Nucleosynthesis: new perspectives from gamma-ray astronomy

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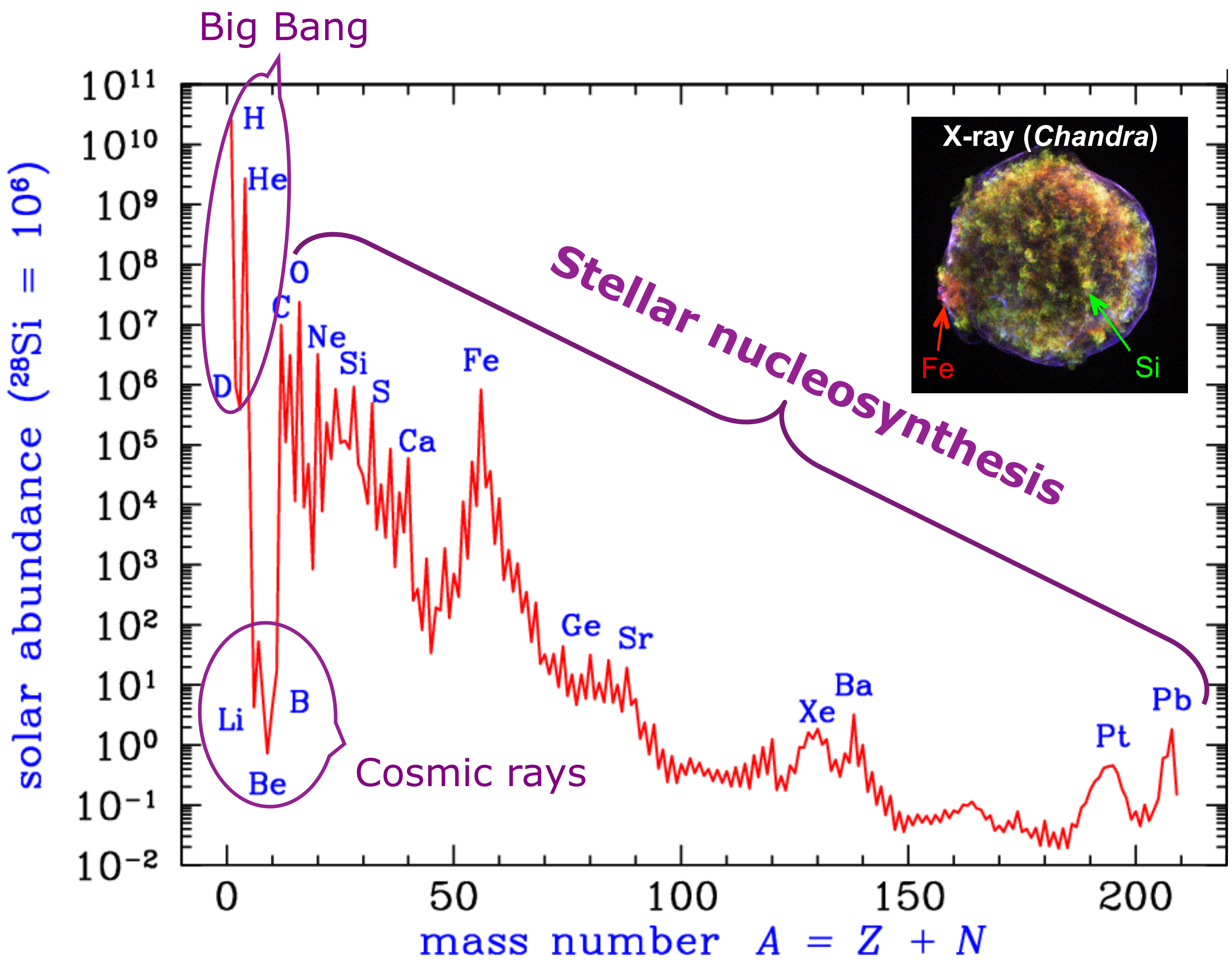
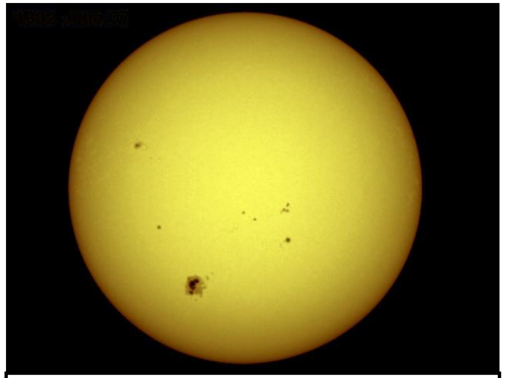
XXIInd GANIL Colloque Vercors Montains Sep 27th - Oct 1st, 2021

