21cm forest と high-z 電波天体 (radio quasars, GRBs + fast radio bursts)

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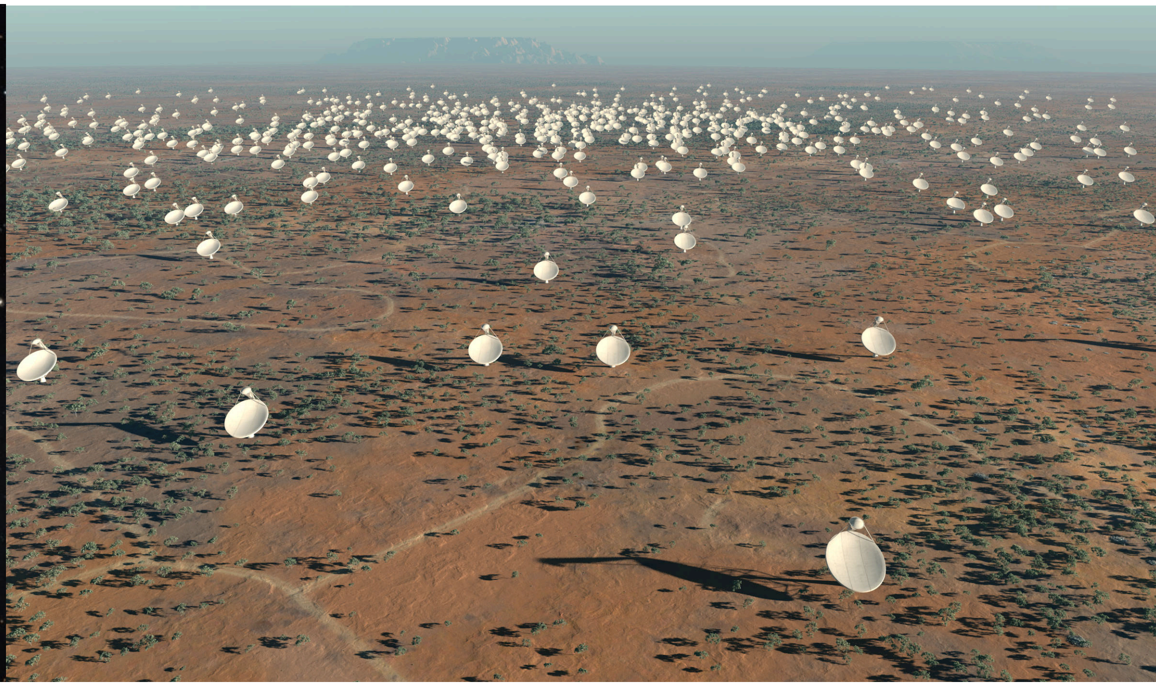
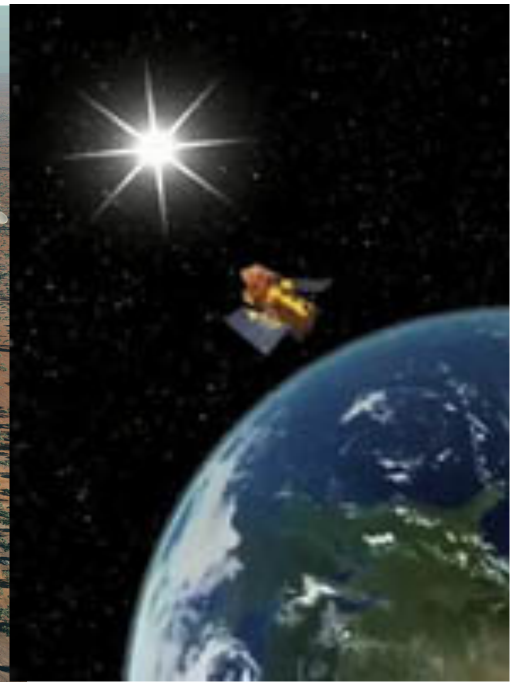



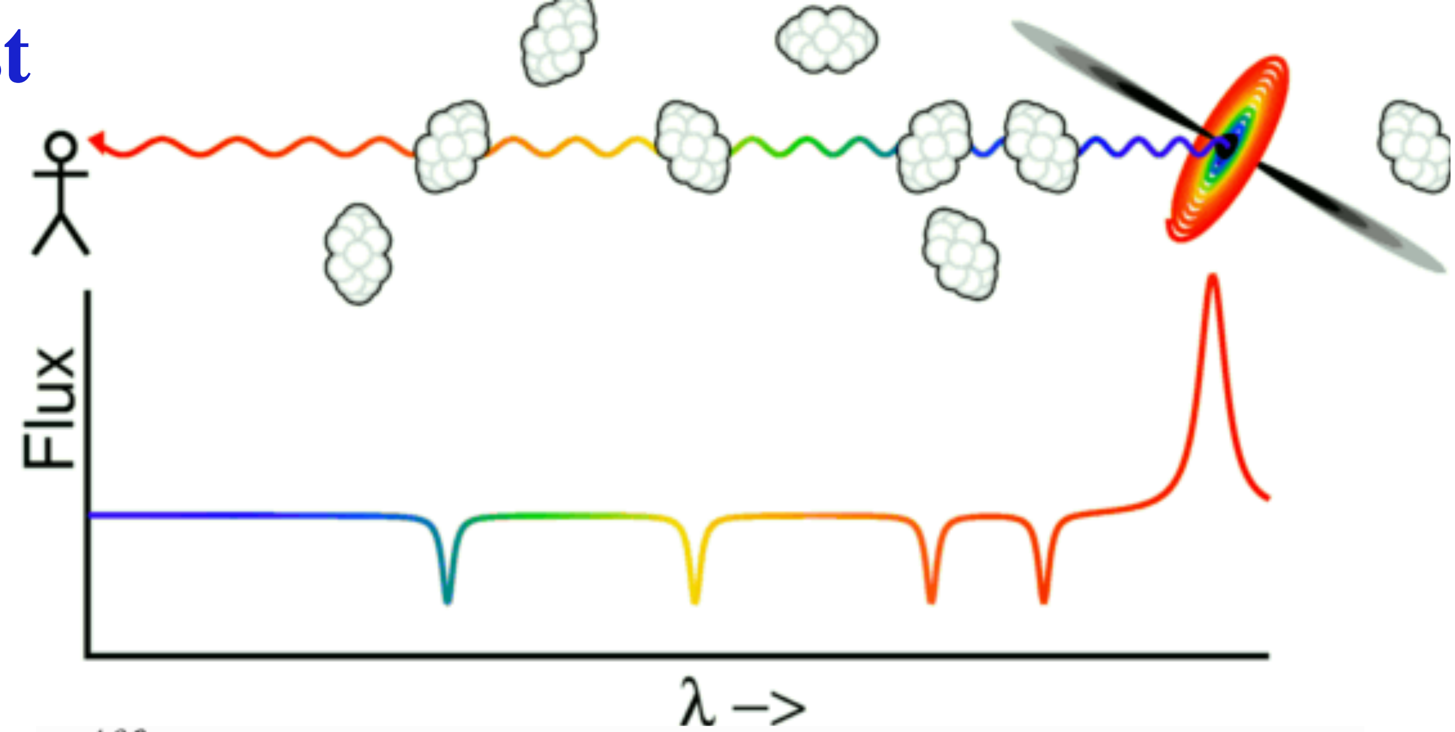
outline

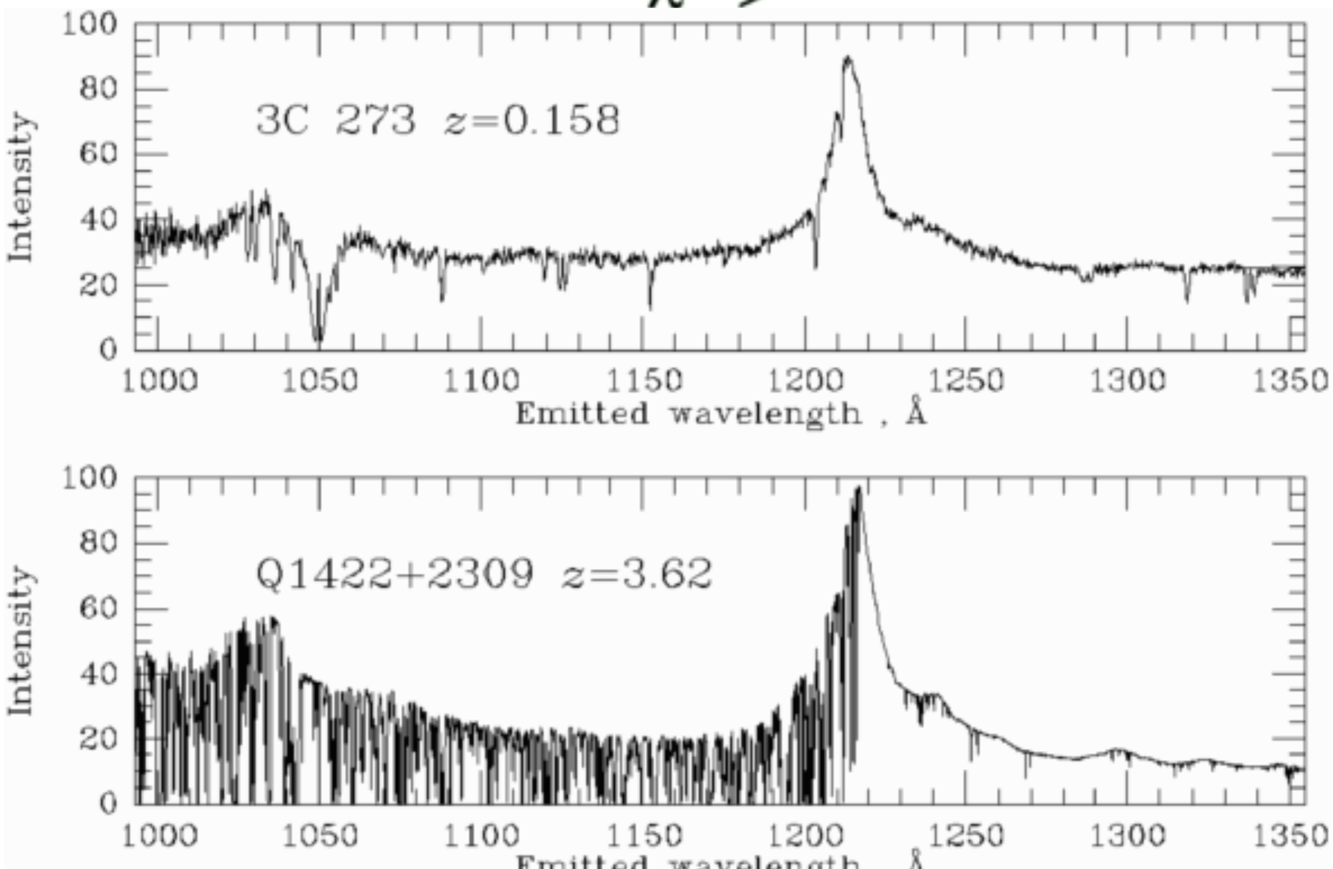
1. **21cm forest**
   probe of cosmic dawn/reionization
   probe of cosmology (small-scale power spectrum)
   Shimabukuro, Ichiki, SI, Yokoyama arXiv:1403.1605

2. **radio sources for 21cm forest studies**
   radio quasars, Pop III GRBs (first SMBHs?)

3. **fast radio bursts:**
   potential probe of ionized IGM
   (missing baryons, reionization)
   Inoue 2004 MNRAS 348, 999

Lyman alpha forest

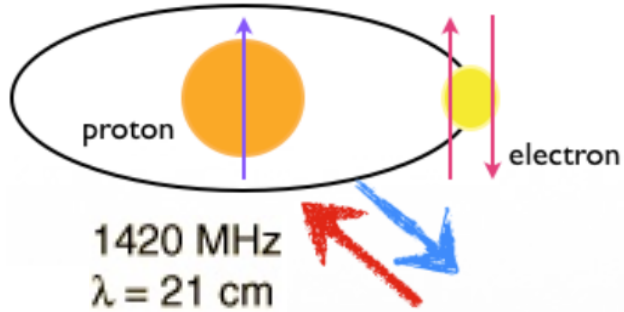




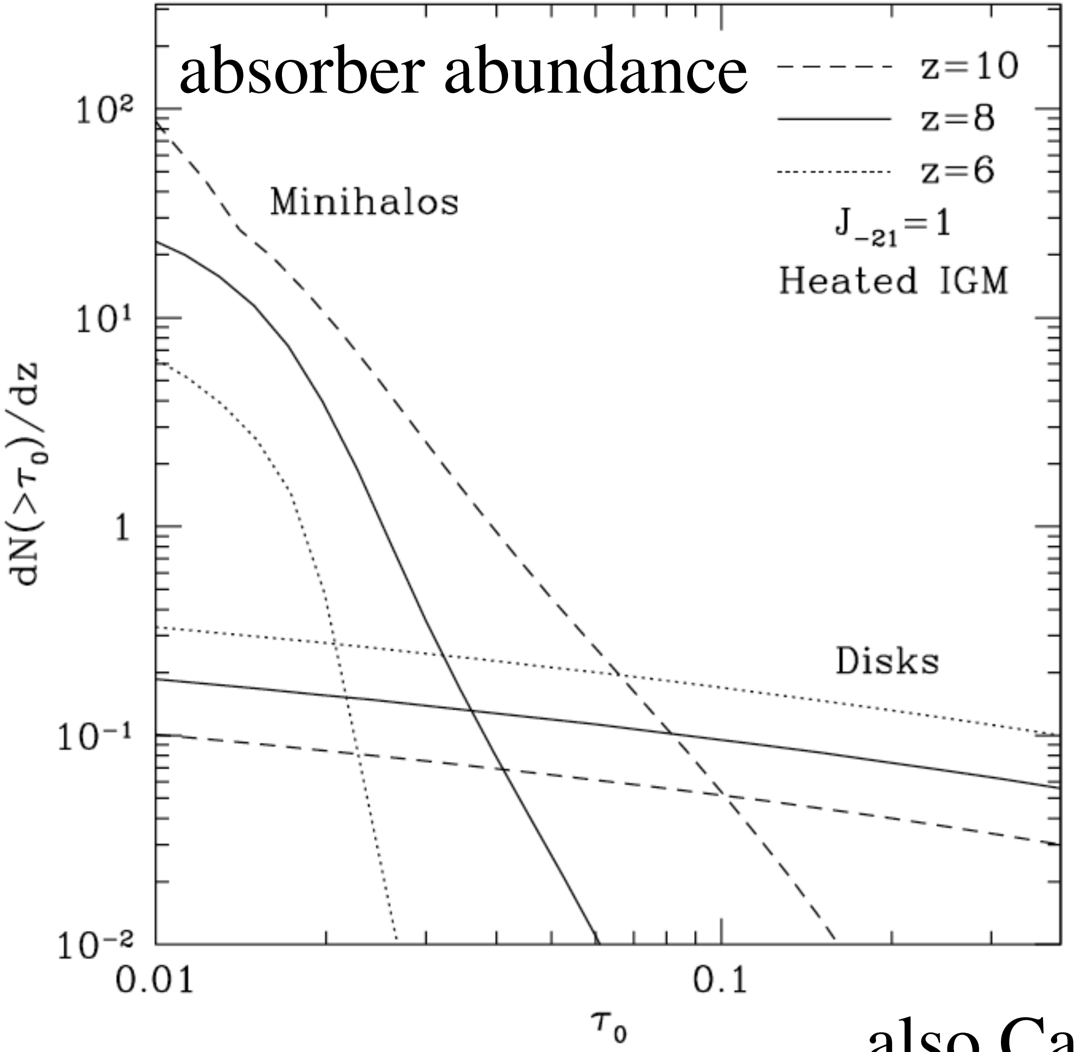
from Ned Wright's webpage

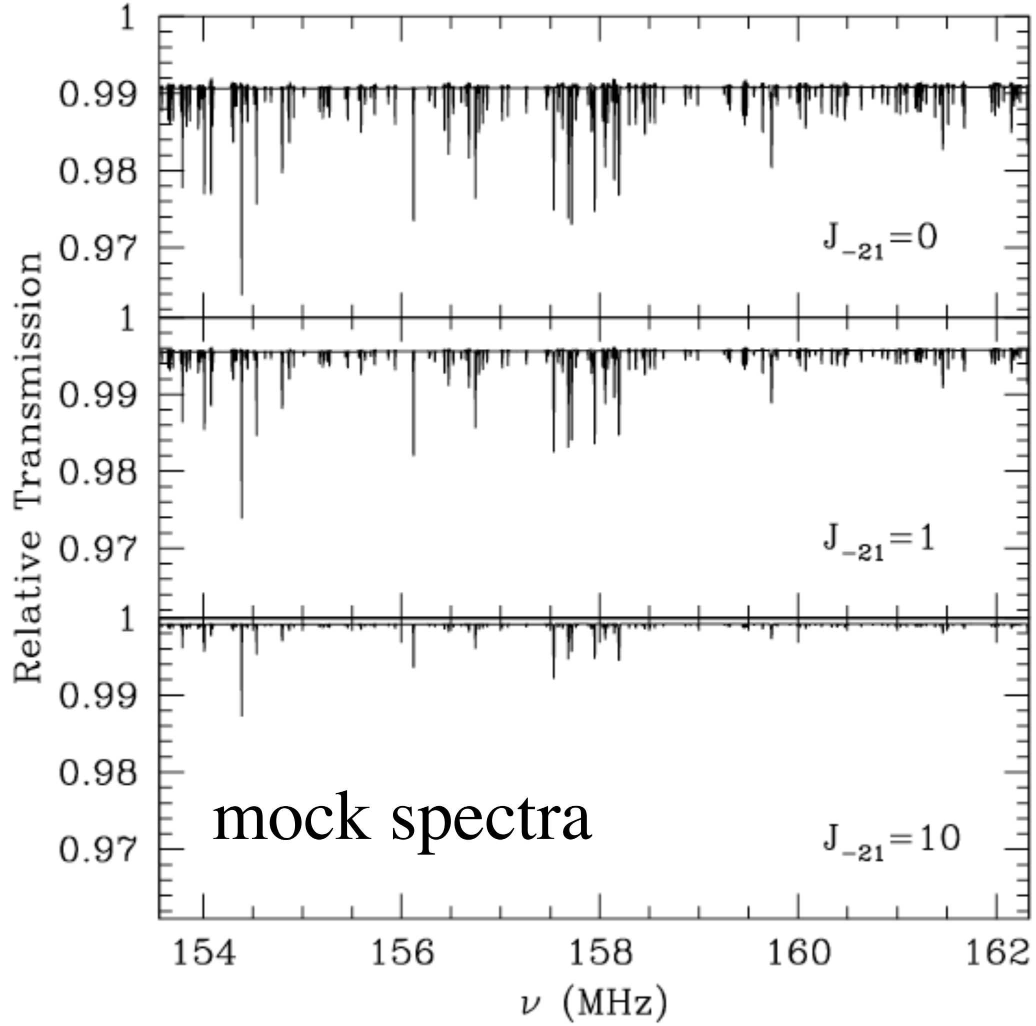
21cm forest (absorption lines)

- significant before cosmic reionization z>6
- dominant signal from minihalos ($M<10^8\ M_\Theta$)
- 10s of narrow lines (dν~ few kHz) out to z>~10
- sensitive to UV background



