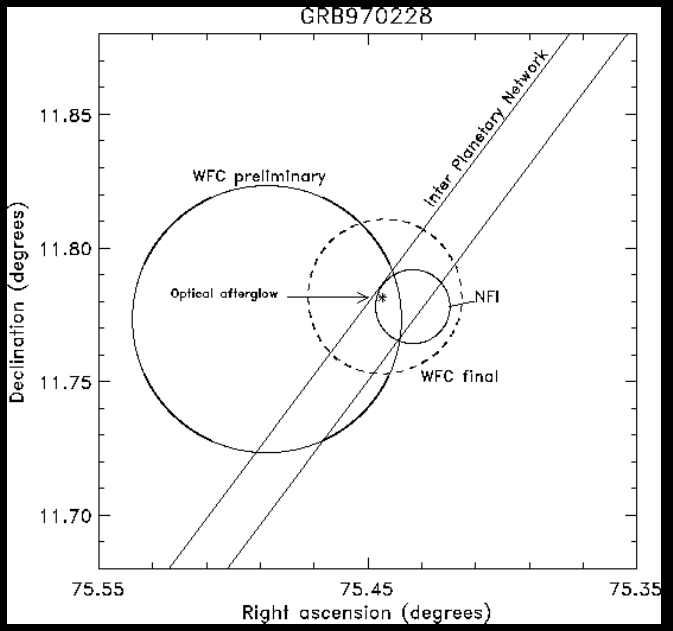
Extragalactic transients: supernovae, gamma-ray bursts, mergers, …

Frédéric Daigne
(Institut d'Astrophysique de Paris)



Preamble

Conditions for an extragalactic transient?

- Large distance: huge energy release
- Transient: short timescale

Conditions for an extragalactic transient?

- Large distance: huge energy release
- Transient: short timescale

- Nuclear energy?

No confinement/control by gravity
-Surface
→ novae, X-ray bursts: too faint
or -Degenerate matter
→ **type Ia supernovae** (exploding WD)

WD close to M_{Ch}: $E_{nuc} > -B$ explosion ; timescale $t_{son} \sim R/c_S \sim 1$ s
Energy release $\varepsilon_{nuc} Mc^2 \sim 10^{44}$ J

- Radioactivity: SN lightcurve
  timescale 100 days (Ni→Co→Fe)
- Kinetic energy: supernova remnant
  timescale 10-10^4 years

Conditions for an extragalactic transient?

- Large distance: huge energy release
- Transient: short timescale

- Gravitational energy? Collapse $R_0 \rightarrow R$: $\Delta E \sim \Xi\, Mc^2$
  with $\Xi = G\, M / R\, c^2$

  $\Delta E \sim 10^{46}$ J for the formation of a NS
  even larger for a BH

  Shortest timescale : $t_{dyn} \sim 1/\sqrt{(G\rho)} \lesssim$ ms for NS, stellar mass BH

  Two channels:

  – Collapse of a single star → **type Ib,Ic,II supernovae**
  → **long GRBs**
  → **intermediate cases?**

  – Merger (NS-NS; NS-BH; BH-BH) → **short GRBs**
  → **other? FRB?**

  → Large diversity of associated phenomena
  → Multiwavelength/multimessenger emission expected
  → Timescales ms → 10^4 yr

Conditions for neutrino/GW emission?

- **Neutrinos:** - neutronization (β inverse)
  - ultra-dense/hot medium:
  formation of a neutrinosphere

  → core-collapse to NS/BH

- **HE neutrinos:** accelerated hadrons+gamma-ray photons

  pp collisions

  → (rel) ejecta/shock waves/dense environment

- **Gravitational waves:** $L_{\mathrm{GW}} \sim \frac{G}{5c^5}\left(\frac{sMR^2}{(v/c)^3}\right)^2 \sim \frac{c^5}{5G}\, s^2 \left(\frac{GM}{Rc^2}\right)^2 \left(\frac{v}{c}\right)^6$

  high velocities
  compact objects
  no spherical symmetry

  → mergers / asymetric core-collapse

Supernovae

Thermonuclear supernovae: type Ia supernovae

SN 2007f (type Ia) in NGC 5584 - VLT

Thermonuclear supernovae: type Ia supernovae

- **Motivation:** Physics of the event + standard candles for cosmology
- **Main issues:**
  - progenitors single degenerate WD+companion
    double degenerate WD+WD
  - explosion mechanism
    -propagation speed for the nuclear flame?
    -off-center?
- **Needed observations:**
  - understand the observed diversity (under/over-luminous Ia supernovae)
  - search for ejected companion
  - gamma-ray lines of the early ejecta
  - detailed chemical composition of the remnant, etc.

Visible+X-rays/gamma-rays
Fast reaction needed mainly for the identification/classification (timescale days/weeks)

Core-collapse supernovae: type Ib, Ic, II supernovae

Crab nebula: Chnadra+HST+Spitzer

Core-collapse supernovae: type Ib, Ic, II supernovae

- **Motivation:** death of massive stars (>8 $M_\odot$)
  formation of compact objects (NS, BH)
  nucleosynthesis: chemical evolution
  Injection of kinetic energy in ISM, feedback on star formation
  acceleration of cosmic rays
  etc.

- **Classification:** -spectroscopy (H, He lines ?)
  -photometry (peak luminosity, shape of light curve)
  great diversity !

Core-collapse supernovae: type Ib, Ic, II supernovae

- **Main issues (non exhaustive list…) :**
  - Explosion mechanism:
    how does the shock reach the stellar surface?
    (role of neutrinos/instabilities/MHD jet/…)
  - Understand the diversity/progenitors
    role of mass, metallicity, binarity, rotation
    explore the most extreme cases (formation of massive BHs?)

    signatures?
  - Understand the nature of the final central object (NS, BH)
  - Understand the post-collapse evolution of the central object
    (pulsar? PWN? …)
  - Understand the late evolution of the ejecta,
    the acceleration of cosmic rays

  etc.

Core-collapse supernovae: type Ib, Ic, II supernovae

- **Emission : (1) neutrinos/GW**
  - Neutrinos: Most of the energy released!

    Galactic supernova only

    A few 10^3 neutrinos: light curve & spectrum
    A detailed view of the collapse & the compact central region

    Timescale : hundreds of ms
  - HE neutrinos: young remnant / Galactic only
    Probe the acceleration of cosmic rays

    Timescale : centuries
  - Gravitational waves: if highly asymetric / Galactic only?

    A direct view of the collapse
    Nature of the central compact object

    Timescale : hundreds of ms

Core-collapse supernovae: type Ib, Ic, II supernovae

- **Emission : (2) Light**
  - Shock breakout — timescale 2h (BSG) / 1.5d (RSG)
UV, X-rays
  - Supernova — 100 days (Ni→Co→Fe)
Visible
  - Pulsar — 100 Myr
Multi-wavelength (non-thermal spectrum)
  - PWN — Young SNR
Multi-wavelength (non-thermal spectrum)
  - SNR — 10 to 10^4 years and more
Multi-wavelength (non-thermal spectrum)

Core-collapse supernovae: type Ib, Ic, II supernovae

- **Needed observations?**
  - A Galactic core-collapse supernova !!!
  - Identification of progenitors: - direct imaging
    - detailed spectro-photometry of the supernova / remnant
  - Good sampling, exploring the full diversity (rare spectral types, under/hyper-luminous supernovae, …)
  - Host galaxy/ISM region
- **Reaction time:**
  - Neutrinos/GW: either the instrument is on, or it is too late…
  - Shock breakout: only by chance (or triggered by neutrinos/GW: reaction in 2h/1.5d)
  - days/weeks: classication, spectro-photometry
  - remnant: no constraint

