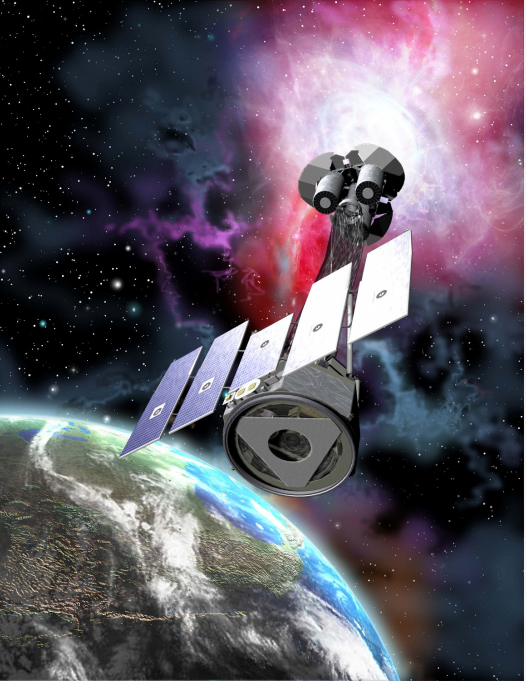


IXPE In-orbit calibration

Status & monitoring

Fabio Muleri, John Rankin (INAF-IAPS)
fabio.muleri@inaf.it
on behalf of the IXPE Science Team
https://ixpe.msfc.nasa.gov/partners_sci_team.html

IACHEC 2022 Spring Virtual Workshop

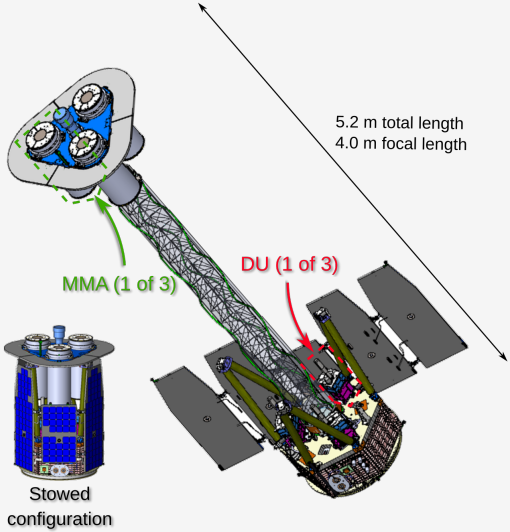
23 May 2022

Contents

Mission status

The Imaging X-ray Polarimetry Explorer

- NASA-ASI SMall EXplorer mission dedicated to (linear) X-ray imaging polarimetry
  - ➥ Energy range: 2–8 keV
  - ➥ Polarimetry: MDP>5.5% in 10 days for 10^{-11} cgs
    - + Imaging (< 30 arcsec)
    - + Timing ($\sim 10\mu s$)
    - + Spectroscopy (<20% at 5.9 keV)
- 3 identical telescopes
  - ➥ Grazing-incidence X-ray mirrors (3+1 spare)
  - ➥ Imaging X-ray photoelectric polarimeters based on GPD design (3+1 spare)
  - ➥ The two are separated by an extensible boom

