Astrofisica Nucleare e Subnucleare
"MeV" Astrophysics

MeV astrophysics techniques

Detection of Gamma Radiation
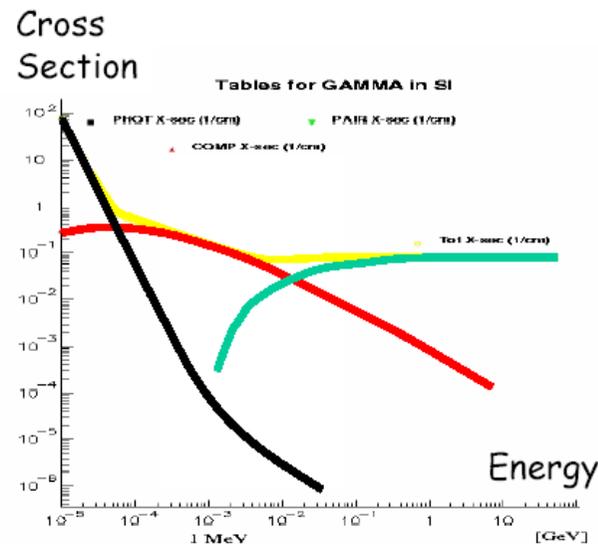
Cross Section

Tables for GAMMA in Si

PHOT X-sec (1/cm)   PAIR X-sec (1/cm)

COMP X-sec (1/cm)

Tot X-sec (1/cm)

Energy

10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 1   10   [GeV]

1 MeV

Photoeffect(< 100 keV)

Photons effectively
blocked and stopped

Telescopes:

Collimators
Coded Mask Systems

Compton Scattering (0.2-10 MeV)
Photon Crossection Minimum
Scattered photons with long range
Telescope:
Compton Camera Coincidence System

Pair Creation (> 10 MeV)
Photons completely
converted to e^+e^-

Telescope:
Tracking chambers
to visualize the pairs

Coded Mask Imaging

The Coded Mask Technique

is the worst possible way of making a telescope

Except when you can 't do anything better !

- Wide fields of view

- Energies too high for focussing, or too low
  for Compton/Tracking detector techniques

- Very good angular resolution

- The best energy resolution

INTEGRAL

INTEGRAL, the International Gamma-Ray Astrophysics Laboratory
Fine spectroscopy (E/dE=500) and fine imaging (angular resolution of 12' FWHM)
Energy range 15 keV to 10 MeV
plus simultaneous X-ray (3-35 keV) and optical (550 nm) monitoring capability
Two main g-ray instruments: SPI (spectroscopy) and IBIS (imager)


http://integral.esa.int
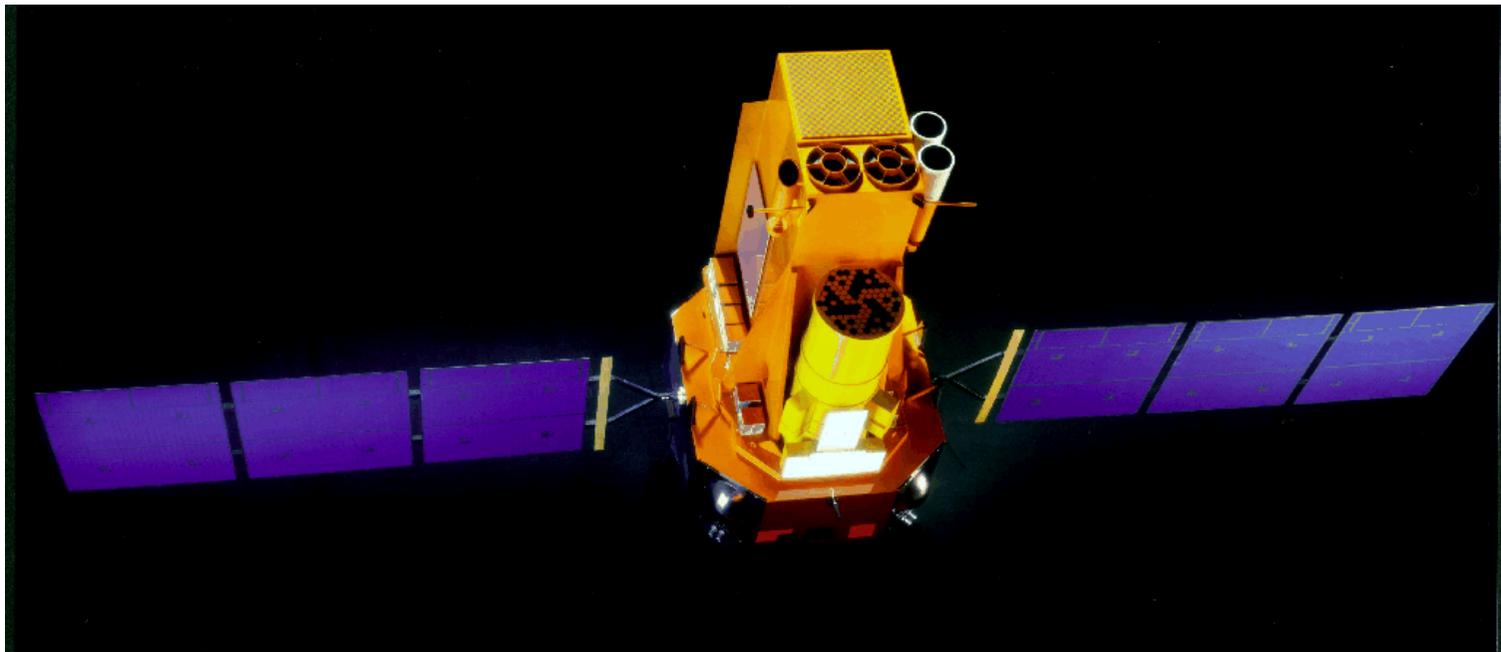
INTEGRAL Science Objectives

Outline INTEGRAL Science Objectives

The scientific goals of Integral are addressed through the use of high resolution spectroscopy with fine imaging and accurate positioning of celestial sources in the gamma-ray domain. The following list of topics will be addressed by Integral:

- Compact Objects *(White Dwarfs, Neutron Stars, Black Hole Candidates, High Energy Transients and Gamma-Ray Bursts)*
- Extragalactic Astronomy *(Galaxies, Clusters, AGN, Seyferts, Blazars, Cosmic Diffuse Background)*
- Stellar Nucleosynthesis *(Hydrostatic Nucleosynthesis (AGB, WR Stars), Explosive Nucleosynthesis (Supernovae, Novae))*
- Galactic Structure *(Cloud Complex Regions, Mapping of continuum and line emission, ISM, CR distribution)*
- The Galactic Centre
- Particle Processes and Acceleration *(Transrelativistic Pair Plasmas, Beams, Jets)*
- Identification of High Energy Sources *(Unidentified Gamma-Ray Objects as a Class)*
- PLUS: Unexpected Discoveries

*Gamma-Ray Astrophysics before INTEGRAL*
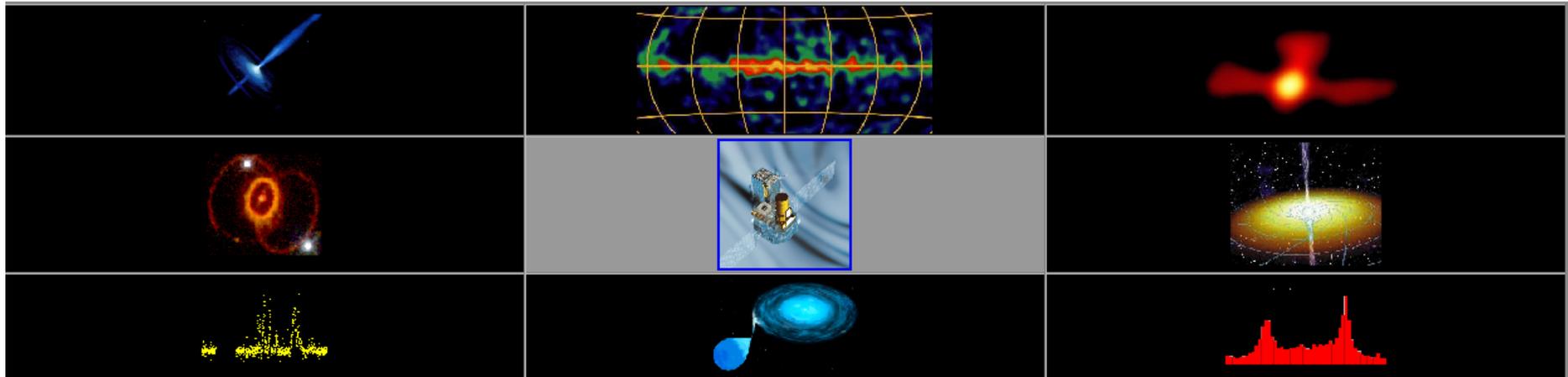
INTEGRAL
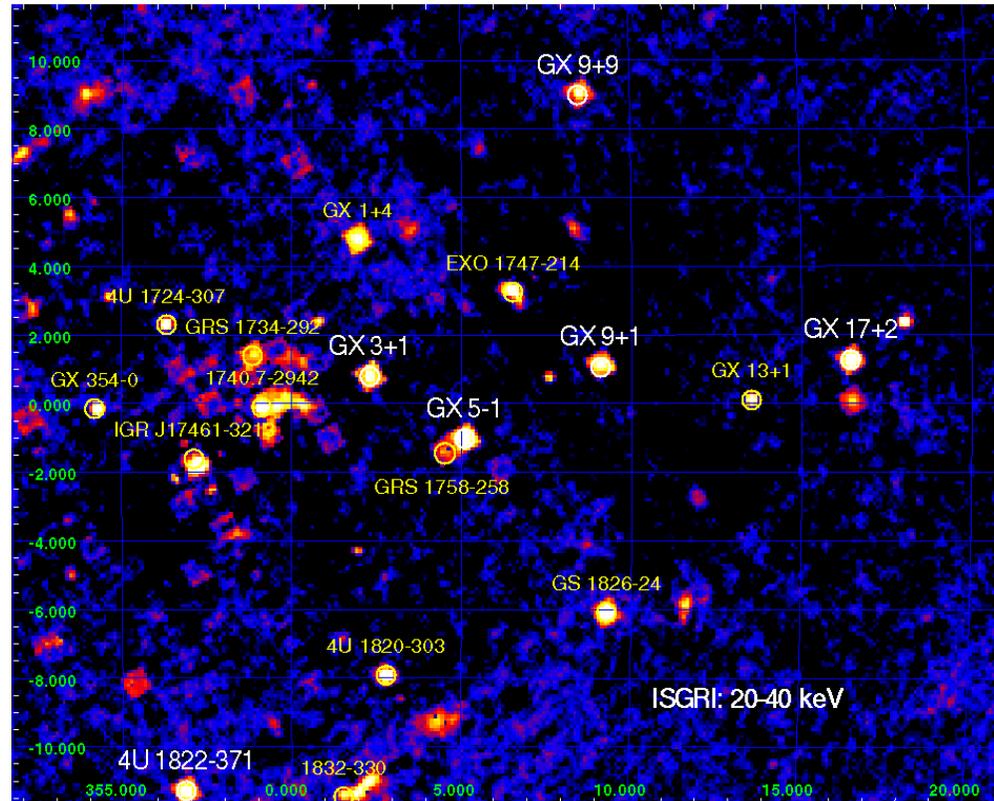
The image is an IBIS/ISGRI image of the Galactic Centre in the 20-40 keV band.
 The analysis of IBIS/ISGRI data is based on GCDE
(Galactic Center Deep Exposure) and GPS (Galactic Plane Scan) data from revolution
30 to 64 i.e. January 11th to April 22nd, 2003 for a total of one thousand pointings
(about 2 Msec exposure)

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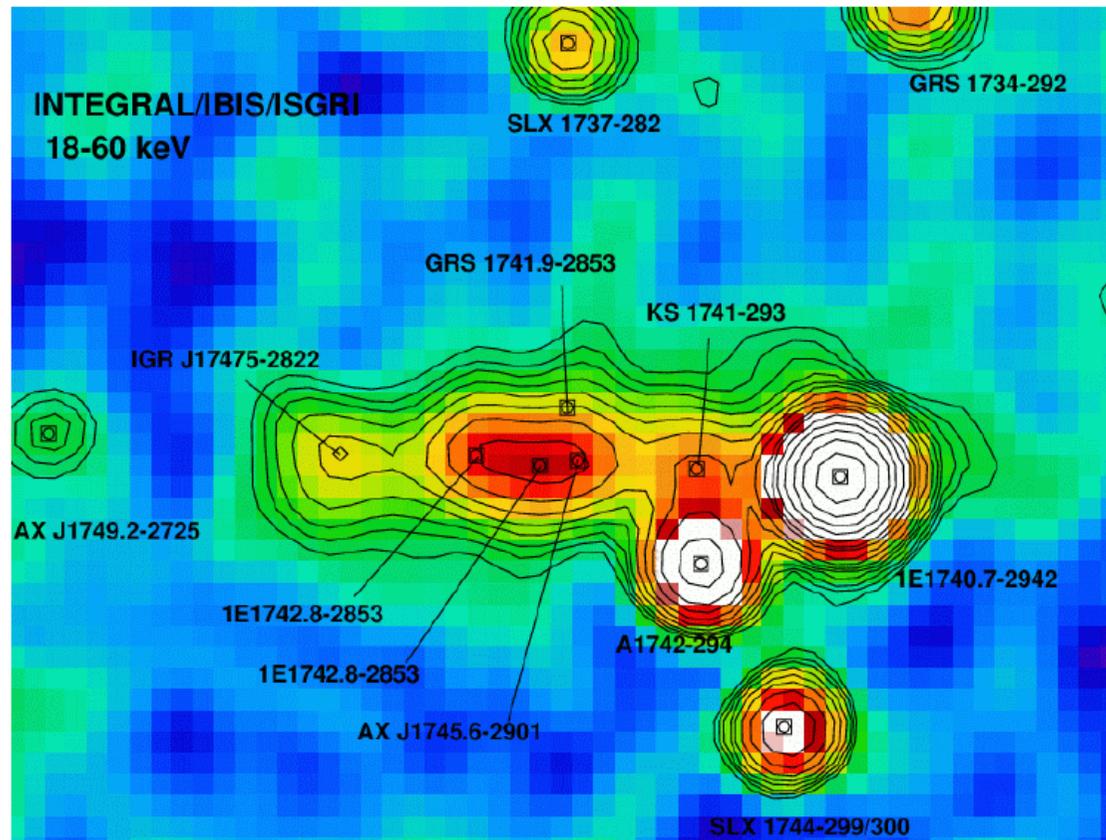
INTEGRAL

INTEGRAL views a Compton mirror at the Galactic Centre. M. Revnivtsev et al. report on the association of IGR J17475-2822, recently discovered by INTEGRAL, with the giant molecular cloud Sgr B2 in the Galactic Center region. Data from different observatories strongly support the idea that the hard X-ray emission of Sgr B2 is Compton scattered and reprocessed radiation emitted in the past by the Sgr A* source, the supermassive black-hole candidate in the center of our Galaxy. The IBIS/ISGRI image (18-60 keV) shows the inner 3.5 degree by 2.5 degree region of the center of the Galaxy. Contours represent signal-to-noise levels starting at S/N = 5 and increasing with a factor 1.4. The image has a total effective exposure time of 2.3 Ms.

INTEGRAL
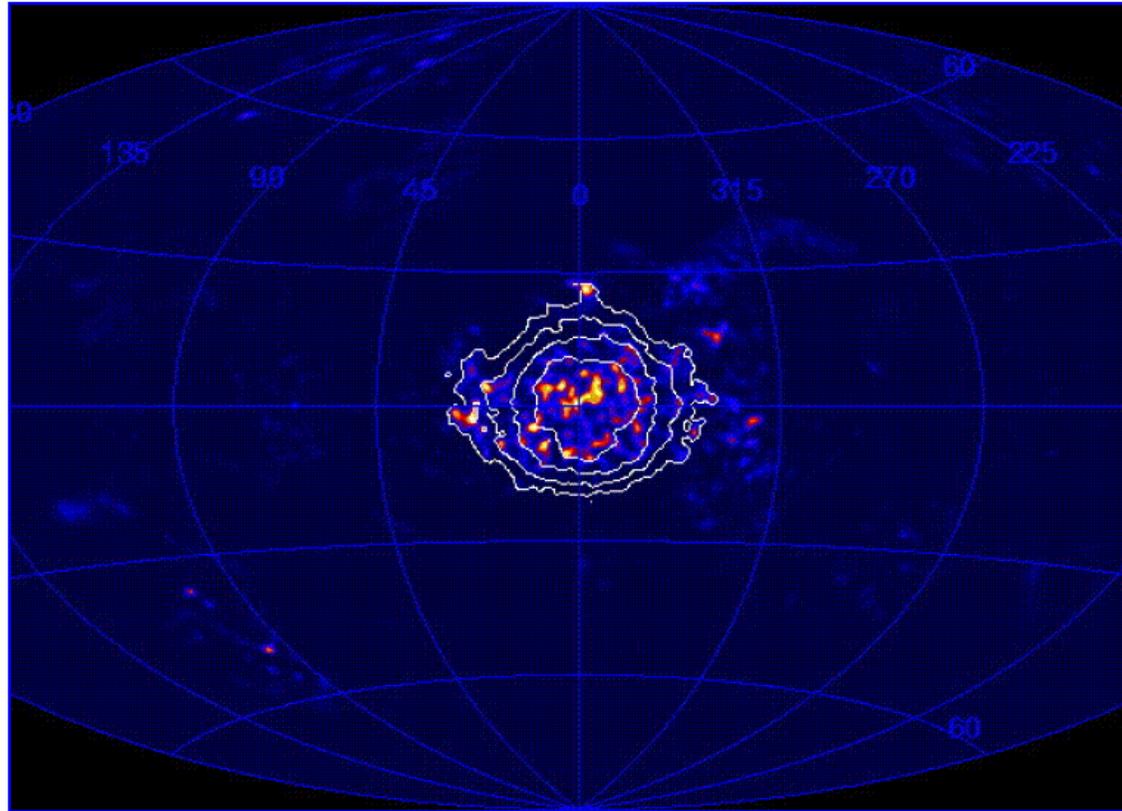
The SPI instrument onboard INTEGRAL has performed a search for 511 keV emission (resulting from positron-electron annihilation) all over the sky. The figure represents the results of this search: the all-sky map in galactic co-ordinates shows that 511 keV emission is - so far - only seen towards the center of our Galaxy. The SPI data are equally compatible with galactic bulge or halo distributions, the combination of a bulge and a disk component, or a combination of a number of point sources. Such distributions are expected if positrons originate either from low-mass X-ray binaries, novae, Type Ia supernovae, or possibly light dark matter.

INTEGRAL
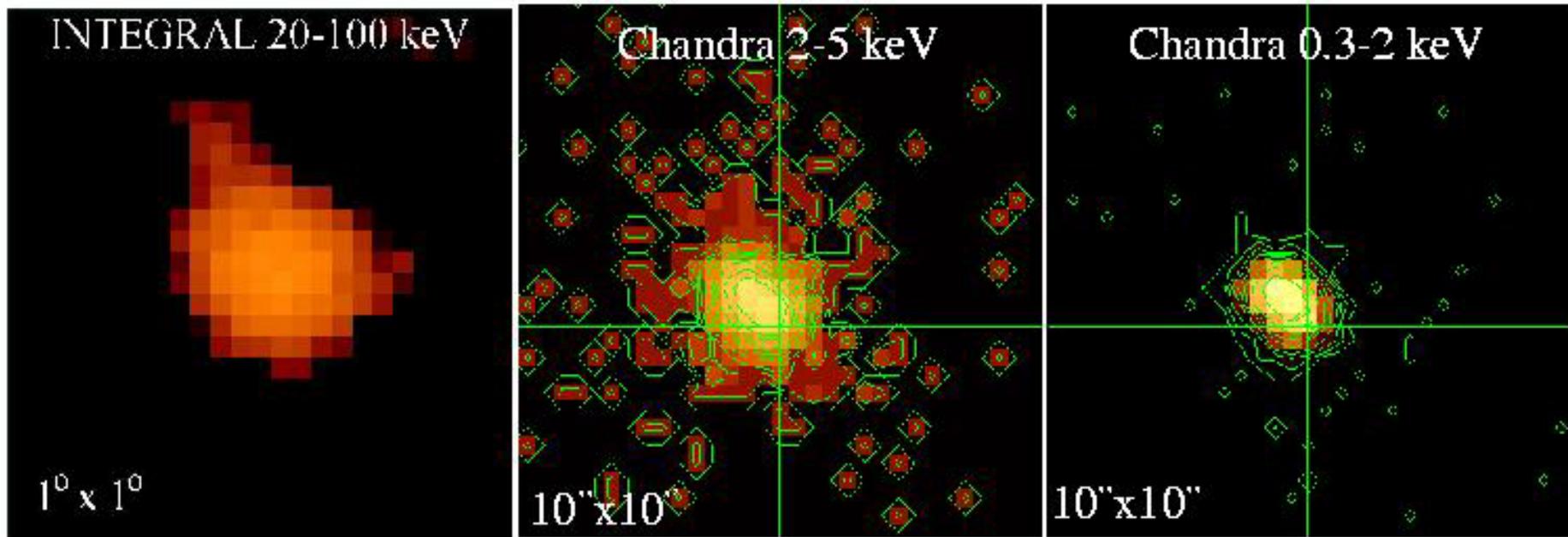
The blazar PKS 1830-211 is one of the most distant objects observed so far by INTEGRAL, it was reported as an ISGRI source in the galactic centre region. The source is clearly detected in 20-100 keV band. The image from IBIS/ISGRI is shown in the left panel. Notwithstanding its high redshift (z=2.507) it is a bright X-ray source, due to gravitational lensing by an intervening galaxy at z=0.89. Radio observations show two compact components separated by about 1 arcsecond; this effect (just at the limit of the angular resolution of Chandra), is clearly visible in the elliptically shaped Chandra images (central and right panels).

By assuming a magnification factor due to the lensing of the order of 10, the bolometric luminosity of PKS 1830-211 is huge: about 10^48 erg/s! The spectrum can be modelled adding an external source of low energy photons scattered up to gamma-ray energies by relativistic electrons. As observed in some high redshift quasars, Chandra spectra of PKS 1830-211 show evidence of absorption below 5 keV (rest frame). This effect could be due either to the lens galaxy at z=0.89 or to an intrinsic warm (ionized) gas at redshift of the source.

