GAMMA-RAY BURSTS IN THE MULTI-MESSENGER ERA

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Kandinksy – Composition 8- 1923
Guggenheim Museum, New-York

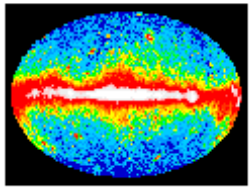
Kandinksy – Curves and sharp angles - 1923
Guggenheim Museum, New-York

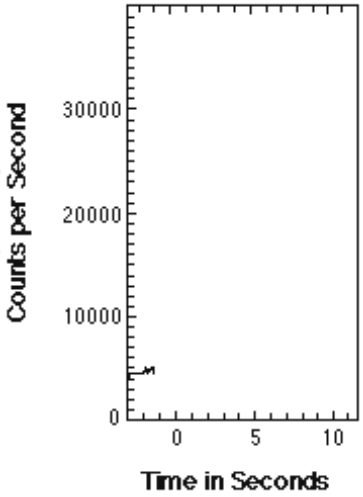
Les rencontres de Noirmoutier 2026 – Thursday 4 June 2026

INTRODUCTION

GAMMA-RAY BURSTS

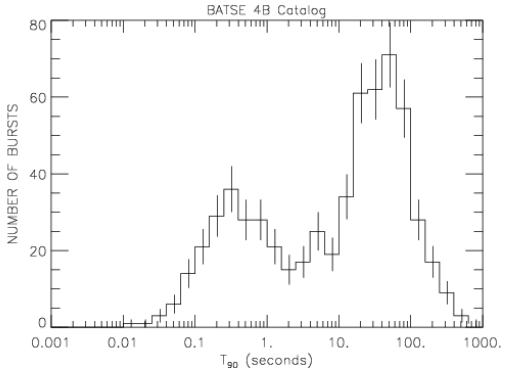
MAIN OBSERVATIONAL FACTS (1) PROMPT EMISSION

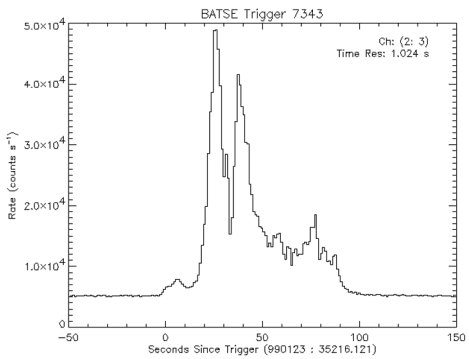


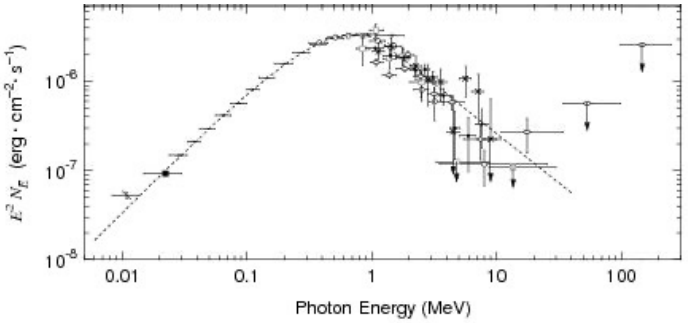


- **High variability :** ms ⟶ 100 ms
- **Short duration:** a few ms to a few min
- **Two classes: short & long GRBs**

BATSE



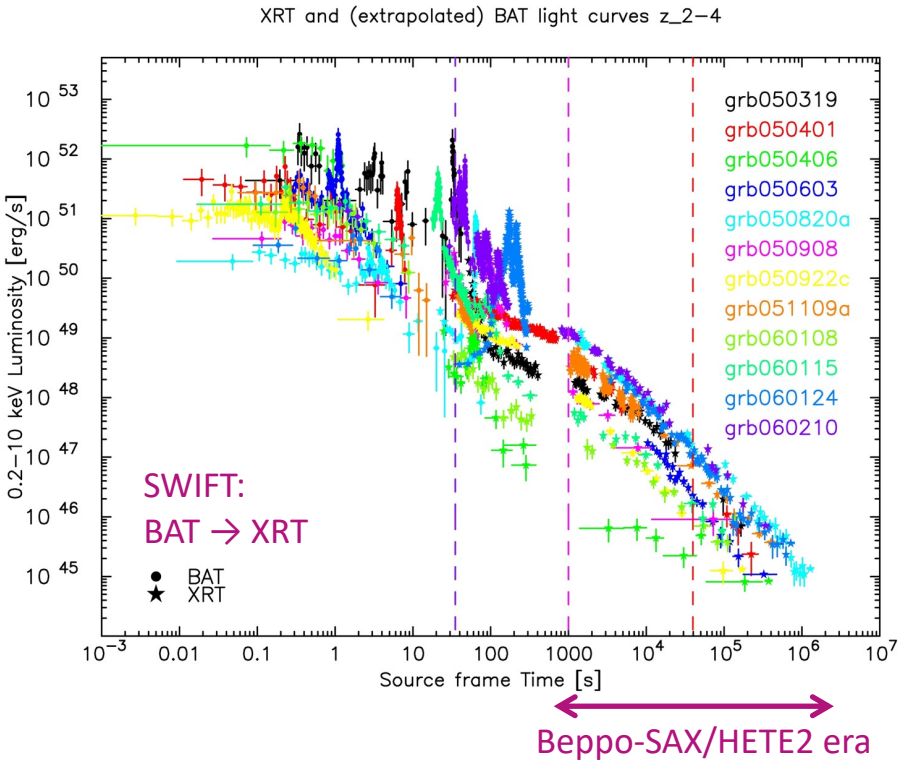




- **Great diversity of lightcurves ; Pulses:** 100 ms ⟶ 10 s
- **Non-thermal spectrum:** peak energy 100 keV ⟶ 1 MeV
- **Spectral evolution**
- **Spectral diversity:** classical GRBs, X-ray rich GRBs, X-ray Flashes, etc.

MAIN OBSERVATIONAL FACTS (2) AFTERGLOW

- **Lightcurves: power-law decay, breaks, variability**
  (flares, plateaus)
- **Spectral evolution:** X-rays to radio

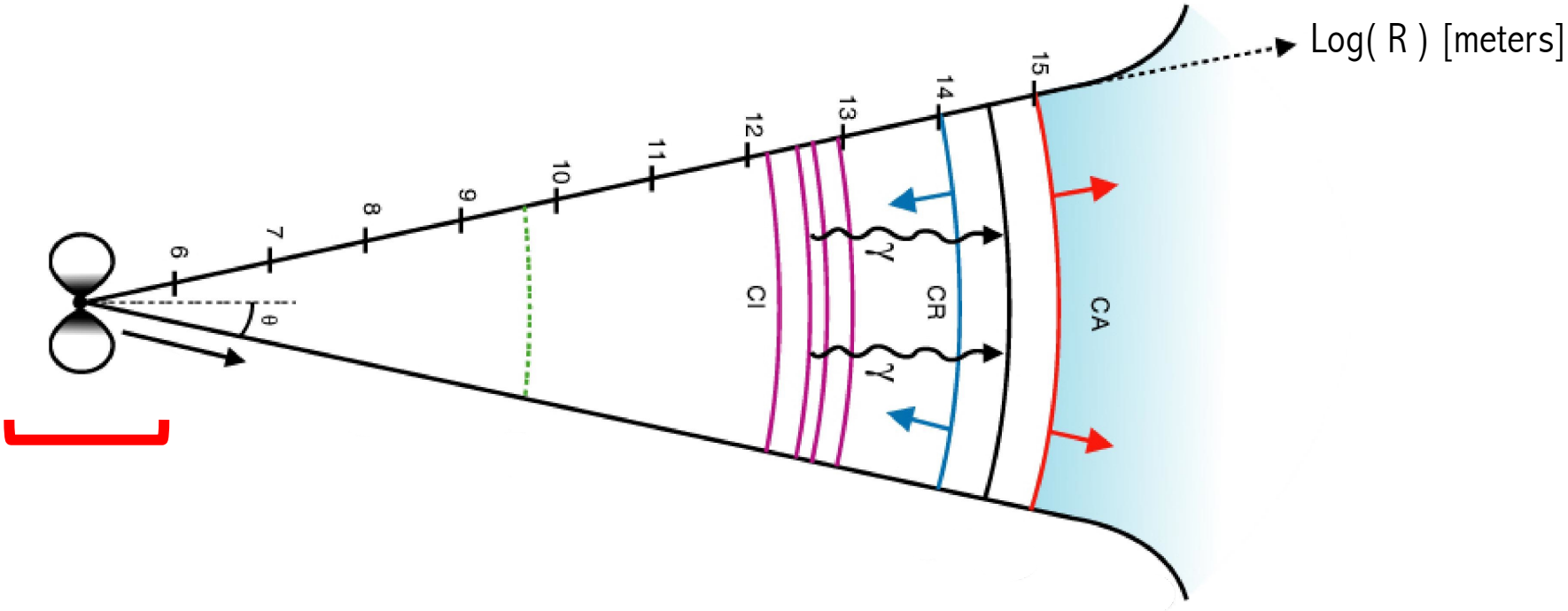


- **Redshift**
  - Mean redshift above 2 for long GRBs
  - Maximum : GRB 090423 at z = 8.2
    GRB 090429B at z = 9.3
  - **E_{iso} ~ 10^{51} to 10^{54} erg**
    (some under-luminous ; some monsters…)

- **Host galaxy**
  - Clear difference between short & long bursts (long GRBs: only star-forming galaxies)
  - Different progenitors

THEORY

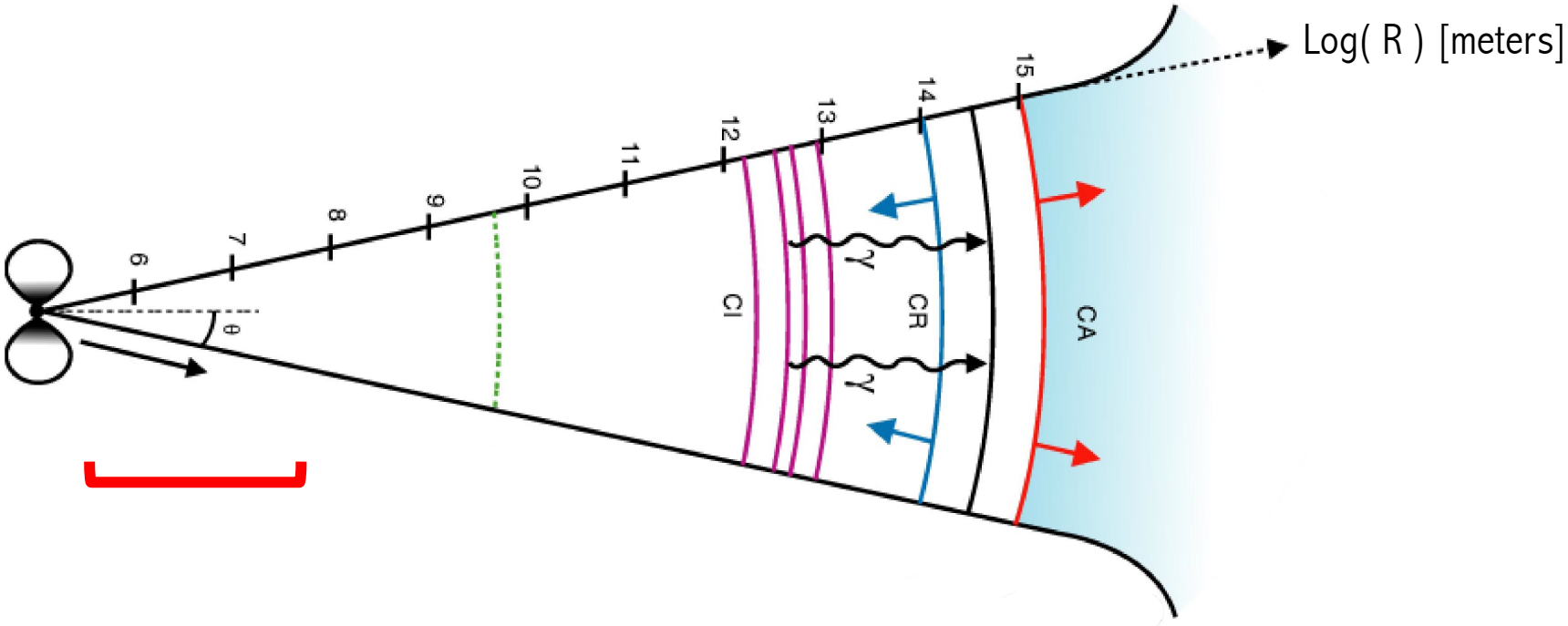
- Cosmological distance: huge radiated energy ($E_{iso,\gamma} \sim 10^{50}$-$10^{55}$ erg)
- Variability + energetics: violent formation of a stellar mass BH/magnetar



Progenitors: Long GRBs: collapse of some massive stars / probable diversity
Short GRBs: NS+NS(/BH ?)merger