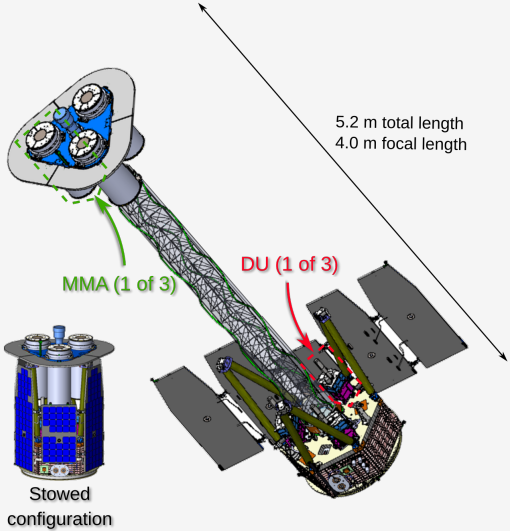


The Imaging X-ray Polarimetry Explorer

- Involved parties

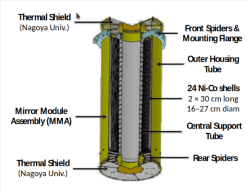
Marshall Space Flight Center PI team, project management, SE and S&MA oversight, mirror module fabrication, X-ray calibration, science operations, and data analysis and archiving	iaps, INAF Istituto Nazionale di Astrofisica / National Institute for Astrophysics, INFN, OAC, OHB Italia Polarization-sensitive imaging detector systems
asi Agenzia Spaziale Italiana Detector system funding, ground station	LASP Mission operations
Ball Spacecraft, payload structure, payload, observatory I&T	Roma Tre University, Stanford University Scientific theory
	Nagoya University Thermal shields
	MIT Massachusetts Institute of Technology Co-Investigator

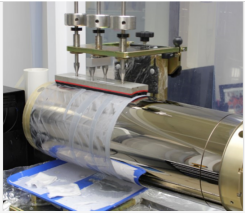
- Outstanding science:
  - ➥ polarimetry of tens of sources belonging to almost all astrophysical classes of sources
  - ➥ Insight in source modelling and fundamental physics

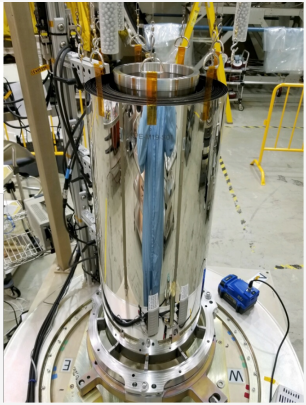


IXPE Mirrors

- Manufactured at NASA/MSFC with replica from mandrels technique
- Nickel-cobalt alloy shells, 24 shells/module
- Heritage from HERO, FOXSI and ART programs
- Contribution from Nagoya University (Japan) for thermal shields
- 4.0 m focal length
- Shell thickness: 178-254 μm
- Mass: 93 kg for three mirrors
- Measured total collecting area: 540 cm^2 at 3 keV
- Measured angular resolution <30 arcsec

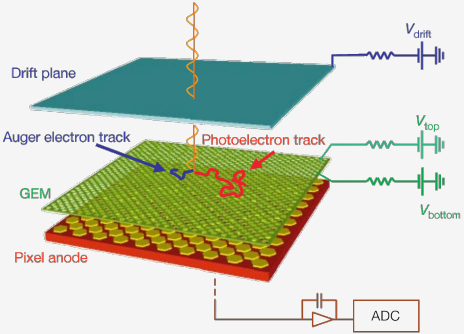


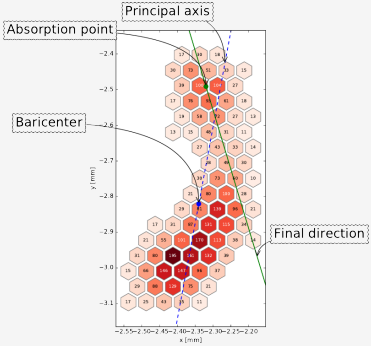


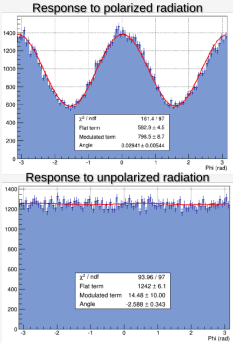


The Gas Pixel Detector

- Developed by INFN-Pisa and INAF-IAPS since 2001
- Photons are absorbed in a gas mixture
- Primary ionization is multiplied with a Gas Electron Multiplier (GEM) and eventually collected on the top layer of a dedicated ASIC
- Polarization is derived from direction of emission of the photoelectron
- All the characteristics of the photons are measured contemporaneously and photon by photon