INTEGRAL
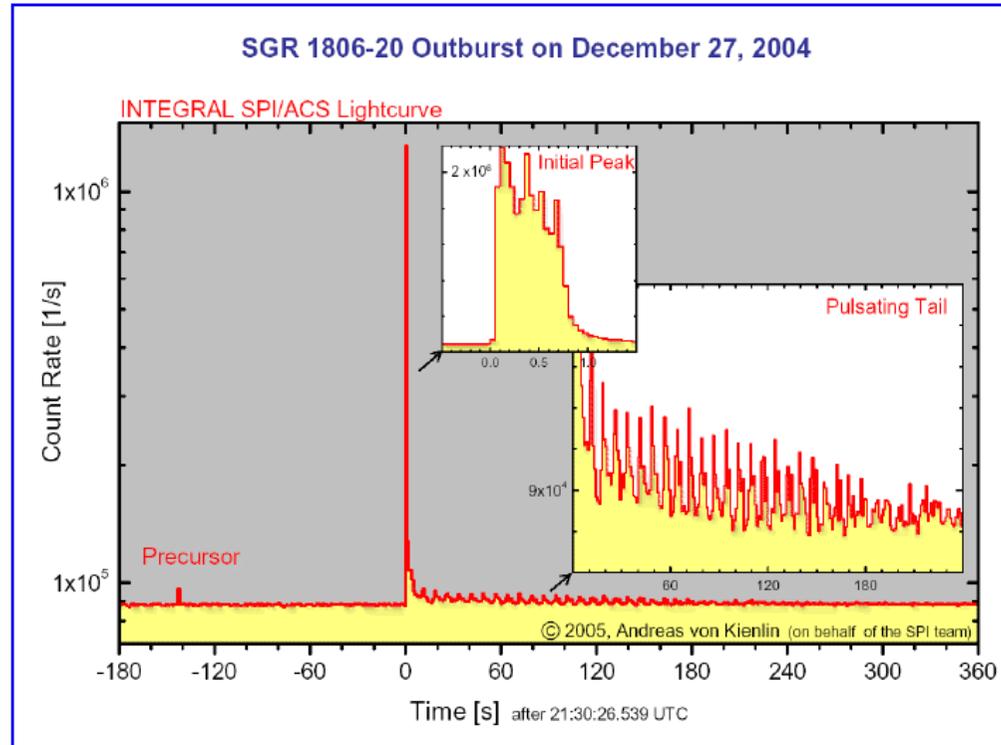
SGR 1806-20 which belongs to the class of soft gamma-ray repeaters (SGR) is believed to be a rotating neutron star with a super-strong magnetic field (10^15 Gauss); a so-called magnetar. The tremendous outburst of SGR 1806-20 on December 27, 2004 as seen by the large anticoincidence shield (ACS) of the INTEGRAL-spectrometer SPI is shown in the figure. The mean veto count rate of the ACS (~88000 counts/s) is interrupted at 21:30:26.539 UTC (T=0) by a steep count-rate increase (about a factor 25) for about 0.7 s. This outburst is thought to be caused by a large-scale rearrangement to a state of lower energy of a magnetar's super-strong magnetic field (10^15 Gauss), which is the current model for soft gamma-ray repeaters. The ~300 s long pulsating tail with a period of 7.56 s is clearly seen and can be explained by a trapped fireball which is co-rotating with the neutron star (magnetar). The initial peak is proceeded at T= -143 s by a small precursor, which could be shown via triangulation to originate from the position of SGR 1806-20.

INTEGRAL
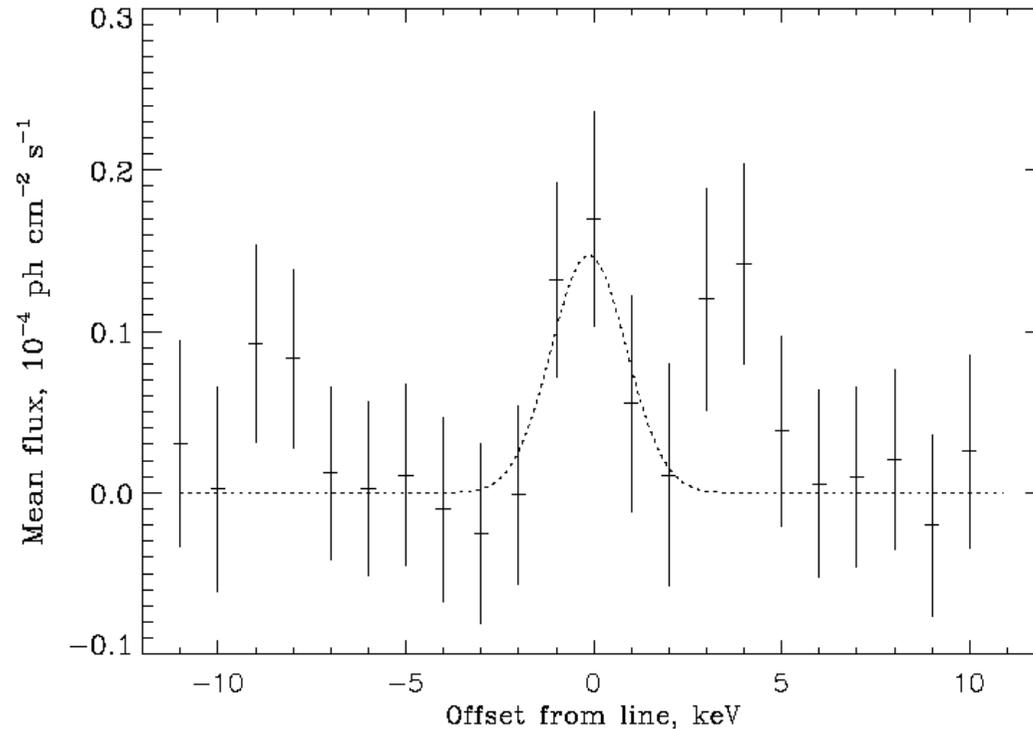
The SPI instrument on board INTEGRAL has observed the ^{60}Fe lines (at 1173 and 1333 keV) from the inner galaxy. The picture shows the combined ^{60}Fe signal from the two lines. The line flux is 3.7 ± 1.1 x 10^5 cm^{-2} s^{-1} per line.
The origin of the iron line is believed to be core-collapse supernovae which seed the interstellar medium with isotopes such as ^{60}Fe. From other SPI measurements of the ^{26}Al line the ratio ^{60}Fe/^{26}Al = 0.11 ±0.03 is derived, which is substantially smaller than predictions (0.40) for massive stars. This ratio supports the idea that there is an extra source of ^{26}Al in addition to the core-collapse supernovae.

INTEGRAL
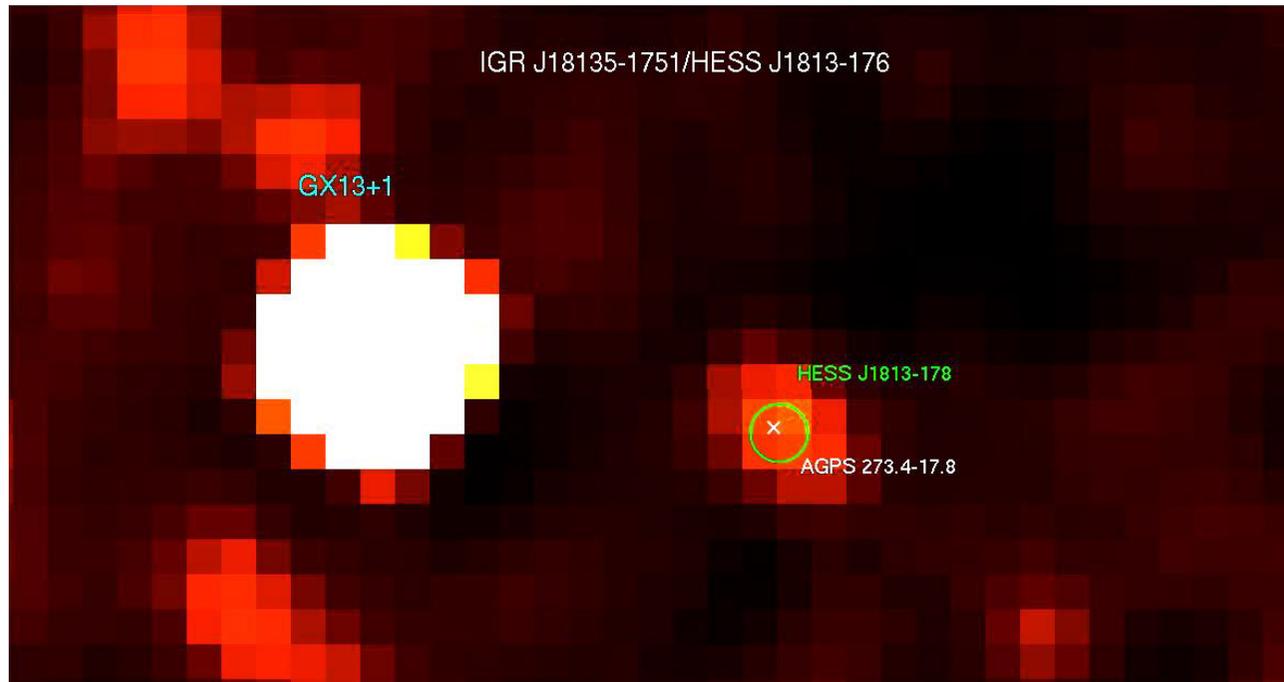
INTEGRAL has discovered, using the IBIS instrument, a new gamma-ray source (IGR J18135-1751). This source is remarkable, since it coincides spatially with one of the ten objects which have been seen during the first survey at TeV energies of the inner part of the galaxy: HESS J1813-178. This source is a powerful ultra-high energy emitter in the 0.2-10 TeV range. The X-ray counterpart (AGPS273.4-17.8) of the INTEGRAL source has an absorbed spectrum and is thought to be either a pulsar wind nebula or a supernova remnant. This picture shows the IBIS/ISGRI 20-100 keV image of IGR J18135-1751 as well as the position of HESS J1813-178 (green circle) and AGPS273.4-17.8 (white cross). The white spot on the left is the saturated image of the bright LMXB GX 13+1.

INTEGRAL

The central regions of our Galaxy, the Milky Way, as seen by INTEGRAL in gamma rays. With its superior ability to see faint details, INTEGRAL reveals the individual sources that comprised the foggy, soft gamma-ray background seen by previous observatories. The brightest 91 objects seen in this image were classified by INTEGRAL as individual sources, while the others appear too faint to be properly characterized at this stage.

INTEGRAL
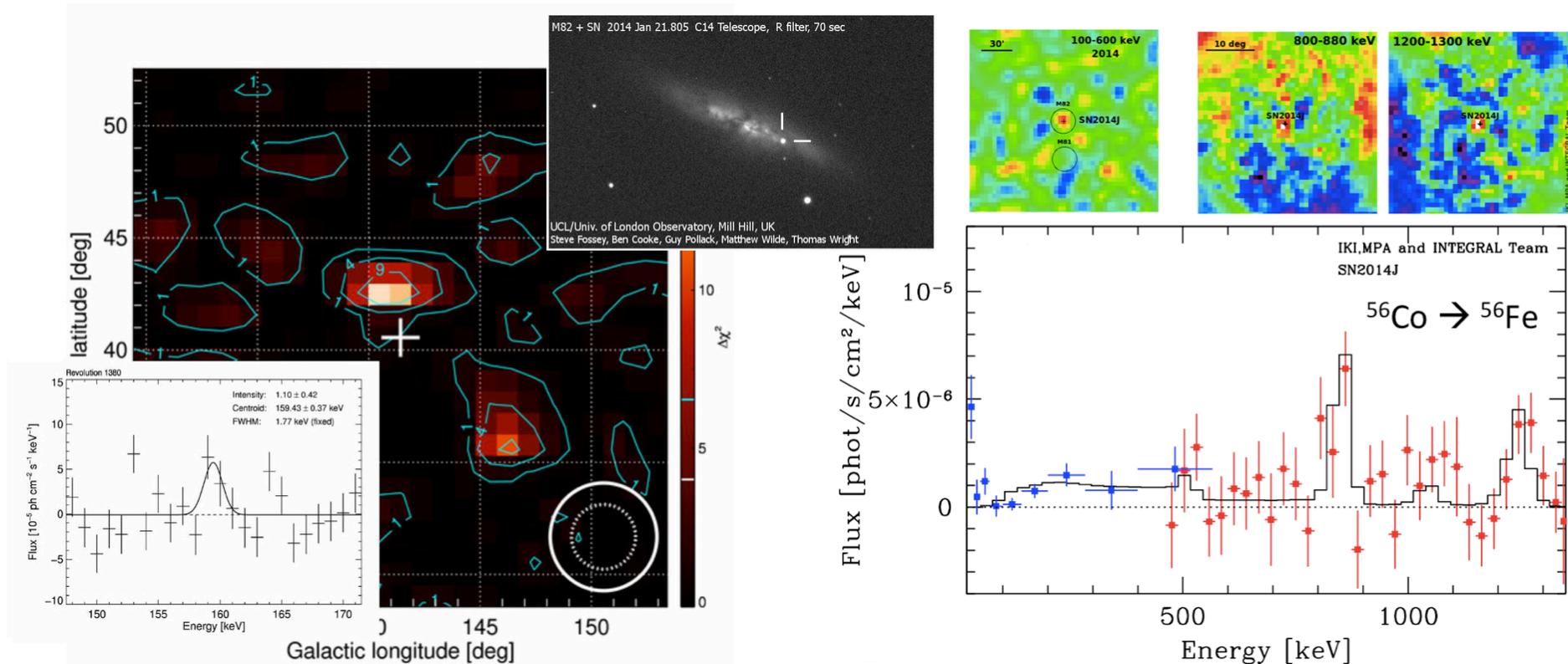
INTEGRAL for the first time, confirms by direct measurement of the primary gamma-ray lines the ^{56}Ni origins of SN light. The INTEGRAL measurements of this sufficiently-nearby SN provide a unique opportunity to compare the direct gamma-rays from the SN's energy source with the more-indirect other radiation. This will help astrophysicists to refine their models on how in fact these explosions do occur, because the explosion details affect how much new nuclei are created, and how they move and interact with the remainder of the exploding star. These observations constitute a reference in SNIa science, and thus an important scientific legacy for years to come.

INTEGRAL
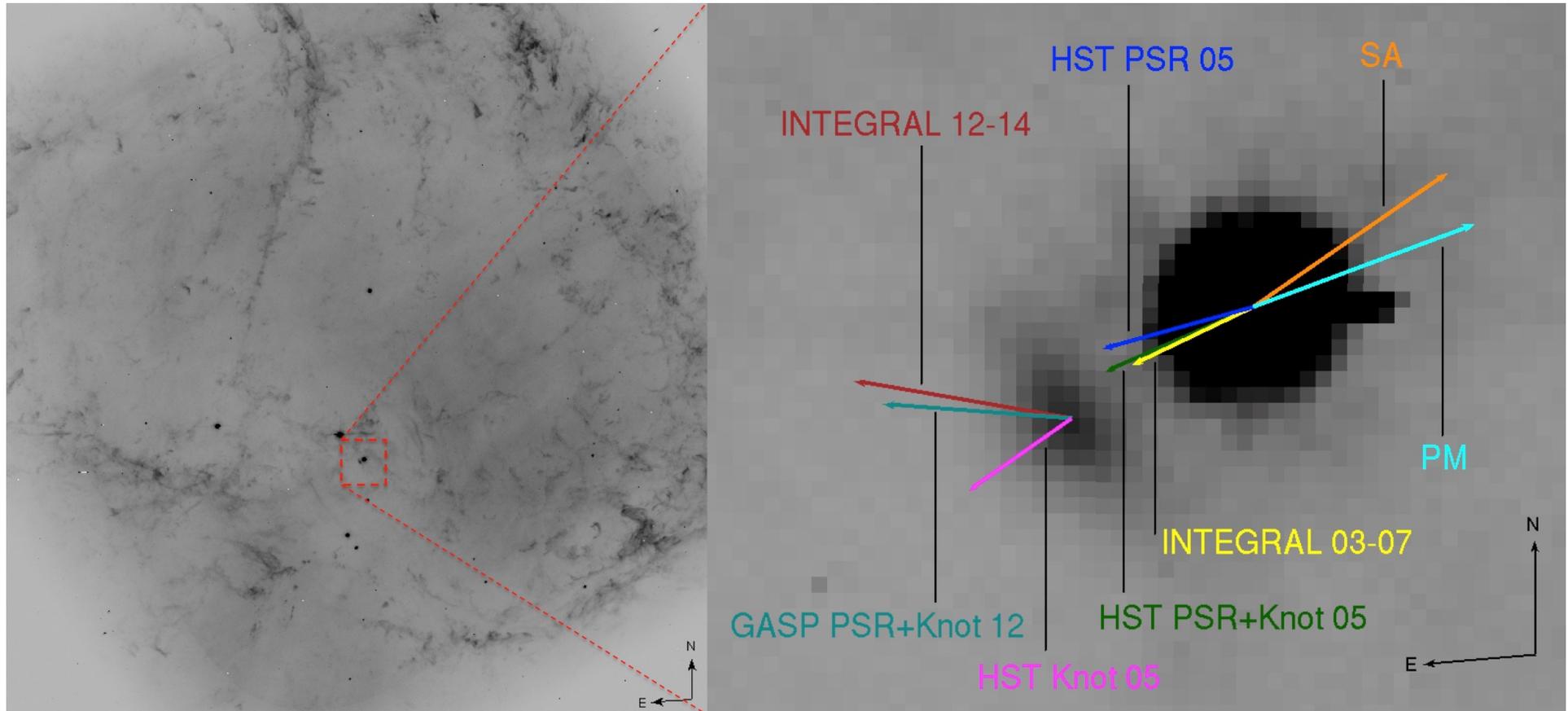
On the left, this HST image shows the inner part of the Crab nebula with the Crab pulsar and its near-by knot located 0.65" (1300 AU) south-east of the pulsar inside the red box. On the right, a zoomed view of the image is shown. The arrows indicate at different periods in time the polarization angle in the optical (HST in 2005 and GASP in 2012) and in hard X-rays (Integral in the period 2003-2007 and 2012-2014). Also indicated are the directions of the proper motion (PM) and spin axis (SA) of the pulsar.

INTEGRAL
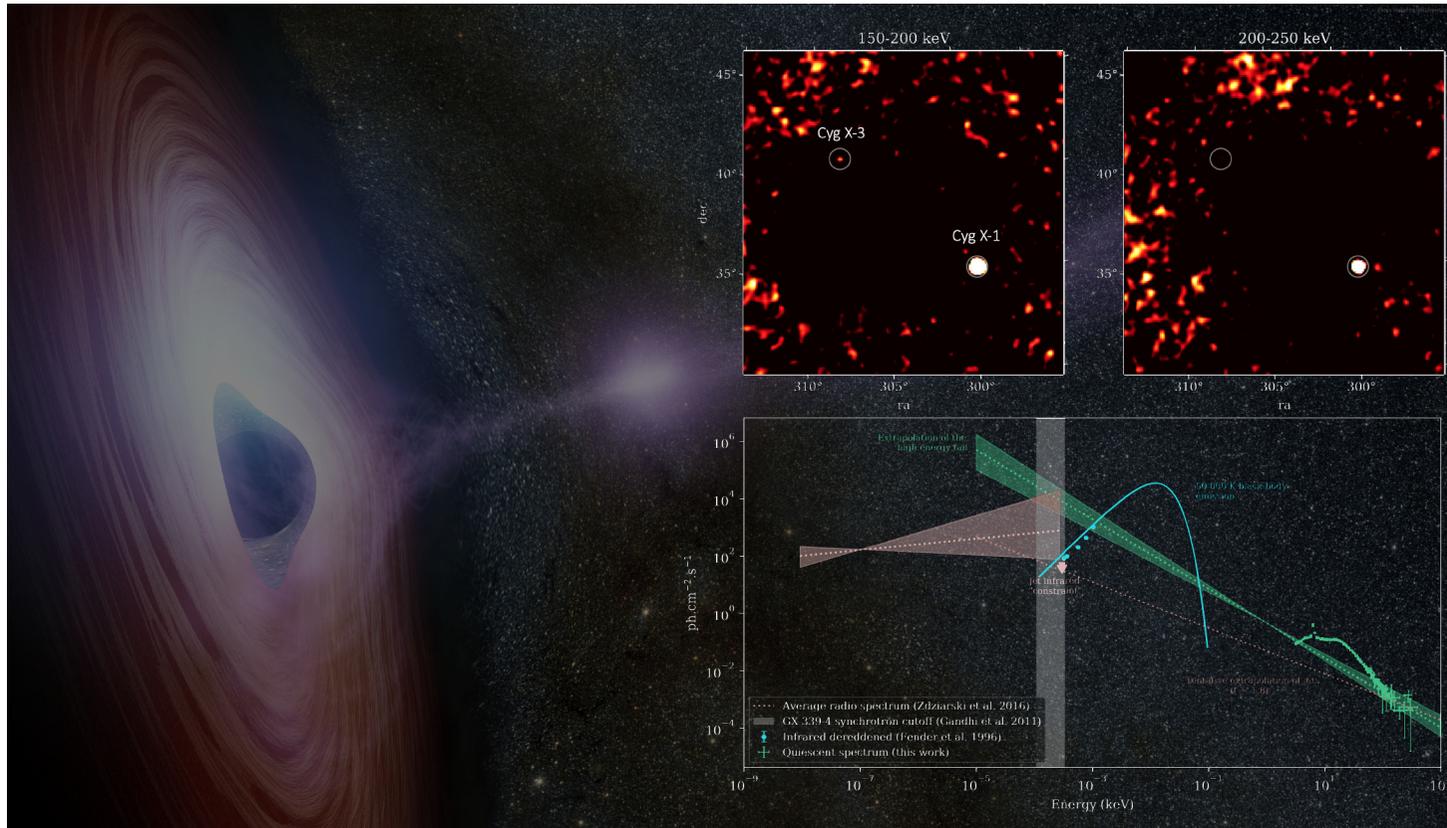
Cygnus X-3 is one of the first discovered X-ray binaries and the only bright compact binary system known to host a Wolf-Rayet star as a companion. The intense stellar wind created by this companion is one of the reasons why Cygnus X-3 exhibits a very peculiar spectral behavior. Indeed, it shows a wider variety of states than the two canonical ones usually observed in other standard X-ray binaries. Despite the fact that the source is well known since many years, very little is known about its spectral behavior beyond 50 keV. This lack of knowledge is especially due to the source being very faint at these energies. Thanks to INTEGRAL, it is possible to explore more than 16 years of observations, and so to probe the sky region of Cygnus X-3 with the best sensitivity ever. As shown at the top of the figure, one can detect the source up to 200 keV. Moreover, one can create six X-ray spectra from 3 to 200 keV, one for each observed spectral state of the source.

INTEGRAL
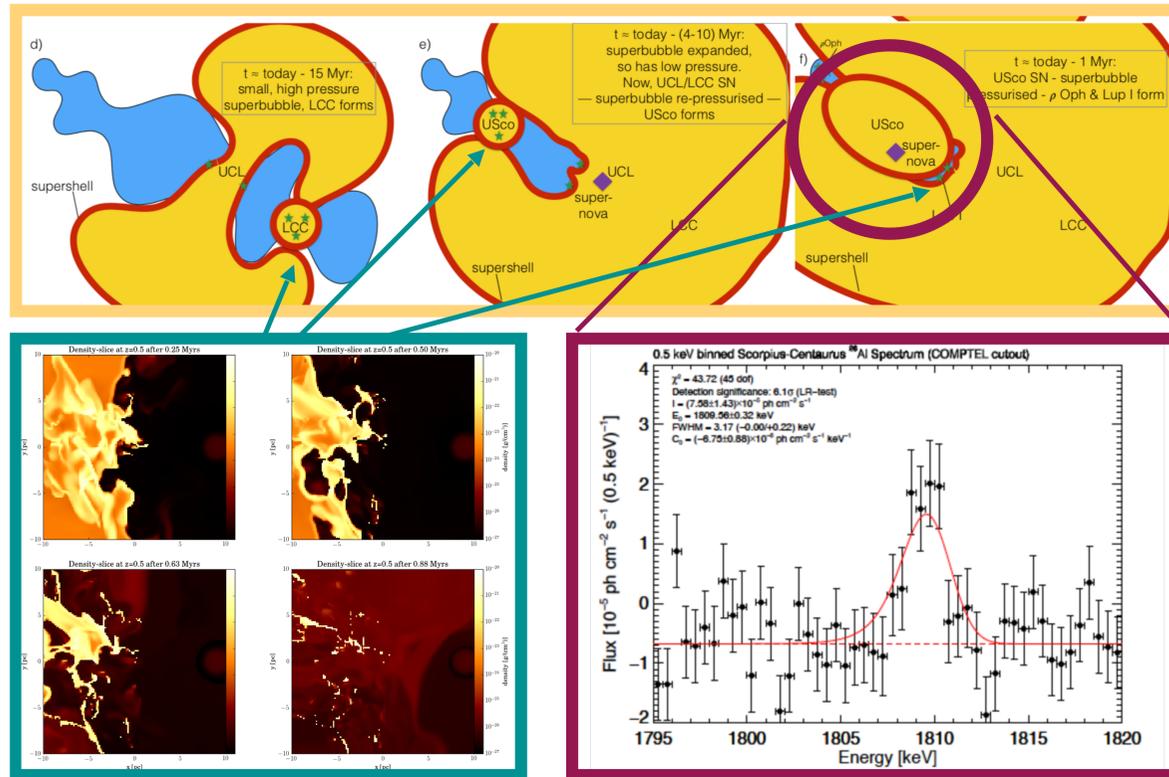
^{26}Al is uniquely produced by massive stars. These stars eject ^{26}Al through their winds and supernova explosions, which have a huge impact on the surrounding interstellar medium. Due to its short, in astronomical terms, decay time of a million years, ^{26}Al serves as evidence of very recent massive star activity. The detection of ^{26}Al towards the Scorpius-Centaurus region, therefore, provides a key piece of evidence in the reconstruction of the history of this massive star forming region.

