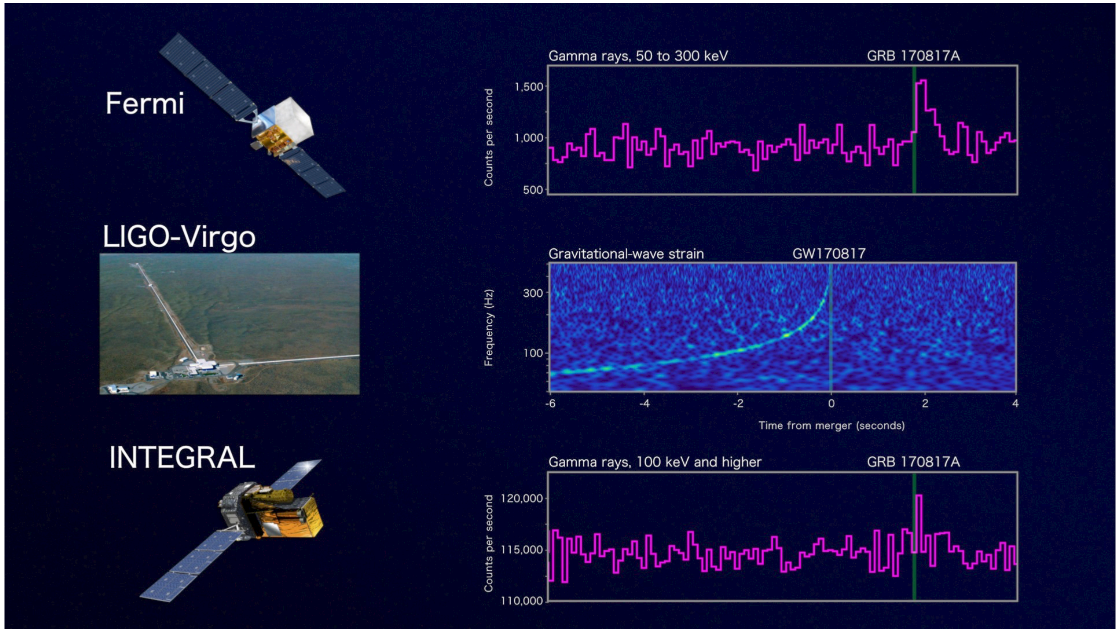
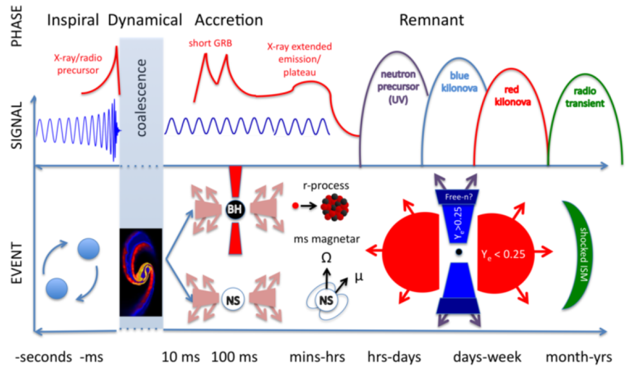
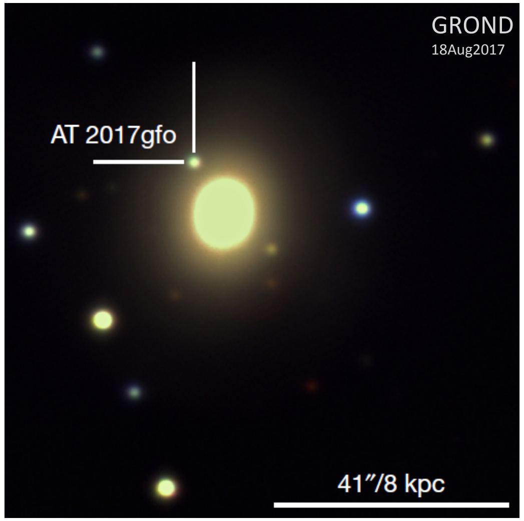
γ-Rays from Gravitational-Wave Source GW170817

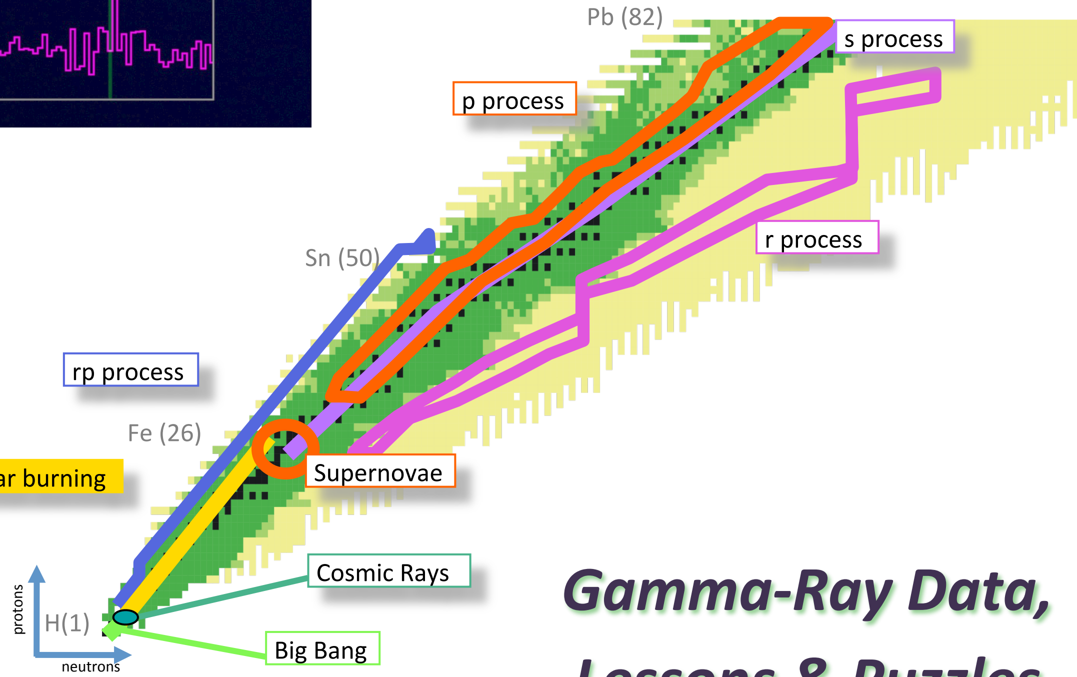


Roland Diehl

(MPE Garching, Germany)







'ESO obs planning of future GW events', Jan 31/Feb 1, 2018

Gamma-Ray Data, Lessons & Puzzles

Outline

Gamma Ray Telescopes
for GW Transients

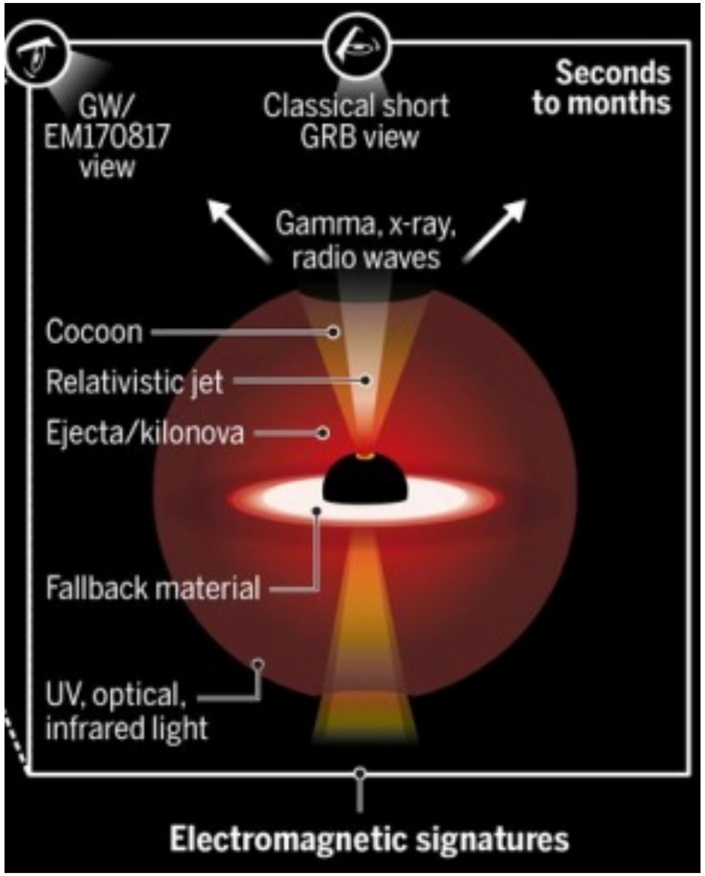
- ☆ Fermi-GBM
- ☆ INTEGRAL

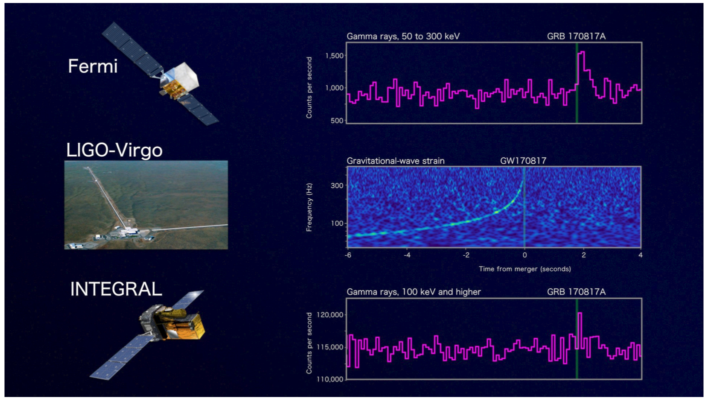
Challenges in Data Analysis

- ☆ Backgrounds
- ☆ Responses
- ☆ Analysis Approaches/Alternatives

Characteristics of Observations
and of Constraints from Gamma-Rays

- ☆ Transient Detection
- ☆ Intensity Constraints
- ☆ Timing Constraints
- ☆ Spectral Constraints



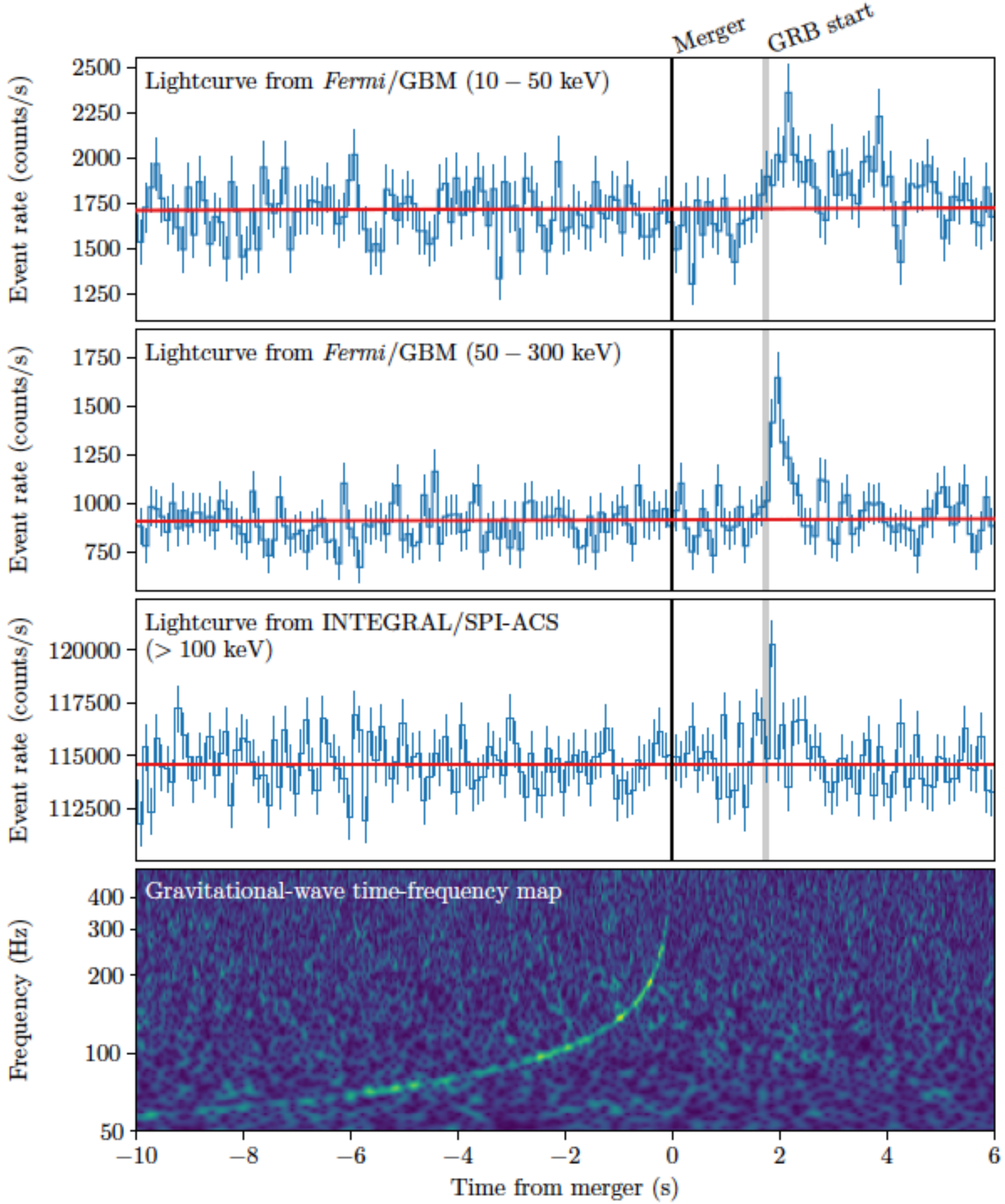


GW170817/GRB170817A

gamma rays

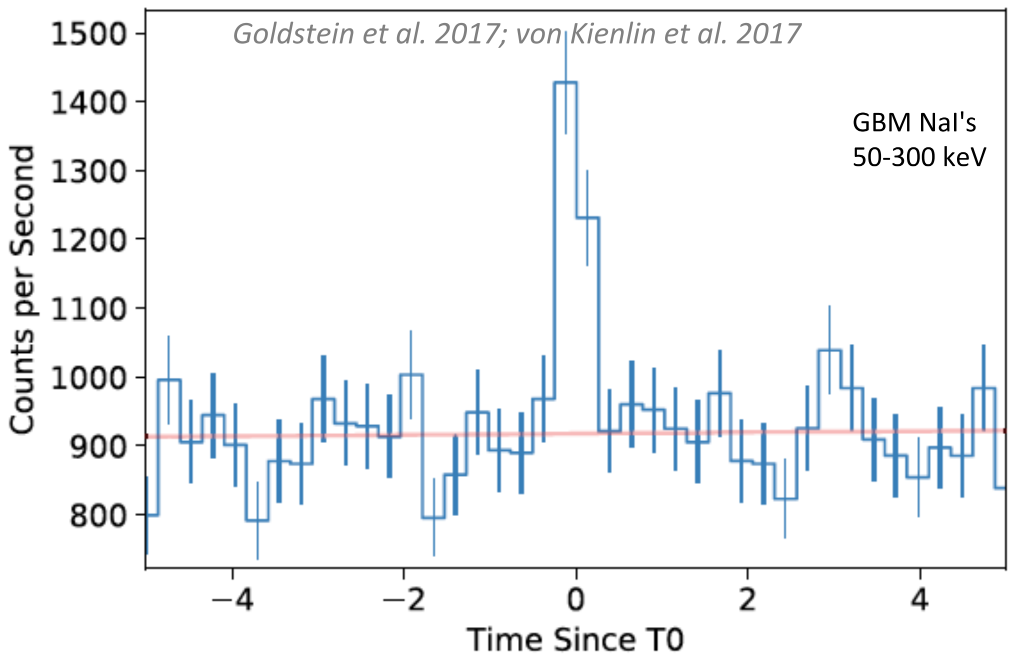
and

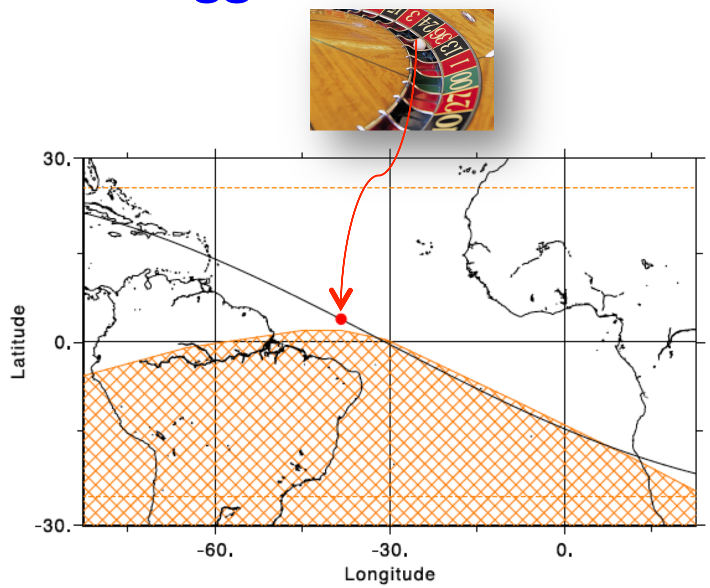
gravitational waves

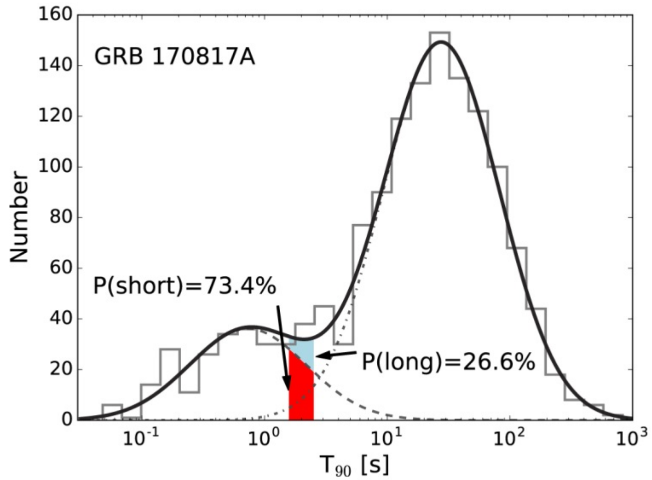


Fermi-GBM γ-ray measurements of GRB 170817A

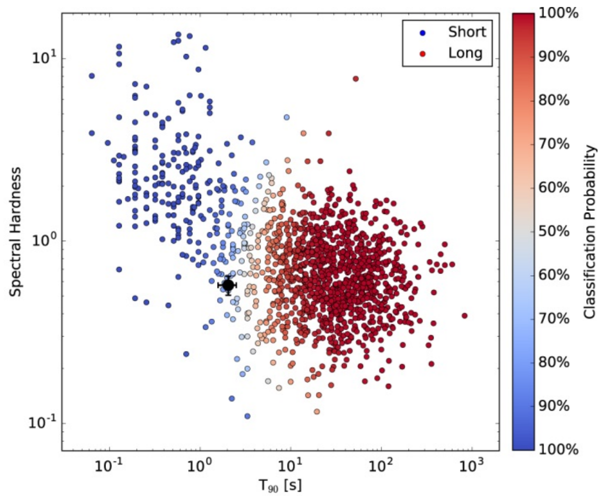
GRB 170817A: a ~normal/common short GRB trigger







(a)



(b)

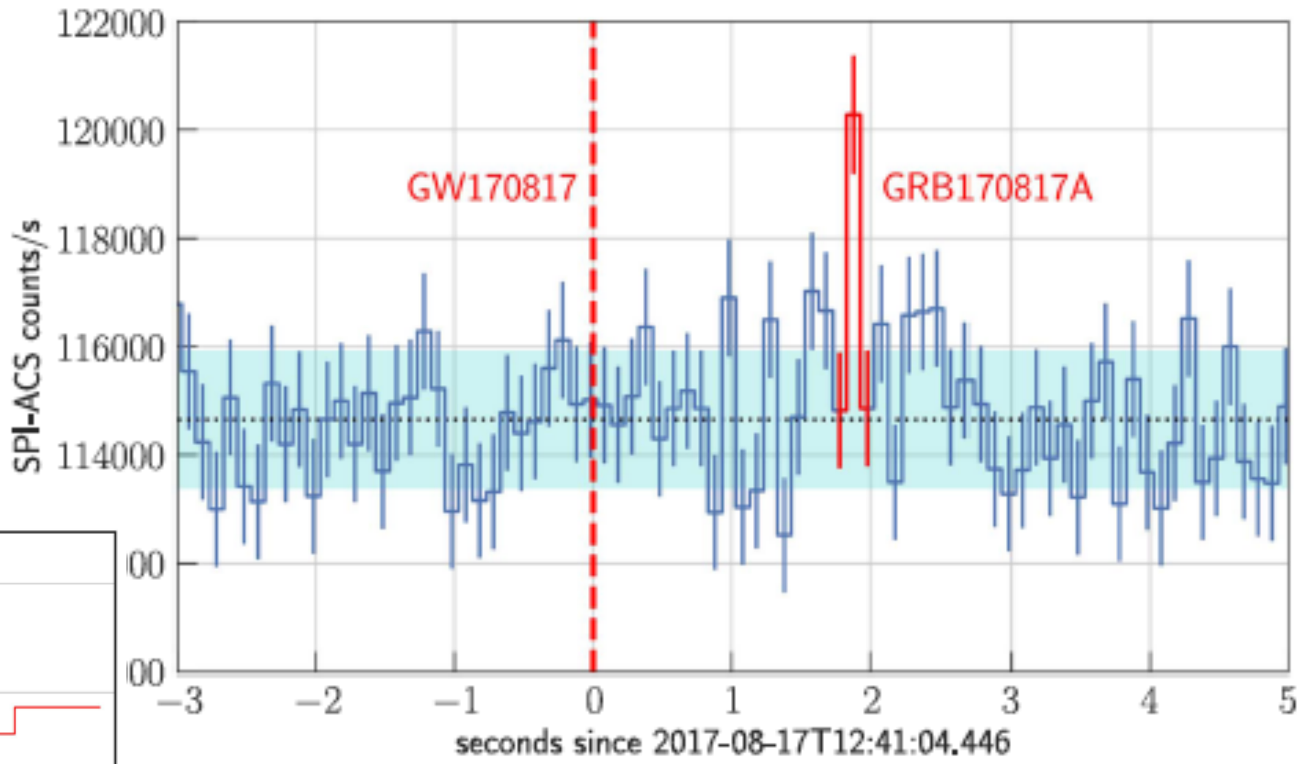
- Duration rather long
- Spectrum on the soft side

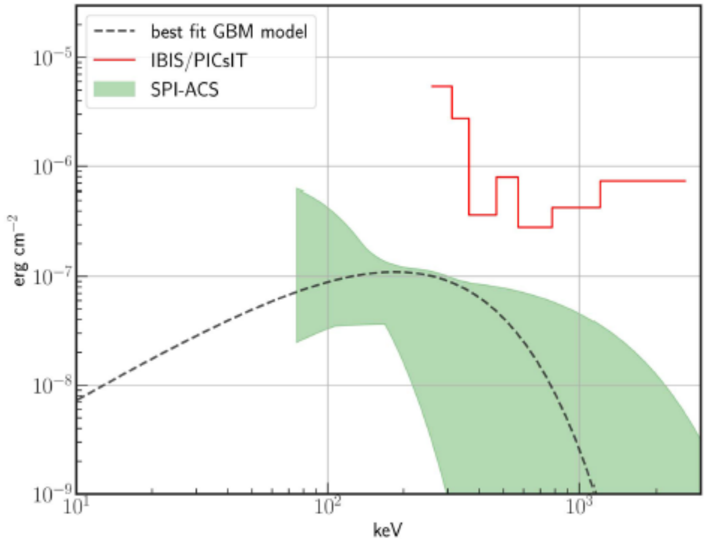
INTEGRAL γ-ray measurements of GRB 170817A

GRB 170817A also seen with SPI/ACS!

