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

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GSI

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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

SFB 1245

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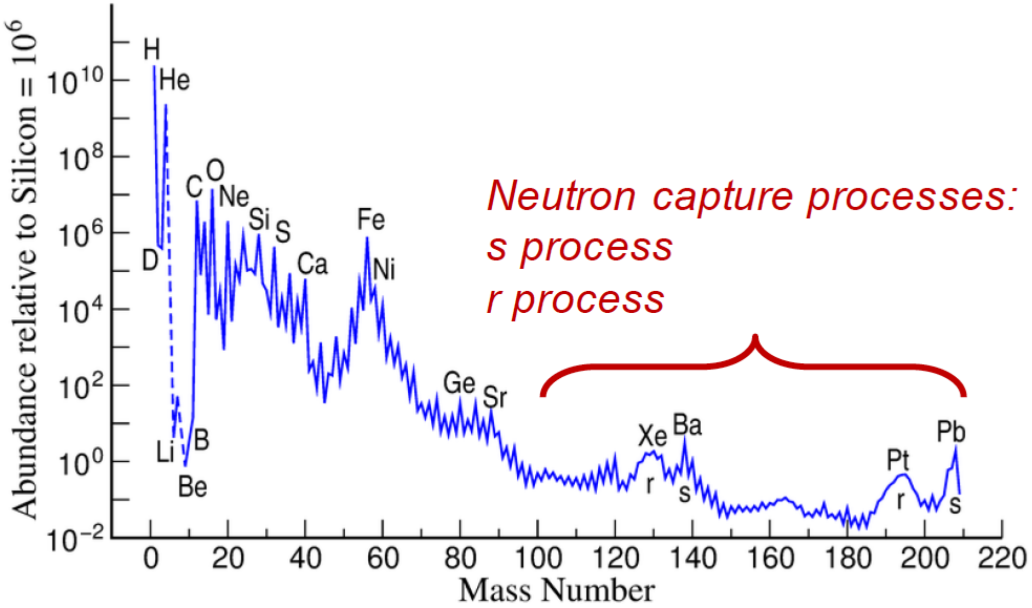
R-process nucleosynthesis in neutron star mergers

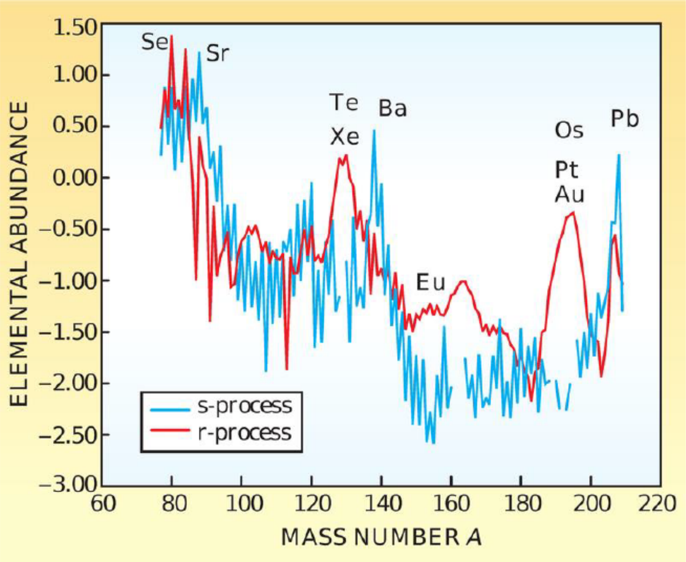
Gabriel Martínez-Pinedo

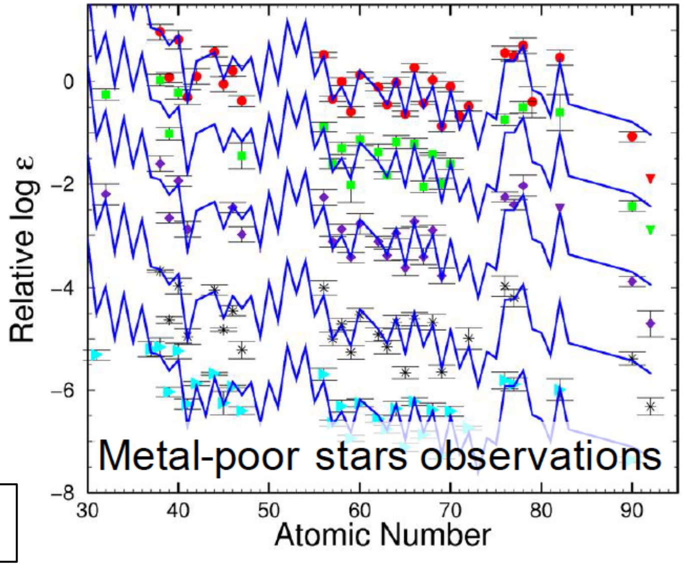
EMMI Workshop: New avenues for low energy
NuSTAR program at GSI-FAIR
GSI, September 16-17, 2021

Signatures of nucleosynthesis



Neutron capture processes:
s process
r process



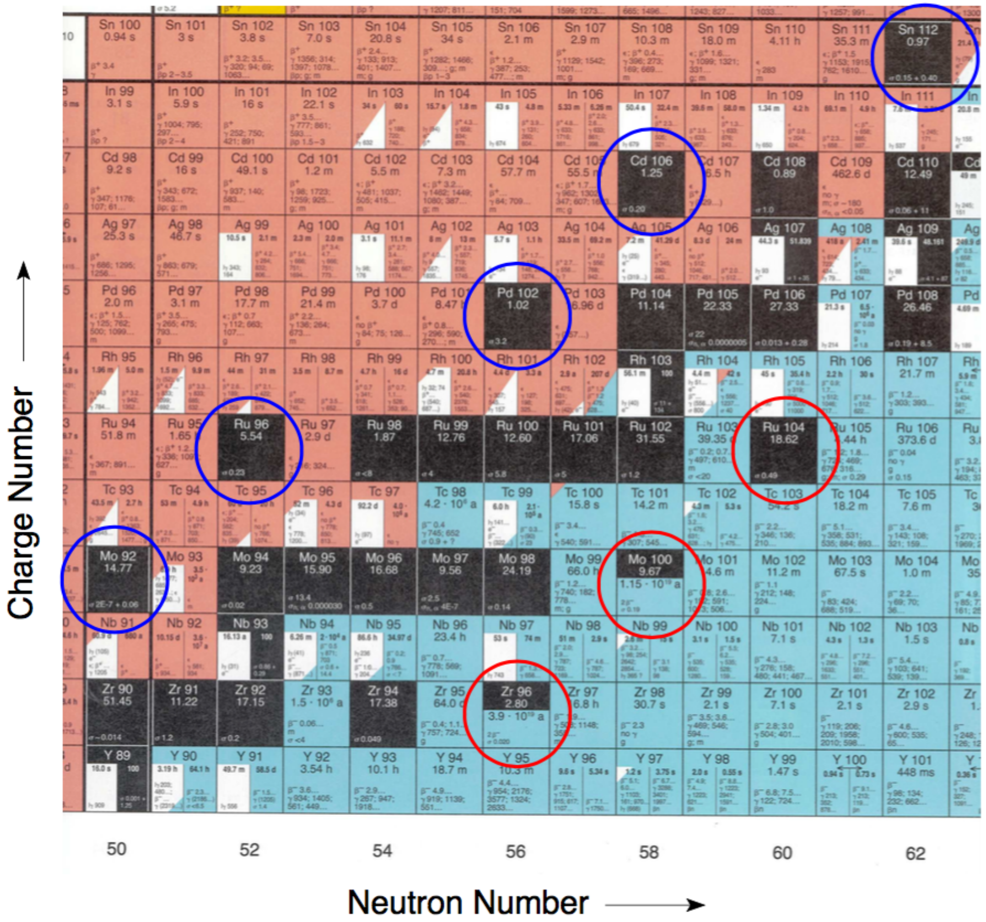


- Heavy elements produced in neutron capture processes

- 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:

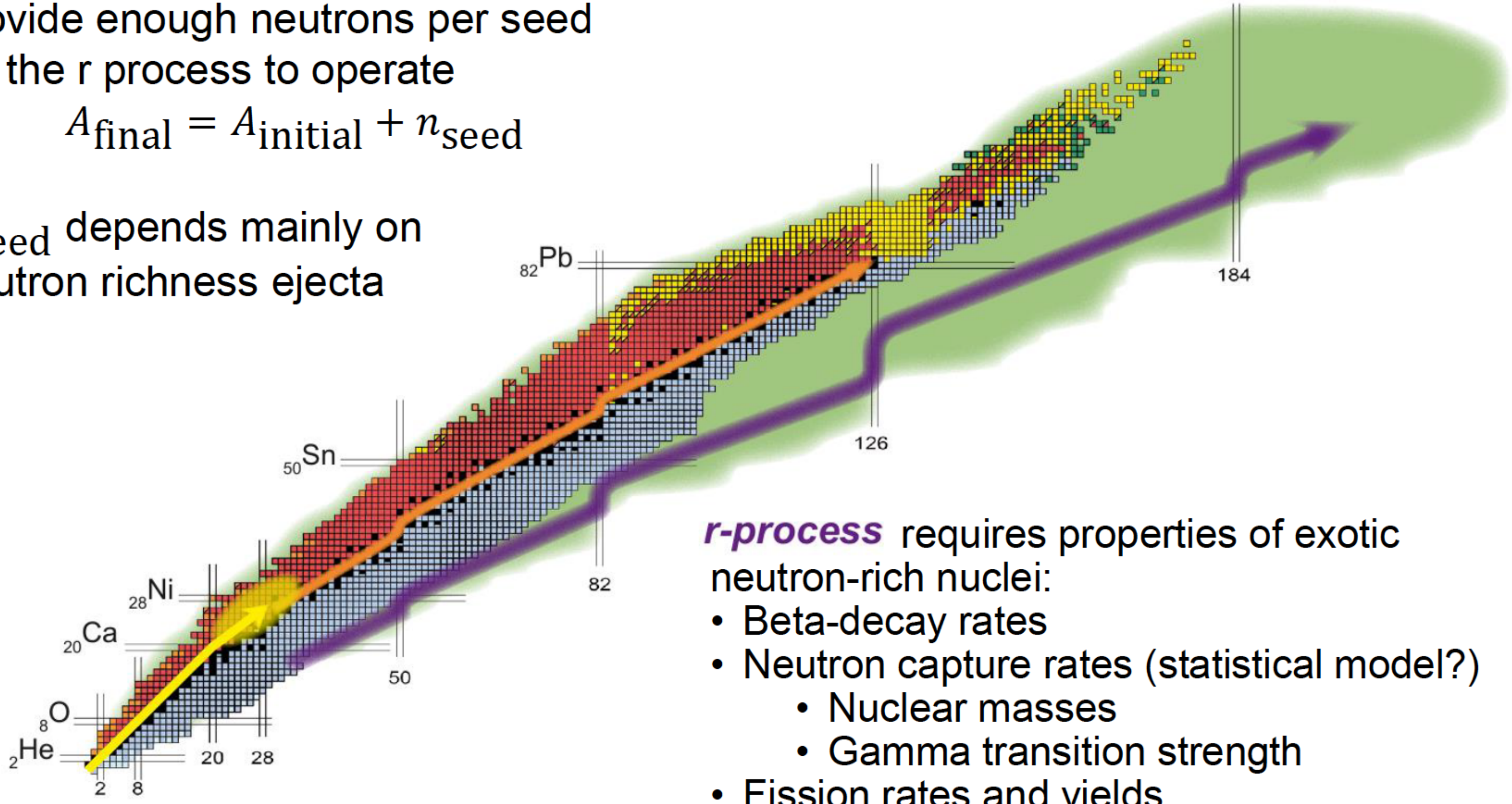
- s-process
- r-process
- p-process (γ-process)

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:

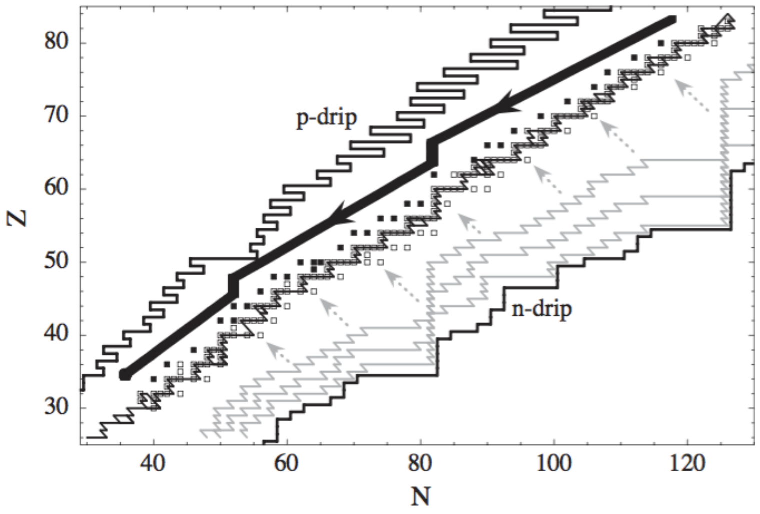
- Beta-decay rates
- Neutron capture rates (statistical model?)
  - Nuclear masses
  - Gamma transition strength
- Fission rates and yields
  - Fission barriers

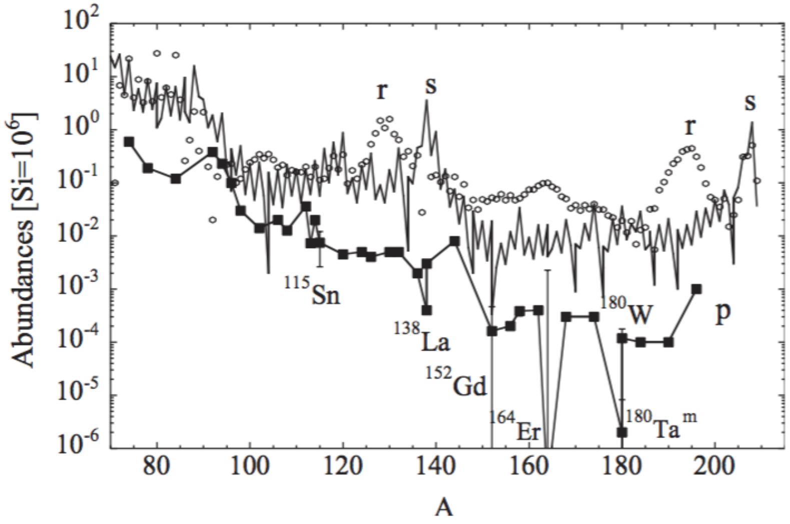
Benchmark against observations:

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

Nucleosynthesis beyond iron

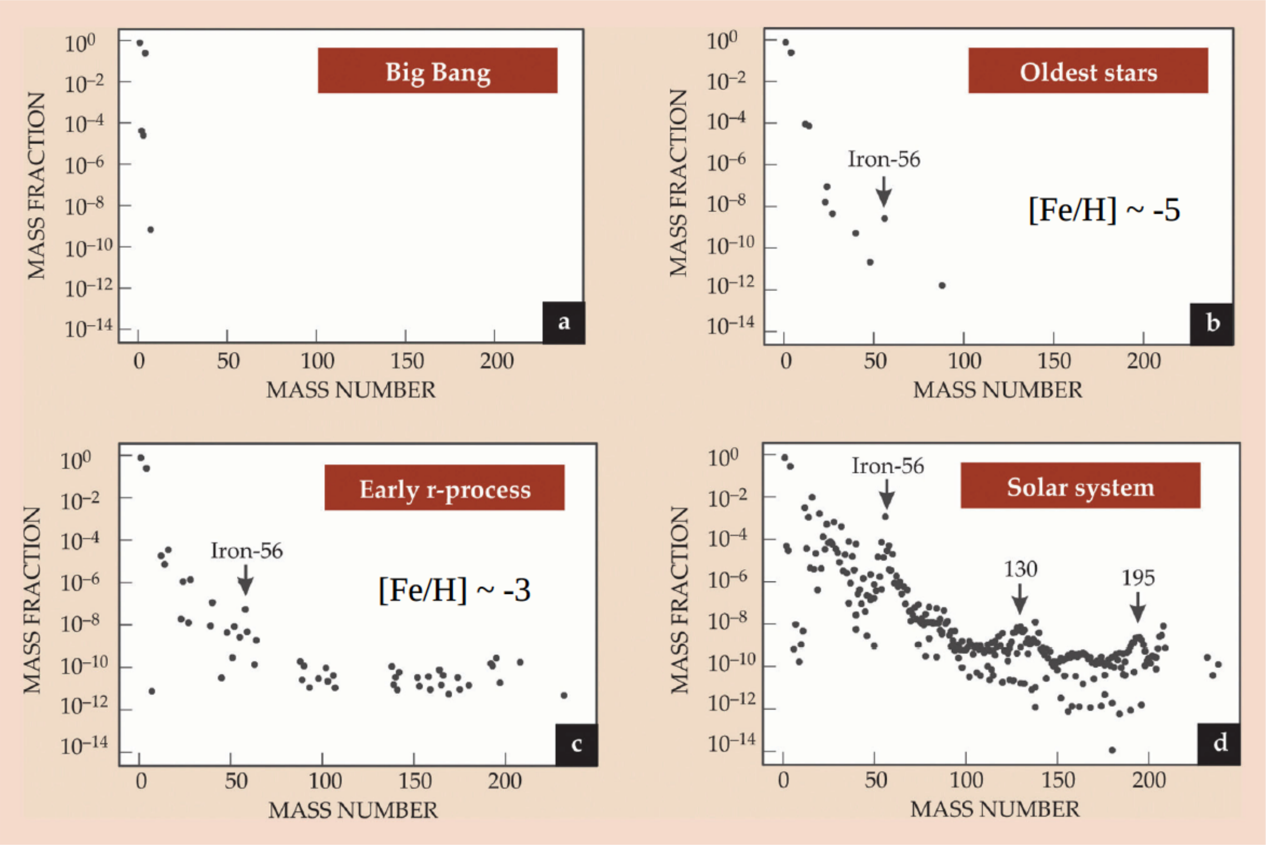
Three processes contribute to the nucleosynthesis beyond iron: s-process, r-process and p-process (γ-process).





