21cm Line and Dark Matter

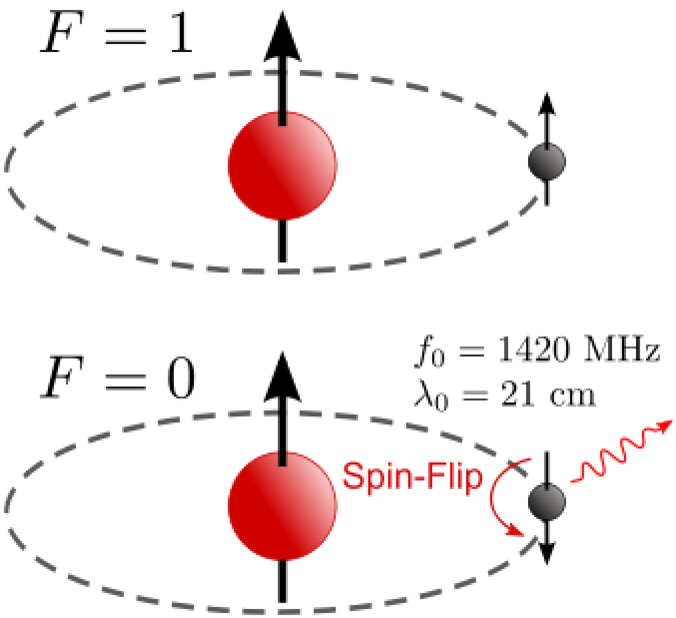
Kiyotomo ICHIKI (Nagoya U.)

review part references
SKA science book
Bullok and Bolan-Kolchin, ARAA, 2017

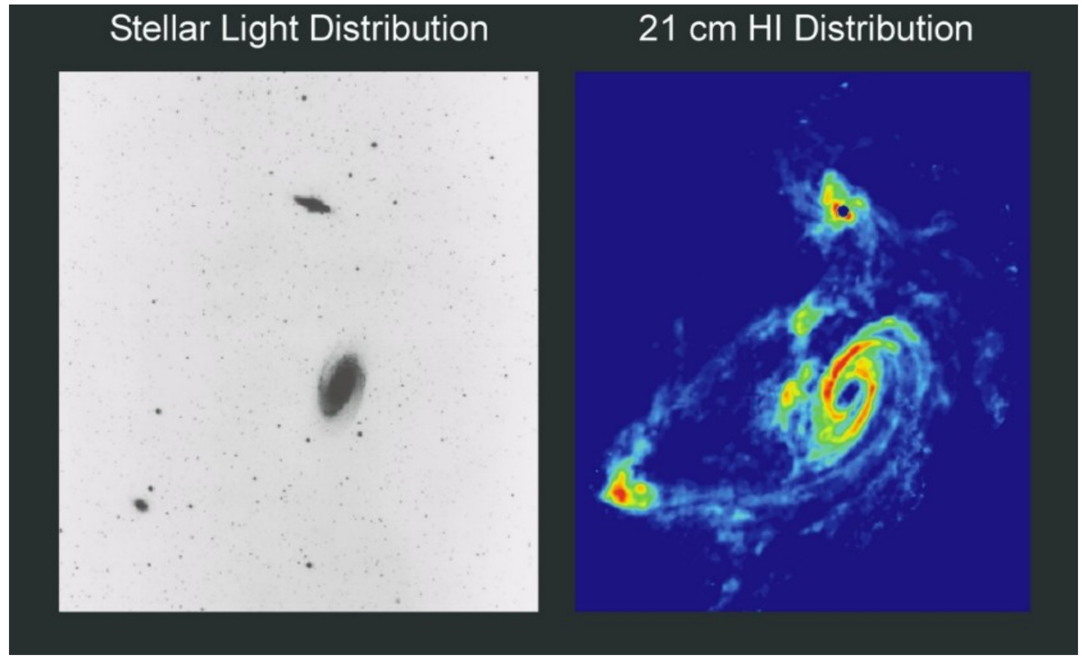
seminar part is based on:
Shimabukuro, Ichiki, Inoue and Yokoyama, PRD '14
Ichiki, Shimabukuro and Inoue, in progress

contents

what is the 21cm line?



21cm line photons are emitted from the hyperfine structure transition of the hydrogen

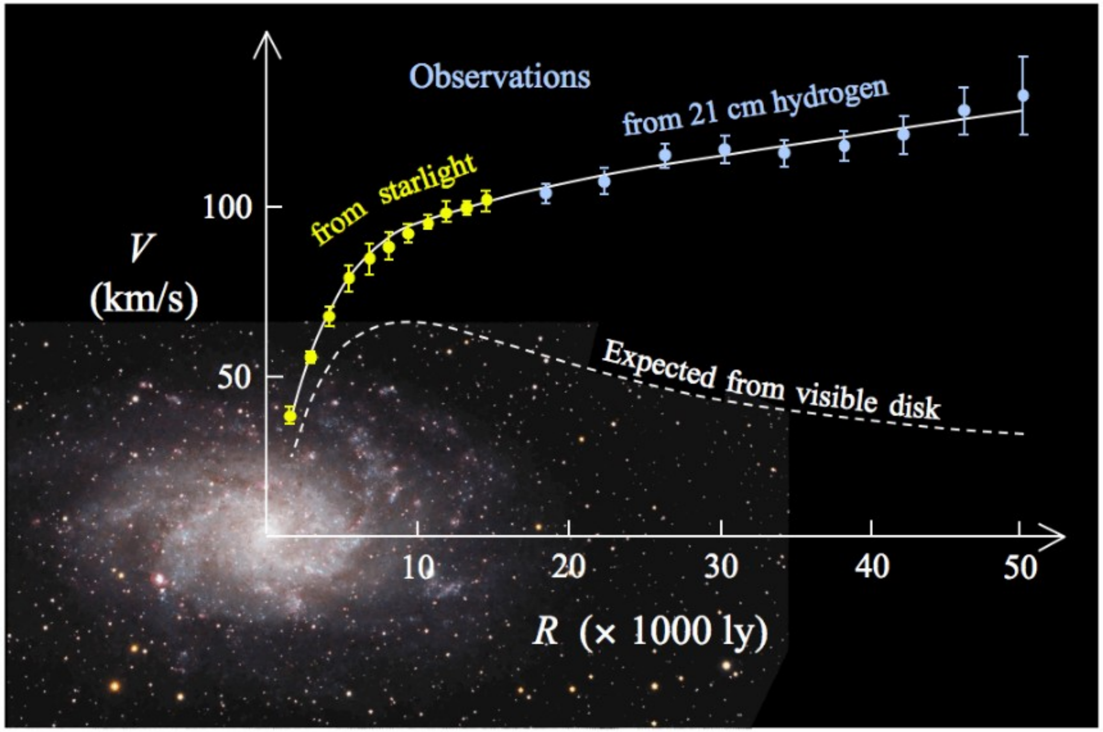


because hydrogen is most abundant in the universe 21cm line is frequently used in radio astronomy

spin temperature determines relative abundance

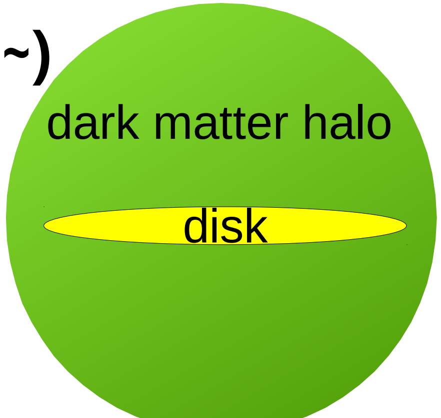
$$\frac{n_{\mathrm{para}}}{n_{\mathrm{anti-para}}} = \frac{3}{1} \exp\left(-\frac{h\nu_{21}}{kT_s}\right)$$

important connection between the 21cm line and Dark Matter



- In 1970s, astronomers found not the Kepler motion, but the flat rotation curve in M31 using 21cm line (V. Rubin+,1970~)

$$v(r) = \sqrt{\frac{GM(r)}{r}} \Rightarrow \rho \propto r^{-2}$$



what is the epoch of reionization (EoR)

$z = 1080$ — recombination (CMB)

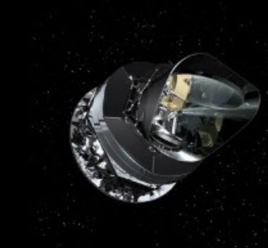
$z \sim 30$ — First star form (Cosmic Dawn)

$z \sim 12$ — galaxies form (EoR start)

$z \approx 6$ — reionization (EoR end)

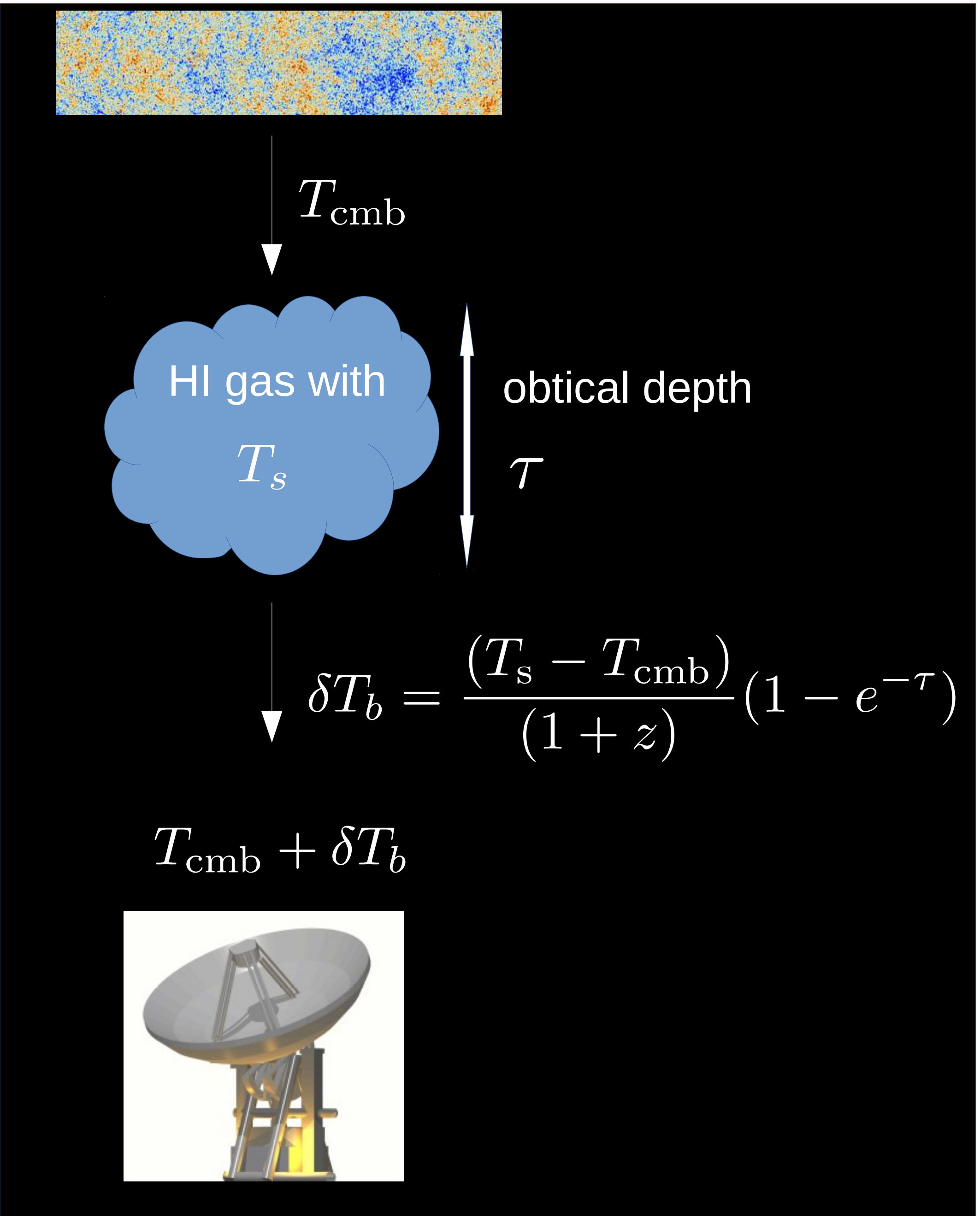
large scale structure

$z = 0$ — today



push the frontier using
21cm observation

EoR 21cm observation



we observe 21cm line with CMB as background light

if $T_s > T_{\rm cmb}$ **emission**

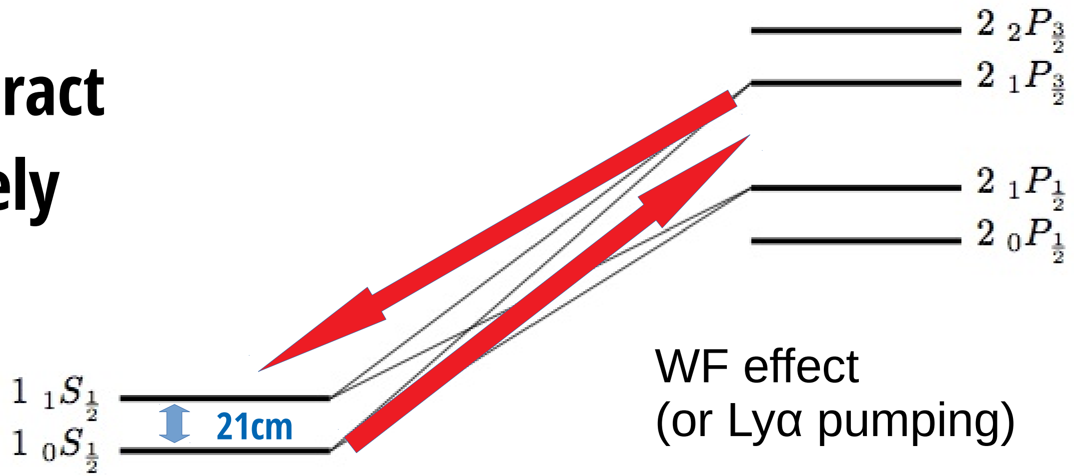
if $T_s < T_{\rm cmb}$ **absorption**

Because it is a line, we can observe the universe at each redshift

redshift	λ	ν
0	21cm	1420MHz
9	2.1 m	142MHz
19	4.2 m	71MHz

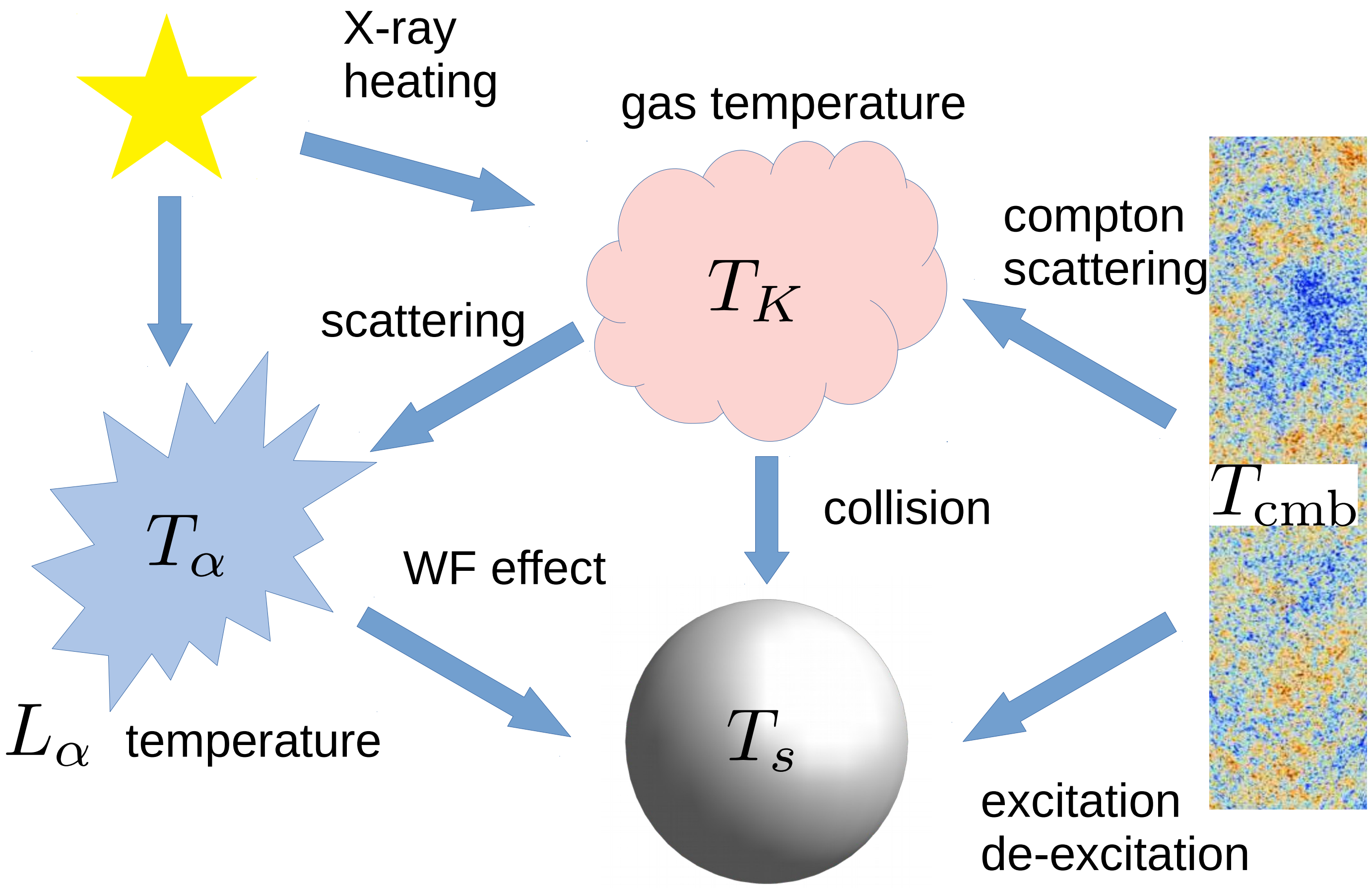
what determines spin temperature ?

- spin temperature (Ts) is affected by CMB (Tcmb), gas temperature (Tk), and by Lyα photons (Tα) (WF effect)
- Wouthuysen Field effect: HI in the grand state is excited into P state by Lyα, then deexcite into the spin-parallel S state (Ly α transition probability >> 21cm transition probability)
- Lyα photons frequently interact with HI gas, so approximately Tα=Tk



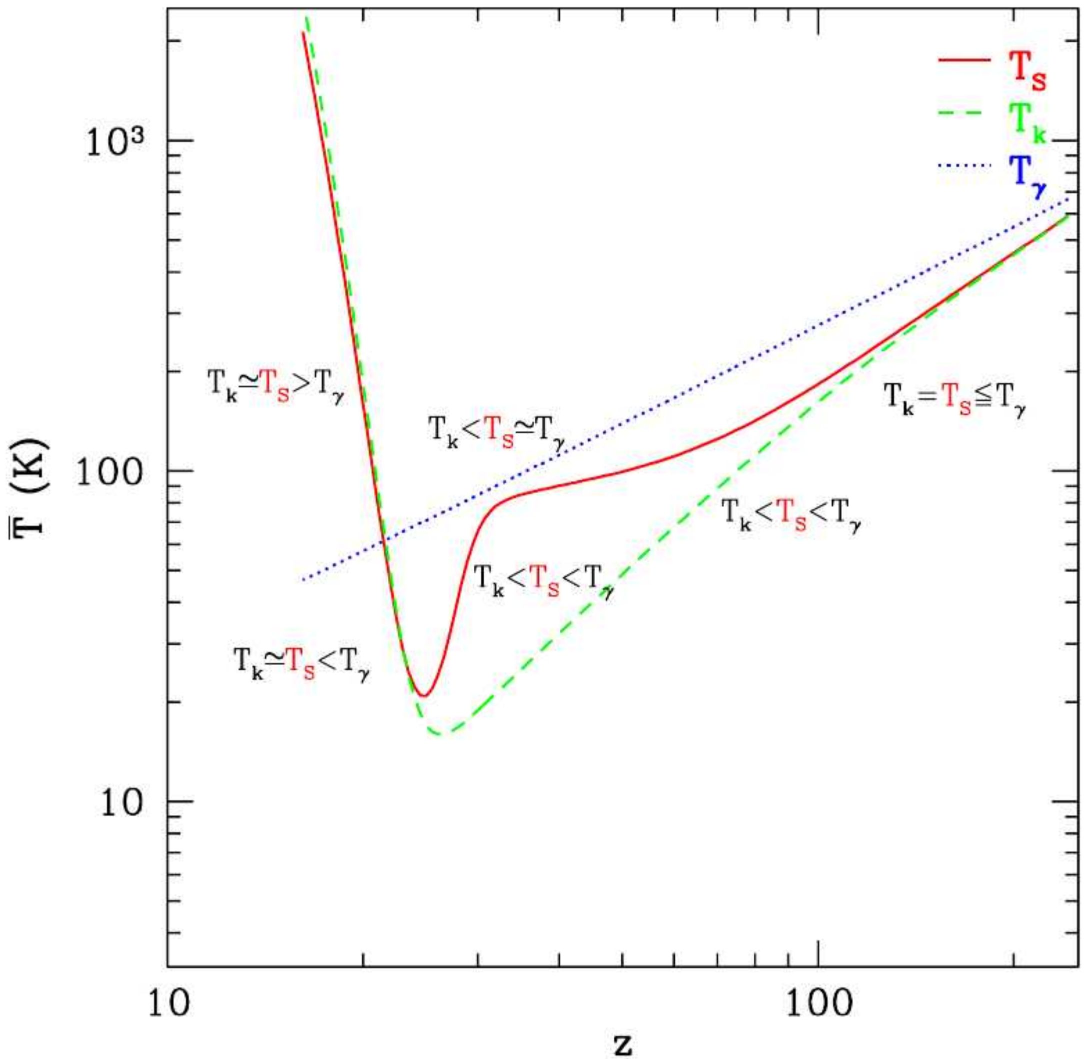
$$T_s^{-1} = (T_{\rm cmb}^{-1} + x_c T_K^{-1} + x_\alpha T_\alpha^{-1})/((1 + x_c + x_\alpha))$$

physics determining spin temperature



$$(1 + x_c + x_\alpha) T_s^{-1} = T_\gamma^{-1} + x_c T_K^{-1} + x_\alpha T_\alpha^{-1}$$

