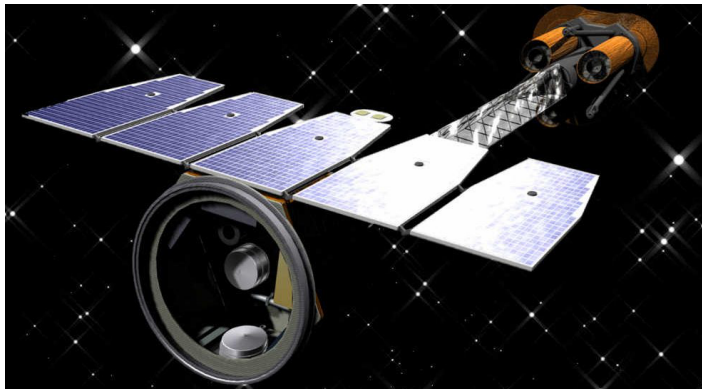
THE IXPE MISSION

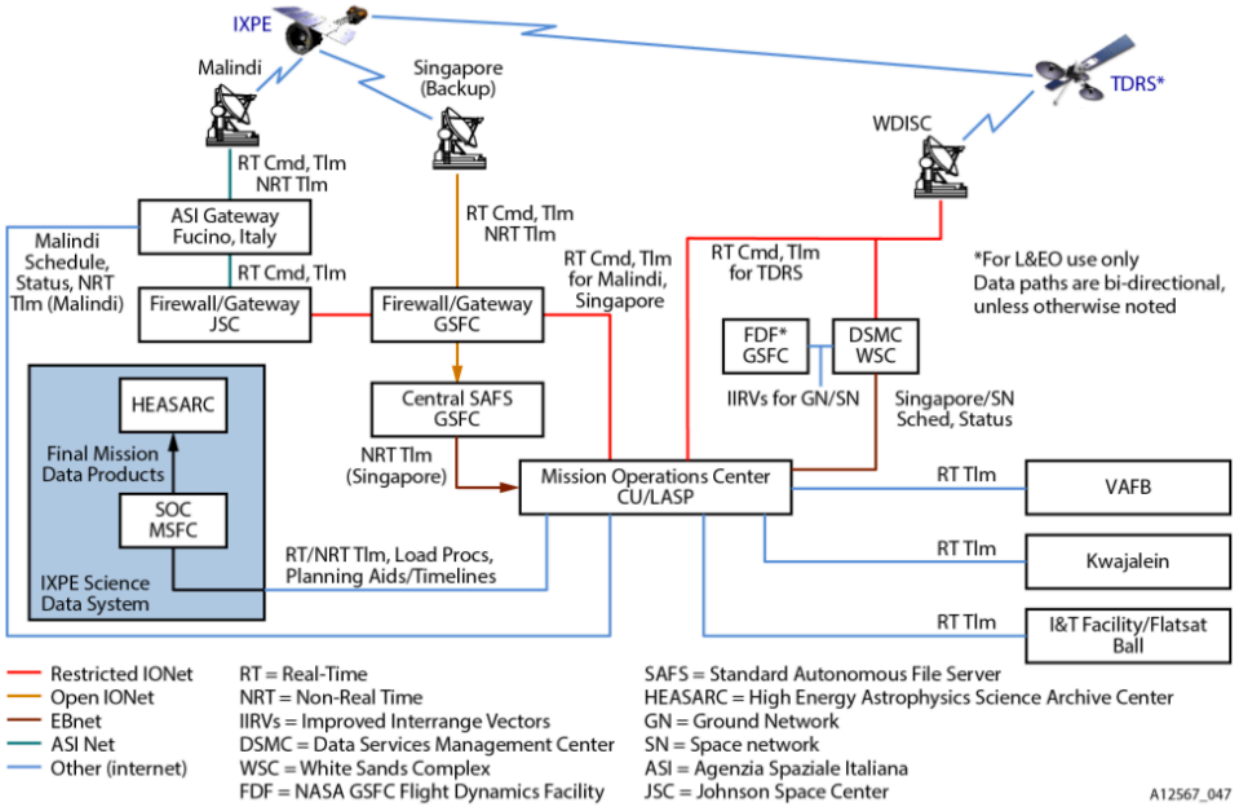
THE MISSION



- Selected for NASA SMEX program Jan 3 2017
  - 180M US$ / 5 years envelope, launch April 2021
- Devoted to polarimetry of 2-8 KeV x-rays
  - for the first time for 10s of sources
  - through enabling Gas Pixel Detectors (GPD) from INFN
    - capitalizes on 10+ years of dedicated detector development
- Italian contribution from INAF/IAPS, INFN, ASI
  - through international agreement between ASI and NASA
- Italian responsibility is whole focal plane, a.k.a. the Instrument
  - Detector Units (DU) and electronics

MISSION OVERVIEW

- Pegasus XL launch from Kwajalein
- 540-km circular orbit at 0° inclination
- 2 year baseline mission, 1 year SEO
- Point-and-stare at known targets (~48 /year)
- Science Operations Center at MSFC
- Mission Operations Center at CU/LASP
- Malindi ground station (Singapore Backup)
- Launch ready by early 2021



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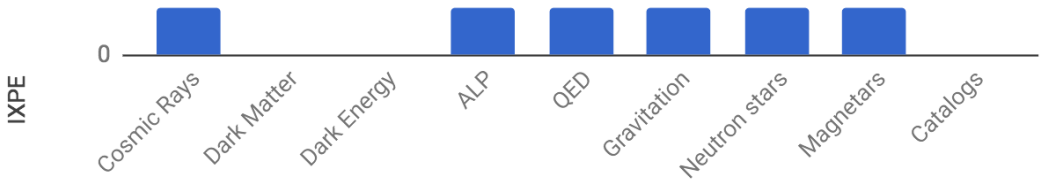
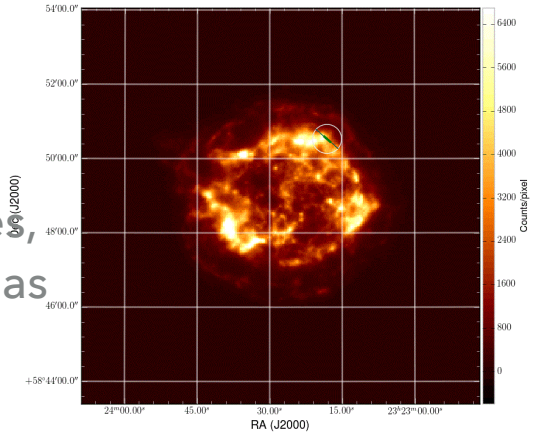
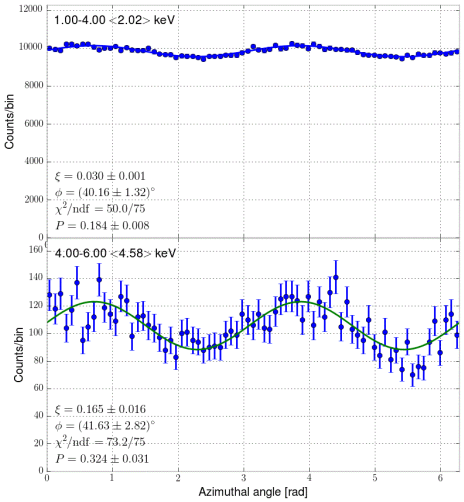
SCIENCE