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

Time evolution: metalicity



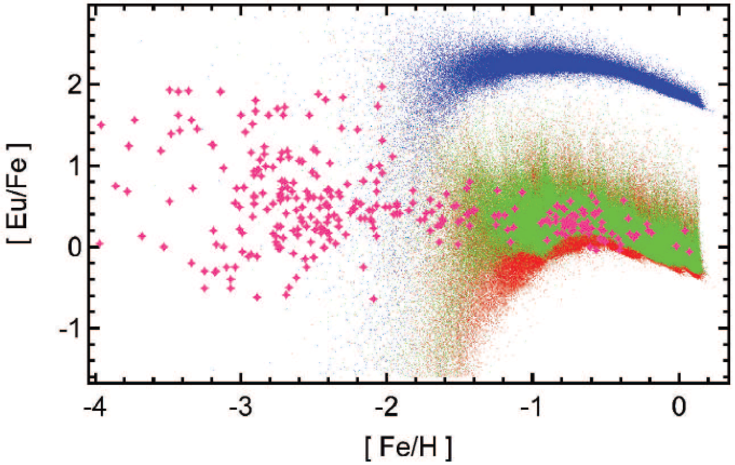
Astronomers use the metalicity:

$$[\mathrm{Fe}/\mathrm{H}] = \log_{10}\left(\frac{N_{\mathrm{Fe}}}{N_{\mathrm{H}}}\right)_* - \log_{10}\left(\frac{N_{\mathrm{Fe}}}{N_{\mathrm{H}}}\right)_\odot$$

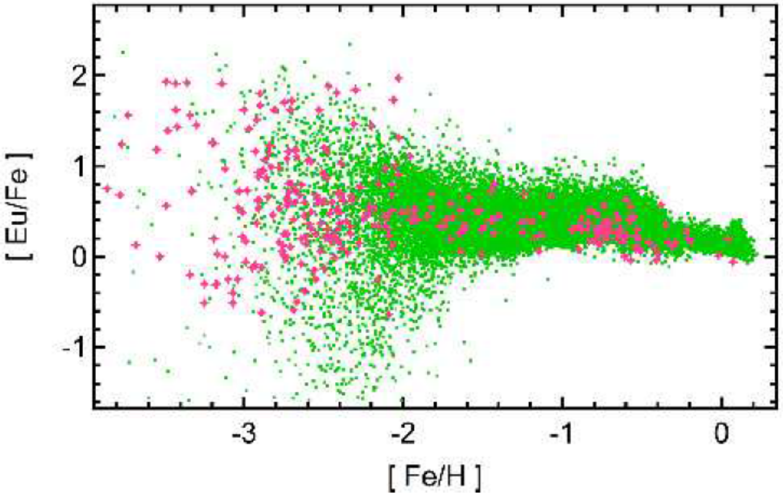
as a proxy for age.

Introduction: Summary

- The r process is a primary process operating in a site that produces both neutrons and seeds. Large neutron densities imply a site with extreme conditions of temperature and/or density.
- There is strong evidence that the bulk of r-process content in the Galaxy originates from a high yield/low frequency events.
- Neutron star mergers may account for most of the r-process material in the galaxy. However, due to the coalescent delay time they may not contribute efficiently at low metalicities. Magneto-rotational supernova may contribute at low metalicities.



- Red dots: 10^8 yr coalescence time
- Green dots: 10^6 yr coalescence time
- Blue dots: larger merger probability.

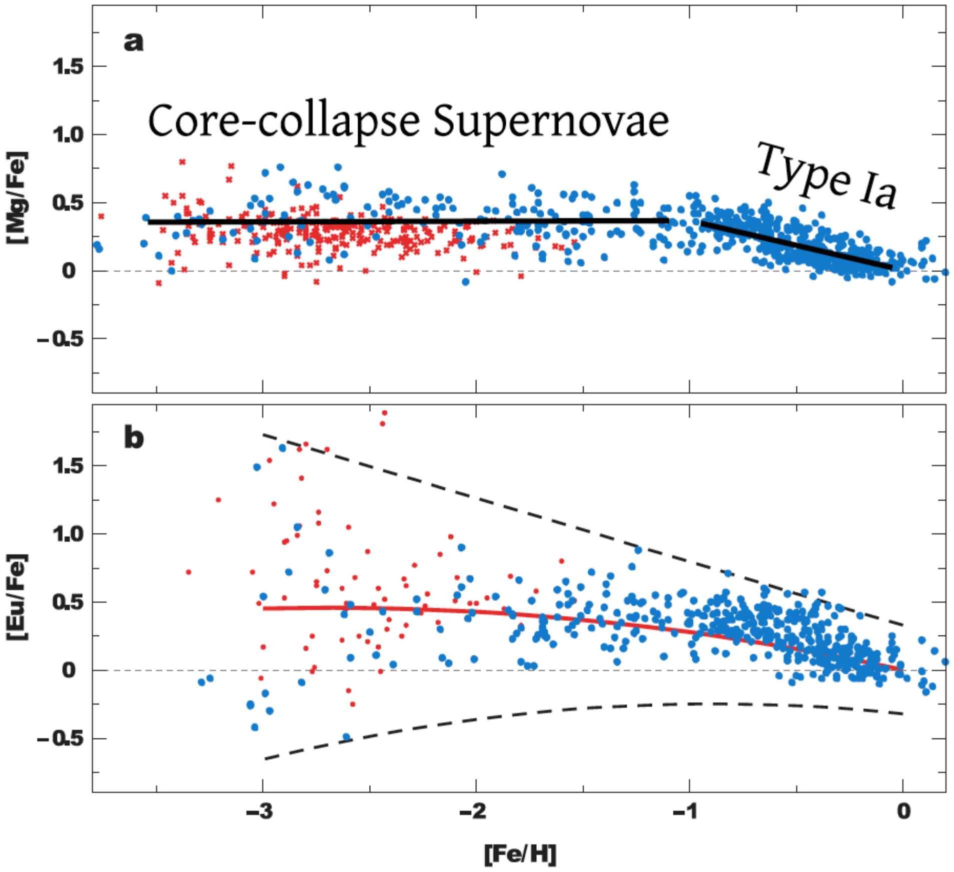


- Including MHD-jet supernovae

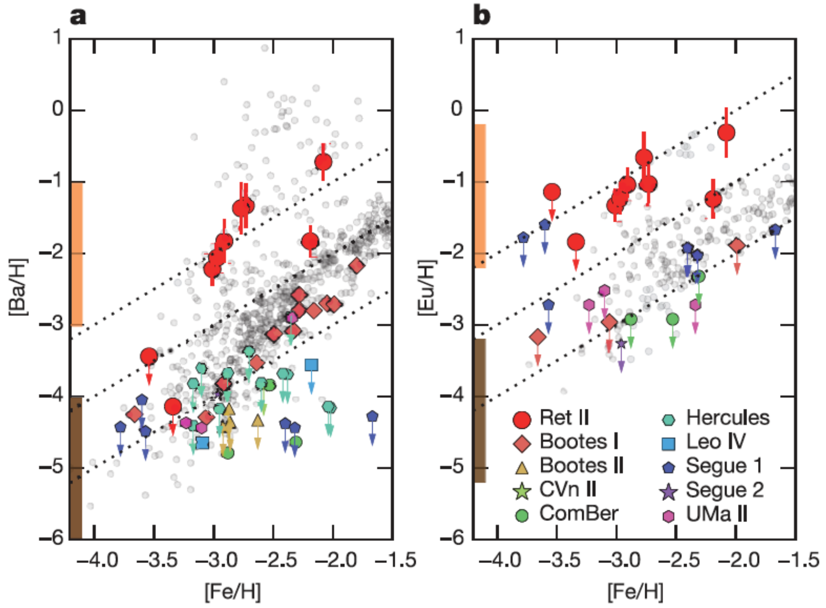
Wehmeyer, B., M. Pignatari, and F.-K. Thielemann , Mon. Not. Roy. Astron. Soc. 452, 1970 (2015)

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)

Types of reactions

In order to dissentangle changes in the density (hydrodynamics) from changes in the composition (nuclear dynamics), the abundance is introduced:

$$Y_a = \frac{n_a}{n}, \quad n \approx \frac{\rho}{m_u} = \text{Number density of nucleons (constant)}$$

- $\sum_i Y_i Z_i = Y_e$ (charge neutrality)

R-process sites

- Any r-process site should be able to produce both the "seed" nuclei where neutrons are captured and the neutrons that drive the r-process. The main parameter describing the feasibility of a site to produce r-process nuclei is the neutron-to-seed ratio: n_n/n_{seed}.
- If the seed nuclei have mass number A_{seed} and we have n_n/n_{seed} neutrons per seed, the final mass number of the nuclei produced will be $A = A_{\mathrm{seed}} + n_n/n_{\mathrm{seed}}$.
- For example, taking $A_{\mathrm{seed}} = 90$ we need $n_n/n_{\mathrm{seed}} = 100$ if we want to produce the 3rd r-process peak ($A \sim 195$) and $n_n/n_{\mathrm{seed}} = 150$ to produce U and Th.

R-process sites

In an astrophysical site there are only two possible ways to achieve large neutron-to-seeds:

1. Let us consider high temperature neutron-rich matter with high entropy that it is ejected at high velocities. As the material expands α particles will be formed. However, the build up of heavy nuclei by 3-body reactions becomes very unefficient by two reasons: 1) Too many photons per nucleon due to the high entropy, 2) Too litle time to produce heavy nuclei due to the fast expansion. It means that we will have an α-rich freeze out with a few heavy nuclei produced and many neutrons left ($Y_\alpha \approx Y_e/2$, $Y_n \approx 1 - 2Y_e$). This is commonly denoted as “high entropy” r-process
2. Let us consider matter very high density matter with low entropies. Due to the high densities electrons have large fermi energies and will drive the composition very neutron rich. At some point the neutron drip line is reached and nuclei start to “drip” neutrons. This is the situation in the crust of neutron stars where densities are 10^{12-13} g cm^{-3} and $Y_e \sim 0.05$: $Y_n = 1 - \langle A \rangle Y_e / \langle Z \rangle$, $Y_s = Y_e / \langle Z \rangle$; $Y_n / Y_s = \langle Z \rangle / Y_e - \langle A \rangle$; $Y_n / Y_s \sim 500 - 2000$. This is commonly denoted as “low entropy” r-process.

r-process nucleosynthesis relevant parameters

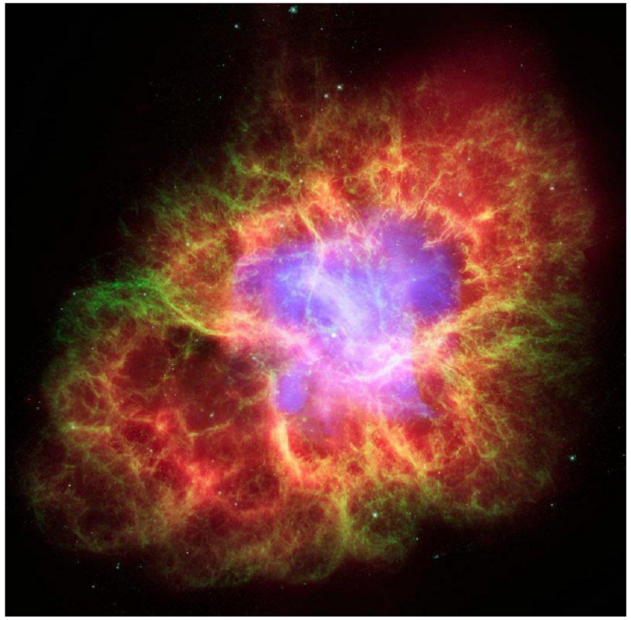
Independently of the astrophysical site the nucleosynthesis is sensitive to a few parameters that determine the neutron-to-seed ratio and the heavier elements that can be produced:

$$A_f = A_i + n_s, \quad n_s = n_n/n_{\text{seed}} \sim s^3/(Y_e^3 \tau_{\text{dyn}})$$

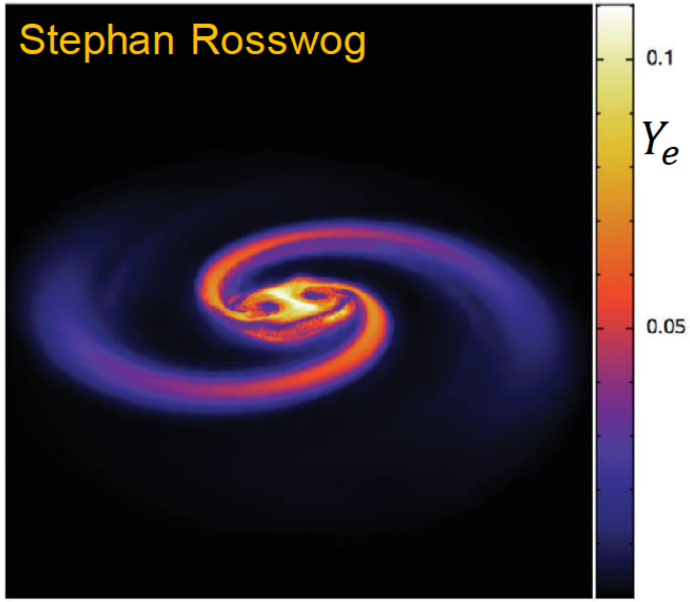
Y_e	The lower the value of Y_e more neutrons are available and the larger n_s
entropy	Large entropy $s \sim T^3/\rho$, means low density and high temperature (large amount of photons). Both are detrimental to the build up of seeds by 3-body reactions.
expansiton time scale	The faster the matter expands, smaller τ_{dyn}, the less time one has to build up seeds

Astrophysical sites

Core-collapse supernova



Compact binary mergers

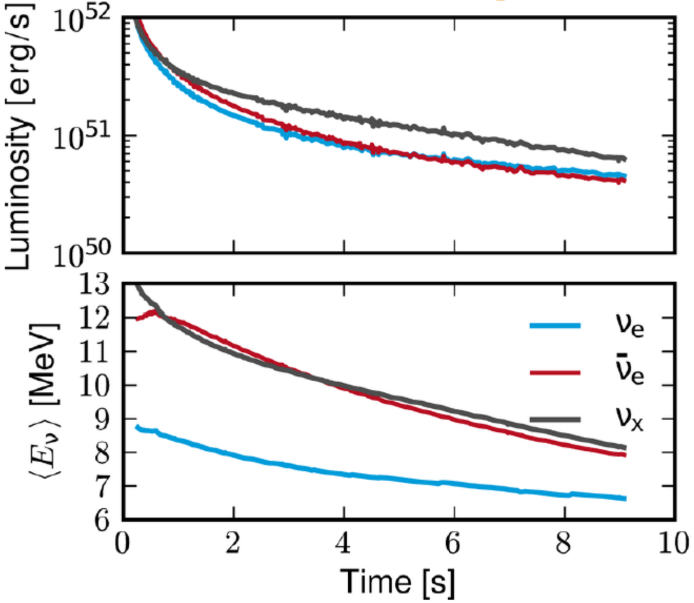


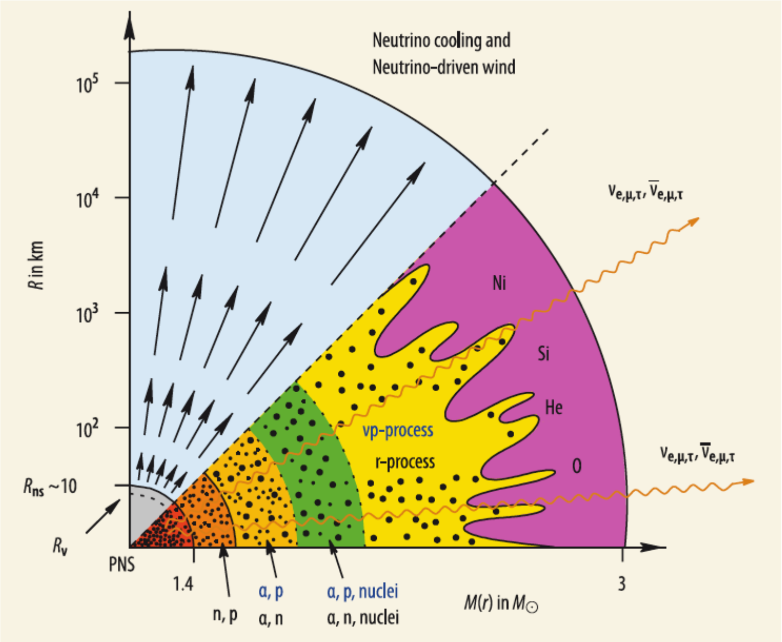
	Supernova	**Mergers**
Optimal conditions	☹	☺
Yield / Frequency	😐	☺
Direct signature	☹	☺

