Unveiling the hard X-ray emission of NGC 1068, a possible high-energy neutrino source

By Antoine Foisseau[1], Alexis Coleiro[1], Floriane Cangemi[1], Andrea Goldwurm[2] and Cyril Lachaud[1]

[1]: Université Paris Cité, CNRS, Astroparticule et Cosmologie, F-75013 Paris, France
[2] : Université Paris Cité, CNRS, CEA, Astroparticule et Cosmologie, F-75013 Paris, France

2024/12/11 - Cosmic rays and neutrinos in the multi-messenger era

Origin of high-energy cosmic rays (HECRs)

NGC 1068 as the most probable source of high-energy neutrinos

High-energy charged particles →deflected by $\overrightarrow{B}$ → hard to follow

Particles (p) interacts with other particles (p, γ) through hadronic processes in the relativistic jets of several sources (AGNs).

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$$\pi^0 \to 2\gamma$$
$$\pi^+ \to \mu^+ + \nu_\mu$$
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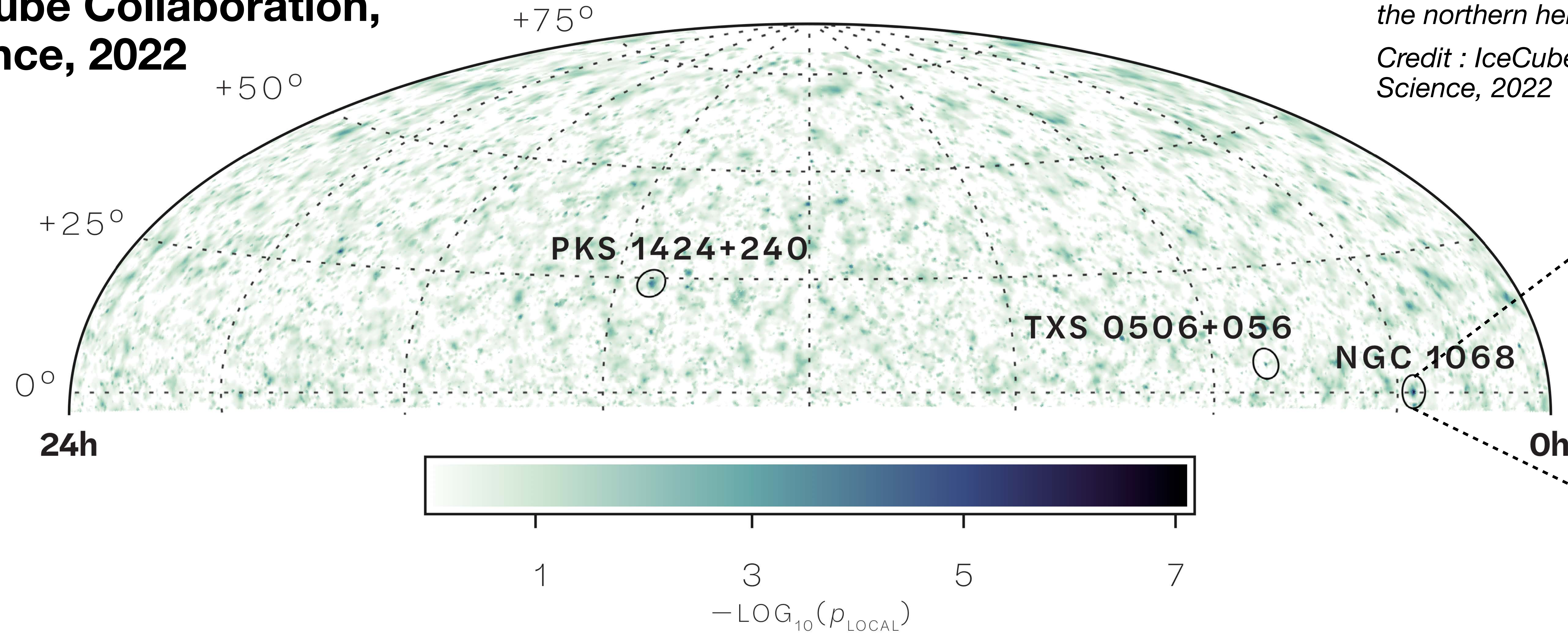
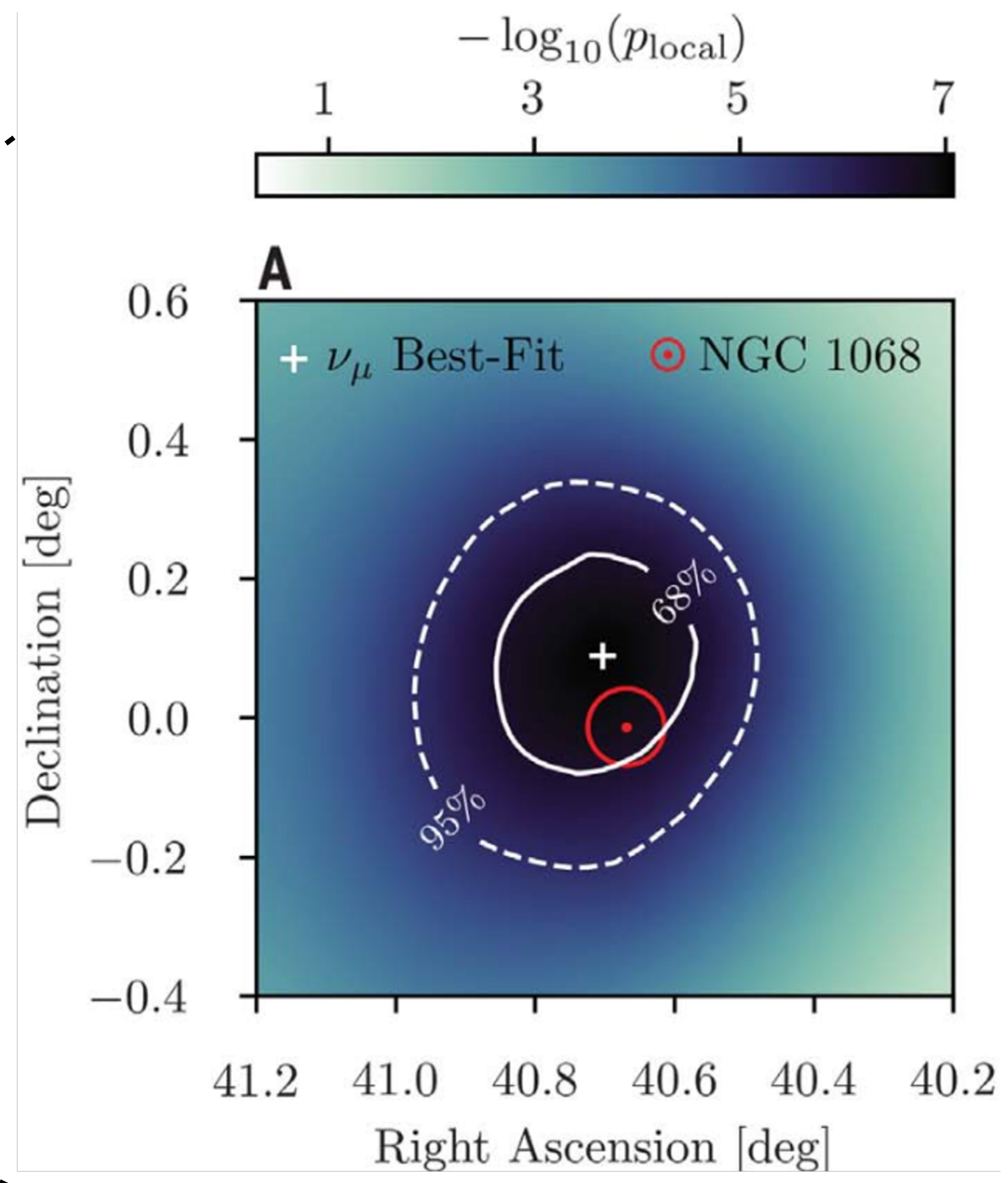
IceCube Collaboration, Science, 2022