Groups of stars first start to form in the densest part of a cloud, which in general may have a filamentary/elongated structure. The massive star activity forms a bubble of hot gas, which would be ^{26}Al enriched from massive-star ejecta. Gas may be compressed locally, leading to more star formation, but may also quickly escape along the minor axis of the cloud. In the tenuous medium around the cloud, the overpressured bubble could progress much more quickly than through the dense cloud, and thus reach and compress far-away regions of the cloud. The details of cloud compression and fragmentation of such a superbubble have been simulated and are shown in the bottom left part of the image. The ^{26}Al signal detected by INTEGRAL/SPI is independent proof for massive-star activity within approximately the last million years, and a key part of the study of how massive-star feedback works.

INTEGRAL
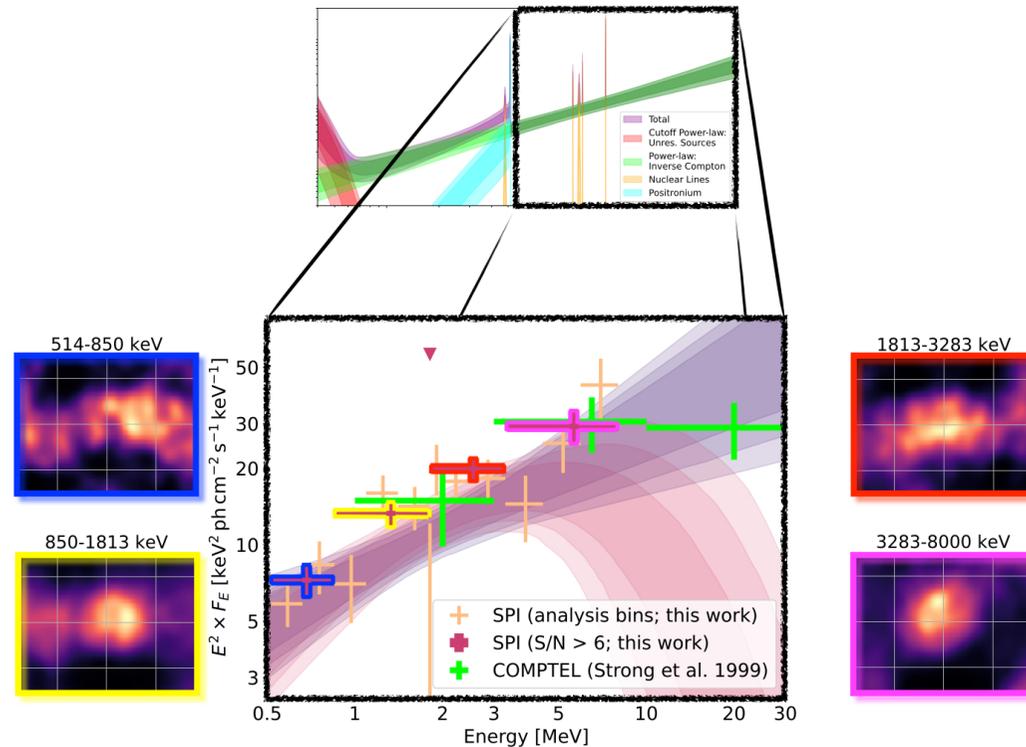
For more than 20 years, the Compton telescope, COMPTEL, onboard NASA's Compton Gamma-Ray Observatory, CGRO, set the standard for measurements of the extended emission of the Milky Way in the MeV range. This photon energy range harbours many emission mechanisms, for example, the annihilation of positrons in the interstellar medium, nuclear decays of radioactive isotopes, or the Inverse Compton scattering of electrons off the interstellar radiation field. These components are indicated in the top panel, showing the diffuse Galactic emission spectrum with its characteristic spectral features [1].

Cosmic-ray GeV electrons scatter off photons from star light in the optical and infrared (IR), as well as the cosmic microwave background (CMB). This scattering produces a smooth spectrum which peaks around 0.1 MeV for the CMB, around 0.5 MeV for IR, and potentially above 10 MeV for optical light. Together this makes the smooth spectrum shown in the zoomed-in panel [2]. Measuring the range between 0.5 MeV up to the limit of INTEGRAL/SPI at 8 MeV therefore constrains the transport properties of electrons as they scatter in IR and optical light.

With more than 16 years of data, SPI was able to set a new record in determining the diffuse emission spectrum in the 0.5-8.0 MeV band. The four coloured data points shown have a signal-to-noise ratio of 6 or more, superseding the data quality and precision of COMPTEL (green). The projections of the measured photons above the strong instrumental background [3] is shown for the four data points surrounding the bottom panel: there is clearly flux originating from the Galactic plane.

In this study, it was possible to test extreme assumptions on the propagation of GeV electrons: it appears that one common diffusion coefficient of 0.5 for the entire cosmic-ray electron spectrum best matches the INTEGRAL/SPI data. Another important finding in the work is that the absolute normalisation of most propagation models is a factor of 2-3 below the measurements, opening up the possibility of even more emission components such as unresolved point sources.

INTEGRAL
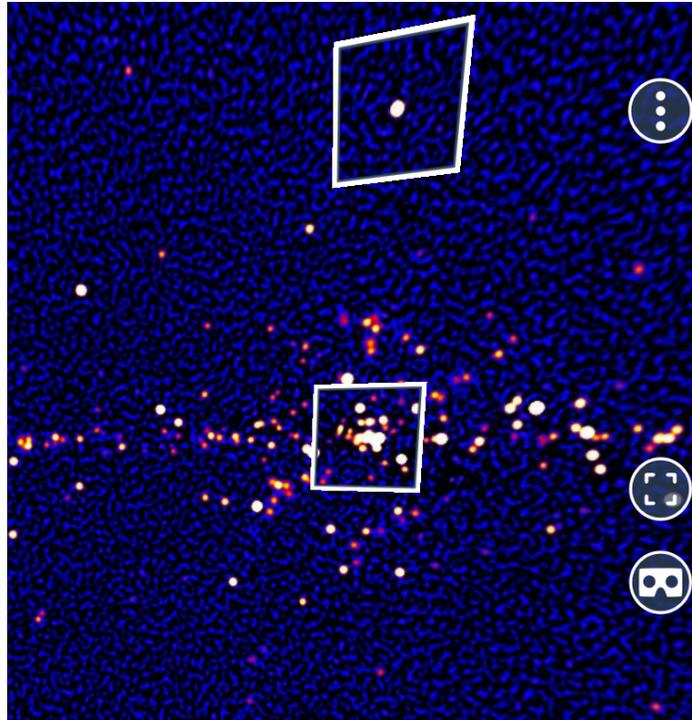
Thanks to the long-term operations of INTEGRAL, a large archive of unique observations of the hard X-ray sky has been accumulated. Taking advantage of the data gathered over 17 years with IBIS, a survey of hard X-ray sources in the 17-60 keV band has been conducted. The survey provides also flux information in different energy bands up to 290 keV. This new hard X-ray all-sky survey includes a number of deep extragalactic fields and the deepest ever hard X-ray survey of our Galaxy. The catalog of sources includes 929 objects detected on time-averaged sky map regions, i.e., mainly dominated by persistent hard X-ray emitters. Among the identified sources of known or suspected nature, 376 are associated with the Galaxy and Magellanic clouds, including 145 low-mass and 115 high-mass X-ray binaries, 79 cataclysmic variables, and 37 of other types. 440 are extragalactic, including 429 active galactic nuclei (AGNs), 2 ultra-luminous sources, one supernova (AT2018cow) and 8 galaxy clusters. 113 sources remain unclassified. 46 of these objects are detected in the hard X-ray band for the first time.

INTEGRAL
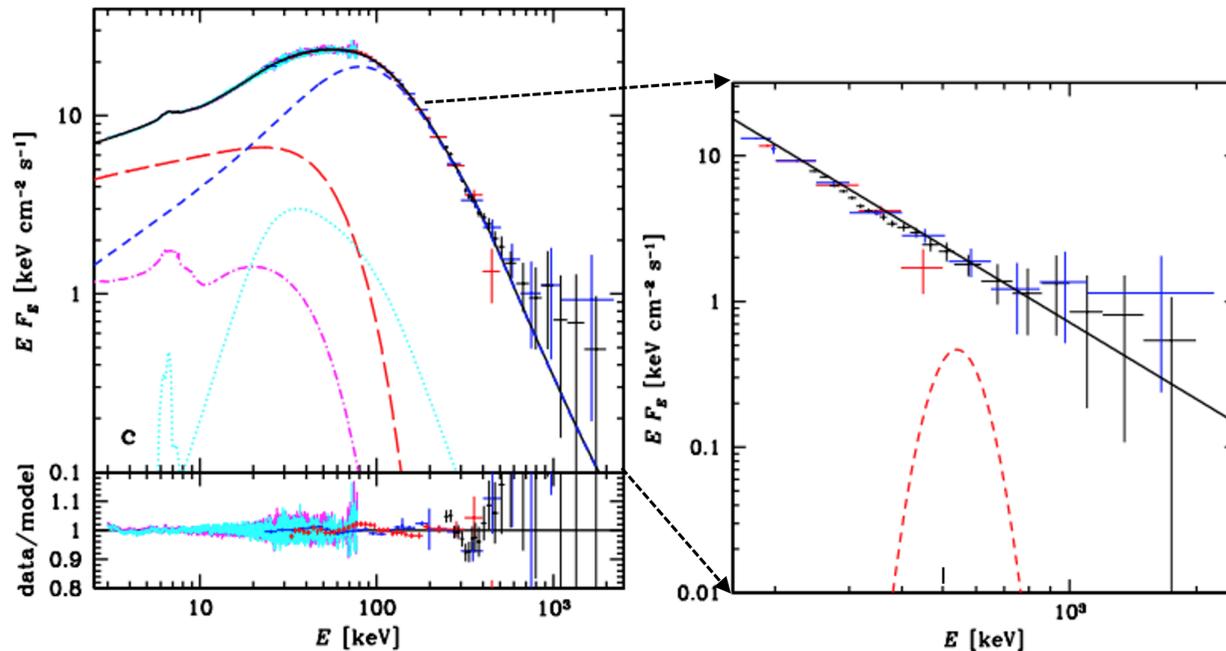
MAXI J1820+070 is a transient X-ray stellar binary, where matter outflowing from a low-mass donor star feeds a black hole. In March 2018, it had a spectacular outburst, during which it shined very bright X-rays and soft gamma-rays, observed by several satellite observatories, including INTEGRAL. The brightening lasted about half a year, during which the heated-up infalling gas shined several tens of thousand times stronger than the Sun.

A study based on INTEGRAL's main instruments, the spectrometer SPI and the imager IBIS, as well as the Nuclear Spectroscopic Telescope Array (NuSTAR) X-ray observatory focuses on modelling physical processes responsible for the observed high-energy photon energy distributions. During the initial rise of the outburst, the dominant physical process is Compton scattering, in which electrons moving with velocities comparable to the speed of light scatter some soft X-rays. In this process, the photon energy is amplified by a large factor, up to the hard X-ray and soft gamma-ray ranges. The electron distribution can be characterized by a temperature of a billion (109) Kelvin.

However, using INTEGRAL data, it appears that this distribution could no longer be described entirely by one temperature, since it showed a strong tail at high energies, consisting of electrons with energies many times the average thermal energy. The broad-band spectrum from Compton scattering is shown in the left panel of the image. The photons produced by the electron distribution tail were found to cross the threshold for production of electron-positron pairs, at 511 keV. Therefore, the presence of such pairs is expected, as well as their subsequent annihilation, which would give rise to a broadened line centred close to 511 keV. However, none was found, as shown in the right panel of the image. The maximum possible strength of such annihilation feature compatible with the data is shown by the red dashed curve. The consequence of this finding is that the size of the emitting plasma is relatively large, at least a few tens times the radius of the gravitational horizon of the black hole. This has important implications for theories of the mass flow onto black holes.

INTEGRAL
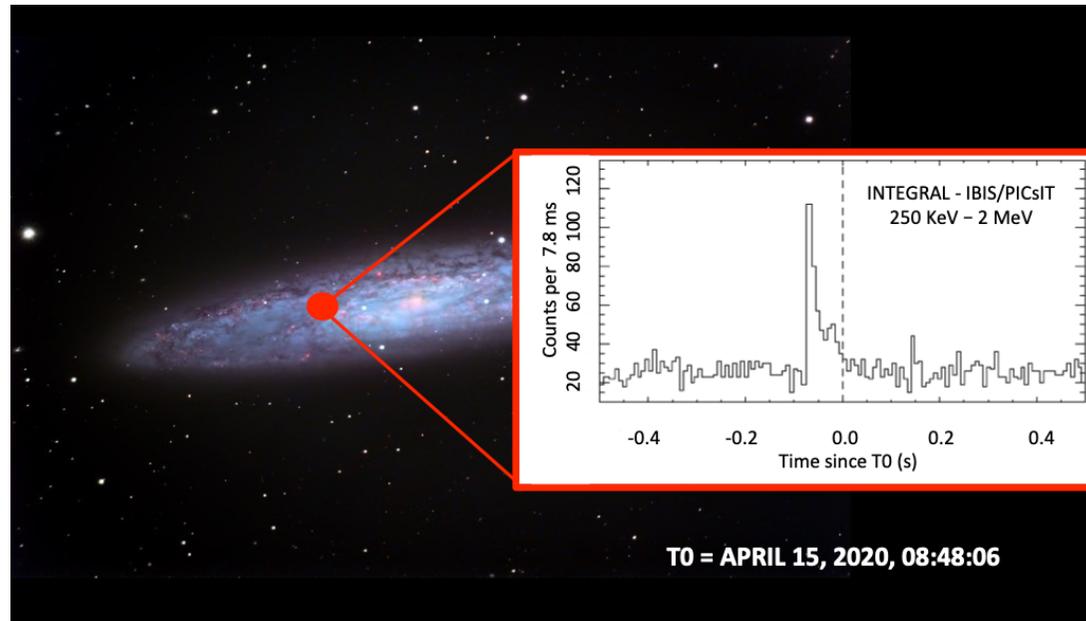
On 15 April 2020 a short and strong gamma-ray burst (GRB) was detected by several Gamma-ray satellites, featuring a fast rise time followed by an order of magnitude weaker tail. Shortly before 8:42 UT, GRB200415A triggered the Russian High-Energy Neutron Detector aboard NASA's Mars Odyssey satellite; about 400 sec later the burst triggered the Russian Konus instrument aboard NASA's Wind satellite. Finally, 4.5 sec later, the signal reached the Earth environment and triggered INTEGRAL's SPI and IBIS instruments, NASA's Fermi instruments and the Atmosphere-Space Interactions Monitor (ASIM) aboard the International Space Station (ISS). The light curve shown in the image is the burst as detected by the bottom layer of INTEGRAL/ISGRI, i.e., the PiCsIT instrument.

Taking advantage of the multiple detections from several spacecrafts orbiting in different parts of the Solar system, it was possible to locate the origin of the GRB emission within a narrow error box region: the radiation came from an extremely magnetized neutron star located in the neigh-boring galaxy NGC 253, know as the Sculptor galaxy. The background image shows an optical image of NGC 253, with a red dot indicating the origin of the burst.

This finding confirms that extremely powerful gamma-ray bursts are possibly generated by magnetars (neutron stars with extremely high magnetic fields of the order of 1014 to 1015 Gauss) in relatively close galaxies. During an active phase magnetars can emit random - milliseconds to several seconds long - hard-X-ray bursts, with peak luminosities of 1036 to 1043 erg per second, while giant flares, which are rare, emit at energies of about 1044 to 1046 erg. Such giant flares from other galaxies are detectable from instruments aboard satellites orbiting Earth or travelling in the Solar system.

A portion of the second-long initial pulse of a giant flare, similar to the one detected from the Sculptor galaxy, in some respect mimics short GRBs, which have recently been identified as the result from the merger of two neutron stars accompanied by gravitational-wave emission, i.e., GRB170817A and GW170817.

INTEGRAL
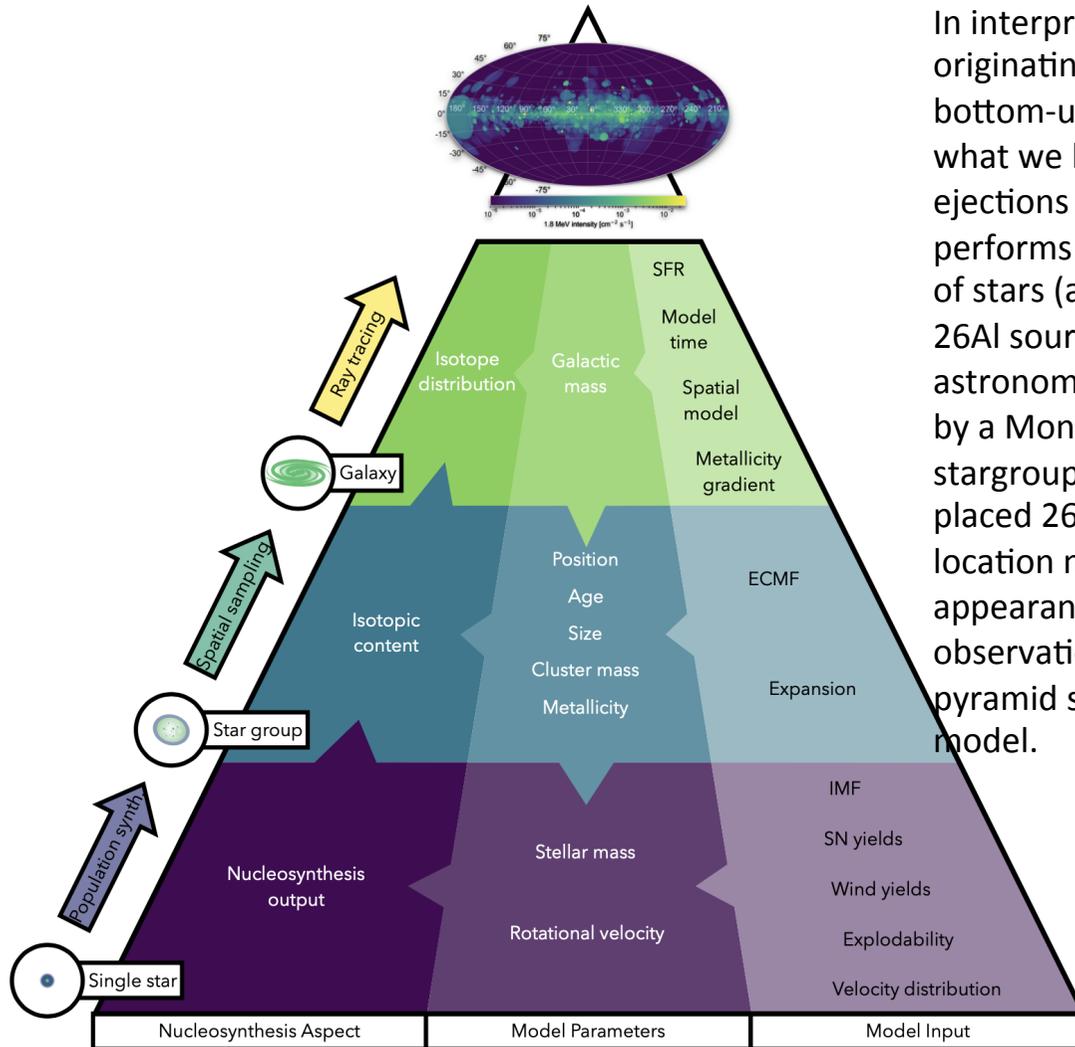
In interpreting the INTEGRAL/SPI data from radioactive 26Al originating from Galactic nucleosynthesis sources, a new bottom-up concept has been established. This starts from what we know about stellar evolution and the yields of 26Al ejections from massive stars and their supernovae, then performs a population synthesis modelling of coeval groups of stars (as done before). Now we exploit this modeling of 26Al sources, and place stellar-group components to where astronomical knowledge tells us they are, supplement this by a Monte-Carlo sample from a large-scale Galactic stargroup distribution, and perform ray tracing of the so-placed 26Al sources to INTEGRAL observations here at our location near the Sun. The top figure shows the modelled appearance of the 26Al sky, which is remarkably close to observations, see, e.g., INTEGRAL POM March 2015. The pyramid shows how different components add up to this model.

INTEGRAL
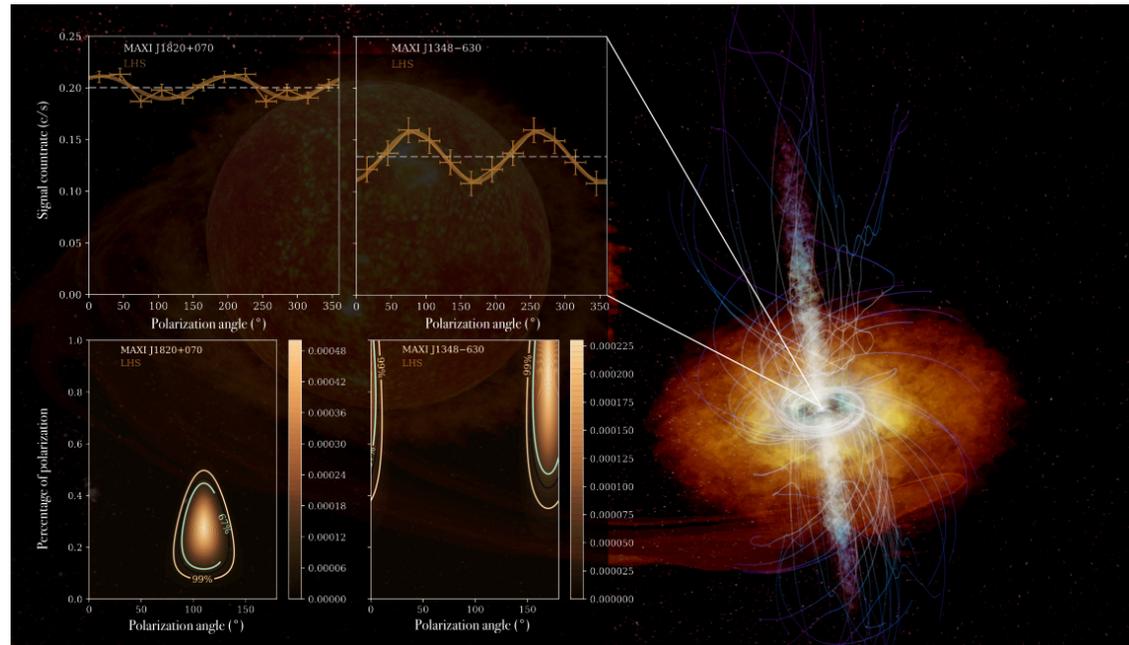
In black hole X-ray binaries, a non-thermal high-energy component is sometimes detected at energies above 200 keV and extending up to 1 MeV (see, e.g., INTEGRAL POM's July 2007, January 2012, December 2018, May 2021). The origin of this high-energy emission is still not well understood and (at least) two scenarios have been invoked to explain its origin. In the first scenario, this component is the extension of the synchrotron spectrum from the basis of the jets. The alternative explanation suggests that this component arises from a non-thermal distribution of electrons in a plasma located close to the black hole. Polarization measurements of the high-energy emission from these sources is probably the best way to disentangle between these different scenarios, as we expect distinct polarization properties between Compton and synchrotron emission. INTEGRAL can bring important insights into polarization measurements (see, e.g., INTEGRAL POM's April 2011, December 2012, July 2021), thanks to the design of the IBIS telescope which can be used as a Compton telescope with its two detector layers, ISGRI and PICsIT. In this study, we present the evolution of the outbursts of three different sources as observed by INTEGRAL: MAXI J1535-571, MAXI J1820+070, and MAXI J1348-630. We make use of INTEGRAL's unique capabilities to probe in particular the polarization properties of the high-energy emission in these three sources. As shown in the figures at the top, a strong modulation of the signal as a function of the angle on the detector plane has been found in the hard states of MAXI J1820+070 and MAXI J1348-630, indicating a polarized emission above 300 keV for these two sources. The measured polarization fraction is 26+/-9% (shown on the left bottom figure) for MAXI J1820+070, which could either indicate emission from the jets base or from a non-thermal plasma located close to the plasma. For MAXI J1348-630, we have measured a strong polarization fraction, >56%, which points towards a jet origin (shown on the right bottom figure).

