Gamma-Ray Bursts at High Redshift

Reporter: S. Basa

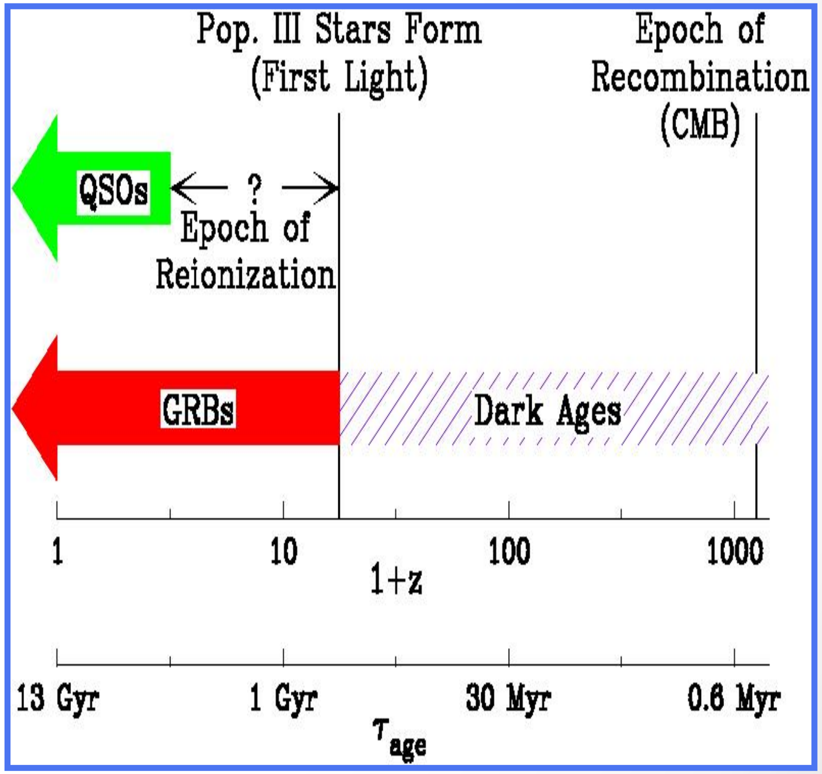
Collaborators (high-z): S. Basa, E.-W. Liang, J.-J. Wei and X.-F. Wu

