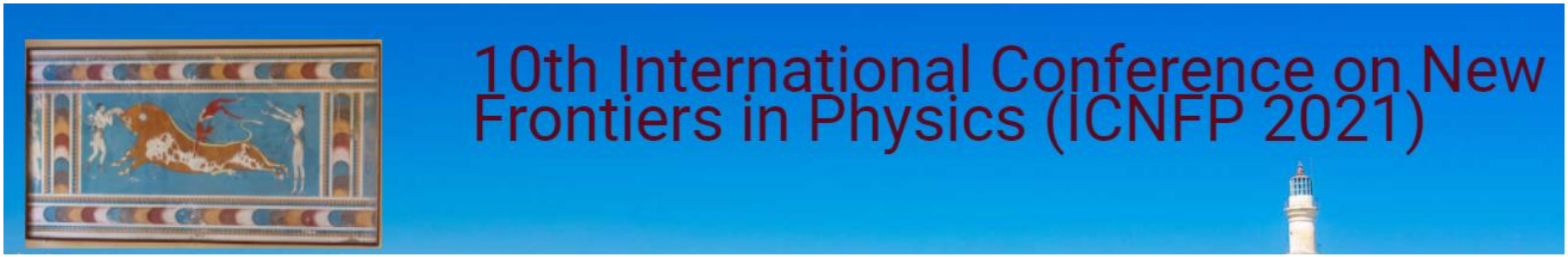
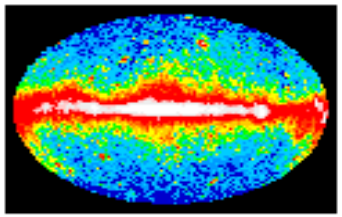
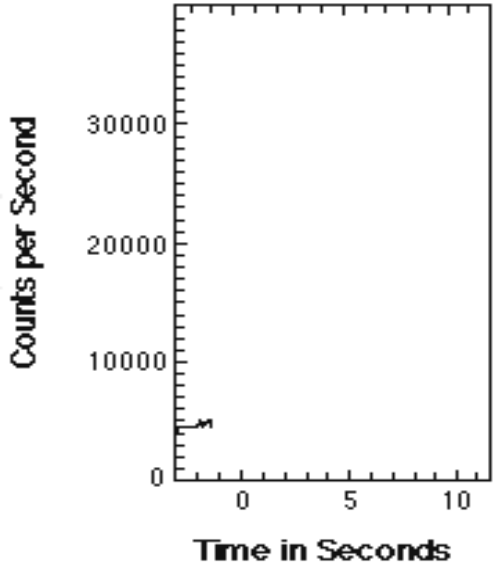
Cosmology and Multi-Messenger Astrophysics with Gamma-Ray Bursts

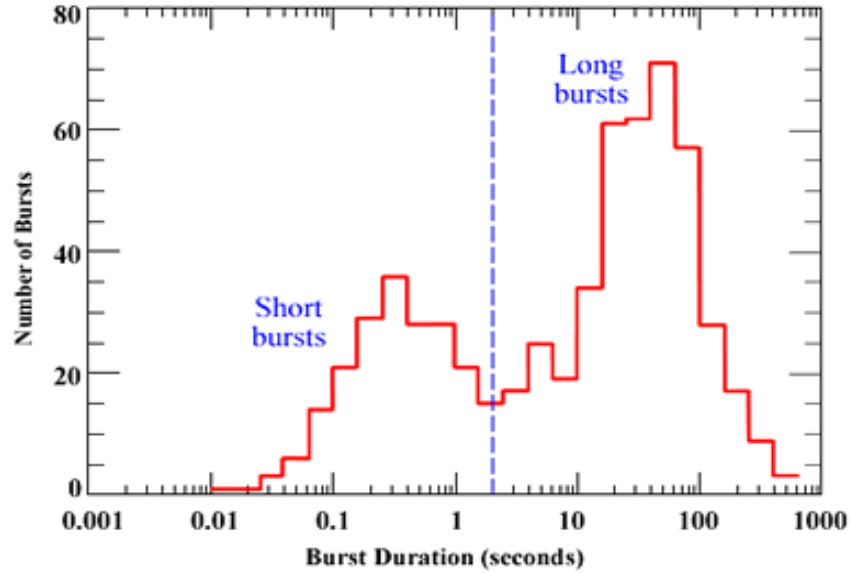
Lorenzo Amati
(INAF – OAS Bologna
(25 August 2021)

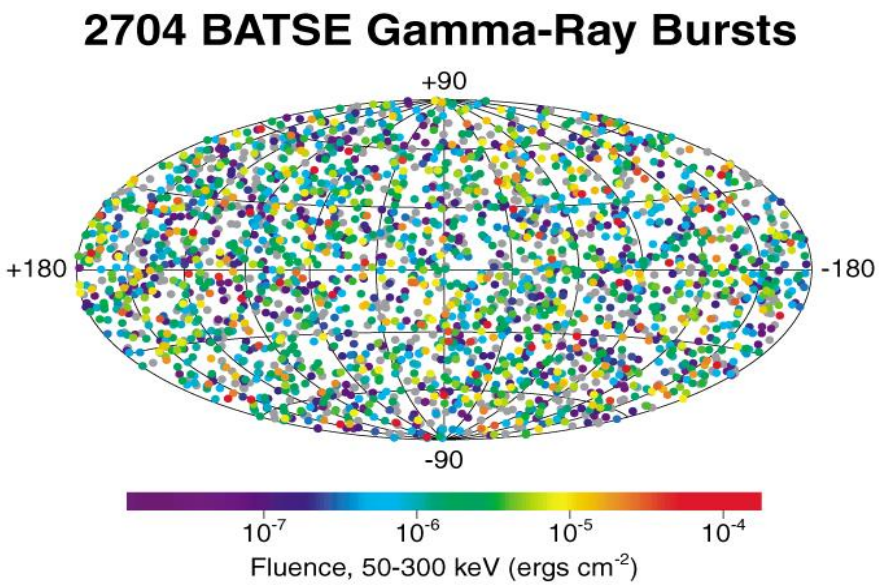


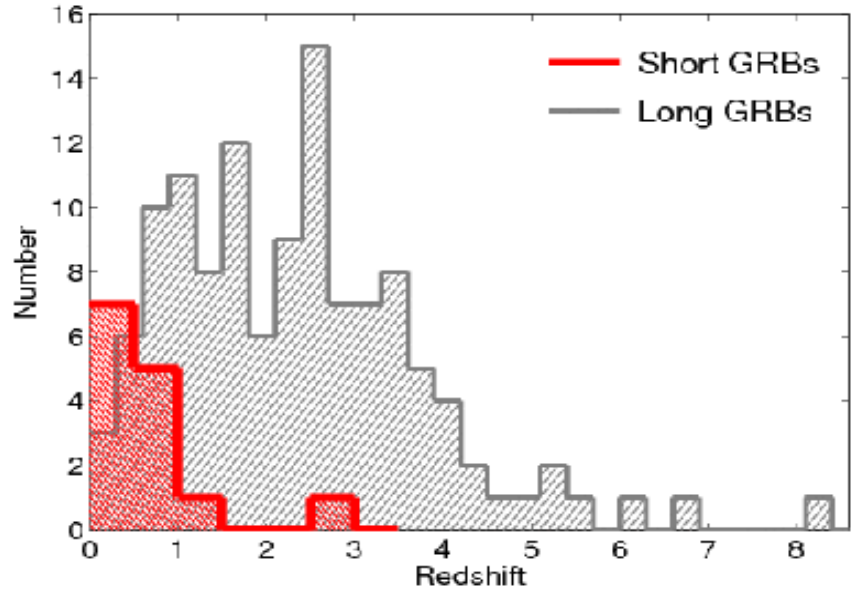
Gamma-Ray Bursts: the most extreme phenomena in the Universe







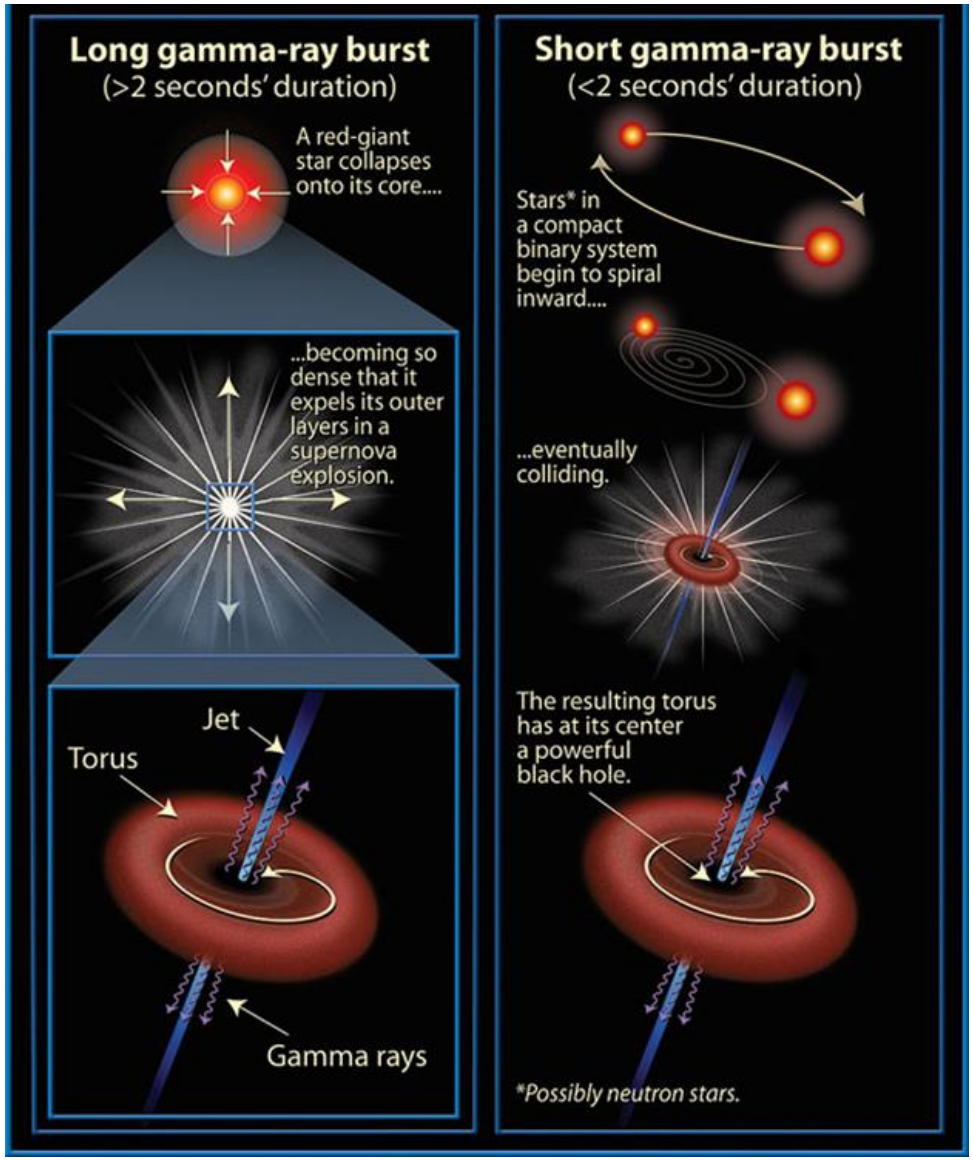




Gamma-Ray Bursts: the most extreme phenomena in the Universe

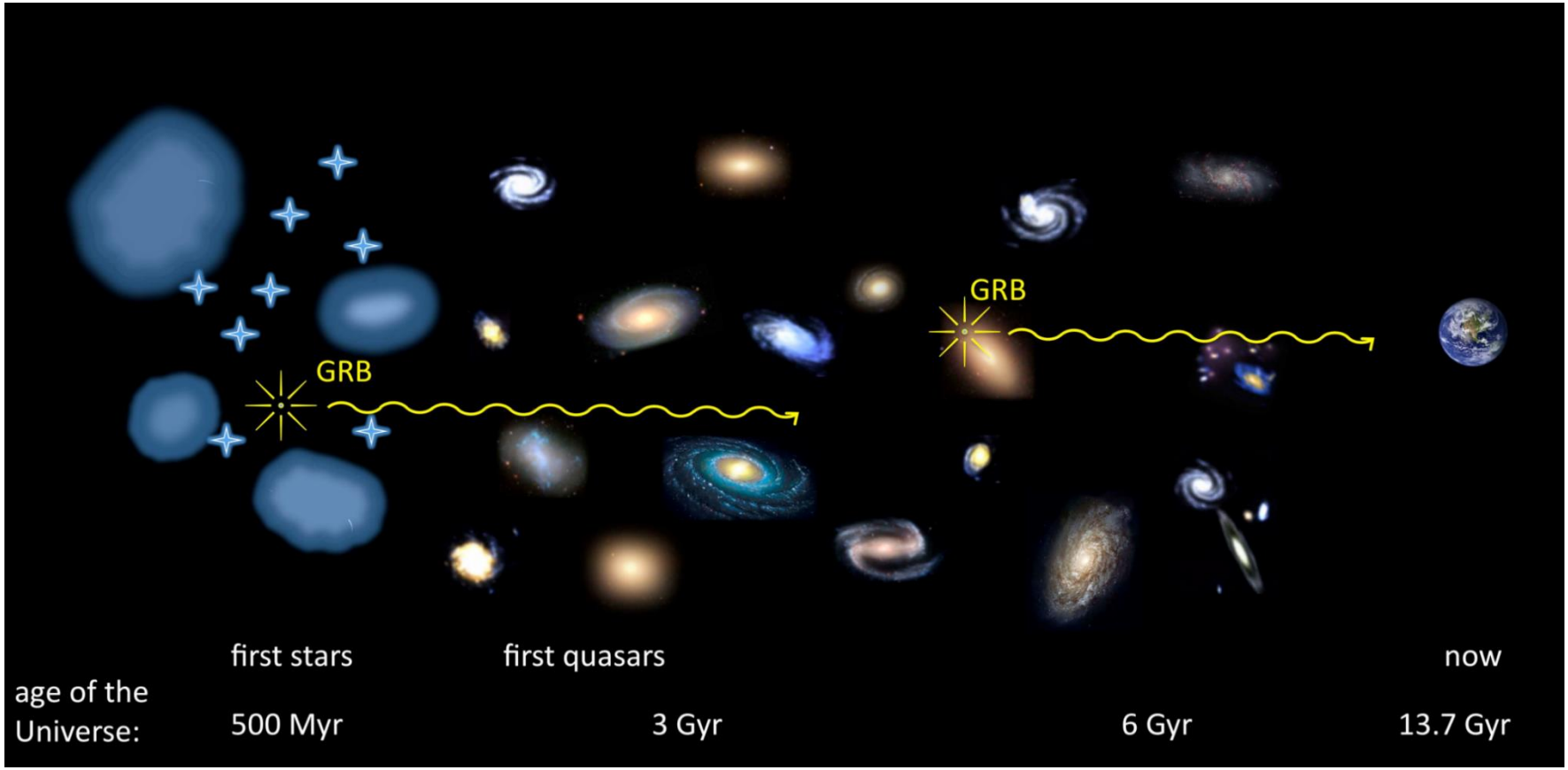
Long GRBs: core collapse of pecular massive stars, **association with SN**

