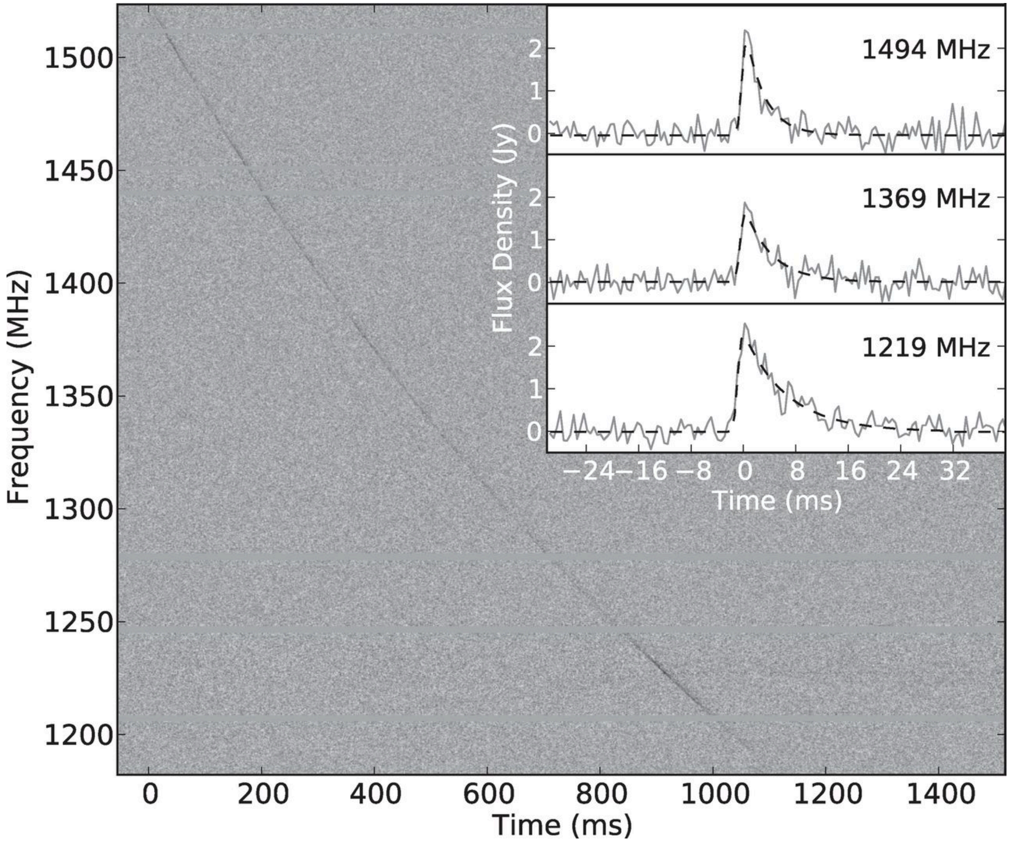
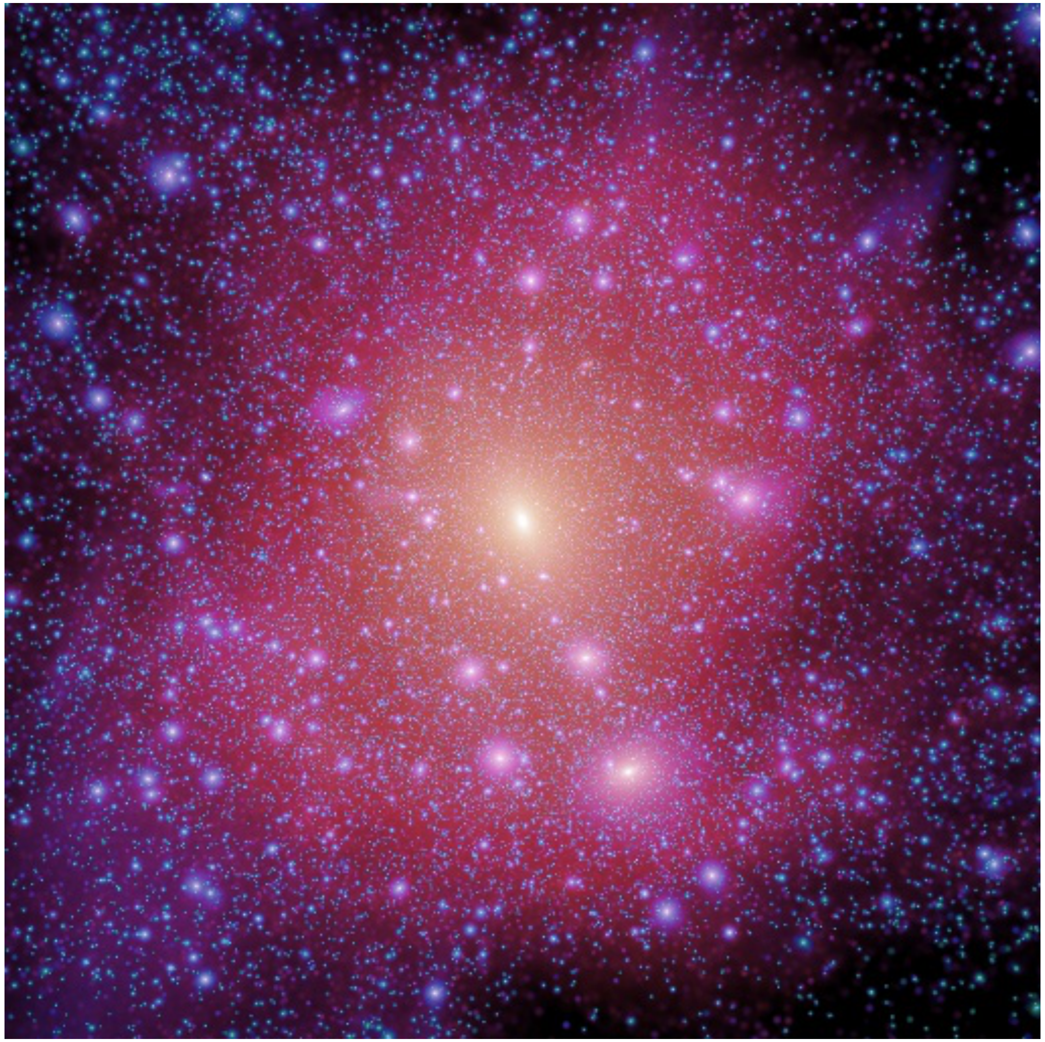
高速電波バースト (FRB) と小スケール揺らぎ

井上 進（理研）、市來淨與、島袋隼人（名大）





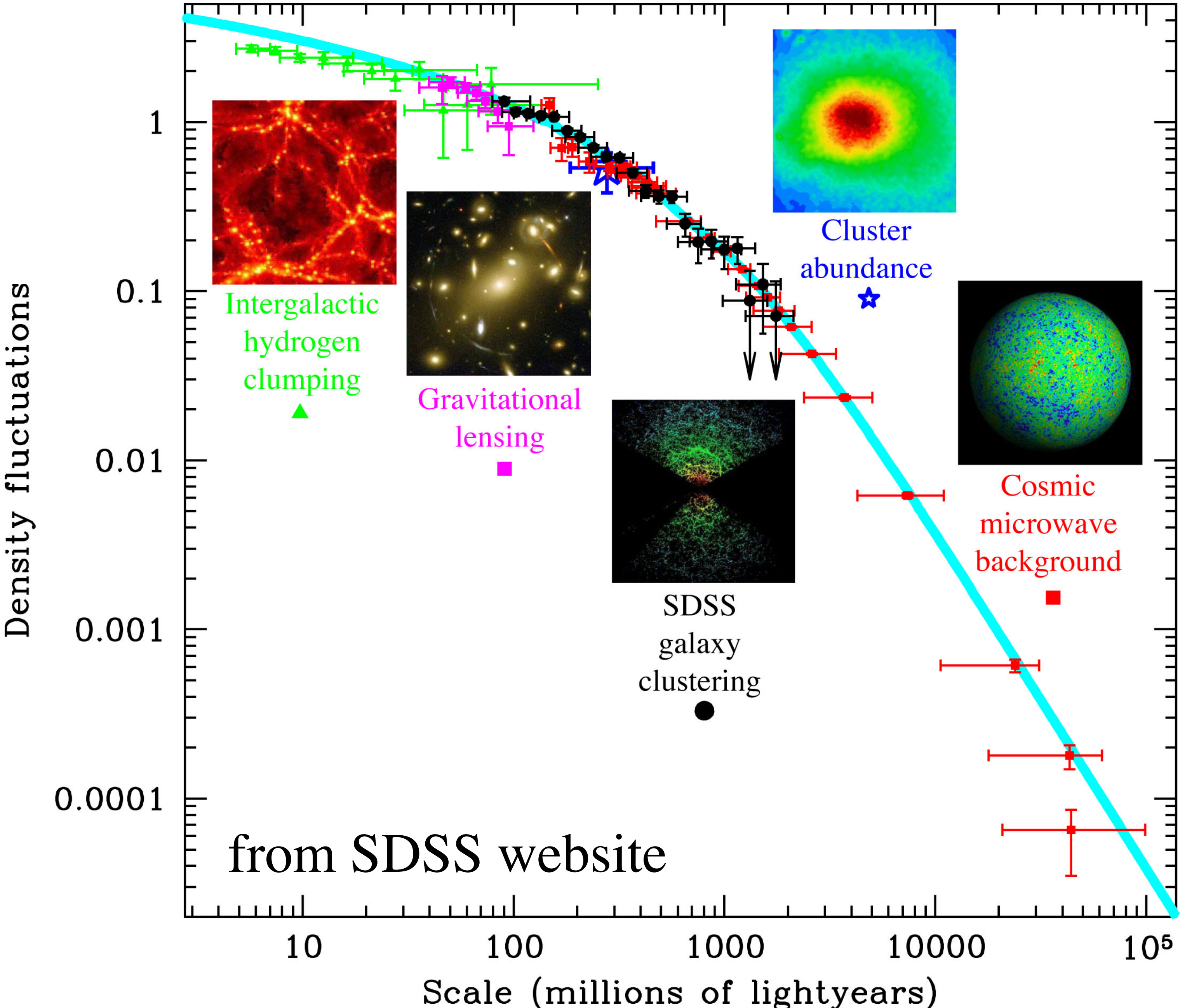
power spectrum of large-scale structure

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

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

- Lyα forest
- lensing
- …

c.f. 井上太郎さん

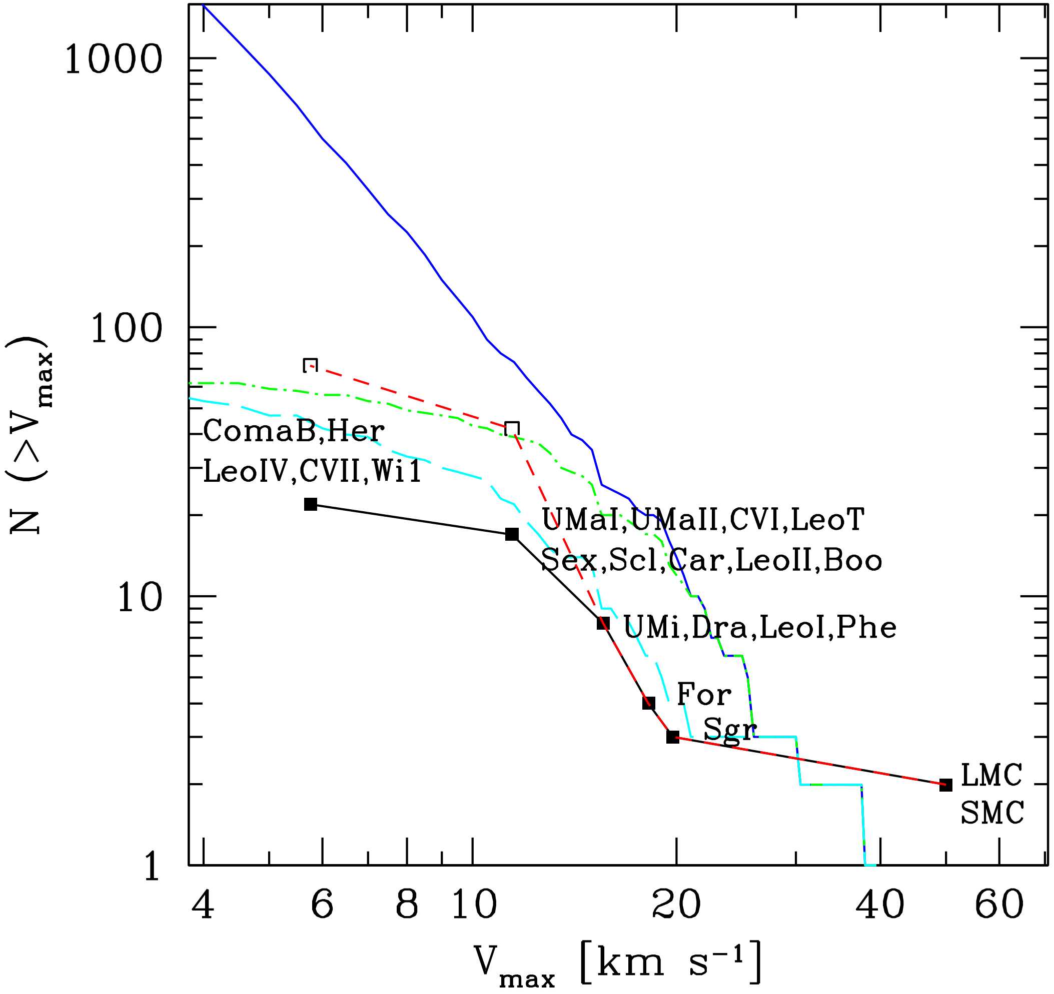


from SDSS website

missing satellite problem: paucity of Milky Way satellites compared to CDM expectations

halo substructure in CDM simulation

number of simulated subhalos vs observed MW satellites



Madau+ 08

- astrophysical feedback?
- modification to CDM?

