Small-scale structure and 21cm fluctuations by Primordial Blackholes

Naoya Kitajima

APCTP Asia Pacific Center for Theoretical Physics

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NAGOYA UNIVERSITY

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in collaboration with Jinn-Ouk Gong (APCTP)

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Outline

1. Introduction / motivation

2. Primordial blackhole and halo mass function

3. 21cm signals

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?

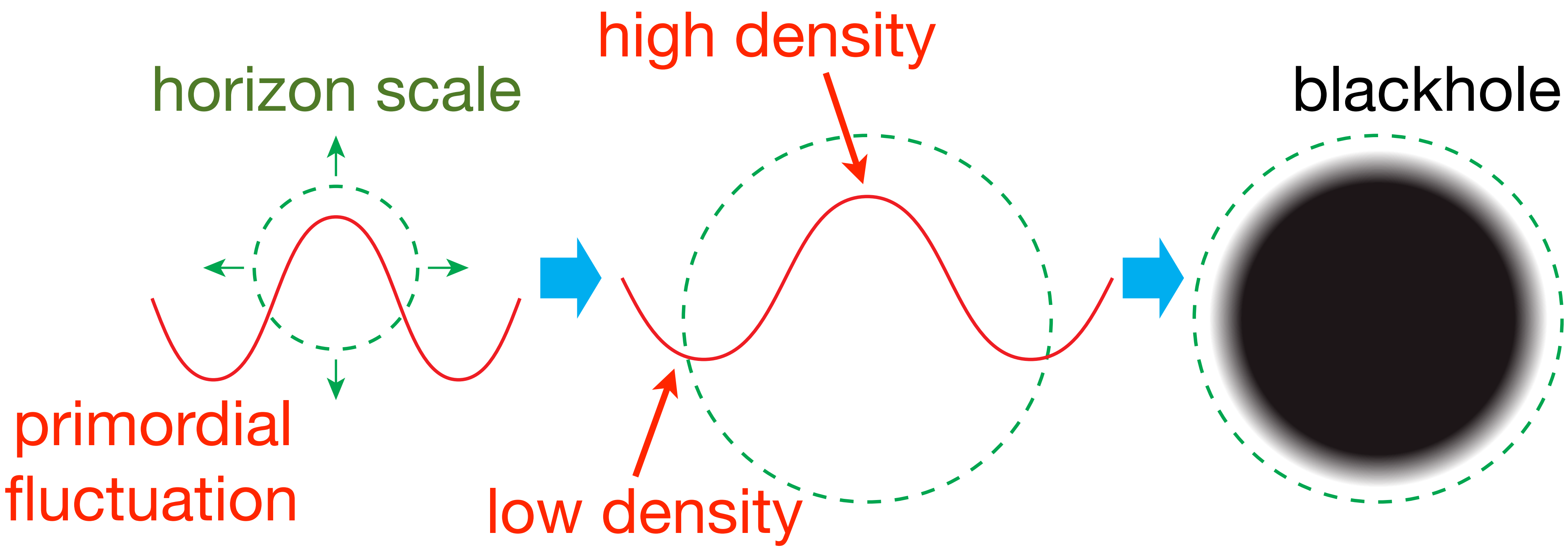
Bird, Cholis, Munoz, Ali-Haimoud, Kamionkowski, Kovetz, Raccanelli, Riess, 1603.00464

