BSM@50

Dark Forest from the Dark Matter

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With Anoma Ganguly and Rishi Khatri (2301.03624)

With Anoma Ganguly and Rishi Khatri (in preparation)

Outline

Let me try to put the talk in context

The most optimistic picture of dark matter physics:
we detect it via the same interaction that also determines its abundance

The most pessimistic scenario : the dark world has its own set of healthy interactions
However, it only talks to us gravitationally.

Somewhere between these worlds lies the vast possibility that the dark world with its own interactions is only slightly connected to us

Outline

Somewhere between these worlds lies the vast possibility that the dark world with its own interactions is only slightly connected to us

This talk contains a proposal for the search of dark matter via absorption of light

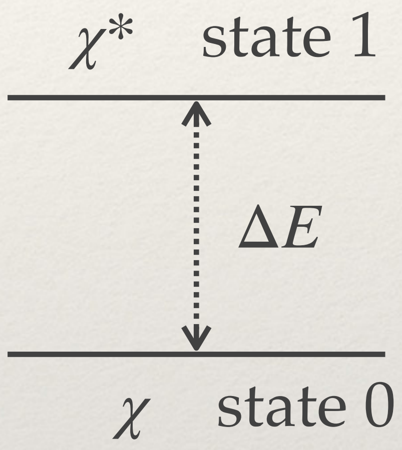
Absorption lines in the spectrum of a background source

Ex, Quirky Composite Dark Matter
Kribs, Roy, Terning, Zurek, 2009

Gives rise to anomalous features (and/or spectral distortions) in the CMB

Dark Matter as a 2-level system

It is easy to model an effective dark sector as a two level system of states between which electromagnetic-transitions take place.



$$\epsilon \frac{e}{m_\chi} \mathrm{Tr}\left(\bar{\chi}_v \sigma^{\mu\nu} \chi_v F_{\mu\nu}\right)$$

Mass scale of dark matter

Strength of the coupling

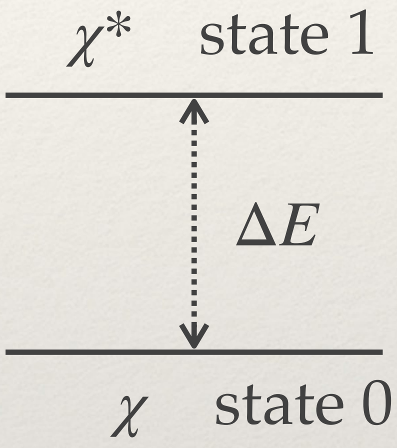
Use a compact notation

$$\chi_v \equiv \frac{1}{2}(1+\not{v})\left(\chi^*_\mu \gamma^\mu - \chi\gamma^5\right)$$

We are interested in the territory $\Delta E \ll m_\chi$

Dark Matter as a 2-level system

Its a story of transition between two states - relevant parameters are:

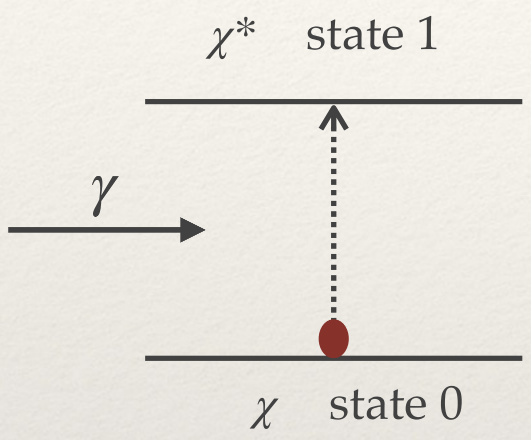


- Energy splitting $\Delta E \;=\; h\nu_0 \;\equiv\; k_B T_*$
- The relative dark matter population: which can be parametrized by the excitation temperature

$$T_{ex} \;\equiv\; T_* \;\log\left(\frac{n_0/g_0}{n_1/g_1}\right)$$

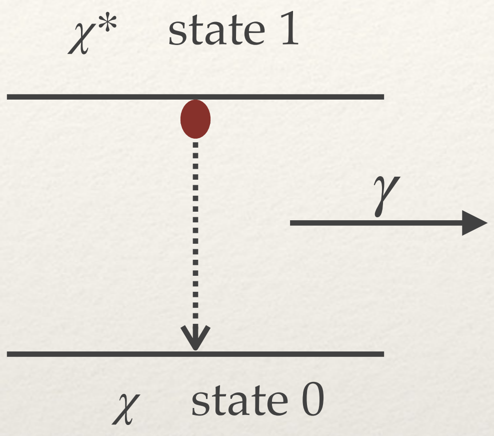
Dark Matter as a 2-level system

Electromagnetic Transitions:



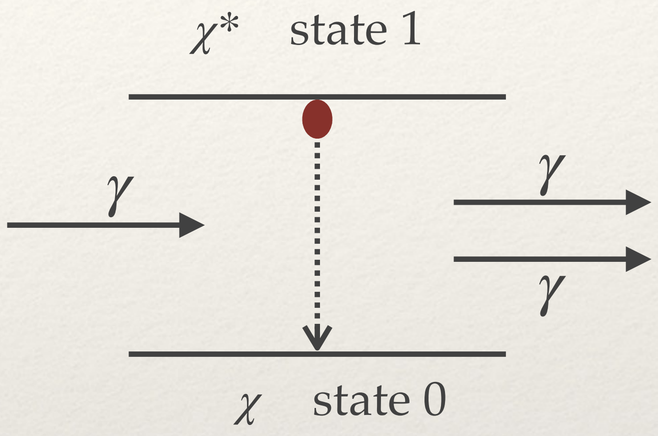
Absorption

$n_0 B_{01} J$



Spontaneous Emission

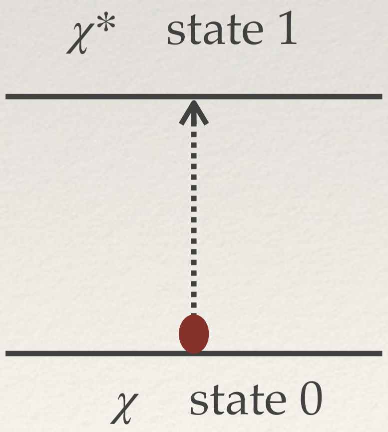
$n_1 A_{10}$



Stimulated Emission

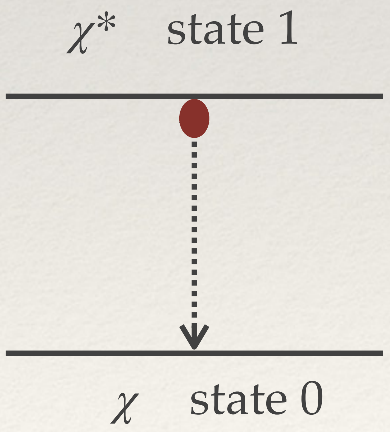
$n_1 B_{10} J$

(Inelastic) collisional Transitions:



Excitation

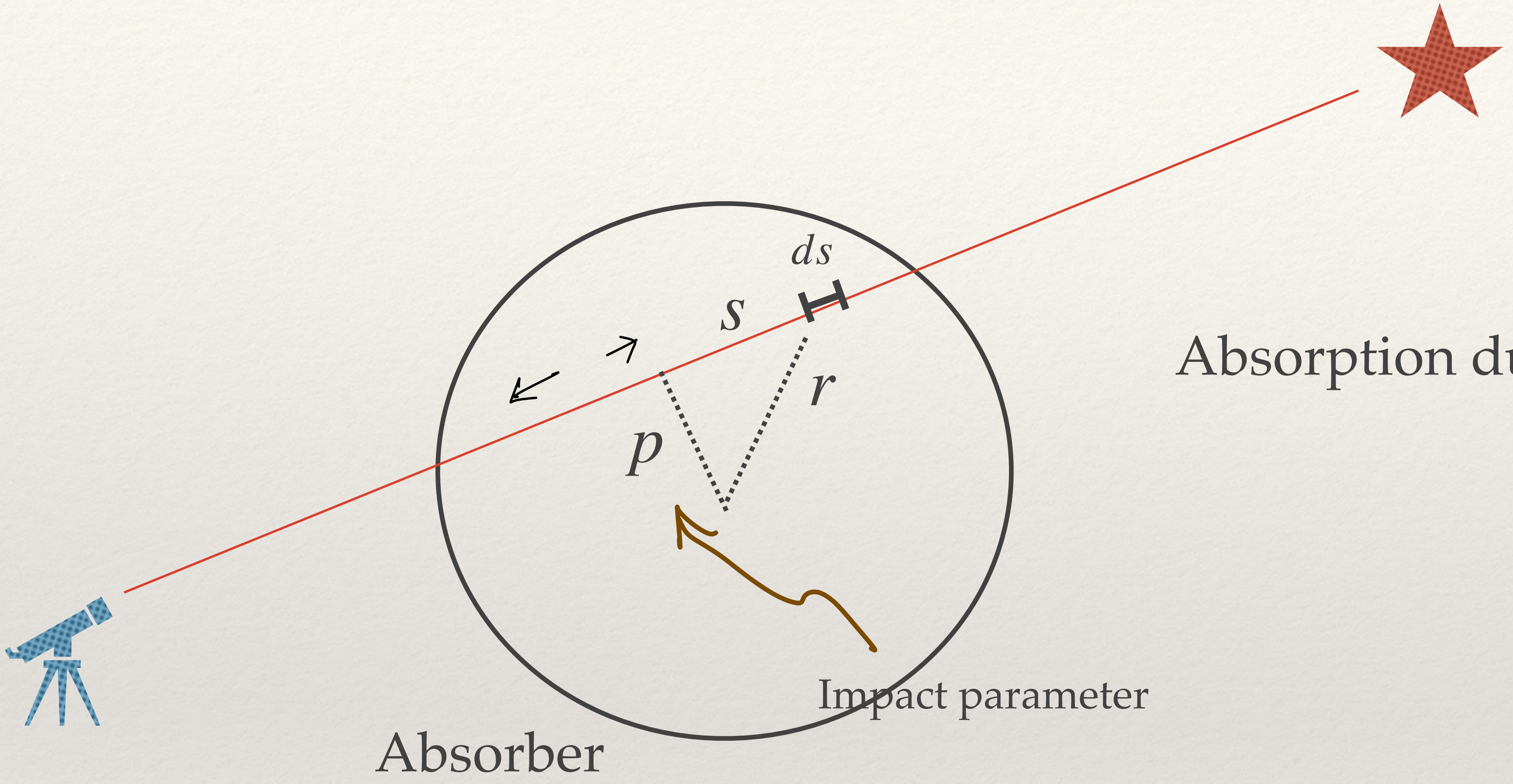
$n_0 C_{01}$



De-excitation

$n_1 C_{10}$

Dark lines from dark matter



Absorption due to dark matter will yield a dip in intensity

A convenient way to represent the dip is via optical depth

$$\tau_\nu \equiv \log \frac{F_\nu^0}{F_\nu}$$

Flux in the absence of the absorber

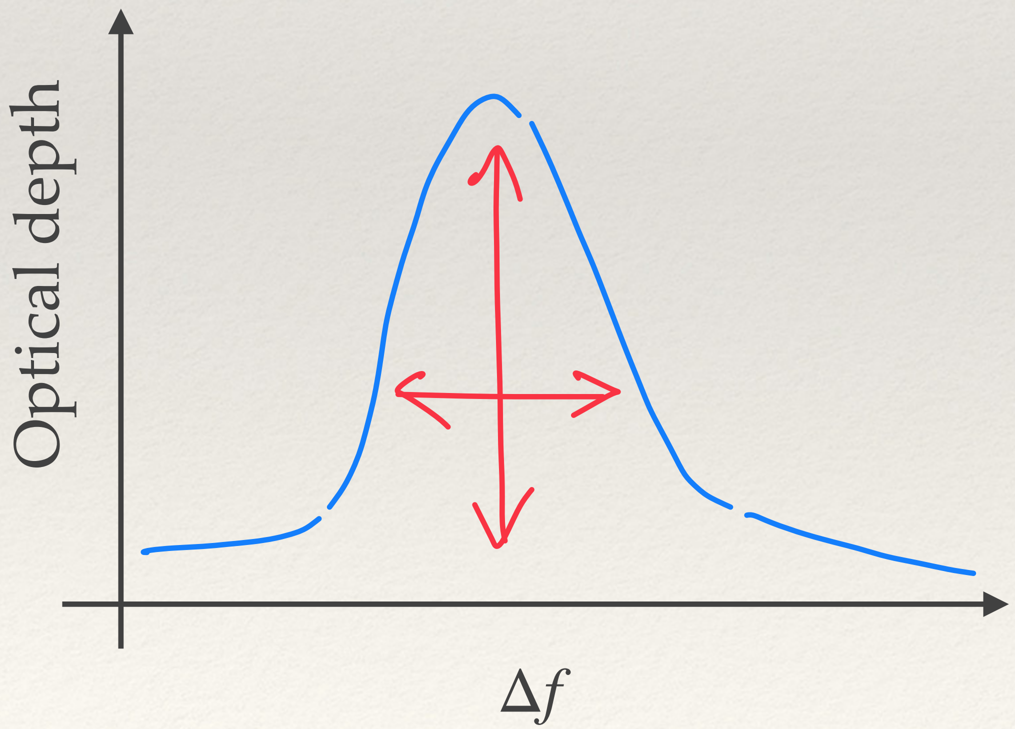
Flux observed

Dark lines from dark matter

Absorption – stimulated emission

$$\tau(\nu, p) \;\propto\; \int ds \frac{A_{10}}{\nu_0^2} \, \frac{\rho_{DM}}{m_\chi} \left(\frac{1 - e^{-T_*/T_{ex}}}{1 + (g_1/g_0) e^{-T_*/T_{ex}}} \right) . \, \phi$$

Doppler line broadening of the absorption line



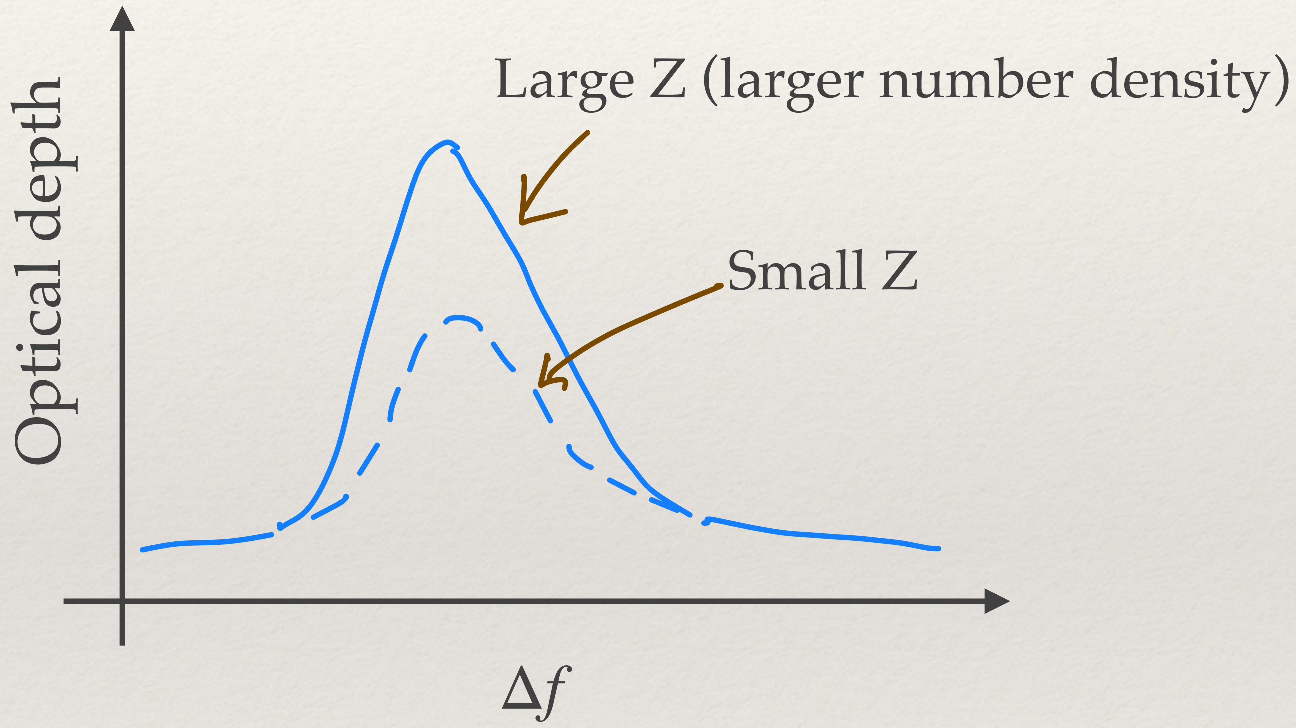
Width & height have non-trivial dependence on Z, Mass of halo, impact parameter s, etc.