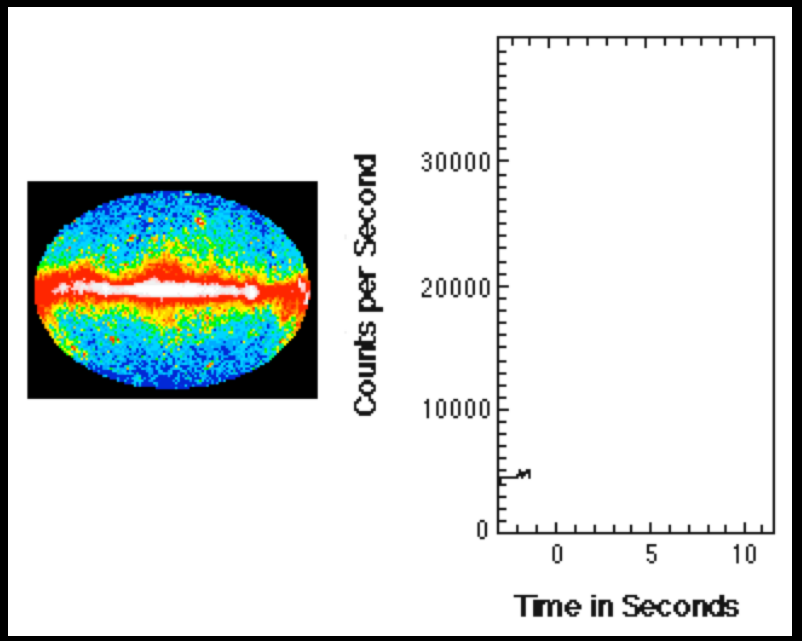
Core-collapse supernovae: type Ib, Ic, II supernovae

- **Alerts?**
  - Many expected in 2020+
  - e.g. LSST = 3 to 4 10^6 supernovae in 10 years…