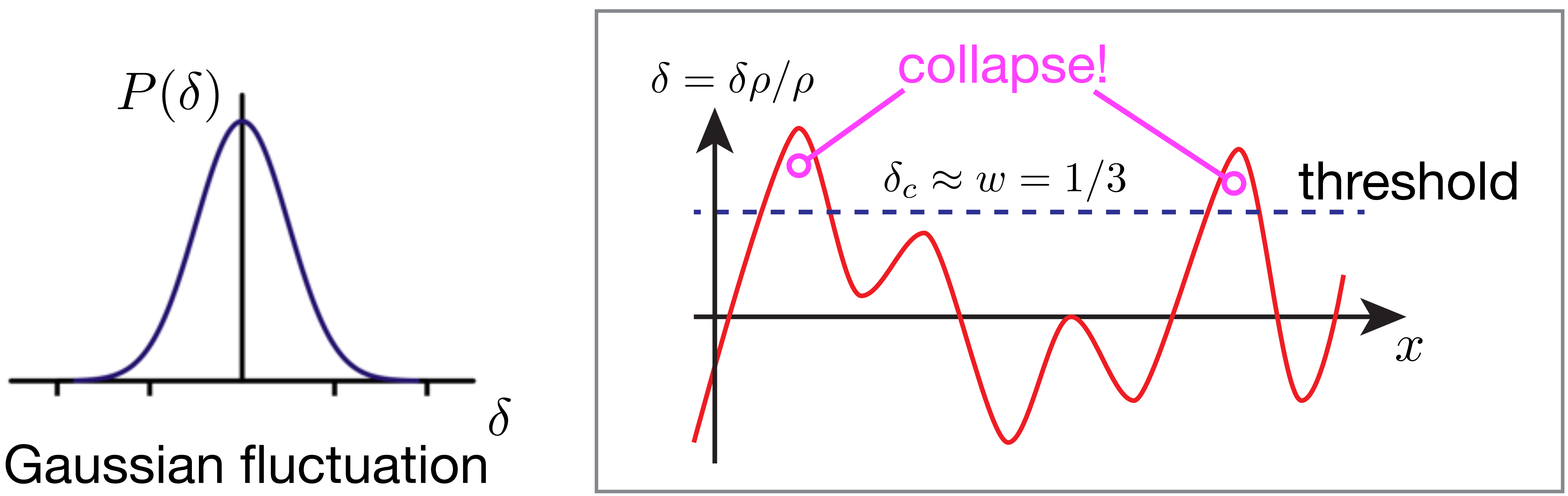
Clesse, Garcia-Bellido, 1603.05234

Sasaki, Suyama, Tanaka, Yokoyama, 1603.05234

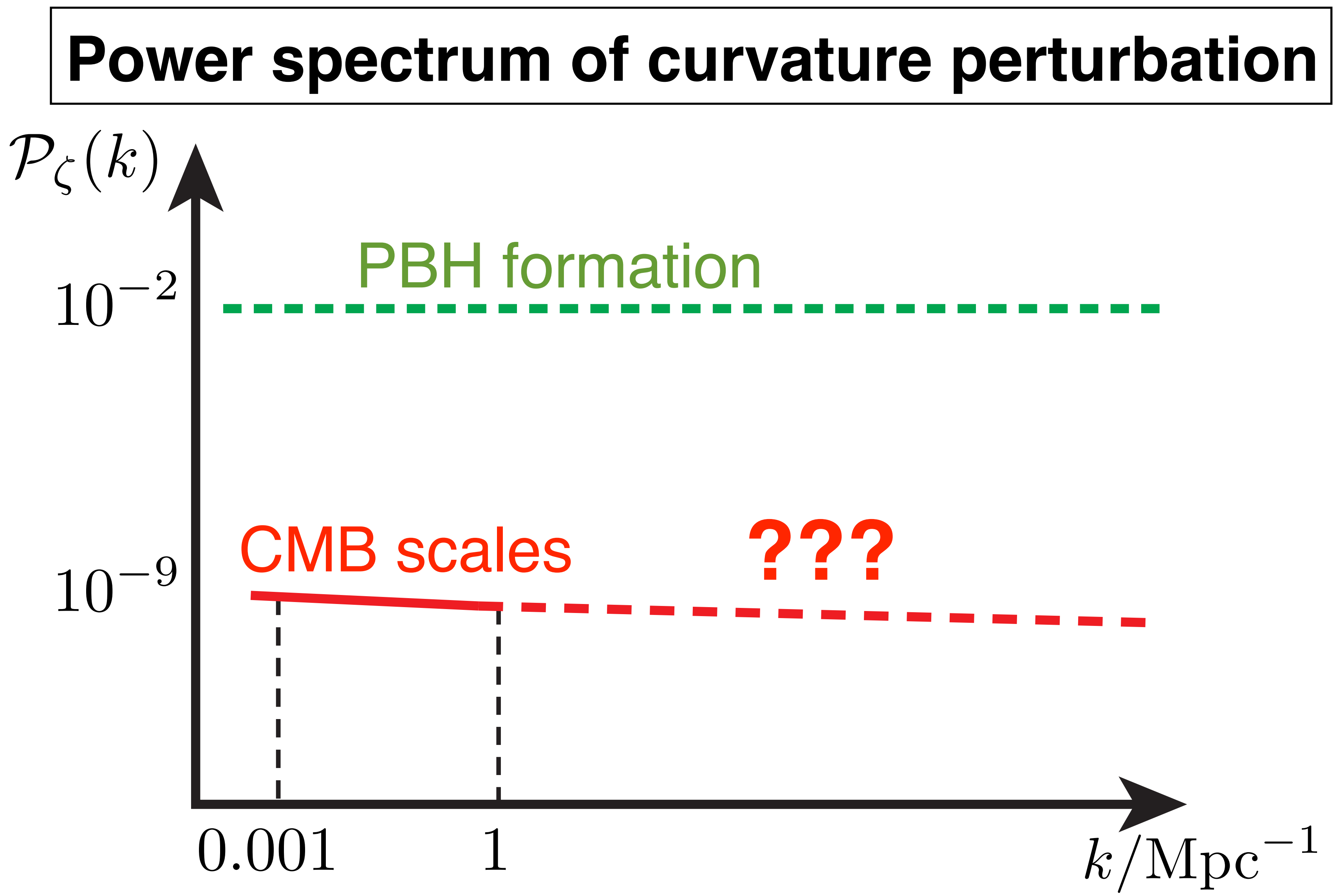
Primordial blackhole (PBH)

