Cosmology, multi-messenger astrophysics and fundamental physics with GRBs

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(31 August 2022)

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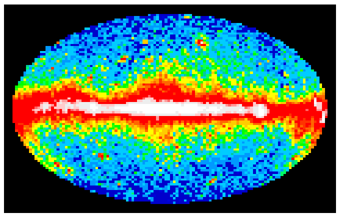
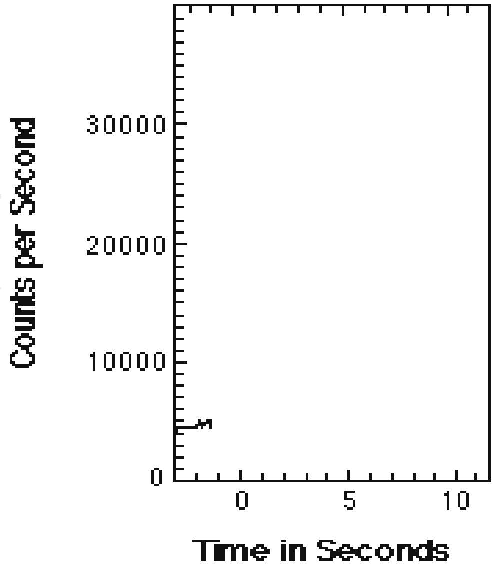
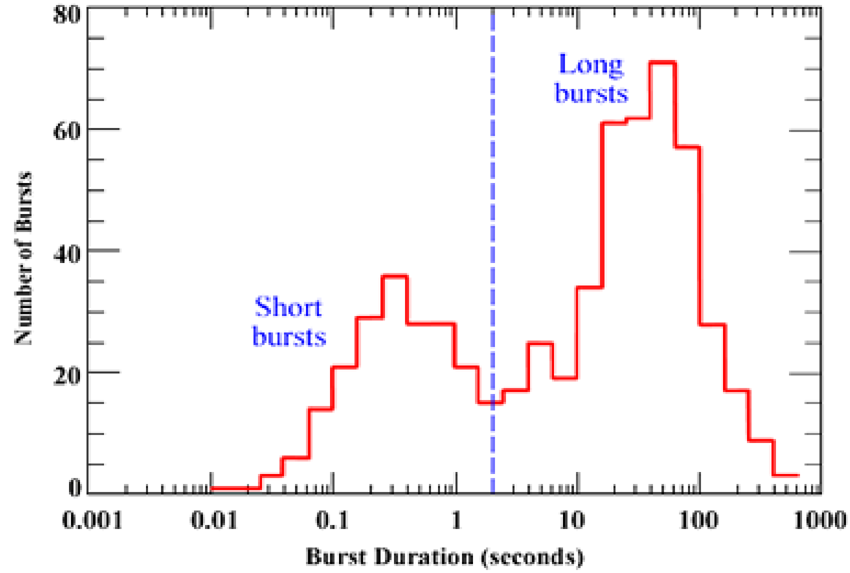
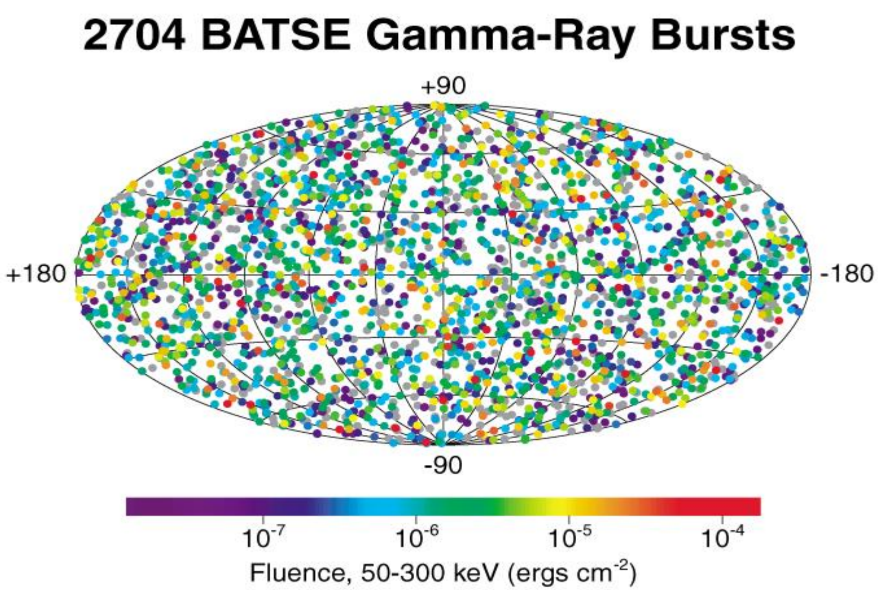
XI International Conference on
New Frontiers in Physics

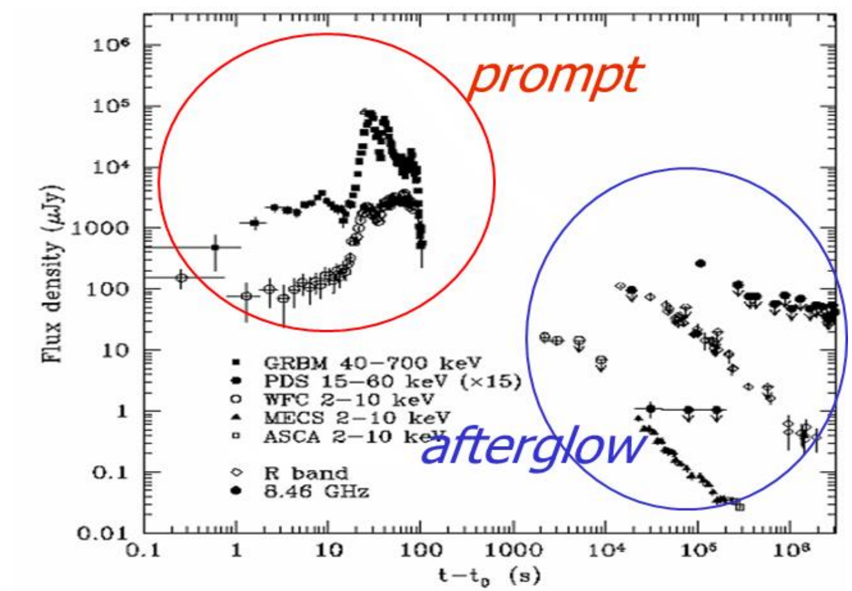
Gamma-Ray Bursts: the most extreme phenomena in the Universe











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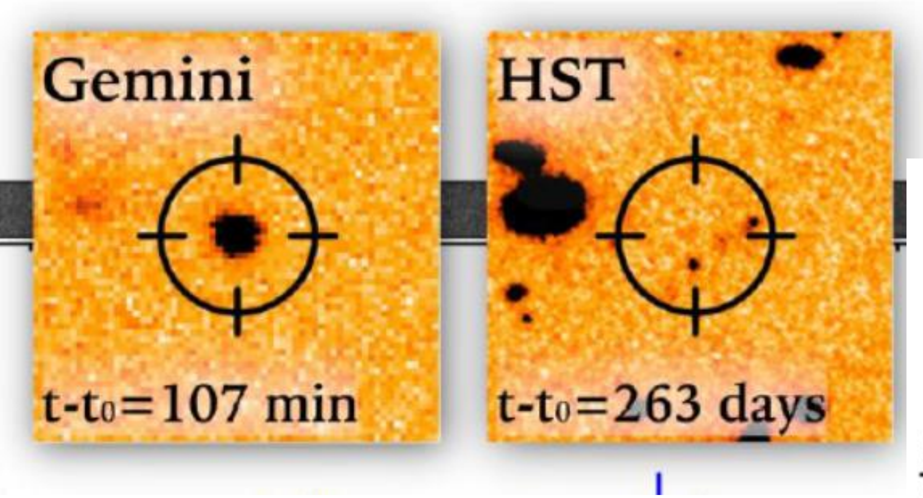
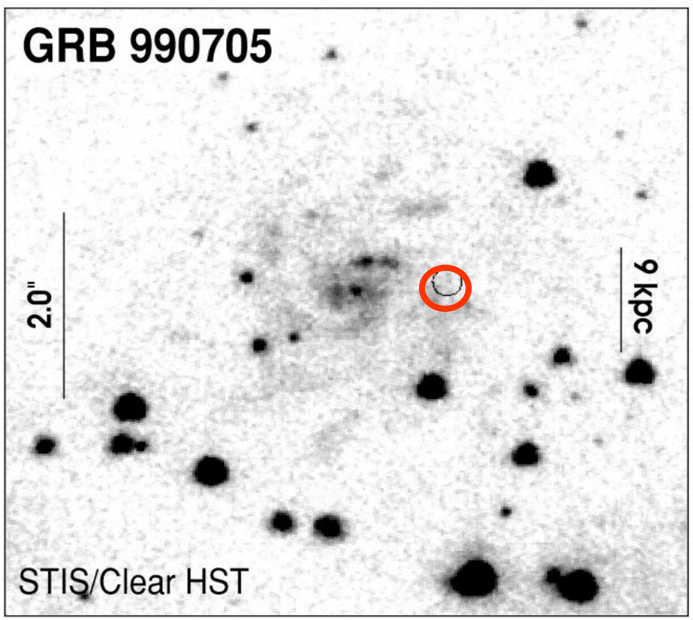
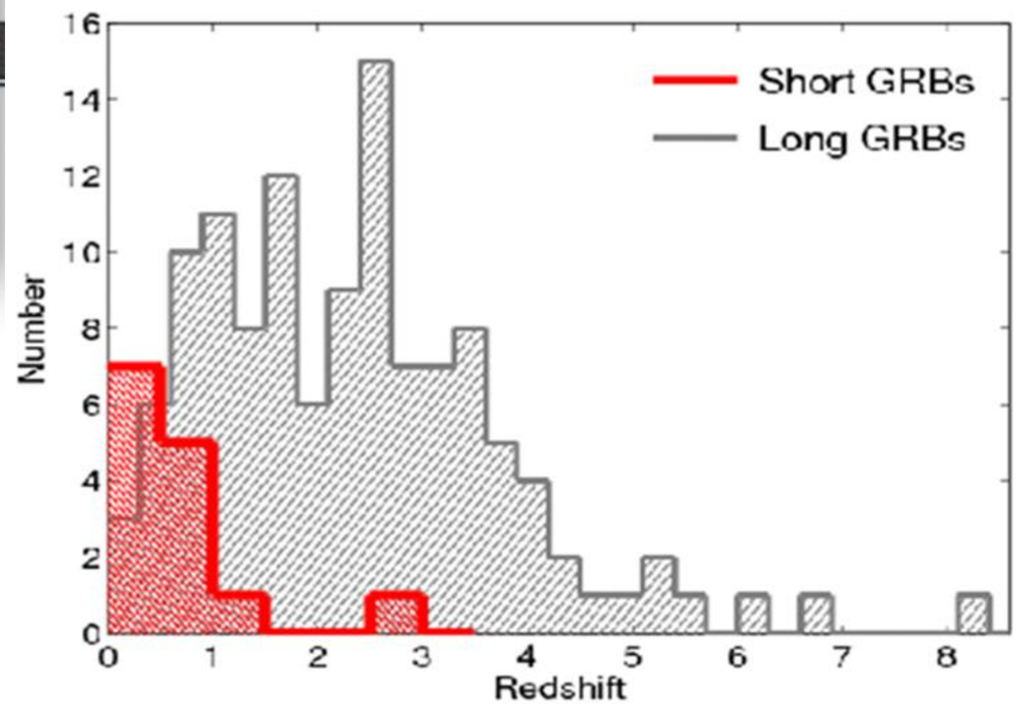


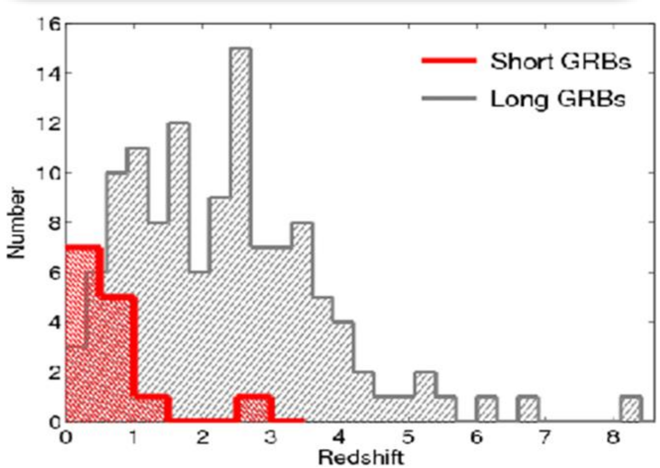


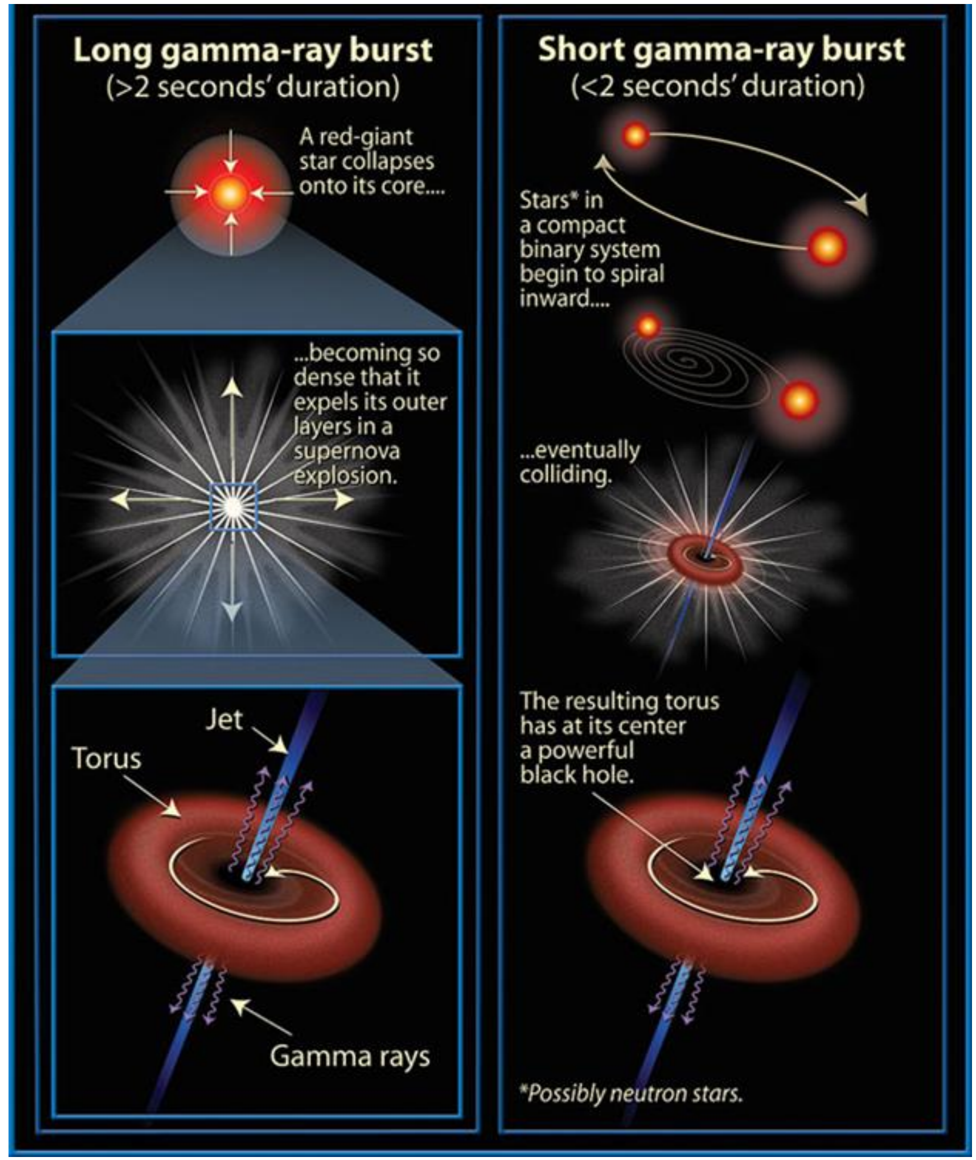


Gamma-Ray Bursts: the most extreme phenomena in the Universe

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

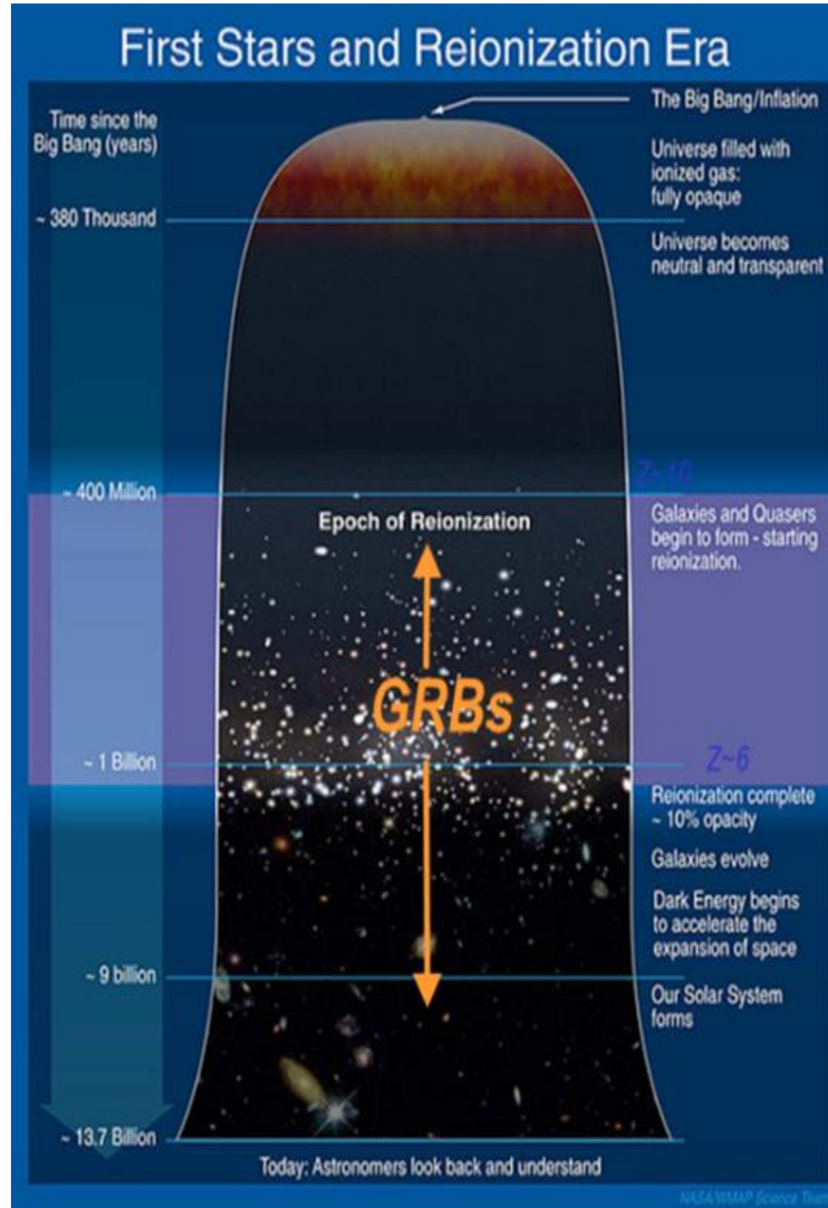
Short GRBs: NS-NS or NS-BH mergers, **association with GW sources**





