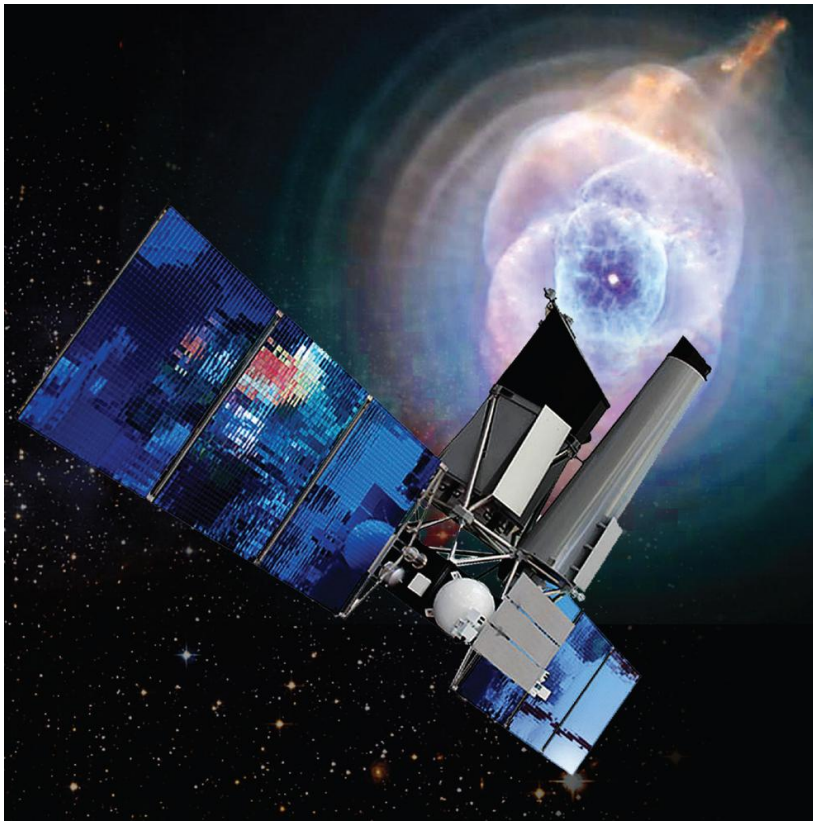
The *Mikhail Pavlinsky* ART-XC telescope onboard SRG mission. Flight characteristics and review of first results

Alexander Lutovinov

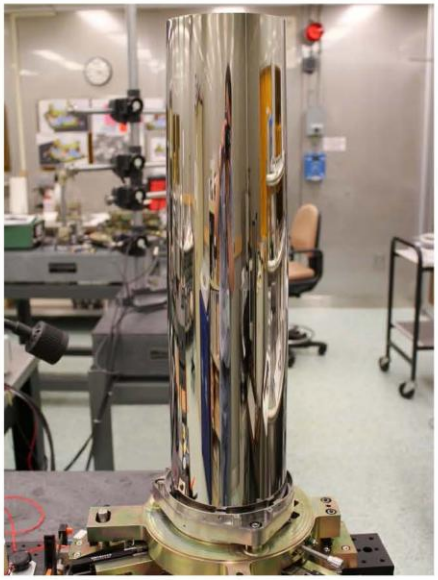
on behalf of the ART-XC team

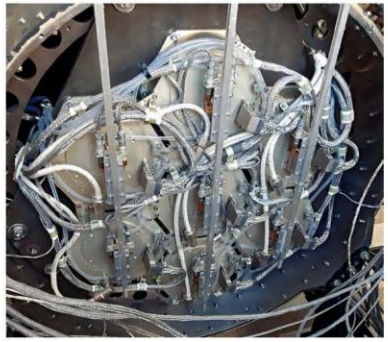


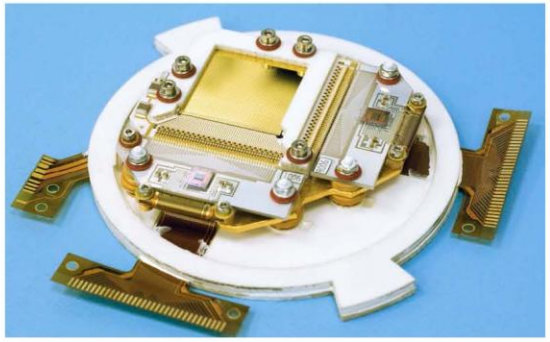
Mikhail Pavlinsky (1959-2020) had been PI for the ART-XC telescope and Co-I for the SRG observatory. He made a decisive contribution to the successful realization of this project and the creation in Russia of a modern school of space instrumentation.
In memory of our outstanding colleague and friend, it was decided to name the ART-XC telescope after Mikhail Pavlinsky –

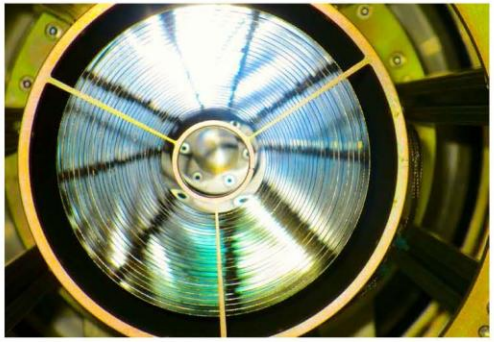
The *Mikhail Pavlinsky* ART-XC telescope.

The *Mikhail Pavlinsky* ART-XC telescope









The ART-XC telescope on board the *SRG* observatory

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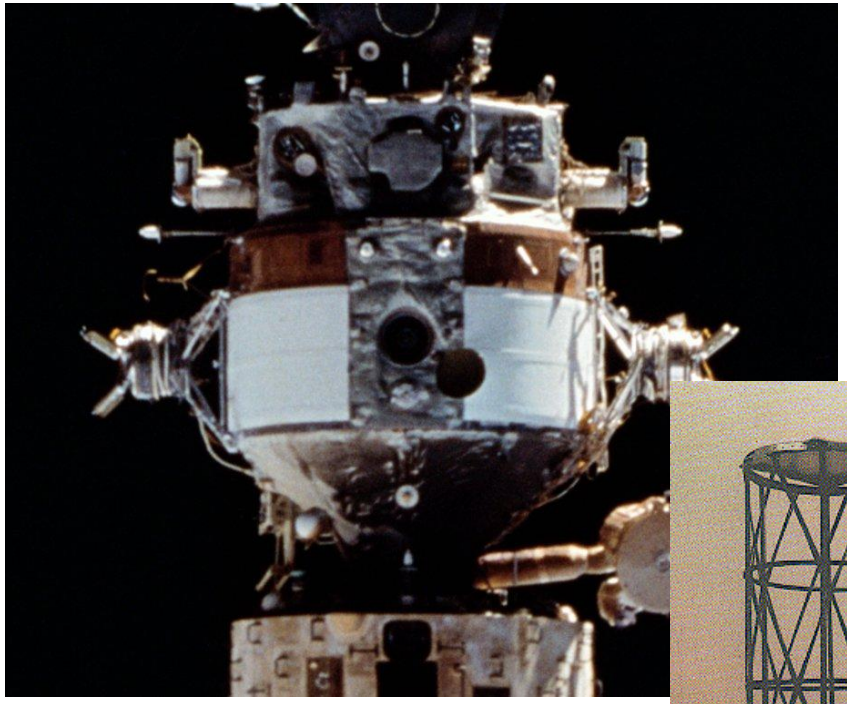
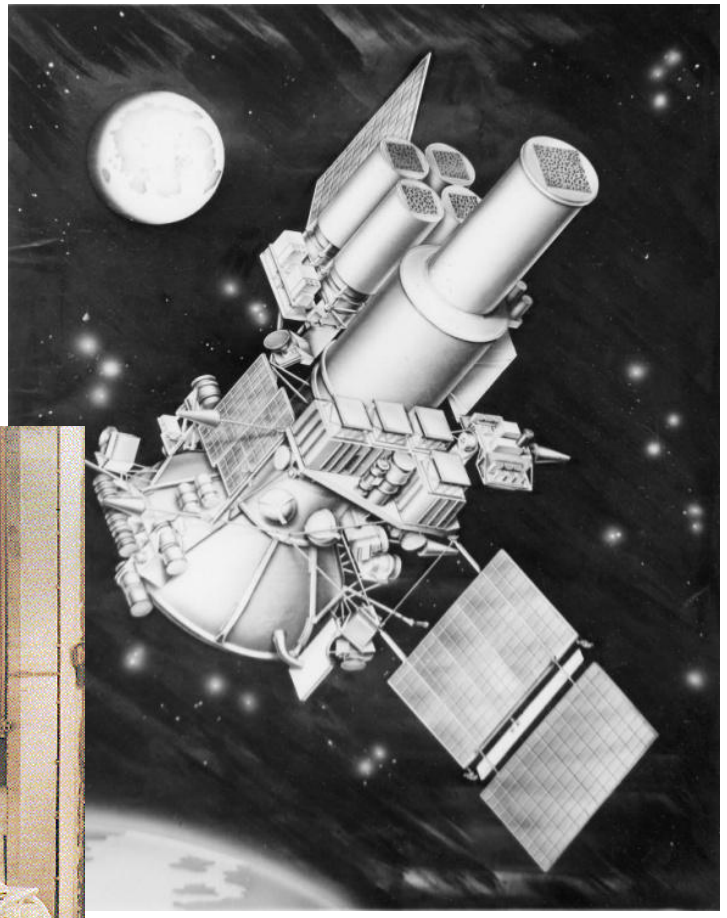
arXiv:2103.12479

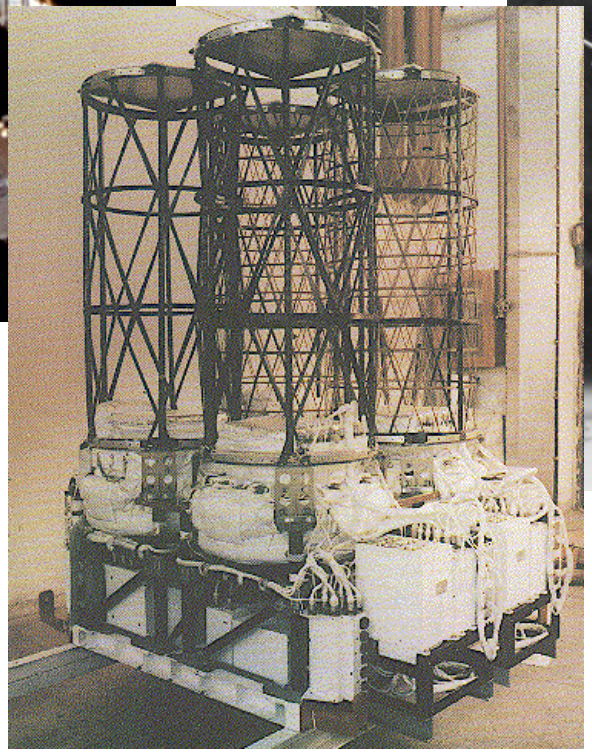
Astrophysical projects of IKI

Roentgen observatory on the KVANT module of the MIR station



GRANAT observatory





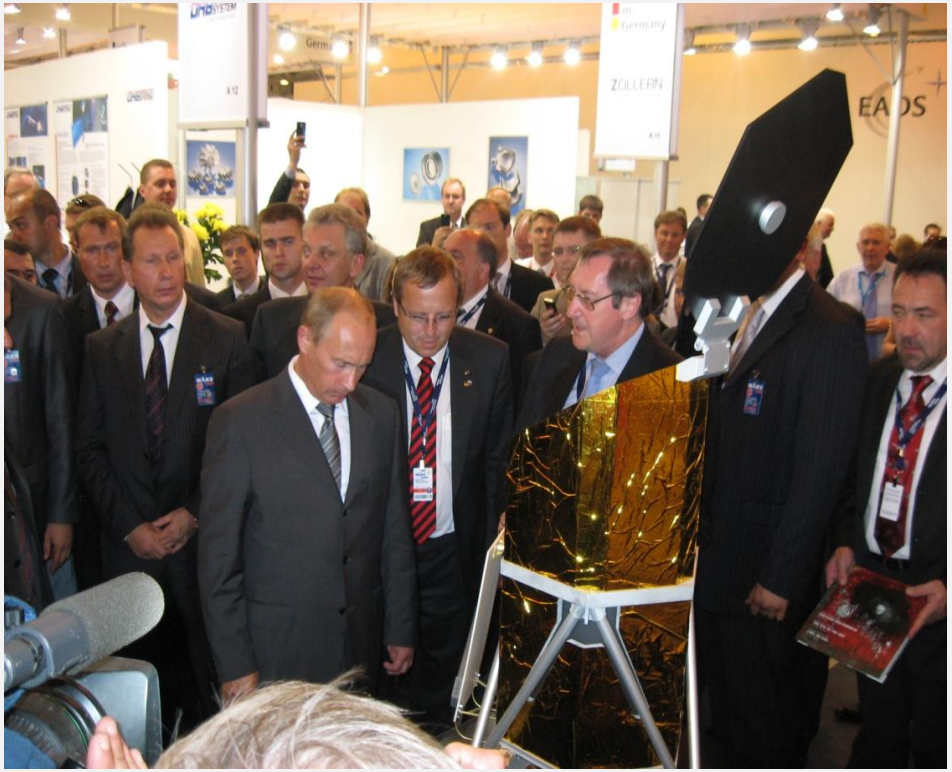
Pulsar X-1
gamma-ray spectrometer onboard Roentgen

ART-P
X-ray telescope onboard GRANAT

Astrophysical projects of IKI

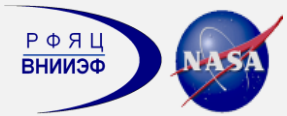
Spektr-Roentgen-Gamma observatory (1990s)

Dozen instruments, dozen countries….



18 Aug 2009, at the airshow MAKS2009 Roscosmos and DLR (Germany) signed Agreement on the Spectrum-Roentgen-Gamma project

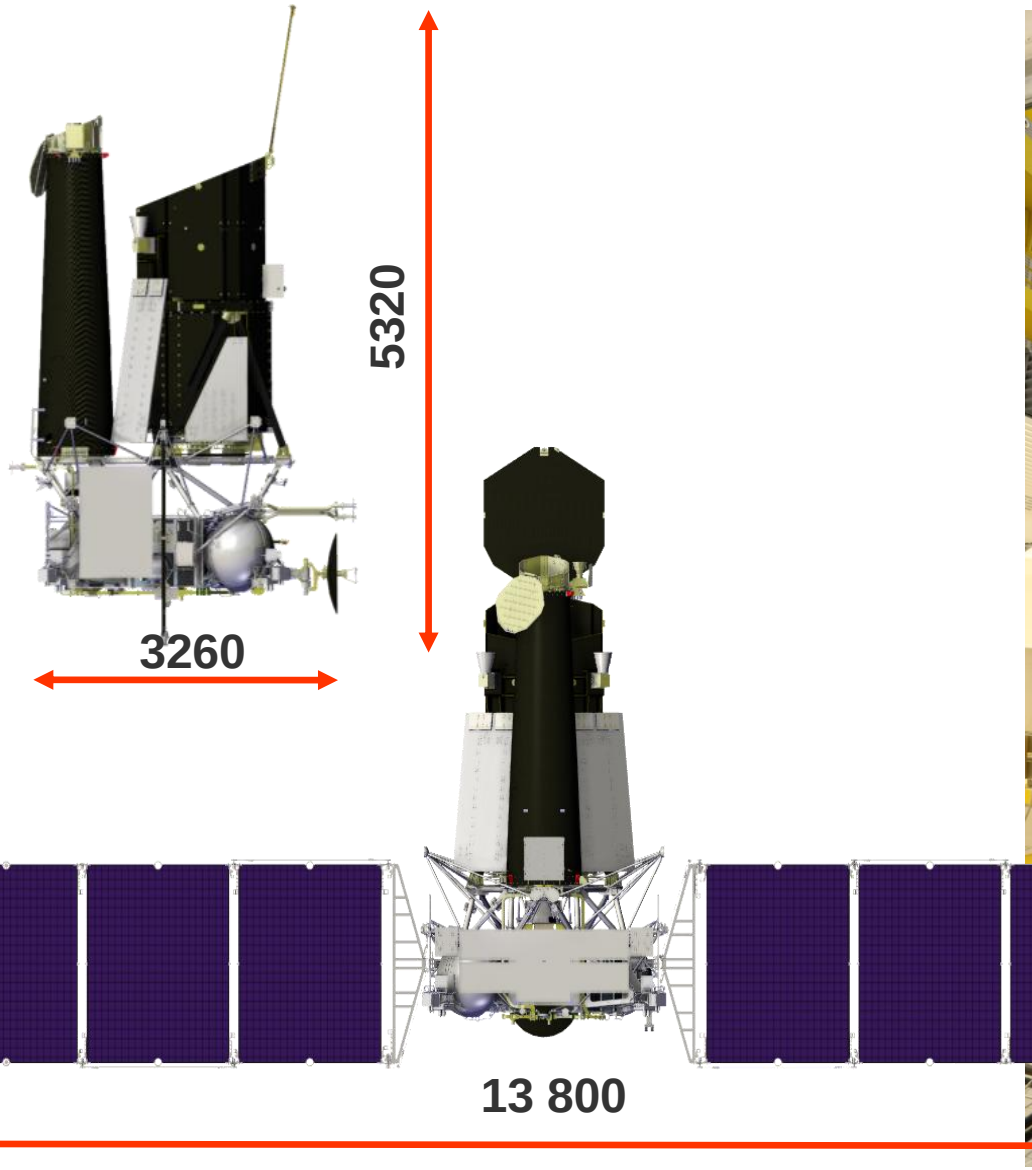




SRG



- Roscosmos
- Space Research Institute RAS (IKI)
- Lavochkin Association (NPOL)
- RFNC-VNIIEF, Sarov
- MSFC/NASA
- Max-Planck-Institute for Astrophysics, Garching
- Istitut fur Astronomie und Astrophysik, Univ. Tubingen
- Astrophysikalishes Institut Potsdam
- University Erlangen-Nuernberg
- Hamburg University
- Max-Planck-Institute for Extraterrestrial Physics
- DLR

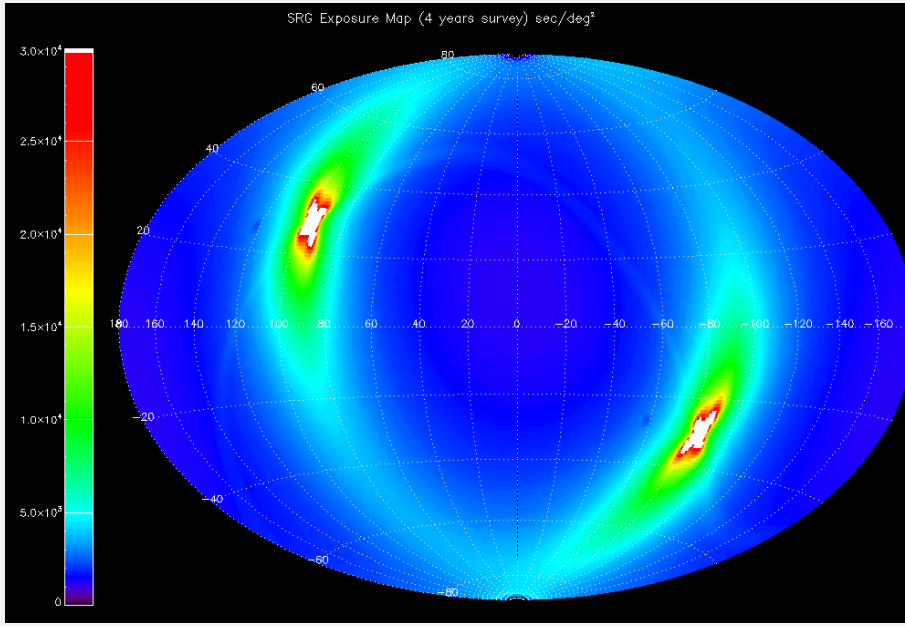

5320
3260
13 800

SRG, Principal Science Goals

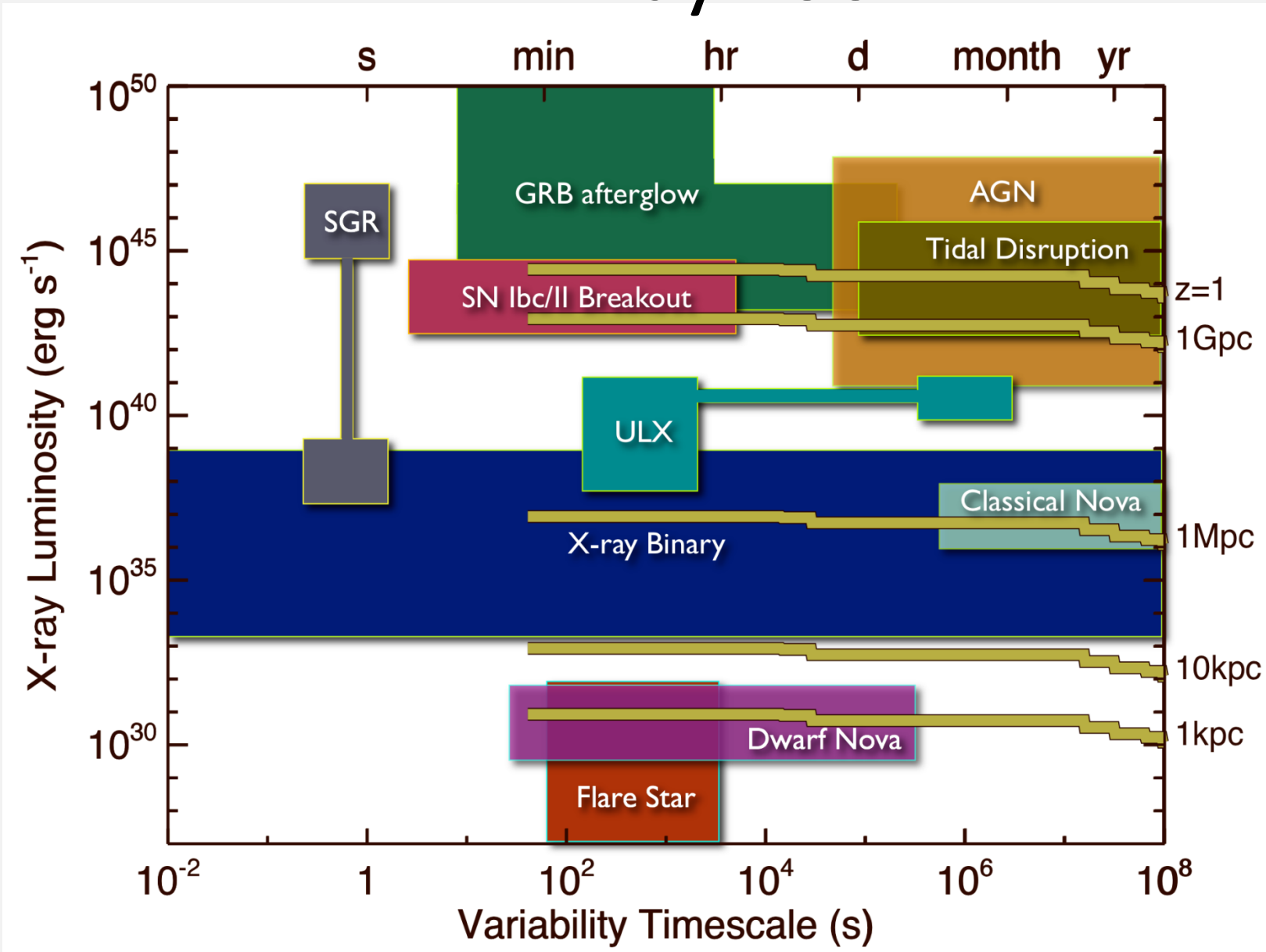
Combination of the large FoV and effective area => probing record volume of the Universe

new sensitive all sky survey (~10^{-14} erg/sec/sq.sm)

- **Clusters of galaxies and cosmology (100 000)**
- **Growth of supermassive black holes (3 000 000)**
- **Complete samples of galactic compact objects (100 000)**
- **Stars (2 000 000)**
- **Diffuse ISM and SNR**
- **Objects in the Solar system**