Area gives the total amount of absorption

Dark lines from dark matter

Turn off C

$T_{ex} \rightarrow T_{CMB}$



Similar behavior for large mass halos

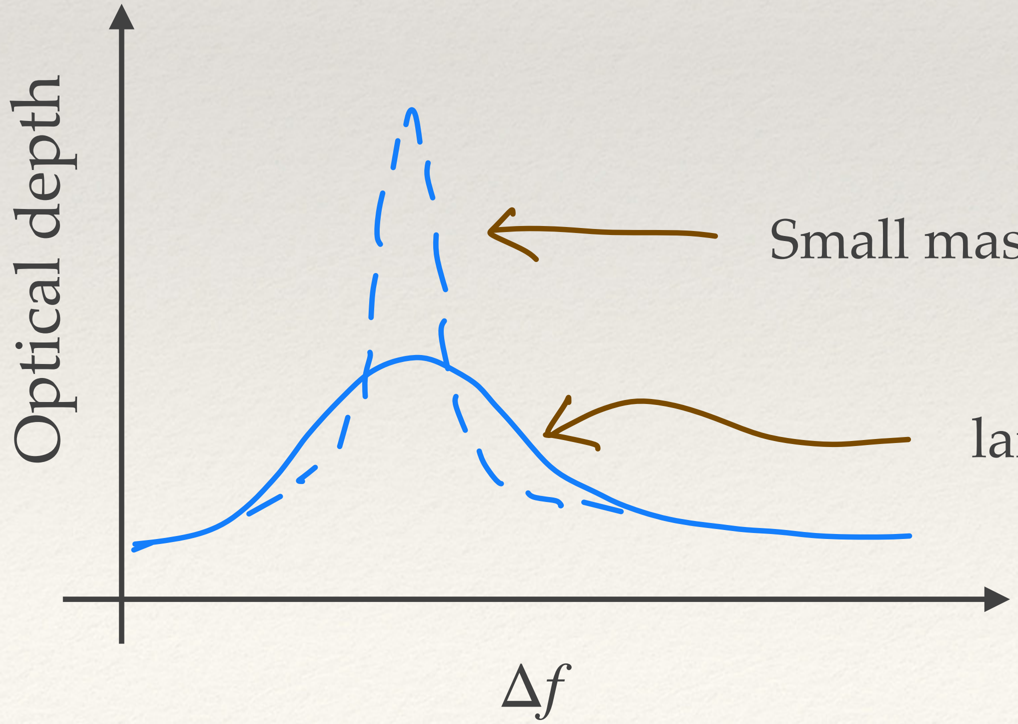
Dark lines from dark matter

Turn on C

$T_{ex} \rightarrow T_{halo} \; < \; T_{CMB}$

n_0/n_1 increases :
Stronger absorption than
collission-less case

However, mass dependence
is non-trivial

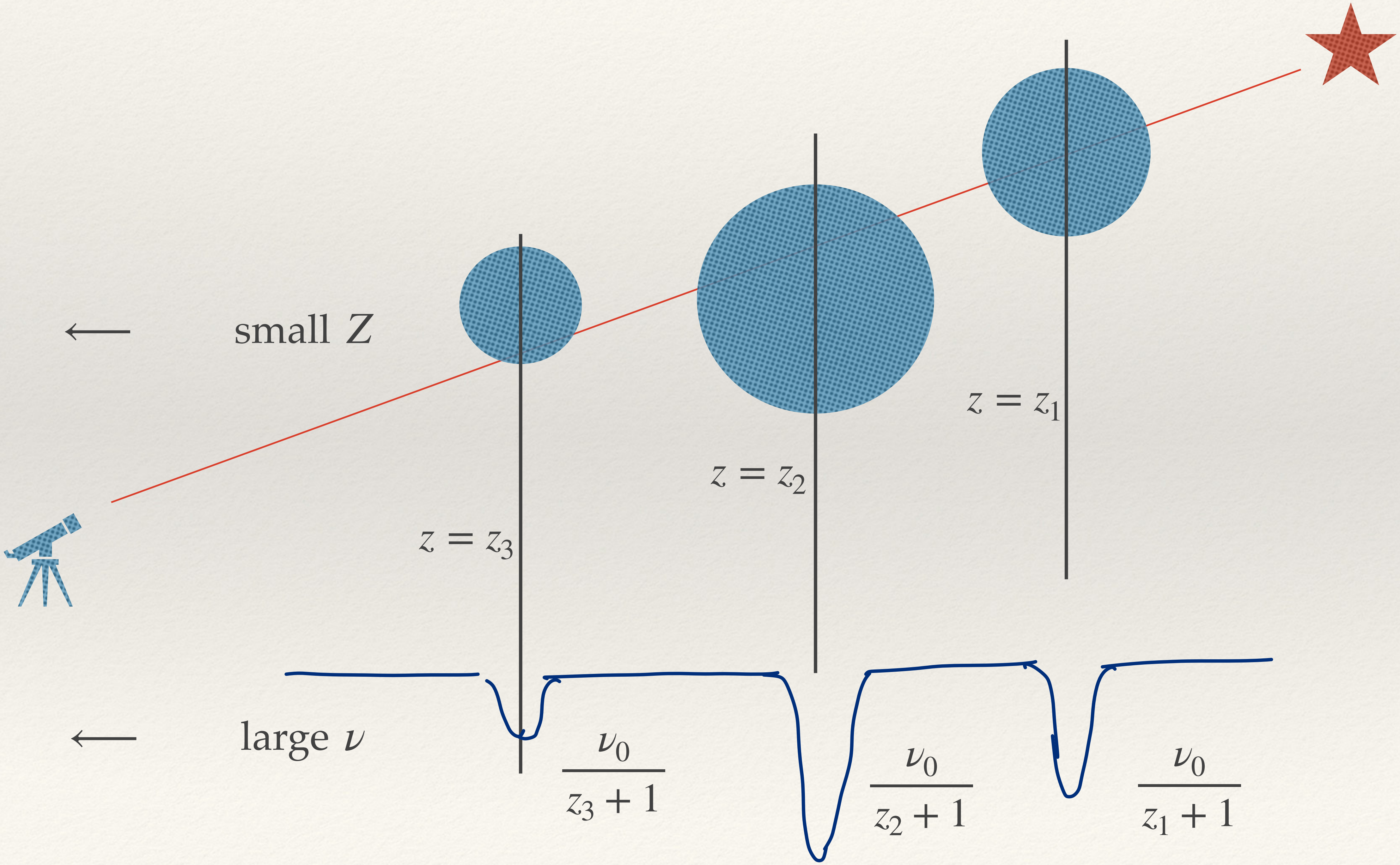


Small mass → small T_{halo} → larger n_0/n_1

large mass → larger T_{halo} → larger width

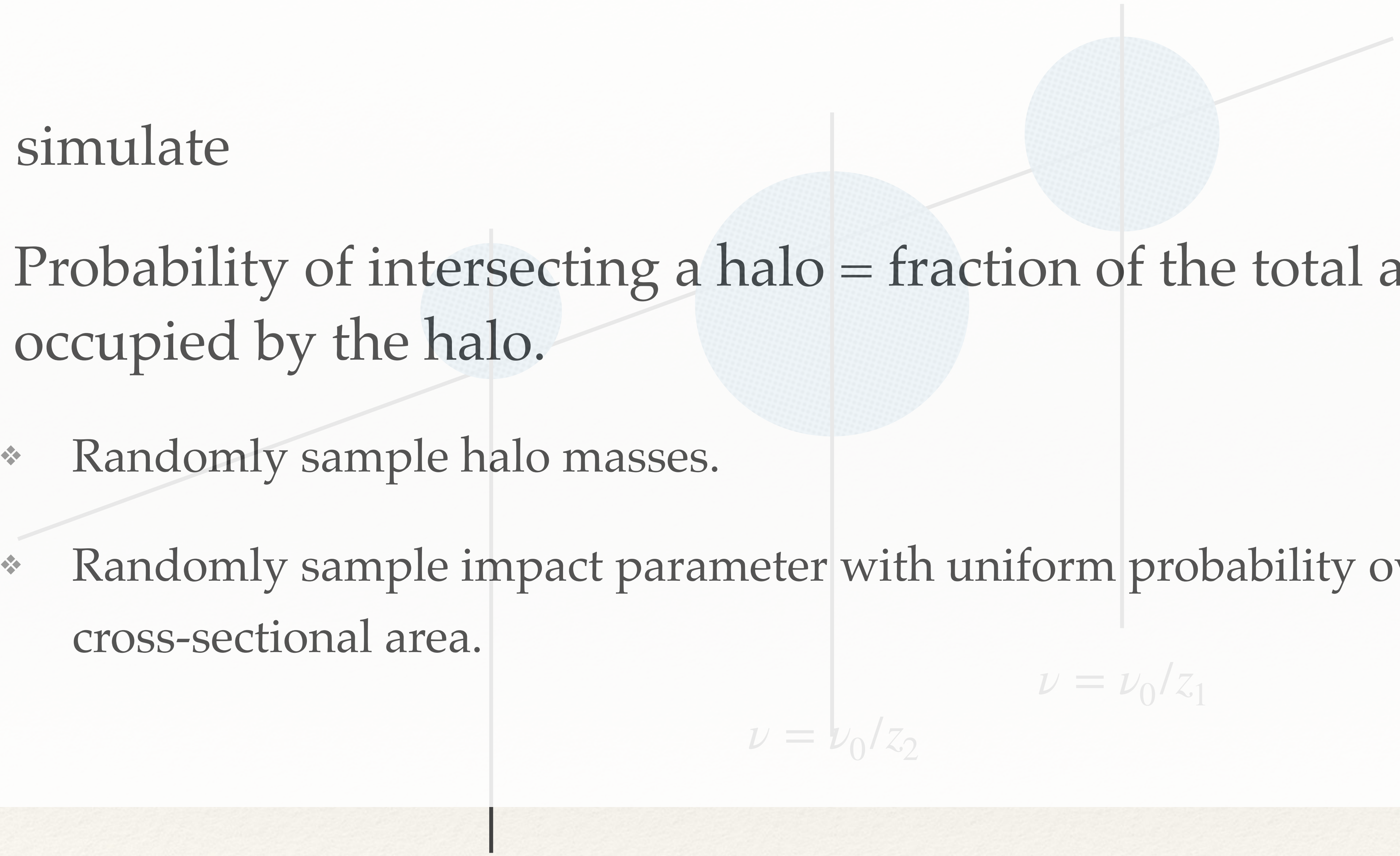
Dark forest from dark matter

Absorption from different halos at different redshifts give rise to the forest of dark-lines



Dark forest from dark matter

Absorption from different halos at different redshifts give rise to the forest of dark-lines

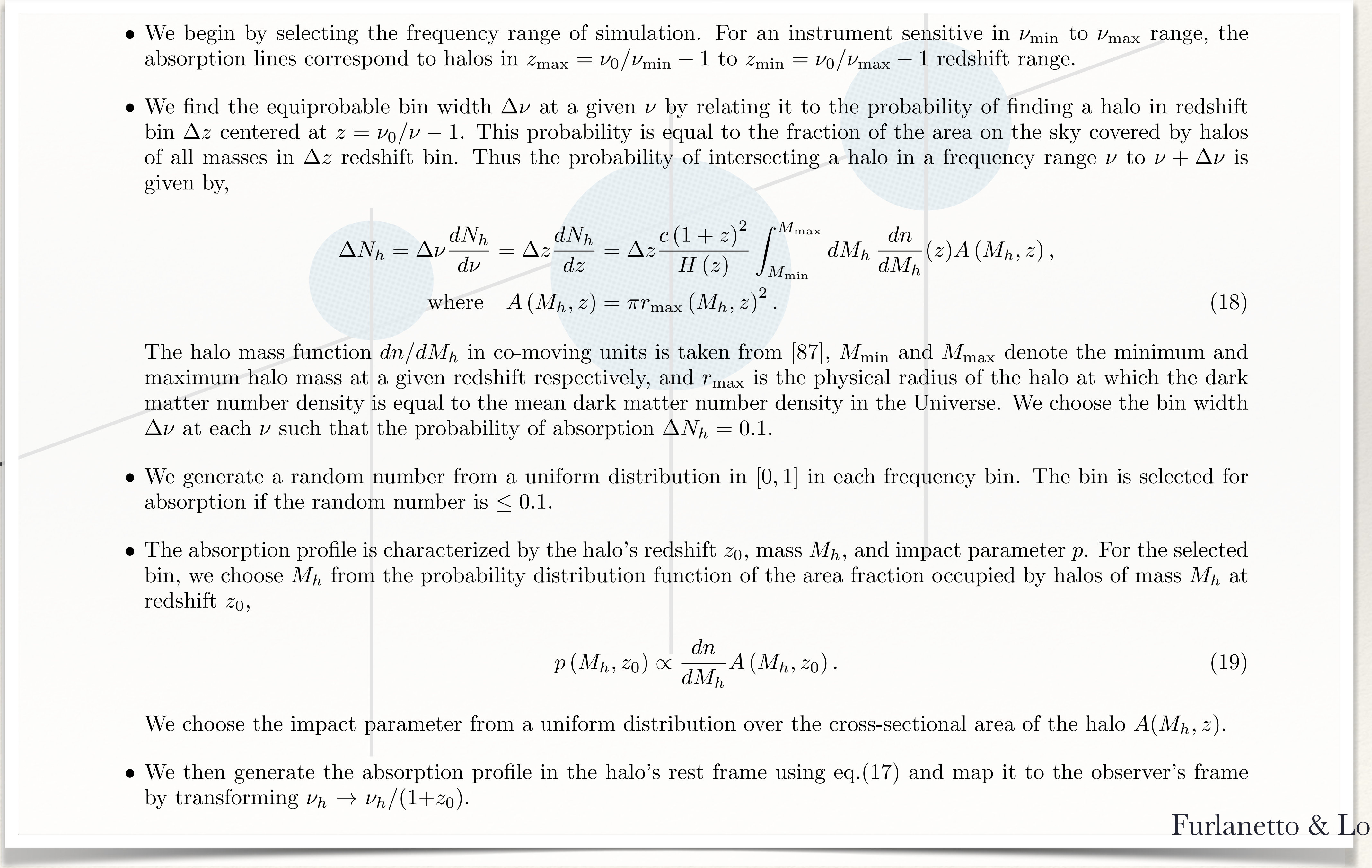


To simulate

- Probability of intersecting a halo = fraction of the total area occupied by the halo.
    - Randomly sample halo masses.
    - Randomly sample impact parameter with uniform probability over the cross-sectional area.

