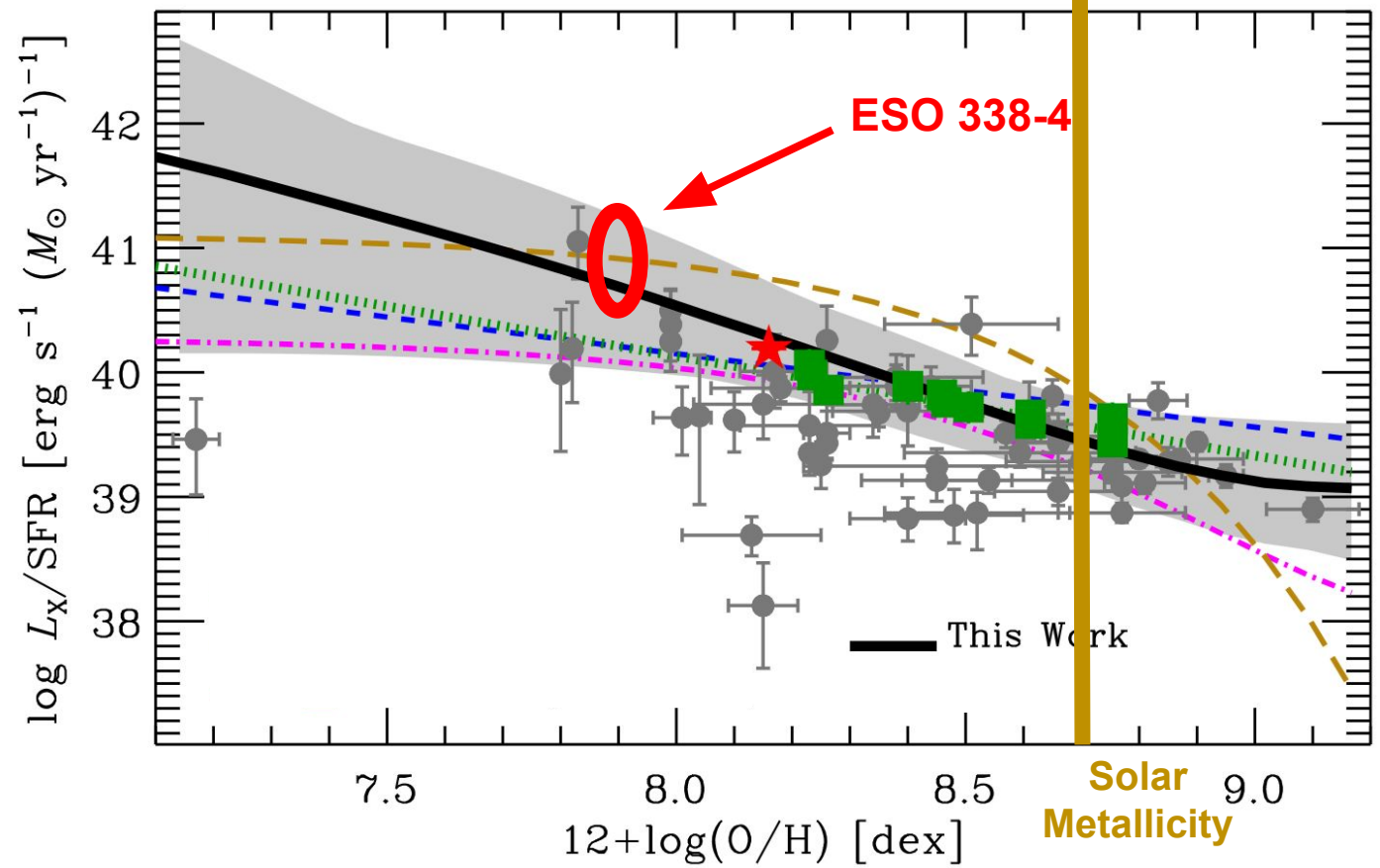
- ❖ Template ***low-metallicity*** starburst dwarf galaxy:
 - **12% solar** or $12+\log(\text{O}/\text{H})=7.9$.
 - SMC: 20% solar. LMC: 50% solar.

- ❖ Distance of **40 Mpc**. Close enough to resolve individual X-ray sources with Chandra!

- ❖ $L_{\text{HeII } \lambda 4686\text{\AA}} \approx 2 \cdot 10^{39} \text{ erg} \cdot \text{s}^{-1}$ from MUSE data. $L_{\text{HeII}}/L_{\text{H}\beta} \approx 0.019$.



- ❖ L_x :
Integrated L_x from
HMXB in galaxies.
- ❖ SFR:
Averaged star
formation rate over
125 Myr.
- ❖ $12+\log(O/H)$:
Metallicity

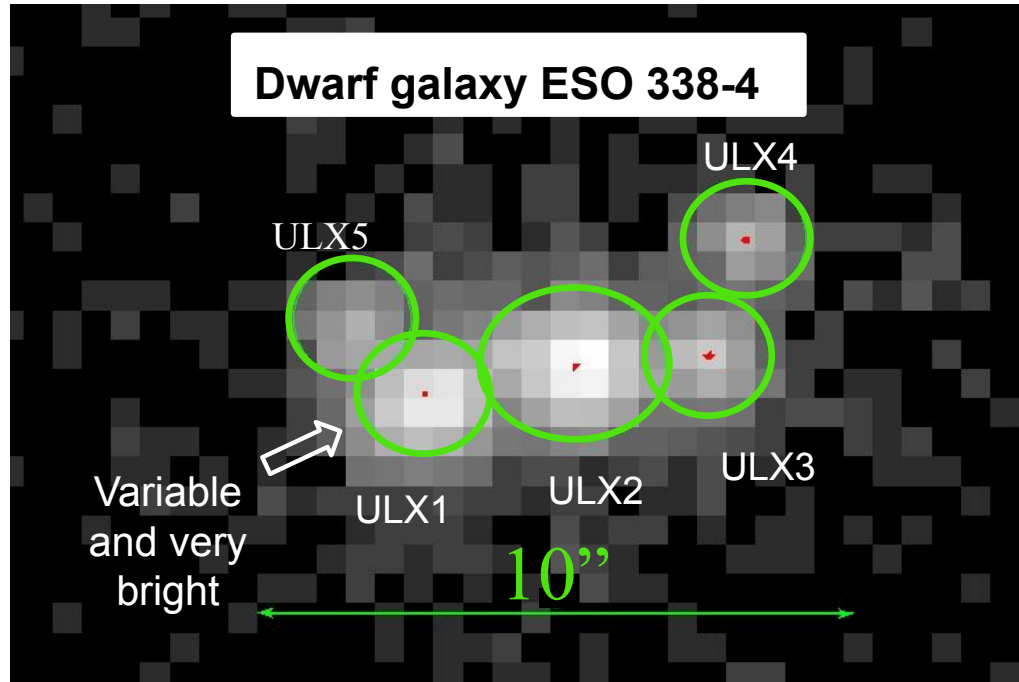


Lehmer et al. 2024,
Chatzis et al. 2026

ESO 338-4 | X-rays across metallicities

- ❖ Joint Chandra/XMM-Newton program.
- ❖ 16 Chandra Observations. Total of 300ks.
- ❖ Very deep data set allows for:
 - Deconvolution of 5 ULX within the galaxy.
 - Chandra has an astrometric accuracy of $\sim 1.4''$. Alignment of the dataset with Gaia EDR3 allows for sub-arcsecond precision.

We can search for multiwavelength counterparts on the sub-arcsecond scale!

