Sunyaev-Zel‘dovich effect induced by First Star Supernova

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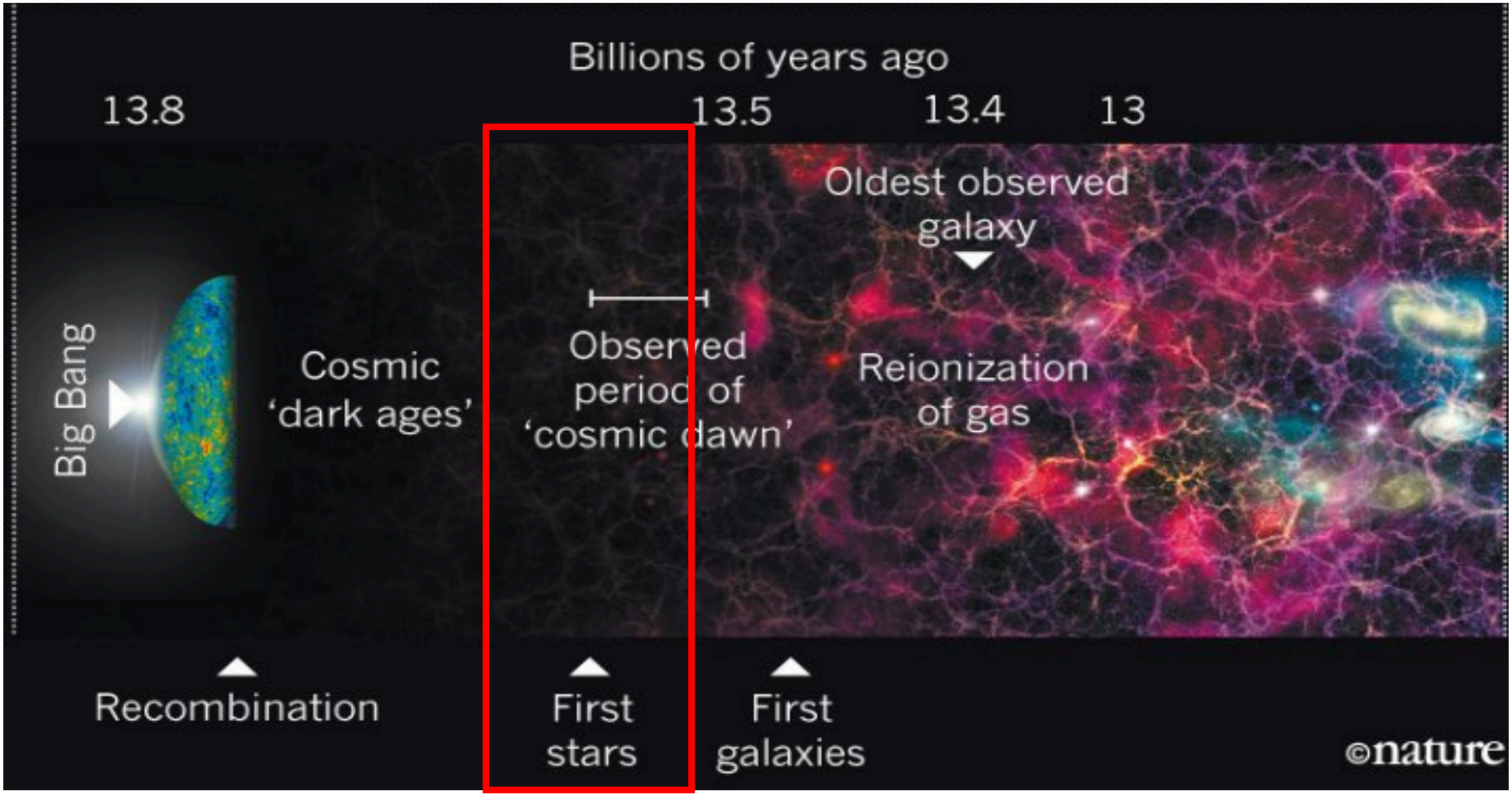
Collaborator: Hiroyuki Tashiro

Arxiv:1911.XXXXX

Motivation



z=20-30

Motivation

First stars are important in Astrophysics & Cosmology

It's difficult to observe them

Really?

We might already catch the signal from First Stars

Oh et al. 2013

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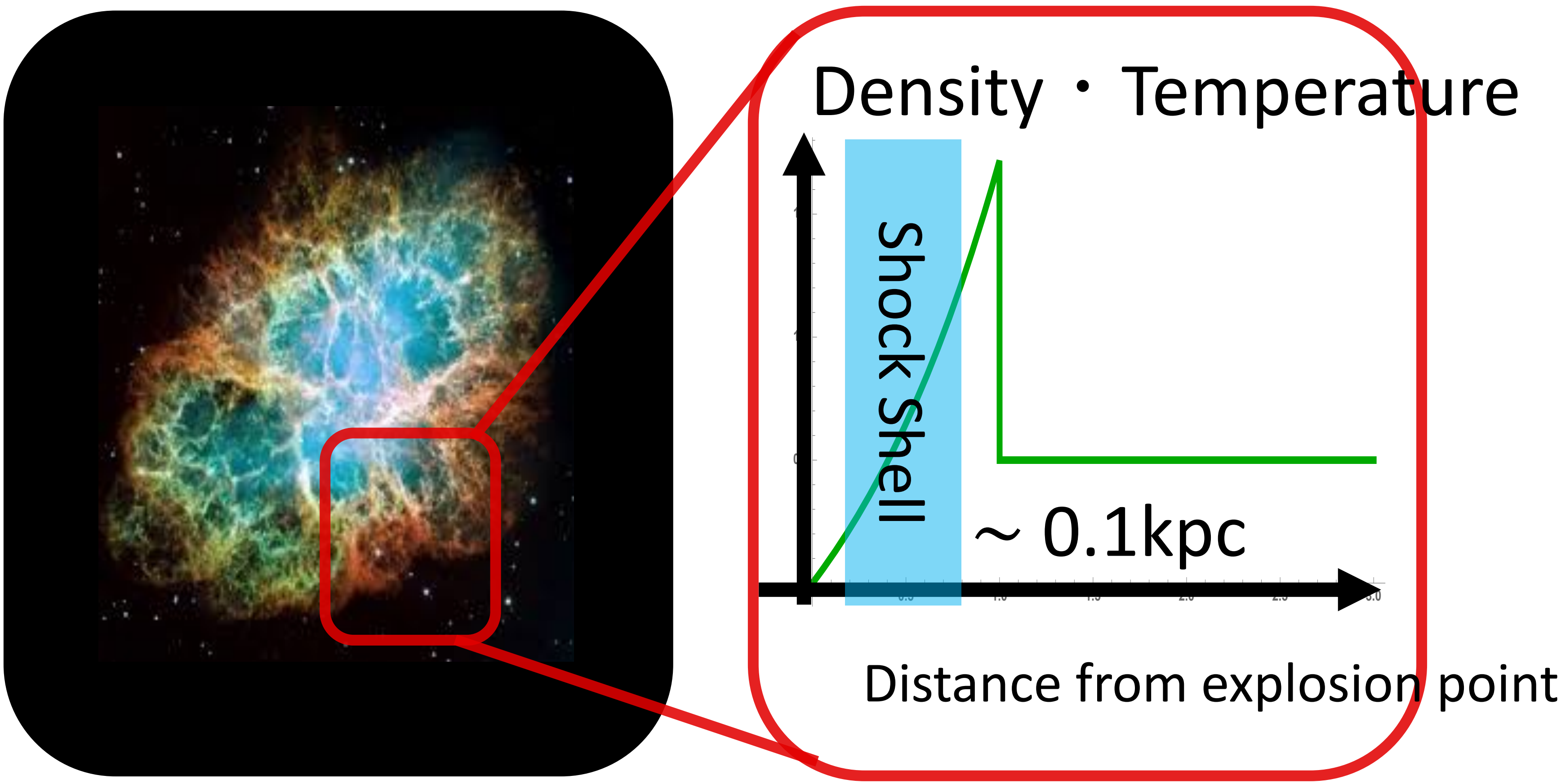
First Star Supernova