Clustering map of neutrinos in the northern hemisphere

Credit : IceCube Collaboration, Science, 2022



⇒ NGC 1068 is the most probable source of emitting neutrinos with a significant neutrinos excess at the confidence level of 4.2σ.

⇒ One way to confirm this is to search for the presence of hadronic processes in the SED of NGC 1068.

Spectrum of NGC 1068

Seyfert 2 AGN $\Rightarrow$ viewed edge-on i.e. : $\theta_{inc} \approx 90$ deg
$\rightarrow$ **Emission in the high energy domain is not dominated by the jet**

Usually we suppose that **hadronic processes occur in the jet** and create gamma-rays and neutrinos in the same amount : $F_\gamma \approx F_\nu \Rightarrow L_\gamma \approx L_\nu$

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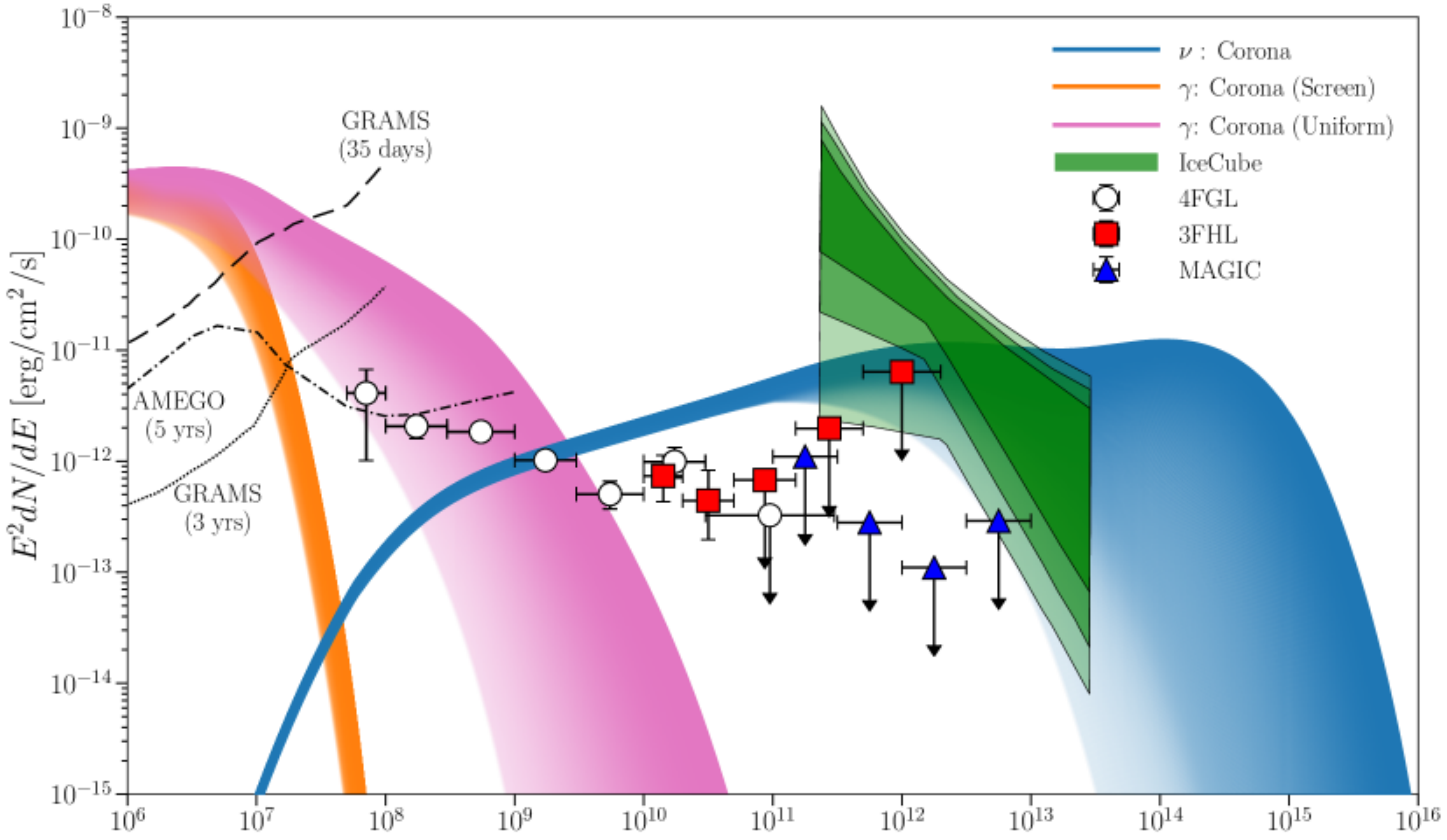
$L_\nu = (2.9 \pm 1.1) \times 10^{42} erg/s$ (1.5-15 TeV) *(IceCube Collaboration, Science 2020)*