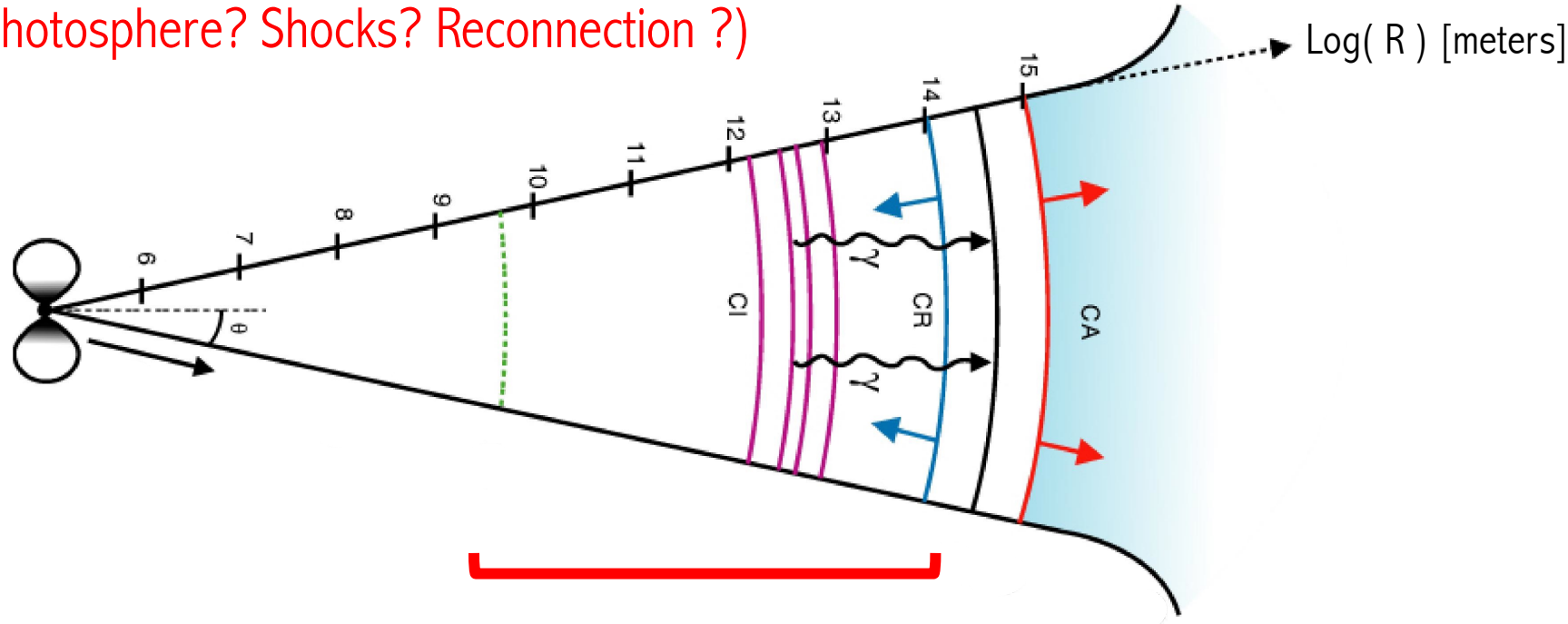
THEORY

- Variability + energetics + gamma-ray spectrum: relativistic ejection



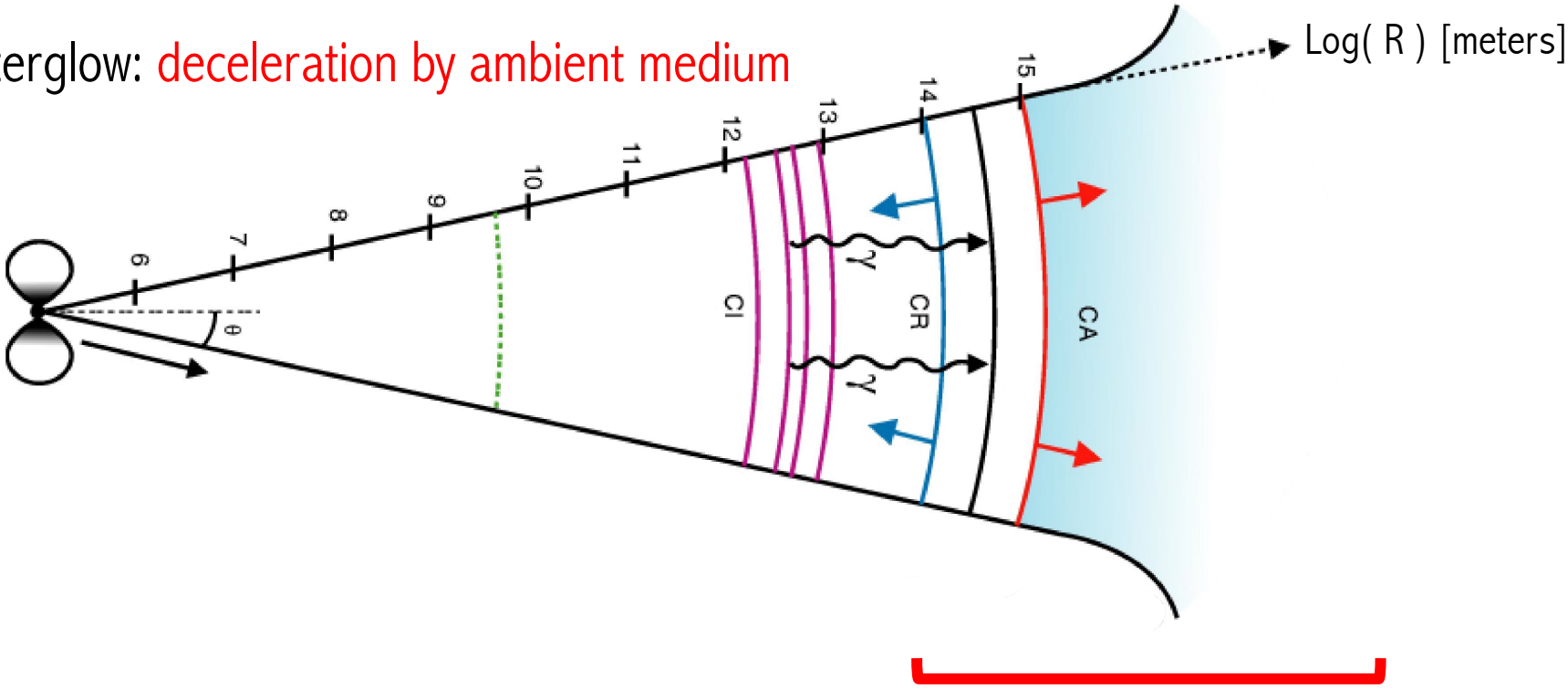
THEORY

- Variability + energetics + gamma-ray spectrum: relativistic ejection
- Prompt keV-MeV emission: internal origin in the ejecta (photosphere? Shocks? Reconnection ?)



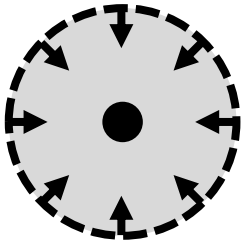
THEORY

- Variability + energetics + gamma-ray spectrum: relativistic ejection
- Prompt keV-MeV emission: internal origin in the ejecta
- Afterglow: deceleration by ambient medium

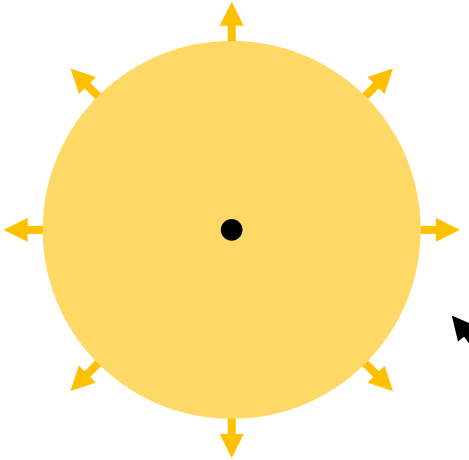


PROGENITORS – SN/KN

Massive stars:
Core-Collapse



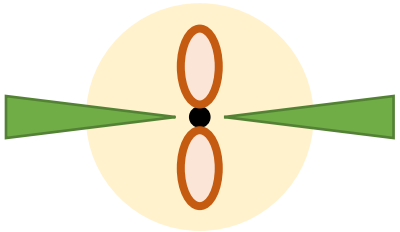
Mass? Metallicity?
Rotation? Binarity?



Supernova

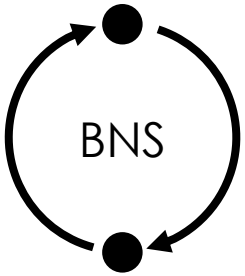
Continuum of events?
Low-L GRBs, XRFs, XRRs, etc.

AND/OR



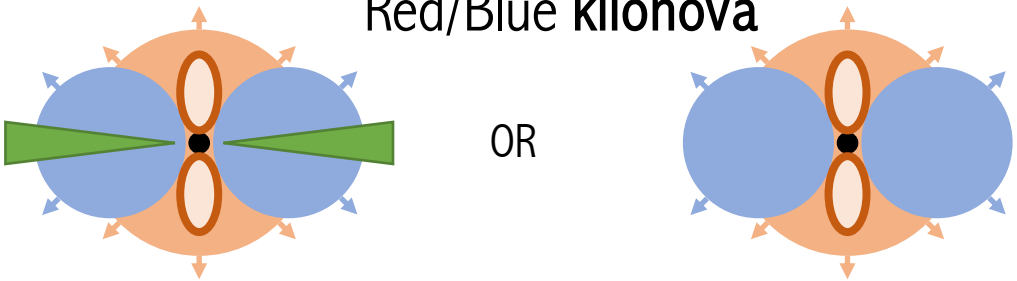
Long GRB (with or w/o **SN**?)

Mergers:



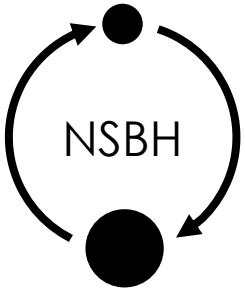
BNS

Red/Blue **kilonova**

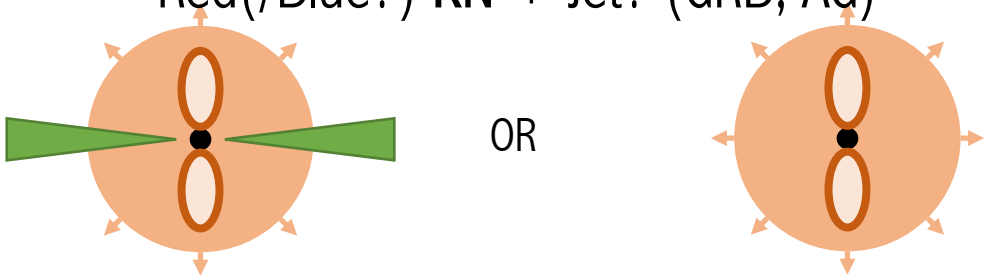


OR

Red(/Blue?) **KN** + Jet? (GRB, AG)



NSBH



OR

Or nothing for a large mass ratio… (« just GW »)

WHY IS IT INTERESTING TO STUDY GRBS?

- **Astrophysics: many open questions**
  - Understand the progenitors, their environments, the link to stellar evolution, the diversity of the GRB population, etc.
  - Understand the nature of the central engine, the mechanism for the relativistic ejection, the properties of the relativistic jet, etc.
  - Understand the dissipation mechanisms in the jet, the particle acceleration mechanisms, the radiation processes, etc.
- **GRBs as a tool for cosmology: very bright sources in the distant Universe.**
  - Study of distant galaxies, chemical evolution, etc.
  - Access to the reionization era? GRBs associated to the first generation of stars?
- **GRBs a a tool to test fundamental physics**
  - Matter at ultra high density (central engine) ; extreme magnetic fields, etc.
  - Distant sources with a short duration: tests related to the propagation (arrival time at different photon energies, or between photons and an other messenger).
- **GRBs are promising multi-messenger sources!**

INTRODUCTION

SVOM, A CHINESE-FRENCH MISSION FOR THE MULTI-WAVELENGTH OBSERVATION OF GAMMA-RAY BURSTS

SVOM

GRB Detection and localization:

ECLAIRs (coded-mask telescope)

GRM (larger fov, no localization)

GRB Prompt emission:

ECLAIRs+GRM (4 keV-5 MeV)

Afterglow:

Space: MXT (X-rays) and VT (visible)

Ground: GWAC, C-GFT, Colibri (visible)

Real-time alerts + partners

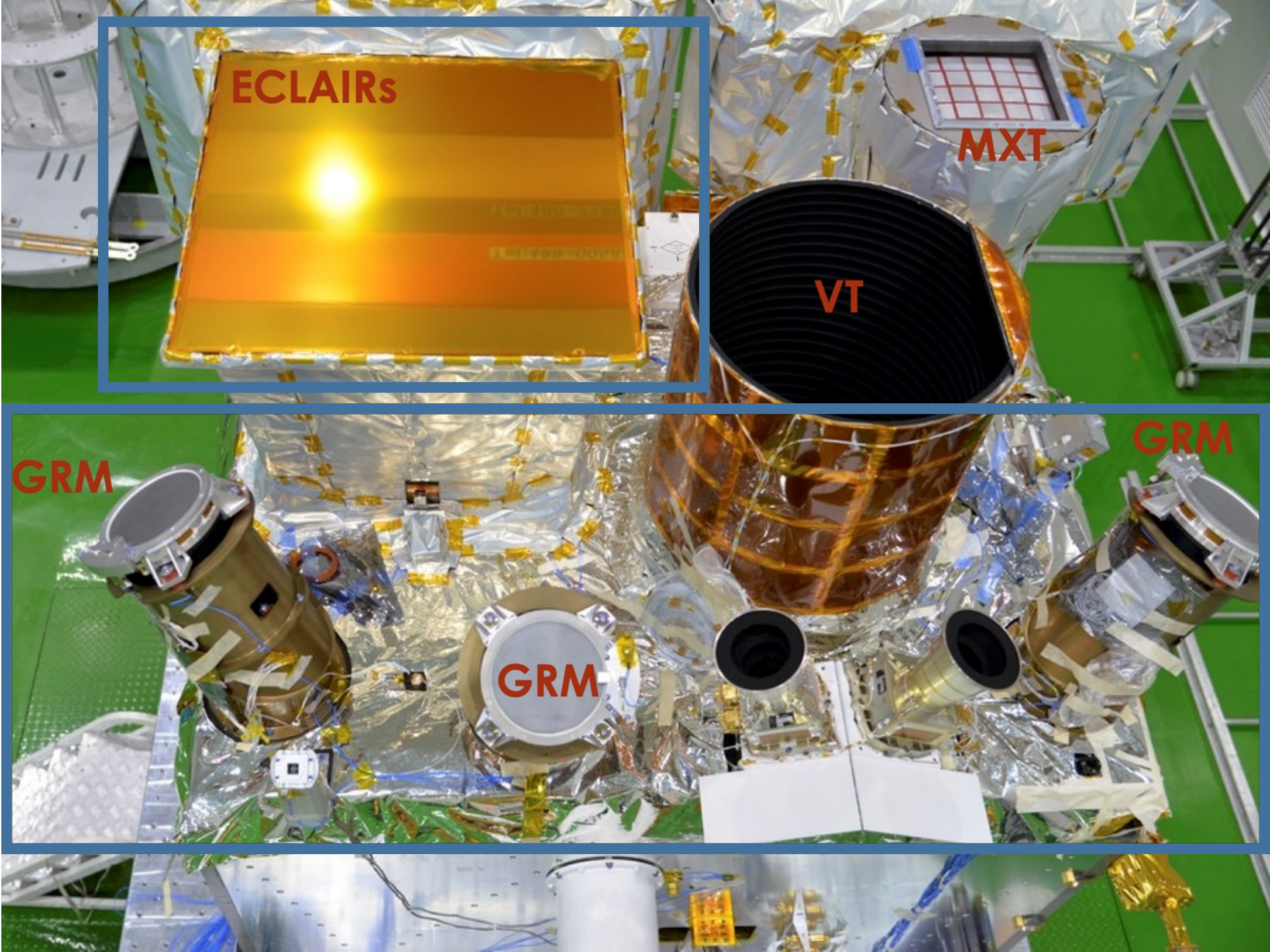
+ other facilities:

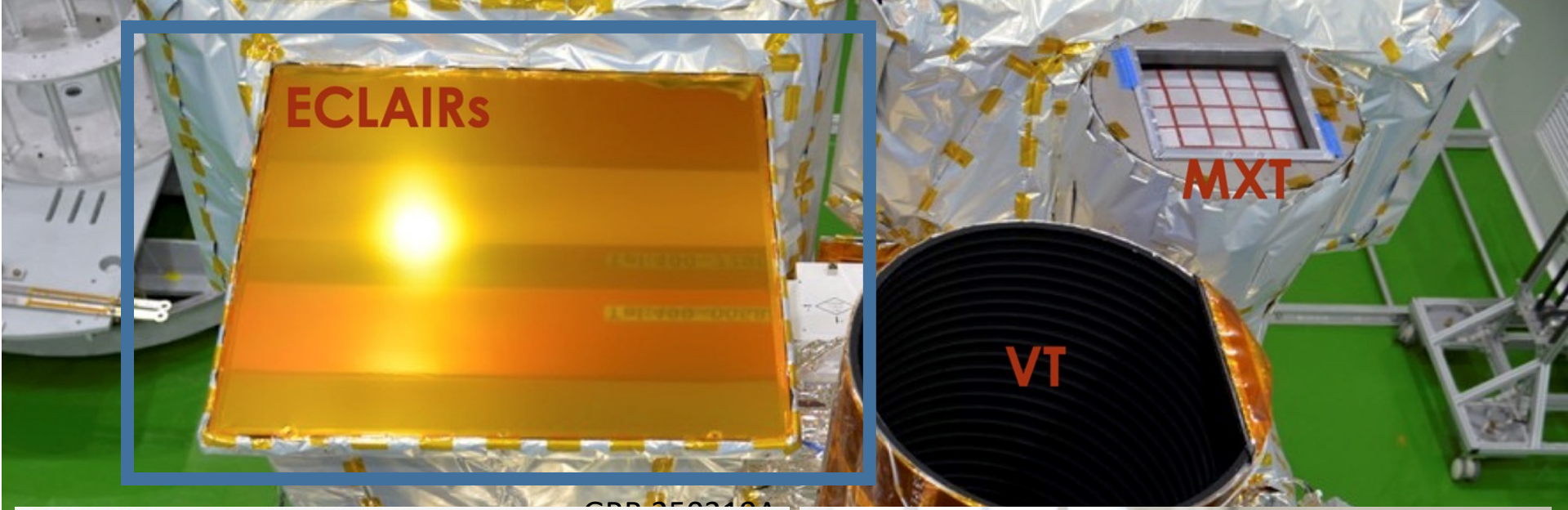
redshift, host galaxy, etc.

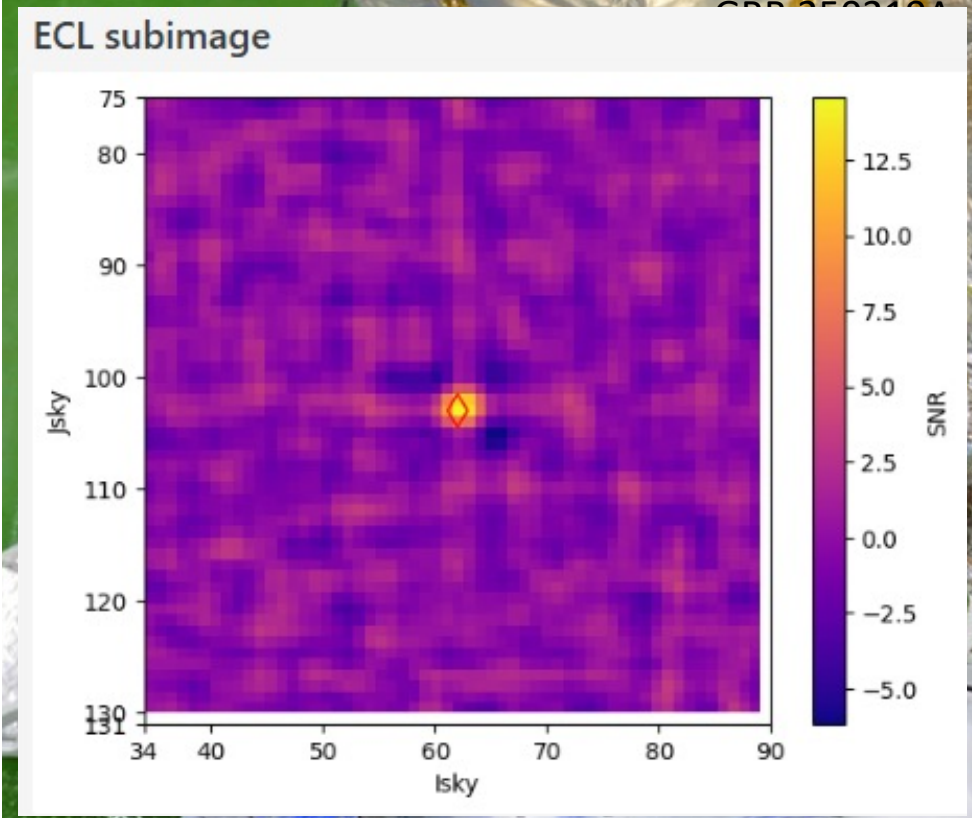
Launched in June 2024

More than 200 GRBs already detected

ECLAIRs: ~50-60 GRBs/year, about ~50% well characterized (including redshift)


ECLAIRs
MXT
VT
GRM
GRM
GRM


ECLAIRs
MXT
VT


ECL subimage
Jsky
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SNR
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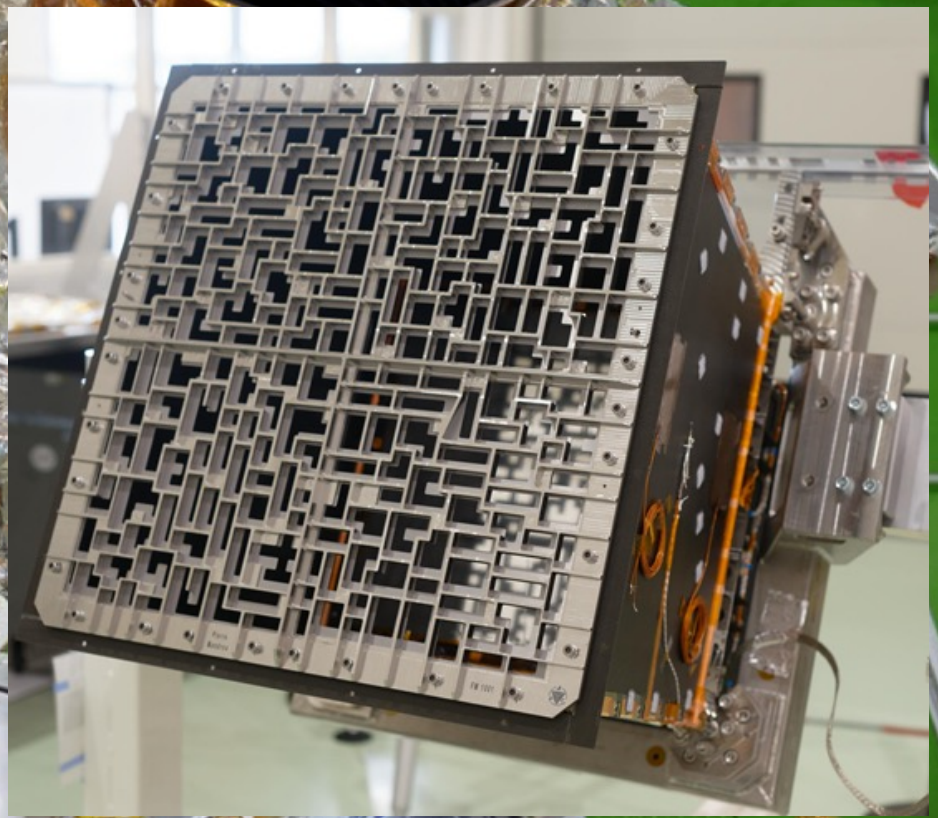
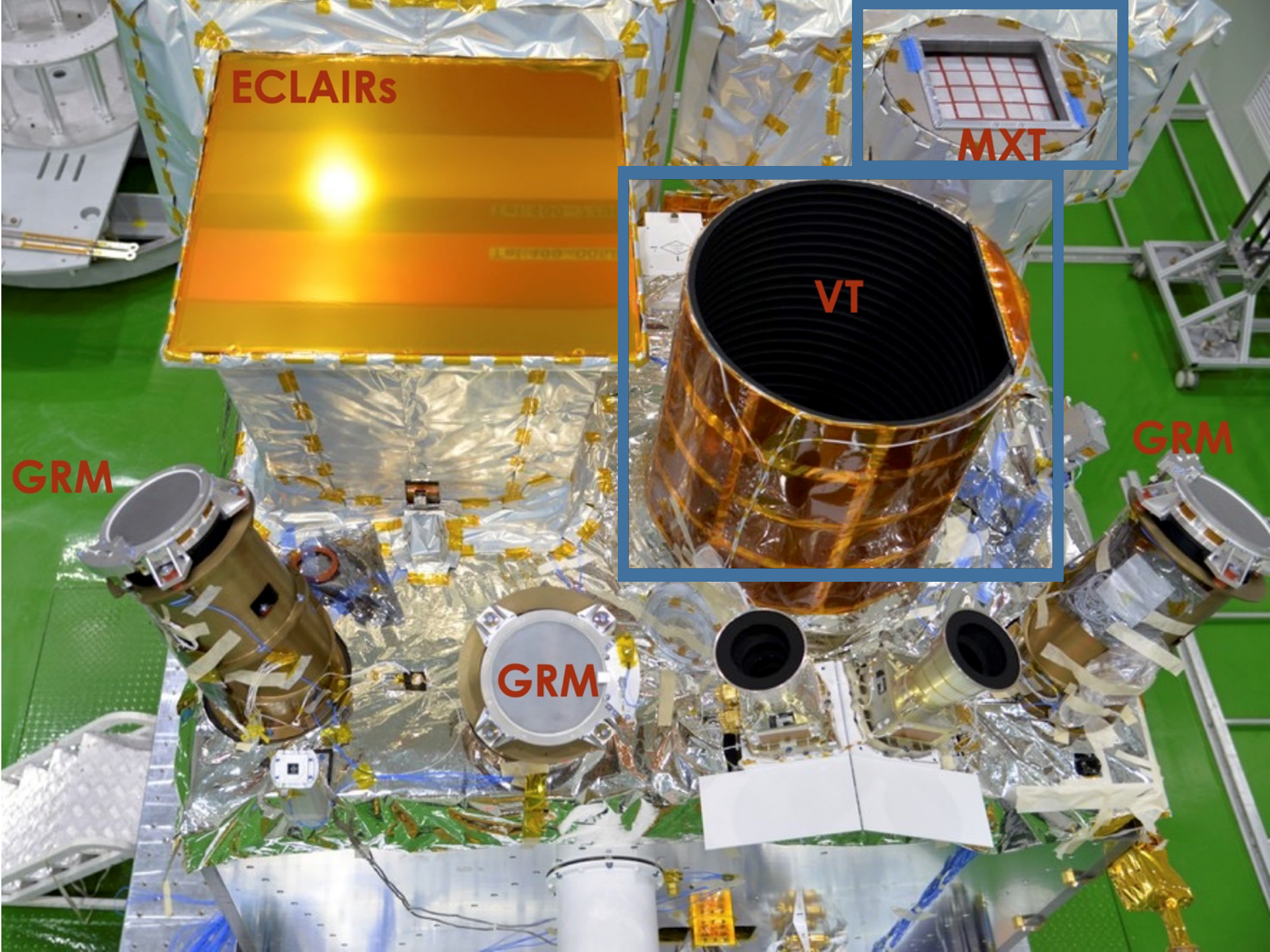
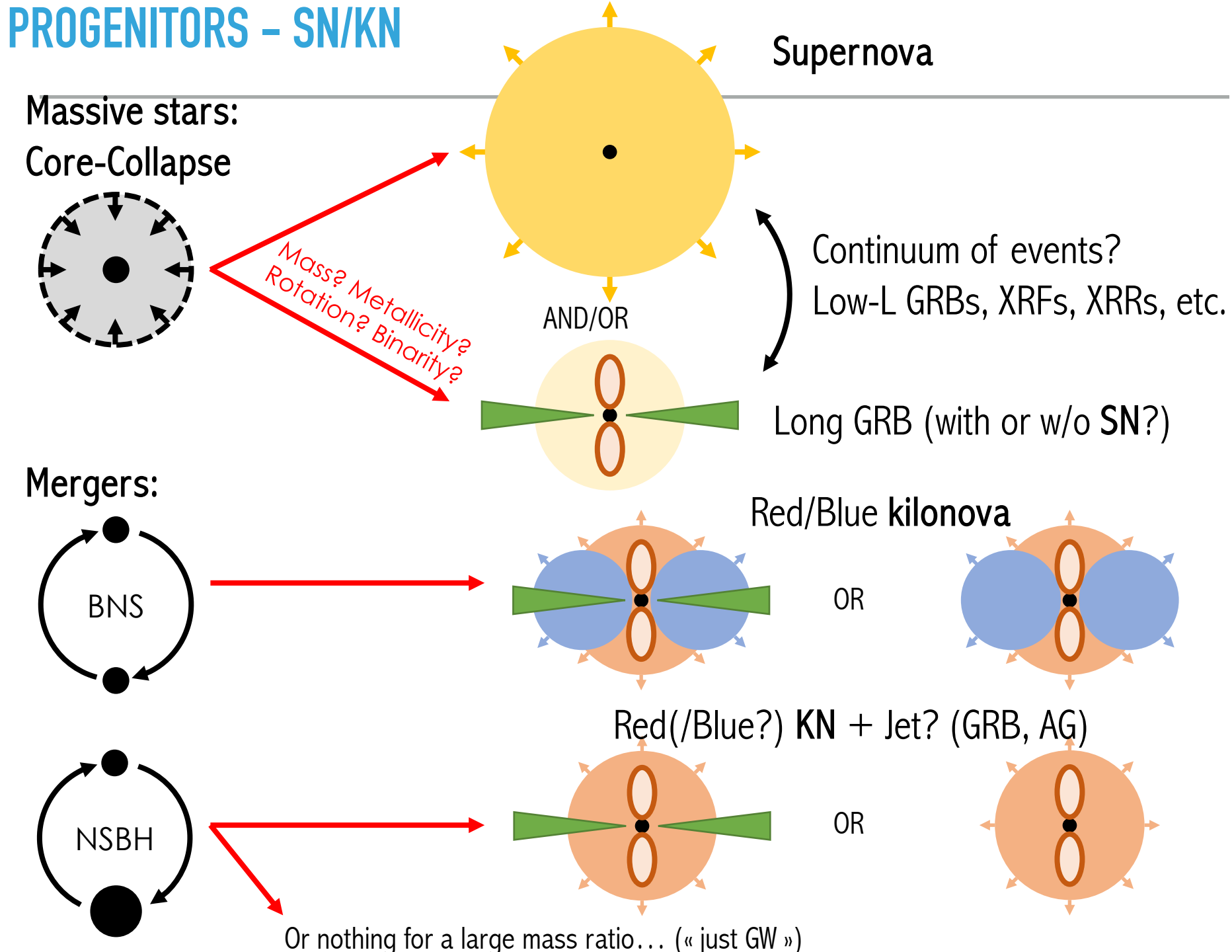