Collaborators (cosmo): S. Basa, Z.-G. Dai and F. Wang

High-z GRBs as a tool

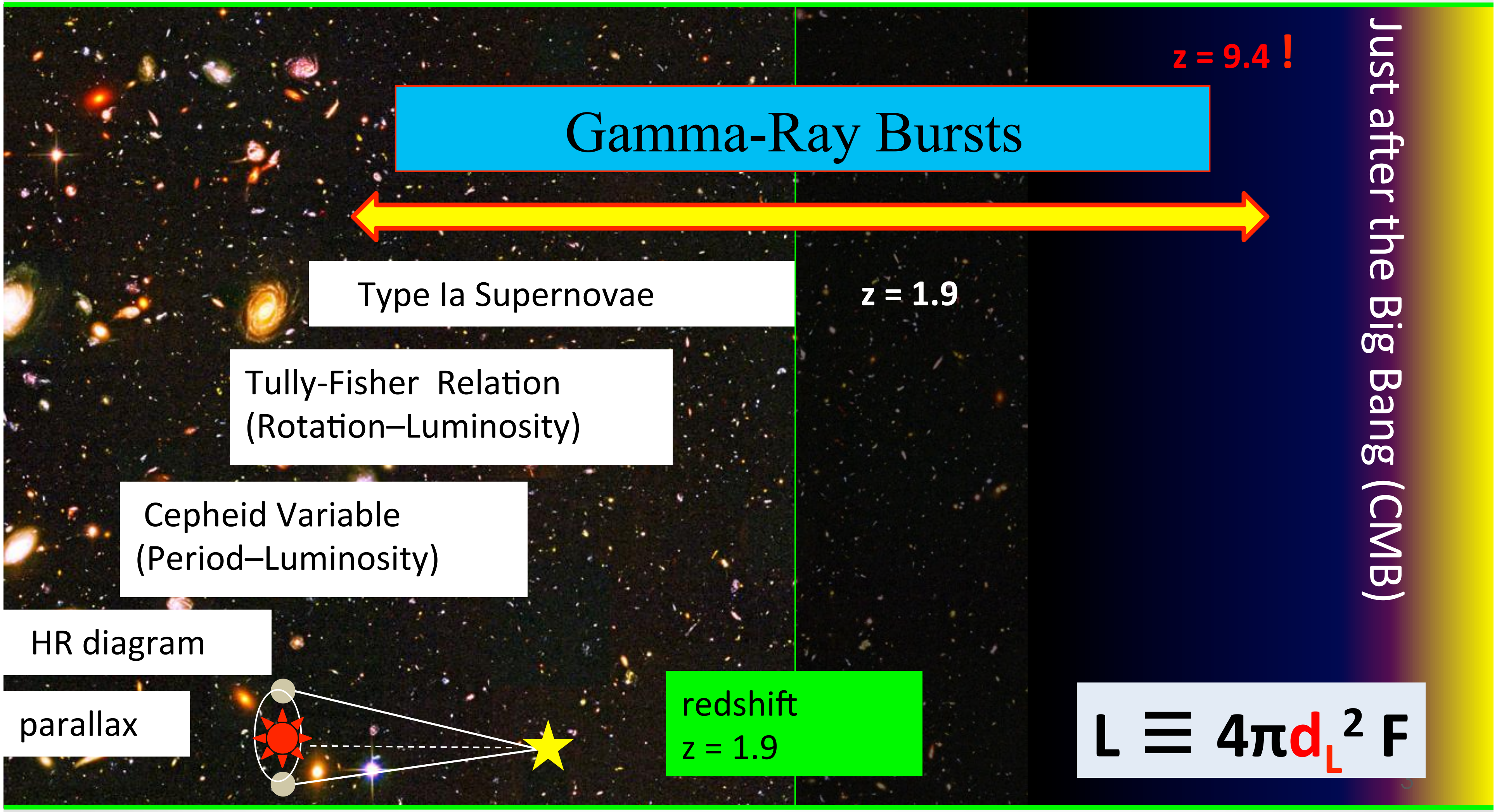
Why GRBs can be used to measure cosmology?

- The brightest event which can be observed.
- Wide redshift range, maybe up to z~15-20 (Lamb & Reichart 2000).
- Gamma ray suffer from no dust extinction.



High-z GRBs as a tool

Constraints on dark energy and cosmological parameters



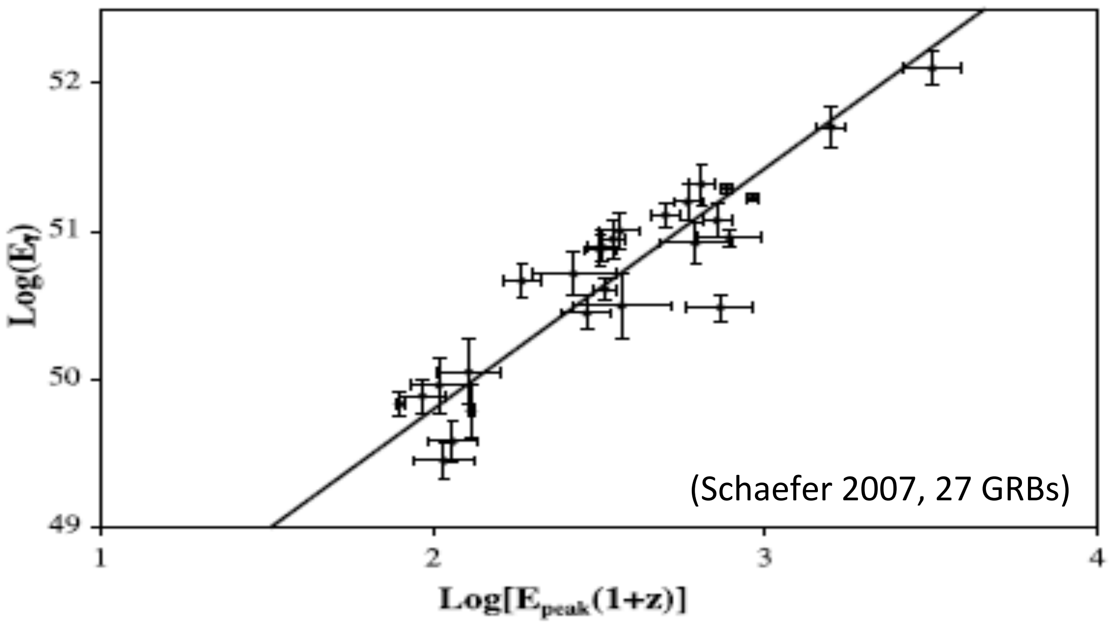
Constraints on the dark energy and the cosmological parameters