Higher than the upper limits reported in gamma-ray above 200 GeV

↓

γ-ray absorption in the GeV-TeV



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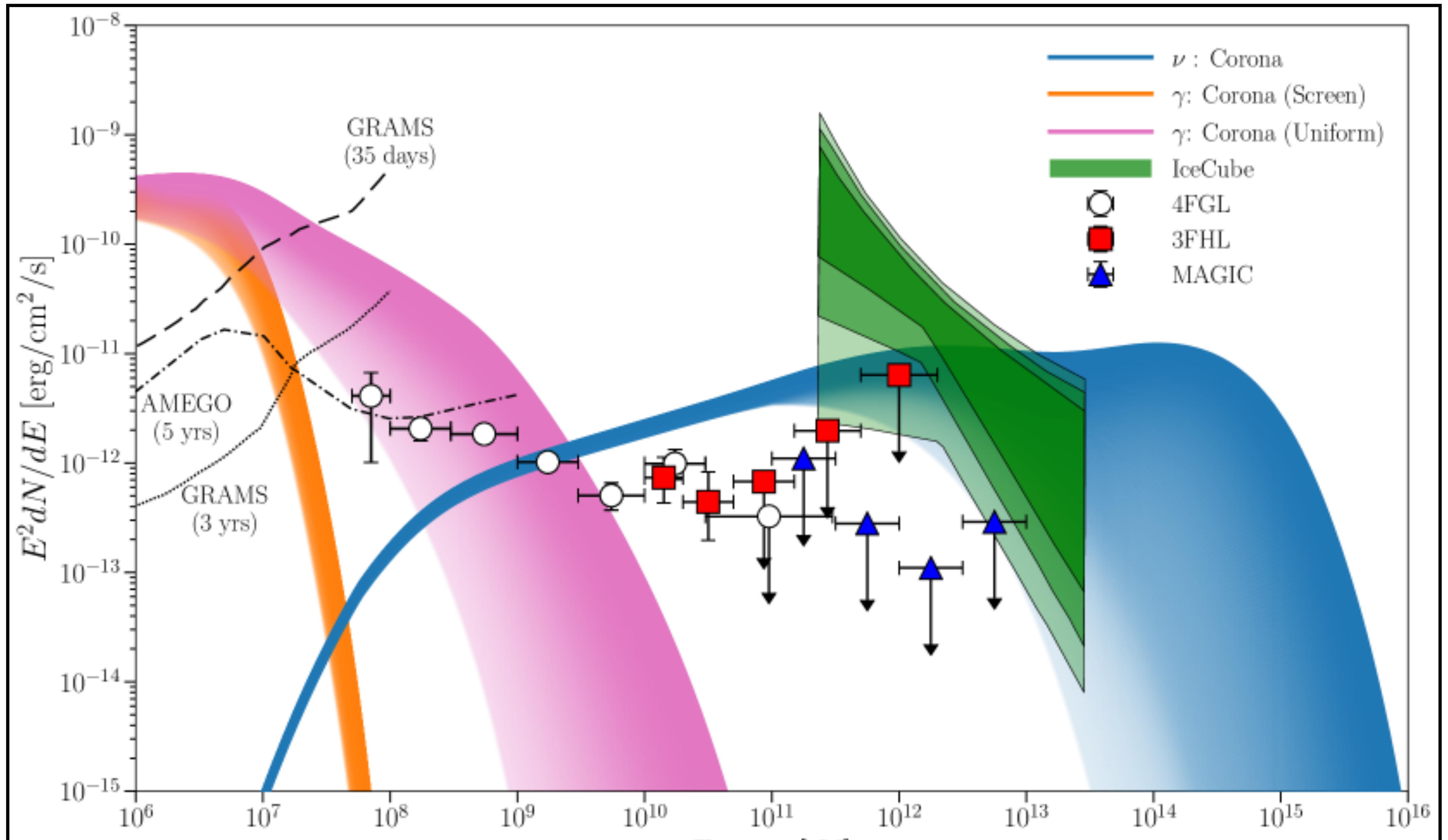