Furlanetto & Loeb 02

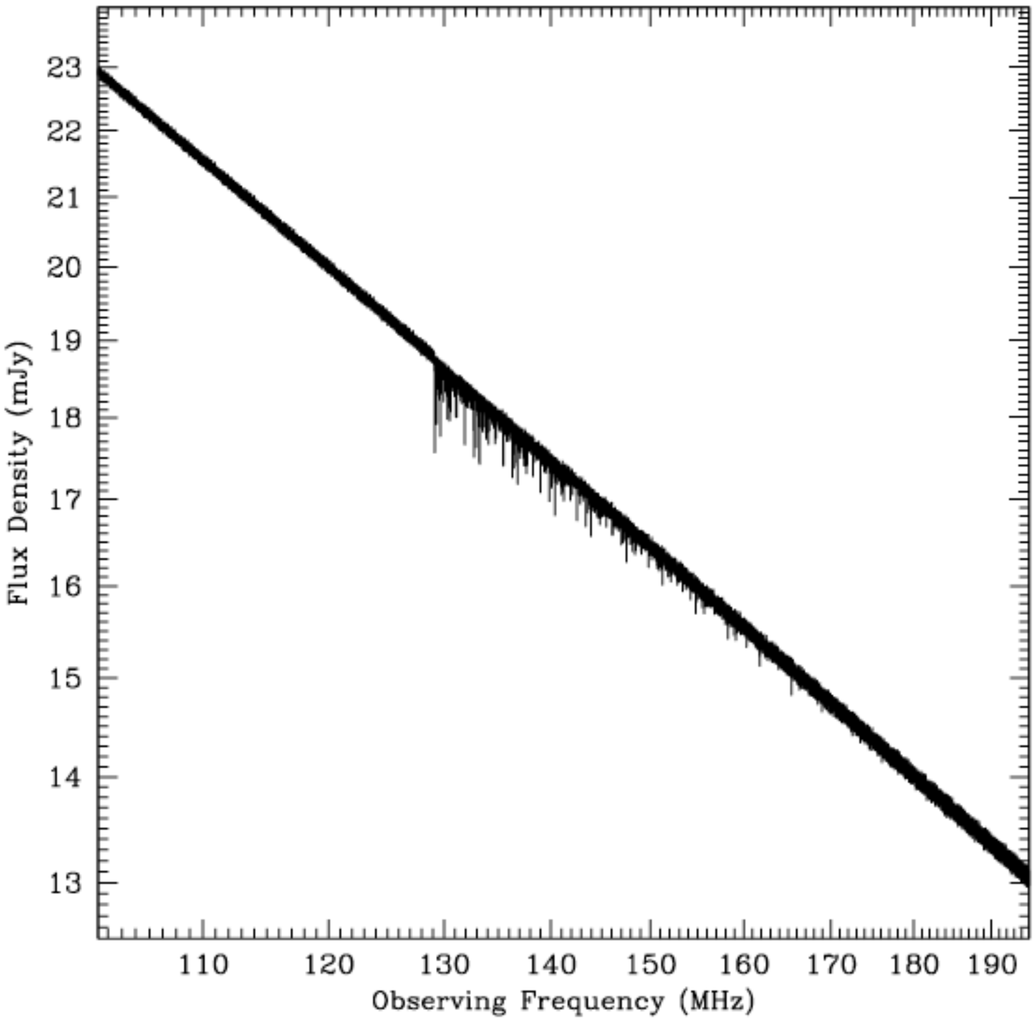


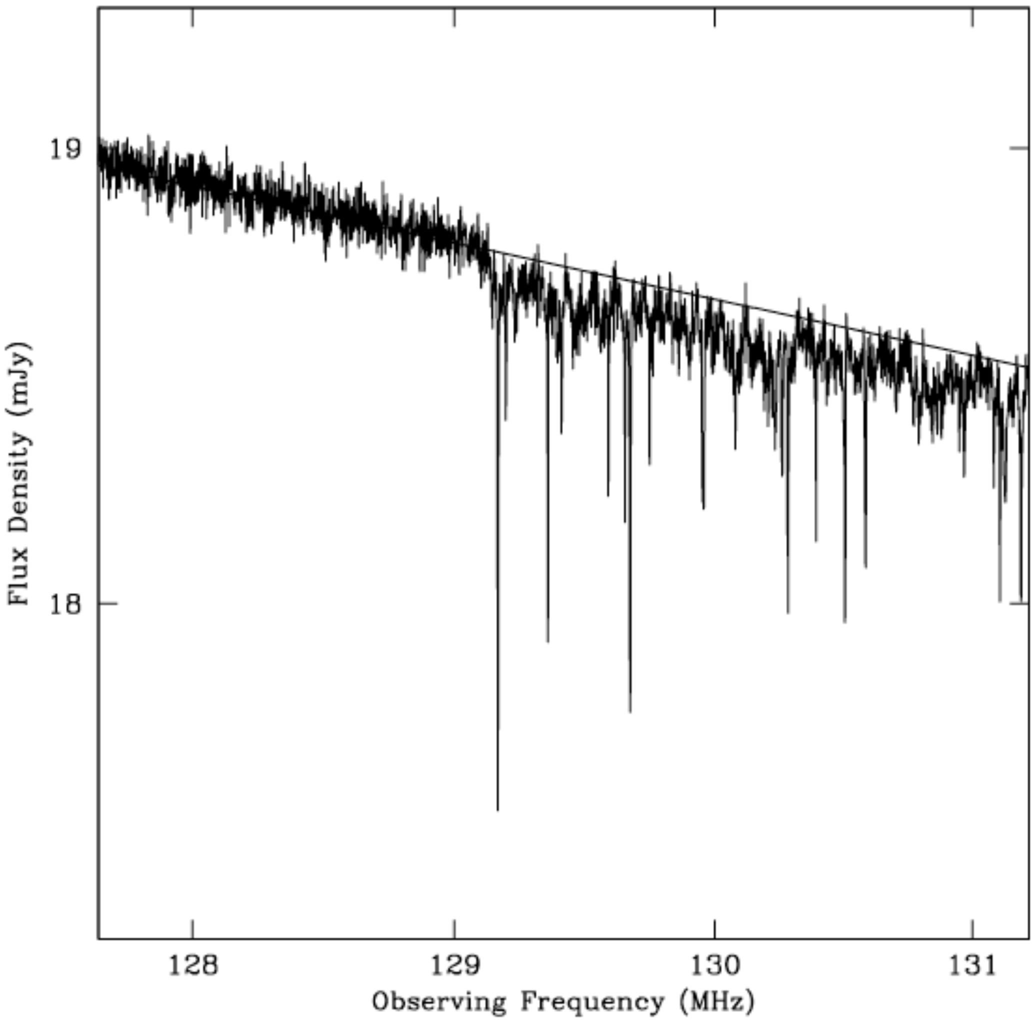


also Carilli+ 02, Furlanetto 06, Xu+ 09, 11, Meiksin 11, Mack & Wyithe 12, Ciardi+ 12

21cm forest + mean IGM absorption Carilli, Gnedin & Owen 02

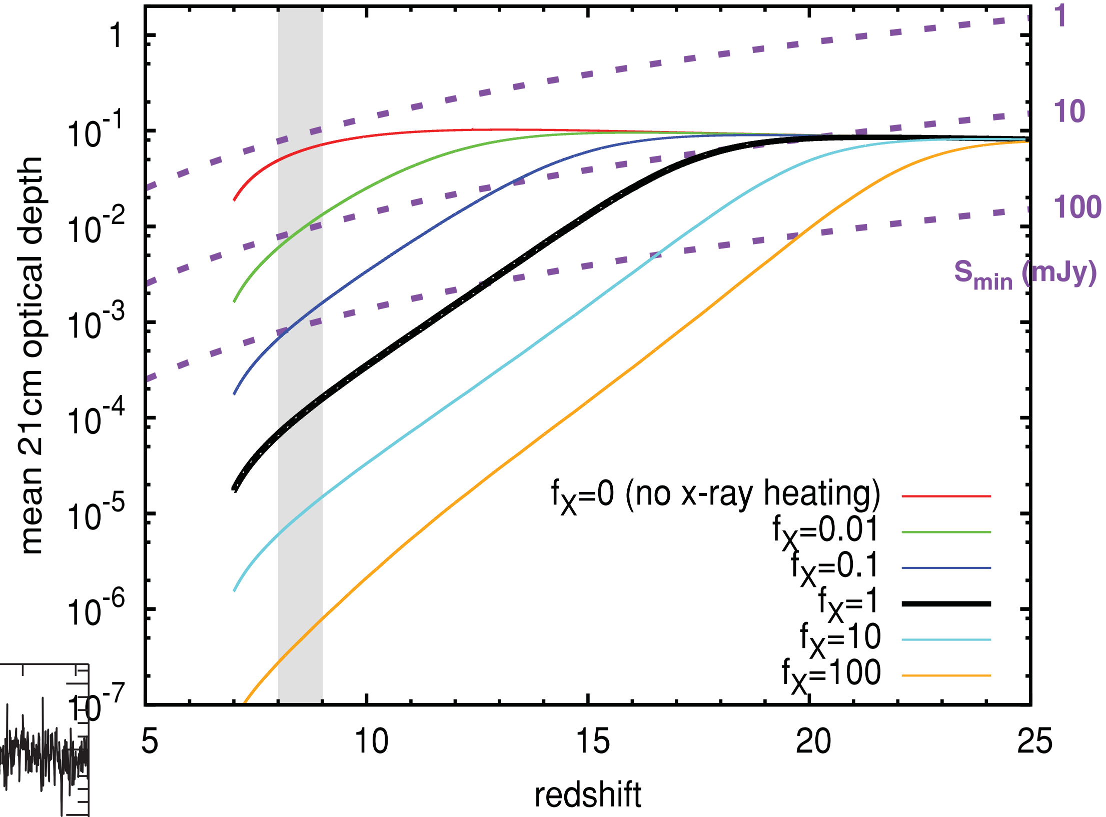
assuming Cyg-A like source at z=10



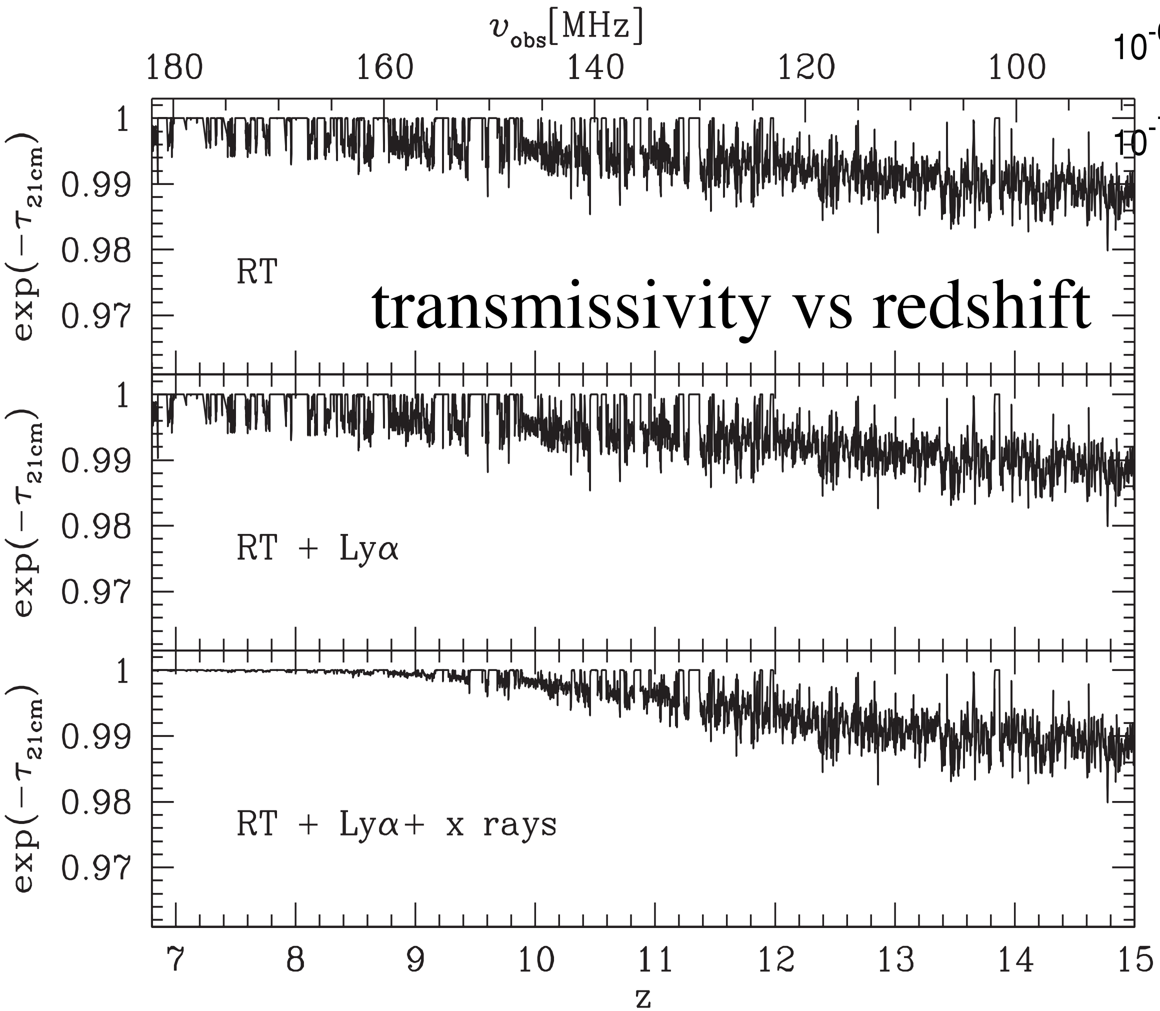


narrow features from dense systems
+ mean absorption from IGM

21cm absorption: effects of X-ray heating



Mack & Wyithe 12

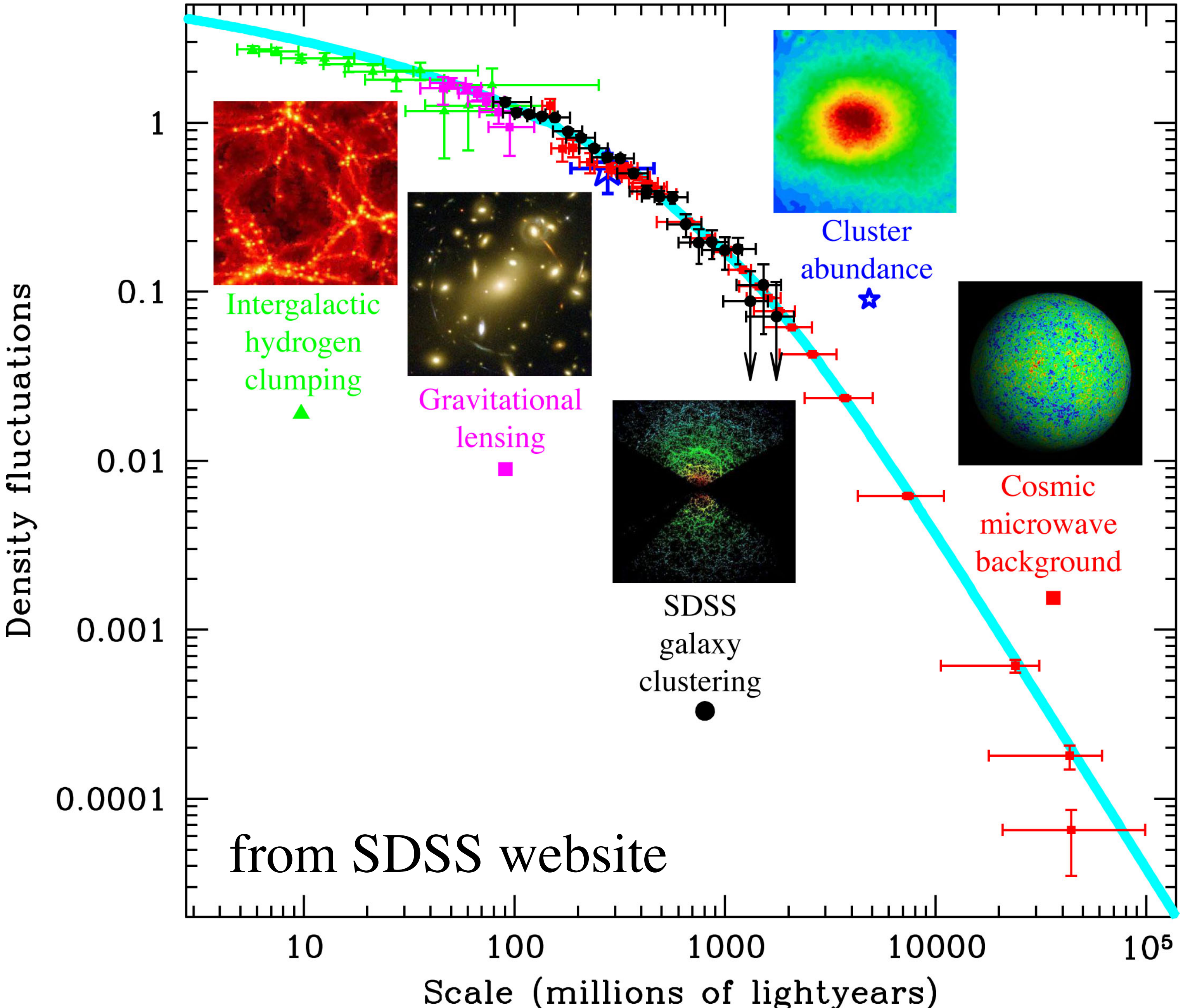


Ciardi+ 12

power spectrum of large-scale structure

consistent with CDM+Λ+adiabatic power-law fluctuations down to galaxy scales

BUT
not yet well
tested on small
(sub-galactic)
scales!



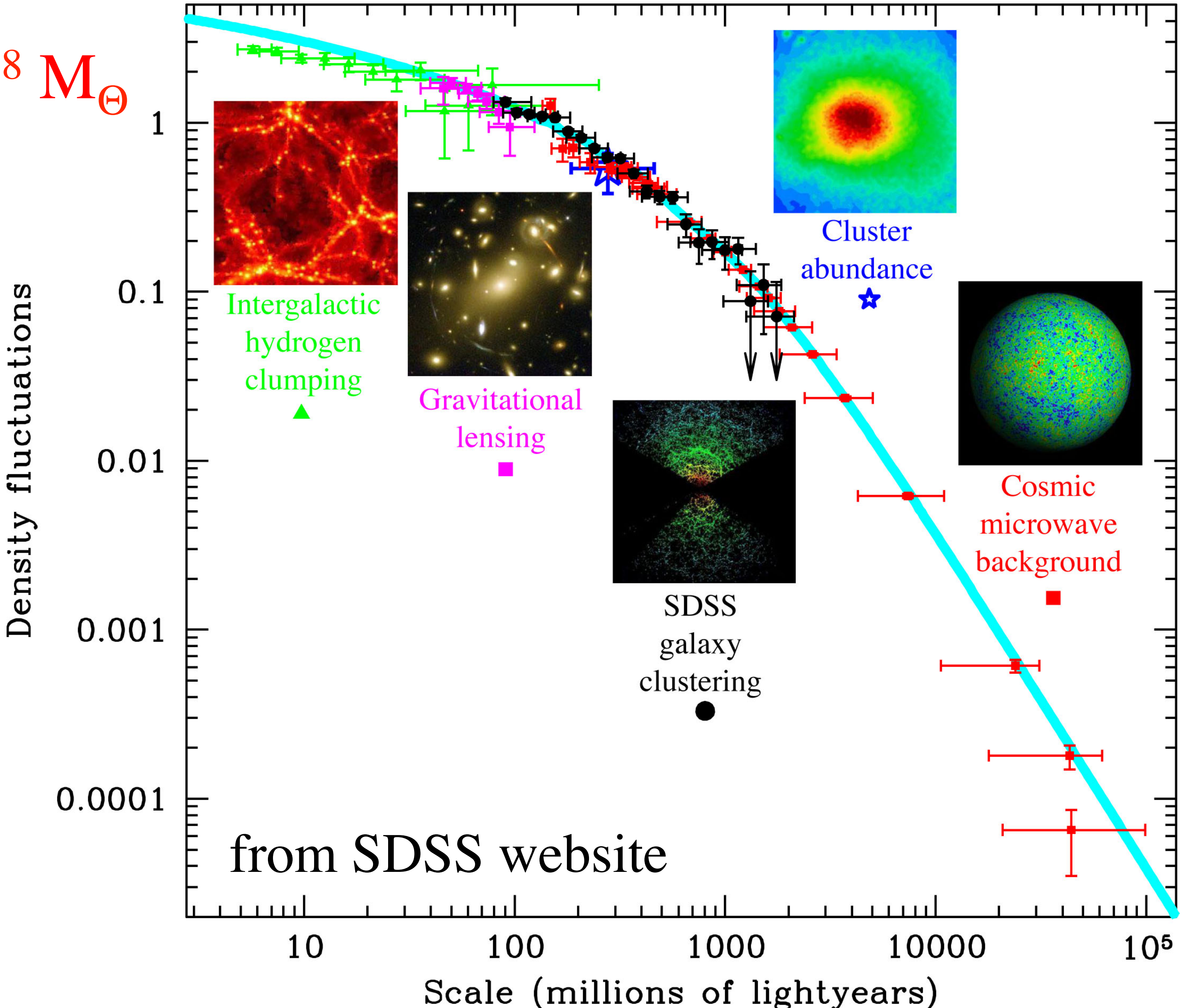
power spectrum of large-scale structure

consistent with CDM+Λ+adiabatic power-law fluctuations down to galaxy scales

minihalos $M<10^8\ M_\Theta$

$k>\sim 10\ Mpc^{-1}$

BUT
not yet well
tested on small
(sub-galactic)
scales!