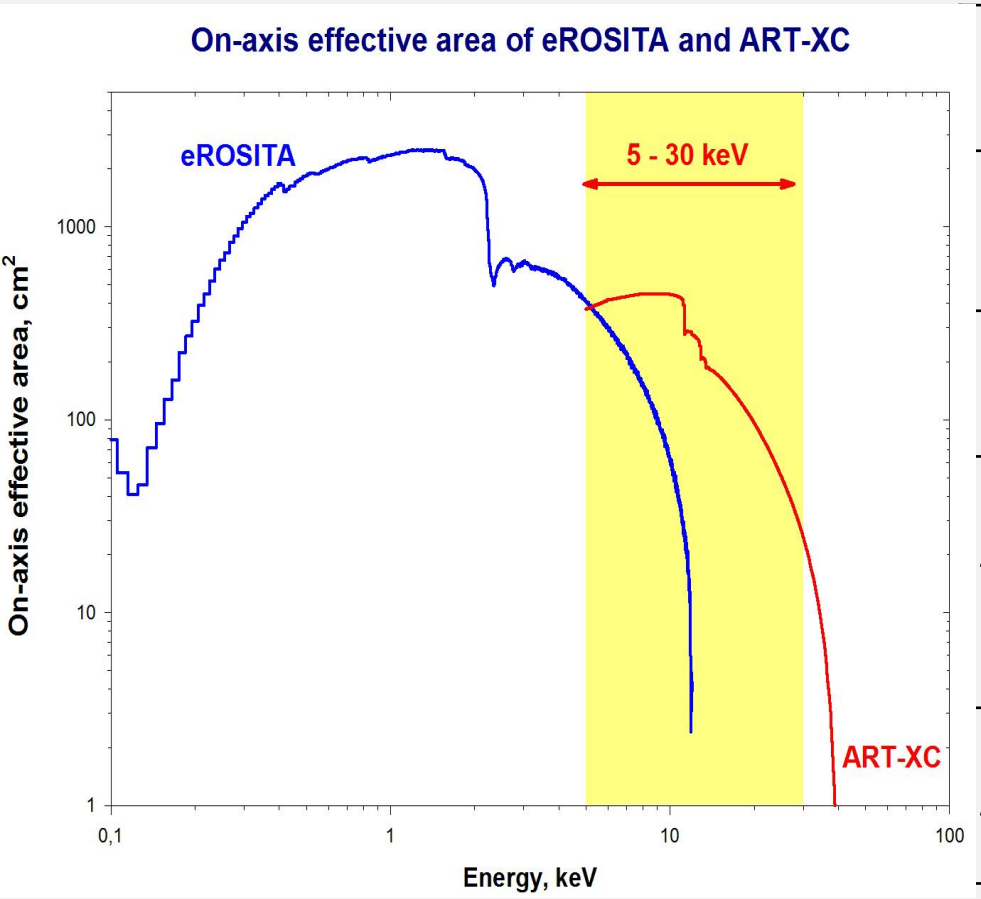


X-ray Zoo



Merloni et al. 2012

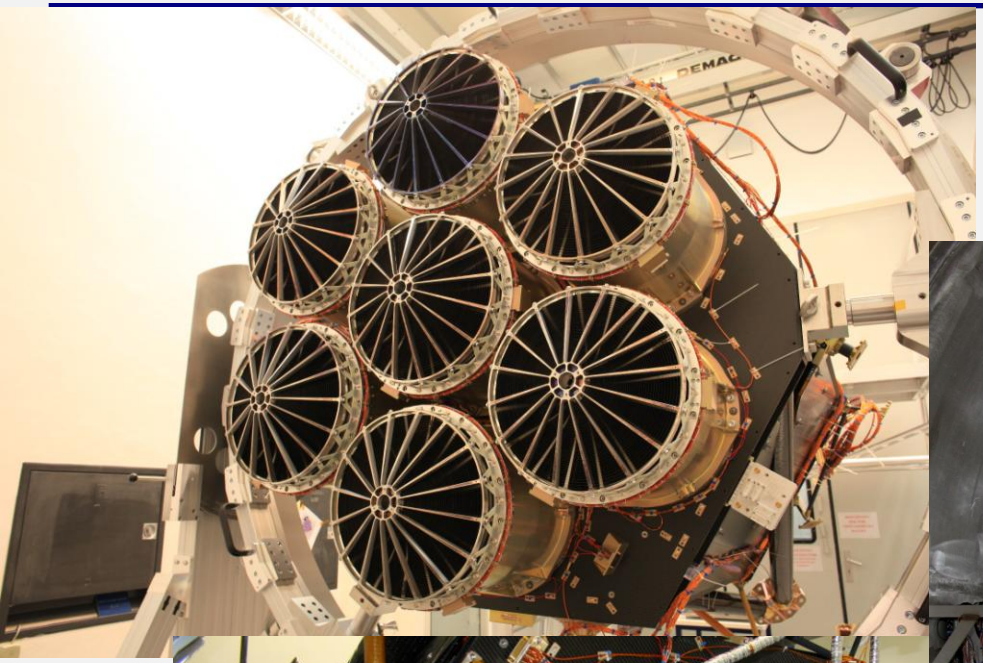
Science Payload

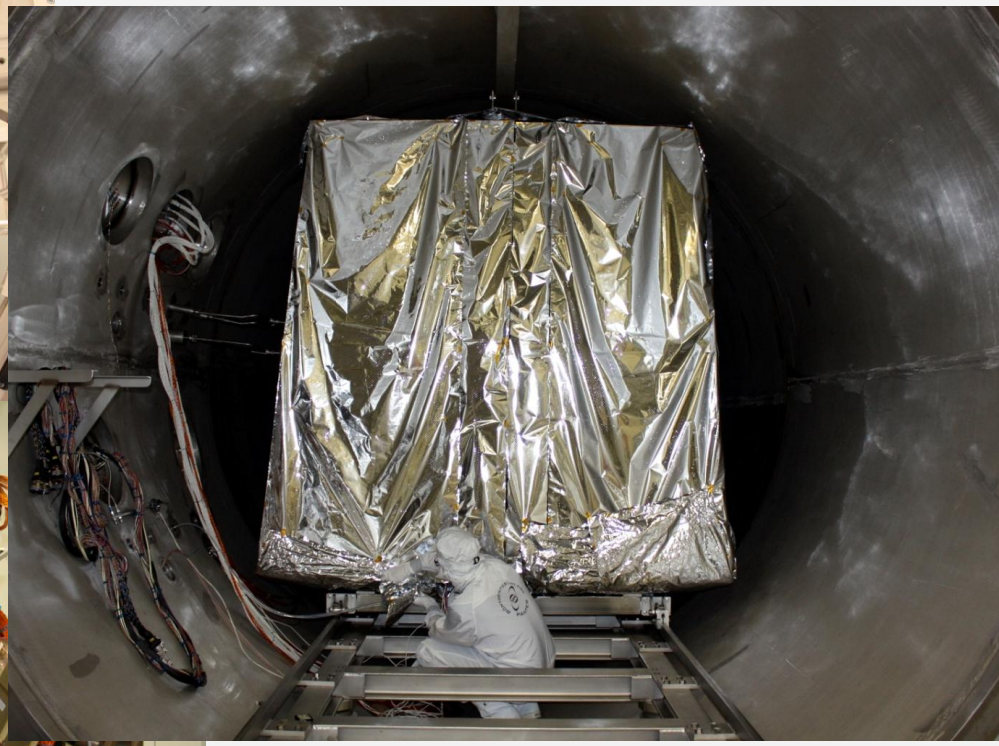


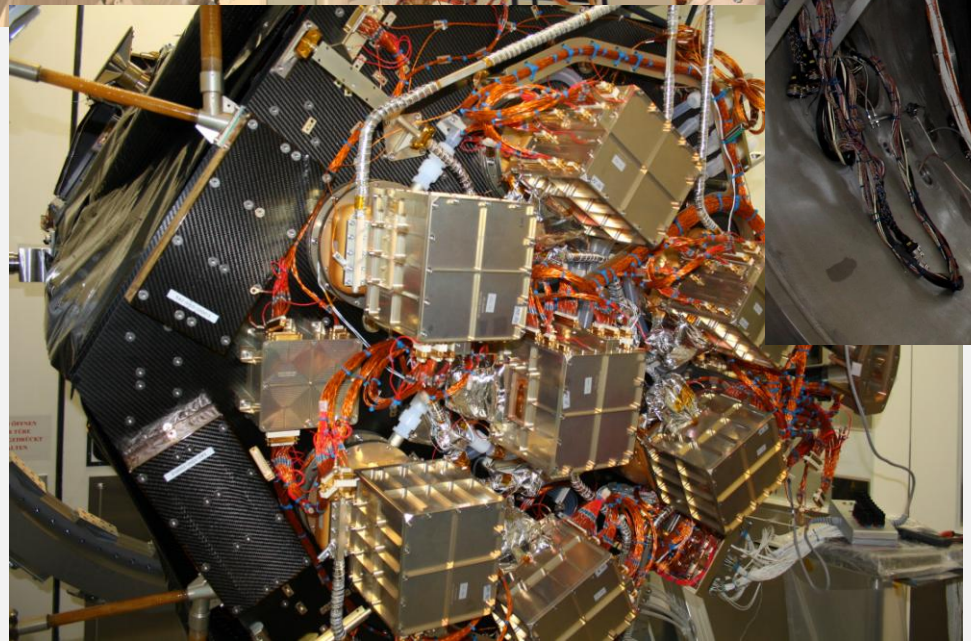
	eRosita	ART-XC
Energy Band	0.3-10 keV	4-30 keV
FoV	1°	36’
Angular resolution	15”	45” (53”)
Area	2400 cm^2 @ 1 keV	~400 cm^2 @ 8 keV

Key property:
Large area x Large FoV

eRosita

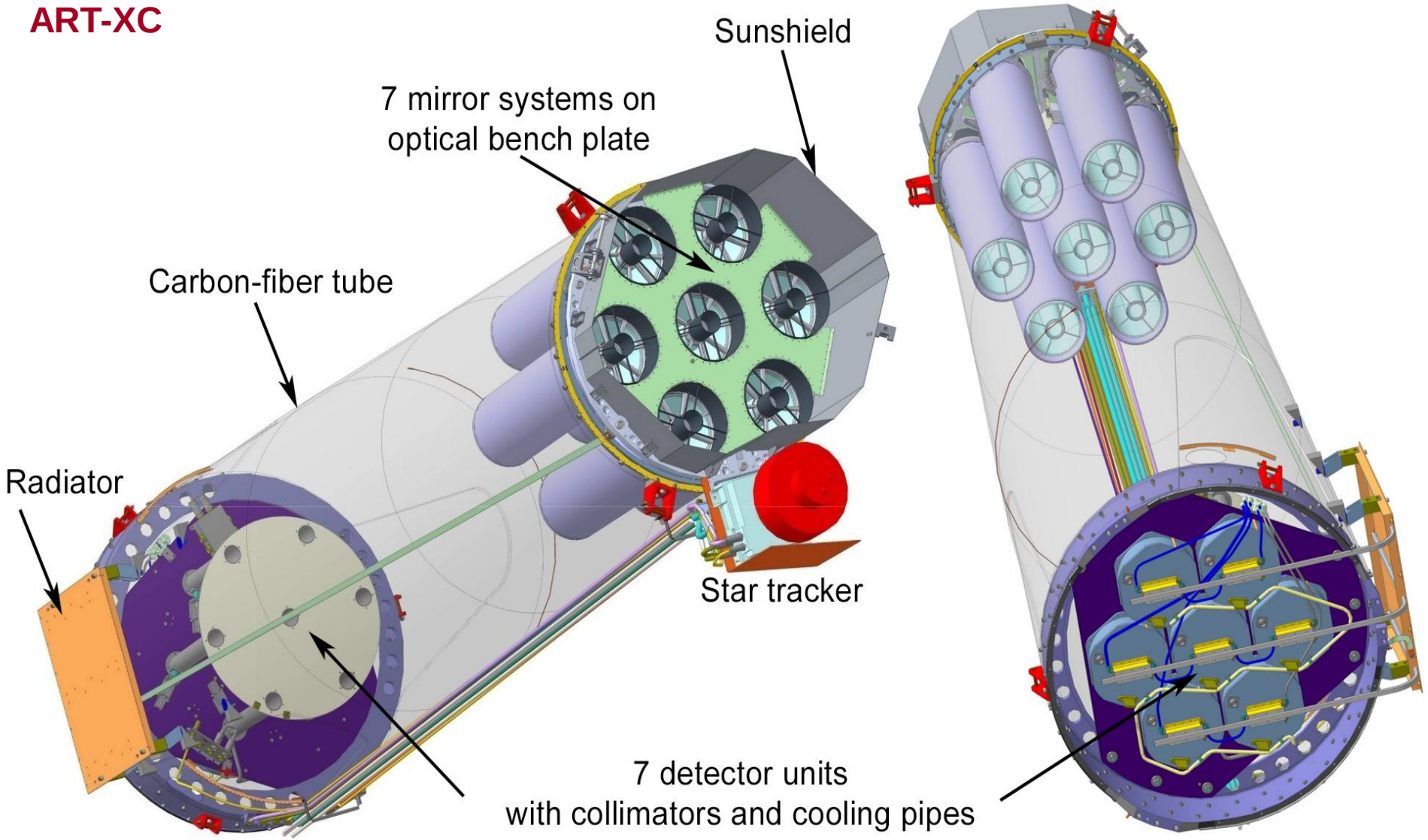




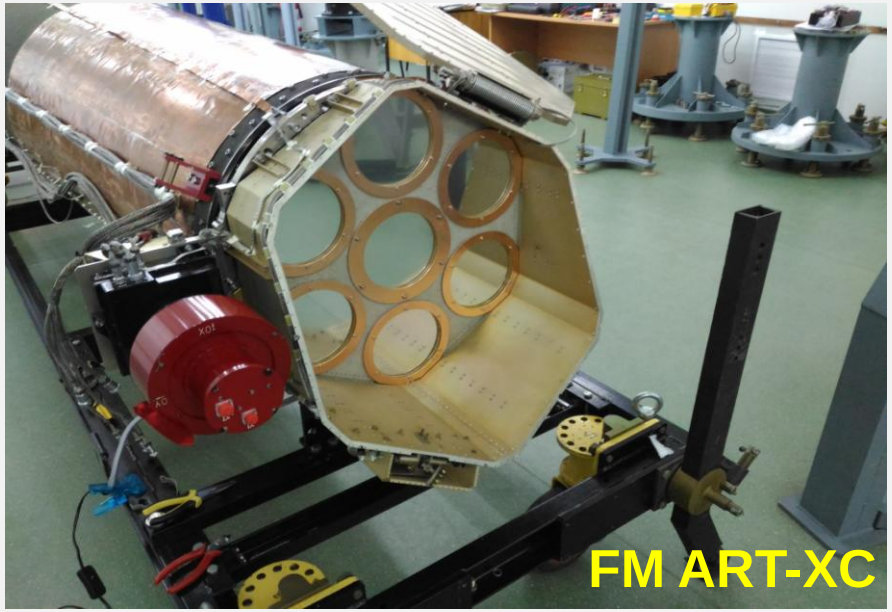


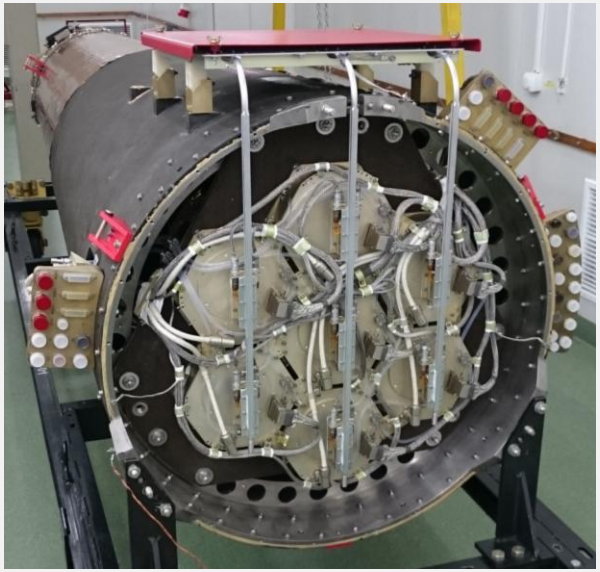
Predehl et al (2021)

ART-XC


Sunshield
7 mirror systems on optical bench plate
Carbon-fiber tube
Radiator
Star tracker
7 detector units with collimators and cooling pipes

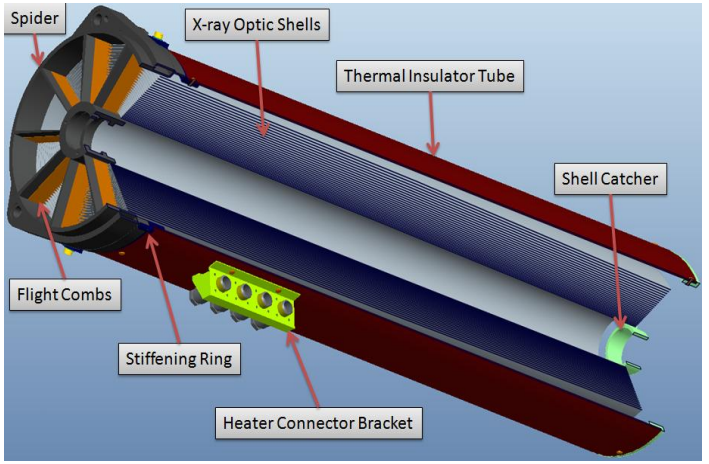
SRG

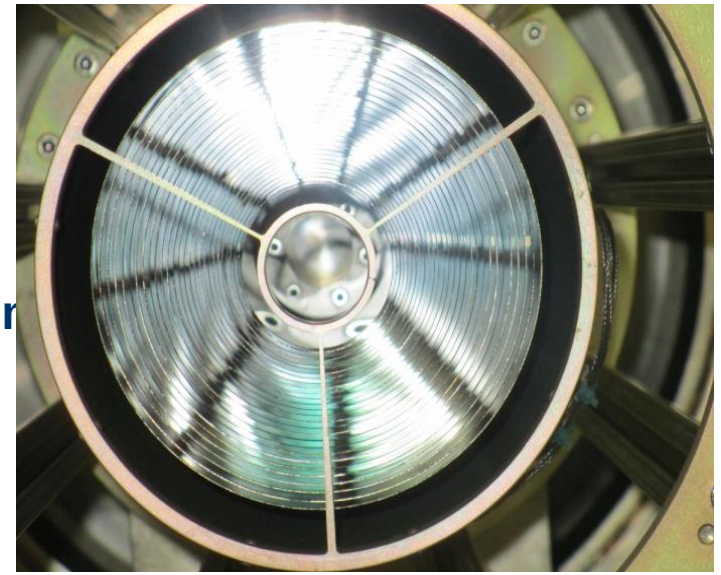




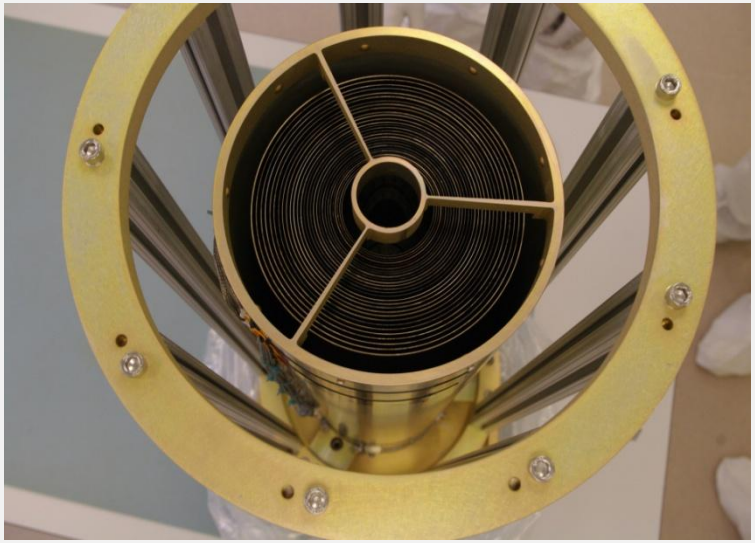
ART-XC: X-ray mirror systems MSFC/NASA

1.	Number of mirror systems	7
2.	Number of nested mirror shells	28
3.	Form of shell	Wolter-I
4.	On-axis angular resolution, HPD	≤35″
5.	Focal length	2700 mm
6.	Length of shell	580 mm
7.	Diameter of mirror shells	49 – 145 mm
8.	Material of shells	Ni/Co
9.	Mirror coating materials	Iridium





SRG



MS characteristics

Module #	1	2	3	4
HPD, arcsec	29,7	31,8	32,3	33,7
W90, arcsec	94,1	108,6	101,1	121,9
on axis Eff. Area, cm^2 at 8 keV	71,0	69,0	67,0	65,2

Module #	5	6-SM	7	8
HPD, arcsec	30,3	40,3	33,0	34,8
W90, arcsec	124,7	139,2	115,9	117,4
on axis Eff. Area, cm^2 at 8 keV	64,0	66,0	67,0	66,6

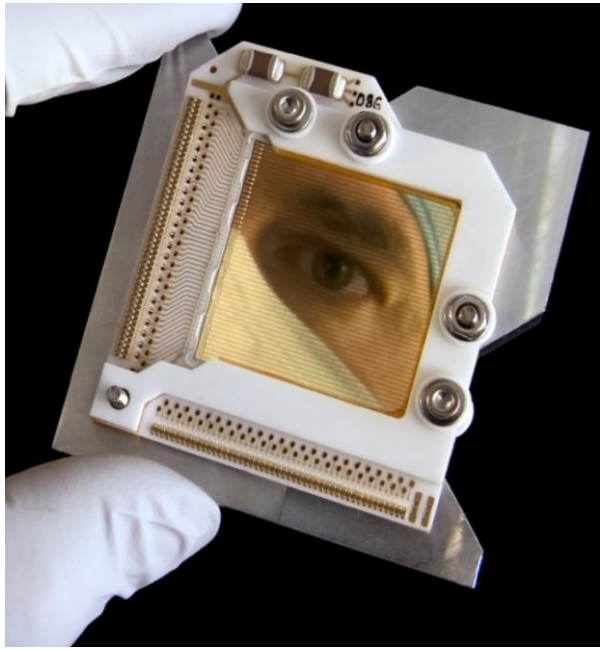
Mikhail Gubarev, PI at MSFC, was awarded in 2015

NASA Exceptional Achievement Medal

The **NASA Exceptional Achievement Medal** is an award of the National Aeronautics and Space Administration established in 1991.
The medal is awarded to both civilian members of NASA and military astronauts.
To be awarded the medal, a NASA employee must make substantial contributions characterized by a substantial and significant improvement in operations, efficiency, service, financial savings, science, or technology which directly contribute to the mission of NASA.
For civilians, the decoration is typically bestowed to mid-level and senior NASA administrators who have supervised at least four to five successful NASA missions. **Astronauts may be awarded the decoration after two to three space flights.**
Due to its prestige, the medal is authorized as a military decoration for display on active duty military uniforms upon application from the service member to the various branch of the military in which they serve.

ART-XC: DSSD CdTe detector IKI RAS

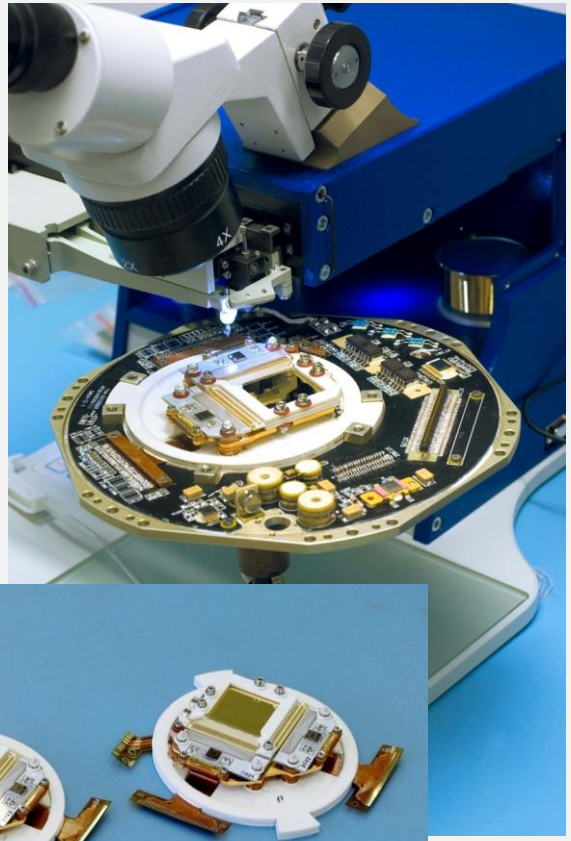
1.	CdTe manufacturer	ACRORAD
2.	Dimensions	30 × 30 × 1 mm^3
3.	Working area	28.56 × 28.56 mm^2
4.	Energy range	4 – 120 keV
5.	Number of strips	48 × 48
6.	Strip pitch	0.595 mm
7.	Be entrance window	∅30 mm × 100 μm
8.	ASIC, 2 pcs.	VA64TA1
9.	Dead time	0.77 ms
10.	Working temperature	– 21° C
11.	Energy resolution	≤8.5% @ 14 keV