First Star SN

The mass of First Stars is large $M_* \sim 100 M_\odot$



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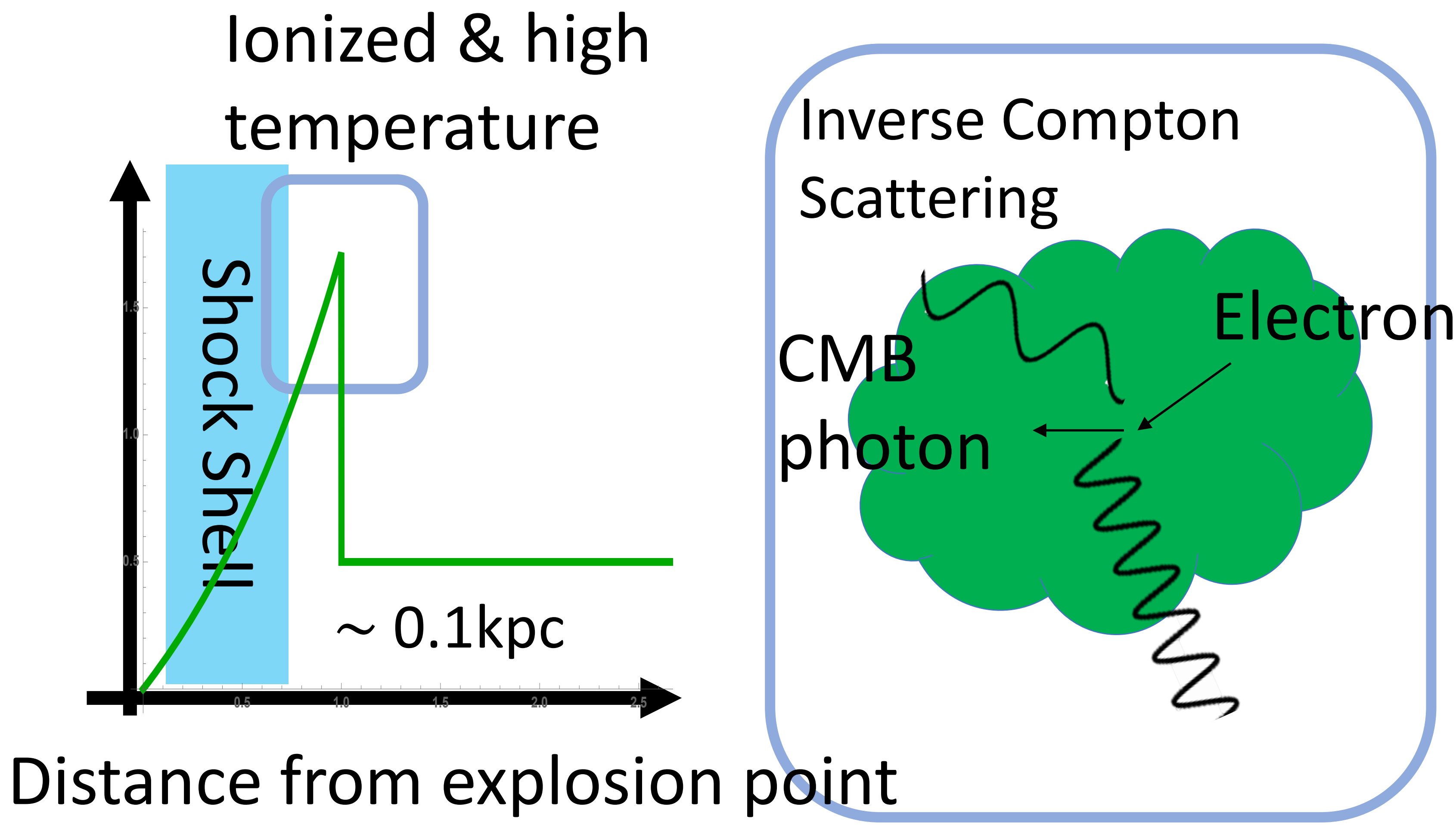
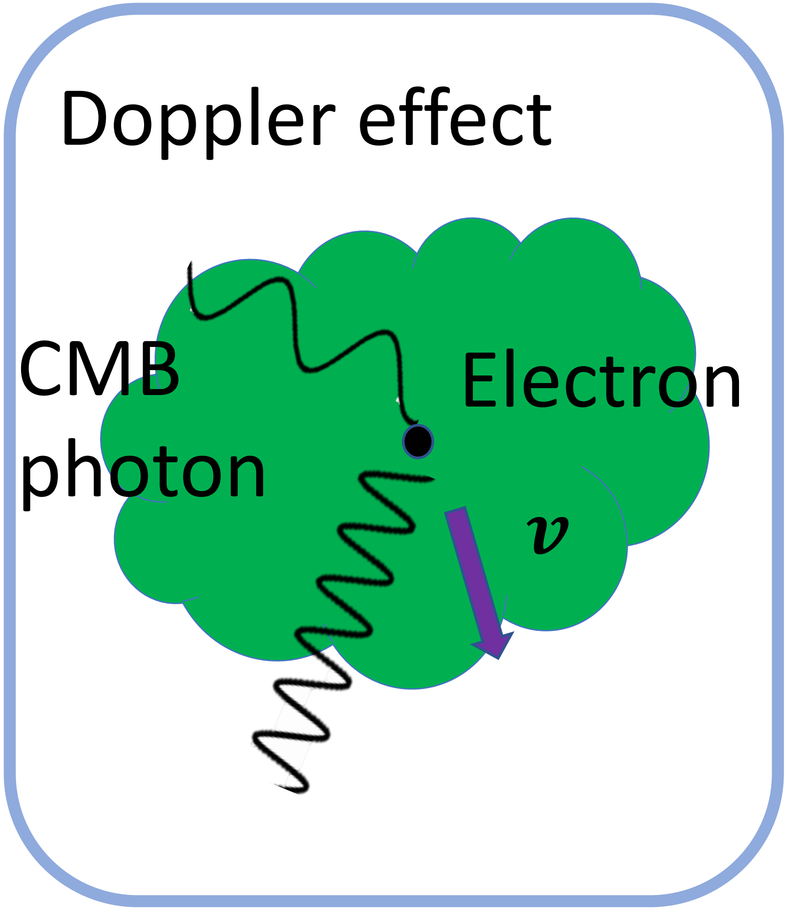
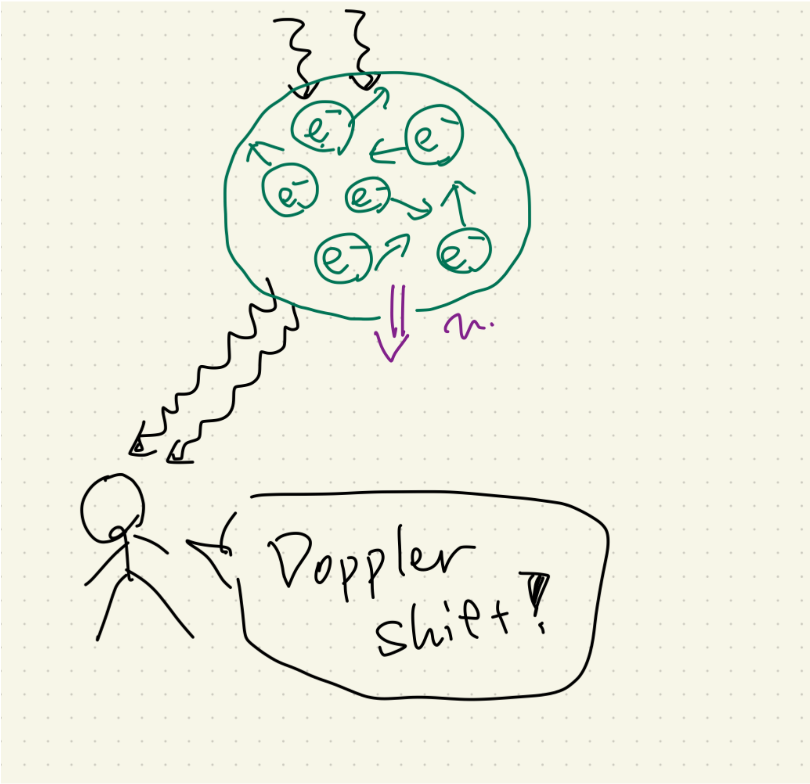
Generation mechanism of CMB anisotropy