forms from direct collapse of the cosmic fluid in the early universe

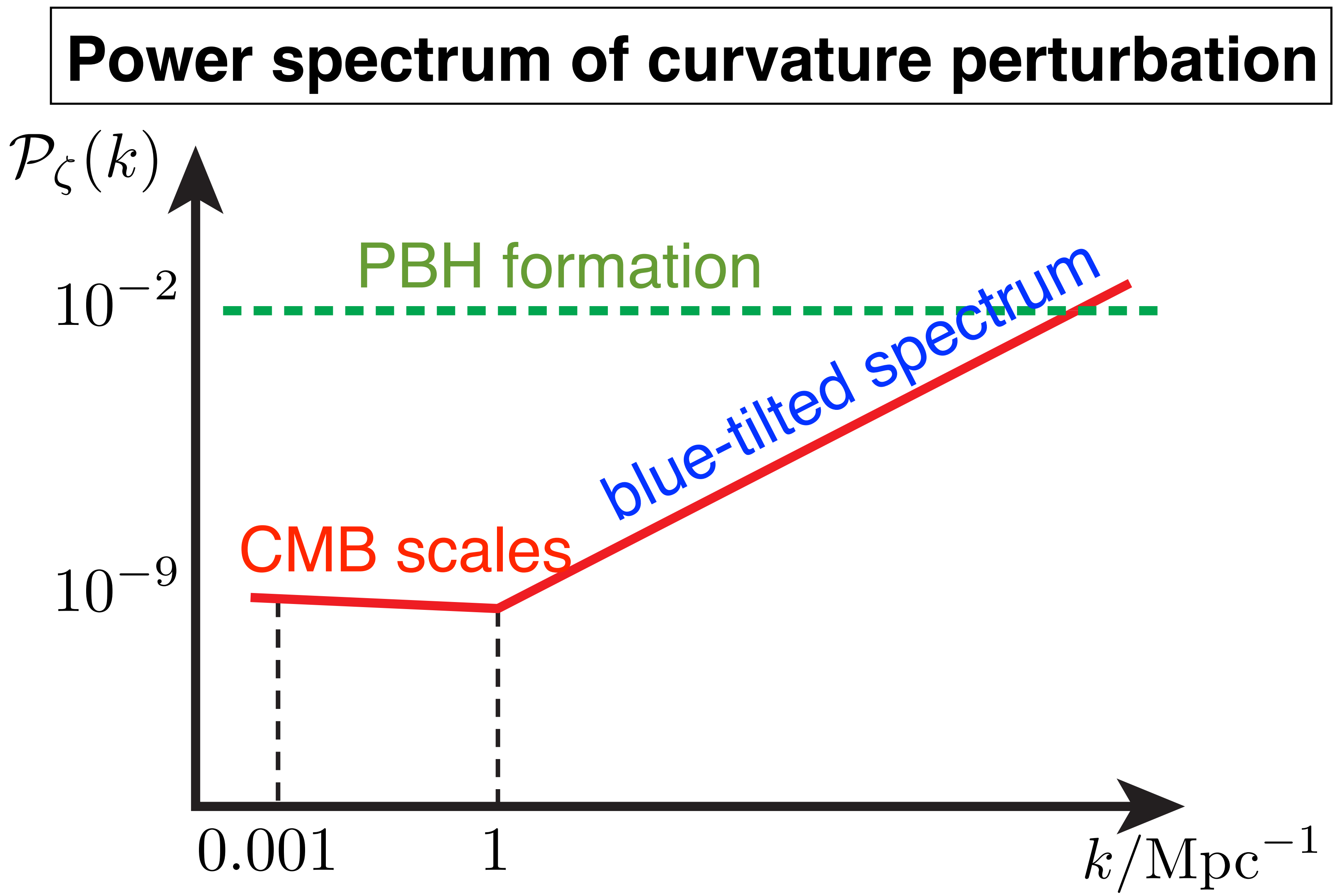




PBH formation



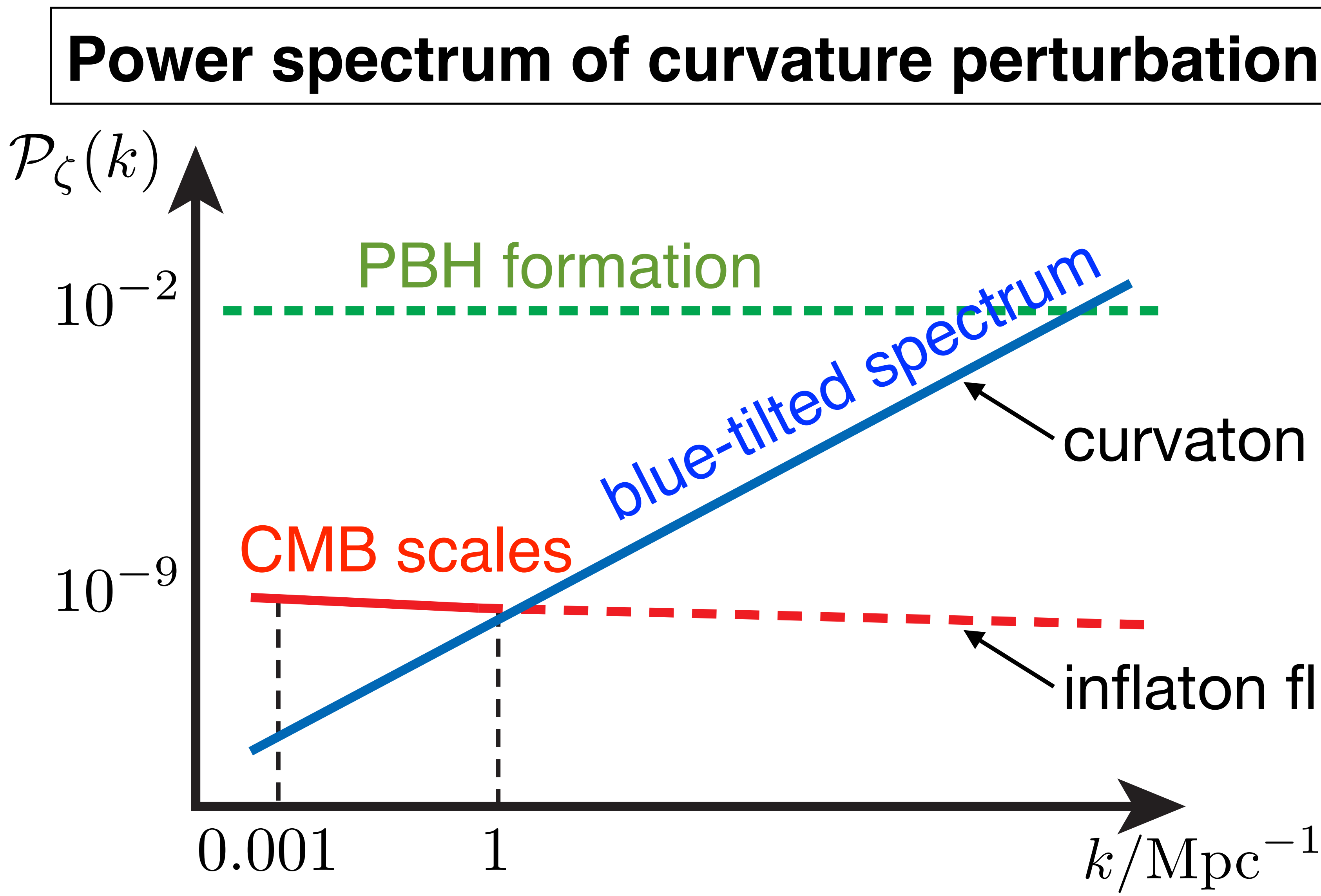
PBH formation



Single component fluctuation (inflaton)

running mass inflation, double inflation, …

PBH formation



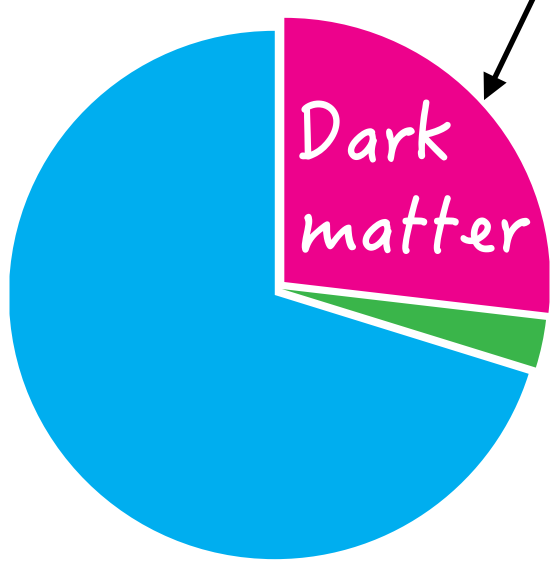
Multi-field fluctuation : inflaton + curvaton