Cosmic abundances of the elements



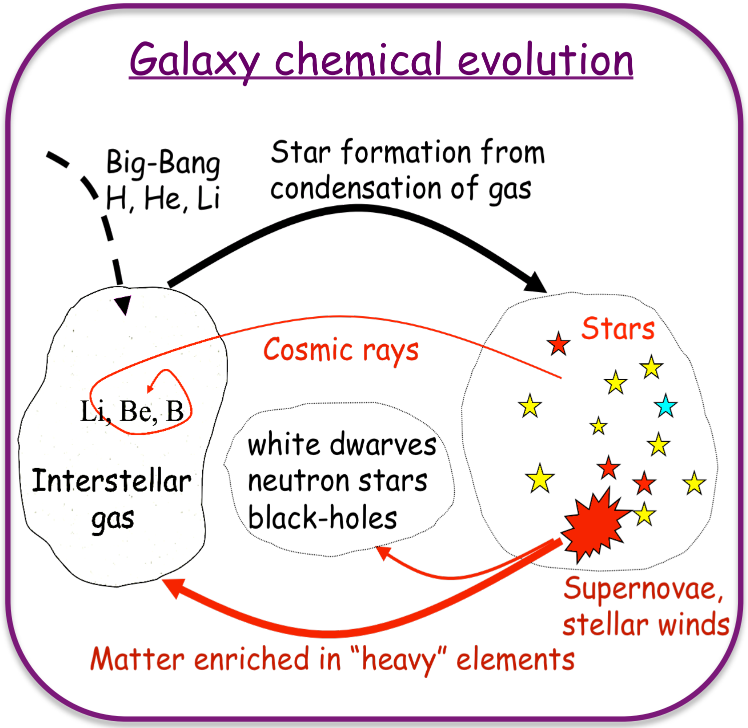


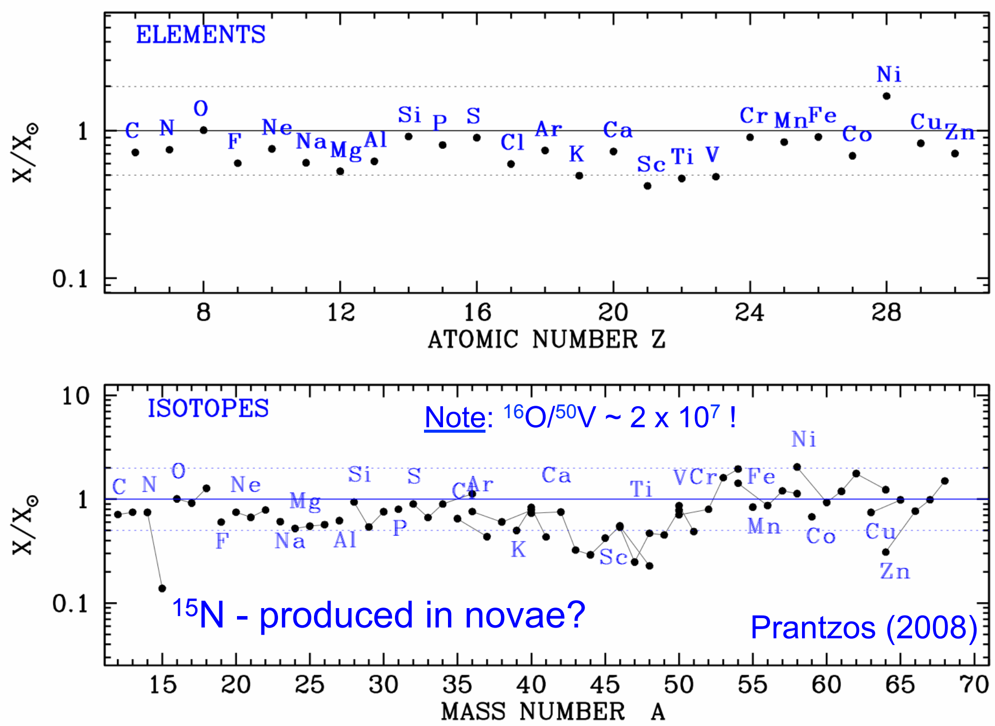
Solar photosphere

Fragment of the Orgueil meteorite

Understanding the origin of the elements

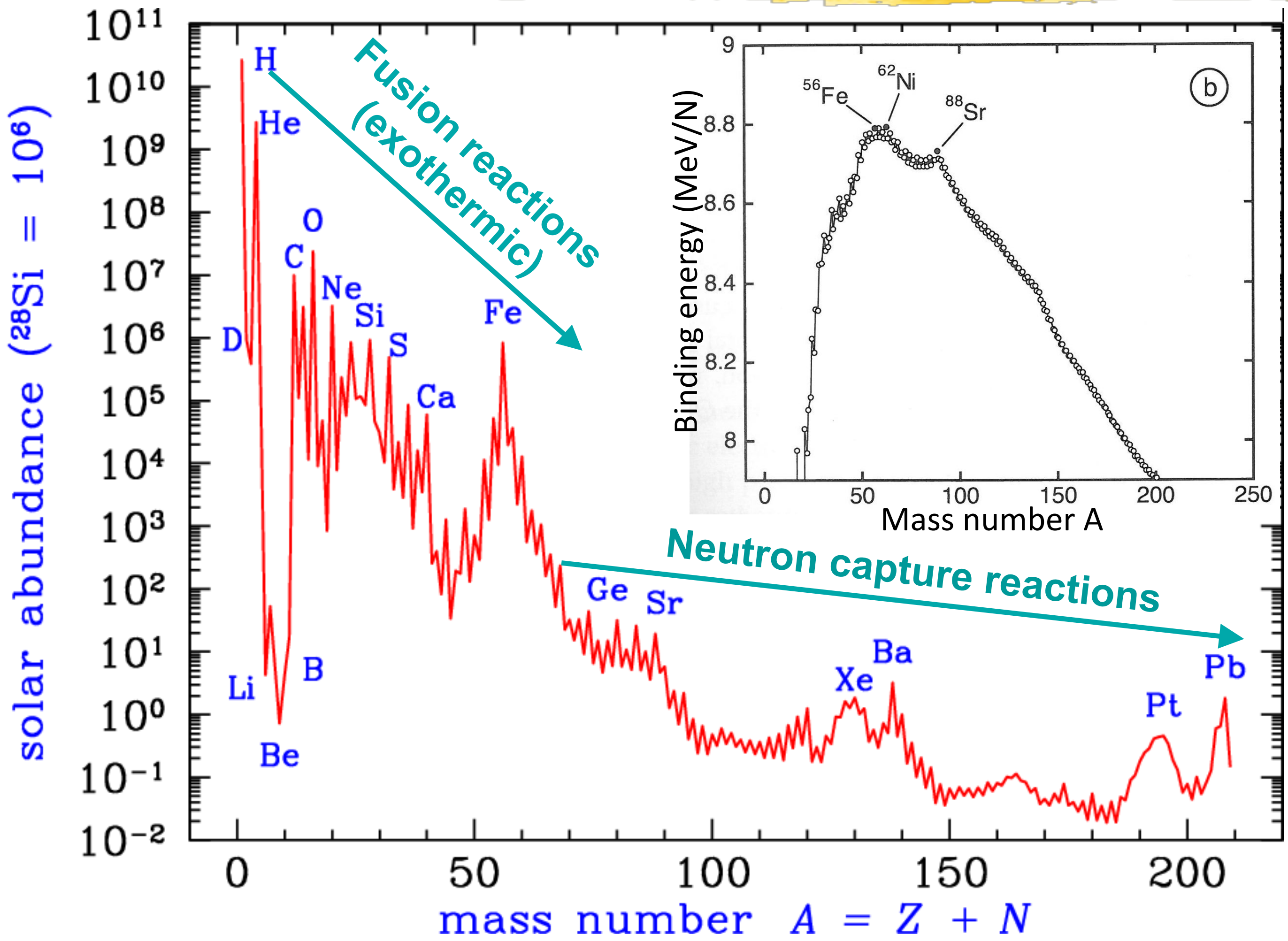
- **1919:** J. Perrin then A. Eddington suggest that the **energy of the stars results from nuclear fusion**
- **1957:** **First overview of nucleosynthesis processes** (Burbidge, Burbidge, Fowler & Hoyle; + Cameron)
- Major advances made since then in the theory of stellar evolution, galaxy chemical evolution models & **nuclear physics experiments and theory**





- **Origin of the elements** now understood **in broad outline** (after centuries of research, e.g. Anaxagoras 500-428 B.C.)
- Abundances in the solar system (formed ~ 9 Gy after the Milky Way) from ^{12}C to ^{68}Zn are reproduced **within a factor of 2**

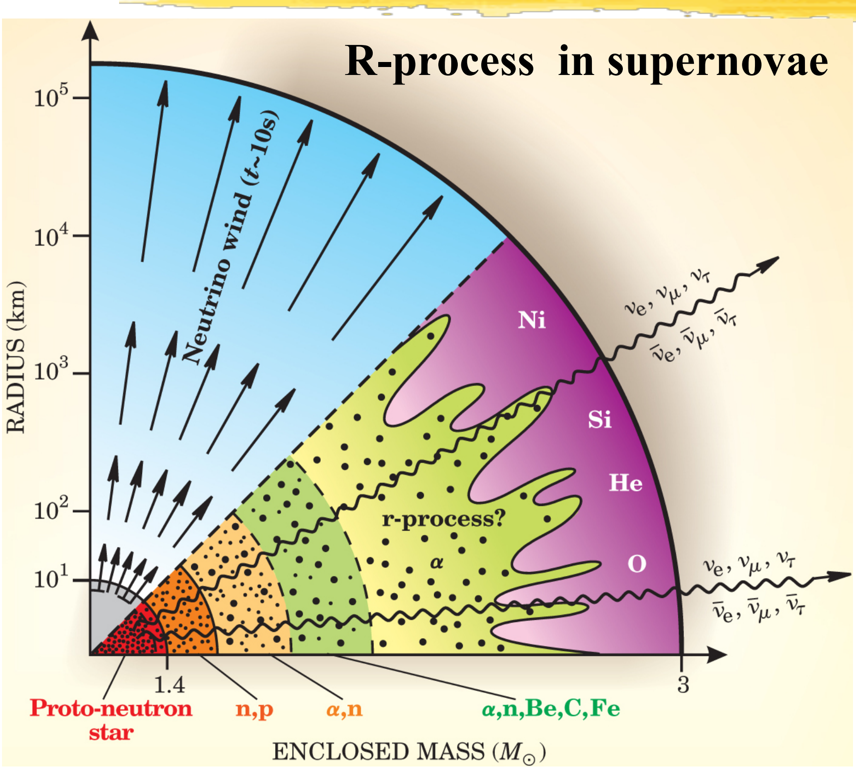
Nucleosynthesis beyond the Fe peak

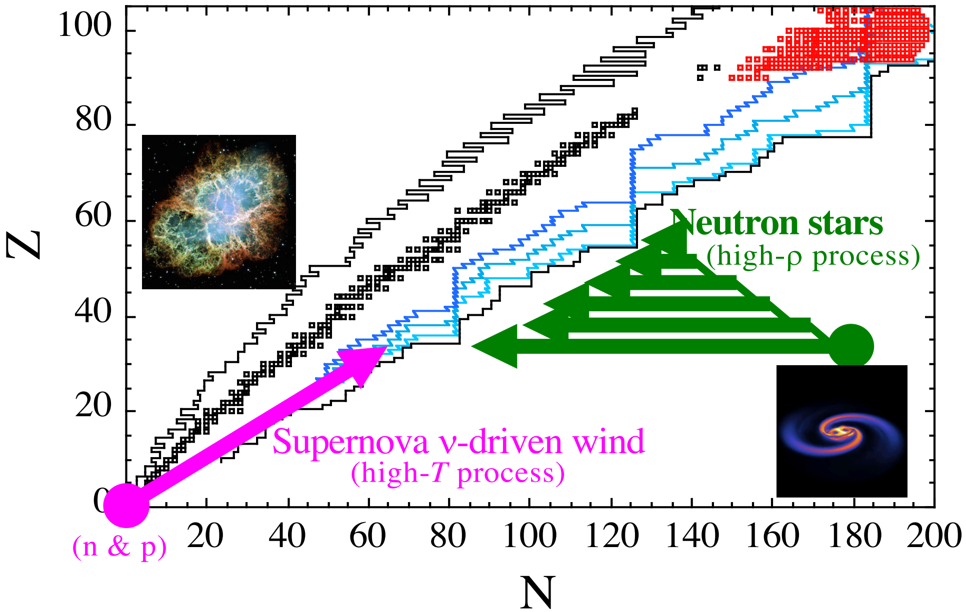


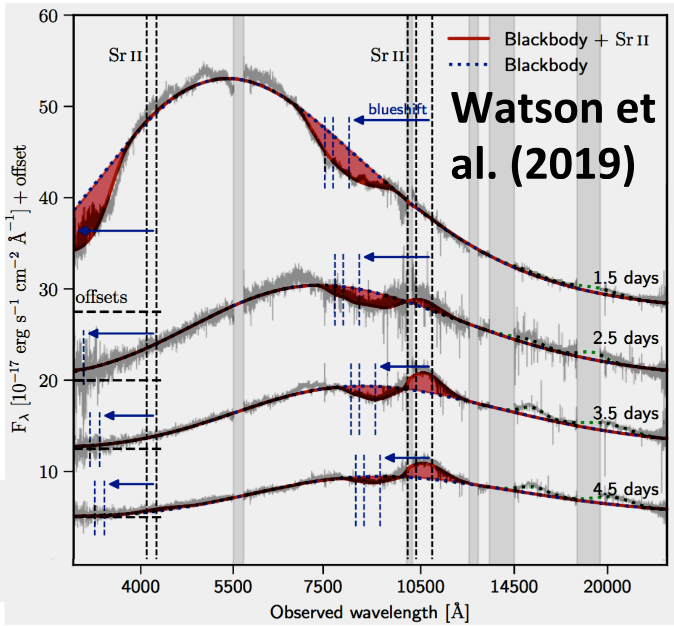
- Remarkable peaks in the abundance curve beyond Fe, corresponding to **neutron shell closure** at N=50 (^{88}Sr) N=82 (^{138}Ba) N=126 (^{208}Pb)
- Double peaks ⇒ two n-capture processes

- **S process (slow)**: $N_n \sim 10^7 \rightarrow 10^{11}$ cm^{-3}; massive stars ($M > 13\ M_\odot$), AGB stars
- **R process (rapid)**: **$N_n > 10^{22}$ cm^{-3}; explosive environment(s) ?**