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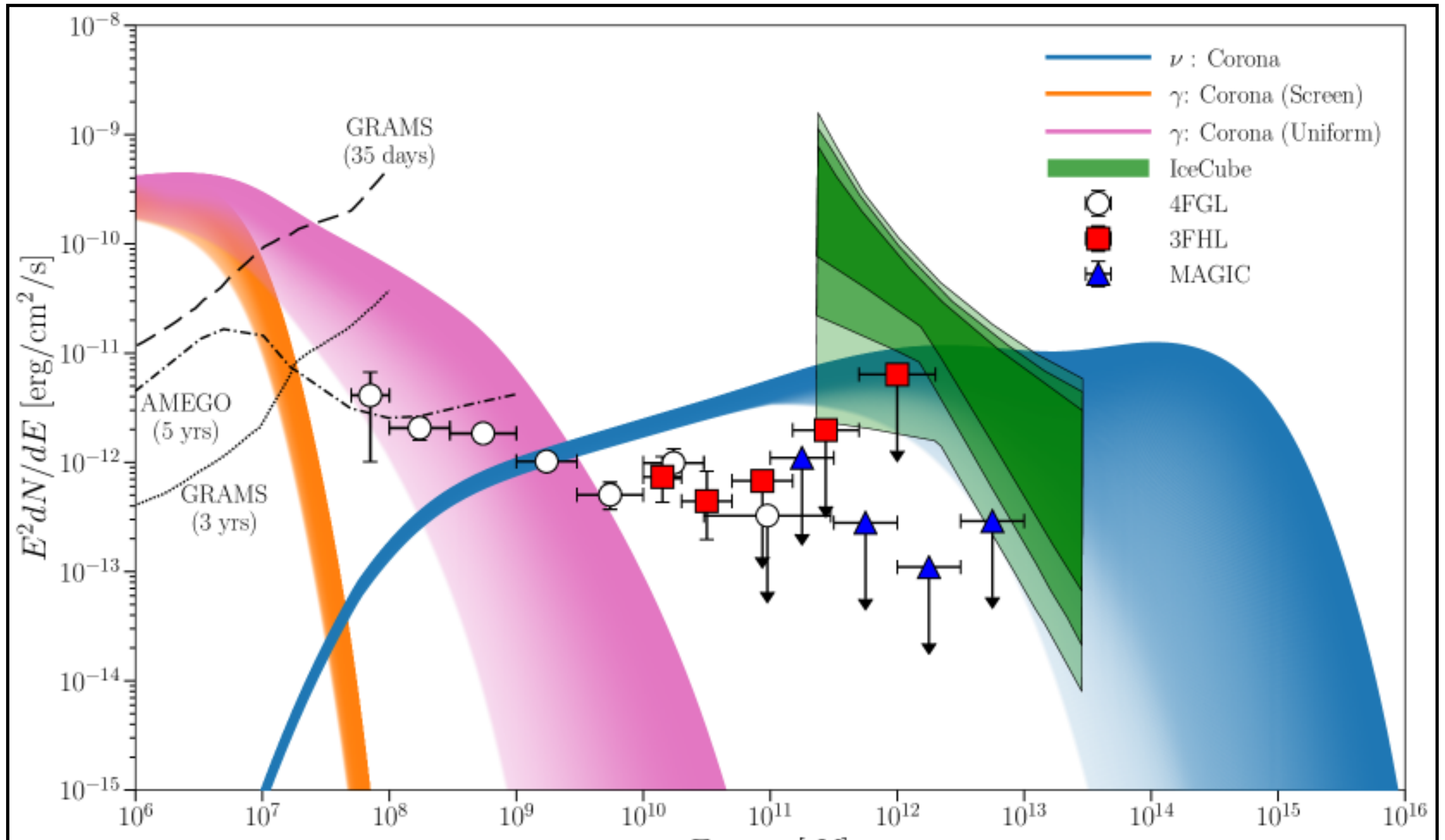

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***pp* and *pγ* could occur near the black hole (corona ?)** → **Pair-production + particles cascades** → $\Rightarrow L_{X,prim} \propto L_\nu$

Dense photon field

Re-emitted in keV-MeV

Hard X-ray study of NGC 1068

Goal of our study ?

- this work has already been done in the past **(without INTEGRAL data)** : Bauer et al, APJ, 2015
  Marinucci et al, MNRAS, 2016
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  → Update with the most recent data those works