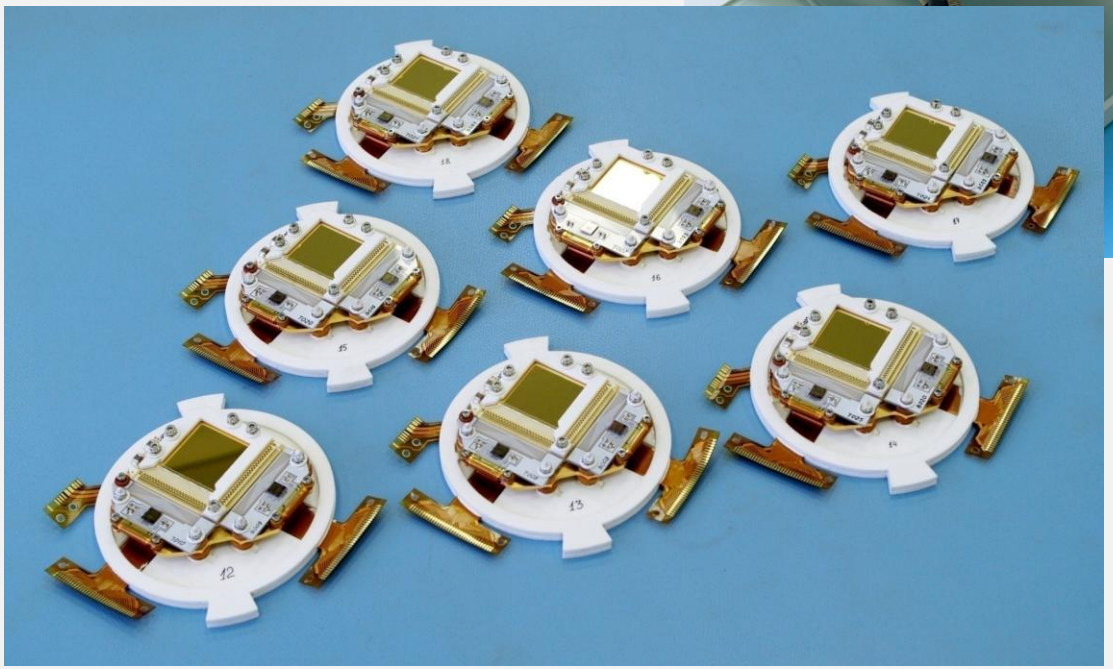


ART-XC: FM DSSD

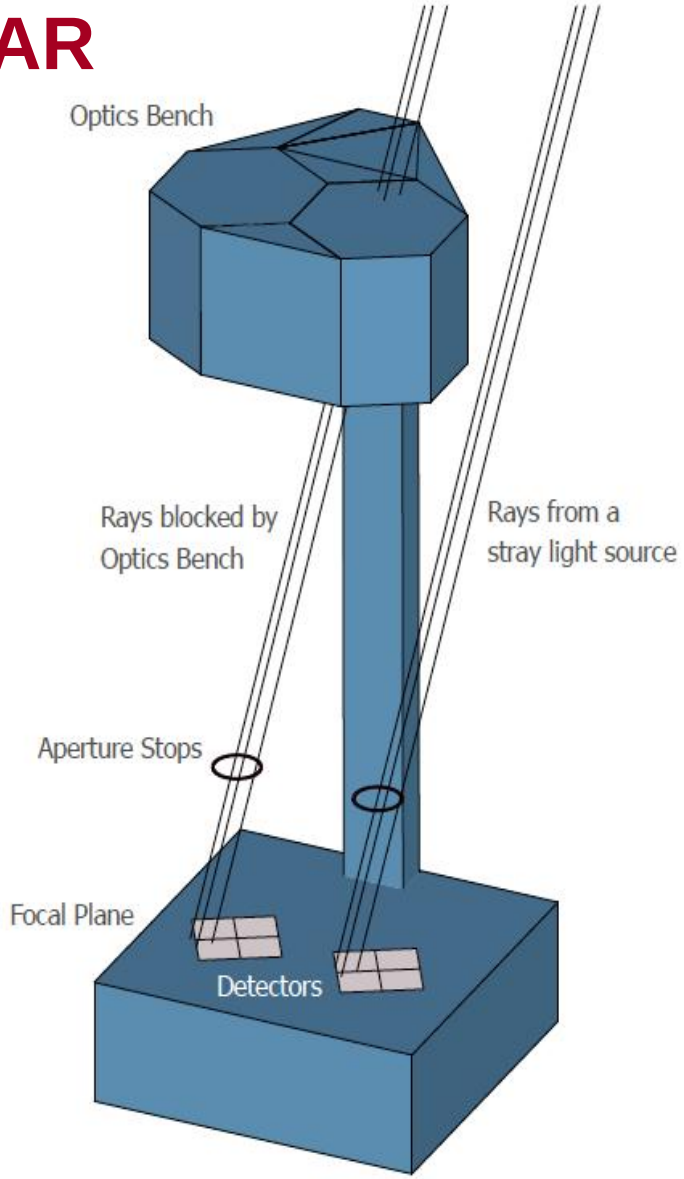
CdTe crystals

Developed and produced at IKI





NuSTAR



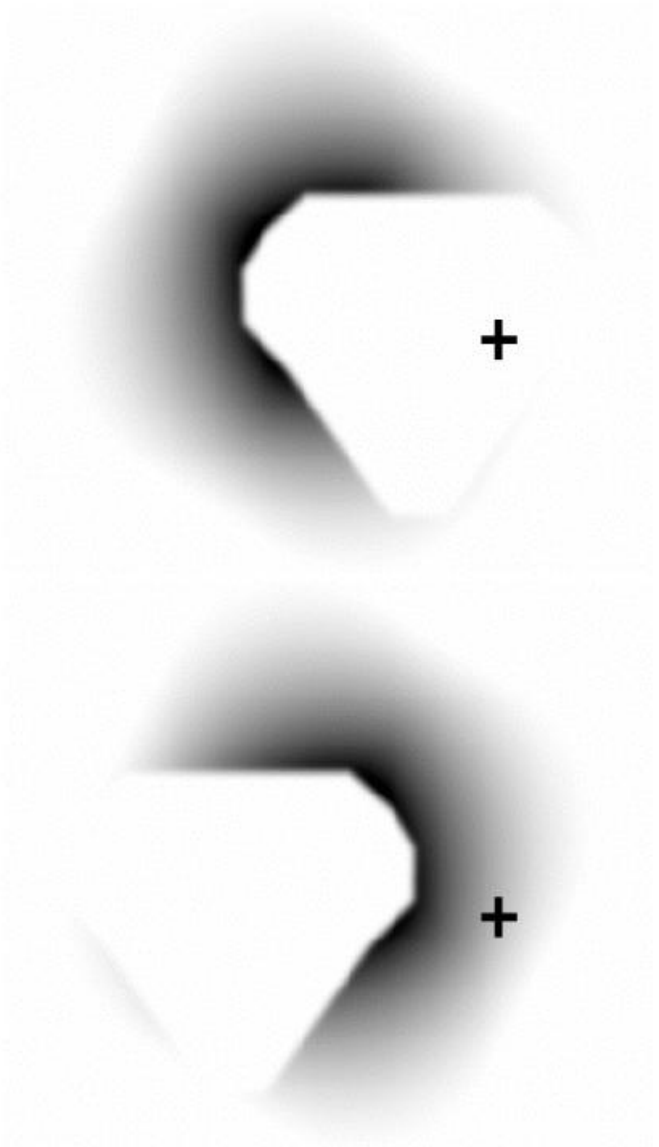
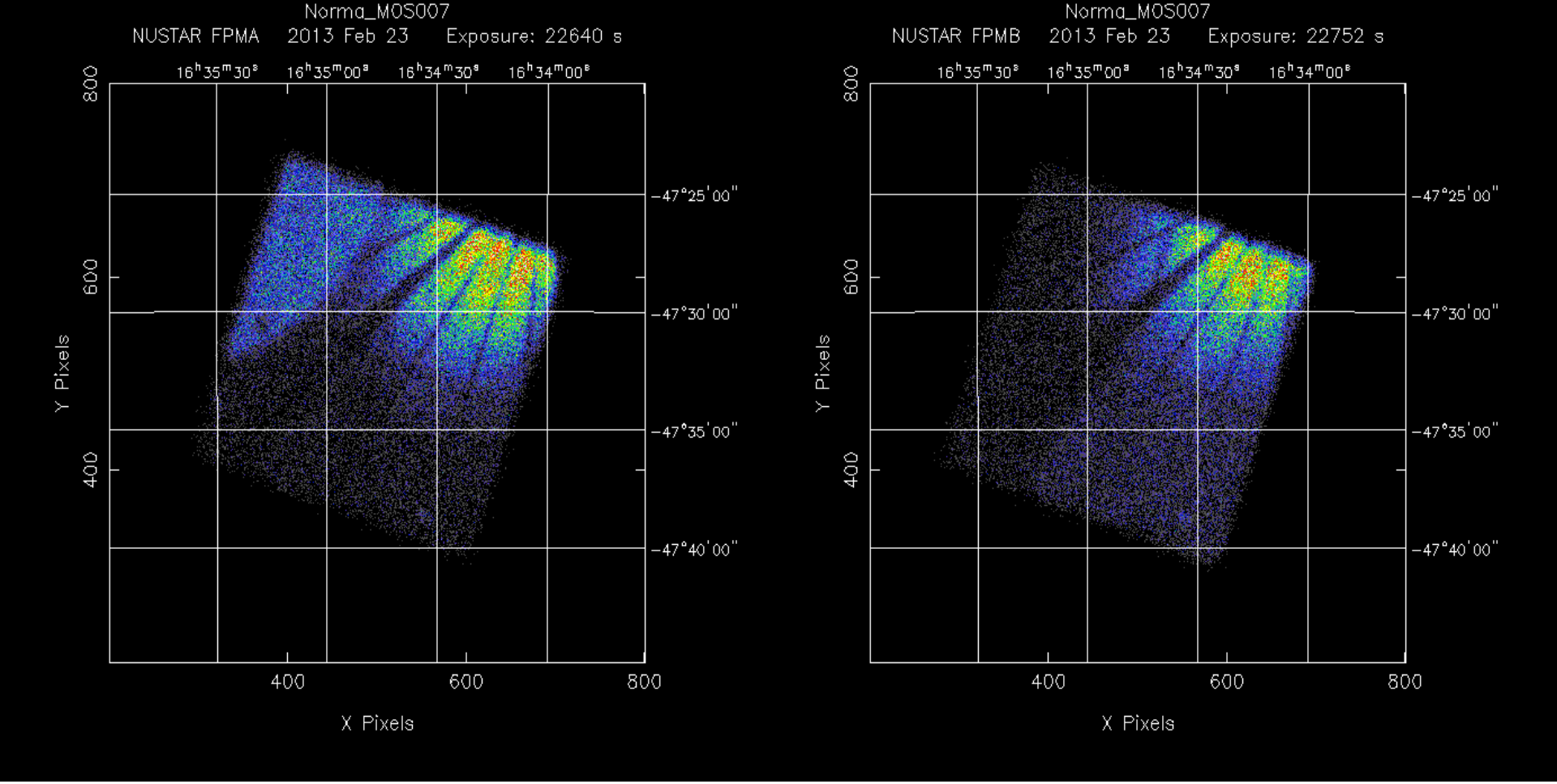
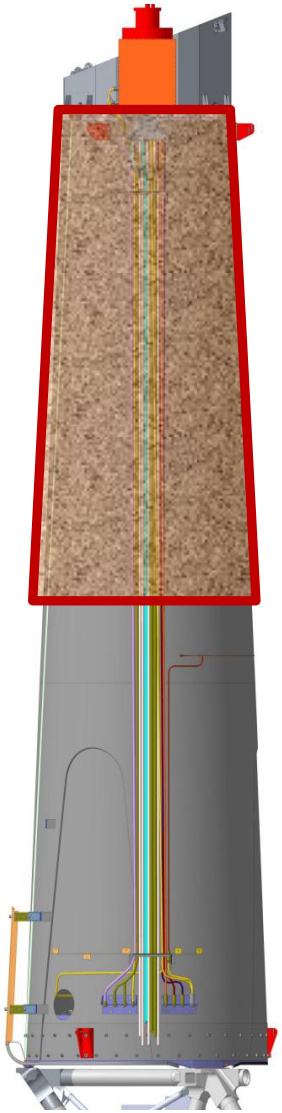


FIG. 8.— *Left:* A schematic of the observatory that illustrates how far off-axis sources can directly shine on the detectors through the aperture stop, producing the "Aperture" background. In this example, rays from the source are shielded from striking the left detector plane by the optics bench, but other rays from the same source have an unimpeded path through the aperture stop to shine on a corner of the right detector plane. *Right:* The location of sources on the sky, as visible from the detector plane, that produce the "Aperture" background for Telescopes A (top) and B (bottom). The images are weighted (darker) by the number of detector pixels a given source shines on. The crosses give the approximate position of the source shown in the left panel.

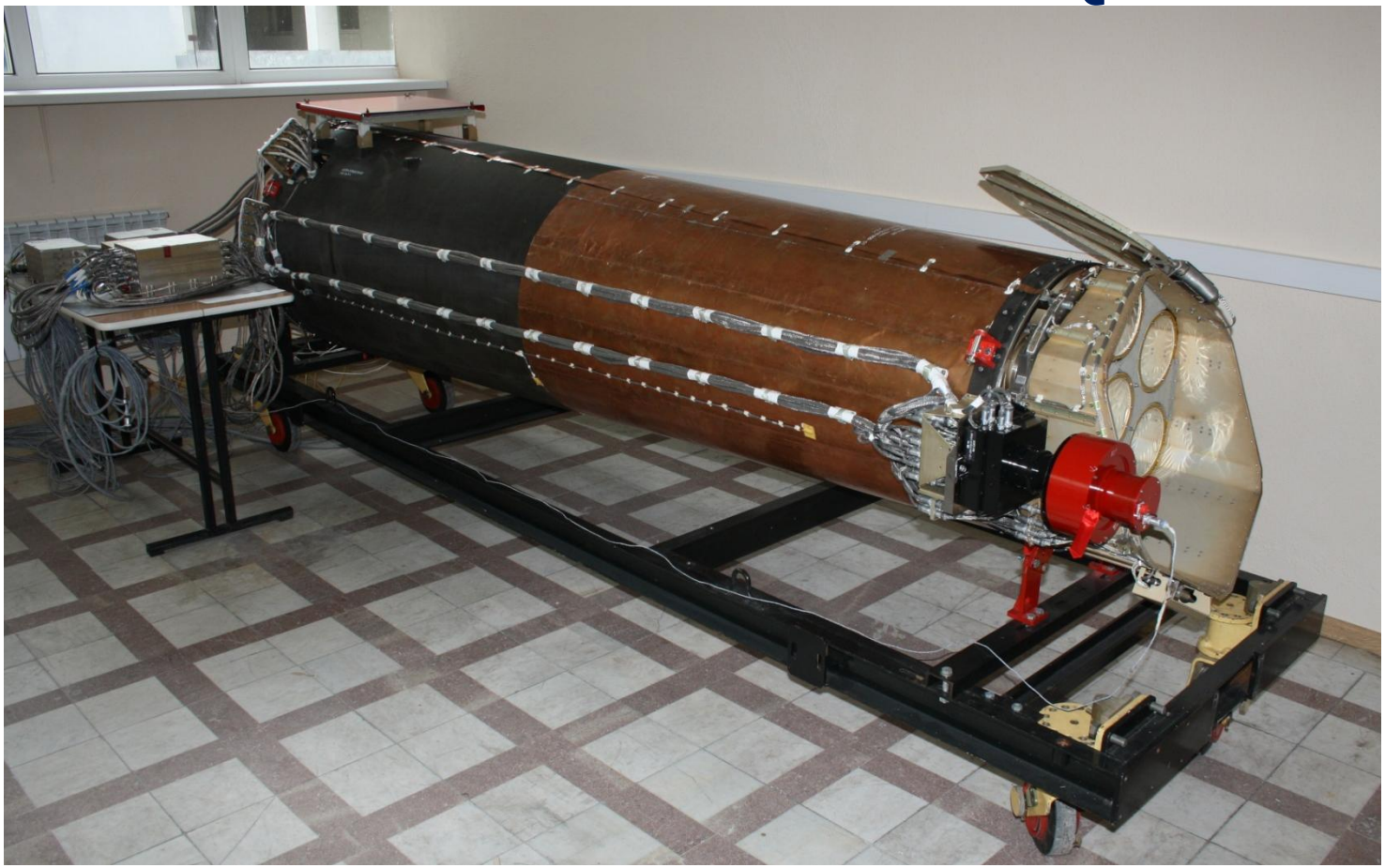


Example Ghost Ray and Stray Light patterns from sources outside *NuSTAR field of view from part of the Norma* region survey (ObsID 40014001001). Sky image from FPMA (North is up, East is to the left). A Ghost Ray petal-like pattern from the bright X-ray source 4U 1630-47 located 11.8 arcmin from the center of the field of view to the NW is evident in both focal plane images. Stray Light is also present in the NE of the FPMA image (*left) and covering the SW* corner of the FPMB image (*right).*

ART-XC – copper shield



QM in IKI



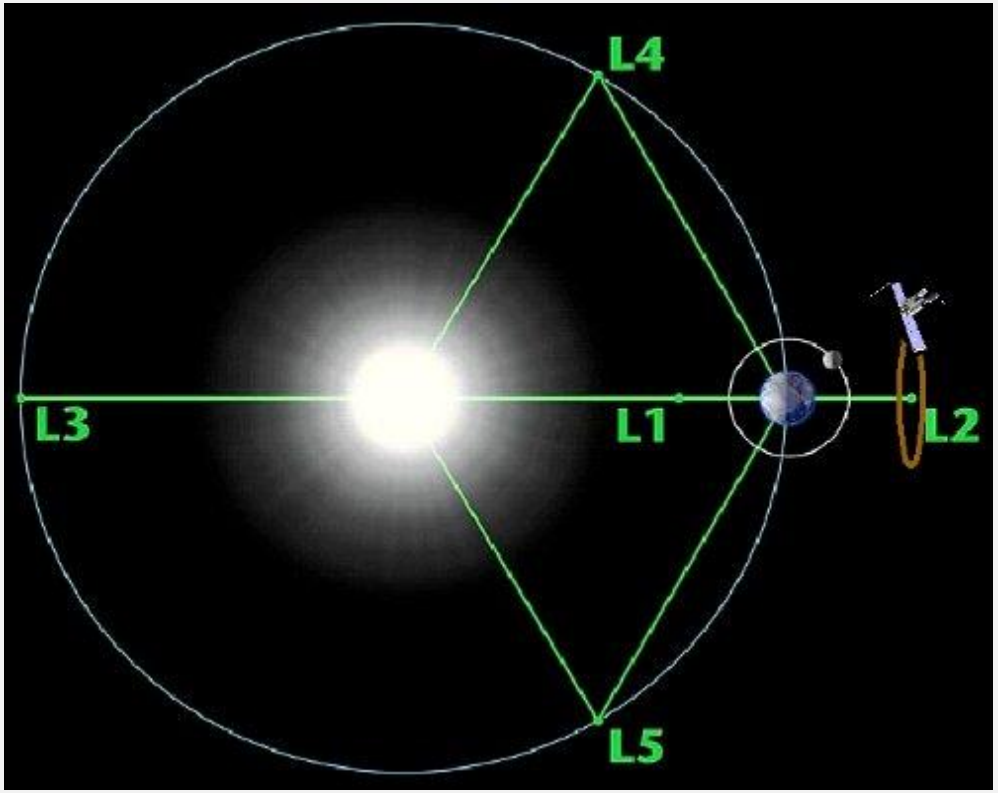
ART-XC key parameters	
Telescope mass	350 kg
Dimensions	$3.5 \times \varnothing 0.9$ m
Power	150 Watts
Energy range	4–30 keV
Effective area for pointed observations	385 cm^2 @ 8.1 keV*
Grasp Angular resolution (FWHM) in the survey mode (limited by detector pixel size)	53″
Detector efficiency	50% @ 4.6 keV, 86% @ 8.1 keV
Energy resolution	9% @ 13.9 keV**
Time resolution	23 μs
Dead time	0.77 ms
ART-XC Optics	
Number of MSs	7
Nominal focal length	2700 mm
Defocusing	−7 mm
Number of nested mirror shells	28
Form of shell	Wolter-I
Diameters of shells (intersection)	49–145 mm
Thickness of shells	0.25–0.35 mm
Material of shells	Ni/Co
Mirror coating	Ir (90% bulk density)
Entrance filter	18.5 μm Mylar film with 0.11 μm Al layer
HPD on-axis, arcsec	30–35″***
ART-XC Detectors	
Detector type	CdTe Schottky Diode double sided strip (Acrorad, Japan)
CdTe crystal's size	$29.95 \times 29.95 \times 1.00$ mm
Working area	28.56×28.56 mm
Number of strips	48×48
Strip width	520 μm
Inter-strip distance	75 μm
ASIC, 2 pcs.	VA64TA1 (Ideas, Norway)
Working energy range	4–120 keV
Entrance window	Be, $\varnothing$30 mm, thickness of 100 μm

SRG

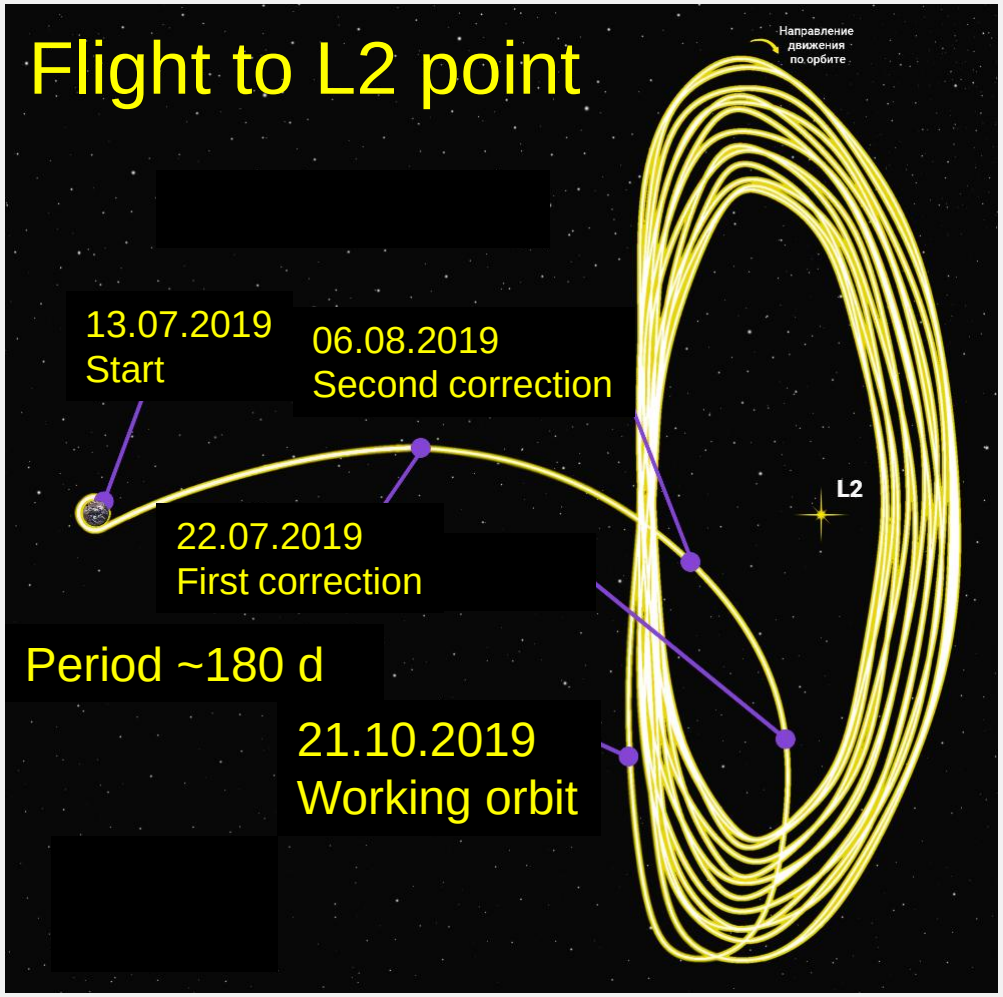
13.07.19 launched to the orbit

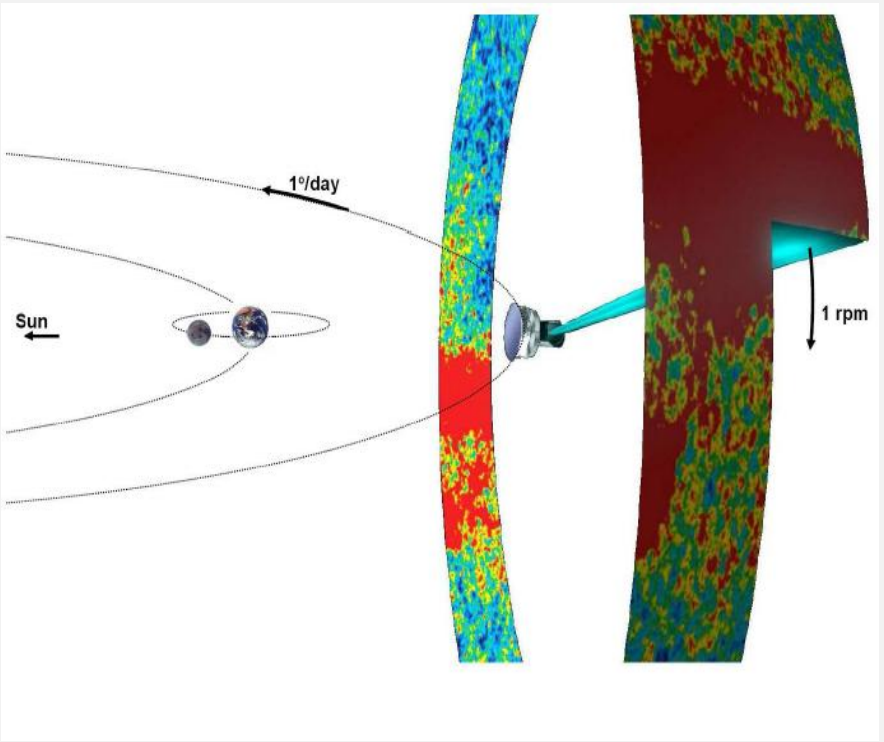
Proton-M

Buster DM-3



All-sky Survey – 4 years
+2.5 years of pointed observations





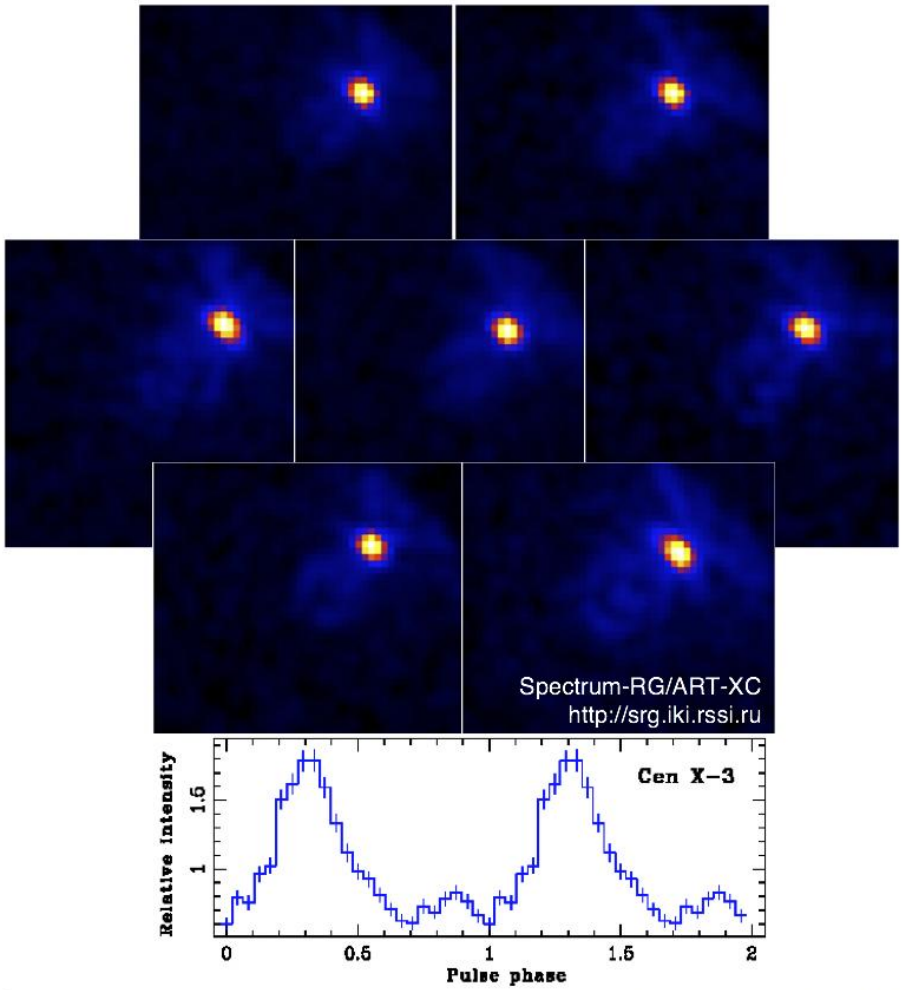
Period 4 hours
Full sky in 6 months,
8 surveys in 4 years

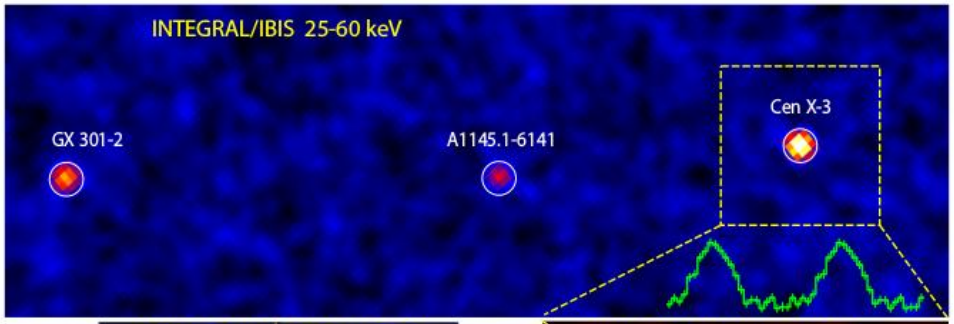
Date	Time	Event
2019/07/13	15:31	Launch
2019/07/13	17:31	End of s/c acceleration and separation of DM-03 booster from s/c
2019/07/13	18:43	Telescope subsystem switched on and stores on-board information
2019/07/13	18:58	Telescope thermal control system switched on
2019/07/18	18:42	First telemetry from first X-ray camera received
2019/07/21		All cameras switched on and reported "healthy"
2019/07/22		First trajectory correction
2019/07/23	18:31	Telescope cover opened
2019/07/27		First X-ray calibration source opened and first calibration of first camera performed, start of cameras commissioning
2019/07/30	17:29	"First Light" (image of Cen X-3 on all cameras)
2019/08/06		Second trajectory correction
2019/08/25		Finish of seven cameras commissioning, EEPROM of first camera successfully reprogrammed to working configuration, start of ART-XC calibration and performance verification phase
2019/10/05		Finish of the ART-XC calibration and performance verification phase
2019/10/21		Third trajectory correction

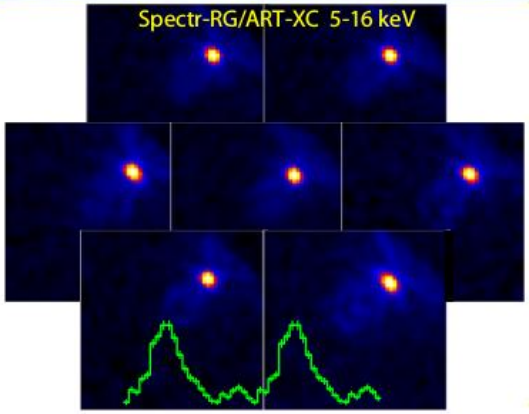
- ➢12/12/19 Start of the all-sky survey
- ➢13/06/20 End of the first all-sky survey and start second one
- ➢15/12/20 End of the second all-sky survey
- ➢Several orbit corrections and calibration observations
  - Axis alignment
  - PSF
  - Spectral resolution and energy scale
  - Timing capabilities

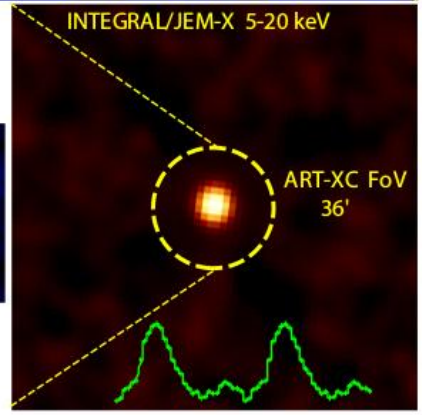
First light of ART-XC

On July 30, 2019 the first images of X-ray pulsar **Cen X-3** have been obtained with **ART-XC/Spectrum-RG**. Pulsations with period of **~4.8 sec** are clearly detected