ECLAIRs
MXT
VT
GRM
GRM
GRM

INTRODUCTION

GAMMA-RAY BURSTS AS MULTI-MESSENGER SOURCES

PROGENITORS – SN/KN



GRBS & GW/NEUTRINO ASSOCIATIONS

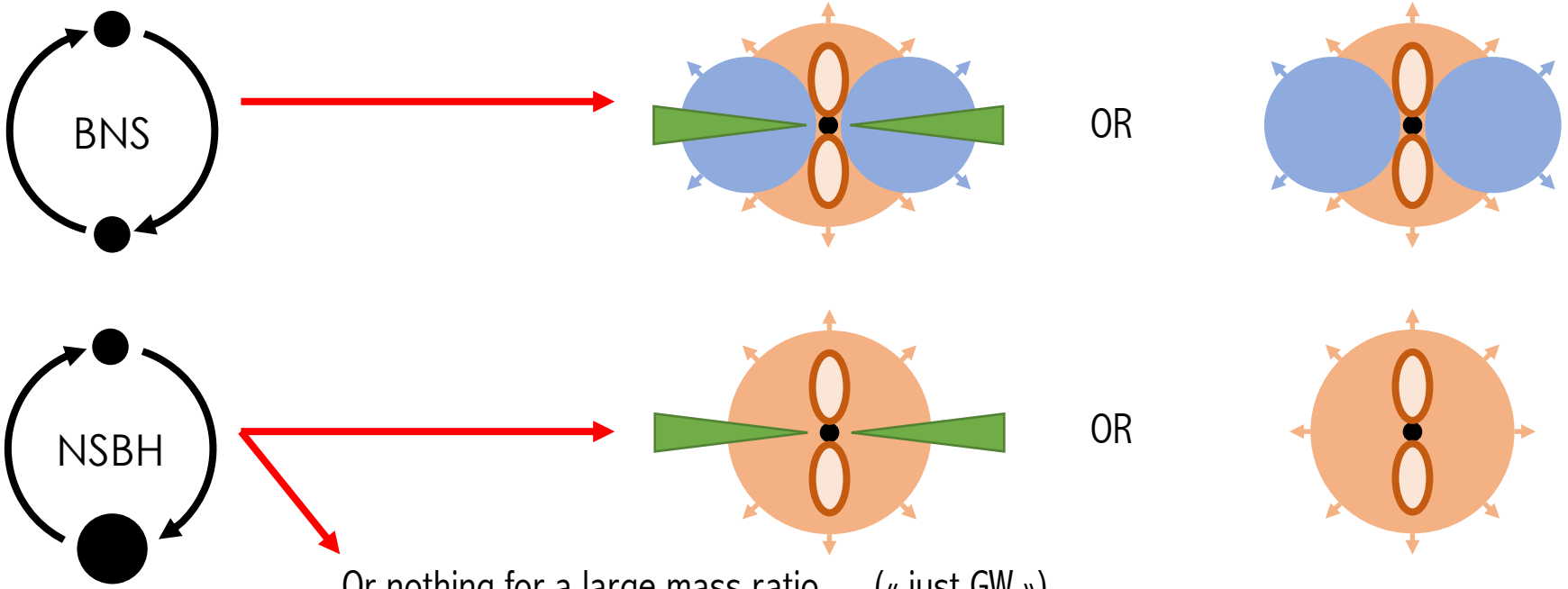
Massive stars:
Core-Collapse

Mass? Metallicity?
Rotation? Binarity?

AND/OR

Best case for GRB-GW associations (already 1 MMA event: 170817 = GW+SGRB+AG+KN)

Mergers:



GRBS & GW/NEUTRINO ASSOCIATIONS

Massive stars:
Core-Collapse

Mass? Metallicity? Rotation? Binarity?

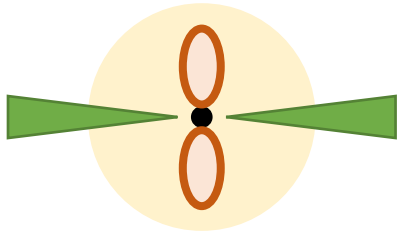
Mergers:

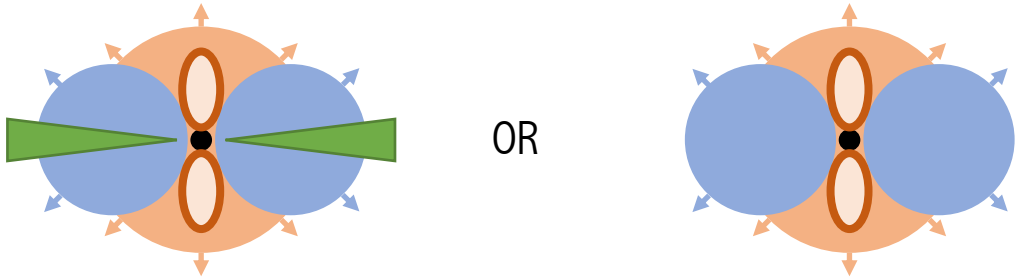
Or nothing for a large mass ratio ? ... (« just GW »)

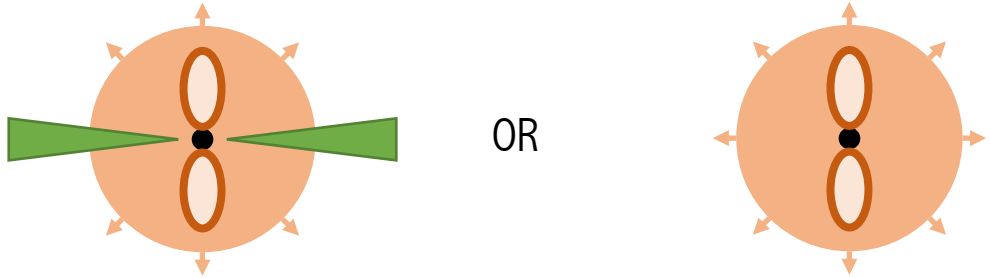
Relativistic jet physics: potential HE neutrino emission

- Early propagation (successful/choked jet)
- Internal dissipation (prompt)
- Deceleration (afterglow)

AND/OR







WHY IS IT INTERESTING TO DETECT NON-ELECTROMAGNETIC EMISSION FROM GRBS?

- **Because physicts love difficult challenges!**
- **Because the information that can be extracted from each messenger is highly complementary!**
  - GW: the nature of the progenitor and initial event
    In the future (post-merger signal): the nature of the central engine
  - Neutrinos: new constraints on the particle acceleration mechanisms, related to the jet physics
  - Light: physics of the jet at large distance, nature of the environment, constraints on the jet geometry and energetics, etc.

GRBS AS NEUTRINO SOURCES

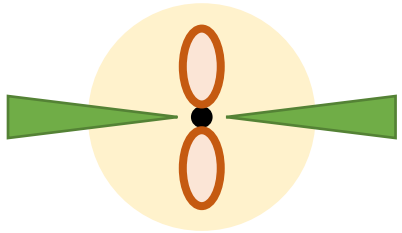
GRBS: NEUTRINO EMISSION?

Relativistic jet physics: potential HE neutrino emission

- Early propagation (successful/choked jet)
- Internal dissipation (prompt)
- Deceleration (afterglow)

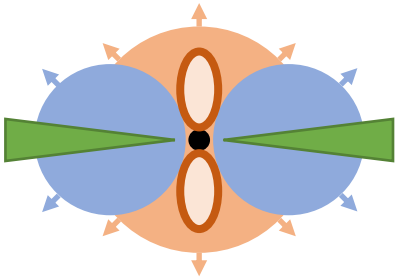
Proton acceleration?

- many possible sites
- no direct evidence from em emission

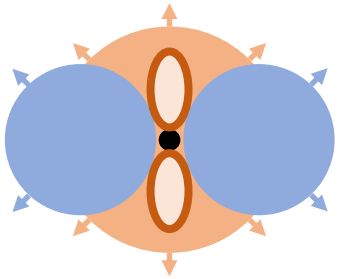


+ photo-hadronic interactions

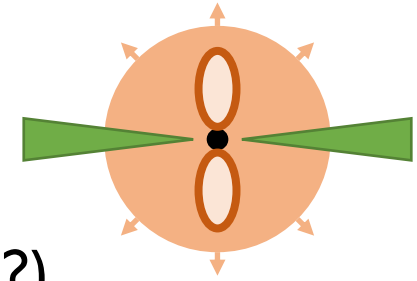
- $10^{14\text{-}15}$ eV neutrinos?
- does not require the production of UHECRs.



OR



(other processes?
neutron decay?
pp collisions in external medium?)



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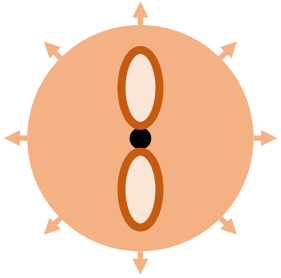
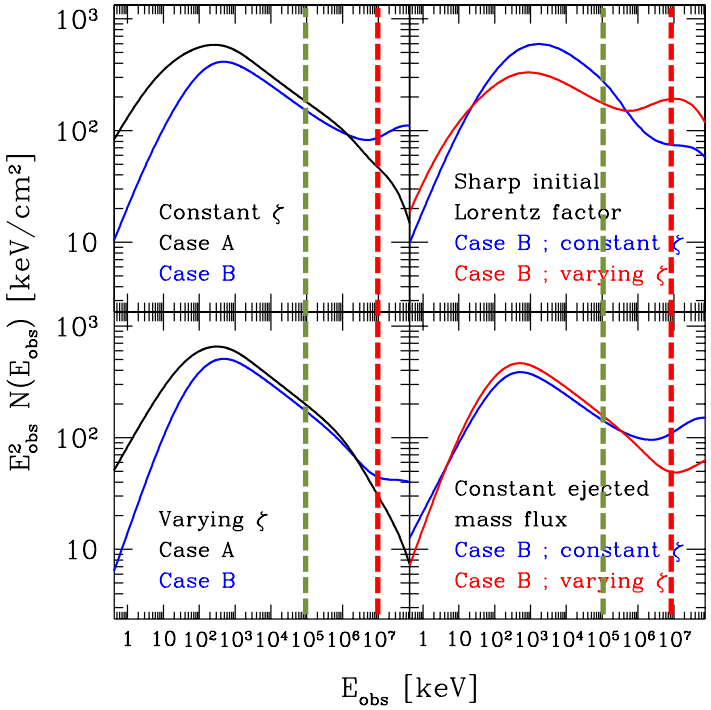


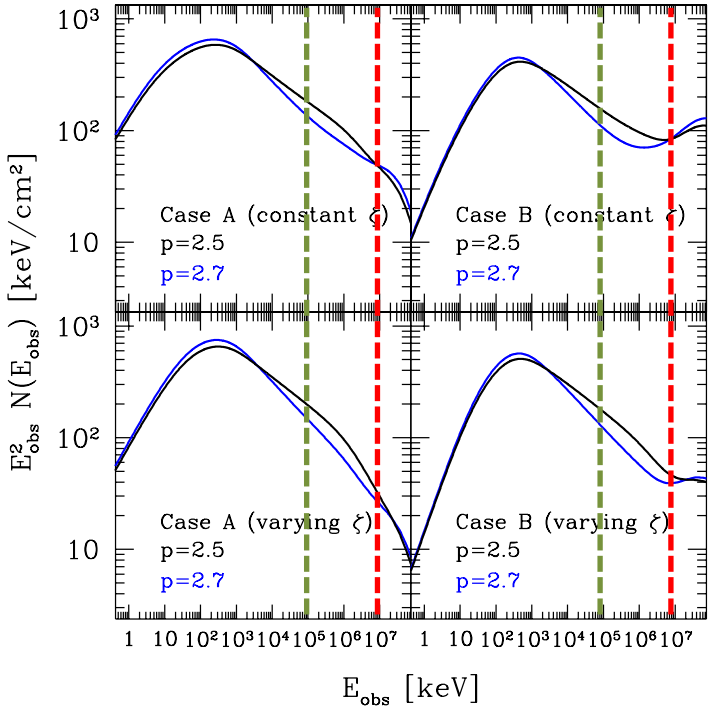
CONSTRAINTS ON PROTON ACCELERATION?

