Particle detection systems for space observatories

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International school on particle detectors

F. Bonaudi - E. Chiavassa

Cogne 17-21 June 2024

Key concepts

Foreword

1. Detection system concept

2. Mission design and lifecycle

3. Upcoming trends

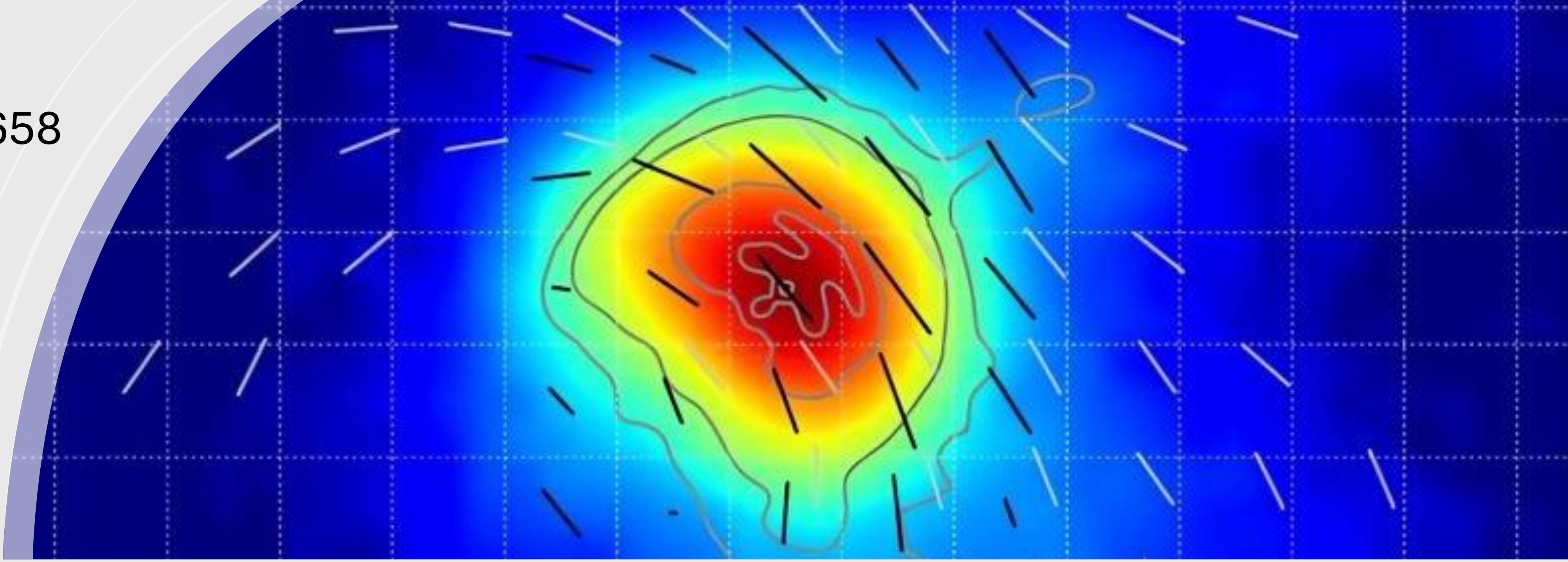
Fermi @ Cape Canaveral - Delta-II heavy - 2008

IXPE @ KSFC 39A – SpaceX Falcon9 - 2021

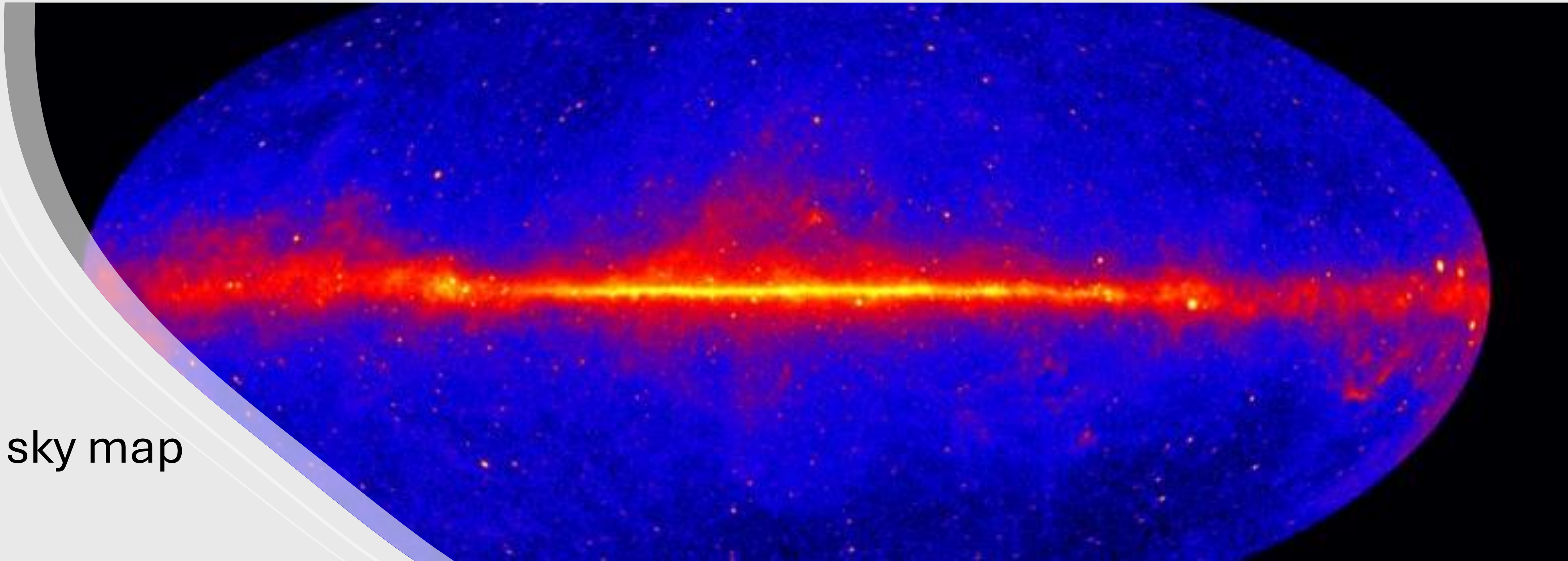

Gamma-ray Large Area Space Telescope
GLAST

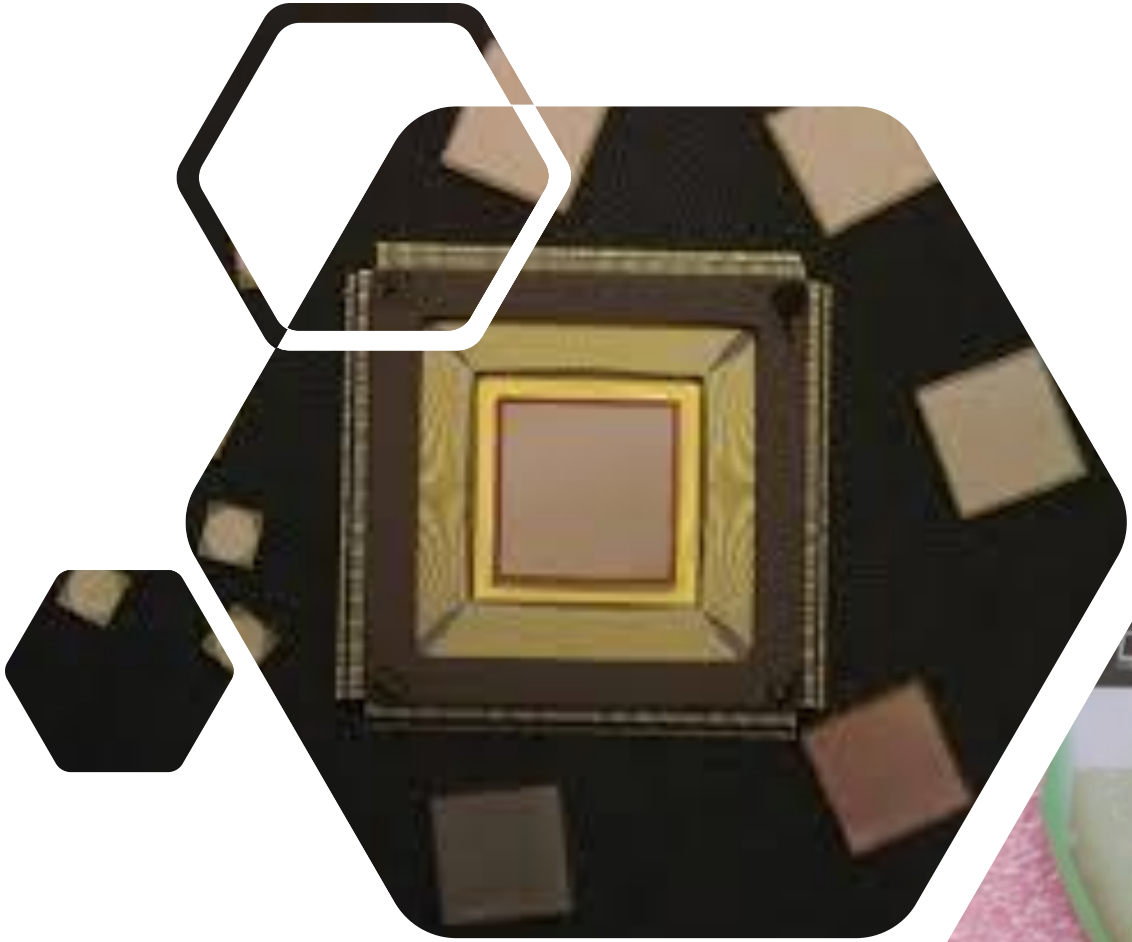

Imaging X-ray Polarimetry Explorer
IXPE
NASA • MSFC • ASI • INAF • INFN • Ball • OHB-I • LASP • MIT • Stanford • Roma Tre • Nagoya

IXPE Vela PWNe
2022 Nature 612 658



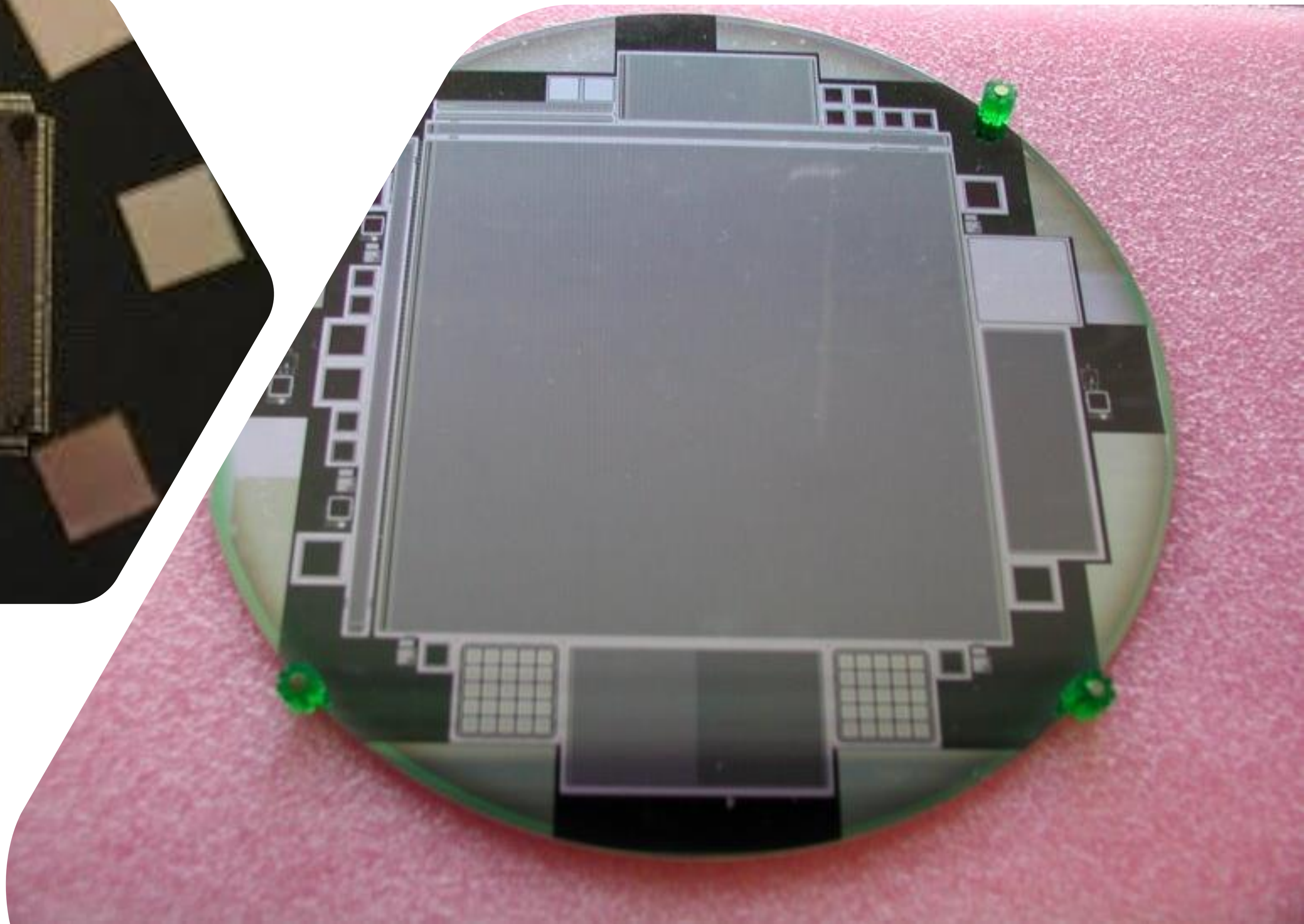
Fermi gamma-ray sky map
2022 ApJS 260 53





IXPE ASIC
2006 NIMA 566 552

Fermi SSD
2005 NIMA 541 29



Fermi LAT Tracker – tower 16 - 2004

IXPE Telescope - DU 4 - 2019

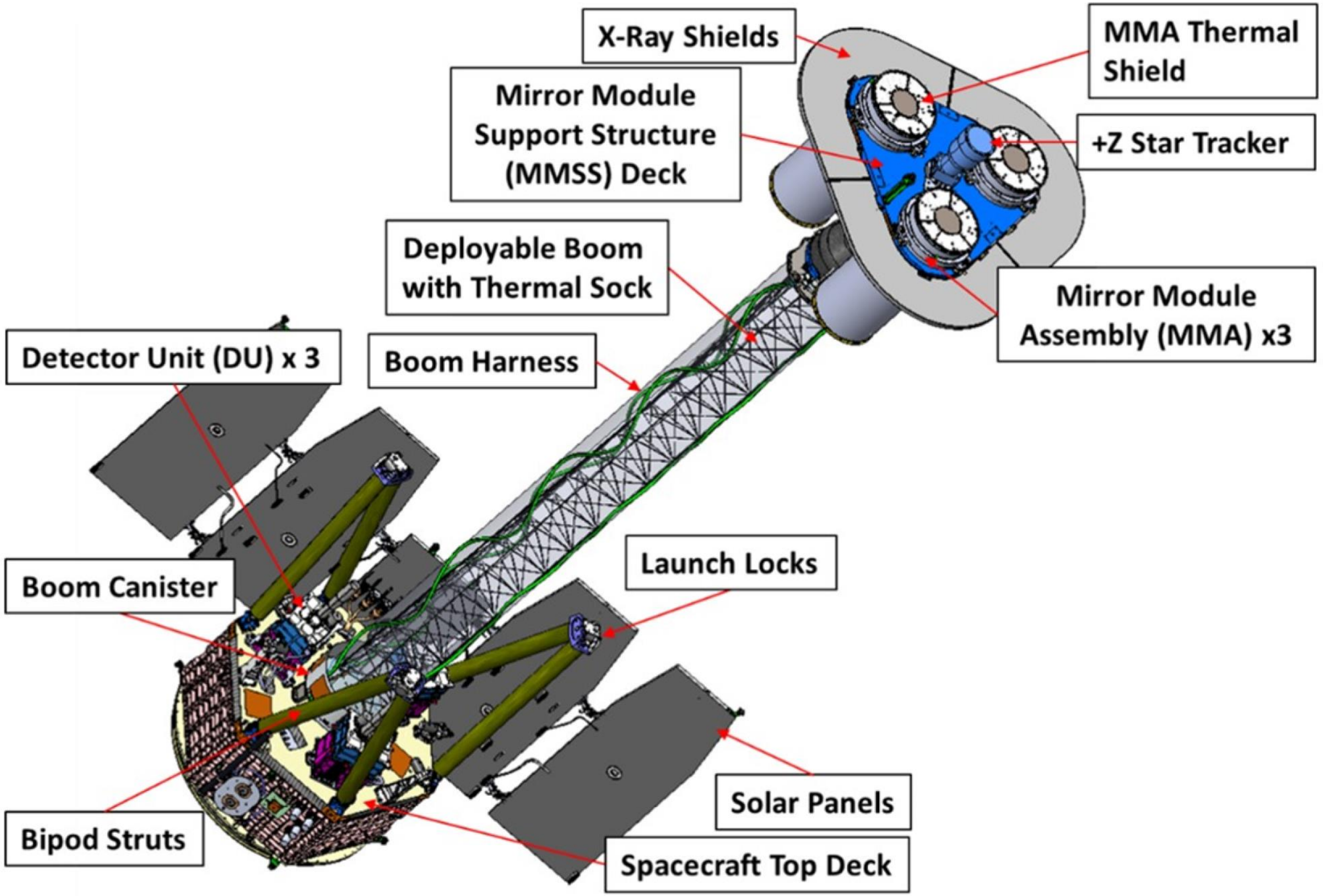
1 – Detection system concept

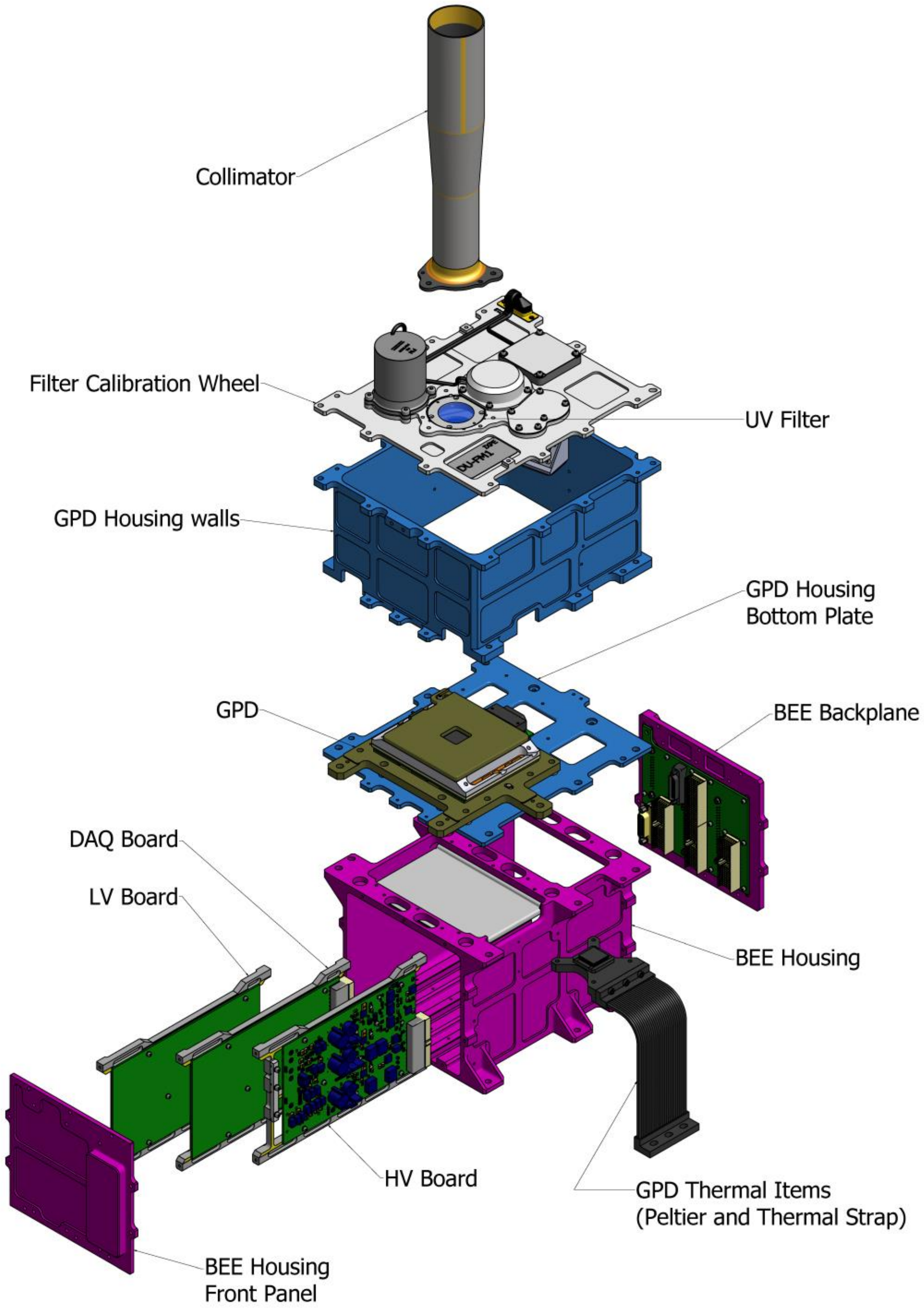
- IXPE Virtual tour
- Tracking X-rays – a focus on the GPD

The IXPE telescope

where are the systems ?

