The legacy of Swift-BAT

A complete census of the heavily obscured AGN population in the local Universe

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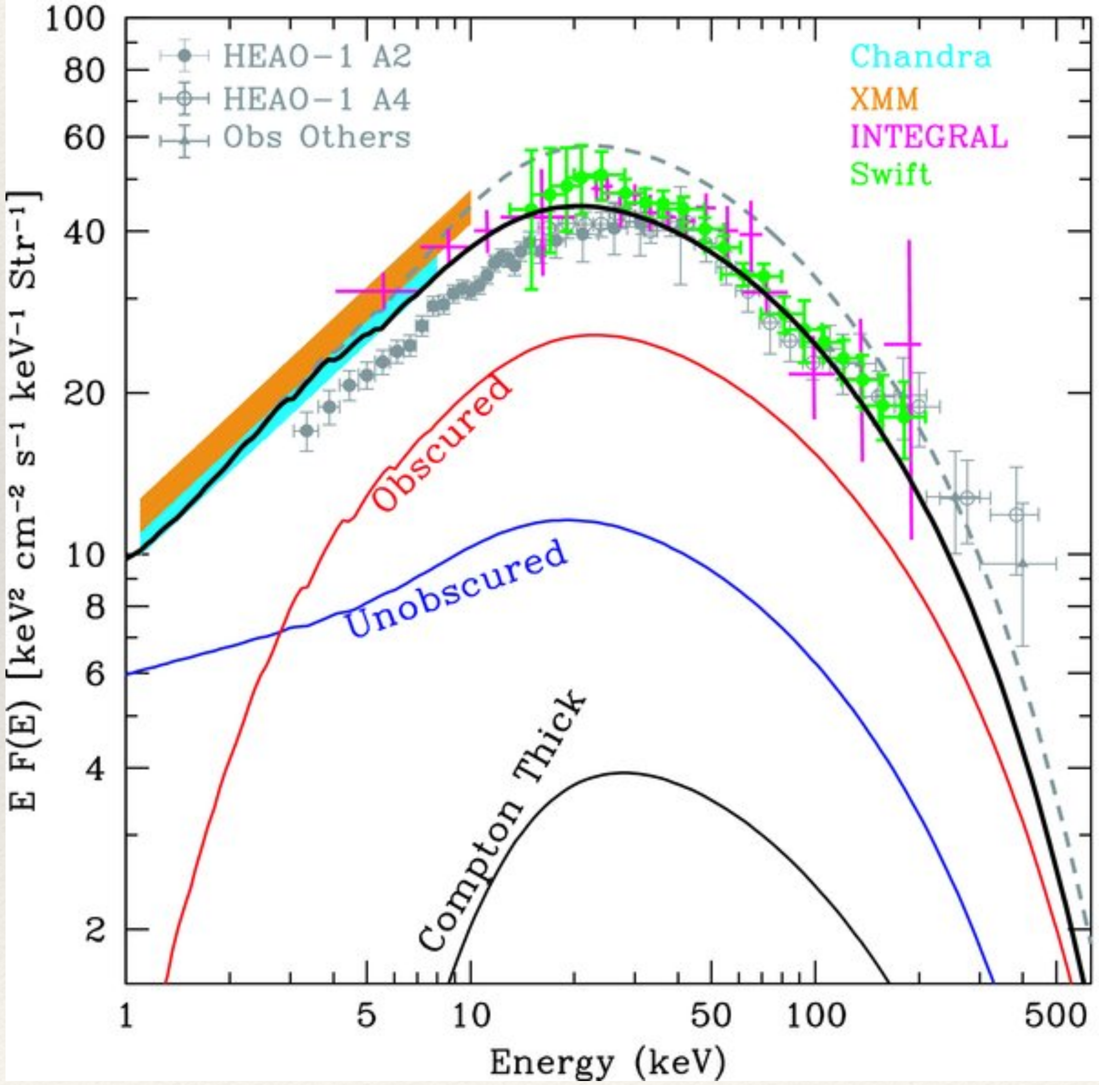
and collaborators

Celebrating 20 years of Swift Discoveries - Firenze - March 28, 2025

The difficult hunt for heavily obscured AGN

- Heavily obscured, and in particular Compton thick AGN ($\tau>1$; $NH>10^{24}$ cm^{-2}) should be numerous (~20-40% of whole AGN X-ray population at CXB peak) based on CXB models, but only ~5-10% have been observationally measured so far in low-z Universe.



See Gilli+07, Ajello+08, Treister+09, Burlon+11, Brightman & Nandra 11, Vasudevan+13, Vignali+13, Balokovic+14, Lanzuisi+15, Ricci+16, Tasnim Ananna+19

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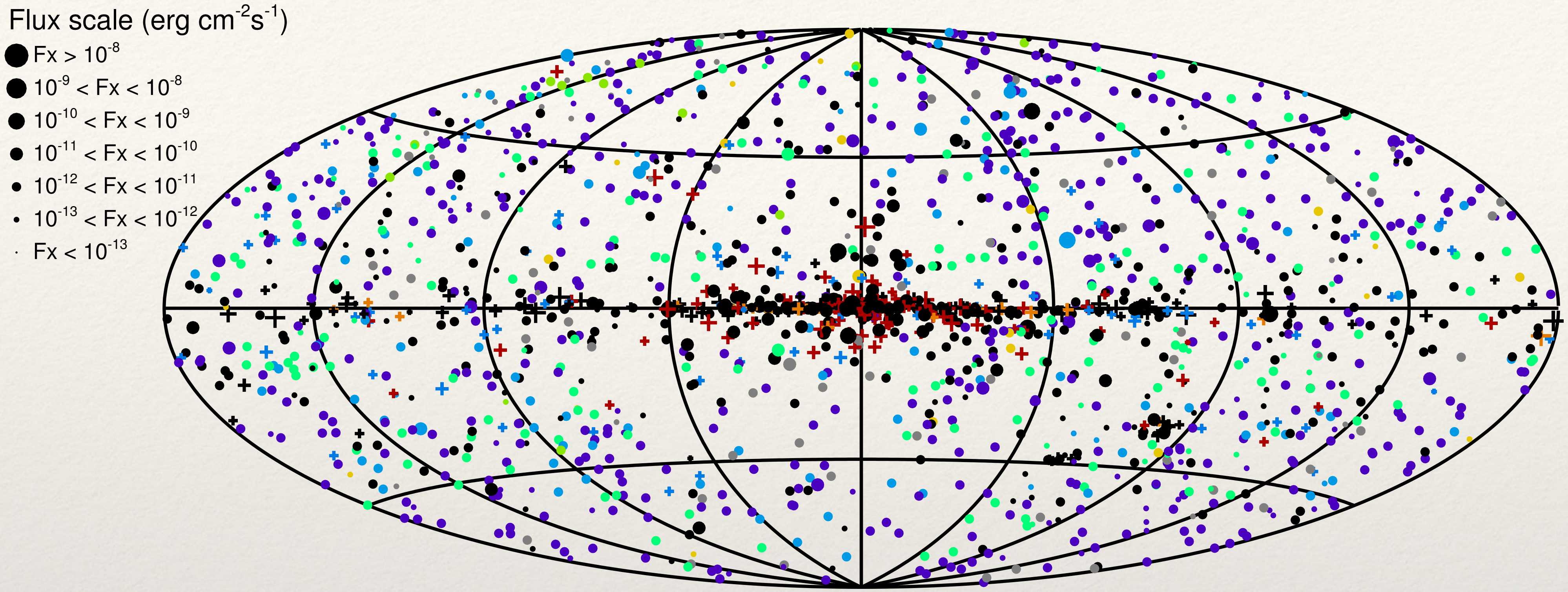
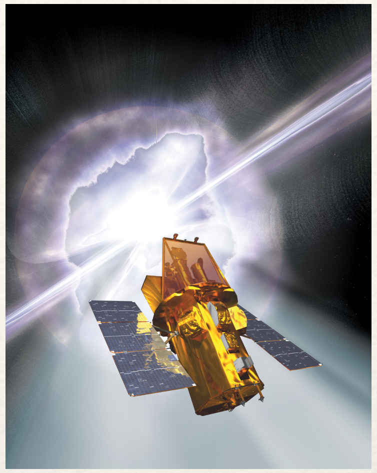
- Ideal alternative: Swift-BAT hard X-ray selected nearby AGN

See Gilli+07, Ajello+08, Treister+09, Burlon+11, Brightman & Nandra 11, Vasudevan+13, Vignali+13, Balokovic+14, Lanzuisi+15, Ricci+16, Tasnim Ananna+19

The Palermo Swift-BAT catalog





- All sky survey in the 15-150 keV (Imam+ in prep.). Detection method presented in Cusumano+10 (key members: A. Segreto, V. La Parola, G. Cusumano at INAF-IASF Palermo)
- Work started with 950 bright (f>=1E-12 erg/s/cm^2) AGN detected in 100 months; currently working with over **1700 sources in 158 months**. Almost 100% completeness in 0.5-10 keV, thanks also to dedicated campaigns with Swift-XRT (PI: Torres-Albà) from our group.
- Ideal sample to characterise bright, nearby targets -> **Least biased against obscuration**.

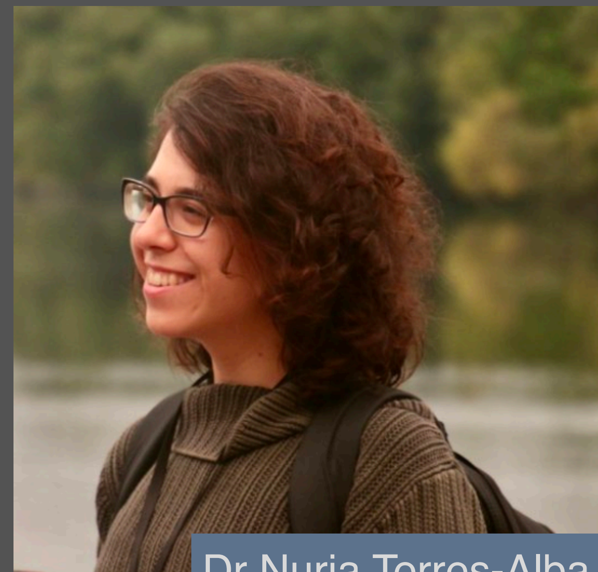
See also Ricci+16,17, Oh+18

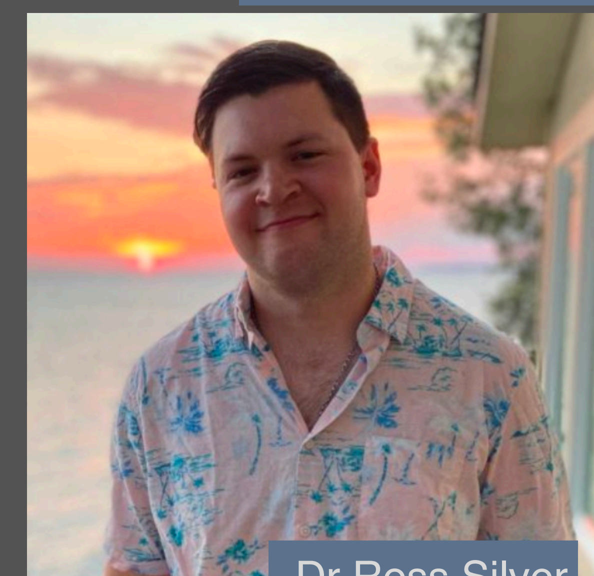
The BAT AGN spectroscopic survey (BASS) project

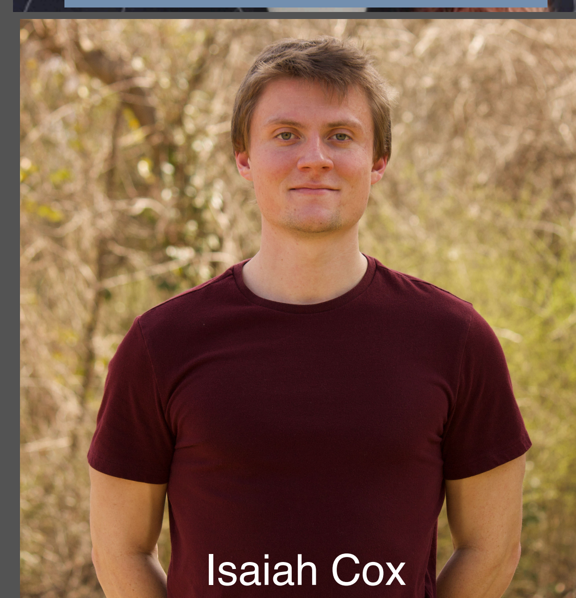
- Parallel effort led by the BASS collaboration, based on the 105-month Swift-BAT all sky survey (Oh+18)
- Excellent multi-wavelength coverage, high spectroscopic completeness: many different works on host properties, black hole masses, Eddington Ratios and trends with different parameters.

