

(Present and) Future of X-ray Binary Research

(Ignoring neutron stars for time reasons)

Jörn Wilms



XMM



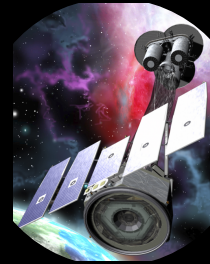
ASTROSAT



SVOM



IXPE



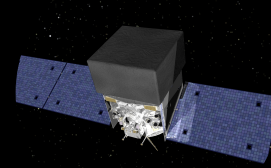
Chandra



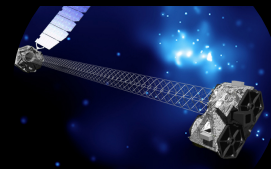
HXMT



Fermi



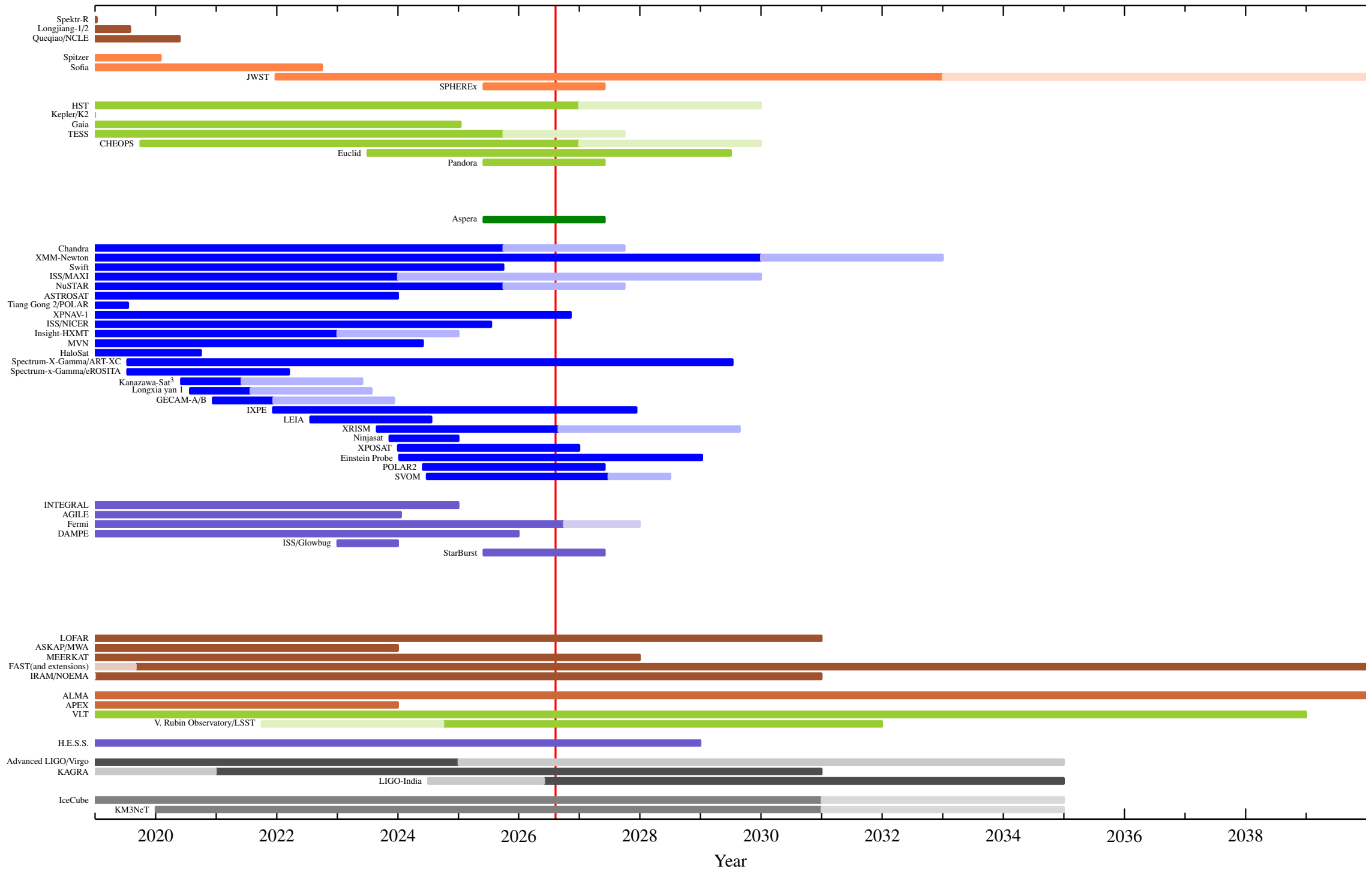
NuSTAR



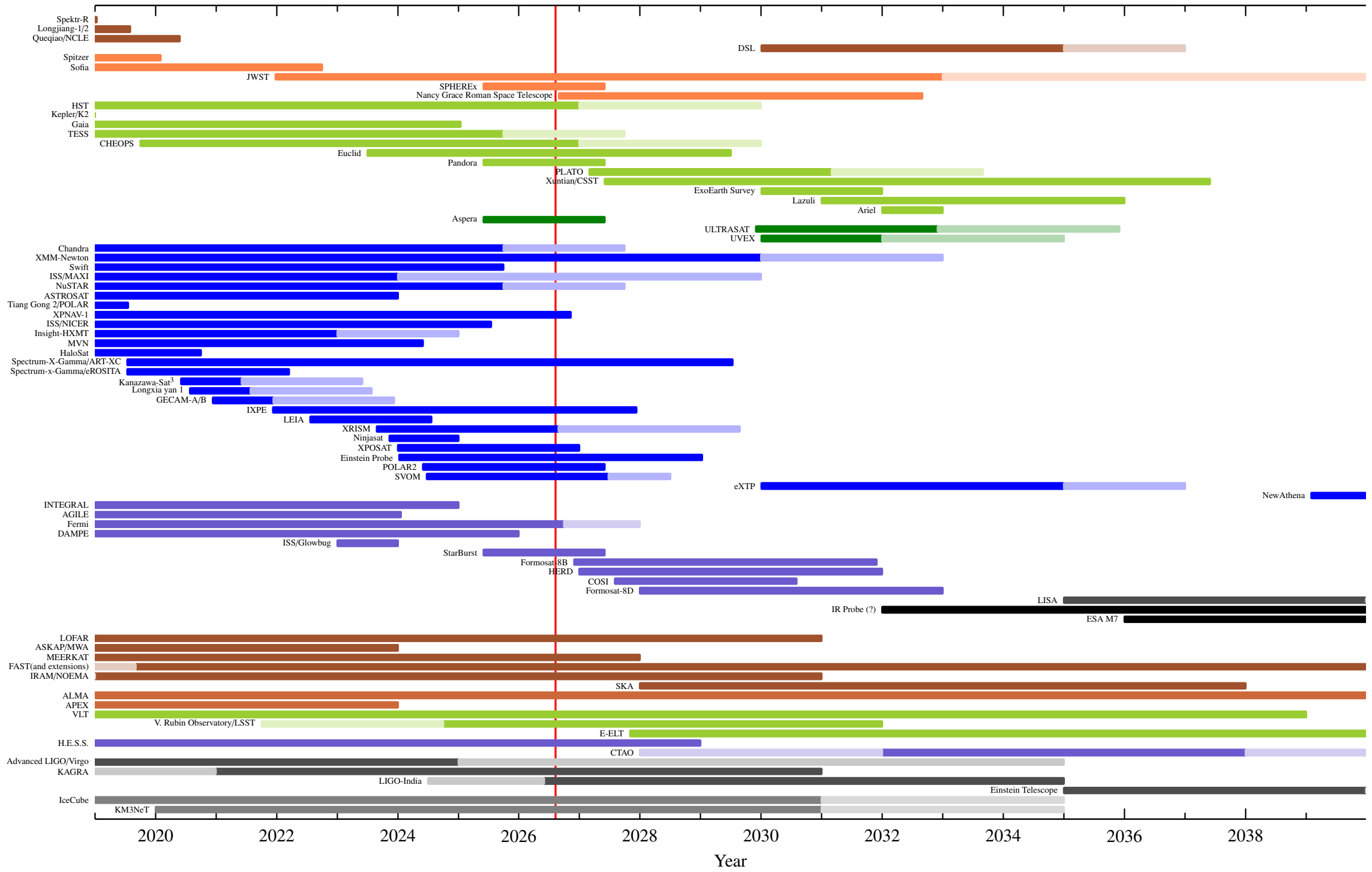
EP



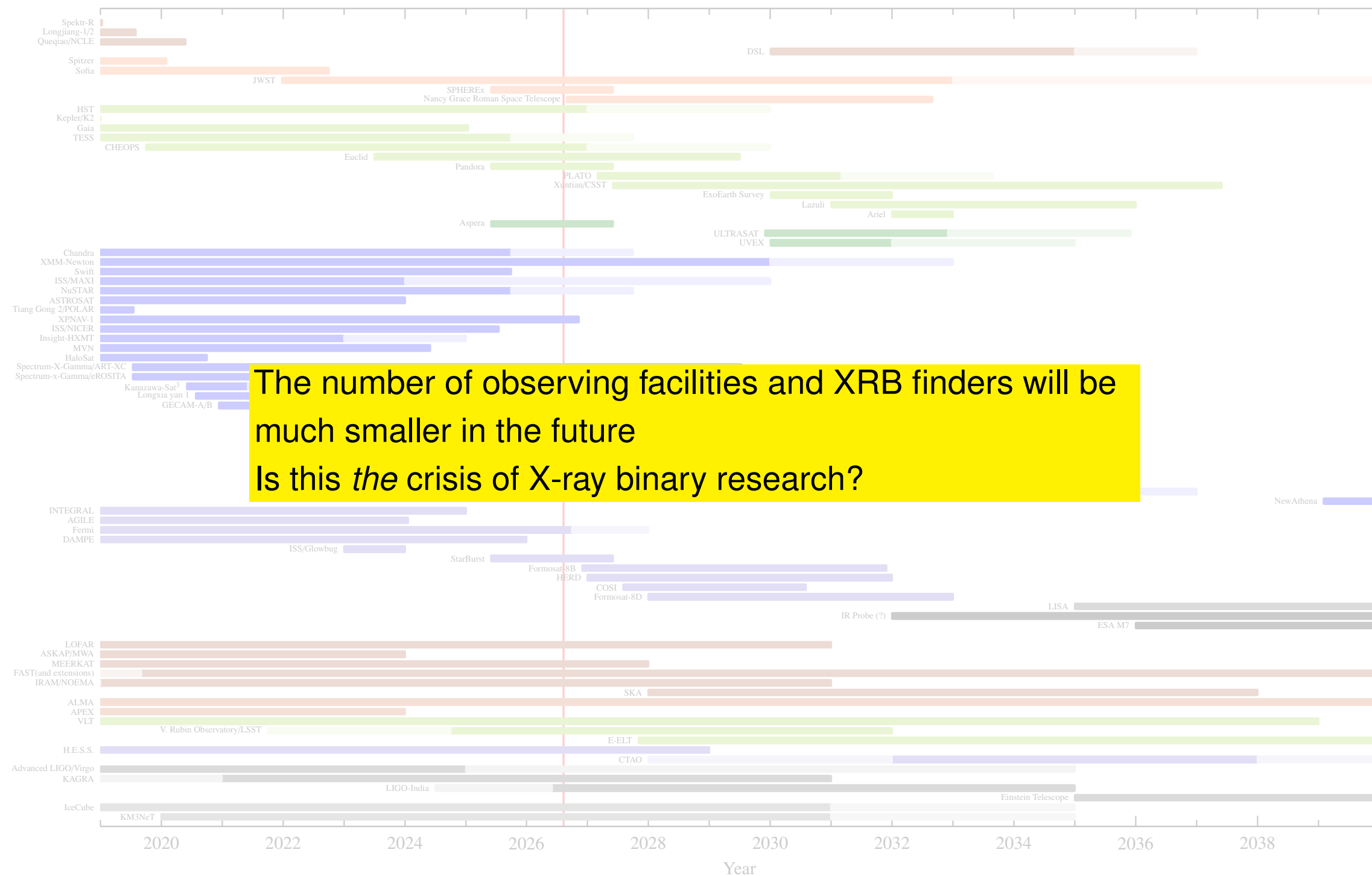
Crisis?



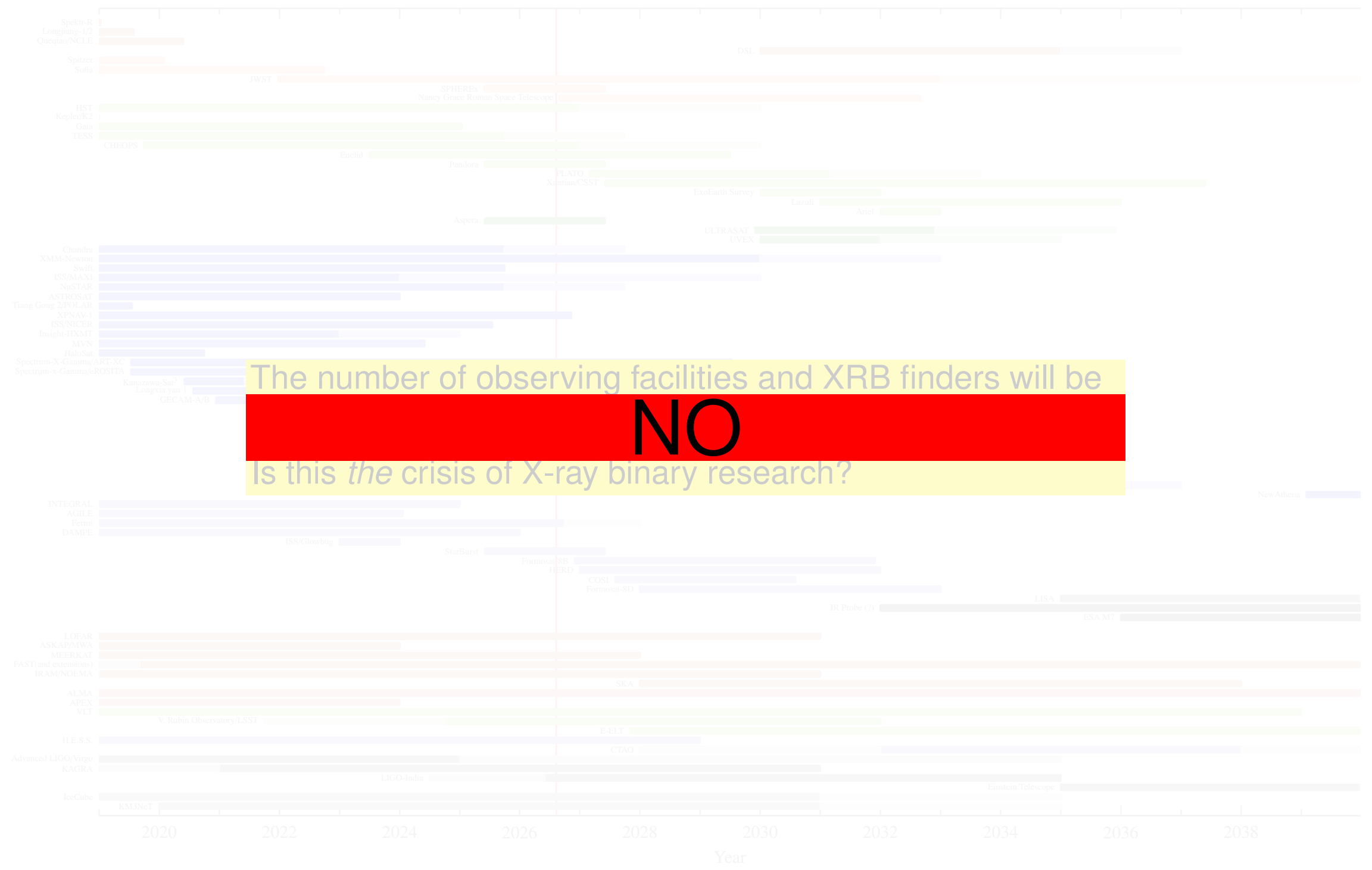
Crisis?