- **Emission from GRBs is usually assumed to be produced by non-thermal electrons.**
- Dissipation mechanism/radiation process still uncertain: electron acceleration poorly constrained.
- **Requires broad-band spectra including VHE gamma-rays.**
- **Specific proton signatures at VHE?**

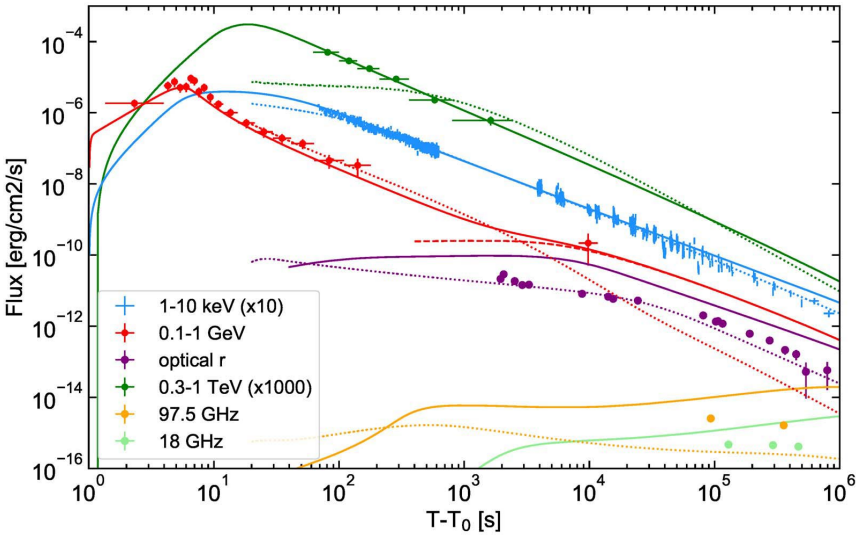
Example: predictions for the internal shock model, purely leptonic (Bosnjak & Daigne 2014)

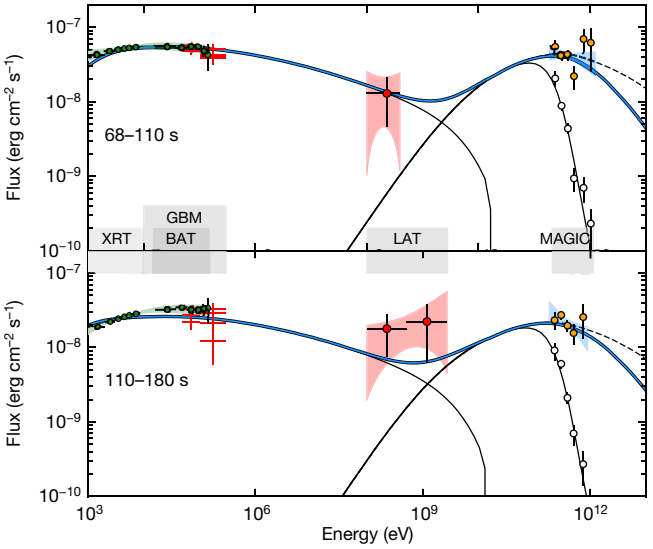
100 MeV 10 GeV



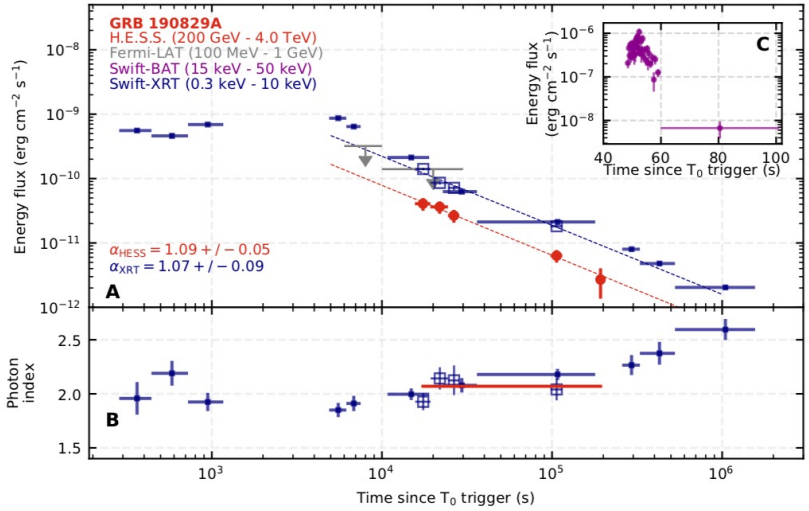


RECENT DETECTIONS OF GRB AFTERGLOWS AT VHE, SOME DIVERSITY





GRB 190114C (MAGIC) @ z=0.14 (MAGIC collab. 2019a,b)



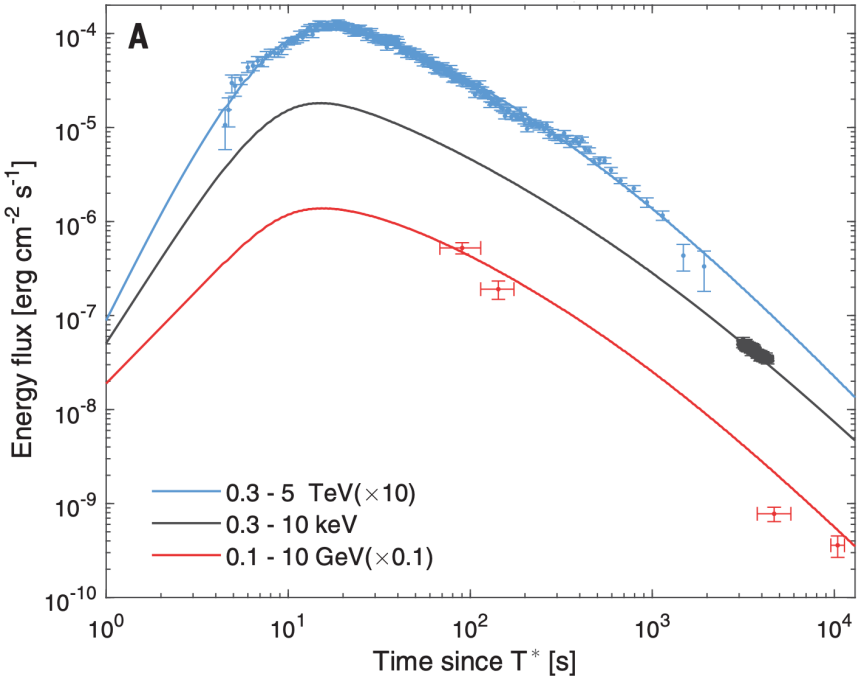
GRB 190829A (HESS) @z = 0.0785 (360 Mpc) (HESS collab. 2021)

Local low-luminosity GRB!

- CTA: better sensitivity, lower low-energy threshold: more detections? rapid reaction (~30 s): prompt VHE emission?

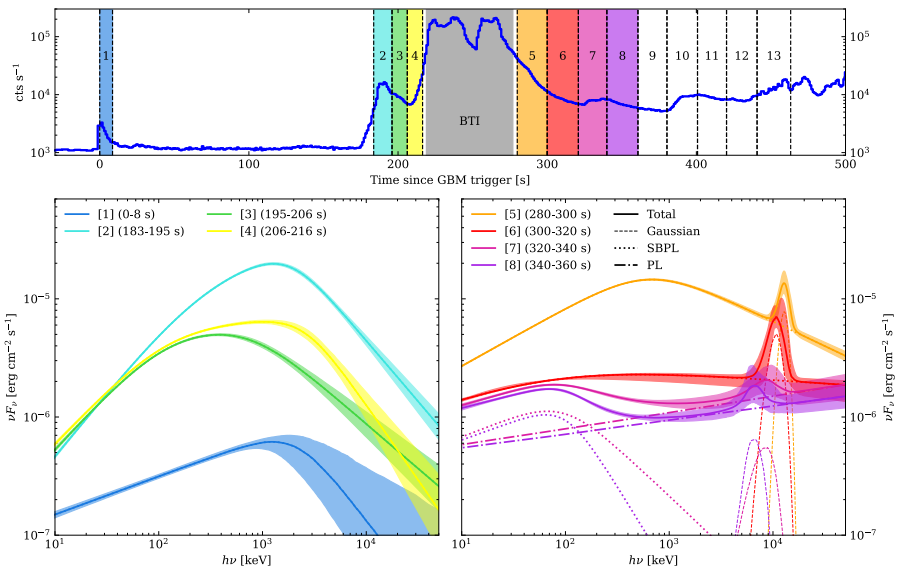
GRB 221009A, THE BRIGHTEST OF ALL TIMES (THE « BOAT »)

- **GRB221009A at z = 0.15: $E_{\gamma,iso}$ ~10^{55} erg!**
- **Early TeV detection by LHASSO, highest energy photon ~13 TeV**
- Complex prompt lightcurve, Fermi/GBM saturated during the main episod
- Emission line at ~10 MeV!
- Complex afterglow: structured jet?
  (excellent follow-up: radio → TeV)



LHAASO Collab 2023

Rise of the TeV afterglow detected by LHASSO



Ravasio et aL. 2023

GRB 221009A, THE BRIGHTEST OF ALL TIMES (THE « BOAT »)

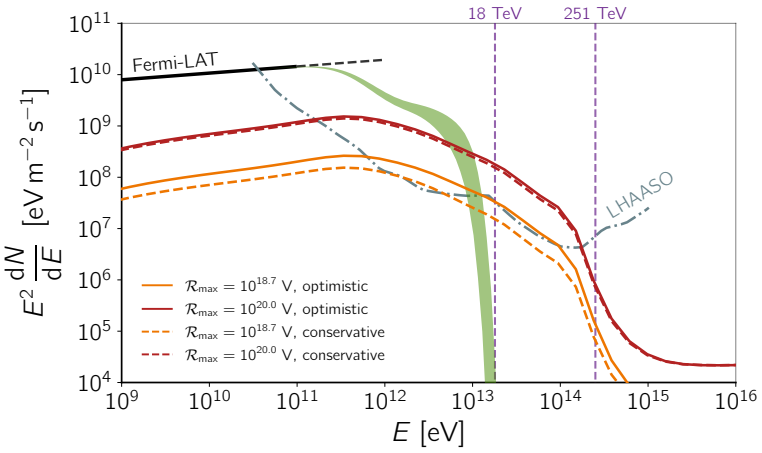
- **No neutrino detection**

despite (a) a huge Eiso ; (b) a short distance ; (c) a VHE gamma-ray emission…

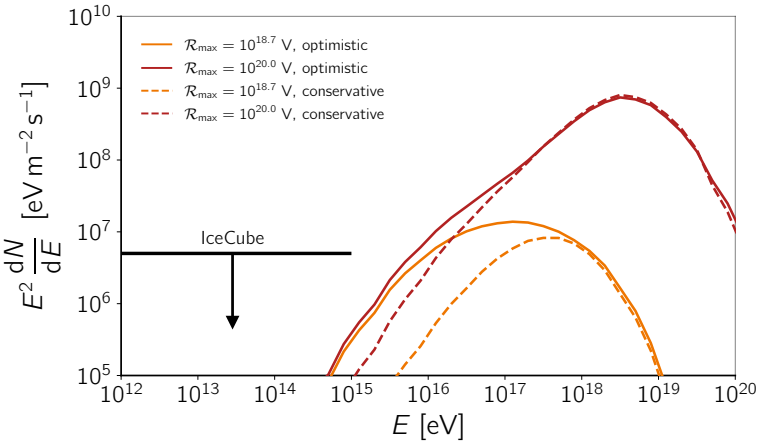
- However=
  - **the highest energy photons detected by LHASSO main hint for CR acceleration.**
  - **Neutrino emission may peak above 10^{16} eV.**

See e.g. model by Alves Batista 2022

Cosmogenic photons



Neutrinos

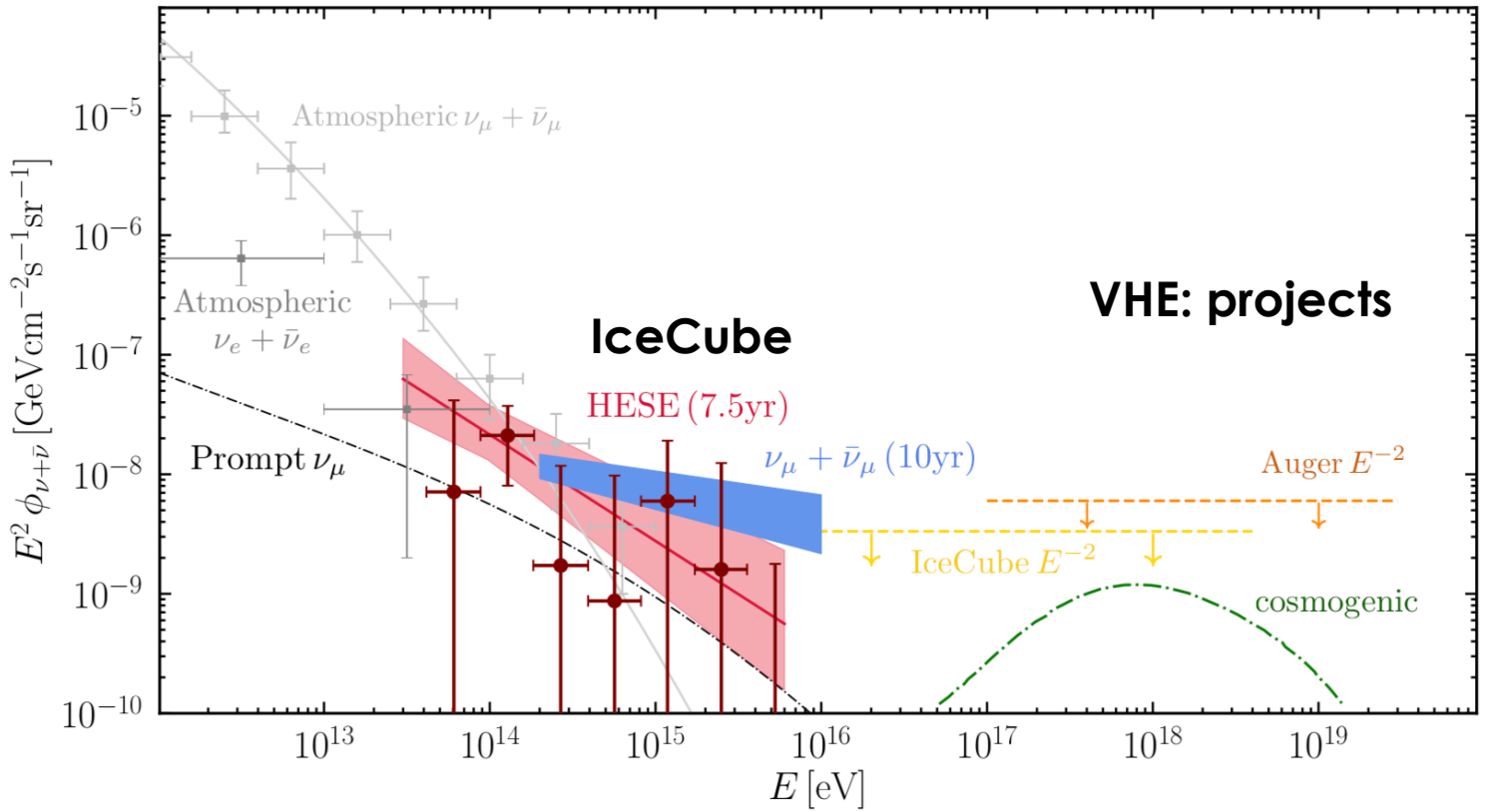


This plot: assume proton acceleration
Conservative scenario: strong magnetic deflection
Optimistic scenario : weaker magnetic field.

Future detectors:
e.g. GRAND?

NEUTRINO BACKGROUND: CONSTRAINTS?

- HE Neutrino background: Sources?
  (a dominant class or several? Small contribution from classical GRBs?)