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

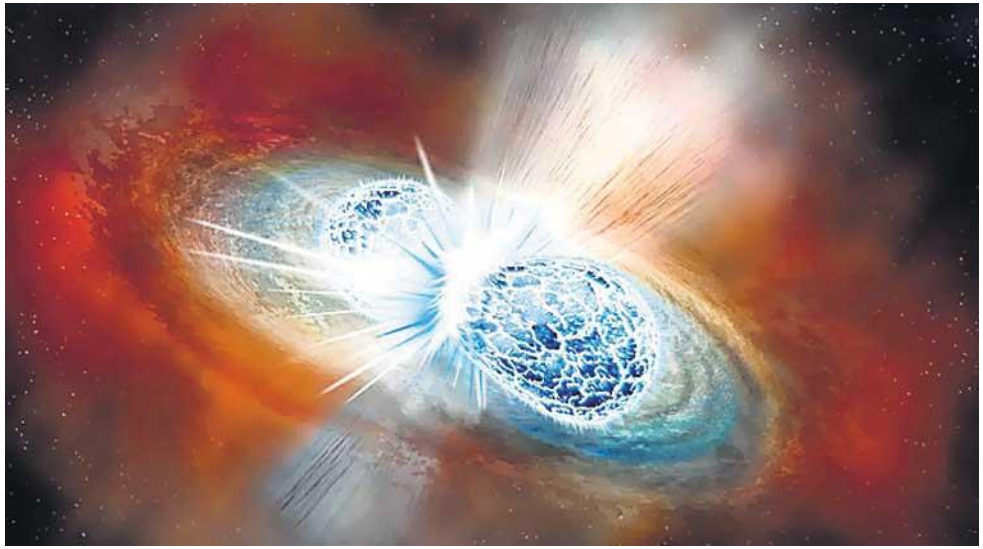


Long GRBs

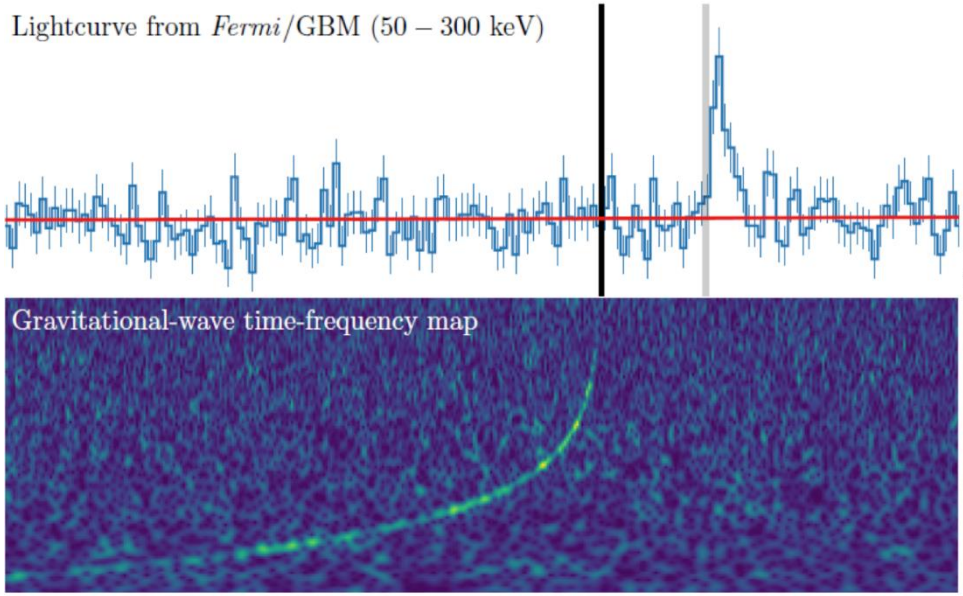
- direct detection and accurate location of exploding stars (and their host galaxies) up to the Cosmic Dawn!
- cosmological «beacons»
- standardizable cosmological candles?

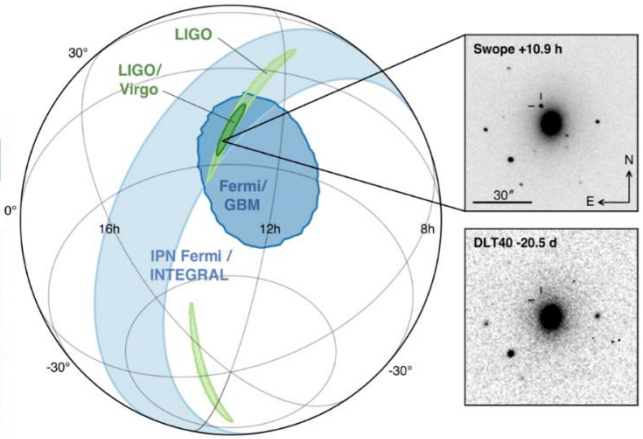


Short GRBs: e.m. counterparts of gravitational-waves sources



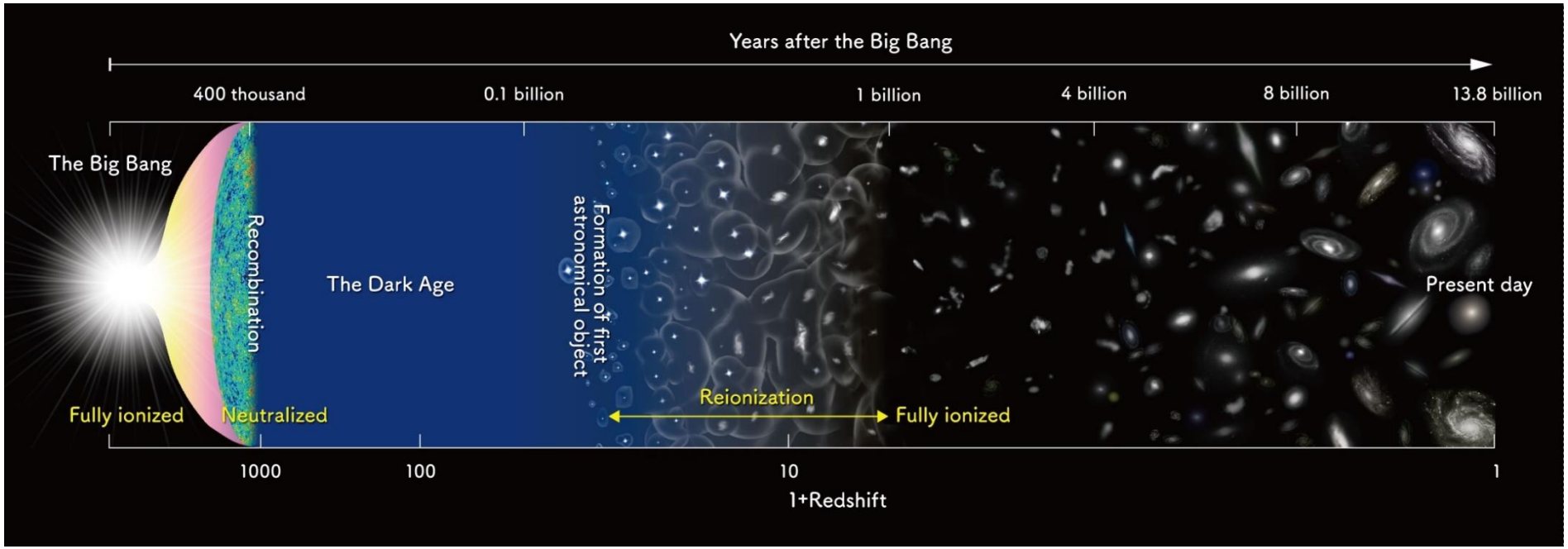
LIGO, Virgo, and partners make first detection of gravitational waves and light from colliding neutron stars





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**



What was the timeline of reionization?

What sources were responsible?

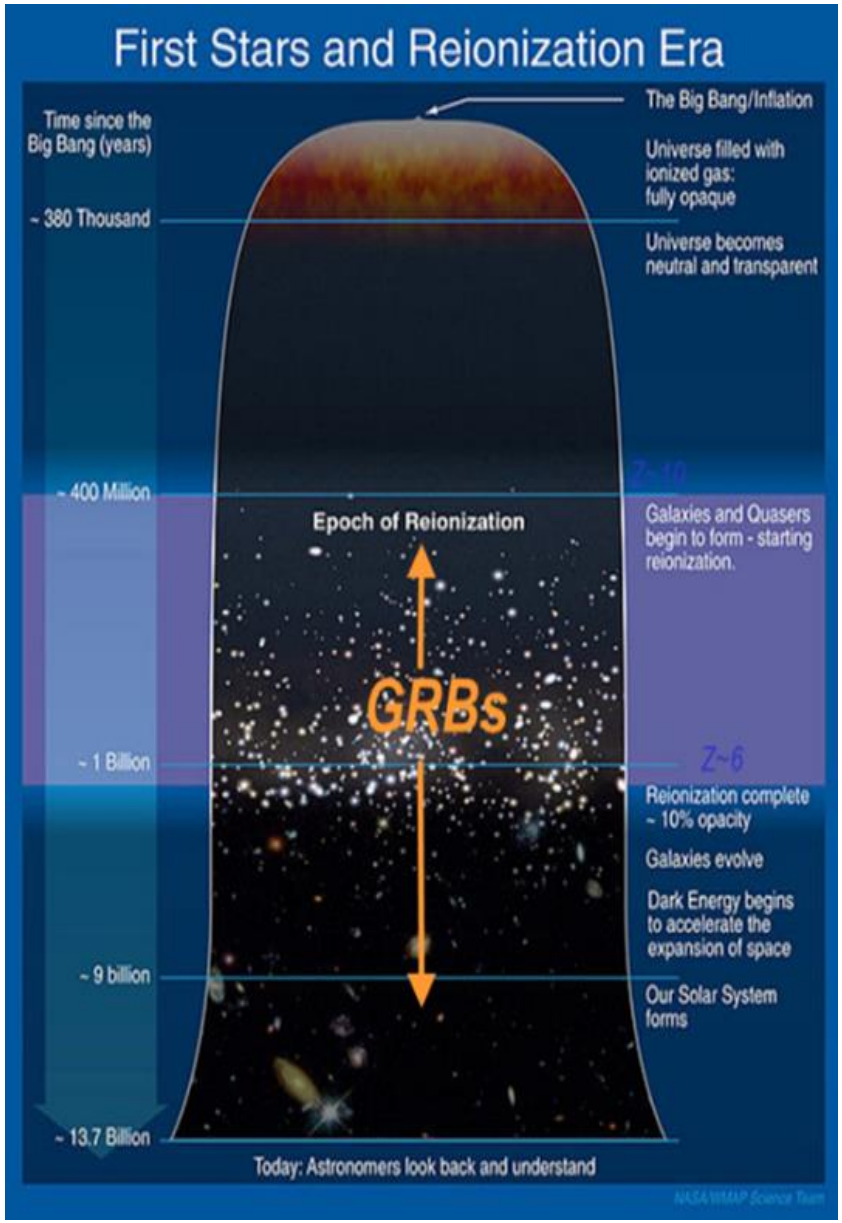
How did the chemical elements build up?

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 ~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

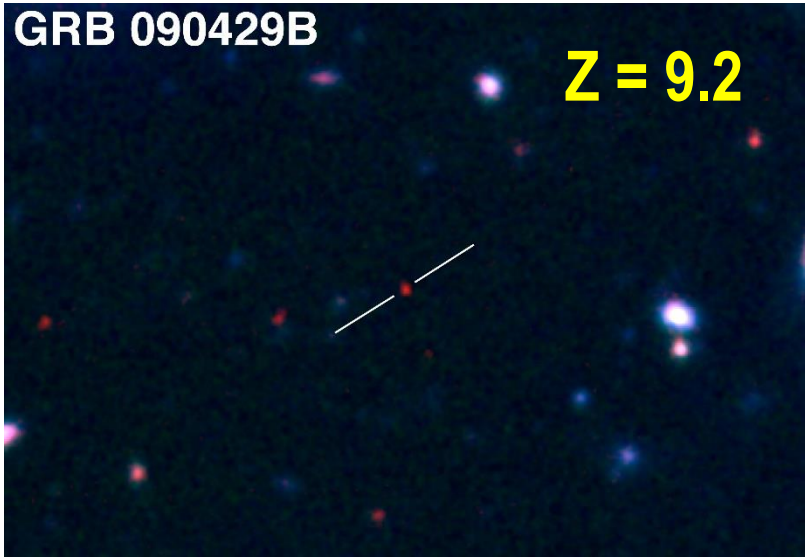


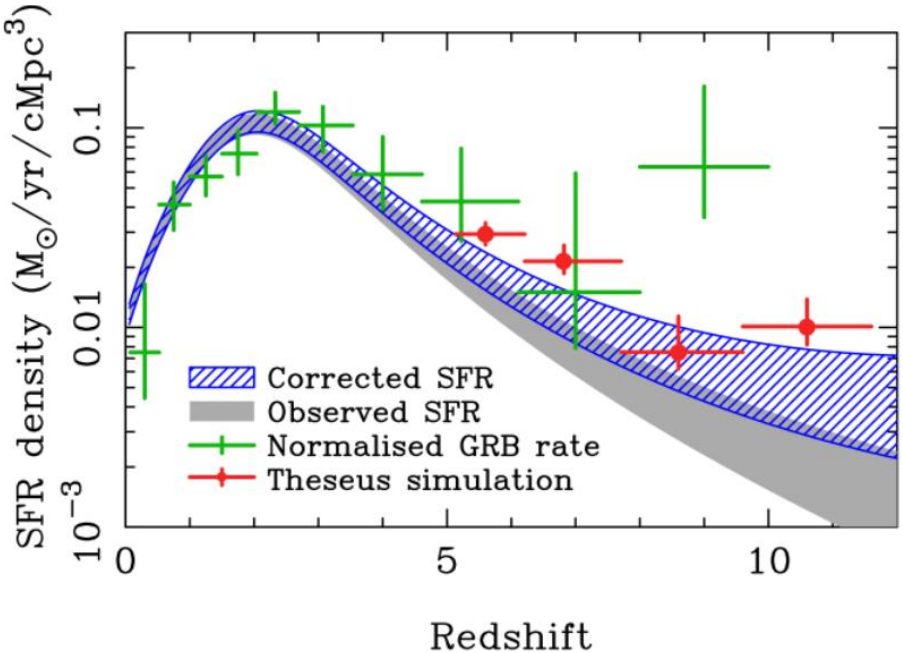
Shedding light on the early Universe with GRBs

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

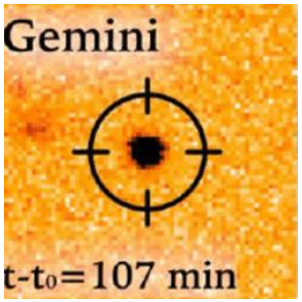
- measure independently the **cosmic star–formation rate**, even beyond the limits of current and future galaxy surveys

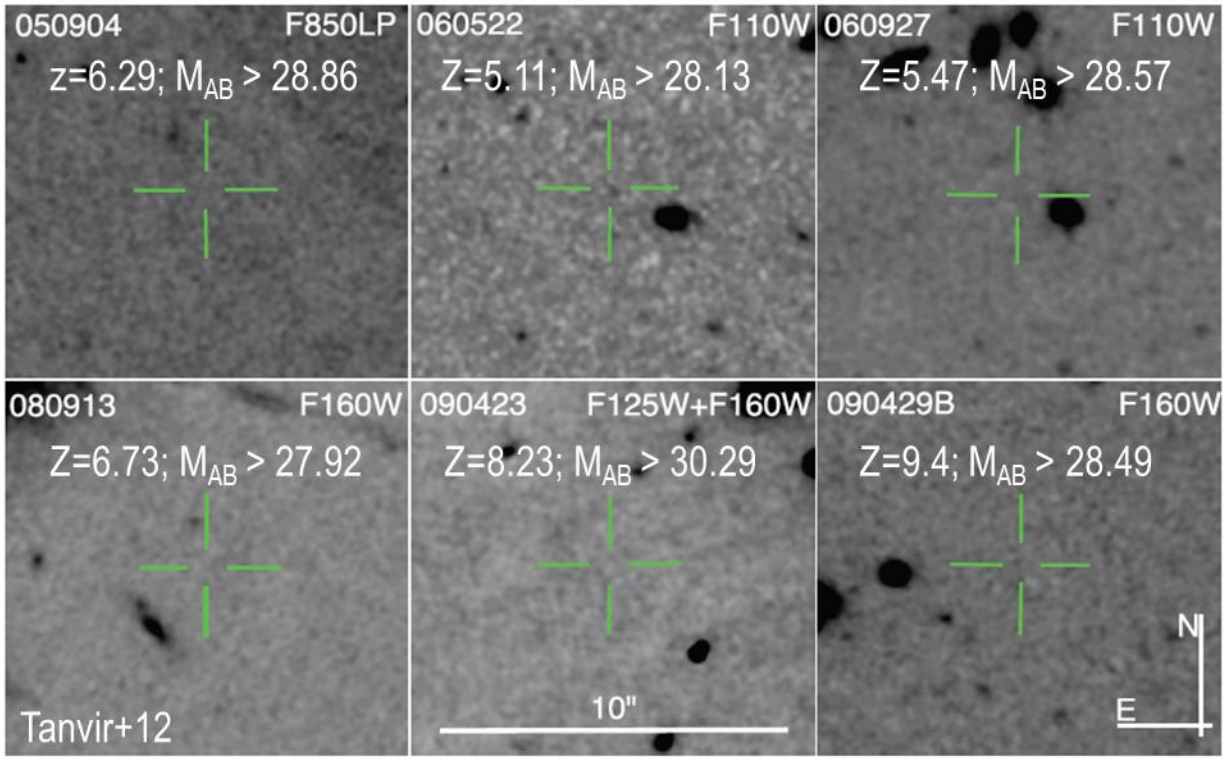
- directly (or indirectly) detect the **first population of stars (pop III)**





