TORUS 2018 - The many faces of the AGN obscuration

Investigating the nature and geometry of NGC 1068 through NuSTAR observations and future X-ray polarimetry

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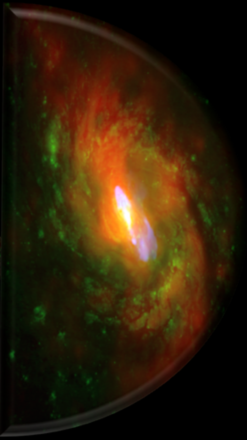
ROMA TRE
UNIVERSITÀ DEGLI STUDI

Marshall Space Flight Center

agenzia spaziale italiana

IXPE
Imaging
X-Ray
Polarimetry
Explorer

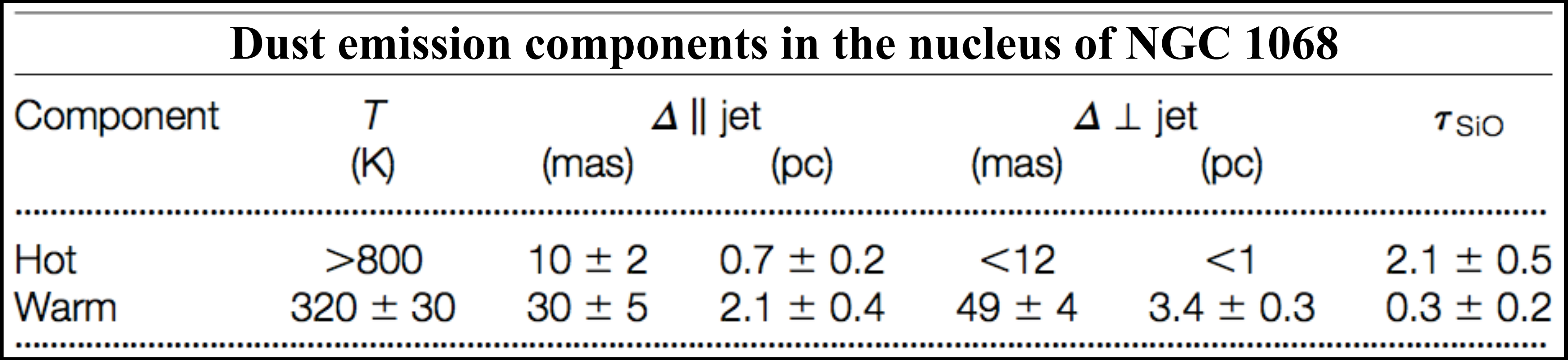
Outline



- 🟡 Unveiling the nucleus of NGC 1068
- 🟠 The 2017-2018 NuSTAR monitoring
- 🟢 What can we expect from X-ray polarimetry?
- 🔵 Summary and conclusions

The dusty torus in NGC 1068

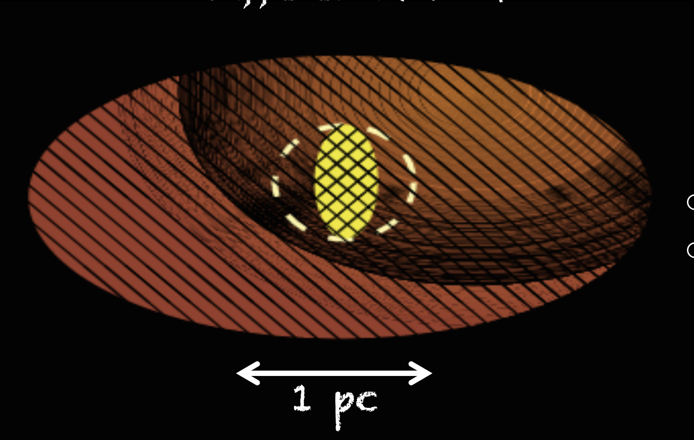
❑ **Interferometric mid-infrared observations of NGC 1068**
  ➢ *spatial resolution of the dust structures*



Dust emission components in the nucleus of NGC 1068

Component	T	$\Delta \parallel$ jet		$\Delta \perp$ jet		τ_{SiO}
	(K)	(mas)	(pc)	(mas)	(pc)	
Hot	>800	10 ± 2	0.7 ± 0.2	<12	<1	2.1 ± 0.5
Warm	320 ± 30	30 ± 5	2.1 ± 0.4	49 ± 4	3.4 ± 0.3	0.3 ± 0.2

Jaffe et al. 2004



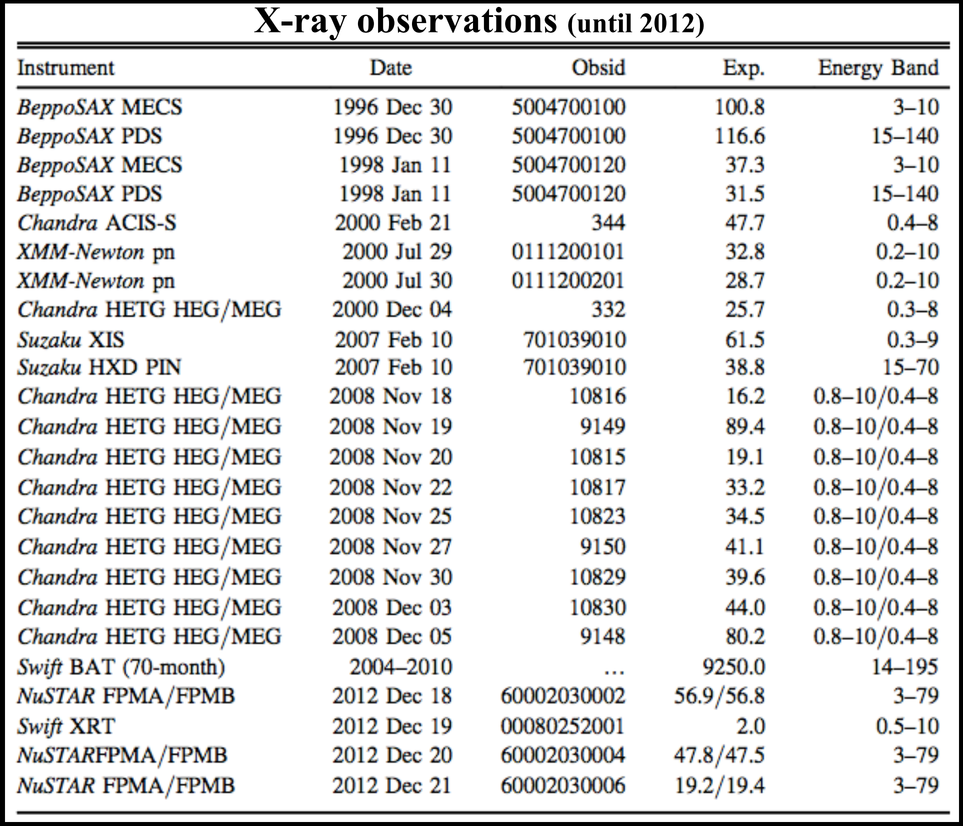
Torus consistent with a two-component dust distribution:

- an inner (0.7±0.2 pc) hot (T > 800 K) component;
- a more extended (~3-4 pc) colder component (T~320 K).