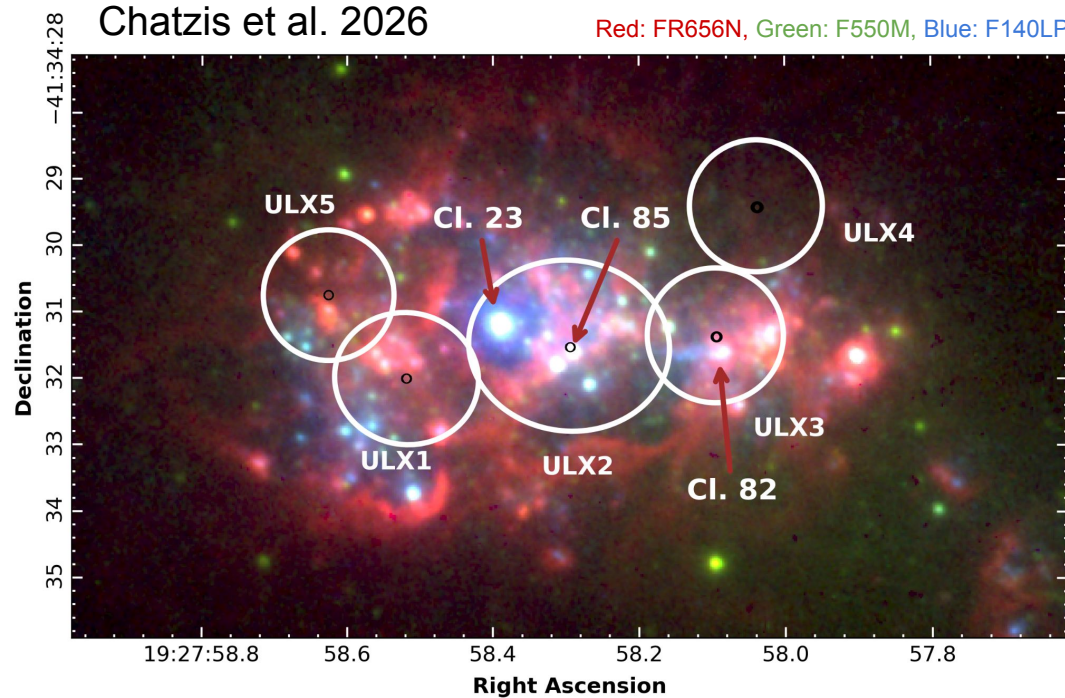


Wavdetect output

GREEN: Ellipse enclosing 3σ of the photons associated with the source

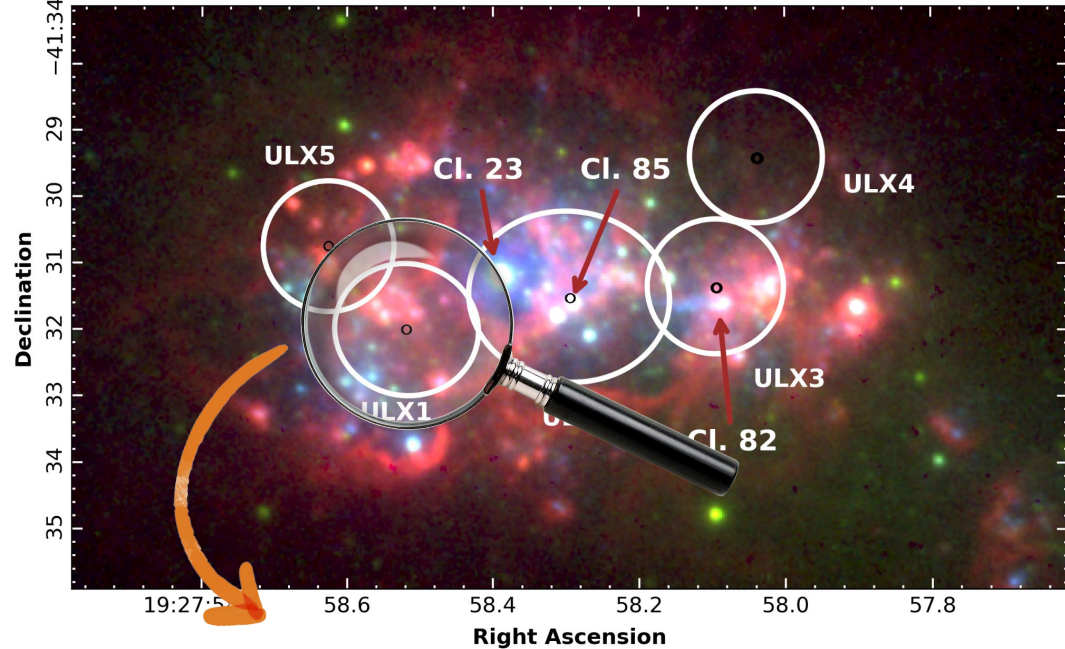
RED: ULX location

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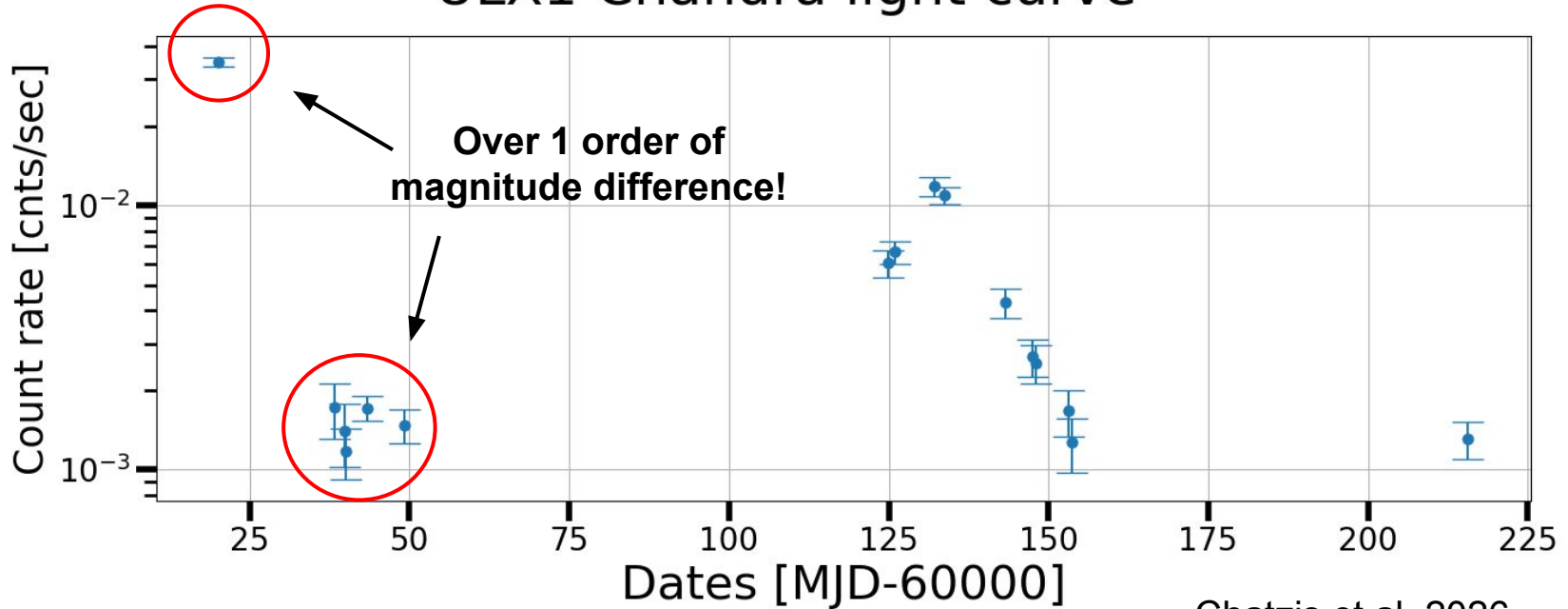
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- ❖ Highly variable on day timescale.
- ❖ $L_X > 10^{41} \text{ erg} \cdot \text{s}^{-1}$. HLX?
- ❖ NS or BH? IMBH?

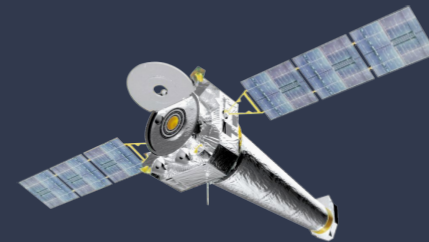
ULX1 Chandra light curve



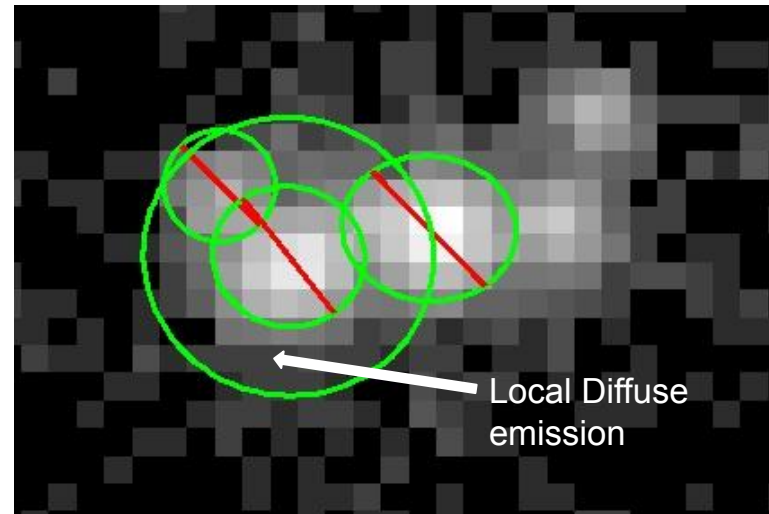
Chatzis et al. 2026

In our analysis we co-add the spectra, effectively taking the average behaviour.

