Cosmology with Gamma-Ray Bursts

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OAS

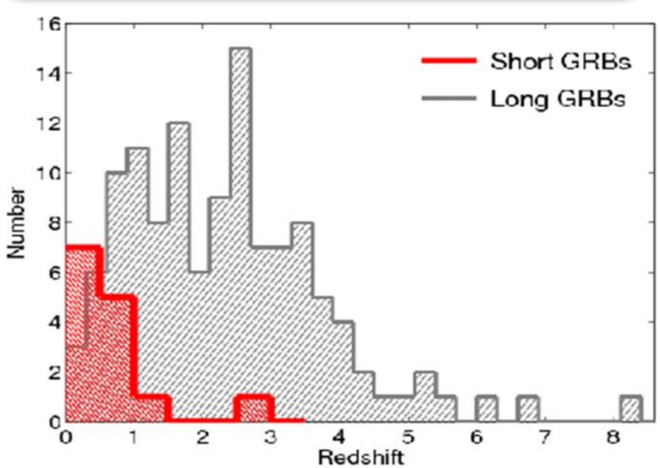
The 6th Bego Rencontre Summer School

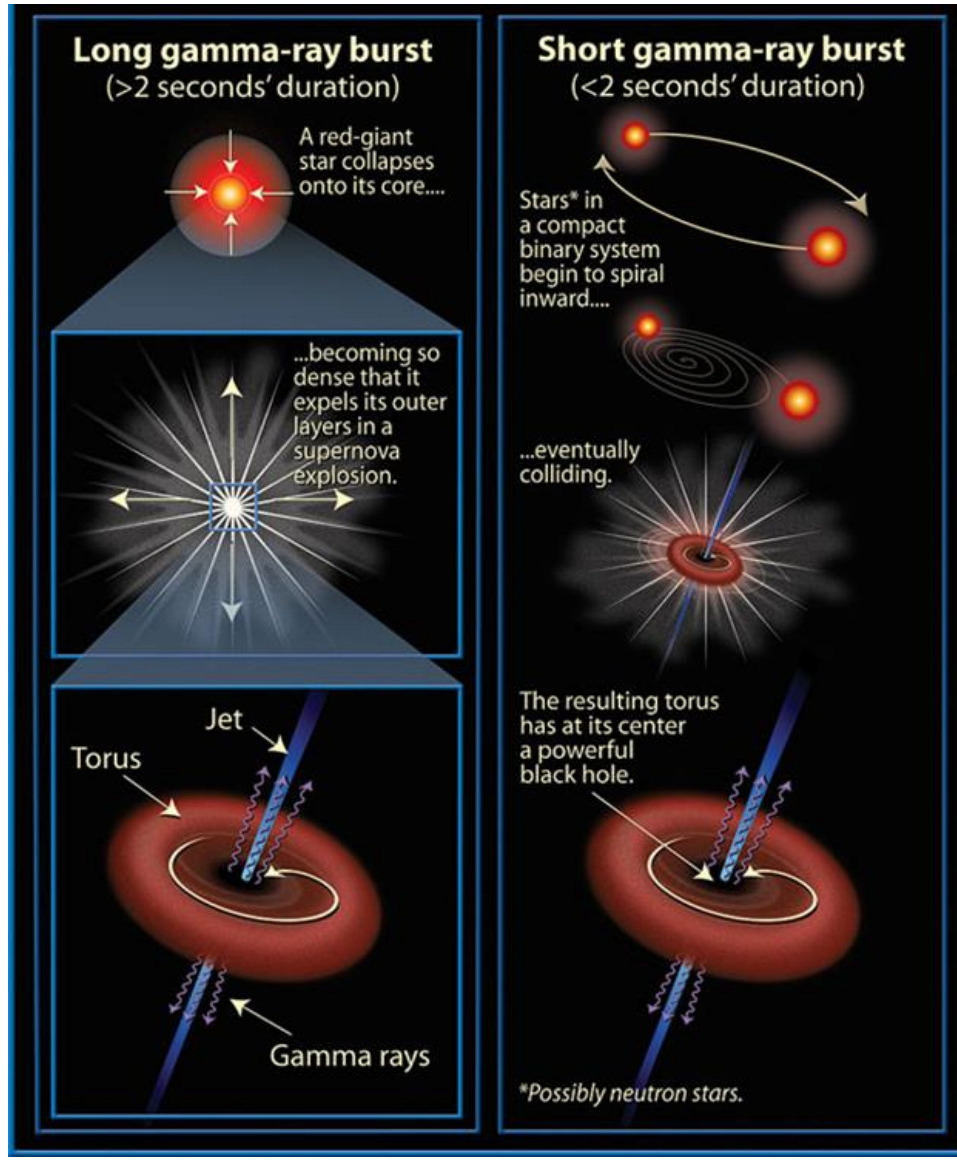
ICRANet
International Center for Relativistic Astrophysics Network

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**





The power of long GRBs for cosmology

Most luminous and remote phenomena in the Universe, with isotropic-equivalent radiated energies in X-gamma rays up to more than **10^{54} erg released in a few tens of seconds** and a redshift distribution extending to at least **z = 9-10**.

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b) **Using GRBs to investigate the expansion rate and geometry of the Universe,** thus getting clues to "dark energy" properties and evolution

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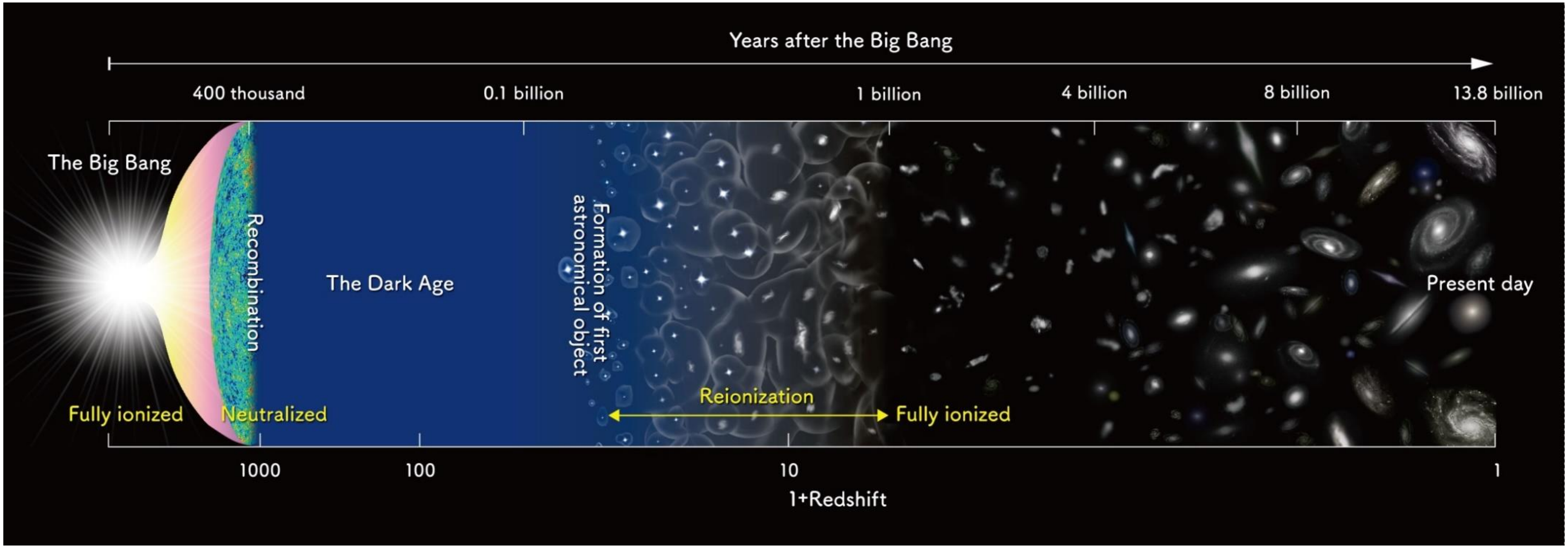
Shedding light on the early Universe with GRBs

- 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**



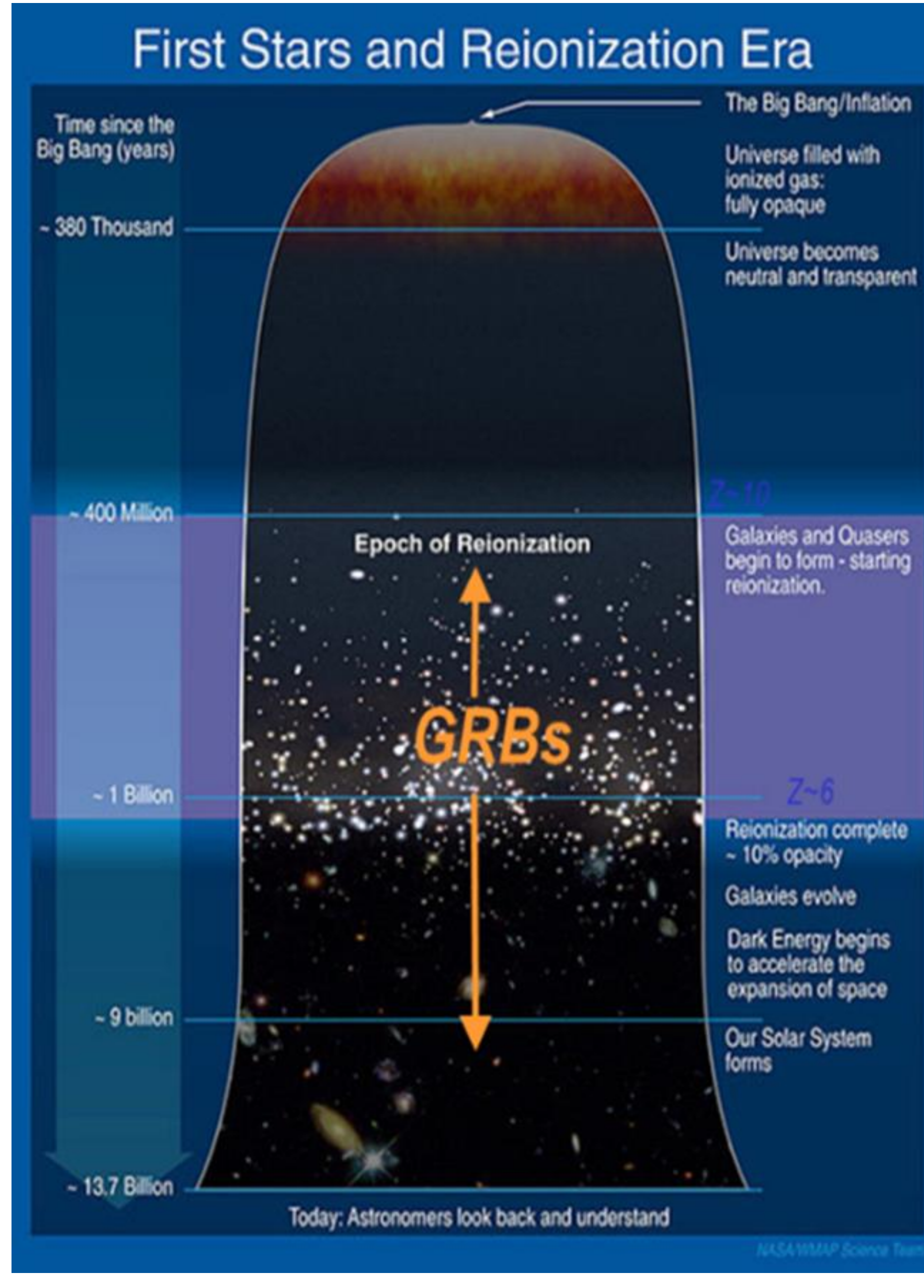
What was the timeline of reionization?

What sources were responsible?

How did the chemical elements build up?

Shedding light on the early Universe with GRBs

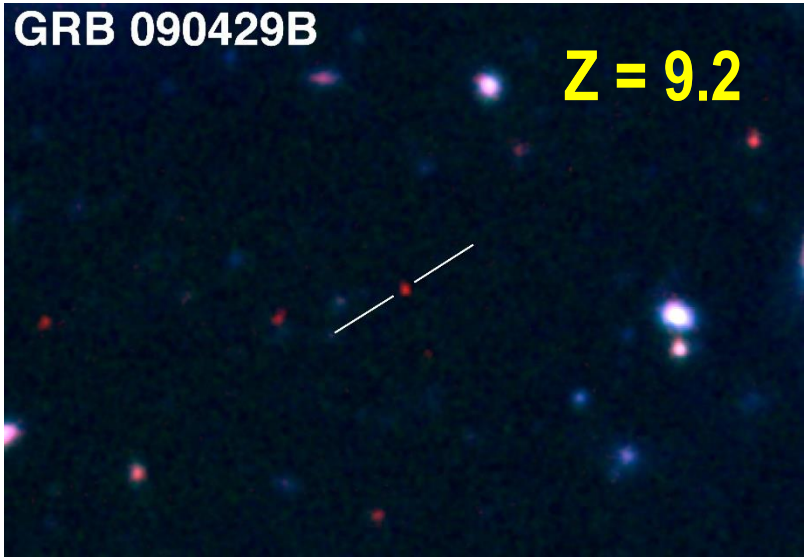
- **Long GRBs:** huge luminosities, mostly emitted in the X and gamma-rays
- **Redshift distribution** extending at least to z ~9-10
- **Association with exploding massive stars** in star forming regions of their host galaxies
- **Powerful tools for early Universe:** SFR evolution, physics of re-ionization, high-z low luminosity galaxies, pop III stars

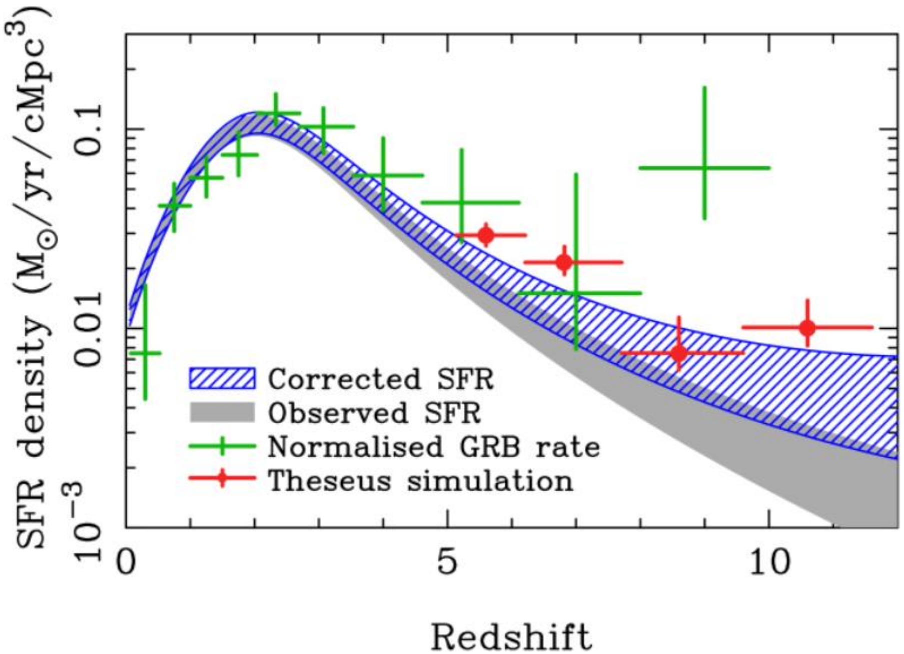


Shedding light on the early Universe with GRBs

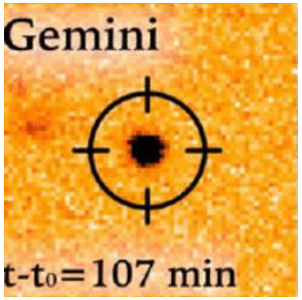
A statistical sample of high–z GRBs can provide fundamental information:

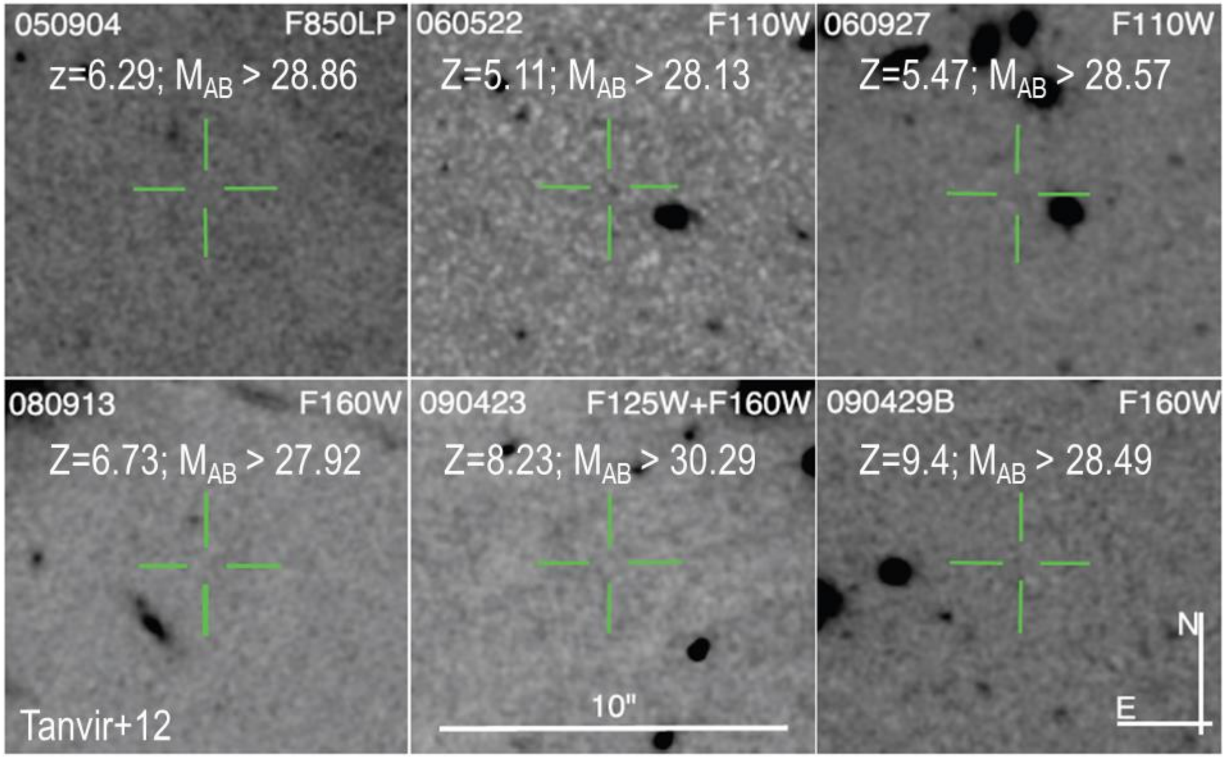
- measure independently the **cosmic star–formation rate**, even beyond the limits of current and future galaxy surveys
- directly (or indirectly) detect the **first population of stars (pop III)**