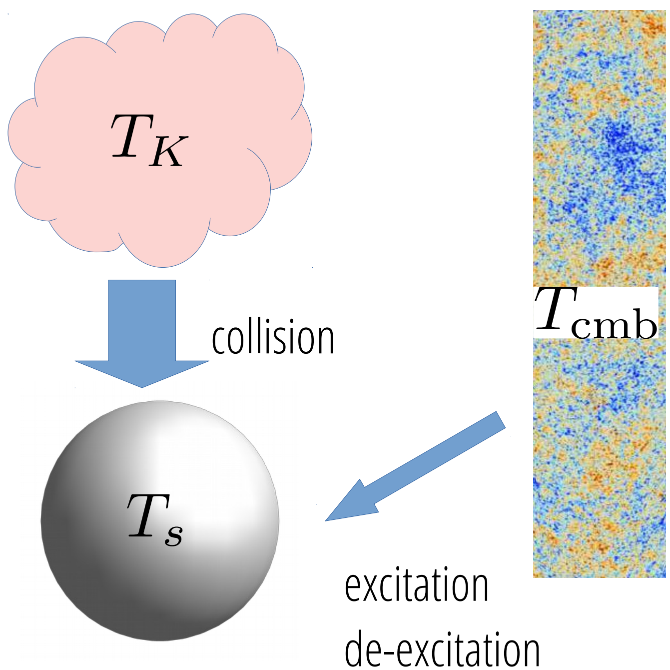
history of Ts

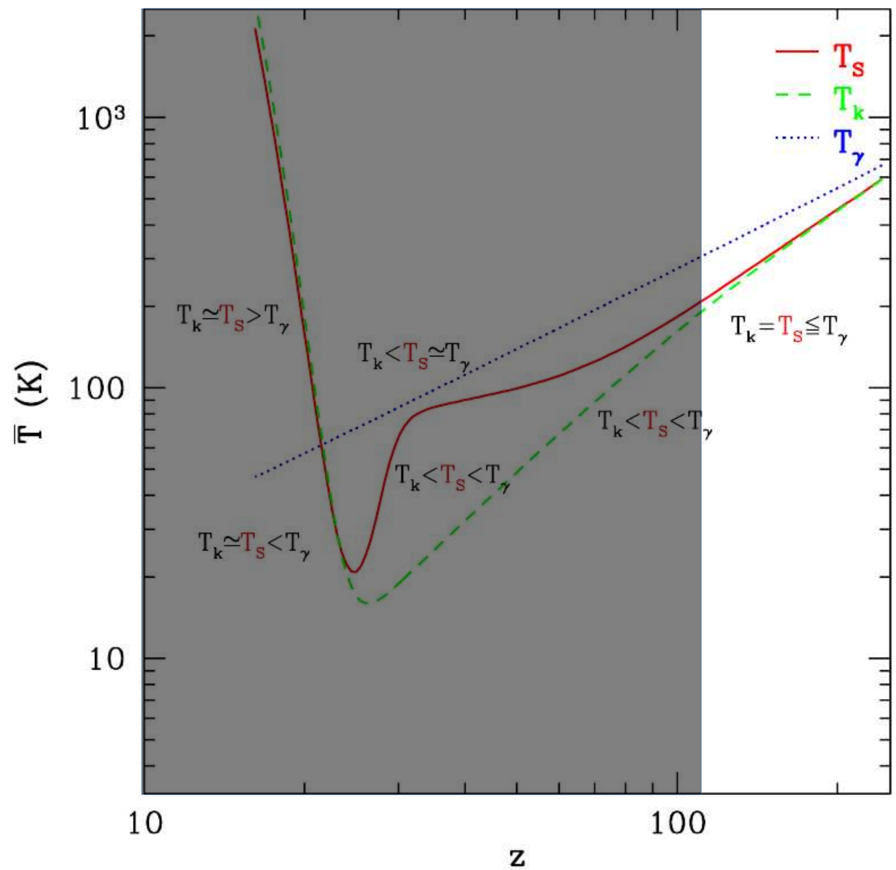


(Mesinger+, MNRAS, '11)

today past

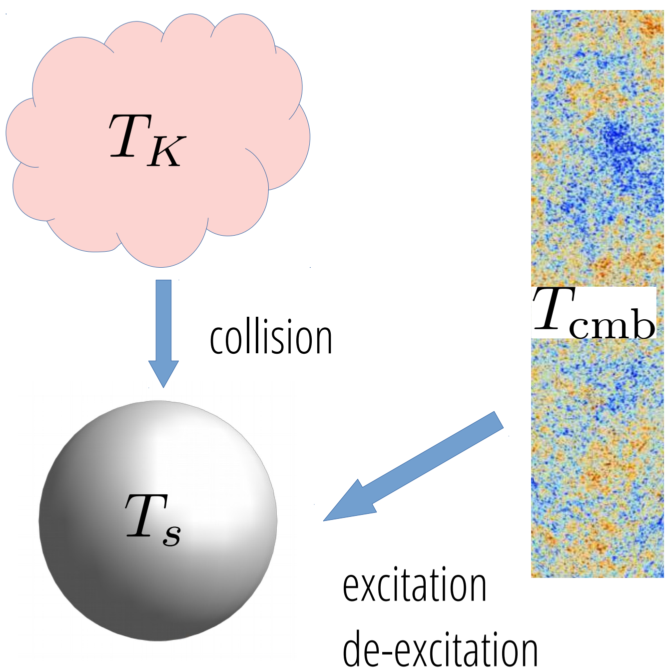
history of Ts

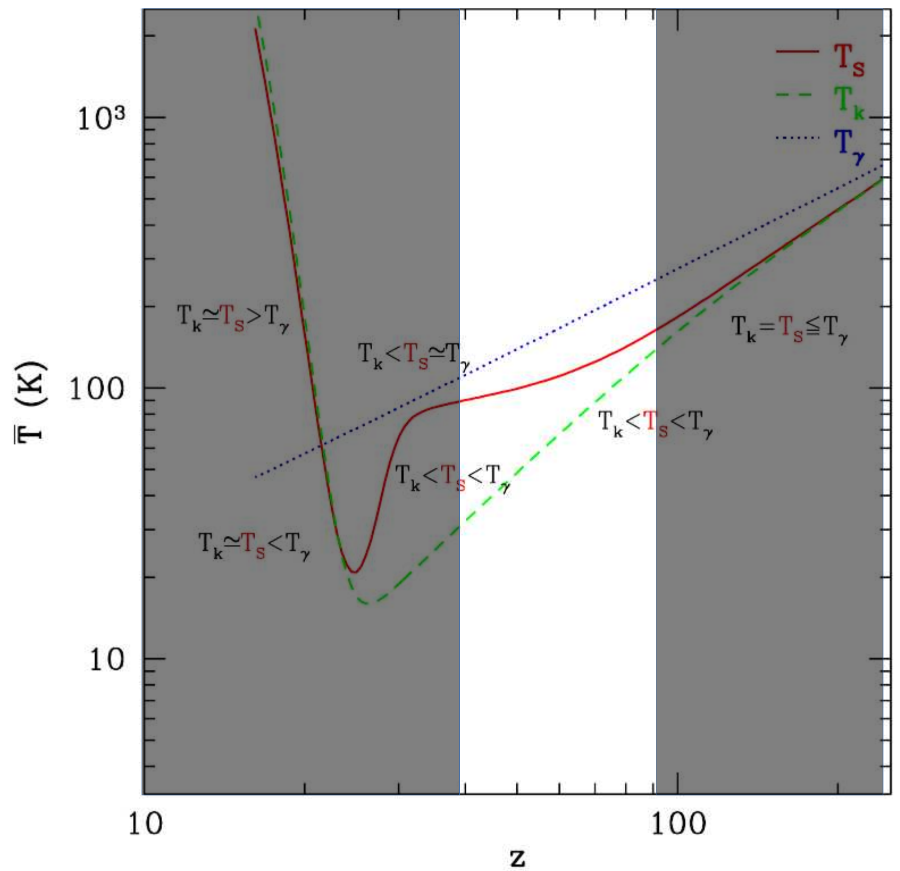




(Mesinger+, MNRAS, '11)

history of Ts





(Mesinger+, MNRAS, '11)

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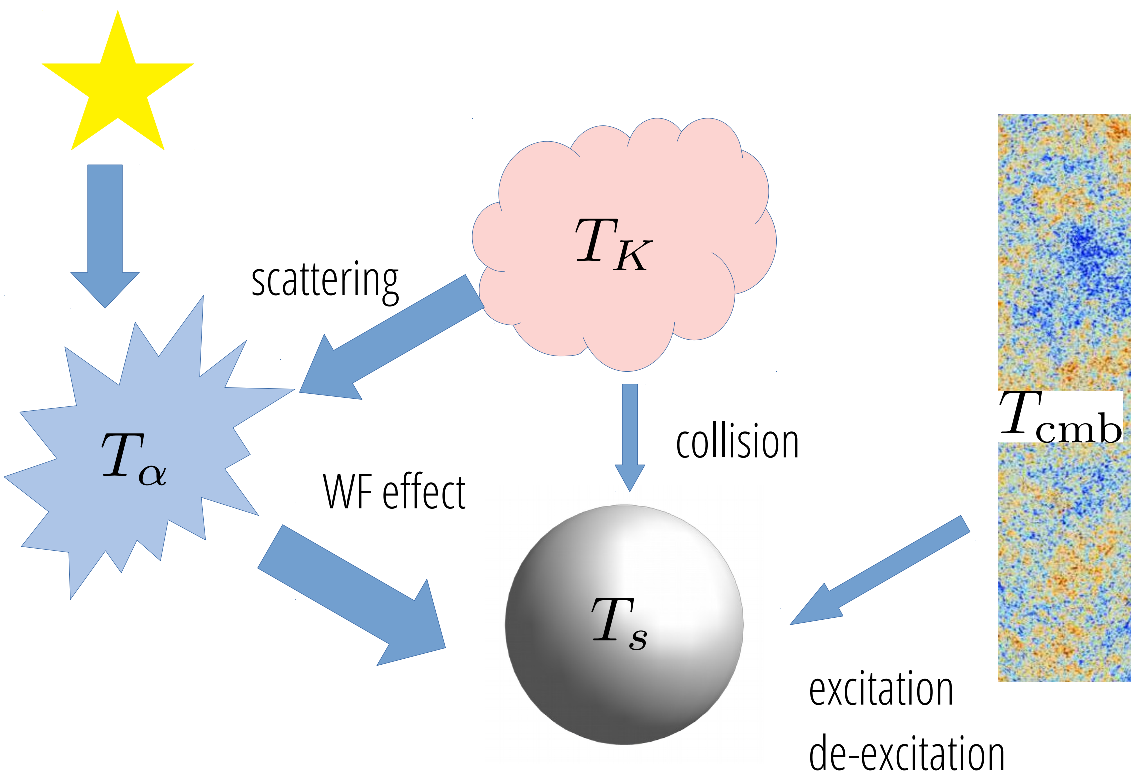

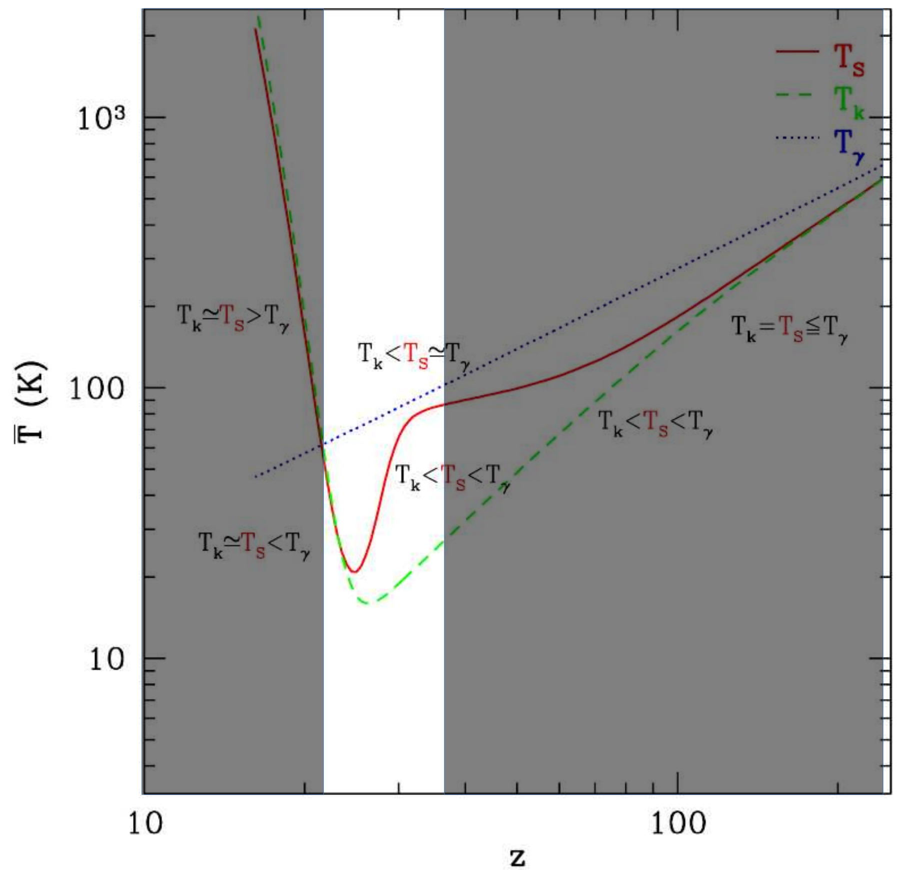

(Mesinger+, MNRAS, '11)

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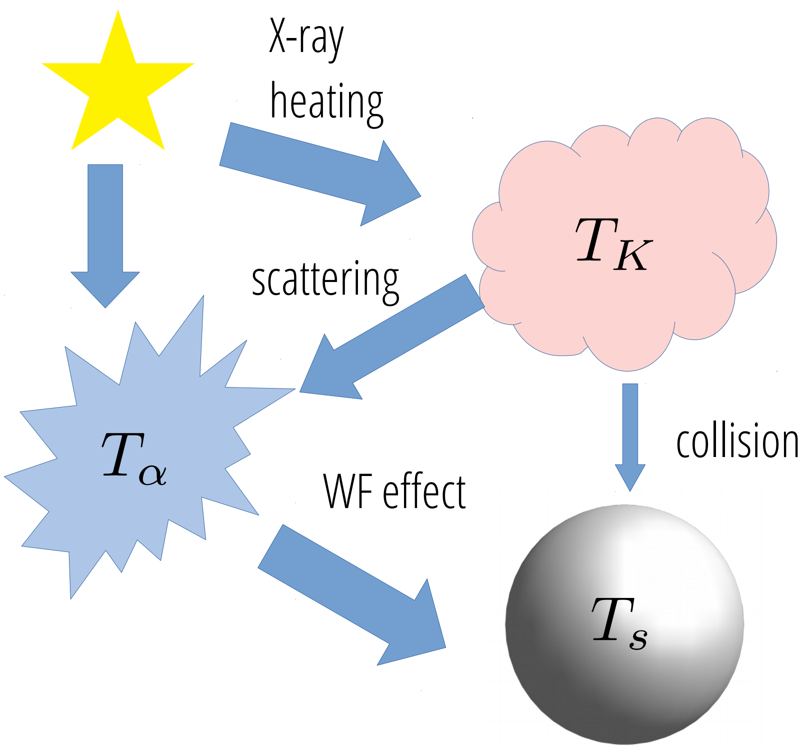
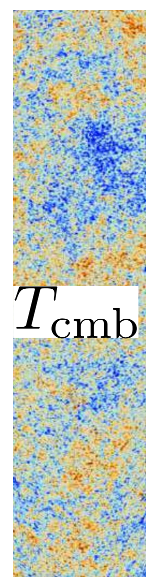
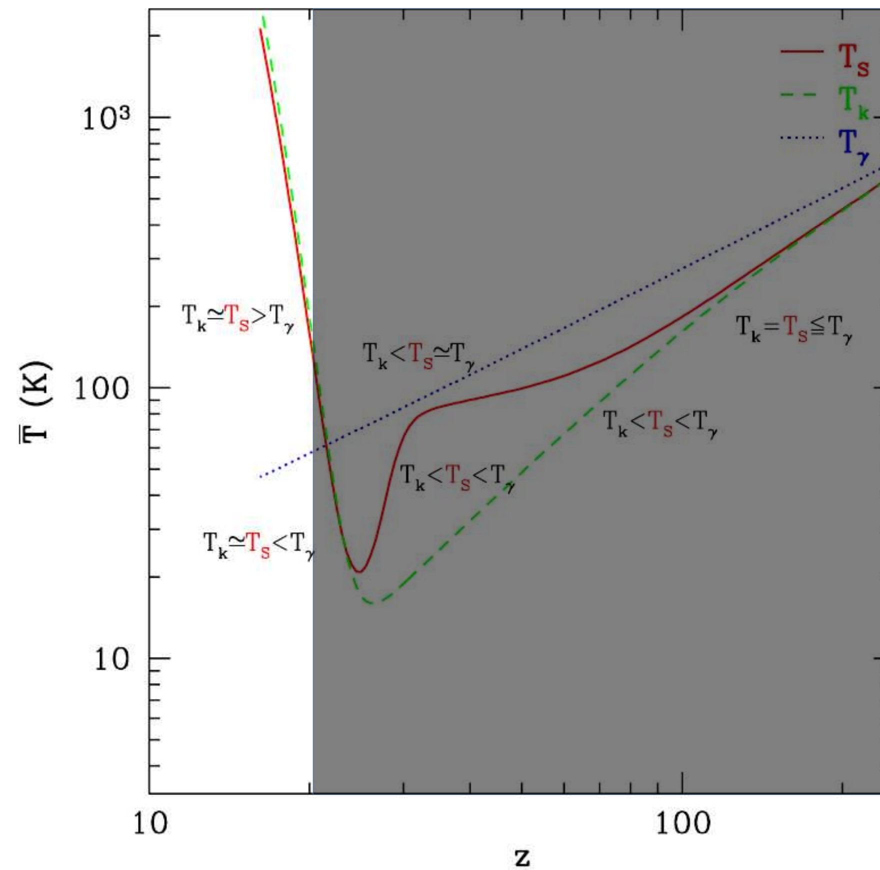


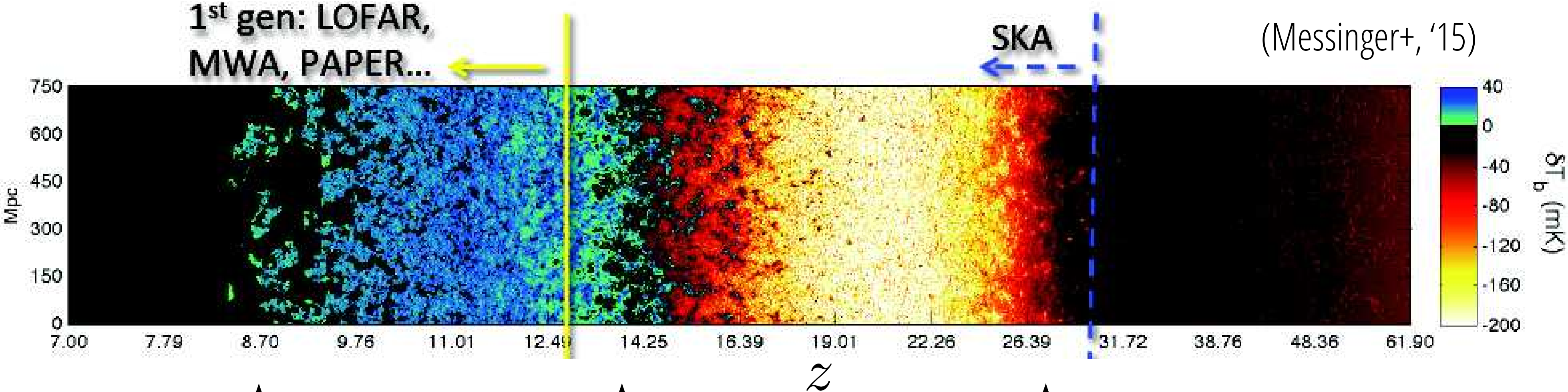




(Mesinger+, MNRAS, ‘11)

How does the EoR look like in 21cm observation?

