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High Energy Astrophysics in Italy

Problems and Perspectives

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Abstract. High Energy Astrophysics lives an epoch of fast evolution on he basis of new data arriving from X-ray and Gamma-ray space missions and from ground based experiments of Gamma-ray astronomy and Cosmic-ray Physics. I discuss some of the new visions and survey the status of experimental activities and of proposed experiments in Italy, trying to identify those of larger strategic impact.

1. Introduction

High Energy Astrophysics lives an epoch of fast evolution, feeded by a large amount of data from the large X-ray and Gamma-Ray Missions, complemented, more recently by results from INTEGRAL, and TeV telescopes, and by the first results of SWIFT. New data have modified many visions on physical processes occurring in the proximity of compact objects, on the mechanisms of acceleration of particles constituent Cosmic Rays and on large scale processes determining the structure of Galaxy Clusters. New and incoming experiments of Cosmic Rays will face problems of fundamental Physics. The Italian Community is actively engaged in this field at the level of experiment design and execution and of data analysis and interpretation. The backbone of this activity is a continuous and substantial Research and Development on experimental techniques. I make a short review of these activities and of the possible future developments.

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2. A large and active community

HEA in Italy has a long tradition. The first measurements of Cosmic Rays were tightly connected with researches on elementary Particles. This line of research has been continuously pursued with the development of important experiments ground and underground based, for Air Showers and Neutrinos (Mont Blanc, Gran Sasso in gallery and on the top of the mountain, Chacaltaya, etc). The first steps in space were performed with balloon experiments for CRs, followed by balloon and rocket experiments on X and Gamma Rays. The participation to satellite missions (OSO-6, COS-B, EXOSAT) increased in parallel, culminating with the Beppo-SAX Mission (1996 - 2002), so far the largest and most successful effort of Italian Space Science.
Behind this activity there is a large and productive community. A snapshot of 2002 gives a total of 163 researchers based on INAF/CNR (289 including post-doc) and 161 based on INFN (220 including post-doc) plus 39 in Universities. In years 2000 - 2002, 1180 pa-

pers were published on refereed journals of Astrophysics, more than 176 on instrumentation and 41 PHD thesis were completed in the context of HEA researches. Other indicators, such as approved observing proposals and contracts of research are extremely positive.

3. Major Operative Experiments of HEA with Italian contribution

A significant fraction of analysis work is based on data retrieved from open access archives. But a continuous injection of new data is coming from active satellite observatories. The Italian share for those distributed on a competitive basis is quite good, included XTE and Chandra, to which Italy did not contribute any hardware. On **XMM-Newton** Italy participated with a share in the process of X-ray optics making, with the PIship of EPIC instrument and with with X-ray filters. Thanks to the large collecting area and to the spectroscopic capabilities this is nowadays the *standard* instrument for observation of faint sources, while Chandra is more effective whenever high resolutions are mandatory. **HETE-2** (Italy maintains one of the VHF ground stations) is continuing the GRB alerts of SAX, with much shorter times. **INTEGRAL** is the major Gamma-ray Mission in activity. The Italian Community contributed to the imager IBIS (PIship), to the spectrometre SPI, to the X-ray monitor JEMX and to the Scientific Data Center. IBIS is providing excellent images of the galactic disk, and, in particular, of the galactic bulge, giving the picture of a continuously varying sky, with frequent on-set of new transient sources (Bird et al. 2004), some heavily absorbed at lower energies (Walter et al. 2003). The contribution to Hard X-rays and soft Gamma-rays of binary systems including neutron stars is higher than expected. SPI and IBIS spectroscopic results, also on the basis of first data, will build a detailed map of emission lines and their association with star forming regions of the Galaxy. The NASA Mission **SWIFT**, is in a very early phase. Italy is contributing the ground station, the X-ray Telescope, and the analysis tools. The first results are very interesting and show the capability to detect breaks in the early phase of the X-ray afterglows, providing the opening angle of jets, and, thence, the energetics of the GRB (Campana et al. 2005). Moreover afterglows show a fast decay in the very beginning, a feature that could correct the standard fire-ball picture (Tagliaferri et al. 2005).

