Gamma-Ray Absorption in High-Redshift Objects and Cosmic Reionization

Susumu Inoue (MPI Munich/ICRR U.Tokyo)

- Model 1: SI, Salvaterra, Choudhury, Ferrara, Ciardi, Schneider
- Model 2: Yoshiyuki Inoue, SI, Kobayashi, Makiya, Niino, Totani
- CTA prospects: SI, Granot, O'Brien et al. (for the CTA Consortium)

Nice to be in Texas!

gamma-ray absorption: probe of diffuse radiation fields

$\gamma + \gamma \rightarrow e^{+} + e^{-}$

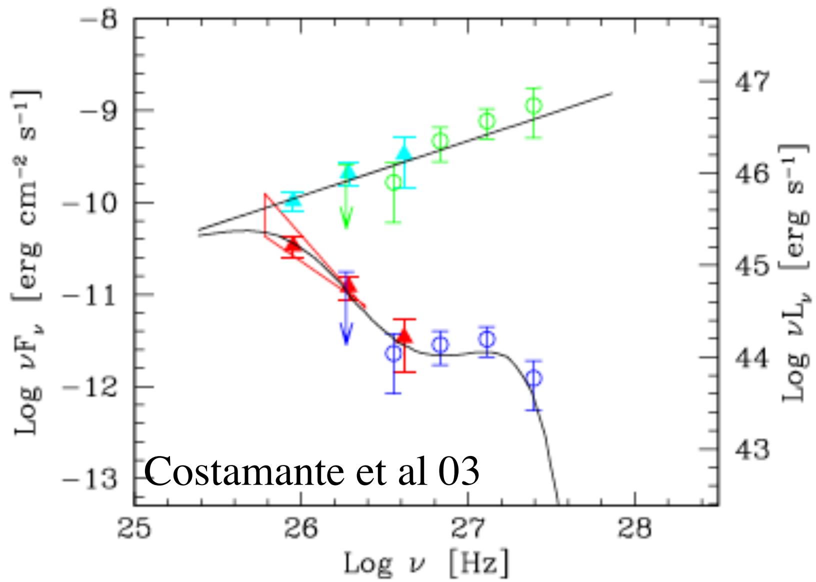
E   ε

threshold condition: $E\,\varepsilon\,(1-\cos\theta) > 2\, m_e^2 c^4$

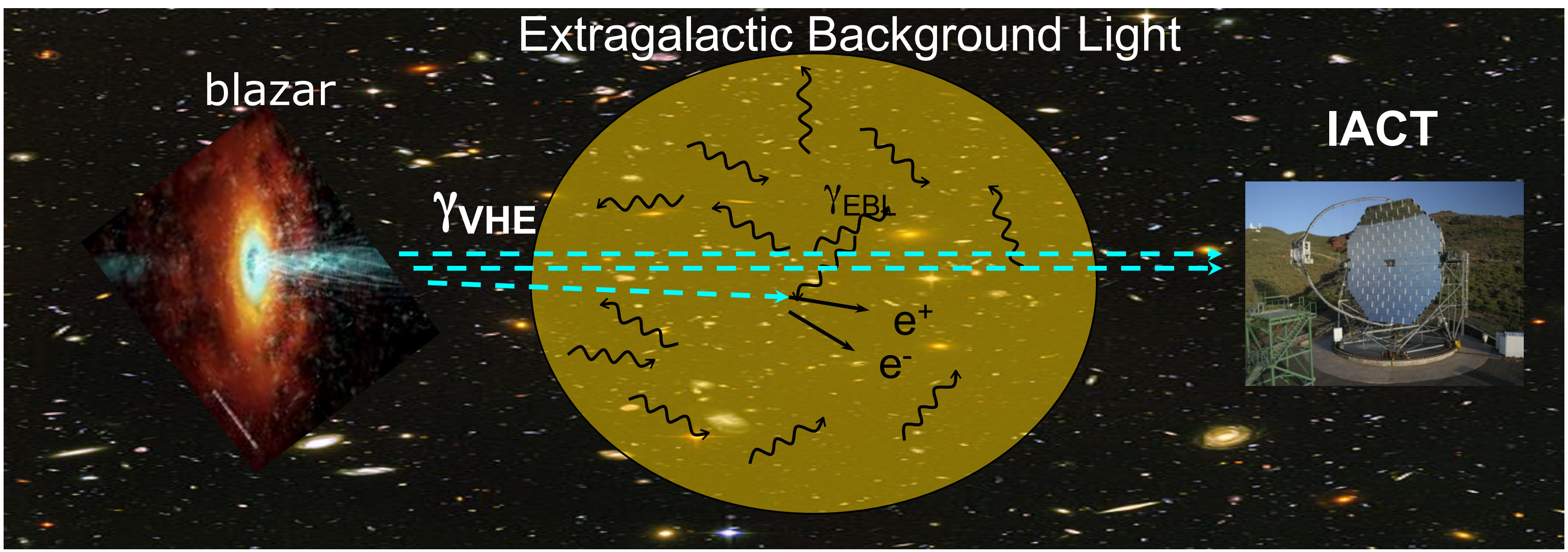
σ peak ,, $= 4\, m_e^2 c^4$

e.g. TeV + 1eV (IR)

100 GeV + 10 eV (UV)

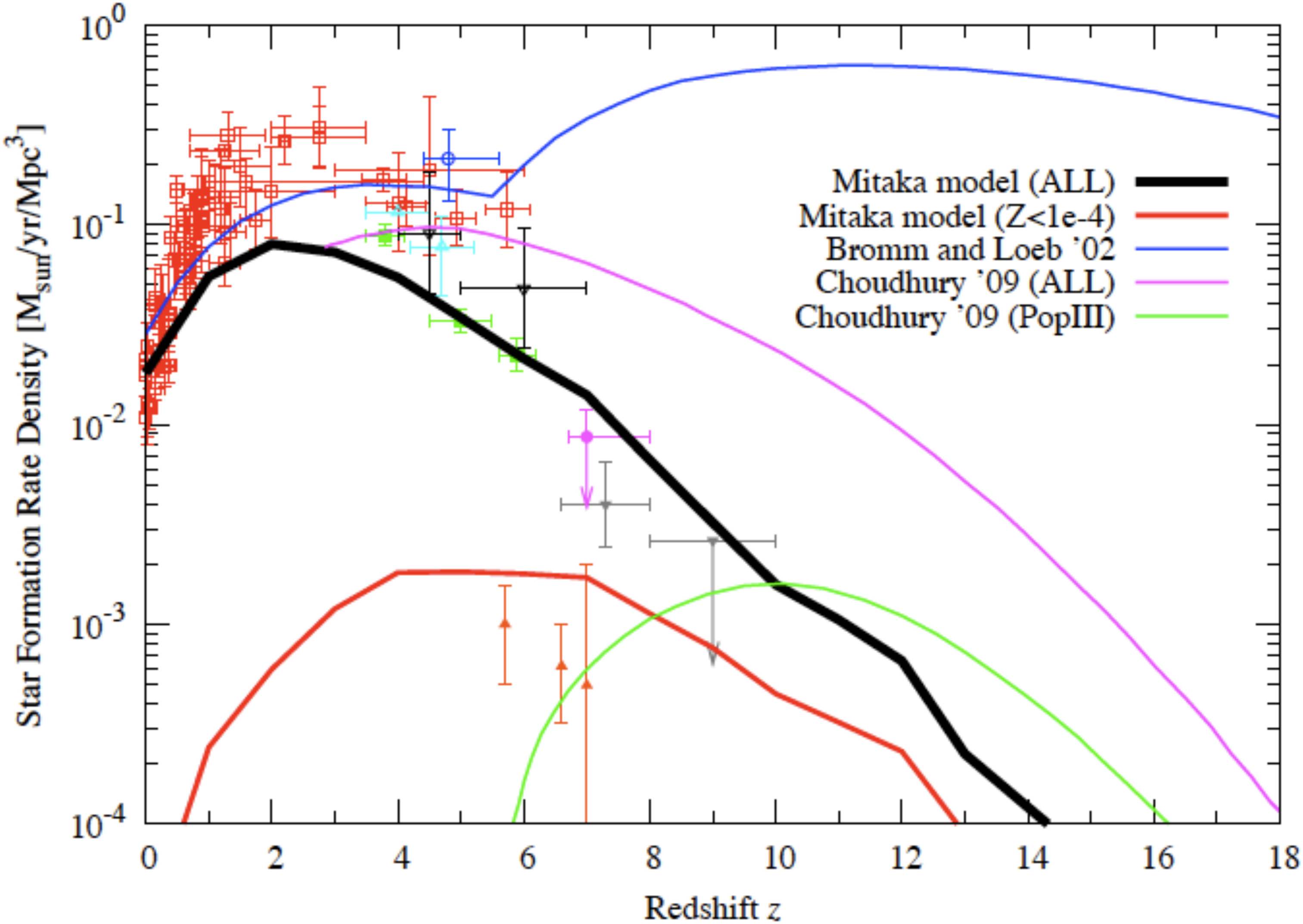


probe of local IRB from γγ absorption in TeV blazars



from M. Teshima

cosmic star formation history vs models



- directly observed UV luminosity at z>6 insufficient for WMAP τ_e ?
- stars (Pop II or Pop III) in faint galaxies below HUDF limit?
- strong evolution in escape fraction? e.g. Haardt & Madau 12

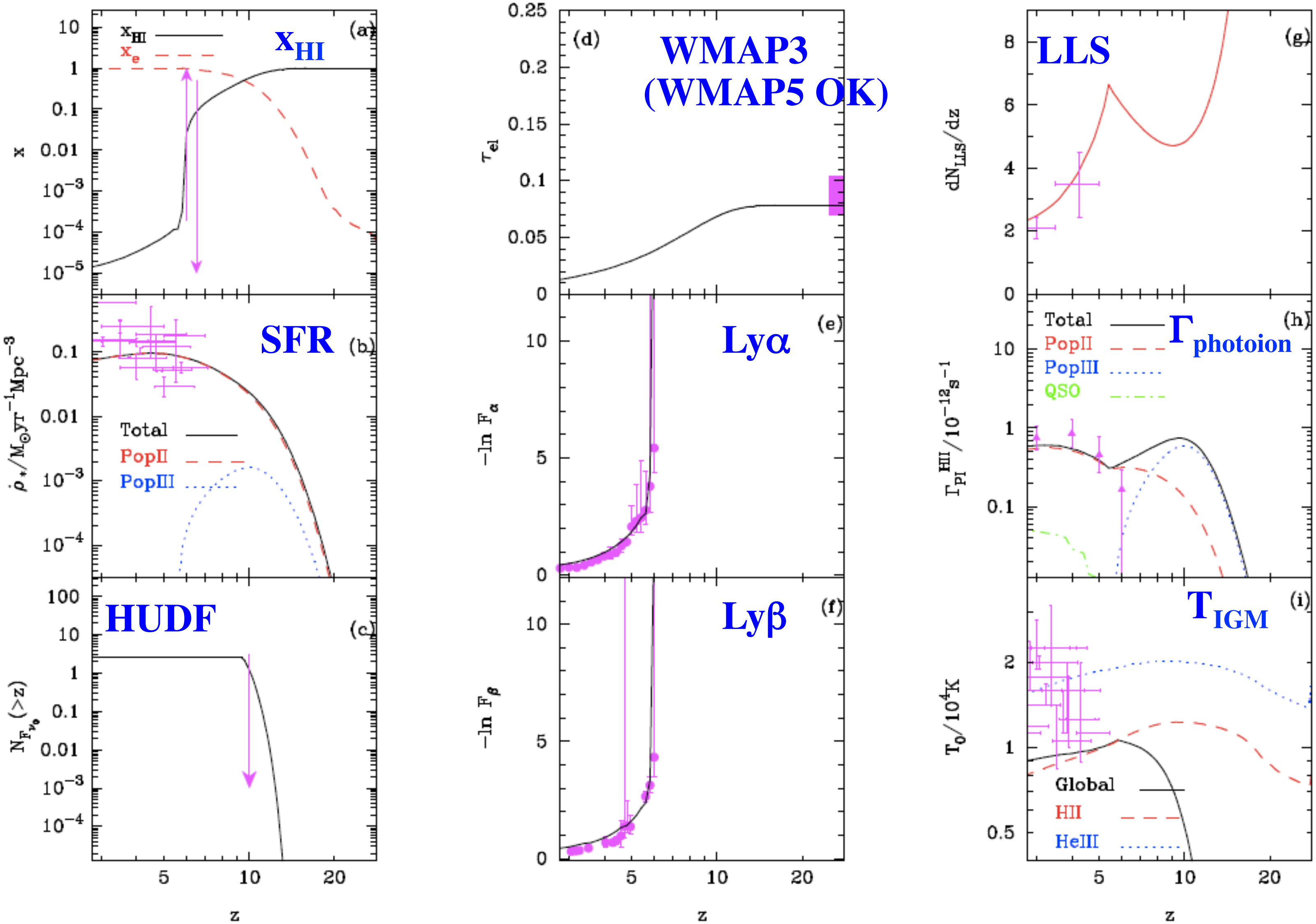
Model 1 model of cosmic reionization

Choudhury & Ferrara 05, 06, Choudhury 09

parameters ε_{*II}, ε_{*III}, η_{esc}, λ_{0IGM}

semi-analytical model with Pop III+II stars+QSOs, radiative+chemical feedback

consistent with large set of high-z observations: WMAP, x_{HI}, HUDF NIR counts, etc.