- **Detecting and studying primordial invisible galaxies**

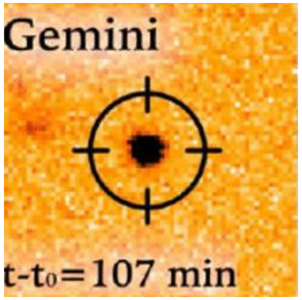


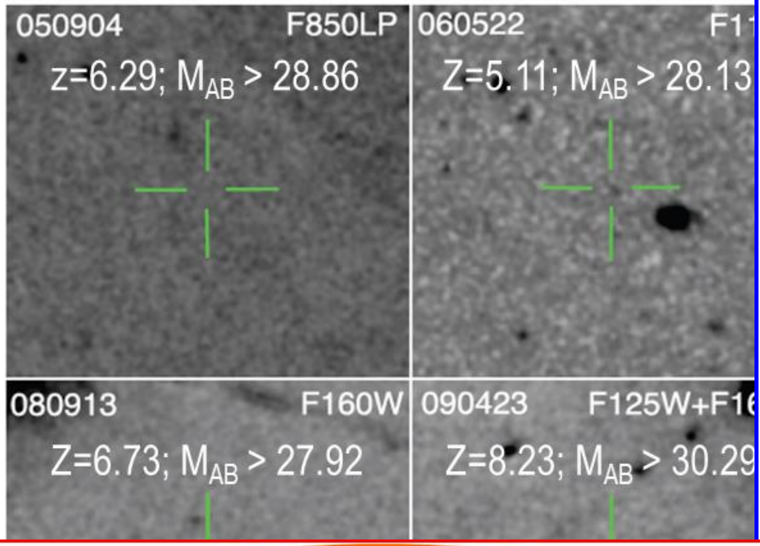


Robertson&Ellis12

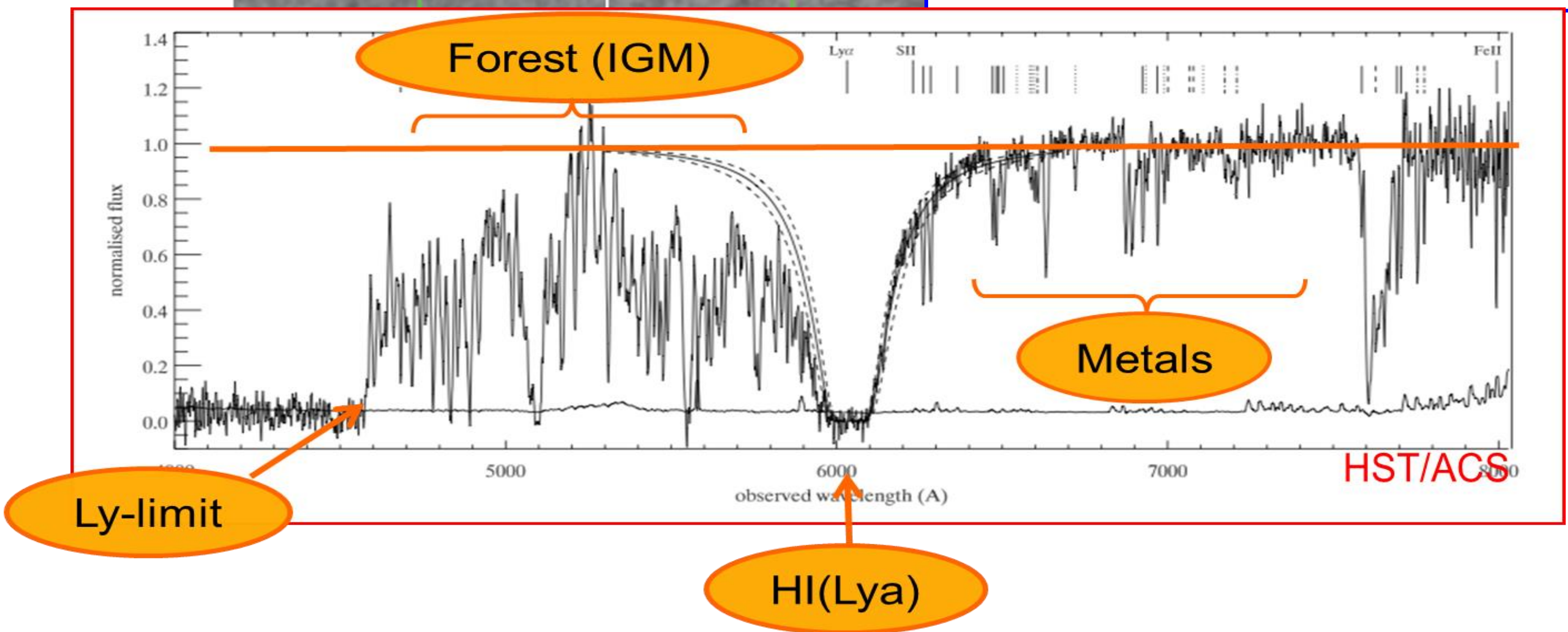
Even JWST and ELTs surveys will be not able to probe the faint end of the galaxy Luminosity Function at high redshifts (z>6-8)

• 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



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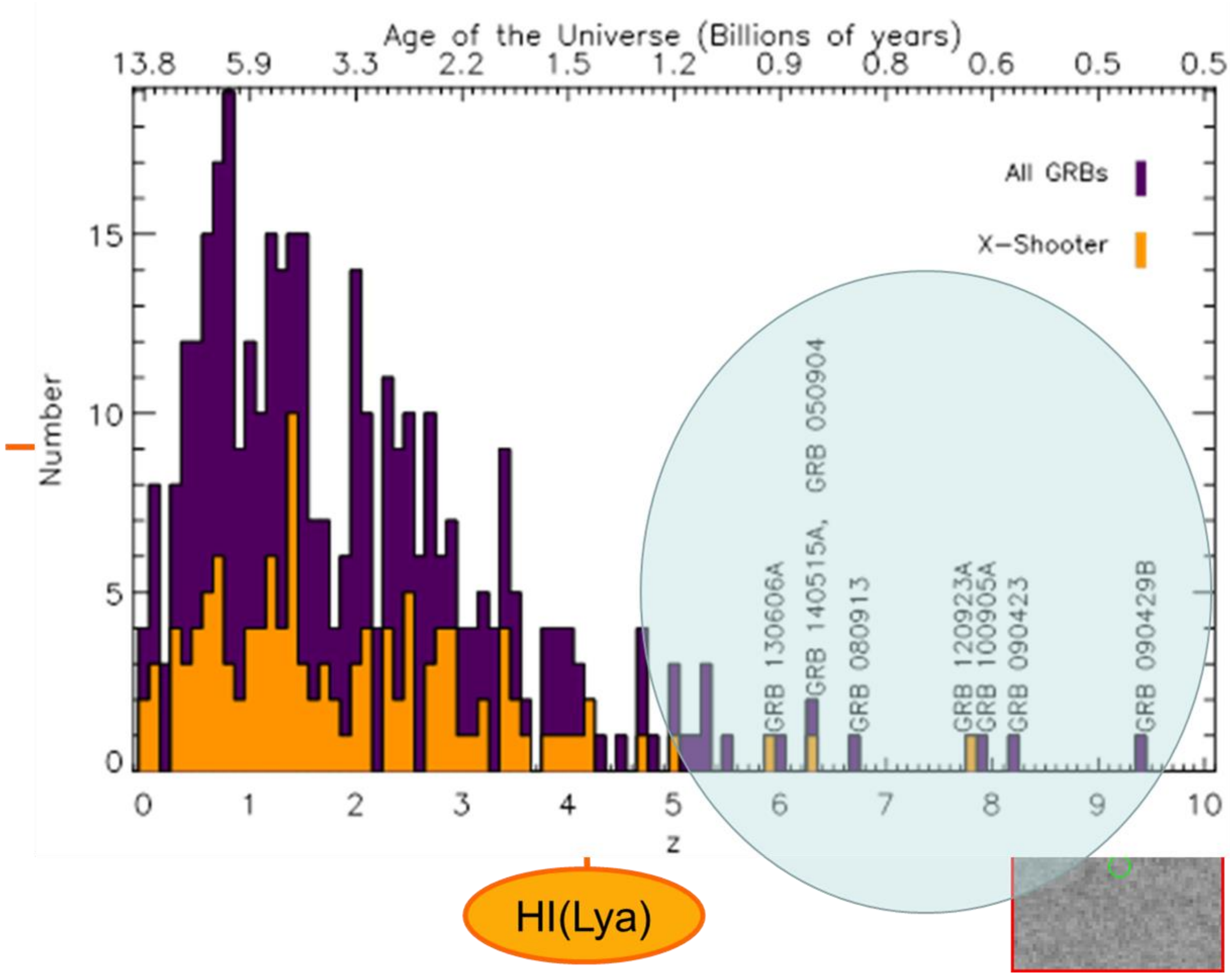
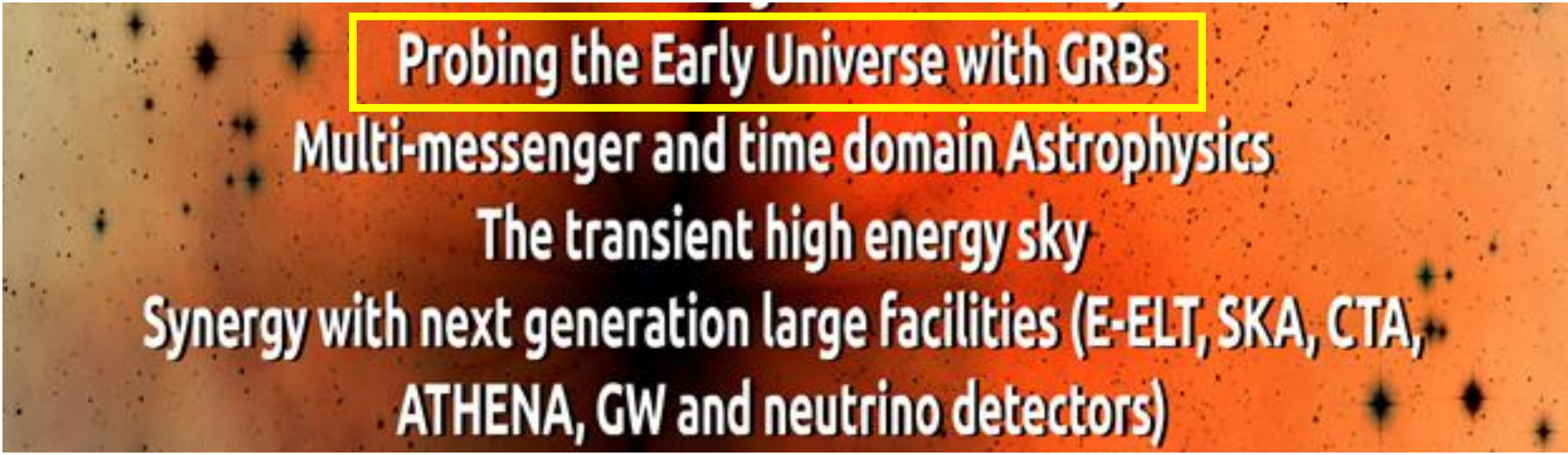


Future GRB missions (late'20s and '30s)



- **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**

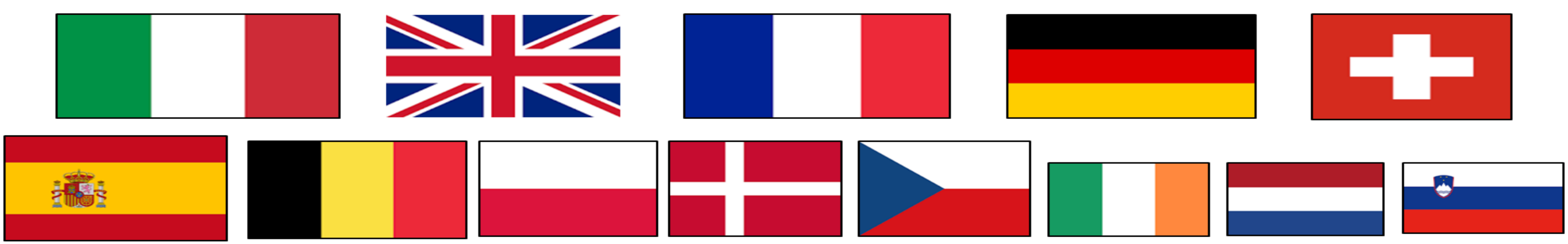
THESEUS

Transient High Energy Sky and Early Universe Surveyor

Lead Proposer (ESA/M5): Lorenzo Amati (INAF – OAS Bologna, Italy)

Coordinators (ESA/M5): Lorenzo Amati, Paul O'Brien (Univ. Leicester, UK), Diego Gotz (CEA-Paris, France), A. Santangelo (Univ. Tuebingen, D), E. Bozzo (Univ. Genève, CH)

Payload consortium: Italy, UK, France, Germany, Switzerland, Spain, Poland, Denmark, Belgium, Czech Republic, Slovenia, Ireland, NL, ESA

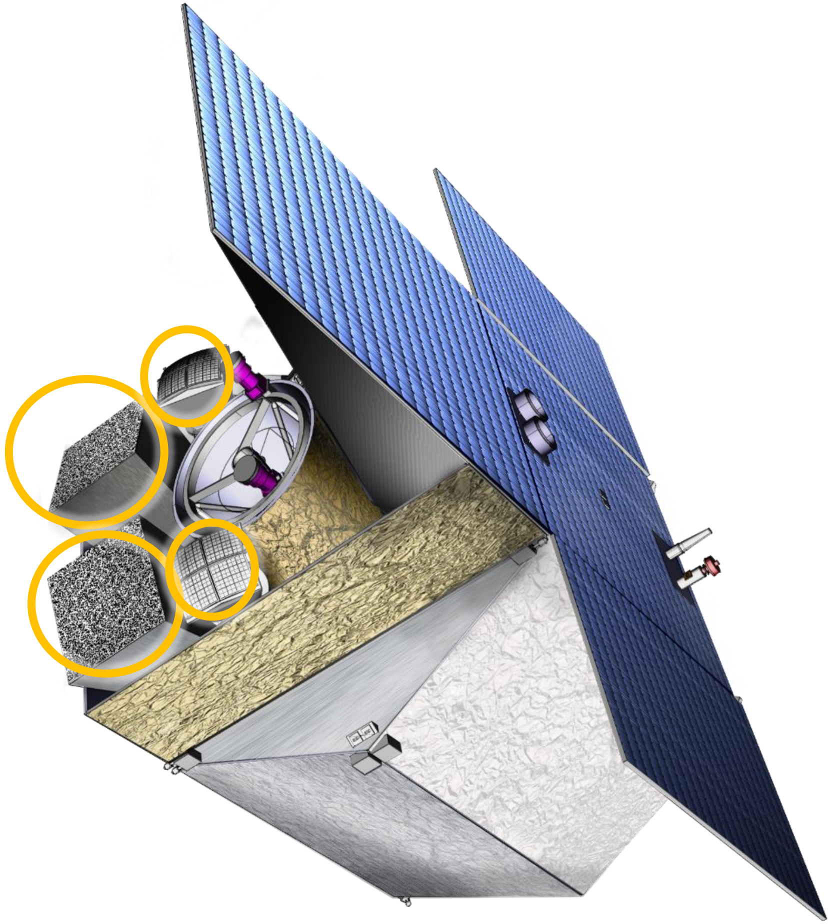


Future GRB missions: the case of THESEUS

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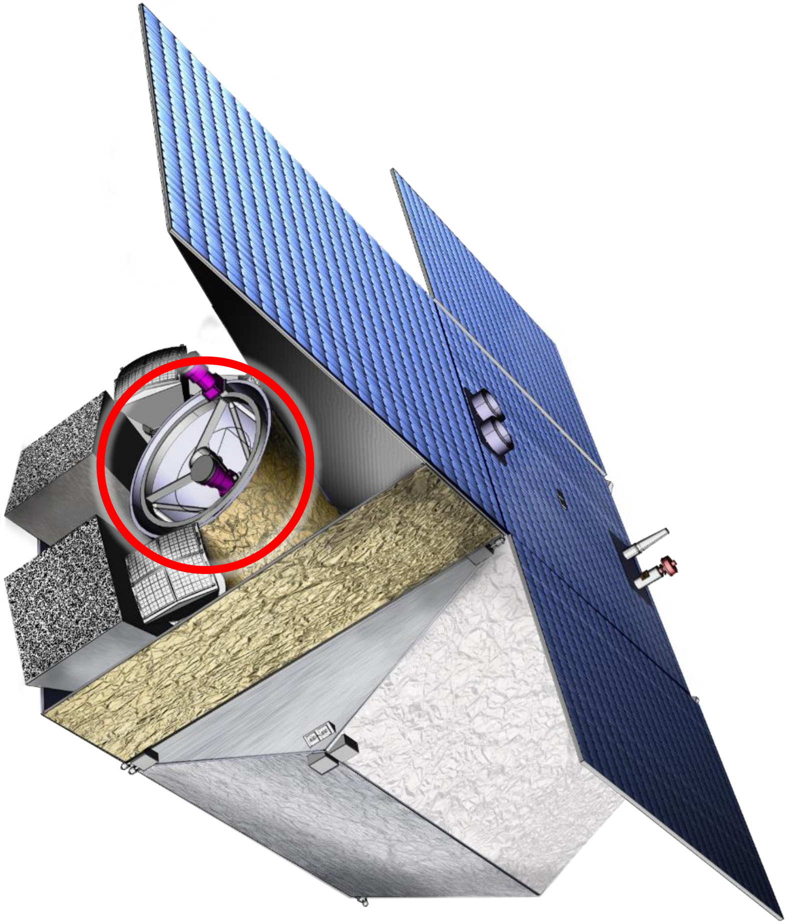
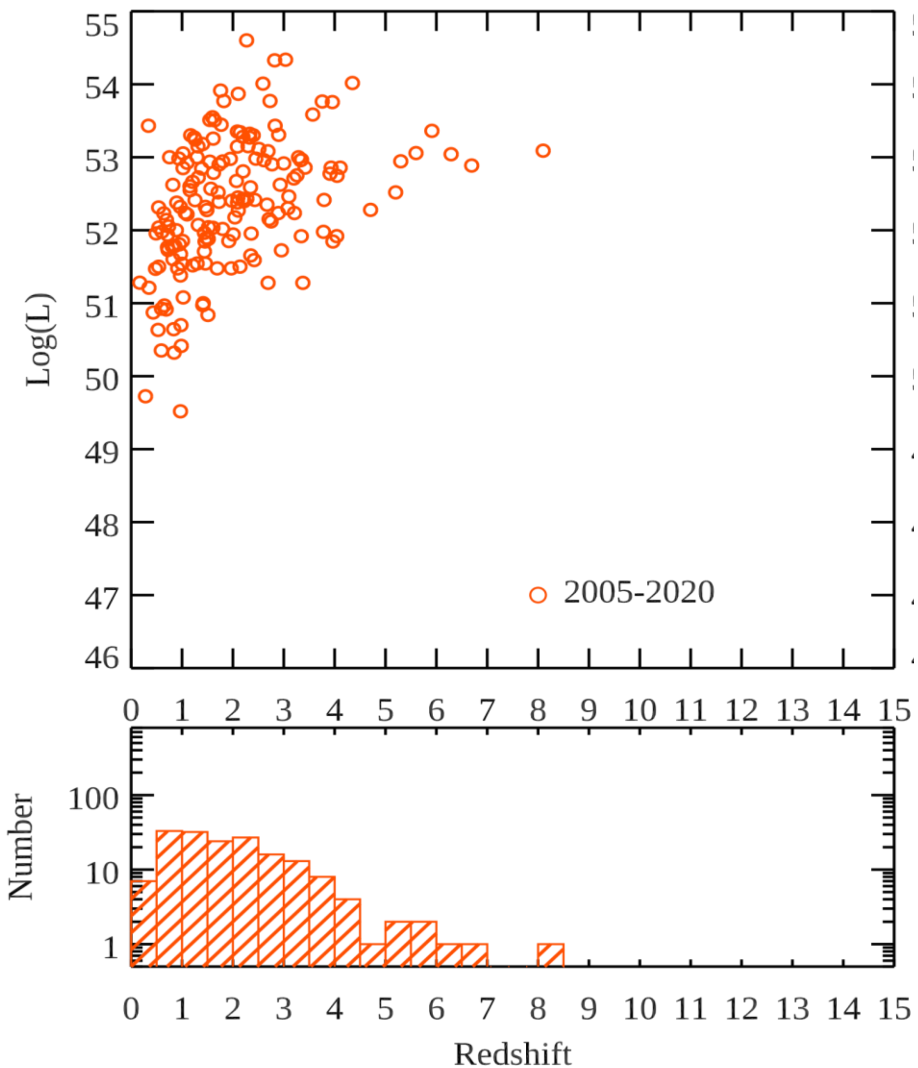
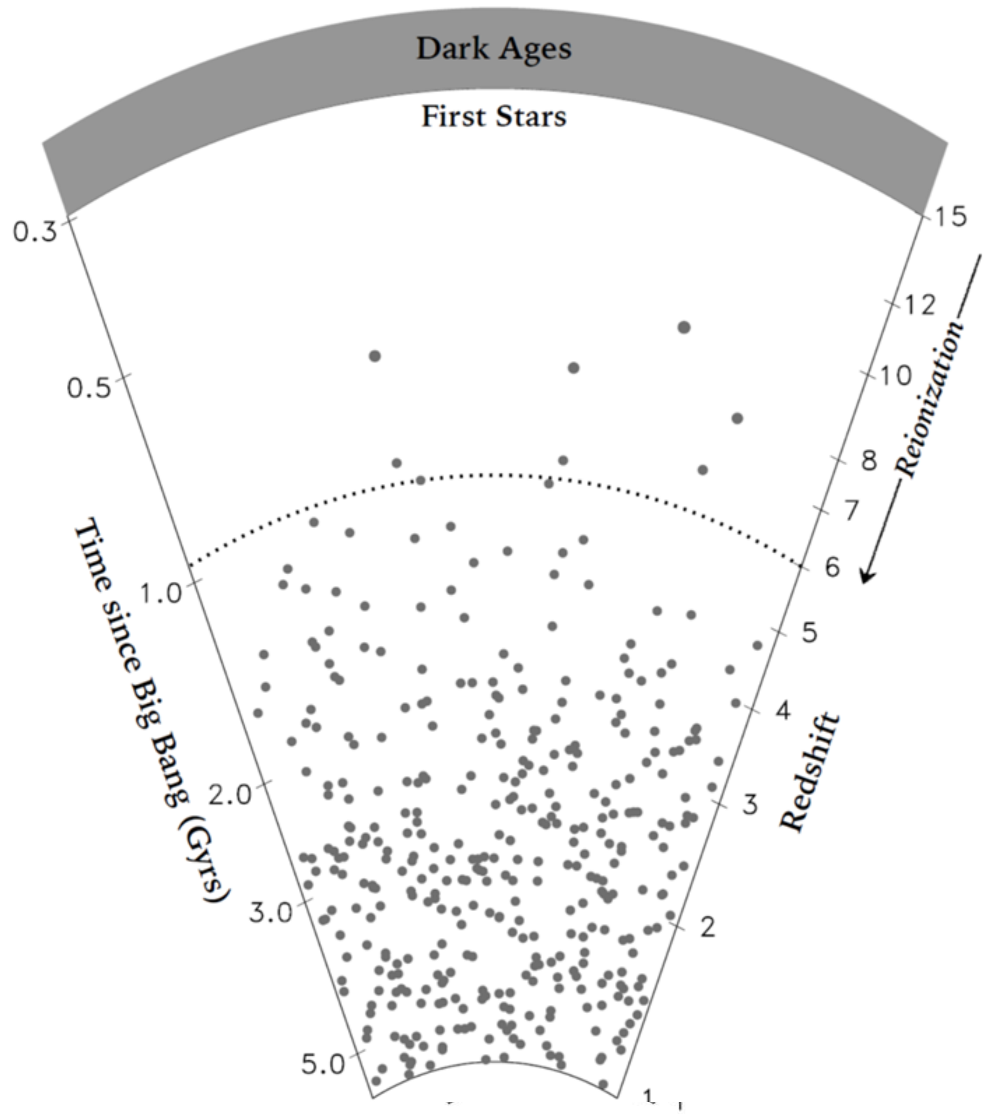
On-board **autonomous fast follow-up** in optical/NIR, arcsec location and **redshift measurement** of detected GRB/transients