Generation mechanism of CMB anisotropy

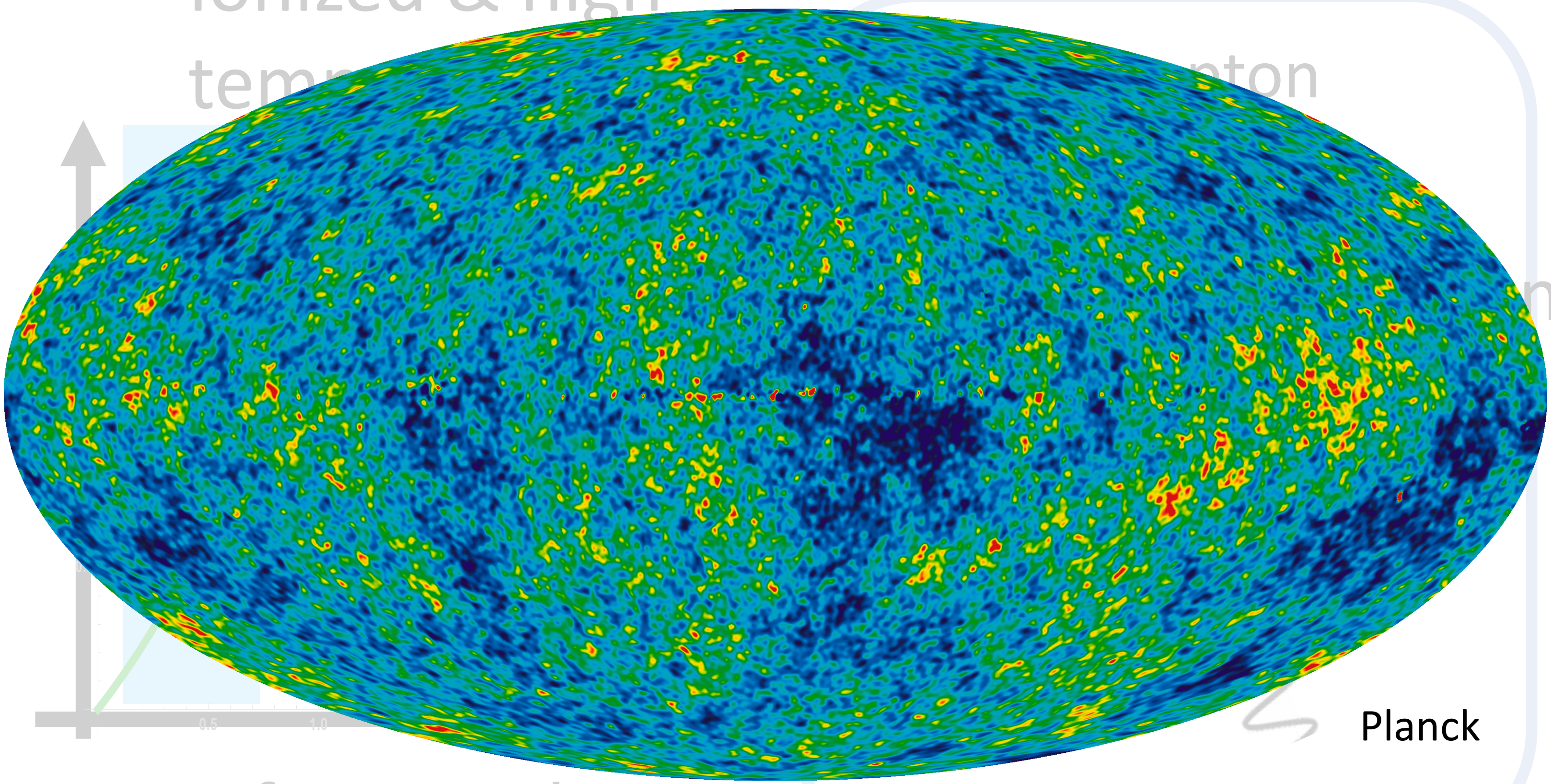




Generation mechanism of CMB anisotropy

CMB anisotropy

Ionized & high



Planck

Distance from explosion point

The First Star SN shell model

Pair-instability explosion Heger & Woosley 2002

$$E_{\rm SN} = 10^{46}\,{\rm J} \quad M_* = 100 M_\odot$$

Linear perturbation theory Hu 2000

$$v_{\rm rms}^2(z) \simeq 5.8 \times 10^{-6}(1+z)^{-1}$$

Other

$$\gamma = 5/3$$

$$\rho_{\rm SN} = \frac{\gamma+1}{\gamma-1}\rho_{\rm out}$$

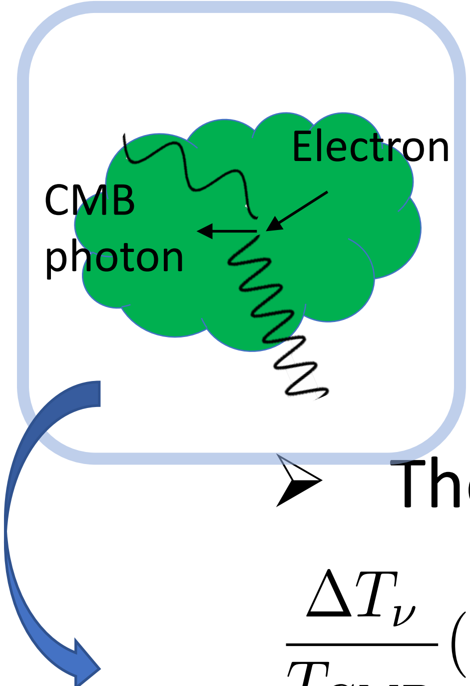
$$x_{\rm e} = 1$$

Sedov-Taylor self similar solution

$$R_{\rm SN}(t) = 12.5\ [{\rm pc}] \left(\frac{t}{10^4 {\rm yr}}\right)^{2/5} \left[\left(\frac{E_{\rm SN}}{10^{44}{\rm J}}\right)\left(\frac{n}{10^6 {\rm m}^{-3}}\right)^{-1}\right]^{1/5}$$

$$V_{\rm SN}(t) = 490 [{\rm km/s}] \left(\frac{t}{10^4 {\rm yr}}\right)^{-3/5} \left[\left(\frac{E_{\rm SN}}{10^{44}{\rm J}}\right)\left(\frac{n}{10^6 {\rm m}^{-3}}\right)^{-1}\right]^{1/5}$$

$$T_{\rm SN}(t) = 3.34 \times 10^6 [{\rm K}] \left(\frac{t}{10^4 {\rm yr}}\right)^{-6/5} \left[\left(\frac{E_{\rm SN}}{10^{44}{\rm J}}\right)\left(\frac{n}{10^6 {\rm m}^{-3}}\right)^{-1}\right]^{2/5}$$



Generation mechanism of CMB anisotropy

- Thermal Sunyaev-Zel'dovich (TSZ) effect

$$\frac{\Delta T_\nu}{T_{\rm CMB}}(b) = g(\nu) y(b) = \frac{h\nu}{k_{\rm B} T_{\rm CMB}} \tanh^{-1}\left(\frac{h\nu}{2 k_{\rm B} T_{\rm CMB}}\right) y(b)$$

