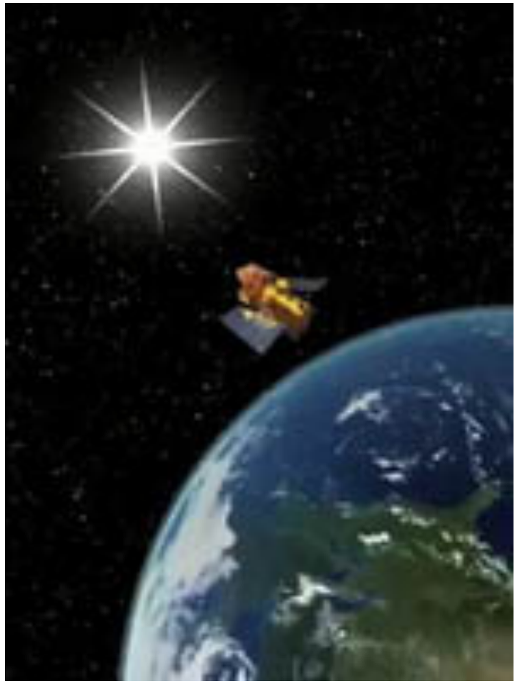
電波分散および21cm吸収線系に基づく観測的宇宙論

井上進（理研）
共同研究者の皆さん

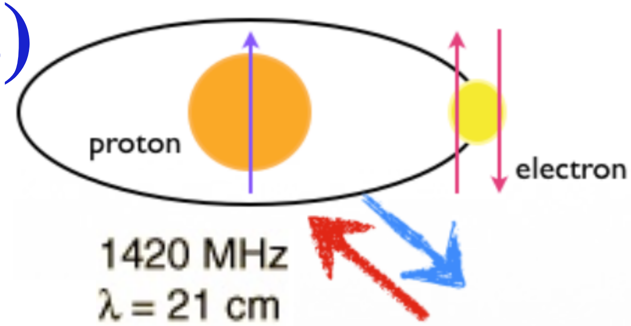


outline

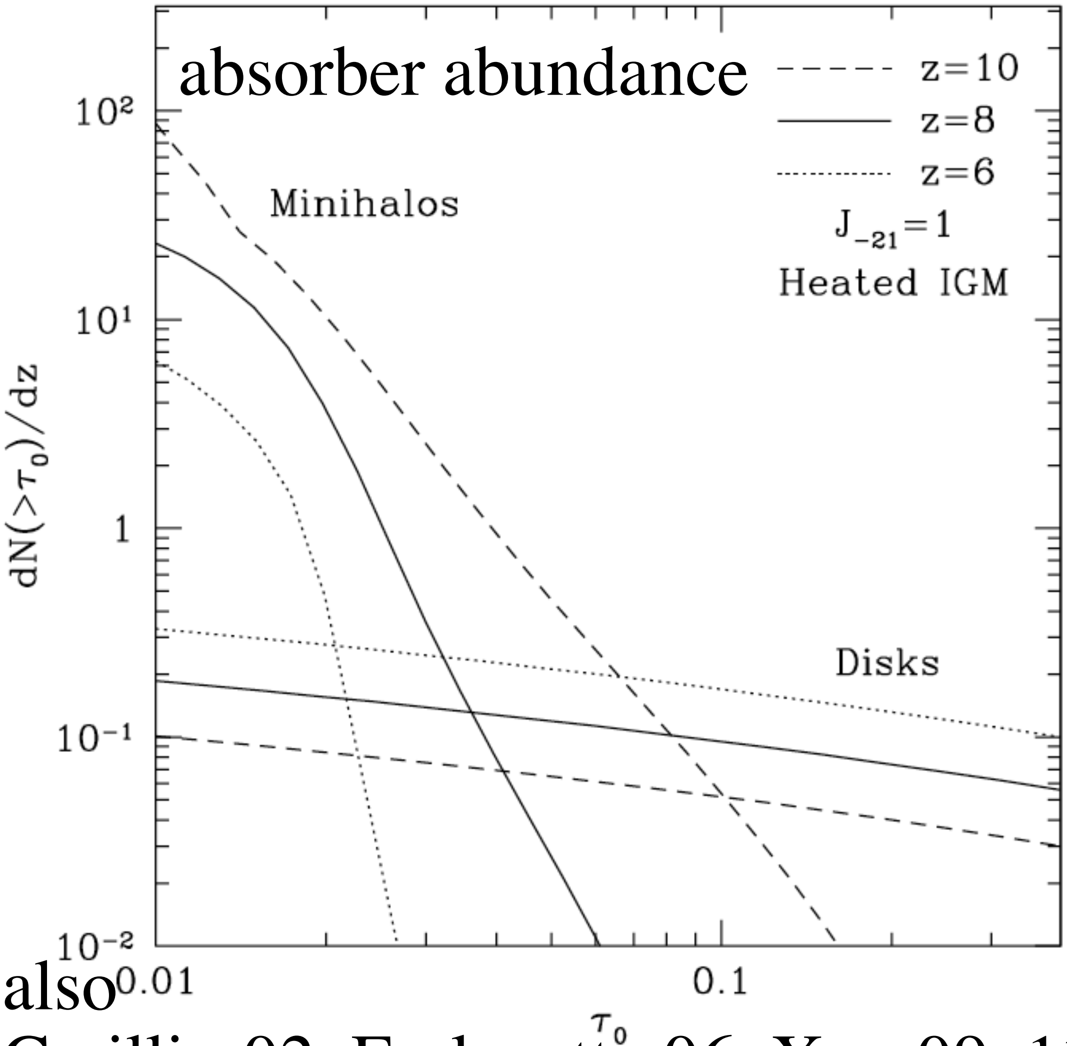
1. 21cm forest
2. high-z radio sources for 21cm forest studies
3. radio dispersion of FRBs and cosmic reionization
4. radio dispersion of FRBs
   and small-scale power spectrum

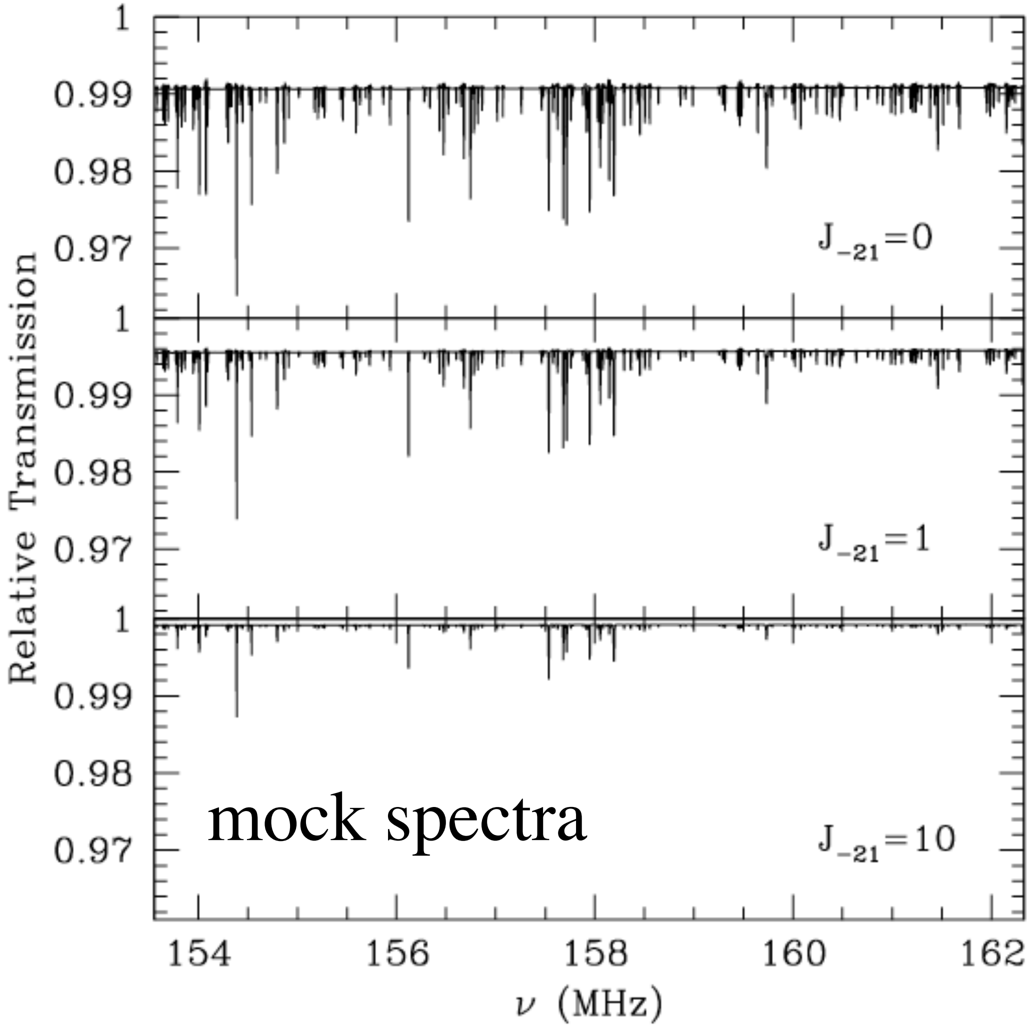
21cm forest (absorption line systems)

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



Furlanetto & Loeb 02

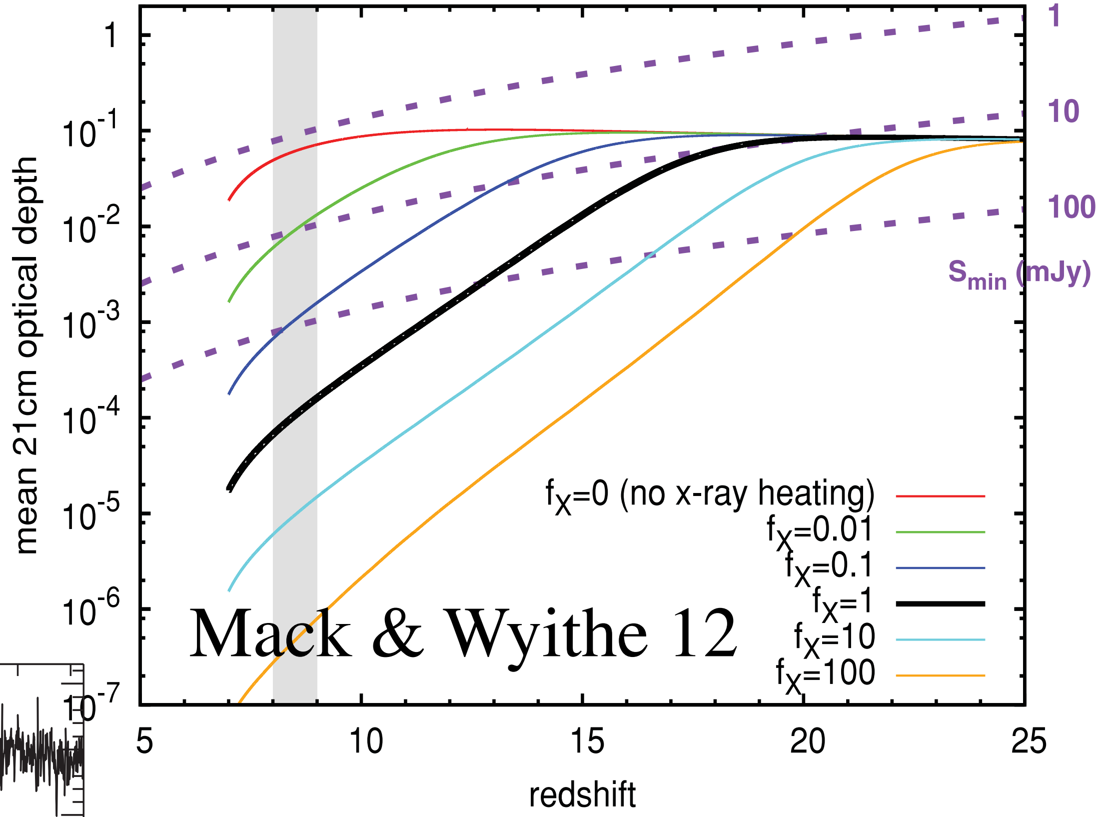


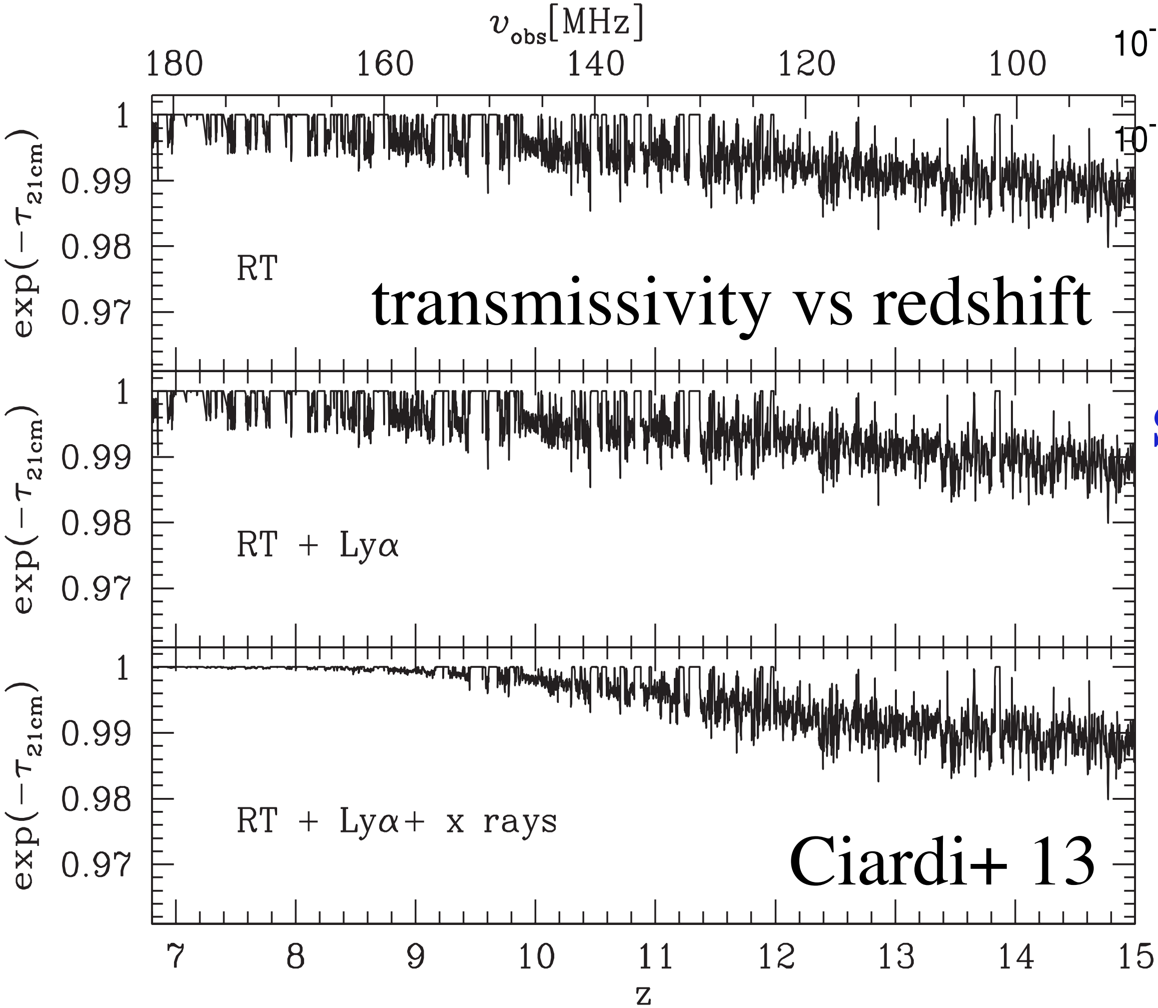


also
Carilli+ 02, Furlanetto 06, Xu+ 09, 11, Meiksin 11, Mack & Wyithe 12, Vasiliev+ 12, Ciardi+ 13,15, Ewall-Wice+ 14, Semelin 15…