- see if **INTEGRAL data** allow us to have **detections at hundred of keV** → **probe the spectrum at energies higher than 195 keV**

- fit a model to have a **good description of the primary X-ray emission** → $L_{X,prim}$

- compare $L_{X,prim}$ to L_ν

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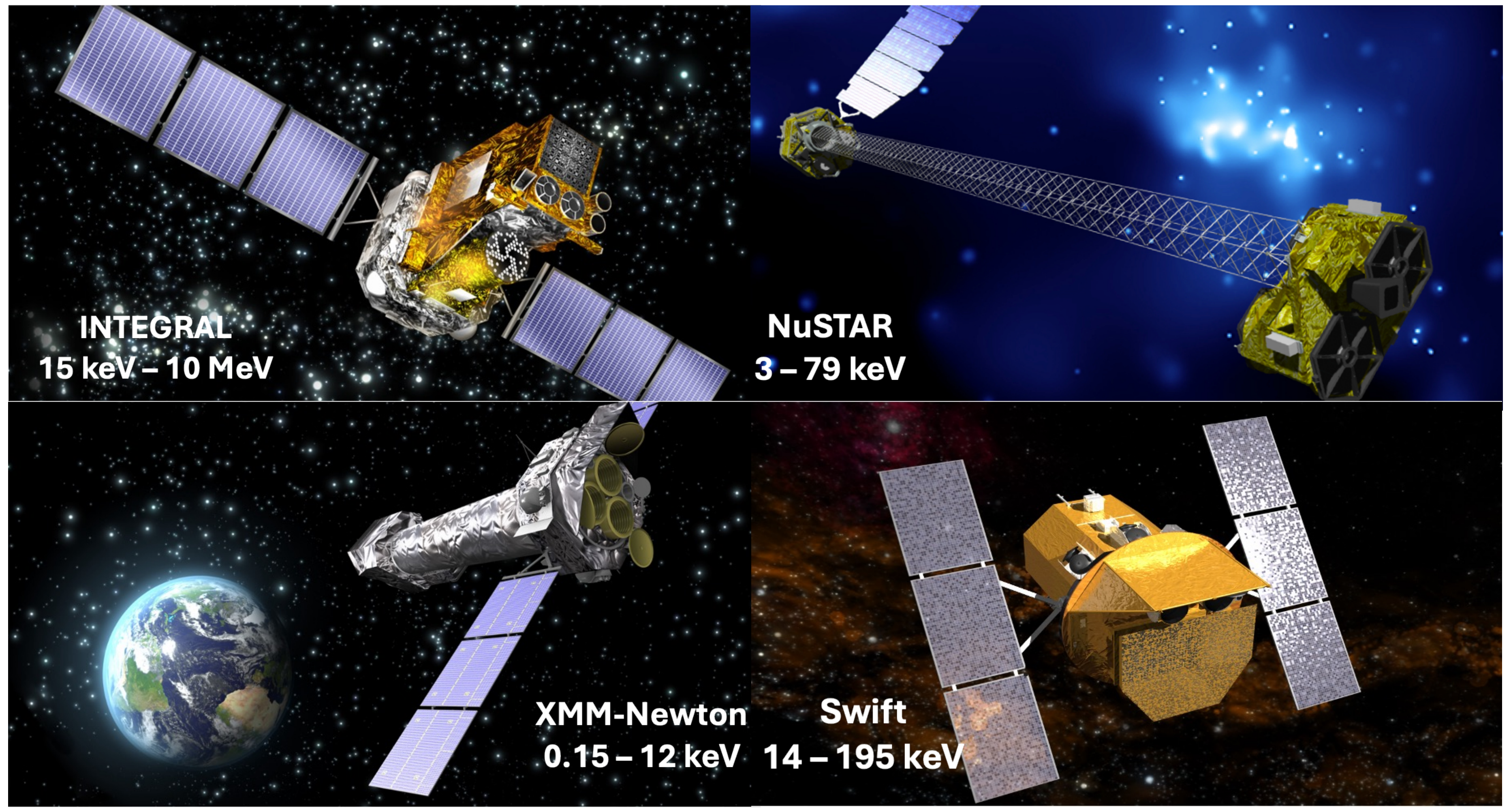
INSTRUMENT	PERIOD	EXPOSURE TIME	EXPOSURE TIME (Bauer)	EXPOSURE TIME (Zaino)
INTEGRAL-IBIS	2003-2022	1.57 Ms	—	—
INTEGRAL-SPI	2003-2022	1.46 Ms	—	—
NuSTAR FPMA/ FPMB	2012-2024	493.25 ks / 491.7 ks	123.9 ks / 123.7 ks	206.8 ks / 206.2 ks
SWIFT-BAT	2004-2018	157 months	70 months	No BAT XRT : 5.7 ks
XMM-Newton	2000	70.36 ks	70.36 ks	—