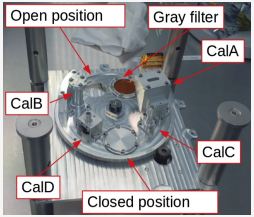


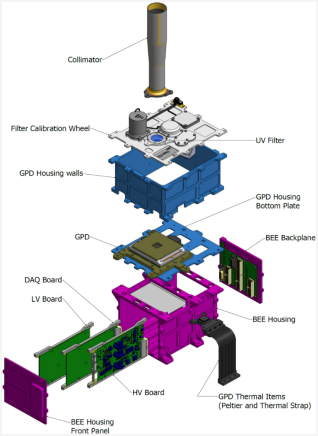


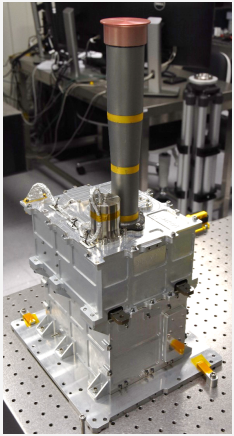


The Instrument on-board IXPE

- The GPD is hosted inside the Detector Unit
- The Back-End Electronics which powers and controls the GPD
- A filter and calibration wheel
  - ➥ 1 polarized at two energies (3.0 and 5.9 keV)
  - ➥ 3 not polarized (5.9 and 1.7 keV)
  - ➥ All powered by ^{55}Fe
  - ➥ Filters for special observations







[Soffitta et al., 2021; Baldini et al., 2021]

Launch!

9th December, 2021 from LC 39A in the “NASA Kennedy Space Center”

Separation...

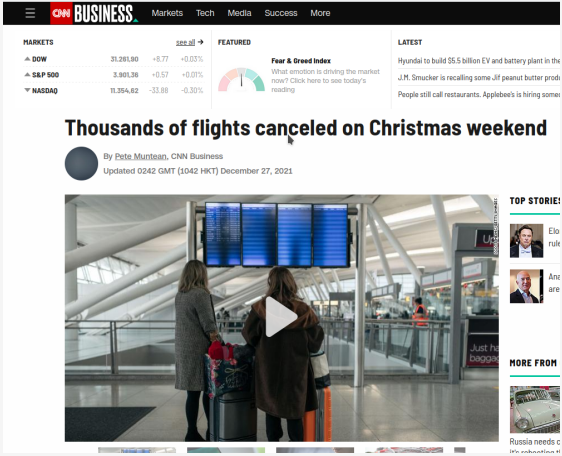

SECO-2
SES-2
DEPLOY
T+00:33:34
IXPE
SPEED
25379
KM/H
ALTITUDE
600
KM
STAGE 2 TELEMETRY
Solar panels fully open!

... and commissioning

- 1 month duration to switch on all systems, including the Instrument

... and commissioning

- 1 month duration to switch on all systems, including the Instrument



... and commissioning

- 1 month duration to switch on all systems, including the Instrument

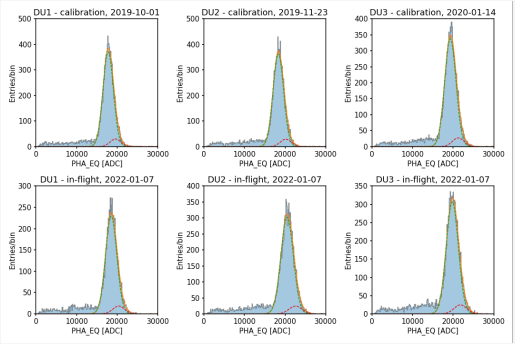
... and commissioning

- 1 month duration to switch on all systems, including the Instrument

... and commissioning

- 1 month duration to switch on all systems, including the Instrument

- All systems were nominal
- First photons acquired!
- (on the left) Spectrum of cal C calibration source
  - ➥ Comparison with on-ground calibration
  - ➥ Measurements 2 years apart



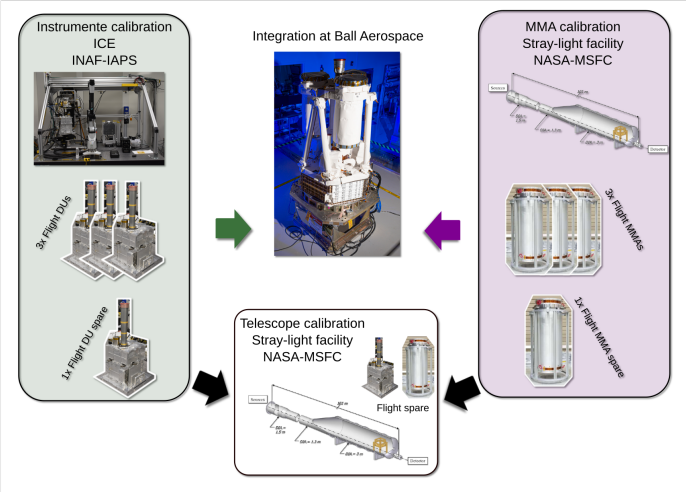
Resolution at 5.9 keV	DU1	DU2	DU3
Calibration (late 2019)	16.93±0.16%	16.66±0.16%	16.95±0.17%
In-flight (Jan-2022)	17.51±0.21%	17.49±0.17%	17.71±0.18%