Shedding light on the early Universe with GRBs





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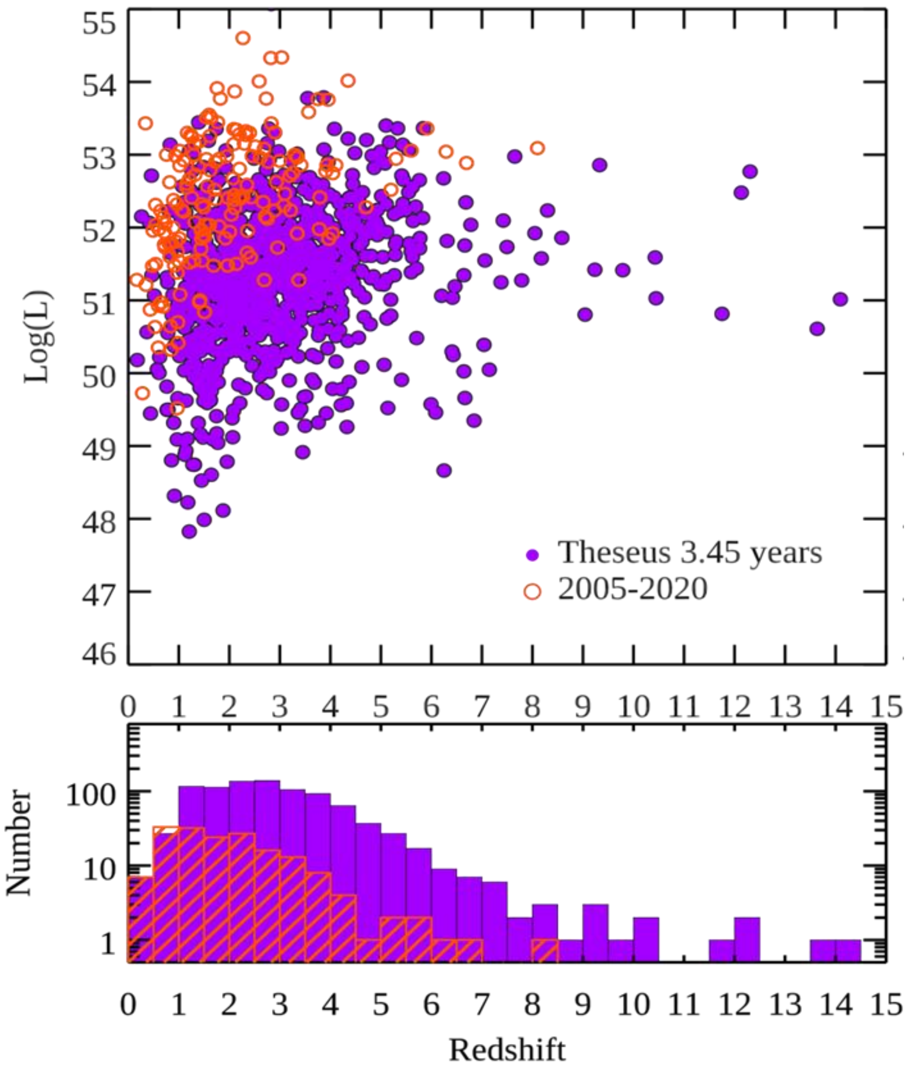
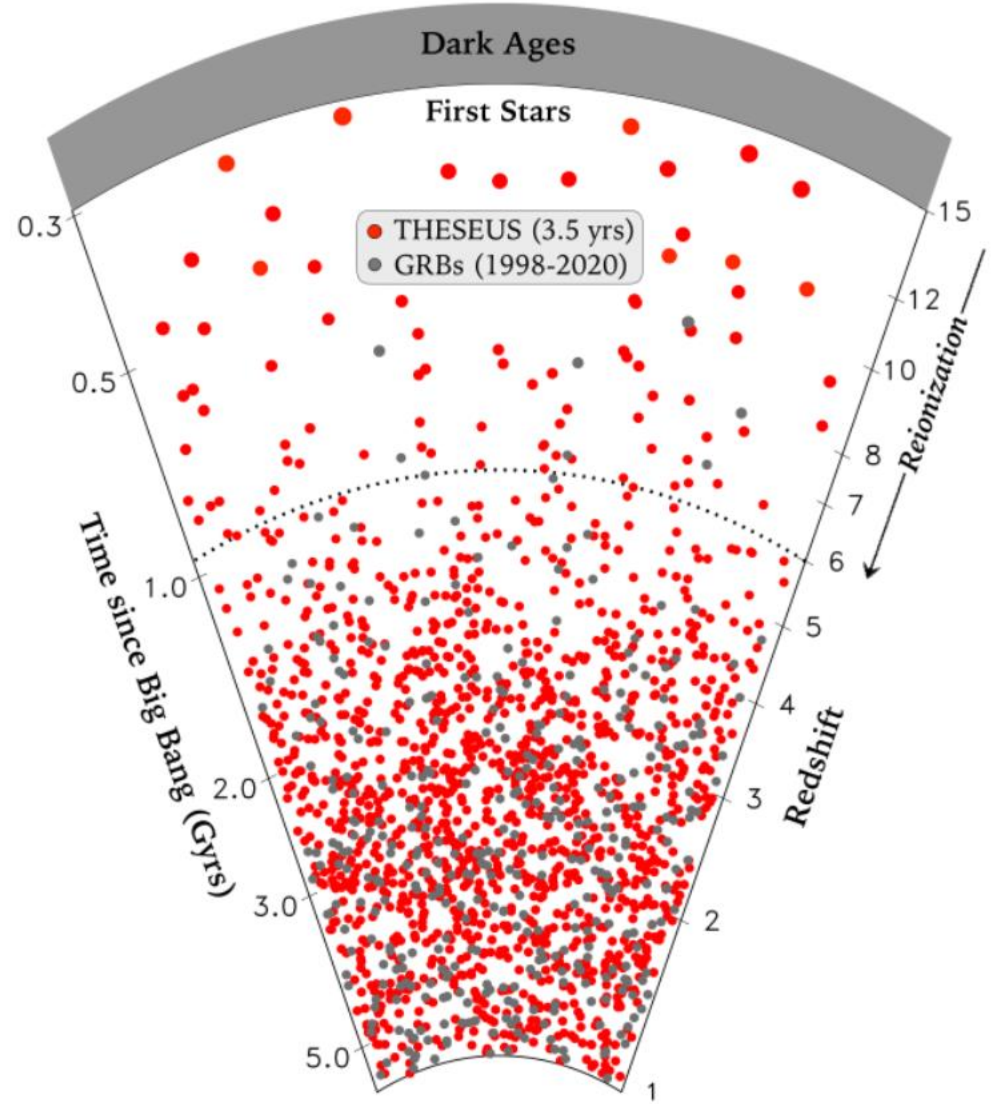
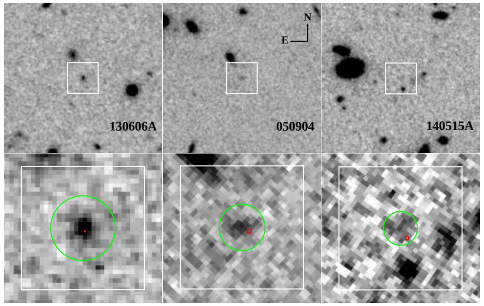
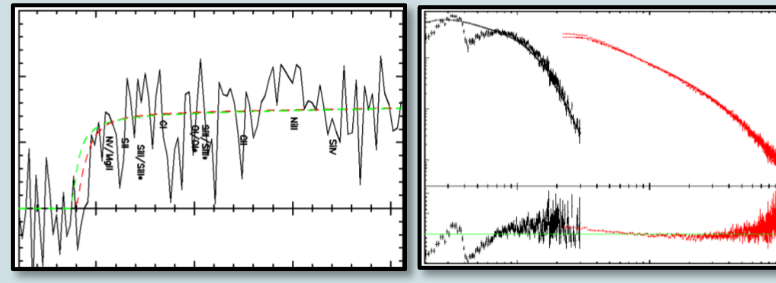


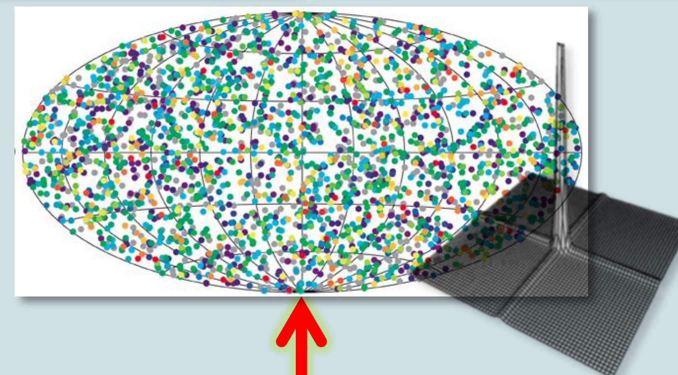


Star formation history, primordial galaxies

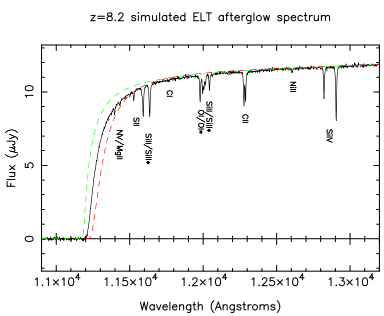


GRB accurate localization and NIR, X-ray, Gamma-ray characterization, redshift

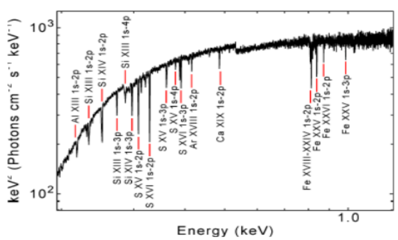




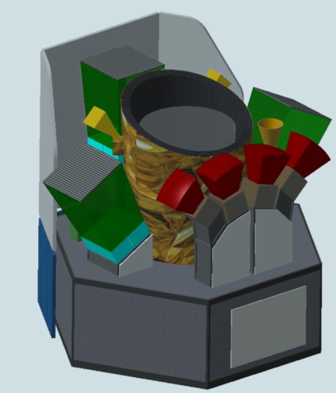
Neutral fraction of IGM, ionizing radiation escape fraction



Cosmic chemical evolution, Pop III

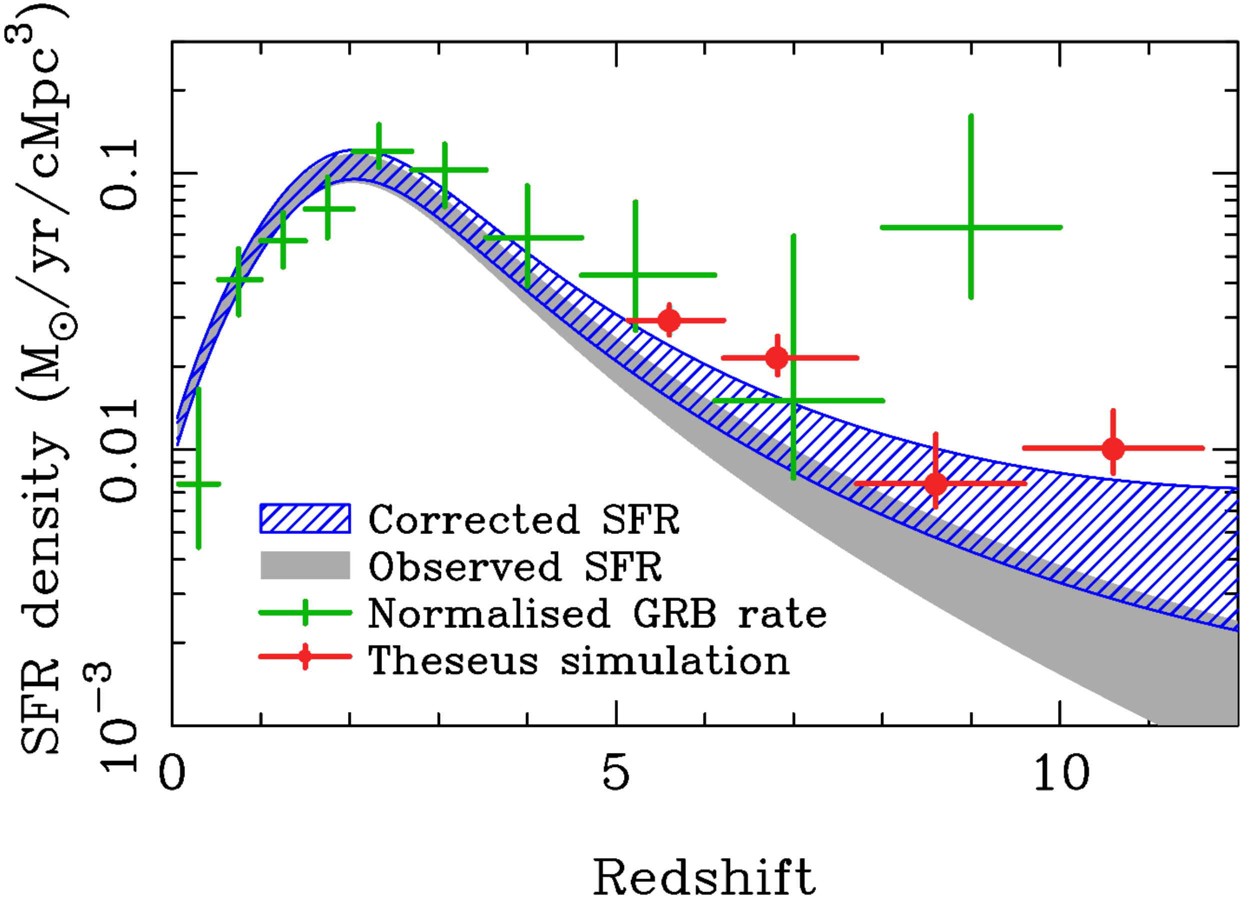


theseus
TRANSIENT HIGH ENERGY SKY AND EARLY UNIVERSE SURVEYOR



THESEUS SYNERGIES

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

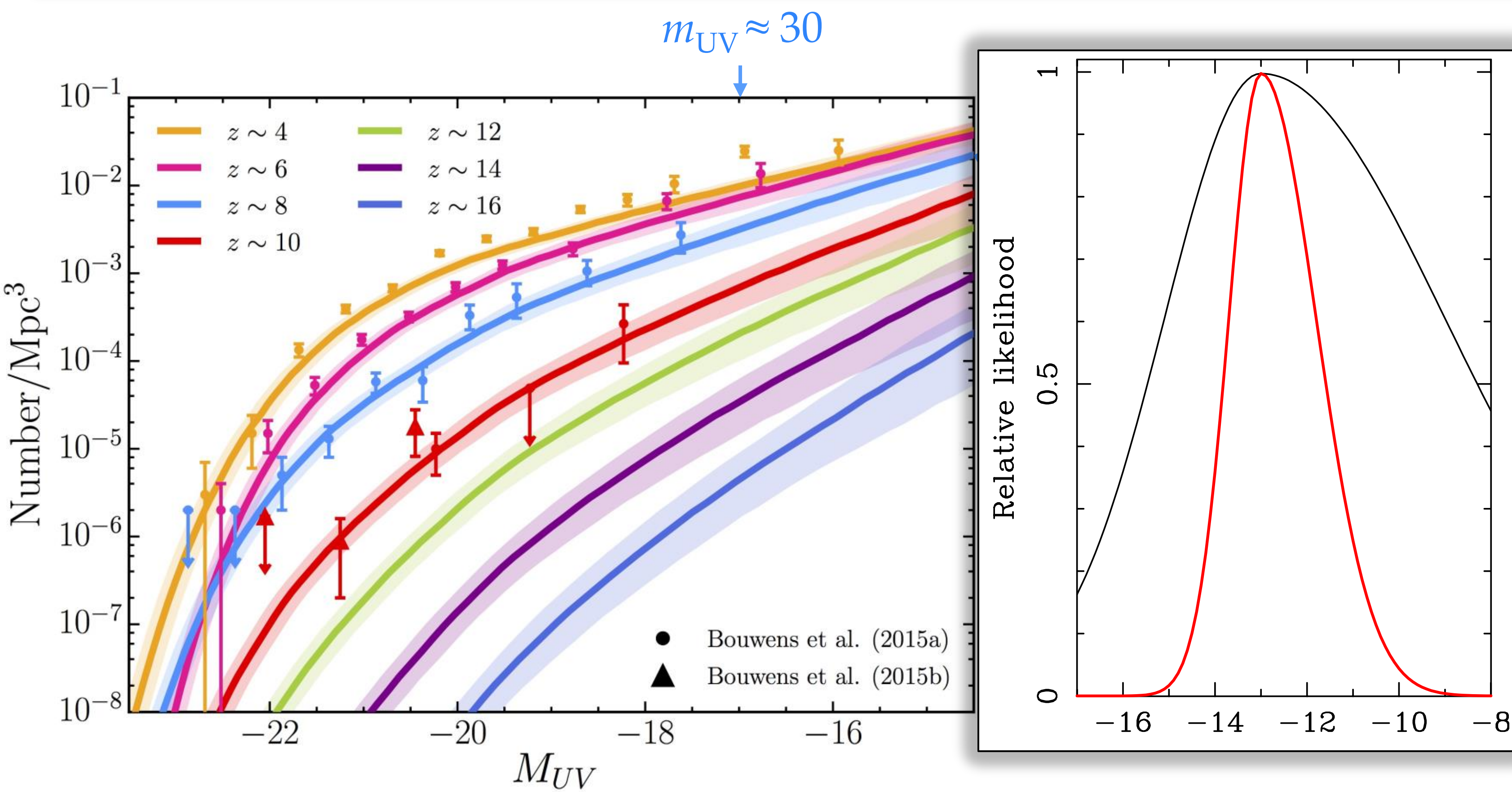


A statistical sample of high–z GRBs will give access to star formation in the faintest galaxies, overcoming limits of current and future galaxy surveys