Shedding light on the early Universe with GRBs

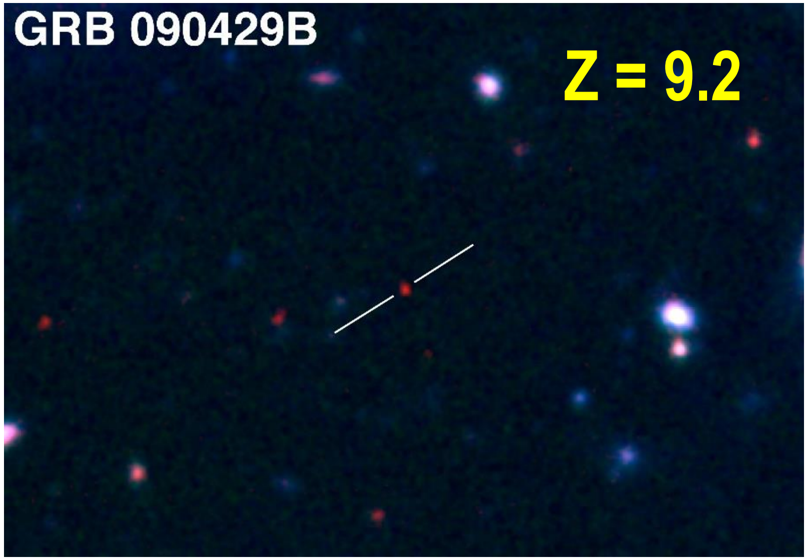
- **Long GRBs:** huge luminosities, mostly emitted in the X and gamma-rays
- **Redshift distribution** extending at least to z ~9 and association with exploding massive stars
- **Powerful tools for cosmology:** SFR evolution, physics of re-ionization, high-z low luminosity galaxies, pop III stars

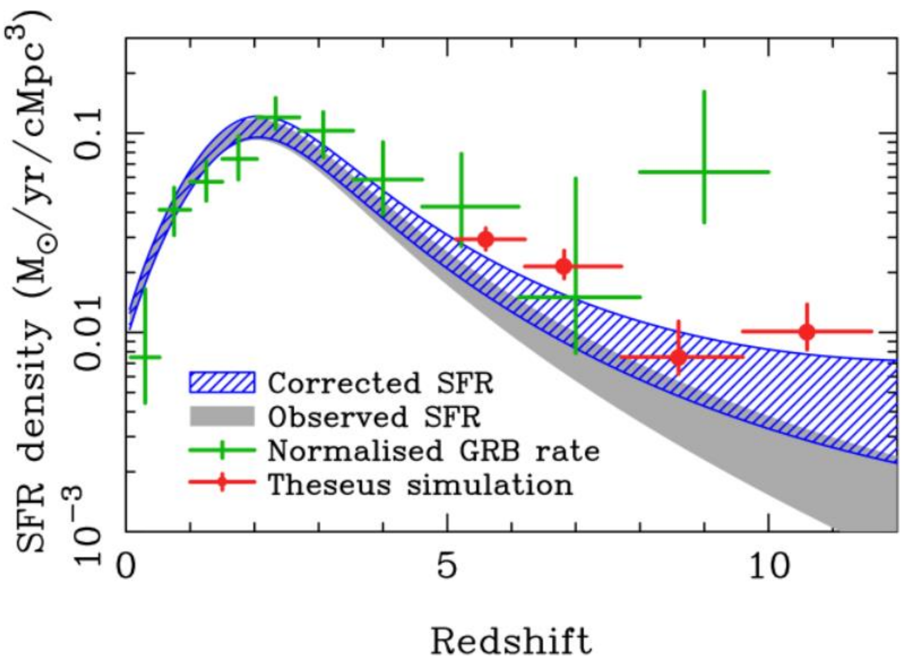


Shedding light on the early Universe with GRBs

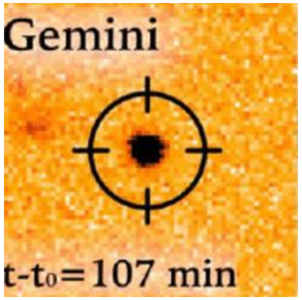
A statistical sample of high–z GRBs can provide fundamental information:

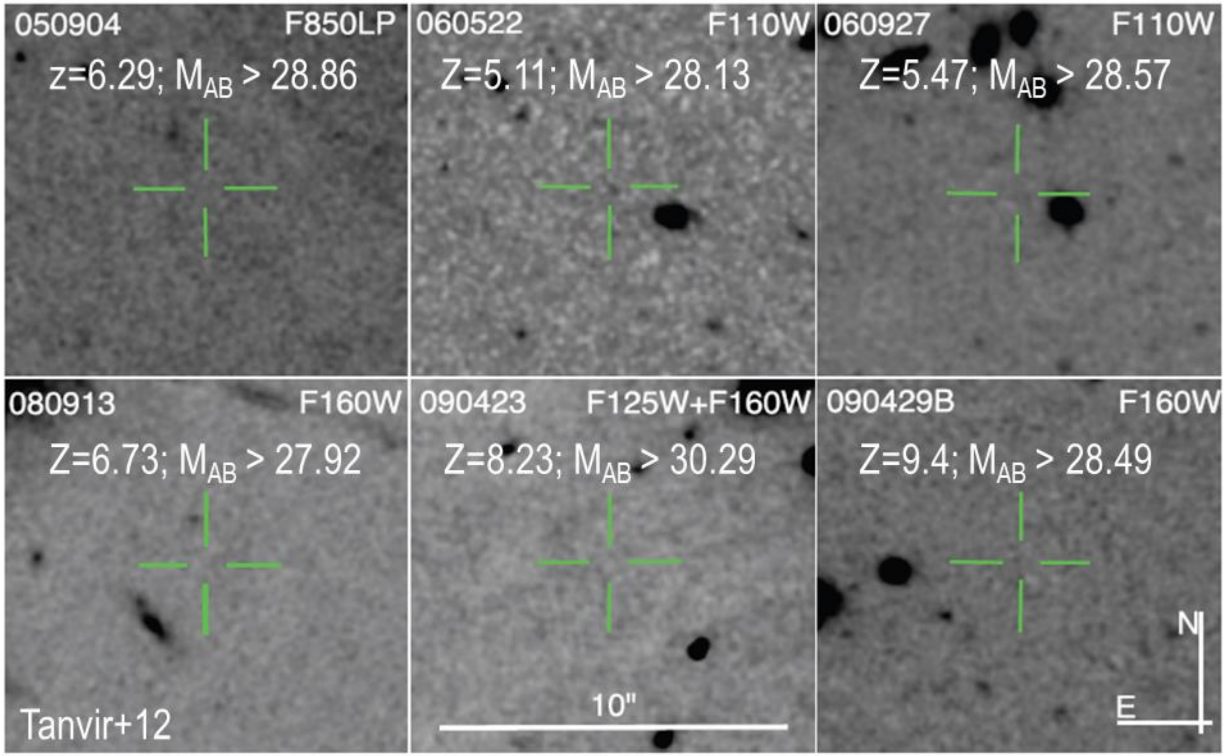
- measure independently the **cosmic star–formation rate**, even beyond the limits of current and future galaxy surveys
- directly (or indirectly) detect the **first population of stars (pop III)**





- **Detecting and studying primordial invisible galaxies**

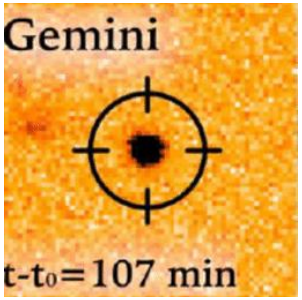


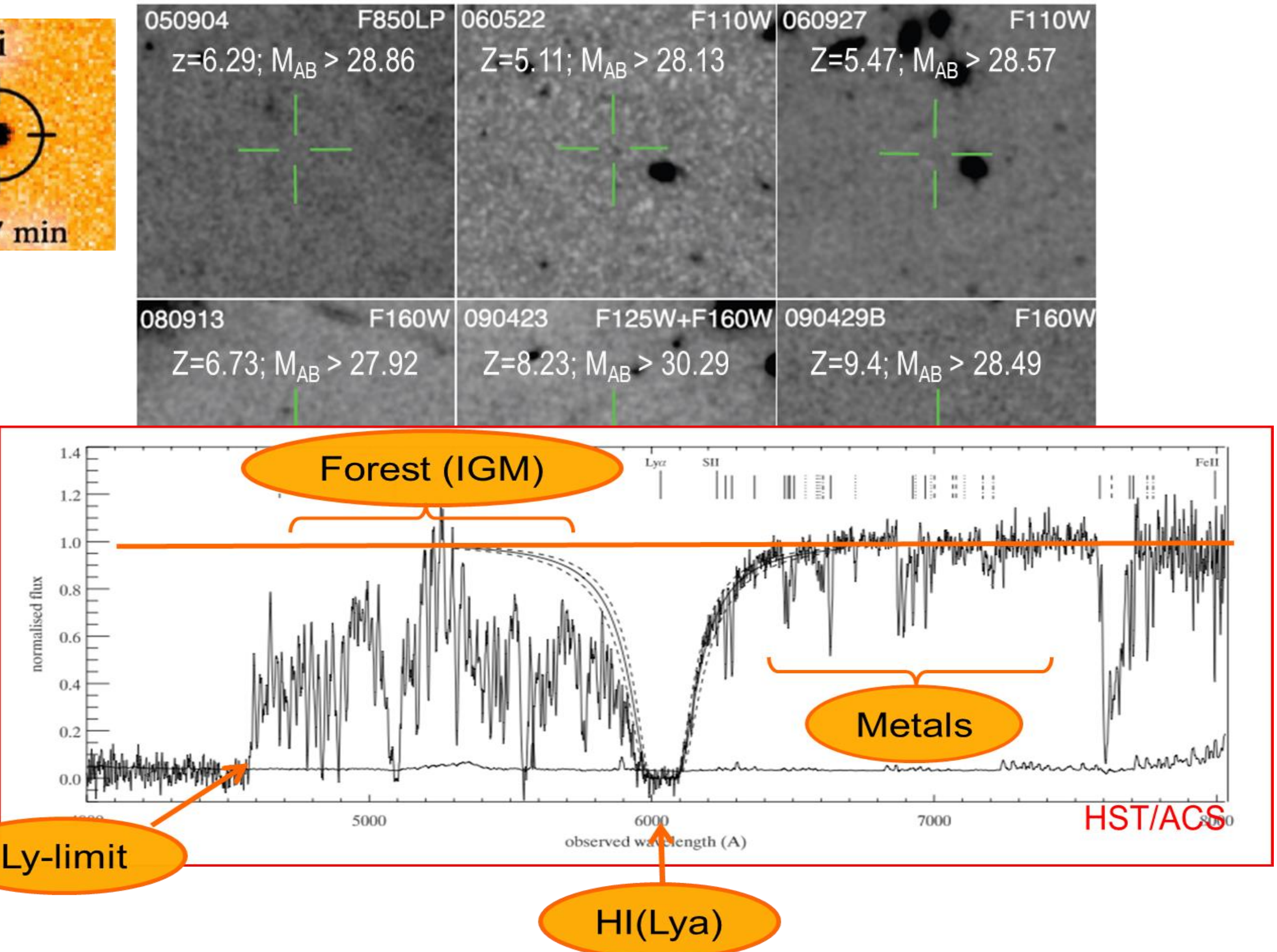


Robertson&Ellis12

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





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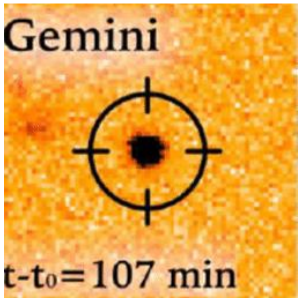
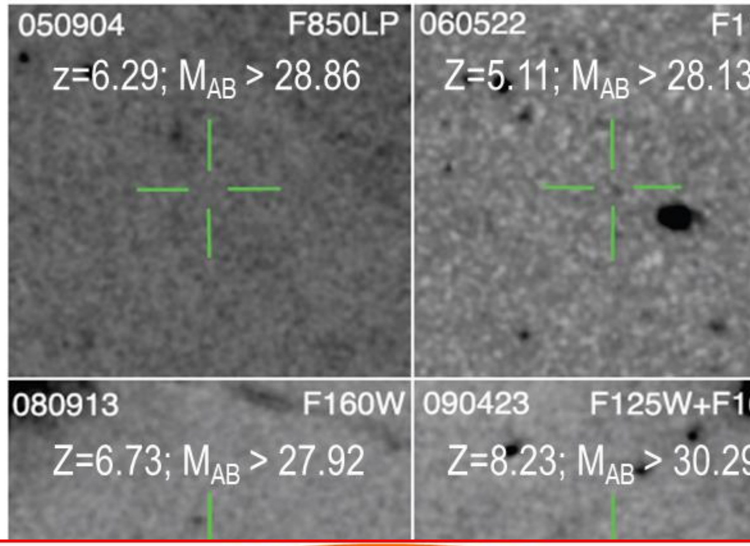
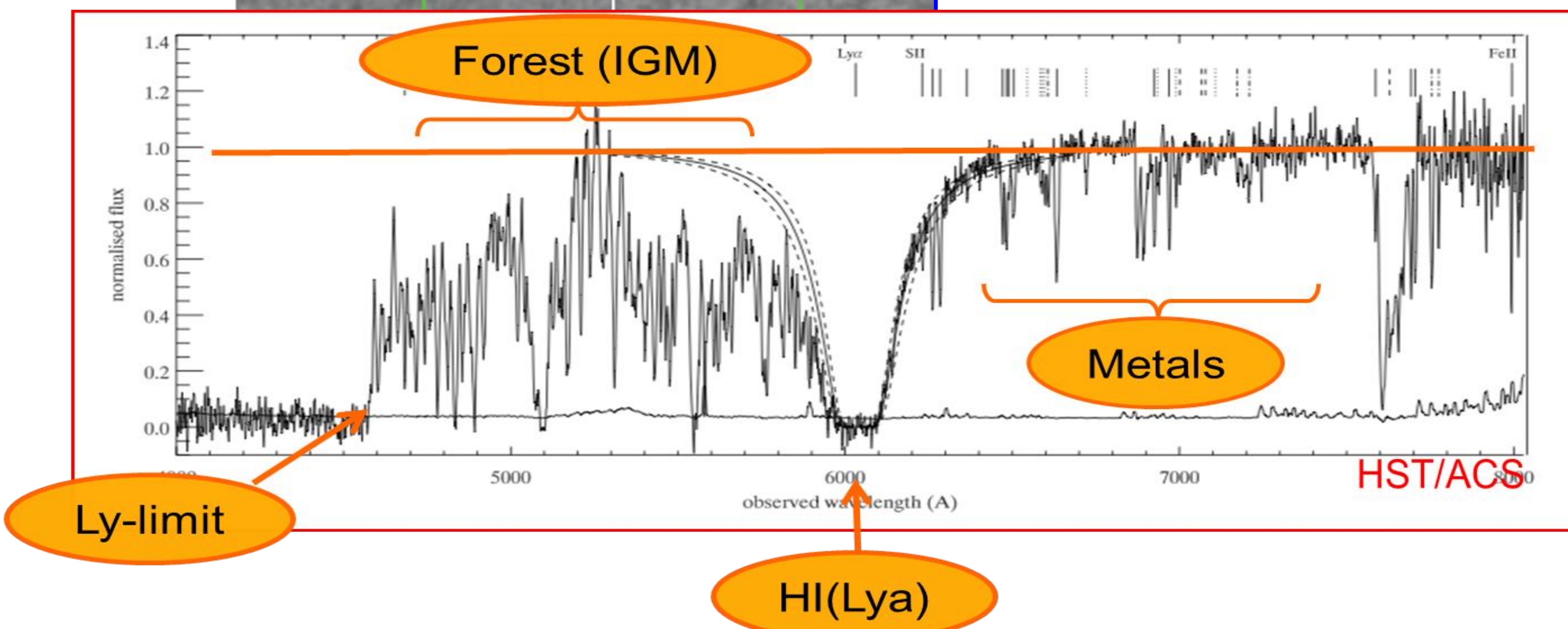