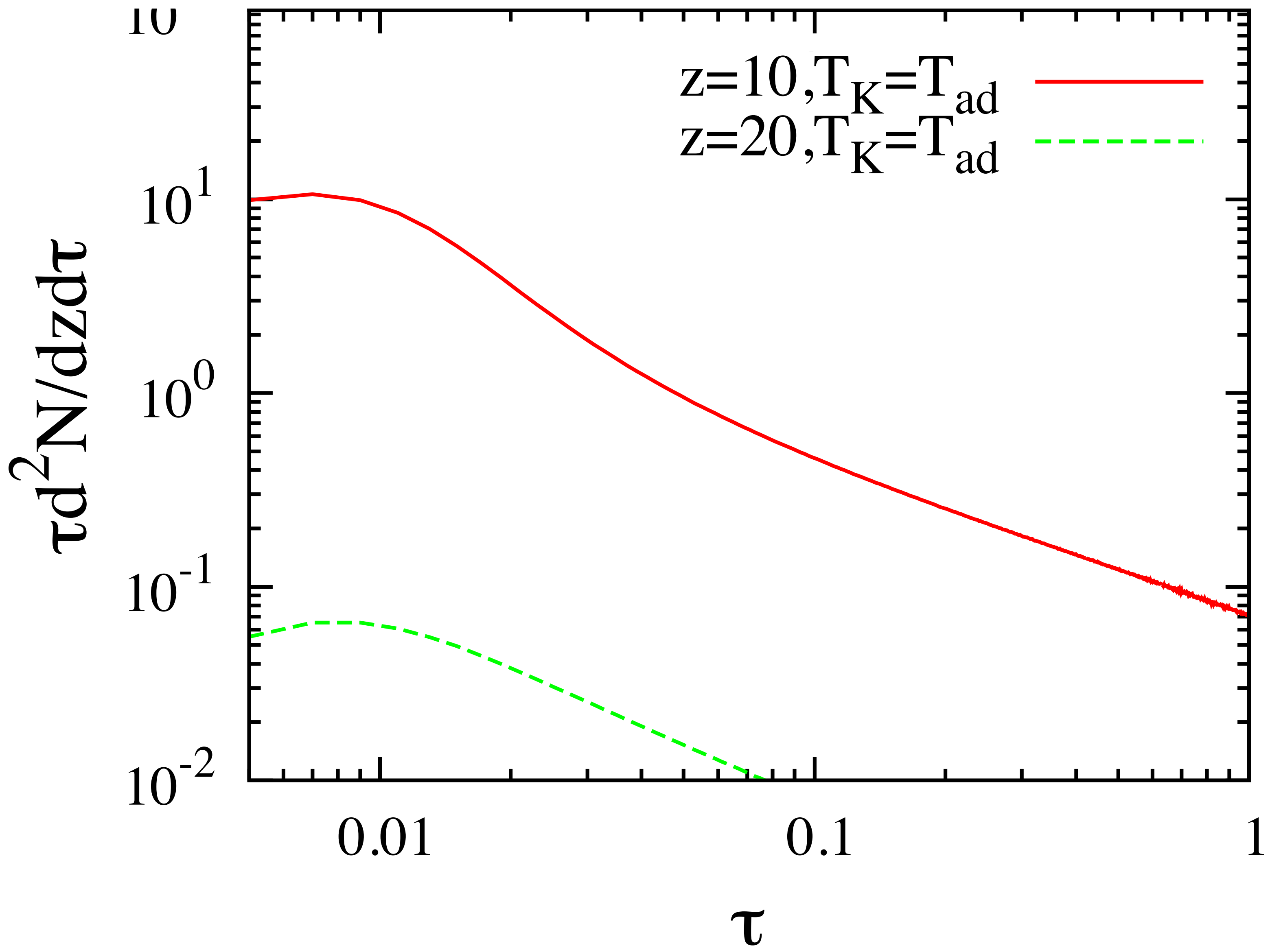


from SDSS website

baseline results CDM+power-law, no massive ν or WDM

absorber abundance per z interval

Shimabukuro, Ichiki
SI, Yokoyama
arXiv:1403.1605



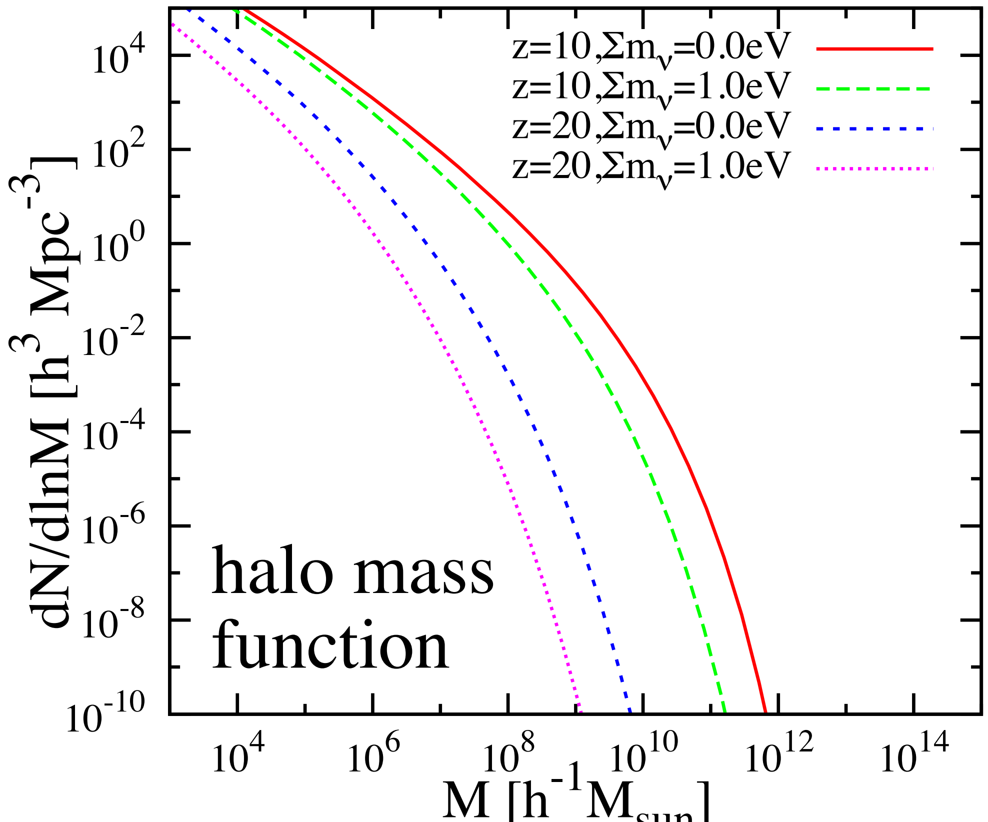
NB: assume
no UV background
no heating

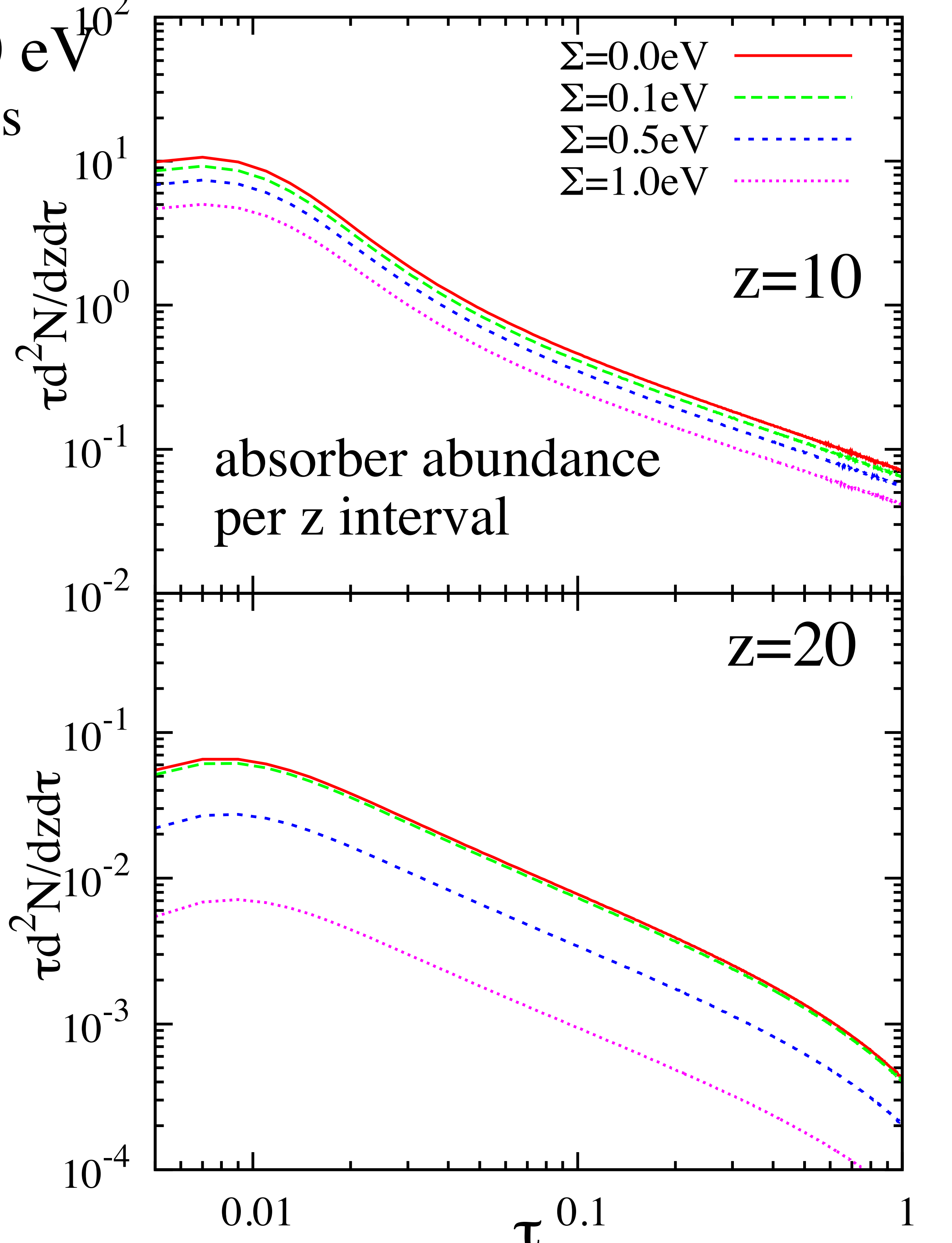
- ~100-1 absorbers with τ~0.01-1 at z=10 -> BUT UV/heating important
- ~1-0.1 absorbers with τ~0.01-0.1 at z=20 -> >~10 lines of sight required

neutrino mass Σm_ν=0-1.0 eV

- light, massive neutrinos suppress LSS below cluster scales depending on Σm_ν
- current limits
  Planck 2013: Σm_ν<0.23 eV

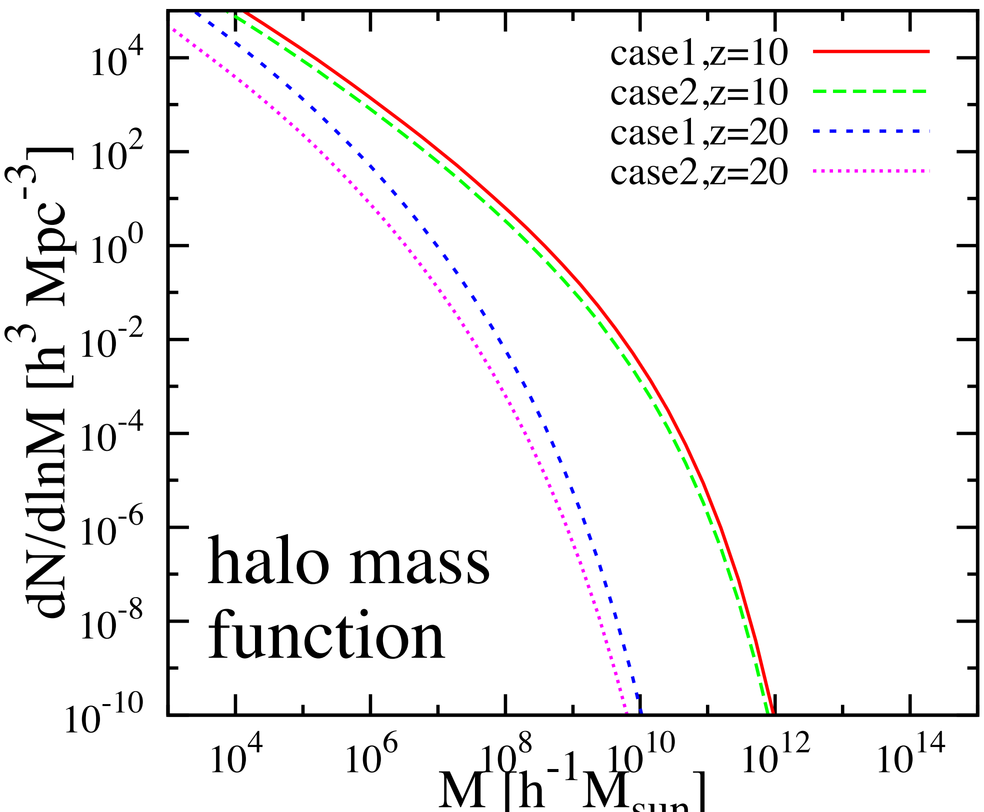
- z=10: differences < factor 2
  z=20: up to order of magnitude

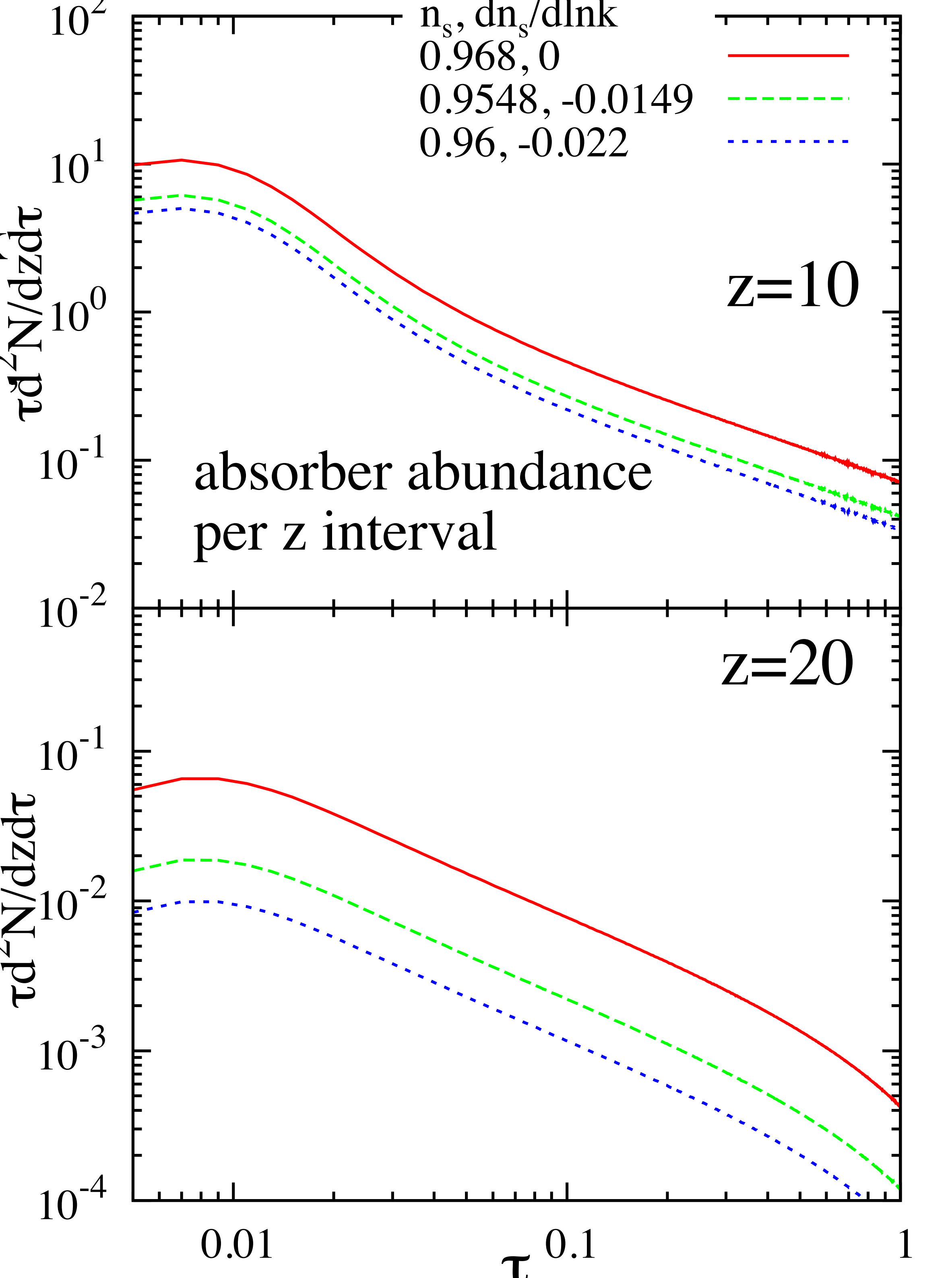




running spectral index

- initial density fluctuations with k-dependent spectral index $p(k) \propto k^{(n_s(k)-1)}$, $\alpha_s = dn_s(k)/dlnk$
- discriminant of inflation models
- Planck 2013: $n_s = 0.9603 \pm 0.0073$, $\alpha_s = -0.015 \pm 0.009$
- z=10: differences < factor 2
  z=20: up to order of magnitude