- emission processes
  - synchrotron, non-thermal bremsstrahlung, Inverse Compton
- geometry
  - scattering in aspherical geometries, propagation in magnetized plasmas
- fundamental physics
  - strong gravitation/magnetic fields (BH spin), propagation through cosmological distances (LIV), unexpected polarization from photon-ALP mixing (Clusters)





IXPE
Imaging
X-Ray
Polarimetry
Explorer

IXPE ACCOMPLISHES NEW SCIENCE WITH NEW CAPABILITIES

- **Opens a new window on the universe — imaging (30“) X-ray polarimetry**
  - Is the science driver that advances and impacts high-energy astrophysics
  - Increases information space and lifts modeling degeneracies
- **Addresses key questions, providing new scientific results and constraints**
  - What is the spin of a black hole?
  - What are the geometry and magnetic-field strength in magnetars?
  - Was our Galactic Center an Active Galactic Nucleus in the recent past?
  - What is the magnetic field structure in synchrotron X-ray sources?
  - What are the geometries and origins of X-rays from pulsars (isolated and accreting)?
- **Provides powerful and unique capabilities**
  - Reduces integration time by a factor of 100 compared to the OSO-8 experiment
  - Simultaneously provides imaging, spectral, timing, and polarization data
  - Is free of false-polarization systematic effects at less than a fraction of a percent
  - Enables meaningful polarization measurements for many sources of different classes

Table E-1 *IXPE Design Reference Mission (DRM). A representative science investigation for the first year of the Baseline Science Mission*

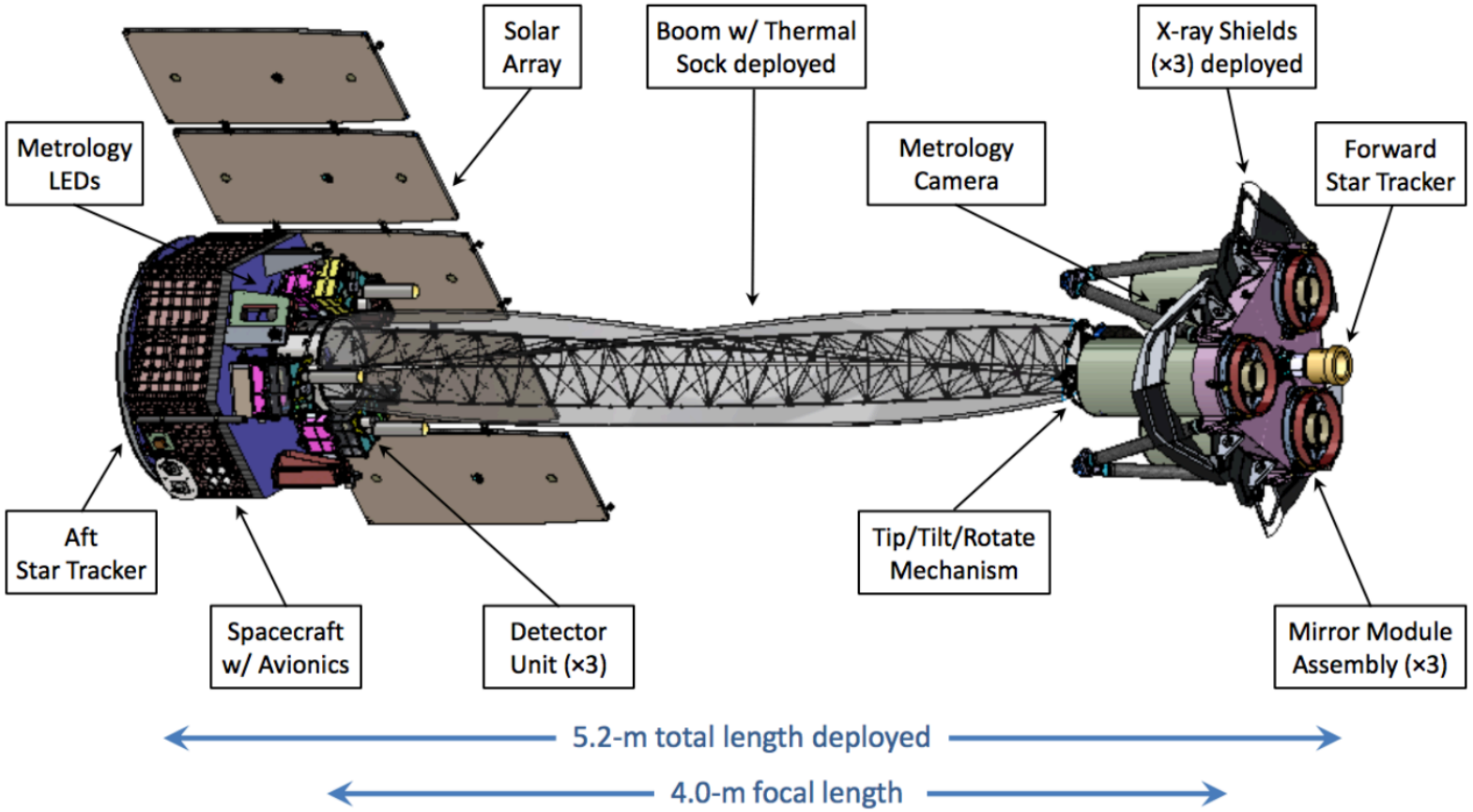
Source name	F_{2-8} 10^{-11} cgs	MDP_{99} %	Δt day	Uncertainty σ_Π and σ_ψ for representative polarization measurements for indicated number of energy × time or pulse phase × spatial bins
MCG-6-30-15 Seyfert	4.3	3.0	4.5	Survey
IC 4329A Seyfert	7.3	2.0	6.2	Survey
3C 273 quasar	6.5	2.0	7.4	(3 bins) Π ±1.1%, ψ±6.5° (if Π≈5%)
PKS 2155-304 blazar	7.3	2.0	5.5	(3 bins) Π ±1.1%, ψ±3.3° (if Π≈10%)
Mkn 501 blazar	3.1	3.0	6.8	(3 bins) Π ±1.7%, ψ±4.9° (if Π≈10%)
Mkn 421 blazar	27.2	2.0	1.6	(3 bins) Π ±1.1%, ψ±3.3° (if Π≈10%)
MCG-5-23-16 blazar	6.1	3.0	3.1	(3 bins) Π ±1.7%, ψ±4.9° (if Π≈10%)
1ES 1101-232 blazar	4.7	3.0	4.1	(3 bins) Π ±1.7%, ψ±4.9° (if Π≈10%)
BL Lac blazar	2.0	4.0	5.9	(3 bins) Π ±2.3%, ψ±6.5° (if Π≈10%)
Galactic Center				
Sgr B2	0.30	7.5	11.6	(3 bins) Π ±4.3%, ψ±2.5° (if Π≈50%), test hypothesis of Sgr A* reflection
Microquasars				
GRS 1915+105	1300.	0.25	2.3	(4 bins) Π ±0.2%, ψ±1.0° (if Π≈5%),with energy, measure black-hole spin
LMC X-3 average	42.	1.0	4.7	(4 bins) Π ±0.7%, ψ±3.8° (if Π≈5%); MDP = 3.1% in low state
GRO J1655 average	2020.	0.4	0.5	(4 bins) Π ±0.3%, ψ±1.5° (if Π≈5%); MDP = 6.2% in low state
SS 433 average	18.	1.5	4.4	(3 bins) Π ±0.9%, ψ±4.9° (if Π≈5%); MDP = 2.8% in low state
Cyg X-3 average	580.	0.4	2.8	(4 bins) Π ±0.3%, ψ±1.5° (if Π≈5%); MDP = 0.7% in low state
Cyg X-1 average	1000.	0.4	0.7	(4 bins) Π ±0.3%, ψ±1.5° (if Π≈5%); MDP = 0.6% in low state