⇒ data can be stacked because :
1) NGC 1068 doesn't show any strong variability in the X-ray domain
2) the IceCube study was integrated in time.



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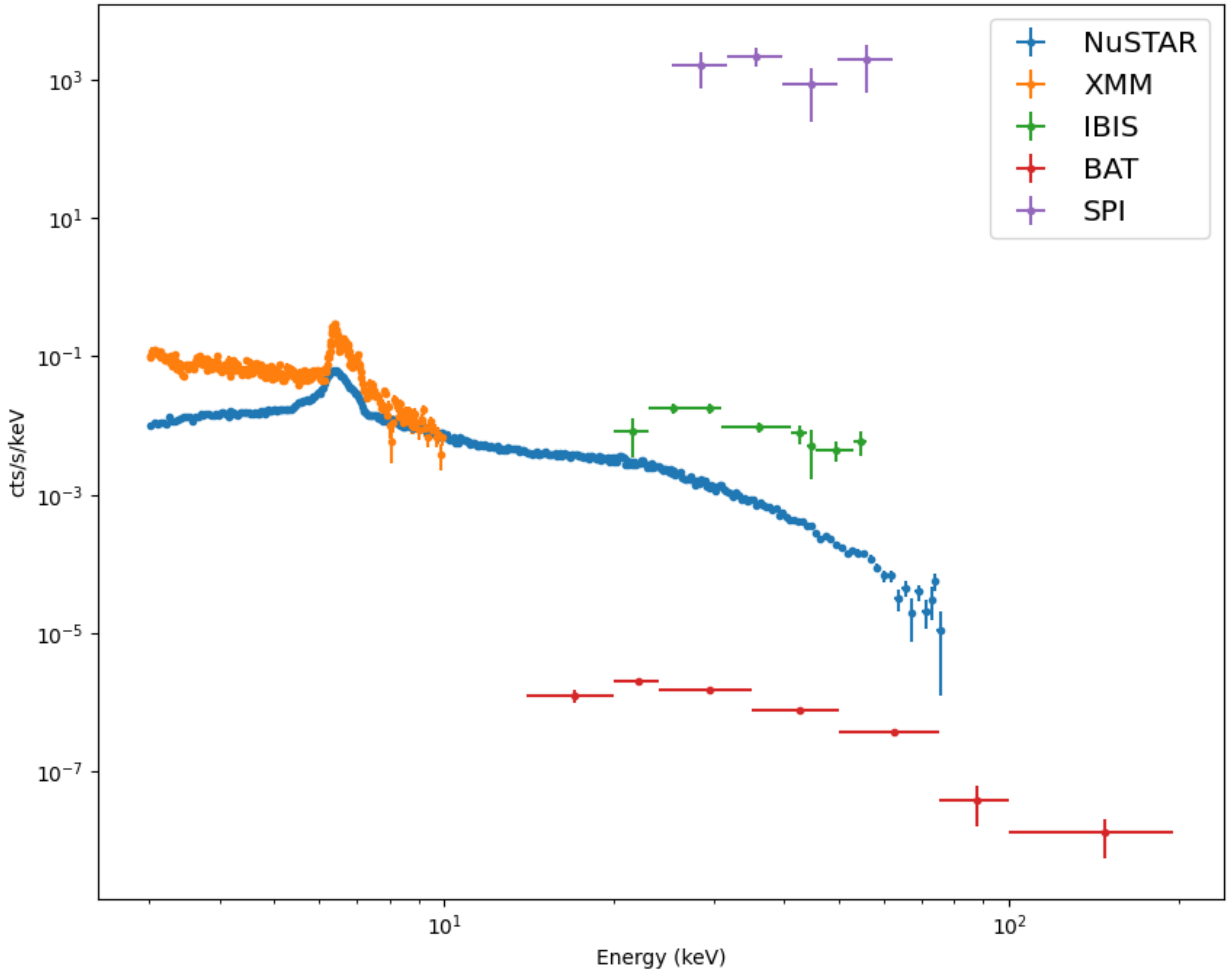
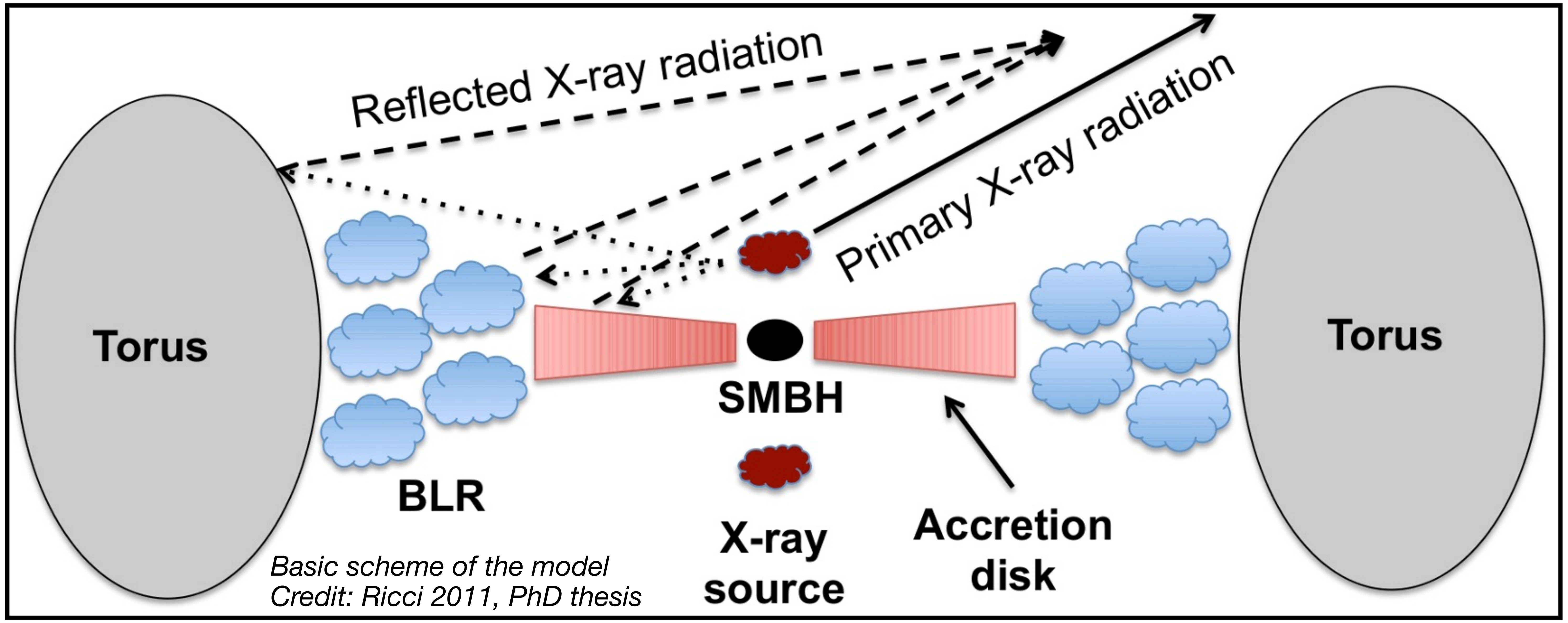