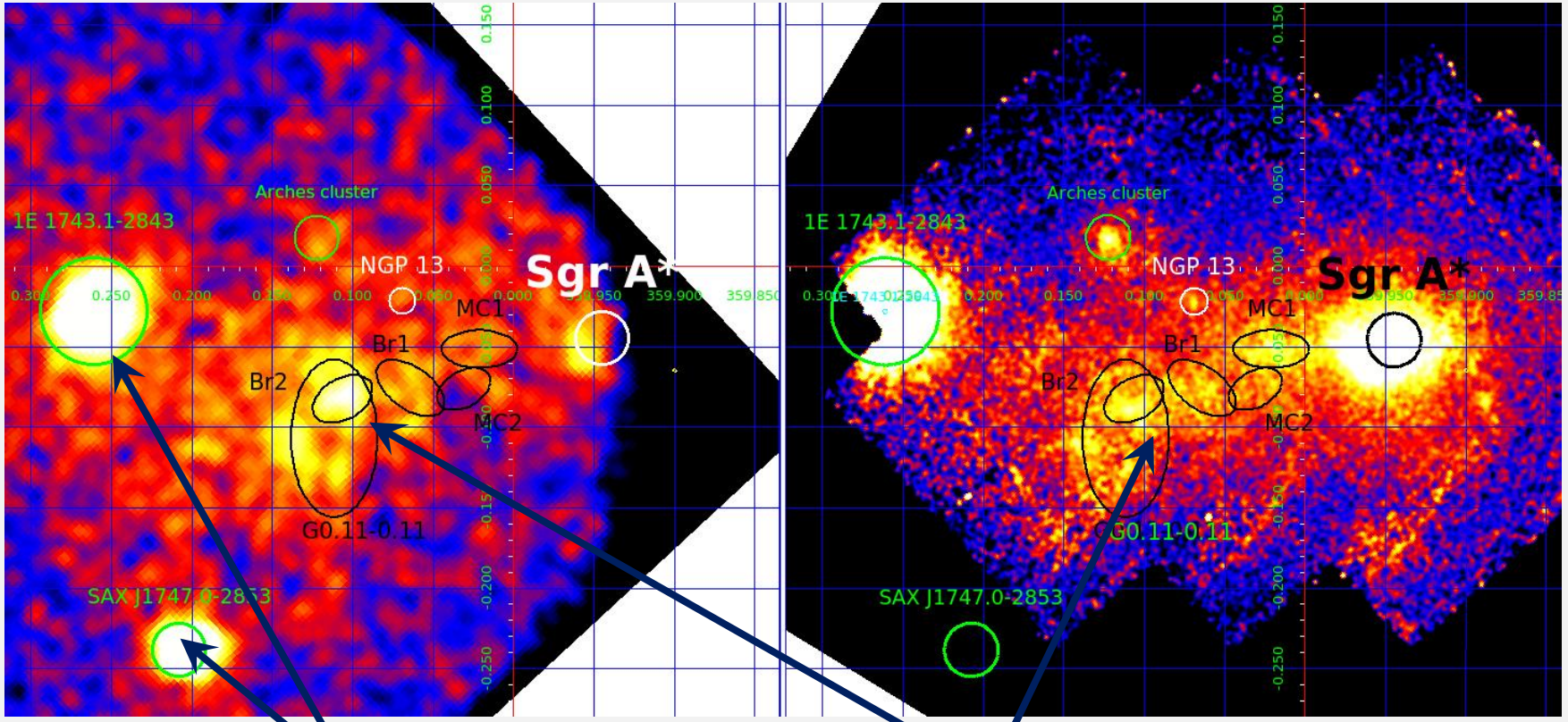



16:34:29
MSK
30.07.2019
16:34:29
UTC

Observations of the Galactic Center with ART-XC

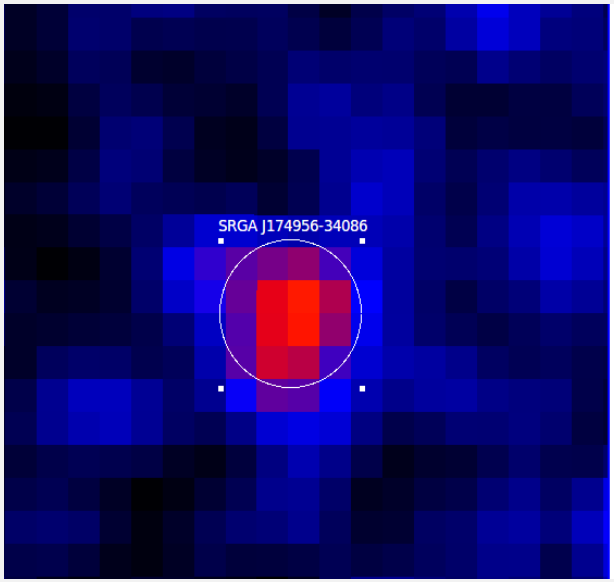
ART-XC/SRG (5-16 keV)

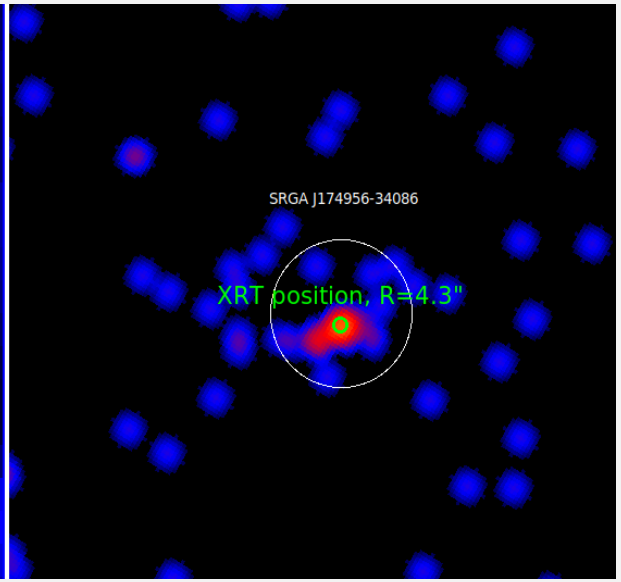
NuSTAR (3-78 keV)



Point sources and diffuse emission

First new source discovered with SRG/ART-XC



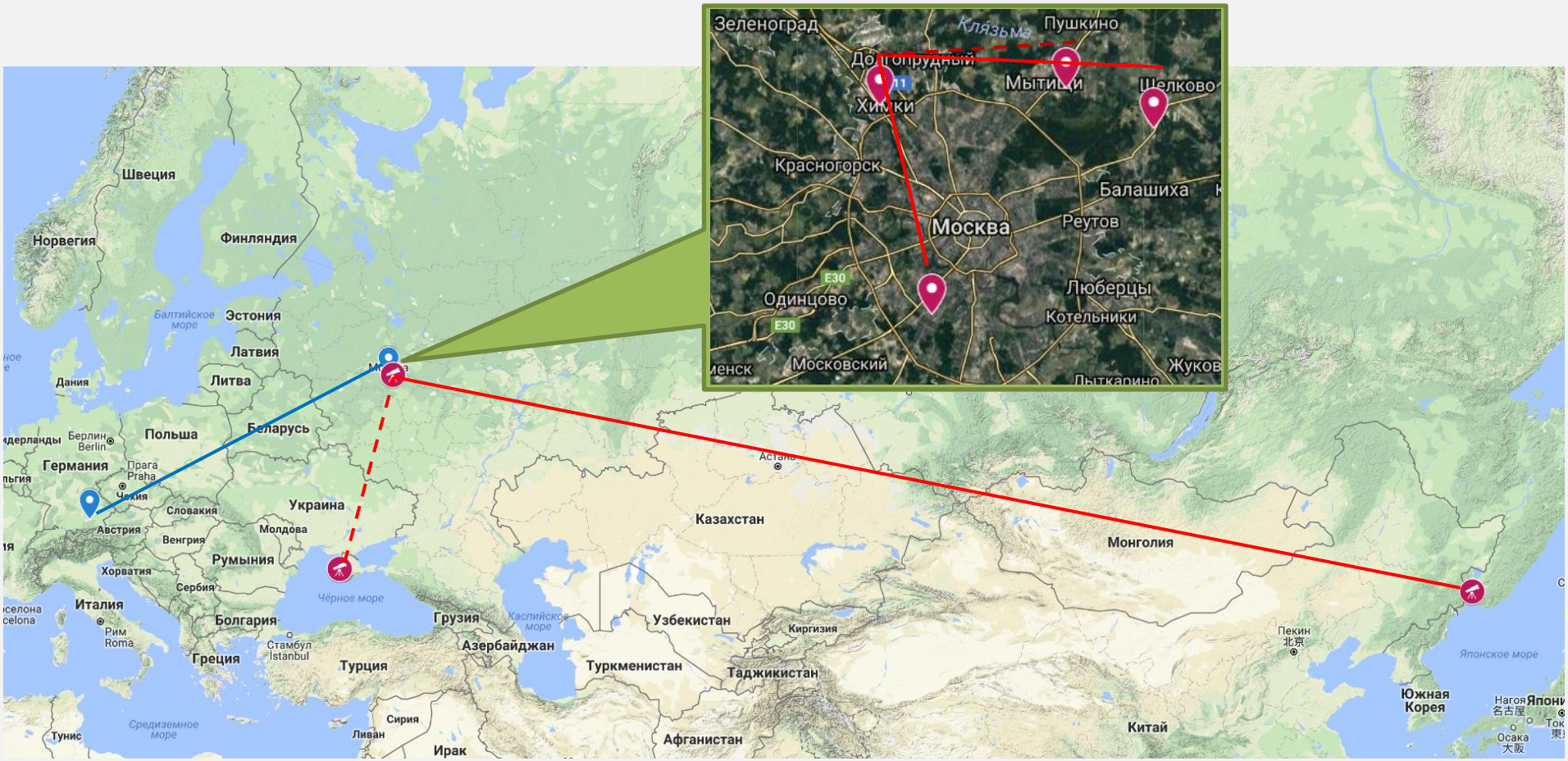


On Sep 3, 2019 the first new source **SRGAJ174956-34086** was discovered by the **ART-XC** telescope during the scanning program of the Galactic bulge

ART-XC Galactic Bulge survey - first results

ATel #13095; *I. Mereminskiy, M. Pavlinsky, I. Lapshov, A. Lutovinov, S. Molkov, A. Semena, A. Shtykovsky, A. Tkachenko (IKI RAS) on behalf of ART-XC collaboration*
on 9 Sep 2019; 20:42 UT

Operational Ground Segment Geography



Ground stations

Bear Lakes «Spectr-X»

12 meter TNA-57

Baykonur «Spectr-X»

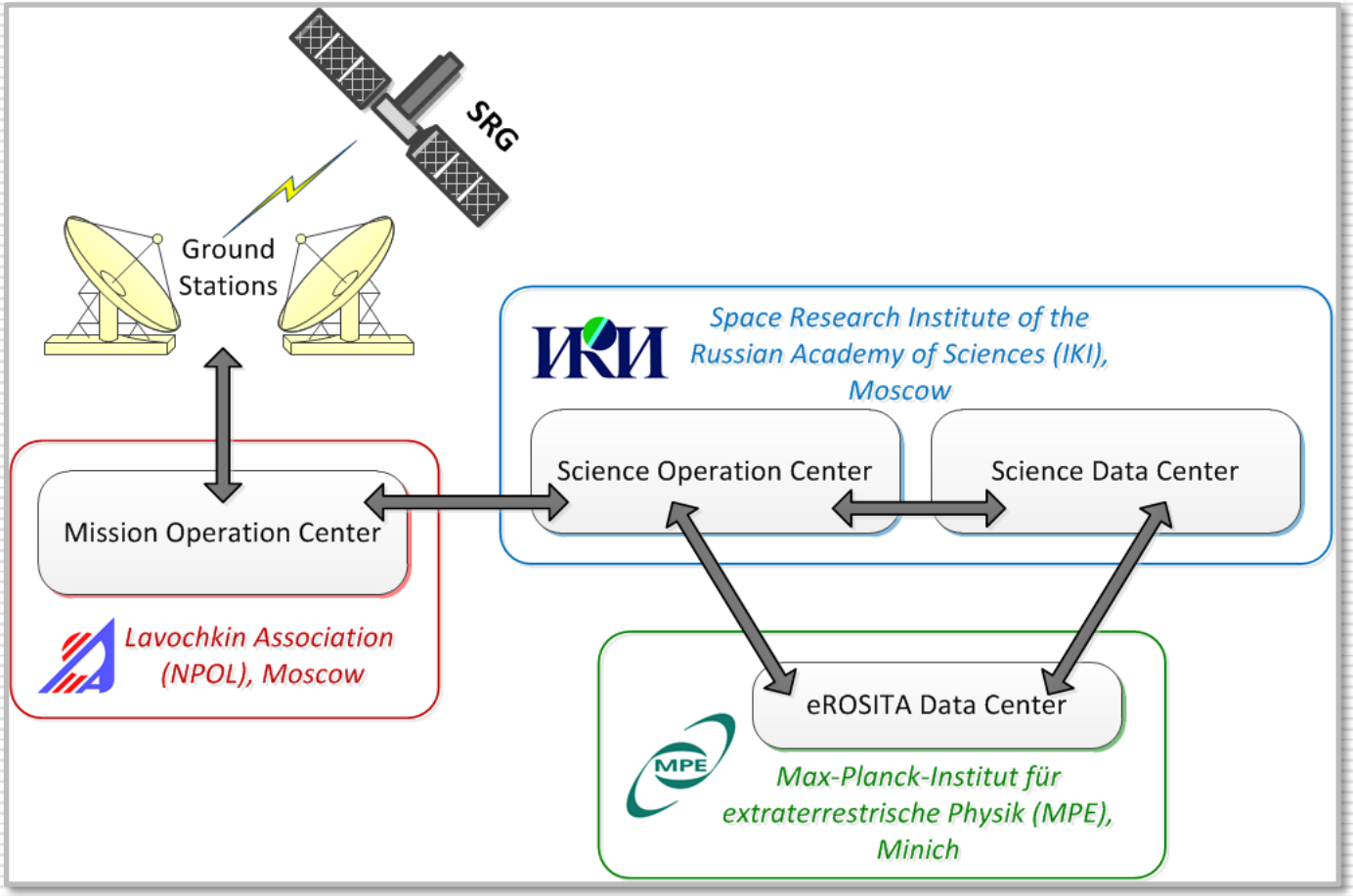
12 meter TNA-57

«Bear Lakes» RT-64

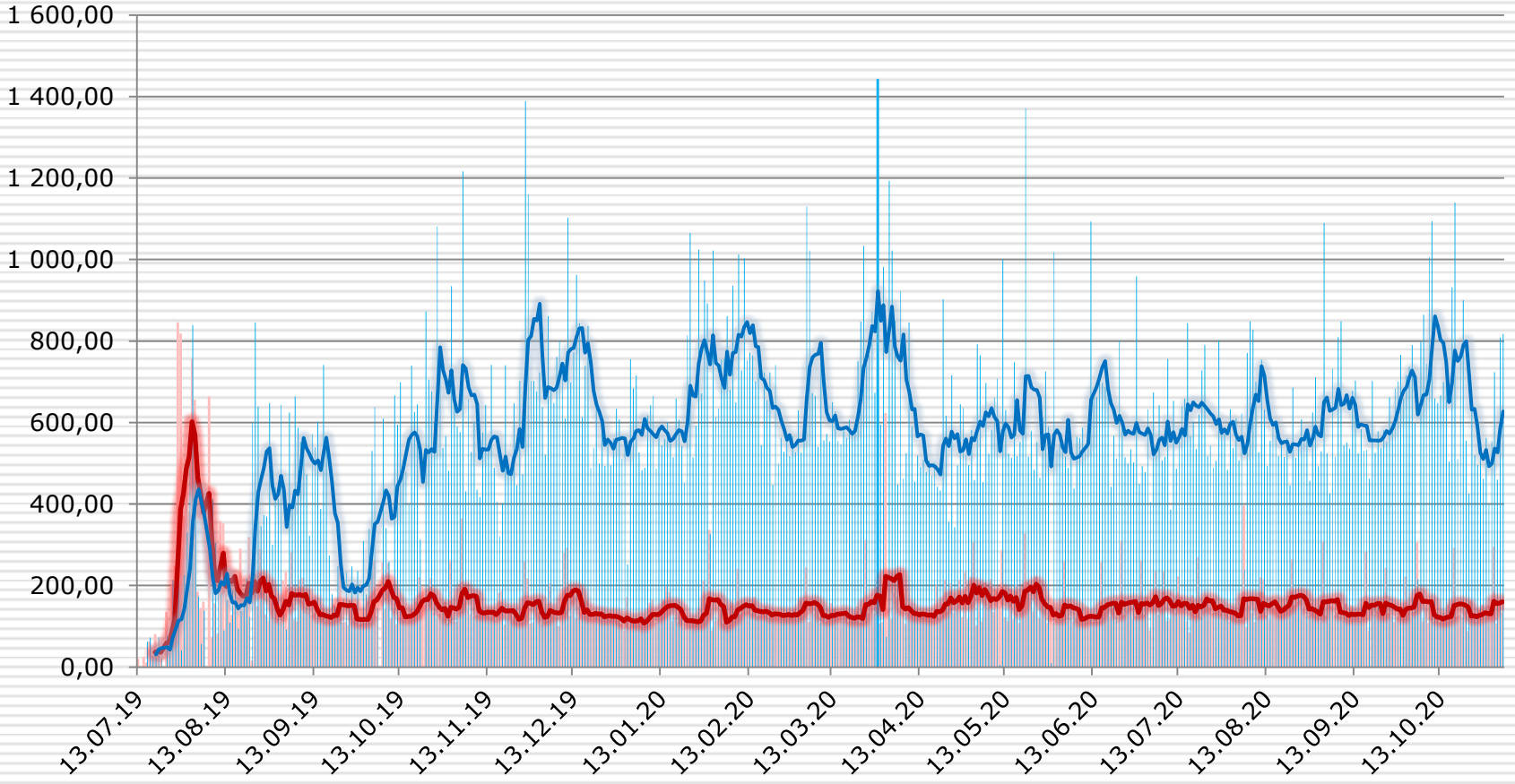
Evpatoria, Crimea

Ussuriisk

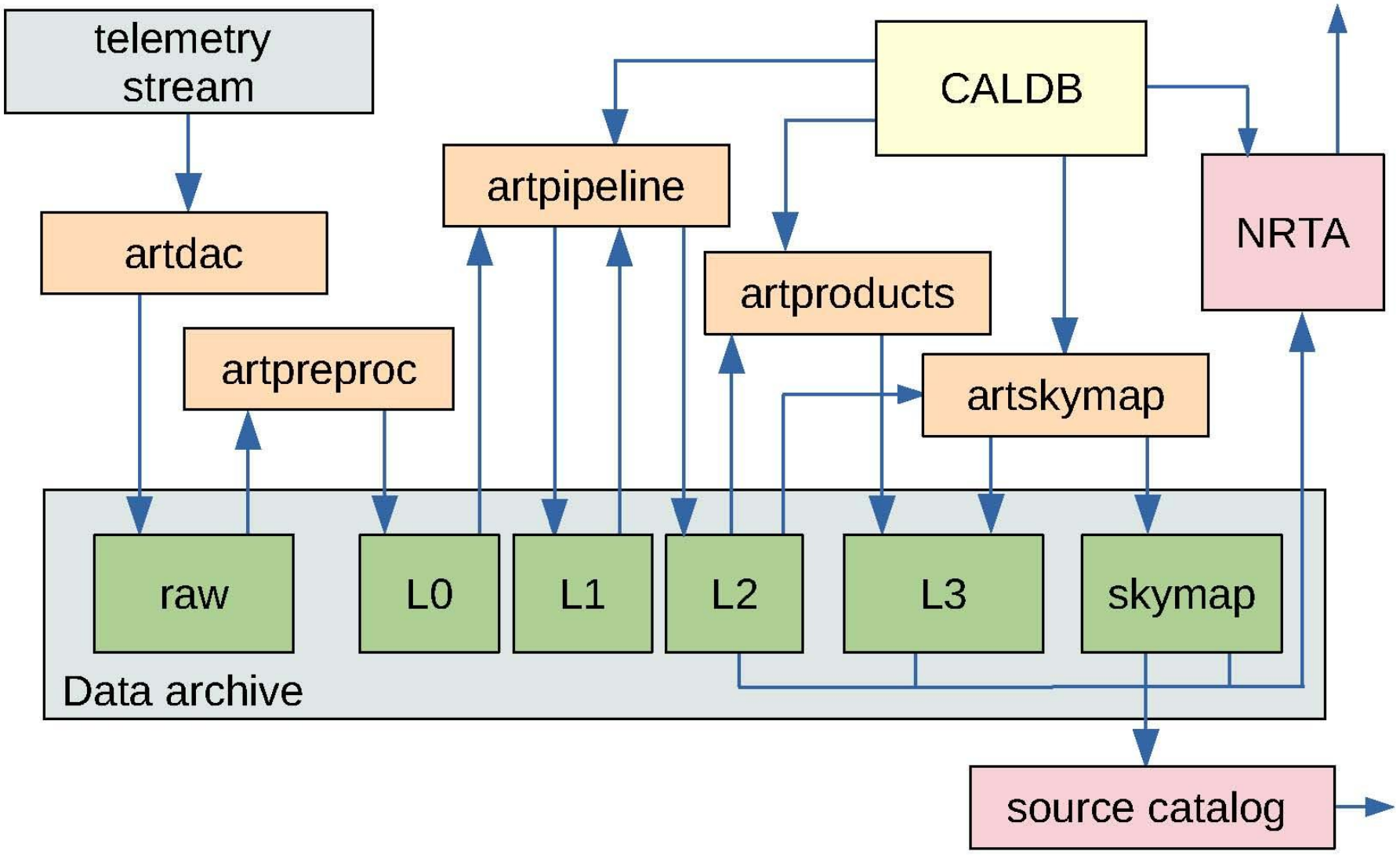
General scheme of the data receiving and distribution



Obtained information from SRG instruments



ART-XC pipeline

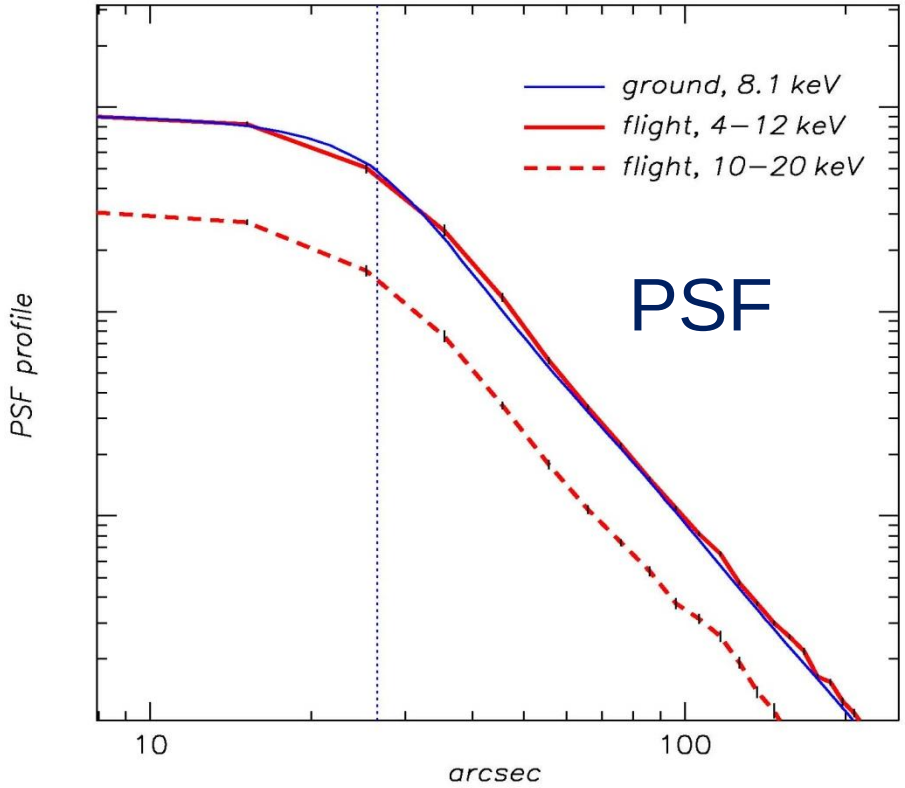


Credit: A.Shtykovsky 2021

ART-XC in-flight performances:

Optical axis alignment and pointing accuracy

- The ART-XC boresight differ by ~12′ from the nominal axis of SRG spacecraft
- Now the accuracy of boresight correction is better then 10″

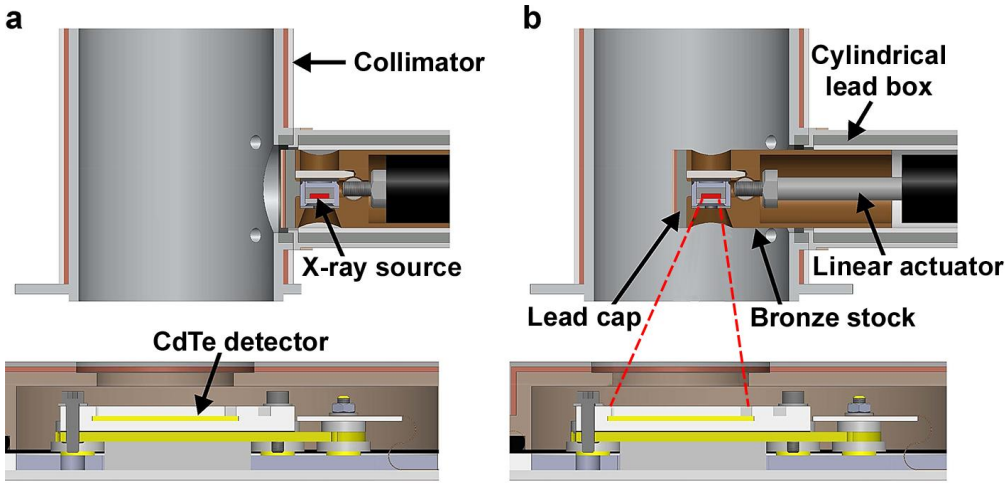


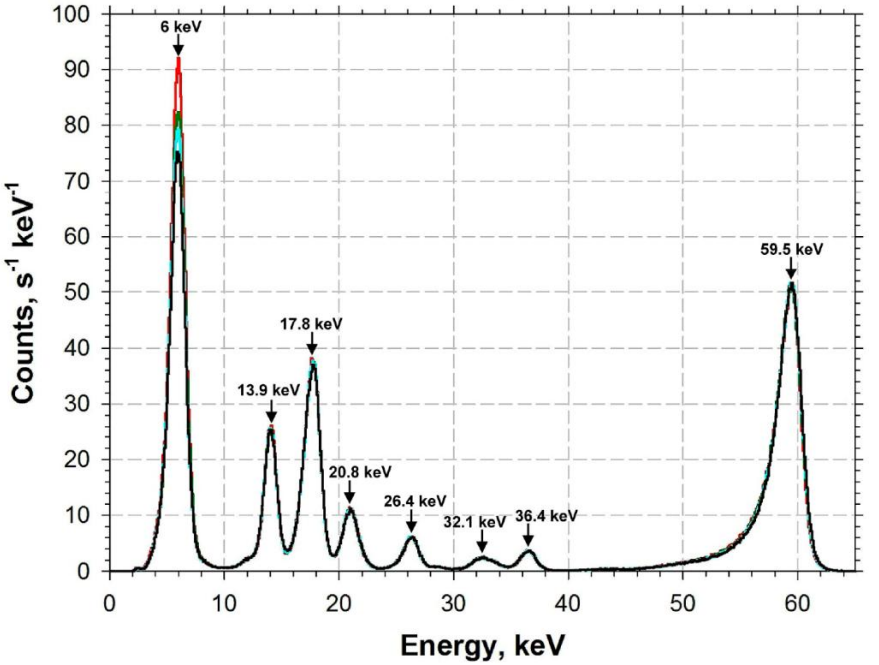
The PSF radial profile measured in scanning mode of GX 3+1 (red) and during calibrations at the Stray Light Test Facility, NASA/MSFC (blue).