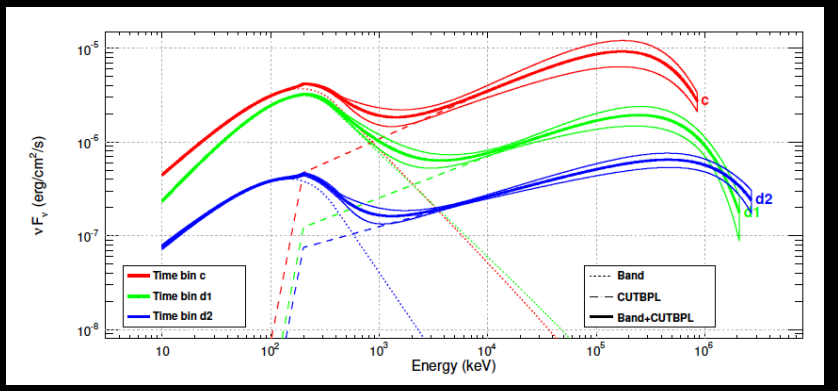
Gamma-ray bursts

Gamma-ray bursts

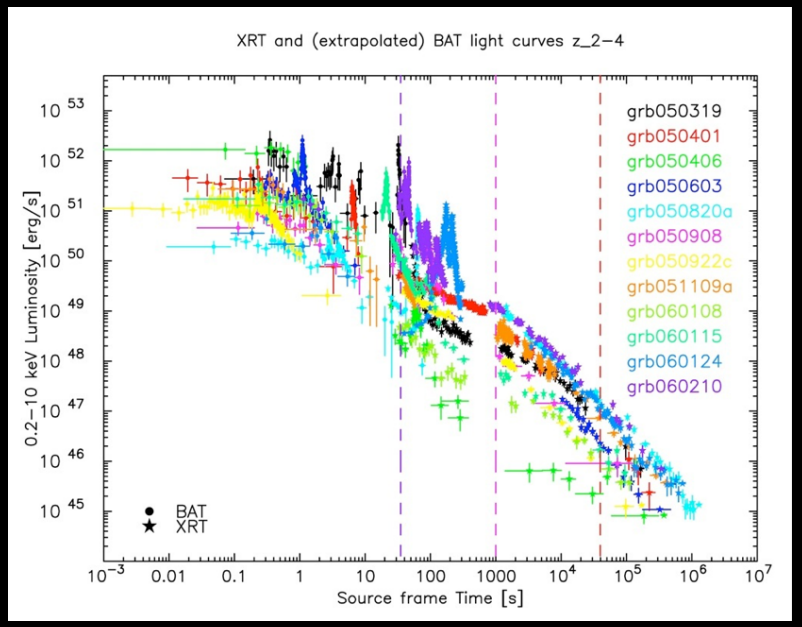
CGRO



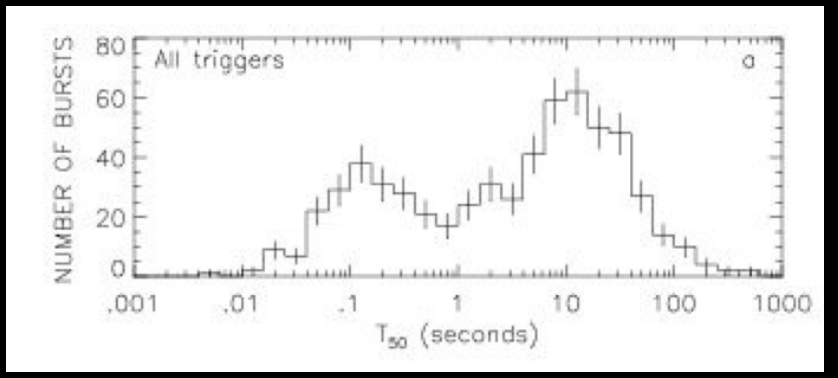
Fermi



Swift

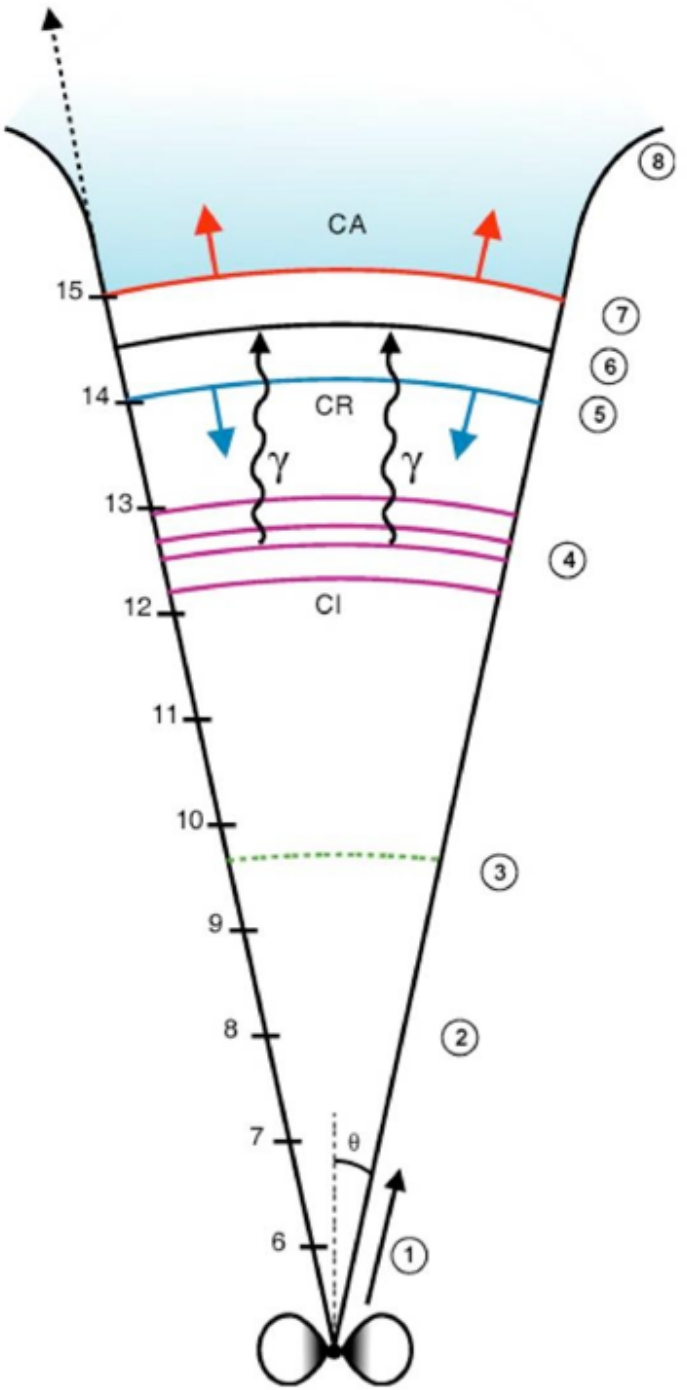


BATSE



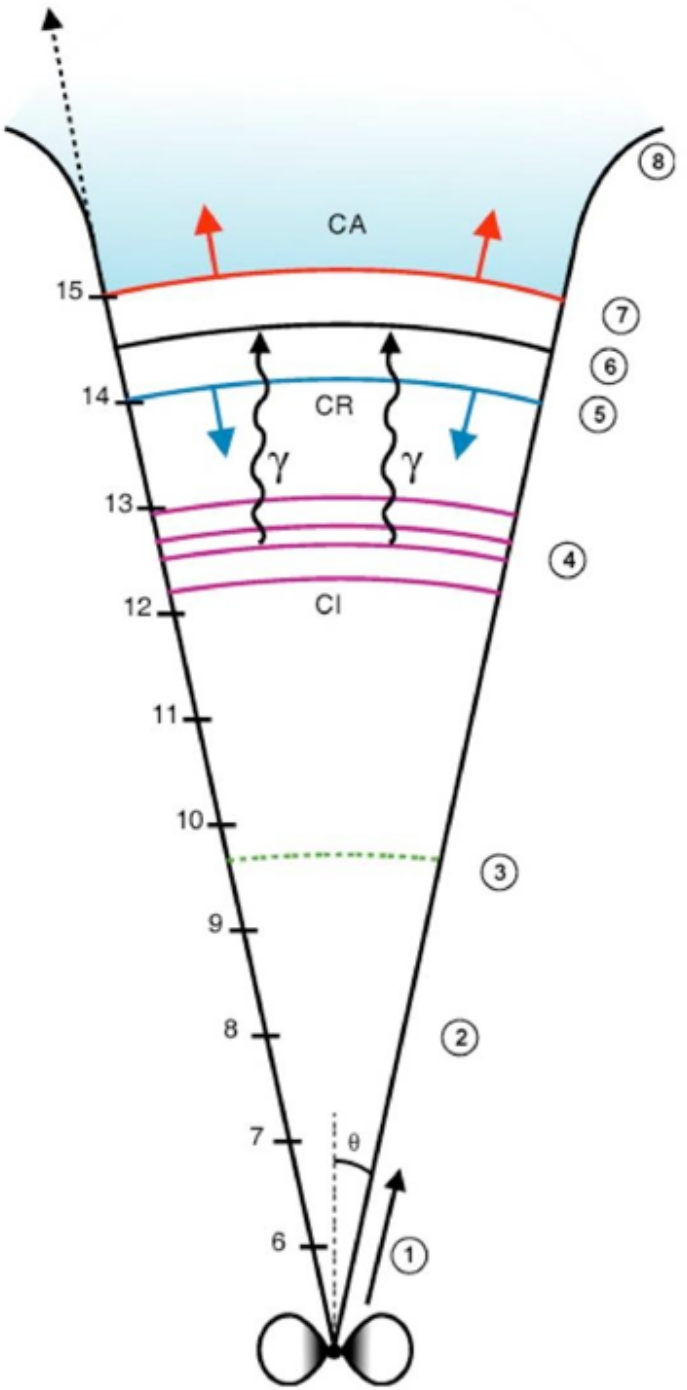
Gamma-ray bursts

- **Motivation:**
  - Fate of massive stars
  - Extreme physics
    (compact objects, relativistic ejection, …)
  - Expected multi-messenger emission
  - Can be observed at very large redshift
    host galaxy
    star formation
    IGM
    firsts stars, …



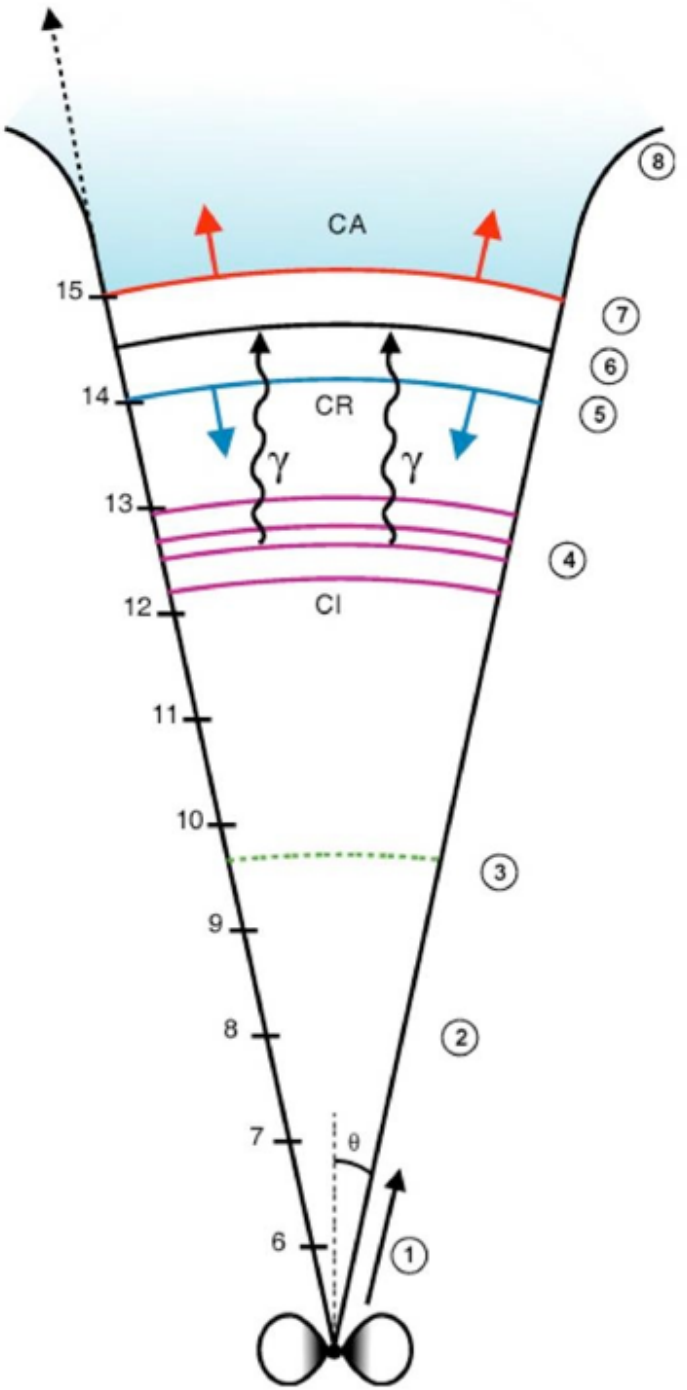
Gamma-ray bursts

- **Open issues (non exhaustive list):**
  - Progenitors
    - long GRBs: collapsar
      mass, metallicity, rotation, binarity, …
      mechanism of the collapse
      associated SN?
    - short GRBs: mergers?
  - Central engine: BH vs magnetar
  - Relativistic ejection:
    mechanism?
    composition, geometry, Lorentz factor
  - Prompt emission/afterglow:
    dissipation? acceleration? radiation?
  - Environment: density?
  - Origin of diversity: X-ray rich GRBs/ X-ray f
    low-L GRBs, ultra-long GRBs, etc.