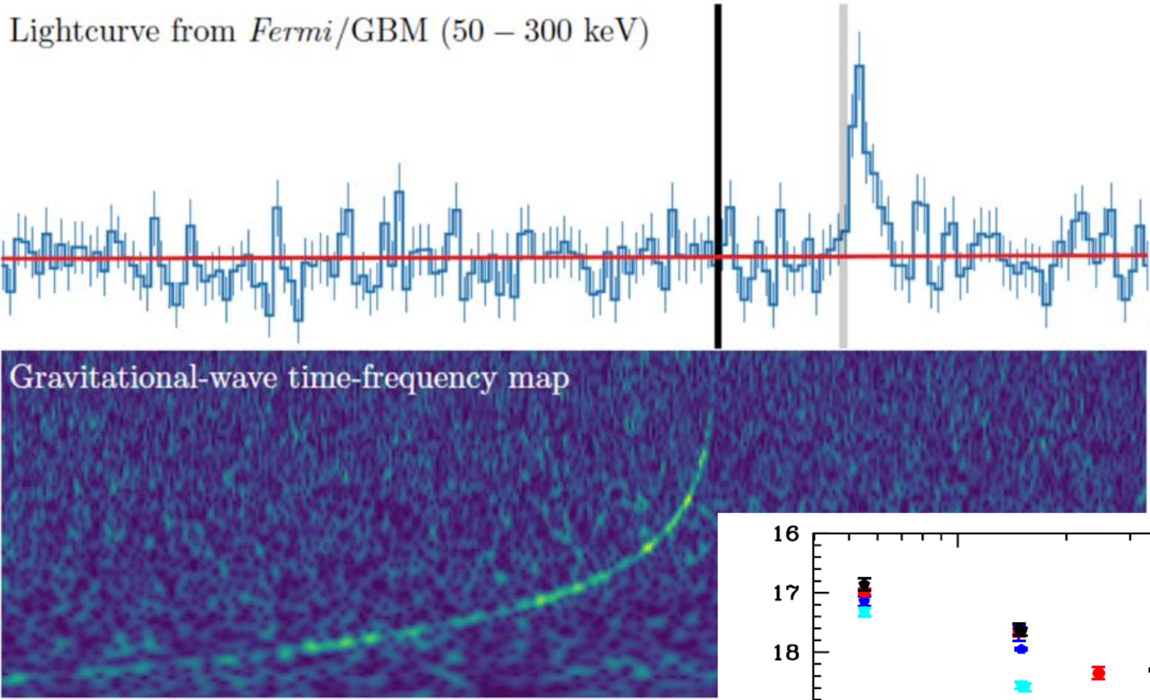
- neutral hydrogen fraction
- escape fraction of UV photons from high-z galaxies
- early metallicity of the ISM and IGM and its evolution

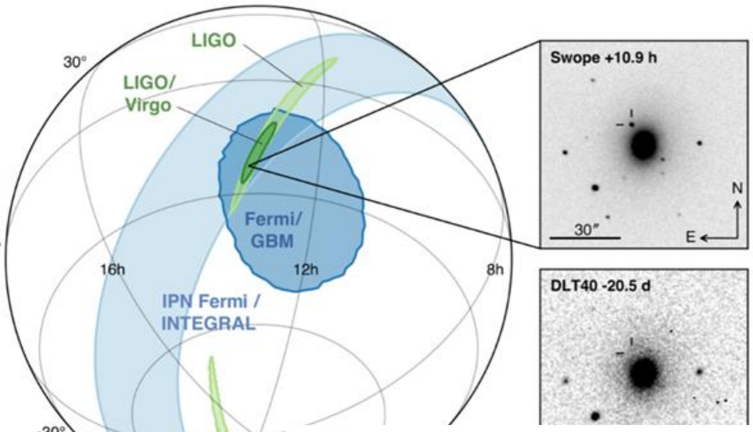


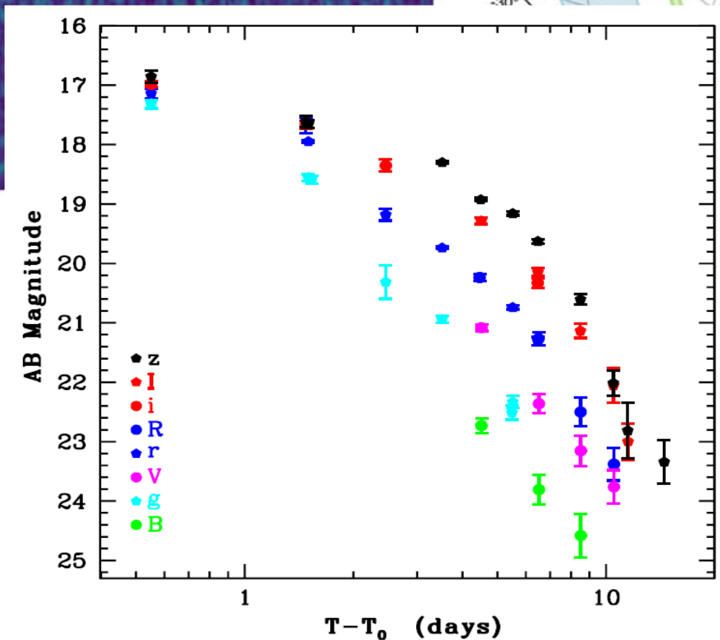
Short GRBs and multi-messenger astrophysics

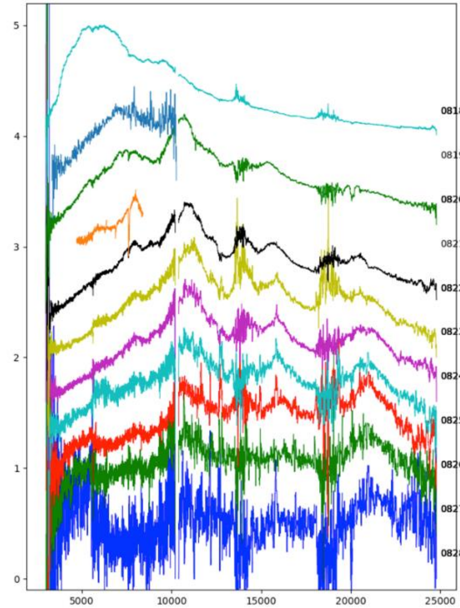
GW170817 + SHORT GRB 170817A + KN AT2017GFO (~40 Mpc):

the birth of multi-.messenger astrophysics









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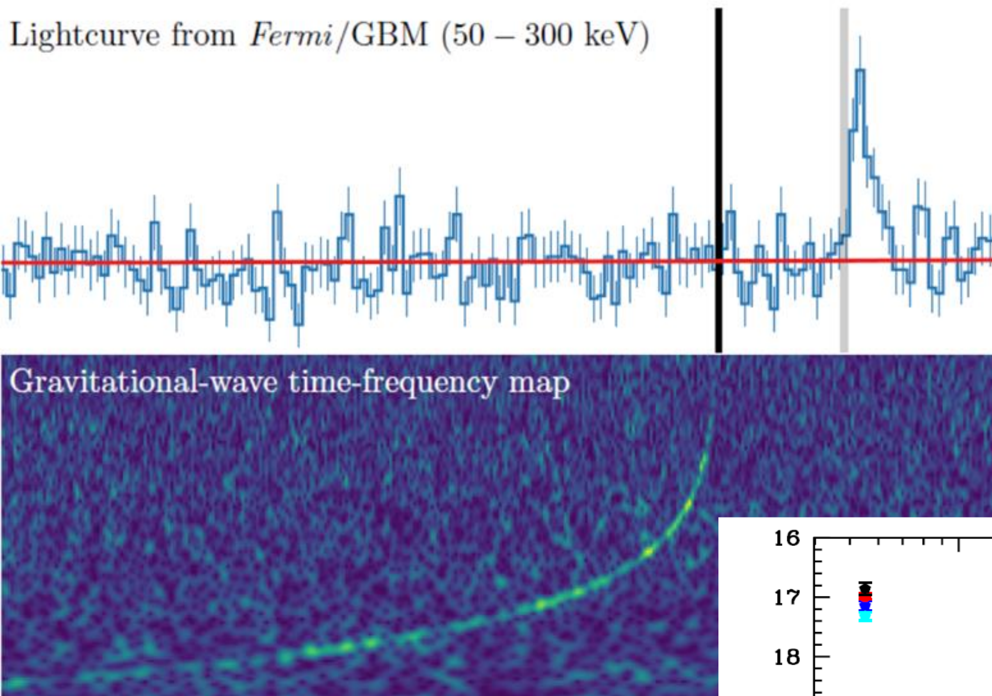
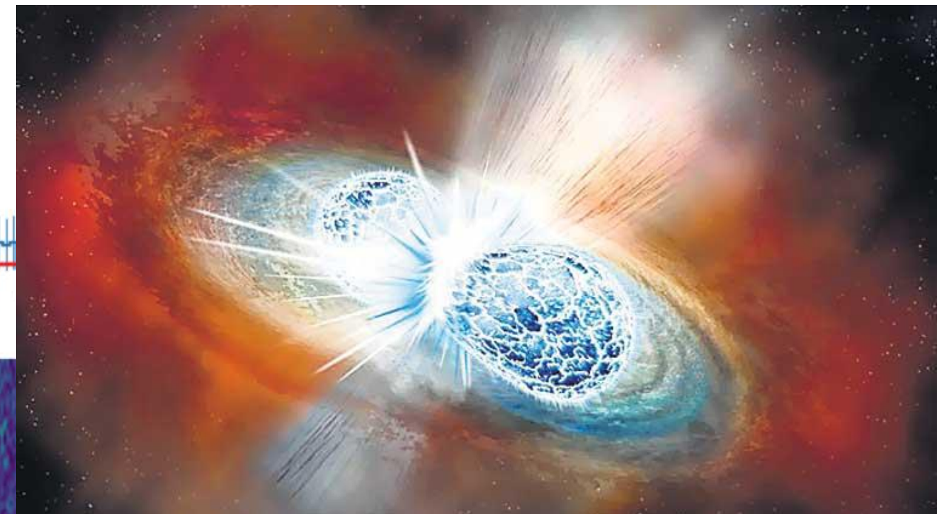
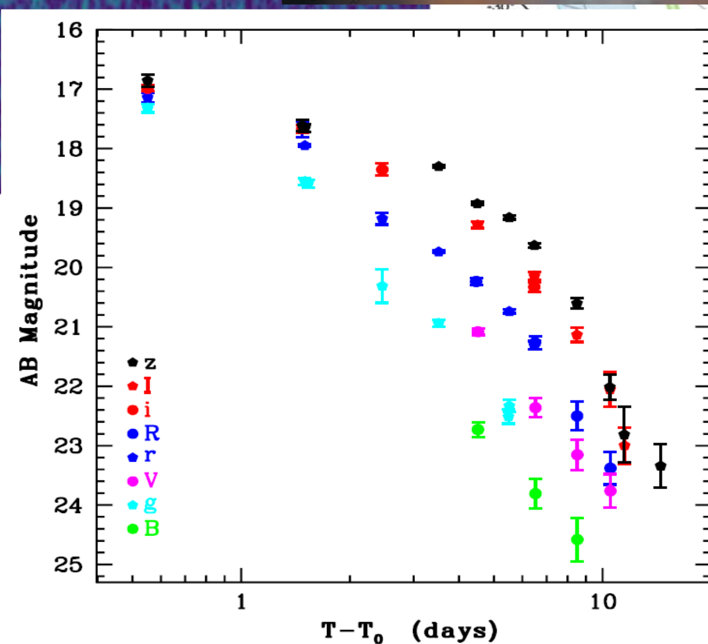
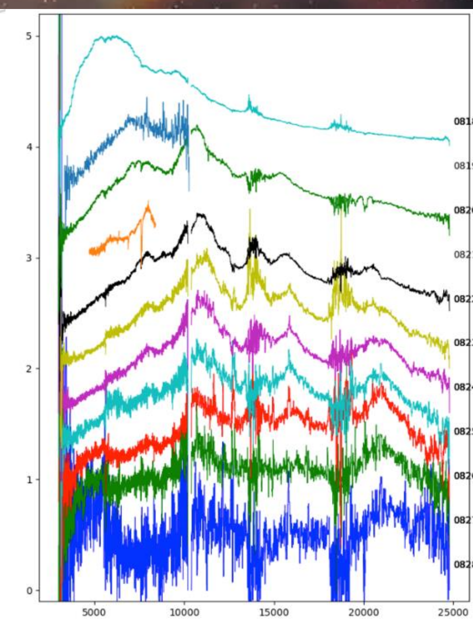




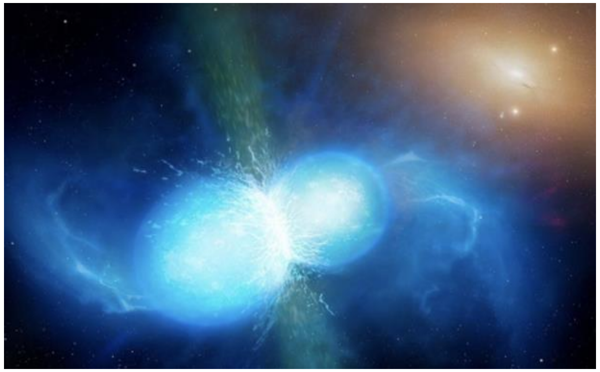




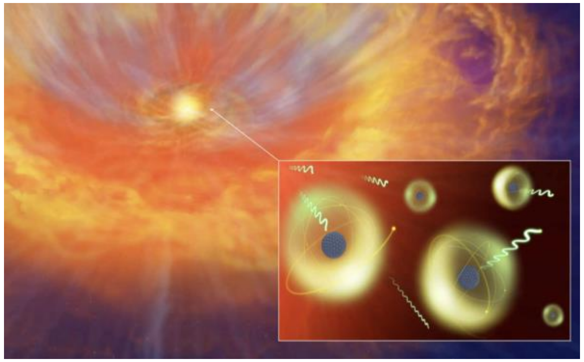
GRB: a key phenomenon for multi-messenger astrophysics (and cosmology)

GW170817 + SHORT GRB 170817A + KN AT2017GFO
THE BIRTH OF MULTI-MESSENGER ASTROPHYSICS

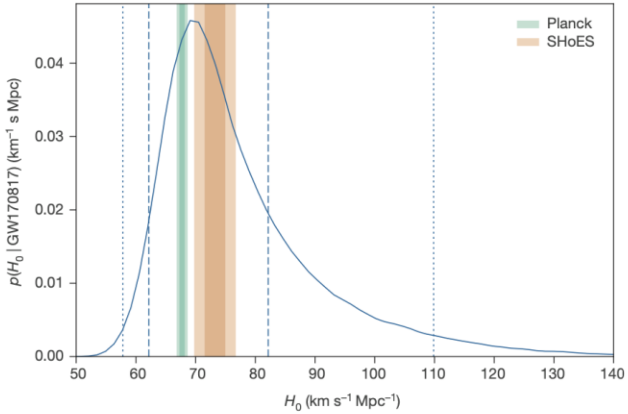
Relativistic jet formation, equation of state, fundamental physics



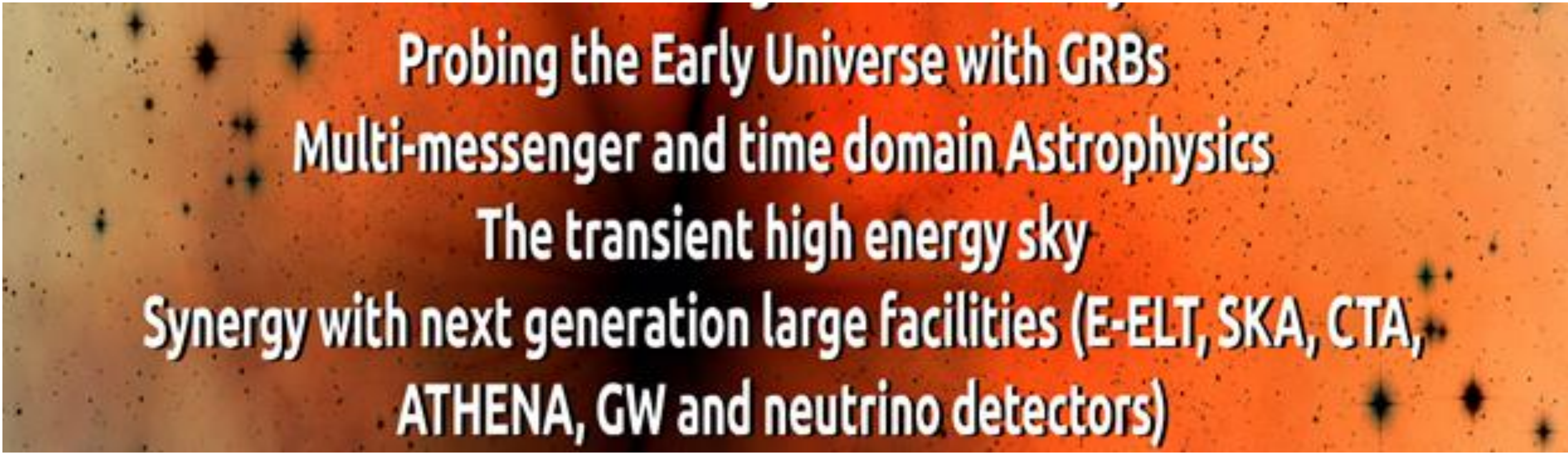
Cosmic sites of r-process nucleosynthesis



