Cosmology with Gamma-Ray Bursts

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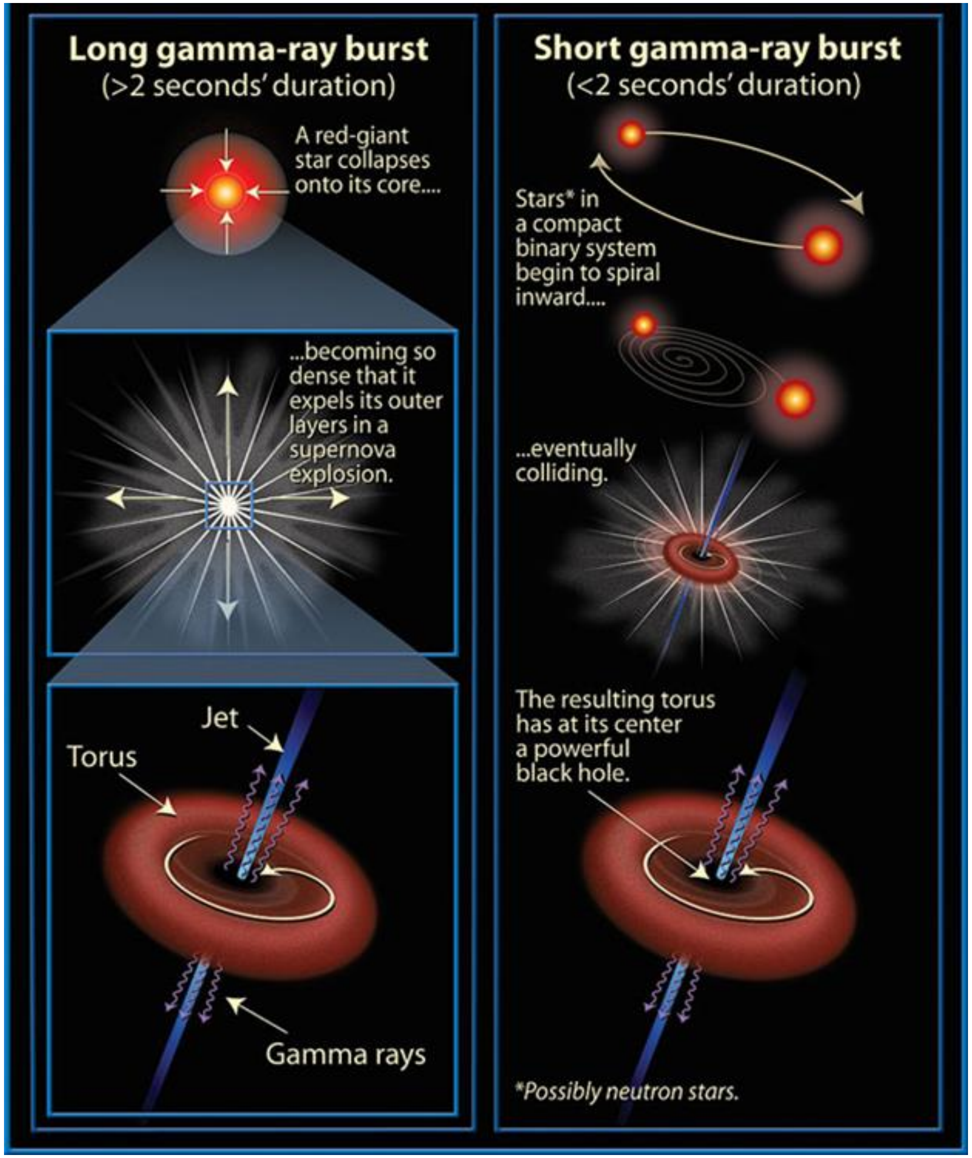
Gamma-Ray Bursts: the most extreme phenomena in the Universe

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

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



The power of long GRBs for cosmology

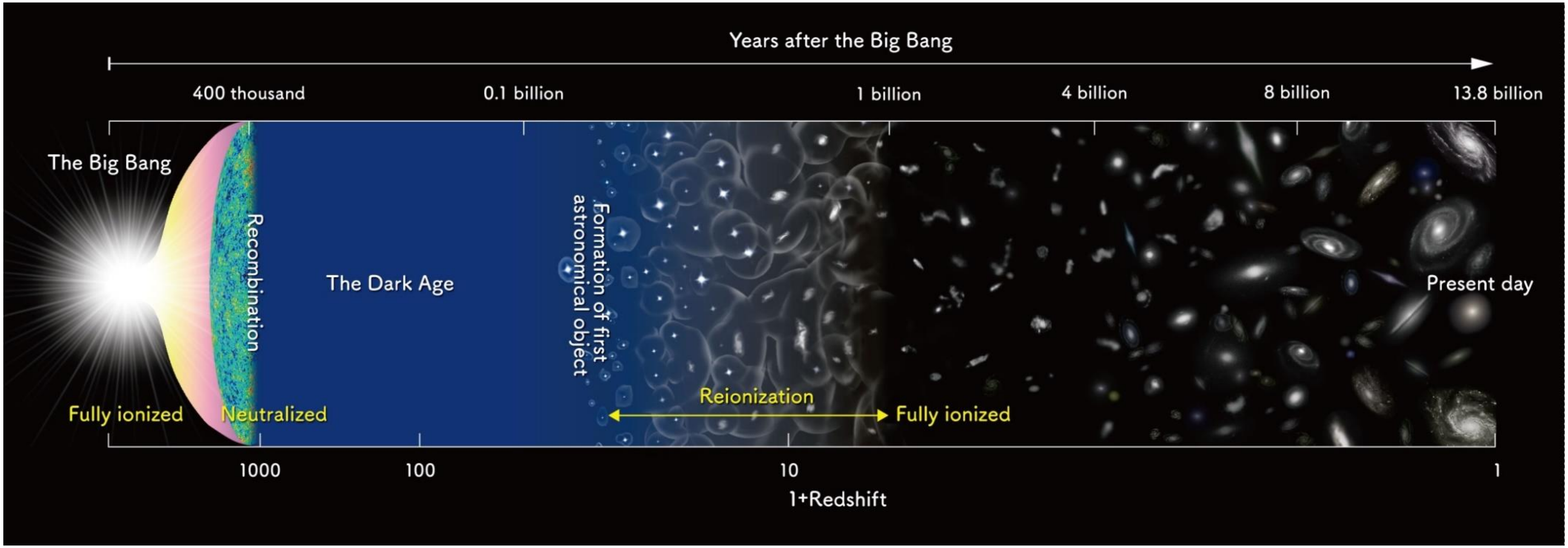
Most luminous and remote phenomena in the Universe, with isotropic-equivalent radiated energies in X-gamma rays up to more than **10^{54} erg released in a few tens of seconds** and a redshift distribution extending to at least **z = 9-10**.

a) **GRBs as tools for exploring the early Universe** at the end of the "dark ages" (reionization, first stars, star formation rate and metallicity evolution in the first billion of years)

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

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**



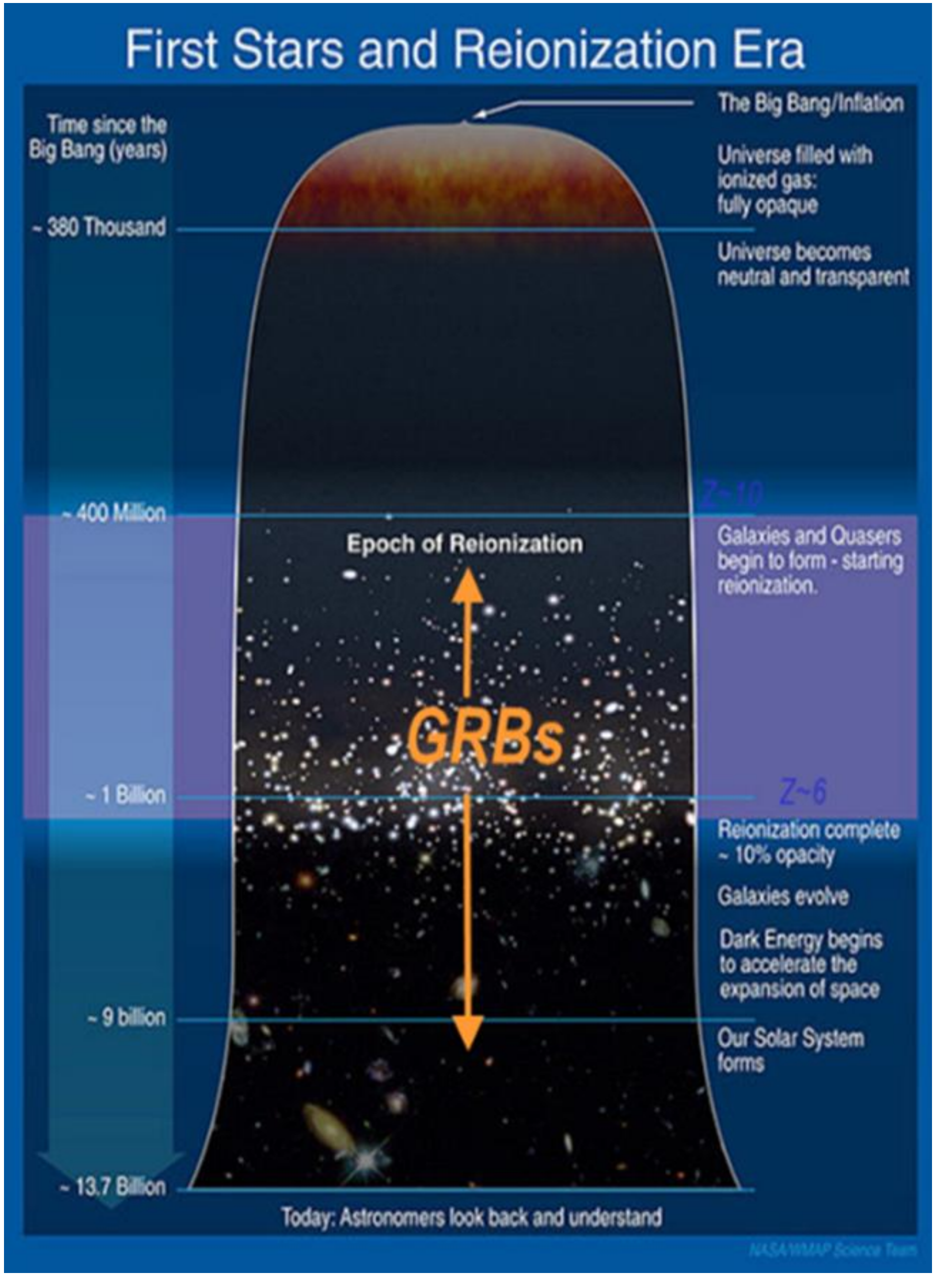
What was the timeline of reionization?

