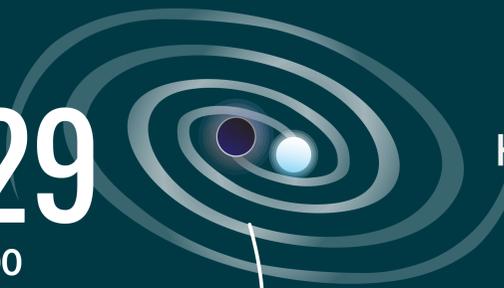


First results from O4

Get to know

GW230529

Full name GW230529_181500



~ 650 million light years away



Detectors



- Offline OR not operational
- Online BUT not used for analysis*
- Online AND used for analysis

Discovered on 29 May 2023 at 18h15 UTC

most likely a merger between a Neutron Star & Black Hole (NSBH)



~1.4 M_{\odot}



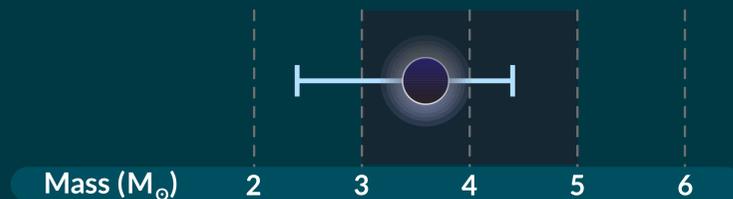
~3.6 M_{\odot}

Most symmetric NSBH event so far

more likely than prior GW NSBHs to have the neutron star ripped apart by the black hole

Primary object in lower mass gap

further supports that this region is not empty



* Although the KAGRA detector was in observing mode, its sensitivity was insufficient to impact the analysis of GW230529

@astronerdika

<https://www.ligo.org/detections/GW230529.php>

Astrofisica Nucleare e Subnucleare
Nuclear Astrophysics – II

Kilonova: An electromagnetic signal of heavy element nucleosynthesis

Gabriel Martínez-Pinedo
IPN Seminar, Orsay, April 11, 2018



Heavy element nucleosynthesis: the r process

Gabriel Martínez Pinedo



TECHNISCHE
UNIVERSITÄT
DARMSTADT

55th Karpacz Winter School of Theoretical Physics
ChETEC COST Action CA16117 training school
Artus Hotel, Karpacz, February 24 - March 2, 2019

HELMHOLTZ
RESEARCH FOR GRAND CHALLENGES



DFG

R-process nucleosynthesis in neutron star mergers

Gabriel Martínez-Pinedo

EMMI Workshop: New avenues for low energy
NuSTAR program at GSI-FAIR
GSI, September 16-17, 2021



TECHNISCHE
UNIVERSITÄT
DARMSTADT

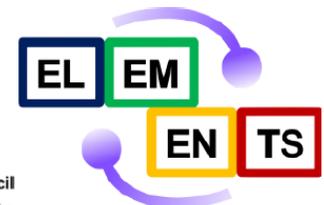


DFGHF 

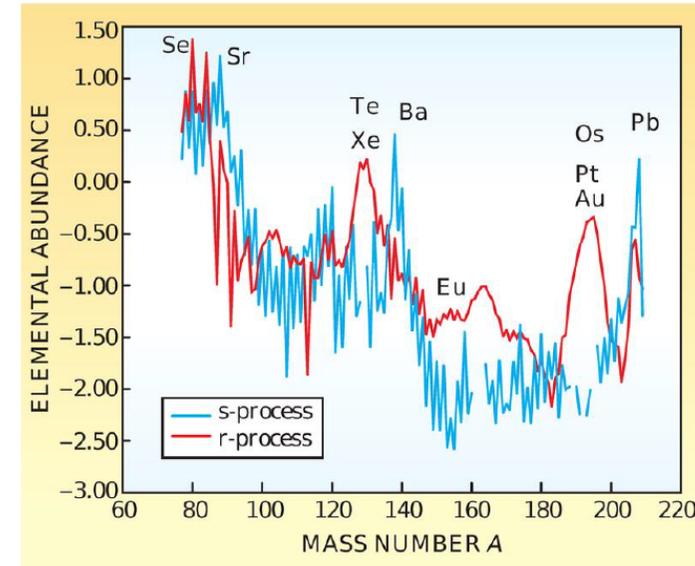
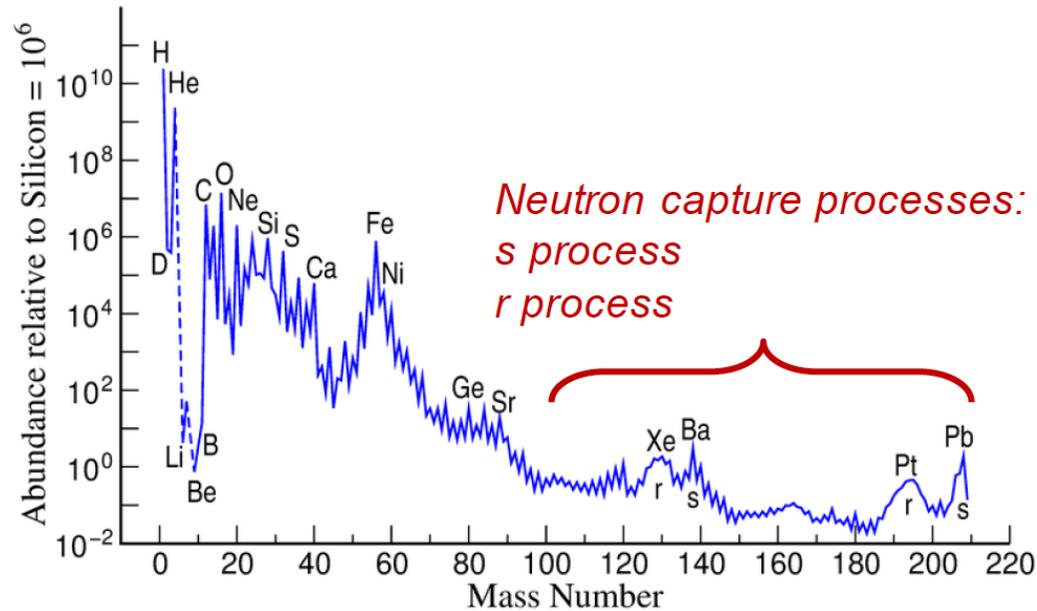
Helmholtz Forschungsakademie Hessen für FAIR



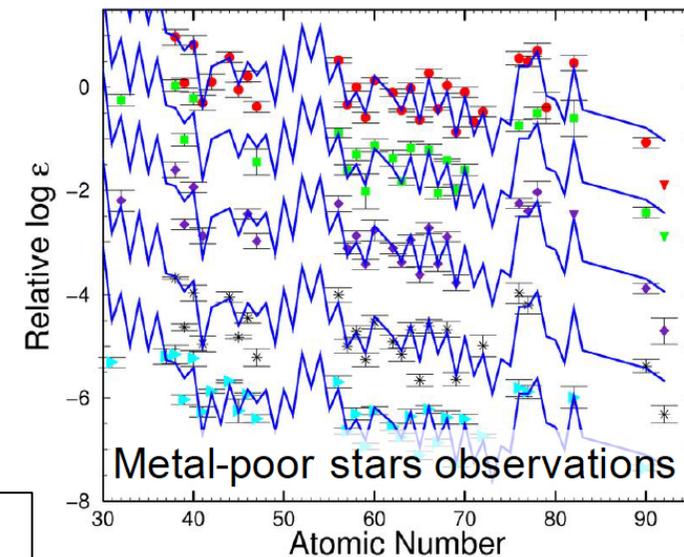
European Research Council
Established by the European Commission



Signatures of nucleosynthesis

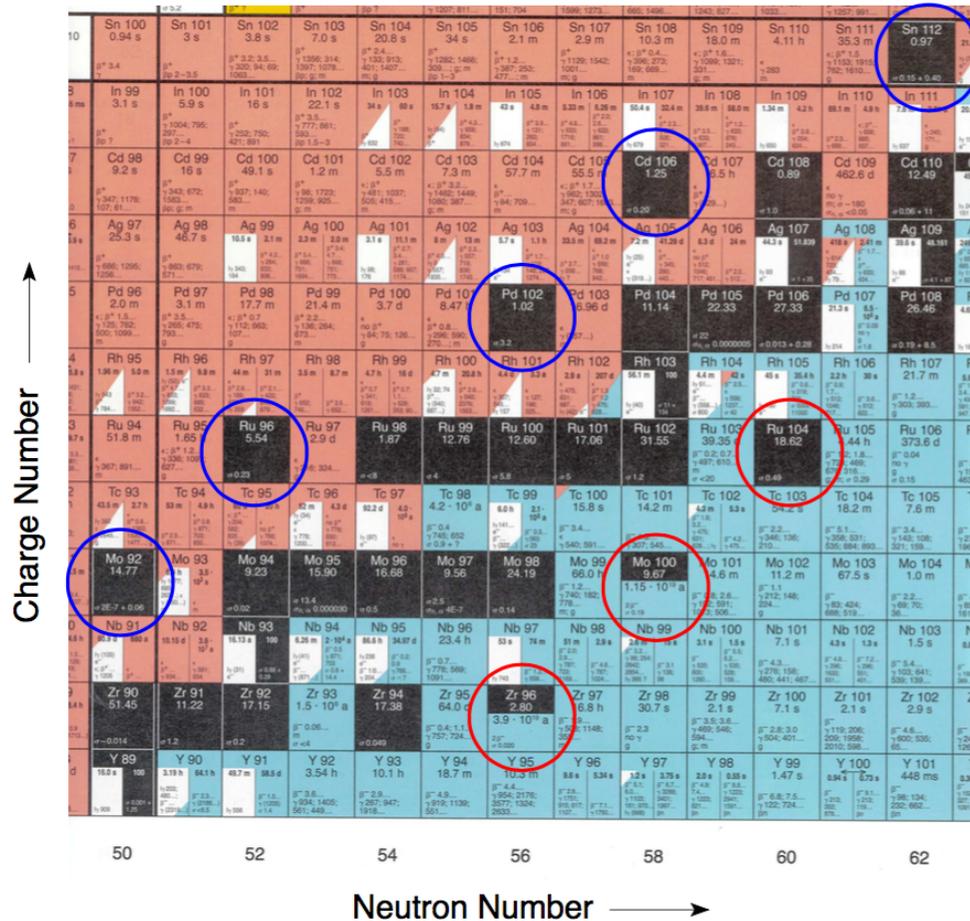


- Heavy elements produced in neutron capture processes
- r process operates at early Galactic history



https://space.mit.edu/home/afrebel/review_frebel.pdf

Nucleosynthesis beyond iron



The stable nuclei beyond iron can be classified in three categories depending of their origin:

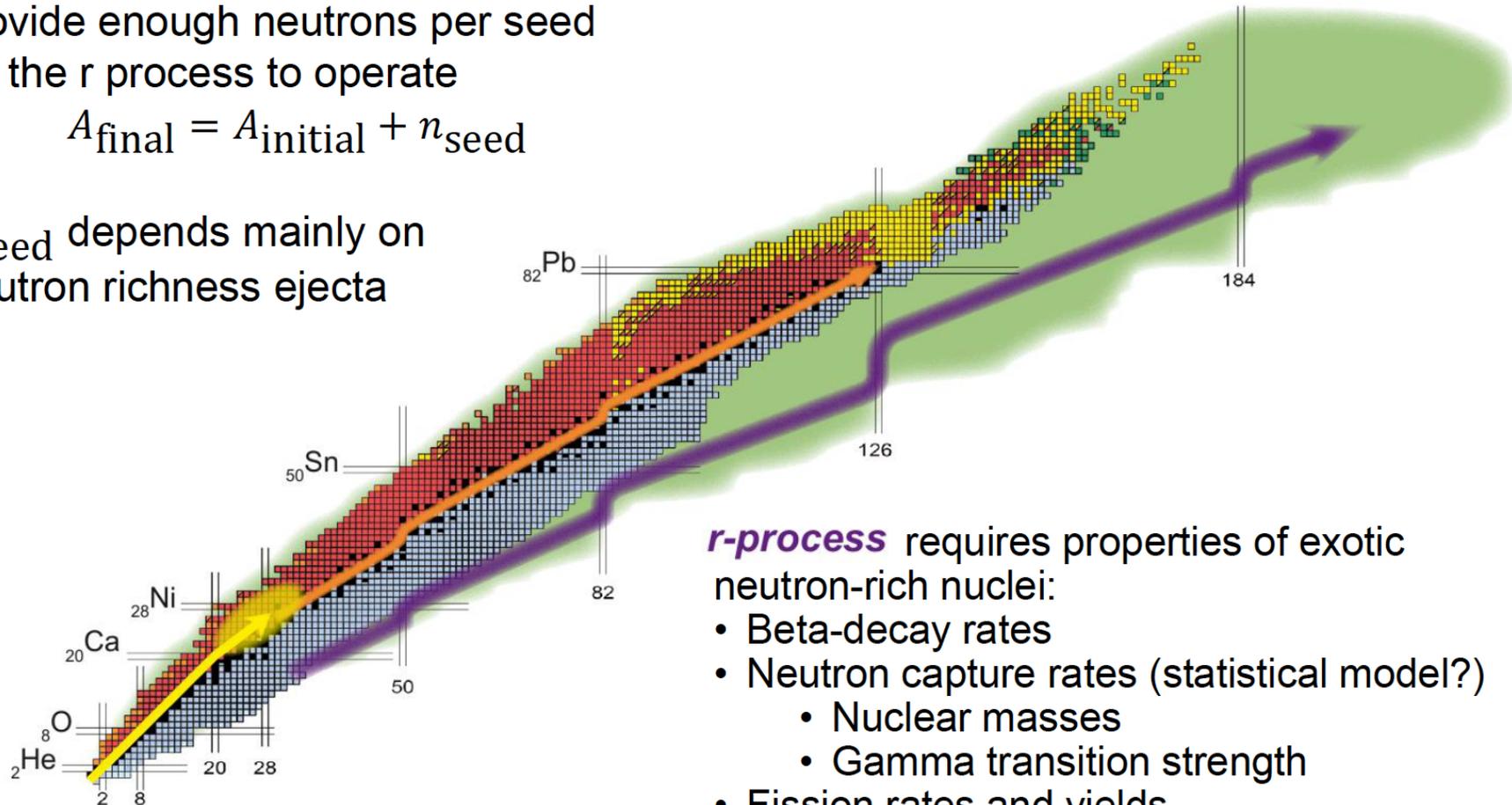
- s-process
- r-process
- p-process (γ -process)

R process nuclear needs

Astrophysical environment should provide enough neutrons per seed for the r process to operate

$$A_{\text{final}} = A_{\text{initial}} + n_{\text{seed}}$$

n_{seed} depends mainly on neutron richness ejecta



r-process requires properties of exotic neutron-rich nuclei:

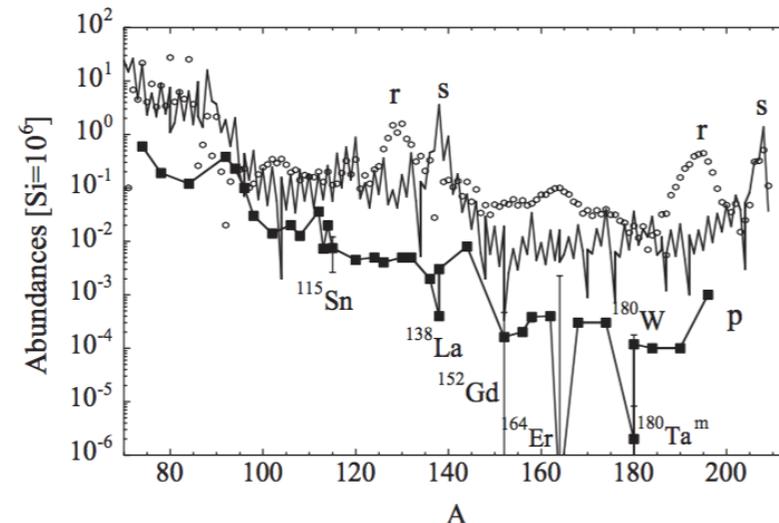
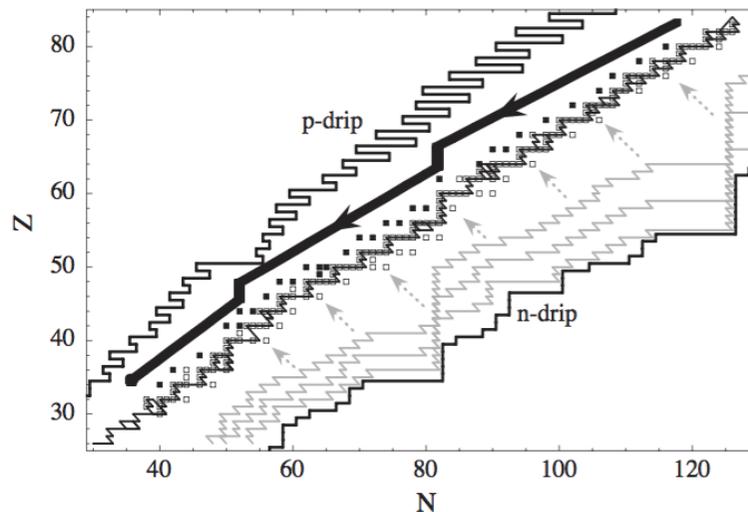
- Beta-decay rates
- Neutron capture rates (statistical model?)
 - Nuclear masses
 - Gamma transition strength
- Fission rates and yields
 - Fission barriers

Benchmark against observations:

- Solar and stellar abundances (indirect)
- Electromagnetic emission, kilonova (direct), sensitive Atomic and Nuclear Physics

Nucleosynthesis beyond iron

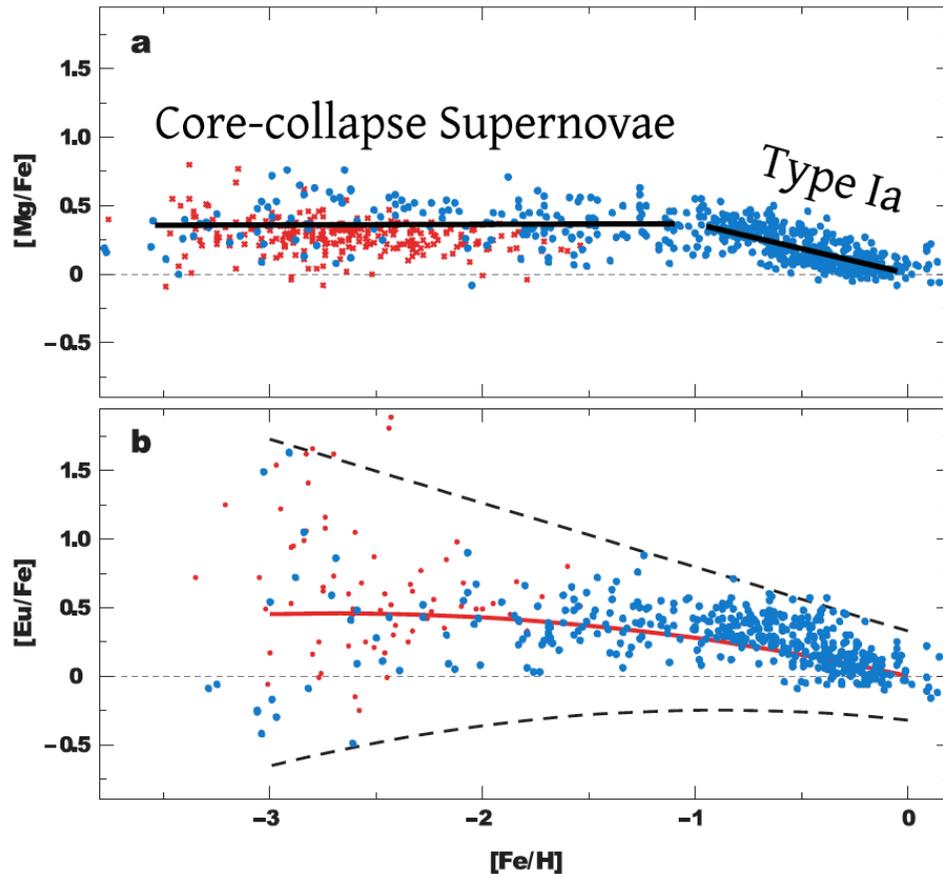
Three processes contribute to the nucleosynthesis beyond iron: s-process, r-process and p-process (γ -process).



