Cosmology and Multi-Messenger Astrophysics with Gamma-Ray Bursts

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Gamma-Ray Bursts: the most extreme phenomena in the Universe

2704 BATSE Gamma-Ray Bursts
Gamma-Ray Bursts: the most extreme phenomena in the Universe

Long GRBs: core collapse of peculiar massive stars, association with SN

Short GRBs: NS-NS or NS-BH mergers, association with GW sources
**Long GRBs**

- Direct detection and accurate location of exploding stars (and their host galaxies) up to the Cosmic Dawn!
- Cosmological «beacons»
- Standardizable cosmological candles?
Short GRBs: e.m. counterparts of gravitational-waves sources

LIGO, Virgo, and partners make first detection of gravitational waves and light from colliding neutron stars

Lightcurve from *Fermi/GBM* (50 – 300 keV)

Gravitational-wave time-frequency map
Shedding light on the early Universe with GRBs

- A major goal of contemporary cosmology is to reveal the emergence of primordial stars and galaxies, and the contemporaneous reionization of the intergalactic medium, in the **first billion years of the Universe**

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**What was the timeline of reionization?**

**What sources were responsible?**

**How did the chemical elements build up?**
Shedding light on the early Universe with GRBs

- **Long GRBs:** huge luminosities, mostly emitted in the X and gamma-rays

- **Redshift distribution**
  extending at least to $z \sim 9$ and association with exploding massive stars

- **Powerful tools for cosmology:** SFR evolution, physics of re-ionization, high-z low luminosity galaxies, pop III stars
Shedding light on the early Universe with GRBs

A statistical sample of high–z GRBs can provide fundamental information:

• measure independently the cosmic star–formation rate, even beyond the limits of current and future galaxy surveys

• directly (or indirectly) detect the first population of stars (pop III)
• Detecting and studying primordial invisible galaxies

Even JWST and ELTs surveys will be not able to probe the faint end of the galaxy Luminosity Function at high redshifts (z>6-8)
• Detecting and studying primordial invisible galaxies

• neutral hydrogen fraction
• escape fraction of UV photons from high-z galaxies
• early metallicity of the ISM and IGM and its evolution
• Detecting and studying primordial invisible galaxies
GRB: a key phenomenon for multi-messenger astrophysics

GW170817 + SHORT GRB 170817A + KN AT2017GFO (~40 Mpc): the birth of multi-messenger astrophysics
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GRB: a key phenomenon for multi-messenger astrophysics (and cosmology)

GW170817 + SHORT GRB 170817A + KN AT2017GFO

THE BIRTH OF MULTI-MESSENGER ASTROPHYSICS

Relativistic jet formation, equation of state, fundamental physics

Cosmic sites of r-process nucleosynthesis

New independent route to measure cosmological parameters
Estimating $H_0$ with GW170817A (LVC 2017)

Investigating dark energy with a statistical sample of GW + e.m. (Sathyaprakash et al. 2019)
GRB: a key phenomenon for multi-messenger astrophysics (and cosmology)

MEASURING THE EXPANSION RATE AND GEOMETRY OF SPACE-TIME
GRB: a key phenomenon for multi-messenger astrophysics (and cosmology)

MEASURING THE EXPANSION RATE AND GEOMETRY OF SPACE-TIME

~20 joint GRB+GW events
GRB: a key phenomenon for multi-messenger astrophysics (and cosmology)

- Short GRBs
- Core-collapse stars
- Soft Gamma-ray Repeaters
- Unexpected transients...
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- Short GRBs
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Future missions (late‘20s and ‘30s)

- **THESEUS** (studied for ESA Cosmic Vision / M5), **HiZ-GUNDAM** (JAXA, under study), **TAP** (under study for NASA decadal survey), **Gamow Explorer** (under study for NASA MIDEX): prompt emission down to soft X-rays, source location accuracy of few arcmin, prompt follow-up with NIR telescope, on-board REDSHIFT
Future missions: the case of THESEUS

THIS BREAKTHROUGH WILL BE ACHIEVED BY A MISSION CONCEPT OVERCOMING MAIN LIMITATIONS OF CURRENT FACILITIES

Set of innovative wide-field monitors with unprecedented combination of broad energy range, sensitivity, FOV and localization accuracy
Future missions: the case of THESEUS

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Set of innovative wide-field monitors with unprecedented combination of broad energy range, sensitivity, FOV and localization accuracy

On-board autonomous fast follow-up in optical/NIR, arcsec location and redshift measurement of detected GRB/transients
Shedding light on the early Universe with GRBs
Shedding light on the early Universe with GRBs
Exploring the multi-messenger transient sky

THESEUS ensures:
• Immediate coverage of gravitational wave and neutrino source error boxes
• Real time sky localizations
• Temporal & spectral characterization from NIR to gamma-rays
LIGO, Virgo, and partners make first detection of gravitational waves and light from colliding neutron stars

Lightcurve from *Fermi/GBM* (50 – 300 keV)

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**THESEUS:**

- short GRB detection over large FOV with arcmin localization
- Kilonova detection, arcsec localization and characterization
- Possible detection of weaker isotropic X-ray emission
Multi-wavelength/messenger synergies