- timing with **50 ms** precision
- spectral shape consistent with GBM's suggested one

Savchenko et al. 2017





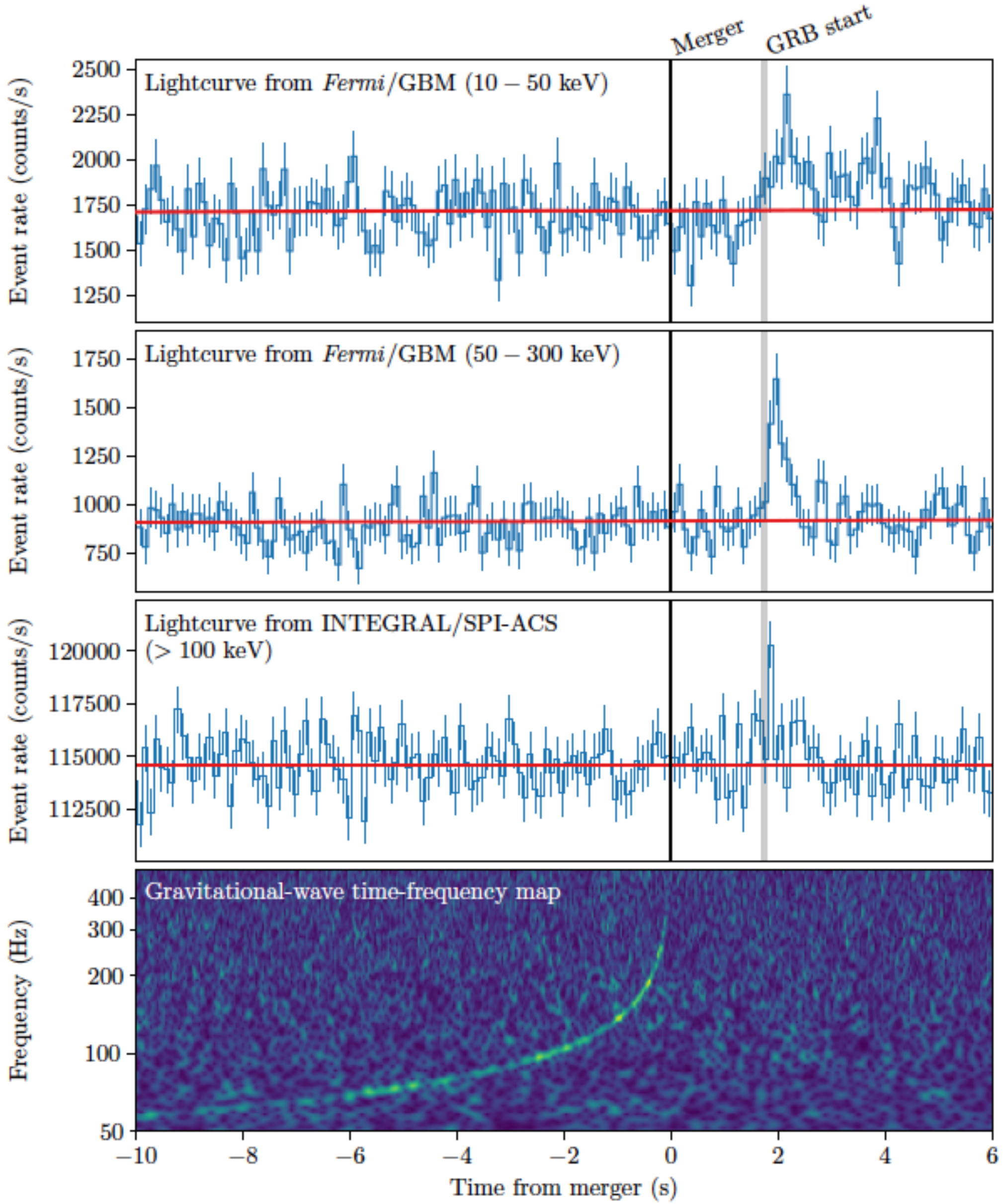
GW170817/GRB170817A

~coincidence

Δ~1.88 sec

→

sGRBs=NSMs(?)



The Gamma-Ray Burst Monitor (GBM) on the FERMI Mission

Germany (MPE, Jena-Optronik) and U.S. (NASA/MSFC)

12 Sodium Iodide NaI(TL) scintillation detectors

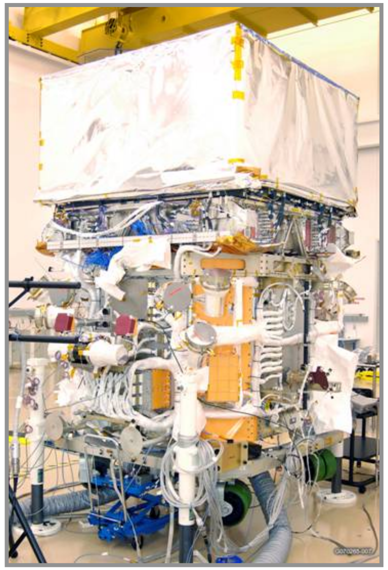
- ☆ Wide Field of View
- ☆ Burst Trigger
- ☆ Cover typical GRB spectrum: 8 – 1000 keV

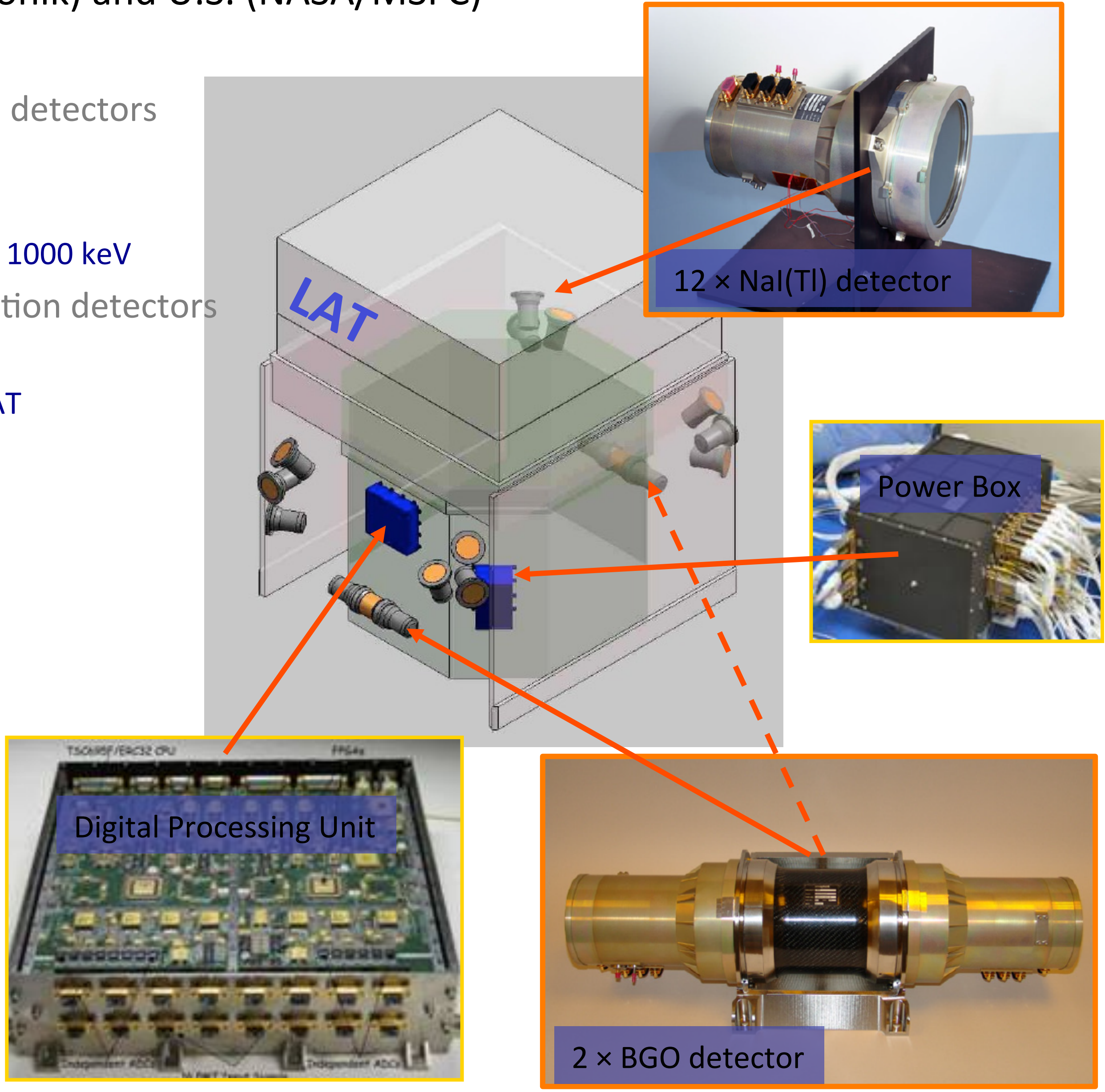
2 Bismuth Germanate (BGO) scintillation detectors

- ☆ Energy range: 150 keV-40 MeV
- ☆ Spectral overlap with NaI and LAT

1 Power Box (PB)

1 Digital Processing Unit (DPU)

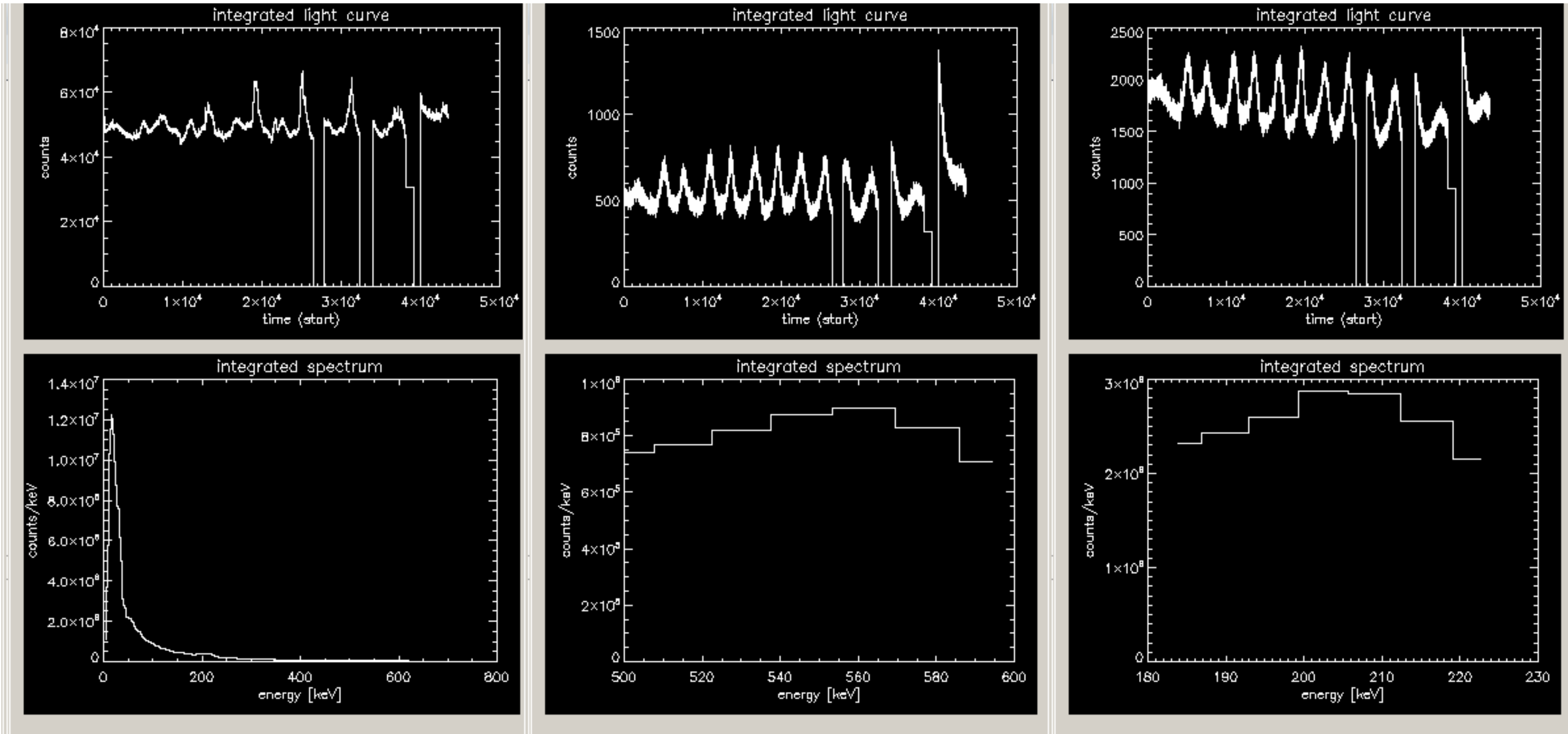




Data from Fermi/GBM

typically dominated by background from cosmic-ray activations

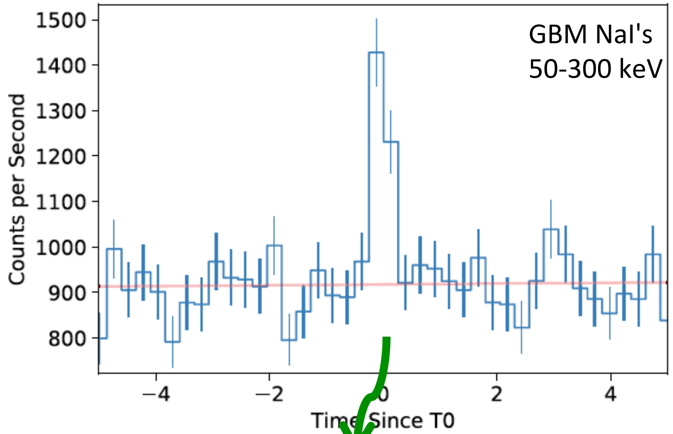
☞ one day of data:



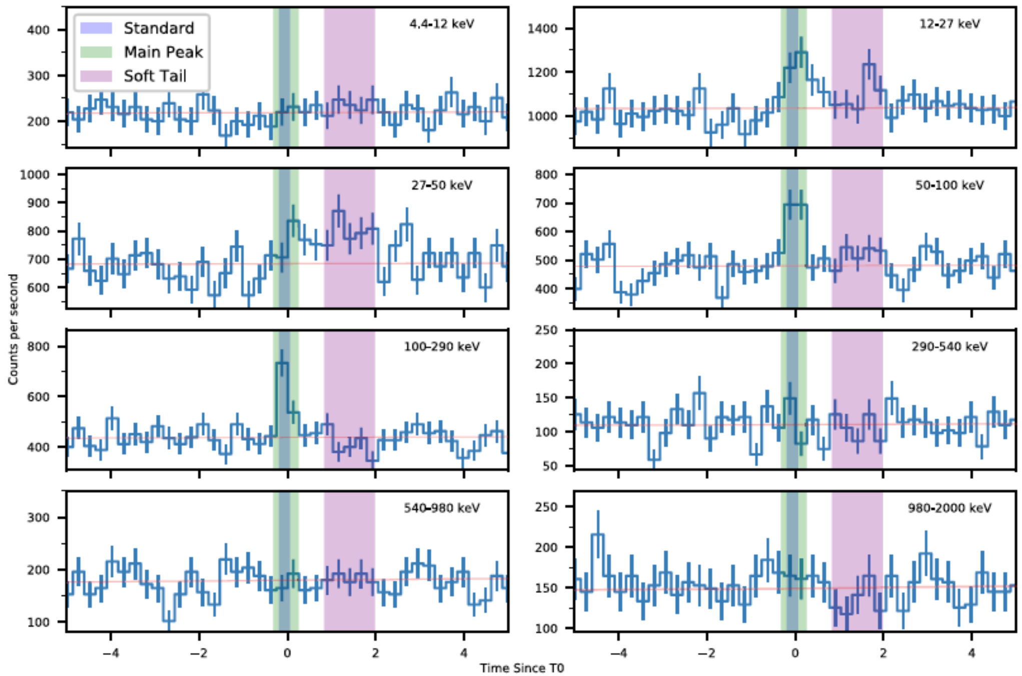
Fermi-GBM γ-ray measurements of GRB 170817A

GRB 170817A: a ~normal/common short GRB trigger

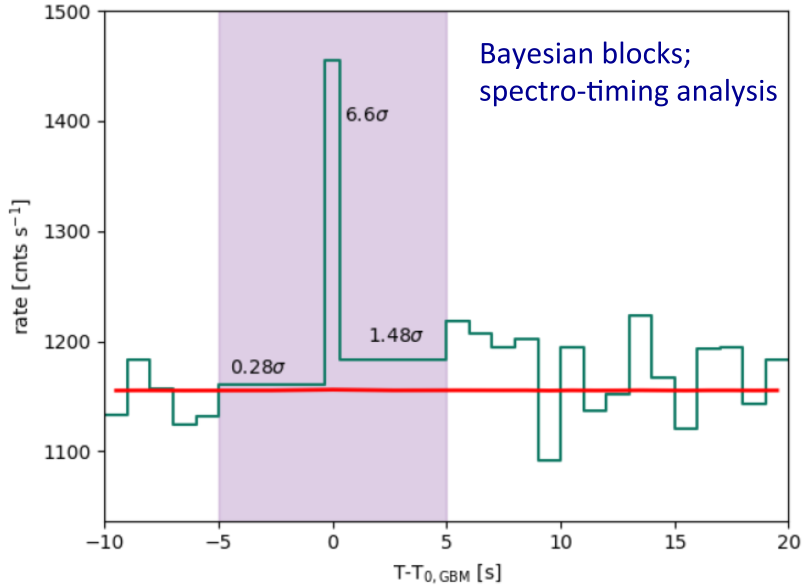
Goldstein et al. 2017



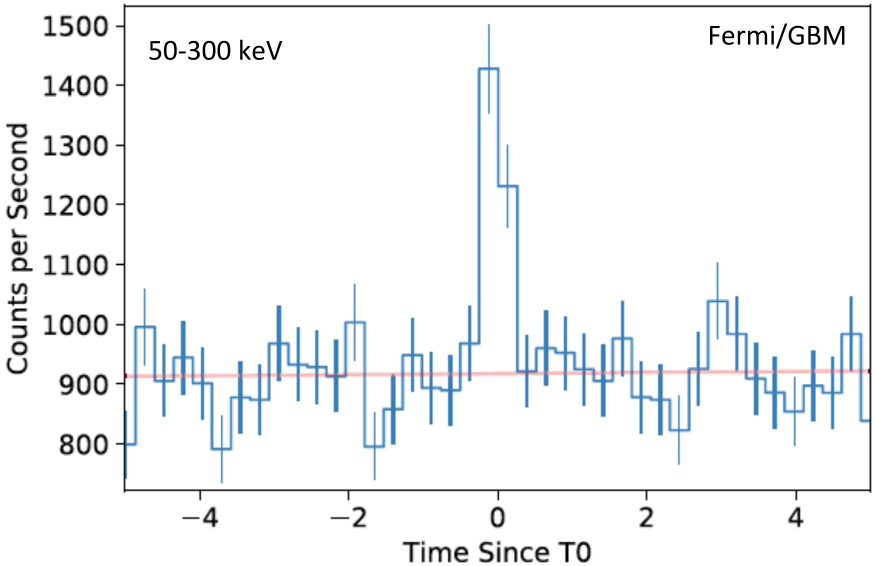
- Duration rather long
- Spectrum very soft
- a "soft tail?"