Unveiling the nucleus of NGC 1068

☐ NGC 1068 in X-rays

- multi-epoch X-ray observations until 2012

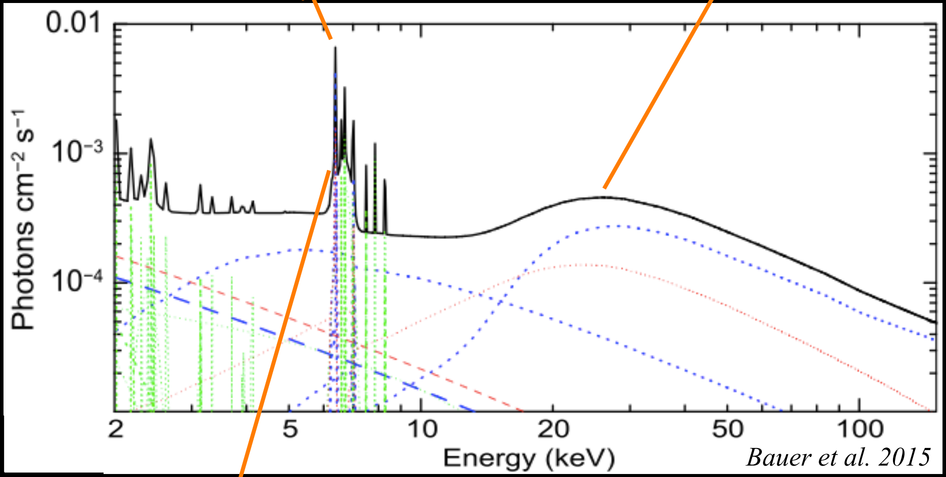


X-ray observations (until 2012)

Instrument	Date	Obsid	Exp.	Energy Band
BeppoSAX MECS	1996 Dec 30	5004700100	100.8	3–10
BeppoSAX PDS	1996 Dec 30	5004700100	116.6	15–140
BeppoSAX MECS	1998 Jan 11	5004700120	37.3	3–10
BeppoSAX PDS	1998 Jan 11	5004700120	31.5	15–140
Chandra ACIS-S	2000 Feb 21	344	47.7	0.4–8
XMM-Newton pn	2000 Jul 29	0111200101	32.8	0.2–10
XMM-Newton pn	2000 Jul 30	0111200201	28.7	0.2–10
Chandra HETG HEG/MEG	2000 Dec 04	332	25.7	0.3–8
Suzaku XIS	2007 Feb 10	701039010	61.5	0.3–9
Suzaku HXD PIN	2007 Feb 10	701039010	38.8	15–70
Chandra HETG HEG/MEG	2008 Nov 18	10816	16.2	0.8–10/0.4–8
Chandra HETG HEG/MEG	2008 Nov 19	9149	89.4	0.8–10/0.4–8
Chandra HETG HEG/MEG	2008 Nov 20	10815	19.1	0.8–10/0.4–8
Chandra HETG HEG/MEG	2008 Nov 22	10817	33.2	0.8–10/0.4–8
Chandra HETG HEG/MEG	2008 Nov 25	10823	34.5	0.8–10/0.4–8
Chandra HETG HEG/MEG	2008 Nov 27	9150	41.1	0.8–10/0.4–8
Chandra HETG HEG/MEG	2008 Nov 30	10829	39.6	0.8–10/0.4–8
Chandra HETG HEG/MEG	2008 Dec 03	10830	44.0	0.8–10/0.4–8
Chandra HETG HEG/MEG	2008 Dec 05	9148	80.2	0.8–10/0.4–8
Swift BAT (70-month)	2004–2010	...	9250.0	14–195
NuSTAR FPMA/FPMB	2012 Dec 18	60002030002	56.9/56.8	3–79
Swift XRT	2012 Dec 19	00080252001	2.0	0.5–10
*NuSTAR*FPMA/FPMB	2012 Dec 20	60002030004	47.8/47.5	3–79
NuSTAR FPMA/FPMB	2012 Dec 21	60002030006	19.2/19.4	3–79

Bauer et al. 2015

The broadband cold reflected emission of NGC 1068 is due to multiple reflectors with three distinct column densities.



Bauer et al. 2015

$N_{H,1} \sim 10^{25}$ cm^{-2}

$N_{H,2} = (1.4 \pm 0.1) \times 10^{23}$ cm^{-2}

$N_{H,3} \sim (4-10) \times 10^{24}$ cm^{-2}

Remember talk by F. Bauer

Unveiling the nucleus of NGC 1068

☐ NGC 1068 in X-rays

- 2014-2015 XMM-Newton & NuSTAR joint campaign

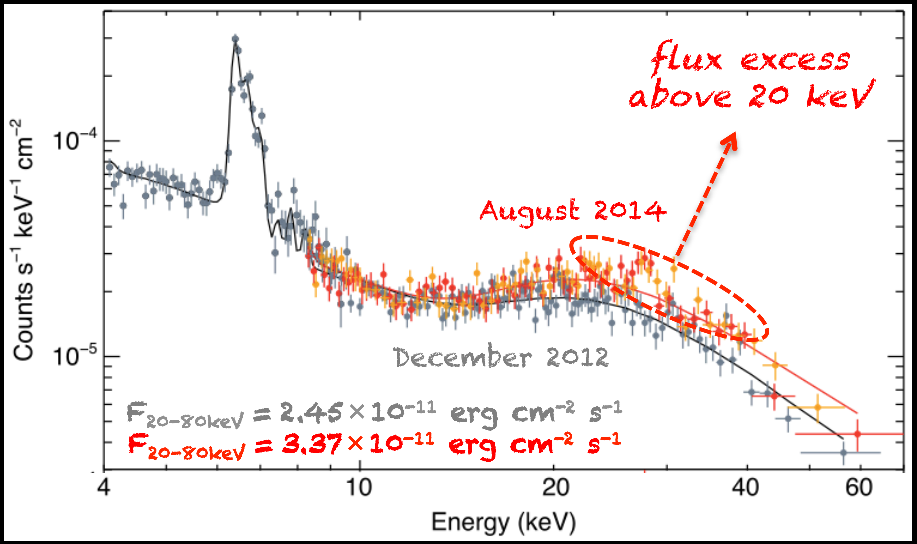
☐ NuSTAR

Obs. ID	Date	Exp. time (ks)
60002033002	2014-08-18	52
60002033004	2015-02-05	53

☐ XMM-Newton

Obs. ID	Date	Exp. time (ks)
0740060201	2014-07-10	44
0740060301	2014-07-18	39
0740060401	2014-08-19	37
0740060501	2015-02-03	37

Marinucci et al. 2016



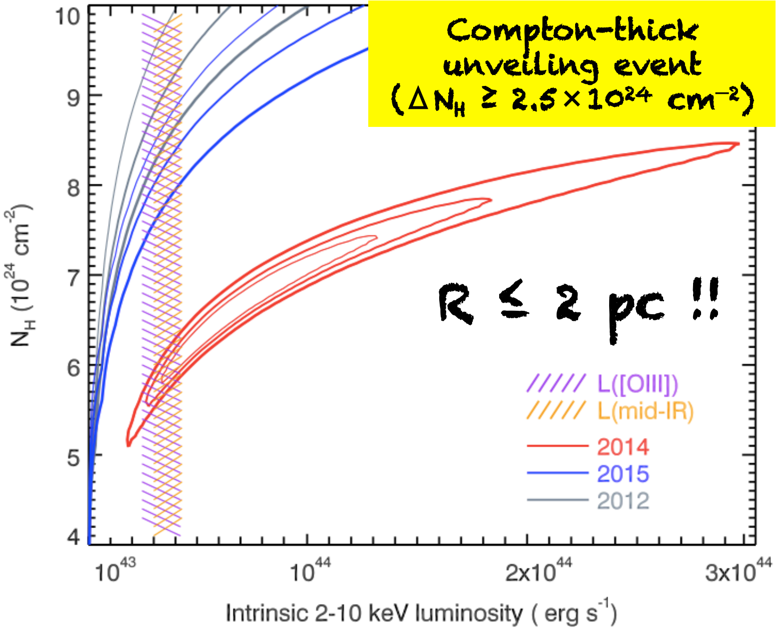
flux excess above 20 keV

August 2014

December 2012

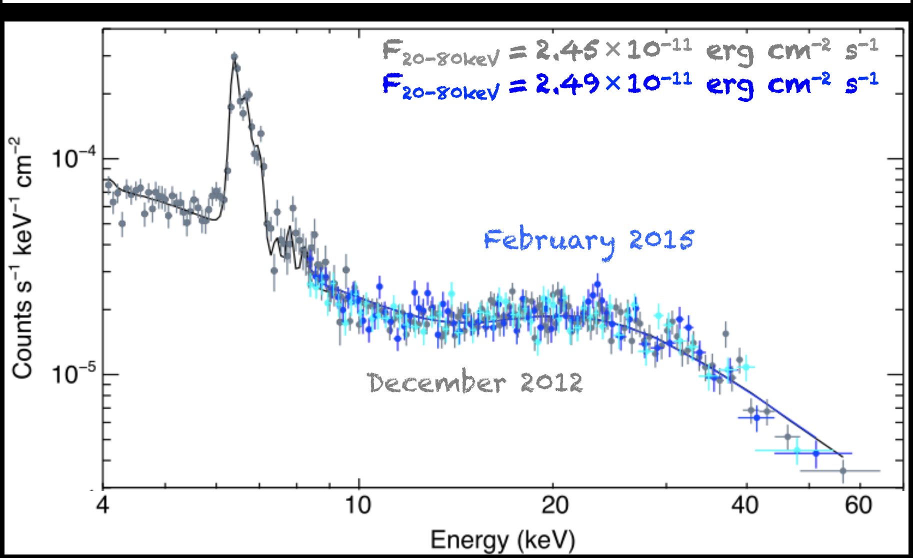
$F_{20-80keV} = 2.45 \times 10^{-11}$ erg cm^{-2} s^{-1}

$F_{20-80keV} = 3.37 \times 10^{-11}$ erg cm^{-2} s^{-1}



Compton-thick unveiling event ($\Delta N_H \geq 2.5 \times 10^{24}$ cm^{-2})

R ≤ 2 pc !!