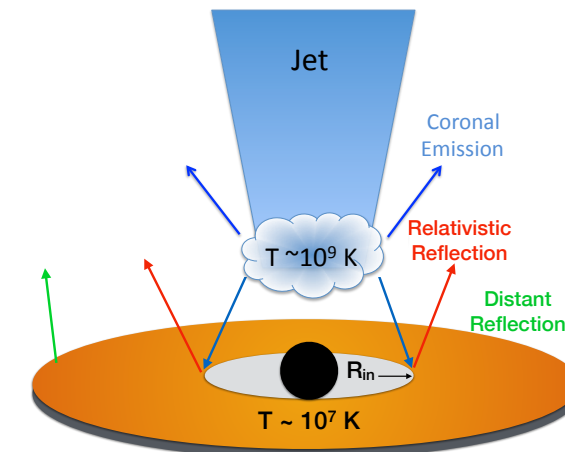
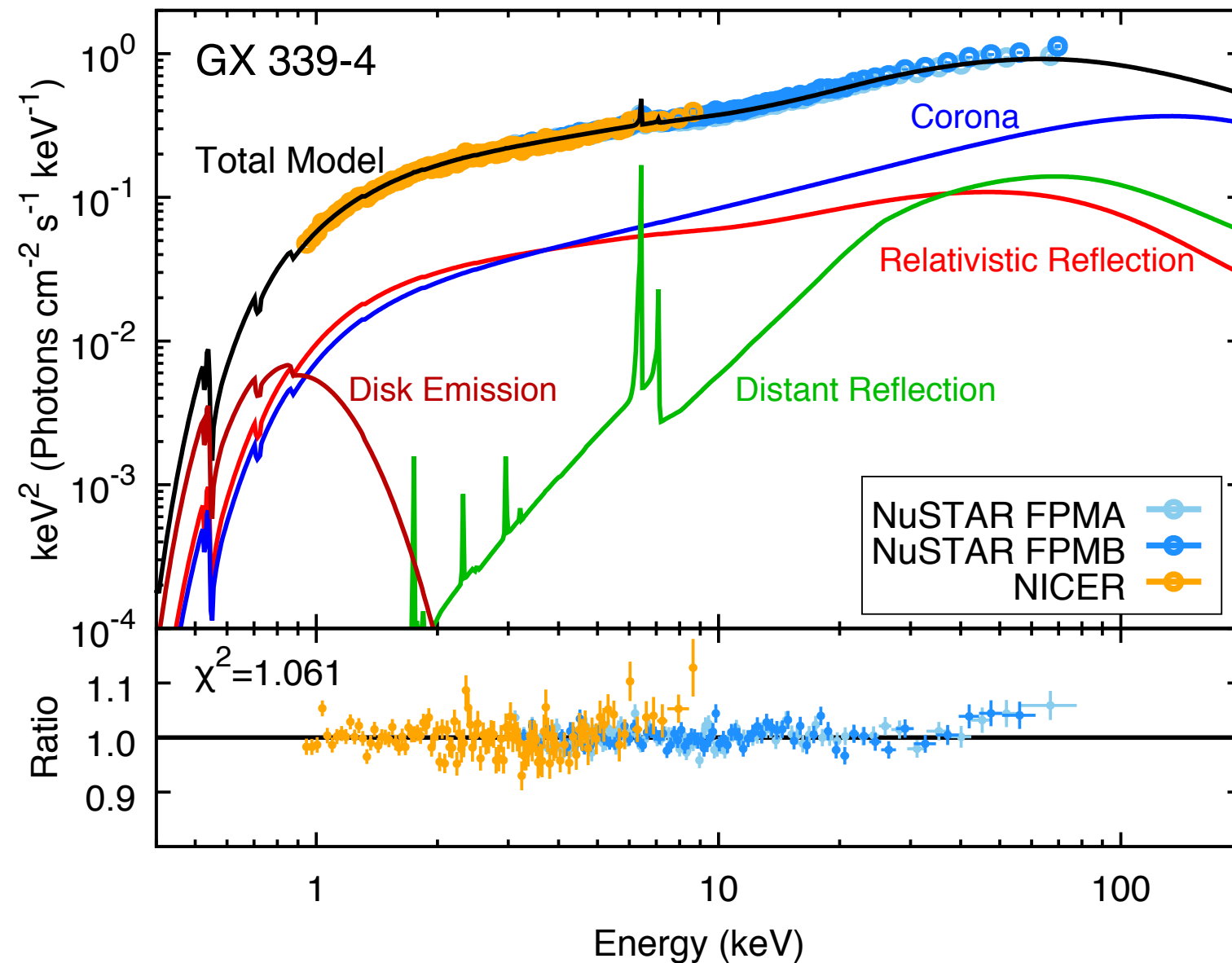
Crisis?



Crisis?



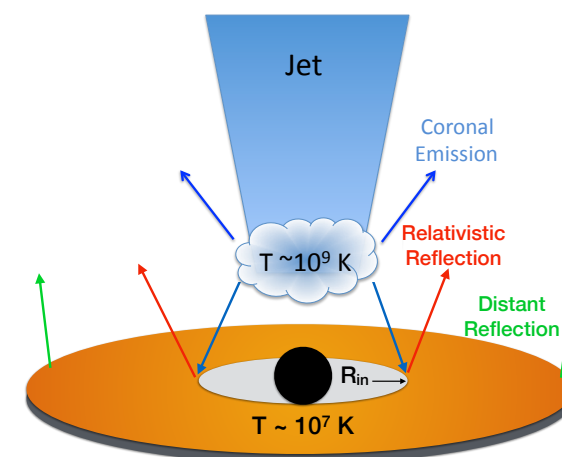
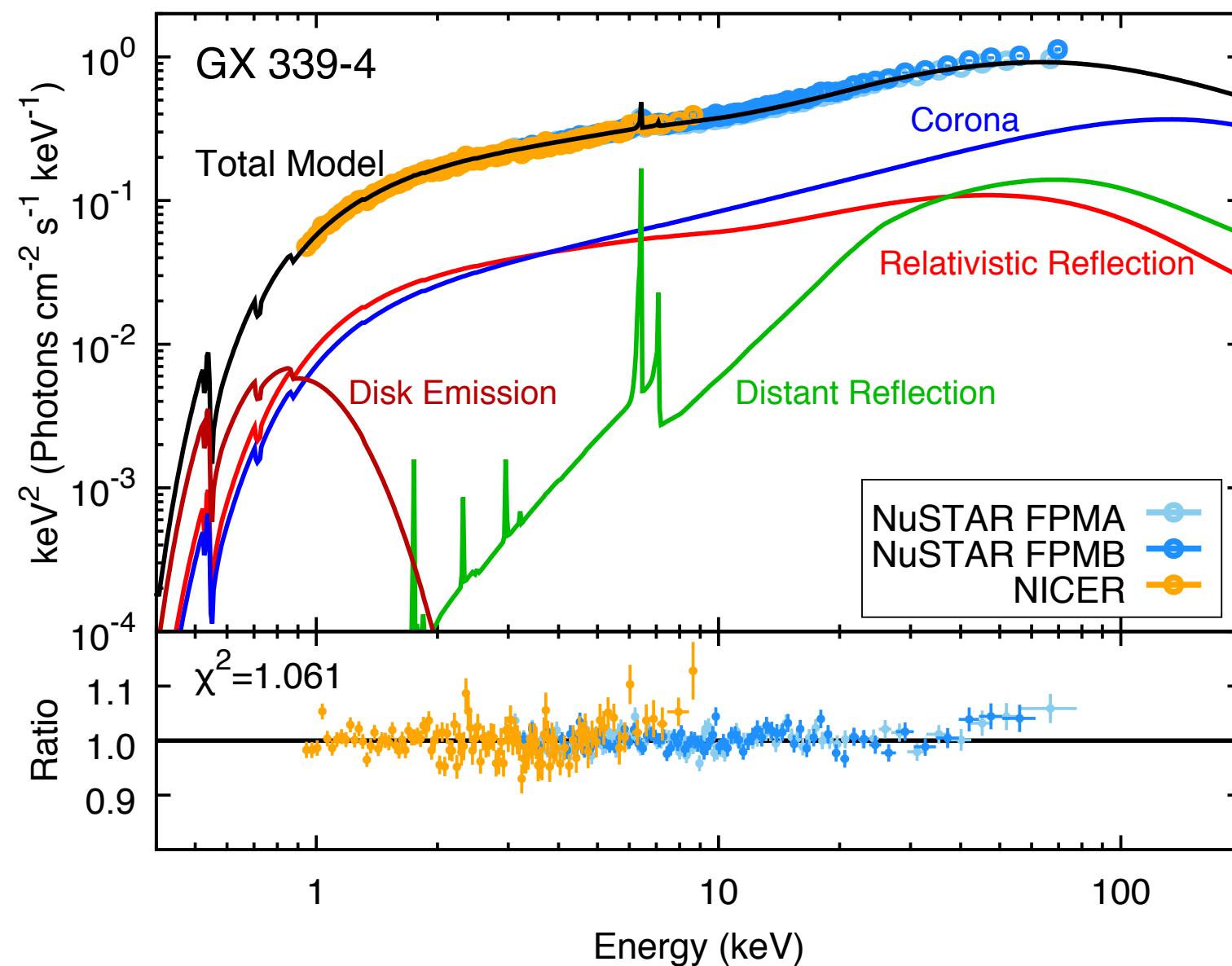
Accepted facts: The “corona”



*Beware: X-ray spectra observed from accretion flows onto black holes are **not** dominated by accretion disk! even less so in AGN!!*

$\Rightarrow$ Dominated by **Comptonization** and **reflection**.
 Disk photons Comptonized in hot electron gas
 sometimes called the “corona” – worst name in all of astrophysics

Accepted facts: The “corona”

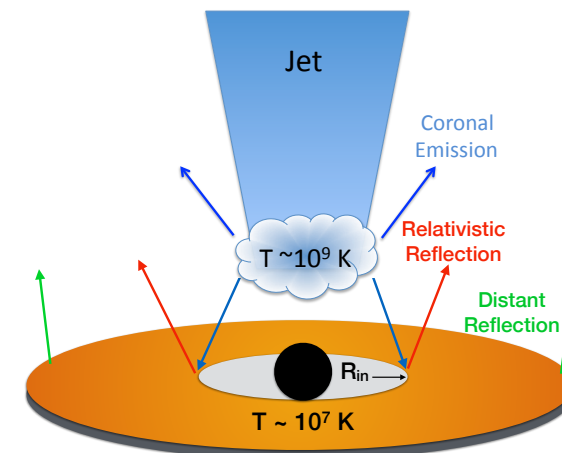
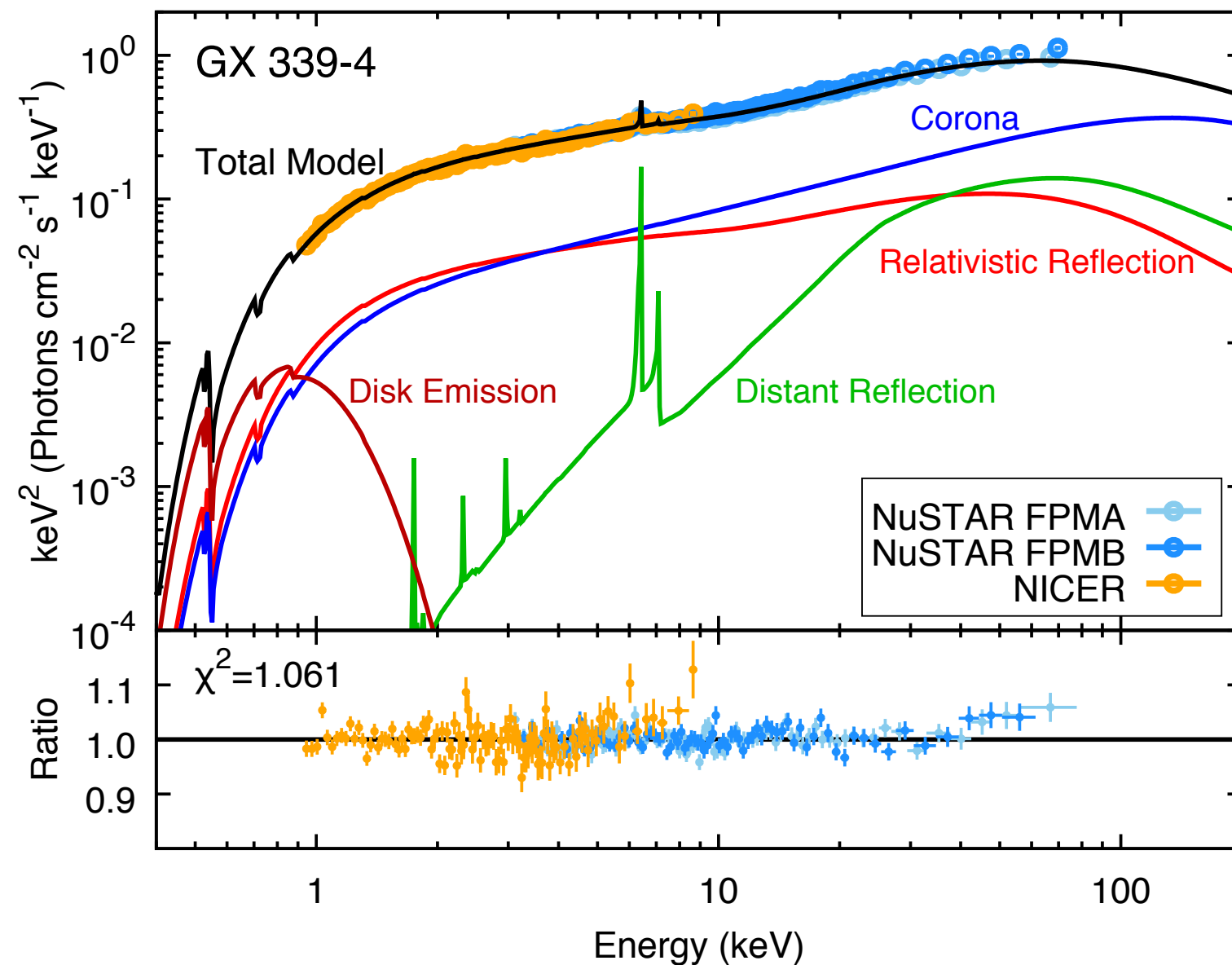


Jet generates radio.
 Also outflow from
 disk

*Beware: X-ray spectra observed from accretion flows onto black holes are **not** dominated by accretion disk! even less so in AGN!!*

$\Rightarrow$ Dominated by **Comptonization** and **reflection**.
 Disk photons Comptonized in hot electron gas
 sometimes called the “corona” – worst name in all of astrophysics

Accepted facts: The “corona”



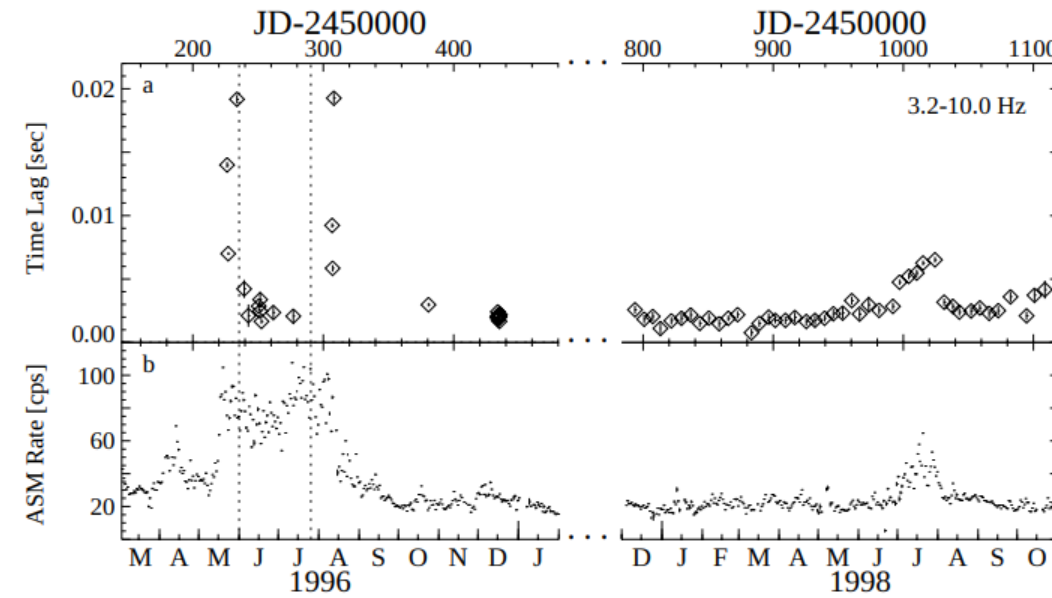
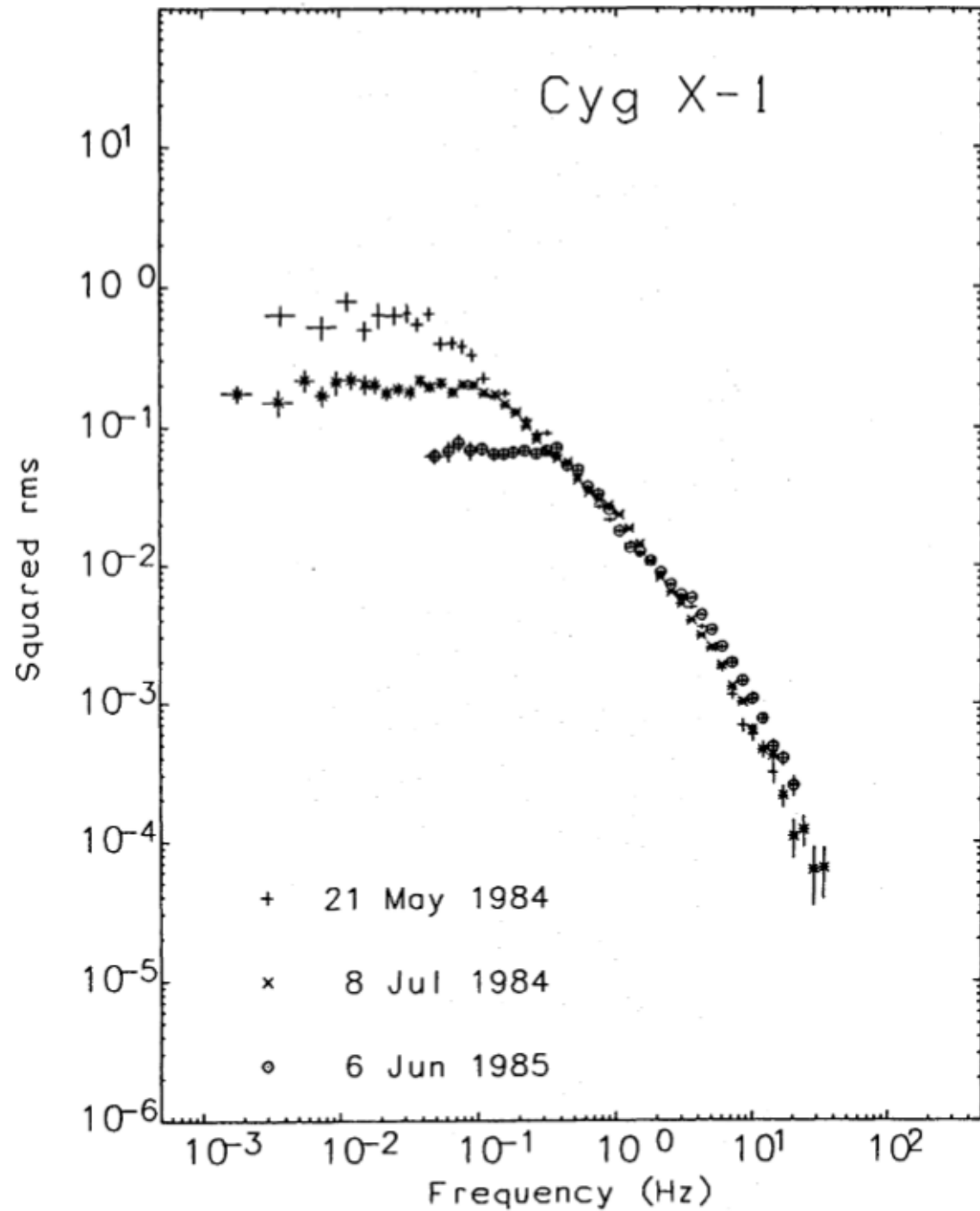
Jet generates radio.
Also outflow from
disk

*Beware: X-ray spectra observed from accretion flows onto black holes are **not** dominated by accretion disk! even less so in AGN!!*

$\Rightarrow$ Dominated by **Comptonization** and **reflection**.
Disk photons Comptonized in hot electron gas
sometimes called the “corona” – worst name in all of astrophysics

Geometry of disk and Comptonizing plasma is 100% unclear

A rant: Do not believe anybody who tells you otherwise! The only thing that is clear is that simple “sandwich geometries” do not work – open question in Galactic and extragalactic BHs since $\gtrsim 30$ years. Polarization has *not* helped.



