Gamma-Ray Bursts as Cosmological Probes

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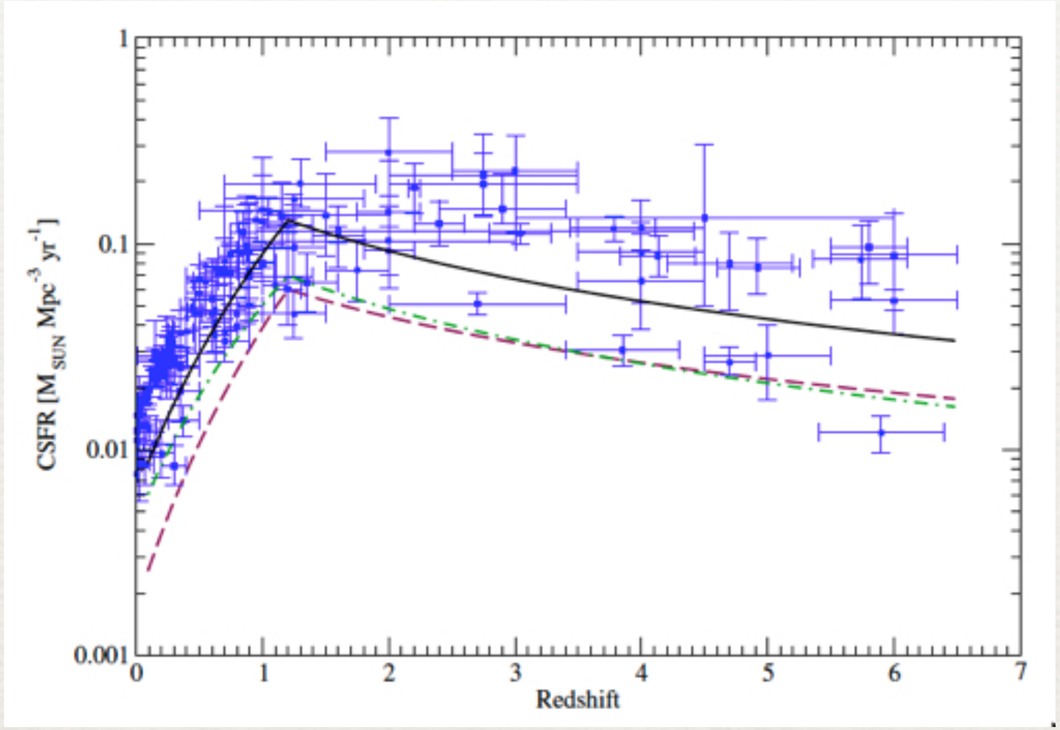
The Next Generation of Physics, Spun from Universality & Emergence
Developing Independent Researchers to Explore New Frontiers

Talk Plan

- GRB as a probe of cosmic star formation history
- GRB as a probe of cosmic reionization
- GRB as a standard candle to study cosmic expansion
- GRB as a probe of cosmic optical/infrared background radiation
- "cosmology" including galaxy formation, high-z universe, in addition to "core" cosmology (cosmological parameters, dark energy, etc.)

GRBs as a Probe of Cosmic Star Formation History

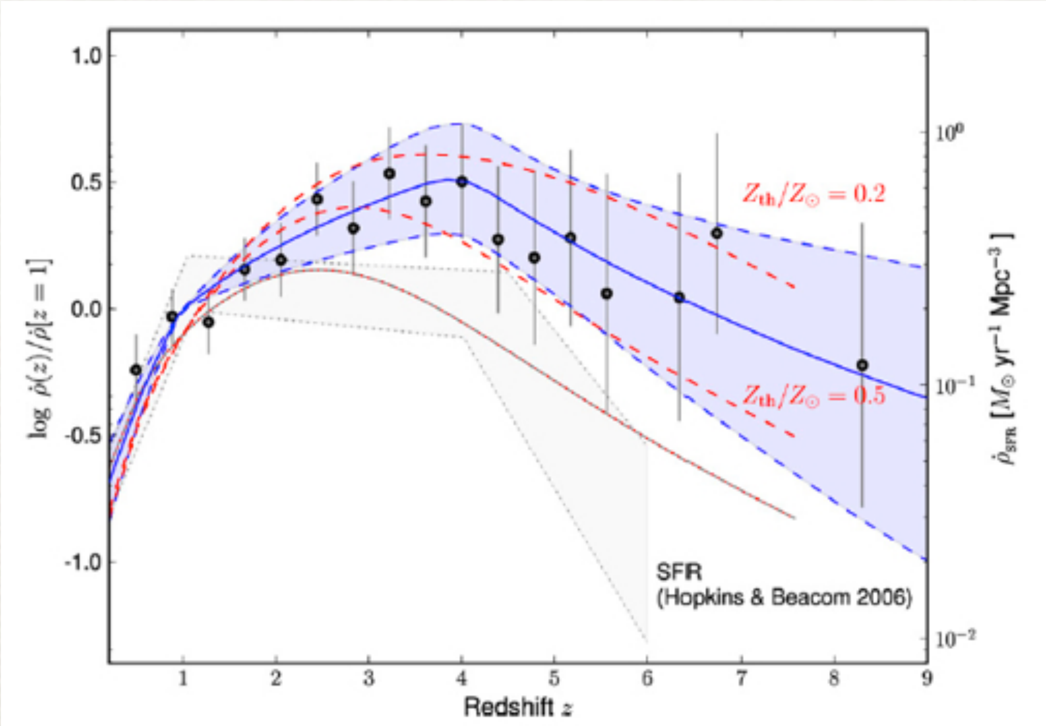
- We expect GRB rate ∝ SFR, making it a SFR indicator (Totani '97; Wijers+'08)
- strength:
  - reaches to very high-redshift
  - no extinction by dust (for gamma-rays)
  - no limit about host galaxy luminosity
- weakness:
  - complicated efficiency for detection and redshift measurements
  - may be a biased SF indicator
    - e.g., metallicity / host galaxy mass
    - can be a probe of GRB progenitor nature, if CSFH is given



Kneiske+'10

GRB rate history different from CSFH?

- various papers found that (long) GRB rate is relatively higher than SFR at high-z
  - RGRB/SFR ∝ $(1+z)^{\alpha}$, α~1
  - e.g., Daigne+'06; Guetta+'07; Le+'07; Salvaterra+'07; Kistler+'08,'09; Li '08; Salvaterra+'09; Campisi+'10; Qin+'10; Wanderman+'10

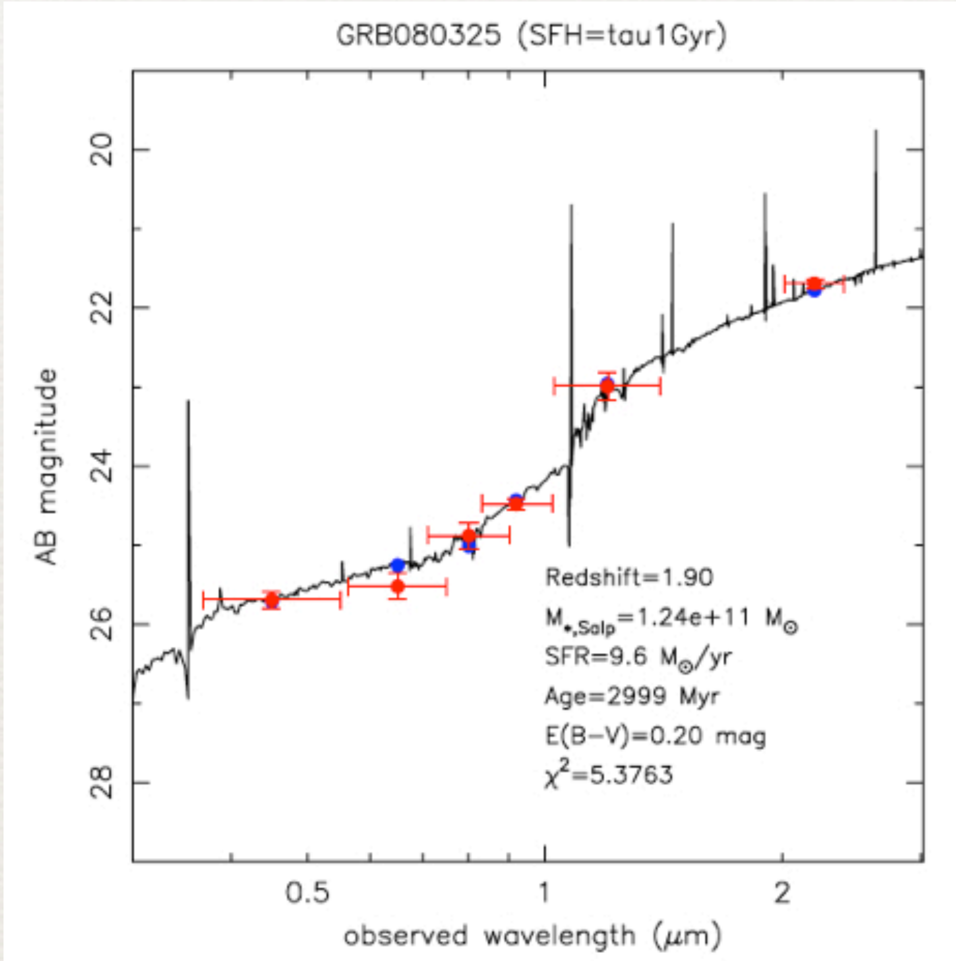


Butler+'10

- indicating low metallicity for GRBs?
- some other selection effects?