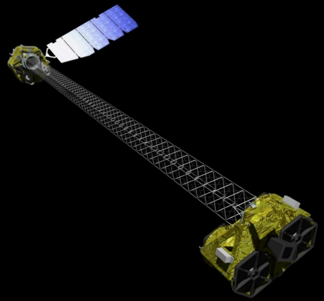
$F_{20-80keV} = 2.45 \times 10^{-11}$ erg cm^{-2} s^{-1}

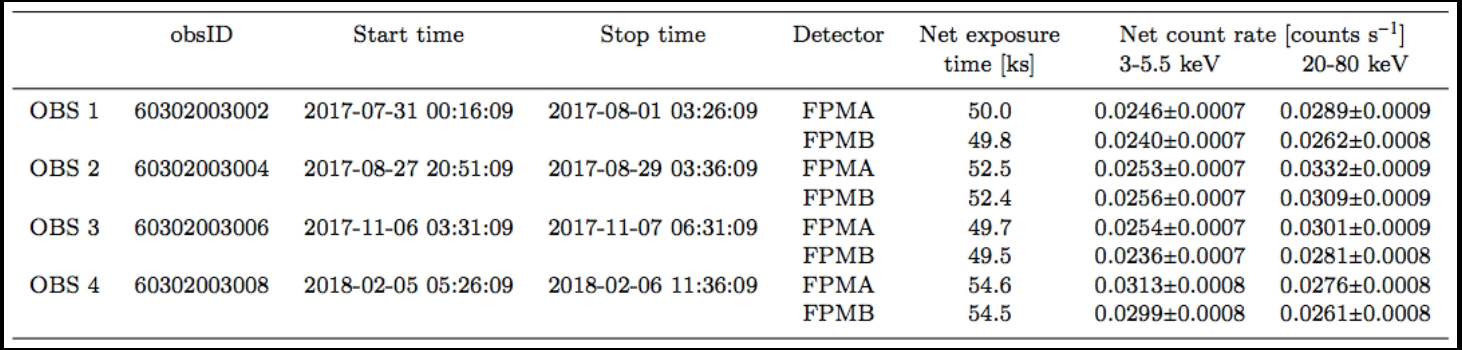
$F_{20-80keV} = 2.49 \times 10^{-11}$ erg cm^{-2} s^{-1}

February 2015

December 2012

The 2017-2018 NuSTAR monitoring

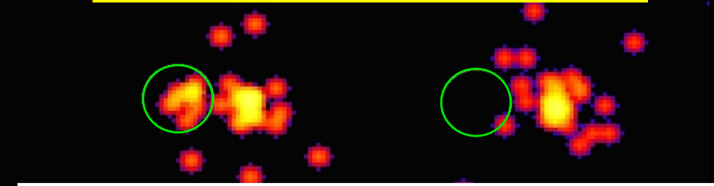


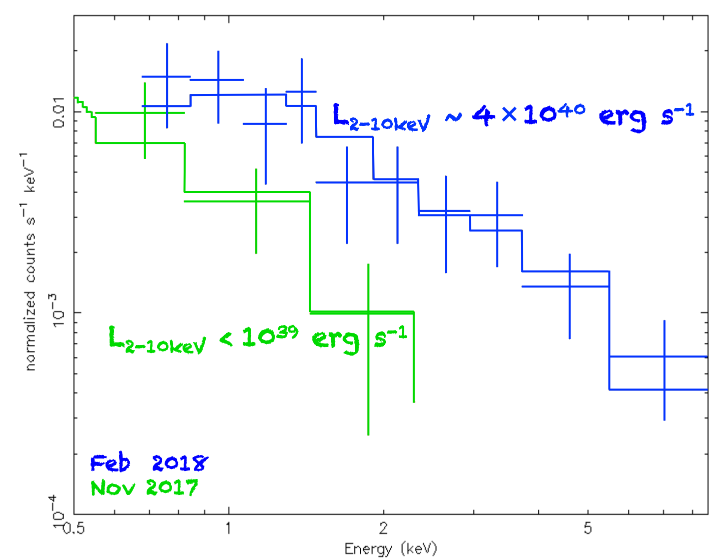


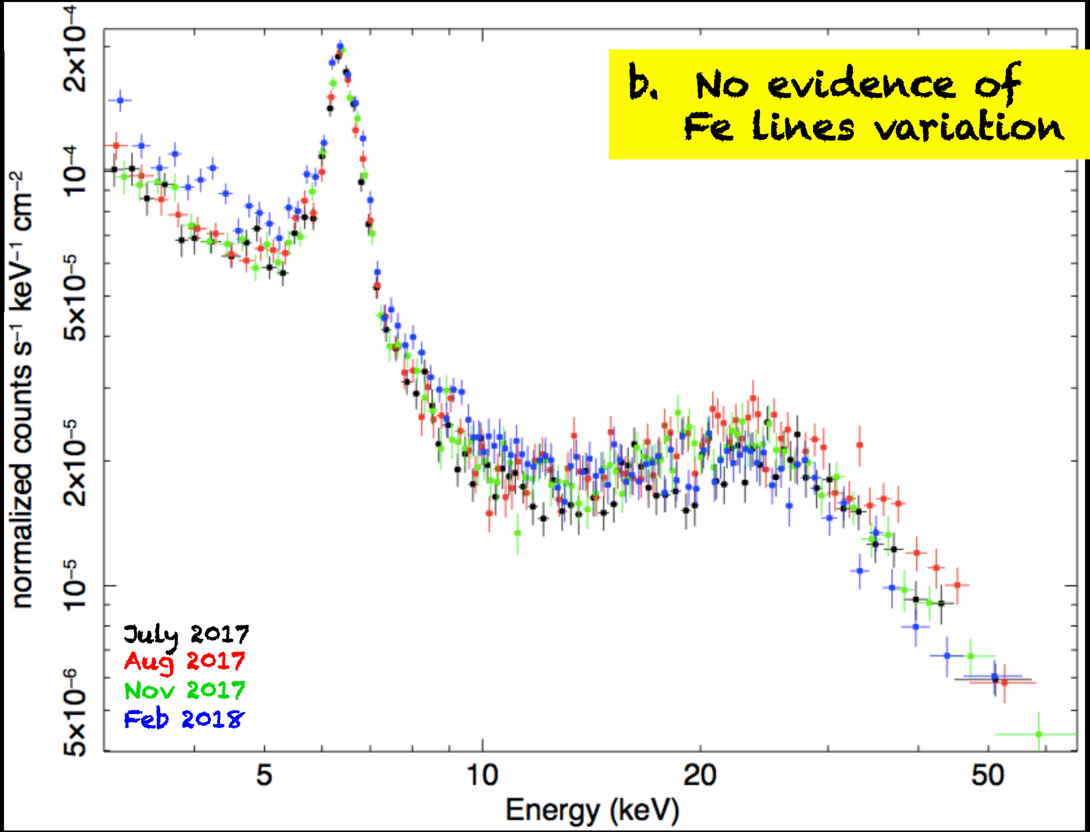
	obsID	Start time	Stop time	Detector	Net exposure time [ks]	Net count rate [counts s^{-1}] 3-5.5 keV	20-80 keV
OBS 1	60302003002	2017-07-31 00:16:09	2017-08-01 03:26:09	FPMA	50.0	0.0246±0.0007	0.0289±0.0009
				FPMB	49.8	0.0240±0.0007	0.0262±0.0008
OBS 2	60302003004	2017-08-27 20:51:09	2017-08-29 03:36:09	FPMA	52.5	0.0253±0.0007	0.0332±0.0009
				FPMB	52.4	0.0256±0.0007	0.0309±0.0009
OBS 3	60302003006	2017-11-06 03:31:09	2017-11-07 06:31:09	FPMA	49.7	0.0254±0.0007	0.0301±0.0009
				FPMB	49.5	0.0236±0.0007	0.0281±0.0008
OBS 4	60302003008	2018-02-05 05:26:09	2018-02-06 11:36:09	FPMA	54.6	0.0313±0.0008	0.0276±0.0008
				FPMB	54.5	0.0299±0.0008	0.0261±0.0008