Pulsar-Wind Nebulae (PWNe) + Pulsars (PSR)				
Crab PWNe + pulsar	1950.	0.24	1.6	PWNe (25 bins) Π ±0.4%, ψ±0.6° (if Π≈20%), image magnetic structure Pulsar (9 bins) Π ±2.6%, ψ±3.7° (if Π≈20%), 34-ms pulse period, PWNe subtracted
Vela PWNe + pulsar	5.2	1.8	11.7	PWNe (18 bins) Π ±2.6%, ψ±3.7° (if Π≈20%), image magnetic structure Pulsar (2 bins) MDP = 19.9%, 89-ms pulse period, PWNe subtracted
MSH 15-52 + B1509-58	7.2	1.5	12.3	PWNe (18 bins) Π ±2.6%, ψ±3.7° (if Π≈20%), image magnetic structure Pulsar (9 bins) Π ±3.1%, ψ±4.4° (if Π≈20%), 151-ms pulse period, PWNe subtracted
G21.50-0.89 + J1833-103	3.9	3.0	5.6	Survey
Kes 75 + J1846-0258	1.4	4.0	8.9	Survey
N158A + B0540-69	2.2	4.0	5.2	Survey
Supernova Remnants (SNR)				
Cas A	116.0	0.35	11.6	(48 bins) Π ±0.8%, ψ±4.6° (if Π≈5%), image magnetic structure
Tycho	16.1	1.0	9.0	(18 bins) Π ±1.4%, ψ±8.0° (if Π≈5%), image magnetic structure
Kepler	2.9	2.5	9.4	(3 bins) Π ±1.4%, ψ±8.2° (if Π≈5%)
Kes 73	1.4	4.0	5.3	Survey
W49B	4.3	3.0	3.7	Survey
MSH 11-54	3.5	3.0	5.4	Survey
G347.3-00.5 (W limb)	3.3	4.0	3.3	(3 bins) Π ±2.3%, ψ±6.5° (if Π≈10%)
RCW 103 (shell)	1.0	5.0	6.8	(3 bins) Π ±2.8%, ψ±8.2° (if Π≈10%)

Magnetars				
Source name	**F_{2-8} 10^{-11} cgs**	**MDP_{99} %**	**Δt day**	**Uncertainty σ_Π and σ_ψ for representative polarization measurements for indicated number of energy × time or pulse phase × spatial bins**
4U 0142+61	5.9	2.0	5.4	(9 bins) Π ±2.0%, ψ±1.1° (if Π≈50%), 8.7-s pulse period, test vacuum birefringence
1RXS J170849.0-400910	4.3	2.5	5.6	(9 bins) Π ±2.5%, ψ±1.4° (if Π≈50%), 11-s pulse period, test vacuum birefringence
Classical Accreting X-ray Pulsars (High-B X-ray Binaries)				
Cen X-3	341.	0.5	2.6	(27 bins) Π ±0.9%, ψ±1.2° (if Π≈20%), 4.84-s pulse period
4U 0900-40	574.	0.5	1.5	(27 bins) Π ±0.9%, ψ±1.2° (if Π≈20%), 283-s pulse period
SMC X-1	64.	1.0	3.8	(27 bins) Π ±1.7%, ψ±2.4° (if Π≈20%), 0.71-s pulse period
Her X-1	87.	1.0	3.2	(27 bins) Π ±1.7%, ψ±2.4° (if Π≈20%), 1.24-s pulse period
4U 1626-27	63.	1.0	2.3	(27 bins) Π ±1.7%, ψ±2.4° (if Π≈20%), 7.7-s pulse period
IGR J1748-2446	78.	1.0	1.5	(27 bins) Π ±1.7%, ψ±2.4° (if Π≈20%), 0.091-s pulse period
GRO J1744-28 bursting	1034.	0.5	0.8	(27 bins) Π ±0.9%, ψ±1.2° (if Π≈20%), 0.467-s pulse period
4U 0115+634 outburst	254.	1.0	0.9	(27 bins) Π ±1.7%, ψ±2.4° (if Π≈20%), 3.61-s pulse period
Accreting Millisecond X-ray Pulsars & other Low-B X-ray Binaries				
Sco X-1 *0.1 transmission	2250.	0.4	0.34	(5 bins) Π ±0.3%, ψ±1.7° (if Π≈5%), with bright-source attenuating filter
Cyg X-2	987.	0.4	1.1	(5 bins) Π ±0.3%, ψ±1.7° (if Π≈5%)
4U 1636-53 burster	352.	0.4	3.1	(27 bins) Π ±0.7%, ψ±3.9° (if Π≈5%), 17-ms pulse period
4U 1728-337 burster	300.	0.4	3.6	(27 bins) Π ±1.7%, ψ±2.4° (if Π≈5%), 28-ms pulse period
4U 1820-303 burster	710.	0.4	1.5	(5 bins) Π ±0.3%, ψ±1.7° (if Π≈5%)
GS 1826-238 clocking	55.	1.0	3.4	(5 bins) Π ±0.7%, ψ±4.2° (if Π≈5%)
J1808.4-3658 outburst	350.	0.4	2.3	(27 bins) Π ±0.7%, ψ±2.4° (if Π≈5%), 25-ms pulse period