c.f. 田中さん

dispersion of EM waves in cold plasma

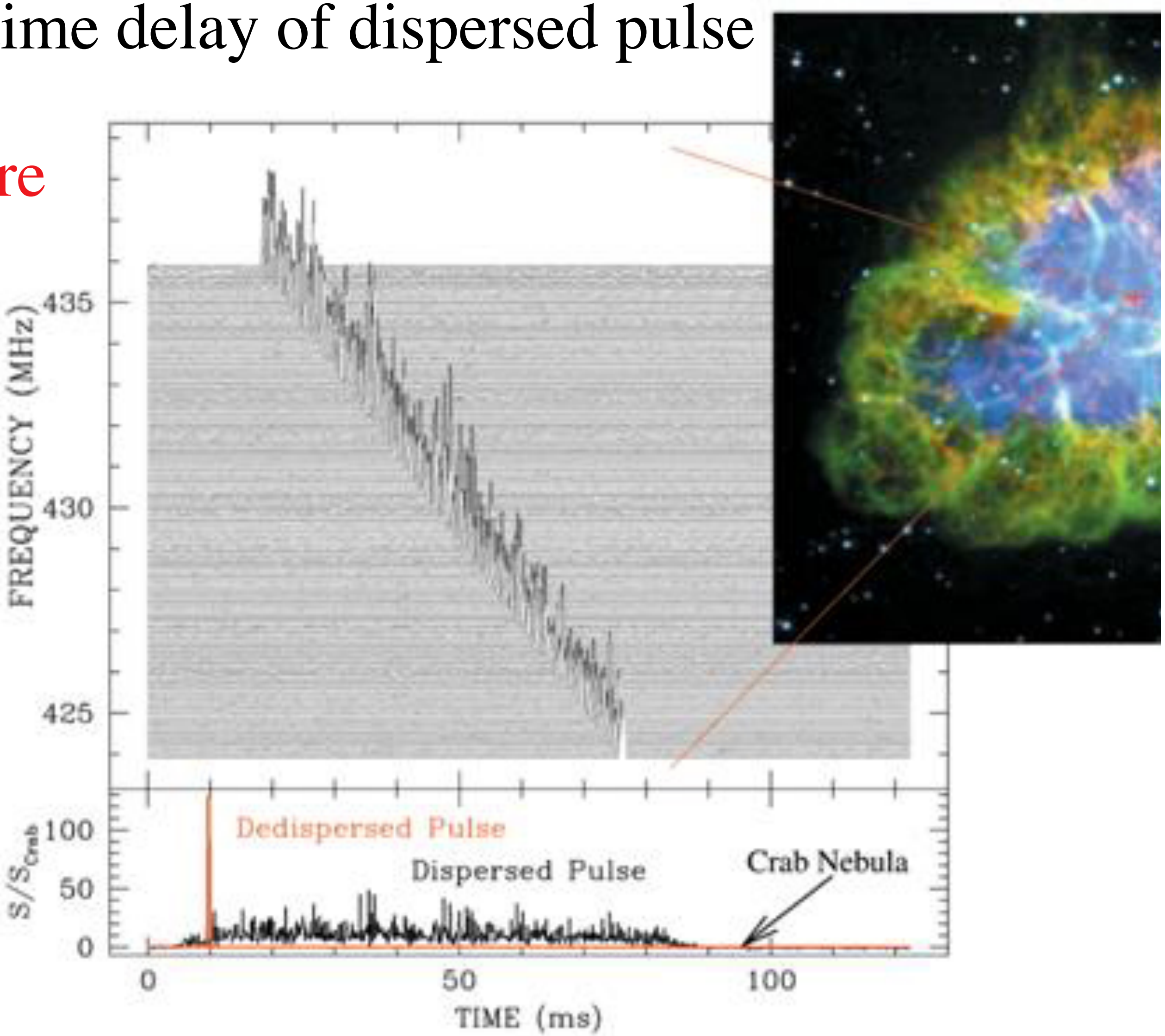
Maxwell’s eq. + electron eq. mot. + charge consv., expand in o(v/c)

$$v_g = c\left[1-\frac{\nu_p^2}{\nu^2}\right]^{1/2}, \quad \nu_p^2 = \frac{4\pi n_e e^2}{m_e}$$

group velocity of propagating EM wave

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

time delay of dispersed pulse

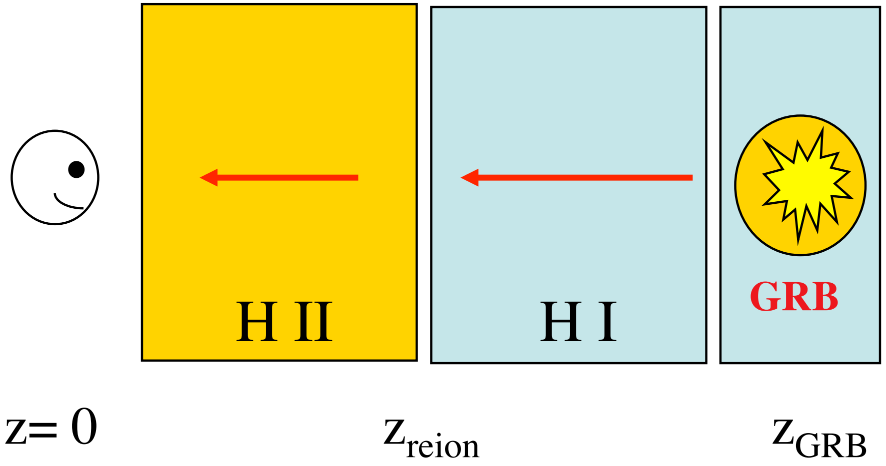


observed dispersion in
Galactic radio pulsars

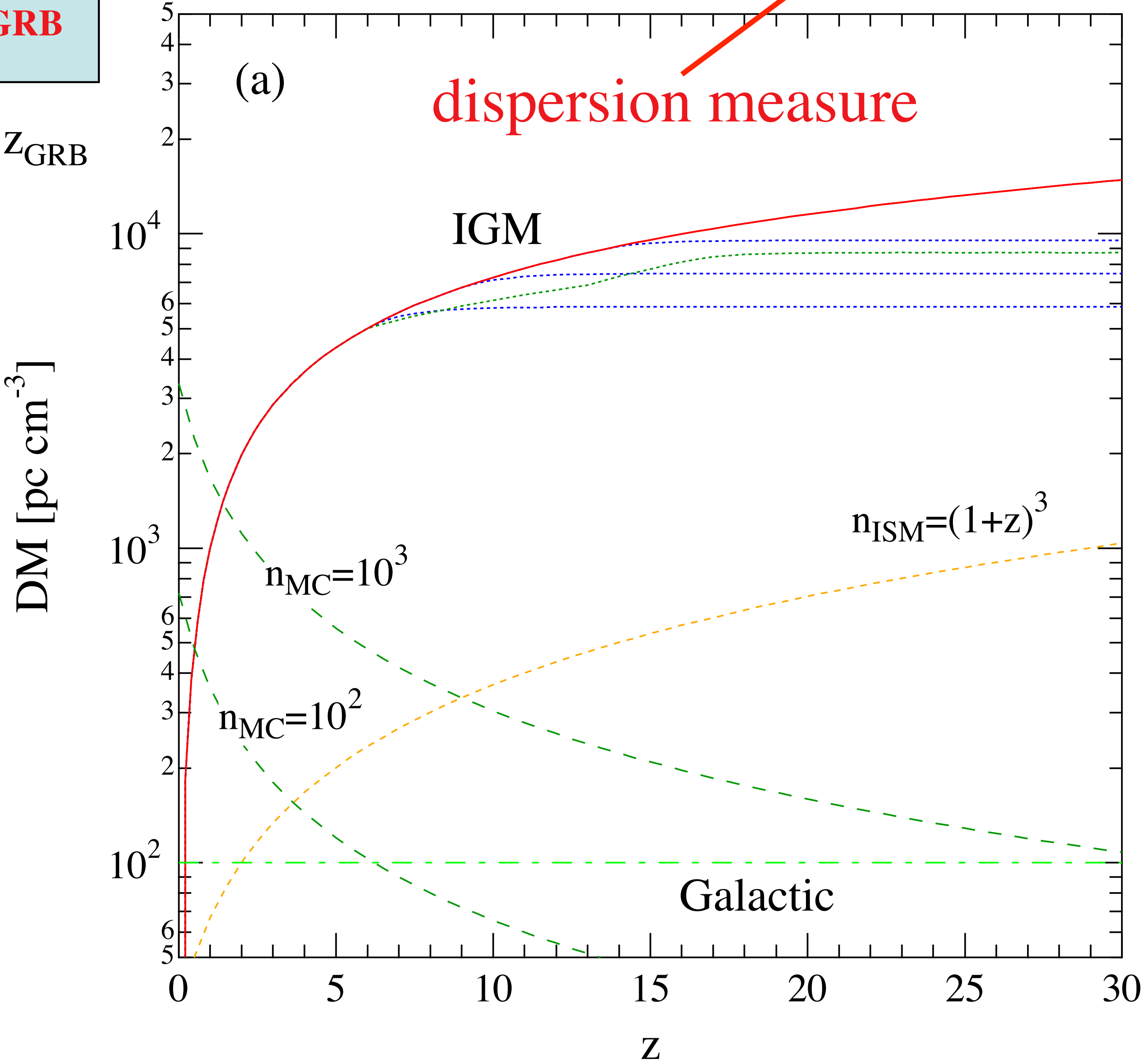
known distance
-> probe intervening
ionized ISM
or
estimates of ionized ISM
-> constrain distance

probing ionized IGM with radio dispersion

SI 04 Ioka 03

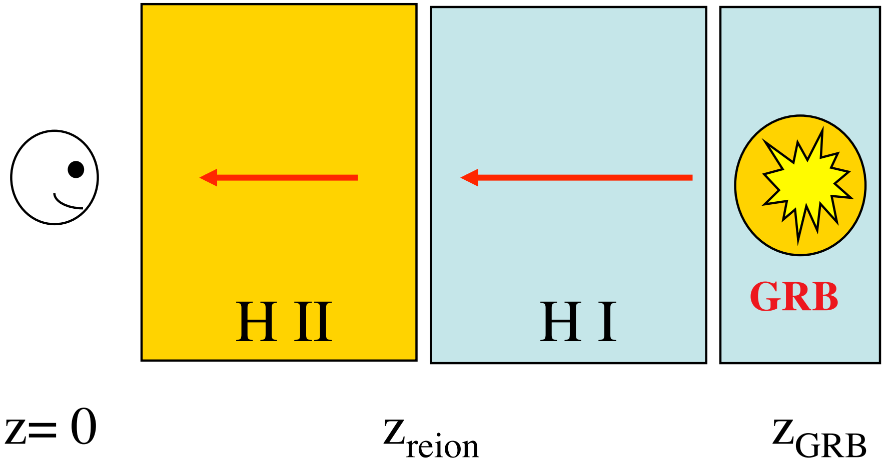


$$\Delta t = \frac{e^2}{2\pi m_e c\,\nu^2}\underbrace{\int dz\,\frac{c\,dt}{dz}\,\frac{x_e(z)\,n_{IGM}(z)}{1+z}}_{\text{dispersion measure}}$$