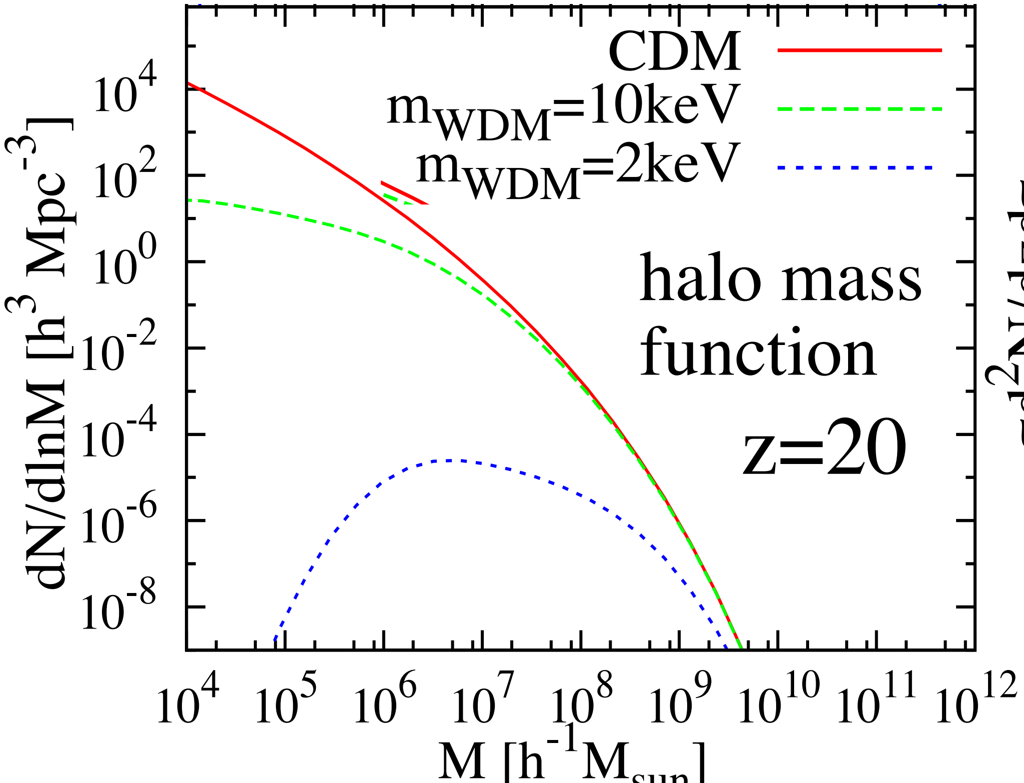


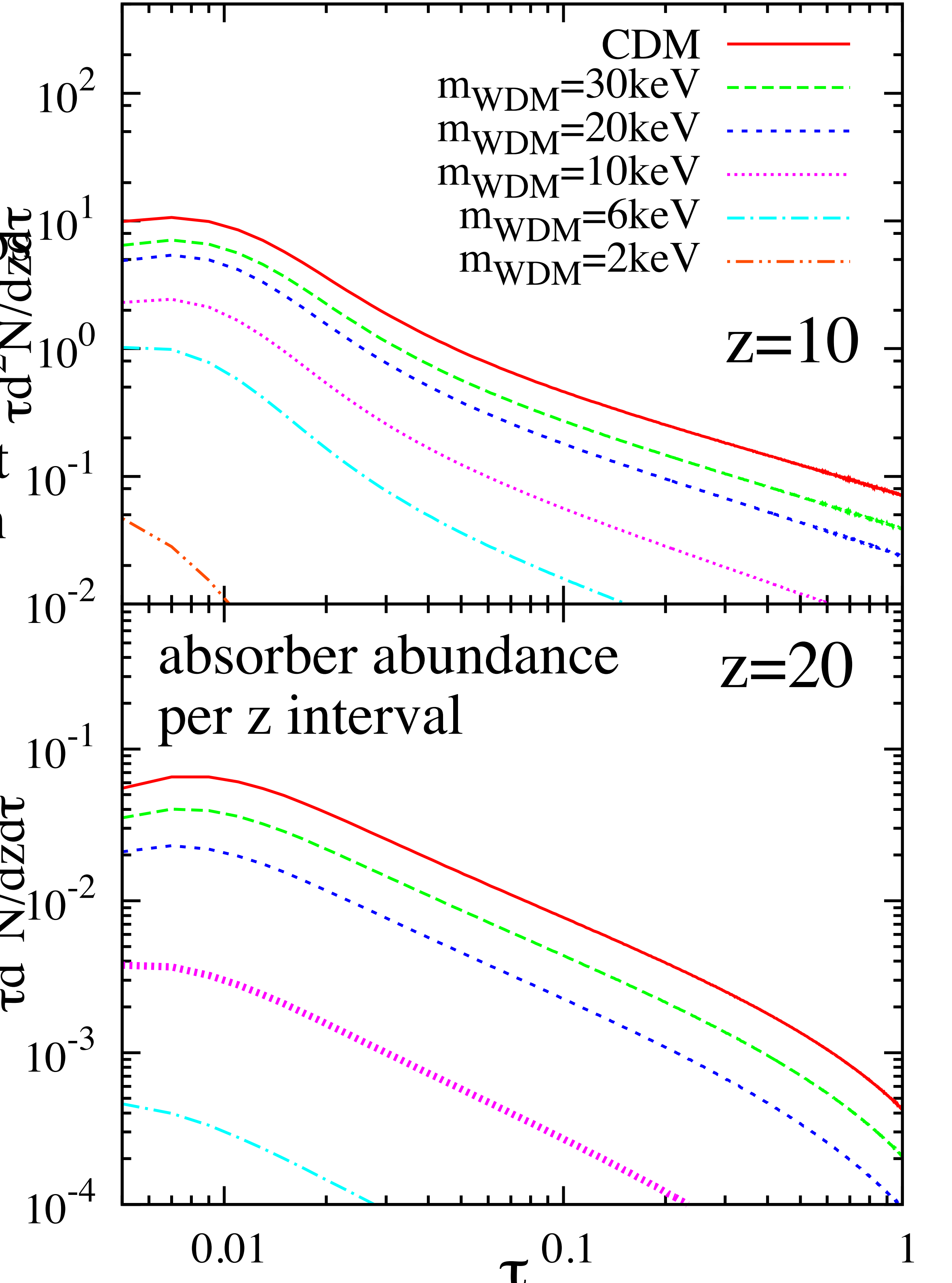


warm dark matter

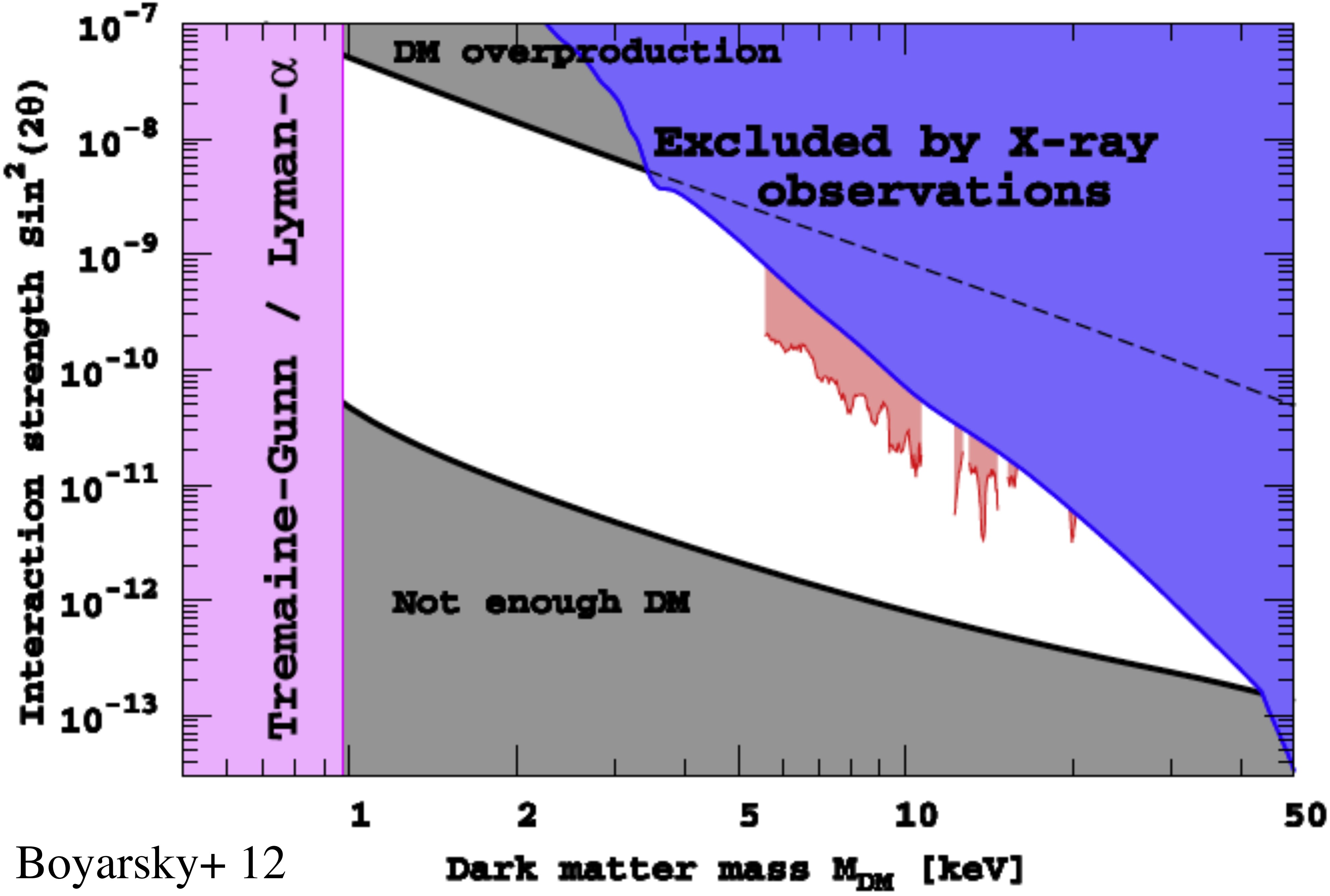
- WDM strongly suppresses LSS below m_{WDM}-dependent scale
- particle candidate: sterile neutrino
- solve missing satellite problem?
- current limits m_{WDM}>~1 keV

- m_{WDM}~<30 keV: significant effect
  m_{WDM}<few keV: total suppression



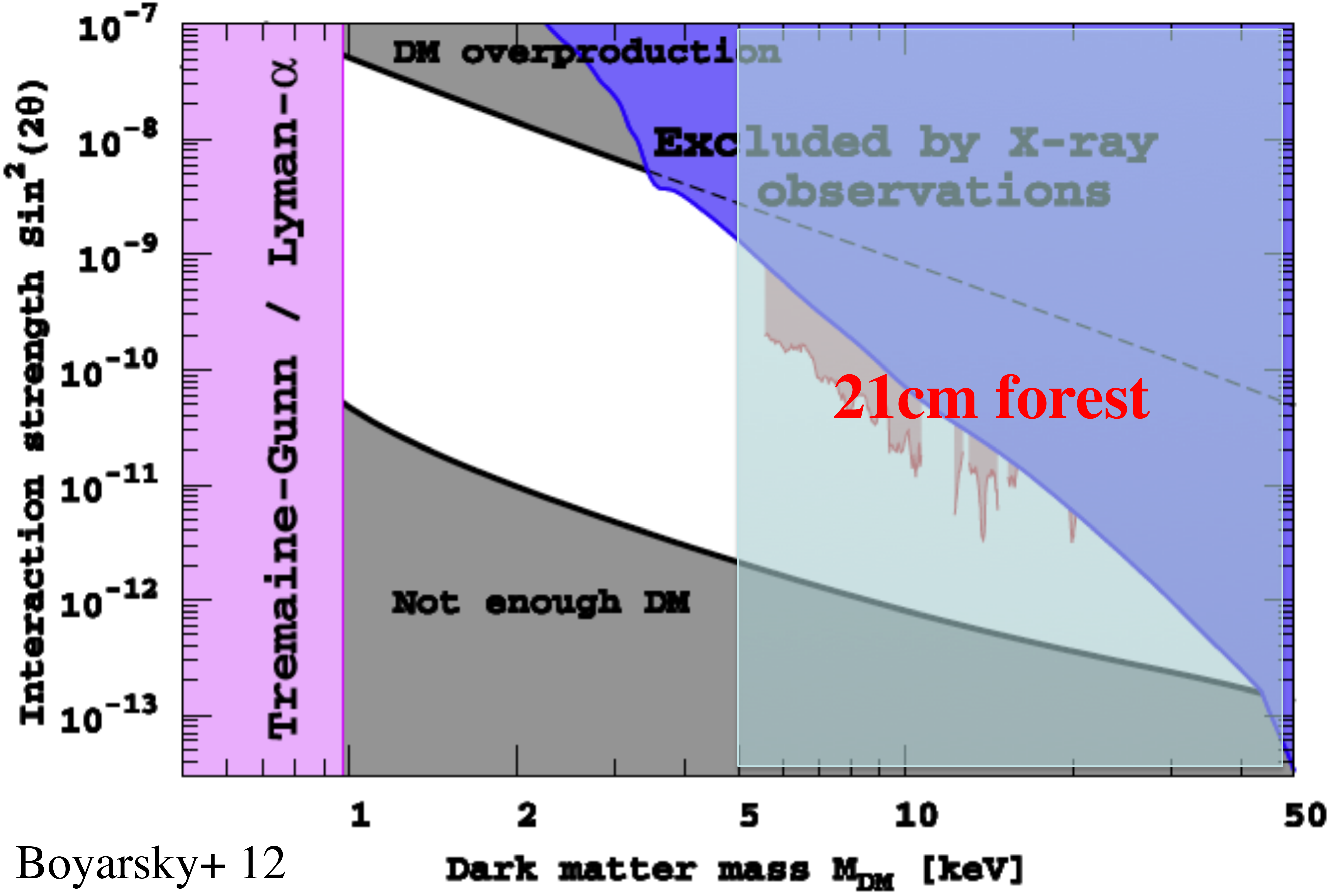


sterile neutrinos as dark matter: current constraints



Boyarsky+ 12

sterile neutrinos as dark matter: current constraints



Boyarsky+ 12

21cm cosmology: emission vs absorption (forest)

- emission (or absorption against CMB)
  pro: 3D (all-sky + z-dependence) <-> 2D CMB
  con: very weak signal << expected foreground

- absorption against high-z radio sources
  pro: limited only by flux and number of sources
  no or little foreground
  con: limited by flux and number of sources
  highly uncertain BUT interesting problem itself

potential background radio sources at very high z

required spectral resolution dν~kHz (3km/s) at ν~<100 MHz

required flux for SKA

$$S_{\rm min} = 16\,{\rm mJy}\left[\frac{S/N}{5}\frac{0.01}{\tau}\frac{10^6\,{\rm m}^2}{A_{\rm eff}}\frac{T_{\rm sys}}{400\,{\rm K}}\right]\sqrt{\frac{1\,{\rm kHz}}{\Delta\nu}\frac{1\,{\rm week}}{t_{\rm int}}}$$

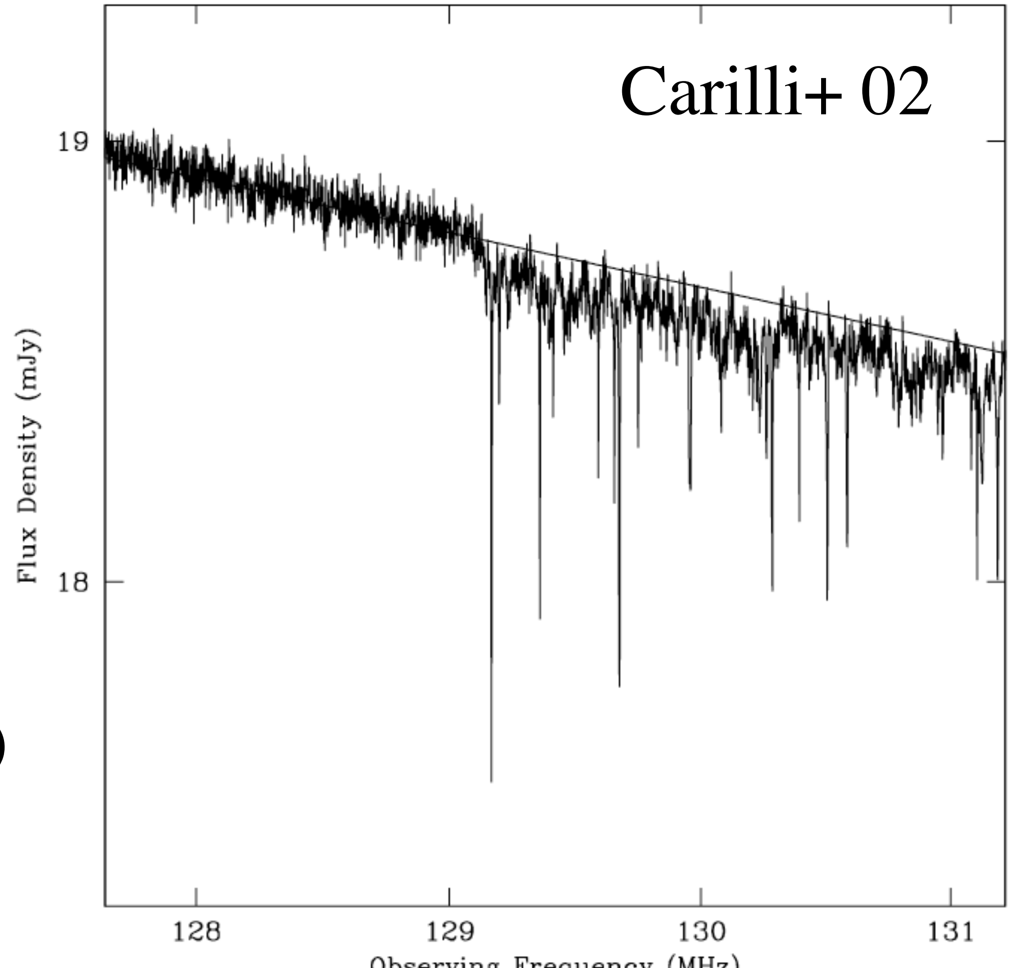
Furlanetto & Loeb 02

radio quasar as background radio source

assuming Cyg-A like source at z=10

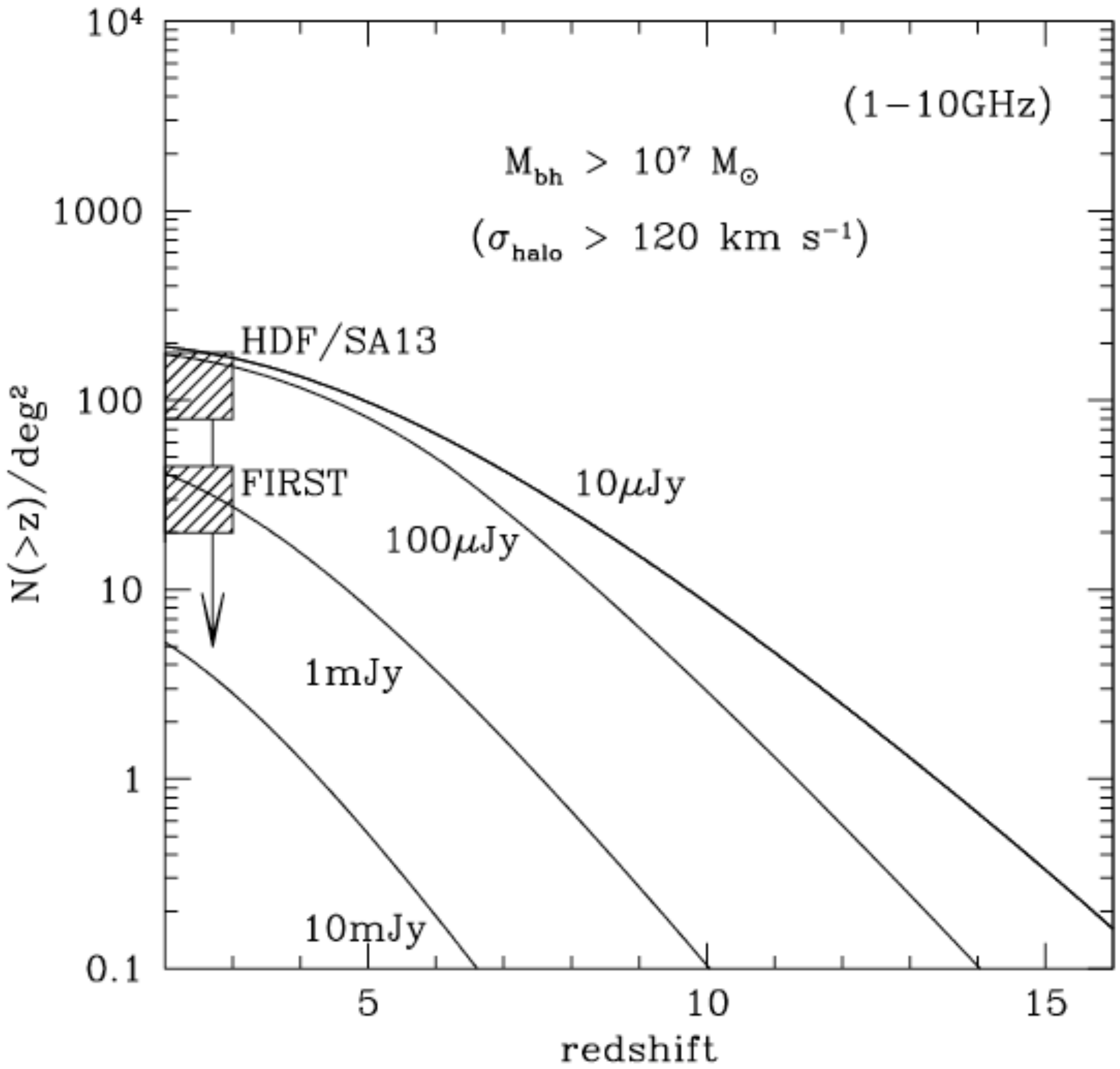
possible even with LOFAR?
Ciardi+ 12

BUT
sufficiently luminous (~massive BH)
+radio-loud AGNs at high-z?



high-z radio-loud quasars: expectations

Haiman+ 04



assume:

- M_{BH} scales with M_{halo} similarly to low z
- radio loudness distribution same as low z

results:

- number overpredicted by ~100 compared to FIRST obs. unless radio-loud only for M_{BH}>~10^7 M_{sun}
- expected no. at z>6
  ~ 4/deg^2 for >mJy
  ~ 0.2/deg^2 for >10mJy

- expected no. at z>10?
  ~ 0.1/deg^2 for >mJy
  ~ 0.005/deg^2 for >10mJy
  (200 all-sky)

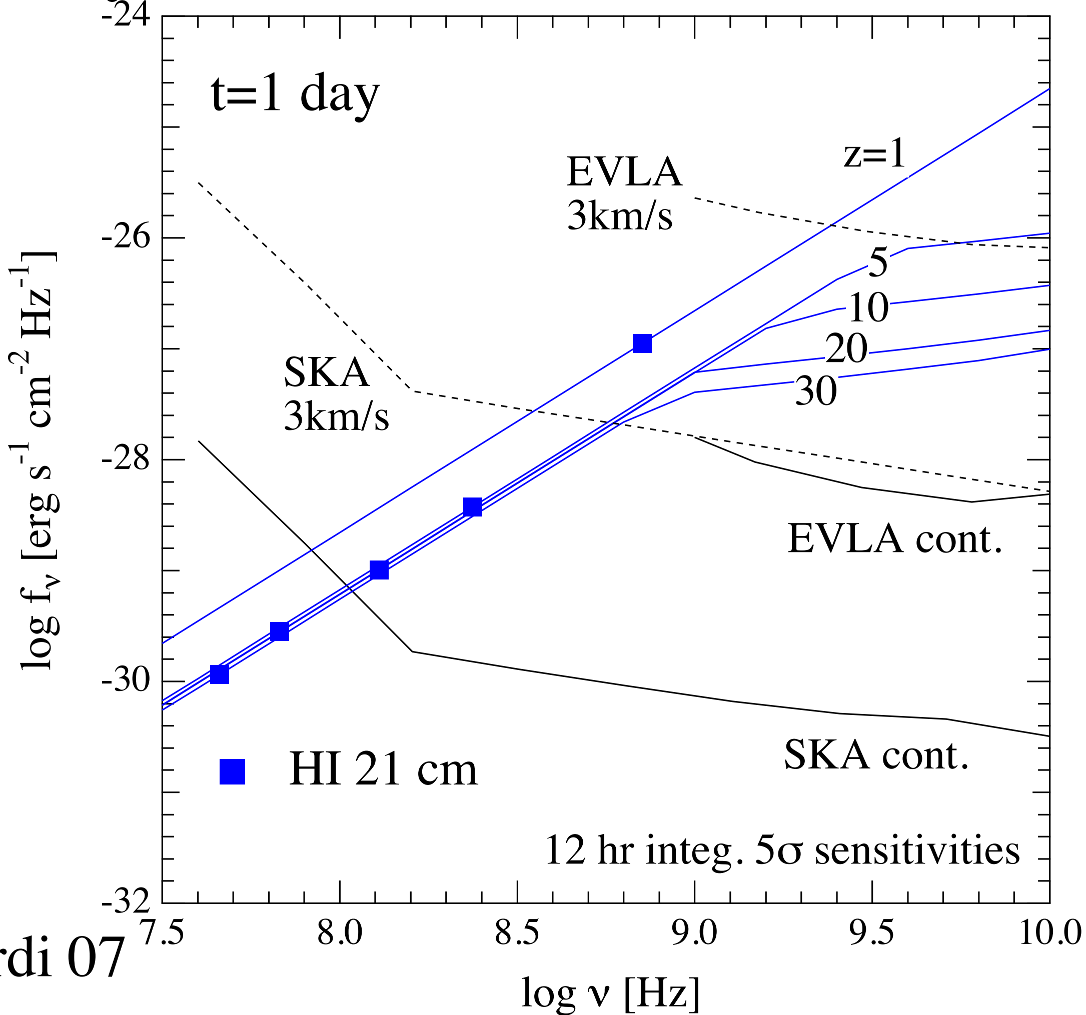
GRBs as background radio source

normal GRB afterglows

sub-GHz afterglow flux strongly suppressed
by sync. self absorption
-> high-res. spectroscopy difficult
(even though continuum detectable by SKA)