Similar to SNe Ia, GRBs luminosity correlations are minimized to measure cosmological parameters:

- ✓ *Liso − τ_{lag} correlation*: luminosity-time lag correlation (Norris et al. 2000).
- ✓ *Liso − V correlation*: time variability correlated with the luminosity of GRBs, which indicates that more luminous bursts have more variable light curves (Fenimore and Ramirez-Ruiz 2000).
- ✓ *Yonetoku correlation*: $L_{iso} \propto E^2_{peak}$ (Yonetoku et al. 2004).
- ✓ *Liang-Zhang correlation*: an empirical correlation among the isotropic energy of the prompt gamma-ray emission E_{iso}, the rest-frame peak energy E_{peak}, the rest-frame break time in the optical band t_{break}.
- ✓ *Amati correlation*: isotropic energy E_{iso} is correlated with the rest-frame peak energy of the prompt spectrum (i.e., $Epeak \propto E^{0.52}_{iso}$).
- ✓ *Ghirlanda correlation*: a tight correlation between spectral peak energy and collimated energy.
- ✓ Etc.

Example of correlation function

The so-called Guirlanda relation



$$E_\gamma - E_p: \qquad \log E_\gamma = a + \left[b(E_p(1+z)/300keV \right]$$

The Circularity problem

In order to measure the cosmological parameters, correlations must be calibrated in a cosmological model independent way:

- ✓ Otherwise a circularity problem appears...
- ✓ In principle, circularity problem can be avoided in two ways (Ghirlanda et al. 2006):
  1) A solid physical interpretation of these relations, which would fix their slope independently from cosmology.
  2) The calibration of these relations by several low redshift GRBs.

Not so easy in fact…

The Circularity problem

Many previous works treated the circularity problem with a statistical approach:

- ✓ Simultaneous fit (Schaefer 2003): parameters in the calibration curves and the cosmology are carried out at the same time.
- ✓ Bayesian method (Firmani et al. 2005).
- ✓ Markov Chain Monte Carlo global fitting (Li et al. 2008).

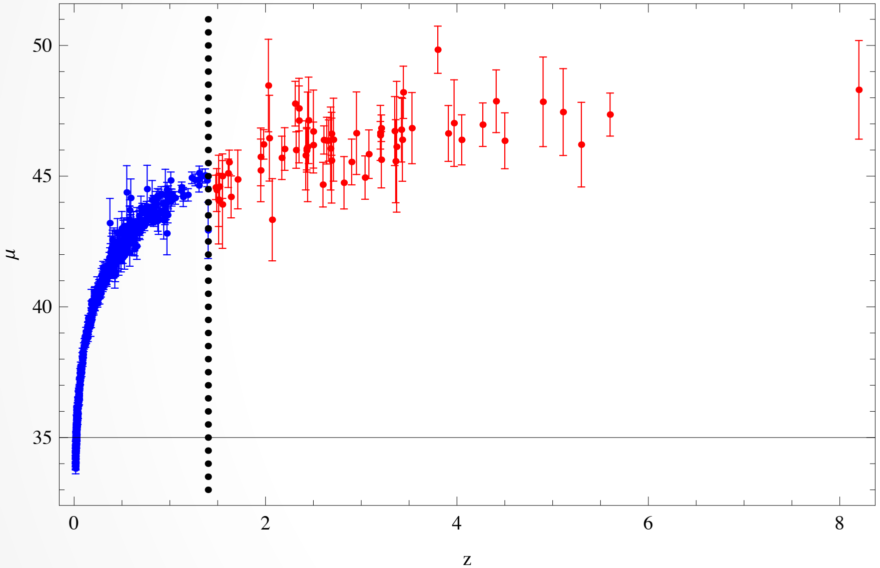
In any case, as a particular cosmology model is required in doing the joint fitting, the circularity problem is not solved completely by means of statistical approaches.