THESEUS Consortium 2021

- **Detecting and studying primordial invisible galaxies**

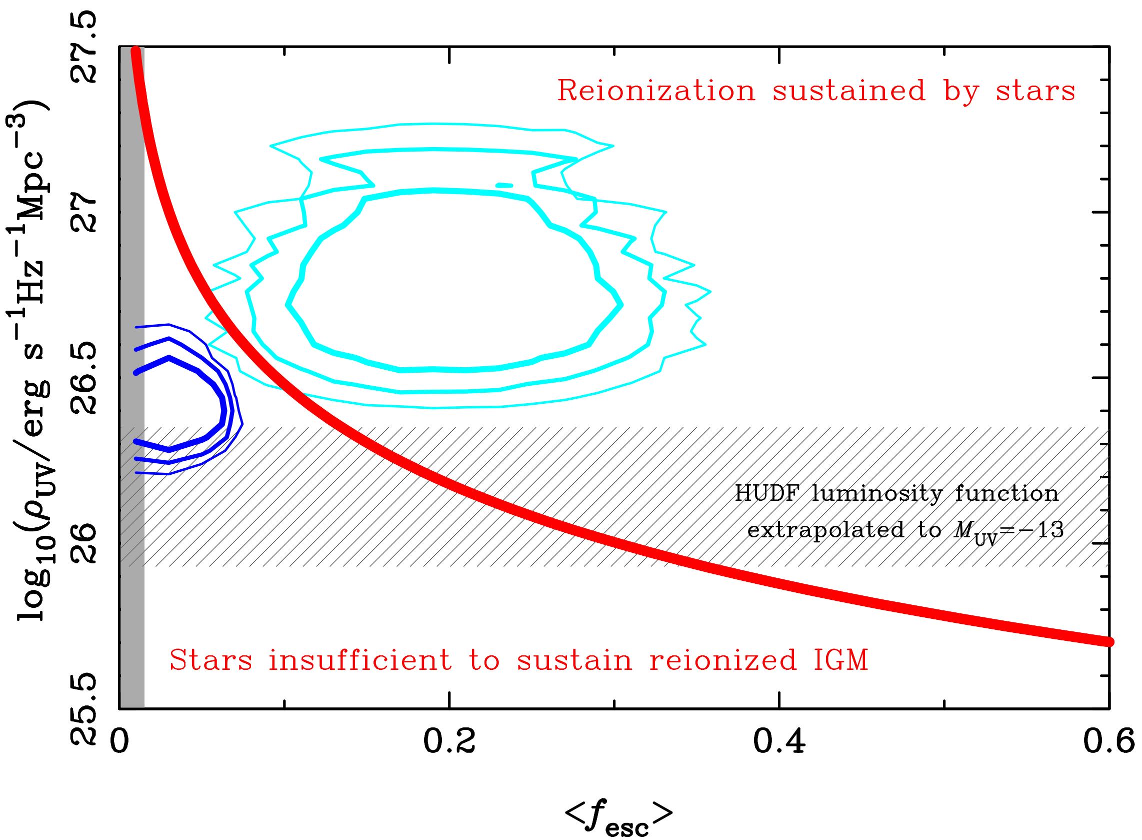
The proportion of GRB hosts below a given detection limit provides an estimate of the fraction of star formation "hidden" in such faint galaxies



Bright ⟷ Faint

THESEUS Consortium 2021

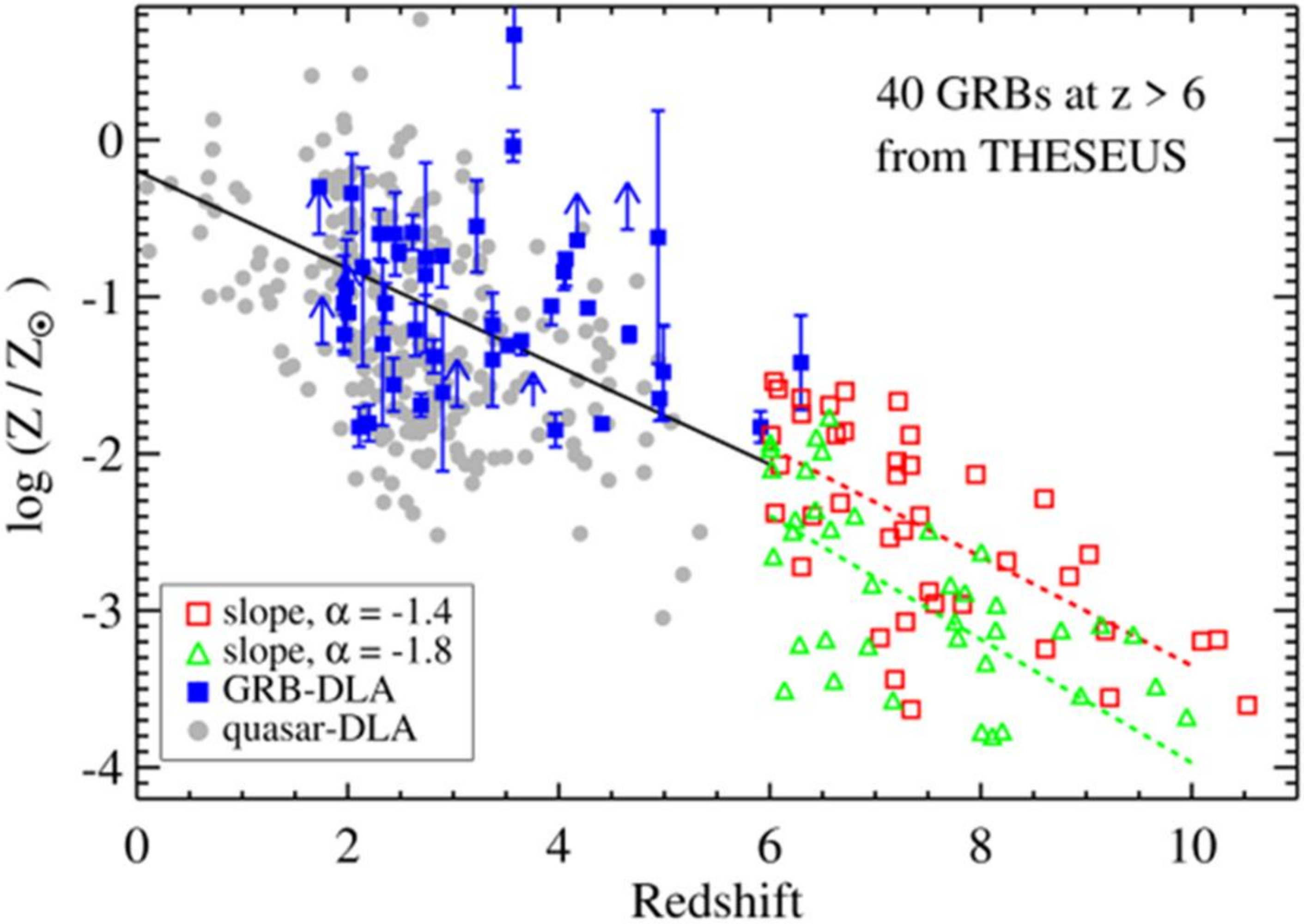
• Shedding light on cosmic reionization



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

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Why looking for more cosmological probes ?

- different distribution in redshift and methods-> different sensitivity to different cosmological parameters

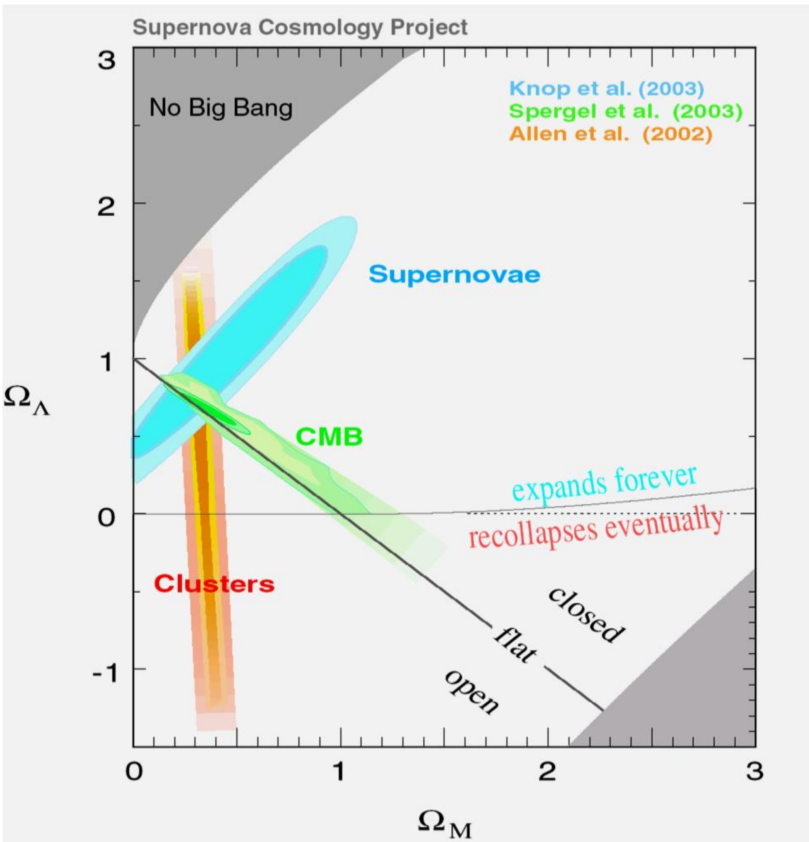
$$\Omega = \Omega_m + \Omega_{rel} + \Omega_\Lambda$$

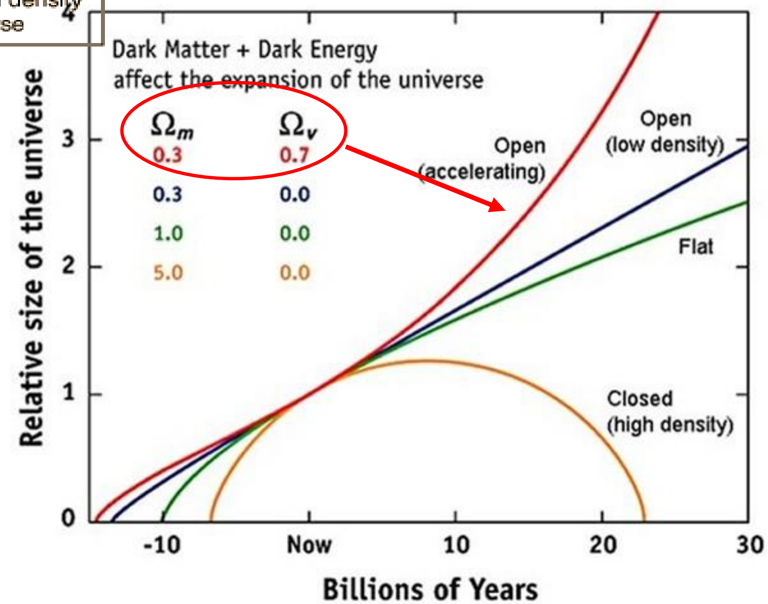
Total density parameter $\Omega = \frac{\rho}{\rho_c}$ $\Omega = 1$ for critical density universe

Mass density including ordinary mass (baryonic mass) plus dark matter.

Effective mass density of relativistic particles (light plus neutrinos).

Effective mass density of the dark energy, taking the role described as the cosmological constant.





$$D_L = (1+z)c \div H_o \,|k|^{0.5} \times S\left\{ |k|^{0.5} \int_0^z \left[k(1+z)^2 + \Omega_M (1+z')^3 + \Omega_\Lambda \right]^{-0.5} dz' \right\}$$

❑ **Each cosmological probe is characterized by possible systematics**

❑ **e.g SN Ia:**

➢ different explosion mechanism and progenitor systems ? May depend on z ?

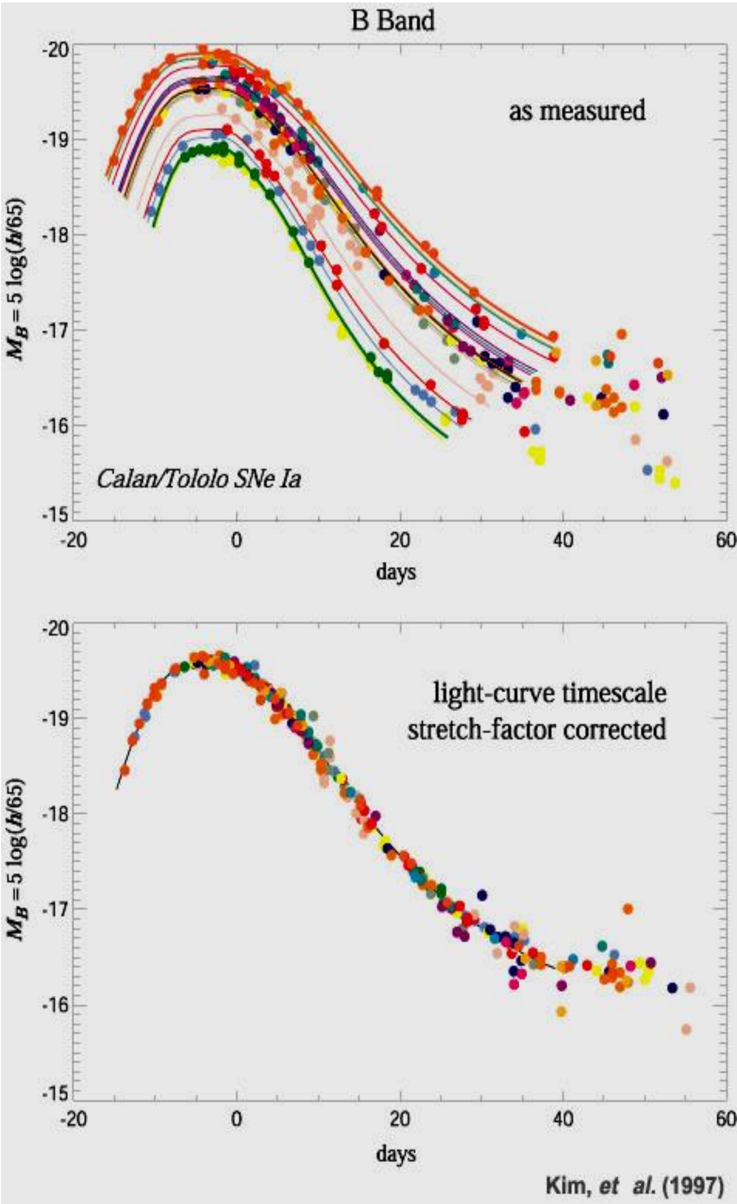
➢ light curve shape correction for the luminosity normalisation may depend on z

➢ signatures of evolution in the colours

➢ correction for dust extinction

➢ anomalous luminosity-color relation

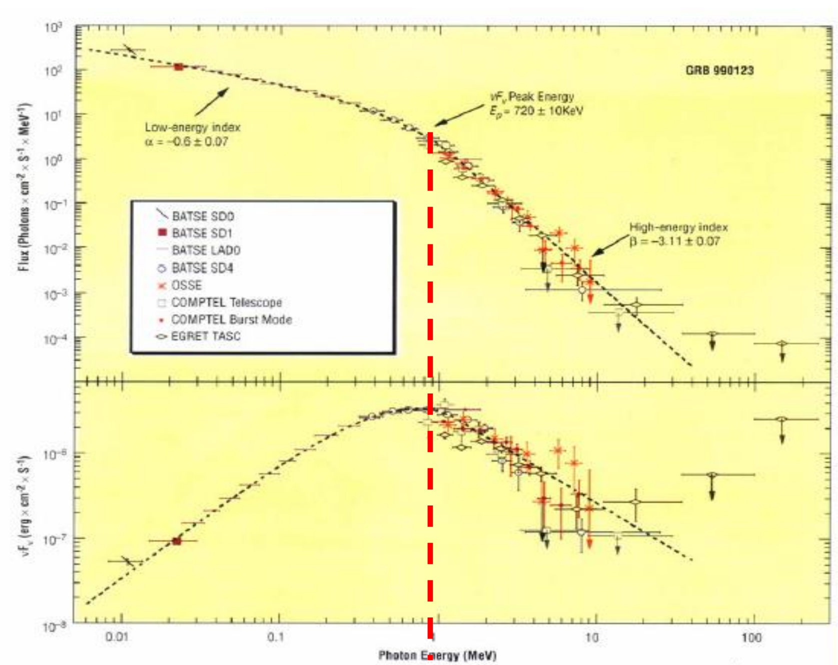
➢ contaminations of the Hubble Diagram by no-standard SNe-Ia and/or bright SNe-Ibc (e.g. HNe)



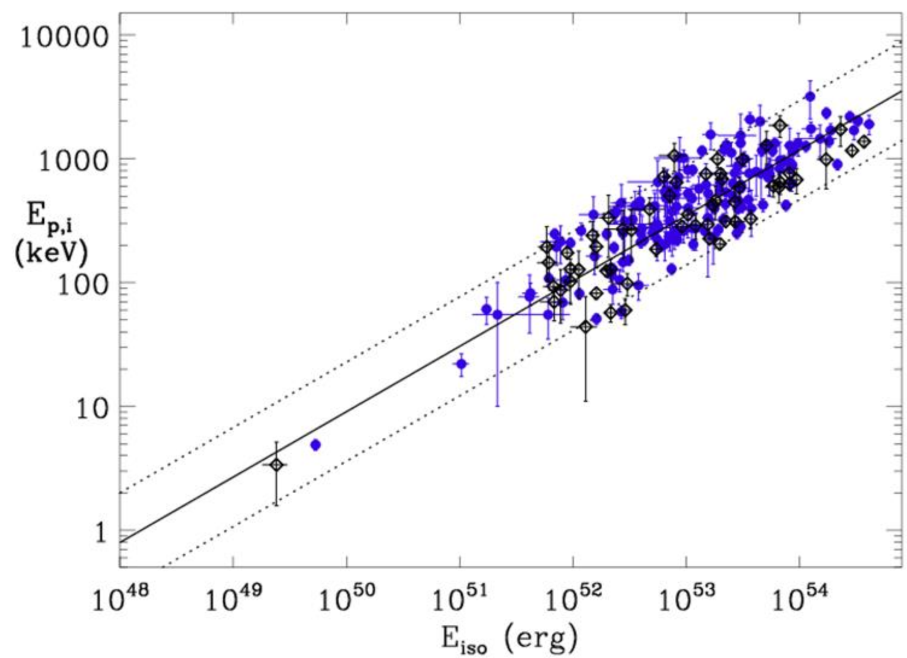
Measuring cosmological parameters with GRBs

- GRB νFν spectra typically show a peak at a characteristic photon energy E_p
- **measured spectrum + measured redshift -> intrinsic peak enery and radiated energy**

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



Ep



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

“Standardizing” GRBs through the Ep-Eiso correlation

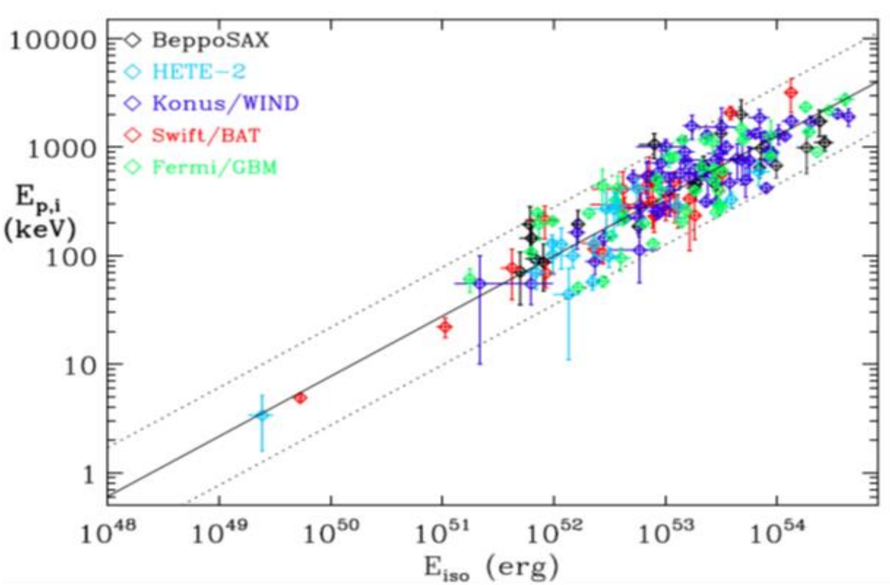
$$E_{p,i} = E_{p,obs} \times (1 + z)$$

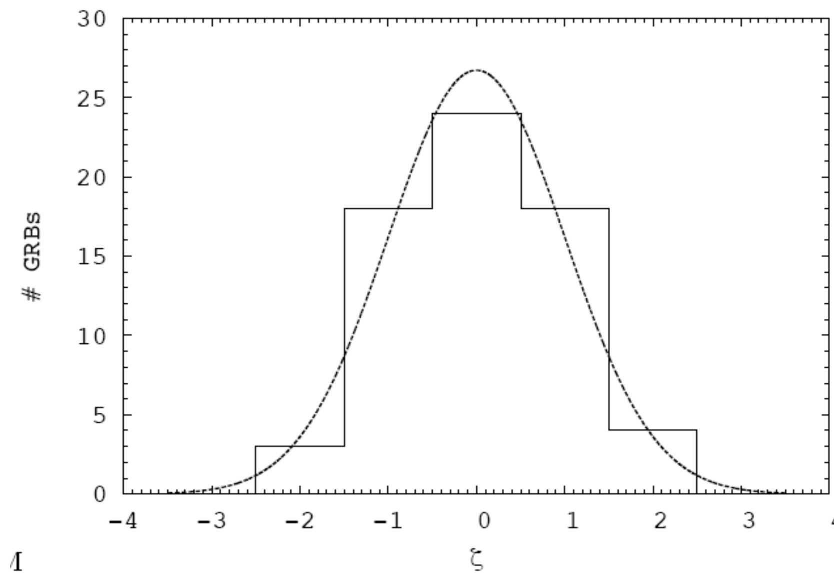
$$E_{\gamma,iso} = \frac{4\pi D_l^2}{(1+z)} \int_{1/1+z}^{10^4/1+z} E\,N(E)\,dE \quad \text{erg}$$

$$D_l = D_l(z, H_0, \Omega_M, \Omega_\Lambda, \ldots)$$

- not enough low-z GRBs for cosmology-independent calibration -> **circularity is avoided** by fitting simultaneously the parameters of the correlation and cosmological parameters