21cm absorption: X-ray heating during reionization

assuming
Cyg-A like background source





small-scale power spectrum

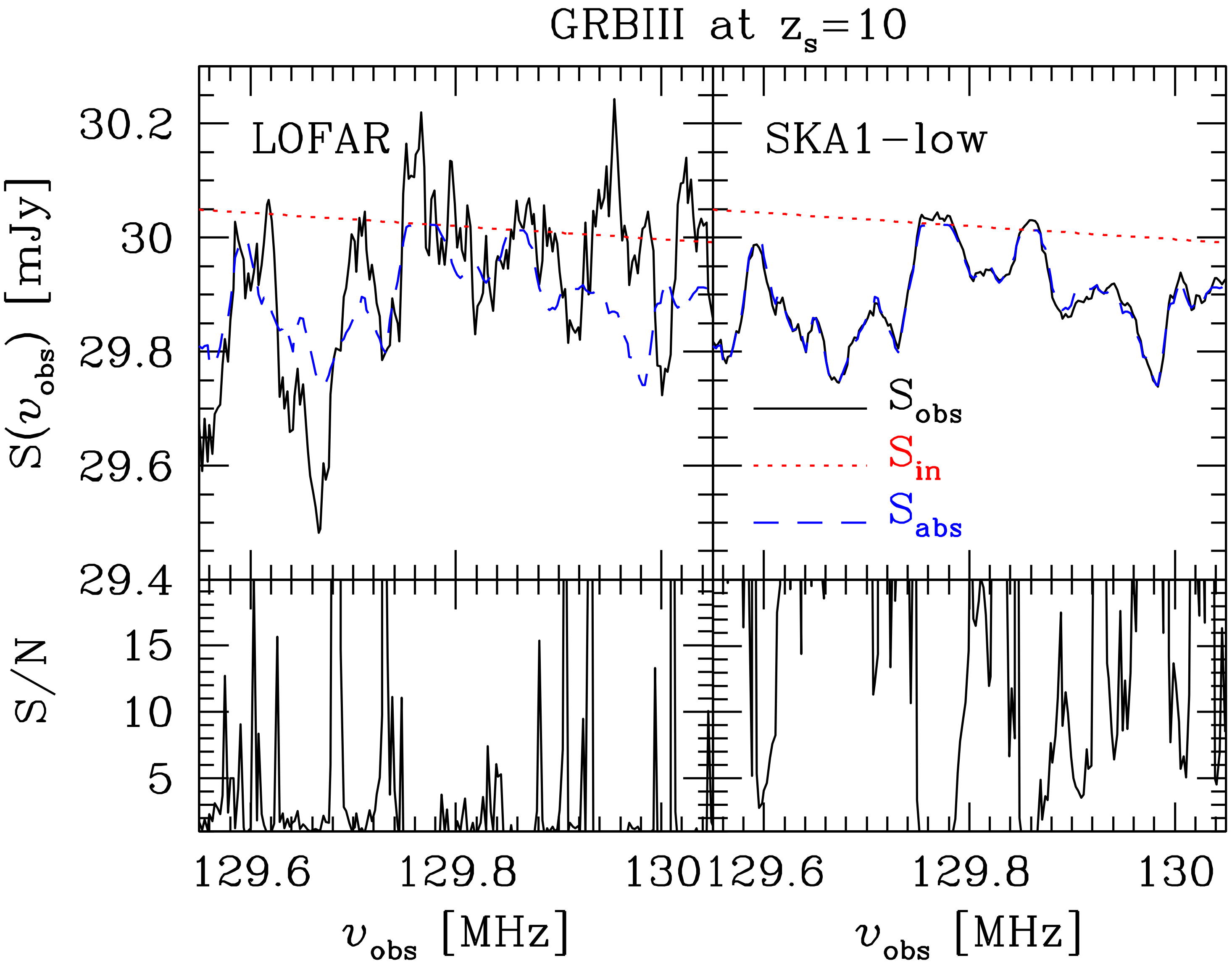
- warm dark matter
- neutrino mass
- running spectral index

…

Shimabukuro, Ichiki, SI, Yokoyama 14

21cm forest in GRBs

Ciardi, SI+ 15



assuming Pop III GRB
S_{in}=30mJy at $z=z_s$

marginally detectable by LOFAR
detection feasible by SKA1 IF Pop III GRB energetic

statistical detection of 21cm absorption in stacked spectra of high-z sources

Koopmans, Ciardi, SI,Mellema, in prep.

SKA-low, 1000 hr per 5MHz bandwidth
detectable for k~<10 cMpc^{-1} at z~7-11
50 sources x 10mJy, 500 sources x 3mJy

optical depth power spectra of sources at z=9

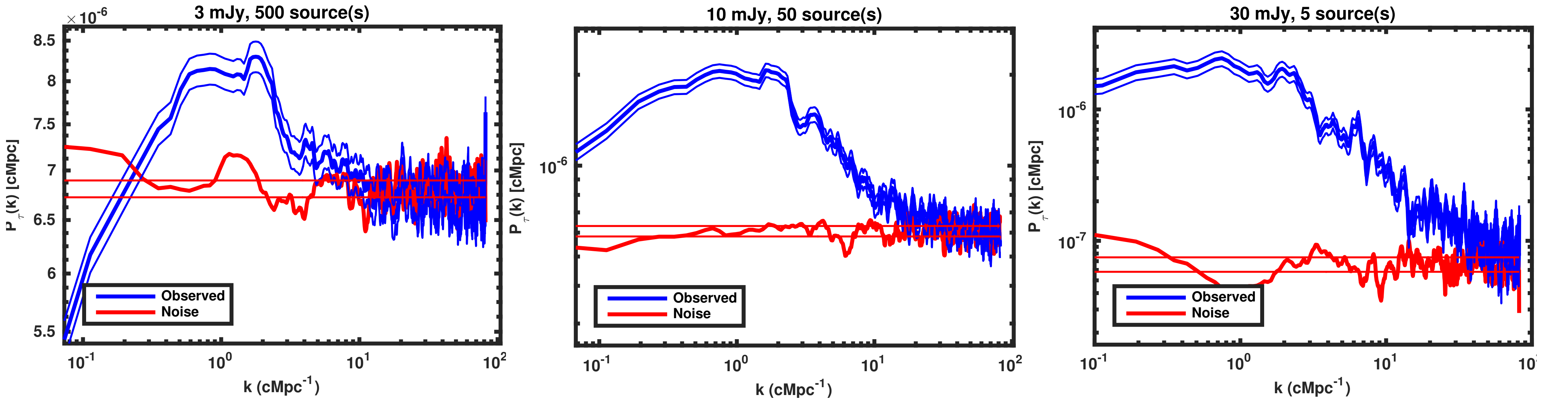


Figure 1. Shown are the stacked and renormalized power-spectra at $z = 9$ as function of source flux-density and number of sources in 1000 hrs of integration for a bandwidth of 5 MHz and 2kHz spectral channels. From top to bottom the source flux increases, but the number of sources decreases. The left panels show the source power-spectra (blue) and calibrator noise power spectra (red), and the constant fit to the latter (the red horizontal lines show the ± 1–σ range), whereas the right panels show the source power-spectra after subtracting the best-fit constant noise power-spectrum. Over-plotted in cyan are the input power-spectra (thick line) and the sample variance (thin cyan lines) based on the input power spectra spectra and the thermal noise power spectra.

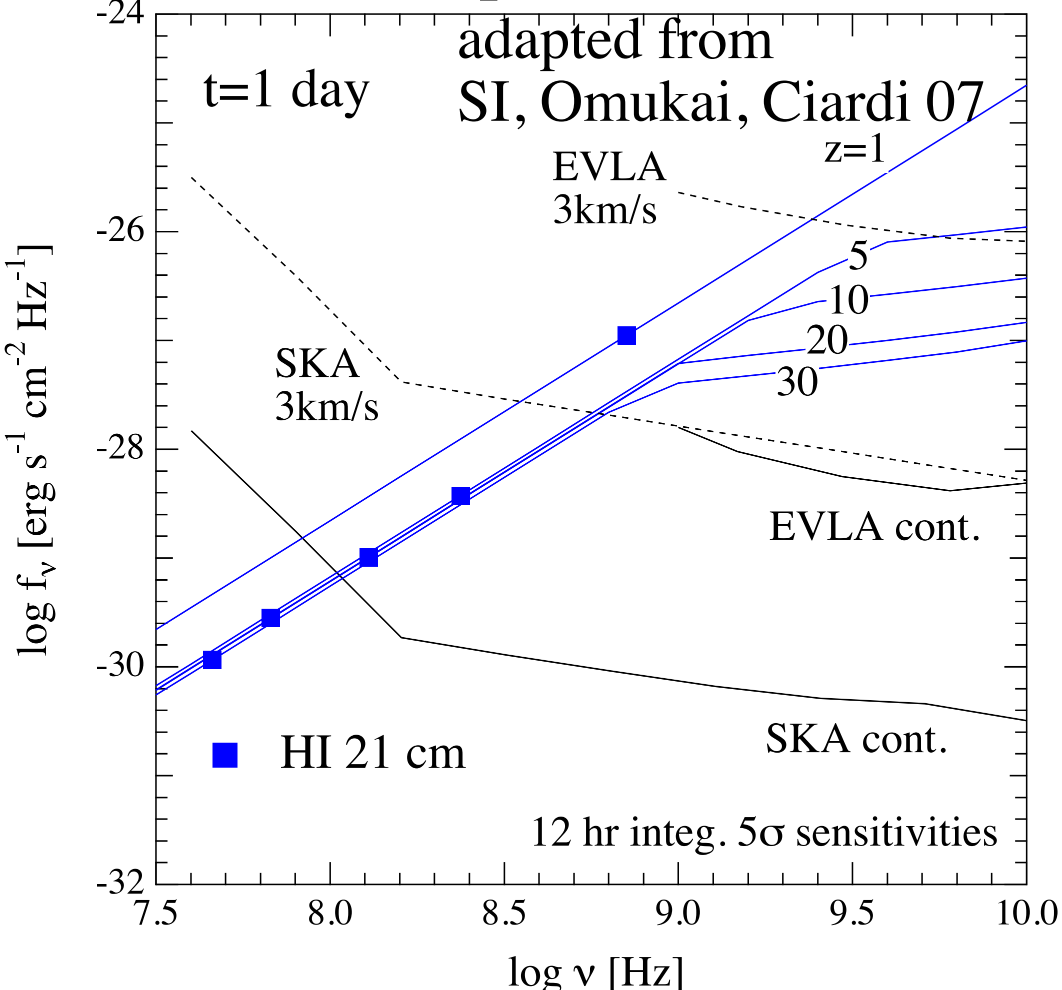
background radio source for 21cm forest

required minimum flux at 1.4 GHz rest frame

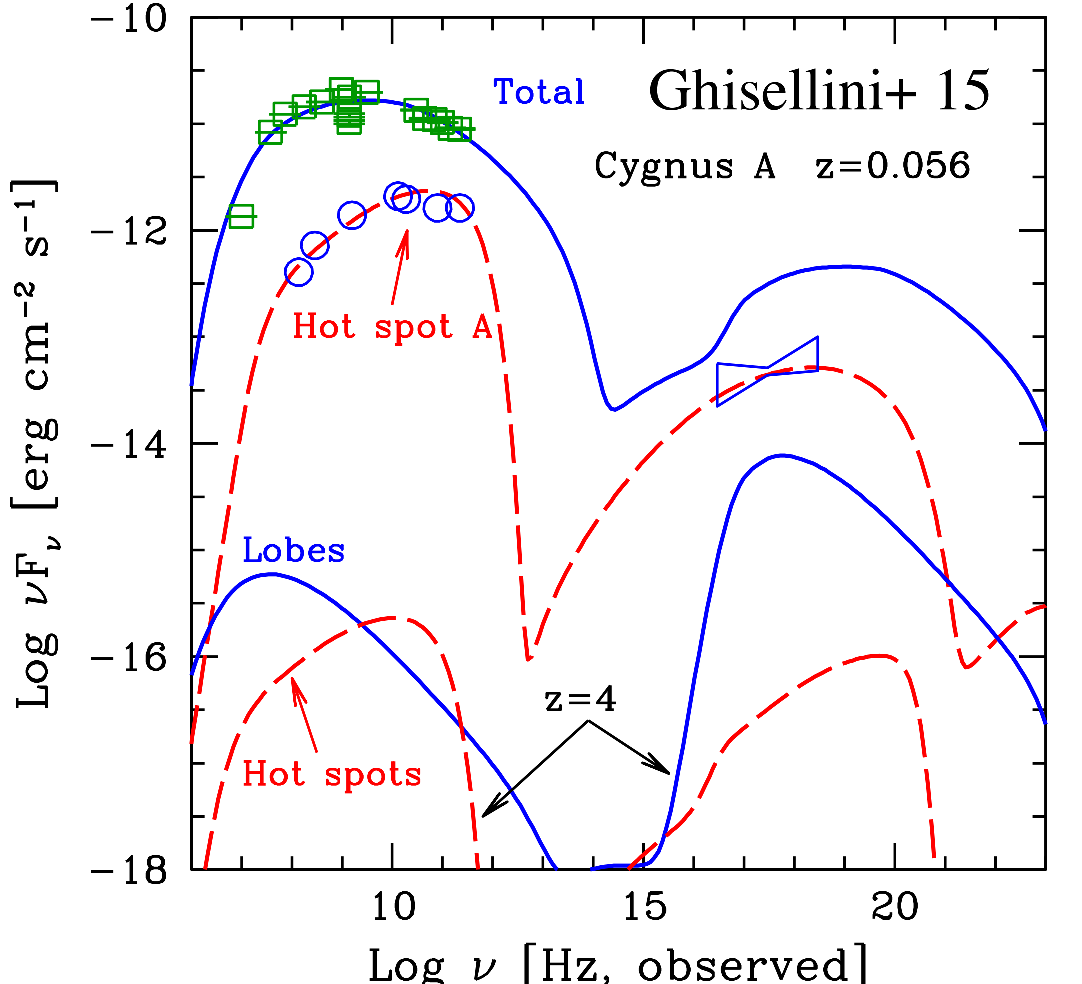
$$S_{\min} = 10.3\mathrm{mJy} \left(\frac{S/N}{5}\right) \left(\frac{0.01}{e^{-\tau_{\mathrm{IGM}}} - e^{-\tau}}\right) \left(\frac{5\mathrm{kHz}}{\Delta\nu}\right)^{1/2} \underbrace{\left(\frac{1000\,\mathrm{m}^2\mathrm{K}^{-1}}{A/T_{\mathrm{sys}}}\right)}_{\text{SKA1 (x4 for SKA2)}} \left(\frac{1000\,\mathrm{hr}}{t_{\mathrm{int}}}\right)^{1/2}$$