Supernova nucleosynthesis

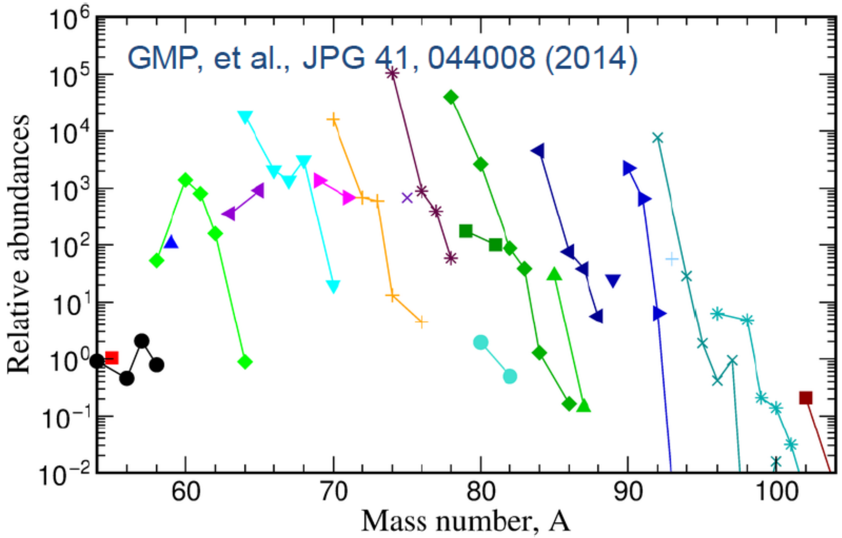
Heavy elements produced in neutrino winds from protoneutron star cooling. Neutrino interactions determine proton-to-nucleon ratio, Y_e

$$\nu_e + n \rightleftarrows p + e^-$$
$$\bar{\nu}_e + p \rightleftarrows n + e^+$$





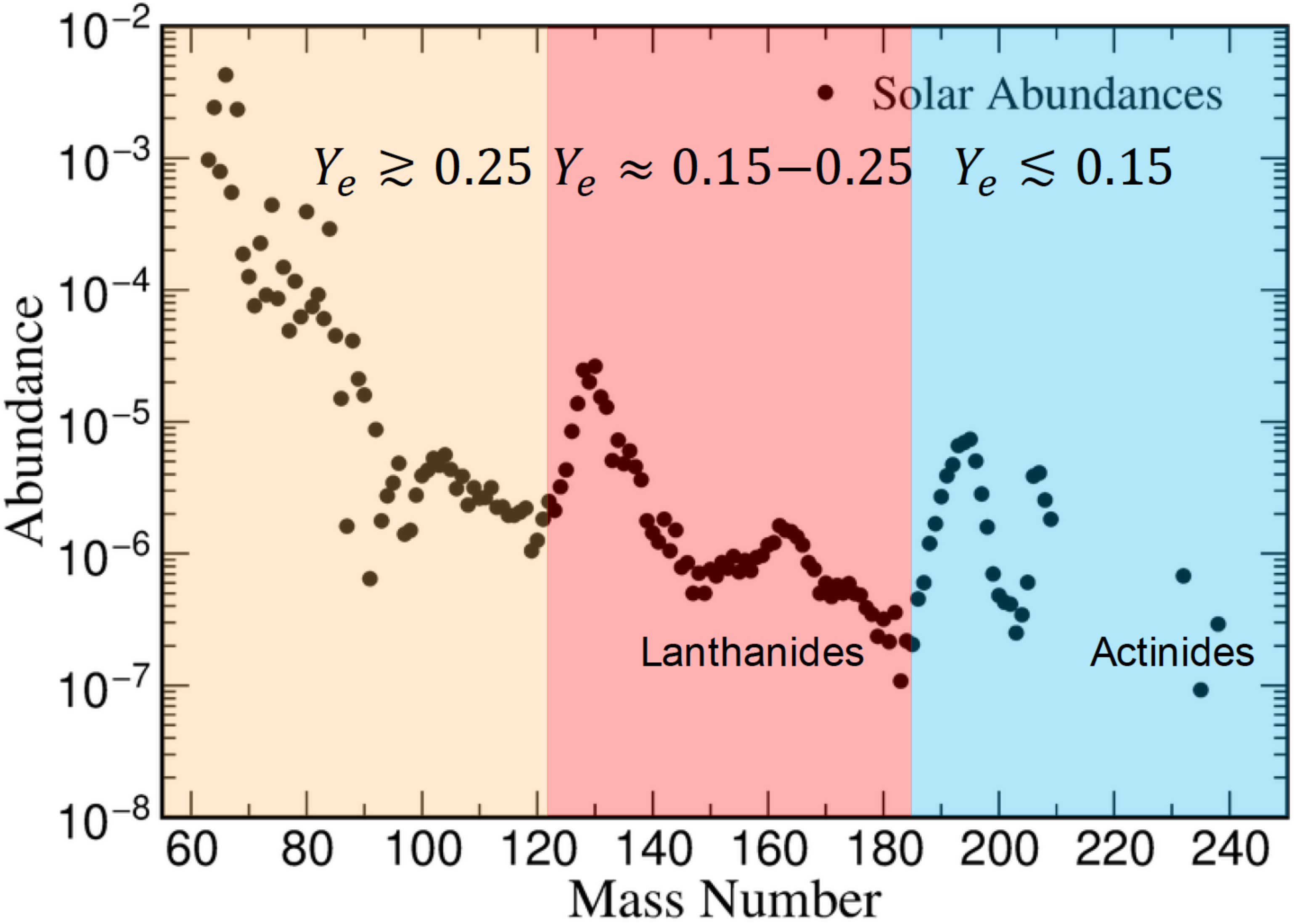
Supernova produce only medium mass nuclei


GMP, et al., JPG 41, 044008 (2014)

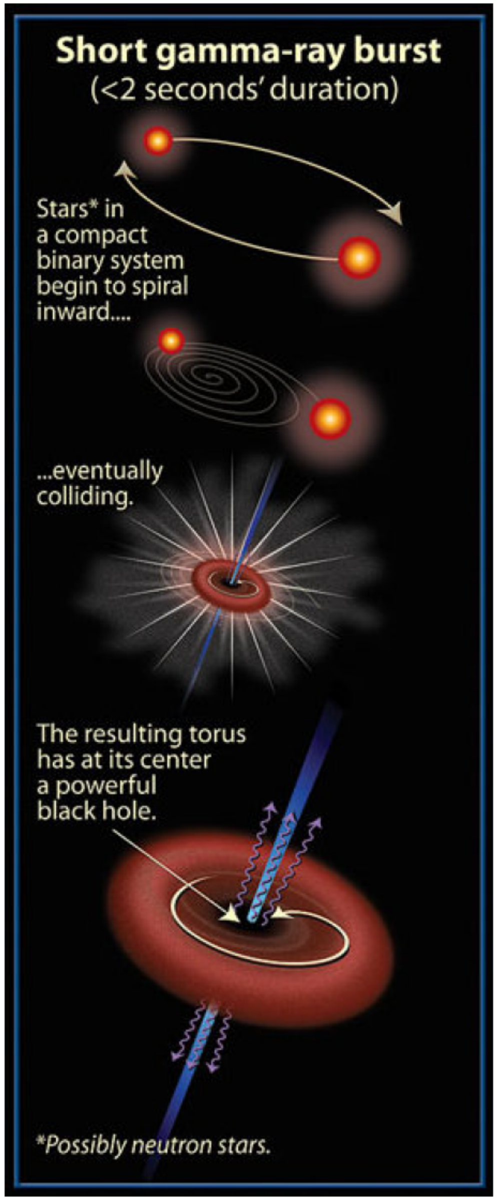
Nucleosynthesis dependence on Y_e

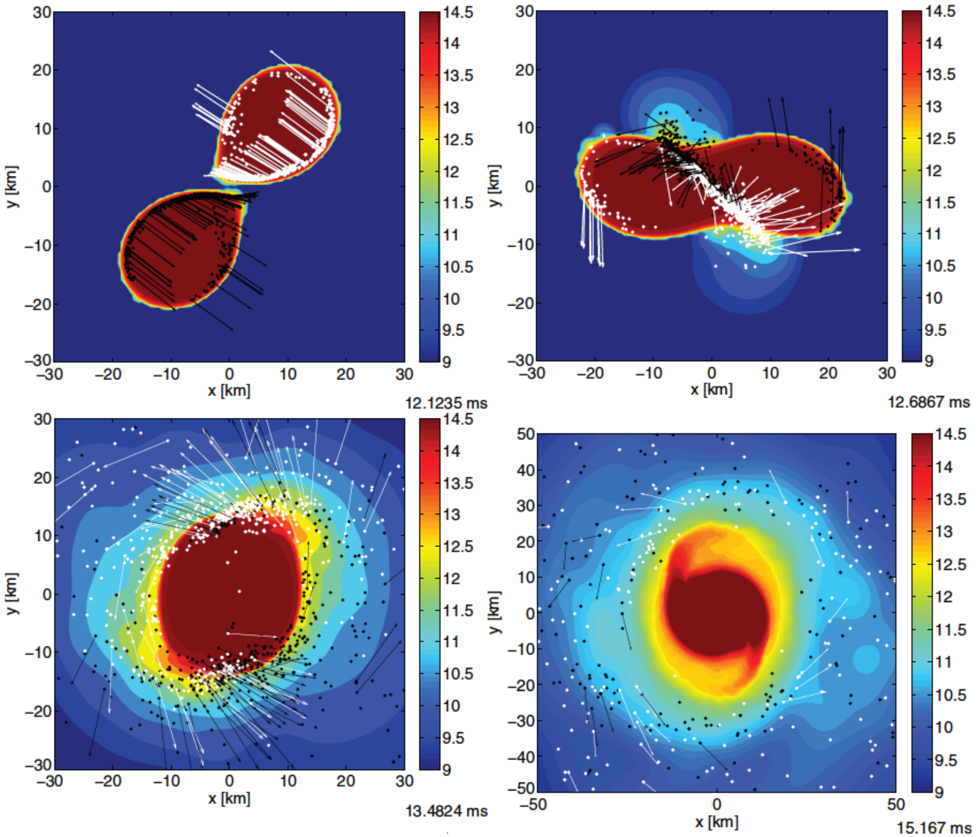
Nucleosynthesis mainly sensitive to proton-to-nucleon ratio, Y_e

$\nu_e + n \rightleftarrows p + e^-$ vs $\bar{\nu}_e + p \rightleftarrows n + e^+$



Neutron star mergers: Short gamma-ray bursts and r-process



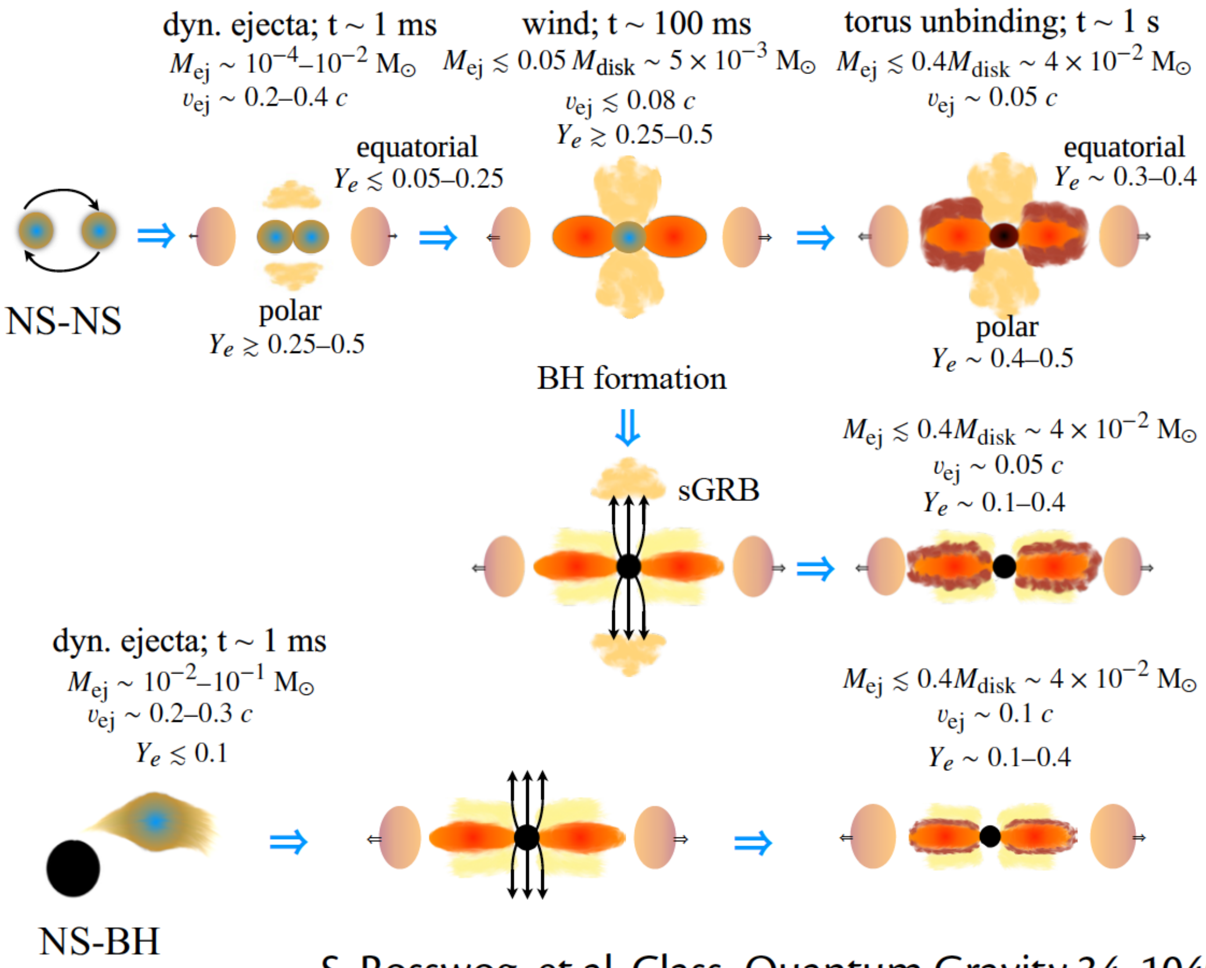


Basuswein, Goriely, Janka, ApJ 773, 78 (2013)

- Mergers are associated with short-gamma ray bursts.
- They are also promising sources of gravitational waves.
- Observational signatures of the r-process?

Merger channels and ejection mechanism

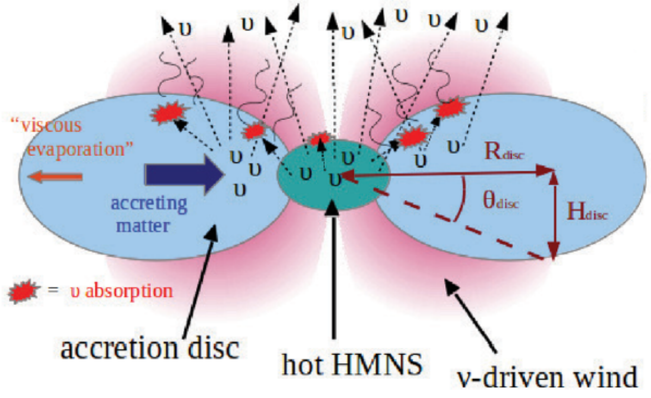
In mergers we deal with a variety of initial configurations (netron-star neutron-star vs neutron-star black-hole) with additional variations in the mass-ratio. The evolution after the merger also allows for further variations.