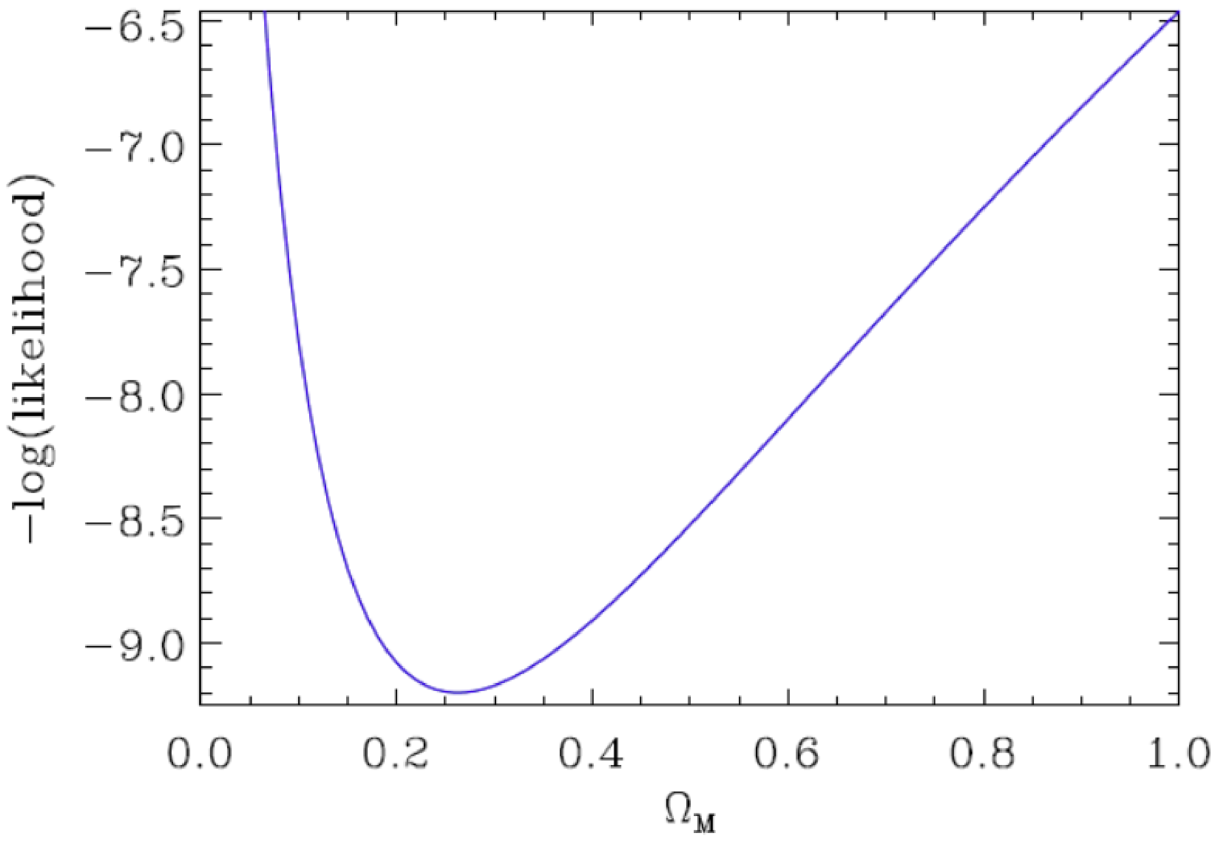
- does the extrinsic scatter and goodness of fit of the Ep,i-Eiso correlation vary with the cosmological parameters used to compute Eiso ?





- 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 Universe , Ω_M is lower than 1 and around 0.3**



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

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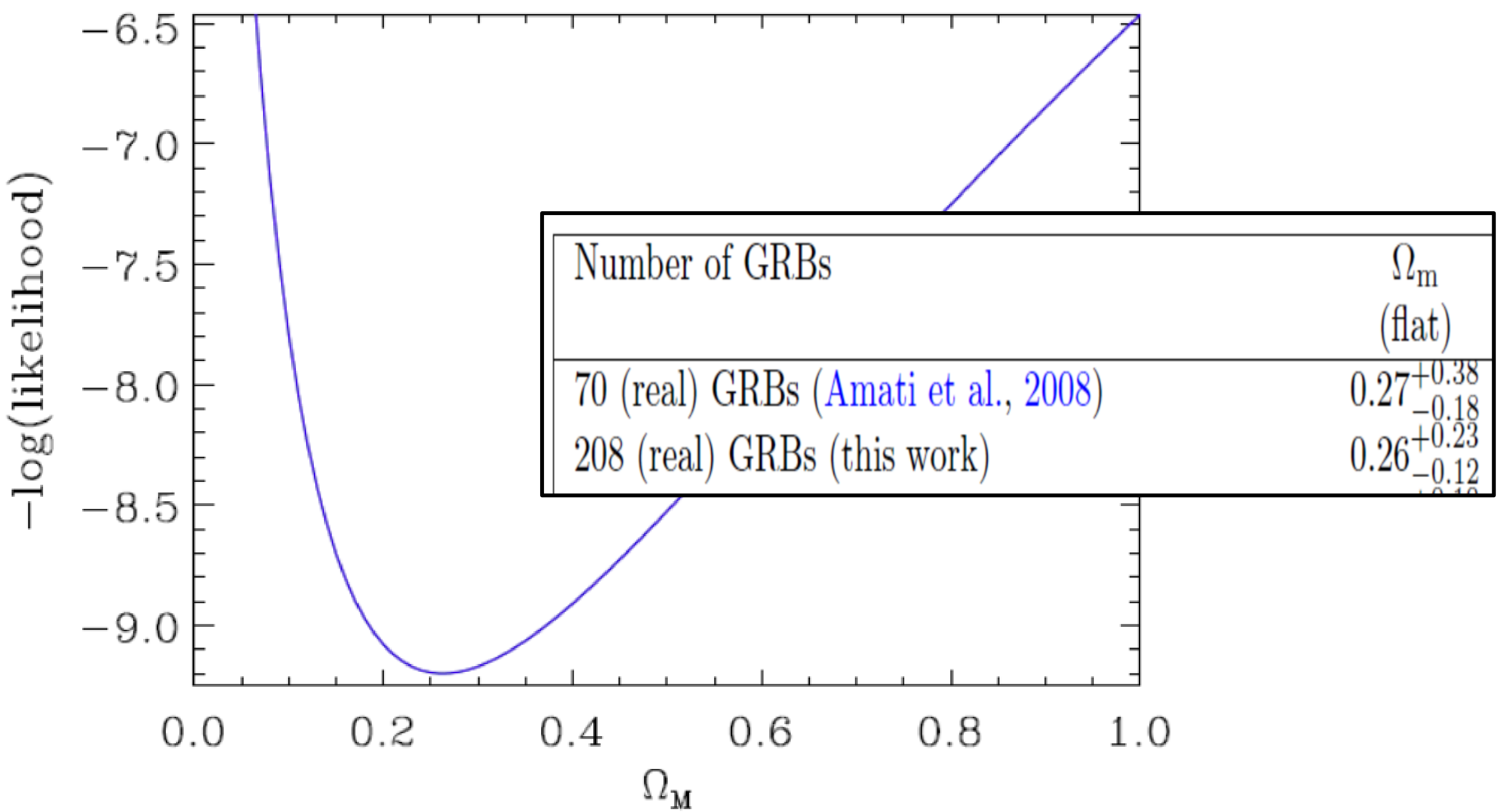
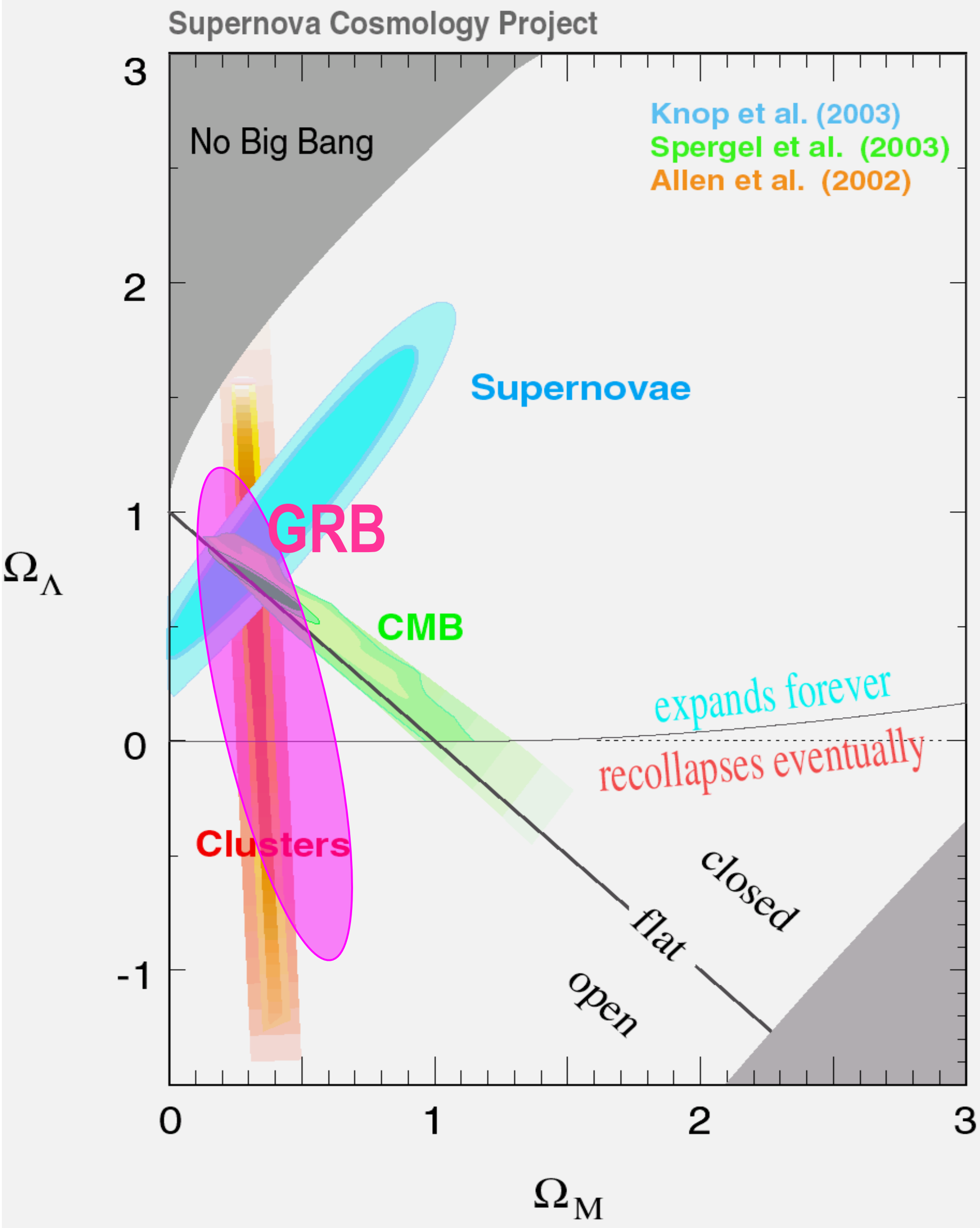


Number of GRBs	Ω_m (flat)
70 (real) GRBs (Amati et al., 2008)	$0.27^{+0.38}_{-0.18}$
208 (real) GRBs (this work)	$0.26^{+0.23}_{-0.12}$

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



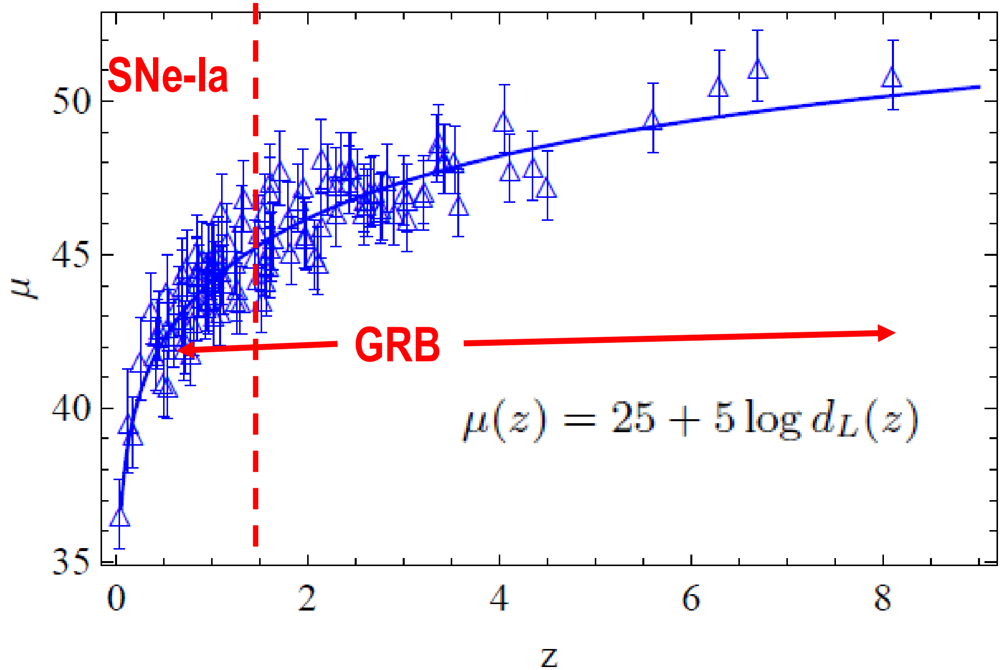
Supernova Cosmology Project
No Big Bang
Knop et al. (2003)
Spergel et al. (2003)
Allen et al. (2002)
Supernovae
GRB
CMB
Clusters
expands forever
recollapses eventually
closed
flat
open
Ω_Λ
Ω_M

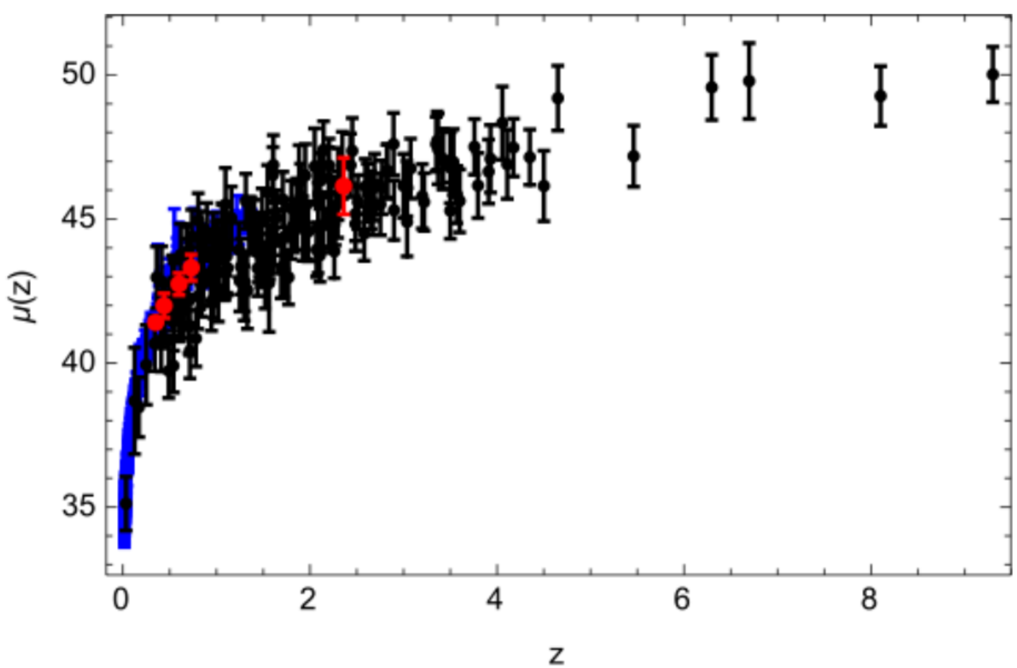
❑ Calibration with SNe-Ia

- ➢ The GRB Hubble diagram extends to much higher z w/r to SNe Ia

- ➢ **The GRB Hubble diagram is consistent with SNe Ia Hubble diagram and BAO points at low redshifts: reliability**

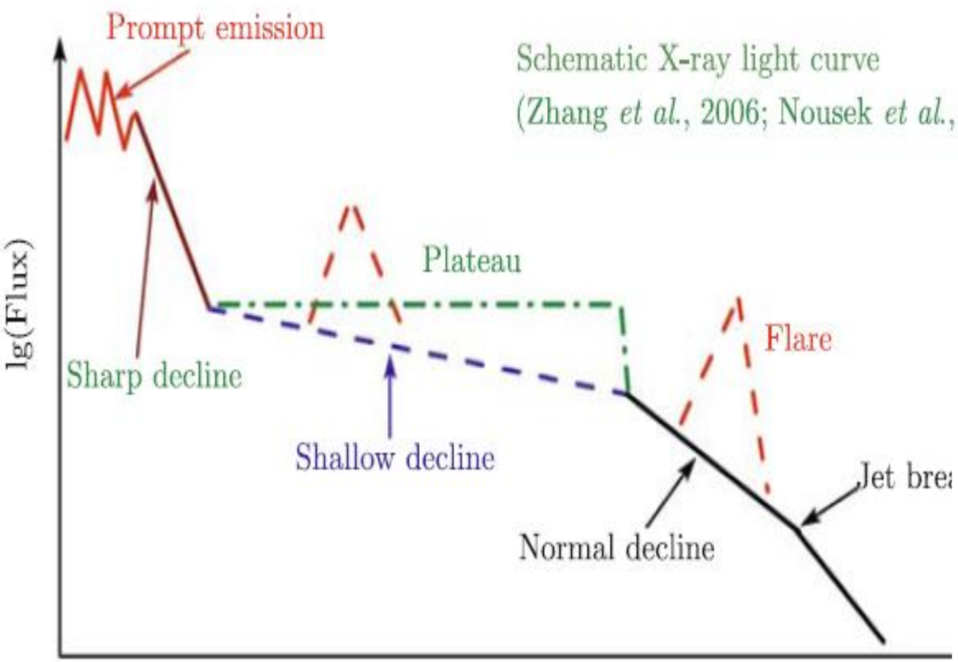
- ➢ e.g., Capozziello et al., Kodama et al., Tsutsui et al., Demianski et al.):





❑ Involving other GRB observables

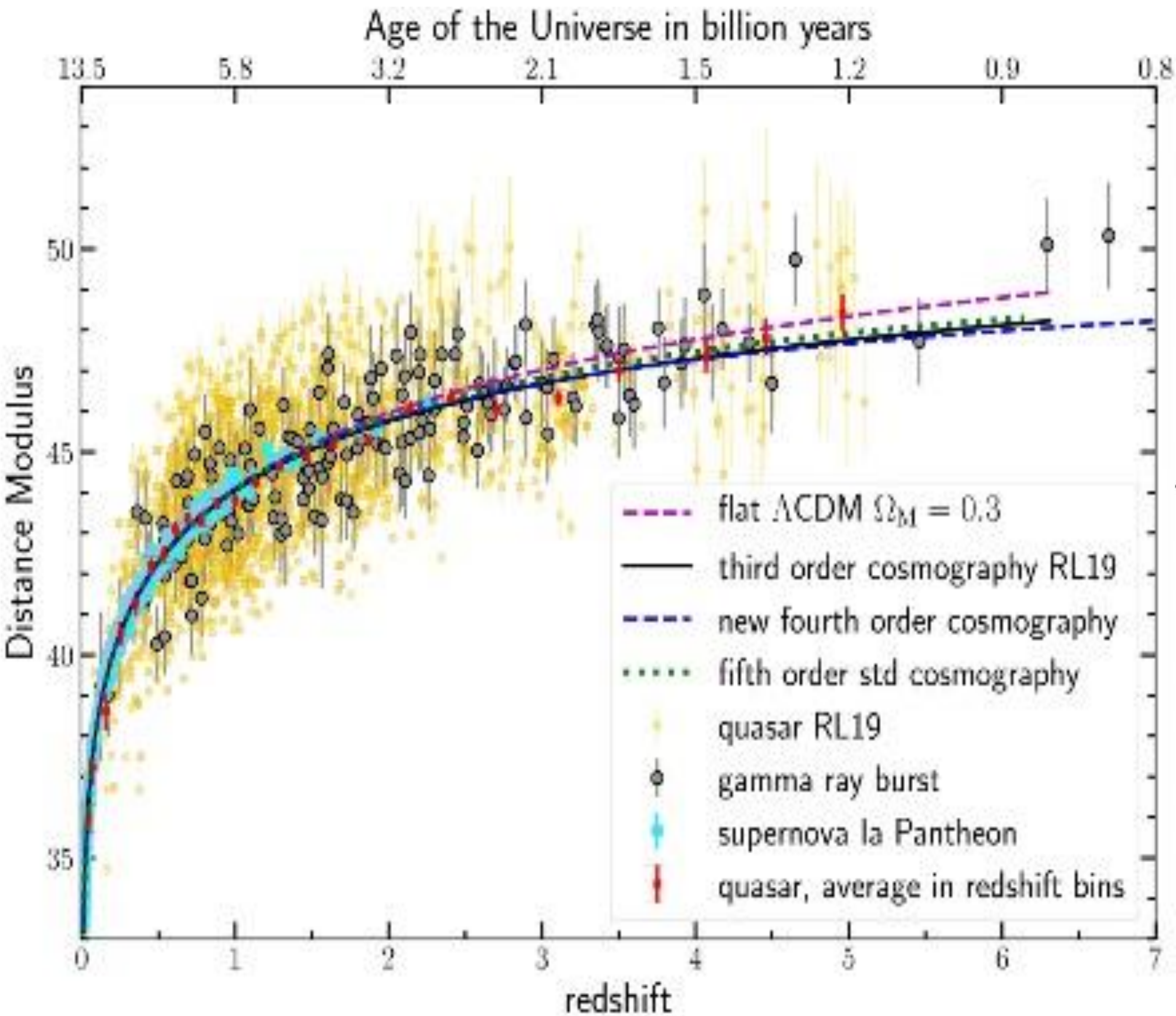
➢ Extending or replacing the Ep-Intensity correlation by involving other prompt or afterglow properties: e.g., “Combo relation” (Izzo et al., Muccino et al.) , Lx-Ta and Lx-Ta-Lp relations (Dainotti et al.)