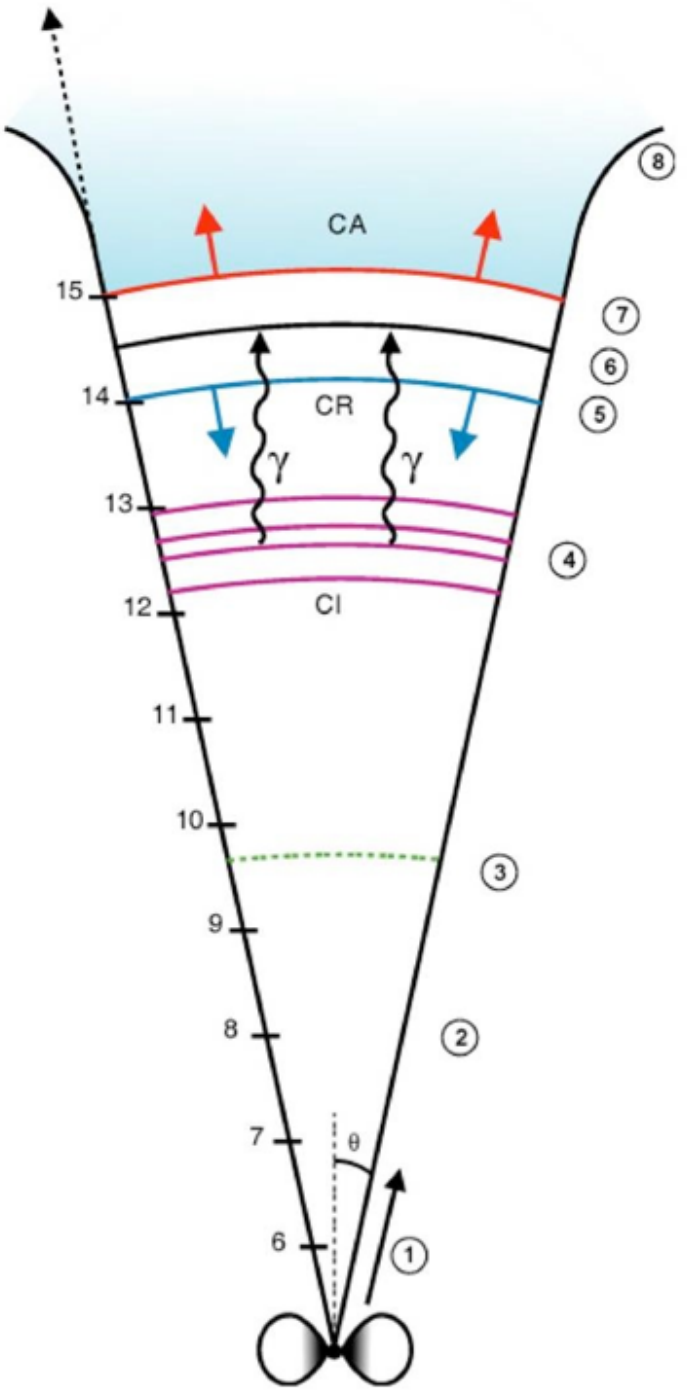
Gamma-ray bursts

- **Emission: (1) main**
  - GW: mergers (i.e. short GRBs)
    - nature of the progenitor
    - nature of the central object
    timescale : ms-s?
  - HE neutrinos: particle acceleration in the ejecta
    timescale: prompt/early AG
  - Prompt emission:
    keV-GeV
    optical
    TeV? (nearby GRB)
    radio?
    timescale: ms to 10^3 s
  - Afterglow:
    multiwavelength (radio to GeV)
    timescale: min to days/weeks/months



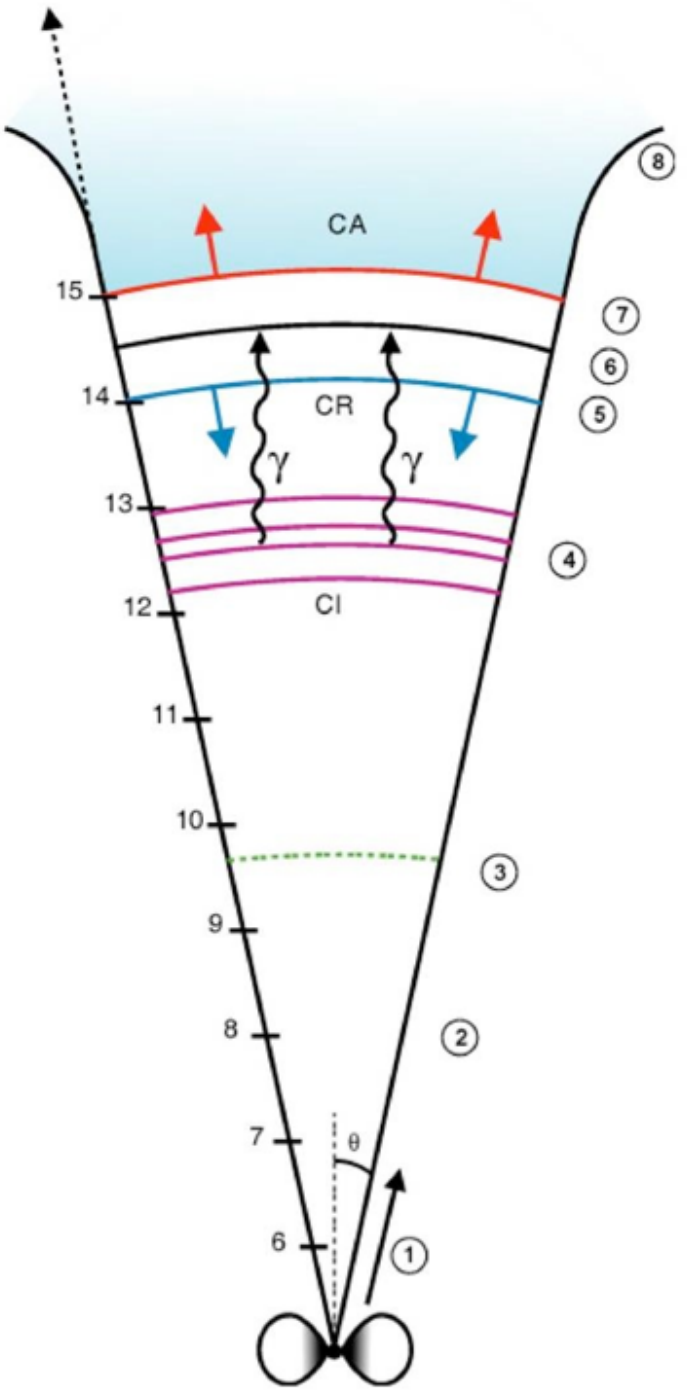
Gamma-ray bursts

- **Emission: (2) others?**
  - HE neutrinos from the central engine (propagation of the ejecta within the collapsing star)
  - Shock breakout, cocoon?
  - Orphan afterglows?



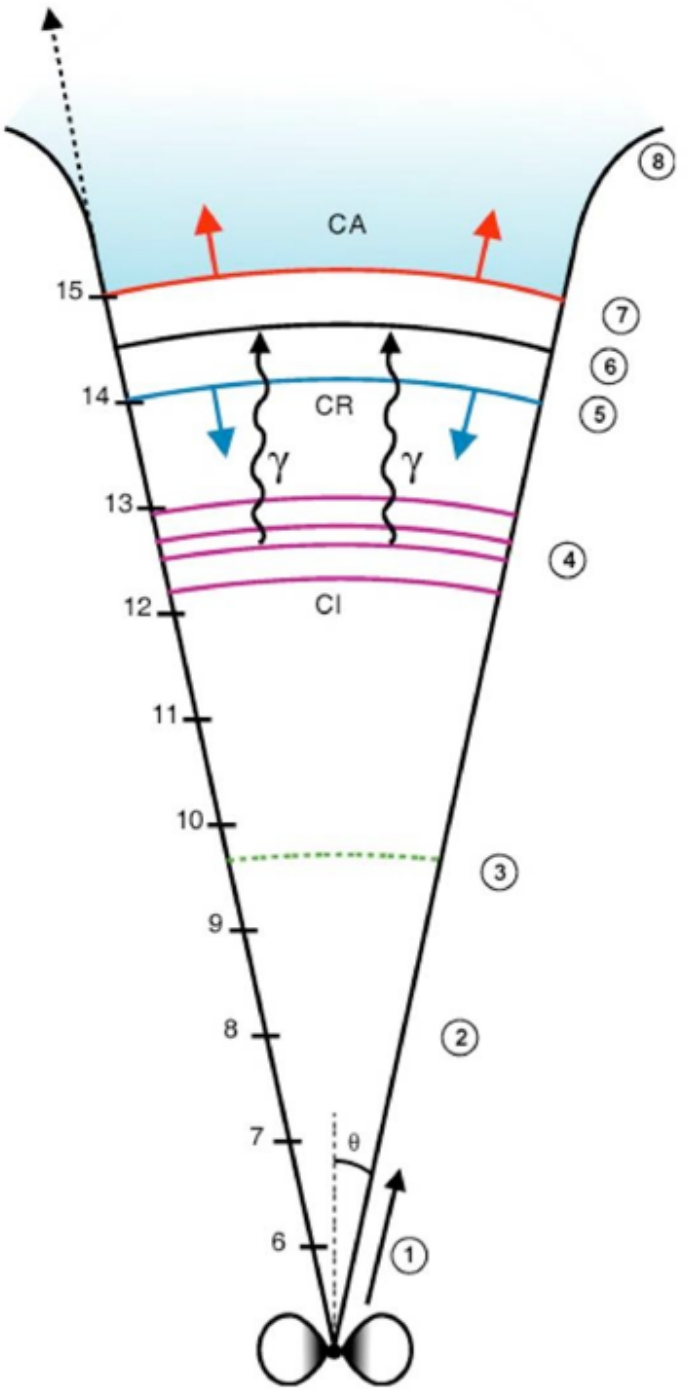
Gamma-ray bursts

- **Needed observations?**
  - Sample with
    good time/spectral coverage of
    -the prompt phase
    -the afterglow phase
    distance (redshift)
    exploring the full diversity of GRBs
    Including nearby events (supernova) and high redshift events (cosmology)
  - GW association (short GRBs)
  - HE neutrino (detection/upper limit) for a nearby GRB
    + TeV (detection/upper limit)
  - Statistics for orphan afterglows
  - High resolution spectroscopy of the AG
  - Host galaxies, etc.