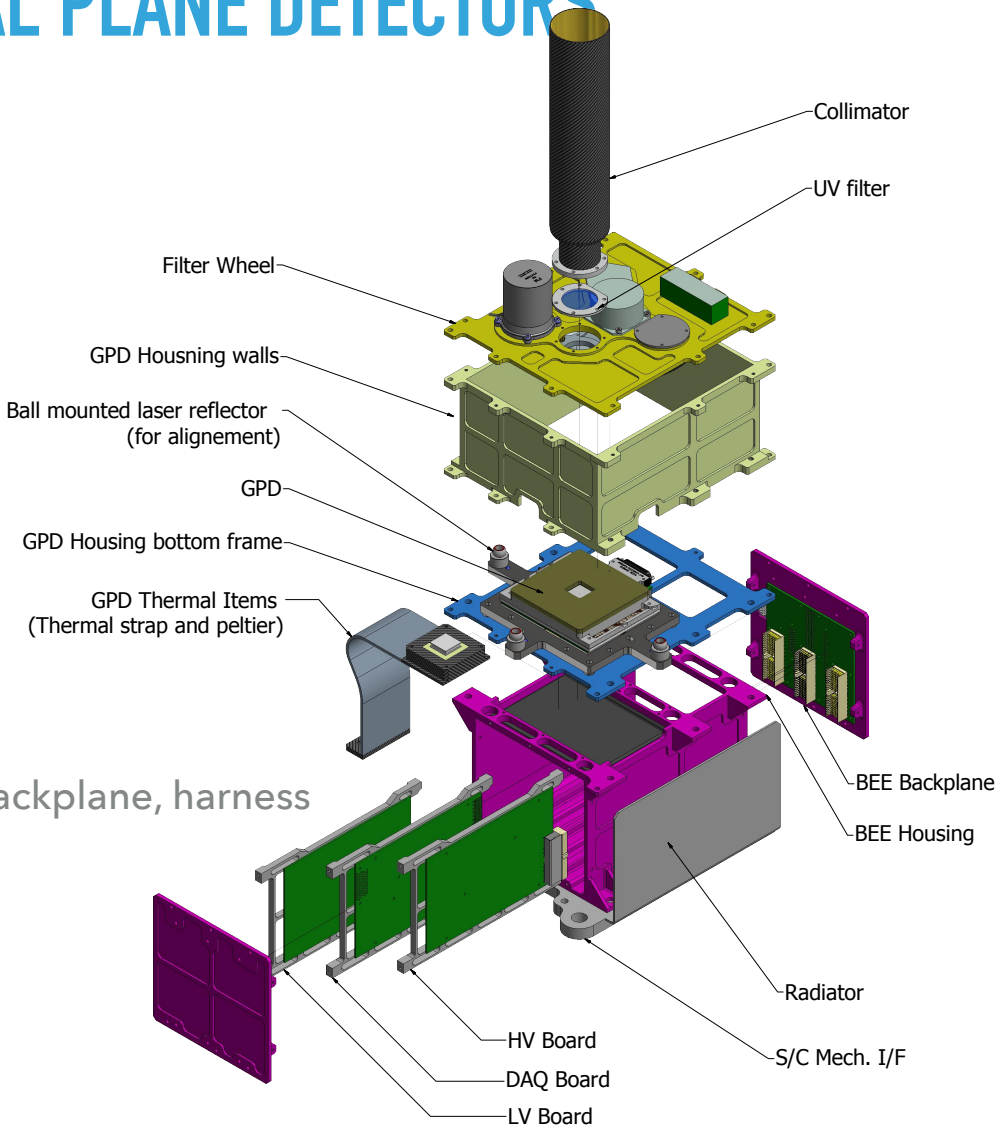
THE TELESCOPE

- Instrument (Italy) - Mirrors (MSFC) - Satellite (Ball Aerospace)



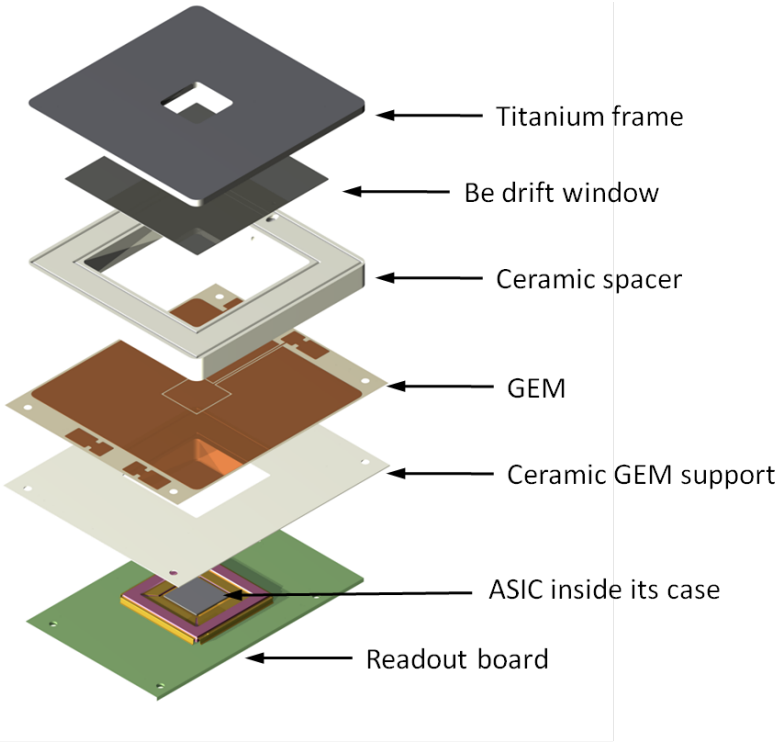
INFN RESPONSIBILITY – FOCAL PLANE DETECTORS

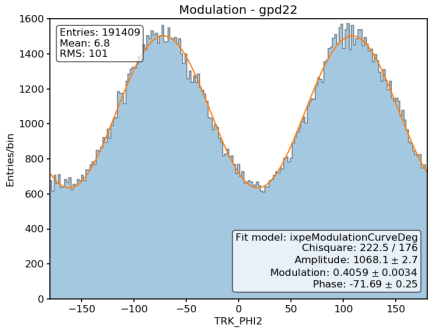
- Gas Pixel Detector (GPD)
  - Bread-Board (BB)
  - Engineering Model (EM)
- Detector Units (DU)
  - 3x Proto Flight Model (PFM)
  - 1x PFM spare
- DU Electronics Boards design and firmware
  - Low Voltage, DAQ, GPD ASIC boards, backplane, harness
- DU Mechanical Housing
- DU Thermal Control System
- Straylight collimator

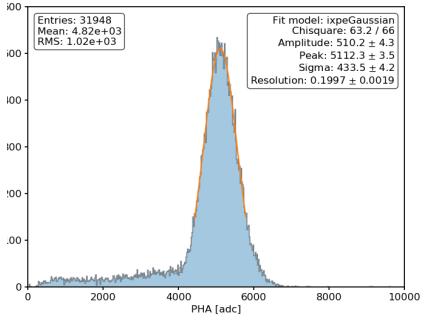


GAS PIXEL DETECTOR

- Gas detector with 50 um pixel custom ASIC readout
- GEM with 50um pitch amplifies primary charge
- Reconstruct photoelectron tracks event by event
- Simultaneously provides photon position (30”), energy (20%), polarization angle and degree







INFN CONTRIBUTIONS

- Historical GPD development
  - ASIC design and production
  - GEM parameter optimization with japanese groups
  - GPD integration and test
  - readout electronics development
- Direct management of ASI contribution for DU (~6M)
  - INFN acts as prime contractor replacing industry for DU

CURRENT STATUS – HIGHLIGHTS

- Instrument Requirements and Design reviews passed (100+ docs)
  - Critical Design Review 14-15/5, then start flight hardware production
- Mission level milestones
  - Payload PDR 23-24/4, Mission PDR 26-29/6
  - Key decision point July 2018
- Prototypes and Qualification Models
  - Breadboards (BB), GPD, electronics
  - DU Thermal Model, GPD Qualification Model, DU Structural Model, DU Engineering Mod.
- Flight parts procurement started
- GPD sim/recon package released
- Science observations simulator ready