Sampling Bias of GRB redshifts

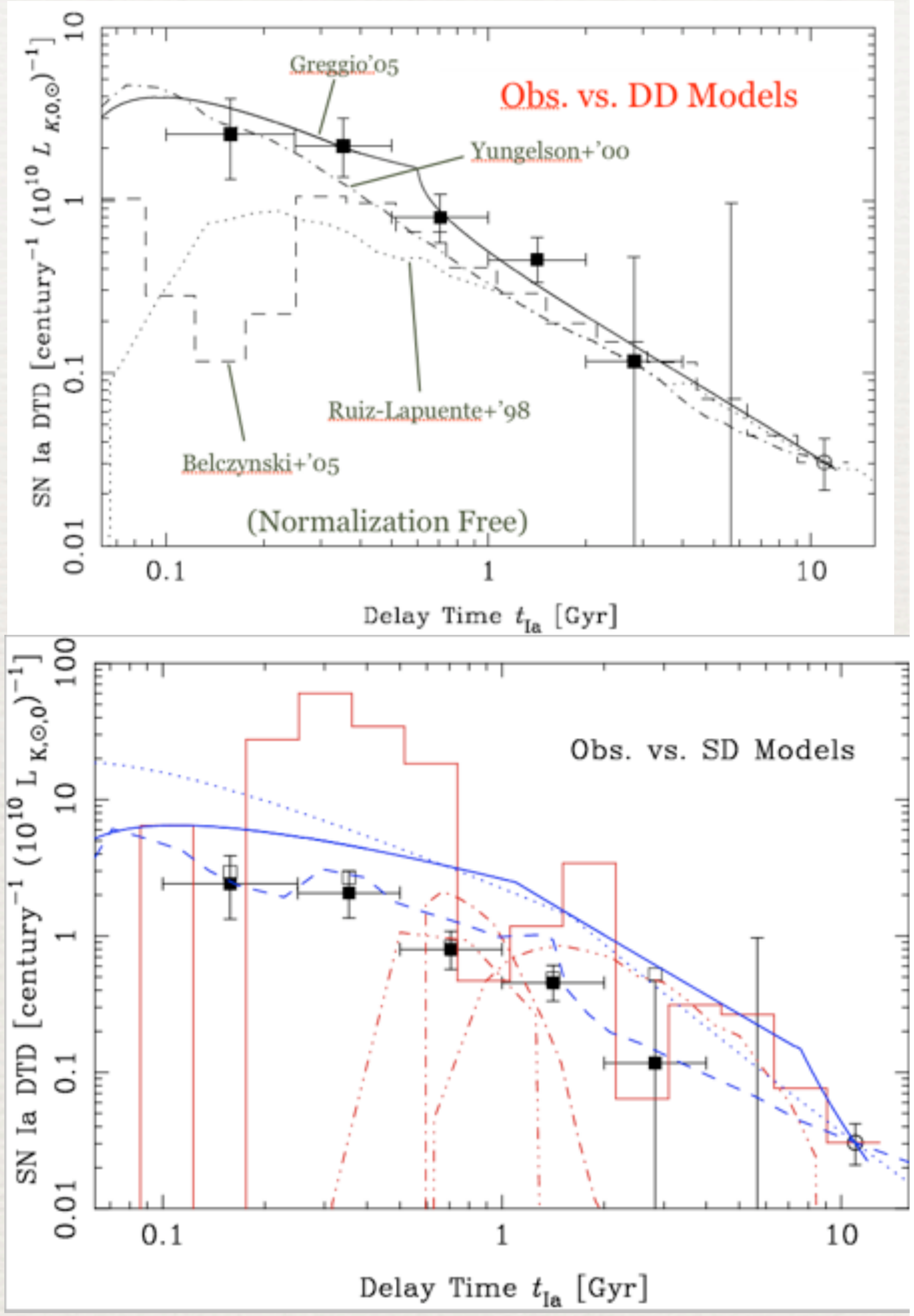
- recent more complete sample indicates that the primary reason of no-afterglow GRBs ("dark GRBs") is large extinction by dust
  - Greiner+'10; Kruhler+'10
  - no low-Z preference?
  - Z dispersion within a host? (Niino '11, see also poster #41
- the past sample with known redshifts is most likely biased to low-mass, low-metallicity galaxies
- the latest sample by GROND is consistent with the simple picture of $R_{GRB} \propto$ SFR
  - Elliott+'12
- secure conclusion: LGRB rate is roughly consistent with simple relation of $R_{GRB} \propto$ SFR
  - sampling bias is the crucial issue to derive stronger conclusions from GRB rate study



Hashimoto+'10

short GRBs vs. CSFH

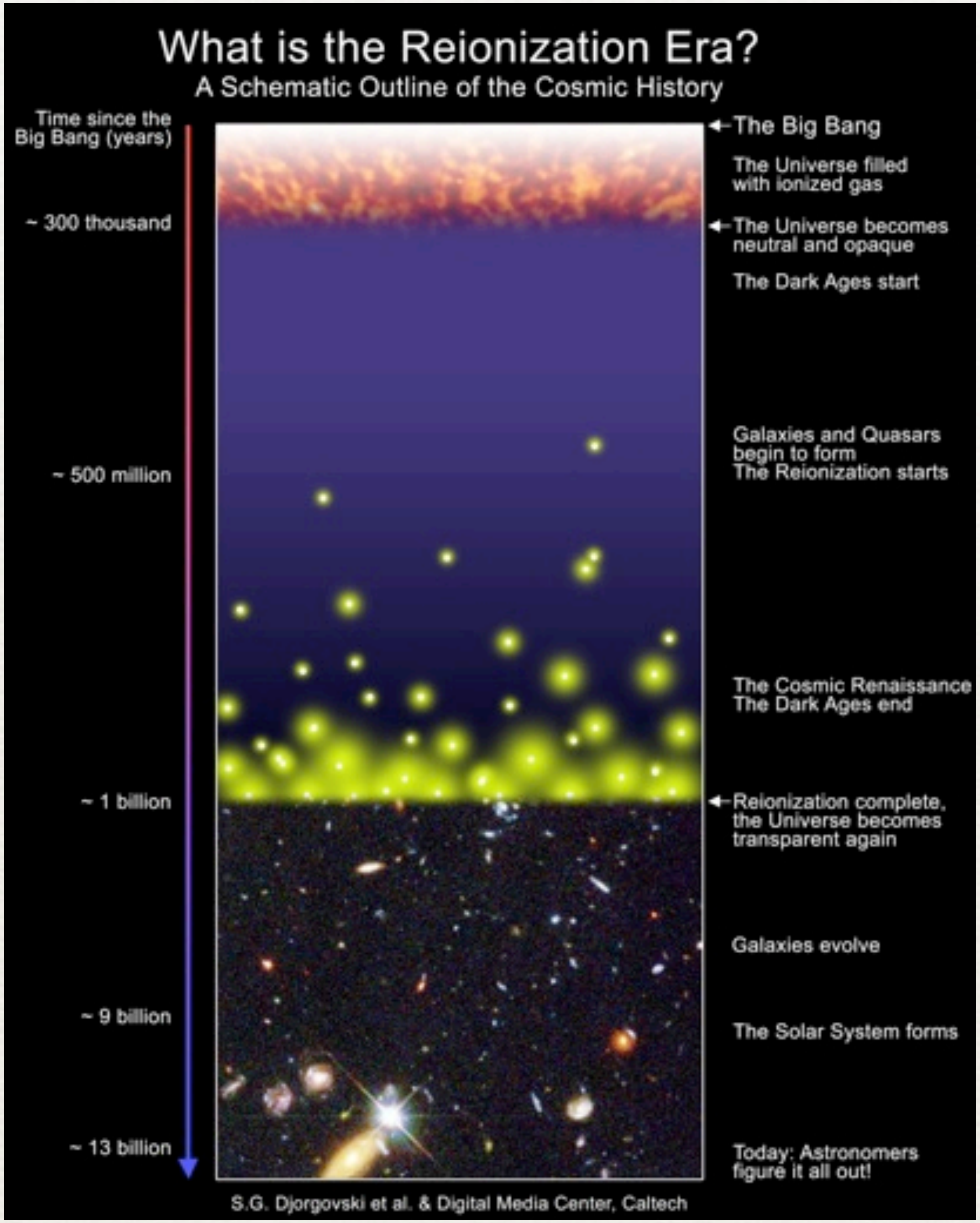
- In the NS-NS(BH) merger scenario, delay time distribution (DTD) of GRB events from star formation should be $\propto t_D^{-1}$
  - $t_{GW} \propto a^4$ (a: initial binary separation)
  - only weakly depends on separation distribution (TT '97)
- Is SGRB rate history consistent with CSFH convolved with DTD?
  - an interesting study if we have enough number of SGRBs with z
- A similar study: type Ia SN rate
  - rate studies now converges to SN Ia DTD of t_D^{-1} (TT+'08; ...)
  - preferring double-degenerate (WD-WD) progenitor scenario