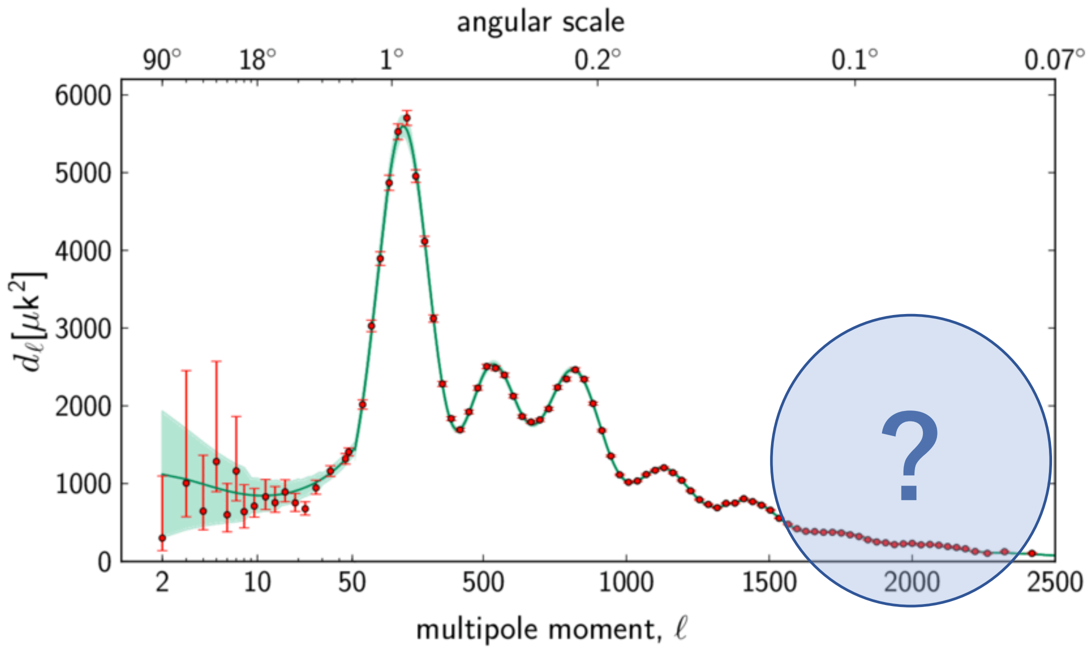
$$y(b) = \int dx \frac{\sigma_{\rm T} n_{\rm H} x_{\rm e}(\sqrt{b^2+x^2})}{m_{\rm e} c} k_{\rm B} T_{\rm gas}(\sqrt{b^2+x^2})$$

- Kinetic Sunyaev-Zel'dovich (KSZ) effect

$$\frac{\Delta T}{T_{\rm CMB}}(\hat{\boldsymbol{n}}) = \sigma_T \int d\eta \, e^{-\tau(\eta)} a n_H x_e \, \hat{\boldsymbol{n}} \cdot \boldsymbol{v}$$

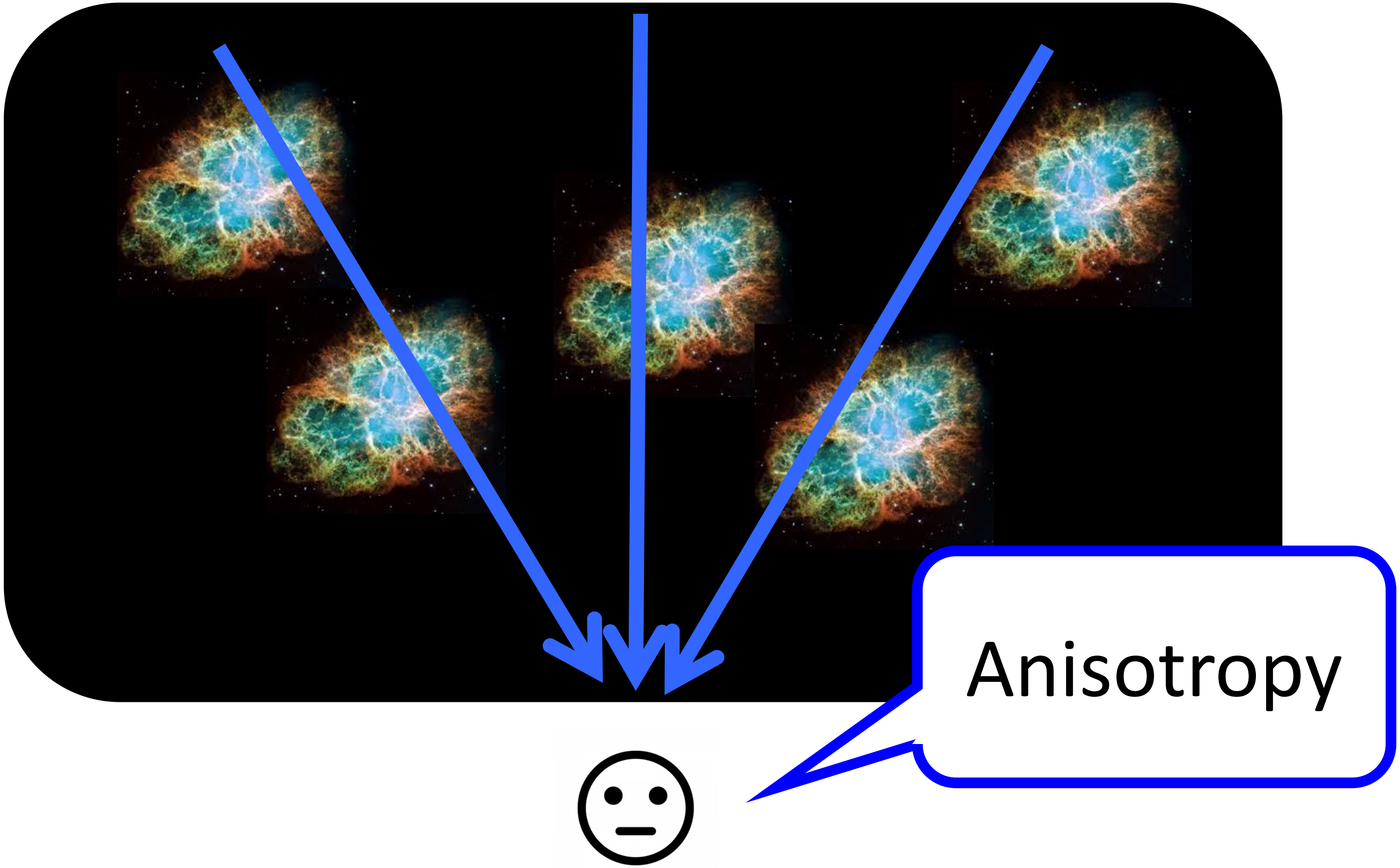
Effect from First Star SNs on the CMB spectrum

Goal:
Calculate the angular power spectrum of the CMB temperature induced by the SNs



Effect from First Star SNs on the CMB spectrum

The distribution of the halo hosting the first star :



Calculation setup

- Apply the Press-Schechter Theory
- Assume all of the First stars have $100 M_{\odot}$ and explode like pair-instability
- Neglect the secondary effect from the radiation emitted by the SN shell
- Use the data summarized in below table

From N-body simulation

$\log M_{\rm vir} [M_{\odot}]$	$f_{\rm host}$	$\log M_{*} [M_{\odot}]$
6.5	2.4×10^{-4}	3.41
7.0	0.052	3.59
7.5	0.28	3.88
8.0	0.90	4.60
8.5	1.0	5.74