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

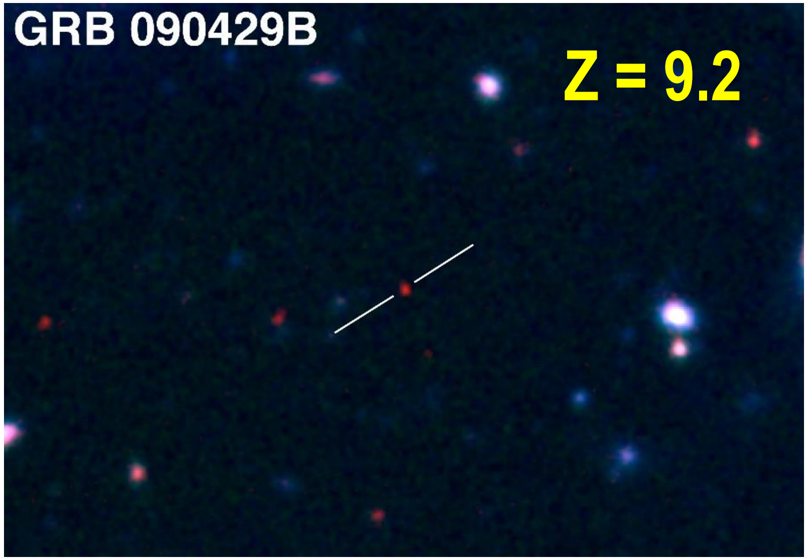


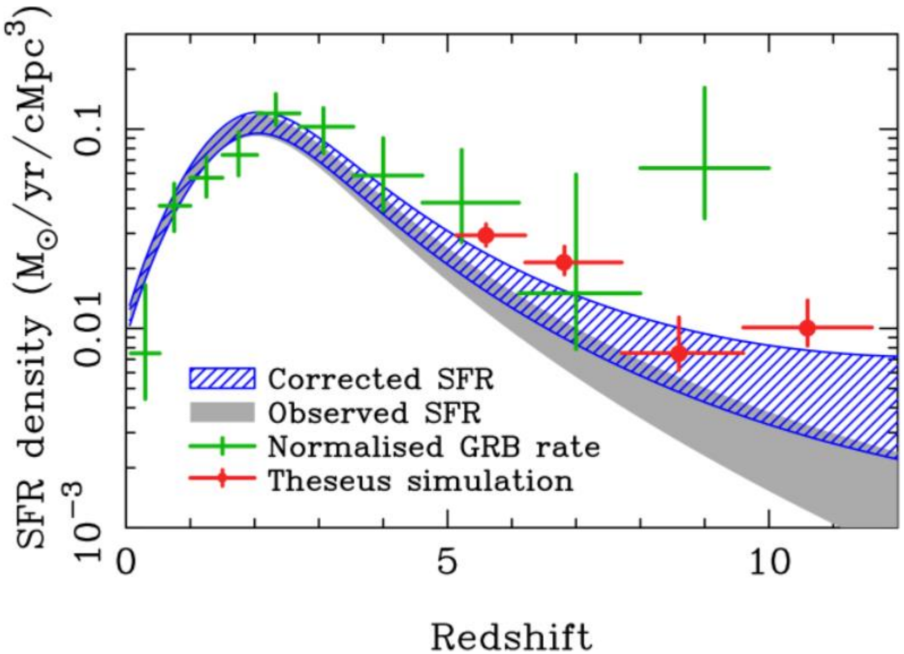
Shedding light on the early Universe with GRBs

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

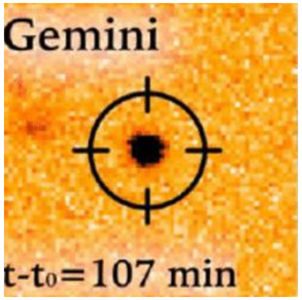
- measure independently the **cosmic star–formation rate**, even beyond the limits of current and future galaxy surveys

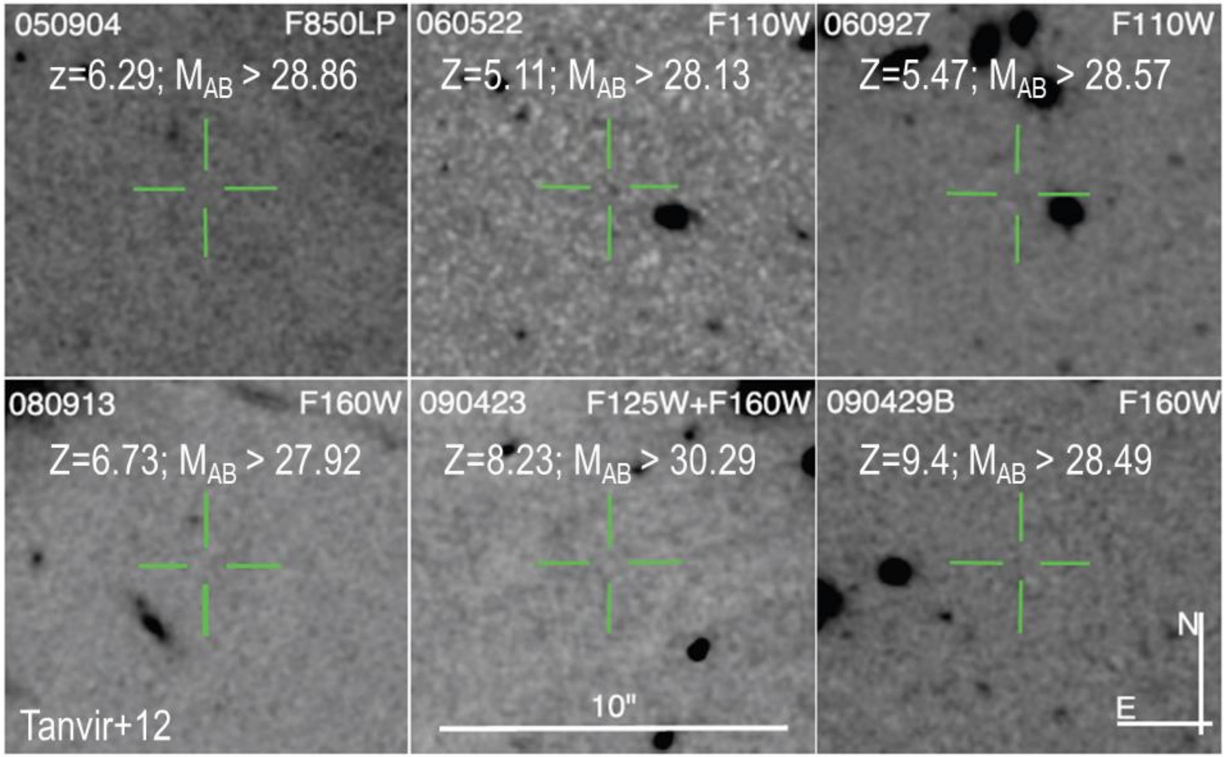
- directly (or indirectly) detect the **first population of stars (pop III)**





• Detecting and studying primordial invisible galaxies

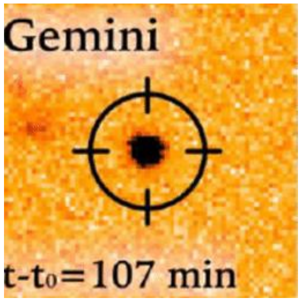


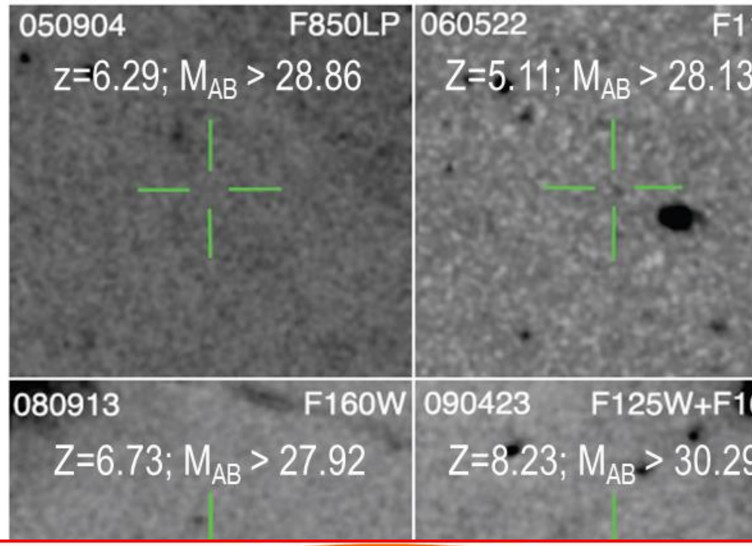


Robertson&Ellis12

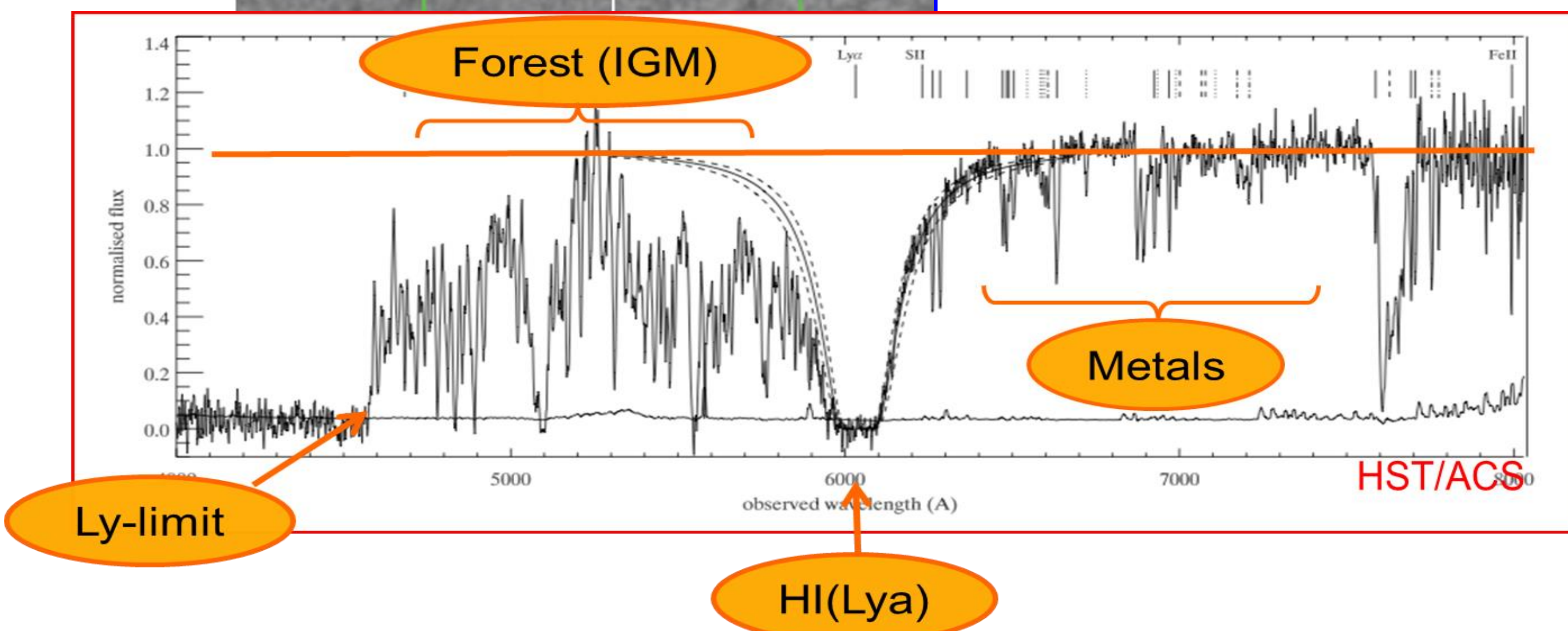
Even JWST and ELTs surveys will be not able to probe the faint end of the galaxy Luminosity Function at high redshifts (z>6-8)