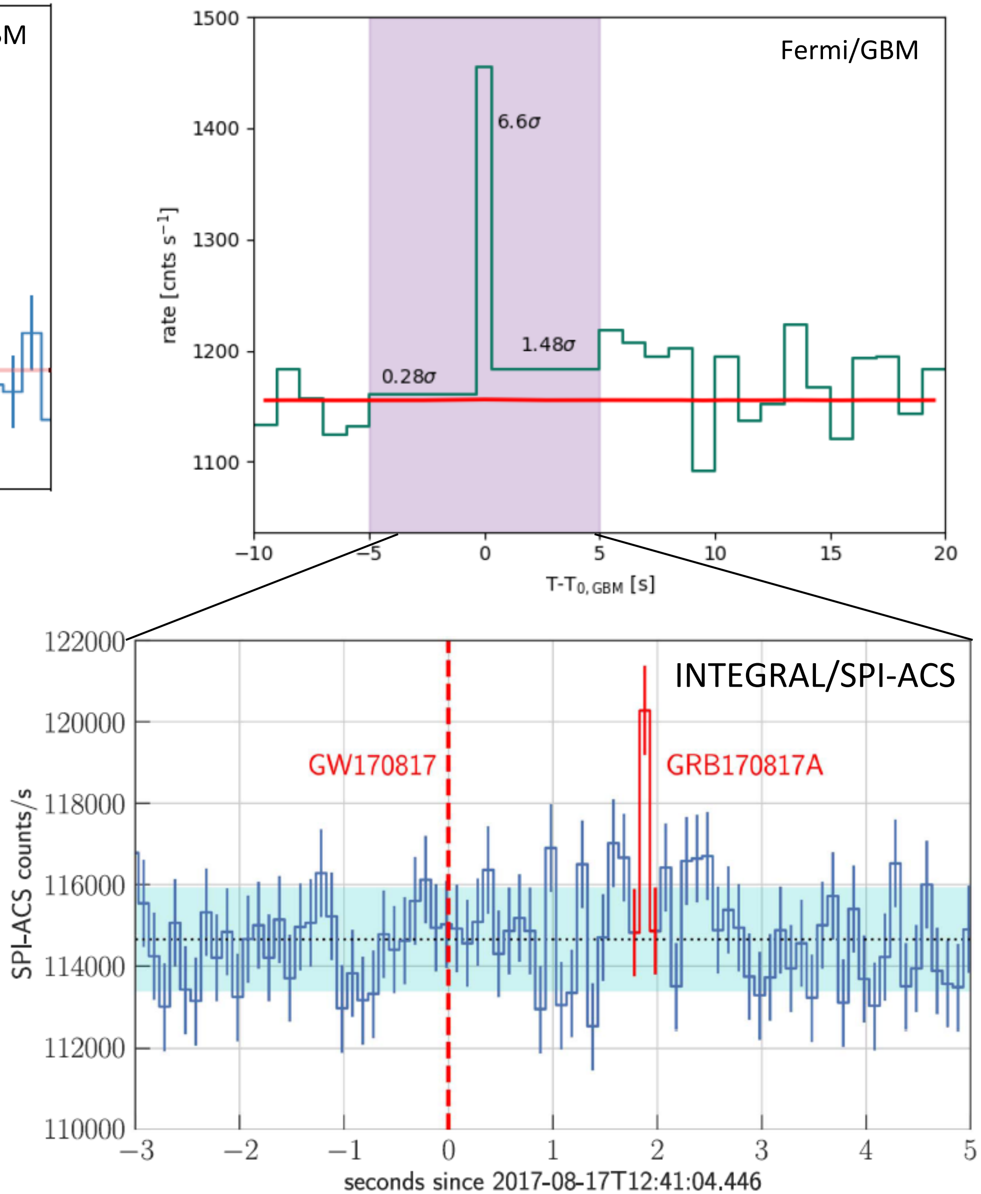


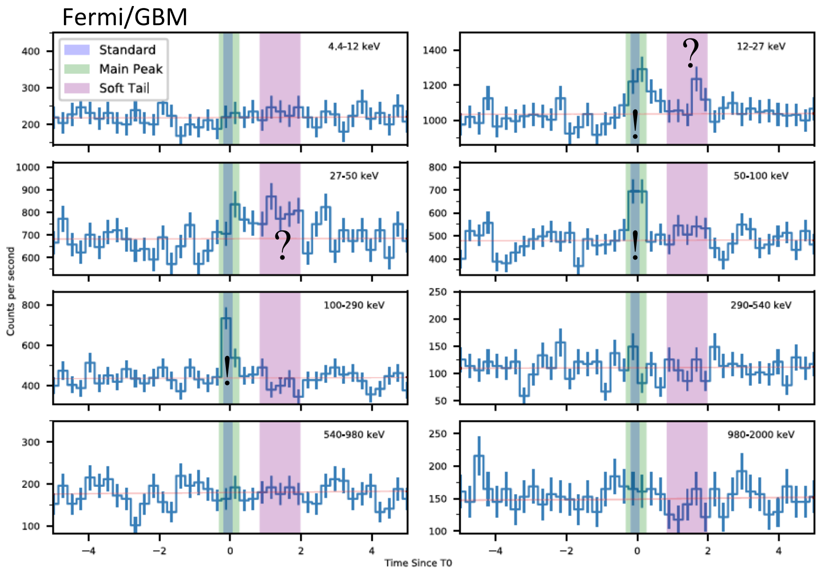
Burgess et al. 2017



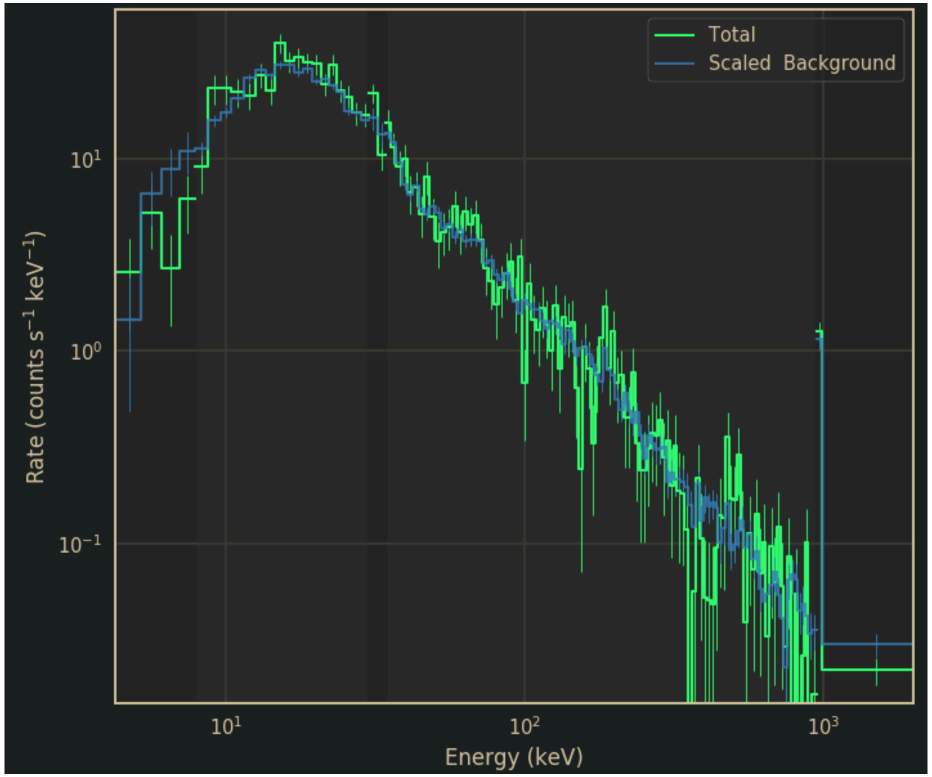
Timing GRB 170817A

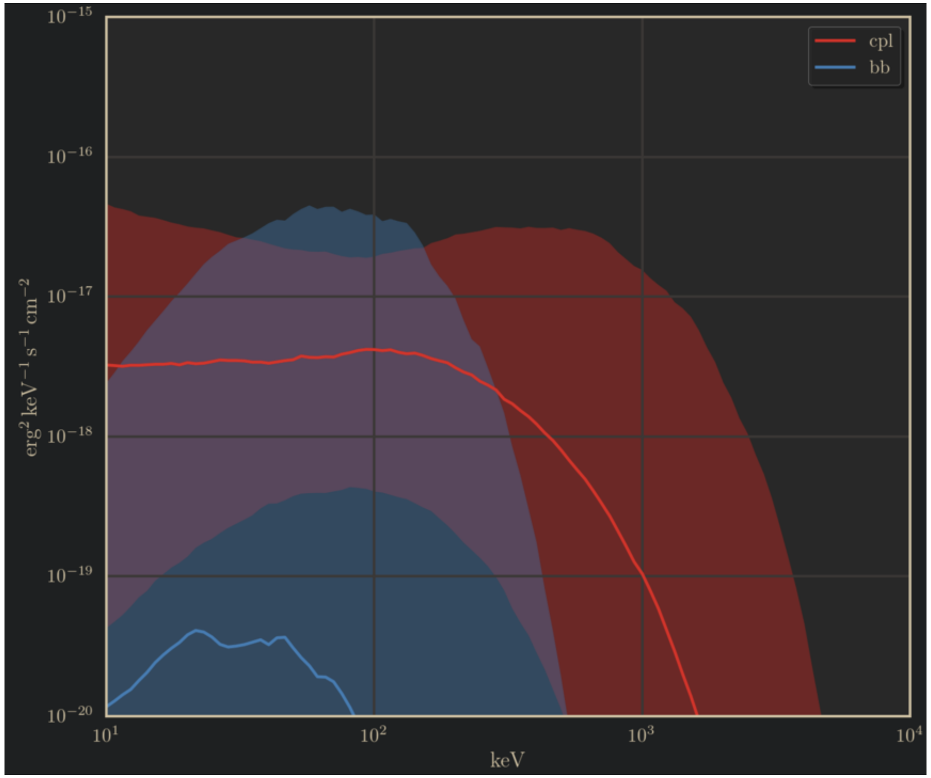






Spectra with GBM



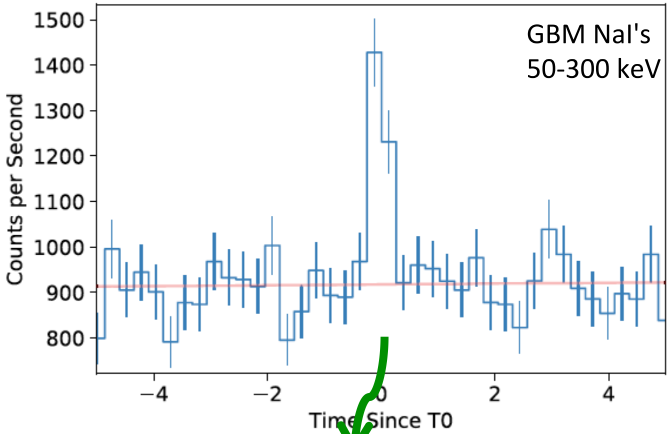


Limitations from spectral resolution of scintillation detectors ~10%

- ☆ Background dominates total countrates (→ no 'subtraction' allowed)
- ☆ Spectral response and background systematics impose limitations

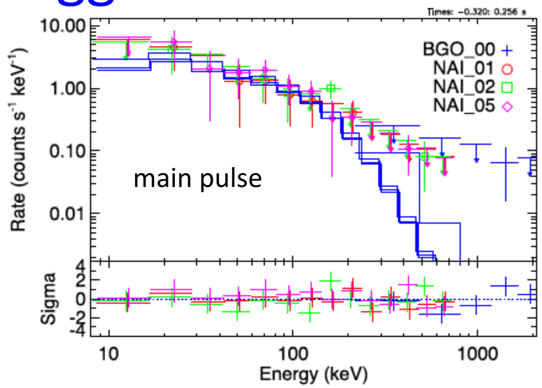
Fermi-GBM γ-ray measurements of GRB 170817A

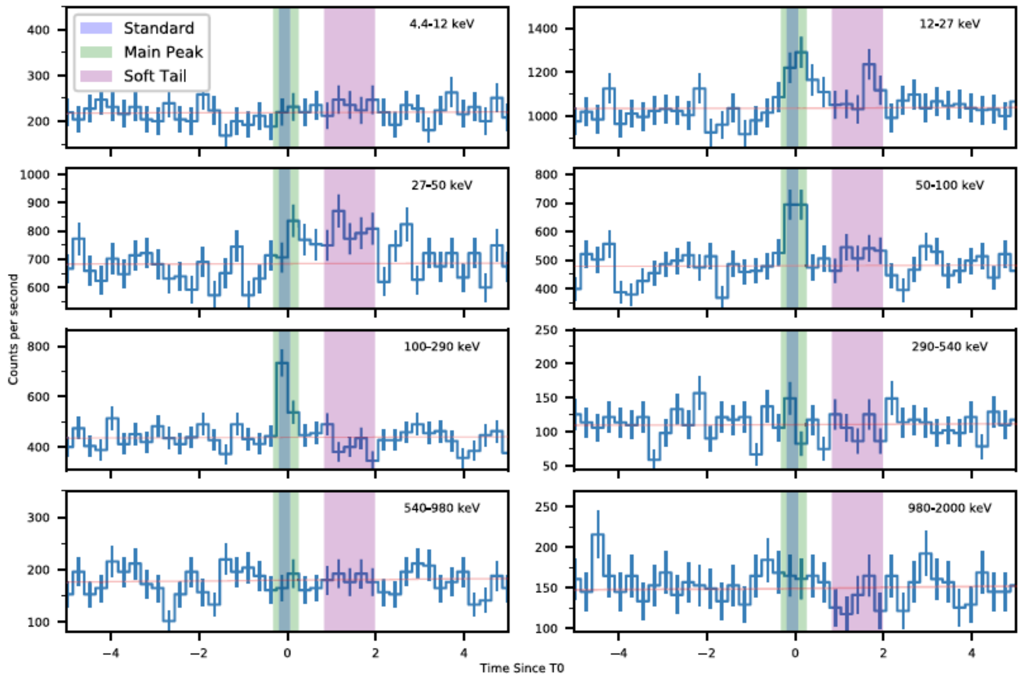
GRB 170817A: a ~normal/common short GRB trigger

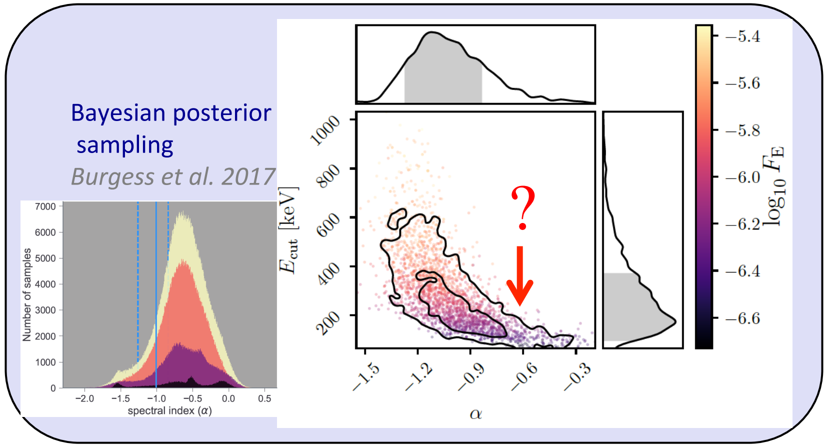


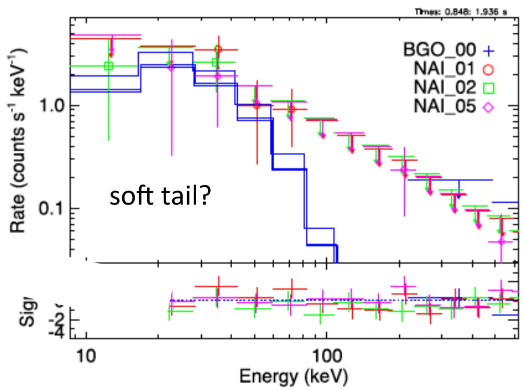
Goldstein et al. 2017

- Duration rather long
- Spectrum very soft
- a "soft tail?"

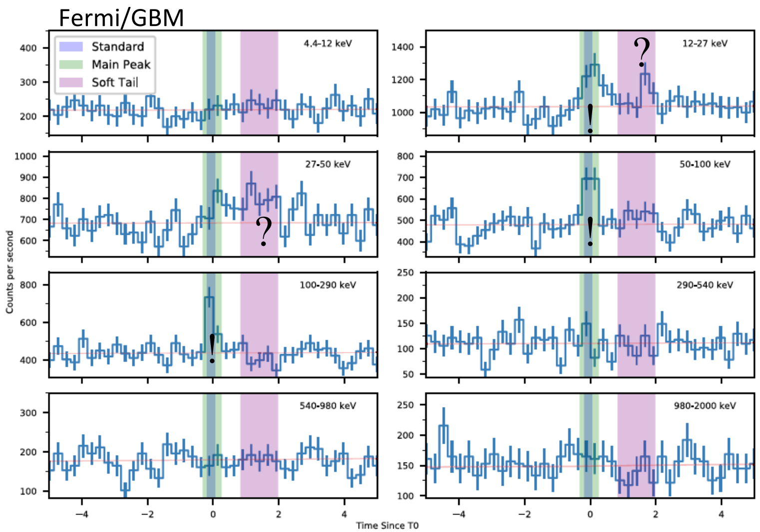


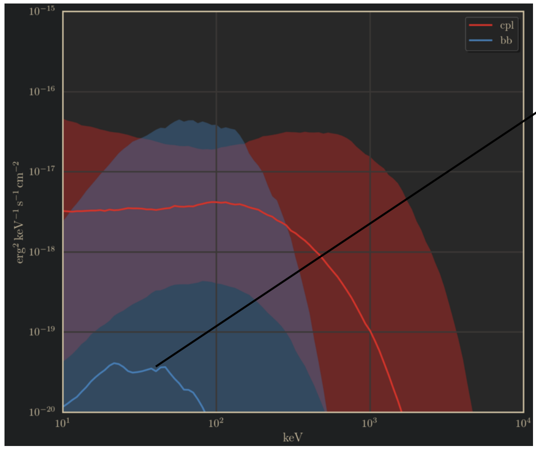


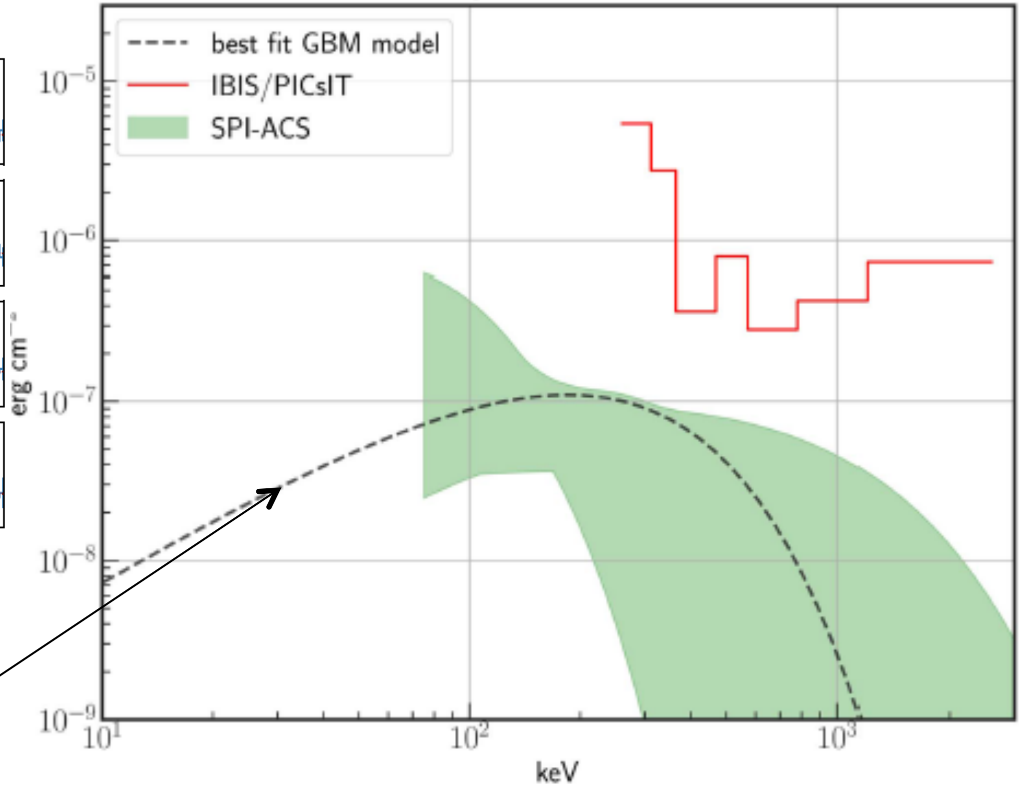


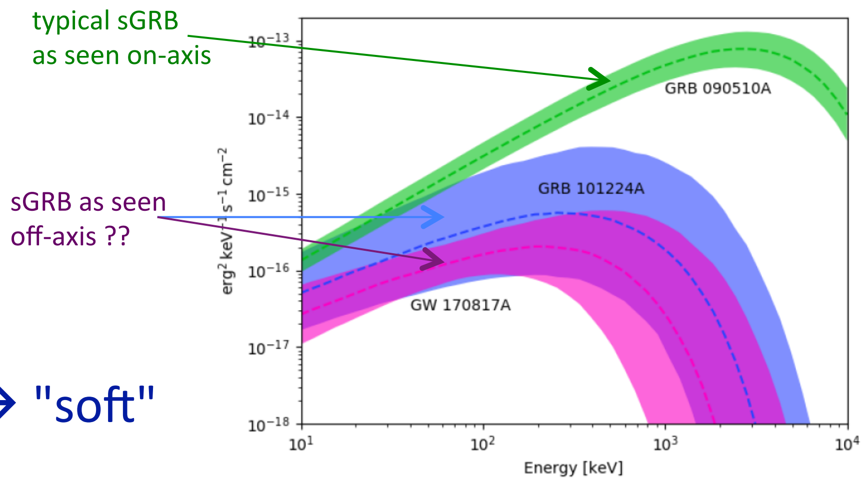


Spectral Constraints: GW170817/GRB170817A









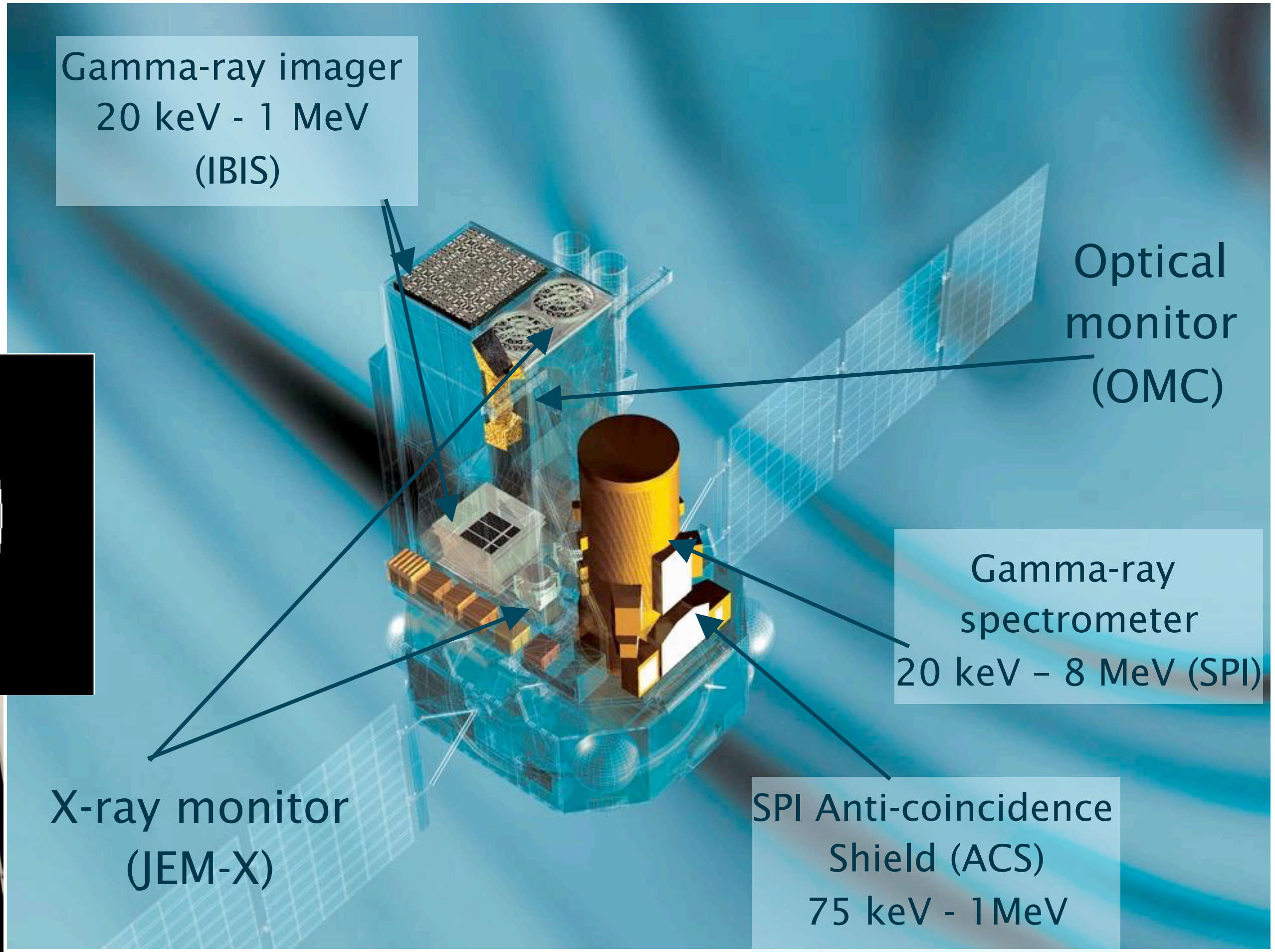
Spectrum poorly constrained

☆ Clear emission at ~100 keV only → "soft"

INTEGRAL Observatory (2002-…(2029))

INTErnational
Gamma-Ray
Astrophysics
Laboratory:

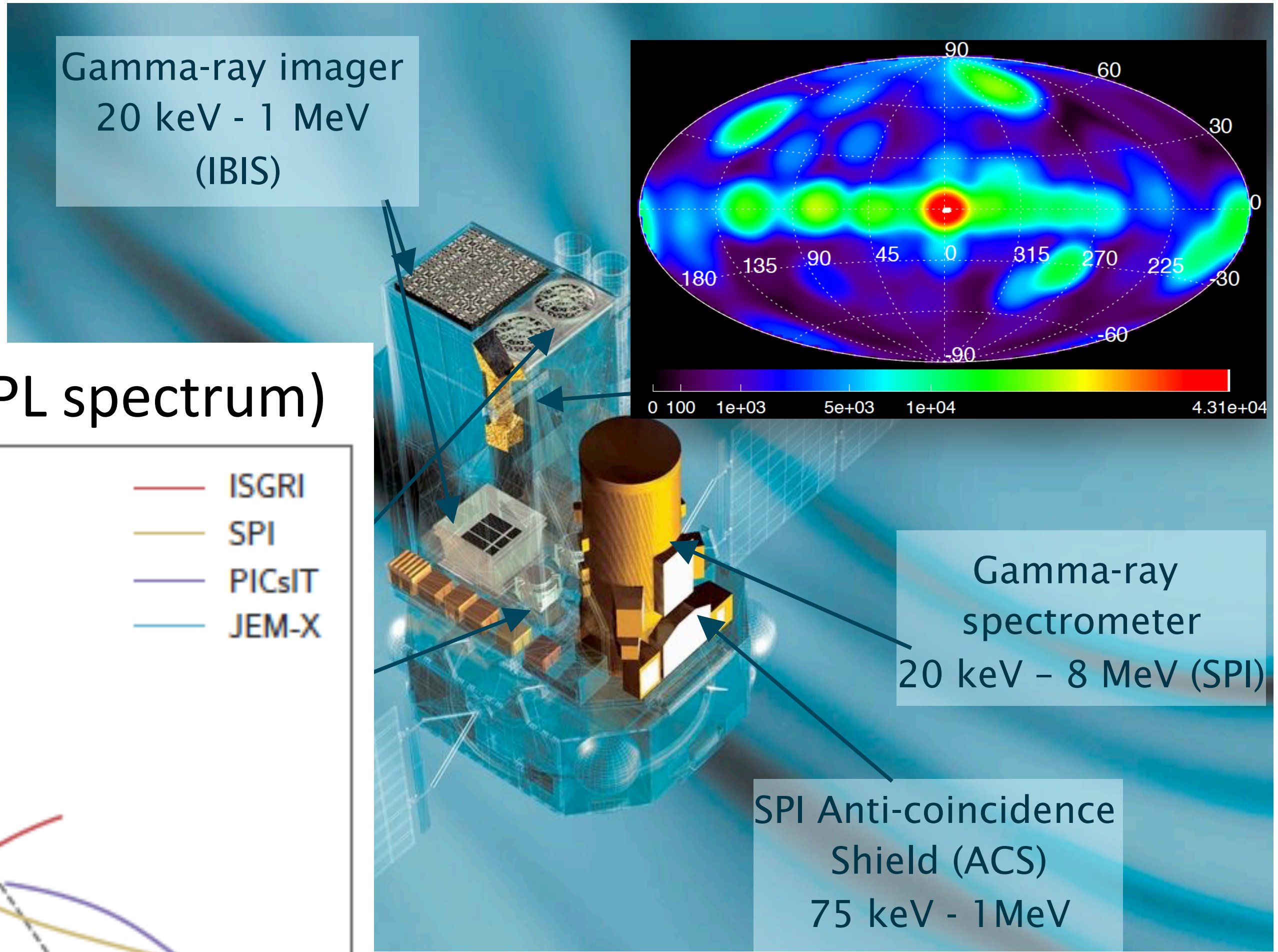
INTEGRAL



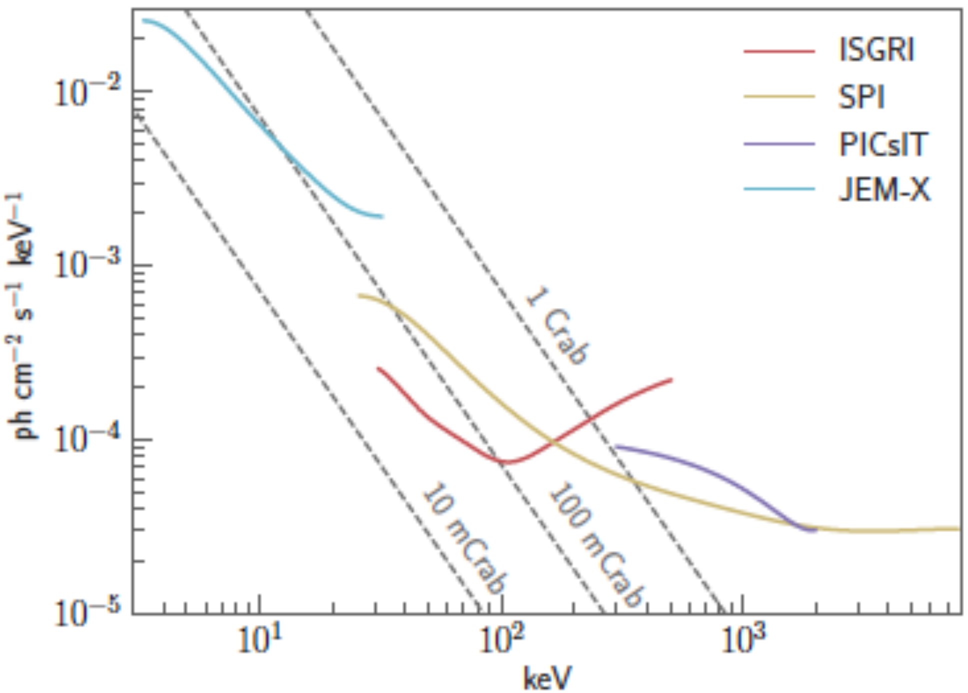
3 keV to 30 MeV

INTEGRAL Observatory (2002-…(2029))

INTErnational
Gamma-Ray
Astrophysics
Laboratory:



Sensitivity (3σ; PL spectrum)

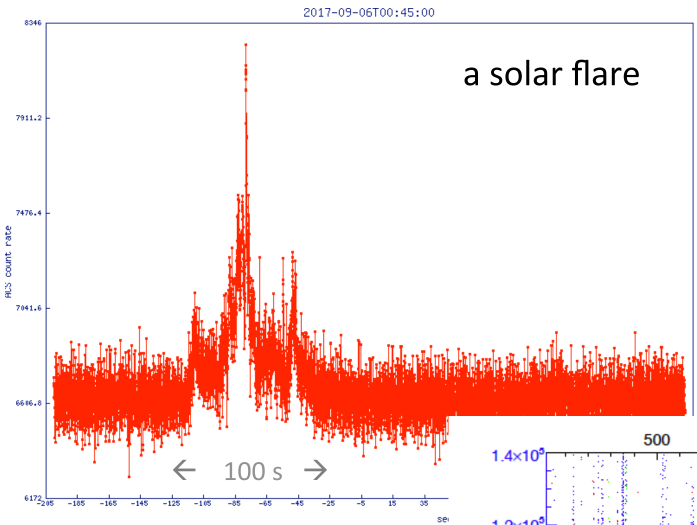


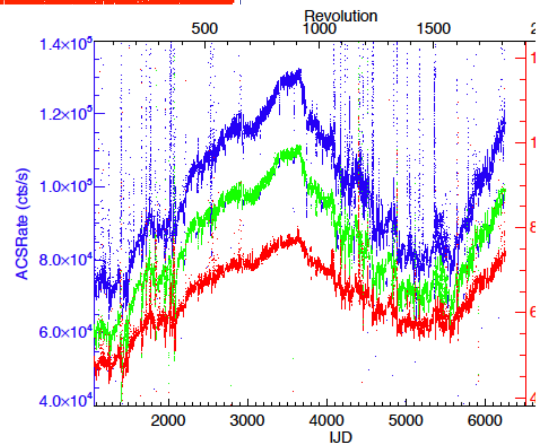
Broad coverage from 3 keV to 30 MeV (unique!)

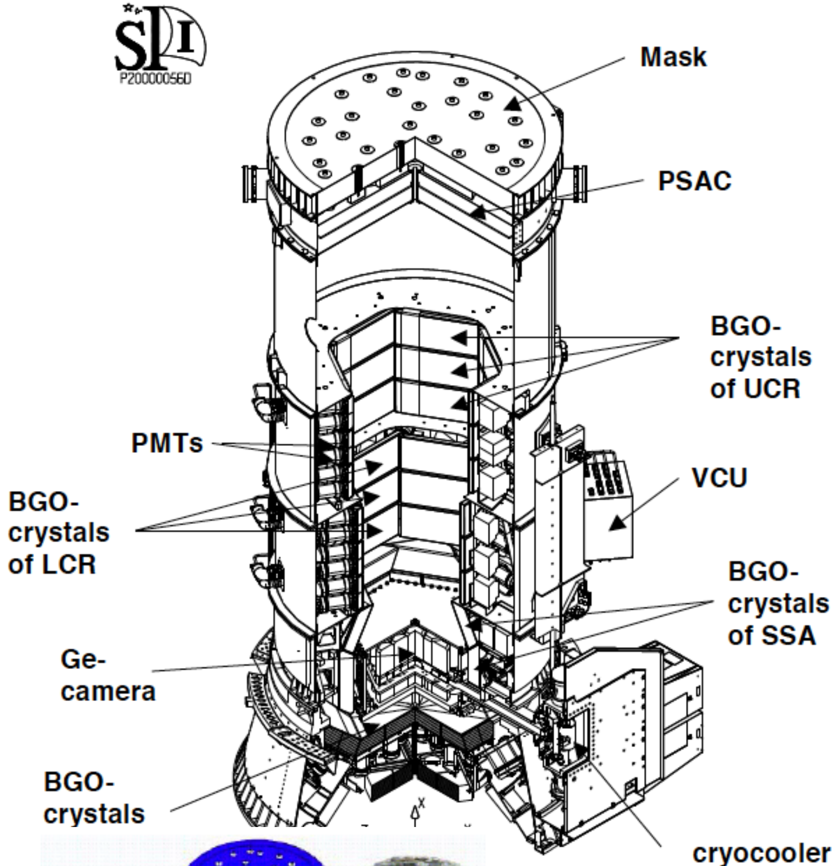
INTEGRAL's most-sensitive GW γ-ray Instrument

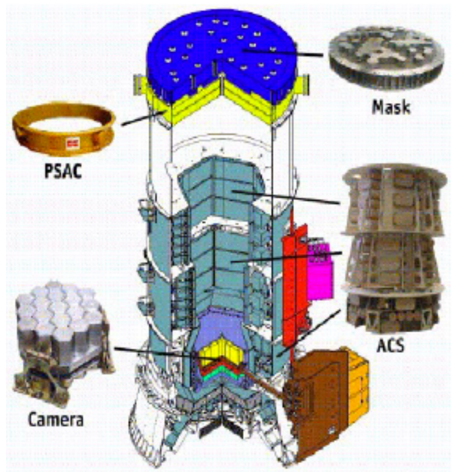
The SPI-AntiCoincidenceSystem (ACS)

- 500 kg (world-largest) BGO scintillation detector, 91 modules
- rate sampling at 50 ms intervals
- used for CR bgd event suppression





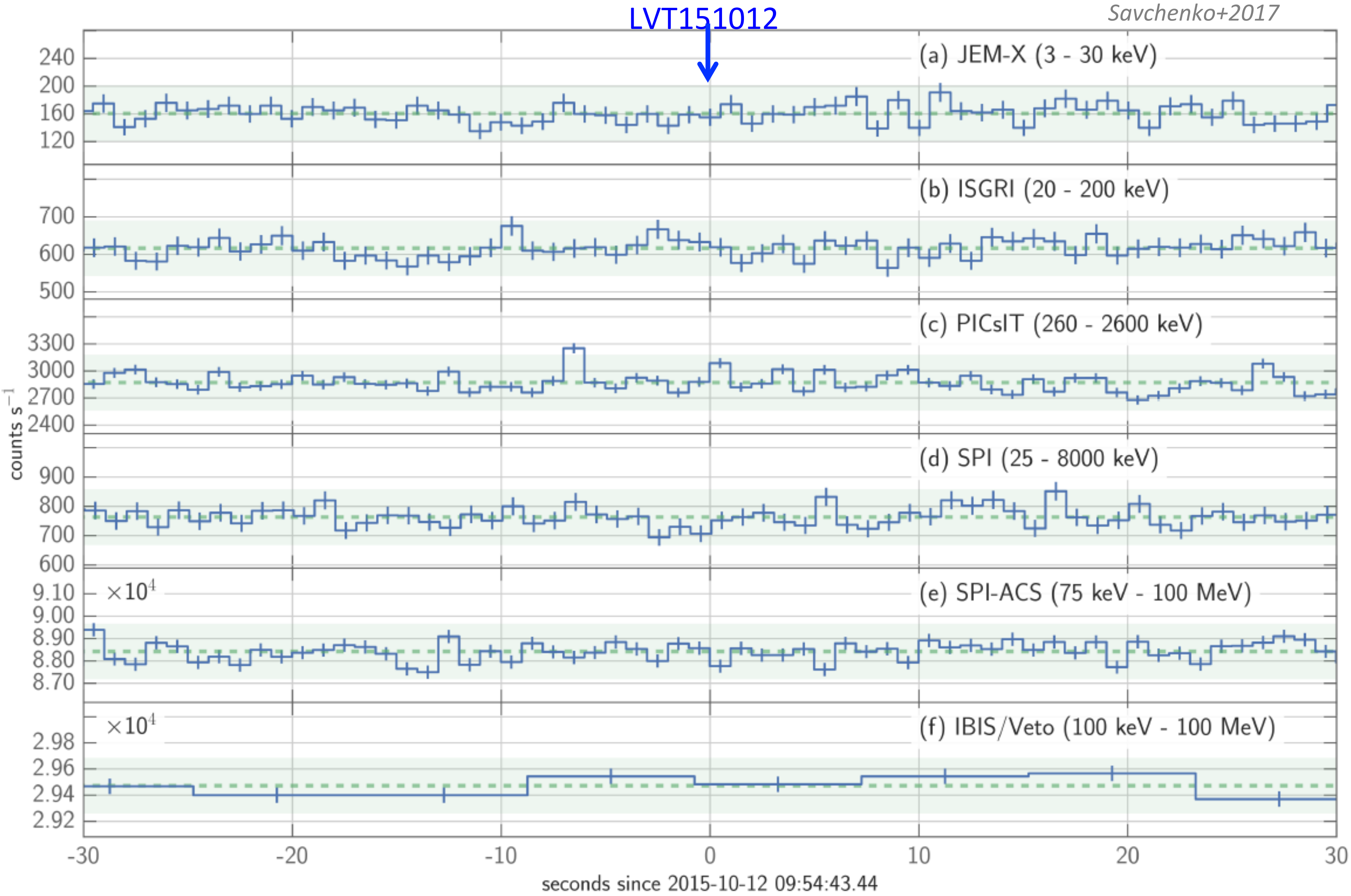




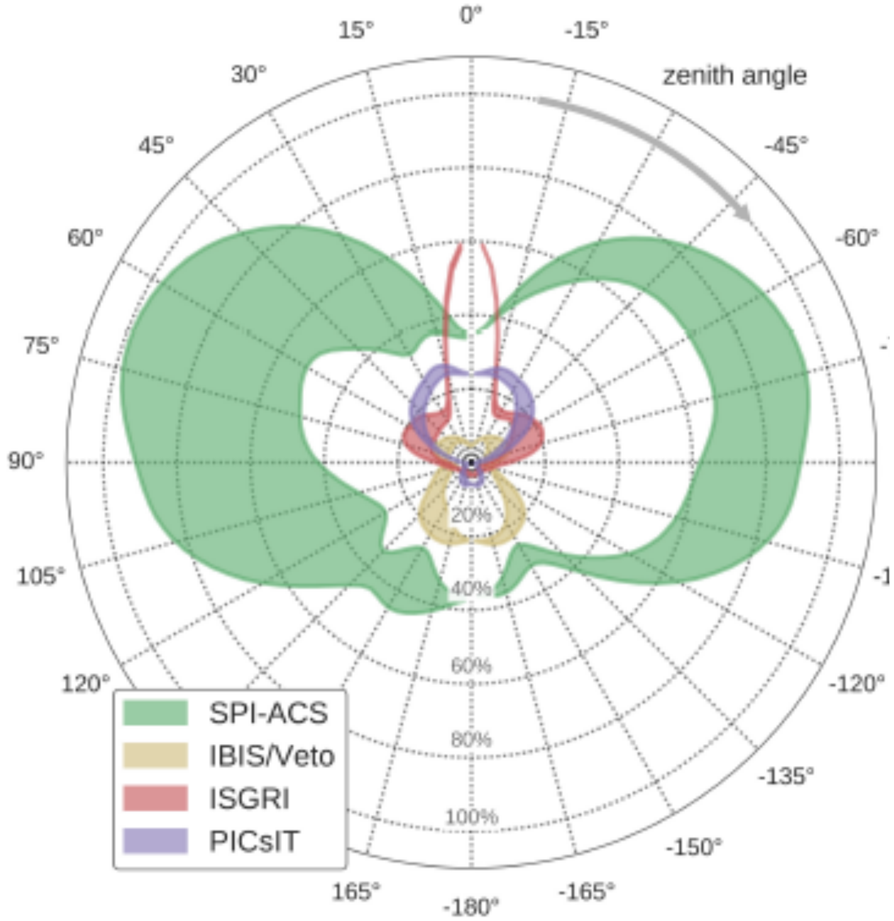
Roland Diehl

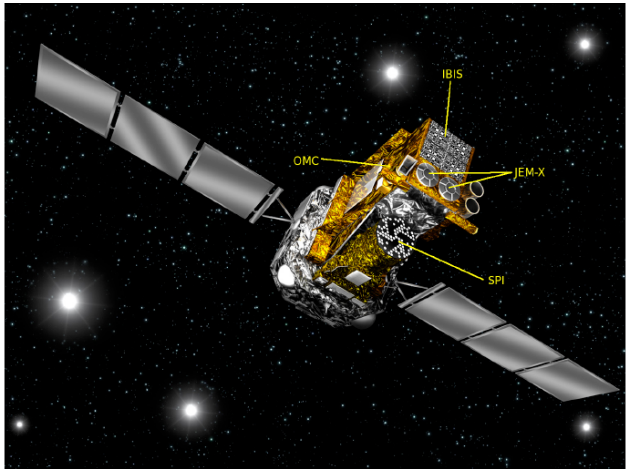
Data from INTEGRAL: LVT151012

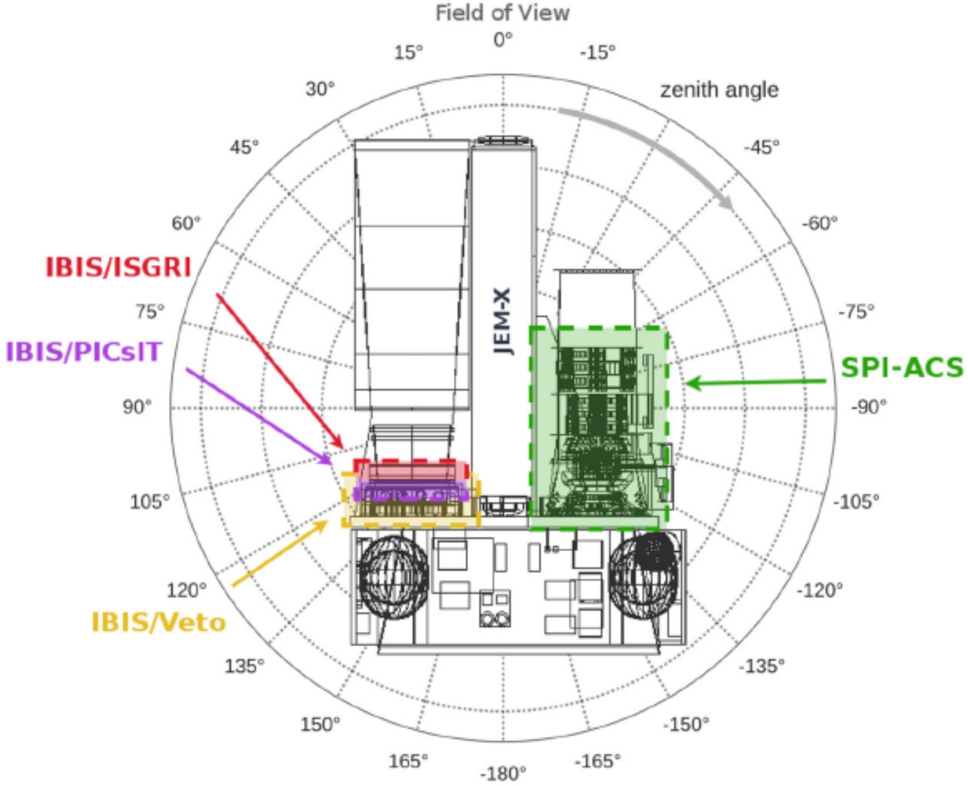
Savchenko+2017



INTEGRAL γ-ray measurements of transients

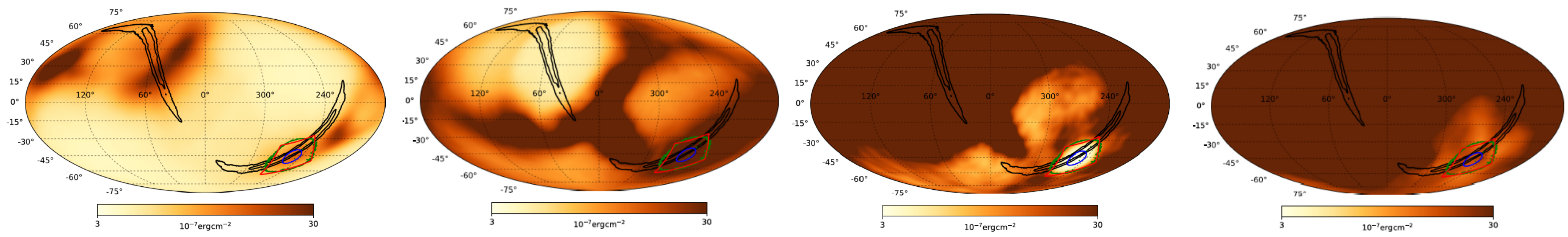






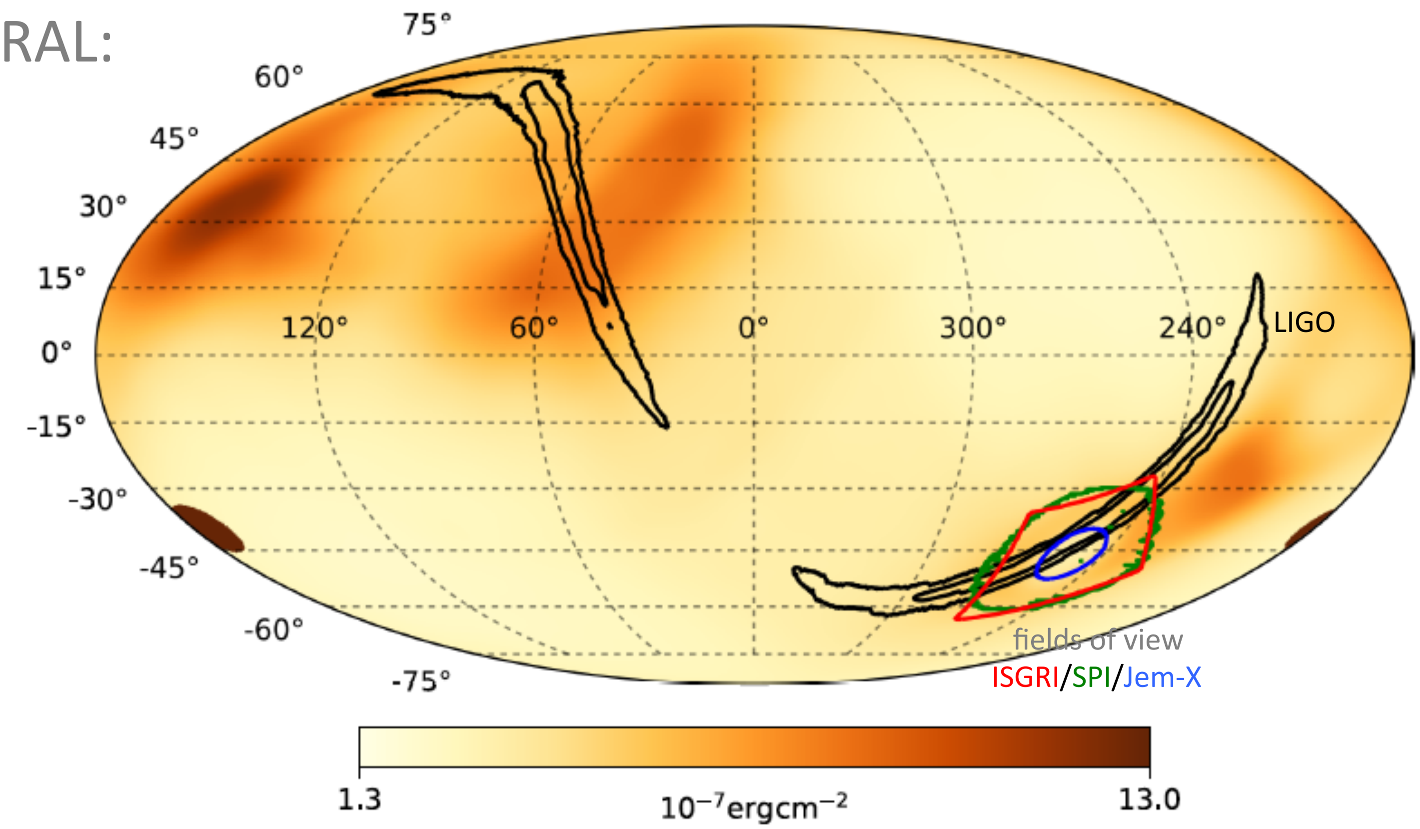
INTEGRAL's spatial information on gamma rays

