原始ブラックホールによるミニハロー形成と２１線観測

北嶋　直弥

名古屋大学

arXiv:1704.04132

共同研究者 Jinn-Ouk Gong (APCTP, 韓国)

観測的宇宙論ワークショップ２０１７＠弘前大学

Outline

1. イントロダクション

2. 原始ブラックホールのPoissonゆらぎとハロー質量関数

3. 21cm線シグナル

Selected for a Viewpoint in *Physics*
PRL **116,** 061102 (2016) PHYSICAL REVIEW LETTERS week ending 12 FEBRUARY 2016

Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.*[*]
(LIGO Scientific Collaboration and Virgo Collaboration)
(Received 21 January 2016; published 11 February 2016)

On September 14, 2015 at 09:50:45 UTC the two detectors of the Laser Interferometer Gravitational-Wave Observatory simultaneously observed a transient gravitational-wave signal. The signal sweeps upwards in frequency from 35 to 250 Hz with a peak gravitational-wave strain of 1.0×10^{-21}. It matches the waveform predicted by general relativity for the inspiral and merger of a pair of black holes and the ringdown of the resulting single black hole. The signal was observed with a matched-filter signal-to-noise ratio of 24 and a false alarm rate estimated to be less than 1 event per 203 000 years, equivalent to a significance greater than 5.1σ. The source lies at a luminosity distance of 410^{+160}_{-180} Mpc corresponding to a redshift $z = 0.09^{+0.03}_{-0.04}$. In the source frame, the initial black hole masses are $36^{+5}_{-4} M_\odot$ and $29^{+4}_{-4} M_\odot$, and the final black hole mass is $62^{+4}_{-4} M_\odot$, with $3.0^{+0.5}_{-0.5} M_\odot c^2$ radiated in gravitational waves. All uncertainties define 90% credible intervals. These observations demonstrate the existence of binary stellar-mass black hole systems. This is the first direct detection of gravitational waves and the first observation of a binary black hole merger.

DOI: 10.1103/PhysRevLett.116.061102

Primordial blackhole?

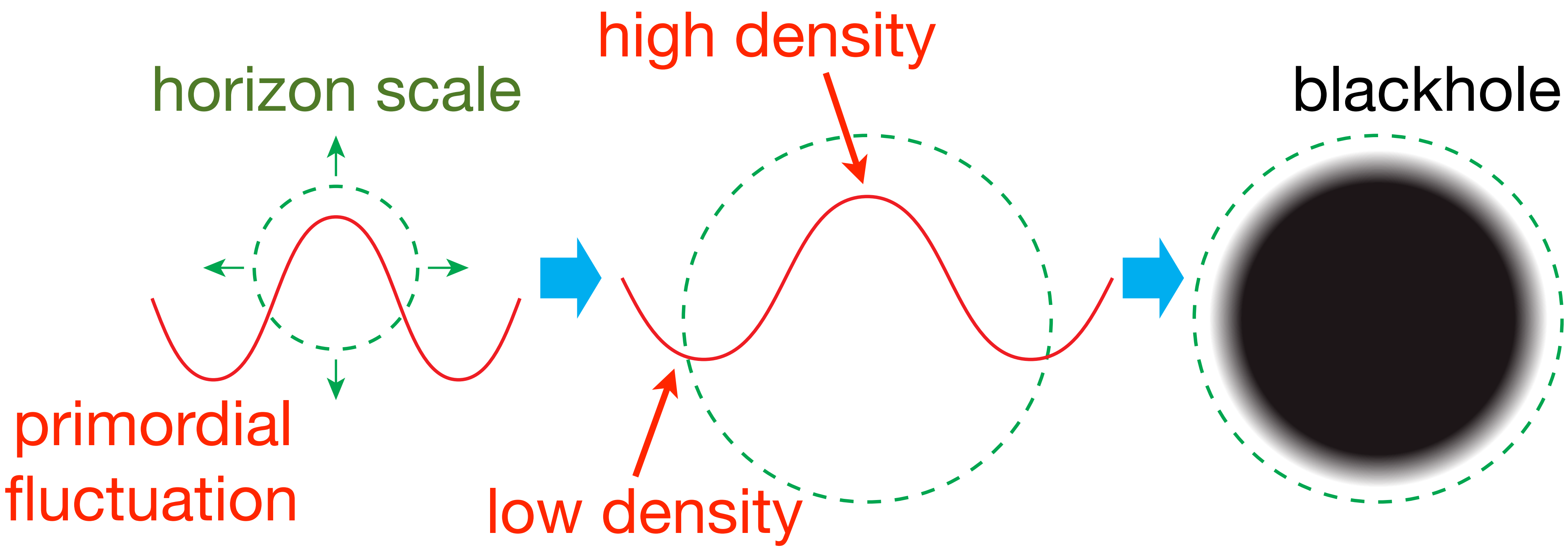
Bird, Cholis, Munoz, Ali-Haimoud, Kamionkowski, Kovetz, Raccanelli, Riess, 1603.00464

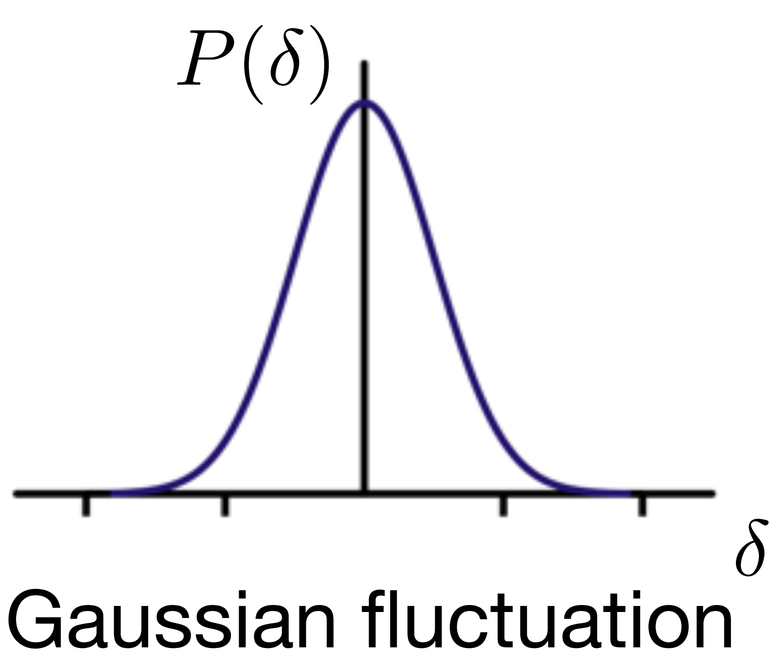
Clesse, Garcia-Bellido, 1603.05234

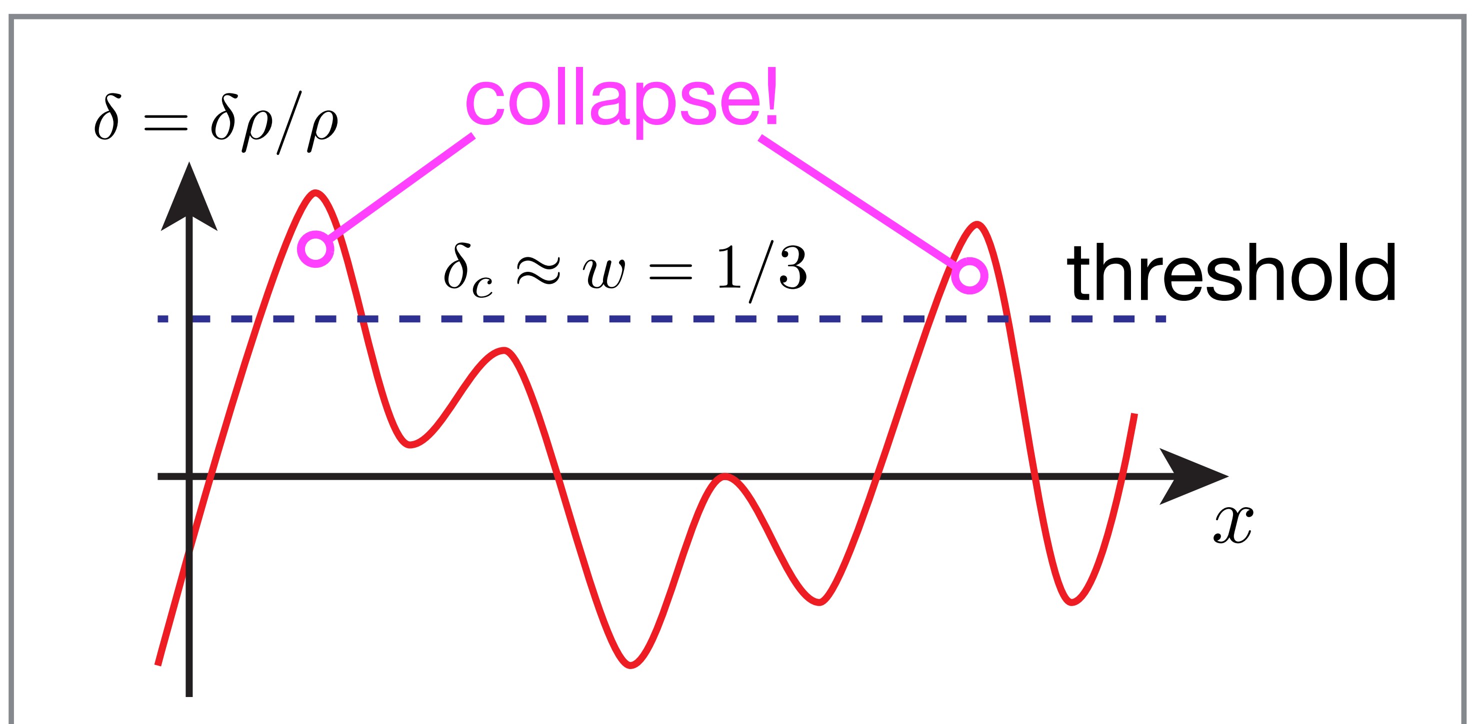
Sasaki, Suyama, Tanaka, Yokoyama, 1603.05234

原始ブラックホール (Primordial blackhole, PBH)