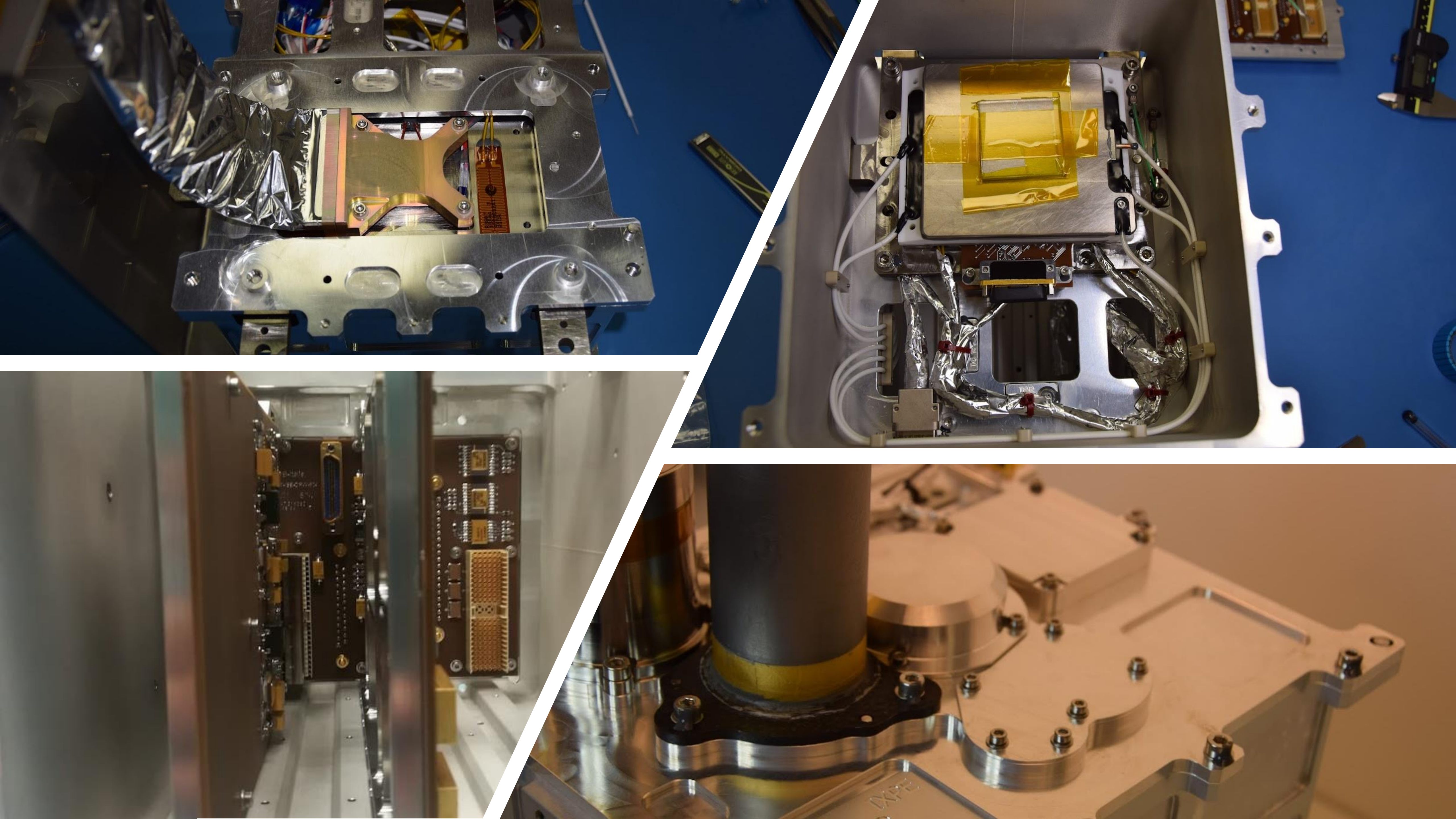
IXPE telescope *artistic map*





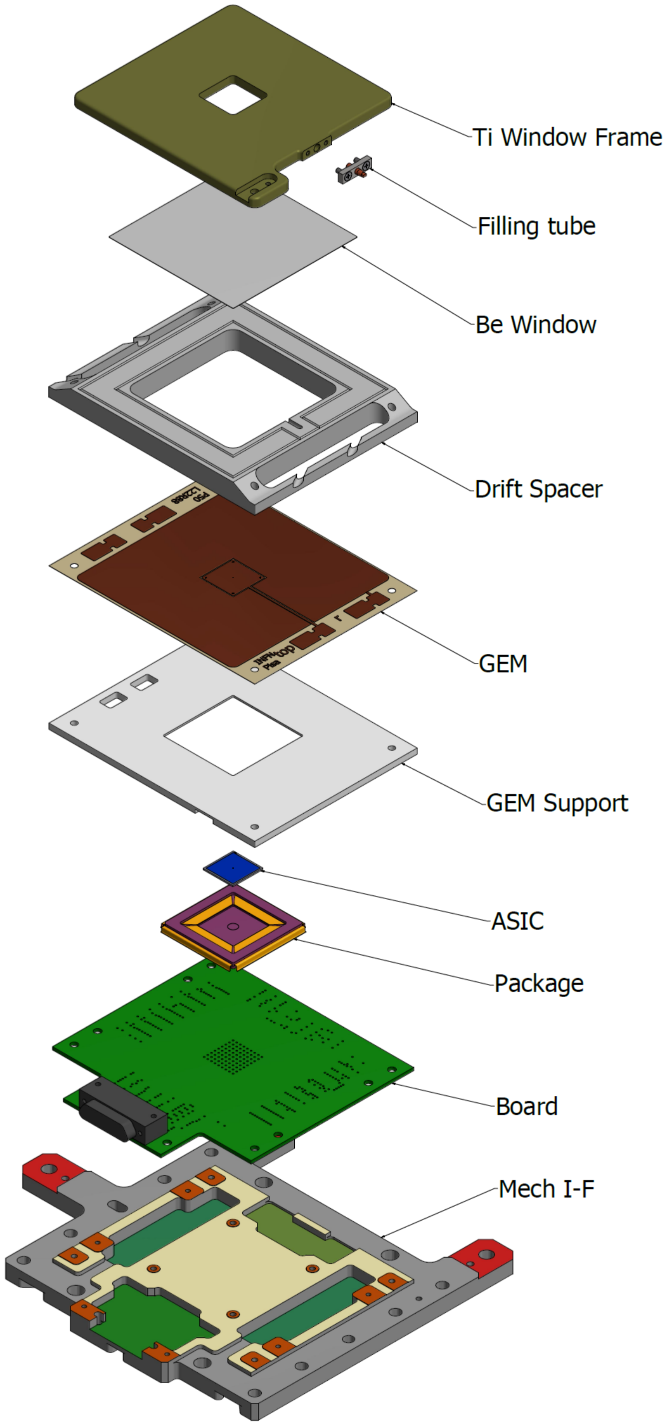
IXPE Detector Unit

Visual Product Breakdown Structure

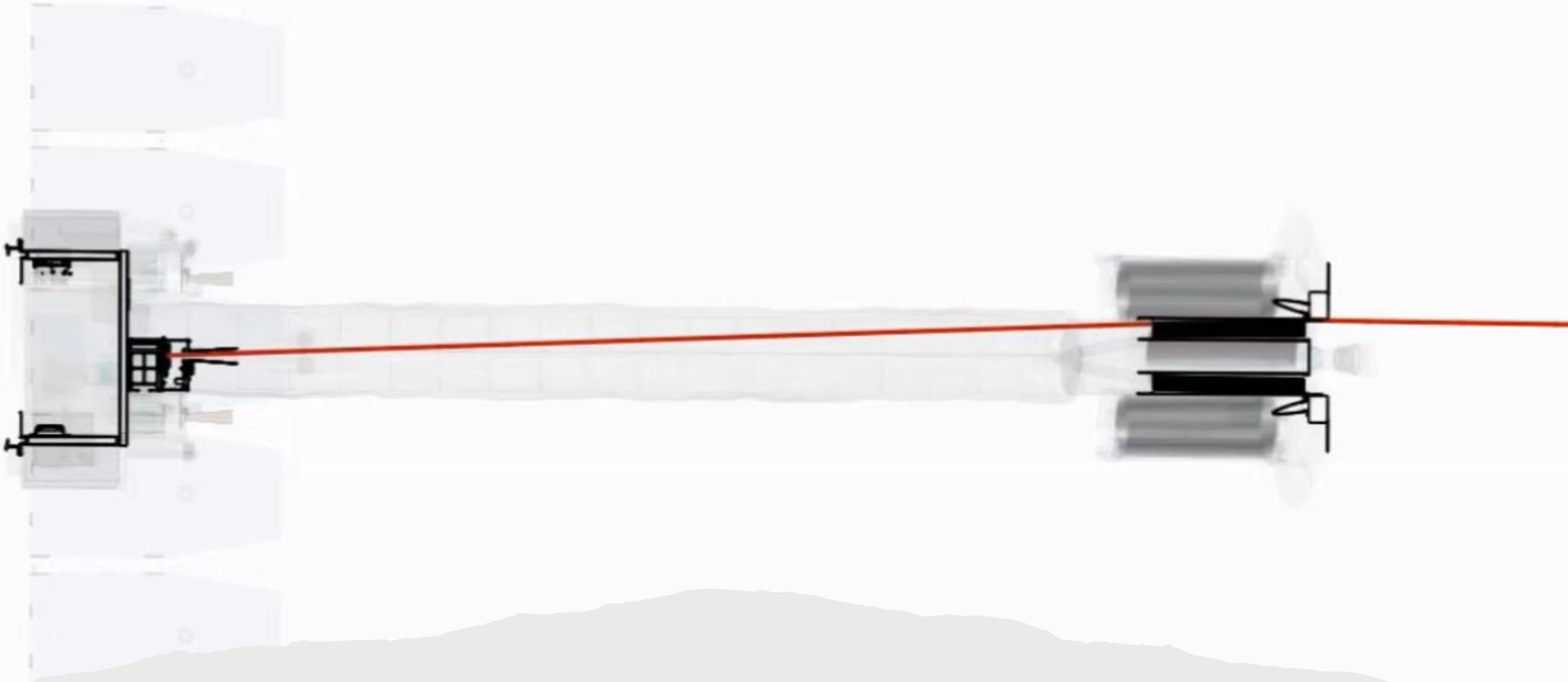

IXPE

Gas Pixel Detector

Engineering view of the actual particle detector

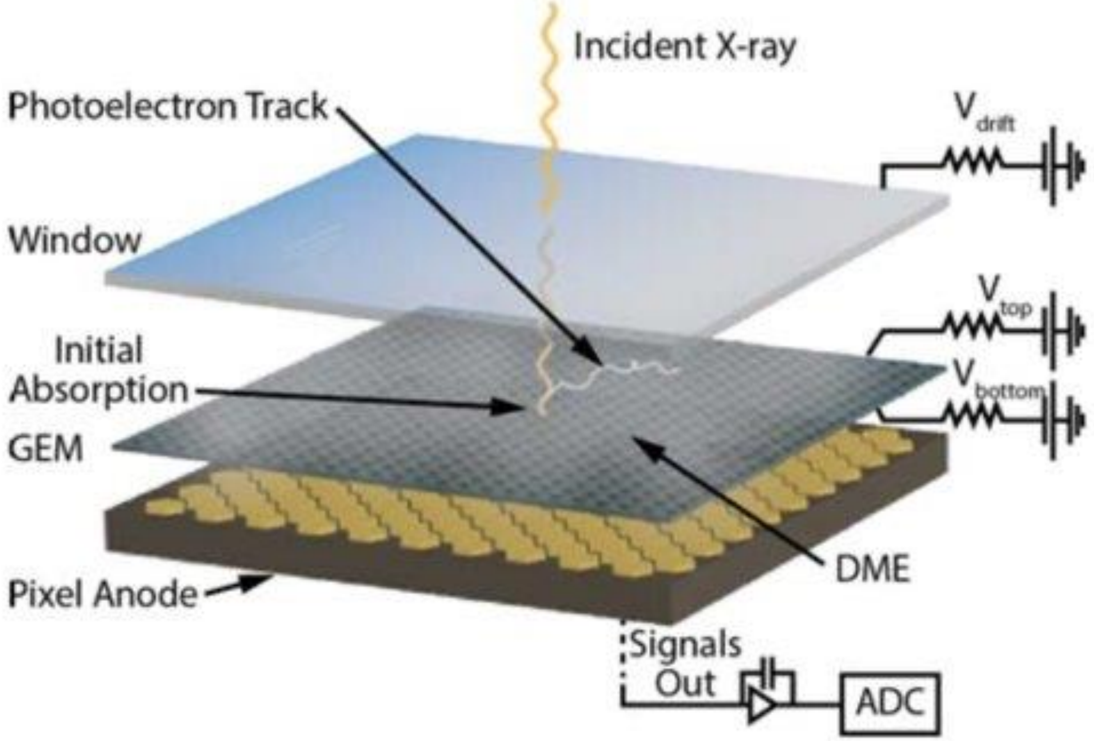


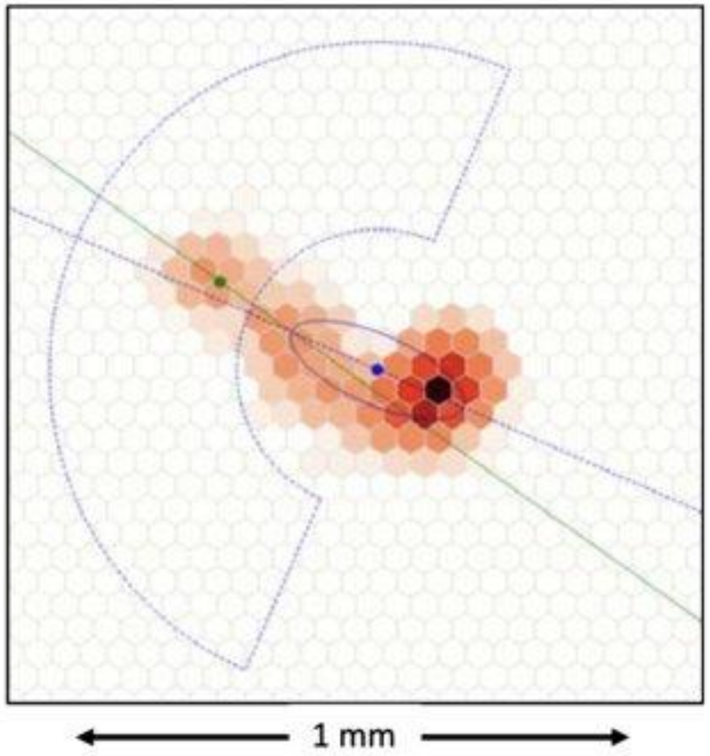

IXPE



IXPE video

The Gas Pixel Detector





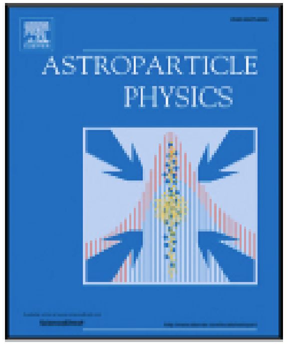
GPD tracks single photons in gas with

- a reasonably efficient photon to charge converter
- a sensor (or amplifier) providing O(10^4) electrons
- a highly efficient, asynchronous, auto trigger
- a high-density array of charge collecting anodes
- a distributed network of low-noise charge amplifiers
- a fast, configurable control readout to transfer data and clear the detector
- good reconstruction algorithms

Contents lists available at ScienceDirect

Astroparticle Physics

journal homepage: www.elsevier.com/locate/astropartphys



https://doi.org/10.1016/j.astropartphys.2021.102628

Design, construction, and test of the Gas Pixel Detectors for the IXPE mission

L. Baldini [a,b], M. Barbanera [c,b], R. Bellazzini [b], R. Bonino [d,e], F. Borotto [e], A. Brez [b], C. Caporale [e], C. Cardelli [b], S. Castellano [b], M. Ceccanti [b], S. Citraro [b], N. Di Lalla [f], L. Latronico [e], L. Lucchesi [b], C. Magazzù [b], G. Magazzù [b], S. Maldera [e], A. Manfreda [b], M. Marengo [e], A. Marrocchesi [b], P. Mereu [e], M. Minuti [b], F. Mosti [e], H. Nasimi [c,b], A. Nuti [b], C. Oppedisano [e], L. Orsini [b], M. Pesce-Rollins [b], M. Pinchera [b], A. Profeti [b], C. Sgrò [b,*], G. Spandre [b], M. Tardiola [e], D. Zanetti [b], F. Amici [g], H. Andersson [h], P. Attinà [i], M. Bachetti [j], W. Baumgartner [k], D. Brienza [g], R. Carpentiero [l], M. Castronuovo [l], L. Cavalli [m], E. Cavazzuti [l], M. Centrone [n], E. Costa [g], E. D'Alba [m], F. D'Amico [l], E. Del Monte [g], S. Di Cosimo [g], A. Di Marco [g], G. Di Persio [g], I. Donnarumma [l], Y. Evangelista [g], S. Fabiani [g], R. Ferrazzoli [g,o,p], T. Kitaguchi [q], F. La Monaca [g], C. Lefevre [g], P. Loffredo [g], P. Lorenzi [m], E. Mangraviti [m], G. Matt [r], T. Meilahti [h], A. Morbidini [g], F. Muleri [g], T. Nakano [q], B. Negri [l], S. Nenonen [h], S.L. O'Dell [k], M. Perri [n], R. Piazzolla [g], S. Pieraccini [m], M. Pilia [j], S. Puccetti [l], B.D. Ramsey [k], J. Rankin [g,o,p], A. Ratheesh [g,o,p], A. Rubini [g], F. Santoli [g], P. Sarra [m], E. Scalise [g], A. Sciortino [m], P. Soffitta [g], T. Tamagawa [q], A.F. Tennant [k],

Electron multipliers options

Gas Electron Multiplier (GEM)

- LCP GEM qualified for space (SciEnergy)
- GEM wet-etched (Techtra, CERN)
- GEM dry-etched (new R&D)

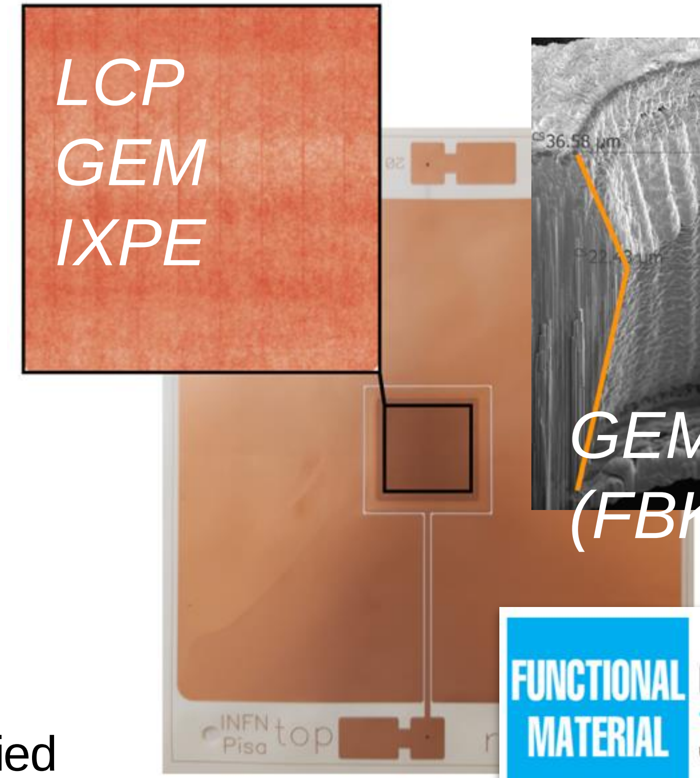
Capillary plates

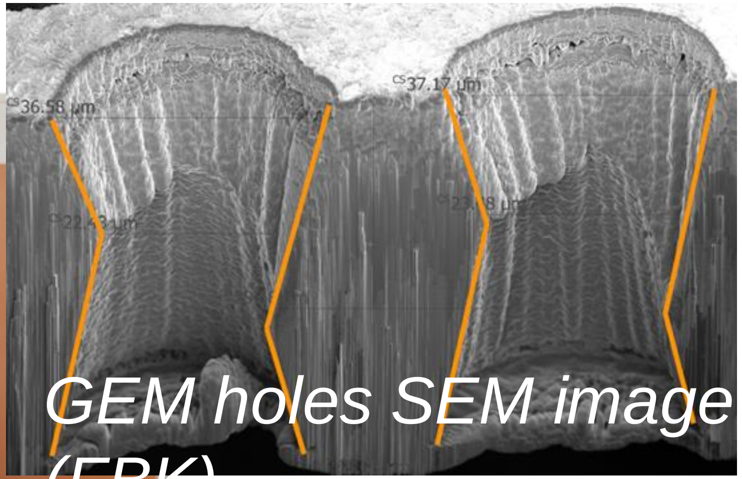
- Demonstrated to work but far from being qualified

Amplifying micrometric structures directly on ASIC

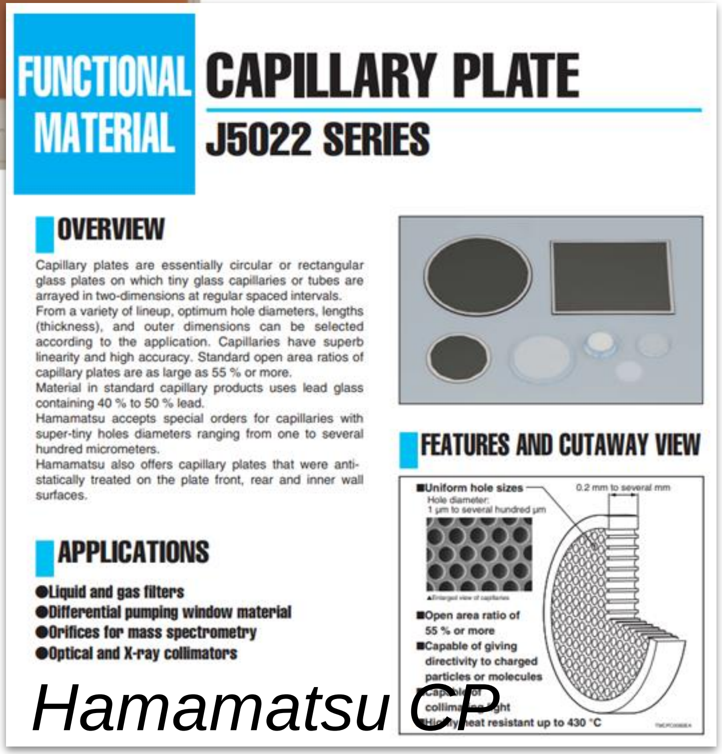
- Post-processing XPOL ASIC for Proof of Concept

Mostly relevant for amplification of the primary charge in gas - no more info on this topic in this talk





GEM holes SEM image (FBK)


FUNCTIONAL MATERIAL

CAPILLARY PLATE

J5022 SERIES

OVERVIEW

Capillary plates are essentially circular or rectangular glass plates on which tiny glass capillaries or tubes are arrayed in two-dimensions at regular spaced intervals.
From a variety of lineup, optimum hole diameters, lengths (thickness), and outer dimensions can be selected according to the application. Capillaries have superb linearity and high accuracy. Standard open area ratios of capillary plates are as large as 55 % or more.
Material in standard capillary products uses lead glass containing 40 % to 50 % lead.
Hamamatsu accepts special orders for capillaries with super-tiny holes diameters ranging from one to several hundred micrometers.
Hamamatsu also offers capillary plates that were anti-statically treated on the plate front, rear and inner wall surfaces.

