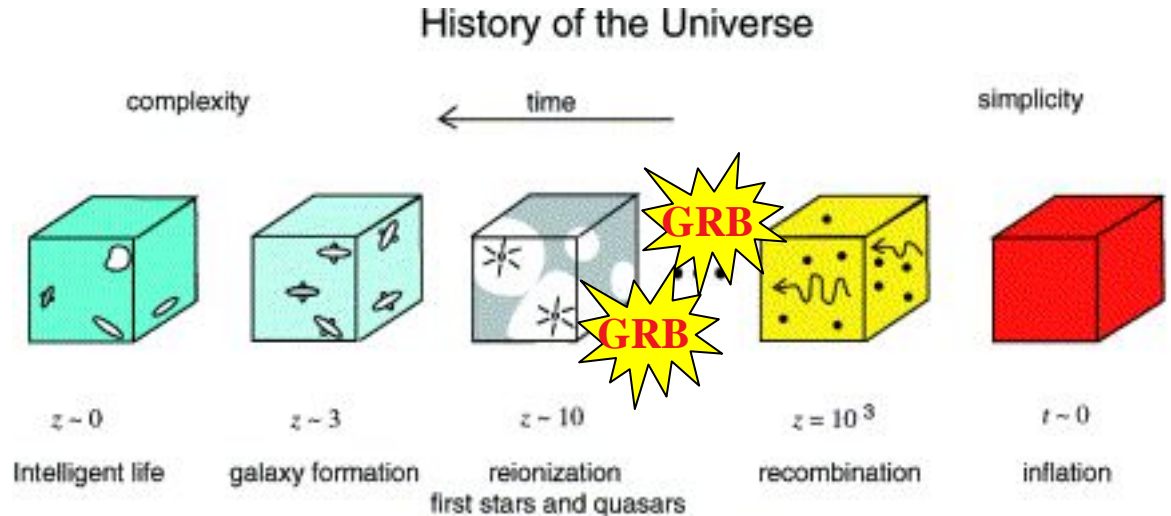
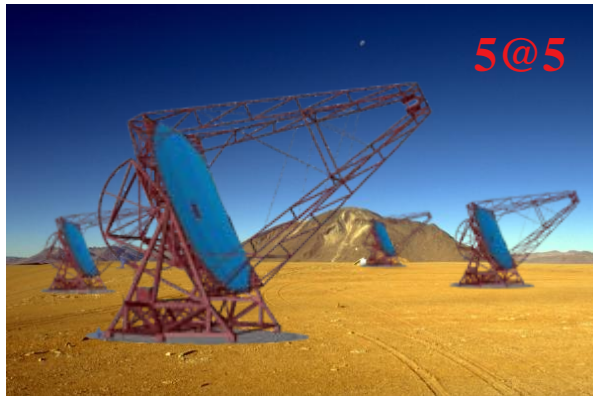


Probing the First Stars & Galaxies with the Broadband Emission of Very High-z GRBs

GeV γ -rays \leftrightarrow Intergalactic Radiation and B fields
Radio \leftrightarrow B fields



Susumu Inoue (NAOJ) and collaborators



“in an interstella burst i am back to reveal the universe”
- after T. Yorke

outline

1. GeV gamma-ray absorption and high-z intergalactic UV/optical radiation fields

Inoue, Salvaterra, Choudhury, Ciardi, Schneider & Ferrara, in prep.

- observability of high-z GRBs in GeV γ -rays

- high-z UV radiation fields and γ -ray absorption optical depths

2. GeV delayed emission and weak intergalactic B fields

Ichiki, Takahashi & Inoue, in prep. -> Ichiki's talk

3. Faraday rotation and strong high-z B fields

Inoue & Ichiki, in prep.

era of first star formation $z \sim 30-10$

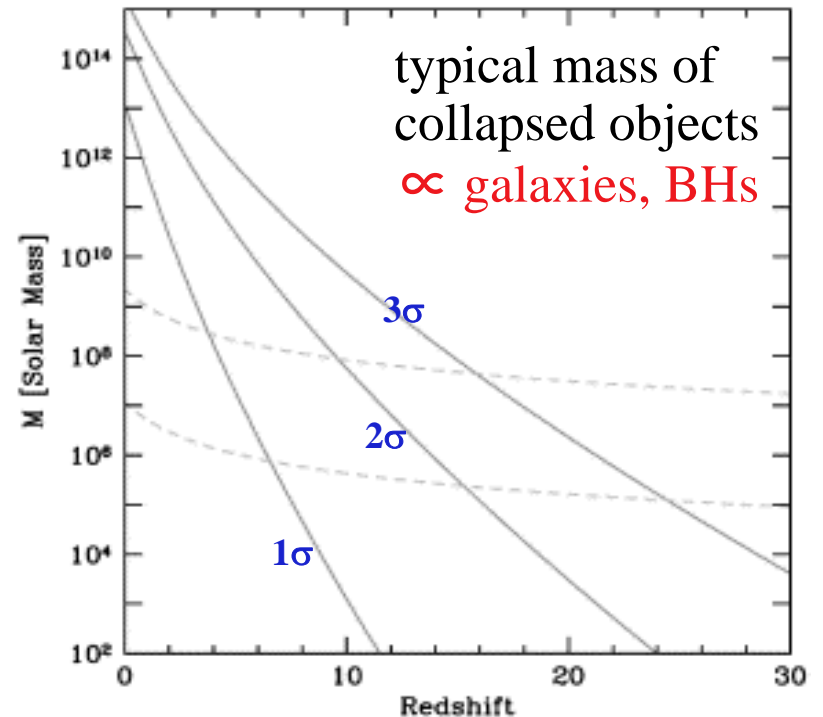
- first stars (Pop III: metal/dust-free, predominantly massive)
- first UV radiation \rightarrow HII regions, IGM reionization
- first supernovae \rightarrow metal/dust enrichment \rightarrow transition to Pop II
- first black holes \rightarrow AGN seed?
- first GRBs!

lots of theory, but almost no observations!!! only WMAP

long GRBs:

- associated with massive stars
- extremely luminous, broadband
- no (little) z-evolution in luminosity

but transient

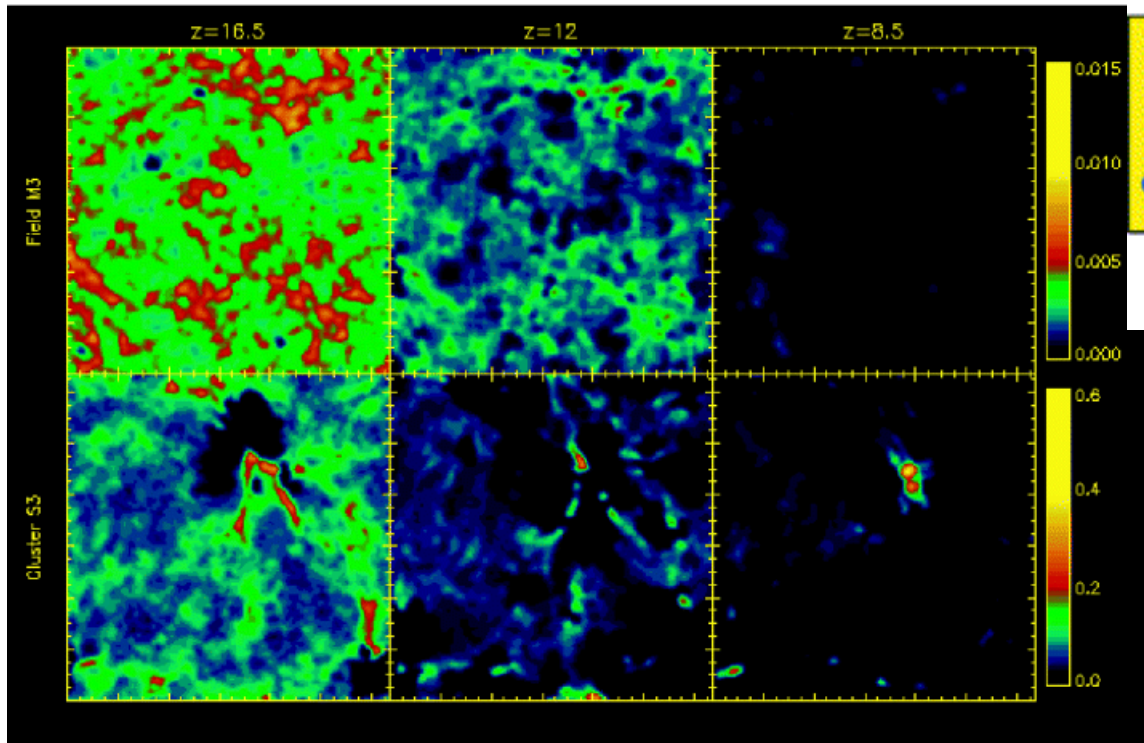
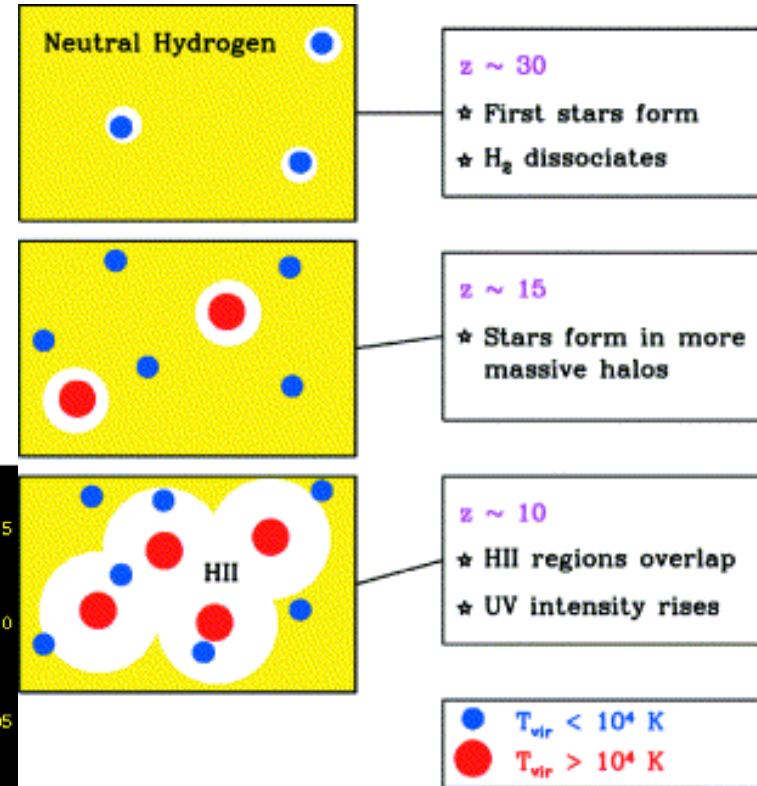