Kawasaki, NK, Yanagida, 1207.2550

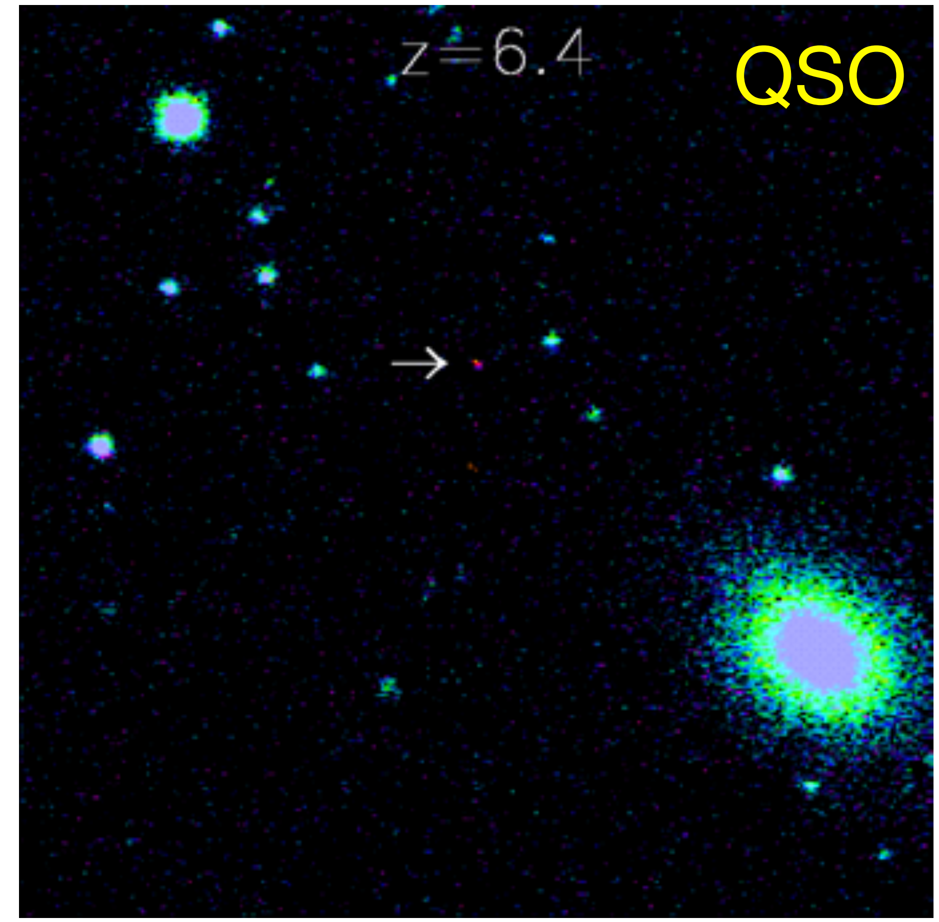
PBH as dark matter / seed of SMBH

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

(partially)