(Messinger+, '15)



$T_s > T_{\rm cmb}$ $T_s < T_{\rm cmb}$ $T_s \approx T_{\rm cmb}$

reionization
no HI gas

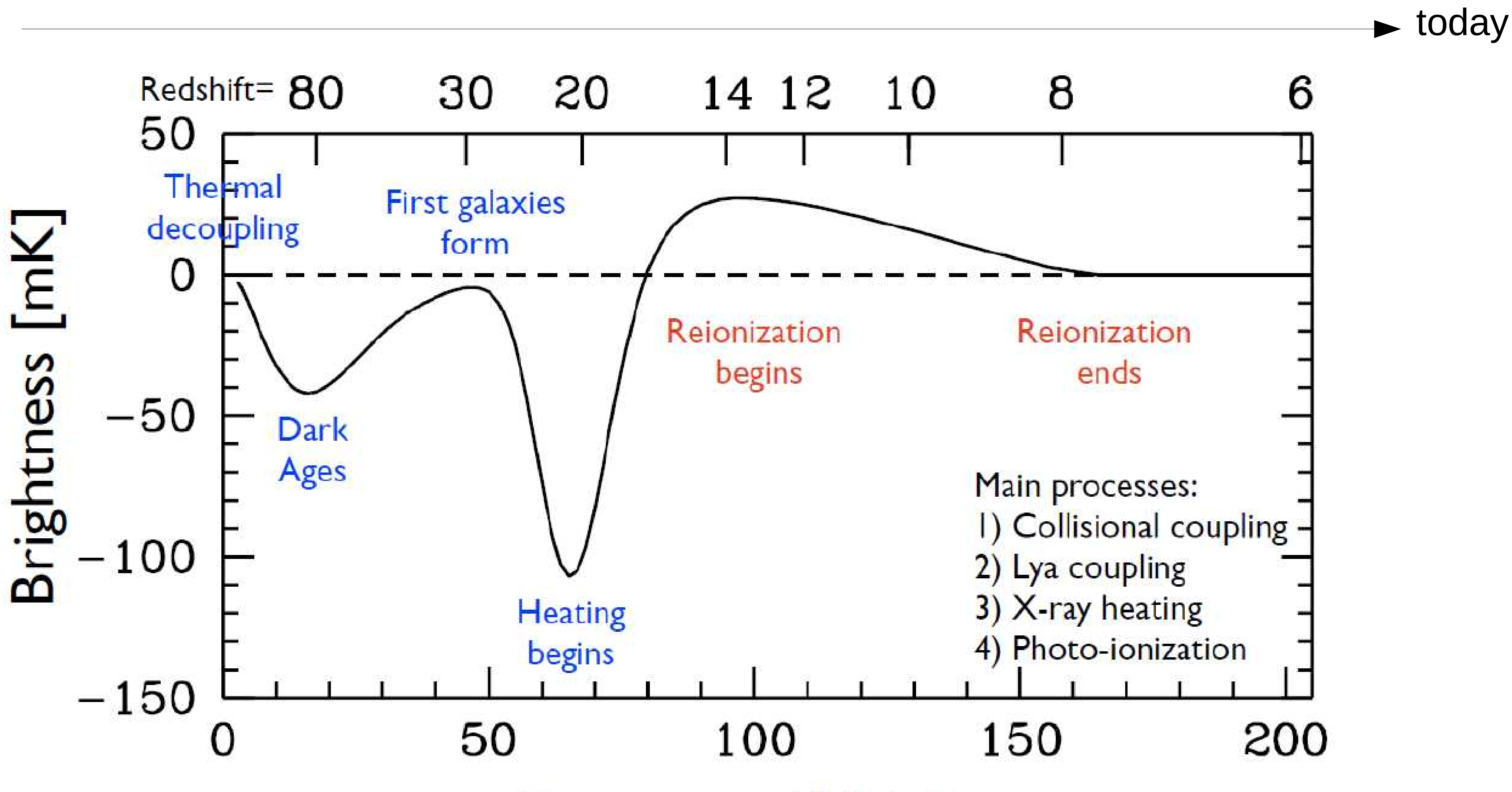
heating become
effective

first galaxy form
WF effect starts

t

today

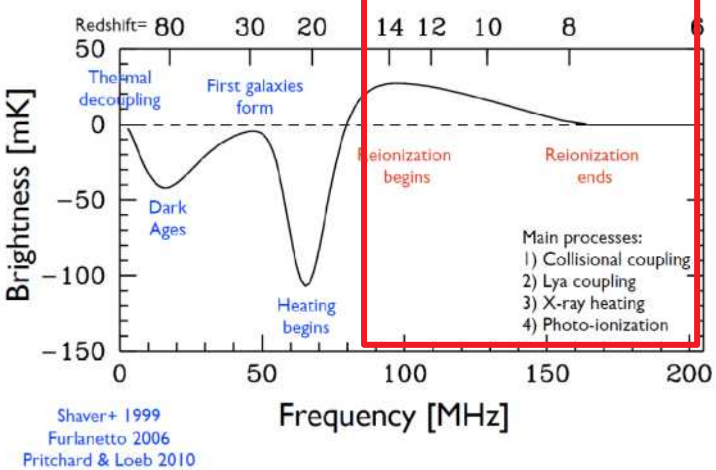
frequency spectrum will reveal the thermal history of the universe



Shaver+ 1999
Furlanetto 2006
Pritchard & Loeb 2010

current situation: latest results from EDGES

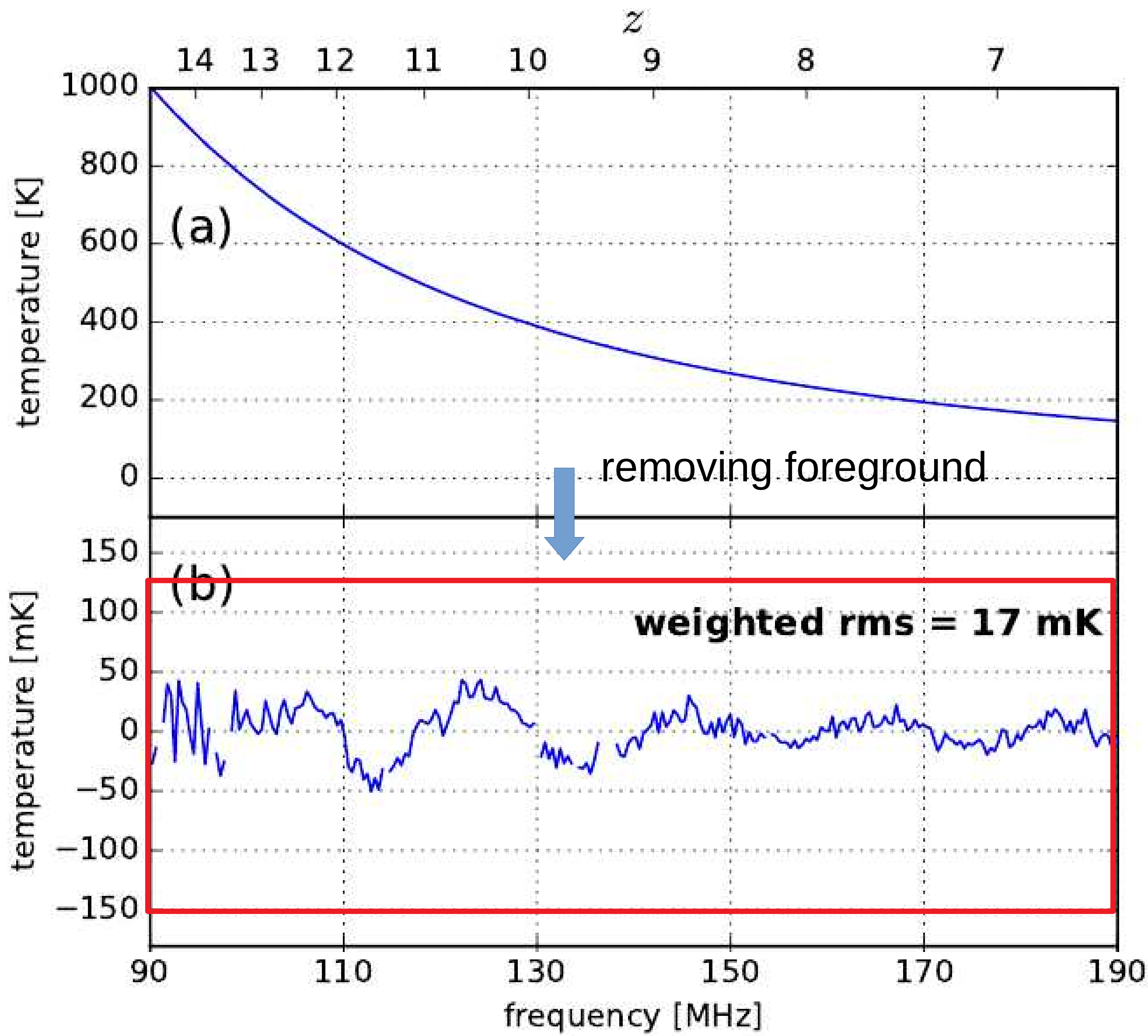
https://www.haystack.mit.edu/ast/arrays/Edges/



some exotic models (such as no heating models) begin to be ruled out

(Monsalve et al., ApJ, ‘17)

EDGES antenna in western Australia (photo credit: Judd Bowman/ASU)

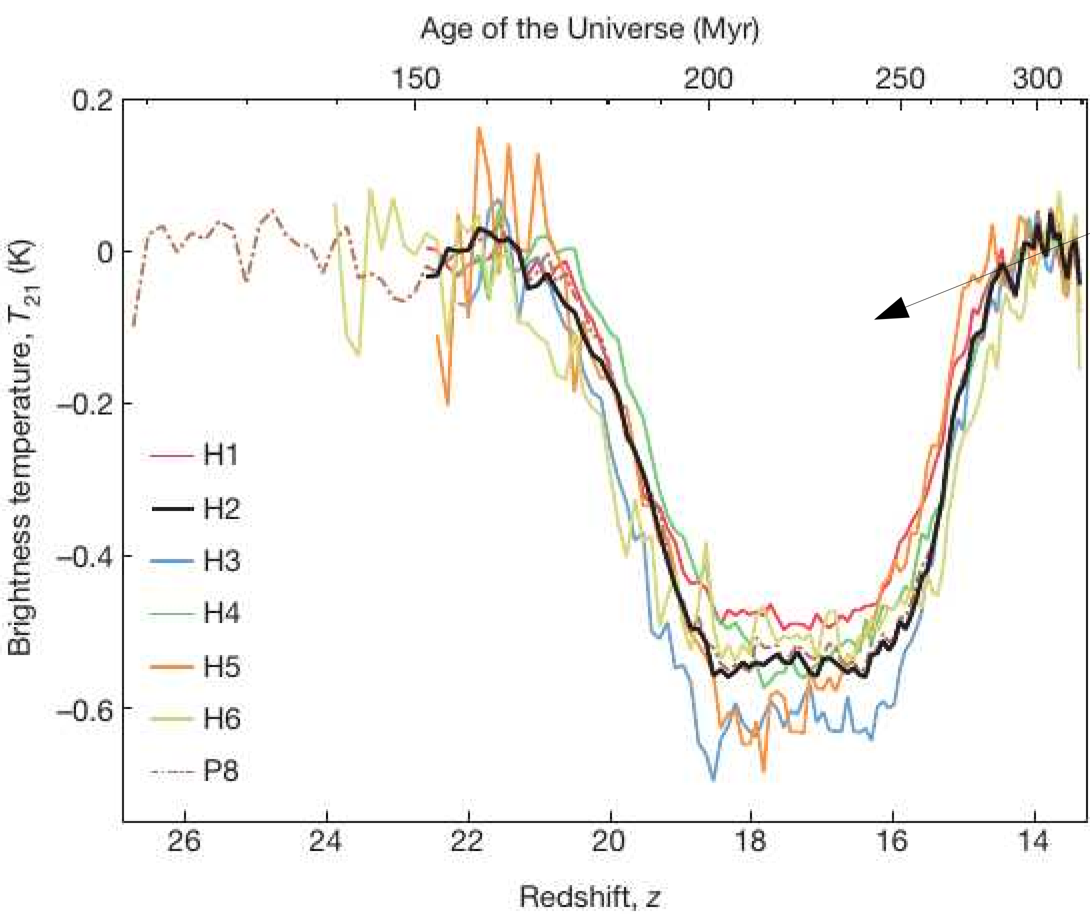


LETTER cosmological 21cm detected !?

doi:10.1038/nature25792

An absorption profile centred at 78 megahertz in the sky-averaged spectrum

Judd D. Bowman[1], Alan E. E. Rogers[2], Raul A. Monsalve[1,3,4], Thomas J. Mozdzen[1] & Nivedita Mahesh[1]



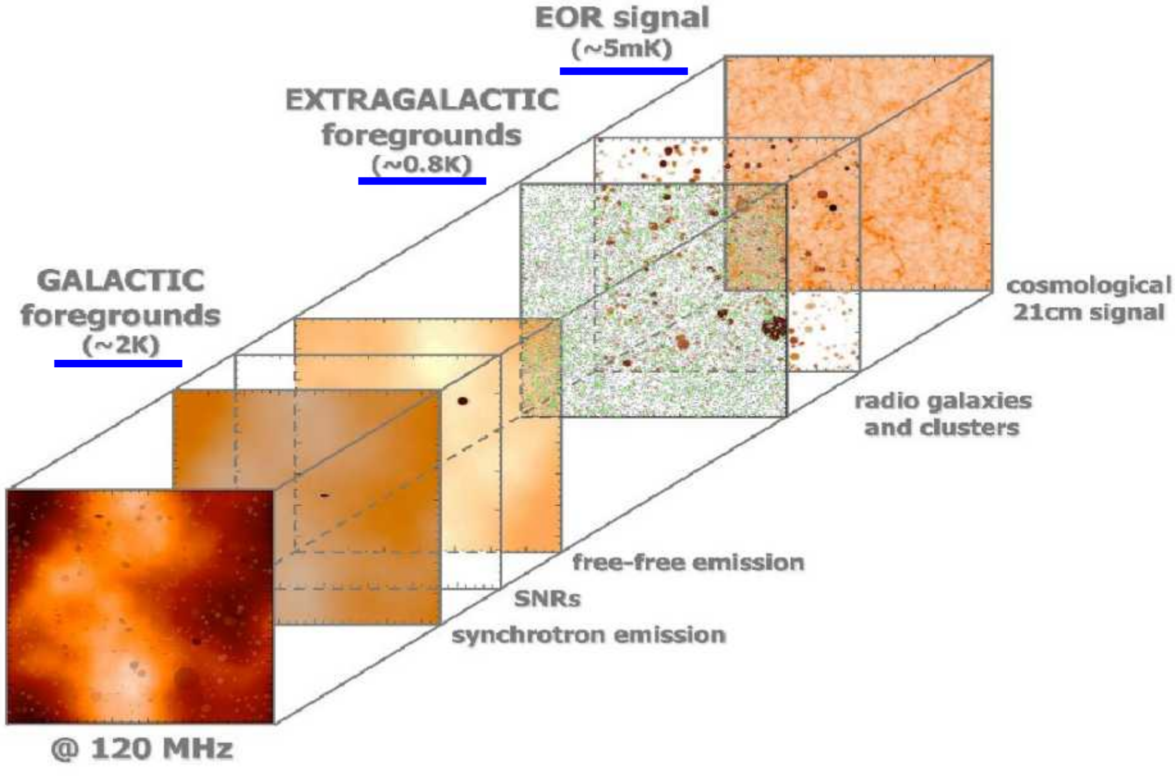
large absorption feature
than expected….

smaller spin temperature
is needed to explain this

some exotic model?
dark matter-baryon interaction?
(e.g., Tashiro,Kadota,Silk,PRD, ‘14)

foreground

- current and future experiment will have enough sensitivity to detect cosmological 21cm signal, but foreground is a sever problem



foreground

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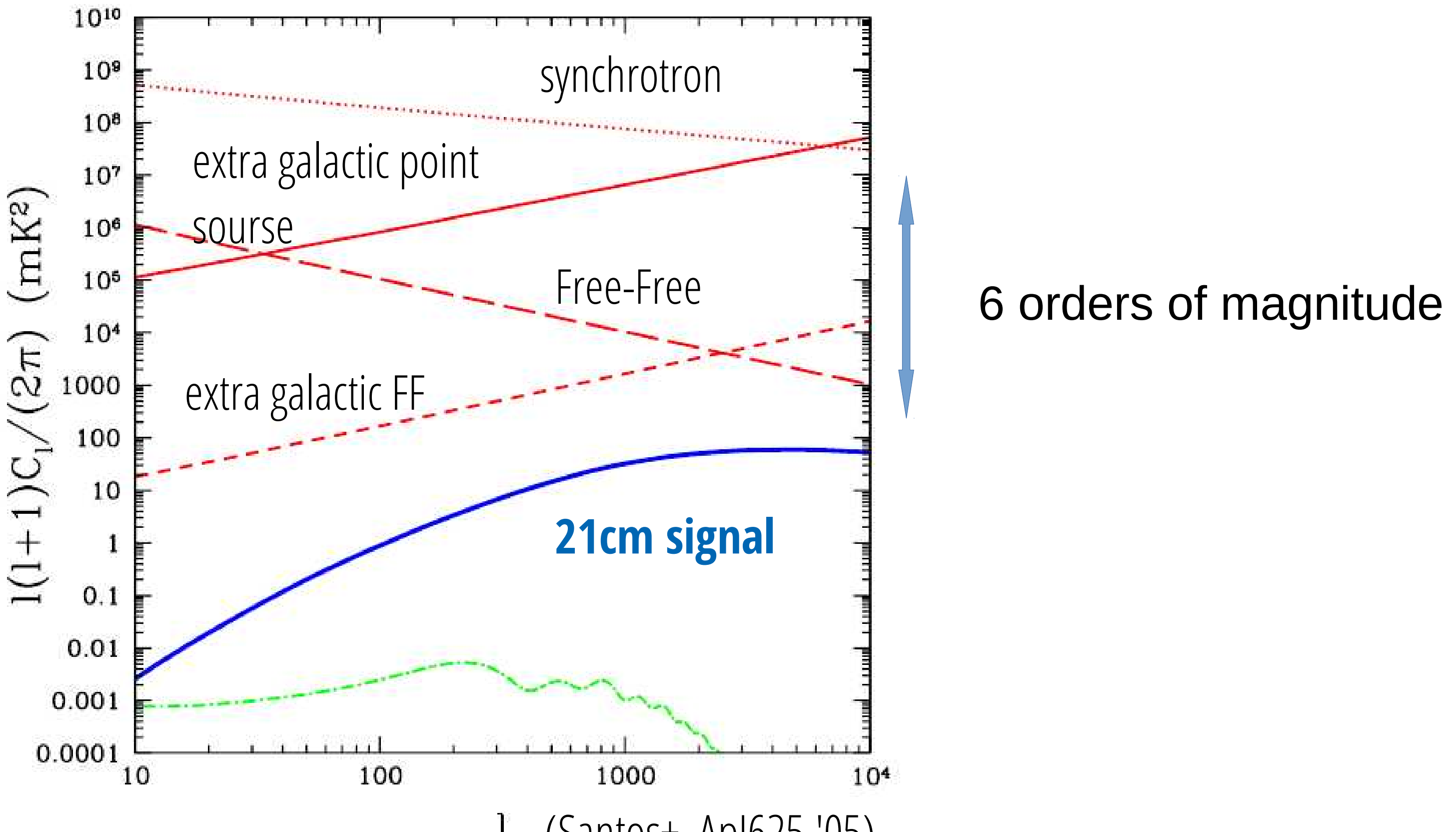


(Santos+, ApJ625,'05)

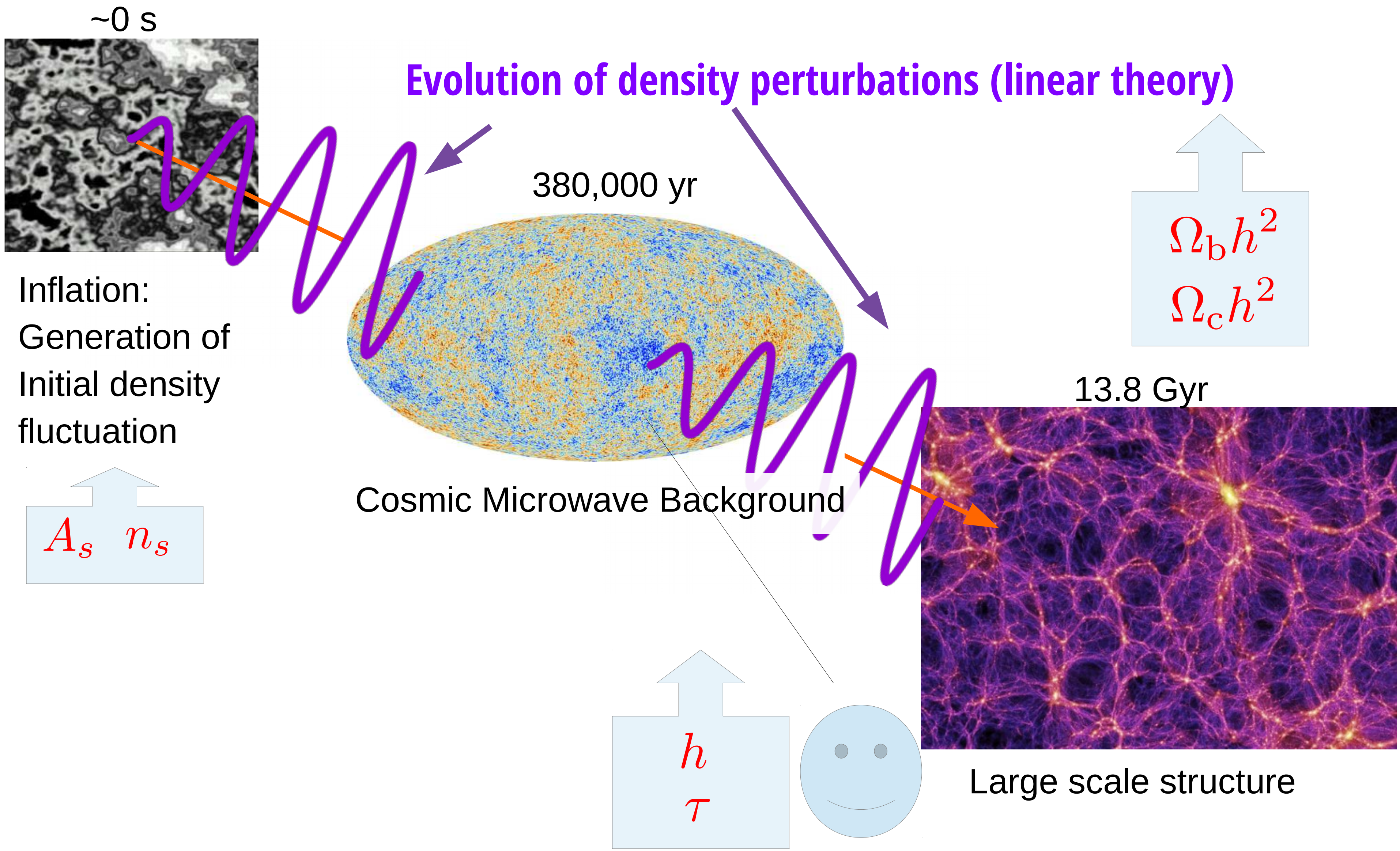
contents

The ΛCDM model

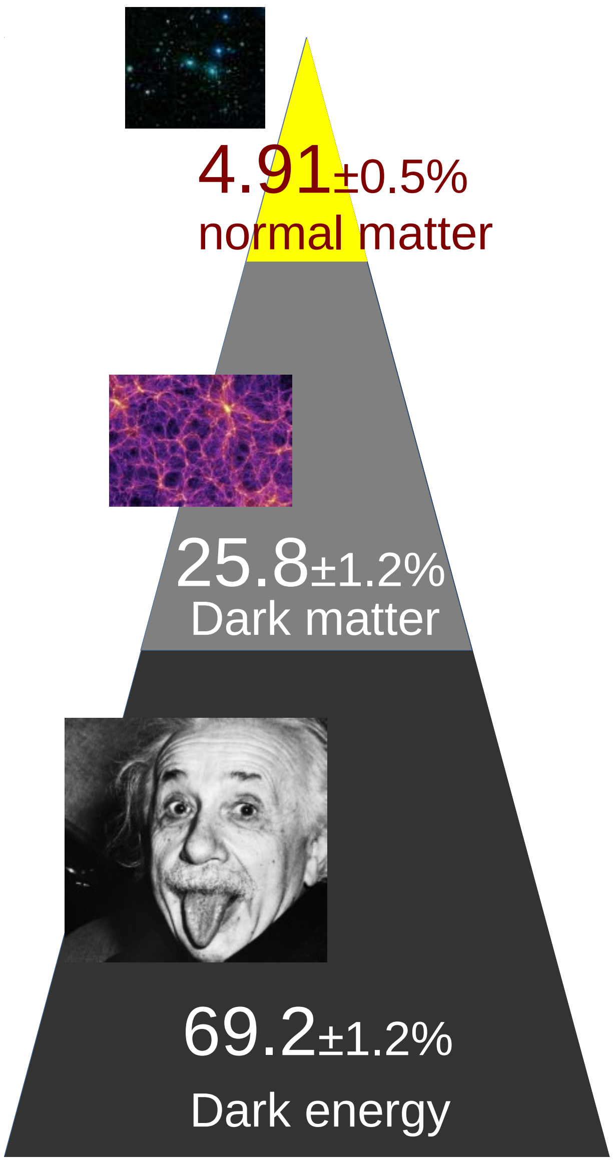
$\vec{\theta} = (h, \Omega_b h^2, \Omega_c h^2, A_s, n_s, \tau)$ only 6 parameters

- **Geometry (size) of the universe**
  - **Hubble parameter...** h
- **Initial conditions**
  - **Baryon and CDM densities...** $\Omega_{\rm b} h^2 \quad \Omega_{\rm c} h^2$
  - **Density fluctuations...** $P(k) = A_s (k/k_0)^{n_s - 1}$
- **astrophysics**
  - **Thomson optical depth...** τ

The ΛCDM model



Planck Cosmological Params



Hubble Parameter

$$H_0 = 67.81 \pm 0.92 \quad \text{[km/s/Mpc]}$$

3 sigma away from direct measurements.