Evolution of the correlation?

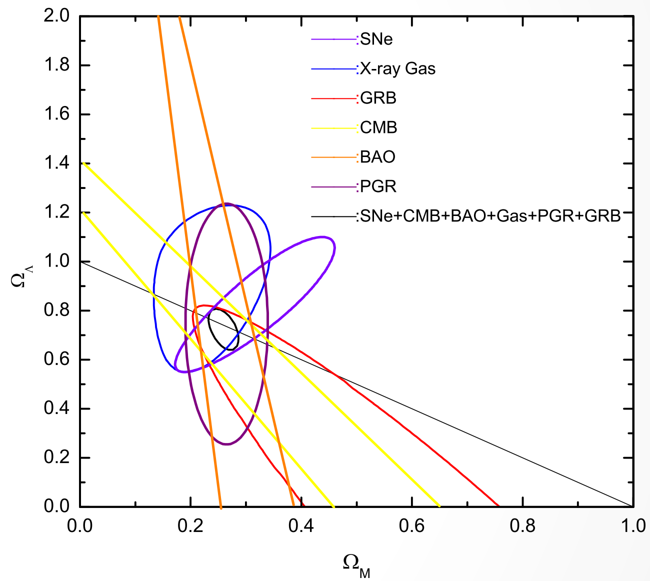
Due to the fact that GRBs cover large redshift range, whether the correlations evolve with the redshift must be studied:

- ✓ The slope of Amati correlation may vary with redshift significantly (Lin et al. 2007 & 2015).
- ✓ At the opposite, for other correlations, no statistically significant evidence for the evolution of the others luminosity correlations with redshift found (Basilakos & Perivolaropoulos 2008, Wang et al. 2001).
- ✓ Meanwhile, instrumental selection effects may affect the observed luminosity correlations (i.e., Nakar & Piran 2005).

Present constraints on the dark energy and the cosmological parameters



Hubble diagram of 557 SNe Ia (blue) and 66 high-redshift GRBs (red) (adapted from Wang & Dai, 2011).

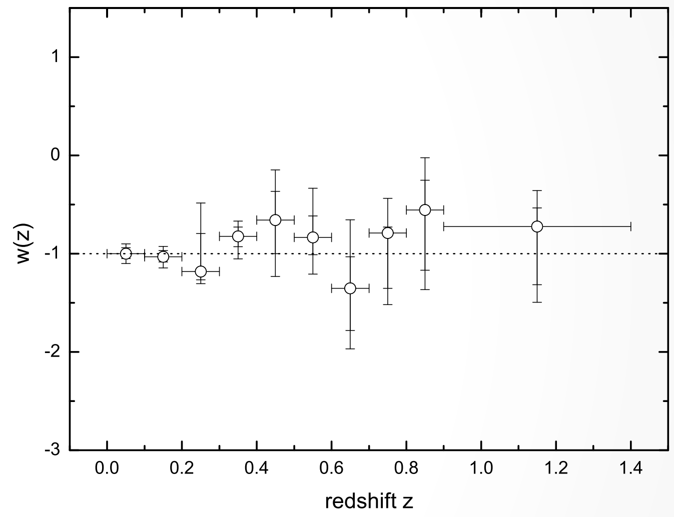


Joint confidence intervals of 1σ for (Ω_M,Ω_Λ) from the observational datasets (adapted from Wang et al. 2007).