SN Ia DTD, Totani+'08

Cosmic Reionization

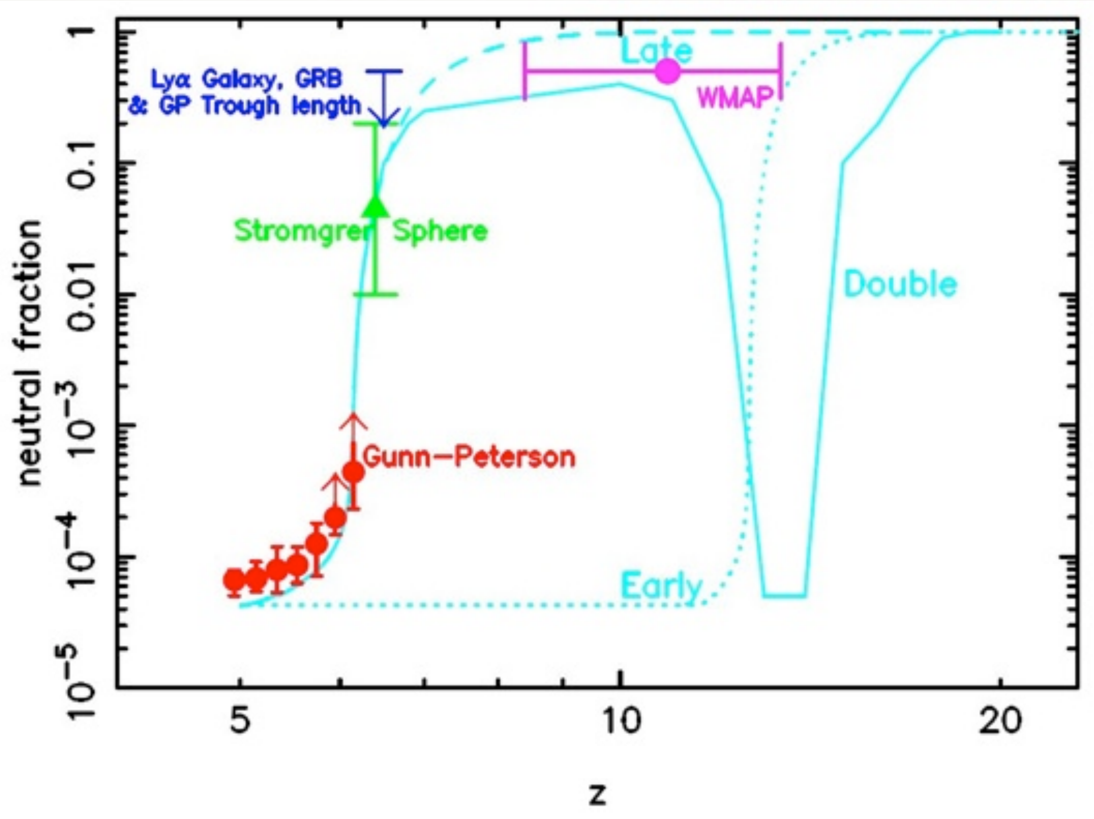
- The Universe (hydrogen) became neutral at z~1100
  - the cosmic recombination
- Hydrogen in IGM today is highly ionized
  - the Gunn-Peterson Test
- The universe must have been reionized at around z~10
  - most likely by UV photons by first stars
  - when? how? important benchmark to understand galaxy formation



Djorgovski+

The Reionization Probes

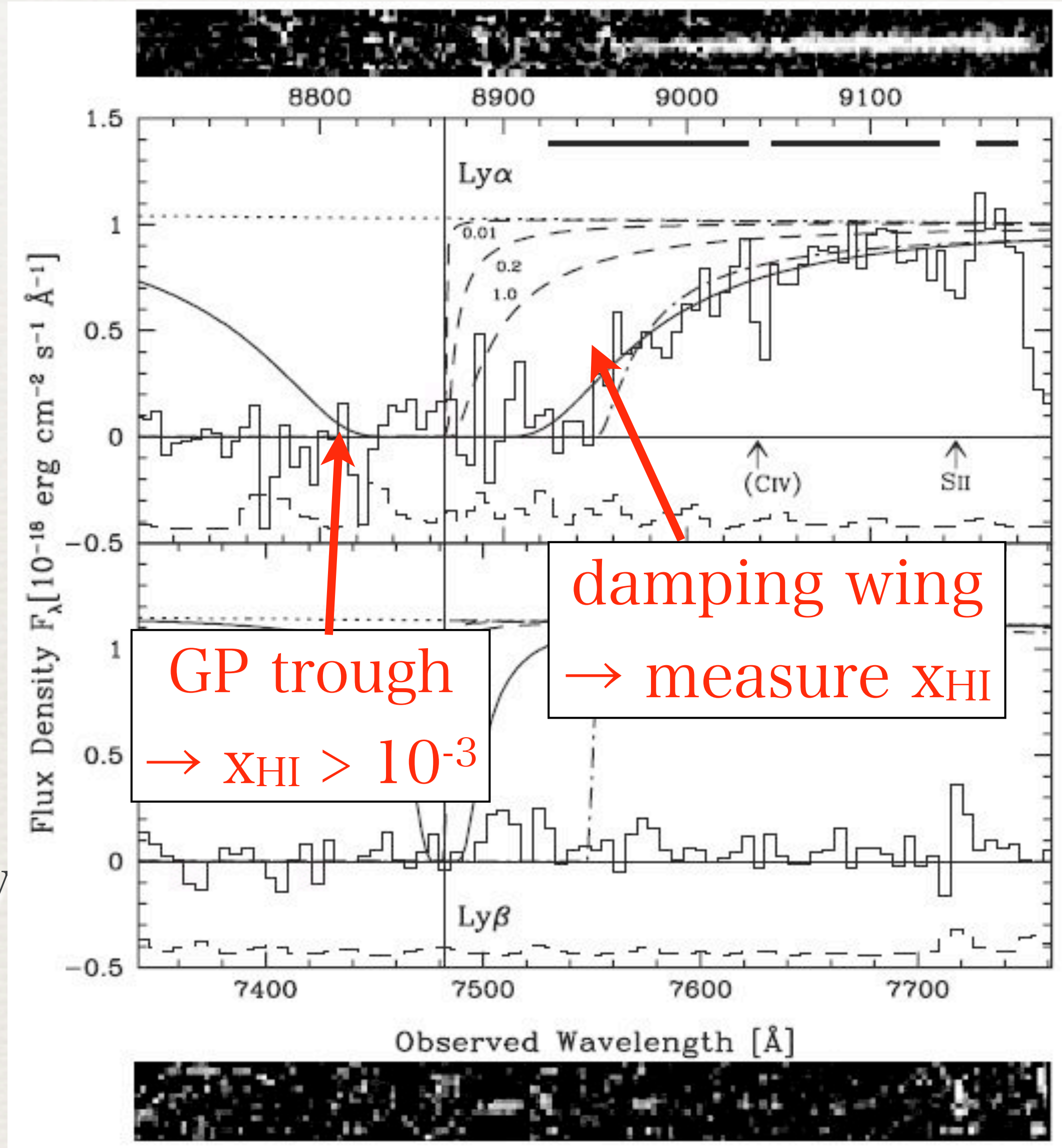
- quasar Gunn-Peterson test:
  - gives only lower limit at z > 6
  - proximity effect
- Cosmic microwave background polarization:
  - only integrated information over z
- Lyα emitter luminosity function:
  - highly model dependent



Fan+'06

GRB as a Reionization Probe

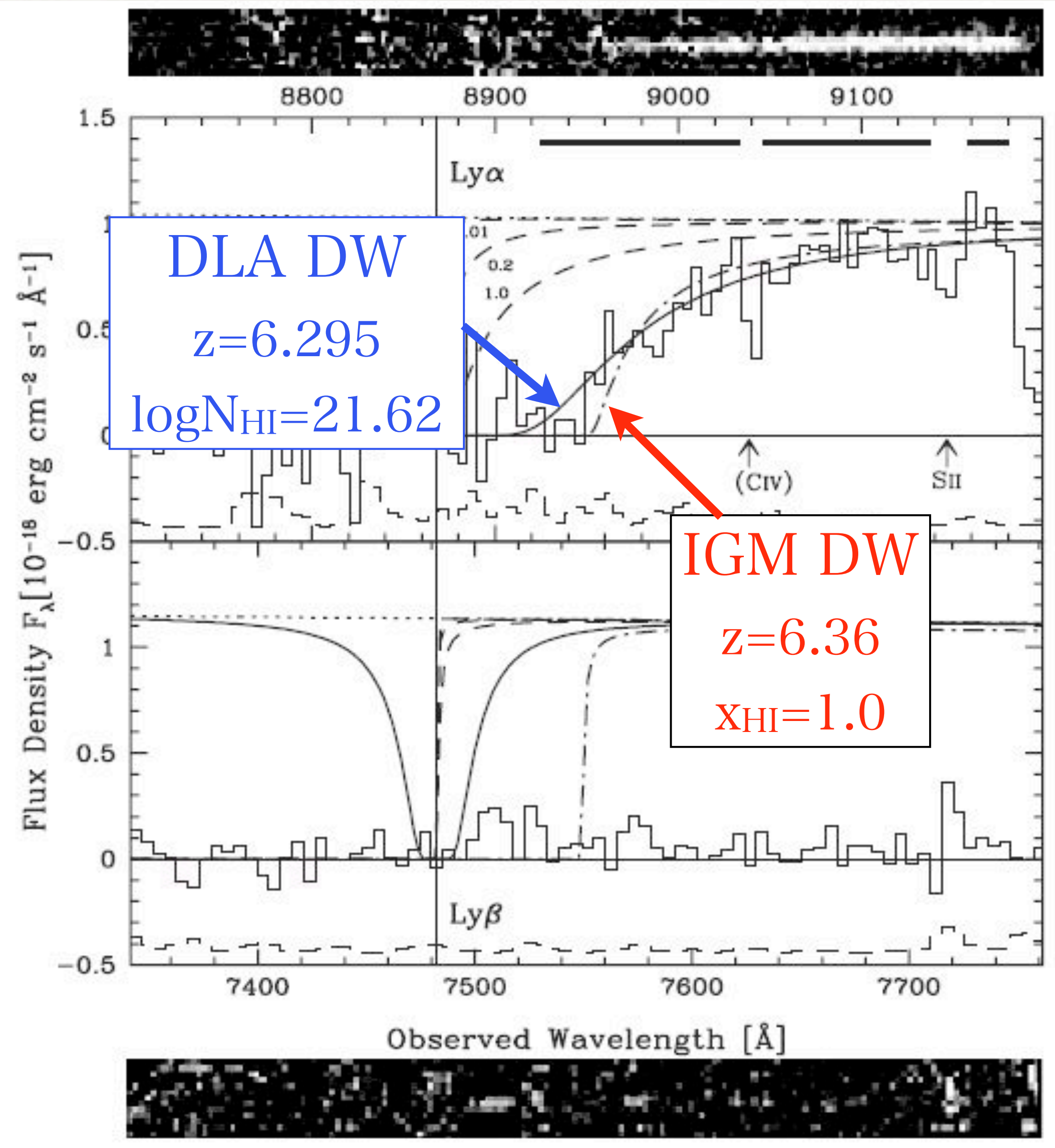
- Strengths:
  - GRBs detectable at z>>6
  - probes more normal (less biased) region in the universe than quasars
    - GRBs detectable even in small dwarf galaxies
    - No proximity effect
  - simple power-law spectrum
    - damping wing analysis to precisely measure x_{HI} (=n_{HI}/n_H)