Zaino et al. in prep.

a. $F_{3-5.5keV}$ increases by ~35% in Feb 2018

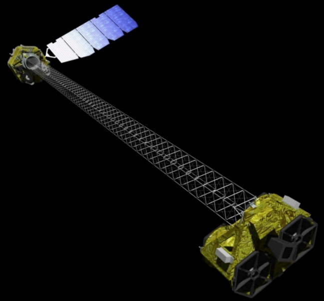


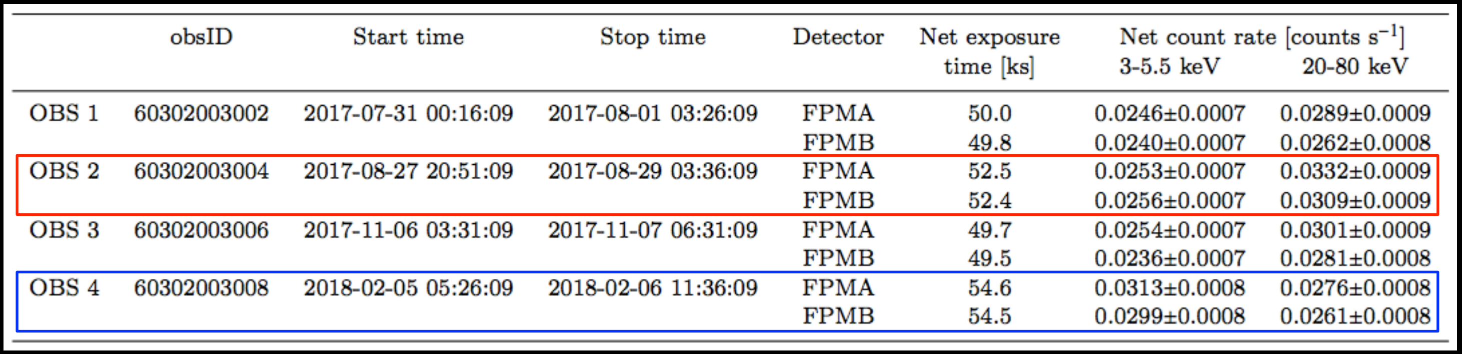




b. No evidence of Fe lines variation

The 2017-2018 NuSTAR monitoring

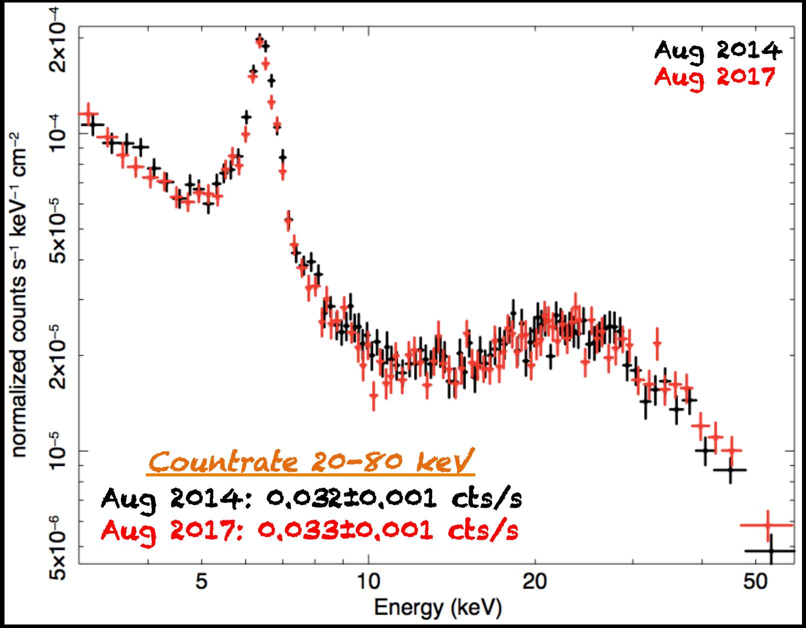




	obsID	Start time	Stop time	Detector	Net exposure time [ks]	Net count rate [counts s^{-1}]	
						3-5.5 keV	20-80 keV
OBS 1	60302003002	2017-07-31 00:16:09	2017-08-01 03:26:09	FPMA	50.0	0.0246±0.0007	0.0289±0.0009
				FPMB	49.8	0.0240±0.0007	0.0262±0.0008
OBS 2	60302003004	2017-08-27 20:51:09	2017-08-29 03:36:09	FPMA	52.5	0.0253±0.0007	0.0332±0.0009
				FPMB	52.4	0.0256±0.0007	0.0309±0.0009
OBS 3	60302003006	2017-11-06 03:31:09	2017-11-07 06:31:09	FPMA	49.7	0.0254±0.0007	0.0301±0.0009
				FPMB	49.5	0.0236±0.0007	0.0281±0.0008
OBS 4	60302003008	2018-02-05 05:26:09	2018-02-06 11:36:09	FPMA	54.6	0.0313±0.0008	0.0276±0.0008
				FPMB	54.5	0.0299±0.0008	0.0261±0.0008

Zaino et al. in prep.

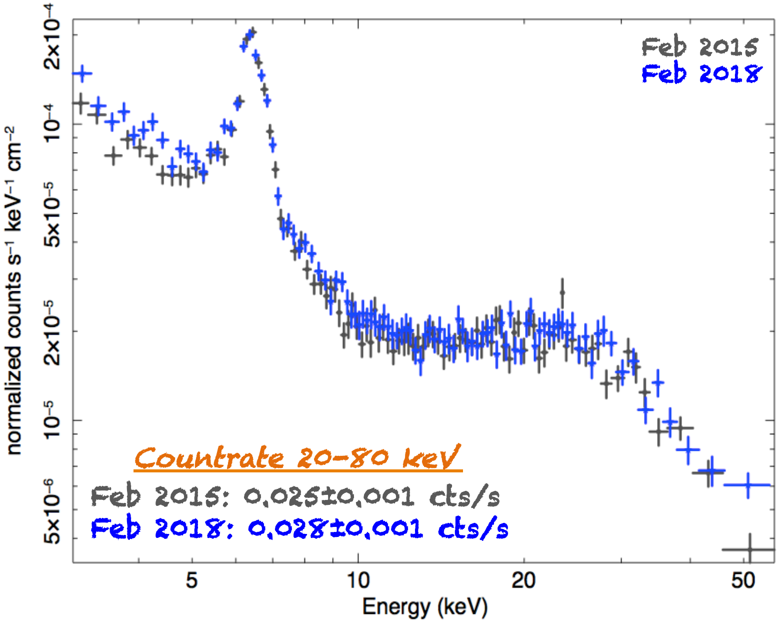
NGC 1068 shows a behaviour similar to that observed three years ago