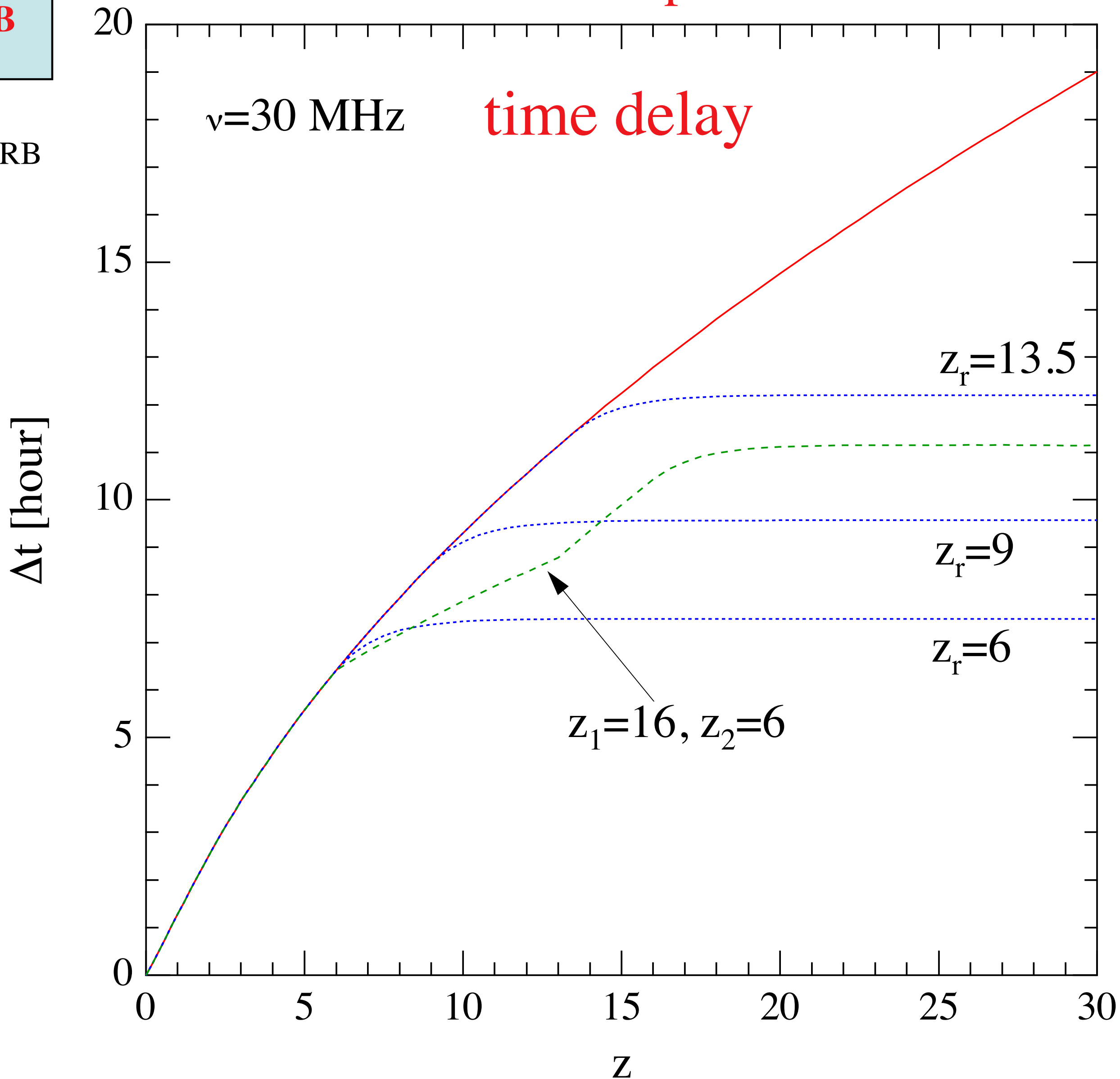


probing ionized IGM with radio dispersion

SI 04 Ioka 03



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



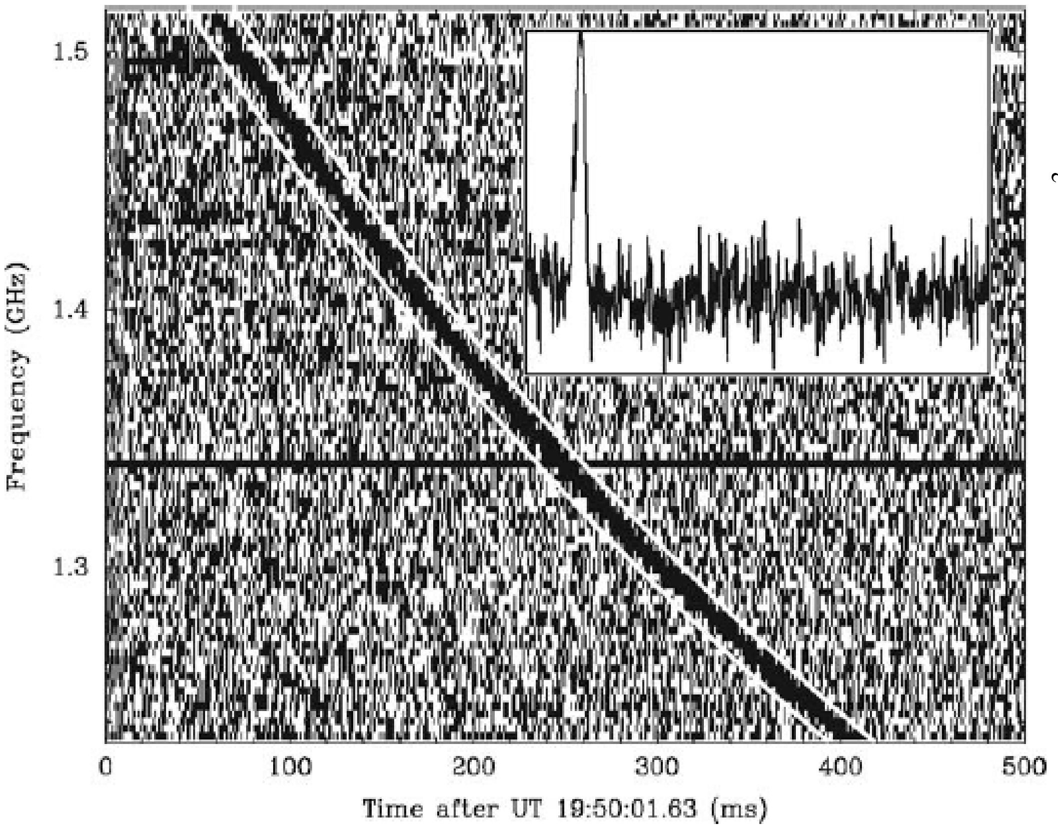
unID extragalactic radio burst

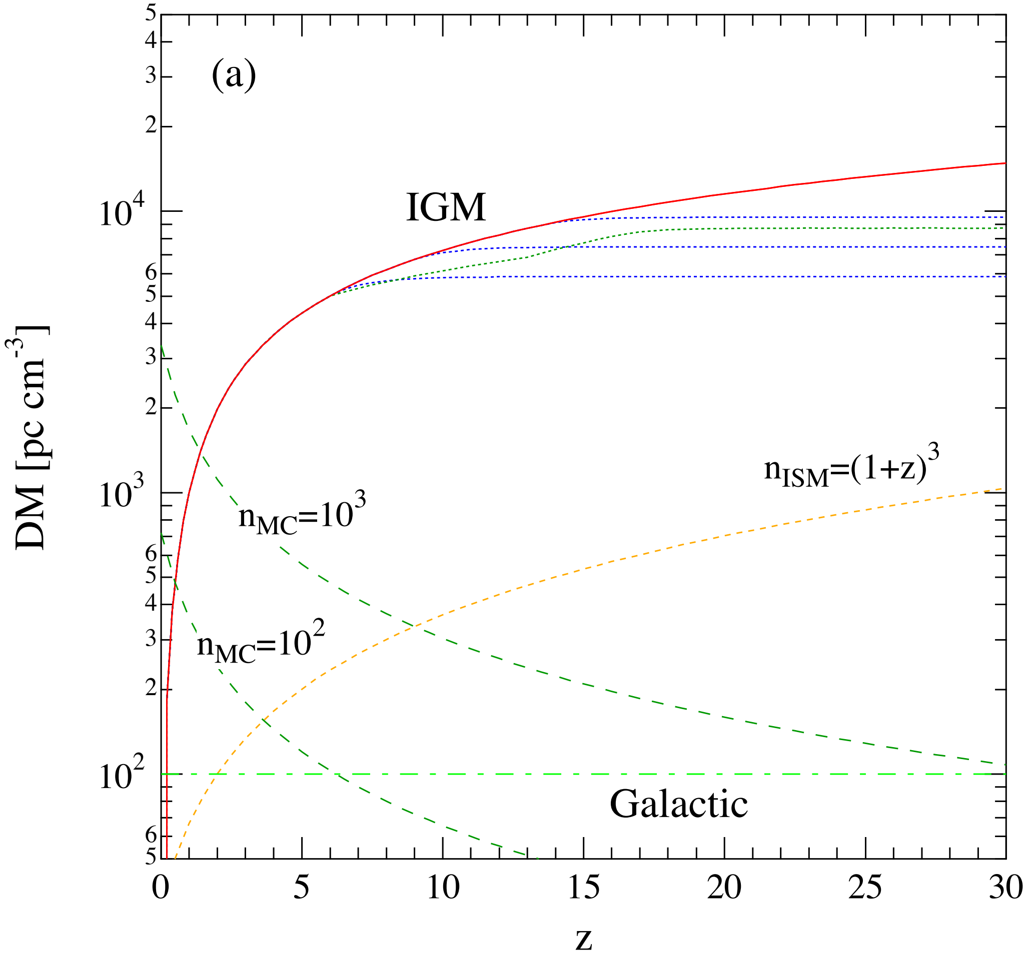
Lorimer+ Science 07

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)





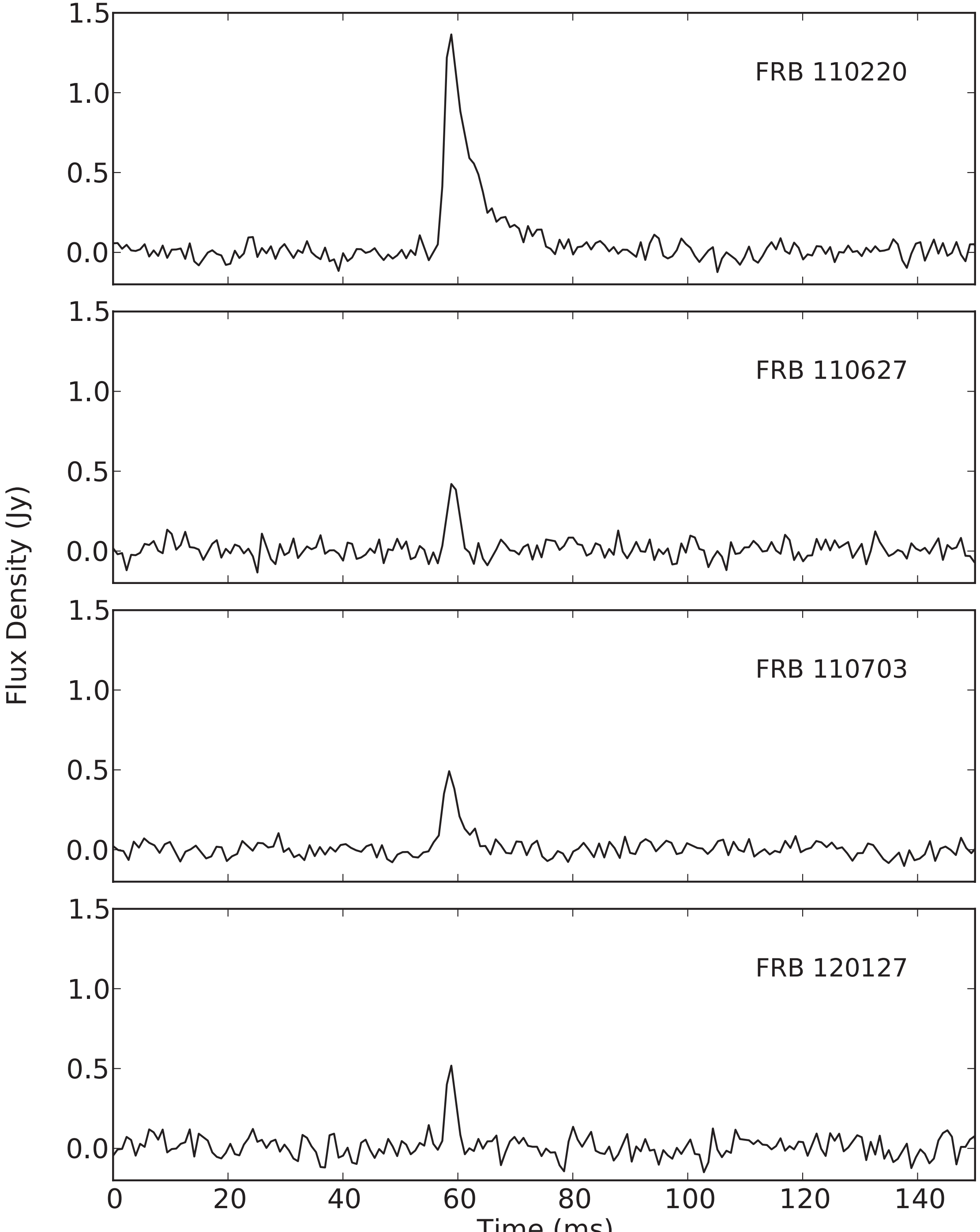
c.f. day time scale transient search by Waseda group