APPLICATIONS

- Liquid and gas filters
- Differential pumping window material
- Orifices for mass spectrometry
- Optical and X-ray collimators

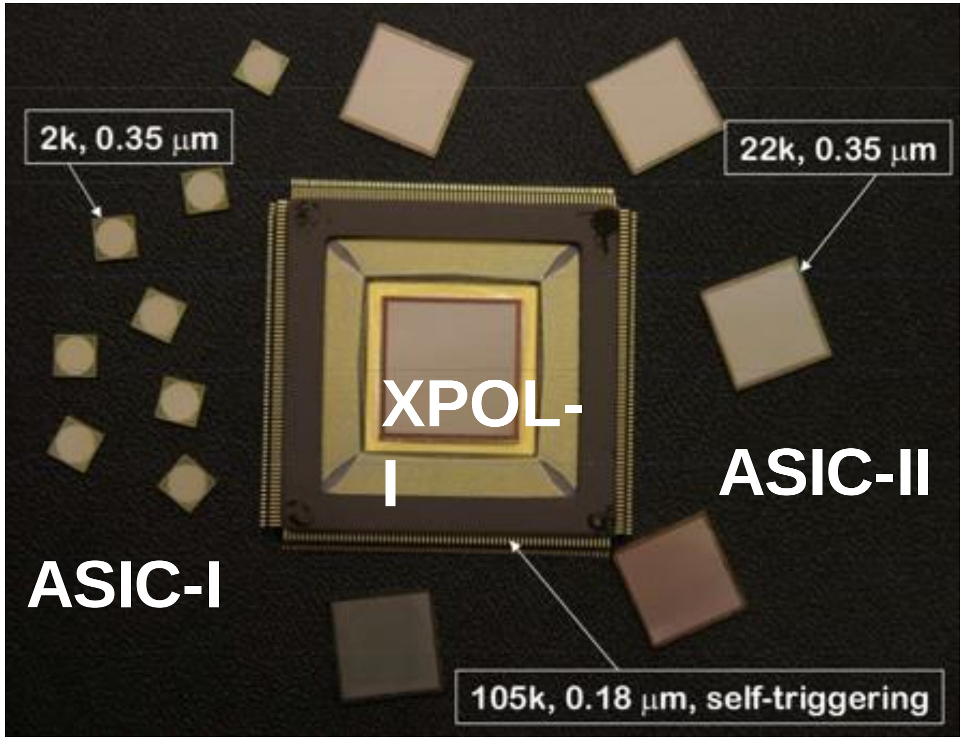
FEATURES AND CUTAWAY VIEW

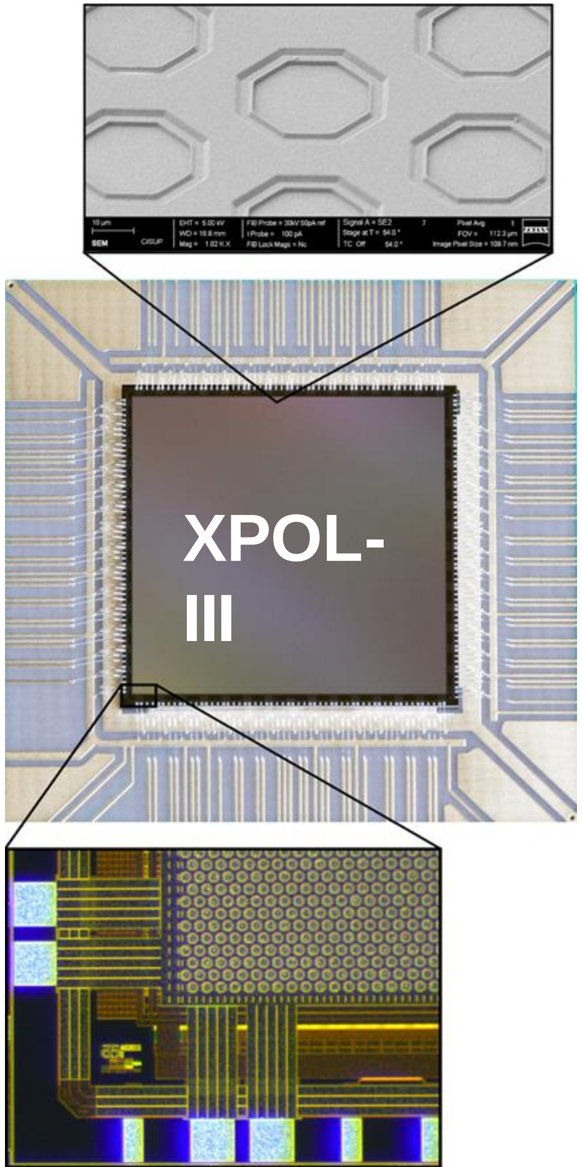
Hamamatsu CP

The XPOL ASICs family - a 20+ years development

Four generations of increasing size, reduced pitch, improved functionality

- First VLSI implementations
- XPOL-I, largest scale
  - Operating onboard Polarlight and IXPE
- XPOL-III, ~10x faster readout
  - Ready to fly on eXTP





References

1. ASIC-I, 2004, NIM-A 535
2. ASIC-II 2006, NIM-A 560
3. XPOL-I 2006, NIM-A 566
4. XPOL-III, 2023, NIM-A, 1046
5. PolarLight, 2019, Exp. Astronomy 47
6. IXPE, 2022 JATIS, 8, 2
7. eXTP, 2019, Sci. China Phys. Mech. Astron. 62

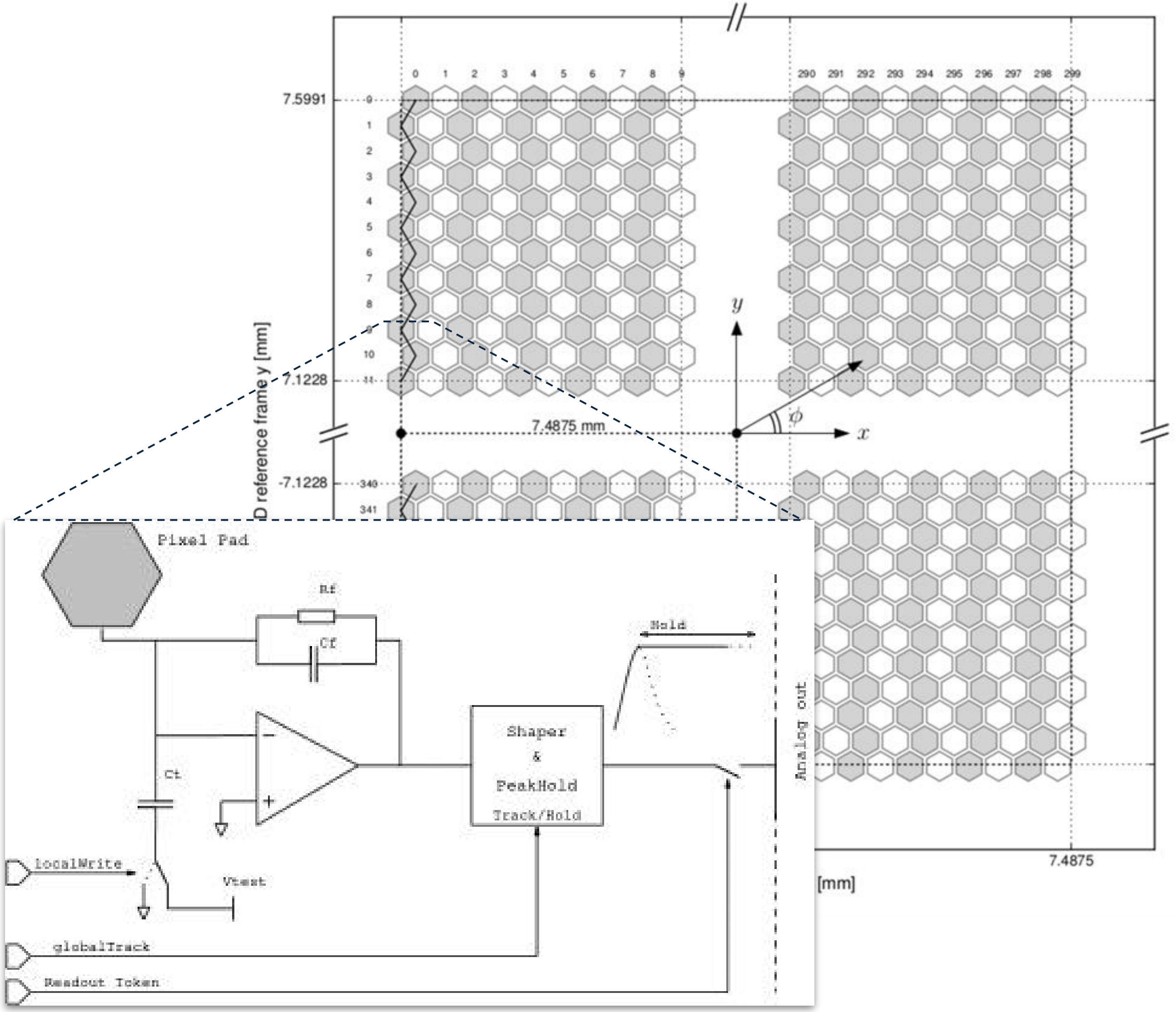
XPOL chip layout and single pixel front-end chain

CMOS VLSI chip built with 180nm technology

- 16M+ transistors
- 105k hexagonal pixels (300x352)
- 15mm^2 - 470 pixel/mm^2 density

Each pixel contains

- Hexagonal metal top layer
- Charge sensitive amplifier
- Shaping circuit
- multiplexer



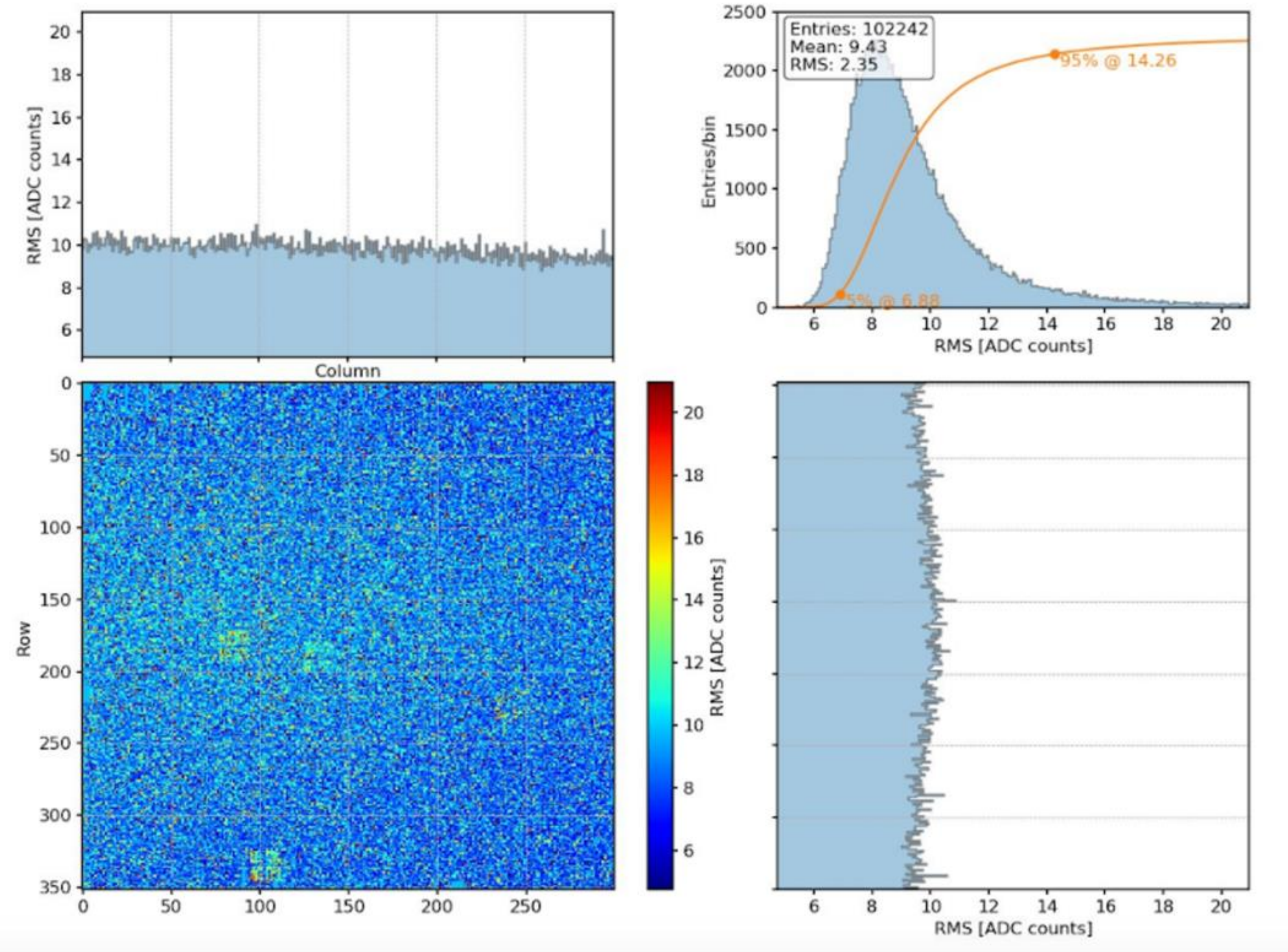
XPOL - electrical properties and typical S/N

1V dynamic range

Typical noise ~10 ADC counts / ~30 electrons

Typical pixel signal O(1000) ADC counts/pixel

5.9 KeV X-rays tracks at normal operating conditions peak at 20k ADC cts



XPOL-I Trigger and readout primitives

2x2 pixels *mini-clusters*

- Trade-off between signal (coherent noise sum) and noise (incoherent sum)
- Threshold is defined by the user

Region of Trigger

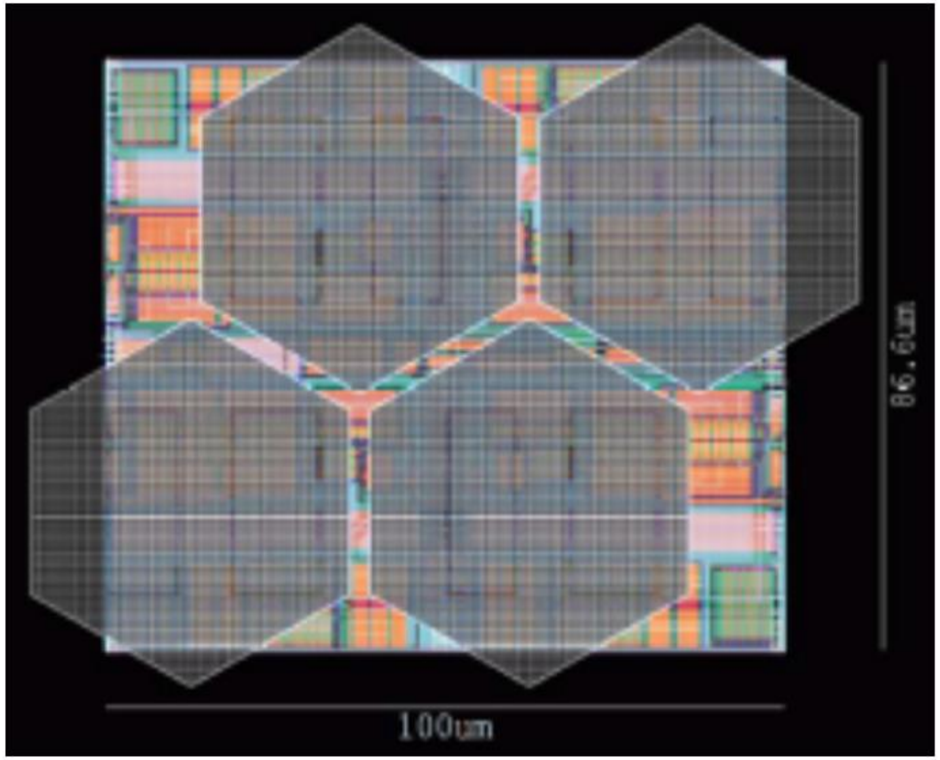
All triggered mini-clusters

Region of Interest

<Xmin,Ymin> - <Xmax, Ymax> around all triggered mini-clusters + padding

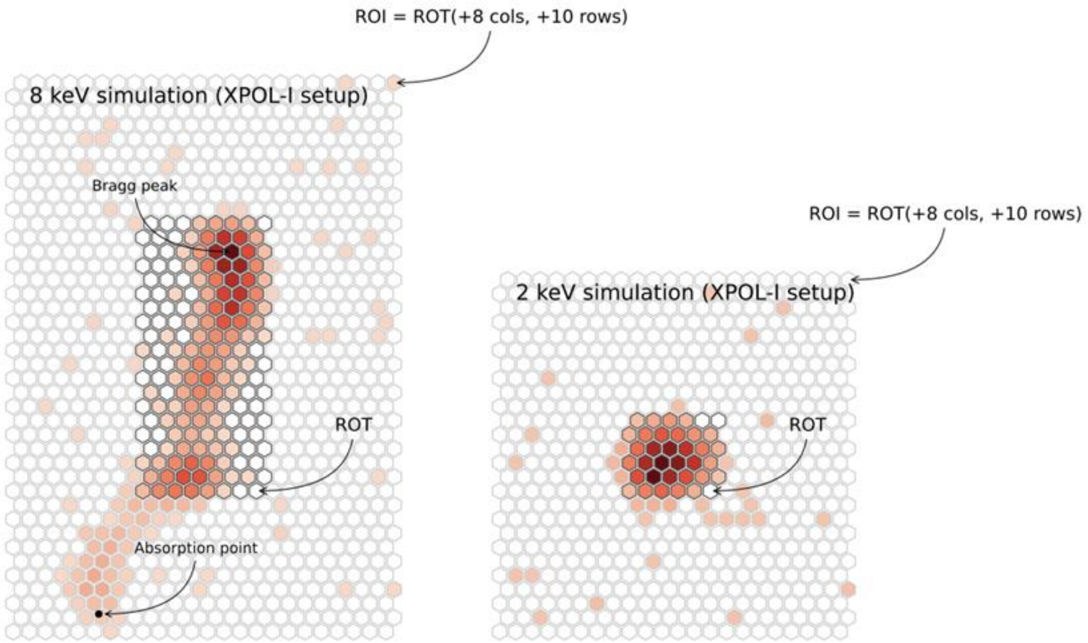
Padding

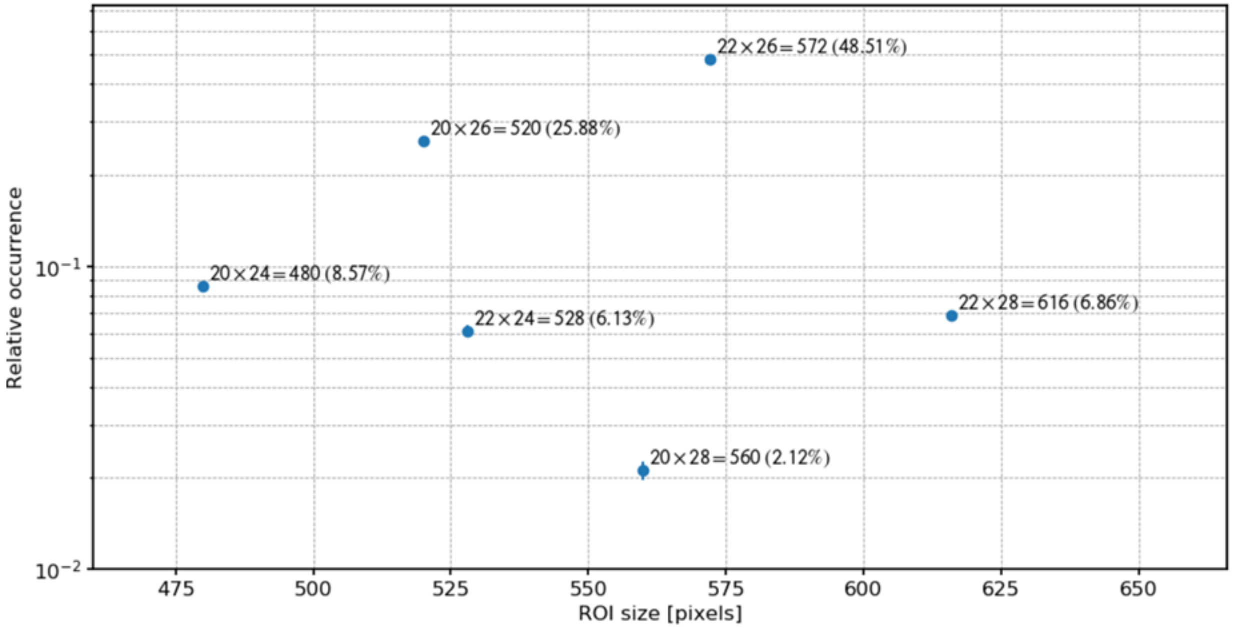
- +4 mini-clusters in X (400 um)
- +5 mini-clusters in Y (430 um)