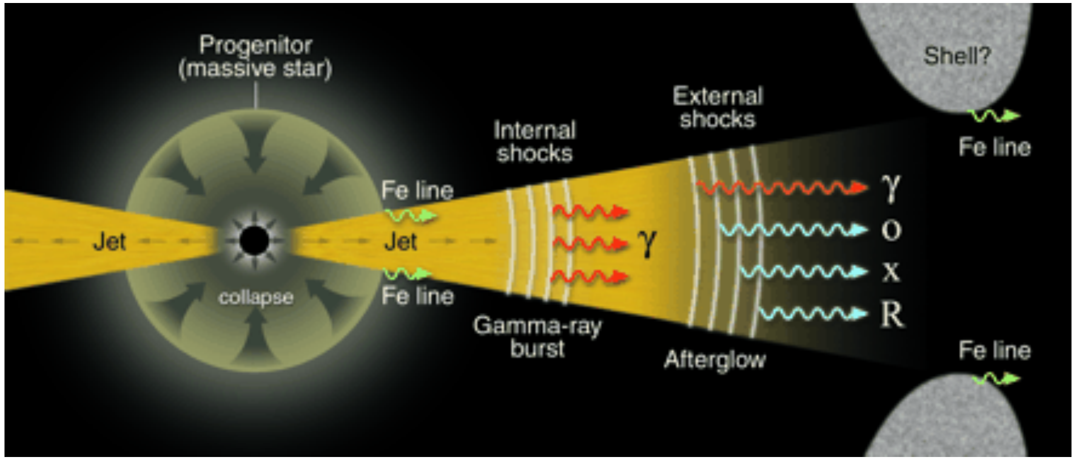
c.f. SI, Omukai, Ciardi 07

also Ioka, Meszaros 04

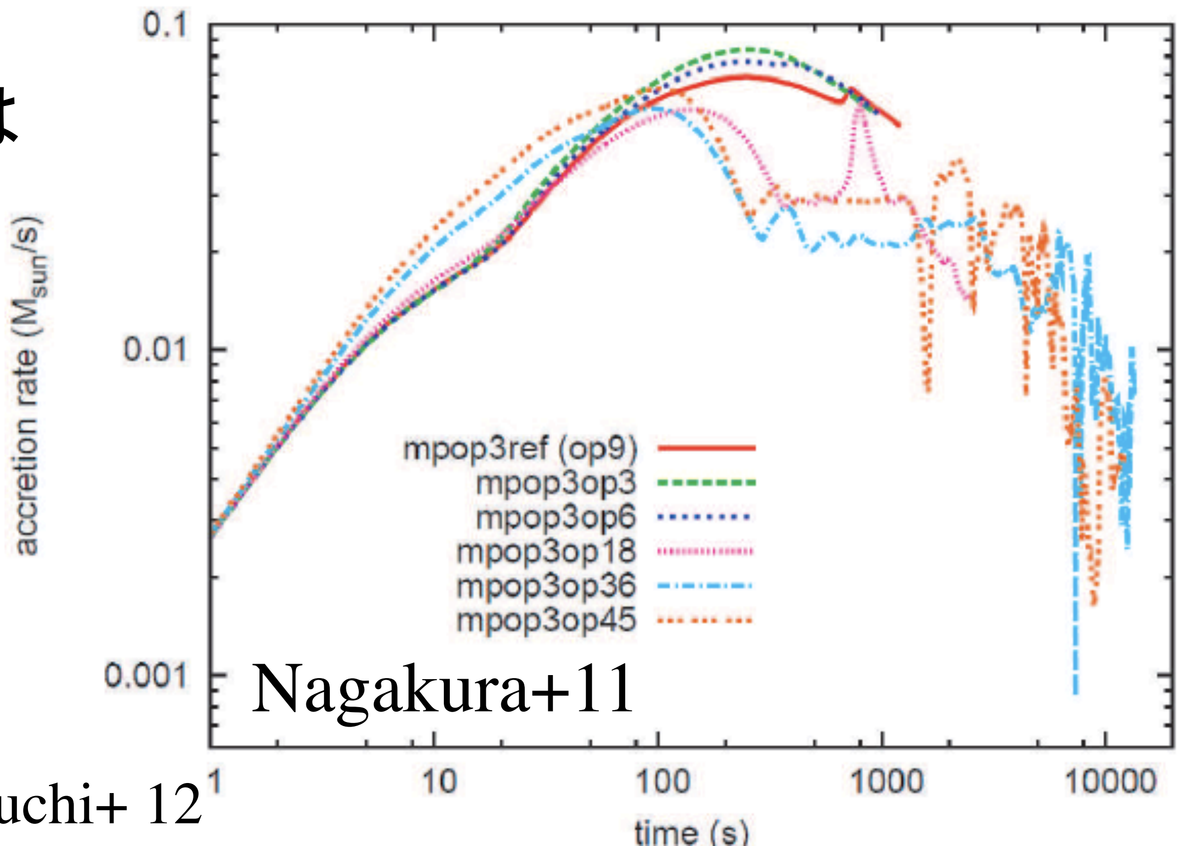


adapted from
SI, Omukai, Ciardi 07

Pop III stars -> GRBs? expectations

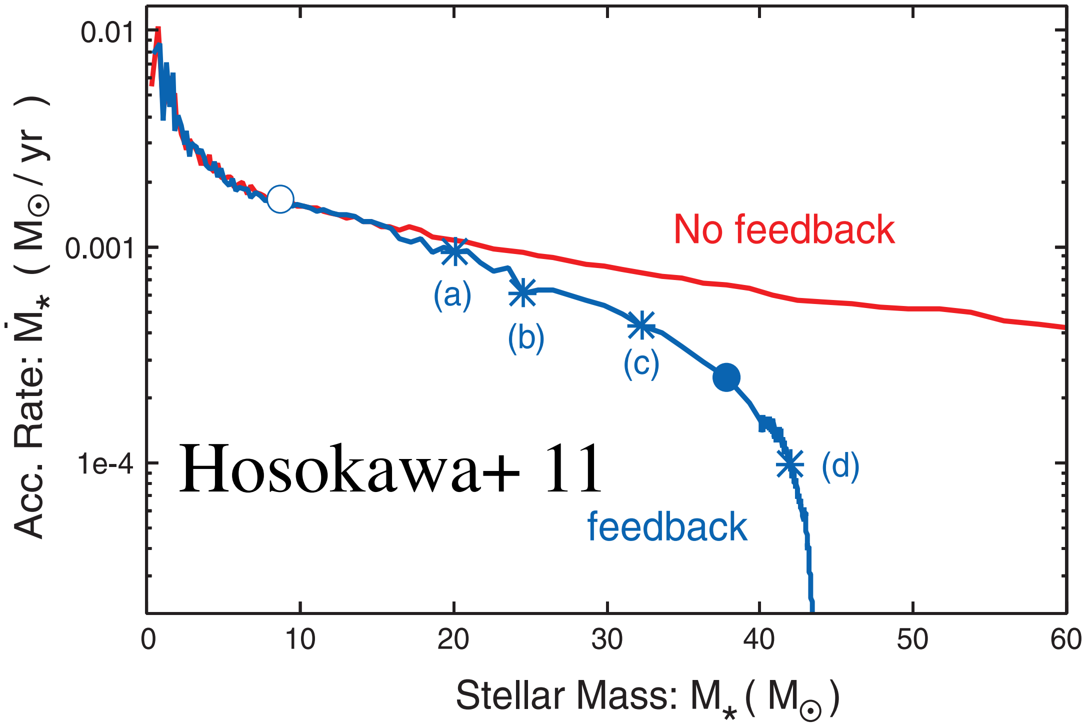


- 通常のGRBと異なりH/He外層を保持したまま爆発
- 光度は通常のGRBと大差ない L_{iso}~10^{53}-10^{54} erg/s
  が外層からBHへ降着する質量が大きく（数10-1000$M_{\odot}$）継続時間が長い T_0 ~<10^4 s
  -> 厚いH/He層でもジェットが貫通できる
  -> promptは暗くSwiftなどではtriggerしにくい
  -> 総エネルギーはでかい E_{iso}~10^{54}-10^{57} erg
  残光が各波長で明るい



Komissarov & Barkov 10
Meszaros & Rees 10
Toma, Sakamoto & Meszaros 10
Suwa & Ioka 10, Nagakura+ 11, Nakauchi+ 12

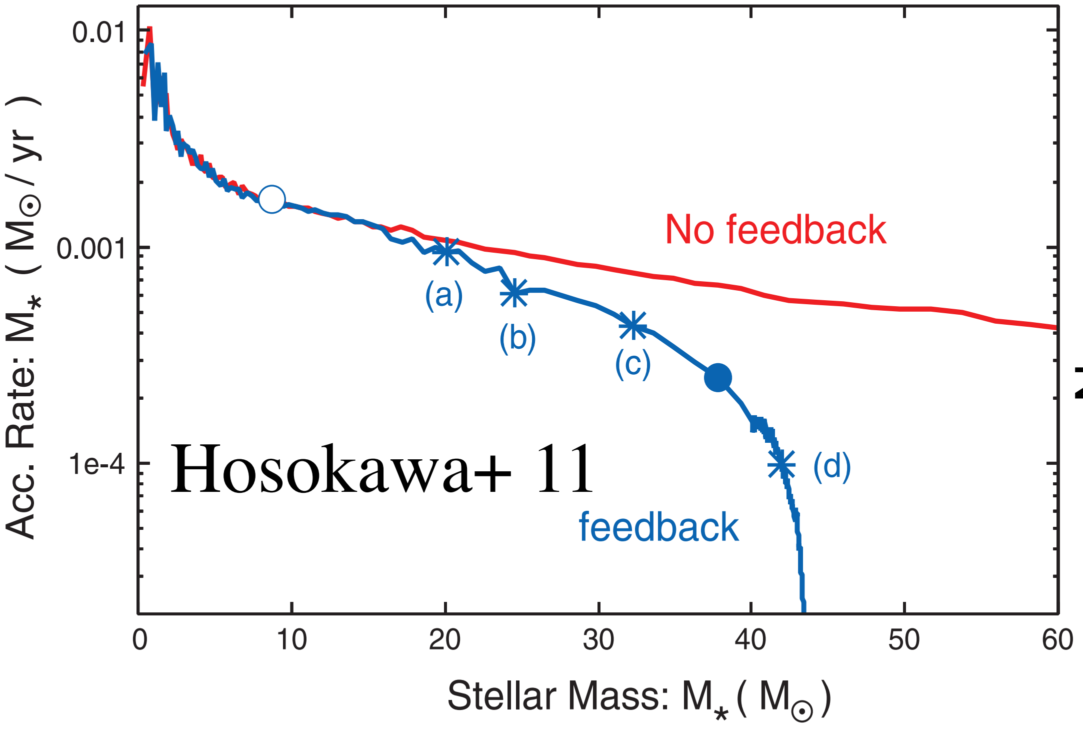
mass of Pop III stars?



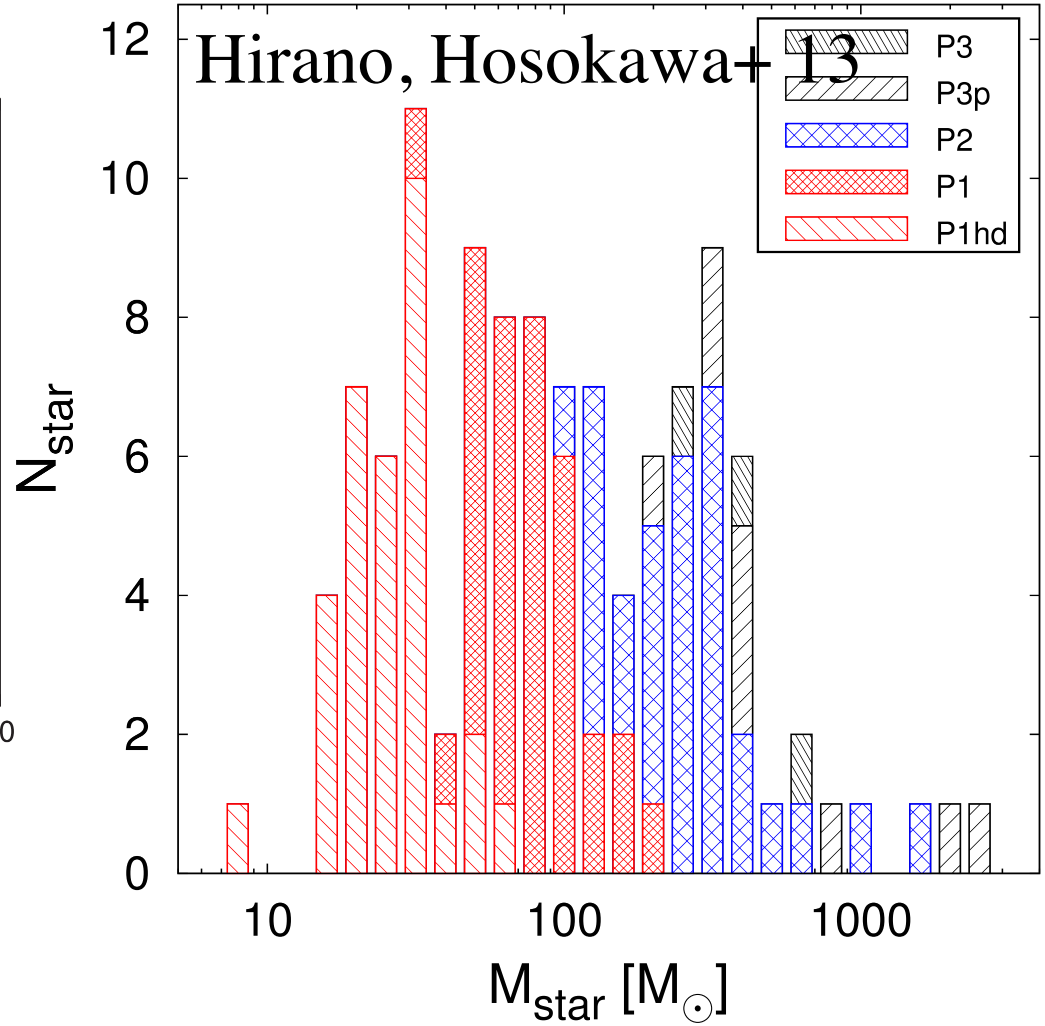
~40 solar以下？

注：
例え40 solarでもH/He層を降着してE$_{iso}$>~10^{55} ergはありかも

mass of Pop III stars?



~40 solar以下？



also Susa+, in prep.

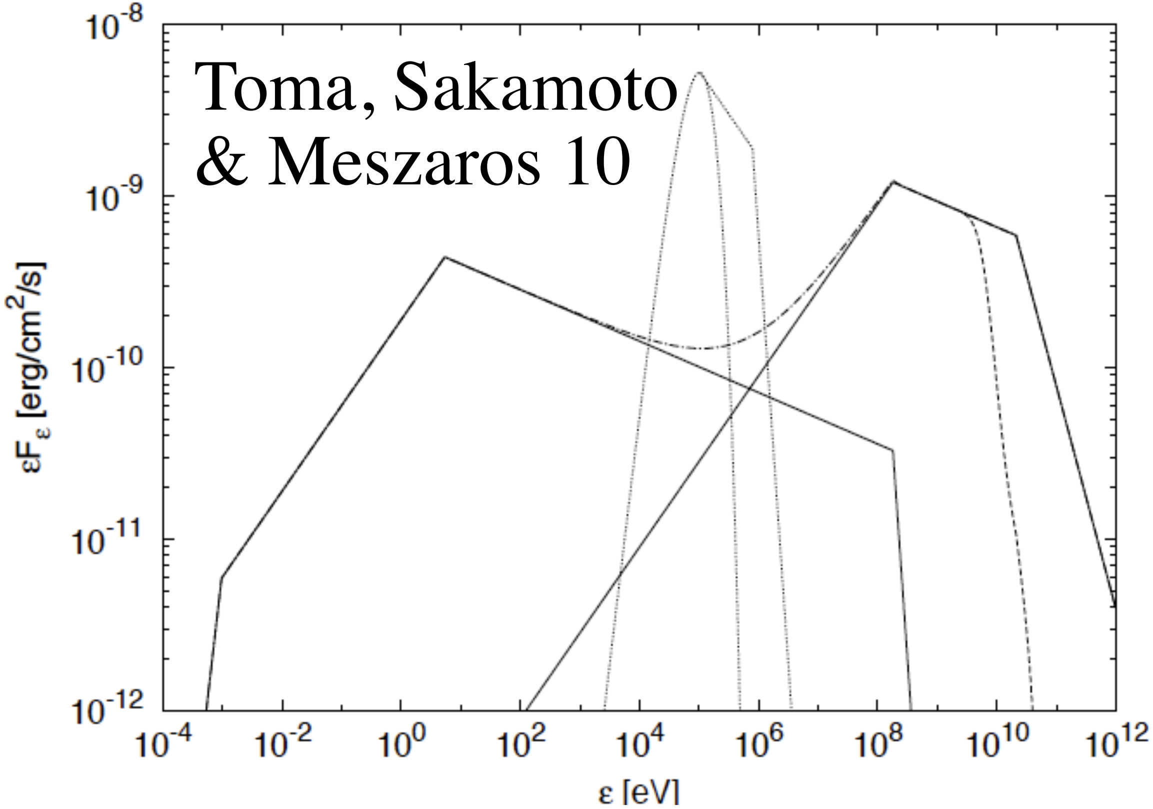
~1000 solarもやっぱりあるやん！

注：

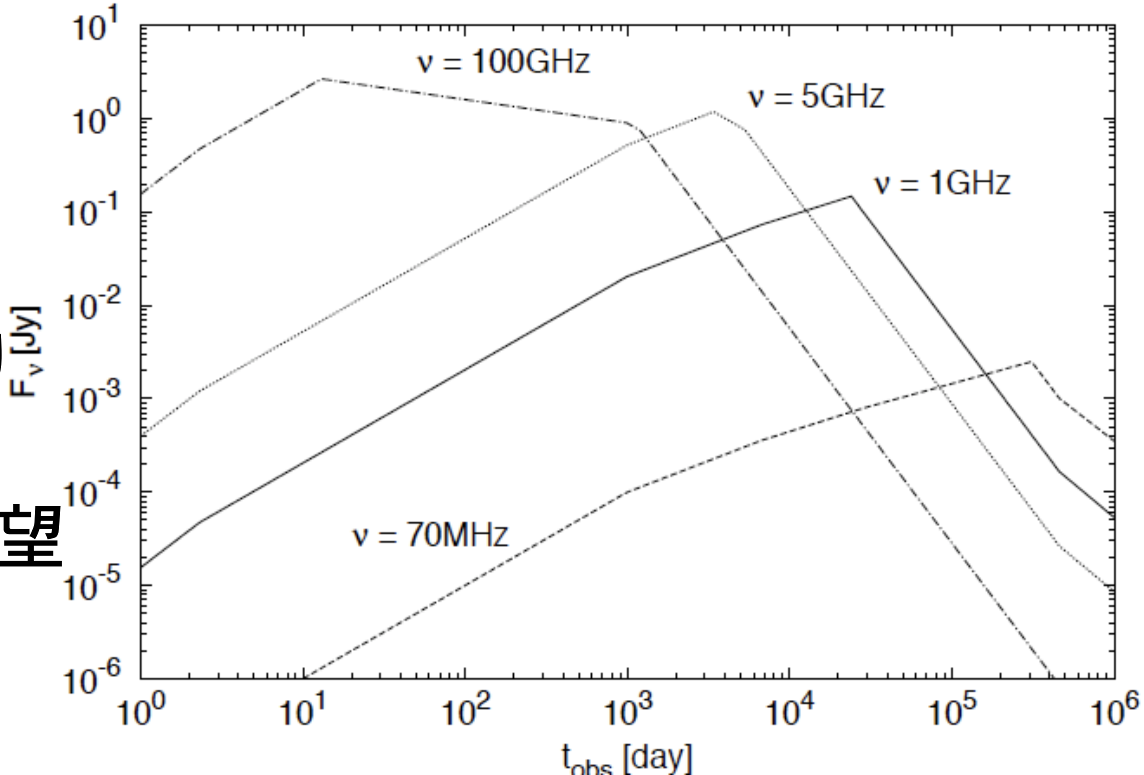
例え40 solarでもH/He層を降着してE$_{iso}$>~10^{55} ergはありかも