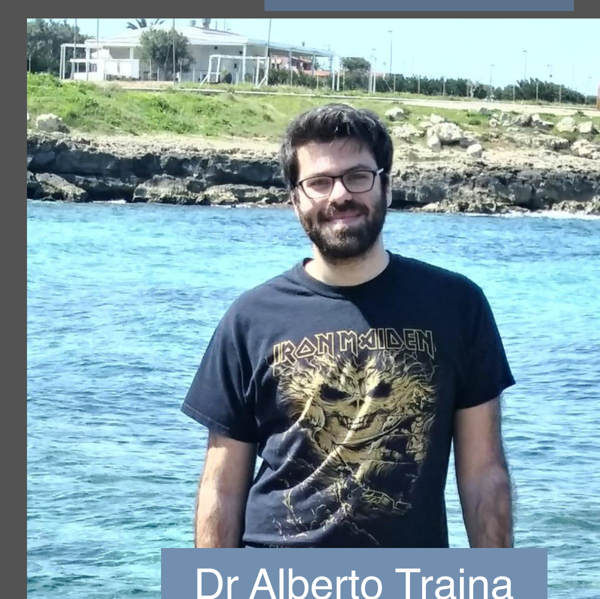
Ricci+16,17, Oh+18, Koss+22a,b, Ananna+22, Powell+22, Caglar+23,Tortosa+23, Ricci+23…

The Clemson-INAF CT-AGN group





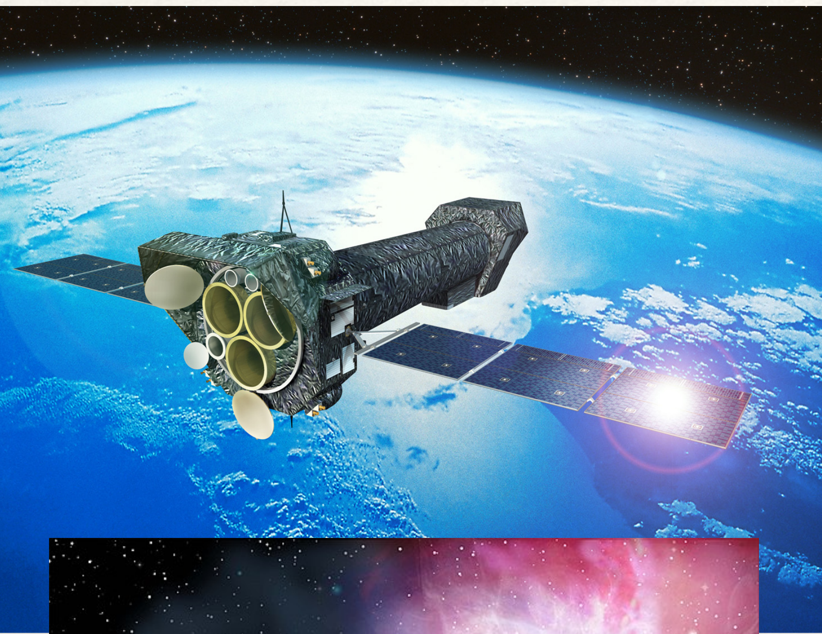


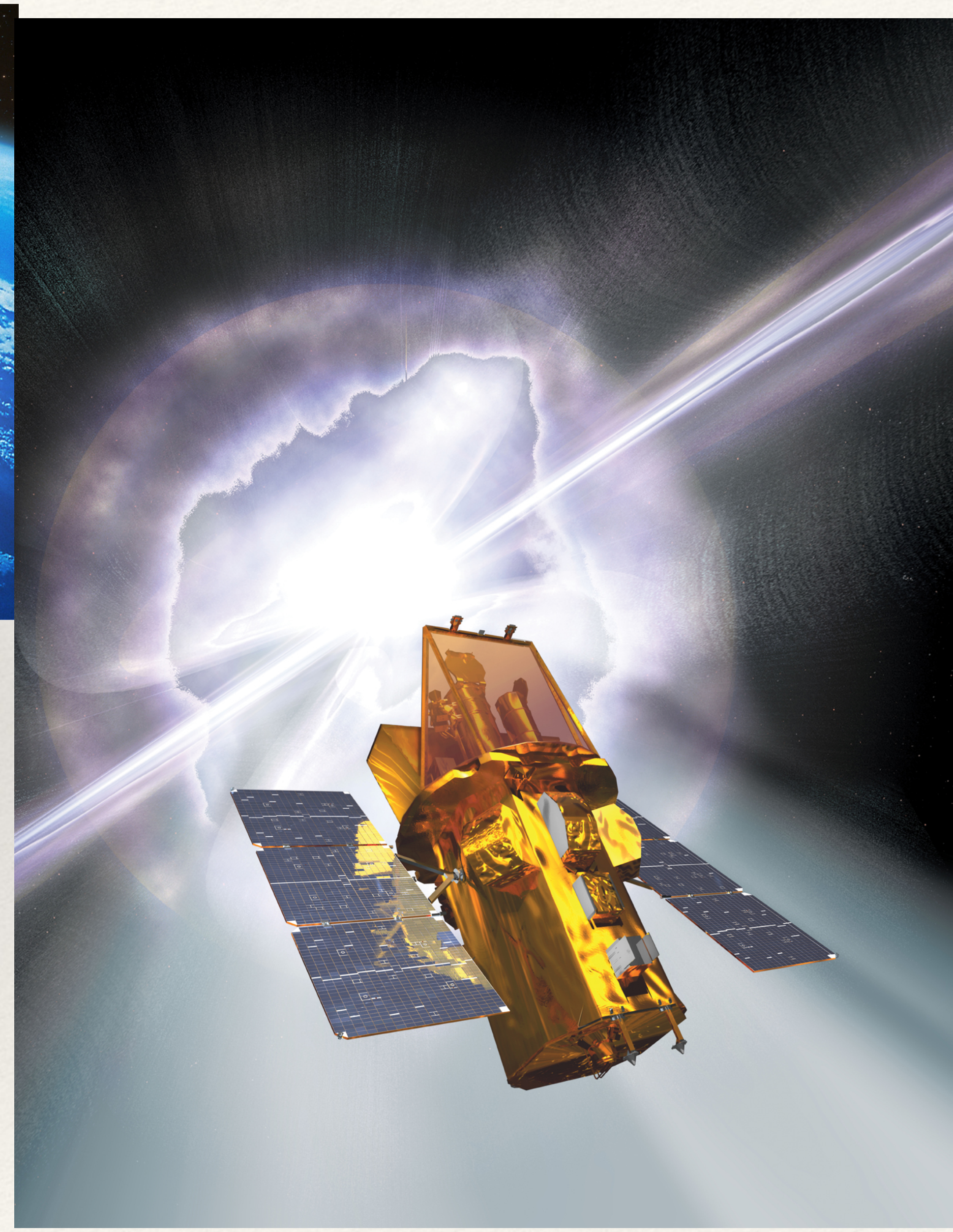


The Clemson-INAF CT-AGN project

A multi-observatory X-ray approach to get a complete census and characterisation of heavily obscured AGN in the Local Universe.

Products and results: https://science.clemson.edu/ctagn/





The Clemson-INAF CT-AGN project

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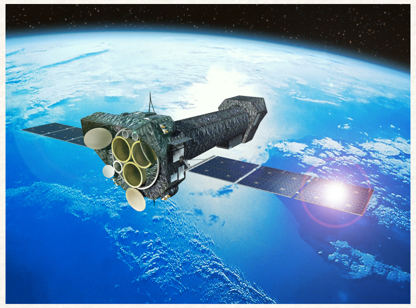
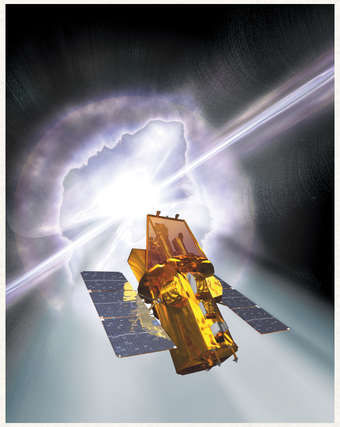
- Starting point: Swift-BAT hard X-ray selected nearby AGN.
- Three lines of work

1. Find new heavily obscured AGN candidates among the BAT sources
2. Confirm the high-NH nature of these targets and characterize their properties.
3. Use multi-epoch observations to characterize the obscuring medium.

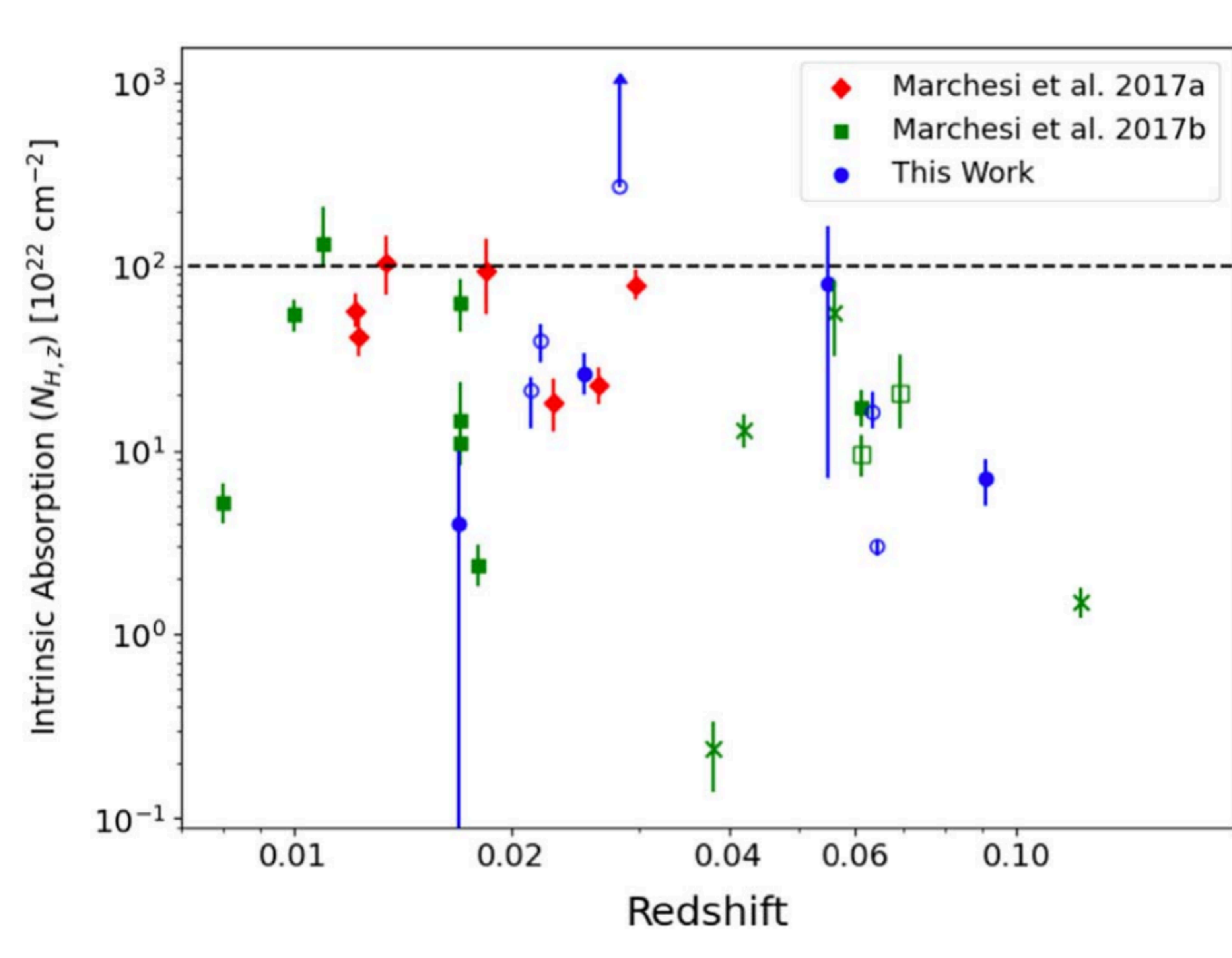
1. Discovering CT-AGN with *Chandra* and BAT



Marchesi et al. (2017a,b) Silver+22, Cox+25



- Follow-up with Chandra of BAT-selected Seyfert 2 with no ROSAT data -> Higher chance of obscuration.
- 28/35 sources (~80%) have N_H>1E23 —> Highly effective method for detecting heavily obscured AGN!
- Blind survey: ~30%>1E23, ~30-50% unobscured (e.g., Burlon et al. 2011)



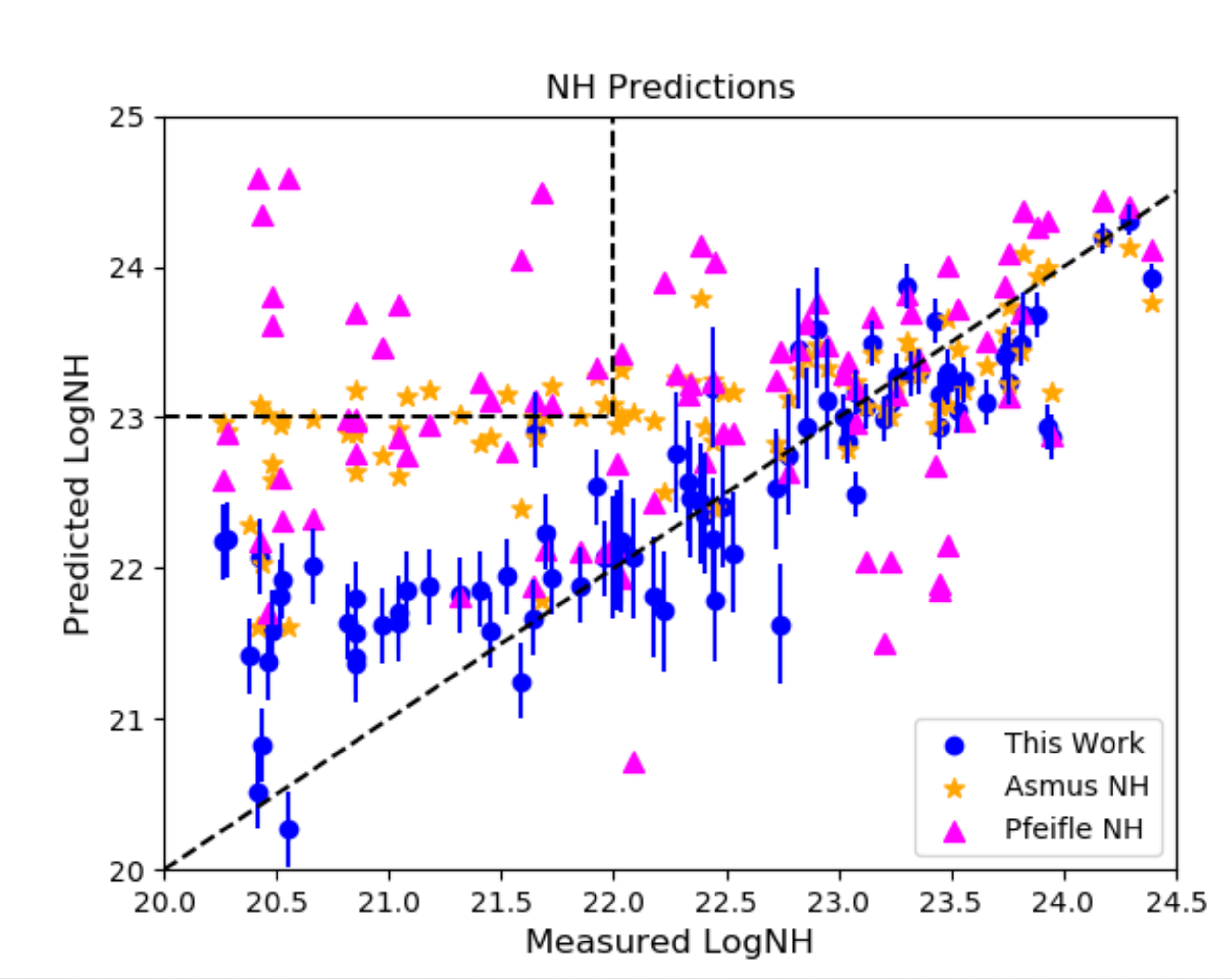
Silver+22

Swift and IR calibrated ML algorithm to predict NH

- Multiple Linear Regression method.
- Parameters:

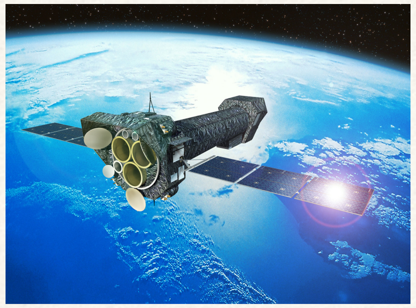
1. Mid-Infrared (MIR, 3.4-22 micron): WISE Colors
2. MIR - Soft X-ray Relation
3. Soft X-rays (0.3-10 keV from Swift-XRT): Two Hardness Ratios (HRs)
4. Hard X-rays (14-150 keV): *Swift*-BAT count rates

- The algorithm was trained using 451 AGN detected by the hard X-ray telescope Swift-BAT (14-150 keV) and with NH values determined through spectral fitting.
- With respect to other models, **low false positives**, excellent measurements for **logNH>23**.