Present constraints on the equation of state of the dark energy

The equation of state *w=p/ρ* is a key parameter to describe dark energy properties:

- ✓ Whether and how it evolves with time is crucial for revealing the physics of dark energy.
- ✓ GRBs can provide the high-redshift evolution property of dark energy.



Estimation of the uncorrelated the EOS parameter at different redshift bins from SNe Ia +BAO+WMAP9+H(z)+GRB data (adapted from Wang & Dai, 2014).

Until now, EOS consistent with the cosmological constant at 2σ confidence level, not preferring a dynamical dark energy model.

Prospect in the SVOM era

GRBs attracted a lot of attention as promising standardizable candles to construct the Hubble diagram at very high redshift:

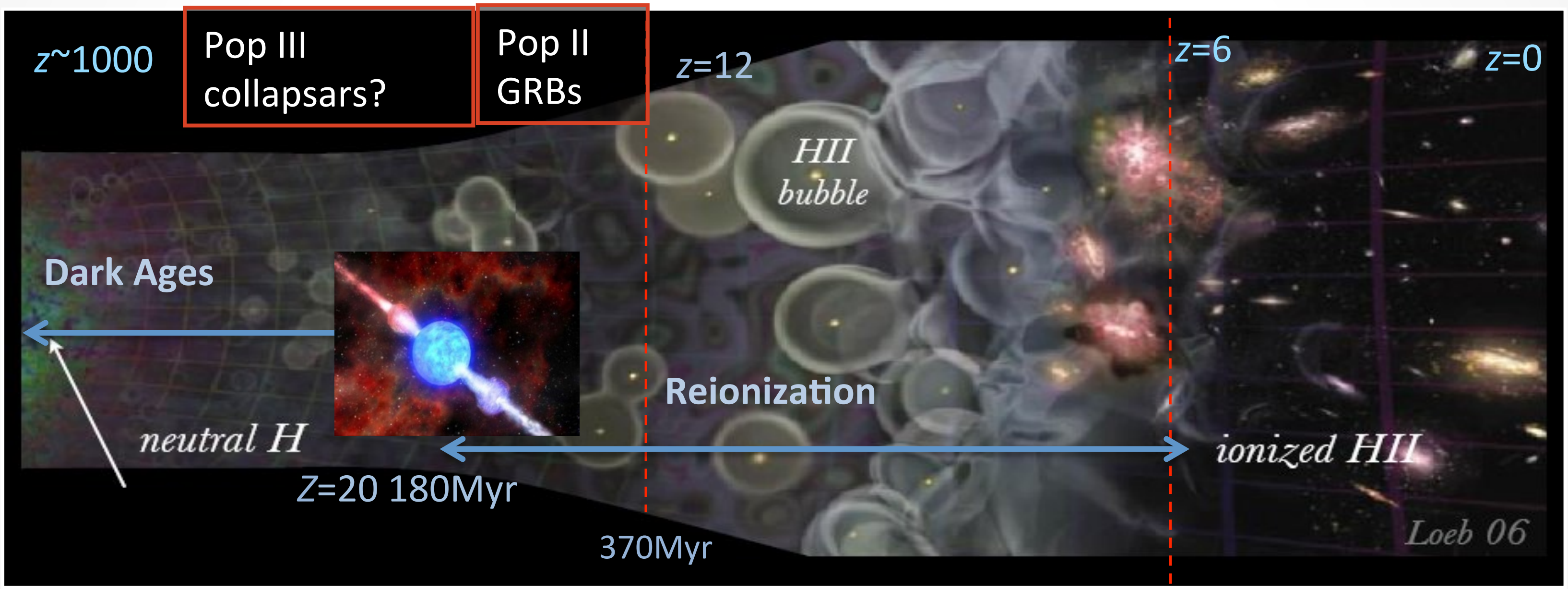
- ✓ Complementarity to other cosmological probes, such as SNe Ia, CMB and BAO.
- ✓ However without reaching the level of details of these probes.