The ART-XC PSF for scanning and survey observing modes is ~53″ (FWHM)

ART-XC in-flight performances:

Spectral resolution and energy scale

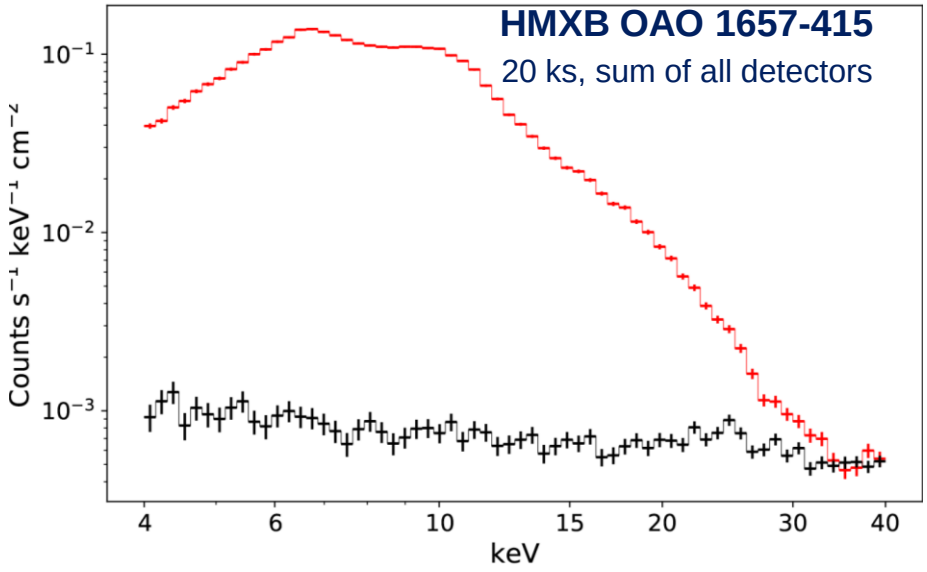




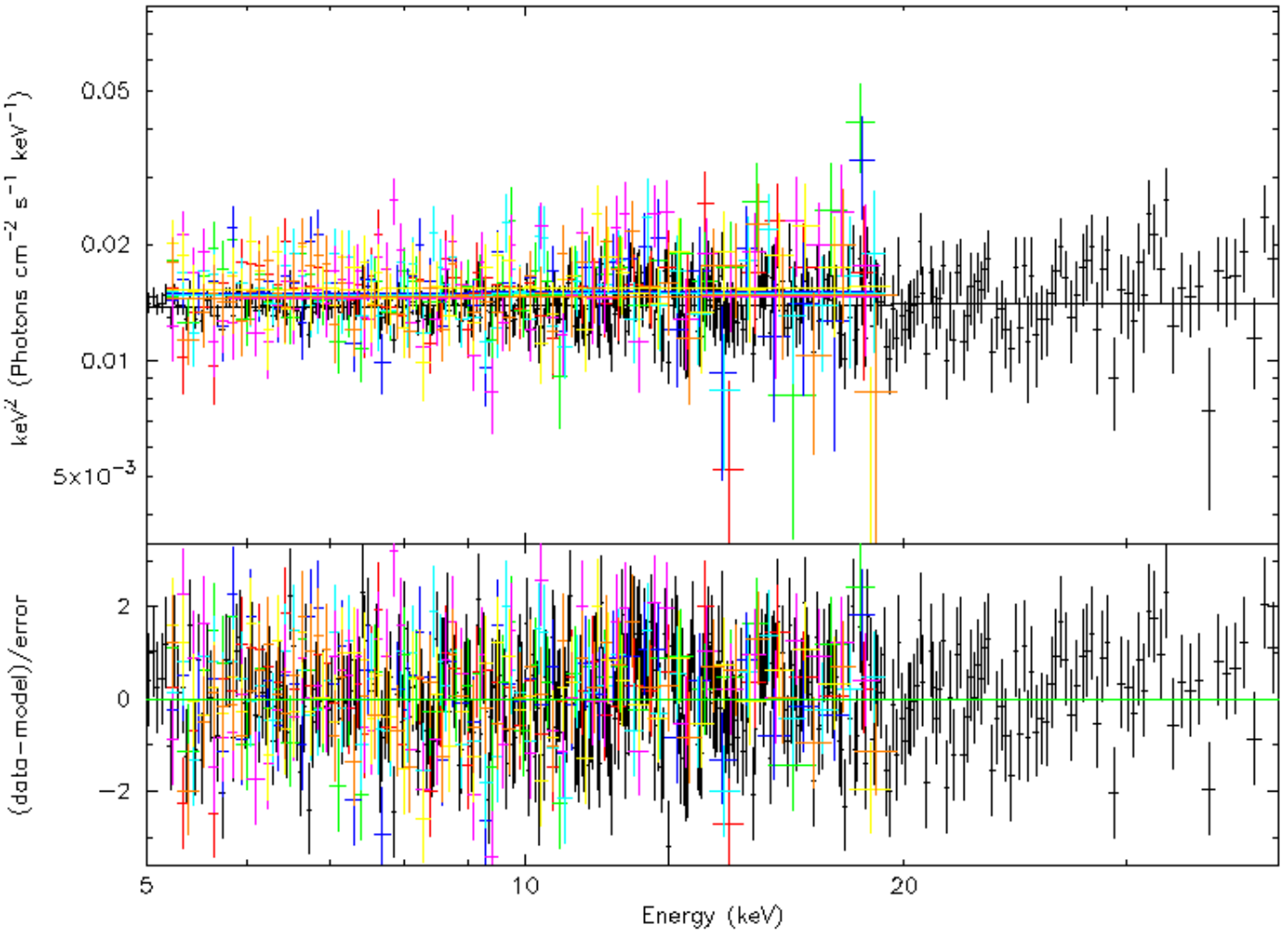
The energy spectra of the internal calibration source obtained during the first year.

Both energy resolution and detector efficiency do not change with time!

ART-XC is able to detect the bright sources up to 30 keV



ART-XC in-flight performances:
Comparison with NuSTAR

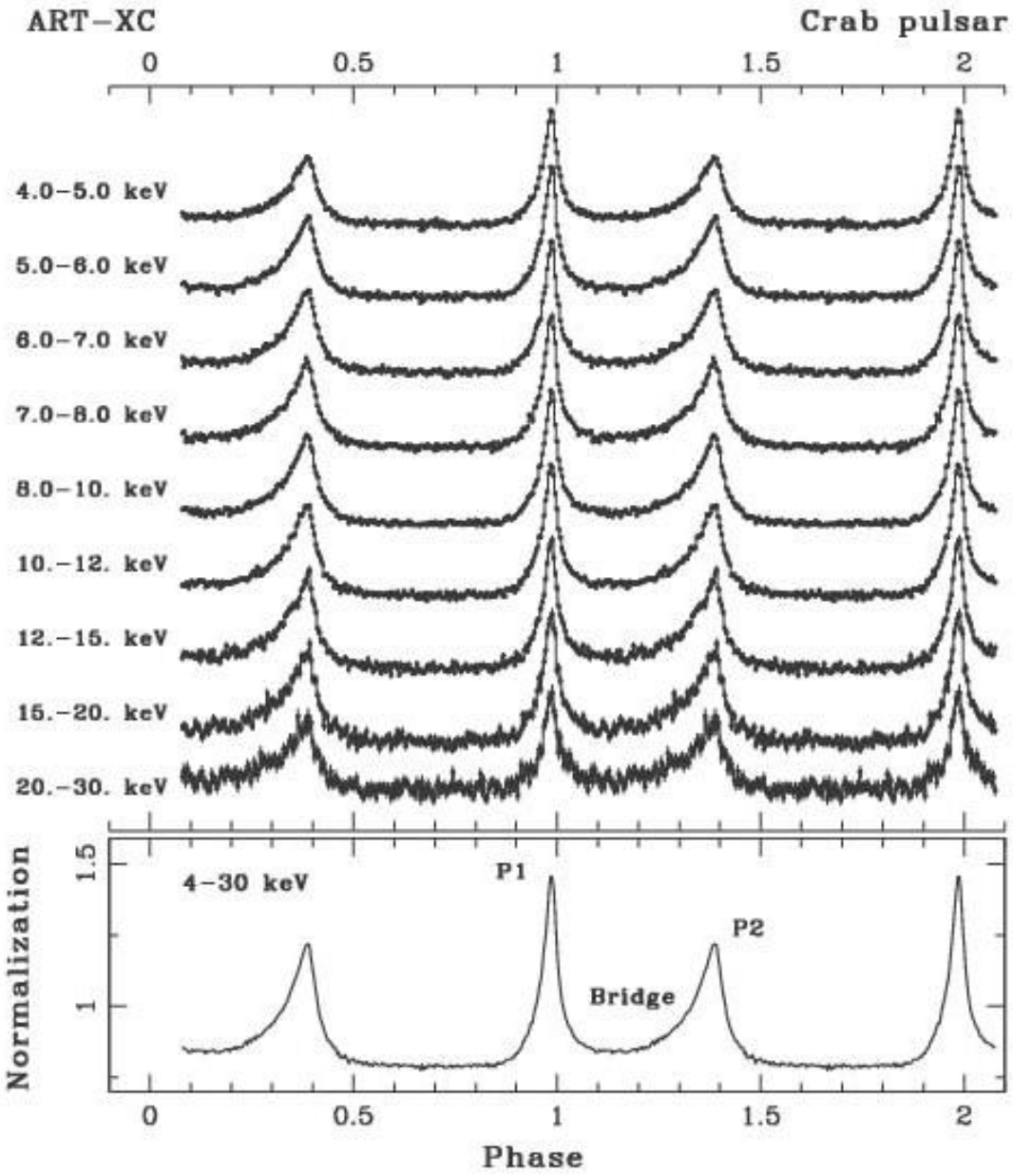


PSRB0540-69

Наклон по данным ART-XC 1.98±0.06 vs 1.99±0.02 NuSTAR FPMA

ART-XC in-flight performances:

Timing capabilities

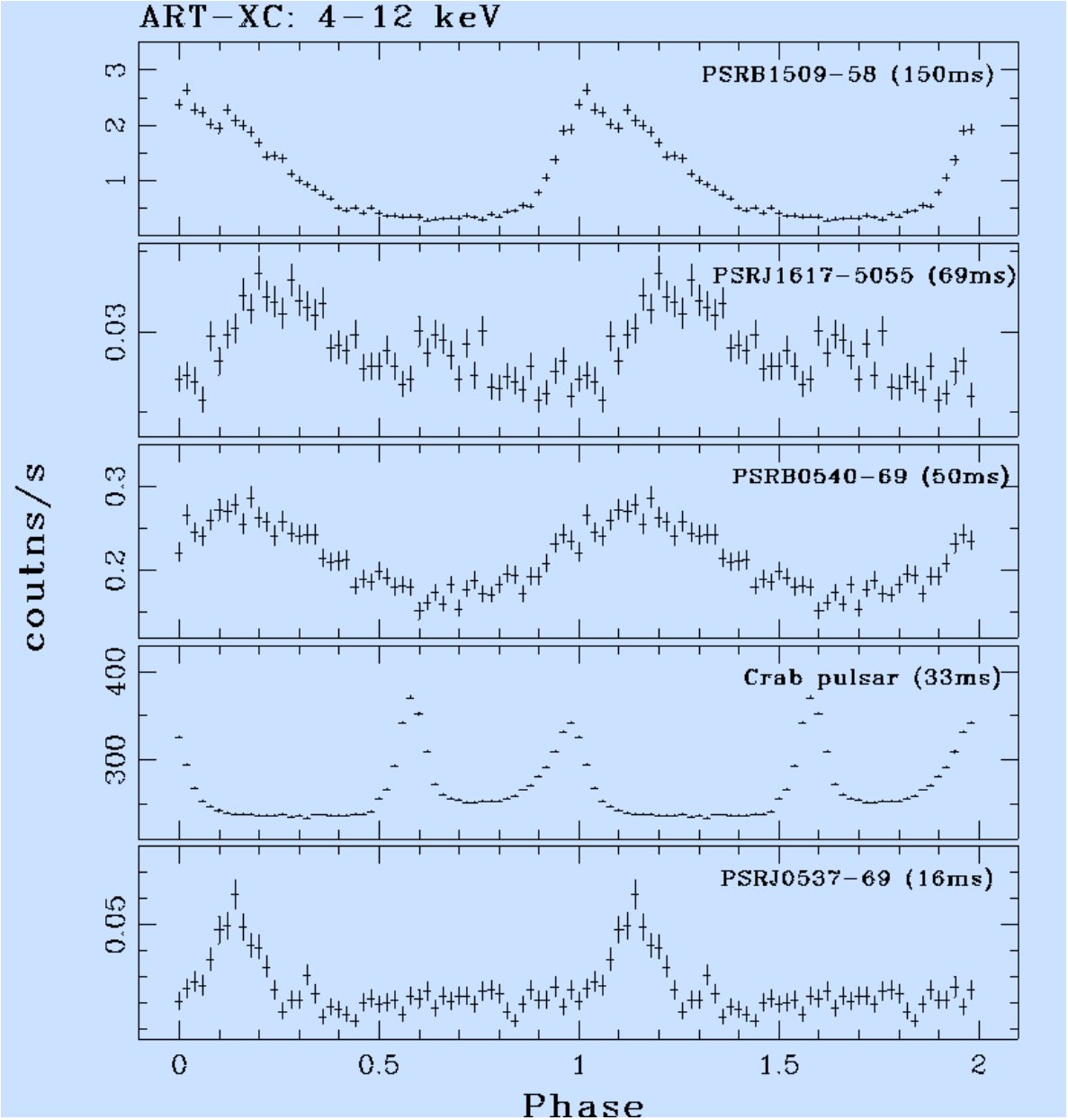


Crab pulsar
Period ~33 ms

Credit: S.Molkov 2021

ART-XC in-flight performances:

Timing capabilities

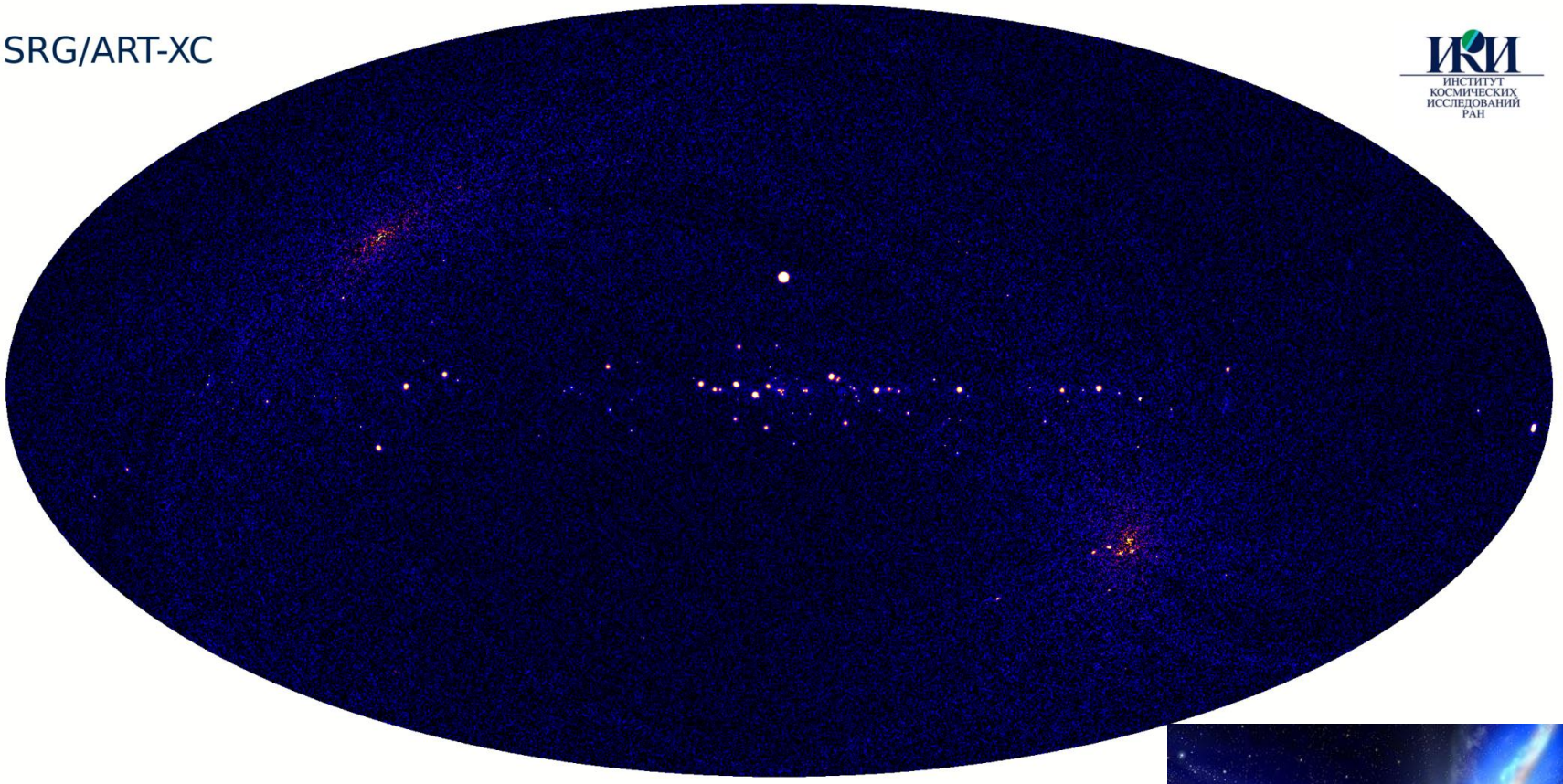


Difference in intensity ~ four orders of magnitude

Pulsations are detected from 16 ms up to thousands s

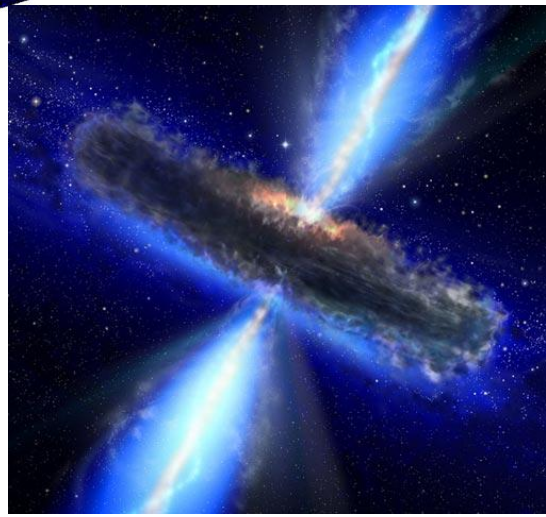
Credit: S.Molkov 2021

First all-skv survev with ART-XC in 4-12 keV

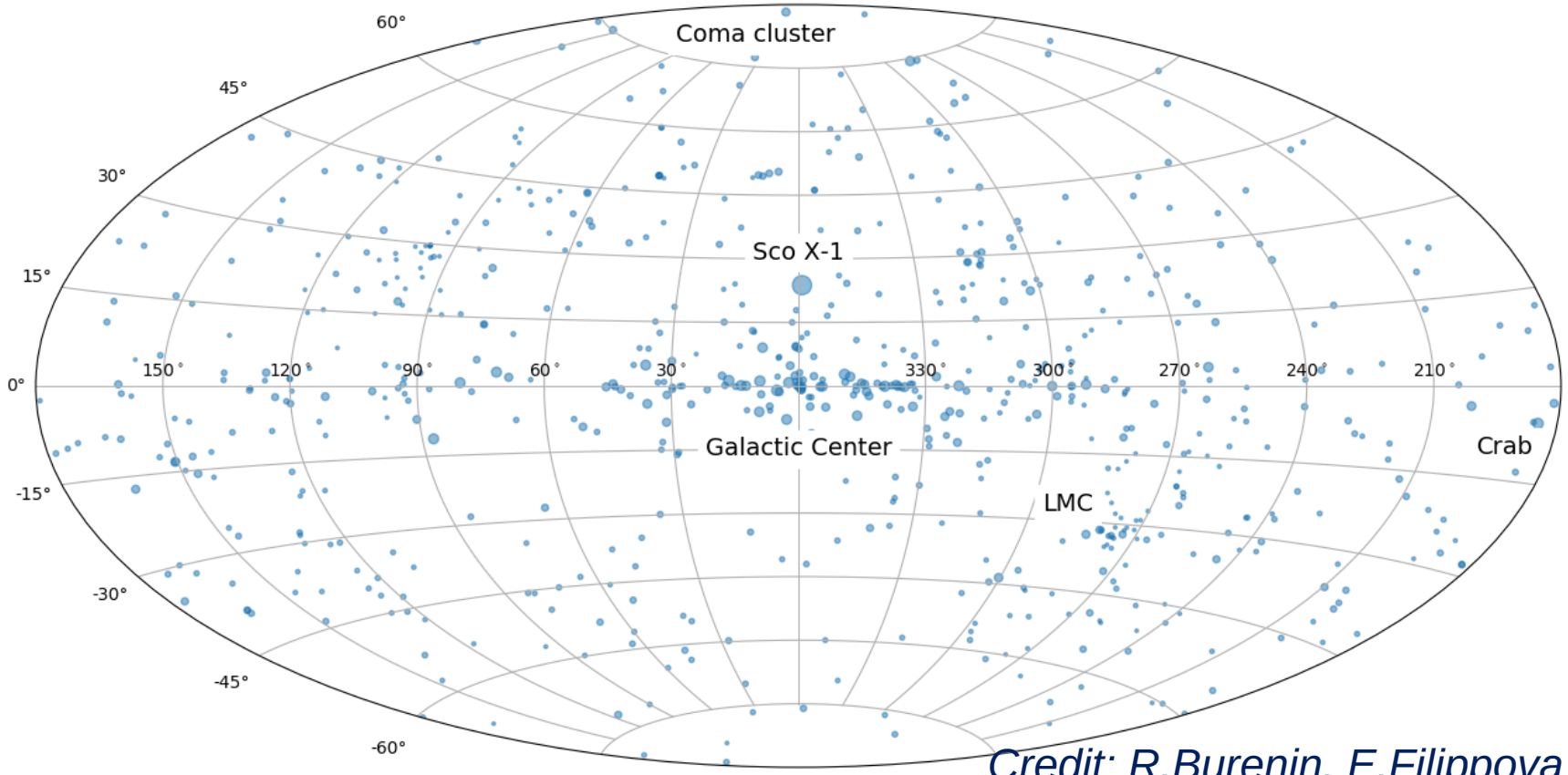


ИКИ
ИНСТИТУТ КОСМИЧЕСКИХ ИССЛЕДОВАНИЙ РАН

Detection threshold (0.5-1)x10^{-11} erg s^{-1} cm^{-2},
~40% extragalactic sources (AGNs, GCs),
other galactic ones
ART-XC found several dozen new sources, some of them are not detected by eRosita.
Analysis and optical observations are in progress



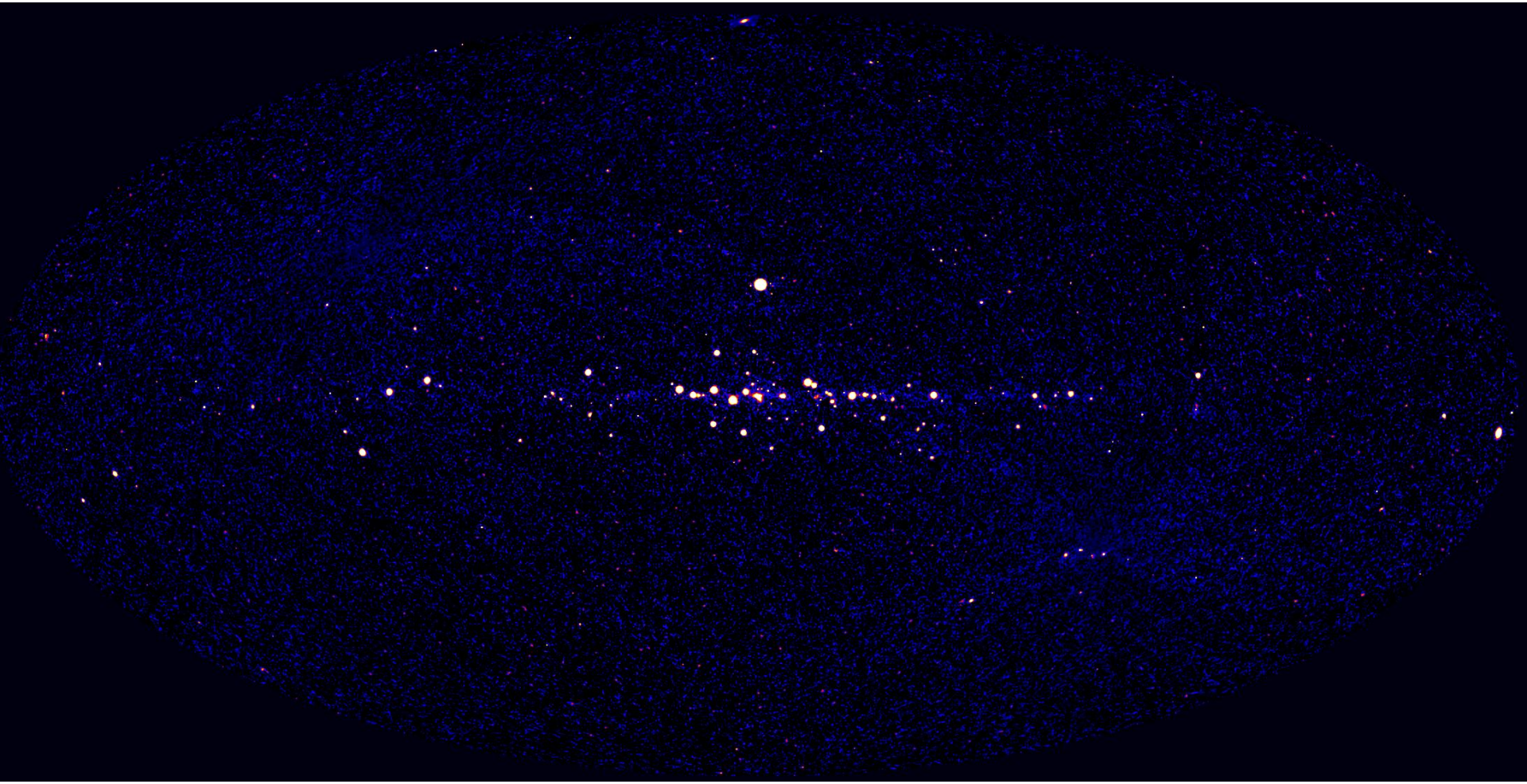
First all-sky survey with ART-XC in 4-12 keV



Credit: R.Burenin, E.Filippova 2021

Detection threshold (0.5-1)x10^{-11} erg s^{-1} cm^{-2},
~40% extragalactic sources (AGNs, GCs),
other galactic ones
ART-XC found several dozen new sources, some of them are not detected by eRosita
Analysis and optical observations are in progress