Silver+23

Limitations in the 0.3-10 keV + BAT approach



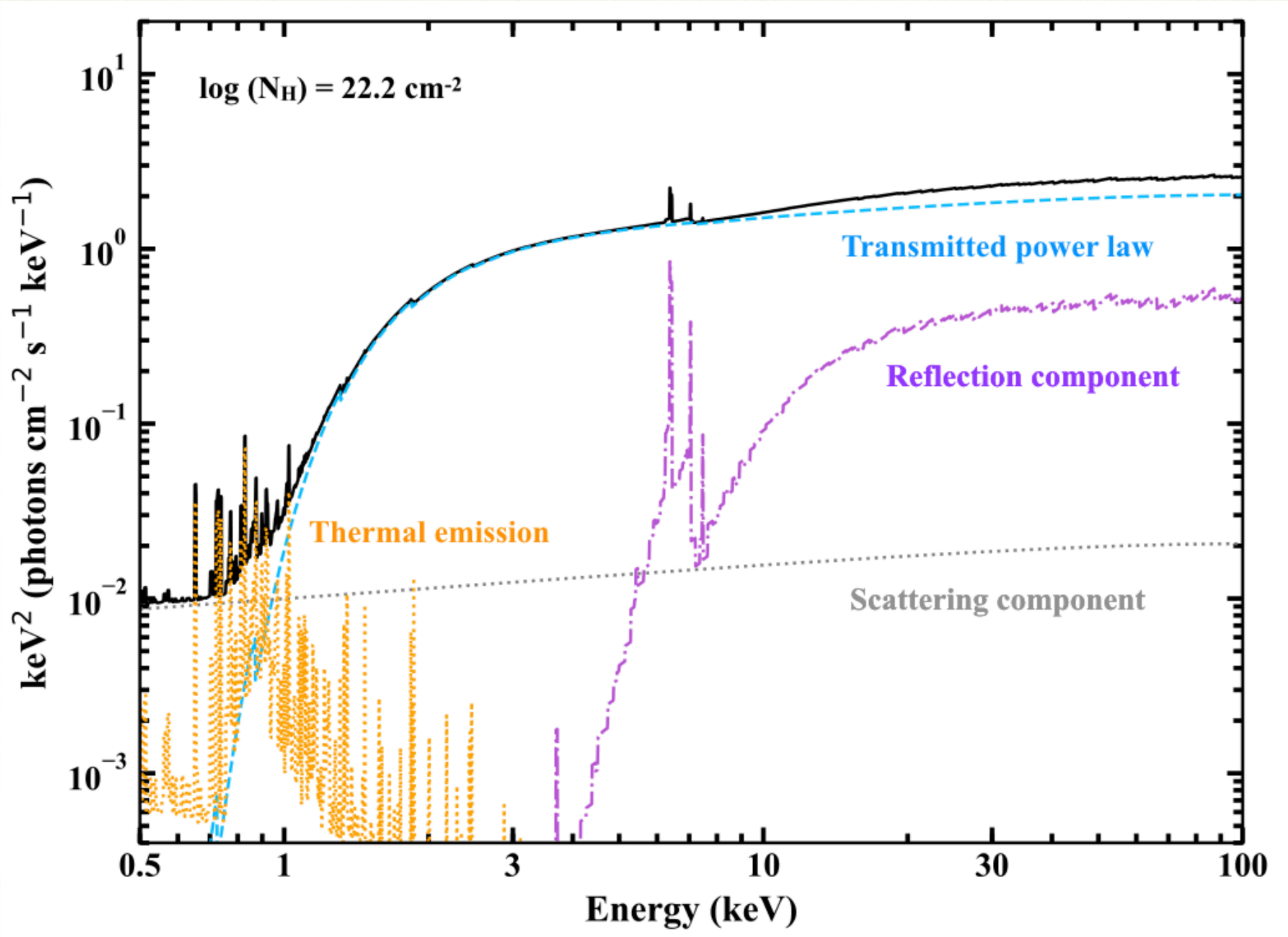
Snapshot programs in the 0.3-10 keV band with instruments like *Chandra* and XRT are effective in finding obscured AGN, but have limitations due to low statistics…

1. Relatively large (30-50%) uncertainties on main spectral parameters (Γ and NH)

2. Other parameters (torus covering factor and average column density, inclination angle…) completely unconstrained

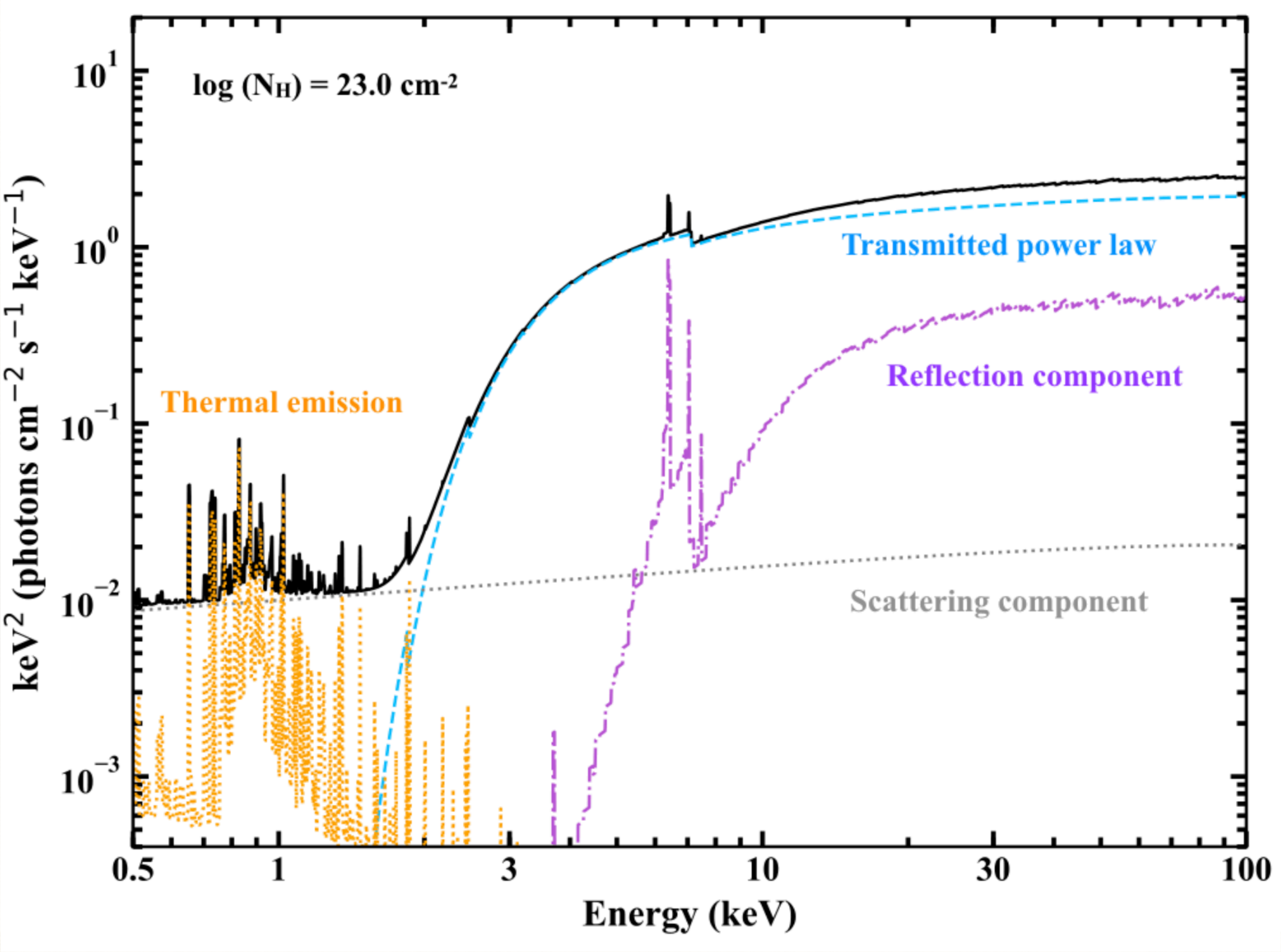
—> We need an instrument that provides us with high count statistic spectra in the 3-70 keV energy range.

Broad band X-ray spectroscopy: a multi-faceted picture of the obscuring medium



Zhao, SM+21

Broad band X-ray spectroscopy: a multi-faceted picture of the obscuring medium



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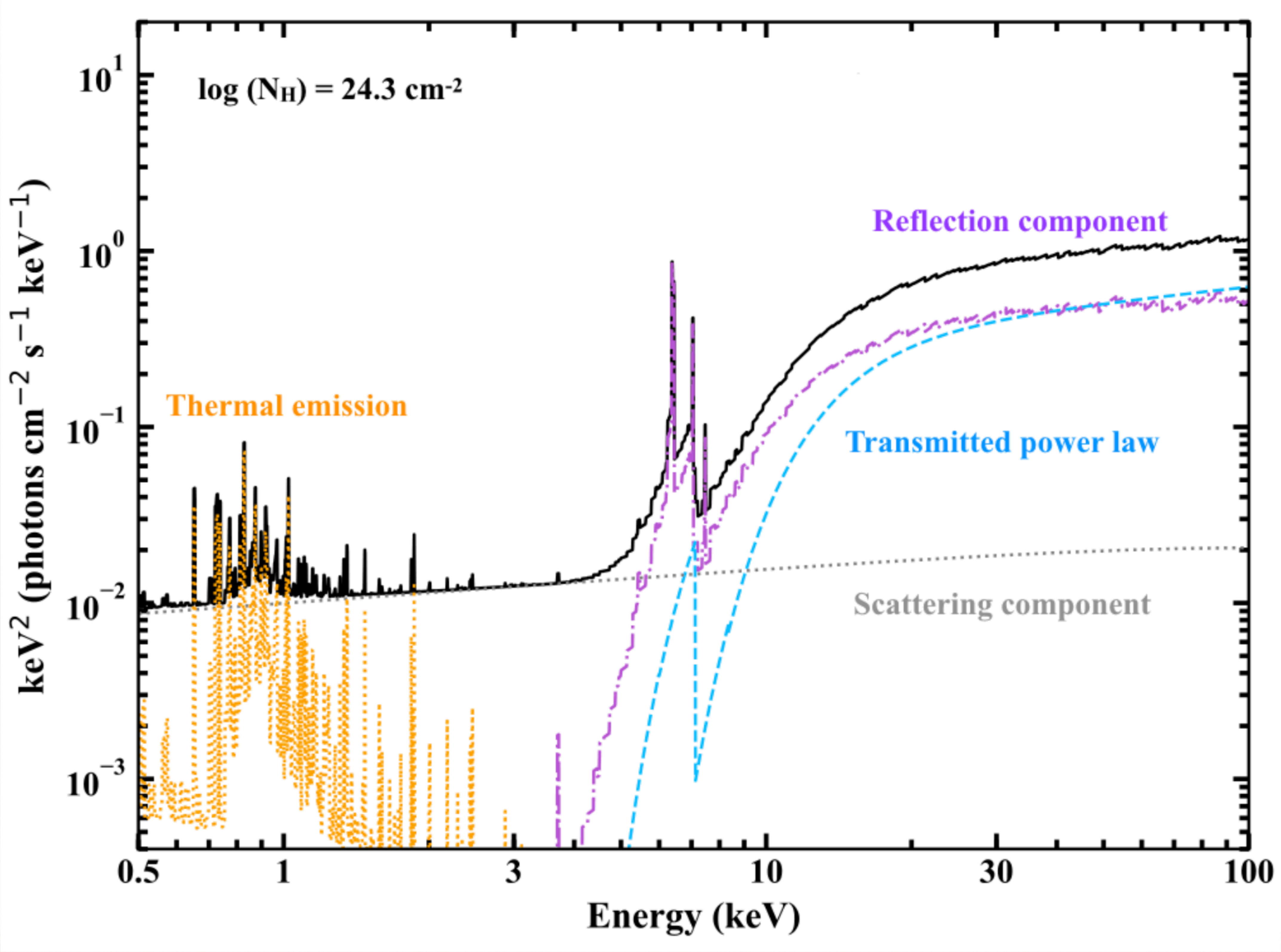