• Detecting and studying primordial invisible galaxies

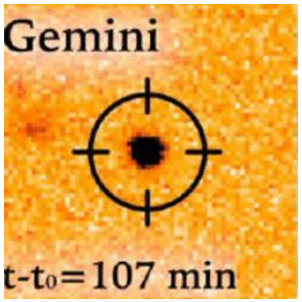


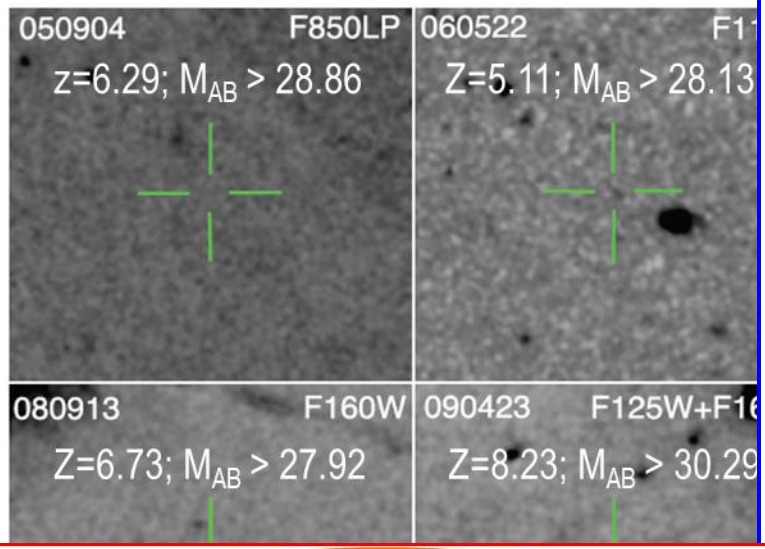


Robertson&Ellis12

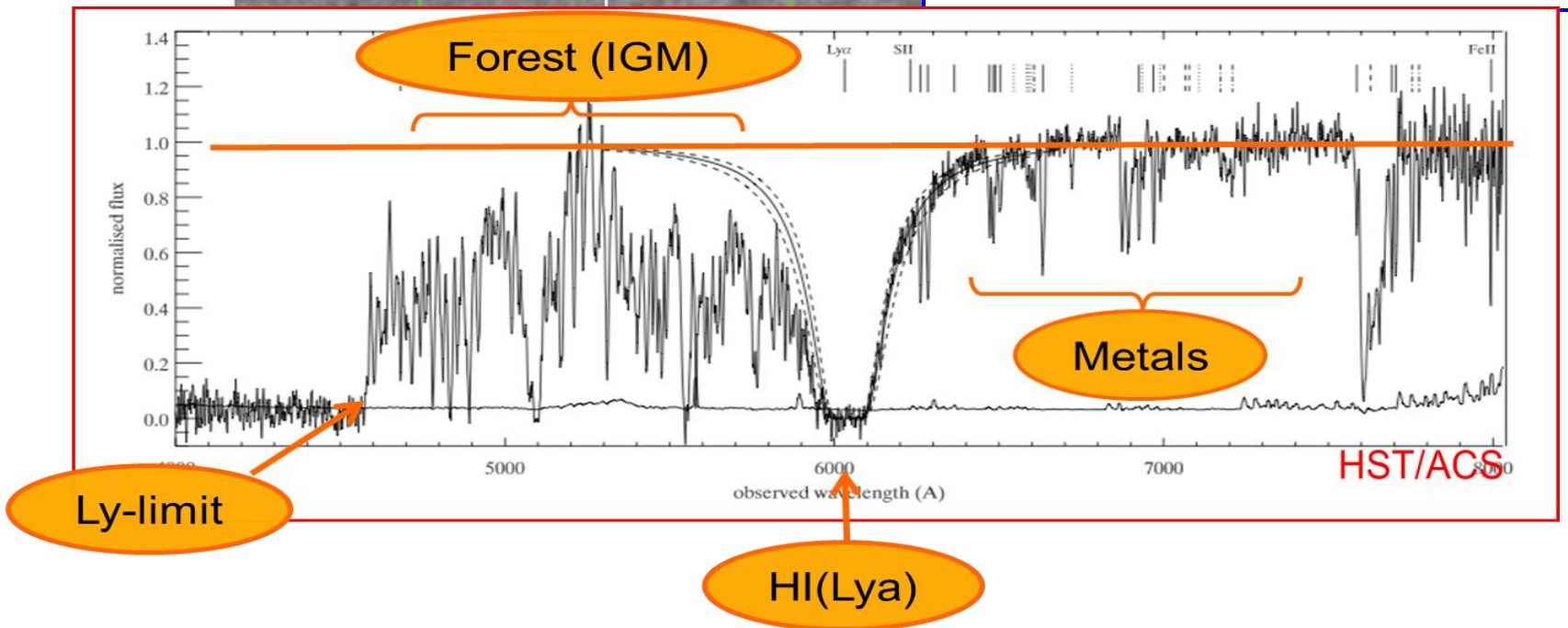
Even JWST and ELTs surveys will be not able to probe the faint end of the galaxy Luminosity Function at high redshifts (z>6-8)

• Detecting and studying primordial invisible galaxies

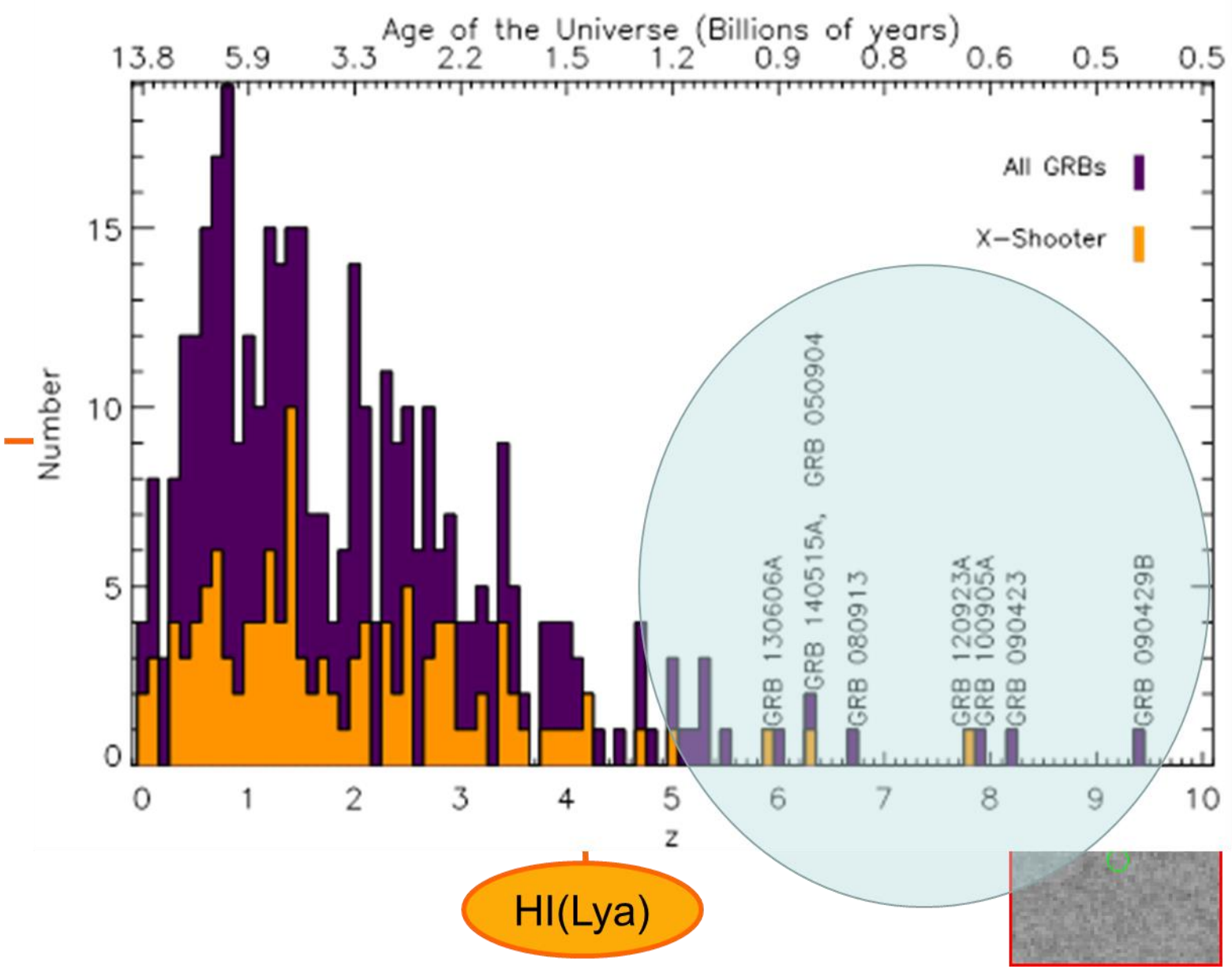




- neutral hydrogen fraction
- escape fraction of UV photons from high-z galaxies
- early metallicity of the ISM and IGM and its evolution

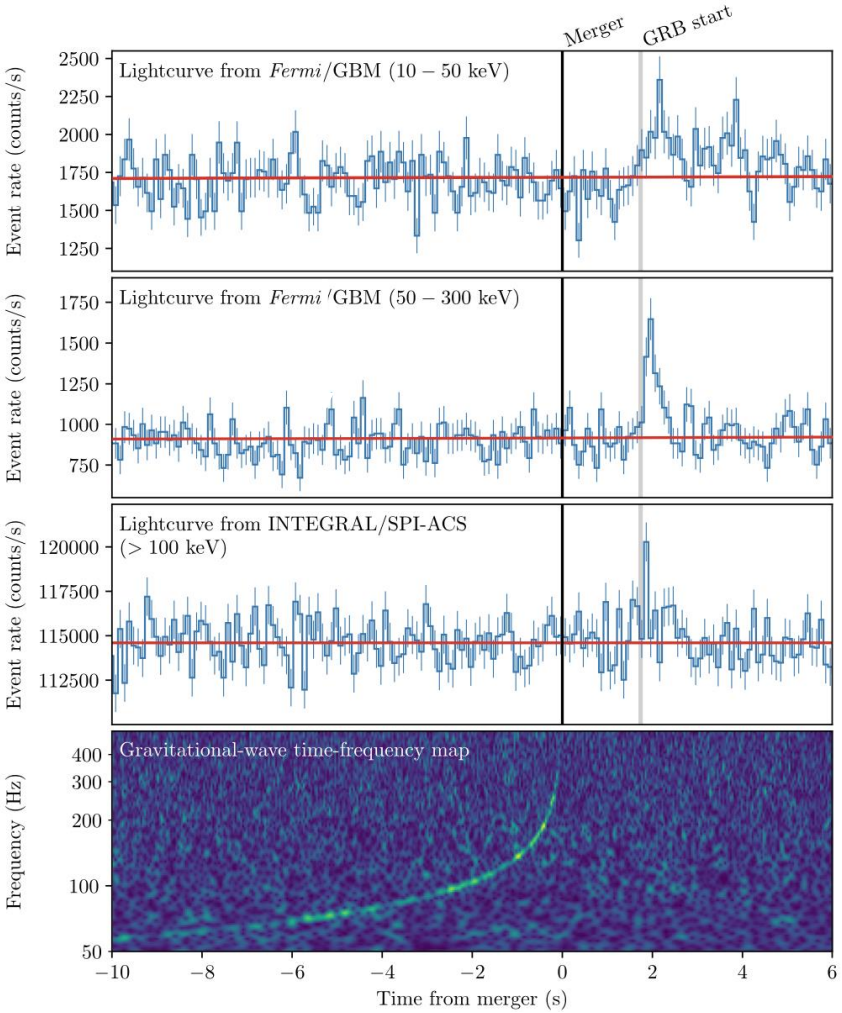


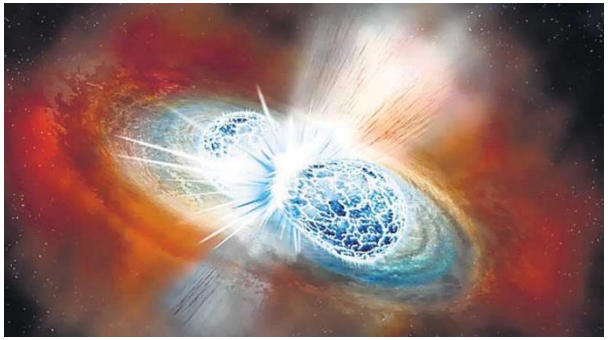
- **Detecting and studying primordial invisible galaxies**



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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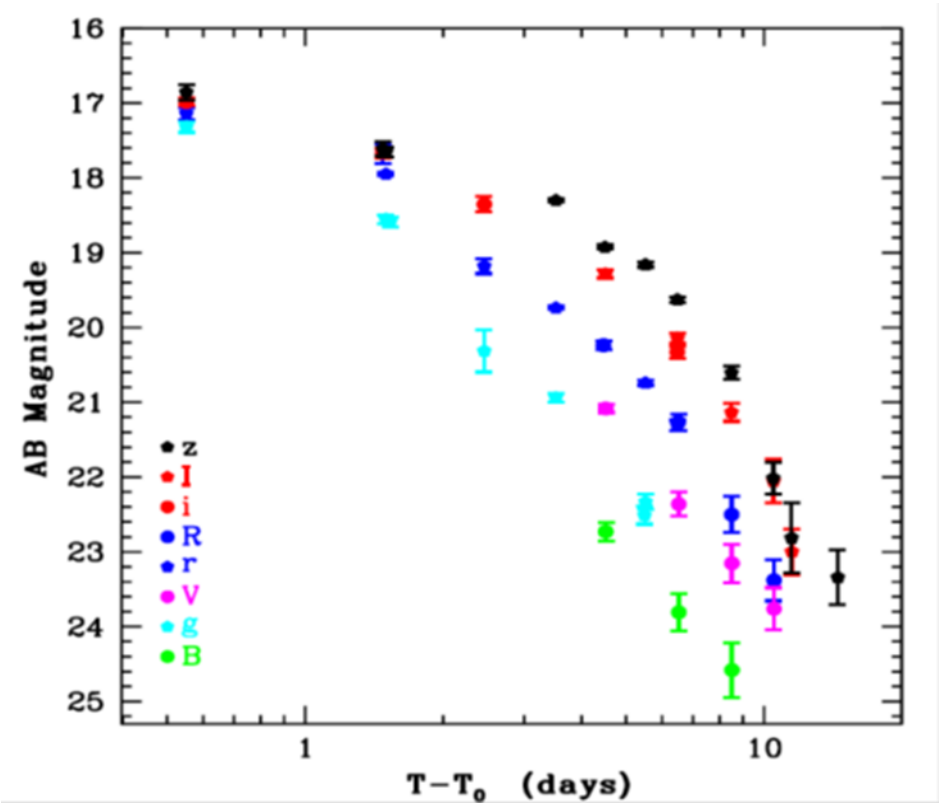
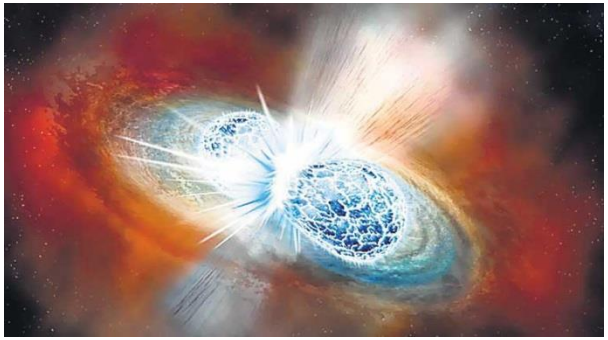
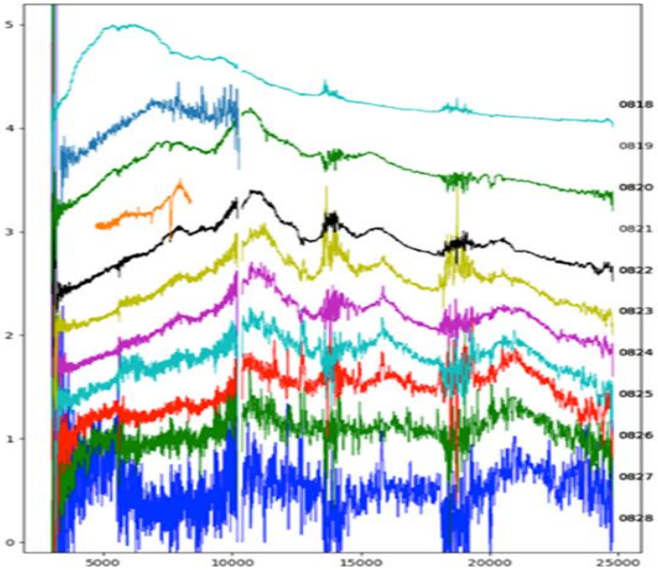