high z UV radiation field (“background”)

crucial for understanding early universe

- reionizes the IGM
 - > suppresses formation of small galaxies
- dissociates H_2 molecules
 - > suppresses early star formation
- determines HI hyperfine (21cm) level population via Ly α pumping

but direct detection impossible!!!



gamma absorption at high-z $\gamma + \gamma \rightarrow e^+ + e^-$

Oh 01: (also Madau & Phinney 96)

reionizing radiation fields
should induce \sim GeV absorption

- pre-WMAP

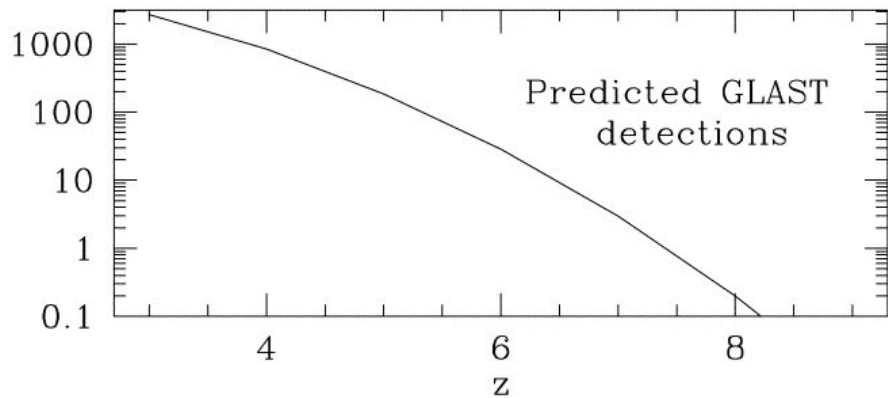
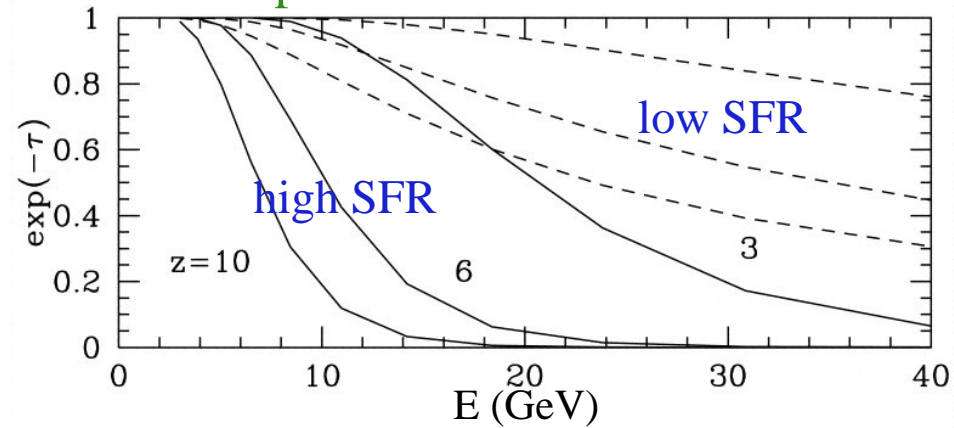
$z < 10$ only, no Pop III

- blazars: potential problems

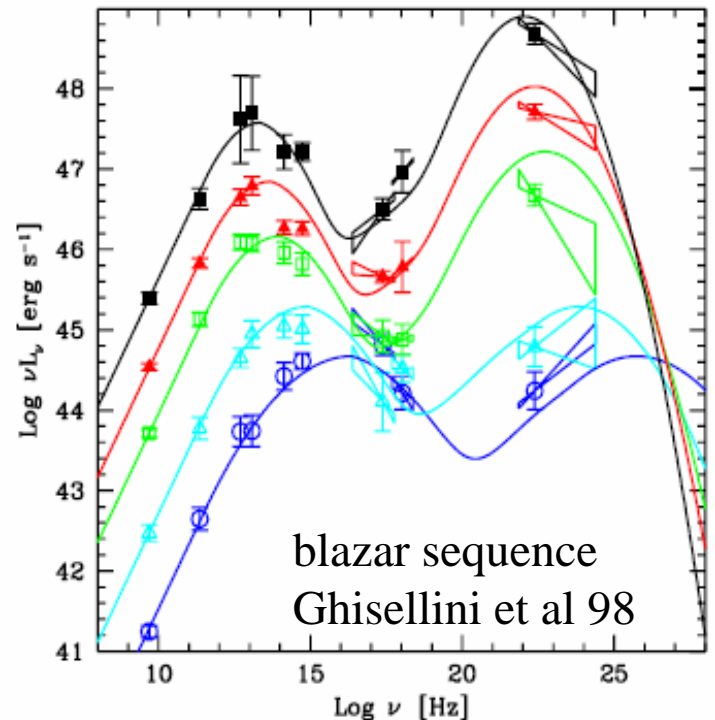
- very rare above $z \sim 8$

- spectral cutoff $< \sim 10$ GeV for bright blazars?

spectral attenuation factor

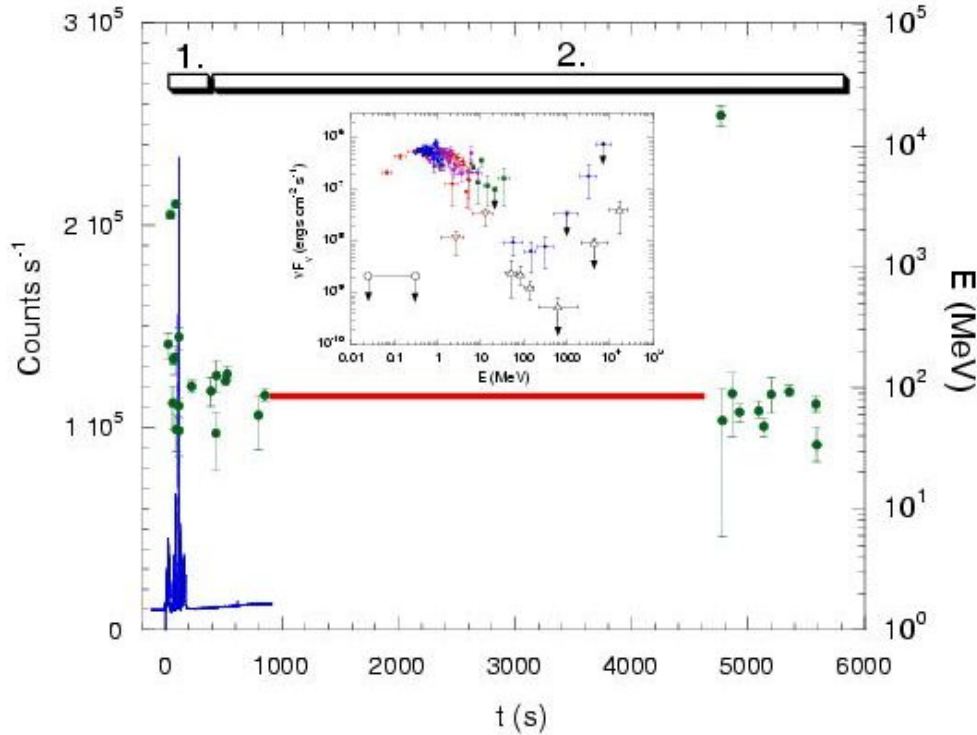


alternative:
GRBs!