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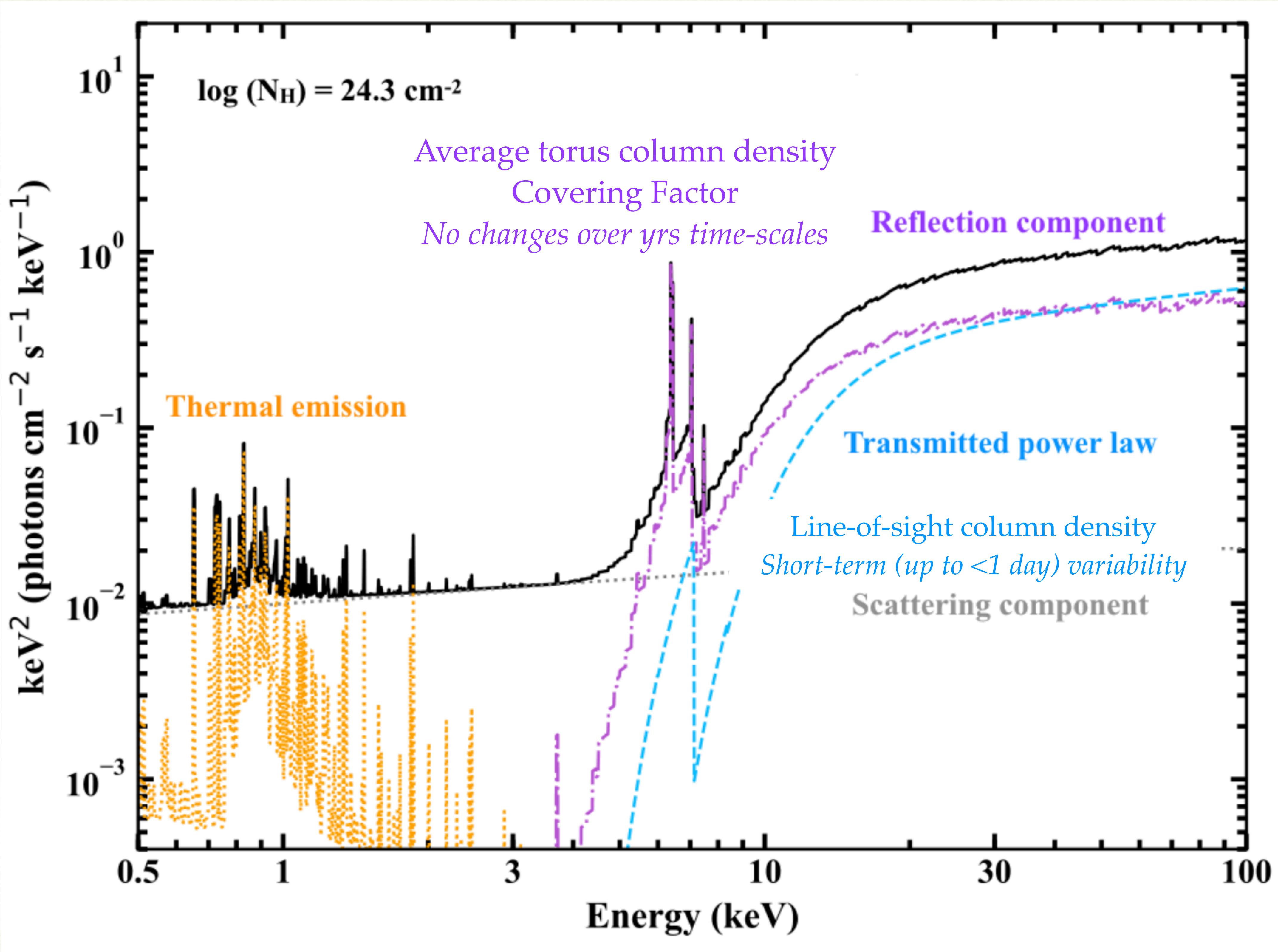
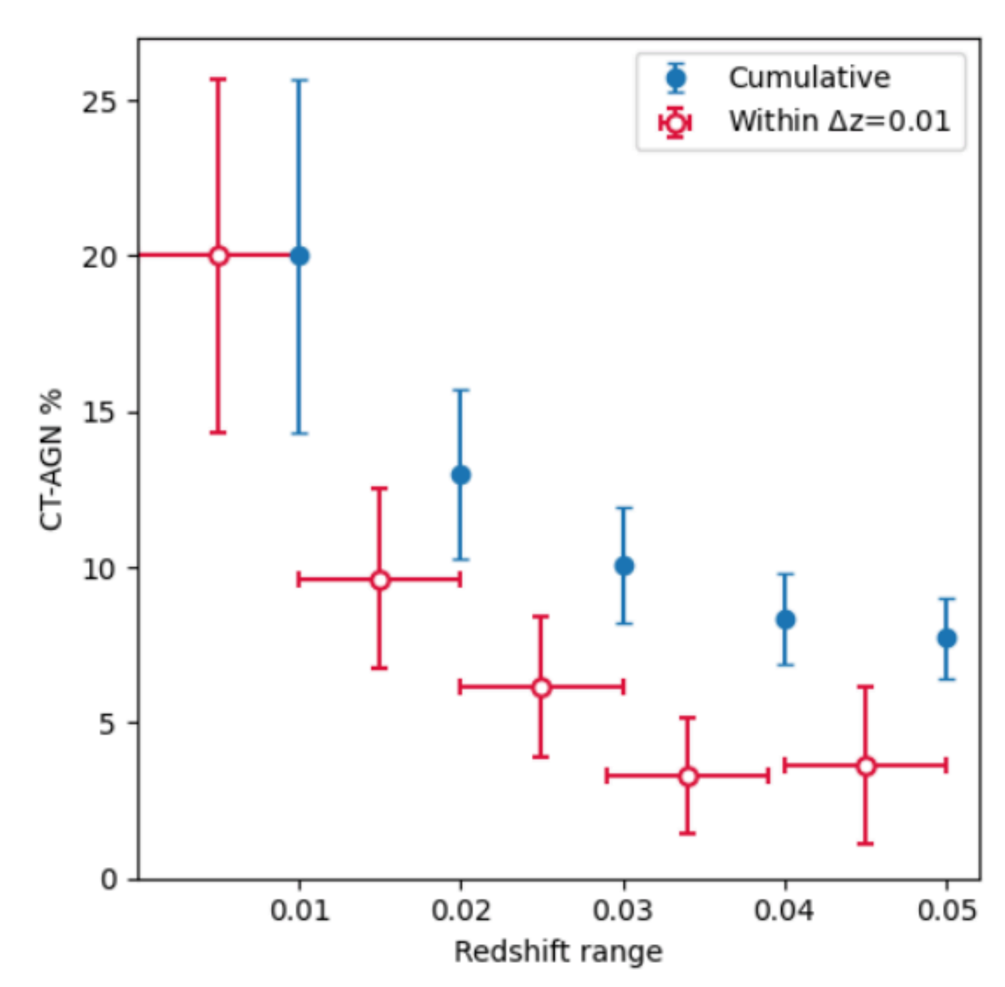


Zhao, SM+21

2. The most complete census of X-ray obscuration in nearby AGN: new constraints on the CT fraction

- Towards a complete census of heavily obscured AGN at z~0 with NuSTAR (with joint Swift-XRT, Chandra, XMM to cover energies <3 keV)
- Sample of over 150 sources with NH>1E23 analyzed over the years (Marchesi+18, 19a,b; Zhao+19a,b; Zhao+20, 21; Torres-Albà+21; Traina+21; Silver+22, in prep.; Sengupta+23; Pal+ in prep.)
- Most accurate, **least biased determination of the CT fraction**: 20% at z<0.01, closing gap with models
- Overall, **32 confirmed, bona fide Compton thick AGN BAT-selected**.



Torres-Albà, SM+21

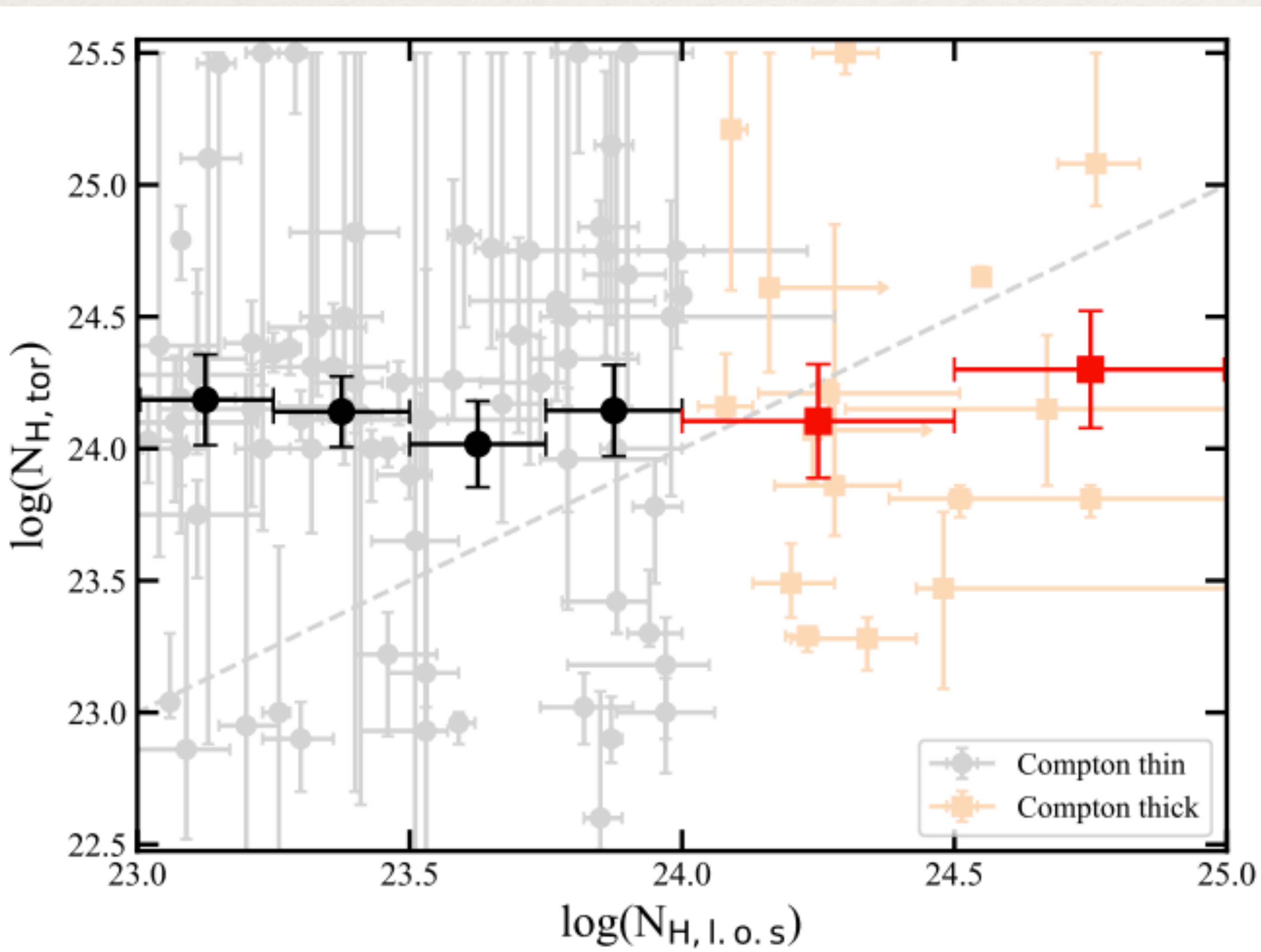
Table 4. CT-AGN fraction in the local Universe.

Redshift	CT-AGN	Total AGN	CT-AGN %
$z \leq 0.01$	10	50	20.0 ± 5.7
$z \leq 0.02$	20	154	13.0 ± 2.7
$z \leq 0.03$	27	268	10.1 ± 1.8
$z \leq 0.04$	30	359	8.4 ± 1.5
$z \leq 0.05$	32	414	7.7 ± 1.3

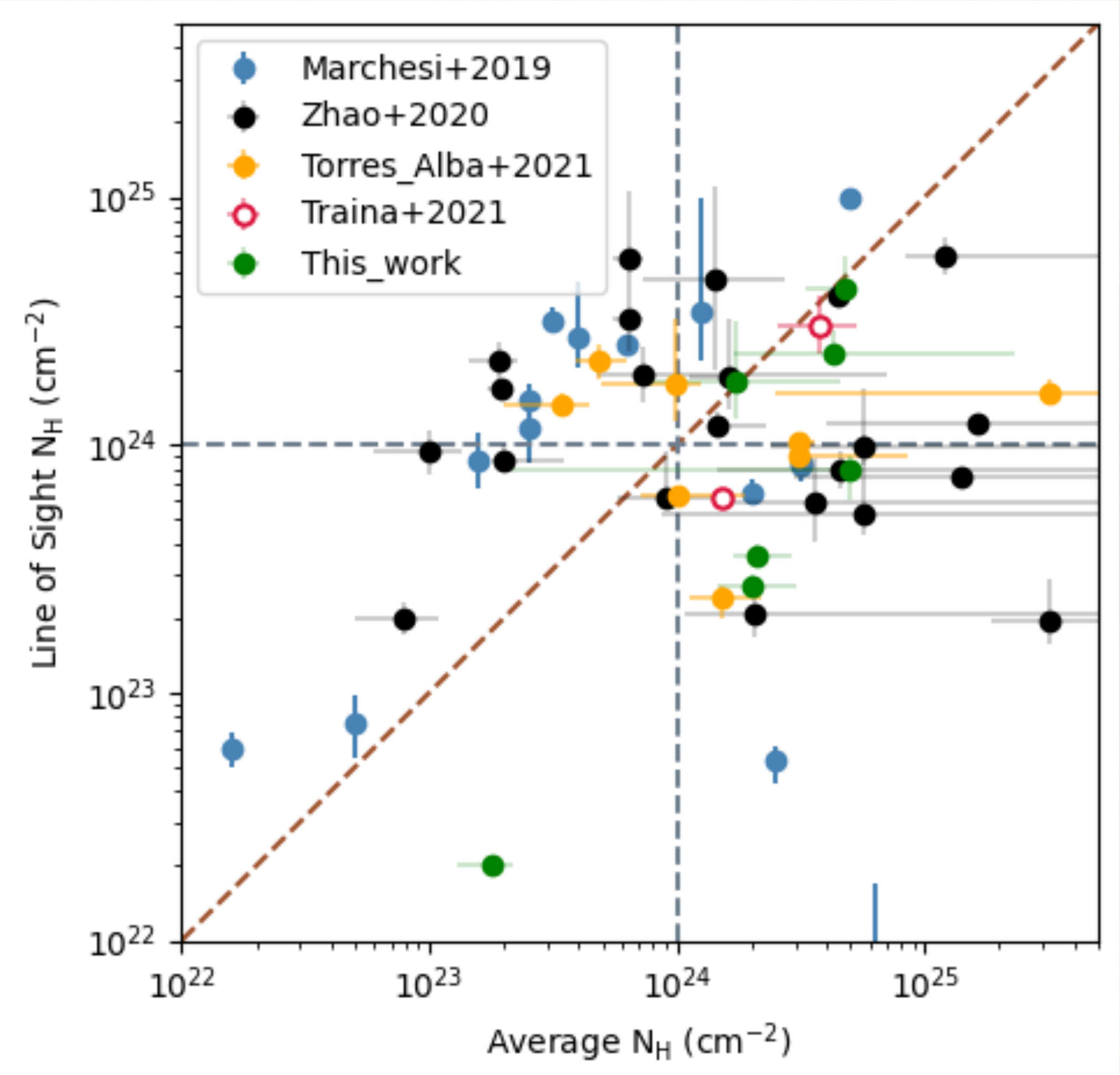
Notes: Observed CT-AGN fraction in the local Universe as a function of redshift. Total AGN include those in the BAT 100-month catalog within a given redshift bin. CT-AGN include those within the mentioned catalog, confirmed by *NuSTAR* as Compton-thick. Errors are binomial.

2. The most complete census of X-ray obscuration in nearby AGN: confirming the clumpy torus scenario

- Towards a complete census of heavily obscured AGN at z~0 with NuSTAR (with joint Swift-XRT, Chandra, XMM to cover energies <3 keV)
- Evidence for **inhomogeneity of the obscuring medium**: $NH_{los} \neq NH_{tor}$.
- Obscuration caused by clumpy material, which can be linked to SMBH feeding and accretion processes on the meso-scale (pc to kpc from SMBH).