New independent route to measure cosmological parameters



Future GRB missions (late‘20s and ‘30s)

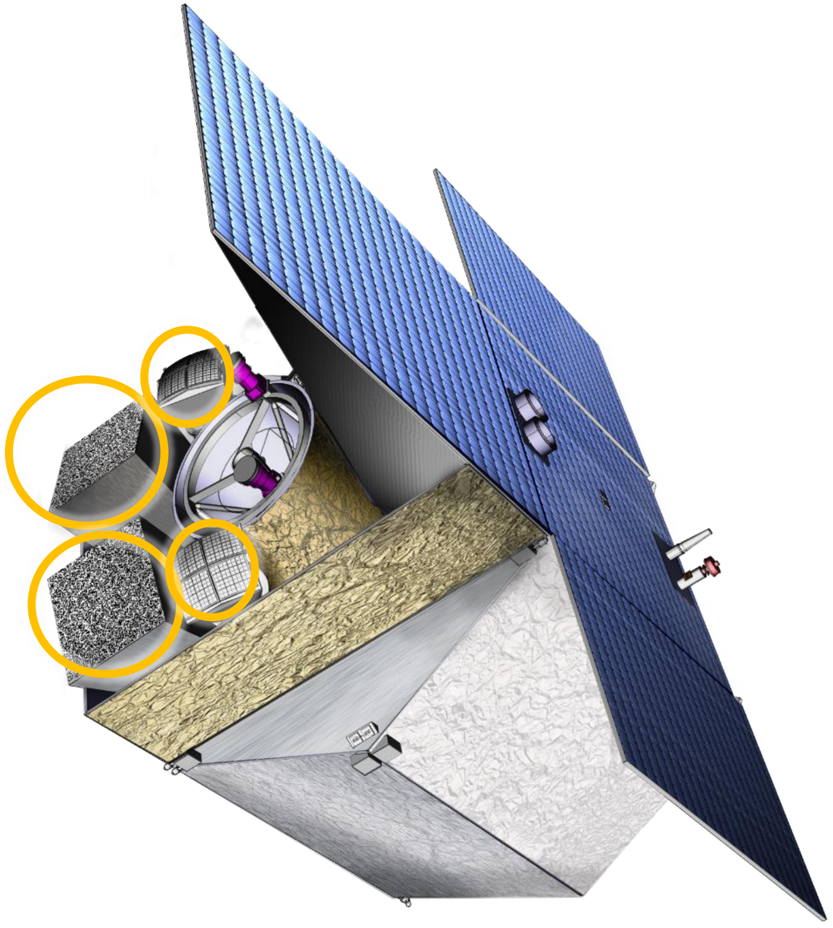


- **THESEUS** (studied for ESA Cosmic Vision / M5), **HiZ-GUNDAM** (JAXA, under study), **TAP** (idea for NASA probe-class mission)**, Gamow Explorer** (proposal for NASA MIDEX)**: prompt emission down to soft X-rays, source location accuracy of few arcmin**, **prompt follow-up with NIR telescope**,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

Future GRB missions: the case of THESEUS
(led by Italy; ESA/M5 Phase-A study, re-proposed for M7)

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**



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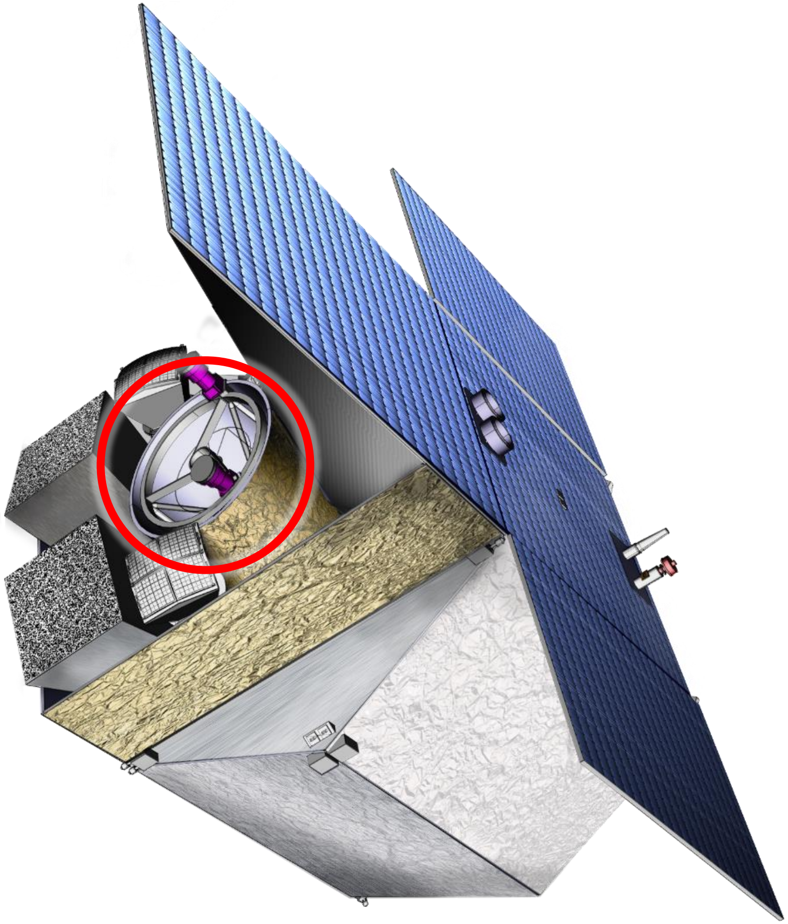
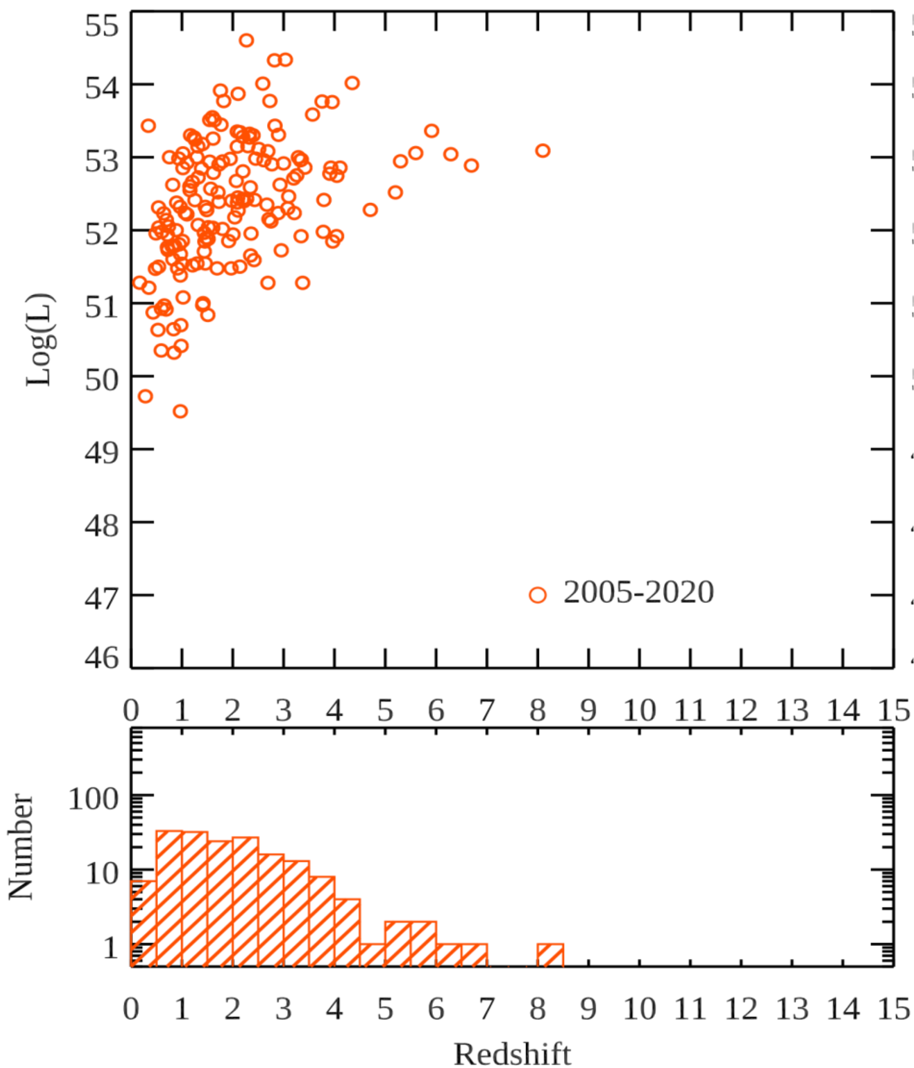
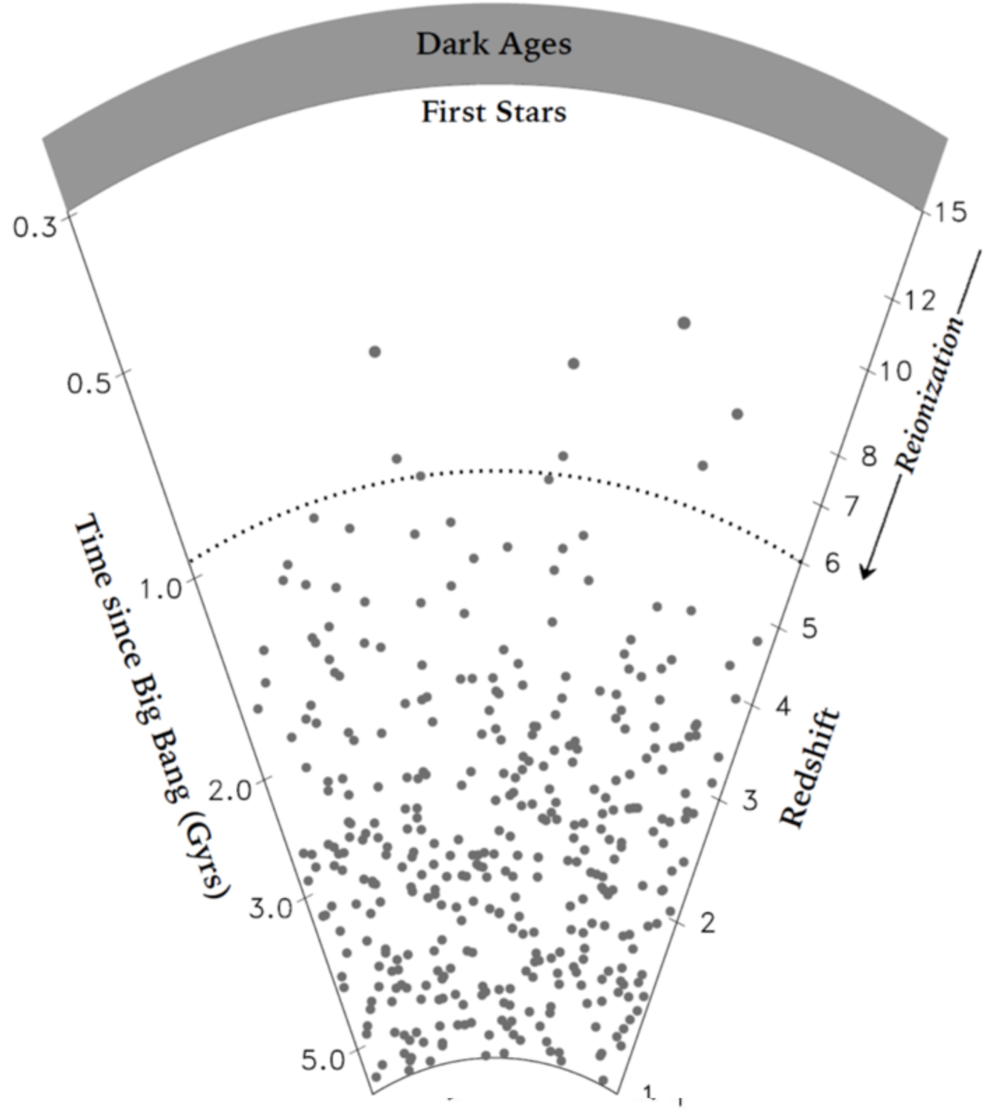
On-board **autonomous fast follow-up** in optical/NIR, arcsec location and **redshift measurement** of detected GRB/transients



Shedding light on the early Universe with GRBs





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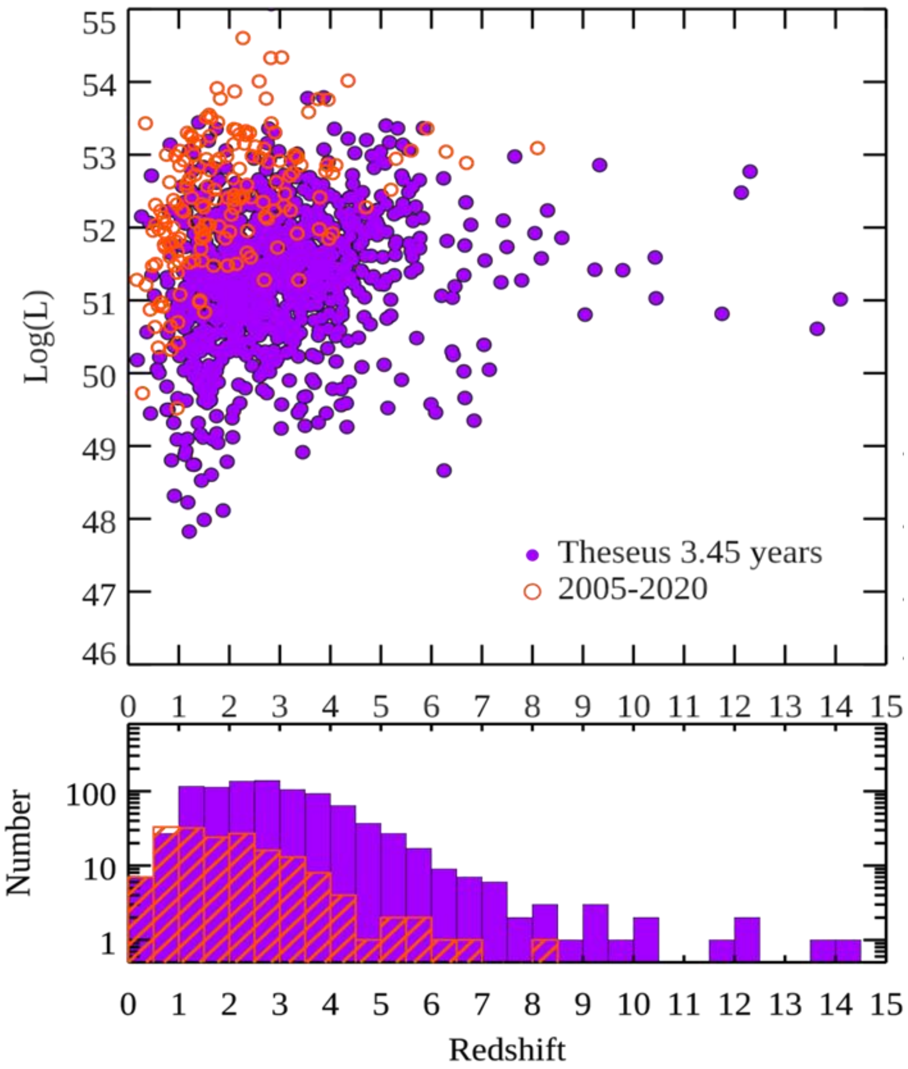
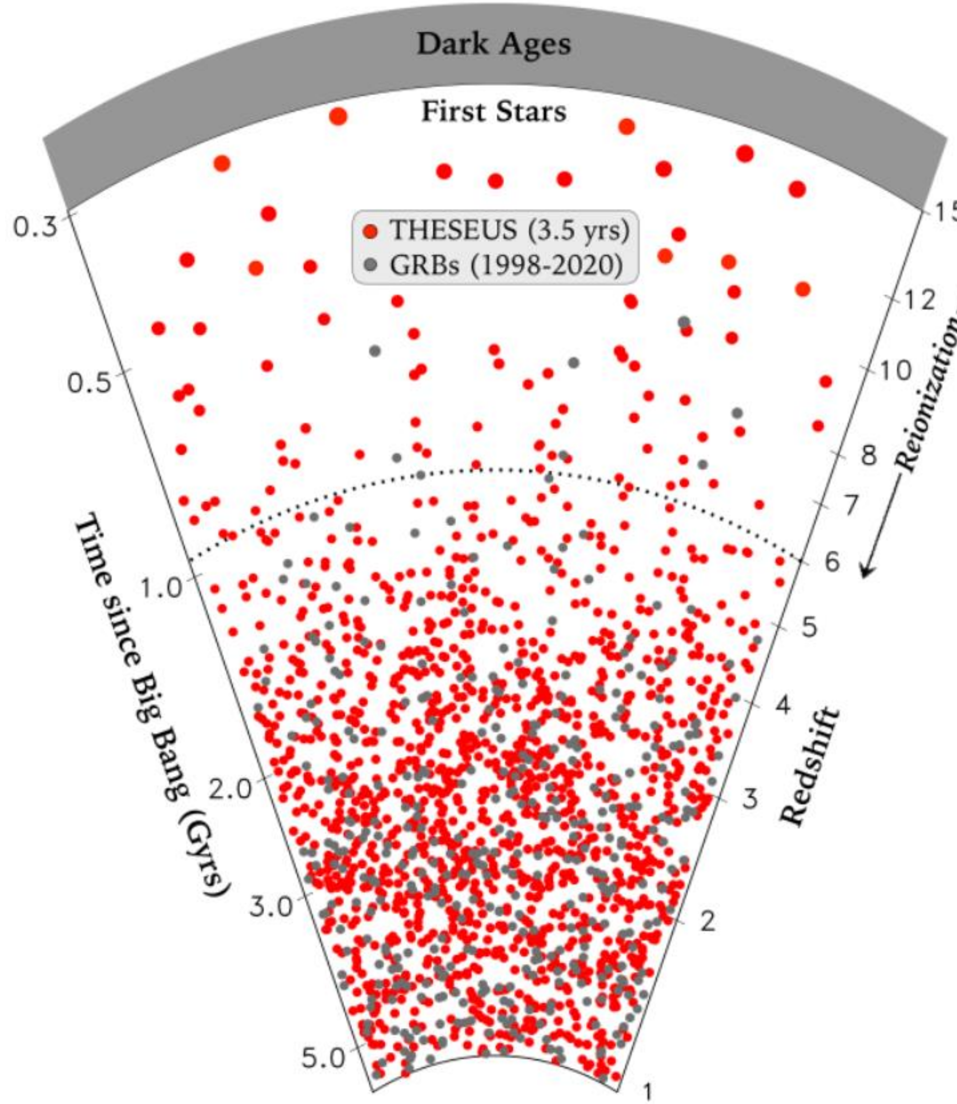
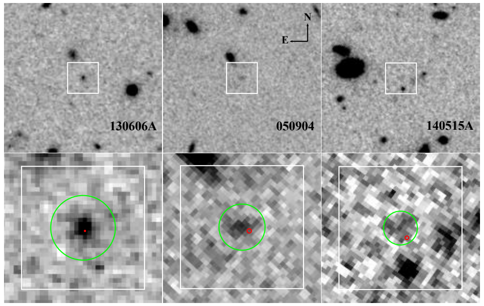
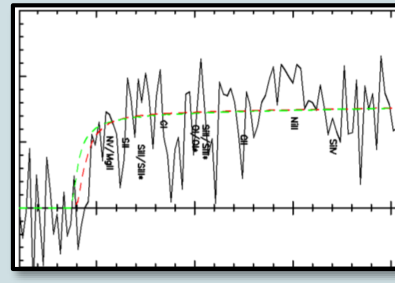