Site(s) of r-process nucleosynthesis





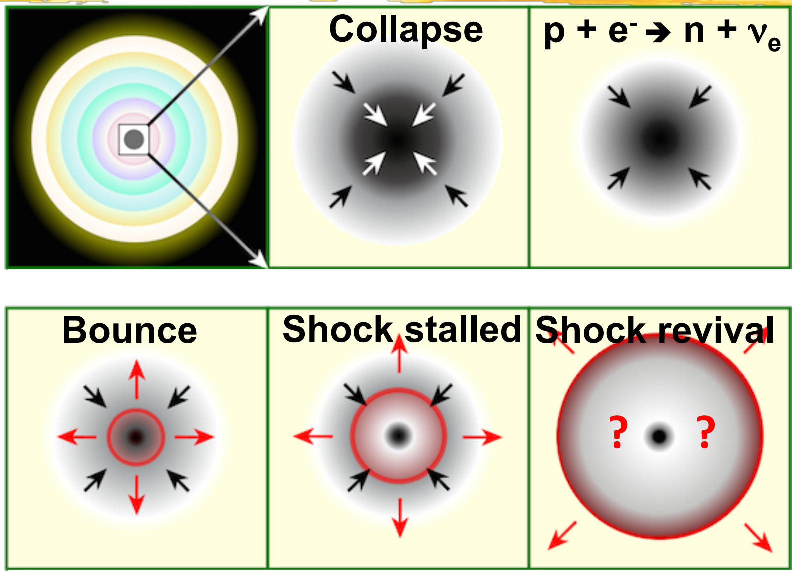


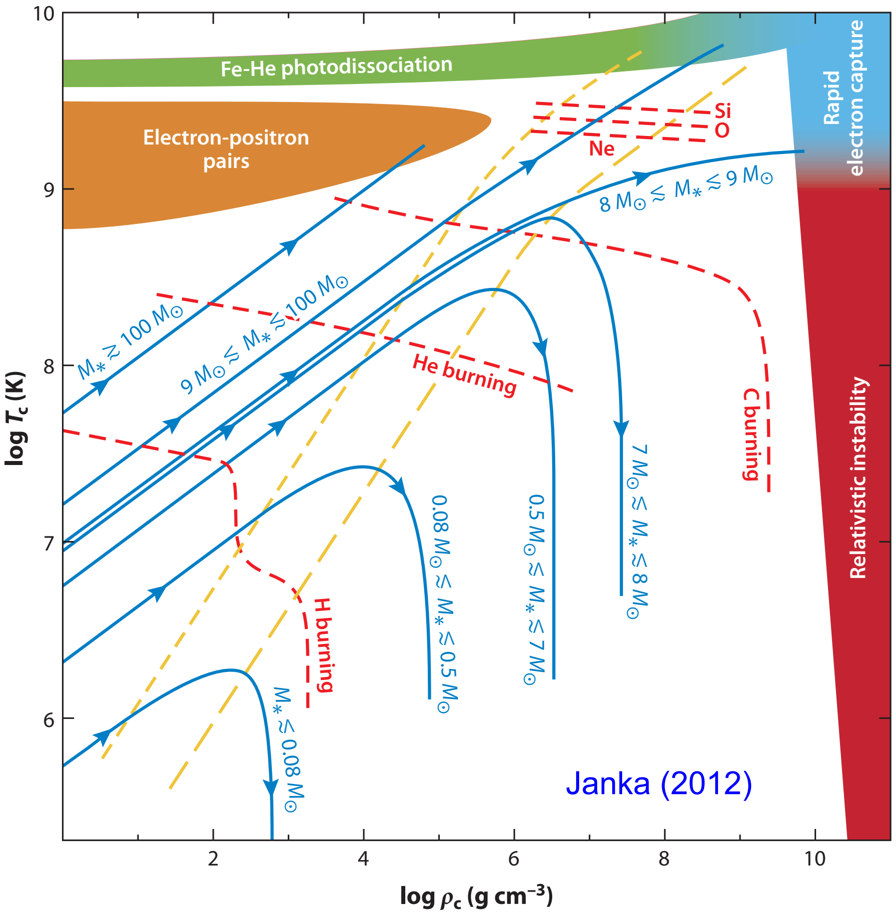
or/ and?
- i. Nucleosynthesis in the **ν-driven wind** of **core-collapse supernovae**?
- ii. Decompression of neutron-rich matter in the **mergers of 2 neutron stars** (or NS-BH)?

ii.confirmed with **GW170817** (LIGO & Virgo) and the associated **kilonova** powered by **r-radioactivites**

Fate of massive stars

- **Collapse** due to an endothermic **instability**: **photodesintegration** of Fe-group nuclei, **electron captures** in a degenerate O-Ne-Mg core, formation of **electron-positron pairs**

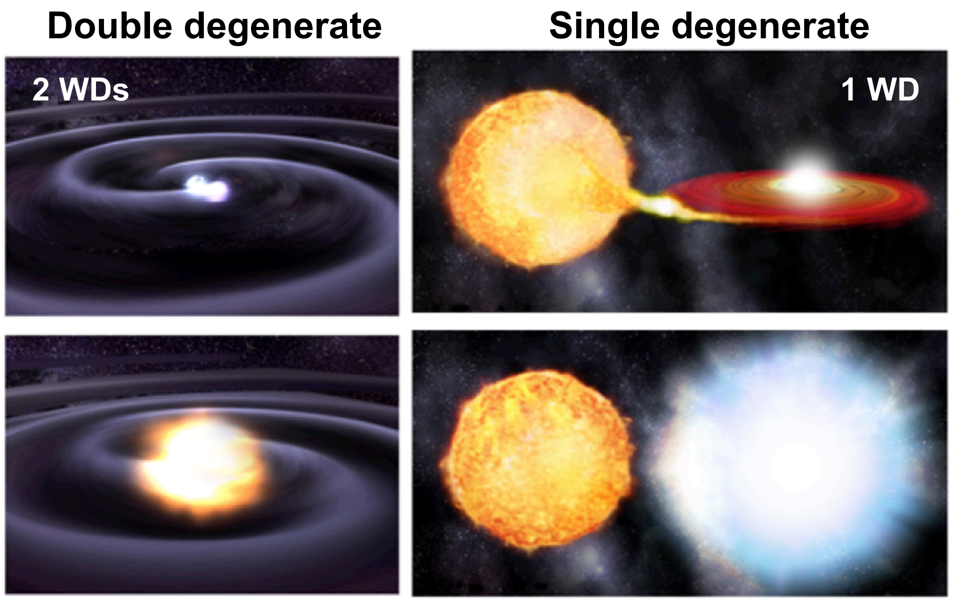


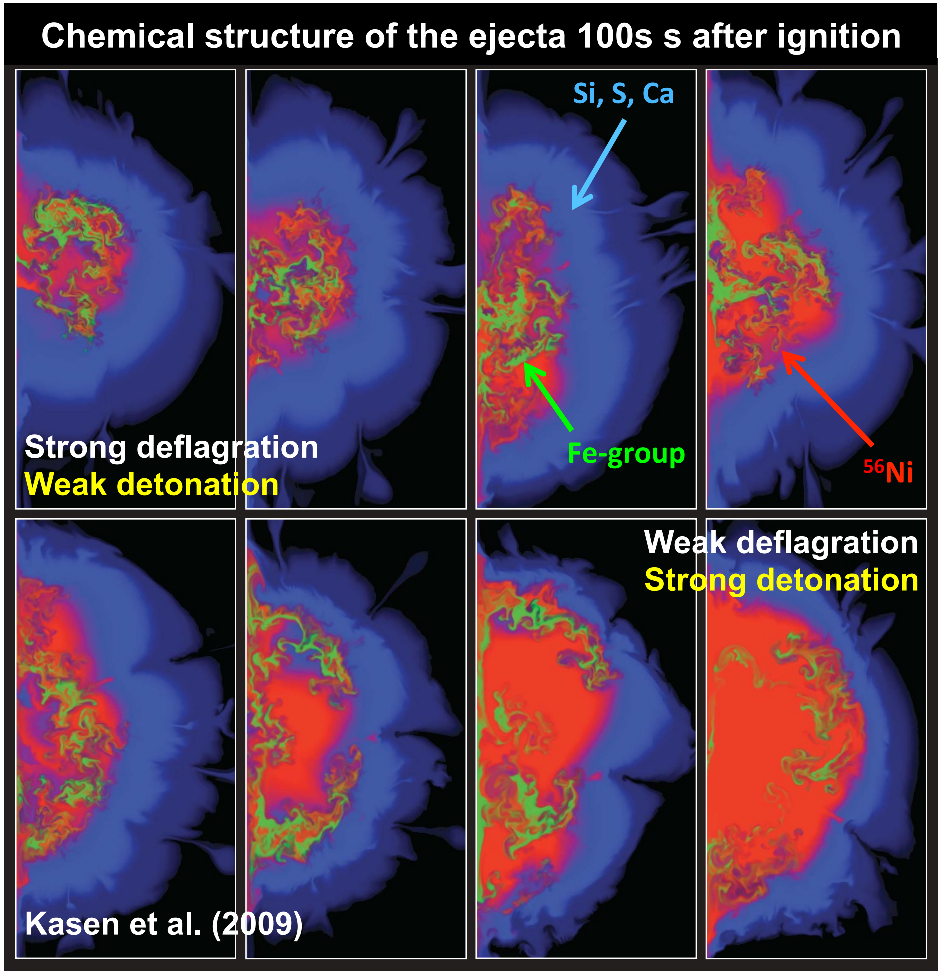


- **Bounce** of the infalling material when ρ_{cent} -> 2.3x10^{14} g/cm^3 = nuclear density
- Outward-moving **shock stalls** as shock energy dissipated in photodesintegration
- **Mechanisms of shock reactivation?** Heating by neutrinos, hydrodynamic instabilities, MHD+rotation mechanism...
- Which fraction of stellar collapses **do not yield a supernova explosion?**