Pop III GRB afterglow

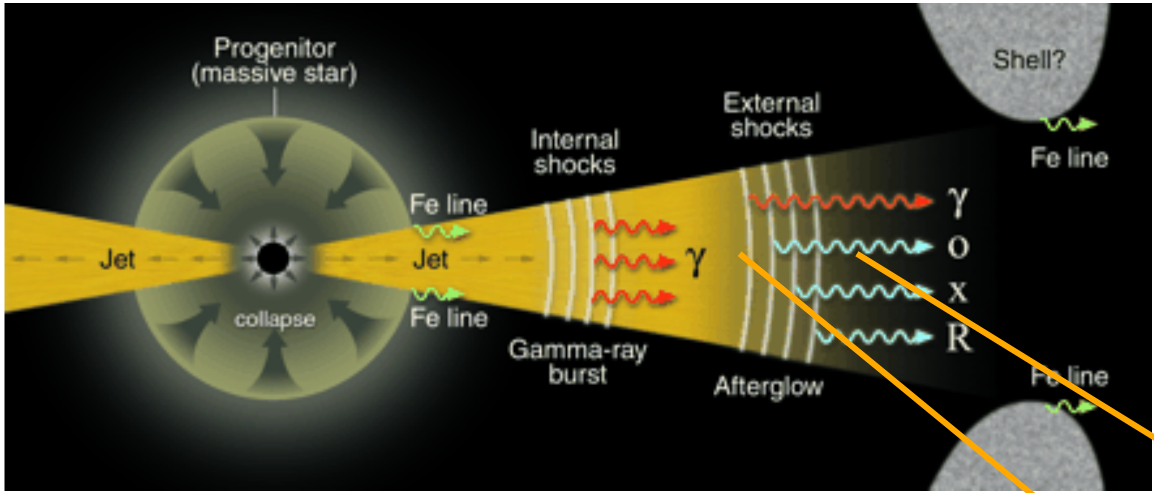
Pop III GRBs:
光度は普通のGRBと大差ないが継続時間が長く
総エネルギーはでかい
$E_{iso}\sim10^{55}$-10^{57} erg
-> afterglowは明るい



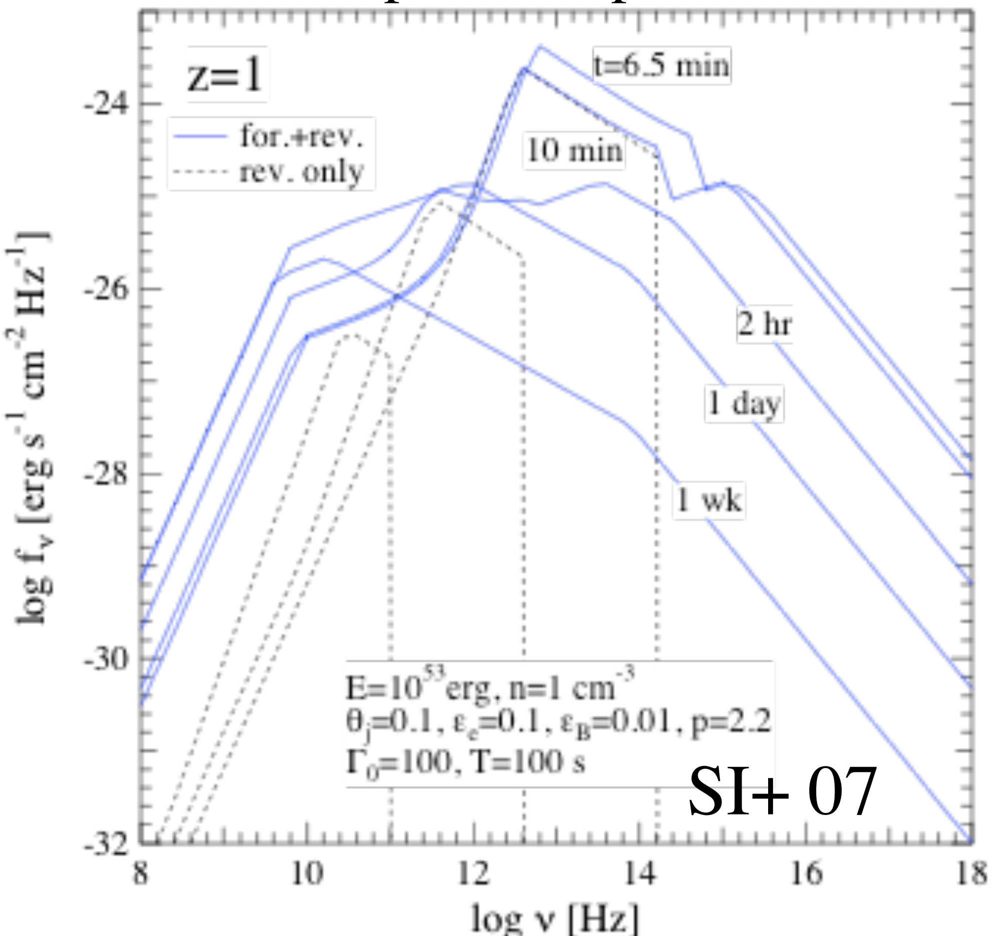
普通のGRBより大きな半径まで広がる
-> シンクロトロン自己吸収が減り
低周波電波でも明るい
-> 21cm吸収線の光源として有望



GRB afterglows: forward+reverse shock emission



t-dependent spectra



ultrarelativistic outflow
+ external medium ->
decelerating shock ->
e acceleration
+synchrotron emission

forward shock:
radio-IR-opt-X afterglow

reverse shock:
optical flash, radio flare

Sari+ 98, 99, Sari & Piran 99
Panaitescu & Kumar 00,01,02
Kobayashi 00…

parameters:

$E=10^{53}$-10^{57} erg

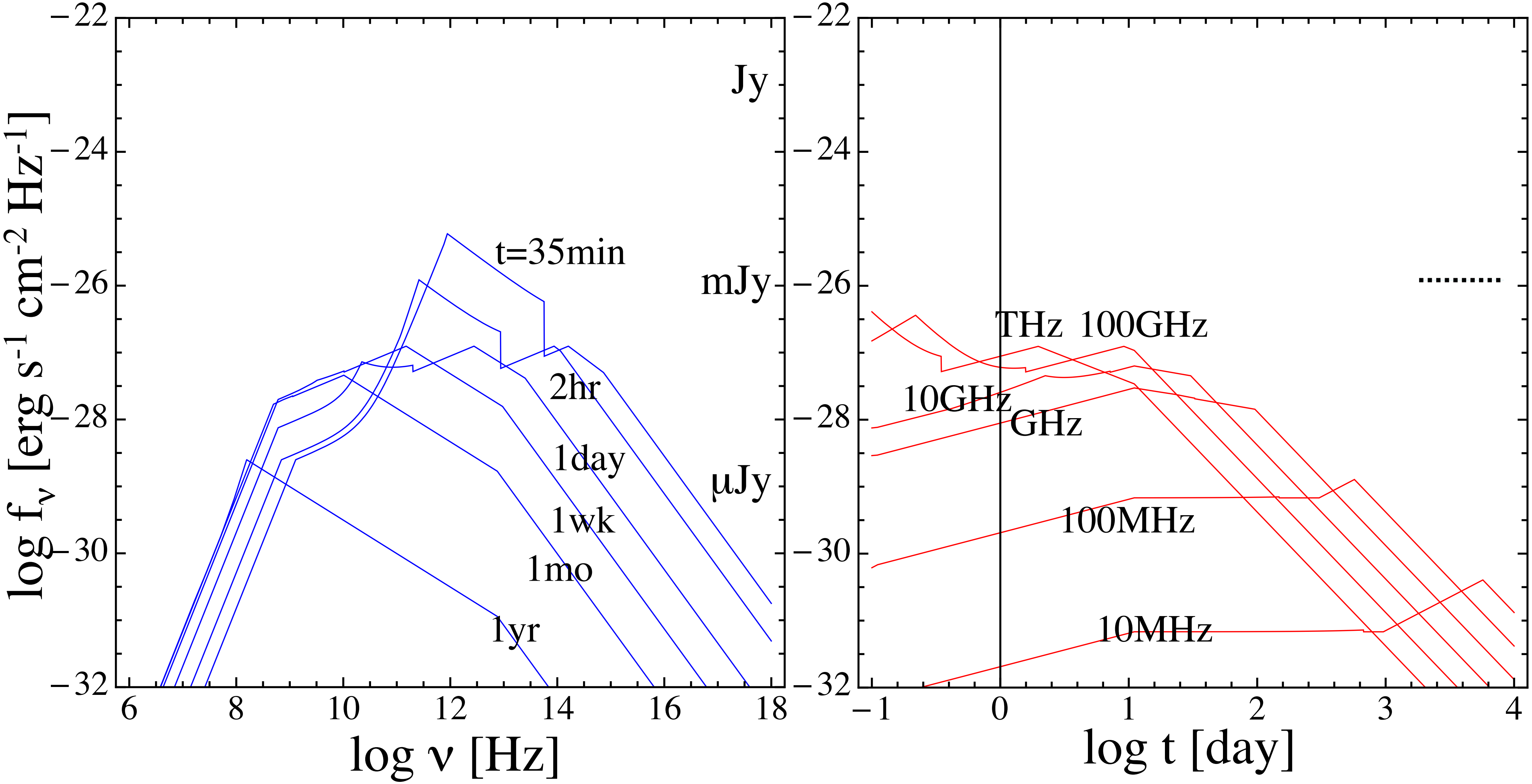
$T_0=100$-10000 s

$n_{ext}=(0.1$-$)1$ cm^{-3}

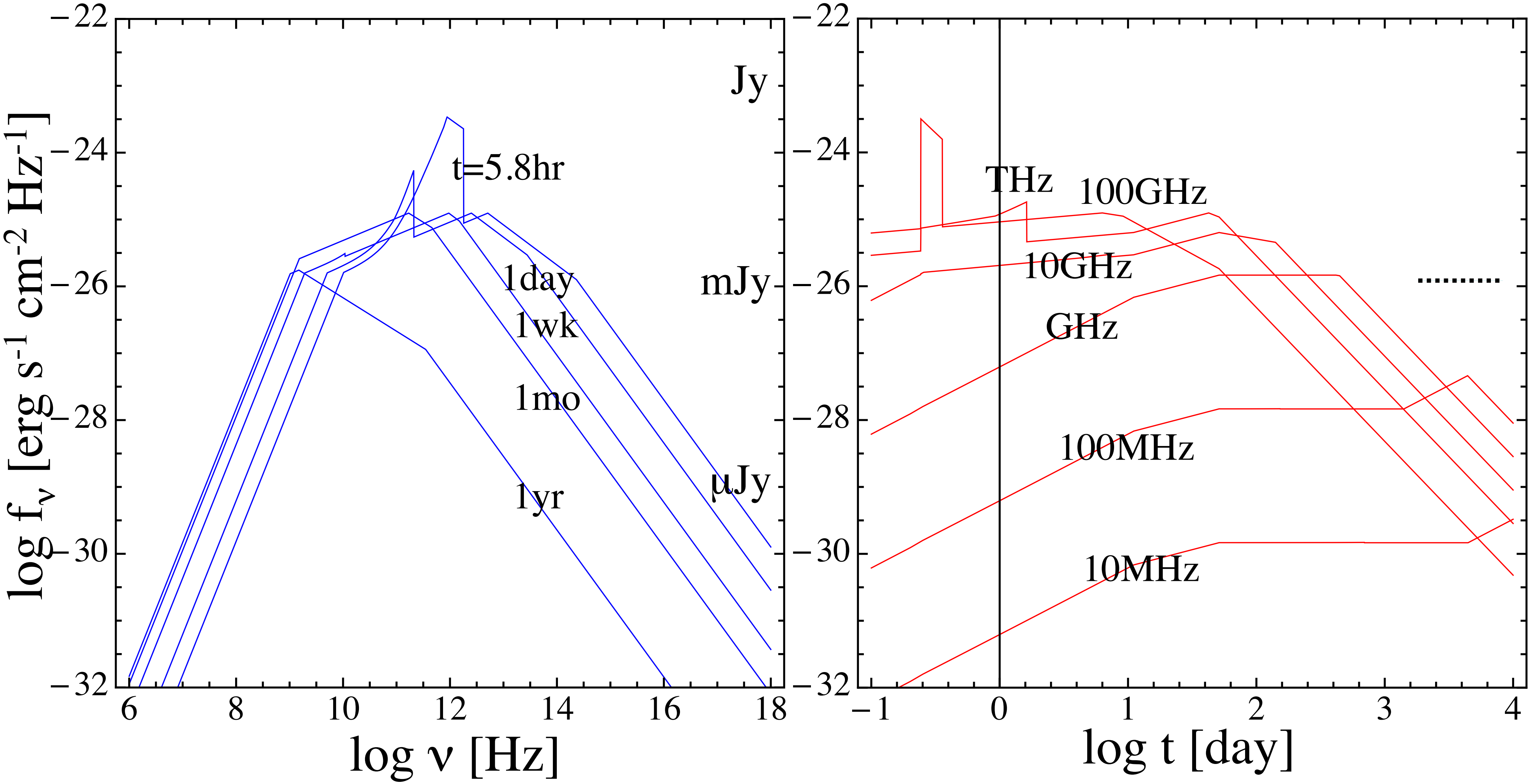
$\theta_j=0.1$, $\varepsilon_{e,f}=0.1$, $e_{B,f}=0.01$

$\Gamma_0=300$, $\varepsilon_{e,r}=0.1$, $e_{B,r}=0.01$

normal GRB afterglow $E=10^{53}$ erg, $T_0=100$ s, $z=20$

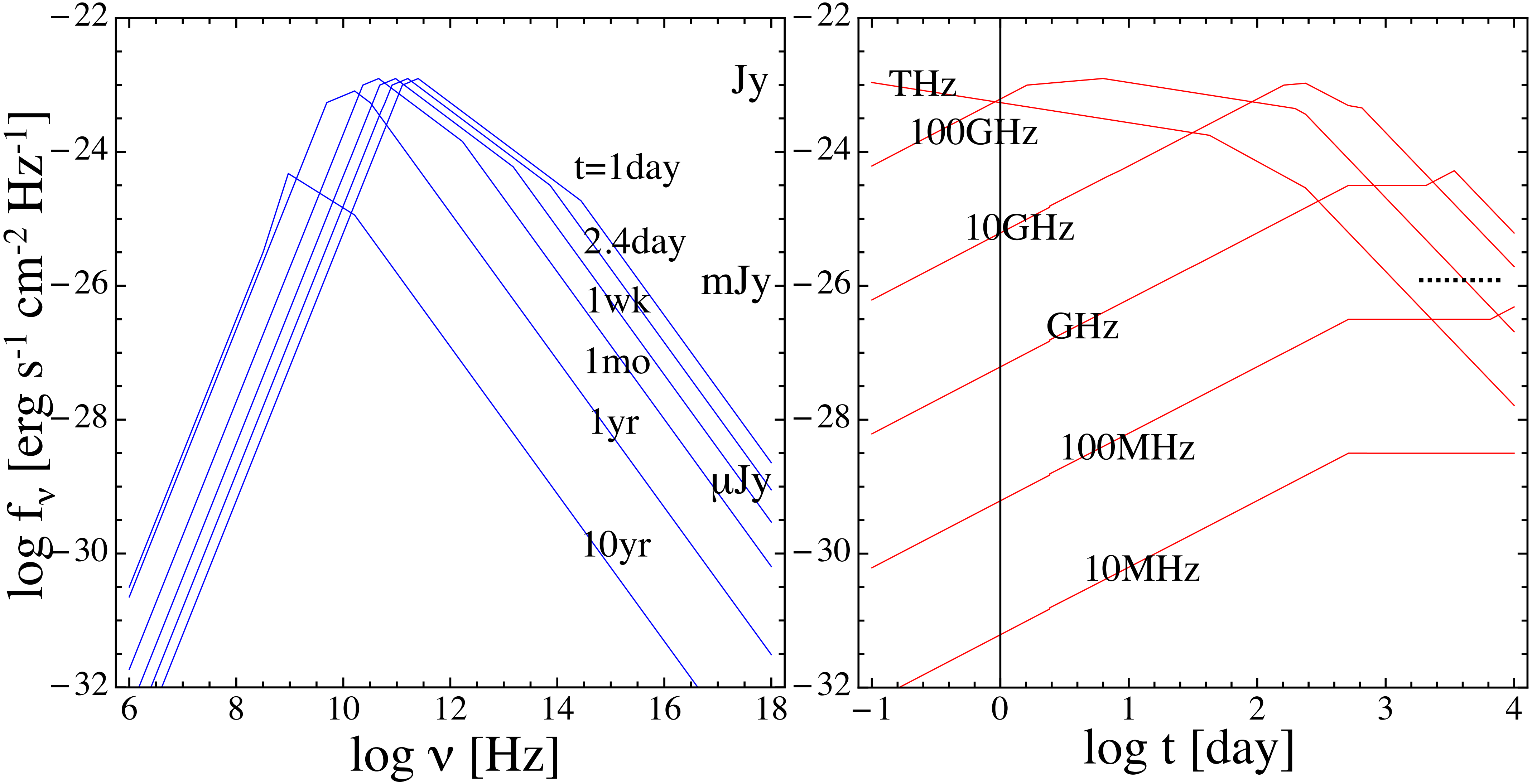


Pop III GRB afterglow　E=10^{55} erg, T_0=1000 s, z=20



- forward shock成分はEにほぼ比例して明るい ~1-10mJy @>10GHz
- HD吸収線観測によりよい >~mJy @100GHz up to t~100 days!
- reverse shock成分は相対的にマイナー

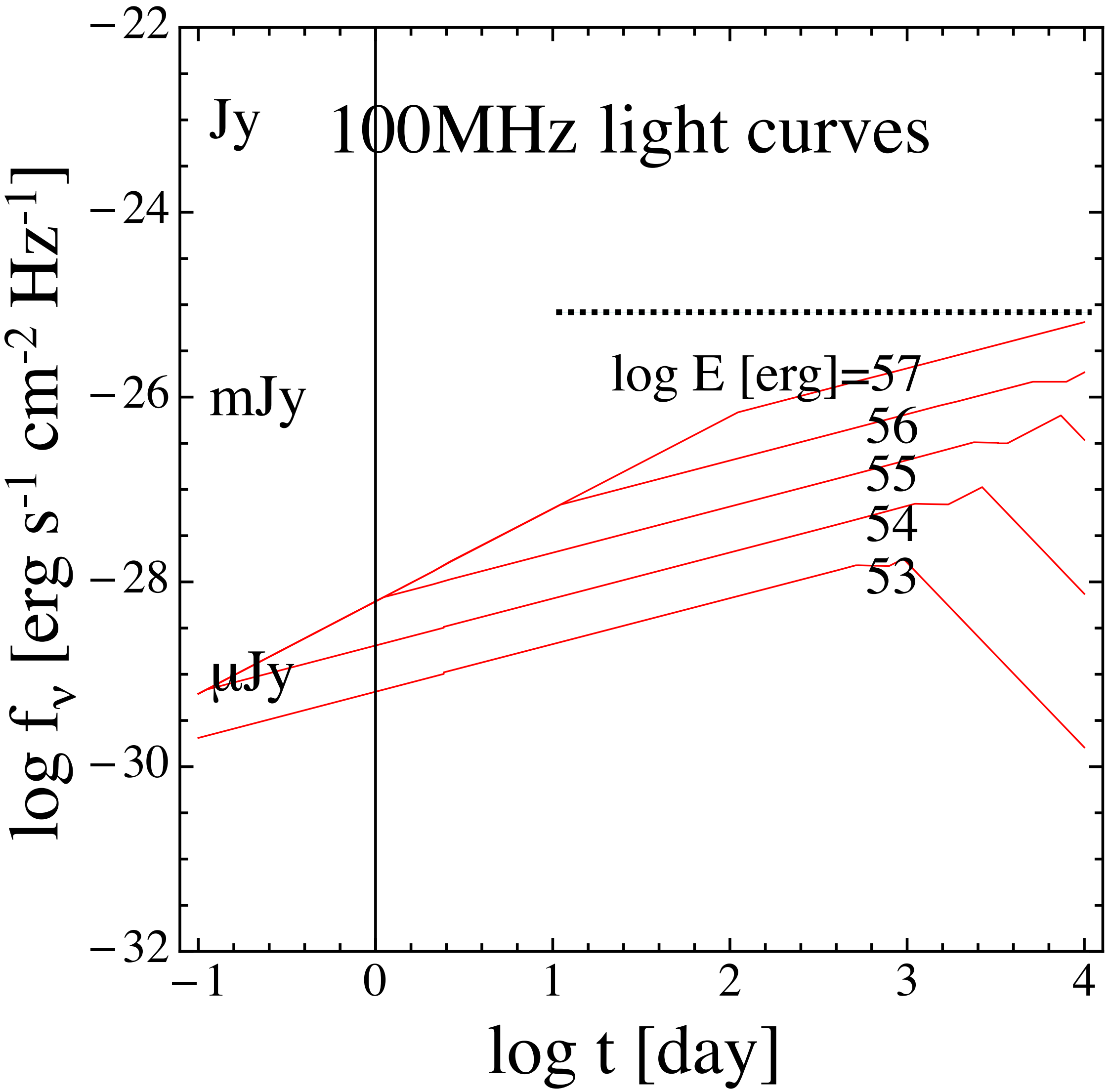
Pop III GRB afterglow　$E=10^{57}$ erg, $T_0=10000$ s, z=20