Zhao, SM+21



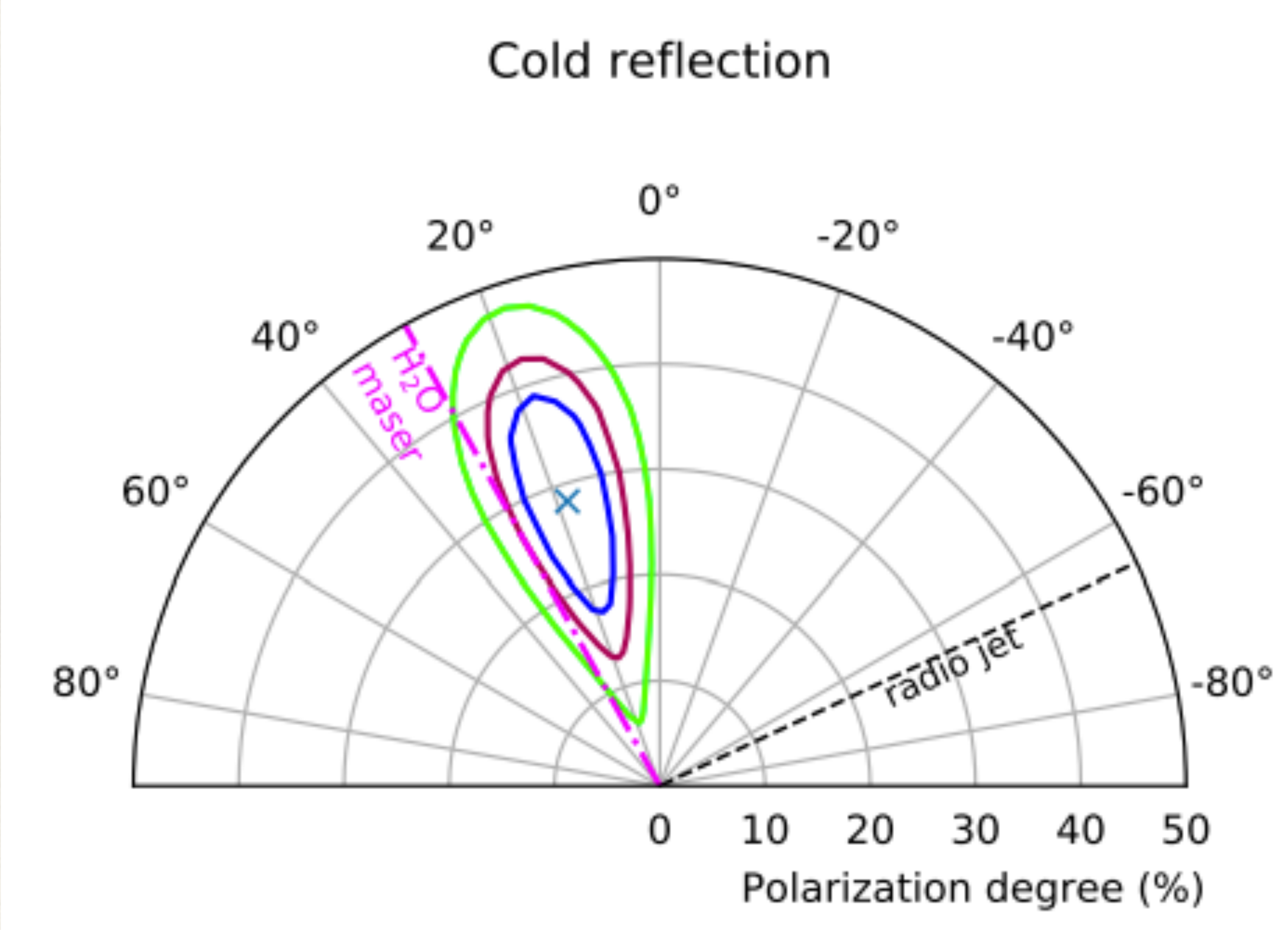
Torres-Albà, SM+21; Sengupta, SM+23

IXPE: a new look at the obscuring material geometry

- IXPE: X-ray **polarimetry** offers new way to study the **obscuring medium geometry**.

- Measurement of polarization from cold reflector in Circinus (Ursini+23): good agreement with covering factor measured with other methods.

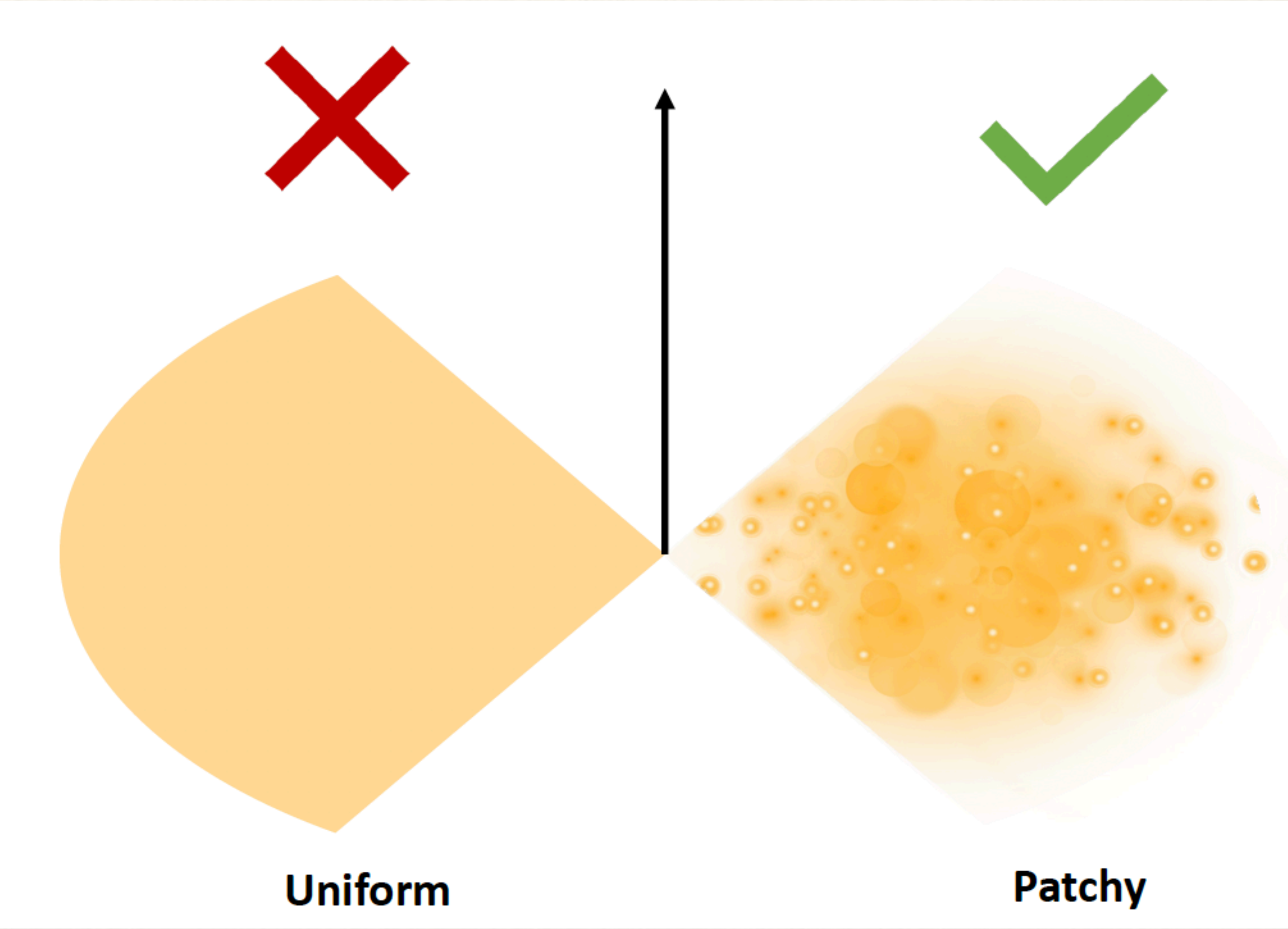
- Our group is currently working on NGC 2110 (Pal+ submitted) and on NGC 4945 (Banjeree+ in prep.).



Ursini+23

3. Clumpy obscuration in AGN: in search of a comprehensive picture

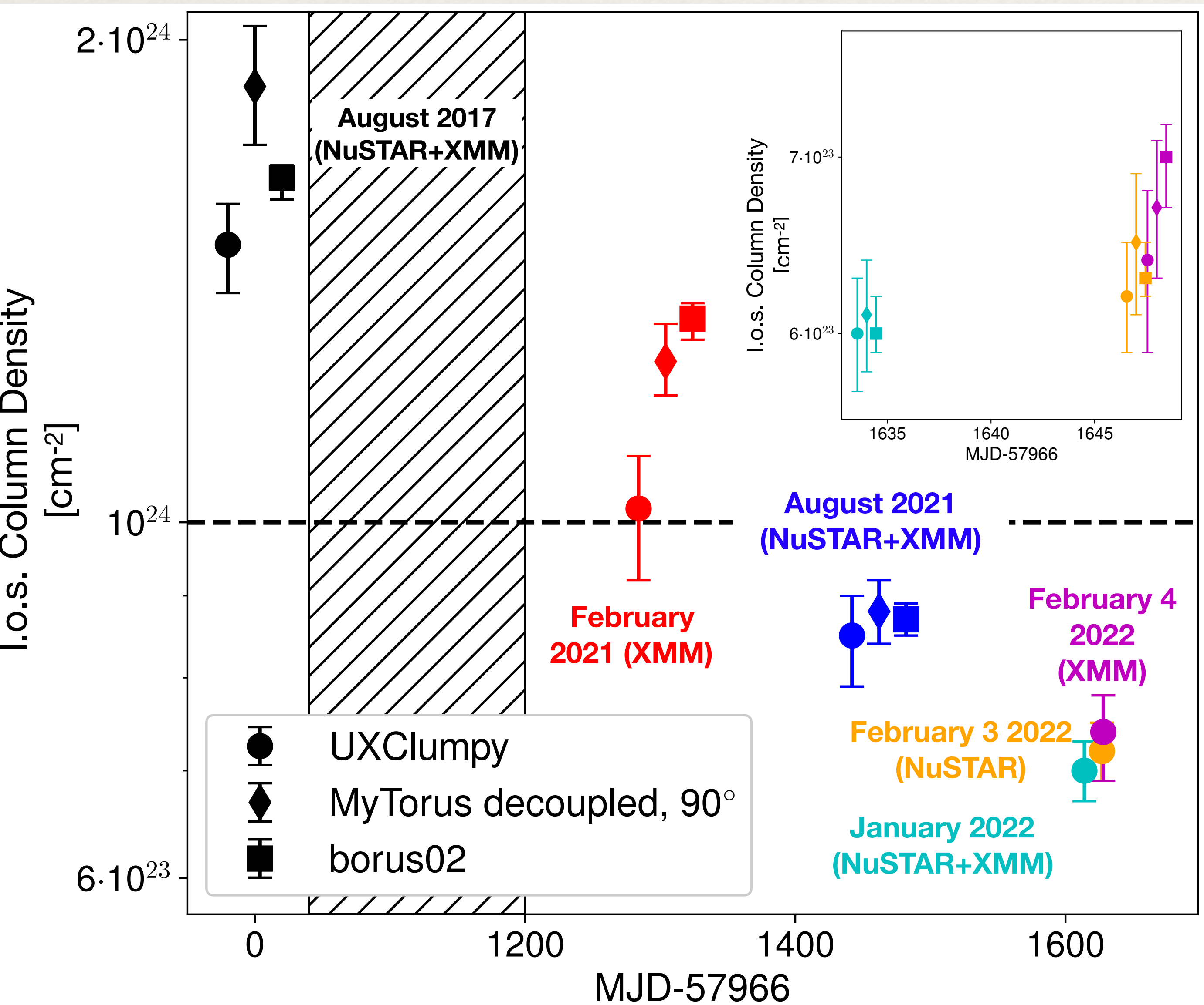
- As just mentioned, many recent works, both in X-ray and IR, support the evidence that the **material surrounding accreting SMBHs is patchy**, or clumpy, rather than uniform
- In the X-rays, occultation events and NH_{los} variability support this scenario (Risaliti+02, Elvis+04, Markowitz+14, Laha+20)
- In the IR, SED modelling allows one to map the dust distribution
- ALMA: first direct imaging on ~pc scale, with further information on kinematics
- Still many open questions on torus structure and its connection with AGN feeding and feedback processes!

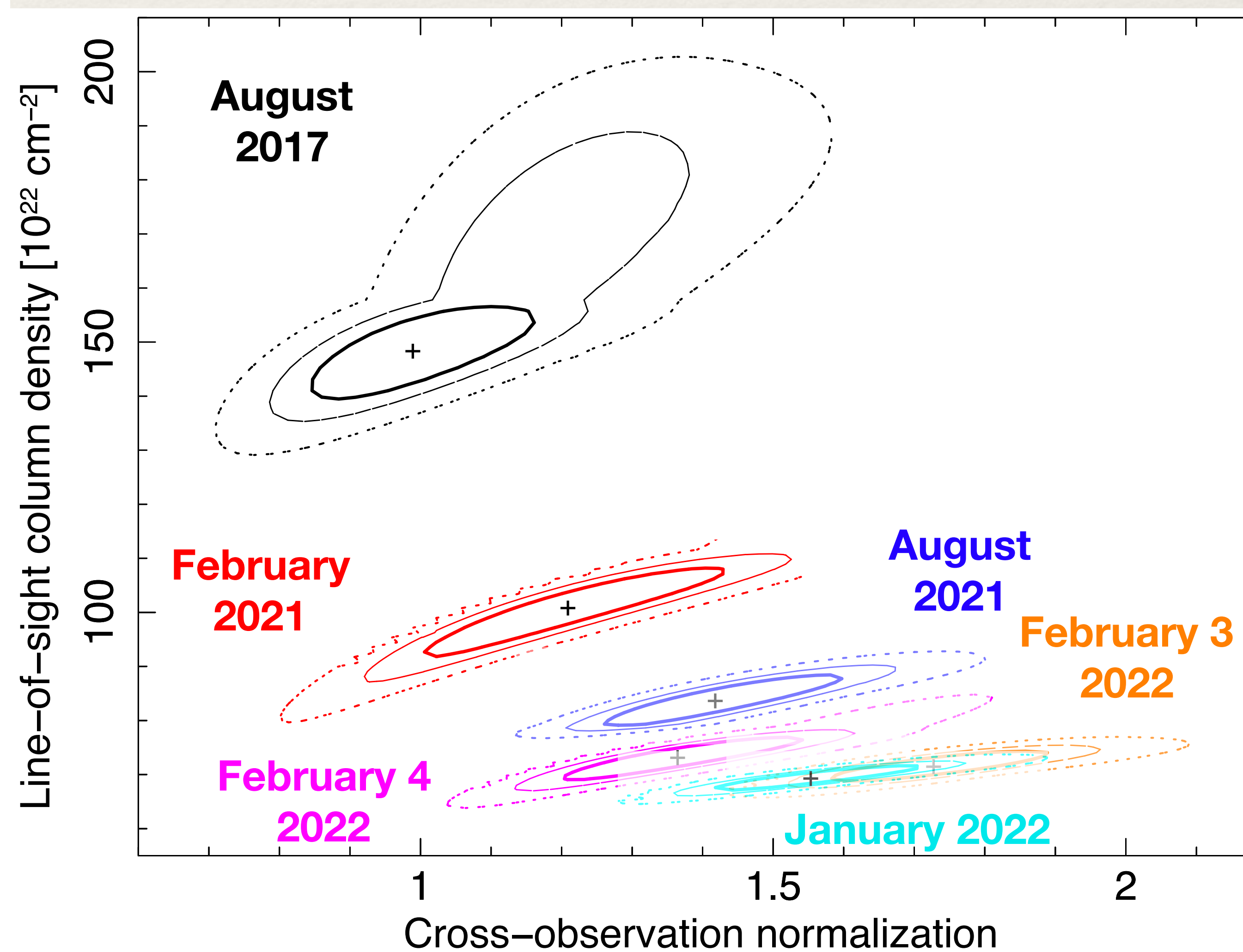


See also Ramos-Almeida & Ricci17, Hickox and Alexander 18, Hönig 19, Giustini & Proga 19…

A test case, NGC 1358:
A new X-ray changing-look Compton thick AGN

- Multi-epoch NuSTAR+XMM-Newton fit: average properties (covering factor, average torus column density, photon index) assumed constant. NH_{los} and flux free to vary.
- Evidence of variability (from ~1.5-2x10^{24} cm^{-2} to 7x10^{23} cm^{-2} in a span of ~5 years) and **transition from Compton thick to Compton thin**: CL-AGN.
- High-quality, multi-epoch data: breaking the NH_{los}-Luminosity degeneracy.