Gamma-ray bursts

- **Rapid response:**
  - Prompt: < 100 s
  - Early afterglow: <1 hour
- **Alerts?**
  - *Fermi*, *Swift* in 2020+ ?
  - SVOM

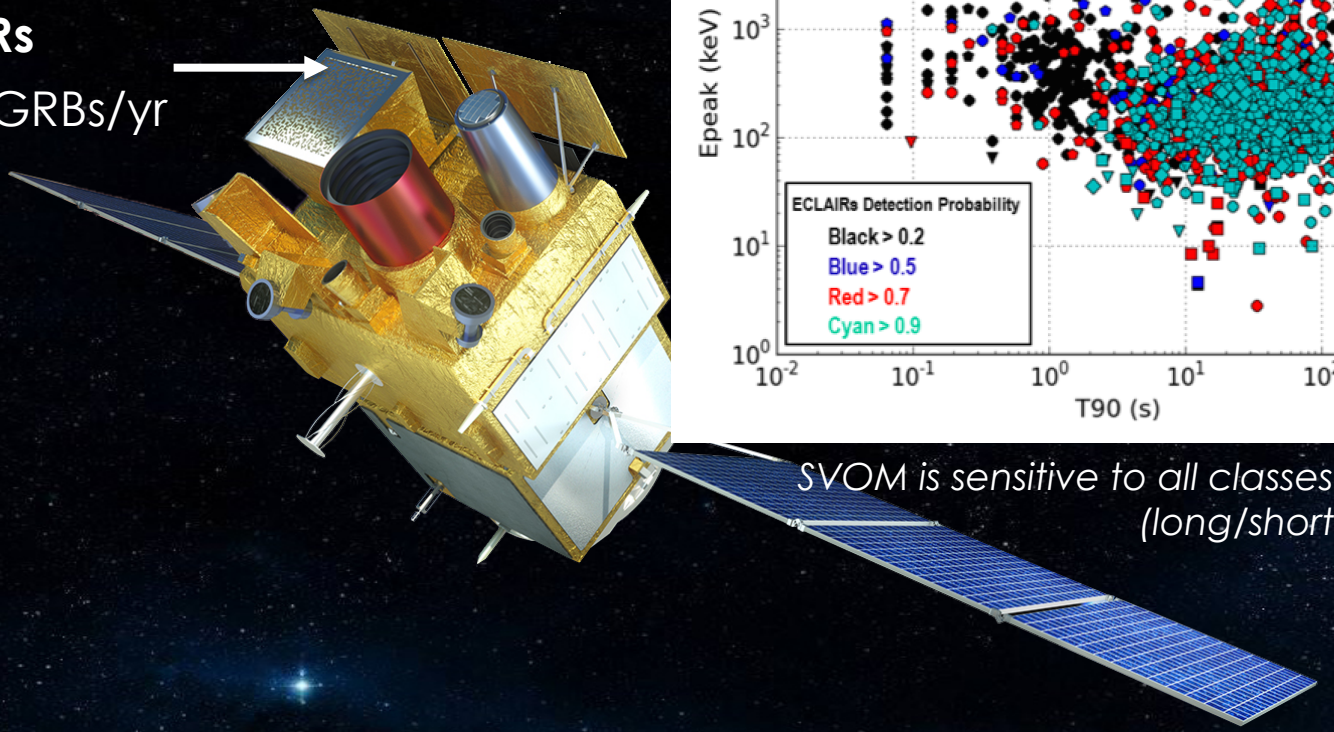


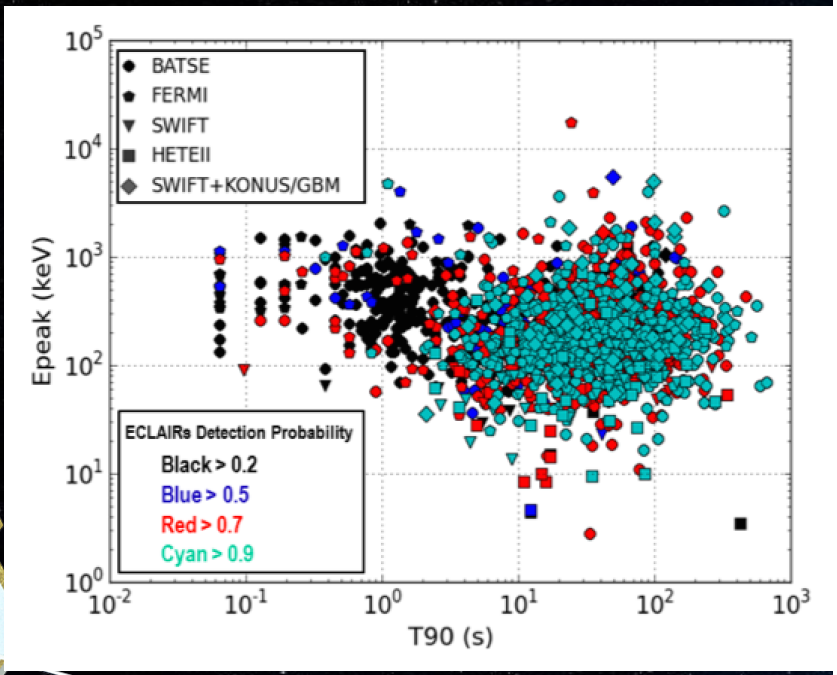
SVOM: a unique sample

GRB trigger

ECLAIRs

42-80 GRBs/yr





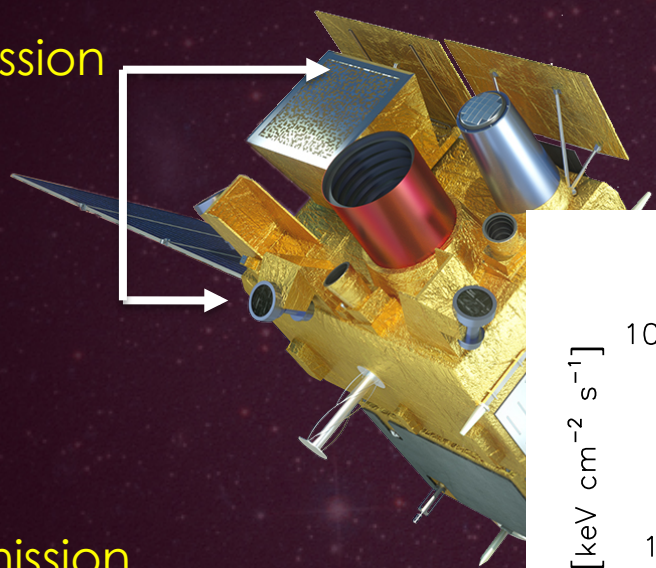
SVOM is sensitive to all classes of GRBs (long/short/soft/…)

SVOM: a unique sample

Prompt emission

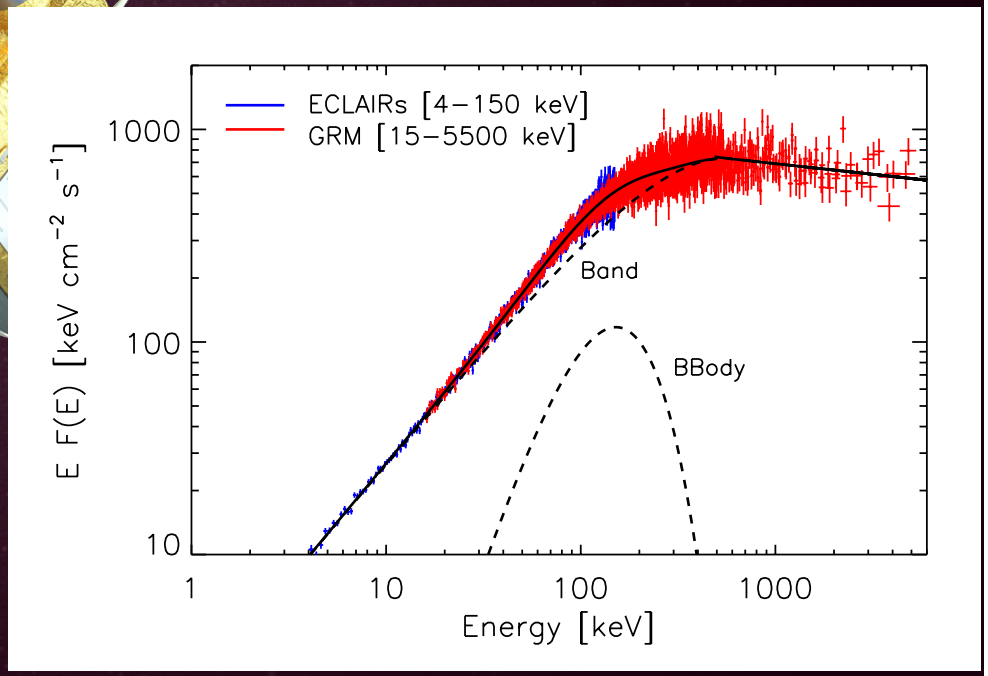
ECLAIRs+GRM

Prompt GRB emission over 3 decades (4 keV-5.5 MeV)



GWAC

prompt visible emission in ~16% of cases



The multi-component spectrum of the Fermi/GBM burst GRB 100724B simulated in ECLAIRs+GRM.