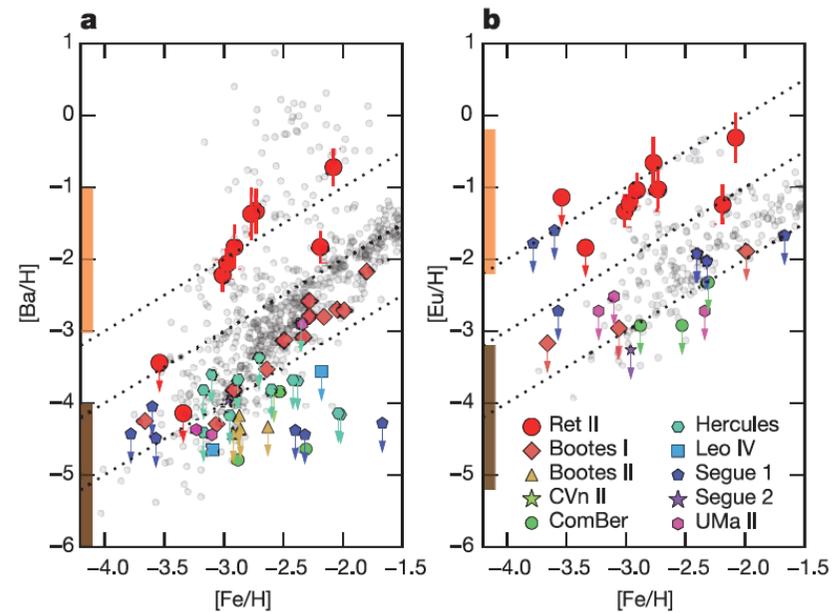
- s-process: relatively low neutron densities, $n_n = 10^{10-12} \text{ cm}^{-3}$, $\tau_n > \tau_\beta$
- r-process: large neutron densities, $n_n > 10^{20} \text{ cm}^{-3}$, $\tau_n < \tau_\beta$.
- p-process: photodissociation of s-process material.

Implications from observations

Individual stars, Milky Way Halo
Sneden, Cowan & Gallino, 2008



Ji et al 2016 found that only 1 of 10 ultrafaint dwarf galaxies is enriched in r-process elements

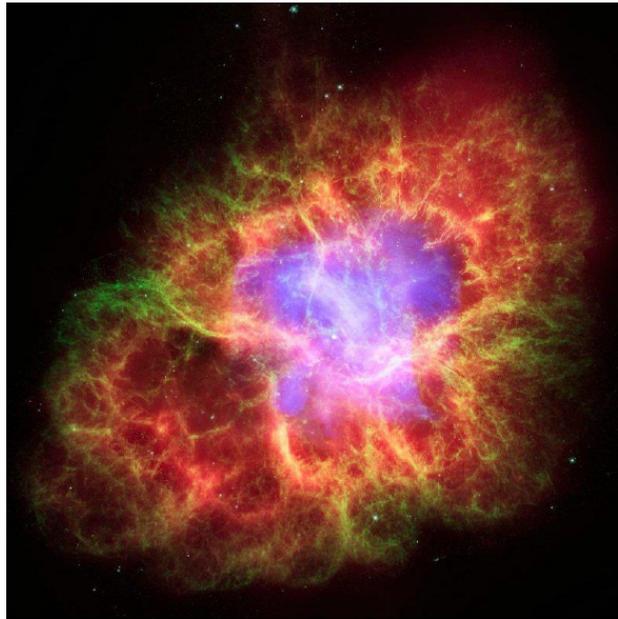


R process related to rare high yield events not correlated with Iron enrichment

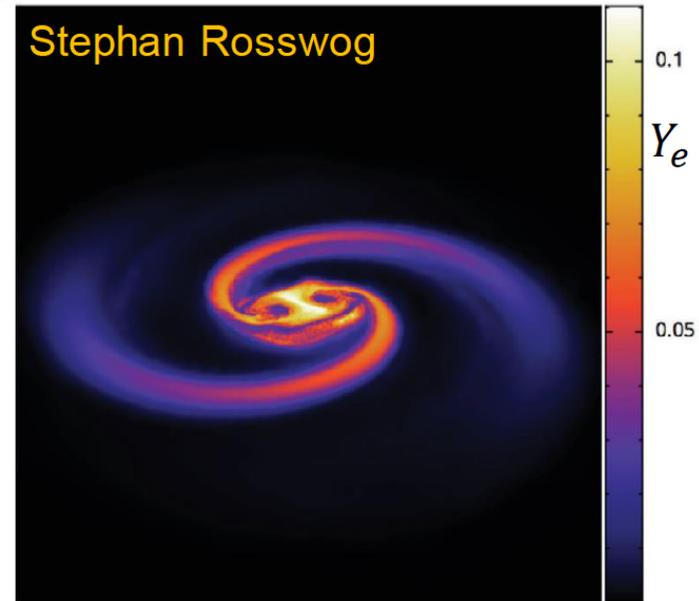
Similar results obtained by ^{60}Fe and ^{244}Pu observations in deep sea sediments (Wallner et al, 2015; Hotokezaka et al, 2015)

Astrophysical sites

Core-collapse supernova



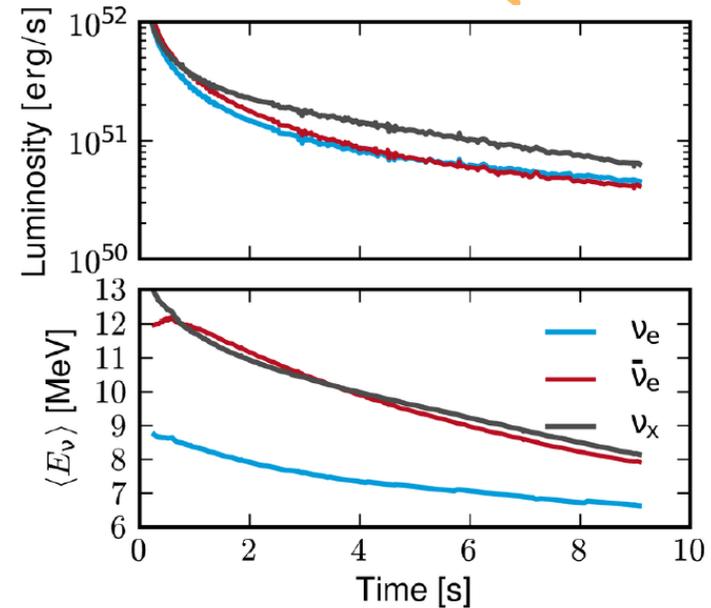
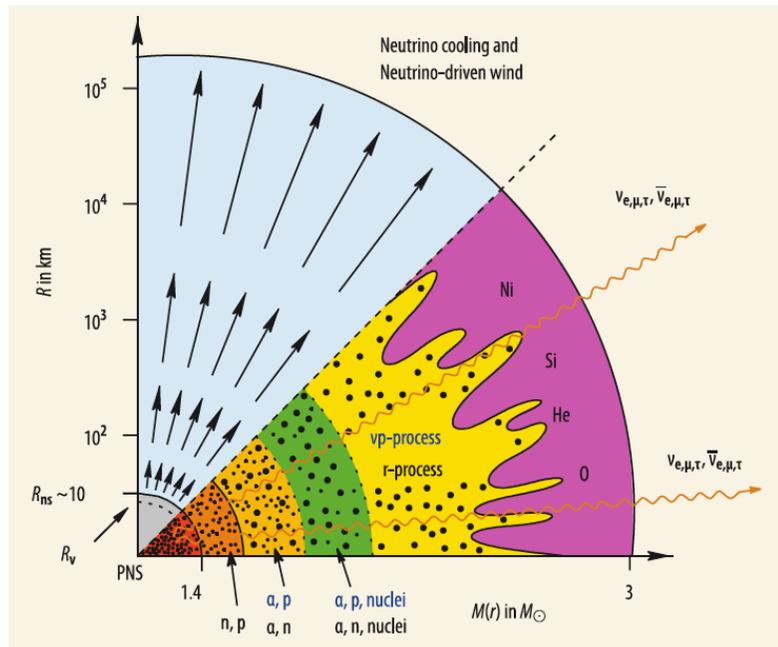
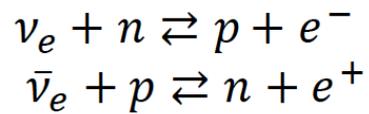
Compact binary mergers



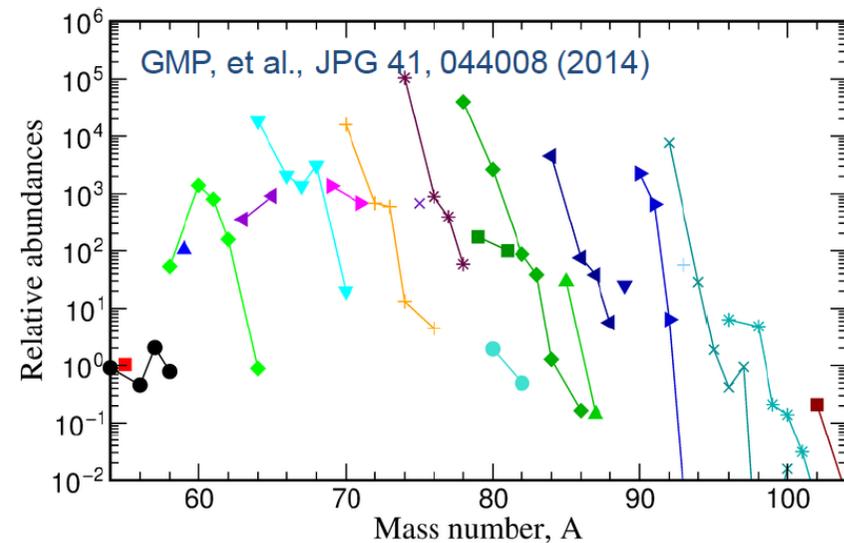
	Supernova	Mergers
Optimal conditions	☹️	☺️
Yield / Frequency	☹️	☺️
Direct signature	☹️	☺️

Supernova nucleosynthesis

Heavy elements produced in neutrino winds from protoneutron star cooling.
Neutrino interactions determine proton-to-nucleon ratio, Y_e

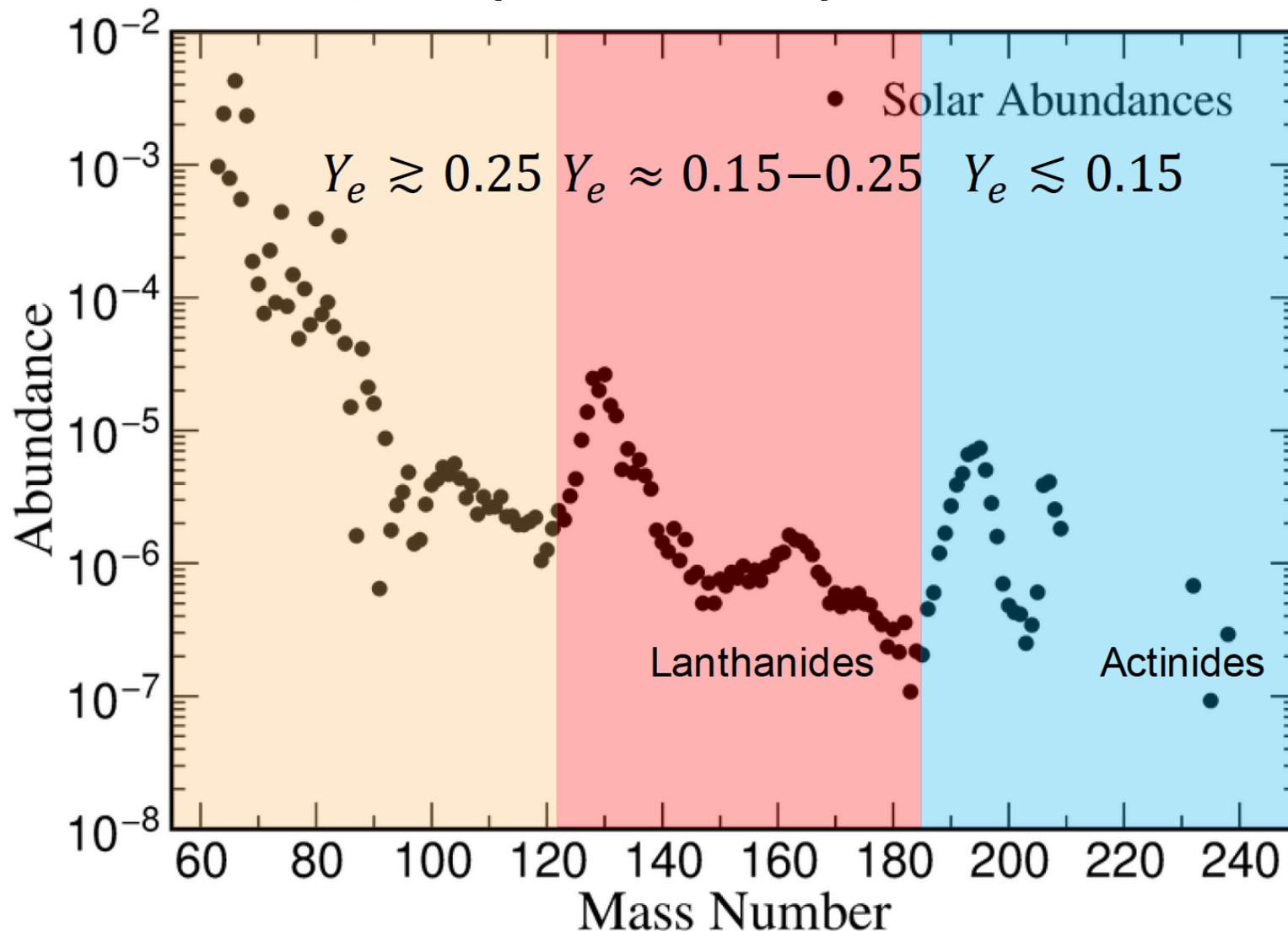
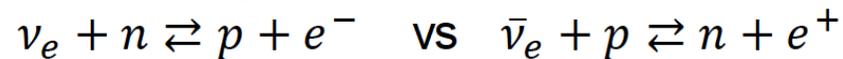


Supernova produce only medium mass nuclei



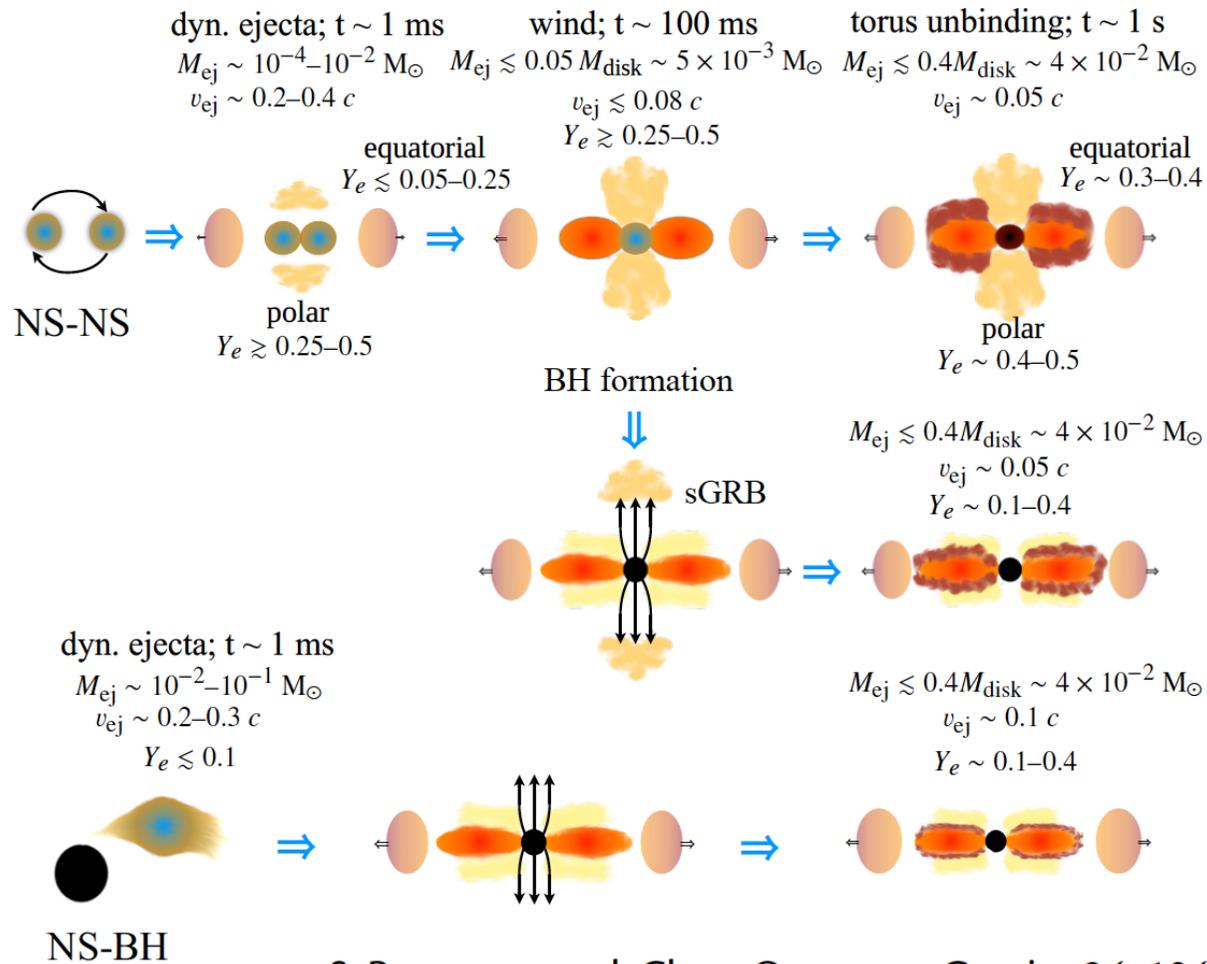
Nucleosynthesis dependence on Y_e

Nucleosynthesis mainly sensitive to proton-to-nucleon ratio, Y_e



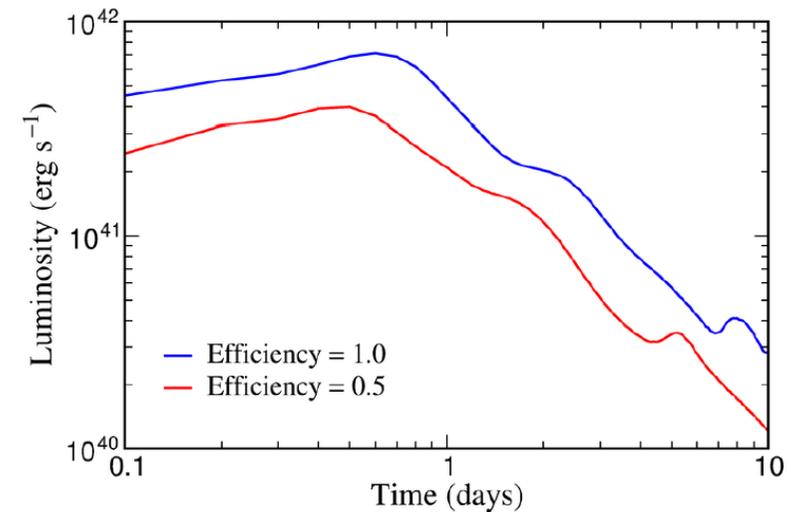
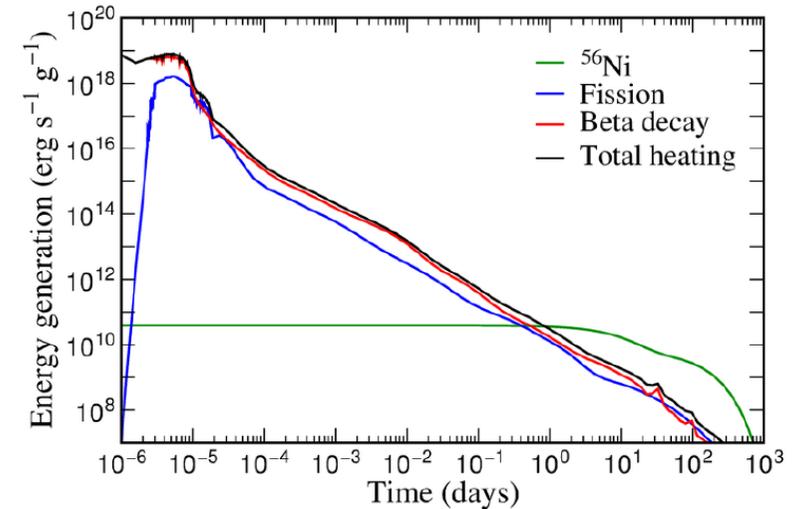
Merger channels and ejection mechanism

In mergers we deal with a variety of initial configurations (neutron-star neutron-star vs neutron-star black-hole) with additional variations in the mass-ratio. The evolution after the merger also allows for further variations.