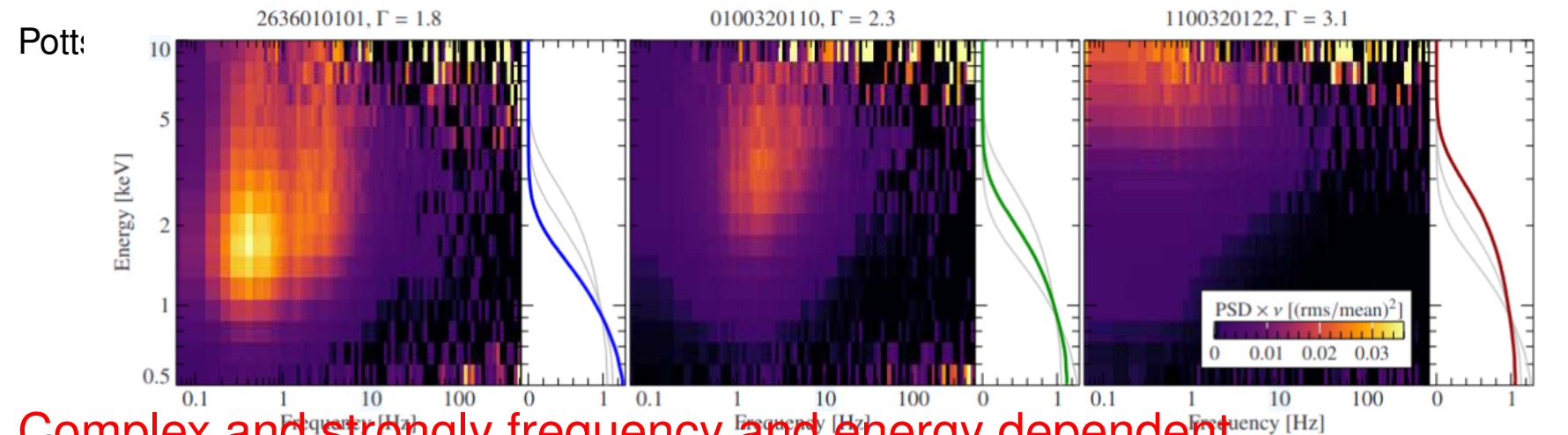
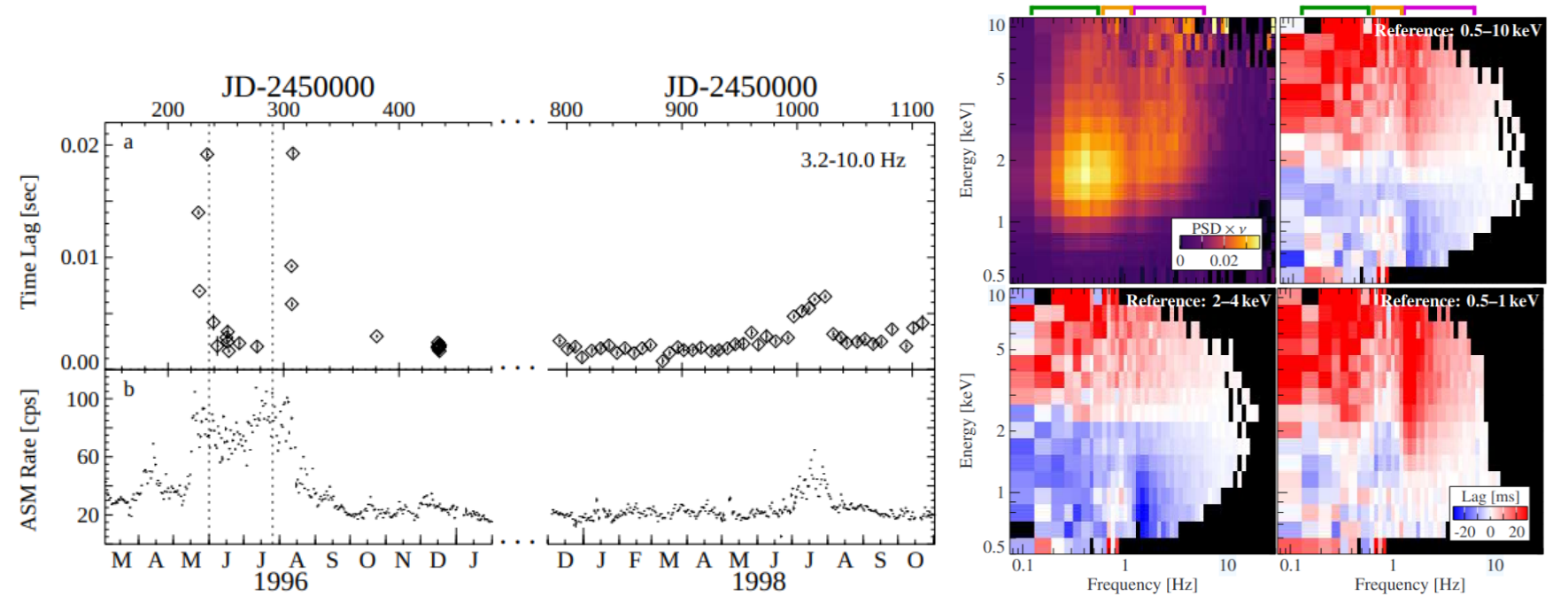
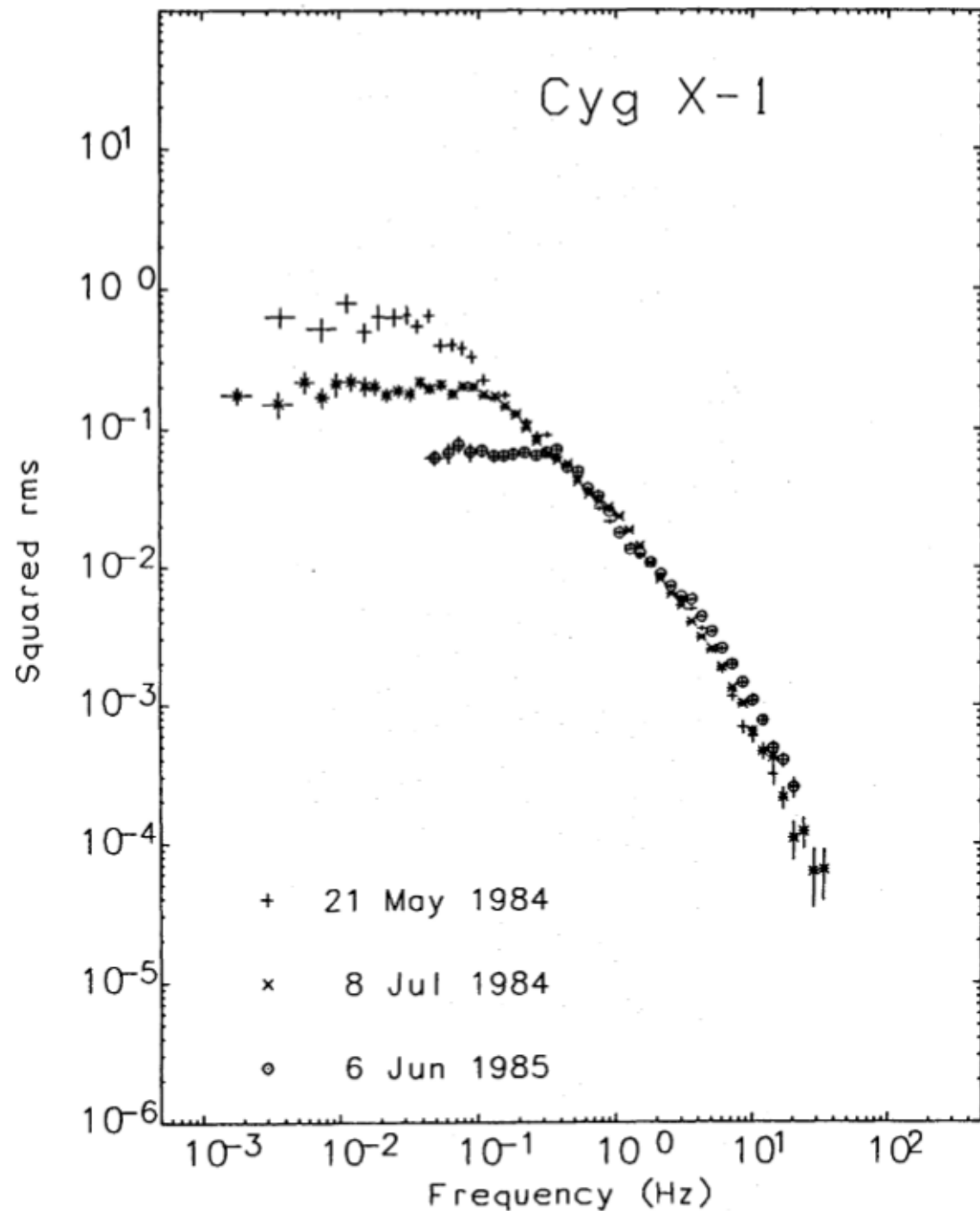
Pottschmidt et al. (2000)

Complex and strongly frequency and energy dependent variability

known since 30+ years, not only since NICER...

Belloni & Hasinger (1990)

Accepted facts: Variability



Complex and strongly frequency and energy dependent variability

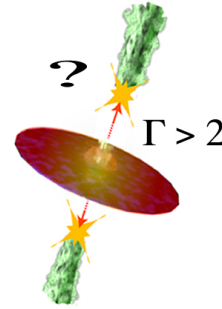
Kong et al. (2024)

known since 30+ years, not only since NICER...

Belloni & Hasinger (1990)

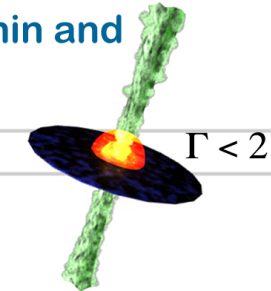
JET LINE AREA:

- 2 - 50% L_{Edd} .
- High-frequency QPOs (after) .
- Type A & B QPOs (after).
- See radio ejecta (fast) each "crossing" of jet line.
- RMS drop ("The Zone") associated with ~ 0.2 Hz lowest frequency Lorentzian, close to ejecta time.



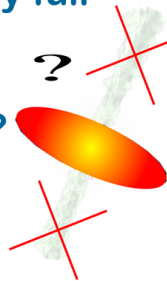
HIMS:

- Disk starts near ISCO.
- Transition starts around 2 - 50% L_{Edd} .
- Type C QPOs.
- IR drops.
- Radio starts going optically thin and variable (new ejecta?).

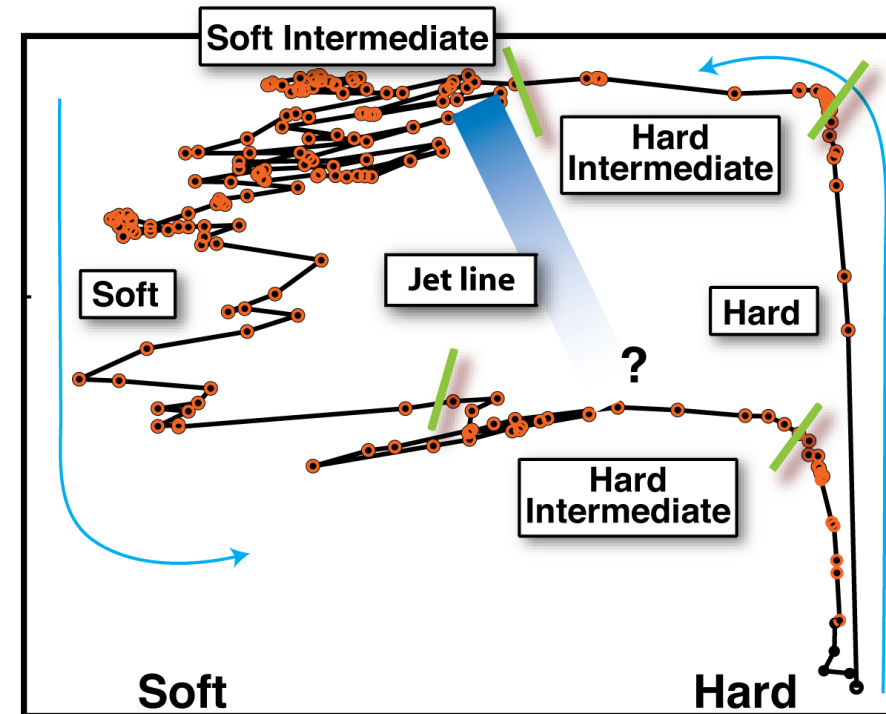


SOFT STATE:

- Optically nuclear thin jet radio emission observed initially, but quenched by at least 20-50x by full transition.
- Detected radio flux not nuclear?
- Type C QPOs.
- Non-thermal power law extending to $\sim \text{MeV}$.
- Thin disk $\sim 0.1\text{-}1.0 L_{\text{Edd}}$ at ISCO.



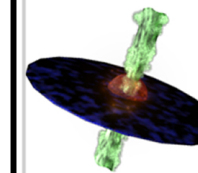
X-ray Luminosity



Spectral Hardness
(spectral slope, soft=steep, hard=flat)

HARD STATE:

- Disk moves in to $\sim \text{few } R_g$ by 10% L_{Edd} .
- Lorentzian/broad noise components.
- High RMS variability.
- Flat spectrum jet up to IR/opt.
- Compact jet sometimes resolved.
- Radio/IR/X-ray correlations.
- Reflection "bump".



T. Belloni
A. Celotti
S. Corbel
R. Fender
E. Gallo
M. Hanke
E. Kalemci

D. Maitra
S. Markoff
I. McHardy
M. Nowak
P.-O. Petrucci
K. Pottschmidt
J. Wilms

HIMS:

- Same as upper branch but:
- No optically thin radio flare.
 - Radio recovers close to hard state.
 - Lower flux level (hysteresis).

QUIESCENCE:

- Thin disk recessed to $> 10^2 R_g$
- BB component seen in UV/Optical.
- Disk 10-100x more luminous than LX. By $\sim 10^{-4} L_{\text{Edd}}$.
- No iron lines?

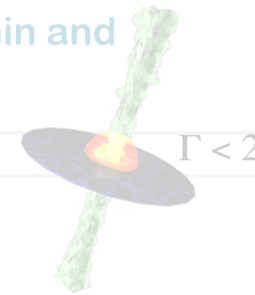
JET LINE AREA:

- 2 - 50% L_{Edd} .
- High-frequency QPOs (after) .
- Type A & B QPOs (after).
- See radio ejecta (fast) each "crossing" of jet line.
- RMS drop ("The Zone") associated with ~ 0.2 Hz lowest frequency Lorentzian, close to ejecta time



HIMS:

- Disk starts near ISCO.
- Transition starts around 2 - 50% L_{Edd} .
- Type C QPOs.
- IR drops.
- Radio starts going optically thin and variable (new ejecta?)



SOFT STATE:

- Optically nuclear radio emission initially, but quenches at least 20-50x by transition. Detected radio flux not nuclear?
- Type C QPOs.
- Non-thermal power law extending to $\sim M$
- Thin disk $\sim 0.1-1$ ISCO.



T. Belloni
A. Celotti
S. Corbel
R. Fender
E. Gallo
M. Hanke
E. Kalemci

D. Maitra
S. Marko
I. McHardy
M. Nowak
P.-O. Petrucci
K. Pottschmidt
J. Wilms

Same as upper branch but:

- No optically thin radio flare.
- Radio recovers close to hard state.
- Lower flux level (hysteresis).

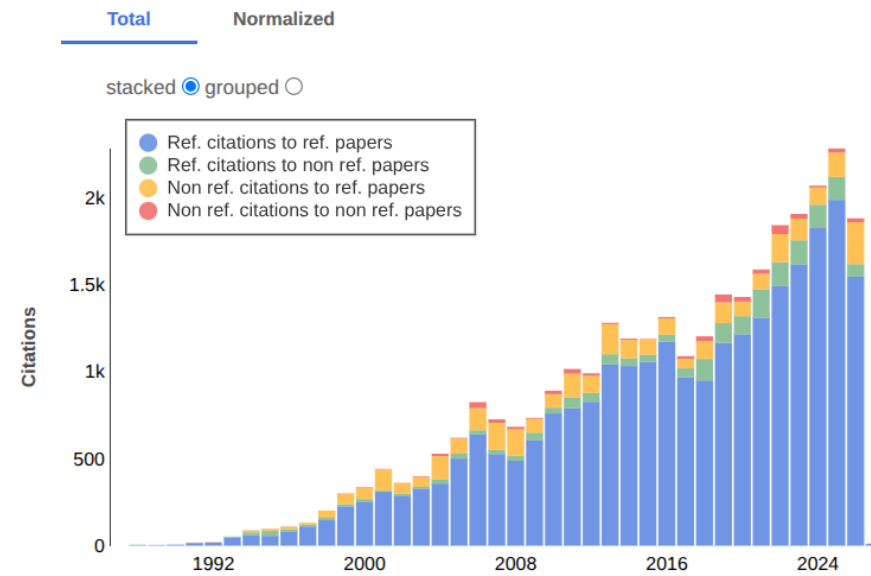
to $\sim$ few R_g by

ad noise

ability.
spectrum jet
R/opt.
act jet
times resolved.
IR/X-ray
ations.
tion "bump".

- Thin disk recessed to $> 10^2 R_g$
- BB component seen in UV/Optical.
- Disk 10-100x more luminous than LX. By $\sim 10^{-4} L_{\text{Edd}}$.
- No iron lines?