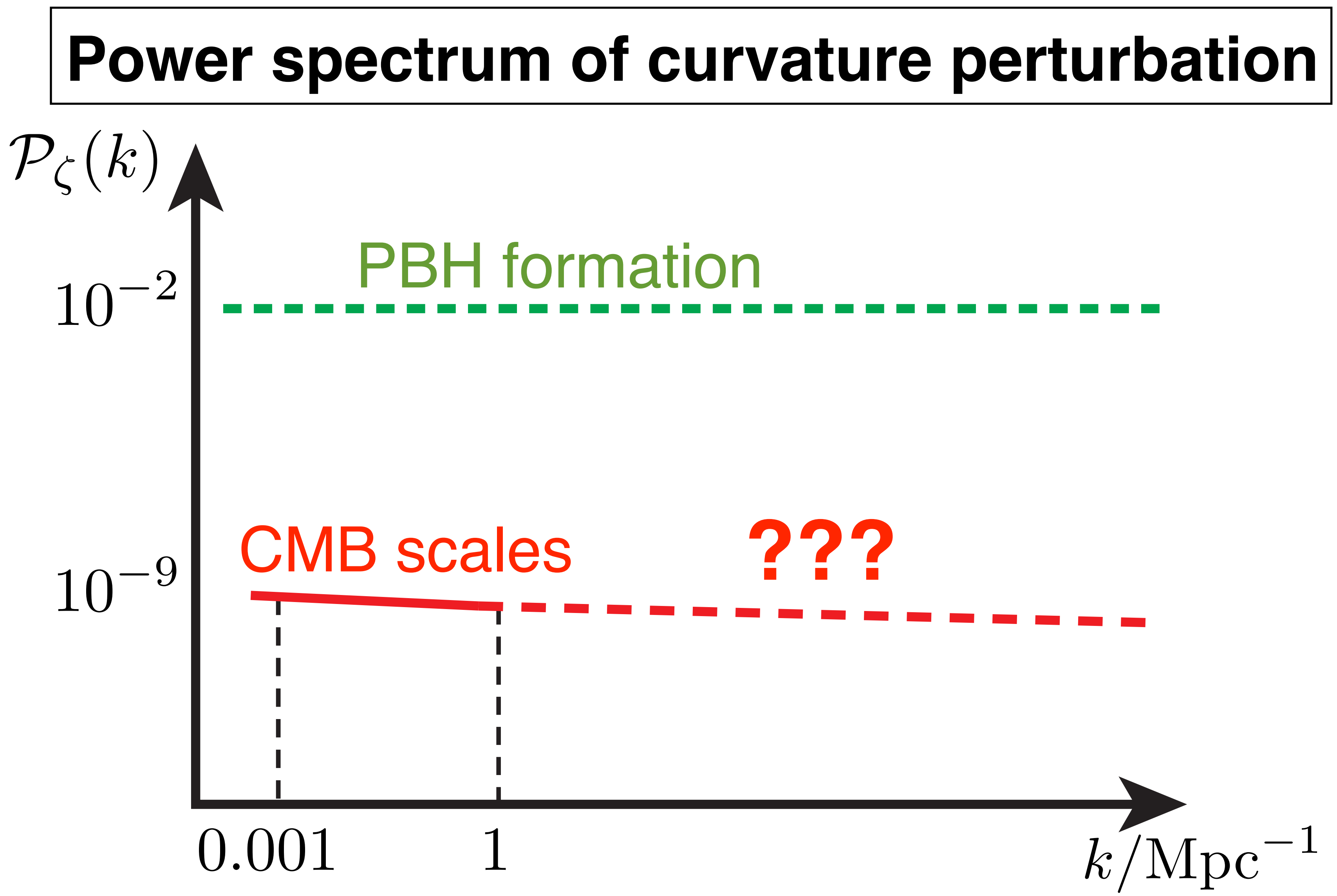
宇宙初期の輻射流体が初期密度ゆらぎによって重力崩壊したもの



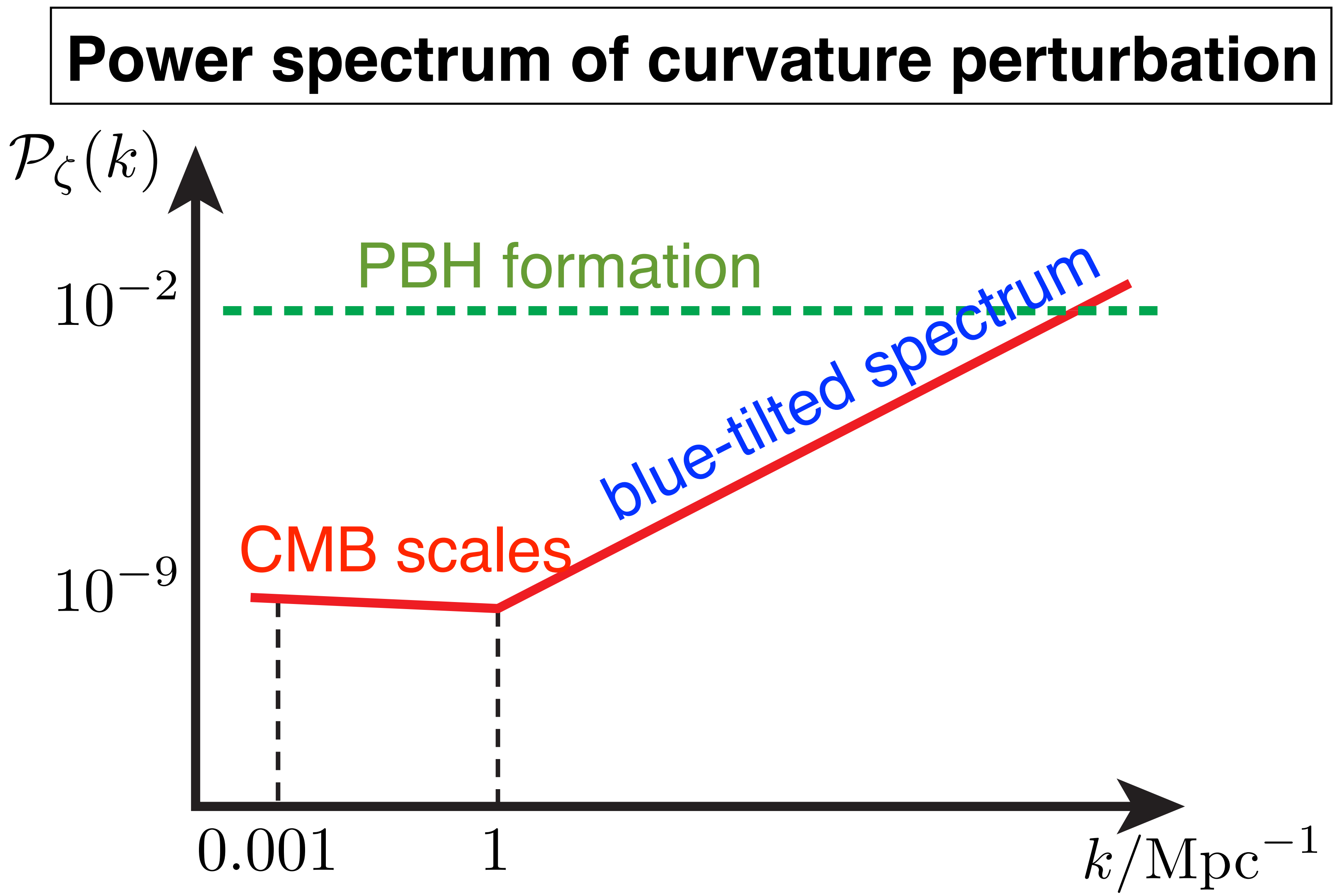




PBH formation



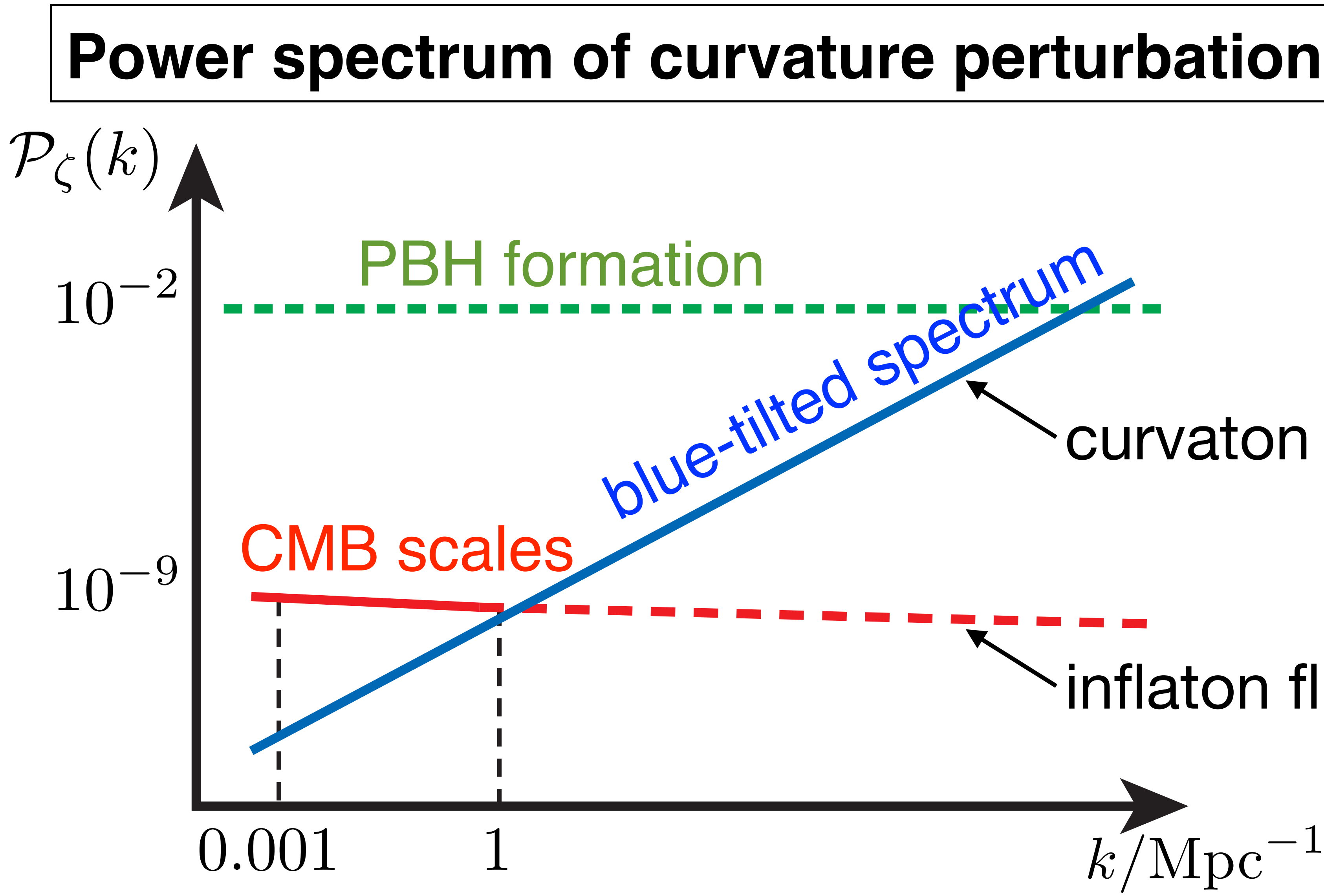
PBH formation



Single component fluctuation (inflaton)

running mass inflation, double inflation, …

PBH formation



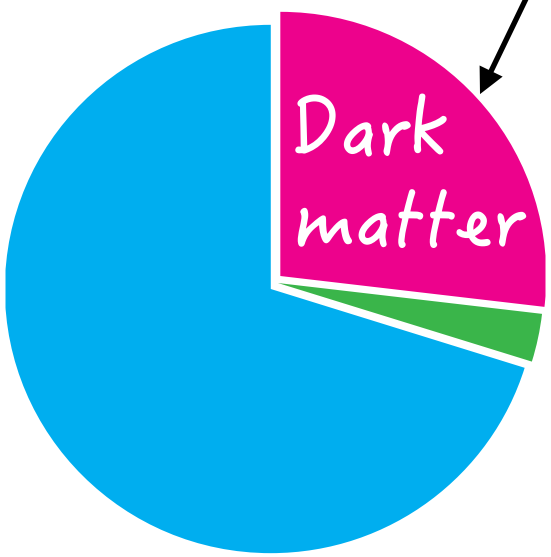
Multi-field fluctuation : inflaton + curvaton