Galactic Sources

Accretion disk formation

Matter circulates around the compact object:

ang mom outwards

matter inwards
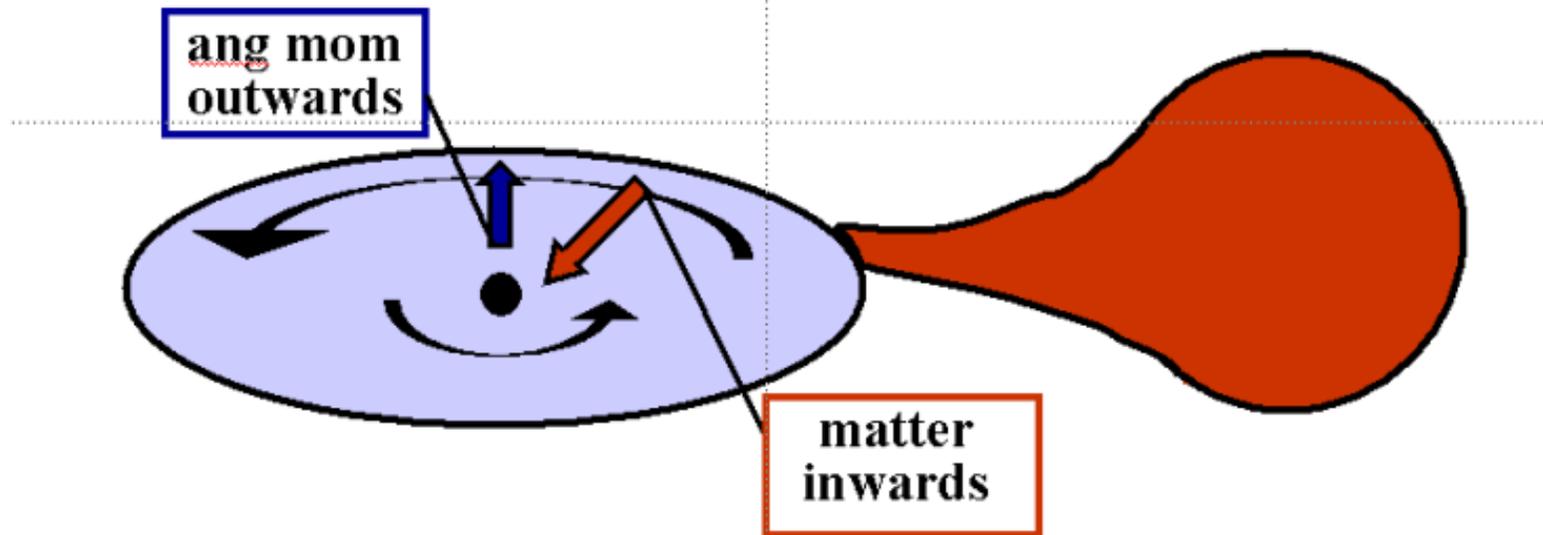
https://mssl.ucl.ac.uk/www_astro/lecturenotes/hea/hea.html

Galactic Sources
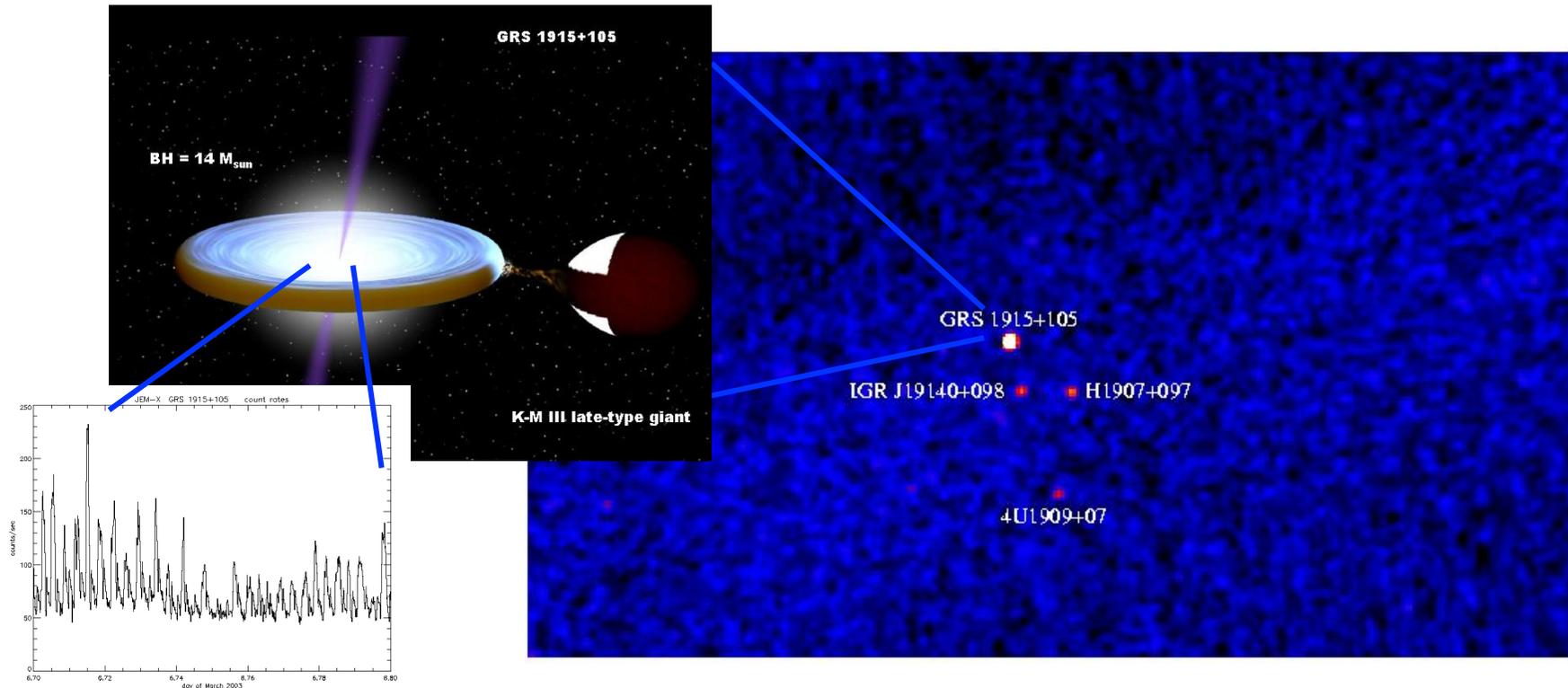
Galactic Sources
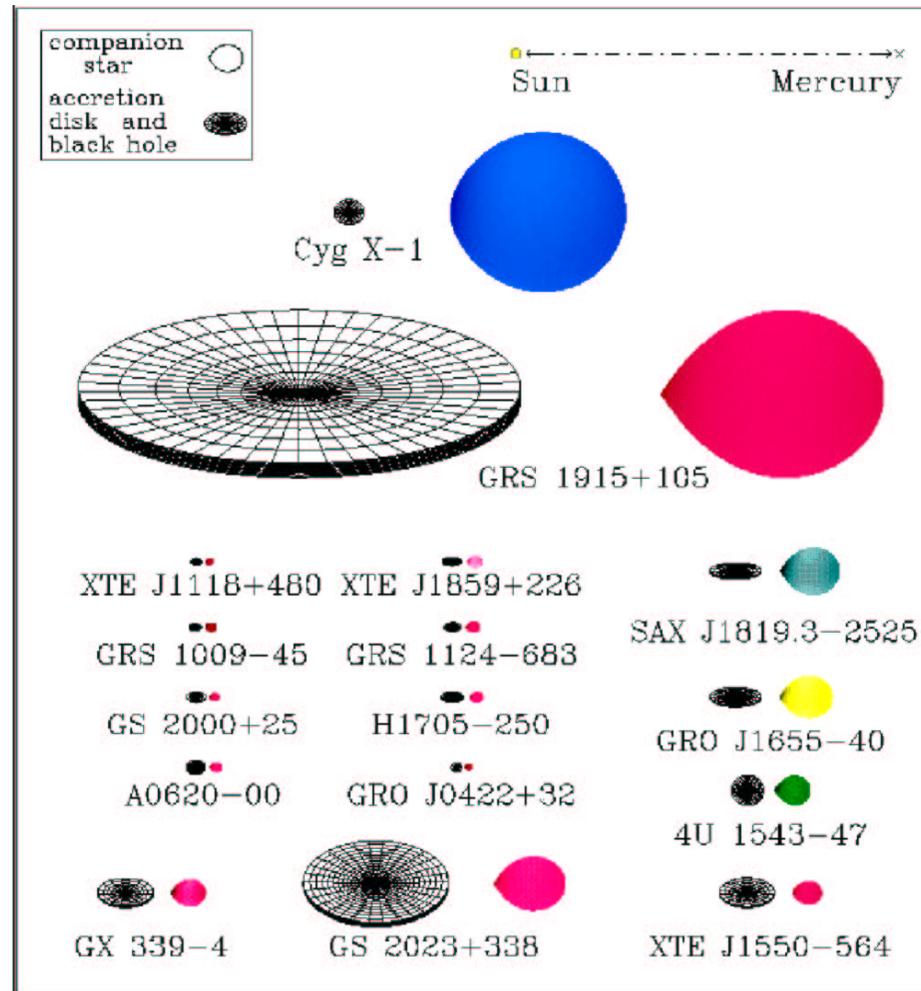
Credit: Jerome A. Orosz

26

Accretion

Types of X-ray Binaries

Group I	Group II
Luminous (early, massive opt countpart) *(high-mass systems)* hard X-ray spectra *(T>100 million K)* often pulsating *X-ray eclipses* Galactic plane *Population I*	Optically faint (blue) opt counterpart *(low-mass systems)* soft X-ray spectra *(T~30-80 million K)* non-pulsating *no X-ray eclipses* Gal. Centre + bulge *older, population II*

Accretion Power

Accretion onto a compact object

- Principal mechanism for producing high-energy radiation

- Most efficient of energy production known in the Universe.

$$E_{acc} = G\frac{Mm}{R}$$

Gravitational potential energy released for body mass M and radius R when mass m accreted

Accretion Power

Example - neutron star

Accreting mass m=1kg onto a neutron star:

$\bullet$ **m**

neutron star mass = 1 solar mass

R = 10 km

=> $\sim 10^{16}$ m Joules,

ie approx 10^{16} Joules per kg of

M

R

accreted matter - as electromagnetic radiation
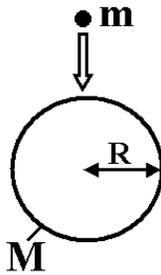
Efficiency of accretion

- Compare this to nuclear fusion
  H => He releases ~ 0.007 mc^2
  ~ 6 x 10^{14} m Joules - **20x smaller** (for ns)

$$E_{acc} = G \frac{Mm}{R}$$

So energy released proportional to M/R ie the more compact a body is, the more efficient accretion will be.

Accretion Power

Origin of accreted matter

- Given M/R, luminosity produced depends on accretion rate, $\dot{m}$.

$$L_{acc} = \frac{dE_{acc}}{dt} = \frac{GM}{R}\frac{dm}{dt} = \frac{GM\dot{m}}{R}$$

- Where does accreted matter come from? ISM? No - too small.   Companion? Yes.

Accretion Power

The Eddington Luminosity

- There is a limit to which luminosity can be produced by a given object, known as the Eddington luminosity.

- Effectively this is when the inward gravitational force on matter is balanced by the outward transfer of momentum by radiation.

Accretion Power

Eddington Luminosity

M   r   m

F_{grav} F_{rad}

Accretion rate controlled by momentum transferred from radiation to mass
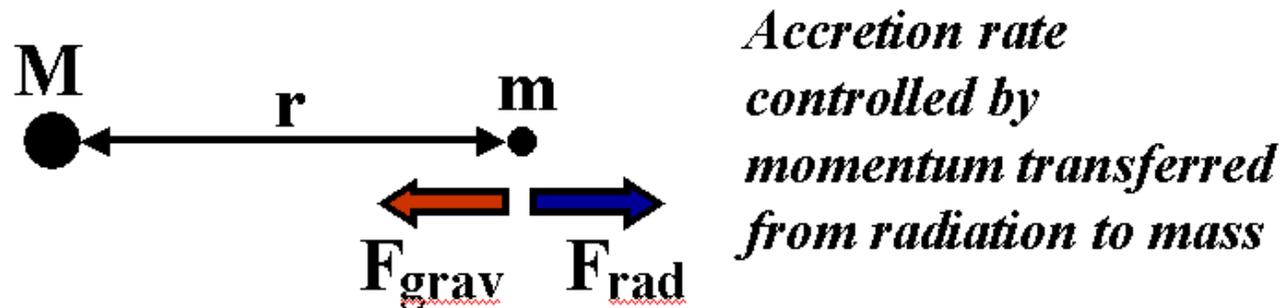
$$F_{grav} = G\frac{Mm}{r^2} Newton$$

Note that R is now negligible wrt r

Outgoing photons from M scatter material (electrons and protons) accreting.

Accretion Power

Scattering

L = accretion luminosity

$$\begin{array}{l}\textbf{no. photons} \\ \textbf{crossing at r} \\ \textbf{per second}\end{array} = \frac{L}{4\pi r^2}\frac{1}{h\nu} \quad \text{photons m}^{-2}\text{ s}^{-1}$$

Scattering cross-section will be Thomson cross-section σ_e; so no. scatterings per sec:

$$\frac{L\sigma_e}{4\pi r^2 h\upsilon}$$

Accretion Power

Momentum transferred from photon to particle:

$$\dfrac{h\nu}{c}$$
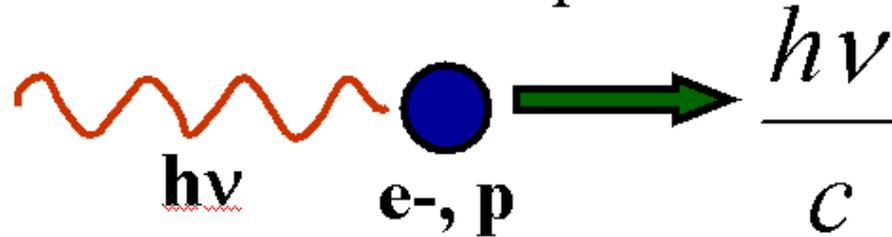
Momentum gained by particle per second
= force exerted by photons on particles

$$\frac{L\sigma_e}{4\pi r^2 h\upsilon}\frac{h\nu}{c} = \frac{L\sigma_e}{4\pi r^2 c}\,Newton$$

34

Accretion Power

Eddington Limit

radiation pressure = gravitational pull

At this point accretion stops, effectively imposing a 'limit' on the luminosity of a given body.

$$\frac{L\sigma_e}{4\pi r^2 c} = G\frac{Mm}{r^2}$$

So the Eddington luminosity is:

$$L = \frac{4\pi c G M m}{\sigma_e}$$

Accretion Power

Assumptions made

- **Accretion flow steady + spherically symmetric:** eg. in supernovae, L_{Edd} exceeded by many orders of magnitude.

- **Material fully ionized and mostly hydrogen**: heavies cause problems and may reduce ionized fraction - but OK for X-ray sources

Accretion Power

Accretion modes in binaries

ie. binary systems which contain a compact
star, either white dwarf, neutron star or
black hole.

(1) <u>Roche Lobe overflow</u>

(2) <u>Stellar wind</u>

- correspond to different types of X-ray
binaries

Accretion

Roche Lobe Overflow

- Compact star M_1 and normal star M_2
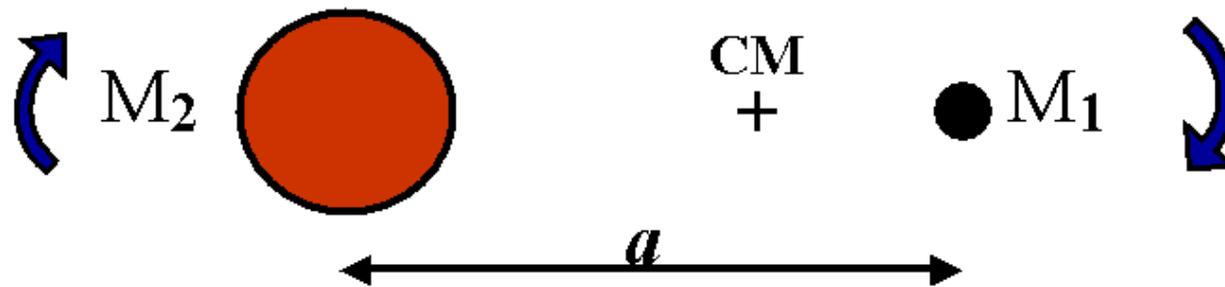
- normal star expanded or binary separation
  decreased => normal star feeds compact

Accretion

Matter circulates around the compact object:

ang mom outwards

matter inwards
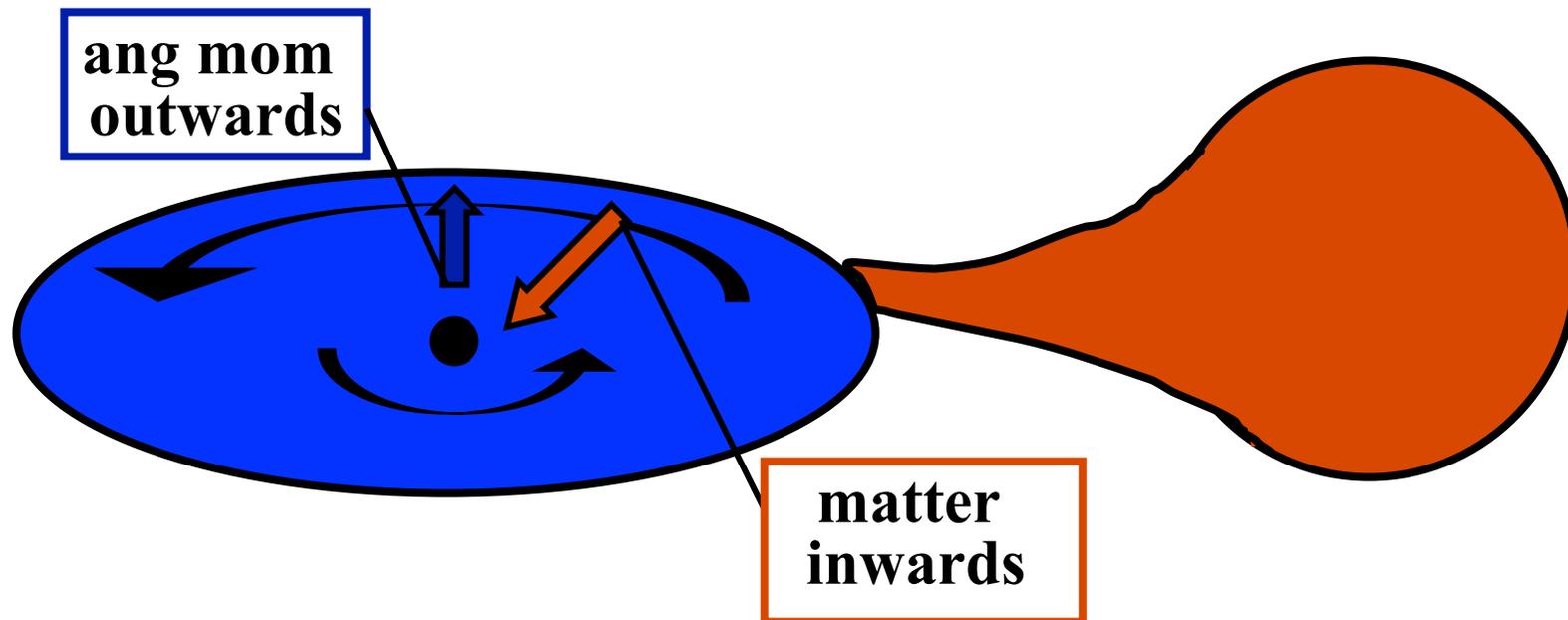
Accretion

Energy losses from the disk

R

$$E_{bind} = \frac{GMm}{2R} \quad \text{and} \quad L_{bind} = \frac{GM\dot{M}}{2R}$$

$$E_{bind} \sim 0$$

So the energy which has been lost in the disk by m is:

$$E_{disk} = \frac{GMm}{2R} \quad \text{and} \quad L_{disk} = \frac{GM\dot{M}}{2R}$$

$$= \tfrac{1}{2}L_{acc}$$
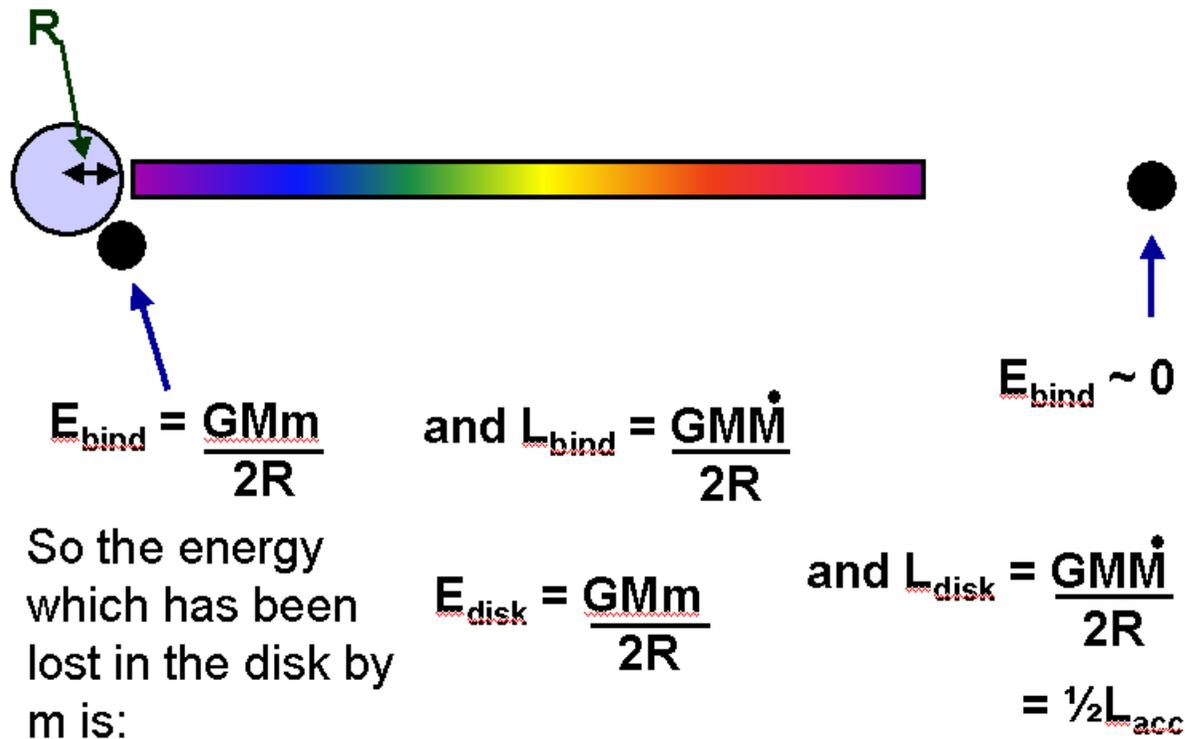
Disk structure

Half of the accretion luminosity is
released very close to the star.