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MODEL PHILOSOPHY

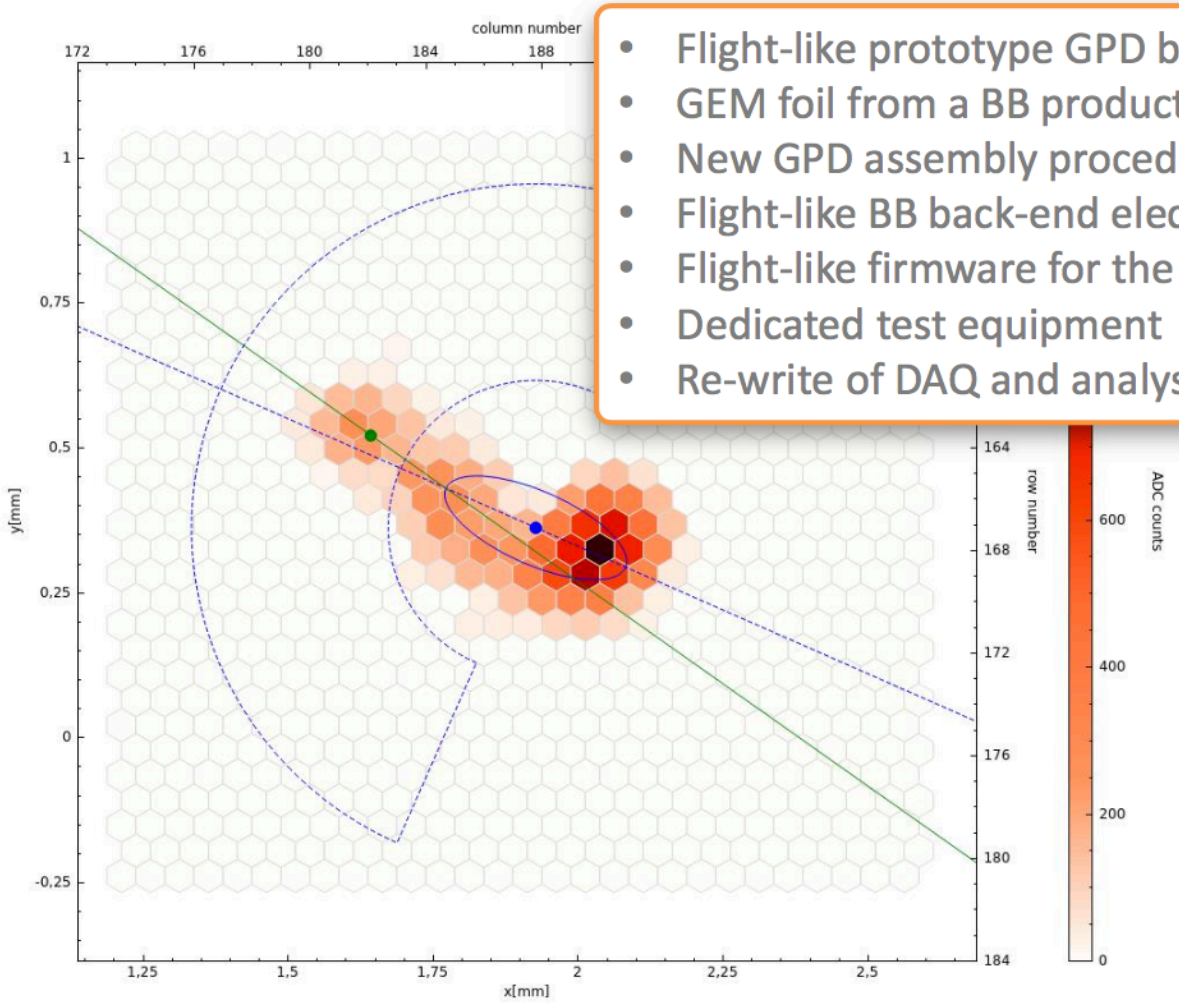
IXPE Instrument HW Matrix	MM	SM set	TM	BB(2)	GPD-EM (3)	EM(5)	QM	PFM	FM	Spare(4)
Detector Unit						1		1	3	1
Gas Pixel Detector	1	1	1	2	1	1	1	1	3	1
GPD Mechanical Interface		1	1	2	1	1	1	1	3	1
GPD Board		1	1	2	1	1	1	1	3	1
Gas Cell		1	1	2	1	1	1	1	3	1
ASIC		1	1	2	1	1	1	1	3	1
Gas Electron Multiplier		1	1	2	1	1	1	1	3	1
Peltier & Thermal Item		1	1	2	1	1	1	1	3	1
Filter & Cal. Wheel	1		1	1		1	1	1	3	1
Holder Wheel & Driver (*)				1		1	1	1	3	1
Lid				1		1	1	1	3	1
Filters & Calibrations set				1		1	1	1	3	1
Stry-Light Collimator	1	1						1	3	1
Collimator Structure		1						1	3	1
Flanges		1						1	3	1
UV Filter		1						1	3	1
Back End Electronic	1	1	1	1		1		1	3	1
DAQ & preprocessing board		1	1	1		1		1	3	1
Backplate & Mother Board		1	1	1		1		1	3	1
LV Power Supply Board		1	1	1		1		1	3	1
HV Power Supply Board		1	1	1		1	1	1	3	1
DU Wiring			1			1		1	3	1
Wiring BEE-GPD			1			1		1	3	1
Wiring GPD Surv Heater								1	3	1
DU Housing	1	1	1			1		1	3	1
GPD Housing		1	1			1		1	3	1
DU Housing		1	1			1		1	3	1
Detectors Service Unit						1		1		
DSU Boards Set	1					1		1		1
Single Board Computer (nom.)	1					1		1		1
Single Board Computer (red.)	1					1		1		
Power & Service Board (nom.)	1					1		1		1
Power & Service Board (red.)	1					1		1		
Mother Board						1		1		
DSU Case	1					1		1		
Harness DSU to DU						1		1		

(1) For B/B Electrical Motor is flight representative while the wheel (as well sources and filters) is a dummy representative of mass and CoG only
(2) 1 B/B is the minimun expected
(3) The GPD EM will be delivered to INAF and MSFC for dry run of calibration at Instrument (INAF) and Telescope (INFN) level with Test Equipment
(4) The Flight Spare will be one of the 4 DU PFMs so it will be qualified at acceptance level as a minimum
(5) The DU-EM will be intragated using BB, EM and QM models
(6) The BEE SM and GPD EM are utilised for the development of Structural test bench for the qualification of FCW reproducing flight configuration

Additional models after I-SRF
(green cells)

- GPD QM
- SM set (BEE, GPD, Collimato
- DU EM

CURRENT STATUS – HIGHLIGHTS



- Flight-like prototype GPD board
- GEM foil from a BB production run
- New GPD assembly procedure
- Flight-like BB back-end electronics
- Flight-like firmware for the DAQ board
- Dedicated test equipment
- Re-write of DAQ and analysis software