Dark forest from dark matter

Absorption from different halos at different redshifts give rise to the forest of dark-lines



- We begin by selecting the frequency range of simulation. For an instrument sensitive in $\nu_{\rm min}$ to $\nu_{\rm max}$ range, the absorption lines correspond to halos in $z_{\rm max} = \nu_0/\nu_{\rm min} - 1$ to $z_{\rm min} = \nu_0/\nu_{\rm max} - 1$ redshift range.

- We find the equiprobable bin width $\Delta\nu$ at a given ν by relating it to the probability of finding a halo in redshift bin Δz centered at $z = \nu_0/\nu - 1$. This probability is equal to the fraction of the area on the sky covered by halos of all masses in Δz redshift bin. Thus the probability of intersecting a halo in a frequency range ν to $\nu + \Delta\nu$ is given by,

$$\Delta N_h = \Delta\nu \frac{dN_h}{d\nu} = \Delta z \frac{dN_h}{dz} = \Delta z \frac{c\,(1+z)^2}{H\,(z)} \int_{M_{\rm min}}^{M_{\rm max}} dM_h \, \frac{dn}{dM_h}(z) A\,(M_h, z)\,, \qquad \text{where} \quad A\,(M_h, z) = \pi r_{\rm max}\,(M_h, z)^2\,. \tag{18}$$

The halo mass function dn/dM_h in co-moving units is taken from [87], $M_{\rm min}$ and $M_{\rm max}$ denote the minimum and maximum halo mass at a given redshift respectively, and $r_{\rm max}$ is the physical radius of the halo at which the dark matter number density is equal to the mean dark matter number density in the Universe. We choose the bin width $\Delta\nu$ at each ν such that the probability of absorption $\Delta N_h = 0.1$.

- We generate a random number from a uniform distribution in $[0, 1]$ in each frequency bin. The bin is selected for absorption if the random number is ≤ 0.1.

- The absorption profile is characterized by the halo's redshift z_0, mass M_h, and impact parameter p. For the selected bin, we choose M_h from the probability distribution function of the area fraction occupied by halos of mass M_h at redshift z_0,

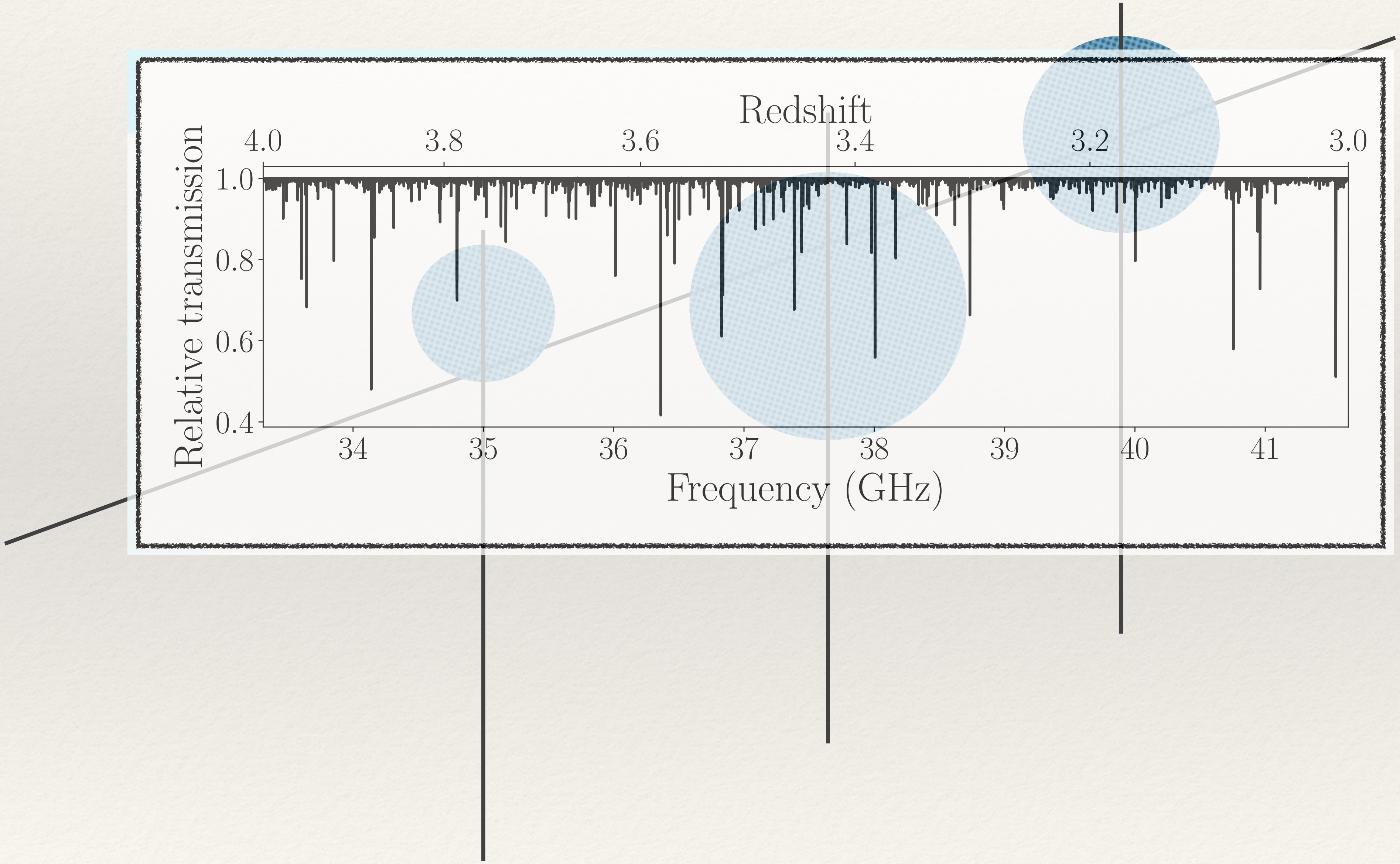
$$p\,(M_h, z_0) \propto \frac{dn}{dM_h} A\,(M_h, z_0)\,. \tag{19}$$

We choose the impact parameter from a uniform distribution over the cross-sectional area of the halo $A(M_h, z)$.

- We then generate the absorption profile in the halo's rest frame using eq.(17) and map it to the observer's frame by transforming $\nu_h \to \nu_h/(1{+}z_0)$.

Furlanetto & Loeb 2002

Dark forest from dark matter



Dark forest from dark matter

Information from a dark forest

Take for an example:

probability of finding a line in between $\nu \rightarrow \nu + d\nu$

$\propto$ probability of the LOS intersecting a halo at some $z \rightarrow z + dz$

$$\propto \int_{M_{\min}}^{M_{\max}} dM_{halo} \frac{dn(z)}{dM_{halo}}$$

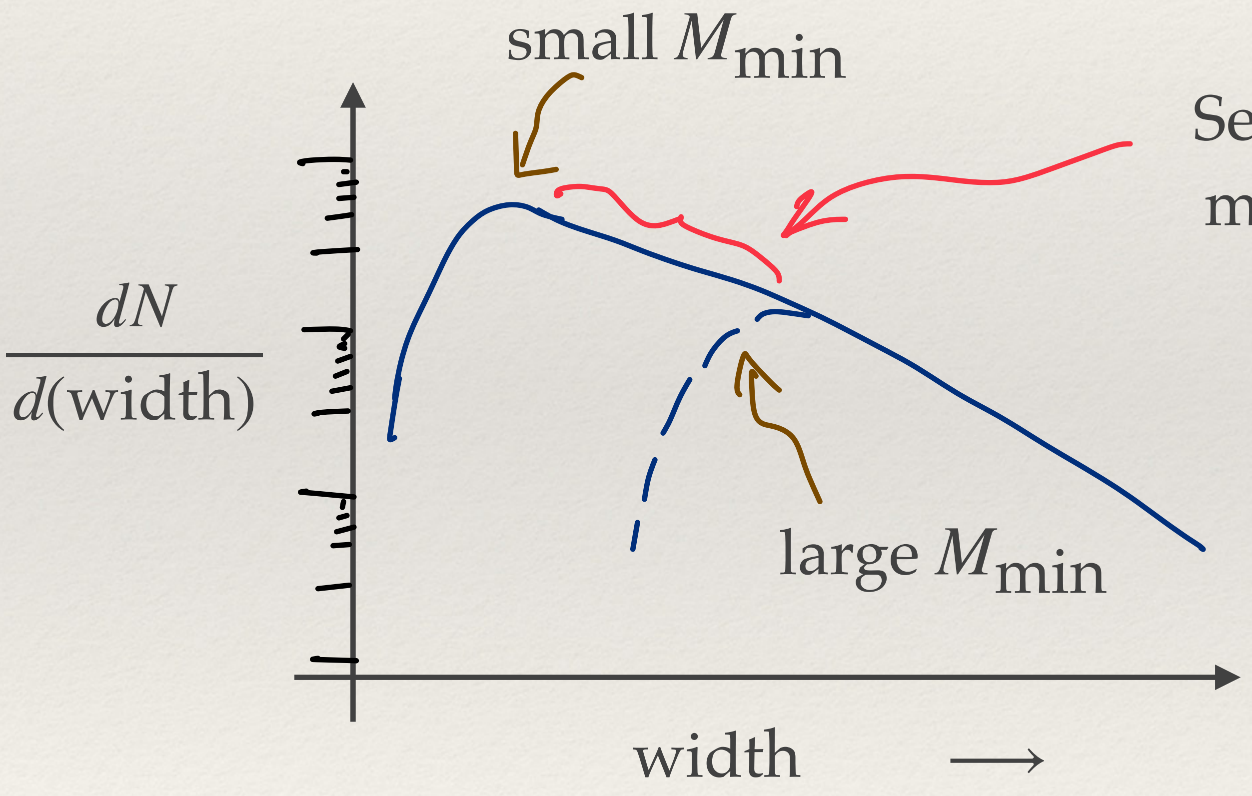
Minimum halo mass at a given Z

Halo mass function

Corresponds to a minimum in width of a dip (since width $\propto \sqrt{T_{halo}}$)