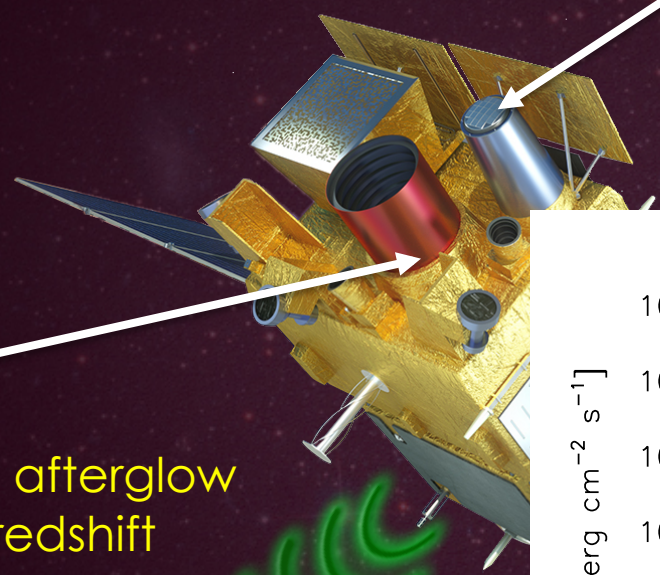
SVOM: a unique sample

Afterglow & distance

slew request: 36-72 GRB/yr

MXT

X-ray afterglow
(>90% of GRBs after a slew)



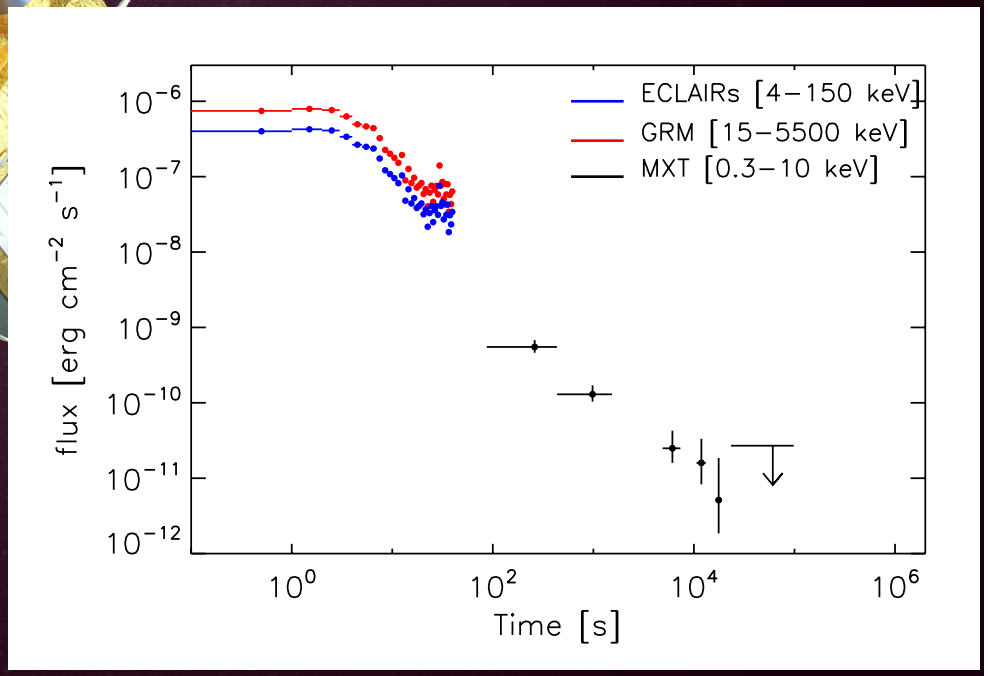
VT

Visible and NIR afterglow
+photometric redshift

GWAC **C-GFT/F-GFT**

Very large telescopes

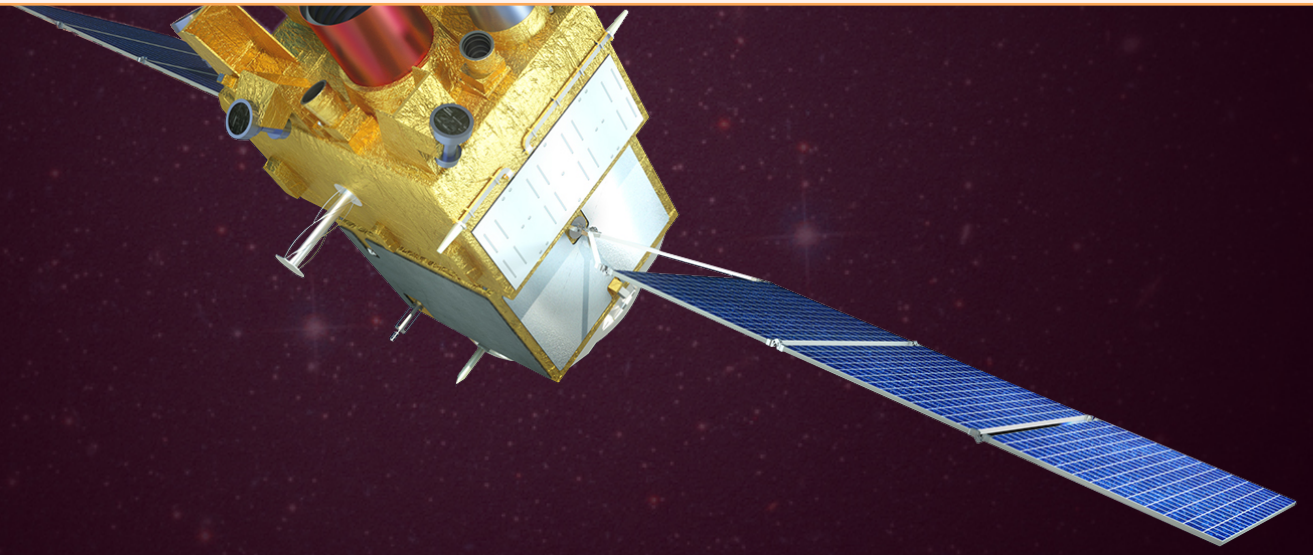
Redshift in ~2/3 of cases



The X-ray afterglow of the Swift burst GRB 091020 simulated in MXT.