Kawasaki, NK, Yanagida, 1207.2550

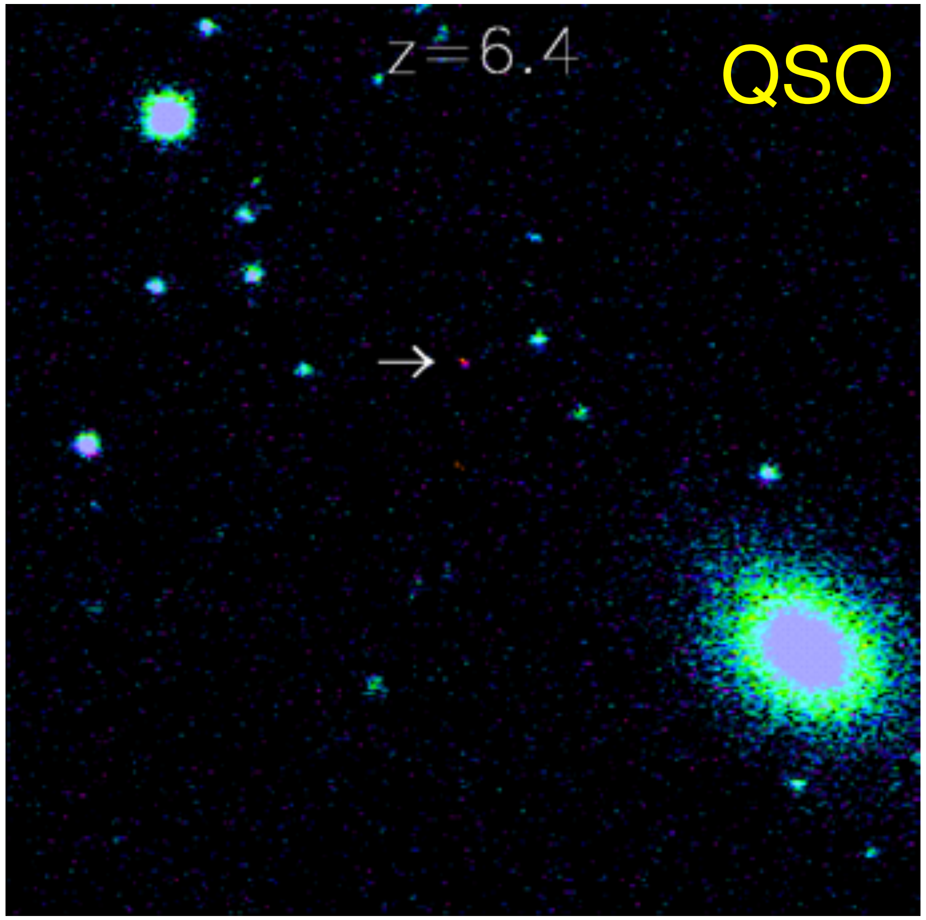
PBH as dark matter / seed of SMBH

PBHs with $M_{\rm PBH} \gtrsim 10^{15}{\rm g}$

(partially)