The most important thing is probably to search for a correlation similar to that used to standardize SNe Ia:

- ✓ In order to obtain these correlations, a better understanding of the physics inside GRBs is probably needed.

High-z GRBs as a tool

First stars and early Universe



Credit L. Piro

- ✓ The first stars, Population III stars, are predicted to form in dark matter mini-halos of typical mass ~10^6 M_{sun} at z~20–30 out of a gas of pristine composition (Ciardi & Ferrara 2005, Bromm & Yoshida 2011).
- ✓ Pop III stars played a crucial role in early universe evolution, including reionization and metal enrichment history.

Catching the first stars: not so easy…

Direct observations of the Pop III stars have so far been out of reach:

- ✓ Will stay difficult even with JWST and the next generation of extremely-large telescopes on the ground (GMT, TMT and E-ELT)
- ✓ Despite their sensitivities, even these observatories may not be able to directly probe the first stars, unless they formed in massive clusters (Pawlik et al. 2011), or were gravitationally lensed (Rydberg et al. 2013).

The only opportunity to probe individual Pop III stars may be to catch them at the moment of their explosive death:

- ✓ Hypernovae or pair-instability SNe.
- ✓ **GRBs.**

Indirect search for Pop III stars

Some studies show that some Pop III stars will end as GRBs (Pop III GRBs):

- ✓ Total isotropic energy could be ~2 orders of magnitude larger than average (Bromm & Loeb 2006; Heger et al. 2003; Stacy et al. 2011).

In this context:

- ✓ Minimum energy expected from a GRB triggered by a Pop III star near the maximum energy recorded for any GRB.
- ✓ **Any GRB of $z \geq 6$ with $E_{iso} \geq 8 \times 10^{54}$ erg and a very long duration, $t_d > 10^4$ s, (the "smoking gun") would potentially have a Pop III progenitor.**

Associate a GRB to a Pop III star

But it is not so easy to associate with certainty a distant GRB to a Pop III star:

- ✓ An unambiguous way is to examine whether the afterglow spectrum from surrounding medium is devoid of iron-group elements through high-resolution IR and X-ray spectroscopy.

- ✓ However, there may also be the case that the surrounding medium is embedded in a region where stellar explosions have already occurred slightly earlier, and the absorption lines of the first heavy elements produced by those explosions are thus imprinted (Wang et al. 2012).

- ✓ In this regard, another proposed way is to focus on the total energies and durations of GRBs estimated by the X-ray and gamma-ray observations of prompt emissions and/or afterglows (Komissarov & Barkov 2010; Meszaros & Rees 2010; Toma et al. 2011; Suwa & Ioka 2011).

Rate of Pop III GRBs

The rate of GRBs triggered by a Pop III Star is probably very low:

- ✓ Campisi et al. 2011 leads to the conclusion that, if at least 10 GRBs are detected at $z > 6$, one should be triggered by a Pop III star.