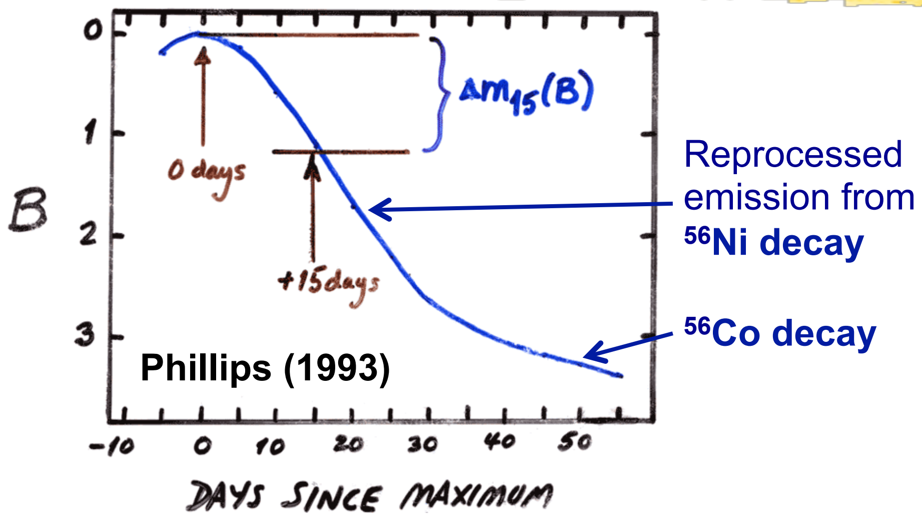
Thermonuclear supernovae

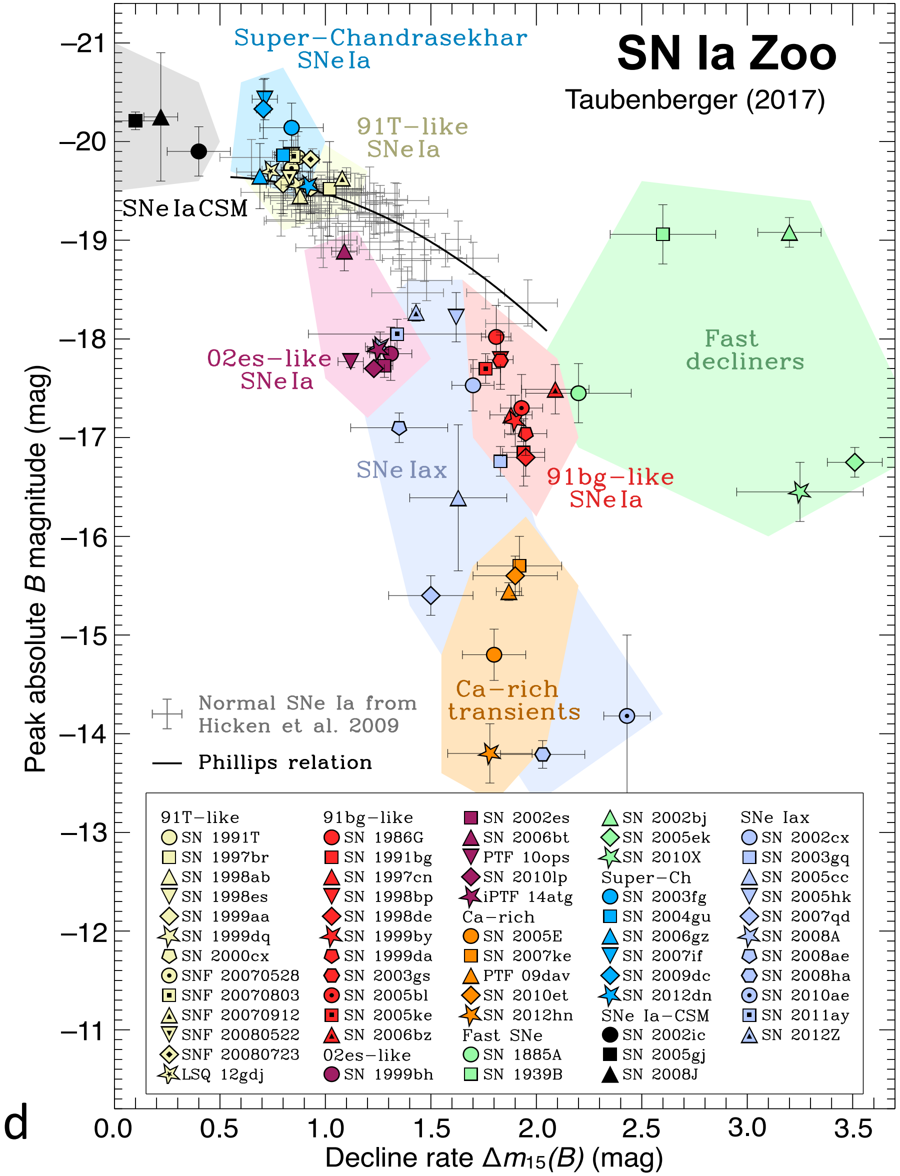
- <u>What we know</u>: thermonuclear explosion of a **carbon-oxygen white dwarf** in a binary system accreting mass from a companion star
- **Nature of the companion?** Another white dwarf or a normal star?
- **Ignition?** Off-centre ? At the surface? WD near the Chandrasekhar mass? He flash in sub-Chandrasekhar WD?
- **Burning front propagation?** Sub-sonic deflagration / Supersonic detonation?





Thermonuclear SNe as standard candles





- **<u>Phillips relation</u>**: brighter SNe (i.e. more ^{56}Ni) have slower declining light curves (higher opacity due to Fe-group elements)

⇒ **Standard candles** for measuring cosmic distances

⇒ **Accelerated expansion of the Universe due to dark energy** (Nobel Prize 2011 for S. Perlmutter, B. P. Schmidt & A. G. Riess)

- But **diversity of Type Ia SNe** not understood

Some important open questions

- **What is (are) the astrophysical site(s) of the r process (synthesis of about 1/3 of the stable nuclei)?**
- **How do massive stars explode?**
- **What are the progenitors and explosion mechanism(s) of thermonuclear supernovae? Can we use them for *precision* cosmology?**

⇒ **Gamma-ray astronomy in the MeV range**

Astronomy with radioactivities

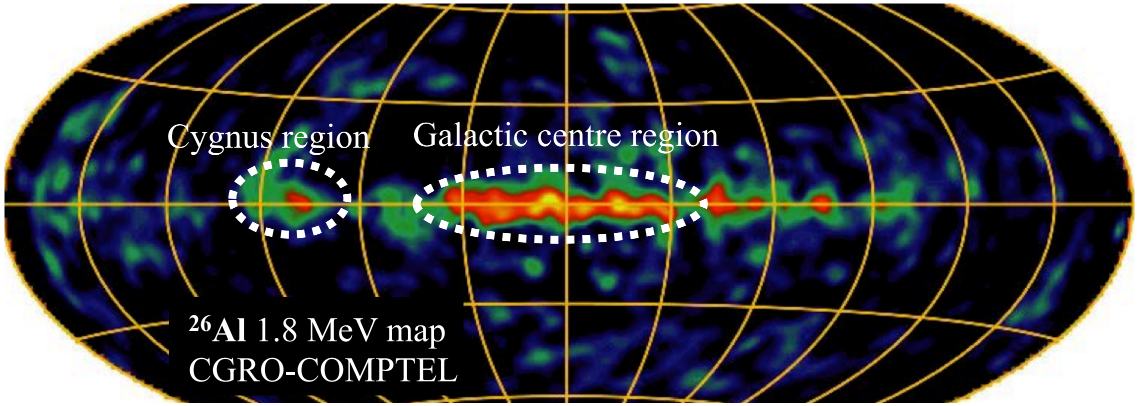
⇒ **Direct view of the central engine** in stellar explosions, stellar yields, mixing in the ISM...

Isotope	Production site	Decay chain	Half-life	γ-ray energy (keV) and intensity
r-process nuclei	Neutron star mergers	β decay, α decay fission	∼ day	∼ 0.1 − 2 MeV
^{7}Be	Novae	$^{7}Be \xrightarrow{\epsilon} {}^{7}Li^*$	53.2 d	478 (0.10)
^{56}Ni	Type Ia SNe, Core-collapse SNe	$^{56}Ni \xrightarrow{\epsilon} {}^{56}Co^*$ $^{56}Co \xrightarrow{\epsilon(0.81)} {}^{56}Fe^*$	6.075 d 77.2 d	158 (0.99), 812 (0.86) 847 (1), 1238 (0.66)
^{57}Ni	Type Ia SNe, Core-collapse SNe	$^{57}Ni \xrightarrow{\epsilon(0.56)} {}^{57}Co^*$ $^{57}Co \xrightarrow{\epsilon} {}^{57}Fe^*$	1.48 d 272 d	1378 (0.82) 122 (0.86), 136 (0.11)
^{22}Na	Novae	$^{22}Na \xrightarrow{\beta^+(0.90)} {}^{22}Ne^*$	2.60 y	1275 (1)
^{44}Ti	Core-collapse SNe, Type Ia SNe	$^{44}Ti \xrightarrow{\epsilon} {}^{44}Sc^*$ $^{44}Sc \xrightarrow{\beta^+(0.94)} {}^{44}Ca^*$	60.0 y 3.97 h	68 (0.93), 78 (0.96) 1157 (1)
^{26}Al	Core-collapse SNe, WR stars AGB stars, Novae	$^{26}Al \xrightarrow{\beta^+(0.82)} {}^{26}Mg^*$	$7.2 \cdot 10^5$ y	1809 (1)
^{60}Fe	Core-collapse SNe	$^{60}Fe \xrightarrow{\beta^-} {}^{60}Co^*$ $^{60}Co \xrightarrow{\beta^-} {}^{60}Ni^*$	$2.6 \cdot 10^6$ y 5.27 y	59 (0.02) 1173 (1), 1332 (1)