- **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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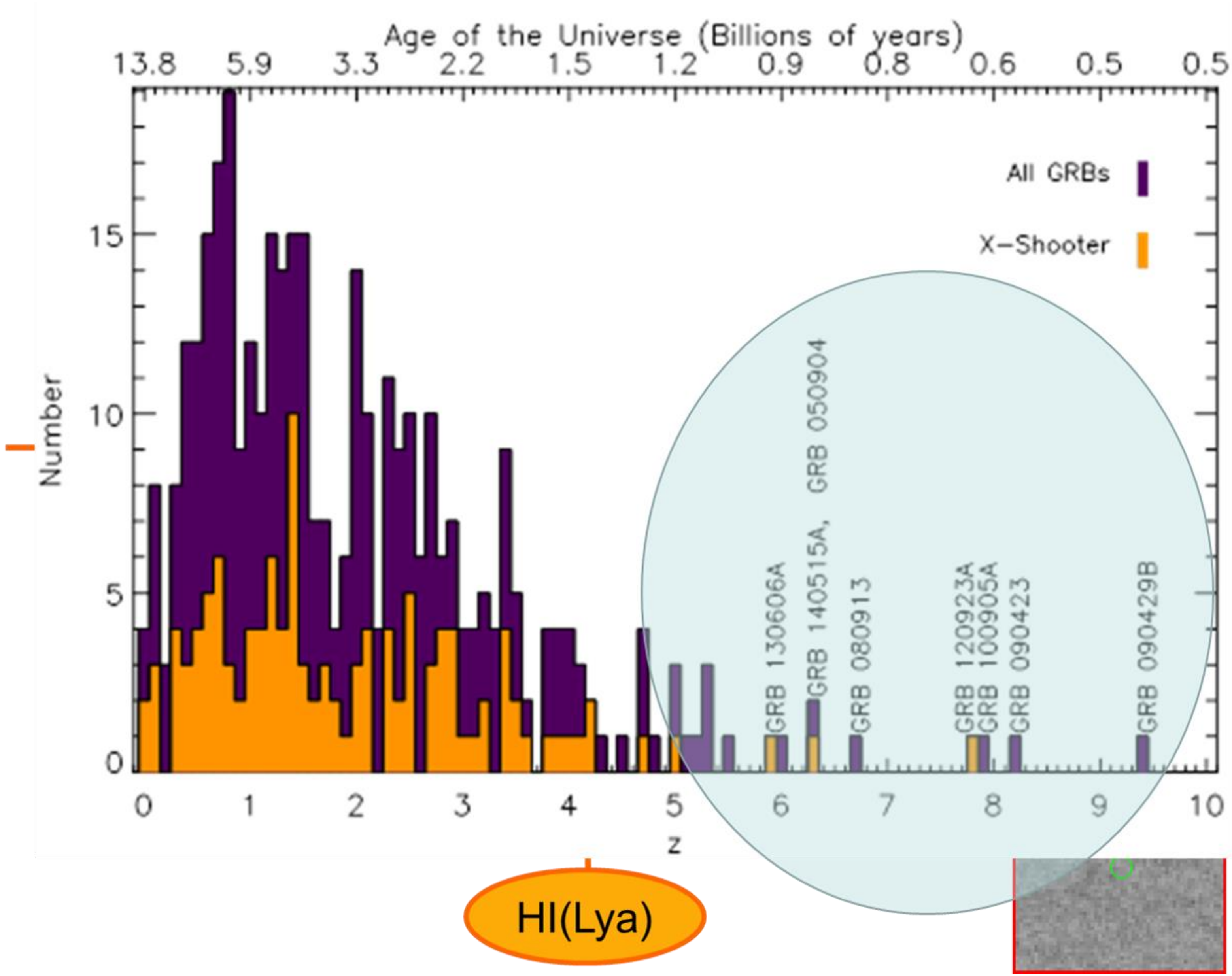
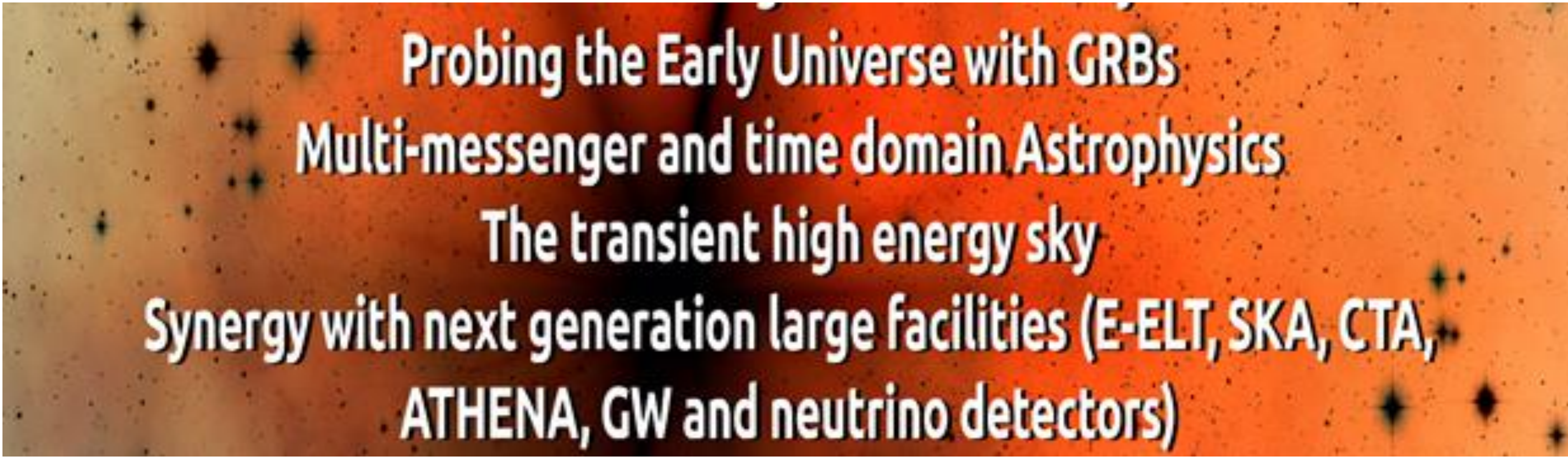


Future GRB missions (late'20s and '30s)



- **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**

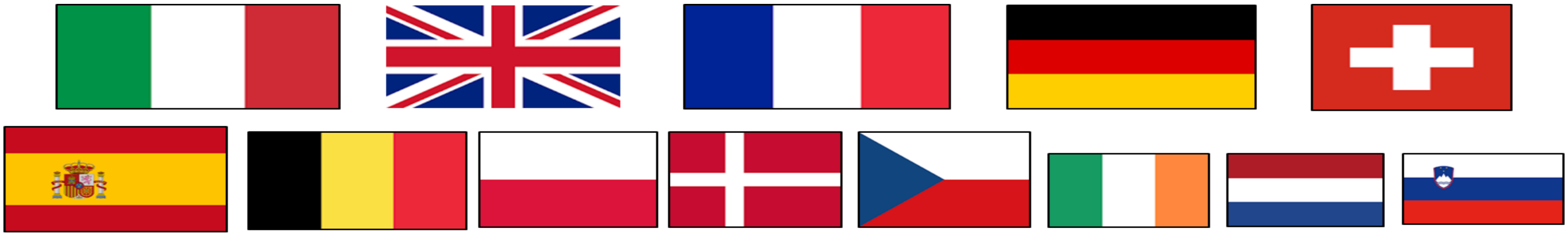
THESEUS

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)

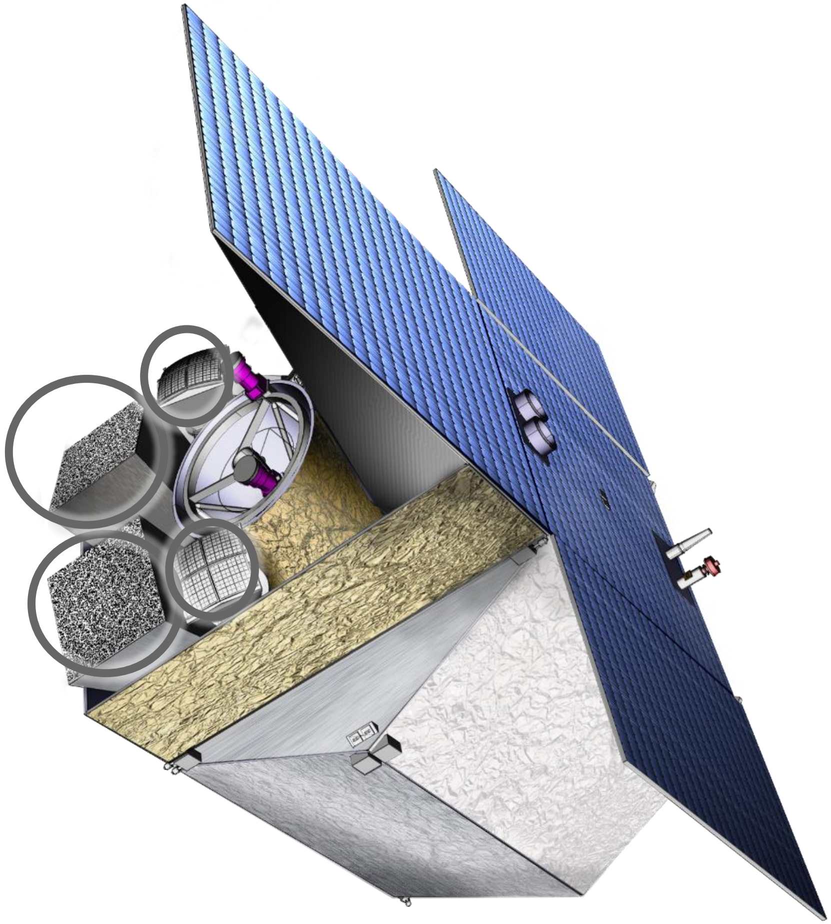
Payload consortium: Italy, UK, France, Germany, Switzerland, Spain, Poland, Denmark, Belgium, Czech Republic, Slovenia, Ireland, NL, ESA



Future GRB missions: the case of THESEUS

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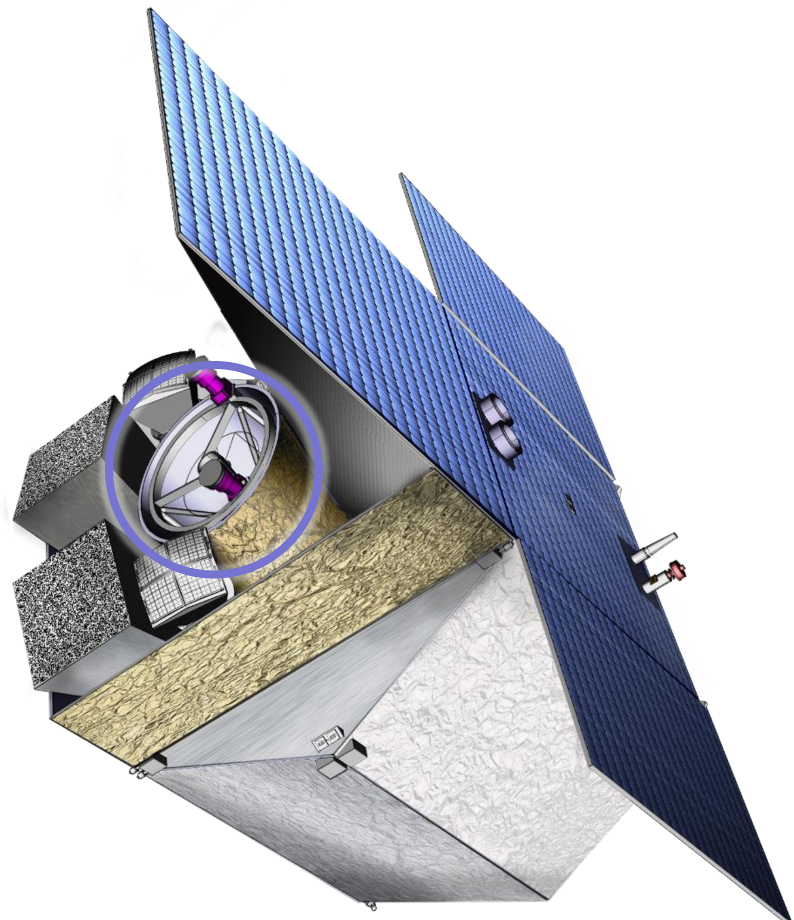
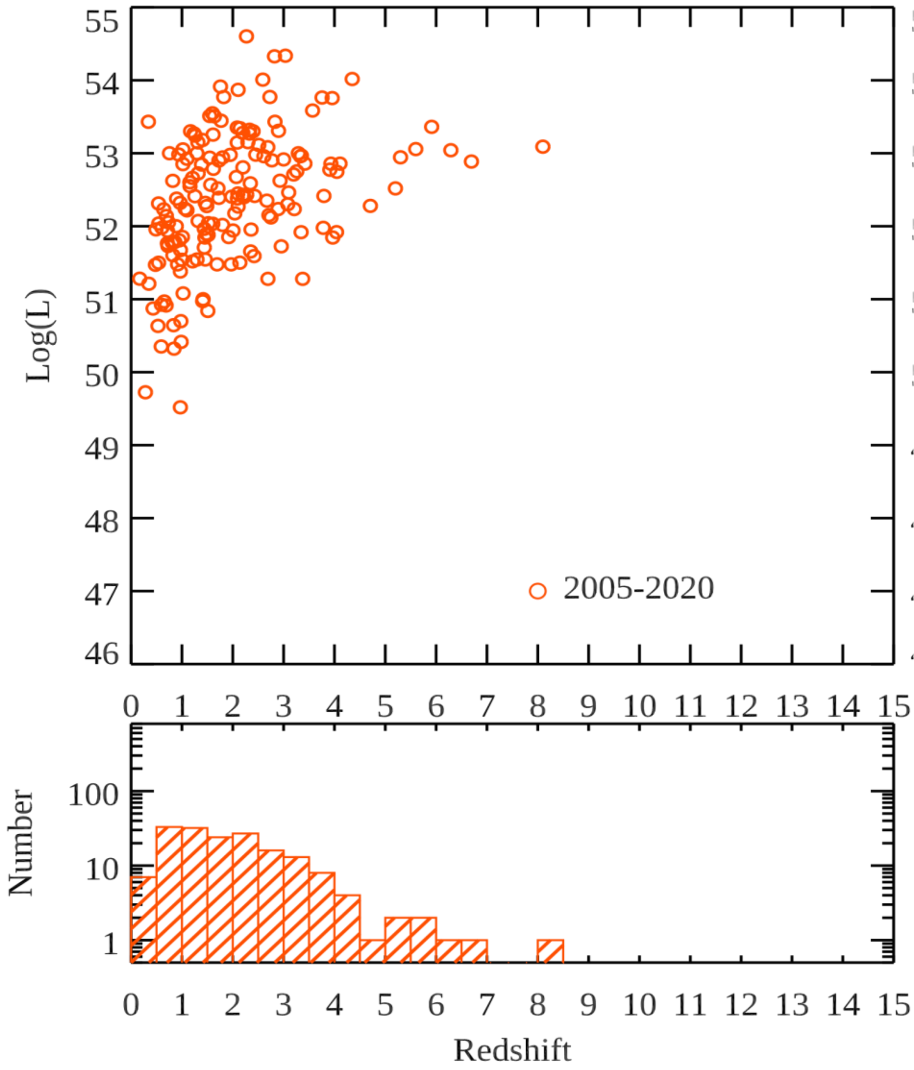
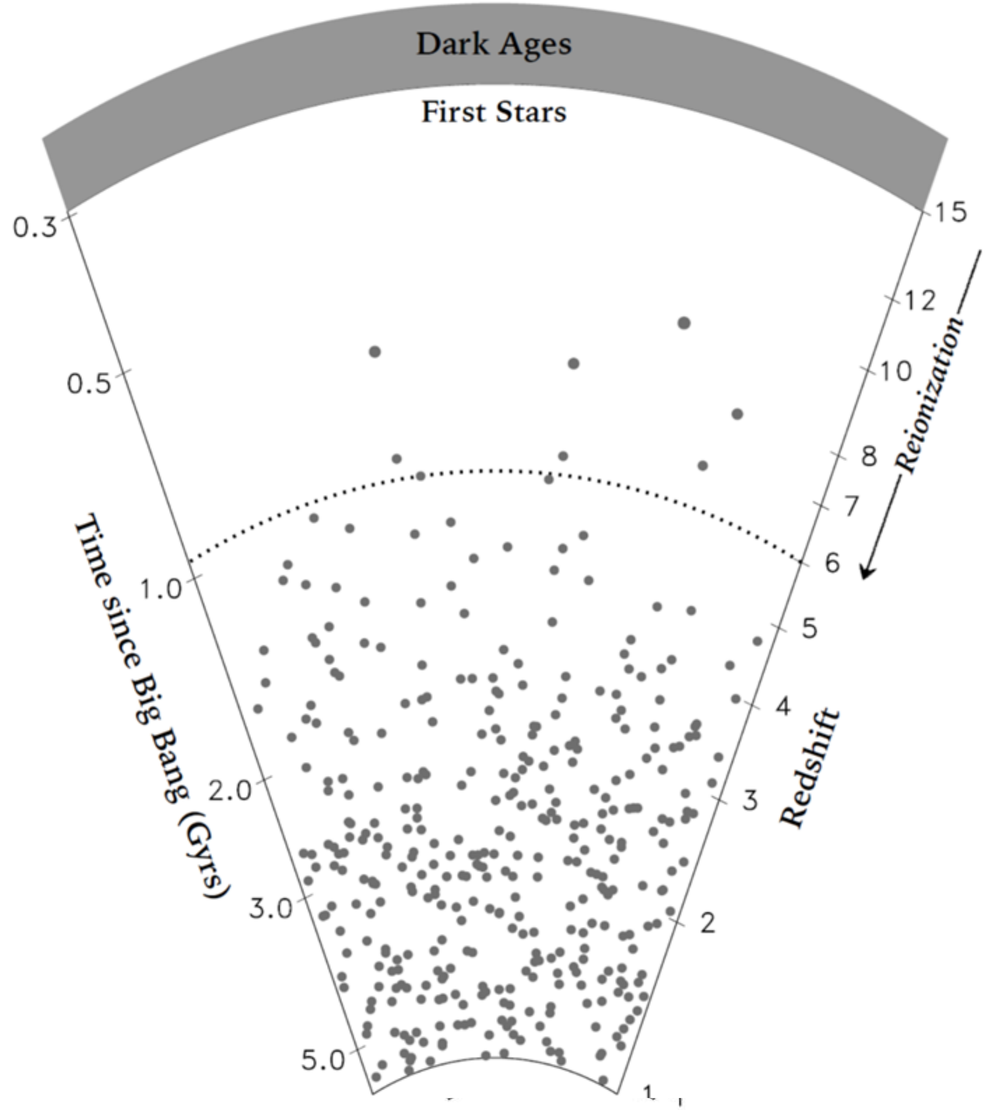
Set of innovative wide-field monitors with **unprecedented combination of broad energy range, sensitivity, FOV and localization accuracy**