PBH fraction : $f_{\rm PBH} = \frac{\Omega_{\rm PBH}}{\Omega_{\rm DM}}$



http://www.sdss3.org/

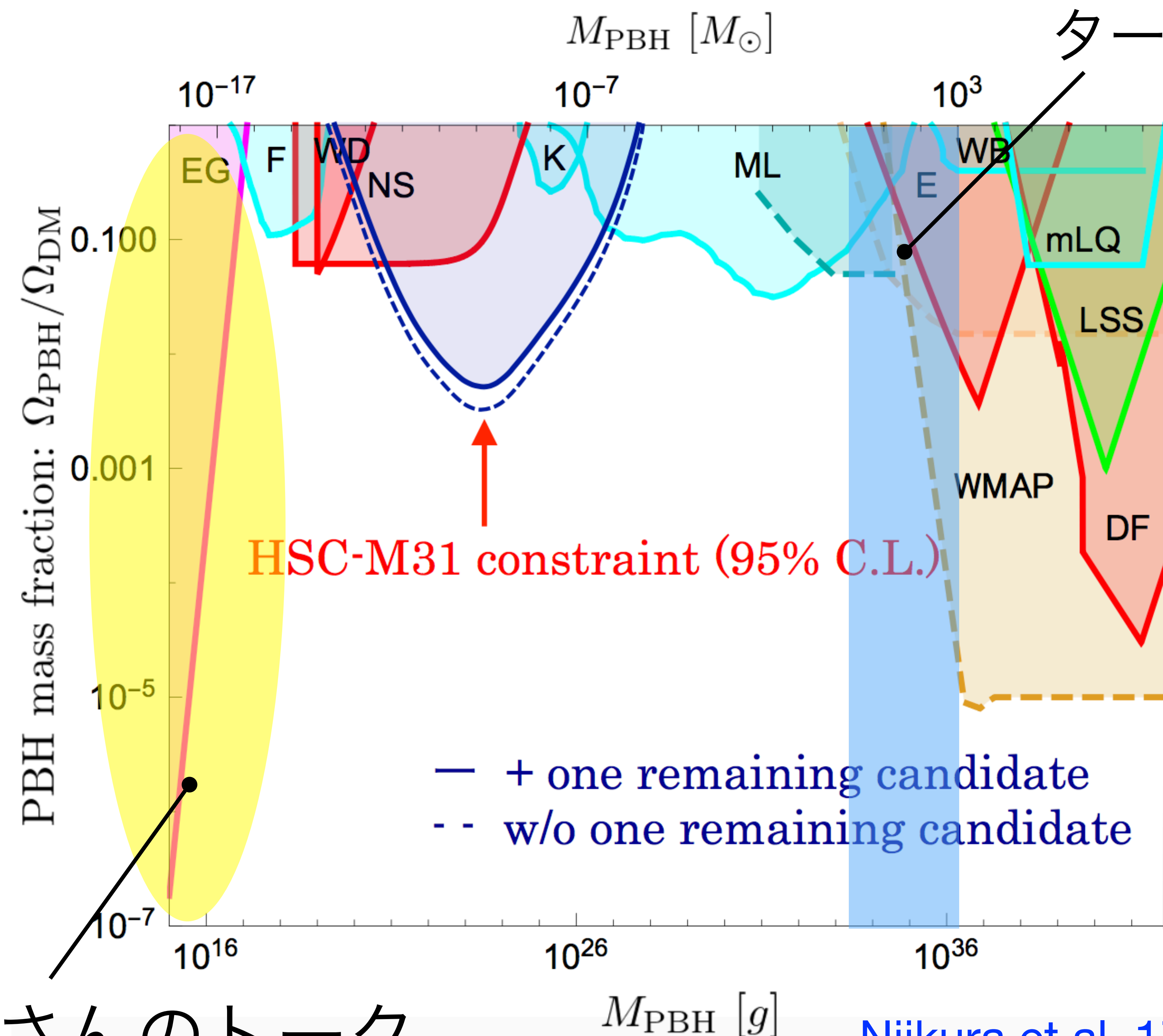
supermassive BH with $10^9 M_\odot$

PBH with $M_{\rm PBH} \gtrsim 10^4 M_\odot$

PBH質量と存在量に関する制限

（単一質量関数を仮定）

ターゲット∋ $30M_\odot$



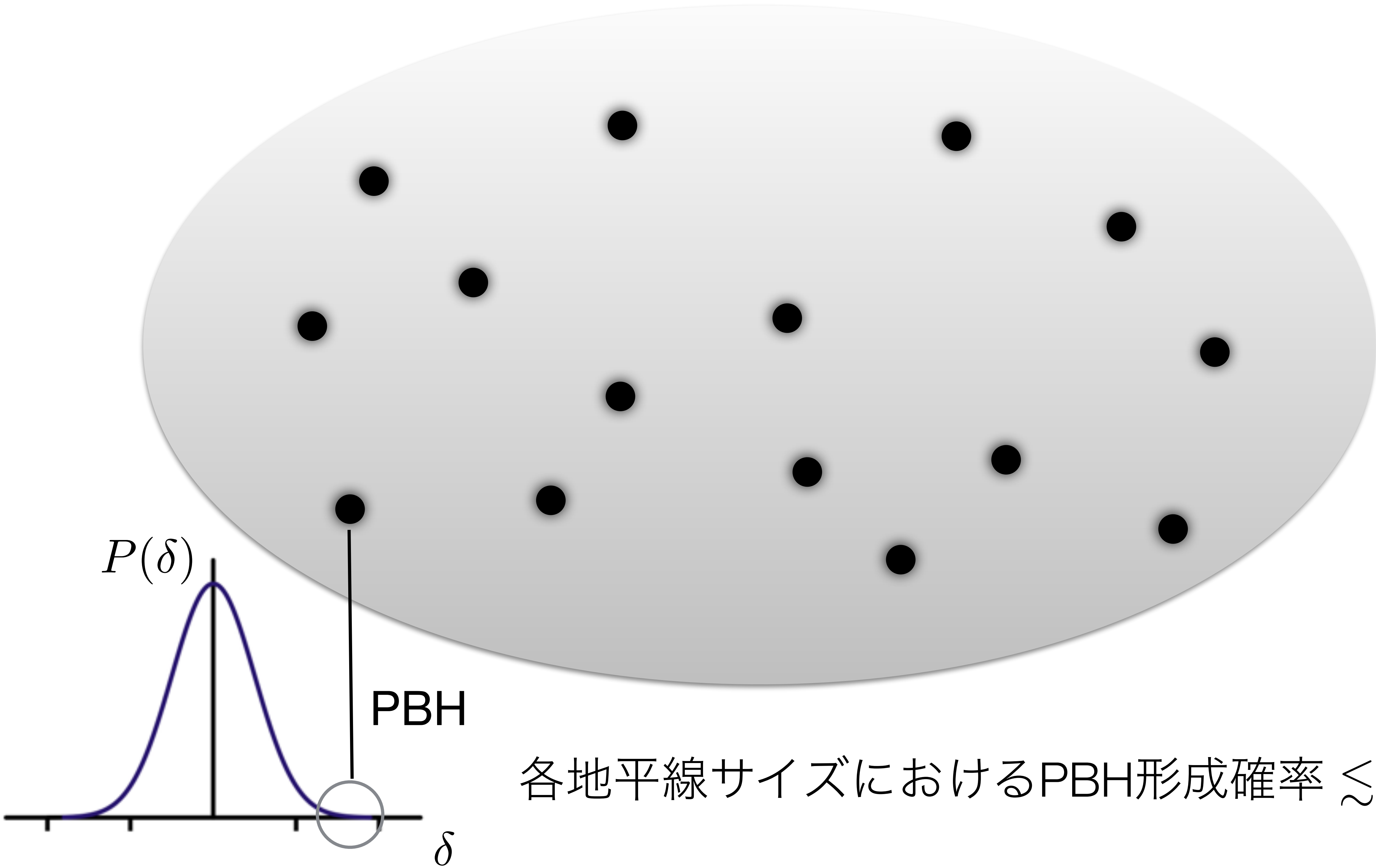
仙洞田さんのトーク

Niikura et al, 1701.02151

PBH number fluctuation and halo mass function

PBH数のポアソン揺らぎ

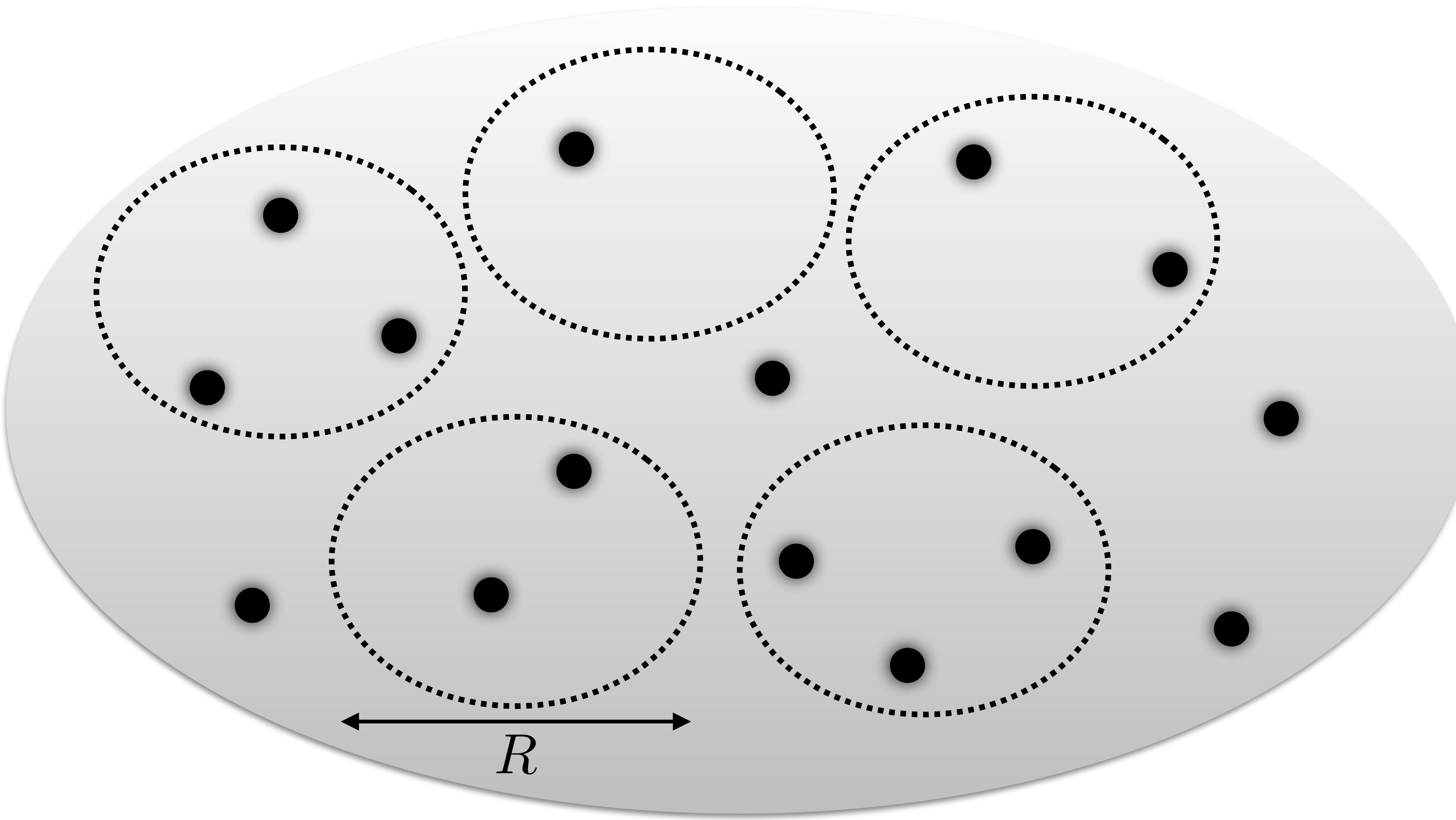
PBHは非常に珍しい物体、空間的にランダム＆疎らに分布



各地平線サイズにおけるPBH形成確率 $\lesssim 10^{-11}$

PBH数のポアソン揺らぎ

PBHは非常に珍しい物体、空間的にランダム＆疎らに分布

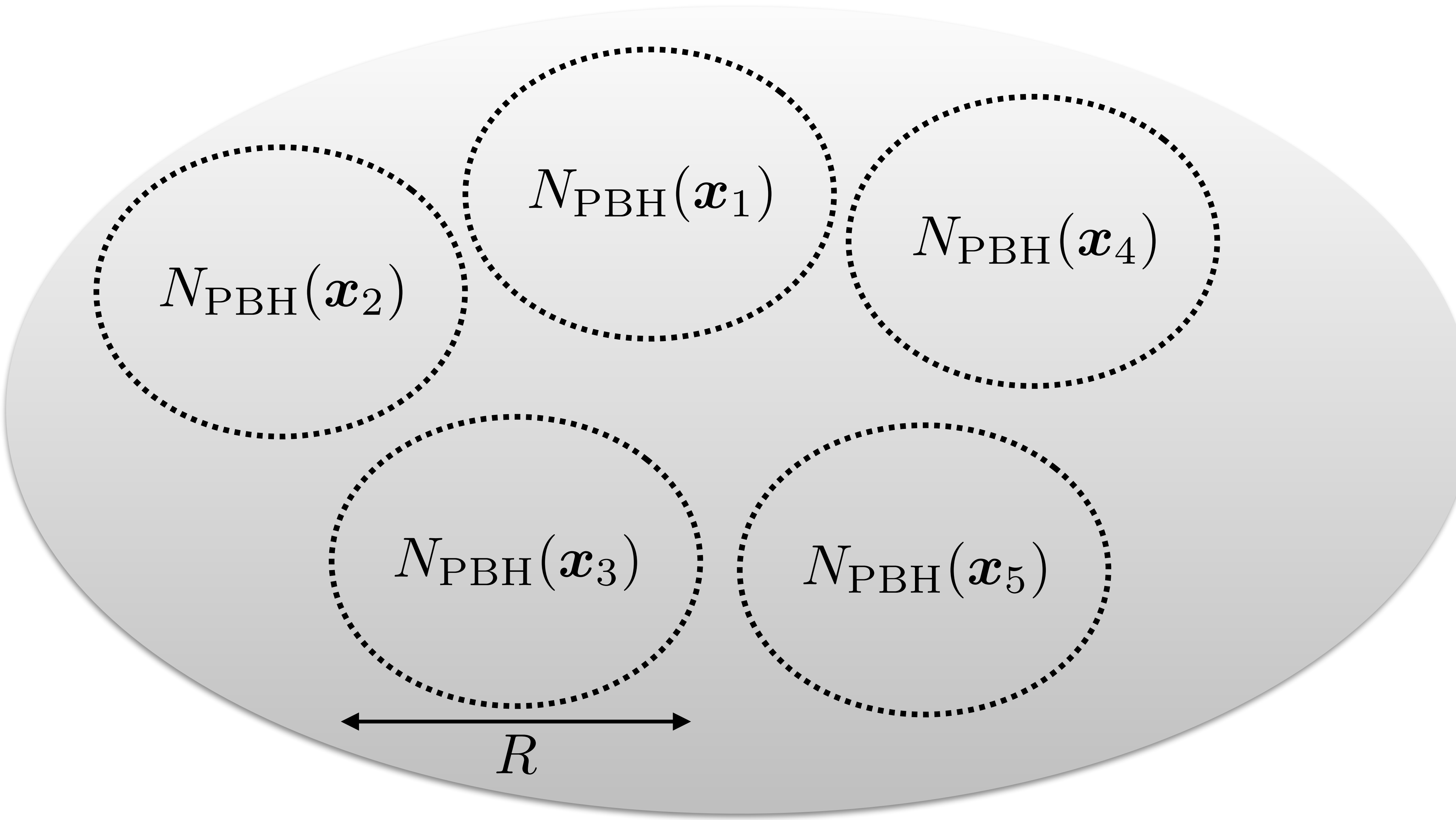


PBH形成時の地平線スケールよりずっと大きいスケールでは

各領域は統計アンサンブルの一つのrealizationと見なせる

PBH数のポアソン揺らぎ

PBHは非常に珍しい物体、空間的にランダム＆疎らに分布



—> $N_{\rm PBH}$ （各領域におけるPBH数）はPoisson分布関数に従う

PBH数のポアソン揺らぎ

Poisson分布関数

$$\mathbb{P}(N_{\rm PBH}) = \frac{\lambda^{N_{\rm PBH}} e^{-\lambda}}{N_{\rm PBH}!} \quad \text{with} \quad \lambda = \langle N_{\rm PBH} \rangle = \langle \delta N_{\rm PBH}^2 \rangle$$

→ PBH数： $N_{\rm PBH} = \bar{N}_{\rm PBH}(1+\delta_P)$

→ PBHエネルギー密度： $\rho_{\rm PBH} = \beta \rho_{r,f}(1+\delta_P) e^{-3(N-N_f)}$

β : initial fraction (PBH formation probability)

$\rho_{r,f}$: radiation energy density @ PBH formation

$N(N_f)$: e-folding nuber (@ PBH formation)

PBH数のポアソン揺らぎ

Poisson分布関数

$$\mathbb{P}(N_{\rm PBH}) = \frac{\lambda^{N_{\rm PBH}} e^{-\lambda}}{N_{\rm PBH}!} \quad \text{with} \quad \lambda = \langle N_{\rm PBH} \rangle = \langle \delta N_{\rm PBH}^2 \rangle$$

→ PBH数： $N_{\rm PBH} = \bar{N}_{\rm PBH}(1+\delta_P)$

→ PBHエネルギー密度： $\rho_{\rm PBH} = \beta \rho_{r,f}(1+\delta_P) e^{-3(N-N_f)}$

→ PBH density contrast : $\delta_{\rm PBH} = \delta_P + \frac{3}{4}\delta_r \quad (\delta_r = -4\delta N)$

CDM isocurvature perturbation : $S = \delta_{\rm DM} - \frac{3}{4}\delta_r = f_{\rm PBH}\delta_P$

PBH fraction : $\Omega_{\rm PBH}/\Omega_{\rm DM}$

Power spectrum

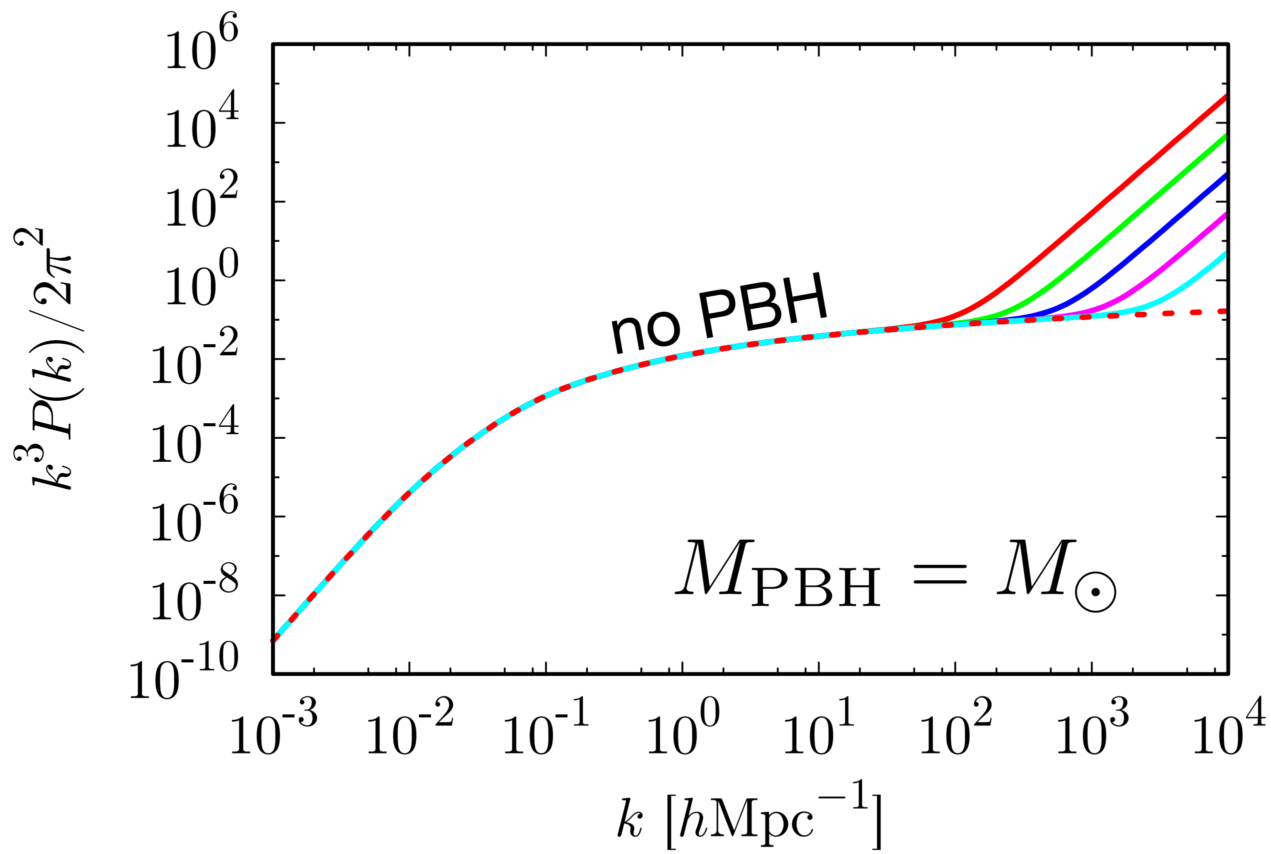
$$P_{\rm iso}(k) = \frac{f_{\rm PBH}^2}{n_{\rm PBH}}$$