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

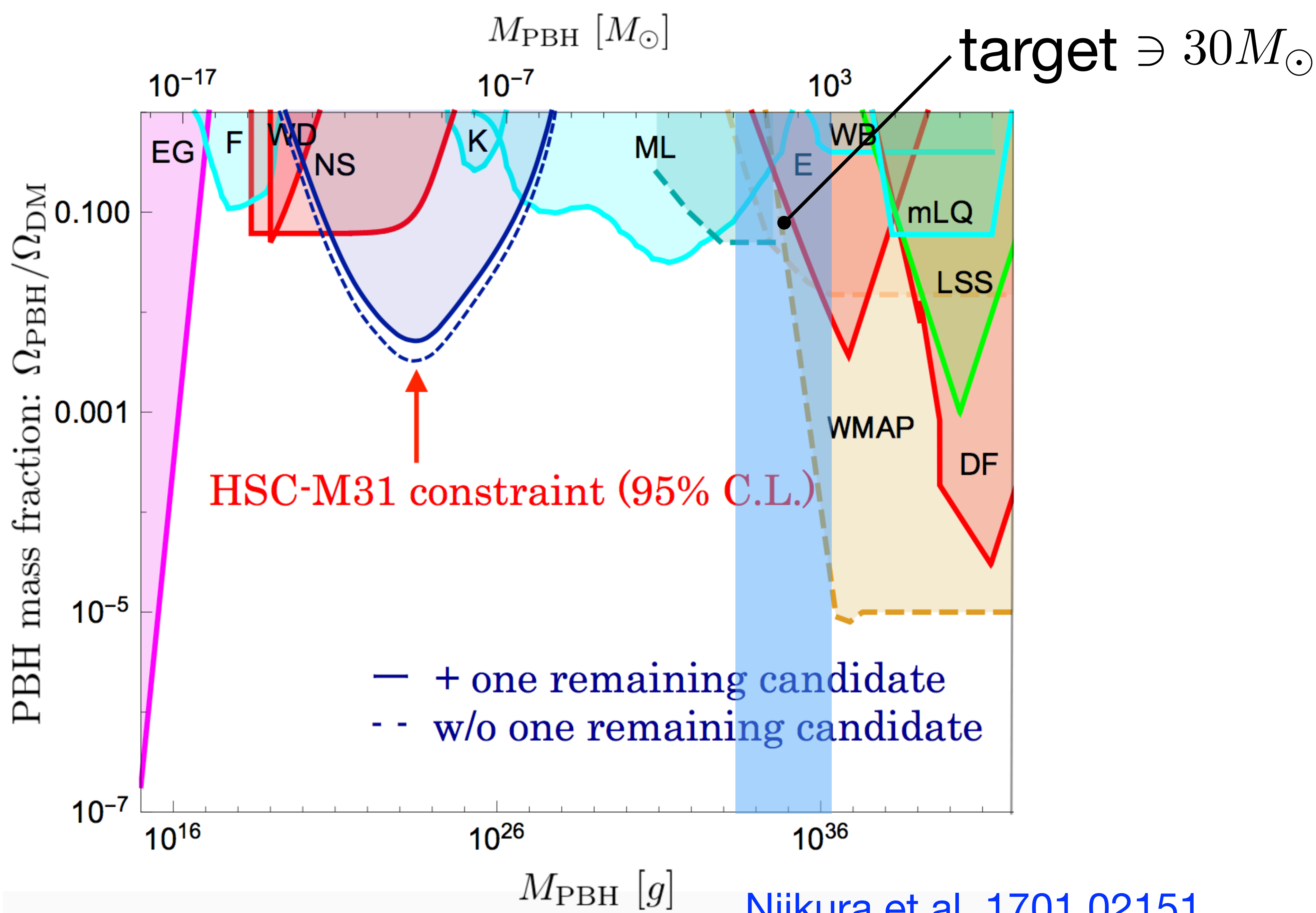


http://www.sdss3.org/

supermassive BH with $10^9 M_\odot$

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

Current constraint on PBH mass & abundance