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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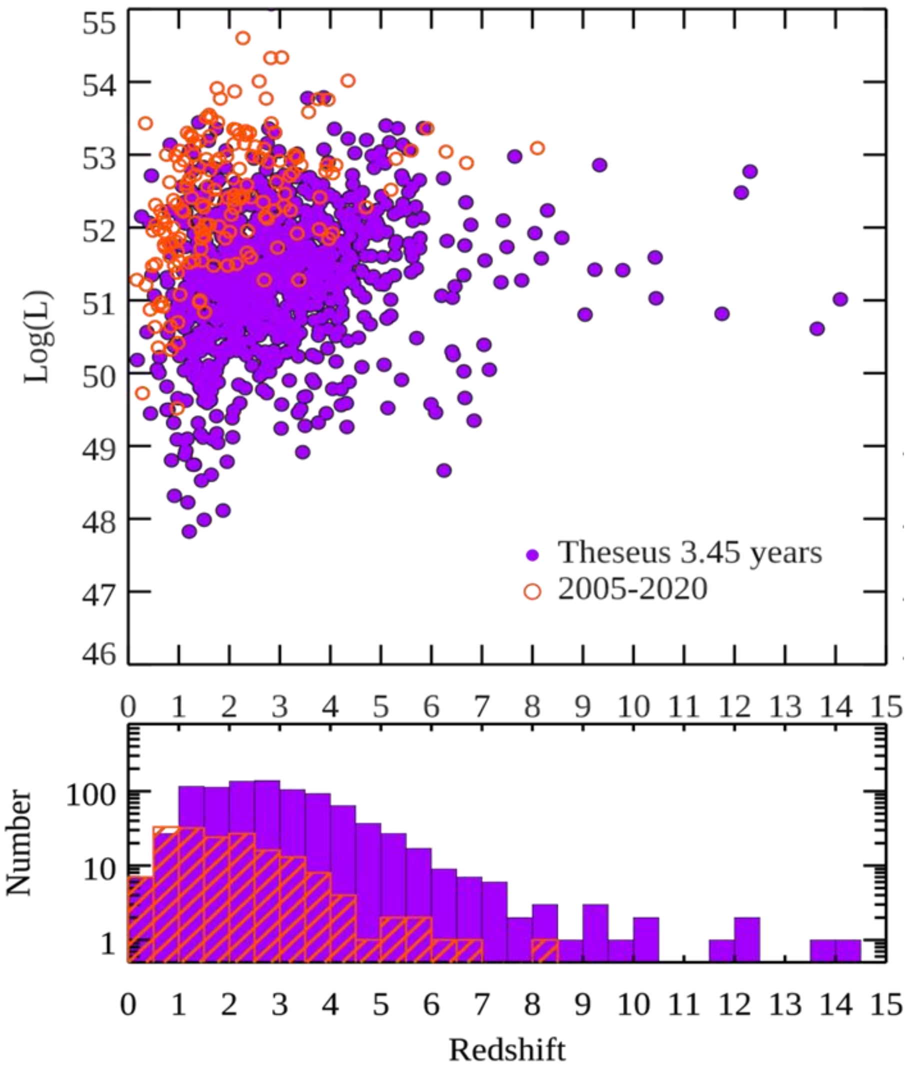
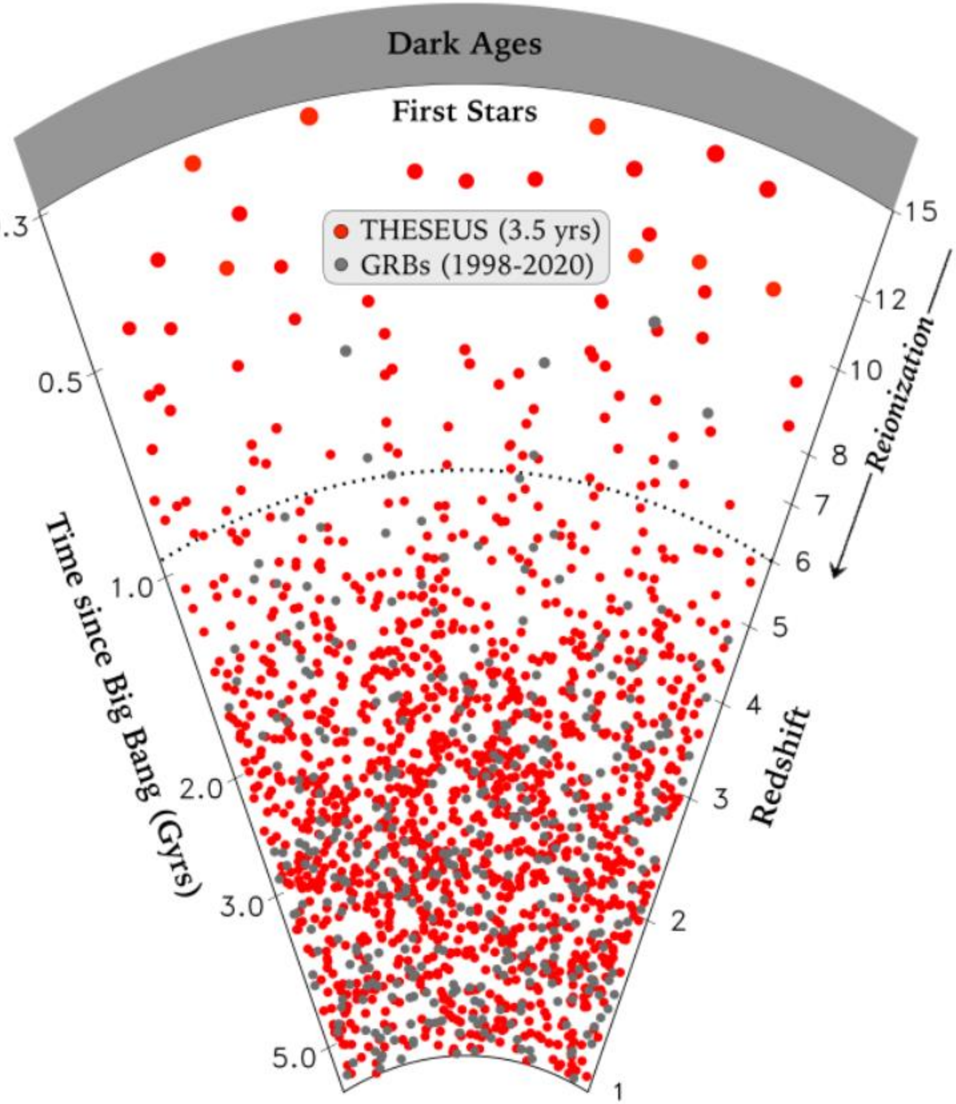
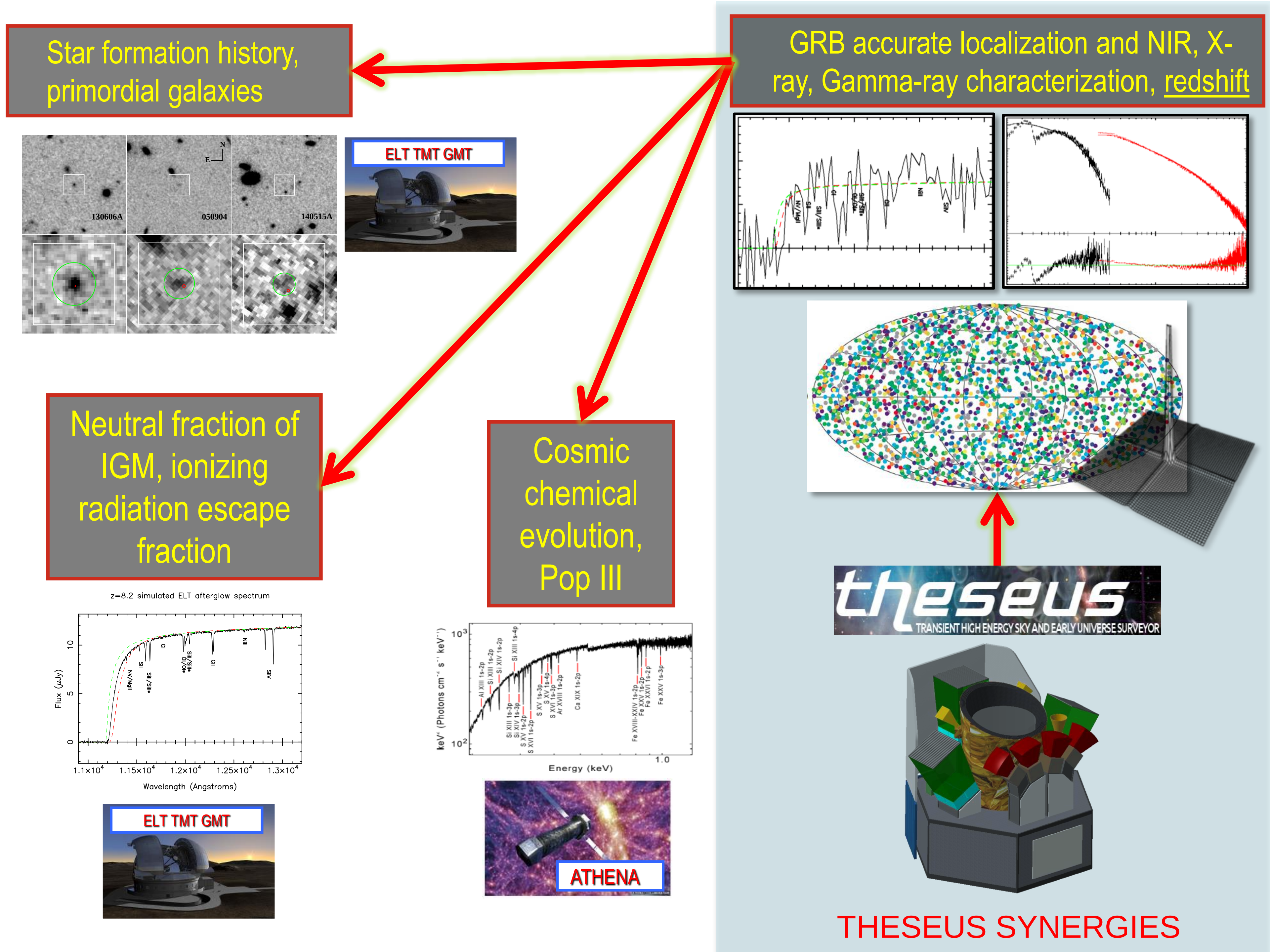
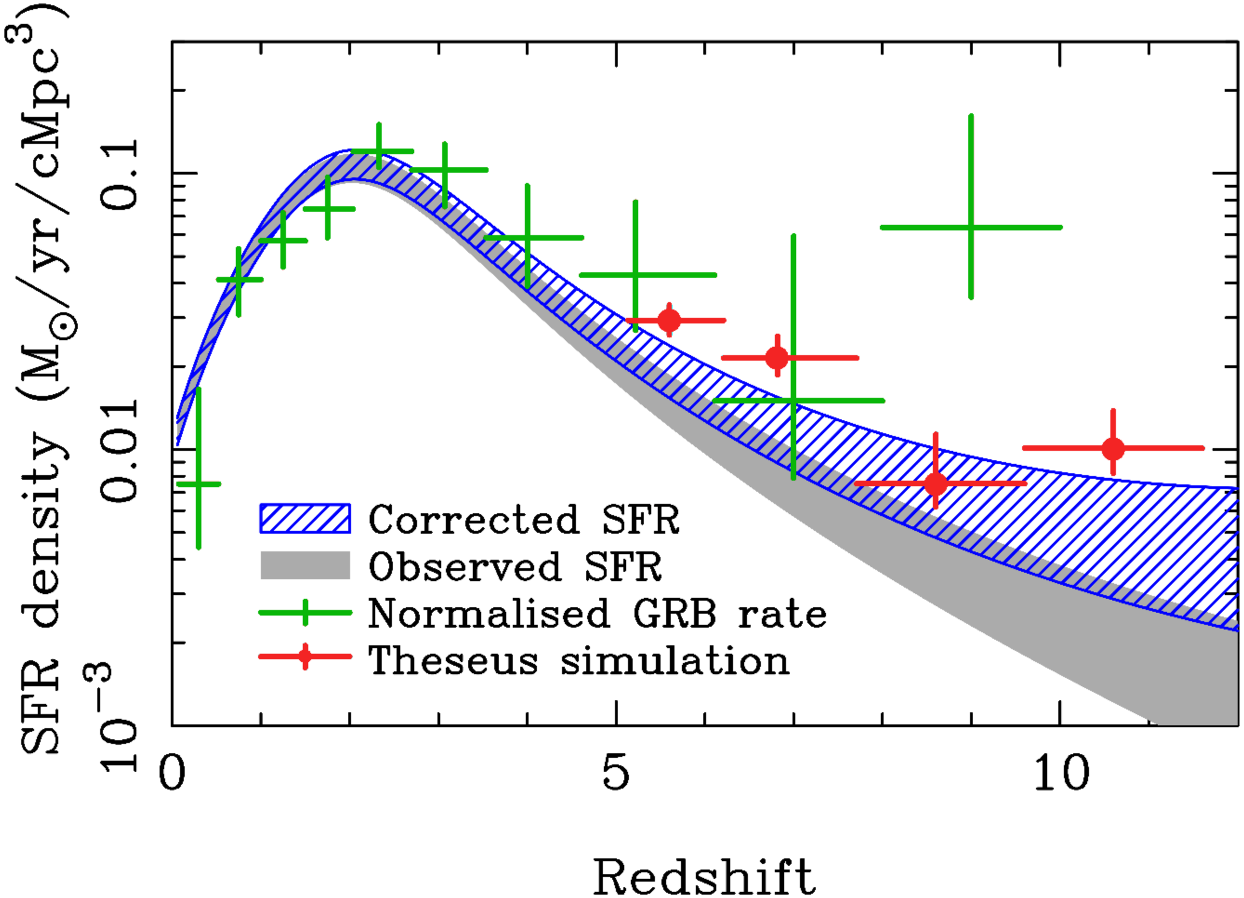