fast radio bursts

Thornton+ Science 13

Parkes High Time Resolution Universe survey

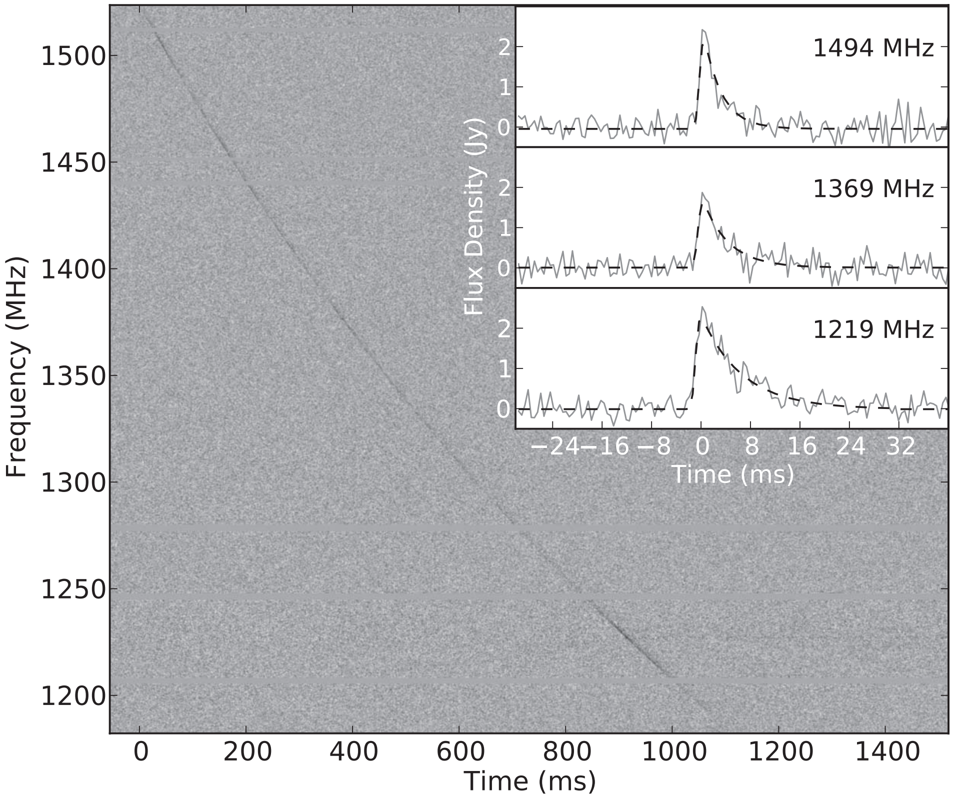
see also Kulkarni+ arXiv:1402.4766



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},10R_{GRB}!



fast radio bursts

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)	$-12^{\circ}\ 24'$	$-44^{\circ}\ 44'$	$-02^{\circ}\ 52'$	$-18^{\circ}\ 25'$
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
$S_\nu D^2$ ($\times 10^{12}$ Jy kpc^2)	10.2	1.9	5.1	1.4
Energy released, E (J)	$\sim 10^{39}$	$\sim 10^{37}$	$\sim 10^{38}$	$\sim 10^{37}$

origin?

from B. Zhang's slides

FRBs: Models proposed so far

as of June 2014

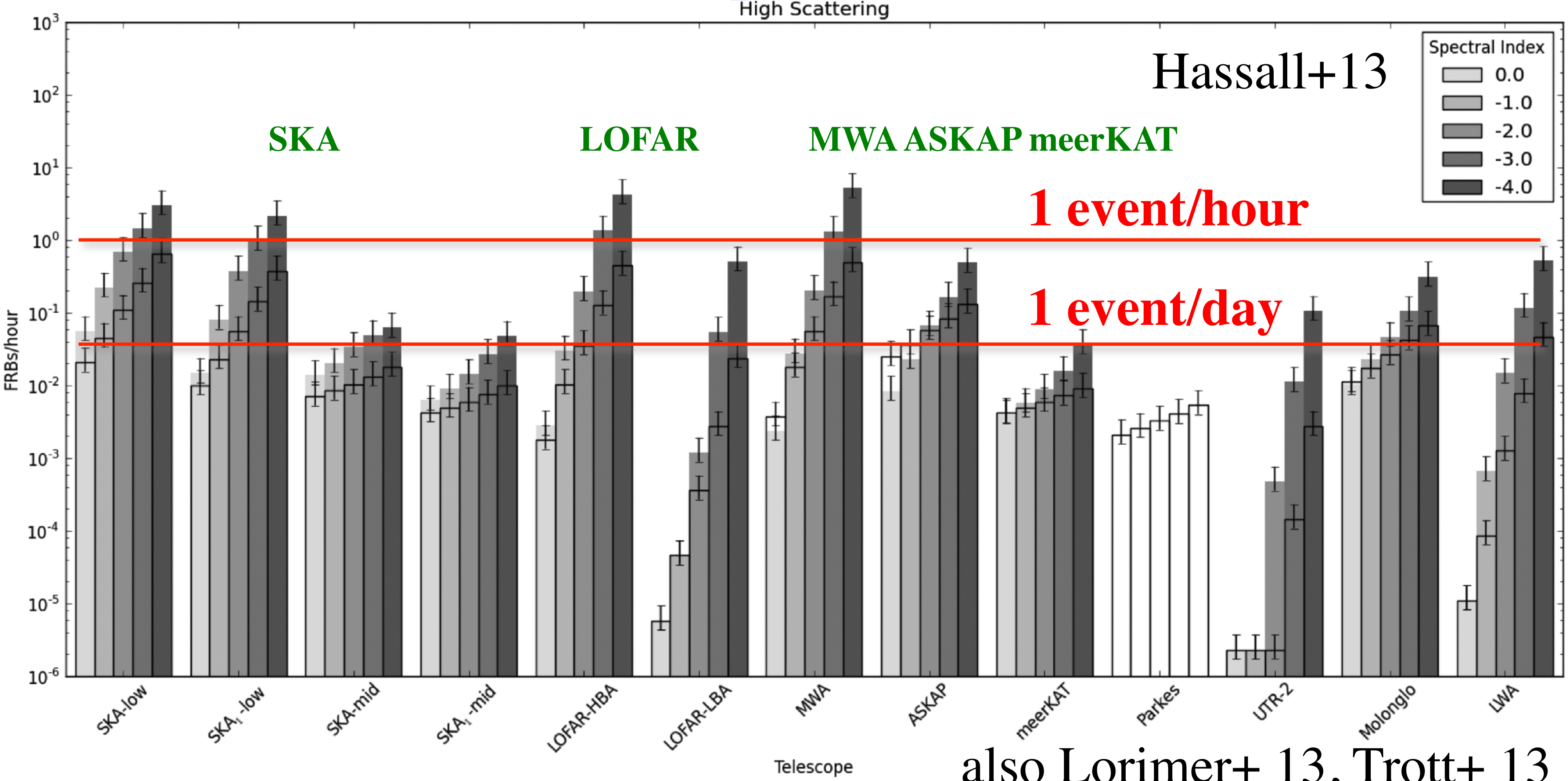
- Collapses of supra-massive neutron stars to black holes (thousands to million years later after their births), ejecting "magnetic hair" (Falcke & Rezzolla 2013)
- Magnetospheric interaction during NS-NS mergers (Totani 2013)
- Mergers of binary white dwarfs (Kashiyama et al. 2013)
- Magnetar radio bursts (Popov et al. 2007, 2013; Kulkarni et al. 2014)
- Cosmic sparks from superconducting strings (Vachaspati 2008)
- Evaporation of primordial black holes (Keane et al. 2012)
- Flaring stars (Loeb et al. 2013)
- Probably just local events, not astrophysical origin (Kulkarni et al. 2014)

……

a lot more since!

partial correlation with GRBs possible?

fast radio bursts: future expectations



Hassall+13

SKA **LOFAR** **MWA ASKAP meerKAT**

1 event/hour

1 event/day

also Lorimer+ 13, Trott+ 13

large sample of IGM dispersion measurements possible

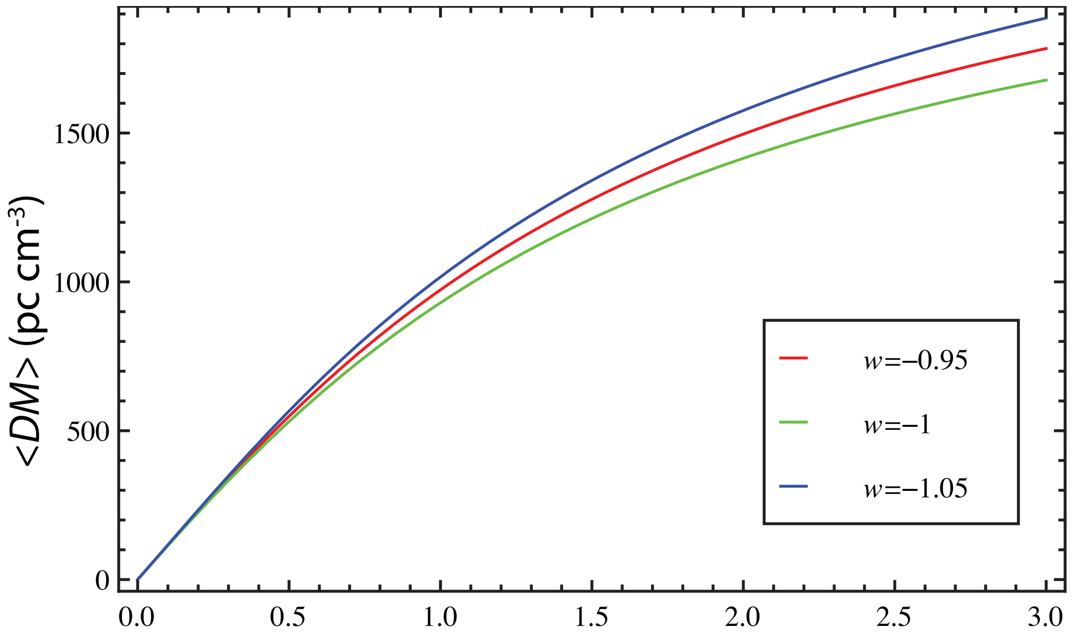
need independent redshift for cosmological use

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

Macquart+ 15, Margalit+ 15

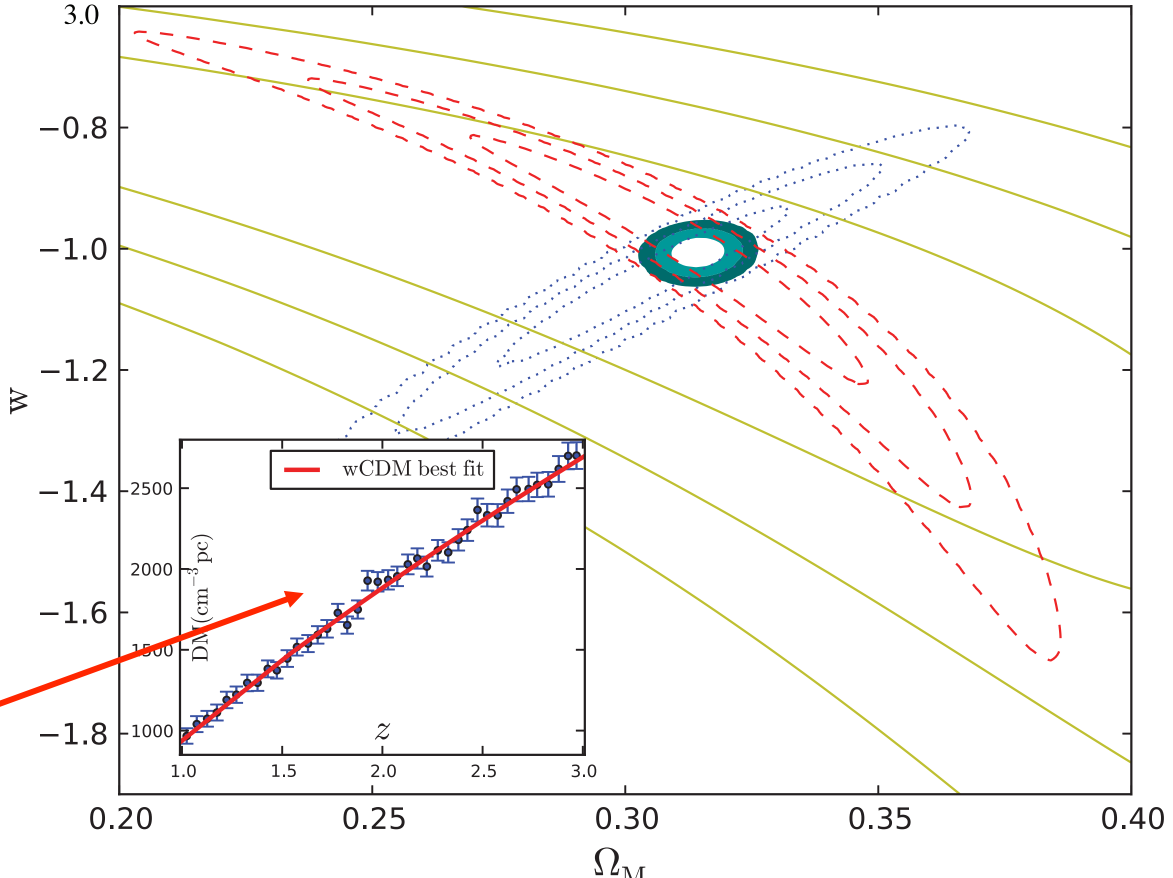
FRBs as probes of dark energy?