In the field of ground based experiments we are assisting to a real revolution determined by data from Cherenkov telescopes operating at energies around TeV. HESS is giving very interesting data on astrophysical systems, site of extreme acceleration of particles, including the detection of an extended TeV emission from the shell like SNR J1713.7-3946 (Aharonian et al. 2004). The other major telescopes are VERITAS and MILAGRO (the latter with a significant italian role). A future evolution of MILAGRO should extend the low energy threshold down to 30 GeV. This overlaps with GLAST and makes possible a mutual calibration of these two instruments based on different techniques (Fort et al. (2005)).

In the proper domain of CR the most interesting topics are related to the two spectral features: the knee (see Morello (2005)) around 10^{16} eV and another feature expected around 10^{19} eV because of the Greissen, Zatsepin and Kuzmin effect (GZK), that predicts a horizon of few tens of Mpc for CRs of energies $\geq 10^{20}$ eV. To confirm or disconfirm GZK we have a few events from different experiments contradictory and poorly significant. The Pierre Auger Observatory (with relevant italian participation), with 3000 km^2 at 1400 m altitude and with the combined use of surface detectors (cherenkov in water) and calorimetry (by air fluorescence) will improve the reliability, the calibration and, most important, the statistics around 10^{19} 10^{20}. First results will be presented next summer.

4. Major Approved Missions of HEA with Italian contribution

Two space based experiments of Gamma-ray Astronomy, are in the building phase. **AGILE** is the first all-italian small satellite. It consists of a subdivided converter alternated with silicon microstrip detectors to track the e^+ -

e^- pair created in the converters. A light, thin microcalorimeter, complements the information on the mean scattering of electrons in converters, to provide an information on the photon energy, while a plastic anticoincidence removes the background of charged particles from CRs, earth albedo and local production. Notwithstanding the limited area (1600 cm^2 geometric), thanks to the first application of the solid state detector technique to Gamma Ray Astronomy, resulting in a very wide field of view, AGILE represents a significant improvement with respect to the best previous experiment: EGRET aboard GRO. **GLAST** is a NASA mission based on the Large Area Telescope, an array of 16 identical *Tower* modules, each with a tracker (Si strips), all built in Italy, a calorimeter (CsI with PIN diode readout) and data acquisition module, surrounded by an anticoincidence made of plastic scintillator, with PMT readout. GLAST is much larger than AGILE and will be launched two years later. It is equipped with a GRB Monitor, while AGILE has an X-ray monitor, **SuperAGILE**, capable to detect bursts and transients with arcminute accuracy and to monitor the flux of hundreds of sources in the same f.o.v. of the Gamma telescope. With these new missions, based on silicon technology, active on fields of view of steradiants and particularly oriented for studis of variability and for multi-wavelength observations, Gamma-ray astronomy is expected to face the major topics left open by EGRET, most of all the problem of sources identification, with particular regard to the class of unidentified sources at moderate galactic latitude and to those confused in the plane. They will also enlighten the physics of acceleration in explosions, shocks and jets and the role of Dark Matter.

In the domain of Cosmic Rays, while the VHE and UHE components are studied by the mentioned ground based experiments the search for primary antimatter, can be only performed in space. Two experiments are planned. **PAMELA** is a small mission based on a magnetic analyzer and a tracking calorimeter, capable to measure the antiproton spectrum from 0.08 to 190 GeV and the positron spectrum from 0.08 to 270 GeV. The sensitivity in the antiHe/He ratio, is improved of more than one order of magnitude with respect to present data. It will also provide monitoring of solar modulation and measurement of particles emitted in solar flares. **AMS-02** is a magnetic spectrometer for the ISS. The aim is the direct detection of primary cosmic rays below the knee, with high resolution, large statistics and very good particle identification. AMS-02 is extremely challenging from the point of view of technologies. It applies all the major techniques to detect particles and derive their charge, energy and mass. The bulk is a mass spectrometer based on a superconductor magnet and a stack of tracking detectors. Also are employed transition radiation detectors, a time of flight telescope, a cherenkov ring imager and a tracking electromagnetic calorimeter. The result is the capability to resolve particles on a large acceptance (0.45 m^2 sterad) disentangling the antimatter component and giving a precise measurement of the energy. It will improve of three orders of magnitude the existing limits, with strong implication on cosmology and on the search for non baryonic dark matter.