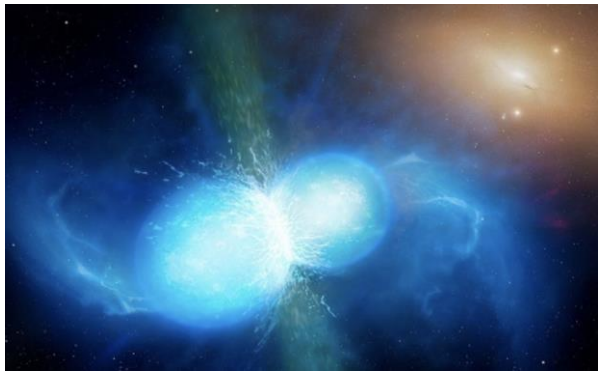




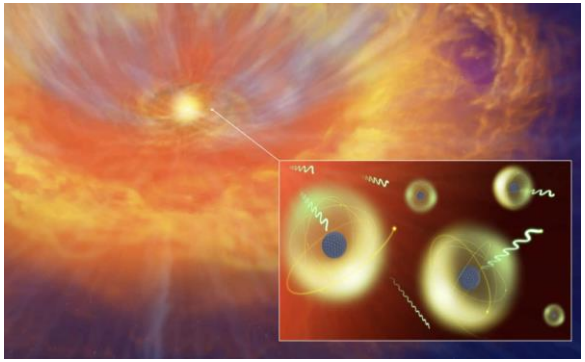
GRB: a key phenomenon for multi-messenger astrophysics (and cosmology)

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

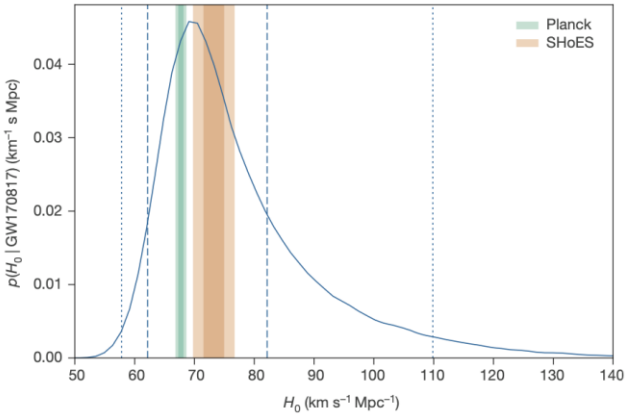
Relativistic jet formation, equation of state, fundamental physics



Cosmic sites of r-process nucleosynthesis

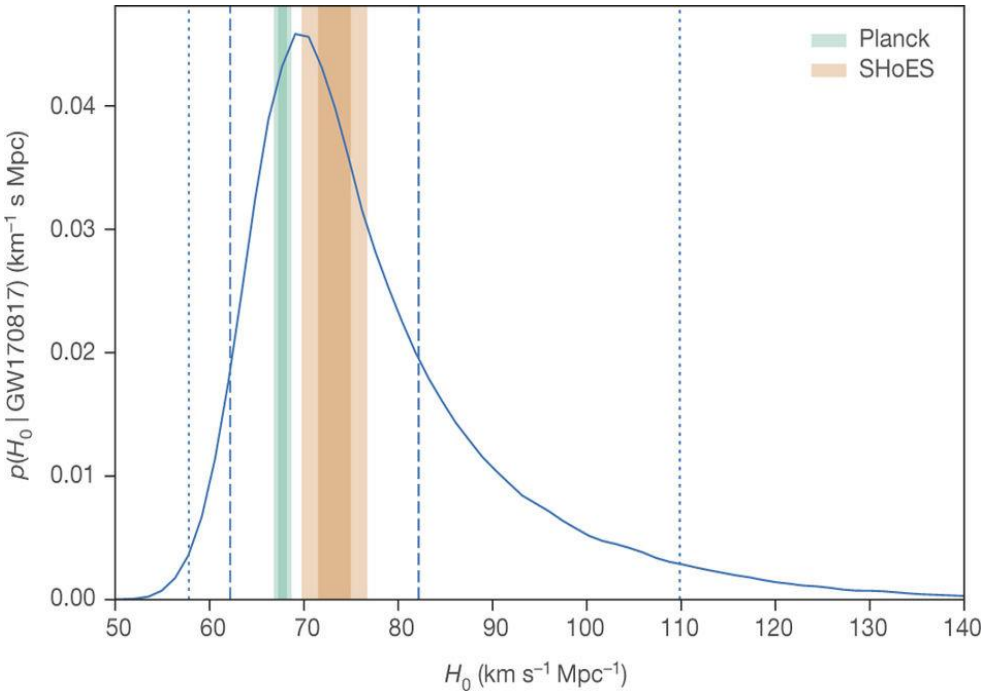


New independent route to measure cosmological parameters

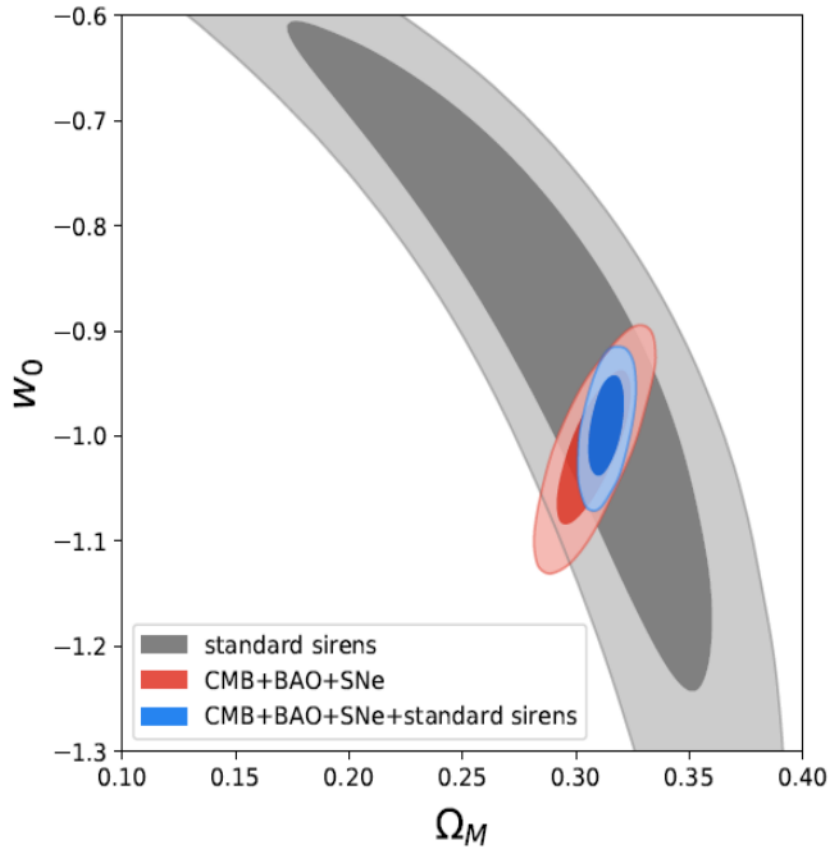


GRB: a key phenomenon for multi-messenger astrophysics (and cosmology)

MEASURING THE EXPANSION RATE AND GEOMETRY OF SPACE-TIME



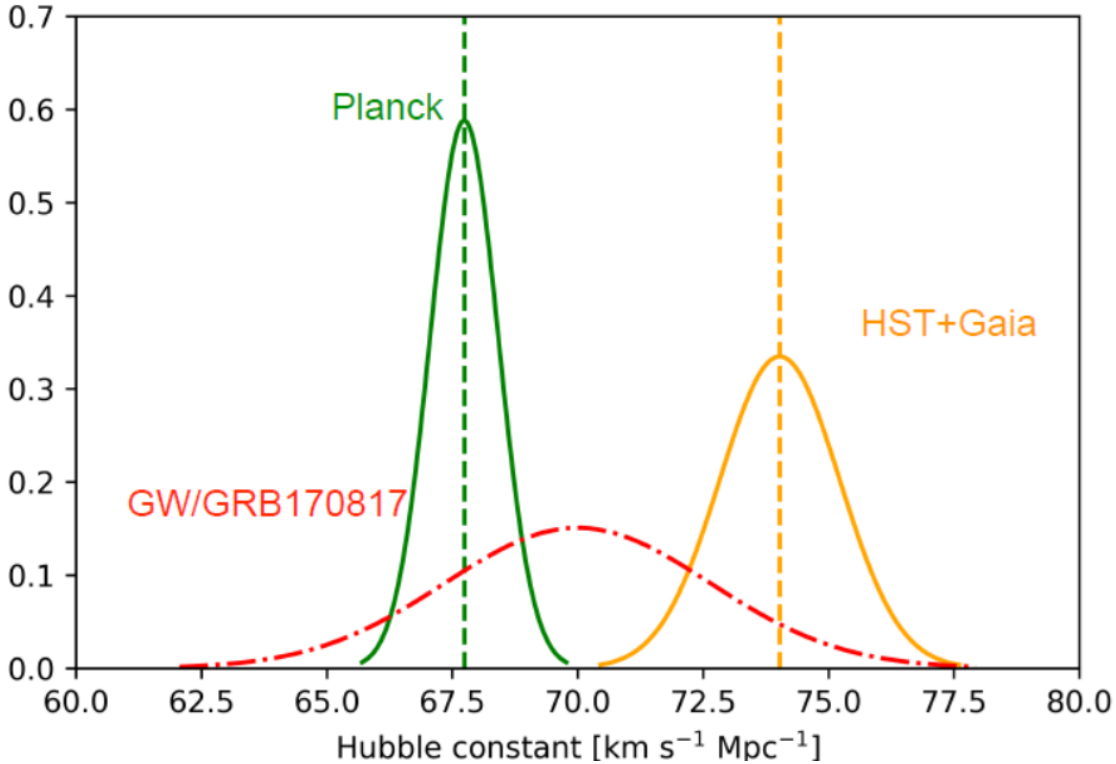
Estimating H0 with GW170817A (LVC 2017)



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



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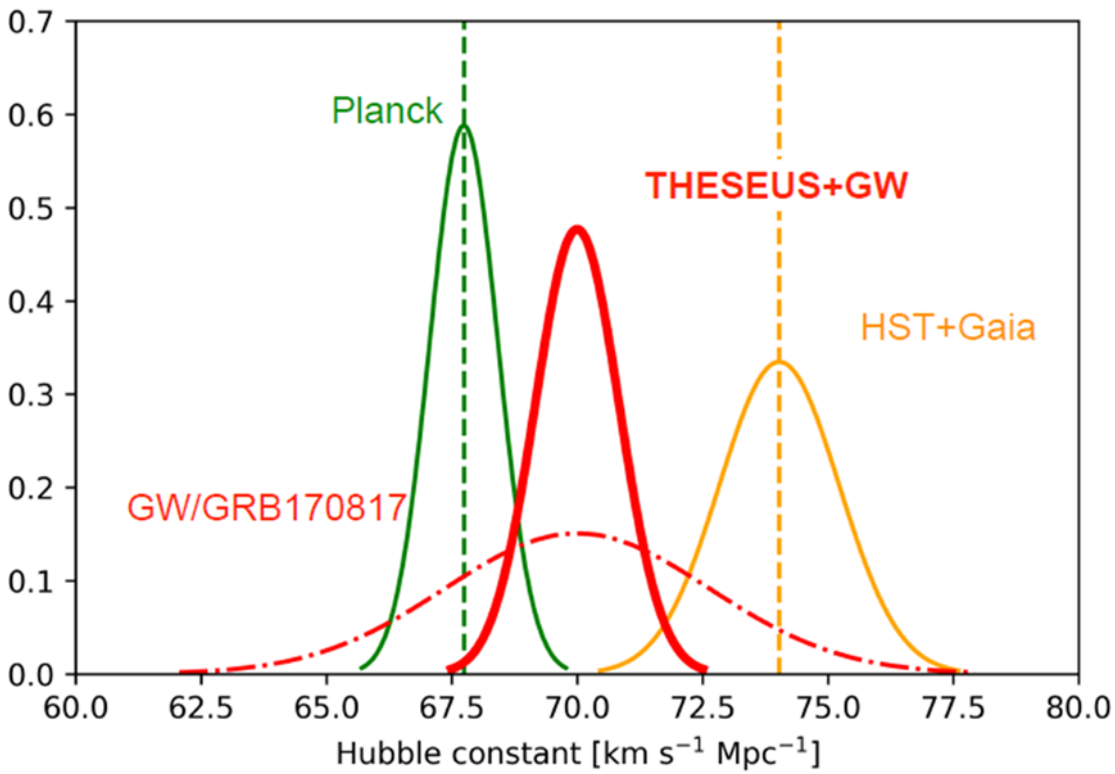
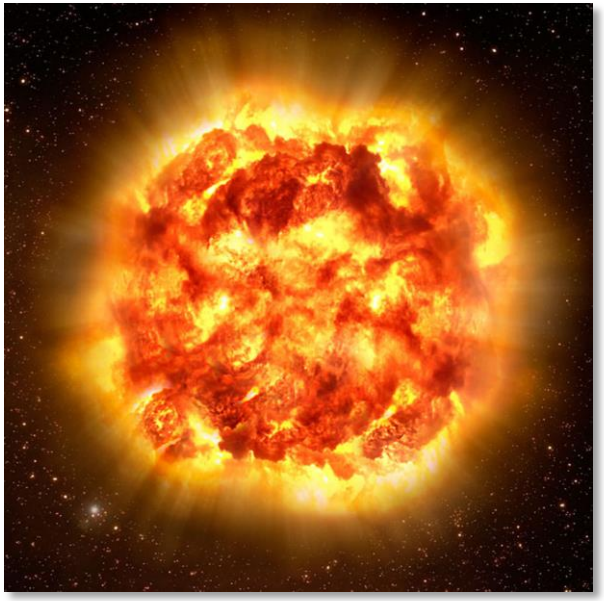
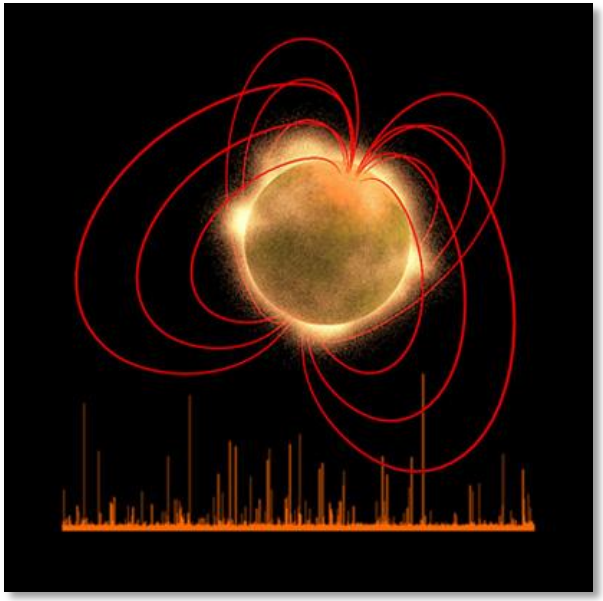