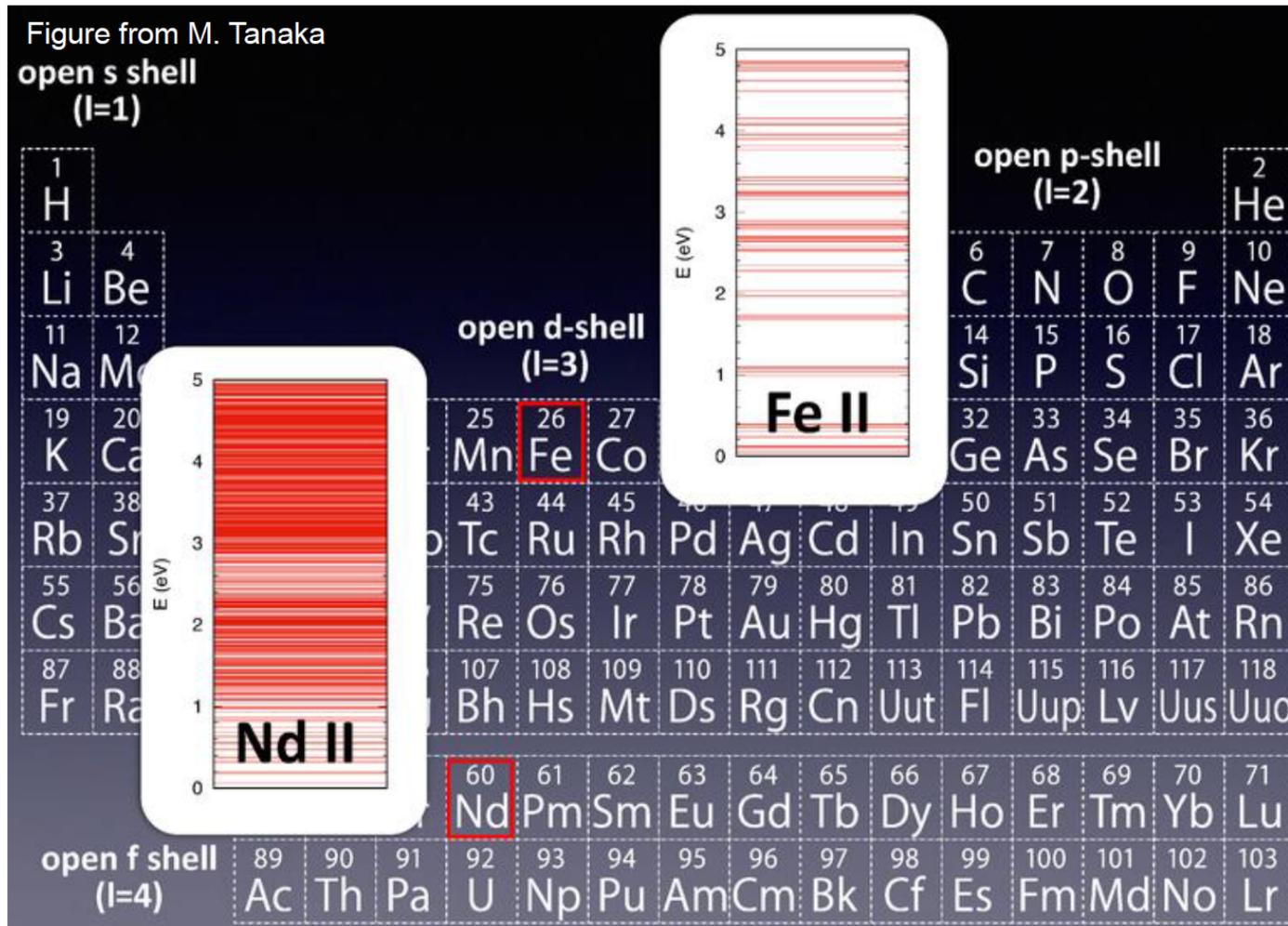
Kilonova: Electromagnetic signature of the r process

- Ejecta produces electromagnetic signatures [Li & Paczyński 1998]
- Transient due to radioactive decay of r-process nuclei [Metzger et al, 2010]
Heating: $\dot{\epsilon} \sim t^{-1.3}$
Luminosity like 1000 novae: Kilonova
Peak on timescales days in optical/blue
- Presence of Lanthanides reduces luminosity and delays peak to \sim week in red/infrared [Barnes & Kasen, 2013]
- Similar effect due to Actinides [Mendoza-Temis et al, 2015]
- Accurate treatment of thermalization of radioactive products [Barnes, et al, 2016]



Metzger, GMP, Darbha, Quataert, Arcones et al, MNRAS 406, 2650 (2010)

Impact Lanthanides



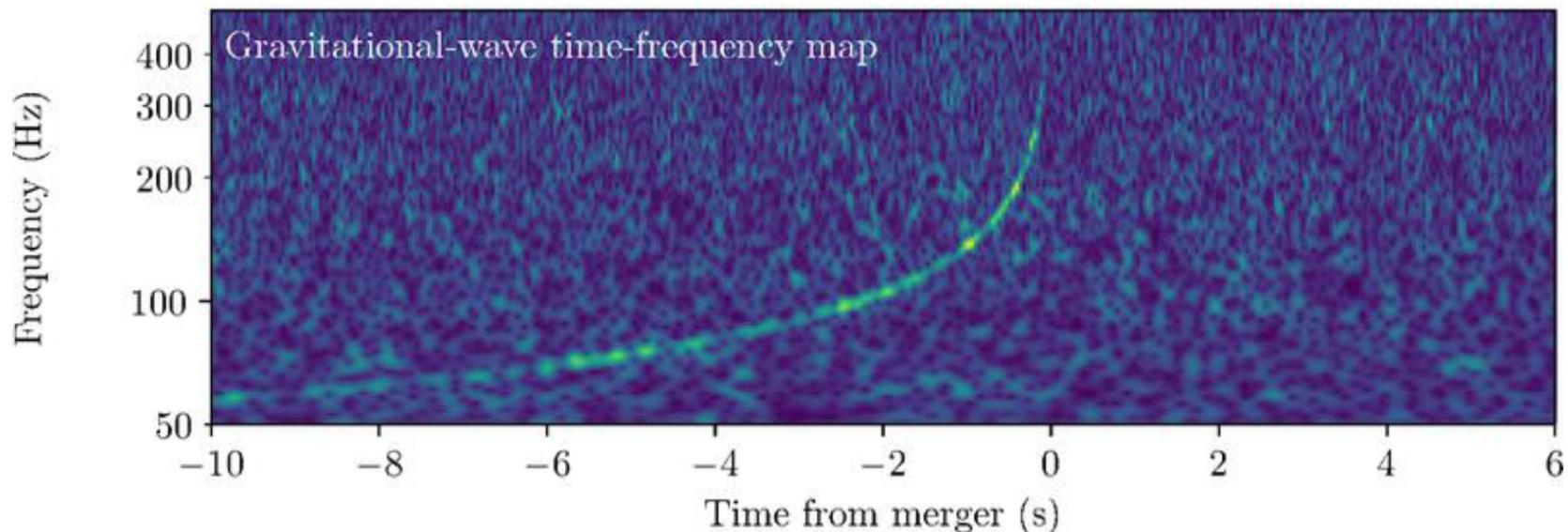
Large number of states of Lanthanides/Actinides leads to a high opacity

Barnes & D. Kasen, *Astrophys. J.* 775, 18 (2013); Tanaka & Hotokezaka, *Astrophys. J.* 775, 113 (2013).

GW170817: First detection gravitational waves from NS merger

On August 17, 12:41:04 UTC advanced LIGO and Virgo detect the first GW signal from a binary neutron star inspiral

Abbott, et al, PRL 119, 161101 (2017).

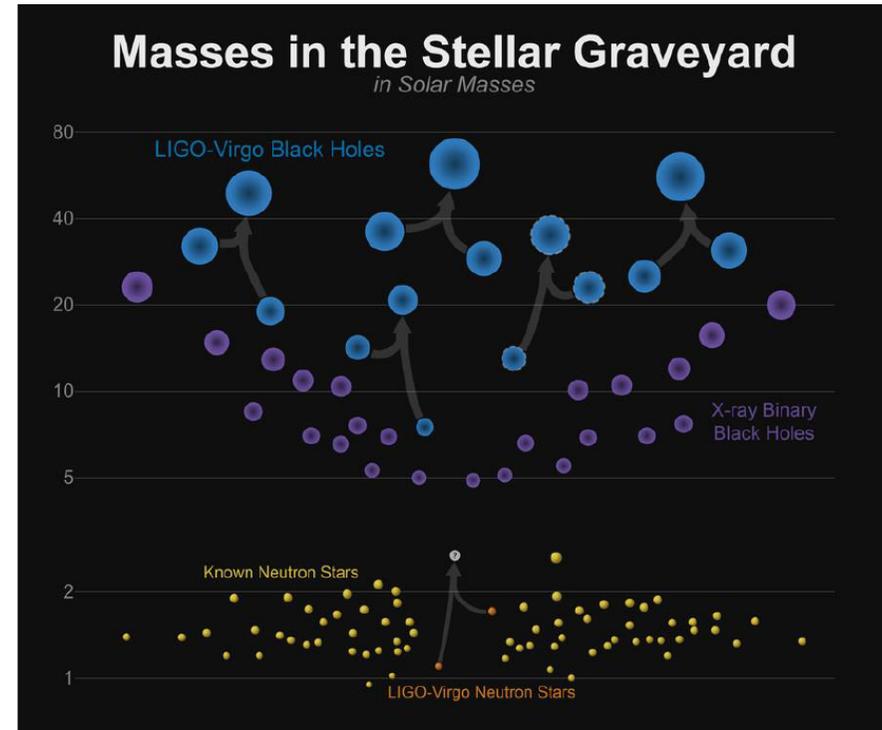
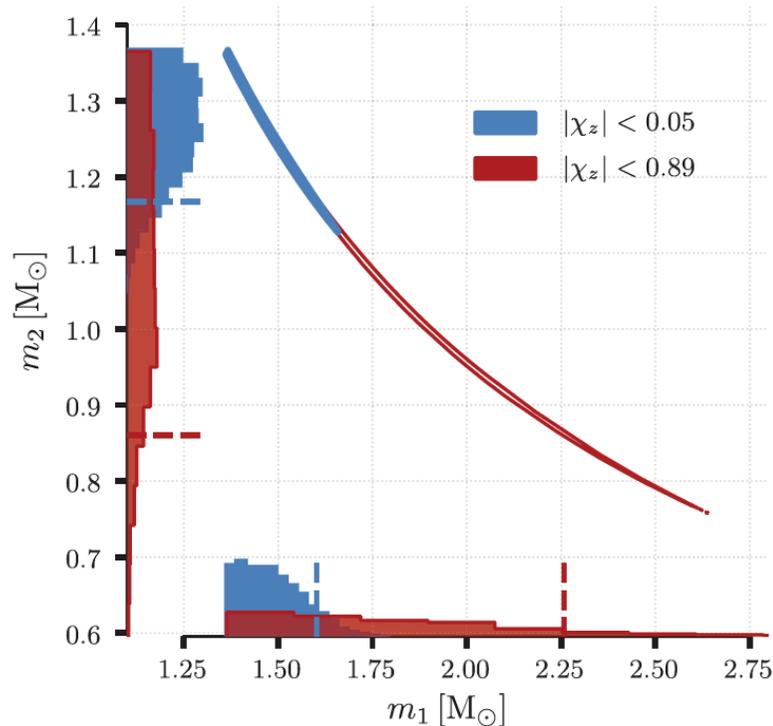


Frequency growth determined by chirp mass $\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}} = 1.188^{+0.004}_{-0.002} M_{\odot}$

$$\frac{96}{5} \pi^{8/3} \left(\frac{G\mathcal{M}}{c^3} \right)^{5/3} t + \frac{3}{8} f^{-8/3} + C = 0$$

GW170817: Individual masses

Individual masses depend on assumed spin parameter $\chi = c J / (GM^2)$



For the low spin case masses are very well constrained

Total mass: $M = 2.74^{+0.04}_{-0.01} M_{\odot}$, $q = m_2/m_1 = 0.7 - 1.0$

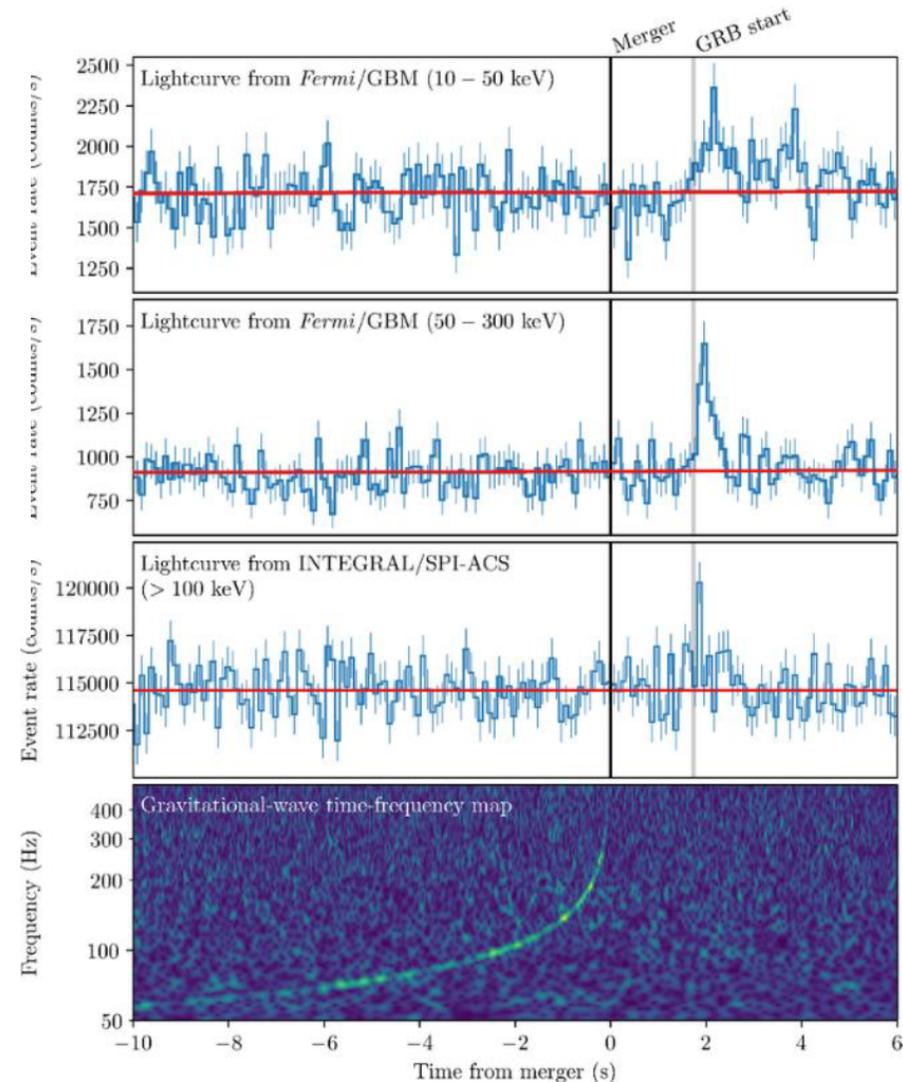
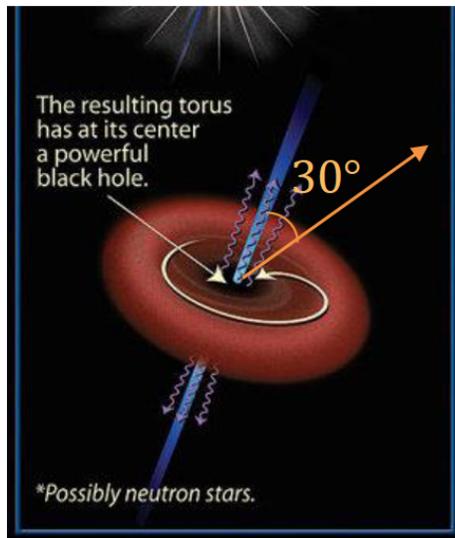
Primary mass: $m_1 \in (1.36-1.60) M_{\odot}$

Secondary mass: $m_2 \in (1.17-1.36) M_{\odot}$

Distance: 40^{+8}_{-14} Mpc

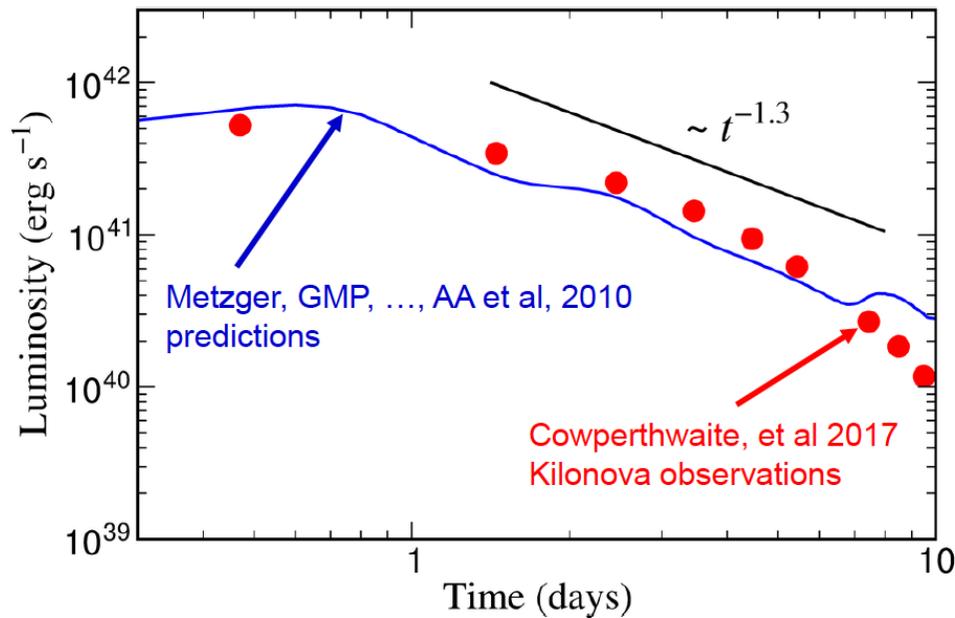
GW170817: A big reveal from the cosmos

- 1.7 s later Fermi and INTEGRAL detected the short GRB 170817 A
- Despite being the closest SGRB is 2-6 order of magnitude weaker than typical SGRBs.
- Explained assuming jet forms $\sim 30^\circ$ with line of view.
- Combined analysis favors formation BH on timescales $\lesssim 100$ ms.