GRB 050904@z=6.3, TT+ '06

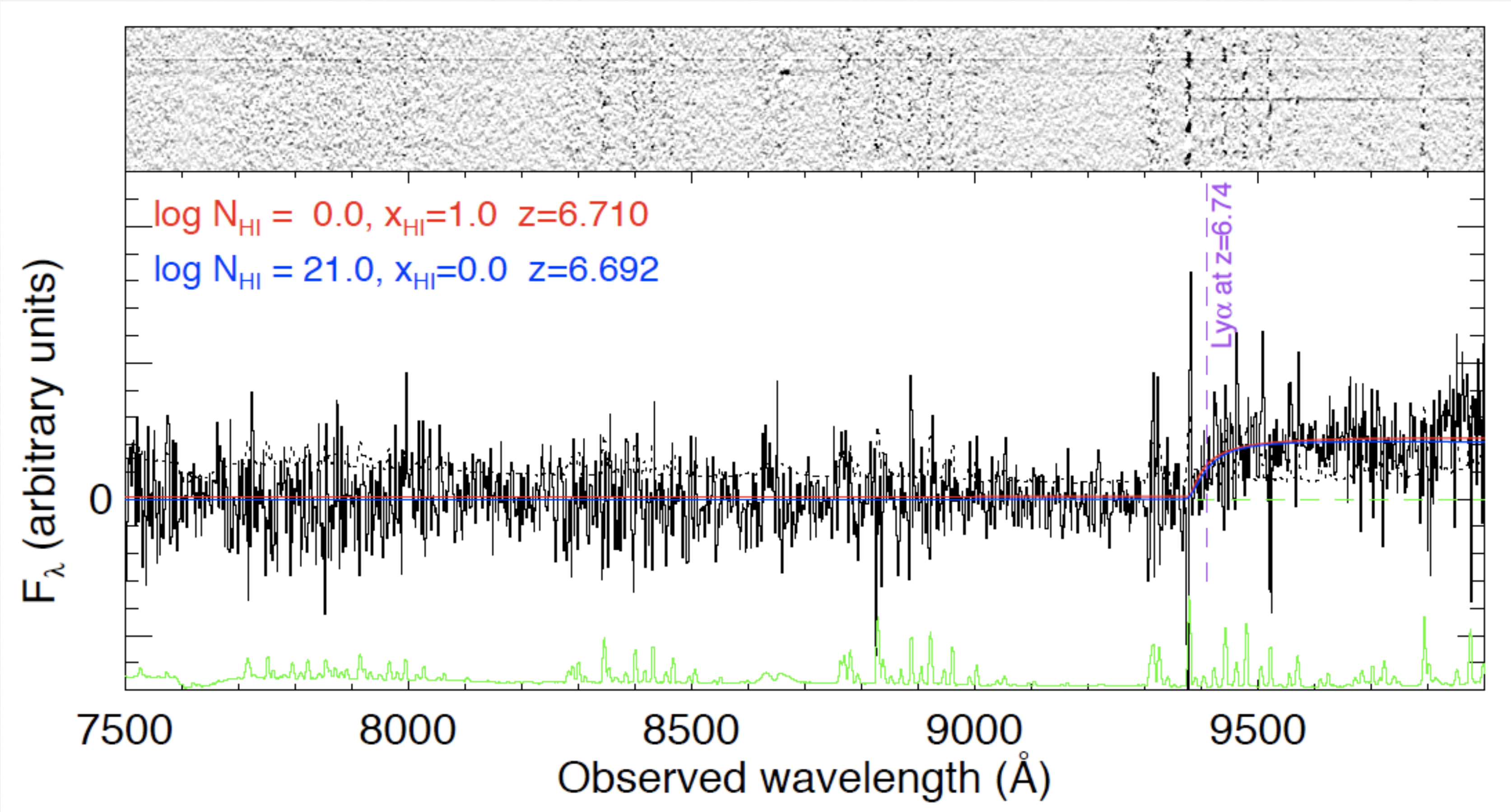
GRB as a Reionization Probe (2)

- Weakness:
  - Degeneracy between damped Ly α (DLA) of host galaxies and IGM damping wing
    - can be broken by metal absorption lines
    - we need low N_{HI} host galaxy to measure x_{HI} accurately
  - event rate not so high
    - GRB 050904 is still the only one useful constraint on reionization by GRBs since 2005!
    - $x_{HI} < 0.17$ (68%C.L) or 0.6 (95%C.L.) by fitting



GRB 050904@z=6.3, TT+ '06

GRB 080913 @ z~6.7



(Greiner+'09)

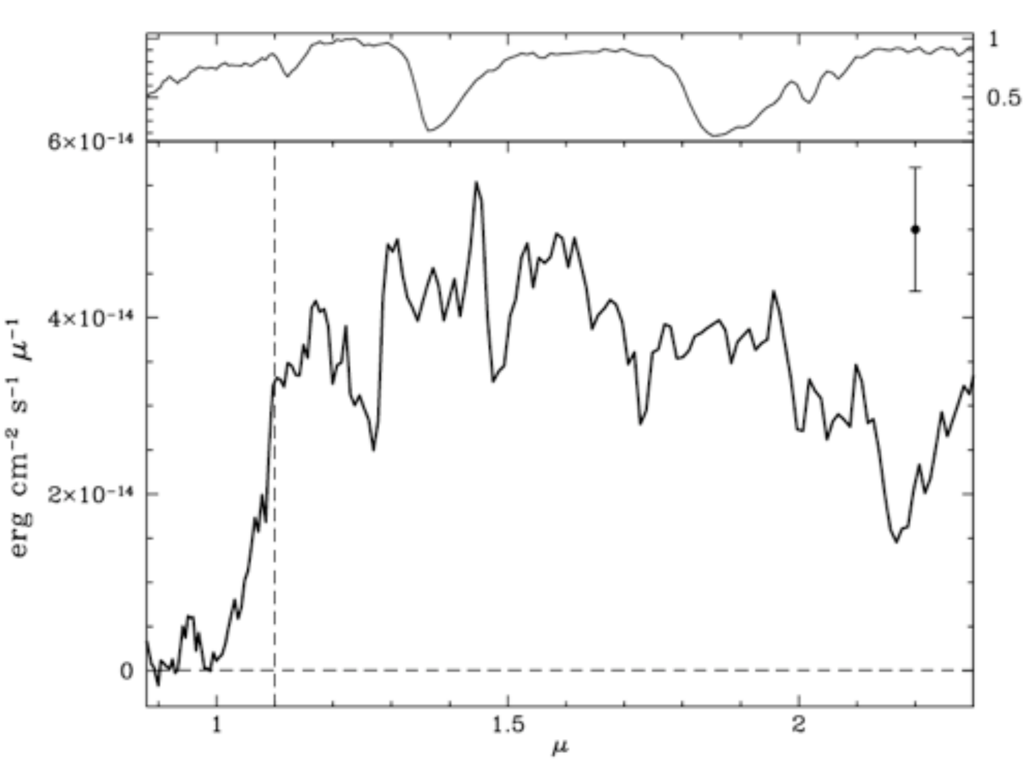
2-3 hrs, z'~24.5(AB), 2400 s exp.