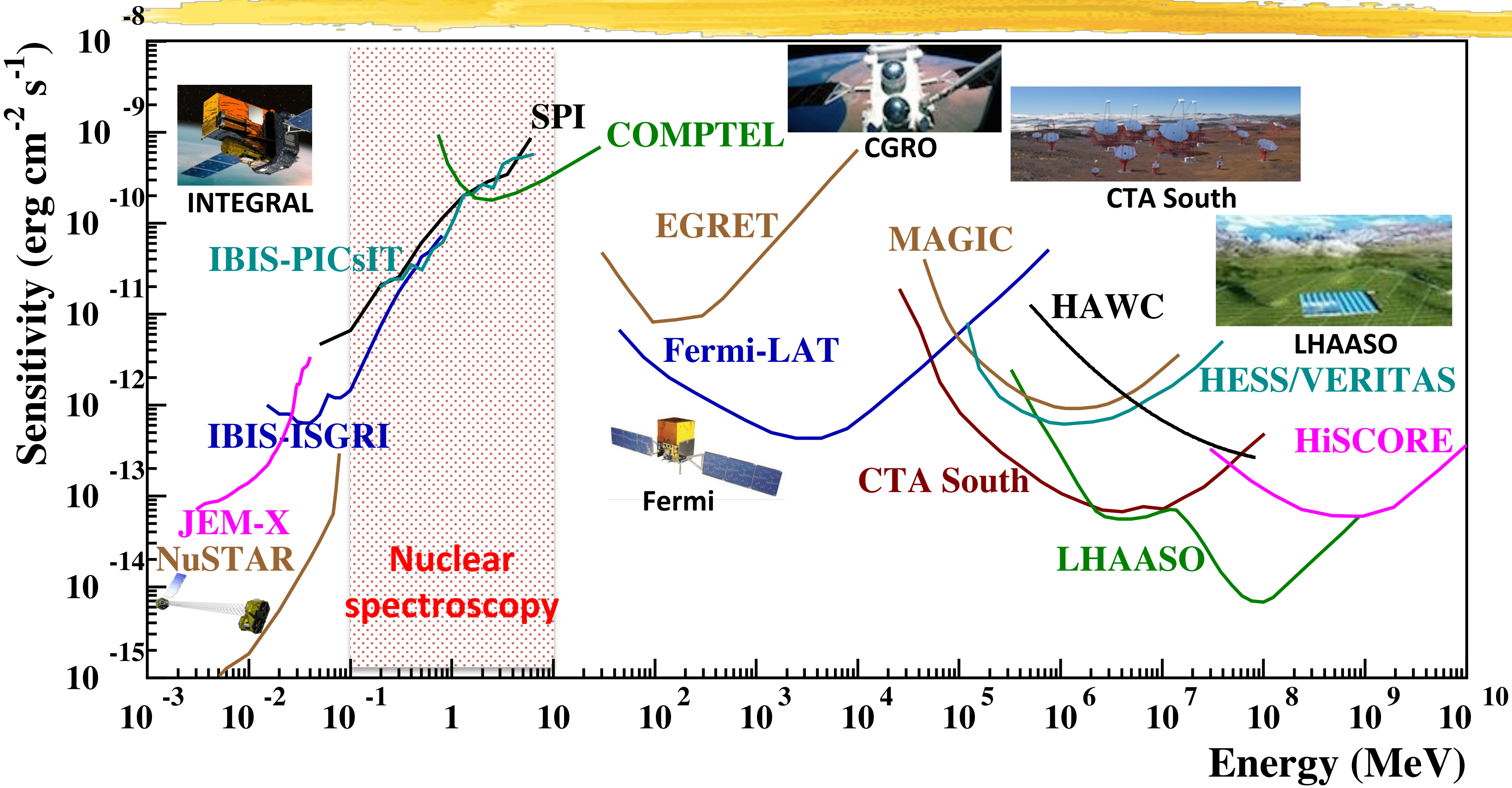
← *C. Fougères's talk*

Individual sources

Diffuse γ-ray emission => sources + ISM

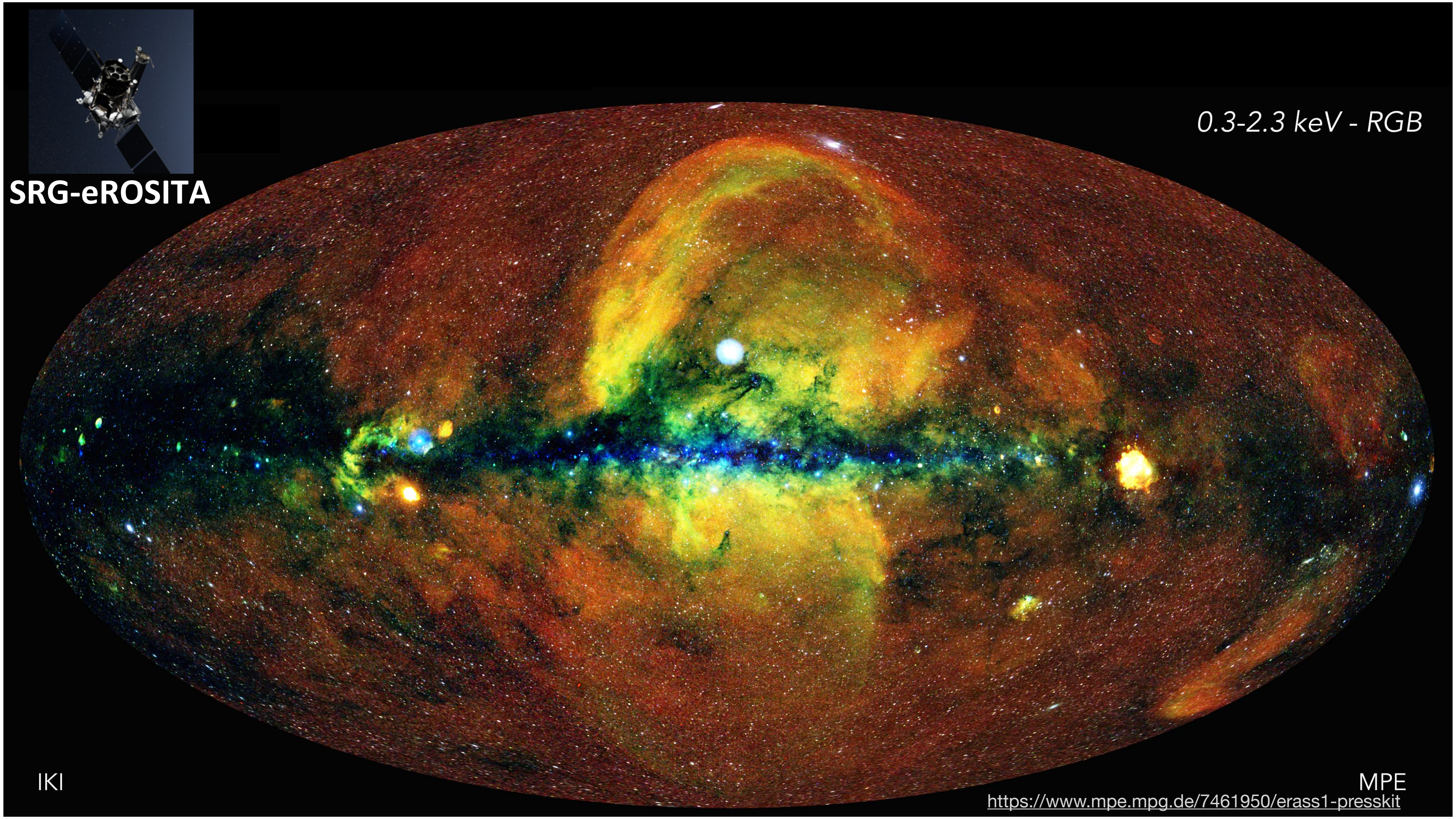


Gamma-ray astronomy in the MeV domain

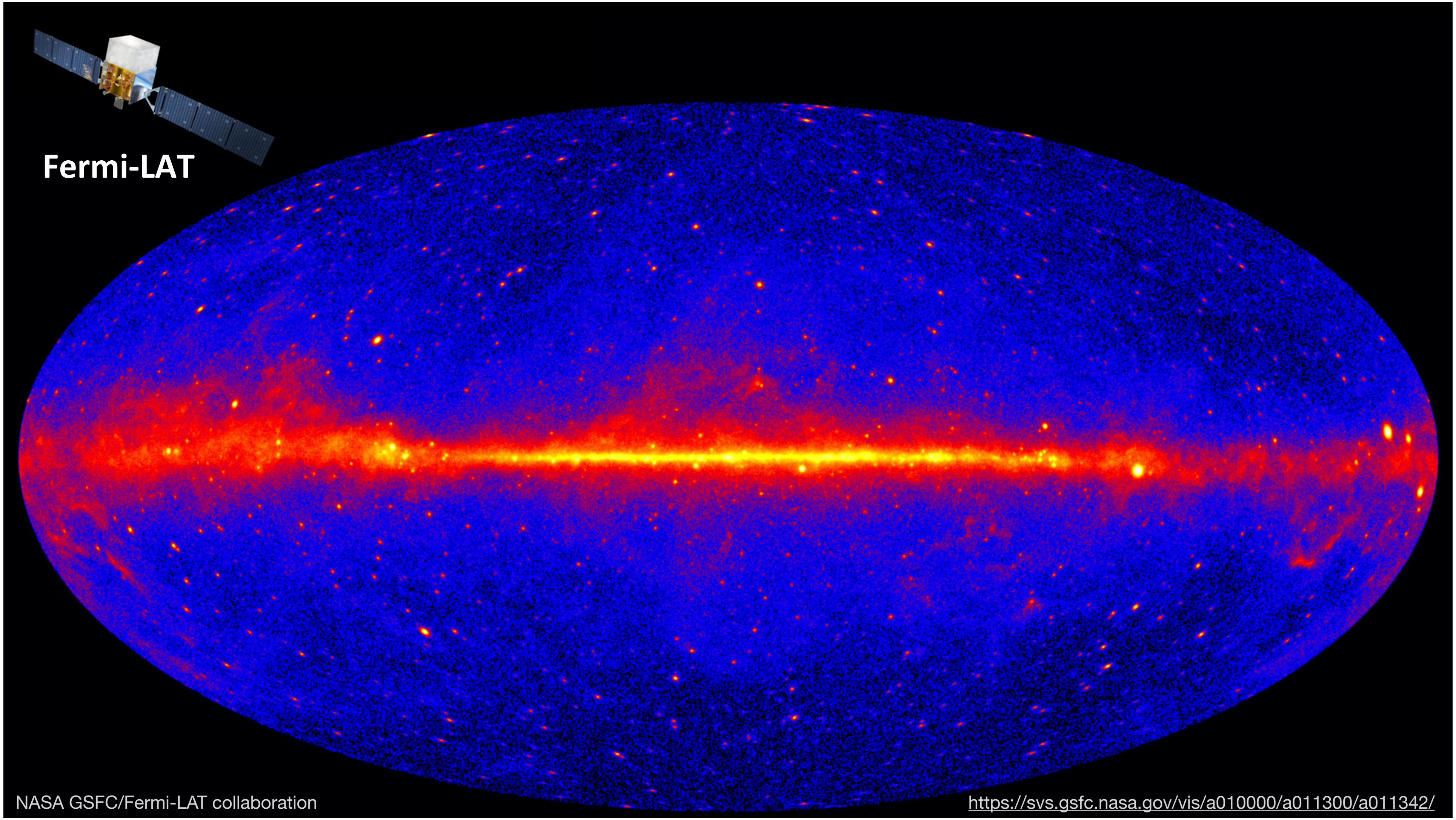


- **Worst covered part of the EM spectrum** (only a few tens of known steady sources so far between 0.5 and 30 MeV vs. 5500+ sources in the current Fermi/LAT catalog)
- Domain of **nuclear spectroscopy**
- Many objects have their **peak emissivity** in this range (GRBs, blazars, pulsars...)