Star formation history, primordial galaxies
GRB accurate localization and NIR, X-ray, Gamma-ray characterization, redshift
130606A
050904
140515A
ELT TMT GMT
Neutral fraction of IGM, ionizing radiation escape fraction
Cosmic chemical evolution, Pop III
z=8.2 simulated ELT afterglow spectrum
Flux (μJy)
Wavelength (Angstroms)
ELT TMT GMT
Energy (keV)
ATHENA
theseus
TRANSIENT HIGH ENERGY SKY AND EARLY UNIVERSE SURVEYOR
THESEUS SYNERGIES

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

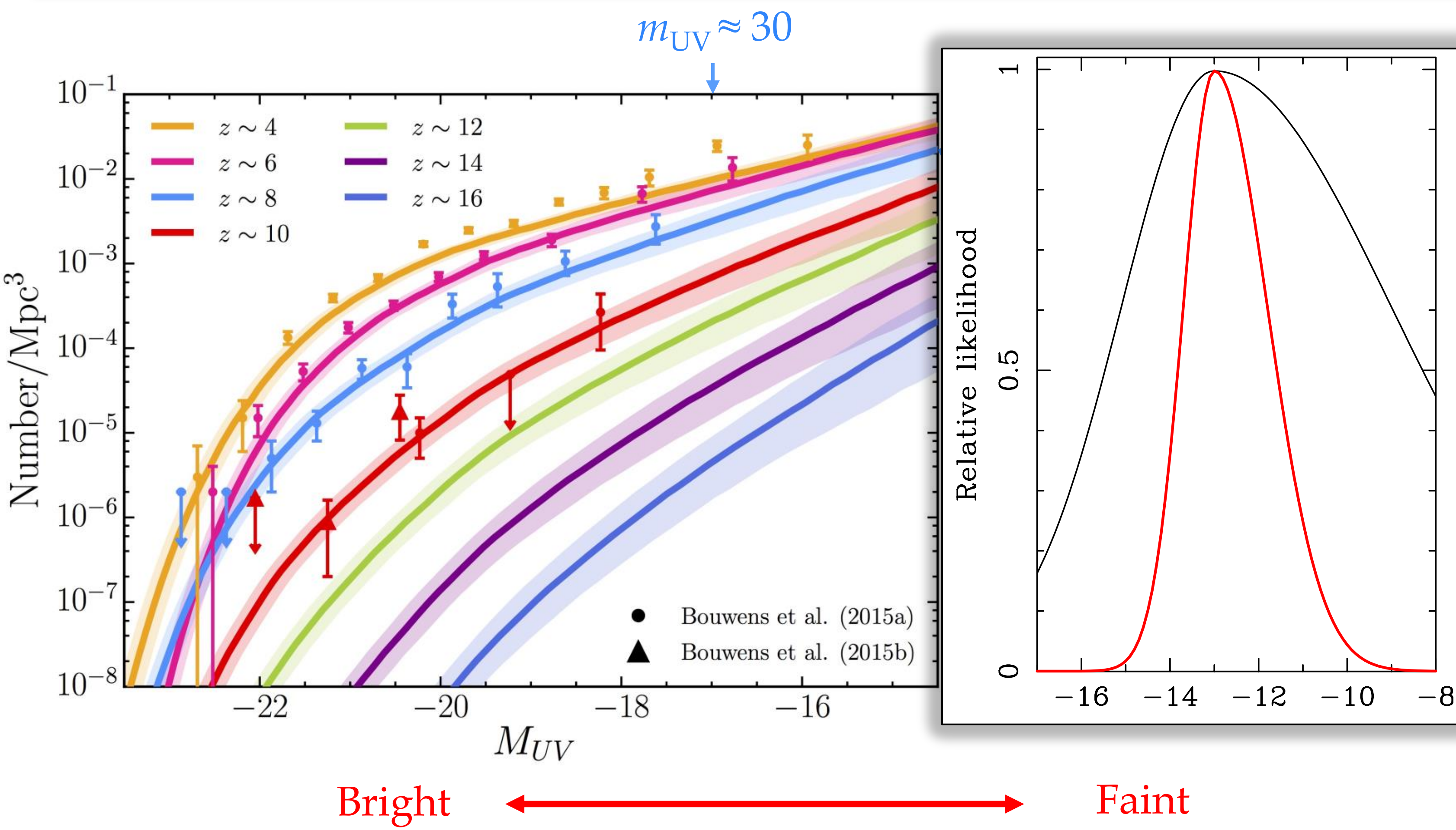


A statistical sample of high–z GRBs will give access to star formation in the faintest galaxies, overcoming limits of current and future galaxy surveys