Ciardi, SI, Mack, Xu, Bernardi 15

GRBs: too compact, self-absorbed

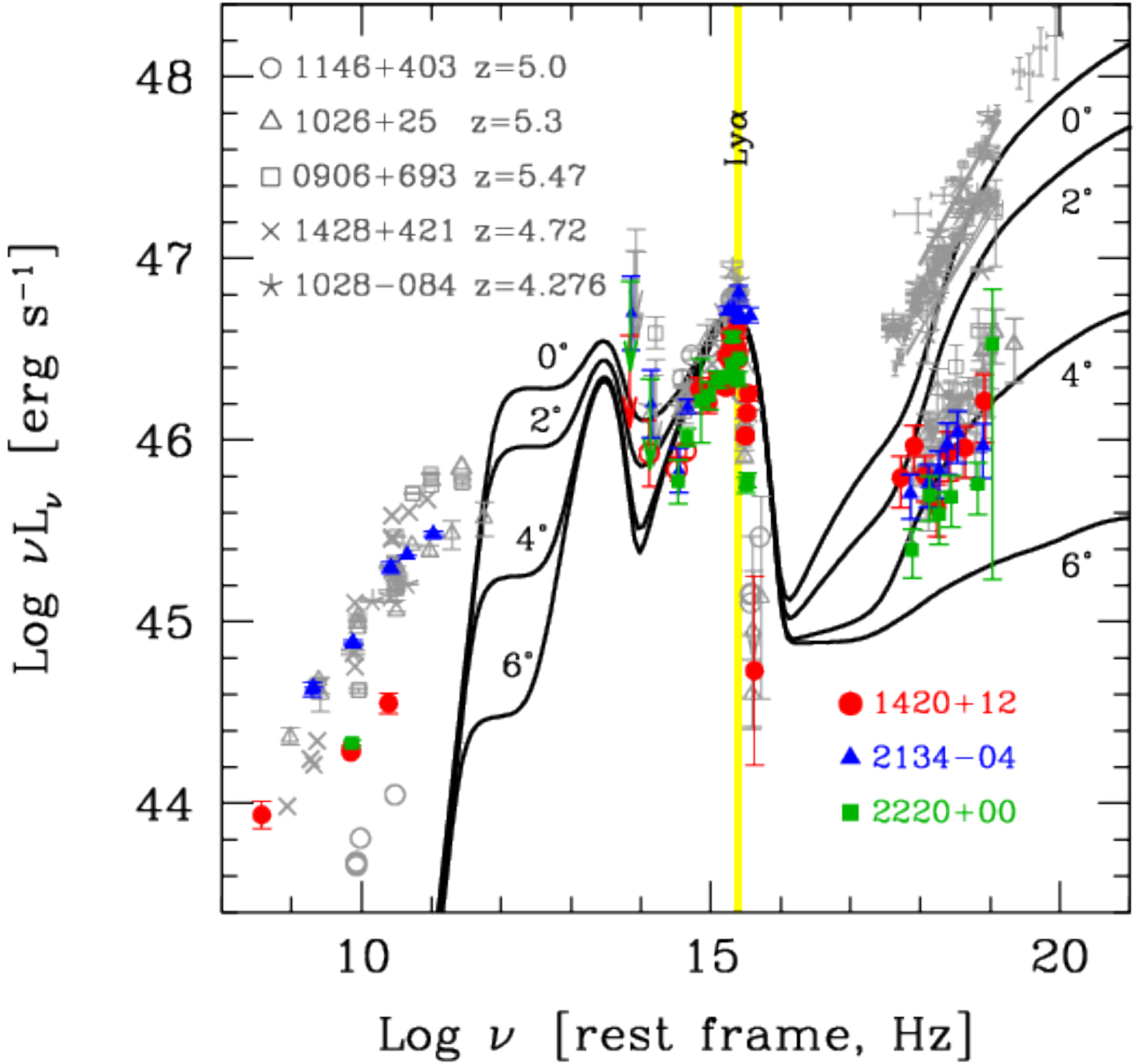


RGs: too extended, CMB-cooled



high-z blazars

Sbarrato+ 15

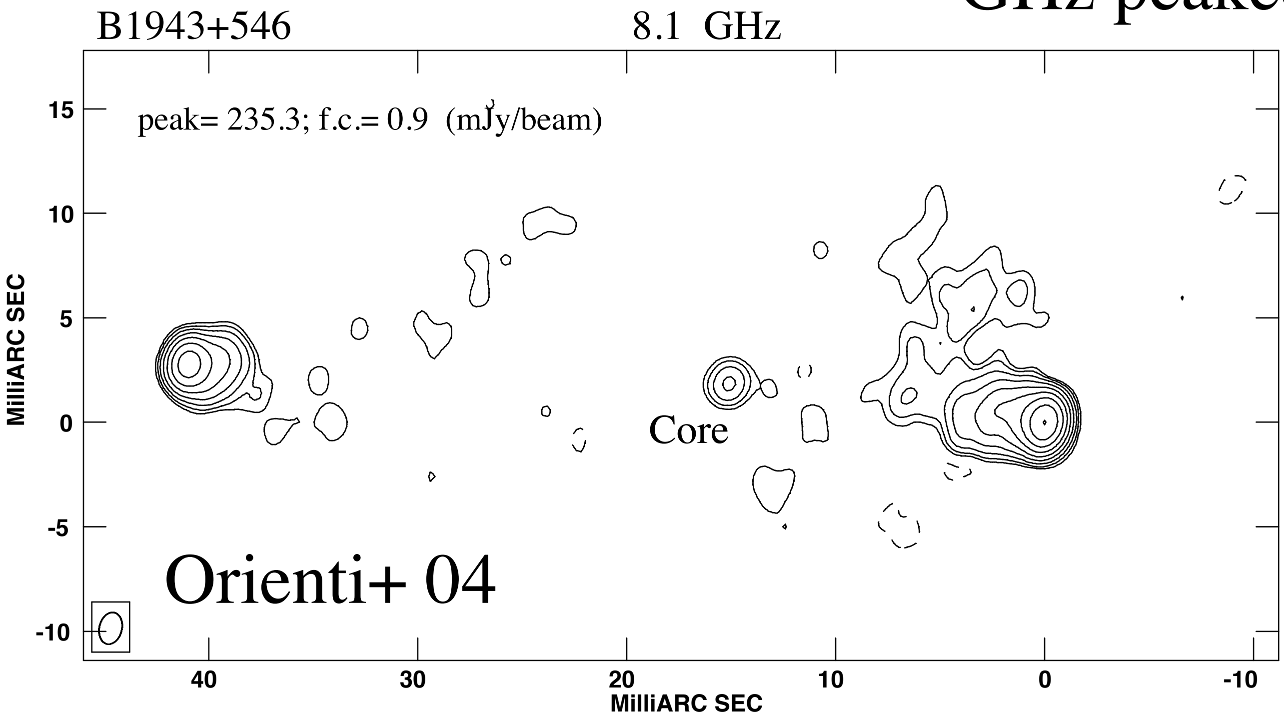


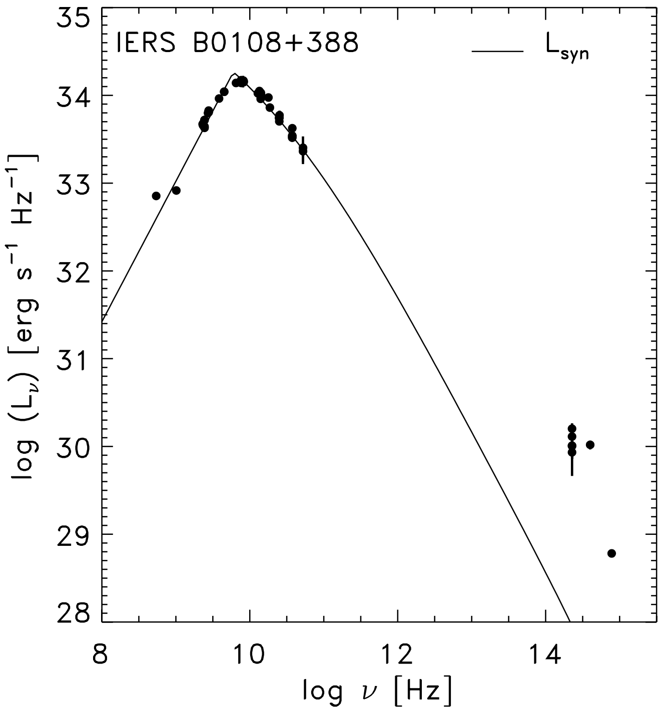
expected number at high z?

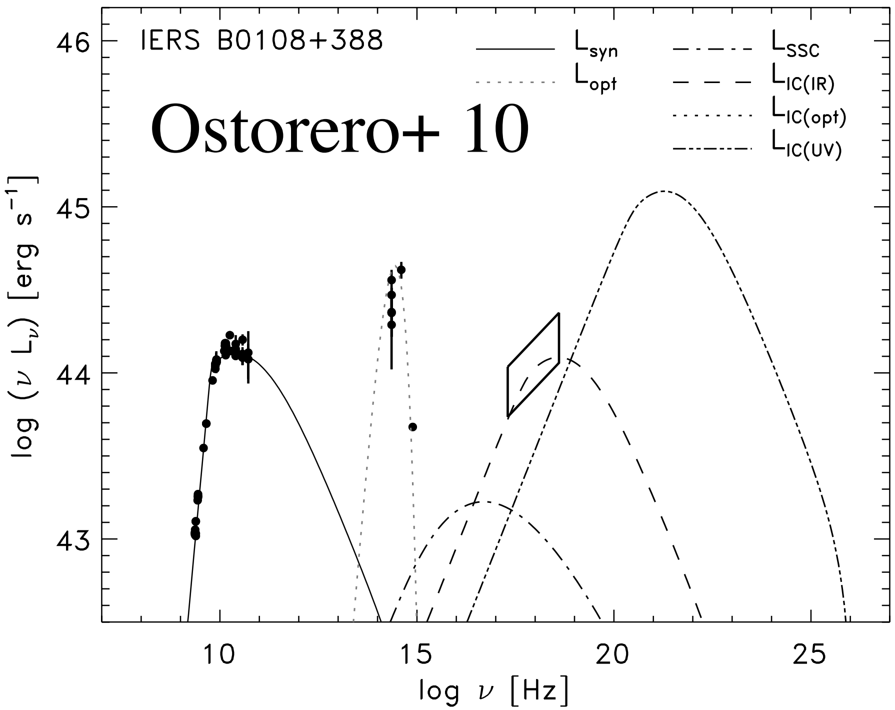
Y. Inoue, SI et al. in prep.

young radio galaxies

compact steep spectrum (CSS) sources
GHz peaked spectrum (GPS) sources



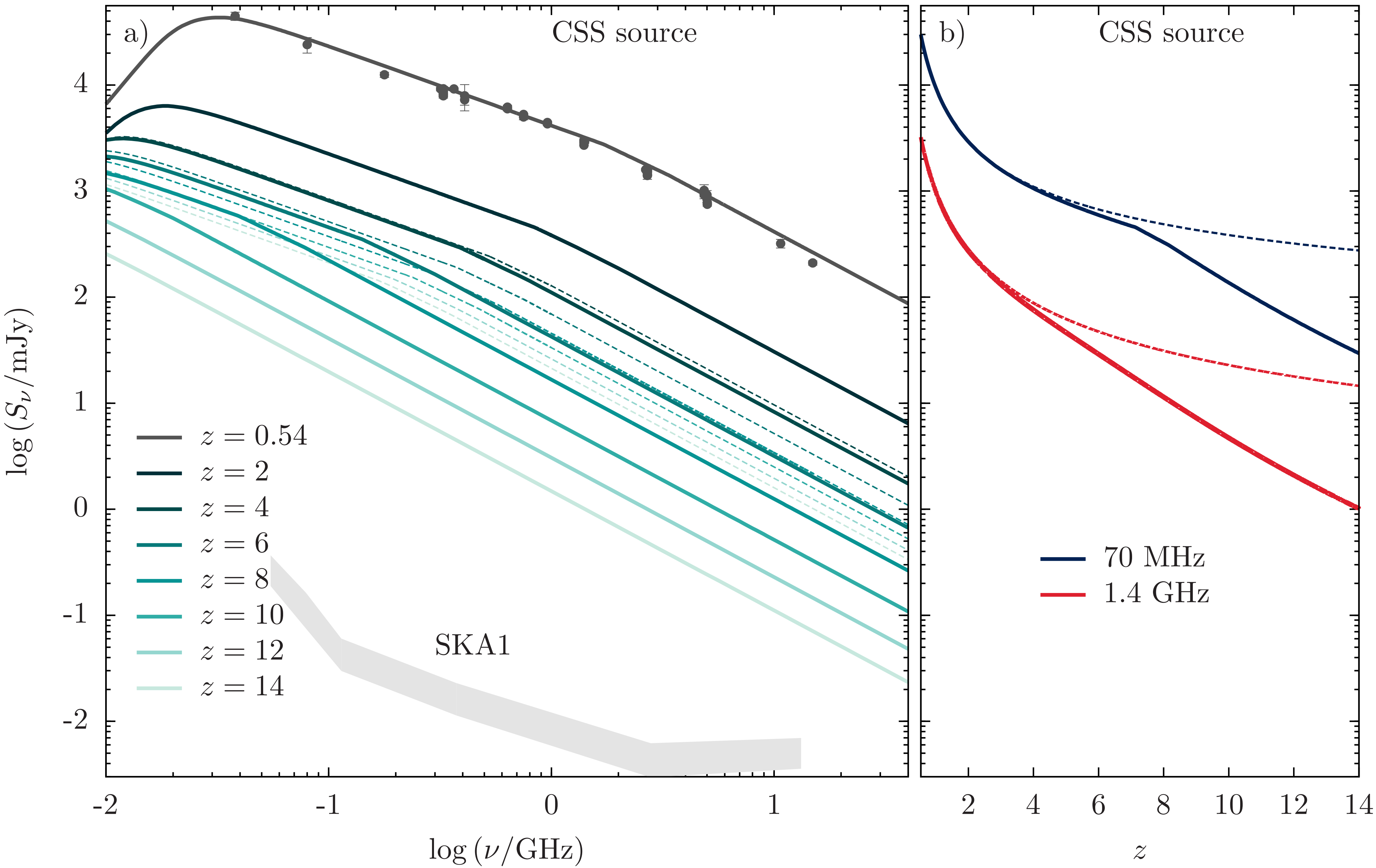




young radio galaxies at high redshift

Afonso+ 15

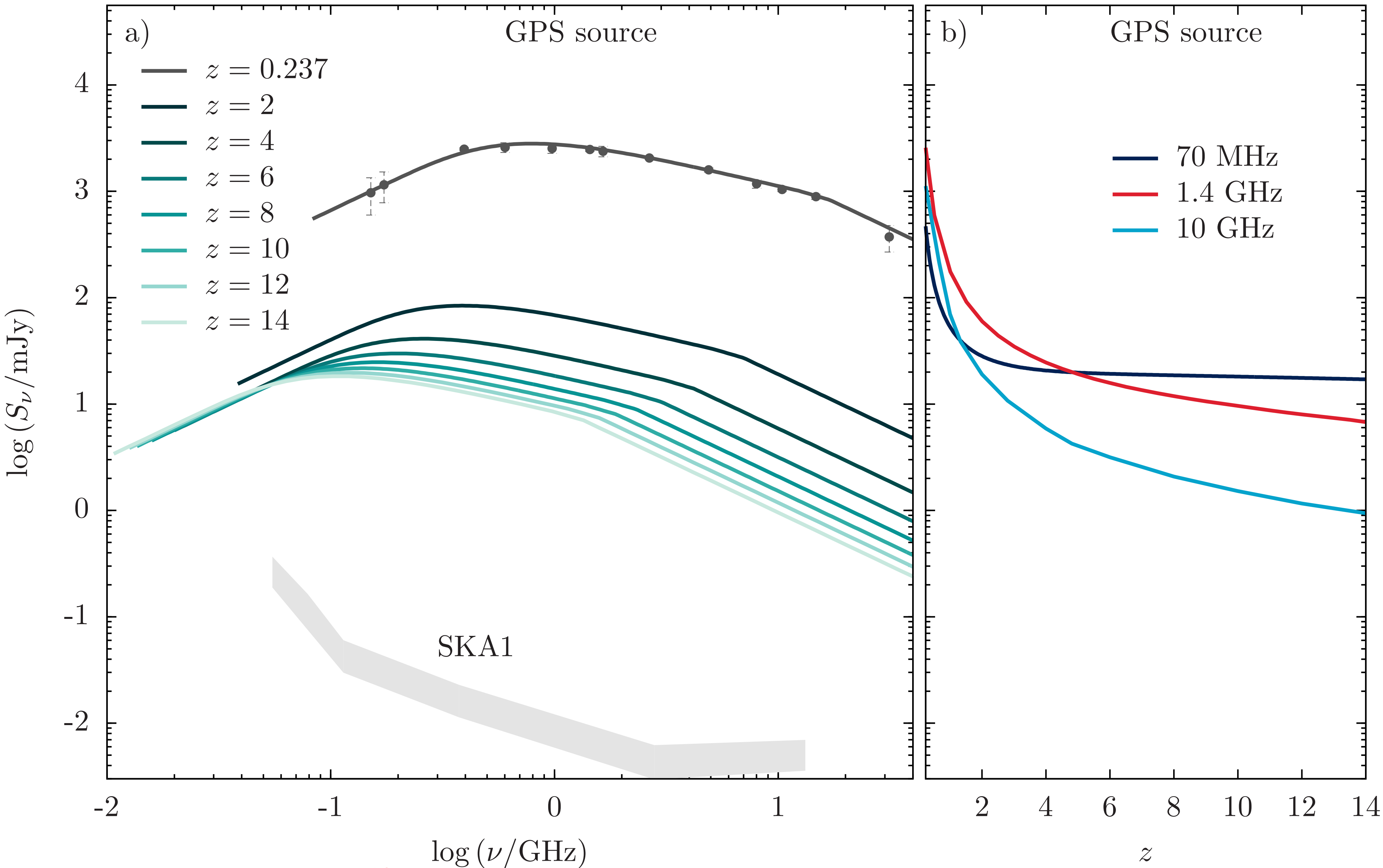
compact steep spectrum (CSS) sources



young radio galaxies at high redshift

Afonso+ 15

GHz peaked spectrum (GPS) sources



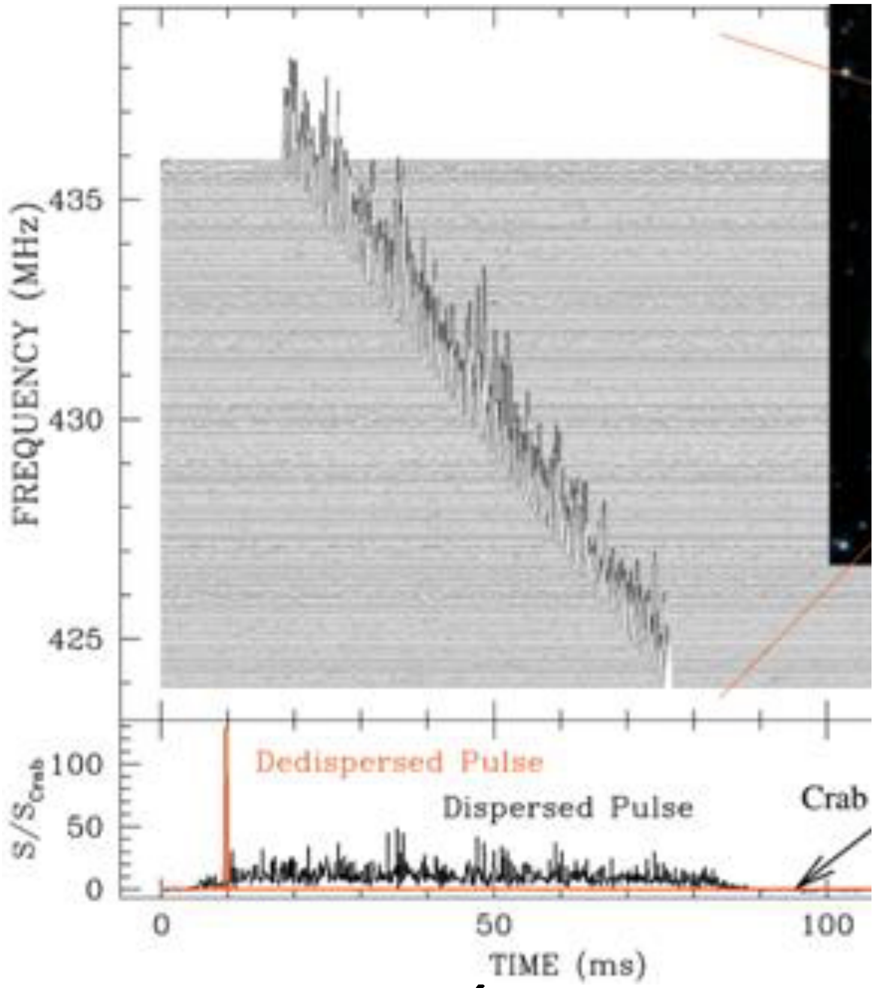
Don't despair! Some sources are likely there! Identification?

fast radio bursts (FRBs) new class of radio transients

- ms duration
- high dispersion measure -> most likely cosmological
  inferred z~0.2-1.3 (up to z~2.1~3.1!)
  one case clearly confirmed (FRB 121102, z=0.193)
- very frequent: ~<10000/sky/day
- extreme brightness temp.-> coherent
- multiple subclasses?
  1 repeating, rest non-repeating (so far)
- origin mysterious!
  no. of models >> no. of known FRBs
- new cosmological probe of ionized baryons

fast radio bursts (FRBs) and dispersion measure

Galactic radio pulsars



$$\Delta t = \frac{e^2}{2\pi m_e c\, \nu^2} \underbrace{\int dl\; n_e(l)}$$

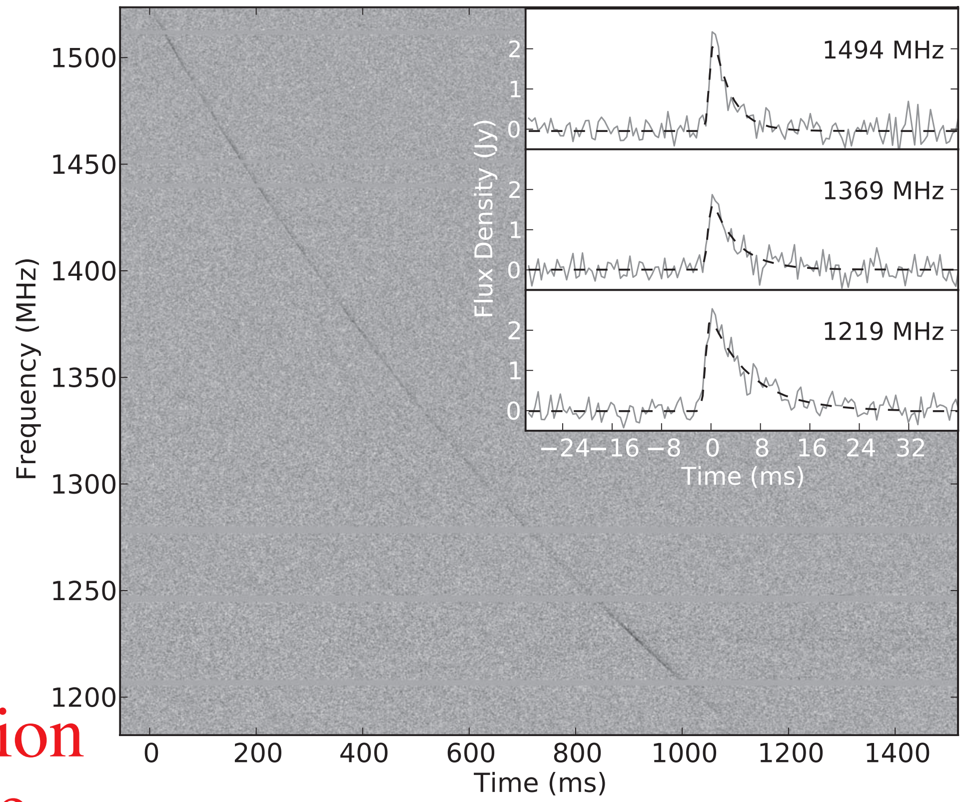
~<200 pc cm^{-3}

known distance -> probe ionized ISM

model ionized ISM dist.