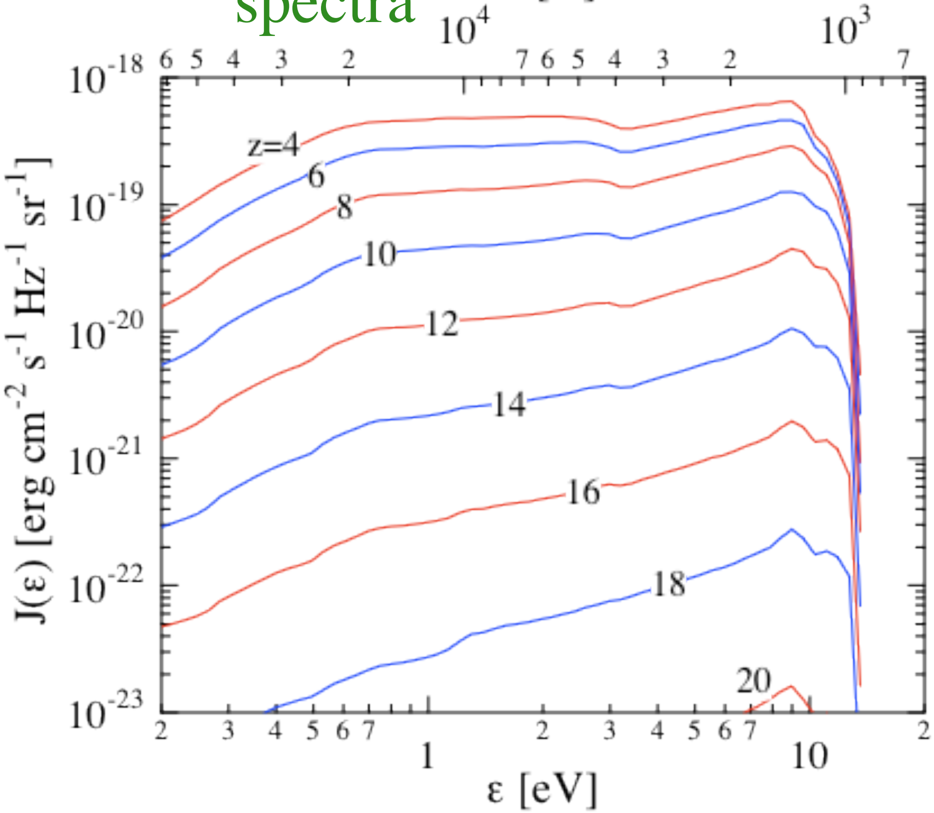
reionization
begins z~15
90% z~8
100% z~6

intergalactic radiation field (volume average)

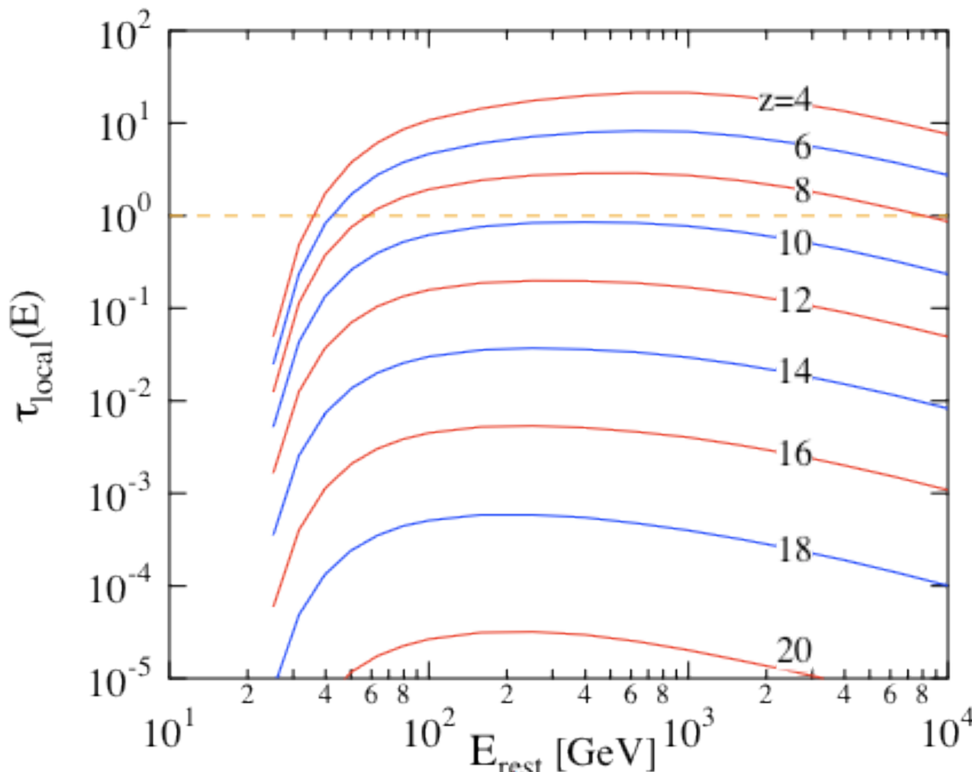
SI, Salvaterra+ 10

caveat: model only for 4<z<22, no Pop I/dust

spectra



"local" optical depth

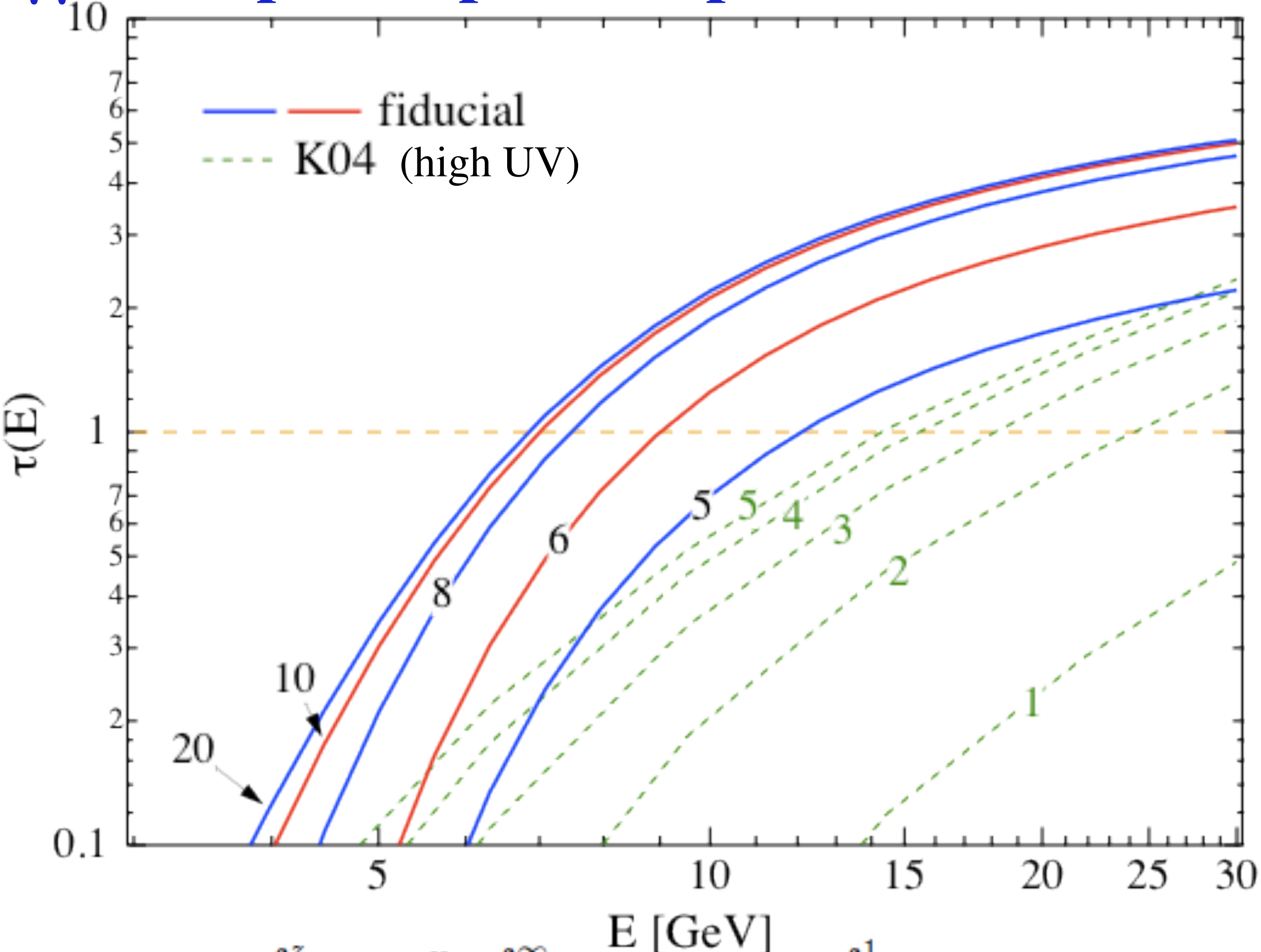


$$\tau_{\rm local}(z,E) = l_H(z) \int_{\epsilon_{\rm th}}^{\infty} d\epsilon \; n(\epsilon,z) \times \frac{1}{2} \int_{-1}^{1} d\mu (1-\mu) \sigma_{\gamma\gamma}(E,\epsilon,\mu)$$

- UV EBL -> opaque for E_{rest}~10's-100's GeV at z<~10
- sharp cutoff at E_{rest}~18 GeV from HI absorption above Ly edge (reionizing radiation cannot be probed directly)

$\gamma\gamma$ absorption optical depth

SI, Salvaterra, Choudhury+ 10



low z model
Kneiske+ 04
(high stellar UV)