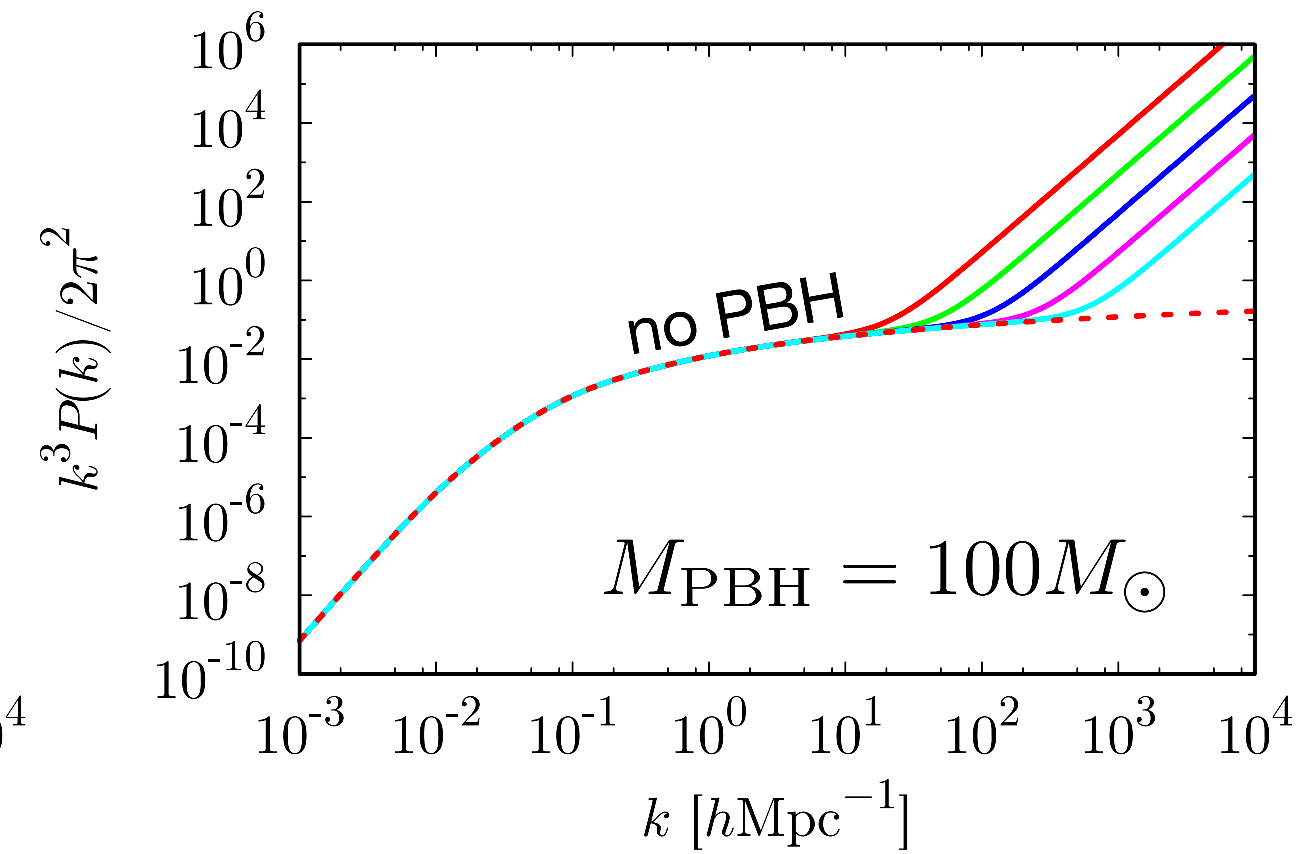
comoving number density

Linear matter power spectrum

$$P_{\rm iso}(k,z) \simeq 0.025\, f_{\rm PBH}\left(\frac{M_{\rm PBH}}{30M_\odot}\right) D^2(z)\ {\rm Mpc}^3 \quad {\rm for} \quad k \gtrsim 0.05\,{\rm Mpc}^{-1}$$

linear growth factor normalized by D(0)



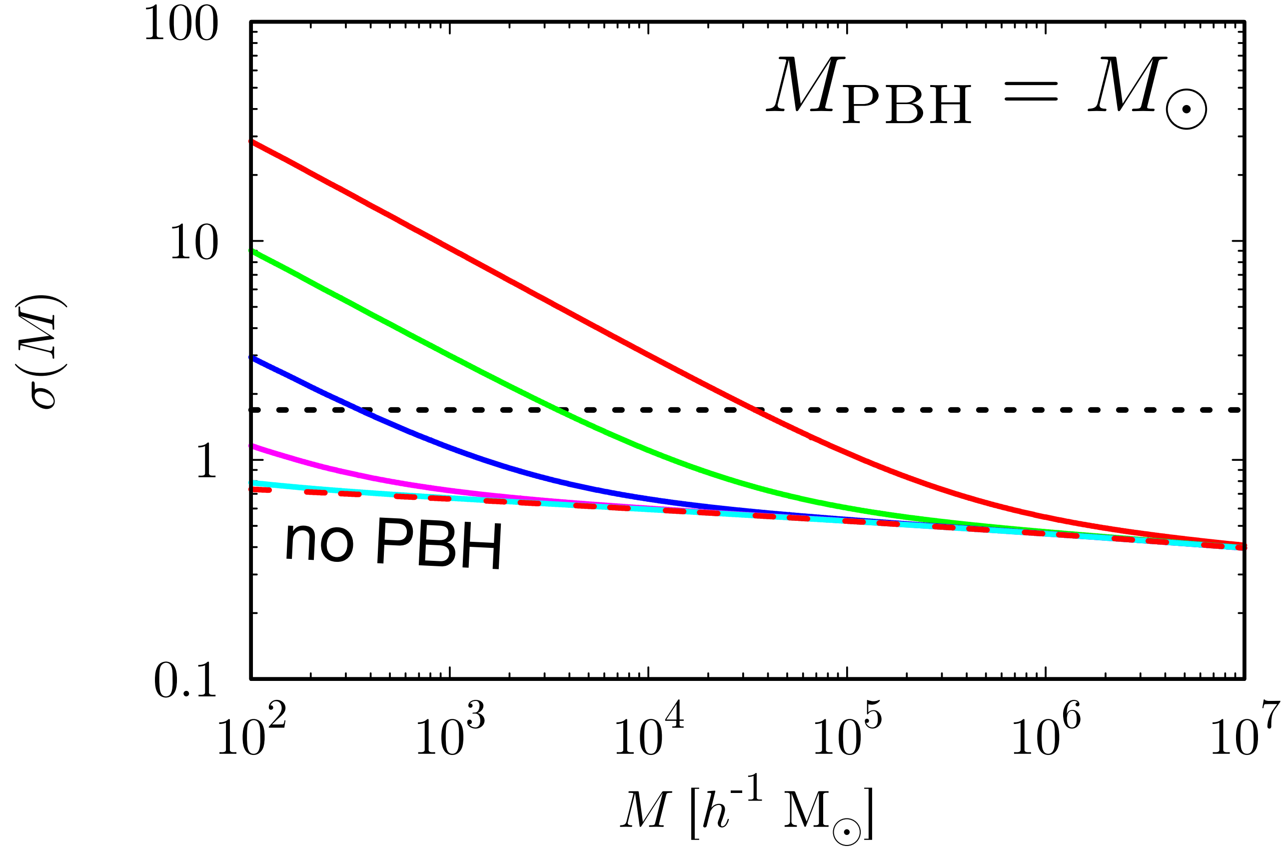


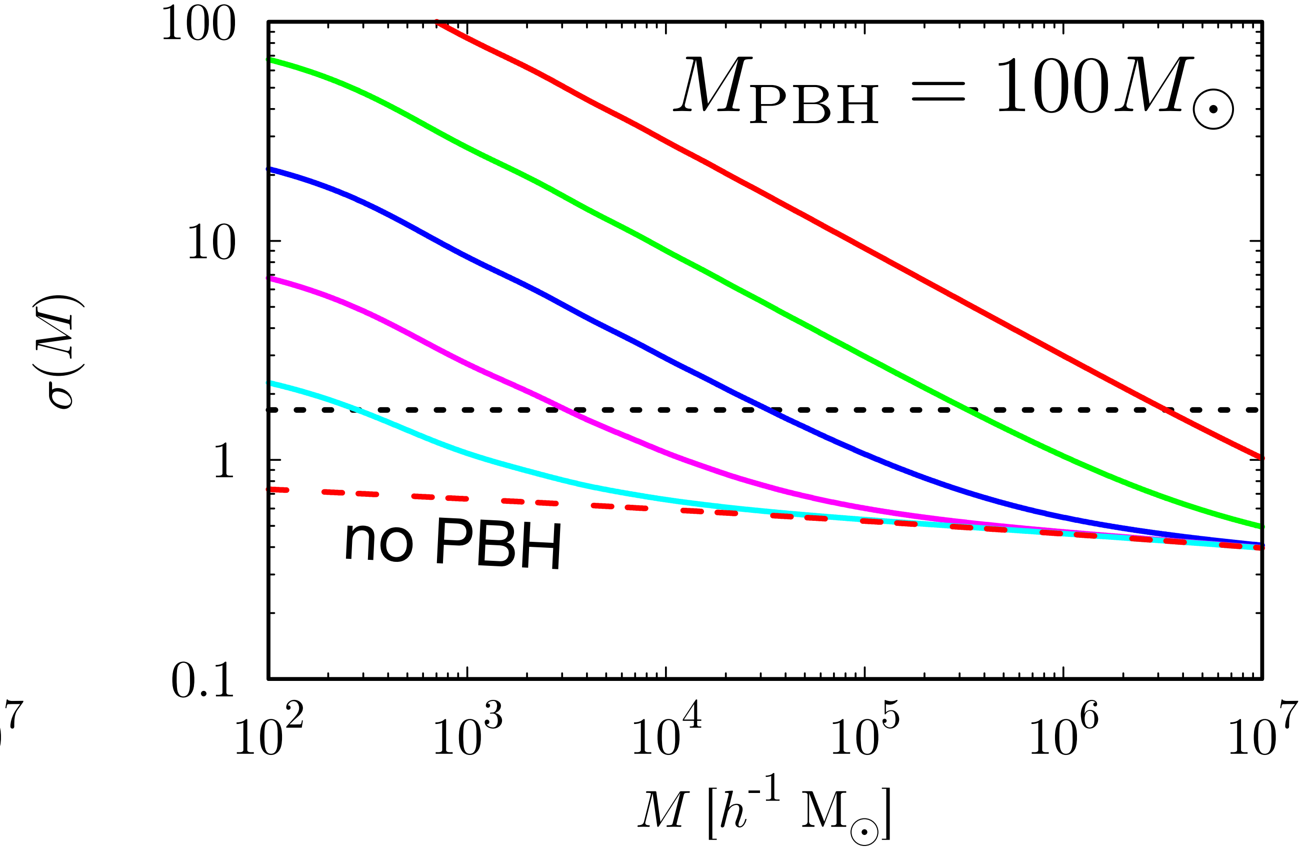
$z = 20,\ f_{\rm PBH} = 10^{-1}, 10^{-2}, 10^{-3}, 10^{-4}, 10^{-5}$ from top to bottom