John H. Wise et al. 2014

Angular power spectrum of the CMB temperature

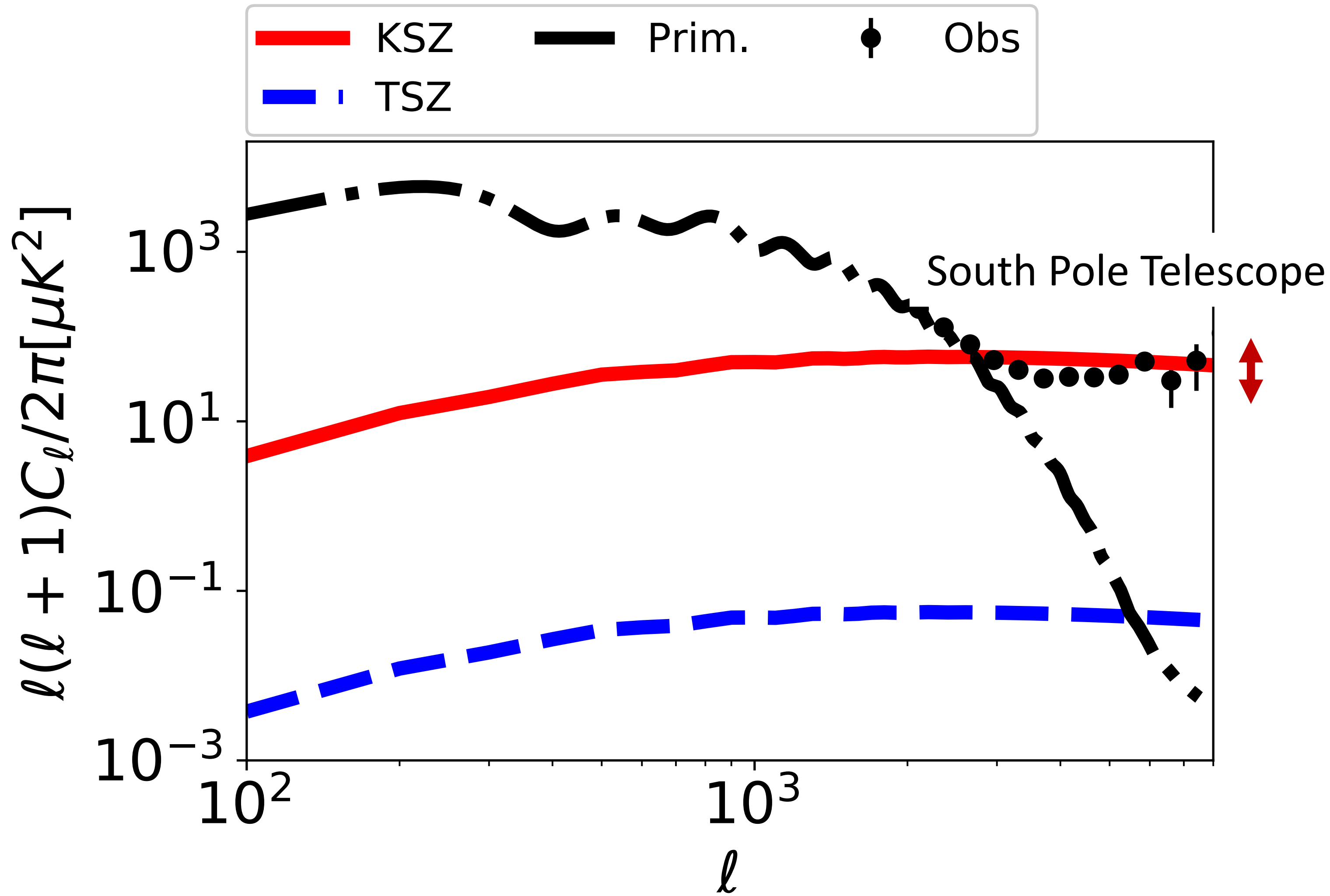
$$C_\ell^{TSZ} = g(\nu)^2 \int dz \frac{dV}{dz d\Omega} \; P_{yy}(k,z)$$

$$g(\nu) = \frac{h\nu}{k_{\rm B}T_{\rm gas}} \tanh^{-1}\left(\frac{h\nu}{2k_{\rm B}T_{\rm gas}}\right) \qquad y(\hat{\boldsymbol{n}},z) = \int dr n_{\rm H}(r,z) x_{\rm e}(r\hat{\boldsymbol{n}},z) \frac{k_{\rm B}T_{\rm gas}(r\hat{\boldsymbol{n}},z)}{m_{\rm e}c^2}$$

$$C_\ell^{\rm KSZ} = (\sigma_T \bar{n}_{\rm H0})^2 \int \frac{dz}{H(z)} \left(\frac{(1+z)^2}{r(z)}\right)^2 P_{q\perp}(\ell/r(z), z)$$

$$\boldsymbol{q}_\perp(\boldsymbol{k}) = \int \frac{d^3\boldsymbol{k}'}{(2\pi)^3} \left[\hat{\boldsymbol{k}}' - \mu' \hat{\boldsymbol{k}}\right] v(\boldsymbol{k}') x_e(|\boldsymbol{k} - \boldsymbol{k}'|)$$

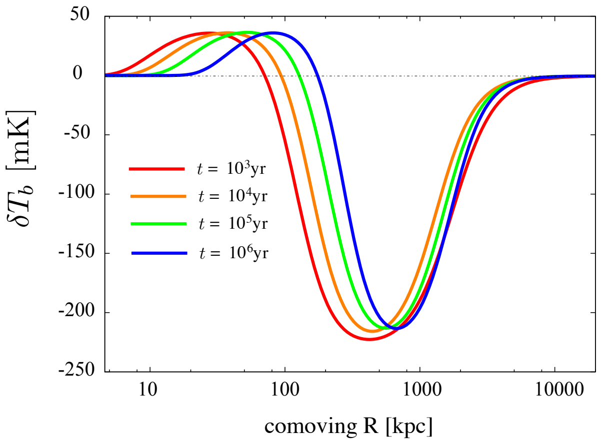
Result


KSZ
Prim.
Obs
TSZ
South Pole Telescope
10^3
10^1
10^{-1}
10^{-3}
10^2
10^3
ℓ
$\ell(\ell+1)C_\ell/2\pi[\mu K^2]$

Summarise & Future work

We calculate the angular power spectrum induced by the SNs
We show that a certain scenario about the SNs
can be excluded by the SPT data.
We might use this spectrum
 to know more information of the First Star

We can consider the secondary-effect
from the radiation emitted by the SNs
Considering this effect,
we can also calculate the 21-cm signal

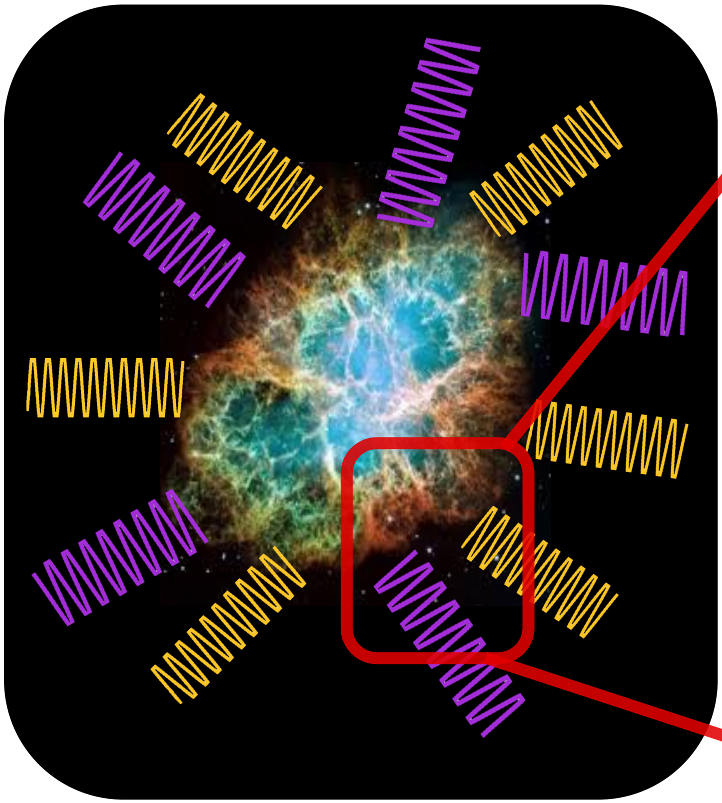


Fin.