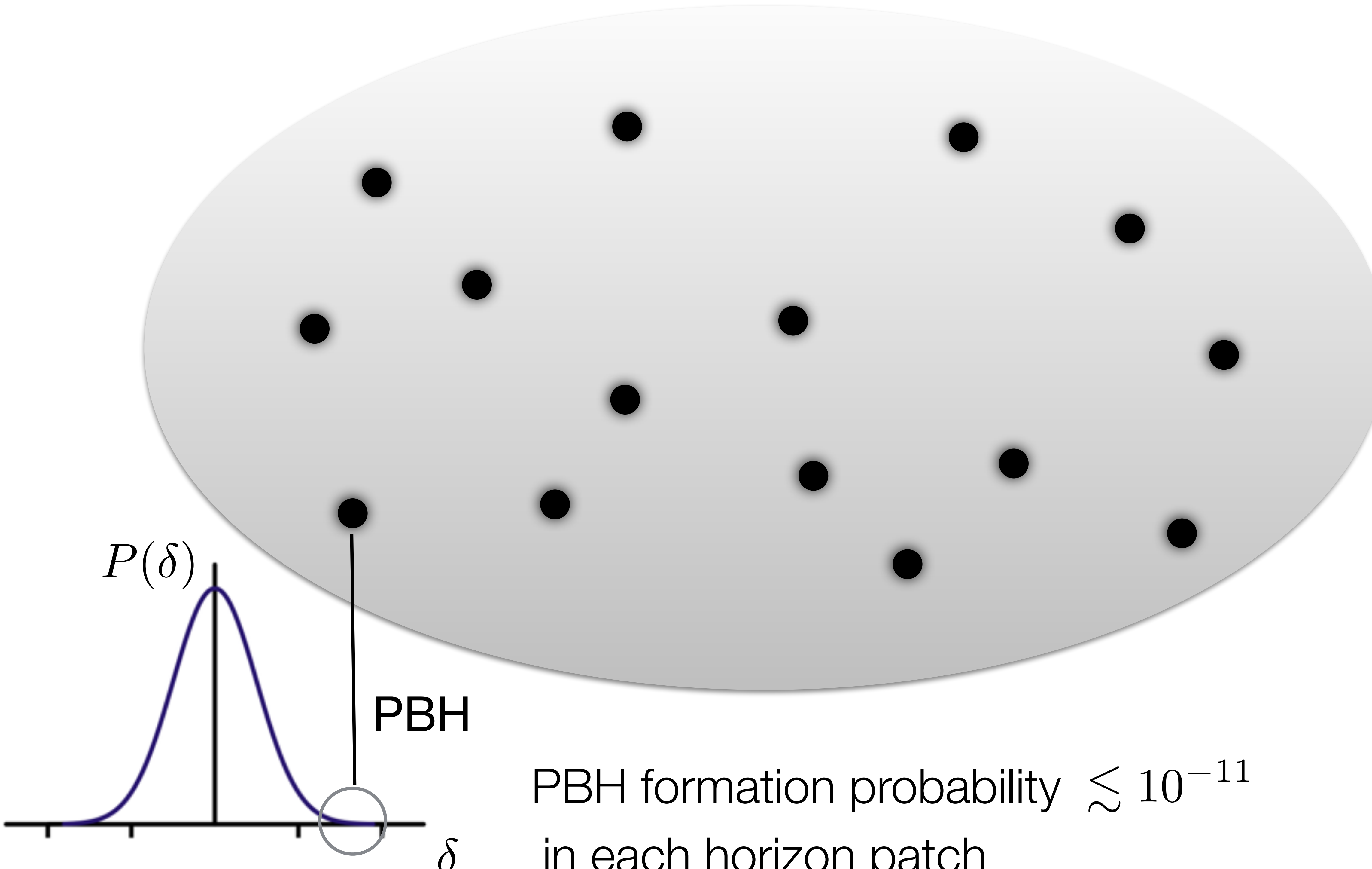


Niikura et al, 1701.02151

PBH number fluctuation and halo mass function

Poisson fluctuation of PBH number

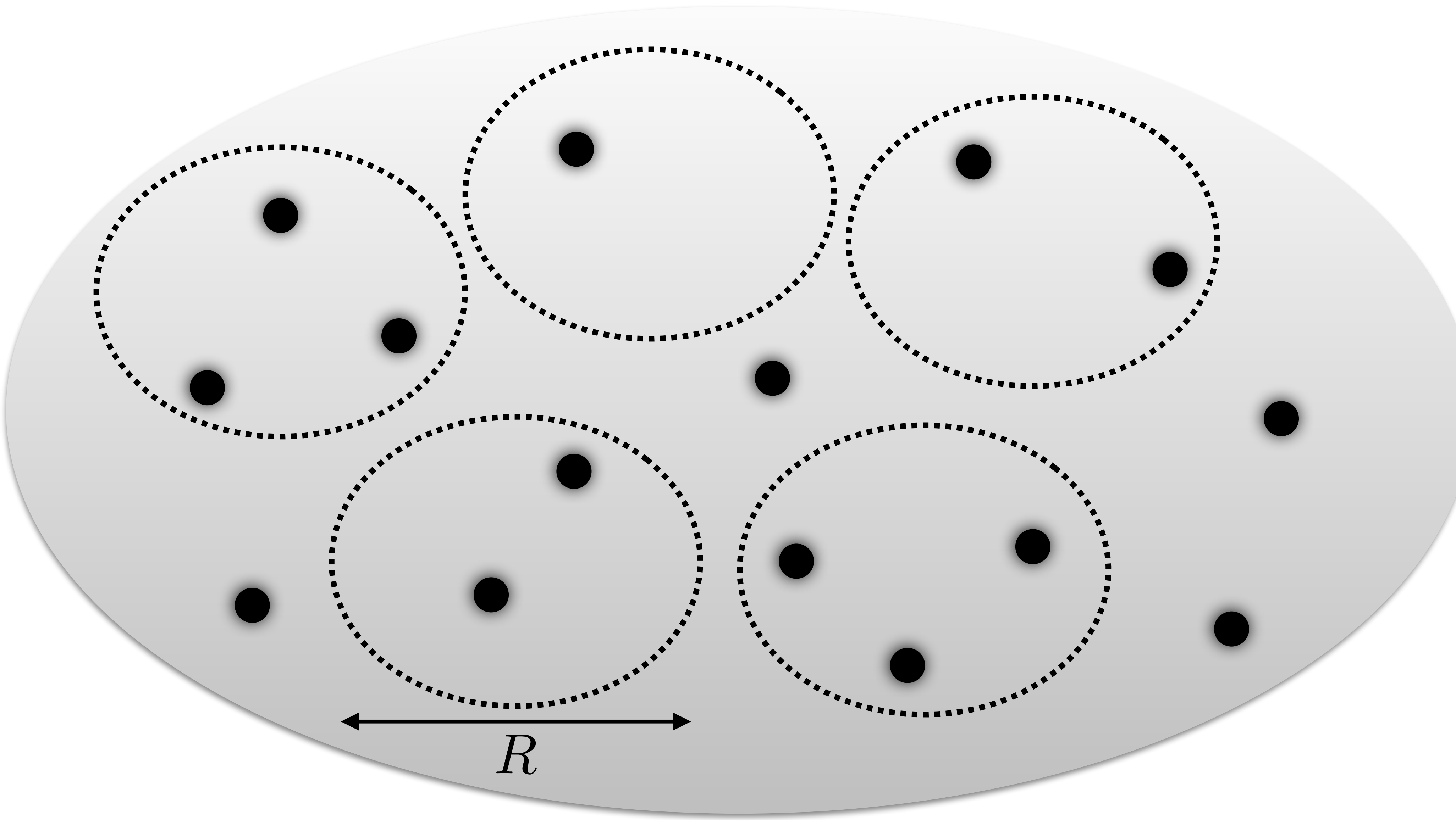
PBH is a rare object, randomly & sparsely forms in space