Chandra | Spectral Analysis

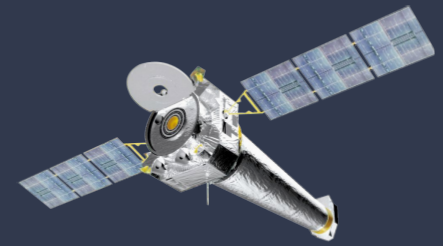


- ❖ Chandra allows us to fit models to both the ULX emission **AND** the *local* diffuse emission.
- ❖ ULX@ model components:
 $tbabs_{Gal} \times tbabs_{int} \times \text{ULX@ model}$
- ❖ Diffuse model components:
 $tbabs_{Gal} \times \text{APEC}$
- ❖ ULX1 spectral model test cases:
 - powerlaw
 - diskbb+diskbb
 - diskpbb



**All model cases have unconstrained parameters.
We need XMM to choose!**

Chandra | Spectral Analysis



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- ❖ ULX@ model components:

$tbabs_{Gal}$ ✘ $tbabs_{int}$ ✘ ULX@

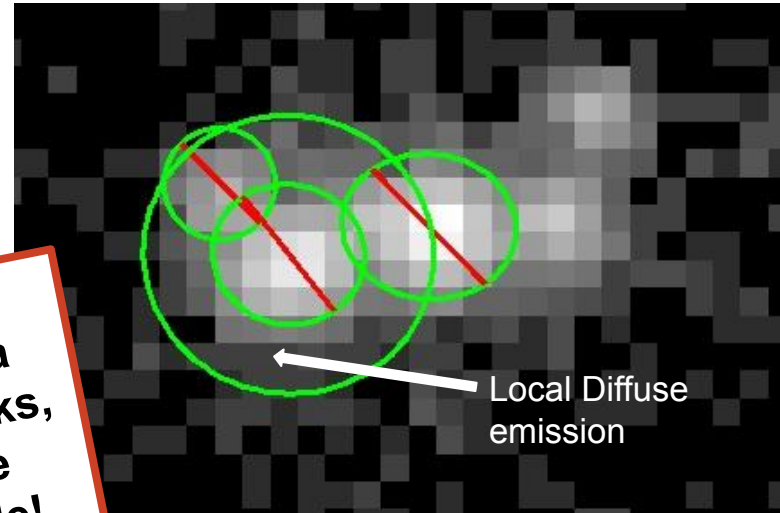
- ❖ Diffuse model components:

$tbabs_{Gal}$ ✘ APEC

- ❖ ULX1 spectral model tests:

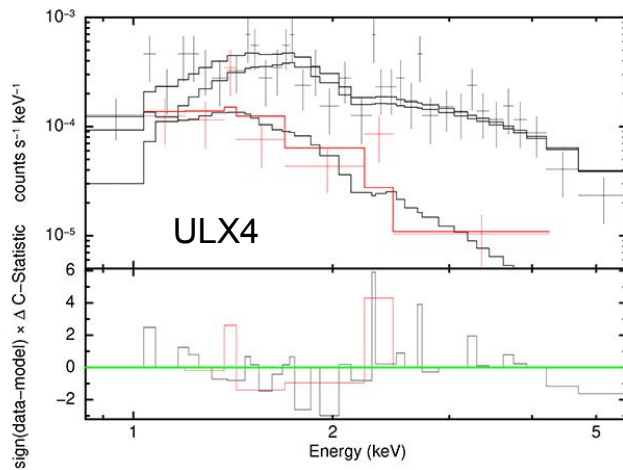
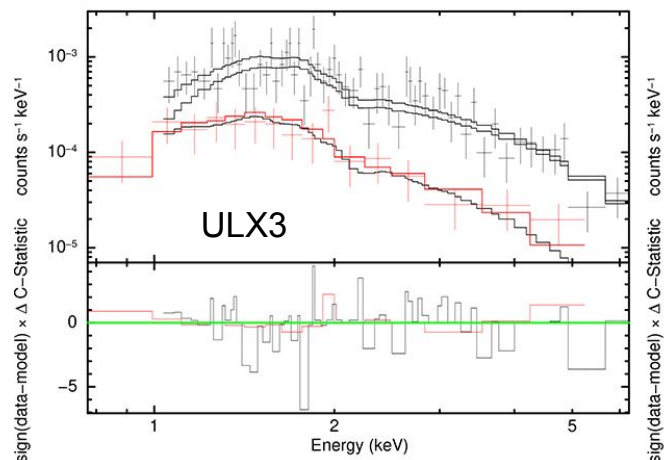
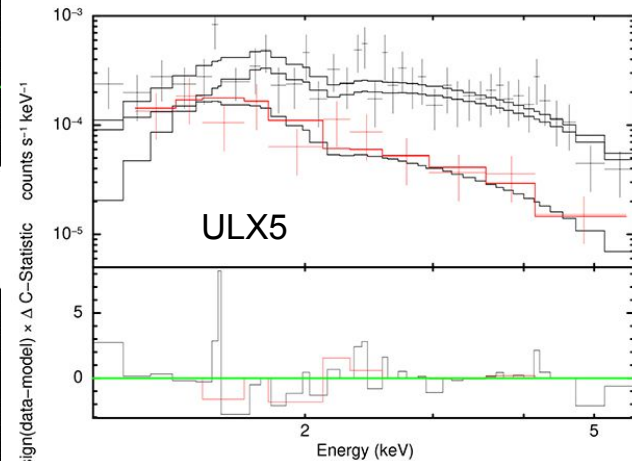
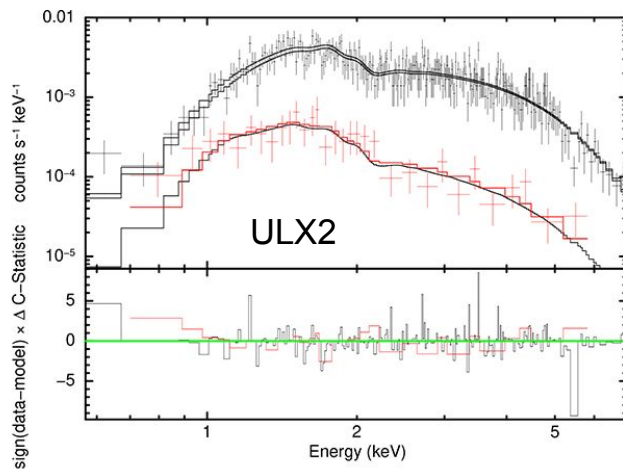
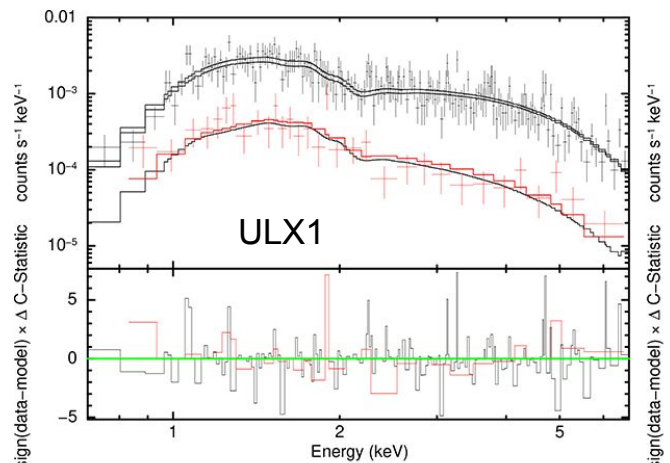
- powerlaw
- diskbb+diskbb
- diskpbb

At 40 Mpc, even with a total exposure of 300ks, fitting more elaborate models is not feasible!