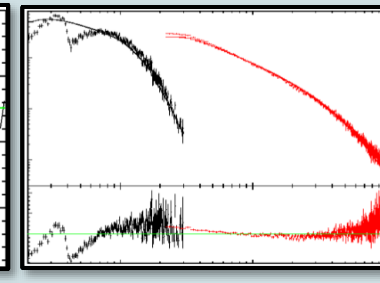


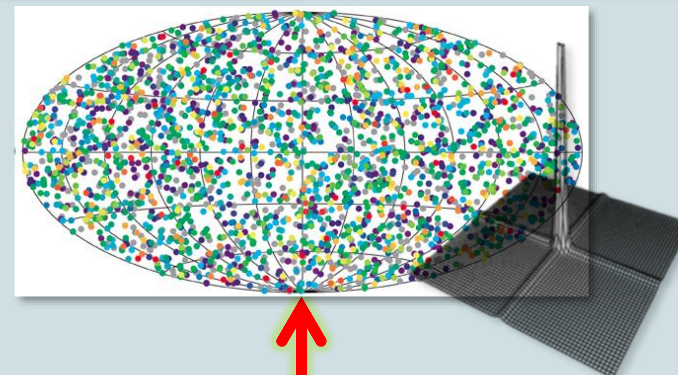
Star formation history, primordial galaxies



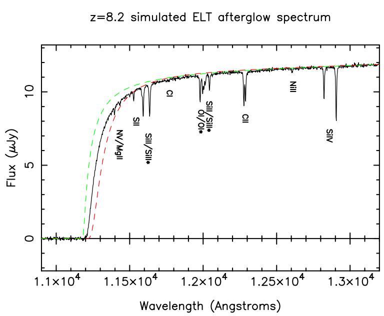
GRB accurate localization and NIR, X-ray, Gamma-ray characterization, redshift



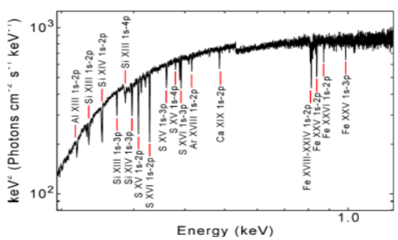




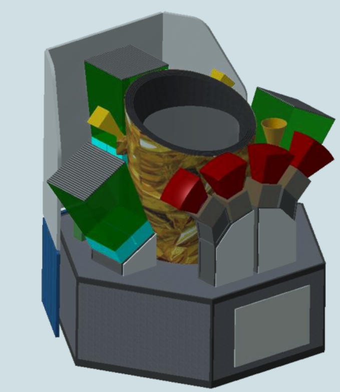
Neutral fraction of IGM, ionizing radiation escape fraction



Cosmic chemical evolution, Pop III

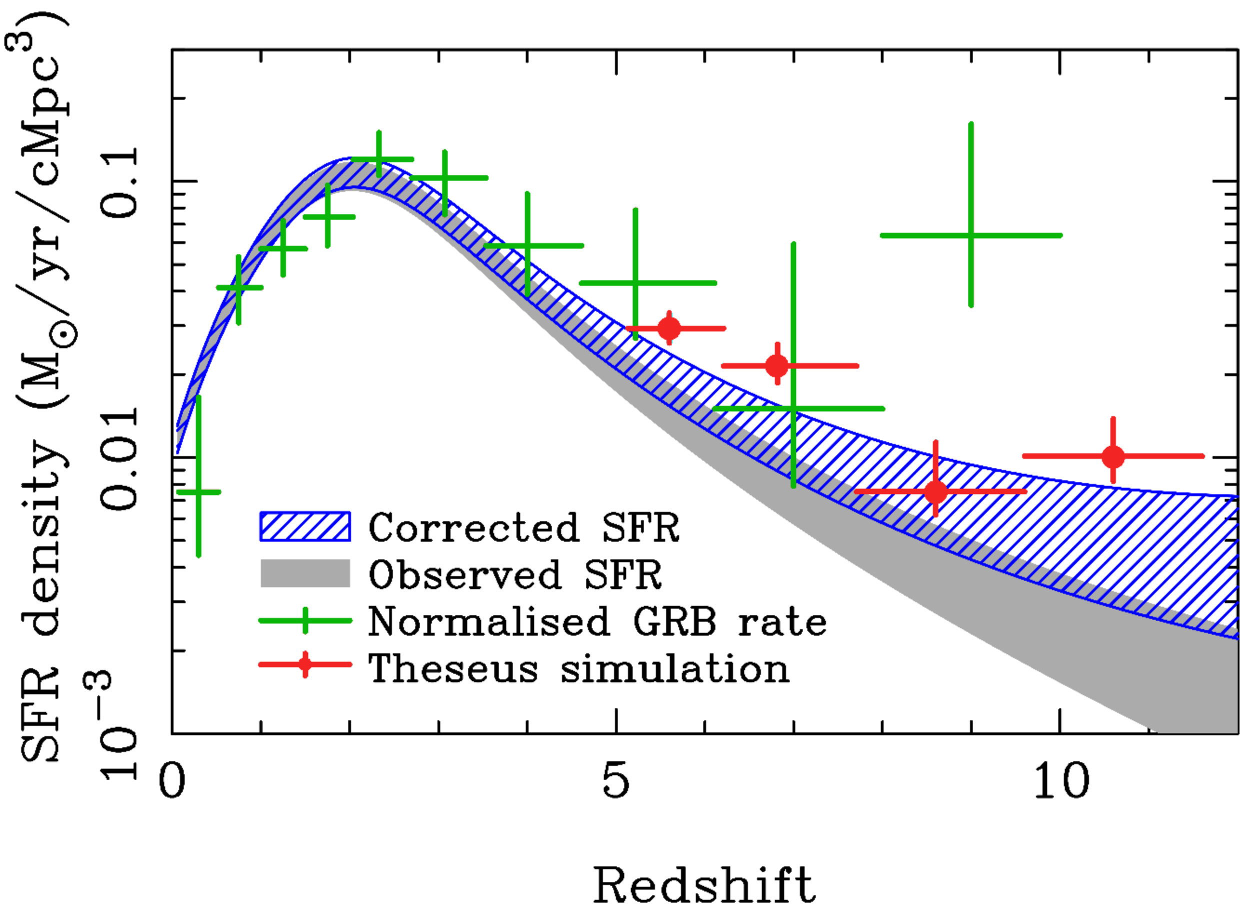


theseus
TRANSIENT HIGH ENERGY SKY AND EARLY UNIVERSE SURVEYOR



THESEUS SYNERGIES

- **Independent measure of cosmic SFR at high-z (possibly including pop-III stars)**

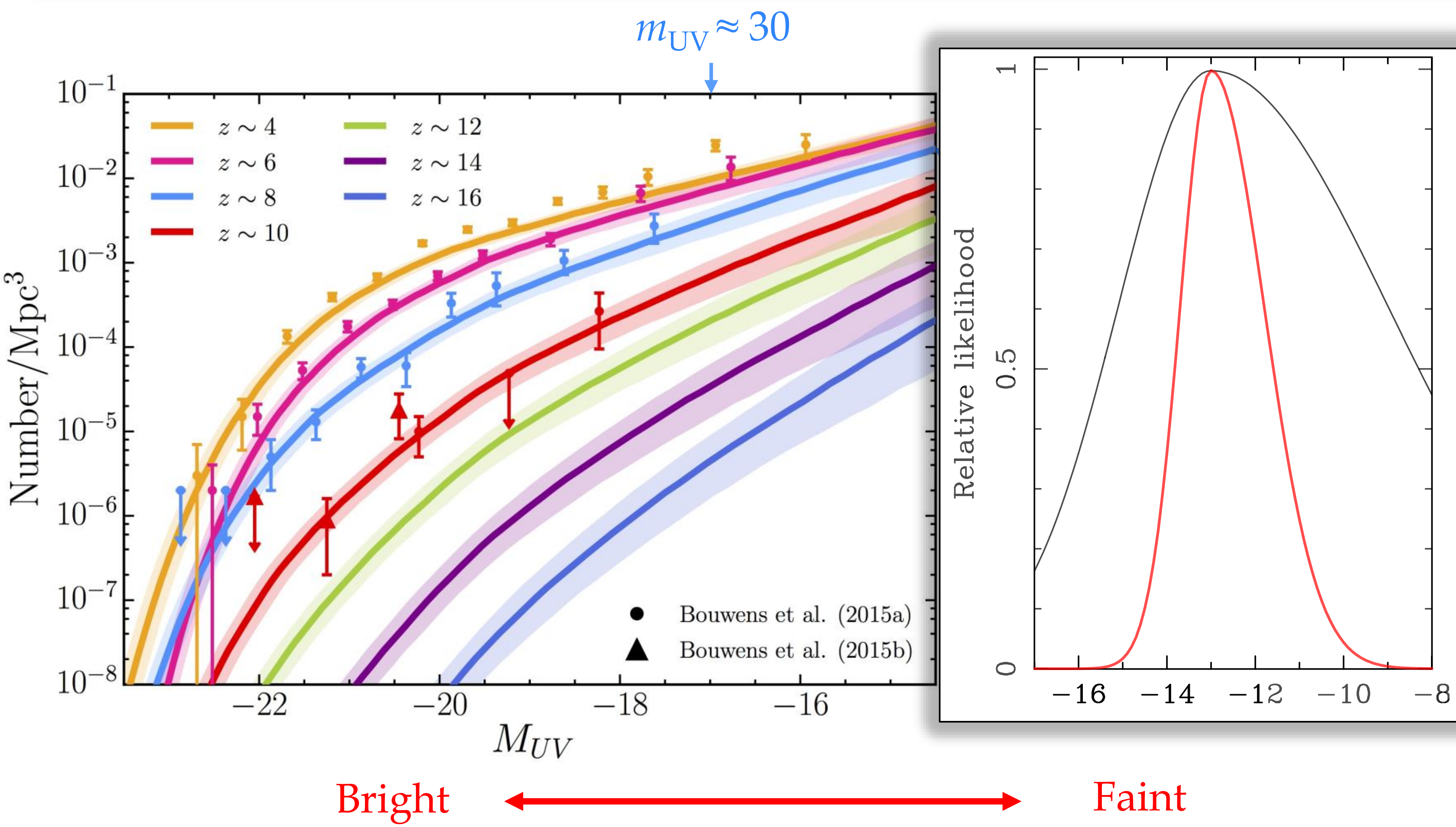


A statistical sample of high–z GRBs will give access to star formation in the faintest galaxies, overcoming limits of current and future galaxy surveys

THESEUS Consortium 2021

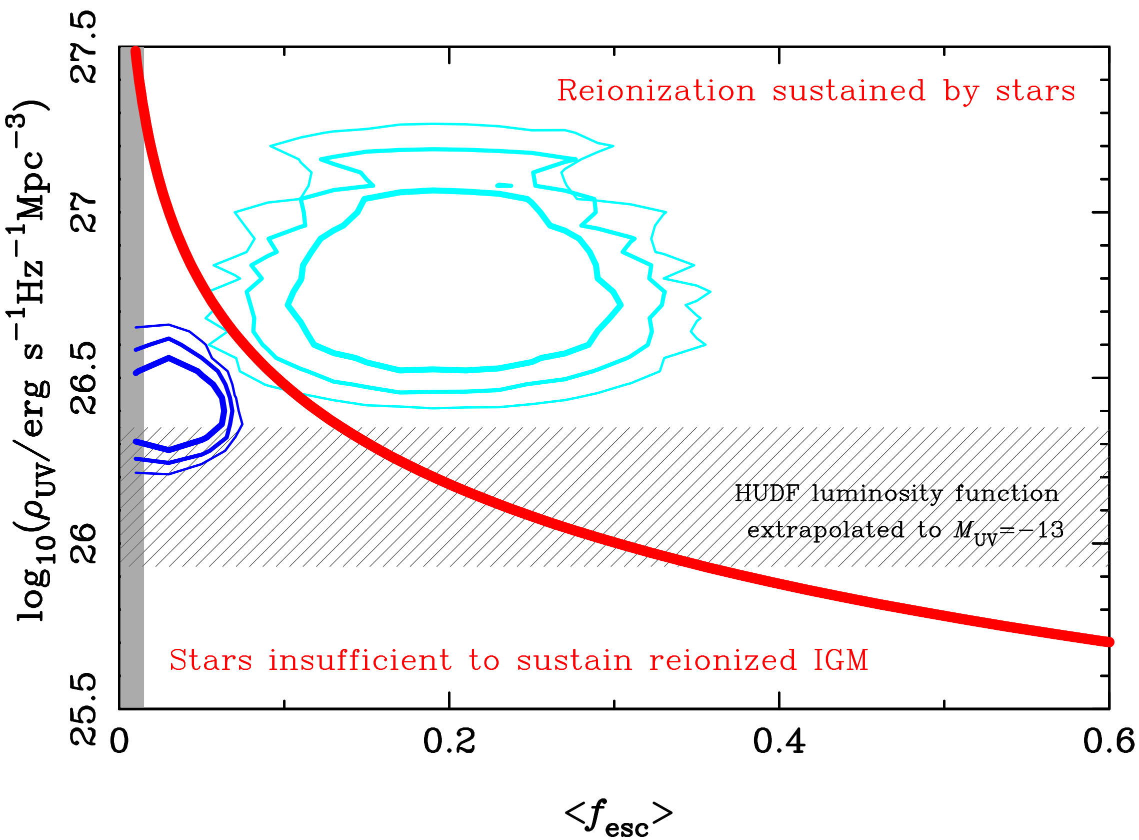
• Detecting and studying primordial invisible galaxies

The proportion of GRB hosts below a given detection limit provides an estimate of the fraction of star formation "hidden" in such faint galaxies



THESEUS Consortium 2021

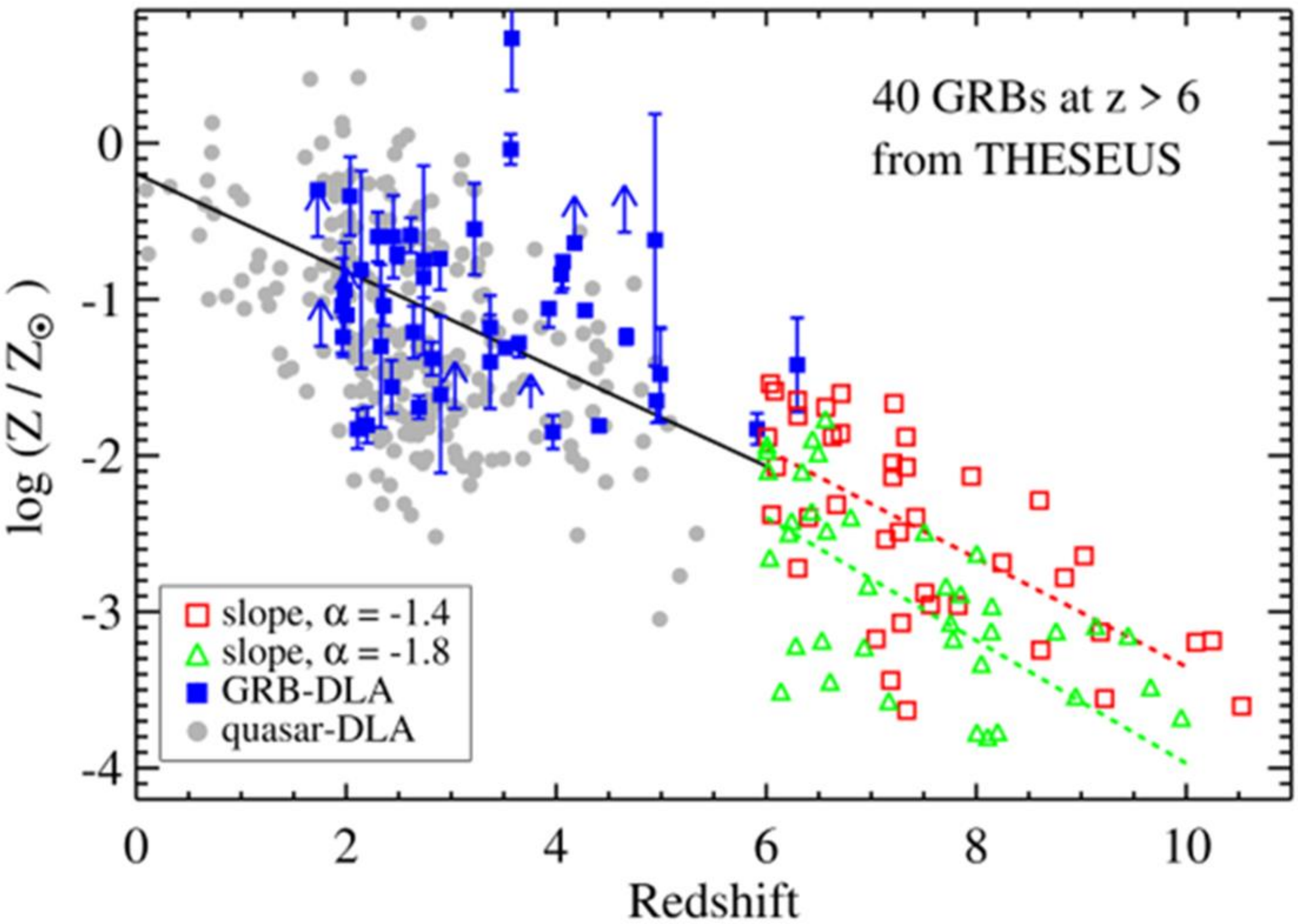
• Shedding light on cosmic reionization



Combination of massive star formation rate and ionizing escape fraction will establish whether stellar radiation was sufficient to reionize the universe, and indicate the galaxy populations responsible