BACK UP

Physics around a SN shell

[1] Meiksin & Whalen, 2013



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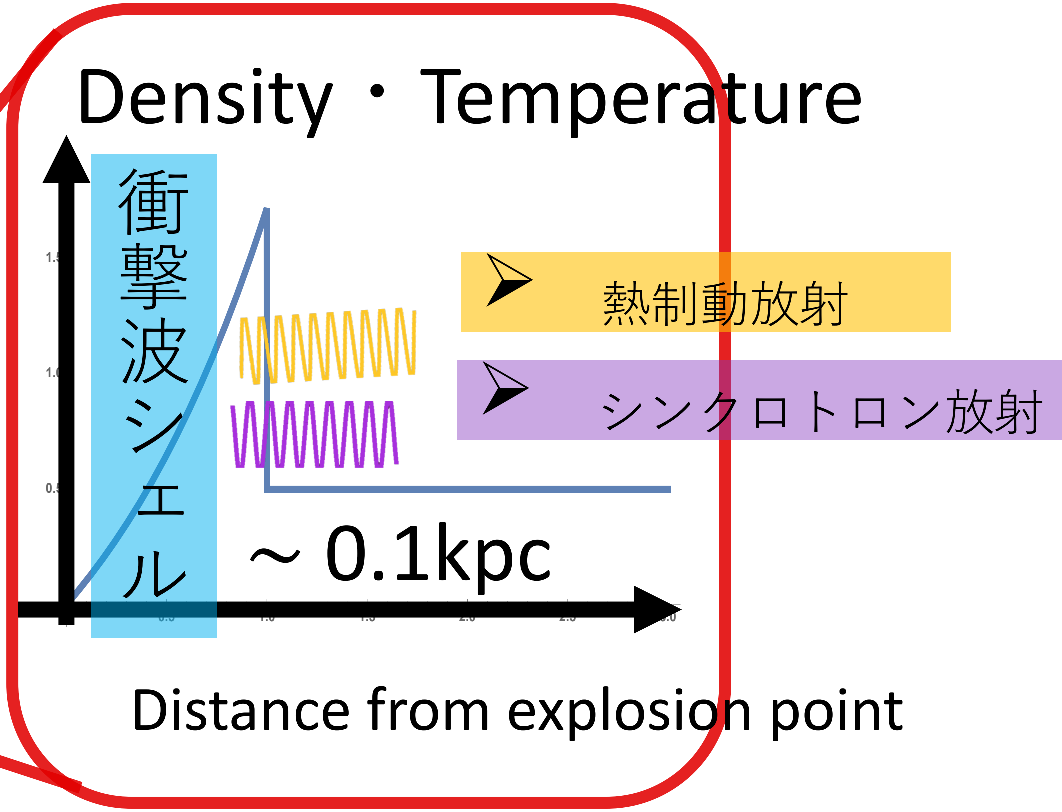
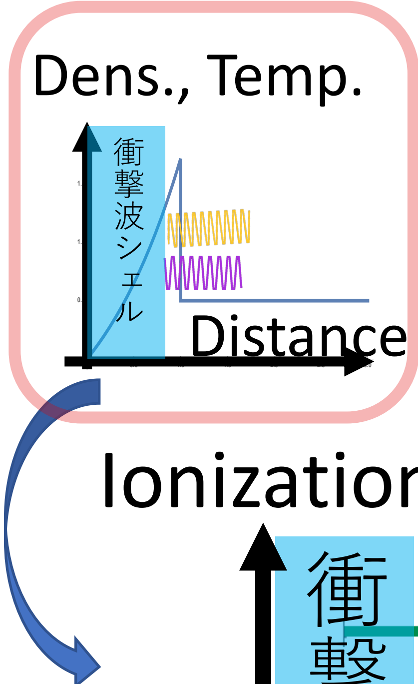
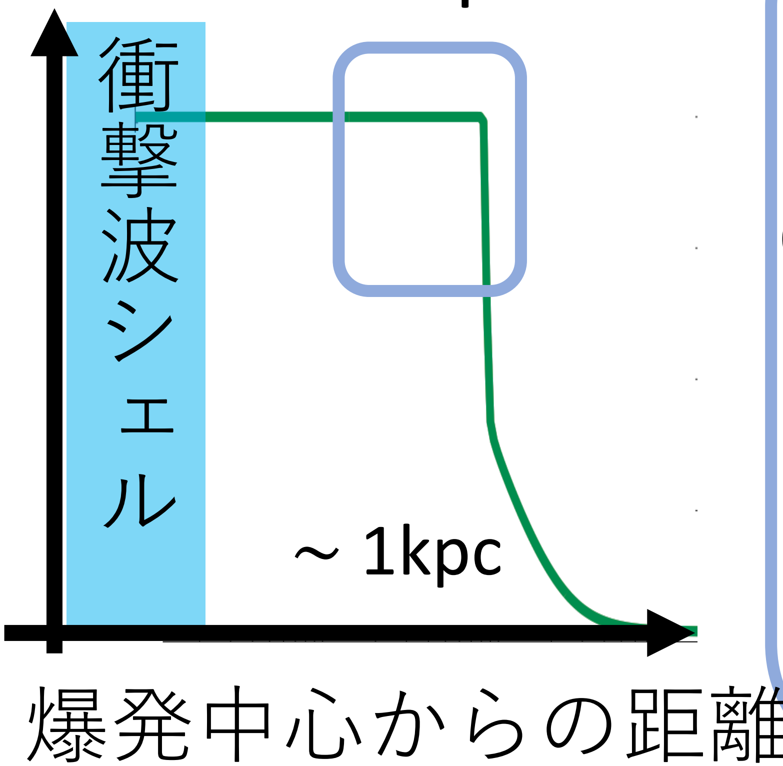
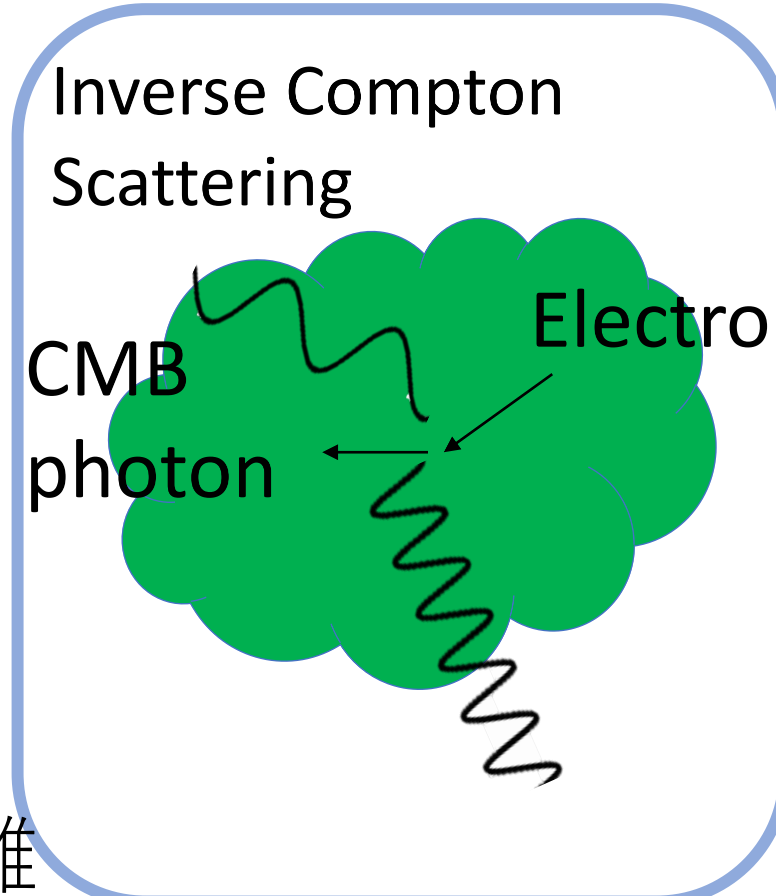


Physics around a SN shell



Ionization・temperature





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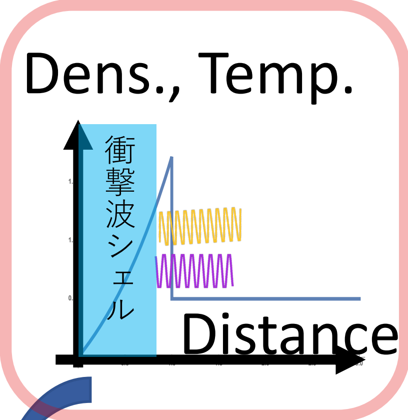