Summary of status quo



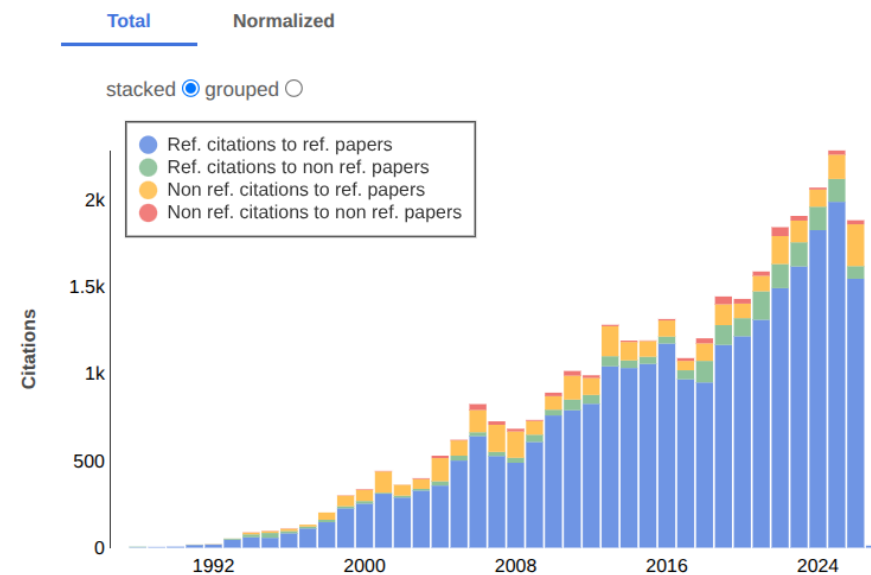
So, to summarize: **Data are good:**

- extremely good monitoring
- extremely well executed multiwavelength campaigns
- well-sampled spectroscopy and timing data available



P. Kretschmar

Summary of status quo



P. Kretschmar

So, to summarize: **Data are good:**

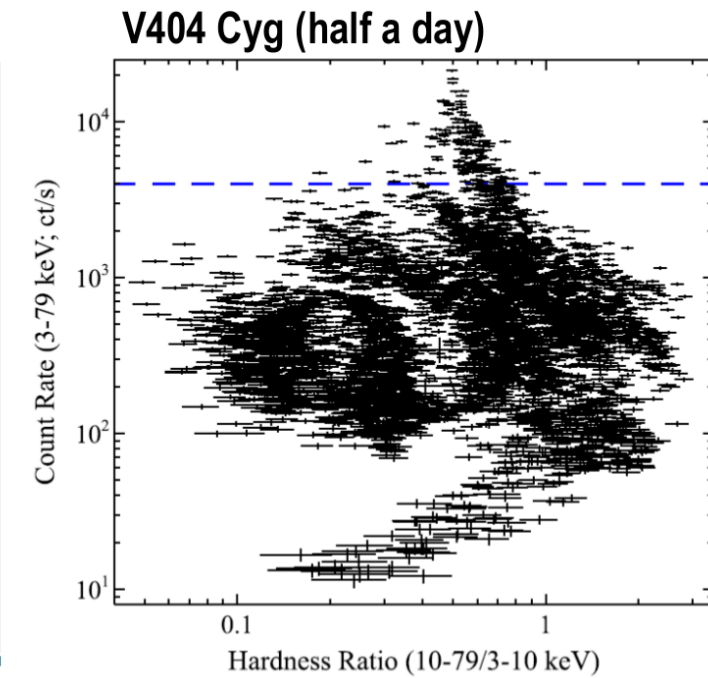
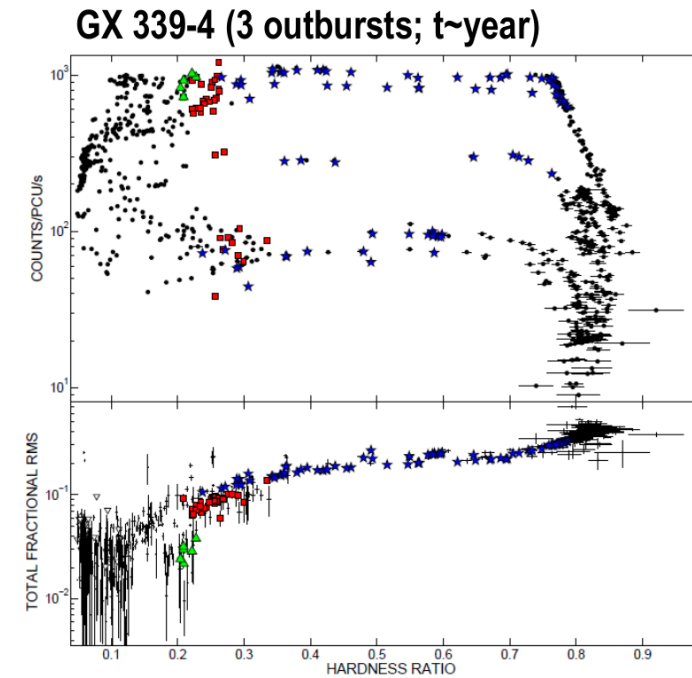
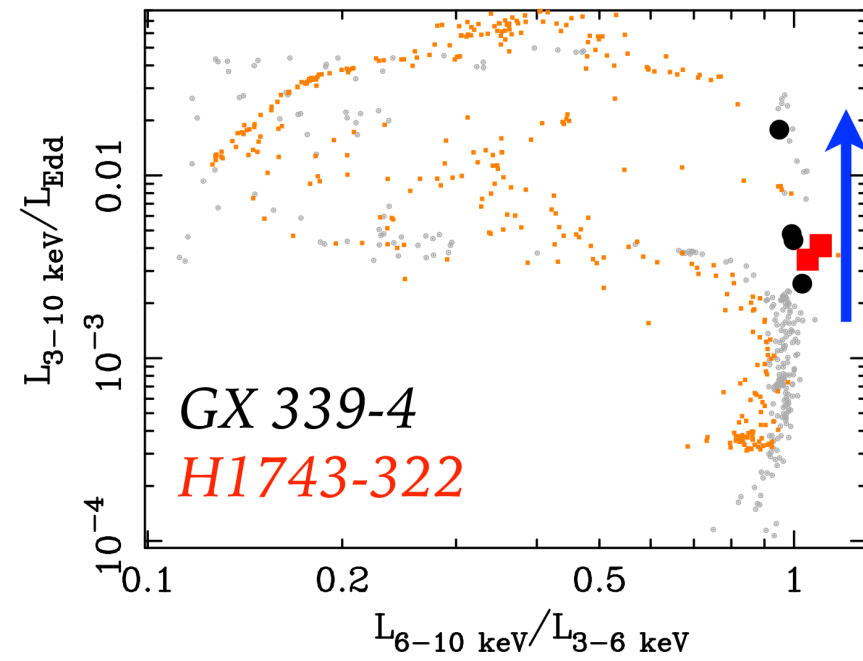
- extremely good monitoring
- extremely well executed multiwavelength campaigns
- well-sampled spectroscopy and timing data available

BUT: I believe, that we're been having a crisis in BH-XRB studies for the past 10–15 years.

Virtually all interpretation of data are done in a **too well-established framework** which is

- far too simplified and dangerously semi-empirical
empirical models to describe behavior is good, but *semi-empirical models* are extremely dangerous: **just because a model fits does not mean it is correct!** – model assumptions introduce systematic errors, different models can produce cutoff power laws!
Just because you can produce a corner plot or apply advanced statistical methods does not mean you're doing cool physics, but mainly emphasizes you don't care about your CO₂ footprint.
- based on models which are typically **even more basic than in early 2000s**
main exception is reflection models, but even these are very simplified
- does **not combine spectral and timing behavior**
... few exceptions of proper joint spectral timing, lots of hand waving

Summary of status quo



The curse of the turtle.

- There is *much more* to explore

Summary of status quo



The curse of the turtle.

- There is *much more* to explore
- Ignored diagnostics:
 - **high resolution spectroscopy**: gratings! XRISM!
 - **polarization**: current models far too simplified
 - **Timing**: Understand spectral-timing variations
 - **Frequency dependency of timing parameters is too often ignored**
There is no such thing as “the lag”!
 - **Archives are underutilized**

Summary of status quo



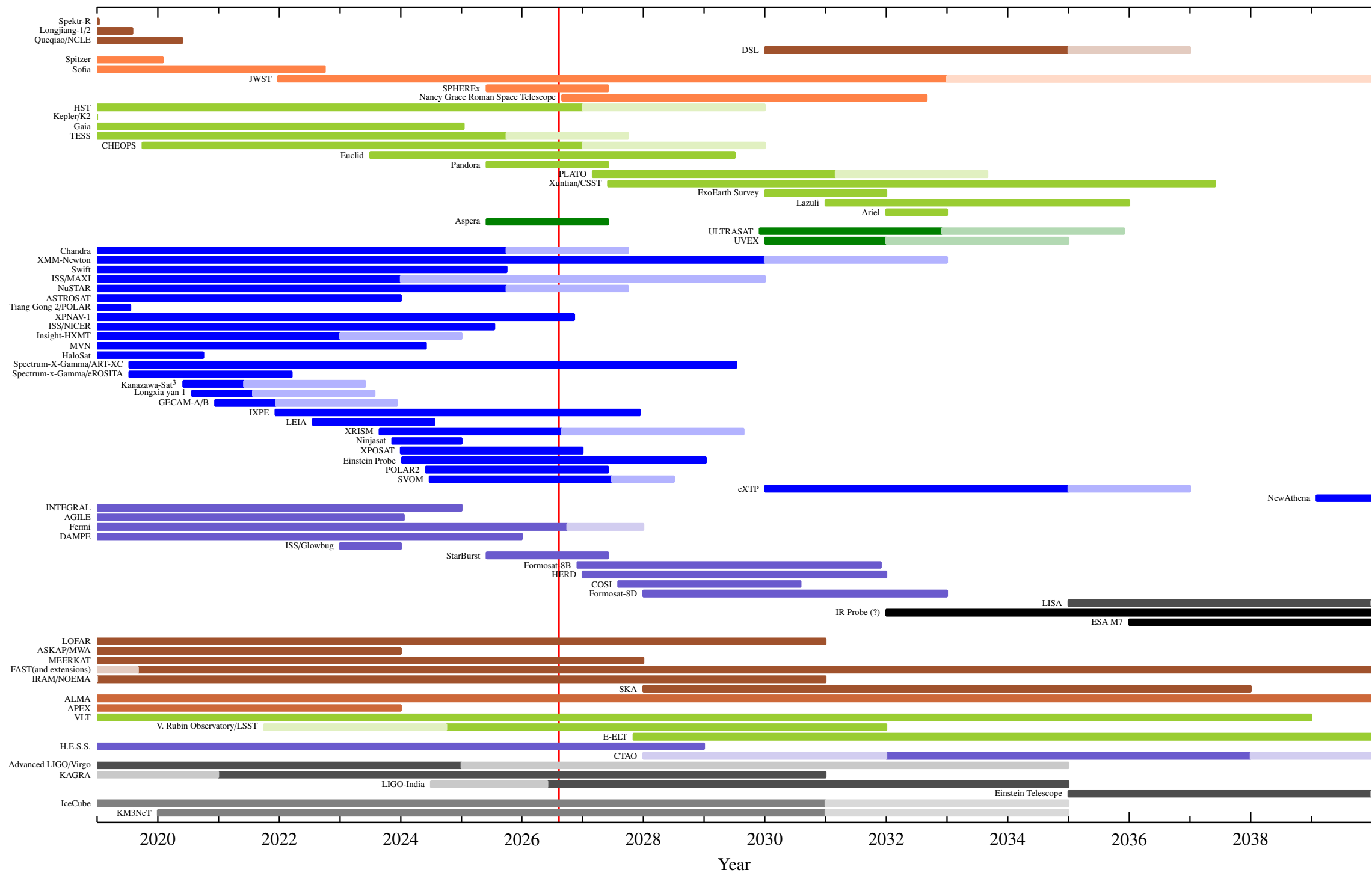
Existing archival data should be good to answer these issues, since we won't be distracted by yet another MW campaign that needs to be quickly published.

The curse of the turtle.

... we have 10–15 years to improve our models!

- There is *much more* to explore
- Not too many physics-based models $\Rightarrow$ we need to be quantitative, not qualitative!

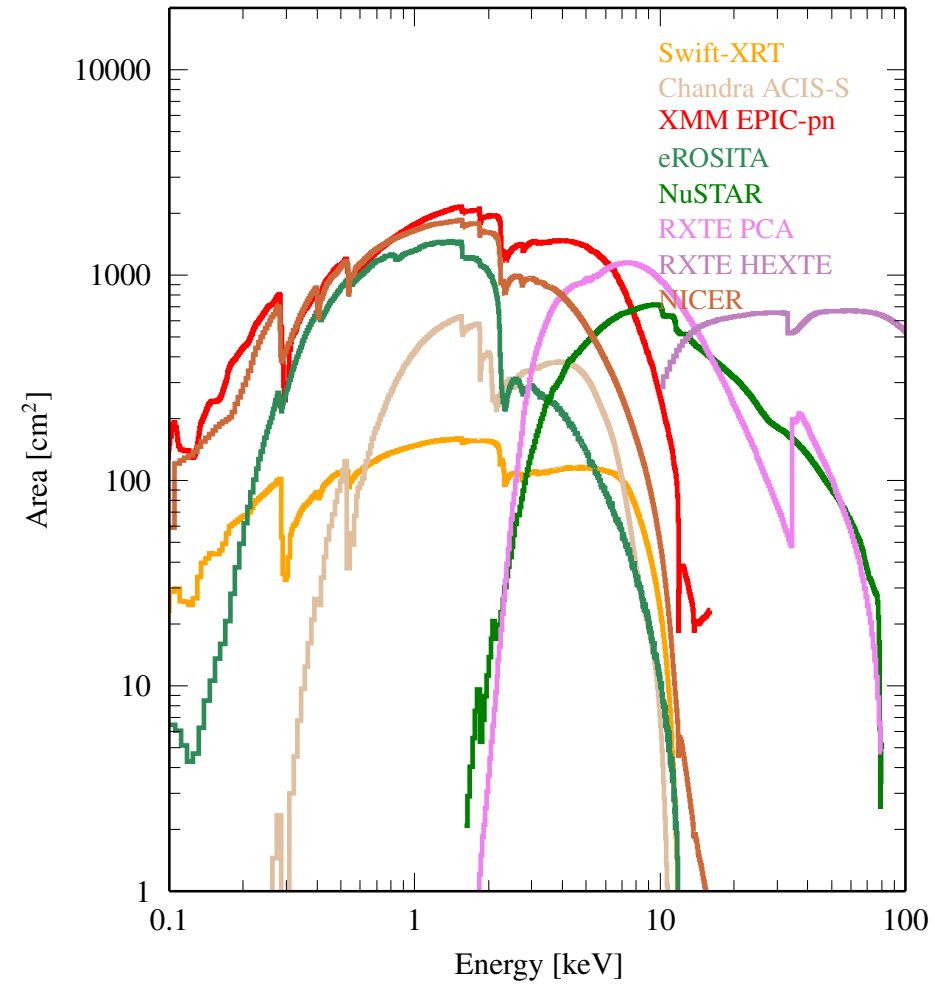
Comptonization models, jet models, line diagnostics, quantitative MW fitting. . . Yes, this is more work, but also results in much stronger constraints and clearer statements.



Effective Areas

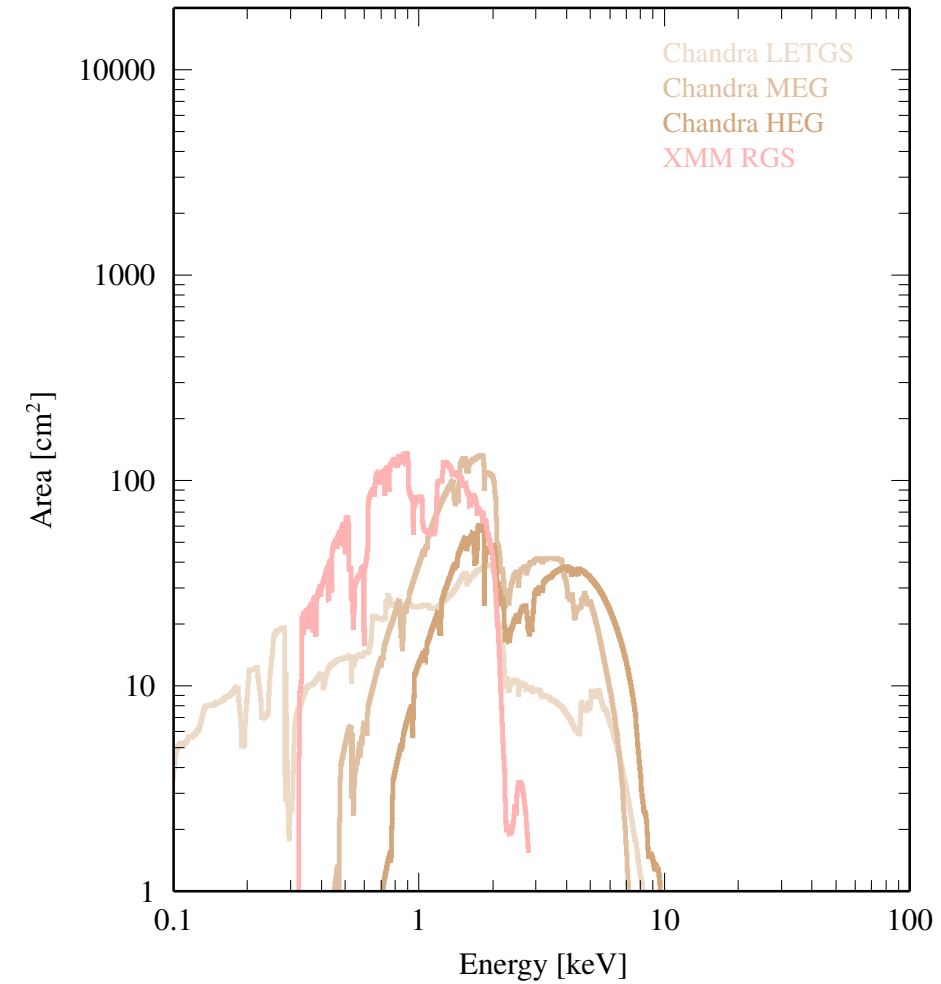
Si-type resolution

(Fano – $\Delta E \sim 150$ eV at 5.9 keV, $R \sim 40$)