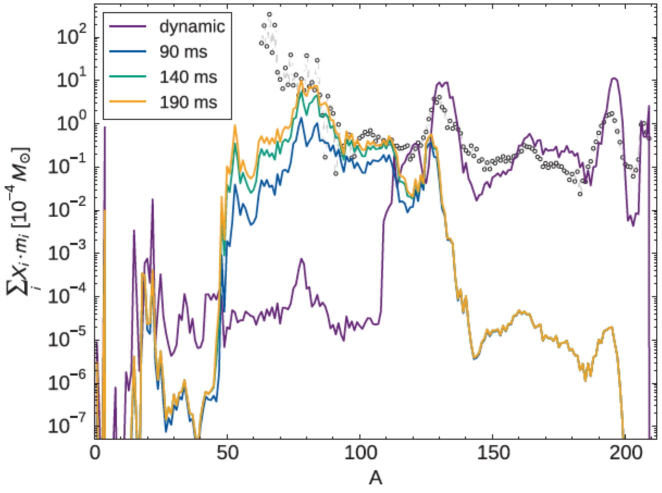
S. Rosswog, et al, Class. Quantum Gravity 34, 104001 (2017).

Post-merger Nucleosynthesis (NS remnant)

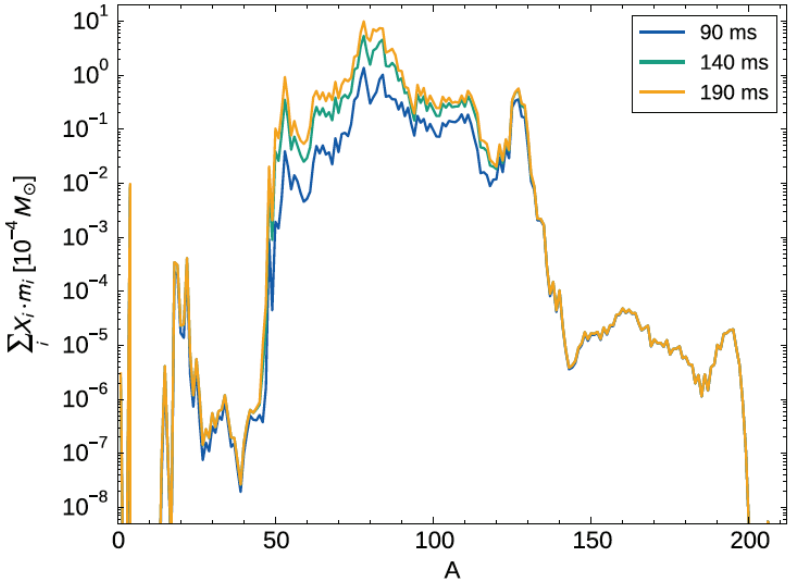
An Hypermassive neutron star produces large neutrino fluxes that drive the composition to moderate neutron rich ejecta.



Perego, *et al*, MNRAS 443, 3134 (2014)



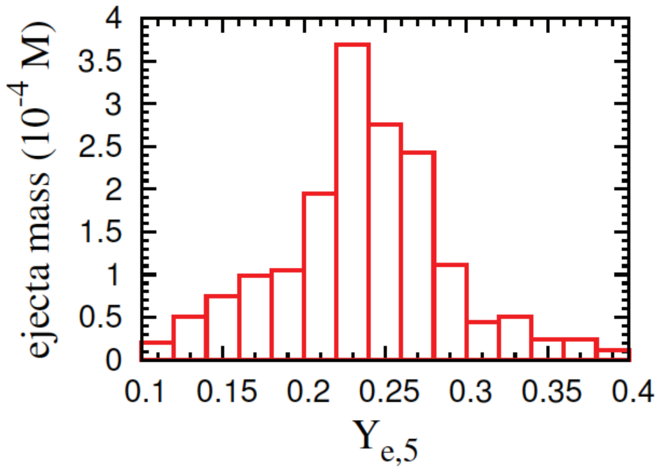
Martin, *et al*, ApJ 813, 2 (2015)



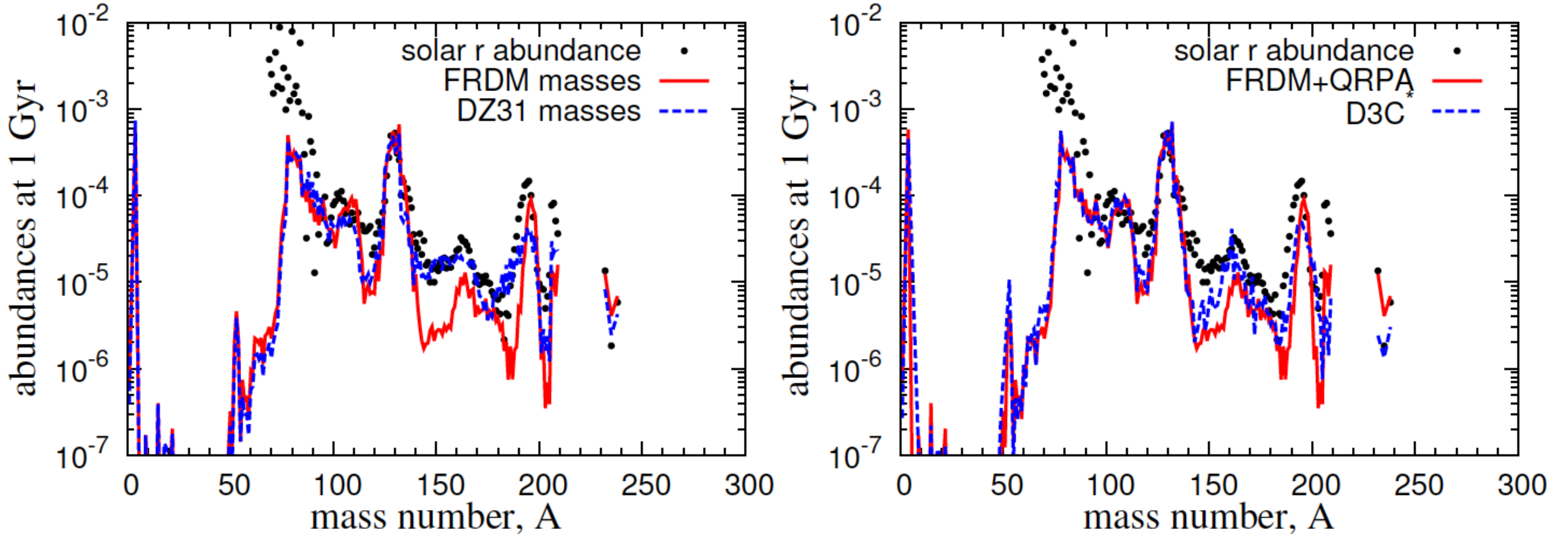
Only nuclei with $A < 120$ are produced (no lanthanides, blue kilonova).

See also Lippuner et al, MNRAS **472**, 904 (2017)

Post-merger nucleosynthesis (BH remnant)



- Accretion disk around BH ejects relatively neutron-rich matter [Fernández, Metzger, MNRAS 435, 502 (2013)]
- Produces all r-process nuclides (Lanthanide/Actinide rich ejecta) [Wu *et al*, MNRAS 463, 2323 (2016)]



See also Just et al, MNRAS 448, 541 (2015), Siegel and Metzger PRL 119, 231102 (2017)

Kilonova: Electromagnetic signature of the r process

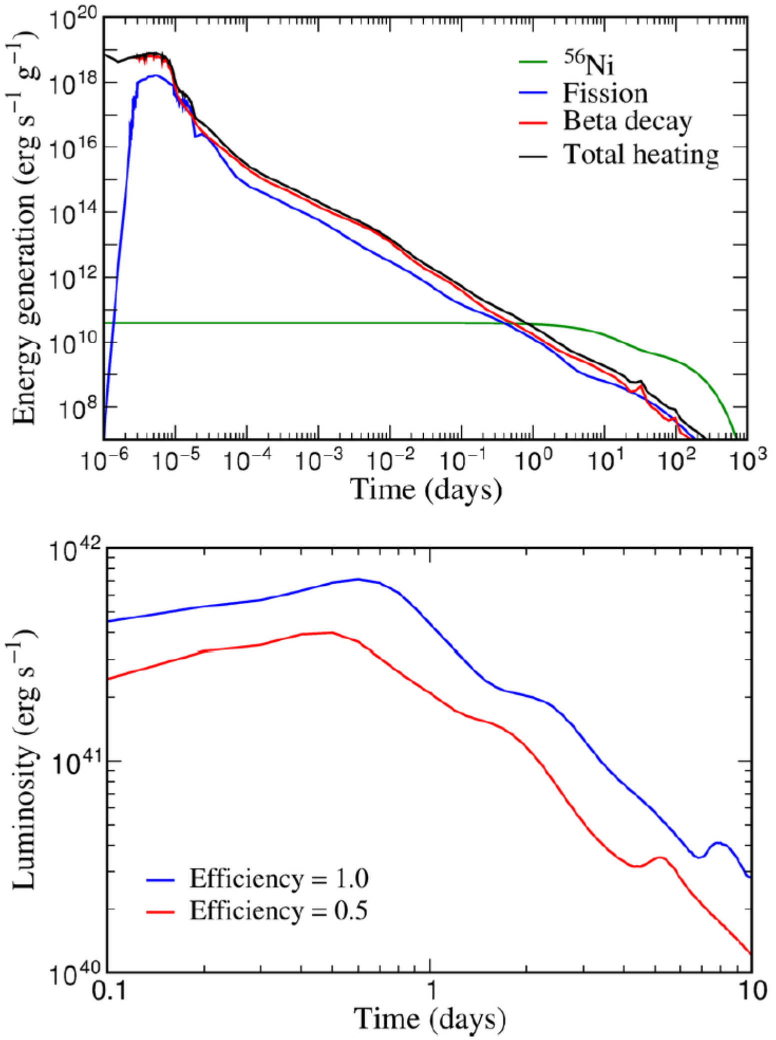
- Ejecta produces electromagnetic signatures [Li & Paczyński 1998]

- Transient due to radioactive decay of r-process nuclei [Metzger et al, 2010]
  Heating: $\dot{\varepsilon} \sim t^{-1.3}$
  Luminosity like 1000 novas: Kilonova
  Peak on timescales days in optical/blue

- Presence of Lanthanides reduces luminosity and delays peak to ~ 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

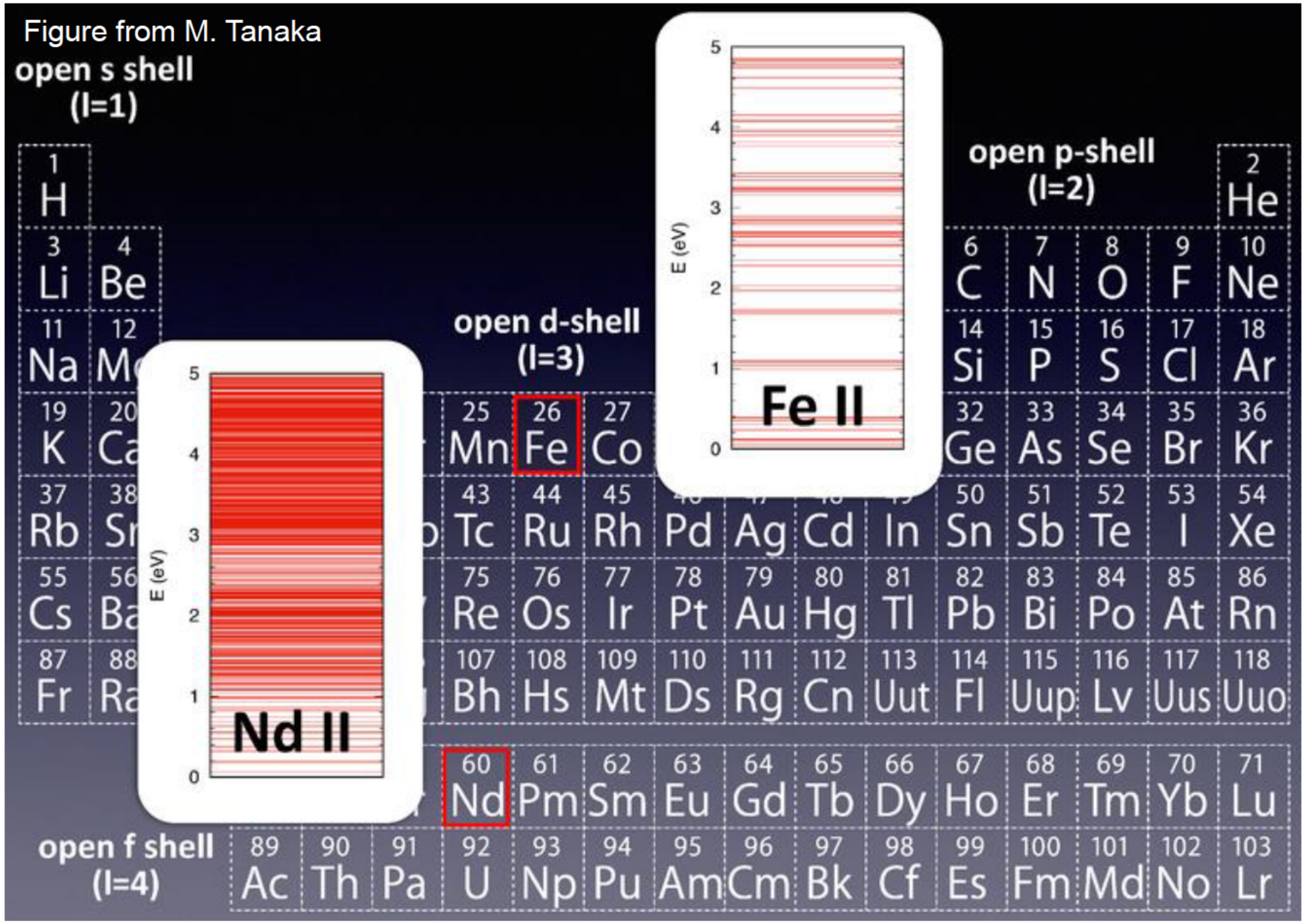


Figure from M. Tanaka

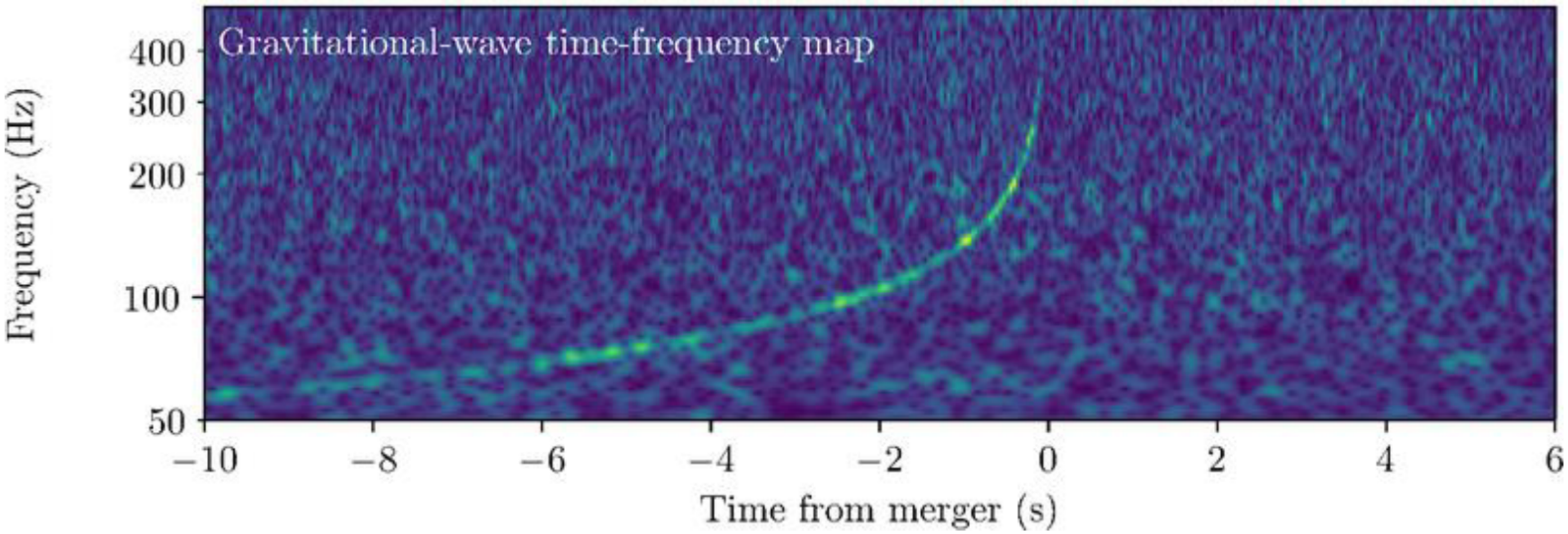
Large number of states of Lanthanides/Actinides leads to a high opacity

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).