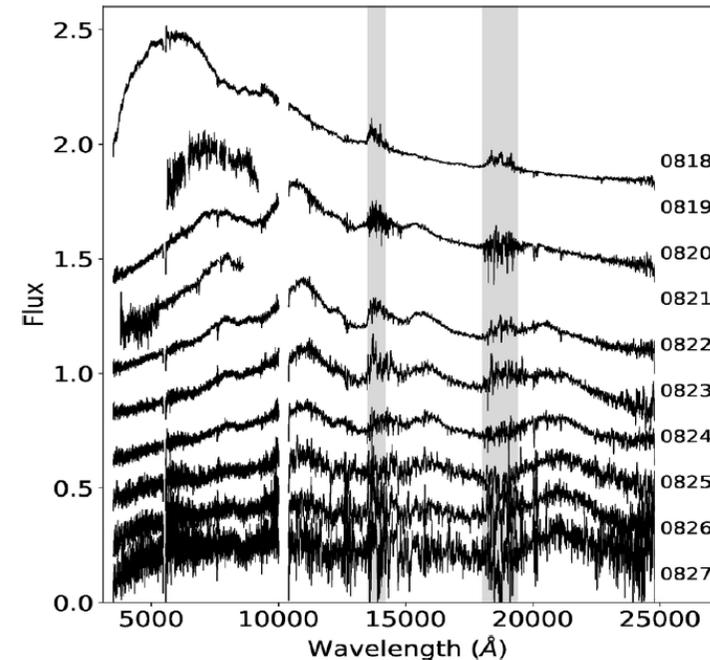


B. P. Abbott, et al, *Astrophys. J.* 848, L13 (2017).

Kilonova: Electromagnetic transient powered by decay of r-process nuclei



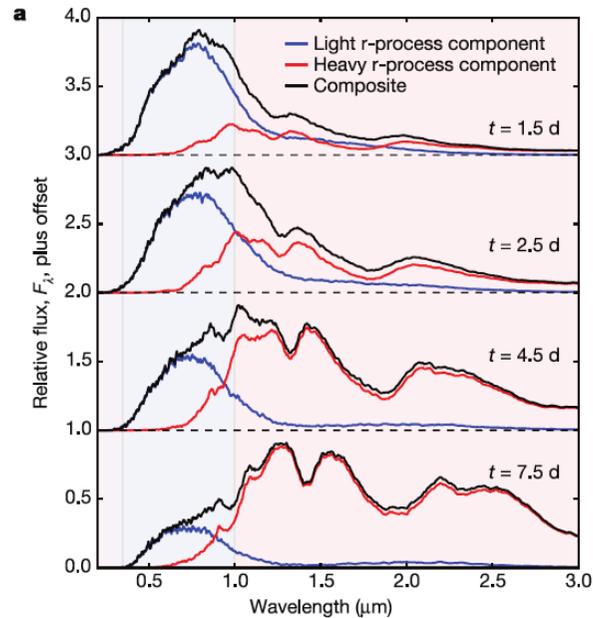
Pian et al., Nature 551, 67 (2017)



- Time evolution determined by the radioactive decay of r-process nuclei
- Two components, Kasen et al, Nature 551, 80 (2017)
 - Blue dominated by light elements ($Z < 50$) ($M = 0.025 M_{\odot}$, $v = 0.3c$, $X_{\text{lan}} = 10^{-4}$, dynamical ejecta?, signature neutrino interactions)
 - Red due to presence of Lanthanides ($M = 0.04 M_{\odot}$, $v = 0.15c$, $X_{\text{lan}} = 10^{-1.5}$, ejecta accretion disk?, points to the formation of a black hole)
- Spectroscopic identification of r-process element Sr (Watson et al, 2019)

Two components model

Kasen et al, Nature 551, 80 (2017)

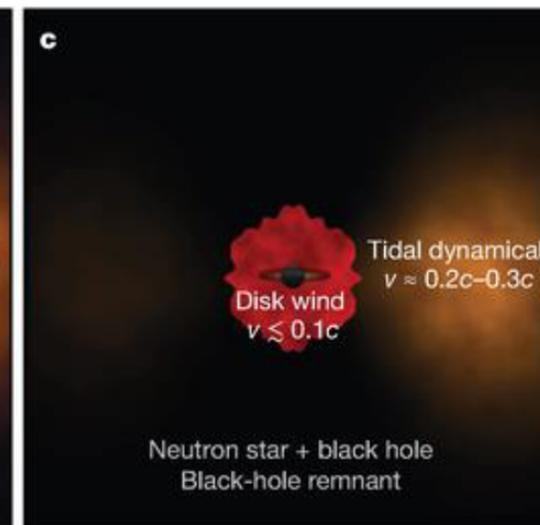
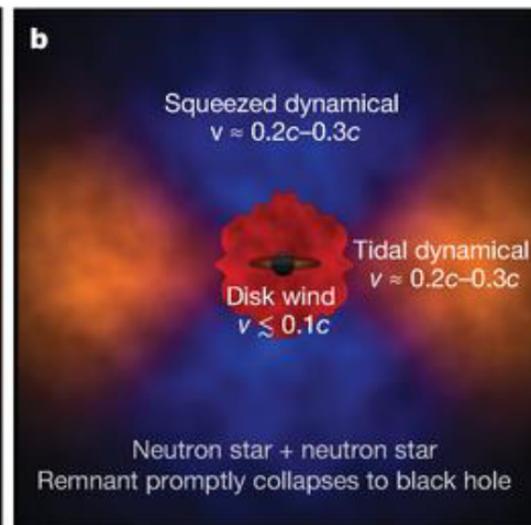
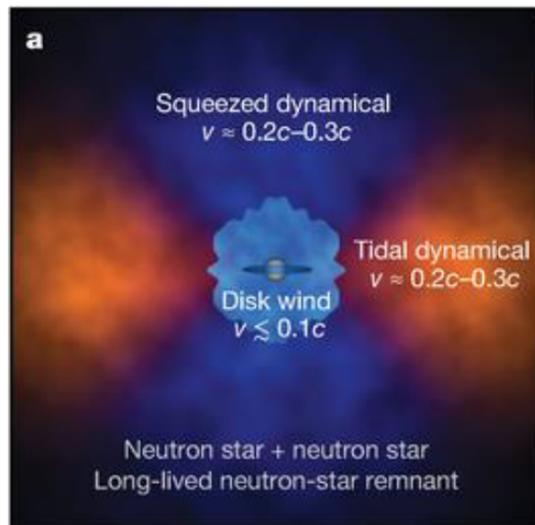


- Blue component from polar ejecta subject to strong neutrino fluxes (light r process)

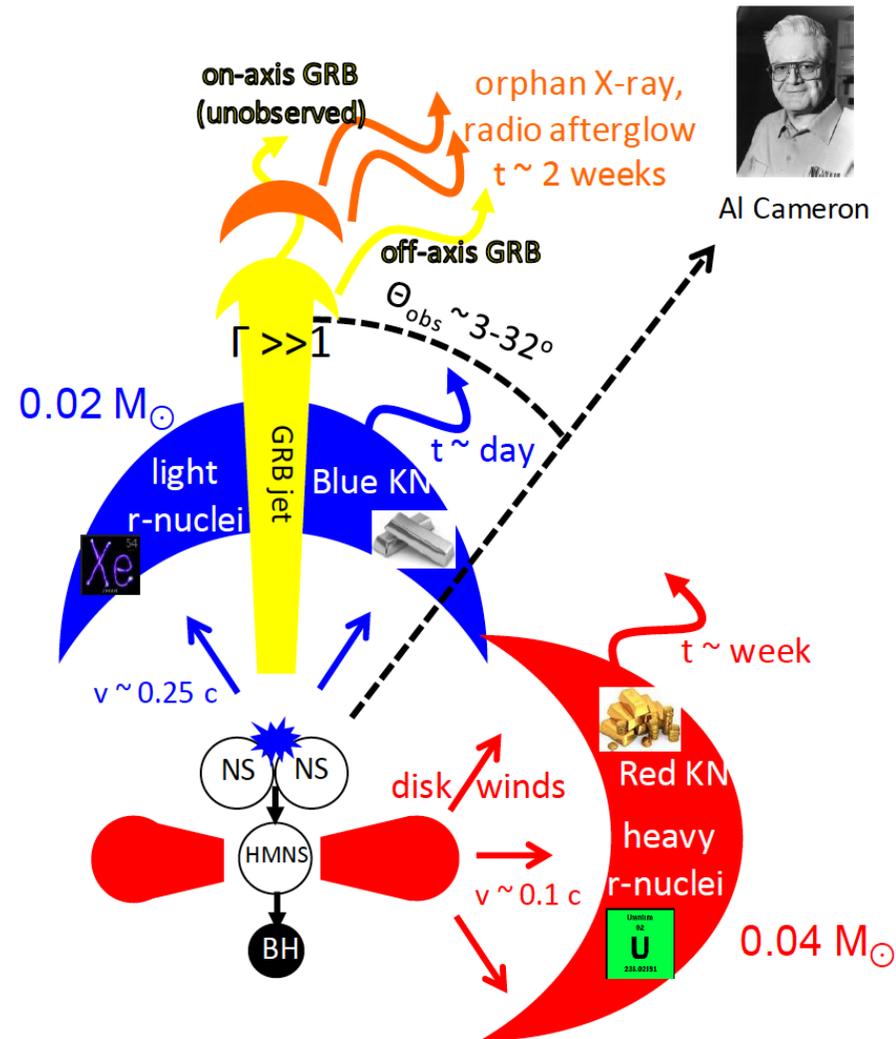
$$M = 0.025 M_{\odot}, v = 0.3c, X_{\text{lan}} = 10^{-4}$$

- Red component disk ejecta after NS collapse to a black hole (includes both light and heavy r process)

$$M = 0.04 M_{\odot}, v = 0.15c, X_{\text{lan}} = 10^{-1.5}$$



Unified scenario EM counterparts



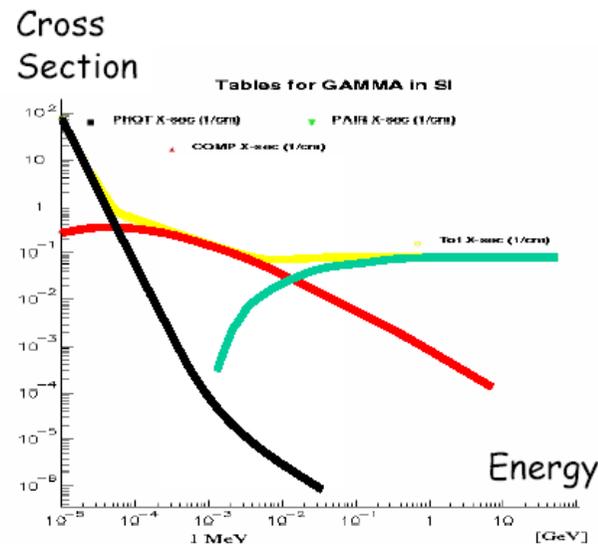
Sketch from B. Metzger

Astrofisica Nucleare e Subnucleare

“MeV” Astrophysics

MeV astrophysics techniques

Detection of Gamma Radiation



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

Telescope:
 Tracking chambers to visualize the pairs

Photoeffect (< 100 keV)

Photons effectively blocked and stopped

Telescopes:

Collimators
 Coded Mask Systems

Compton Scattering (0.2-10 MeV)

Photon Crosssection Minimum
 Scattered photons with long range

Telescope:

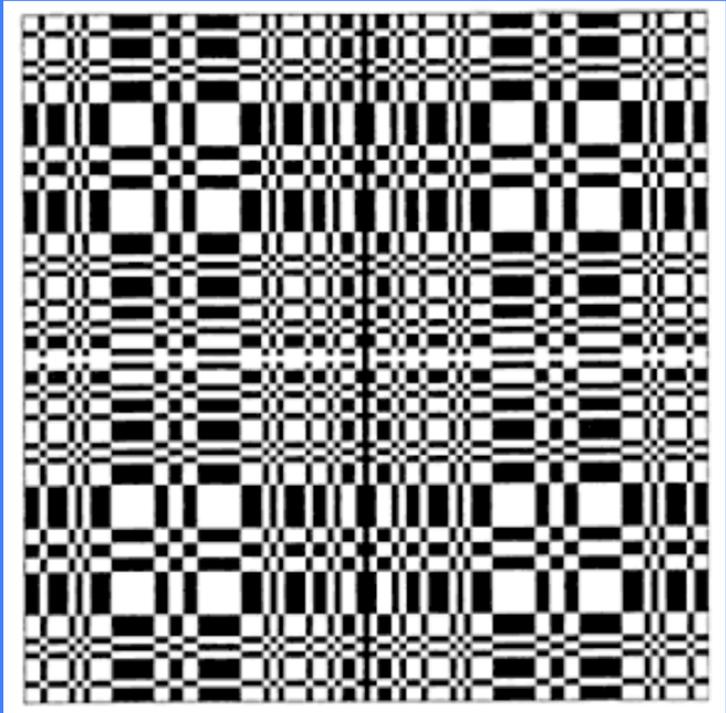
Compton Camera Coincidence System

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



**Mask of IBIS (15 keV – 10 MeV)
onboard *INTEGRAL***



Coded Mask Imaging

The Coded Masks for Integral

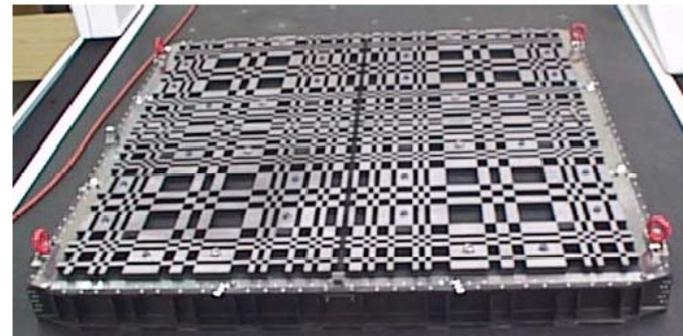


JEM-X

Energy: 3-100 keV
535mm dia
0.5mm Tungsten
3.3 mm pitch
Resolution 3 arc min

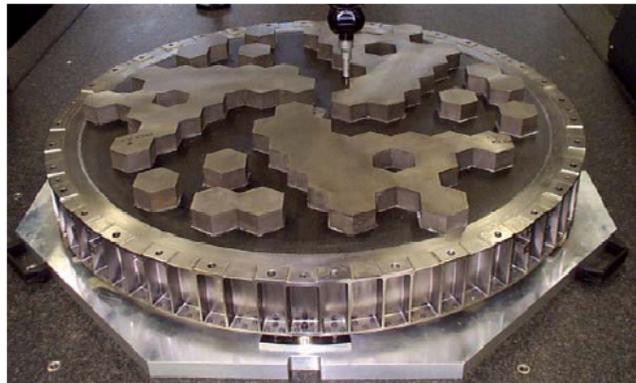
IBIS

Energy: 15-10000 keV
1064 mm square
16 mm Tungsten
11.2 mm pitch
Resolution 12 arc min



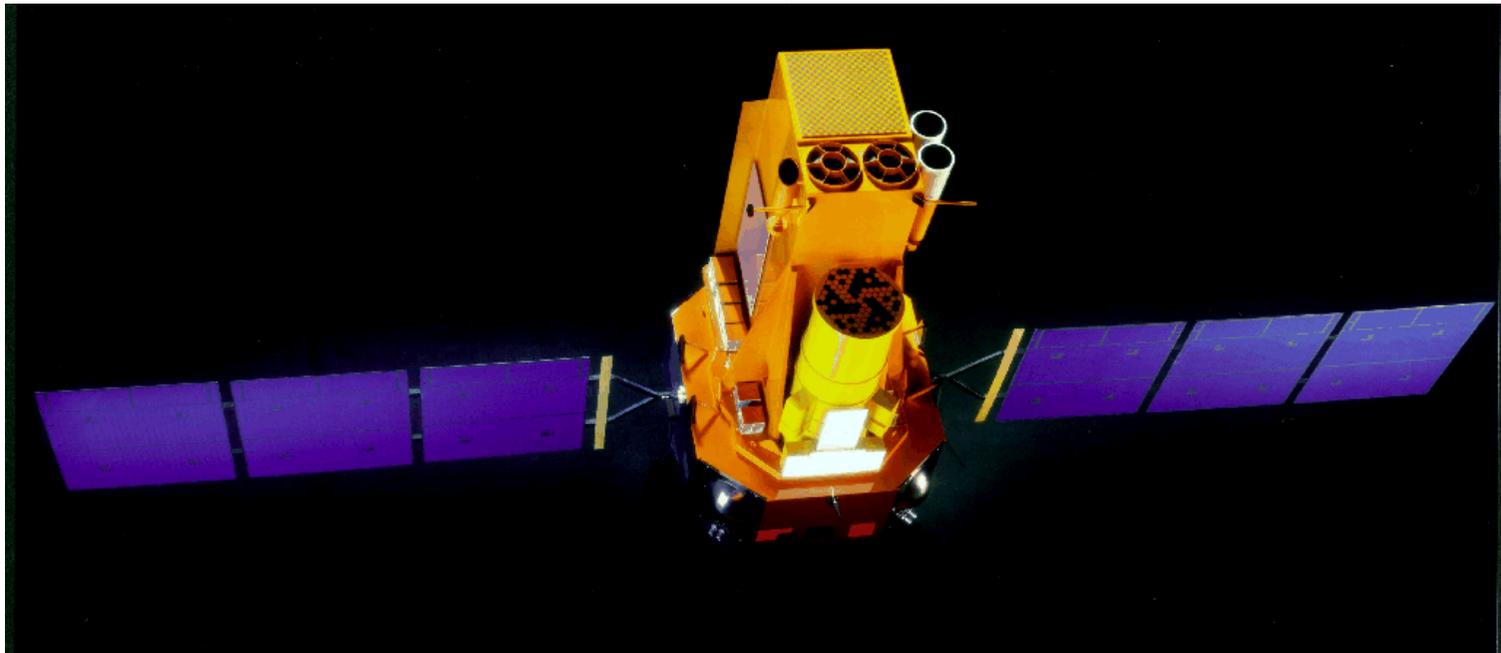
SPI

Energy: 20-8000 keV
770 mm dia
3 cm thick Tungsten
60 mm pitch
Resolution $\sim 2.5^\circ$



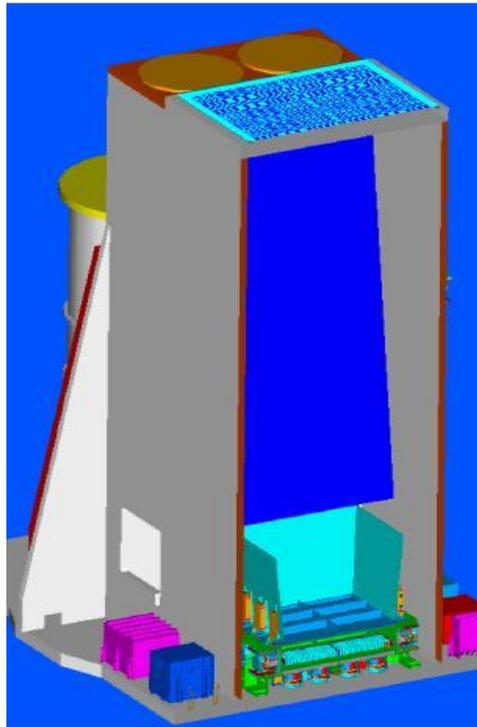
INTEGRAL

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)

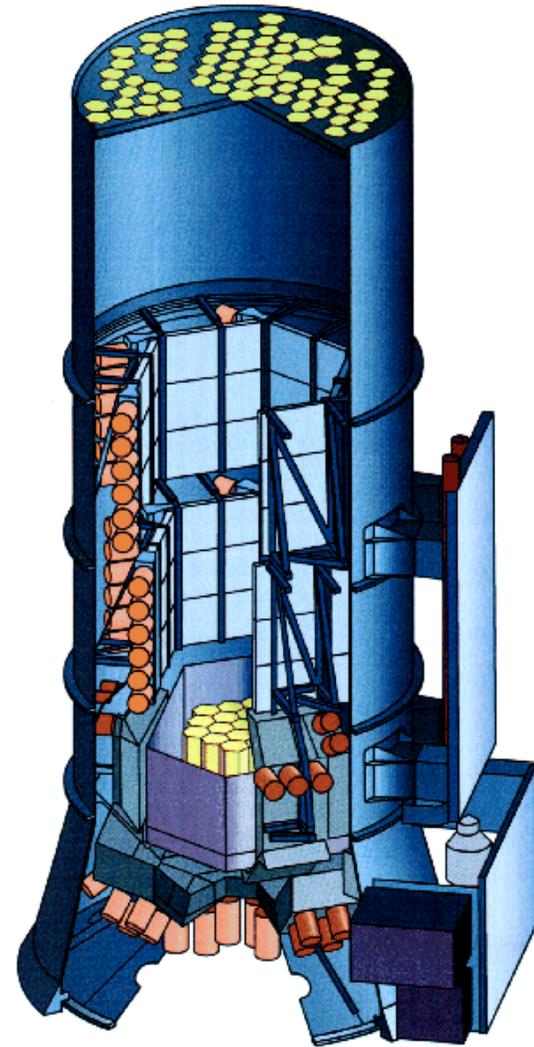


<http://integral.esa.int>

INTEGRAL

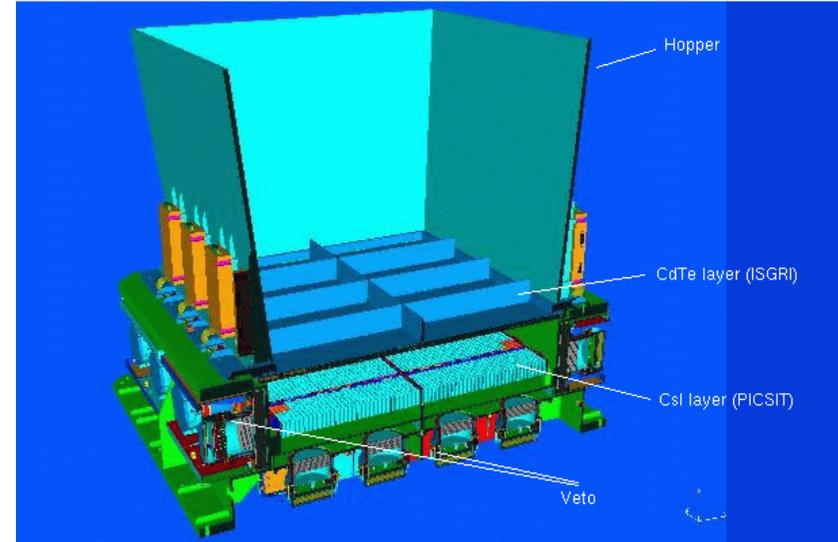
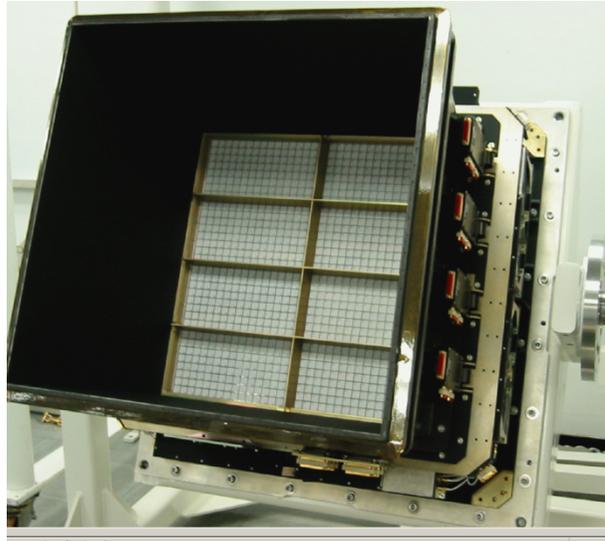