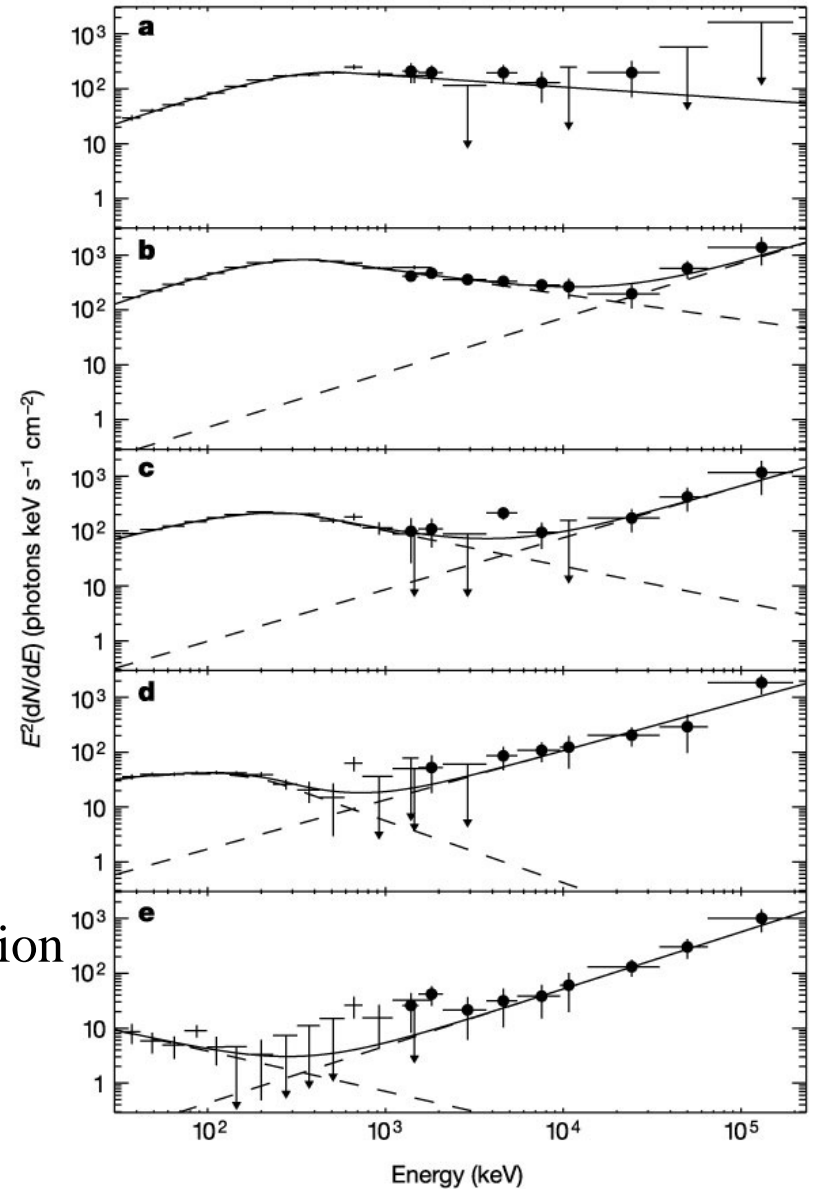
GRB940217

Hurley et al 94



- currently not well constrained, but
- at least some GRBs show strong GeV emission
 - often spectrally and/or temporally distinct component at $> \sim 30$ MeV
 - sometimes energetically dominant

prompt? afterglow?



GRB970417 TeV? Atkins et al 02

GRB GeV-TeV emission: assumptions

prompt

extension to $< \sim 100$ GeV with $\Gamma=2$ with typical or bright flux
(in internal shock models, depends sensitively on parameters e.g. Γ , δt
e.g. Guetta & Granot 03)

afterglow

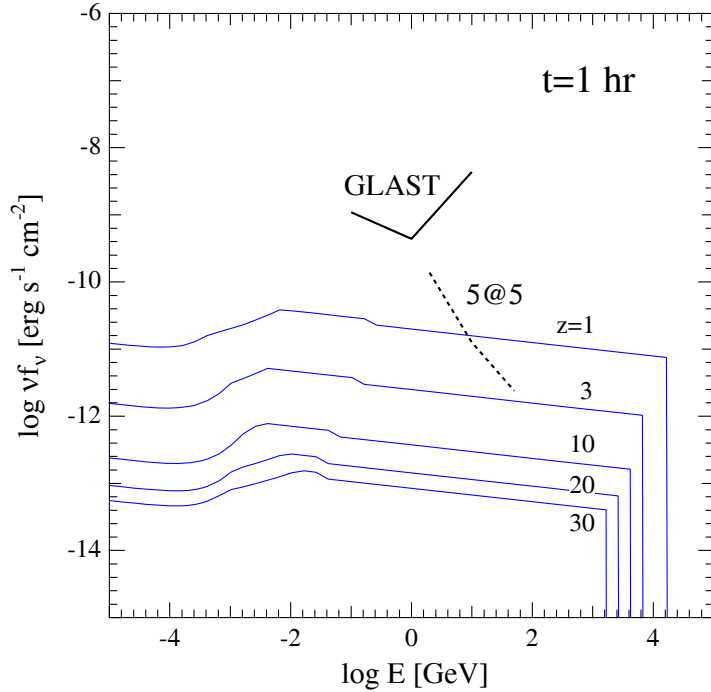
SSC emission from forward shock for typical or bright cases
simple treatment of KN effects,
internal $\gamma\gamma$ absorption (effective only $> \sim$ TeV)
e.g. Dermer & Boettcher 00, Zhang & Meszaros 01, Sari & Esin 01

+possibly also
reverse shock,
hadronic components,
etc...

prompt + afterglow: typical GRB

$$E_{53}=1, n=1, \epsilon_e=0.1, \epsilon_B=0.01, p=2.2$$

$$L_{52}=1, \Delta T_1=1, \epsilon_e=0.5, \epsilon_B=0.1, p=2.0$$



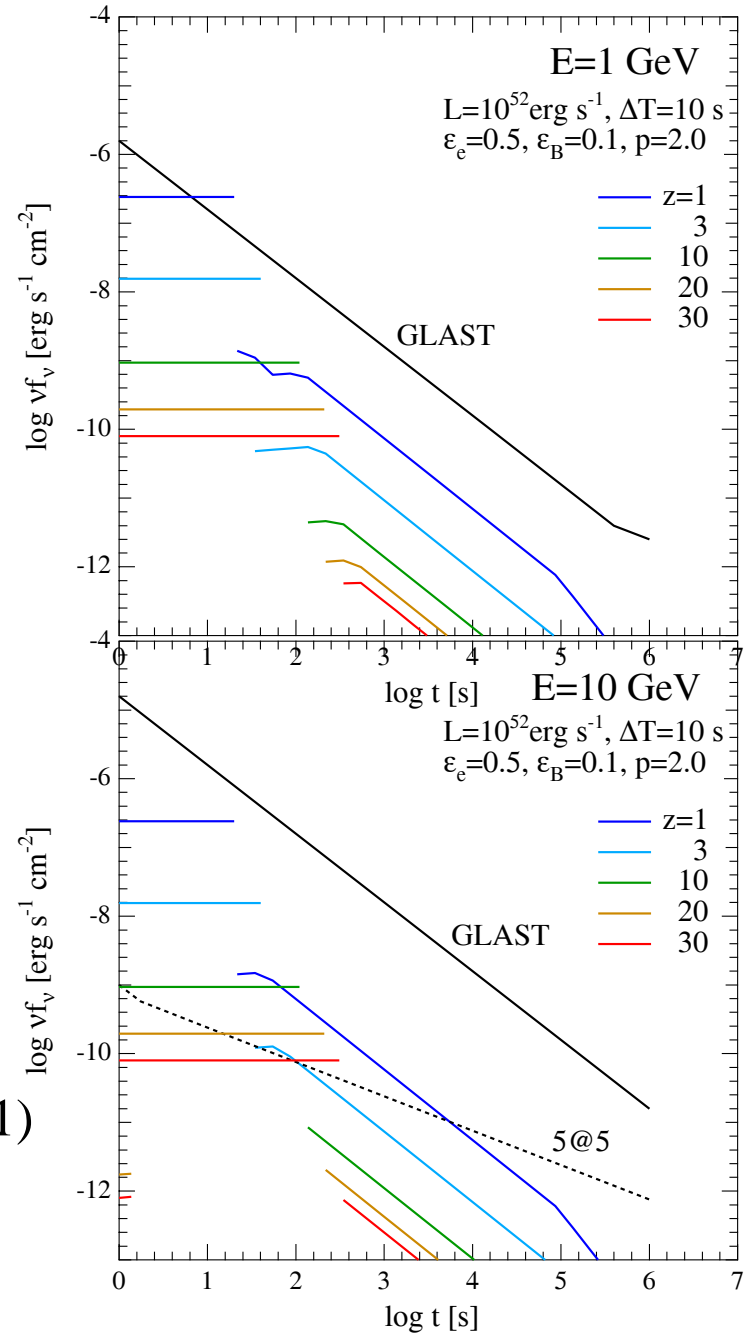
detectability:

GLAST $z < \sim 1 @ 1 \text{ GeV}$

($A_{\text{eff}}=10^4 \text{ cm}^2$, $t_{\text{integ}}=0.5 t_{\text{obs}}$, >5 photons in $\Delta E/E \sim 1$)