damping wing detected, but difficult to discriminate DLA or IGM

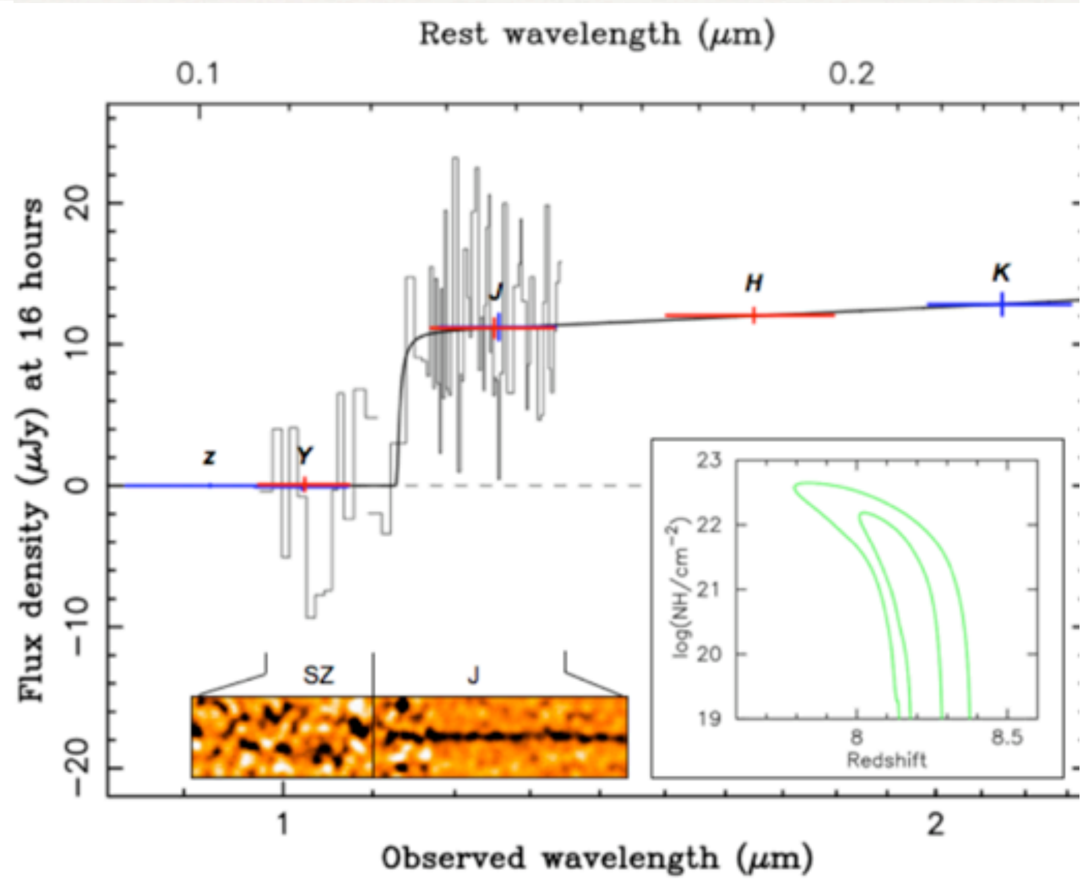
c.f. GRB 050904, z~6.3

3.4 days, z'=23.7(AB), 4 hr exp.

GRB 090423 @ z~8.2



Salvaterra+'09



Tanvir+'09, ~20 hr, J~20.8

Only upper bound on N_{HI} (=no detection of damping wing)

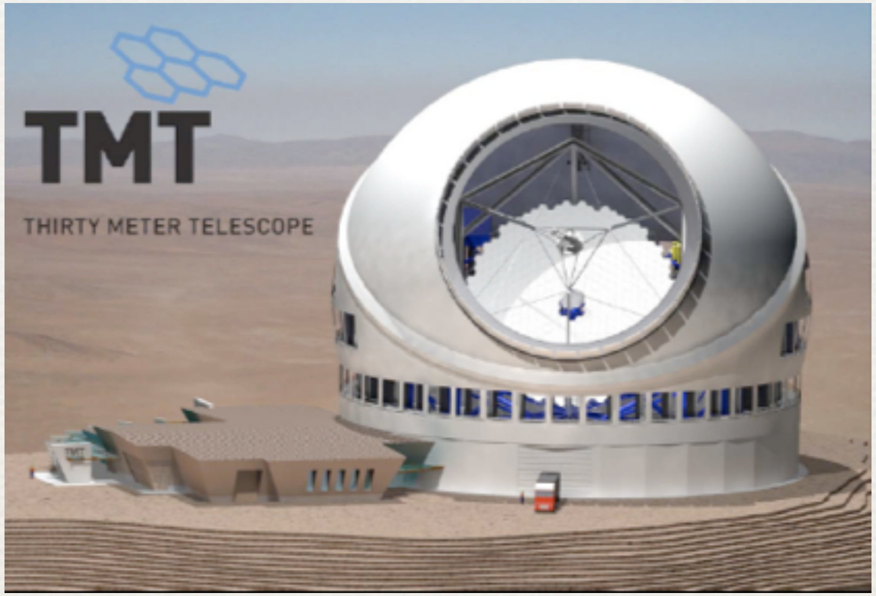
What do we need to increase the rate of GRBs useful for reionization?

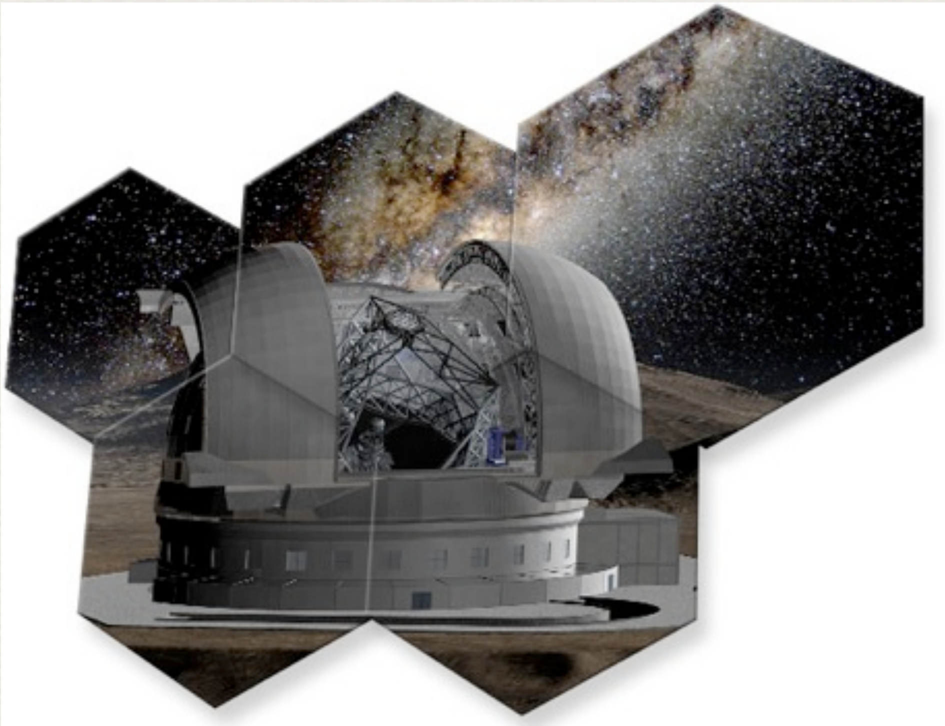
- GRB rate study indicate that >1% of GRBs are at z>6
  - e.g. Elliott+'12

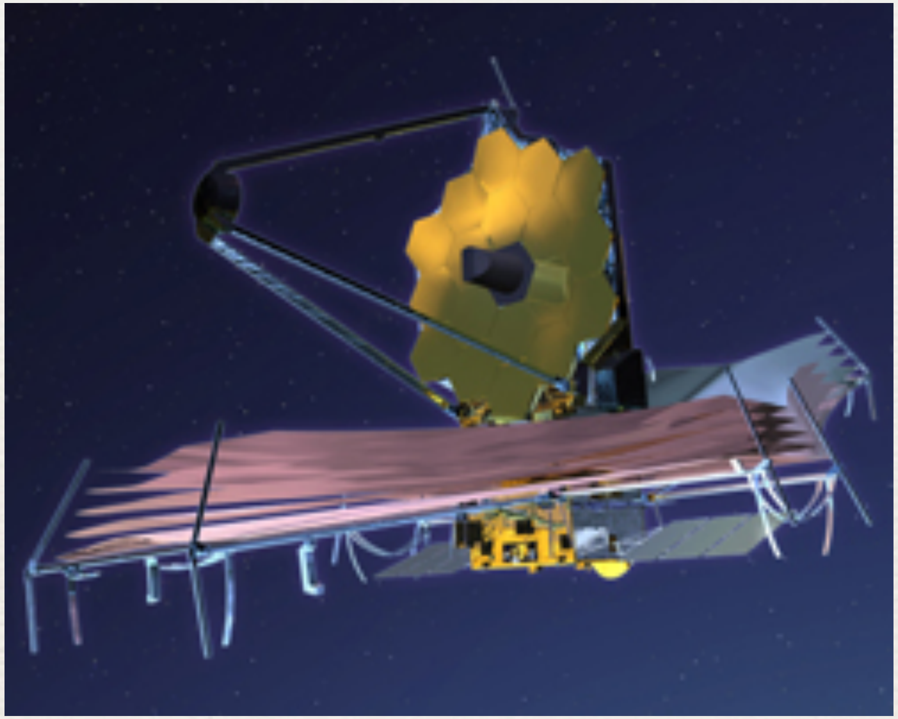
- Current 8m telescopes are not sufficient to measure the damping wing for typical GRB luminosities
  - GRB 050904 was exceptionally bright!