Dark forest from dark matter

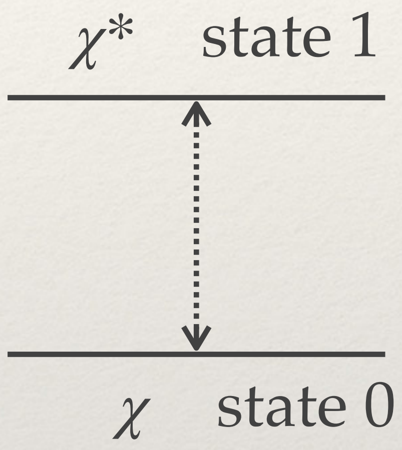
Information from a dark forest



Sensitive probe of the halo mass function at low halo masses

Dark Matter as a 2-level system

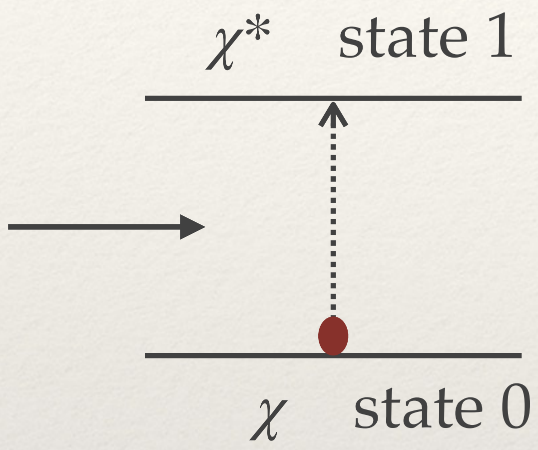
Transitioning dark matter also leaves complementary imprints on CMB as well


χ^* state 1

χ state 0

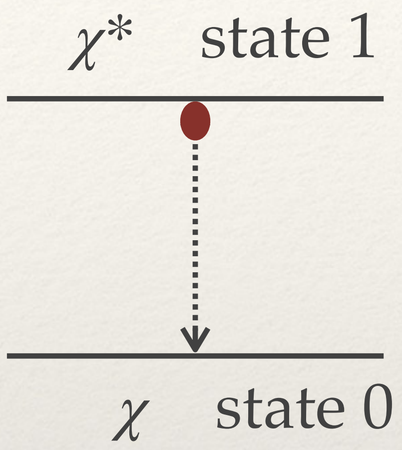
Dark Matter as a 2-level system

Electromagnetic Transitions:



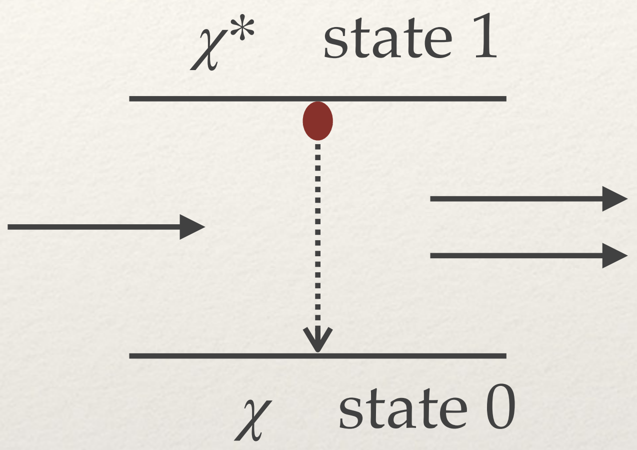
Absorption

$n_0 B_{01} J$



Spontaneous Emission

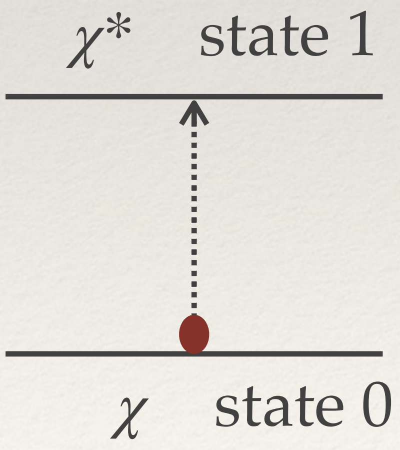
$n_1 A_{10}$



Stimulated Emission

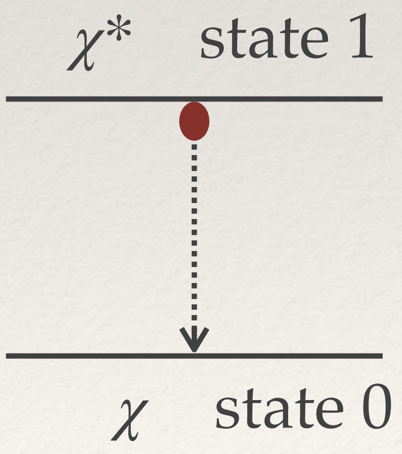
$n_1 B_{10} J$

(Inelastic) collisional Transitions:



Excitation

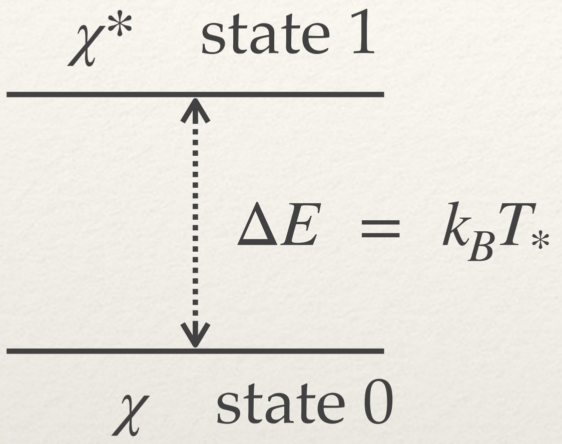
$n_0 C_{01}$



De-excitation

$n_1 C_{10}$

Global absorption from Dark Matter



$$\frac{n_1}{n_0} = \frac{g_1}{g_0} \exp\left(-\frac{T_*}{T_{ex}}\right)$$

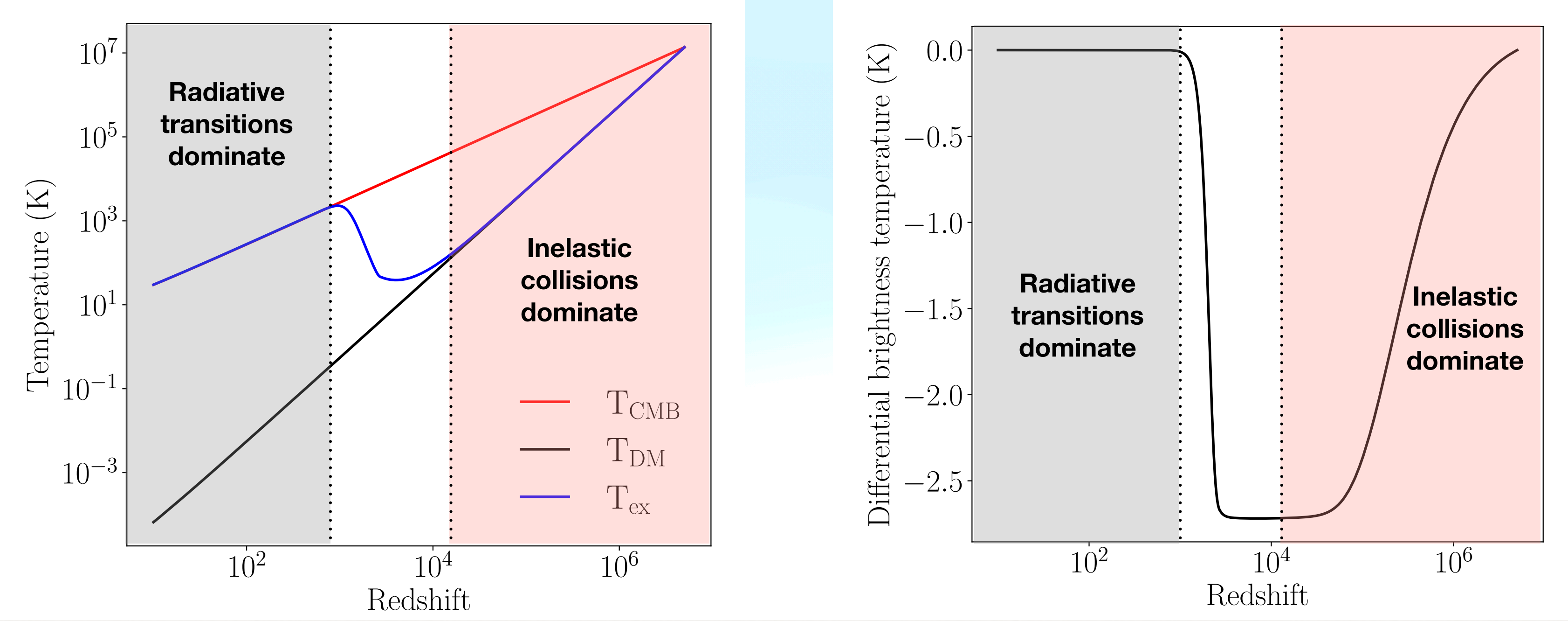
T_{ex} determines the relative population of two states

$$\frac{dT_{ex}}{dz} \propto C_{10}\left(1 - e^{-T_*\left(\frac{1}{T_{DM}} - \frac{1}{T_{ex}}\right)}\right) + A_{10}\left(\frac{1 - e^{-T_*\left(\frac{1}{T_{CMB}} - \frac{1}{T_{ex}}\right)}}{1 - e^{-T_*/T_{CMB}}}\right)$$

$T_{ex} \to T_{DM}$ if collision dominates

$T_{ex} \to T_{CMB}$ if radiative transition dominates

Global absorption from Dark Matter



At high redshift collision dominates: $T_{ex} \to T_{DM} \ll T_{CMB}$: absorption begins

As DM number falls, radiative transitions take over: absorption disappears

Mod. Kompaneets Eqn for CMB

Electromagnetic interaction of DM brings it into contact with baryonic-photon plasma

$$\begin{aligned}\frac{\partial n(x_\mathrm{e},t)}{\partial t} &= K_\mathrm{C}\frac{1}{x_\mathrm{e}^2}\frac{\partial}{\partial x_\mathrm{e}}x_\mathrm{e}^4\left(n+n^2+\frac{\partial n}{\partial x_\mathrm{e}}\right)+(K_\mathrm{br}+K_\mathrm{dC})\,\frac{e^{-x_\mathrm{e}}}{x_\mathrm{e}^3}\left[1-n(e^{x_\mathrm{e}}-1)\right]\\ &\quad +x_\mathrm{e}\frac{\partial n}{\partial x_\mathrm{e}}\frac{\partial}{\partial t}\left[\ln\frac{T_\mathrm{e}}{T_\mathrm{CMB}}\right]+\frac{1}{x_\mathrm{e}^2}\frac{\mathcal{I}_2}{b_\mathrm{R}T_\mathrm{e}^3}\dot{N}_{\chi\gamma}\,\delta(x_\mathrm{e}-x_0(t)),\end{aligned}$$