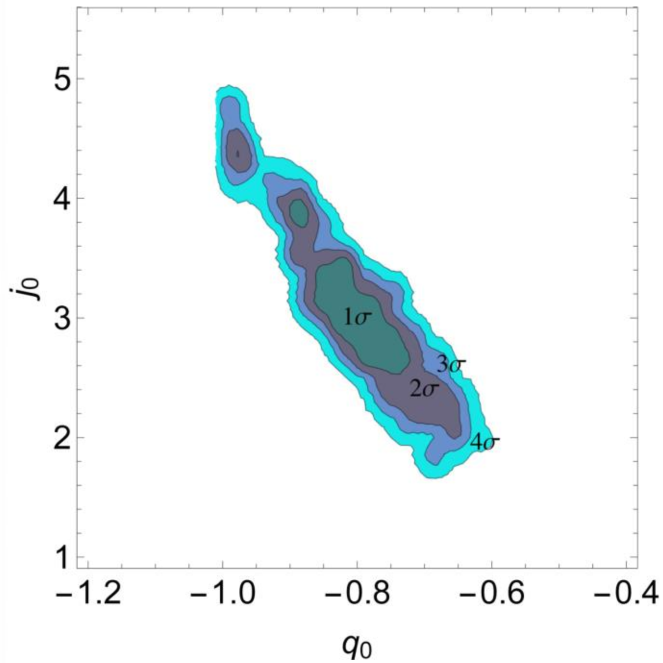


Correlation	Reference
$E_{\rm p,i}$–$E_{\rm iso}$	Amati et al. (2002)
$E_{\rm p,i}$– E_γ	Ghirlanda et al. (2004)
$E_{\rm p,i}$–$L_{\rm iso}$	Yonetoku et al. (2004)
$L_{\rm peak} - \tau_{\rm lag}$	Azzam (2012)
$L_{\rm iso} - V$	Fenimore and Ramirez-Ruiz (2000)
$L_{\rm iso} - E_{\rm p,i} - T_{0.45}$	Firmani et al. (2006)
$L_{\rm iso} - E_{\rm p,i} - t_{\rm break}$	Liang and Zhang (2005)
$L_X - T_a$	Dainotti et al. (2008)
$E_{X,iso} - E_{\gamma,iso} - E_{pk}$	Bernardini et al. (2012)
$E_{\gamma,iso} - E_{X,iso} - E_{pk}$	Izzo et al. (2015)

Moresco et al. 2022

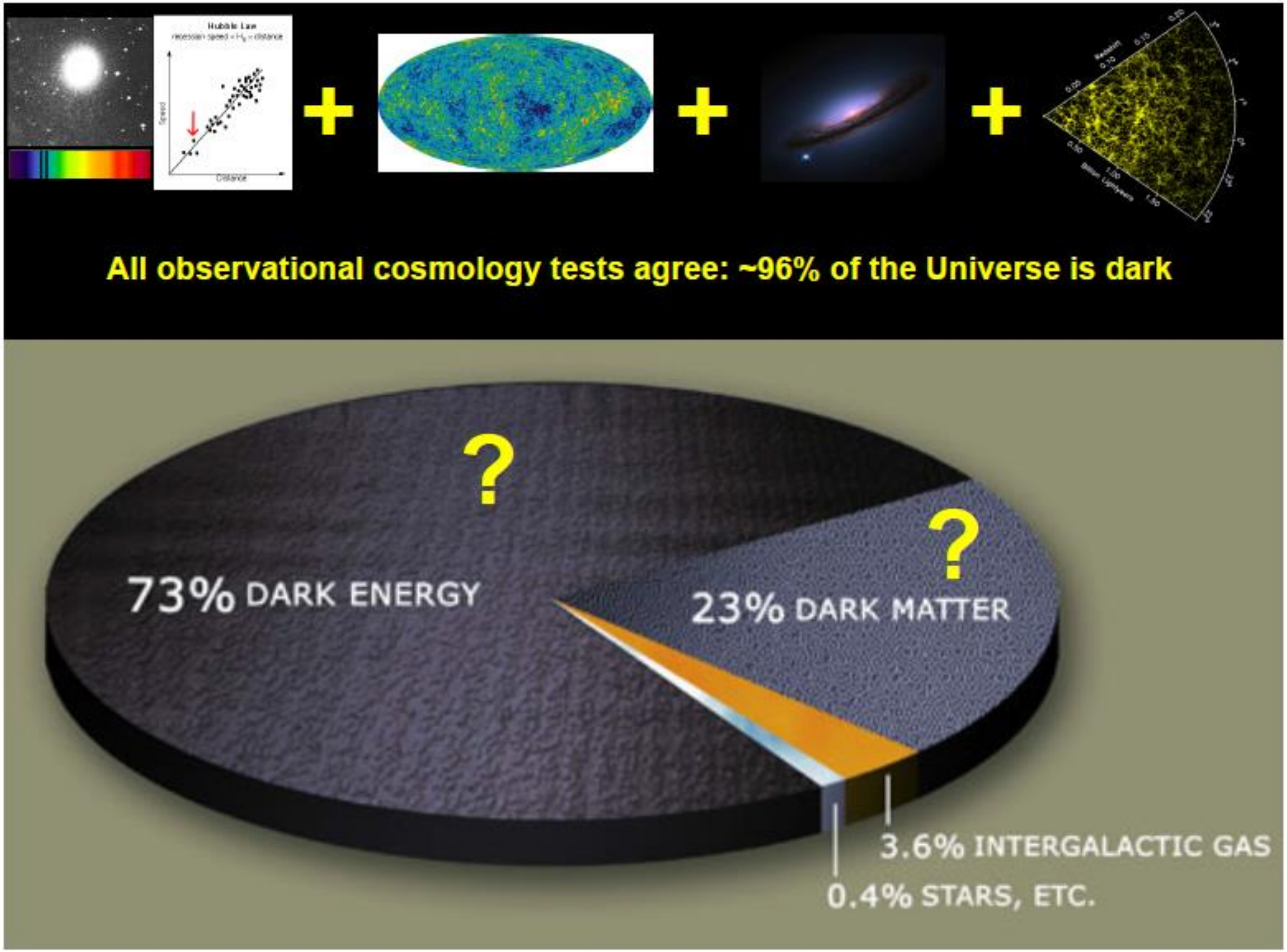
❑ Joining GRBs with other probes: e.g., high-z GNs





Lusso et al. 2019

What we are aiming at ?



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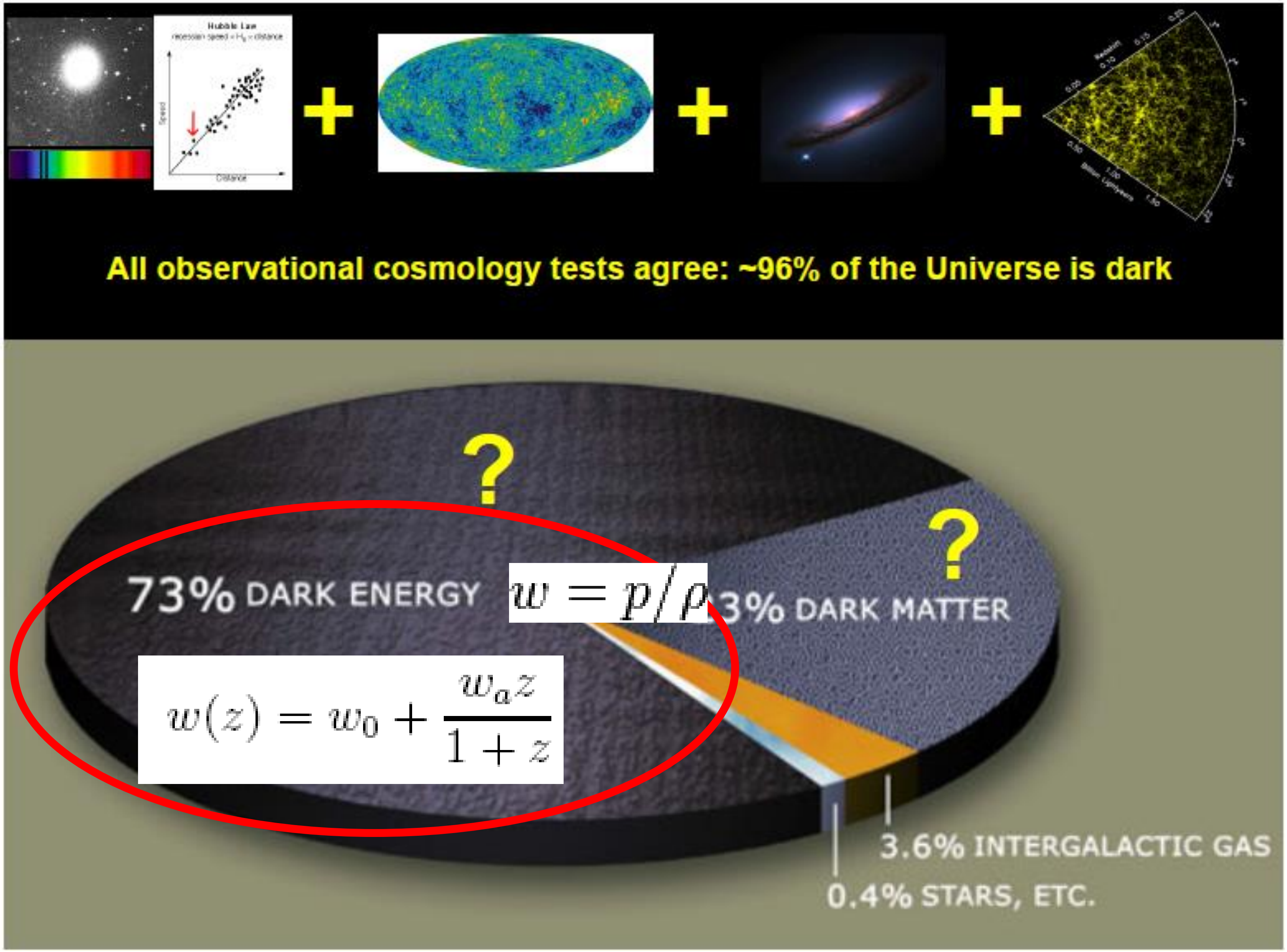

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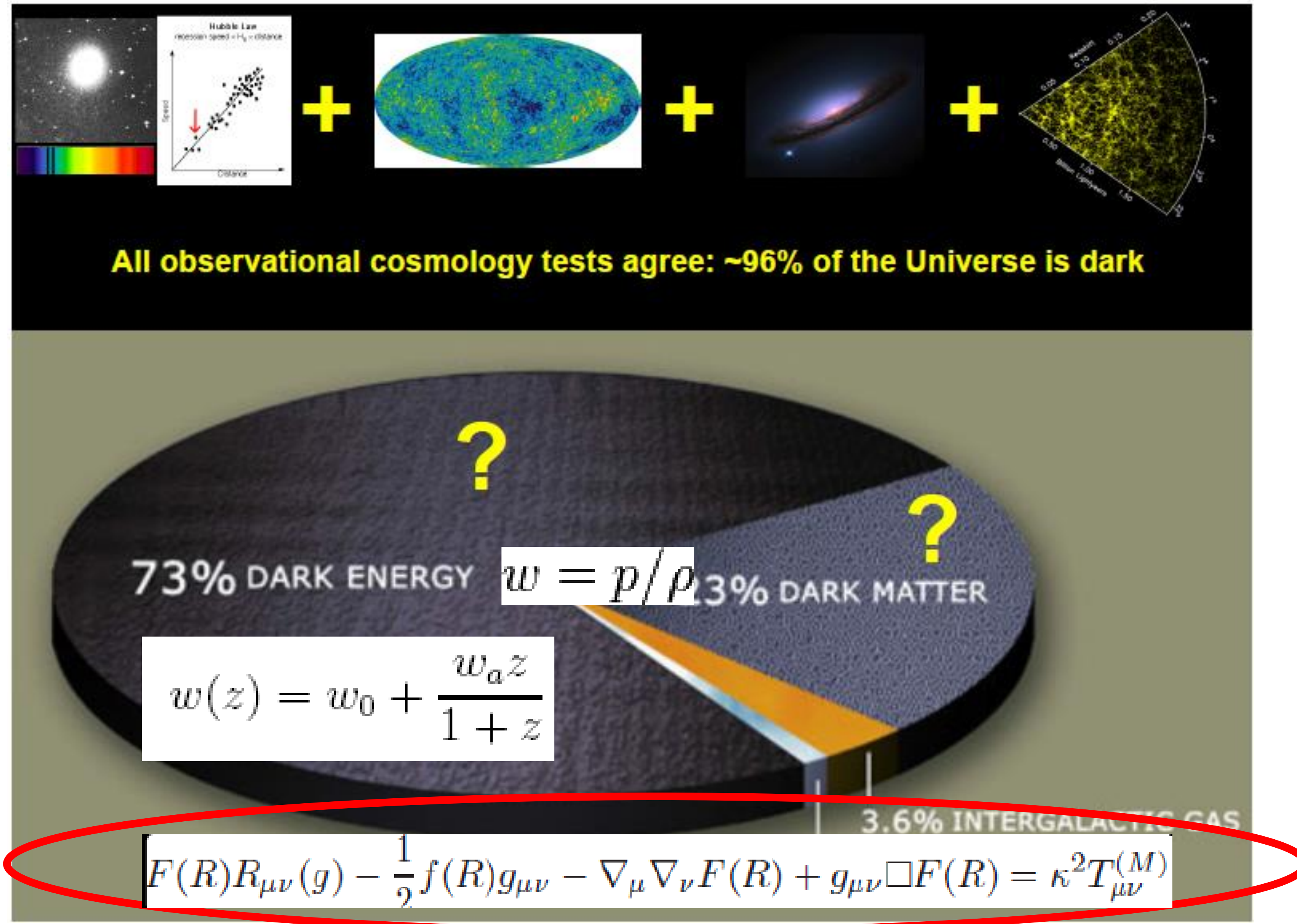
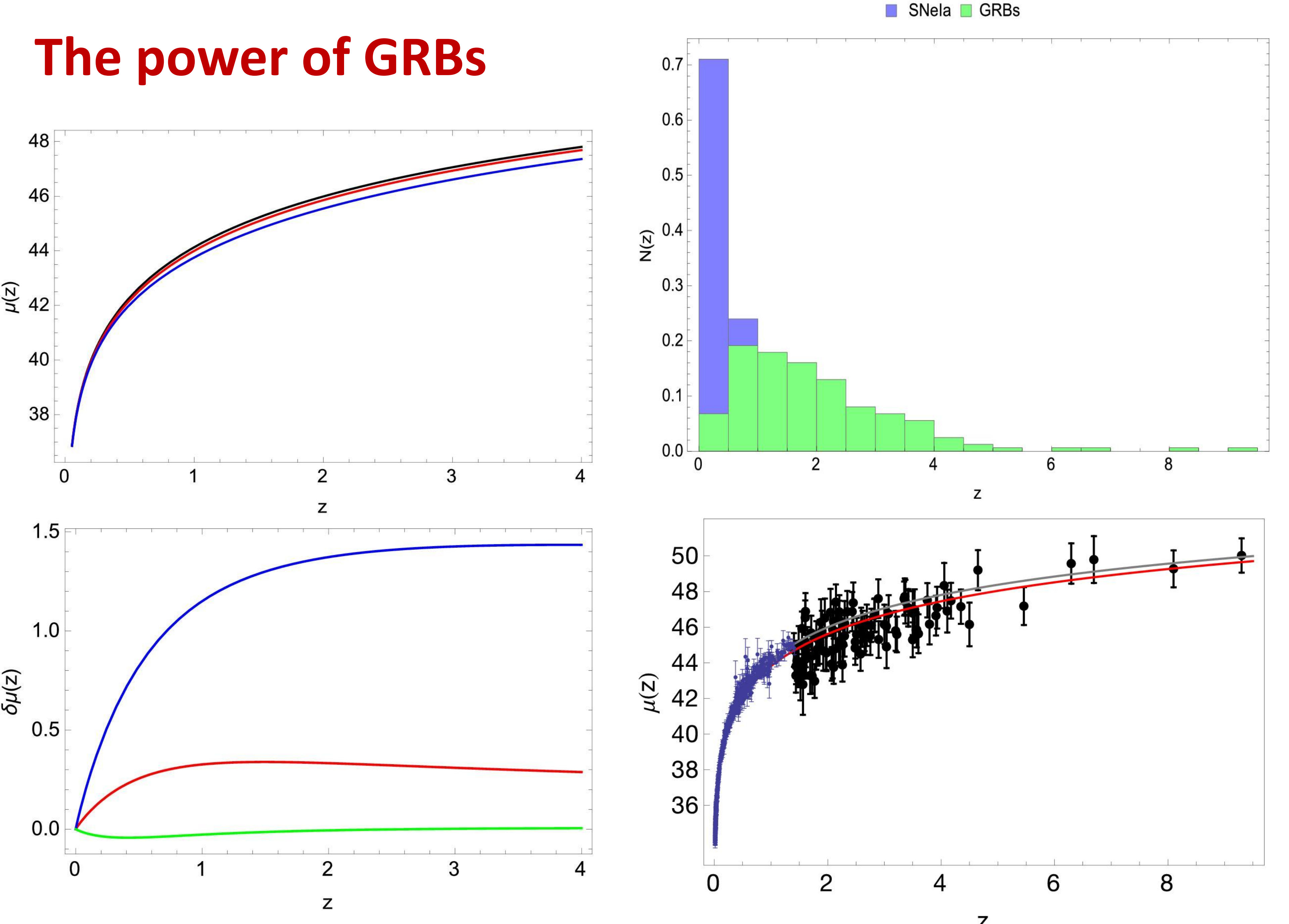
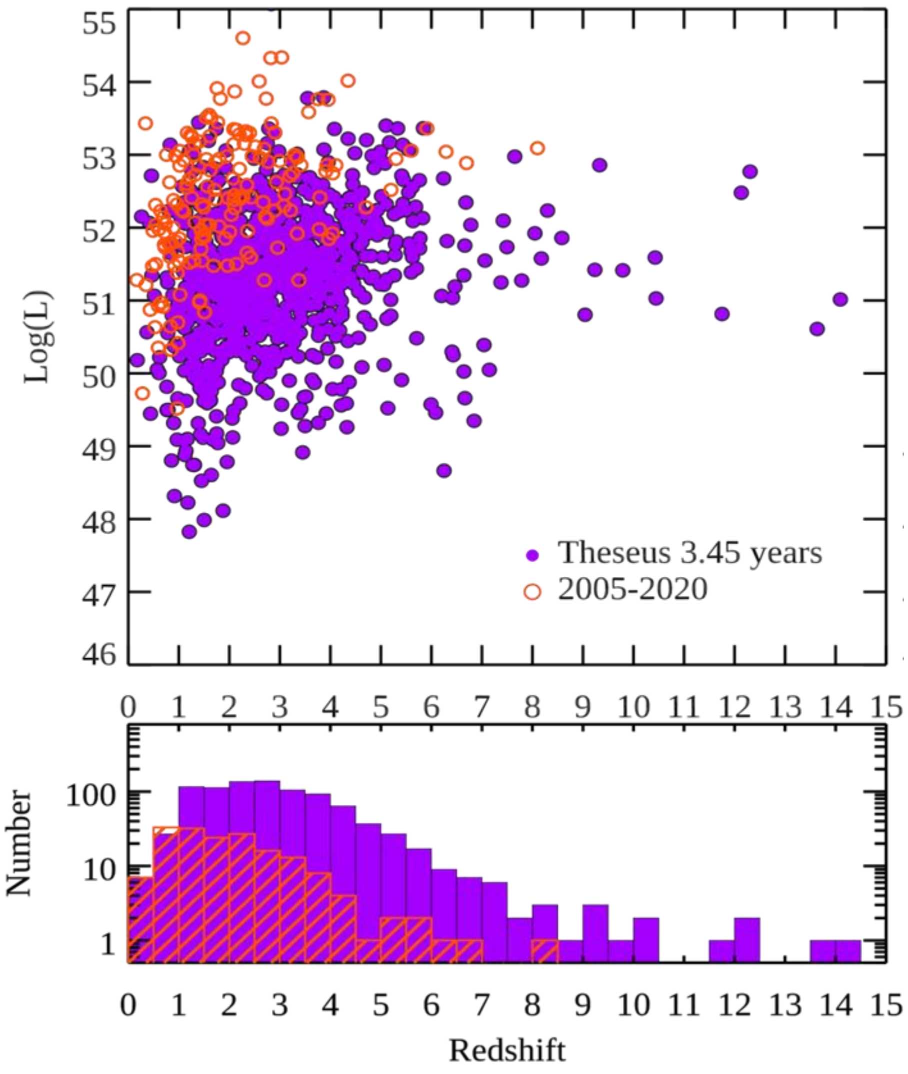