Countrate 20-80 keV

Aug 2014: 0.032±0.001 cts/s

Aug 2017: 0.033±0.001 cts/s



Countrate 20-80 keV

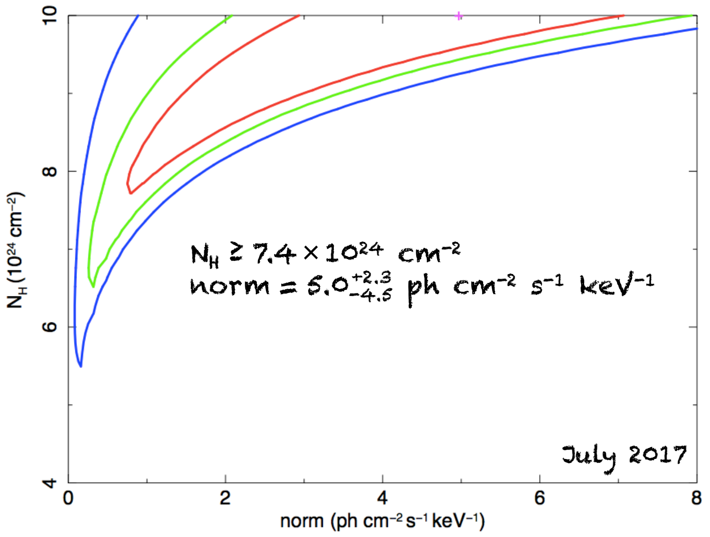
Feb 2015: 0.025±0.001 cts/s

Feb 2018: 0.028±0.001 cts/s

But now, we have two more observations...

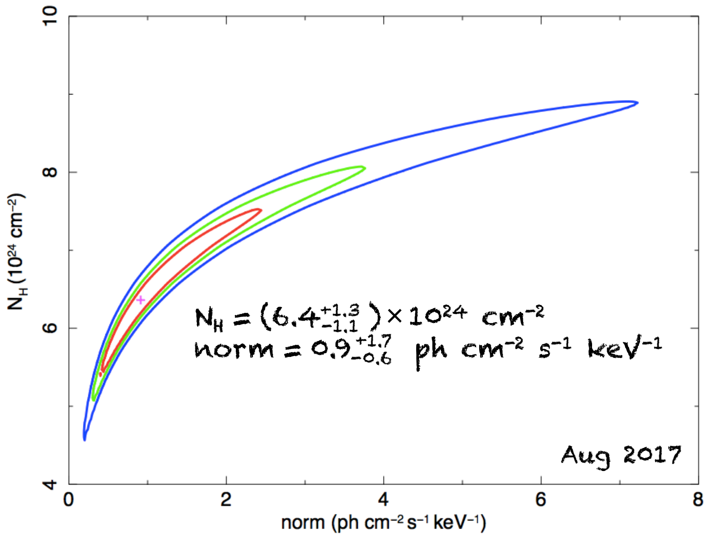
Results

We adopt the Bauer +15 model leaving only the obscuring N_H and flux of the primary component free to vary.



$N_H \gtrsim 7.4 \times 10^{24}$ cm^{-2}
norm $= 5.0^{+2.3}_{-4.5}$ ph cm^{-2} s^{-1} keV^{-1}

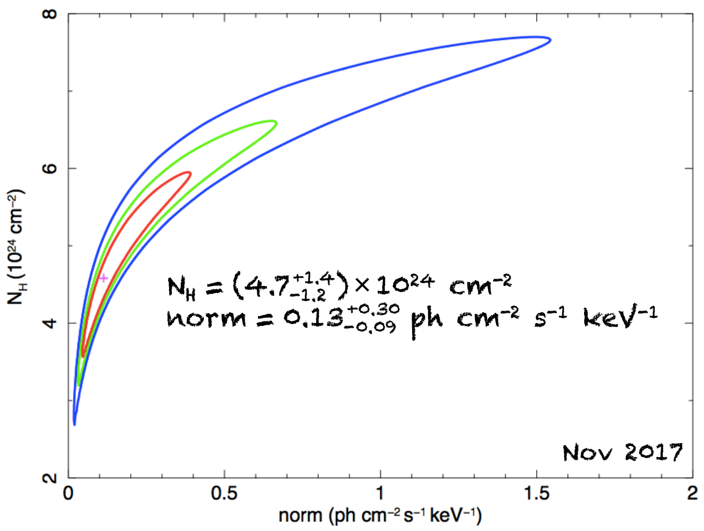
July 2017



$N_H = (6.4^{+1.3}_{-1.1}) \times 10^{24}$ cm^{-2}
norm $= 0.9^{+1.7}_{-0.6}$ ph cm^{-2} s^{-1} keV^{-1}

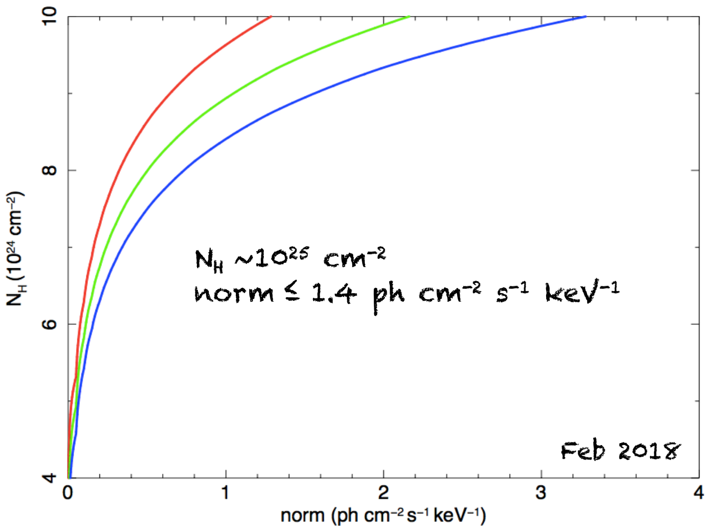
Aug 2017

Zaino et al. in prep.



$N_H = (4.7^{+1.4}_{-1.2}) \times 10^{24}$ cm^{-2}
norm $= 0.13^{+0.30}_{-0.09}$ ph cm^{-2} s^{-1} keV^{-1}