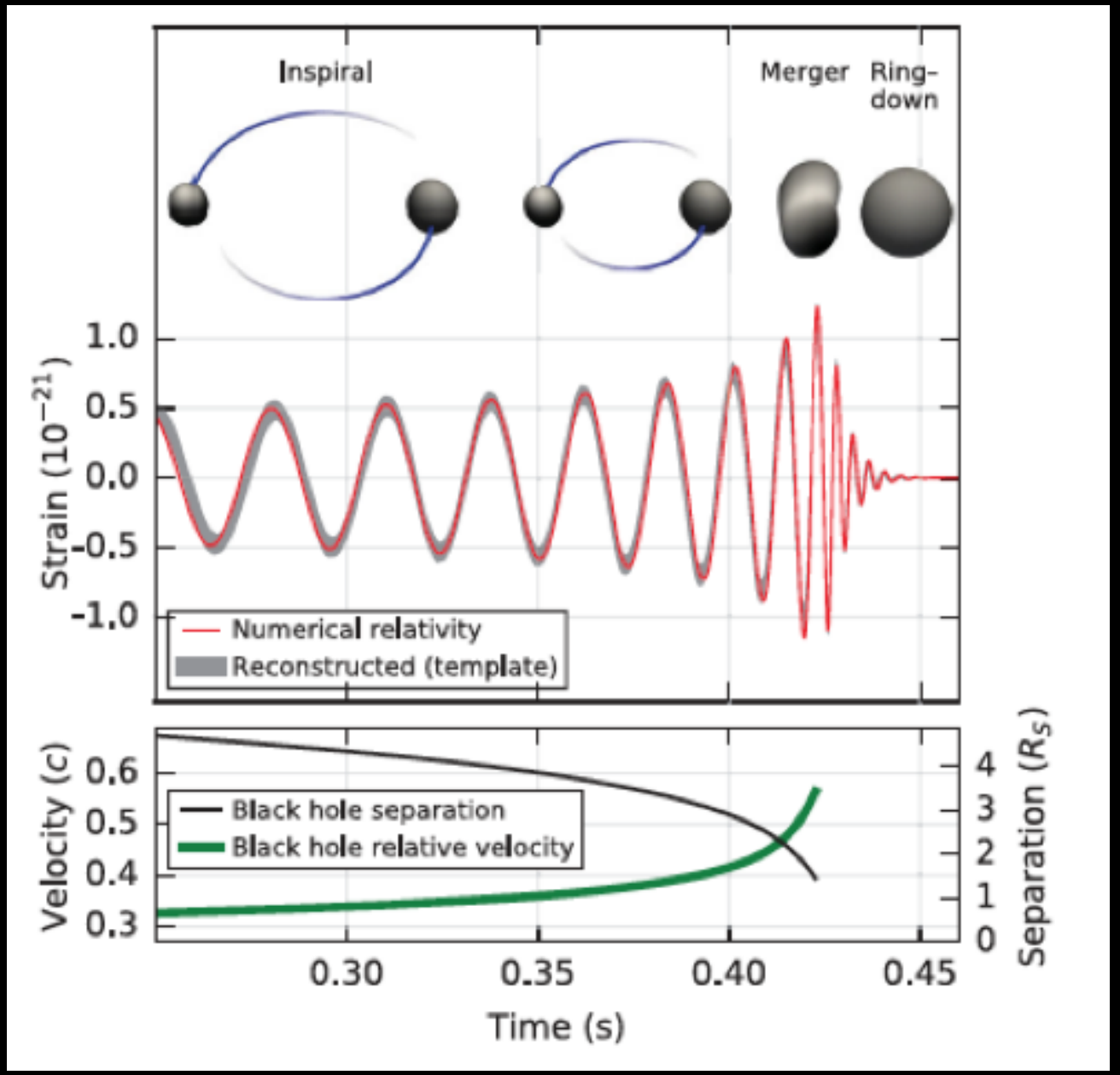
SVOM: a unique sample

	Swift	Fermi	SVOM
Prompt	Poor	Excellent 8 keV-100 GeV	Very good 4 keV-5.5 MeV + visible
Afterglow	Excellent	/	Excellent
Redshift	~1/3	/	~2/3



Mergers

Mergers:



GW150914: BH+BH (LIGO)

Mergers:

- **Motivation:** extreme relativistic sources
  new window on Universe

- **Three detected events:** BH+BH mergers

- **Open questions:** NS+BH?
  NS+NS?

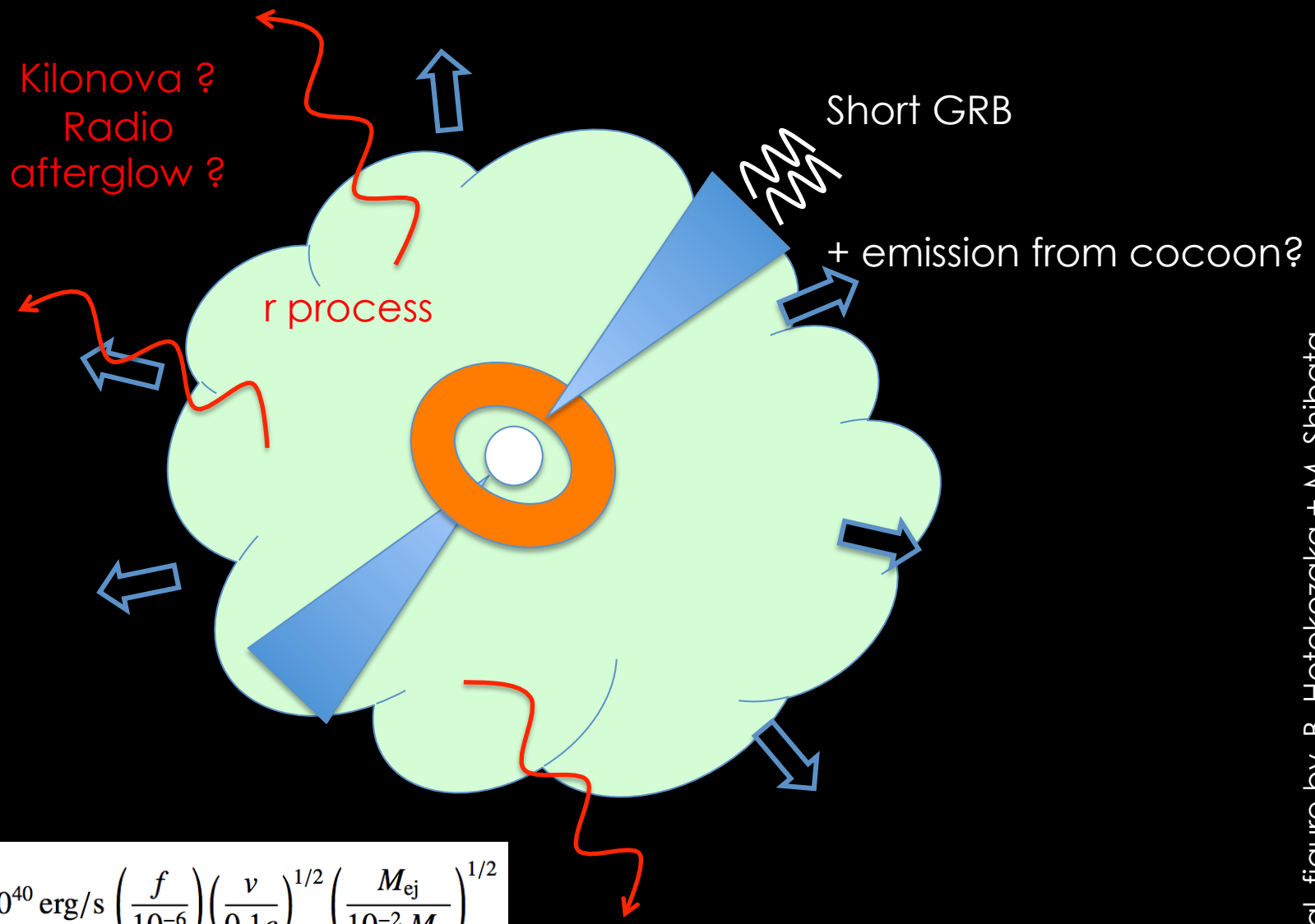
  Rates?
  Formation of the binary systems?

  Nature of the final compact object (BH vs massive NS)
  Distribution of mass, spin, …

  Final state of a merger?
  Nucleosynthesis (r process?)
  Ejection (relativistic/non relativistic?)
  Electromagnetic counterparts?