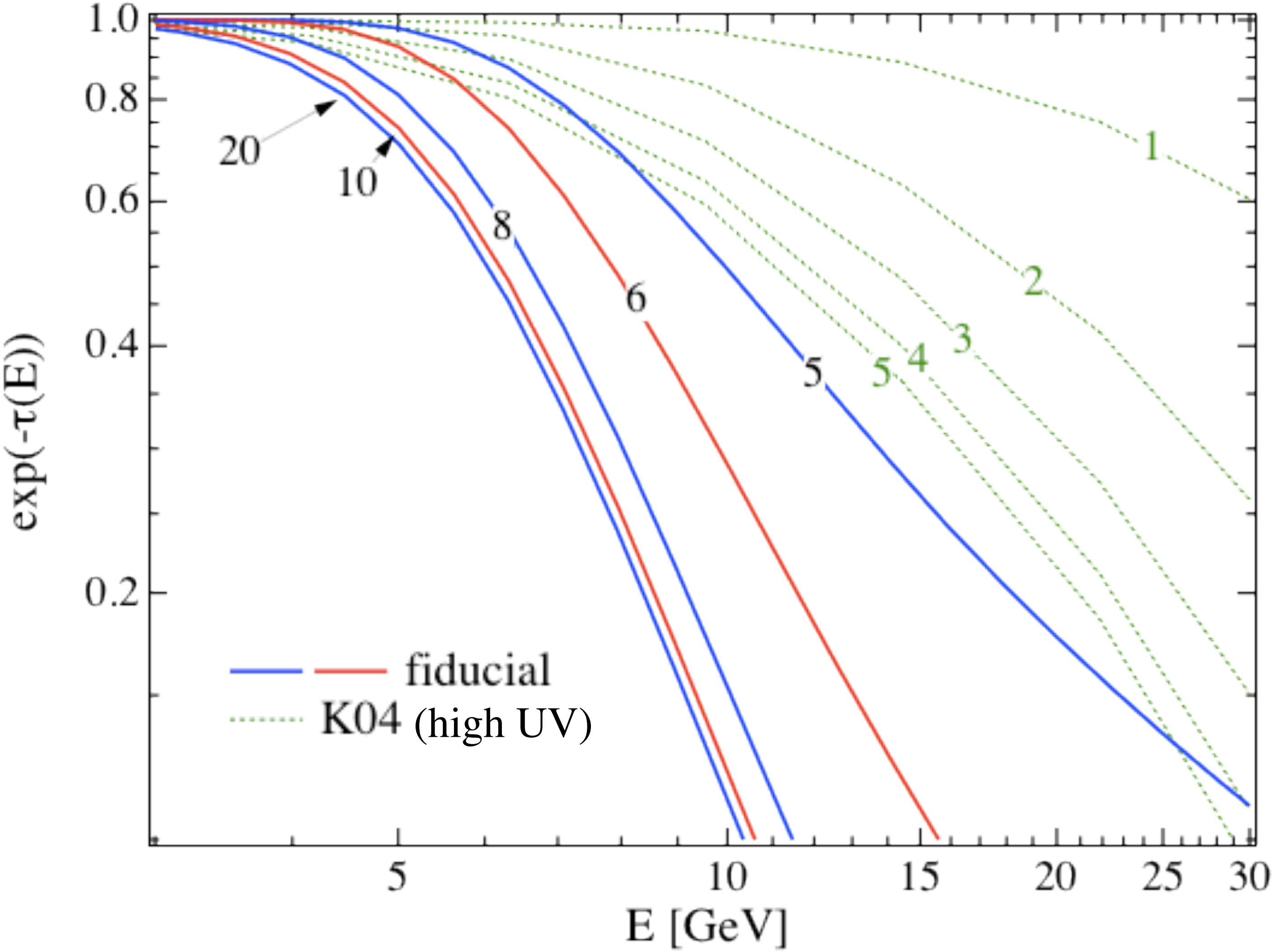
see also e.g.
Stecker+ 06
Razzaque+ 09
Gilmore+ 09

$\tau_{\gamma\gamma}$>~0.4
@z=4.35, E=13.2GeV
<-> GRB 080916C

$$\tau(z,E) = \int_{z_{\rm min}}^{z} dz' \frac{dl}{dz'} \int_{\epsilon_{th}}^{\infty} d\epsilon\, n(\epsilon, z') \times \frac{1}{2} \int_{-1}^{1} d\mu (1-\mu) \sigma(E(1+z'), \epsilon, \mu)$$

significant optical depth >12 GeV at z~5, down to 6-8 GeV at z~8-10
but not much effect z>~8 due to declining star formation, path length

γγ absorption attenuation factor

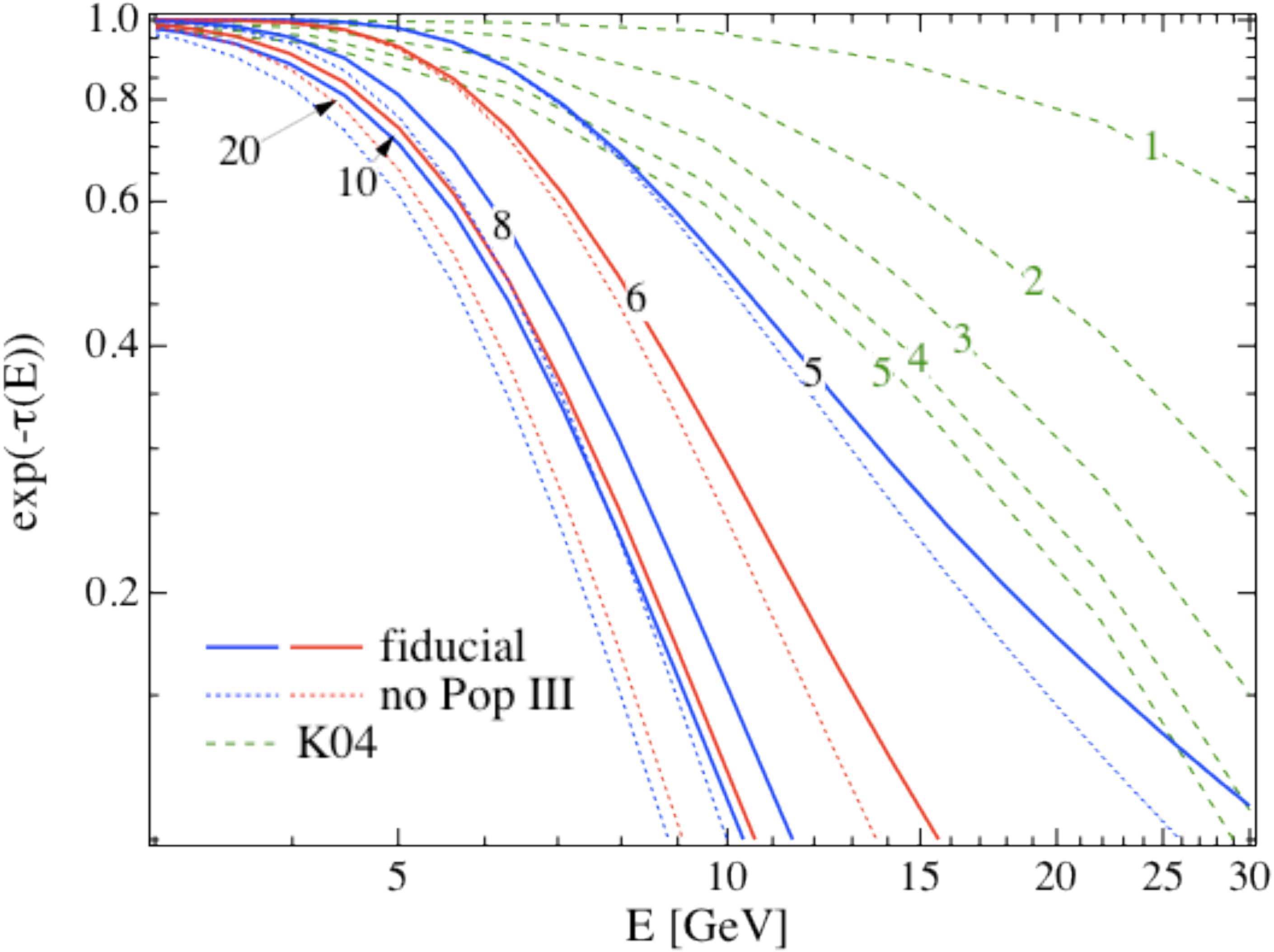


low z model
Kneiske+ 04
(high stellar UV)

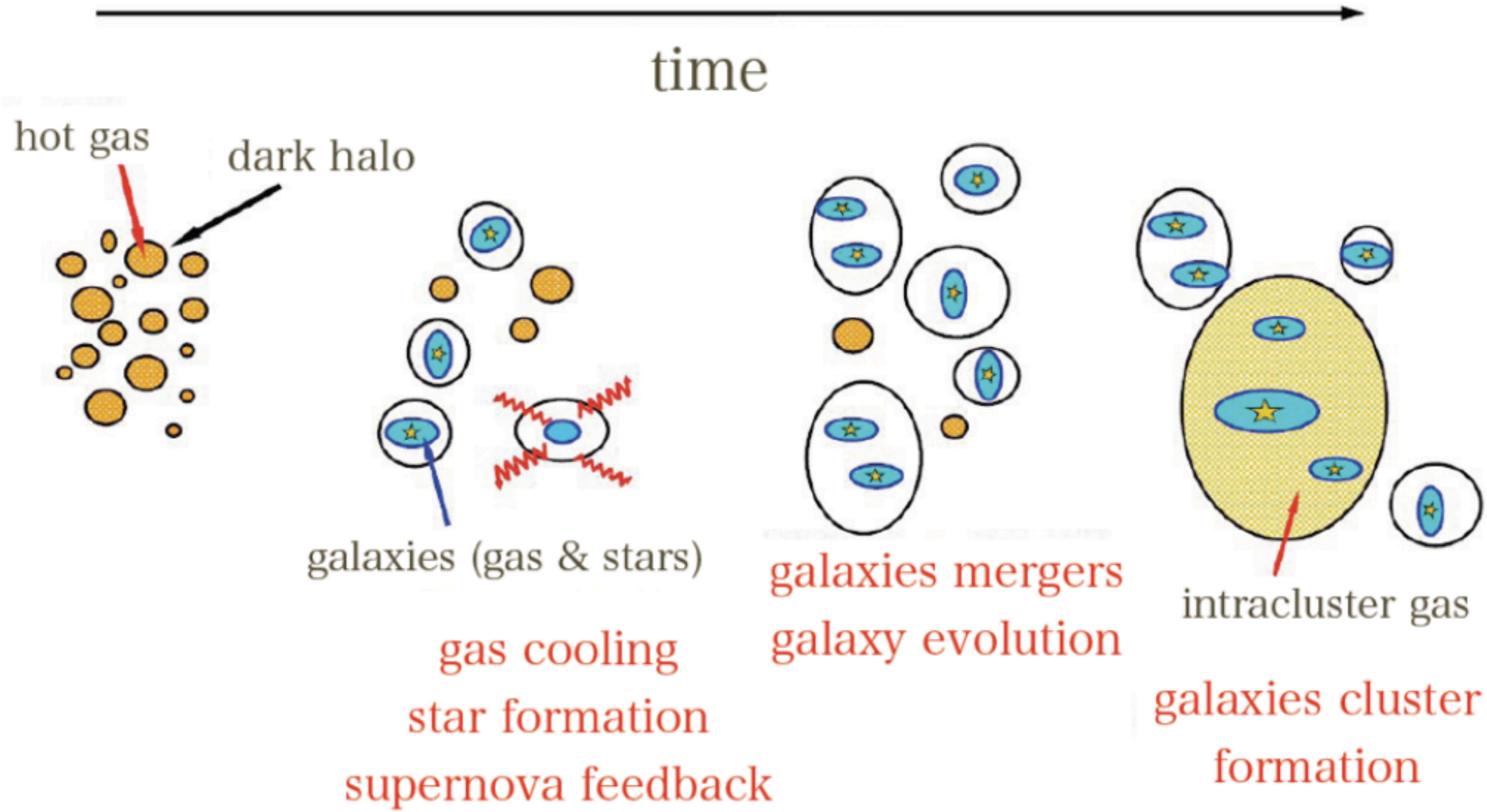
appreciable differences in attenuation between z~5-8 at several GeV
→ unique, important info on evolution of UV EBL below Ly edge
during cosmic reionization/first star formation