Nov 2017

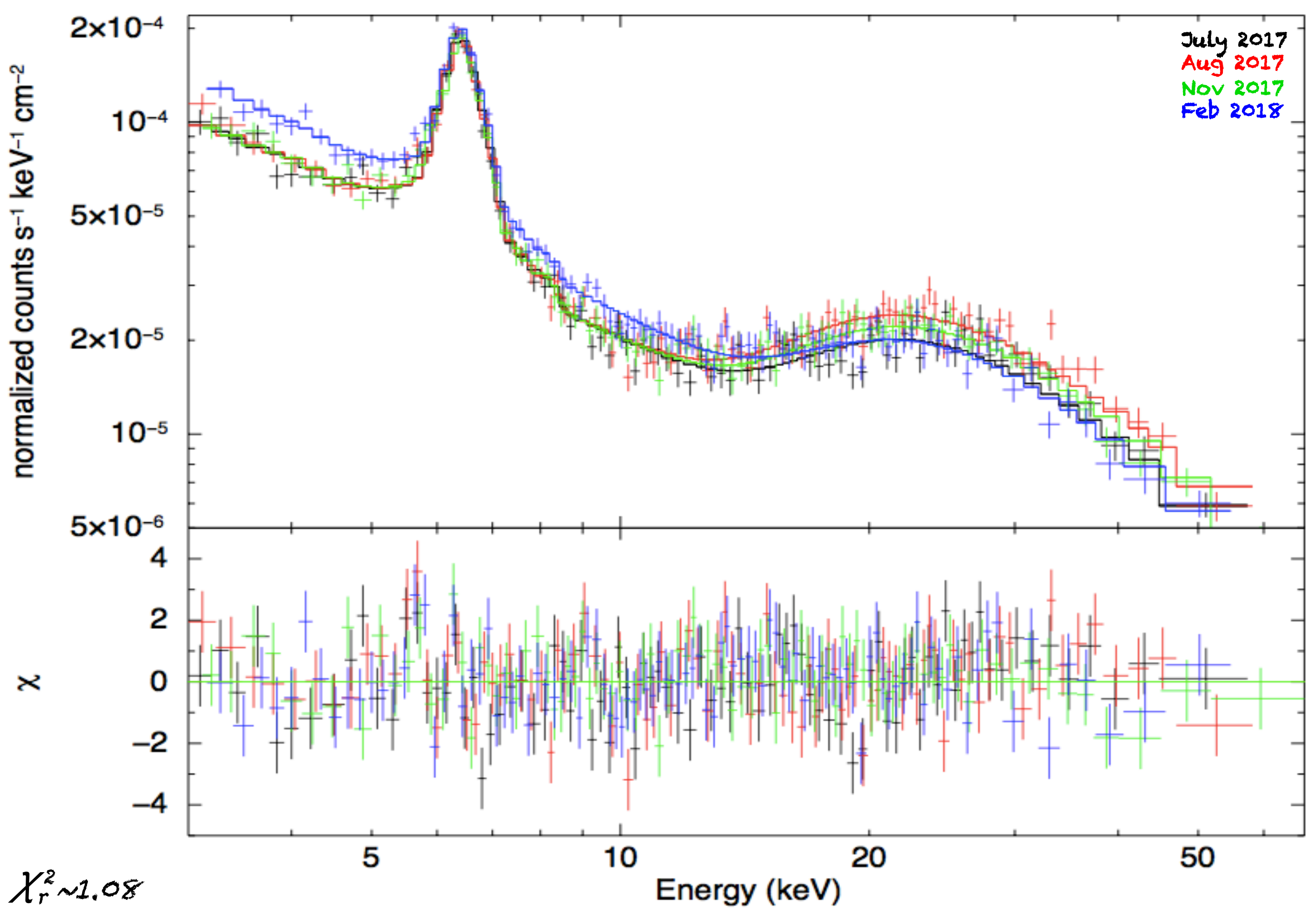


$N_H \sim 10^{25}$ cm^{-2}
norm $\lesssim 1.4$ ph cm^{-2} s^{-1} keV^{-1}

Feb 2018

Results

To break the N_H-norm degeneracy, we assume the same intrinsic X-ray luminosity during the whole monitoring...

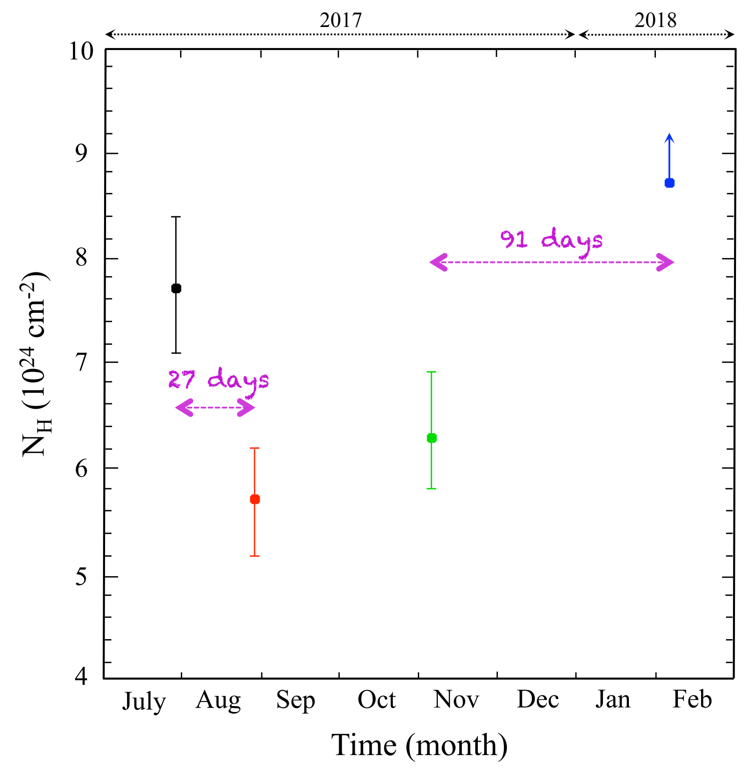


Zaino et al. in prep.

We obtain an intrinsic X-ray luminosity of 3.5×10^{43} erg/s, fully consistent with those inferred using other proxies (e.g. mid-IR and [OIII]).

Results

To break the N_H-norm degeneracy, we assume the same intrinsic X-ray luminosity during the whole monitoring...



Zaino et al. in prep.

$$R = \frac{G \overset{10^7 M_\odot}{\boxed{M_{BH}}} t^2 \overset{10^{10}\ cm^{-3}}{\boxed{n^2}}}{N_H^2} \sim 1.334 \times 10^{53} \frac{t^2}{N_H^2}\ cm$$

OBS1 -- OBS2

$$\Delta N_H = (2.0^{+1.2}_{-1.1}) \times 10^{24}\ cm^{-2}$$

$$R = (0.06^{+0.10}_{-0.03}) M_7\, n_{10}^2\ pc$$

OBS3 -- OBS4

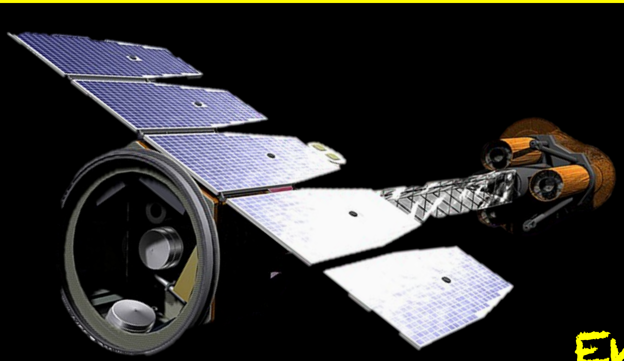
$$\Delta N_H \gtrsim (2.4^{+0.5}_{-0.6}) \times 10^{24}\ cm^{-2}$$

$$R \leq (0.46^{+0.36}_{-0.14}) M_7\, n_{10}^2\ pc$$

We observe two unveiling events due to Compton-thick material located in the innermost part of the torus or even more inside.

Imaging X-ray Polarimetry Explorer (IXPE)

- NASA SMEX mission
- NASA-ASI collaboration
- Launch: April 2021
  (now in phase C)



Marshall Space Flight Center

PI team, project management, SE and S&MA oversight, mirror module fabrication, X-ray calibration, science operations, and data analysis and archiving

Detector system funding, ground station

Spacecraft, payload structure, payload, observatory I&T

INAF ISTITUTO NAZIONALE DI ASTROFISICA NATIONAL INSTITUTE FOR ASTROPHYSICS

Polarization-sensitive imaging detector systems

LASP Mission operations

ROMA TRE UNIVERSITÀ DEGLI STUDI · Stanford University Scientific theory

McGill Co-Investigator

Massachusetts Institute of Technology Co-Investigator

A12567-151

Energy band: 2-8 keV

Three polarization sensitive X-ray detector units (DUs), each paired with a corresponding grazing incidence mirror module assembly (MMA)

❑ *MMA*

Parameter	Value
Number of shells per mirror module	24
Shell material	nickel-cobalt alloy
Effective area per mirror module	$230\ \text{cm}^2$ (@ 2.3 keV) $>240\ \text{cm}^2$ (3-6 keV)
Angular resolution (HPD)	$\lesssim$ 25 arcsec
Field of view (detector limited)	12.9 arcmin square

❑ *DUs*

Parameter	Value
Sensitive area	15 mm × 15 mm
Fill gas and composition	He/DME (20/80) @ 1 atm
Detector window	50-μm thick beryllium
Spatial resolution (FWHM)	$\lesssim$ 123 μm (6.4 arcsec) @ 2 keV
Energy resolution (FWHM)	0.54 keV @ 2 keV