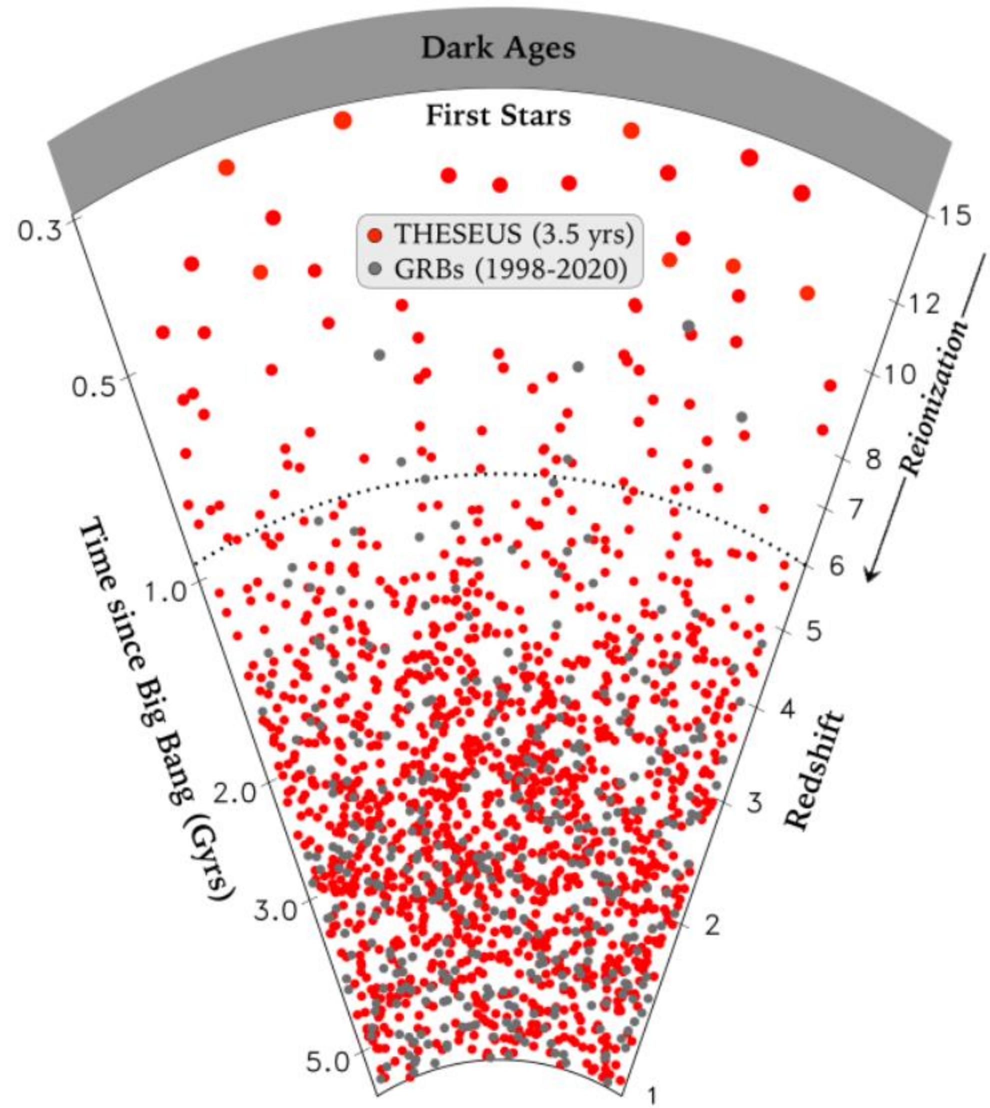
The power of GRBs



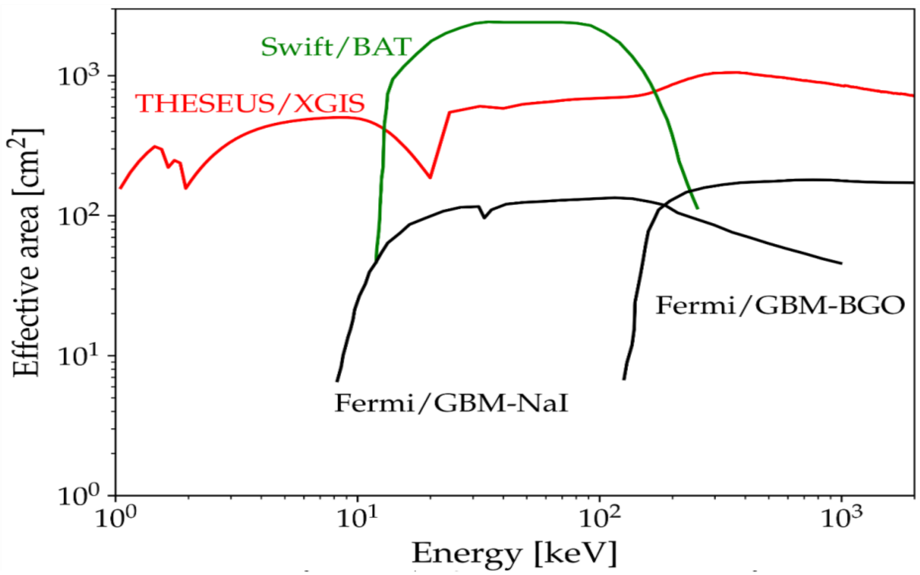
Demianski et al. 2017

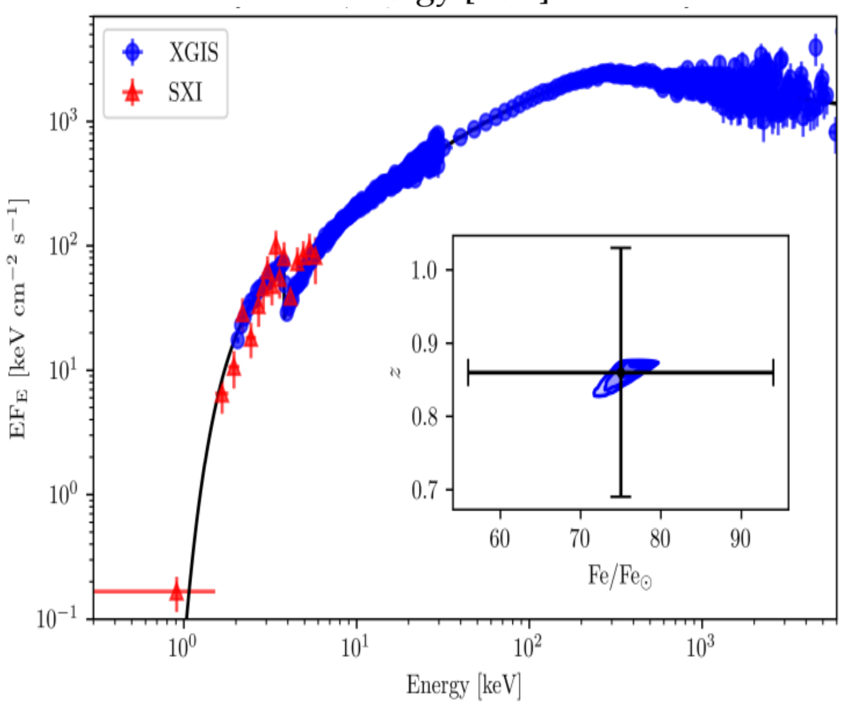
THESEUS: substantial leap in GRB with redshift

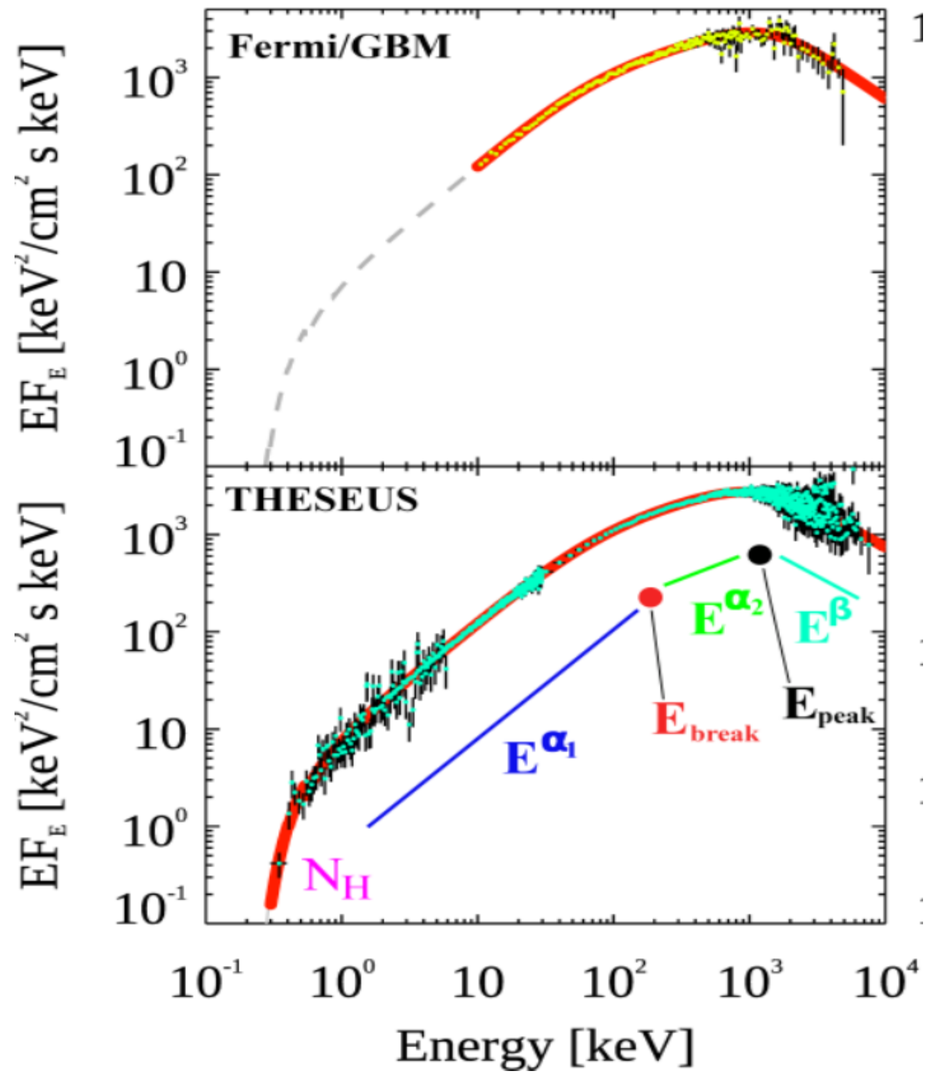




THESEUS: unprecedented spectroscopy of GRB

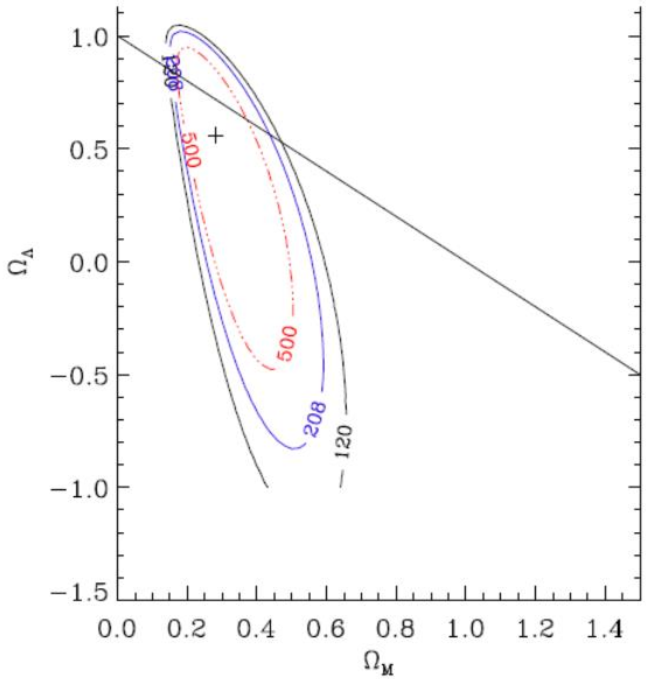


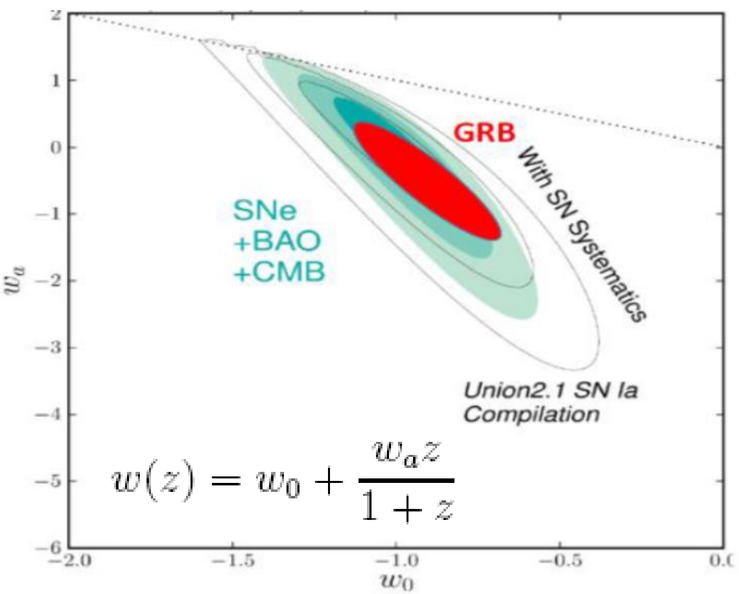




- Future GRB experiments (e.g., SVOM, HERMES, THESEUS, …) and more investigations (in particular: reliable estimates of jet angles and self-calibration) will improve the significance and reliability of the results and allow to go beyond SN Ia cosmology (e.g. investigation of dark energy)

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	$0.30^{+0.03}_{-0.03}$	$-1.1^{+0.12}_{-0.15}$



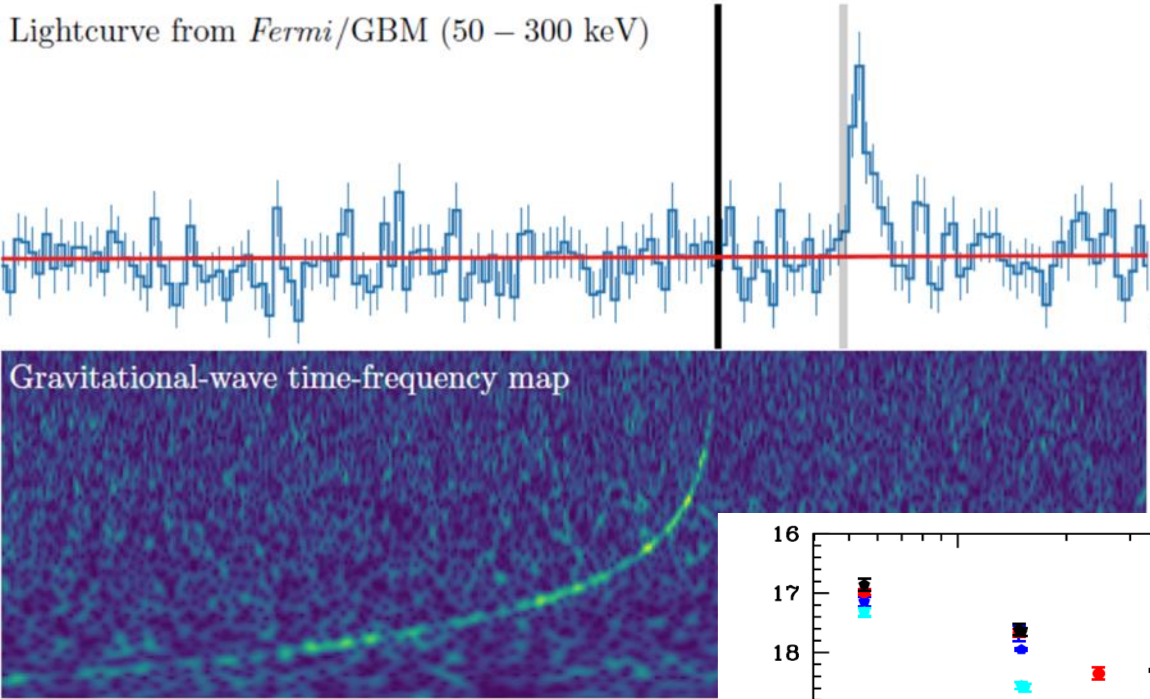


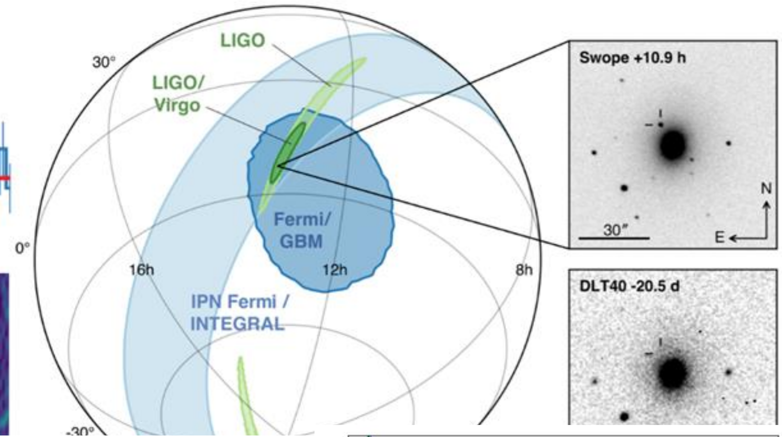
Moresco et al. 2022, Amati & Della Valle 2013

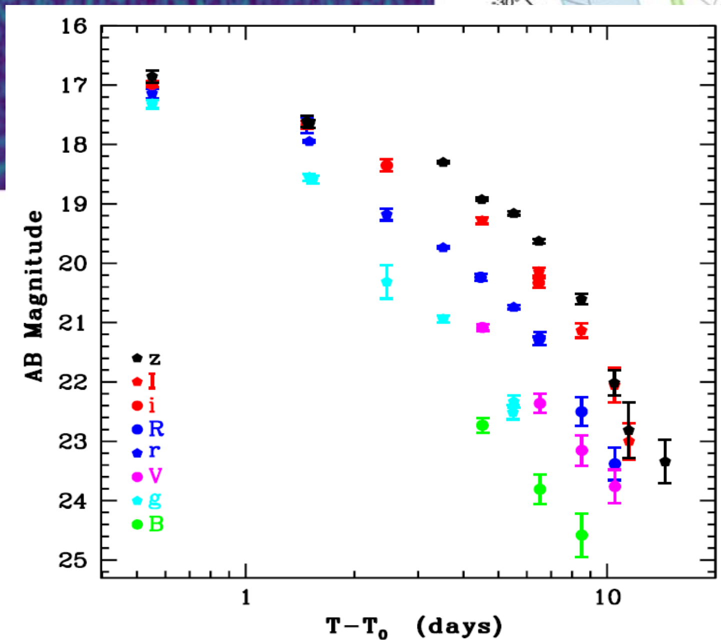
Short GRBs and multi-messenger astrophysics