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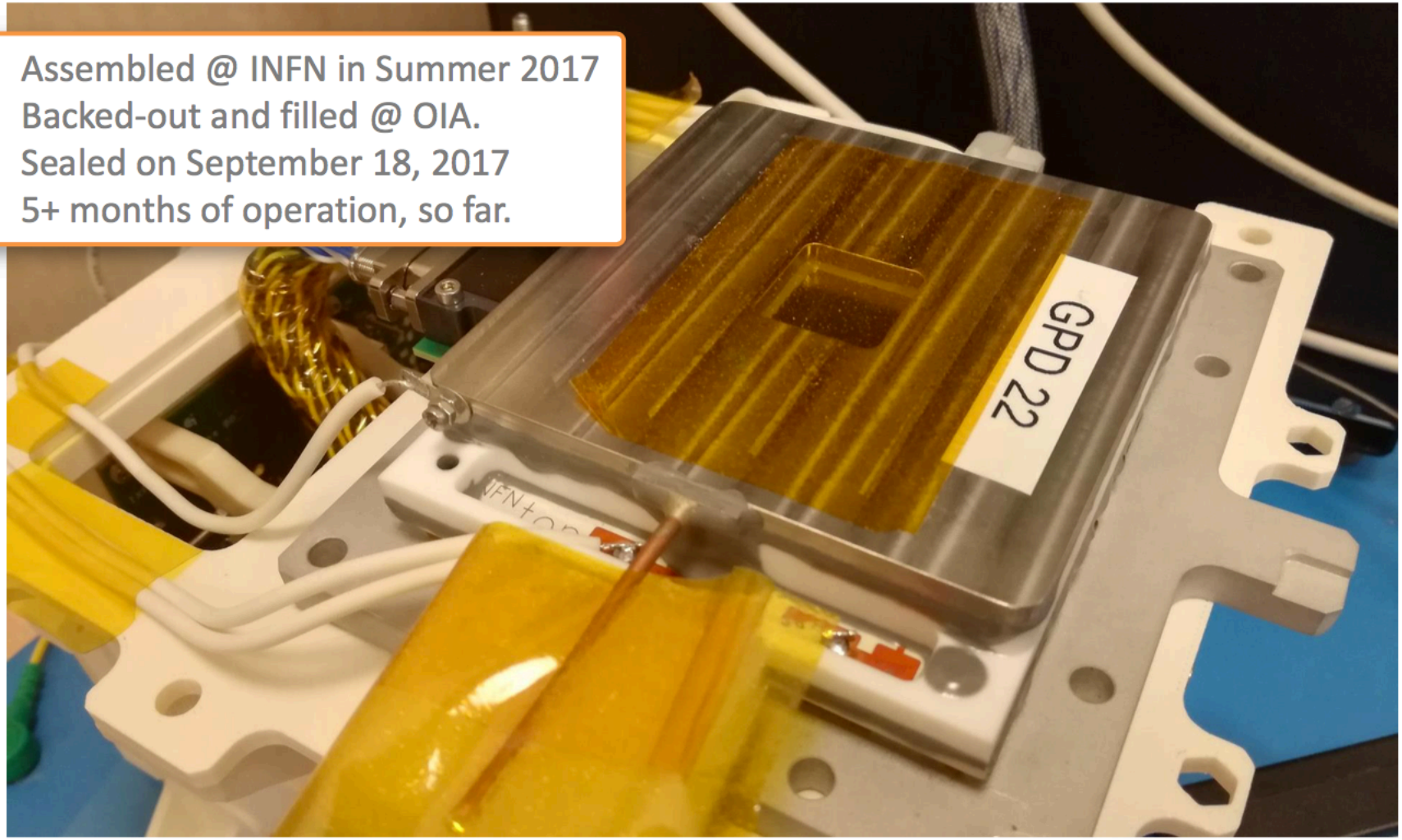
GPD Detector Prototype

- Assembled @ INFN in Summer 2017
- Backed-out and filled @ OIA.
- Sealed on September 18, 2017
- 5+ months of operation, so far.



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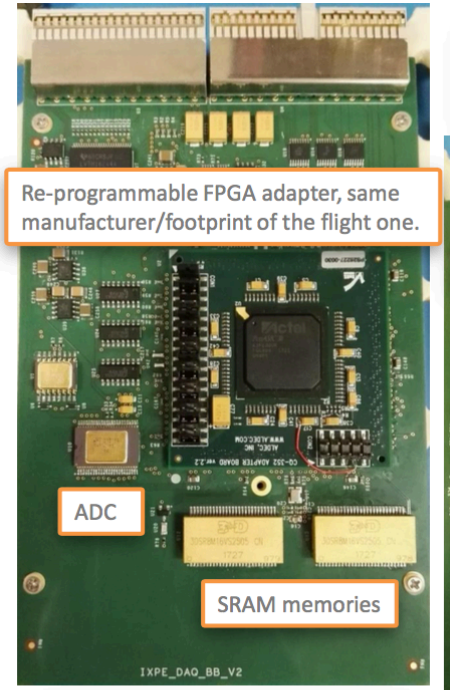
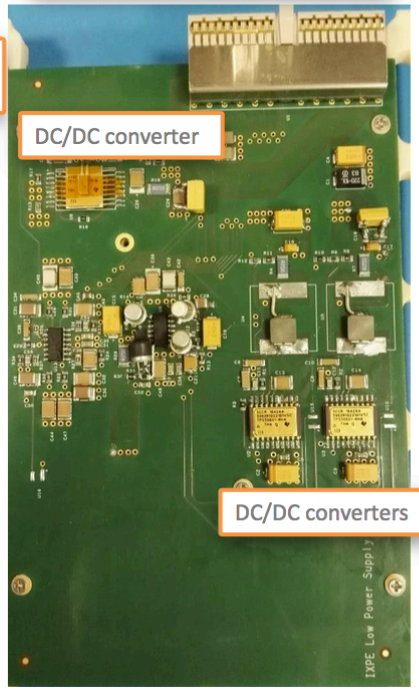
GPD READOUT ELECTRONICS SYSTEM

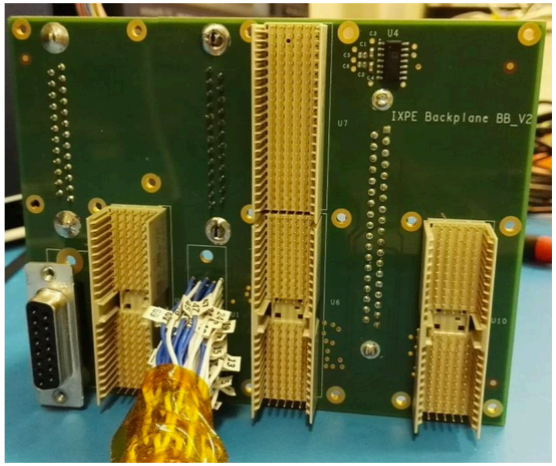
- **Two generations of readout breadboards with flight design developed for onboard DAQ**



DAQ board

Low-voltage power supply board





Backplane

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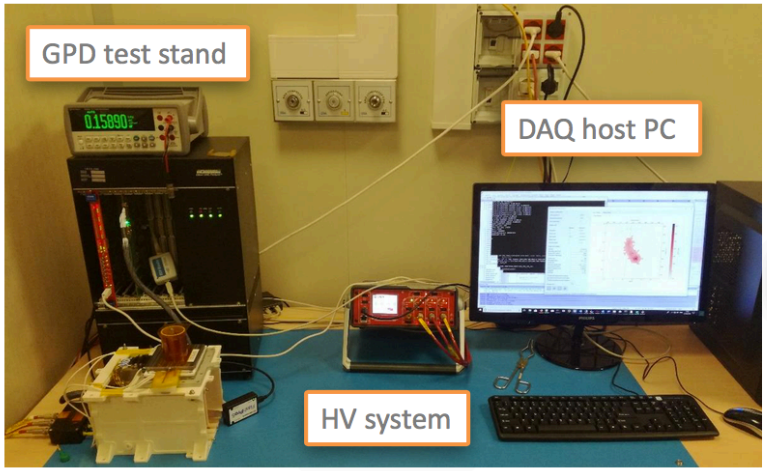
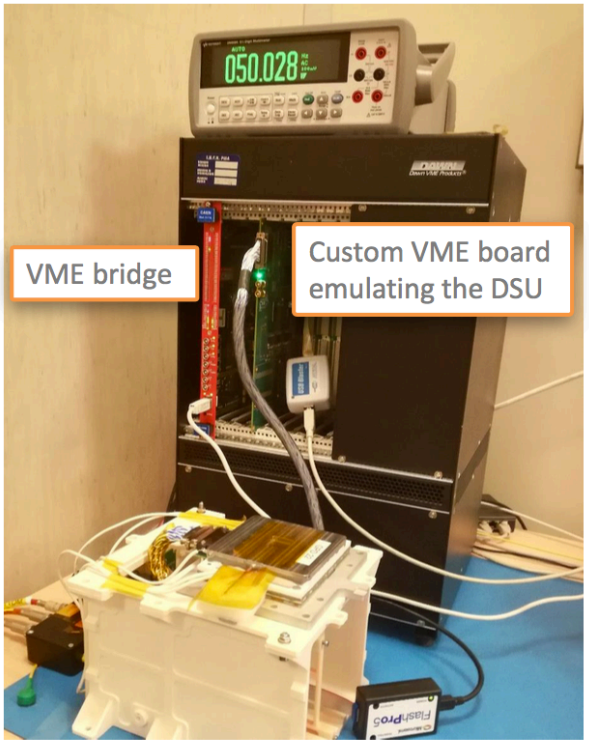
GPD Readout Electronics system