X-ray   UV   optical   bulge

**Hot, optically-thin
inner region; emits
bremsstrahlung**

**Outer regions are cool,
optically-thick and emit
blackbody radiation**
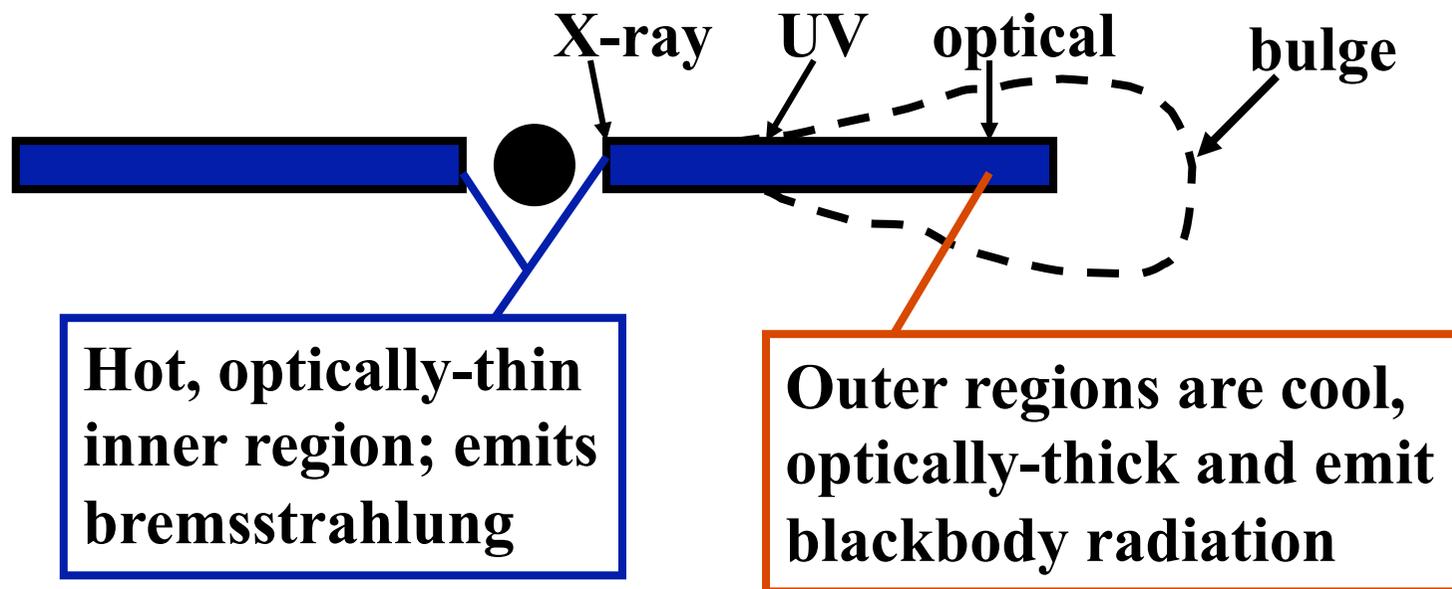
Stellar Wind Accretion

Stellar Wind Model

Early-type stars have intense and highly supersonic winds. Mass loss rates - 10^{-6} to 10^{-5} solar masses per year.

For compact star - early star binary, compact star accretes if

$$\frac{GMm}{r} > \frac{1}{2} m(v_w^2 + v_{ns}^2)$$

Stellar Wind Accretion

Thus :

$$r_{acc} = \frac{2GM}{v_w^2 + v_{ns}^2}$$

r_{acc}

bow shock
matter collects in wake
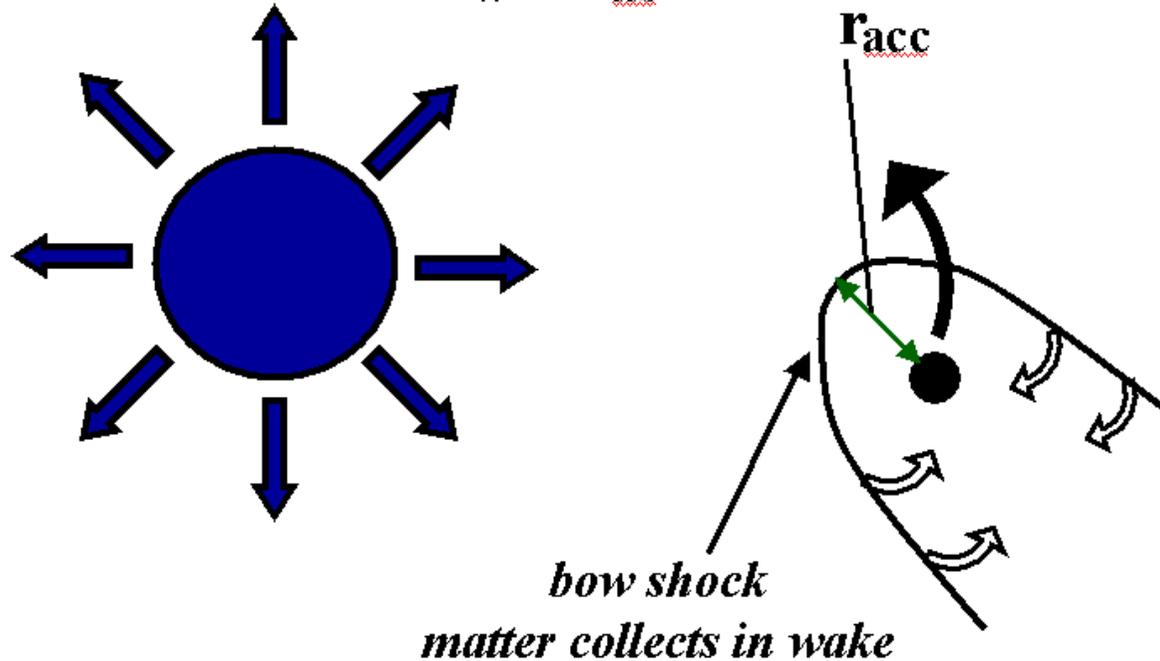
Compton Imaging

Detection of Gamma Radiation
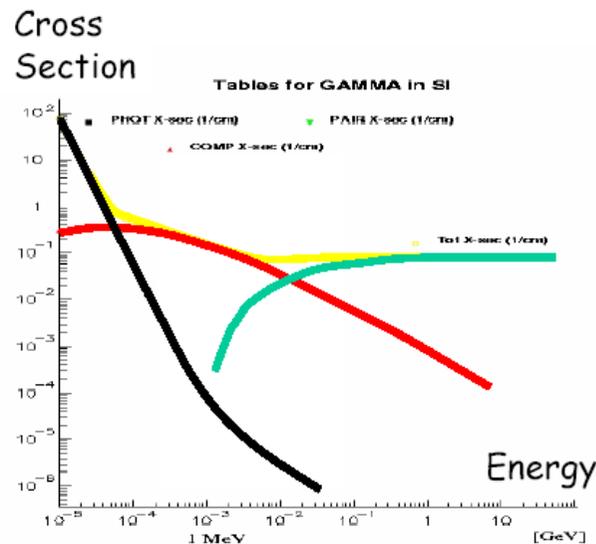
Photoeffect(< 100 keV)

Photons effectively blocked and stopped

Telescopes:

Collimators
Coded Mask Systems

Compton Scattering (0.2-10 MeV)
Photon Crossection Minimum
Scattered photons with long range
Telescope:
Compton Camera Coincidence System

Pair Creation (> 10 MeV)
Photons completely converted to e⁺e⁻

Telescope:
Tracking chambers to visualize the pairs

The Compton Gamma Ray Observatory

http://cossc.gsfc.nasa.gov

The Instruments on CGRO Cover Six Orders of Magnitude in Photon Energy

BATSE · OSSE · COMPTEL · EGRET

10 keV · 100 keV · 1 MeV · 10 MeV · 100 MeV · 1 GeV · 10 GeV · 100 GeV

COMPTON OBSERVATORY INSTRUMENTS
COMPTEL · EGRET · OSSE · BATSE TWO OF EIGHT
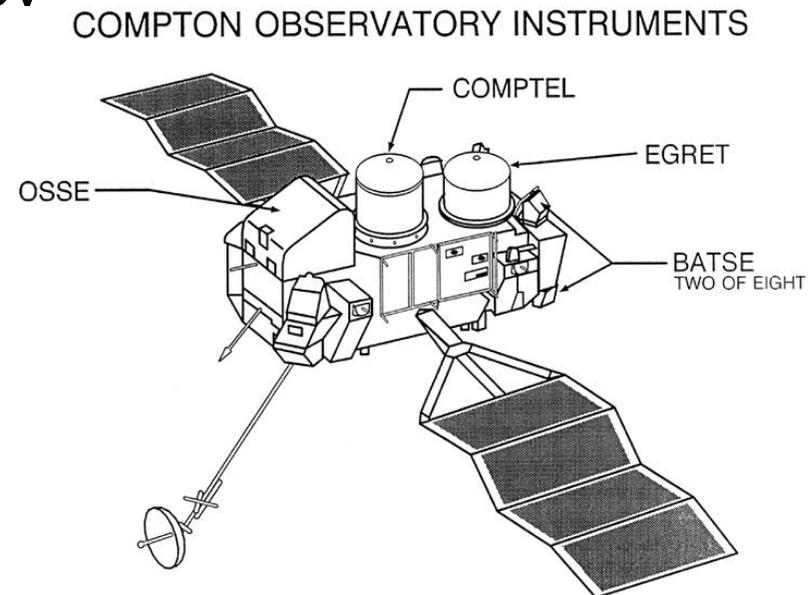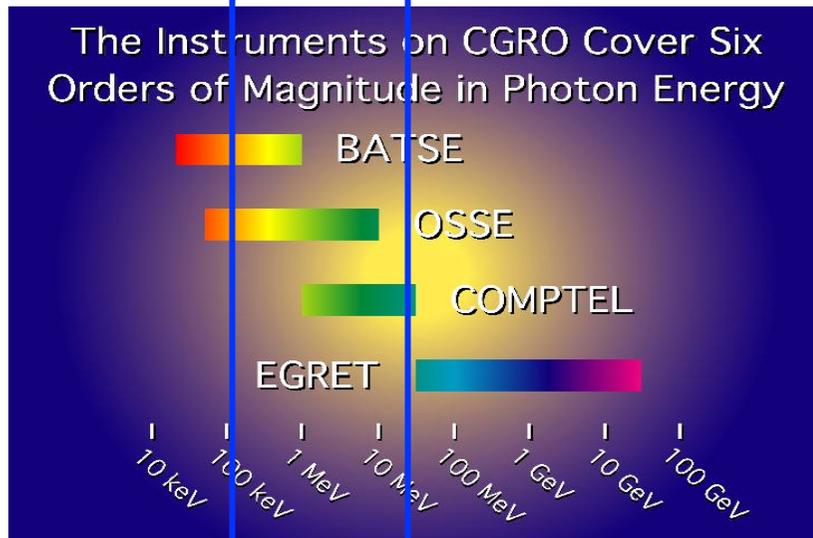
The Compton Gamma Ray Observatory (CGRO) is a sophisticated satellite observatory dedicated to observing the high-energy Universe. It is the second in NASA's program of orbiting "Great Observatories", following the Hubble Space Telescope.

While Hubble's instruments operate at visible and ultraviolet wavelengths, Compton carries a collection of four instruments which together can detect an unprecedented broad range of high-energy radiation called gamma rays. These instruments are the Burst And Transient Source Experiment (BATSE), the Oriented Scintillation Spectrometer Experiment (OSSE), the Imaging Compton Telescope (COMPTEL), and the Energetic Gamma Ray Experiment Telescope (EGRET).

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The Compton Gamma Ray Observatory
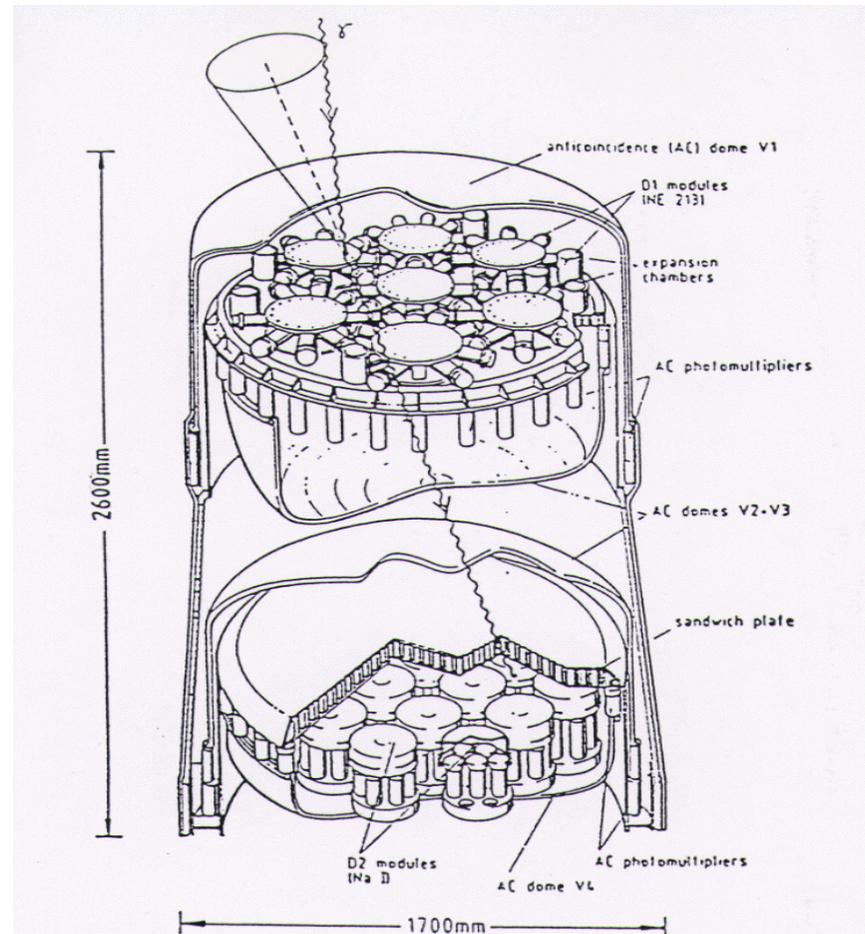
COMPTEL
- 0.05-30 MeV
- Radioactive elements map, pulsars, a flaring black hole candidates, blazars, solar flares

Telescopi Compton

COMPTEL

Gamma-ray

Gamma-ray scattered; light emitted.

Compton scattering

Light recorded.

Gamma-ray absorbed, light pulse emitted, and recorded

Photon absorption
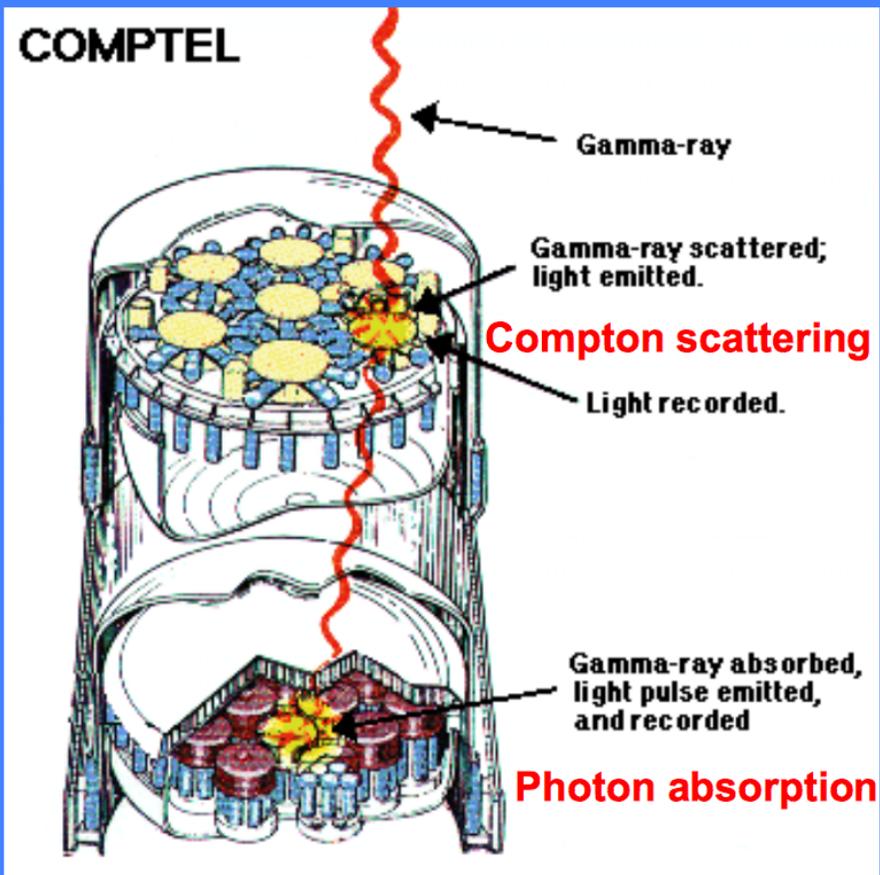
Two-level instruments:
1st level: the γ-ray Compton scatters off an electron in a **liquid scintillator**. The scattered photon enters into a **2nd level scintillator** (NaI) and is absorbed. Phototubes can determine the interaction points at the two layers and record the amount of energy deposited in each layer.

It is possible to reconstruct the angle of incidence the photon made wrt the original direction using the Compton scattering law, linking this angle and the energy of the scattered photon
(2nd level) and the scattering electron (1st level).

"Event circle" (ring on the sky), poor angular resolution (but multiple photons can help to reconstruct the position)

Compton Imaging

COMPTEL on CGRO
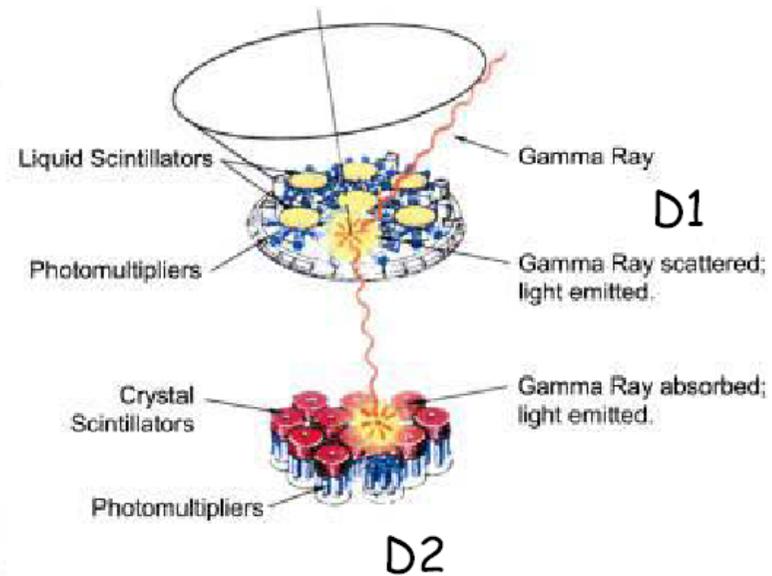
The Compton Gamma Ray Observatory

Table 1: SUMMARY OF *COMPTON* GRO DETECTOR CHARACTERISTICS

	OSSE	COMPTEL	EGRET	BATSE	
				LARGE AREA	SPECTROSCOPY
ENERGY RANGE (MeV)	0.05 to 10.0	0.8 to 30.0	20 to 3 x 10⁴	0.03 to 1.9	0.015 to 110
ENERGY RESOLUTION (FWHM)	12.5% at 0.2 MeV 6.8% at 1.0 MeV 4.0% at 5.0 MeV	8.8% at 1.27 MeV 6.5% at 2.75 MeV 6.3% at 4.43 MeV	~20% 100 to 2000 MeV	32% at 0.06 MeV 27% at 0.09 MeV 20% at 0.66 MeV	0.2% at 0.09 MeV 7.2% at 0.66 MeV 5.8% at 1.17 MeV
EFFECTIVE AREA (cm^2)	2013 at 0.2 MeV 1400 at 1.0 MeV 568 at 5.0 MeV	25.8 at 1.27 MeV 29.3 at 2.75 MeV 29.4 at 4.43 MeV	1200 at 100 MeV 1600 at 500 MeV 1400 at 3000 MeV	1000 ea. at 0.03 MeV 1800 ea. at 0.1 MeV 550 ea. at 0.66 MeV	100 ea. at 0.3 MeV 127 ea. at 0.2 MeV 52 ea. at 3 MeV
POSITION LOCALIZATION (STRONG SOURCE)	10 arc min square error box (special mode; 0.1 x Crab spectrum)	0.5 - 1.0 deg (90% confidence 0.2 x Crab spectrum)	5 to 10 arc min (1σ radius; 0.2 x Crab spectrum)	3° (strong burst)	-------
FIELD OF VIEW	3.8° x 11.4°	~ 64°	~ 0.6 sr	4 π sr	4 π sr
MAXIMUM EFFECTIVE GEOMETRIC FACTOR (cm^2 sr)	13	30	1050 (~ 500 MeV)	15000	5000
ESTIMATED SOURCE SENSITIVITY (5 x10⁵ sec; on source, off Galactic Plane) — LINE	$(3-8)$ x 10^{-5} cm^{-2} s^{-1}	1.5 x 10^{-5} to 6 x 10^{-5} cm^{-2} s^{-1}			0.4% equivalent width (5 sec integration)
ESTIMATED SOURCE SENSITIVITY — CONTINUUM	3 x 10^{-7} cm^{-2} s^{-1} keV^{-1} (@1 MeV)	1.6 x 10^{-4} cm^{-2} s^{-1} (3 σ detection, 1-30 MeV)	7 x 10^{-8} cm^{-2} s^{-1} (> 100 MeV) 2 x 10^{-8} cm^{-2} s^{-1} (> 1000 MeV)	3 x 10^{-8} erg cm^{-2} (1 sec-burst)	

CGRO performance

	BATSE	OSSE	COMPTEL	EGRET
Developer	NASA/Marshall	Naval Research Lab	Univ. N.H. & MPE	NASA/Goddard
Energy Range (MeV)	0.03 to 1.9	0.05 to 10.0	0.08 to 30.0	30.0 to 30000.0
Field of View	entire sky	3.0 x 11.4 degrees	64 degrees	0.6 steradians
Spectral Resolution (FWHM)	32 % at 0.06 MeV 27 % at 0.09 MeV 20 % at 0.66 MeV	12.5 % at 0.2 MeV 5. % at 1.0 MeV 4.0 % at 5.0 MeV	8.8 % at 1.27 MeV 6.5 % at 2.75 MeV 6.3 % at 4.43 MeV	20 %
Effective Area (cm^2)	1000 ea. at 0.03 MeV 1800 ea. at 0.1 MeV 550 ea. at 0.55 MeV	2013 at 0.2 MeV 1400 at 1.0 MeV 55 at 5.0 MeV	25.0 at 1.27 MeV 29.3 at 2.75 MeV 29.4 at 4.43 MeV	1200 at 100 Mev 1600 at 500 MeV 1400 at 3000 MeV
Spatial Resolution (for strong sources)	3 degrees	10 x 10 arcminutes	0.5 - 1.0 degrees	5 - 10 arcminutes