Smoothed variance

$$\sigma^2(R) = \int_0^\infty \frac{dk}{k} \frac{k^3 P(k)}{2\pi^2} W^2(kR)$$

$$P(k) = P_{\rm adi}(k) + P_{\rm iso}(k)$$

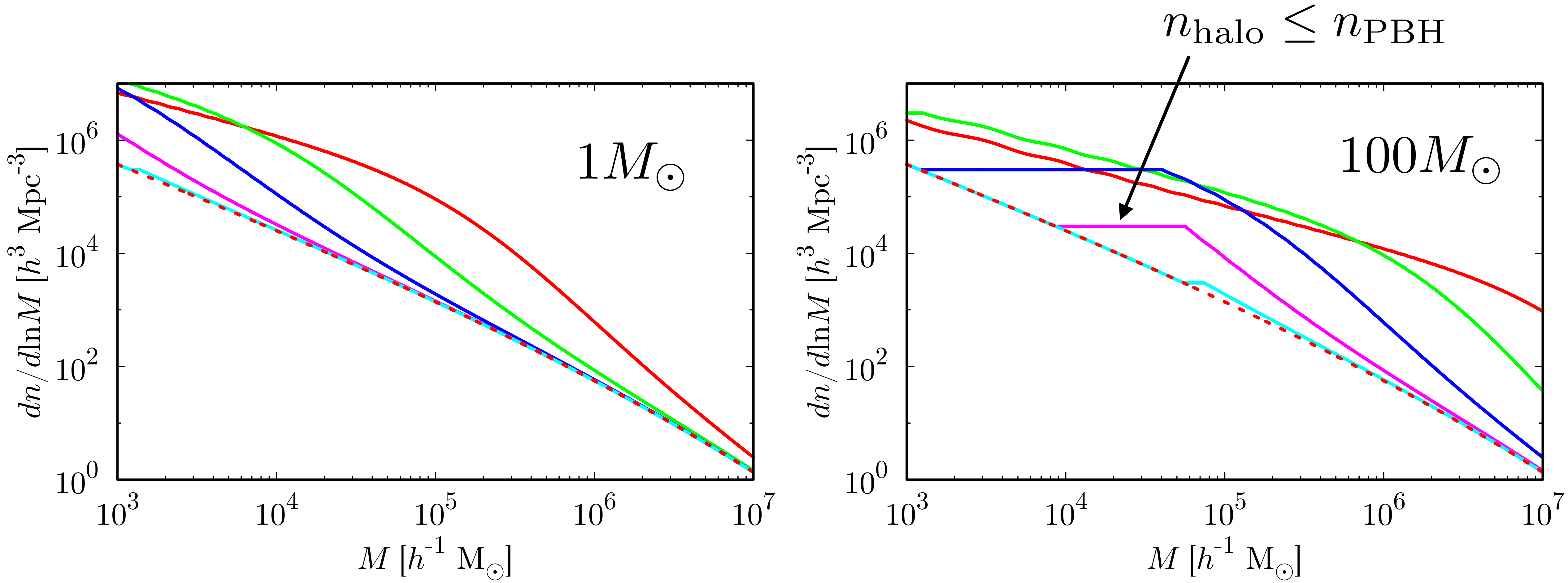




$z = 20,\ f_{\rm PBH} = 10^{-1}, 10^{-2}, 10^{-3}, 10^{-4}, 10^{-5}$ from top to bottom

Halo mass function

$$\frac{dn}{dM} = \frac{\rho_m}{M}\frac{d\ln\sigma^{-1}}{dM}f(\sigma)$$



Gong, NK,1704.04132

$z = 20,\ f_{\rm PBH} = 10^{-1}, 10^{-2}, 10^{-3}, 10^{-4}, 10^{-5}$ from top to bottom

21cm fluctuations from minihaloes

関連する先行研究１
PBHと21cm線シグナル

1. PBHへ物質が降着する時に出るX線で付近のIGMが温められる。

$$M_{\rm PBH} \sim 10^2 M_\odot - 10^8 M_\odot,\ \Omega_{\rm PBH} \sim 10^{-7} - 10^{-5}$$

Tashiro & Sugiyama, 1207.6405

2. PBHからのHawking放射で付近のIGMが温められる。

$$M_{\rm PBH} \sim 10^{10}{\rm kg} - 10^{11}{\rm kg},\ \Omega_{\rm PBH} \gtrsim 10^{-12}$$

Mack & Wesley, 0805.1531

関連する先行研究２
isocurvatureによるミニハロー形成と21cm線

Takeuchi & Chongchitnan, 1311.2585
Sekiguchi, Tashiro, Silk & Sugiyama, 1311.3294

(tilted) isocurvatureのパワースペクトル

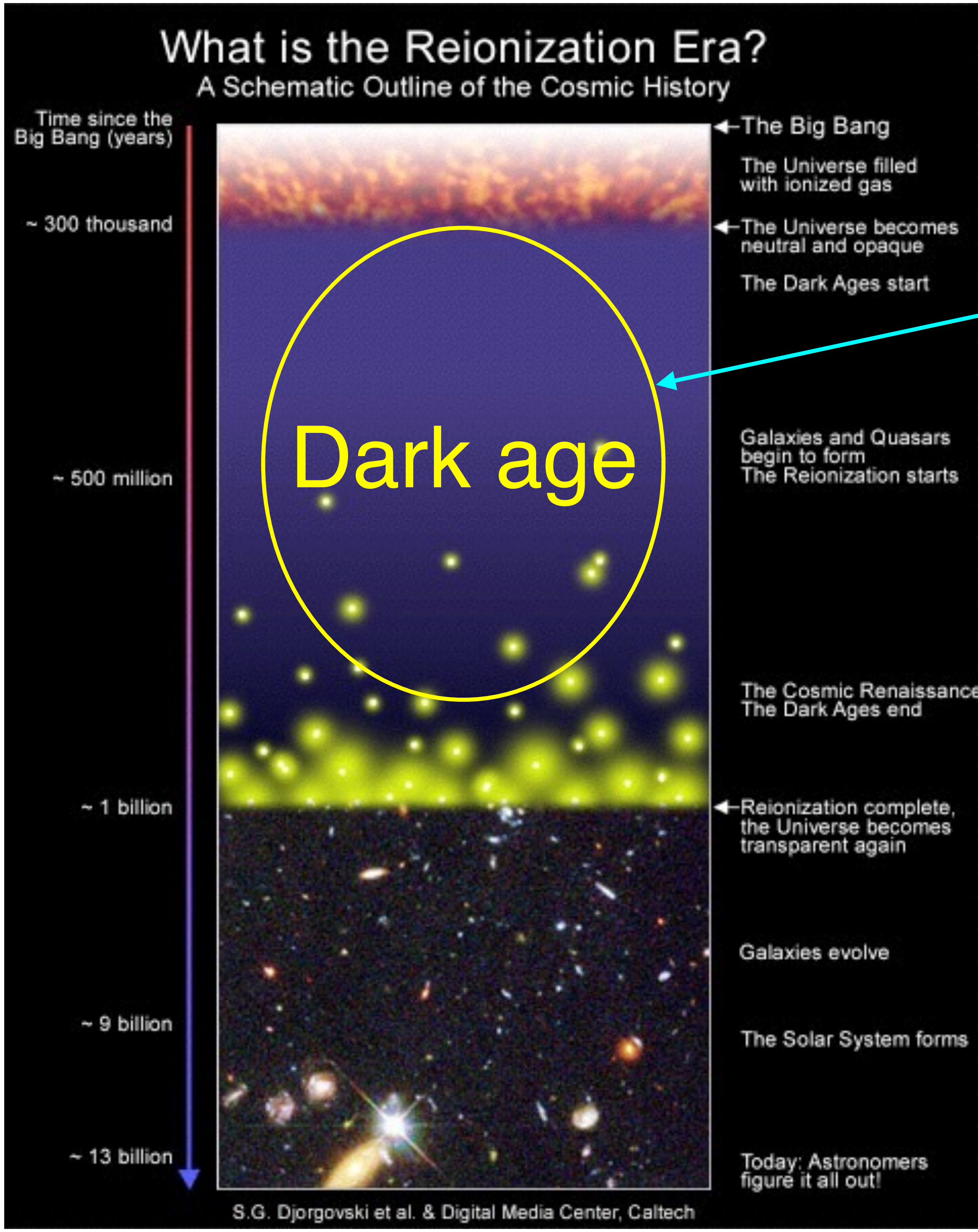
$$P_{\rm iso}(k) = \frac{2\pi^2}{k^3} A_{\rm iso} \left(\frac{k}{k_0} \right)^{n_{\rm iso}-1}$$

PBH Poissonゆらぎの場合

$n_{\rm iso} = 4$ & $A_{\rm iso} = 3.2 \times 10^{-12} f_{\rm PBH} (M_{\rm PBH}/30 M_\odot)$

or $A_{\rm iso}/A_{\rm adi} = 1.5 \times 10^{-3} f_{\rm PBH} (M_{\rm PBH}/30 M_\odot)$