XPOL-I Region Of Interest

Distribution of ROI sizes for 2.7KeV X-rays





track

XPOL - considerations about Padding

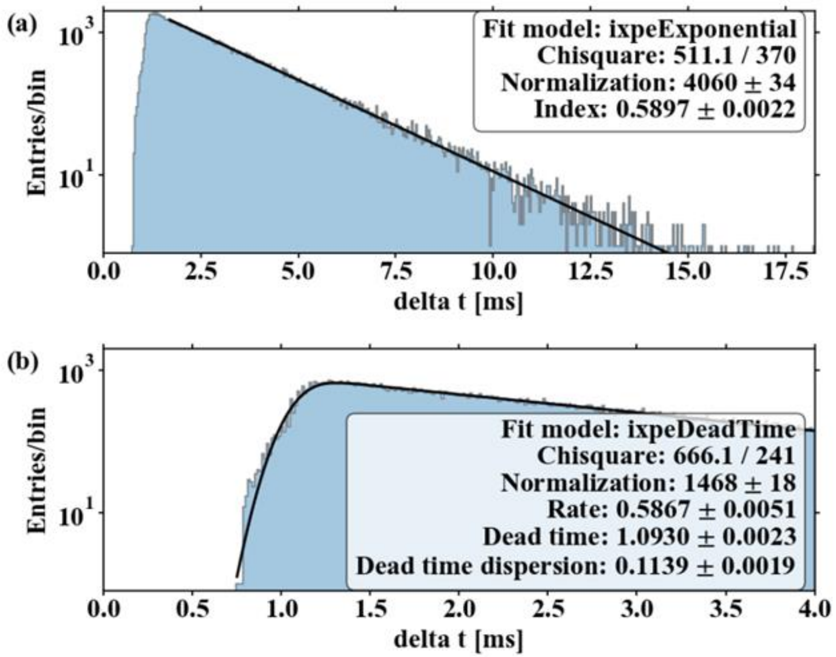
ROI dimension drives event readout time

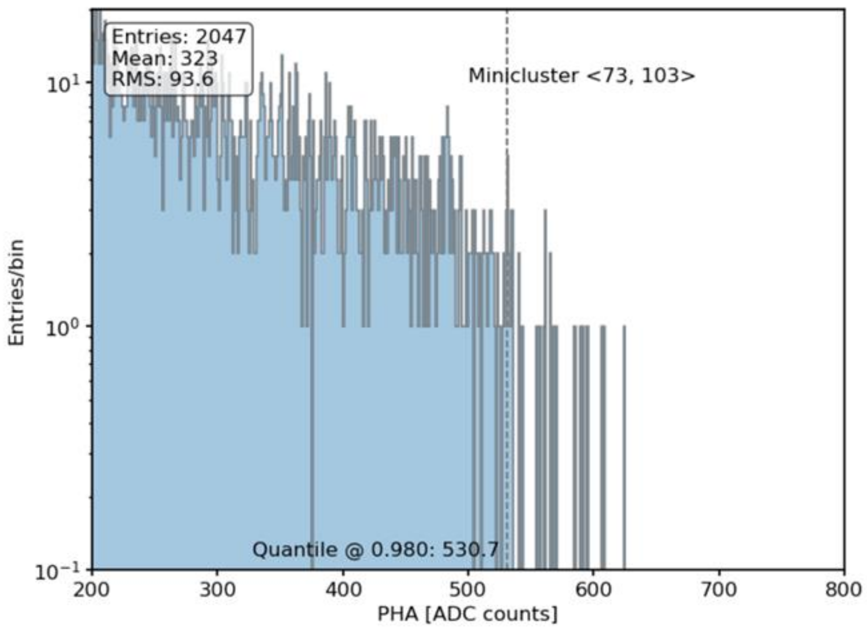
- ~600 pixels evt readout at 5MHz needs 120usec
- ROI should be ideally minimized around track

NOTE: actual deadtime for XPOL-I on IXPE is higher and ~1ms because of

- event-by-event pedestal subtraction (2x)
- System internal delays
  - Most notably Sample & Hold reset to allow pedestal readout (500usec)

But padding (ie no signal) pixels are useful to measure trigger threshold by measuring PH distribution endpoint





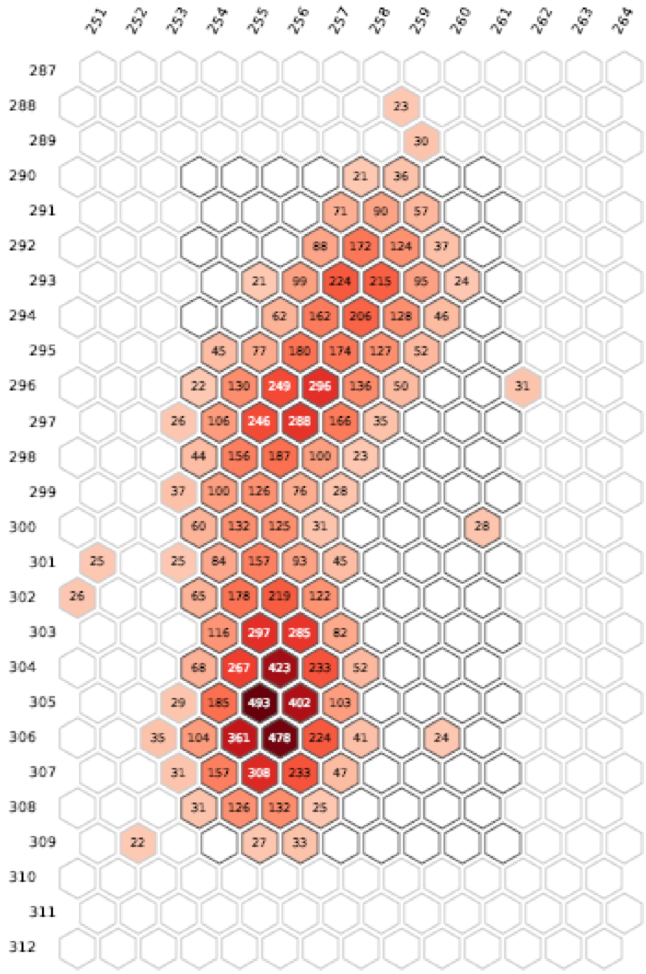
Moving to XPOL-III

Project goal was to readout ~10x faster to match eXTP mirrors effective area

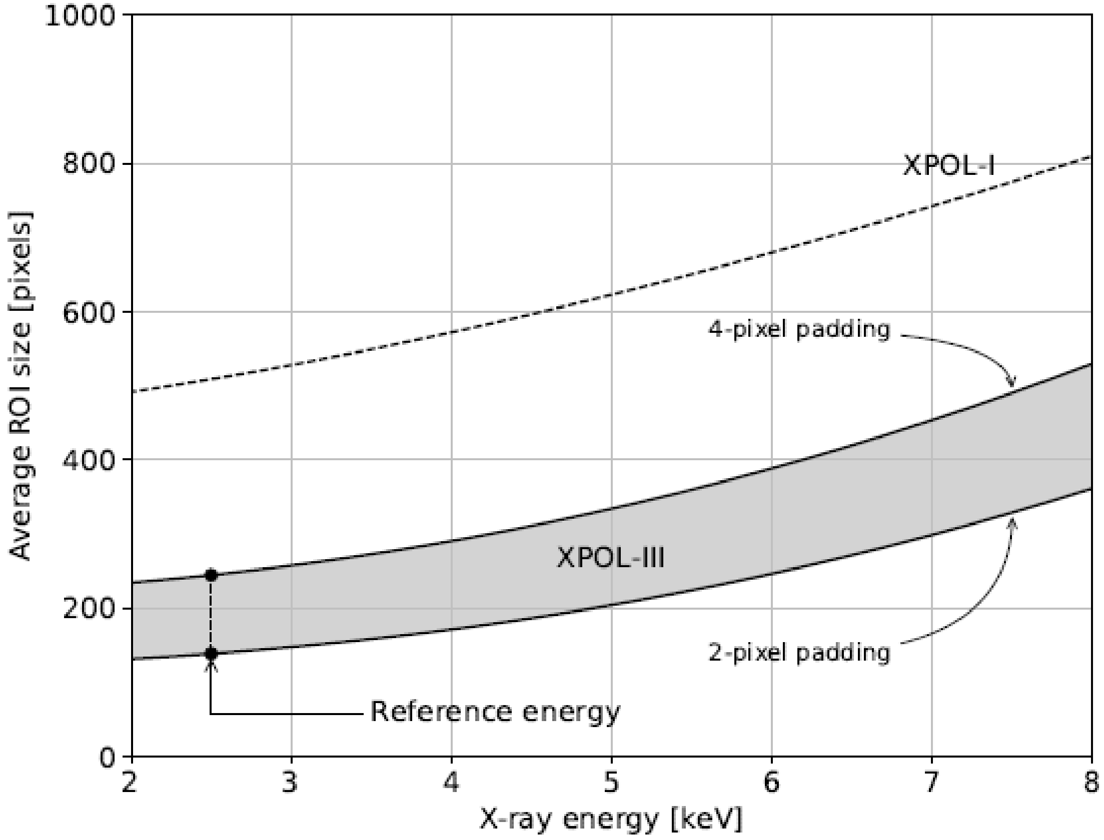
XPOL-III ASIC implementation relies upon

- Same design center and production technology to preserve heritage
- 2x faster clock - 10 MHz
- 10x faster recovery from hold - 50 μsec
- Flexible ROI definition to reduce event readout time
- Trigger mask available for single pixel

XPOL-III The role of padding

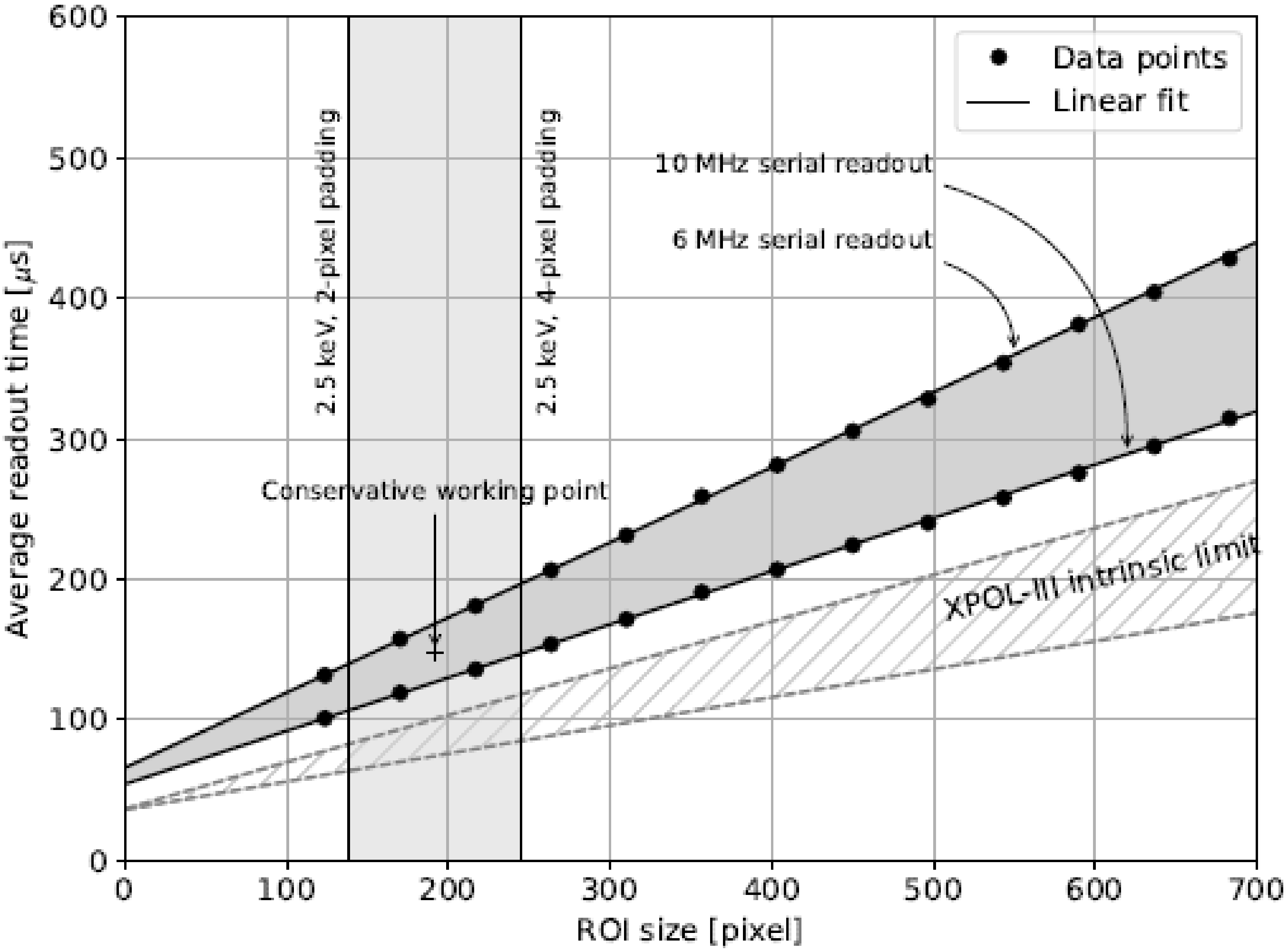


Lower trigger threshold confines track inside ROT



Flexible padding configuration minimizes readout time

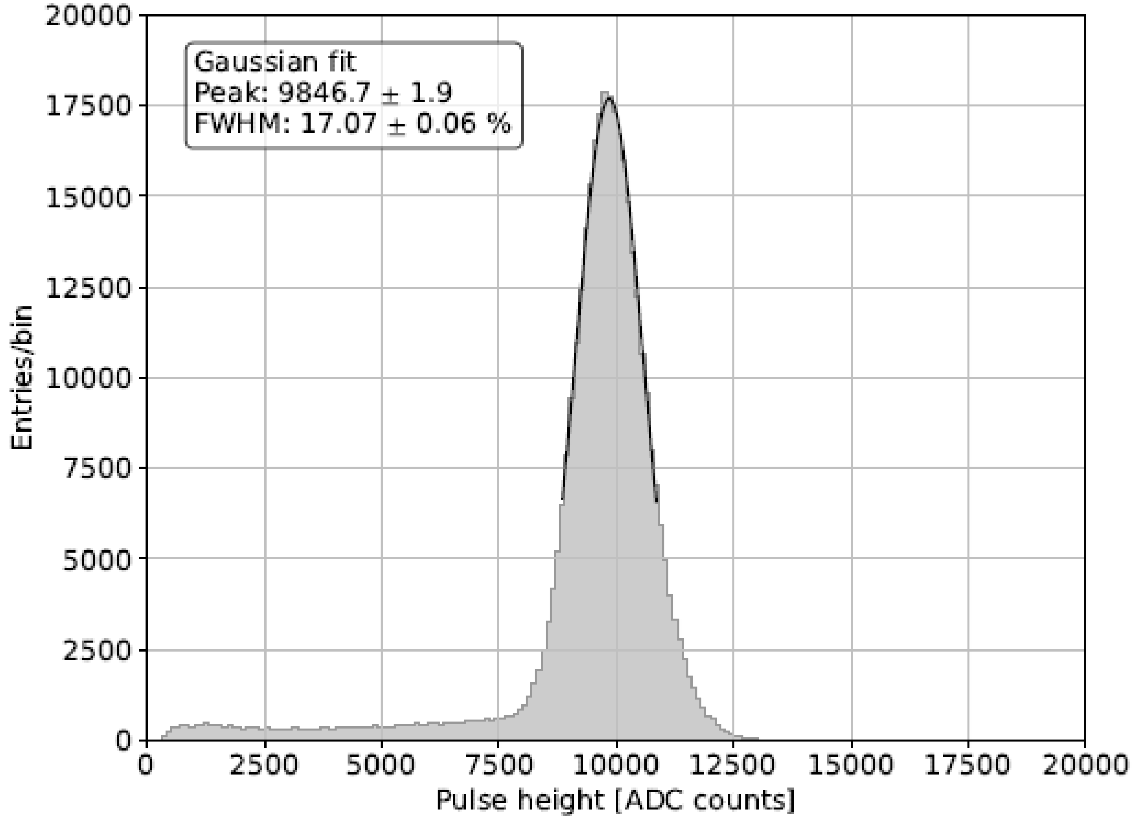
XPOL-III readout time

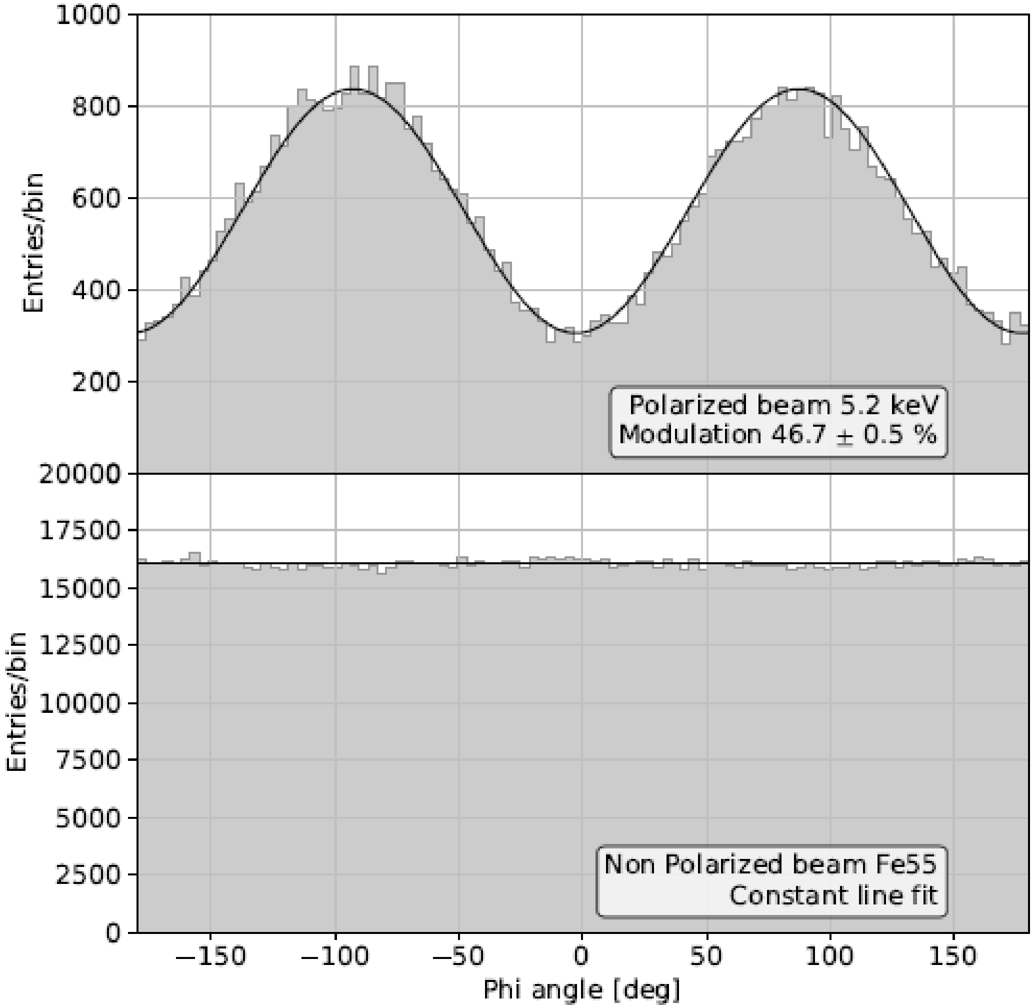


~<150μsec (vs ~1ms XPOL-I) from faster clock, smaller padding, minimized delays in the readout

2023, NIM-A, 1046

Spectral and polarization performance





Pure Be window eliminates low energy tail

Modulation factor and azimuthal asymmetry as known

~ 7 x 10^5 cm^2 silicon active area
900k digital channels
40cm x 200μm single channel dimensions
~100 Kg mass
~100 W power