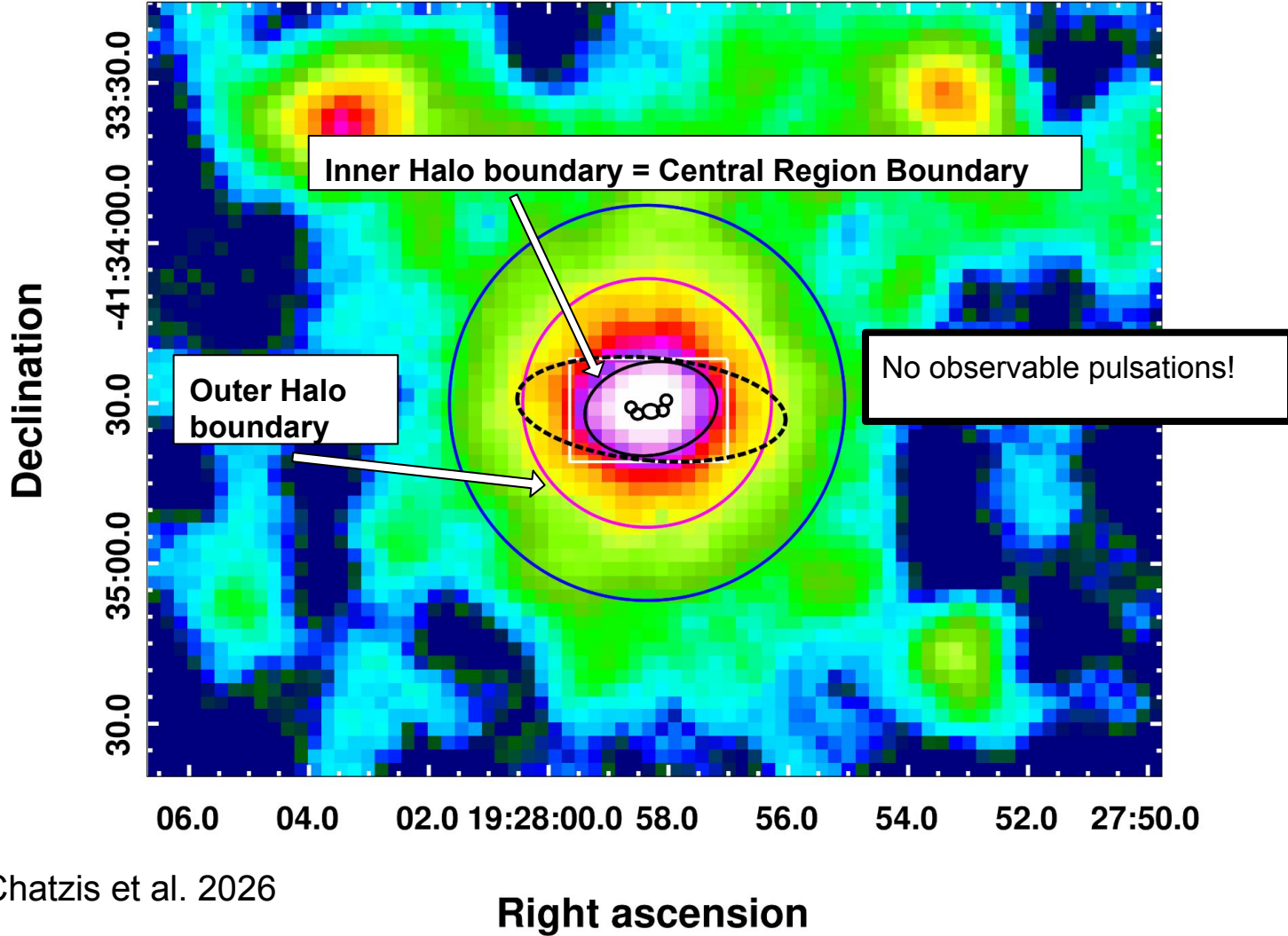


All model cases have unconstrained parameters. We need XMM to choose!

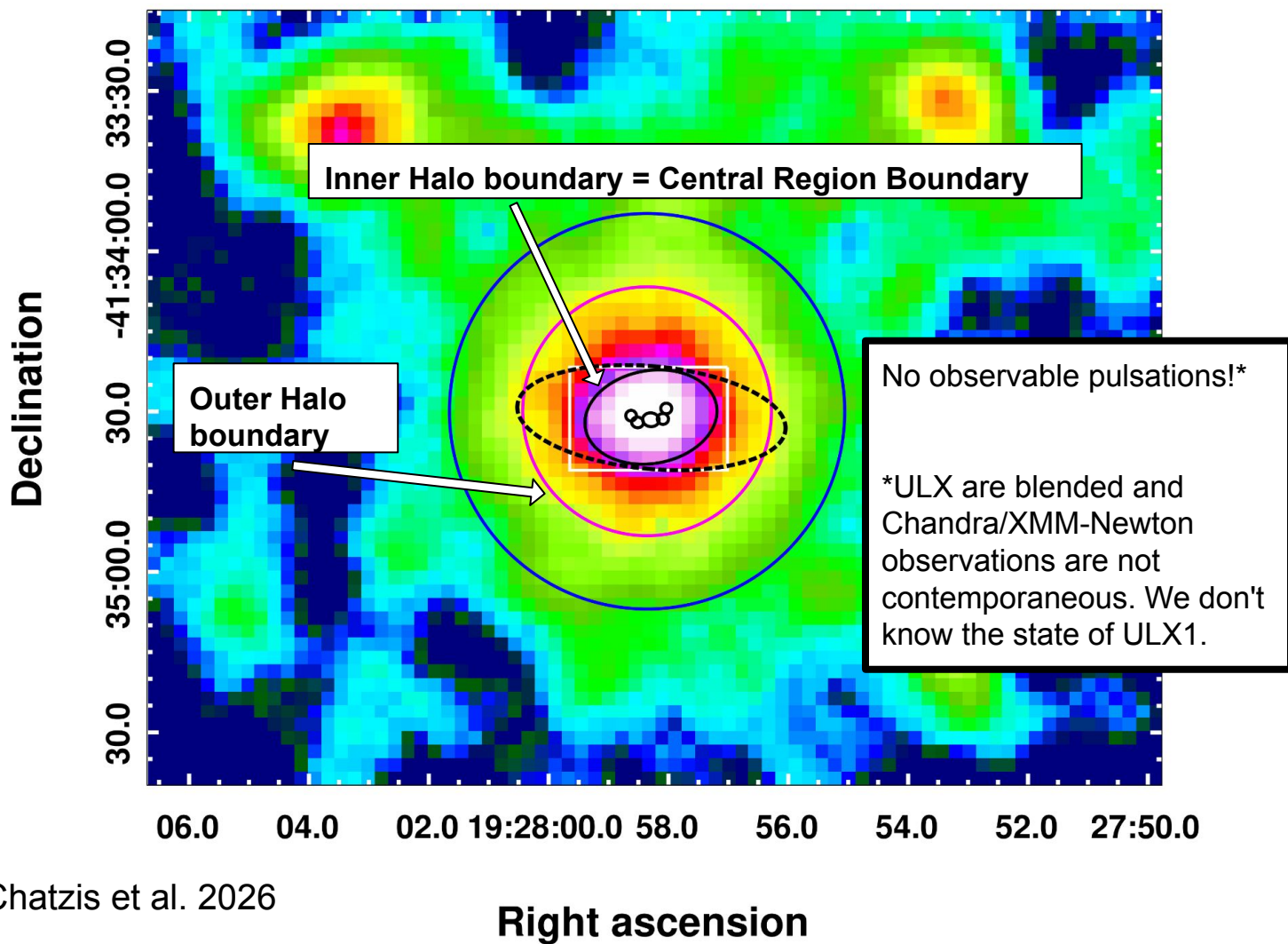
ULX Chandra Spectra



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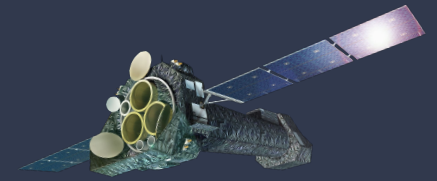