The search for gravitational waves bridges HEA with Cosmology and fundamental Physics. After the era of resonant antennae and ground based interferometers the new frontier is the space based instrumentation, down to the mHz range. Experiments are aboard Cassini and foreseen aboard Bepi Colombo. The major mission in this domain is **LISA**. The principal scientific objectives are supernovae, massive black holes and their merging, fluctuations from Early Universe before recombination. The passage of a GW is measured from the displacement of 3 bodies in free fall (actually 3 pairs of bodies). The displacements is measured by interferometers with laser transponders at a distance of 5×10^6 km. To make sure that the displacement is due to GWs and not to one of the numerous stray effects (such radiation pressure, particle drag, electromagnetic torques) each pair of test masses is encased within a shield satellite, namely a satellite contouring the test masses with transducers and thruster actuators to compensate with movements all the stray effects. The technologies are so sophisticated that an intermediate mission, **LISA Pathfinder**, is needed to qualify technologies.

5. How to build a Strategy for the future?

Italian HEA needs a strategy adequate to guarantee, at least, the maintenance of the achieved level of excellence. The selection of future missions deserves an adequate effort and science must be the driver.
In 2004 a "Feasibility study on High Energy Astrophysics: fields of interest and perspectives for the national community", has been performed by more than 50 researchers of the field, coordinated by G. C. Perola, G. Puglierin and by the author of this contribute. The study was performed for ASI and its results have been assumed by INAF as a strategic indication. The Study has outlined a path articulated on 4 steps:

a Status of science, perspectives, Hot Topics, requirements for measurements capable of leading to significant step forwards.
b Compare performances of missions/experiments already approved with the requirements from a). Emphasize what would remain uncovered but that could be accomplished using the technology already available or in advanced development.
c Outline ideas of possible new missions, which must comply with a) and b), and would represent effective breakthrough, over time scales of about 5-7 years to about 10 years.
d Compare these ideas with the main (relevant) mission projects known to be in a process of selection, approval, funding.

Also the study over viewed the scientific-technological activities relevant for space projects, developed within the national community, to identify those deserving support to either maintain or achieve an internationally competitive level.

6. The leading lines for new HEA Missions matching the level of excellence

The leading lines emerged from the Study, specifically from those Hot Topics, which are not yet satisfied by operative or already planned missions, but could be pursued with advanced technology are in the electromagnetic domain:

- Spatially resolved spectroscopic observations from about 1 keV to about 70 keV (multilayer optics).
- Spatially resolved spectropolarimetry in the 1 to 10 keV range (photoelectic polarimeter)
- Wide Field (about 1 sq deg), high angular resolution, deep survey instrument in the 1 to 10 keV range (single telescope with polynomial profile and multilayer coating)
- Imaging spectroscopy in 80 to 400 keV range(Laue optics)
- High spectral resolution (with microcalorimeters) and polarimetry in the X-ray band of Gamma Ray Bursts and other transients, starting from their earliest phases.

And in Cosmic Ray Physics:

- Studies of UHE CR and neutrinos, exploiting the Earth atmosphere as a fluorescent converter seen from space

7. Mission ideas.

In the following I shall briefly describe the scientific rationale of the mission ideas, each one of them regarded as a breakthrough with respect to the leading lines just described. They are proposed as a baseline for proper preliminary studies (some are more advanced than others in this respect), and for sustainable initiatives, either led from within Italy, or linkable to opportunities arising outside.

- EUSO (UHECR and Neutrinos)
- HEXIT-SAT (Hard X-rays: to be compared with Simbol-X, NuStar, NeXT)
- POLARIX (X-ray spectropolarimetry)
- Wide Field X-Ray Imager

- HAXTEL-P (Hard X/Soft Gamma-rays balloon with Laue optics)
- ESTREMO (post-SWIFT)

XEUS, considered by ESA for the Cosmic Vision 2020, will be the further big step, for many Hot Topics, on longer timescale.

7.1. UHE-CR beyond Auger

As mentioned above data from AUGER will enormously improve the statistics of CRs around 10^{19} 10^{20} eV. Going further, in energy the number of events expected is too small. Which are the scientific objectives for this extension? Either AUGER confirms or disconfirms GZK cut-off, very detailed measurement of the CR spectrum from 5×10^{19} eV (UHECR) to more than 10^{21} eV , and mapping their arrival directions, will test:

- Bottom-up models: processes and objects that can generate these extreme energies?
- Top-down models: must we postulate topological defects and/or supermassive relic particles to explain the observations?
- Lorenz Invariance: is special relativity valid at extreme energies ($\gamma \sim 10^{11}$)?
- new Physics: are the UHECR a window to new physics at the ZeV energy scale, well beyond the accelerators?
- Possibly open the channel of UHE Cosmic Neutrino Astronomy.