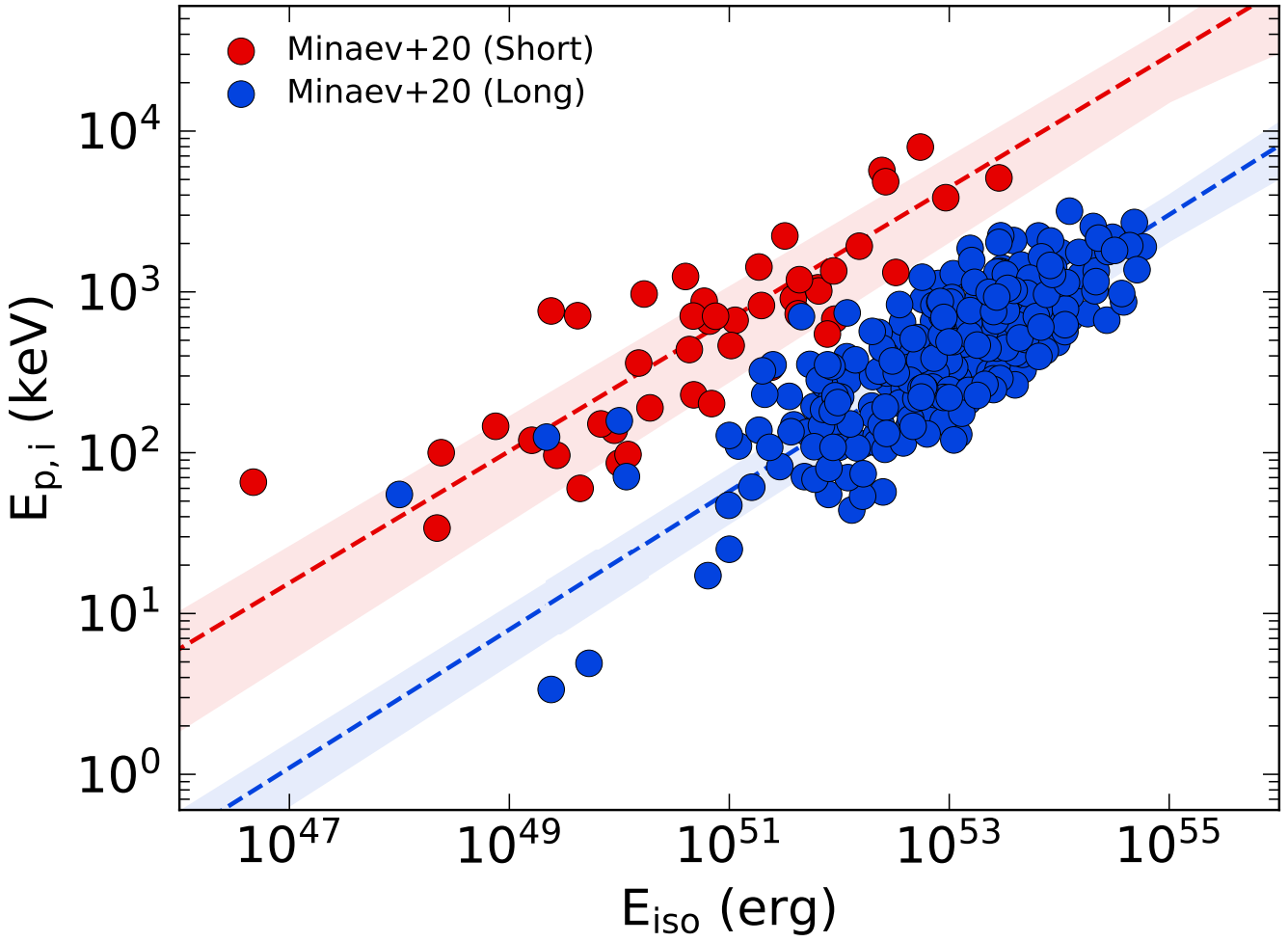


Halzen & Kheirandish 2022

- Several uncertainties can impact the constraint on the GRB contribution:
  - emission from a given burst
  - intrinsic population (diversity)
  - best constrained population = bright long GRBs.

DIVERSITY IN THE GRB POPULATION

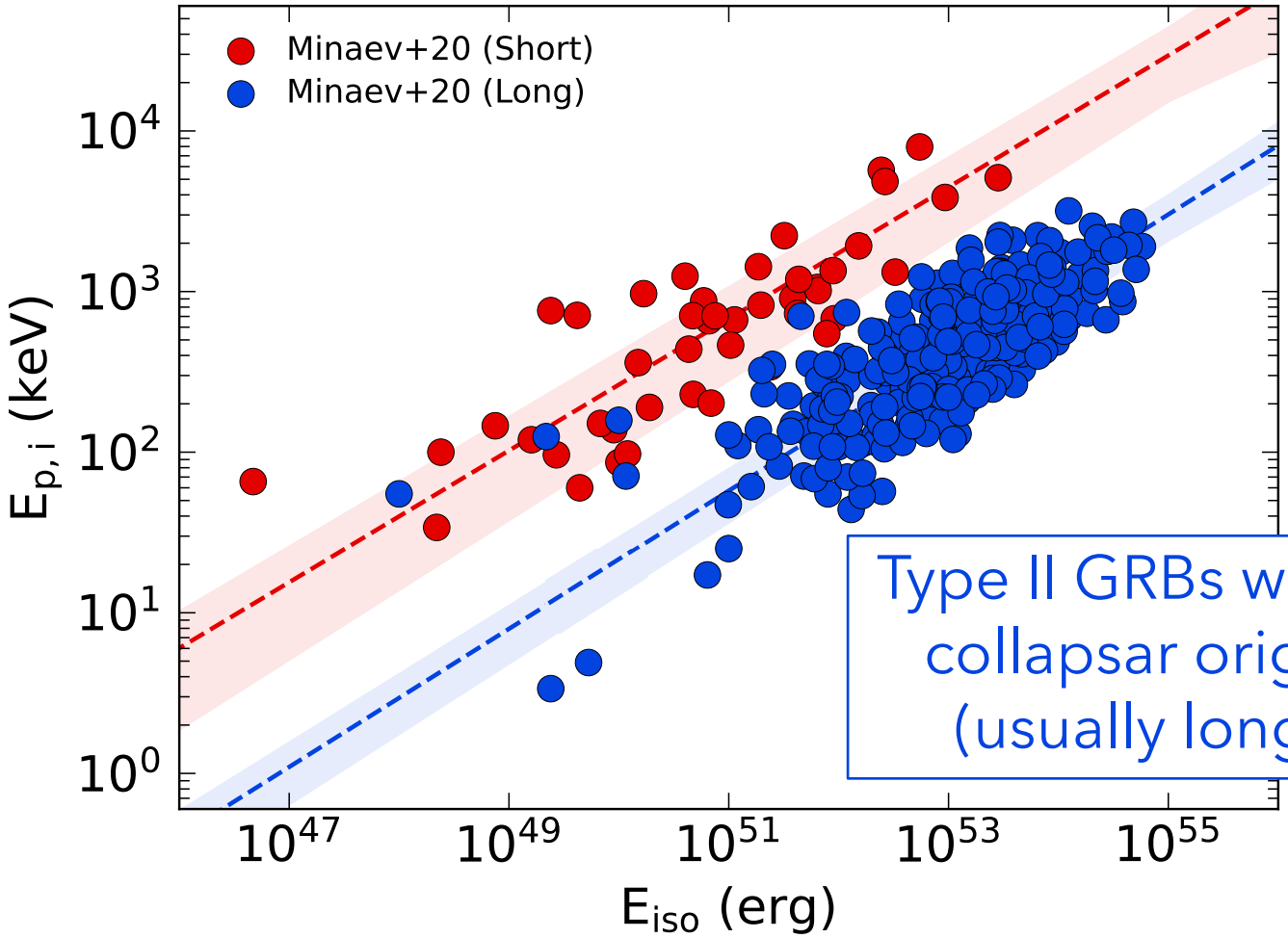
Peak Energy in Source Frame
= Spectral Properties
of the Prompt Emission



Isotropic equivalent energy
released in gamma-rays

DIVERSITY IN THE GRB POPULATION

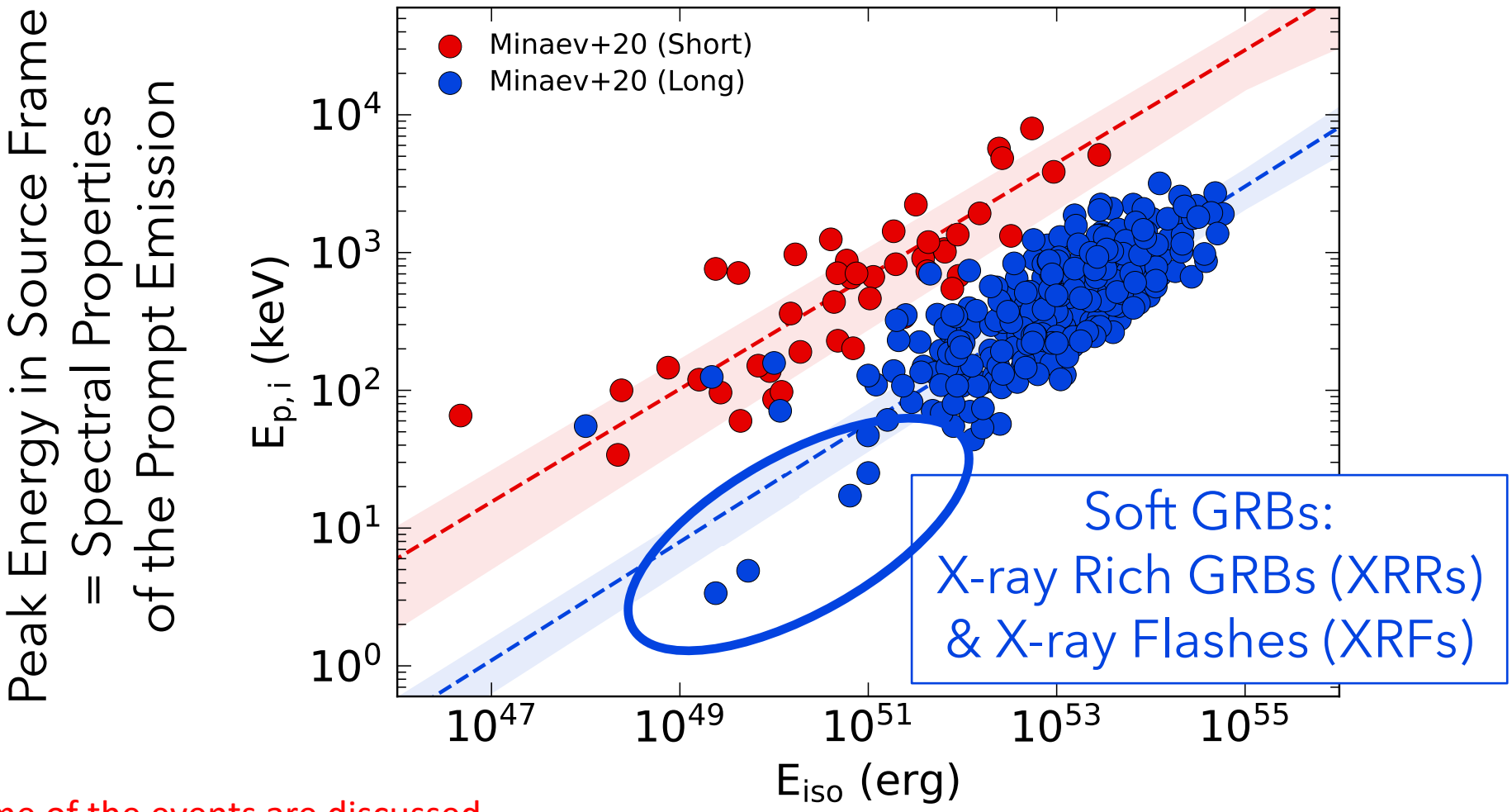
Peak Energy in Source Frame
= Spectral Properties
of the Prompt Emission



Type II GRBs with a collapsar origin (usually long)

Isotropic equivalent energy released in gamma-rays

DIVERSITY IN THE GRB POPULATION

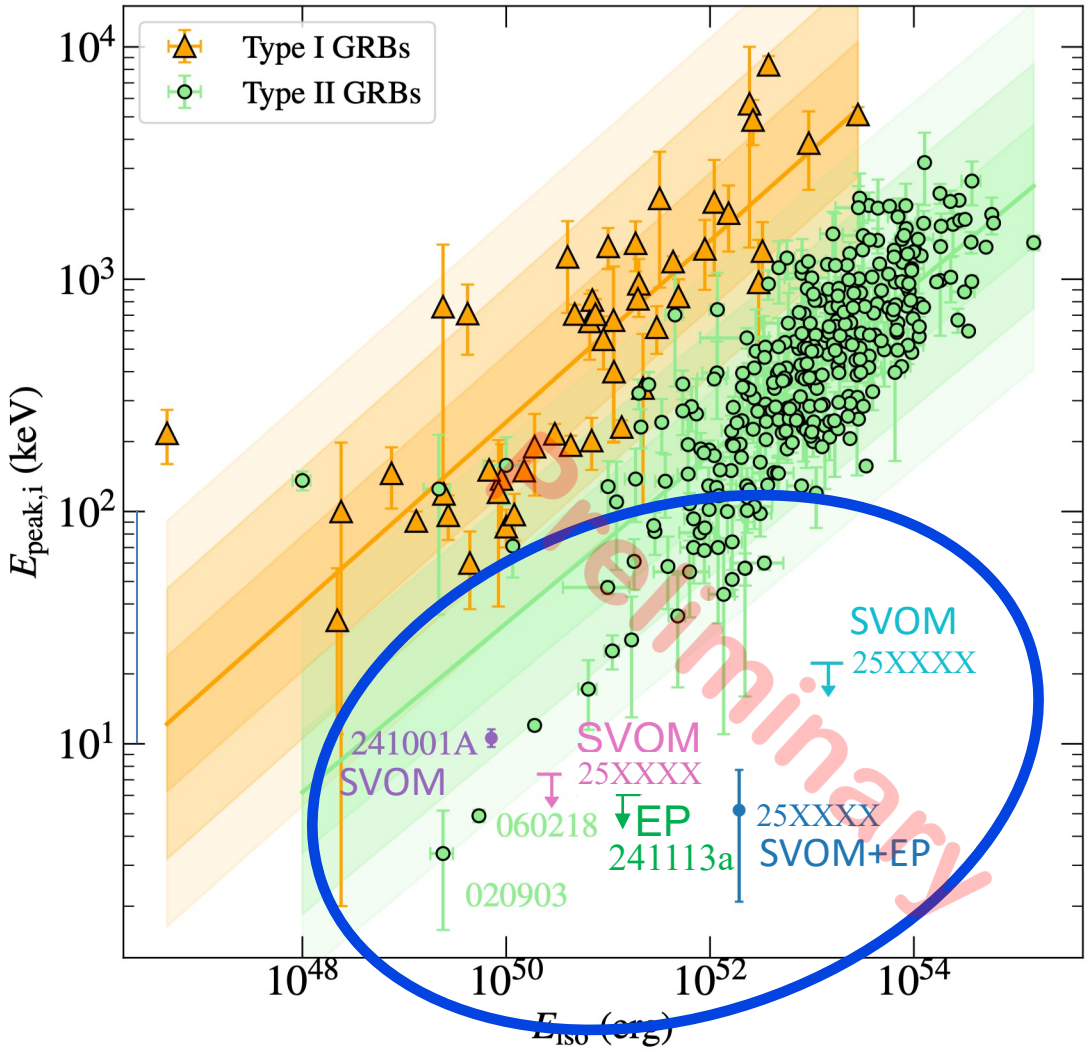


Isotropic equivalent energy
released in gamma-rays

Some of the events are discussed
as promising sources of HE neutrinos
(choked jets,
less relativistic/energetic jets, etc.)