Sensitivity
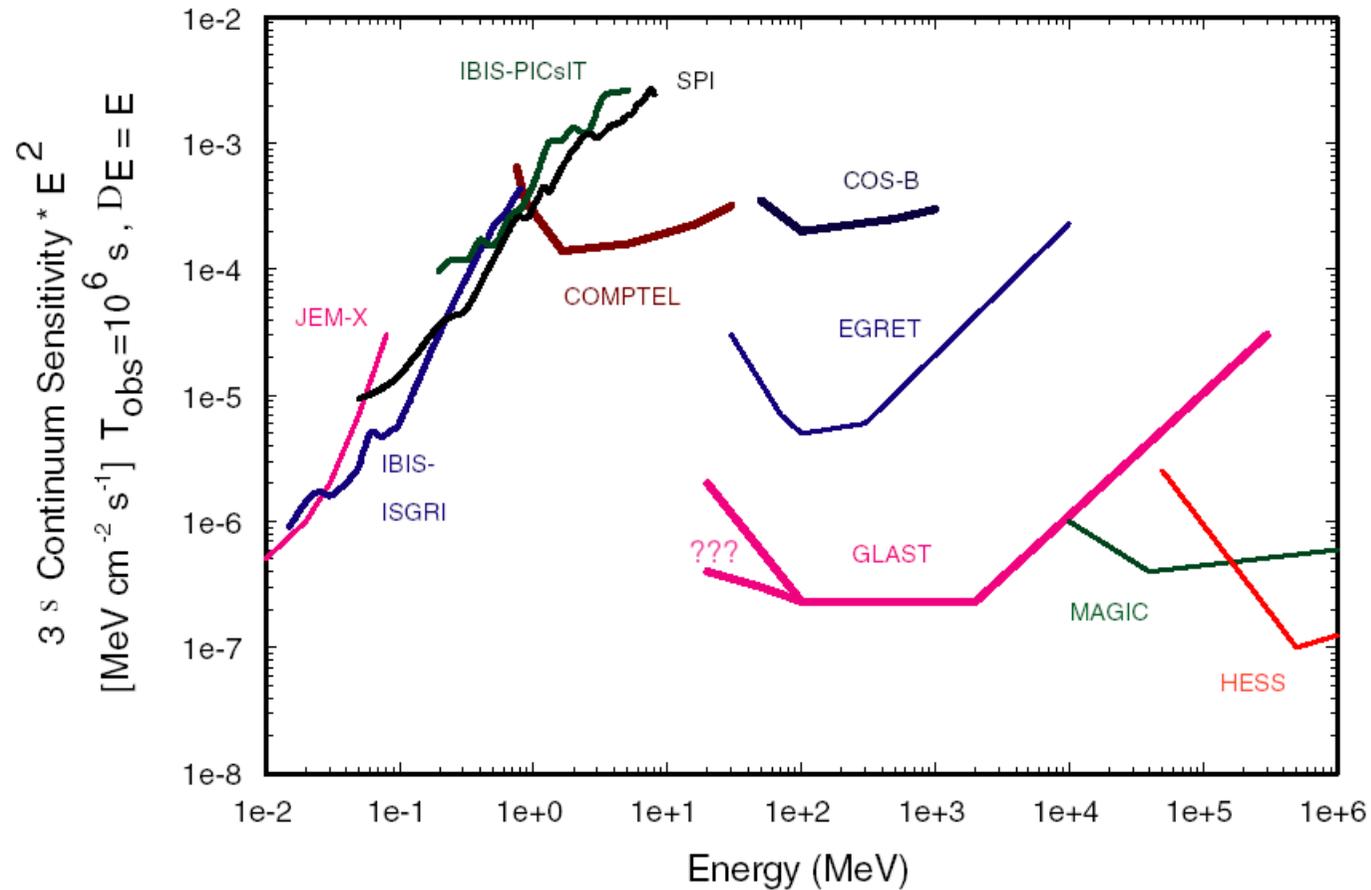
Compton Imaging

Low to Medium Energy Gamma-Ray
Astronomy

or

what is the promise and hope for
astrophysics in the energy range

" few 100 keV to ~ 50 MeV "

???

Compton Imaging

Kinematics
(target at rest)

γ_1, ε_1 , $p_1 = \varepsilon_1/c$

γ_o, ε_0 , $p_o = \varepsilon_o/c$

φ

e^-, $m_o c^2 + T$, p_e
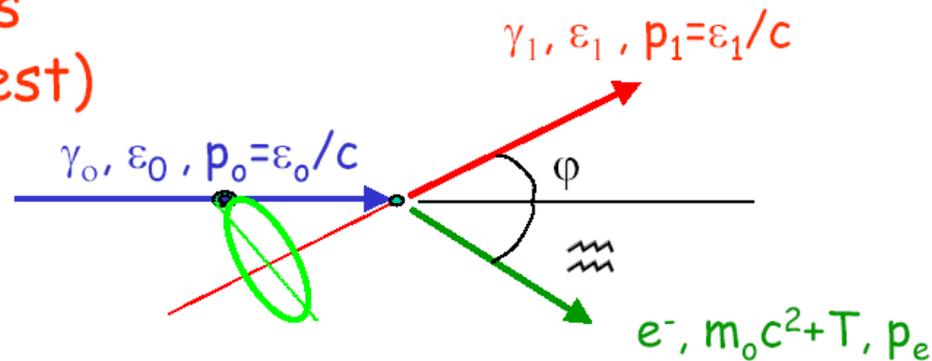
Energy: $\varepsilon_0 = \varepsilon_1 + T$

Momentum:

$\varepsilon_0 = \varepsilon_1 \cos\varphi + pc \cos\vartheta$ where $pc = \sqrt{T(T + 2m_0 c^2)}$

$\varepsilon_1 \sin\varphi = pc \sin\vartheta$

Compton Equation: $\boxed{\cos\varphi = 1 - m_0 c^2 \left(\dfrac{1}{\varepsilon_1} - \dfrac{1}{\varepsilon_0} \right)}$

Compton Imaging

The ‚classical' Compton telescope

$$\cos \varphi = 1 - m_0 c^2 \left(\frac{1}{\varepsilon_1} - \frac{1}{\varepsilon_0} \right)$$
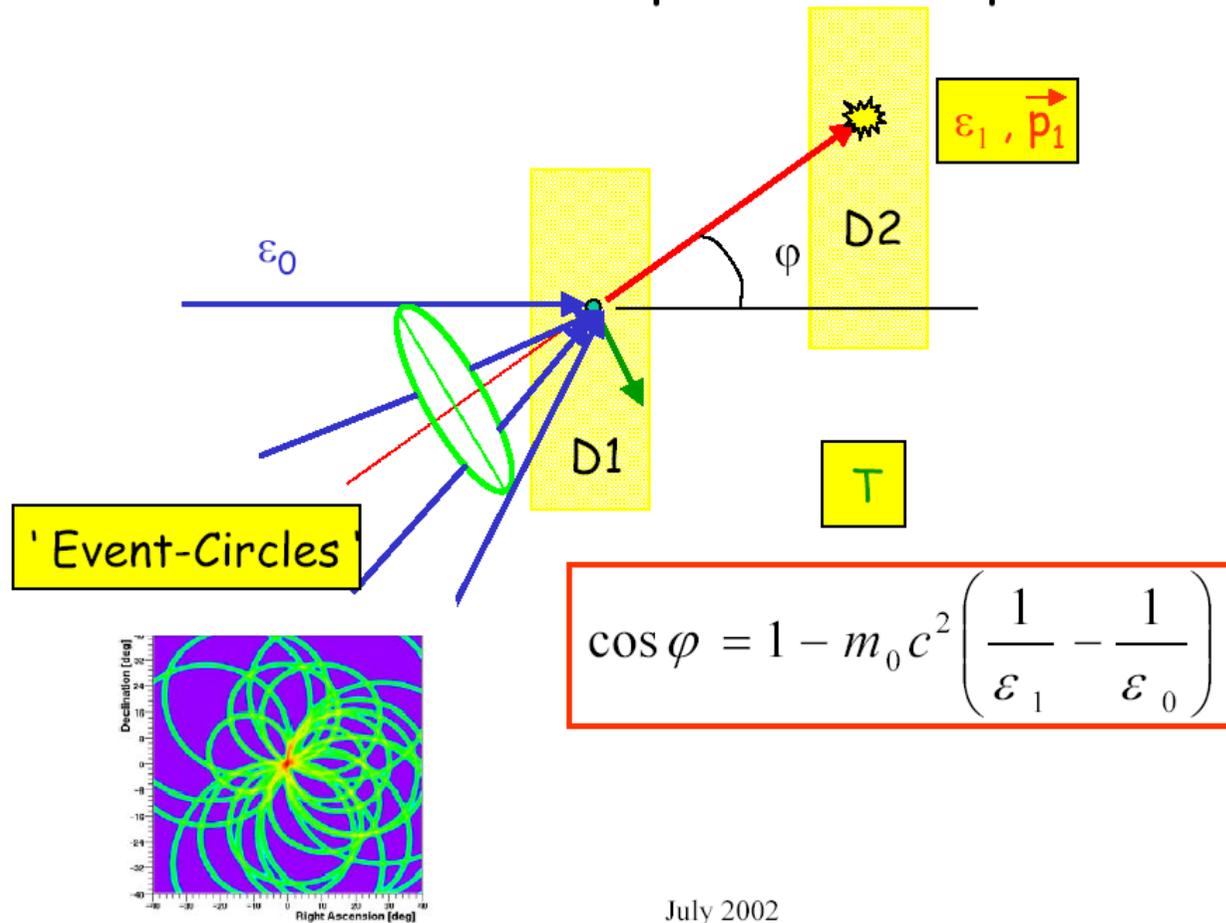
July 2002
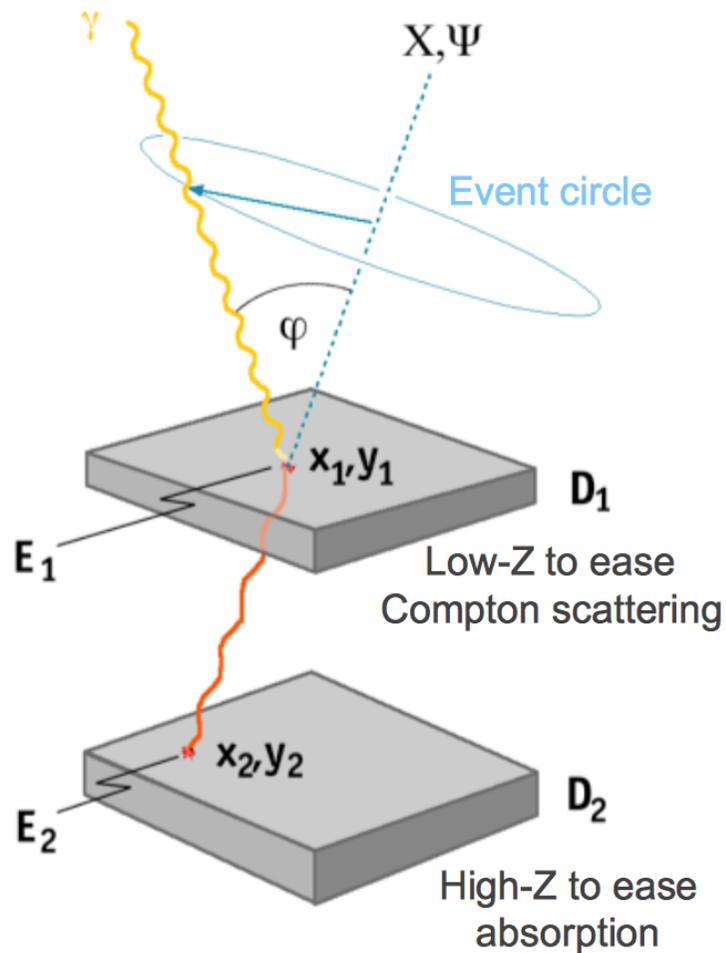
measured parameters :

x_1, y_1	:	interaction location in D_1
E_1	:	energy deposit in D_1
x_2, y_2	:	interaction location in D_2
E_2	:	energy deposit in D_2
$t, \Delta t$	:	arrival time, TOF D_1-D_2

derived parameters :

$$x_1, y_1, x_2, y_2 \Rightarrow \quad \chi, \psi$$
$$E_1, E_2 \Rightarrow \quad \bar{\varphi}$$

$$\cos \phi = 1 - m_e c^2 \left(\frac{1}{E_2} - \frac{1}{E_1} \right)$$

encoding of the two dimensional source
distribution into a 3-D dataspace (X, Ψ, φ)
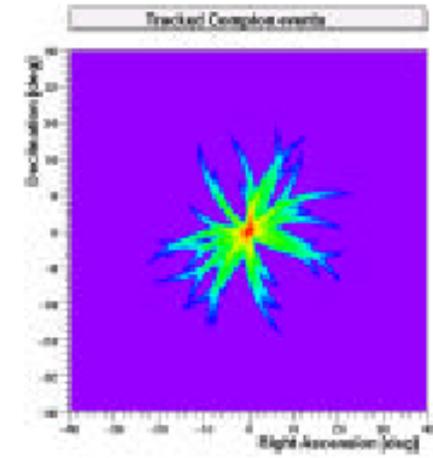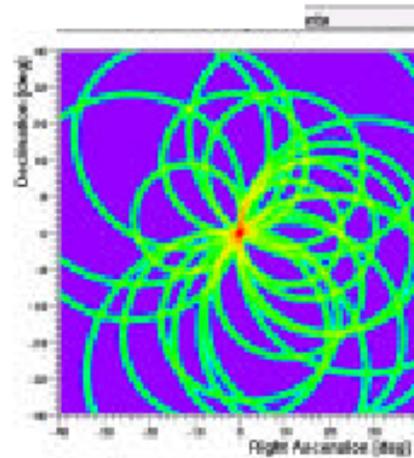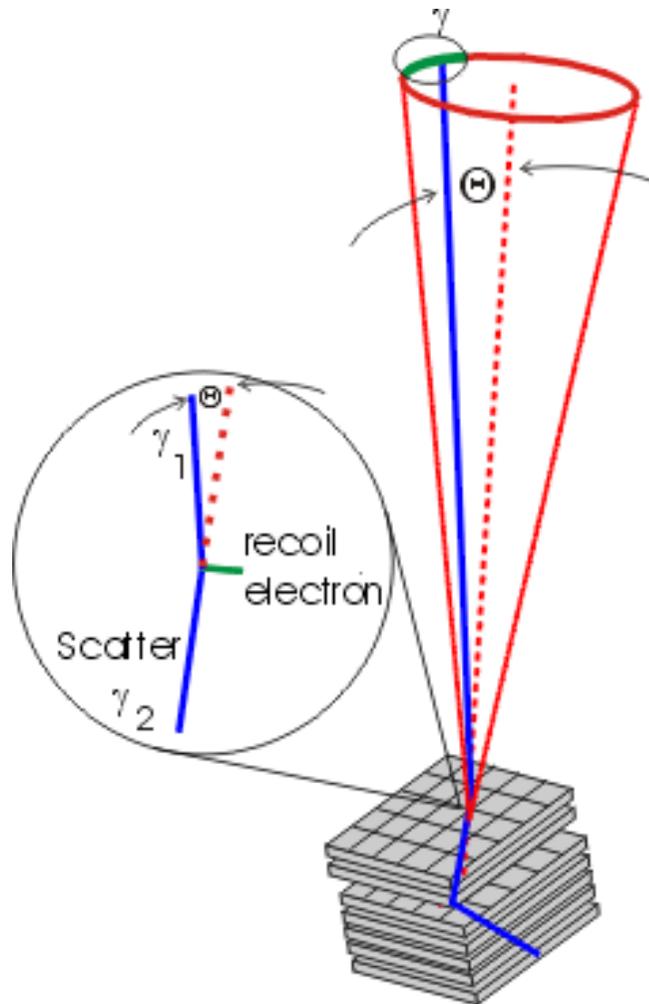
Compton Imaging

Compton Imaging

Coincidence Detector Schematics

Classical Compton Event Circles (no electron tracking)	Reduced Compton circles of events with electron track	Direct imaging of pair-creation events
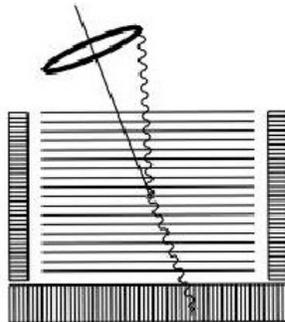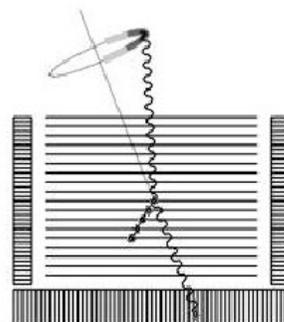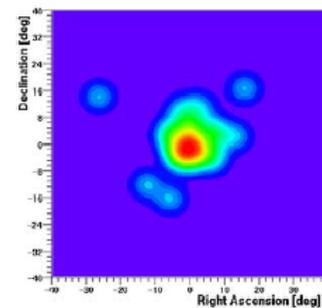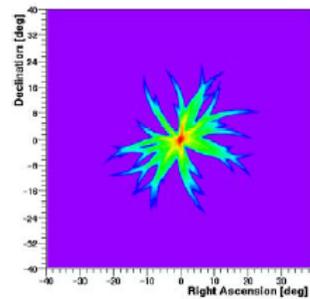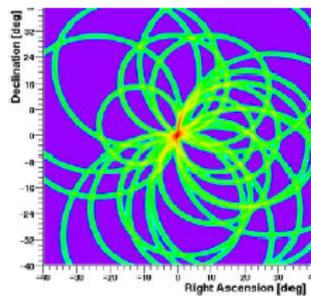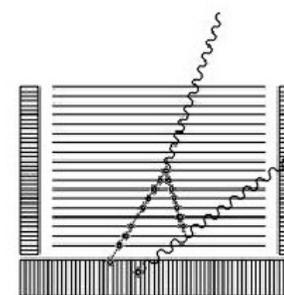
Compton Imaging
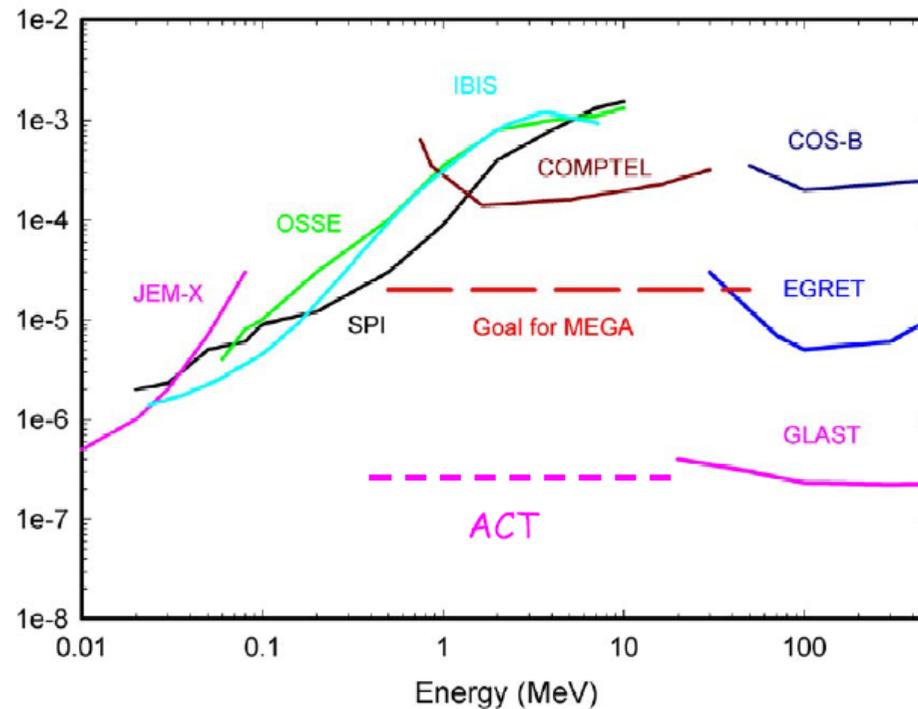
Compton Polarimetry

Compton Polarimetry

Unpolarized Beam

$$\frac{d\sigma_{KN,U}}{d\Omega} = \frac{1}{2}r_0^2\varepsilon^2[\varepsilon + \varepsilon^{-1} - \sin^2\theta]$$
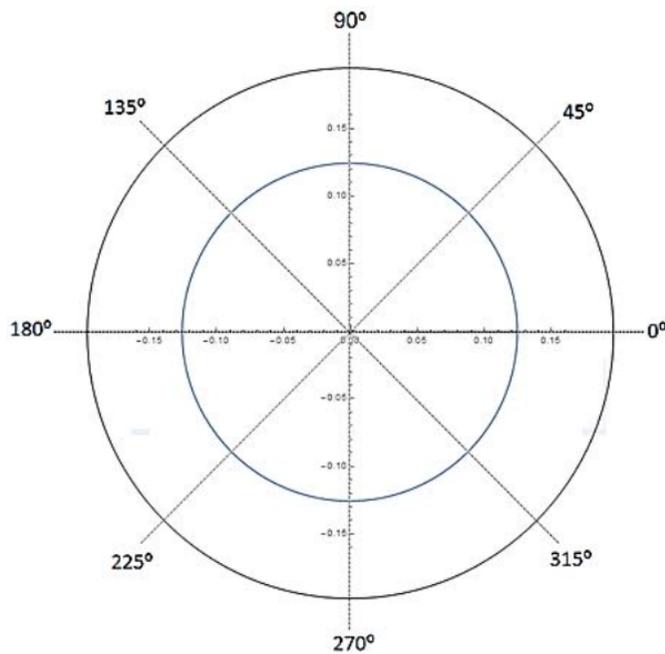
Polarized Beam

$$\frac{d\sigma_{KN,P}}{d\Omega} = \frac{1}{2}r_0^2\varepsilon^2[\varepsilon + \varepsilon^{-1} - 2\sin^2\theta\cos^2\eta]$$

100%

Polarization direction

3
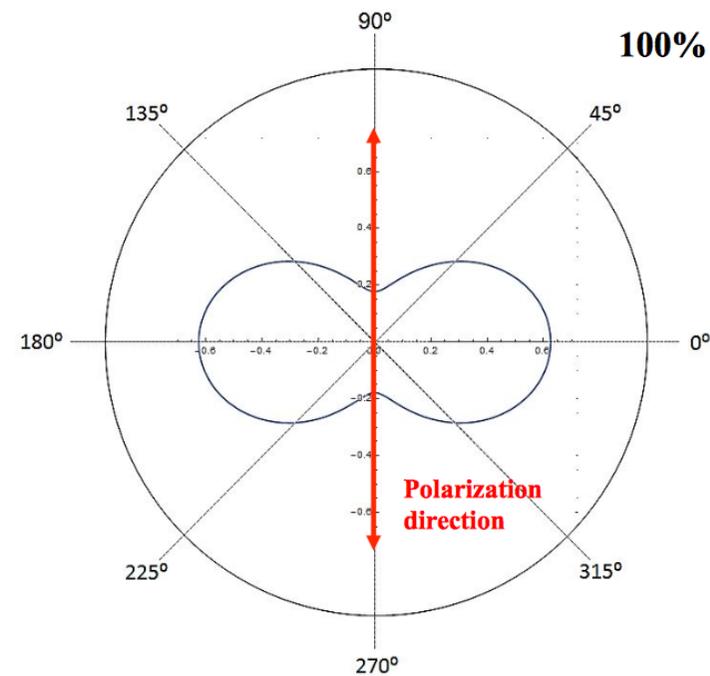
Compton Polarimetry

Compton Polarimetry

Polarization modulation factor

Klein-Nishina cross-section for linearly polarized photons:

$$\frac{d\sigma}{d\Omega} = \frac{r_0^2}{2}\left(\frac{E'}{E}\right)^2\left[\frac{E'}{E} + \frac{E}{E'} - 2\sin^2\theta\cos^2\varphi\right]$$

$$Q = \frac{N_\perp - N_\parallel}{N_\perp + N_\parallel} \qquad Q = \frac{d\sigma(\varphi=90) - d\sigma(\varphi=0)}{d\sigma(\varphi=90) + d\sigma(\varphi=0)}$$

$$Q = \frac{\sin^2\theta}{\dfrac{E'}{E} + \dfrac{E}{E'} - \sin^2\theta}$$

Minimum Detectable Polarization 3σ

$$MDP = \frac{4.29}{A.\varepsilon.\phi_s.Q_{100}}\sqrt{\frac{A.\varepsilon.(\phi_s + \phi_B)}{T}}$$