Gratings

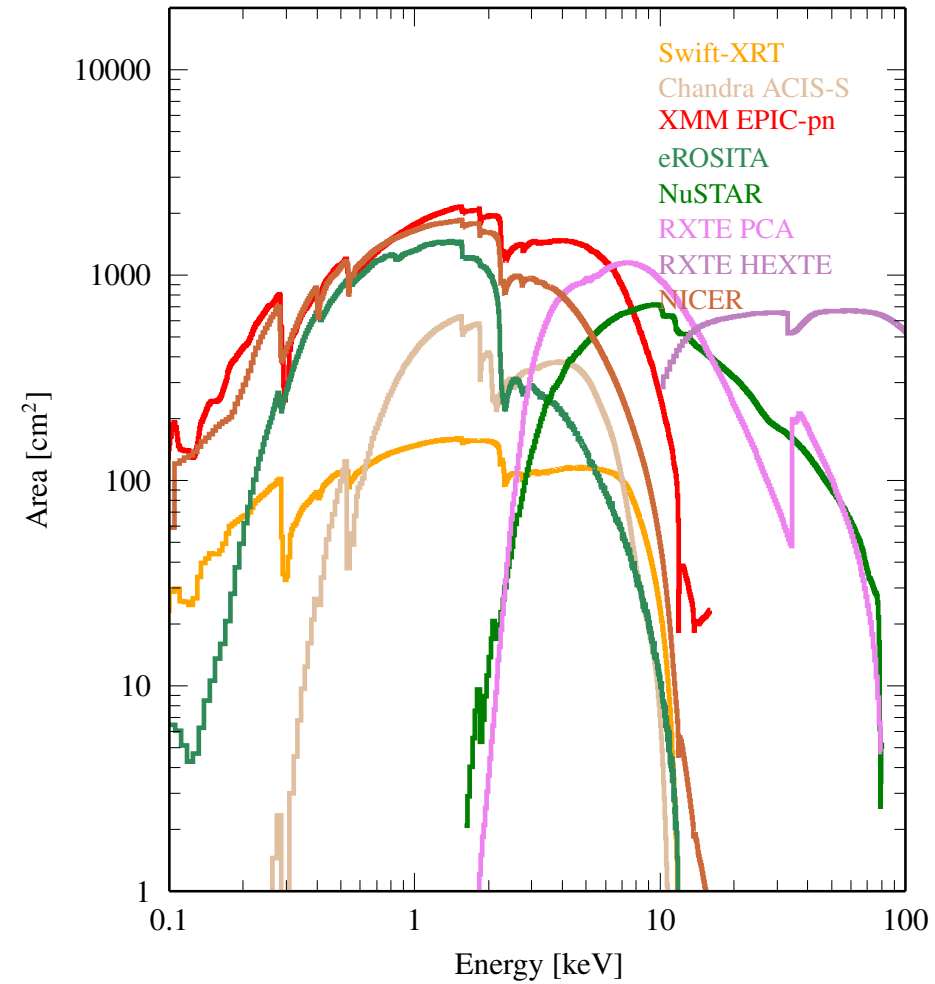
($R \sim 1000$)



Effective Areas

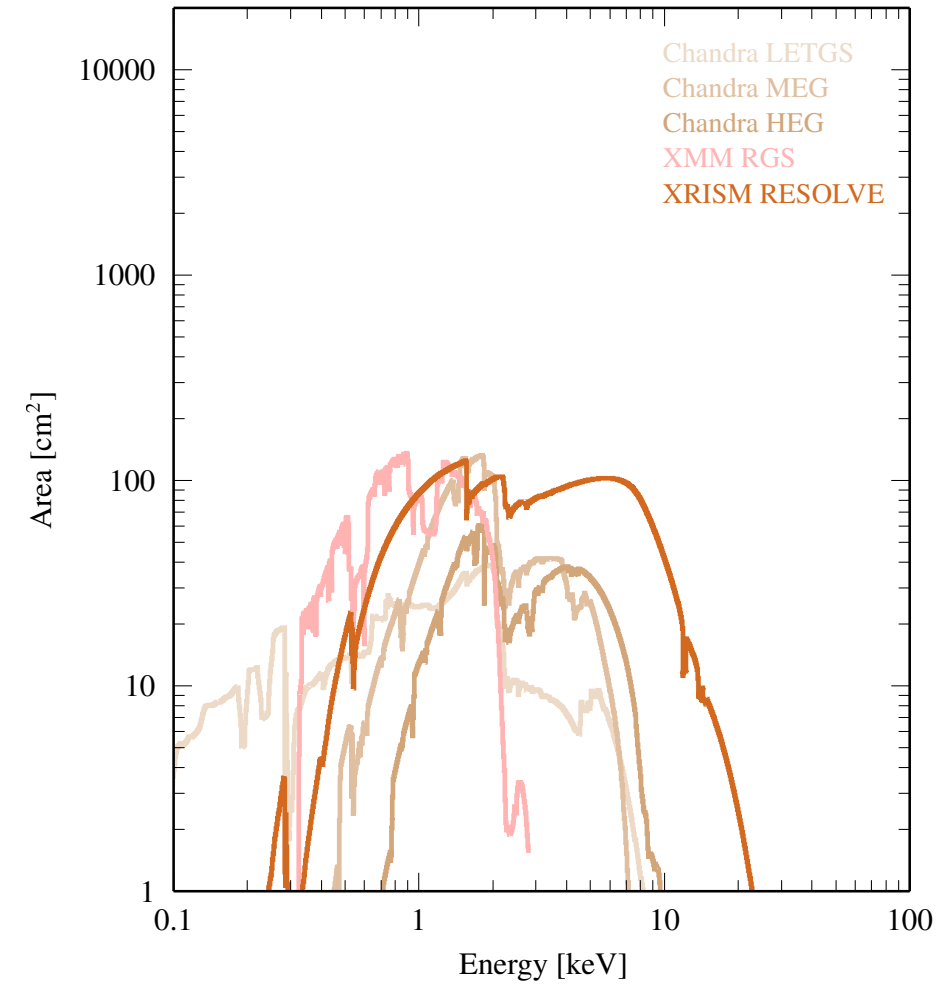
Si-type resolution

(Fano – $\Delta E \sim 150$ eV at 5.9 keV, $R \sim 40$)



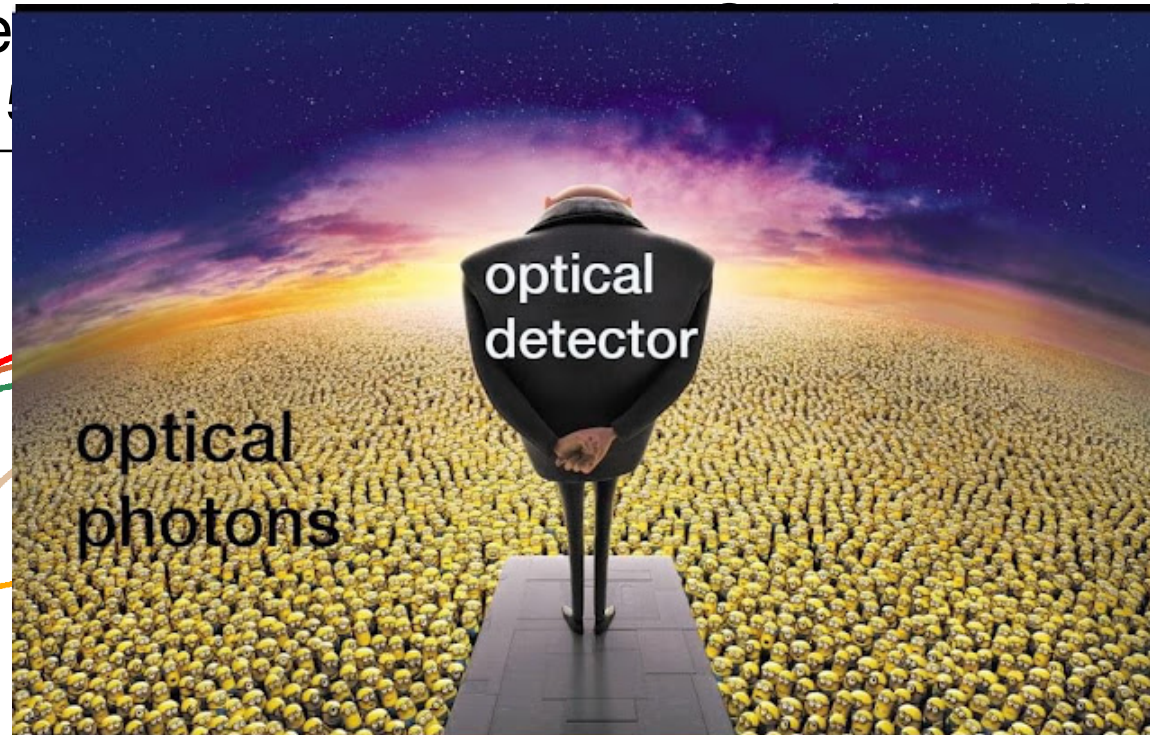
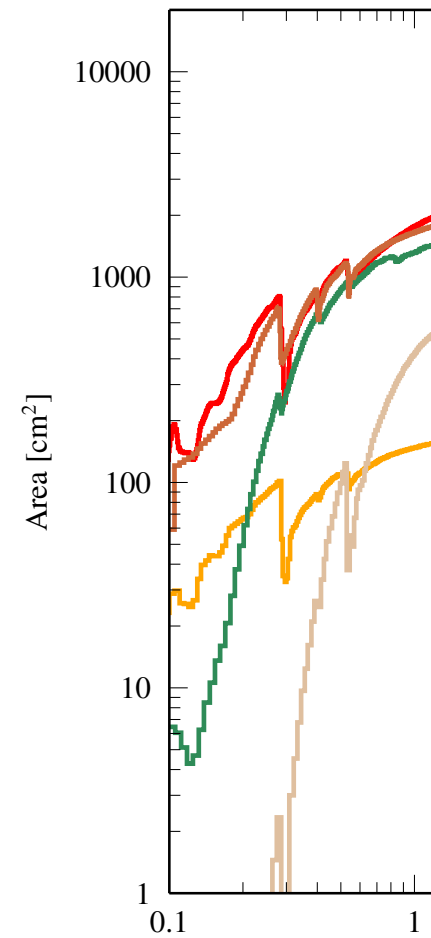
Gratings & Microcalorimeters

($R \sim 1000$, $R \sim 70 \dots 4000$)

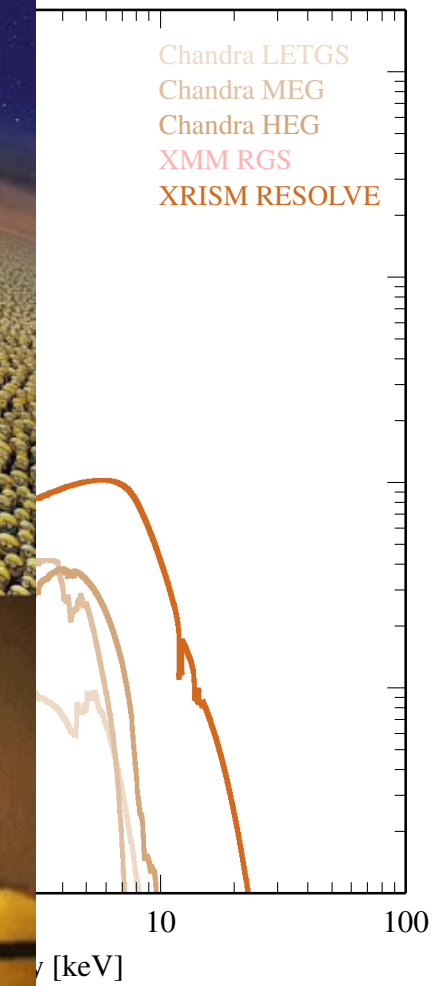


Effective Areas

Si-type
(Fano – $\Delta E \sim 1$)



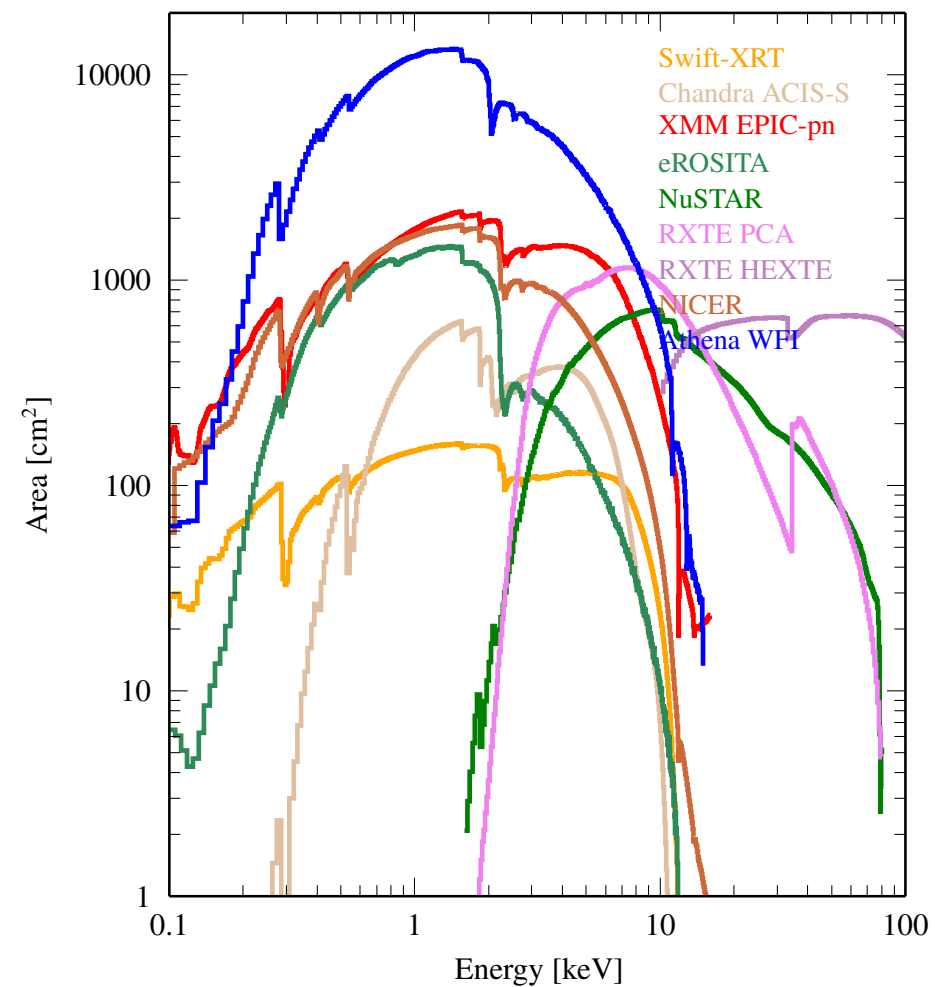
calorimeters
(70 ... 4000)