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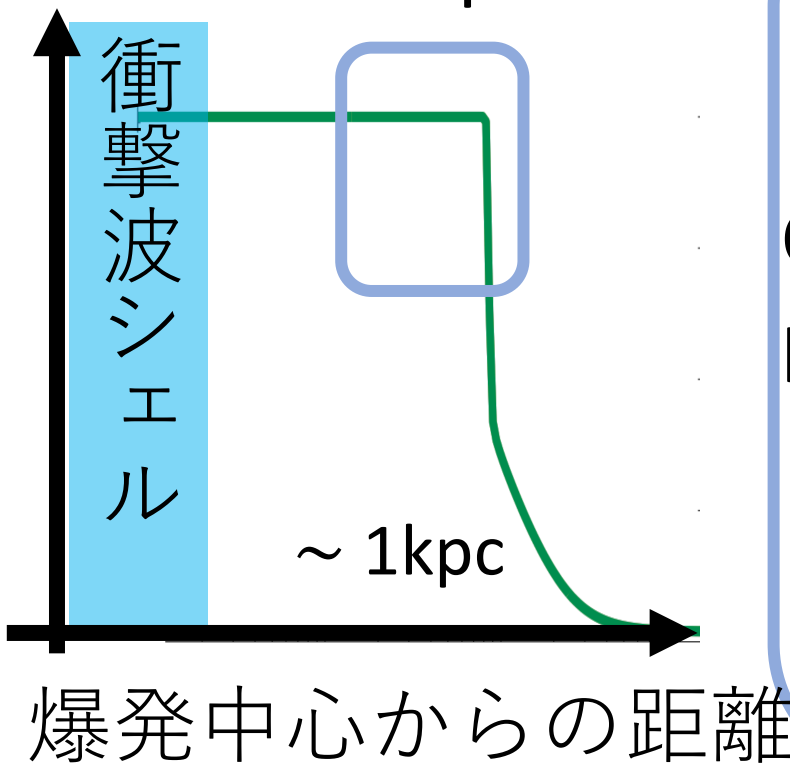
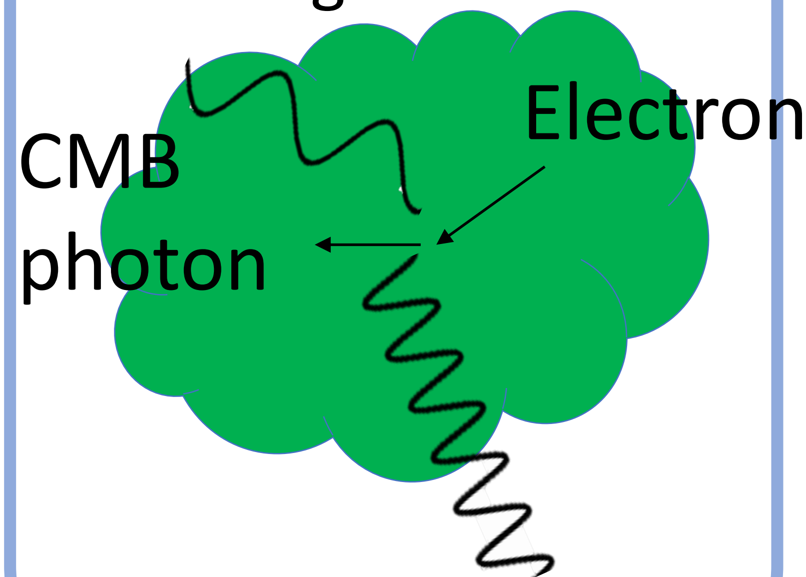


Inverse Compton Scattering



But the synchrotron radiation is emitted by…

- Magnetic field
- Relativistic electrons

There’re many uncertaintity ☹

But the synchrotron radiation is emitted by…

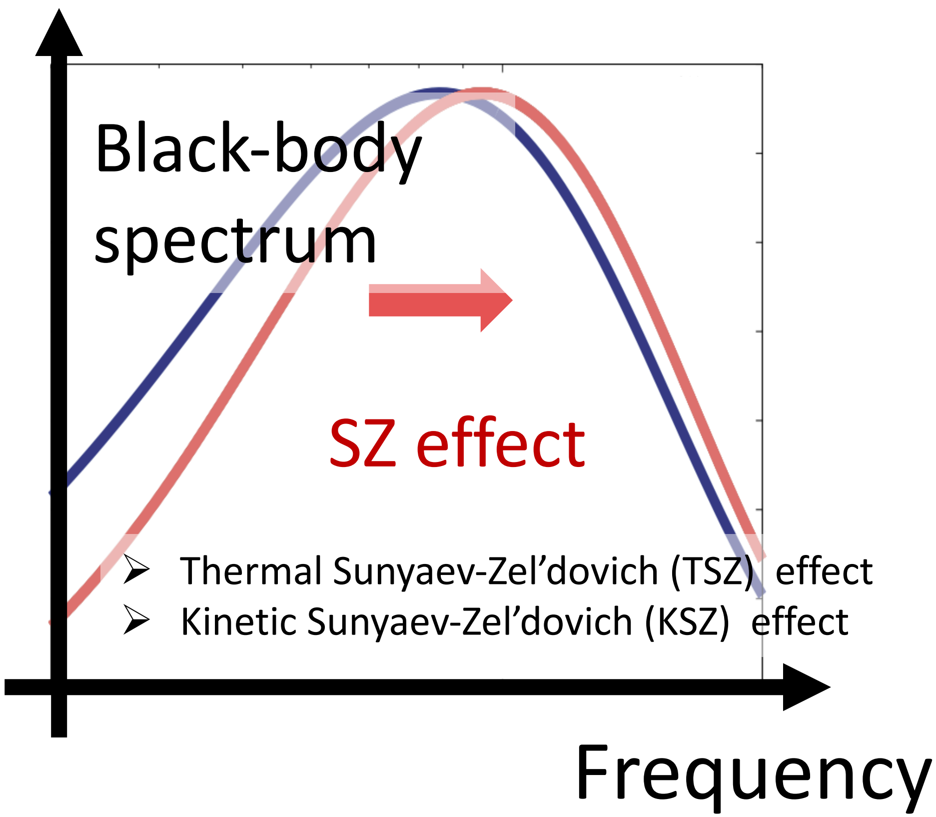
- Magnetic field
- Relativistic electrons