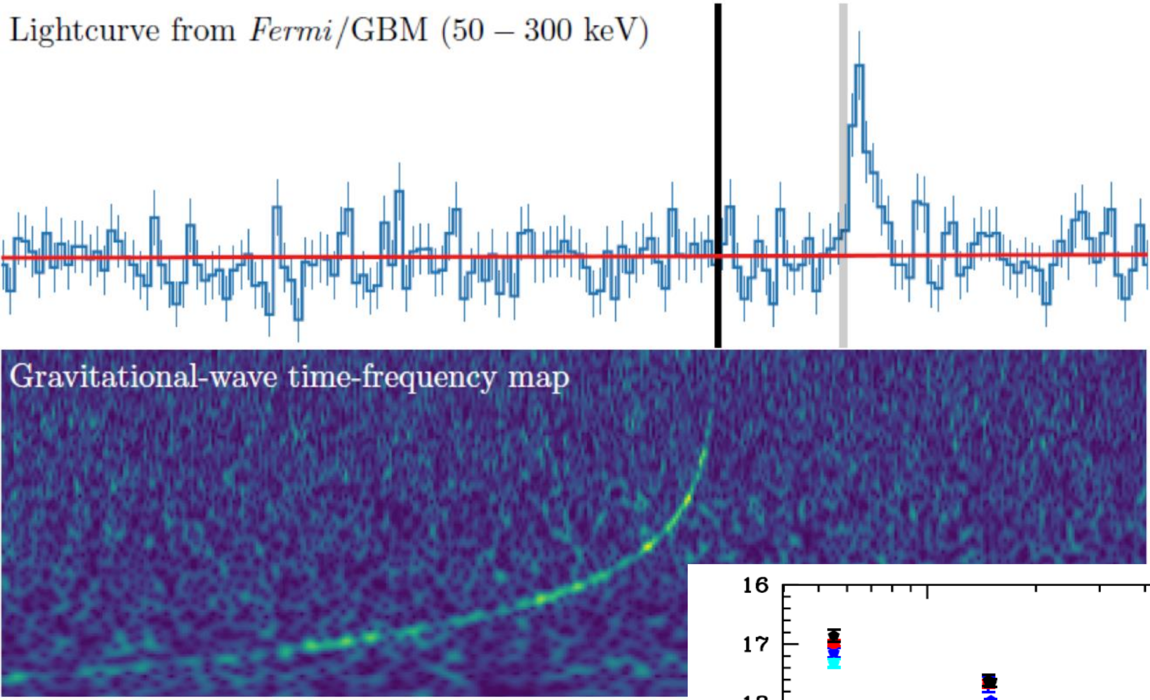
THESEUS Consortium 2021

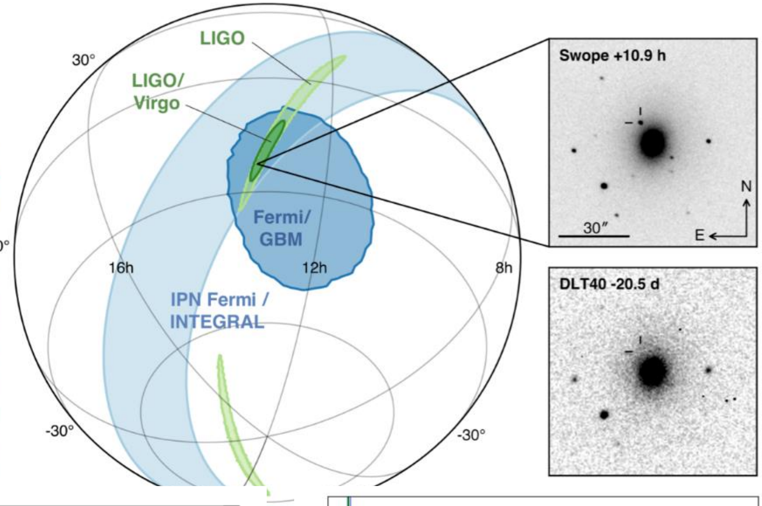
- **Cosmic chemical evolution at high-z**

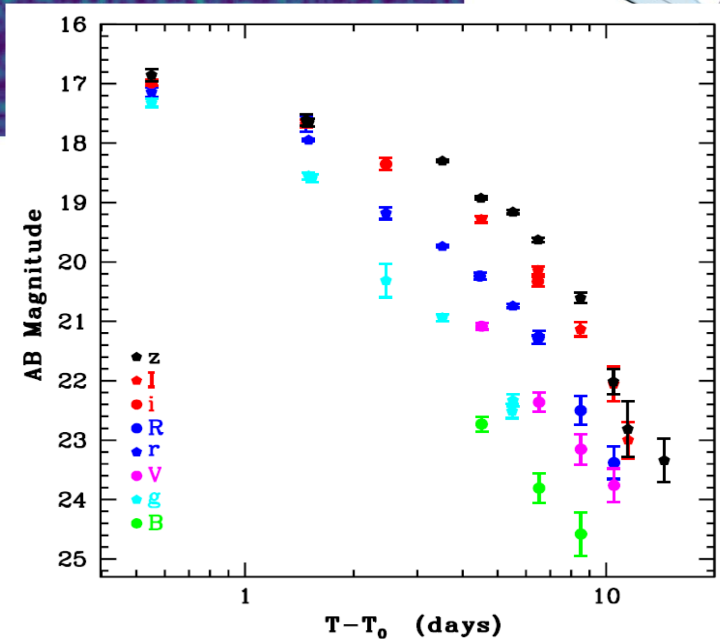


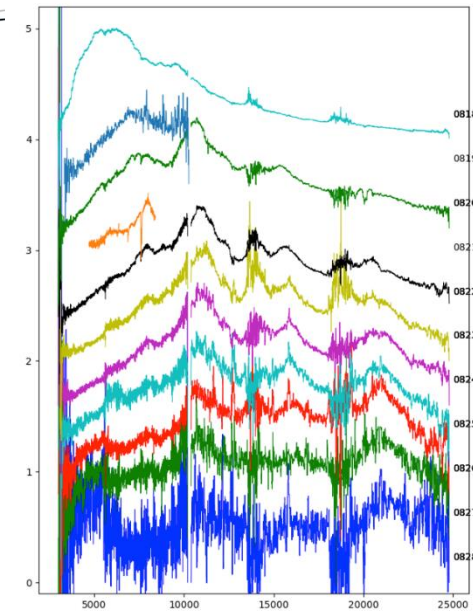
THESEUS Consortium 2021

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



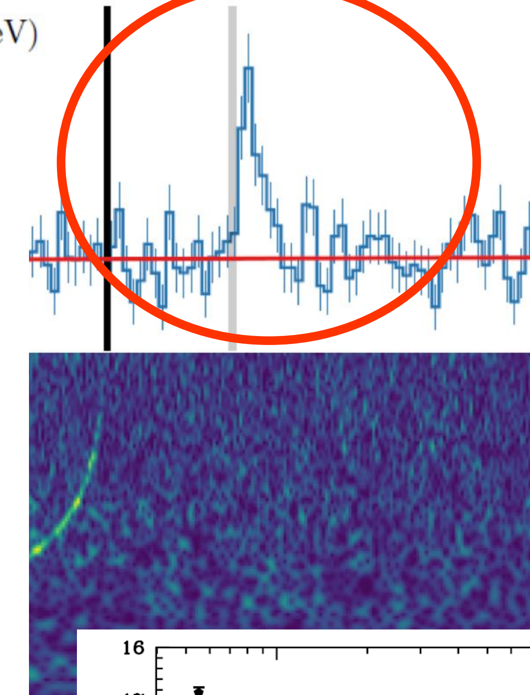






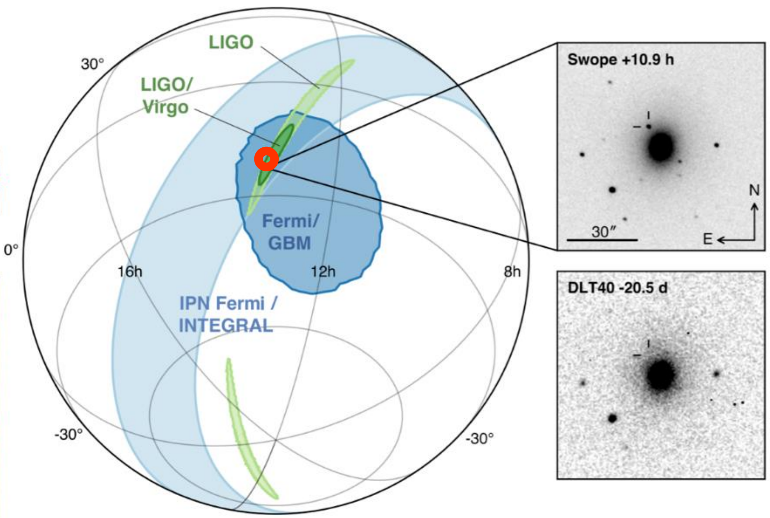
LIGO, Virgo, and partners make first detection of gravitational waves and light from colliding neutron stars

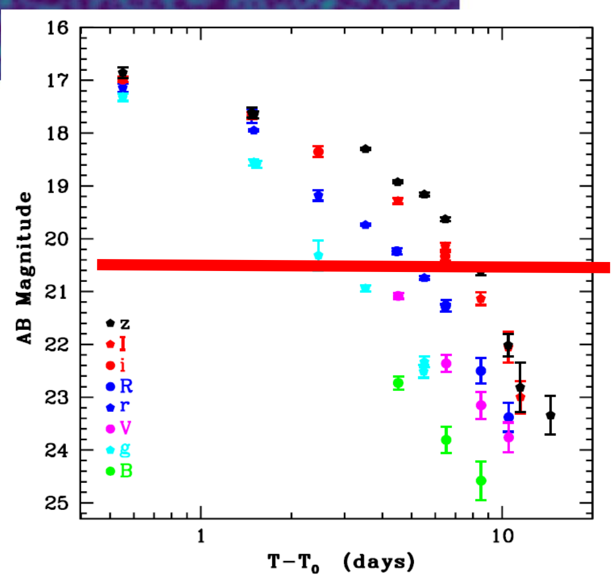
Lightcurve from *Fermi*/GBM (50 – 300 keV)

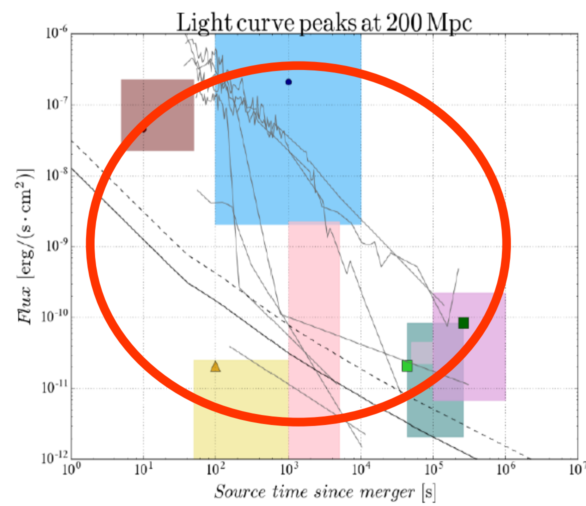


THESEUS:

- ✓ **short GRB detection over large FOV with arcmin localization**
- ✓ **Kilonova detection, arcsec localization and characterization**
- ✓ **Possible detection of weaker isotropic X-ray emission**



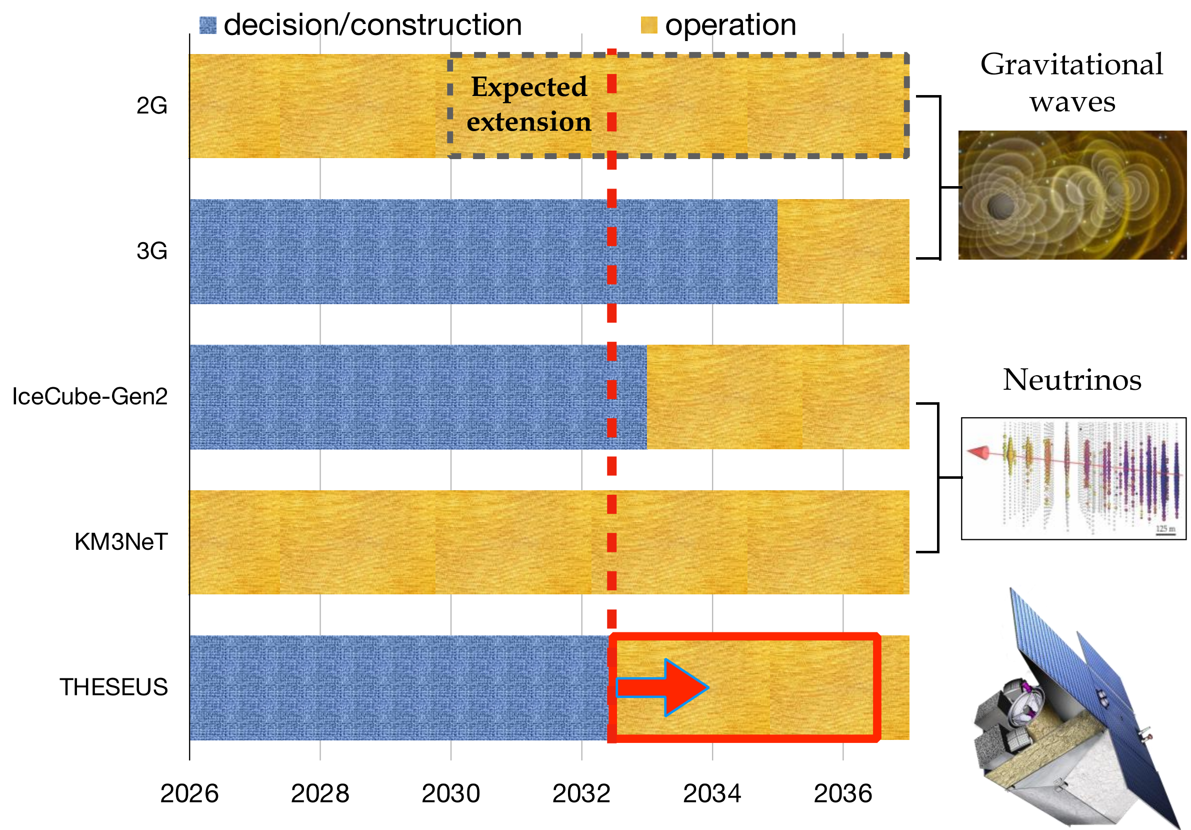




Future GRB missions: synergies

ENTERING THE GOLDEN ERA OF MULTI-MESSENGER ASTROPHYSICS

Synergy with future GW and neutrino facilities will enable transformational investigations of multi-messenger sources



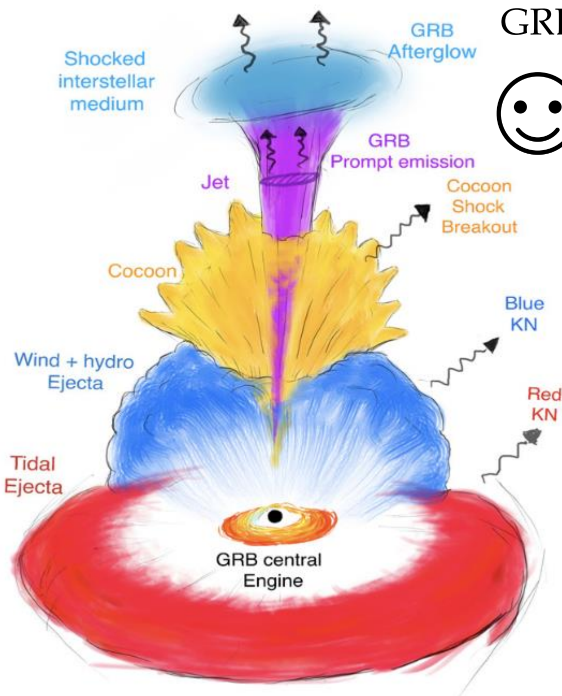
Multi-messenger science with THESEUS

INDEPENDENT DETECTION & CHARACTERISATION OF THE MULTI-MESSENGER SOURCES

Lessons from GRB170817A

Aligned GRBs

Misaligned GRBs



Expected rates:

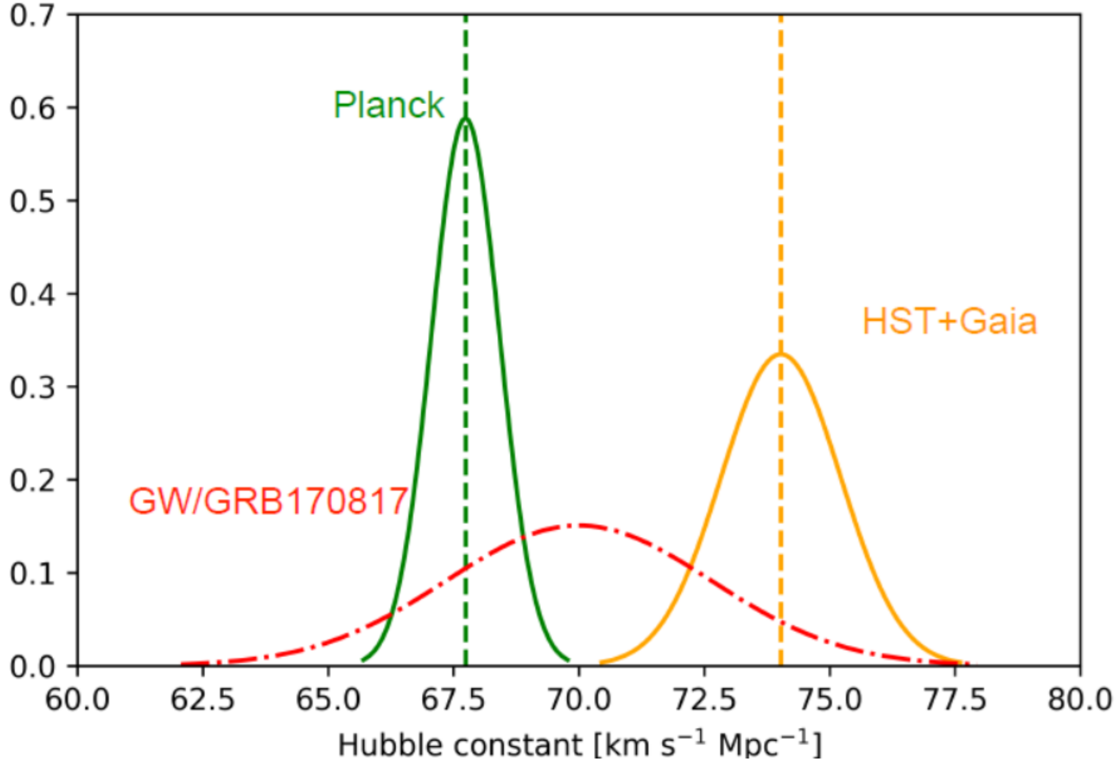
THESEUS + 3G:

- ~50 aligned+misaligned short GRBs
- ~200 X-ray transients

Higher redshift events – X/γ is likely only route to EM detection: larger statistical studies including source evolution, probe of dark energy and test modified gravity on cosmological scales

GRB: a key phenomenon for multi-messenger astrophysics (and cosmology)

MEASURING THE EXPANSION RATE AND GEOMETRY OF SPACE-TIME



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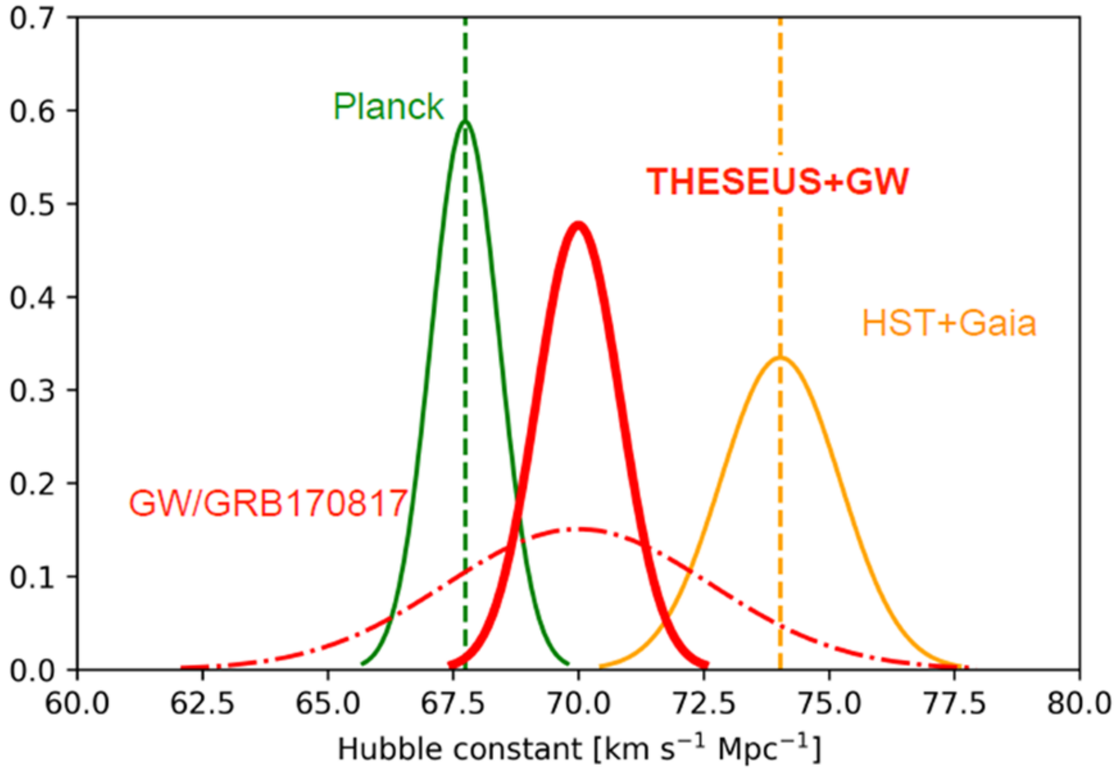
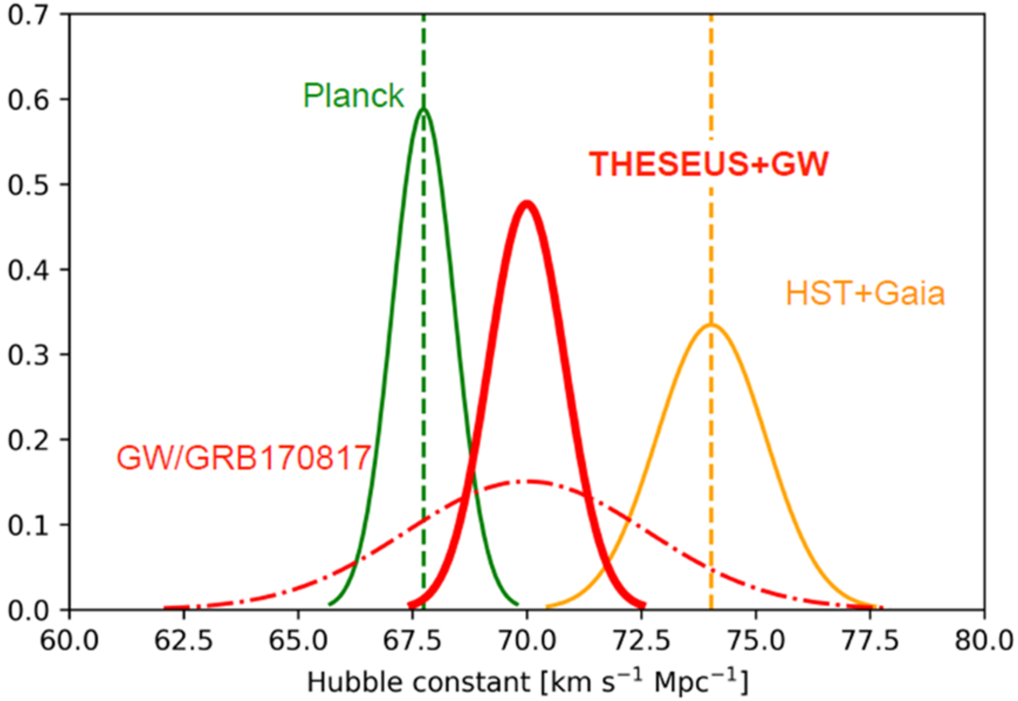
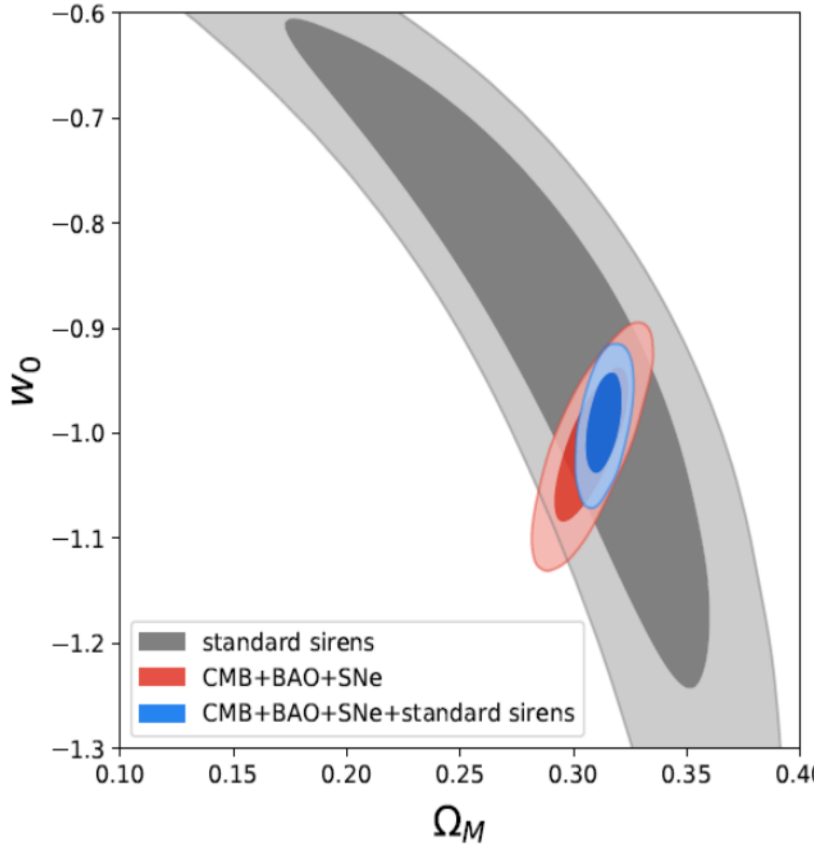


~20 joint GRB+GW events

Multi-messenger cosmology through GRBs

MEASURING THE EXPANSION RATE AND GEOMETRY OF SPACE-TIME





~20 joint GRB+GW events

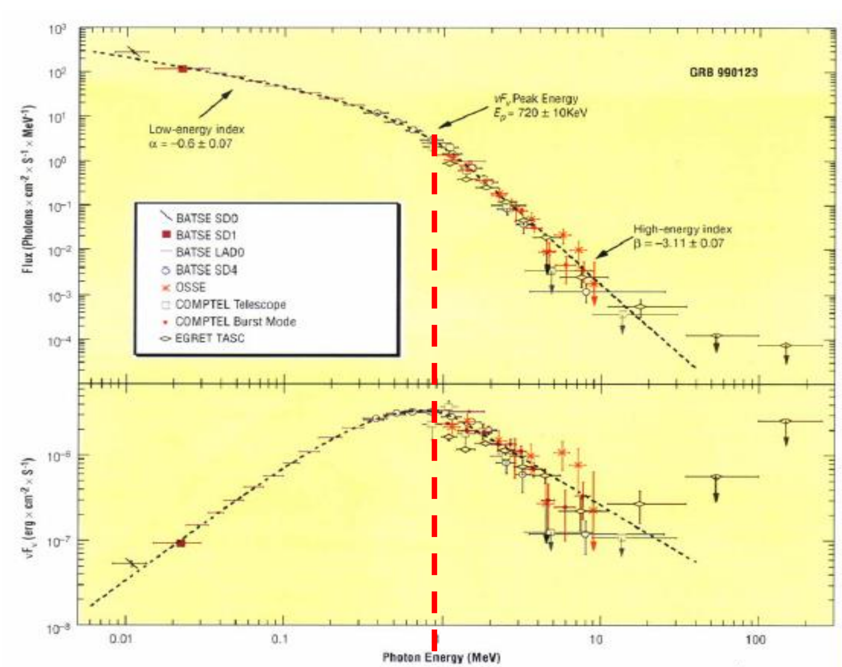
ET collaboration

Measuring cosmological parameters with GRBs

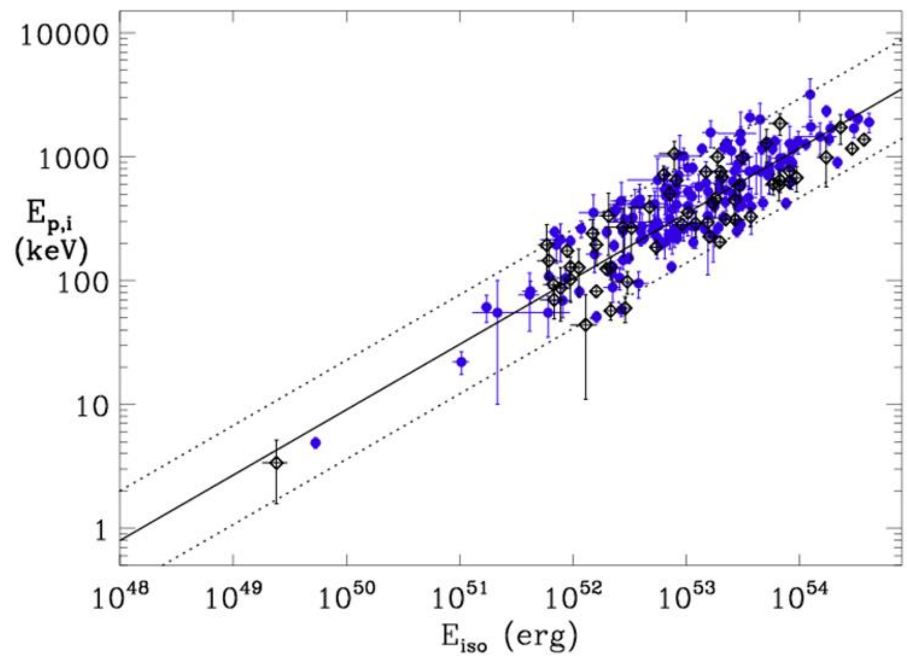
- GRB nFn spectra typically show a peak at a characteristic photon energy E_p

- **measured spectrum + measured redshift -> intrinsic peak enery and radiated energy**

$$E_{p,i} = E_p \times (1 + z) \qquad\qquad E_{\gamma,iso} = \frac{4\pi D_l^2}{(1+z)} \int_{1/1+z}^{10^4/1+z} E\,N(E)\,dE \quad \text{erg}$$



Ep

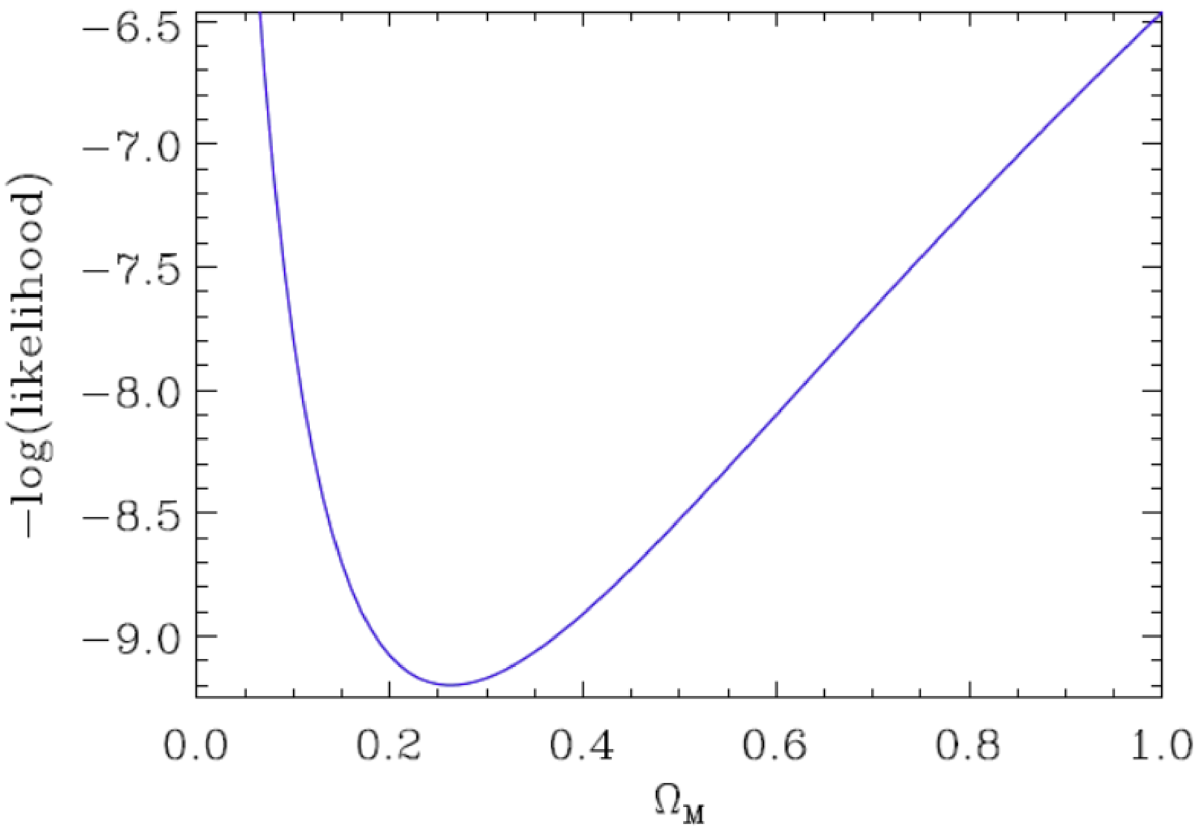


Amati et al. (2002,2006,2008, 2013)