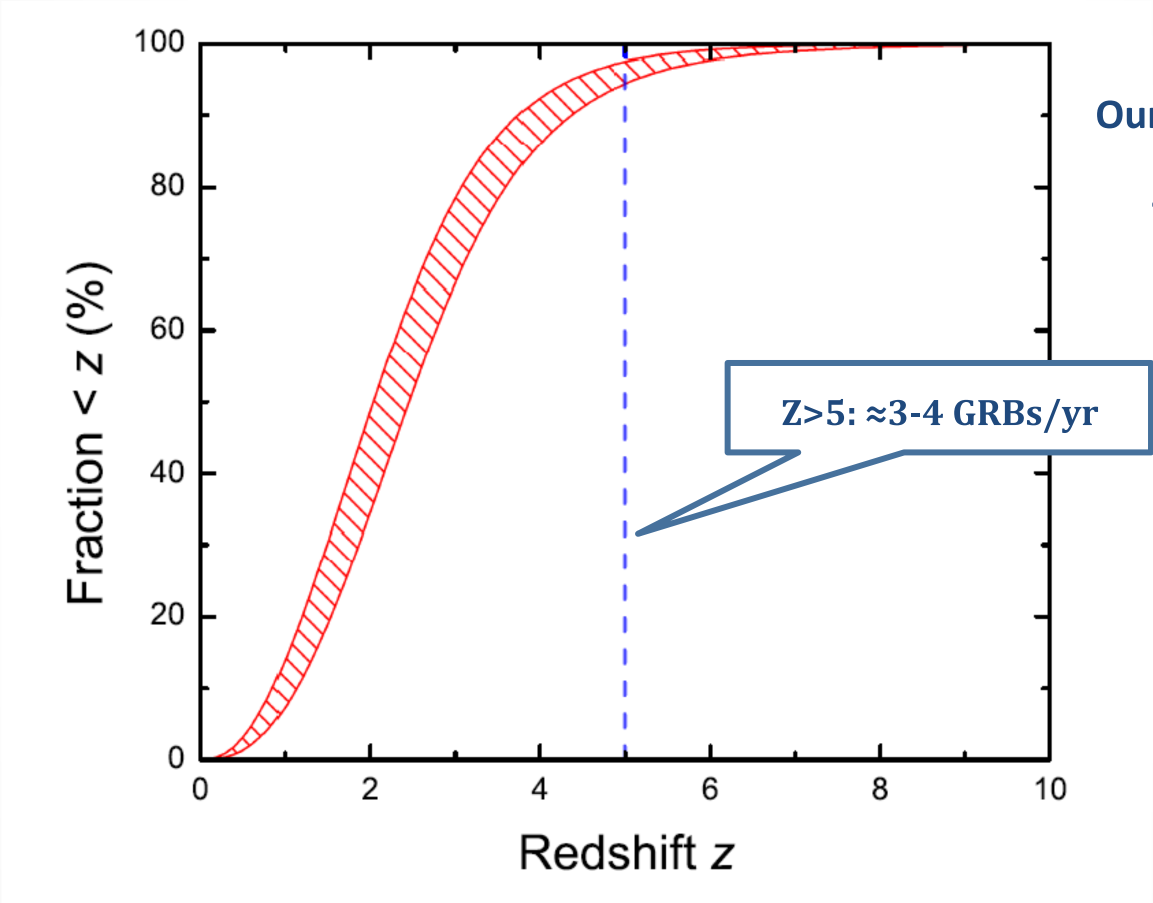
- ✓ Salvaterra et al. 2011 is more (too?) optimistic: 100 times larger than previous estimations.

- ✓ At the present, though, the number of such high-z GRBs is too small and the available data not good enough to discriminate their origin.

High-z GRB rate

SVOM/ECLAIRs

Field-of-view: 2 sr   Energy band: 4-150 keV   Sensitivity (@10s): 7.2E-8 erg/s/cm^2



Simulated redshift distribution of GRBs to be detected by ECLAIRs

Our simulations show that ECLAIRs will detect 70-77 GRBs per year

Nearly 4%-5% of ECLAIRs GRBs could be situated at high redshift (z > 5)

Prospect in the SVOM era

Nearly 4%-5% of ECLAIRs GRBs are expected to be high-*z* GRBs (*z*>5).

The rate of GRBs triggered by Pop-III stars is so small:

- ✓ About 1 GRB triggered (Campisi's rate) by a Pop-III during the lifetime of SVOM…
- ✓ It may well be easier to detect the Pop III stars from their orphan afterglows than by their prompt gamma-ray emission:
  - ✓ It is not a deficiency on the part of any GRB detector, simply a fact that the beaming reduces the number of observable events by more than two orders of magnitude.
  - ✓ Pop III GRBs could be at the end more easily detected by their isotropic emissions (i.e. orphan afterglows) rather than by their prompt emissions (Macpherson et al. 2013).