~20 joint GRB+GW events

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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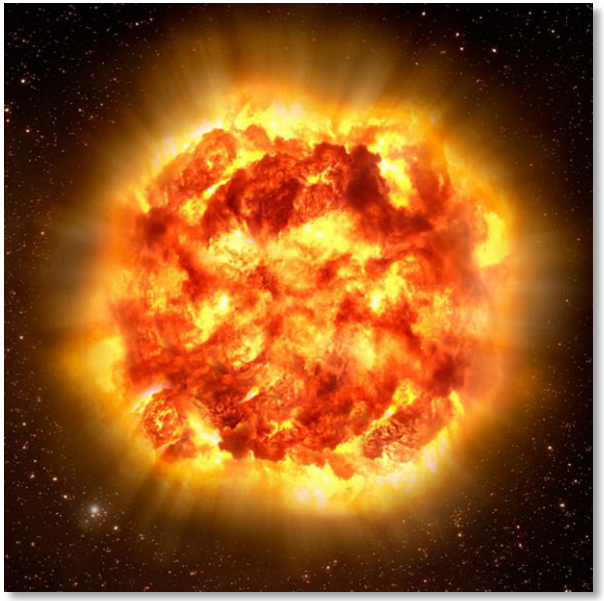
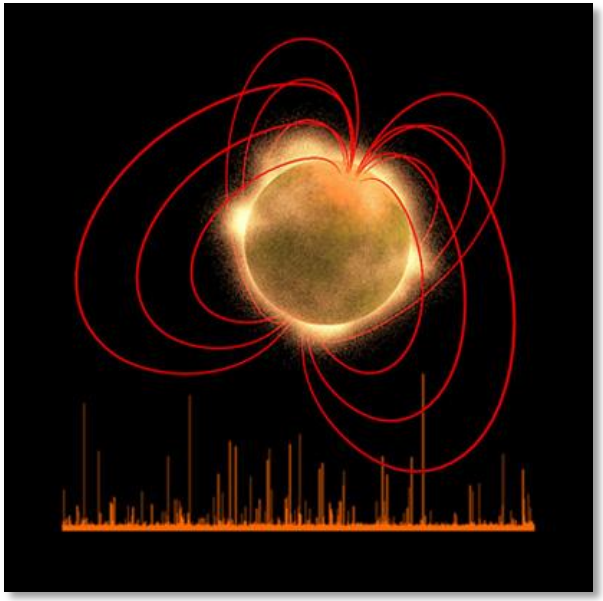
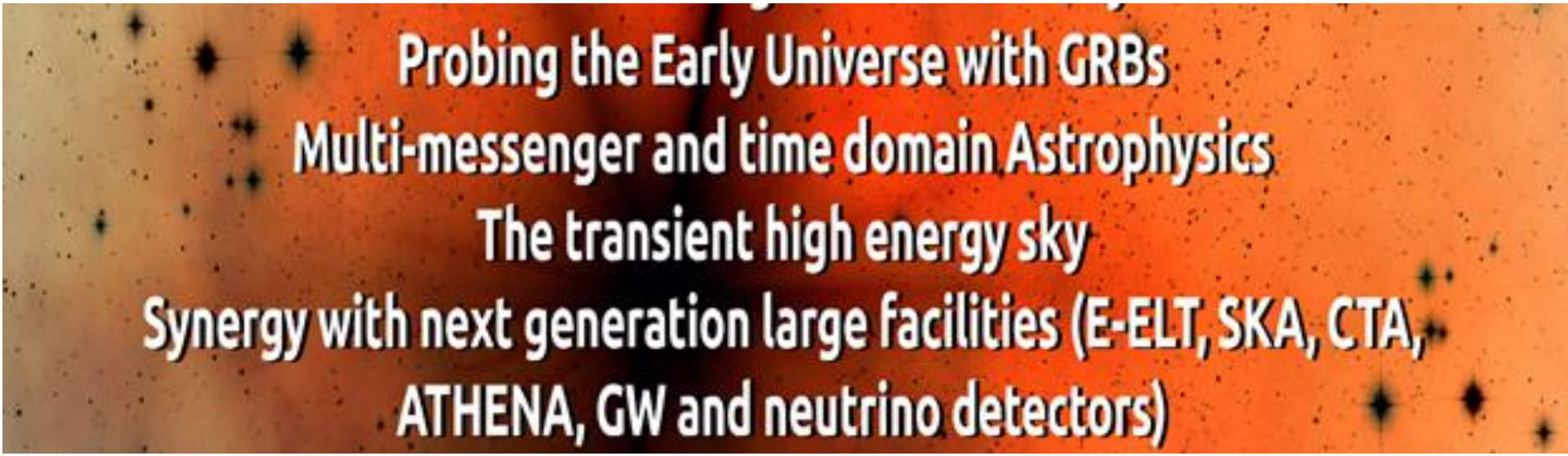




Future missions (late‘20s and ‘30s)

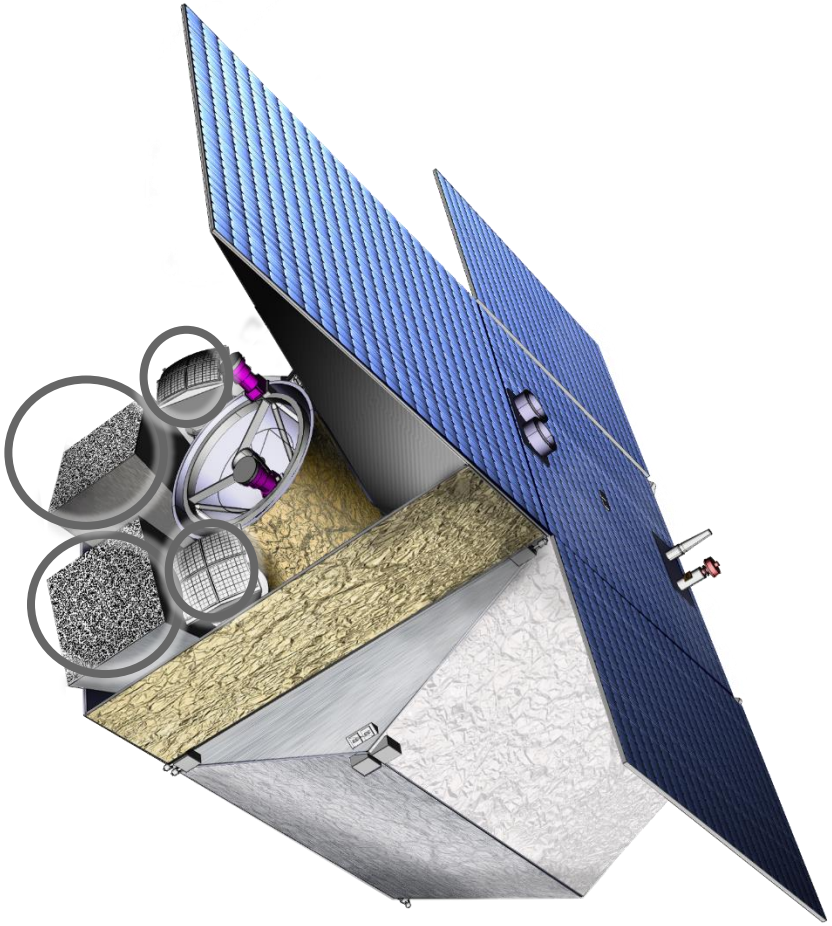


- **THESEUS** (studied for ESA Cosmic Vision / M5), **HiZ-GUNDAM** (JAXA, under study), **TAP** (under study for NASA decadal survey**), Gamow Explorer** (under study for NASA MIDEX**): prompt emission down to soft X-rays, source location accuracy of few arcmin**, **prompt follow-up with NIR telescope**,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



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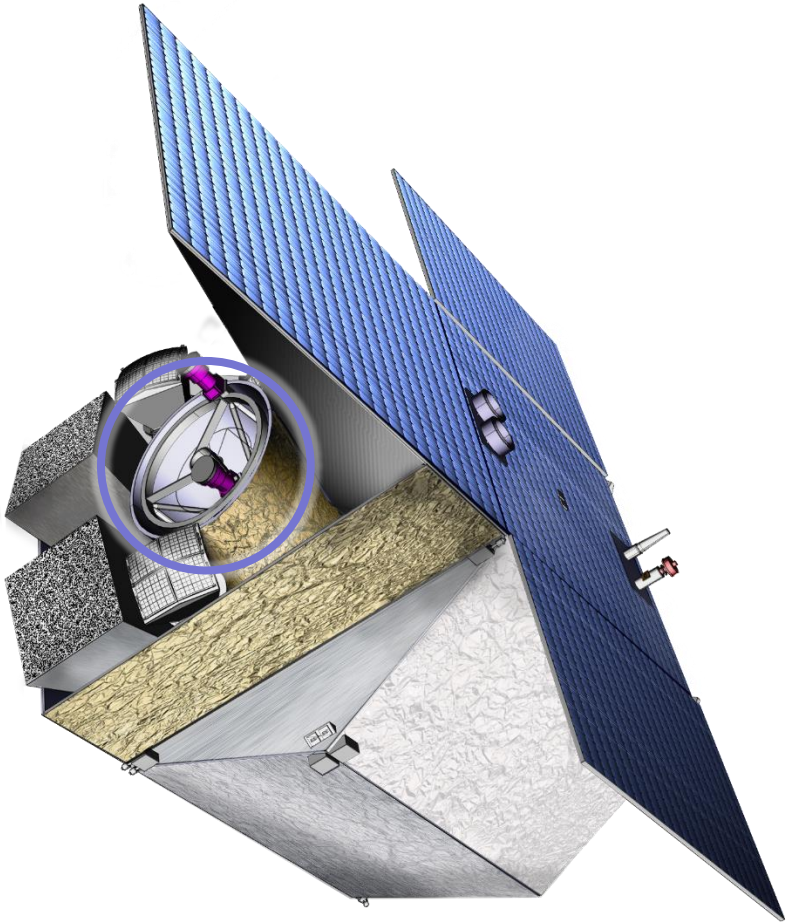
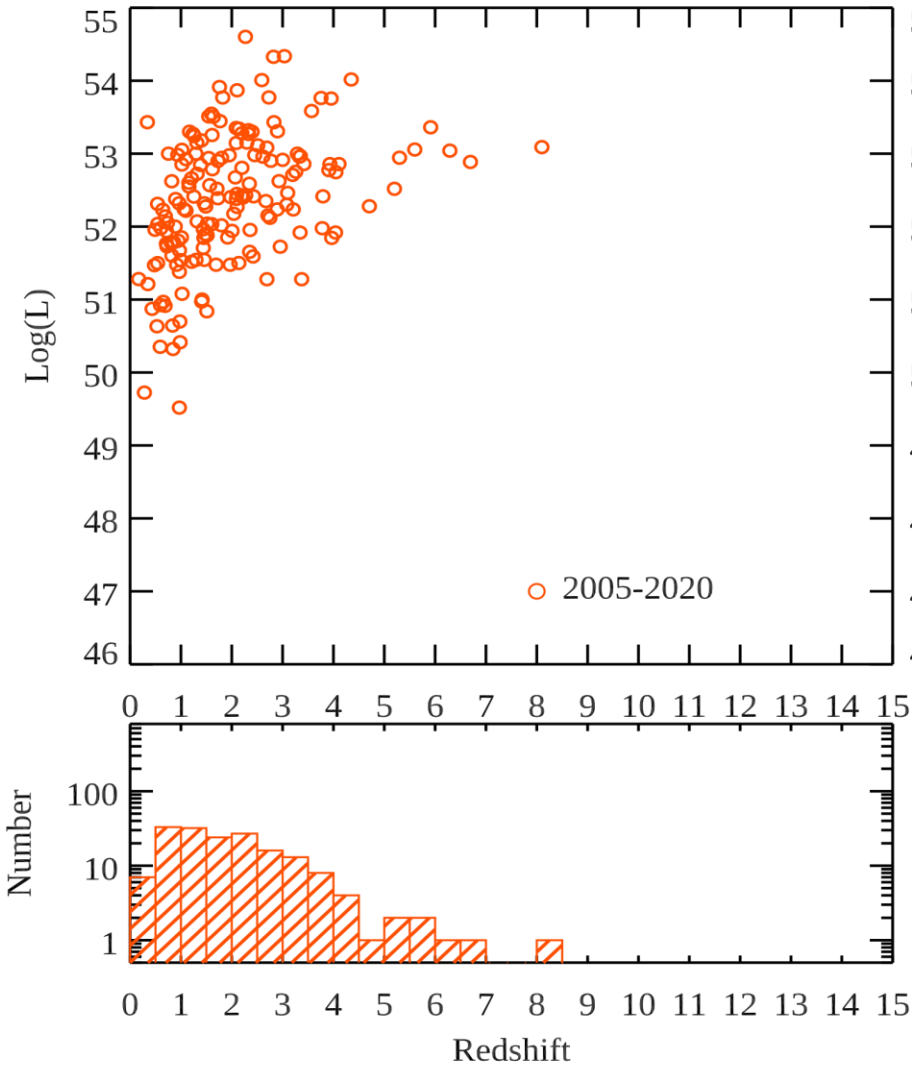
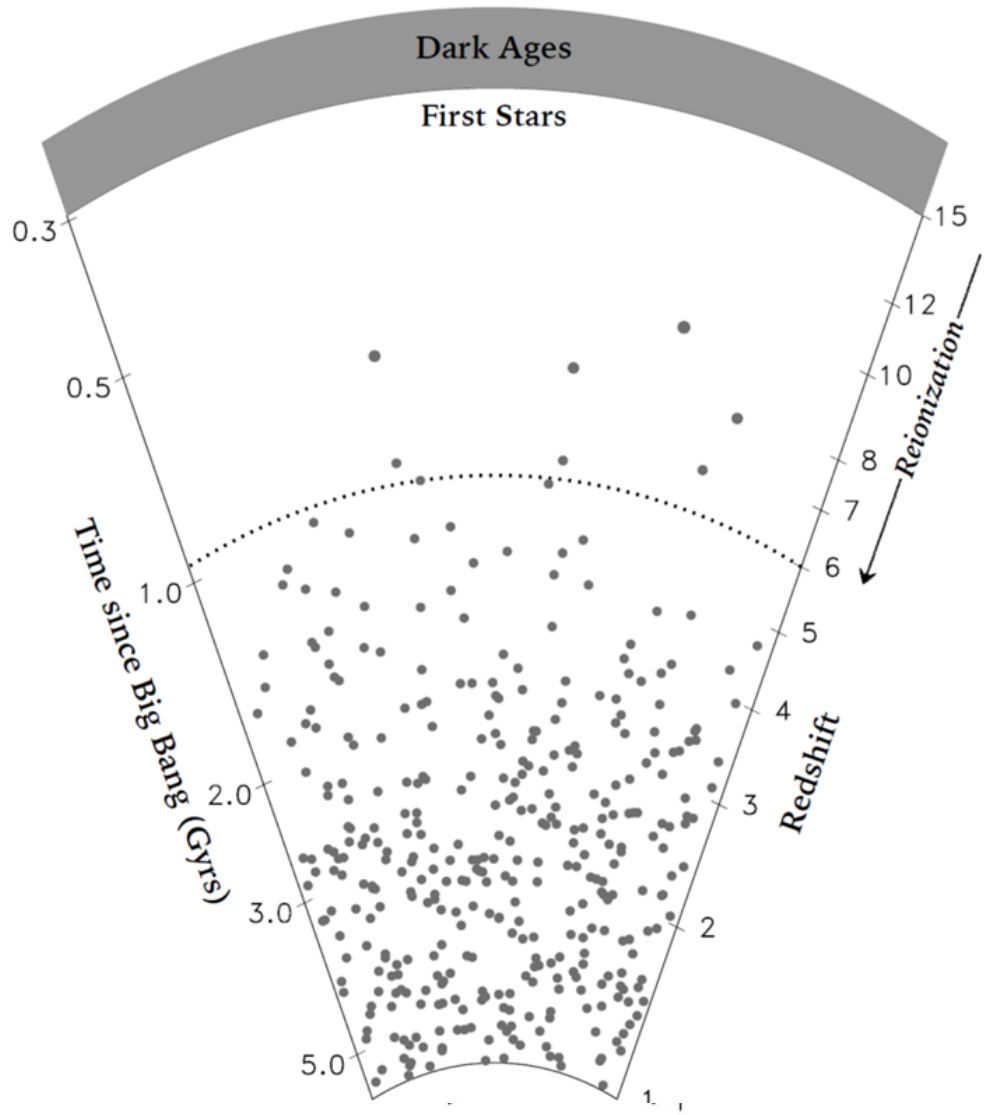
Set of innovative wide-field monitors with **unprecedented combination of broad energy range, sensitivity, FOV and localization accuracy**