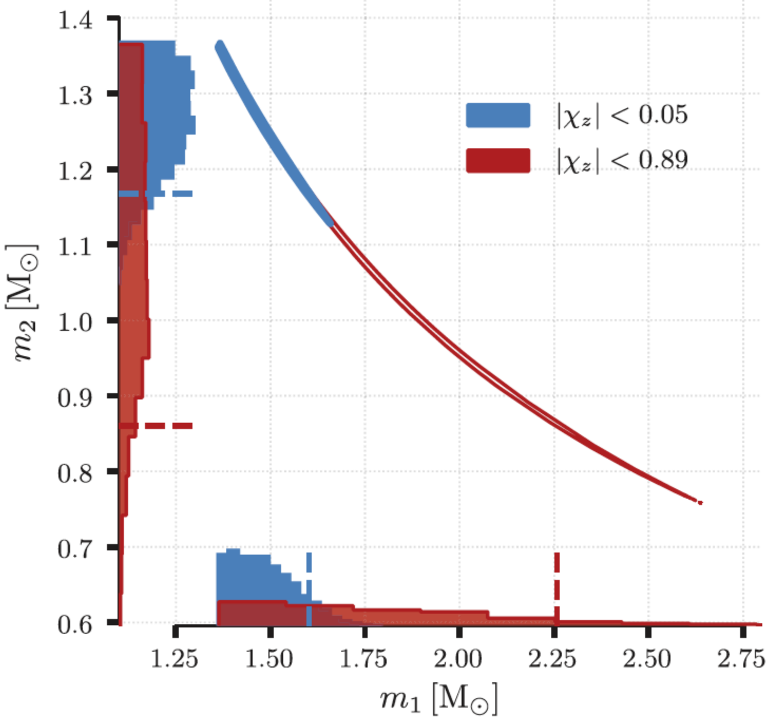


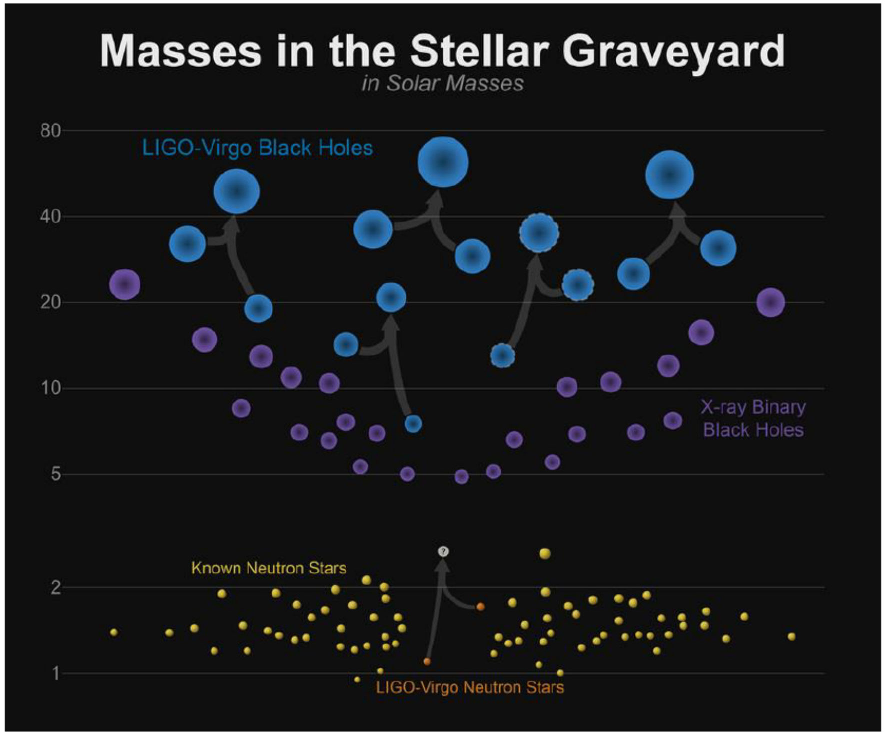
Frequency growth determined by chirp mass $\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1+m_2)^{1/5}} = 1.188^{+0.004}_{-0.002}\ \mathrm{M}_\odot$

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

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

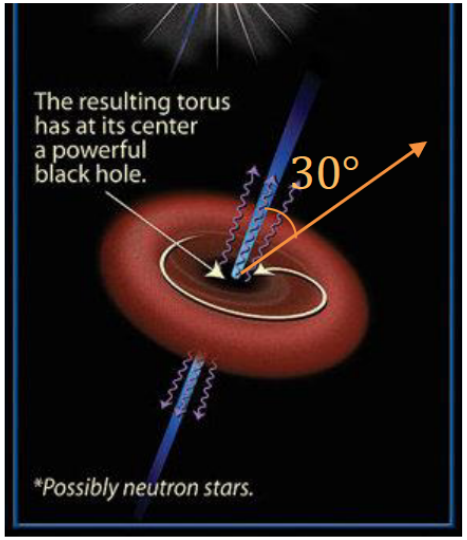
Primary mass: $m_1 \in (1.36\text{–}1.60)\,\mathrm{M}_\odot$

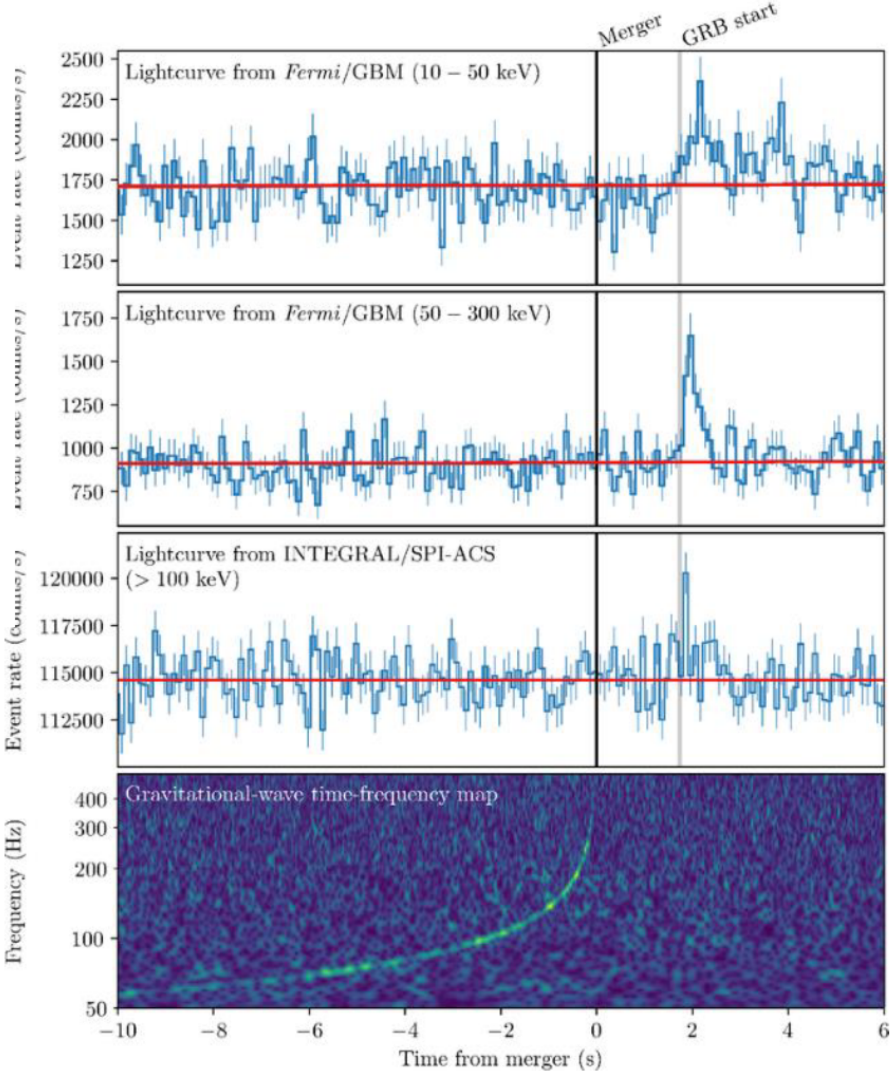
Secondary mass: $m_2 \in (1.17\text{–}1.36)\,\mathrm{M}_\odot$

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 ~ $30°$ with line of view.
- Combined analysis favors formation BH on timescales $\lesssim 100$ ms.

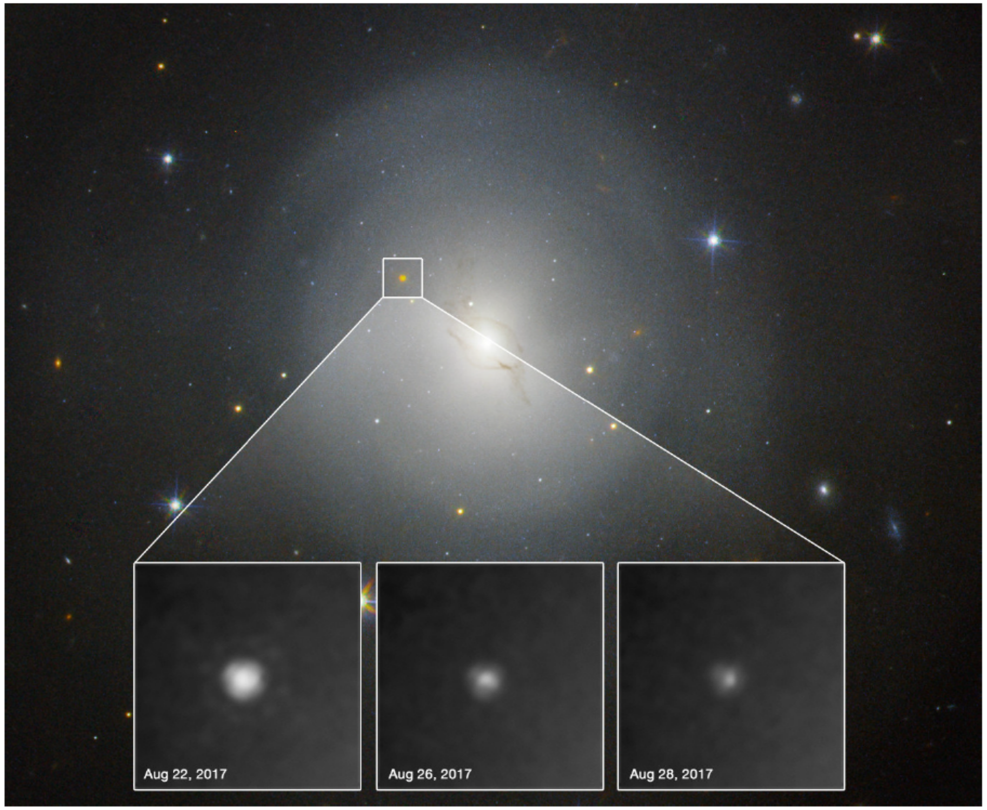




B. P. Abbott, et al, Astrophys. J. 848, L13 (2017).

AT 2017 gfo: electromagnetic signature from r process

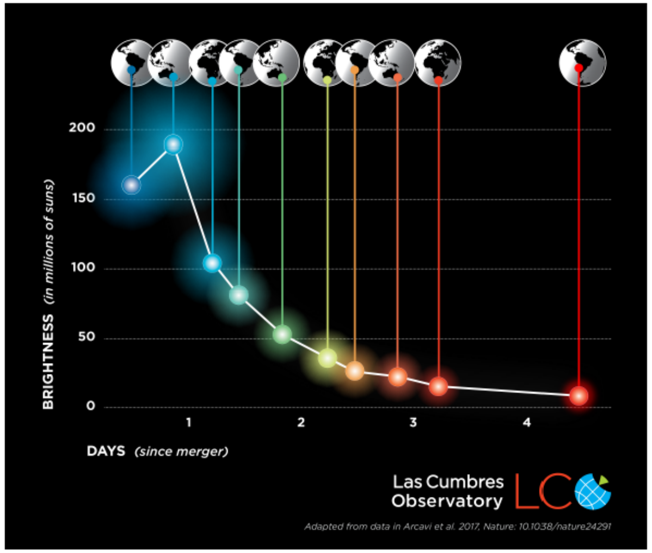
In-situ signature of r process nucleosynthesis



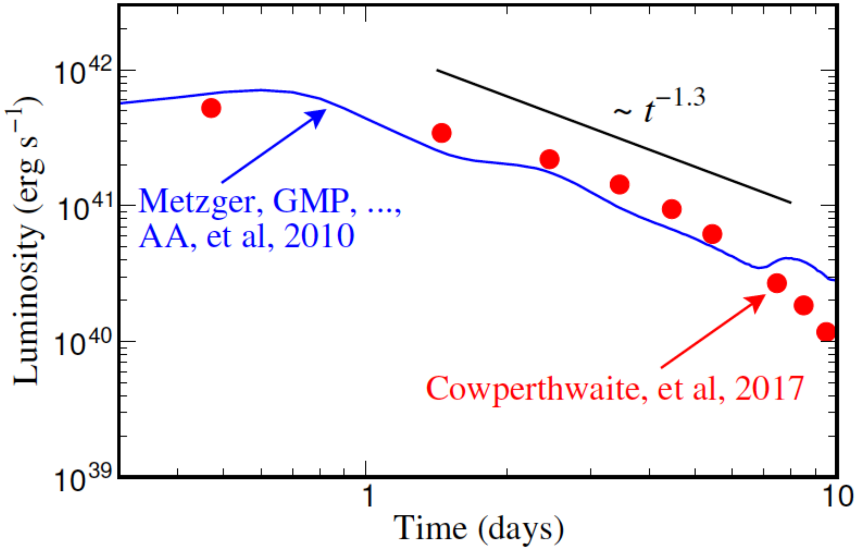
NASA and ESA. N. Tanvir (U. Leicester), A. Levan (U. Warwick), and A. Fruchter and O. Fox (STScI)

- Novel fastly evolving transitent
- Signature of statistical decay of fresly synthesized r process nuclei

AT 2017 gfo: interpretation

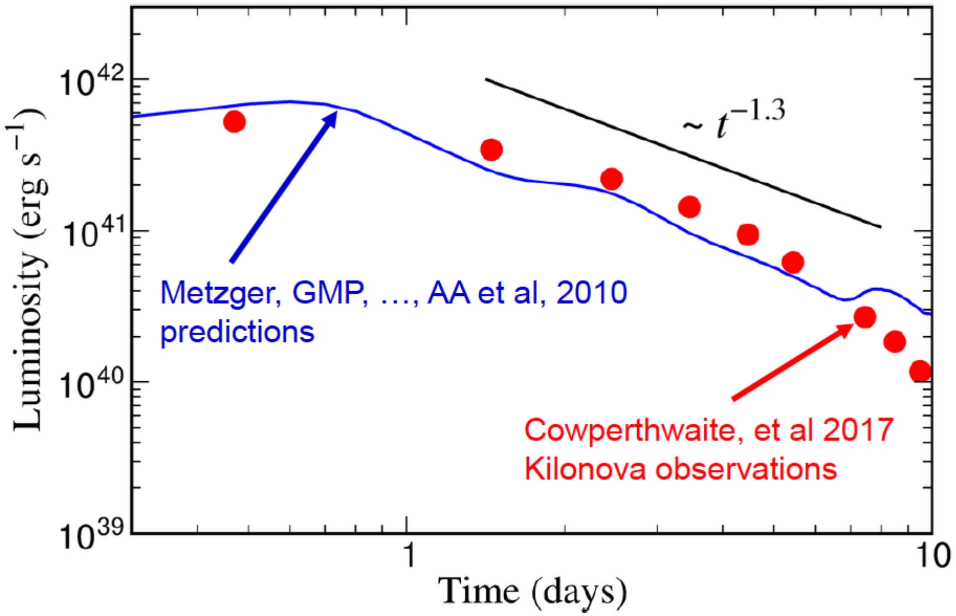


Adapted from data in Arcavi et al. 2017, Nature: 10.1038/nature24291

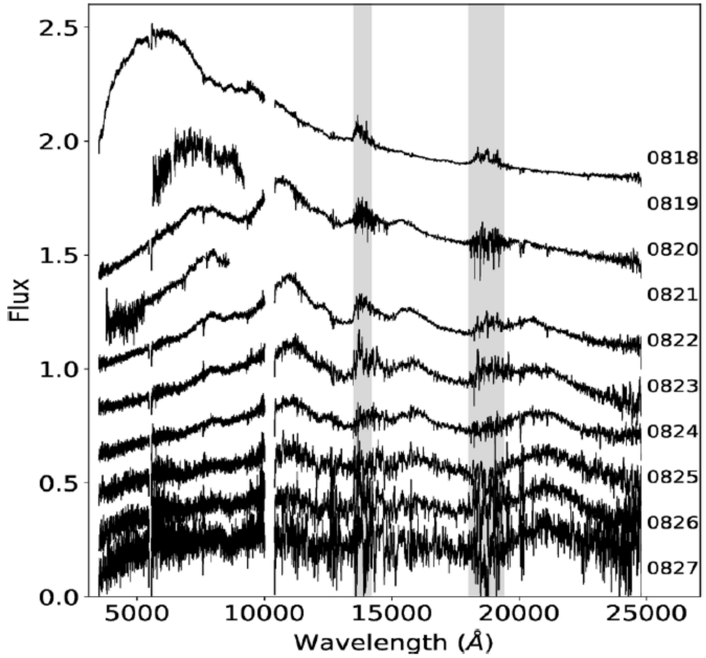


- Time evolution determined by the radioactive decay of r-process nuclei
- Two components:
  - blue dominated by light elements ($Z < 50$)
  - Red due to presence of Lanthanides ($Z = 57$–71) and/or Actinides ($Z = 89$–103)
- Likely source of heavy elements including Gold, Platinum and Uranium