Compton scattering

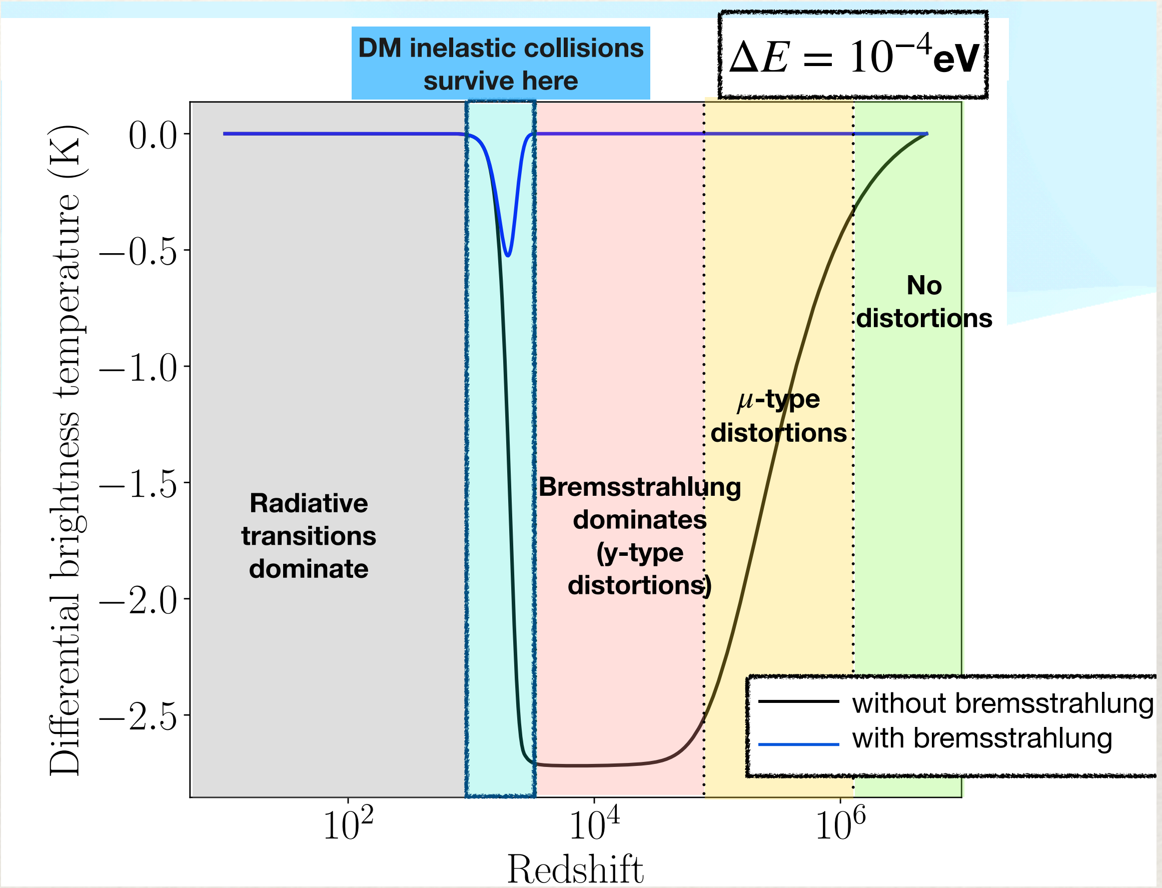
Double-Compton +
Bremsstrahlung

injected spectra by dm

$x_\mathrm{e}\equiv h\nu/(k_\mathrm{B}T_\mathrm{e}).$

CMB distortions from dark matter

- Prior to recombination, bremsstrahlung is important in establishing a black body spectrum at low frequencies.

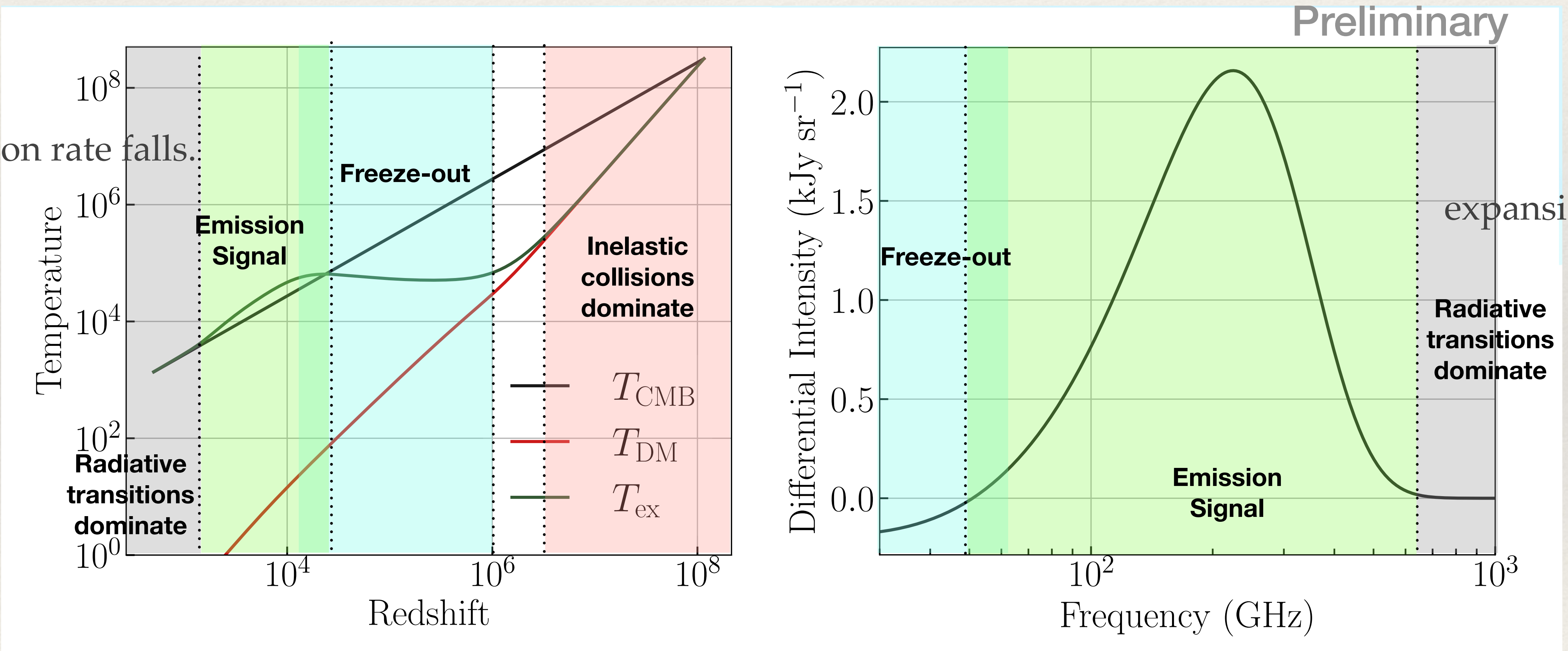


CMB distortions from dark matter

Low collision rate/H, low transition energy

-> T_{ex} freezes out -> no absorption

expansion rate falls.



expansion rate falls.

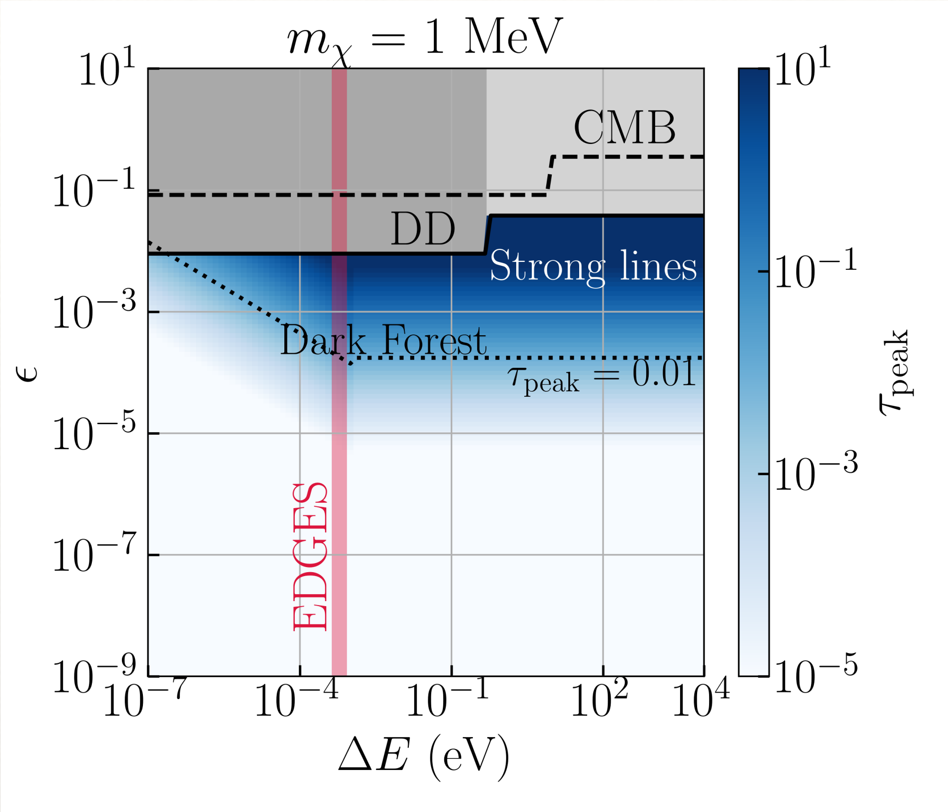
$T_{ex} > T_{CMB}$ —> you get emission signal

Constraintology

Constraintology: Direct-detection

- Inelastic scattering: magnetic moment of dark matter interacts with the magnetic field of electron causing χ-χ^* transition.

- elastic scattering: Charge radius of dark matter interacts with the electric field of electron.
  - Included XENON10, XENON100, Dark-Side, SENSEI, CDMS-HVeV etc..