-> constrain distance

FRBs (likely extragalactic)



dispersion measure

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

~400-1600 pc cm^{-3}

model ionized IGM dist.

-> constrain distance

measure distance ->

probe ionized IGM

c.f. SI04, Ioka 03

FRBs: new class of transients

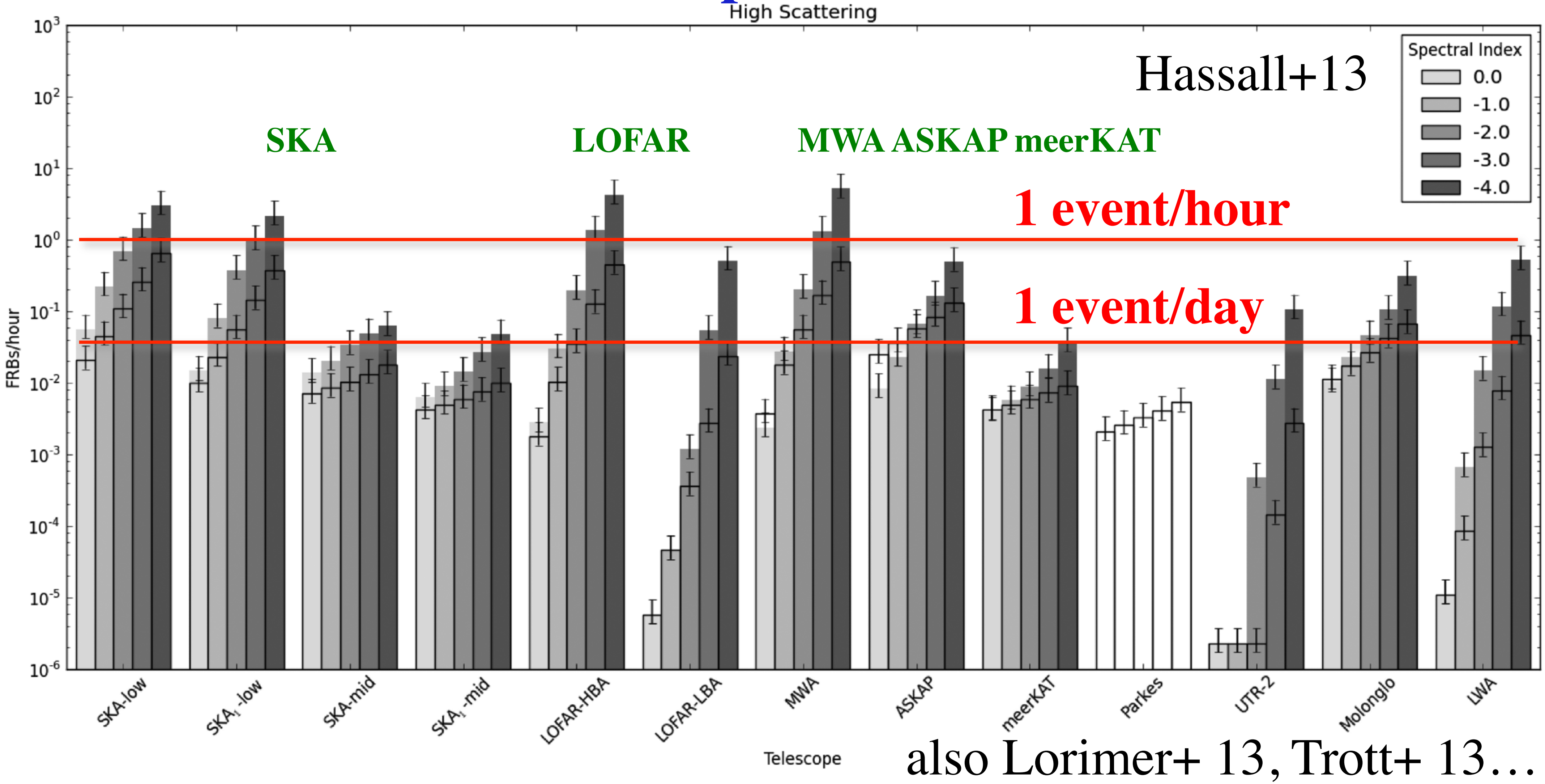
Thornton+ Science 13

	FRB 110220	FRB 110627	FRB 110703	FRB 120127
Beam right ascension (J2000)	$22^h\ 34^m$	$21^h\ 03^m$	$23^h\ 30^m$	$23^h\ 15^m$
Beam declination (J2000)	−12° 24′	−44° 44′	−02° 52′	−18° 25′
Galactic latitude, b (°)	−54.7	−41.7	−59.0	−66.2
Galactic longitude, l (°)	+50.8	+355.8	+81.0	+49.2
UTC (dd/mm/yyyy hh:mm:ss.sss)	20/02/2011 01:55:48.957	27/06/2011 21:33:17.474	03/07/2011 18:59:40.591	27/01/2012 08:11:21.723
DM (cm^{-3} pc)	944.38 ± 0.05	723.0 ± 0.3	1103.6 ± 0.7	553.3 ± 0.3
DM_E (cm^{-3} pc)	910	677	1072	521
Redshift, z (DM_{Host} = 100 cm^{-3} pc)	0.81	0.61	0.96	0.45
Co-moving distance, D (Gpc) at z	2.8	2.2	3.2	1.7
Dispersion index, α	−2.003 ± 0.006	–	−2.000 ± 0.006	–
Scattering index, β	−4.0 ± 0.4	–	–	–
Observed width at 1.3 GHz, W (ms)	5.6 ± 0.1	<1.4	<4.3	<1.1
SNR	49	11	16	11
Minimum peak flux density S_ν(Jy)	1.3	0.4	0.5	0.5
Fluence at 1.3 GHz, F (Jy ms)	8.0	0.7	1.8	0.6
$S_\nu D^2$ (× 10^{12} Jy kpc^2)	10.2	1.9	5.1	1.4
Energy released, E (J)	$\sim10^{39}$	$\sim10^{37}$	$\sim10^{38}$	$\sim10^{37}$

DM measured to <0.1% accuracy

main uncertainty: host galaxy contribution

fast radio bursts: future expectations



also Lorimer+ 13, Trott+ 13…

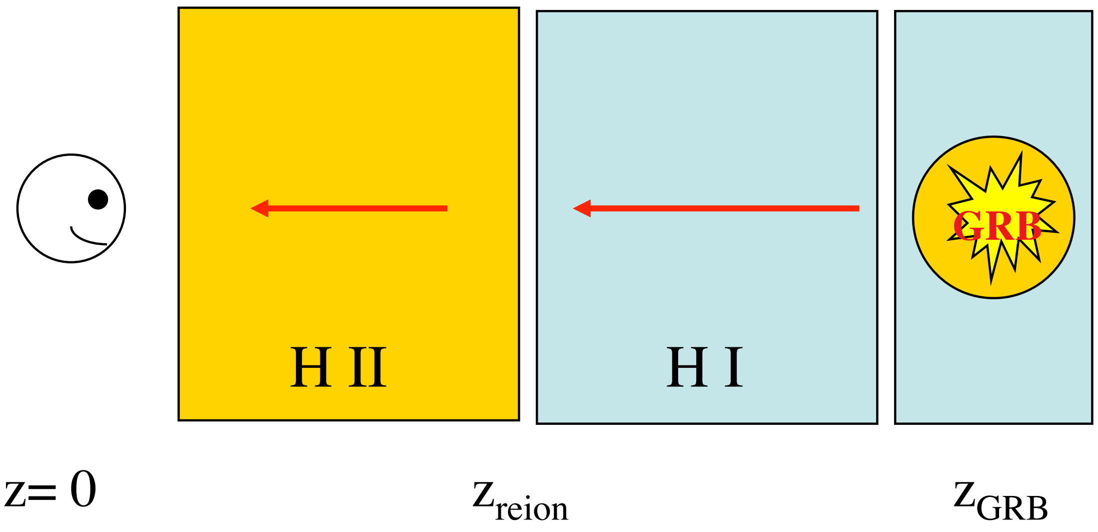
large sample of IGM dispersion measurements possible

need independent redshift for cosmological use

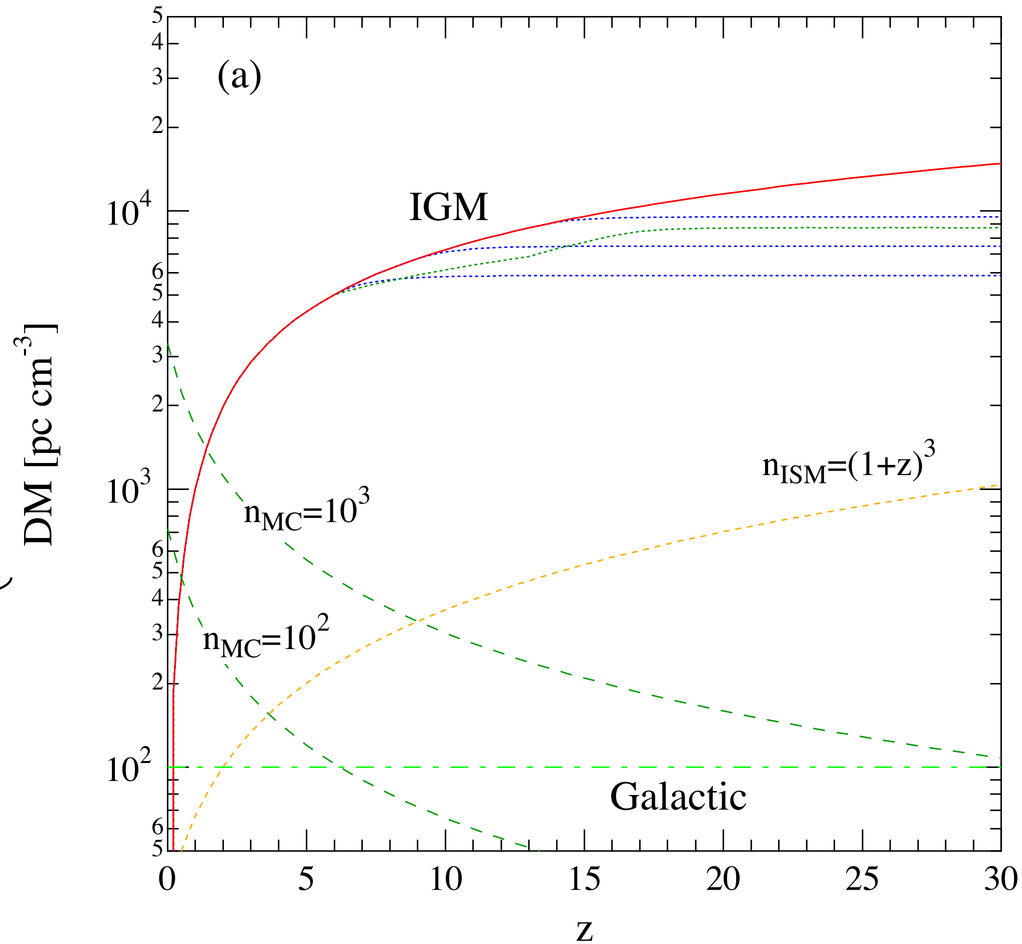
1. arcsec localization -> host galaxy ID + z measurement
2. 21cm absorption by host galaxy

Macquart+ 15, Margalit+ 15

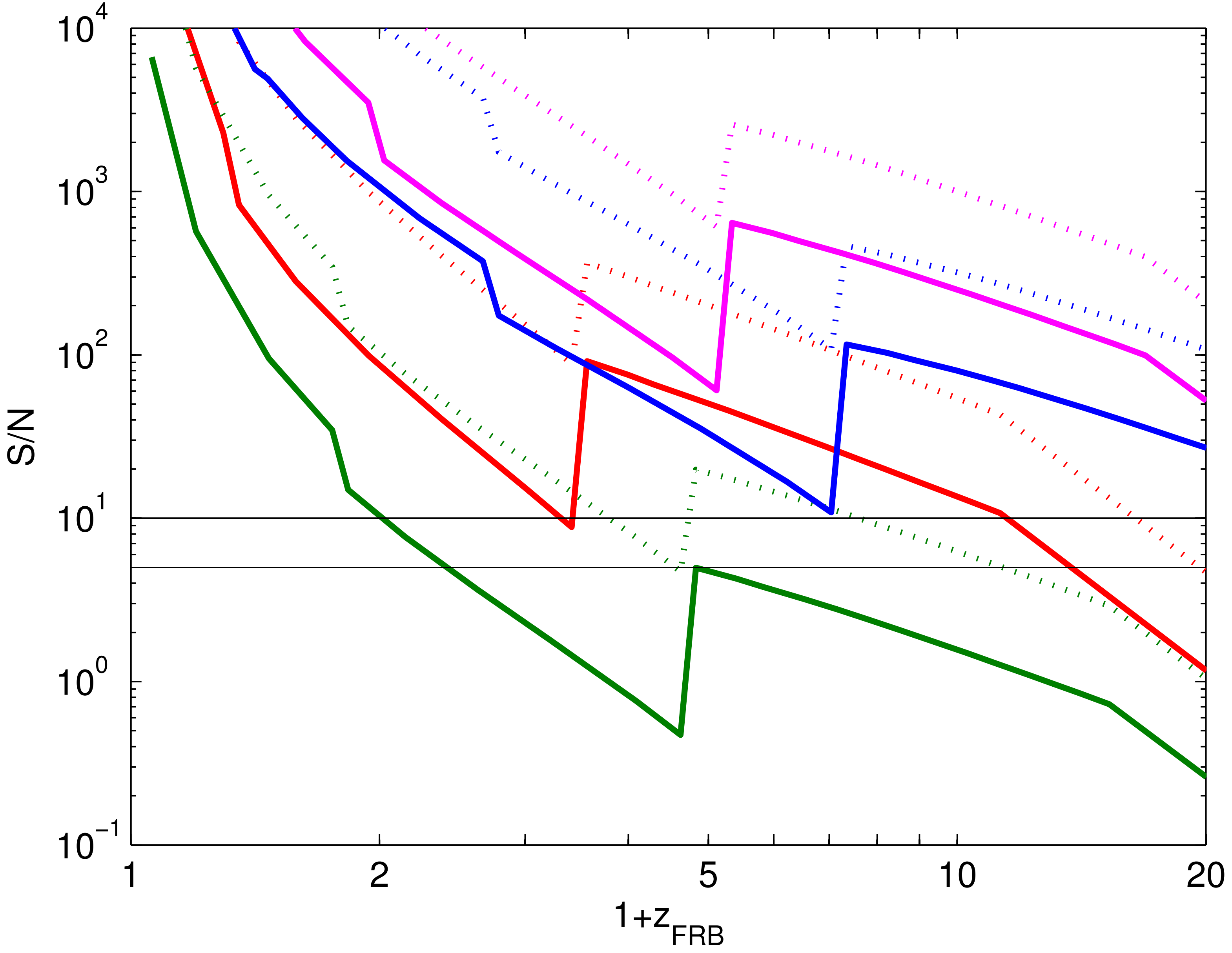
probing ionized IGM with radio dispersion **SI 04** Ioka 03