φ_s – source flux
φ_B – background flux
Q_{100} – polarimetric modulation factor for 100% radiation
ε – detector double event efficiency
A – detector area
T – observation time
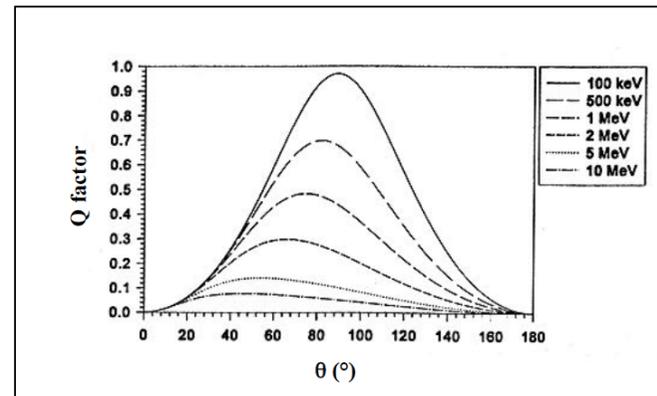
Il background- 1

- **Il fondo di un telescopio X e gamma consiste dei segnali misurati dal rivelatore NON dovuti alla sorgente osservata**

- **Parametro fondamentale nel calcolo della sensibilità**

- **Difficilmente calcolabile con precisione PRIMA della operatività in orbita del telescopio:**
  - **Simulazioni MC**
  - **Valutazioni geometriche**
  - **Environment dello spacecraft**
  - **Orbita**
  - **Attività solare**
  - **Geometria dello strumento e del telescopio**

# Cosmic Ray interactions and γ-ray background
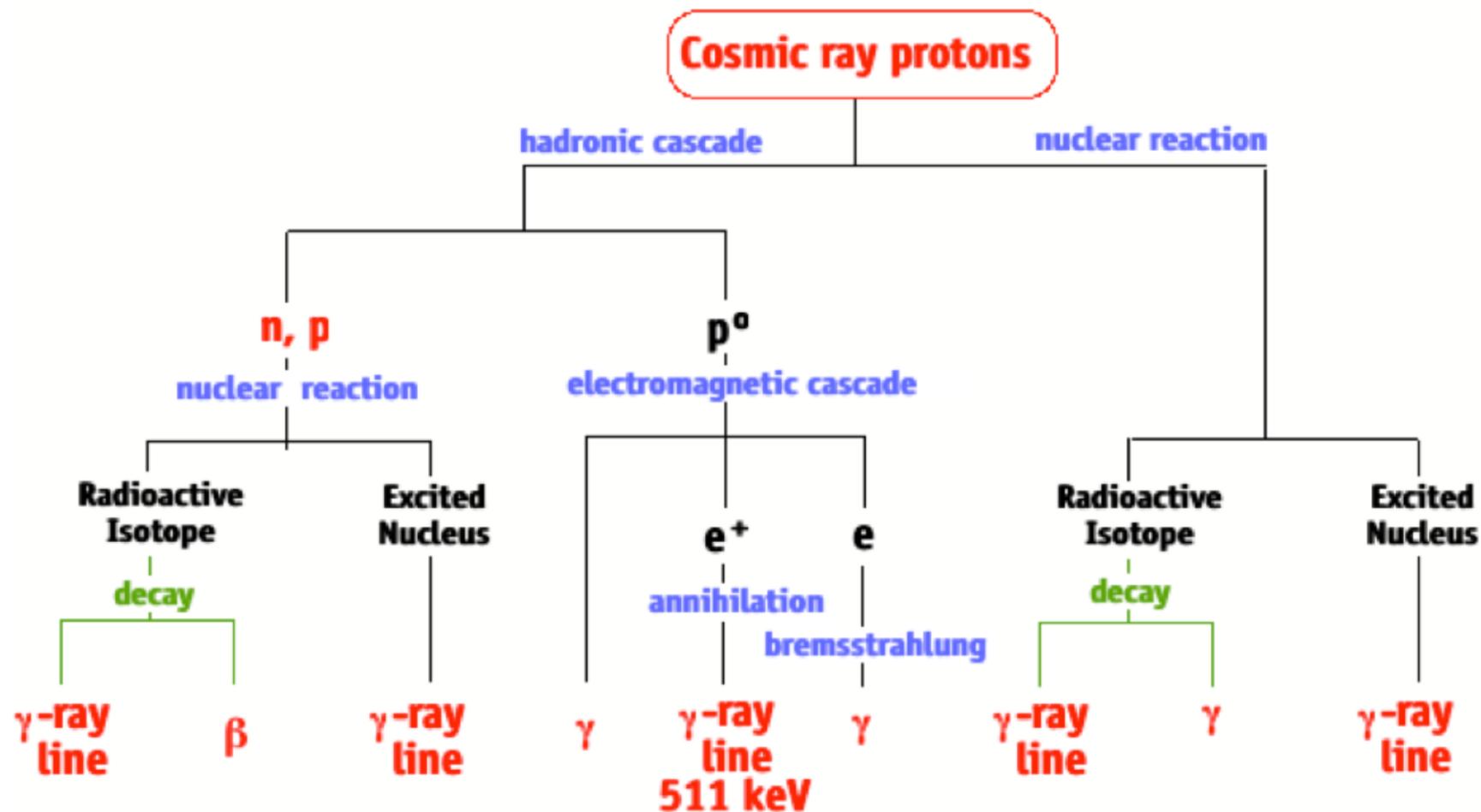
Background
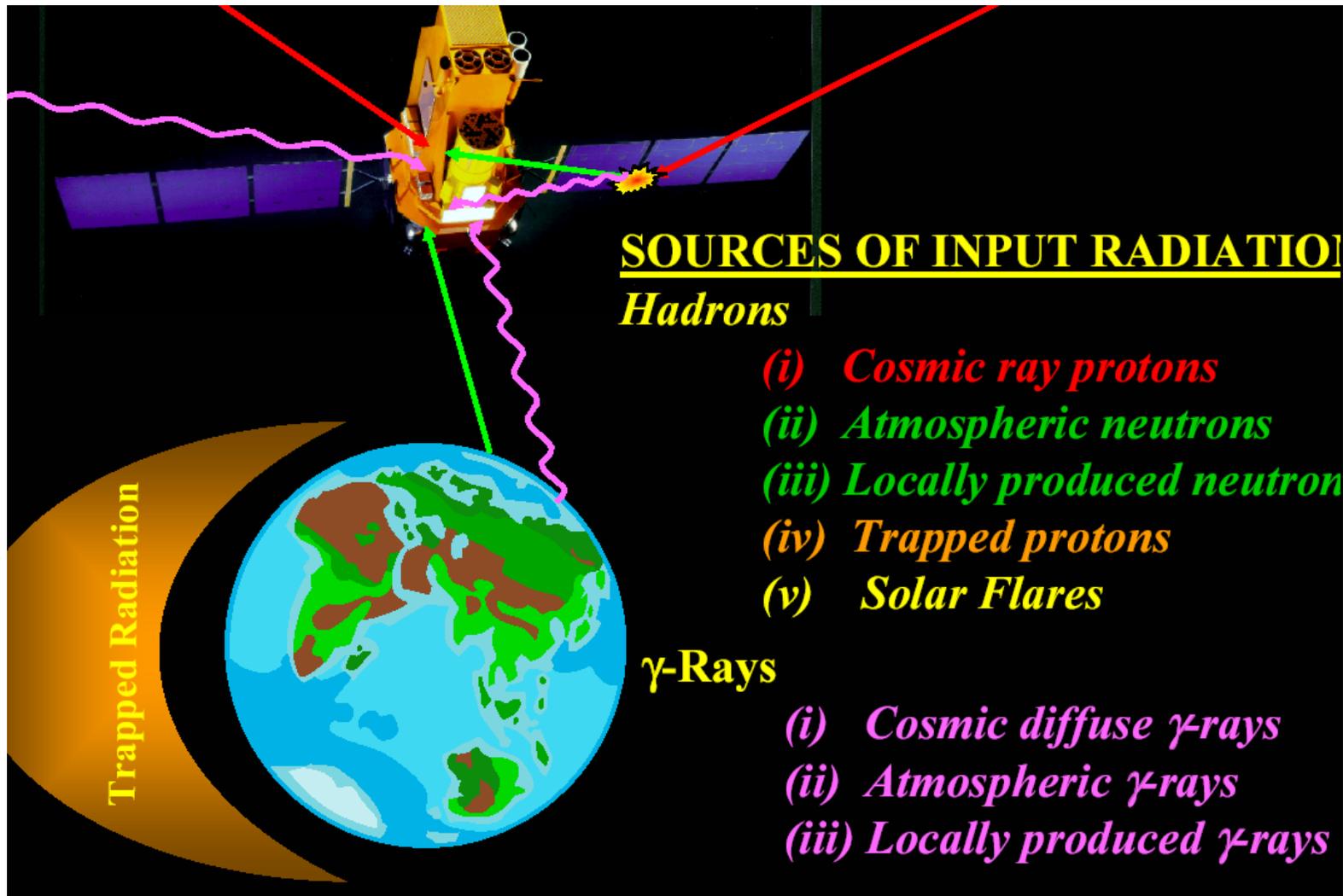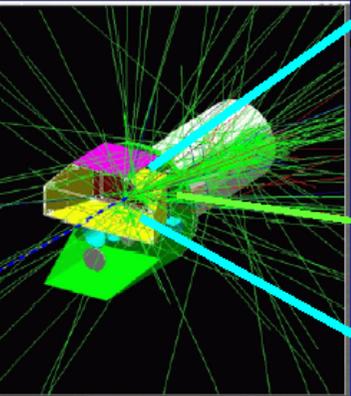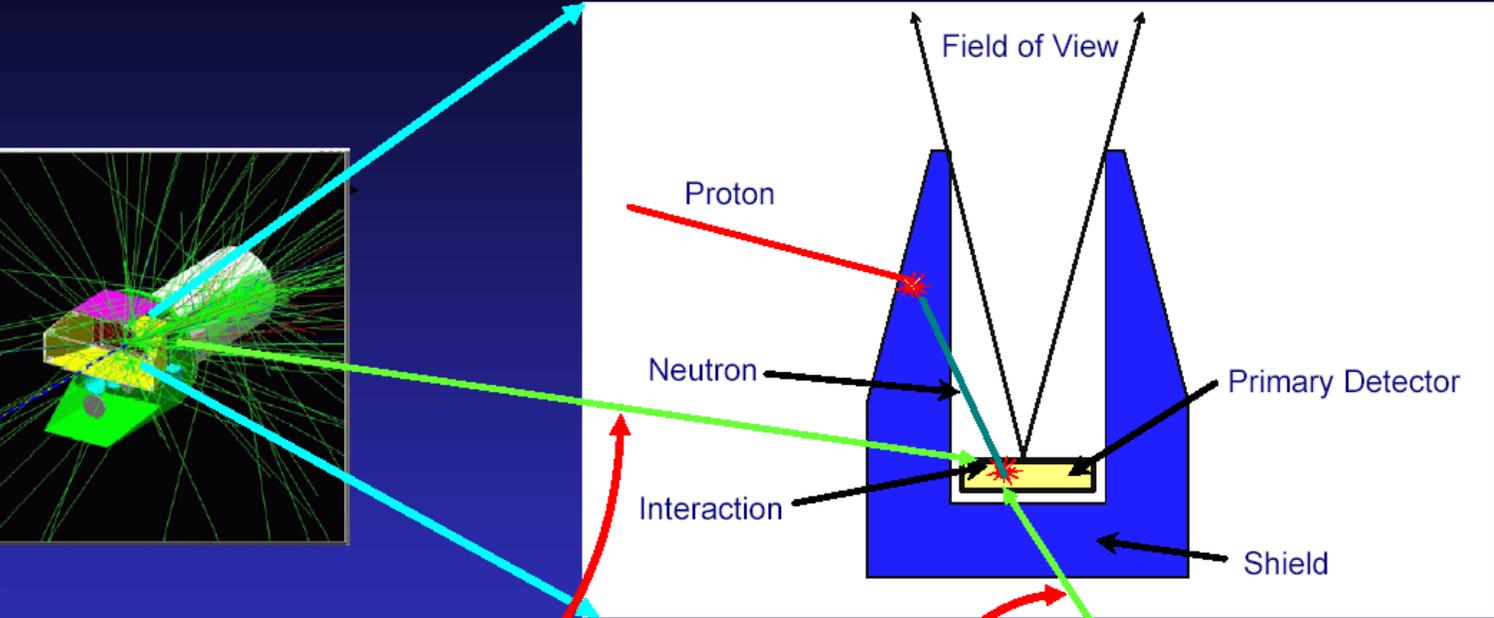
Background
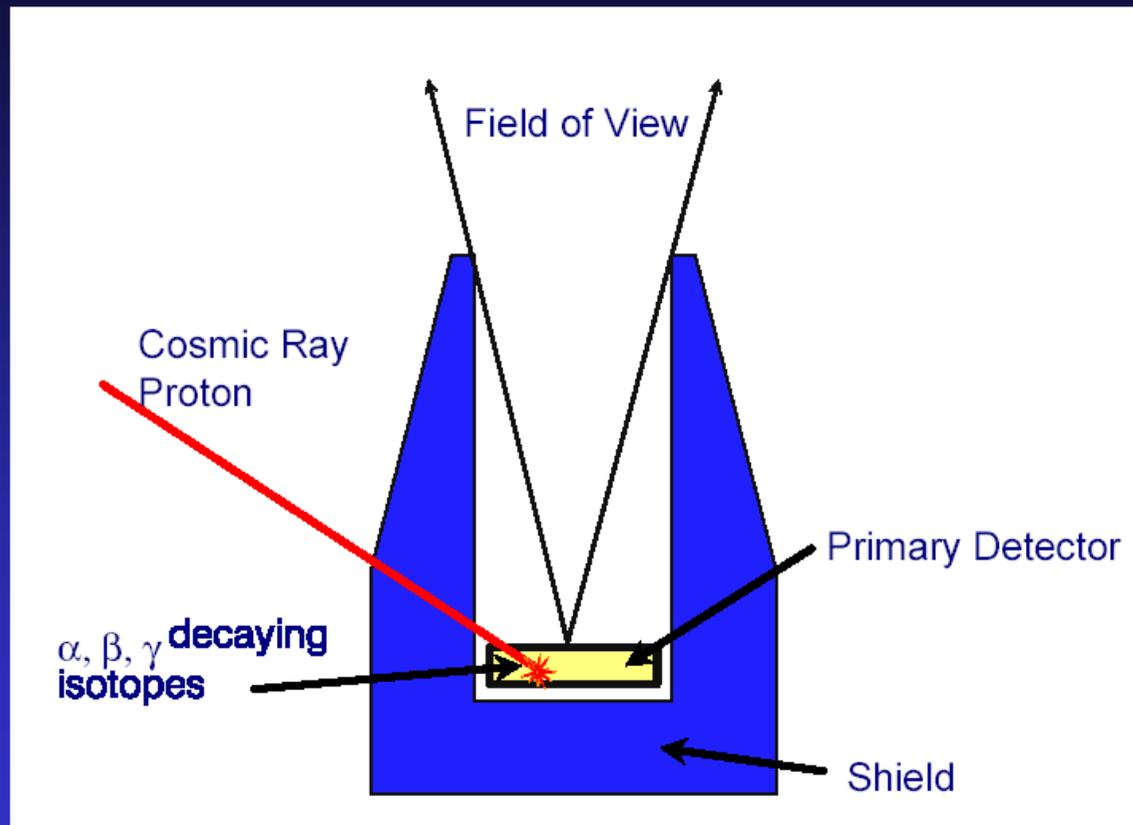
Background

Background

Radioactivity Caused by Particle Bombardment in the Trapped Radiation Belts

# Background

Solar Flares

Flare Particle Fluxes & Duration
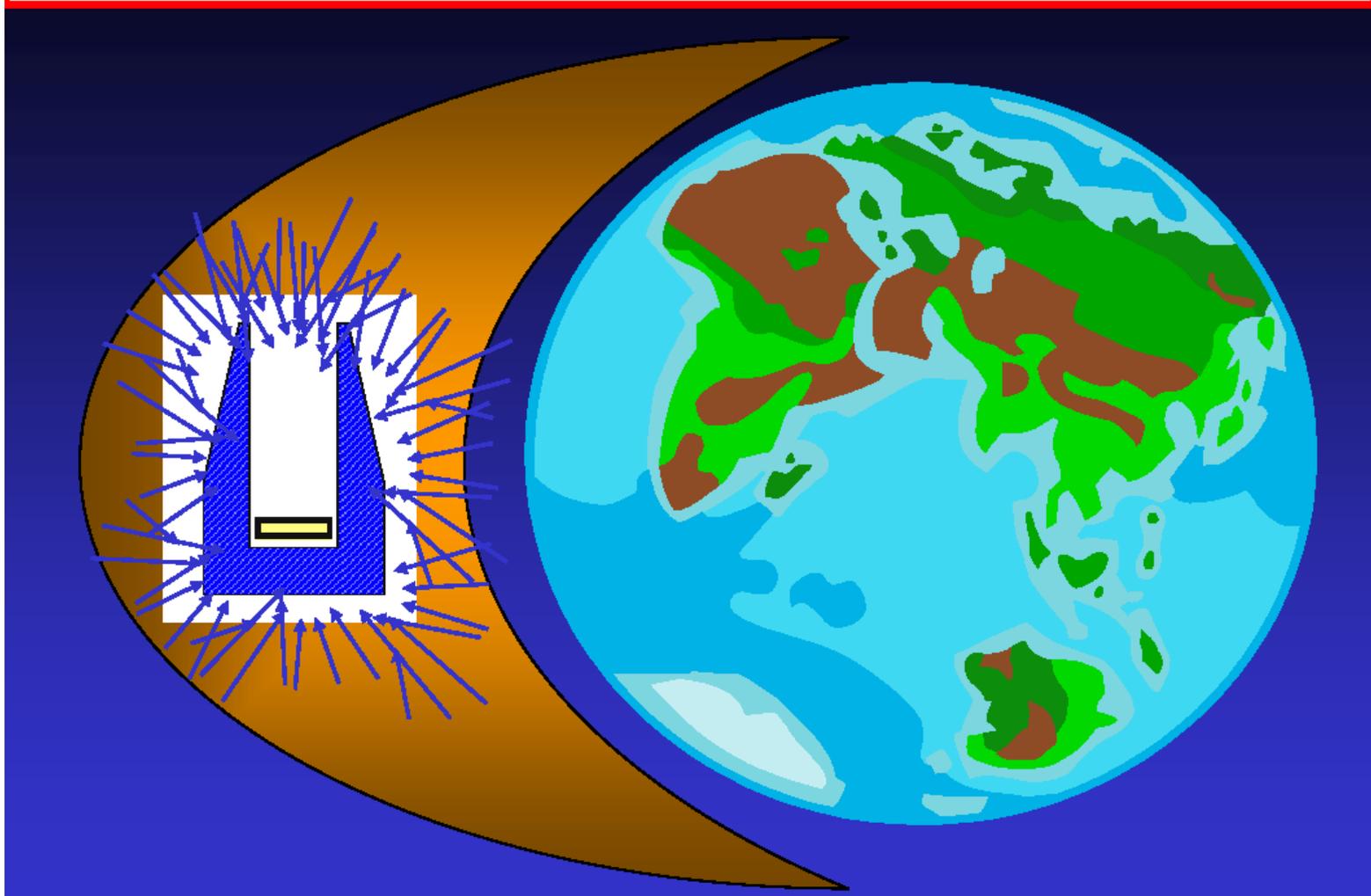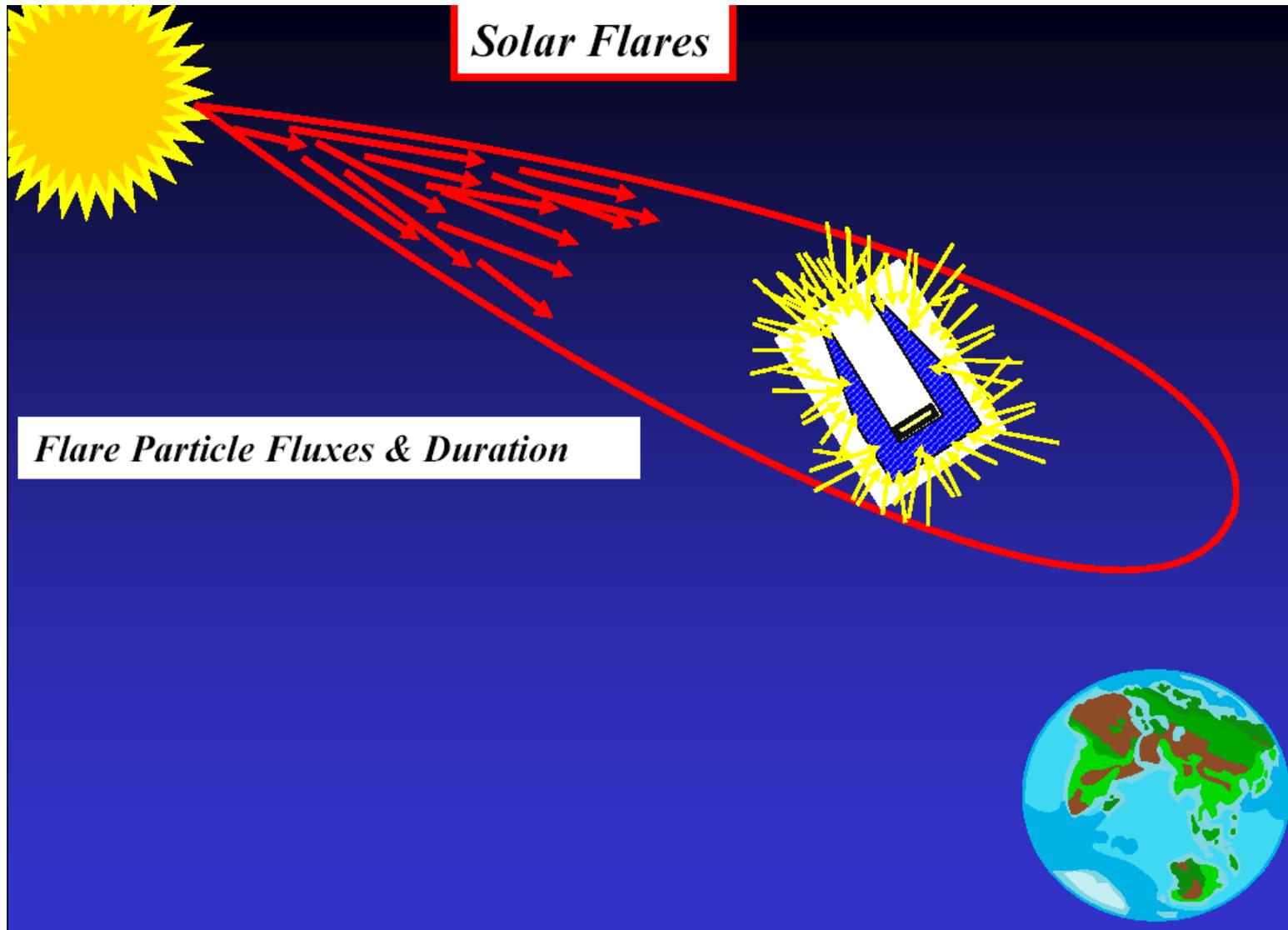
Background