EUSO can perform this science, by moving to space to measure UHE showers by the fluorescence from Earth atmosphere only, with the substantial advantage that uses a huge mass of atmosphere (10^{12} ton), and covers all the sky (North and South). But the technological requirements are very tough, demanding for a consistent R&D activity. A field of view ±45° wide, is obtained with Fresnel lenses of ∼ 2.5 m Ø. The Electronics is able to manage more than 250 000 channels from fast MAPMT (10 ns resolution time). Lidar and IR camera are also needed to probe the atmosphere transparency.
EUSO, in the present design, is an external payload for the ISS. The AWG of ESA has recommended to wait for the first data from AUGER, before EUSO is passed to the operative phase. To overcome programmatic difficulties of ISS it has been proposed that EUSO moves to a free flyer.

7.2. Hard X-rays a large space of discovery

Many open problems of HEA might be solved in the Hard X-ray Band. These include:

- Resolving the CXB: at few keV, for a very large fraction, it is the superimposition of faint extragalactic sources. At ∼ 30 keV, where it peaks only a few % of the CXB is resolved in sources.
- Accreting binaries in this range show a phenomenology directly linked to the emission mechanism: cyclotron features in HMXB, hard excess in BHXC in low state, hard tails of LMXB.
- Correct modelling of the continuum in AGN spectra, to reliably measure the reflection component, the relativistic lines and their variability.
- Search for very obscured AGN and investigate variability in their obscuration.
- Explore the spectral transition from Synchrotron to IC, in Blazars, especially during flares.
- Detect and localize non-thermal emission from SNRs and Clusters.

In Italy there is a long tradition of HXR Experiments and SAX-PDS is the most sensitive ever flown. Yet the scientific requirements demand for a further improvement in sensitivity of orders of magnitude: **HEXIT-SAT** can achieve this improvement, because the multilayer mirror technique, can extend to higher energies the use of optics and the related huge increase of sensitivity. The present flux limit of 1 mCrab (10-30 keV) will go as down as 0.1 μCrab. The full band sensitivity (1- 80 keV) is of 0.5 μCrab.
HEXIT-SAT includes four identical optical moduli; 8 m focal length (A_{eff} @ 30 keV: 400 cm^2); f.o.v.: 15 arcmin; angular resolution: 15 arcsec. In each of the four focal planes there will be two stacked position sensitive detectors one made of Silicon, sensitive up to 10 keV (δE

$\sim$100 eV), one made with a high Z semiconductor, sensitive to those radiations for which the first detector is transparent (10 up to 80 keV) (δE/E a few % @ 30 keV).
In the international landscape NuSTAR, still under evaluation by NASA is also oriented to the Hard X-rays imaging. Its capabilities are similar to those of HEXIT-SAT, but substantially reduced because of a single telescope, a smaller f.o.v. and the high Z detector only. NEXT is a mission under study at JAXA that will include a set of hard X-ray multilayer telescopes. The major limit is the resolution of the optics and the reduced f.o.v.. **SIMBOL-X**, proposed to CNES for a formation flight, uses conventional monolayer mirrors and exploits the long focal length (30 m of separation of the two satellites) to extend the band with low reflection angles. Compared to the other missions based on multilayer the collecting area is good at 20 - 40 keV but quickly decreases with energy. Another draw-back is the small f.o.v. and the large plate-scale resulting in a high background. While for energies $\leq$ 40 keV SIMBOL-X is less sensitive than HEXIT-SAT of a factor from 3 to 5, @ 60 kev it is less sensitive than SAX or INTEGRAL. By increasing the diameter of the optics of a 30%, stiffening the shells to improve the angular resolution and adopting a multilayer coating, SIMBOL-X could became a very competitive mission: an interesting alternative to HEXIT-SAT, because of the international frame, and has been indicated by ASI as a possible priority.