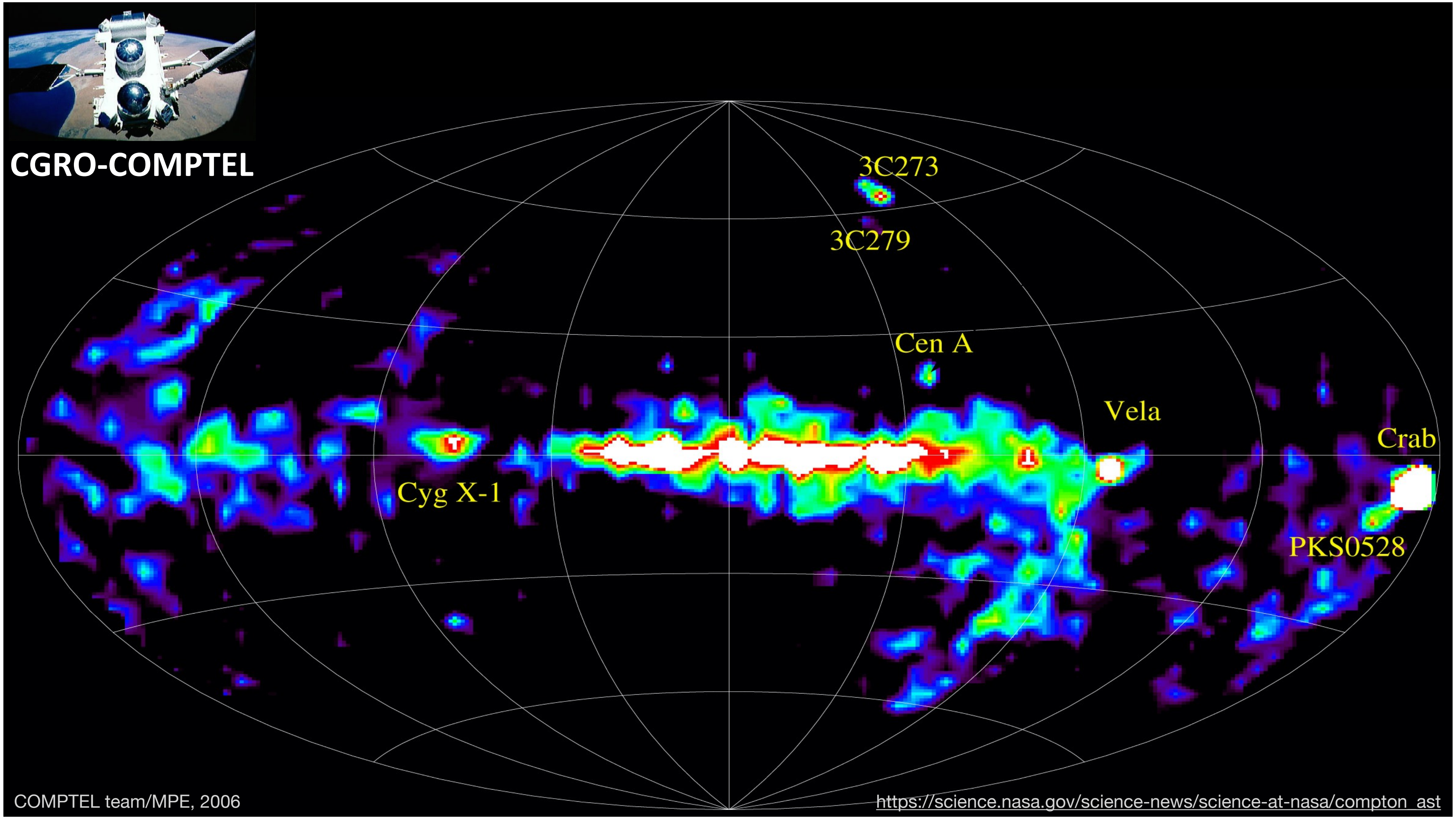
X-ray sky in the keV range



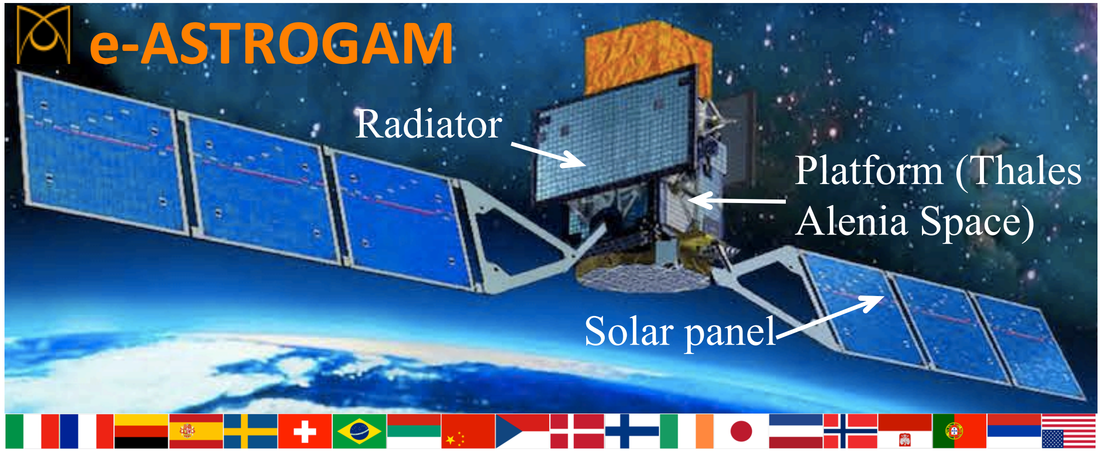
Gamma-ray sky > 1 GeV

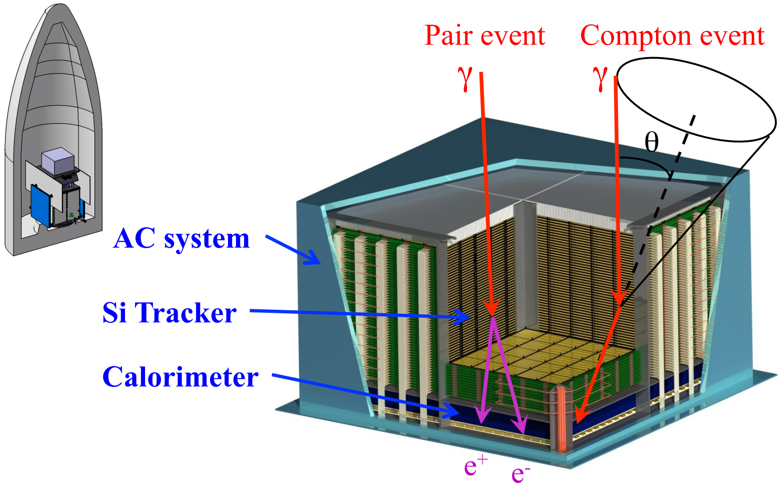


Gamma-ray sky in 1 - 30 MeV

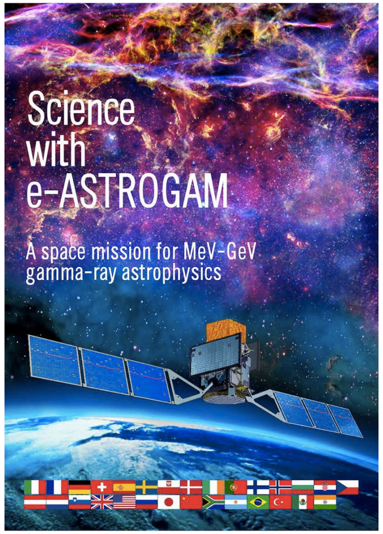


Gamma-ray mission proposed to ESA in 2017



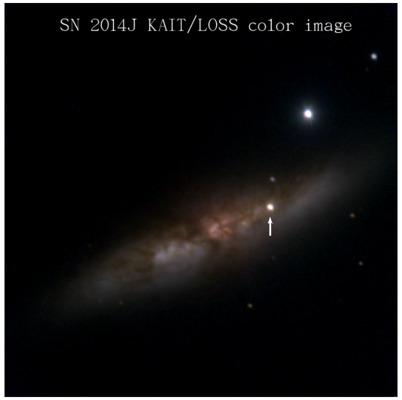


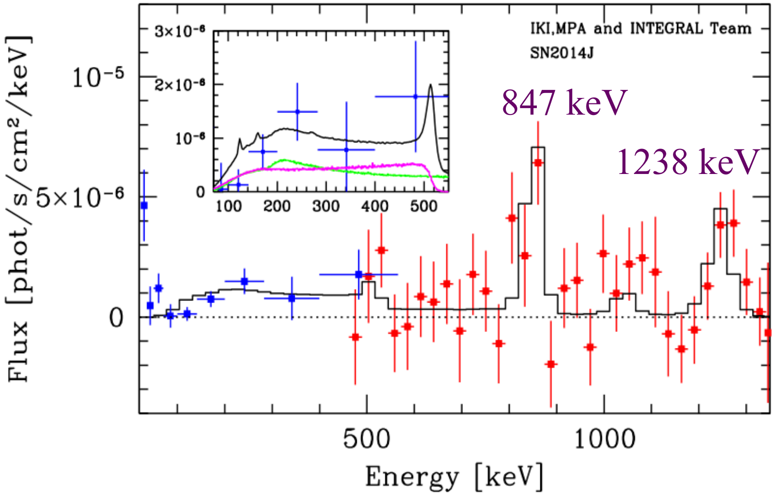
- **<u>Science White Book</u>** (245 authors), see https://arxiv.org/abs/1711.01265

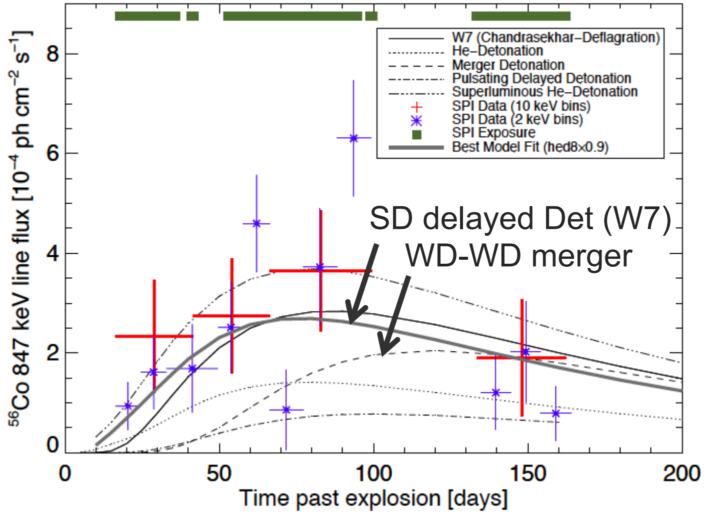


E (keV)	FWHM (keV)	Origin	SPI sensitivity (ph cm^{-2} s^{-1})	e-ASTROGAM sensitivity (ph cm^{-2} s^{-1})	Improvement factor
511	1.3	Narrow line component of the e+/e- annihilation radiation from the Galactic center region	5.2×10^{-5}	4.1×10^{-6}	13
847	35	^{56}Co line from thermonuclear SN	2.3×10^{-4}	3.5×10^{-6}	66
1157	15	^{44}Ti line from core-collapse SN remnants	9.6×10^{-5}	3.6×10^{-6}	27
1275	20	^{22}Na line from classical novae of the ONe type	1.1×10^{-4}	3.8×10^{-6}	29
2223	20	Neutron capture line from accreting neutron stars	1.1×10^{-4}	2.1×10^{-6}	52
4438	100	^{12}C line produced by low-energy Galactic cosmic-ray in the interstellar medium	1.1×10^{-4}	1.7×10^{-6}	65