Cosmic Diffuse γ-rays

These γ-rays enter directly through the aperture of the telescope

Field of View

Aperture Leakage

Primary Detector

Shield

The Spectrum

HEAO–1 A4 MED (Kinzer et al. 1997)
NRL BALLOON (Kinzer et al. 1978)
COMPTEL (Kappadath et al. 1996)
EGRET (Sreekumar et al. 1997)
SMM (Watanabe et al. 1999)

FLUX (Photons cm^{-2} s^{-1} ster^{-1} KeV^{-1})

ENERGY (keV)
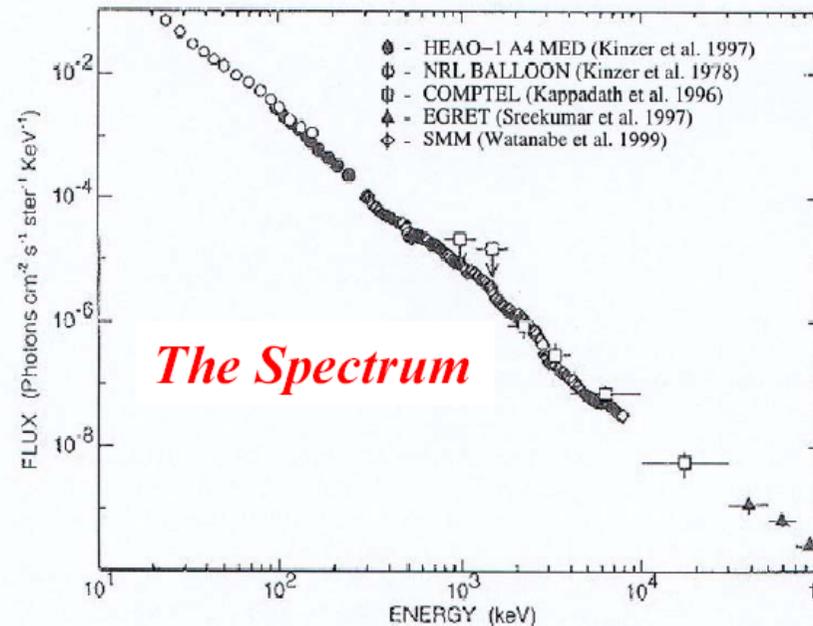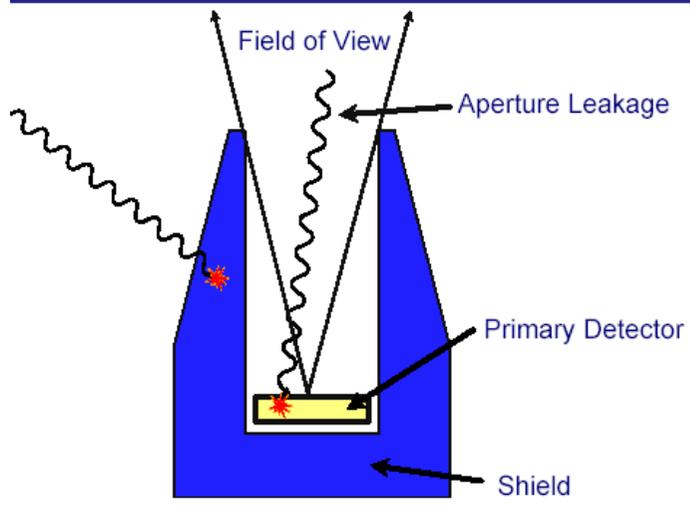
Background
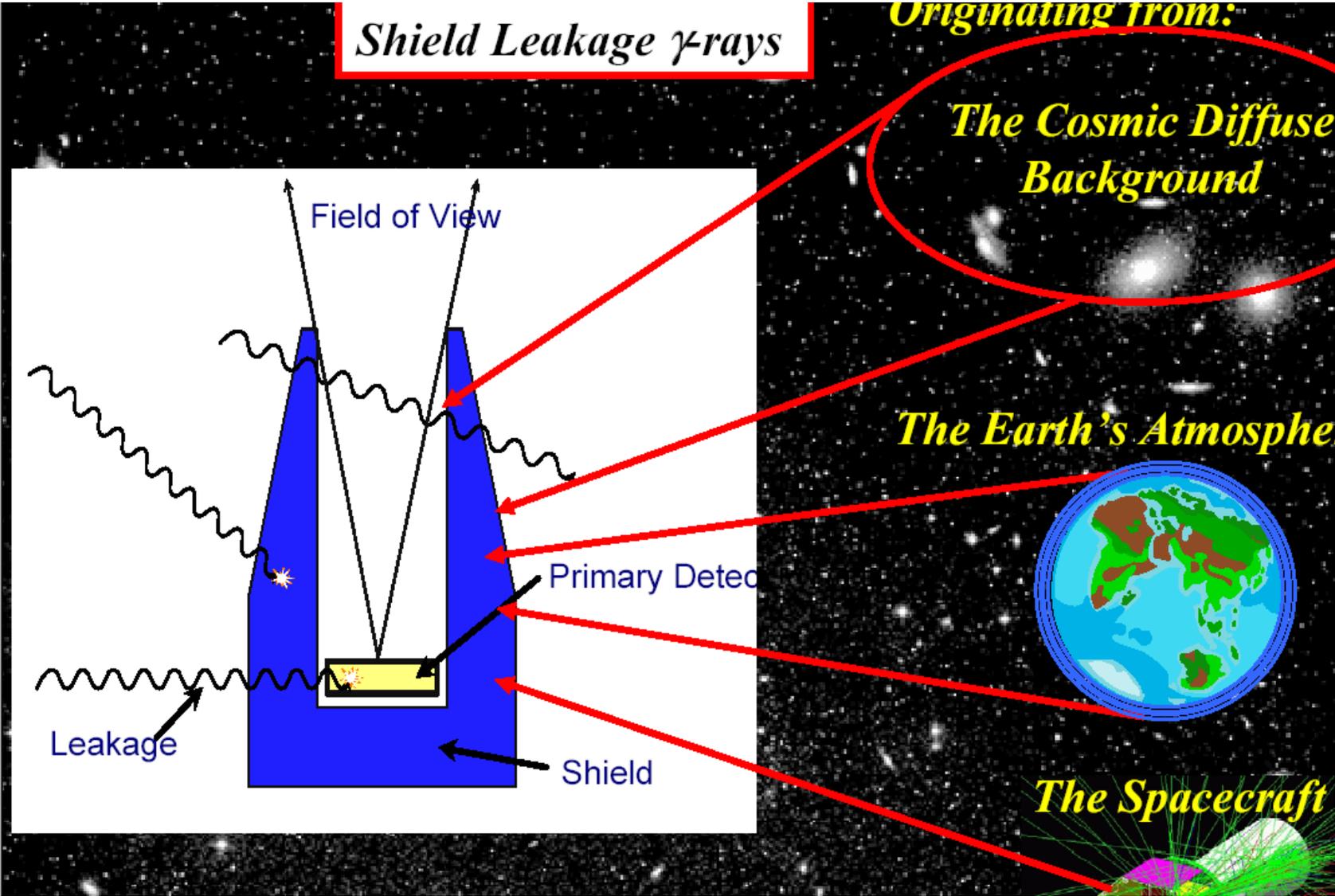
The Compton Gamma Ray Observatory
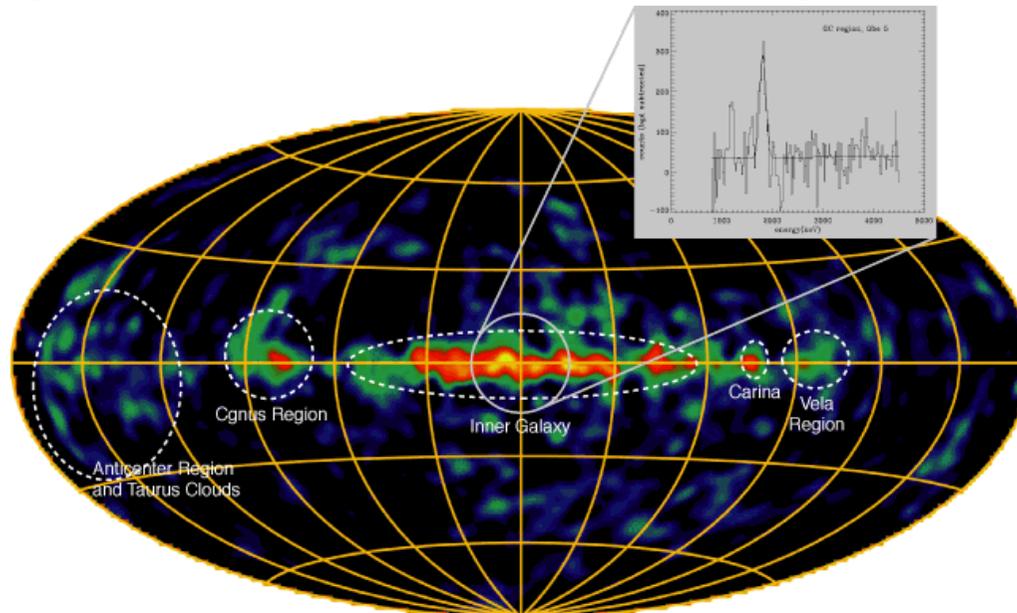
This COMPTEL image is taken at energy of 1.809 MeV, which corresponds to the gamma-ray line produced by the radioactive decay of the ^{26}Al isotope. ^{26}Al has a decay time of a million years, and is produced along with other elements in trace quantities at cosmic sites of nucleosynthesis. Therefore, the sky image in these gamma-rays integrates nucleosynthesis events over millions of years and shows the spatial distribution of these events. From the above image we learn that ^{26}Al-producing events are predominantly Galactic sources. Several localized regions appear prominent (Inner Galaxy, Cygnus, Vela), suggesting that massive stars (via their Wolf-Rayet winds and core-collapse supernovae) are the true sources. The insert shows the spectral information captured by COMPTEL. The ^{26}Al line at 1.809 MeV is clearly seen above the large instrumental background. COMPTEL is the first imaging instrument with a spatial resolution of roughly degrees, and thus made possible this all-sky survey of ^{26}Al radioactivity. The Galaxy is transparent to gamma-rays, therefore this image has, for the first time, shown us the locations of nucleosynthesis and massive stars throughout the Galaxy.

The Compton Gamma Ray Observatory
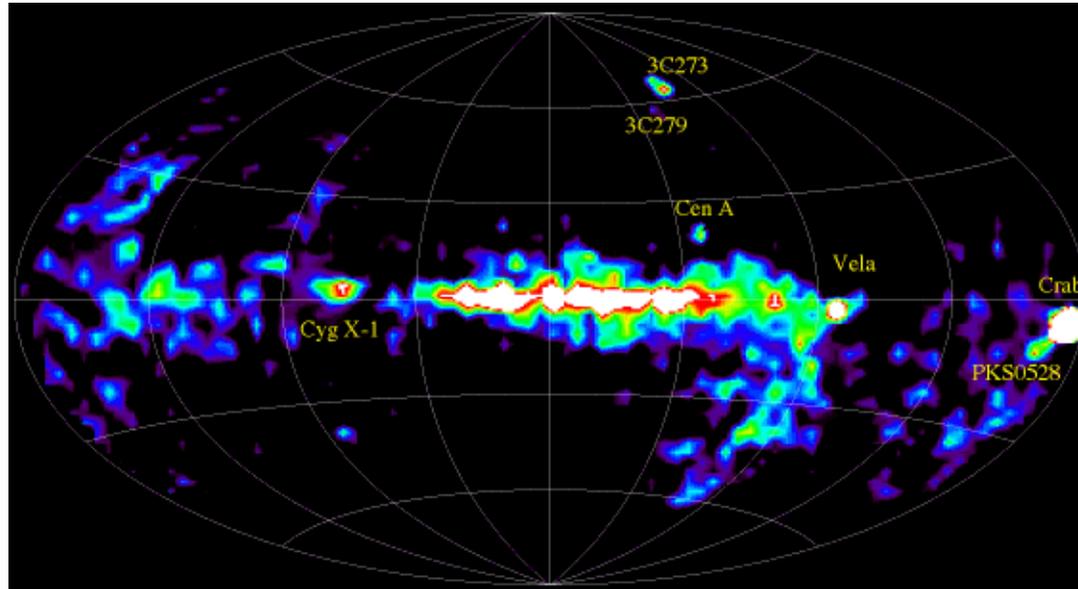
The COMPTEL 1 to 30 MeV all-sky map in continuum gamma radiation represents the results of the first-ever survey of the sky at these energies. The concentration of the emission along the Galactic plane is the most striking aspect of the map. The plane stands out clearly against the rest of the sky indicating that most of the measured gamma-ray fluxes come from regions or objects inside the Galaxy. The dominant Galactic continuum emission seems to come from interstellar space and is visible as diffuse Galactic radiation. Superimposed on the large-scale Galactic emission are point-like sources (like Crab, Vela, Cyg X-1), but many of the Galactic point sources remain unidentified at this time. A significant contribution of unresolved point sources to the apparently diffuse Galactic emission cannot be excluded. At medium and high Galactic latitudes, a few of the gamma-ray blazars, discovered by EGRET, are visible in the COMPTEL map as well. Examples are 3C 273, 3C 279, and PKS 0528+134. The radio galaxy Cen A is also visible at MeV gamma rays. Some of the extragalactic objects detected by COMPTEL are not visible in this map, because they flare up only occasionally: on average they are too weak to be visible in this time-averaged all-sky map.

Compton Astrophysics

Astrophysics of low/medium Energy γ - rays

The energy range from a few 100 keV to several 10 MeV is scaled by the electron rest mass $m_o c^2 = 0.511$ MeV

- continuous γ-ray spectra from sites of high-energy particle acceleration are mostly produced in e-m interactions:
  Bremsstrahlung, inverse Compton scattering, Synchrotron
  Many of these sources have their maximum Luminosity at MeV energies

and by the nuclear energy levels
- Signatures of cosmic radioactivity through γ-ray lines: the direct observation of nucleosynthesis, i.e. the creation of the elements,

Compton Astrophysics
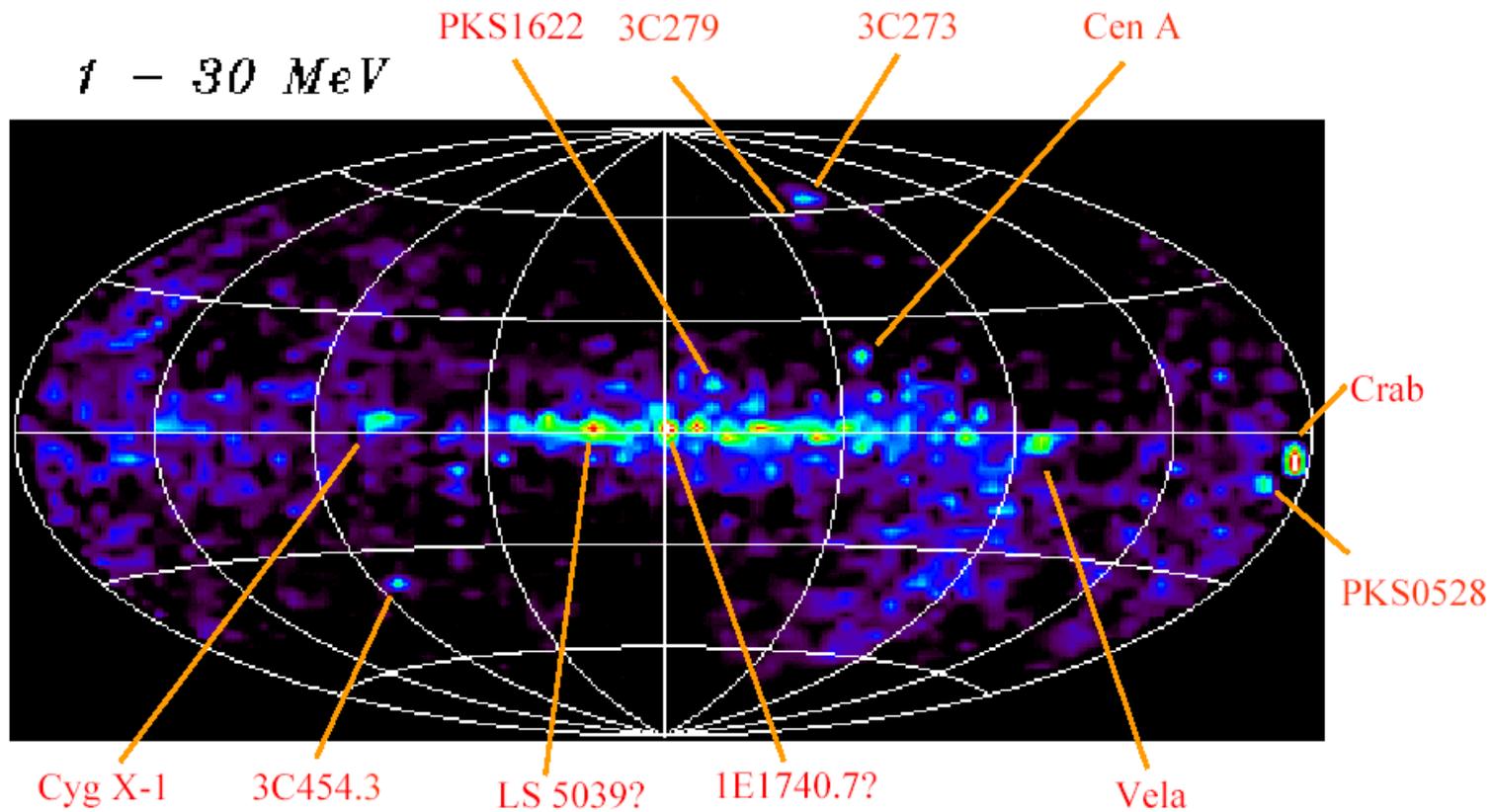
Compton Astrophysics

Catalog of Gamma-Ray-Sources
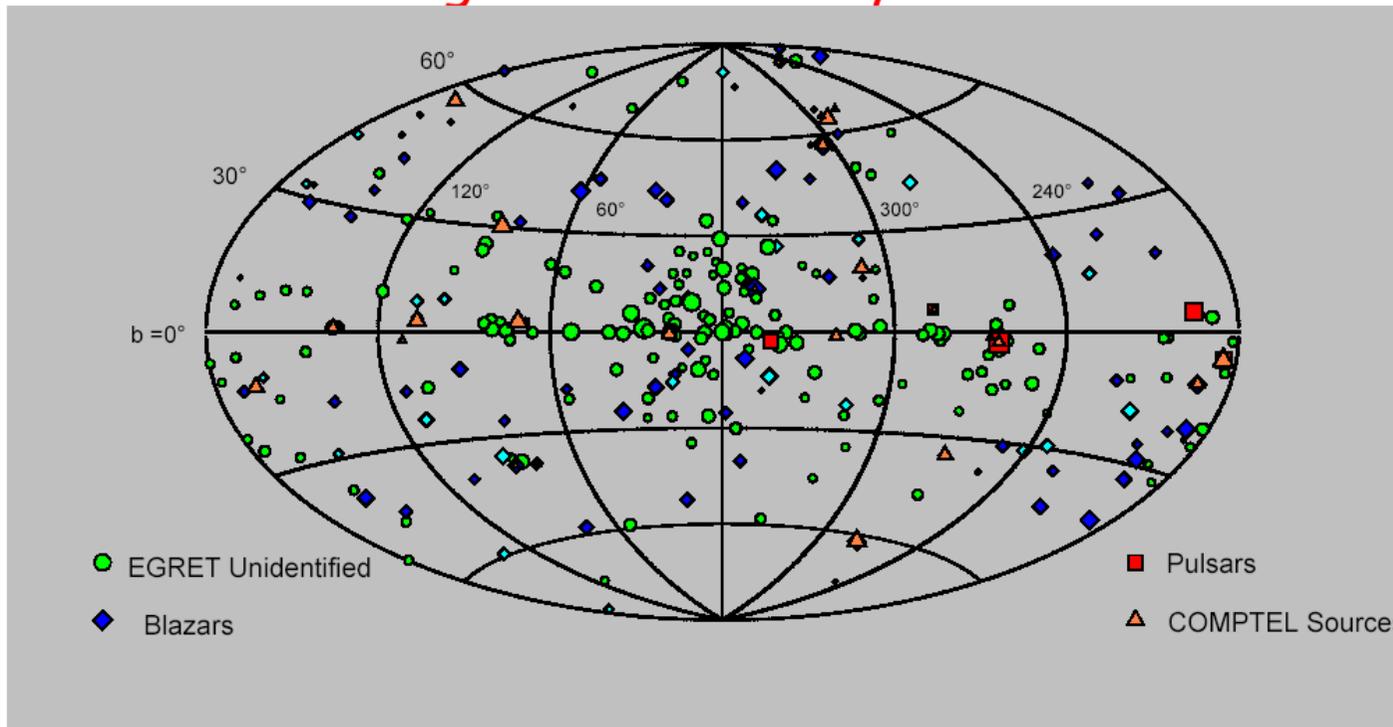
3. EGRET Catalog: 271 Sources   1. COMPTEL Katalog: 32 constant Srces.
(3EG)   80-90 AGN   Schönfelder et al., 2000   39 transient
Hartman et al, 1999   6-8 PSR   A&AS, 143, 145   11 AGN
ApJS, 123, 79   ~170 Unid..   3 PSR
                                                            4 EGRET Unid.

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Compton Astrophysics

Cosmic Accelerators:

- **Accretion** on compact objects (relativistic jets):

   AGN, µBlazars, Binaries

- **Explosions and Shocks:**   GRBs, SNRs, mass. stellar winds, ISM
                               Novae, Supernovae

- **Rotation of NS:** pulsars

    0   33 ms
    Crab

-
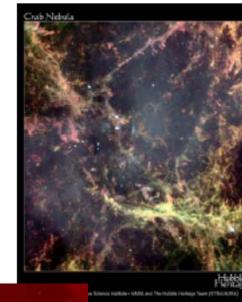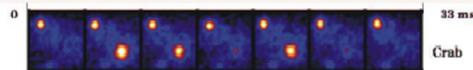
electro-magnetic dissipation: solar flares
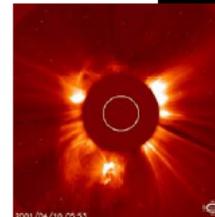
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Compton Astrophysics

Origin and characteristics of astrophysically important
γ-ray lines

Isotope	Energy	$t_{1/2}$	origin
^{57}Ni	1378 keV	2.14 d	SN
^{56}Ni	812 keV	8.5 d	SN
^{56}Co	847 keV 1238 keV	111.5d	SN
^{22}Na	1275 keV	3.8 yr	Novae
^{44}Ti	1157 keV	79 yr	SNR
^{26}Al	1809 keV	1Myr	AGB and massive stars (O & WR), Novae, core-collapse SNe
$^{12}C*$ $^{16}O*$	4.4 MeV 6.1 MeV	prompt	cosmic ray induced ISM lines, flares
e^+, e^-	511 keV		β^+ activity, jet sources, PSR, Novae, flares etc.
$n+p \rightarrow d$	2.21 MeV		flares, flare stars?