7.3. A new window in the sky: X-ray Polarimetry

By measuring the linear polarization of X-rays one could perform crucial tests of Astrophysics and Fundamental Physics. Possible targets are:

- Isolated magnetic neutron stars (pulsars, Soft Gamma Repeaters)for tests of birefringence predicted by Quantum Electro Dynamics.
- Accreting Pulsars: to directly measure the geometric parameters of the system and understand the emission mechanism.
- variability of the polarization angle with energy for galactic black hole binaries and with time for AGN to proof bending of radiation in strong gravitational fields.
- galactic and extragalactic jets to test the nature of the jet.
- SNR both plerionic and shell-like to test acceleration mechanisms
- test effects of Quantum Gravity by birefringence on very long distance scales.

Polarimetry has been tried in the first decade of X-ray Astronomy, with the only positive measurement of the Crab Nebula. When the introduction of optics produced a huge increase of sensitivity for imaging and spectroscopy, polarimetry was put aside, mainly due to the poor sensitivity and the cumbersomeness of conventional techniques. Recently a new technique, based on photoelectric absorption in finely subdivided gas detectors was developed in Italy. In a focal plane can measure polarization, position, energy and time. Combined with an optics, like that proposed for XEUS, gives the possibility to perform all the mentioned measurements. But since the status of polarimetry is so behind, a small dedicated mission, capable to study galactic sources and a limited number of the brighter extragalactic objects, makes sense as well. **POLARIX** follows this concept. Since the telescopes of JET-X/SWIFT can be replicated with a moderate expense, the baseline is an array of 5 such telescopes, with 3.5 m focal length, f.o.v. of $12 \times 12'$, angular resolution of 20 arcseconds, for a total area is 1000 cm^2. In the focal plane it will host 5 photoelectric spectropolarimeters. The whole is compatible with a cheap small launcher.

7.4. An experiment for low brightness extended sources

The vision of large scale processes producing the present structure of Galaxy Clusters and determining the structure in extension, temperature and metallicity of Inter Galactic Medium is evolving in a way that puts in evidence the connection of High Energy Astrophysics with Cosmology (see e.g. Schuecker (2005)). This new view derives from Chandra and XMM data of the inner parts of clusters (within about 1/3 of their virial radius), demands for a wide field (1 sqdeg) and very low background imager to investigate low surface brightness regions, measuring temperature and Fe distribution, up to at least the virial radius. The **Wide Field X-R Imager** is a mission concept based on single, telescope with focal length of 3.5 m, f.o.v. of $\tilde{1}$ square degree, Area of 750 cm2 @1 keV, 150 cm2 @6 keV, enhanced to 500 cm2 (with multilayer non-graded coating) in a 1.5 keV wide band around 7 keV. An angular resolution of 5 arcseconds is also needed to resolve and subtract the individual sources constituent of the Diffuse X-ray Background. The trade-off of wide field (low off-axis aberrations) and high resolution is achieved with polynomial profile optics, with short mirrors built with a technology to make them very stiff, but thin. Very low background is achieved with a short focal length and a Low Equatorial Orbit.

7.5. Gamma-Ray Bursts after SWIFT

Another mission, on a longer timescale is **ESTREMO** that evolves the concept of BeppoSAX (a wide field instrument and a fast follow-up on transient sources with a telescope) in the same line of SWIFT, but with a substantial improvement in the scientific capabilities, sice the telescope has in the focal plane a microcalorimeter and a polarimeter. A low energy WFC will detect bursts and transients, down to 1 keV, a range not covered by SWIFT, but of the highest interest because of the possible existence of transient absorption features, and needed to explore the real extension to the lower energies of the continuous GRB/XRF distribution. A High Energy Wide Field camera, based on CdTe (or CZT) technology will detect bursts in the harder range.
The core science of ESTREMO are GRBs by themselves and as probes of the medium in the line of sight. GRB spectra studied at very high spectral resolution with a Transition Edge Sensor will be absorbed in the surrounding medium allowing for the measurement of redshift even if the optical afterglow is not detected (very far GRBs, dark GRBs). The polarization of the afterglow will give a direct evidence of the structure of magnetic fields in the fireball, so far only derived from spectral evidences. The sudden decrease of the baryon density in the local ($z < 1$) Universe is one of the unresolved issues of Cosmology. They could be in a hot phase, that can be detected primarily through X-ray measurements. At $z < 1$, most of the baryons should fall onto the cosmic web pattern of the dark matter, and be heated at $T \approx 10^6$K by shock mechanisms, forming filamentary structures. Such gas is called Warm-Hot Intergalactic Medium (WHIM). ESTREMO will search for the narrow absorption features imprinted by the WHIM on the X-ray spectrum of GRB afterglows and map WHIMS out to large distances.
ESTREMO can also perform important measurements on many other fast transients such as Soft Gamma Repeaters and X-ray bursters. The spectroscopy of XRB can provide direct evidence of the Equation of State of NS.