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





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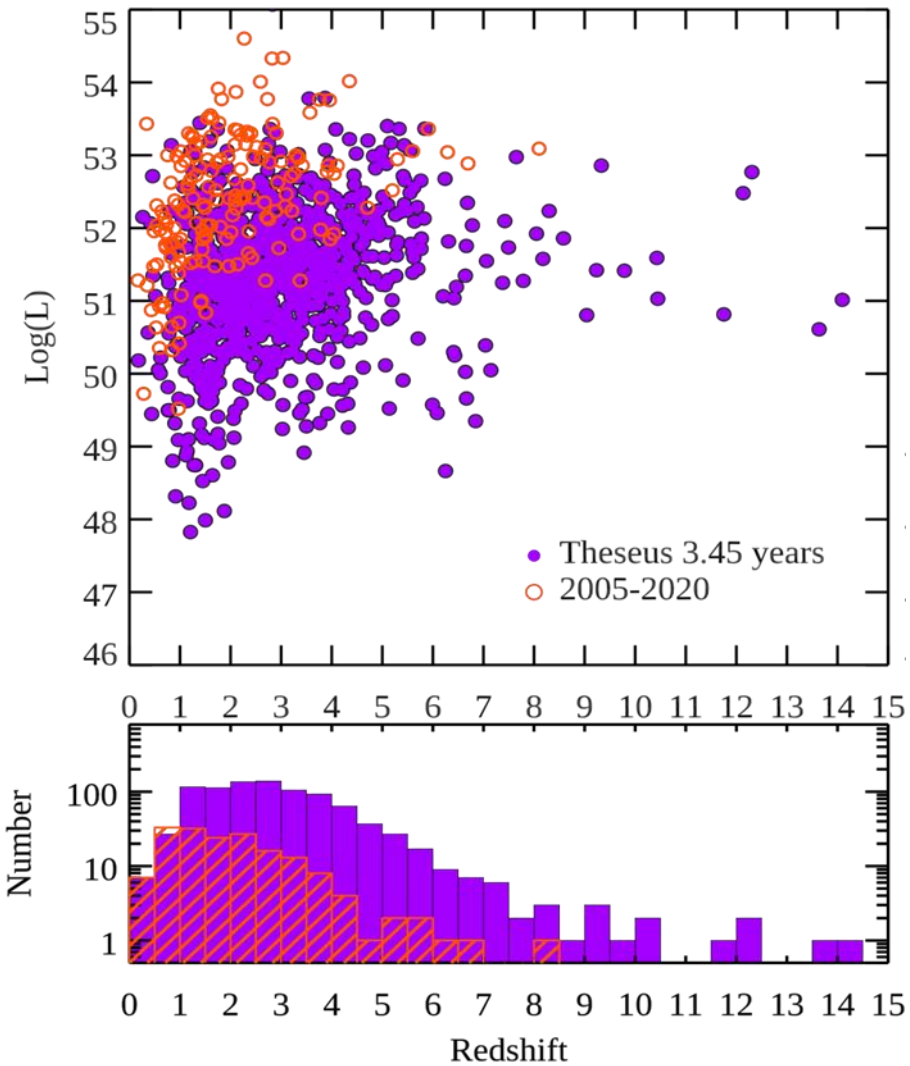
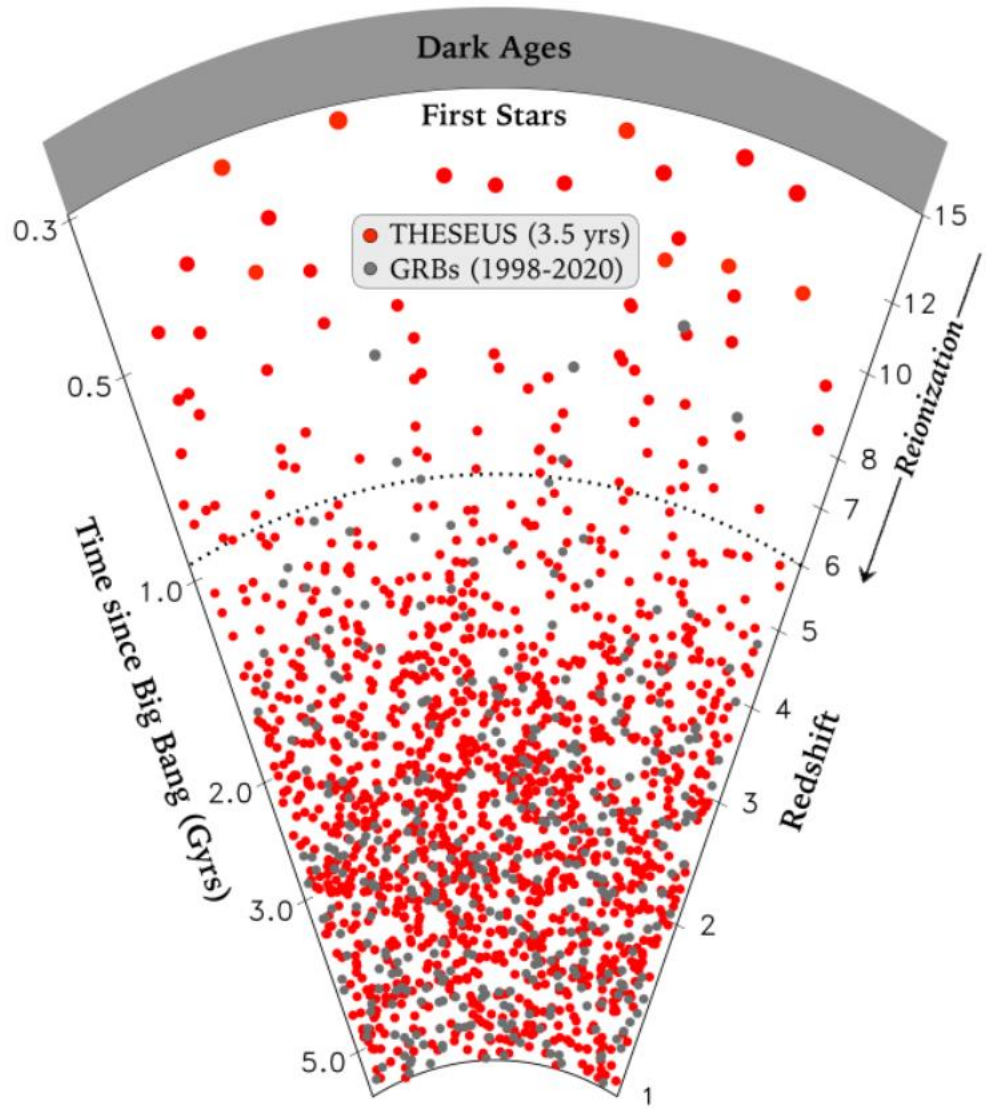
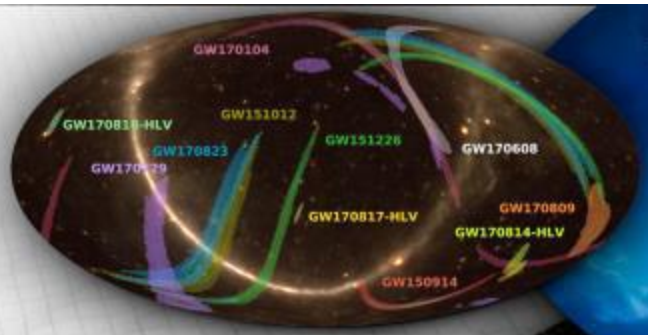


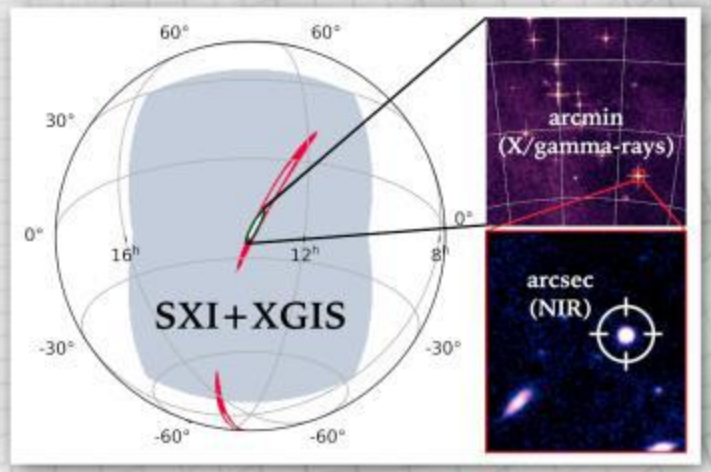


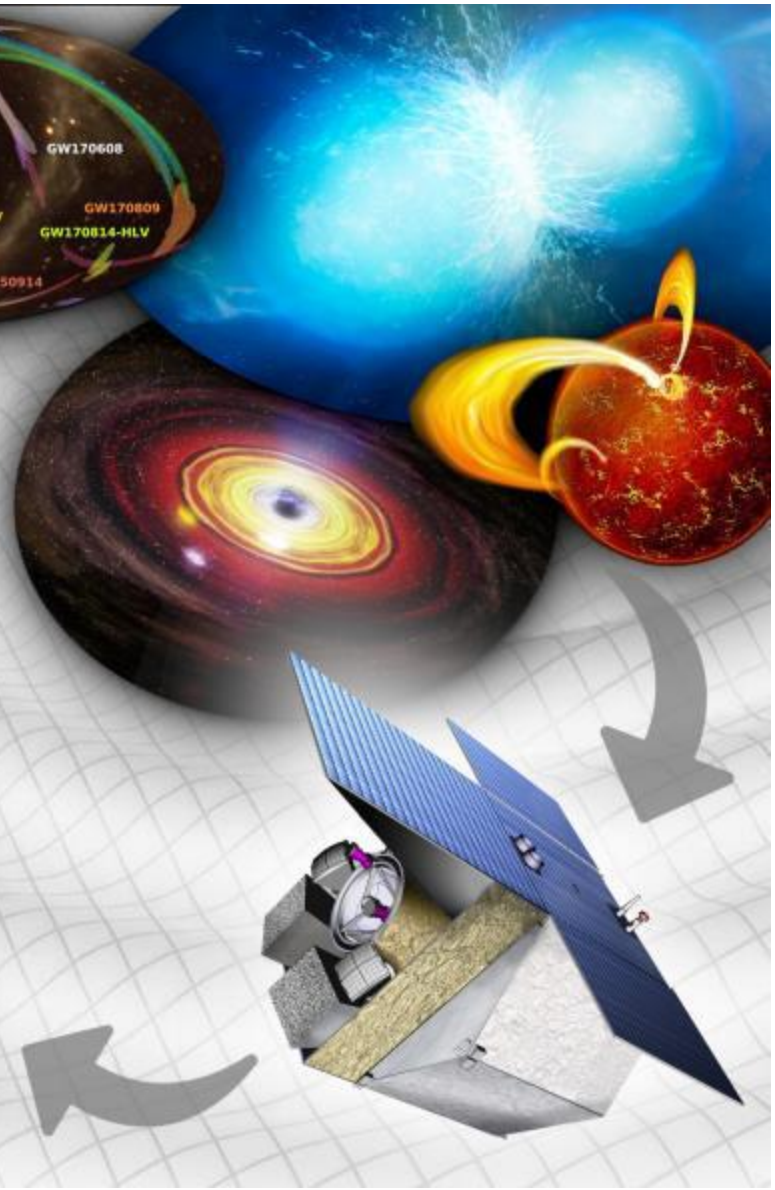
Exploring the multi-messenger transient sky



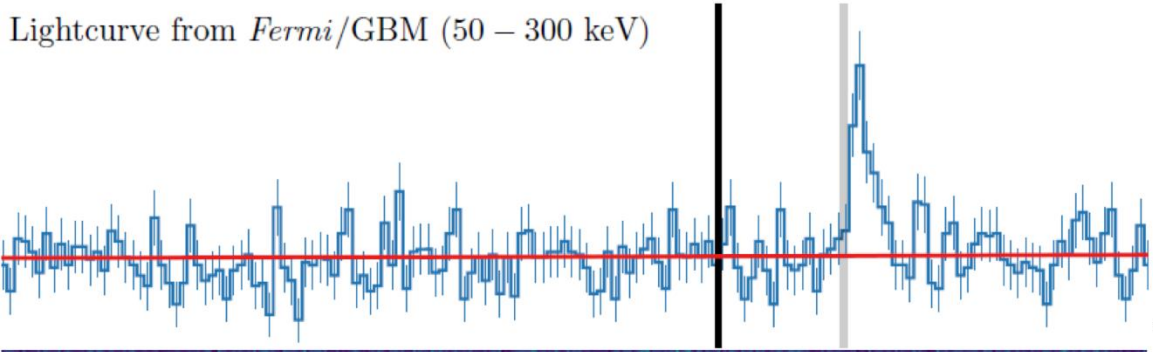
THESEUS ensures:

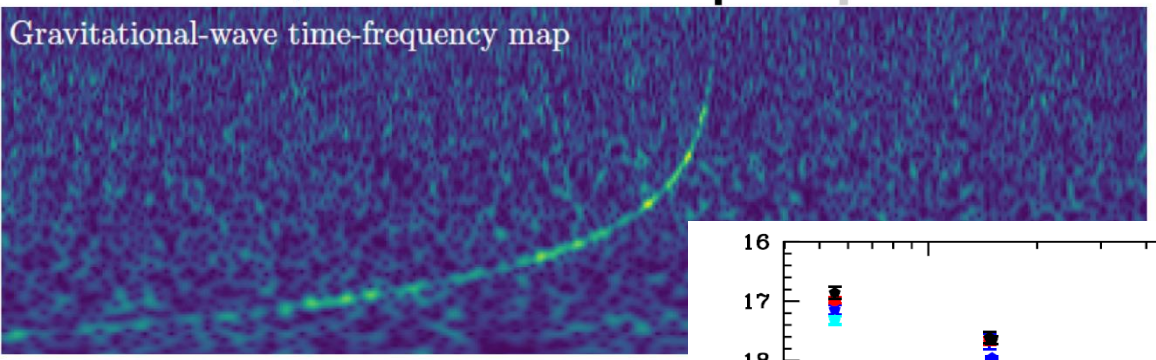
- Immediate coverage of gravitational wave and neutrino source error boxes
- Real time sky localizations
- Temporal & spectral charaterization from NIR to gamma-rays