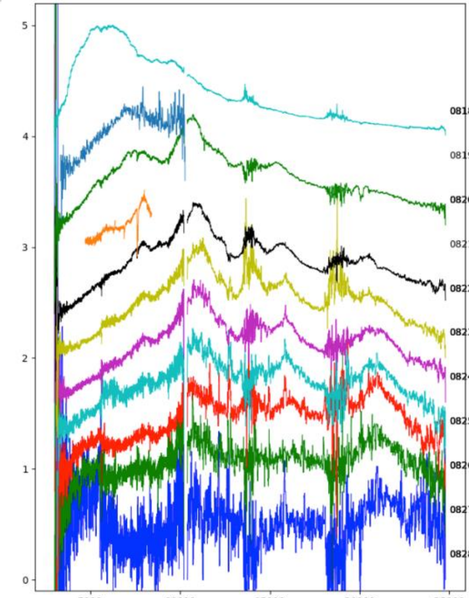
GW170817 + SHORT GRB 170817A + KN AT2017GFO (~40 Mpc):

the birth of multi-.messenger astrophysics









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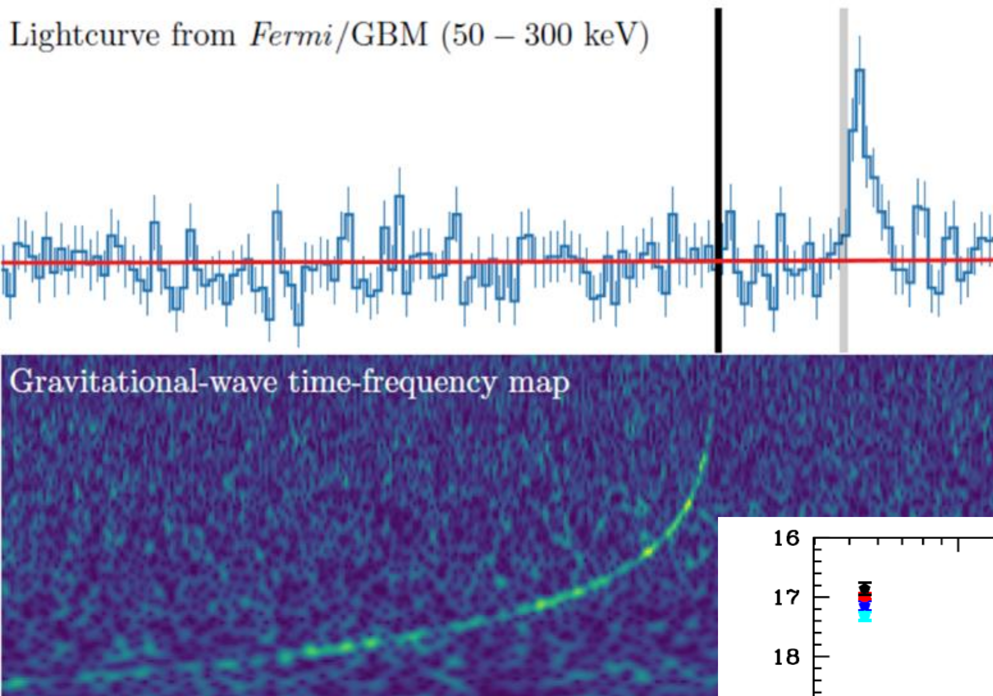
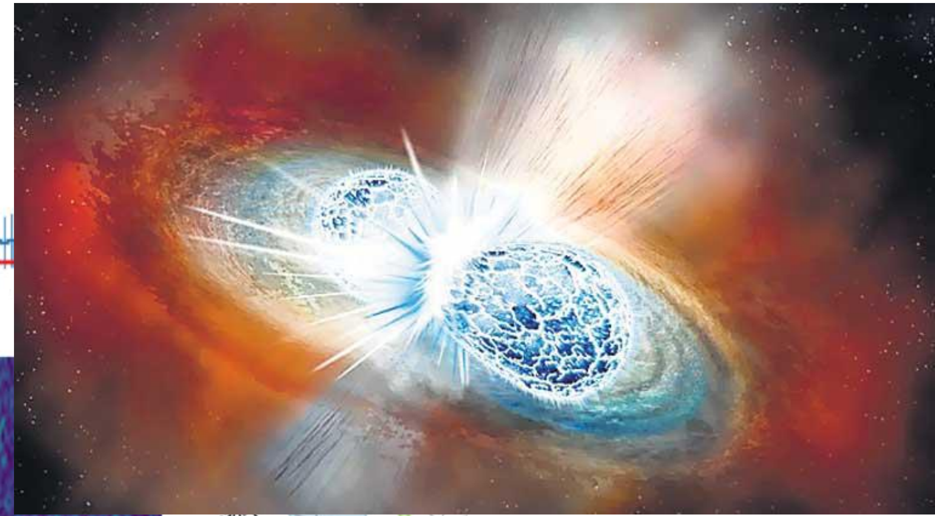
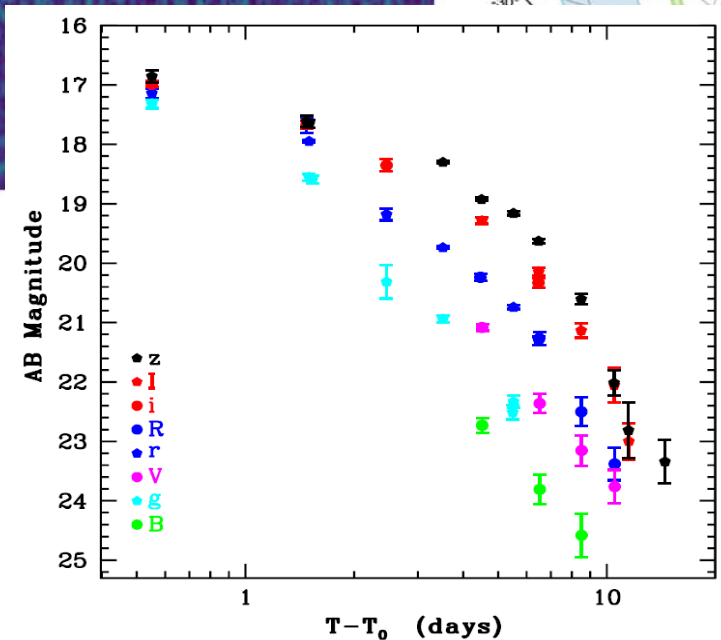
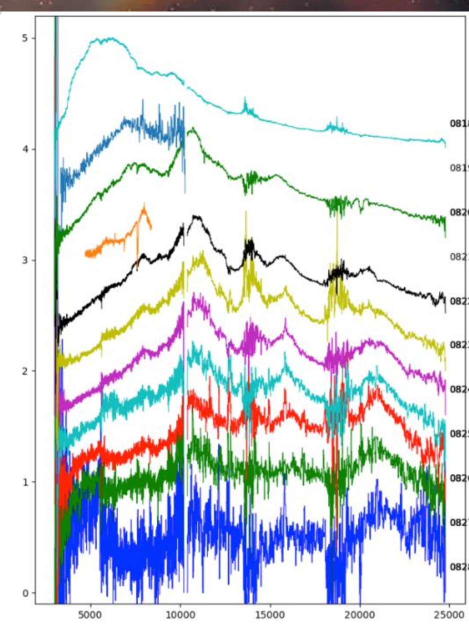


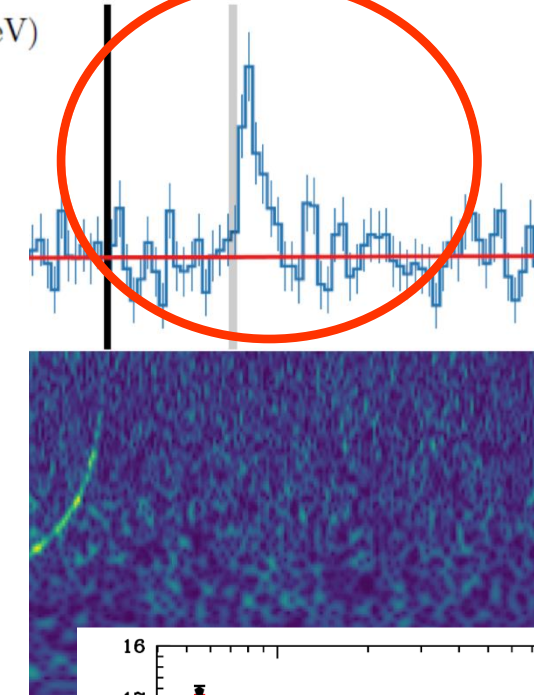






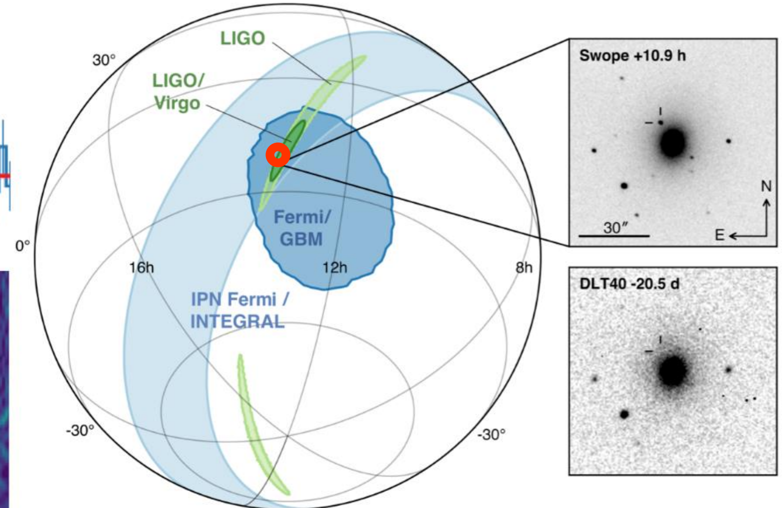
LIGO, Virgo, and partners make first detection of gravitational waves and light from colliding neutron stars

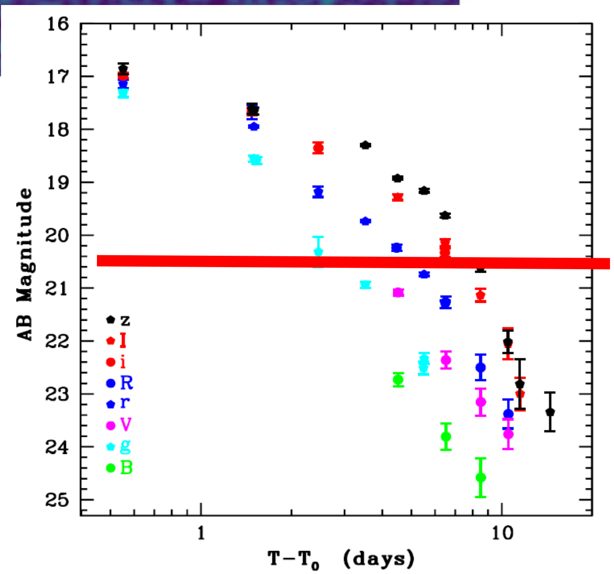
Lightcurve from *Fermi*/GBM (50 – 300 keV)

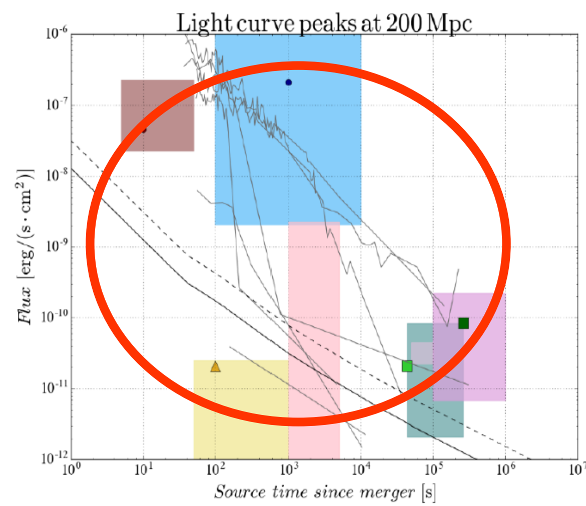


THESEUS:

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

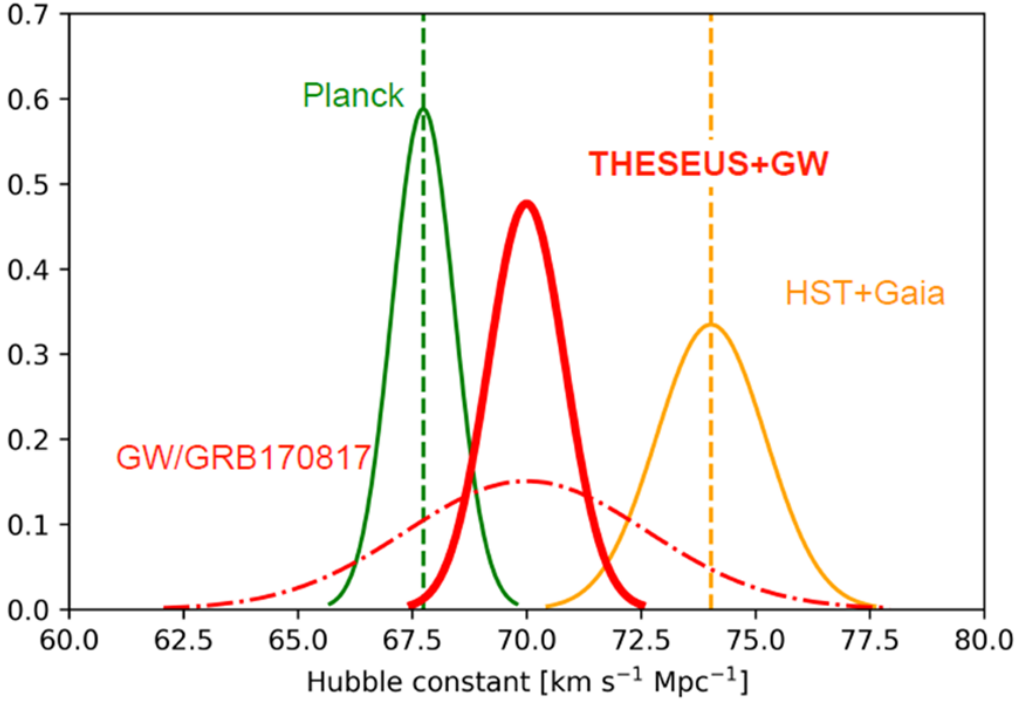


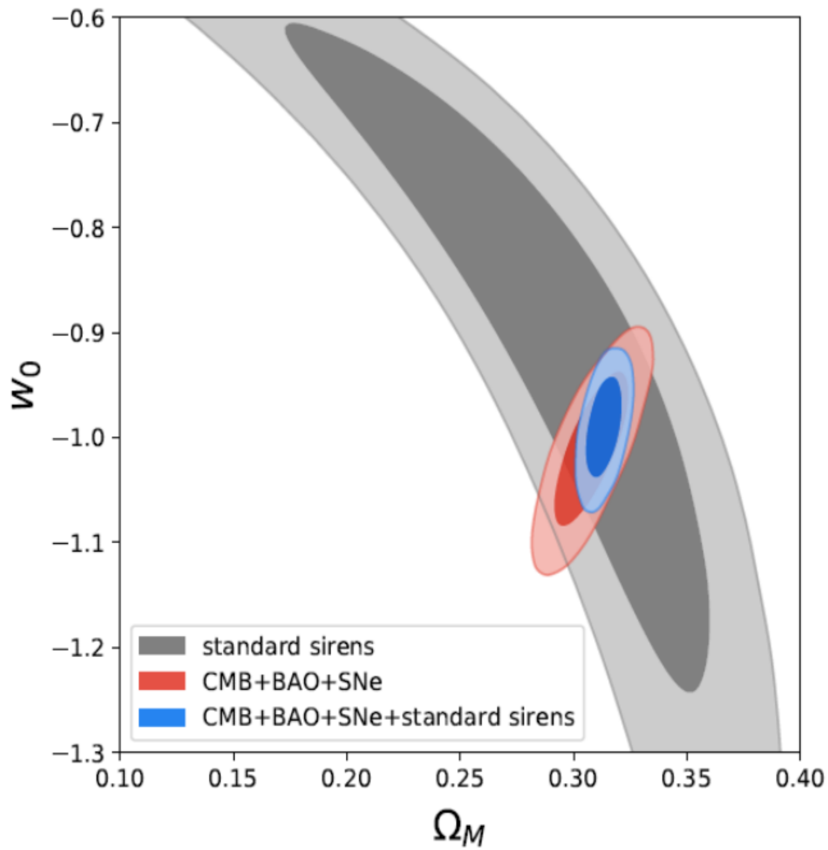




Multi-messenger cosmology through GRBs

MEASURING THE EXPANSION RATE AND GEOMETRY OF SPACE-TIME





~20 joint GRB+GW events

Fundamental physics with GRBs: testing LI / QG

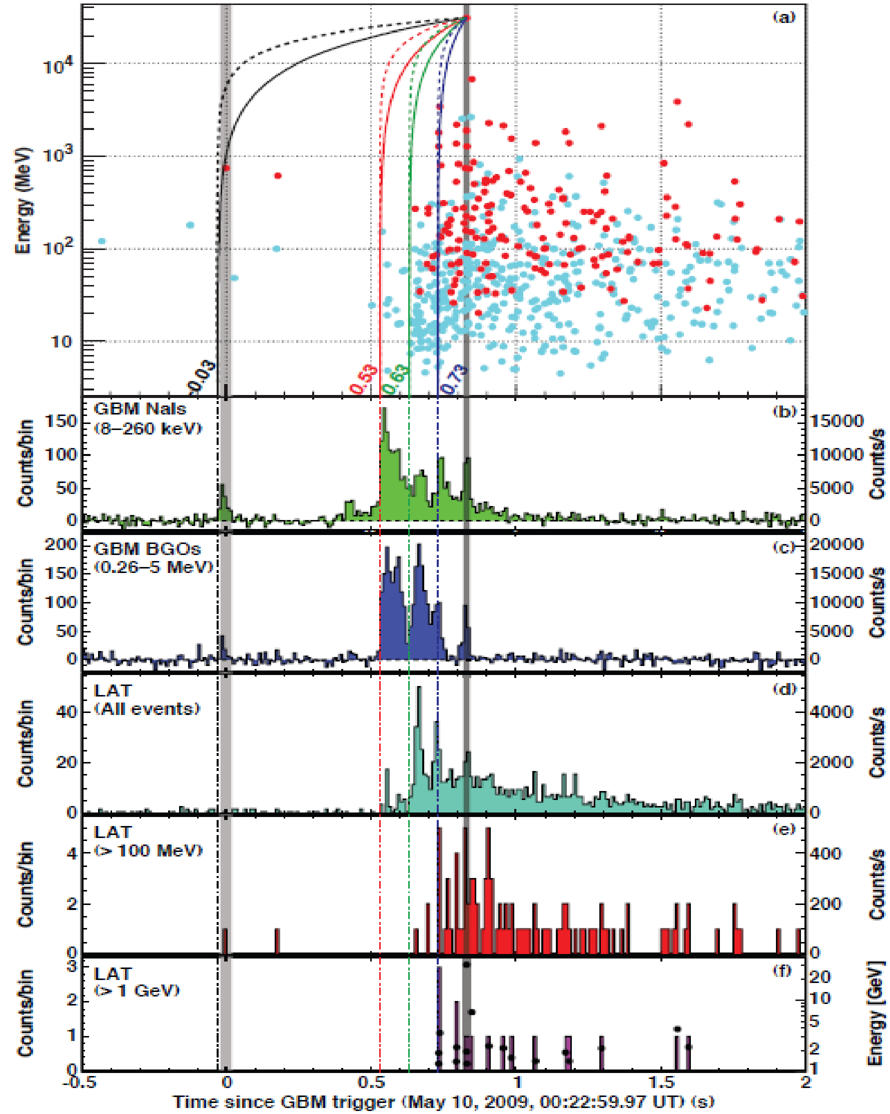
- ❑ Using time delay between low and high energy photons to put Limits on Lorentz Invariance Violation (allowed by unprecedent Fermi GBM + LAT broad energy band)

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

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

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



In summary

- GRBs are a key phenomenon for cosmology (ealry Universe, cosmological parameters) 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/