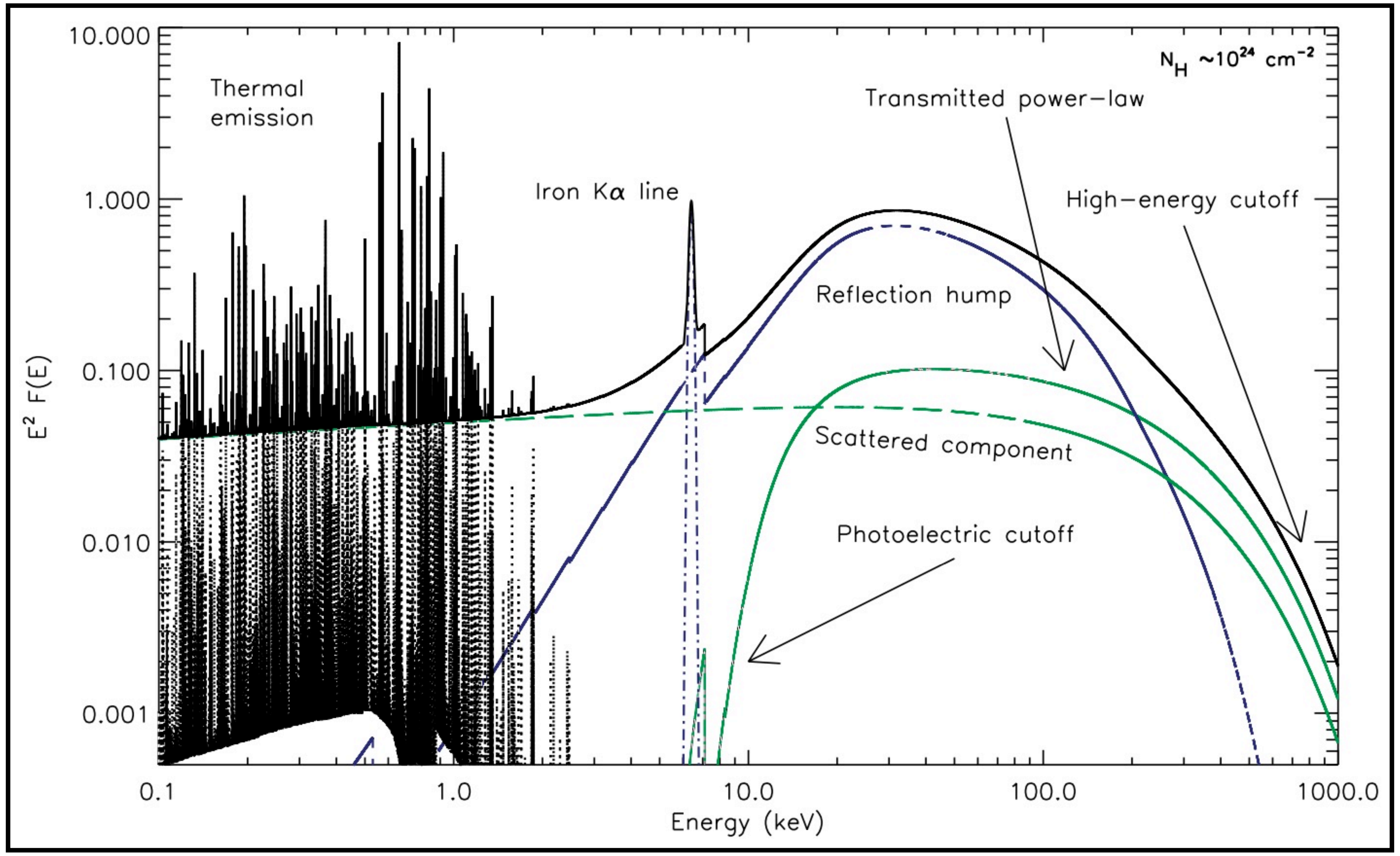
X-ray model

Model :

- Double reflection emission which are then reprocessed in the l.o.s
- Primary X-ray emission from the corona
- Emission from the host galaxy (XBRs, ULXs etc..)



Basic scheme of the model
Credit: Ricci 2011, PhD thesis



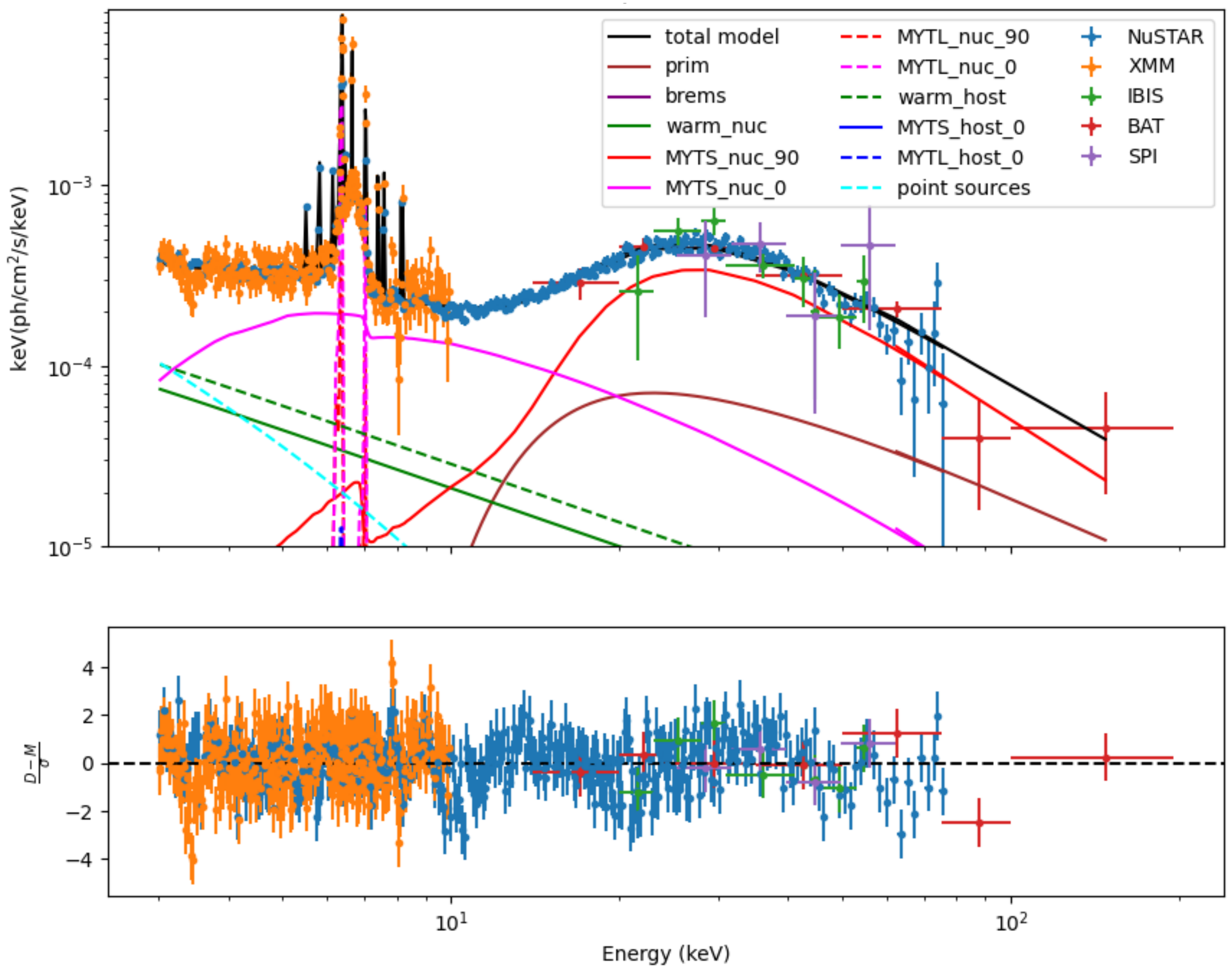
Source is viewed edge on i.e. $\theta_{inc} \approx 90$ deg → X-ray primary emission passes through the torus → highly absorbed in the soft X-ray

Typical SED of Compton thick Seyfert 2 galaxy.
Credit: Ricci 2011, PhD thesis

Results

Spectrum cover the range **[3;195] keV** → INTEGRAL doesn't allows us to have detection beyond 200 keV.
⇒ we can't investigate the presence of a cutoff around the MeV