Imager IBIS



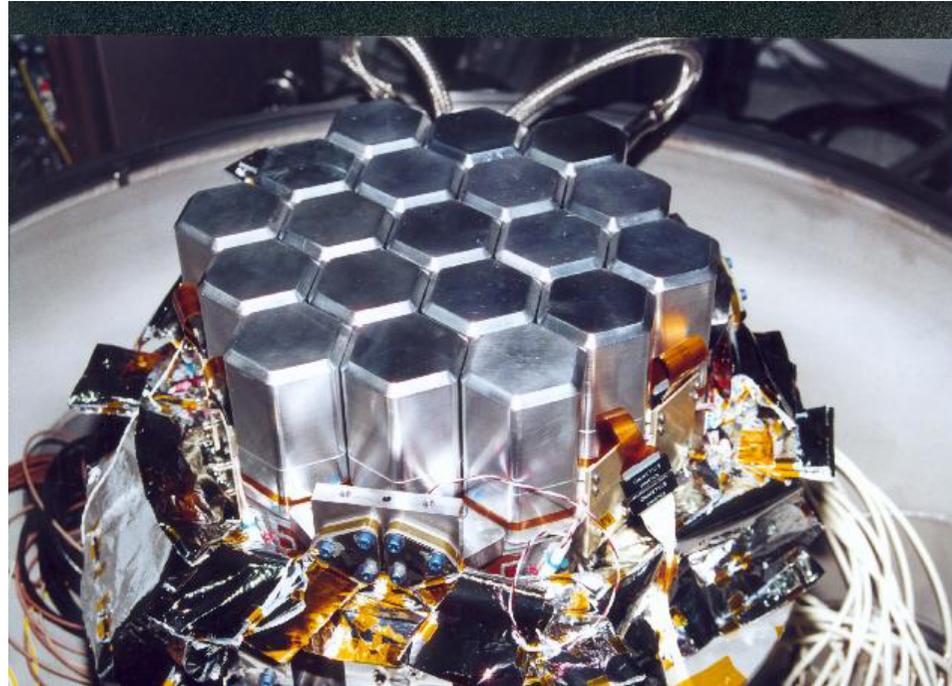
Spectrometer SPI

IBIS



The Imager IBIS (Imager on Board the Integral Satellite) provides diagnostic capabilities of fine imaging (12 arcmin FWHM), source identification and spectral sensitivity to both continuum and broad lines over a broad (15 keV - 10 MeV) energy range. The Imager will exploit simultaneously with the other instruments on Integral celestial objects of all classes ranging from the most compact galactic systems to extragalactic objects. A tungsten coded-aperture mask (located at 3.2 m above the detection plane) is optimised for high angular resolution. As diffraction is negligible at gamma-ray wavelengths, the angular resolution obtainable with a coded mask telescope is limited by the spatial resolution of the detector array. The Imager design takes advantage of this by utilising a detector with a large number of spatially resolved pixels, implemented as physically distinct elements. The detector uses two planes, one 2600 cm² front layer of CdTe pixels, each (4x4x2) mm (width x depth x height), and a 3000 cm² layer of CsI pixels, each (9x9x30) mm. The CdTe array (ISGRI) and the CsI array (PICsIT) are separated by 90 mm. The detector provides the wide energy range and high sensitivity continuum spectroscopy required for Integral. The division into two layers allows the paths of the photons to be tracked in 3D, as they scatter and interact with more than one element. Events can be categorised and the signal to noise ratio improved by rejecting those which are unlikely to correspond to real (celestial) photons, e.g. towards the high end of the energy range. The aperture is restricted by a lead shielding tube and shielded in all other directions by an active BGO scintillator veto.

SPI



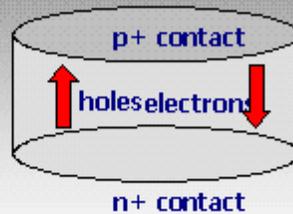
The spectrometer SPI (Spectrometer on INTEGRAL) will perform spectral analysis of gamma-ray point sources and extended regions in the 18 keV - 8 MeV energy range with an energy resolution of 2.2 keV (FWHM) at 1.33 MeV. This will be accomplished using an array of 19 hexagonal high purity Germanium detectors cooled by a Stirling cooler system to an operating temperature of 85 K. A hexagonal coded aperture mask is located 1.7 m above the detection plane in order to image large regions of the sky (fully coded field of view = 16 degrees) with an angular resolution of 2.5 degrees. In order to reduce background radiation, the detector assembly is shielded by a veto (anticoincidence) system which extends around the bottom and side of the detector almost completely up to the coded mask. The aperture (and hence contribution by cosmic diffuse radiation) is limited to ~ 30 degr. A plastic veto is provided below the mask to further reduce the 511 keV background.

Gamma Spectroscopy

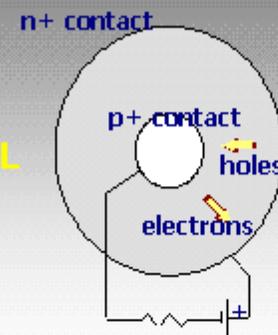
Gamma ray astronomy - Germanium detectors

Available as either:

PLANAR
devices



or **COAXIAL**



PLANAR

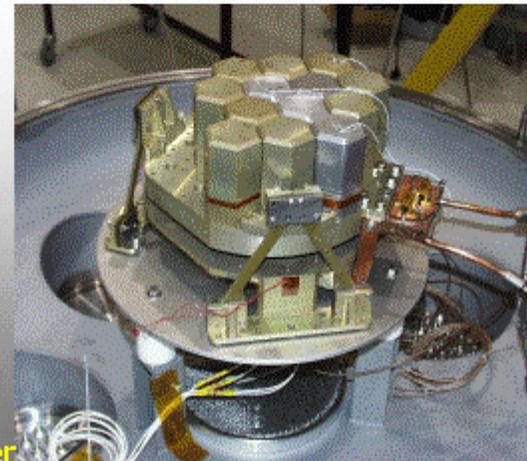
Better at low energies
Limited size & stopping
power

COAXIAL

Slightly poorer resolution
Much larger

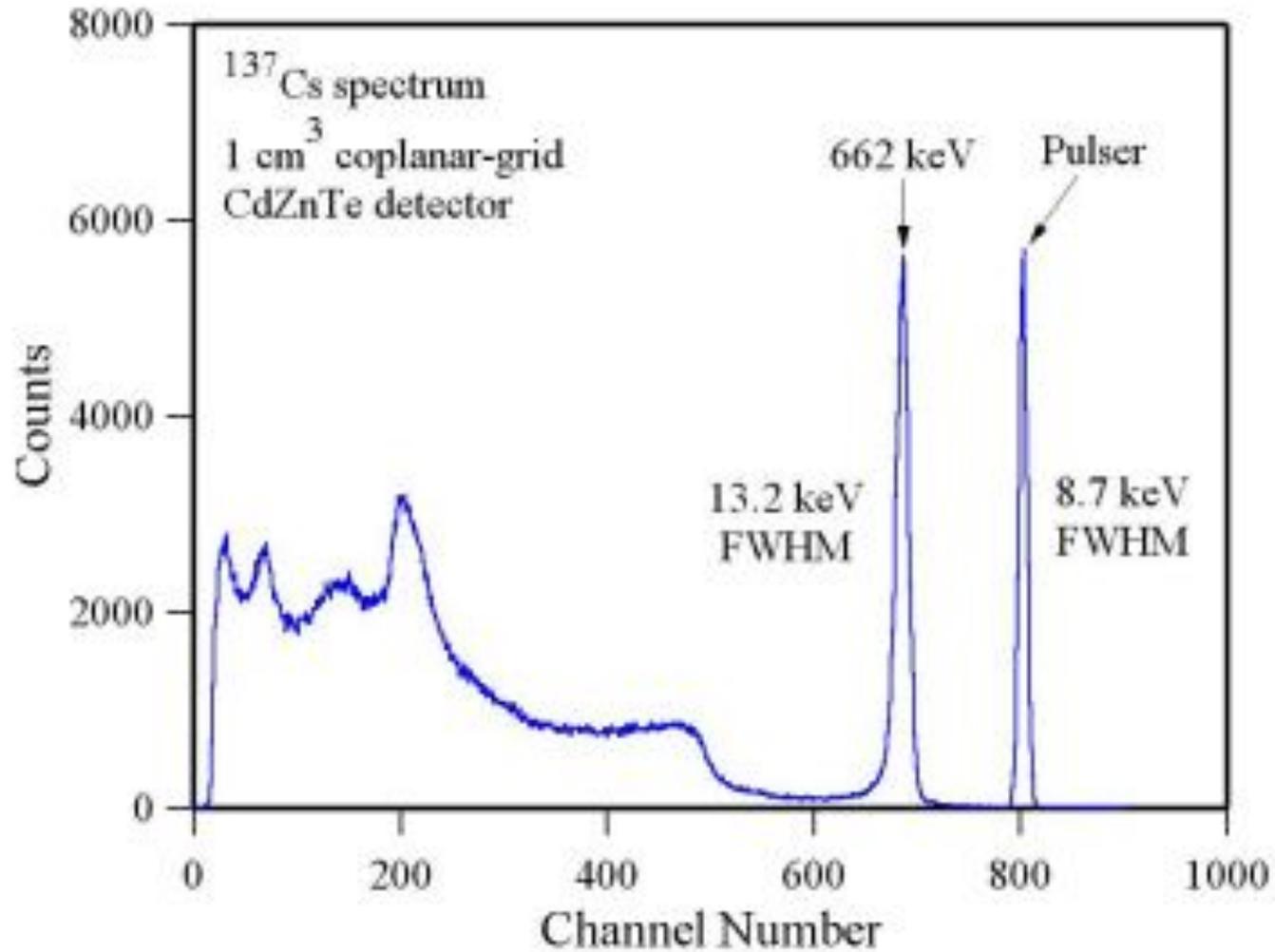
BOTH

Ultimate in spectral
resolution
Must be cooled to $\sim 70\text{K}$ in
use
May be arrayed to build an
imaging detector



SPI @ INTEGRAL – a Ge spectrometer

Gamma Spectroscopy



Rivelatori al Germanio

- Good response to high-energy photons
- Germanium is the best choice for high-energy ($E > 100 \text{ keV} - 10 \text{ MeV}$) spectroscopy

Very thin surface dead layers may give Ge an advantage where response from $1 \text{ keV} - 100$'s of keV is desired

- Disadvantages (compared to compound semiconductors or scintillation detectors)
 - Requires cooling (complexity and cost)
 - Surfaces sensitive to contamination (handling/packaging more difficult)
 - For fine ($Dx < 1 \text{ mm}$) position-sensitive detectors, segmented contact technology not well developed.

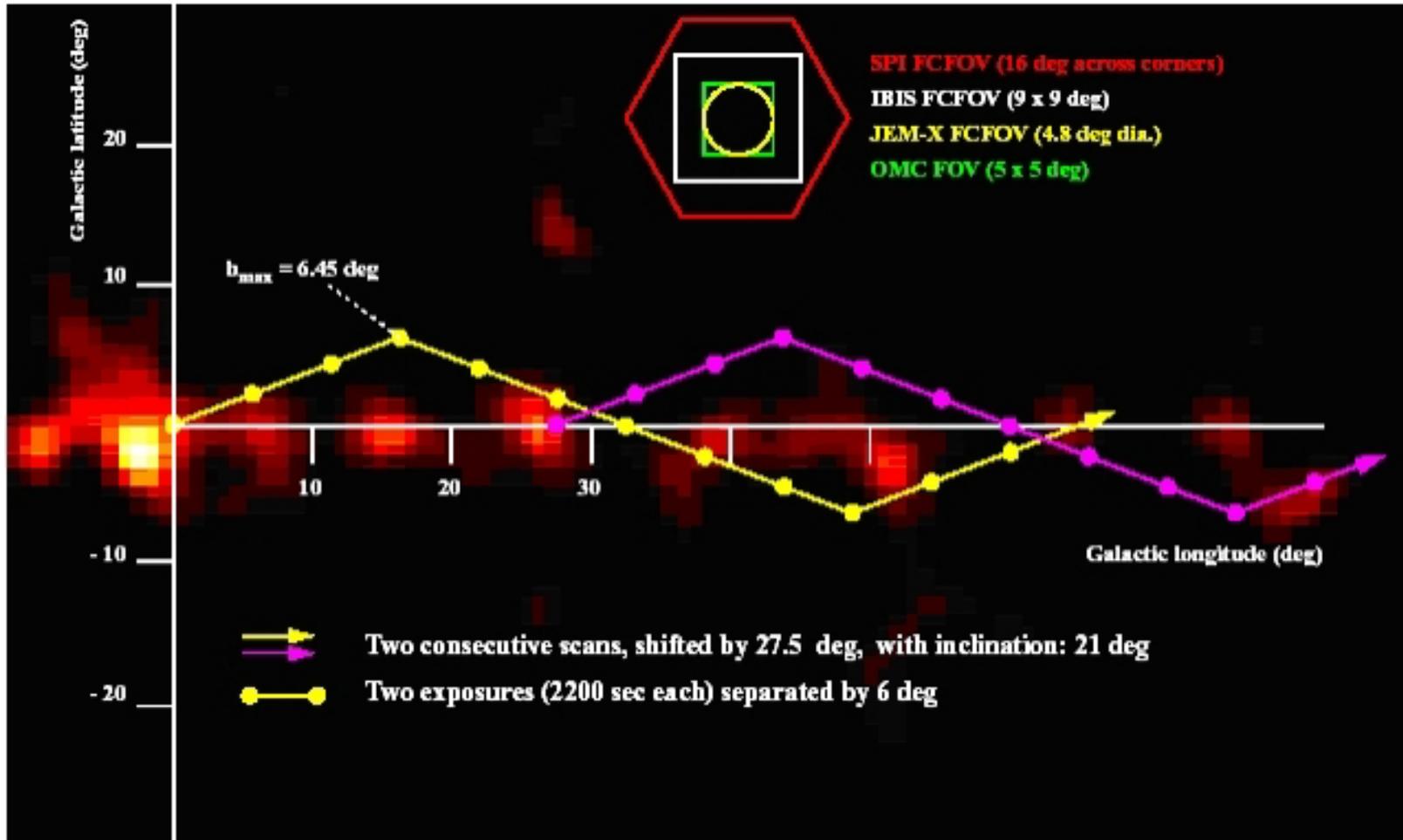
Examples CdTe: *Integral/IBIS (SPI)*

Rivelatori a stato solido a temperatura ambiente: Cd(Zn)Te – Cadmium Zinc Telluride (CZT)

- **Energy gap (1.4-2.2 eV)**
 - **Non necessaria criogenia (a differenza del Ge)**
- **Alta ρ ($\sim 6 \text{ g cm}^{-3}$) per massimizzare l'efficienza**
- **Alto Z (48, 52) per effetto fotoelettrico:**
 - **10 volte il μ_{Compt} fino a 110 keV (60 il Ge, 25 il Si);**
 - **Single site ok per imaging**
- **Facilmente segmentabile a piccole dimensioni:**
 - **\Rightarrow risoluzione spaziale**