Initial Power Spectrum

$$P(k) = 2.198 \times 10^{-9} \left(\frac{k}{k_0}\right)^{0.9655}$$

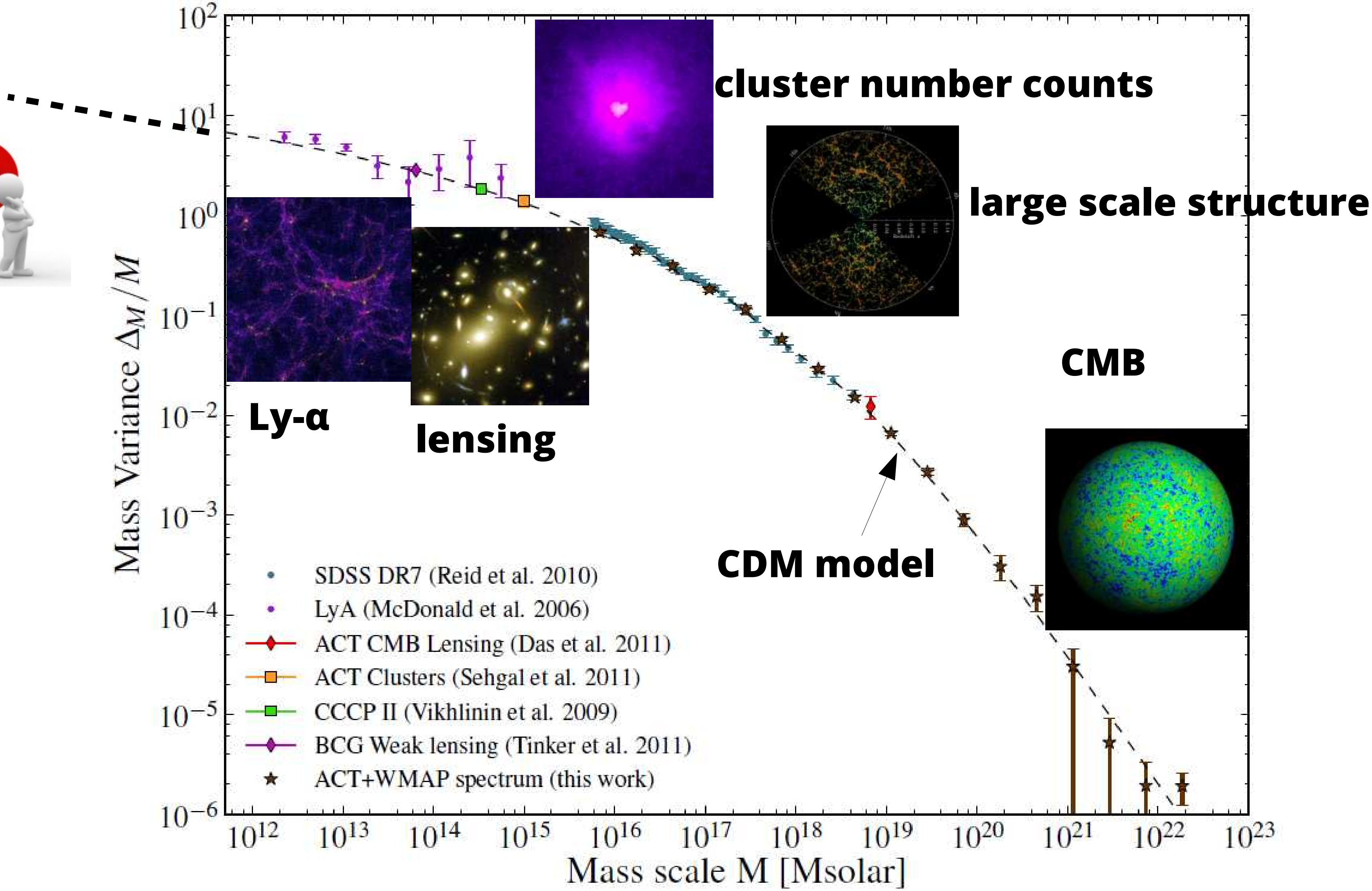
Consistent with inflation theory

Optical Depth

$$\tau = 0.055 \pm 0.009$$

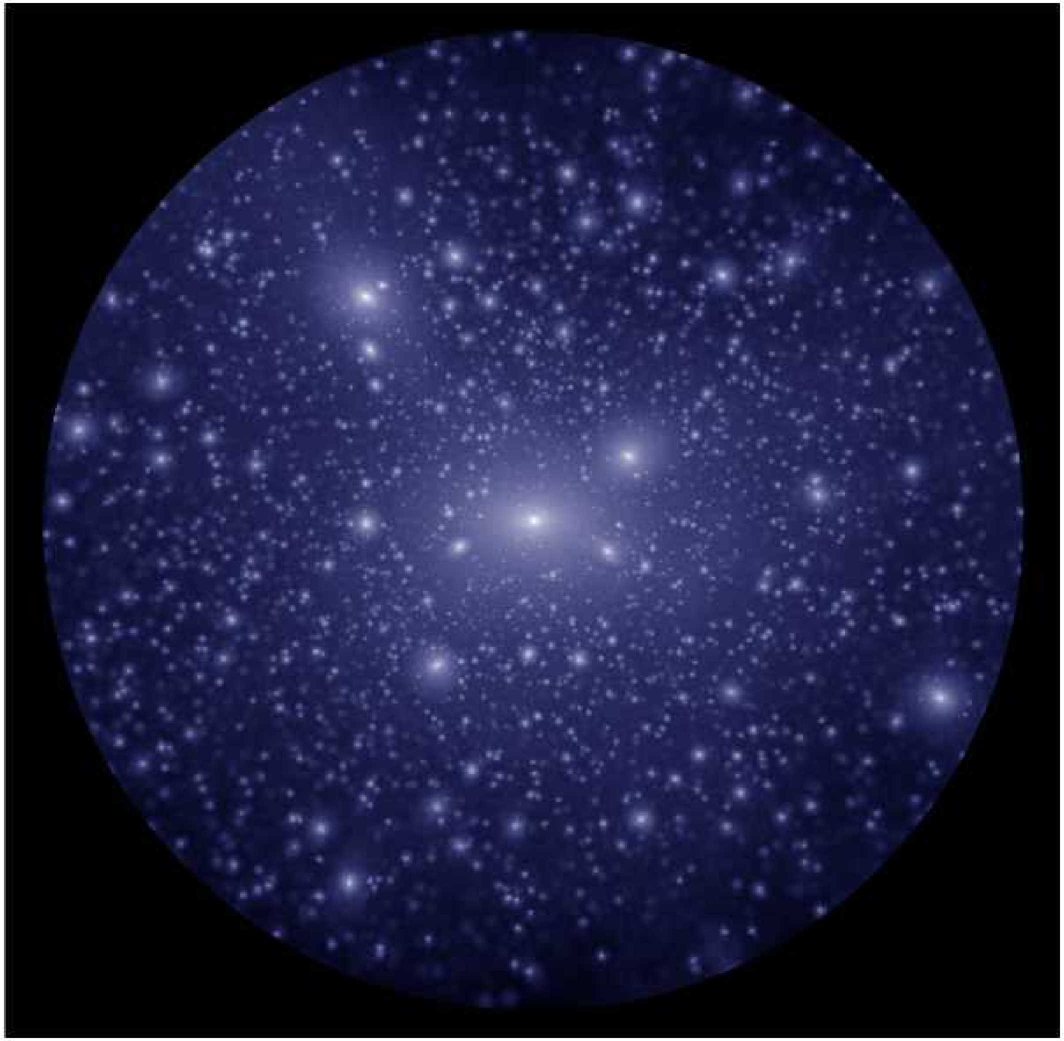
Consistent with astronomy based observations. the universe was reionized when its size was 1/9 of the present one.

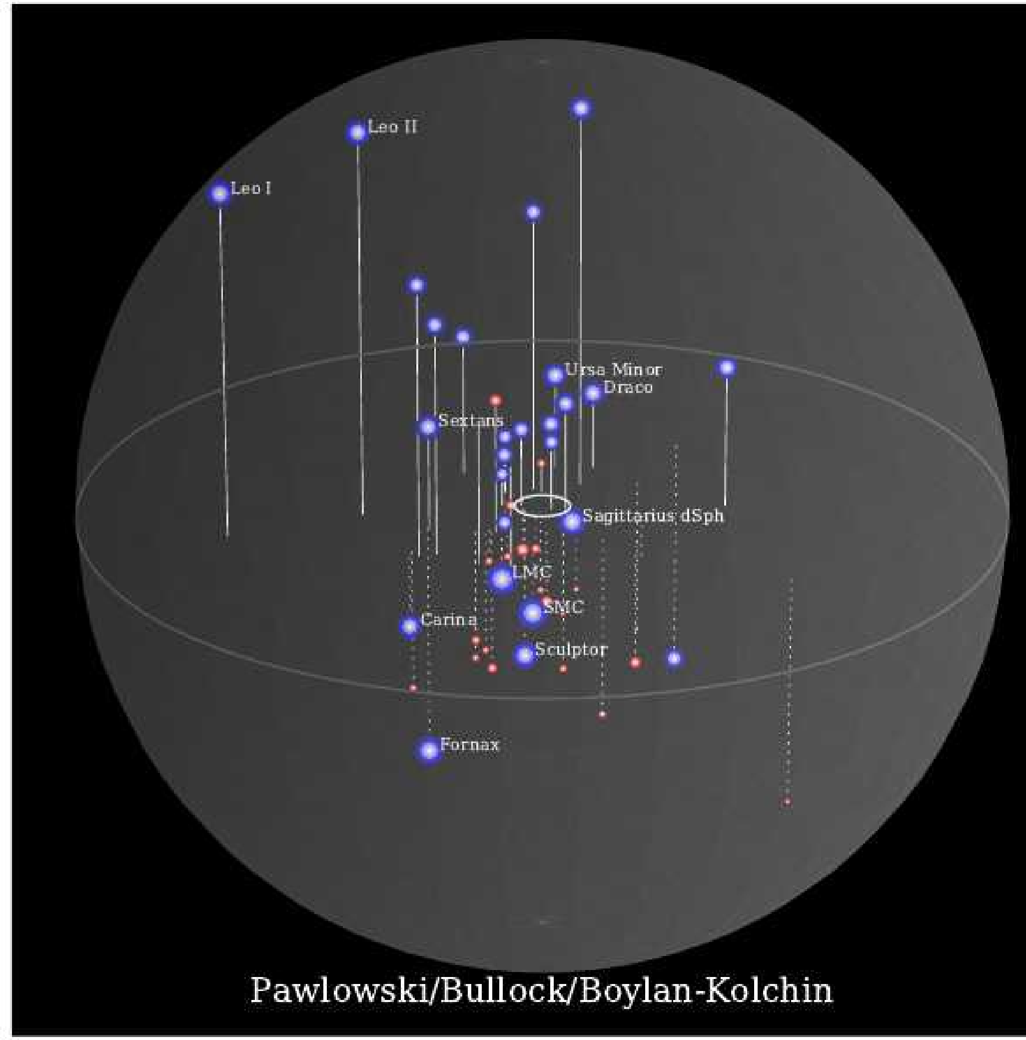
the CDM model is excellent on large scales



(Hlozek+, ApJ, ‘12)

CDM crisis (1) missing satellite problem





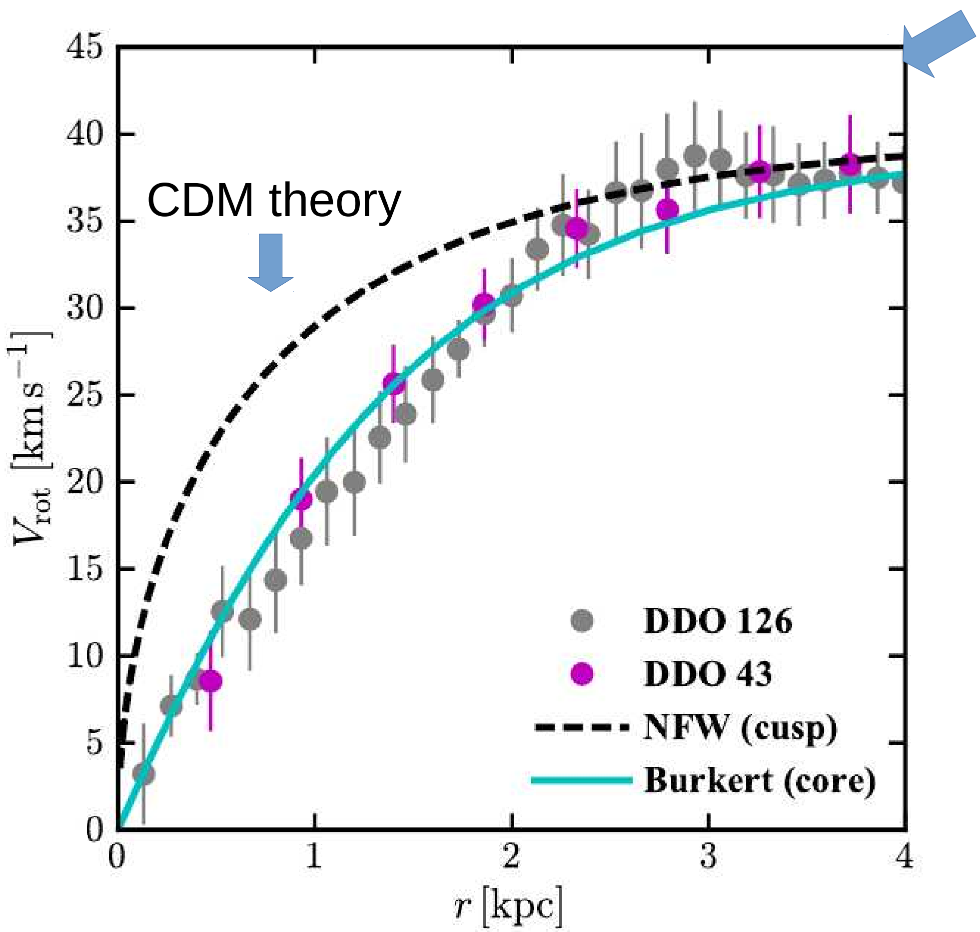
CDM simulation

Milky way satellites

～1000 **sub-halos**

only ～50 satellite gals down to 300M_sun

CDM crisis (2) core cusp problem



(Bullok&Boylan-Kolchin 1707.04256)

rotation curves of dwarf, dark matter dominated galaxies

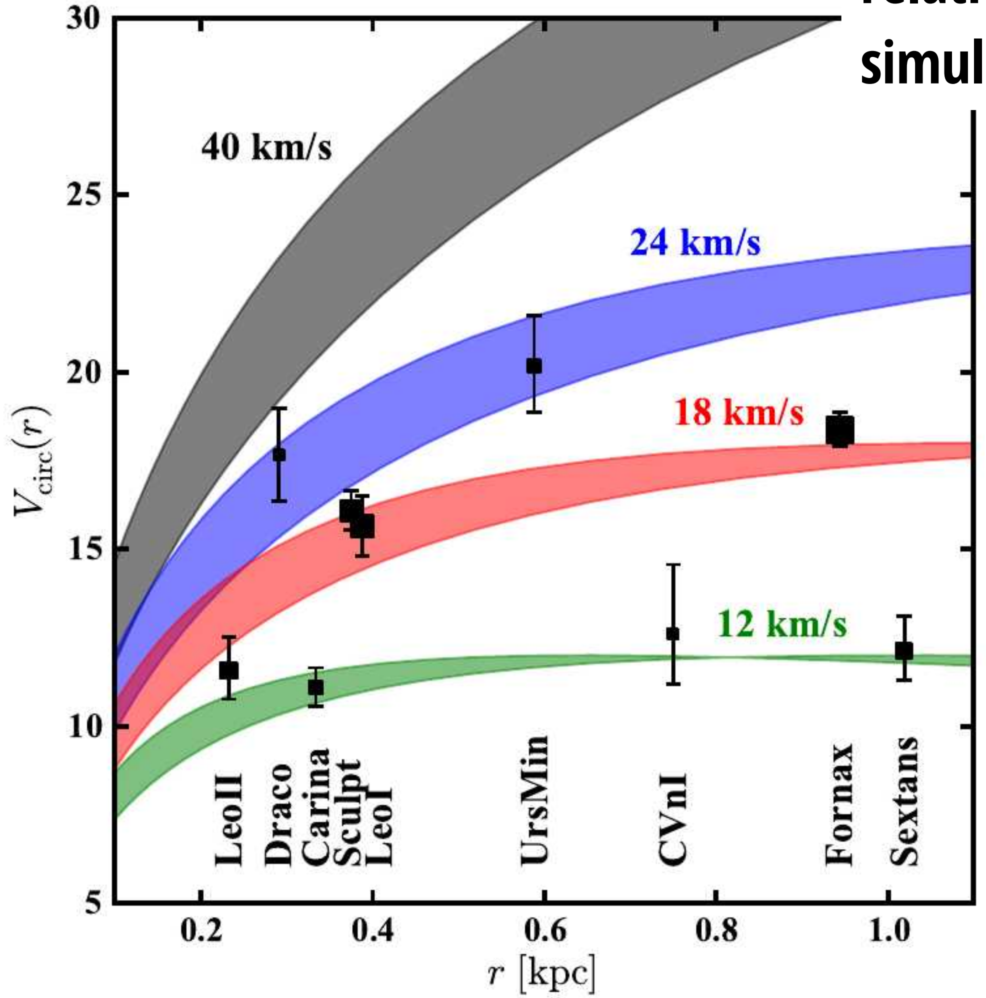
dark matter simulations predict

$$\rho \propto r^{-1} \ (\text{cusp})$$

but observations show

$$\rho \propto r^{0} \ (\text{core})$$

CDM crisis (3) too big to fail problem



relations between Vcirc and radius from N-body simulation compared with the Milky-Way satellites

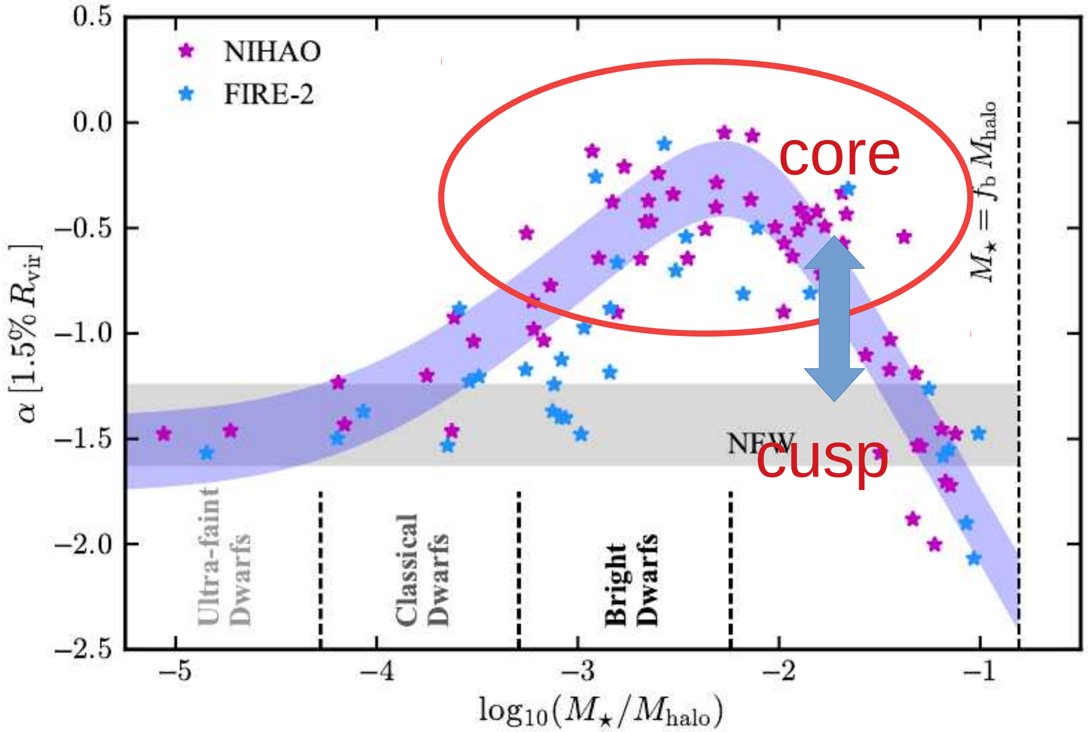
Name	M_{vir} ($M_\odot$)	N_{20}	N_{30}	N_{40}	N_{50}
Aq-A	2.19×10^{12}	105	33	15	6
Aq-B	9.54×10^{11}	60	16	7	1
Aq-C	1.99×10^{12}	81	28	12	4
Aq-D	2.19×10^{12}	111	31	15	10
Aq-E	1.39×10^{12}	85	25	11	3
Aq-F	1.32×10^{12}	99	29	12	5