SPI-ACS | IBIS/Veto | IBIS/PICsIT | IBIS/ISGRI

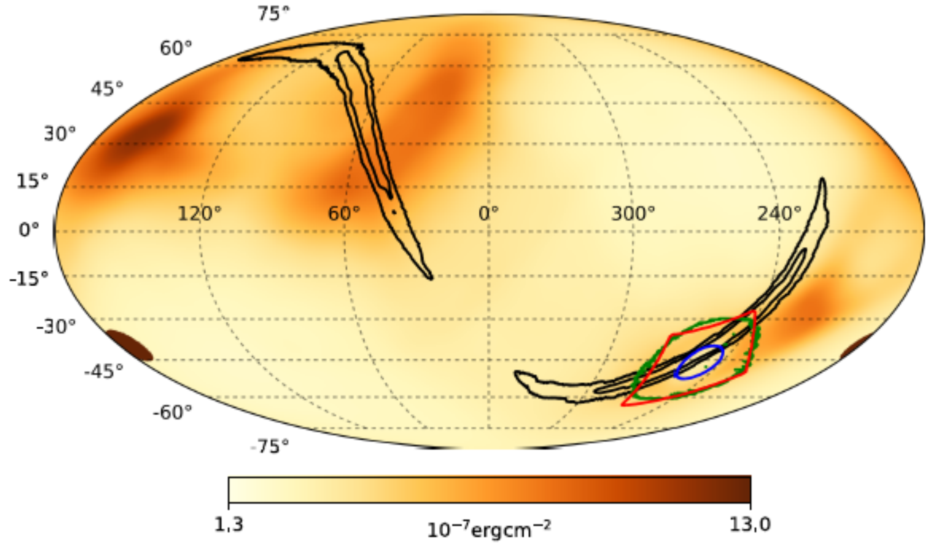


combined INTEGRAL:

LVT151012



INTEGRAL's spatial information on gamma rays

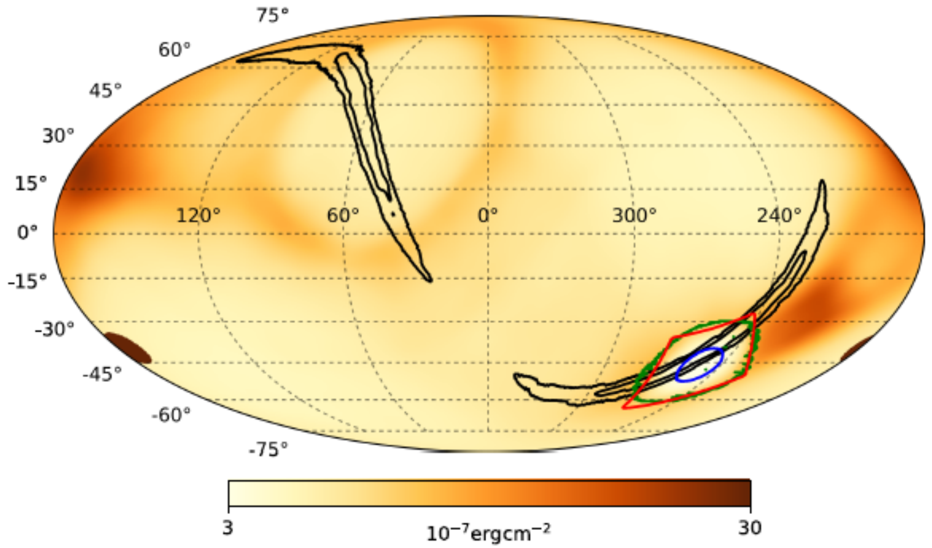


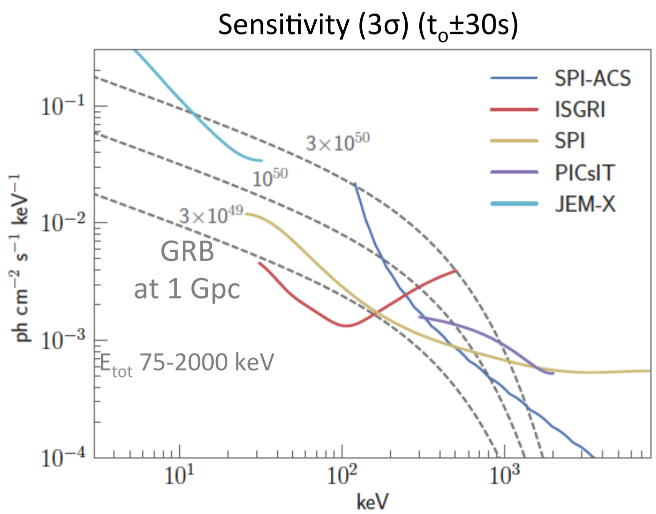
Dependence on adopted spectral model:

1s GRB from LVT151012

☆ Comptonised

☆ Band fct





Response of GBM Detectors

- Effective sensitivity versus incidence angle:
  - ☆ NaI's (~slice of scintillator) directional, especially at low energy
  - ☆ BGO 'blocks': all-sky

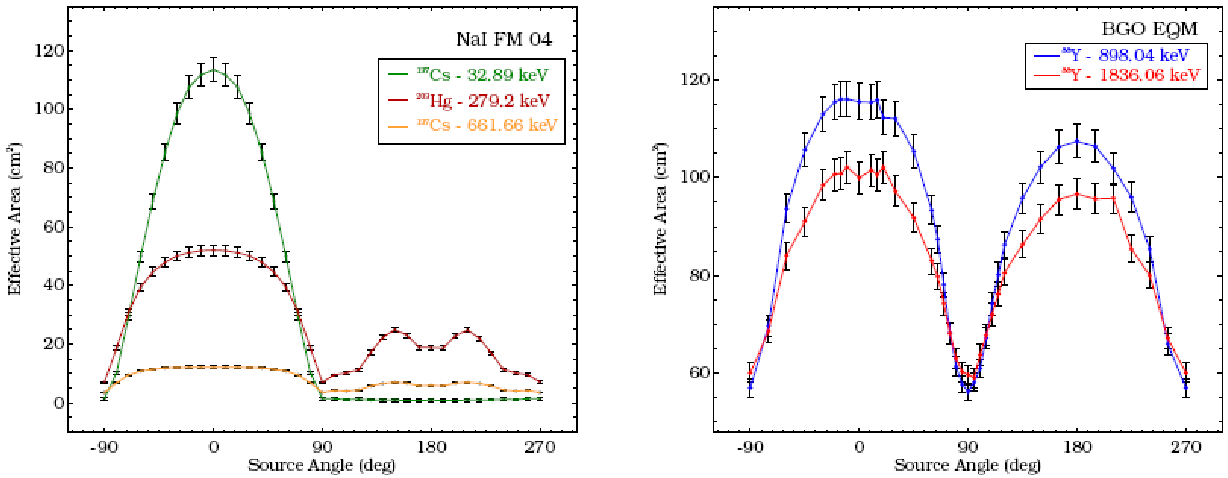
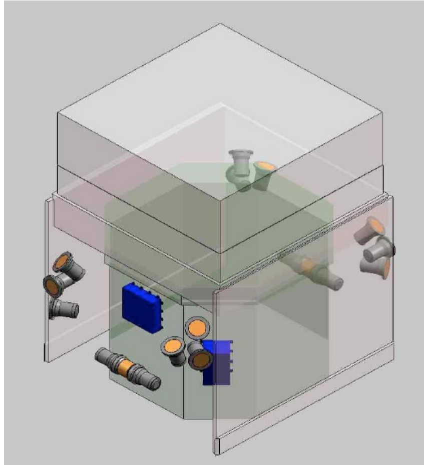


Fig. 26 Off–axis effective area as a function of the irradiation angle (from -90° to 270 °) for NaI FM 04 (*left panel*) and BGO EQM (*right panel*). In the case of NaI, results for three radioactive lines are shown, namely: Different curves represent different NaI line–energies: 32.06 keV from ^{137}Cs (*top green curve*), 279.2 keV from ^{203}Hg (*middle red curve*), and 661.66 keV from ^{137}Cs (*bottom yellow curve*). For BGO, two lines from ^{88}Y are shown: 898.04 keV (*blue curve*) and 1836.06 keV (*red curve*).

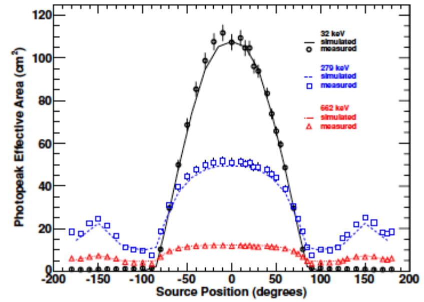
Locating Gamma Ray Burst Sources with GBM

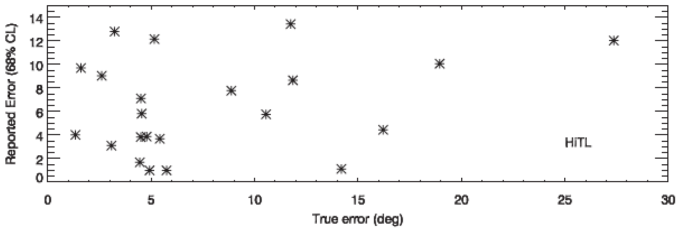
Exploiting Count Rate Differences Among Detectors:

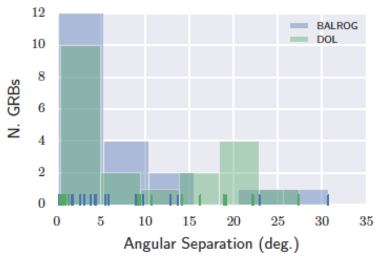
(Connaughton+2015; Burgess+2018)

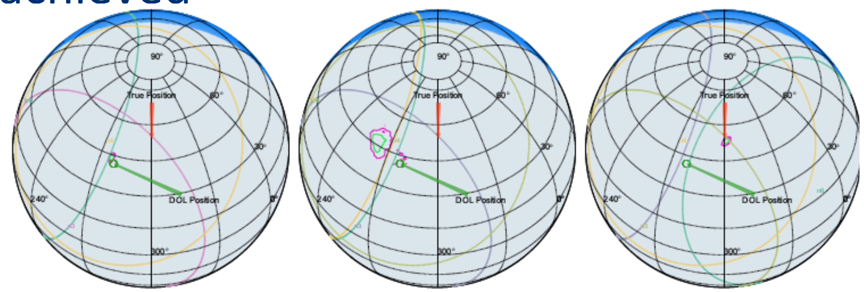


- Shadowing and aspect angle sensitivity provide individual detector responses for the 12 NaI's
- Earth albedo & scattering needs to be accounted for
- Monte-Carlo simulated responses have been assembled for ~100 sky directions
- a "best-fitting" direction thus can be evaluated
- Checking in hindsight (from afterglows, host galaxies), an offset of 8-13 degrees shows the limitations
- A finer (unbinned) sky direction treatment and inclusion of spectral properties in a Bayesian framework reduces systematics → locations within ~5 degrees achieved





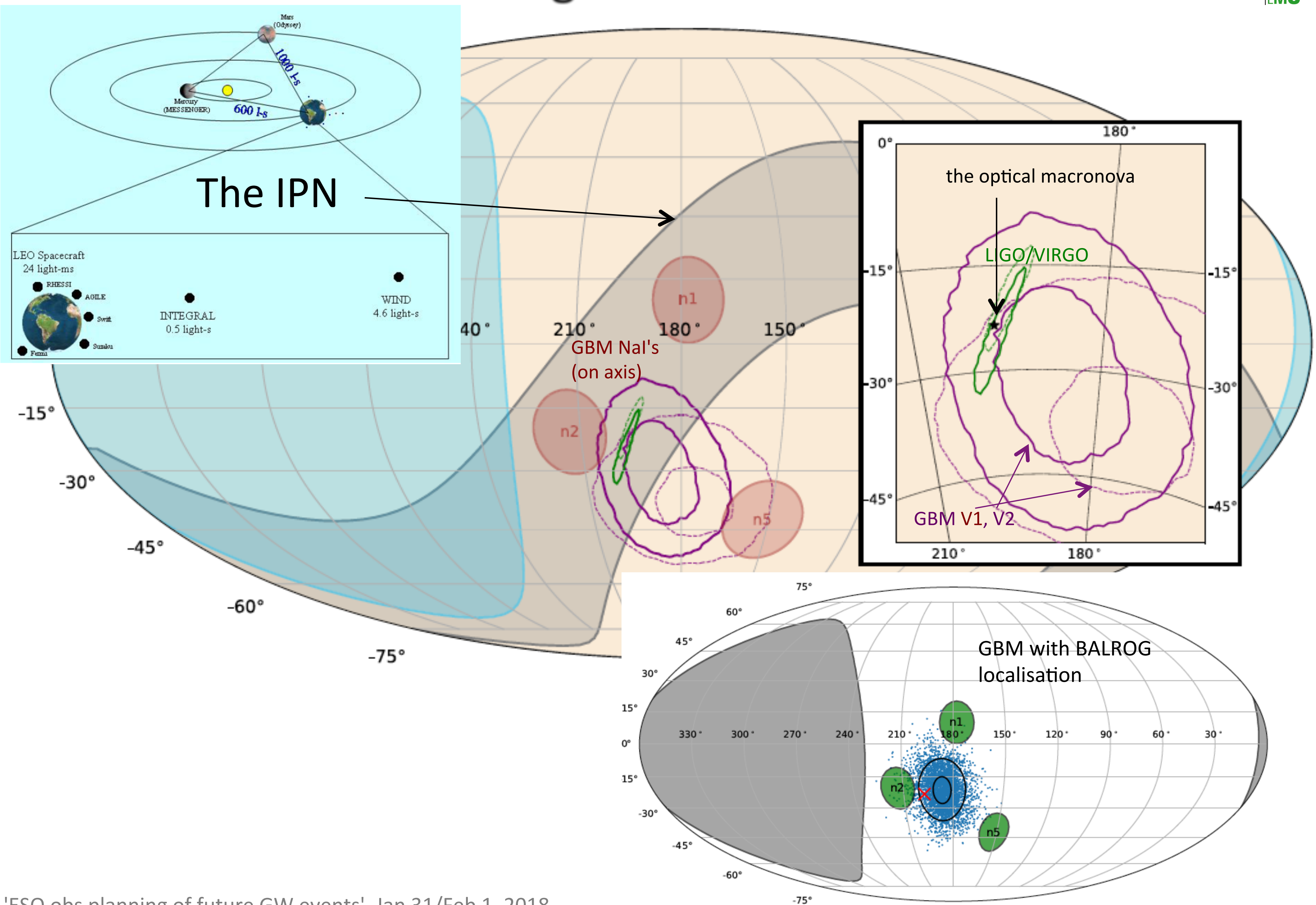




all det's cnts cnts + spectral template BALROG

Roland Diehl

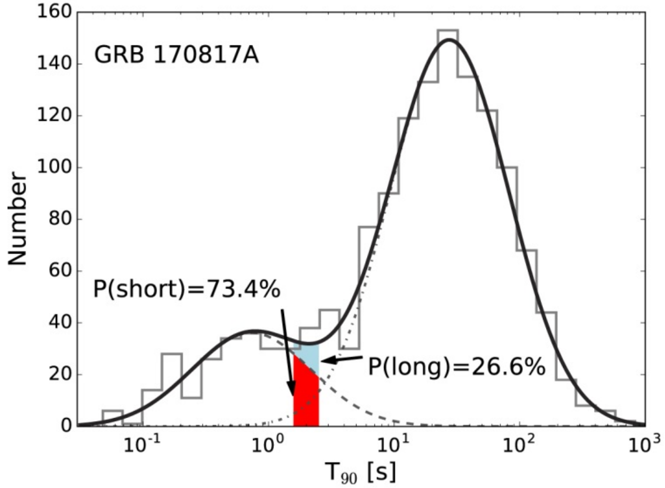
Locating GRB 170817A



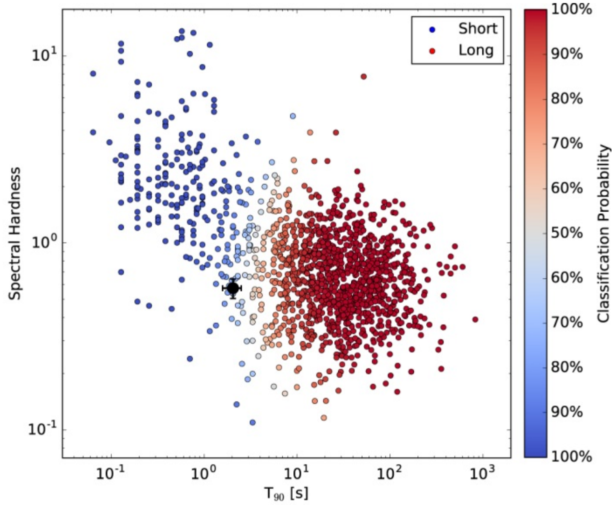
Fermi-GBM γ-ray measurements of GRB 170817A

GRB 170817A, as compared to "typical short GRBs":

Goldstein et al. 2017



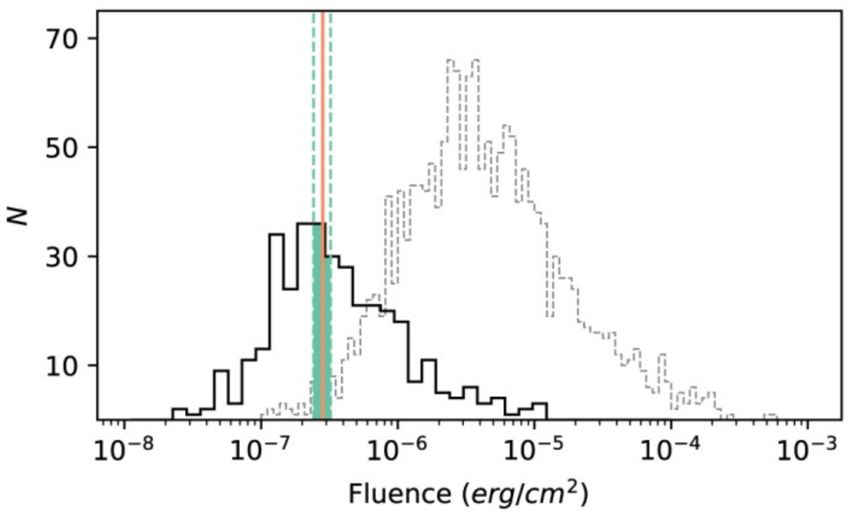
(a)

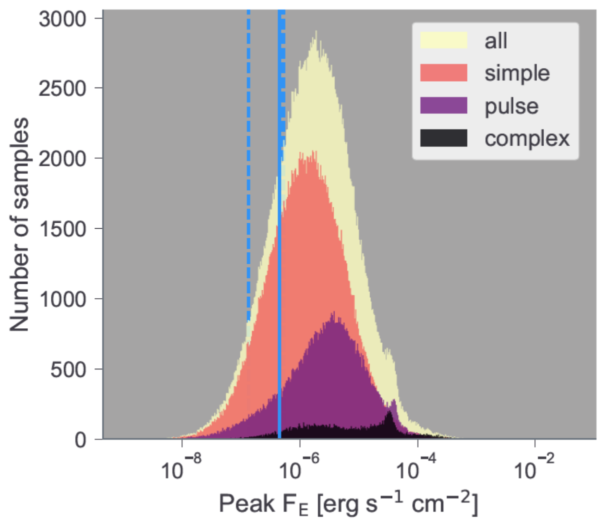


(b)