Examples CdTe: *Integral/IBIS (ISGRI) – Swift/BAT*

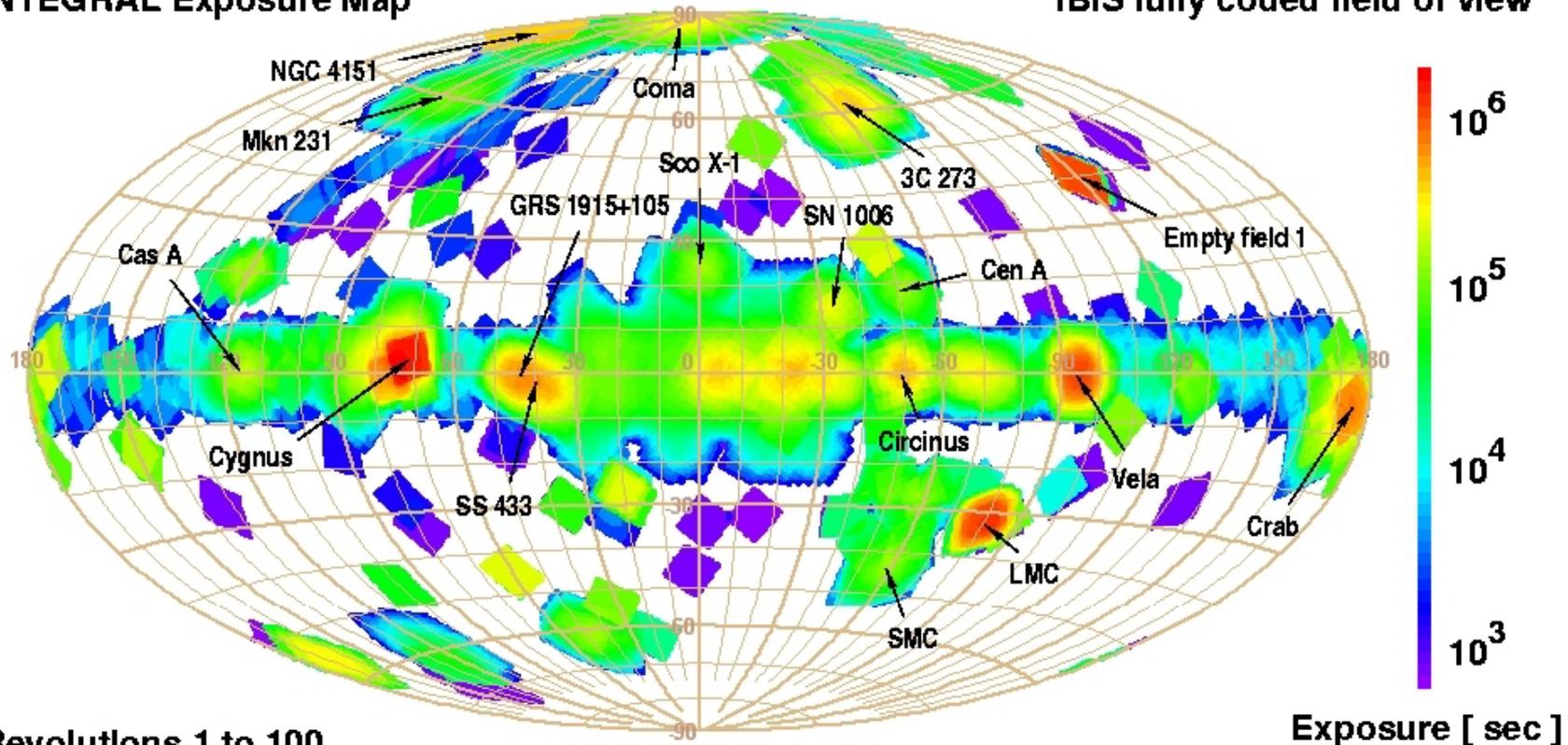
INTEGRAL



INTEGRAL

INTEGRAL Exposure Map

IBIS fully coded field of view

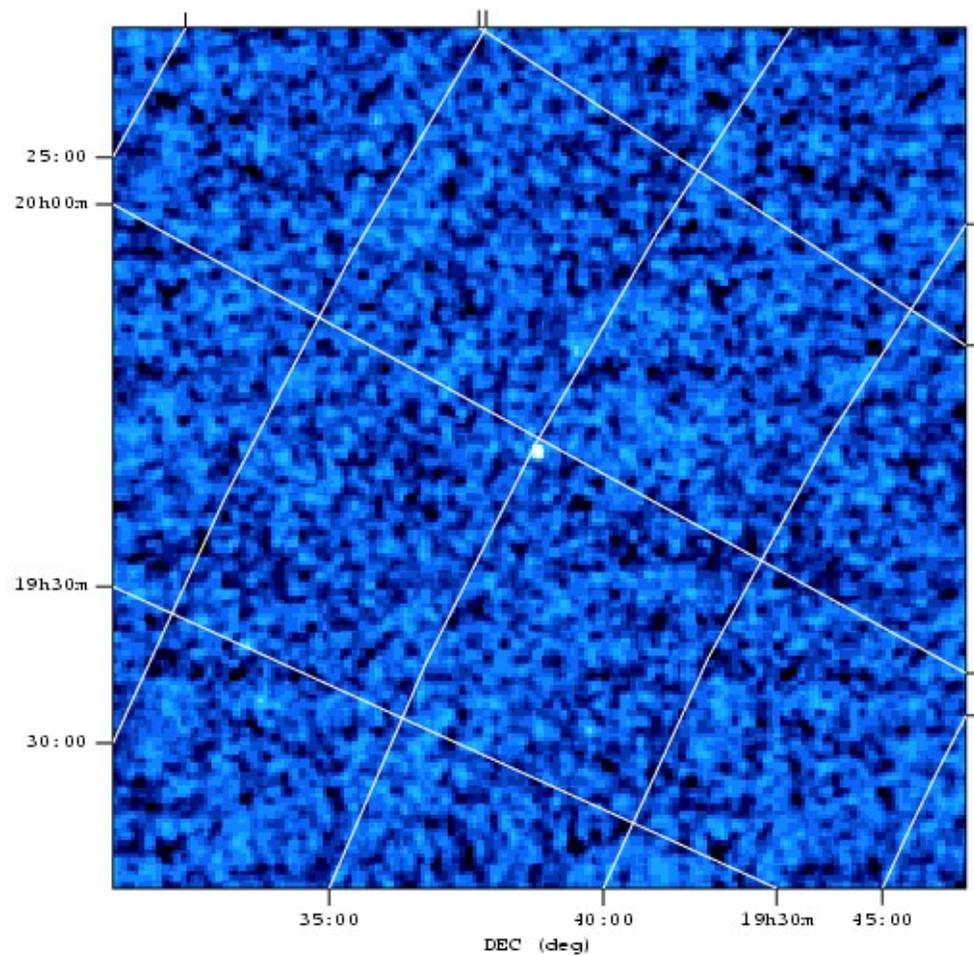


INTEGRAL

ISGRI 40-100 keV

isgr_sky._ima_idx.fits_8

CYG-X1 17.11.02



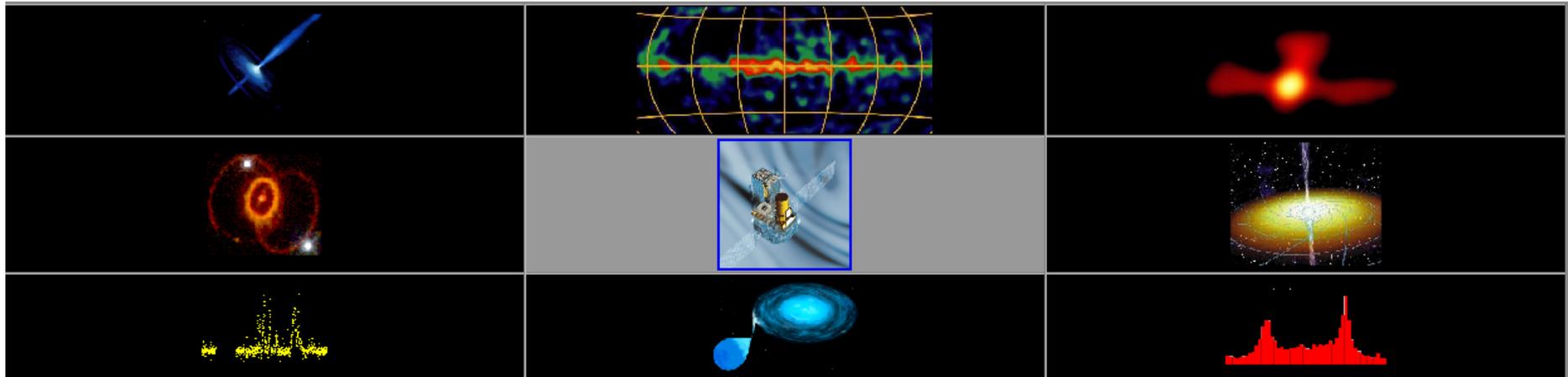
INTEGRAL Science Objectives

Outline INTEGRAL Science Objectives

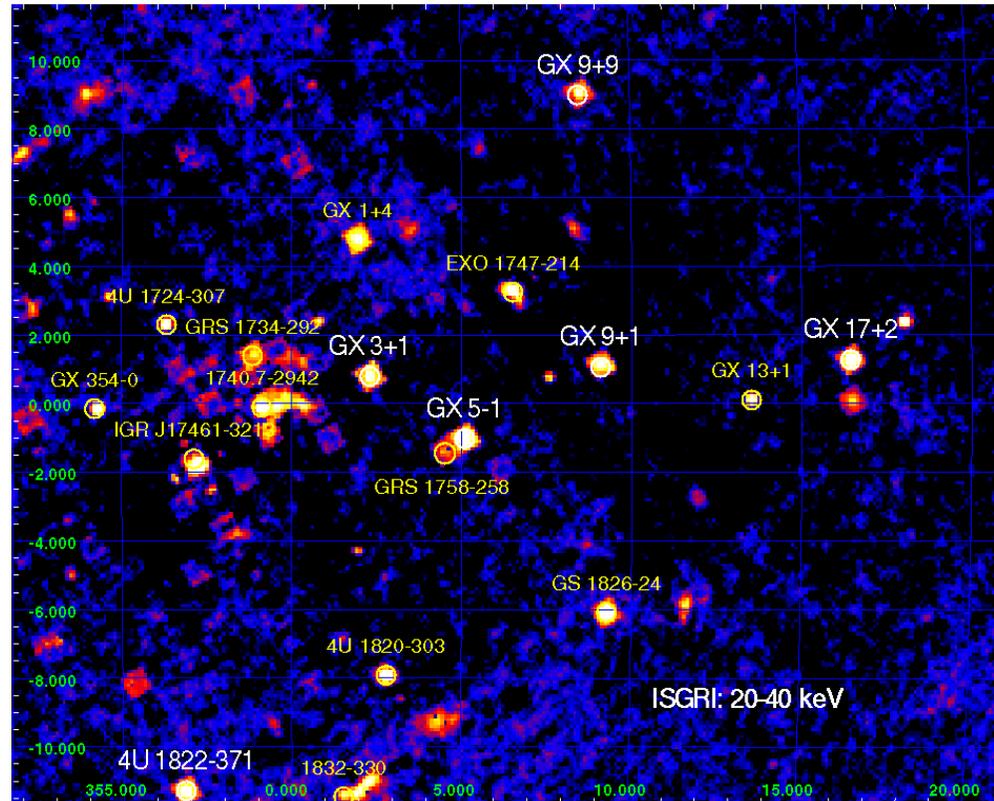
The scientific goals of Integral are addressed through the use of high resolution spectroscopy with fine imaging and accurate positioning of celestial sources in the gamma-ray domain. The following list of topics will be addressed by Integral:

- 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

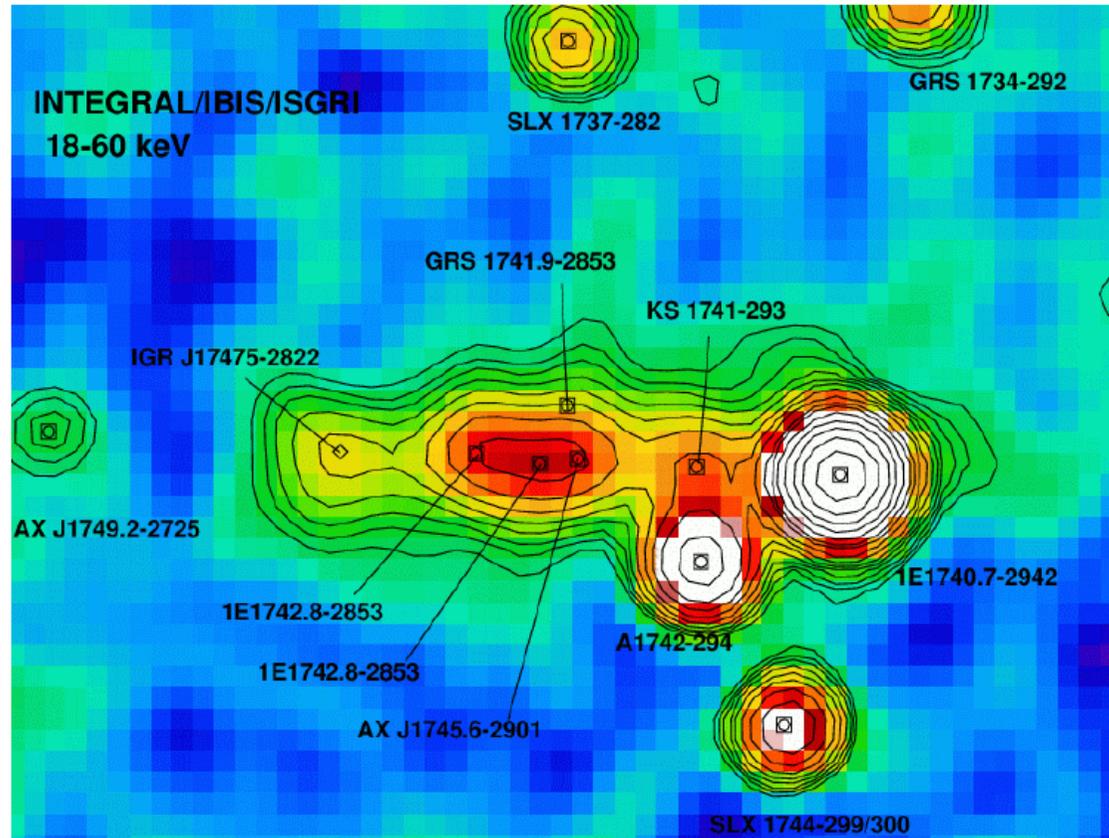


INTEGRAL



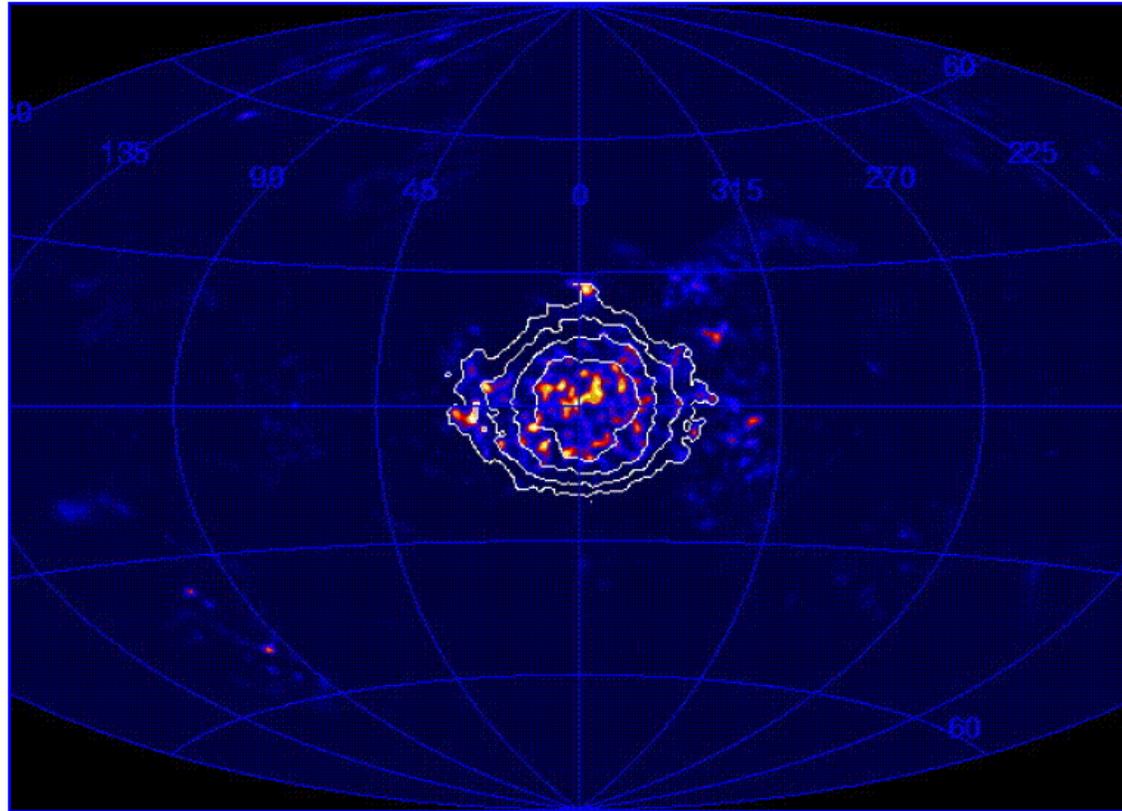
The image is an IBIS/ISGRI image of the Galactic Centre in the 20-40 keV band.
The analysis of IBIS/ISGRI data is based on GCDE (Galactic Center Deep Exposure) and GPS (Galactic Plane Scan) data from revolution 30 to 64 i.e. January 11th to April 22nd, 2003 for a total of one thousand pointings (about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

INTEGRAL



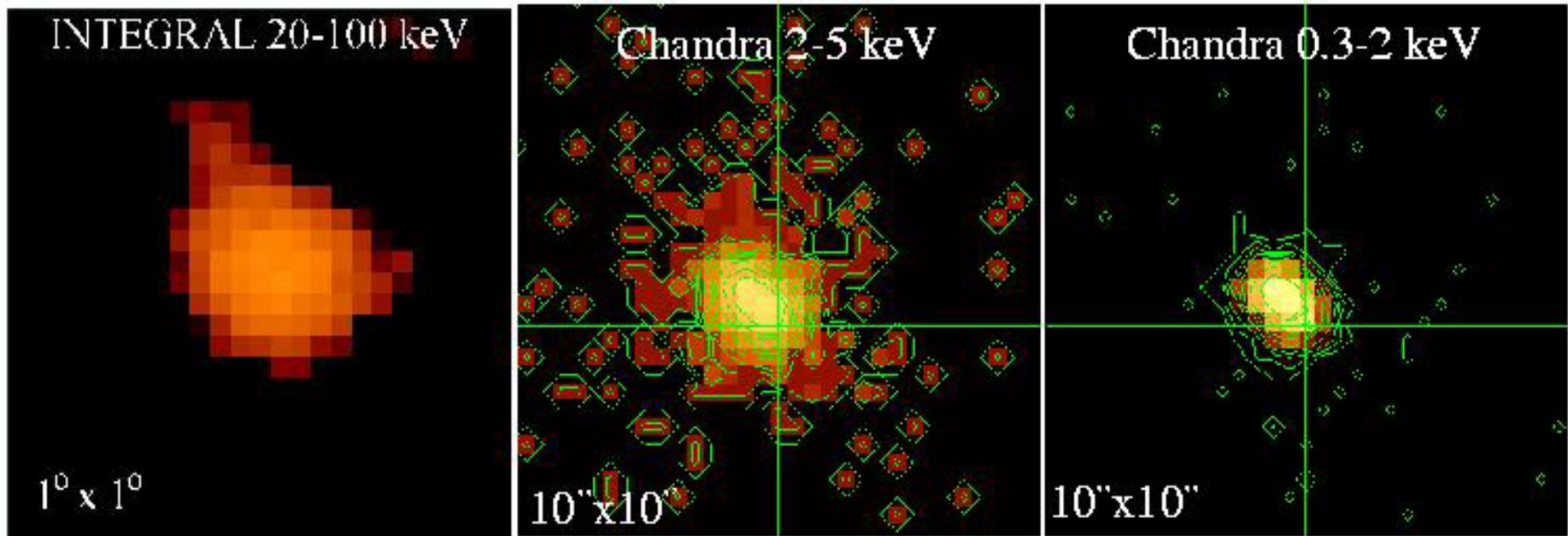
INTEGRAL views a Compton mirror at the Galactic Centre. M. Revnivtsev et al. report on the association of IGR J17475-2822, recently discovered by INTEGRAL, with the giant molecular cloud Sgr B2 in the Galactic Center region. Data from different observatories strongly support the idea that the hard X-ray 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

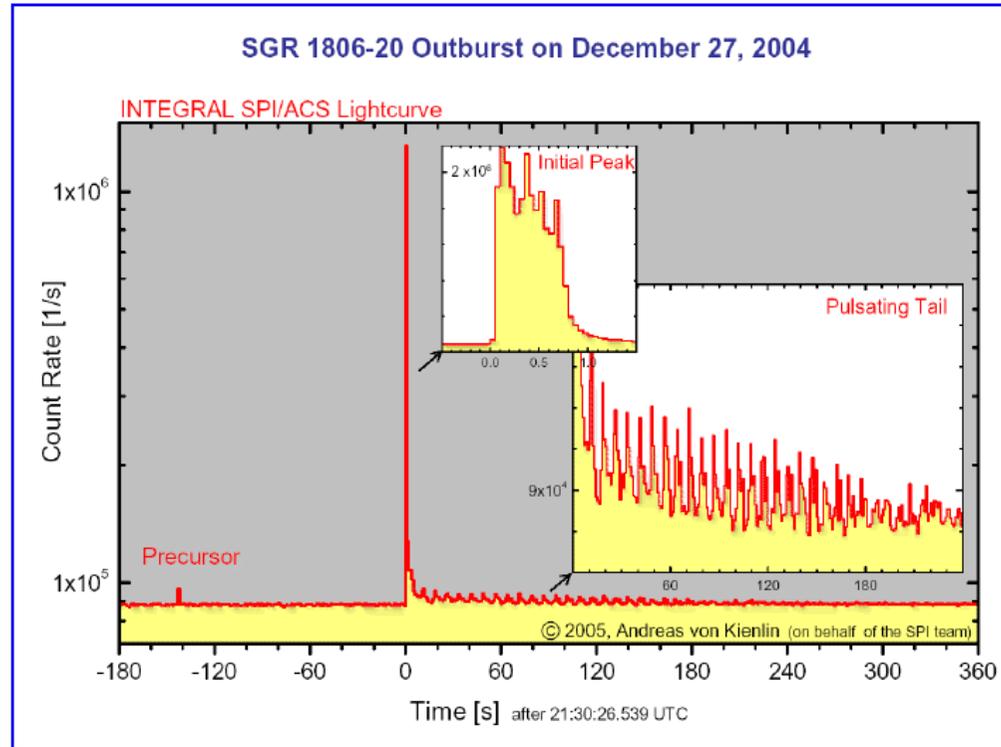


The blazar PKS 1830-211 is one of the most distant objects observed so far by INTEGRAL, it was reported as an ISGRI source in the galactic centre region. The source is clearly detected in 20-100 keV band. The image from IBIS/ISGRI is shown in the left panel.

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).