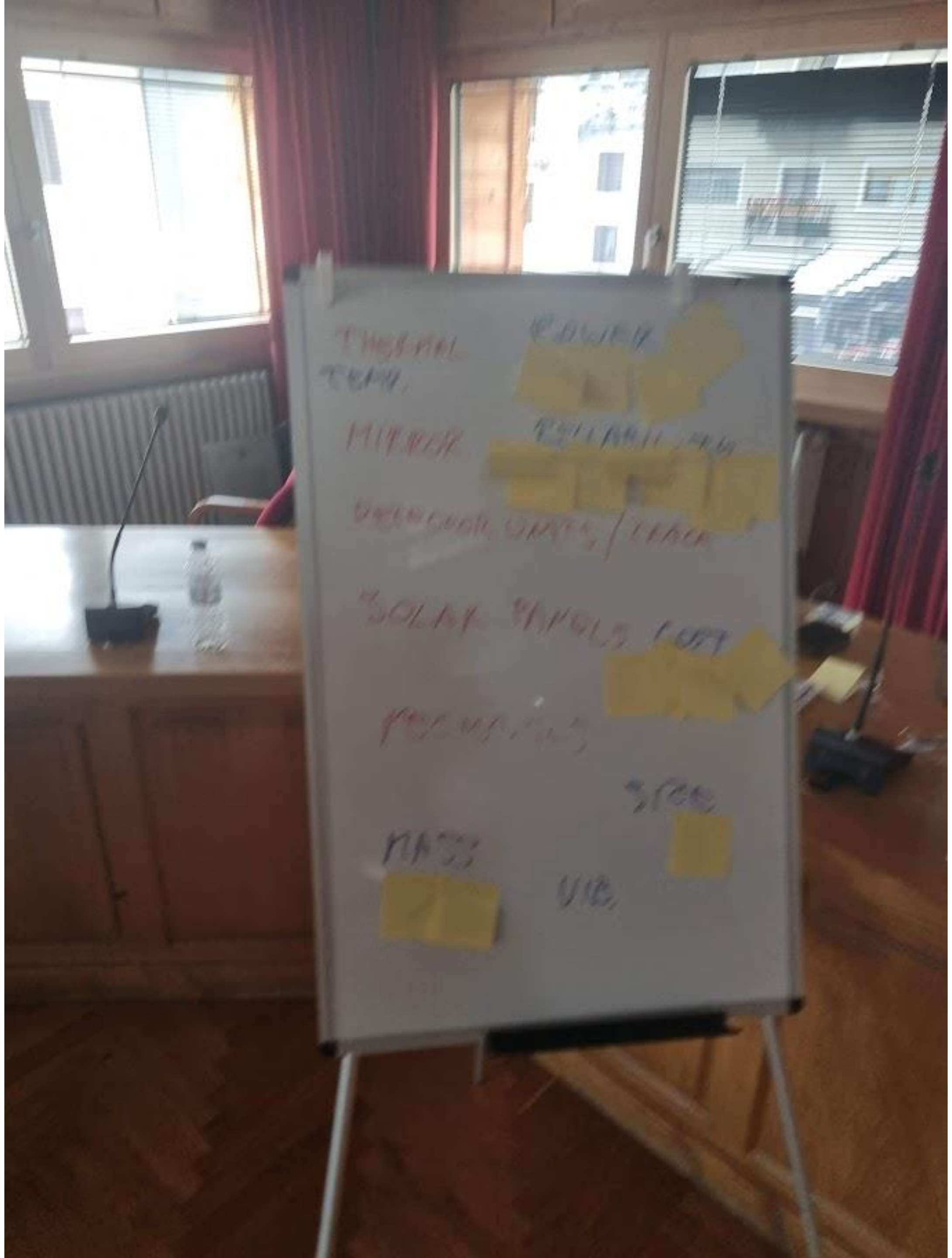
~ 7 cm^2 silicon active area
400k analog channels
50μm^2 single channel dimensions
~1Kg mass
~1W power

2 – Mission design and lifecycle

- Mission phases, requirements management and tailoring
- Notions of system engineering, product assurance and space qualifications
- Discussion of requirements and constraints for example systems

Group sprint

List most relevant constraints for a space mission


THERMAL
POWER
MIRROR
SOLAR
MASS
VIB.

The requirement flow-down

How does one go about designing an experiment?

- A space mission is all about science
- When you go and ask money you will be asked
  1. What do you want to measure (and why is that important)?
  2. How are you going to measure it (and are you sure you can do it)?
- Normal flow down of requirements is from science to the instrument
  - Several different levels, from the very top to the single sub-systems
- Requirement *flow-up* is not uncommon, too :-)
  - I happen to have this neat detector—what can I do with it?
- In practice the mission design is a complex, iterative process
- Completely different perspective with respect to operating a detector in the lab
  - Need to consider all the different aspects of the system

The Fermi Observatory

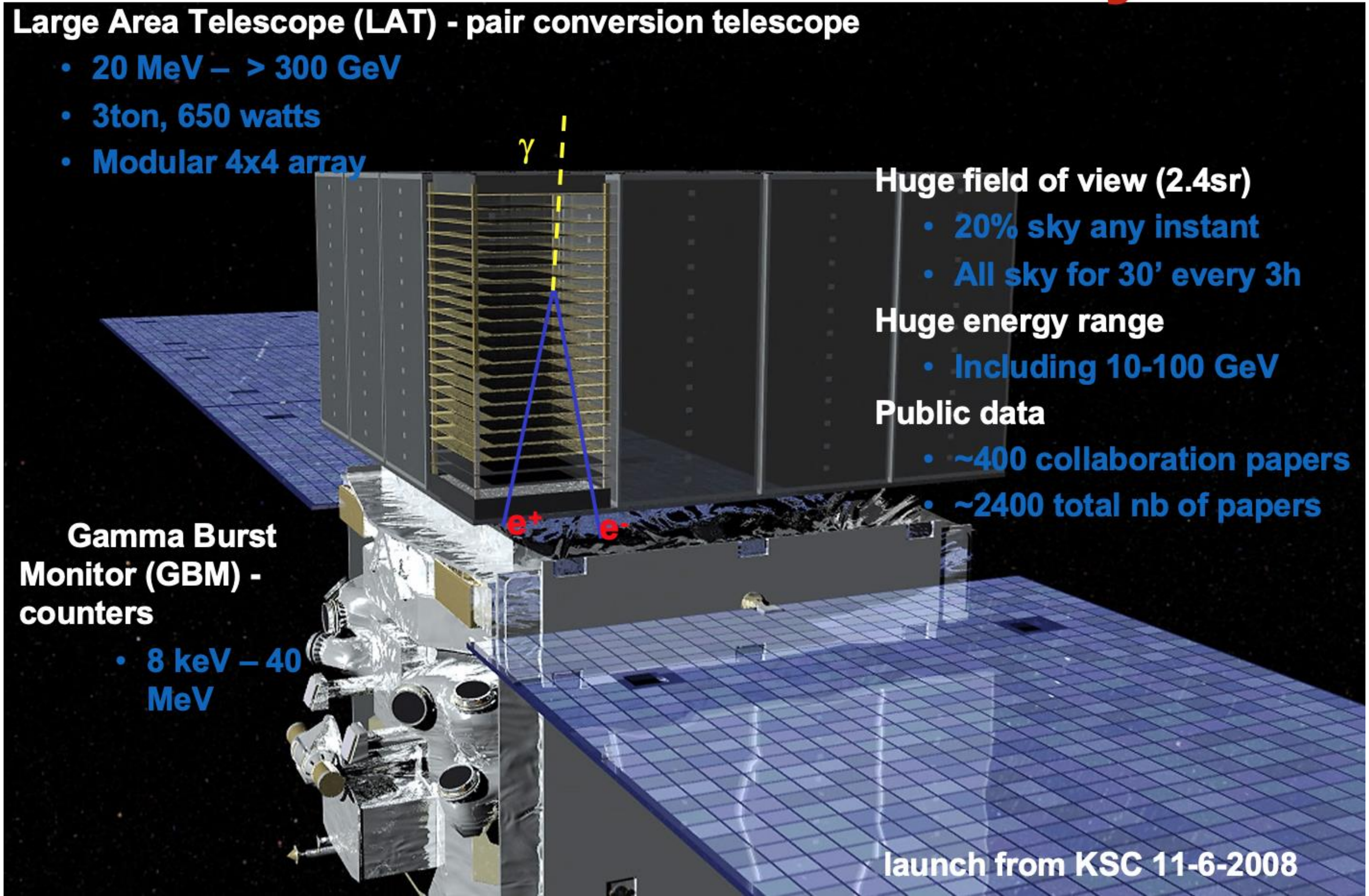
Large Area Telescope (LAT) - pair conversion telescope
- 20 MeV – > 300 GeV
- 3ton, 650 watts
- Modular 4x4 array

Huge field of view (2.4sr)
- 20% sky any instant
- All sky for 30' every 3h

Huge energy range
- Including 10-100 GeV

Public data
- ~400 collaboration papers
- ~2400 total nb of papers

Gamma Burst Monitor (GBM) - counters
- 8 keV – 40 MeV



launch from KSC 11-6-2008

LAT TKR Requirements flowdown

- **30-100x EGRET sensitivity O(10)MeV - O(100)GeV**
  - High efficiency
  - Large area
    - low cost per unit area
    - low power
- **Large field of view for transients**
  - Many thin converting layers
- **Long stable operations**
  - No consumables
  - High reliability
  - Uniform and stable response
  - Low operating voltage (~100V)

Calorimeter Concept

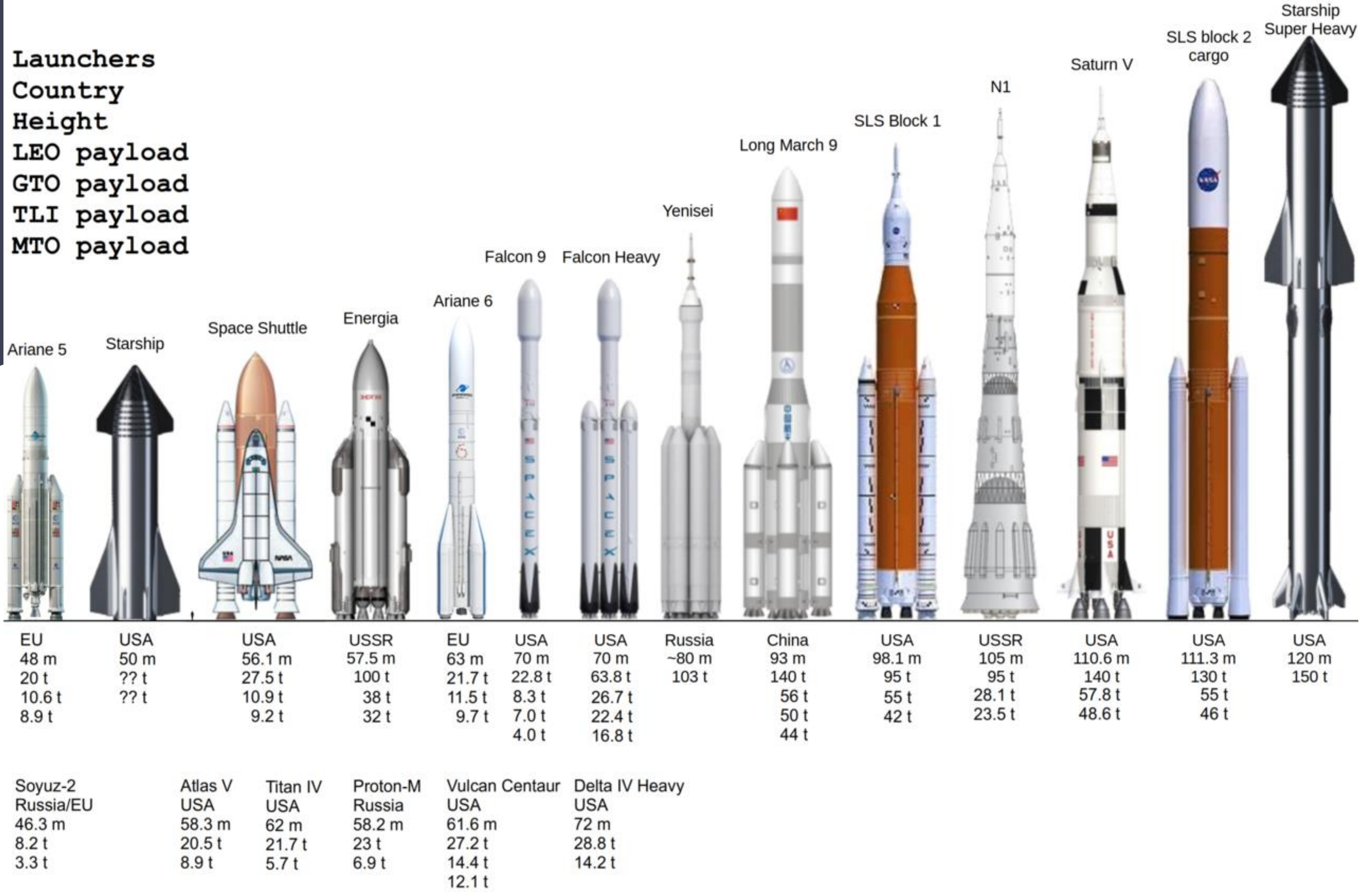
- **Calorimeter Concept, or, How we got there from here….**
- **LAT is modular**
  - So CAL is modular
- **Active CAL or Sampling CAL?**
  - Low E performance rules out sampling
  - Maintain high stopping power for EM showers within the mass budget
- **Imaging CAL**
  - Energy-profile fitting improves energy resolution
  - Background rejection
  - CAL-only events
- **Segmentation**
  - Moliere radius is 38 mm
  - Radiation length is 19 mm
  - Bkg rejection requires positioning on same order
    - Xtals have cross section with dimension on this order
    - Xtals give longitudinal positions better than this order

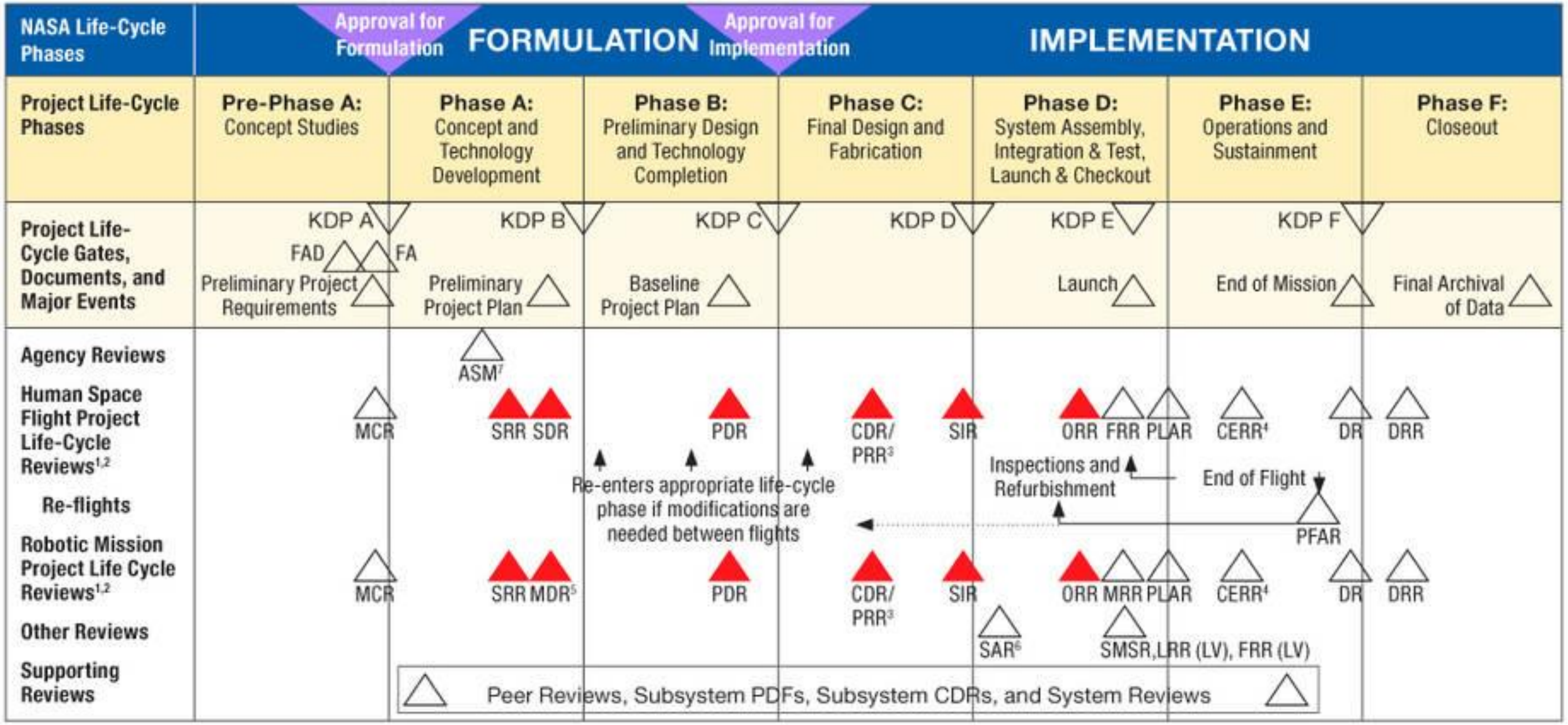
IXPE Launch

Astronomy Picture of the Day 22 Dec. 2021

Full video at https://www.youtube.com/watch?v=JGij0x0PA_Q

The other relevant system





FOOTNOTES

1. Flexibility is allowed as to the timing, number, and content of reviews as long as the equivalent information is provided at each KDP and the approach is fully documented in the Project Plan.
2. Life-cycle review objectives and expected maturity states for these reviews and the attendant KDPs are contained in Table 2-5 and Appendix D Table D-3 of this handbook
3. PRR is needed only when there are multiple copies of systems. It does not require an SRB. Timing is notional.
4. CERRs are established at the discretion of program .
5. For robotic missions, the SRR and the MDR may be combined.
6. SAR generally applies to human space flight.
7. Timing of the ASM is determined by the MDAA. It may take place at any time during Phase A.

▲ Red triangles represent life-cycle reviews that require SRBs. The Decision Authority, Administrator, MDAA, or Center Director may request the SRB to conduct other reviews.

ACRONYMS

ASM – Acquisition Strategy Meeting
CDR – Critical Design Review
CERR – Critical Events Readiness Review
DR – Decommissioning Review
DRR – Disposal Readiness Review
FA – Formulation Agreement
FAD – Formulation Authorization Document
FRR – Flight Readiness Review
KDP – Key Decision Point
LRR – Launch Readiness Review
LV – Launch Vehicle
MCR – Mission Concept Review
MDR – Mission Definition Review
MRR – Mission Readiness Review
ORR – Operational Readiness Review
PDR – Preliminary Design Review
PFAR – Post-Flight Assessment Review
PLAR – Post-Launch Assessment Review
PRR – Production Readiness Review
SAR – System Acceptance Review
SDR – System Definition Review
SIR – System Integration Review
SMSR – Safety and Mission Success Review
SRB – Standing Review Board
SRR – System Requirements Review

FIGURE 3.0-1 NASA Space Flight Project Life Cycle from NPR 7120.5E

ECSS Disciplines

ECSS-S-ST-00 System description

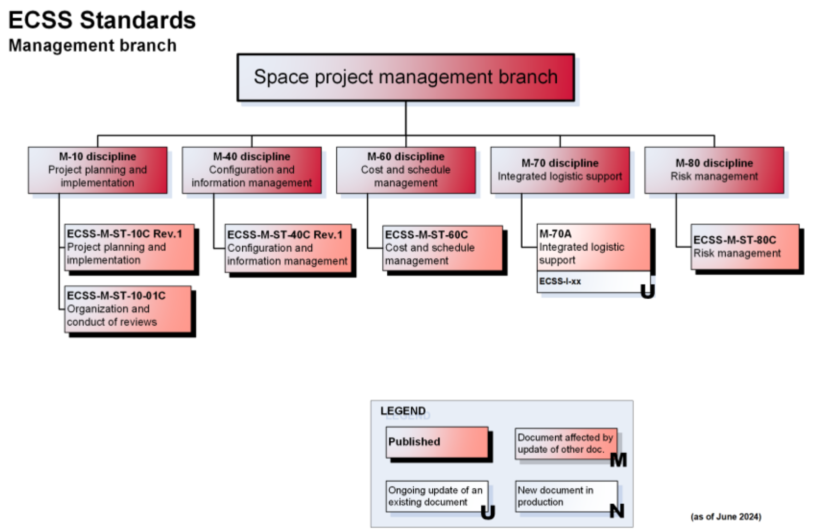
ECSS-S-ST-00-01 Glossary of terms

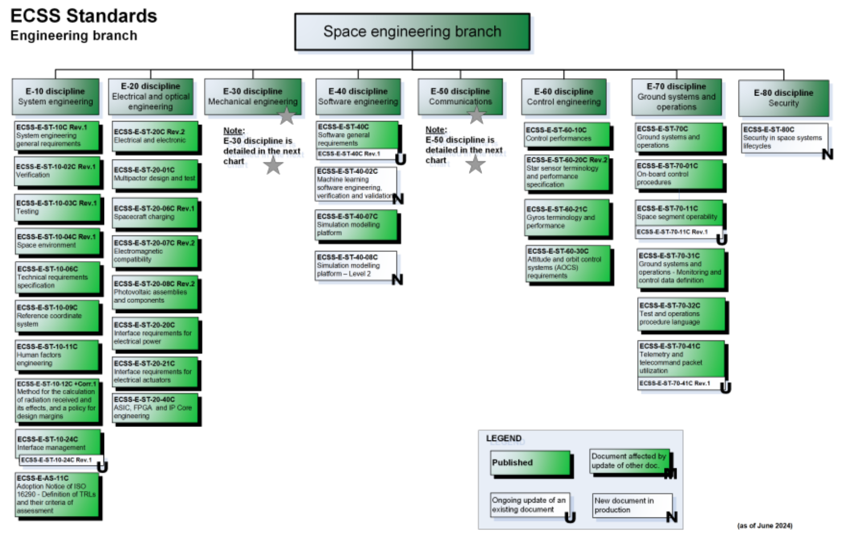
- Space project management branch
  - **M-10 discipline** Project planning and implementation
  - **M-40 discipline** Configuration and information management
  - **M-60 discipline** Cost and schedule management
  - **M-70 discipline** Integrated logistic support
  - **M-80 discipline** Risk management
- Space product assurance branch
  - **Q-10 discipline** Product assurance management
  - **Q-20 discipline** Quality assurance
  - **Q-30 discipline** Dependability
  - **Q-40 discipline** Safety
  - **Q-60 discipline** EEE components
  - **Q-70 discipline** Materials, mechanical parts and processes
  - **Q-80 discipline** Software product assurance
- Space engineering branch
  - **E-10 discipline** System engineering
  - **E-20 discipline** Electrical and optical engineering
  - **E-30 discipline** Mechanical engineering
  - **E-40 discipline** Software engineering
  - **E-50 discipline** Communications
  - **E-60 discipline** Control engineering
  - **E-70 discipline** Ground systems and operations
  - **E-80 discipline** Security
- Space sustainability branch
  - **U-10 discipline** Space debris
  - **U-20 discipline** Planetary protection
  - **U-30 discipline** Space situational awareness
- Industrialization, production and maintenance branch