- **Laboratory test equipment to interface to onboard DAQ boards to support GPD and associated electronics development**





- Command-Control Interface (CCI)
- Science Data Interface (SDI)
- Power distribution (5 and 25 V, regulated)
- Timing (1-PPS, 1 MHz clock)

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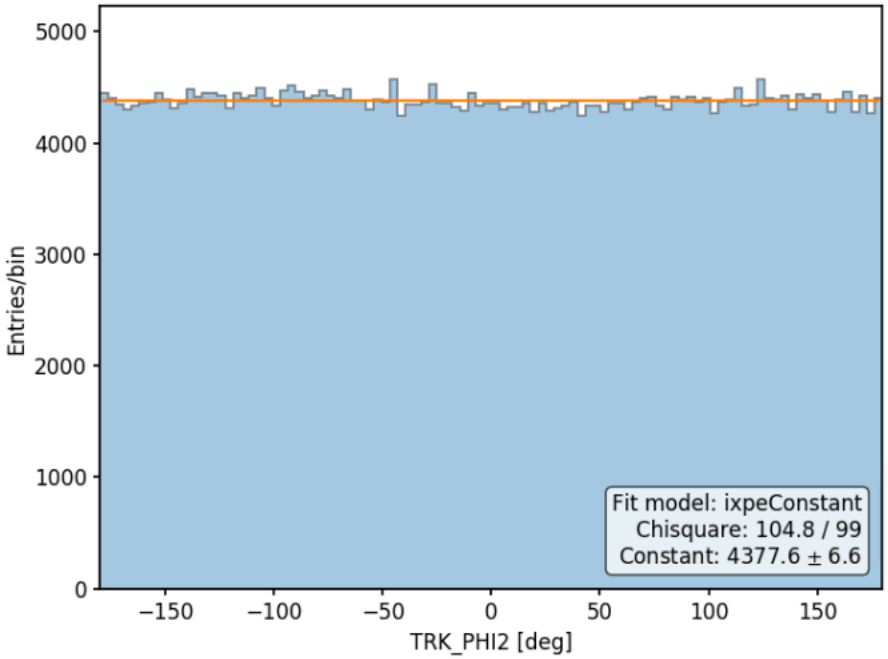
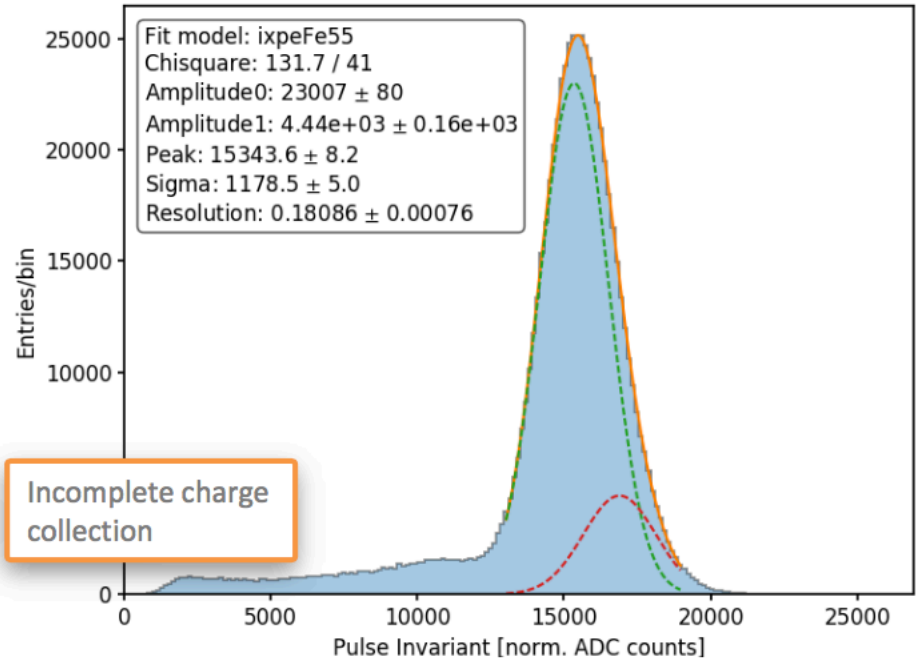
PUTTING EVERYTHING TOGETHER





- Basic performance tests with a ^{55}Fe source
  - Flat azimuthal response
  - 18 % energy resolution over the entire detector (after gain equalization)
- Caveat: this is not a thorough GPD characterization nor calibration
- Yet no evidence of performance degradation in 6 months of operation

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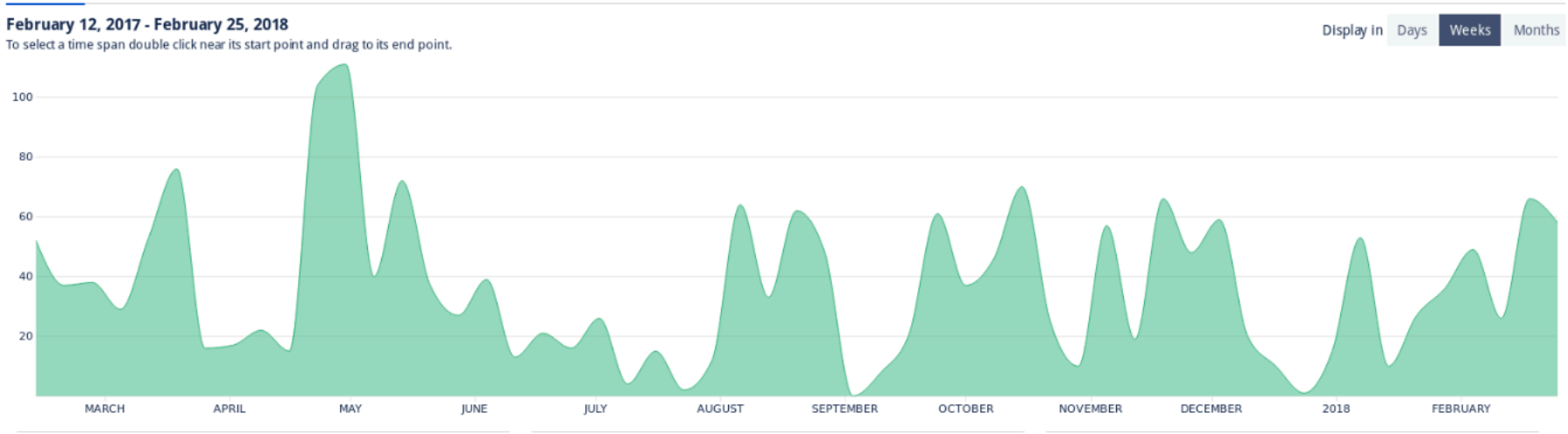
SOFTWARE ACTIVITIES