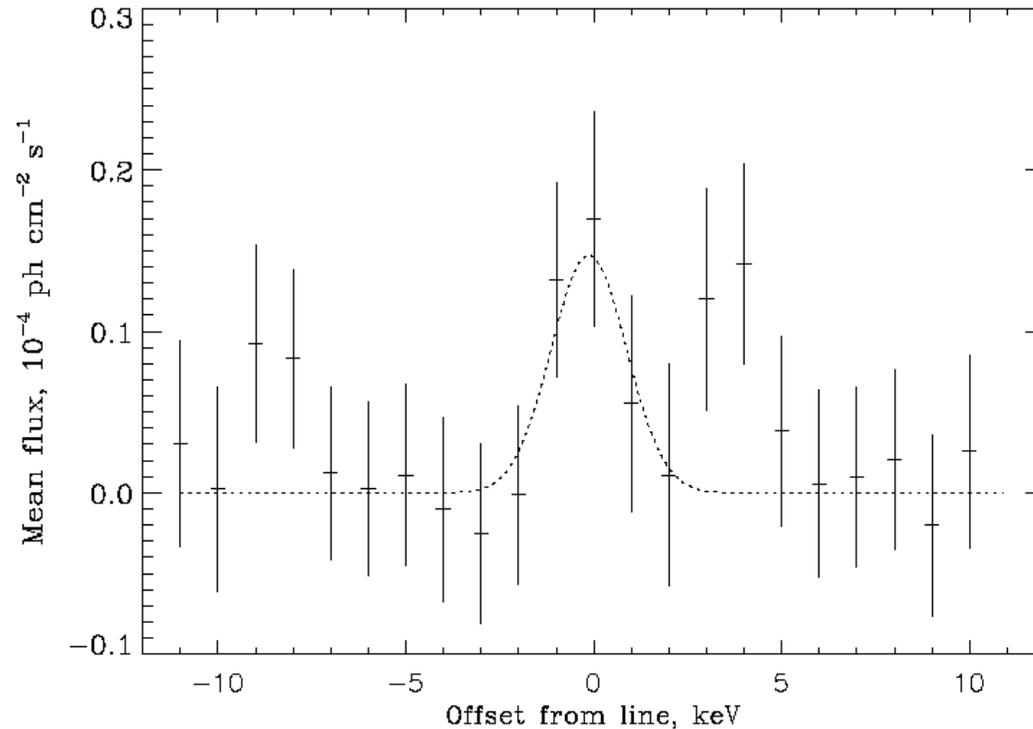
By assuming a magnification factor due to the lensing of the order of 10, the bolometric luminosity of PKS 1830-211 is huge: about 10^{48} erg/s! The spectrum can be modelled adding an external source of low energy photons scattered up to gamma-ray energies by relativistic electrons. As observed in some 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



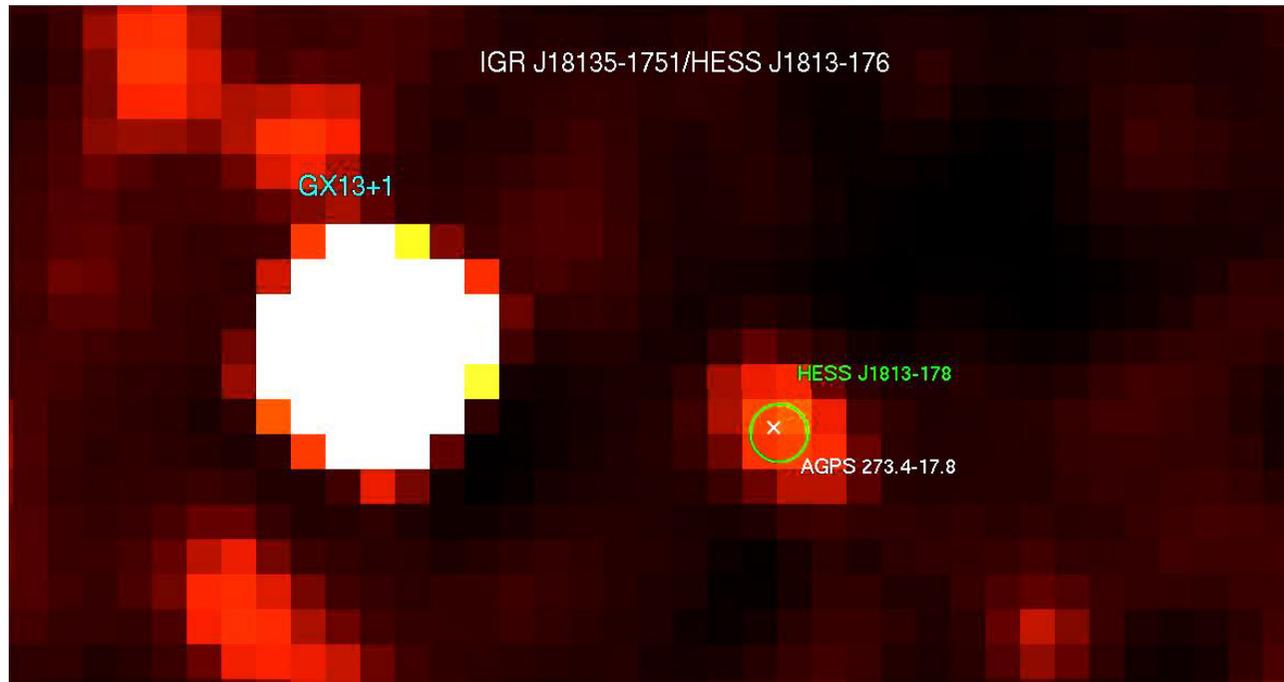
SGR 1806-20 which belongs to the class of soft gamma-ray repeaters (SGR) is believed to be a rotating neutron star with a super-strong magnetic field (10^{15} Gauss); a so-called magnetar. The tremendous outburst of SGR 1806-20 on December 27, 2004 as seen by the large anticoincidence shield (ACS) of 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 preceded 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 $3.7 \pm 1.1 \times 10^5 \text{ cm}^{-2} \text{ s}^{-1}$ 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 $^{60}\text{Fe}/^{26}\text{Al} = 0.11 \pm 0.03$ 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



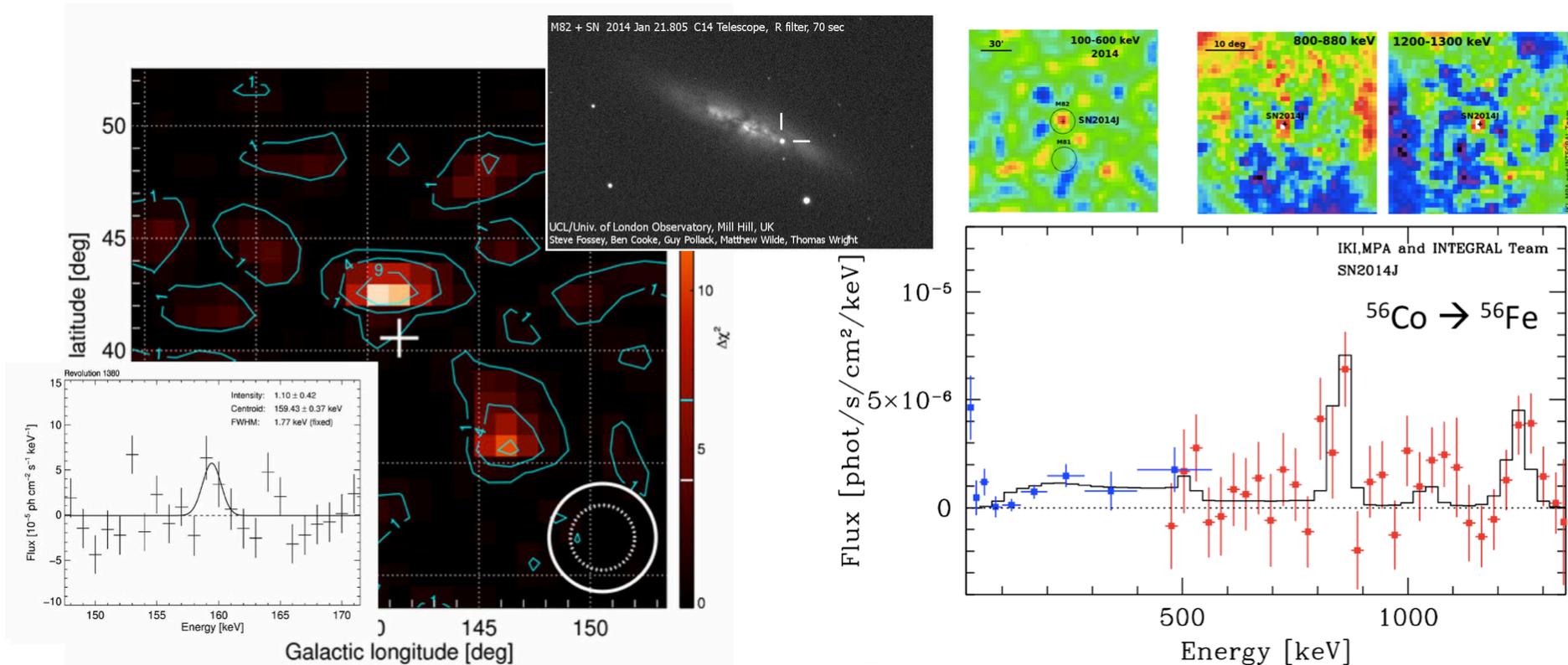
INTEGRAL has discovered, using the IBIS instrument, a new gamma-ray source (IGR J18135-1751). This source is remarkable, since it coincides spatially with one of the ten objects which have been seen during the first survey at TeV energies of the inner part of the galaxy: HESS J1813-178. This source is 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



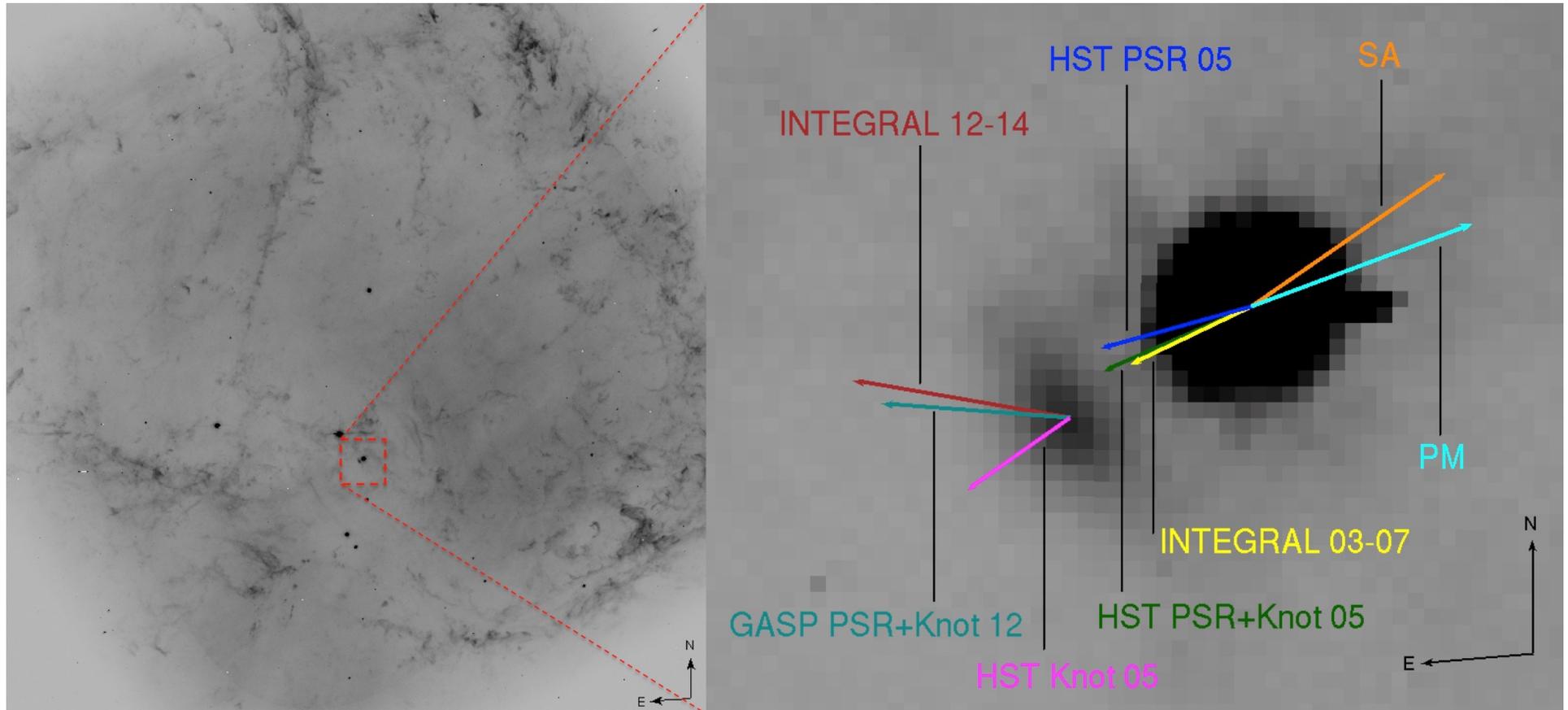
The central regions of our Galaxy, the Milky Way, as seen by INTEGRAL in gamma rays. With its superior ability to see faint details, INTEGRAL reveals the individual sources that comprised the foggy, soft gamma-ray background seen by previous observatories. The brightest 91 objects seen in this image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

INTEGRAL



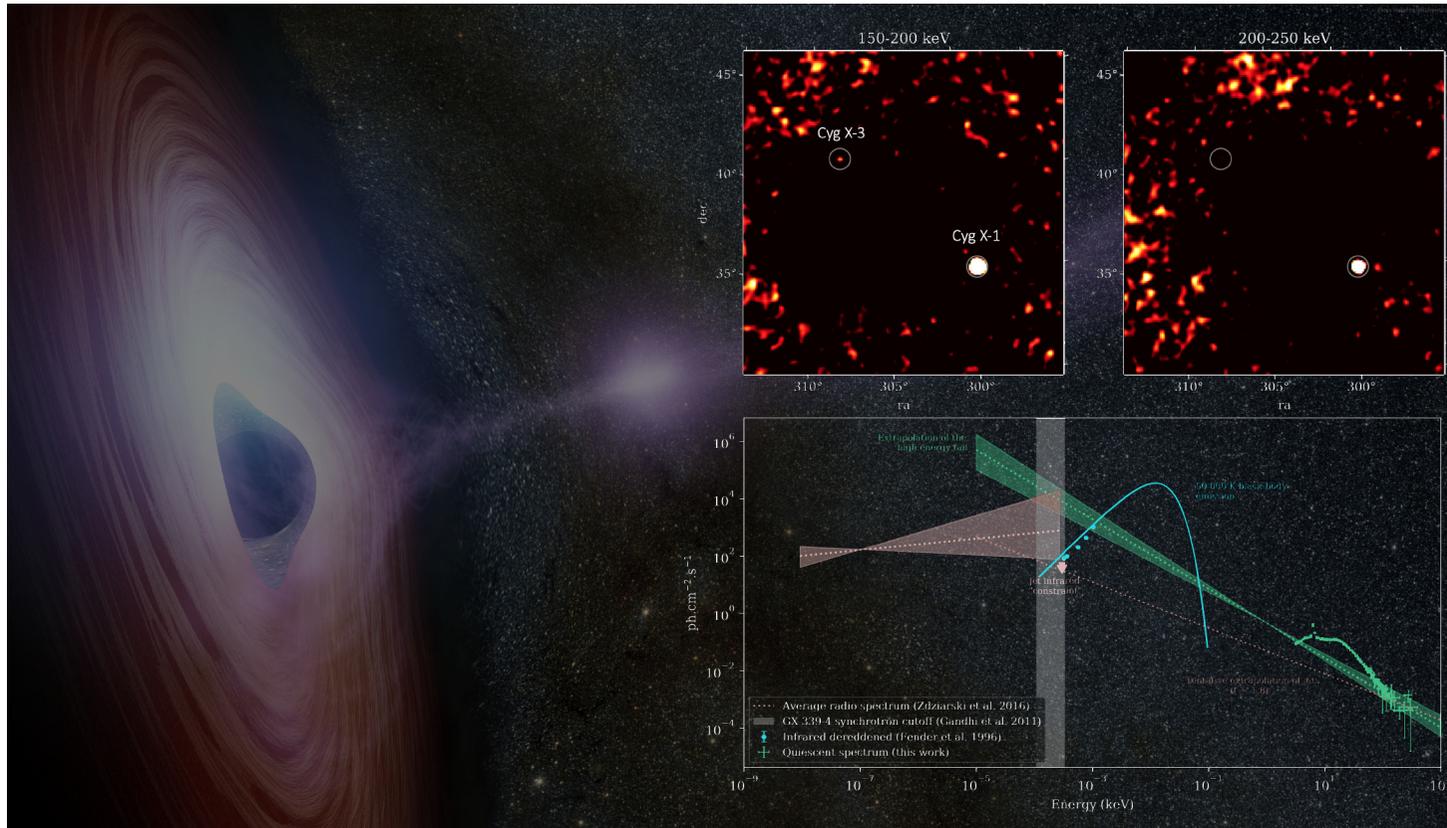
INTEGRAL for the first time, confirms by direct measurement of the primary gamma-ray lines the ^{56}Ni origins of SN light. The INTEGRAL measurements of this sufficiently-nearby SN provide a unique opportunity to compare the direct gamma-rays from the SN's energy source with the more-indirect other radiation. 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



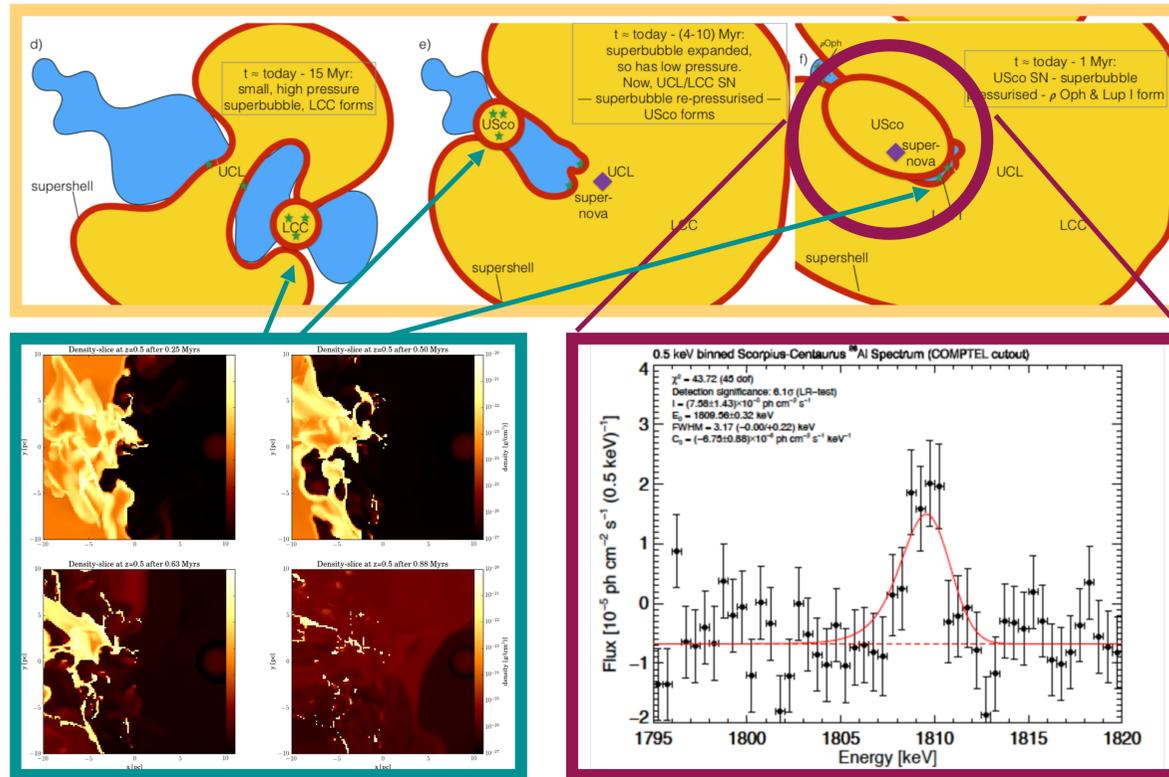
On the left, this HST image shows the inner part of the Crab nebula with the Crab pulsar and its near-by knot located $0.65''$ (1300 AU) south-east of the pulsar inside the red box. On the right, a zoomed view of the image is shown. The arrows indicate at different periods in time the polarization angle 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.