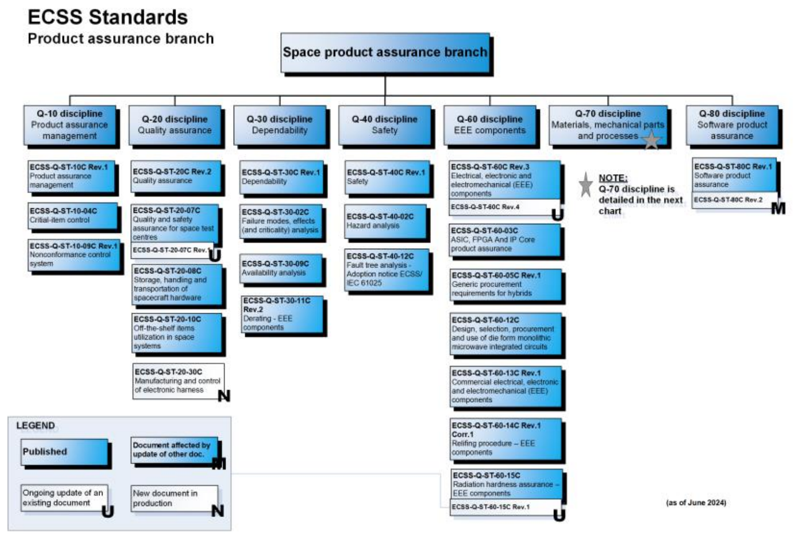
The ESA approach

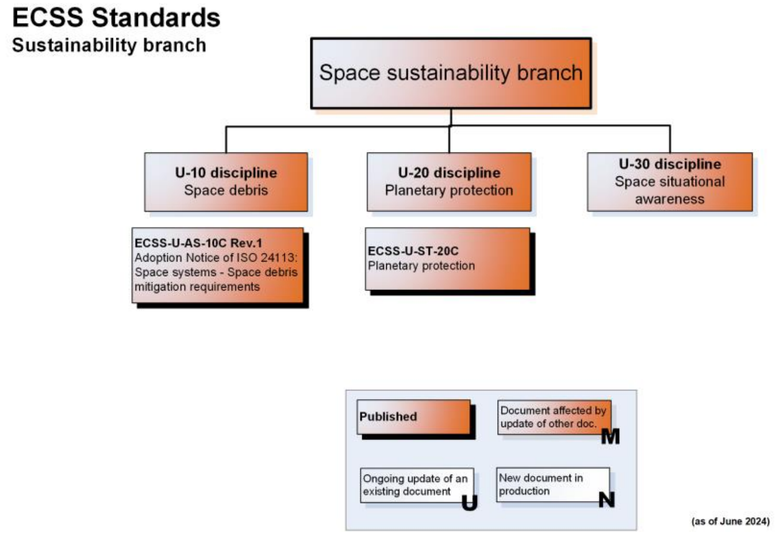
ECSS | European Cooperation for Space Standardization

(as of June 2024)









Reference standards and useful guidelines and material at https://ecss.nl/standards

The concept of tailoring

Image from *Bedtime stories for Project Managers*, Marisa Silva

IXPE - Example SMEX timeline

IXPE
Imaging
X-Ray
Polarimetry
Explorer

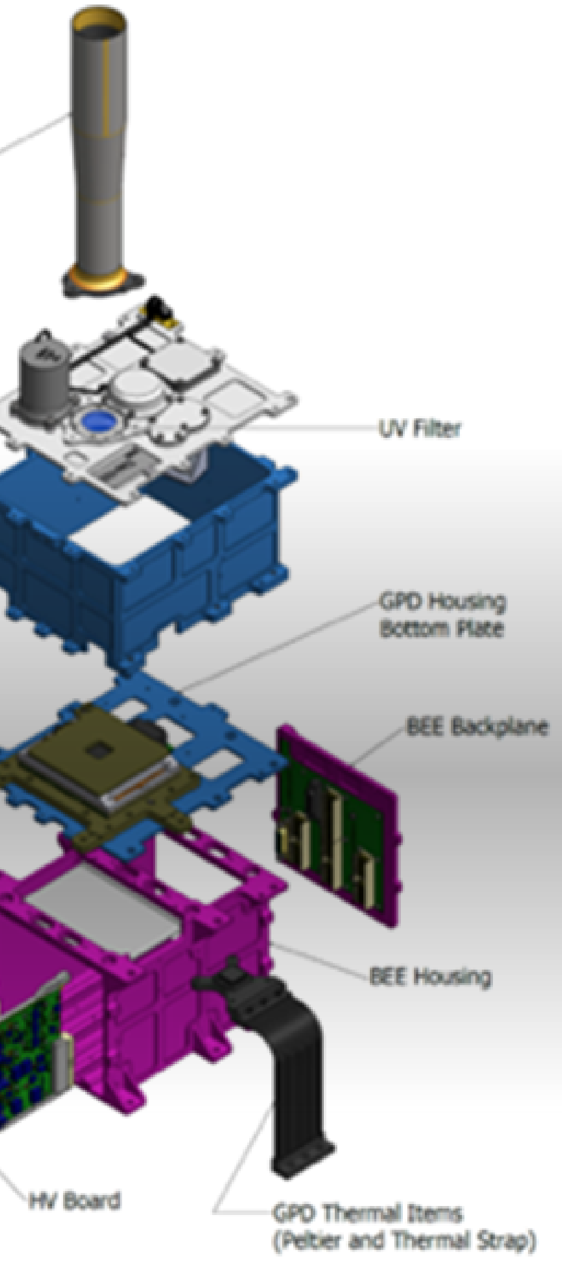
2017 PhaseB	2018 Phase C-D1	2019 Phase C-D1	2020 Phase D2

2017 – PhaseB
- Contracts KO
- Prototypes
- Requirements definition

2018 – Phase C-D1
- Design reviews
  - Preliminary
  - Critical
- Prototype completion
  - Eng. Mod.
  - Qual. Mod.

2019 – Phase C-D1
- Flight units AIVT
- Mission Critical Design Review

2020 – Phase D2
- Instrument handoff to NASA
- Telescope calibration
- Instrument integration



ID: DET-5
Parent ID: IINT-328

GPD energy resolution – The GPD shall have a Full Width Half Maximum energy resolutio
1.5 keV at 5.9 keV

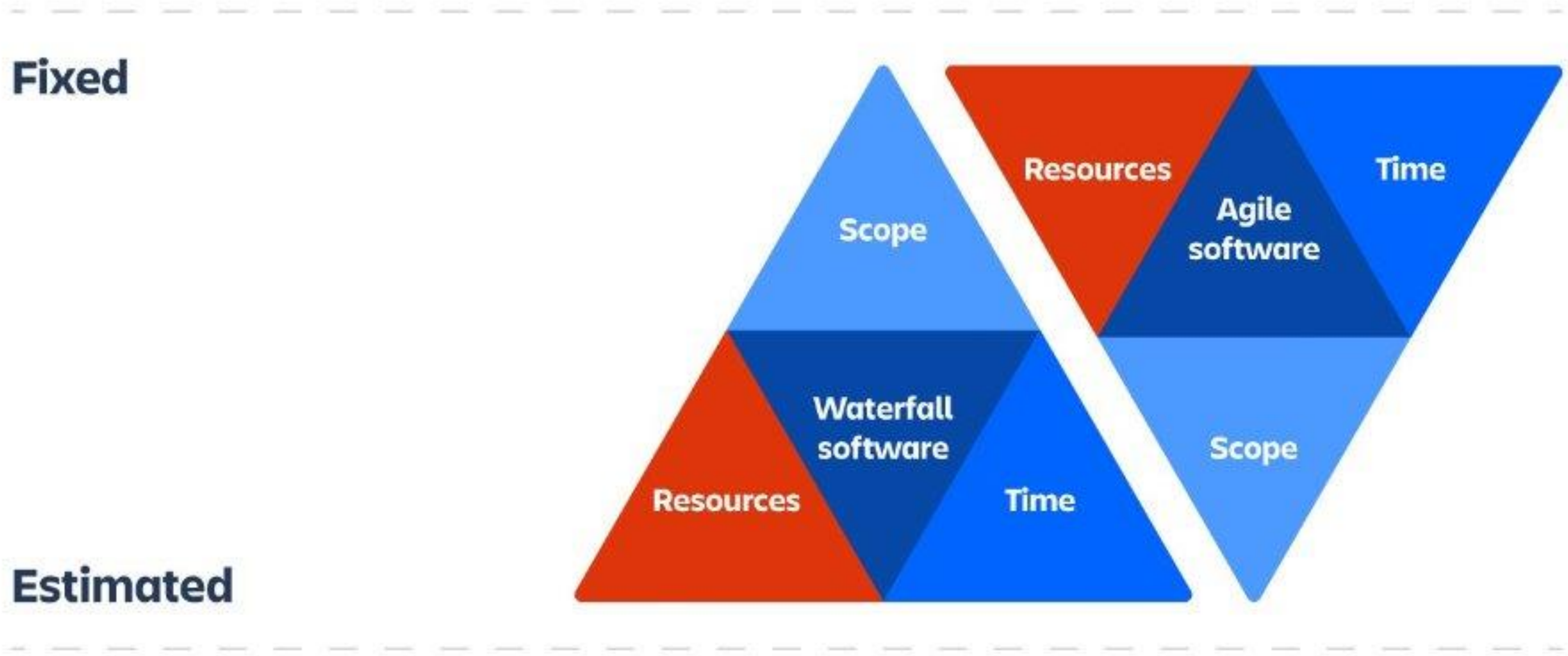
ID: DET-1
Parent ID: INT-47; from L4 Inst. req.
DU description - Each DU shall contain:
1. a Gas Pixel Detector (GPD) with thermal items, which is the polarization sensitive detector
2. a Back End electronics (BEE), which comprises the electronic boards to manage and power the GPD, including the required High Voltage lines
3. a Filter & Calibration Wheel (FCW), whose purpose is to be able to place filter and calibration sources in front of the GPD
4. a Stray-light Collimator (STC), to reduce flux of photons coming from outside the mirror field of view
5. a DU housing (DUH), which provides the mechanical and thermal interface of the DU to the S/C
6. a DU wiring (DUW), meaning the electrical interface, internal to the DU, between the BEE and the GPD

ID: DET-4
Parent ID: IINT-13
DU energy range – The DU shall operate in the 2 – 8 keV energy rar

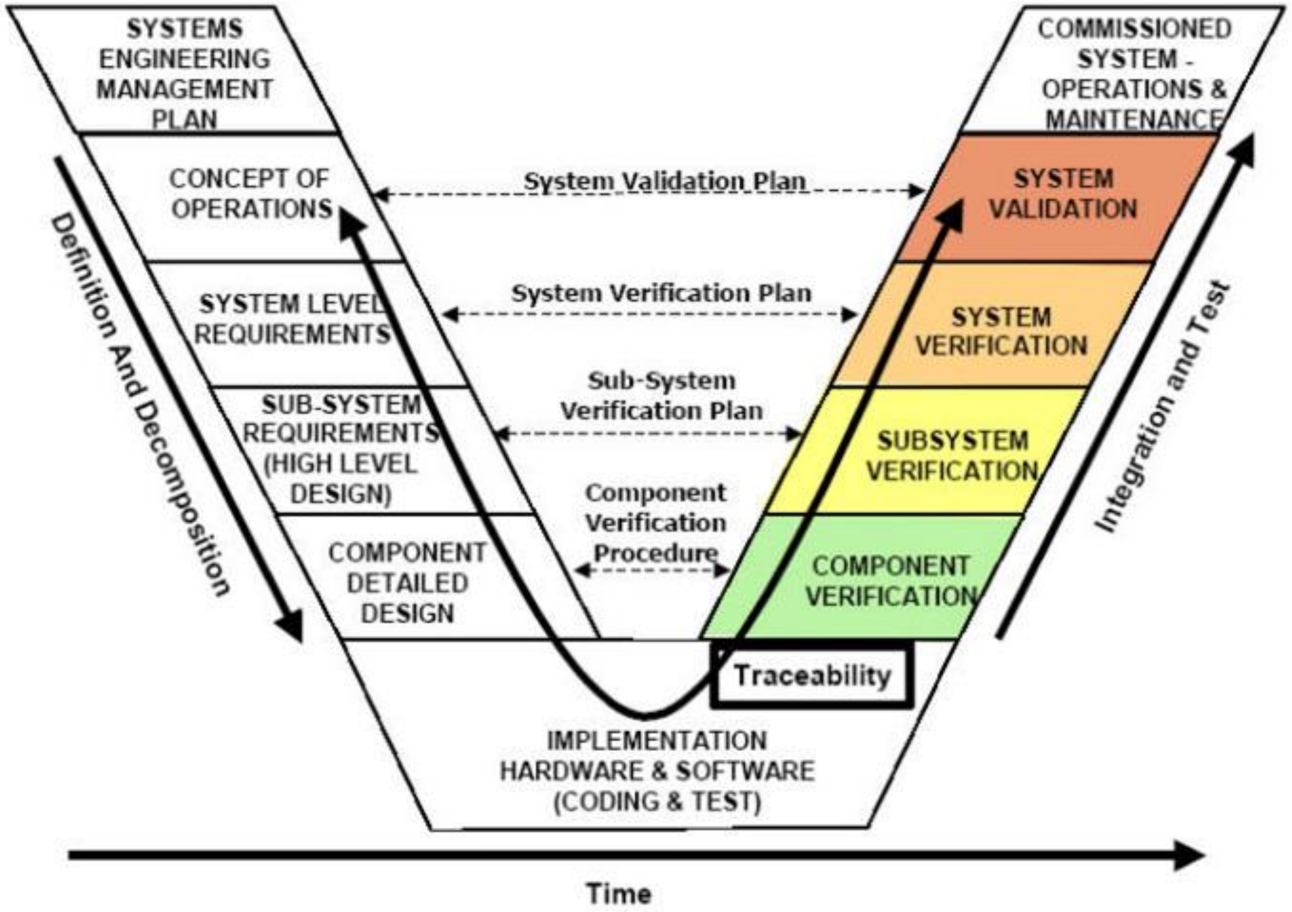
ID: DET-104
Parent ID: IINT-96
Mass allocation – DU sub-units/main items mass shall not to exceed the following values:
- Filter and Calibration Wheel: 1.780 Kg, including 0.185 Kg for the Filter and Calibration Set.
- HV Power Board (Board+connectors): 0,440 Kg
- UV Filter: 0.015 Kg
- All remaining sub-units/main items: 5.665 Kg

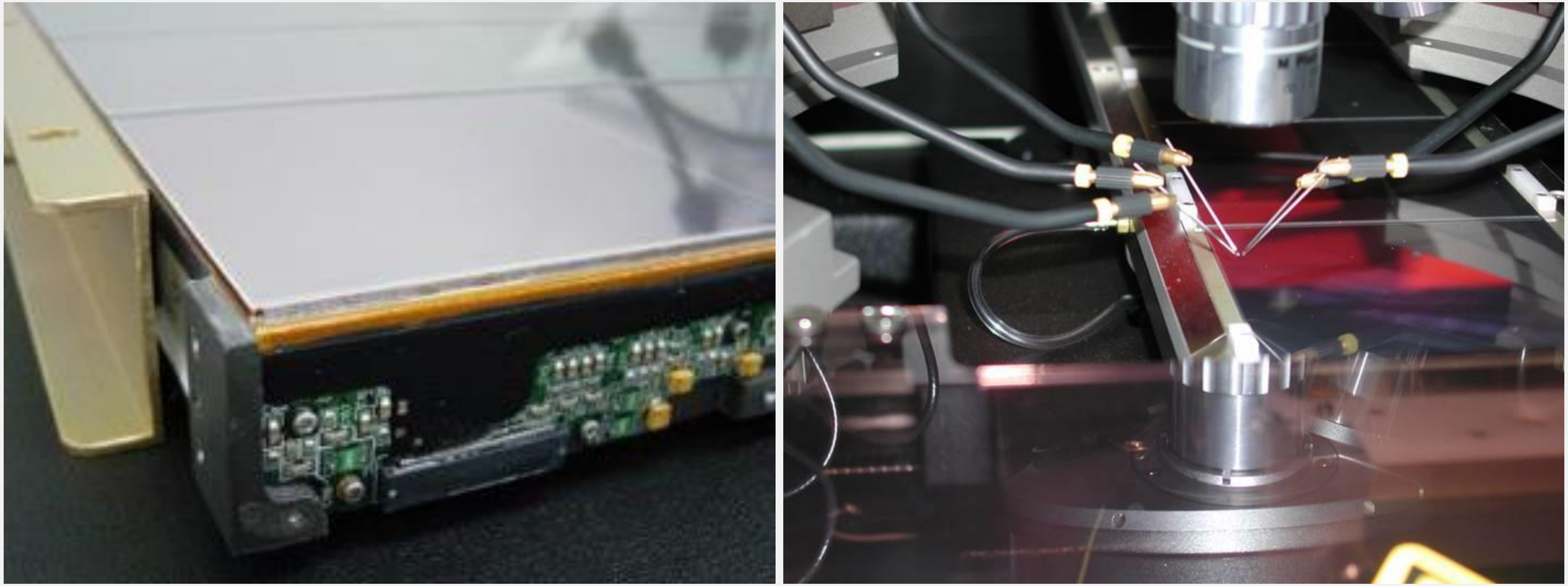
For a total allocated mass of 7.9 Kg (i.e. 23.7 Kg for the 3 DUs)

Project Management approaches
iron vs inverted triangle



V model and system engineering





Fermi LAT Tracker salient I&T moments

which requirement are they addressing ?

which constraints are we competing with ?