Zhou+ 14, Gao+ 14



DM as distance indicator:
precise measurement of
DE EOS with large sample?

--- 580 SN Ia
--- BAO inc. forecast
--- 1000 FRBs



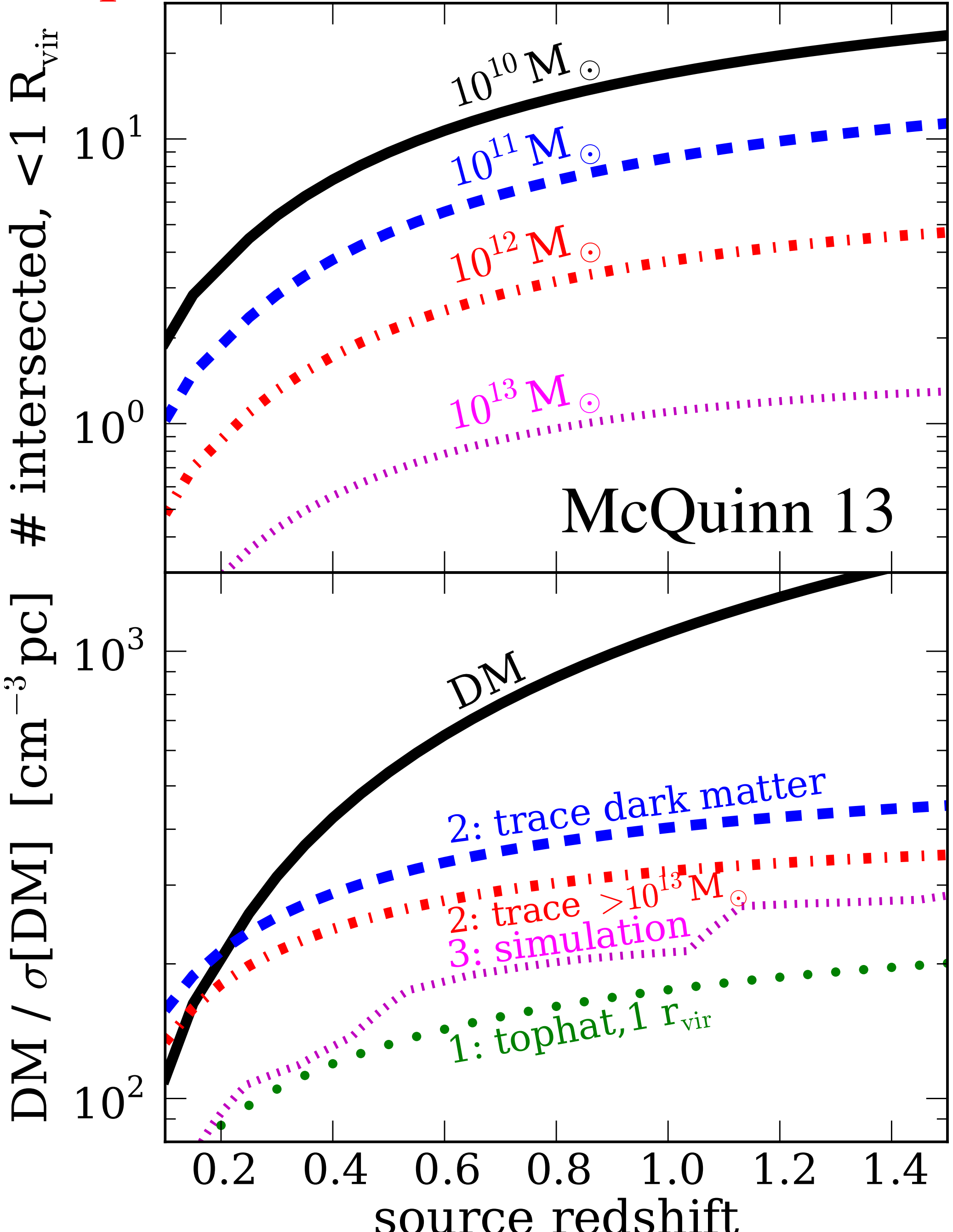
mean of DMs per z bin
in 40 bins up to z~3
for 1000 simulated FRBs

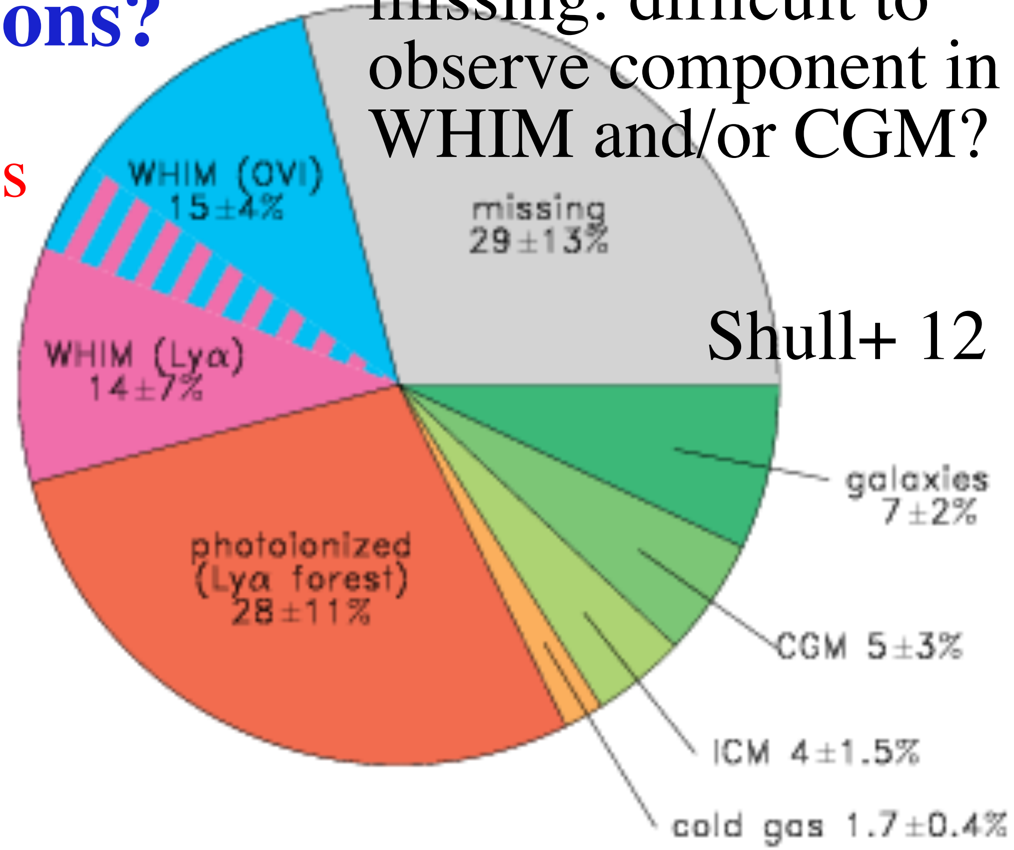
FRBs as probes of missing baryons?