Chatzis et al. 2026



Chatzis et al. 2026

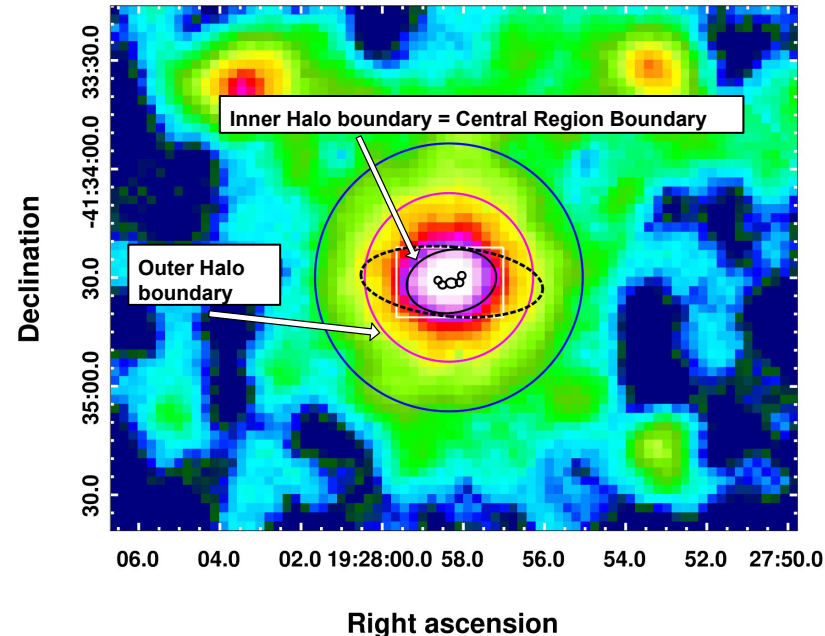
XMM-Newton | Spectral Analysis



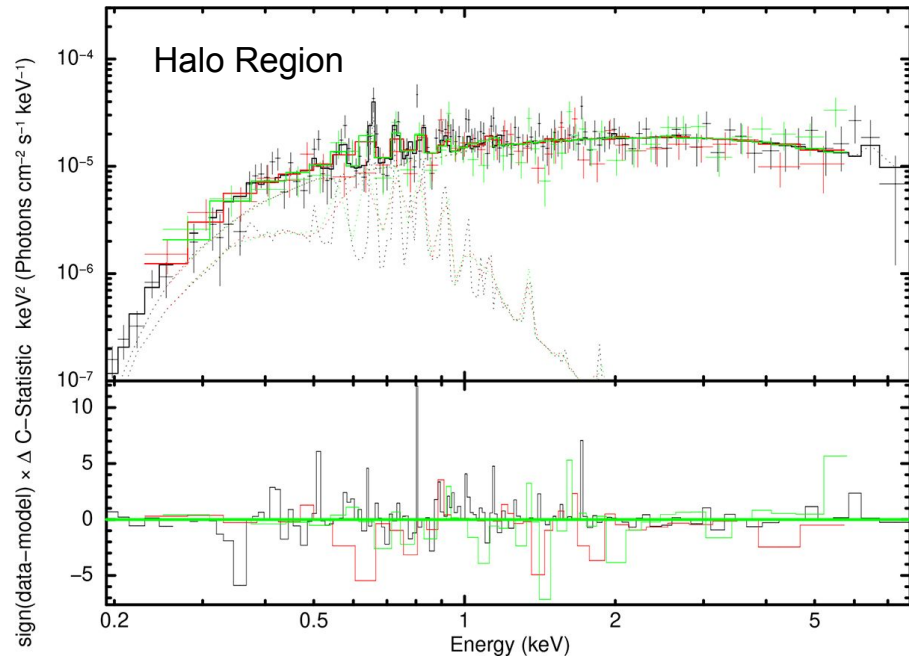
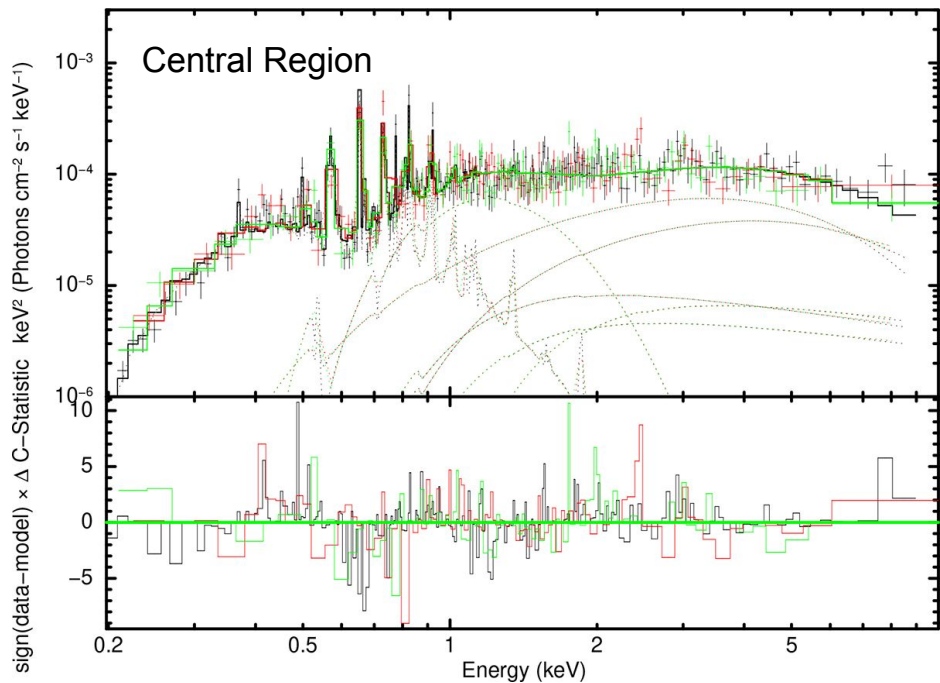
- ❖ Central region:
 $tbabs_{Gal} \times (\text{APEC} + \text{Sum of } \{tbabs_{int} \times \text{ULX@ model}\})$.
- ❖ ULX2-5 and well-constrained ULX1 parameters from Chandra analysis \rightarrow Fixed in XMM-Newton spectral fit.
- ❖ Halo region:
 $tbabs_{Gal} \times (\text{APEC}_{soft} + \text{APEC}_{hard})$.

Joint Central/Halo region analysis confirms diskbb+diskbb as the correct ULX1 spectral model choice.

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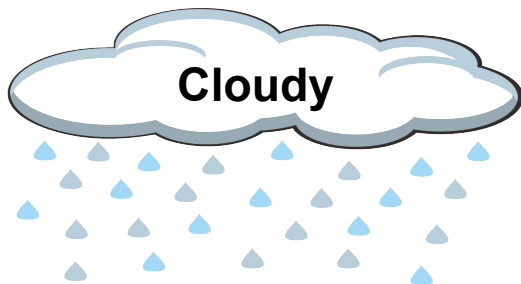
XMM-Newton Spectra



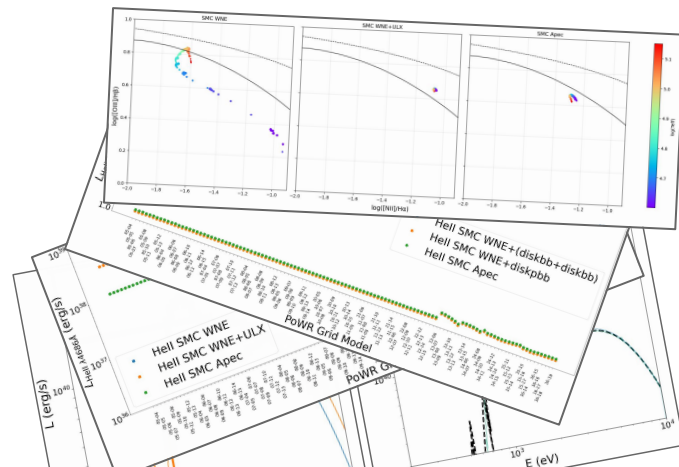
Chatzis et al. 2026

- ❖ Incident emission:
 - ULX spectrum. Taken from our analysis.
 - Very hot Star. Grid models from the Potsdam Wolf-Rayet Stellar Atmospheres (PoWR) code.

- ❖ Main cloud properties:
 - Metallicity
 - Cloud density.
 - Stopping criterion.

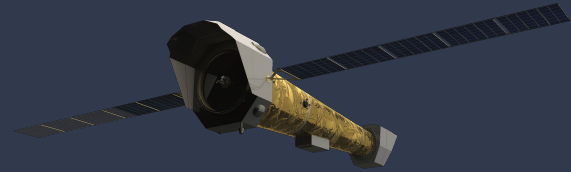


- ❖ Nebular SED + line strengths.
- ❖ Information about the extreme-UV ULX SED.



**See you next week in Elche @
X-ray Universe.
Tue June 9th, 15:30, Room 1.
OR
Let's talk during a coffee break!**

NewAthena in the Early Universe



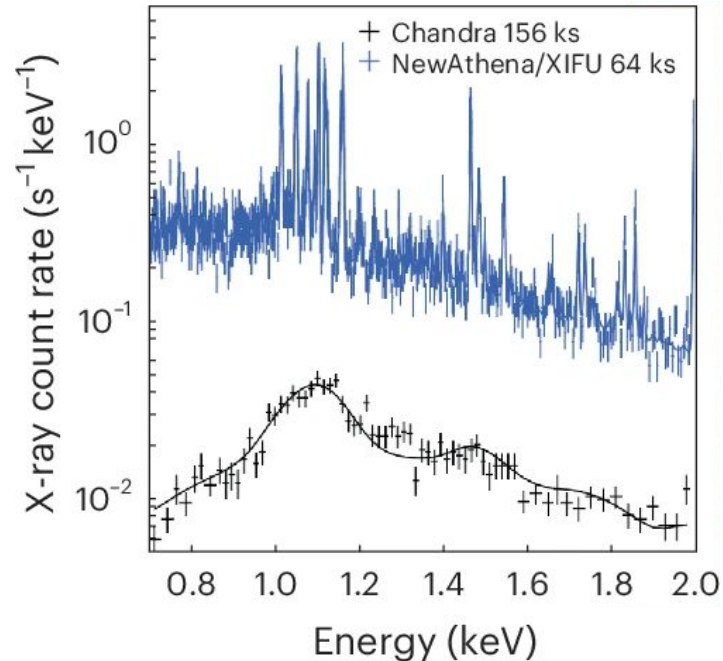
Assuming 1 dominant point source &
diffuse emission