2007, Astropart. Phys., 28, 422

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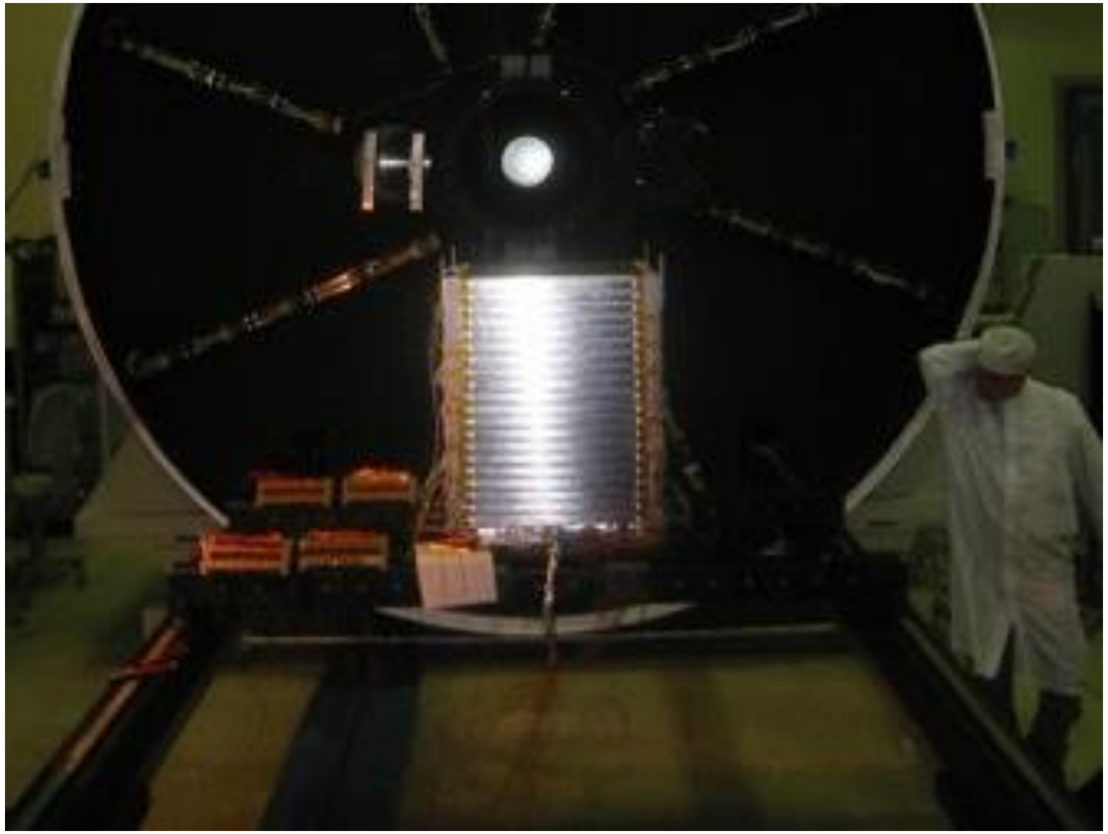
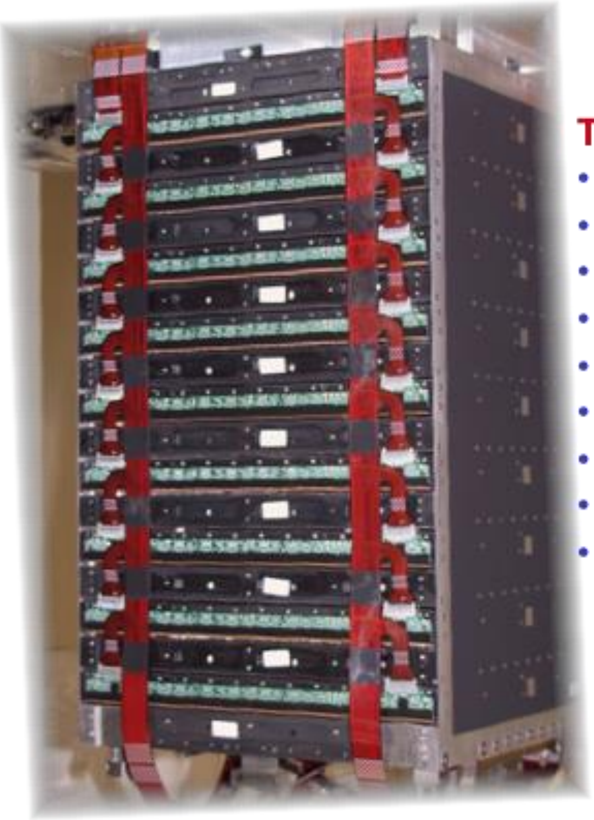
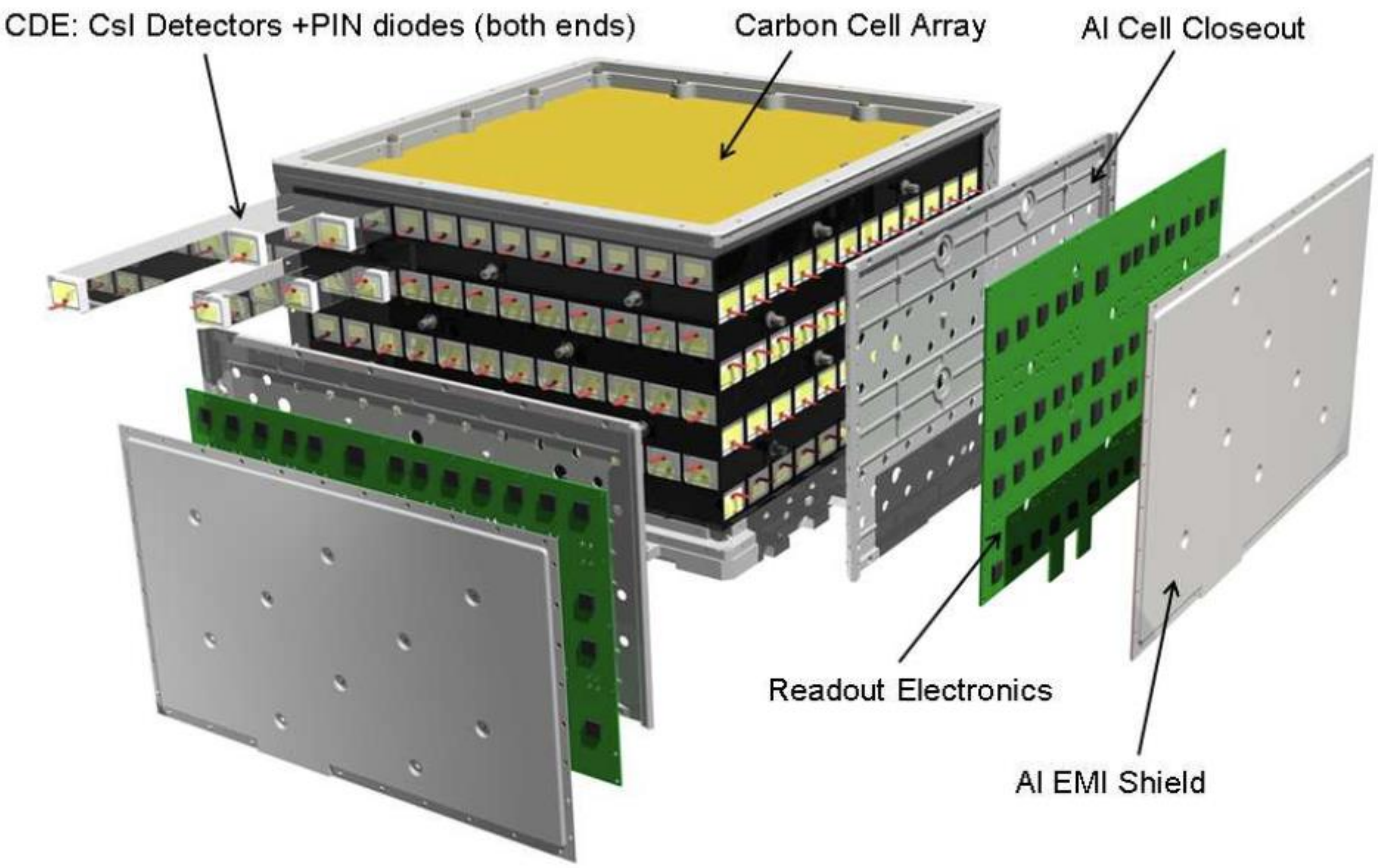




Tracker/Converter (TKR):
- Si-strip detectors
- ~80 m^2 of silicon (total)
- W conversion foils
- **1.5 X0 on-axis**
- 18XY planes
- **~10^6 digital elx chans**
- Highly granular
- High precision tracking
- Average plane PHA

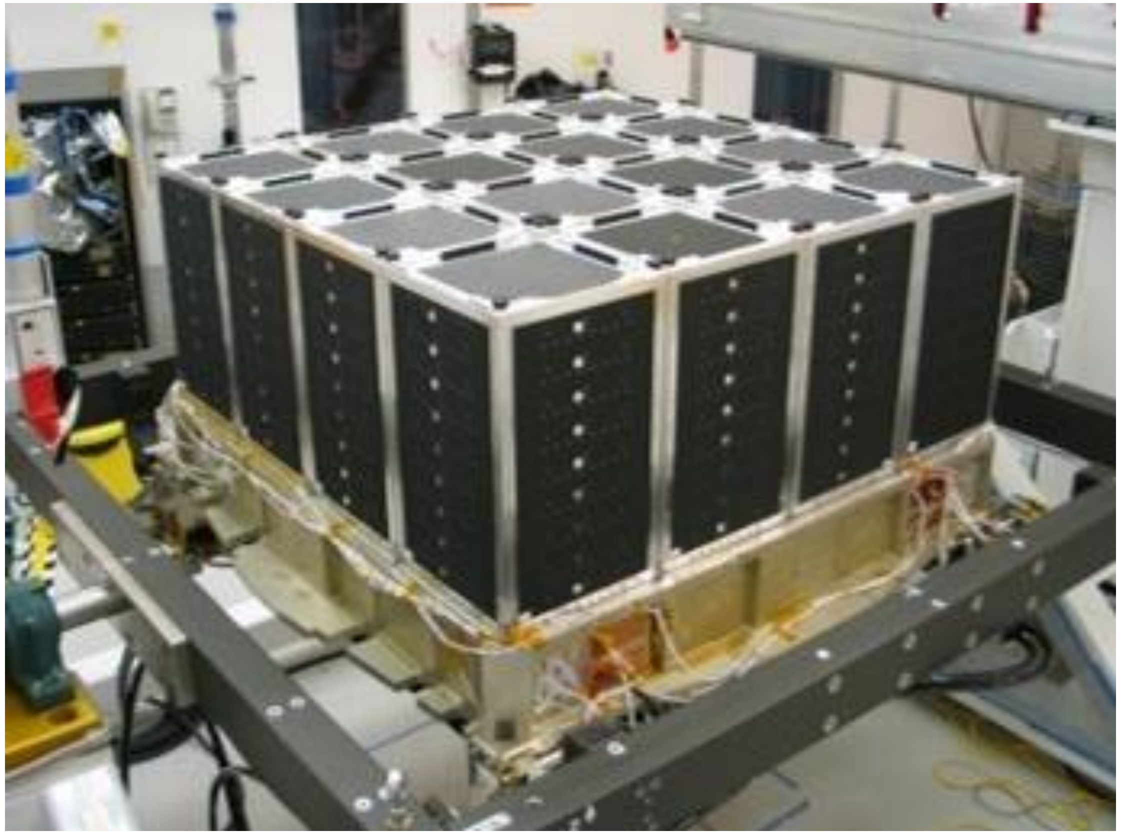
2007, Astropart. Phys., 28, 422

Fermi LAT Calorimeter salient I&T moments
which requirement are they addressing ?
which constraints are we competing with ?



2009, ApJ, 697, 1071

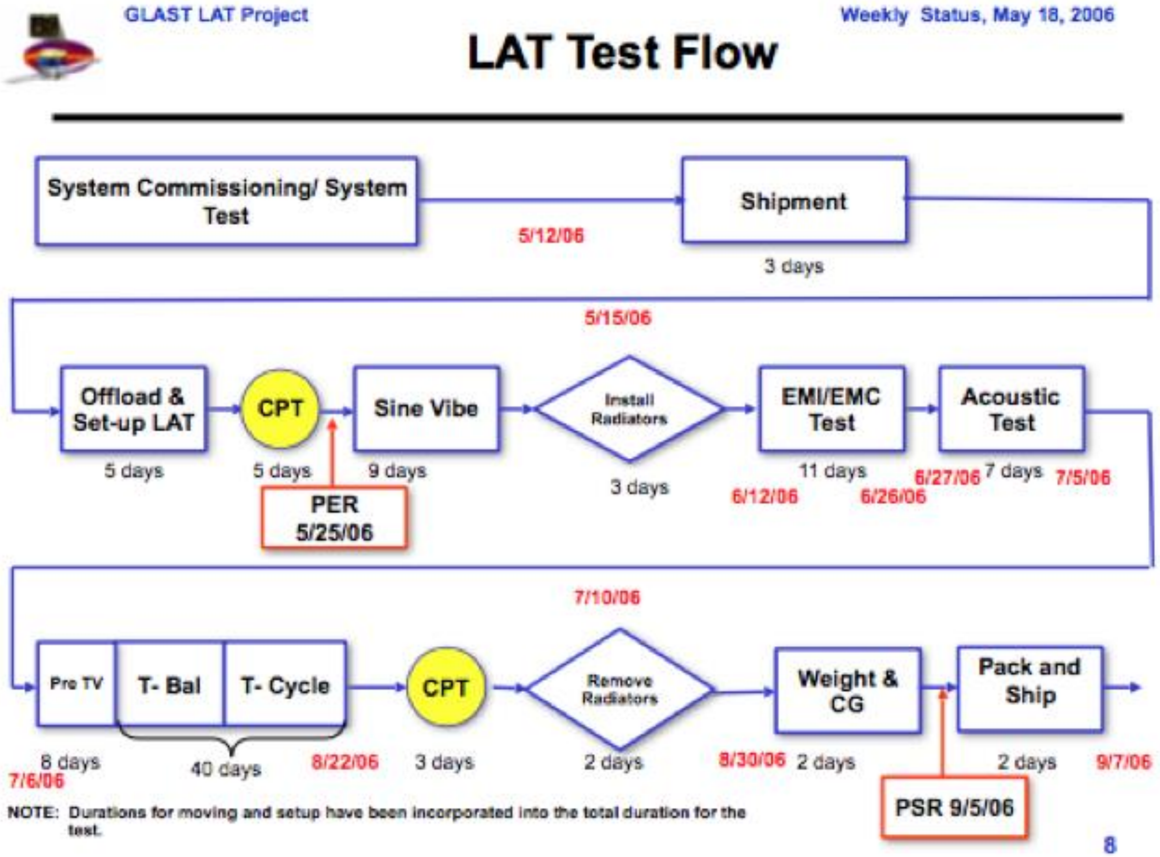
Fermi LAT telescope salient I&T moments
which requirement are they addressing ?
which constraints are we competing with ?

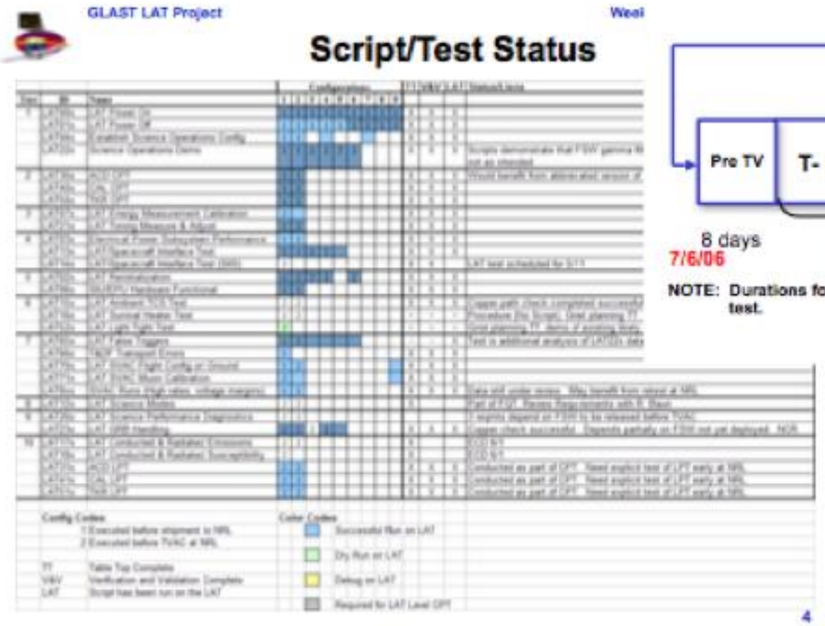


2009, ApJ, 697, 1071

Commissioning

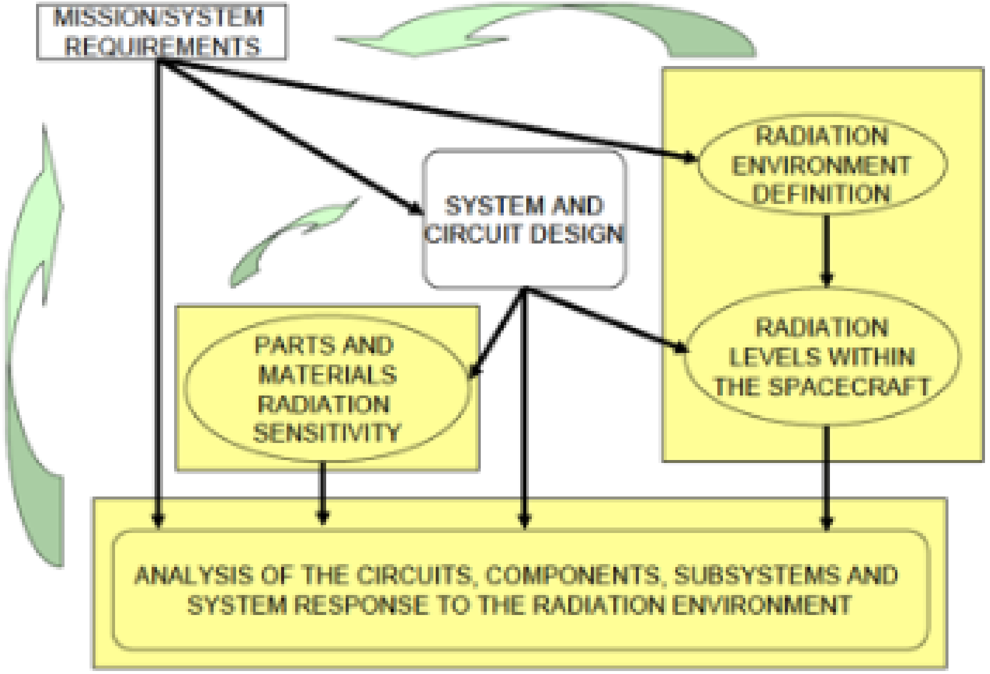
- Test, calibrate, verify every requirement
- Shake it. Scream at it. Bake it. Freeze it.
- Send every command





Radiation effects countermeasures

- Shielding (expensive)
  - requires tradeoff with system requirement
  - Not applicable to SEE (ions are penetrating)
- Specific Rad-Hard design
  - Single components, eg Silicon On Insulator
  - Circuit design, eg redundancy
- Radiation Hardness Assurance (RHA)
  - Iterative design and test methodology



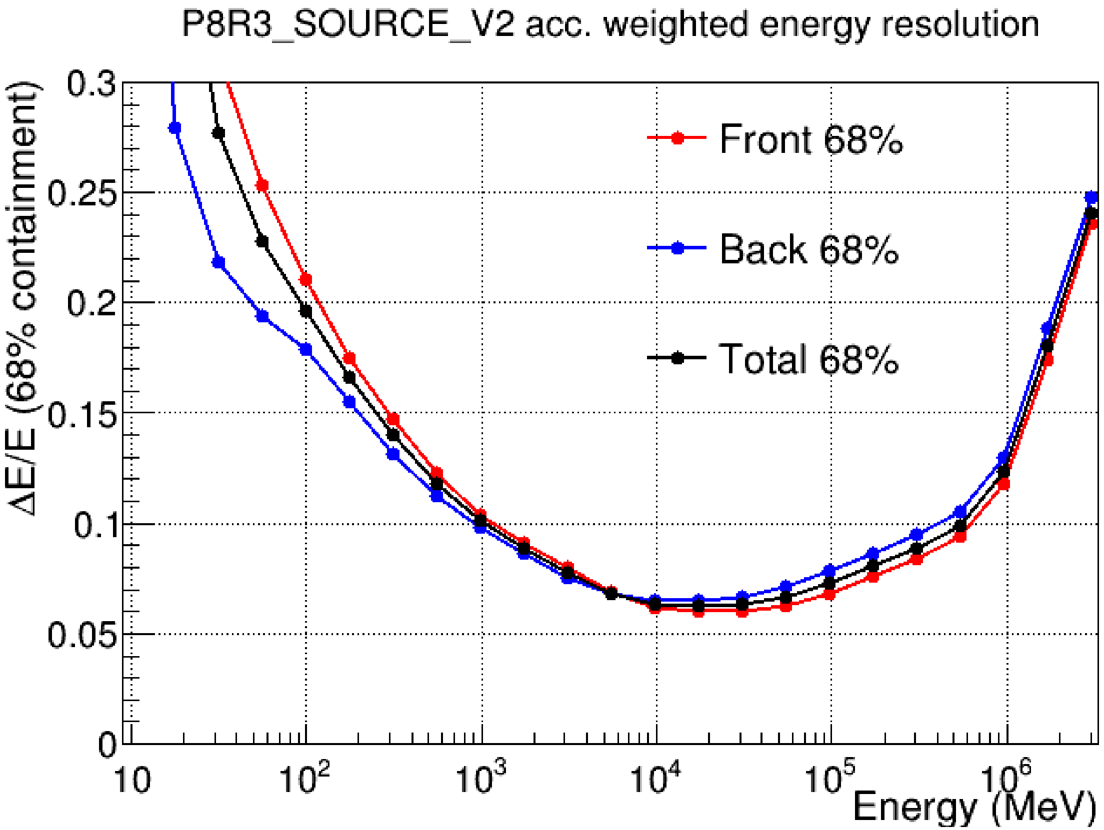
→ ground irradiation tests in representative environments are needed