X-ray polarimetry of NGC 1068

✧ Geometry

the ionization cone is perpendicular to the torus' plane

✧ Warm polarization

Brown & McLean 1977

$$P = P(\gamma, i) = \frac{\sin^2 i}{2\alpha + \sin^2 i}$$

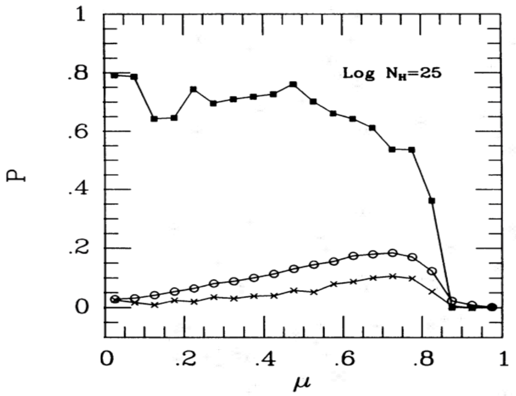
$$\alpha = \frac{1+\gamma}{1-3\gamma}$$

$$\mu = \cos\theta$$

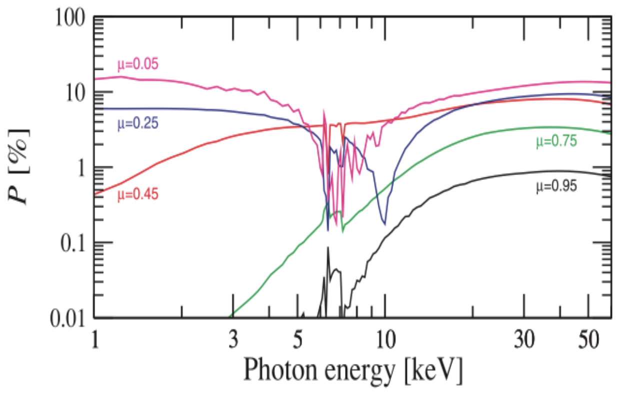
$$\gamma = \frac{\int_{r=0}^{\infty}\int_{\mu=-1}^{1} n(r,\mu)\mu^2 dr d\mu}{\int_{r=0}^{\infty}\int_{\mu=-1}^{1} n(r,\mu) dr d\mu}$$

✧ Cold polarization

Ghisellini, Haardt & Matt 1994



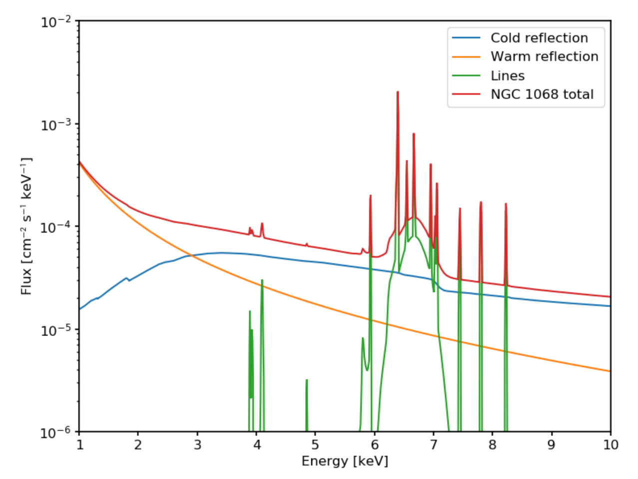
Goosmann & Matt 2011



accr. disc + equatorial torus ($N_H = 10^{25}$ cm^{-2})

I case ($\theta = 30°$; $i=75°$)
cold: $P = 72\%$; $\Psi = 0°$
warm: $P = 67\%$; $\Psi = 0°$

II case ($\theta = 60°$; $i=75°$)
cold: $P = 6\%$; $\Psi = 0°$
warm: $P = 28\%$; $\Psi = 0°$



✧ Input model

Total flux: $F_{2\text{-}8keV} = 4.2 \times 10^{-12}$ erg cm^2 s^{-1}

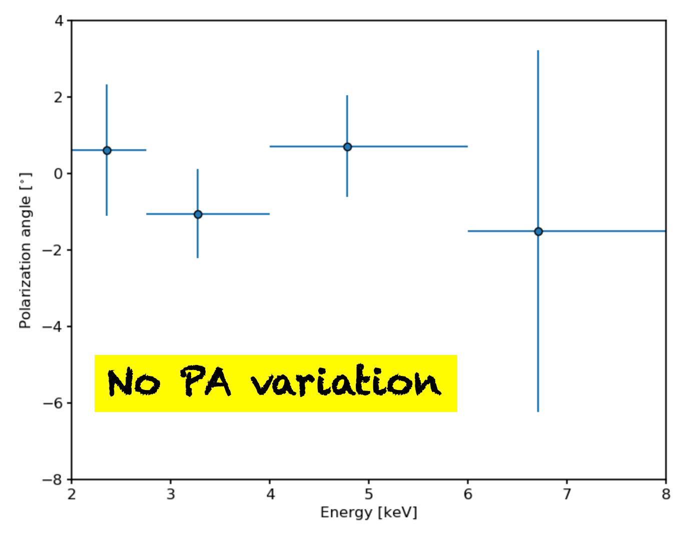
Warm reflection continuum from the cone:
$F_{2\text{-}8keV} = 10^{-12}$ erg cm^2 s^{-1}

Cold reflection continuum from the torus:
$F_{2\text{-}8keV} = 1.8 \times 10^{-12}$ erg cm^2 s^{-1}

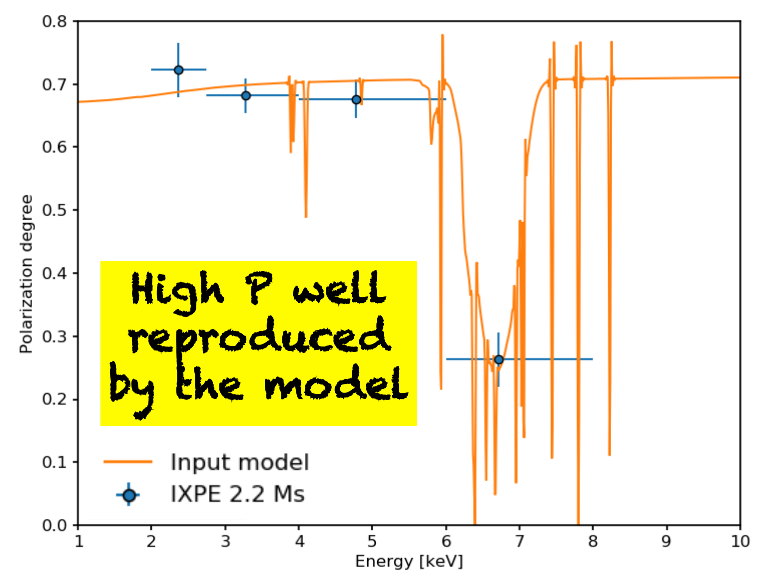
Emission lines (warm+cold):
$F_{2\text{-}8keV} = 1.4 \times 10^{-12}$ erg cm^2 s^{-1}

2.2 Ms IXPE simulation

I case (θ = 30°)

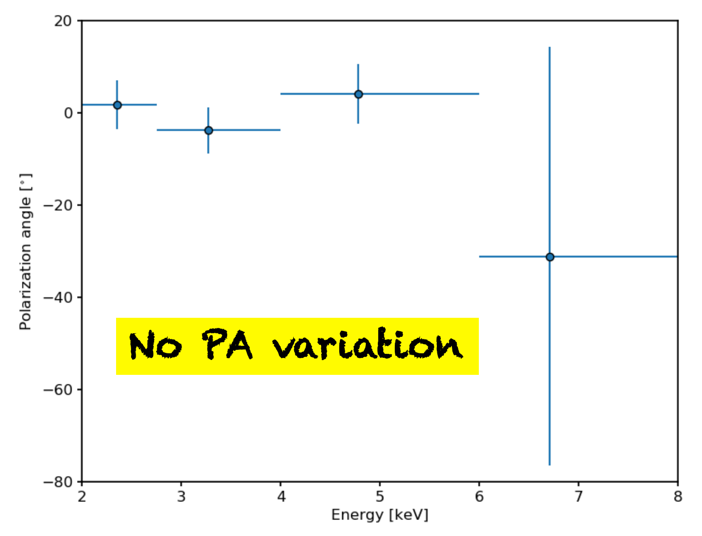


No PA variation

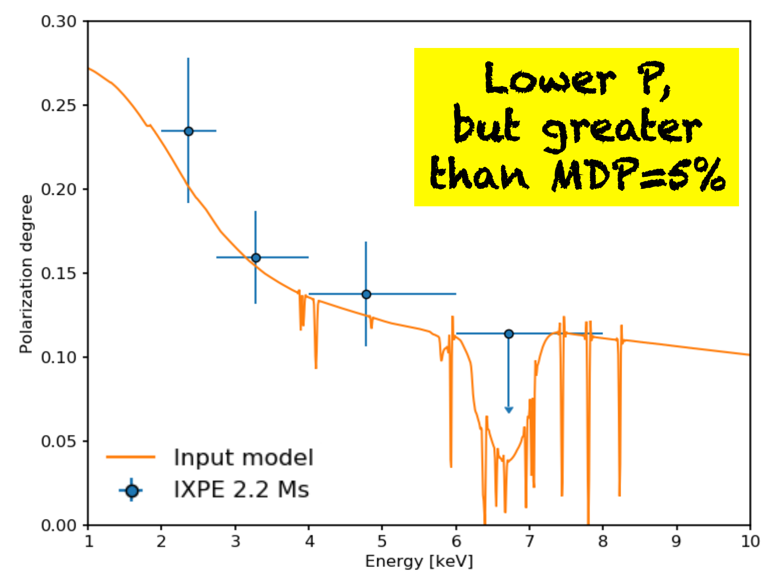


High P well reproduced by the model

II case (θ = 60°)