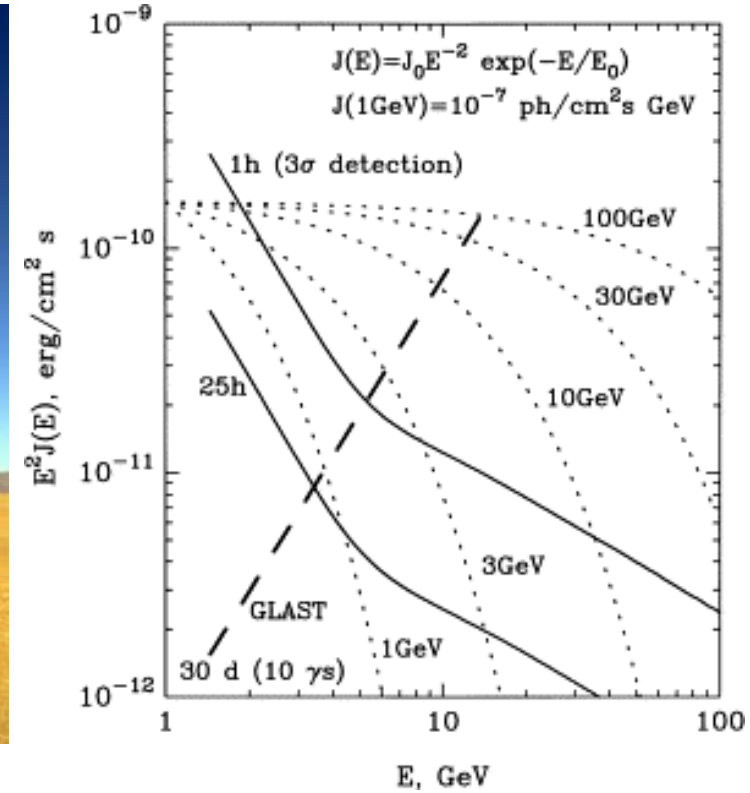
5@5 $z > \sim 10!!$

(Aharonian et al 01)



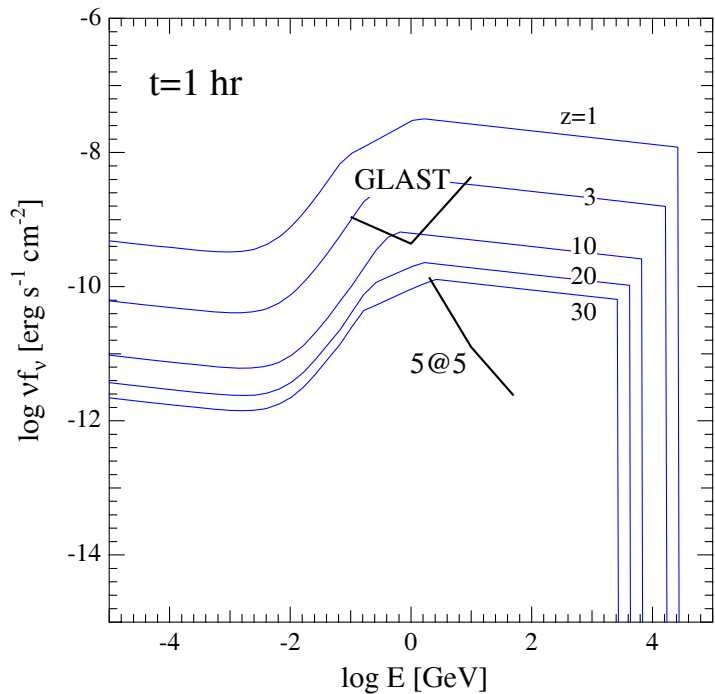
5@5 γ -ray Cerenkov detector with 5 GeV threshold at 5000 km altitude

Aharonian et al 01 **major, next generation ground-based project: 2010+**



prompt + afterglow: bright GRB

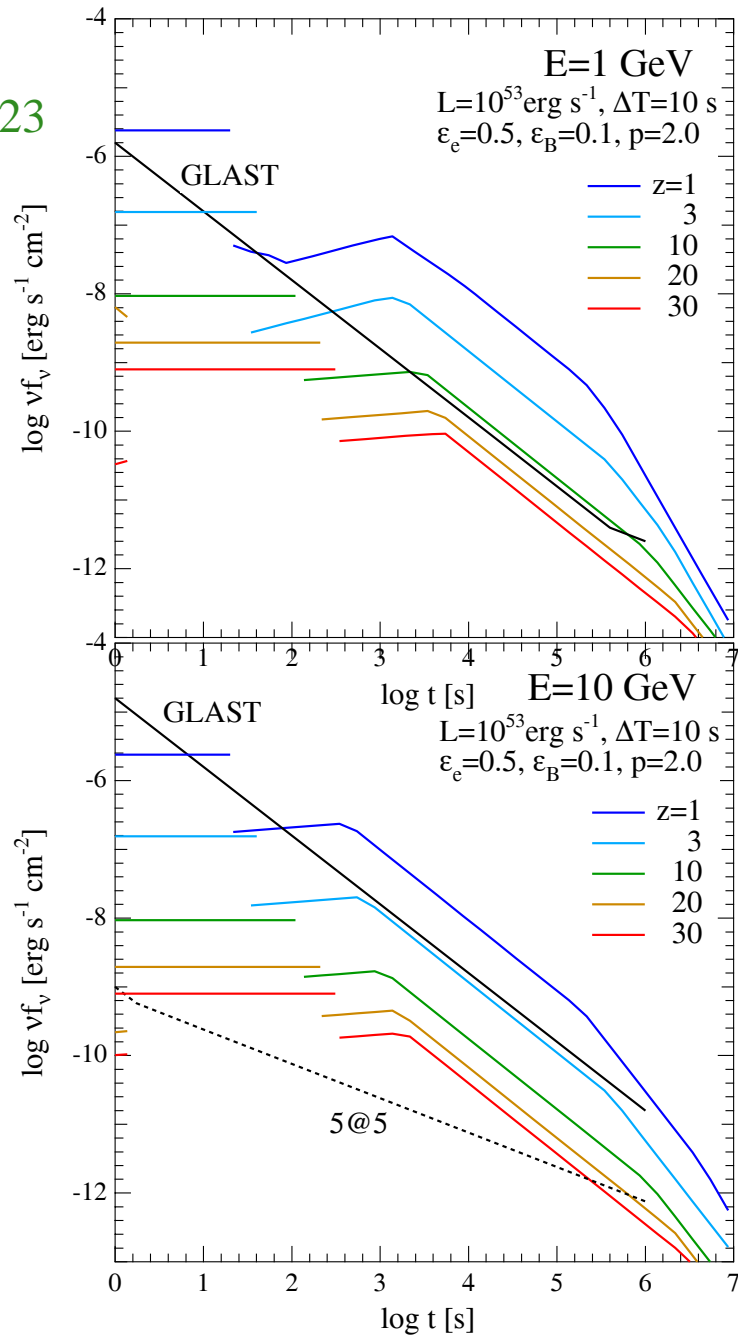
$E_{53}=10$, $n=1$, $\epsilon_e=0.5$, $\epsilon_B=0.001$, $p=2.2$ e.g. GRB990123
 $L_{52}=10$, $\Delta T_1=1$, $\epsilon_e=0.5$, $\epsilon_B=0.1$, $p=2.0$



detectability:

GLAST $z < \sim 10 @ 1 \text{ GeV?}$

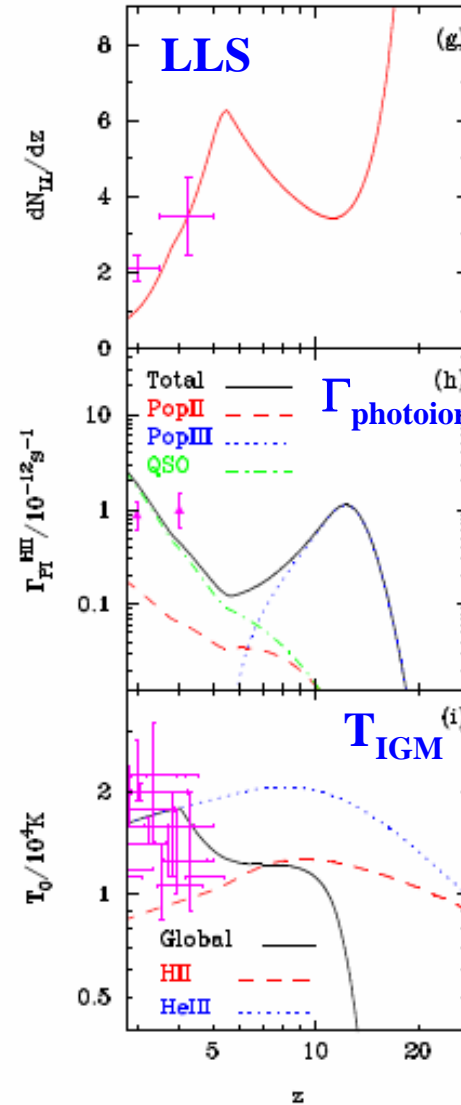
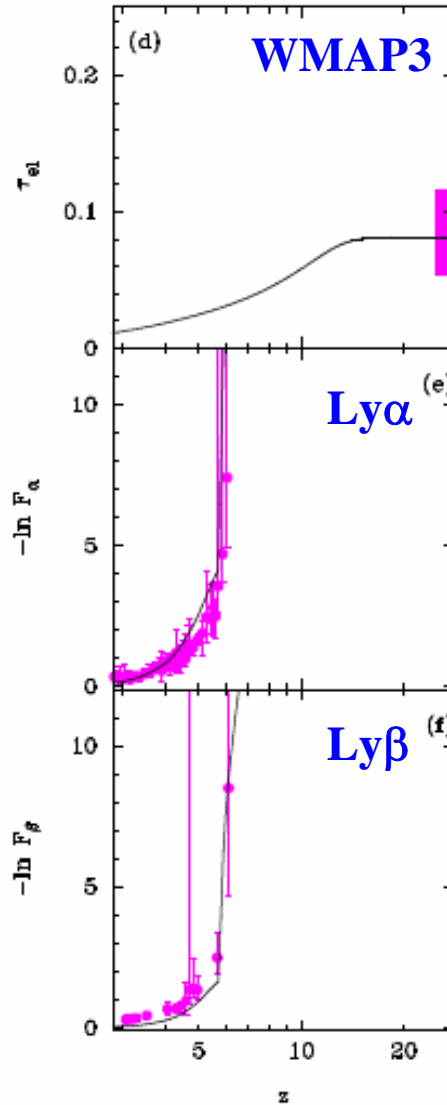
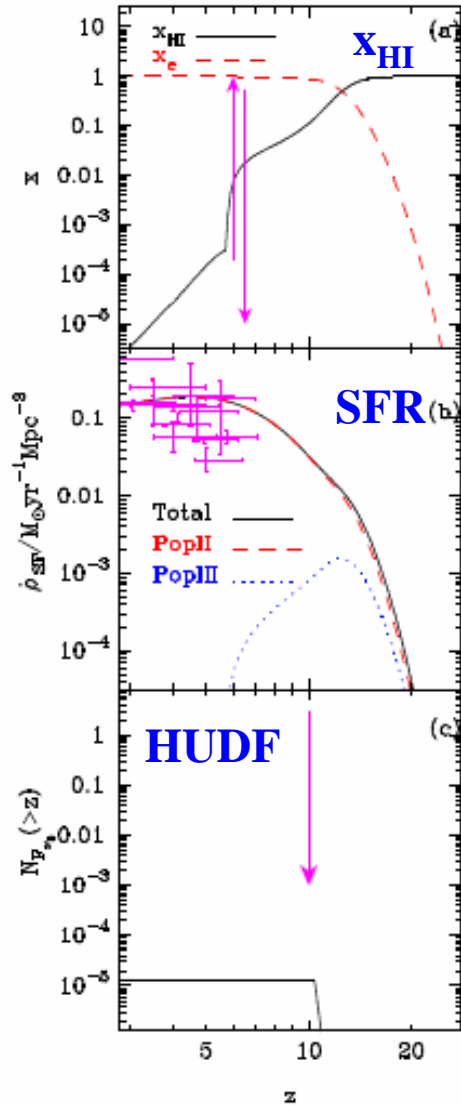
5@5 $z > \sim 30!!$



high-z radiation fields from cosmic reionization model

Choudhury & Ferrara 05, astro-ph/0603617

semi-analytic treatment with radiative+chemical feedback parameters ε_{*II} , ε_{*III} , η_{esc} , λ_{0IGM}
 consistent with large set of high-z observations inc. WMAP3, x_{HI} , HUDF NIR counts, etc.



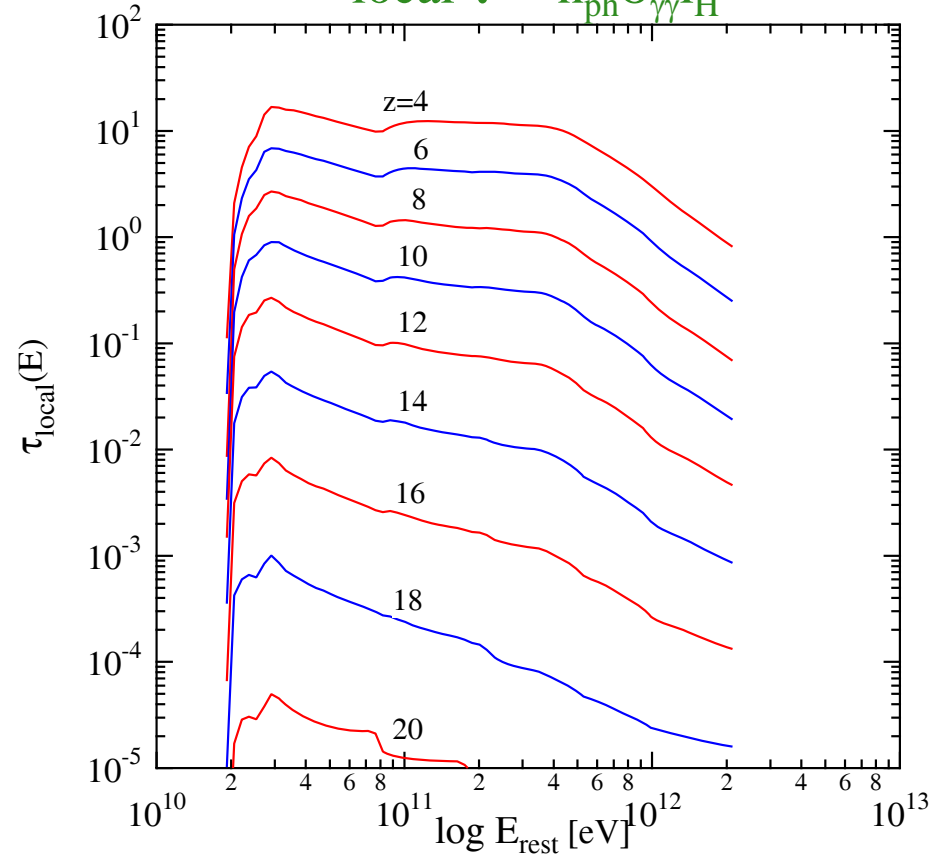
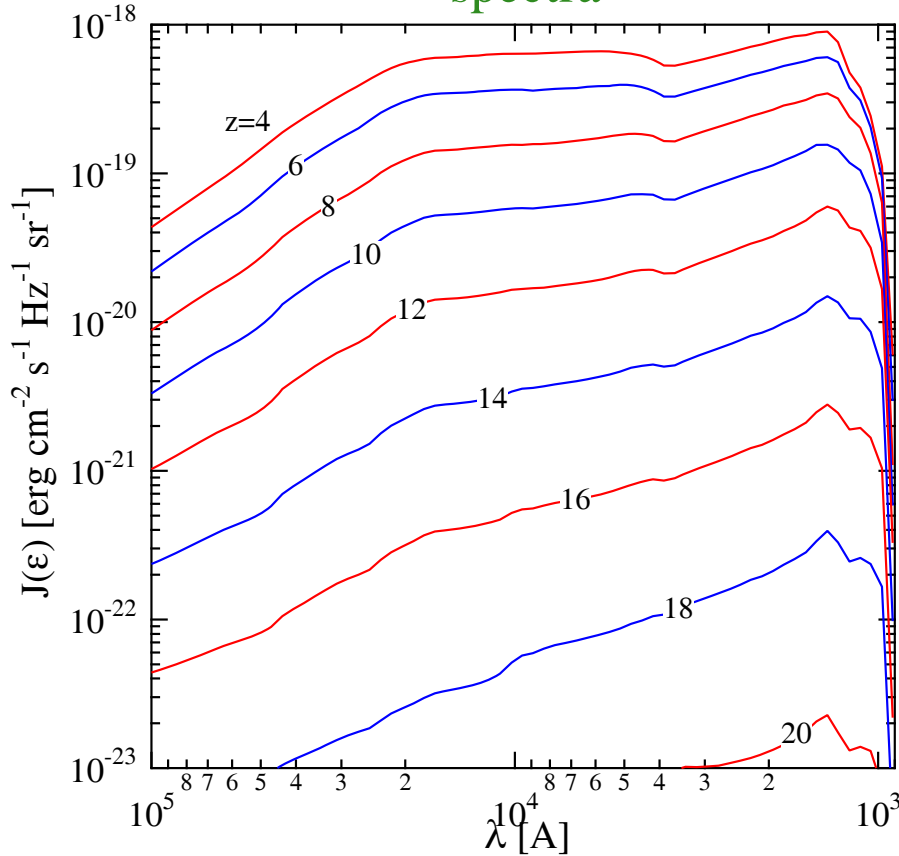
reionization
 begin $z \sim 15$
 90% $z \sim 10$
 100% $z \sim 6$

radiation field (volume average)