+

NewAthena X-IFU's spectral resolution
and large effective area

=

**High quality spectra of unresolved
early universe galaxies**



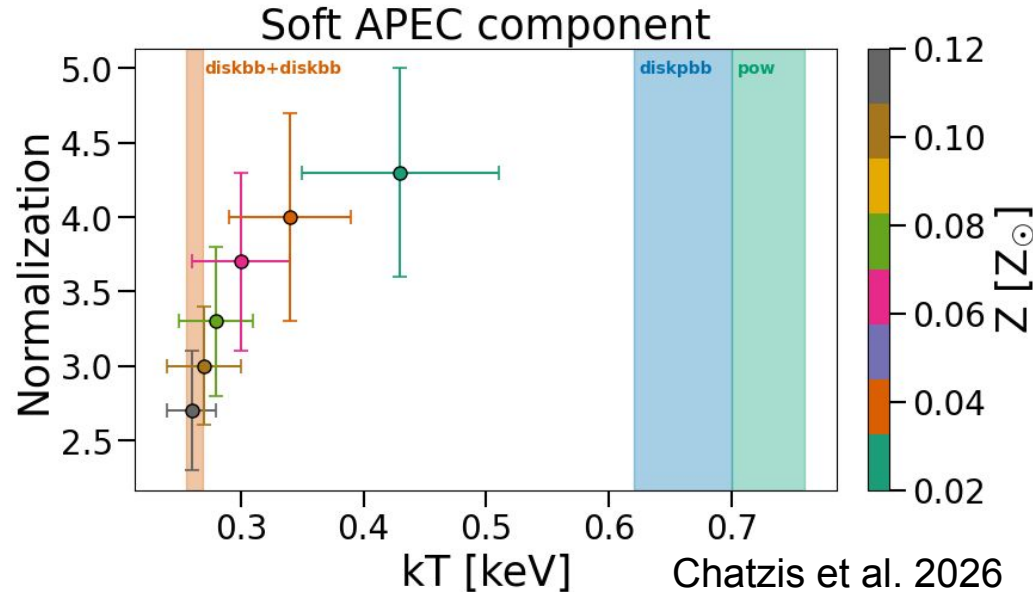
- ❖ Discovery and deconvolution of 5 ULX in a nearby template low-metallicity starburst galaxy.
- ❖ Multiwavelength counterpart mapping thanks to astrometric corrections with Gaia EDR3.
- ❖ Spectral modelling of point sources and diffuse gas in and around the galaxy.
- ❖ ULX1 variable on the day scale but does not exhibit pulsations. Nature still an open question.
- ❖ Photoionization modeling shows X-rays as significant ionizing photon contributors.
- ❖ NewAthena will provide high quality spectra of unresolved far away galaxies.



Backup Slides

XMM-Newton | Halo metallicity and ULX1 model

- ❖ Explored halo metallicities from **0.02–0.12** Z_{\odot} to test parameter degeneracies.
- ❖ Central region fit: Includes an APEC component and unresolved point source population.
- ❖ Different ULX1 spectral models return APEC components of varying temperature ranges.
- ❖ Halo fit: $\text{tbabs}_{\text{Gal}} \times (\text{APEC}_{\text{soft}} + \text{APEC}_{\text{hard}})$.



The ULX1 diskbb+diskbb model remains the only central-region solution whose APEC component has a temperature range that overlaps with the halo.

X-ray spectral analysis | Best fit model parameters

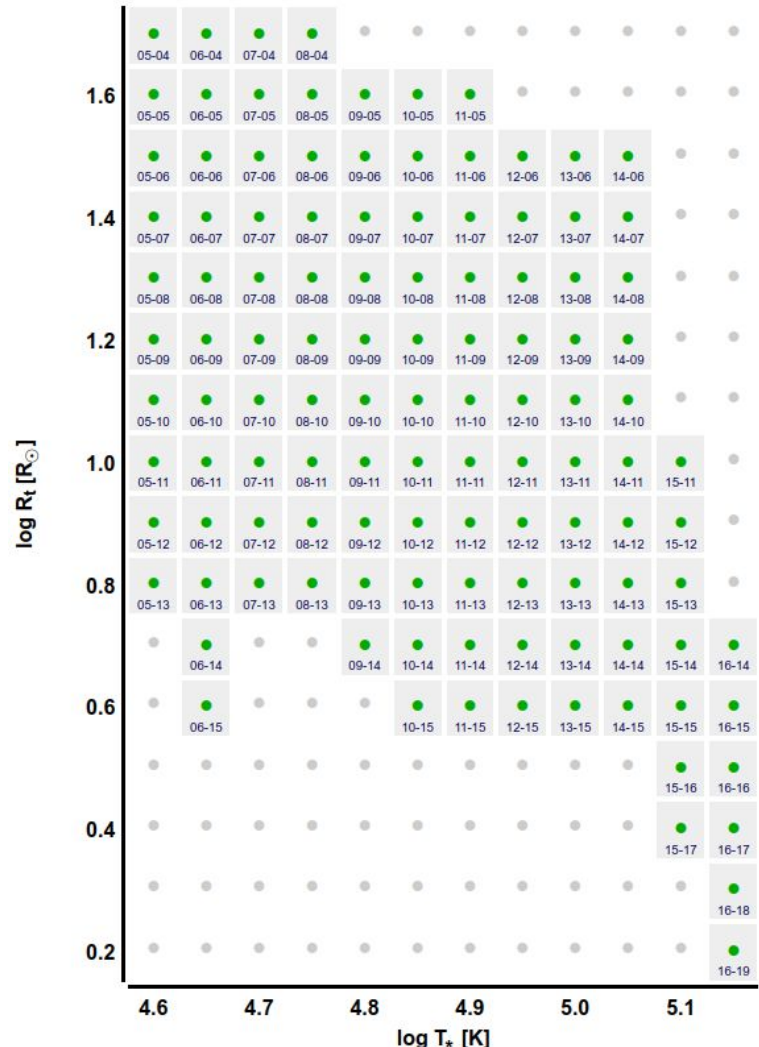
Model parameter	Best-fit value
Point sources	
ULX1: $\text{tbabs}_{\text{Gal}} \times \text{tbabs}_{\text{int}} \times (\text{diskbb}_1 + \text{diskbb}_2)$	
$N_{\text{H,int}} (10^{22} \text{ cm}^{-2})$	0.6 ± 0.3
$T_{\text{in,1}} (\text{keV})$	1.7 ± 0.2
Norm ₁	$(8 \pm 3) \times 10^{-4}$
$T_{\text{in,2}} (\text{keV})$	0.215 ± 0.009
Norm ₂	30 ± 10
ULX2: $\text{tbabs}_{\text{Gal}} \times \text{tbabs}_{\text{int}} \times \text{diskpbb}$	
$N_{\text{H,int}} (10^{22} \text{ cm}^{-2})$	0.1 ± 0.2
$T_{\text{in}} (\text{keV})$	1.2 ± 0.1
Norm	$(7 \pm 9) \times 10^{-3}$
Γ	1.0 ± 0.8
ULX3: $\text{tbabs}_{\text{Gal}} \times \text{tbabs}_{\text{int}} \times \text{powerlaw}$	
$N_{\text{H,int}} (10^{22} \text{ cm}^{-2})$	0.7 ± 0.3
Norm (photons $\text{keV}^{-1} \text{ cm}^{-2} \text{ s}^{-1}$ at 1 keV)	$(1.8 \pm 0.8) \times 10^{-5}$
Γ	2.7 ± 0.3
ULX4: $\text{tbabs}_{\text{Gal}} \times \text{tbabs}_{\text{int}} \times \text{powerlaw}$	
$N_{\text{H,int}} (10^{22} \text{ cm}^{-2})$	0.9 ± 0.6
Norm (photons $\text{keV}^{-1} \text{ cm}^{-2} \text{ s}^{-1}$ at 1 keV)	$(1.0 \pm 0.7) \times 10^{-5}$
Γ	(2.5 ± 0.6)
ULX5: $\text{tbabs}_{\text{Gal}} \times \text{tbabs}_{\text{int}} \times \text{powerlaw}$	
$N_{\text{H,int}} (10^{22} \text{ cm}^{-2})$	2.1 ± 0.8
Norm (photons $\text{keV}^{-1} \text{ cm}^{-2} \text{ s}^{-1}$ at 1 keV)	$(1.6 \pm 1.2) \times 10^{-6}$
Γ	2.5 ± 0.6

Diffuse sources	
Halo: $\text{tbabs}_{\text{Gal}} \times (\text{APEC}_1 + \text{APEC}_2)$	
$kT_1 (\text{keV})$	0.26 ± 0.02
Norm ₁ (cm^{-3})	$(2.7 \pm 0.4) \times 10^{-5}$
$kT_2 (\text{keV})$	3.5 ± 0.3
Norm ₂ (cm^{-3})	$(6.1 \pm 0.2) \times 10^{-5}$
Central: $\text{tbabs}_{\text{Gal}} \times (\text{APEC} + \text{Point-source contribution})$	
$kT (\text{keV})$	0.262 ± 0.007
Norm (cm^{-3})	$(3.7 \pm 0.1) \times 10^{-4}$

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Incident emission:

- ❖ ULX spectrum. Taken from our analysis.
- ❖ Very hot Stars. Grid models from the Potsdam Wolf-Rayet Stellar Atmospheres (PoWR) code.
 - T_* : Stellar temperature
 - R_t : Transformed radius. Proxy of wind strength.
 - Metallicity: LMC, SMC, subSMC
 - Type: E.g., Wolf-Rayet Nitrogen stars



Cloudy | Cloud properties

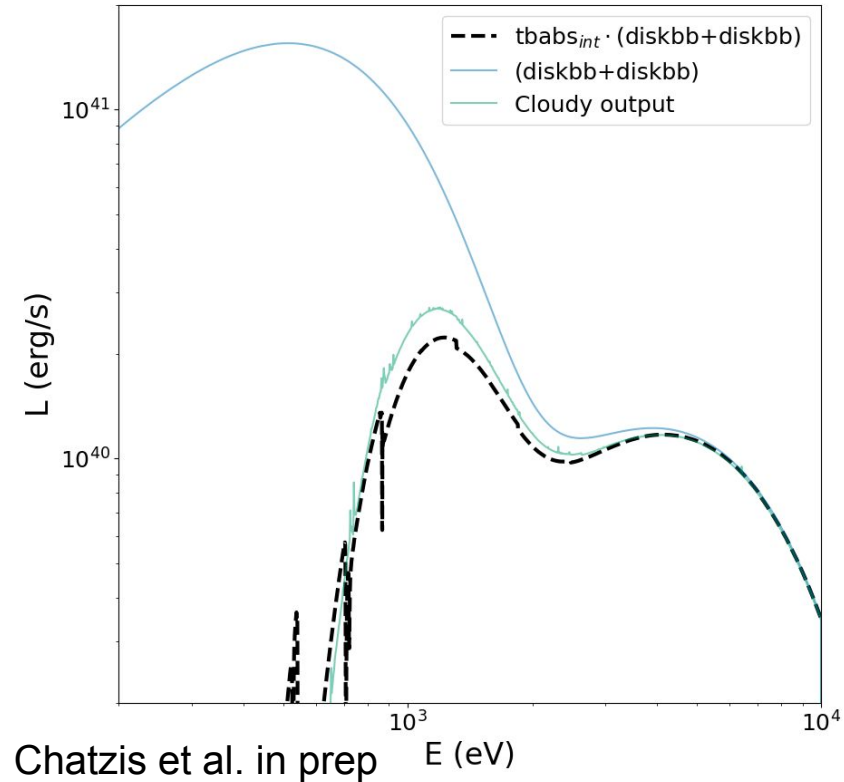
❖ Metallicity: 12% solar. Host galaxy metallicity.

❖ Spherical Geometry.

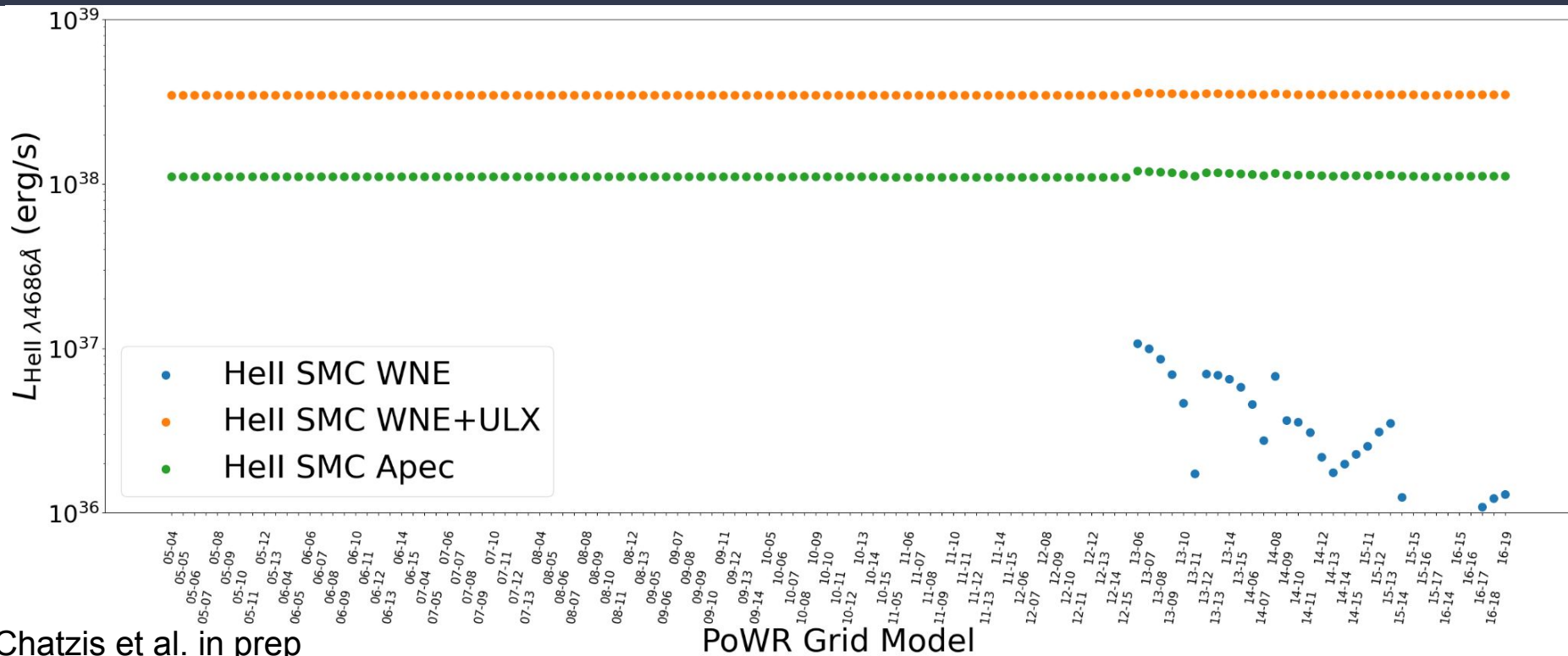
❖ $n_{\text{H}} = 10^{2.4} \text{cm}^{-3}$.

❖ Stopping criterion:
 $N_{\text{H}} = 10^{22.5} \text{cm}^{-2}$.

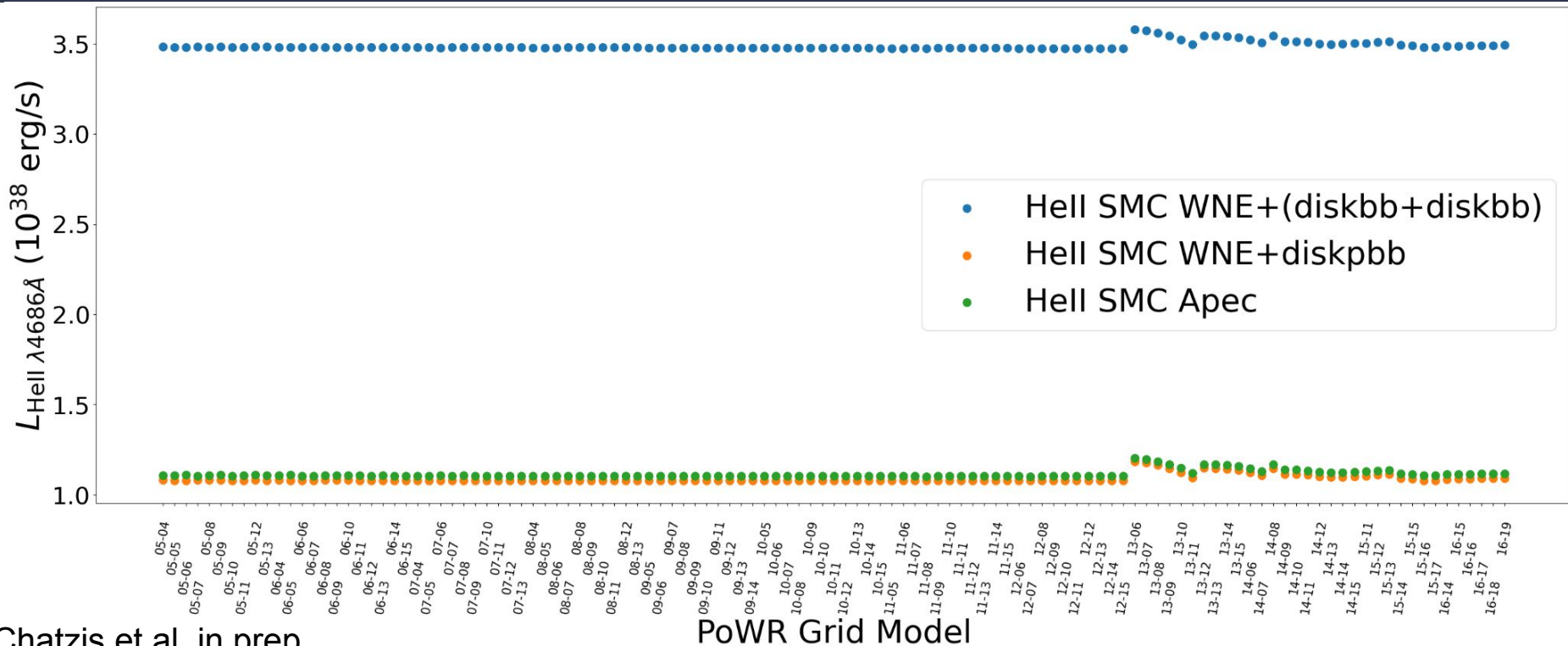
} **Approximates
internal ULX
absorption**