alternative models

e.g. late reionization model
with no Pop III stars



Model 2
hierarchical galaxy formation

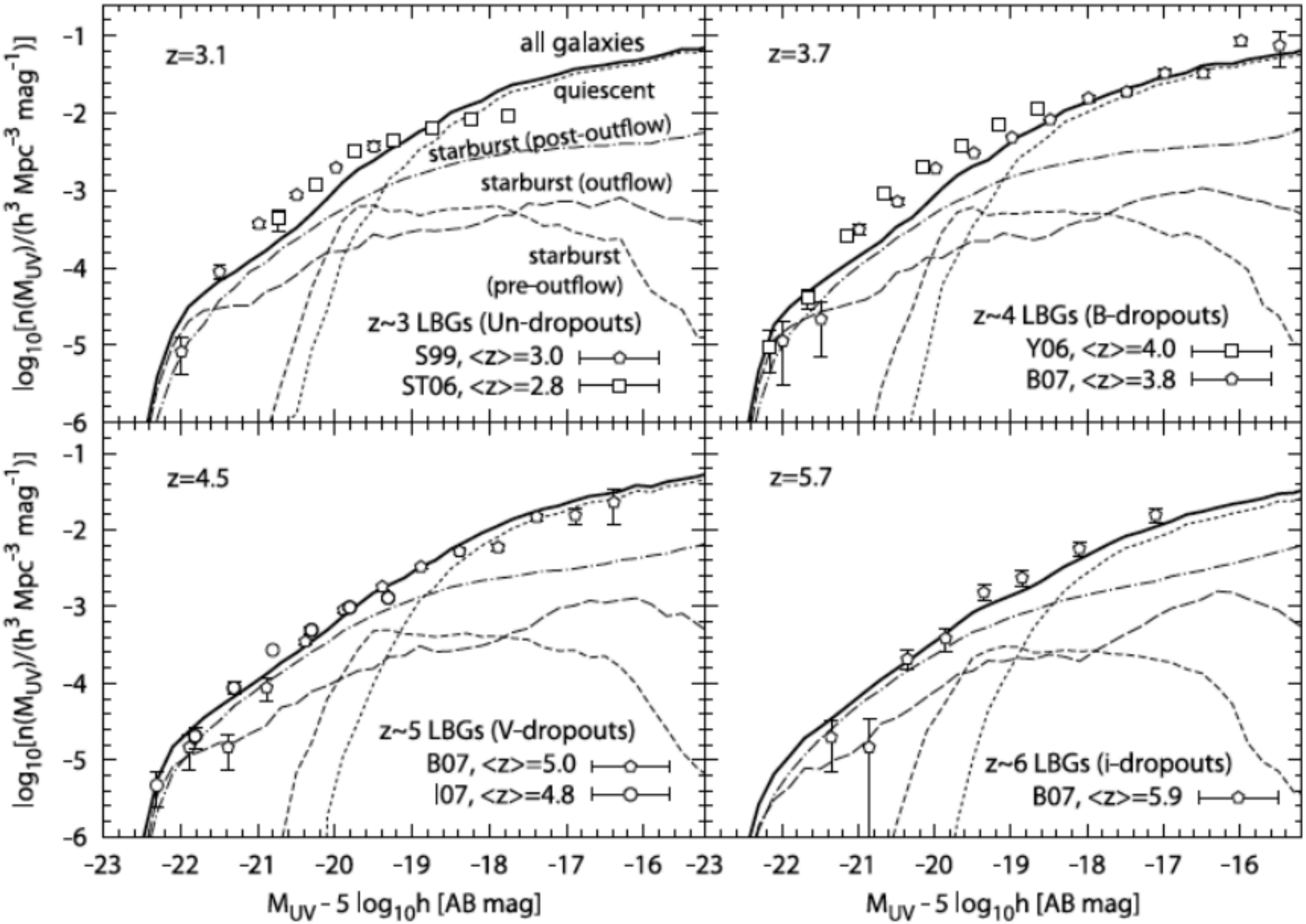


from M. Nagashima

galaxy formation model (Mitaka model)

semi-analytical model following halo merger histories
consistent with galaxy properties at z<6

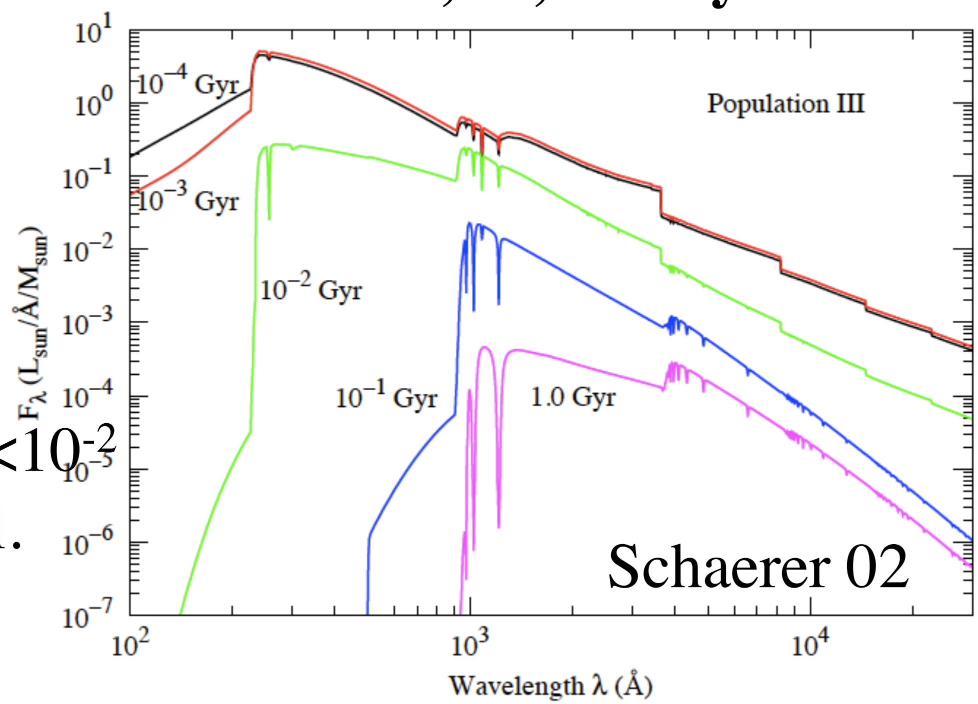
galaxy LF Kobayashi+ 10



simple modeling of reionization by Pop III stars

Y. Inoue, SI, Kobayashi+ 10

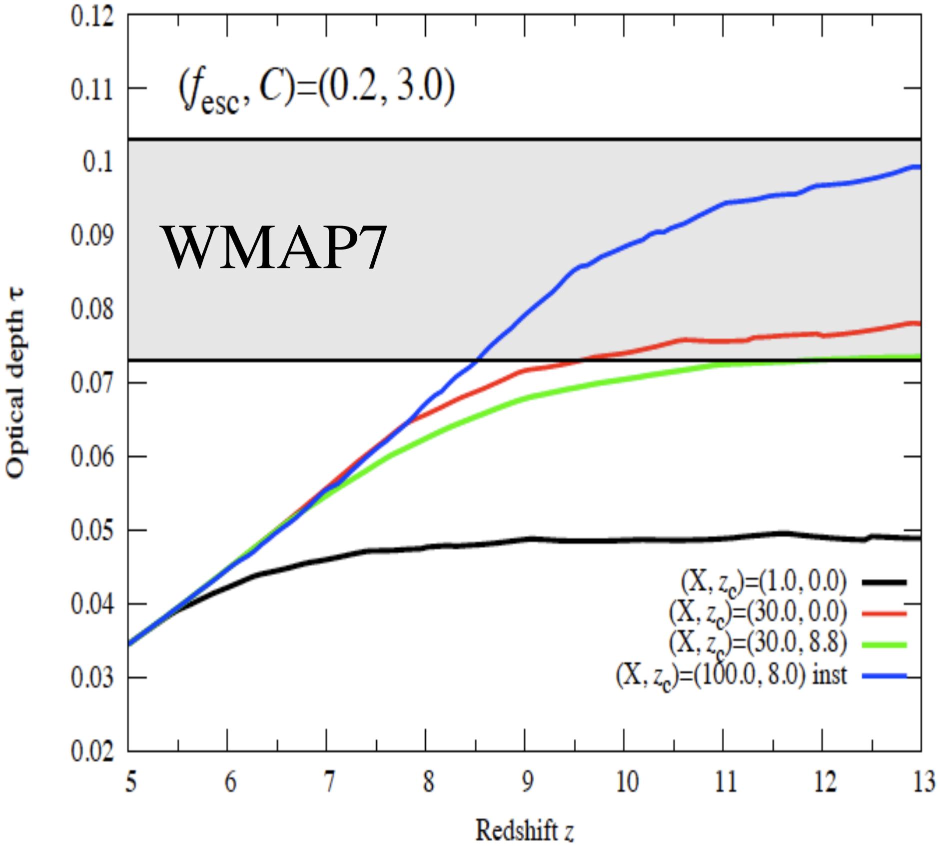
- enhance efficiency of low metal ($Z<10^{-4}$) star formation by factor X at $z>z_c$
- assume Salpeter IMF
  $0.1M_{sun}<M<100M_{sun}$
  Schaerer 02 for $Z<10^{-4}$
  Bruzual & Charlot 03 for $10^{-4}<Z<10^{-2}$
- solve equation of ionization equil. in cosmological HII regions a la Madau, Haardt & Rees 99
- further parameters: clumping factor $C=\langle n_{HII}^2\rangle/\langle n_{HII}\rangle^2$
  UV escape fraction f_{esc}



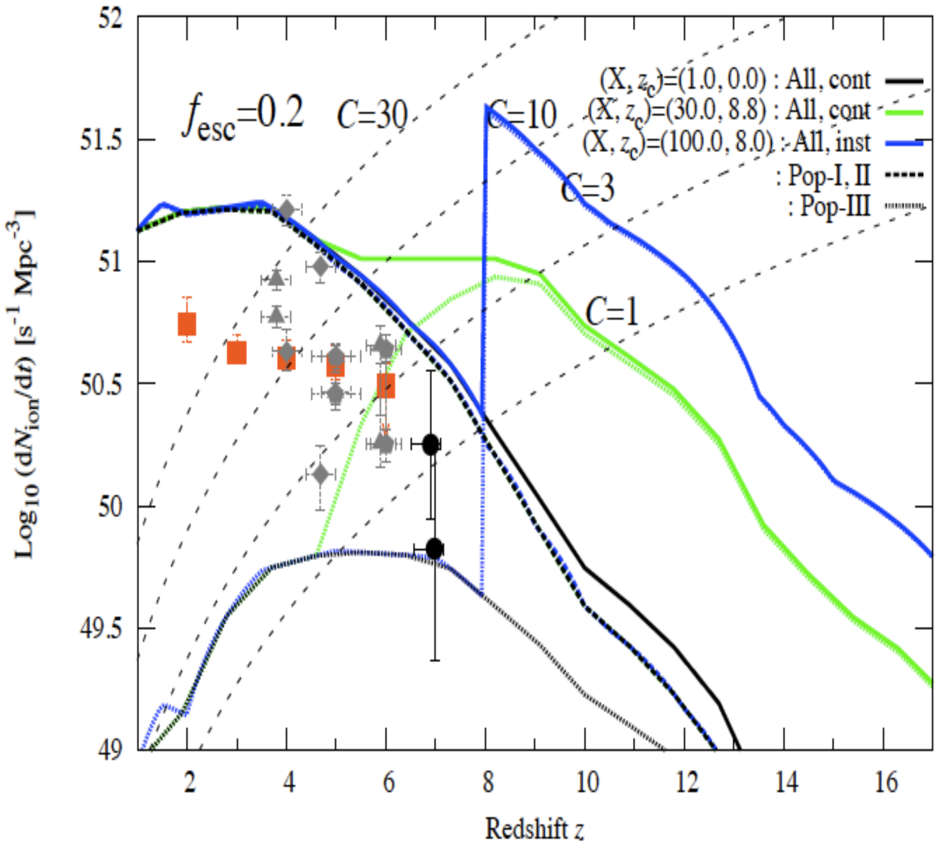
$$\bar{n}_{\rm H}\left(\frac{{\rm d}V_p}{{\rm d}t}-3HV_p\right)=\frac{{\rm d}N_\gamma}{{\rm d}t}-\alpha_{\rm B}\langle n_{\rm H}^2\rangle V_p$$