- We need more sensitive NIR spectrograph
  - LGS-AO by 8m telescopes
  - 30m-class telescopes / JWST

30m/JWST

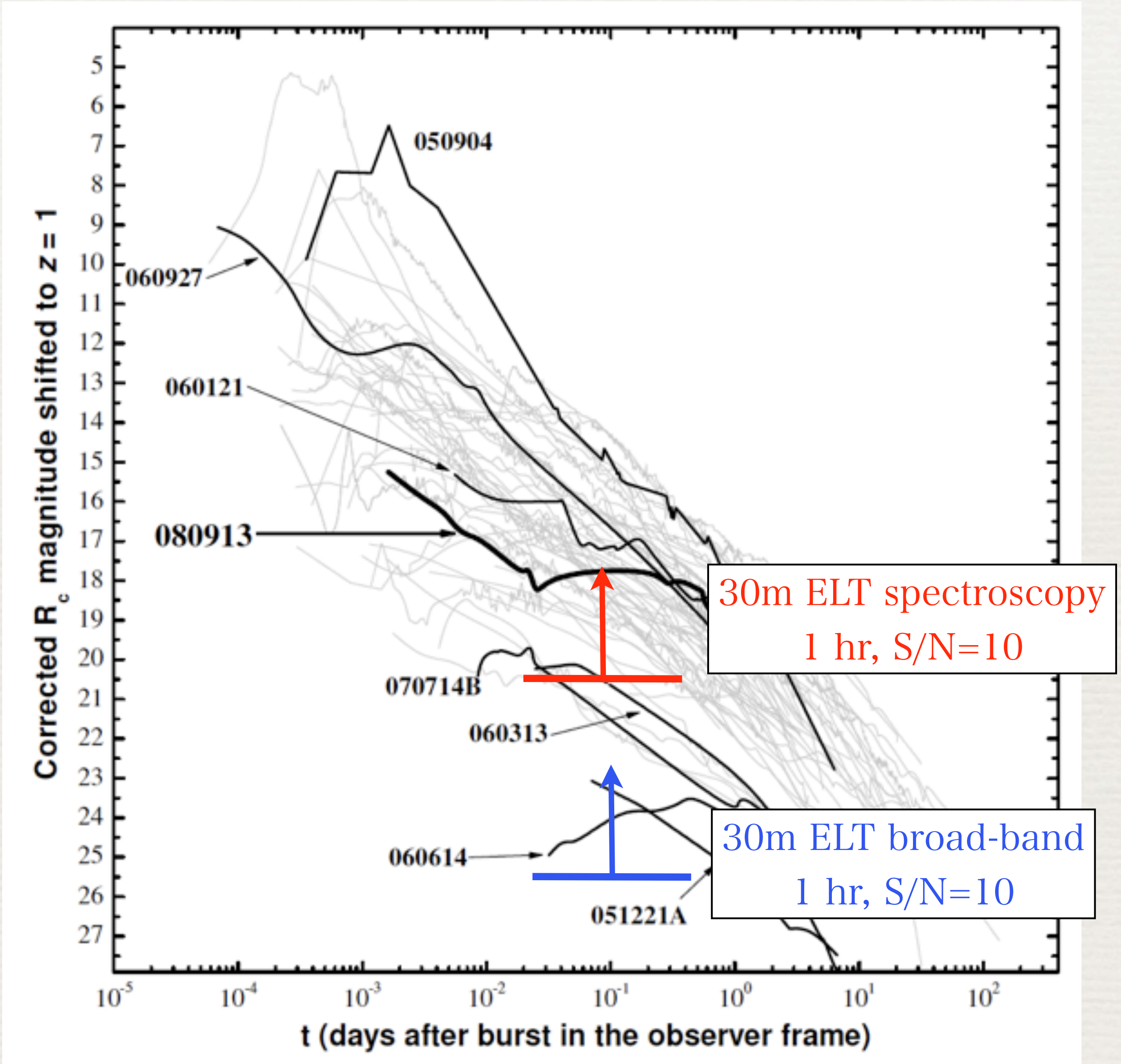






30m telescope sensitivity vs. GRBs

- convert into R mag, z=1
  - $F_{\nu} \propto t^{-1} \nu^{-1}$
  - observe at 1 day after z=10 burst → ~0.1 day for z=1



(original figure from Greiner+'09)

remarks on reionization study by GRBs

- The number of reionization-constraining GRBs still very limited by
  - insufficient sensitivity of NIR spectroscopy
  - needs of low N_{HI} host galaxy
- NIR spectroscopic sensitivity will greatly improve in the near future
- Even a few measurements of IGM neutral fraction by GRBs would have significant impact on reionization community!

GRBs as the standard candle

- correlation between isotropic energy E_{iso} or luminosity L_{iso} and spectral peak energy E_{peak} has been known
  - Amati+’02; Yonetoku+’04

- This can be used as a standard candle, to make the Hubble diagram (distant vs. redshift), and then constrain cosmological parameters
  - constraint on cosmic expansion history, like SN Ia
  - many papers already appeared to give such constraints

- However, GRB results have not yet had a strong impact on the general cosmology community
  - why?
  - a critical view from a “cosmologist” point of view

Frontiers of Precision Cosmology

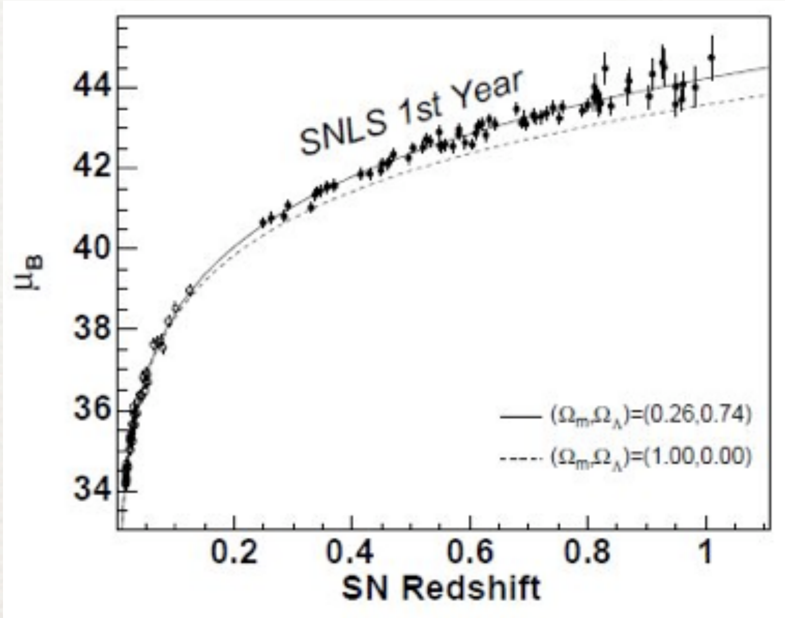
- ΛCDM universe already established

- next interest: the origin of the acceleration of cosmic expansion
  - dark energy (including the cosmological constant)?
  - modification of gravity theory on cosmological scale?

- Observational approach:
  - precise geometrical test to constrain the equation-of-state of dark energy (SN Ia, baryon acoustic oscillation, ...)
  - measurement of structure growth rate to test gravity theory

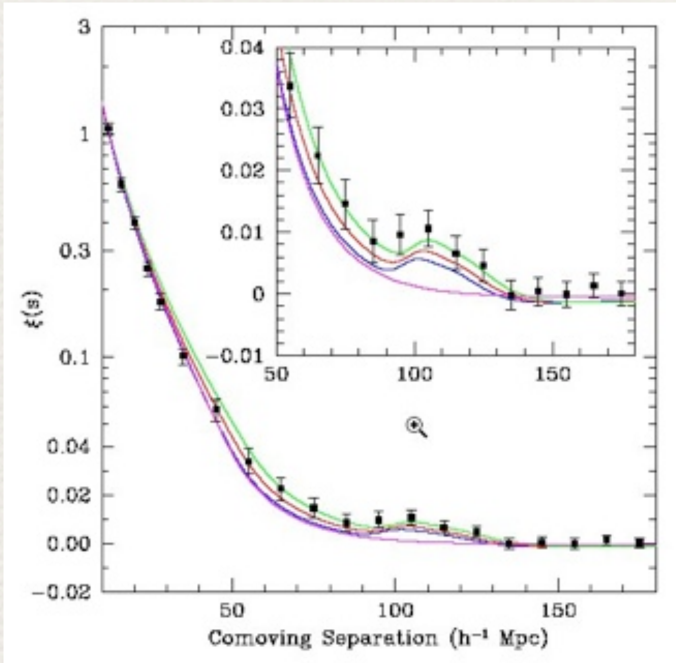
Geometrical Tests

- supernova Ia (standard candle)
  - now sufficient statistics
  - systematics limited!
  - a lot of effort for "standardization" for the next-generation cosmology



Astier+'06

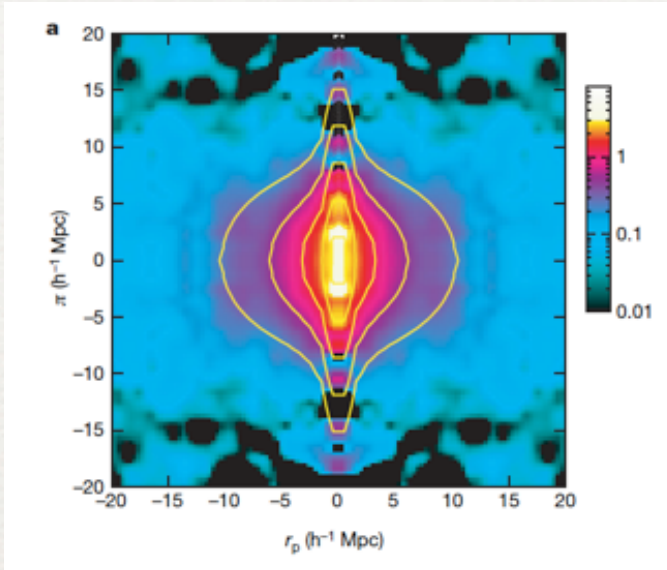
- baryon acoustic oscillation (standard ruler)
  - perhaps the "cleanest" geometrical test
  - expensive, requires > 100k galaxy redshifts in wide area