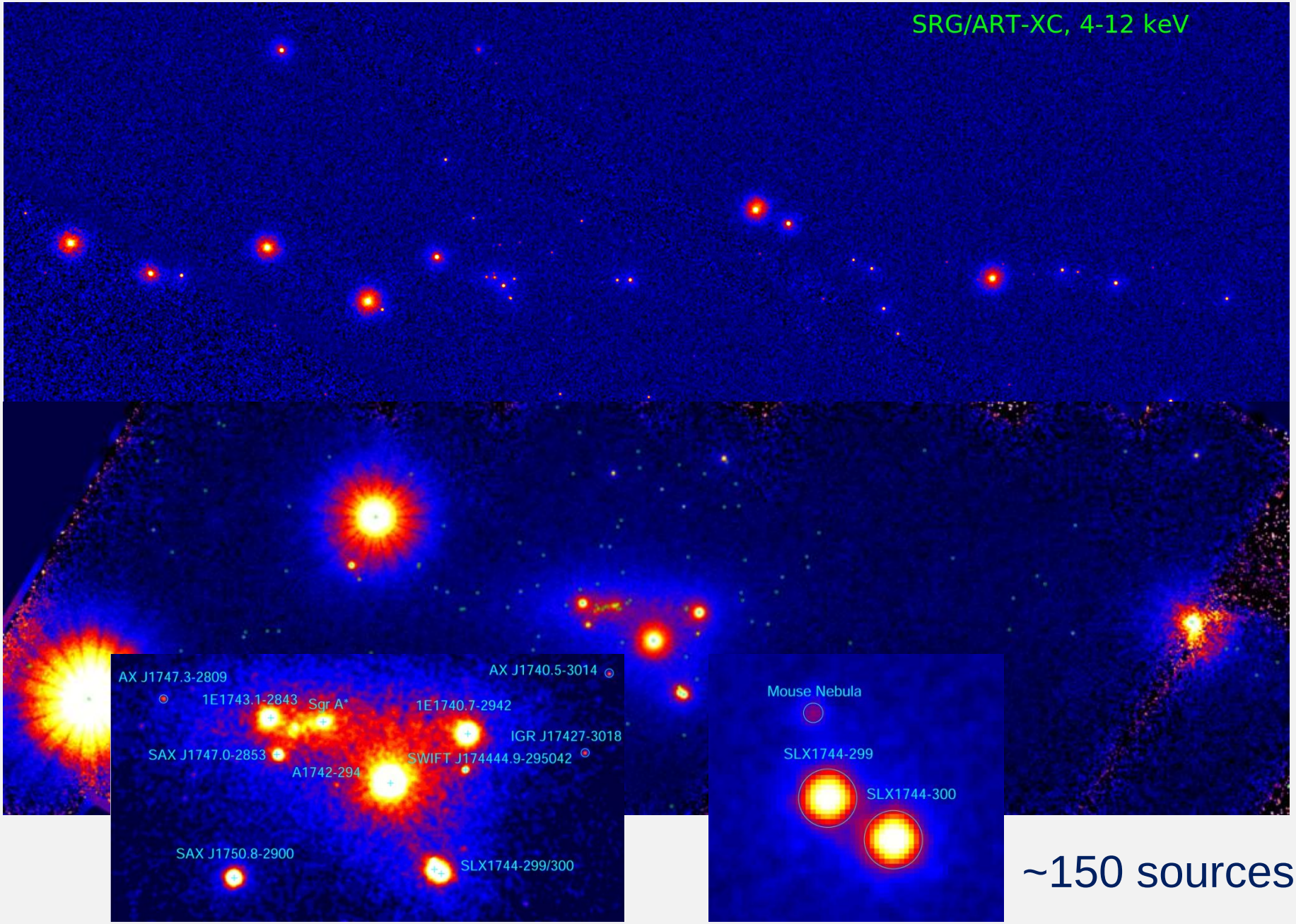
One year all-sky-survey with ART-XC



~ 700 sources (4-12 keV), ~ 400 (7-12 keV), ~100 are **not** in 4-7 keV.
Upon completion of 4-year all-sky survey, ART-XC is expected to detect ~5000 sources in 4-12 keV

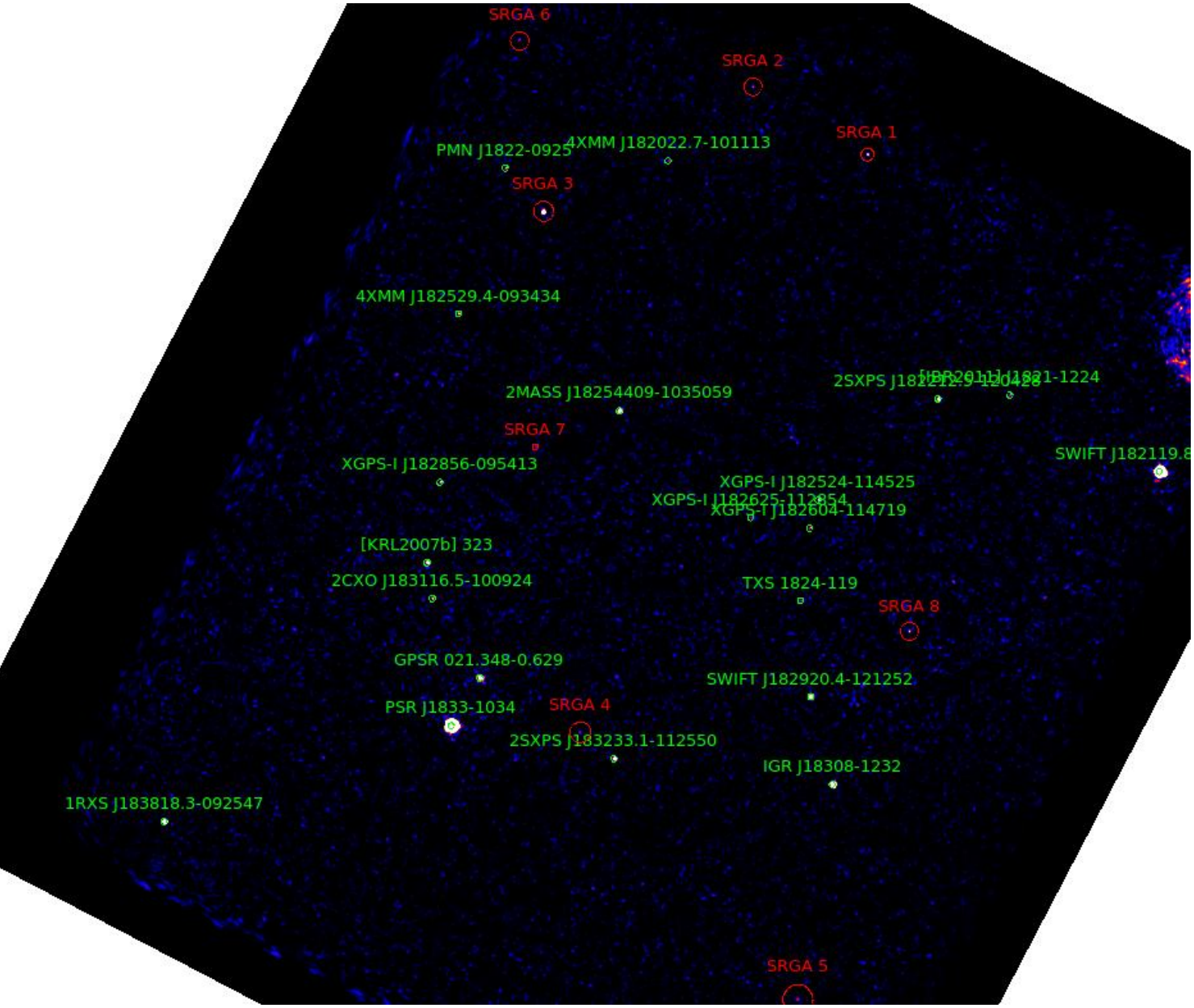
Variability at the time scale of a half of year

Galactic plane + deep survey of Galactic center



~150 sources

Deep surveys of the Galactic plane with ART-XC:



L+20
Area: 24.5 sq.deg

Depth: ~2.2 times deeper than expected in all sky survey

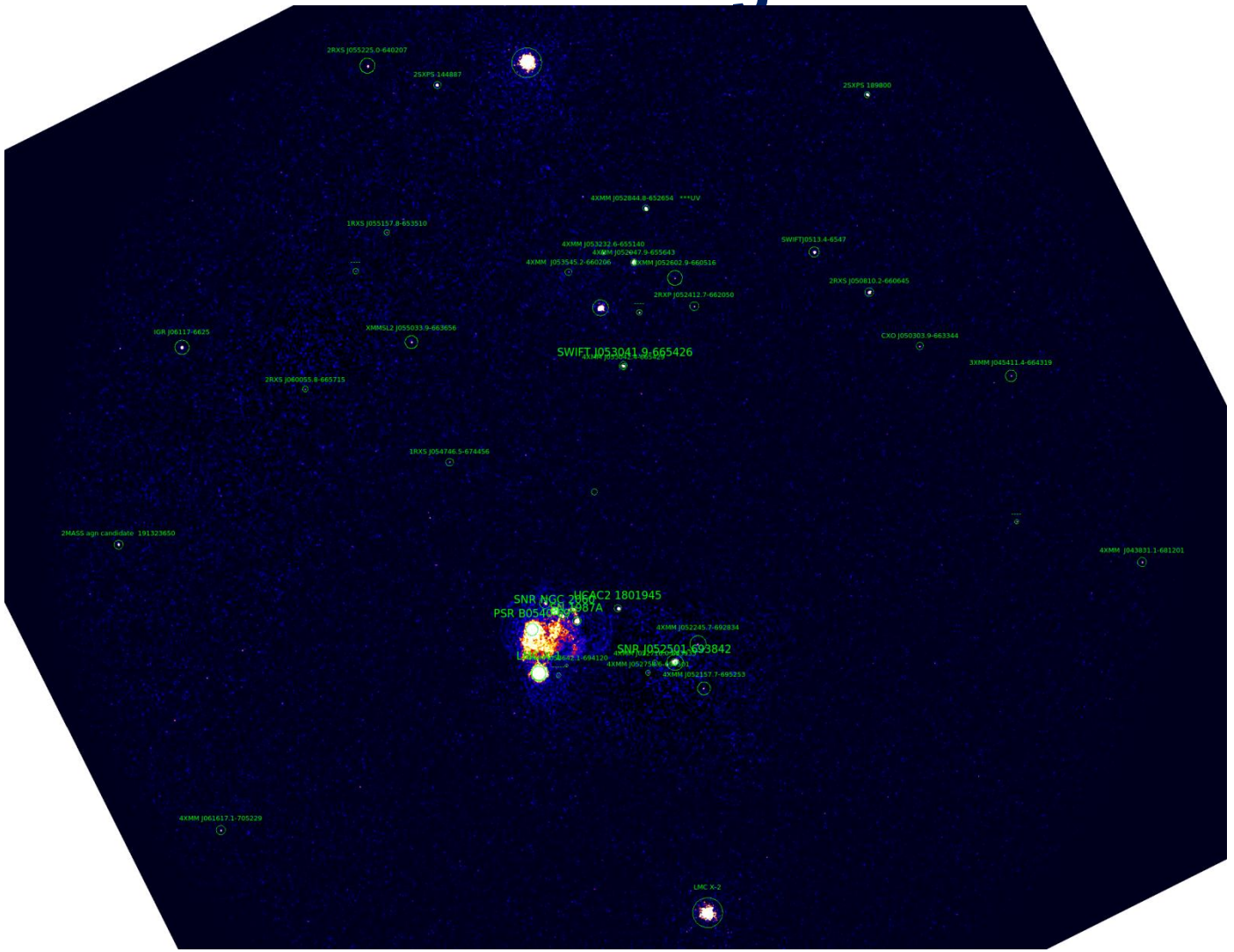
Total of 30 detections at the flux limit of $5.5\ 10^{-13}$ erg/s/cm^2

13 of 30 are new detected sources in X-rays

Norma Arm

Semena et al. 2021

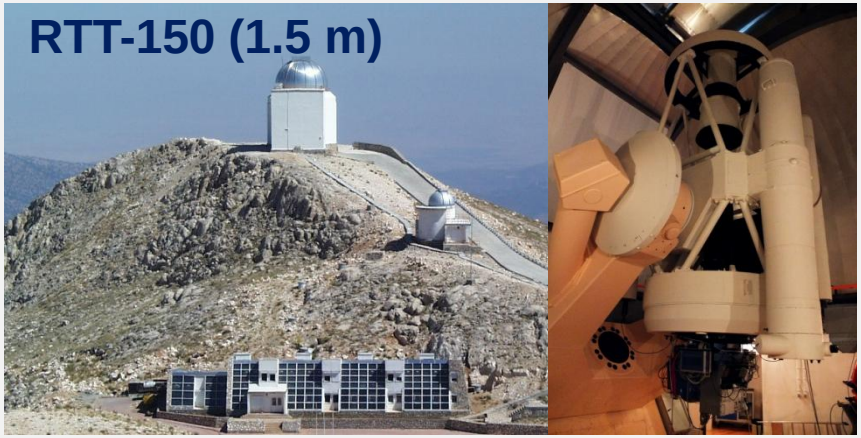
LMC region

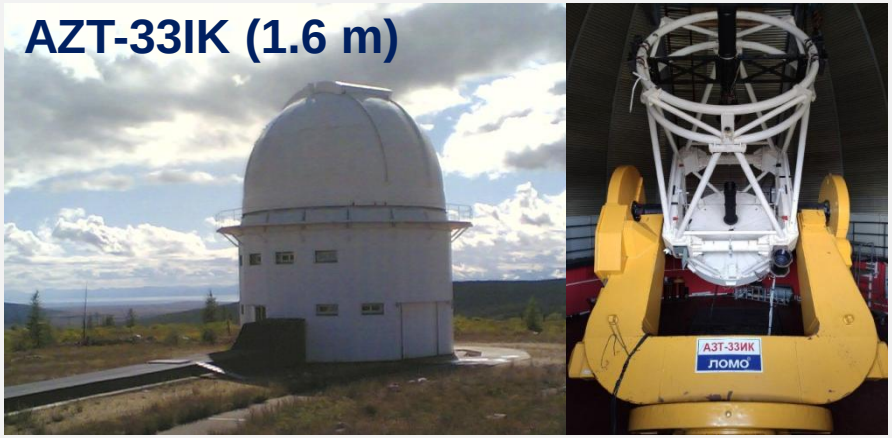


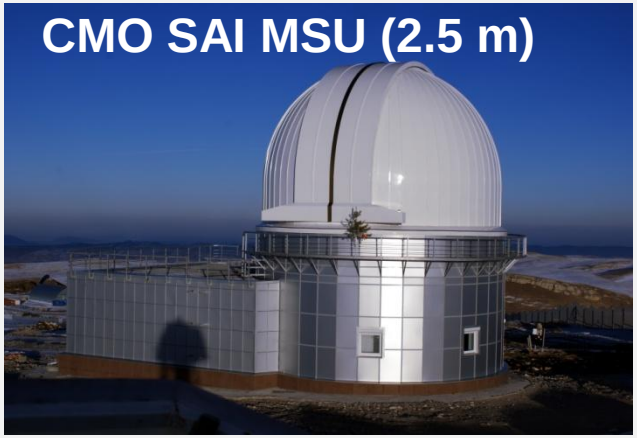
~70 sq.deg. 44 sources detected.

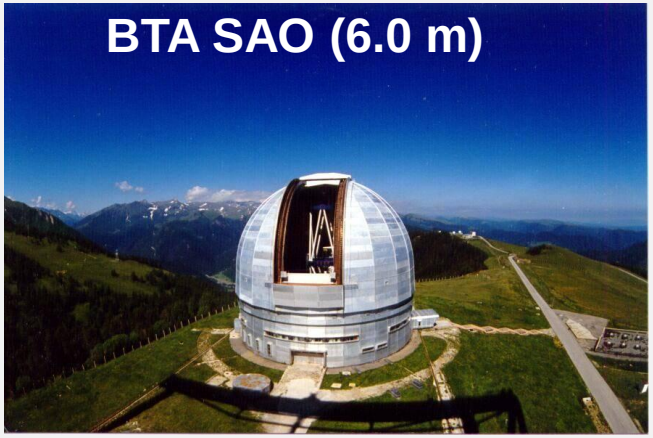
detection flux limit with the largest exposure of ~ 1.5 10^{-13} erg/s/cm^2

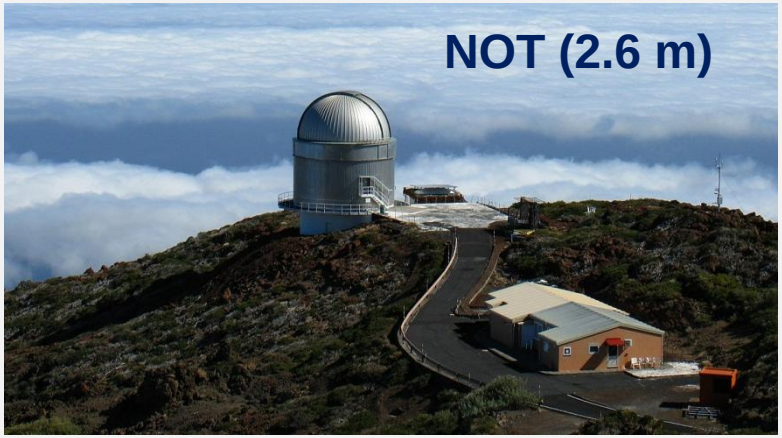
Ground-based support of SRG/ART-XC observations







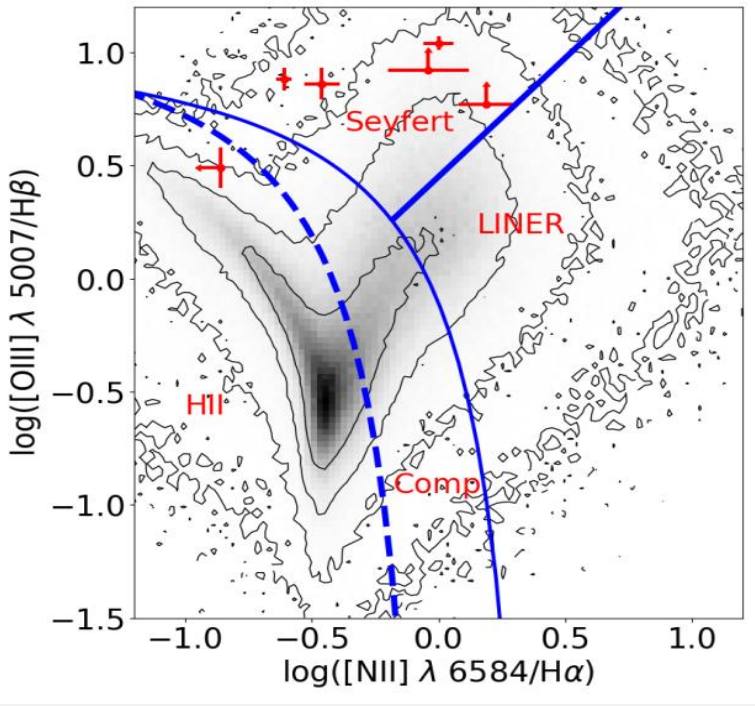




AGNs in the ART-XC catalog

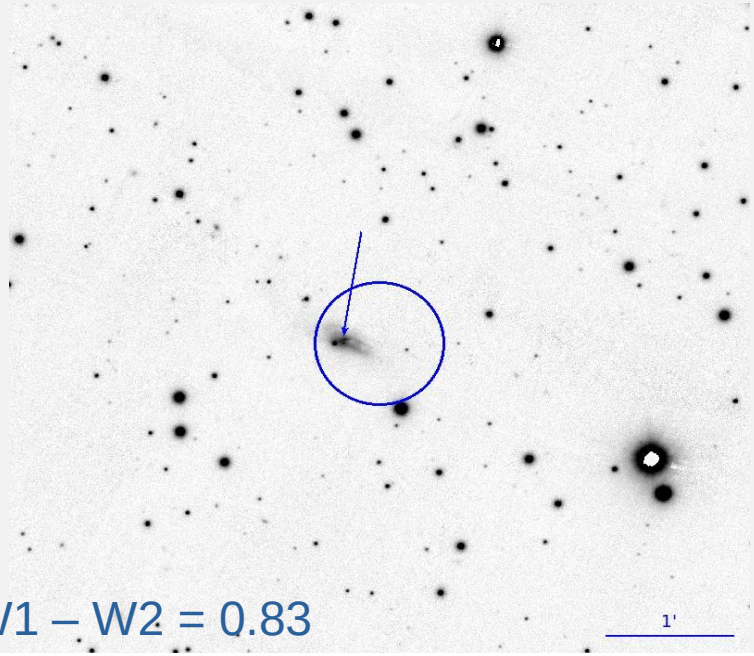
Source	Optical type[1]	z	N_H[2]	$\log L_X$[3]
SRGA J005751.0+210846	Sy2[4]	0.04798 ± 0.00002	$> 1 \times 10^3$	$43.7^{+0.2}_{-0.3}$
SRGA J014157.0−032915	Sy2	0.01878 ± 0.00003	$> 3 \times 10^2$	$42.5^{+0.3}_{-1.2}$
SRGA J043209.6+354917	Sy1	0.0506 ± 0.0010	$3.0^{+0.8}_{-0.7}$	$43.8^{+0.2}_{-0.3}$
SRGA J045049.8+301449	Sy1.9	0.03308 ± 0.00004	38^{+11}_{-10}	$43.4^{+0.2}_{-0.3}$
SRGA J152102.3+320418	Sy2	0.1143 ± 0.0003	25^{+6}_{-6}	$44.1^{+0.2}_{-0.4}$
SRGA J200431.6+610211	Sy2	0.05866 ± 0.00013	$4.7^{+2.2}_{-1.4}$	$43.6^{+0.2}_{-0.3}$
SRGA J224125.9+760343	NLSy1	0.2834 ± 0.0004	< 0.4	$44.9^{+0.2}_{-0.6}$
SRGA J232446.8+440756	Sy2	0.0462 ± 0.0002	$> 3 \times 10^2$	$43.5^{+0.2}_{-0.3}$

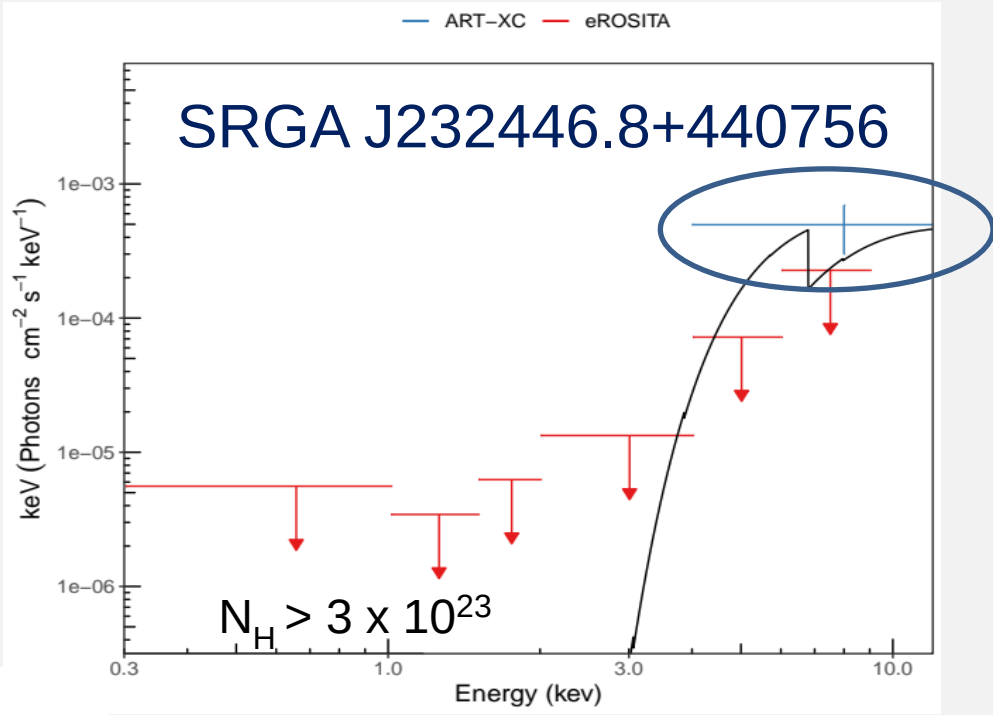
[1] Sy1, Sy1.9, Sy2 are Type 1, 1.9, 2 Syfert galaxies correspondingly,
[2] In units of 10^{21} cm^{-2}, the errors and limits correspond to the 90
SRGA J014157.0−032915 the 68% level is presented.
[3] The luminosity not corrected for absorption in the observed 4 – 1
[4] The classification is conditional, since the galaxy is observed from