Highly uncertain…

Mergers: NS+NS

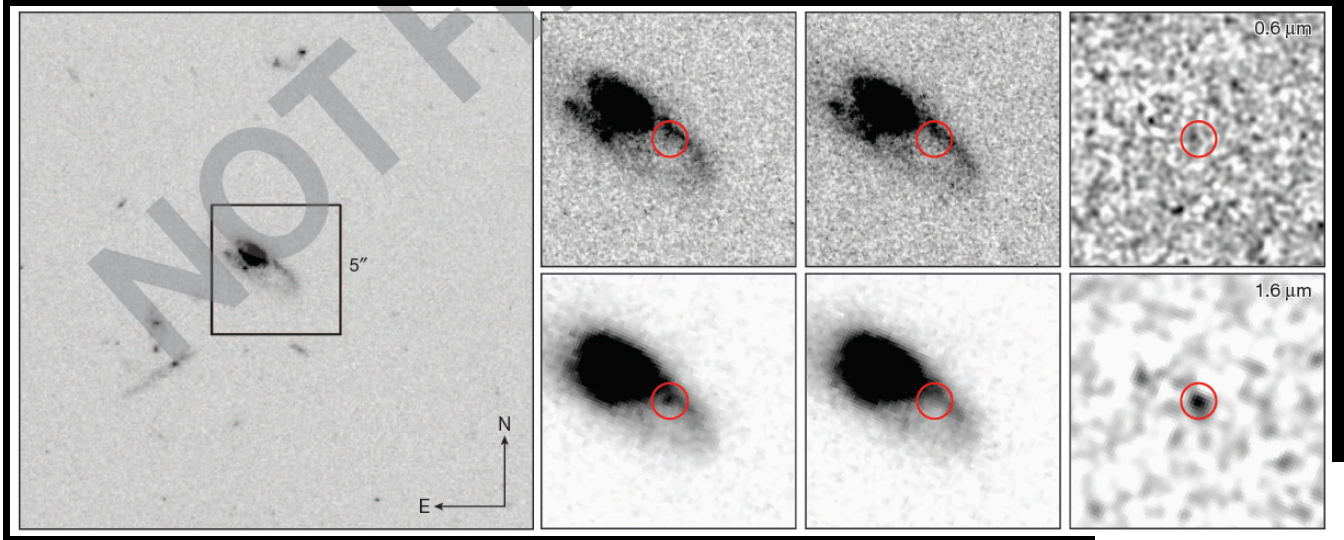


$$L_{\rm KN,peak} \simeq 5\times10^{40}\,{\rm erg/s}\left(\frac{f}{10^{-6}}\right)\left(\frac{v}{0.1c}\right)^{1/2}\left(\frac{M_{\rm ej}}{10^{-2}\,M_\odot}\right)^{1/2}$$

(Metzger et al. 2010)

Original figure by B. Hotokezaka + M. Shibata

Kilonova?



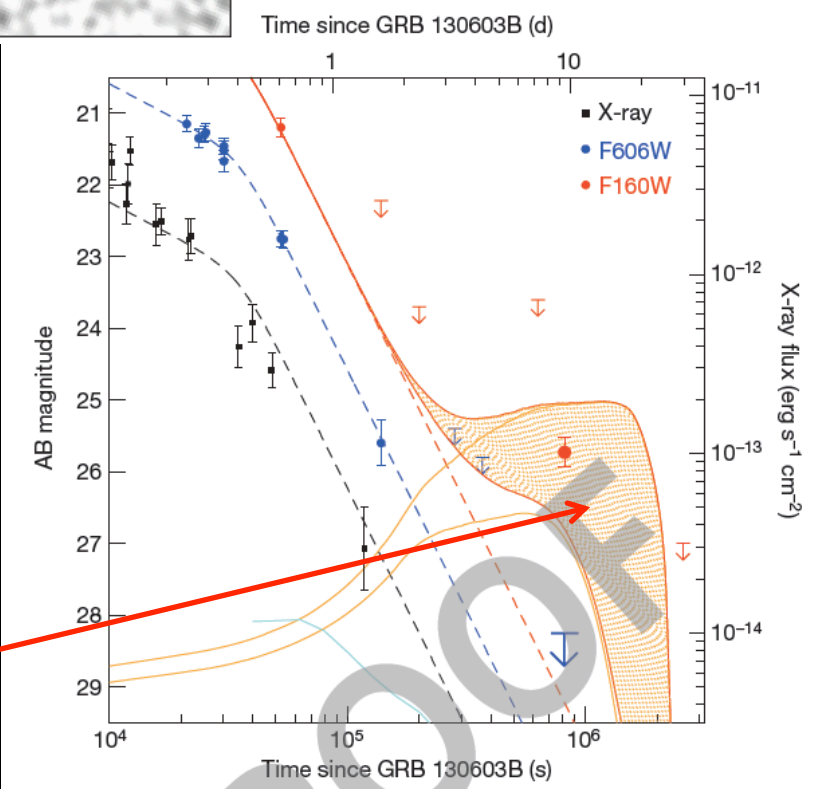
Tanvir et al. 2013

GRB 130603B (short GRB)

A few other candidates…

Still very uncertain!

Kilonova ?



Mergers: NS+NS

- **Expected electromagnetic emission: all numbers are highly uncertain!**
  - short GRB: gamma-rays
    - bright but beamed
    - association probability in 2020+: low

    ~ 3-30/yr GRB+GW pointing towards us (within GW horizon)
    with detection efficiency: SVOM/ECLAIRs: 0.3-3/yr ?
    GRM: 1-8/yr ?
  - short GRB: X-ray afterglow
    - bright but beamed
    - needs repointing of an X-ray telescope within hours

    SVOM/MXT: 1-10/yr ?
  - short GRB: visible afterglow
    - bright but beamed
    - needs large f.o.v or rapid pointing

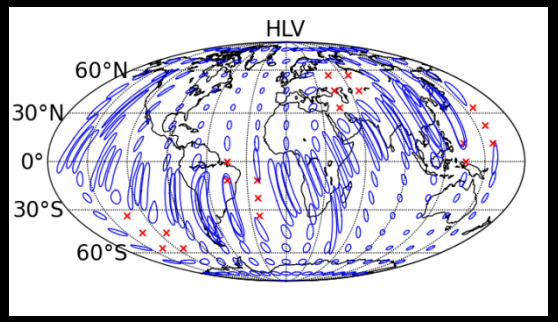
    SVOM/GWAC: 1-10/yr ?
  - kilonova: - faint but quasi isotropicvisible/NIR
    - timescale=day, week

Mergers: NS+NS

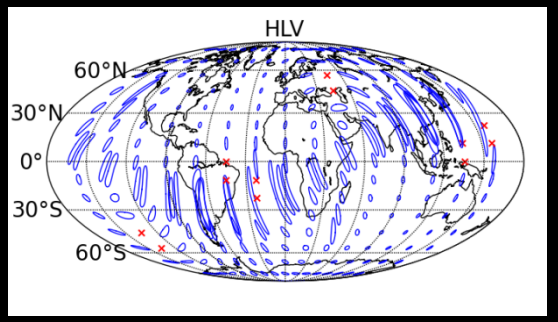
- **Expected electromagnetic emission: all numbers are highly uncertain!**
  - short GRB: gamma-rays
  - short GRB: X-ray afterglow
  - short GRB: visible afterglow
  - kilonova
  - emission of the cocoon:
    - faint but less beamed than the GRB
    - visible ? timescale ~10h ?
  - orphan afterglow: same strategy than for the afterglow
  - afterglow of the non relativistic ejecta: (Xrays), radio
    - faint but quasi-isotropic
    - timescale: weeks, month, year
  - other? (connection with fast radio burst?)

Mergers:

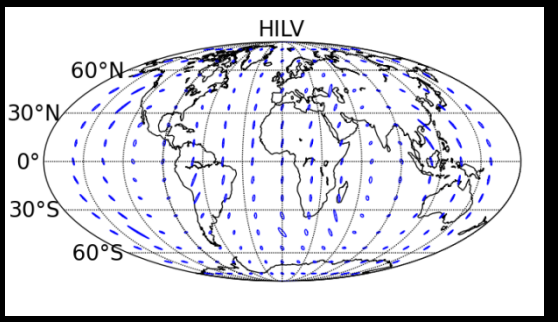
- **Alerts?**



2015



2019



2022

- 2020+ : localization of NS+NS/BH mergers within a few deg^2.
- Expected NS-NS detection rate: about 40/year within 445 Mpc (z~0.1)
- Expected BH-NS detection rate: about 10/year within 927 Mpc (z~0.2)

(Abadie et al. 2010: large uncertainties, at least factor of 10)

Summary

Summary:

- **Supernovae:**
  - too many alerts?
  - spectro-photometric follow-up?
  - shock breakout (cc-SN) ?
  - neutrinos ?
- **Gamma-ray bursts and mergers:**
  - small number of alerts: use the full potential of all of them!
  - fast multi-wavelength response is mandatory (prompt: <100 s)
  - cosmology: NIR follow-up, rapid high resolution spectroscopy
  - electromagnetic counterparts to mergers: many uncertainties
  - the most difficult challenge: GW-electromagnetic association
neutrinos-em association
(GW-neutrinos ?)
- Core-collapse: continuum of events from standard SNae to GRBs?
- Mergers: WD+WD/NS/BH?