no. of H atoms | ionizing photon input rate | recombination rate

electron scatt. optical depth

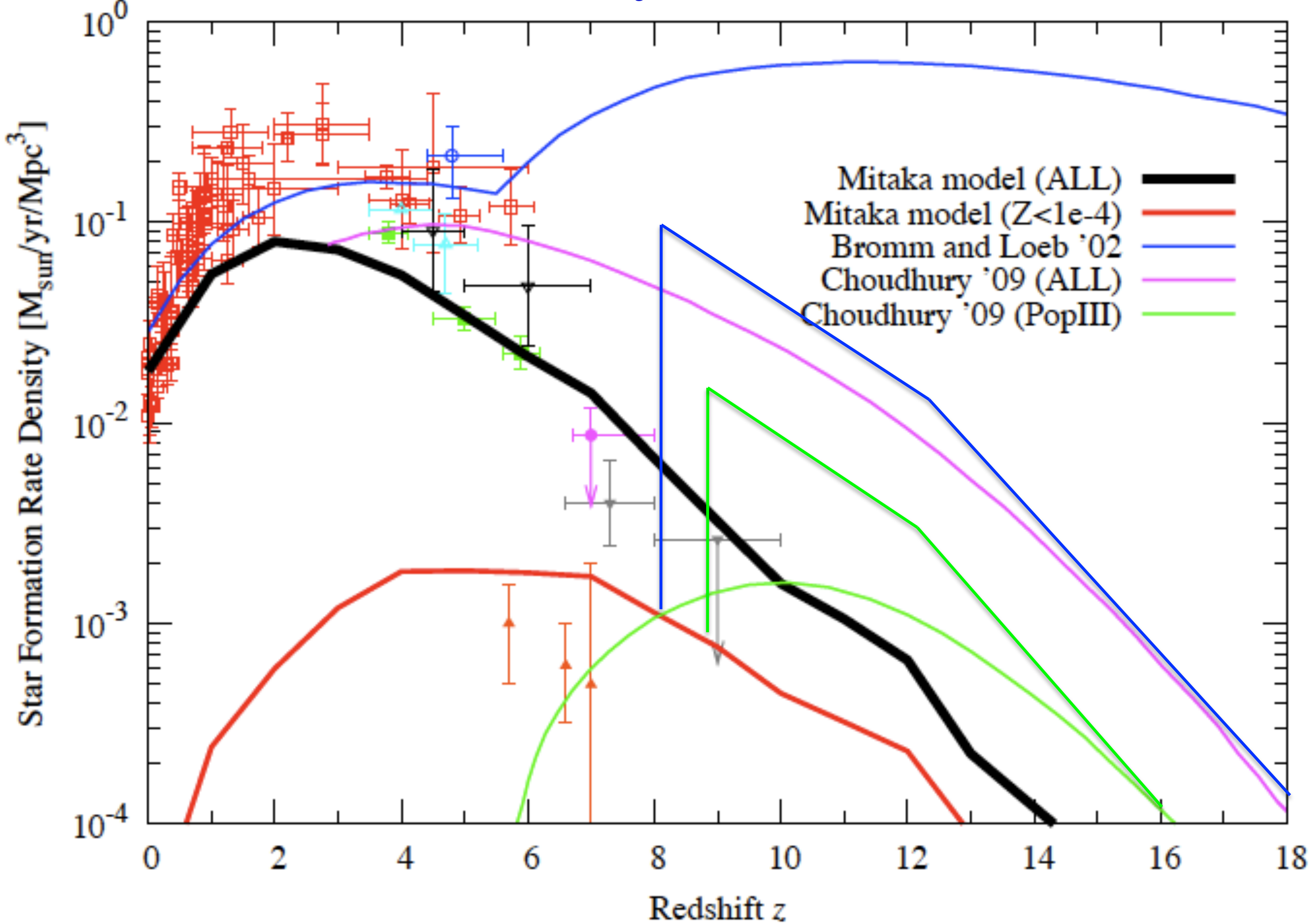


ionizing photon density

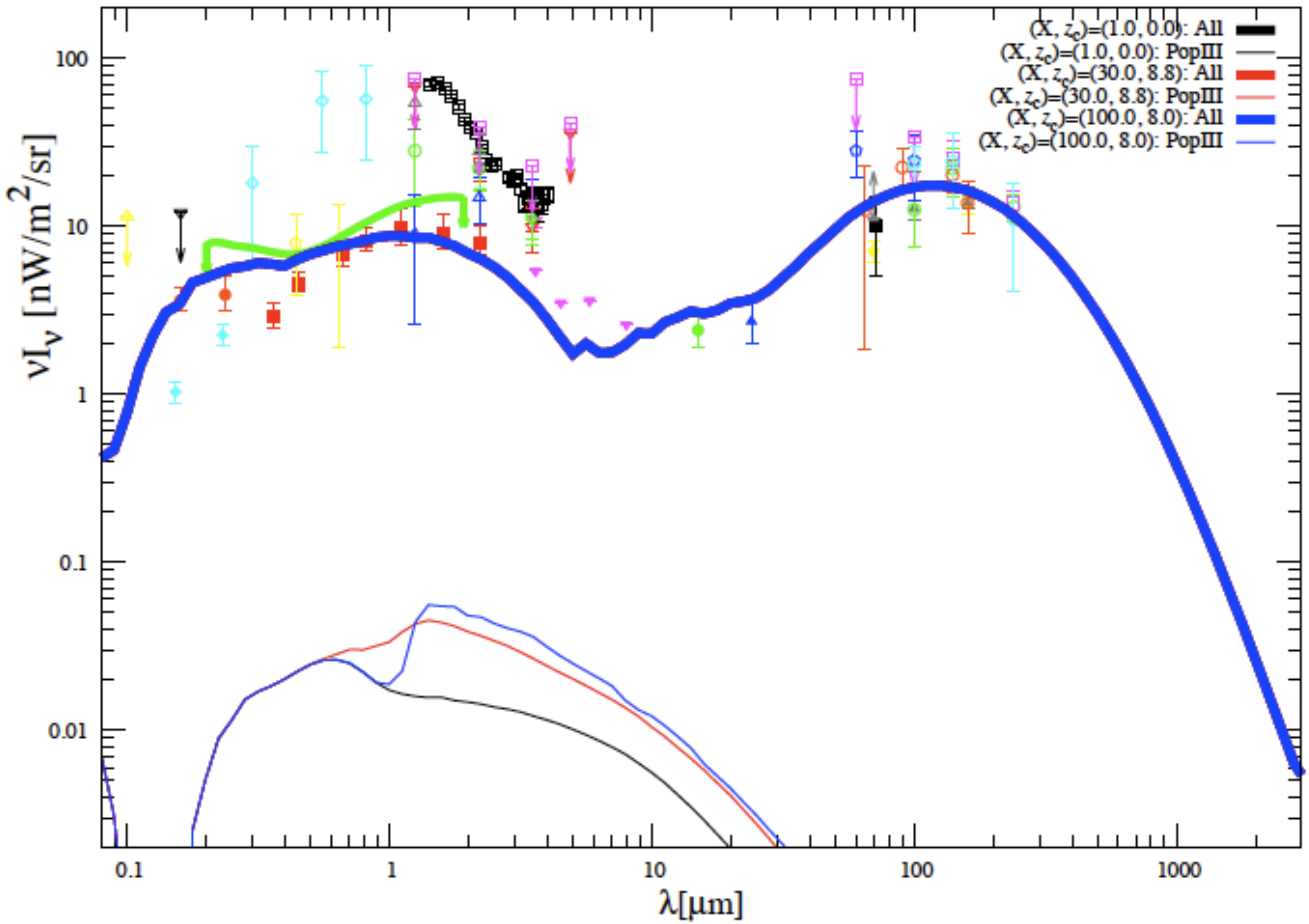


- range of parameters consistent with WMAP7
- also broadly consistent with QSO GP measurements