Eisenstein+'05

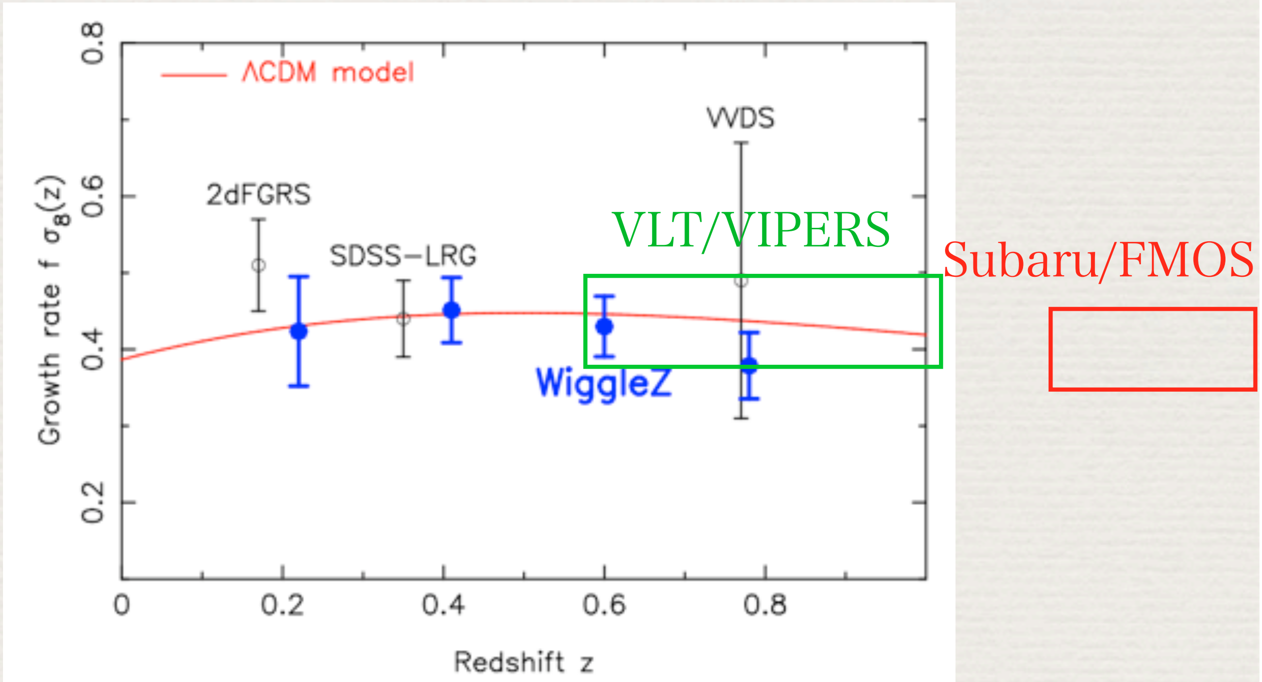
Measuring Structure Growth Rate: A Test of Gravity

- redshift space distortion (RSD) in galaxy redshift surveys
  - distortion by peculiar velocities
  - RSD gives a measure of structure growth rate f [=d(ln δ)/d(ln a)]
  - several measurements at z < 1
  - will soon extend to z > 1



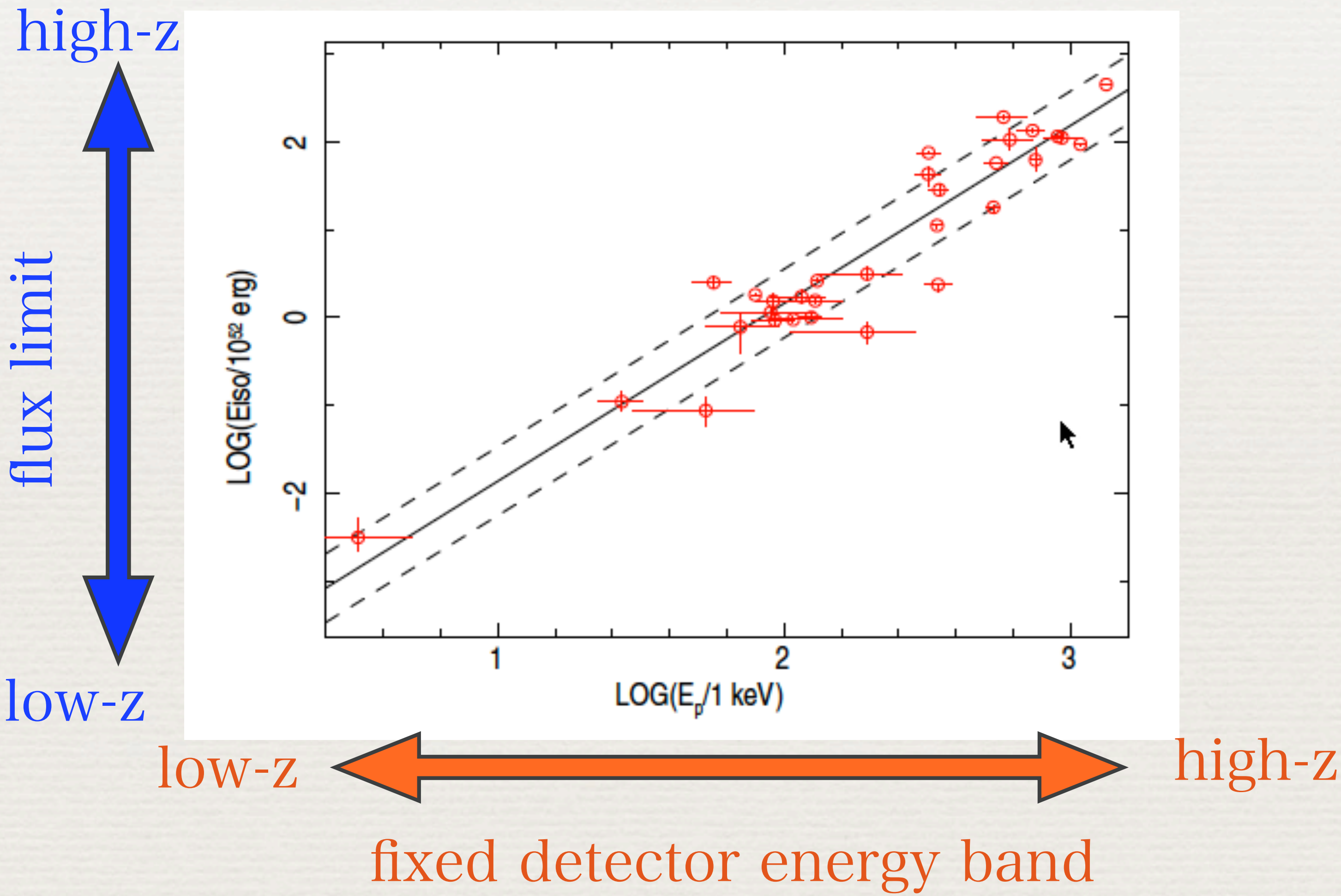
2D correlation function in redshift space (Guzzo+'08)

- weak lensing experiments will also deliver growth rate measurements by wide field imaging surveys