SN 2014J: first SN Ia detected in γ rays



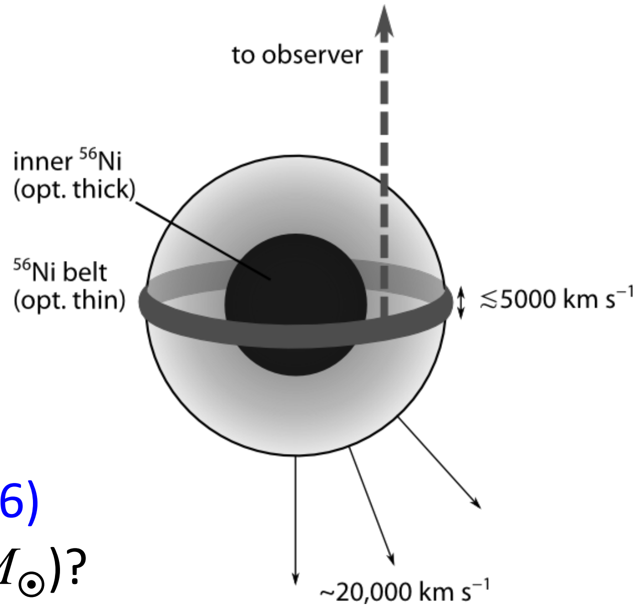




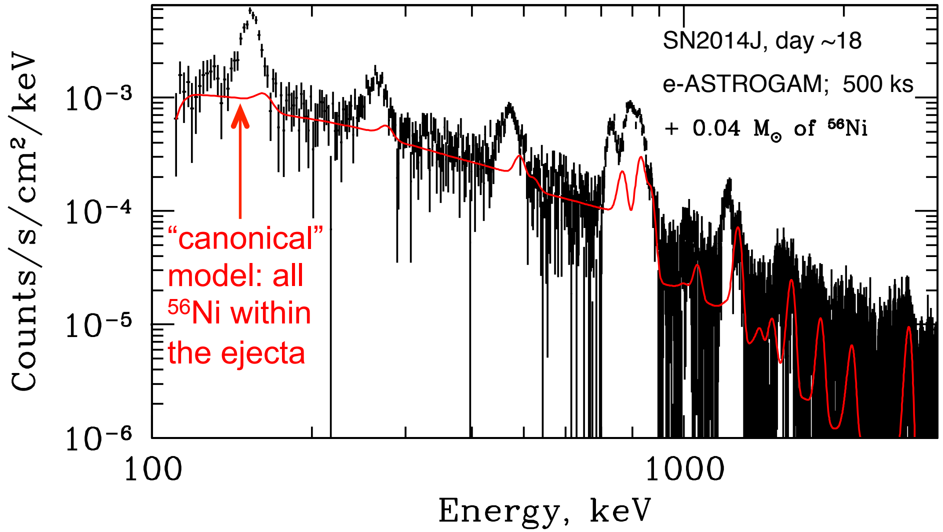
- Nearest thermonuclear supernova in last 50 years, occurred in the starburst galaxy M82 at $D = 3.5$ Mpc

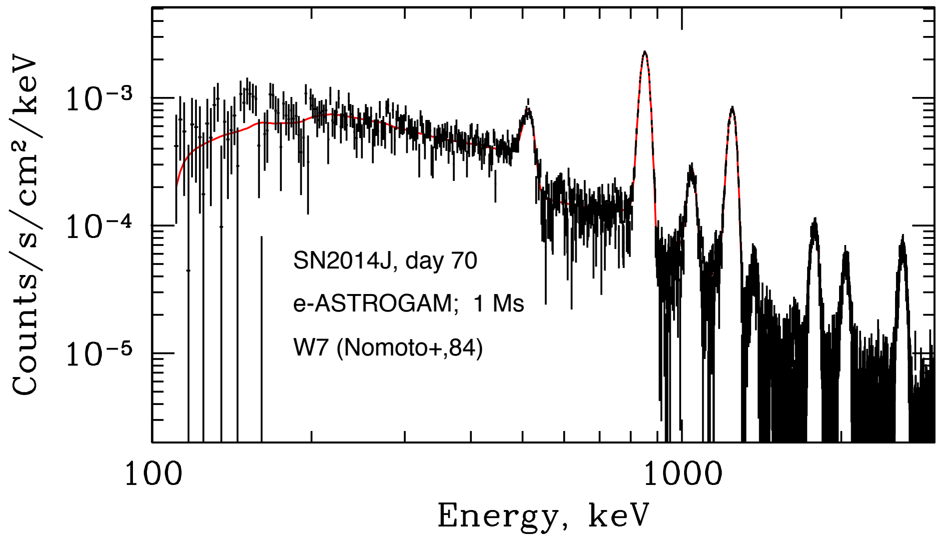
- *INTEGRAL* detection of the ^{56}Co ($T_{1/2}$=77 d) γ-ray lines
  ⇒ synthesis of 0.6 ± 0.1 $M_\odot$ of ^{56}Ni in the explosion
  (Churazov et al. 2014, 2015; see also Diehl et al. 2015)

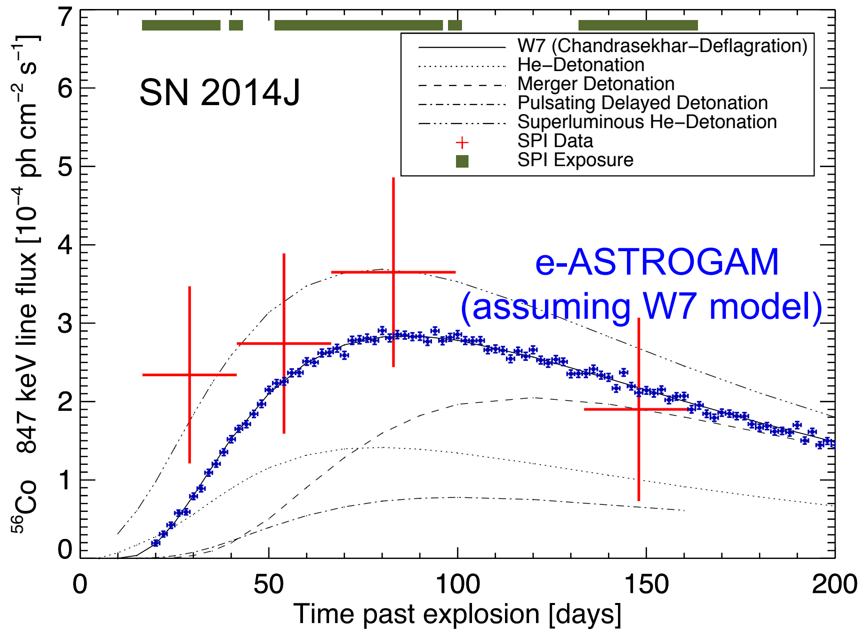
- Unexpected detection of the ^{56}Ni ($T_{1/2}$=6.1 d) γ-ray lines
  ~ 20 d after the explosion (Diehl et al. 2014; Isern et al 2016)
  ⇒ Surface explosion? High-speed plume of ^{56}Ni (~0.05 $M_\odot$)?



Thermonuclear SNe with e-ASTROGAM



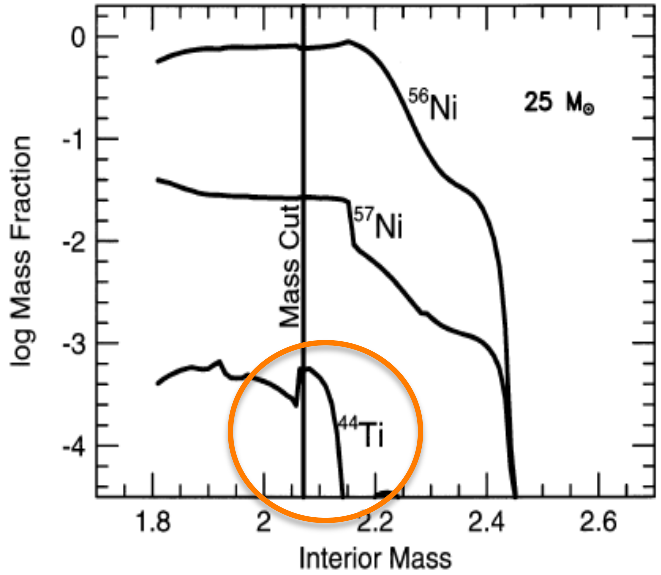


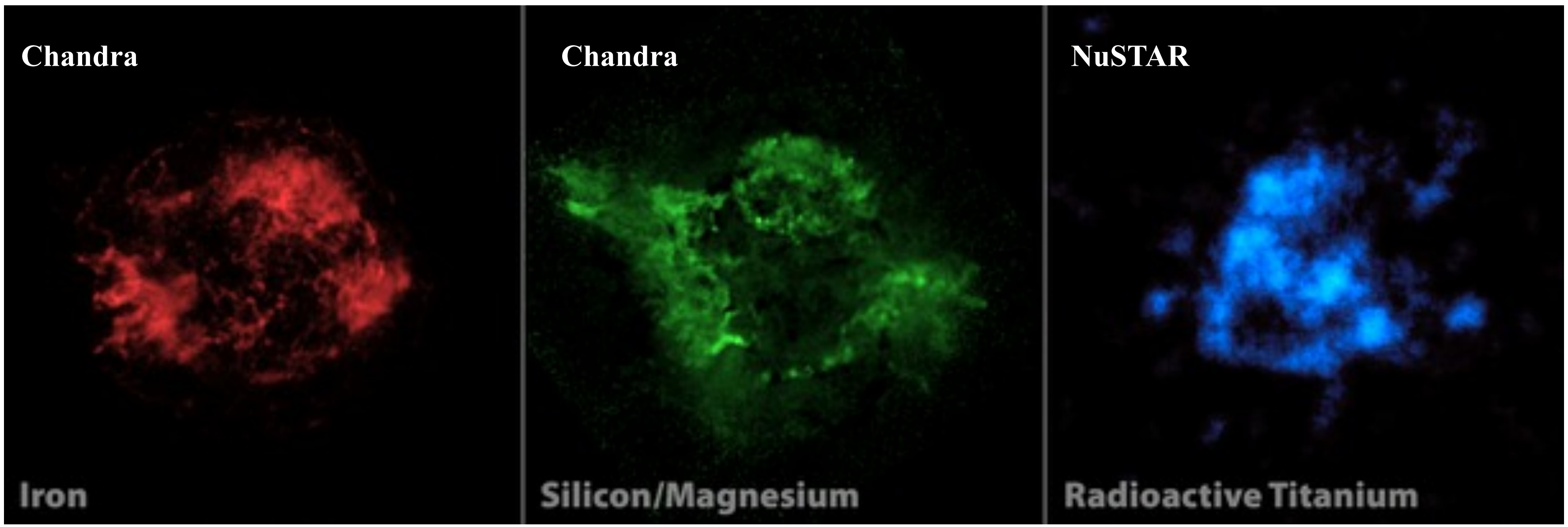


- For events like SN 2014J, **e-ASTROGAM** would detect **very small amount of ^{56}Ni** at the surface (~2x10^{-3} $M_{\odot}$) and clearly identify the **explosion asymmetry**
- **e-ASTROGAM** should detect **15 - 20 SN Ia in 5 years** up to a distance of ~ 35 Mpc, thus elucidating the nature of the Phillips relation for **precision cosmology**