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

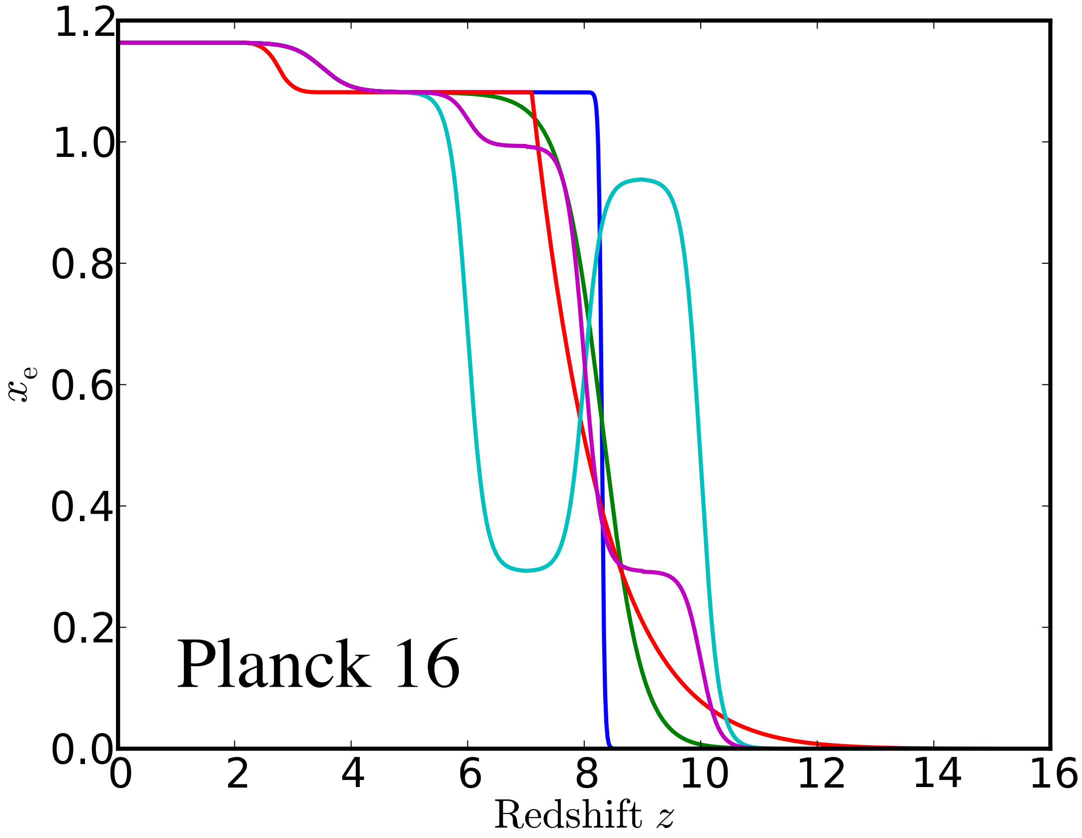


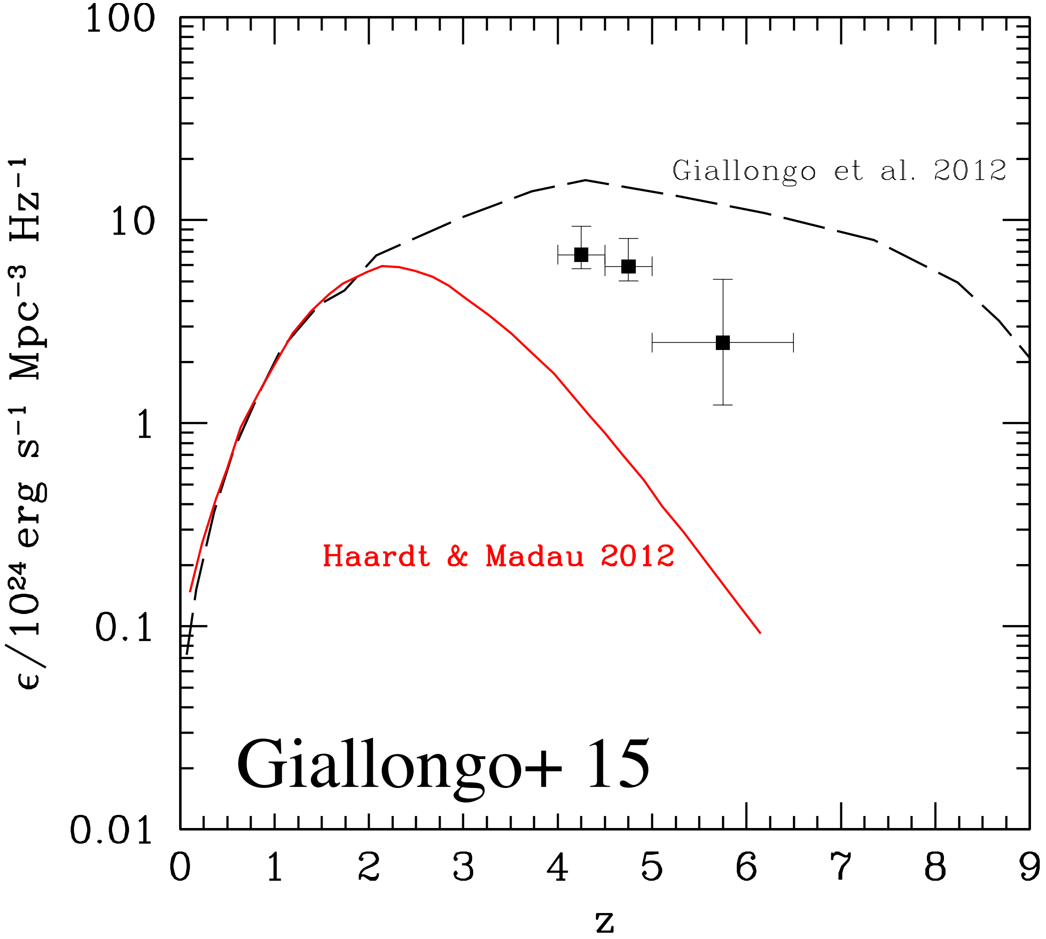
SKA detectability of high-z FRBs (IF they exist)



Fialkov & Loeb 16

revival of quasar dominant reionization?

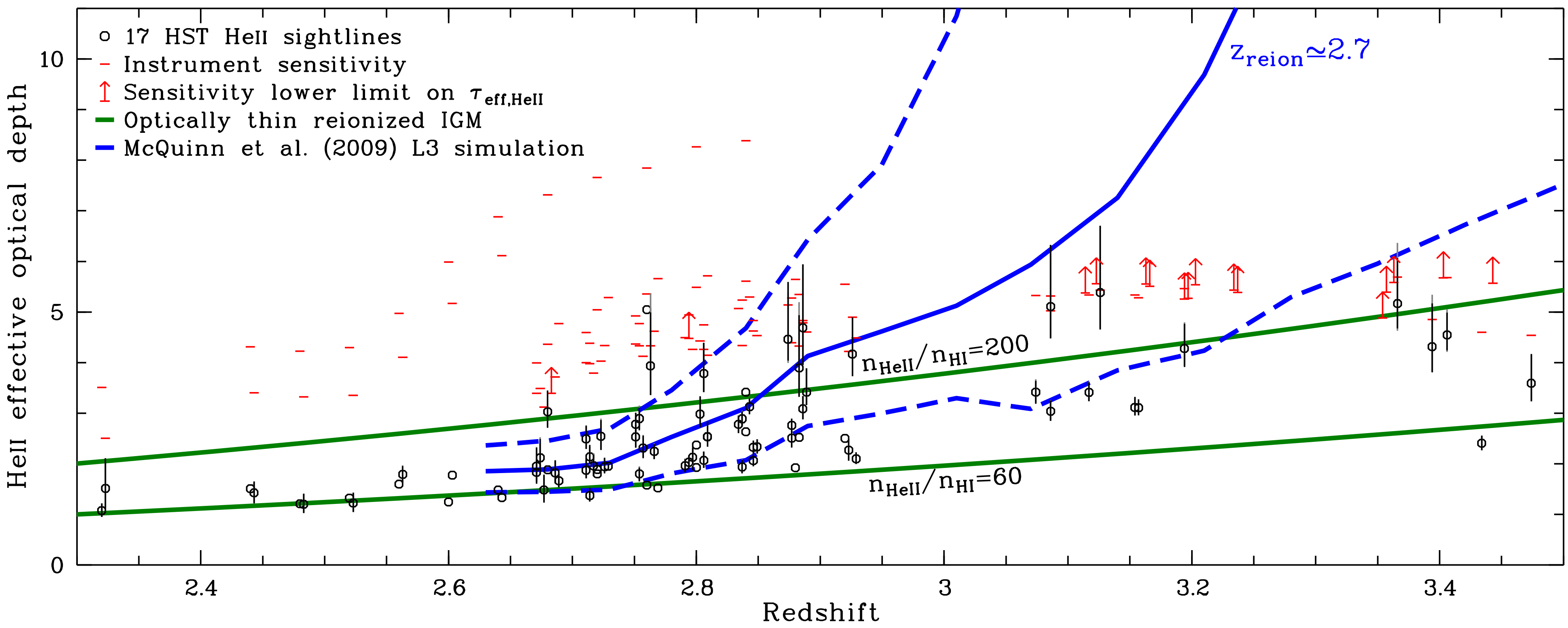




implies extended He reionization

HeII Gunn-Peterson effect

Worseck+ 16



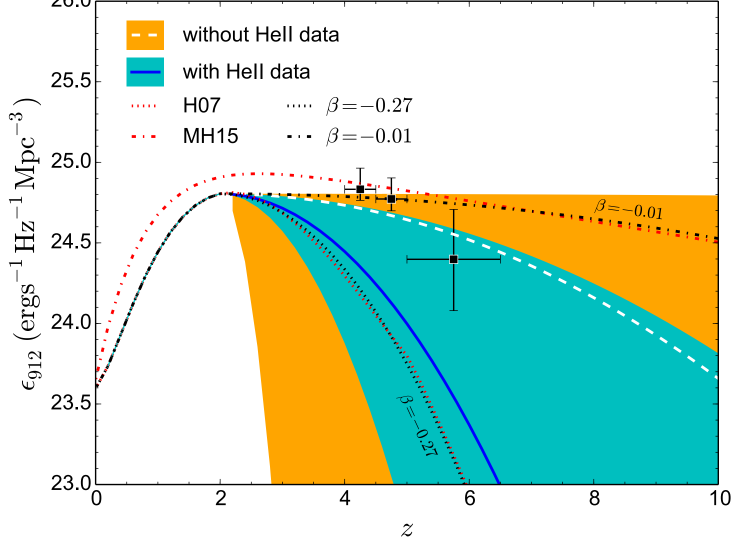
evidence of extended He reionization

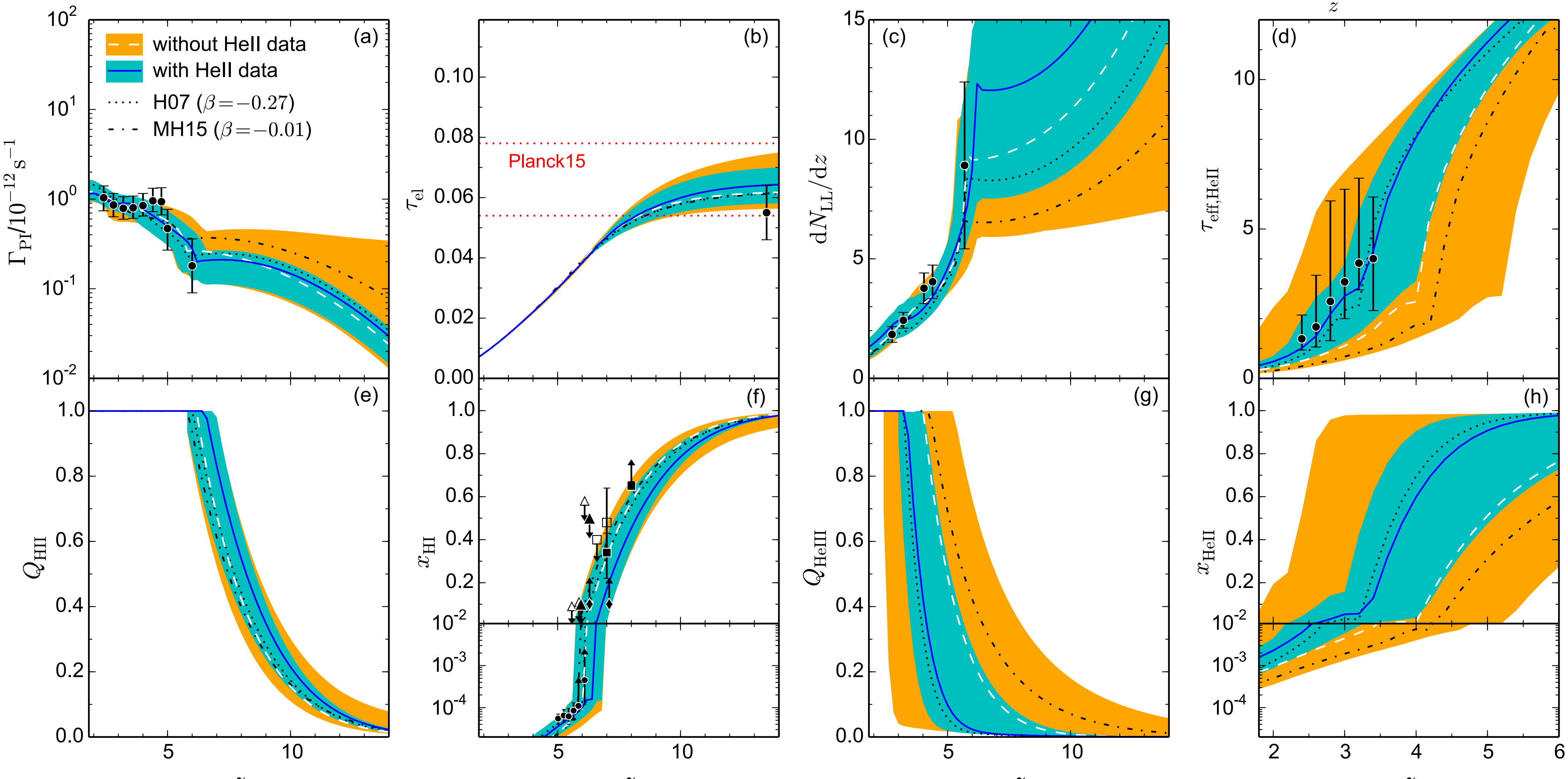
ionization energy:
HeI – 24.6 eV
 near-simultaneous with
 H reionization (massive stars?)
HeII – 54.4 eV   quasars only!

quasar contribution to reionization

Madau & Haardt 15, Yoshiura et al. 16
D'Aloisio et al. 16…

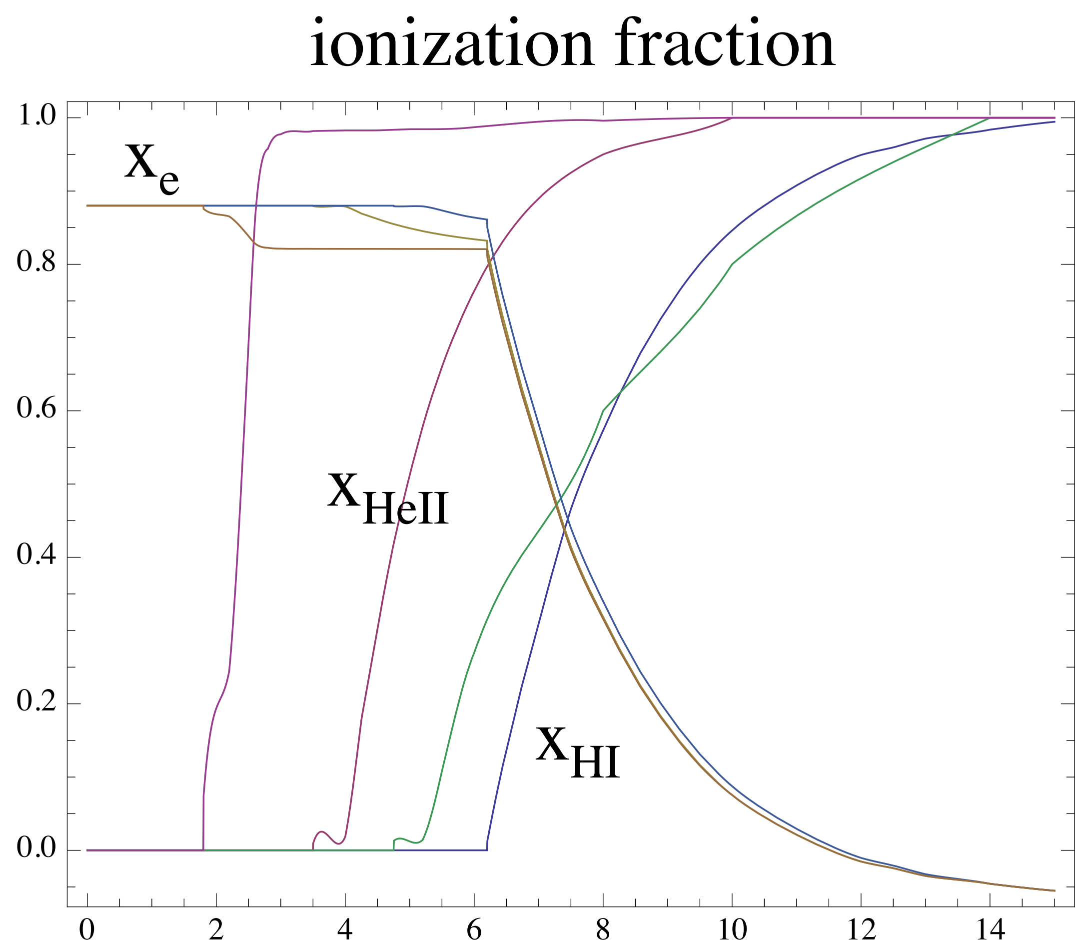
Mitra, Choudhury & Ferrara 16
HeII GP strongly constrain quasar contribution