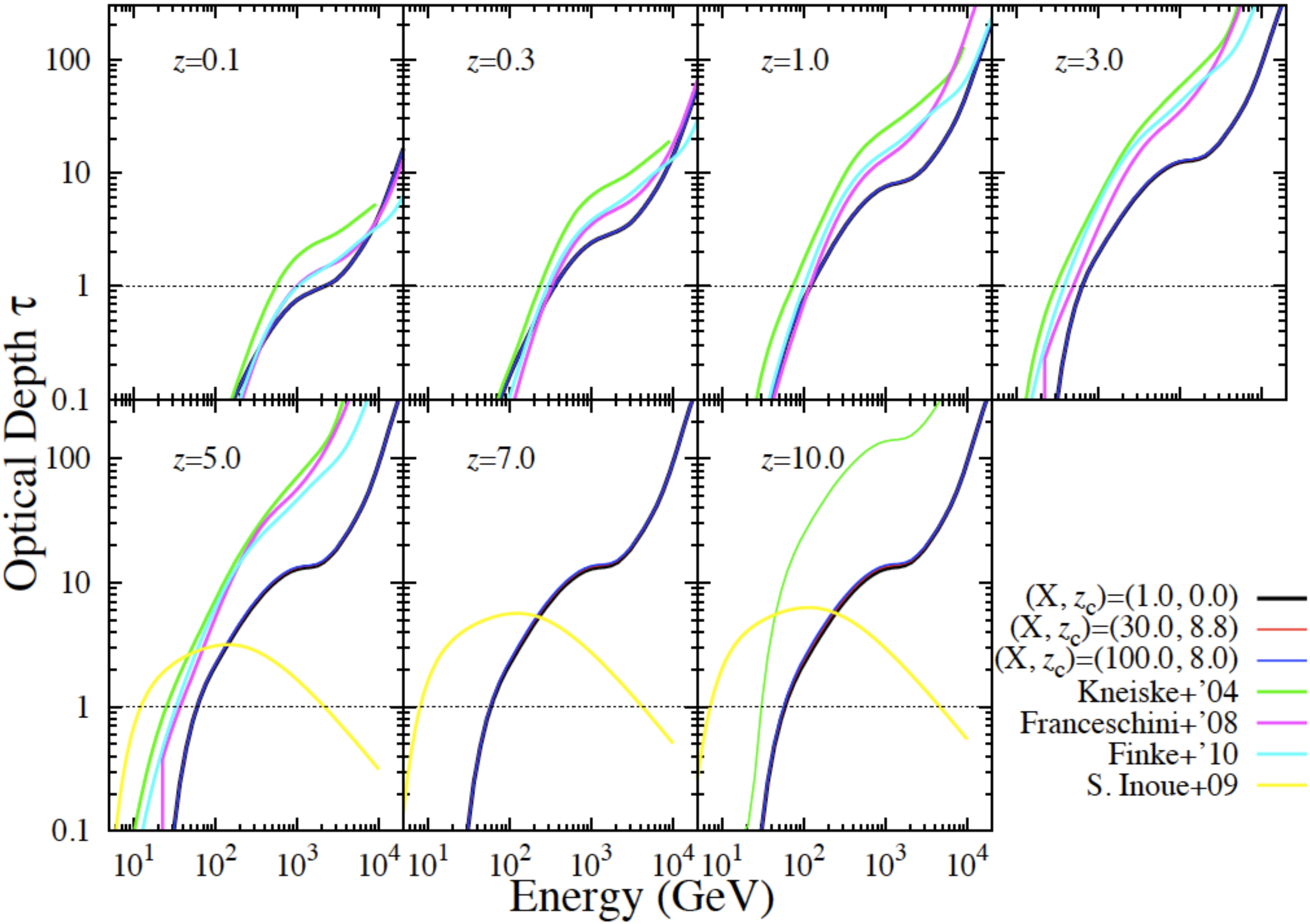
cosmic star formation history vs models



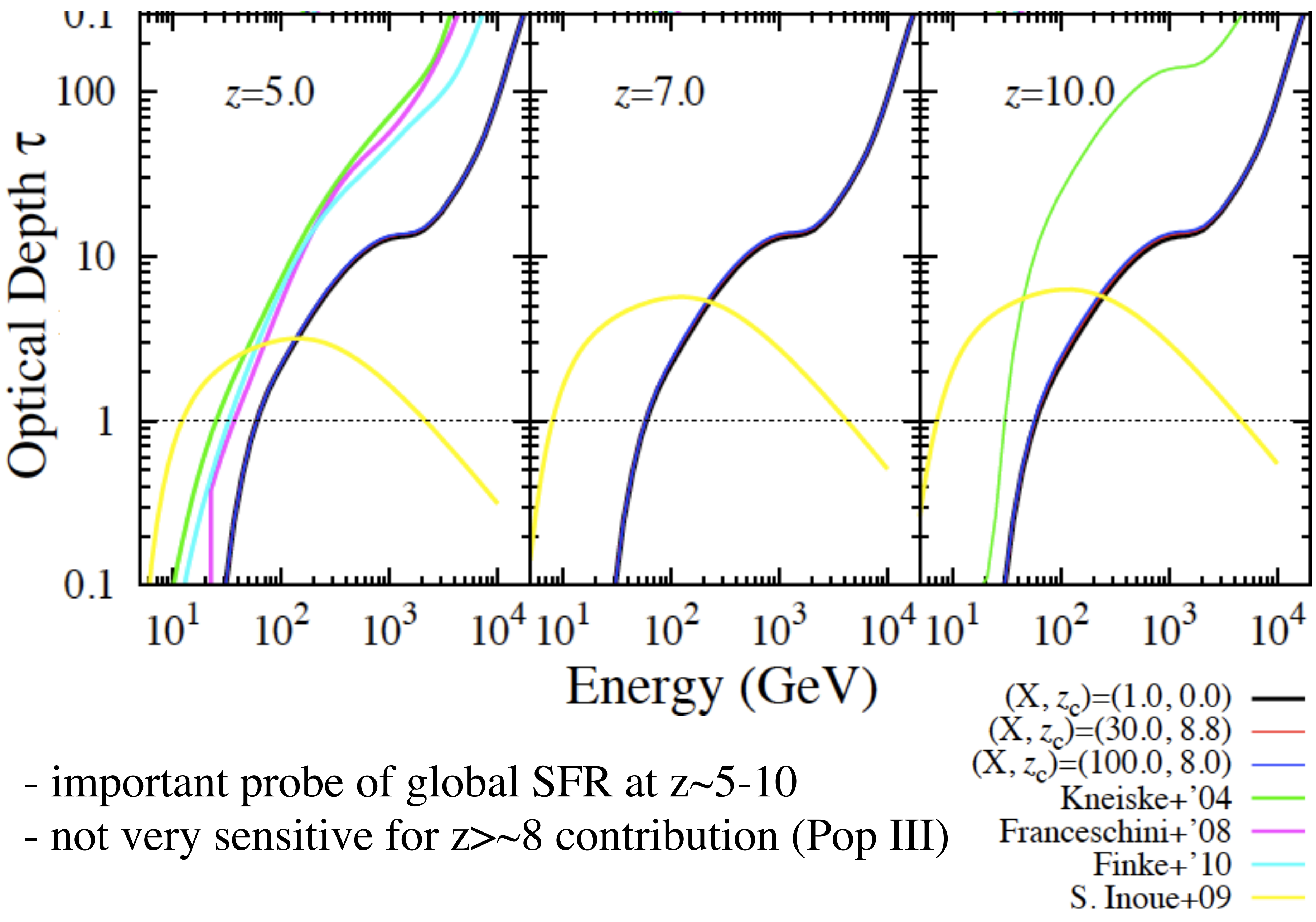
local EBL: Pop III contribution



gamma-ray opacity



gamma-ray opacity



- important probe of global SFR at z~5-10
- not very sensitive for z>~8 contribution (Pop III)

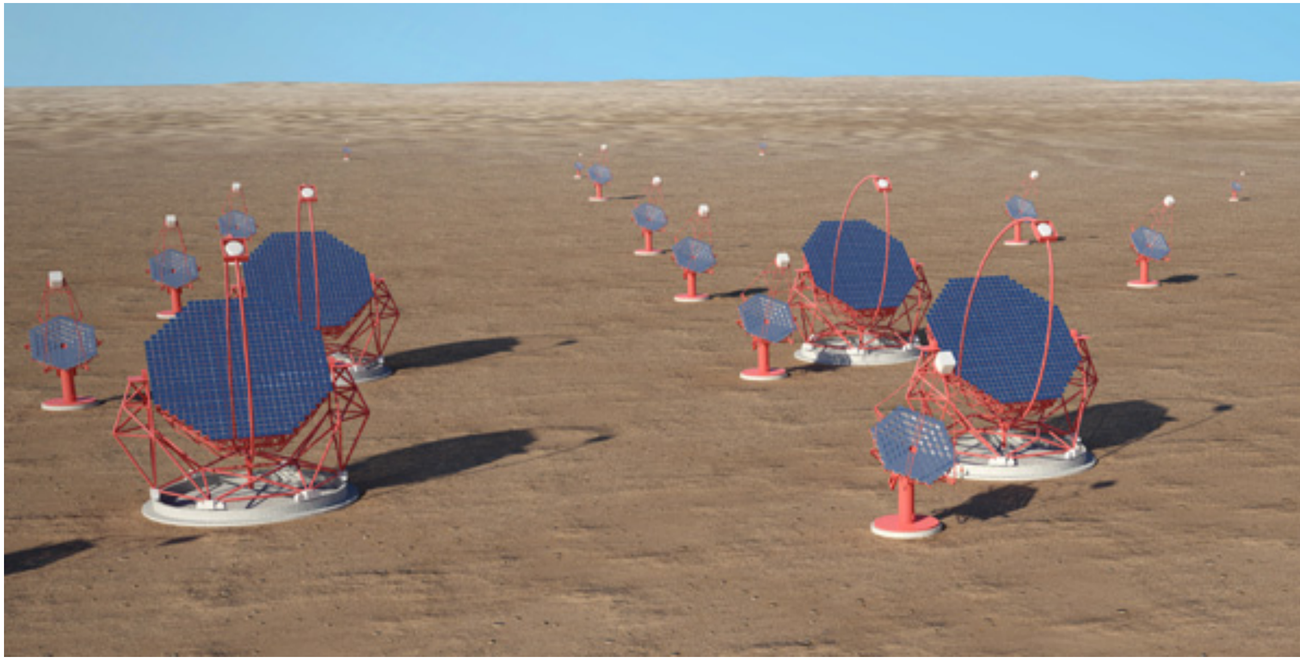
GRB observations with CTA

1. energy threshold 20 GeV or less (< current IACT)
-> less affected by γγ absorption with EBL

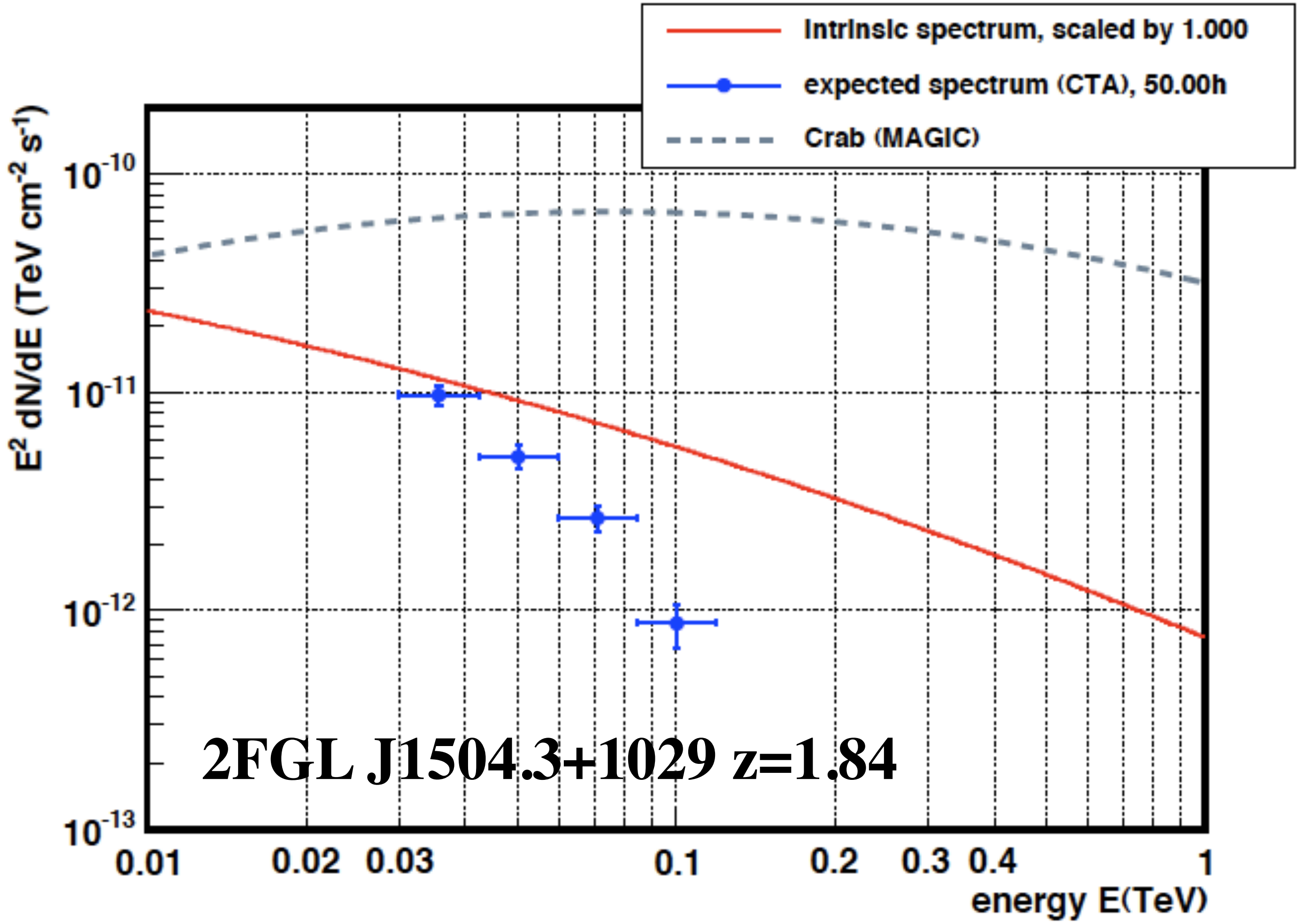
2. fast slewing: 180deg/20sec for LSTs (similar to MAGIC2)
-> observations during prompt phase for some long GRBs

3. large effective area: $>10^4 m^2$@30GeV (10^4 x Fermi)
-> high photon statistics, detailed spectral & variability info