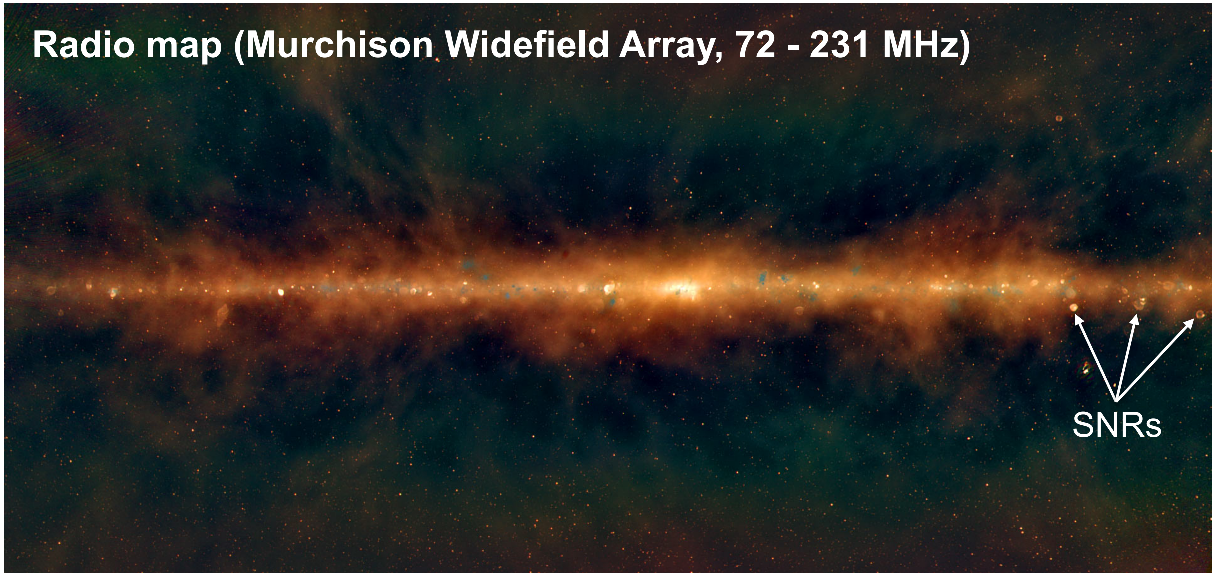
Radioactivites from core-collapse supernovae

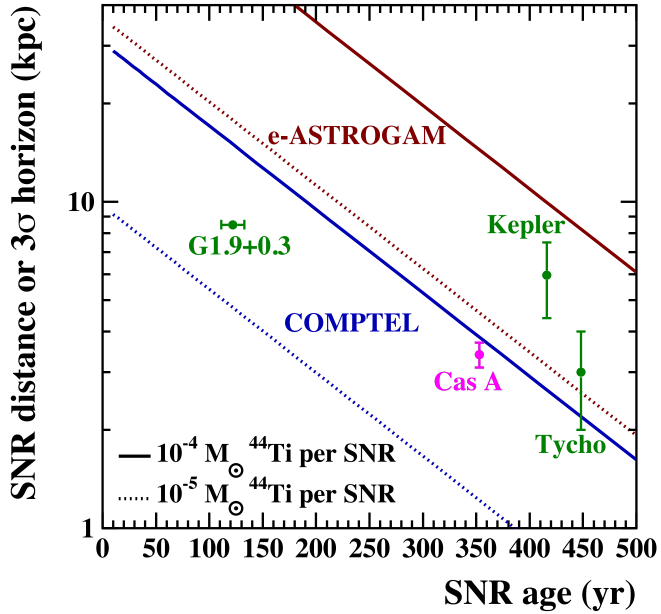
- **e-ASTROGAM** should detect the ^{56}Ni decay chain in **rare core-collapse events** such as **pair-instability supernovae** and **magnetar-powered jet explosions**
- ^{44}Ti expected from **~10 young supernova remnants** ⇒ **unique probe of the explosion mechanism**
- ***NuSTAR****'s* mapping of radioactivity in Cas A SNR: explosion asymmetries probably caused by **low-mode convective instabilities** (Grefenstette et al. 2014, 2017)





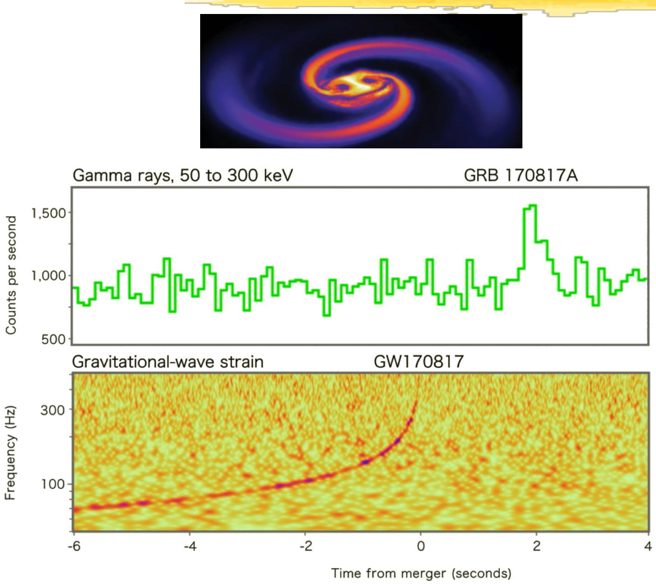
Supernova history in the Milky Way

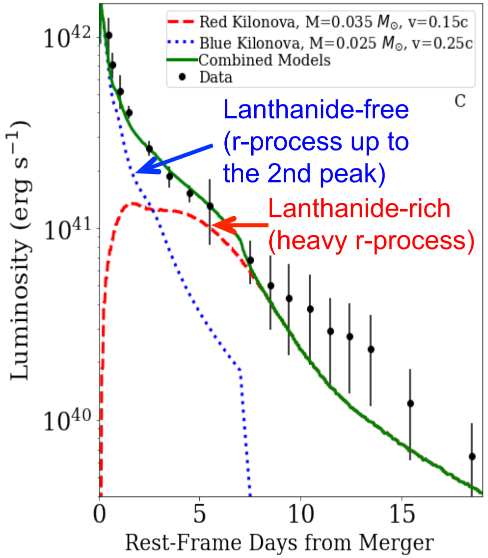


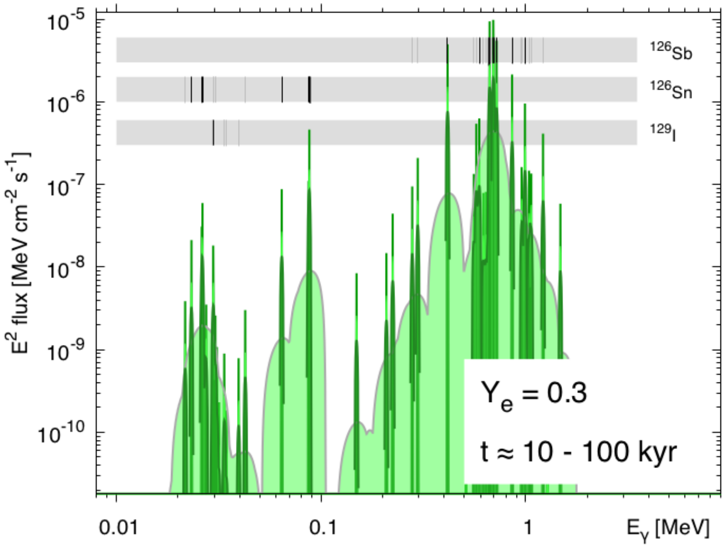


- ~300 SN remnants have been identified in the Milky Way, 4 being less than 500 years old: 3 SNe Ia (G1.9+0.3, Kepler, Tycho) and **only 1 core-collapse SN (Cassiopea A)**
- CCSN rate (estimated from ^{26}Al mass, 2.8 ± 0.8 $M_\odot$): ~2 per century => **~10 in 500 yrs**
- With **e-ASTROGAM**, **missing SN remnants** (probably hidden in highly obscured clouds) could be **uncovered by their ^{44}Ti emission**
- Mass of ^{44}Ti ejected in Cas A (only Galactic SNR detected so far): (1.2 – 2) × 10^{-4} $M_\odot$
- Expected ^{44}Ti production in CCSNe: 10^{-5} to 2 × 10^{-4} $M_\odot$

Neutron star mergers and kilonovae







- **GW170817** (LIGO & Virgo) associated with the **short GRB** 170817A (*Fermi* and *INTEGRAL*) & the optical/NIR transient AT2017gfo => **kilonova** (powered by radioactivity of r-nuclei)
- **e-ASTROGAM** would detect **~60 sGRB per year**, and localize them to within ~2 square degrees to **initiate observations at other wavelengths**
- **Prompt γ-ray line emission** from a kilonova detectable to a distance of ~**10 Mpc**
- Delayed γ-rays (^{126}Sn, fission) detectable from a **10-100 kyr old remnant in the Galaxy**

  (see Li 2019; Wu et al. 2019; Korobkin et al. 2020; Wang et al. 2020...)

Conclusions

Future gamma-ray space observatory can shed light on several important questions for nucleosynthesis:

- What is (are) the astrophysical site(s) of the **r process**?
- How do **massive stars** explode?
- What are the progenitors and explosion mechanism(s) of **thermonuclear supernovae** (cosmology)?
- What is the contribution of **novae** to the chemical enrichment of the Milky way?
- ...

Cross section measurements of key nuclear reactions are needed to make the most of current and future gamma-ray observations, e.g. $^{22}Na(p,\gamma)^{23}Mg$, $^{25}Al(p,\gamma)^{26}Si$, $^{59}Fe(n,\gamma)^{60}Fe$...