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



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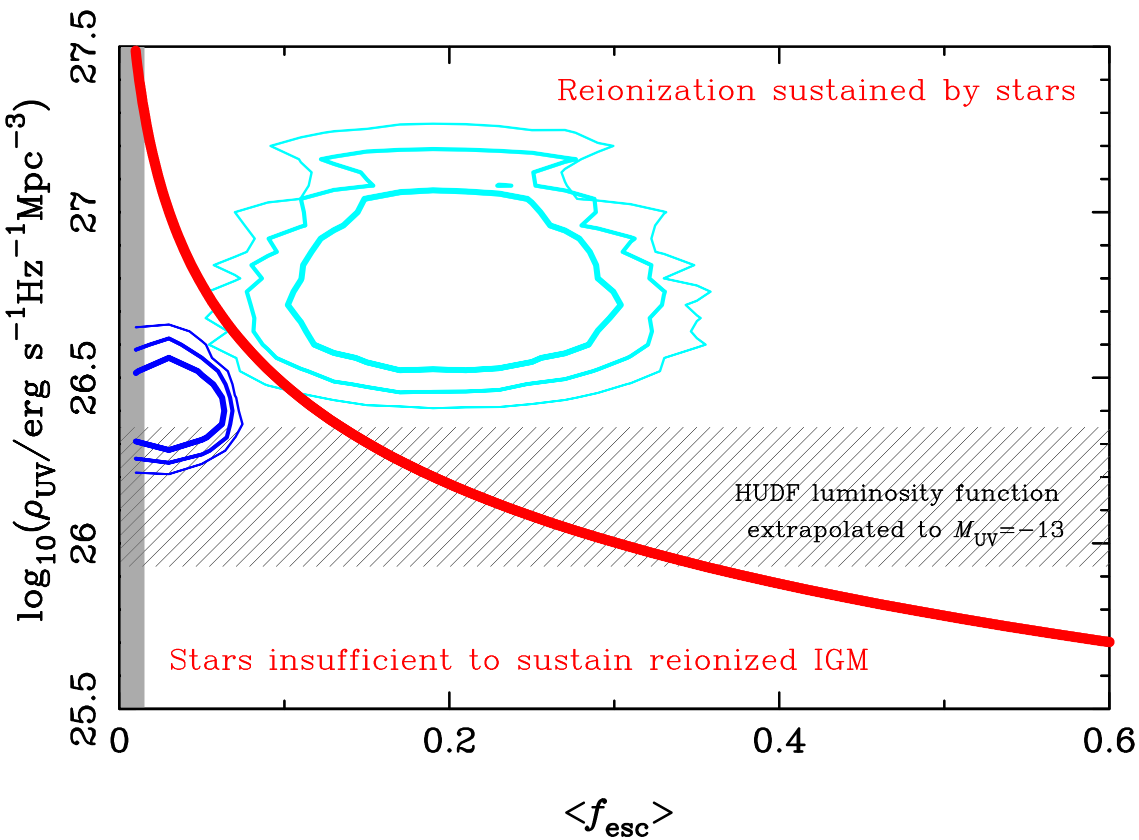
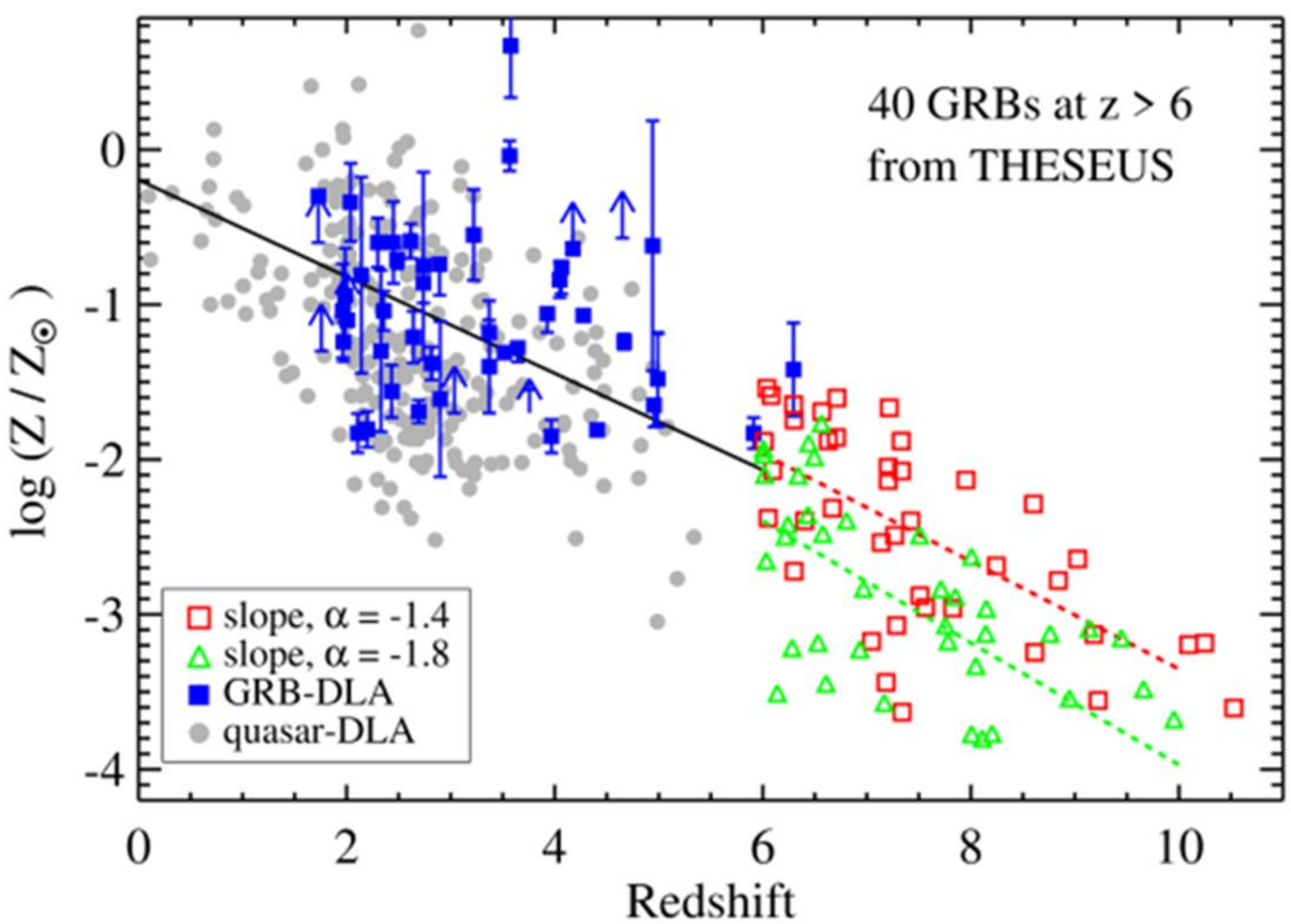
- **Shedding light on cosmic reionization**



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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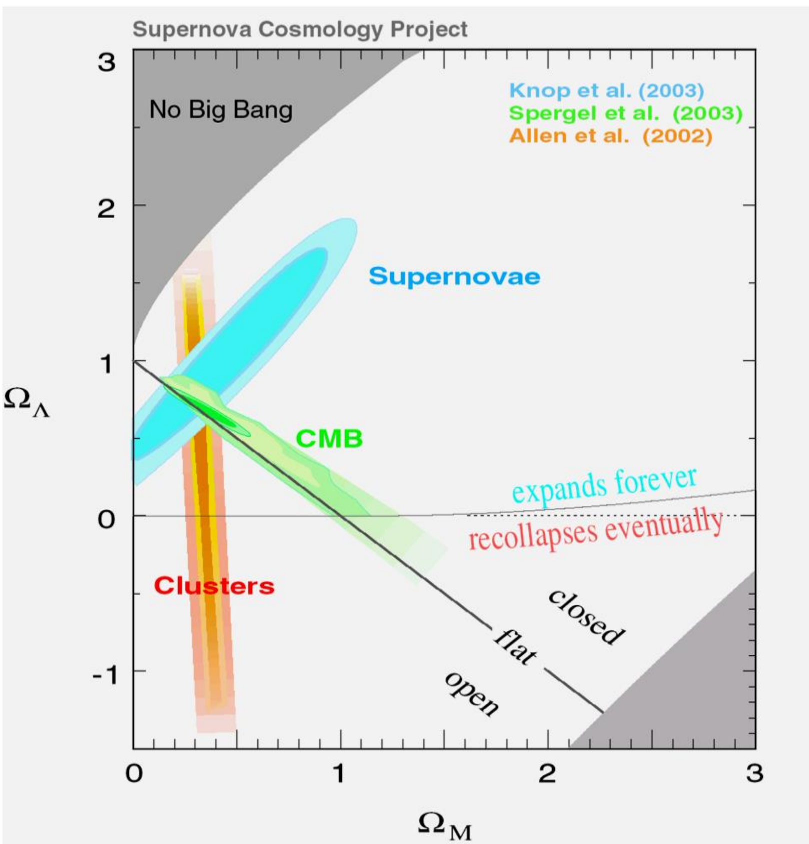
Why looking for more cosmological probes ?

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



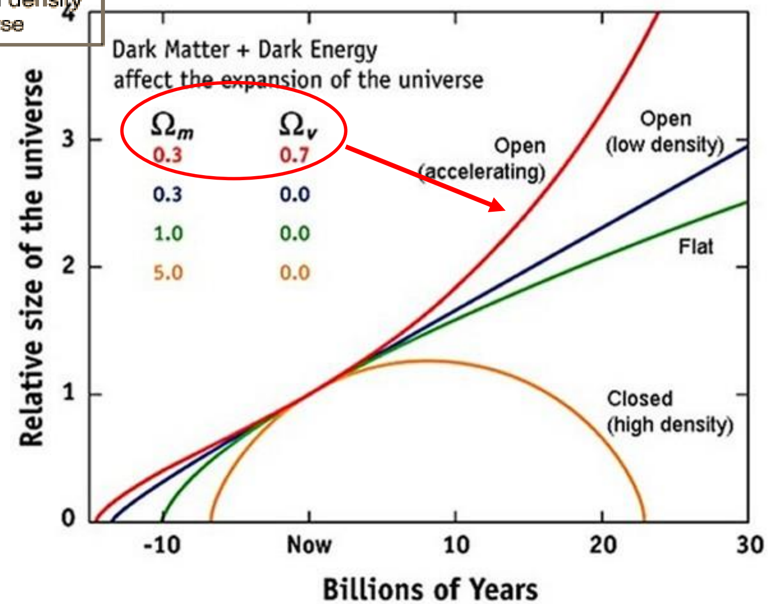
$$\Omega = \Omega_m + \Omega_{rel} + \Omega_\Lambda$$

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 ?

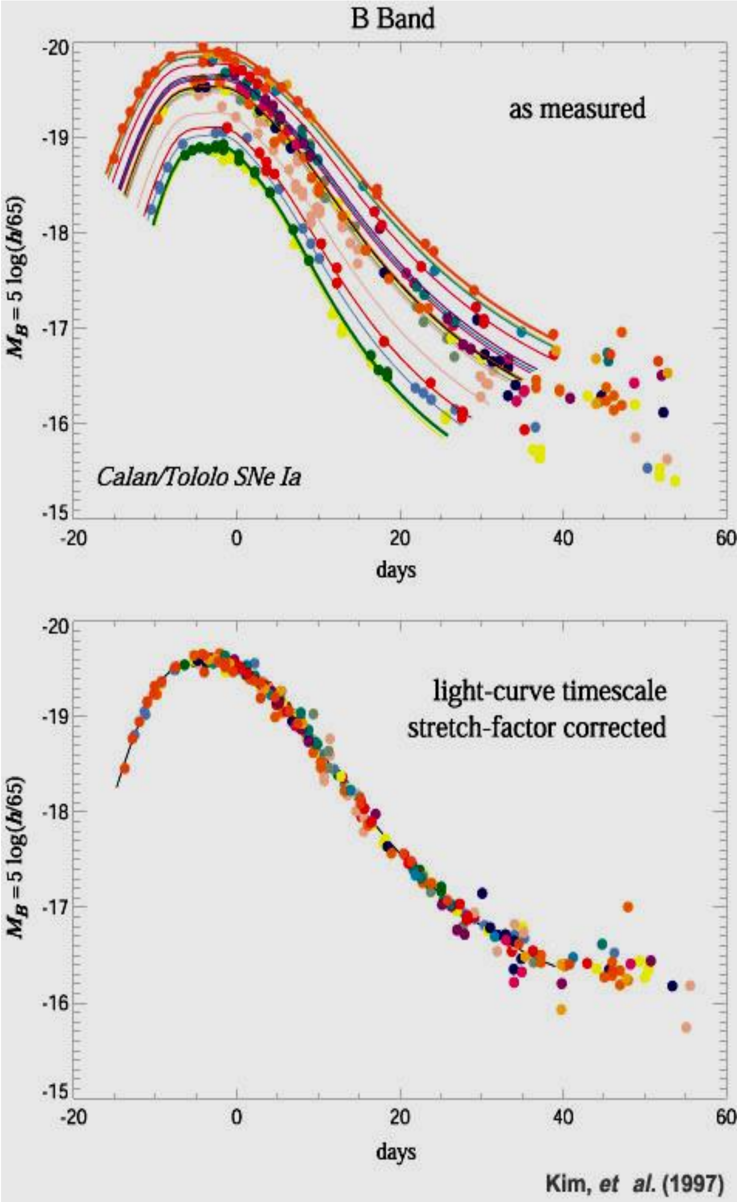
➢ light curve shape correction for the luminosity normalisation may depend on z