Calibration

An extensive on-ground calibration

Can not rely on previous experience or standard candles

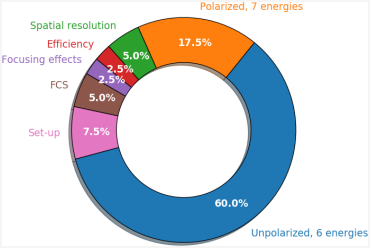
- DU and MMA are first calibrated separately
  - ➥ DUs are calibrated at INAF-IAPS
  - ➥ MMAs are calibrated at NASA-MSFC
- 3x Flight Models are delivered to Ball for integration
- Spare DU and spare MMA are calibrated jointly at NASA-MSFC



The IXPE Instrument calibration

- Nominally, 40 days for each of the 4 DUs
- ∼80% of time dedicated to polarized and unpolarized response
  - ➥ Requirement on knownledge of the response <0.1%
  - ➥ Required custom sources and procedures
- Started on 26th July 2019, last measurement on the spare on 14th September 2020
  - ➥ Source set-up and alignment during working hours, 7 days per week
  - ➥ Data acquisition round the clock with remote monitoring
  - ➥ 530 measurements, 4052.3 hr acquisition and 2.250 billion counts collect

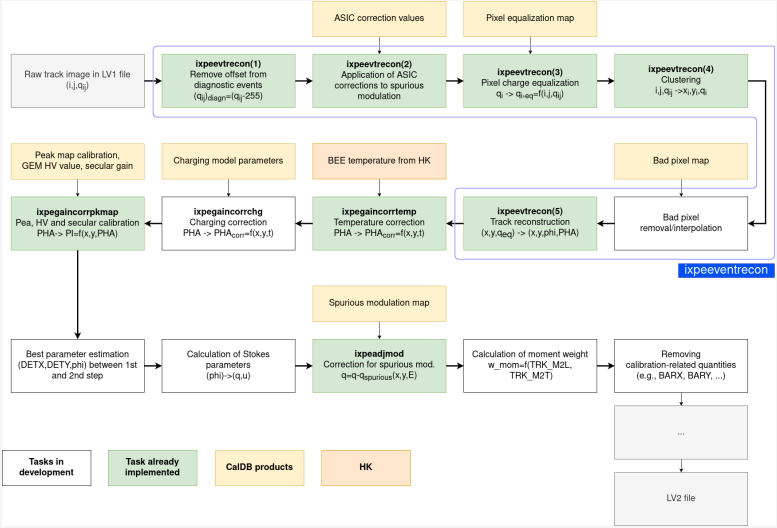
- Other calibrations:
  - ➥ Absolute quantum efficiency
  - ➥ Pixel-to-pixel equalization
  - ➥ Gain disuniformities
  - ➥ Energy resolution
  - ➥ Dead time
  - ➥ Spatial resolution
  - ➥ Response to inclined beam



The (instrument) pipeline

Provided and maintained by Italian partners (ASI-SSDC, INAF, INFN)

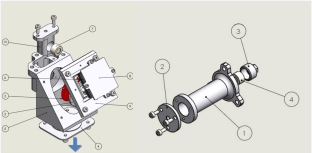
1. Pixel equalization
   - ➥ Affect track reconstruction
2. Event energy calibration
   - ➥ Correction for temperature, charging and secular
3. Spurious modulation subtraction
   - ➥ Depends on the energy
4. Normalization by the modulation factor



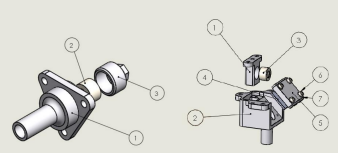
On-board calibration sources I

- Used for monitoring performance, on-ground and in-flight
- Update response matrices as needed
- Each is powered by a single ^{55}Fe
- A set in each DU

Cal A	polarized X-rays at 3.0 and 5.9 keV
Cal B	unpolarized spot at 5.9 keV
Cal C	unpolarized flat field at 5.9 keV
Cal D	unpolarized flat field at 1.7 keV