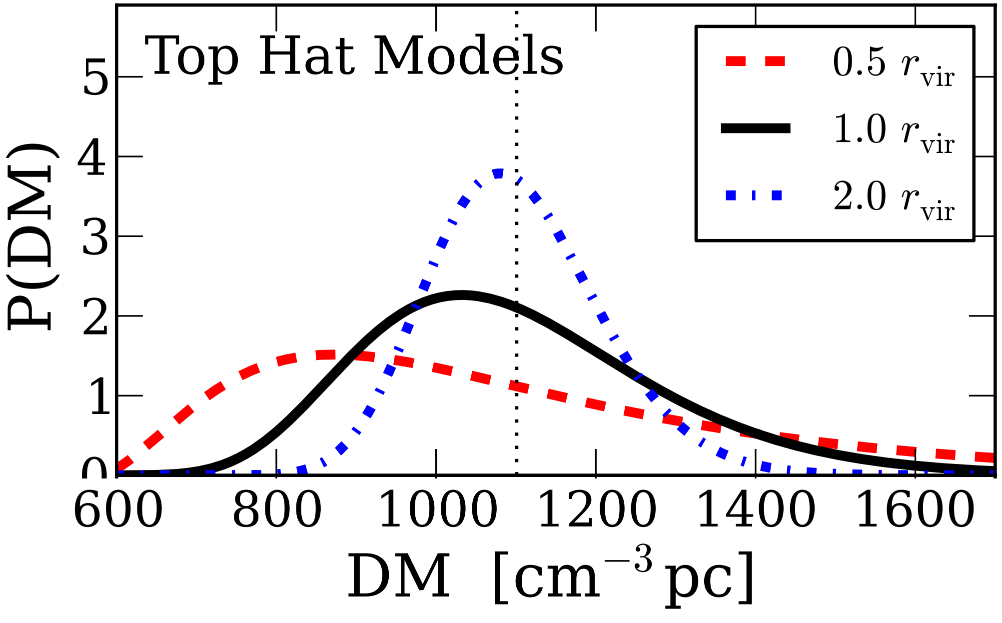
large variance expected due to LSS

-> probe distribution of ionized baryons

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



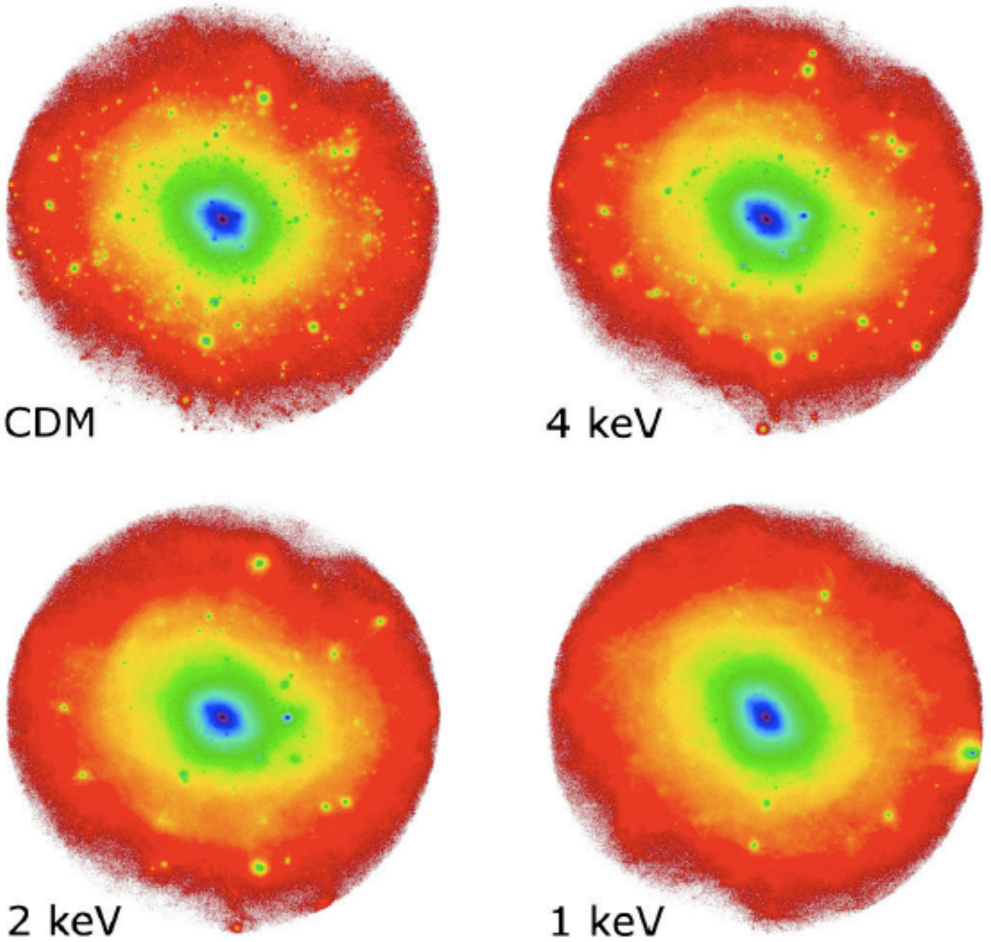




cross correlation with galaxies

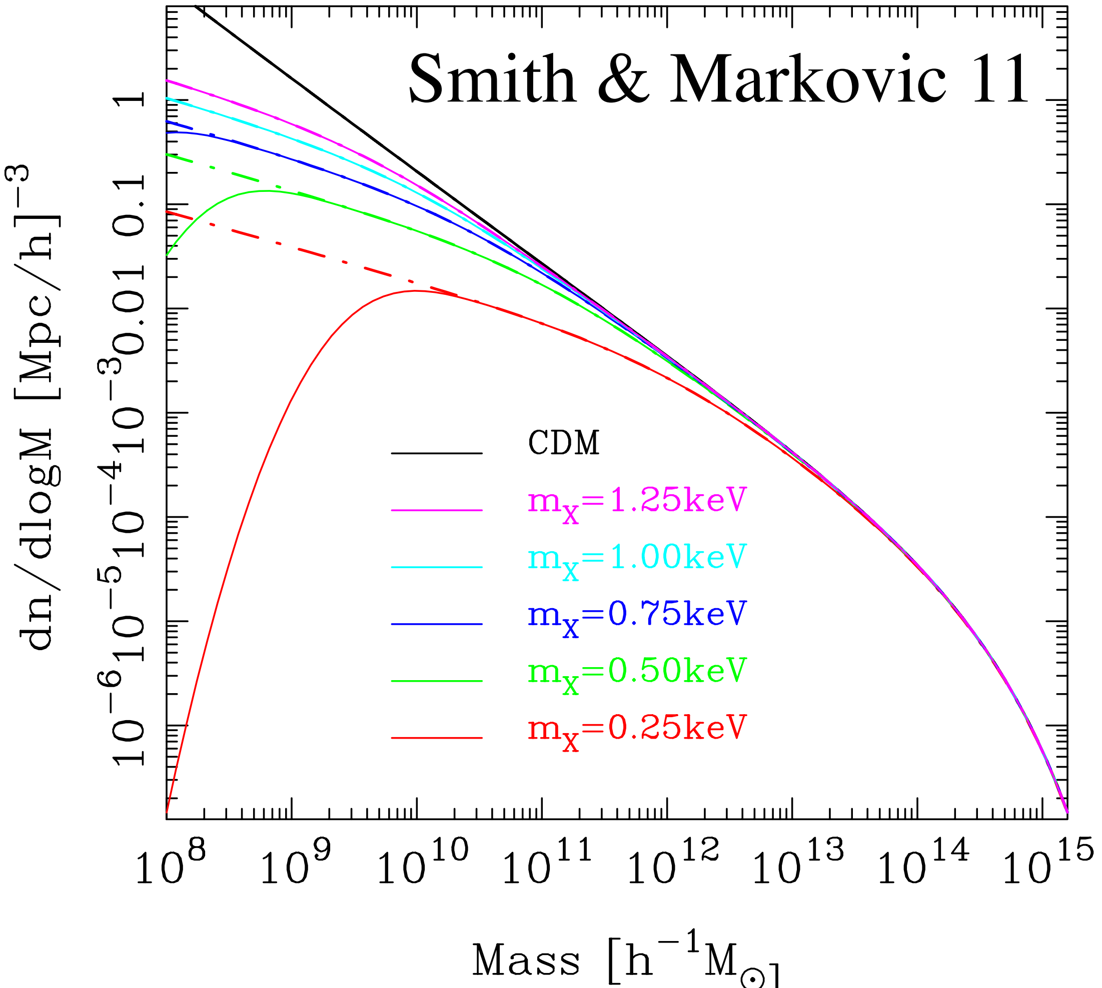
warm dark matter

- warm dark matter becomes non-rela. when galactic scales enter horizon
  -> suppress LSS by free streaming below m_{WDM}-dependent scale
- particle physics motivation, e.g. sterile neutrinos
- solve missing Galactic satellite problem? <-> astrophysical feedback
- current lower limits $m_{\mathrm{WDM}} >\sim 1$ keV   Viel+ 05, Smith & Markovic 11

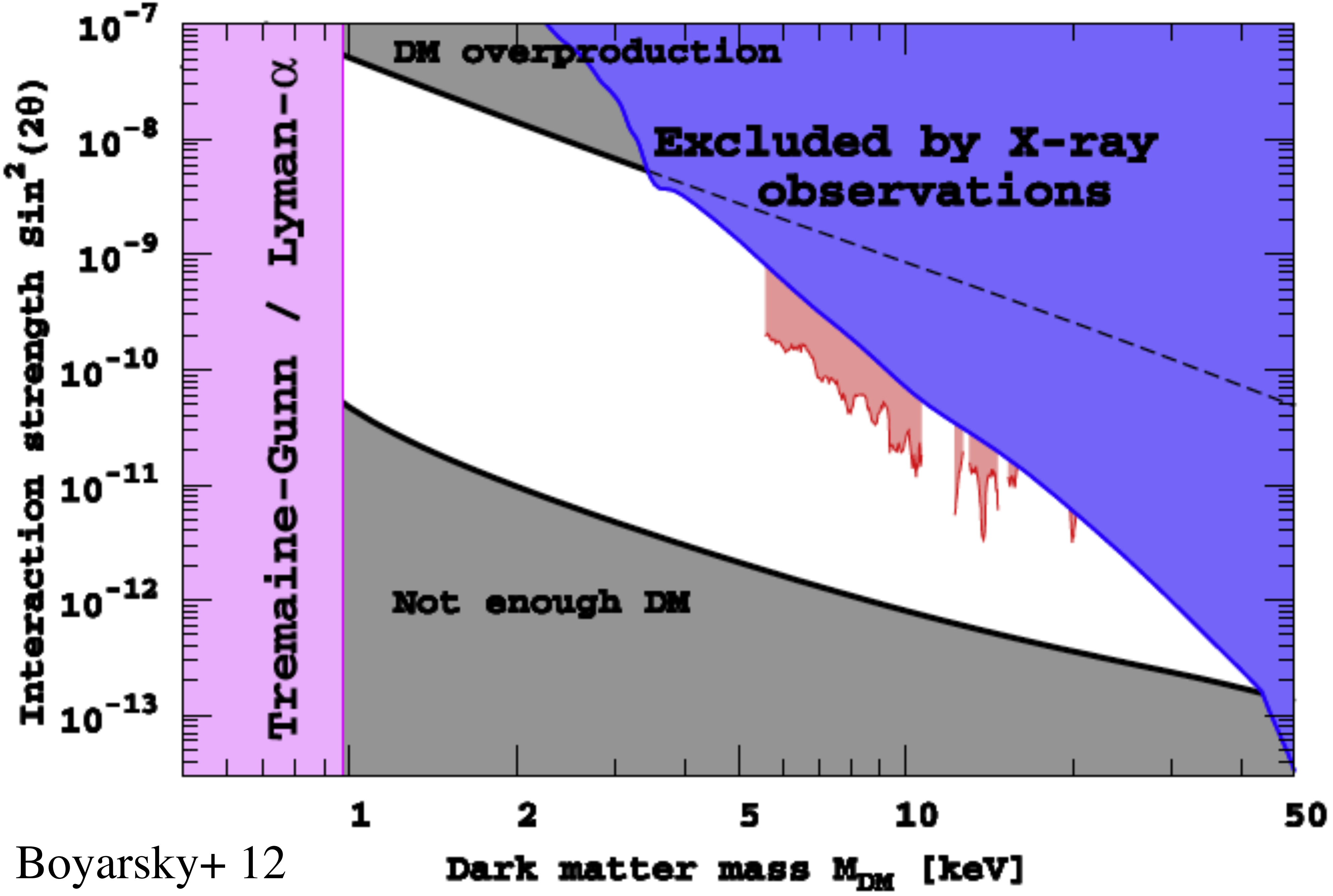


WDM simulation Polisensky & Ricotti 11

halo mass func. at z=0



sterile neutrinos as dark matter: current constraints



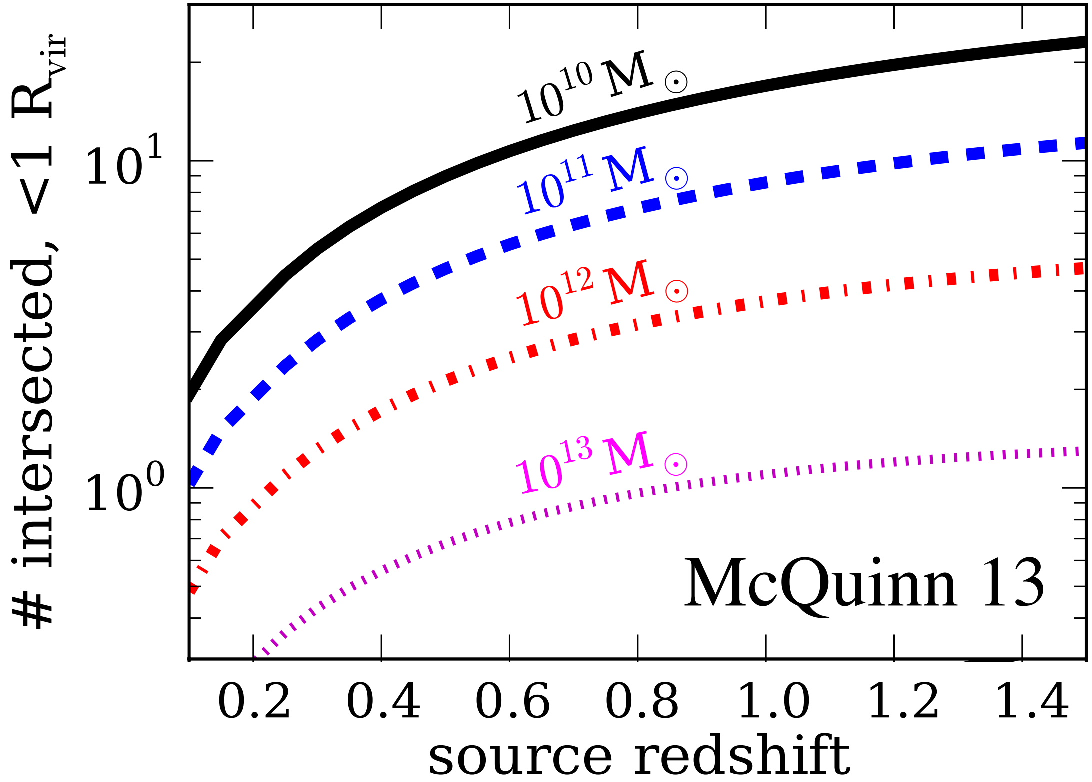
Boyarsky+ 12

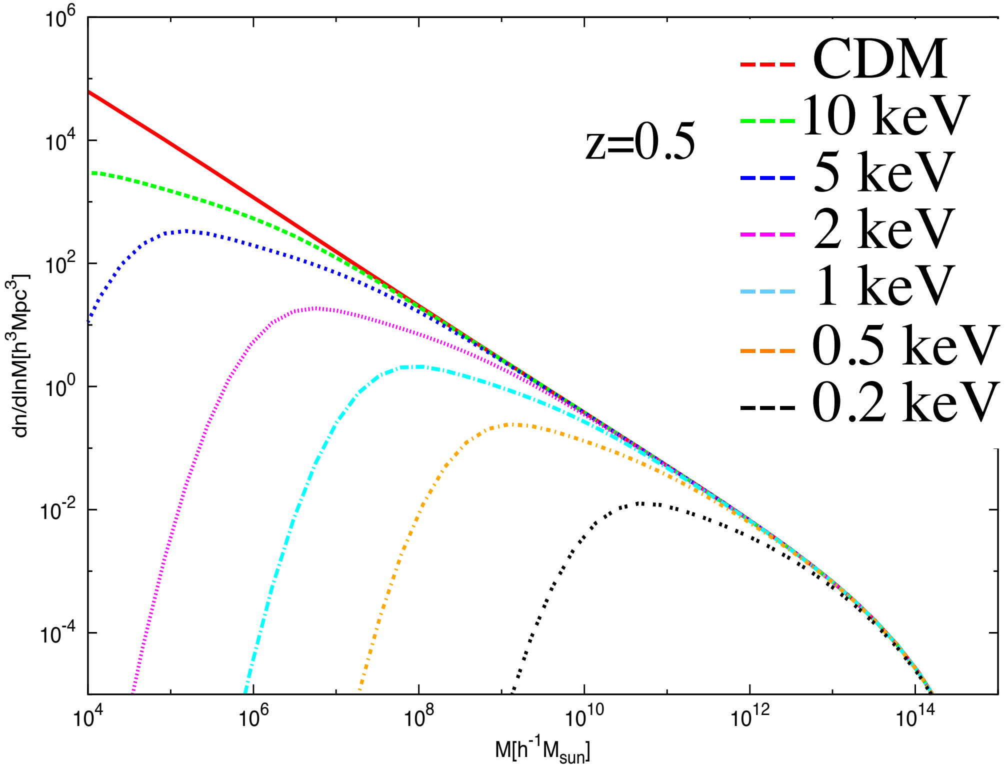
FRBs as probes of missing satellite problem?