EXPLORING THE POPULATION OF THE SOFTEST « GRBS » WITH EINSTEIN PROBE AND SVOM

Lin+ 2026 in preparation



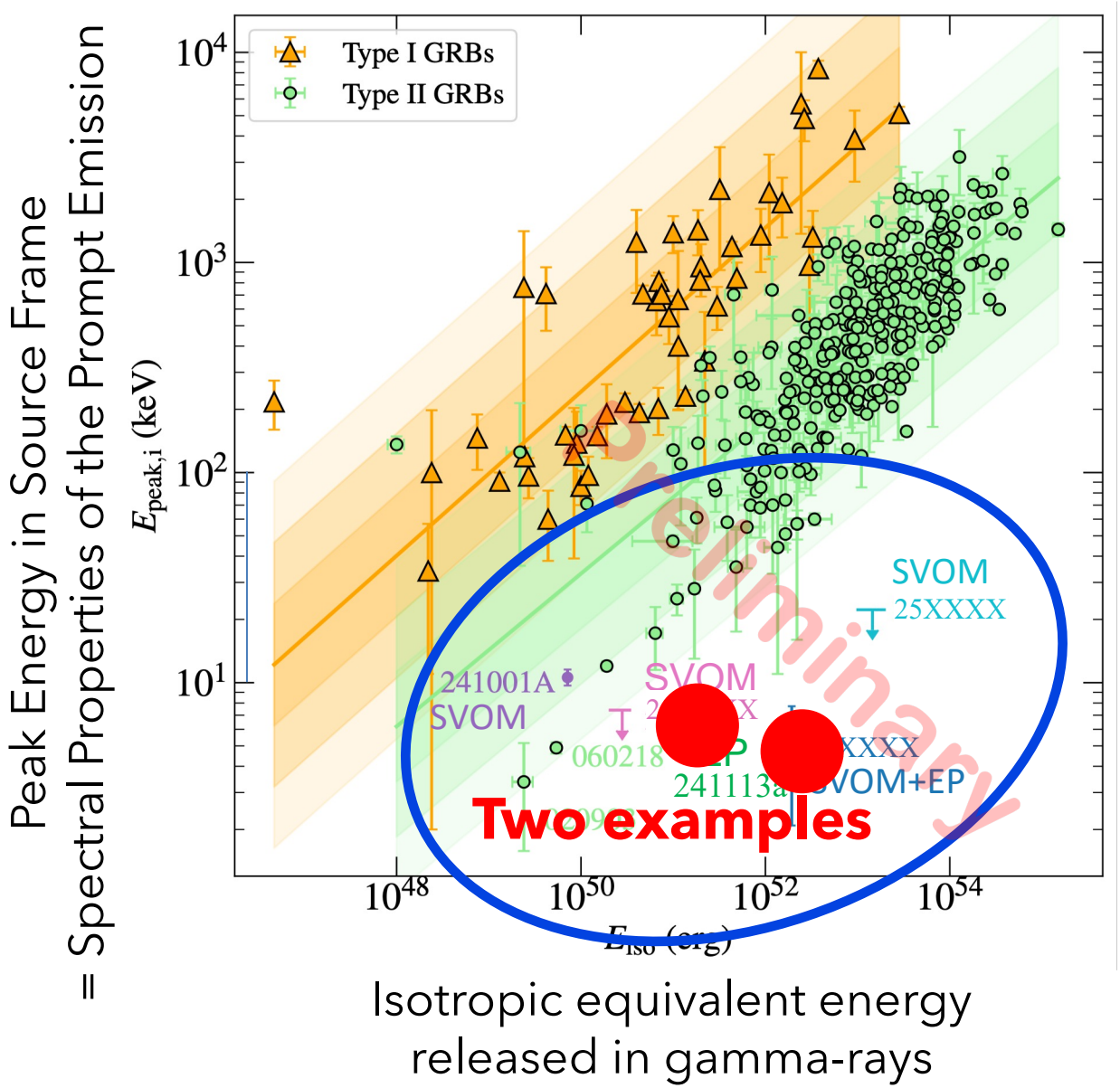
Peak Energy in Source Frame
= Spectral Properties of the Prompt Emission

Isotropic equivalent energy released in gamma-rays

- **Low-luminosity XRFs** are detected and well characterized by SVOM, e.g. XRF241001A, Schneider+ 2026 (submitted)
- **Einstein Probe & SVOM reveal a new population of *energetic XRFs!***
- SVOM can well characterize them (already three papers in preparation on such events detected in 2025)
- **More to come, long GRB population model will be updated!**

EXPLORING THE POPULATION OF THE SOFTEST « GRBS » WITH EINSTEIN PROBE AND SVOM

Lin+ 2026 in preparation

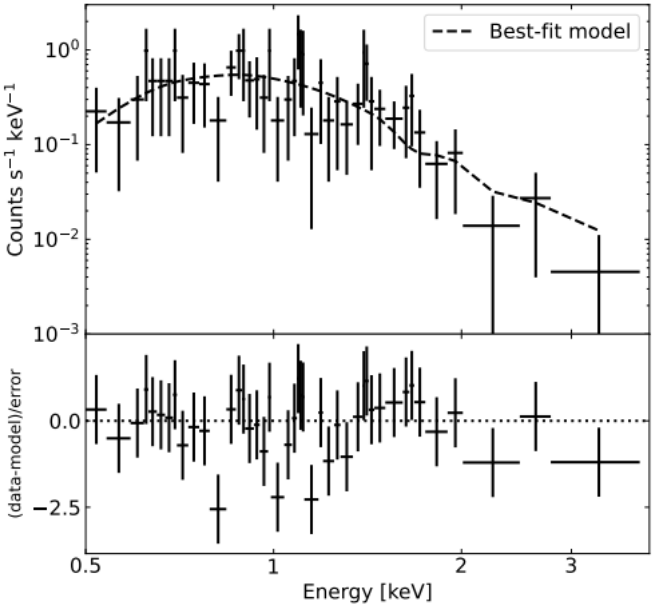


- **Einstein Probe & SVOM reveal a new population of *energetic XRFs!***
- SVOM can well characterize them (already three papers in preparation on such events detected in 2025)

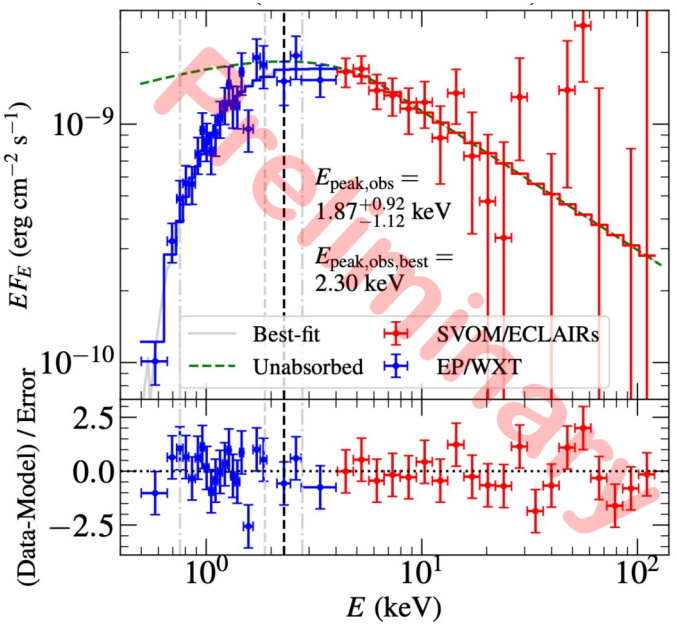
ENERGETIC XRFS! TWO EXAMPLES

Spectrum of the prompt emission of these two X-Ray Flashes

EP211113a: WXT



25XXXX: ECLAIRs+EP/WXT



$E_{p,obs}$ < 2.4 keV

Dai+ 2026 (submitted)

Trigger EP only

z = 1.53 (Keck)

$E_{p,obs}$ = (1.87+0.92-1.12) keV

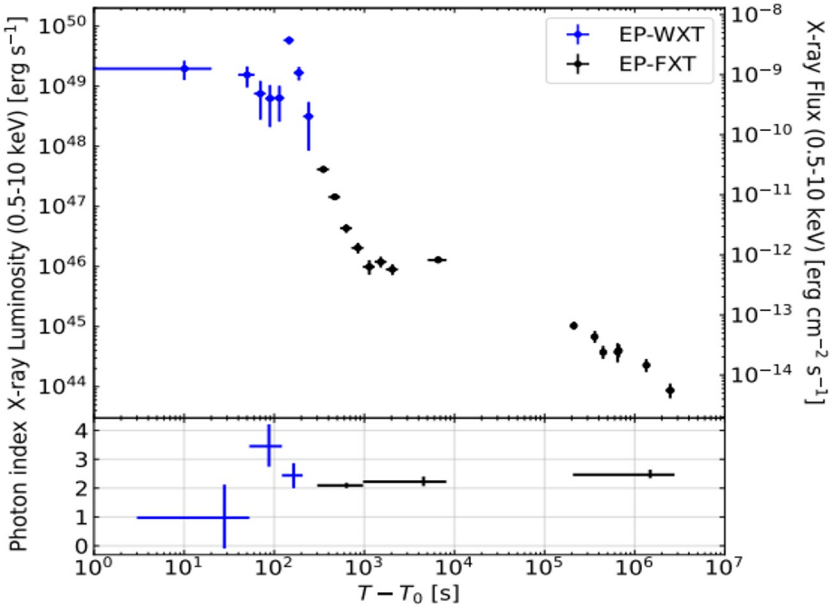
Lin+ 2026 (in preparation)

Trigger EP+SVOM

z = 1.765 (VLT/XSHOOTER, Stargate)

ENERGETIC XRFS! TWO EXAMPLES

EP211113a: EP/WXT & EP/FXT

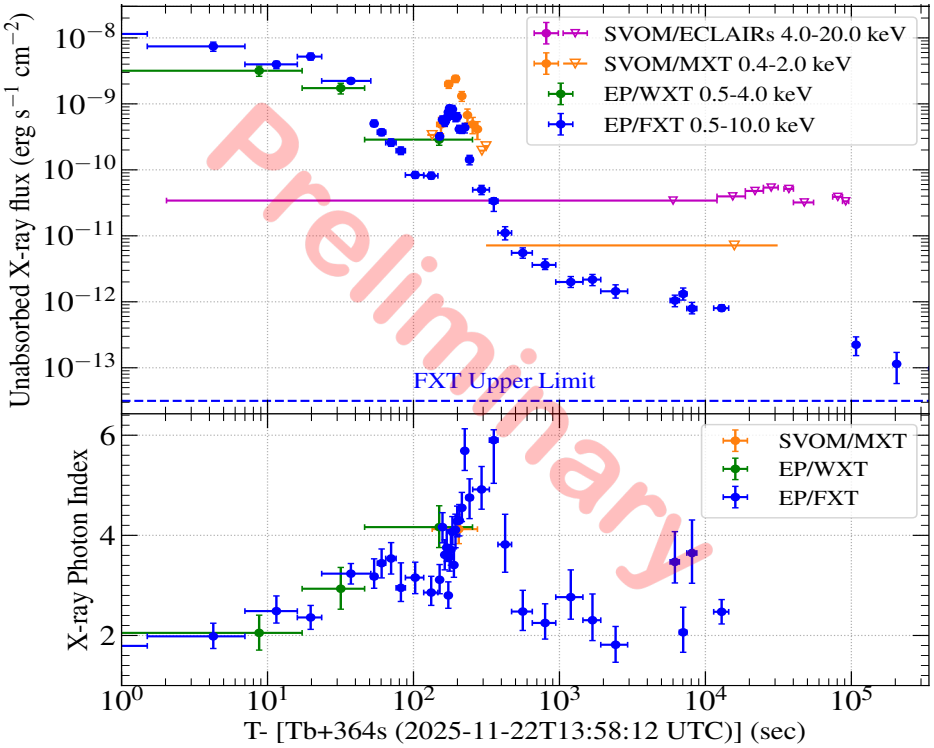


Dai+ 2026 (submitted)

Trigger EP only

z = 1.53 (Keck)

25XXXX: SVOM/ECLAIRS & MXT, EP/WXT & FXT



Lin+ 2026 (in preparation)

Trigger EP+SVOM

z = 1.765 (VLT/XSHOOTER, Stargate)

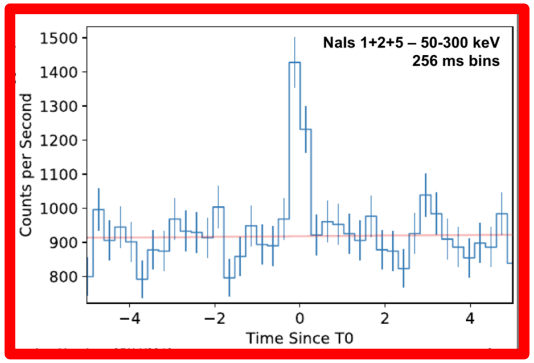
Very detailed afterglow ligtcurve, can constrain the jet properties (low Γ?) and the external medium density.

GRBS AS GW SOURCES

GRBS AND GRAVITATIONAL WAVES

- One multi-messenger detections (170817)!