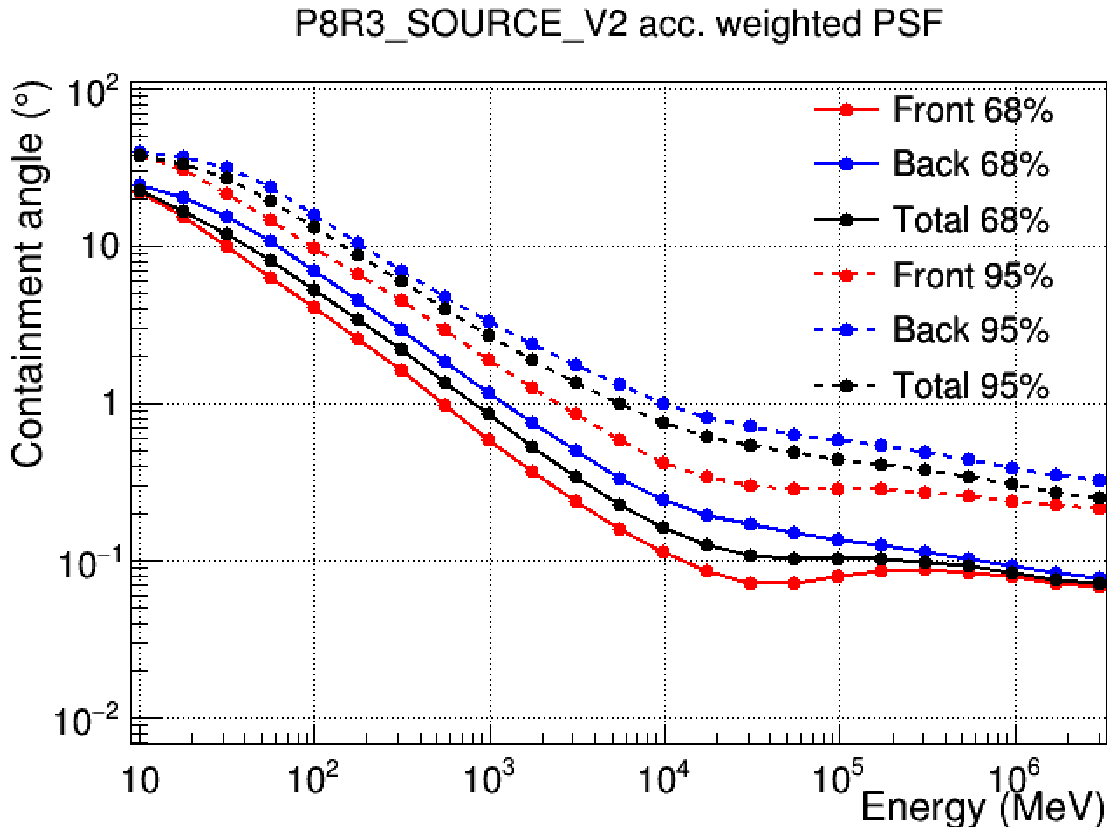
ECSS-Q-ST-60-15C

Radiation effects on electronic components

	TID ***Total Ionizing Dose***	**TNID / NIEL / DD** ***Total Non-Ionizing Dose*** ***Non-Ionizing Energy Loss*** ***Displacement Damage***	**SEE** ***Single Event Effect***
Effect	Cumulative long-term degradation	Cumulative long-term non-ionizing damage	Bit flips from single energetic particles From harmless (eg SE-Upset) to severe (eg SE-Latchup or SE-GateRupture)
Caused by	Proton, electron	p, e, n, ions	p, ions
Unit	dose (Krad/gray)	fluence (part/cm2)	Linear Energy Transfer (LET, MeV*cm2/mg

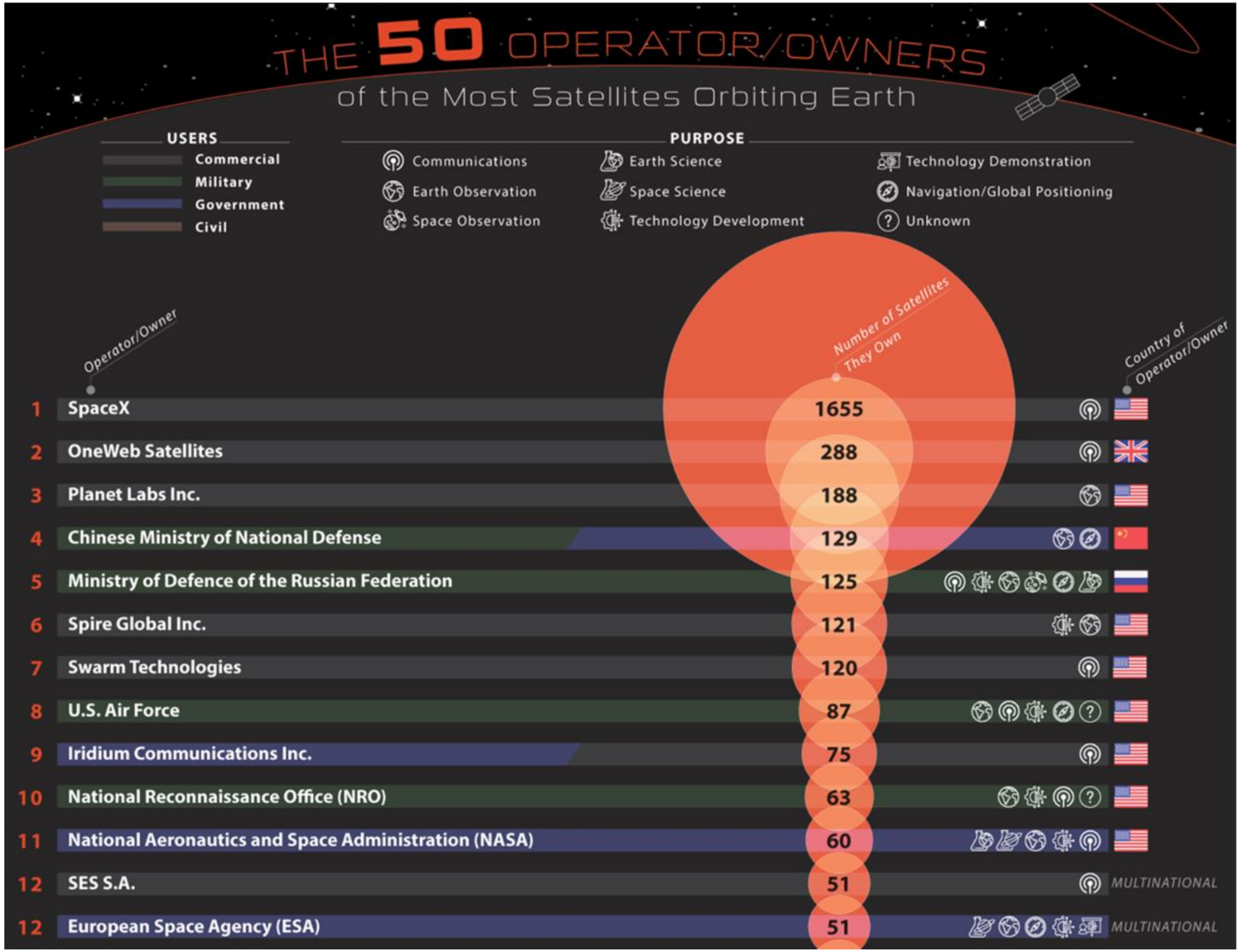
Fermi LAT performance metrics





3 – Upcoming trends

- New scenarios
- Emerging scientific needs
- Technology gaps and solutions
- Changing space protocols


THE 50 OPERATOR/OWNERS
of the Most Satellites Orbiting Earth
USERS
Commercial
Military
Government
Civil
PURPOSE
Communications
Earth Observation
Space Observation
Earth Science
Space Science
Technology Development
Technology Demonstration
Navigation/Global Positioning
Unknown
Operator/Owner
Number of Satellites They Own
Country of Operator/Owner
1 SpaceX 1655
2 OneWeb Satellites 288
3 Planet Labs Inc. 188
4 Chinese Ministry of National Defense 129
5 Ministry of Defence of the Russian Federation 125
6 Spire Global Inc. 121
7 Swarm Technologies 120
8 U.S. Air Force 87
9 Iridium Communications Inc. 75
10 National Reconnaissance Office (NRO) 63
11 National Aeronautics and Space Administration (NASA) 60
12 SES S.A. 51 MULTINATIONAL
12 European Space Agency (ESA) 51 MULTINATIONAL

What is the Space Economy? [Oct/2019]

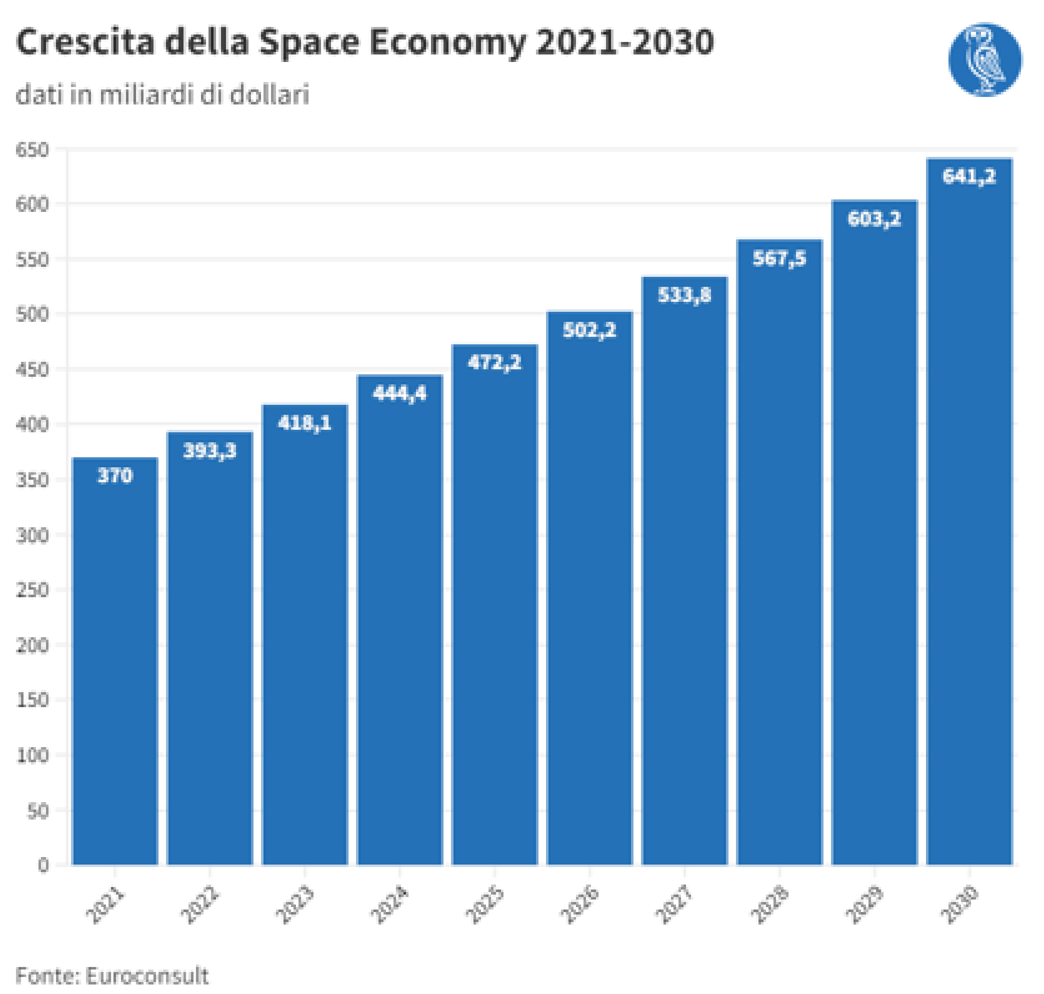
The Space Economy is defined by OECD as the full range of activities and the use of resources that create value and benefits to human beings in the course of exploring, researching, understanding, managing, and utilising space.[1]

The Space Economy is growing and evolving, together with the development and profound transformation of the space sector and the further integration of space into society and economy. Today, the deployed space infrastructure makes the development of new services possible, which in turn enables new applications, in sectors such as meteorology, energy, telecommunications, insurance, transport, maritime, aviation and urban development leading to additional economic and societal benefits. The space sector is not only a growth sector itself, but is the vital enabler of growth in other sectors.

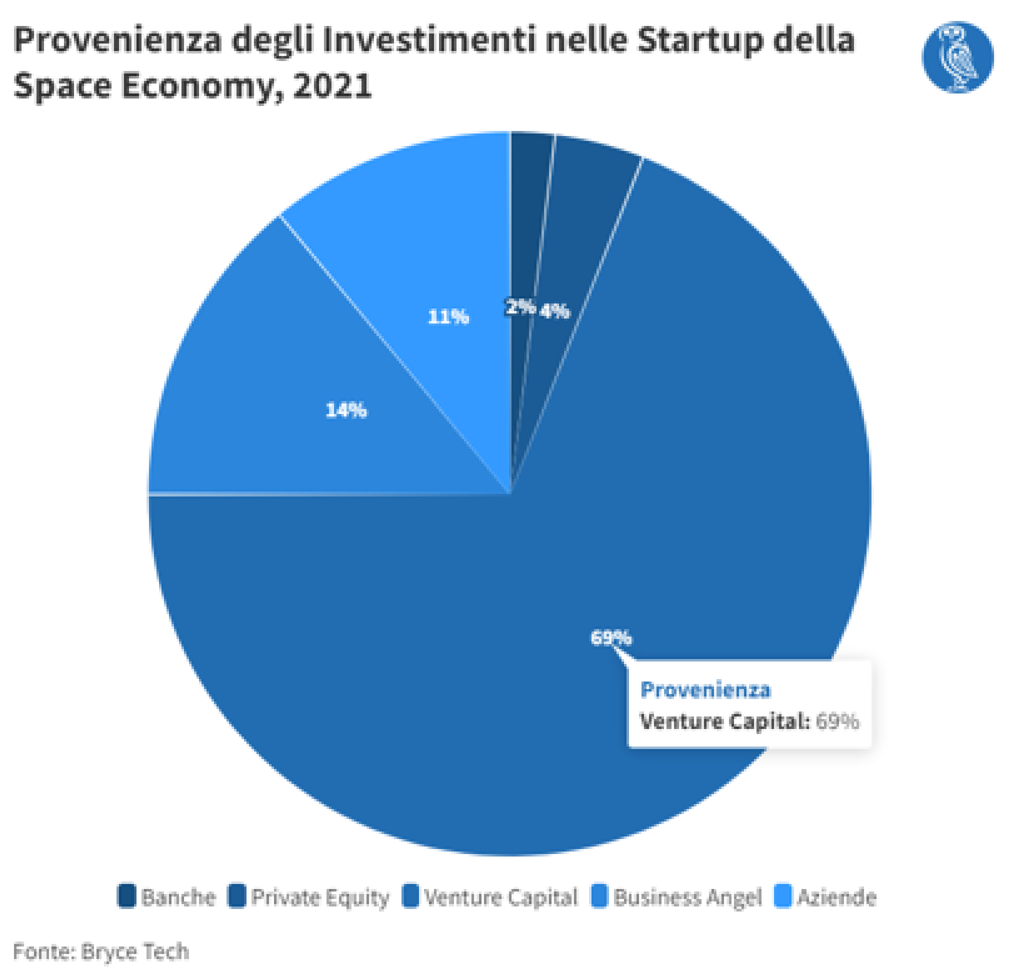
This dynamics led some analysts to declare that the space industry could become the next trillion-dollar industry by 2040. The main current trends which are impacting the Space Economy include:

- A still increasing public interest and investment in space activities worldwide;
- An unprecedented level of private investment in space ventures, linked to a higher attractiveness and expected profitability and a growing Venture Capital (VC) market;
- An ever increasing number of actors;
- Still growing space industry revenues;
- The further development of commercial activities worldwide, including ones based on smallsats/cubesats, and the development of commercial activities in new fields, e.g. micro-launchers and space flight;
- A traditional space industry, still generating the main share of revenues, but facing more competitive and uncertain markets;
- The further development of the New Space worldwide; and
- The further integration of space into the society and economy leading to more value creation and more socio-economic benefits.

NSE figures - globally



Towards 1T$ in the 30s

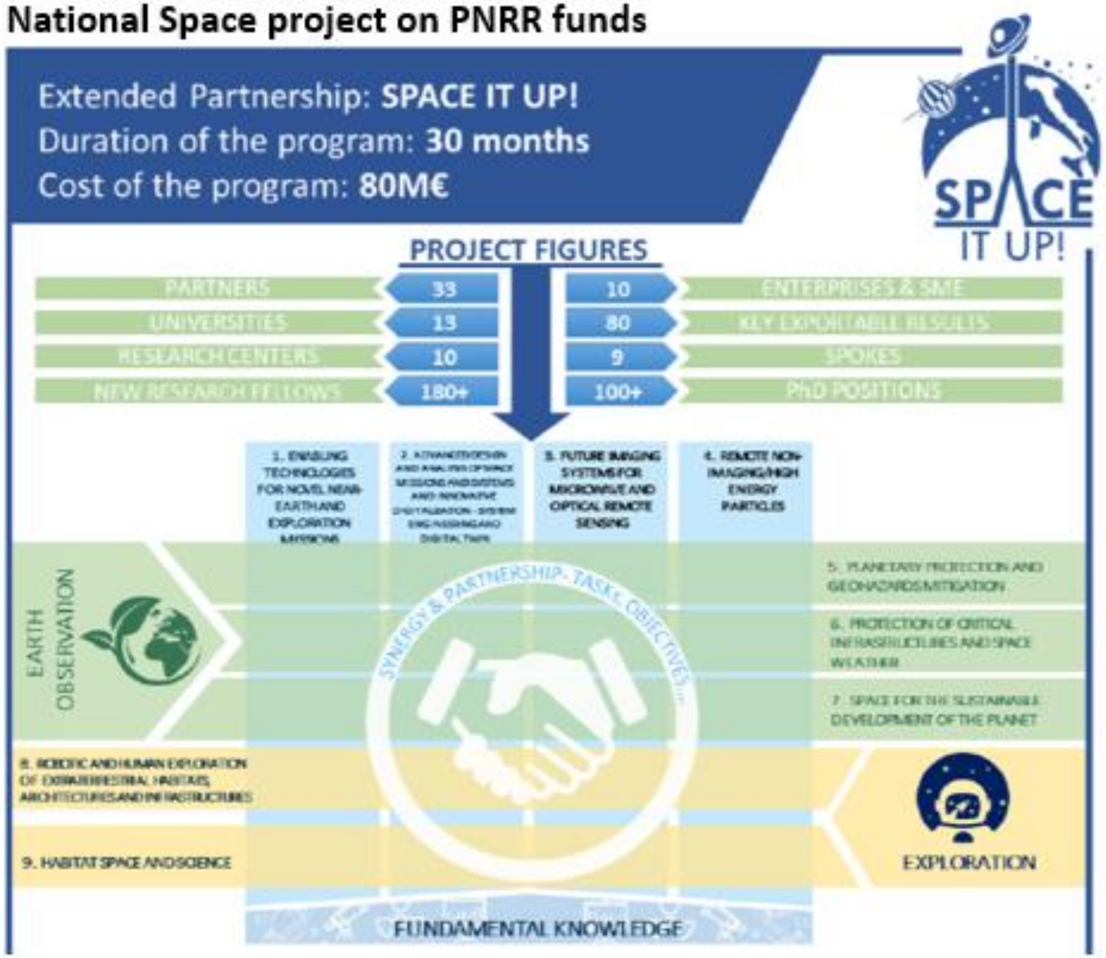


130+ agencies, 150+ research centres, 10k+ companies

NSE figures – in Italy

Reflects trends in *upstream – midstream – downstream*

National Space project on PNRR funds



Built on established knowledge and education system

Current Technology Gap Priorities

Following a multi-month prioritization process involving managers, technologists, scientists, and subject-matter experts from NASA's Astrophysics Division (APD) and the Program Offices, as well as independent reviewers, the following is the Astrophysics Technology Gap Priority List. This list will inform APD technology development planning as well as decisions on what technologies to solicit and will be considered when making funding decisions. Tiers are in descending priority order. All gaps within any given tier are to be considered equally prioritized (which is why the gaps are arranged alphabetically within each tier). Tier 5 is reserved for gaps deemed not to enable or enhance any strategic Astrophysics mission, and as such will not automatically be included in the next prioritization cycle.

Tier 1 Technology Gaps

- Advanced Cryocoolers
- Coronagraph Contrast and Efficiency
- Coronagraph Stability
- Cryogenic Readouts for Large-Format Far-IR Detectors
- Heterodyne Far-IR Detector Systems
- High-Performance, Sub-Kelvin Coolers
- High-Reflectivity Broadband Far-UV-to-Near-IR Mirror Coatings
- High-Resolution, Large-Area, Lightweight X-ray Optics
- High-Throughput Bandpass Selection for UV/VIS
- High-Throughput, Large-Format Object Selection Technologies for Multi-Object and Integral Field Spectroscopy
- Large Cryogenic Optics for the Mid IR to Far IR
- Large-Format, High-Resolution Focal Plane Arrays
- Large-Format, Low-Darkrate, High-Efficiency, Photon-Counting, Solar-blind, Far- and Near-UV Detectors
- Large-Format, Low-Noise and Ultralow-Noise Far-IR Direct Detectors
- Long-Wavelength-Blocking Filters for X-ray Micro-Calorimeters
- Low-Stress, High-Stability, X-ray Reflective Coatings
- Mirror Technologies for High Angular Resolution (UV/Vis/Near IR)
- Stellar Reflex Motion Sensitivity – Astrometry
- Stellar Reflex Motion Sensitivity – Extreme Precision Radial Velocity
- Vis/Near-IR Detection Sensitivity

Tier 2 Technology Gaps

- Broadband X-ray Detectors
- Compact, Integrated Spectrometers for 100 to 1000 μm
- Far-IR Imaging Interferometer for High-Resolution Spectroscopy
- Far-IR Spatio-Spectral Interferometry
- Fast, Low-Noise, Megapixel X-ray Imaging Arrays with Moderate Spectral Resolution
- High-Efficiency X-ray Grating Arrays for High-Resolution Spectroscopy
- High-Resolution, Direct-Detection Spectrometers for Far-IR Wavelengths
- Improving the Calibration of Far-IR Heterodyne Measurements
- Large-Aperture Deployable Antennas for Far-IR/THz/sub-mm Astronomy for Frequencies over 100 GHz
- Large-Format, High-Spectral-Resolution, Small-Pixel X-ray Focal-Plane Arrays
- Polarization-Preserving Millimeter-Wave Optical Elements
- Precision Timing for Space-Based Astrophysics
- Rapid Readout Electronics for X-ray Detectors
- Starshade Deployment and Shape Stability
- Starshade Starlight Suppression and Model Validation
- UV Detection Sensitivity

Final remarks

- Detectors are not automatically systems
  - *Define functions and interfaces*
  - *Breakout can be that of self-contained working units*
    - *Cognizant engineer or single procurement*
- A space mission brings a detection system onboard a complex technology platform
  - *Launch, navigation, onboard processing, communications*
  - *Well established protocols apply*
- New business opportunities in space are changing the reference for space exploration
  - *Fundamental physics missions should explore this new scenario*