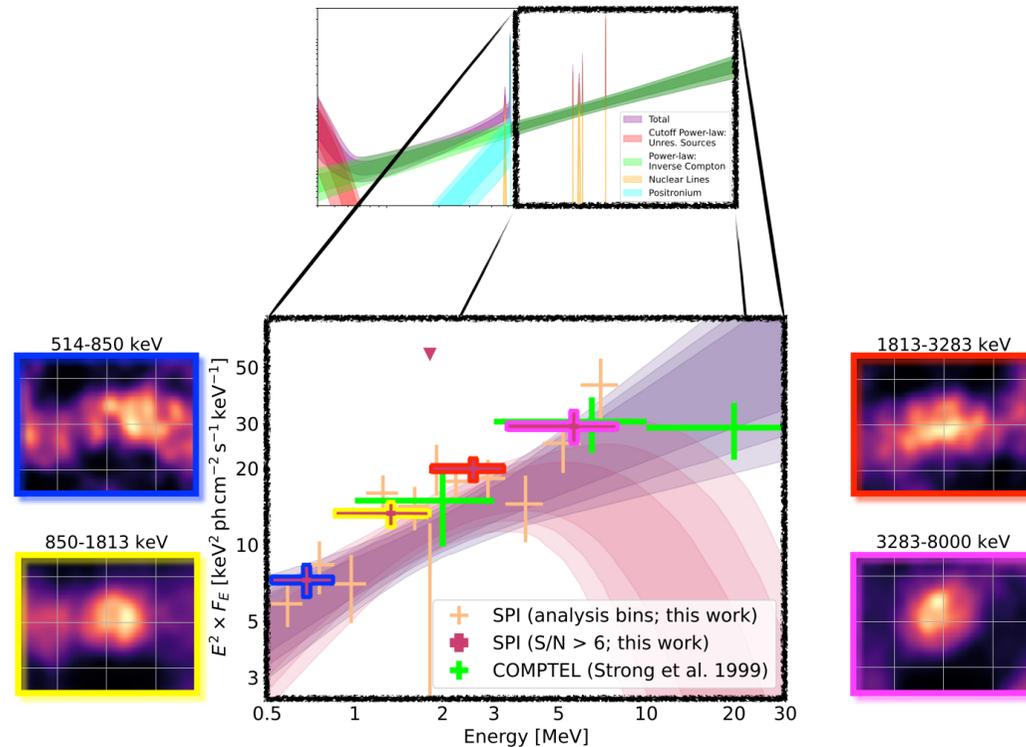
INTEGRAL



^{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 Scorpions-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



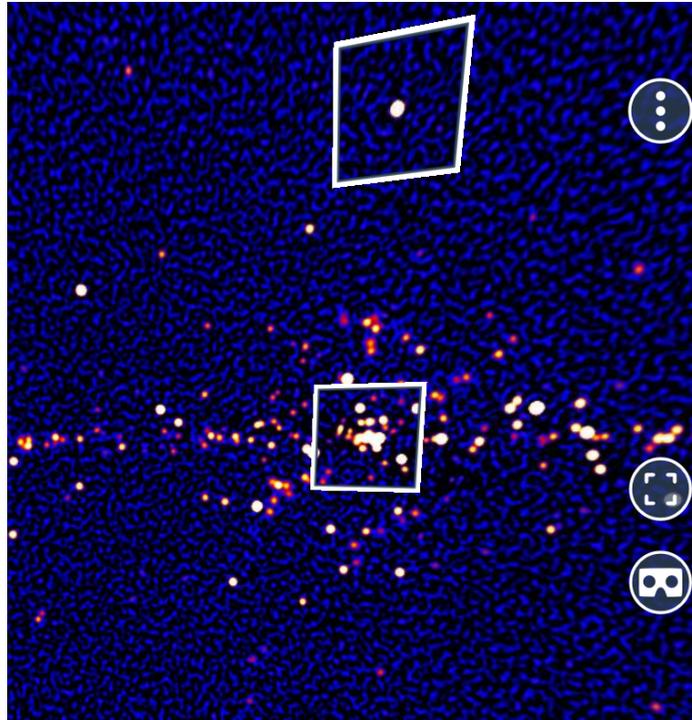
For more than 20 years, the Compton telescope, COMPTEL, onboard NASA's Compton Gamma-Ray Observatory, CGRO, set the standard for measurements of the extended emission of the Milky Way in the MeV range. This photon energy range harbours many emission mechanisms, for example, the annihilation of positrons 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.

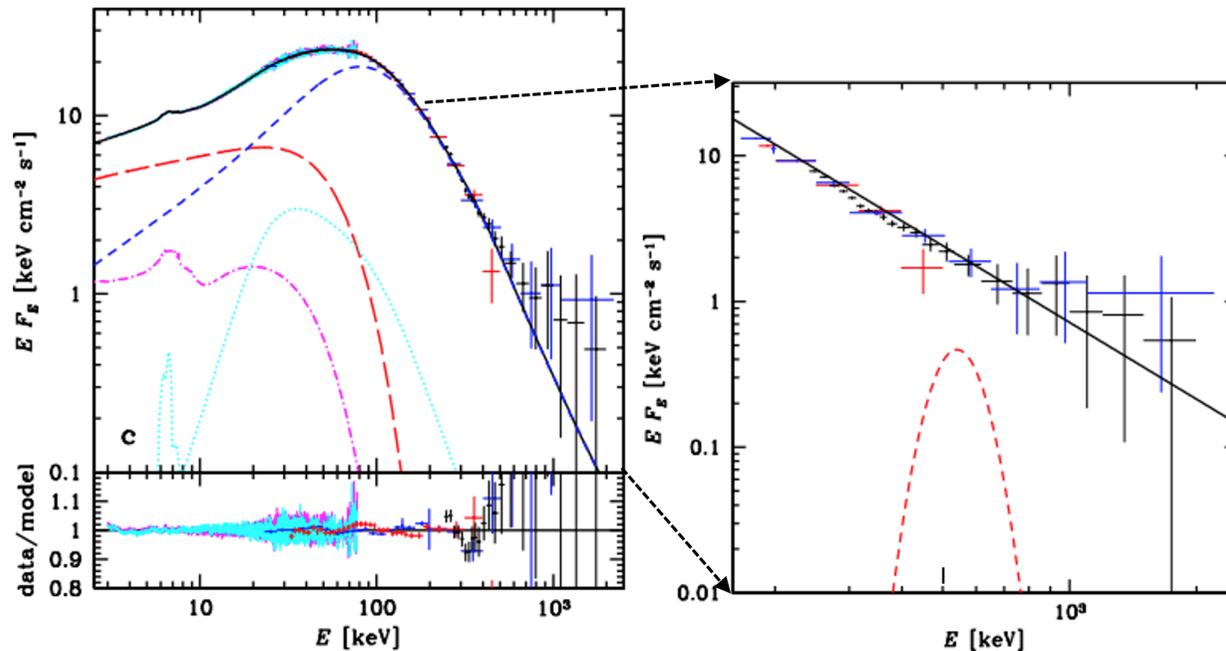
In this study, it was possible to test extreme assumptions on the propagation of GeV electrons: it appears that one common diffusion coefficient of 0.5 for the entire cosmic-ray electron spectrum best matches the INTEGRAL/SPI data. Another important finding in the work is that the absolute normalisation 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

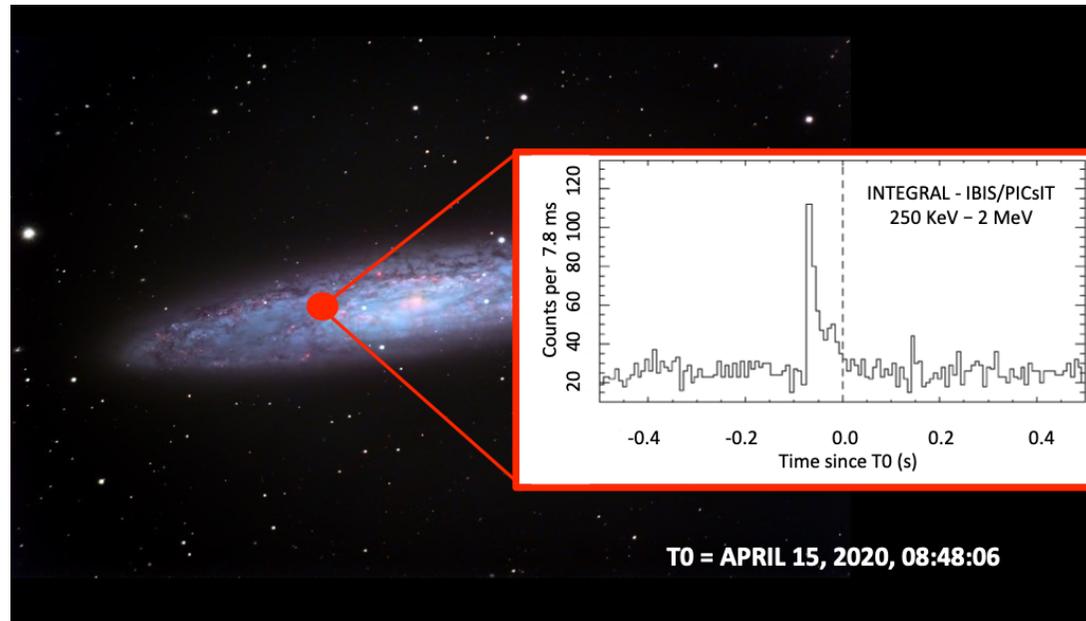


MAXI J1820+070 is a transient X-ray stellar binary, where matter outflowing from a low-mass donor star feeds a black hole. In March 2018, it had a spectacular outburst, during which it shined very bright X-rays and soft gamma-rays, observed by several satellite observatories, including INTEGRAL. The 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



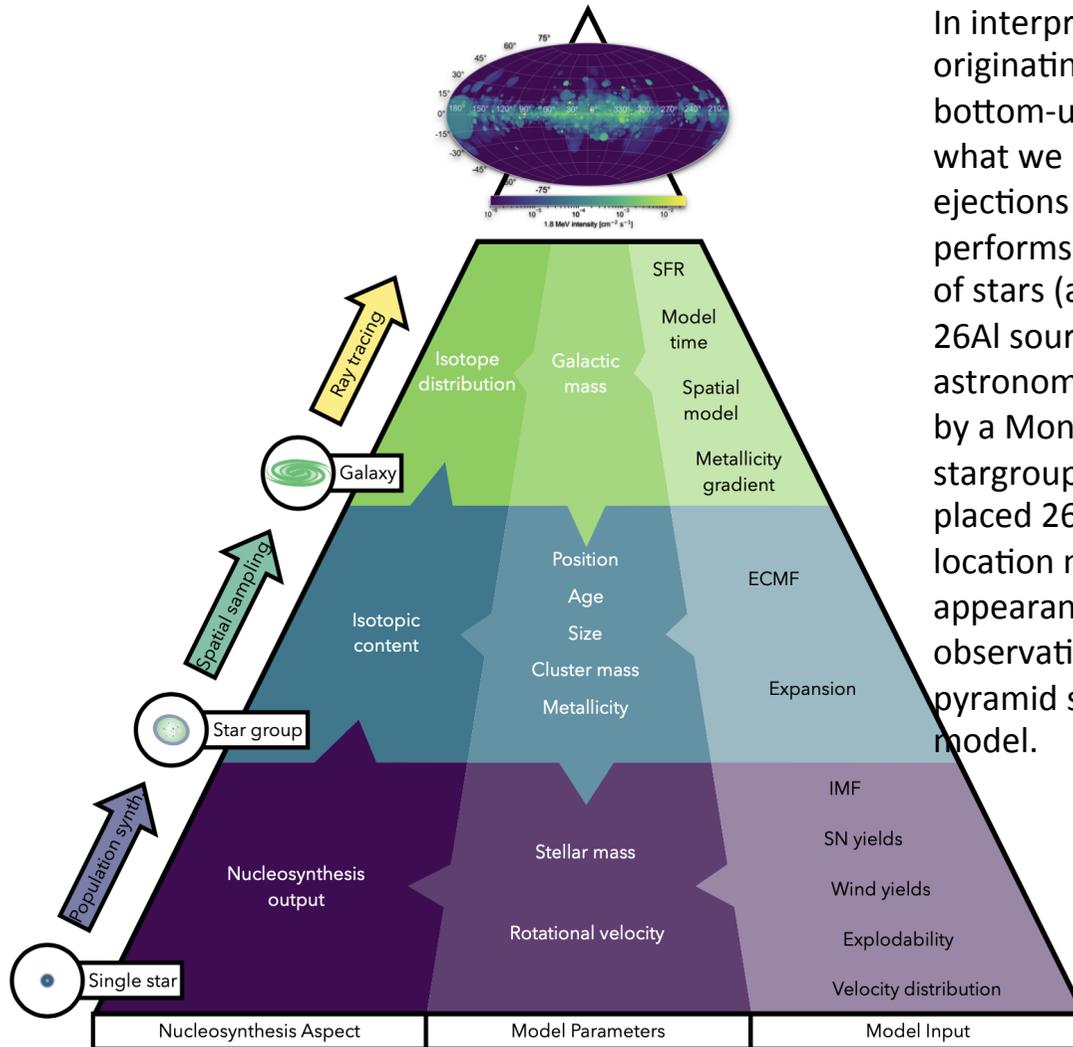
On 15 April 2020 a short and strong gamma-ray burst (GRB) was detected by several Gamma-ray satellites, featuring a fast rise time followed by an order of magnitude weaker tail. Shortly before 8:42 UT, GRB200415A triggered the Russian High-Energy Neutron Detector aboard NASA's Mars Odyssey satellite; 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 neighboring galaxy NGC 253, known 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 10^{14} to 10^{15} 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 10^{36} to 10^{43} erg per second, while giant flares, which are rare, emit at energies of about 10^{44} to 10^{46} erg. Such giant flares from other galaxies are detectable from instruments aboard satellites orbiting Earth or travelling in the Solar system.

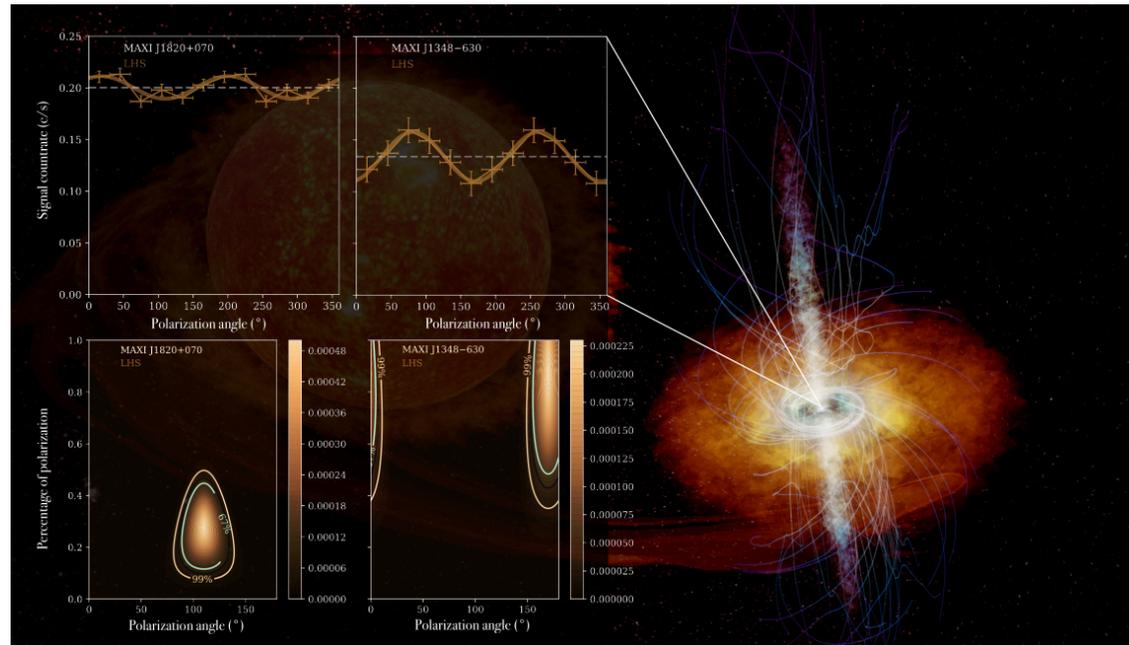
A portion of the second-long initial pulse of a giant flare, similar to the one detected from the Sculptor galaxy, in some respect mimics short GRBs, which have recently been identified as the result from the merger of two neutron stars accompanied by gravitational-wave emission, i.e., GRB170817A and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

INTEGRAL



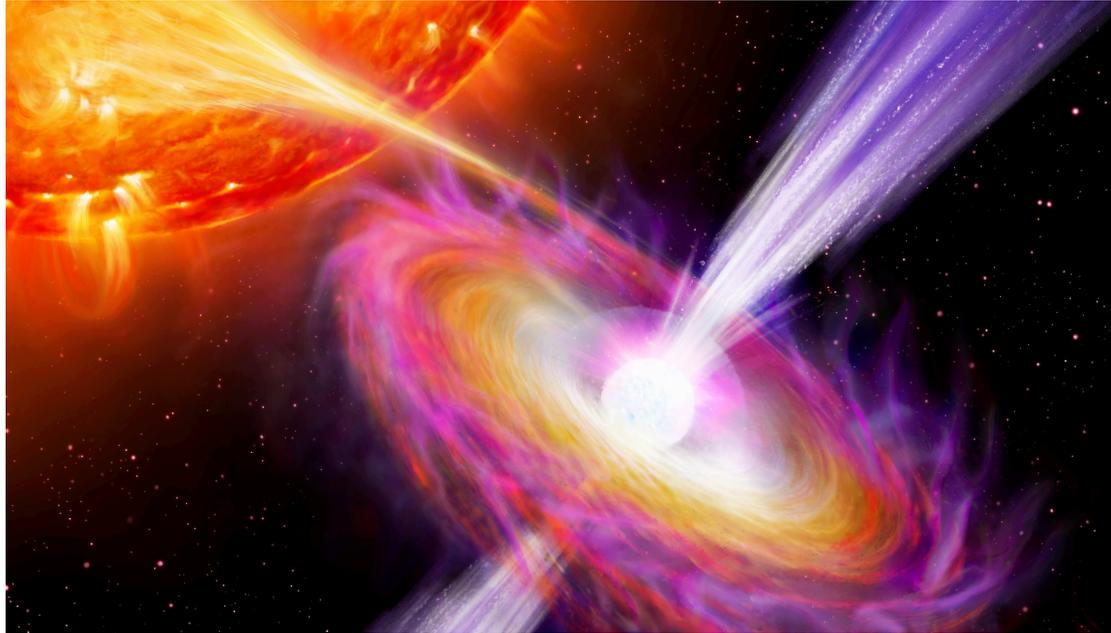
In interpreting the INTEGRAL/SPI data from radioactive ²⁶Al originating from Galactic nucleosynthesis sources, a new bottom-up concept has been established. This starts from what we know about stellar evolution and the yields of ²⁶Al ejections from massive stars and their supernovae, then performs a 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 $26 \pm 9\%$ (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).

INTEGRAL



Relativistic jets are fast, collimated outflows that are observed from accreting compact objects on all physical scales, from neutron stars or stellar-mass black holes feeding on a nearby companion star (X-ray binaries), to supermassive black holes at the centres of galaxies. These jets release huge amounts of energy, having a profound impact on their surroundings. However, how jets are launched remains a fundamental astrophysical question. Using X-ray observations from INTEGRAL and radio observations from CSIRO's Australia Telescope Compact Array (ATCA), a remarkable new connection between the accretion inflow and the outflowing jets has been discovered that will provide a new and much needed tool to begin to solve the jet launching problem.

Neutron stars that are accreting matter from a nearby companion can often display extreme explosions on their surfaces as recently accreted material undergoes thermonuclear burning. These bright bursts are visible in the X-ray band and generally last a few to tens of seconds. During the X-ray bursts, the exploding material interacts with the accretion flow, increasing the rate at which matter falls onto the star by up to a factor of ten.

Using strictly simultaneous X-ray (INTEGRAL) observations to detect the X-ray bursts and radio (ATCA) observations to track the jets, it was found that in the minutes after every X-ray burst, a bright jet flare was observed. This flare was a result of extra material being input into the jet due to the X-ray burst-induced increase in accretion rate. Measuring the time delay between the X-ray bursts and the jet flare at different radio frequencies (where different radio frequencies probe different distances along the jet) allows the speed of the jet flow to be measured. This was the very first time that such a measurement has been made for a neutron star system.

Neutron stars act as ideal laboratories for jet studies, as they can have measurable spin rates, well determined masses, and possibly even magnetic field strengths, all of which are believed to be key ingredients for jet launching. This new and repeatable study is now being expanded to explore how the jet speeds differ between neutron star systems that have different properties, which can uniquely disentangle the key properties responsible for the launching of the jets.