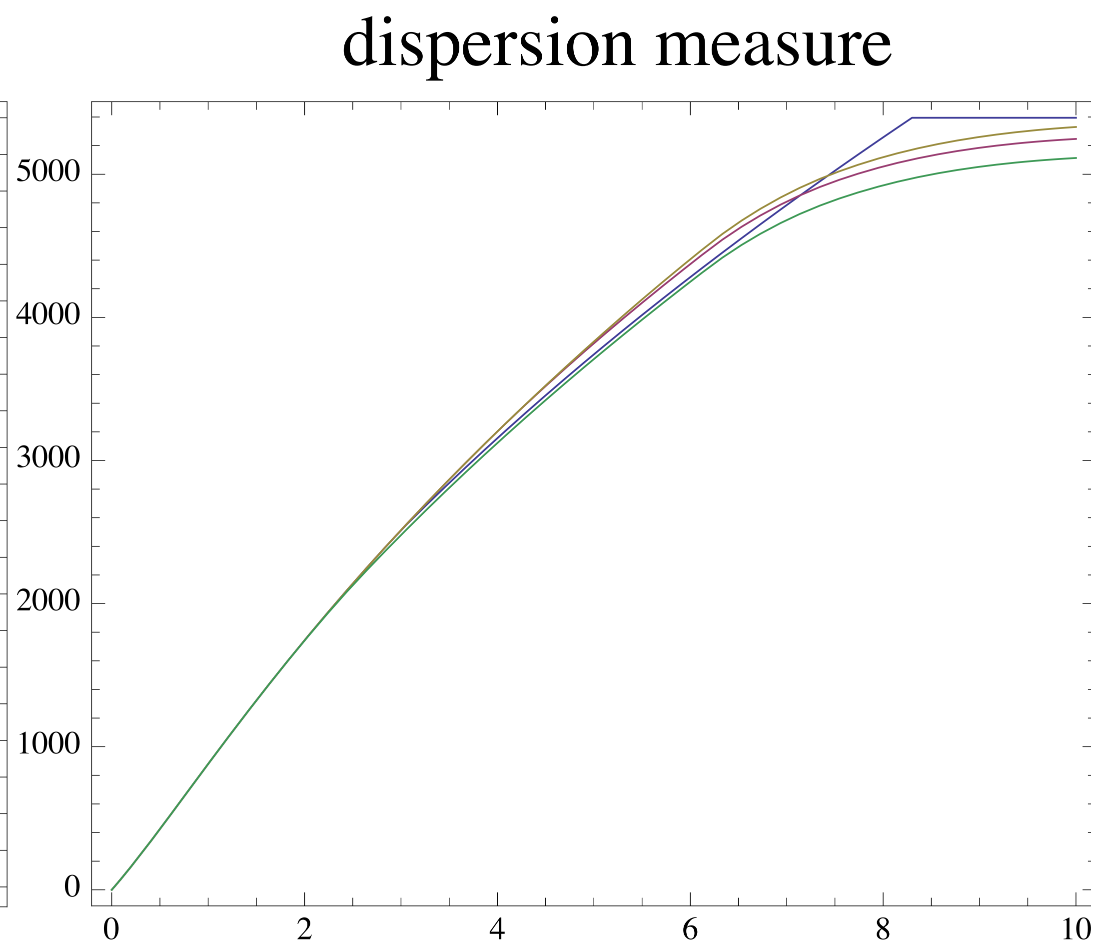




dispersion measure for stellar+QSO reionization

Mitra+16 model without HeII GP constraint

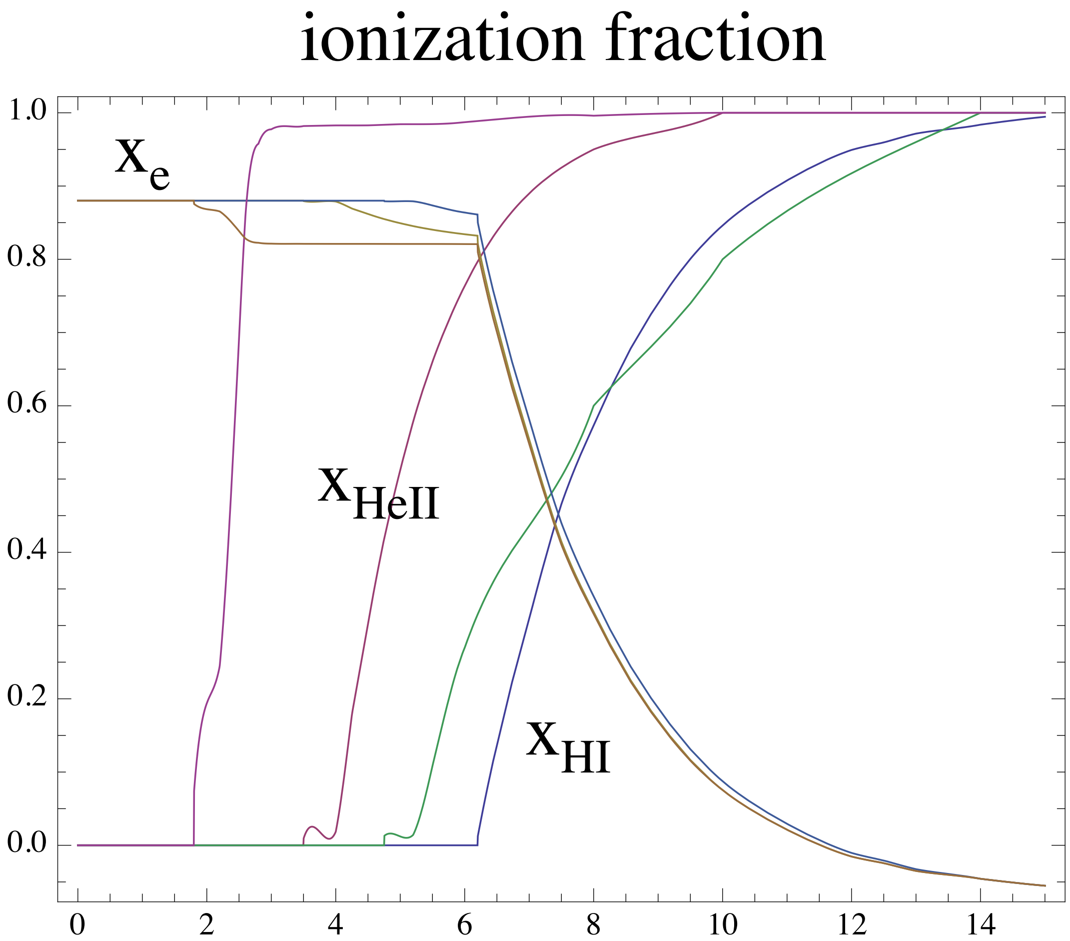


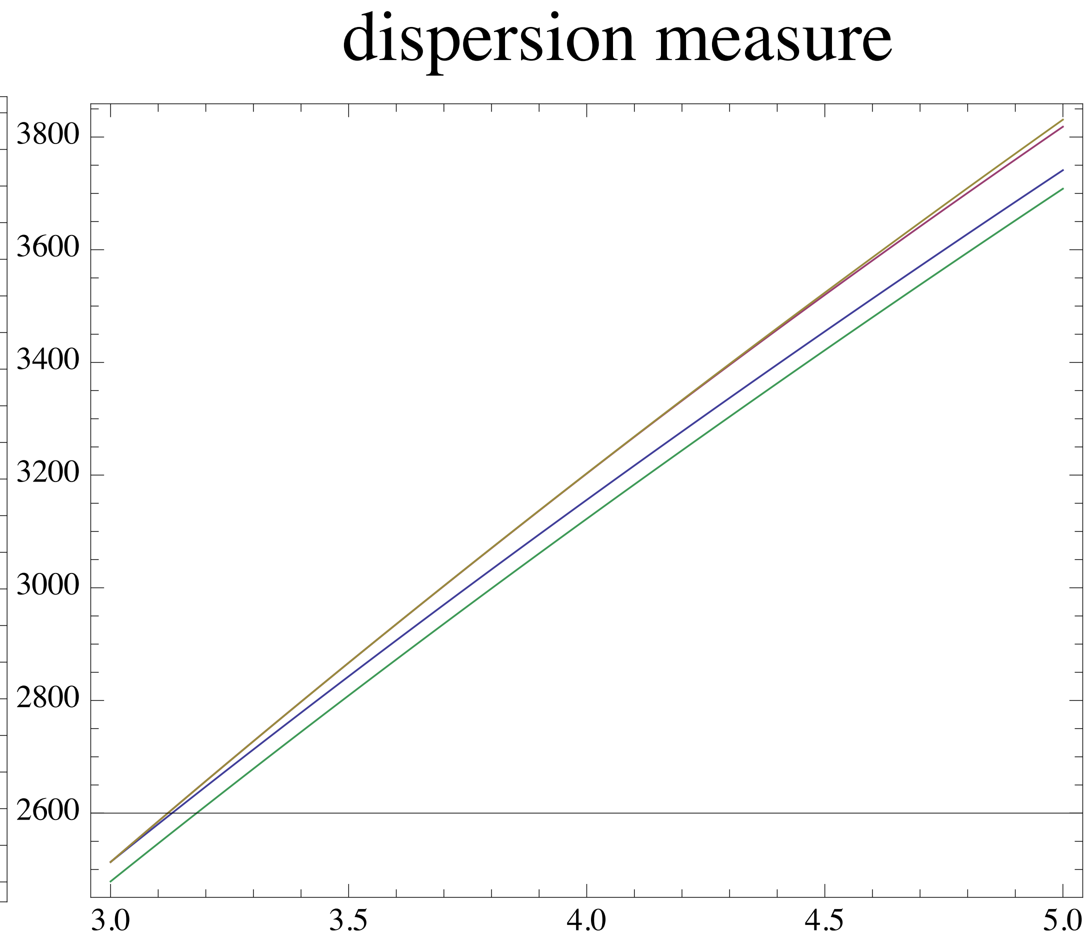


$$x_e=[1-Y(x_{HII})+(Y/4)(x_{HeII}+2x_{HeIII})]$$

dispersion measure for stellar+QSO reionization

Mitra+16 model without HeII GP constraint



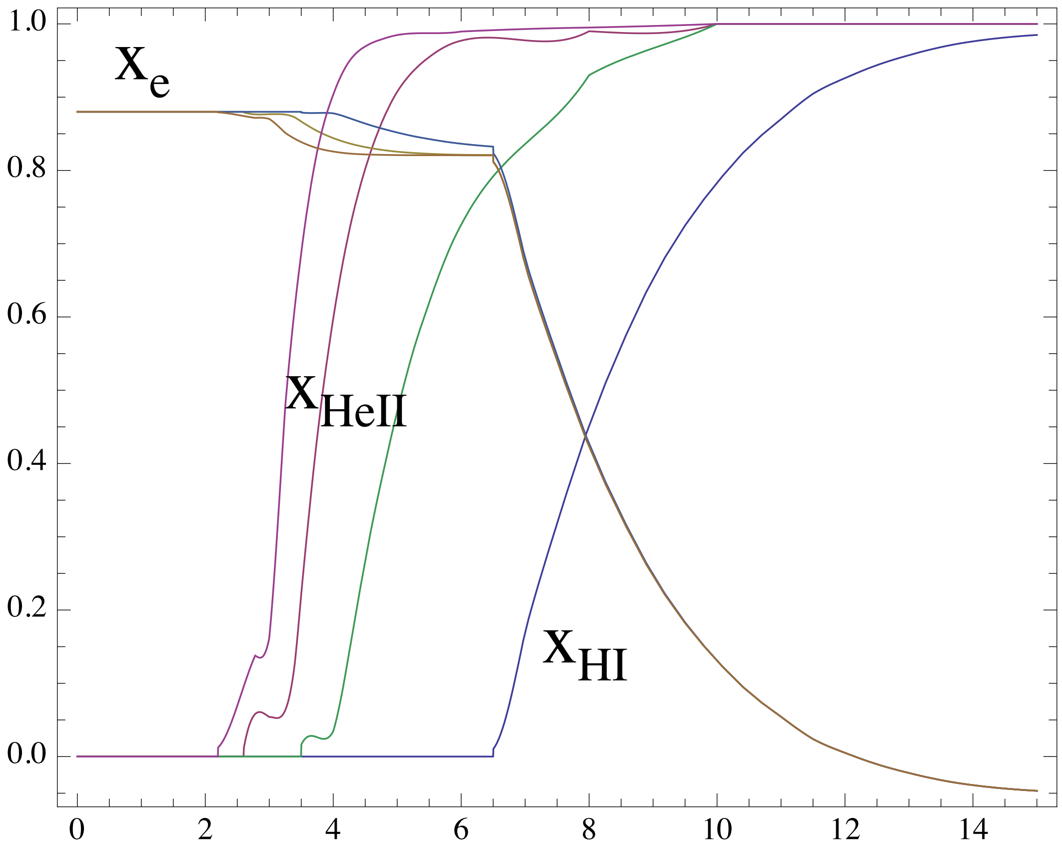


$$x_e = [1 - Y(x_{HII}) + (Y/4)(x_{HeII} + 2x_{HeIII})]$$

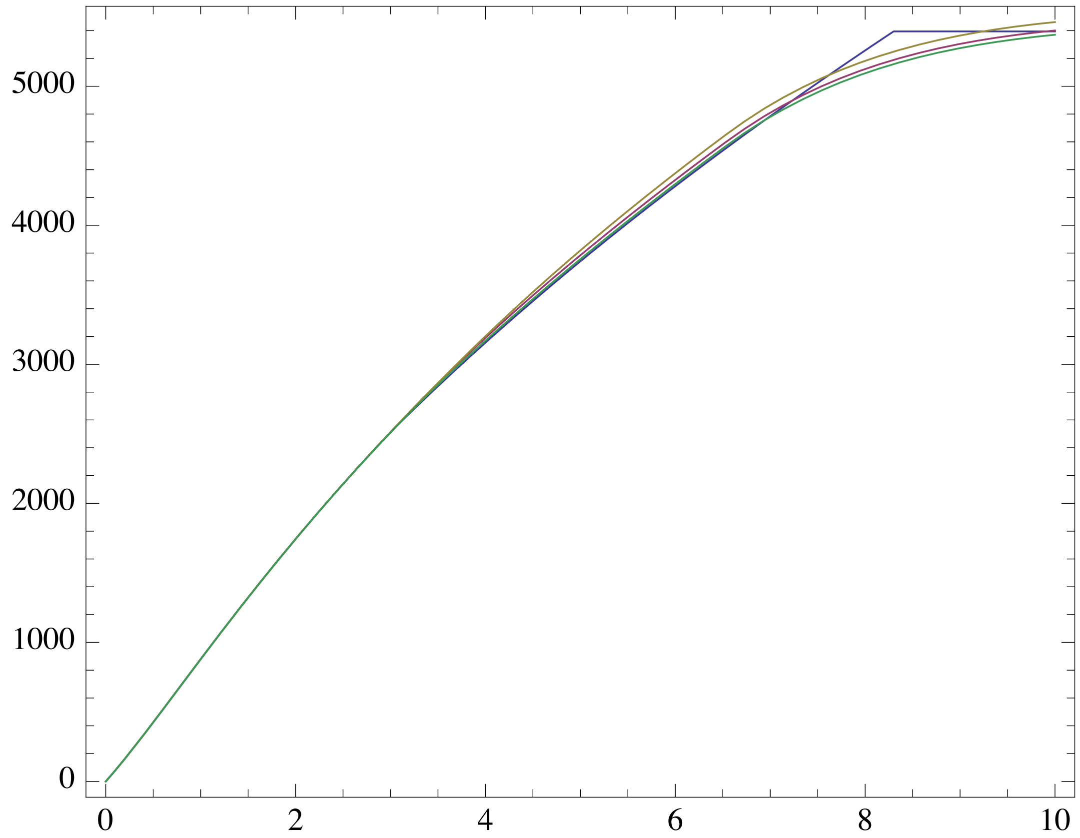
dispersion measure for stellar+QSO reionization