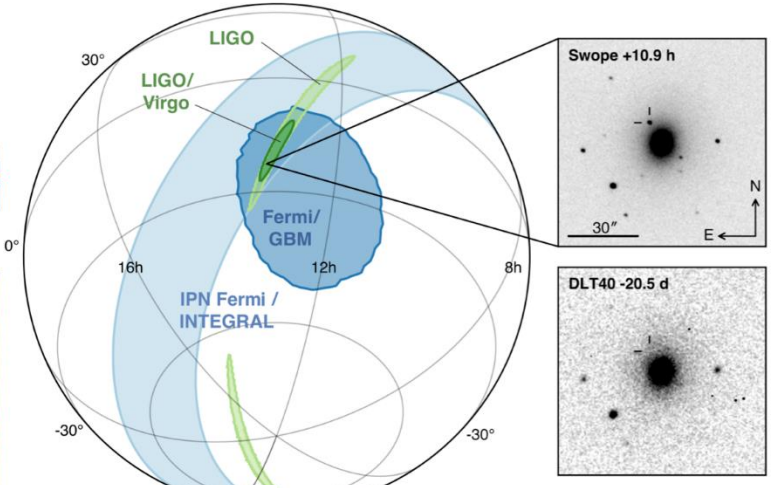


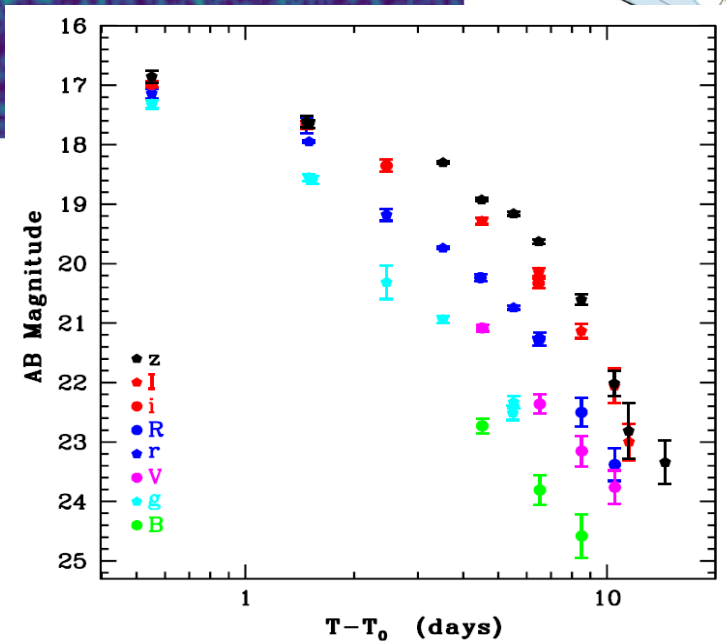


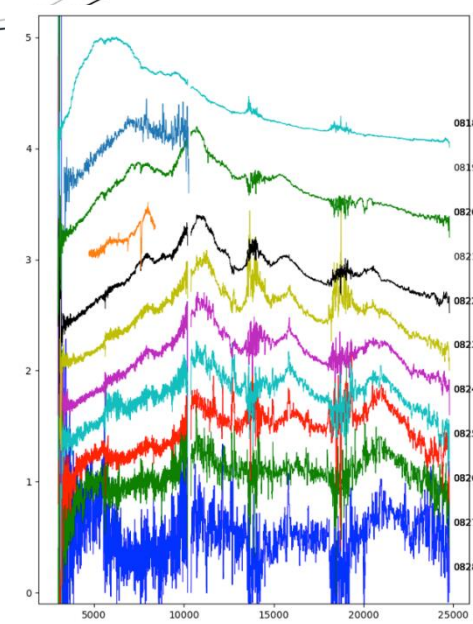
LIGO, Virgo, and partners make first detection of gravitational waves and light from colliding neutron stars





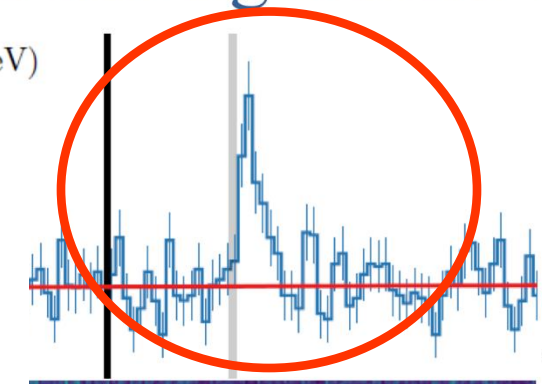


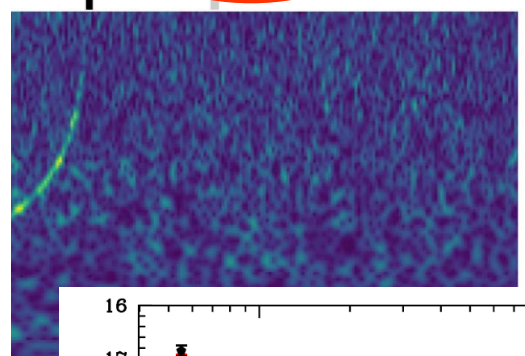


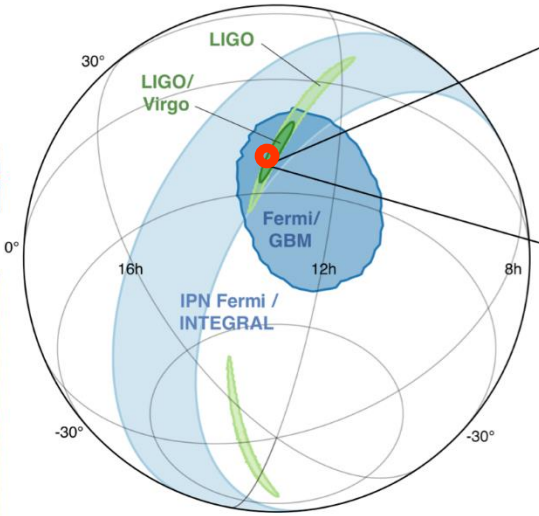


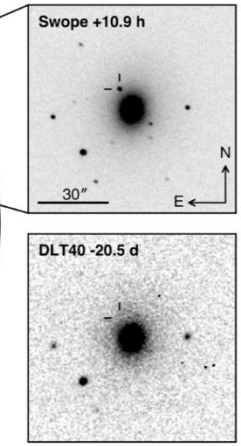
LIGO, Virgo, and partners make first detection of gravitational waves and light from colliding neutron stars

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



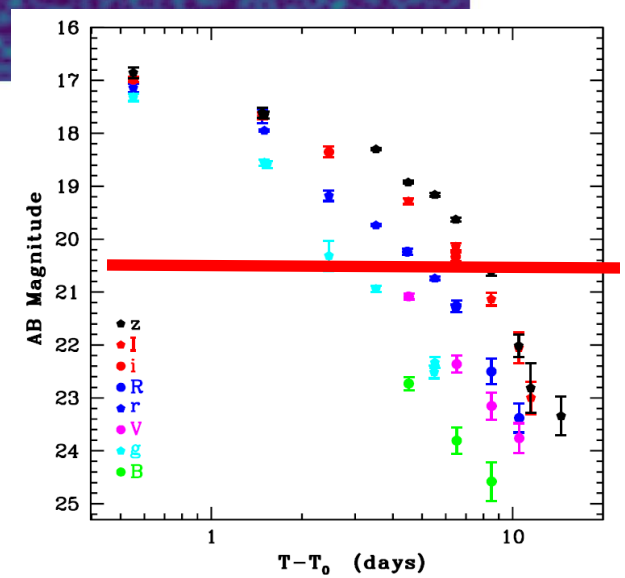


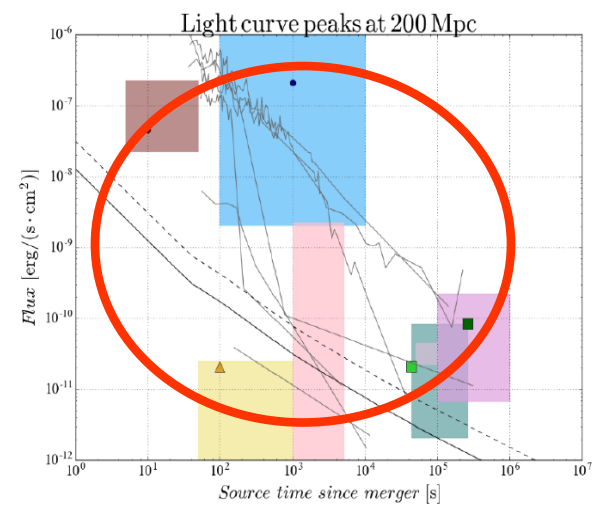




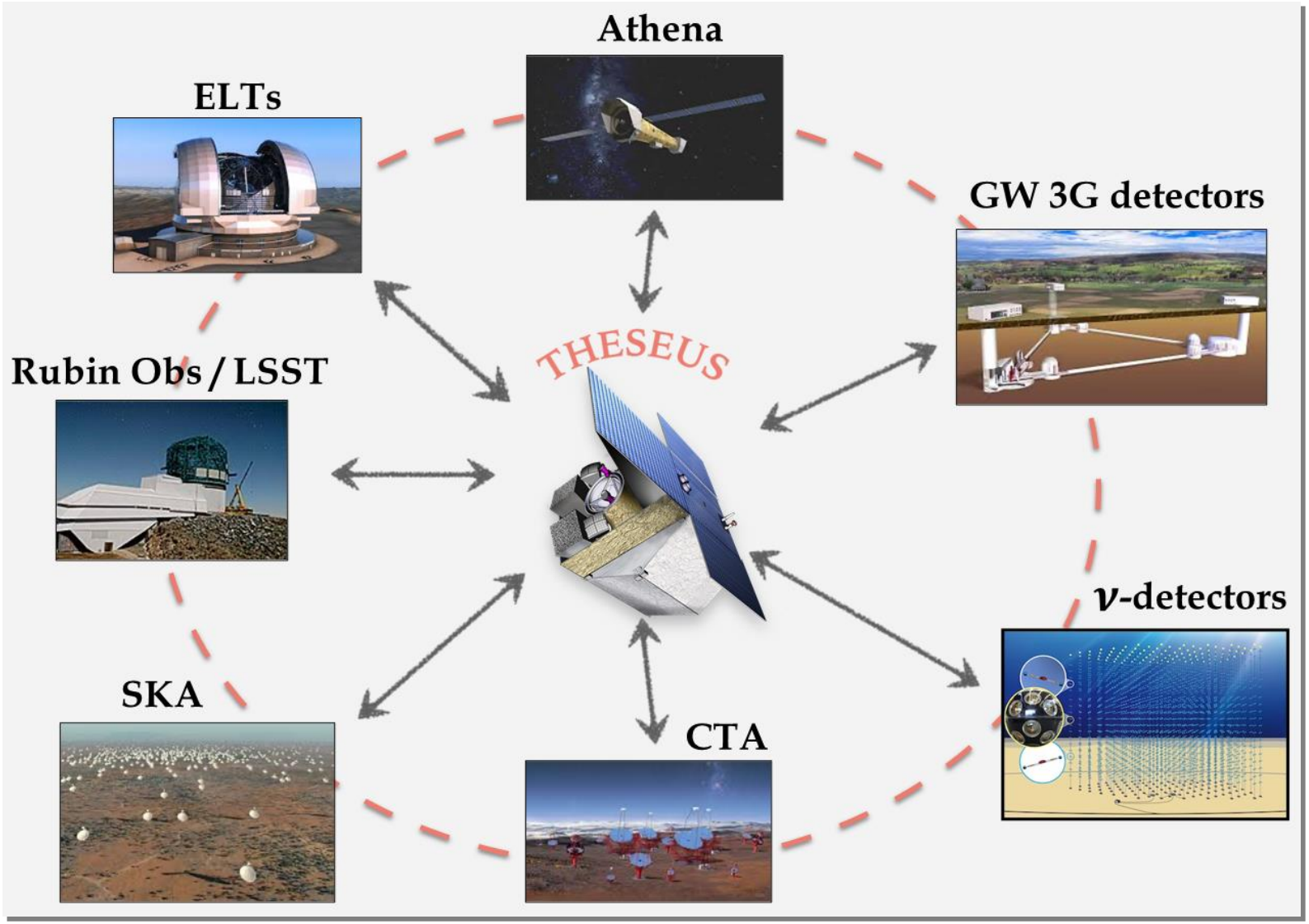
THESEUS:

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





Multi-wavelength/messenger synergies



Amati+ 2021

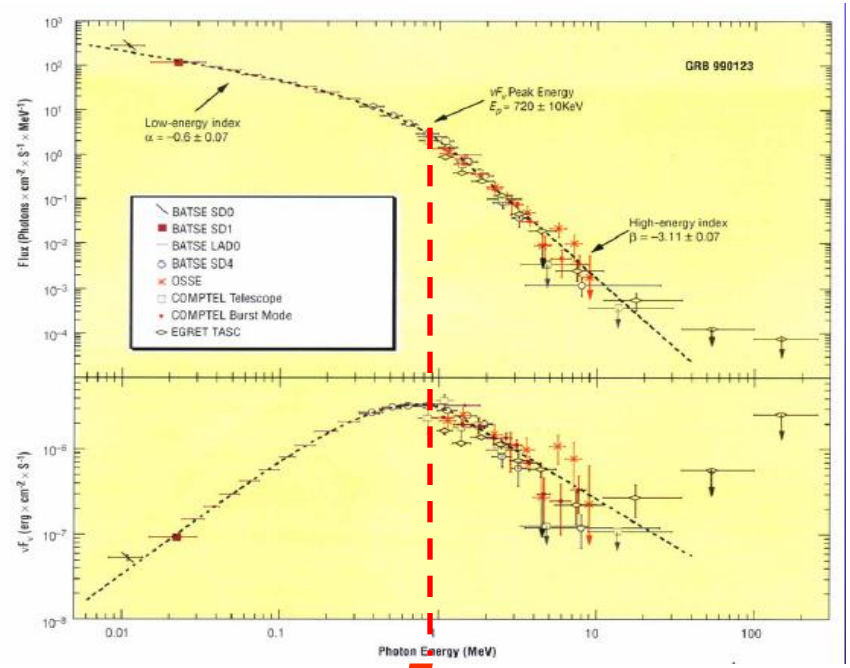
Measuring cosmological parameters with GRBs

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

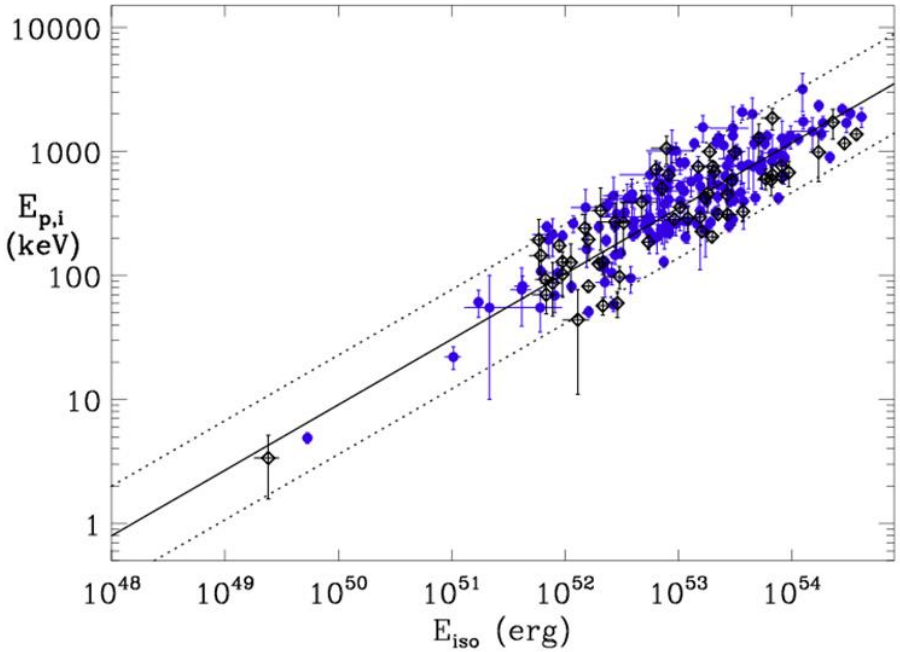
- **measured spectrum + measured redshift -> intrinsic peak enery and radiated energy**