- forward shock成分 ~<1Jy! @>10GHz
  既存の変動天体探査ですでに制限?(要チェック)
- reverse shock成分は完全にsubdominant

Pop III GRB afterglow: $E=10^{57}$ erg, $T_0=10000$ s, $z=20$

21cm absorption? $n_{ext}=0.1$ cm^{-3}, $\theta_j=0.3$



21cm吸収線背景光源としてSKA観測で要求される強度は~10mJy

$E=10^{57}$ ergならt~30~1000 yrで~10mJy

see also Toma+ 11

$N_{allsky} \sim R_{GRB,57} t_{rad}$

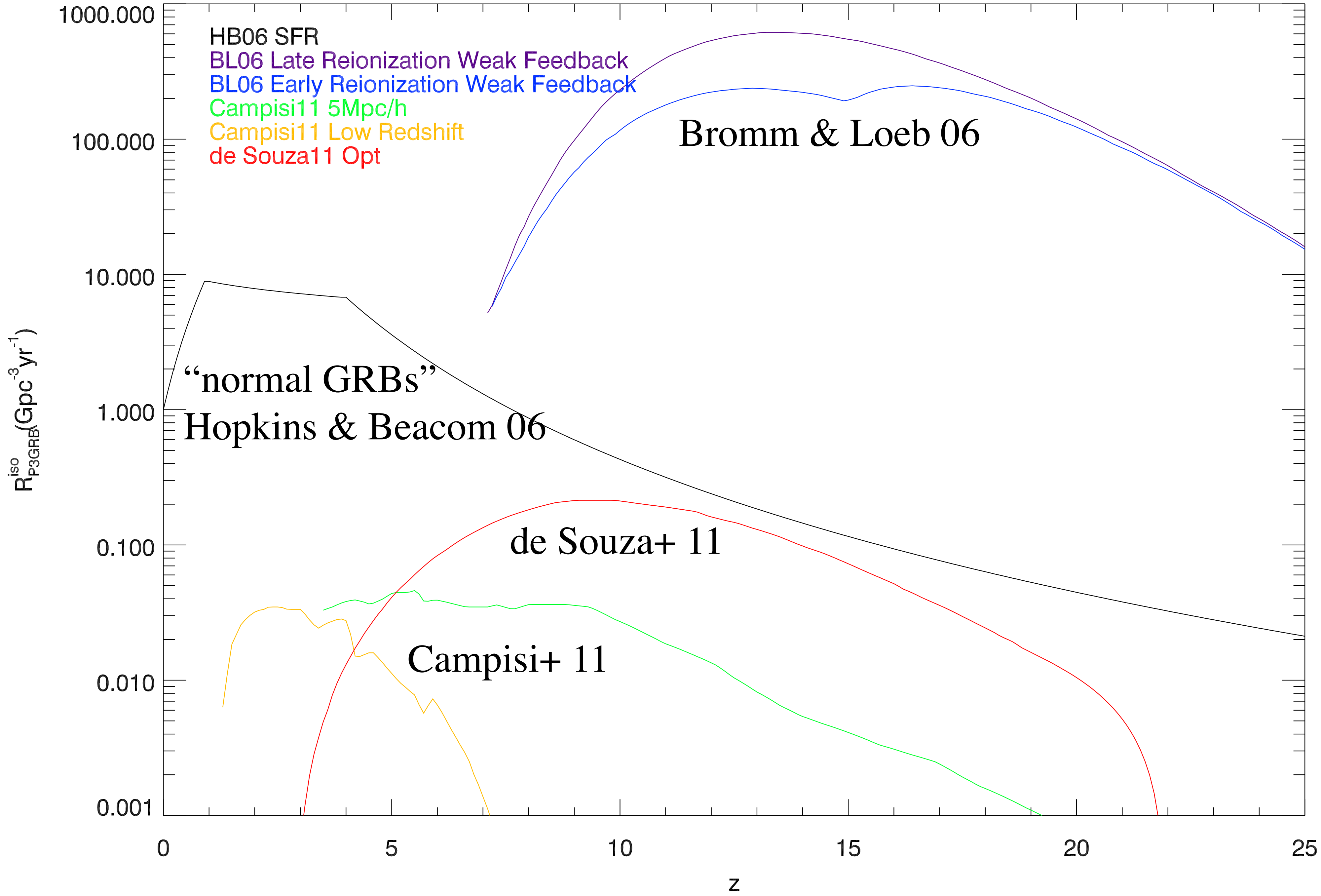
全天10-100個あるには

$R_{GRB,57} \sim 0.01\text{-}0.1$/yr

$$S_{min} = 16\,\mathrm{mJy}\left[\frac{S/N}{5}\,\frac{0.01}{\tau}\,\frac{10^6\,\mathrm{m}^2}{A_{eff}}\,\frac{T_{sys}}{400\,\mathrm{K}}\right]\sqrt{\frac{1\,\mathrm{kHz}}{\Delta\nu}\,\frac{1\,\mathrm{week}}{t_{int}}}$$

Pop III GRB rates

adapted from Liu, SI, Wang & Aharonian, in prep.



first supermassive black holes

$E \sim L_{Edd}\, t_{Sal}$

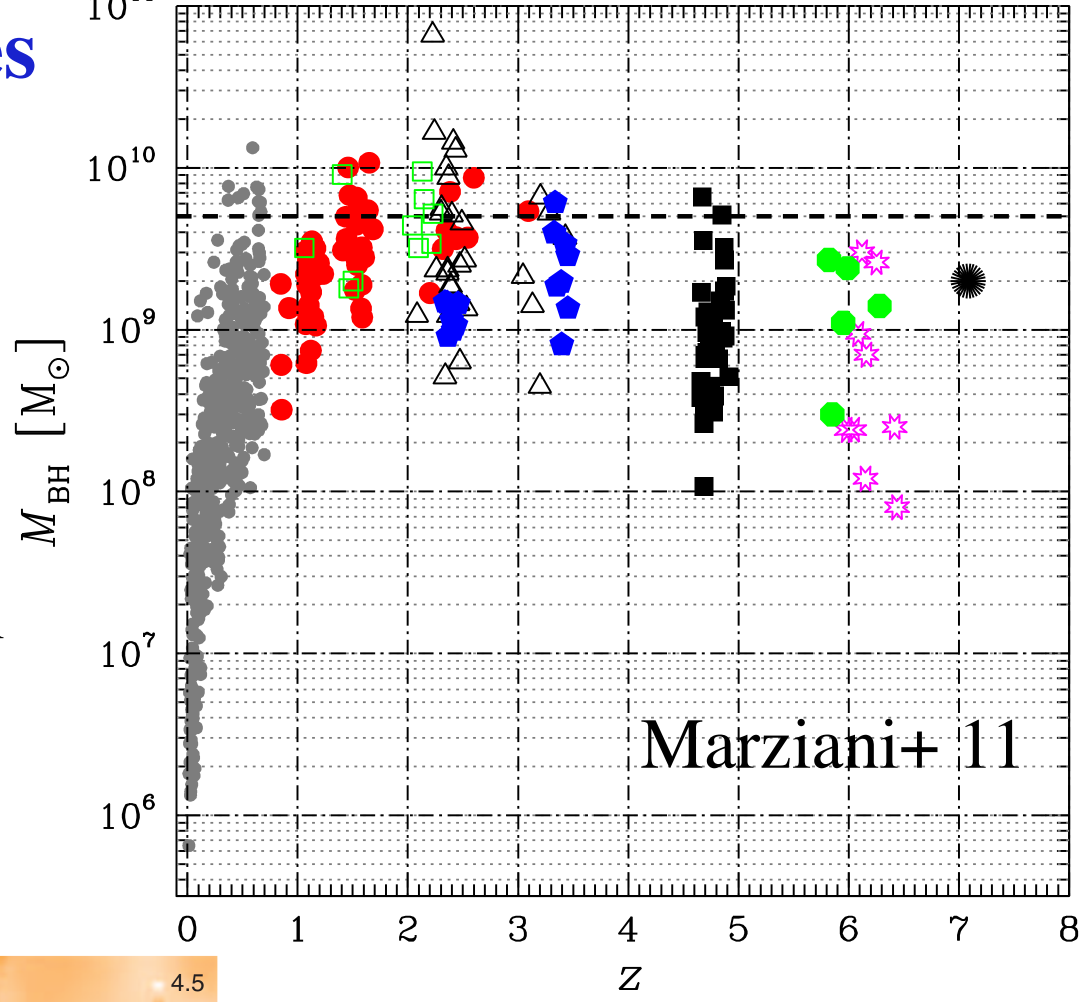
$\sim$ few $\times 10^{58}$ erg

for $M_{BH} \sim 10^{6}\, M_{sol}$

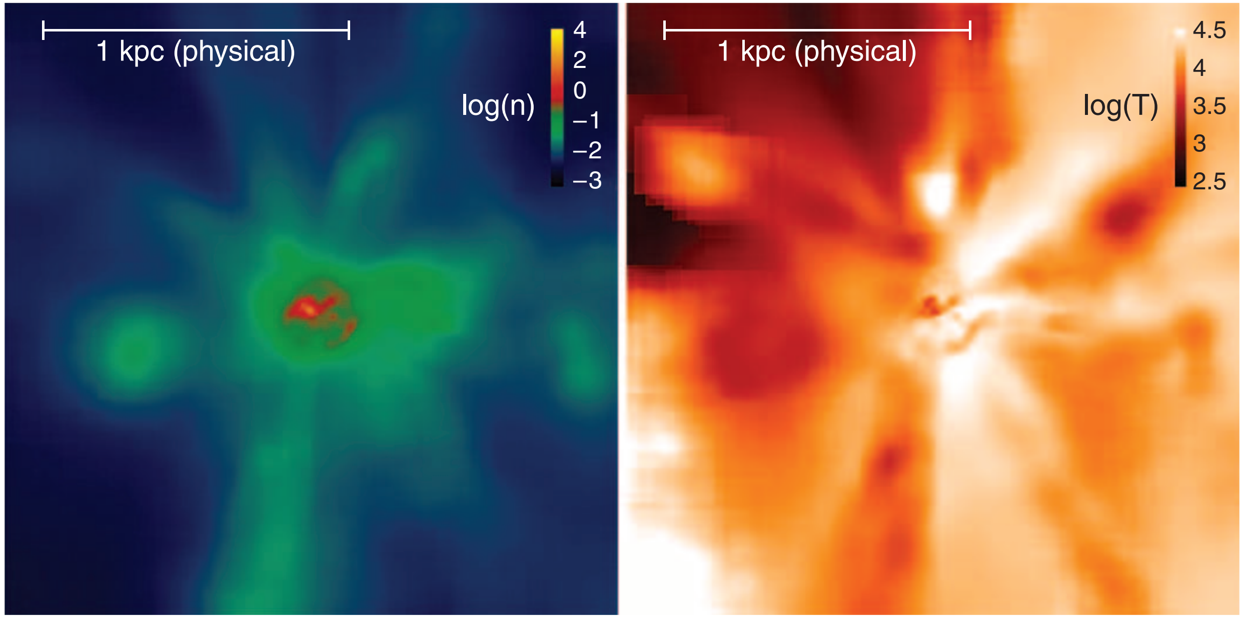
early, gas-rich environment

-> ubiquitous blastwave formation

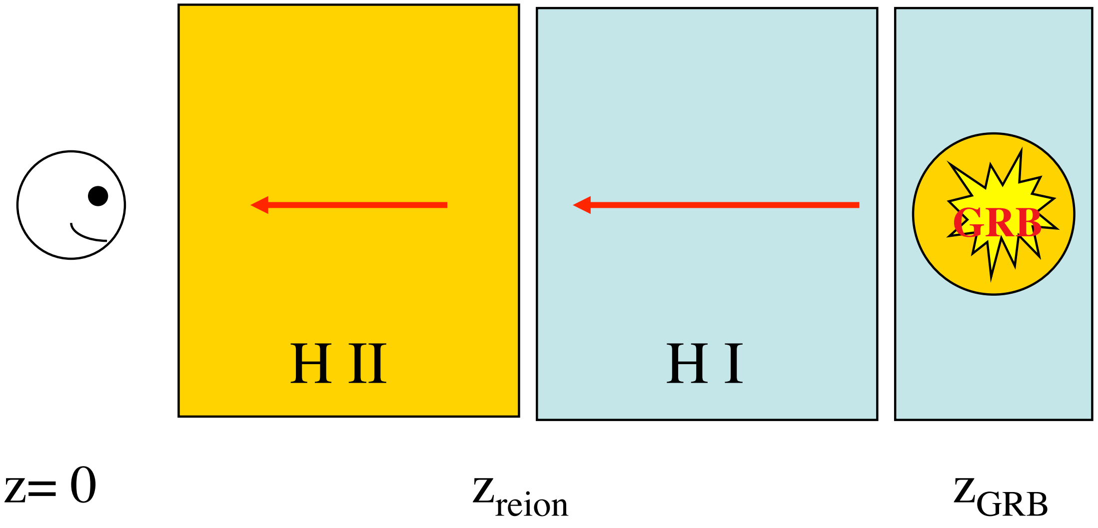
+ radio emission??



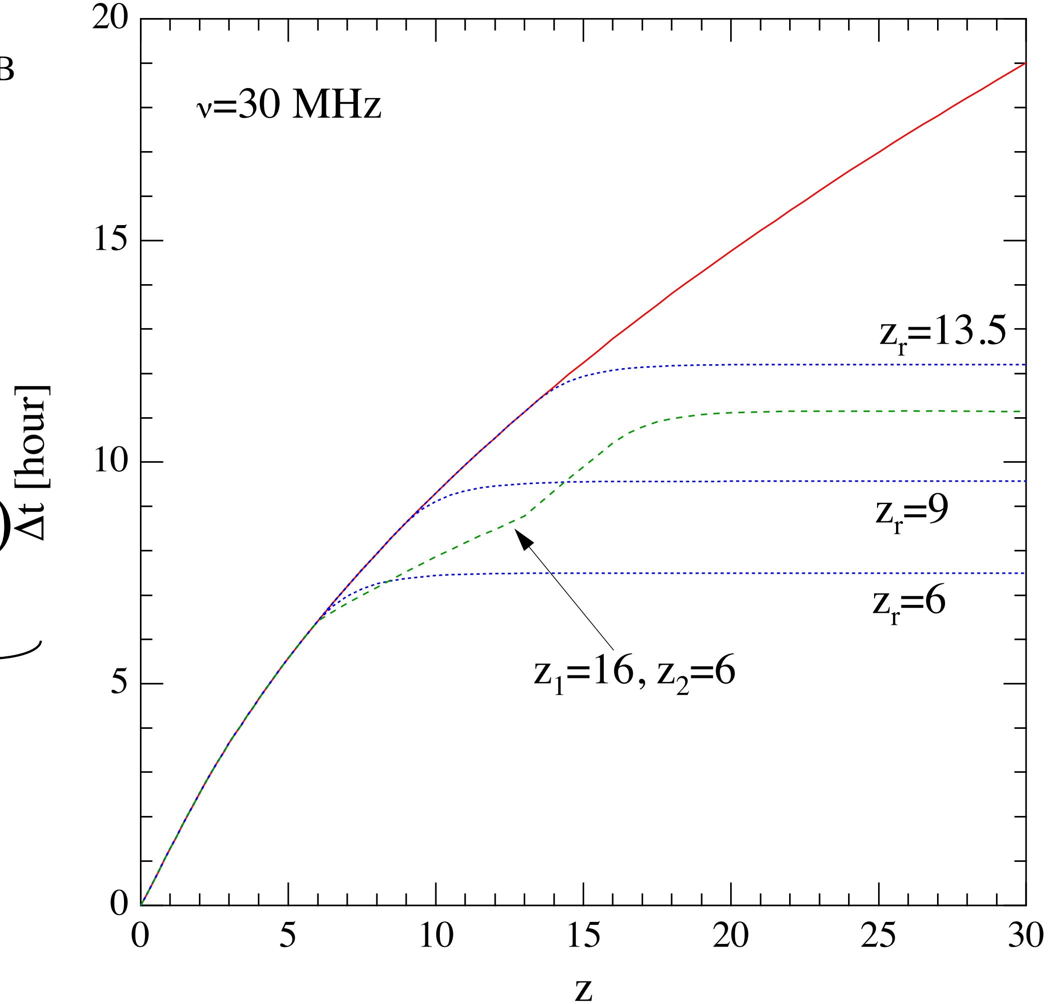
Johnson+ 11



probing ionized IGM with radio dispersion   **SI 04**   Ioka 03



$$\Delta t = \frac{e^2}{2\pi m_e c\, \nu^2} \underbrace{\int dz\, \frac{cdt}{dz} \frac{x_e(z) n_{IGM}(z)}{1+z}}_{\text{dispersion measure}}$$



unID extragalactic radio burst

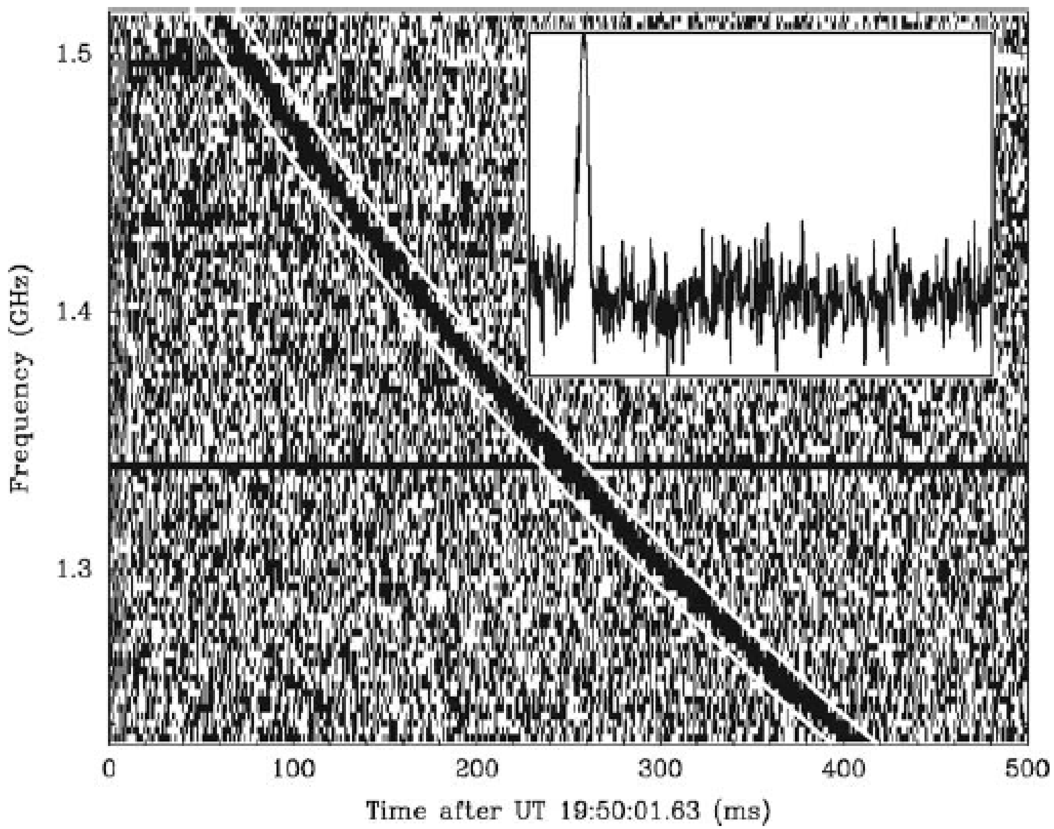
Lorimer+ Science 07

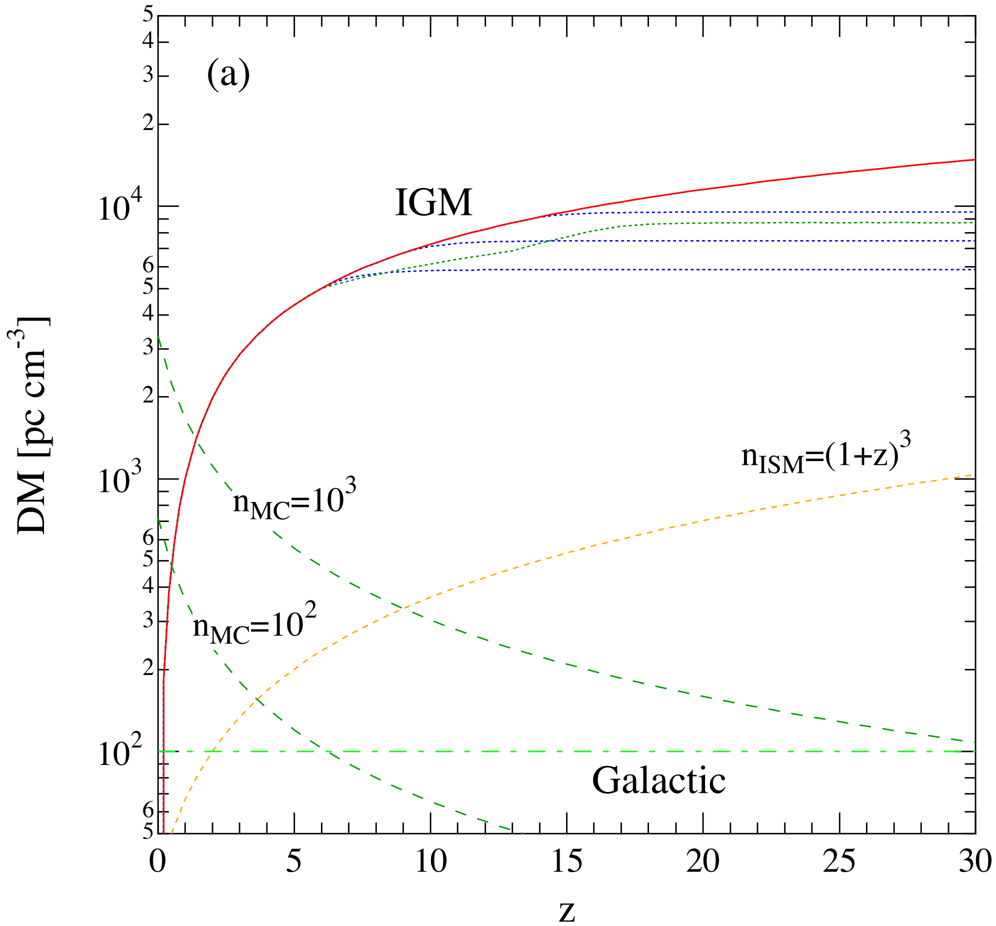
Parkes multi-beam pulsar survey

S_ν~30 Jy @1.4GHz!
Δt~5ms

DM=375 pc cm^{-3} >>DM_{Gal}
-> D~0.5 Gpc (z~0.1)