There’re many uncertaintity ☹

➡ Bremsstrahlung emissioin

Physics around a SN shell

Spectrum of CMB photon



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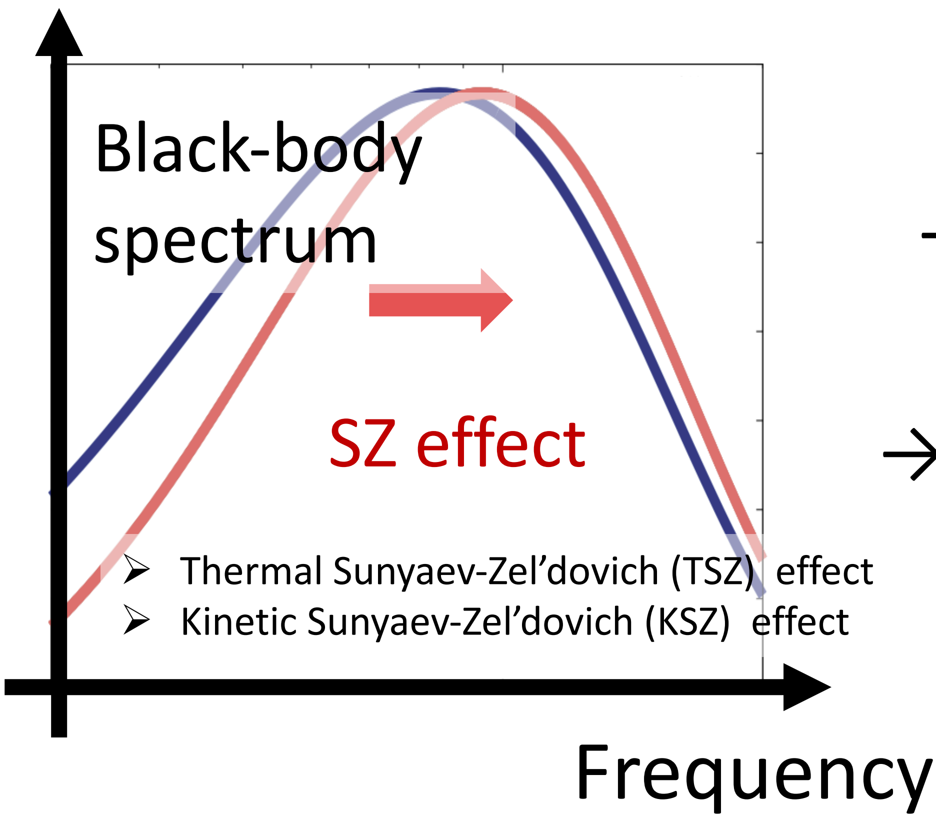
- Kinetic Sunyaev-Zel’dovich (KSZ) effect

Physics around a SN shell

Spectrum of CMB photon



SN explosion

→Wide region (～0.1kpc) is ionized and heated

→The distortion of the CMB spectrum

Effect from SNs on the CMB spectrum

Goal:
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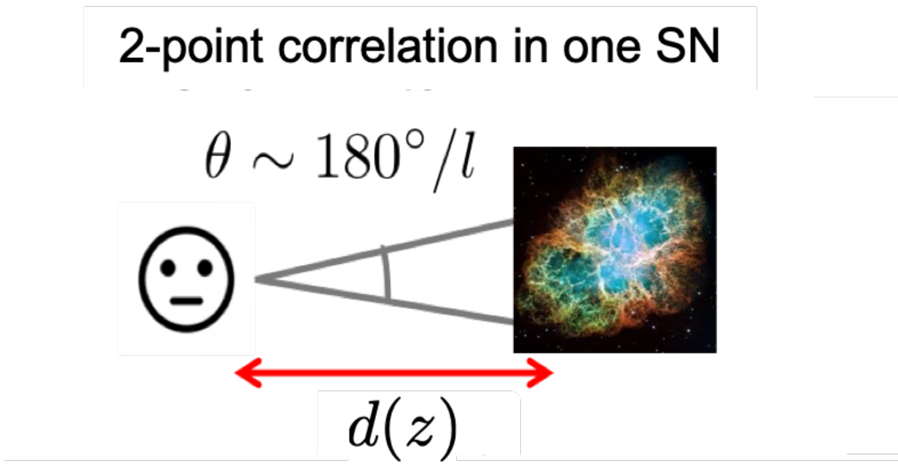

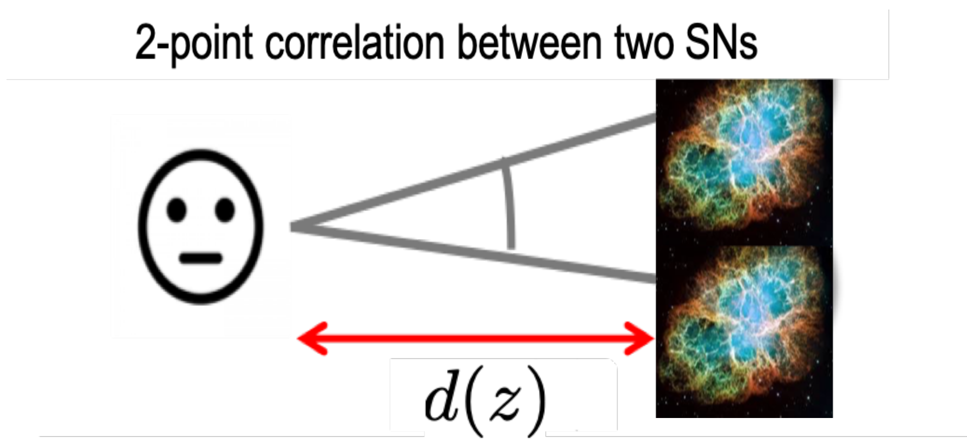

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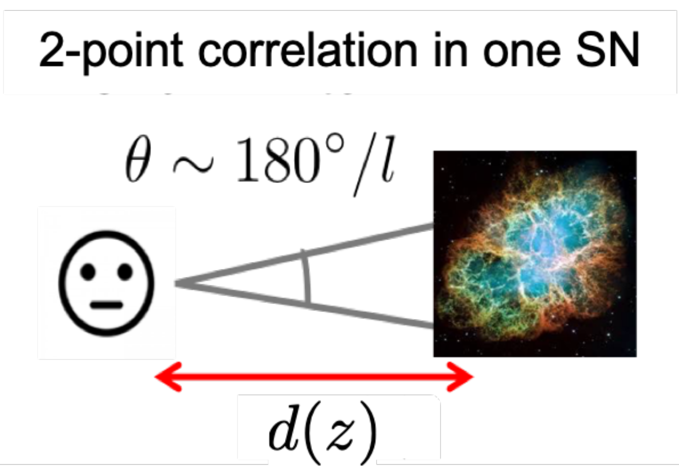

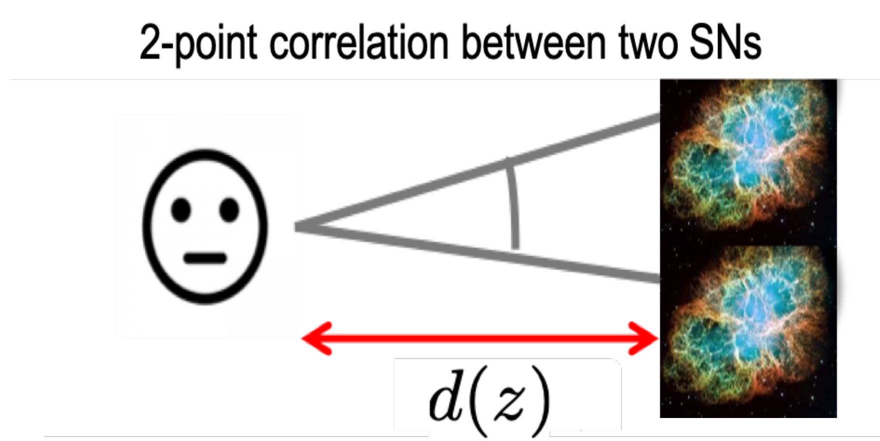

Mo & White 1996

$$b_{\rm SN} = 1 + \frac{(\delta_{\rm c}^2/\sigma^2 - 1)}{\delta_{\rm c}}$$

$$\begin{aligned} P_{q_\perp}(k,z) = \frac{1}{2}\int \frac{d^3\boldsymbol{k}'}{(2\pi)^3} & (1-\mu'^2) P_{vv}(k',z) P_{x_e x_e}(|\boldsymbol{k}-\boldsymbol{k}'|,z) \\ & - \frac{(1-\mu'^2)k'}{|\boldsymbol{k}-\boldsymbol{k}'|} P_{x_e v}(k',z) P_{x_e v}(|\boldsymbol{k}-\boldsymbol{k}'|,z)] \\ + \int \frac{d\boldsymbol{k}' d\boldsymbol{k}''}{(2\pi)^6} & \sqrt{(1-\mu'^2)(1-\mu''^2)} \cos(\phi'-\phi'') \\ & \times P_{x_e x_e vv}(\boldsymbol{k}-\boldsymbol{k}', -\boldsymbol{k}-\boldsymbol{k}'', \boldsymbol{k}', \boldsymbol{k}'', z), \end{aligned}$$

Effect from SNs on the CMB spectrum

The distribution
of the halo hosting the first star :
Matter Power spectrum $\times$ Bias