Effective Areas

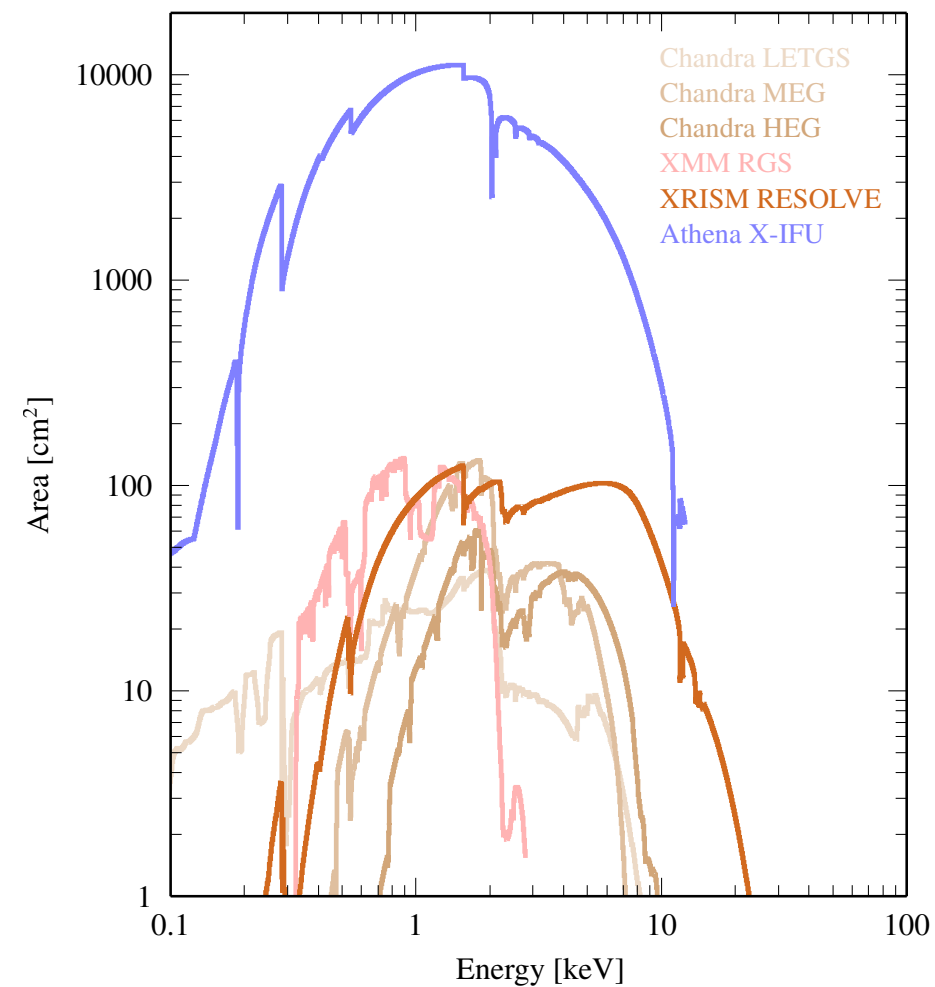
Si-type resolution

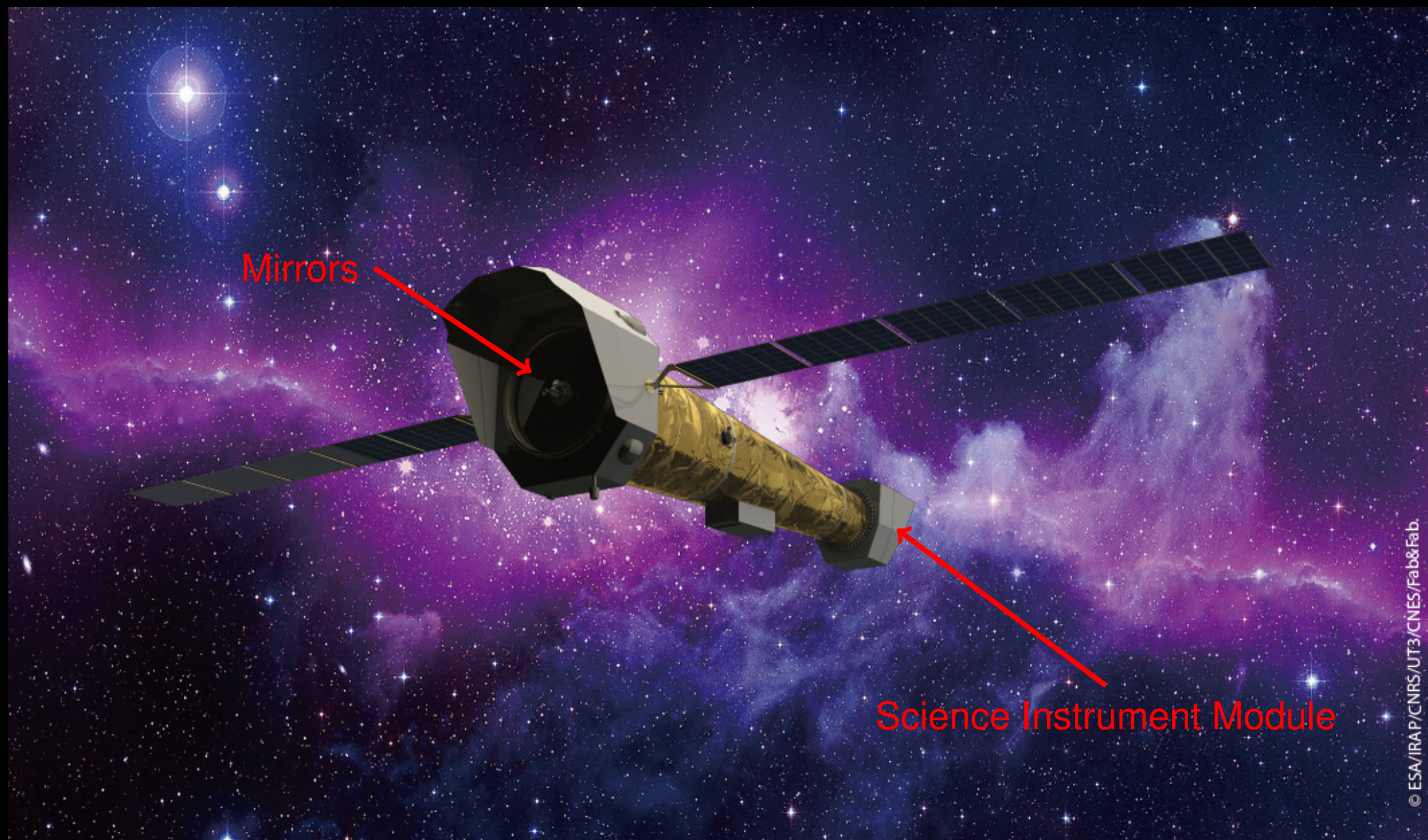
(Fano – $\Delta E \sim 150$ eV at 5.9 keV, $R \sim 40$)



Gratings & Microcalorimeters

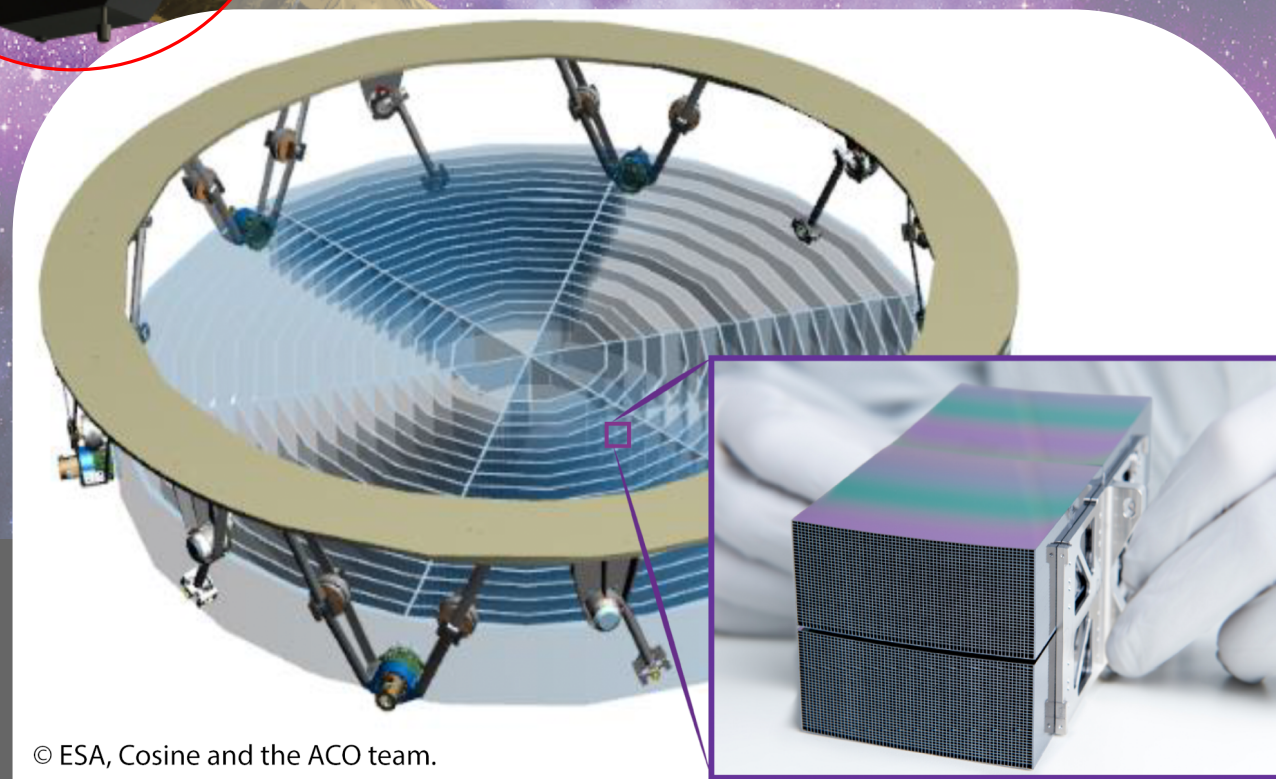
($R \sim 1000$, $R \sim 70 \dots 4000$)





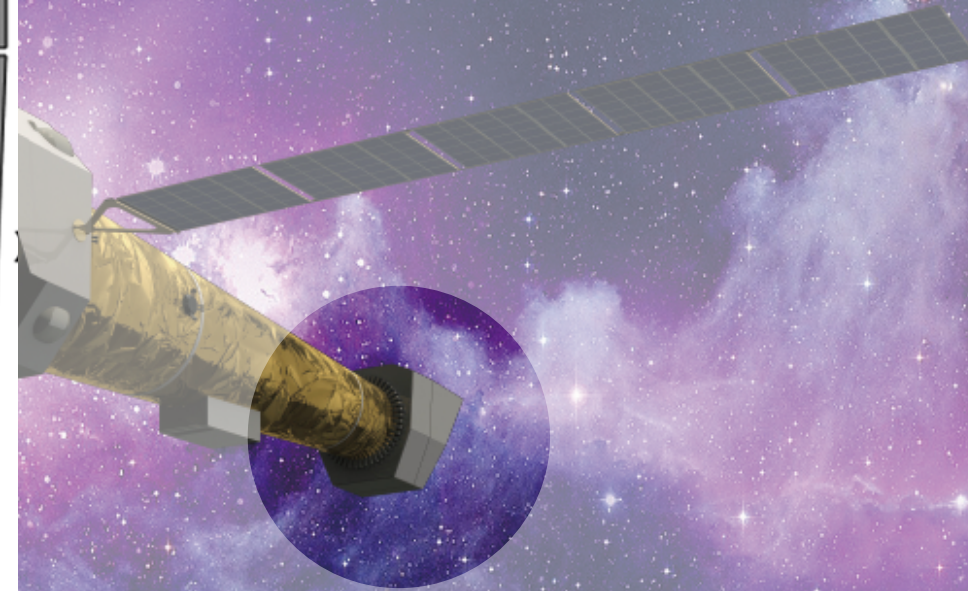
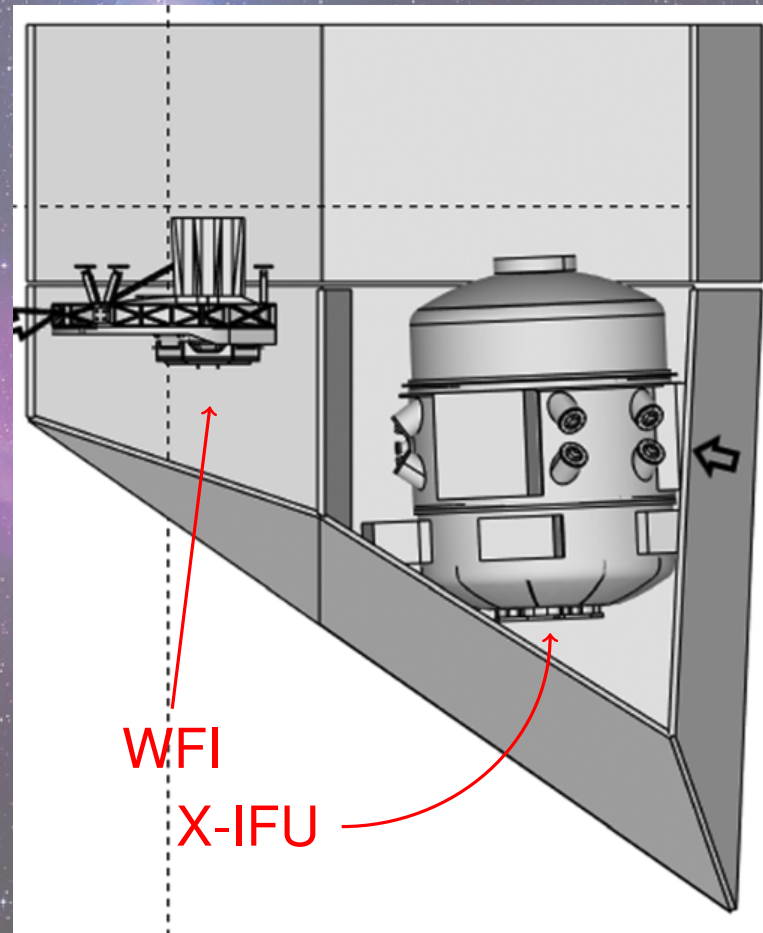
Yes, the spacecraft structure is outdated...

Mirrors: Silicon pore optics (Cosine, Leiden)



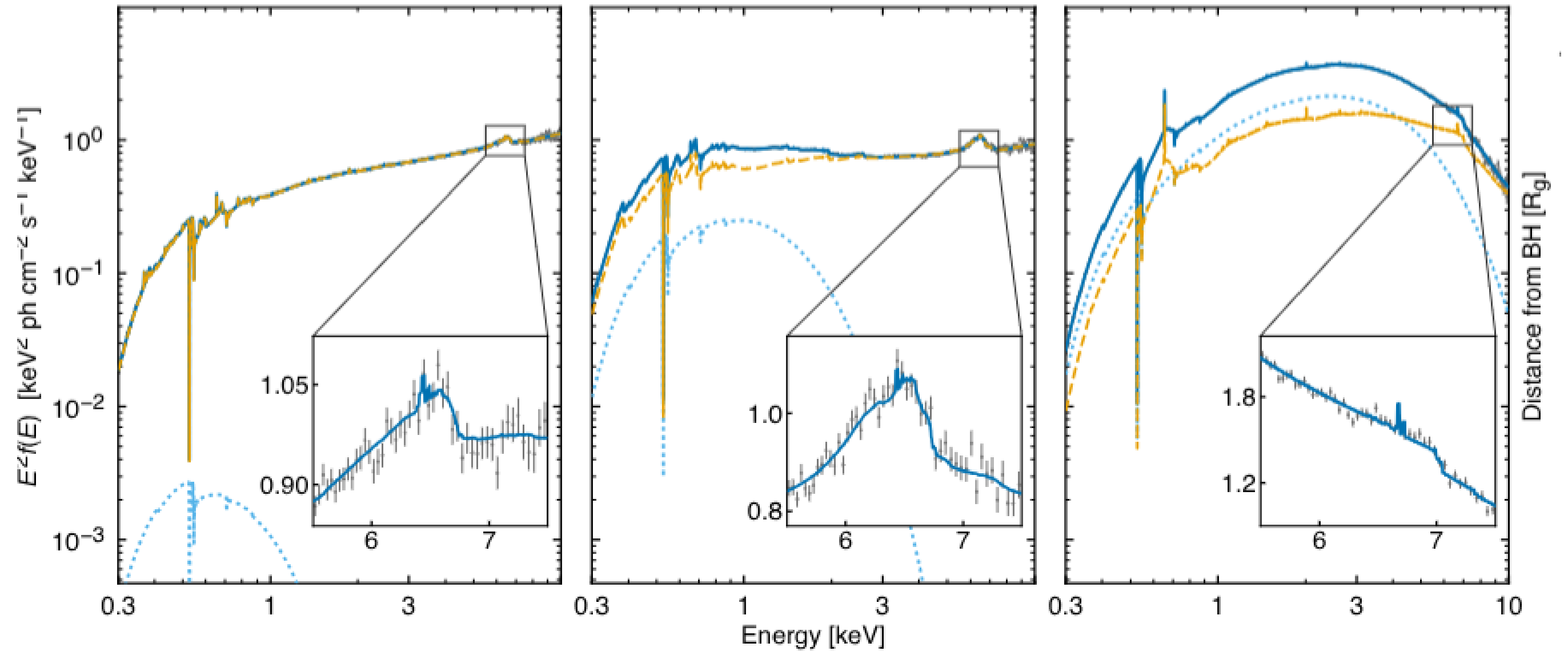
© ESA, Cosine and the ACO team.

Yes, the spacecraft structure is outdated...

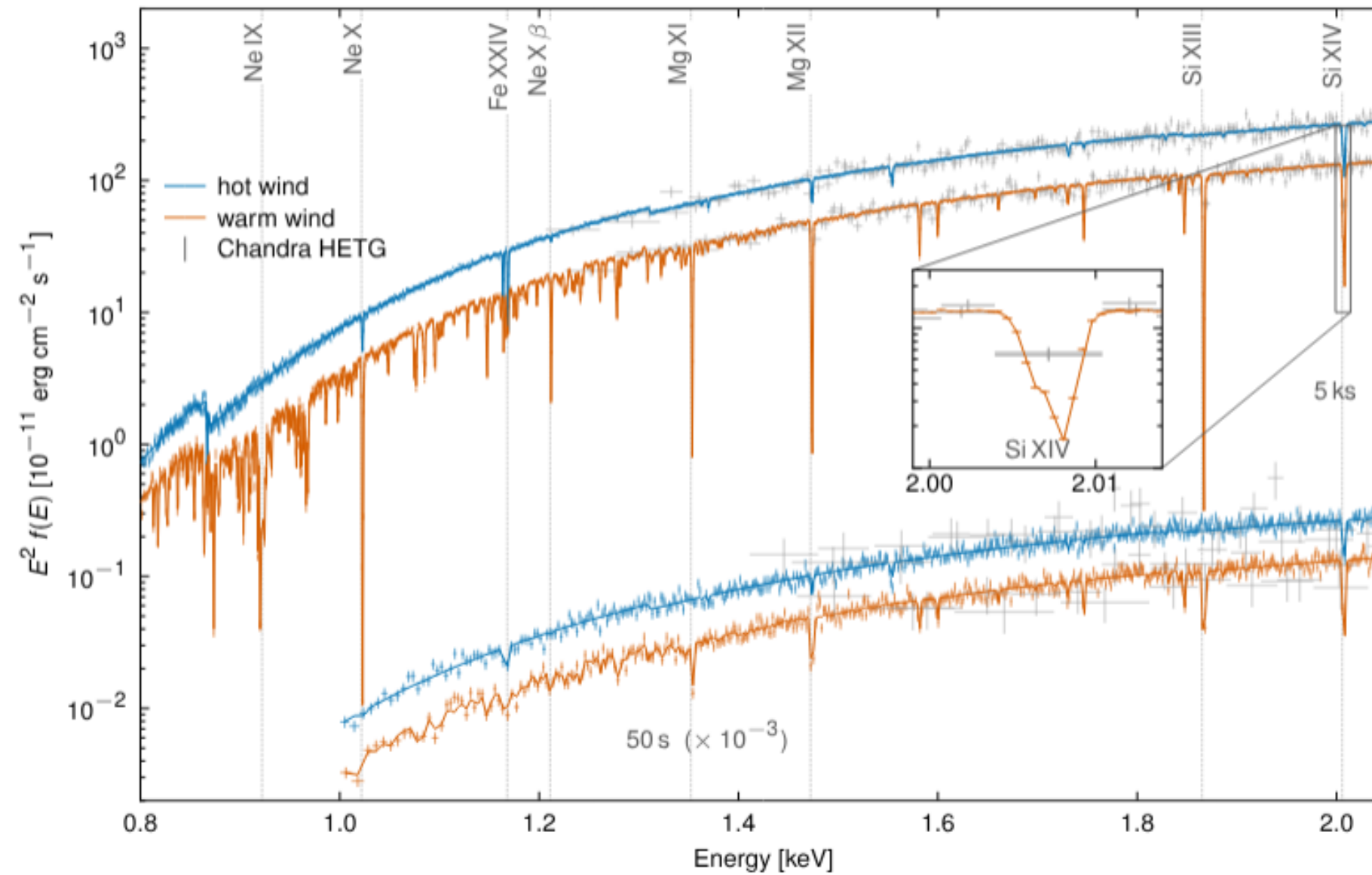


© ESA/IRAP/CNRS/UT3/CNES/Fab&Fab.