>10 GeV photons
Fermi: few
CTA: >
fewx100-1000

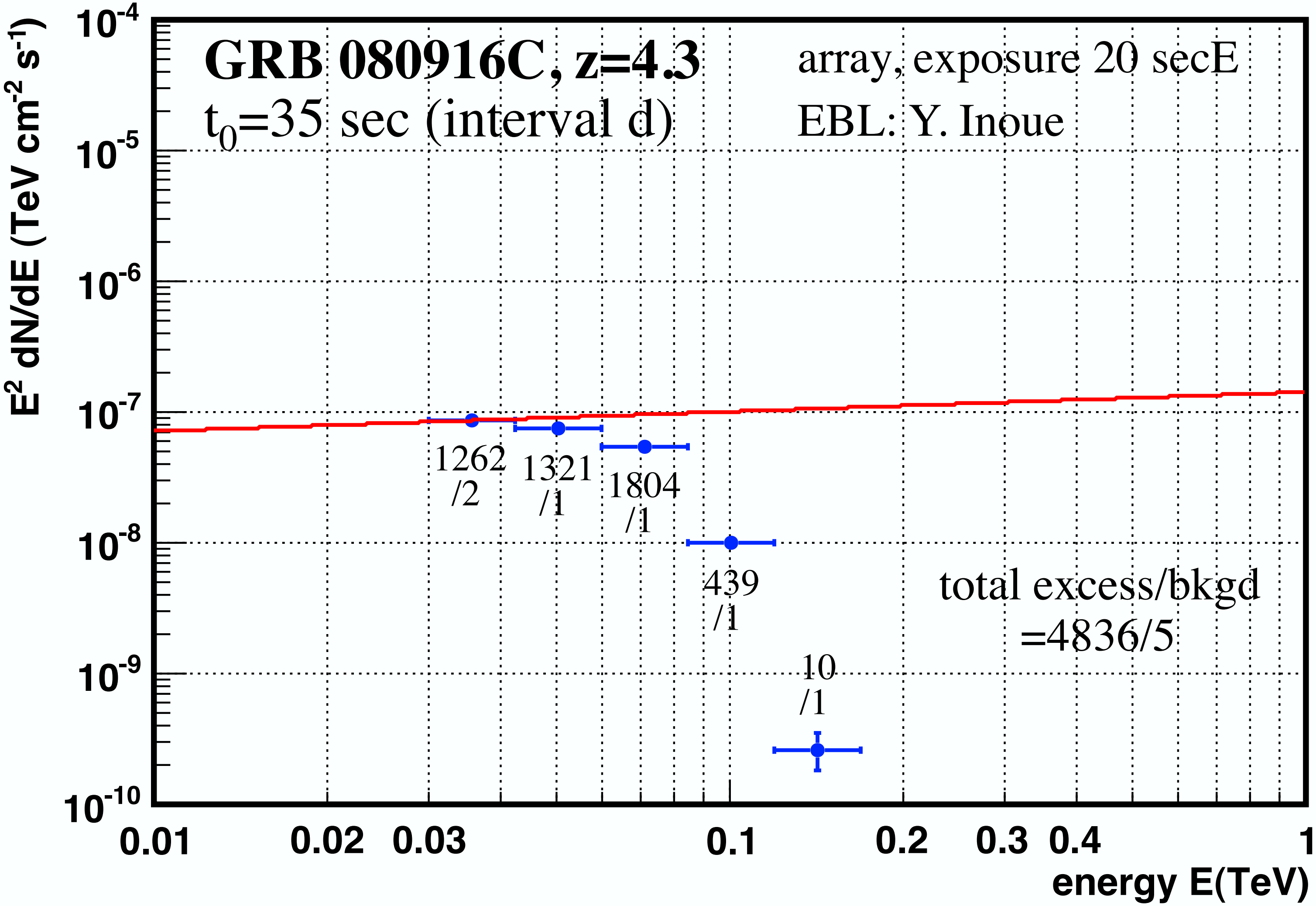


CTA observation of high-z blazars

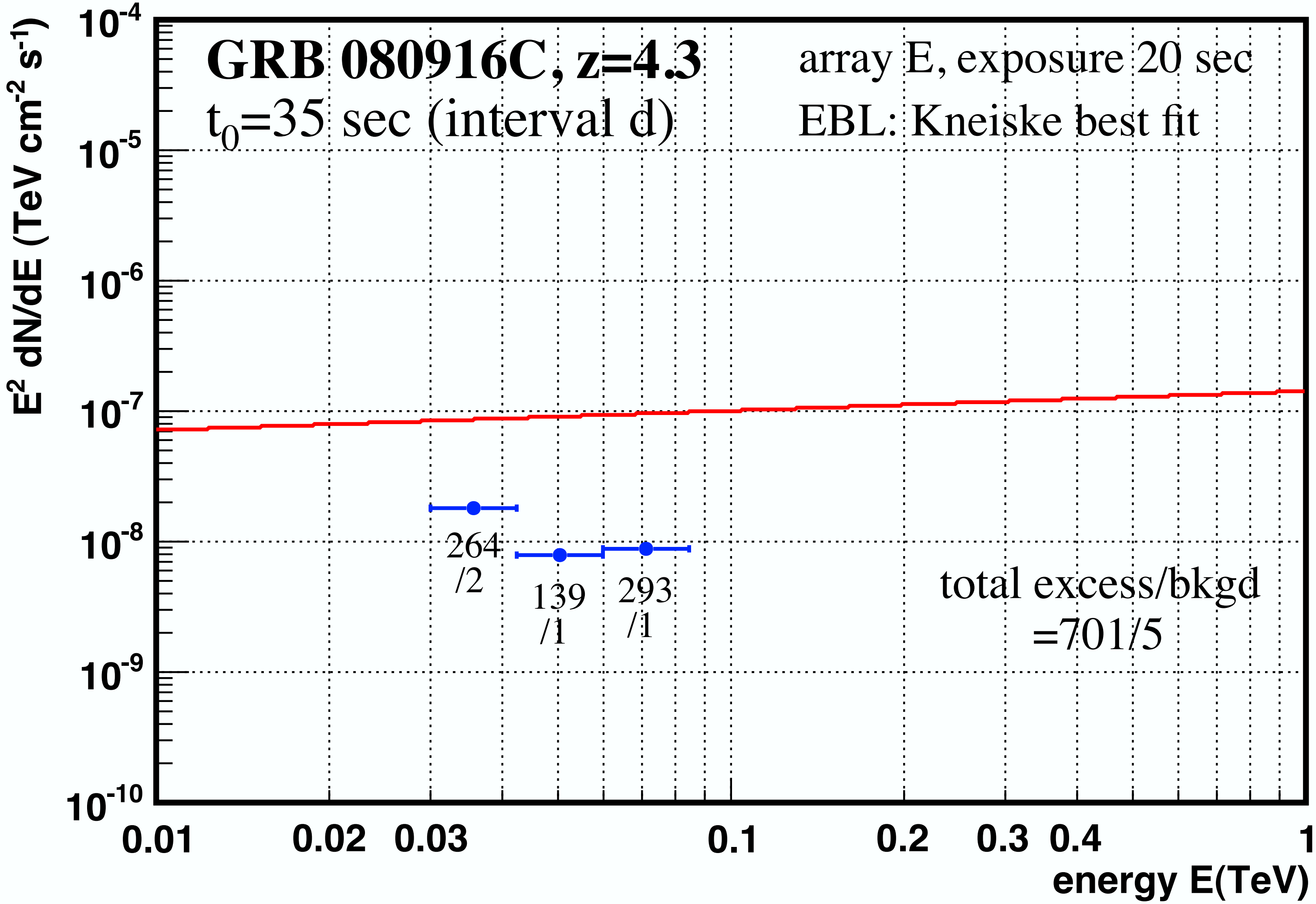


maximum z~2.5 for blazars

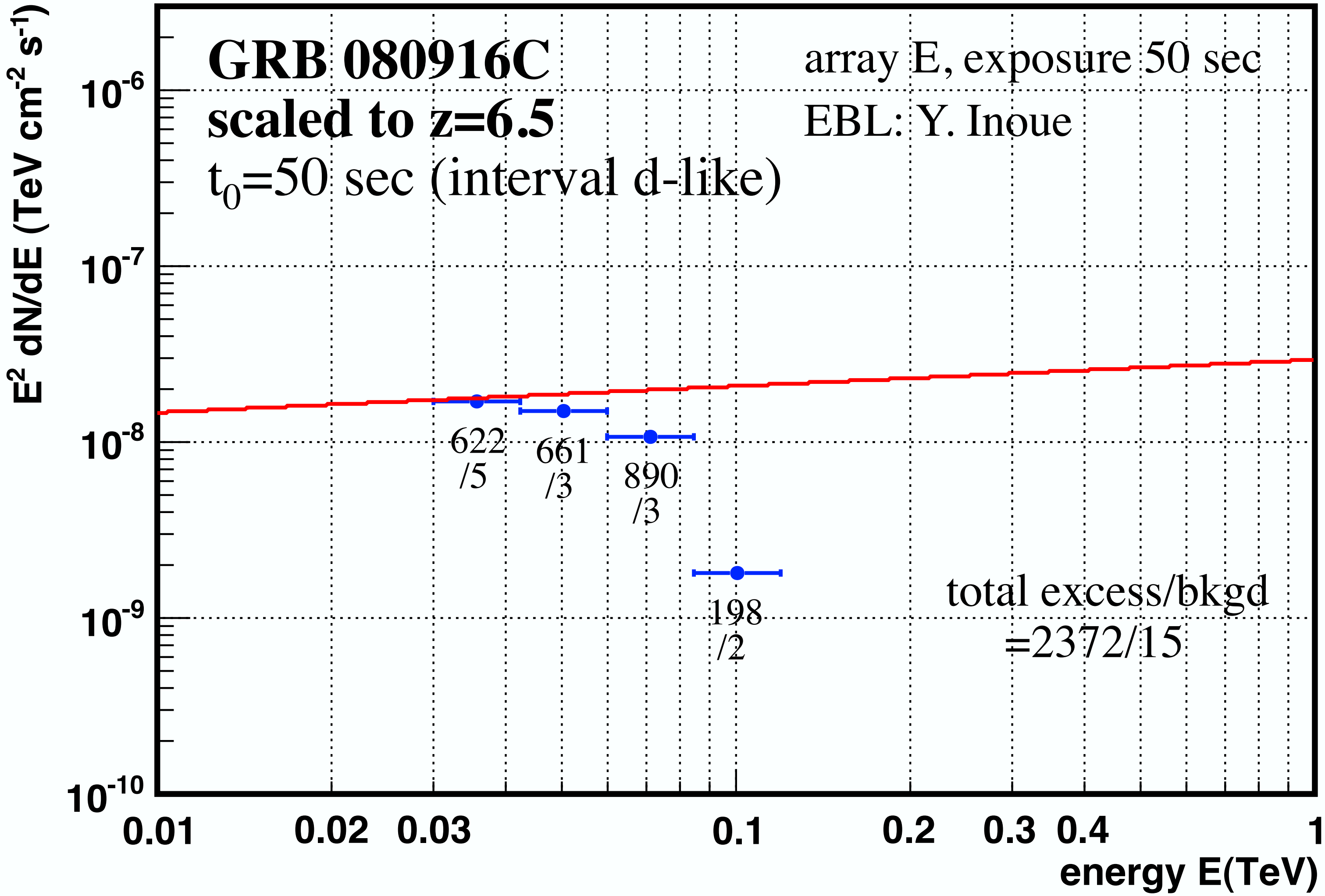
Sol, Zech, Boisson et al. (for the CTA Consortium)
To appear in Astropart. Phys.