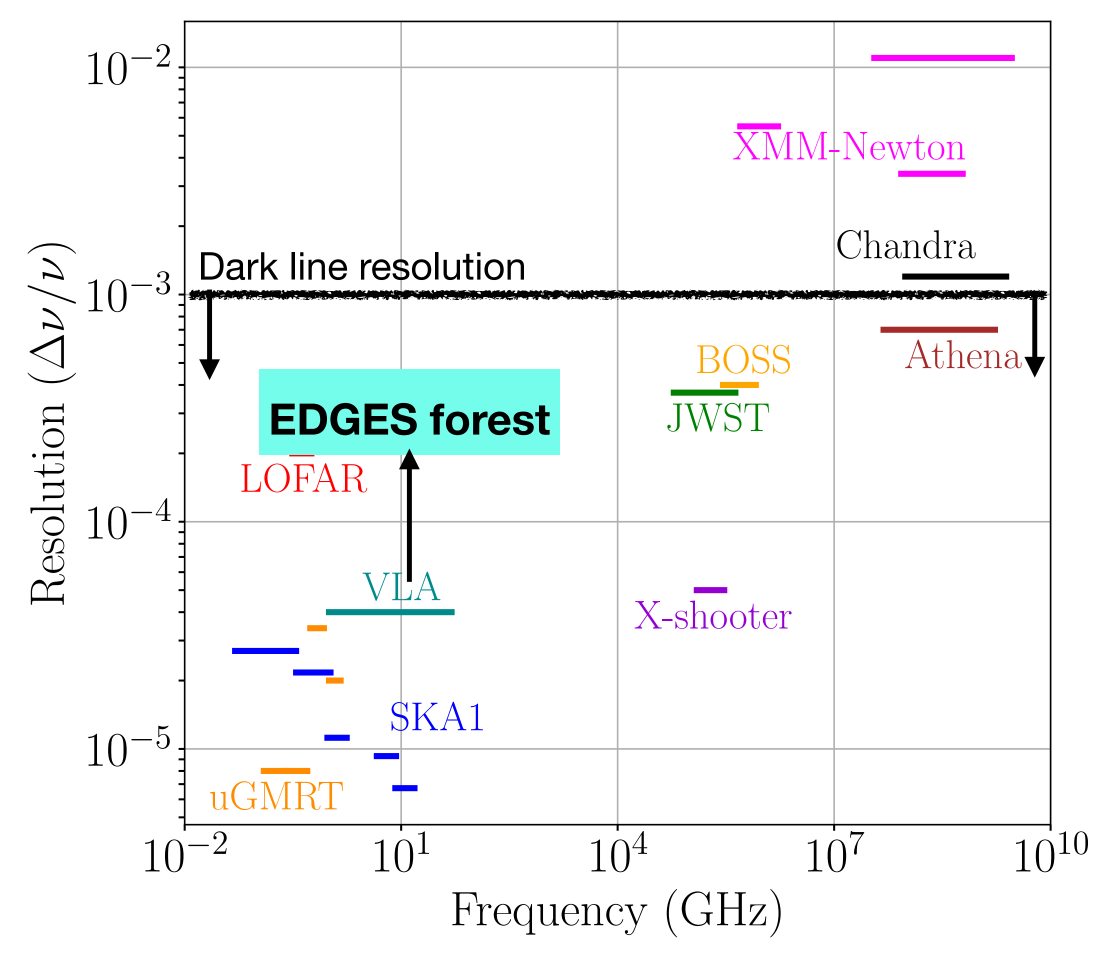
- We considered many many more constraints — from early universe to late universe — a lot of them are model-dependent

➡ I am pretty sure there exists many more!

Dark forest from dark matter

Detectability of dark forest

- Spectroscopic experiments in optical and radio wave bands can detect dark forest!
- Line width is independent of dark matter self interactions.

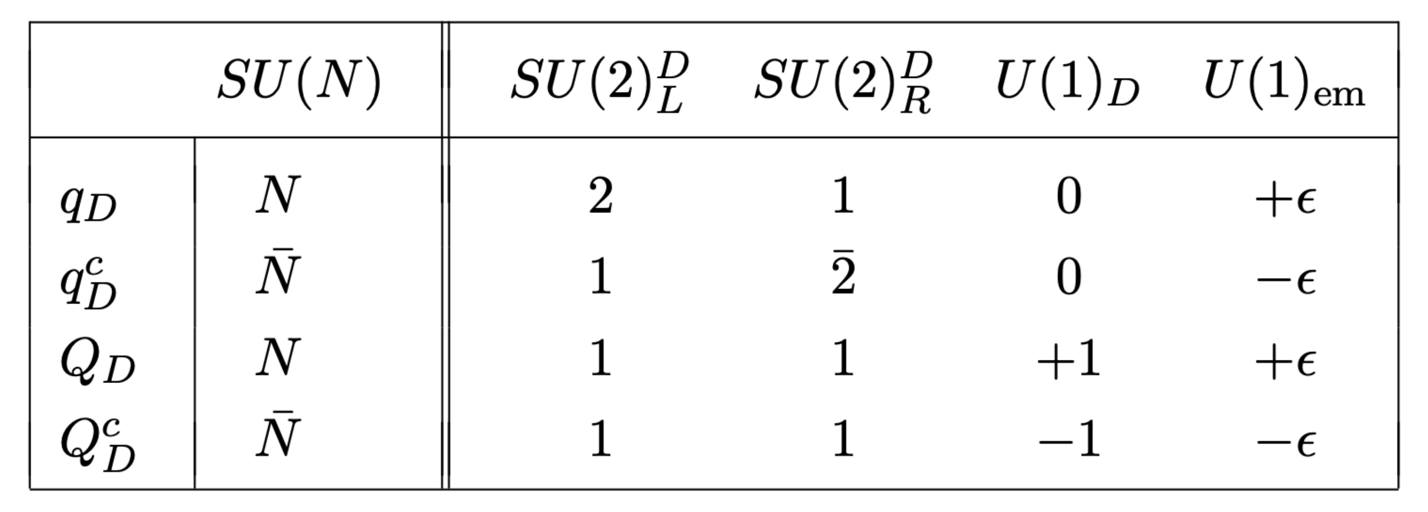


Conclusion

- The proposal is to look for dark matter via forest in the spectrum of strong sources — carries non trivial information of LSS, dark matter interactions etc.
- It often accompanies distortion in the CMB spectrums - sometime competing and sometime complementary
- Hunting for dark lines/forest and distinguish from the ones due to visible transitions is challenging — though there are ‘deserts’ - where it is relatively easy.

Extra

Proof of principle model



	$SU(N)$	$SU(2)^D_L$	$SU(2)^D_R$	$U(1)_D$	$U(1)_{\text{em}}$
q_D	N	2	1	0	$+\epsilon$
q^c_D	$\bar{N}$	1	$\bar{2}$	0	$-\epsilon$
Q_D	N	1	1	$+1$	$+\epsilon$
Q^c_D	$\bar{N}$	1	1	-1	$-\epsilon$

Modeling dark transitions

Scaling the hydrogen atom parameters

Radiative coupling: $A_{10}^{\mathrm{DM}} \approx \epsilon^2 \left(\frac{\Delta E_{\mathrm{hf}}^{\mathrm{DM}}}{\Delta E_{\mathrm{hf}}^{\mathrm{HI}}}\right)^3 \left(\frac{m_e}{m_q}\right)^2 A_{10}^{\mathrm{HI}}$

Bohr radius: $r_{\mathrm{HI}} = \frac{\alpha}{E_{\mathrm{binding}}^{\mathrm{HI}}}$

Geometric cross-section: $\sigma_{\mathrm{DM}} \approx r_{\mathrm{DM}}^2 \approx \left(\frac{\alpha_s(m_\chi)}{\alpha}\right)^2 \left(\frac{E_{\mathrm{binding}}^{\mathrm{HI}}}{E_{\mathrm{binding}}^{\mathrm{DM}}}\right)^2 r_{\mathrm{HI}}^2$

Global absorption from Dark Matter

Global absorption feature gets contribution from dark matter + bremsstrahlung

- Specific intensity into brightness temperature

$$\boxed{T_b = \frac{c^2}{2\nu^2 k_B} I_\nu}$$

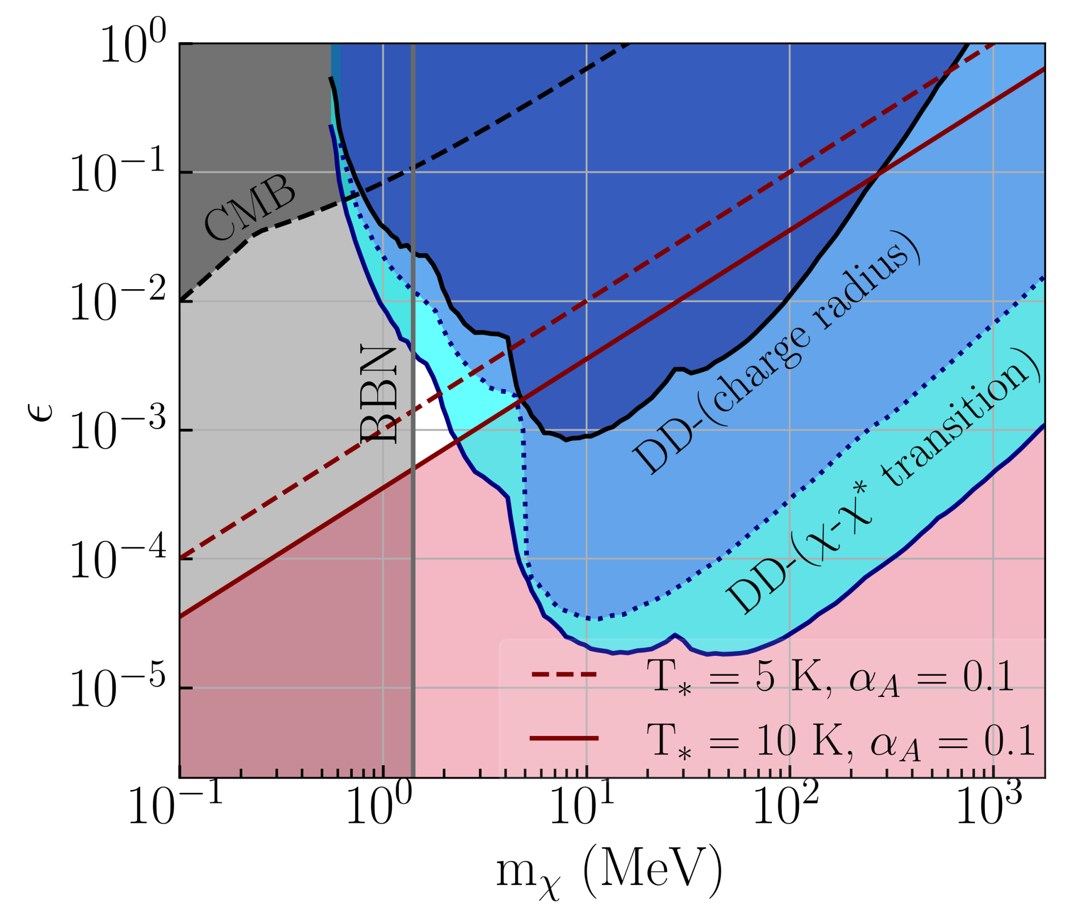
$$\frac{dT_b(\nu)}{dz} - \frac{T_b(\nu)}{1+z} = \frac{d\tau_\chi}{dz}\left(-T_b(\nu) + \frac{h\nu}{k_B}\frac{1}{(e^{h\nu/k_B T_{ex}(z)} - 1)}\right) + \frac{d\tau_{br}(x)}{dz}\left(-T_b(\nu) + T_g\right)$$