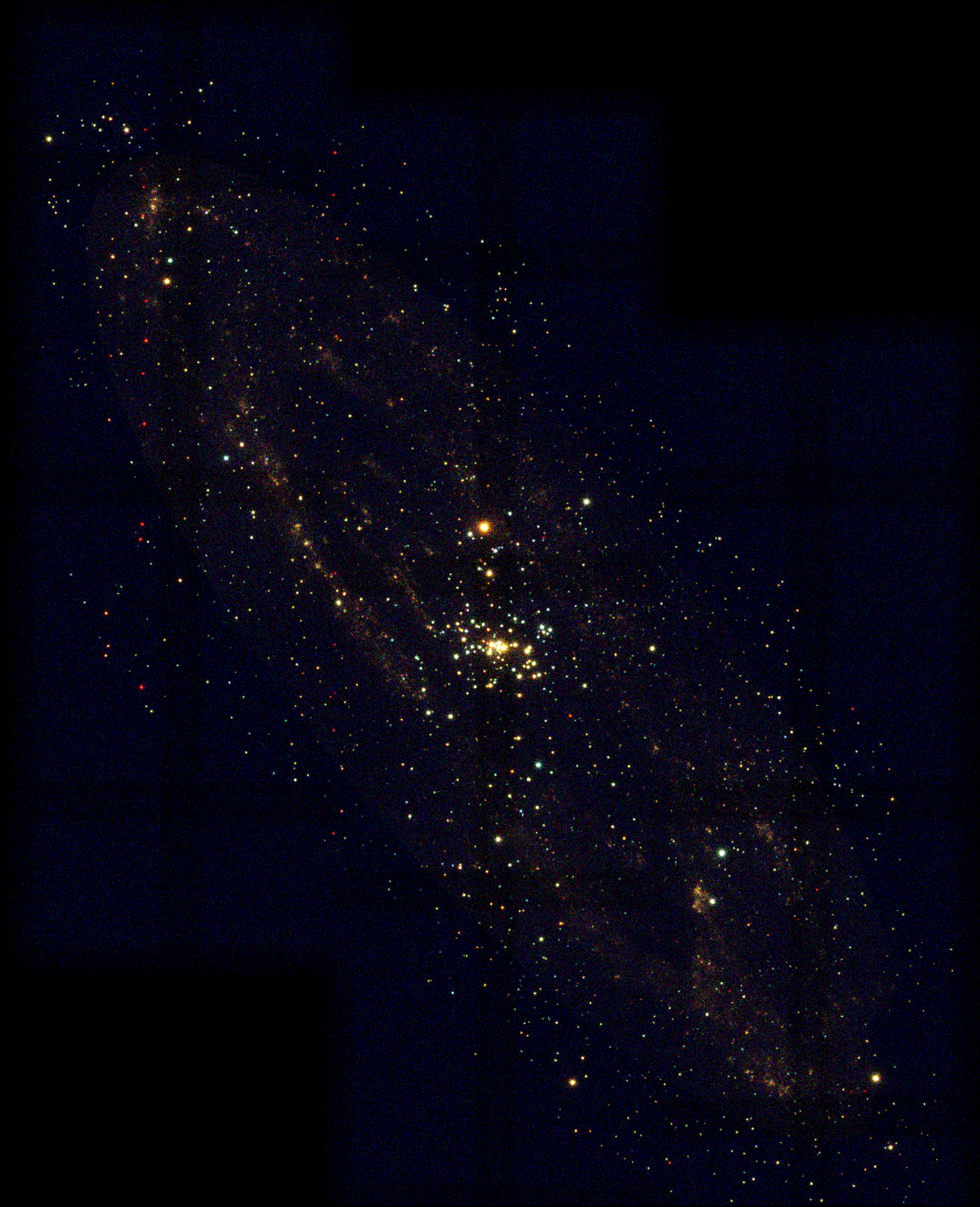
Yes, the spacecraft structure is outdated...



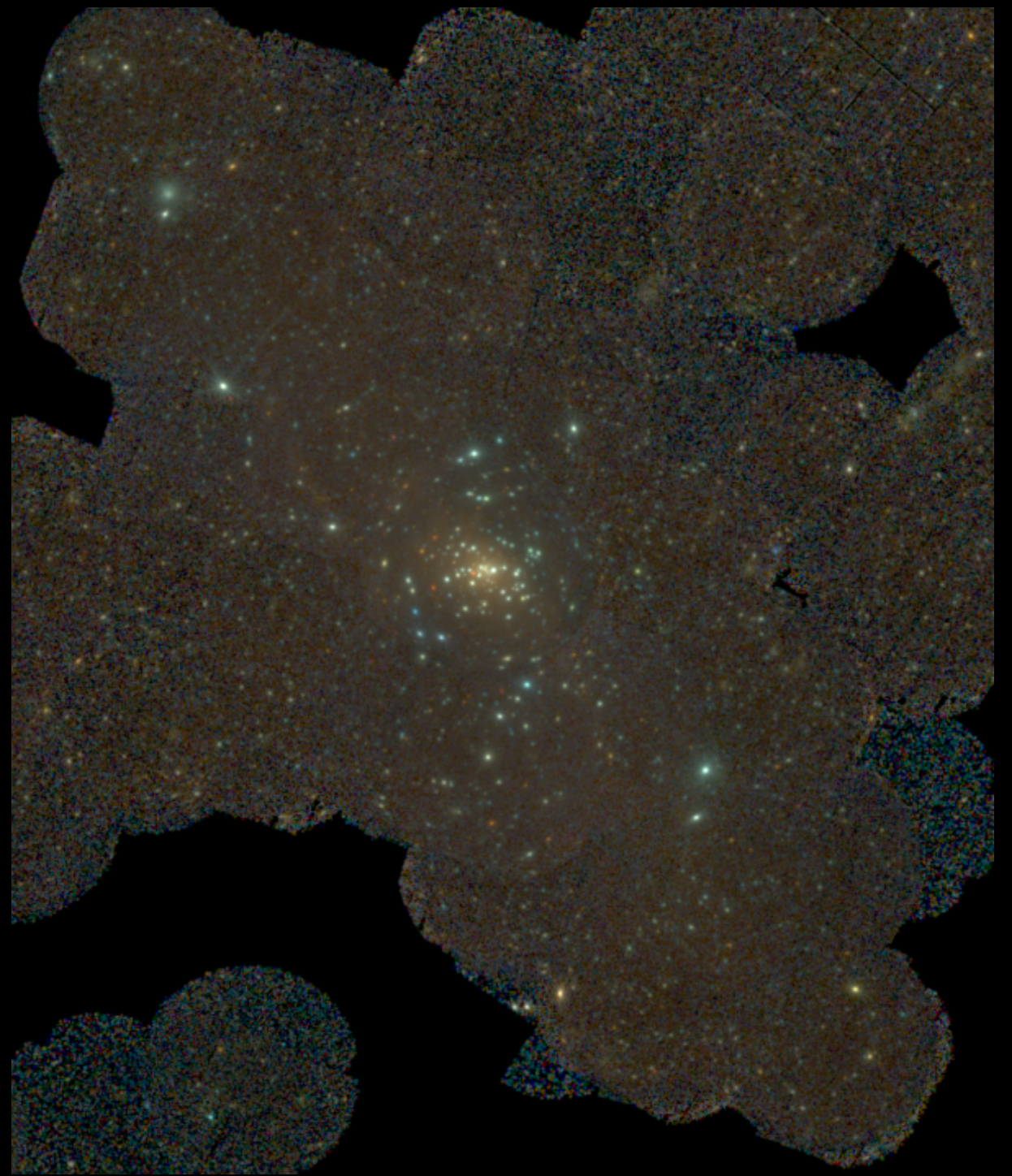
States w/X-IFU (T. Dauser, priv. comm., to not distribute)



Absorption in BHB (3 ks; T. Dauser, priv. comm., to not distribute)

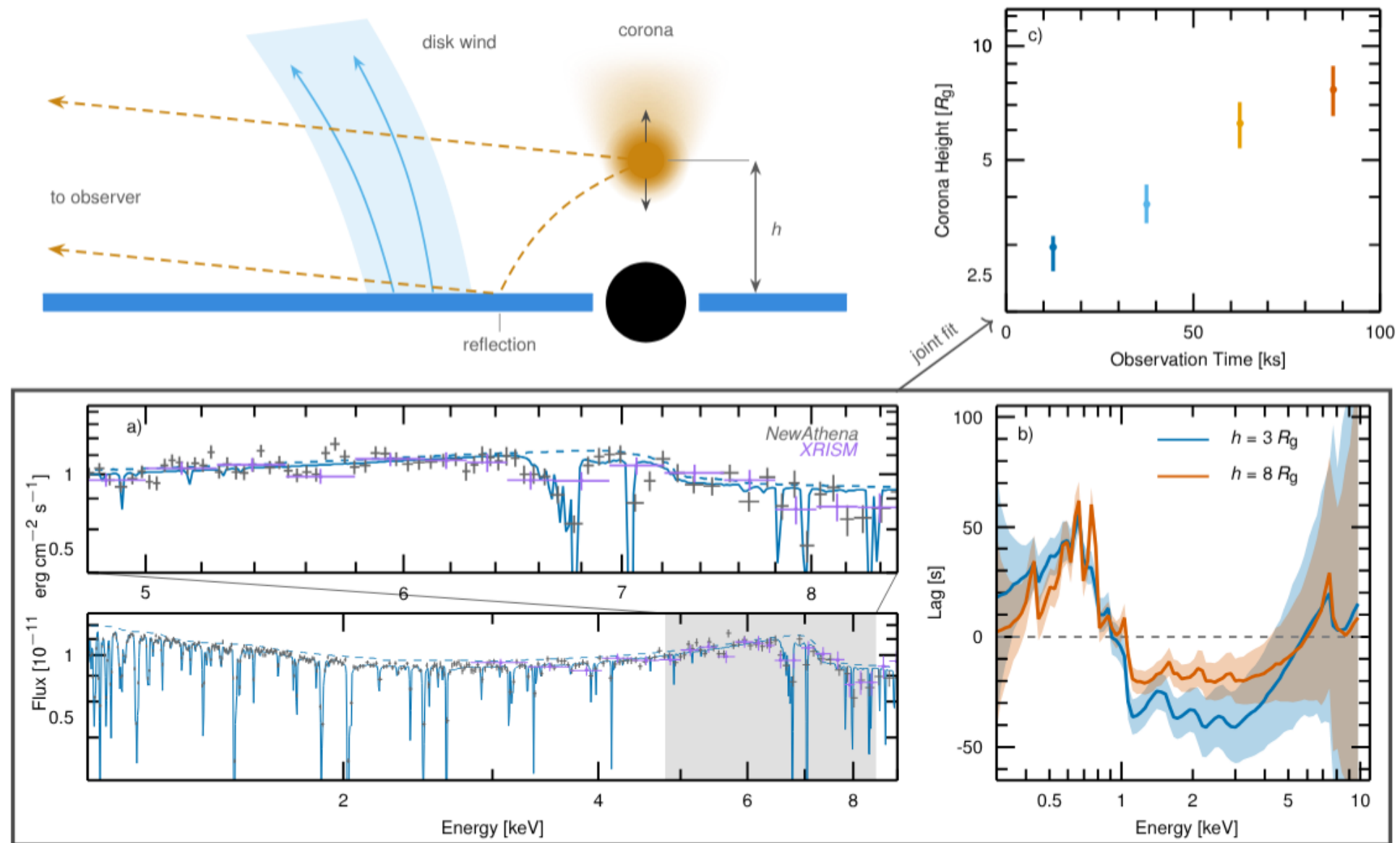


100 ks, Athena (H. Fritze, JW)



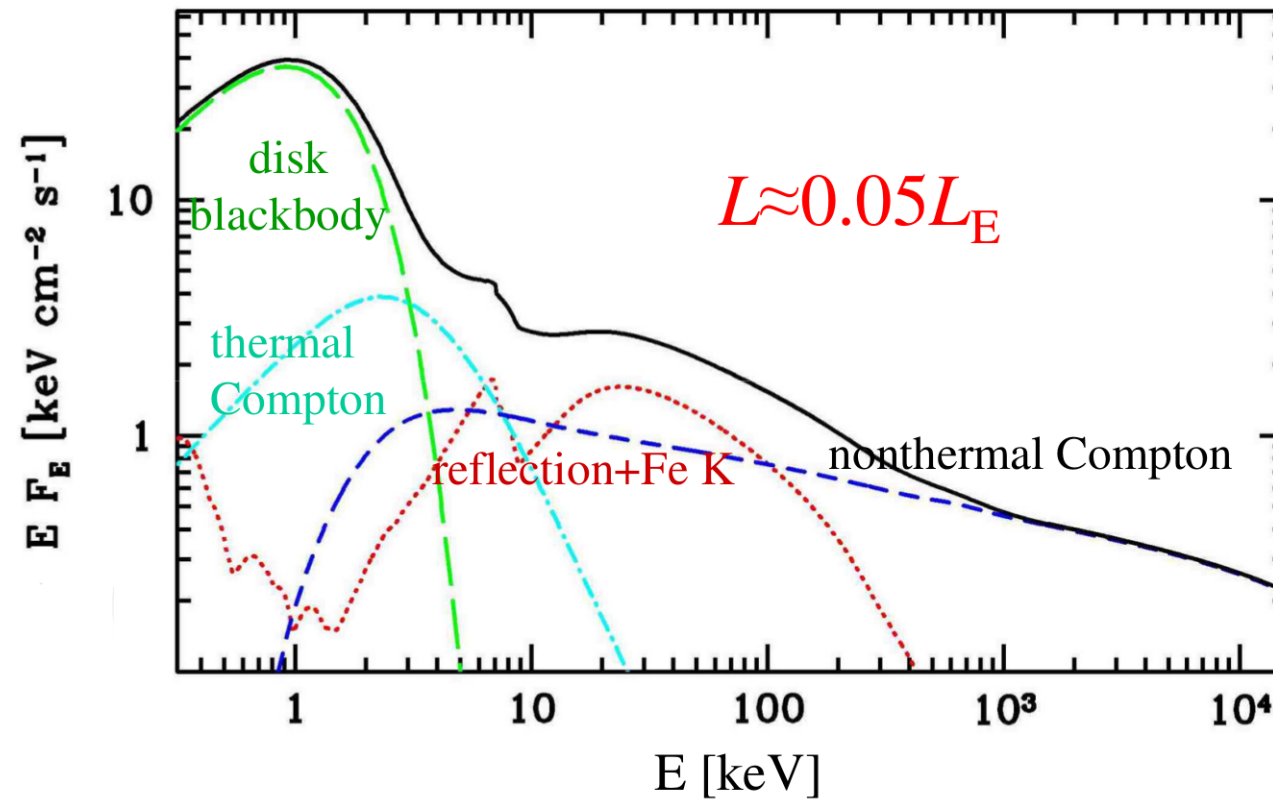
~ 1 Ms, XMM (all EPIC; F. Haberl)

(New)Athena



AGN wind obs (25 ks; T. Dauser, priv. comm., to not distribute)

What about higher energies?