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



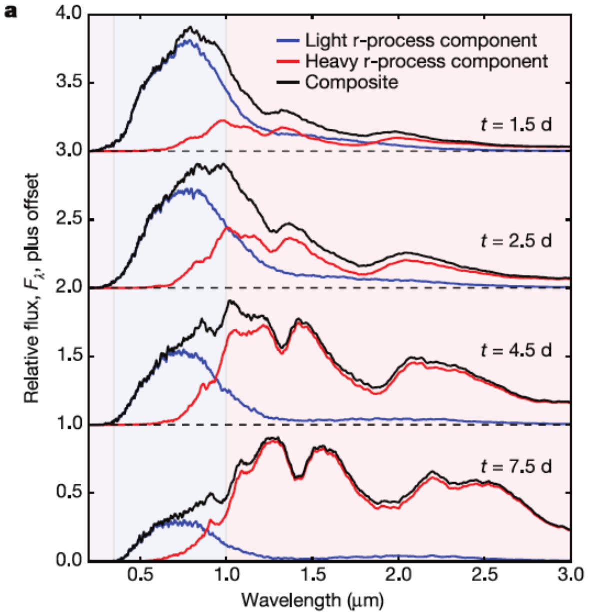
Pian et al., Nature 551, 67 (2017)



- 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)

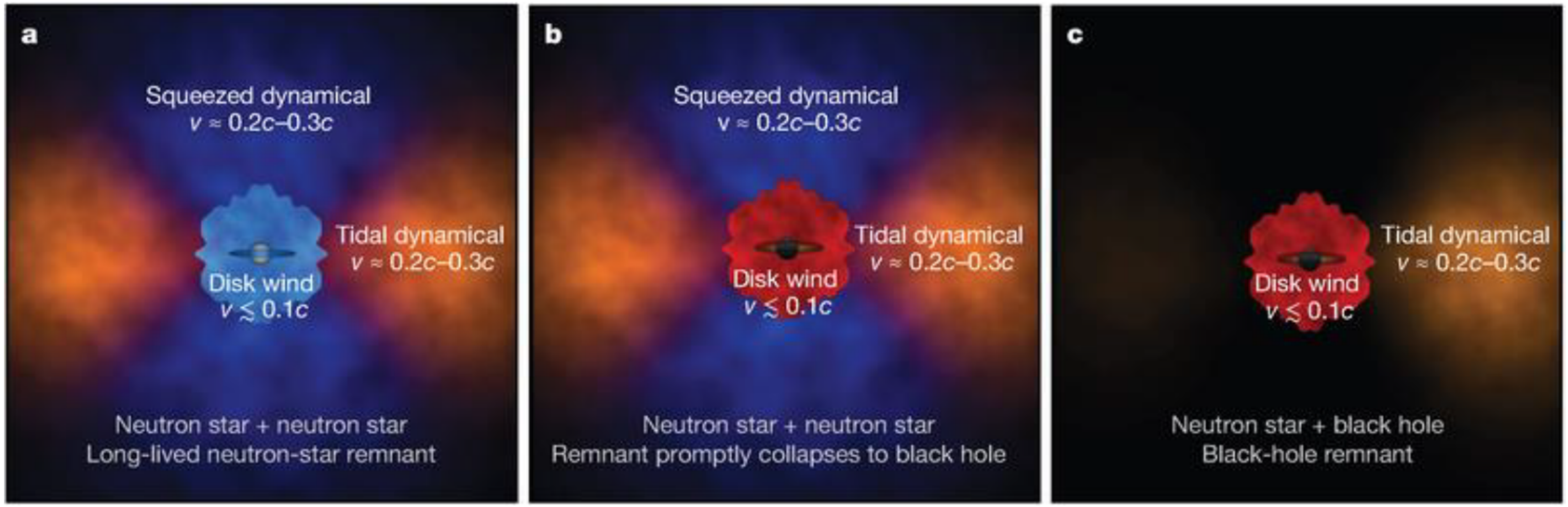


- Blue component from polar ejecta subject to strong neutrino fluxes (light r process)

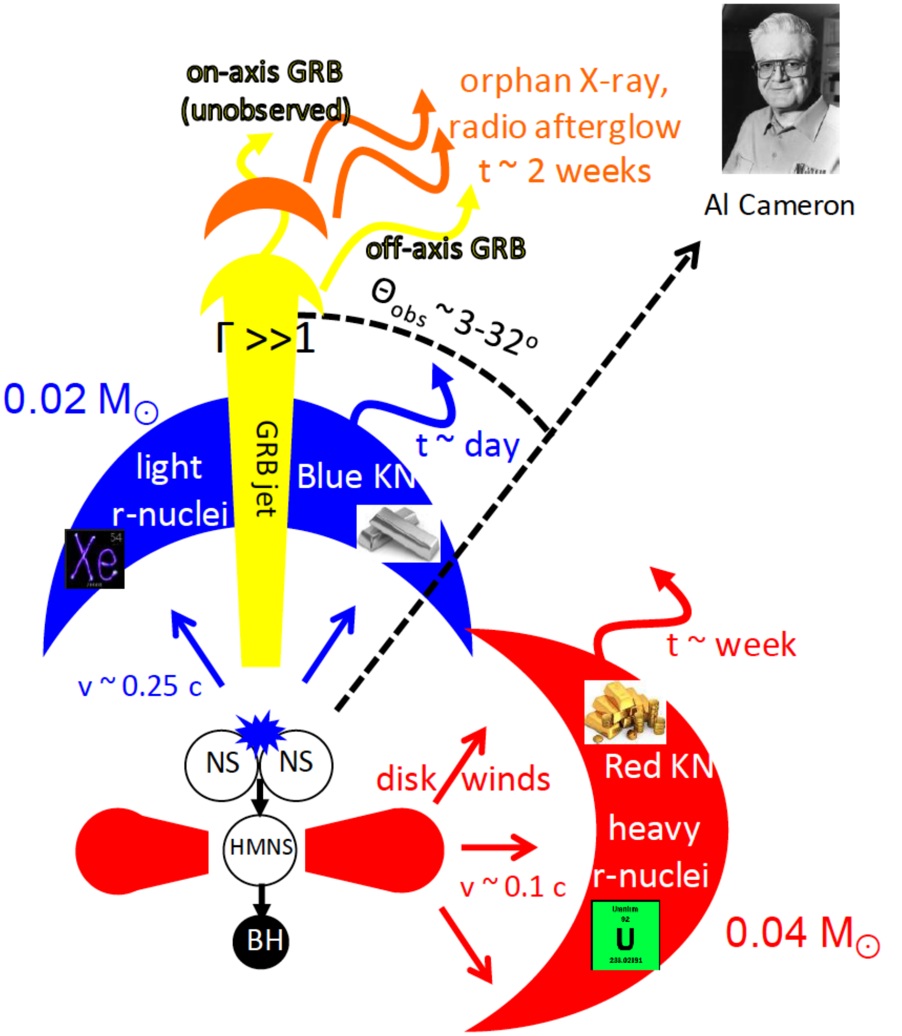
  $$M = 0.025\,M_{\odot}, v = 0.3c, X_{\text{lan}} = 10^{-4}$$

- 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

Summary

- Heavy elements are observed at very early times in Galactic history. Produced by a primary process that creates both neutrons and seeds.
- Neutron star mergers are likely the site where the "main r process" takes place.
- Radioactive decay of r-process ejecta produces an electromagnetic transient observed for the first time after GW170817.
- Observations of Blue and Red kilonova components show that both light ($A \lesssim 120$) and heavy ($A \gtrsim 120$) elements are produced. No direct evidence of individual elements.
  - How can we determine composition?
  - What were the heavier elements produced in the merger?
  - How does the nucleosynthesis depends on merging system?
  - What is the contribution of mergers to light r process elements?

Bibliography:

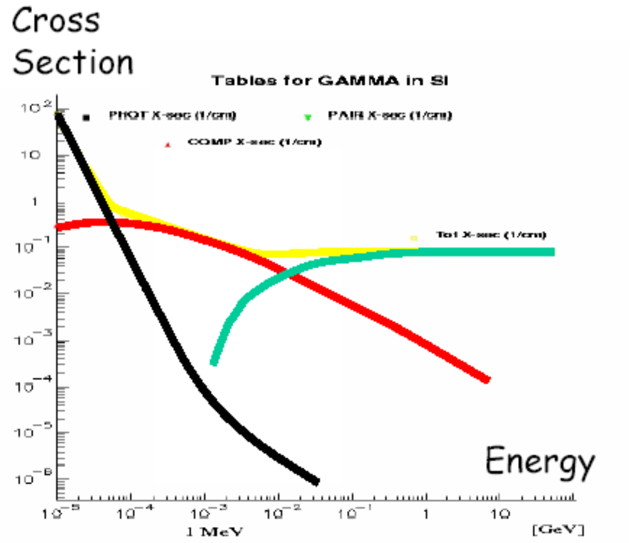
Cowan, *et al.*, *Making the Heaviest Elements in the Universe: A Review of the Rapid Neutron Capture Process*, arXiv:1901.01410 [astro-ph.HE]

Astrofisica Nucleare e Subnucleare

“MeV” Astrophysics

MeV astrophysics techniques

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

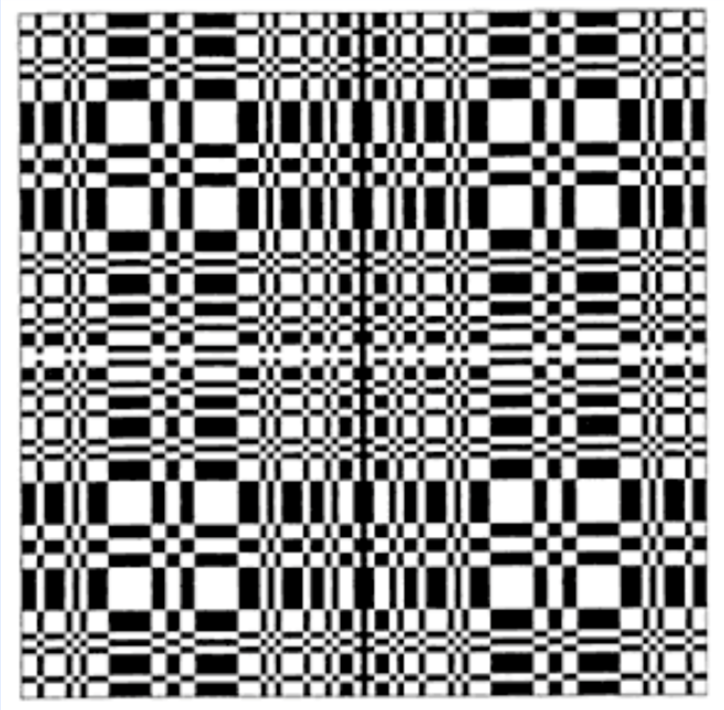
Coded Mask Imaging

The Coded Mask Technique

is the worst possible way of making a telescope

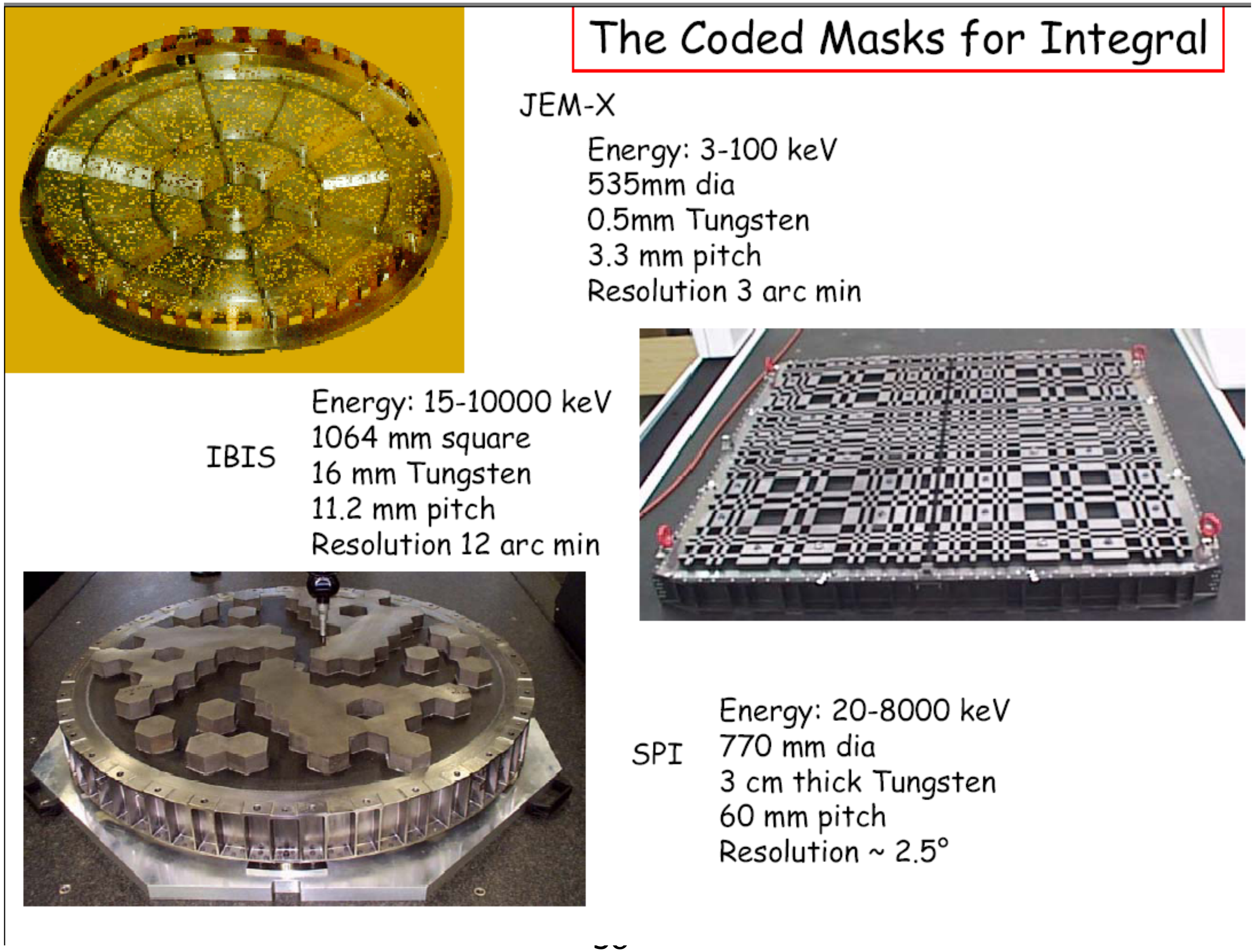
Except when you can 't do anything better !