- **Substantial re-write of all the basic software components:**
  - Data acquisition
  - Detector Monte Carlo simulation
  - Track reconstruction, analysis and monitoring tools
  - Observation simulation framework
- **Tentative definition of all the relevant data formats**
  - FITS LV1 event files, CALDB
  - Active involvement of all the I2T components (including SSDC) and the SOC at MSFC
- **Processing tests and calibration data in the same fashion as flight data**

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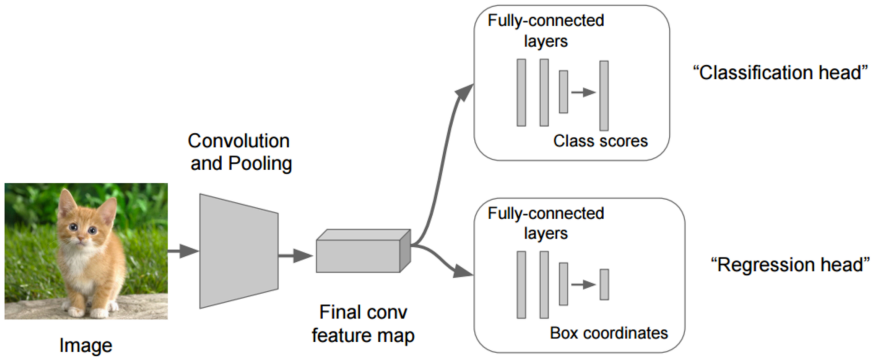
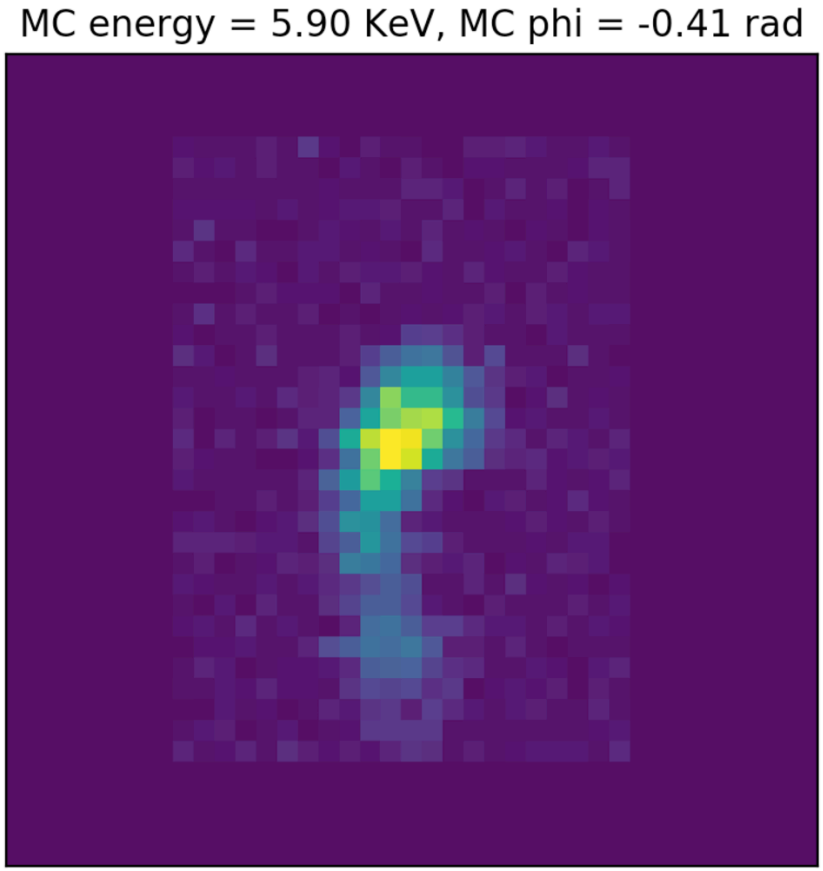
GPD Reconstruction software

- **Testing AI methods (Convolutional Neural Network) to improve recon**
- **Training on MC events**
- **CNN regression to extract track parameters**





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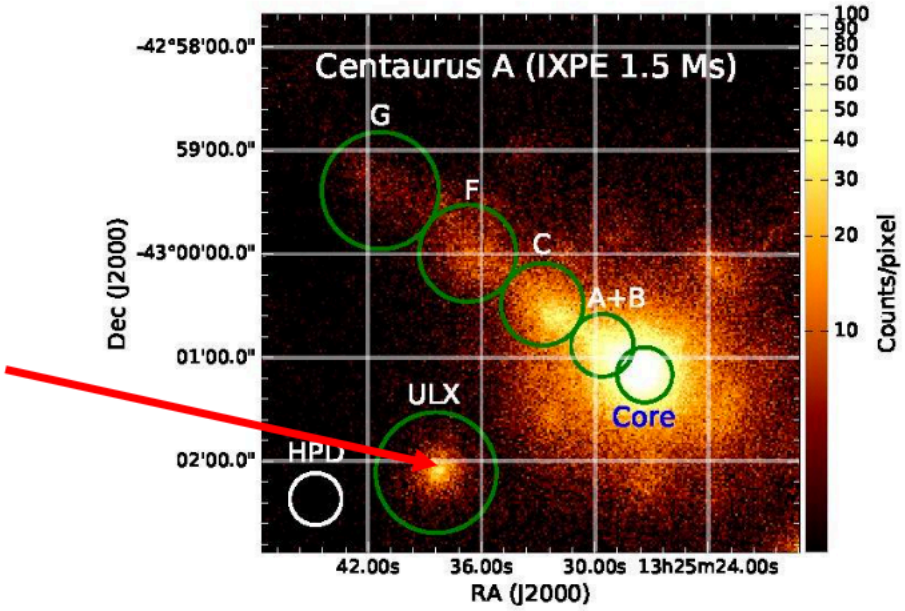
OBS. SIMULATOR FOR SCIENCE PREP

- **Active galaxies are powered by supermassive BHs with jets**
  - Radio polarization implies the magnetic field is aligned with jet
  - Different models for electron acceleration predict different dependence in X-rays
- **Imaging Cen A allows isolating other sources in the field (2 Ultra Luminous X-ray sources)**



Region	MDP_{99}
Core	**<7.0%**
Jet	**10.9%**
Knot A+B	17.6%
Knot C	16.5%
Knot F	23.5%
Knot G	30.9%
ULX	**14.8%**

Includes effects of dilution by unpolarized diffuse emission

CHALLENGES

- Engineering design
  - thermal - assessing additional radiators on the S/C to meet GPD thermal requirement, under study with simulations and DU TM
  - structural - vertical structure imposed by limited focal space on focal plane might amplify loads, to be verified with DU SM
- Detectors - residual <~8% charging on GPD GEM
- Schedule and Procurement - ~3M in 18 months