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

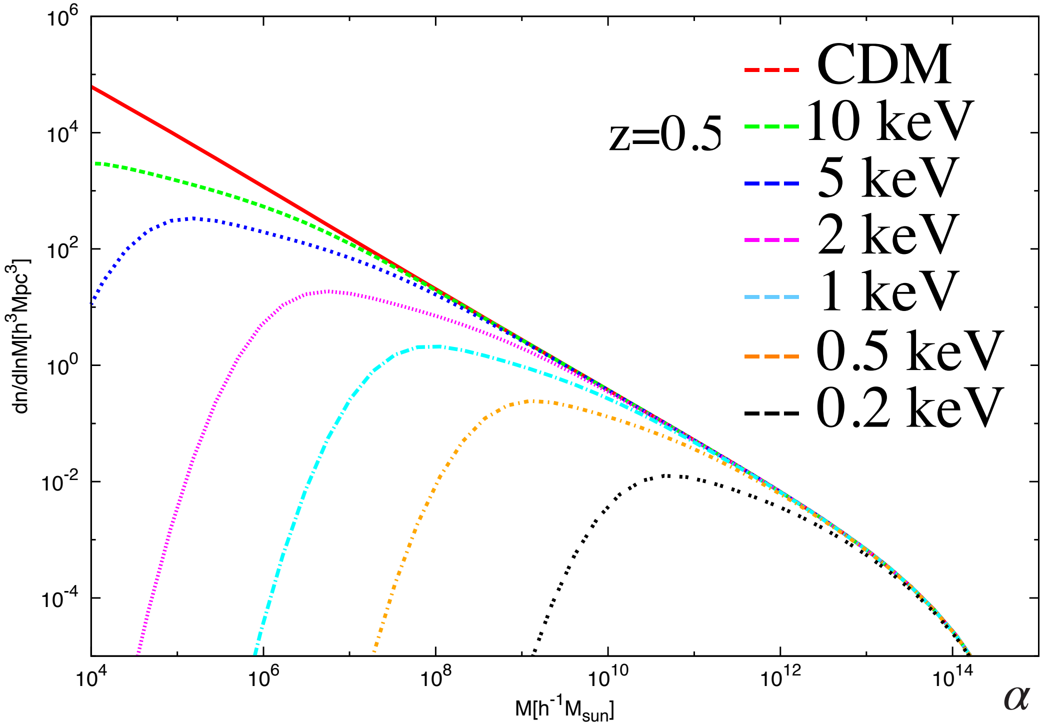
SI, Ichiki, Shimabukuro, in prep.





halo mass function for WDM

follow Smith & Markovic 11



$$\frac{dn}{dM}(M,z) = \frac{1}{2}\left\{1+\mathrm{erf}\left[\frac{\log_{10}(M/M_{\rm fs})}{\sigma_{\log M}}\right]\right\}\left[\frac{dn}{dM}\right]_{\rm PS}$$

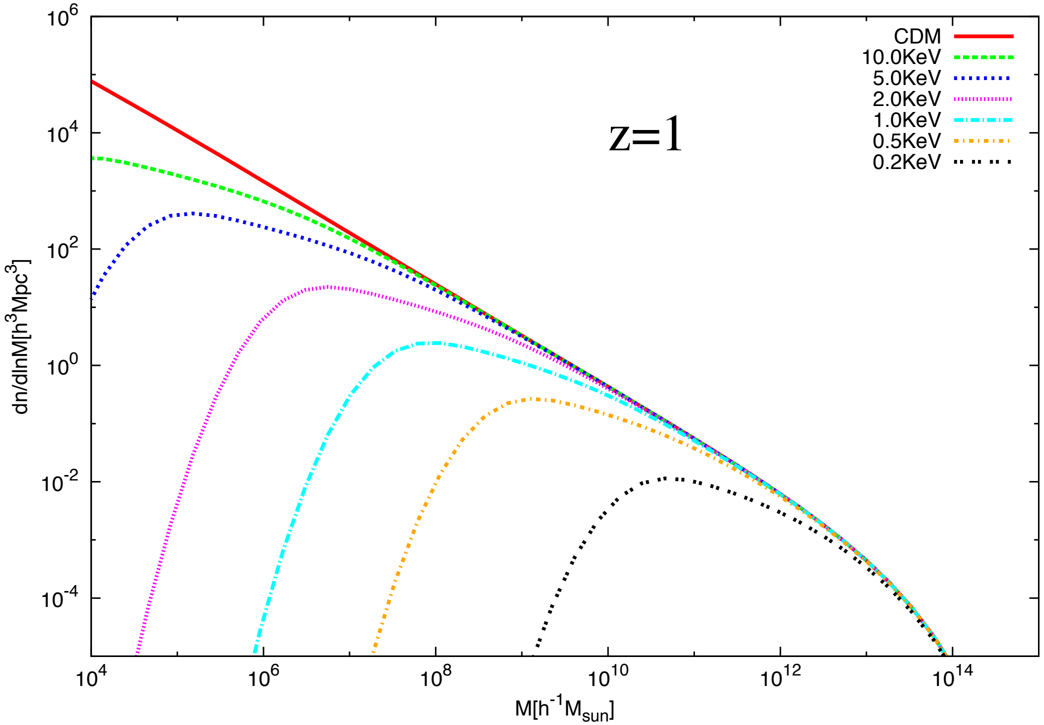
$$M_{\rm fs} = \frac{4}{3}\pi\left(\frac{\lambda_{\rm fs}}{2}\right)^3 \bar{\rho}_m$$

$$\lambda_{\rm fs} \sim 0.11\left(\frac{\Omega_{\rm WDM}h^2}{0.15}\right)^{1/3}\left(\frac{m_{\rm WDM}}{\rm keV}\right)^{-4/3} \quad [\mathrm{Mpc}]$$

$$P_{\rm WDM}(k) = P_{\rm CDM}(k)\{[1+(\alpha k)^{2\mu}]^{-5/\mu}\}^2,$$

$$\alpha = 0.049\left(\frac{m_{\rm WDM}}{\rm keV}\right)^{-1.11}\left(\frac{\Omega_{\rm WDM}}{0.25}\right)^{0.15}\left(\frac{h}{0.7}\right)^{1.22} h^{-1}\ \mathrm{Mpc}]$$

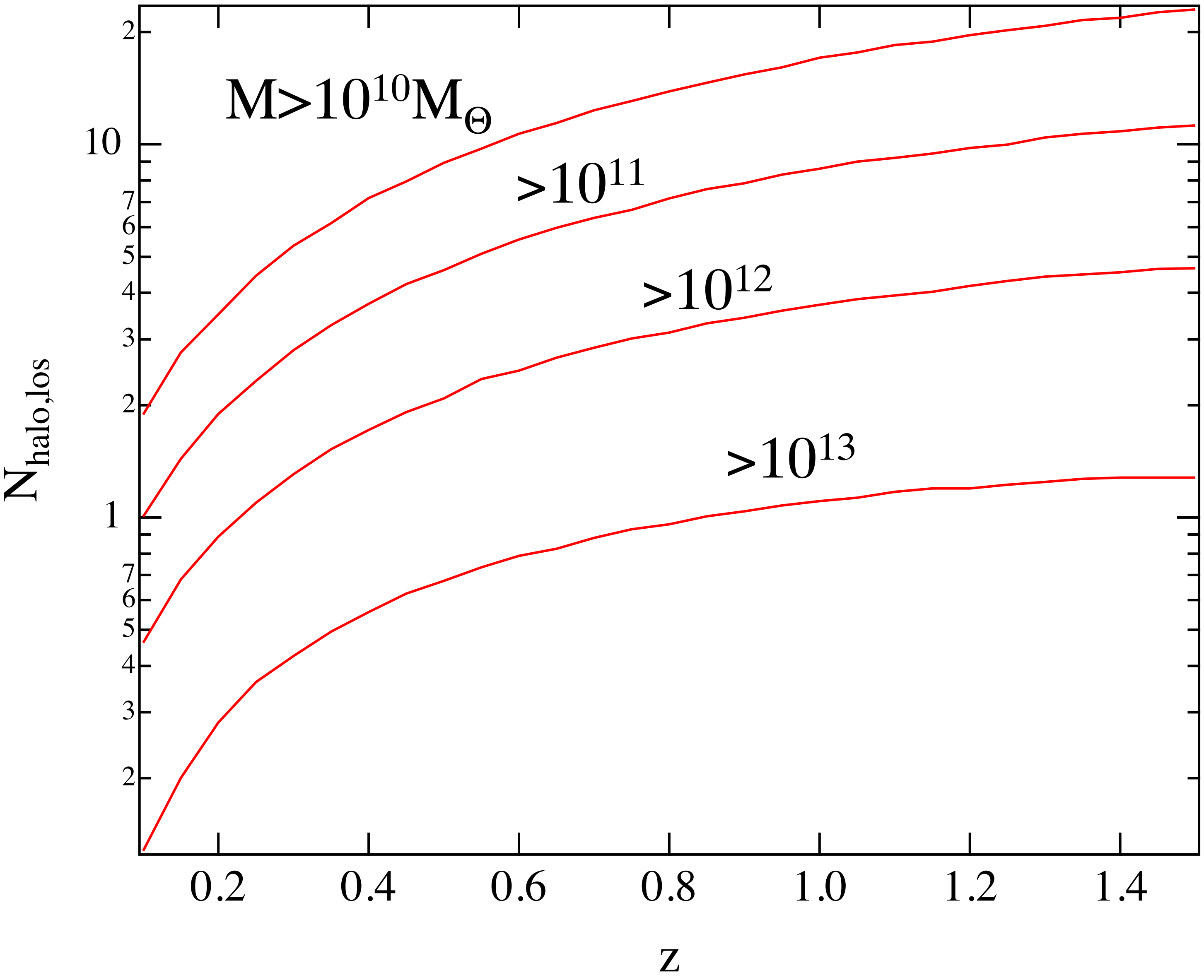
$$\mu = 1.12$$



halos intersecting along line of sight

CDM

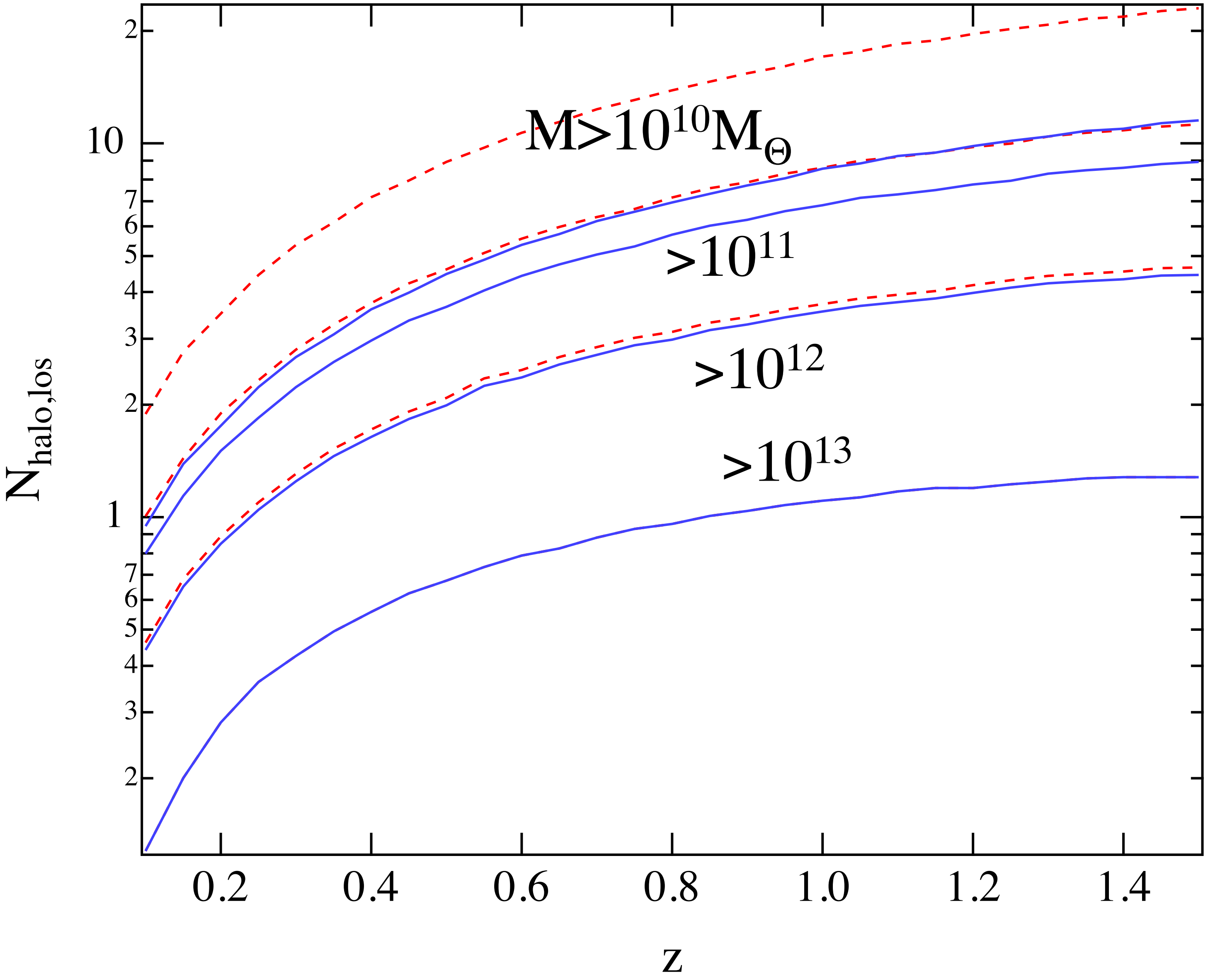
$N_{halo,los} = \iint dM\, dz\, (cdt/dz)$
$x\ (R_{vir}\ (M,z))^2\ dN/dM\ (M,z)$