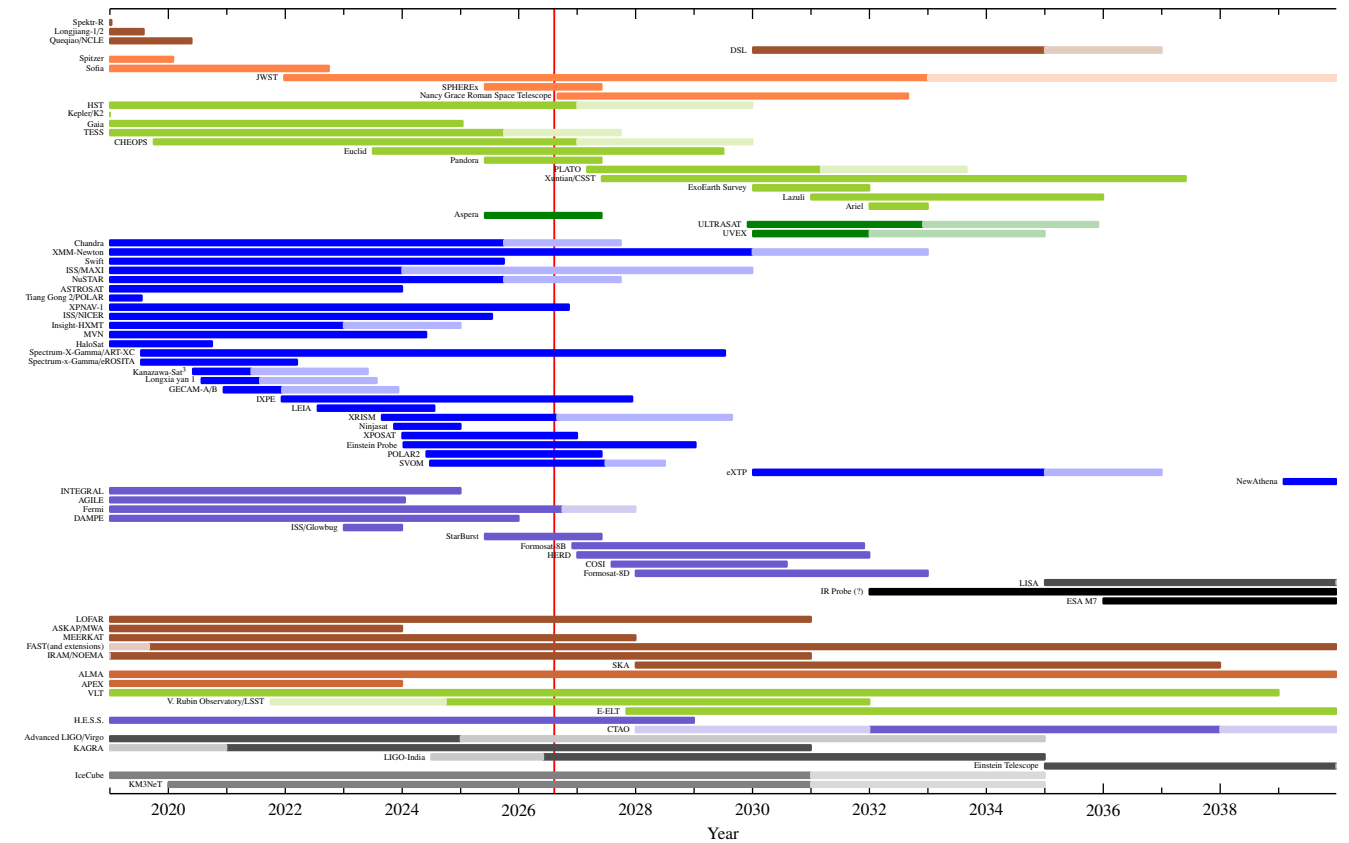
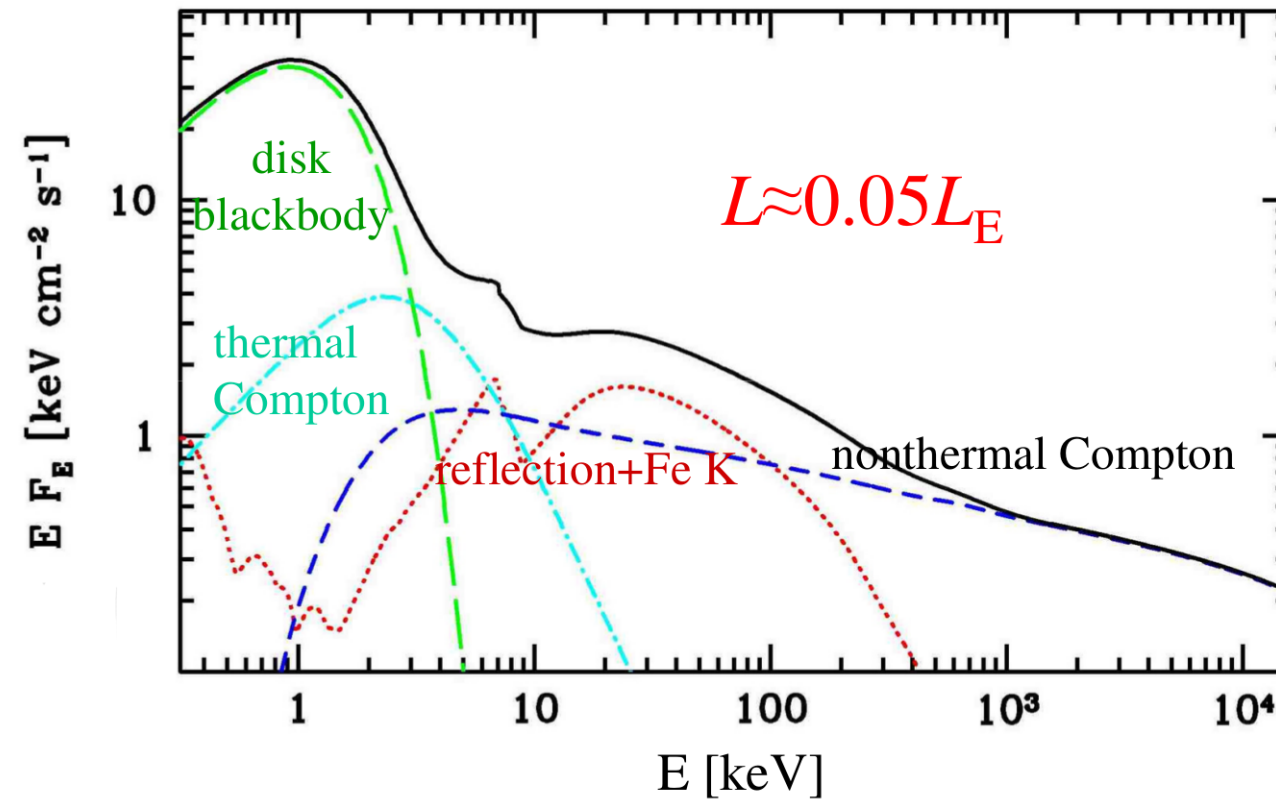


There are some things missing, however:

- **There will be no good X-ray transient finders in the 2020s and 2030s**

Opt/Radio [SKA] might help, but different selection function?

What about higher energies?

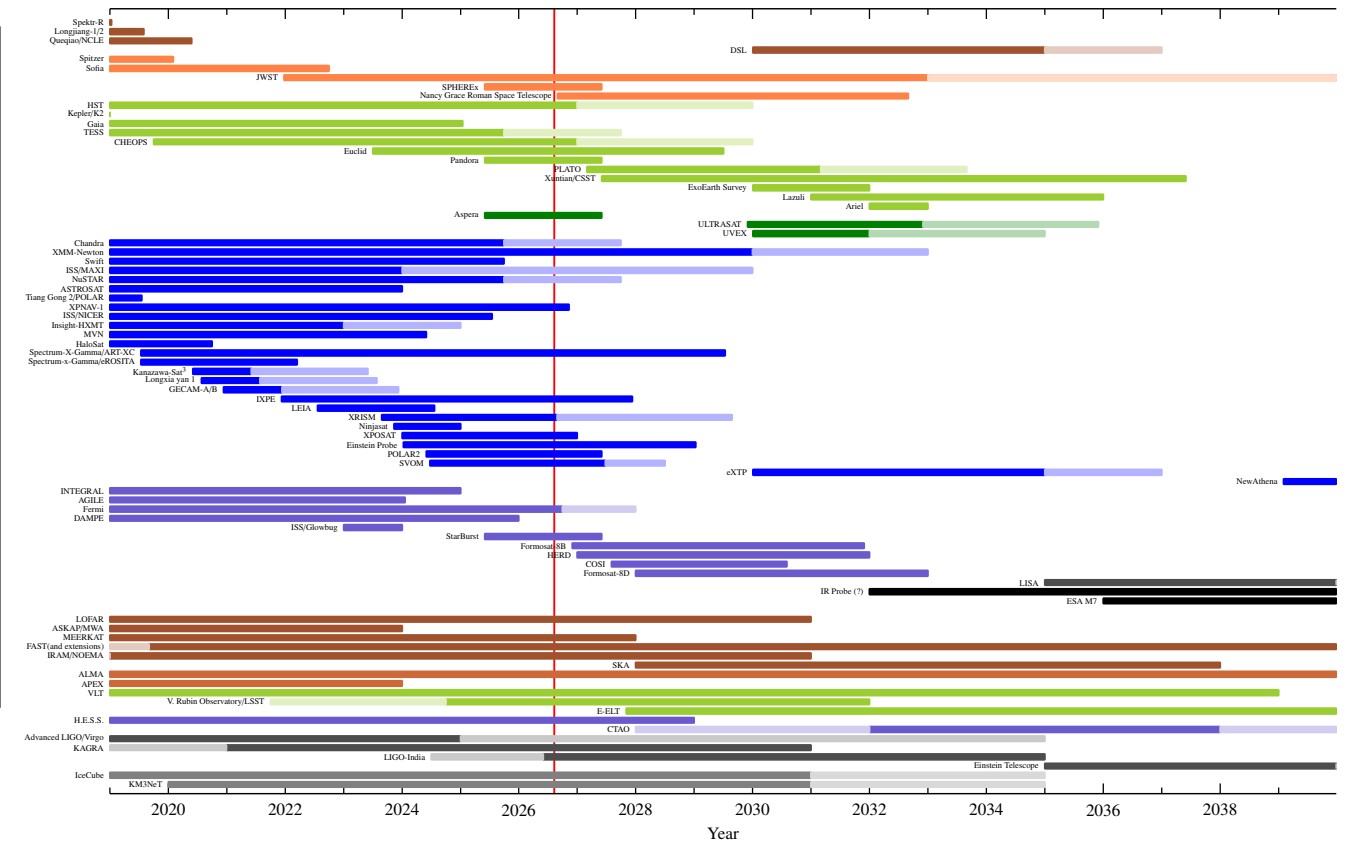
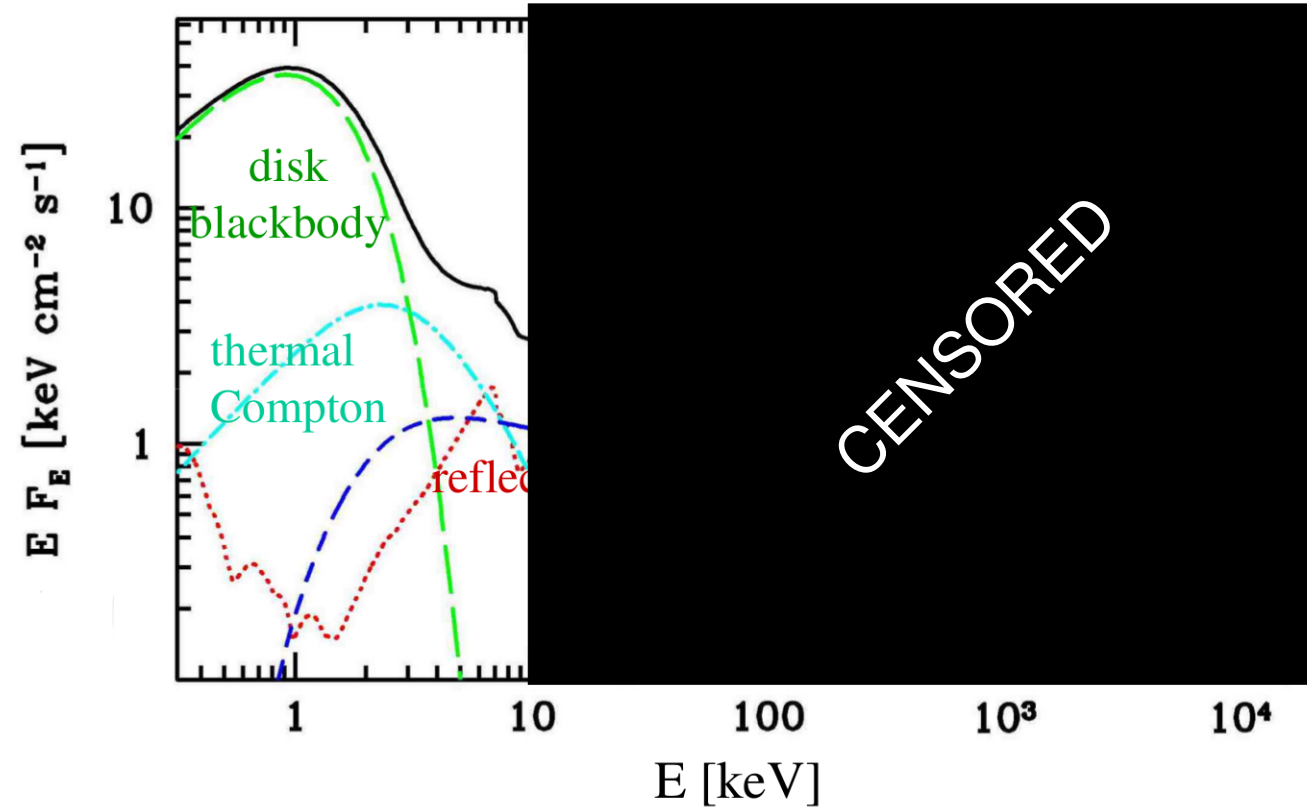


There are some things missing, however:

- There will be no good X-ray transient finders in the 2020s and 2030s

Opt/Radio [SKA] might help, but different selection function?

What about higher energies?



There are some things missing, however:

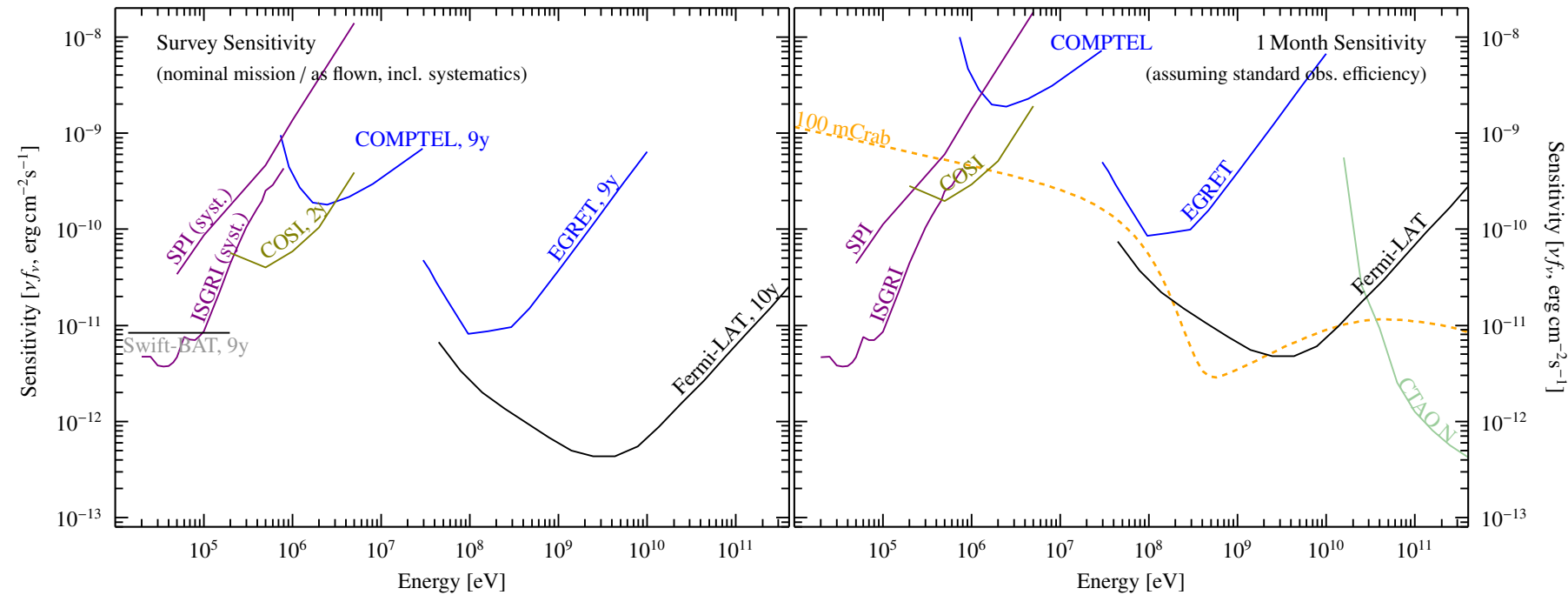
- **There will be no good X-ray transient finders in the 2020s and 2030s**

Opt/Radio [SKA] might help, but different selection function?

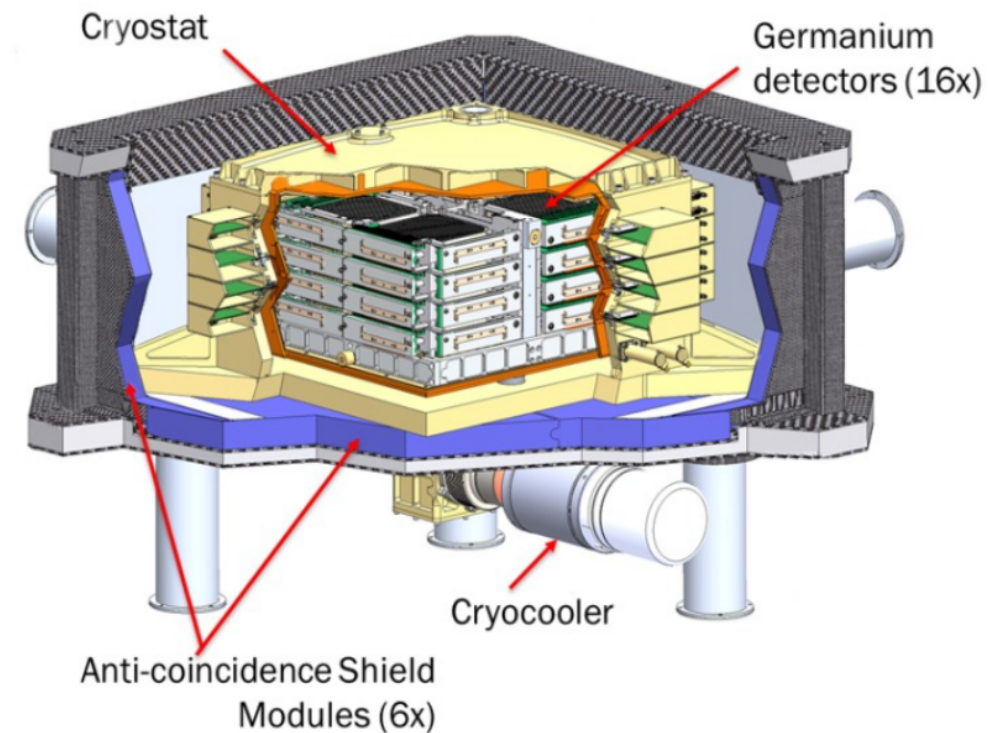
At higher energies there *will* be a data crisis:

- **Lack of >10 keV coverage will *hurt* Reflection, turn over, hard tails – while at the same time radio coverage will be finally perfect!** remark Fe-line detection is *not* detection of reflection!

What about higher energies?



MeV-Gap: no foreseeable mission in West to cover band $>$ few 10 keV band (w/exception of COSI [Compton imager, launch 2025])
in my opinion this is the real data crisis...





P. Kretschmar

- **Push for facilities > 10 keV as highest priority**

...by connecting them to big questions in astrophysics, *not* big questions in X-ray binary or X-ray astronomy.

It's a shame that Tomaso isn't here anymore to tell me why I'm wrong.

The future of X-ray binary research:

- **Current data are good enough for physics driven work!**

just because you use MCMC or some advanced, complex Bayesian statistics to model your data does not mean that you're doing physics

scientific epistemology: showing you that your model fits doesn't mean that the model describes the system and is unique

- We have **about 15 years to consolidate**, helped by eXTP, because NewAthena will bring a new deluge of data that

if we don't improve models – will bring another level of hurt.