Milky Way size

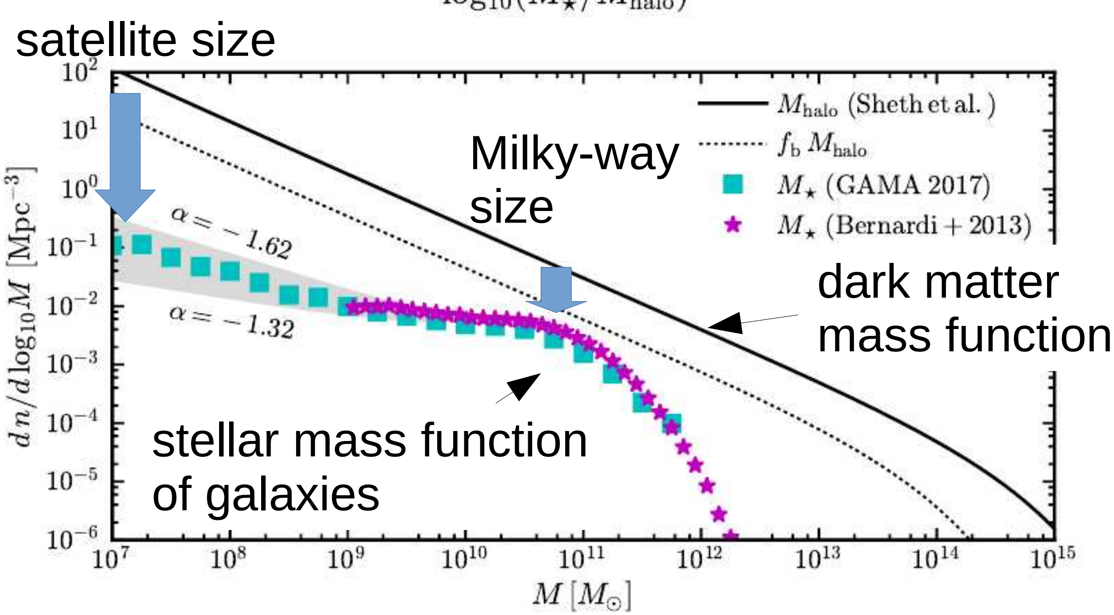
there should be a number of more massive sub-halos around MW that are believed to be too big to have failed to form stars

(Boylan-Kolchin, Bullock, Kaplinghat, MNRAS, '12)

- **solution 1: astrophysical feedback** (see, e.g., Bullok&Boylan-Kolchin 1707.04256)

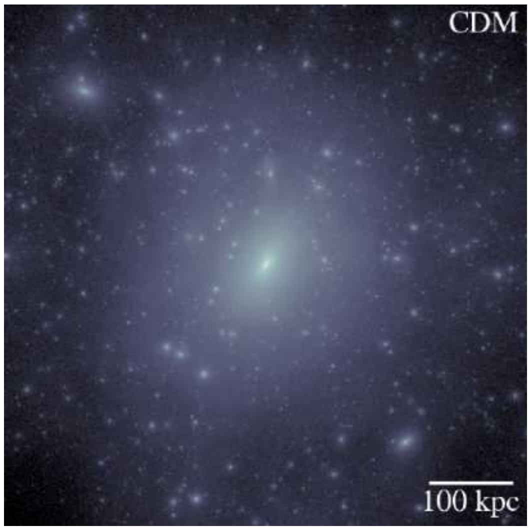


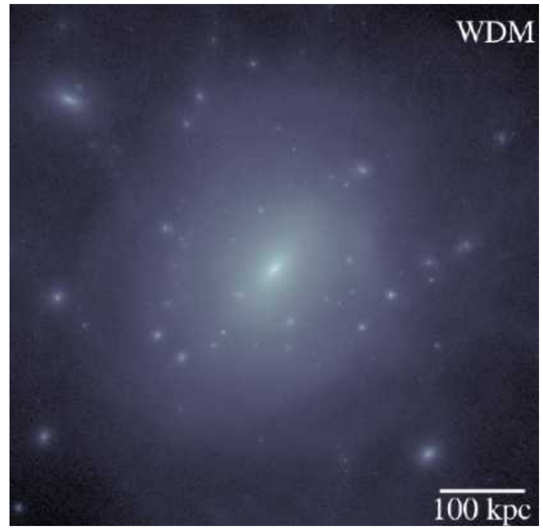
Kinetic energy from SN destroies the central structure, forming the core

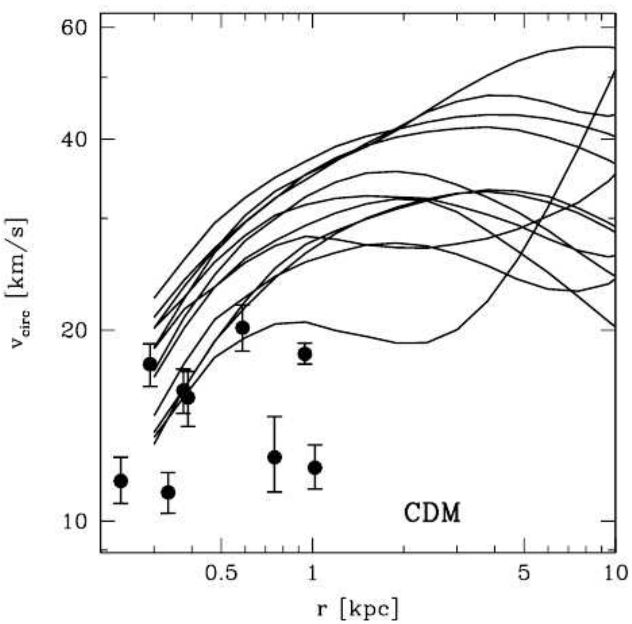


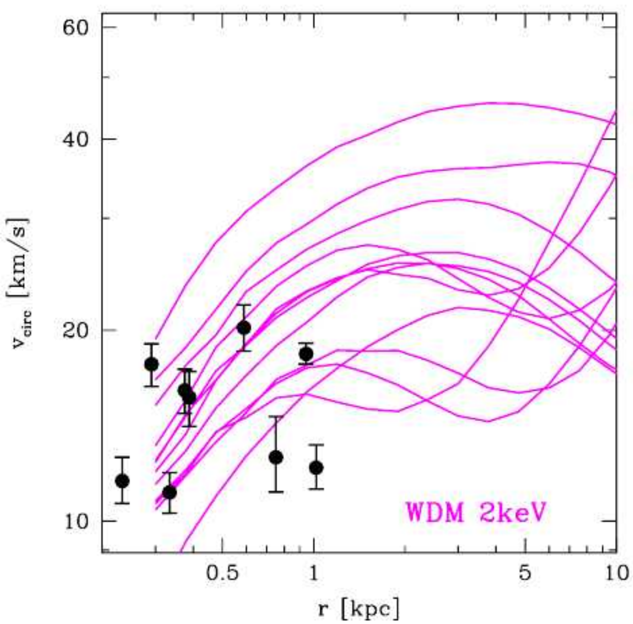
less star formation efficiency in smaller scale halos decreases the number of satellite-size galaxies compared with that of dark matter satellite halos

solution 2: modifying the nature of DM









WDM erase small scale structure, solving the missing satellite problem

WDM delay structure formation and decrease density of a halo, solving the too big too fail problem

WDM with mass of

$$\approx 2\ \mathrm{keV}$$

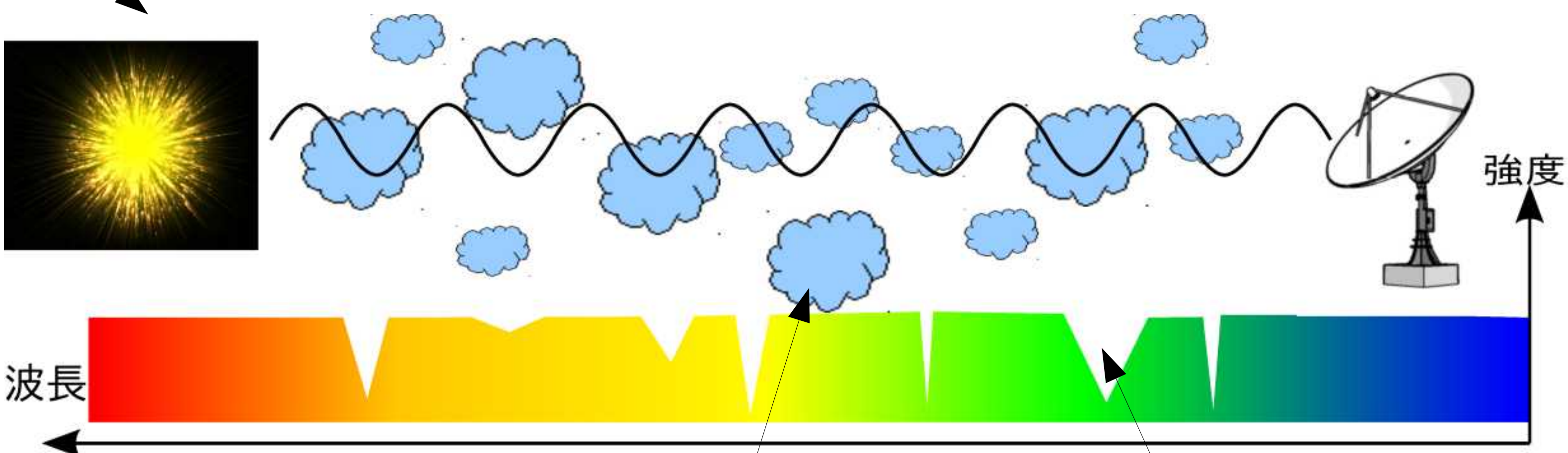
may explain observations

(Bozek+, MNRAS, ‘15; Anderhalden+, JCAP, ‘12)

contents

21cm forest (e.g., Carilli, Gnedin, Owen, ApJ, '02)

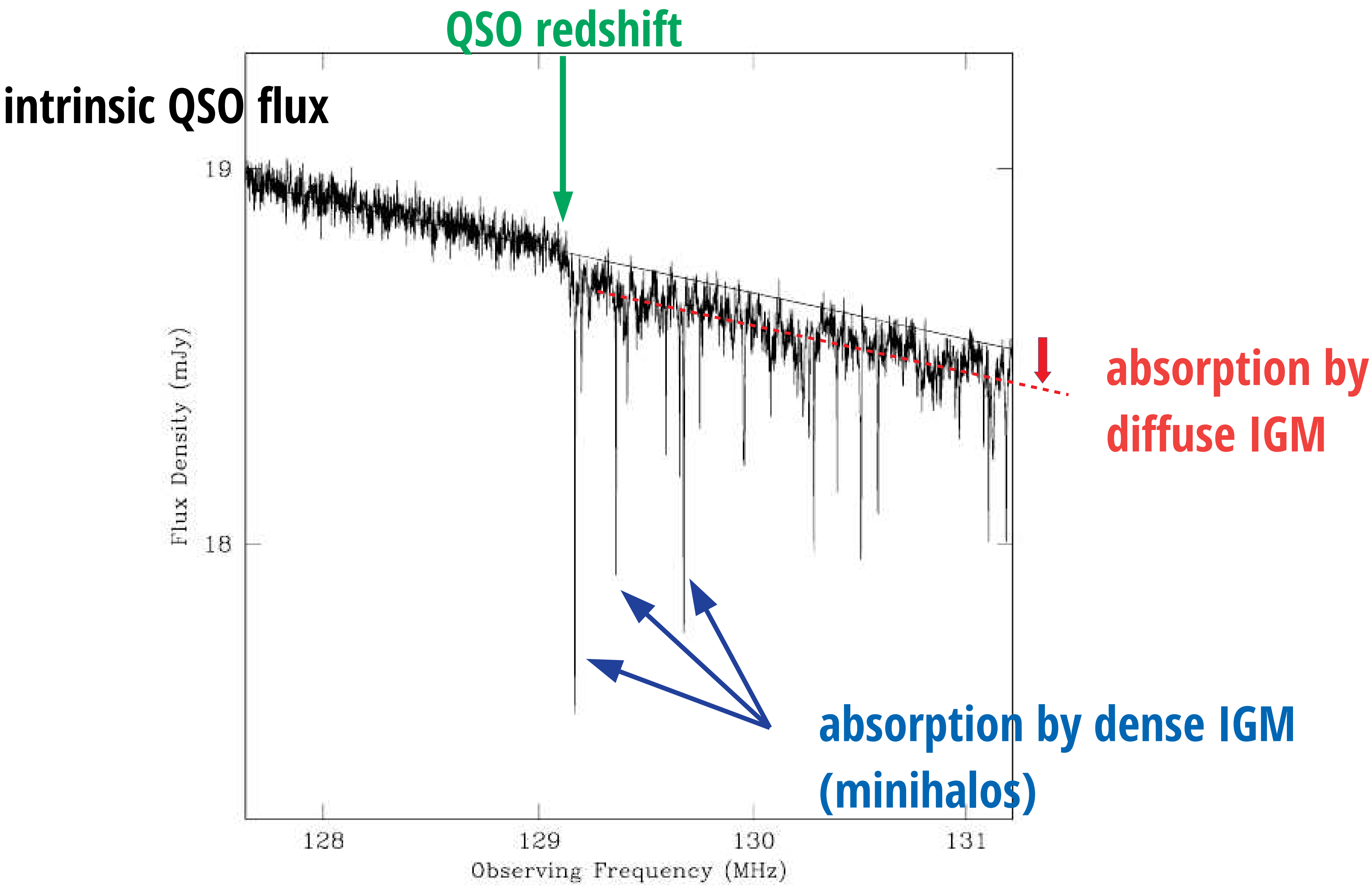
Bright radio source (QSO, GRB etc.)



Hydrogen cloud (minihalos)

absorption lines at (redshifted) 21cm wavelength

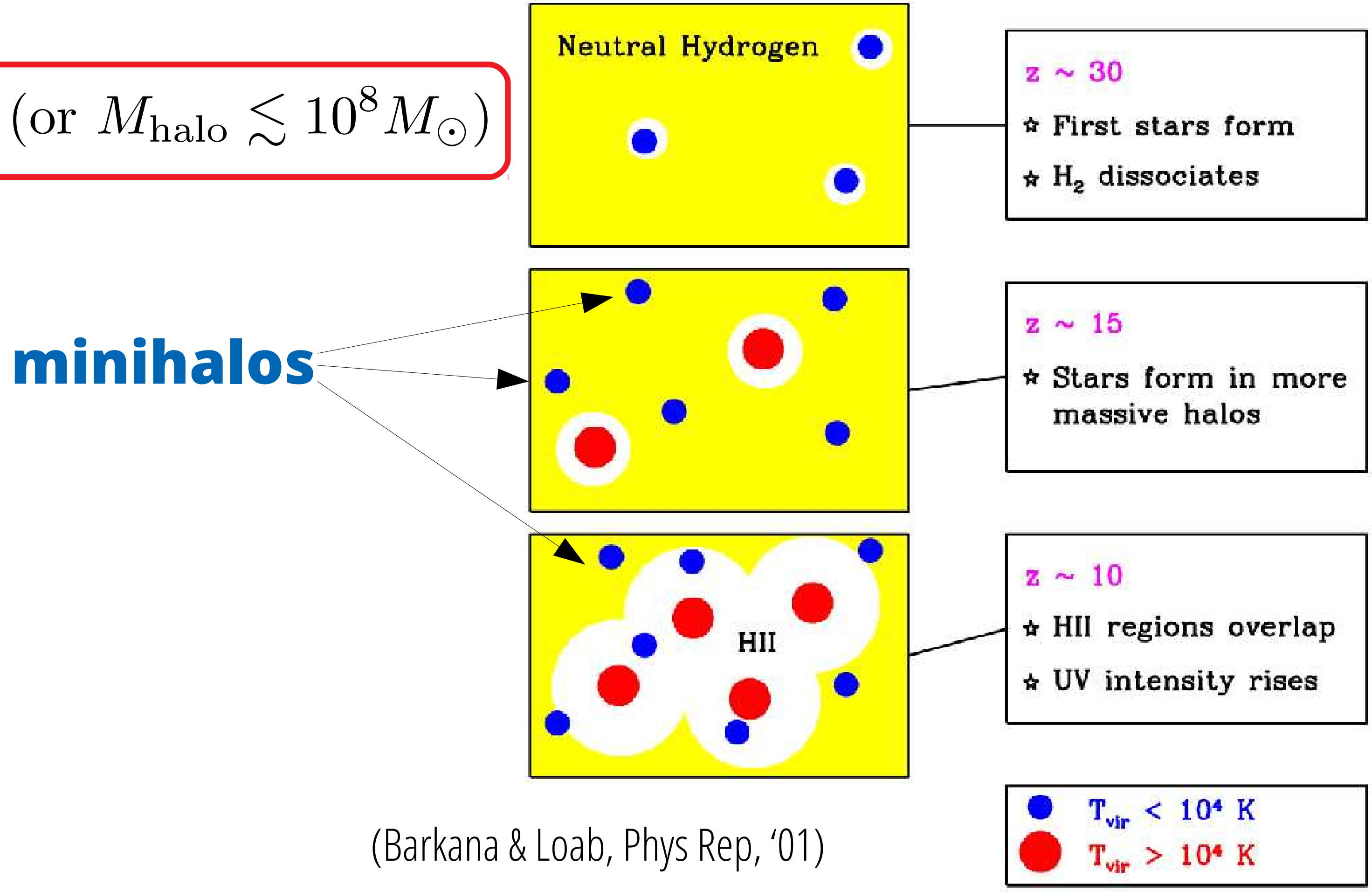
21cm forest (e.g., Carilli, Gnedin, Owen, ApJ, '02)



what are minihalos ?