Marchesi+22

From variability to geometry: mapping the cloud distribution

- Risaliti et al. (2002,05) equation to link variability to distance cloud-SMBH

- Our observational strategy allows for a sampling of multiple time-scales, and therefore multiple cloud-SMBH distances.

- NH variability gives us information on obscuring **clouds size and distance from SMBH** (up to 1E-3 pc).

- Scales also related to different feeding and feedback processes (Gaspari+20), hinting at ongoing interplay SMBH-galaxy.

$$d_{\rm BH} = 600\, t_{100}^2\, n_{10}^2\, N_{\rm H,24}^{-2}\, R_{\rm S}$$

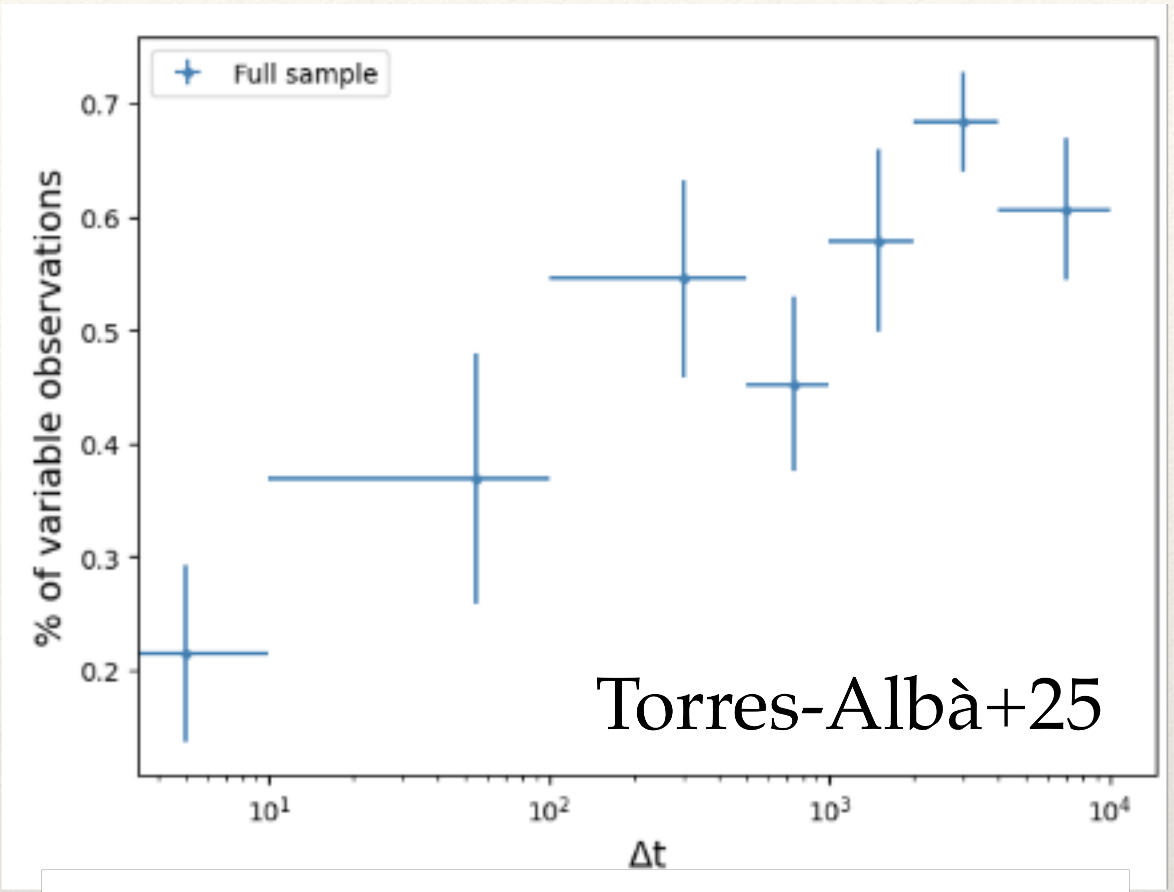
Obs. range	t_{100}	$\Delta N_{\rm H,24}$	$d_{\rm BH,3RS}$	$d_{\rm BH,15RS}$
MM/YYYY–MM/YYYY	100 ks	10^{24} cm^{-2}	pc	pc
08/2017–02/2021	1126.7	0.61±0.35	5.6×10^3	224
02/2021–08/2021	136.5	0.38±0.15	82.2	3.3
08/2021–01/2022	148.6	0.17±0.10	97.5	3.9
01/2022–02/2022	11.2	<0.14	0.56	0.02
02/2022–02/2022	0.9	<0.13	3.3×10^{-3}	1.3×10^{-4}

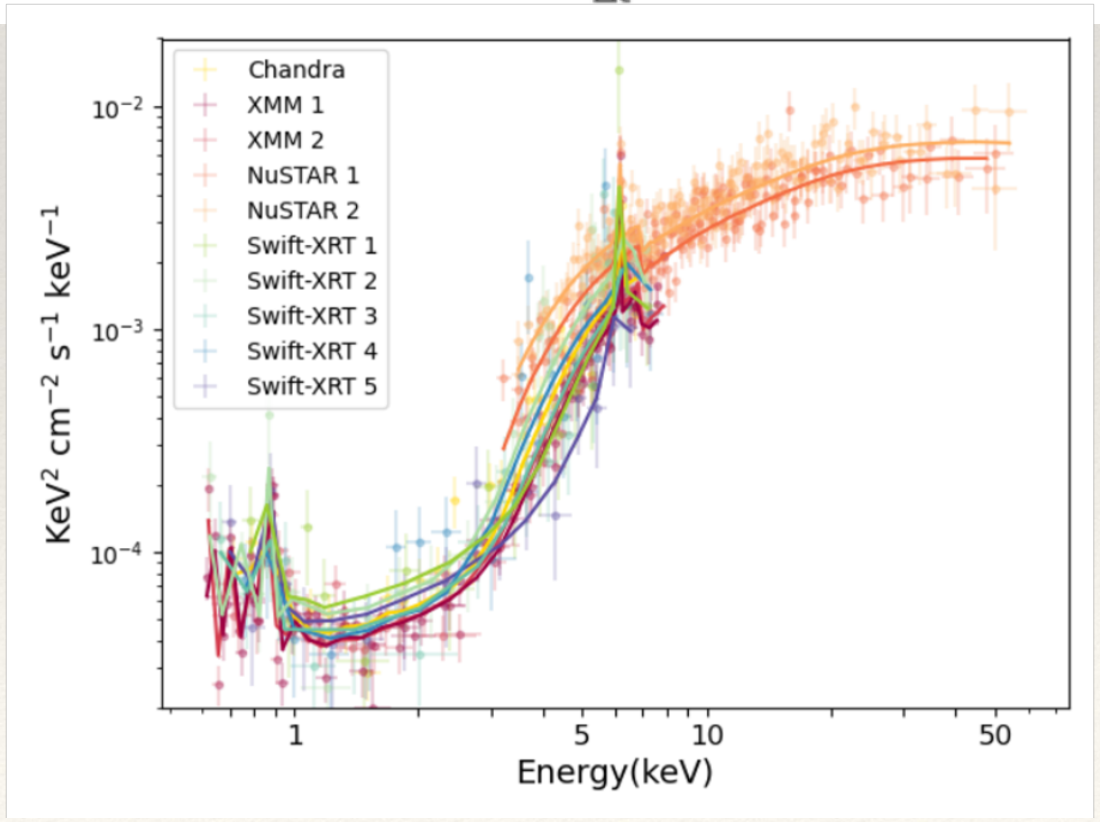
Marchesi+22

Building on the legacy of 20+ years of X-ray observations
The multi-epoch approach

- Our group is also running a huge analysis and interpretation effort on archival and new observations (from Swift-XRT, Chandra, XMM-Newton, and NuSTAR), searching for **flux and NH variability over time-scales ranging from days to years**.
- Overall, over **150 observations analyzed**!

1. Pilot project on NGC 7479 (Pizzetti+22)
2. Sample of 12 BAT-selected sources (Torres-Albà+23)
3. Sample of 13 BAT-selected sources (Pizzetti+25)
4. Monitoring campaign of Mrk 477 (Torres-Albà+25)
5. In-depth analysis of NGC 6300 (Sengupta+25)
6. Control sample of 12 sources (Gianolli+ in prep.)

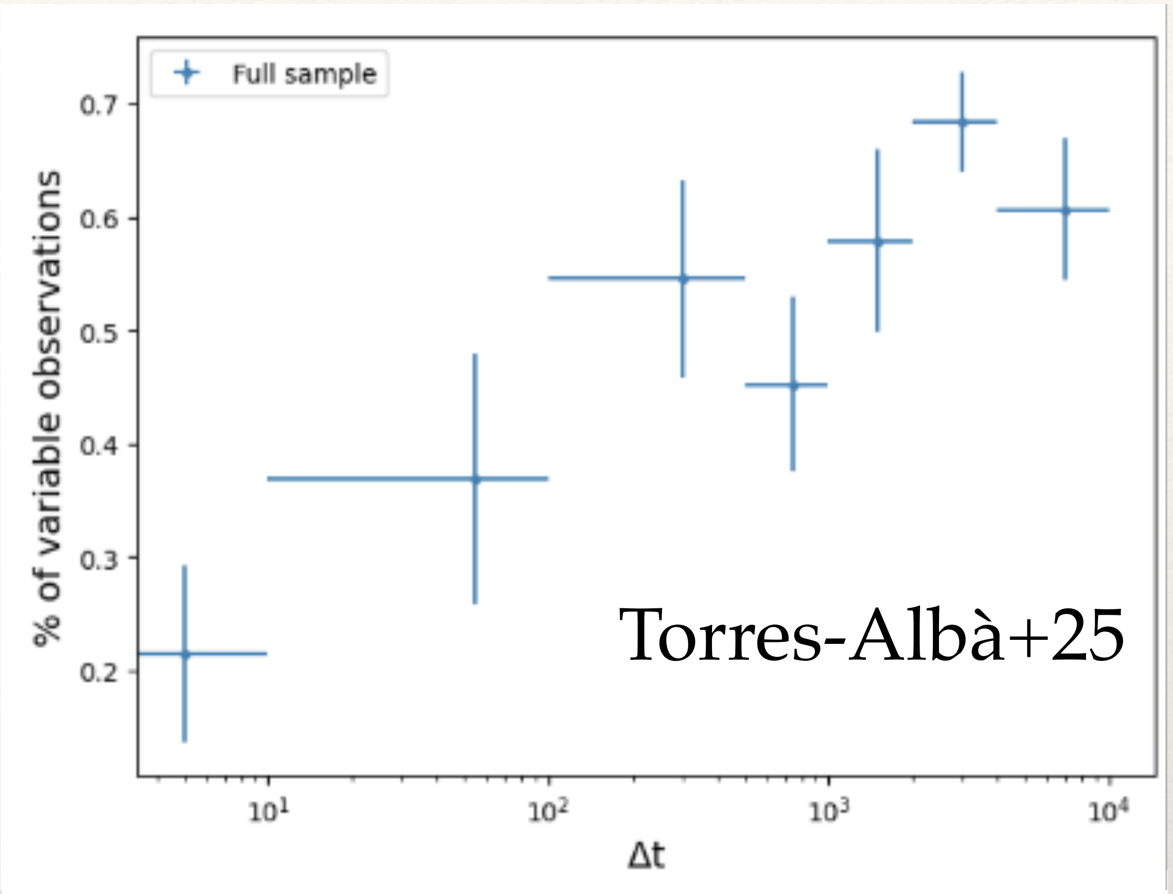


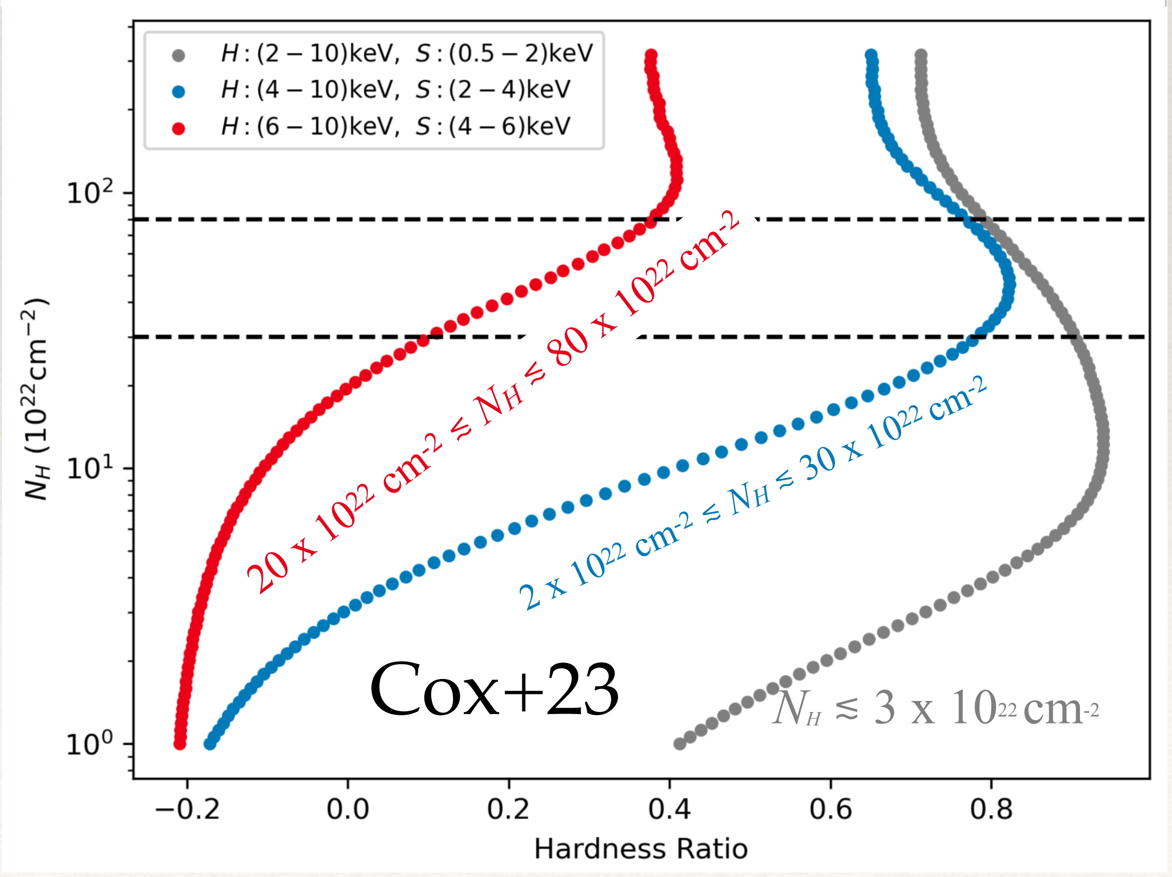


Building on the legacy of 20+ years of X-ray observations
The multi-epoch approach

- Main results so far from multi-epoch campaign:

1. Torres-Albà+25: **probability of NH variability between two observations increases with time** (20% at t<100 days; 60-70% at t>500 days) -> Results disfavour a scenario where NH variability is uniquely due to BLR clouds.
2. Towards an era of large datasets: **NH variability predictor** based on X-ray **hardness ratio multi-band variability** (Cox+23).