Amati+ 2021
GRB nFn spectra typically show a peak at a characteristic photon energy $E_p$

measured spectrum + measured redshift $\rightarrow$ intrinsic peak energy and radiated energy

$$E_{p,i} = E_p \times (1 + z)$$

Measuring cosmological parameters with GRBs

- a fraction of the extrinsic scatter of the $E_{p,i}$-$E_{iso}$ correlation is indeed due to the cosmological parameters used to compute $E_{iso}$

- Evidence, independent on other cosmological probes, that, if we are in a flat $\Lambda$CDM universe, $\Omega_M$ is lower than 1 and around 0.3

Measuring cosmological parameters with GRBs

- Future GRB experiments (e.g., SVOM) and more investigations (in particular: reliable estimates of jet angles and self-calibration) will improve the significance and reliability of the results and allow to go beyond SN Ia cosmology (e.g. investigation of dark energy)

<table>
<thead>
<tr>
<th>GRB #</th>
<th>$\Omega_M$ (flat)</th>
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<tbody>
<tr>
<td>70 (real) GRBs (Amati+ 08)</td>
<td>0.27$^{+0.38}_{-0.38}$</td>
</tr>
<tr>
<td>156 (real) GRBs (Amati+ 13)</td>
<td>0.29$^{+0.28}_{-0.18}$</td>
</tr>
<tr>
<td>250 (156 real + 94 simulated) GRBs</td>
<td>0.29$^{+0.16}_{-0.12}$</td>
</tr>
<tr>
<td>500 (156 real + 344 simulated) GRBs</td>
<td>0.29$^{+0.10}_{-0.09}$</td>
</tr>
<tr>
<td>156 (real) GRBs, calibration</td>
<td>0.30$^{+0.06}_{-0.06}$</td>
</tr>
<tr>
<td>250 (156 real + 94 simulated) GRBs, calibration</td>
<td>0.30$^{+0.04}_{-0.05}$</td>
</tr>
<tr>
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<td>0.30$^{+0.03}_{-0.03}$</td>
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$w(z) = w_0 + \frac{w_\Lambda z}{1+z}$
Using time delay between low and high energy photons to put Limits on Lorentz Invariance Violation (allowed by unprecedented Fermi GBM + LAT broad energy band)

\[ v_{ph} = \frac{\partial E_{ph}}{\partial p_{ph}} = c \left[ 1 - s_n \frac{n + 1}{2} \left( \frac{E_{ph}}{M_{QG, n} c^2} \right)^n \right] \]

\[ \Delta t = s_n \frac{(1 + n)}{2H_0} \frac{(E_h^n - E_l^n)}{(M_{QG, n} c^2)^n} \int_0^z \frac{(1 + z')^n}{\sqrt{\Omega_m (1 + z')^3 + \Omega_\Lambda}} \, dz' \]

GRB 990510

\[ E_h = 30.53^{+5.79}_{-2.56} \text{ GeV} \]

| \( t_{start} \) (ms) | limit on \( |\Delta t| \) (ms) | Reason for choice of \( t_{start} \) or limit on \( \Delta t \) | \( E_l \) (MeV) | valid for \( s_n \) | lower limit on \( M_{QG, 1}/M_{Plack} \) |
|---------------------|-----------------|-------------------------------------------------|----------|----------------|-----------------|
| -30                 | < 859           | start of any observed emission                   | 0.1      | 1              | > 1.19           |
| 530                 | < 299           | start of main <1 MeV emission                    | 0.1      | 1              | > 3.42           |
| 630                 | < 199           | start of > 100 MeV emission                      | 100      | 1              | > 5.12           |
| 730                 | < 99            | start of > 1 GeV emission                        | 1000     | 1              | > 10.0           |
| -                   | < 10            | association with < 1 MeV spike                   | 0.1      | ±1             | > 102            |
| -                   | < 19            | if 0.75 GeV \( \gamma \) is from 1st spike      | 0.1      | ±1             | > 1.33           |
| \( |\Delta E| \) < 30 ms GeV | lag analysis of all LAT events                   | —        | ±1             | > 1.22           |
Fundamental physics with GRBs: GW vs. light speed

GW170817/GRB170817A, D ~ 40 Mpc

\[ V_{gw} / c < 4 \times 10^{-16} \]

\[ \Delta t = (\Delta t_{\text{jet}} + \Delta t_{\text{bo}} + \Delta t_{\text{GRB}})(1 + z) \]

\[ \Delta t_{\text{GRB}} \approx (1 - \beta \cos \theta) \frac{R_{\text{GRB}}}{c} \sim \frac{R_{\text{GRB}}}{\Gamma^2 c} \]
In summary

- GRBs are a key phenomenon for cosmology (early Universe, cosmological parameters), multi-messenger astrophysics (GW, neutrinos) and fundamental physics

- Next generation GRB missions, like THESEUS, developed by a large European collaboration and already studied by ESA (M5 Phase A) will fully exploit these potentialities and will provide us with unprecedented clues to GRB physics and sub-classes.

- THESEUS is a unique occasion for fully exploiting the European leadership in time-domain and multi-messenger astrophysics and in related key-enabling technologies

- THESEUS observations will impact on several fields of astrophysics, cosmology and fundamental physics and will enhance importantly the scientific return of next generation multi messenger (aLIGO/aVirgo, LISA, ET, or Km3NET;) and e.m. facilities (e.g., LSST, E-ELT, SKA, CTA, ATHENA)

- THESEUS Phase A study by ESA very successful and base for further dev. SPIE articles on instruments and Exp.Astr. Articles on science on arXiv

http://www.isdc.unige.ch/theseus/