21cm Cosmology –probe of the DARK AGE–

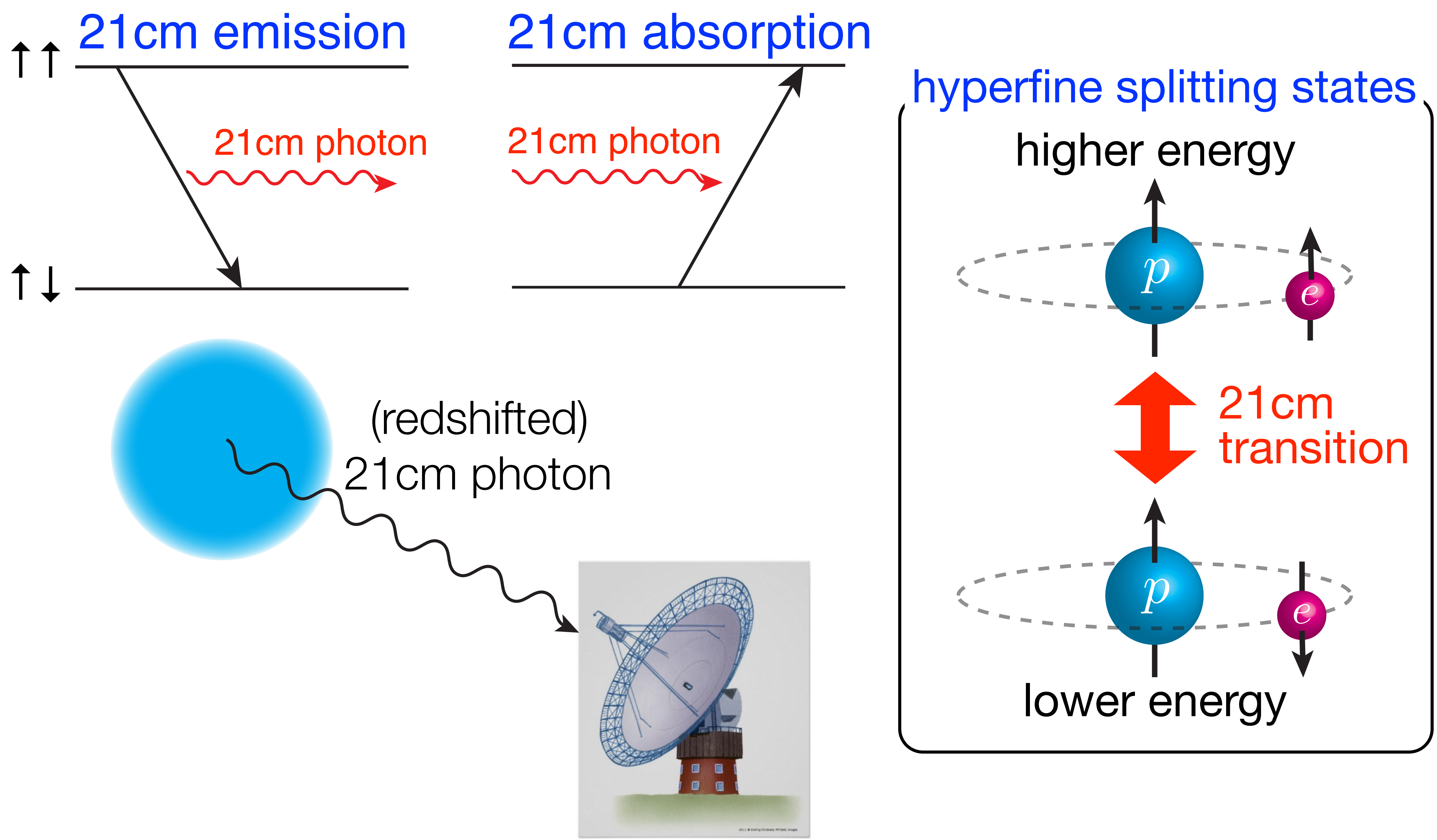


- The universe is filled with neutral hydrogen atoms
- non-linear objects appear

↓

small-scale power affects the minihalo abundance, 21cm emission signal

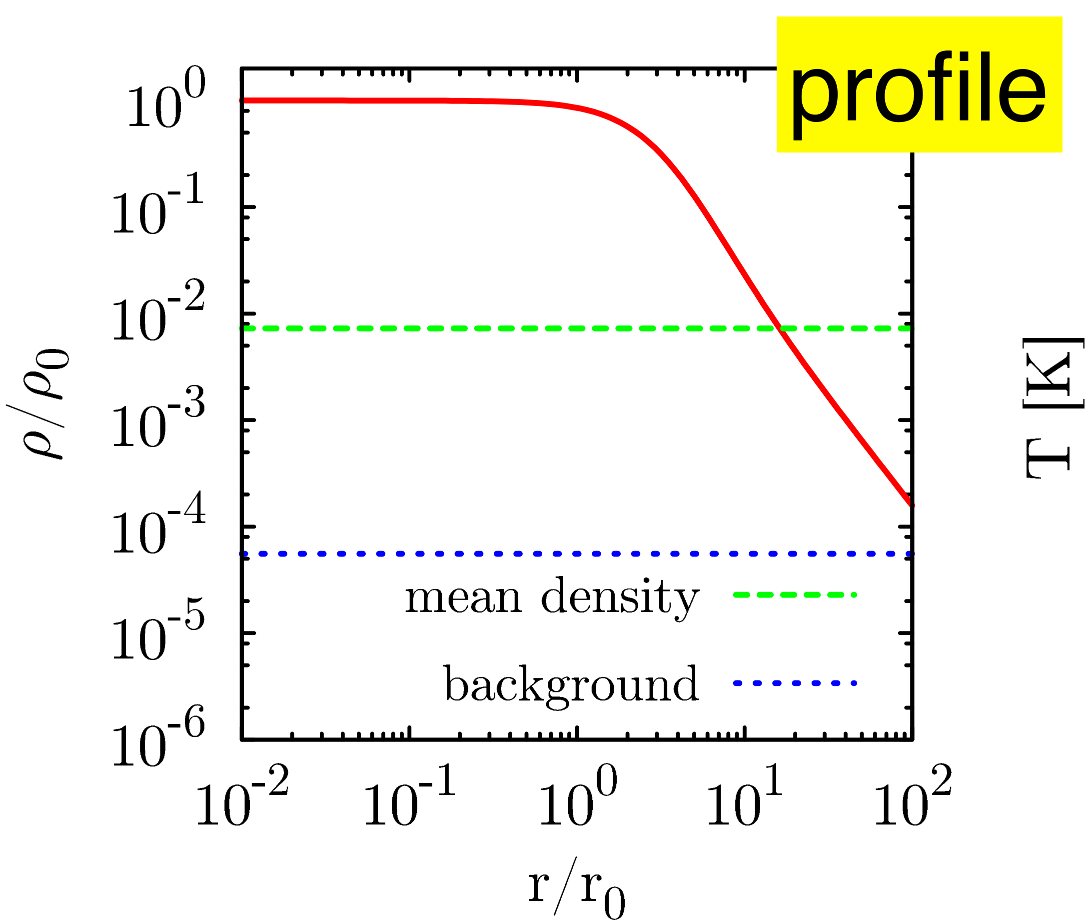
21cm emission/absorption signal

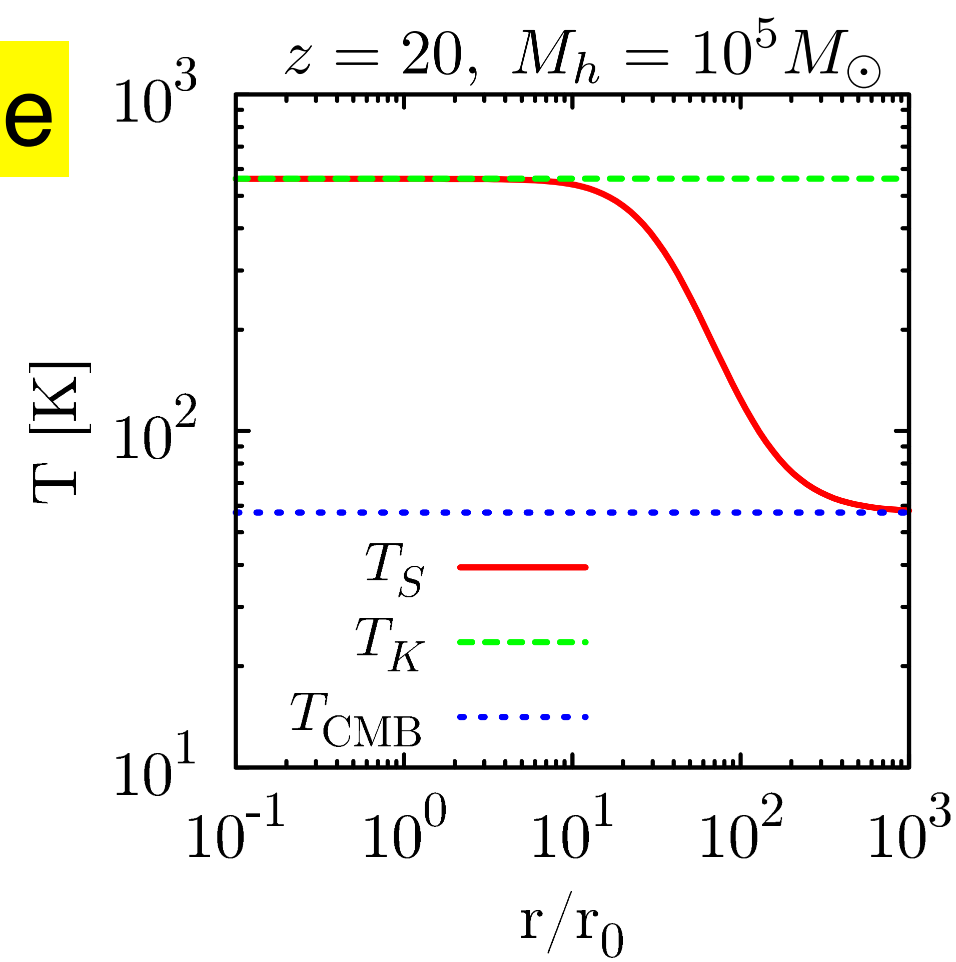


Density & temperature profile of minihalo (TIS model)

Spin temperature: $$\frac{n_1}{n_0} = 3\exp\left(-\frac{T_*}{T_s}\right)$$ energy splitting: $T_* = 0.068$ K

21cm differential brightness temperature





minihalo contribution ➢ $T_S \gg T_{\rm CMB}$ ➢ emission signal

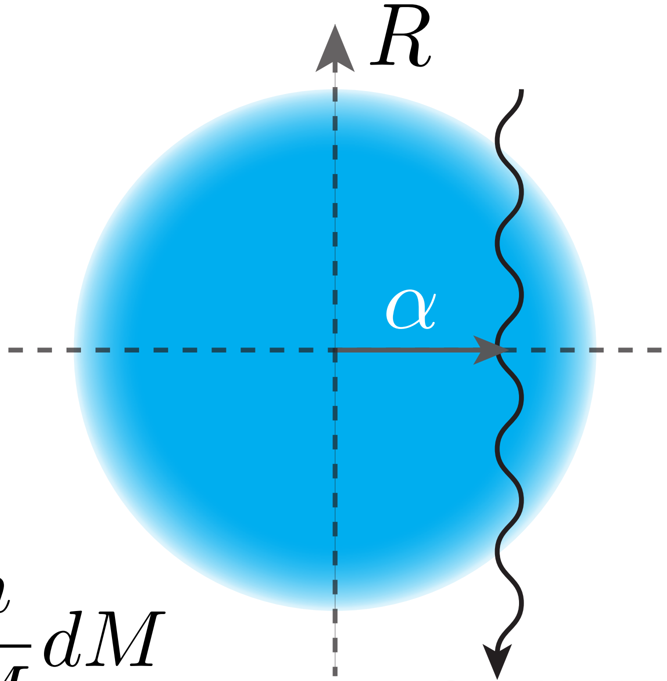
Brightness temperature for photons coming through a single minihalo

$$T_b(\nu, \alpha, z) = T_{\rm CMB}(z) e^{-\tau(\nu)} + \int_{-\infty}^{\infty} dR \, T_S(\ell) e^{-\tau(\nu, R)} \frac{\partial \tau}{\partial R}$$

Iliev, Shapiro, Ferrara, astro-ph/0202410

Differential brightness temperature w.r.t. CMB

$$\delta T_b = \frac{\langle T_b \rangle}{1+z} - T_{\rm CMB}(0)$$



Average over halo masses

$$\overline{\delta T_b} = \frac{c(1+z)^4}{\nu_* H(z)} \int_{M_{\rm min}}^{M_{\rm max}} \Delta\nu_{\rm eff} \delta T_b(M) A \frac{dn}{dM} dM$$

r.m.s smoothed over a survey volume

$$\langle \delta T_b^2 \rangle^{1/2} = q \sigma_p(\Delta\theta_{\rm beam}, \Delta\nu_{\rm band}) \beta(z) \overline{\delta T_b}$$

SKA (-like) observation

$$\delta T_{\rm noise} = 20\ {\rm mK}\ \frac{10^4\ {\rm m}^2}{A_{\rm tot}} \left(\frac{10\ {\rm arcmin}}{\Delta\theta_{\rm beam}}\right)^2 \left(\frac{1+z}{10}\right)^{4.6} \left(\frac{\rm MHz}{\Delta\nu_{\rm band}}\,\frac{100h}{t_{\rm int}}\right)^{1/2}$$

Furlanetto, Oh, Briggs, astro-ph/0608032

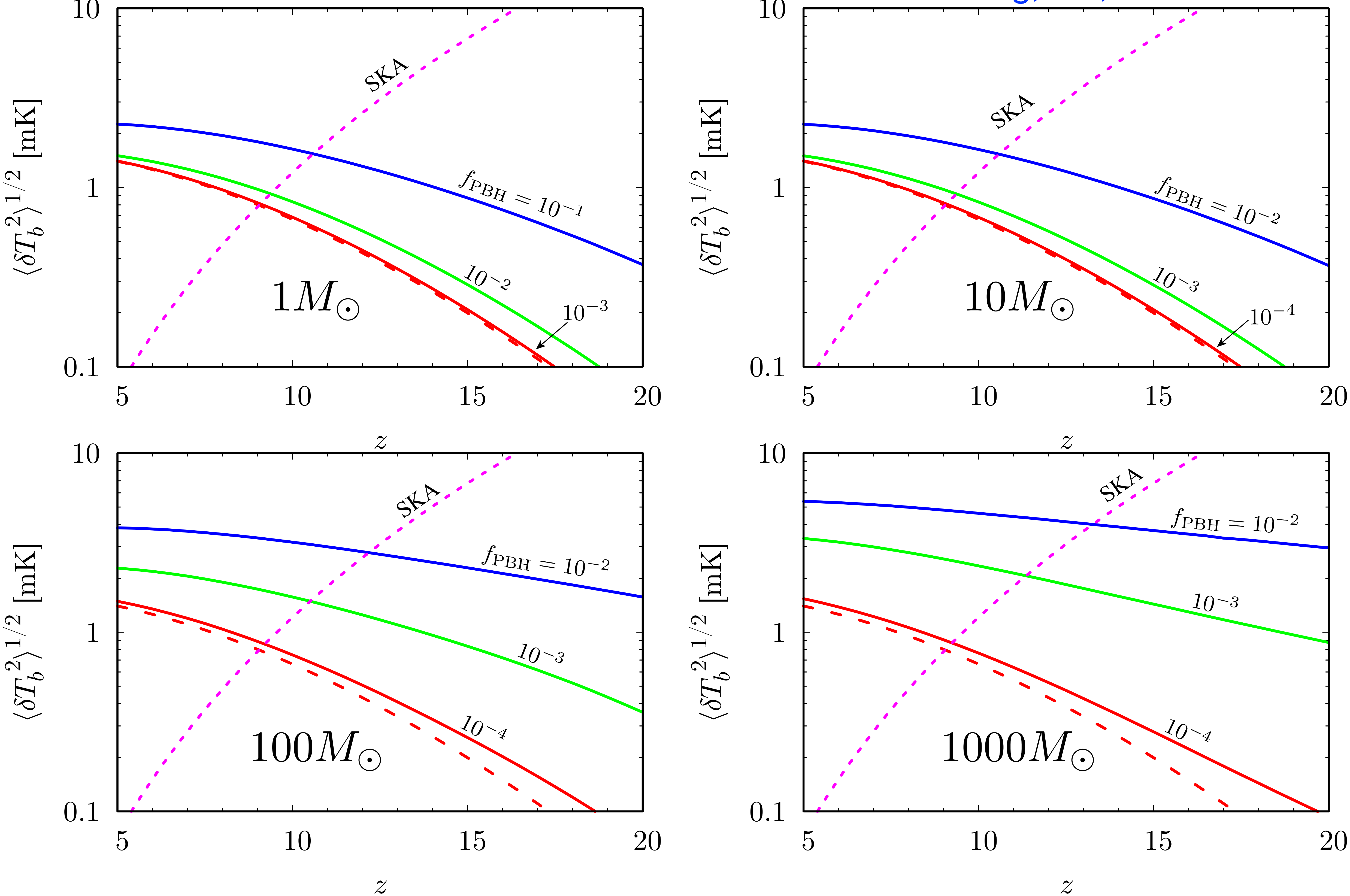
$A_{\rm tot} = 10^5\ {\rm m}^2$, $\Delta\theta_{\rm beam} = 9$ arcmin, $\Delta\nu_{\rm band} = 1$ MHz and $t_{\rm int} = 1000$ h