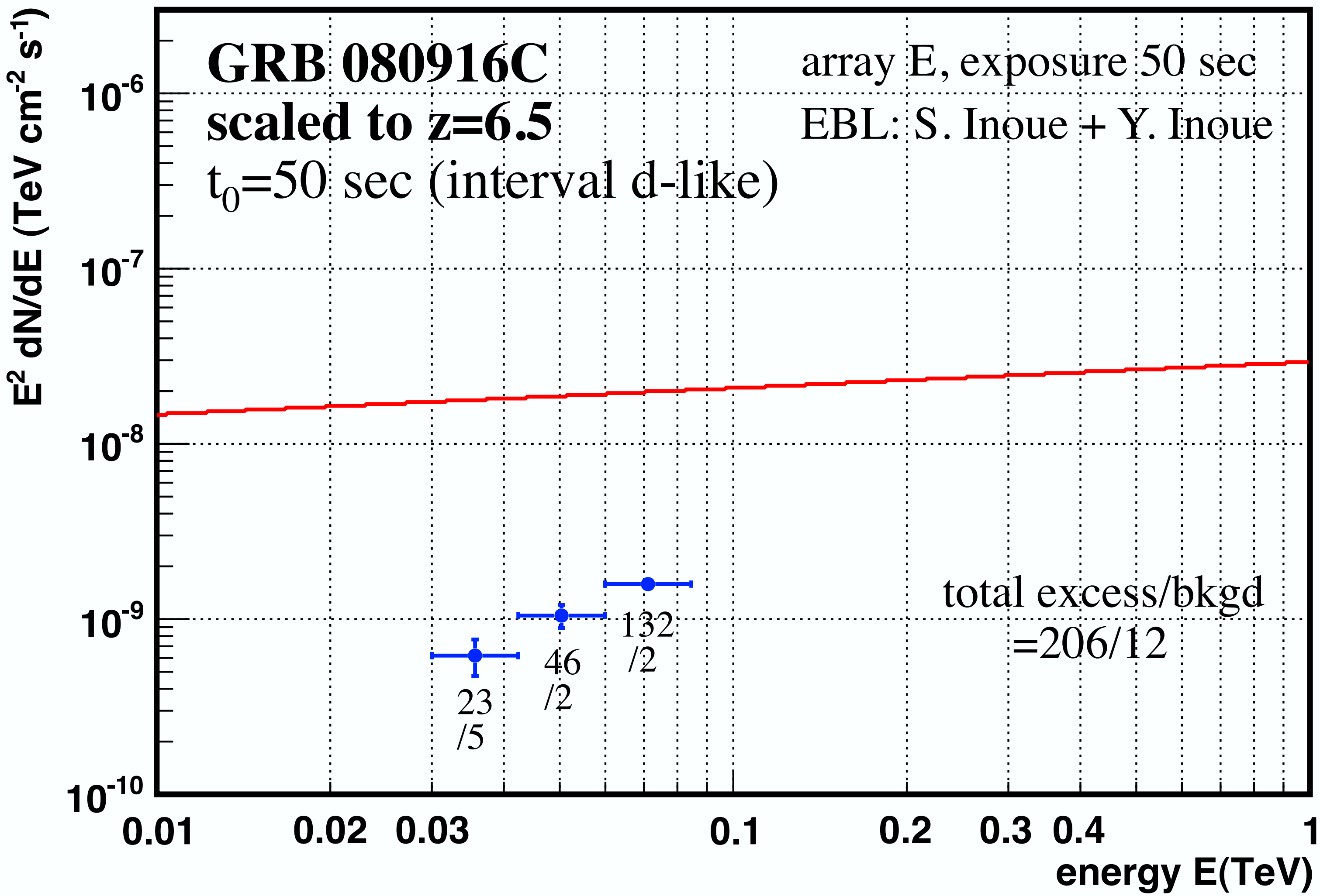


SI, J. Granot, P. O'Brien et al. (for the CTA Consortium)
To appear in Astropart. Phys. special issue article

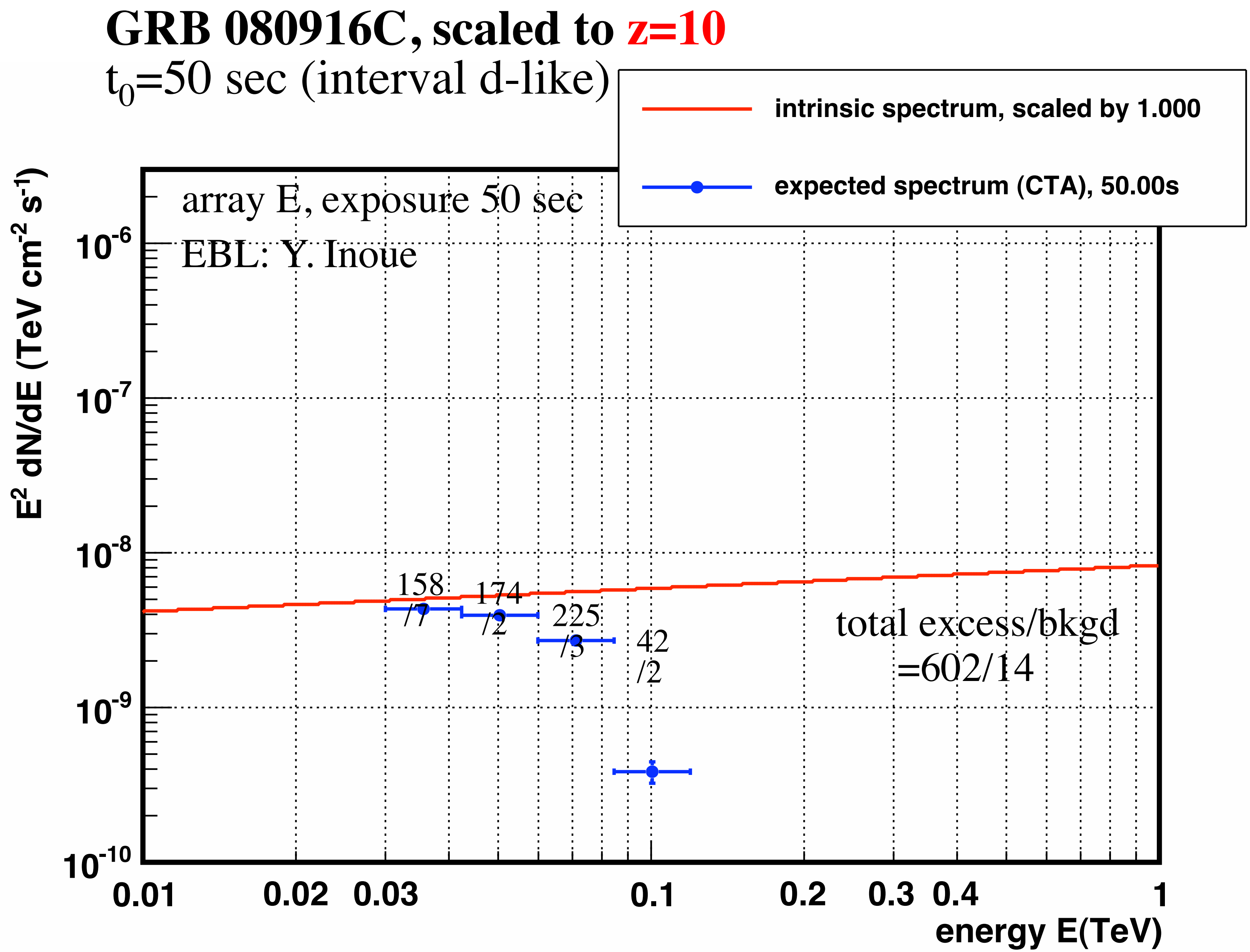


effective probe of high-z EBL:
valuable info on cosmic star formation/galaxy formation


GRB 080916C
scaled to z=6.5
t0=50 sec (interval d-like)
array E, exposure 50 sec
EBL: Y. Inoue
622
/5
661
/3
890
/3
198
/2
total excess/bkgd
=2372/15
E2 dN/dE (TeV cm-2 s-1)
10-6
10-7
10-8
10-9
10-10
0.01
0.02
0.03
0.1
0.2
0.3
0.4
1
energy E(TeV)



GRB 080916C
scaled to z=6.5
t0=50 sec (interval d-like)
array E, exposure 50 sec
EBL: S. Inoue + Y. Inoue
total excess/bkgd
=206/12
23
/5
46
/2
132
/2
E2 dN/dE (TeV cm-2 s-1)
energy E(TeV)
10-6
10-7
10-8
10-9
10-10
0.01
0.02
0.03
0.1
0.2
0.3
0.4
1


GRB 080916C, scaled to z=10
t0=50 sec (interval d-like)
intrinsic spectrum, scaled by 1.000
expected spectrum (CTA), 50.00s
array E, exposure 50 sec
EBL: Y. Inoue
E2 dN/dE (TeV cm-2 s-1)
10-6
10-7
10-8
10-9
10-10
158 /7
174 /2
225 /3
42 /2
total excess/bkgd =602/14
0.01
0.02
0.03
0.1
0.2
0.3
0.4
1
energy E(TeV)

redshift distribution expected for CTA

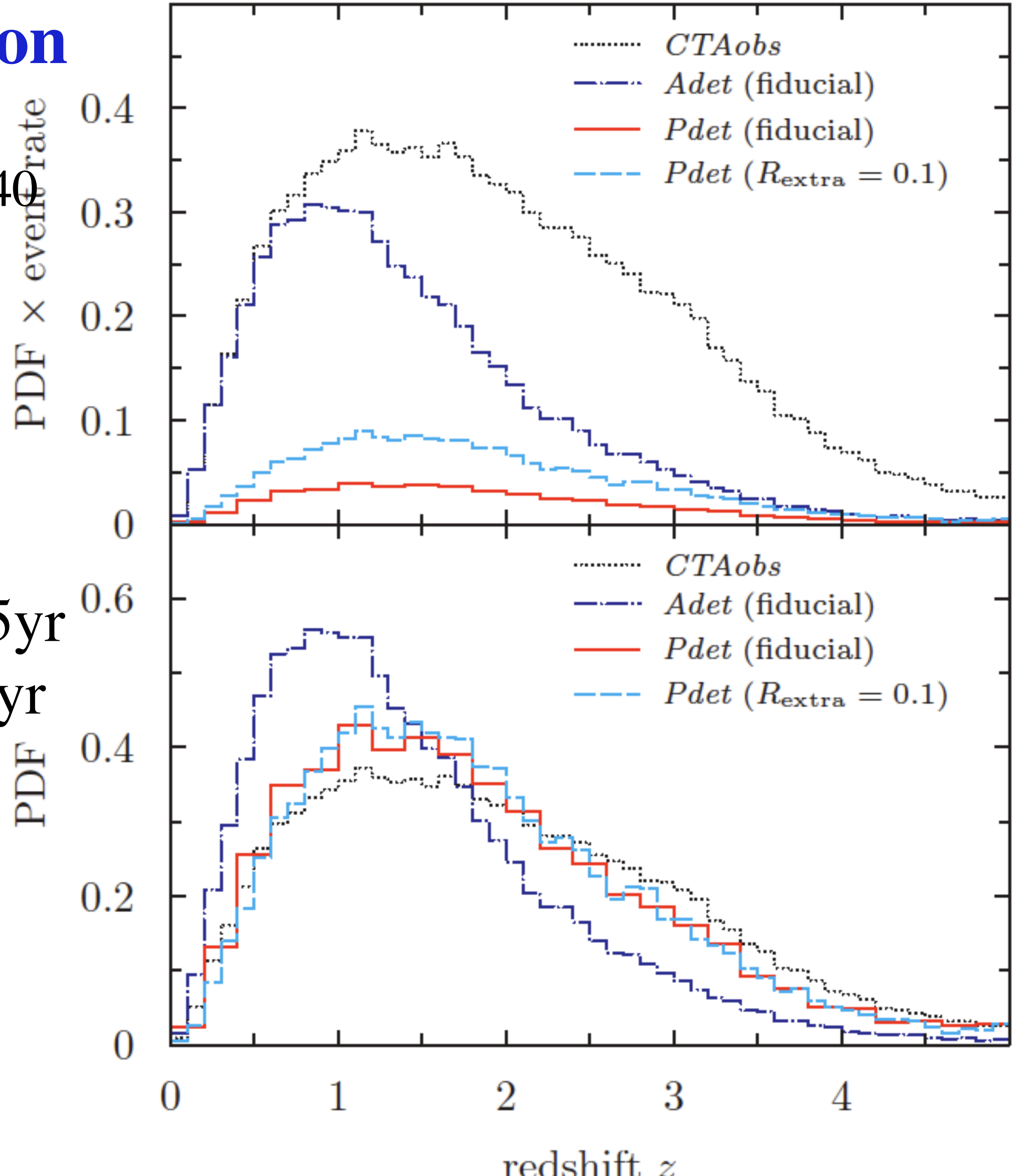
Kakuwa+ arXiv:1112.5940
see also Gilmore+ arXiv:1201.0010

SVOM+GBM alerts

afterglow z>3 1/2.5-5yr
z>4 1/5-10yr

should be larger with JANUS or LOBSTER

c.f. Fermi
expected z_{max}~2
observed z_{max}=4.35



summary

gamma-ray absorption in high-z objects (GRBs)
= probe of high-z diffuse UV radiation
= probe of high-z cosmic star formation rate

range of models consistent with cosmic reionization imply absorption in the 10-100 GeV range for z~5-10

but not very sensitive to contribution from z>~8

potentially observable by CTA in GRBs at z>5

unique information on the high-z Universe from high energy gamma rays