➢ signatures of evolution in the colours

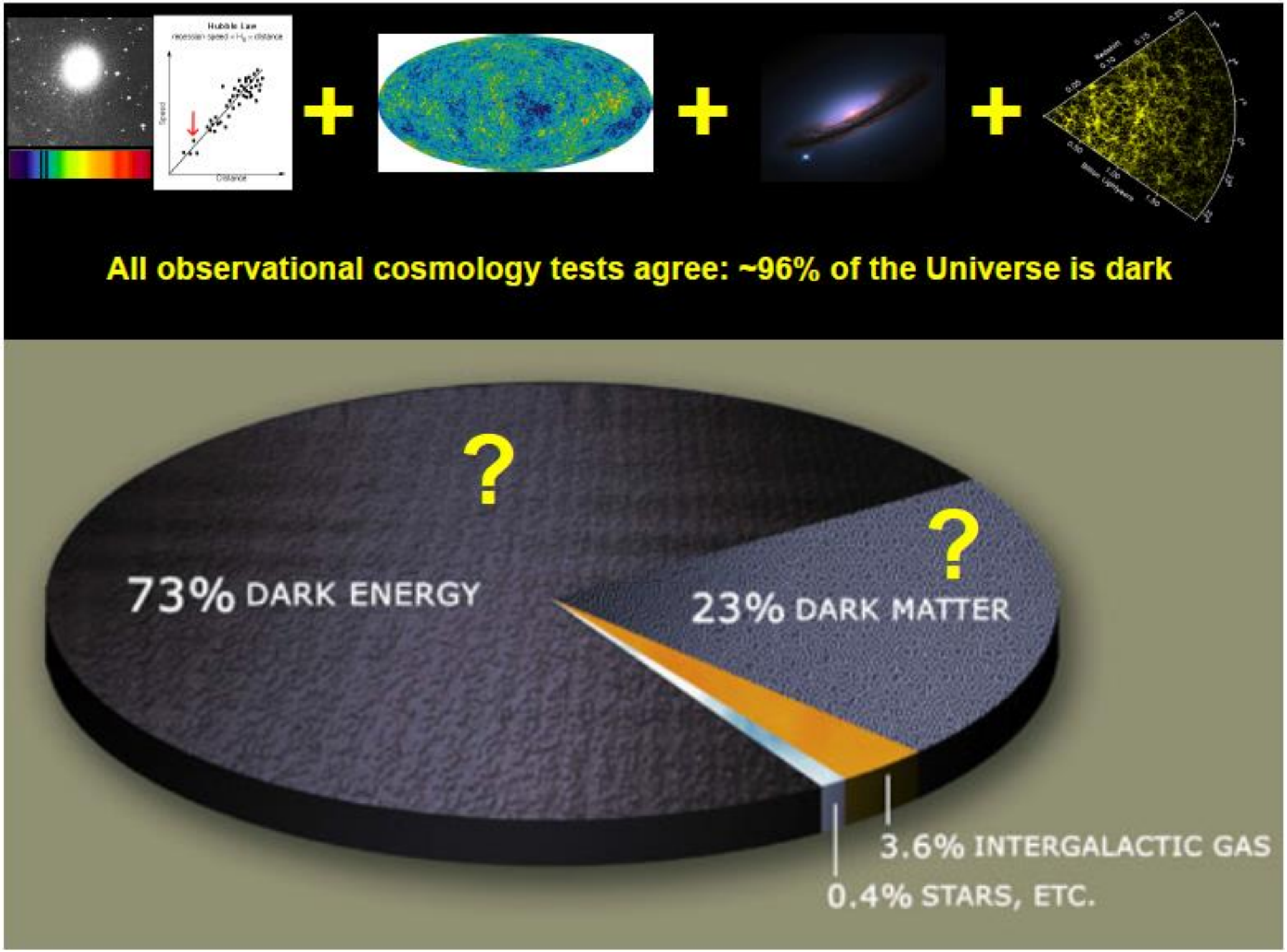
➢ correction for dust extinction

➢ anomalous luminosity-color relation

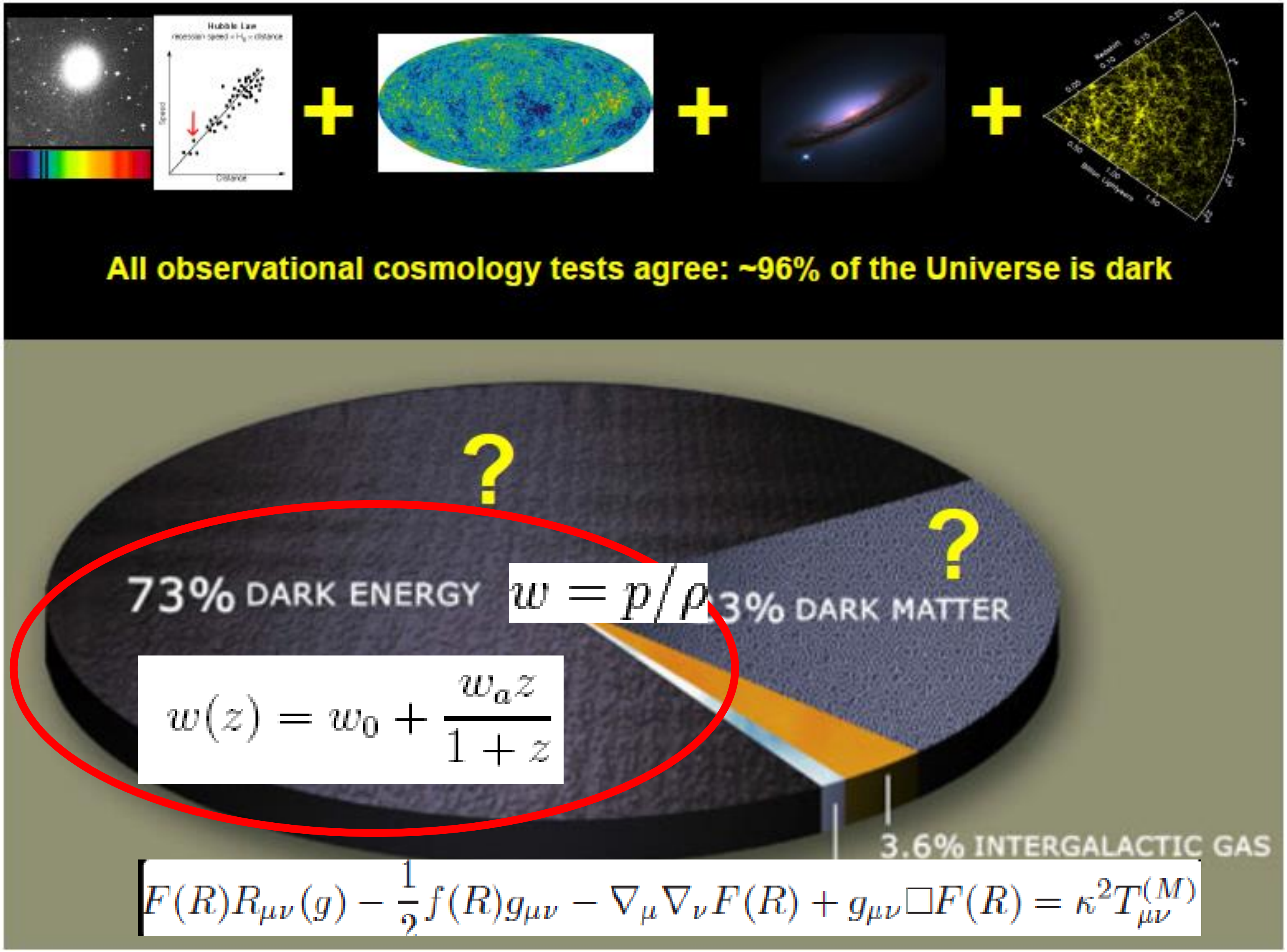
➢ contaminations of the Hubble Diagram by no-standard SNe-Ia and/or bright SNe-Ibc (e.g. HNe)



What we are aiming at ?



What we are aiming at ?

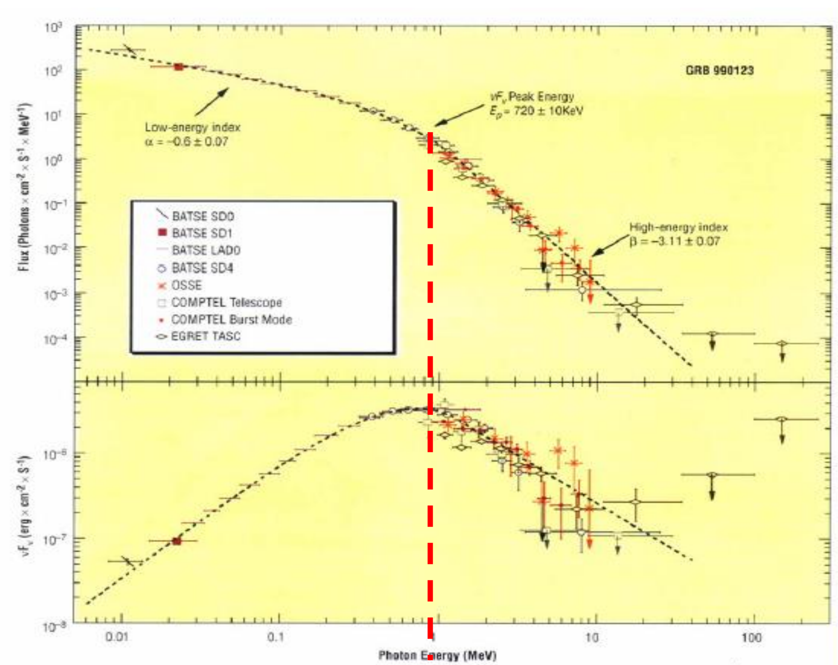


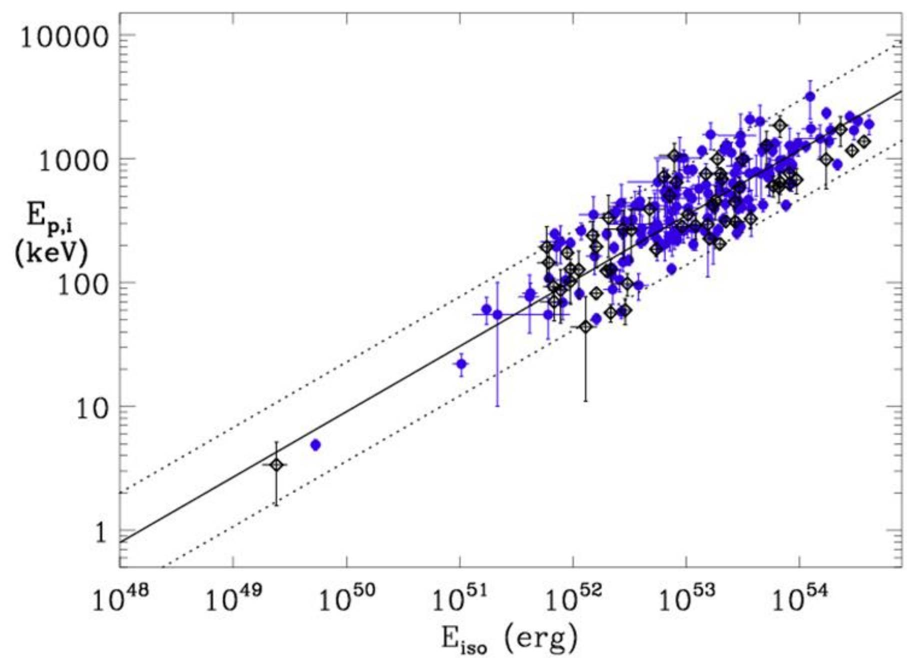
Measuring cosmological parameters with GRBs

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

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

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





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

Standardizing GRBs through the Ep-Eiso correlation

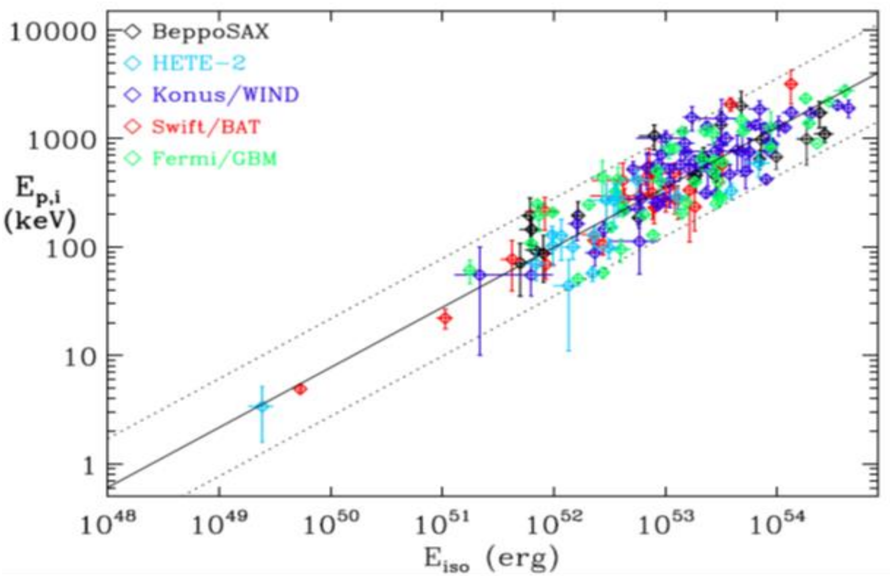
$$E_{p,i} = E_{p,obs} \times (1 + z)$$

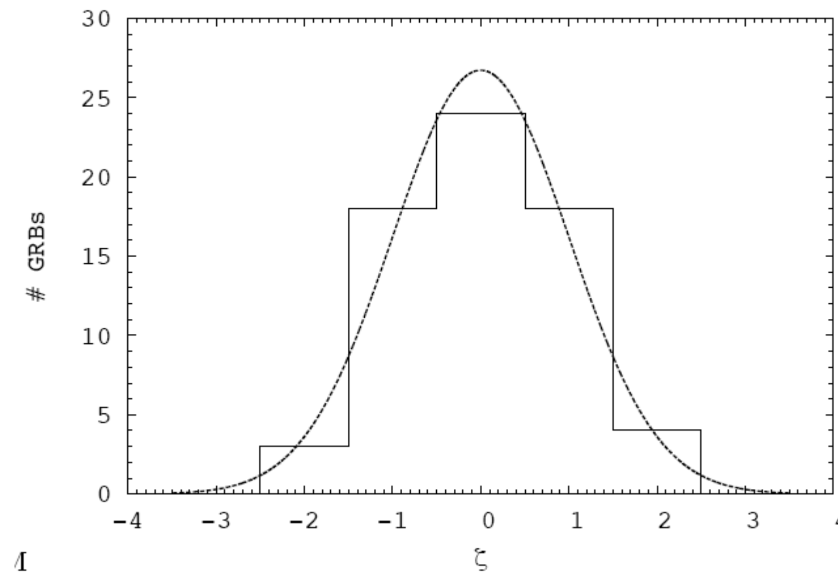
$$E_{\gamma,iso} = \frac{4\pi D_l^2}{(1+z)} \int_{1/1+z}^{10^4/1+z} E\,N(E)\,dE \quad \text{erg}$$