SKA SQUARE KILOMETRE ARRAY

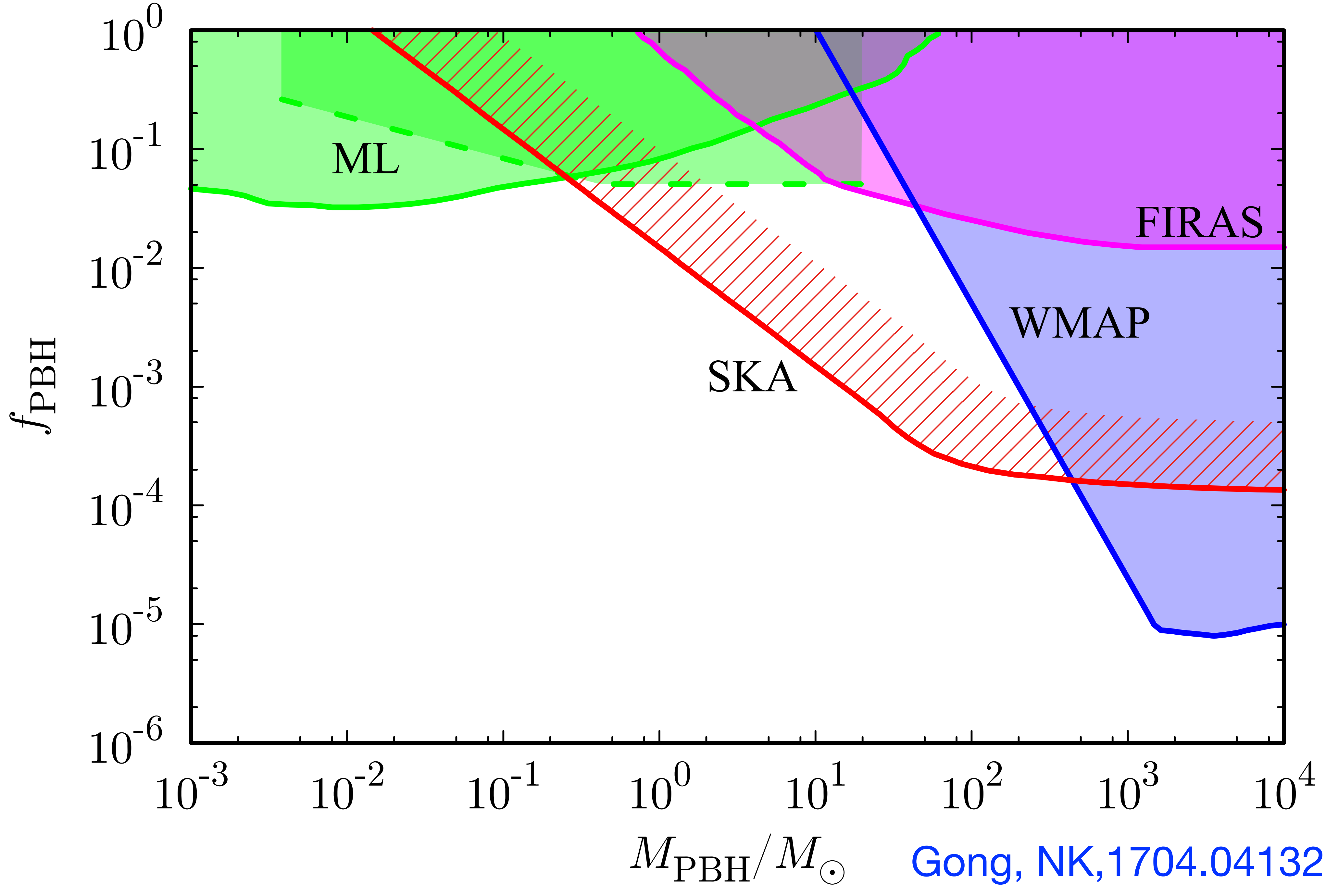
http://www.skatelescope.org

Fluctuation of brightness temperature

Gong, NK,1704.04132

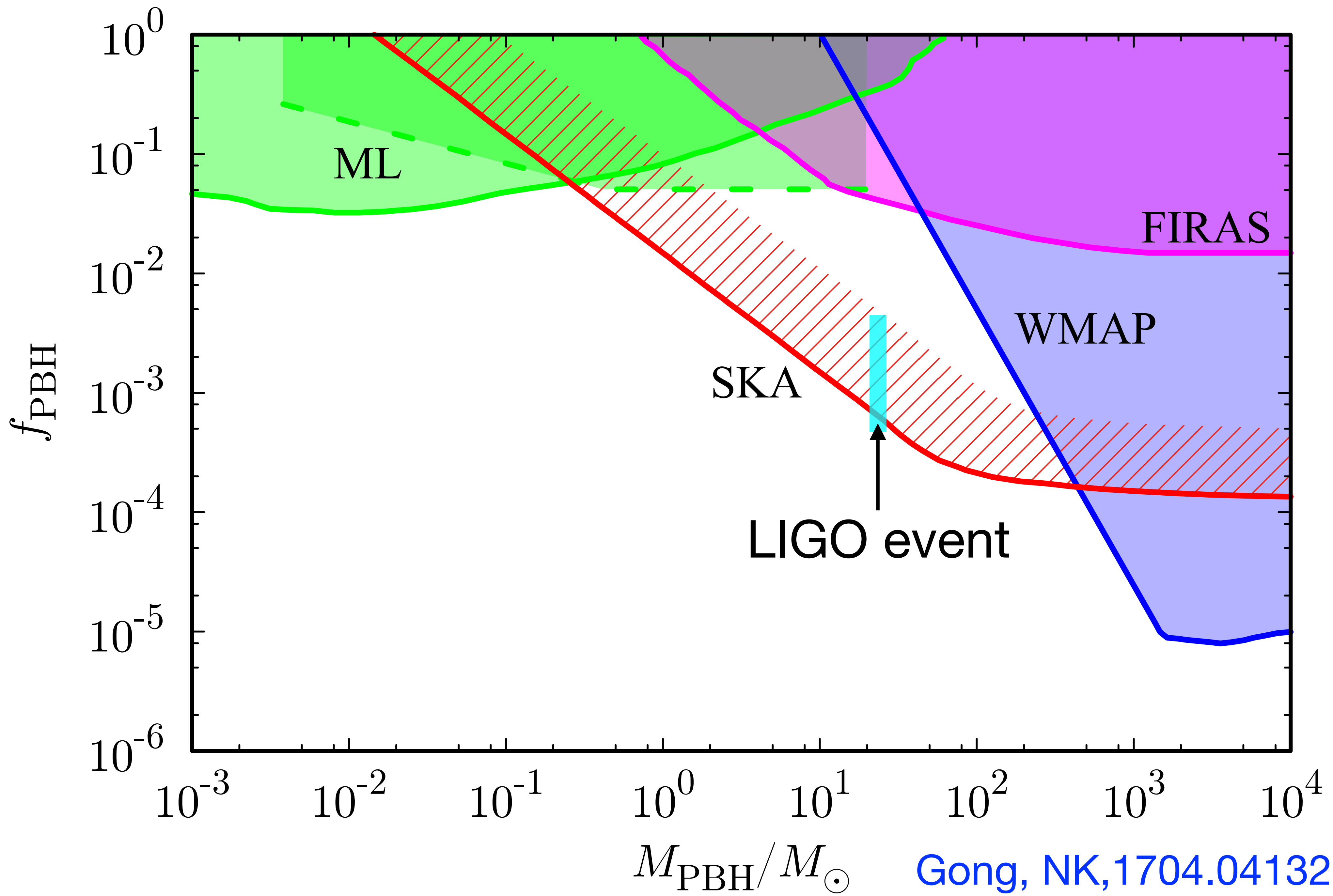


PBH constraint from SKA



Gong, NK,1704.04132

PBH constraint from SKA



Gong, NK,1704.04132

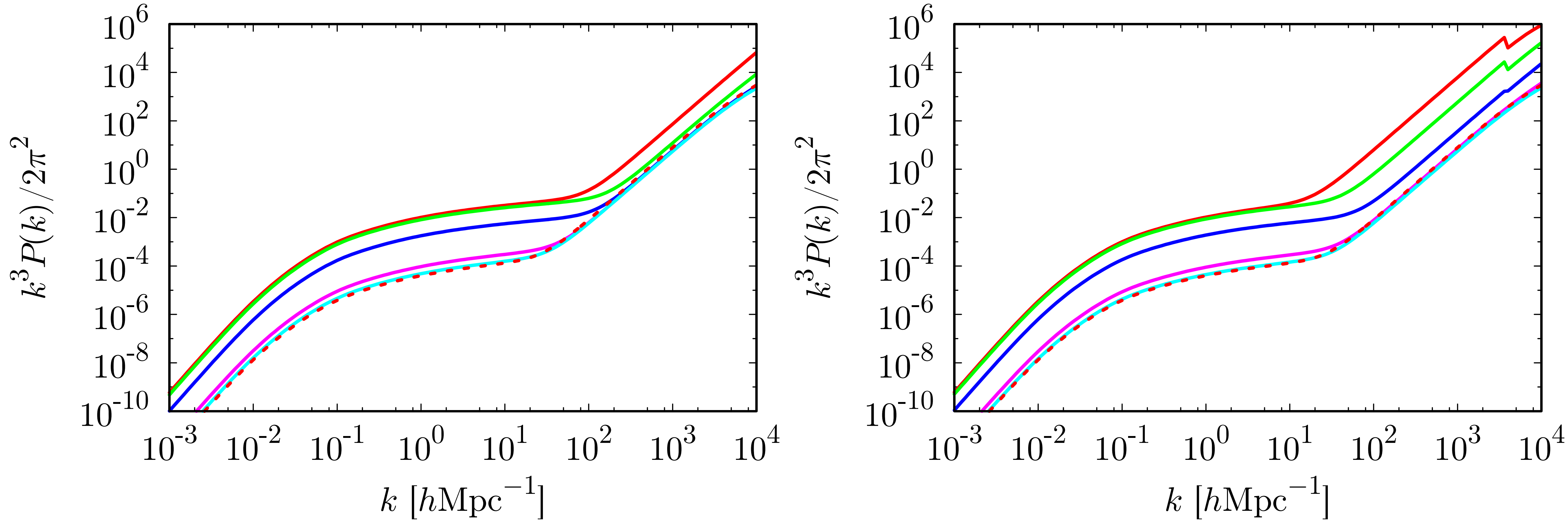
Summary

- PBH数はPoisson分布に従ったゆらぎを持ち、
isocurvatureとして寄与する。小スケールで支配的となる。

- Poissonゆらぎはハロー質量関数に影響。
特に小さいハローの数が劇的に増える。

- 21cm emission signal can be enhanced
and SKA can put a new constraint on PBH mass/abundance

Halo power spectrum



$$z = 20,\ f_{\rm PBH} = 10^{-1}, 10^{-2}, 10^{-3}, 10^{-4}, 10^{-5}\ \ \text{from top to bottom}$$