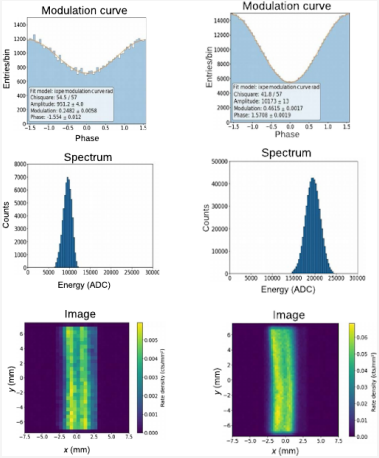
calA calB



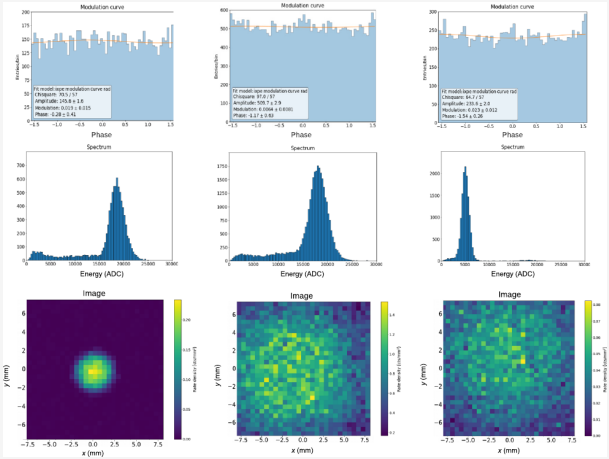
calC calD

[Ferrazzoli et al., 2020]

On-board calibration sources II



Cal A at 3.0 and 5.9 keV

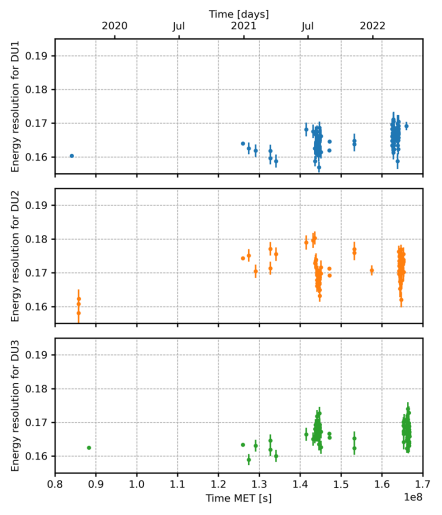


Cal B, C and D

Detector health: energy resolution

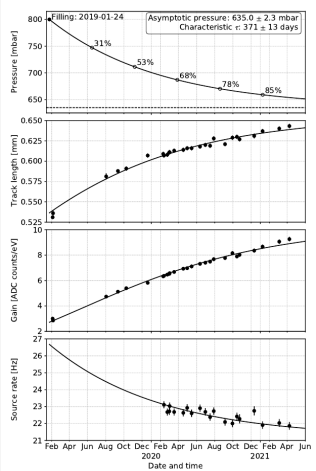
- Nearly constant for 3 years now
- .. and much better than requirement (<25%)
- Indicator of good health

- Measured for really monochromatic X-rays from Cal A



Detector quantum efficiency

- Pressure (and hence quantum efficiency) inside the GPD is decreasing
- Associated to adsorption on the glue
- Effect nearly saturated by the launch
- Monitored with source counting rate
- Included in response matrices

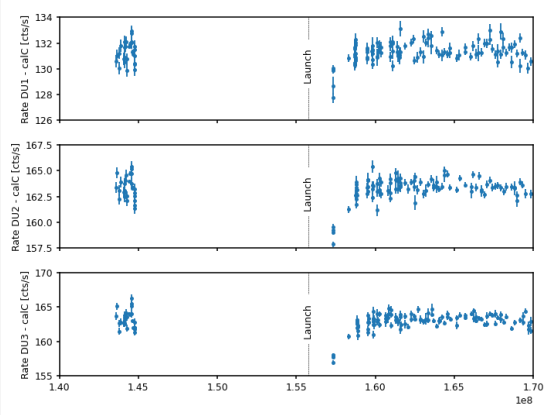


[Baldini et al., 2022]