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

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

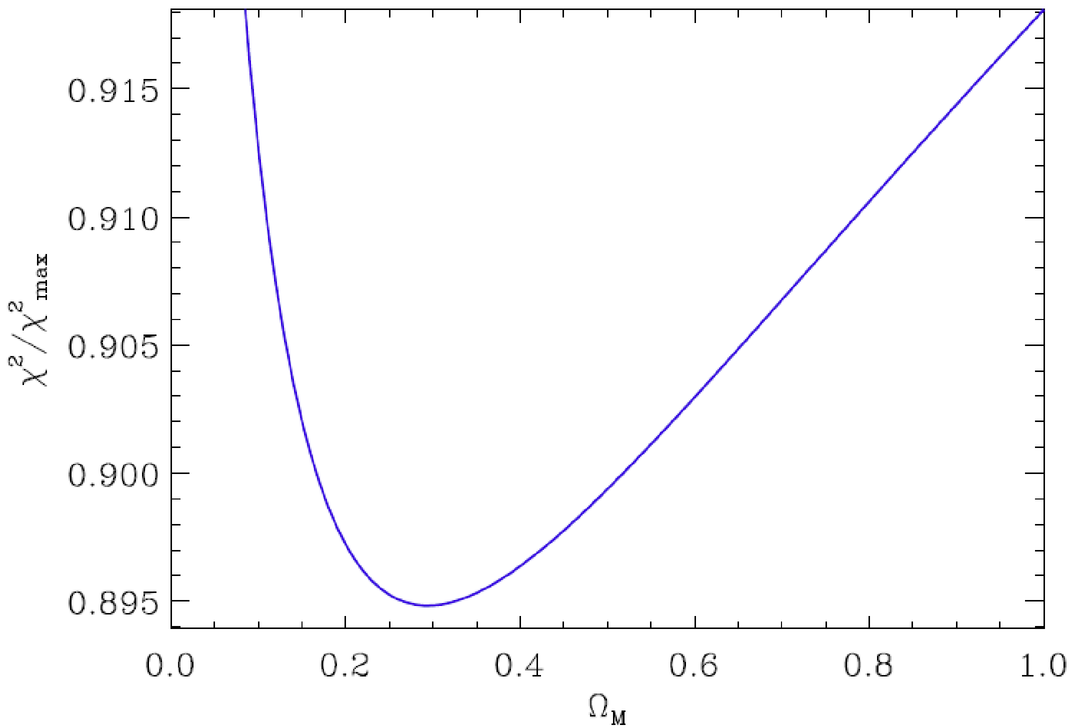
- does the extrinsic scatter and goodness of fit of the Ep,i-Eiso correlation vary with the cosmological parameters used to compute Eiso ?



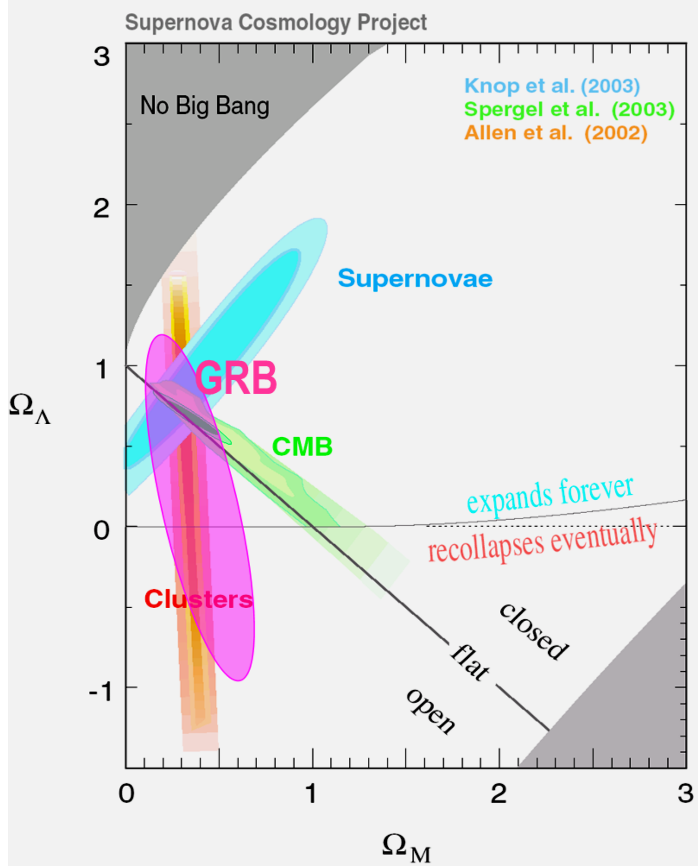


Measuring cosmological parameters with GRBs

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



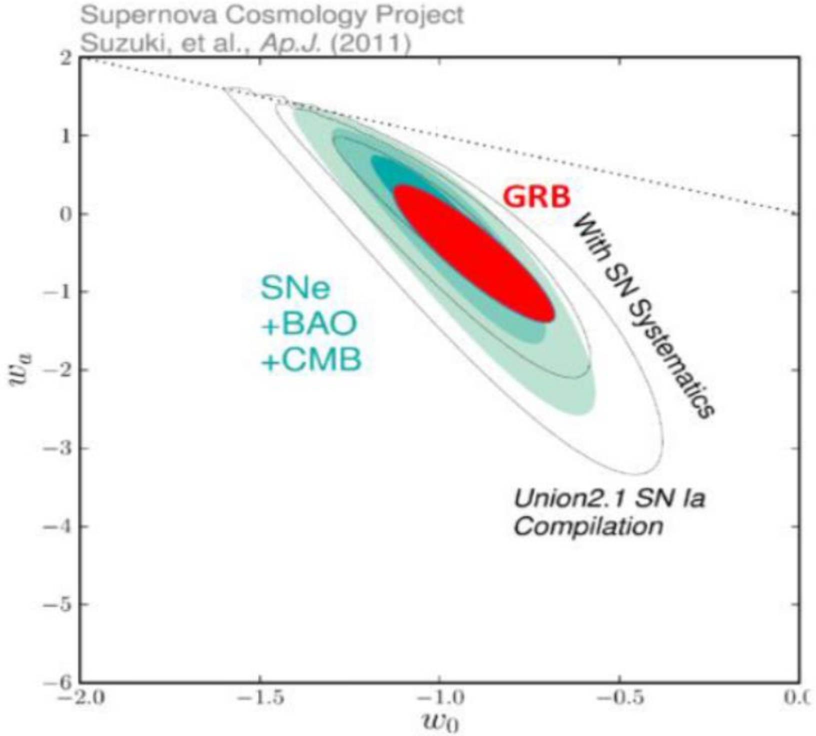
Amati et al. 2008, Amati & Della Valle 2013



Measuring cosmological parameters with GRBs

- Future GRB experiments (e.g., SVOM, 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)

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	$0.30^{+0.03}_{-0.03}$



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

❑ Other approaches investigated

- using Lp instead of Eiso in the correlation with Ep,i (Yonetoku et al., and many): evidence of a general Ep,I – "Intensity" correlation (also time-resolved)

- cosmographic calibration of the Ep,i – Intensity (Eiso or Lp) correlation against Type-Ia SNe (e.g., Capozziello et al., Kodama et al., Tsutsui et al., Demianski et al.): GRBs extending SNe-Ia Hubble diagram but no more independent probes

- "self-calibration" of the correlation with a large enough number of GRBs lying within a narrow (Dz = 0.1-0.2) range of z): promising, requires sample enlargement

- Extending 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.)

Fundamental physics with GRBs: testing LI / QG

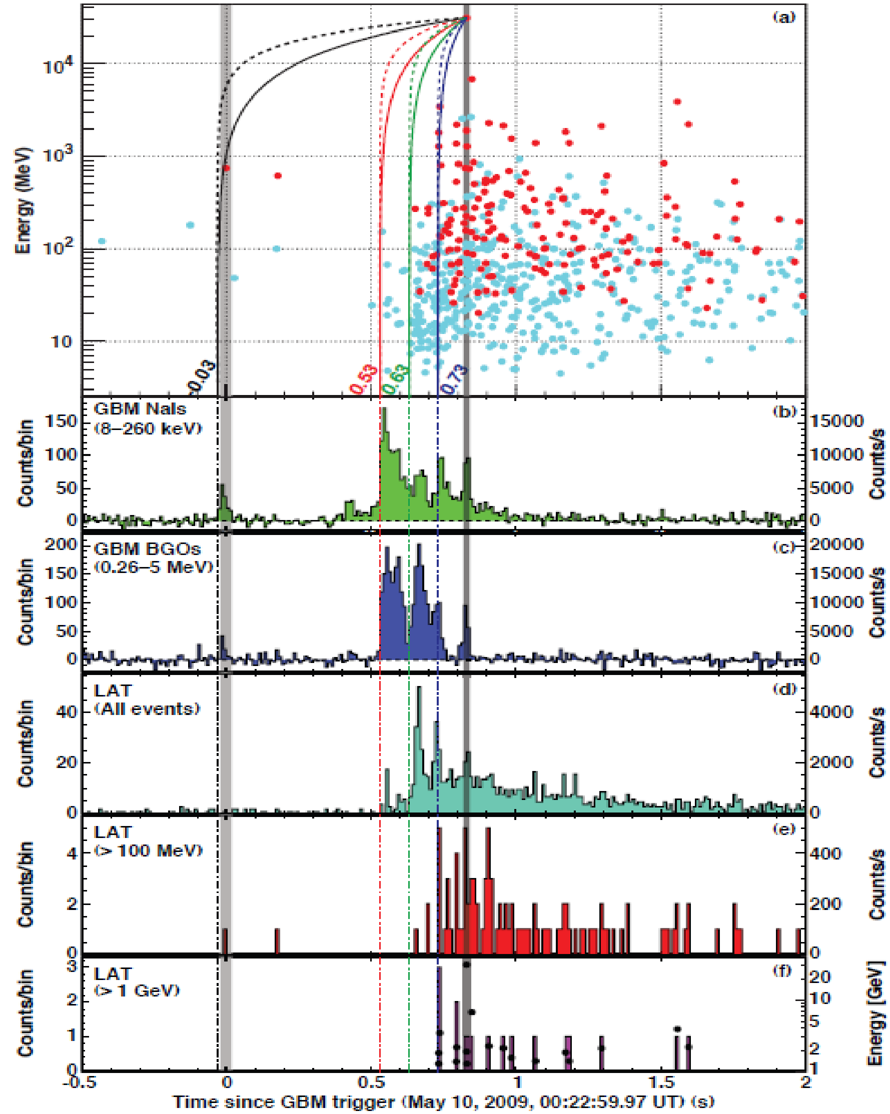
- Using time delay between low and high energy photons to put Limits on Lorentz Invariance Violation (allowed by unprecedent Fermi GBM + LAT broad energy band)

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

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

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/