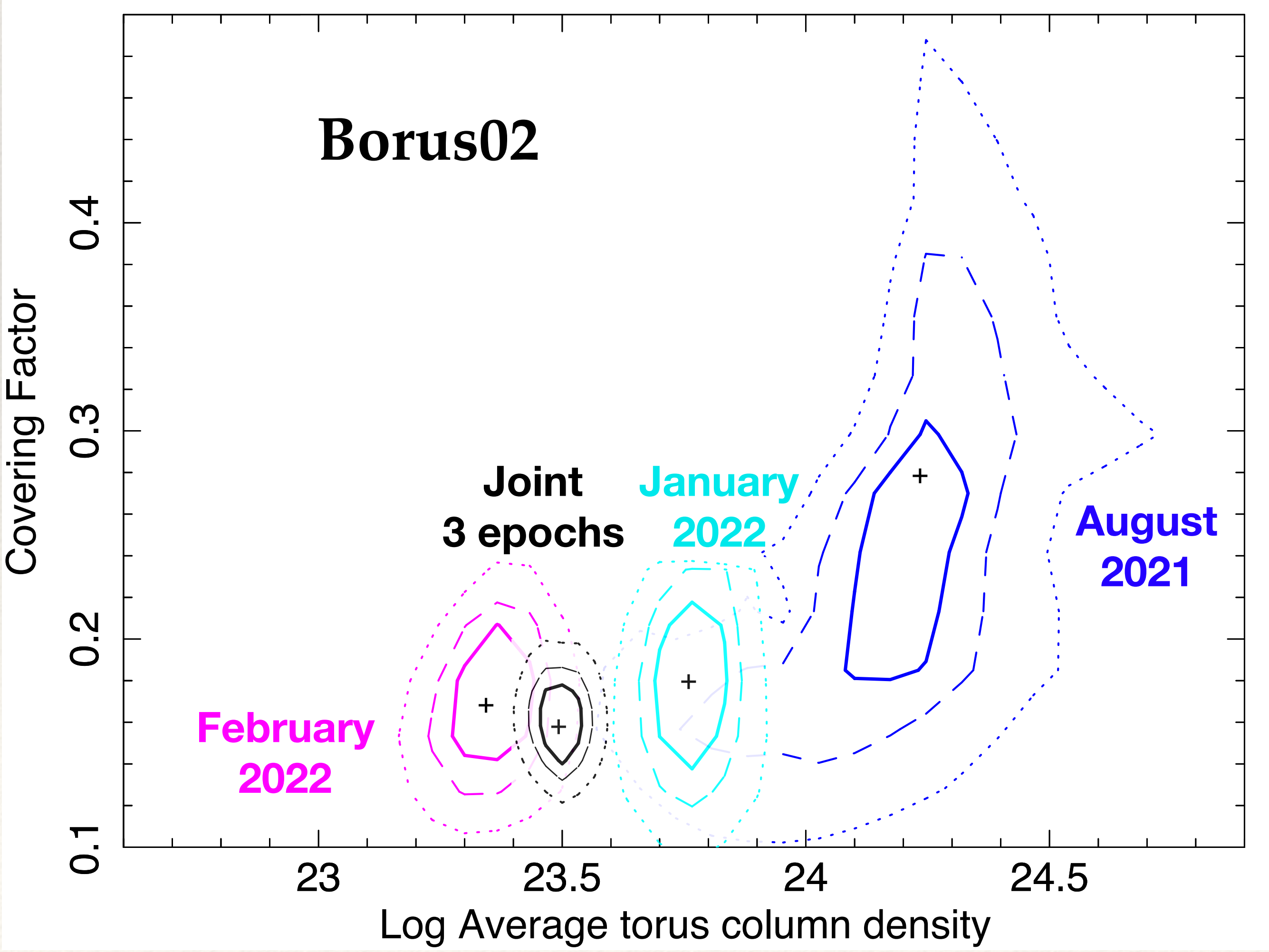
Summary

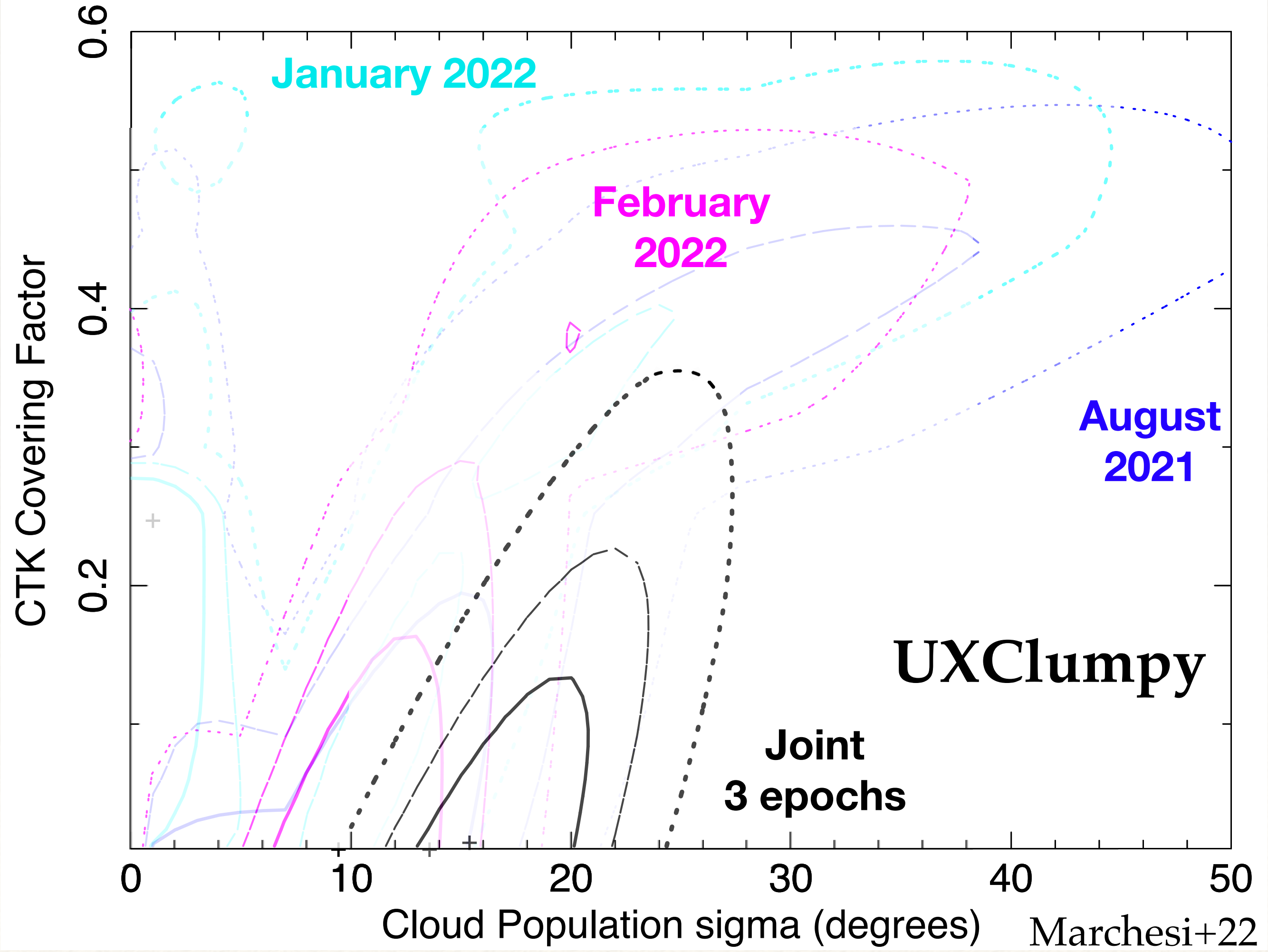
- The **Clemson-INAF Compton Thick AGN project** builds on the **legacy of 20 years of observations with Swift-BAT** of the hard X-ray sky.
- Synergies with other X-ray telescopes (as well as with Swift-XRT) have been instrumental to provide us with one of the most accurate **X-ray characterisations of the obscuring medium surrounding accreting supermassive black holes**.
- BAT with snapshot X-ray observations (Chandra, Swift-XRT) provided us with candidate heavily obscured AGN with limited telescope investment.
- NuSTAR with soft X-ray allowed us to provide most accurate measurement of CT fraction at z~0 (key parameter for AGN population models), and infer properties of the **obscuring medium** (**clumpy**, rather than uniform, with **average NH decoupled from l.o.s. one**).
- Due to clumpy nature of the obscuring medium, **multi-epoch observations are key** for full characterisation! Working on dedicated campaigns with NuSTAR and XMM-Newton, as well as on fully exploiting the Swift, Chandra, XMM archives.
- Data support **complex interplay between SMBH and host**, and place **obscuration on a variety of scales**, not exclusively in the BLR.

Backup

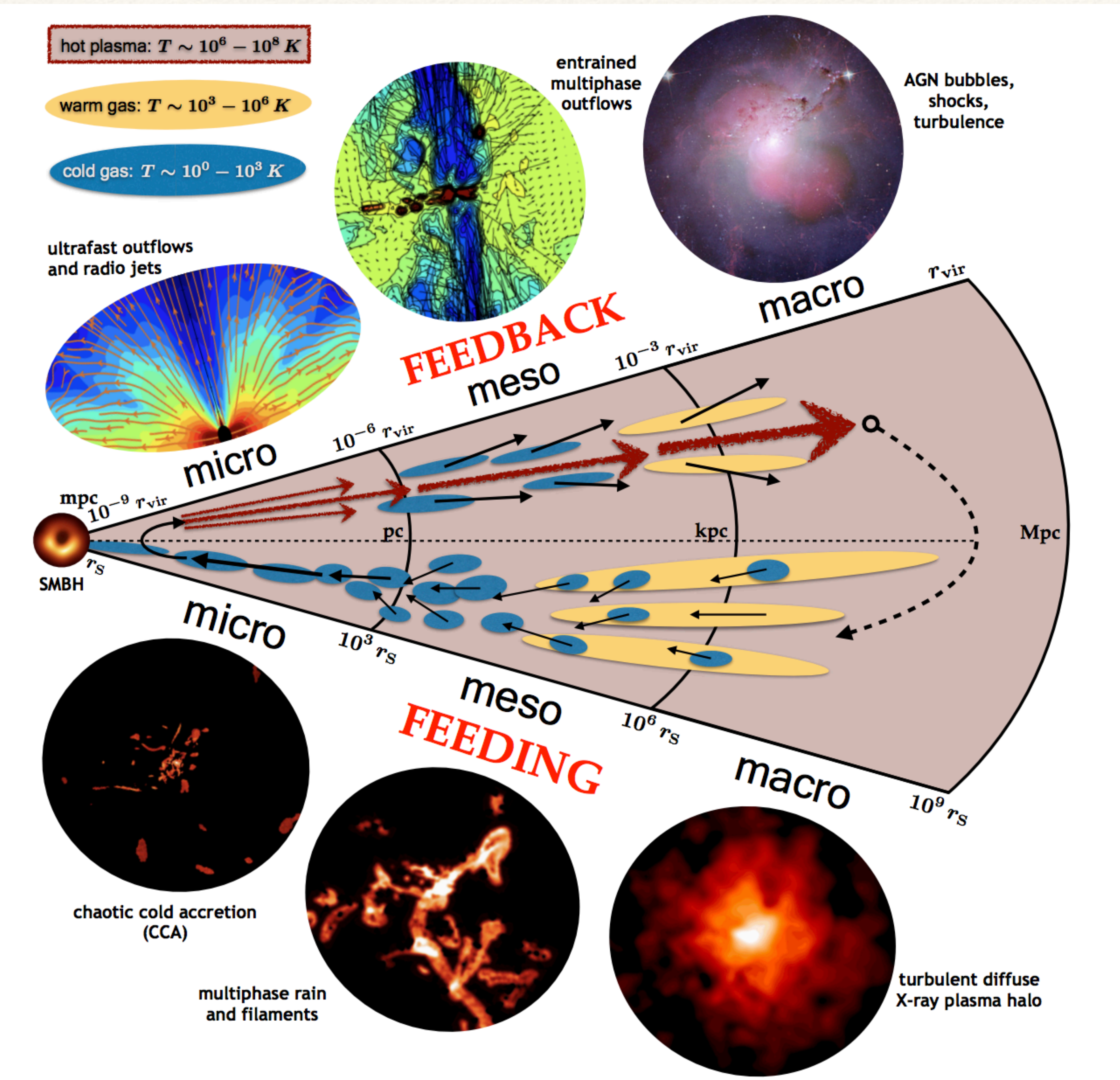
The need for a multi-epoch monitoring: breaking parameter degeneracies

- It has also been shown (e.g. Balokovic+18, Saha+22), that single-epoch observations can be affected by degeneracy primary vs reprocessed component.
- NuSTAR+XMM-Newton break this degeneracy: most accurate measurement of parameters associated to reprocessed emission (covering factor, average column density).
- Consequently, much better constraints on NHlos and AGN intrinsic luminosity too.