PARAMETER	MY STUDY	ZAINO+20
Γ	$2.07^{+0.02}_{-0.03}$	$2.10^{+0.01}_{-0.01}$
$E_c(keV)$	$120.1^{+21.5}_{-17.0}$	128
$K(ph/cm^2/s/keV)$	$4.4^{+2.6}_{-1.6} \times 10^{-2}$	$0.5^{+0.5}_{-0.2}$
$N_H(cm^{-2})$	$3.38^{+0.40}_{-0.37} \times 10^{24}$	$5.9^{+1.0}_{-0.8} \times 10^{24}$
χ^2_r	1.27	1.07



- $E_c = 120.1^{+21.5}_{-17.0}$ keV → **consistent with a leptonic scenario.**

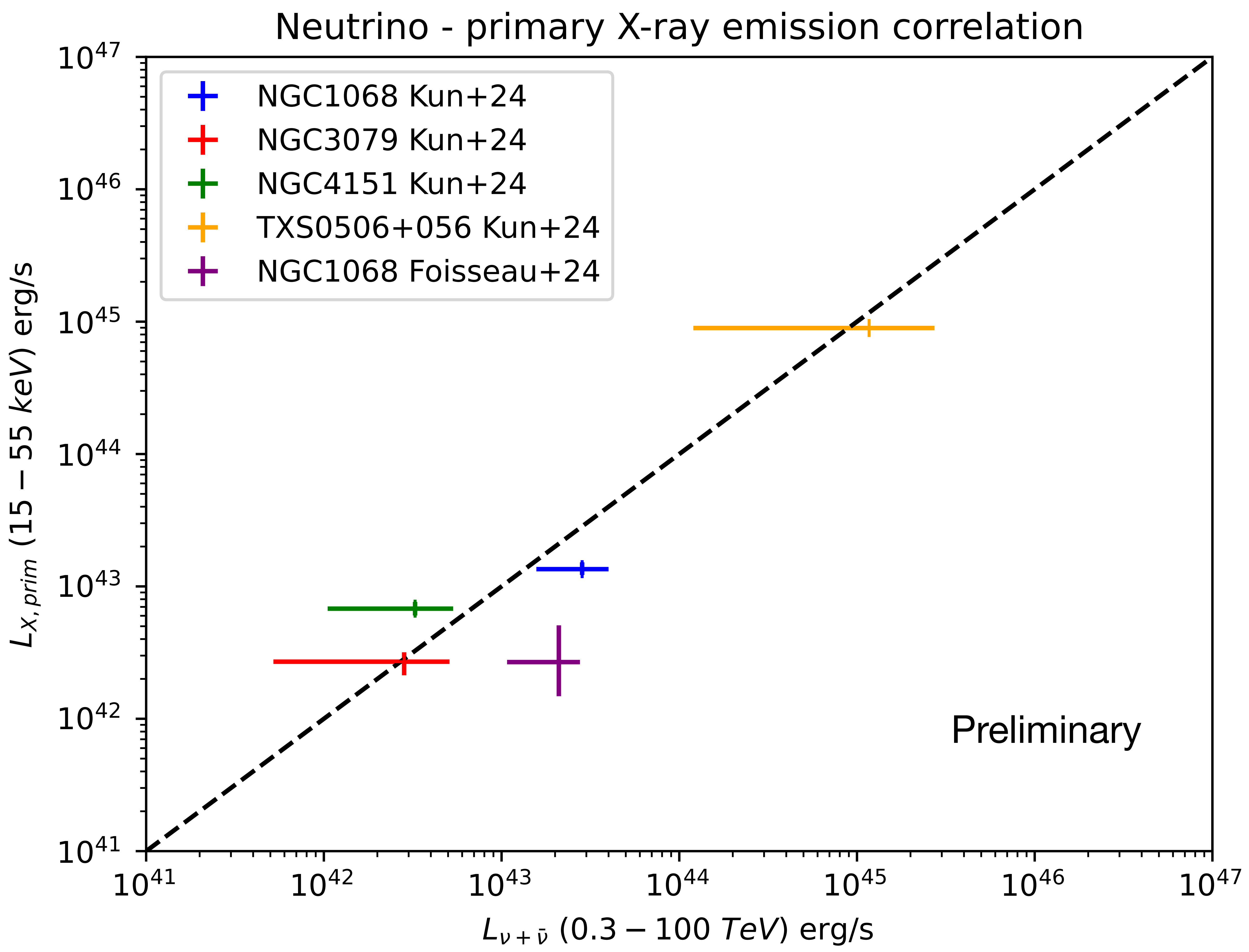
- Hard to investigate the presence of the hadronic processes because our spectrum does not extend beyond 200 keV.
  → primary X-ray emission will dominate at higher energy.

Results

$L_{X,prim} = 2.7^{+2.4}_{-1.2} \times 10^{42}$ erg/s (15-55 keV)
$L_\nu = 2.1^{+0.7}_{-1.2} \times 10^{43}$ erg/s (0.3-100 TeV)
(IceCube Collaboration, Science 2020)

$\Rightarrow L_{X,prim} = 0.13^{+0.44}_{-0.05}\ L_\nu$

We correct the value presented in Kun+24 for NGC 1068.
⇒ Doing the same analysis with the other sources ?



Conclusion

- Updated the precedent X-ray spectra of NGC 1068 in adding new data (NuSTAR, BAT, **IBIS and SPI**)
  ⇒ spectrum covering the range **3-195 keV**

- INTEGRAL-IBIS/SPI don't allow to have detection above 200 keV.

- Spectrum is dominated by the reflections (as expected)

- X-ray emission of the corona is still **consistent with a leptonic scenario** $\rightarrow E_c = 120.1^{+21.5}_{-17.0}$ keV

- **However :**
  1 - primary X-ray emission seems to dominate at hundreds of keV (more than 200 keV)
  2 - $L_{X,prim} = 0.13^{+0.44}_{-0.05}\ L_{\nu}$

⇒ **we can't reject the hypothesis of hadronic processes in the close environment of the black hole**
⇒data at higher energies could help to investigate the presence of an other cutoff as expected in some models.

Estimations for IBIS :
With 2 Ms more we would have detections up to ~300 keV