- duration rather long
- spectrum rather soft

Goldstein et al. 2017

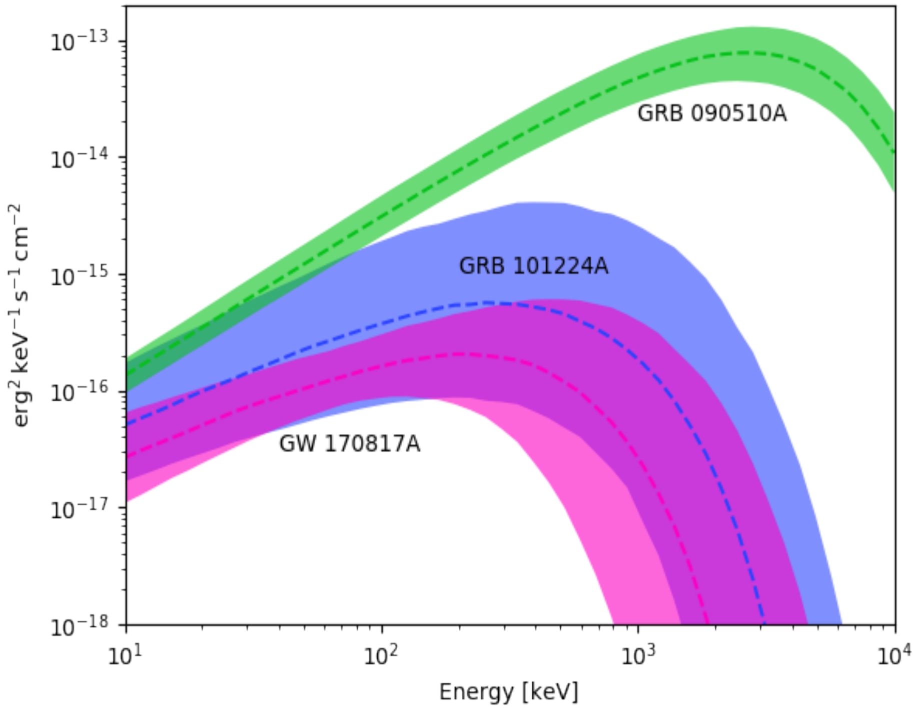


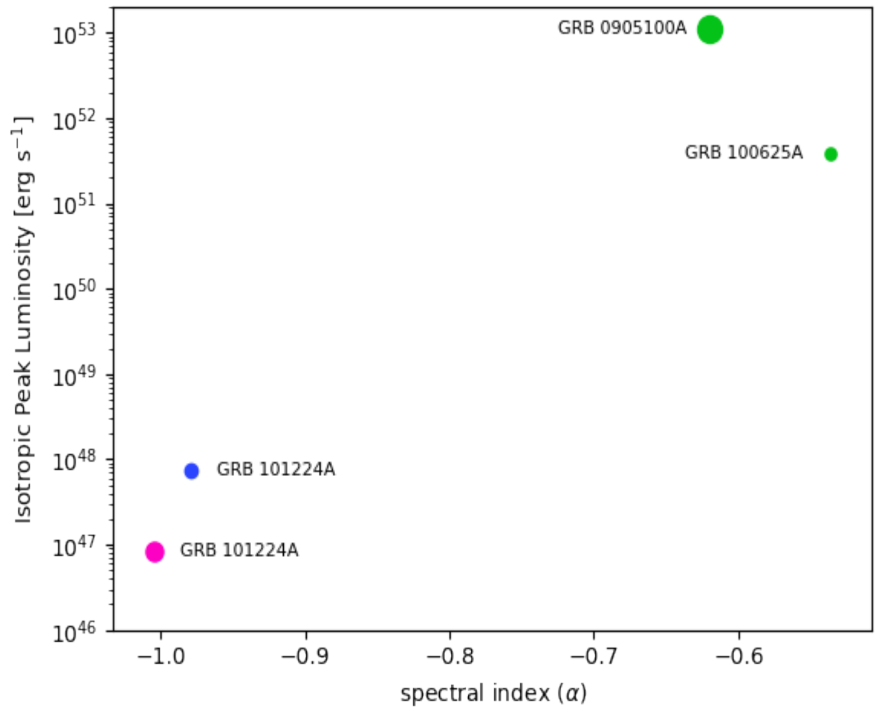


z=0.01, while all other short GRBs 0.1<z<2

→ under-luminous by 10^4x

Similar short GRBs





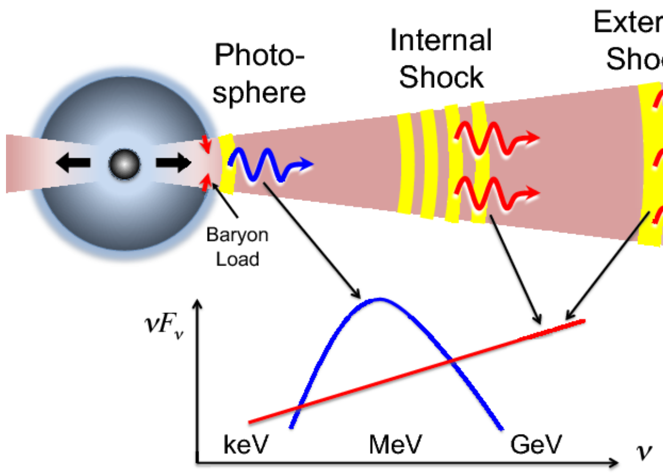
- at least one other good candidate for nearby low-L GRB
- in total ~10 out of 50 short GRBs have similar spectral properties, and thus could be local and off-axis

Models for prompt gamma-ray emission

Standard model:

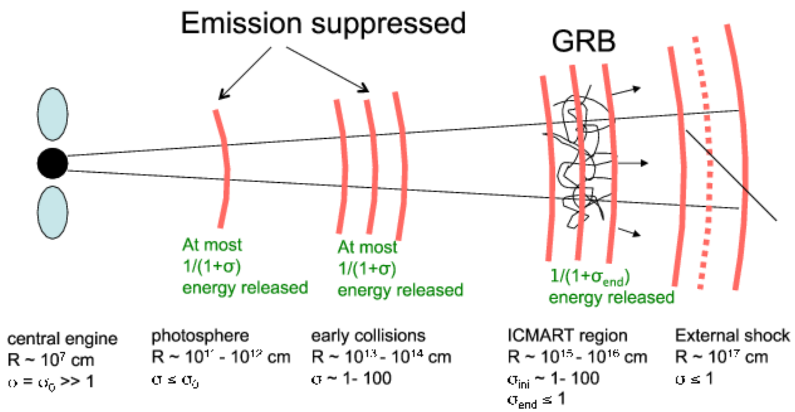
Synchrotron emission from the electrons that were Fermi-accelerated in these internal shocks

(but not undisputed: main problem is the necessary high efficiency)



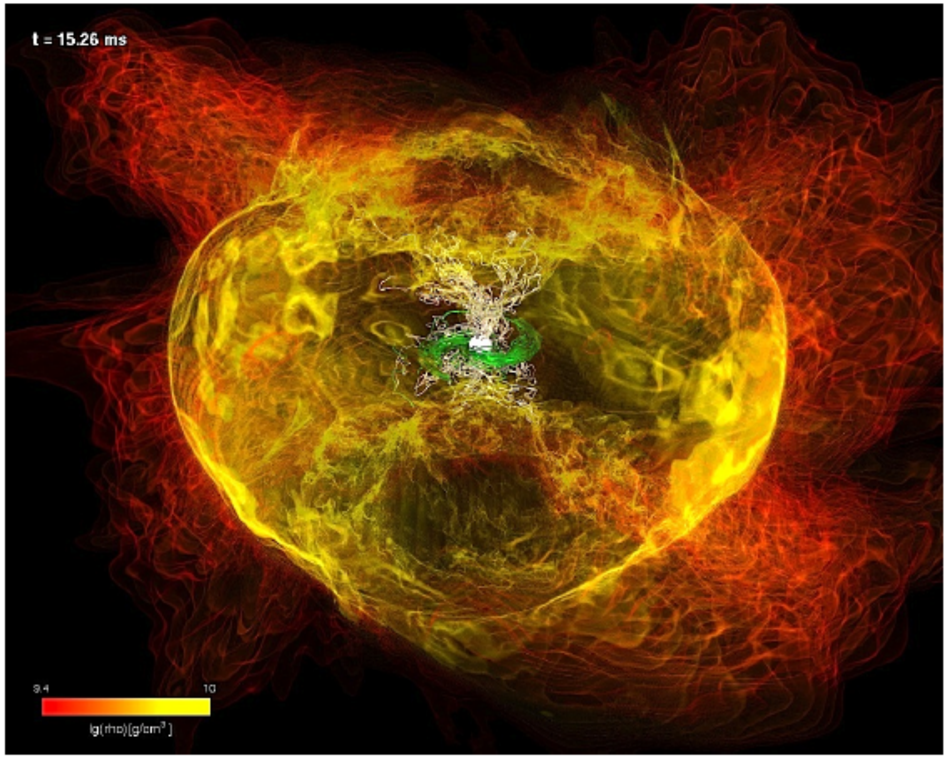
Alternative models

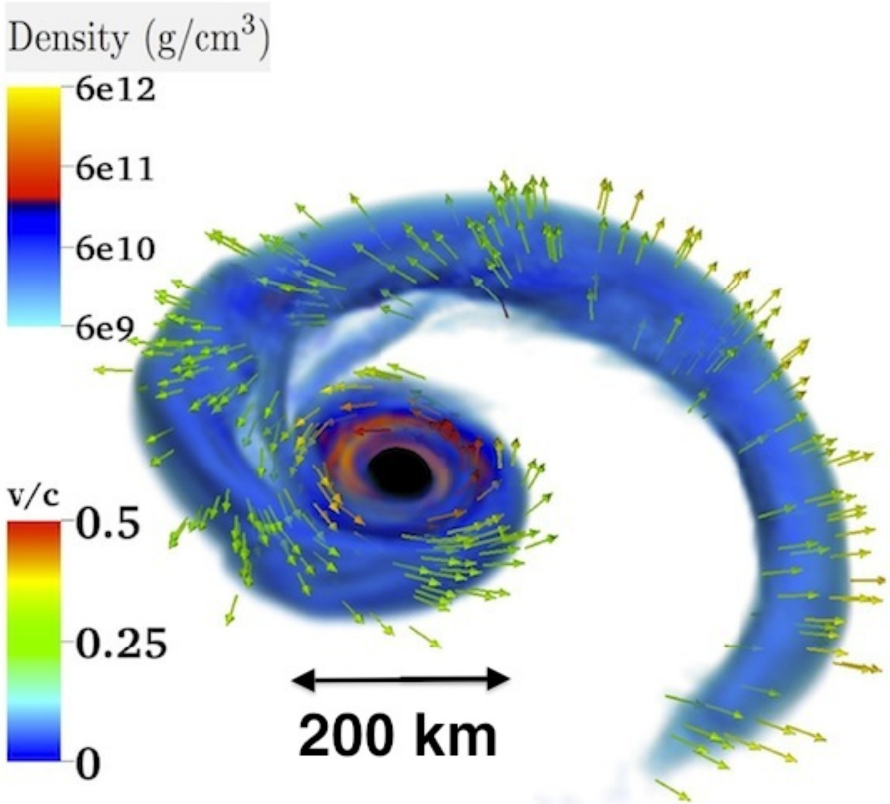
- Photospheric emission:
  sub-photospheric heating leads to broadening of Planck spectrum
- Magnetically dominated jet:
  magnetic reconnection leads to broad-band spectrum



Post-merger dynamics

disruption of less-massive neutron star → ejection, nuclear reactions

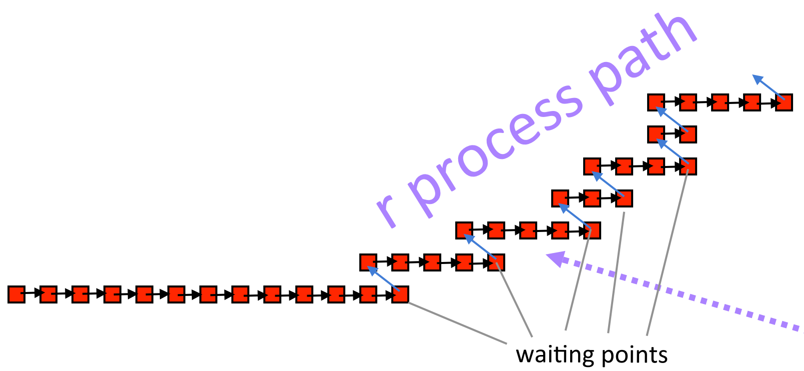


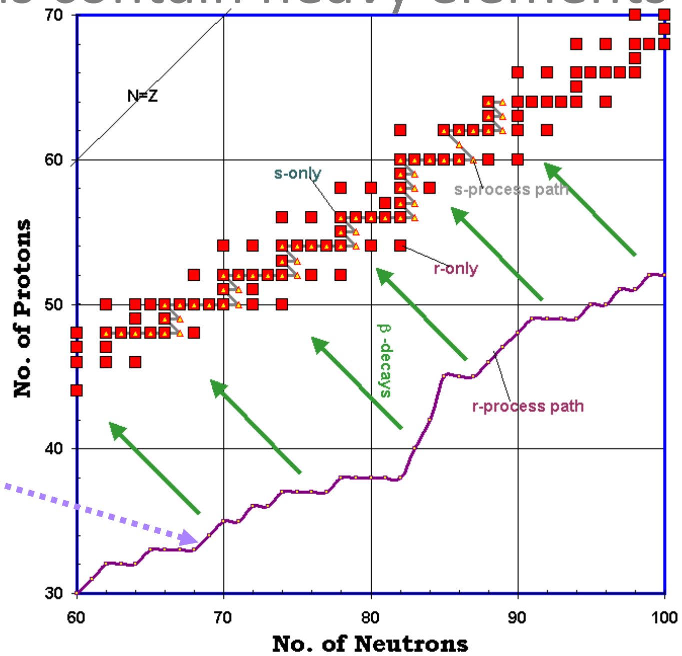


Fernández & Metzger 2016 from Rezolla+ 2011, and Fouchart+ 2014

Candidate r-process sources

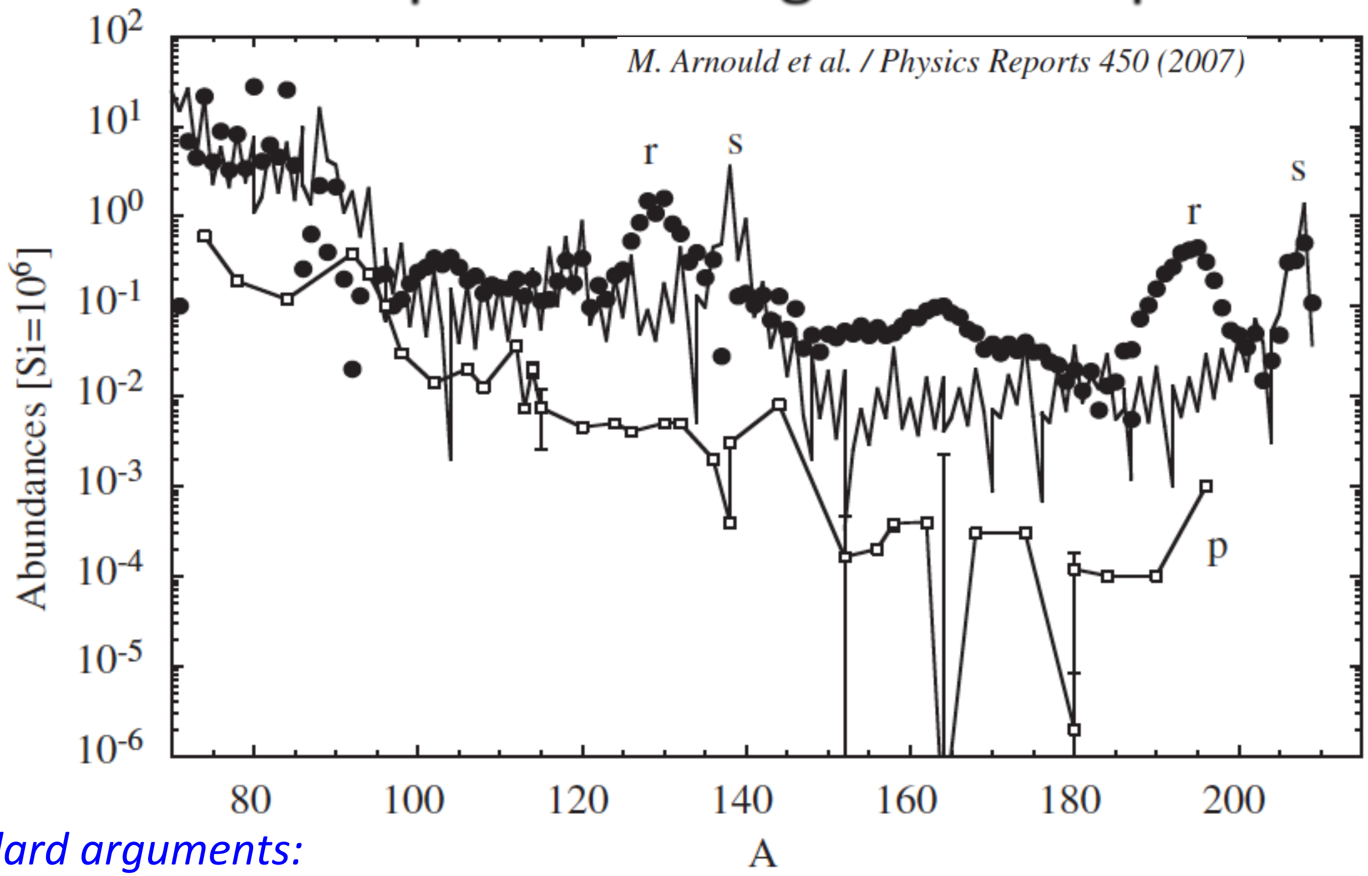
neutron capture in an intense flash; seeds contain heavy elements





- ☆ Need neutron-rich nuclear plasma (free nucleons)
- ☆ Explosive environment
  - ☞ Supernova explosions; regions near proto-neutron star (ν-driven wind)
  - ☞ Neutron star's violent interactions (→ ejected material??)
- ☆ Y_e (neutron richness of nucleon ensemble) is a key parameter
- ☆ Nuclear fission (cycling) may regulate towards a homogeneous outcome

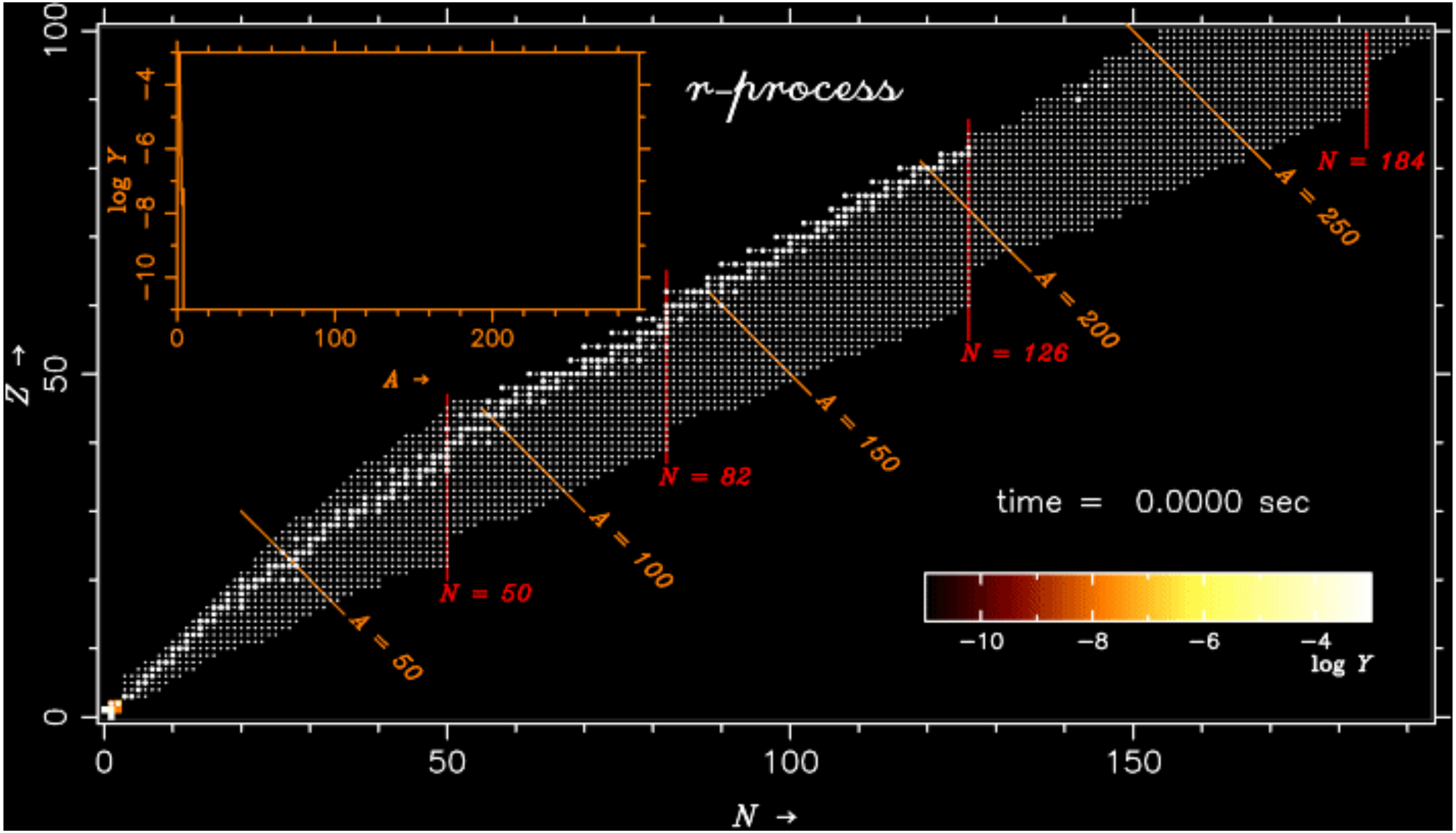
The scientific question "origin of the r process"



Standard arguments:

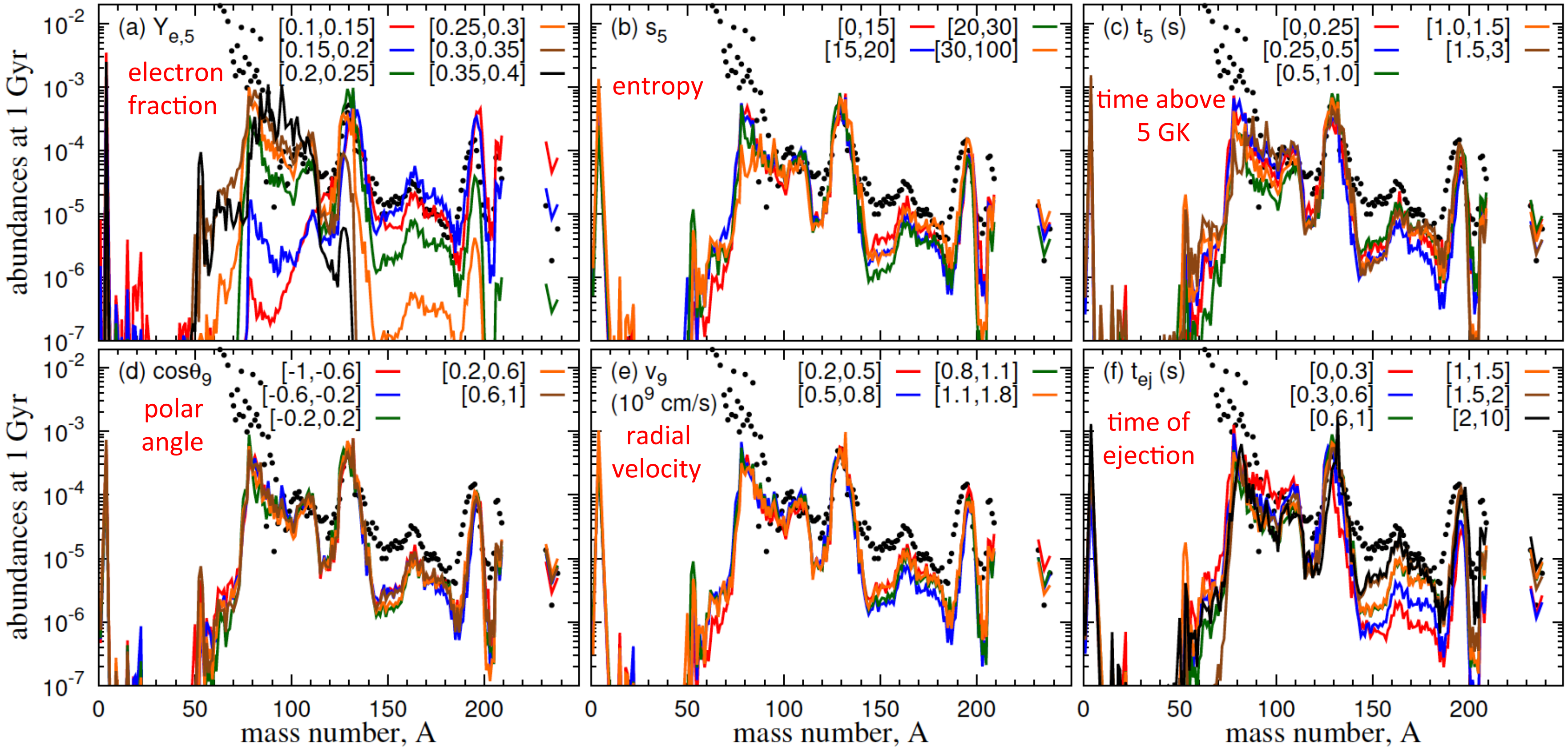
- Solar-system elemental abundances of heavy elements originate from the r-, s- and p- processes
- The s process is "known" and can be subtracted
- The remaining r process pattern is due to well-regulated astrophysical and nuclear processes → *the quest*

r process nuclear reaction dynamics



Nuclear processing of NS merger material

neutron capture in an r-process near colliding neutron stars



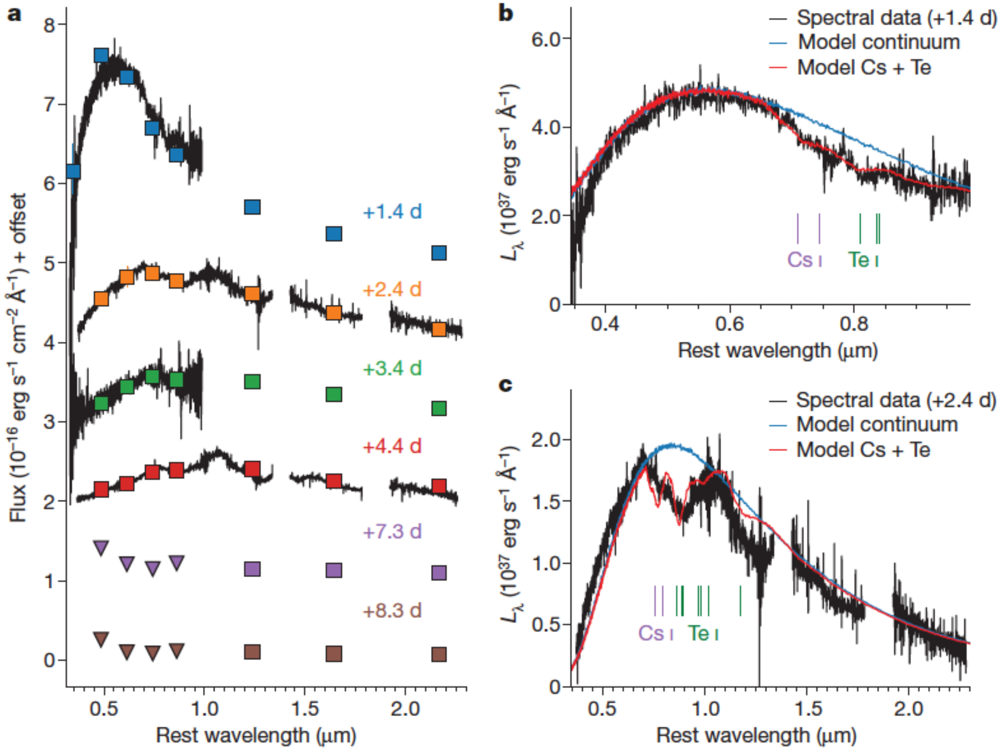
Electron fraction is most critical, otherwise well regulated

Wu, Fernández, Martinez-Pinedo, & Metzger 2015

Nucleosynthesis from a NSM

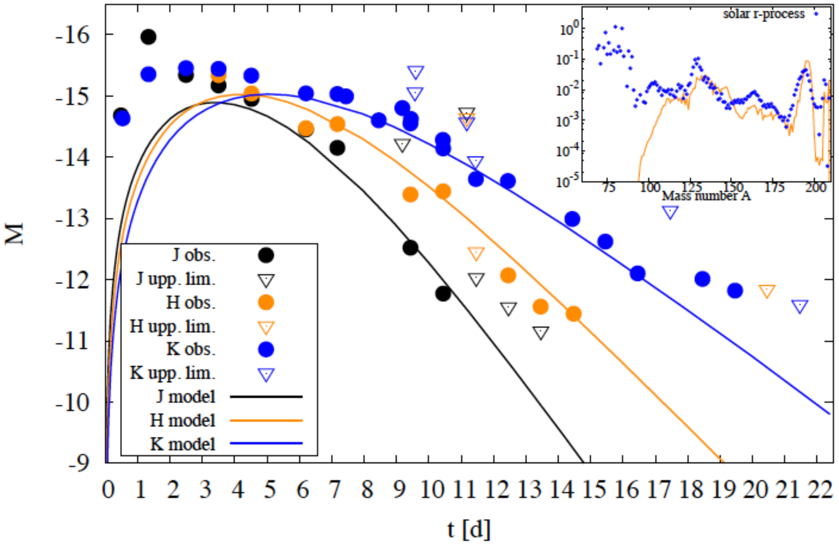
radioactivity from r-process isotopes !

Smartt+2017

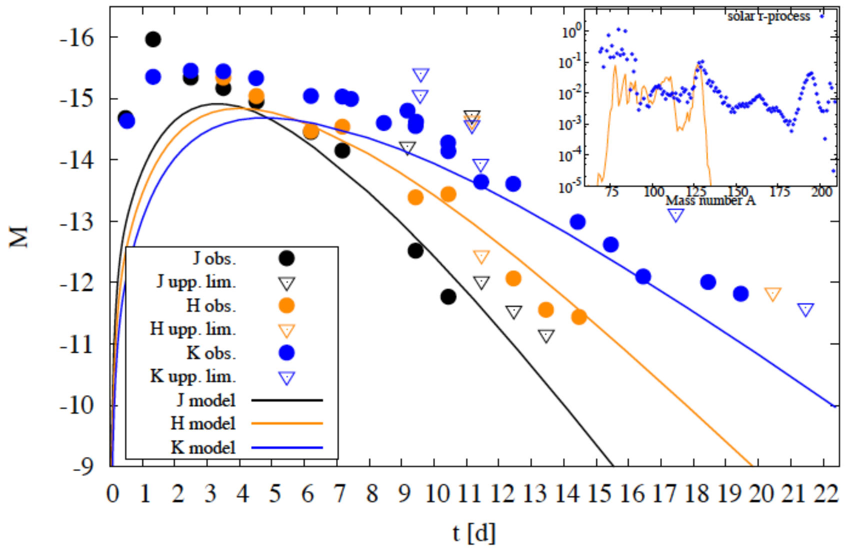


Rosswog+2018

m_{ej}= 0.015 M_{sol}, Y_e= 0.1, v_{ej}= 0.15c, κ= 10 cm^2/g



m_{ej}= 0.05 M_{sol}, Y_e= 0.28, v_{ej}= 0.10c, κ= 1 cm^2/g



☆ which isotopes?

- heavy (up to A~195) ??
- lighter (A<130) ??

Emergent Radiation: Opacities

•

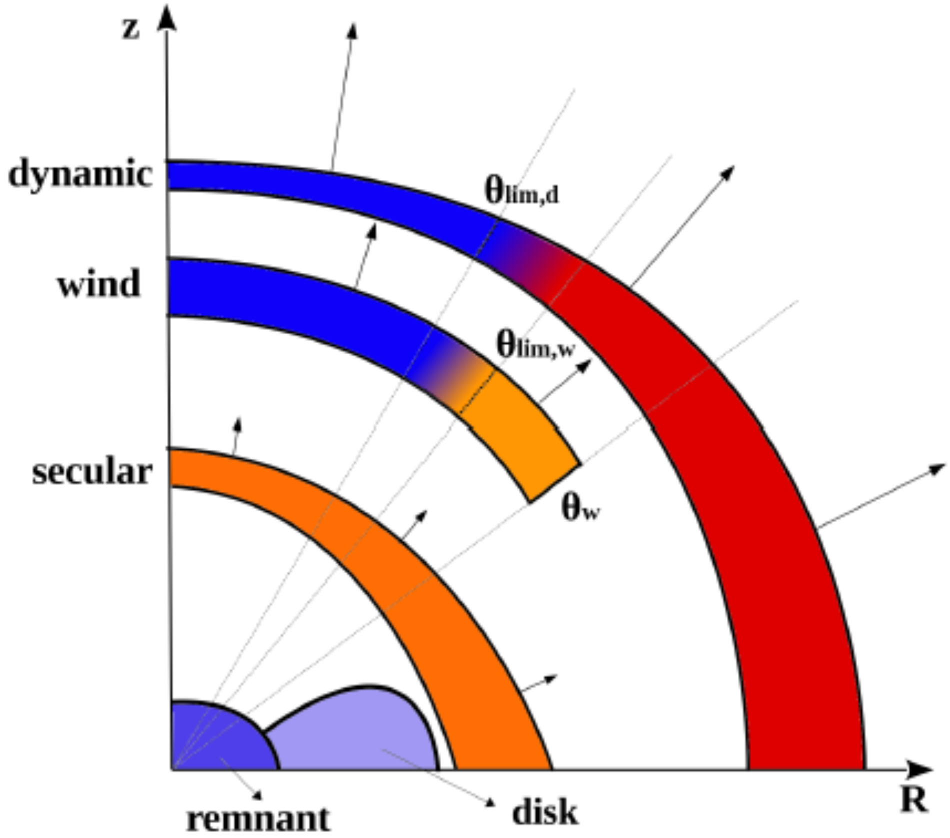
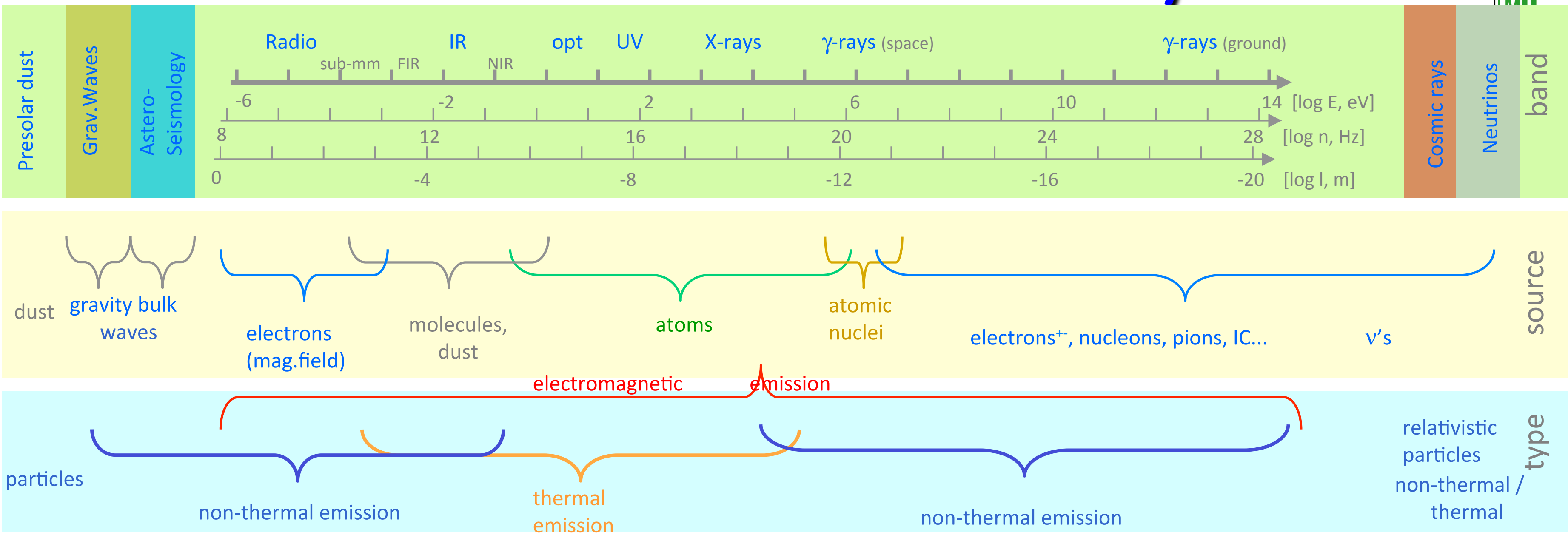


Figure 2. Graphical sketch of the three ejecta components radially expanding from the remnant. Different colors correspond to different matter opacity: high (red), intermediate (orange), low (blue).

Perego+2017

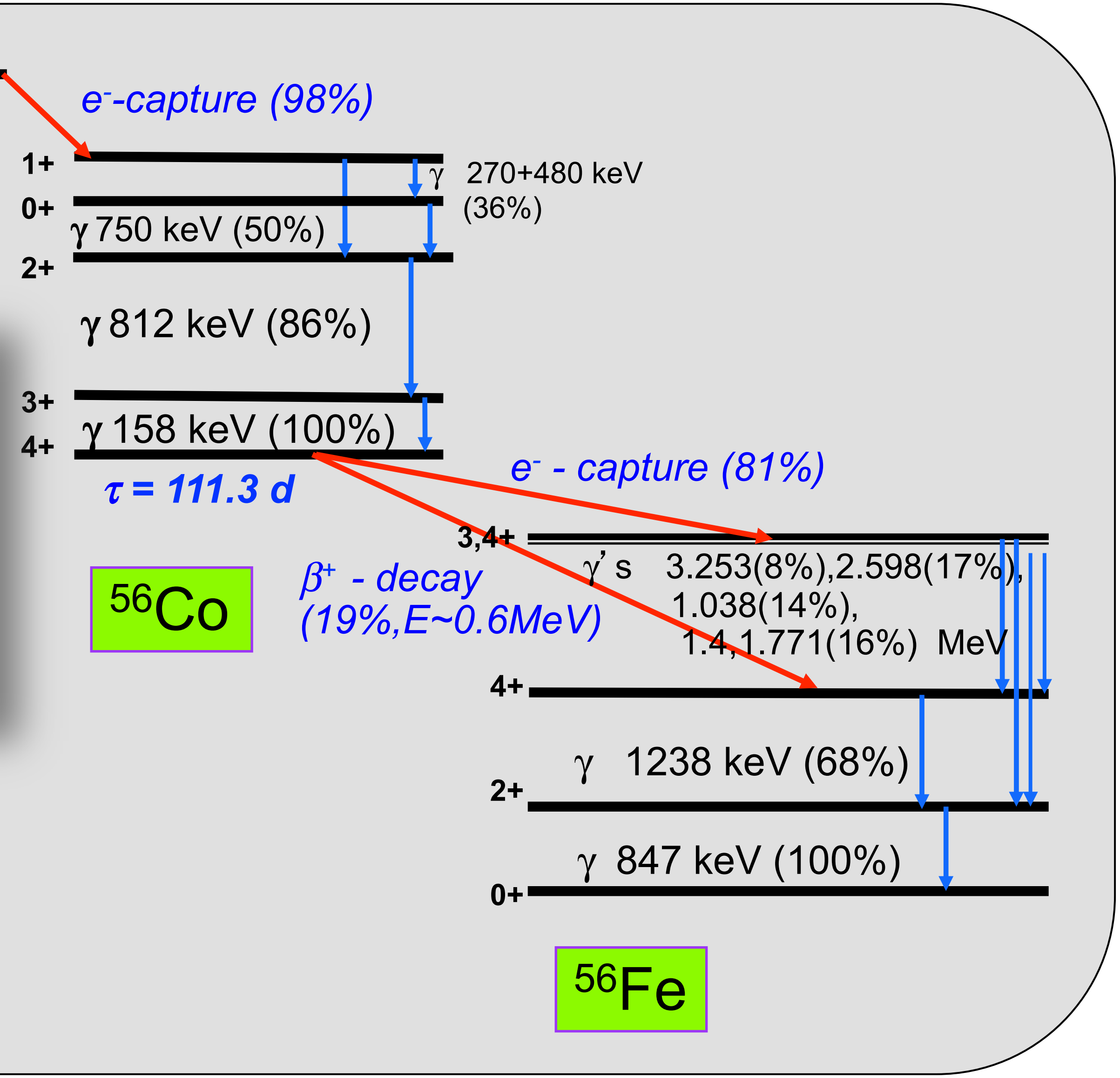
Nuclear-line astronomy

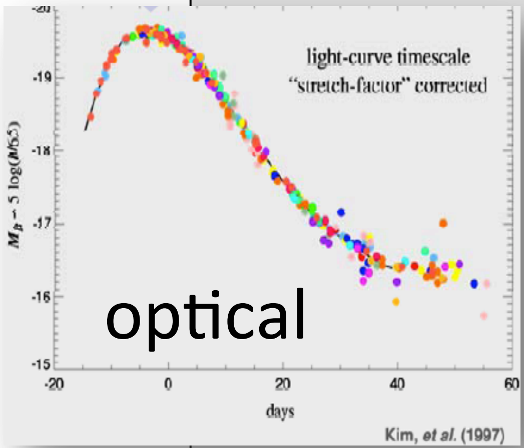


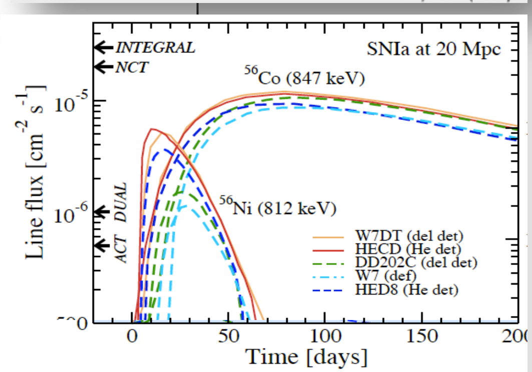
Nuclei (=isotopes!) reveal nucleosynthesis by their decays.

Indirectly, the radioactive decay produces hot envelopes, and radioactive afterglows.

^{56}Ni Radioactivity → Gamma-Rays, e$^+$ (...→ hot gas)