- 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

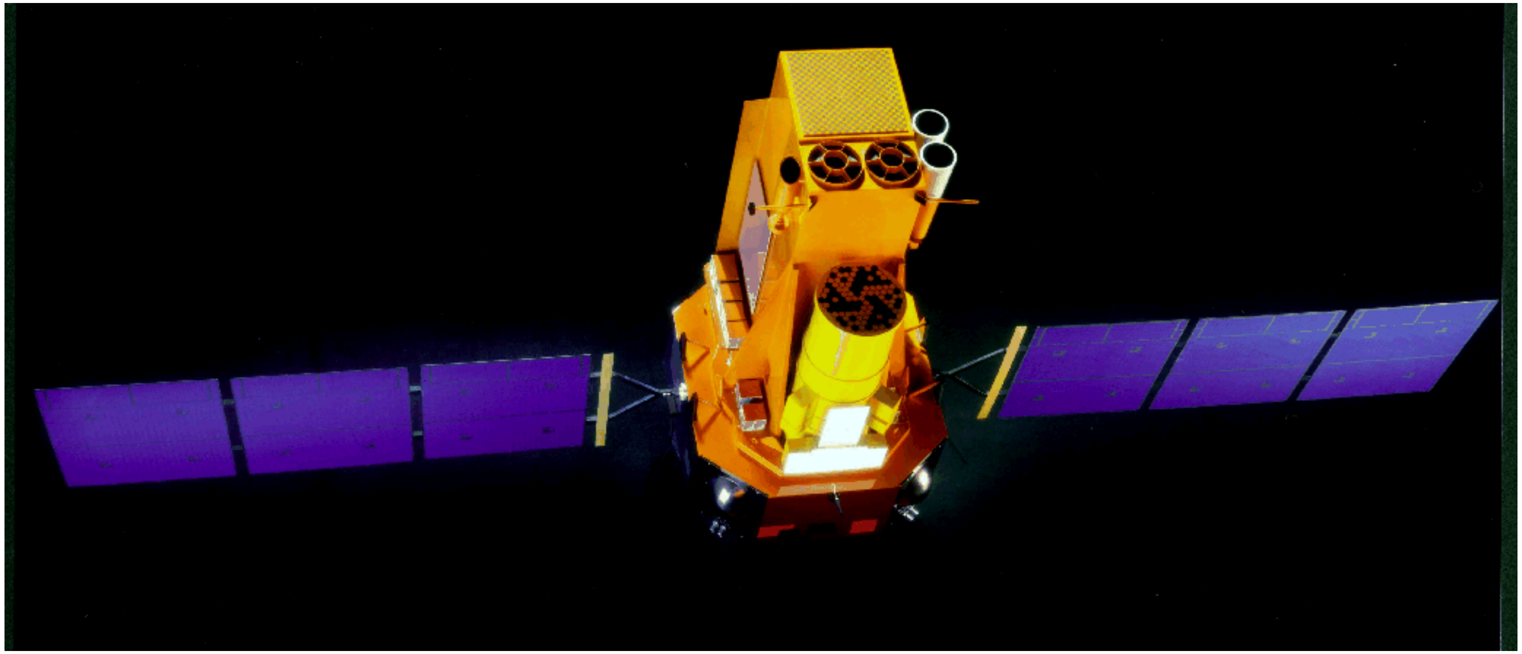
Energy: 15-10000 keV
1064 mm square
16 mm Tungsten
11.2 mm pitch
Resolution 12 arc min

SPI

Energy: 20-8000 keV
770 mm dia
3 cm thick Tungsten
60 mm pitch
Resolution ~ 2.5°

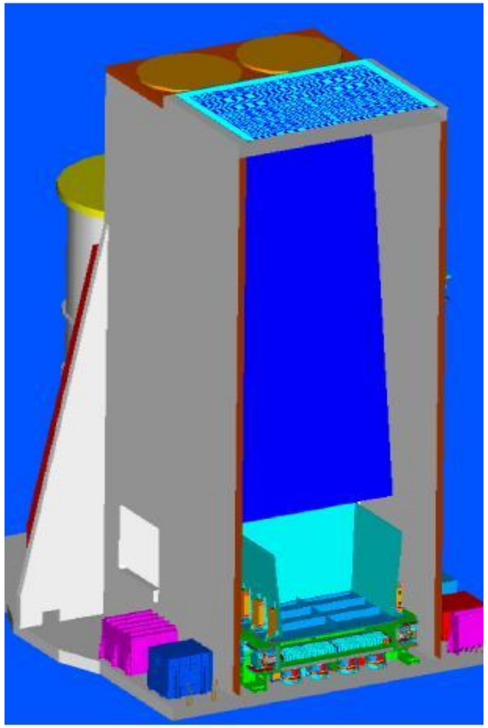
INTEGRAL

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)

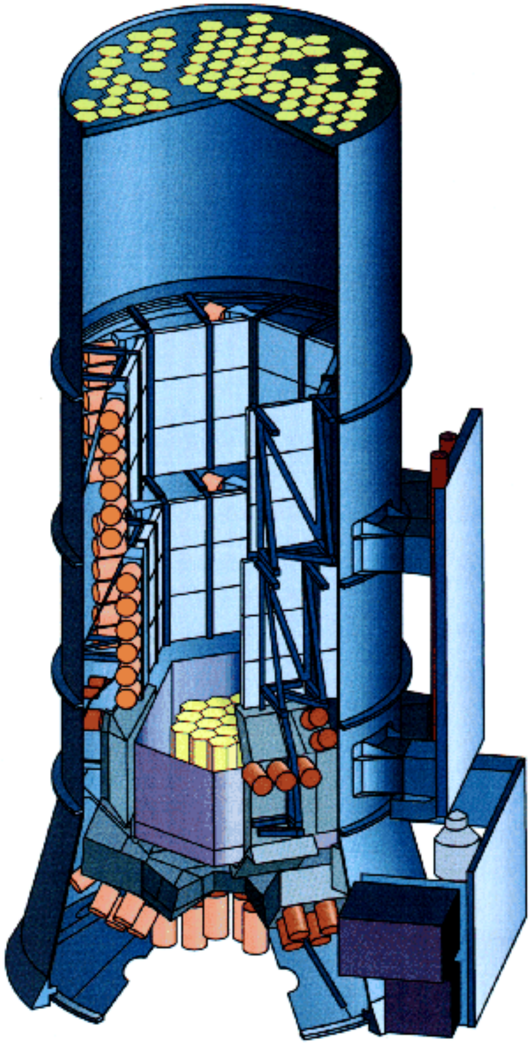


http://integral.esa.int

INTEGRAL

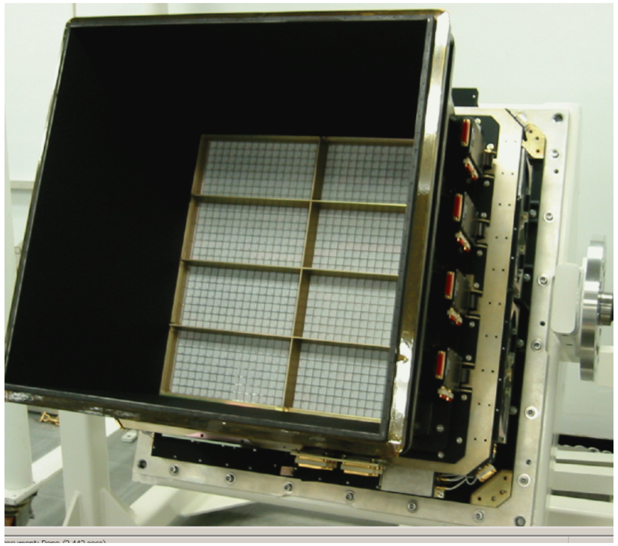


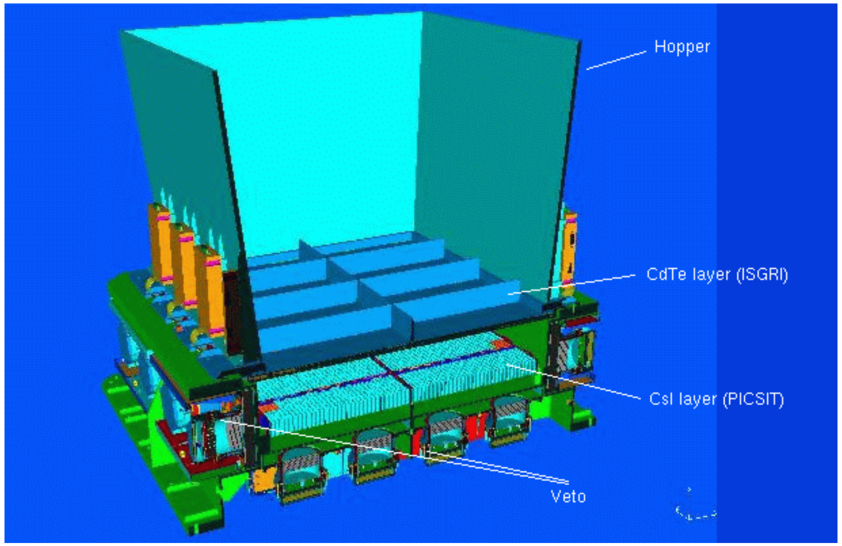
Imager IBIS



Spectrometer SPI

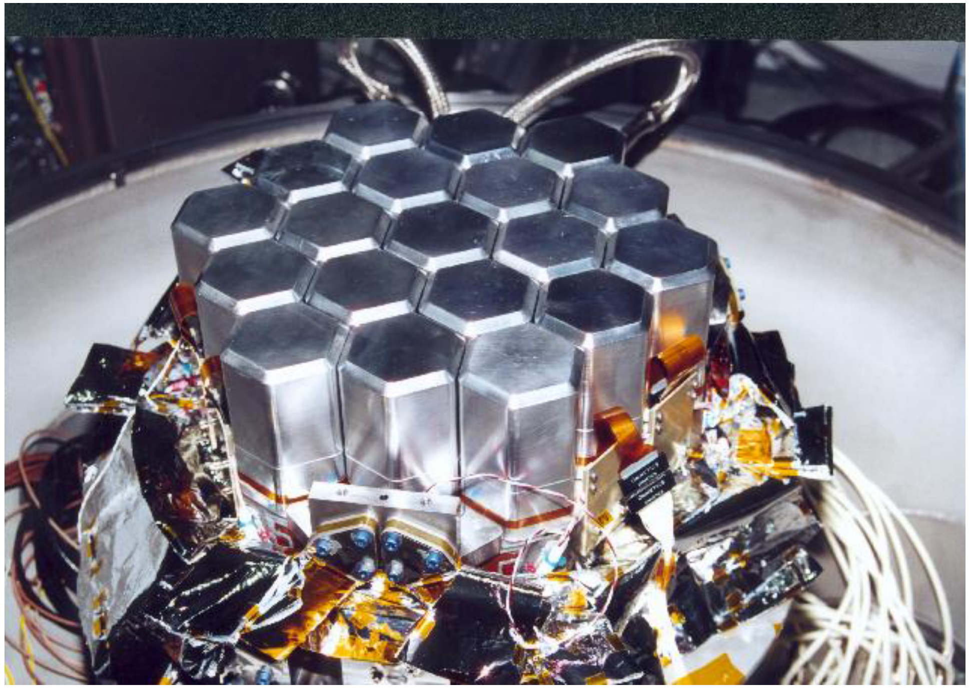
IBIS





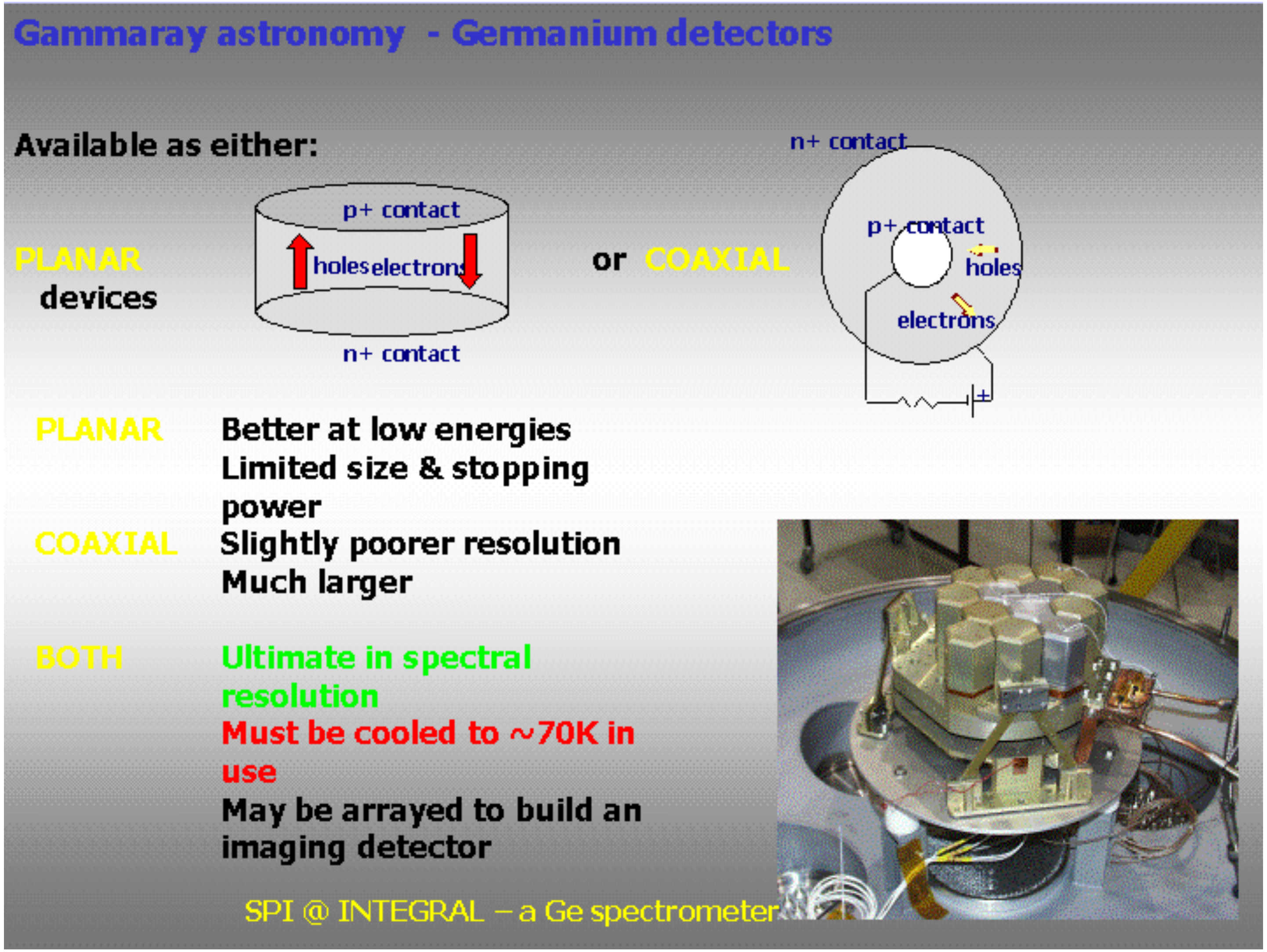
The Imager IBIS (Imager on Board the Integral Satellite) provides diagnostic capabilities of fine imaging (12 arcmin FWHM), source identification and spectral sensitivity to both continuum and broad lines over a broad (15 keV - 10 MeV) energy range. The Imager will exploit simultanesously with the other 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 cm^2 front layer of CdTe pixels, each (4x4x2) mm (width x depth x height), and a 3000 cm^2 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



Gammaray astronomy - Germanium detectors

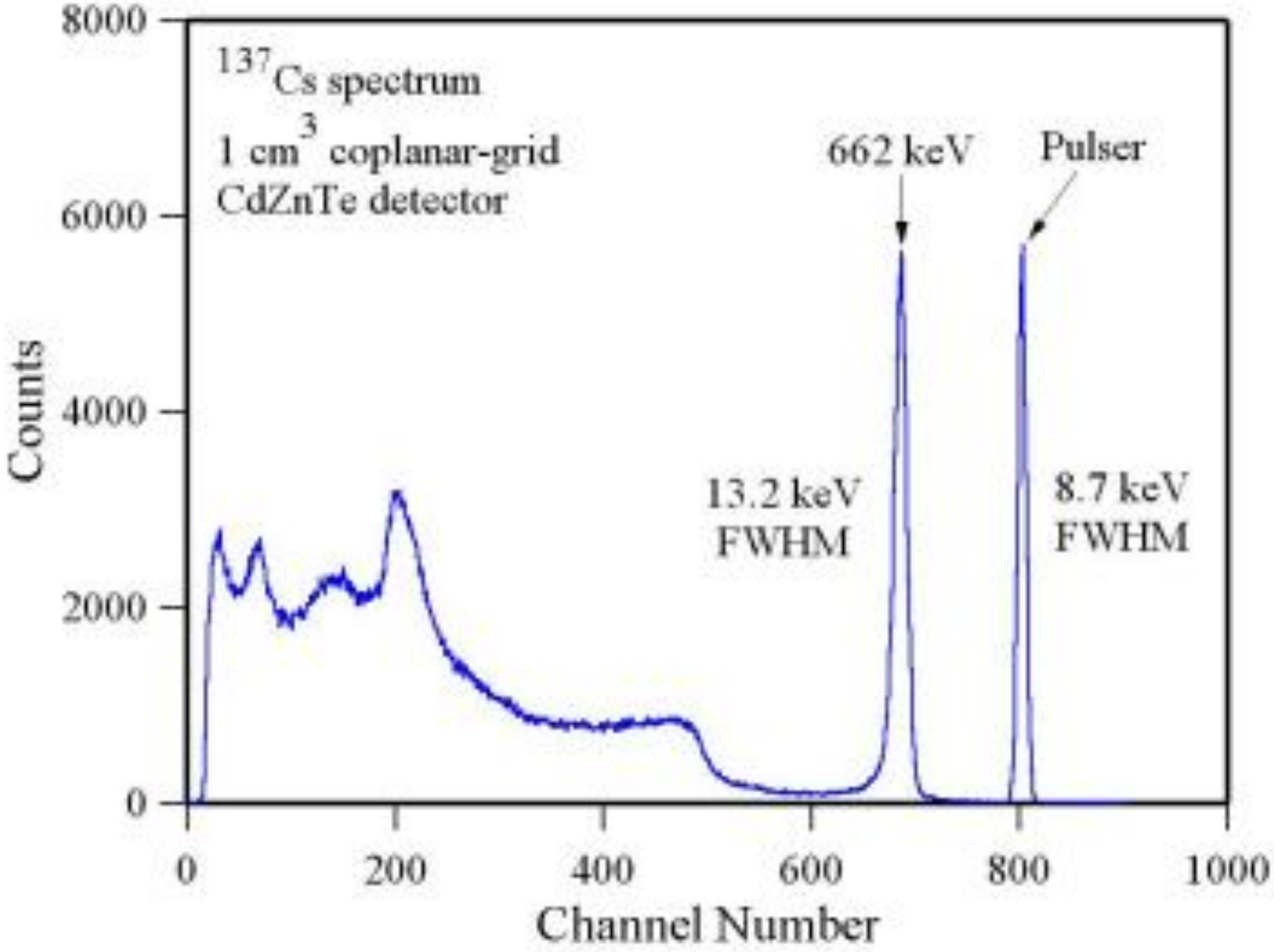
Available as either:

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 ~70K 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 keV – 10 MeV) spectroscopy

Very thin surface dead layers may give Ge an advantage where response from 1 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 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)**

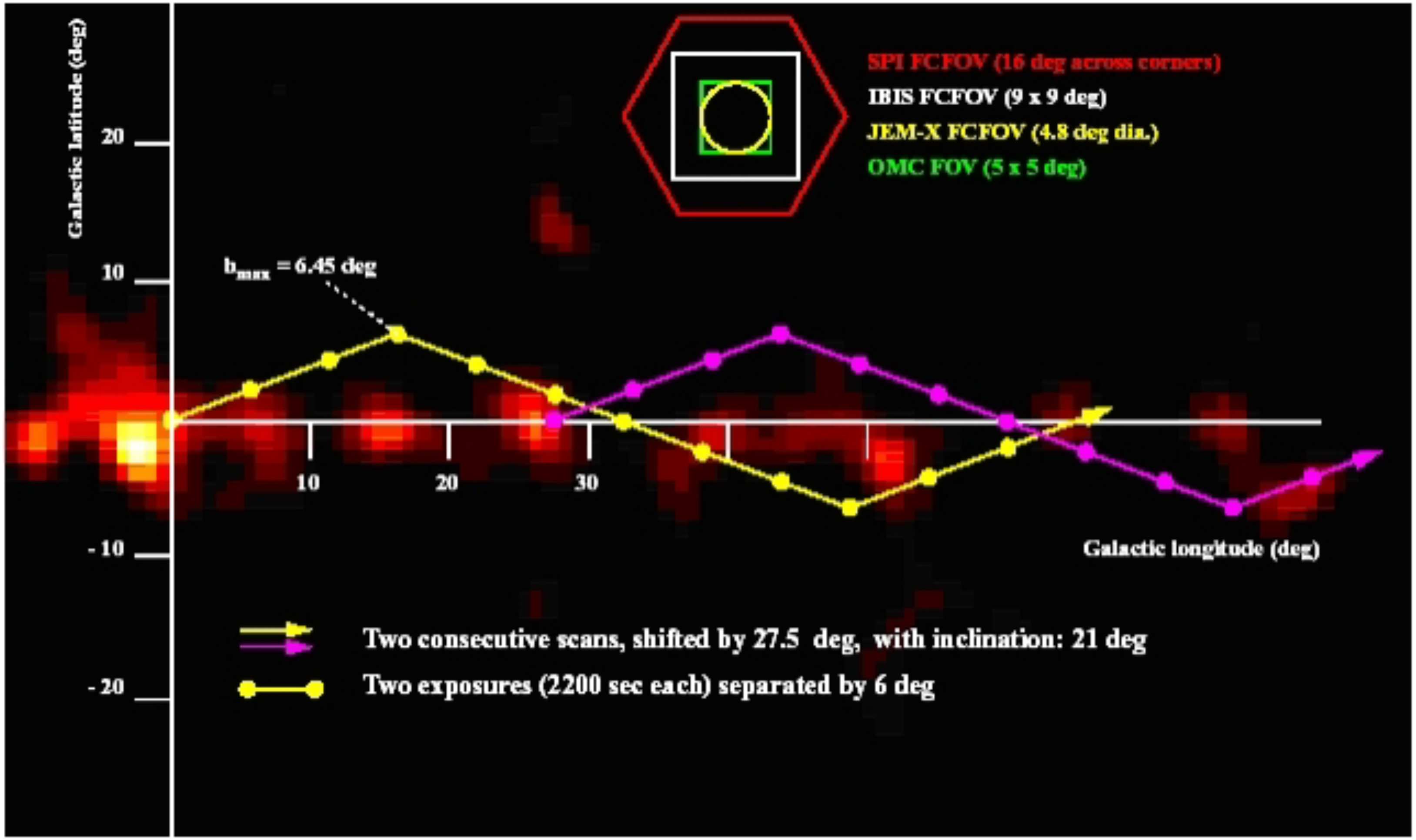
- **Alta ρ (~6 g cm^{-3}) per massimizzare l'efficienza**

- **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**

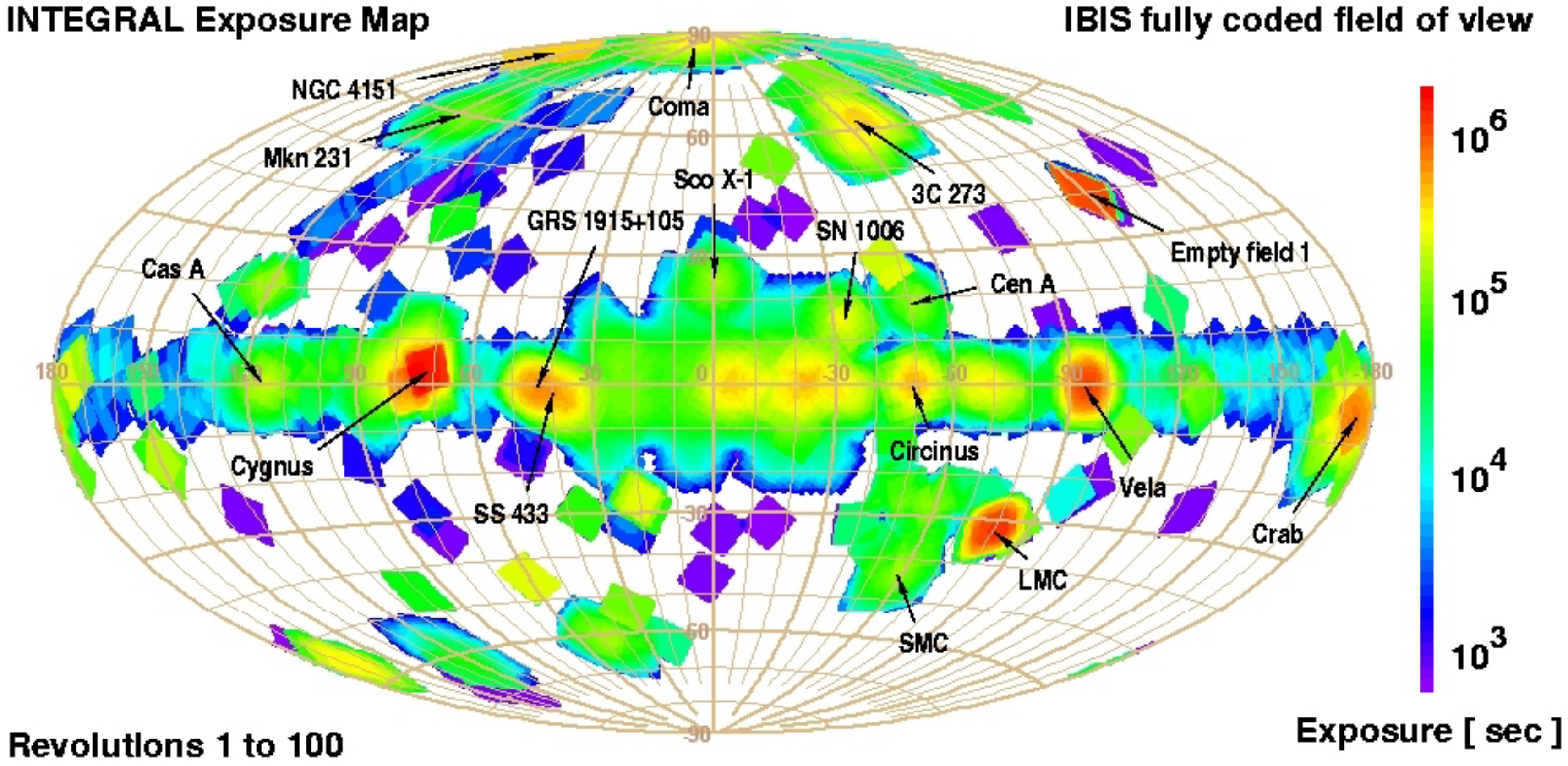
- **Facilmente segmentabile a piccole dimensioni:**
  - **⇒ risoluzione spaziale**

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

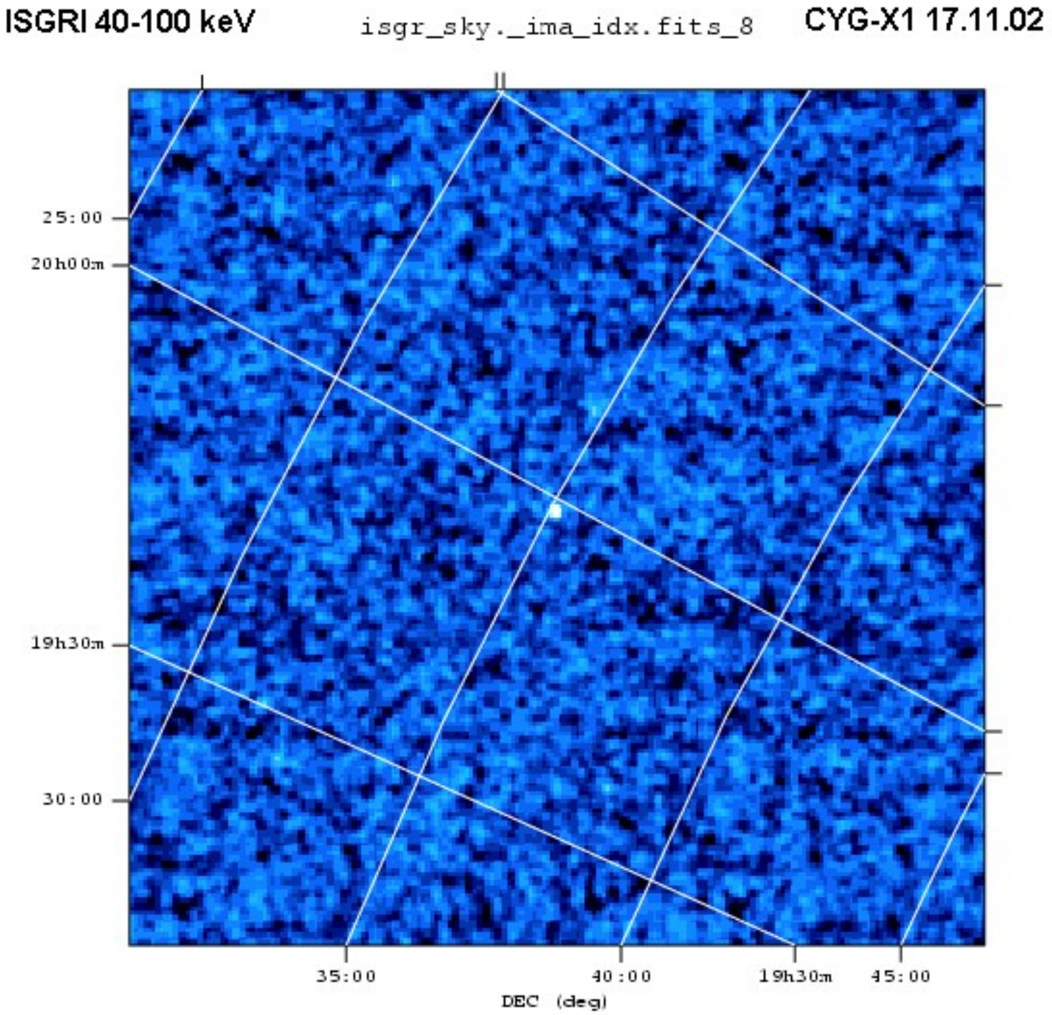
INTEGRAL


SPI FCFOV (16 deg across corners)
IBIS FCFOV (9 x 9 deg)
JEM-X FCFOV (4.8 deg dia.)
OMC FOV (5 x 5 deg)
Galactic latitude (deg)
20
10
- 10
- 20
b_{max} = 6.45 deg
10
20
30
Galactic longitude (deg)
Two consecutive scans, shifted by 27.5 deg, with inclination: 21 deg
Two exposures (2200 sec each) separated by 6 deg

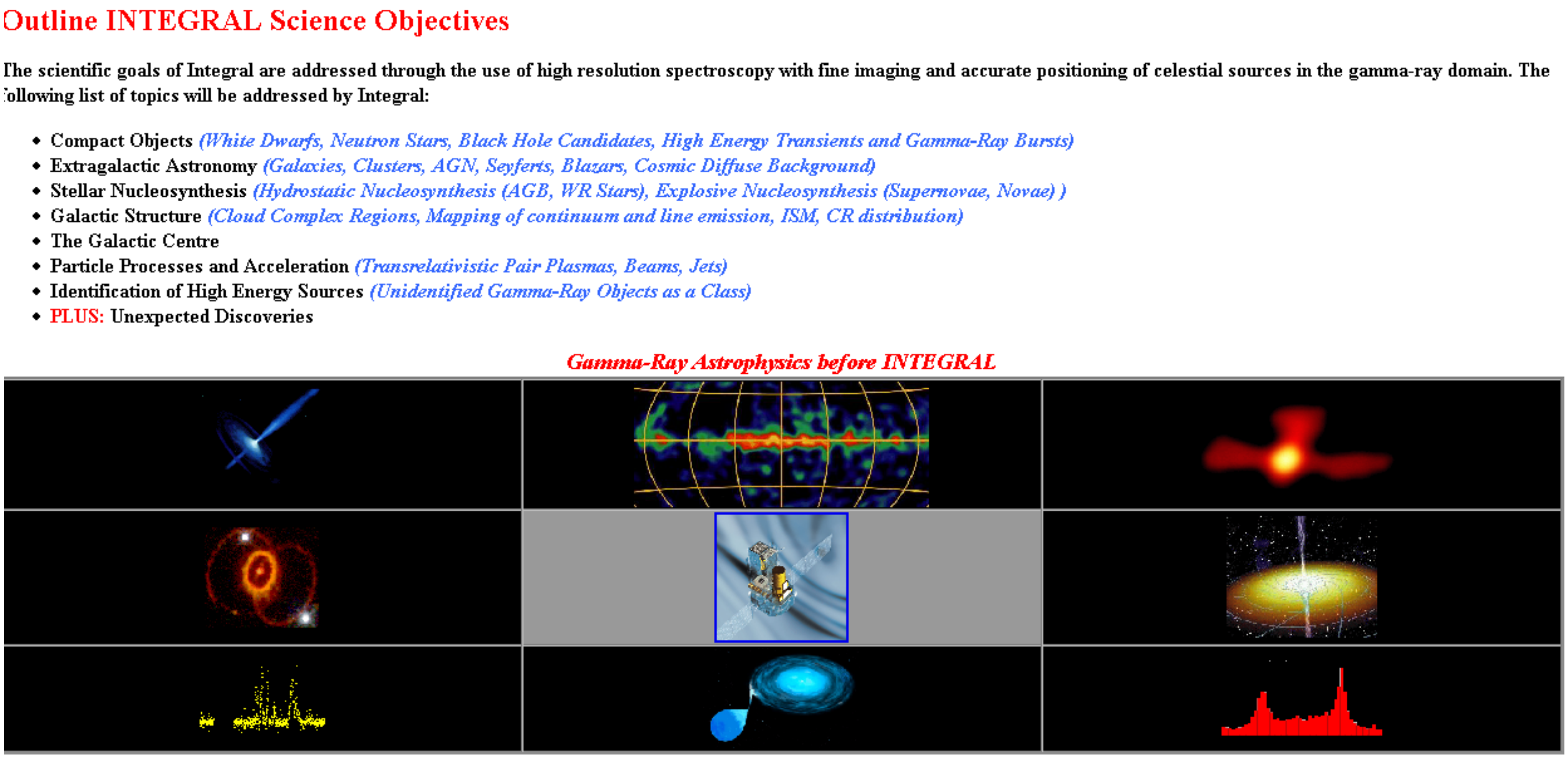
INTEGRAL


INTEGRAL Exposure Map
IBIS fully coded field of view
NGC 4151
Coma
Mkn 231
3C 273
Sco X-1
GRS 1915+105
SN 1006
Empty field 1
Cas A
Cen A
Cygnus
SS 433
Circinus
Vela
Crab
LMC
SMC
90
60
30
-30
-60
-90
180
150
120
90
60
30
0
-30
-60
-90
-120
-150
-180
10^6
10^5
10^4
10^3
Exposure [sec]
Revolutions 1 to 100

INTEGRAL


ISGRI 40-100 keV
isgr_sky._ima_idx.fits_8
CYG-X1 17.11.02
25:00
20h00m
19h30m
30:00
35:00
40:00
19h30m
45:00
DEC (deg)

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