7.6. From Hard X to Soft Gamma-rays

A last mission concept is based on the application of the technique of focussing soft Gamma-rays (60 - 300 keV), with an array of mosaic crystals, through the Laue Diffraction. This band is very difficult because the Compton effect is the prevailing interaction and it is difficult to stop or collimate the photons. Laue diffraction allows for real focussing devices in the band 0.1 - 1 MeV. This seems the best way do astrophysics in Hard X/Soft-Gamma Rays going beyond INTEGRAL sensitivity. Data in this band (especially if complemented by measurements at lower energies) would enlighten the physics of extreme objects:

- Radiation processes in presence of super-strong magnetic fields (Accreting X-ray pulsars, Anomalous X-ray Pulsars).
- Radiation processes in Gamma Ray Bursts (role of Inverse Compton with respect to synchrotron or thermal processes).
- Role of non thermal mechanisms in extended objects (Supernova Remnants, Galaxy Clusters).

- Broad band spectra of AGNs, inclusive of high energy cut-offs also to evaluate their contribution to the CXB.
- Nuclear lines (e.g. Ti^{44}) produced in SN explosions.
- Polarization of the sources of high energy radiation.

Recent developments in technology of mosaic crystals and the evolution of space technology make possible to convert this concept into a more realistic design. A first application could be **HAXTEL-P**: a balloon borne experiment for hard X-ray astronomy. The band 15-400 keV is covered with a combination of Laue lenses (1 Medium Energy lens plus 4 High Energy lenses) and one multilayer optics. Lenses are spherical, built with mosaic crystals of Cu (111) (spread 7 arcmin FWHM); Crystal thickness: 2 mm (for ME); 4 mm (for HE). Focal plane detectors: 5 PSD (CZT) optimized for polarization measurements. Notwithstanding the low fluxes at these energies the telescope, mounted aboard a long duration balloon, could already perform highly competitive measurements in this band. A long term activity of Research & Development on these crystals has been performed in Italy. In France the same technique has been studied more oriented to line spectroscopy: the crystal angles are not distributed for a uniform coverage of the continuum but concentrated around ranges of interest for lines and the continuum is only sampled in these regions. In general this also implies higher energies to be achieved with a longer focal length, suitable for formation flights. A Soft-Gamma-ray mission based on Laue Optics that could combine the two concepts and experiences is under study for the ESA Cosmic Vision 2015 -2025.

8. R&D: a national priority

In all these missions the Italian Community could play an important role but we stress that they are intrinsically valid and could be part of the planning of any national or international Agency: in fact many of the outlined missions already are. Italy must do a further step selecting the HEA mission of highest priority, but it is possible (or likely) that the next opportunity will not be a fully national effort. Moreover the proposed mission concepts are not equivalent in terms of time-scale and costs. In a moving international landscape, it is possible that the first choice will not convert into reality and we should be ready to convoy efforts to other, more realistic opportunities. It is therefore mandatory that a sound activity of R&D is performed to preserve the capability to participate to a mission with a significant level of involvement (e.g. mission or instrument PIship). Neglecting the domains (e.g. CR and GW from Space) where a very demanding R&D activity is performed for missions already approved or in advanced stage, the technologies where the Italian Community has a level of excellence, are strategic for a qualified participation to future missions and require substantial financial and human resources are:

- X-ray Optics. Multilayer technology. Polynomial mirrors.
- X-ray Spectroscopy: Transition Edge Sensors in arrays
- X-ray Polarimetry: Micropattern Gas Chambers
- Hard X-rays imaging: CdTe, CZT arrays, Si Drift Chambers
- Soft Gamma-ray imaging: Laue lenses

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