From variability to geometry: sampling all the scales



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Gaspari+20

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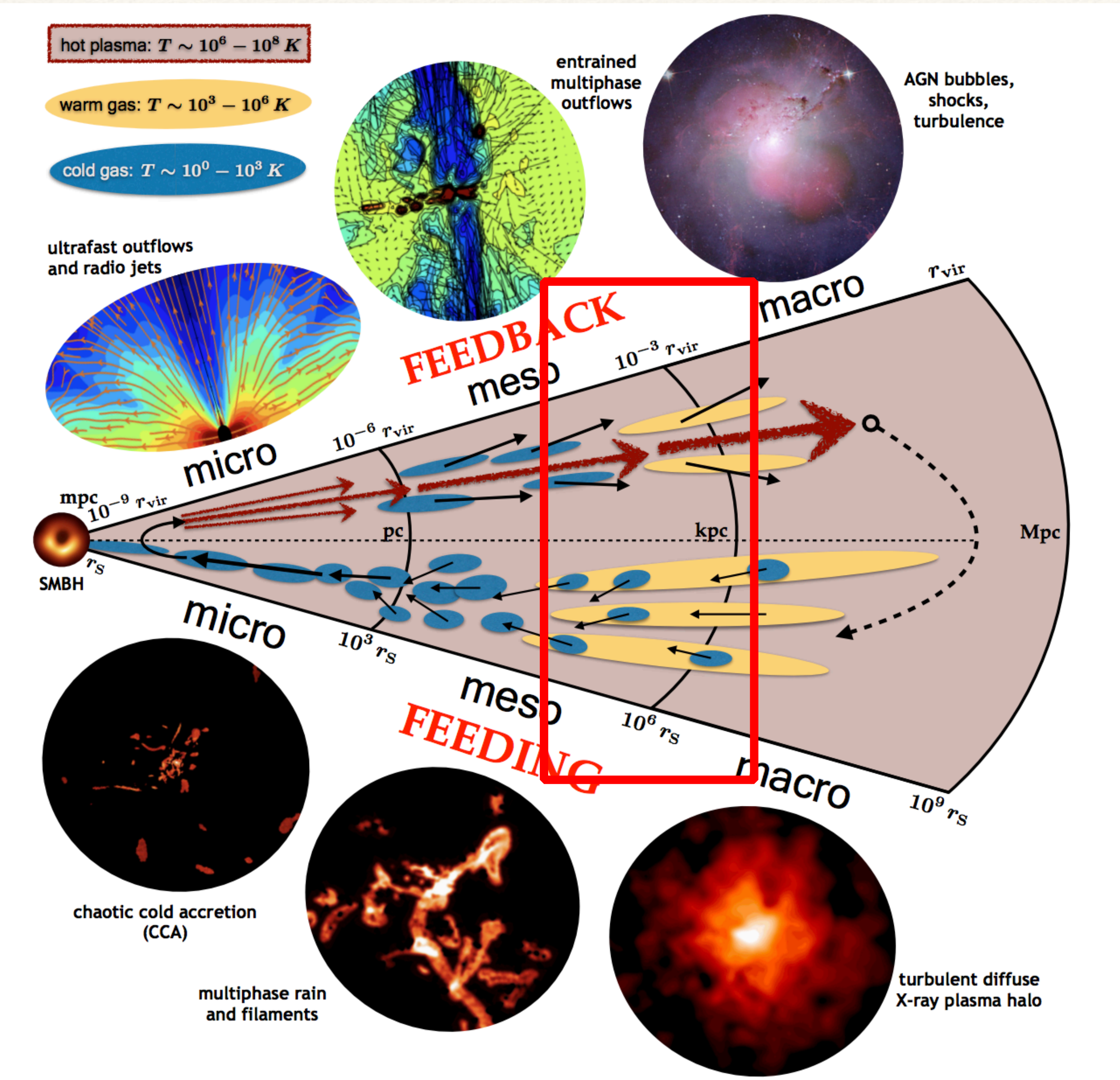

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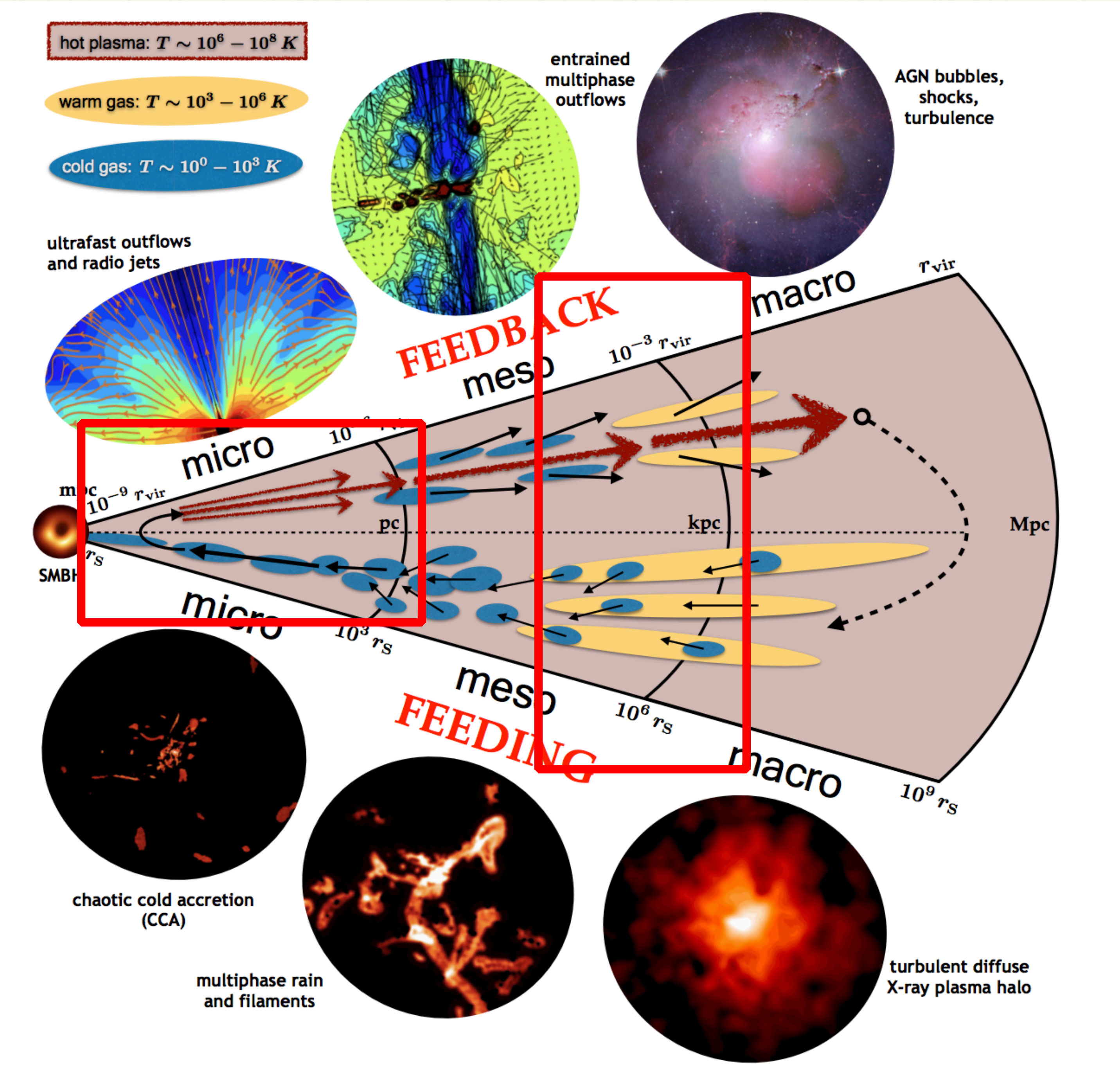
Gaspari+20

From variability to geometry: sampling all the scales



Obs. range	t_{100}	$\Delta N_{H,24}$	$d_{BH,3RS}$	$d_{BH,15RS}$
MM/YYYY–MM/YYYY	100 ks	10^{24} cm^{-2}	pc	pc
08/2017–02/2021	1126.7	0.61±0.35	5.6×10^3	224
02/2021–08/2021	136.5	0.38±0.15	82.2	3.3
08/2021–01/2022	148.6	0.17±0.10	97.5	3.9
01/2022–02/2022	11.2	<0.14	0.56	0.02
02/2022–02/2022	0.9	<0.13	3.3×10^{-3}	1.3×10^{-4}

Gaspari+20

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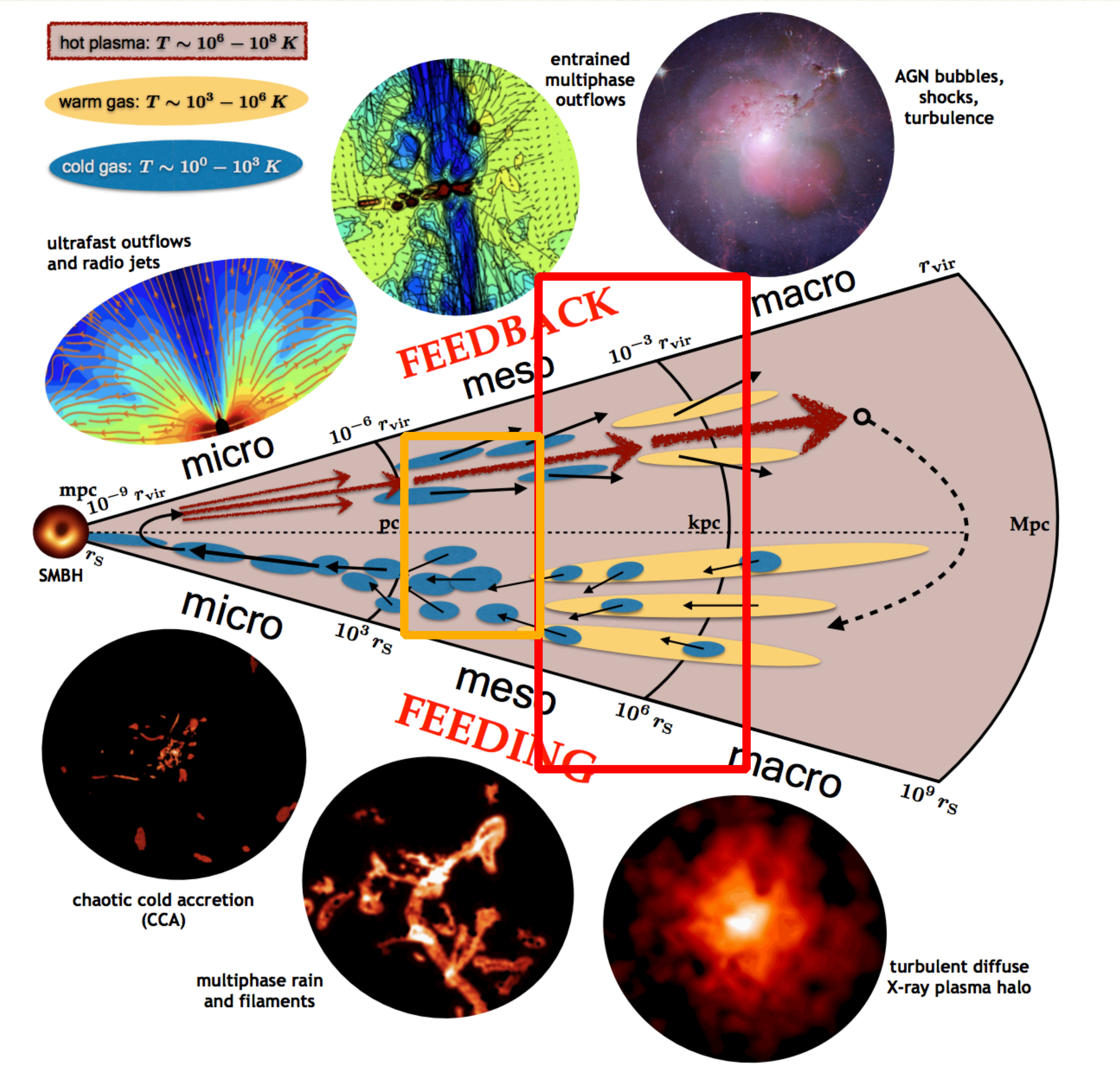

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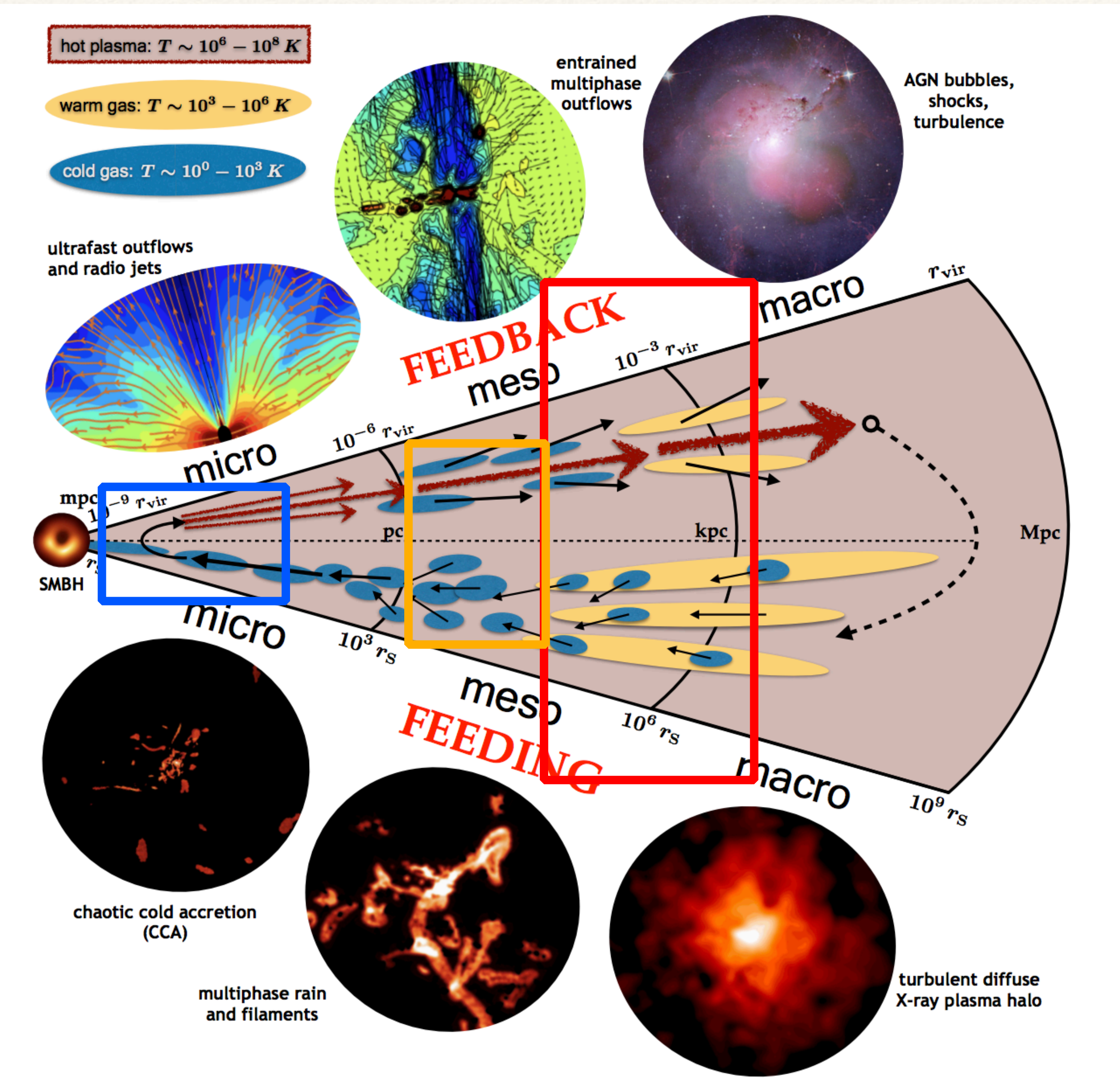

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