halos intersecting along line of sight

WDM m=1keV vs CDM

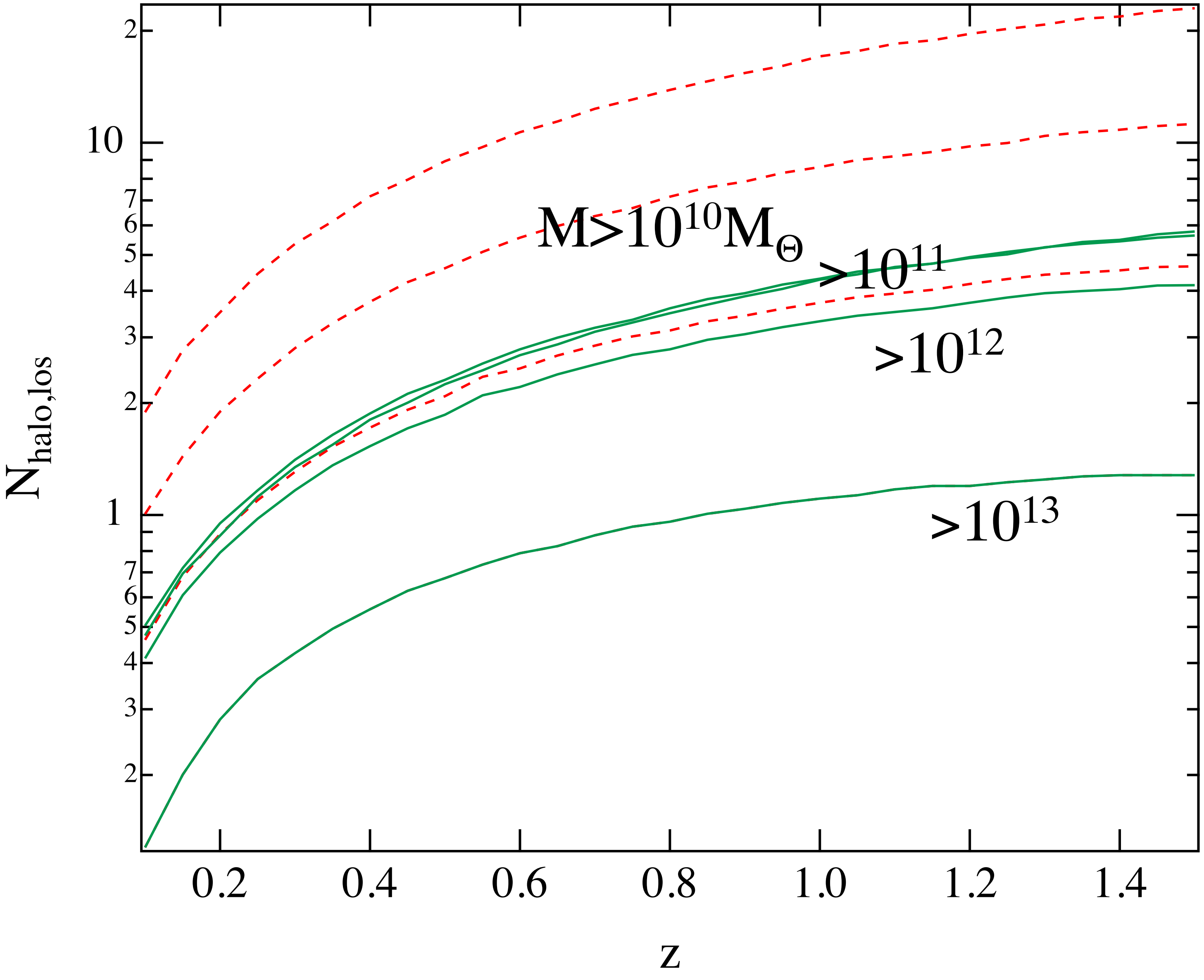
$N_{\mathrm{halo,los}} = \iint dM\, dz\, (c dt/dz)$
$\times\, (R_{\mathrm{vir}}(M,z))^2\, dN/dM\, (M,z)$



halos intersecting along line of sight

WDM m=0.5keV vs CDM

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



dispersion measure: mean and variance

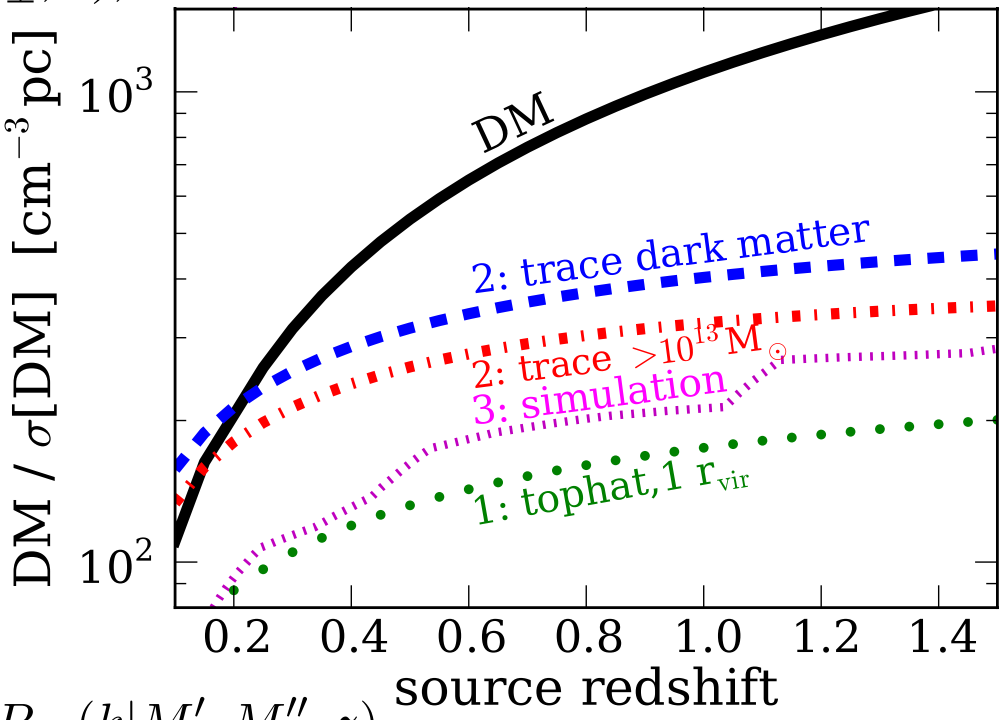
McQuinn 13

$$\mathrm{DM}(z_s) = \int_0^{\chi(z_s)} d\chi \, \frac{\rho_e(z,\hat{n})}{(1+z)^2} \qquad d\chi = c\,dz/H(z)$$

$$\sigma^2[\mathrm{DM}] = \int_0^{z_s} \frac{c\,dz_1}{a_1 H(z_1)} \int_0^{z_s} \frac{c\,dz_2}{a_2 H(z_2)} \, \bar{\rho}_e^2(0) \, \langle \delta_e(z_1)\delta_e(z_2) \rangle$$

$$\approx \int_0^{z_s} \frac{c\,dz}{H(z)} (1+z)^2 \bar{\rho}_e^2(0) \int \frac{d^2k_\perp}{(2\pi)^2} P_e(k_\perp, z),$$

$$P_e(k,z) = \langle |\tilde{\delta}_e(k,z)^2| \rangle$$



standard halo model

$$P(k) = P_{1h}(k) + P_{2h}(k)$$

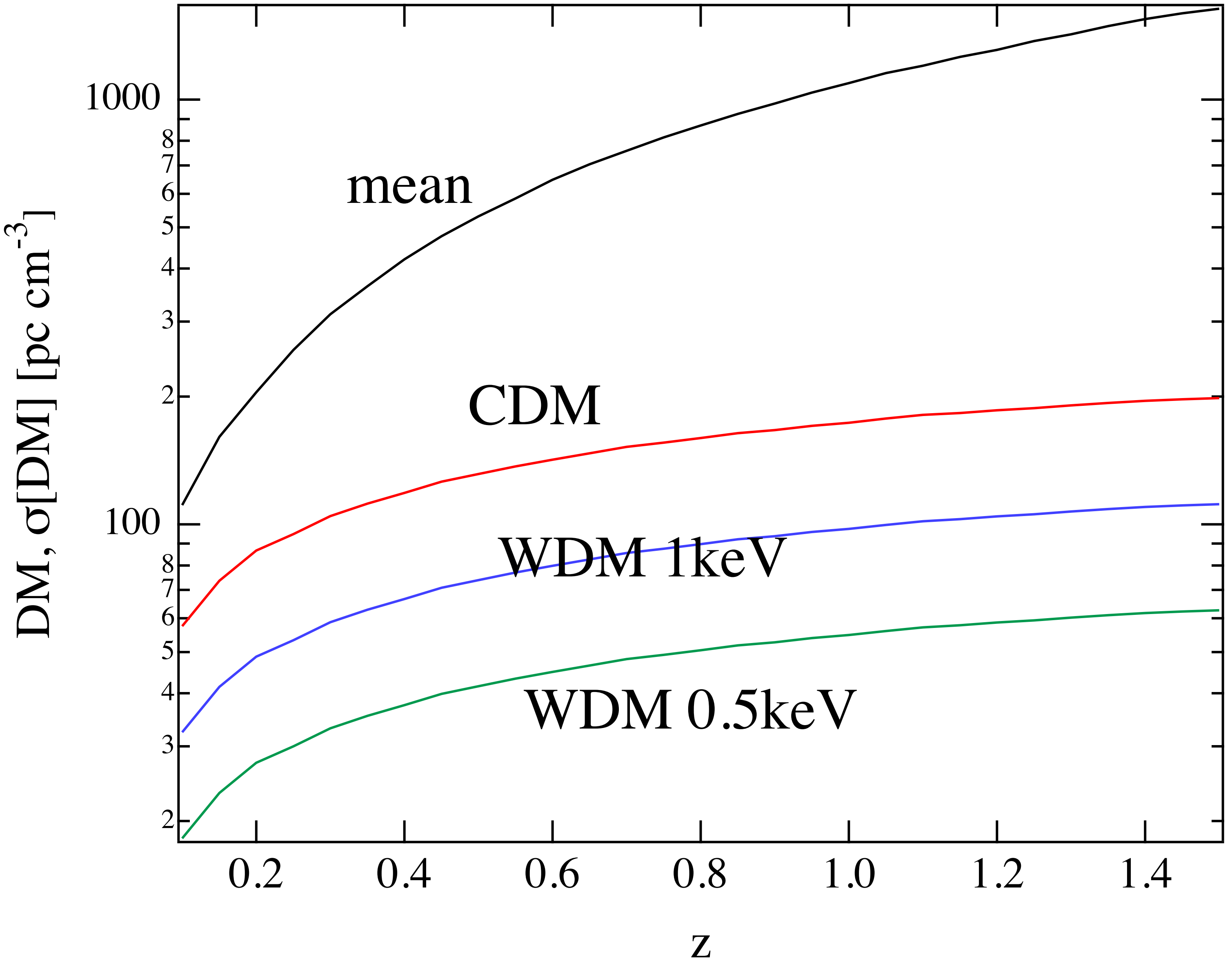
$$P_{1h}(k,z) = \int_0^\infty dM \, n(M,z) \left(\frac{M}{\bar{\rho}}\right)^2 |u(k|M)|^2$$

$$P_{2h}(k,z) = \int_0^\infty dM' \, n(M',z) \, \frac{M'}{\bar{\rho}} \, u(k|M') \times \int_0^\infty dM'' \, n(M'',z) \, \frac{M''}{\bar{\rho}} \, u(k|M'') \, P_{hh}(k|M',M'',z)$$

$$P_{hh}(k|M',M'',z) = b(M',z)b(M'',z)P^L(k,z)$$

$$u(k|M) = \int_0^{R_v} dr \, 4\pi r^2 \, \frac{\sin(kr)}{kr} \, u(r|M) \qquad b(M) = 1 + \frac{\nu^2 - 1}{\delta_c}$$

dispersion measure: mean and variance



top hat profile
$<R_v$

今後： m_{WDM}に対する制限の定量化
missing satellite問題との関連（WDM解に限らず）
光赤外、X線とのcross correlationの検討

まとめ

- 銀河スケール以下の揺らぎの性質は未解明
- 最近発見されたFRBは大きな電波分散を示す
  -> z~1程度の距離で電波分散は主にIGM起源
- 将来は大きなサンプルで独立にz測定が期待できる
  -> z~1までのIGM電離成分の総量+揺らぎのプローブ
- WDMに対する新たな制限?
  missing satellite問題解決の糸口?
  他の方法と相補的