- small collapsed objects where atomic cooling is **not effective**

$$T_{\rm vir} \lesssim 10^4 {\rm K} \quad ({\rm or}\ M_{\rm halo} \lesssim 10^8 M_\odot)$$



(Barkana & Loab, Phys Rep, '01)

21cm forest observation

- pros
  - small optical depth, thus one can probe deep (z>10) universe, compared to Lyα
  - less foreground problem (compared to HI tomography) because bright background QSOs are used
- cons
  - the number of QSOs is highly uncertain
  - sensitive to the IGM temperature

our model: DM profile

Assumptions:

1) DM density profile of mini-halo is given by the NFW profile

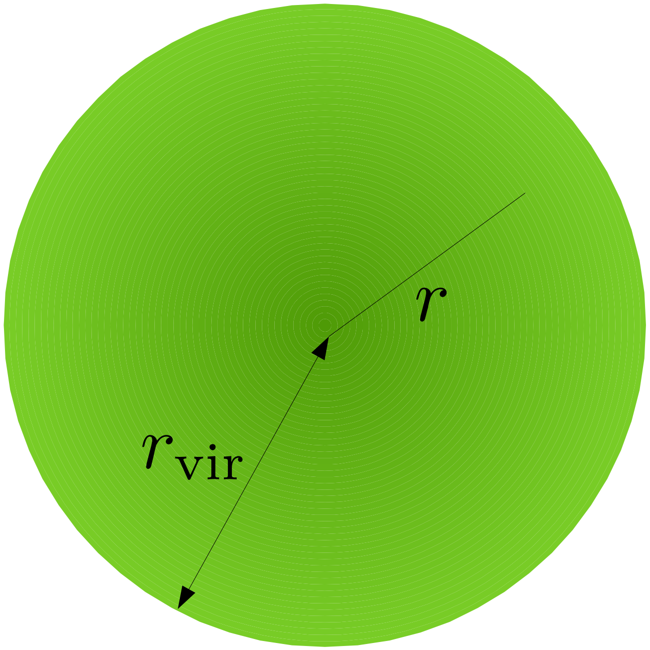
(Navarro, Frenk, White, ApJ, '96)

$$\rho(r) = \frac{\rho_{\mathrm{m}}(1+z)^3\delta_c}{c(r/r_{\mathrm{vir}})(1+c(r/r_{\mathrm{vir}}))^2}$$

$$c = \frac{9}{1+z}\left(\frac{M}{1.5\times 10^{13}h^{-1}M_\odot}\right)^{-0.13}$$

(Bullok+, MNRAS, '01)

$$r_{\mathrm{vir}} = 0.784\left(\frac{M}{10^8 h^{-1}M_\odot}\right)^{1/3}\left[\frac{\Omega_m}{\Omega_m^z}\frac{\Delta_c}{18\pi^2}\right]^{-1/3} \times\left(\frac{1+z}{10}\right)^{-1} h^{-1}[\mathrm{kpc}]$$



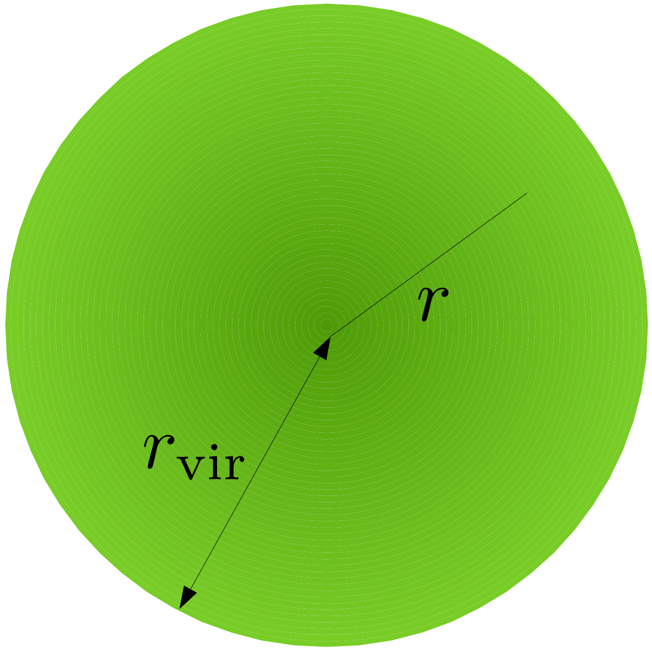
minihalo

our model: gas profile

Assumptions:

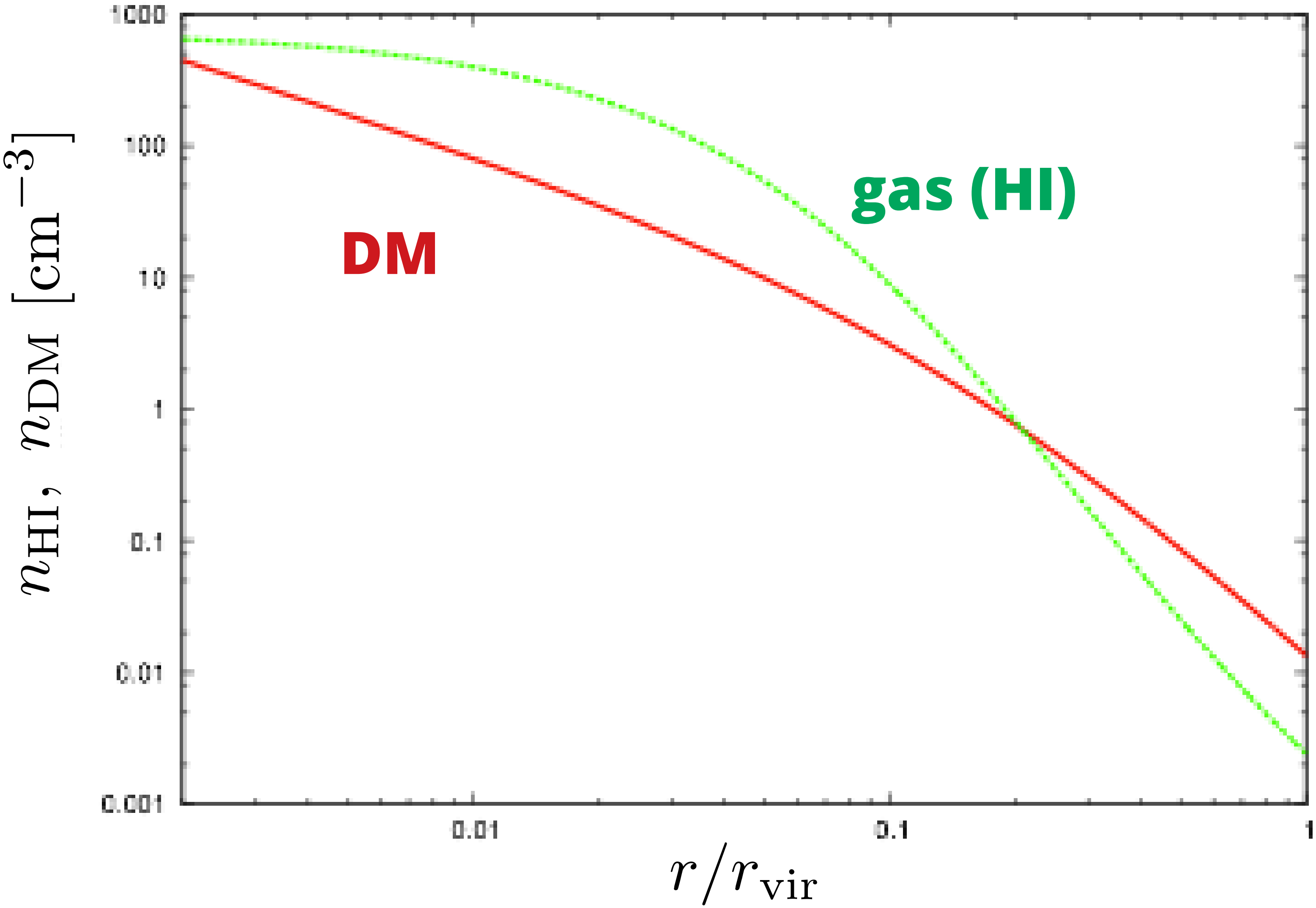
2) If one assumes that gas density profile of mini-halo is determined via hydrostatic equilibrium, the profile is analytically described by the escape velocity (gravitational potential) (Makino,Sasaki,Suto, ApJ, '98)

$$\rho_{\rm gas}(r) = \rho_{\rm gas}(0) \exp\left(-\frac{m_p}{2kT_{\rm vir}} \left[v_{\rm e}^2(0) - v_{\rm e}^2(r) \right] \right)$$



minihalo

visual description of density profile of minihalo



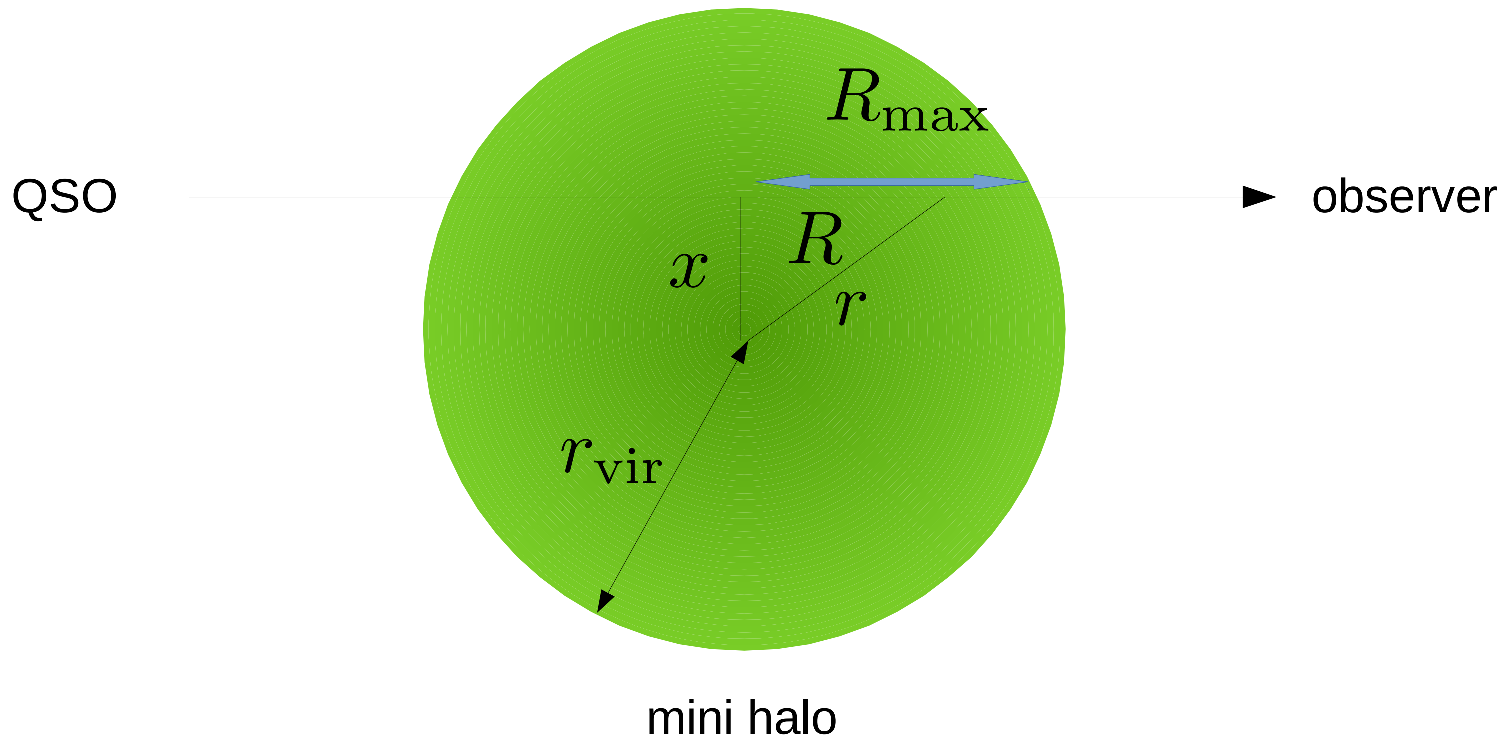
simple model (optical depth)

optical depth of a minihalo is given by an integration of the number density of HI along the line of sight:

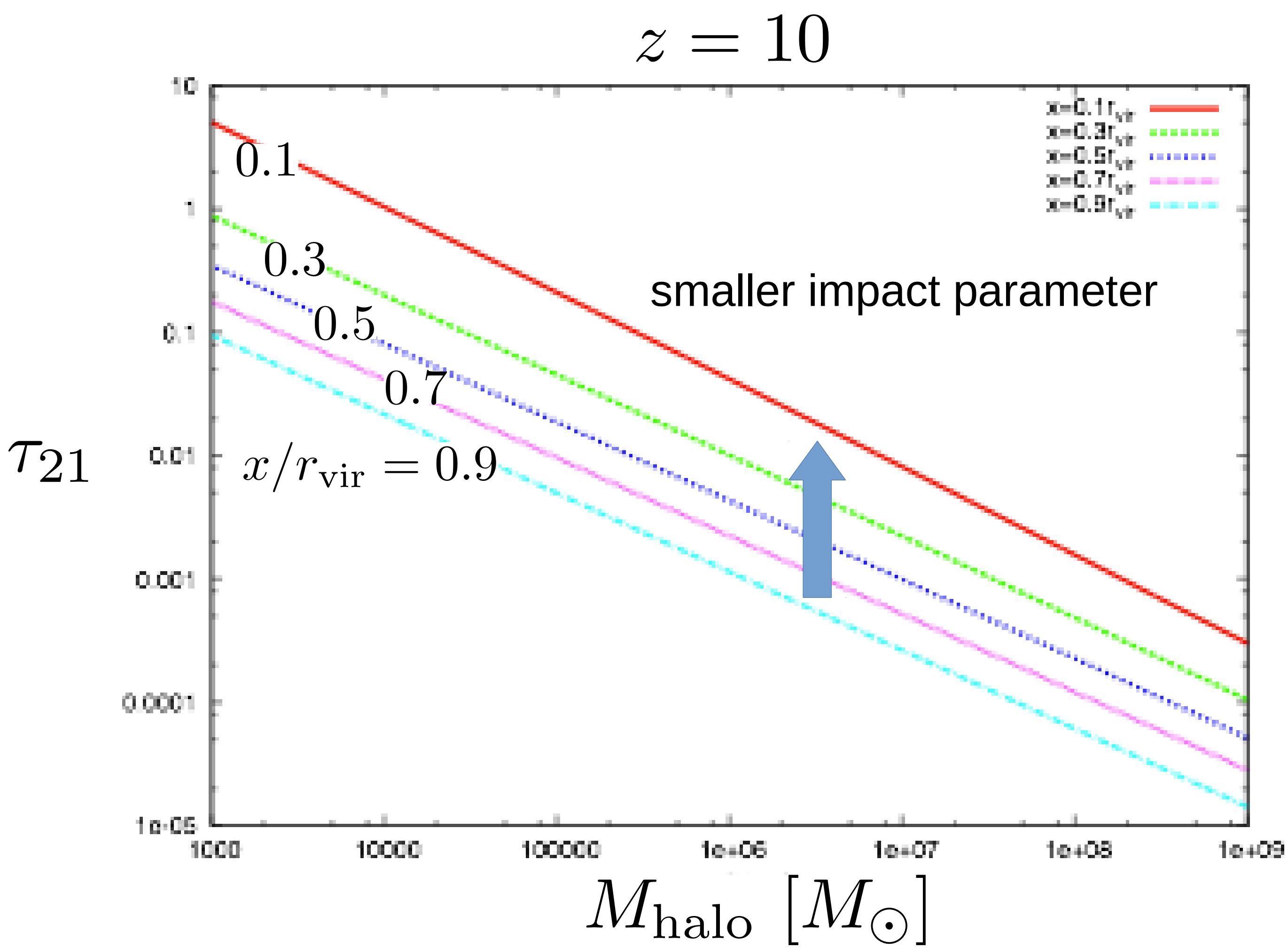
$$\tau_{21} = \frac{3hc^2 A_{10}}{32\nu_{21}^2} \int_{-R_{\rm max}}^{R_{\rm max}} dR \frac{n_{\rm HI}(r)}{T_s(r) v_{\rm th}} \exp\left[-\frac{v^2(\nu)}{v_{\rm th}^2} \right]$$

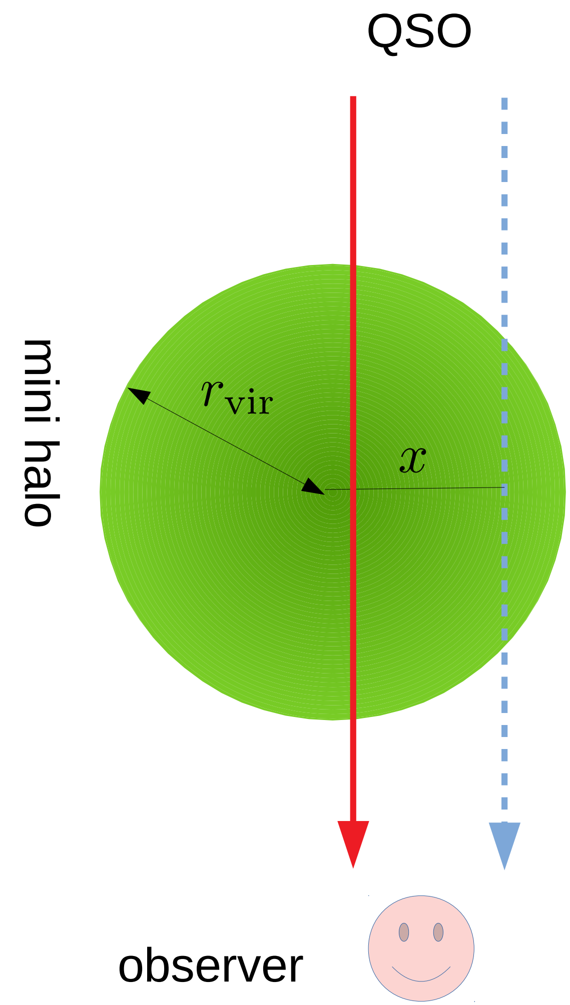
$$v(\nu) = c(\nu - \nu_{21})/\nu_{21}$$

$$v_{\rm th}^2 = 2kT_{\rm vir}/m_p$$



simple model (optical depth)





Smaller mass halos and smaller impact parameters give larger optical depth

simple model (line abundance)

- **mini-halo line abundance that has an optical depth larger than τ is given by**

virial mass corresponding to $T_{vir}=10^4$ K

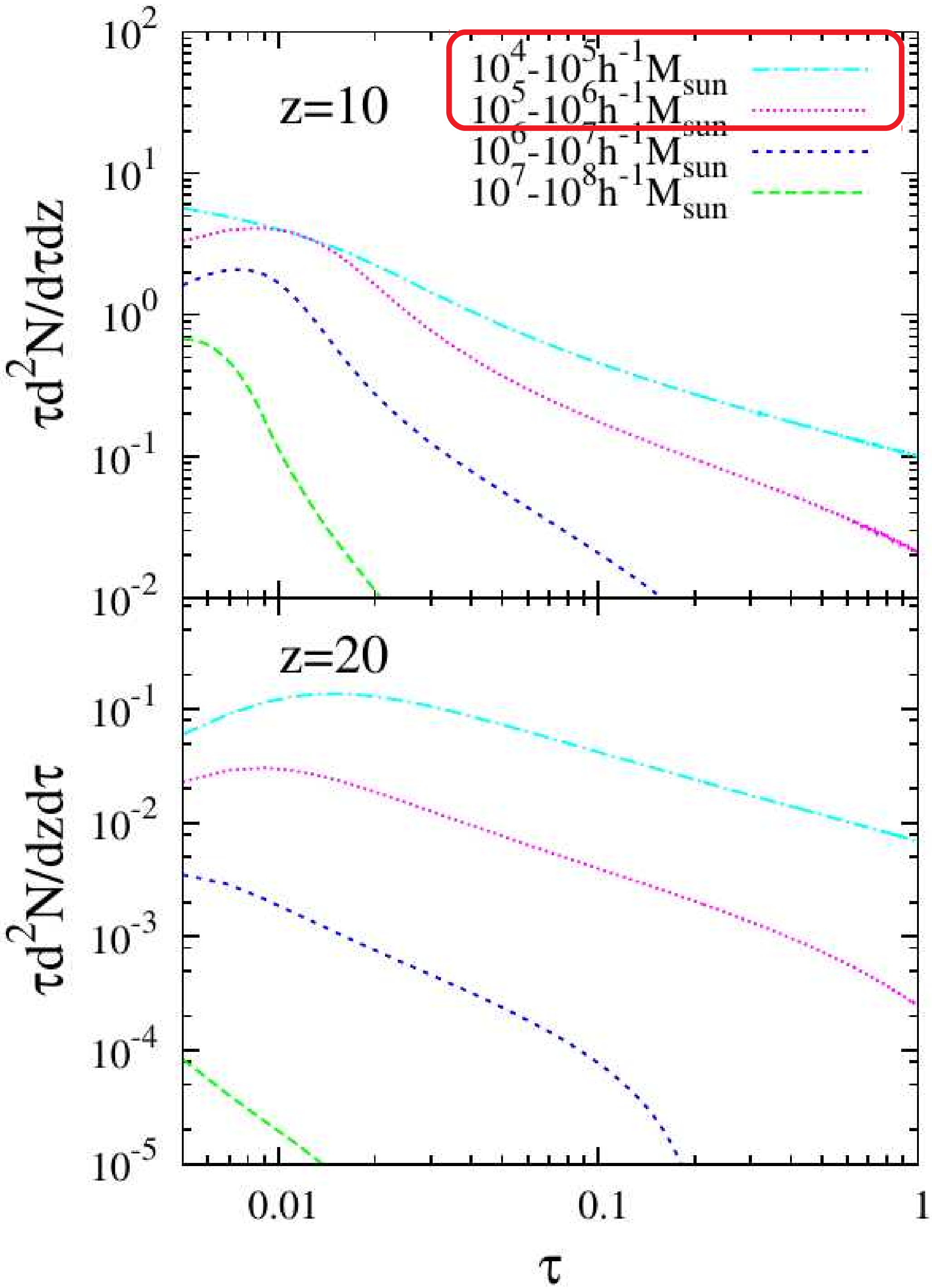
maximum impact parameter that gives an optical depth greater than τ

$$\frac{dN}{dz}(>\tau) = \frac{dr}{dz}\int_{M_{\rm min}}^{M_{\rm max}} dM \frac{dN}{dM}(M)\pi x_\tau^2(M)$$

Jeans mass to $T=T_{IGM}(z)$

mass function of DM halo

Strongly depends on cosmological models and warm dark matter mass



Shimabukuro, KI, Inoue, Yokoyama, PRD, '14

absorption line abundance

Smaller mass halos give dominant contribution to the line abundance

target mass range of 21cm forest:

$$10^4 M_\odot \lesssim M \lesssim 10^6 M_\odot$$

we want to see 'clean' universe (z>10)

trade-off

less abundant at higher z

contents

mass function of WDM cosmology

(M. Viel, et al., PRD, '05, Smith & Markovic, PRD, '11)

free streaming scale

$$\lambda_{\rm fs}^{\rm WDM} = 0.11{\rm Mpc}\left(\frac{\Omega_{\rm WDM}h^2}{0.15}\right)^{\frac{1}{3}}\left(\frac{m_{\rm WDM}}{\rm kev}\right)^{-\frac{4}{3}}$$

$$\lambda_{\rm fs}^{\rm CDM} \approx 0$$

mass function is approximately modeled as

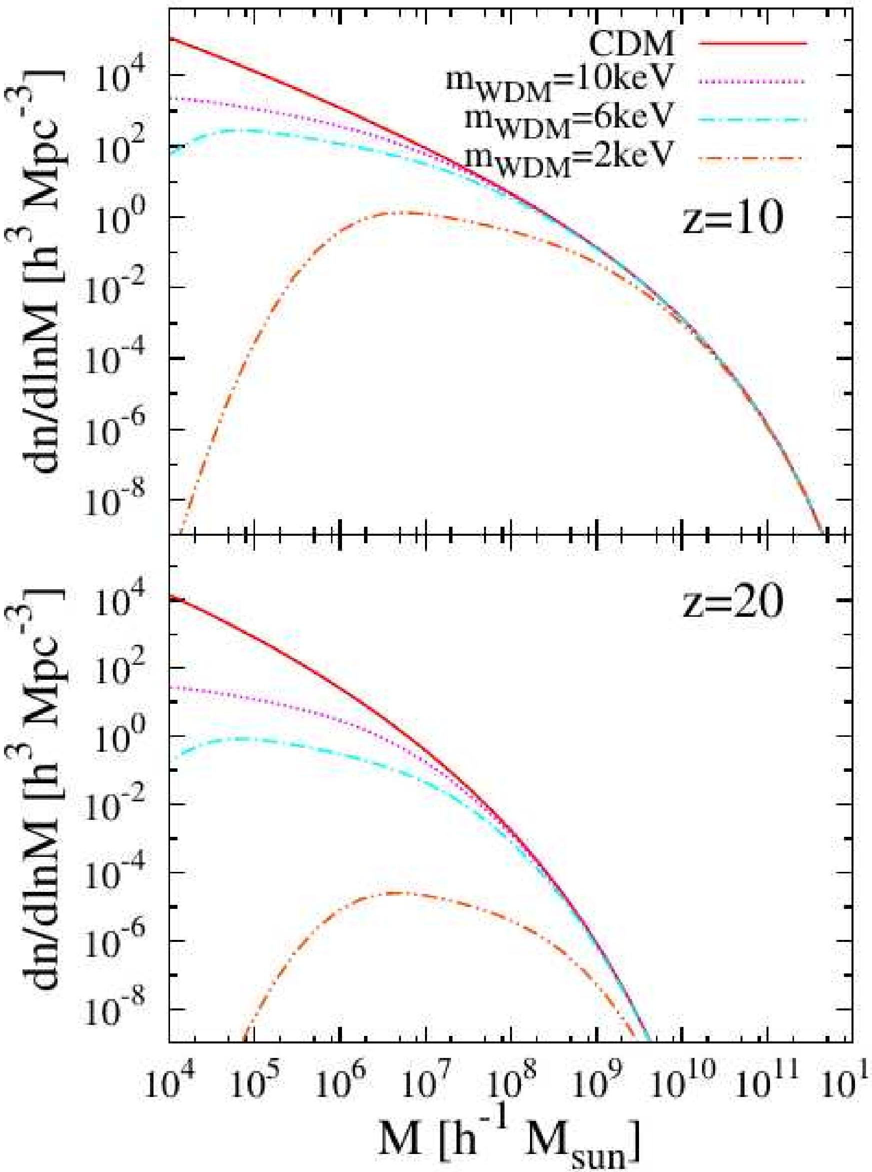
$$\frac{dn}{dM} = \frac{1}{2}\left\{1+\left[\frac{\log_{10}(M/M_{\rm fs})}{0.5}\right]\right\}\left(\frac{dn}{dM}\right)_{\rm PS}$$

with the WDM power spectrum (fitting formula)