-> LOFAR, SKA



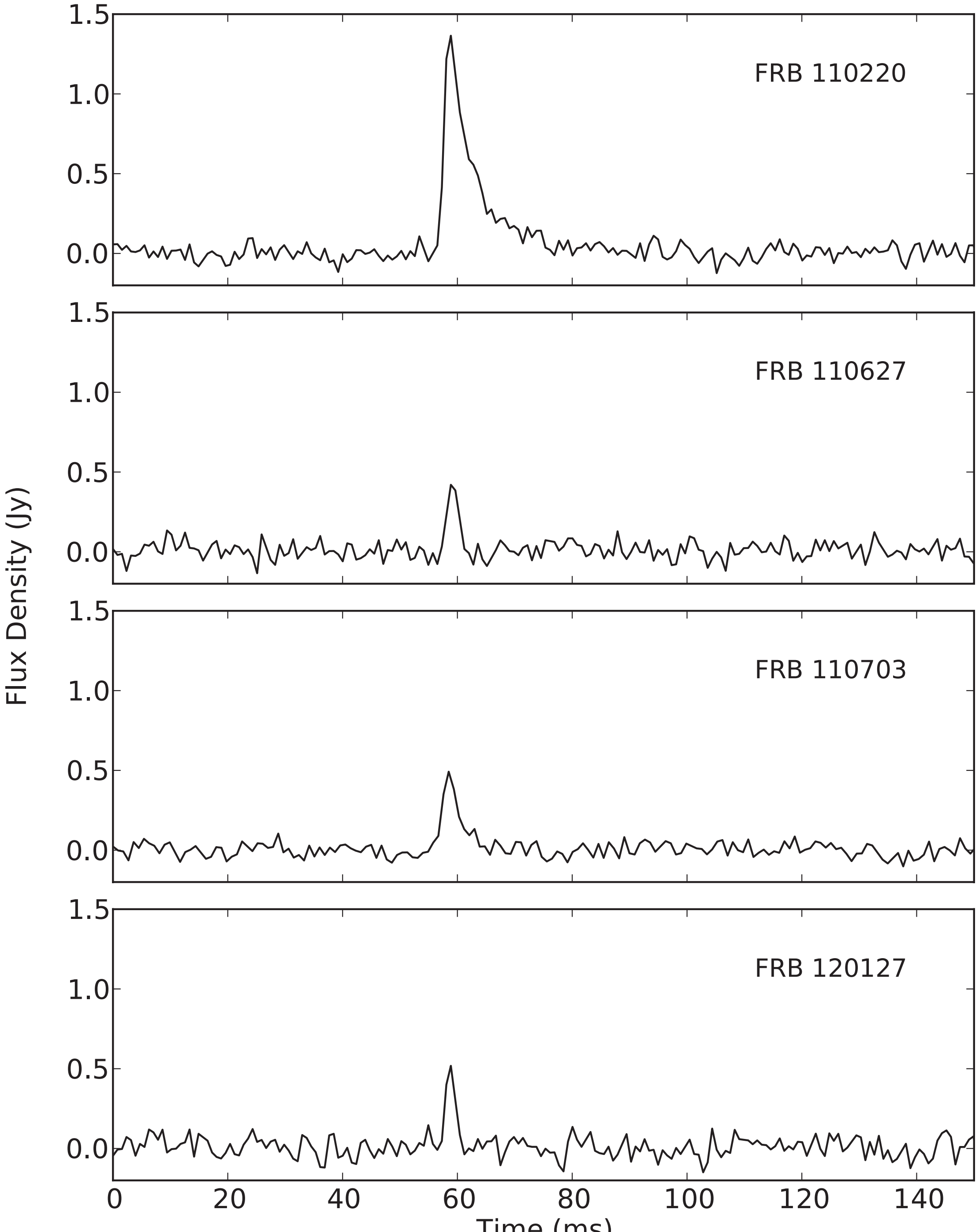


fast radio bursts

Thornton+ Science 13

see also Kulkarni+ arXiv:1402.4766

Parkes High Time Resolution Universe survey



S_ν~0.4-1.3 Jy @1.28-1.52 GHz

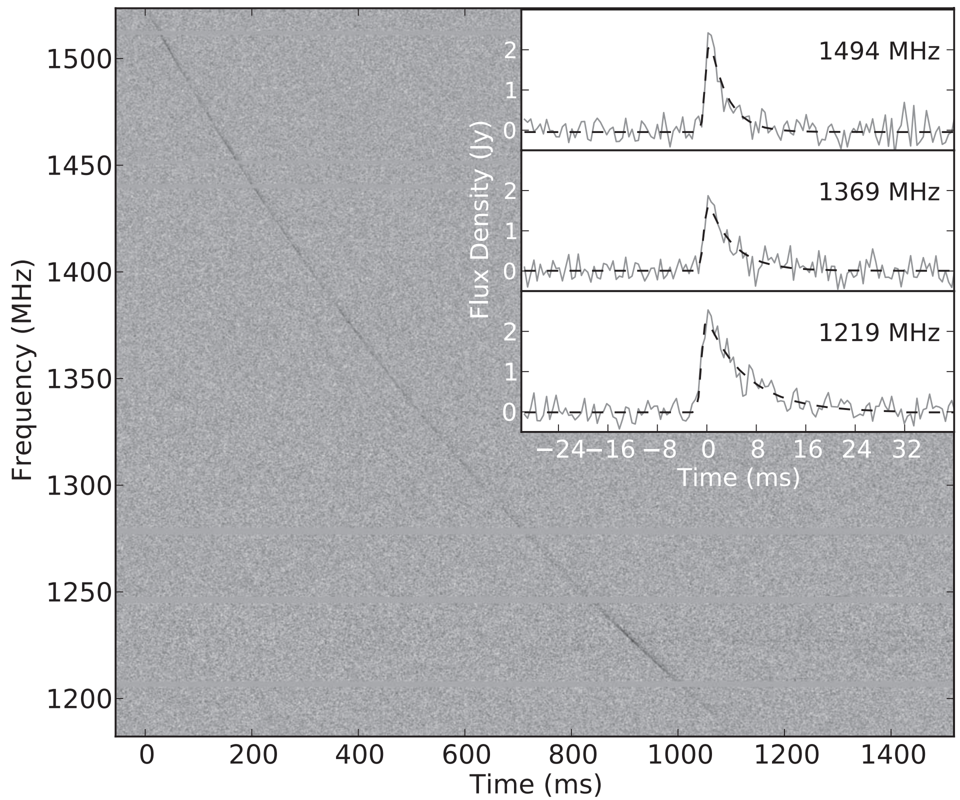
Δt~<5 ms

DM~550-1100 pc cm^{-3}

-> D~1.7-3.2 Gpc (z~0.45-0.96)

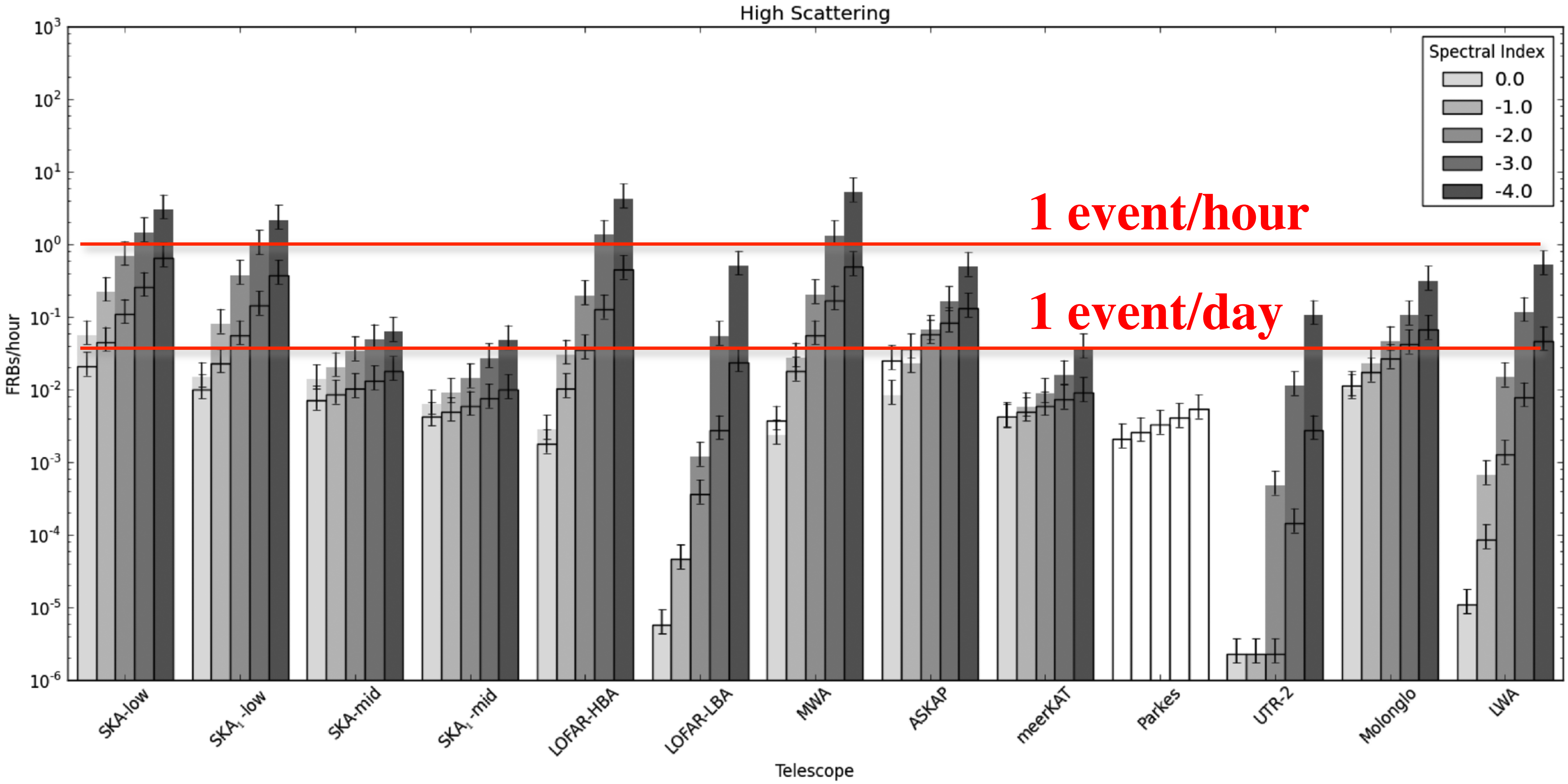
-> E~10^{37}-10^{39} erg

R_{FRB}~10^4 day^{-1}! ~$0.1R_{SN}$



fast radio bursts: future expectations

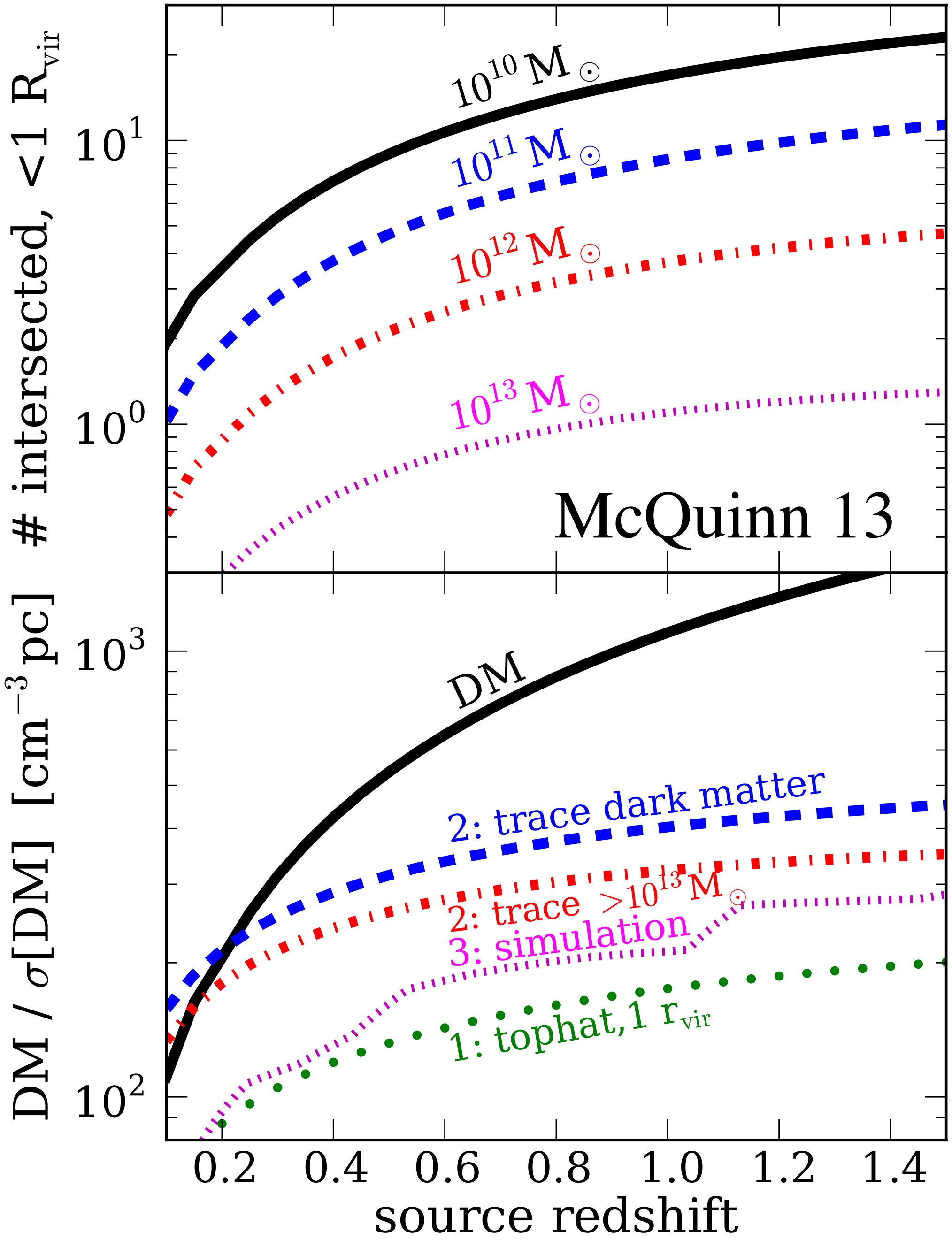
Hassall+13



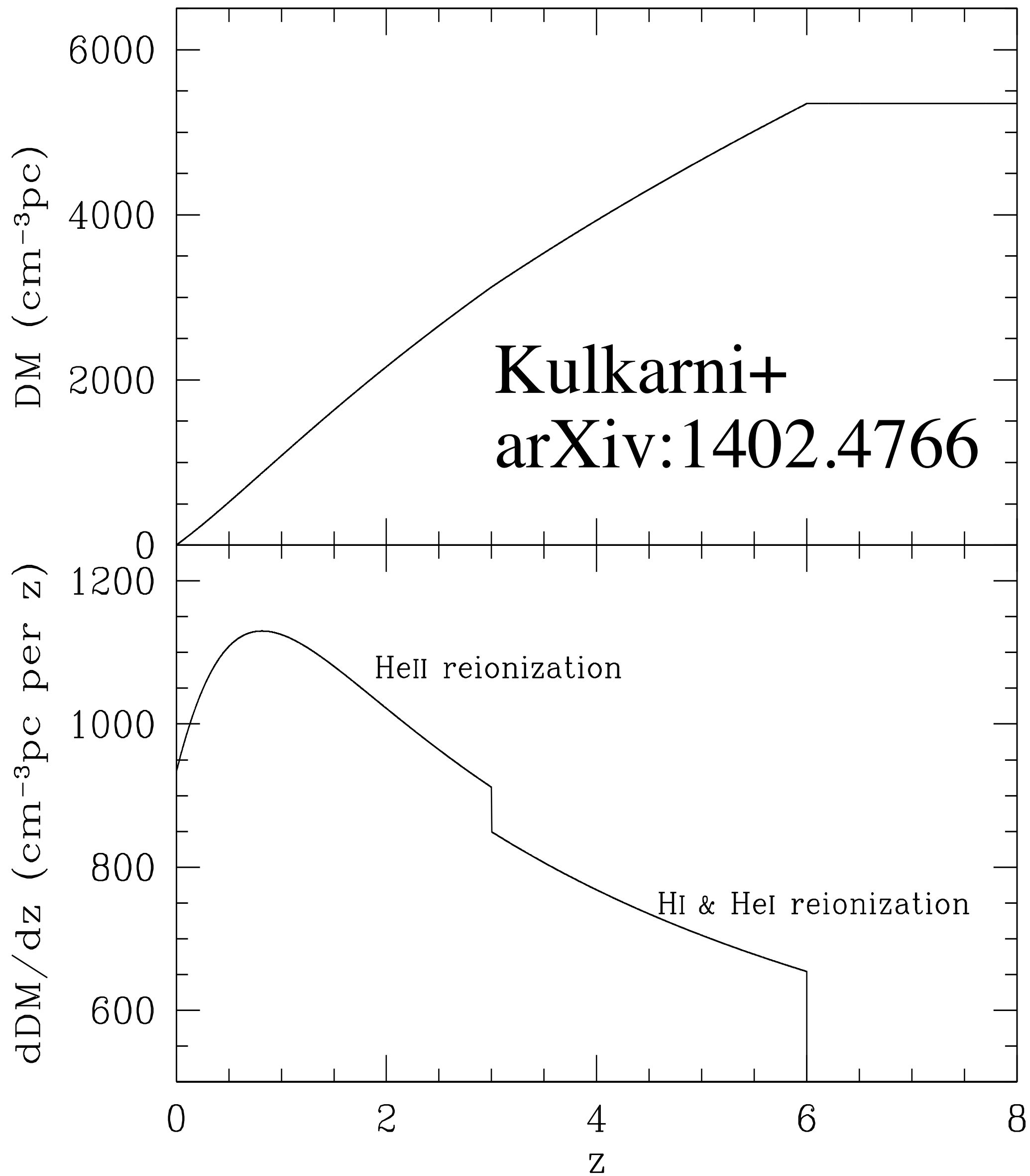
also Lorimer+ 13, Trott+ 13

fast radio bursts: potential cosmological probes

missing baryons (WHIM)



HeII reionization



BUT need redshift measurement!
21cm absorption?
GRB association?

まとめ

- 21cm forest: 21cm emissionと相補的な
  宇宙黎明期・再電離期・宇宙論のプローブ
  まだ研究の余地あり!

- 背景電波光源：quasar? Pop III GRB? first SMBH??
  不定性大きいがそれ自体おもしろい研究課題

- fast radio bursts: 正体不明の新種突発電波源
  redshiftが測定できるようになれば電離ガスの
  ユニークなプローブ