Detector quantum efficiency

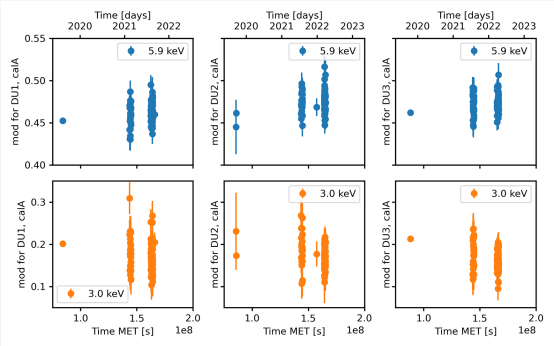
- Pressure (and hence quantum efficiency) inside the GPD is decreasing
- Associated to adsorption on the glue
- Effect nearly saturated by the launch
- Monitored with source counting rate
- Included in response matrices

- Rate corrected for deadtime, ^{55}Fe decay and modelled pressure decay
  - ➥ Pressure effectively saturated as expected
- Drop after launch associated to storage at survival temperature



Modulation factor with Cal A

- Generate polarized X-rays at two energies
  - ➥ First and second order diffraction of graphite crystal
  - ➥ Polarization smaller that 100%
- Monitored since the DU thermo-vacuum test (with different nuclides)
- Increase <1% for pressure decrease
  - ➥ modeled with Monte Carlo
  - ➥ included in the response matrices



Energy calibration I

Important per se and for polarimetric response calibration

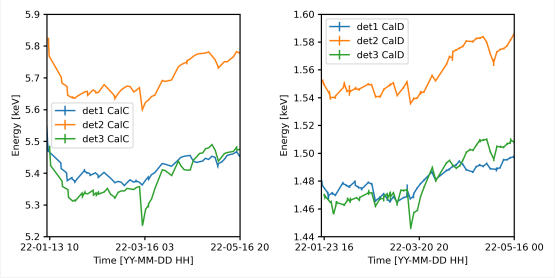
- Calibration for spurious modulation

$$q_{\rm cal} = 2\cos 2\varphi_k - q_{\rm sm}(x, y, E)$$
$$u_{\rm cal} = 2\sin 2\varphi_k - u_{\rm sm}(x, y, E)$$

➥ $q_{\rm sm}$ and $u_{\rm sm}$ are measured on-ground and interpolated at the event energy [Rankin et al., 2022]

- Normalization by the modulation factor

$$\mu = \mu(E)$$

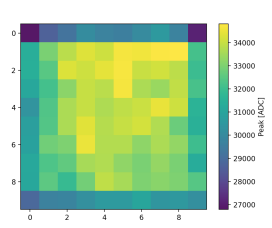


"Raw" energy reconstructed for

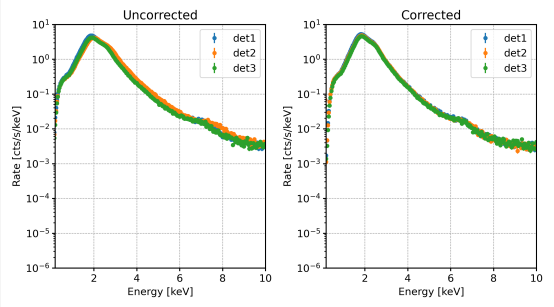
- Cal C at 5.89 keV (left)
- Cal D at 1.74 keV (right)

Energy calibration II

- Each day either Cal C or Cal D for all detectors
- 10×10 bins gain maps are generated with Cal C and Cal D
  - ➥ Two energies, allows to derive slope and offset
  - ➥ Interpolated at intermediate energies



- Calibration during target occultation



Results of energy calibration with on-board sources

Conclusions

- Telescopes are perfectly cross-calibrated
  - ➥ Calibration is being monitored
  - ➥ Energy adjusted with frequent calibration
- Polarization detection with high-significance on ∼40% of objects belonging to different classes:
  - ➥ Isolated neutron stars...
  - ➥ Binary systems with either neutron stars and black holes
  - ➥ Blazars...
- Magnetic field the main player, but also scattering at work!
- Just 4.5 months of observations

- **X-ray polarization window is eventually open!**
- Long term observing plan: https://ixpe.msfc.nasa.gov/for_scientists/ltp.html

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