Mitra+16 model with HeII GP constraint

ionization fraction



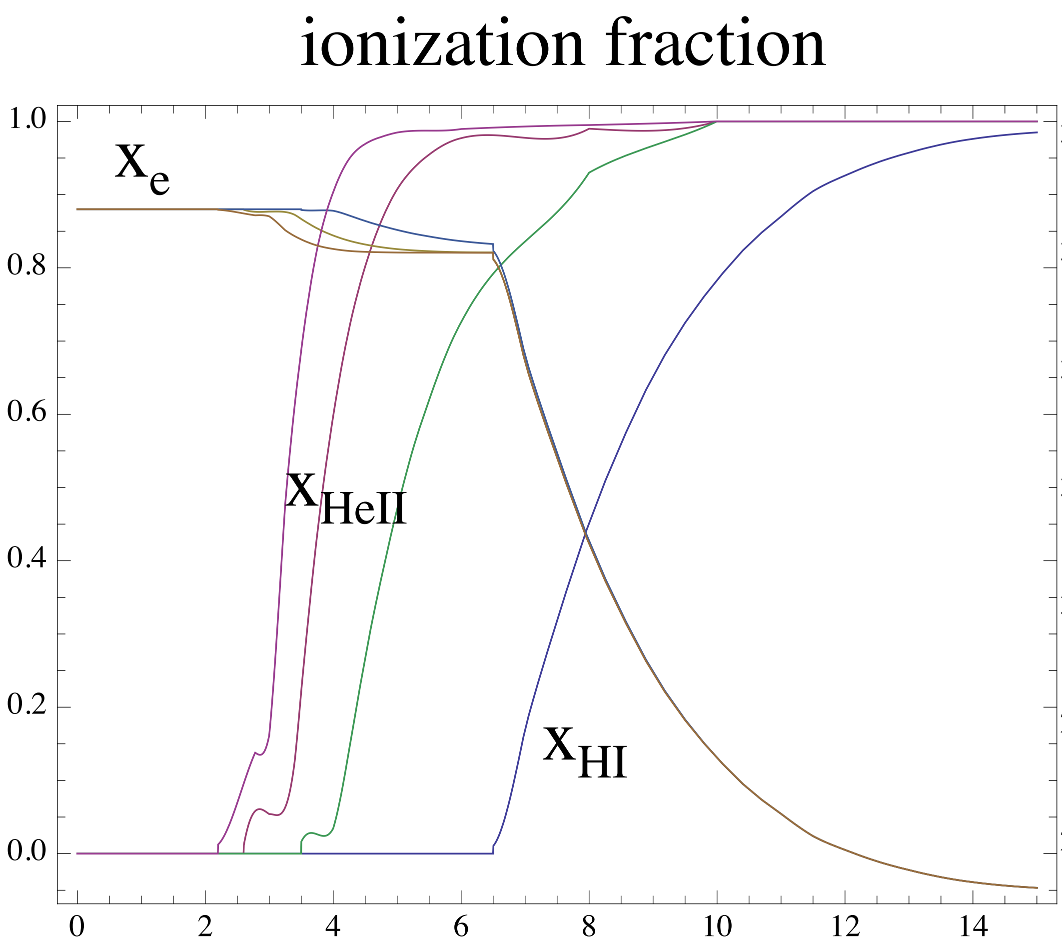
dispersion measure

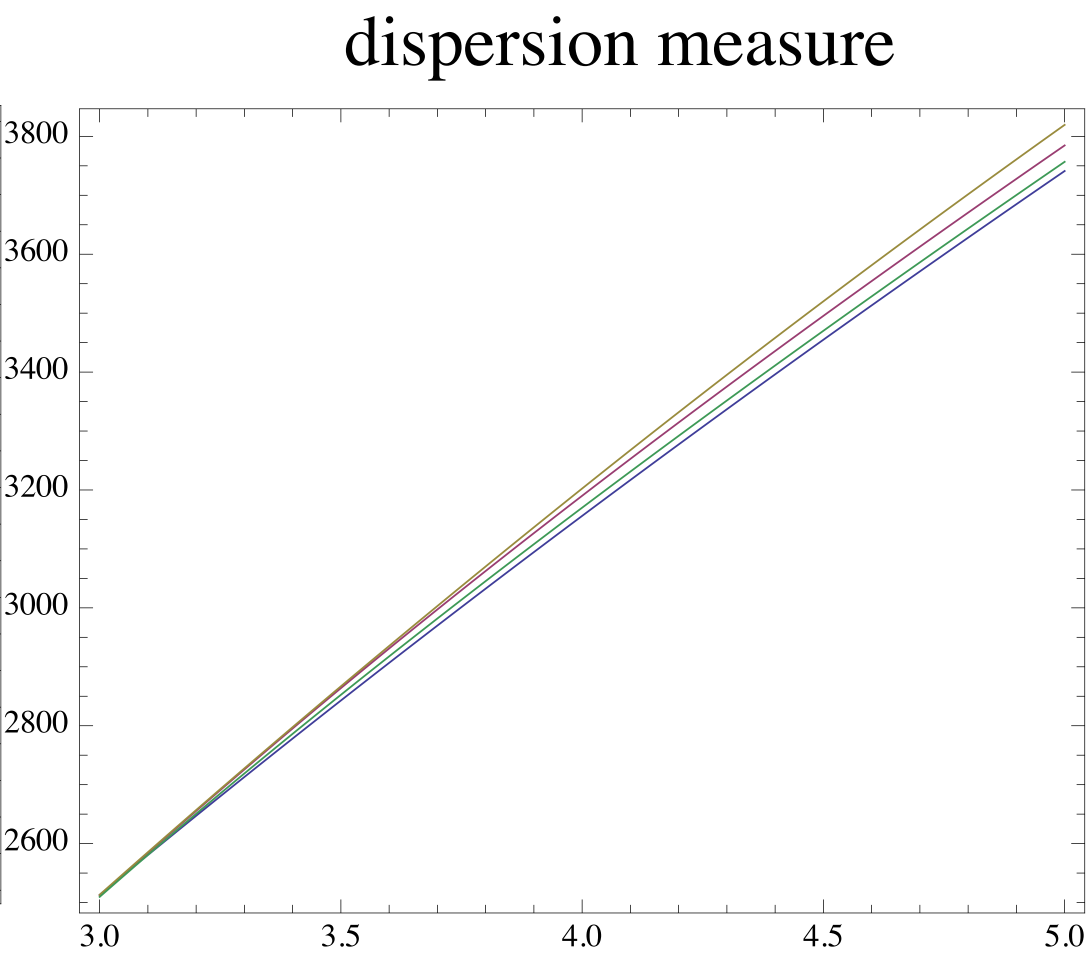


$$x_e=[1-Y(x_{HII})+(Y/4)(x_{HeII}+2x_{HeIII})]$$

dispersion measure for stellar+QSO reionization

Mitra+16 model with HeII GP constraint





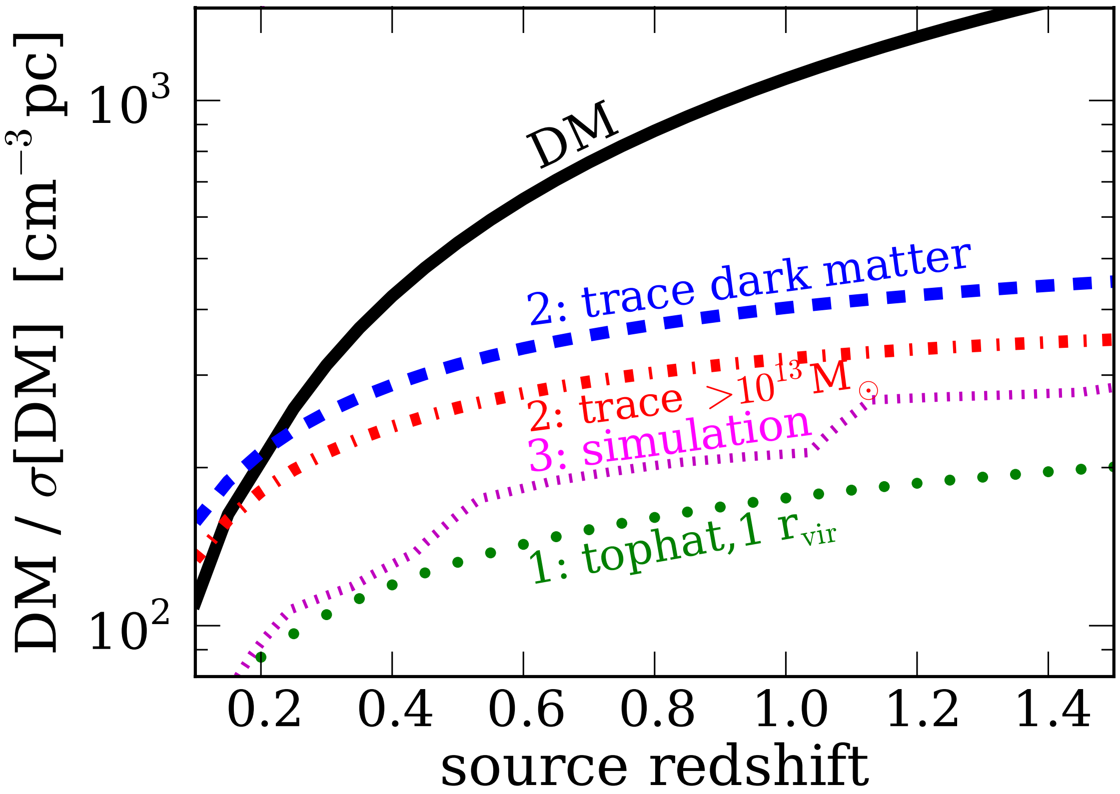
$$x_e=[1-Y(x_{HII})+(Y/4)(x_{HeII}+2x_{HeIII})]$$

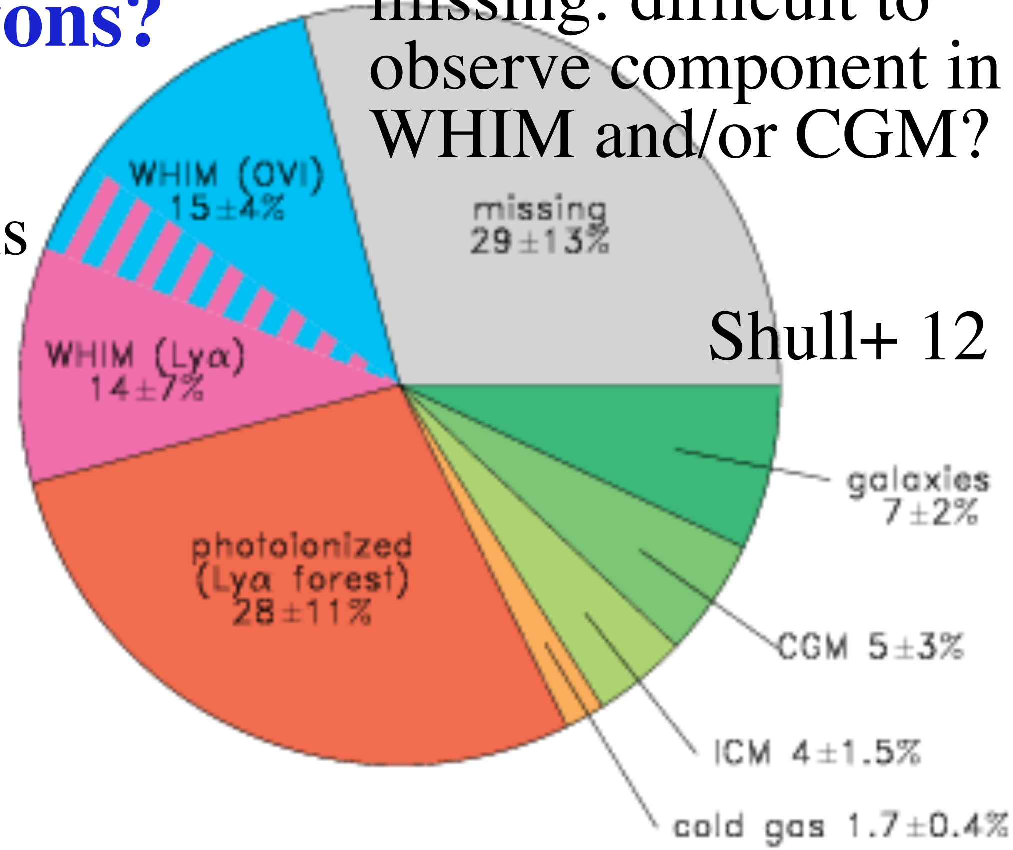
FRBs as probes of missing baryons?

missing: difficult to observe component in WHIM and/or CGM?

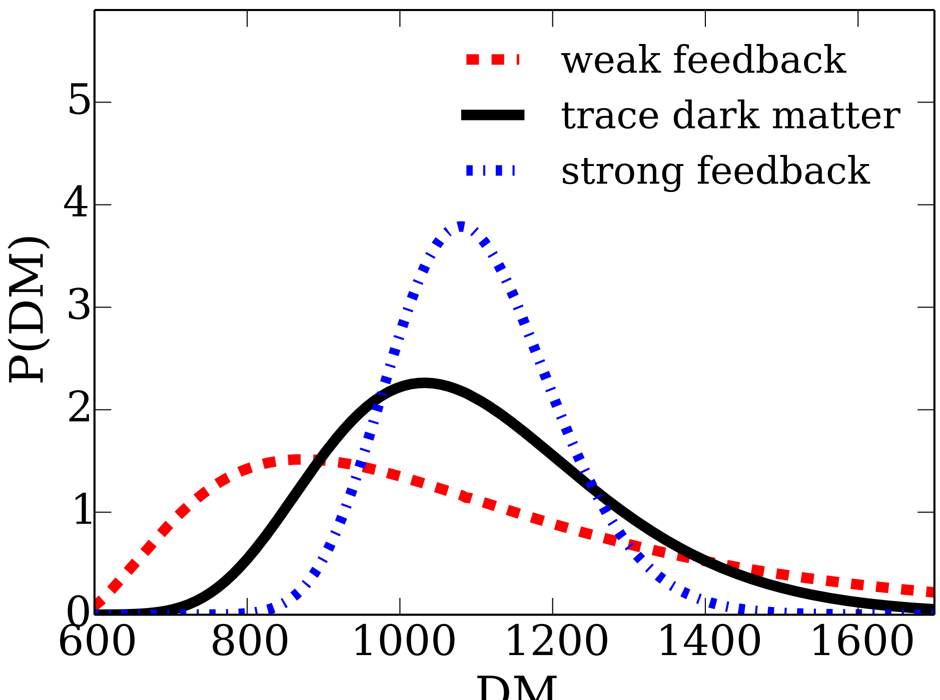
sizable variance expected due to LSS
-> probe distribution of ionized baryons

McQuinn 13



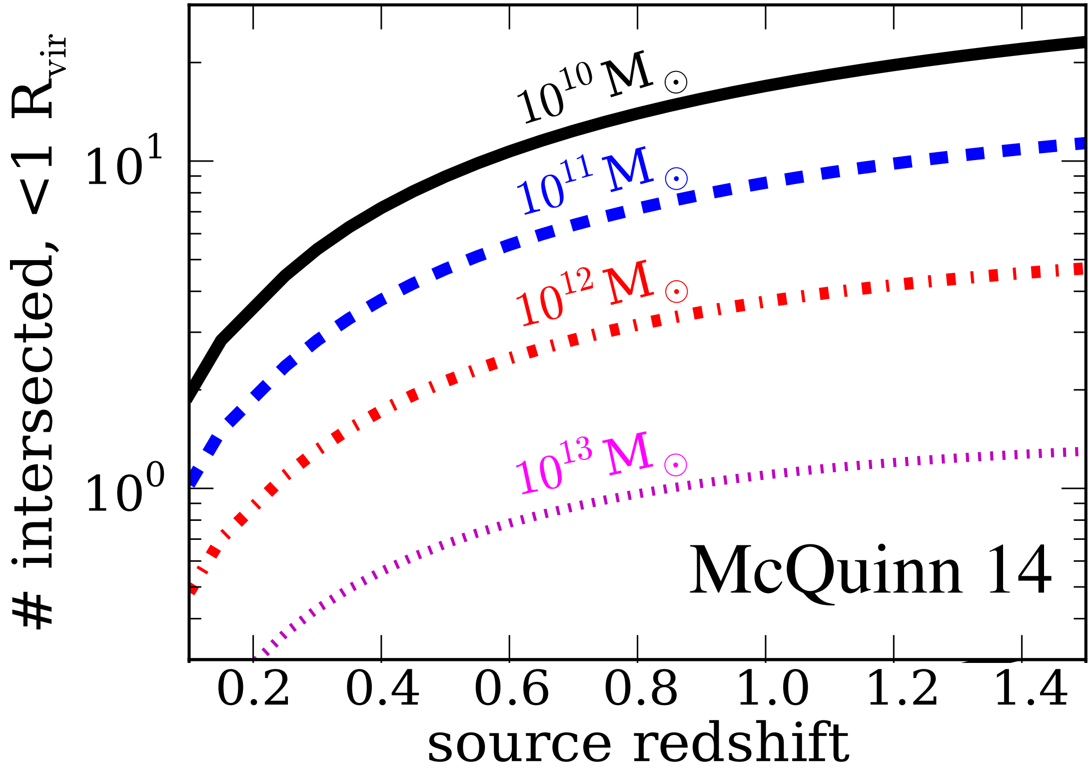


Shull+ 12

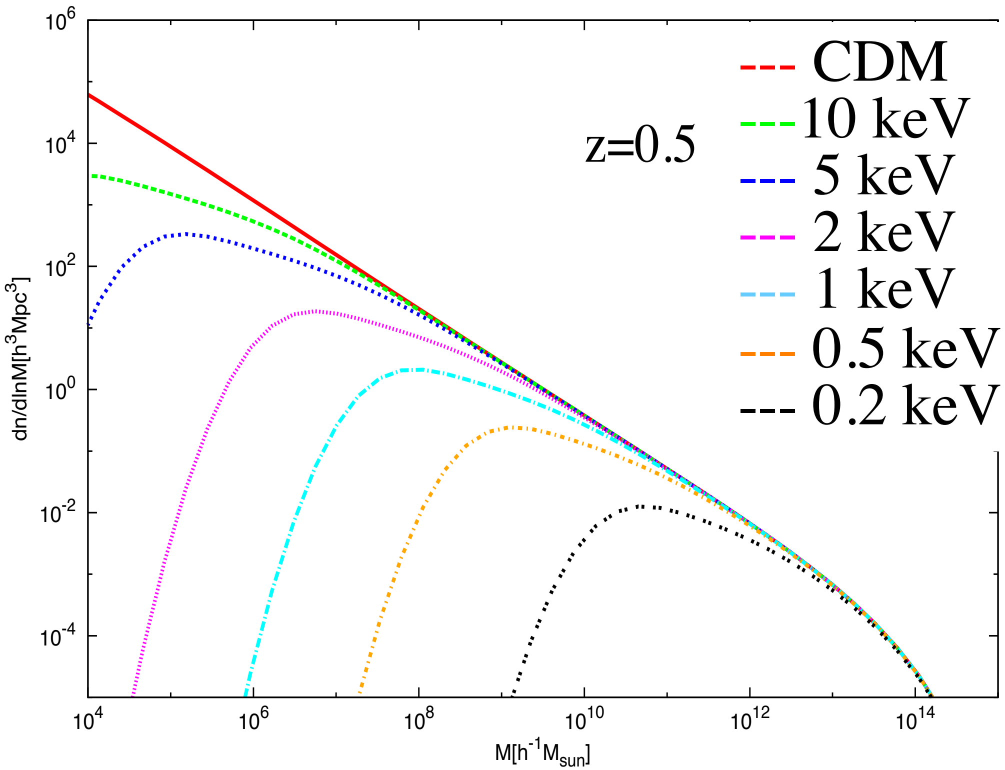


FRBs as probe of small scale power spectrum (warm dark matter and/or small-scale feedback)

lines of sight out to z~1 intersect
large number of ~10^{10} M_{sun} halos
-> variance of DM sensitive to abundance and
baryon distribution of ~10^{10} M_{sun} halos