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 ΛCDM universe , Ω_M is lower than 1 and around 0.3**



Amati et al. 2008, Amati & Della Valle 2013, Moresco et al. 2022

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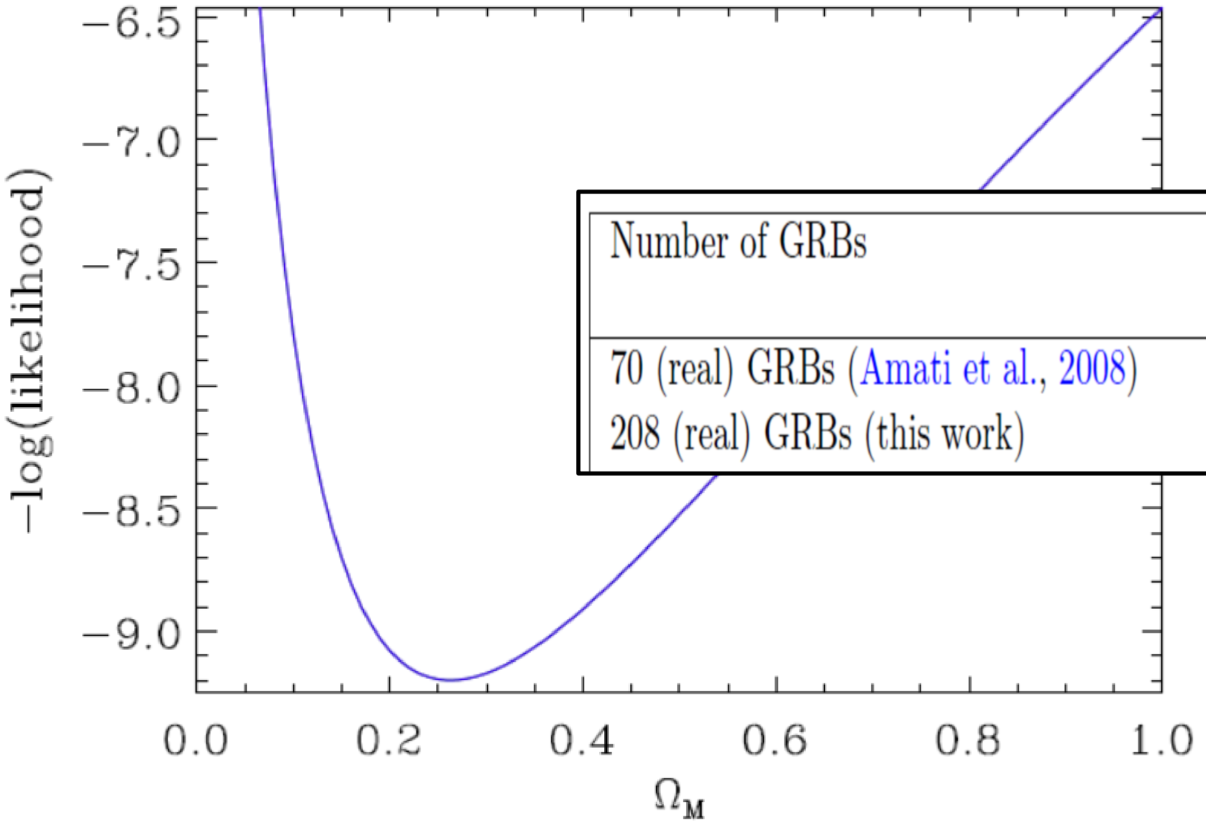
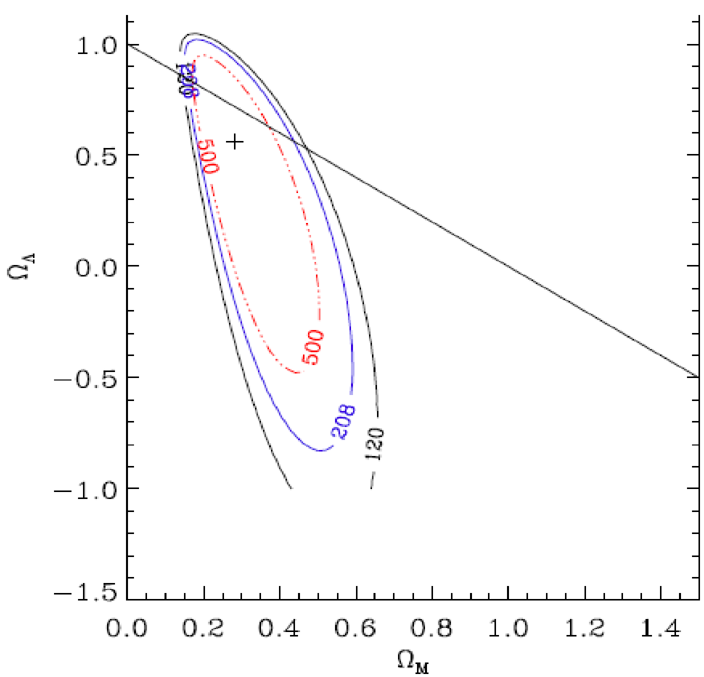


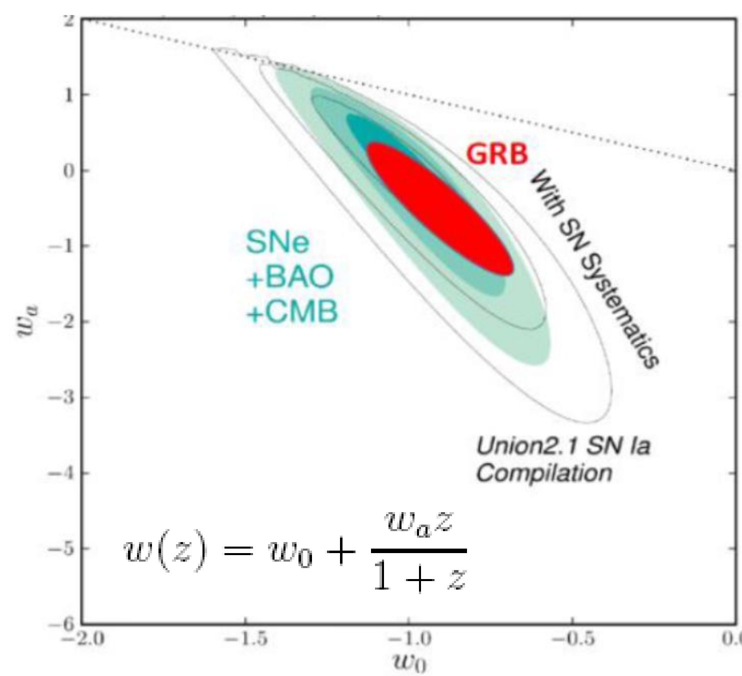
Number of GRBs	Ω_m (flat)
70 (real) GRBs (Amati et al., 2008)	$0.27^{+0.38}_{-0.18}$
208 (real) GRBs (this work)	$0.26^{+0.23}_{-0.12}$

Amati et al. 2008, Amati & Della Valle 2013, Moresco et al. 2022

- Future GRB experiments (e.g., SVOM, HERMES, THESEUS, …) 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)

Number of GRBs	Ω_m (flat)	w_0 (flat, Ω_m=0.3,w_a=0.5)
70 (real) GRBs (Amati et al., 2008)	$0.27^{+0.38}_{-0.18}$	<-0.3 (90%)
208 (real) GRBs (this work)	$0.26^{+0.23}_{-0.12}$	$-1.2^{+0.4}_{-1.1}$
500 (208 real + 292 simulated) GRBs	$0.29^{+0.10}_{-0.09}$	$-0.9^{+0.2}_{-0.8}$
208 (real) GRBs, calibration	$0.30^{+0.06}_{-0.06}$	$-1.1^{+0.25}_{-0.30}$
500 (208 real + 292 simulated) GRBs, calibration	$0.30^{+0.03}_{-0.03}$	$-1.1^{+0.12}_{-0.15}$





Fundamental physics with GRBs: testing LI / QG

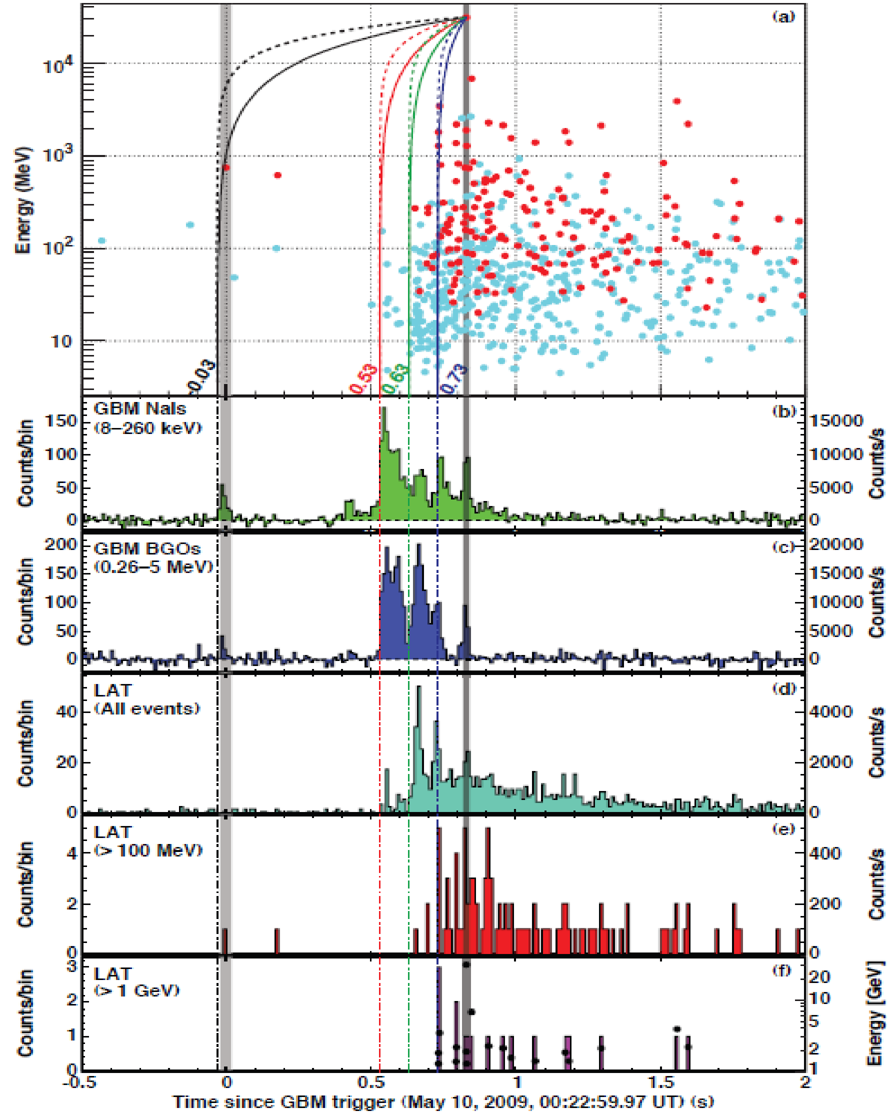
❑ Using time delay between low and high energy photons to put Limits on Lorentz Invariance Violation (allowed by unprecedent Fermi GBM + LAT broad energy band)

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

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

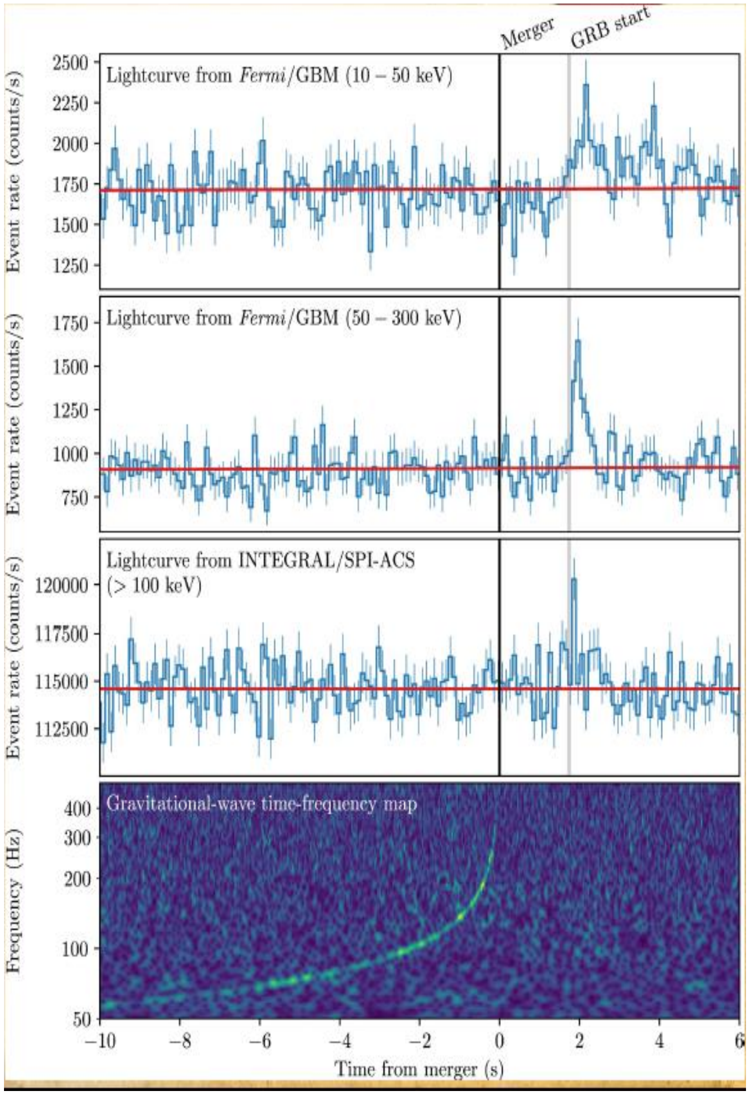
GRB 990510 $E_h = 30.53^{+5.79}_{-2.56}$ GeV

$t_{\rm start}$ (ms)	limit on $\lvert\Delta t\rvert$ (ms)	Reason for choice of $t_{\rm start}$ or limit on Δt	E_l (MeV)	valid for s_n	lower limit on $M_{\rm QG,1}/M_{\rm Planck}$
−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 γ is from 1st spike	0.1	±1	> 1.33
$\left\lvert\frac{\Delta t}{\Delta E}\right\rvert < 30\,\frac{\rm ms}{\rm GeV}$		lag analysis of all LAT events	—	±1	> 1.22



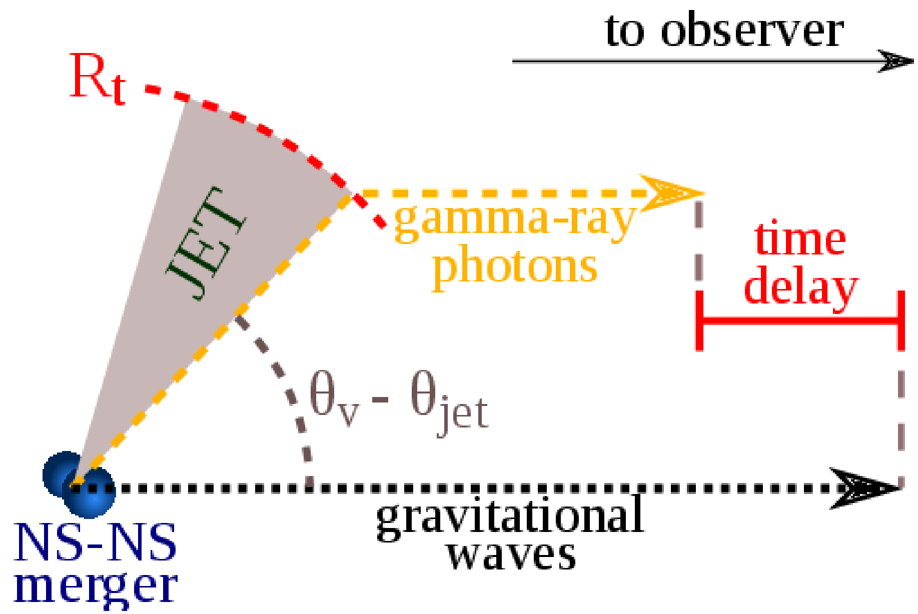
Fundamental physics with GRBs: GW vs. light speed

GW170817/GRB170817A, D ~ 40 Mpc



A short GRB at +1.7 s

$|V_{gw}-C| / C < 10^{-16}$



$$\Delta t = (\Delta t_{\rm jet} + \Delta t_{\rm bo} + \Delta t_{\rm GRB})(1+z)$$

$$\Delta t_{\rm GRB} \simeq (1-\beta\cos\theta)\frac{R_{\rm GRB}}{c} \simeq \frac{R_{\rm GRB}}{\Gamma^2 c}$$

In summary

- GRBs are a key phenomenon for cosmology (ealry 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 ESA/M5 Phase A study successful -> reproposed for M7 (2037)**

SPIE articles on instruments, Adv.Sp.Res. & Exp.Astr. articles on science

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