Systematics of GRB standard candle

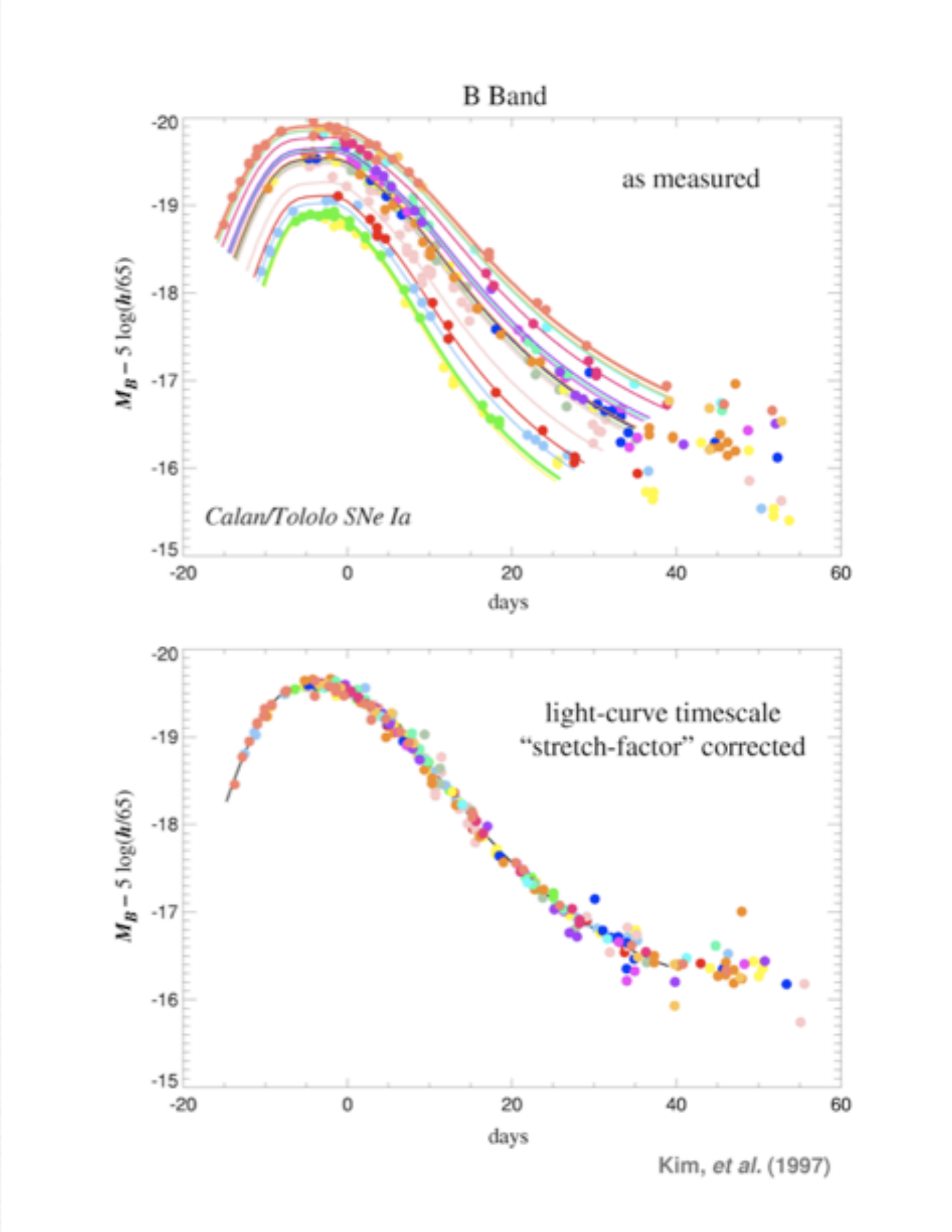
- The correlation (larger E_{iso} or L_{iso} for large E_{peak}) is in line with the selection effect about detecter energy band

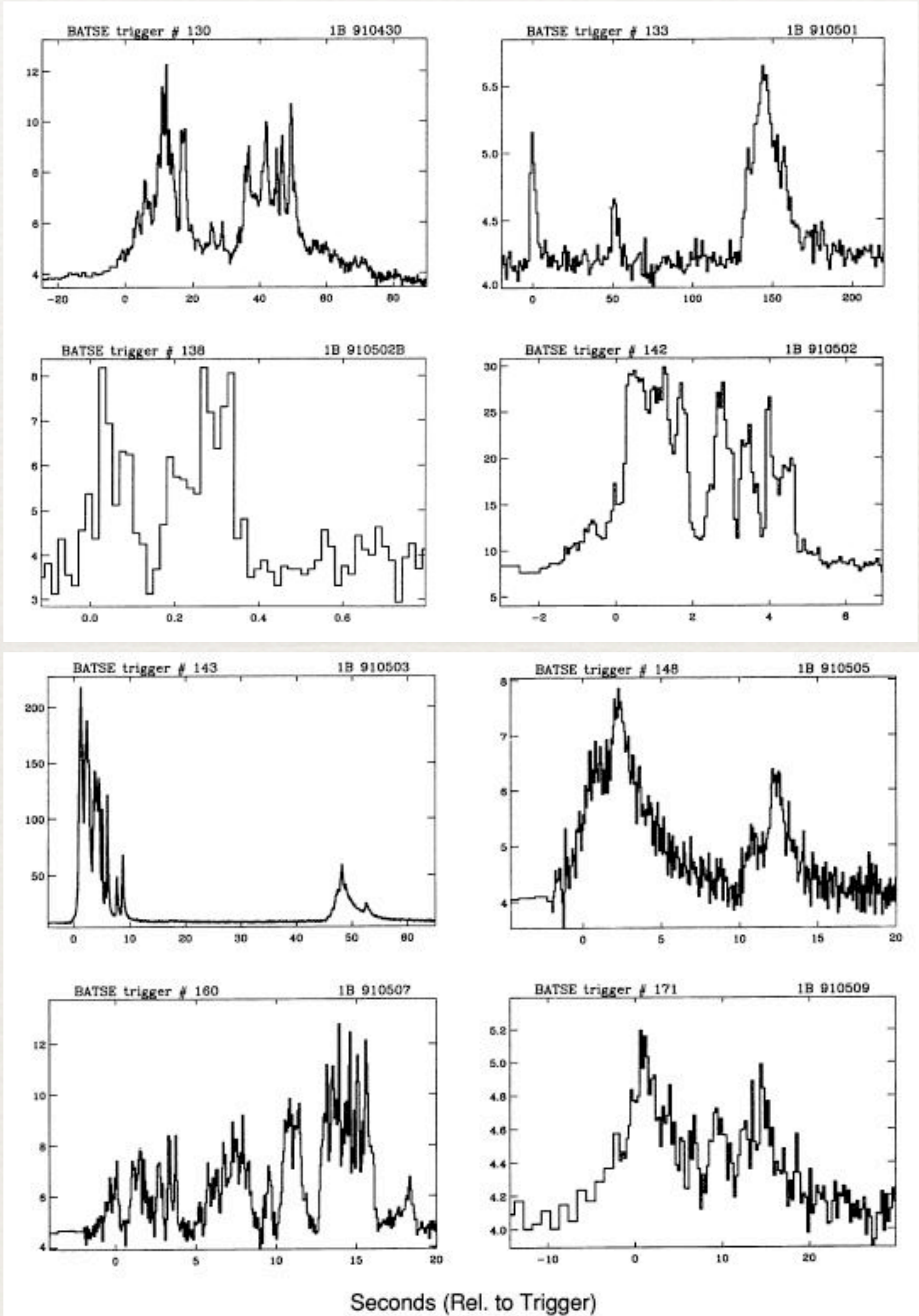


- it may not explain all the observed correlation, but should certainly affect the precise cosmological analysis!

SN Ia vs. GRB as standard candles

- GRBs are fundamentally stochastic events!





remarks on GRBs as a standard candle

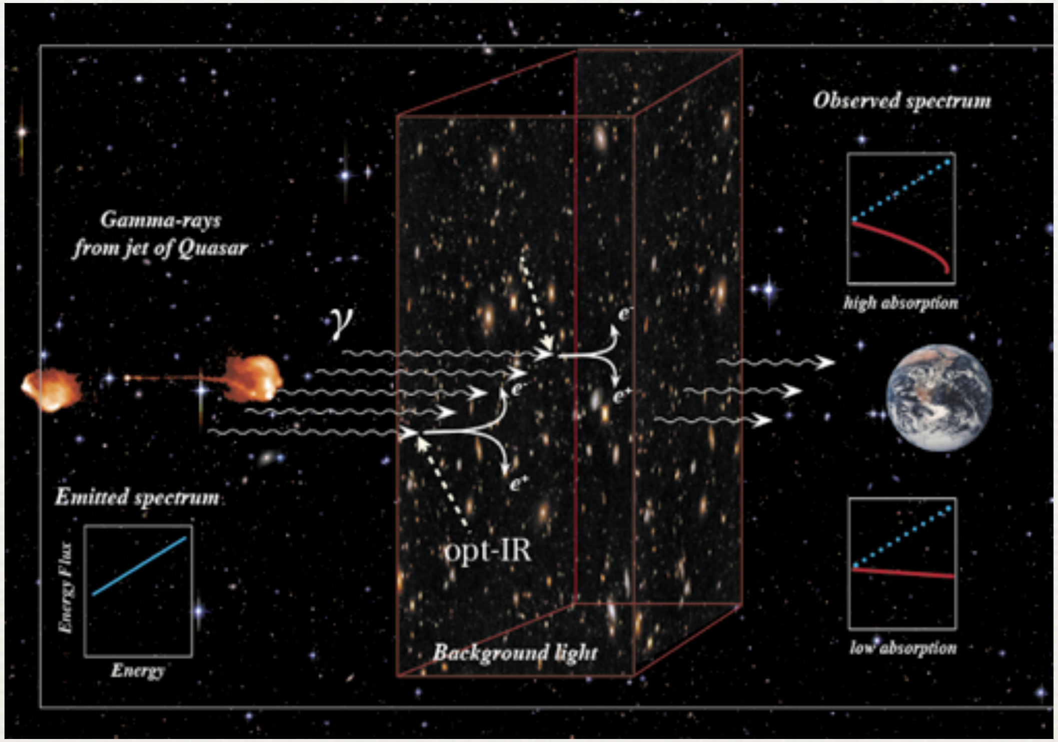
- The physical origin of the spectrum-energy(luminosity) correlation is a very interesting issue

- However, there are still many steps for GRBs as a standard candle to provide a result having a significant impact to the general cosmology community

- Strength of GRB against SN Ia is reach to high-z
  - but, note that the standard dark energy appears at z <~1

GRBs as a Probe of Cosmic Opt./IR Background

- intergalactic absorption of high-energy gamma-rays gives an important measure of opt/NIR backgroud, i.e., history of galaxy formation
- current limits come from blazars (z < 1)
- GRBs provide alternative background source, which would extend even higher-z
  - may probe star formation activity in reionization era (S. Inoue+'10)
  - highest-z blazars are at z~2, even by the Cerenkov Telescope Array (Y. Inoue +'10)
  - event rate may not be so large (~0.1-1 event/yr, Kakuwa+'11)
    - but may extend to z~4



Cerenkov Telescope Array