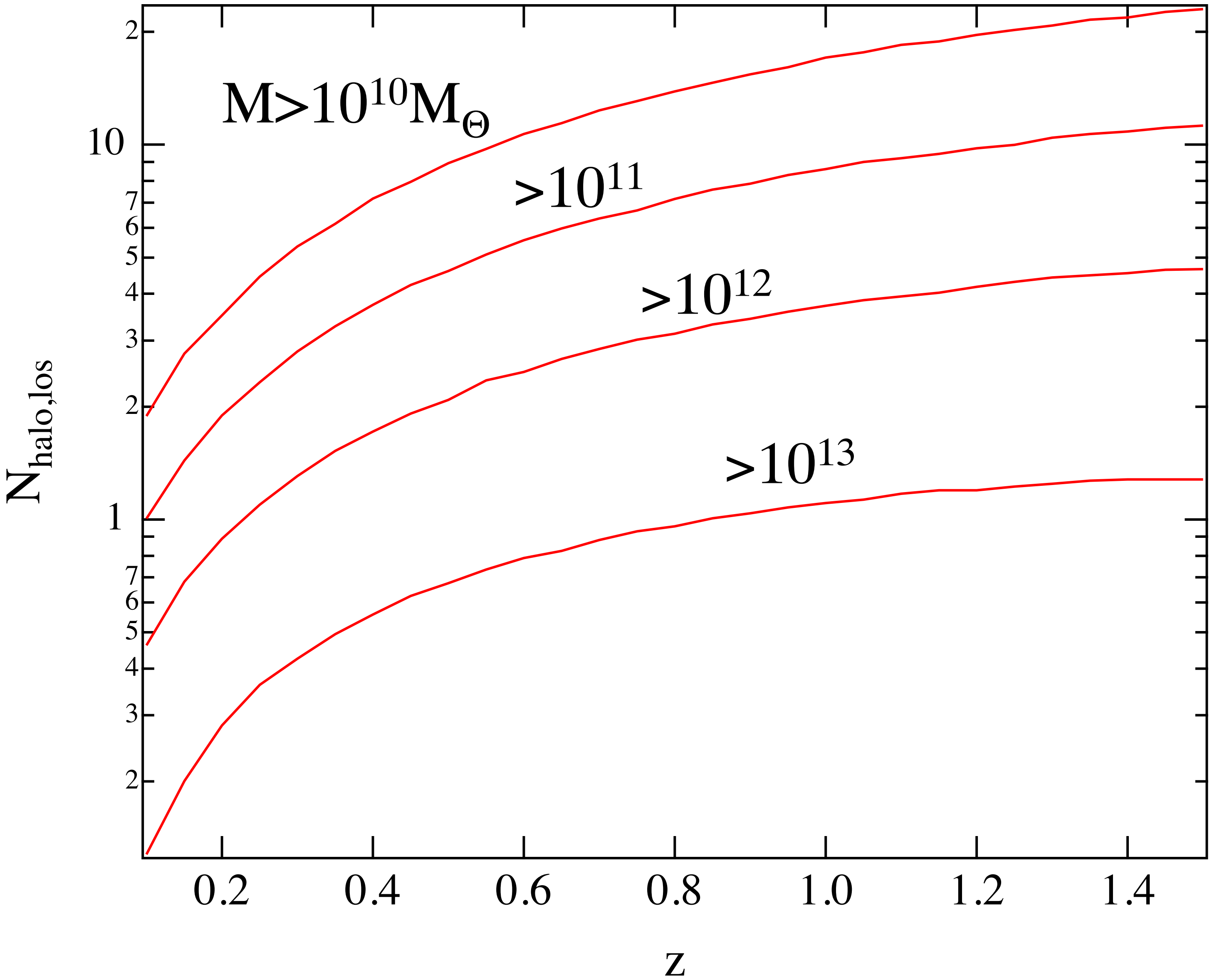
WDM halo MF



halos intersecting along line of sight

CDM

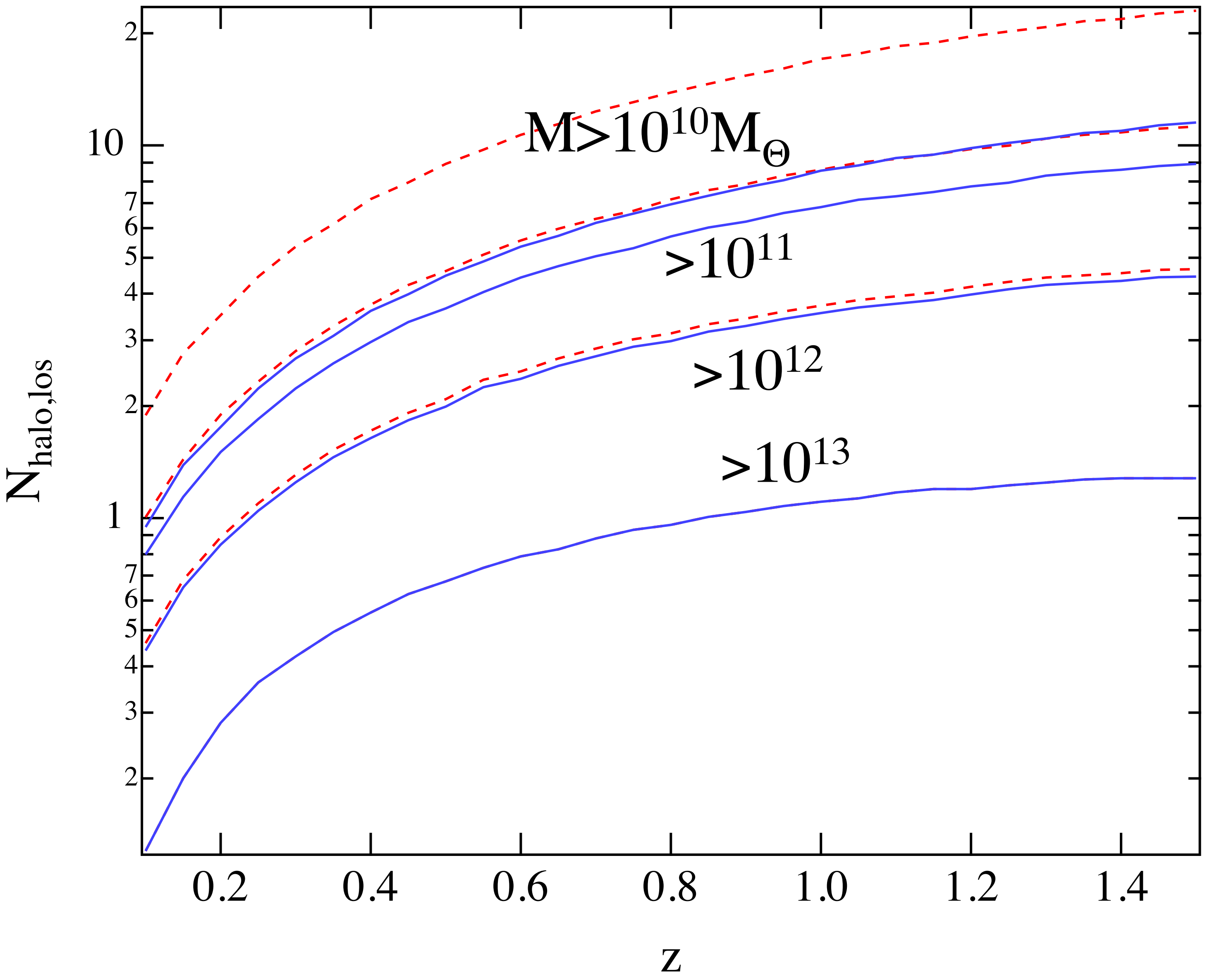
$N_{halo,los} = \iint dM\, dz\, (cdt/dz)$
$\times\, (R_{vir}(M,z))^2\, dN/dM\, (M,z)$



halos intersecting along line of sight

WDM m=1keV vs CDM

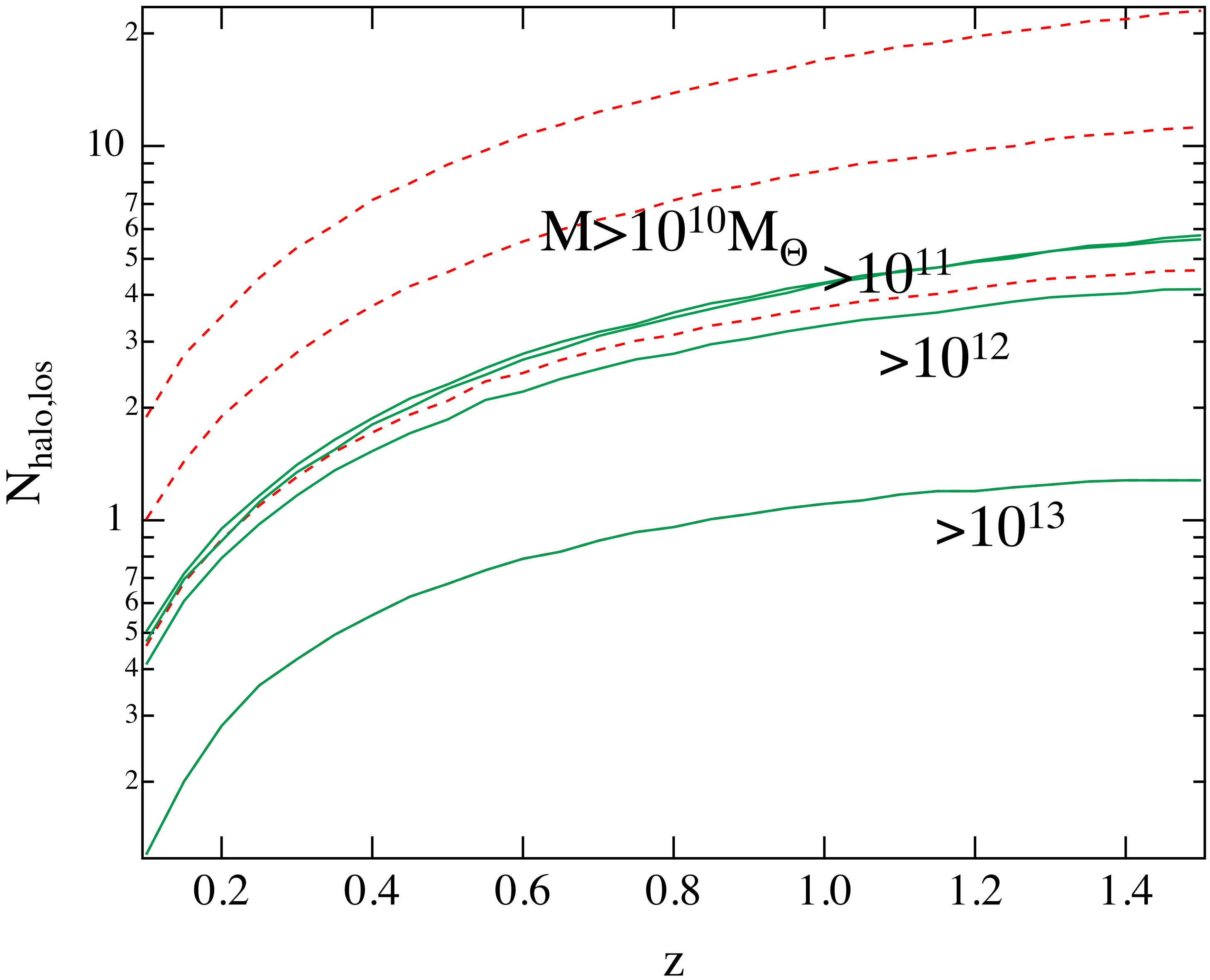
$$N_{halo,los} = \iint dM\, dz\, (cdt/dz) \times (R_{vir}(M,z))^2\, dN/dM\,(M,z)$$



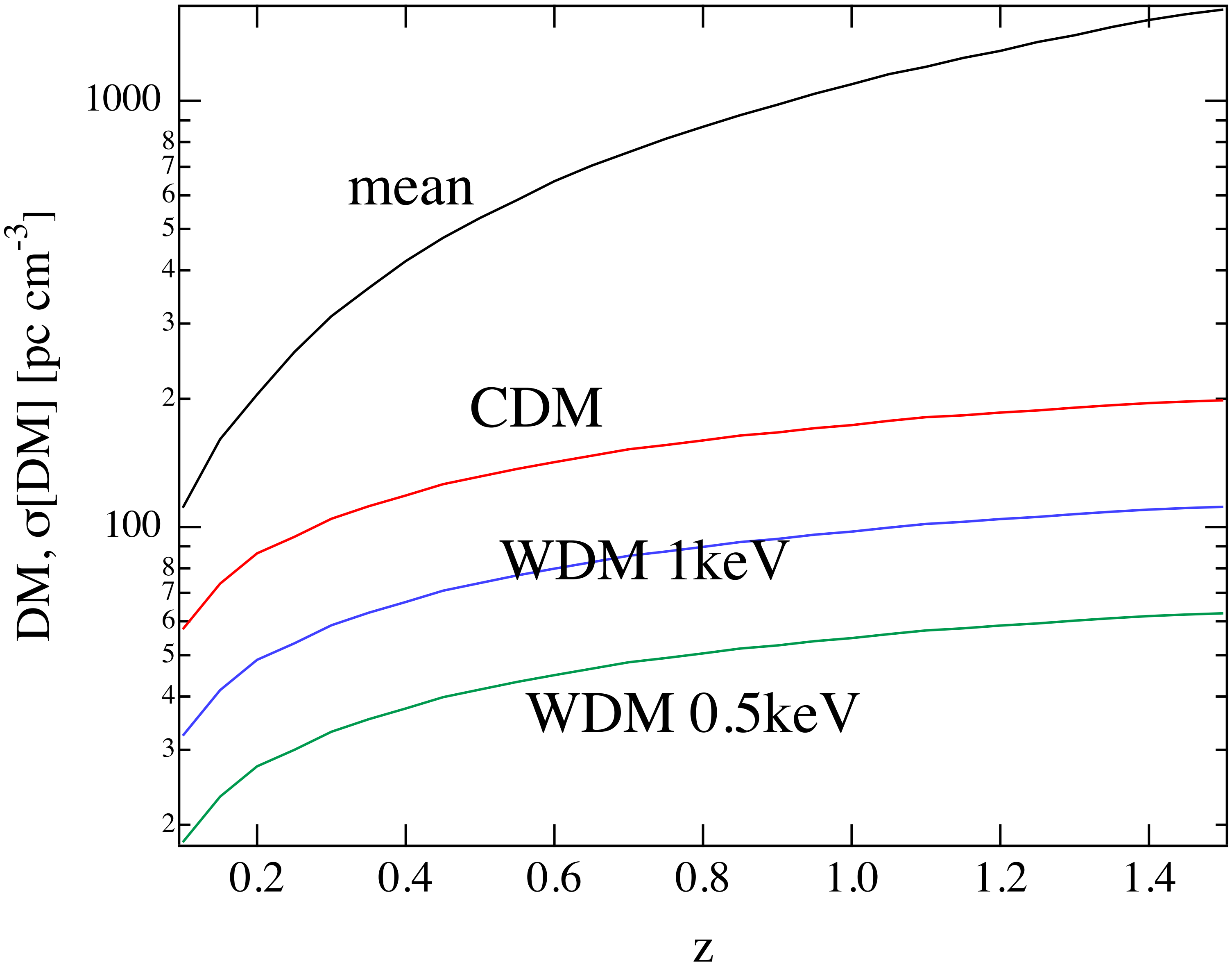
halos intersecting along line of sight

WDM m=0.5keV vs CDM

$N_{halo,los} = \iint dM\, dz\, (cdt/dz)$
$x\, (R_{vir}(M,z))^2\, dN/dM\, (M,z)$



dispersion measure: mean and variance



variance computed via std. halo model as in McQuinn 13

profile: top hat $<R_v$

$M_{min}=10^{10}\ M_\Theta$

$\sim M_{J,IGM}$

In progress: quantify constraints on m_{WDM}

prospects for probing small-scale feedback

prospects for cross correlations with galaxy surveys…

summary

- 21cm forest: unique, valuable probe of cosmic reionization,
  nonstandard physics
  new approach of statistical detection via stacking
  of moderate sources
- background sources: young radio galaxies (CSS/GPS),
  blazars more promising than GRBs or mature radio galaxies
- fast radio bursts: (potentially) unique, new probe of
  ionized intergalactic baryons
  -> cosmic H+He reionization by stars+quasars
  -> small scale fluctuations, feedback in dwarf galaxies…