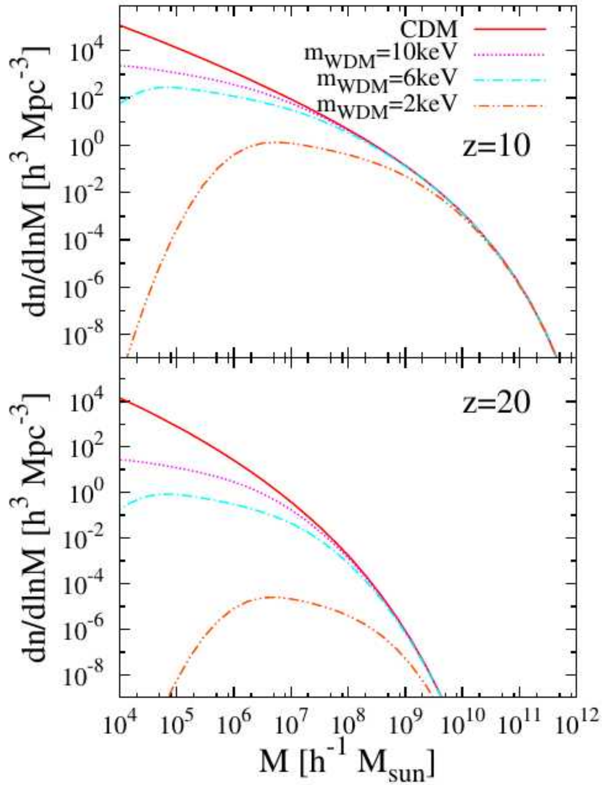
$$P_{\rm WDM}(k) = P_{\rm CDM}(k)\left\{\left[1+(\alpha k)^{2\mu}\right]^{-5/\mu}\right\}^2$$

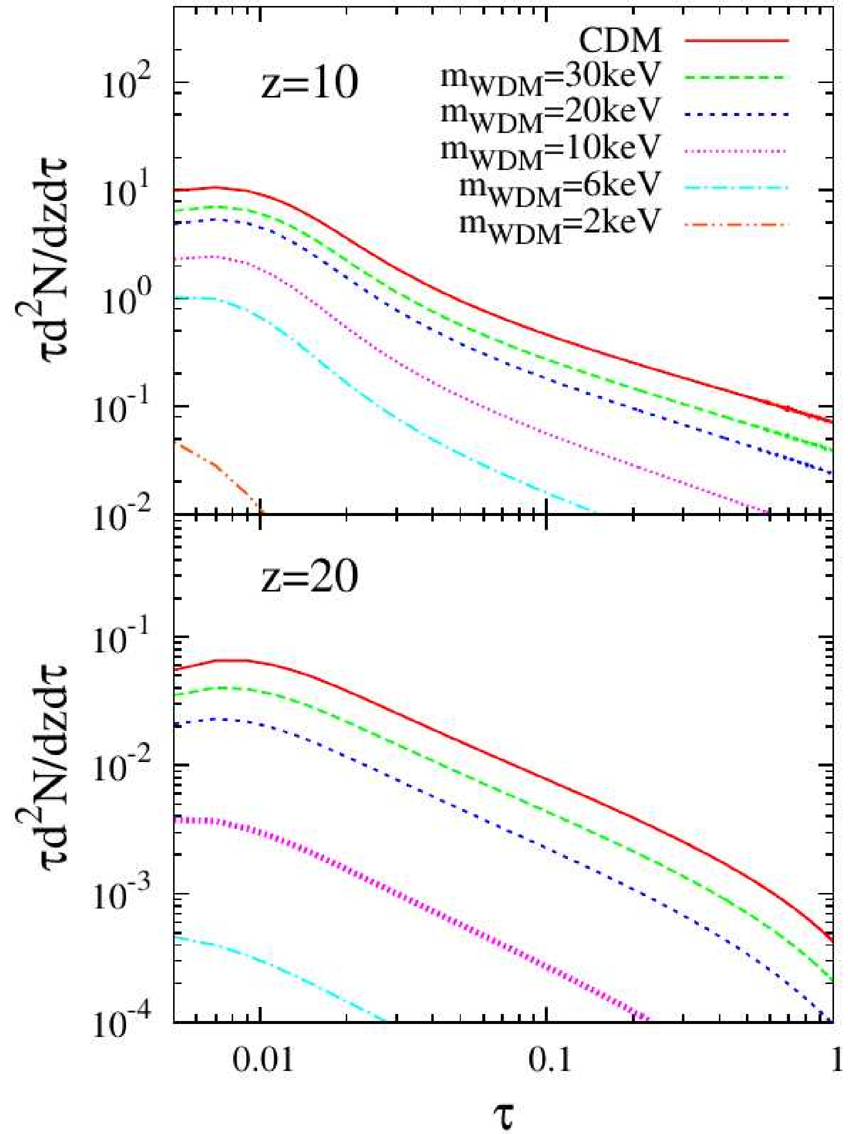
$$\alpha = 0.049\left(\frac{m_{WDM}}{\rm kev}\right)^{-1.11}\left(\frac{\Omega_{\rm WDM}}{0.25}\right)^{0.15}\left(\frac{h}{0.7}\right)^{1.22}h^{-1}{\rm Mpc}$$

$$\mu = 1.12$$



new probe to m_{WDM}





Even mass of **>10keV** alters the number of lines significantly

Fisher analysis

- **Fisher matrix:** $$F_{ij} \equiv -\frac{\partial^2 \ln \mathcal{L}}{\partial\theta_i \partial\theta_j}\Big|_{\theta=\theta_{\rm fid}}$$

- **If your likelihood function for parameters θ_i is Gaussian**

$$\ln \mathcal{L} = -\frac{1}{2}\theta_i C_{ij}^{-1}\theta_j$$

(covariance matrix)$^{-1}$ ~ (error)$^{-1}$

- **the fisher matrix is equal to the inverse of the covariance**

$$F_{ij} = C_{ij}^{-1}$$

Fisher matrix is useful in estimating errors of model parameters given the likelihood function, and therefore widely used in considering observational strategies.

Fisher analysis

- **We assume that the number of absorption lines obeys Poisson statistic and hence the likelihood function:**

$$\mathcal{L}(n, \bar{n}) = \bar{n}^n e^{-\bar{n}} / n!$$

n : total number of absorption lines

$\bar{n}$: its expectation value in the fiducial model

$$n = \int_{\boxed{\tau_{\rm min}}}^{\infty} \boxed{\frac{d^2 N}{d\tau dz}} d\tau \Delta z$$

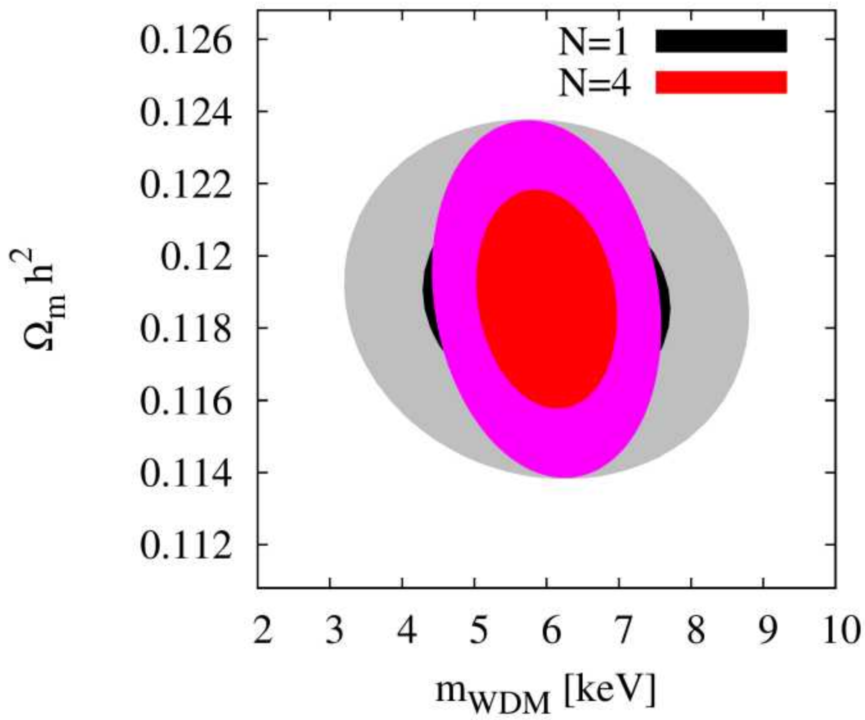
observation sensitivity

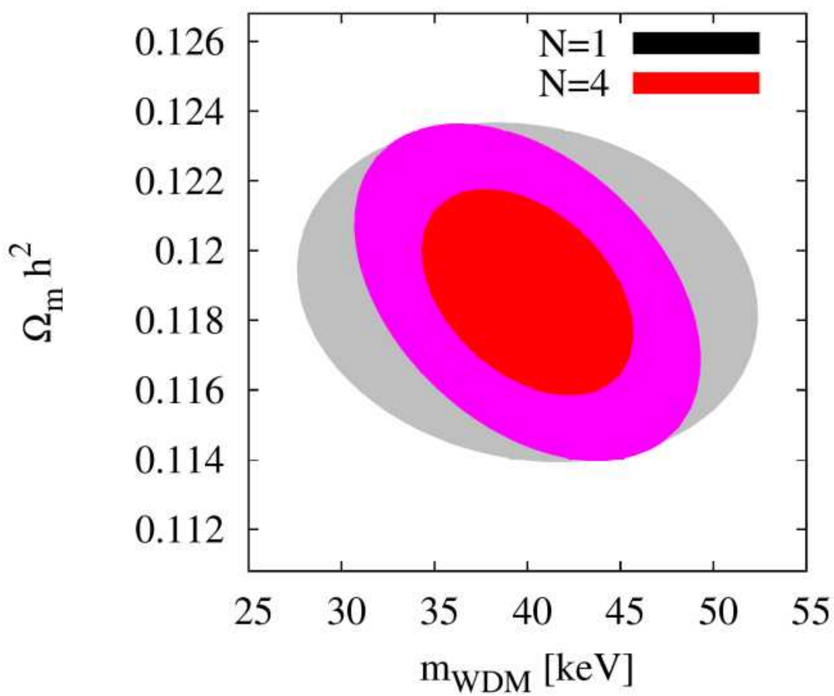
(we assume $\tau_{\rm min} = 0.01$)

WDM mass changes this

(shimabukuro, yokoyama, KI, inoue, PRD, '12)

Result (z=10)





- **because strong degeneracy is expected with** $\Omega_m h^2$ **, we put a weak prior** $\Delta\Omega_m h^2 = 0.002$

(Ichiki, Shimabukuro, Inoue, in progress)

WDM constraint summary

	6.0 keV	10 keV	30 keV	40 keV
N_{lines} z=10	3.54	11.8	59.33	72.87

expected number is very sensitive to m_{wdm}

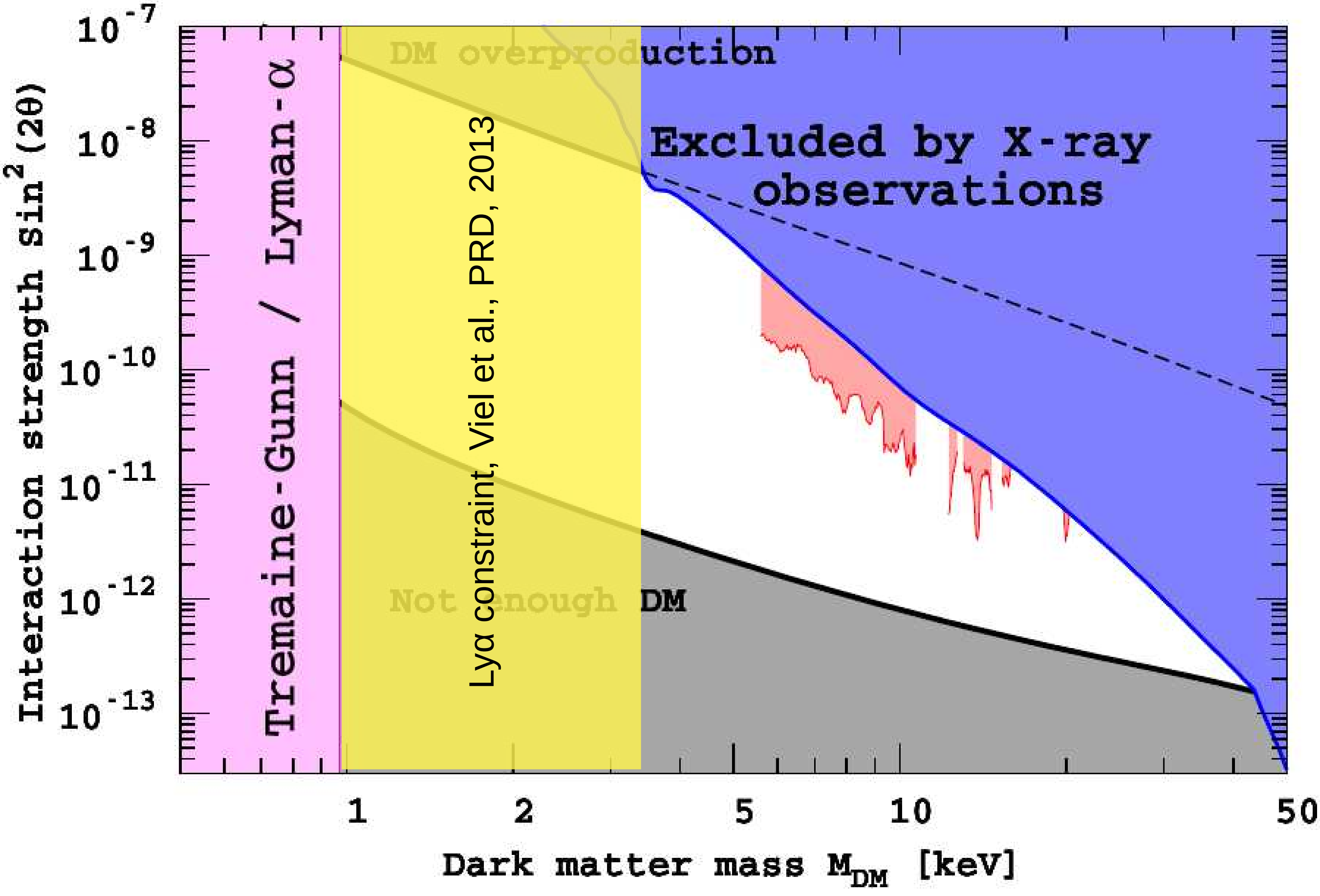
$\frac{dN_{\rm lines}}{dm_{\rm wdm}}$ decreases with larger m_{wdm}
but larger N_{line} enables us to have comparable constarint on m_{wdm}

	error at 6.0 keV	error at 10 keV	error at 30 keV	error at 40 keV
N_{QSO}=1	1.1 keV	1.3 keV	3.9 keV	5.0 keV
N_{QSO}=4	0.6 keV	0.7 keV	2.0 keV	3.7 keV

$$\left(\frac{\Delta m_{\rm wdm}}{m_{\rm wdm}}\right)_{40{\rm keV}} \approx \left(\frac{\Delta m_{\rm wdm}}{m_{\rm wdm}}\right)_{6{\rm keV}}$$

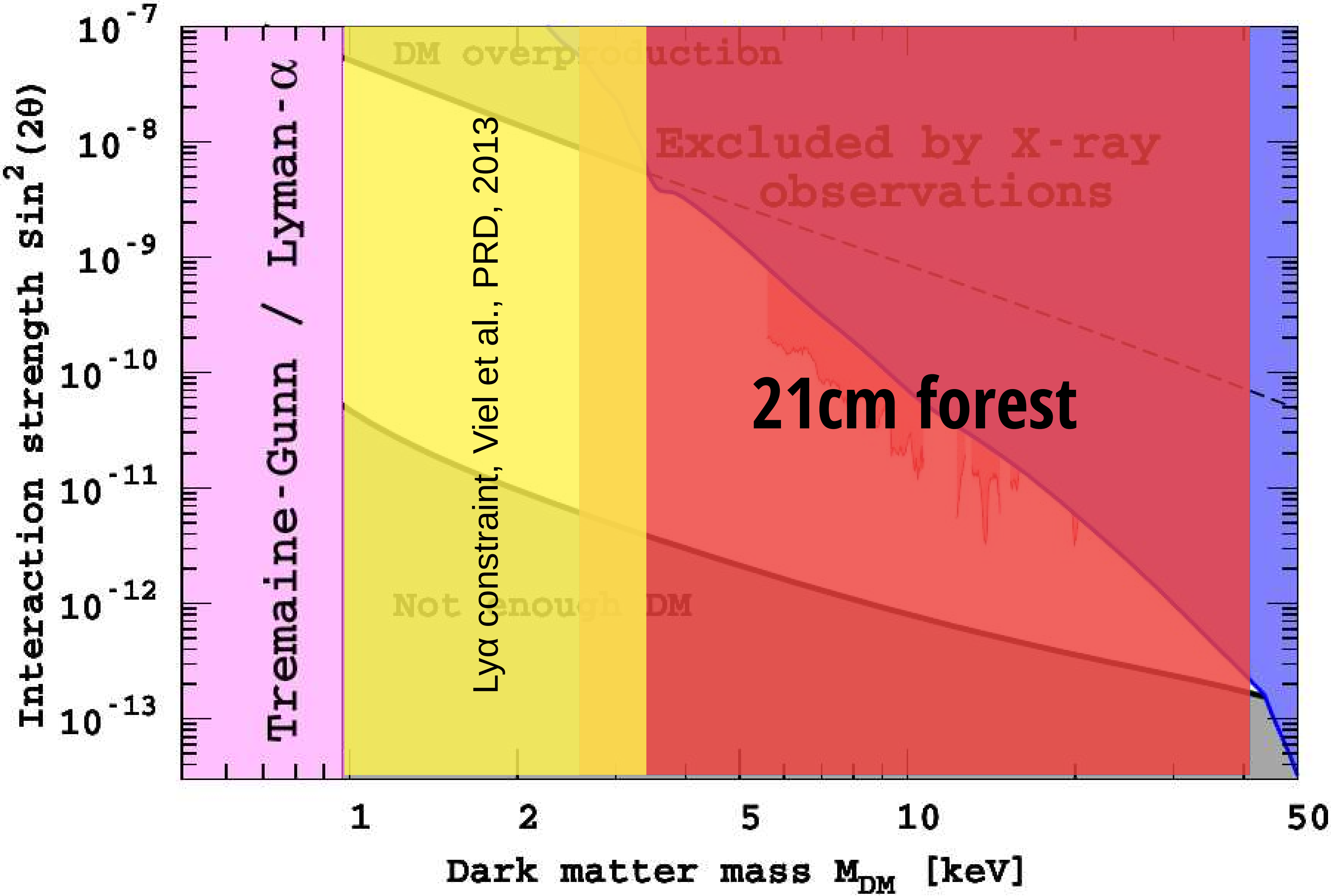
(Ichiki, Shimabukuro, Inoue, in progress)

WDM (sterile neutrino) constraints



(figure taken from Boyarsky, 1306.4954)

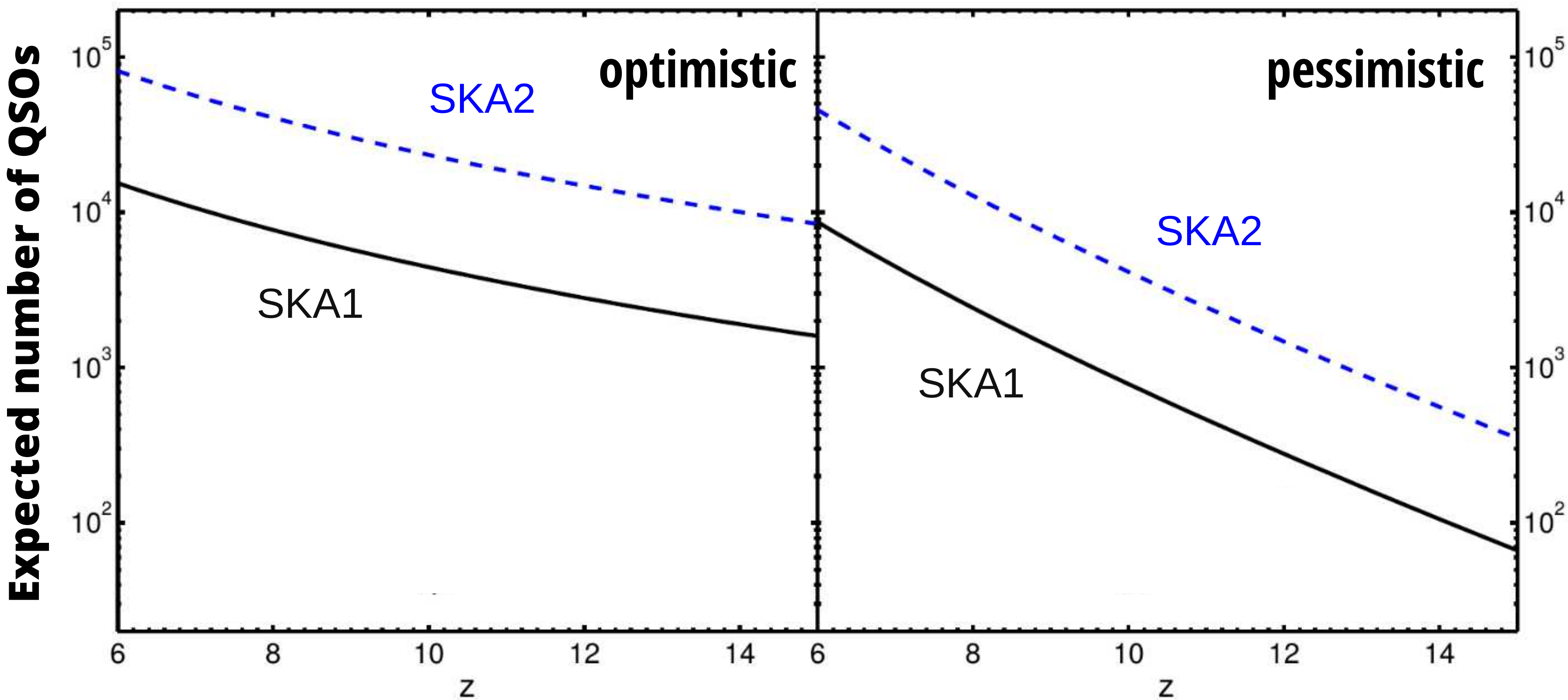
WDM (sterile neutrino) constraints



(figure taken from Boyarsky, 1306.4954)

Challenges: How many radio-loud objects can we expect ?