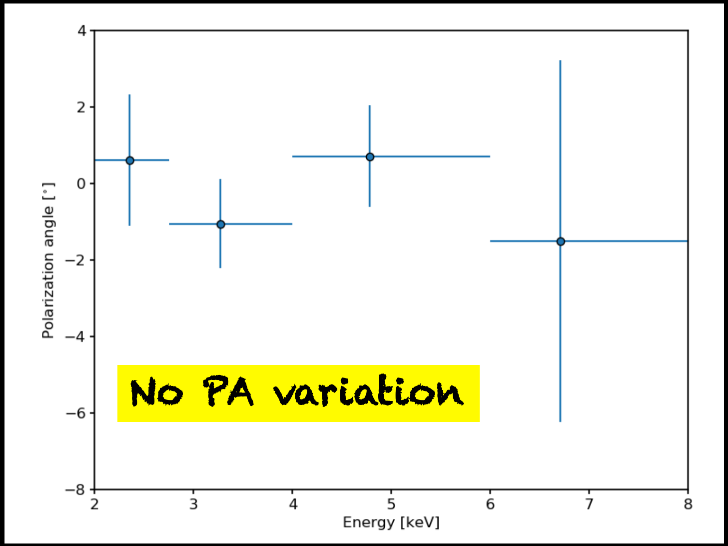
No PA variation



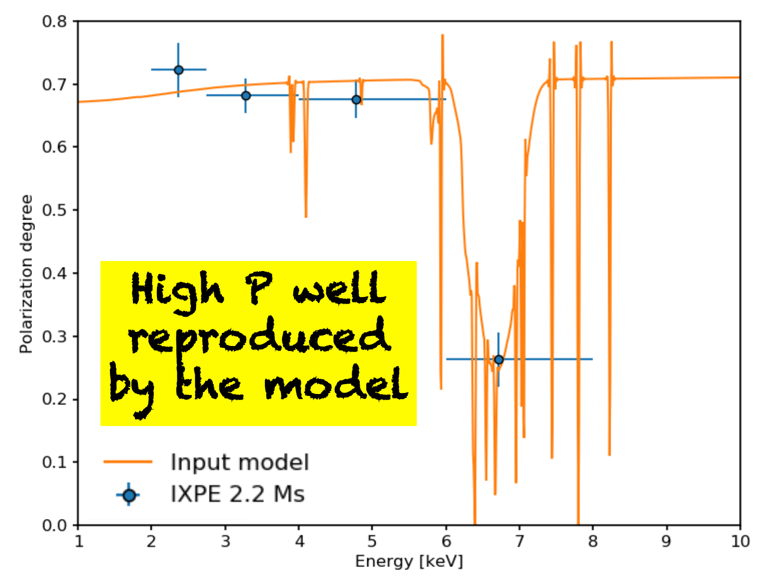
Lower P, but greater than MDP=5%

2.2 Ms IXPE simulation

I case ($\theta=30°$)

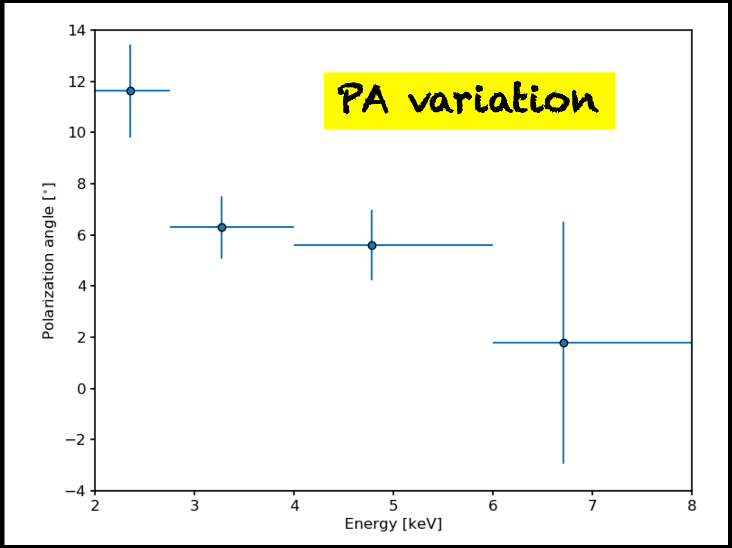


No PA variation

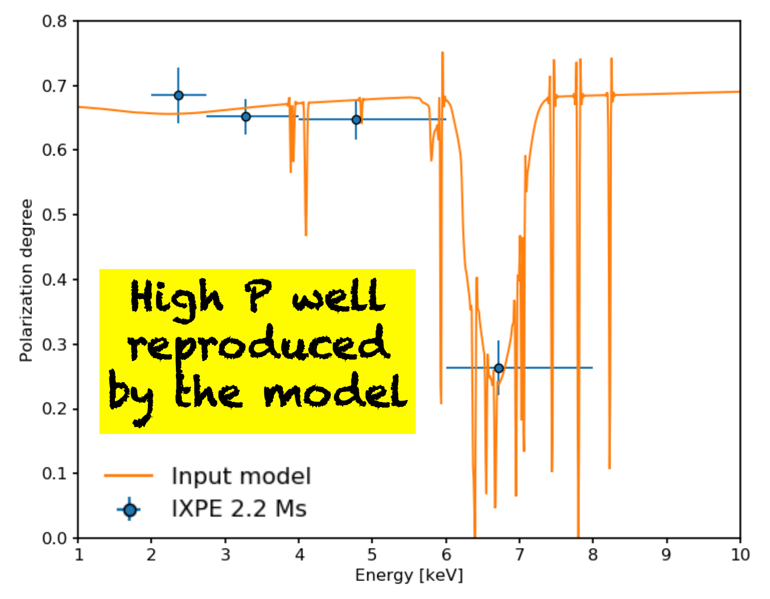


High P well reproduced by the model

Tilted cone hypothesis ($\Psi_{\omega}=18°$)



PA variation



High P well reproduced by the model

Summary and conclusions

☐ Analysis of the latest NuSTAR monitoring of NGC 1068, composed of 4 observations of ~50 ks each probing time-scales from 1 to 6 months.

① A brand new flaring ULX reaching a luminosity of ~ 4×10^{40} erg/s in three months and disappearing in the following four months;

② Two unveiling events due to Compton-thick material located in the innermost part of the torus or even more inside.

☐ 2.2 Ms IXPE simulations for two different geometries of NGC 1068

WARNING

① θ=30°: high polarization degree and possibility to check the tilted cone hypothesis;

② θ=60°: lower polarization degree, but greater than MDP=5%.

Challenging (source complexity, high t_{exp}, ...), but still possible measures

The ideal source for this kind of analysis would seem to be Circinus

Source	$F_{2\text{-}8\,keV}$ ($\times 10^{-12}$ erg/cm^2/s)	t_{exp} (MDP=5%) (ks)
Circinus	15.0	600
NGC 7582	6.5	1400
Mrk 3	5	1800
NGC 1068	4.2	2200

Thank you for your attention!

Any questions?
Just ask!