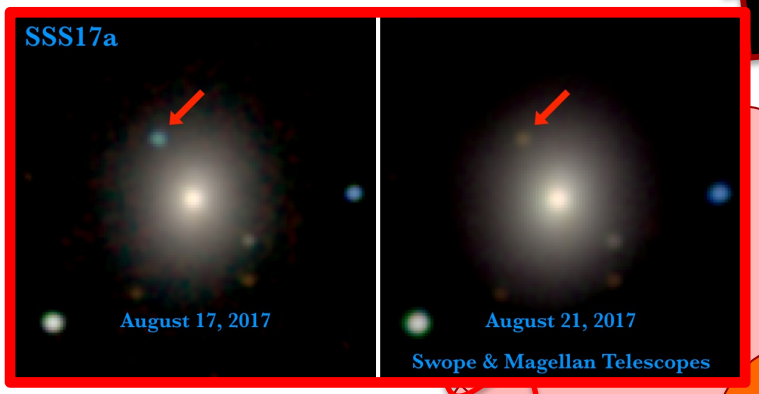
Observer

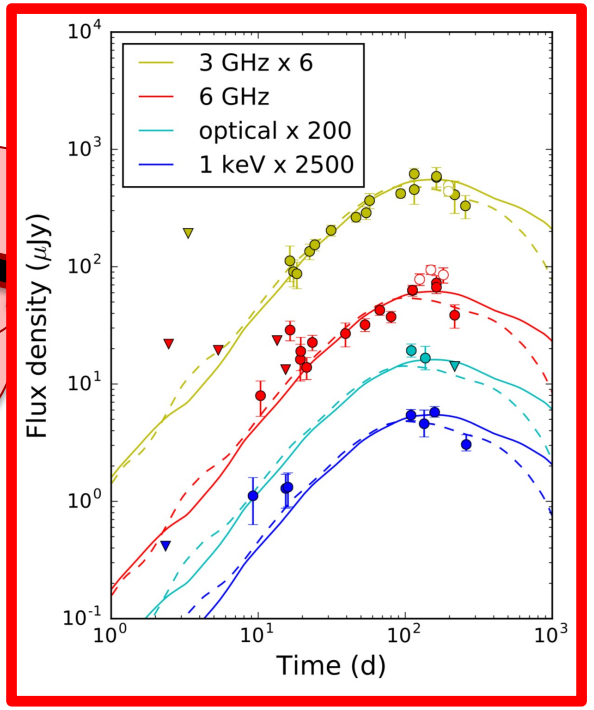


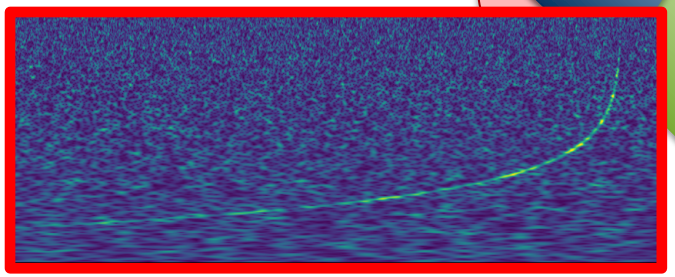
Short GRB: relativistic jet
Shock breakout?

Bright short GRB
for on-axis observer?

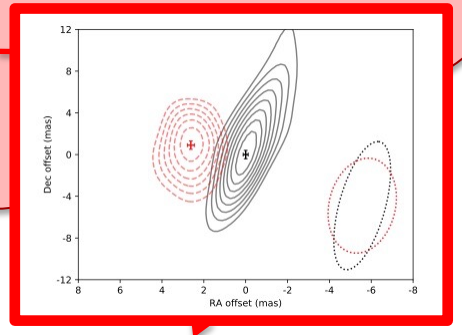
Kilonova: ejecta during the merger
Nucleosynthesis of heavy elements







Gravitational Waves
Inspiral phase of a BNS



Superluminal motion:
Relativistic jet!

Afterglow: deceleration
of a structred relativistic jet

GRBS AND GRAVITATIONAL WAVES

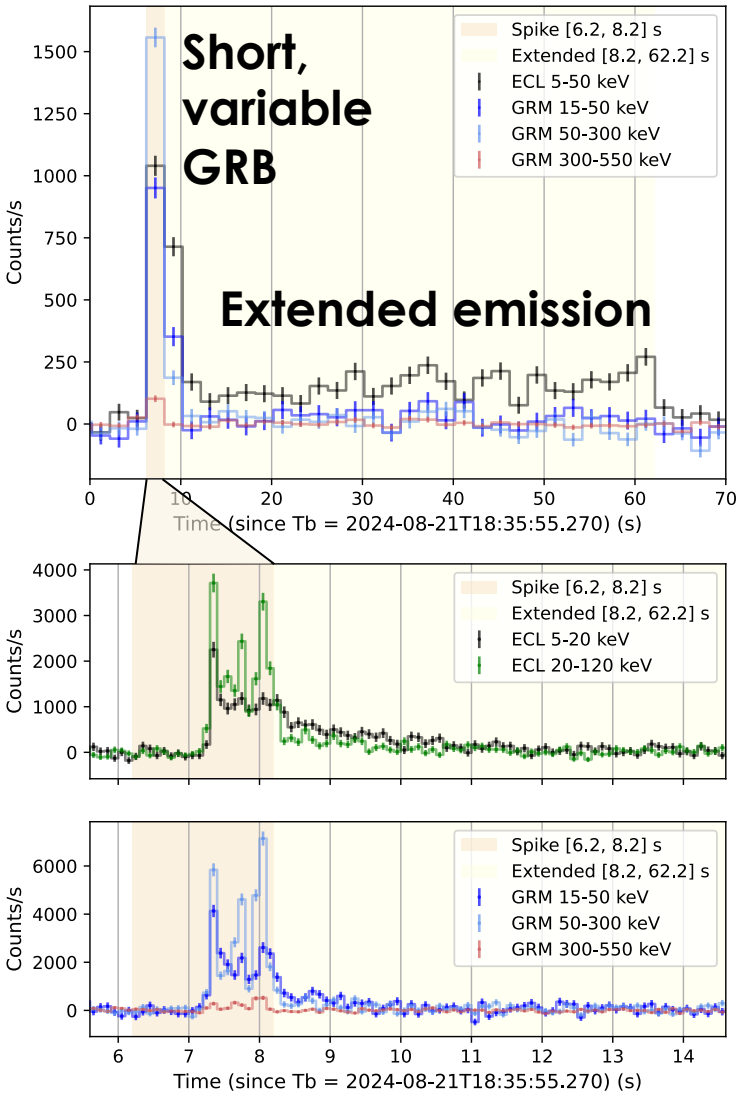
- One multi-messenger detections (170817)!
- But only one multi-messenger detection…
- GW: more than 200 sources but 2-3 BNS, 170817 the only one well localized
  5-6 NSBH, probably only direct plunges
- Limitation: sensitivity + localization
  - Current: low BNS detection rate and large error boxes: very difficult! Short GW horizon: probe local events, less favorable for GRB detection (offaxis events) – best candidate = kilonova
  - Future: sensitivity will improve with O5, third generation (Einstein Telescope, Cosmic Explorer)
  - More detectors (Kagra,Ligo-India) will improve the localization.
- GW signal only probes the inspiral phase. Post-merger signal would be extremely valuable = signature of the formation of the GRB central engine.

GRBS AND GRAVITATIONAL WAVES

- In-between, without multi-messenger detections, the different channels can be probed independtly.
- Kilonova: in association with GRBs + future orphan KN detections? (Vera Rubin)
- Short GRBs: more difficult to localize, less characterized population

GRBS AND BNS MERGERS

An example of a short GRB + extended emission fully characterized by SVOM: GRB240821A



ECLAIRs+GRM lightcurve

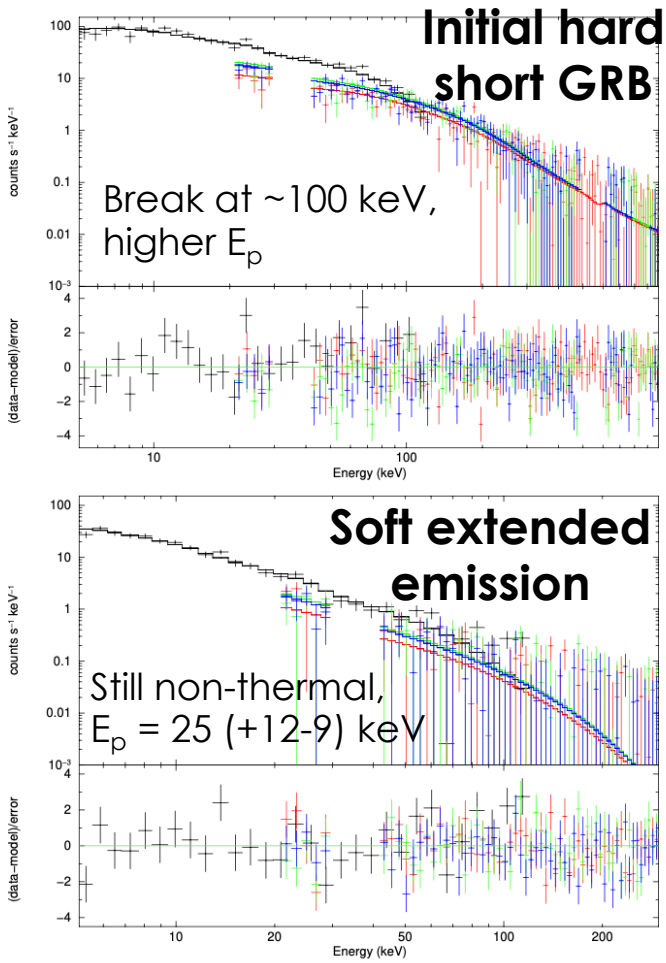
Daigne, F. et al., 2026, RAA (in prep)

- No slew at that time
- **X-ray afterglow** (Swift/XRT+EP/FXT)
- **Visible afterglow** (detection Gemini N., VT late upper limit)
- **Redshift z = 0.238, host galaxy** (VLT/XSHOOTER, GTC)

AG+host galaxy: merger scenario

An example of a short GRB + extended emission fully characterized by SVOM: GRB240821A

ECLAIRs+GRM spectrum

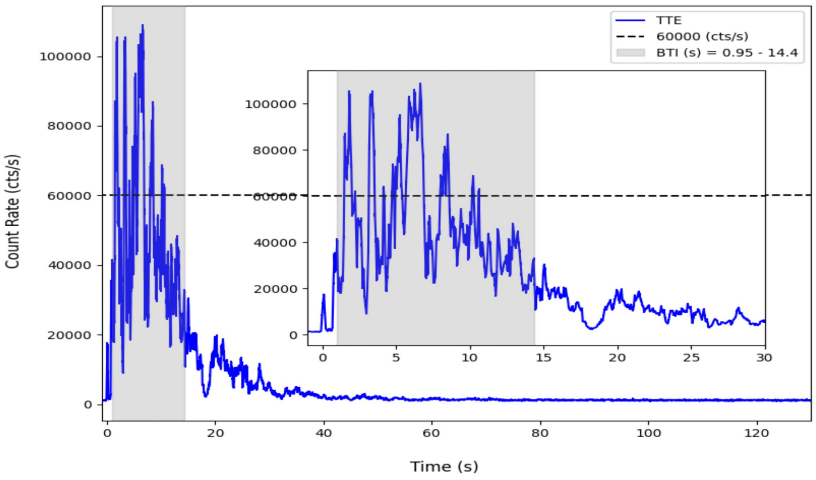


Daigne, F. et al., 2026, RAA (in prep)

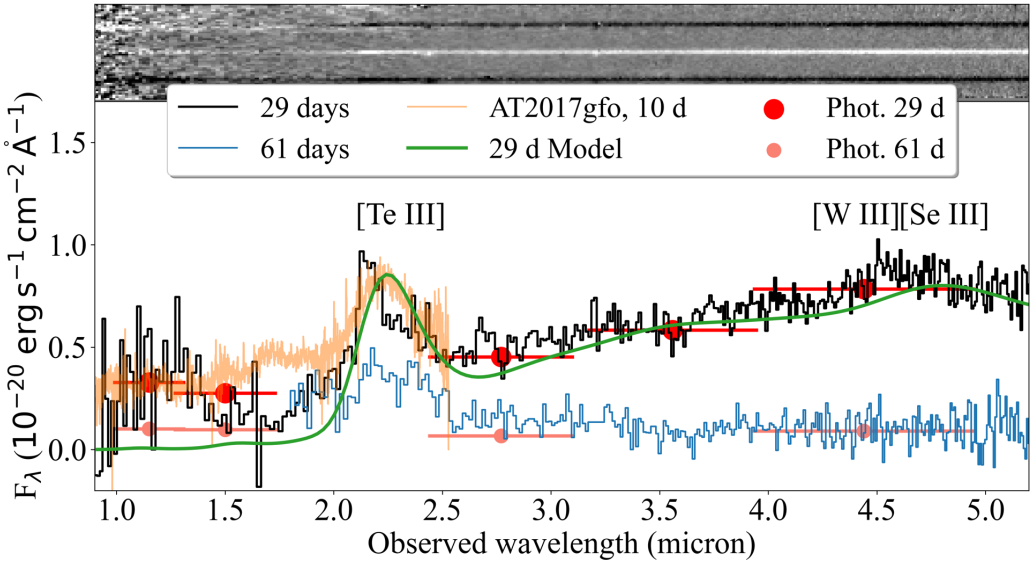
- ECLAIRs+GRM: good spectral coverage of the initial short GRB and the extended emission.
- **Origin of the extended emission? (post-merger physics)**

GRBS AND BNS MERGERS

A surprise: GRB 230307A @ z=0.065 (very bright!)
A very bright long GRB associated to a kilonova! (JWST spectrum!)



Fermi GBM lightcurve



Levan et al. 2023

CONCLUSION

CONCLUSION

- Gamma-Ray Bursts are promising multi-messenger sources. However there is only one multi-messenger detection to date (170817: GW+em).
- Gravitational waves: current limitation = sensitivity + localization.
  Future: O5, more detectors (Kagra, LIGO-India), 3rd gen (Einstein Telescope)
- Neutrinos: current limitation = sensitivity + possibly the energy range.
  Future: KM3Net, IceCube-Gen2, future VHE detectors (e.g. GRAND).
- In the meantime, our physical understanding of GRBs and their diversity continues to improve (SVOM, Einstein Probe, VHE instruments, CTA to come).
- GRB detectors when the new generation of VHE/GW/neutrino instruments will be operational? (THESEUS not selected by ESA)

Kandinksy – Composition 8- 1923
Guggenheim Museum, New-York

Kandinksy – Curves and sharp angles - 1923
Guggenheim Museum, New-York

THANKS!