only in range $4 < z < 22$

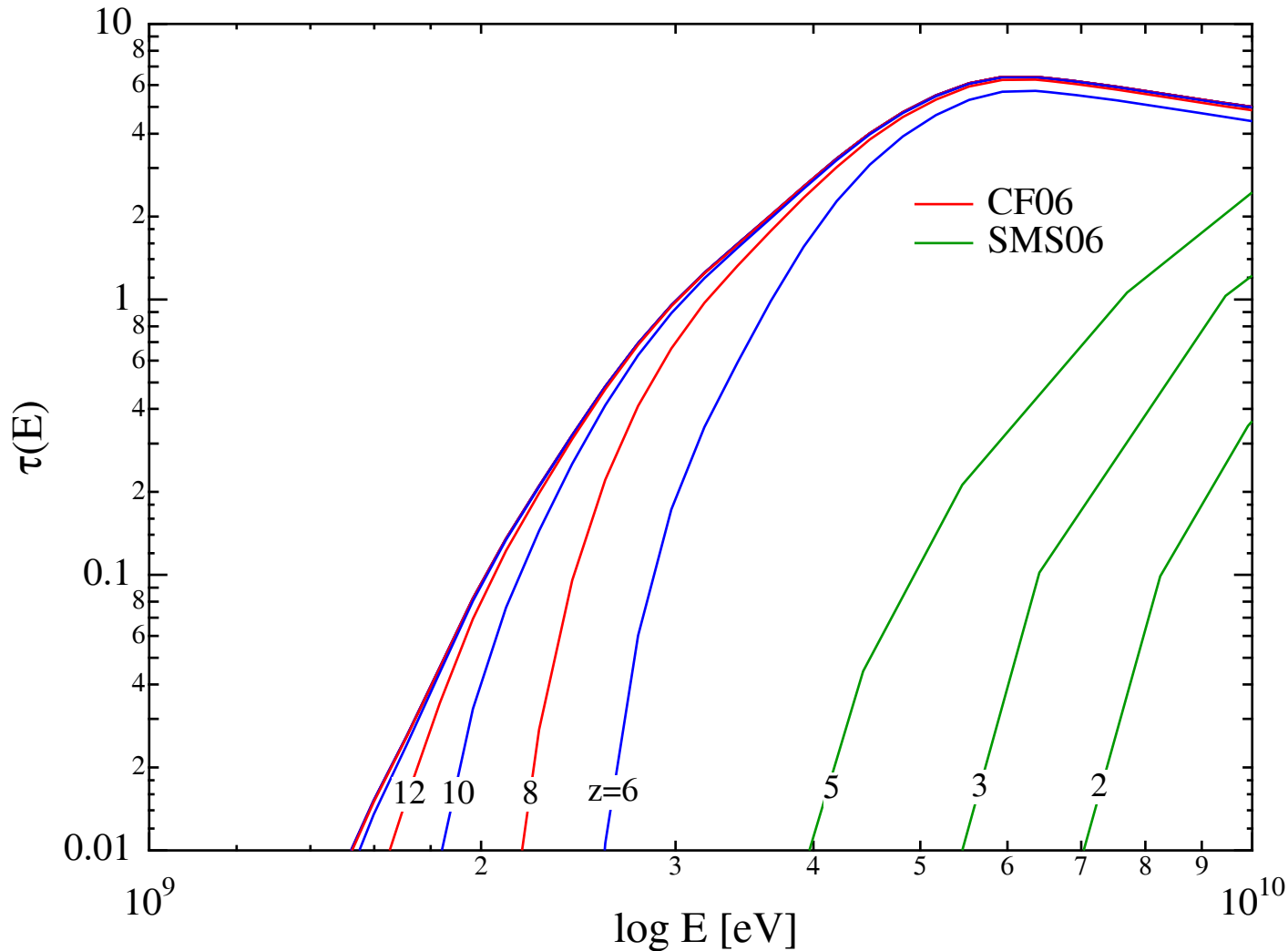
spectra

“local τ ” $\sim n_{\text{ph}} \sigma_{\gamma\gamma} l_{\text{H}}$



- reionizing UV field -> absorption in $E_{\text{rest}} \sim 10$'s- 100 's GeV at $z > \sim 10$
- sharp cutoff at $E_{\text{rest}} \sim 18$ GeV from Ly edge
- depends on different reionization models

gamma absorption optical depth

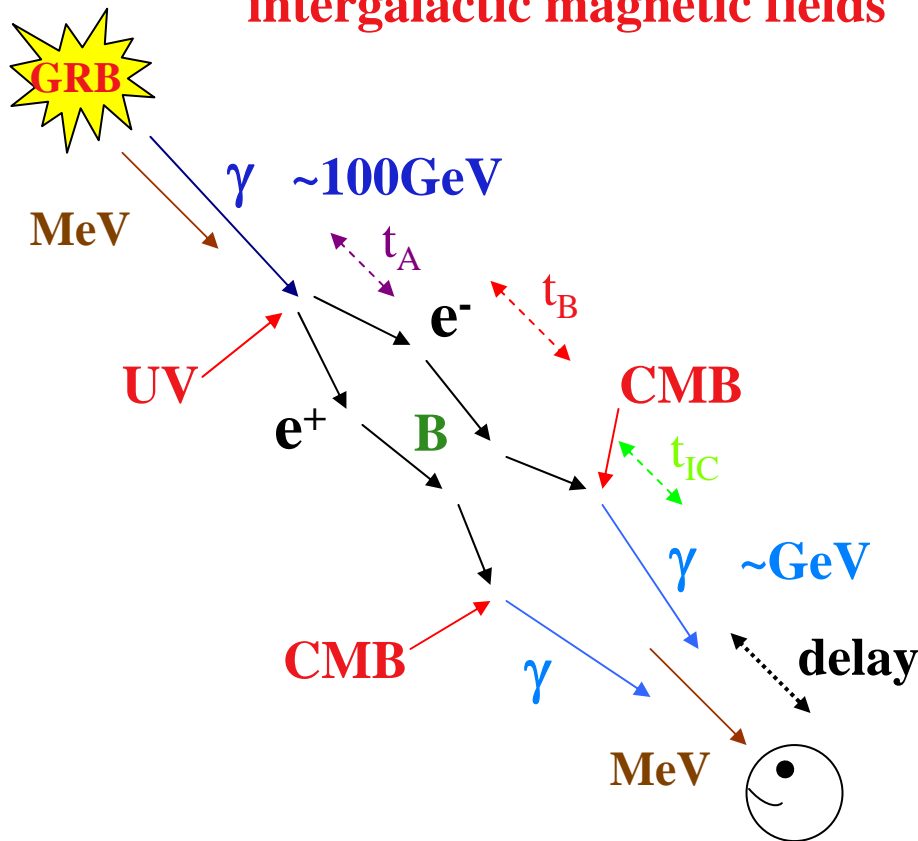


- each z can absorb only down to $E \sim 18 \text{ GeV} / (1+z)$ c.f. Madau & Phinney 96, Oh 01
important contribution from $z > \sim 6$ at few GeV
- important dependence on different models
(Pop III efficiency, IMF, escape fraction, etc.)

delayed GeV emission and intergalactic magnetic fields

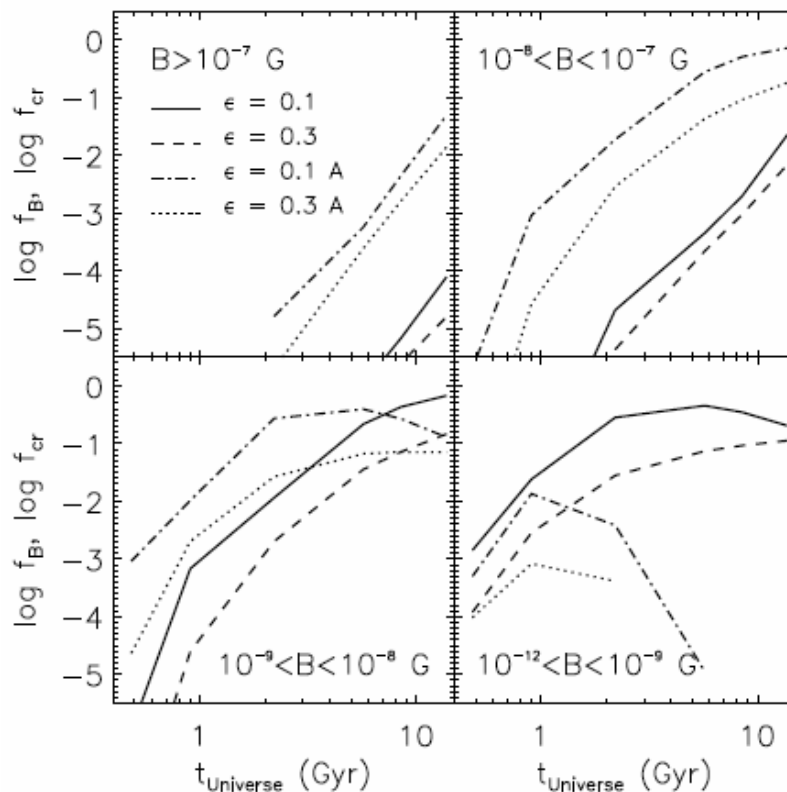
Plaga 95

sensitive to very weak intergalactic magnetic fields



high-z interesting because:
 - even lower B can be probed due to shorter t_{IC} , t_A
 - larger fraction of universe weakly magnetized

Bertone et al 06



Ichiki, Takahashi & Inoue, in prep.