SPI Ge γ-ray Spectrometer on INTEGRAL satellite

Coded-Mask Telescope w Ge Detectors

Energy Range 15-8000 keV

Energy Resolution ~2.2 keV @ 662 keV

Spatial Precision 2.6° / ~2 arcmin

Field-of-View 16x16°

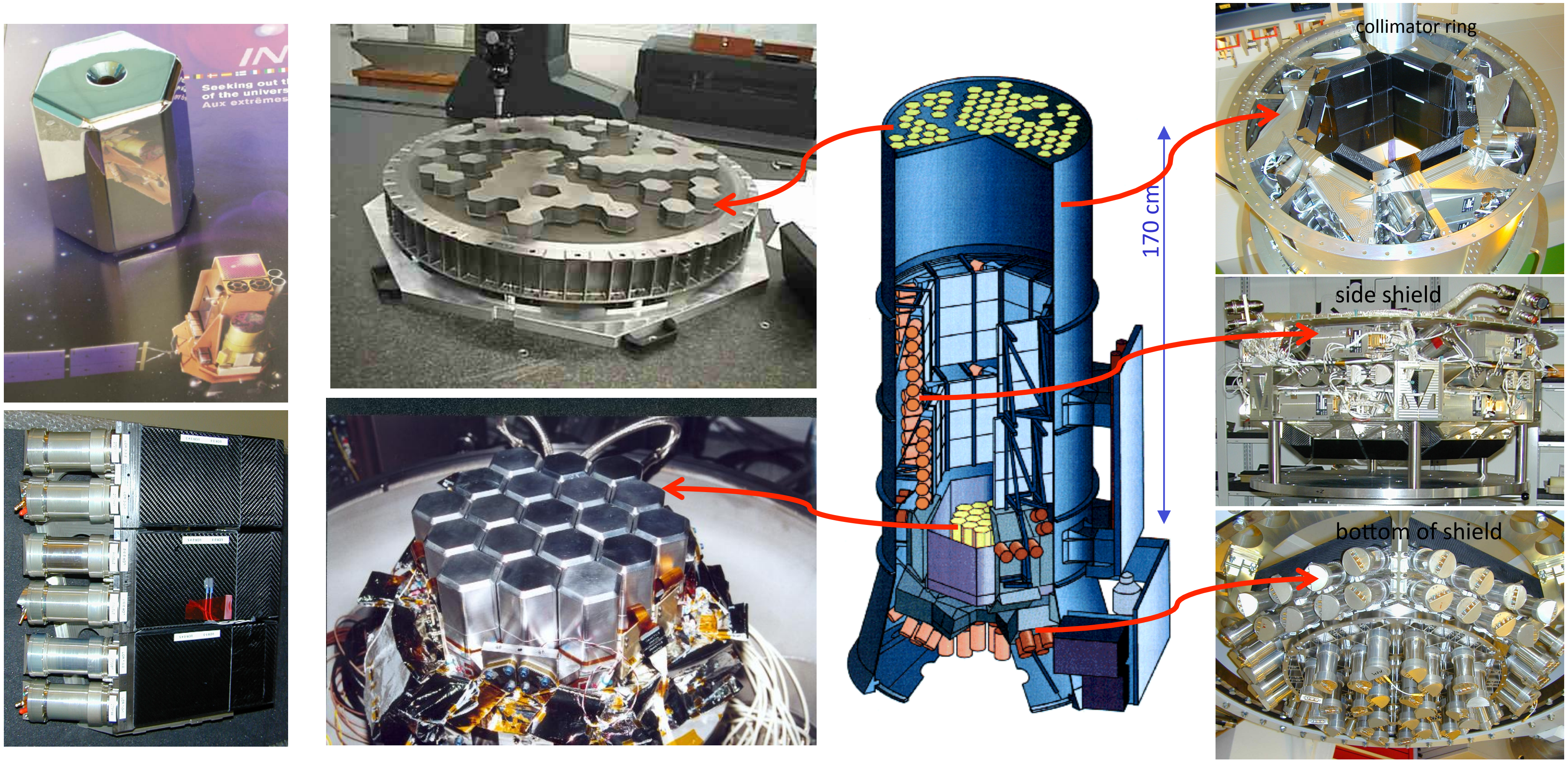
large BGO detector

used as CR AntiCoincidence

E >75 keV, A_{eff} ~0.7 m^2

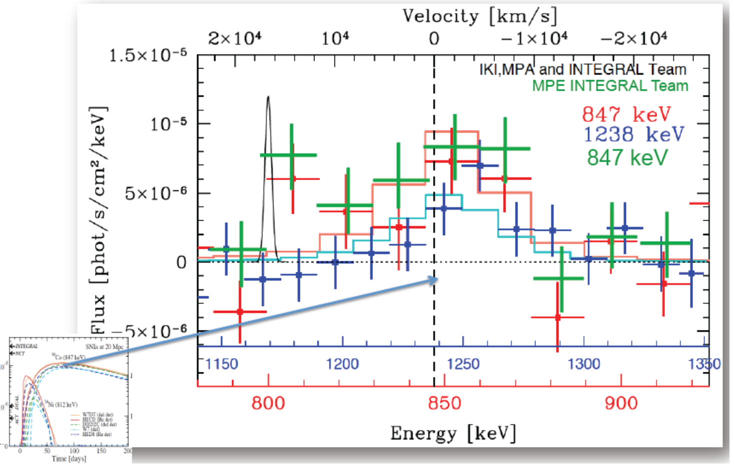
omnidirectional gamma-ray

transients detector



SN2014J data Jan – Jun 2014: ^{56}Co lines

☆ Doppler broadened ✓



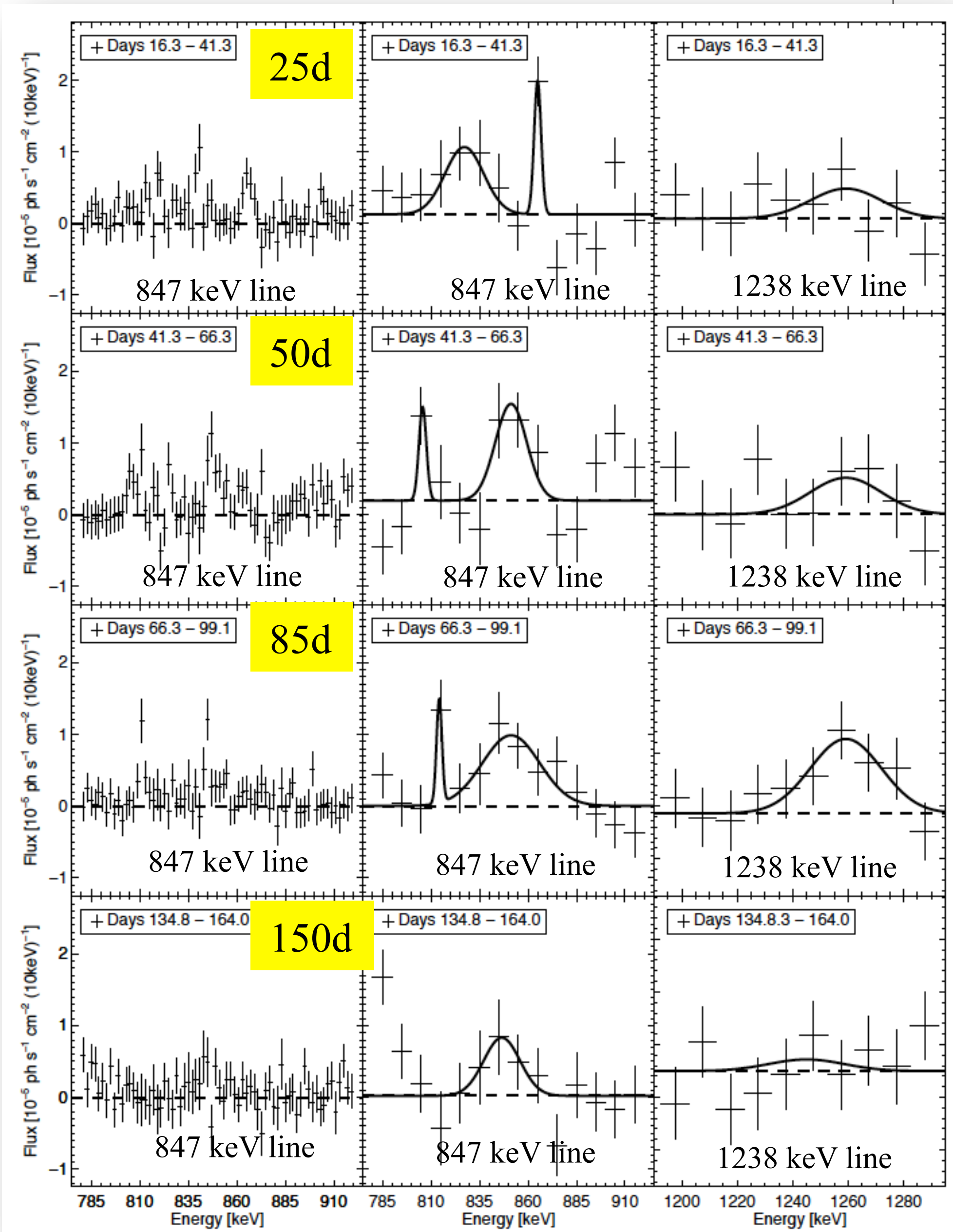
☆ Coarse & fine spectral binning

→ Observe a structured and evolving spectrum

– expected: gradual appearance of broadened ^{56}Co lines

☞ *Diehl et al., A&A (2015)*

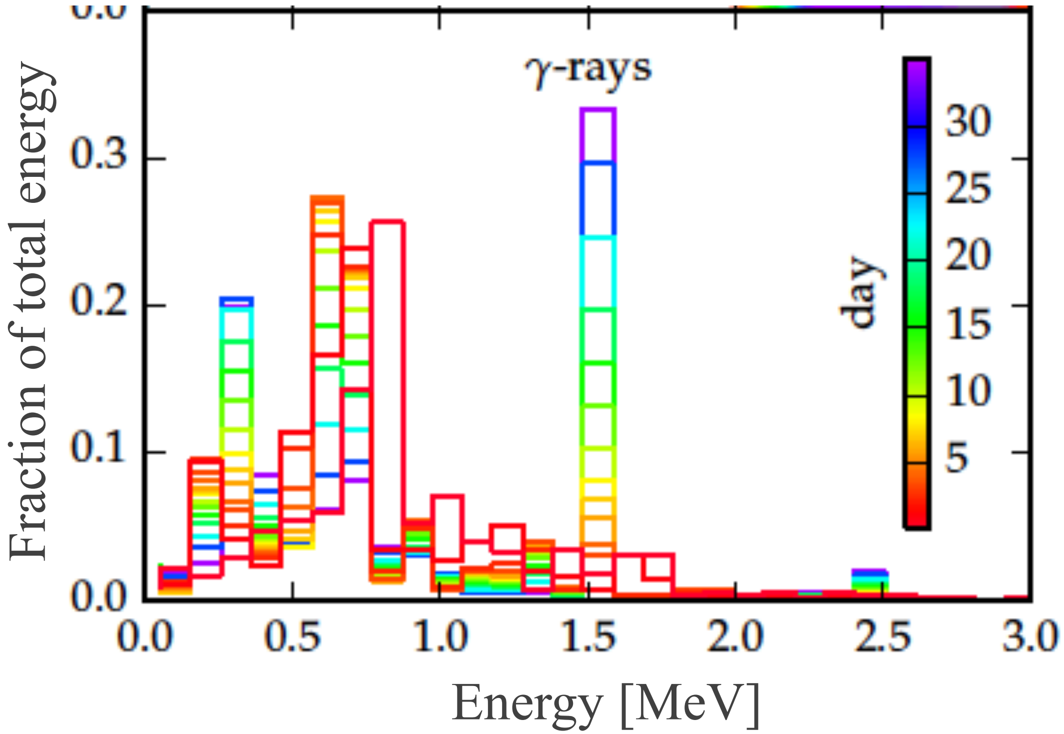
☆ ***How an envelope becomes transparent after an explosion***



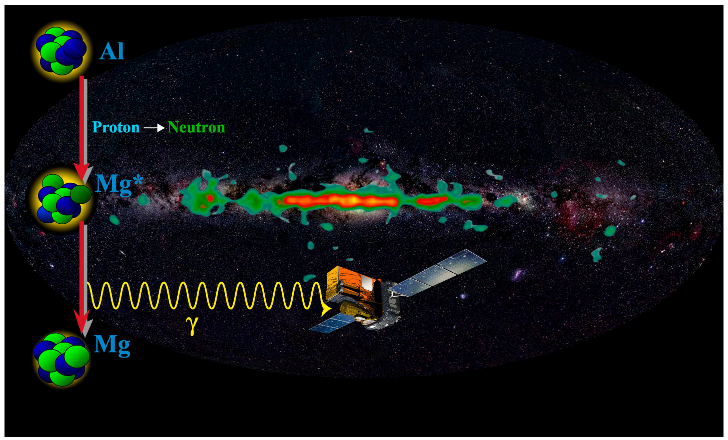
Gamma rays from NSM r-process radioactivities

Superposition of many radioactive species

Barnes et al. 2016

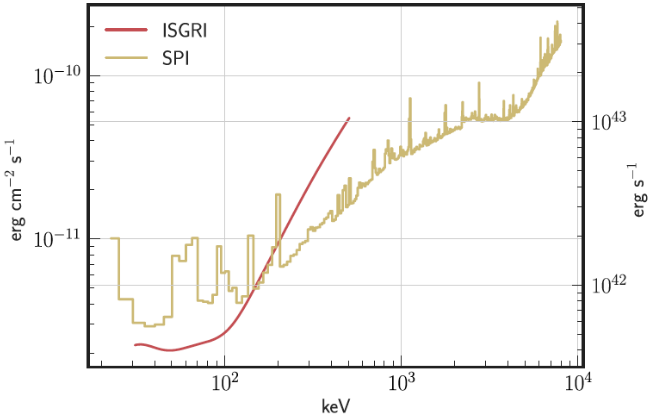


…we know gamma-ray lines from radioactivity:

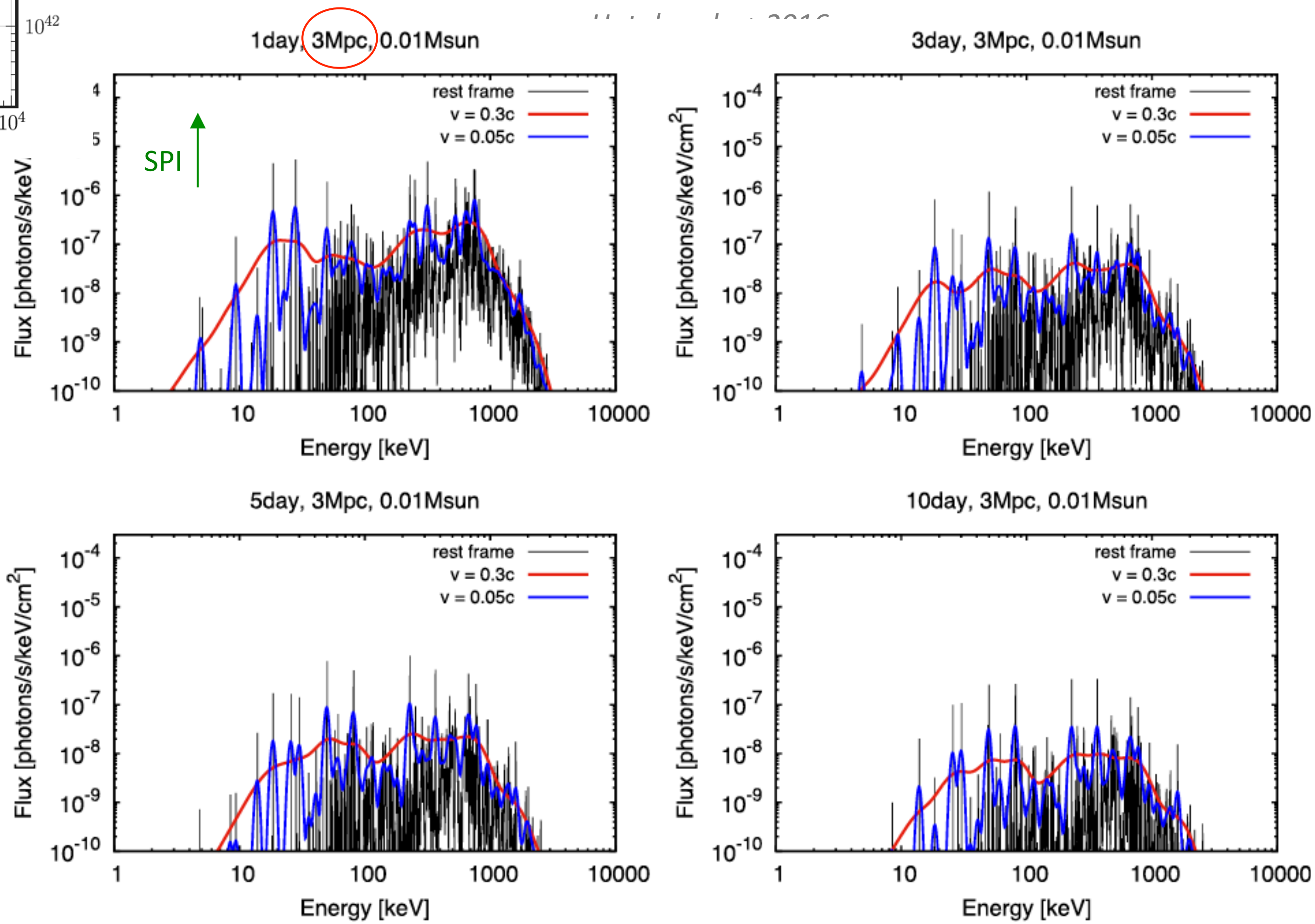


INTEGRAL γ-ray line measurements of GW170817?

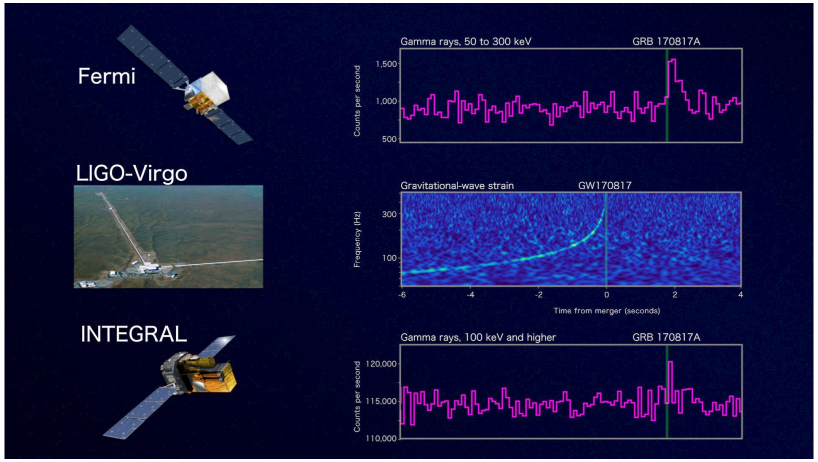
GW170817 is too distant!

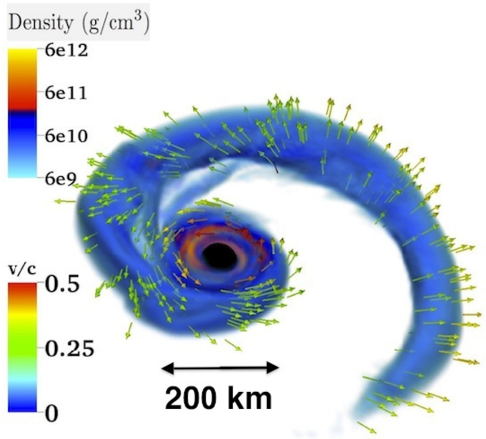


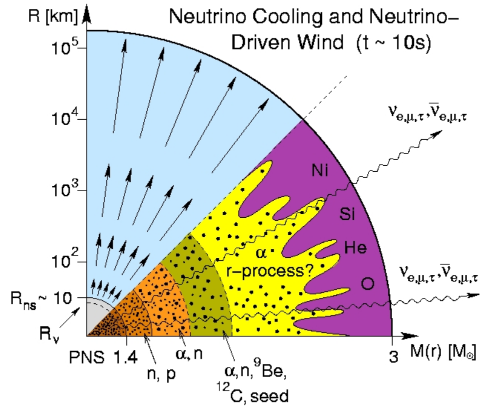
Savchenko et al. 2017



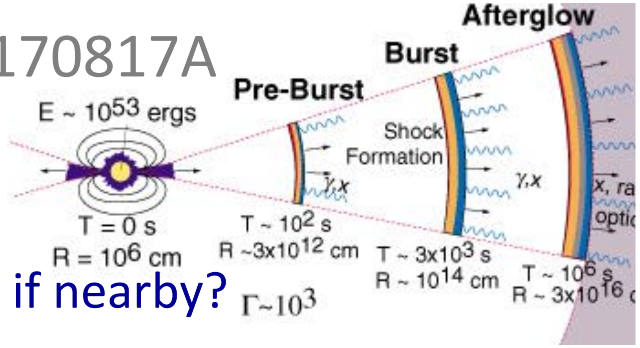
Summary: Gamma-rays from GW170817







Gamma-ray signal seen from GW170817 as GRB170817A

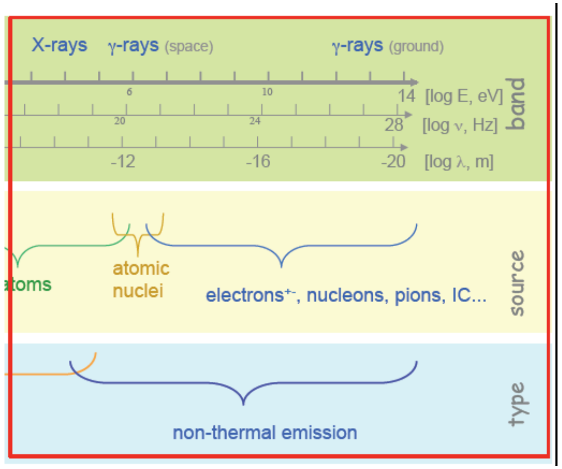


- ☆ clear detection of emission at ~100 keV – a short GRB
- ☆ ~2 sec after GW chirp
- ☆ surprisingly faint → sGRBs different from expectations if nearby?

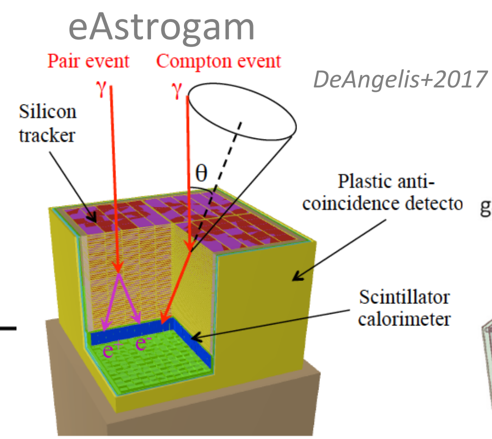
Radioactivity powers electromagnetic afterglow

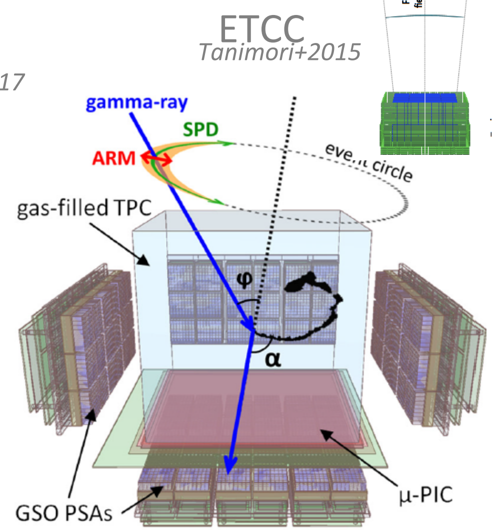
- ☆ nuclear burning → heating of an envelope → 'macronova'
- ☆ probably related to r process (so: observationally-confirmed source)
  - ☞ we still do not know which objects contribute how much to trans-Fe element synthesis
- ☆ too faint to use characteristic gamma-ray lines as unique diagnostic

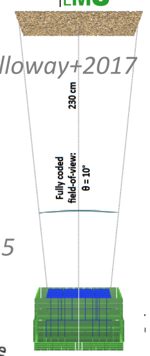
Perspectives: New/better observations?

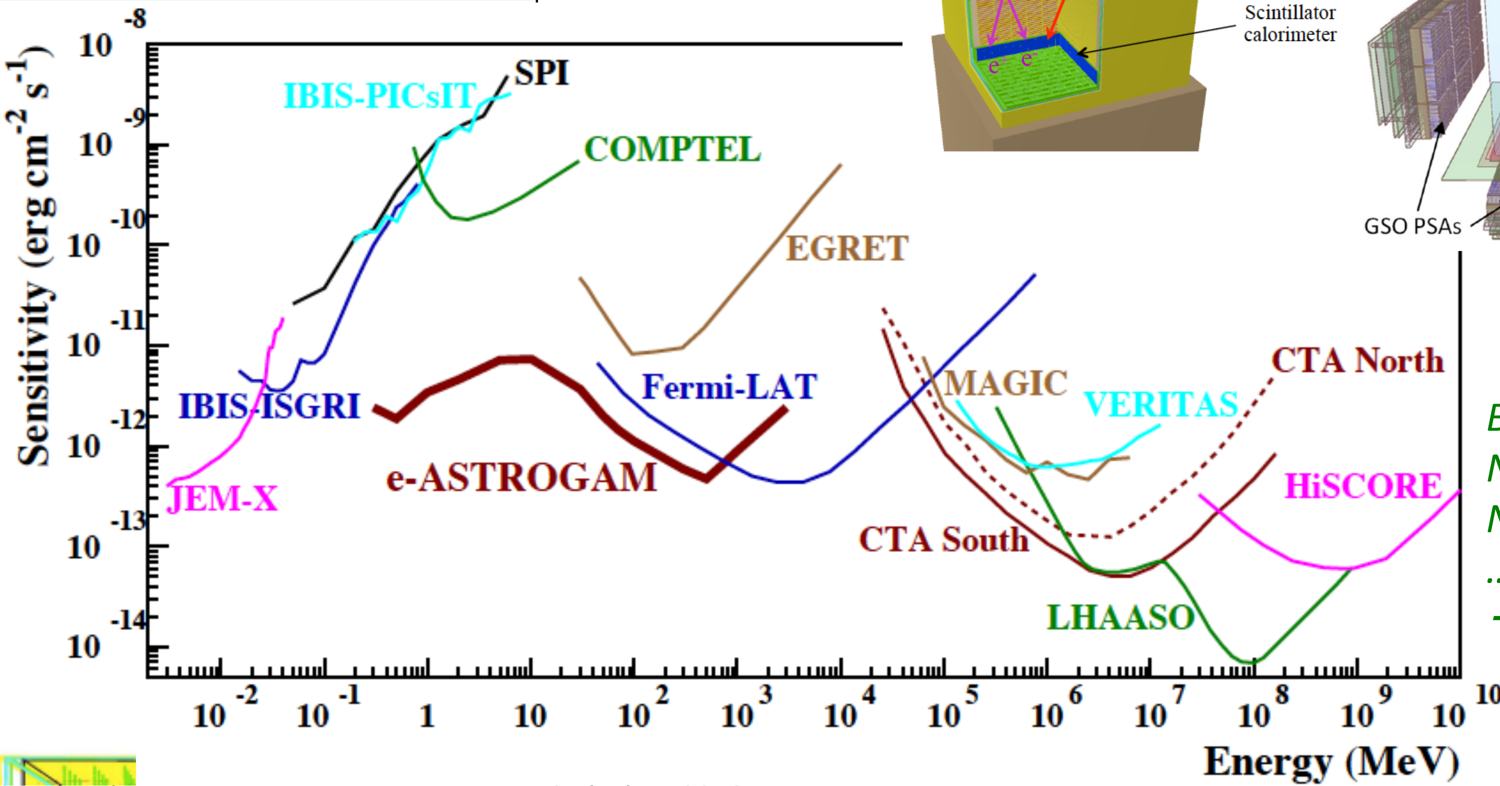


- Can do now >one o.o.m. better now
  - ☆ Compton Telescope most promising









But:
Not before >10 years
Not for narrow lines
…
→ Maintain INTEGRAL/SPI !!