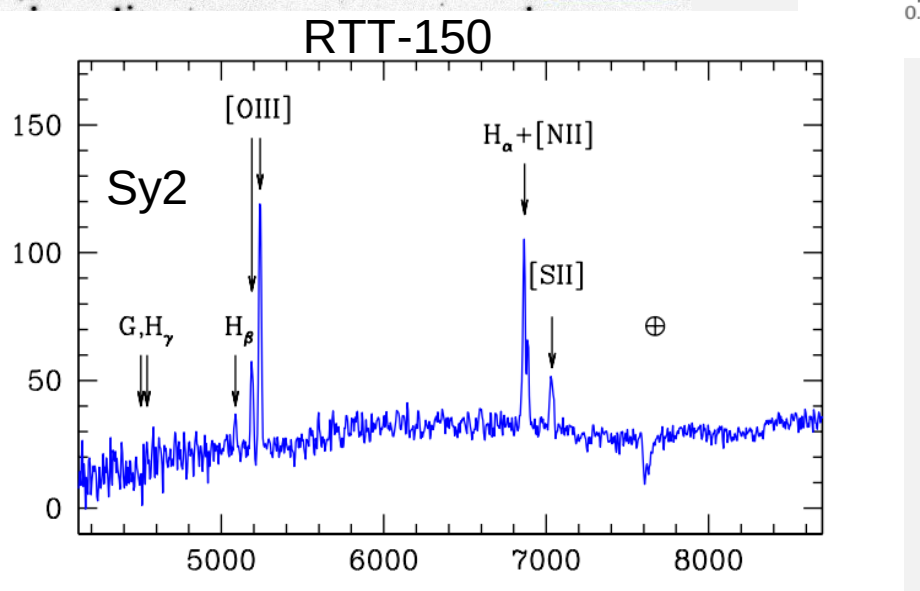


Zaznobin et al. 2021

Absorbed AGNs in the ART-XC catalog





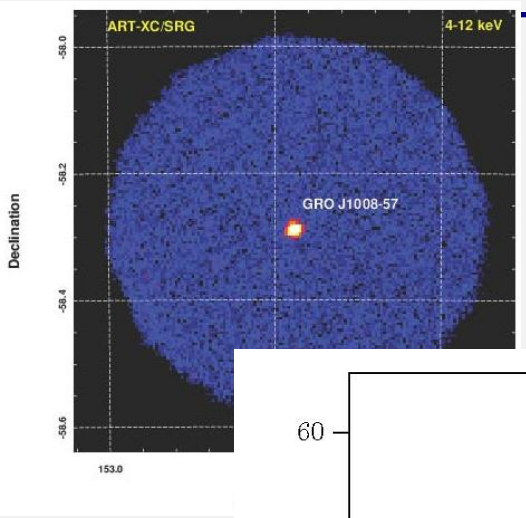


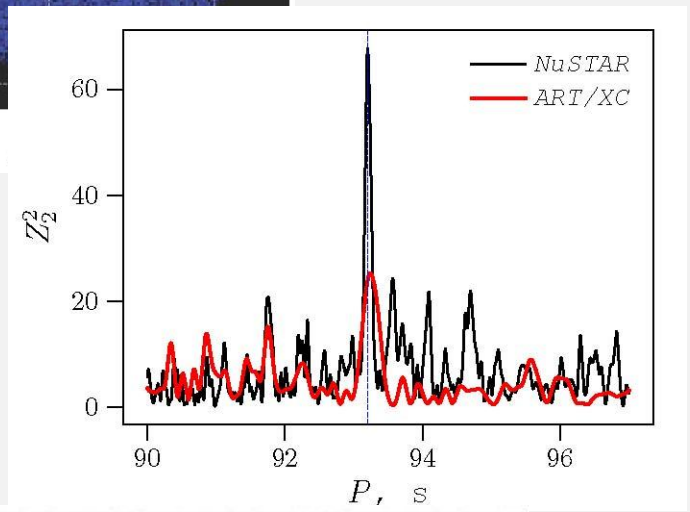
2MASX J23244834+4407564

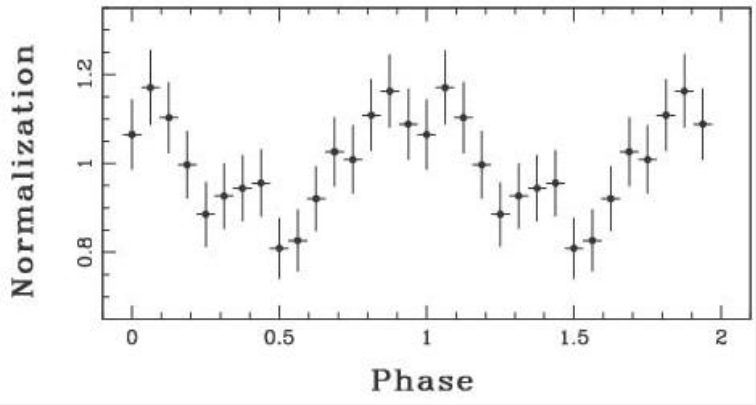
z = 0.0462 ± 0.0002

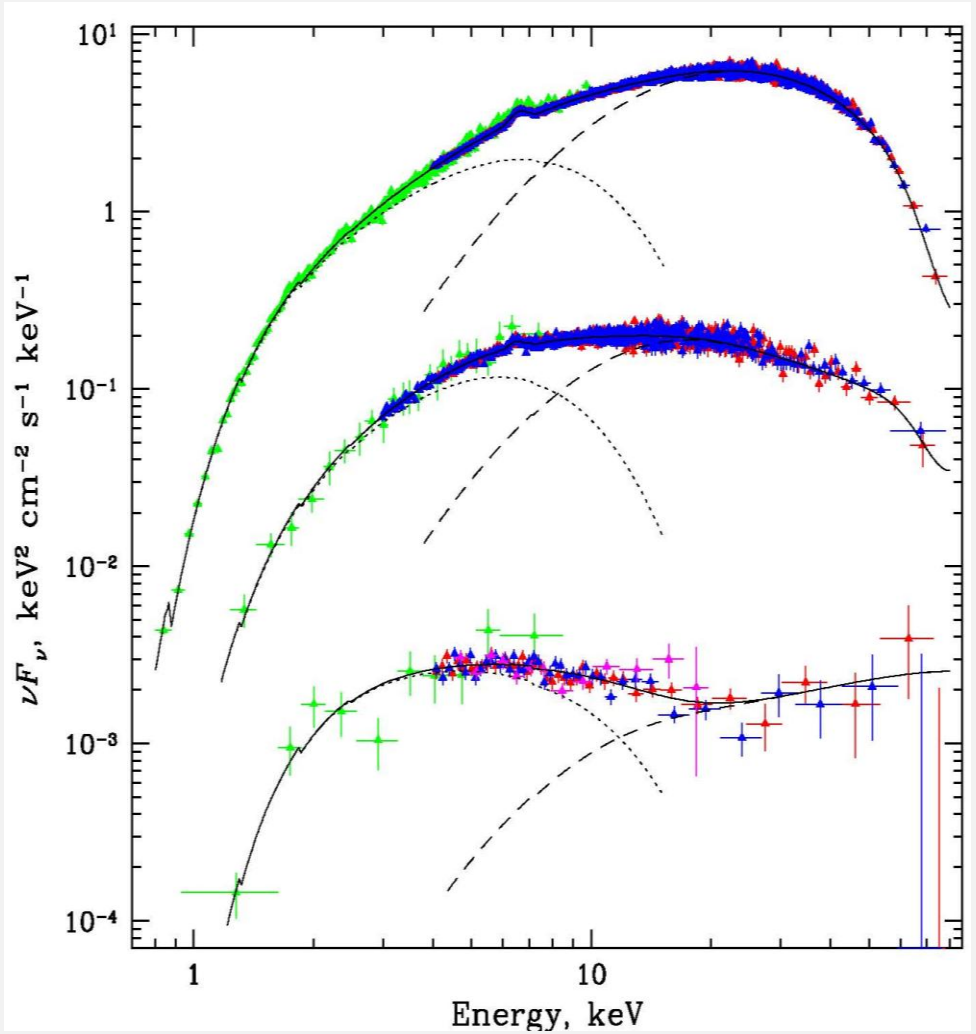
Zaznobin et al. 2021

GROJ1008-57



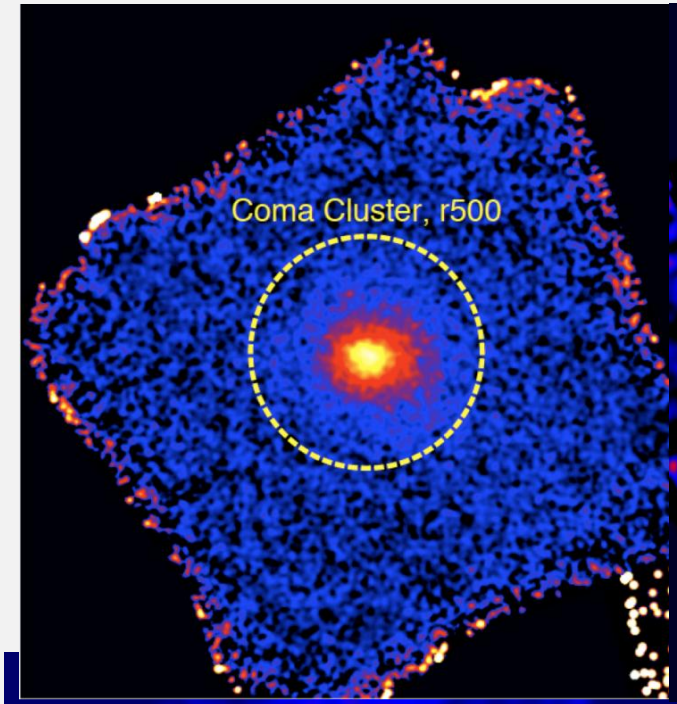


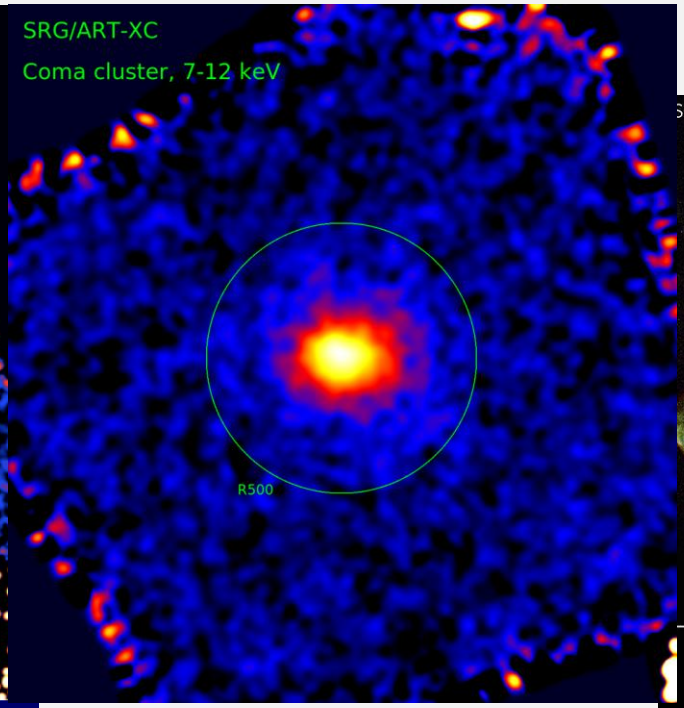




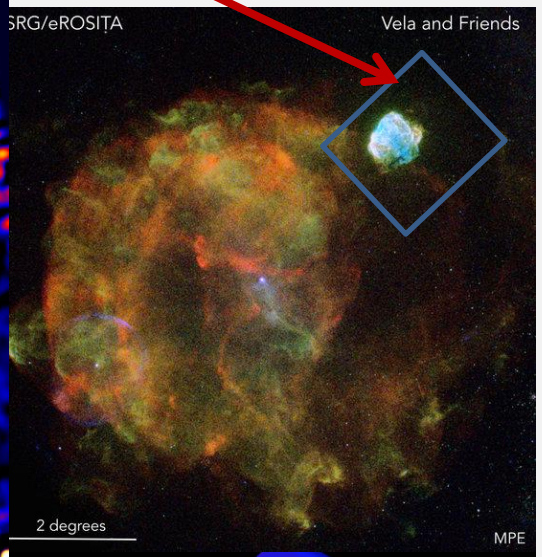
Lutovinov et al. 2021

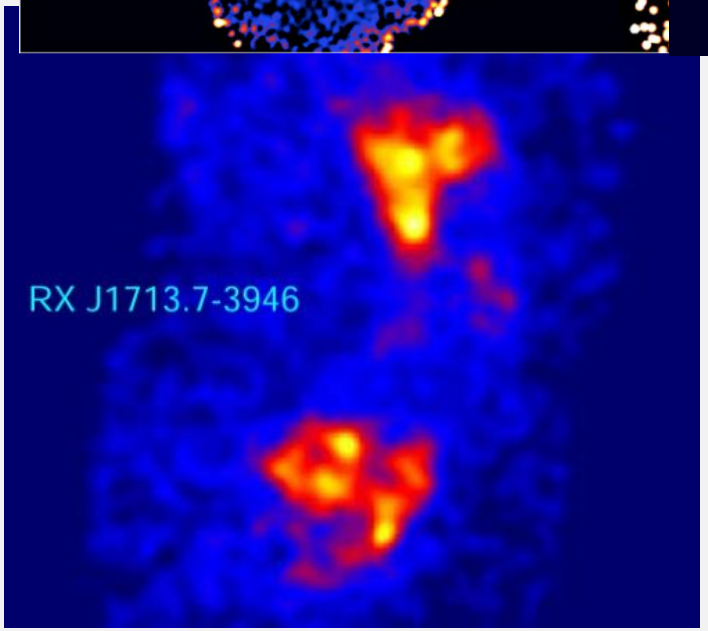
Extended sources observed with ART-XC in hard X-rays





SNR Puppis A



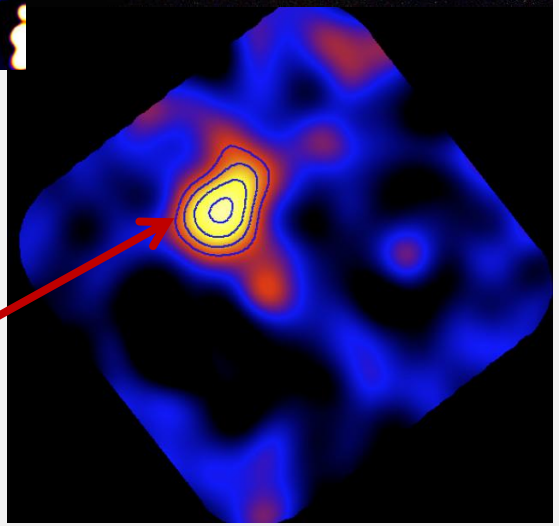


Scan of the Puppis A field

4,5 град^2 (100 s)

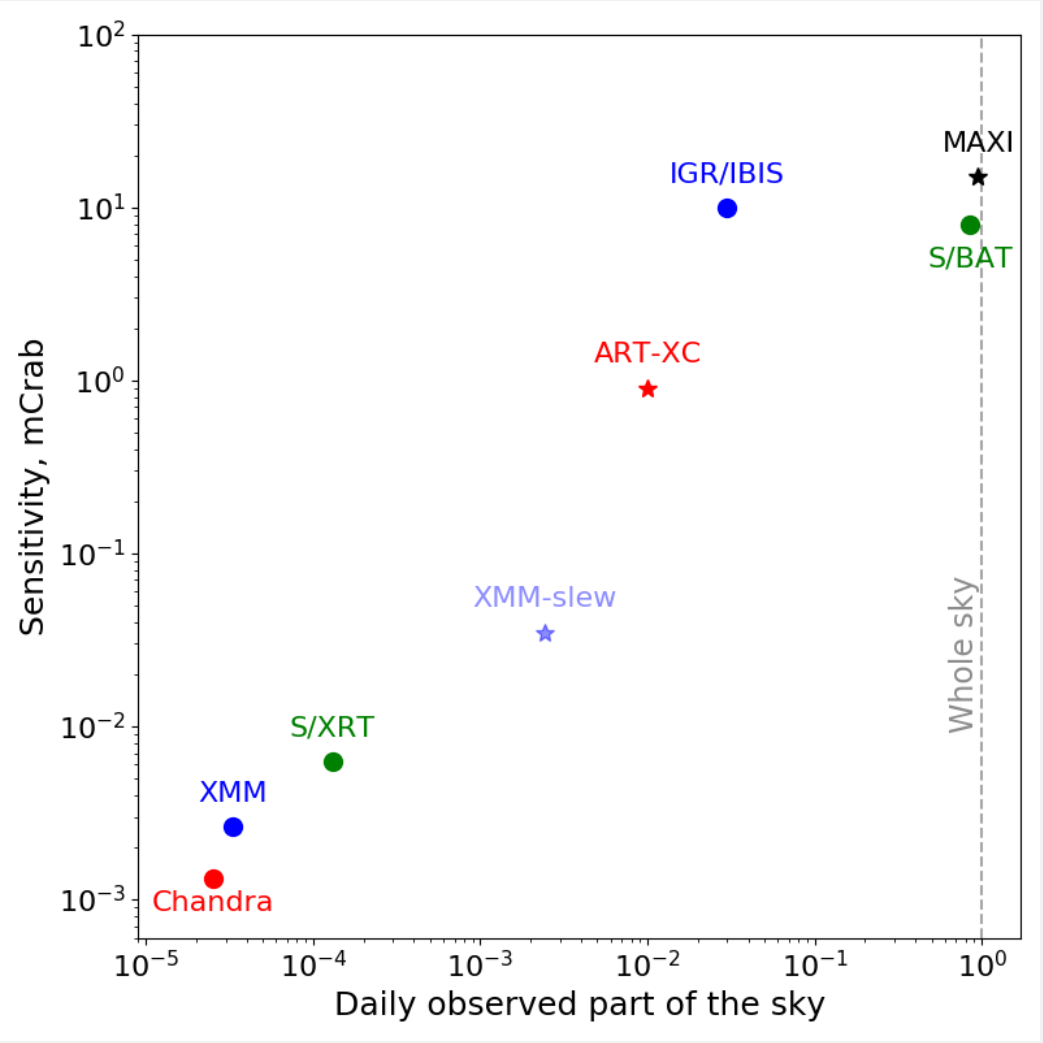
2 град^2 (4000 s)

Excess at 4-6 keV



Burenin et al. 2021; Krivonos et al. 2021a,b

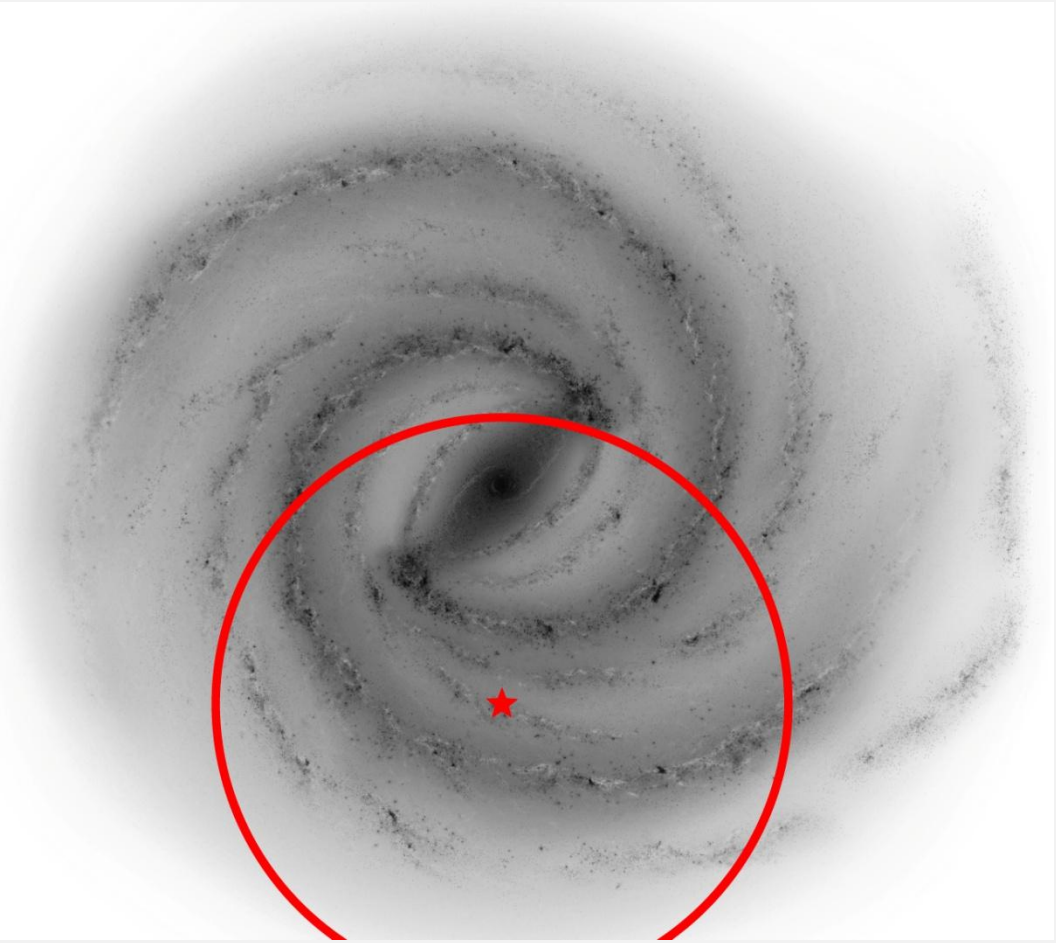
Variable X-ray sky as seen by ART-XC



1% of sky daily
reaching down to ≈10^{-11} erg cm^{-2} s^{-1}
=10^{35} erg s^{-1} @10 kpc
=10^{42} erg s^{-1} @30 Mpc
Localization accuracy <20″
Fast responce — 1-2 hours after
downlink

+GRB through shielding

Variable X-ray sky as seen by ART-XC



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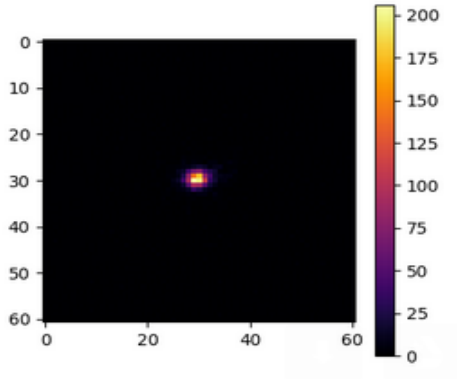
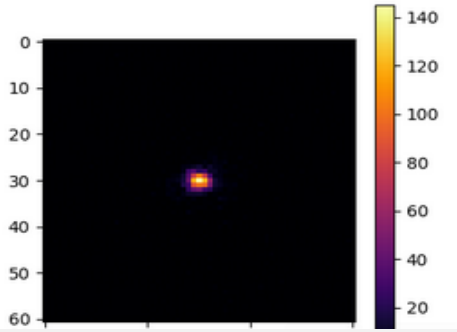
Fast responce — 1-2 hours after
downlink

+GRB through shielding

NRTA of ART-XC data

ART-XC NRT report

Click on source id to open Simbad search in new tab

SrcID	CrossID	RA	Dec	Counts in 4-12	Rate, cts/s	Picture
artxc_20200113_17_0	Cen X-3 (4")	170.3139	-60.6221	1835.0	39.35	
artxc_20200201_18_0	GX 301-2 (11")	186.6639	-62.7703	1463.0	28.31	

Credit: I.Mereminsky, A.Semena

Main catch:

not-so-bright and not-so-frequent X-ray transients

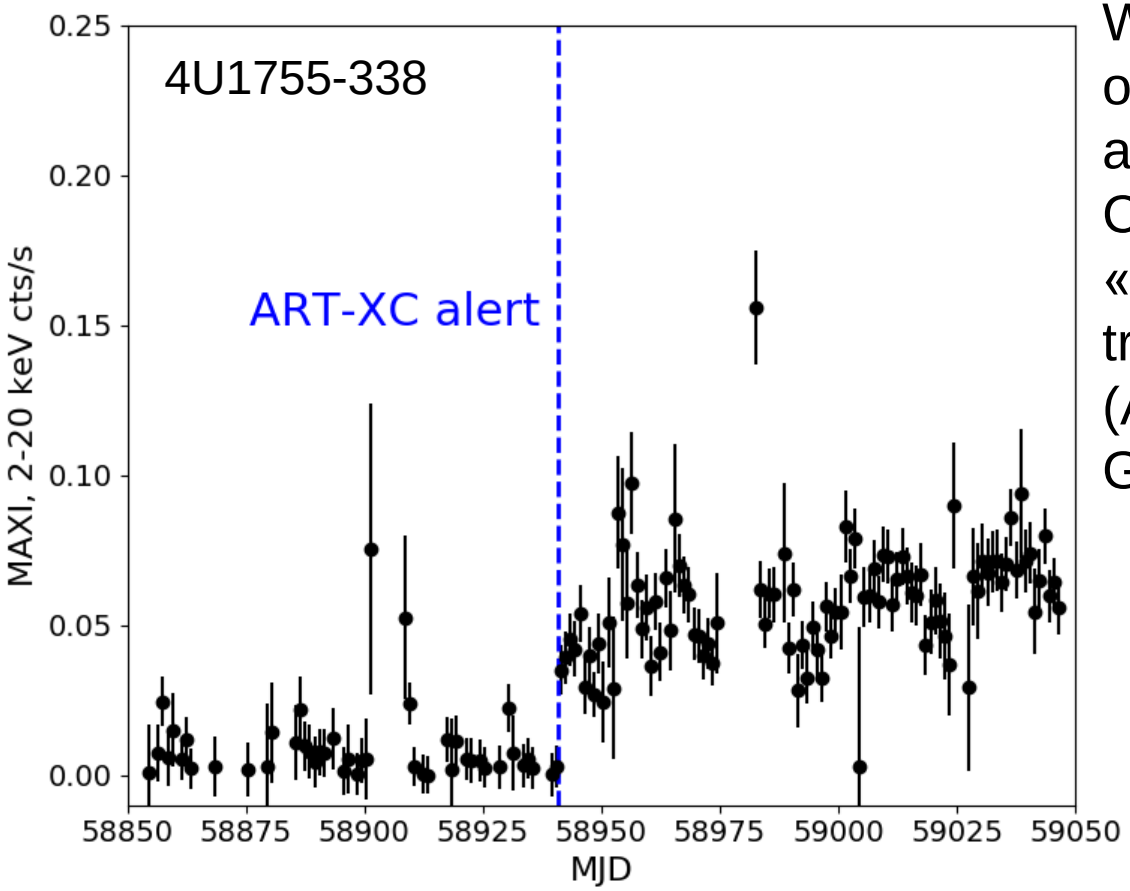
First 15 months of the survey:

- new microquasar (SRGA J043520.9+552226/AT2019wey)
  - two new HMXB candidates (SRGA J124404.1/J204318.2)
  - XRF(?)
  - new nova-like CV

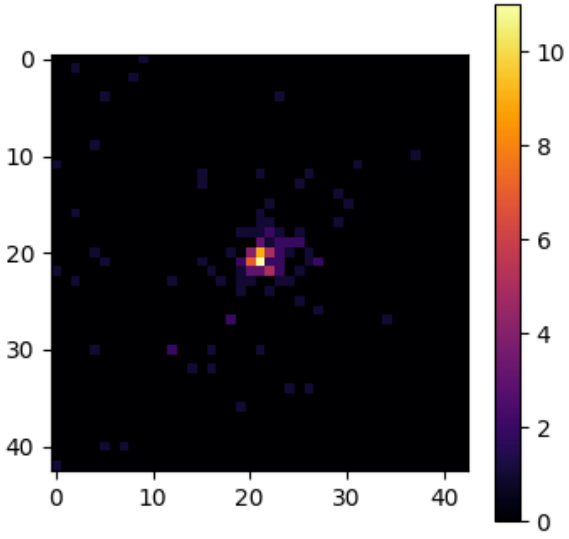
  - new outburst of historical μQSO (24 years of silence)
  - new outbursts of known sources - AMXP, poorly studied BeXRB, e.t.c...

  - few GRB

ART-XC: not *Swift*, still quick

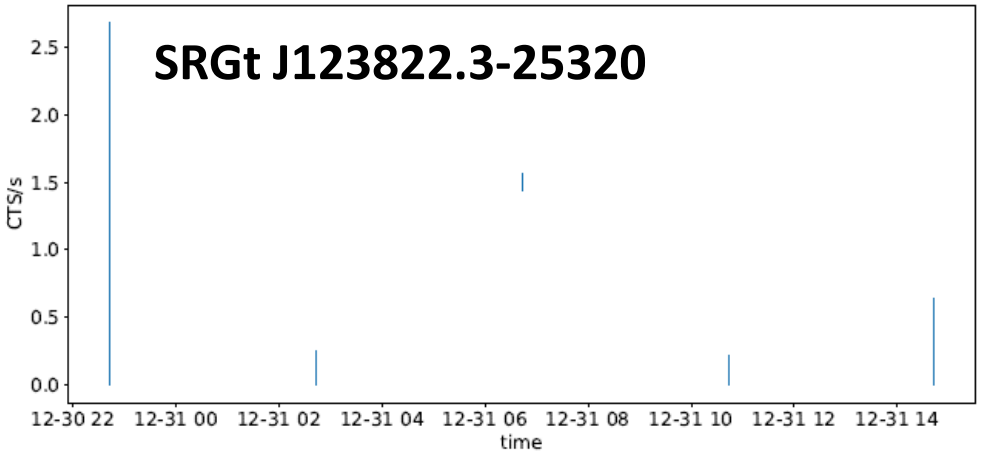


We strive to provide rapid alerts on new, interesting events — so a community can join in.
Could be crucial for studies of «fast-rise» stages of XRBs, transients with short outbursts (AMXBs), burst-only sources, GRBs,...