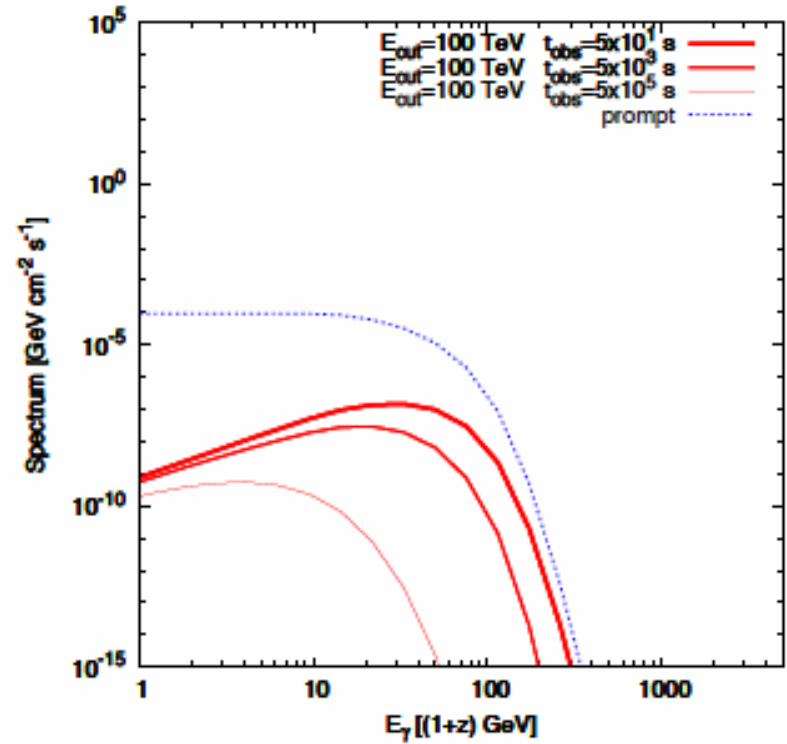
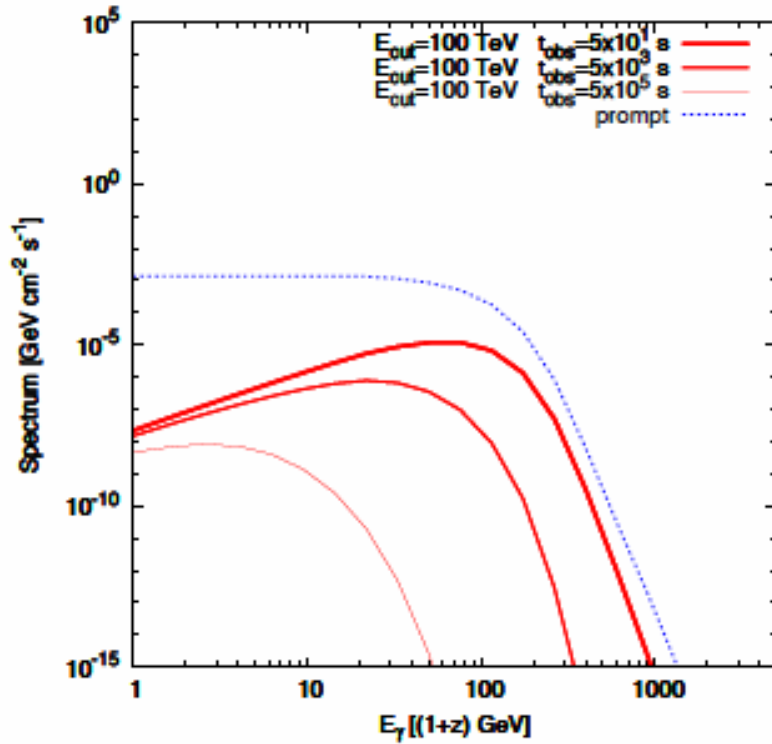
new formulation

previous formulations problematic

e.g. Razzaque et al 04

different for random or coherent B

Delayed spectrum (Random; $B=10^{-17} \text{ G}$; $z=1.0$ (left), $z=3.0$ (right))



- IRB absorption will be important $E_\gamma > 100 \text{ GeV}$.

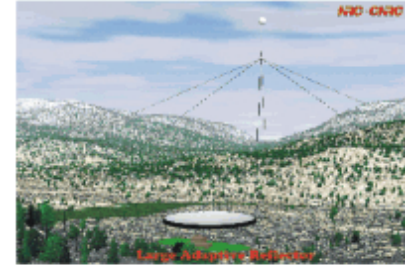
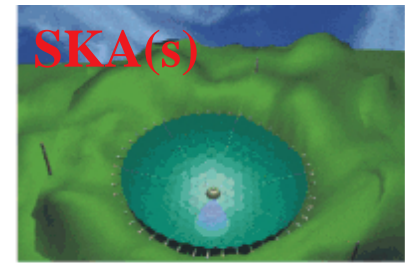
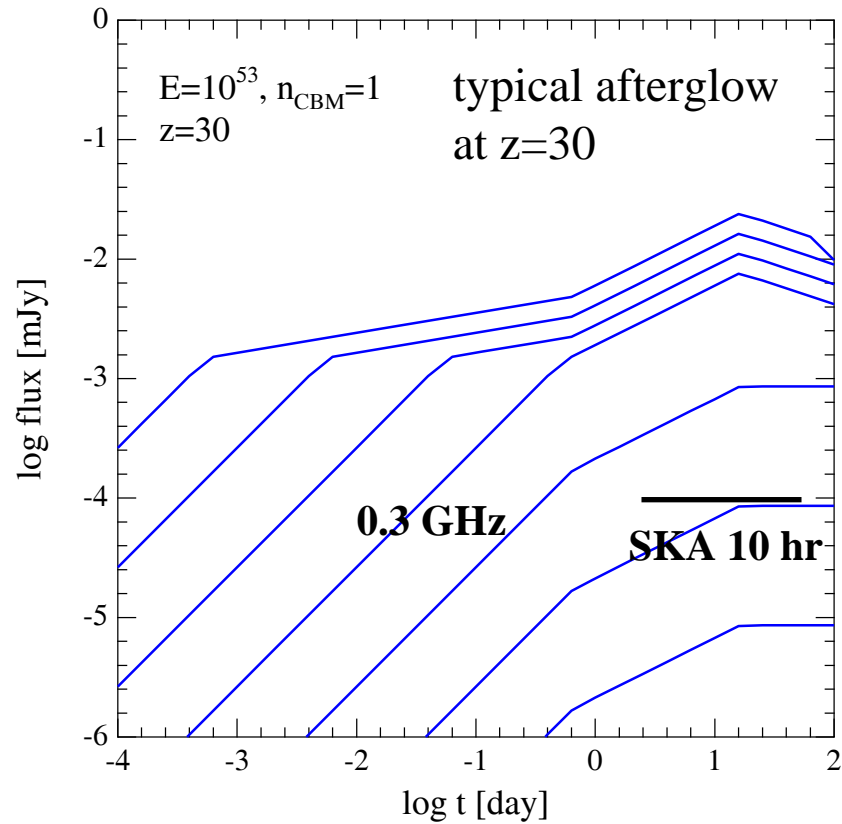
polarization in high-z GRBs

linear polarization in GRB afterglows
few % optical, similar expectation for radio

c.f. Taylor et al. 04

<2% upper limit @ 1.4-8.5 GHz

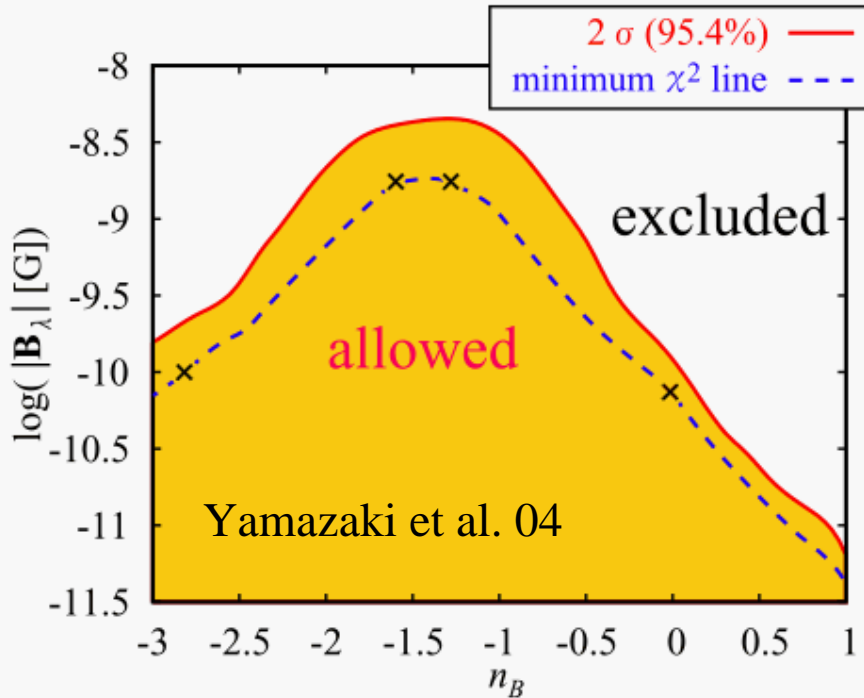
for GRB030329



high-z intergalactic magnetic fields through Faraday rotation

Inoue and Ichiki, in prep.