- QSOs are observed even at high-z universe (z=7.54). We do not know whether they are radio loud. We extrapolate their number abundance assuming the radio loud/quit ratio at lower redshift.



Ciardi et al., SKA science book, 2015

Challenges: How many radio-loud objects can we expect ?

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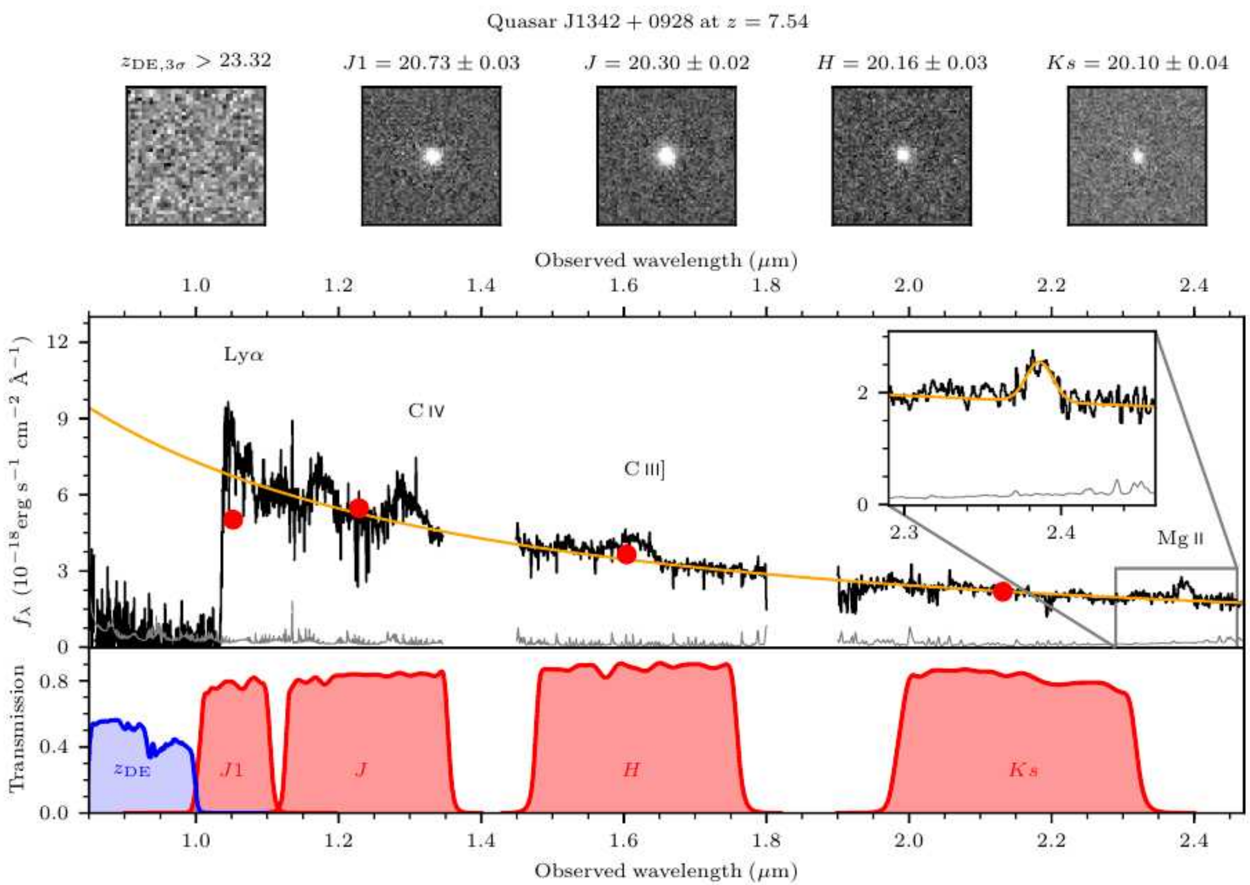


$$L = 4 \times 10^{13} L_\odot$$

$$M = 8 \times 10^8 M_\odot$$

$1000 M_\odot$ required at z=40

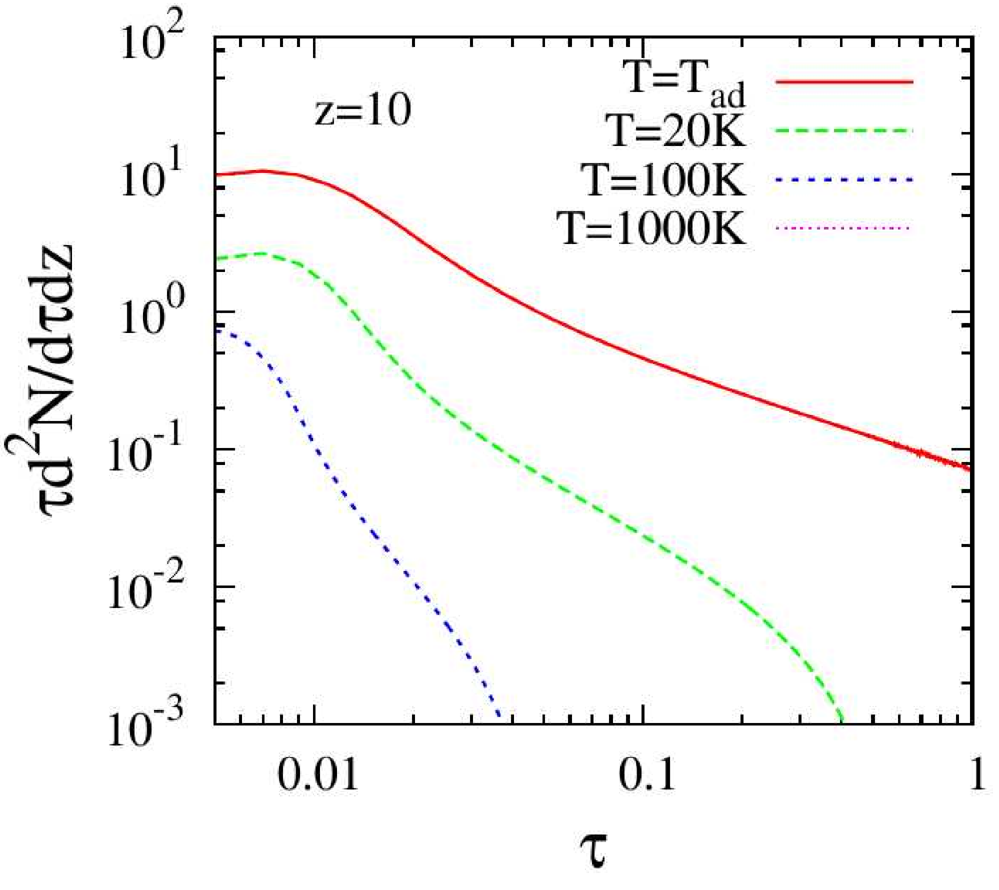
$$x_e = 0.55^{+0.22}_{-0.17}$$

well within the EoR

Banados+, Nature, ‘17

Challenges: IGM temperature ?

- **the number of absorption lines (mini-halos) highly depends on the global IGM temperature**



(X-ray) heating the IGM

↓

Jeans mass gets larger

↓

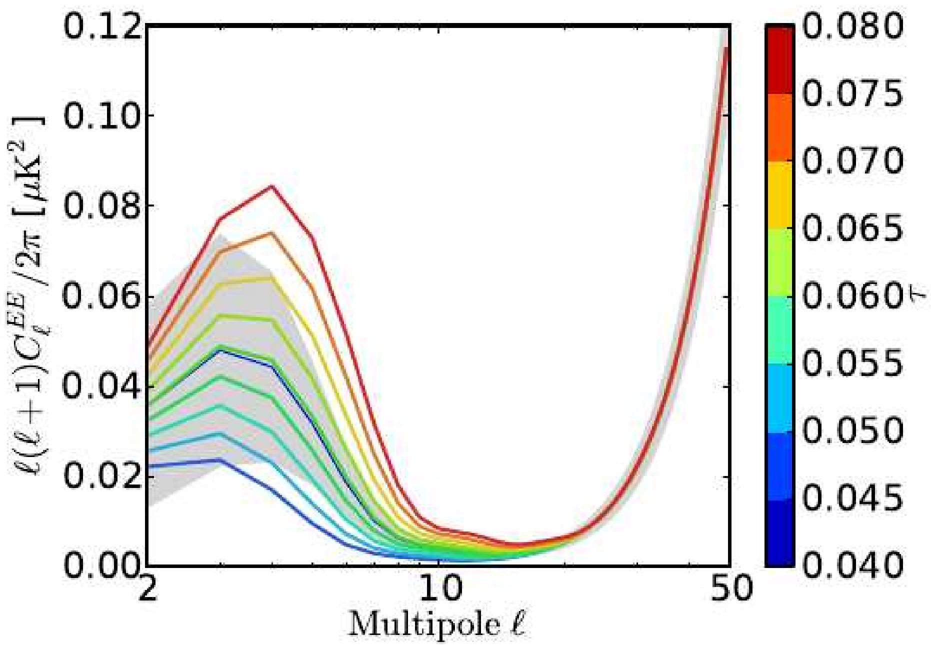
less (small) mini-halos

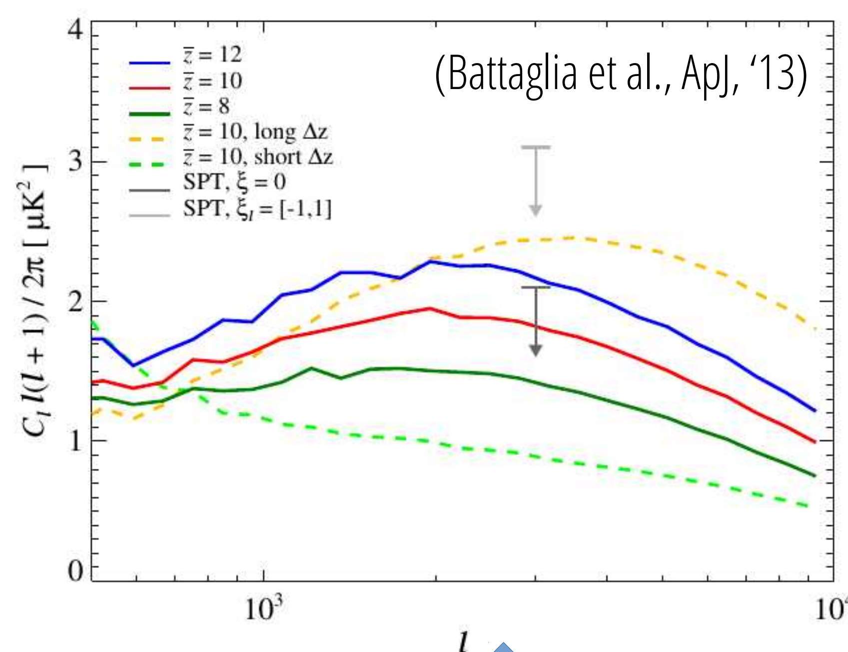
↓

less number of large τ lines

Challenges: IGM temperature ?

- **(good) news from Planck results (XLVII), constraints on reionization from Planck-HFI (polarization) and ACT+SPT (kSZ)**



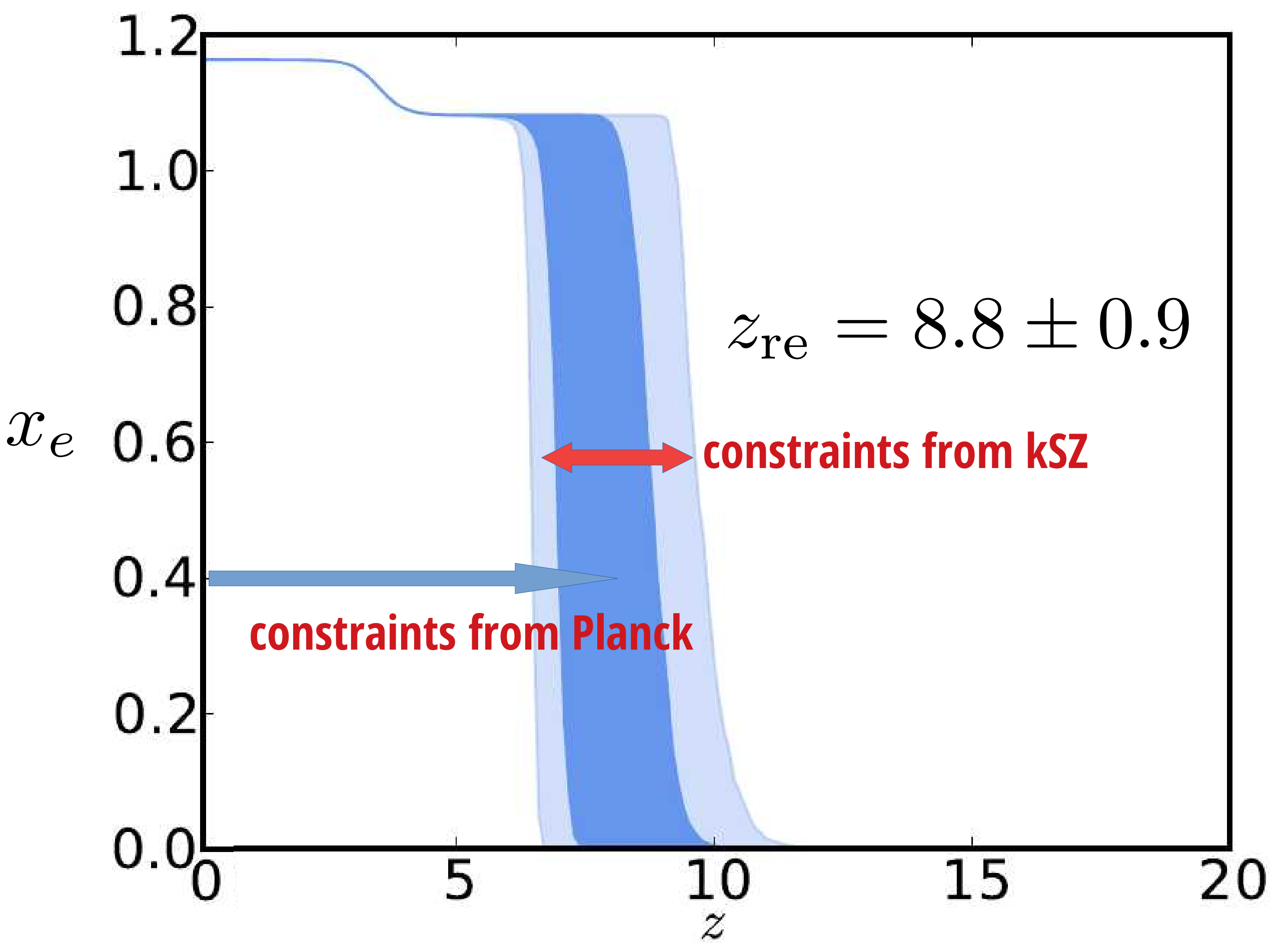


free electrons created by reionization re-scatter CMB photons to produce plarization on large angular scales

large duration (⊿z) means that ionized bubble is small, and small scale fluctuation dominates

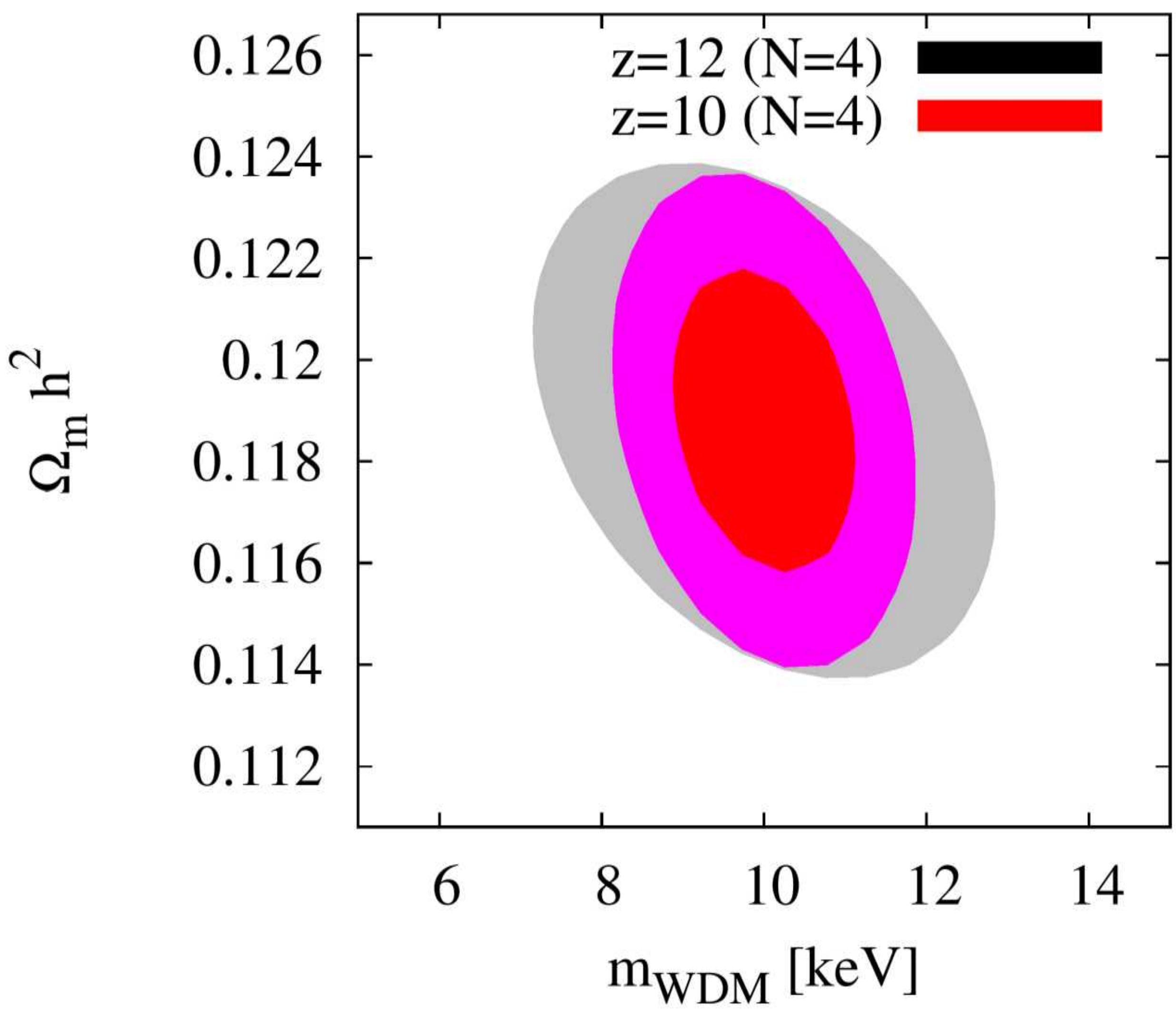
Challenges: IGM temperature ?

- (good) news from Planck results (XLVII), constraints on reionization from Planck-HFI (polarization) and ACT+SPT (kSZ)



the IGM might be cooler than expected at high z (say, z>12)

higher redshift ?



At higher redshifts, the number of mini-halos decreases, but preliminary study suggests that we may be able to constrain m_{wdm} even at z=12
(if QSOs exist)

summary of this seminar

- cosmological 21cm observation will give us information how the universe is reionized around z=9
- The CDM model is successful on largest scales, but still needs to be tested on galactic scale, and the WDM model may solve the CDM crisis on that scale.
- 21cm forest is very sensitive to WDM mass
- 6 keV $< m_{wdm} <$ 50 keV WDM mass can be tested by future 21cm forest observations