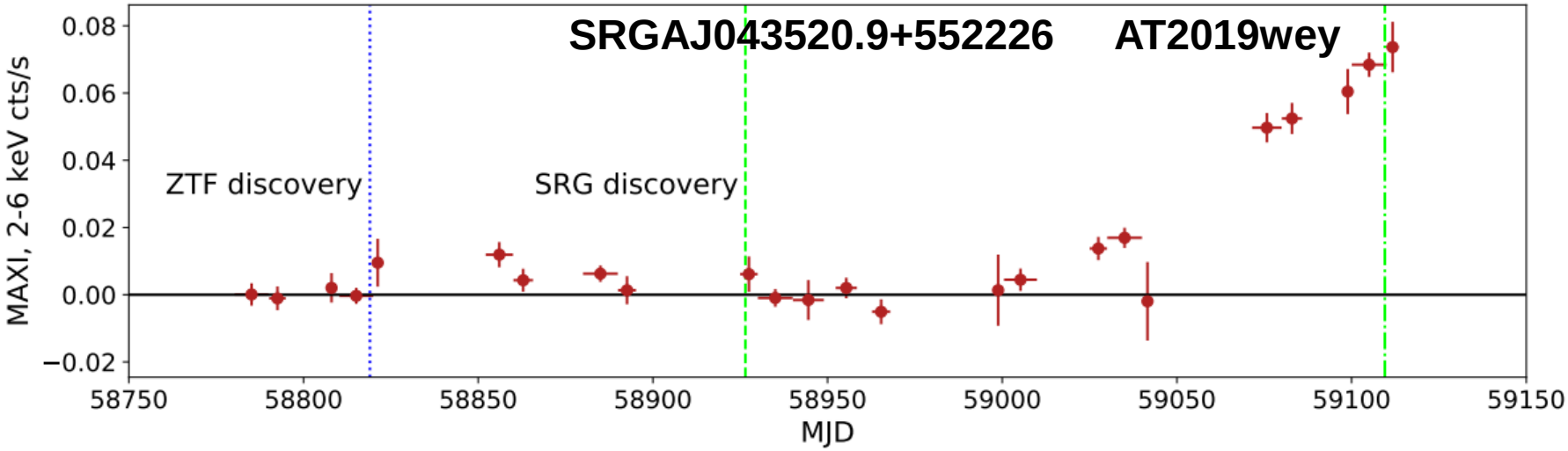


Mereminsky et al. 2020

ART-XC transients



ART-XC Atel #13415 The source flux to be $7x10^{-11}$ and $6x10^{-11}$ ergs/cm2/s in the 4-10 keV and 10-16 keV bands.
RA, Dec = 189.5912, -25.5332 (J2000) with the 15" uncertainty

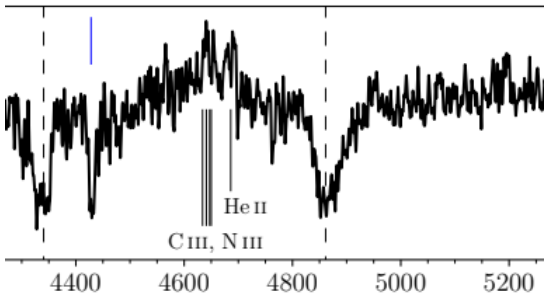


ART-XC could provide the community with early triggers on new, exciting events in X-rays — before anybody else (MAXI, Swift-BAT, INTEGRAL, etc.) will see them

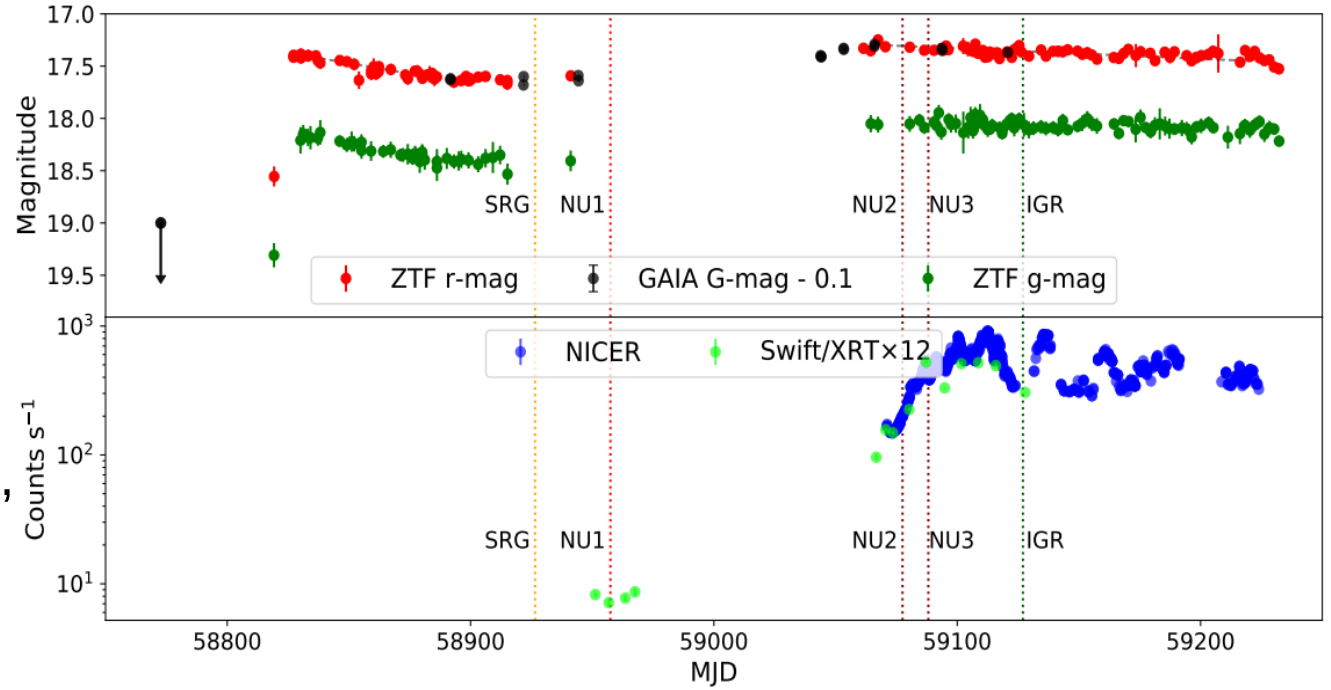
Peculiar transient
SRGA J043520.9+552226/ ZTF19acwrvzk/AT2019wey

New Galactic LMXB μquasar with resolved compact jet (Yadlapalli+21),unusual L_X-L_{opt} (Yao+20a), strong reflection (Yao+20b), bowen blend, QPOs (in hard state too), etc.

CMO SAI 2.5m

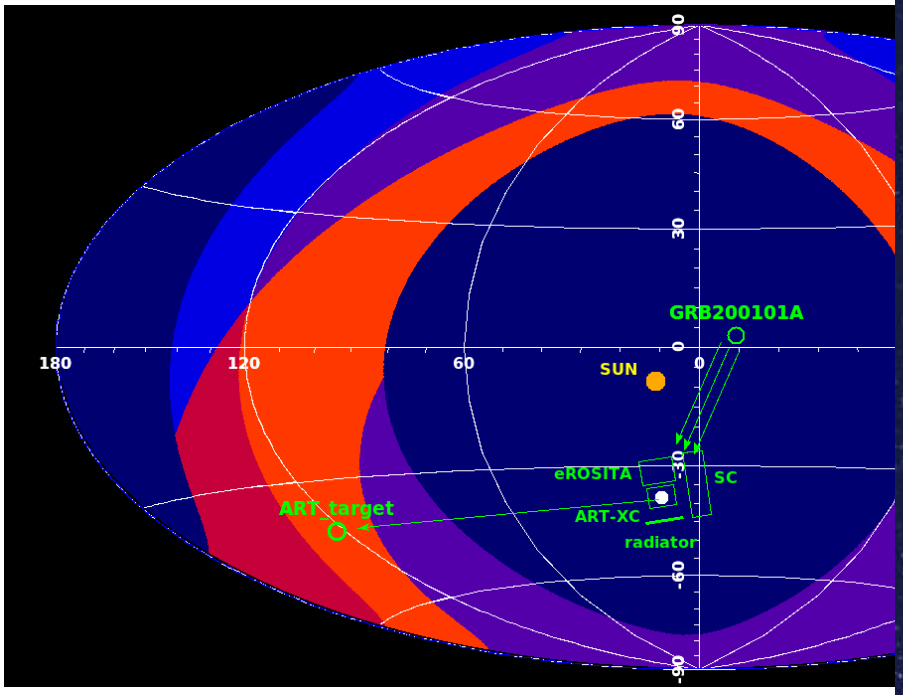


Additional dedicated optical/X-ray (ART-XC, INTEGRAL) observations to be published soon



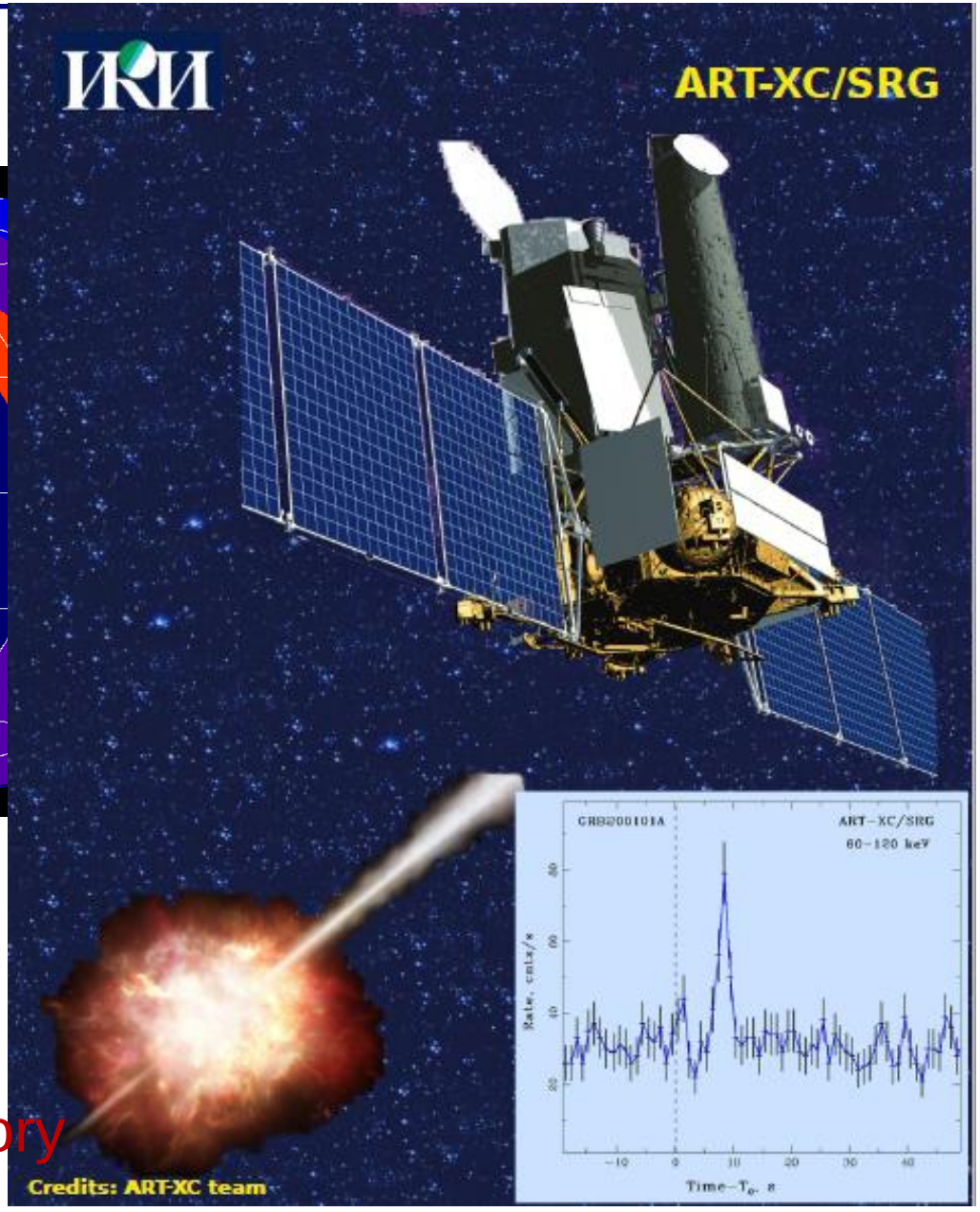
Mereminsky et al. 2021

Side GRBs

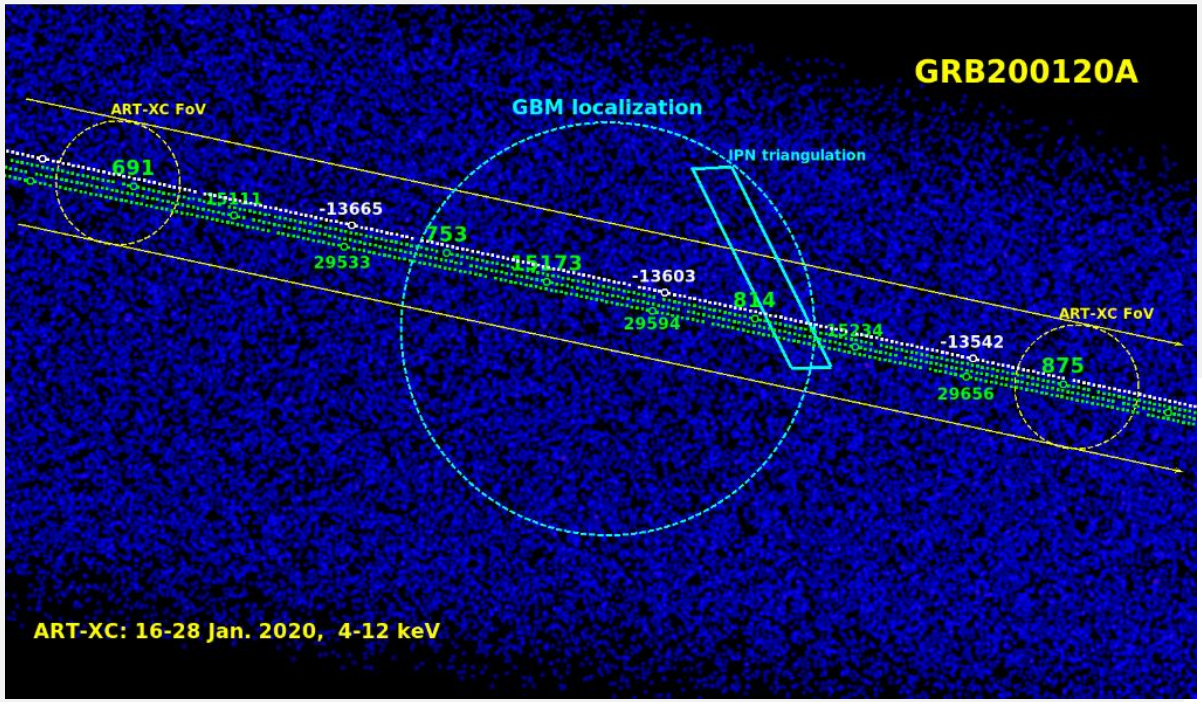


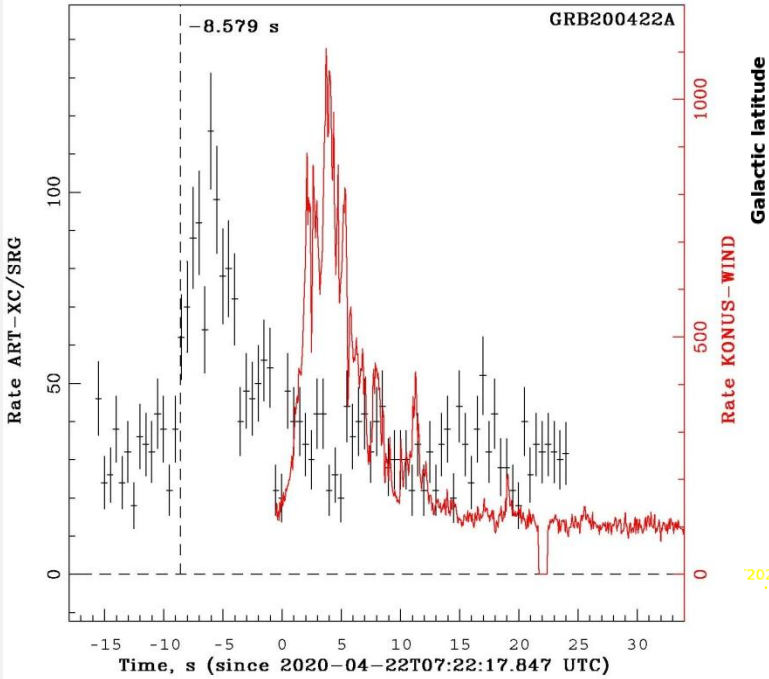
Detections in 60-120 keV
IPN triangulation

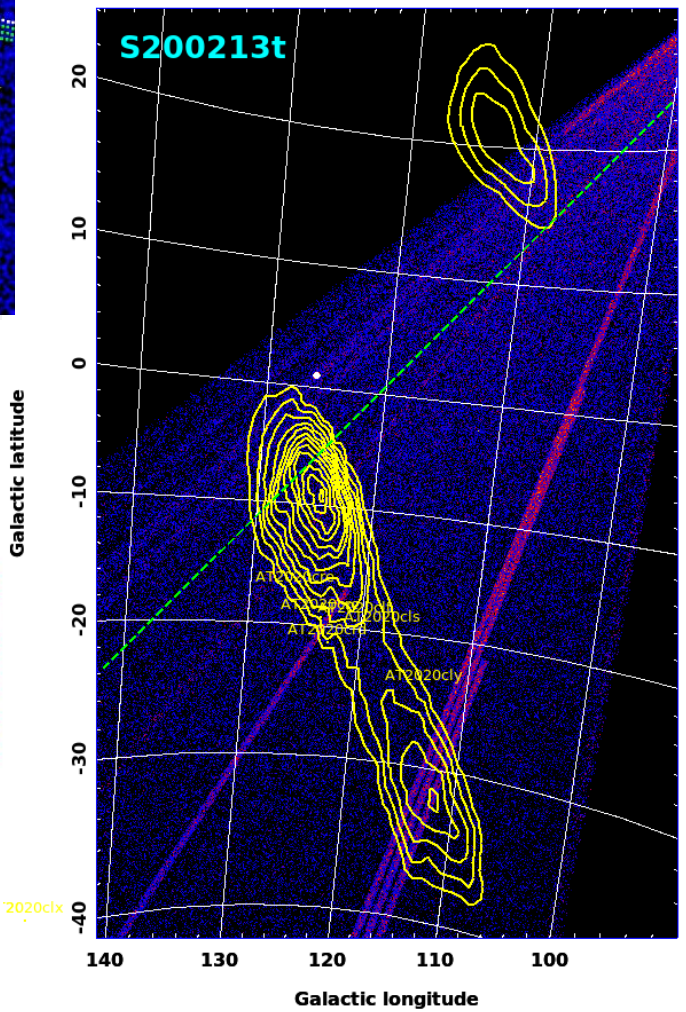
Spektr **R**eal **G**amma observatory



GRBs,
GW events



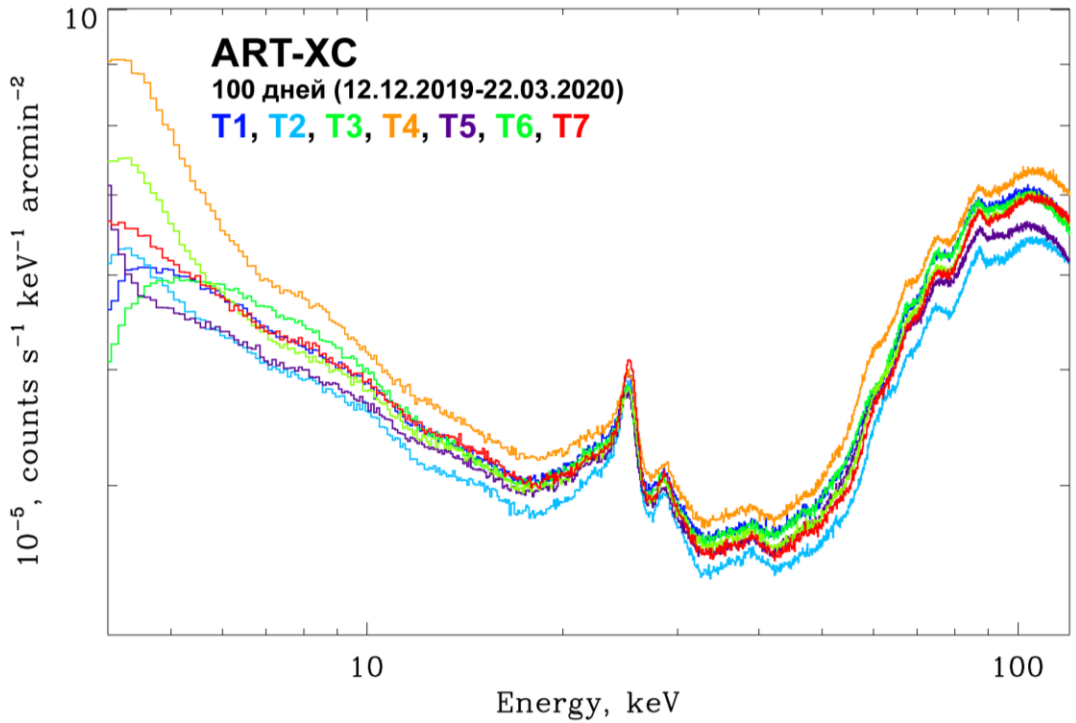


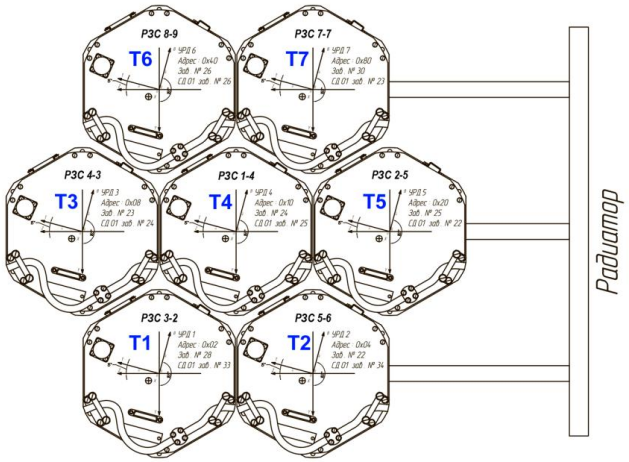


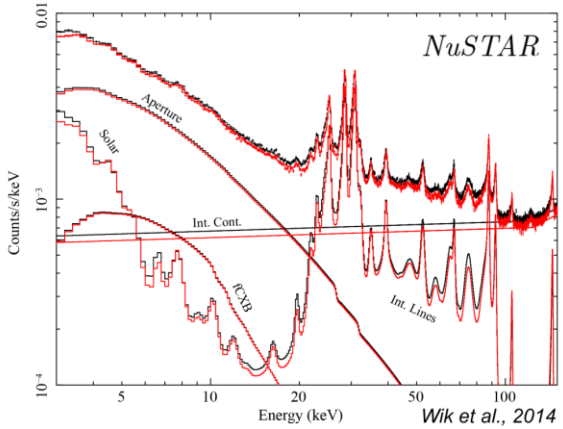
Triangulation
IKI +
IPN (Ioffe Institute)

ART-XC in-flight performances:
Detector background at the L2 halo orbit

SRG is the first X-ray observatory near the L2 point, and there are no previous data on the background conditions in this location. ART-XC measurements are very important

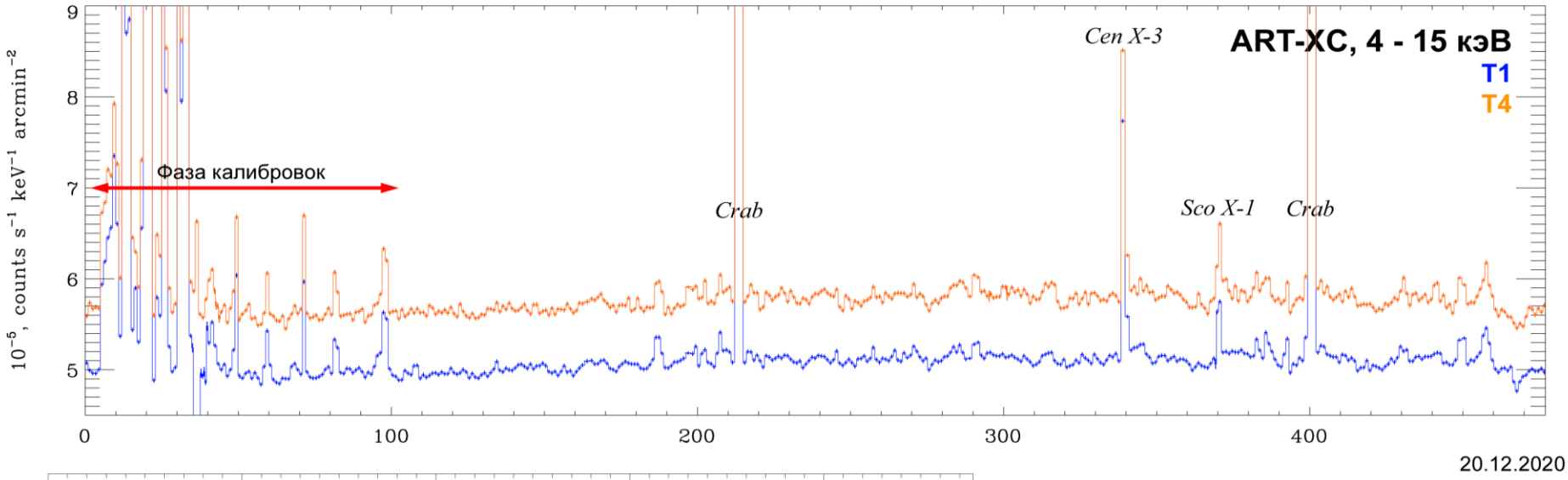


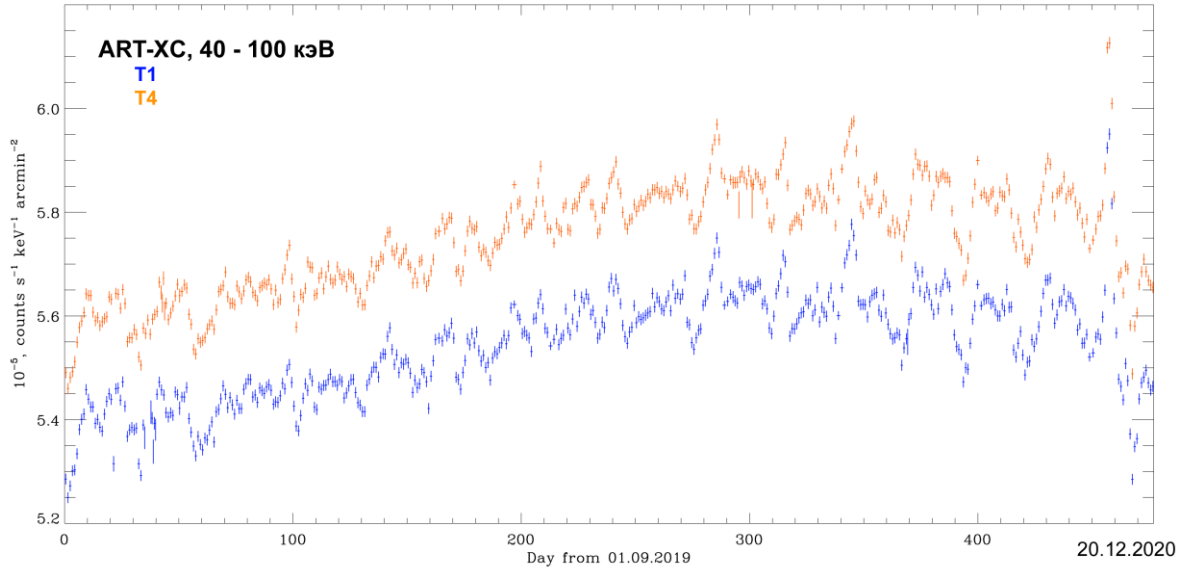




Credit: Tkachenko A.

ART-XC in-flight performances:
Detector background at the L2 halo orbit





Weekly-averaged rate of events, which dominated the charged particle.

The week-to-week variations of just a few percent. Reasons are under investigations

Credit: Tkachenko A.

Conclusions about ART-XC current status

Instrument's health and characteristics ……. OK

Survey …. OK

Search for transients (NRTA) ….. OK

First scientific papers are ready and partially submitted

Thank you for attention!