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

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



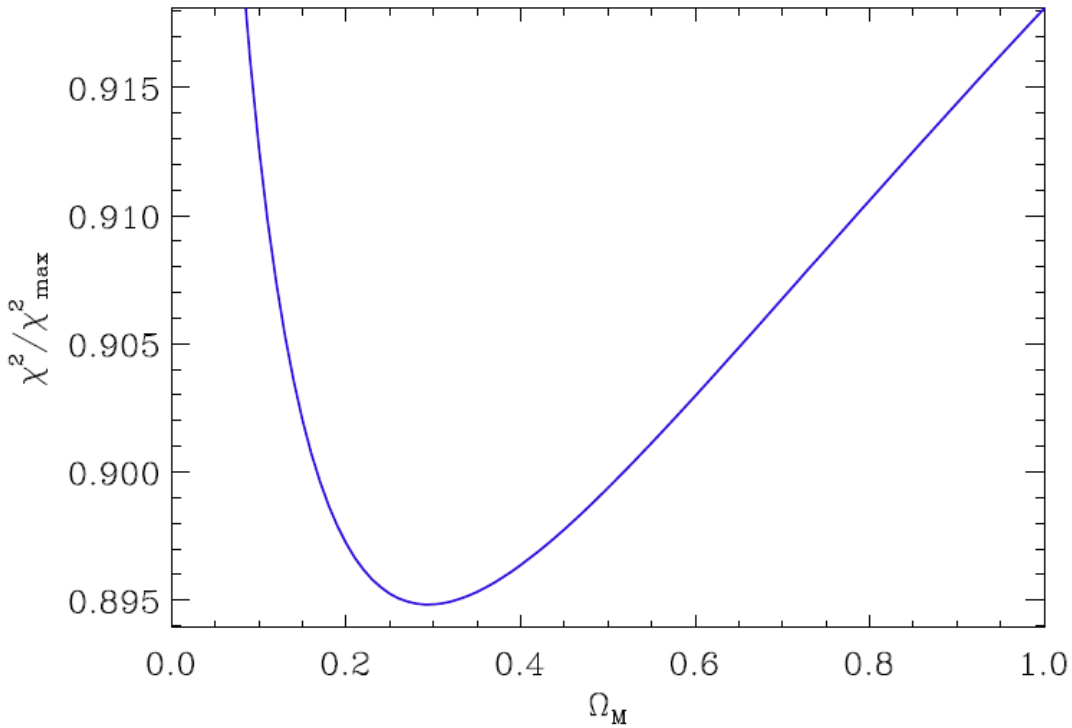
Ep



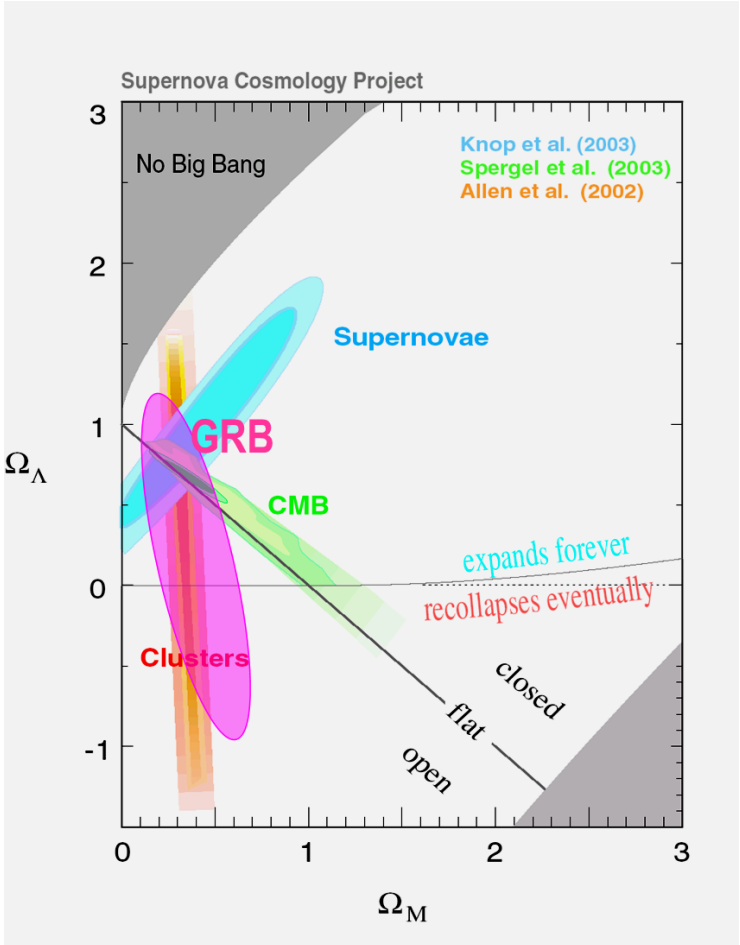
Amati et al. (2002,2006,2008, 2013)

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**



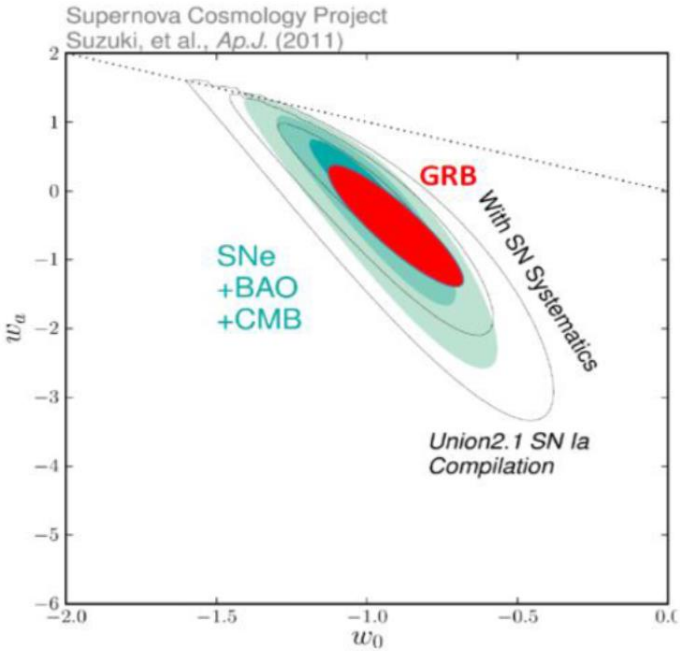
Amati et al. 2008, Amati & Della Valle 2013



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)

GRB #	Ω_M (flat)
70 (real) GRBs (Amati+ 08)	$0.27^{+0.38}_{-0.18}$
156 (real) GRBs (Amati+ 13)	$0.29^{+0.28}_{-0.15}$
250 (156 real + 94 simulated) GRBs	$0.29^{+0.16}_{-0.12}$
500 (156 real + 344 simulated) GRBs	$0.29^{+0.10}_{-0.09}$
156 (real) GRBs, calibration	$0.30^{+0.06}_{-0.06}$
250 (156 real + 94 simulated) GRBs, calibration	$0.30^{+0.04}_{-0.05}$
500 (156 real + 344 simulated) GRBs, calibration	$0.30^{+0.03}_{-0.03}$



$$w(z) = w_0 + \frac{w_a z}{1+z}$$

Fundamental physics with GRBs: testing LI / QG

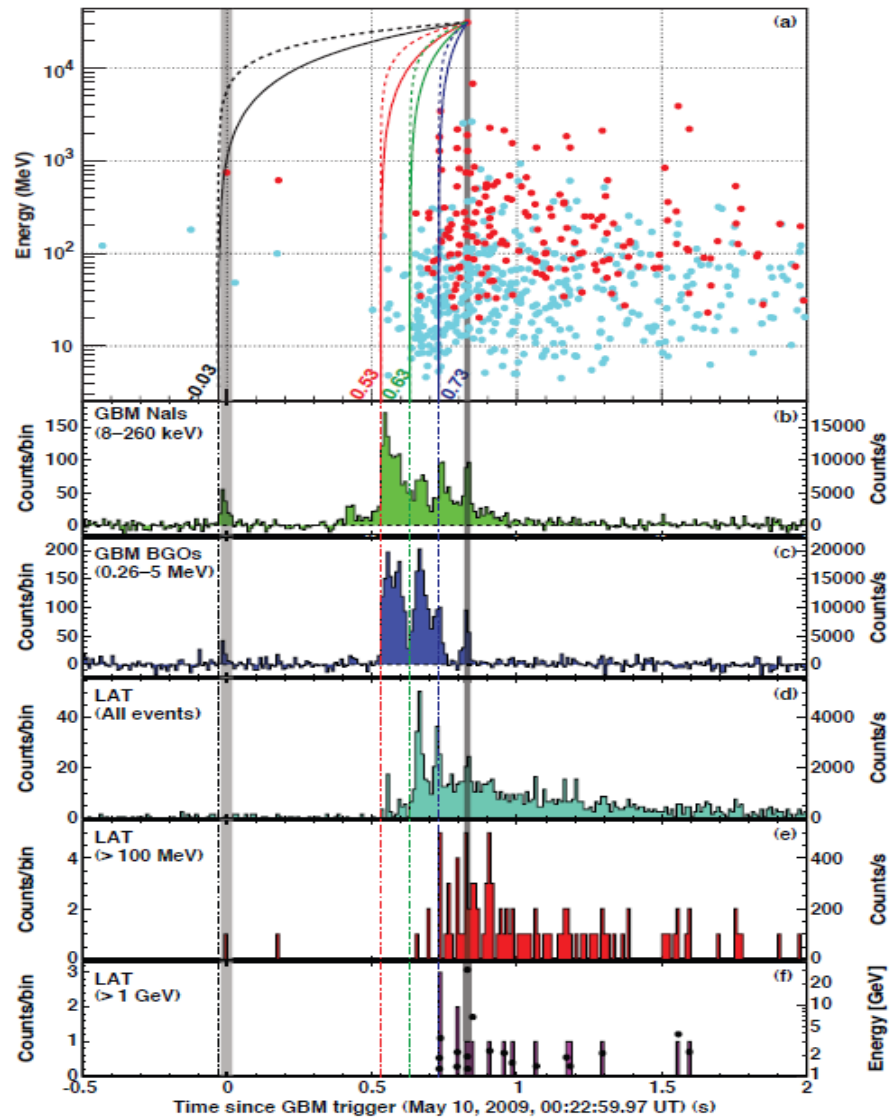
- Using time delay between low and high energy photons to put Limits on Lorentz Invariance Violation (allowed by unprecedent Fermi GBM + LAT broad energy band)

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

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

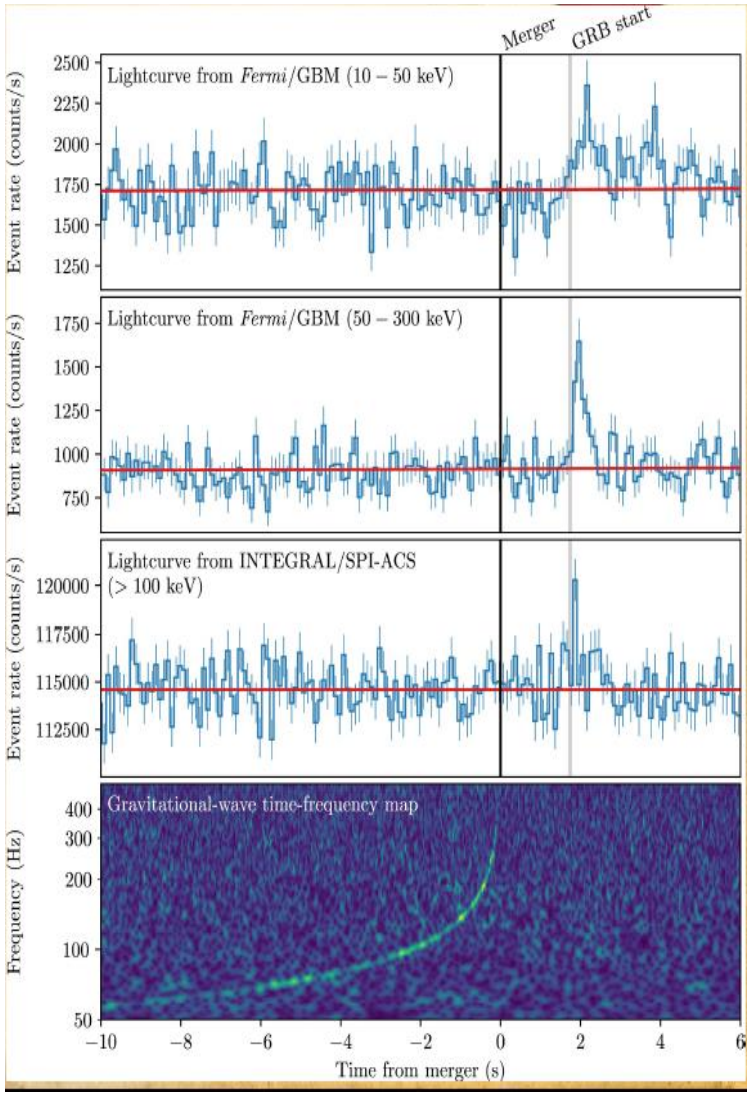
GRB 990510 $E_h = 30.53^{+5.79}_{-2.56}$ GeV

$t_{\rm start}$ (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
$\lvert\frac{\Delta t}{\Delta E}\rvert < 30\ \frac{\rm ms}{\rm GeV}$		lag analysis of all LAT events	—	±1	> 1.22



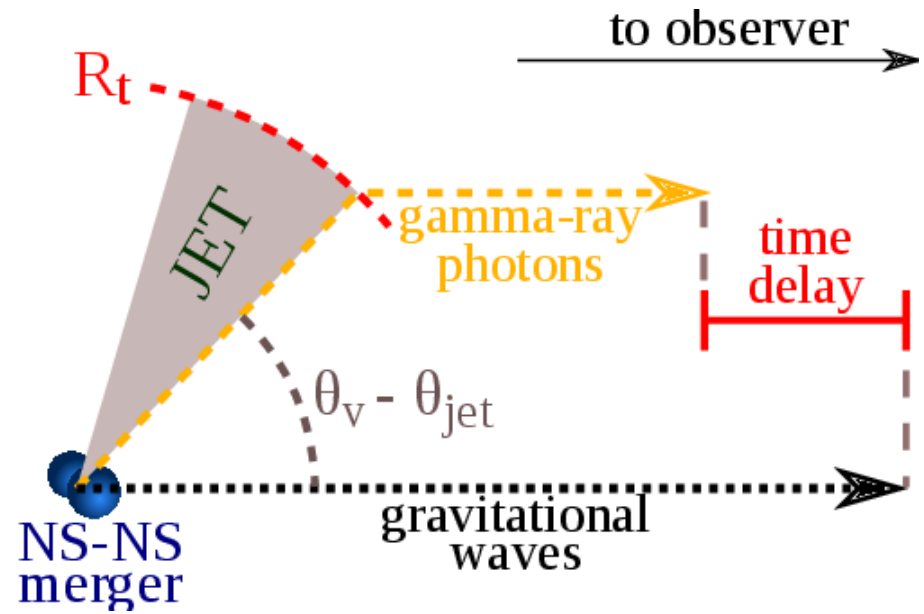
Fundamental physics with GRBs: GW vs. light speed

GW170817/GRB170817A, D ~ 40 Mpc



A short GRB at +1.7 s

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



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

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

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 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/