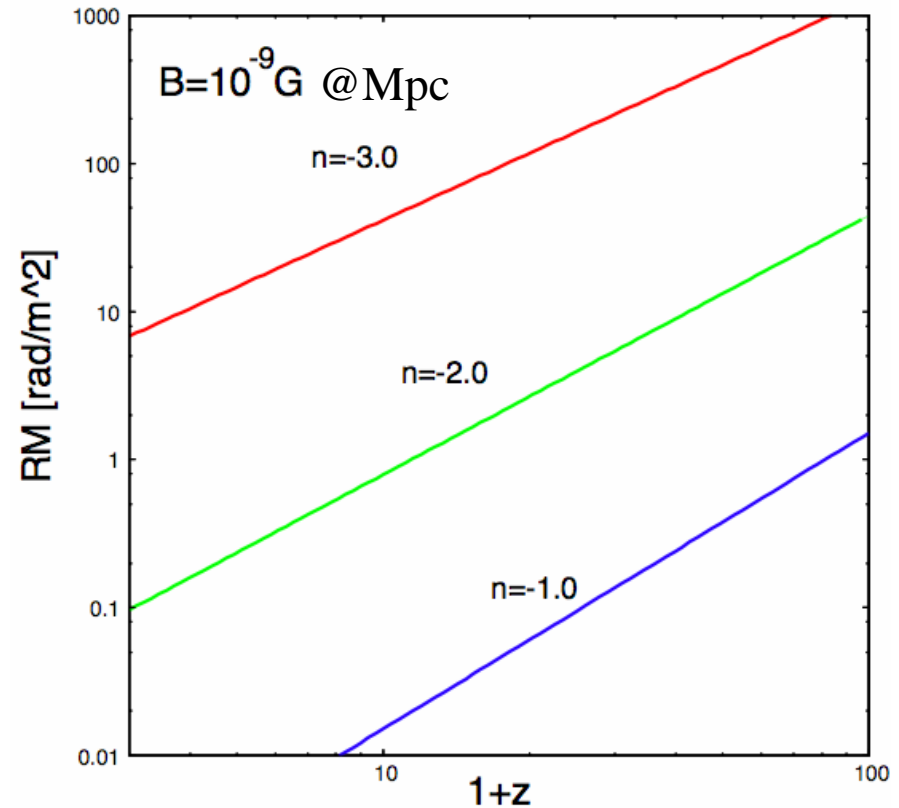
high-z B consistent with CMB



$$\langle B^2 \rangle_{|\lambda} = B_{\lambda=1\text{Mpc}}^2 \left(\frac{\lambda}{\text{Mpc}} \right)^{-n-3} \text{ [Gauss}^2\text{]}$$

$$RM = 13.1 \Omega^{-\frac{n+3}{2}} x_e \left(\frac{B_{\lambda=1\text{Mpc}}}{10^{-8}\text{G}} \right) (1+z)^{\frac{n+17}{4}} \left(\frac{\Omega_m h^2}{0.12} \right)^{\frac{n+1}{4}} \left(\frac{\Omega_b h^2}{0.022} \right)$$

IGM RM at high-z



+contribution from local magnetic fields

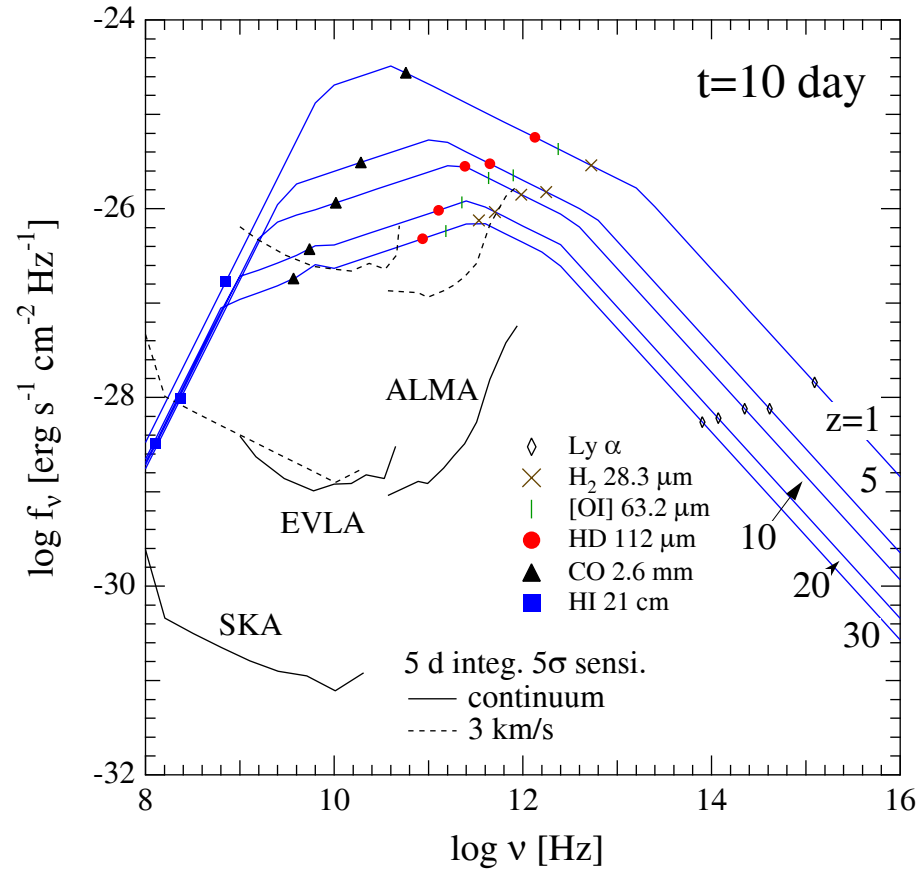
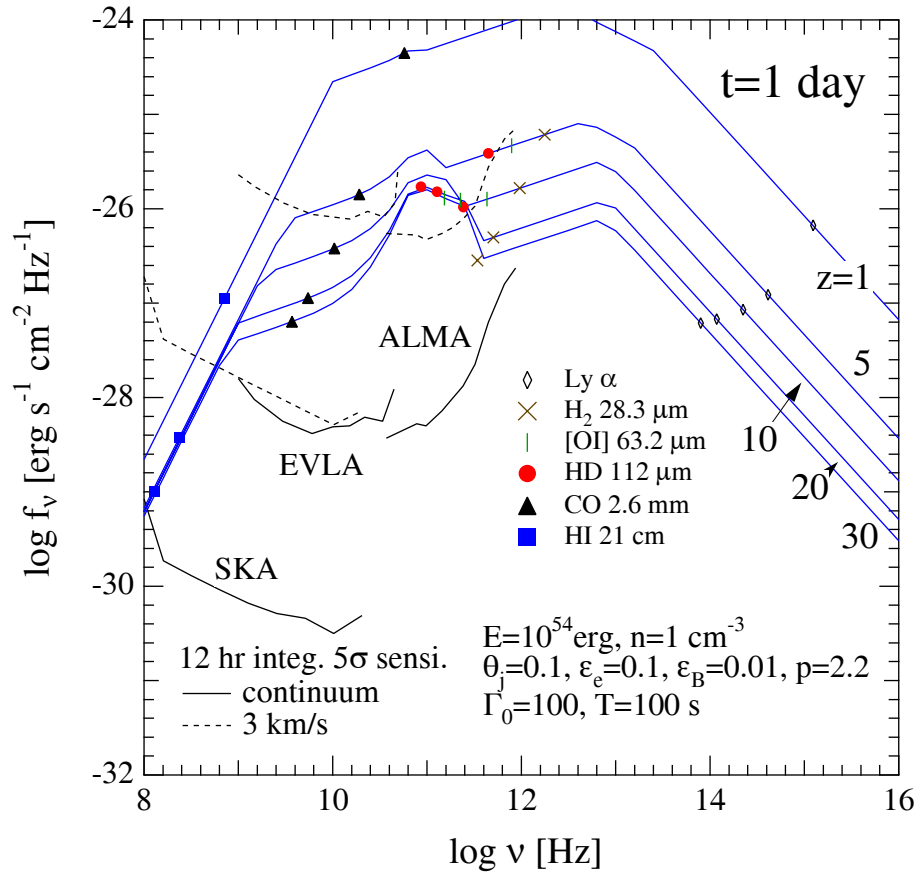
c.f. Tan & McKee 04, Maki & Susa 04
Machida et al 06, Silk & Langer 06

summary: probing high-z with GRB broadband emission

- GRBs more promising GeV-TeV sources than blazars at high z
detectability of prompt+afterglow SSC emission
GLAST: $z < \sim 10$ for bright cases?
5@5: $z > \sim 30$ even for typical cases!
- GeV absorption: unique potential probe of high-z UV background
 - important contribution from $z > \sim 6$ at few GeV
 - probe reionization history, Pop III stars
 - crucial for understanding early star/galaxy formation
- secondary GeV delay: potential probe of high-z weak intergalactic B
sensitive to very weak B, favorable for higher z
distinguish between coherent vs tangled B
- radio Faraday rot.: potential probe of high-z strong intergalactic B
% order polarization detectable by SKA to $z \sim < 30$
important constraints from RM on intergalactic(+local) B

atomic/molecular absorption lines in GRB radio-IR spectra

Inoue, Omukai & Ciardi, astro-ph/0502218



SKA: • CO (low) probe physical conditions (different J)

ALMA: • HD
• CO (high) probe Pop III
• [OI] Pop III- \rightarrow II transition