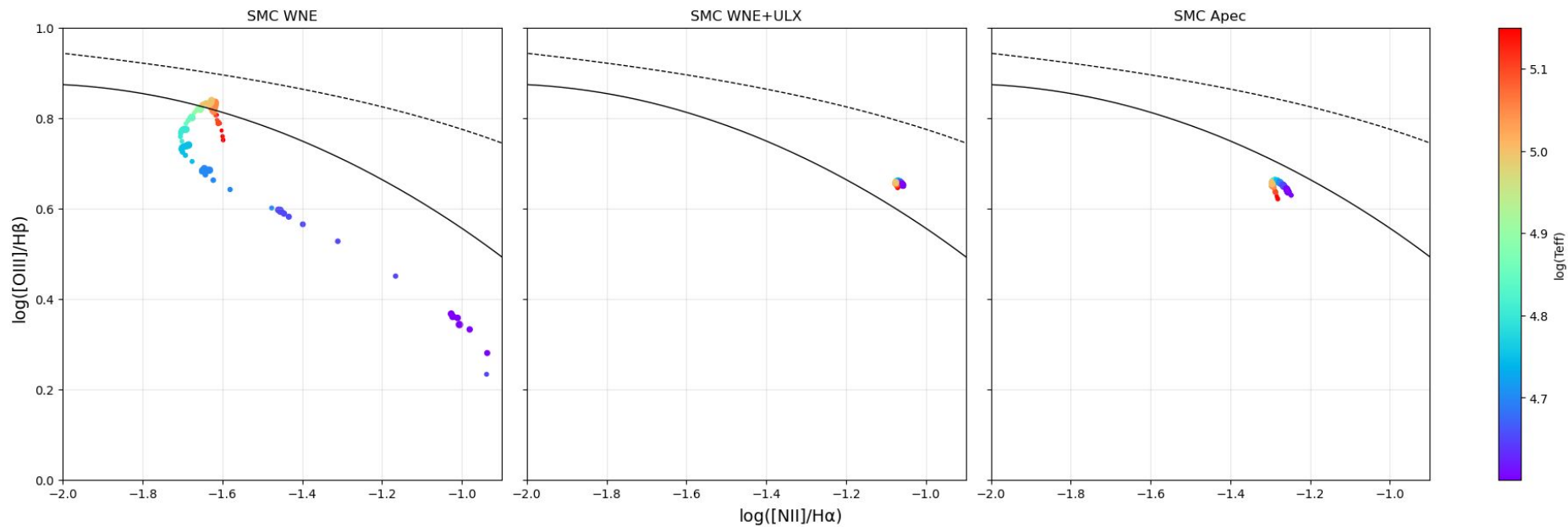
Cloudy | HeII $\lambda 4686\text{\AA}$ luminosity - Preliminary results

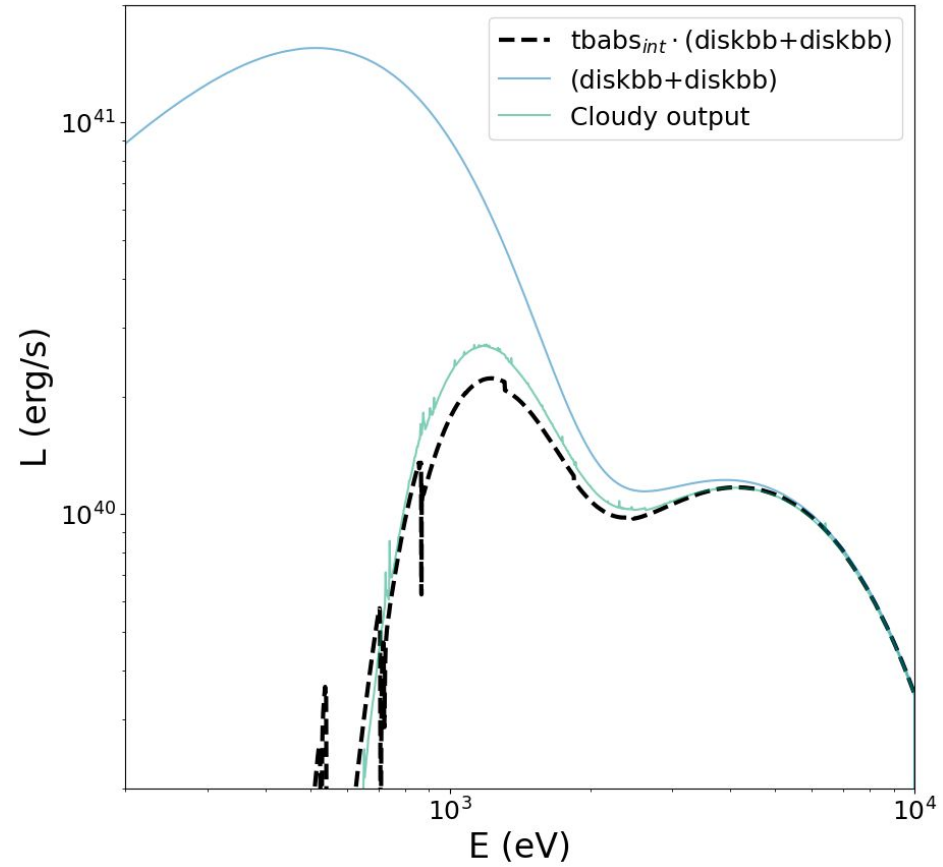
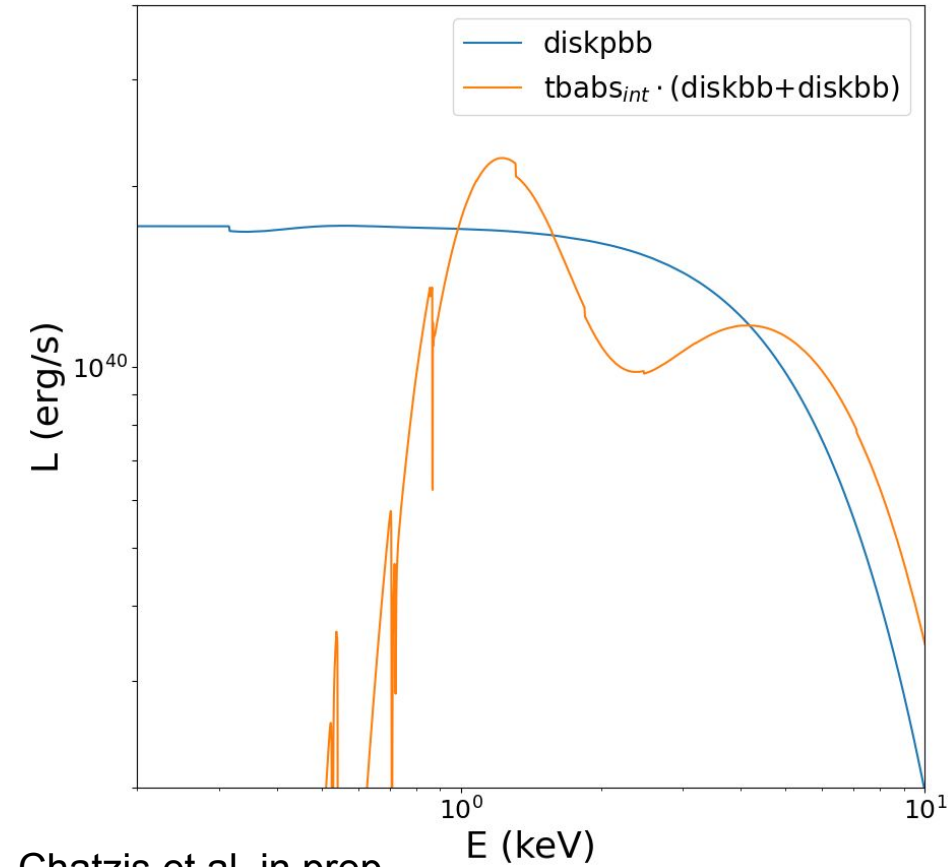


Cloudy | X-ray model comparison - Preliminary results



Cloudy | BPT diagram





Internal absorption and Cloudy