Redshifting **DM transitions** **Bremsstrahlung**

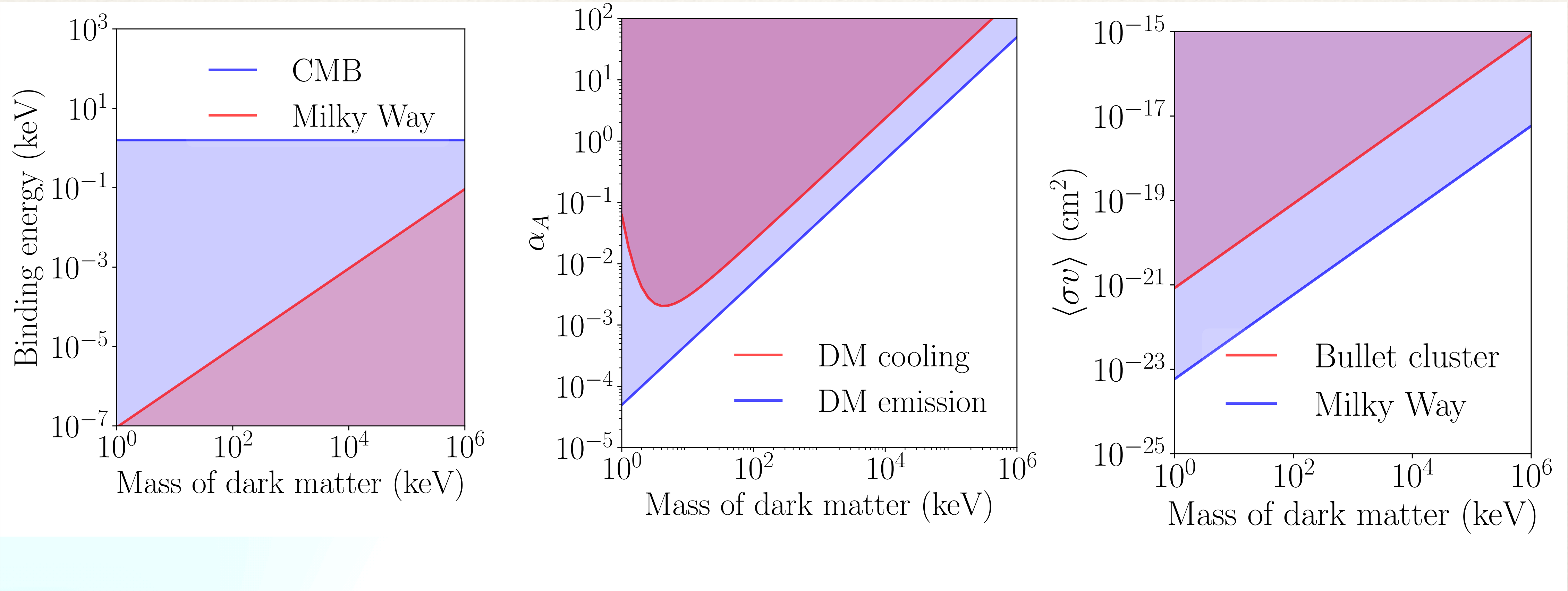
No approximation made between $T_\star$, T_{ex} and T_{CMB}

New term not present in the standard 21 cm cosmology

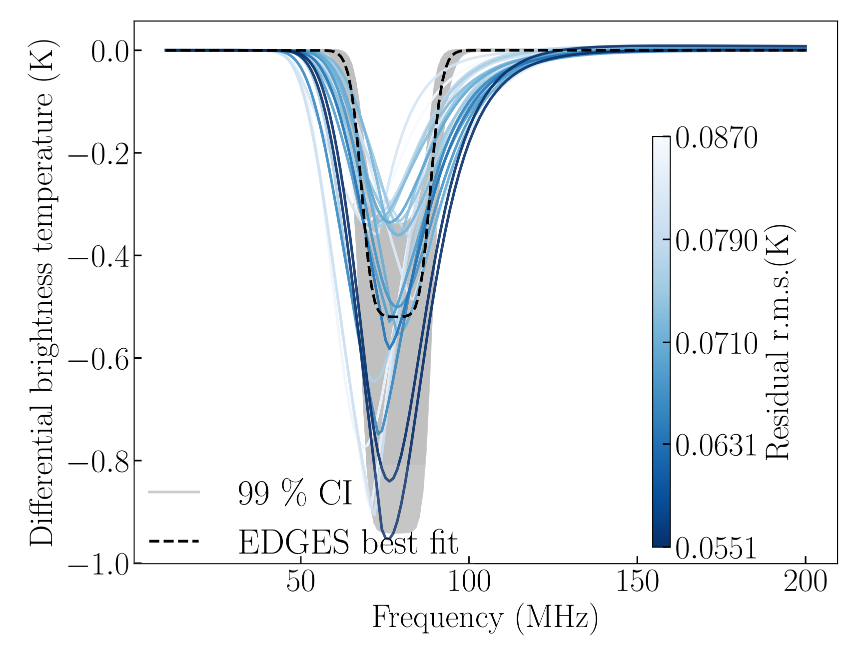
Constraintology



Constraintology: Milky Way



EDGES



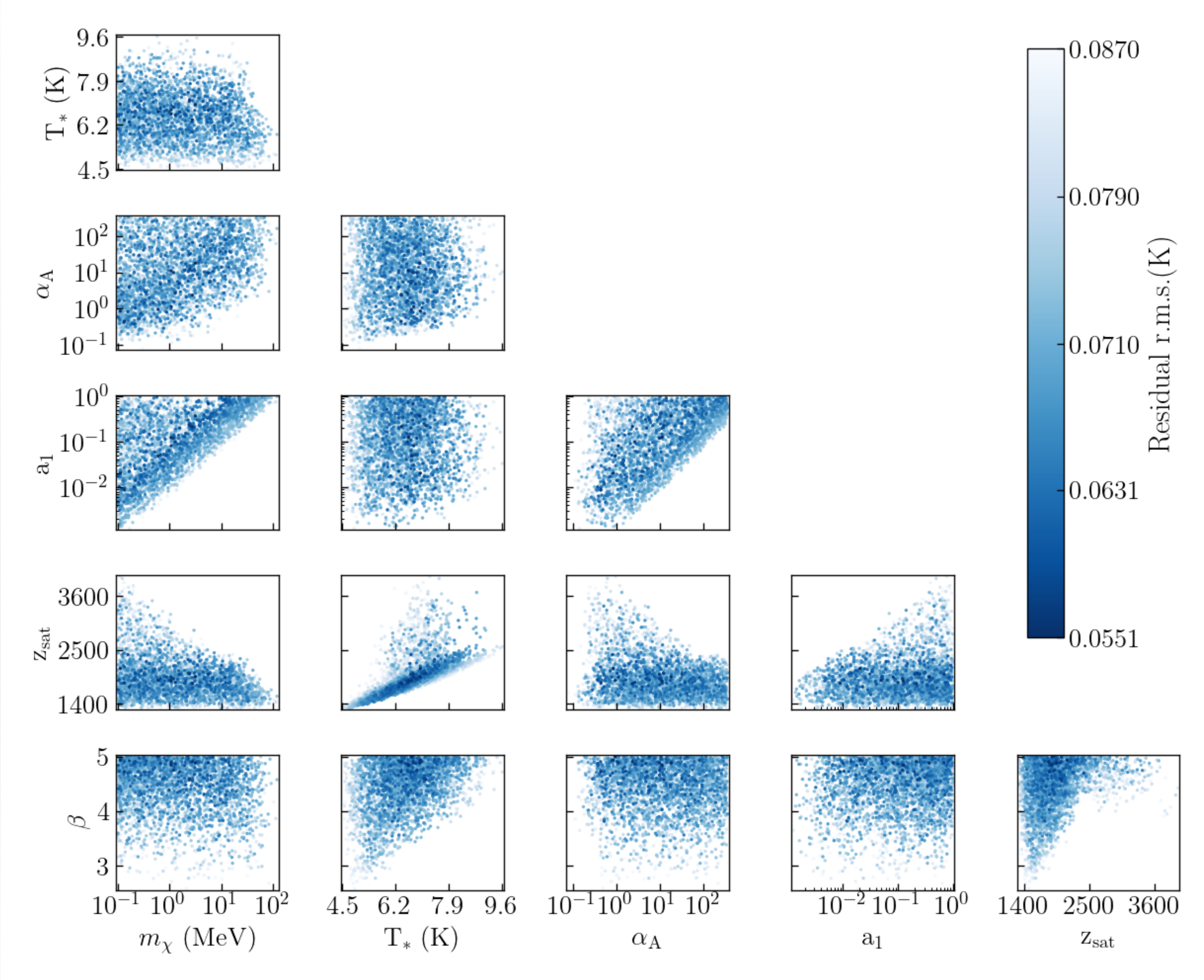


FIG. 11: The viable parameter space of the dark matter model shown as points in the 2-D plots for fifteen combinations of different model parameters. The color shade of each sample point is represented by the r.m.s. value of the residual when the EDGES data is fitted with the the EDGES foreground model + dark matter signal of the sample.