PBH formation probability $\lesssim 10^{-11}$
in each horizon patch

Poisson fluctuation of PBH number

PBH is a rare object, randomly & sparsely forms in space

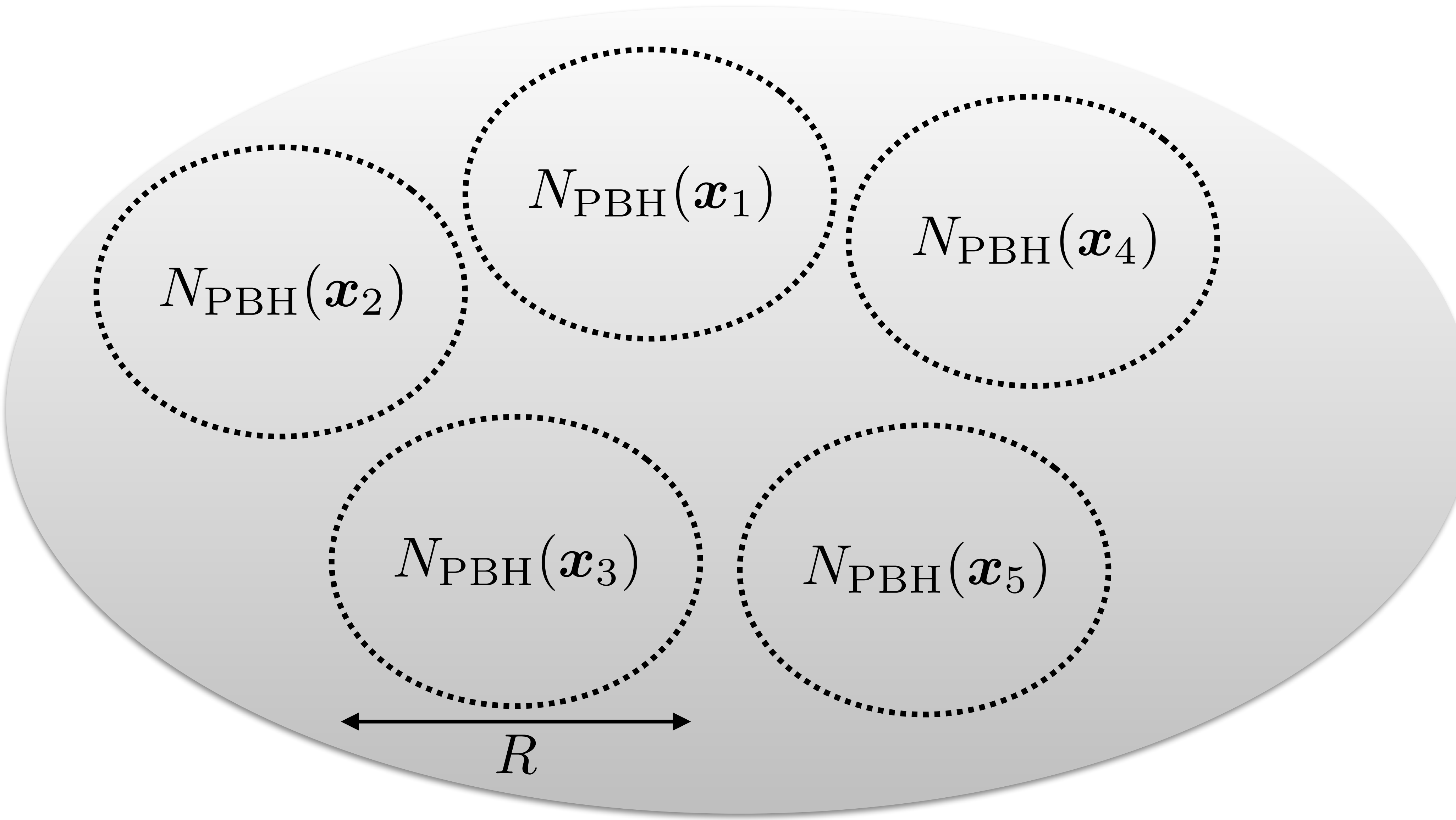


comoving scale much larger than the horizon scale at formation

—> each region can be one realization of statistical ensemble

Poisson fluctuation of PBH number

PBH is a rare object, randomly & sparsely forms in space



—> $N_{\rm PBH}$ follows the Poisson distribution function

Poisson fluctuation of PBH number

Poisson distribution function

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

$$\rho_{\rm PBH} = \bar{\rho}_{\rm PBH}(1+\delta_P)e^{-3\delta N} \quad \text{at PBH formation}$$

Poisson fluctuation

—> PBH density contrast : $\delta_{\rm PBH} = \delta_P + \frac{3}{4}\delta_r$

PBH fraction

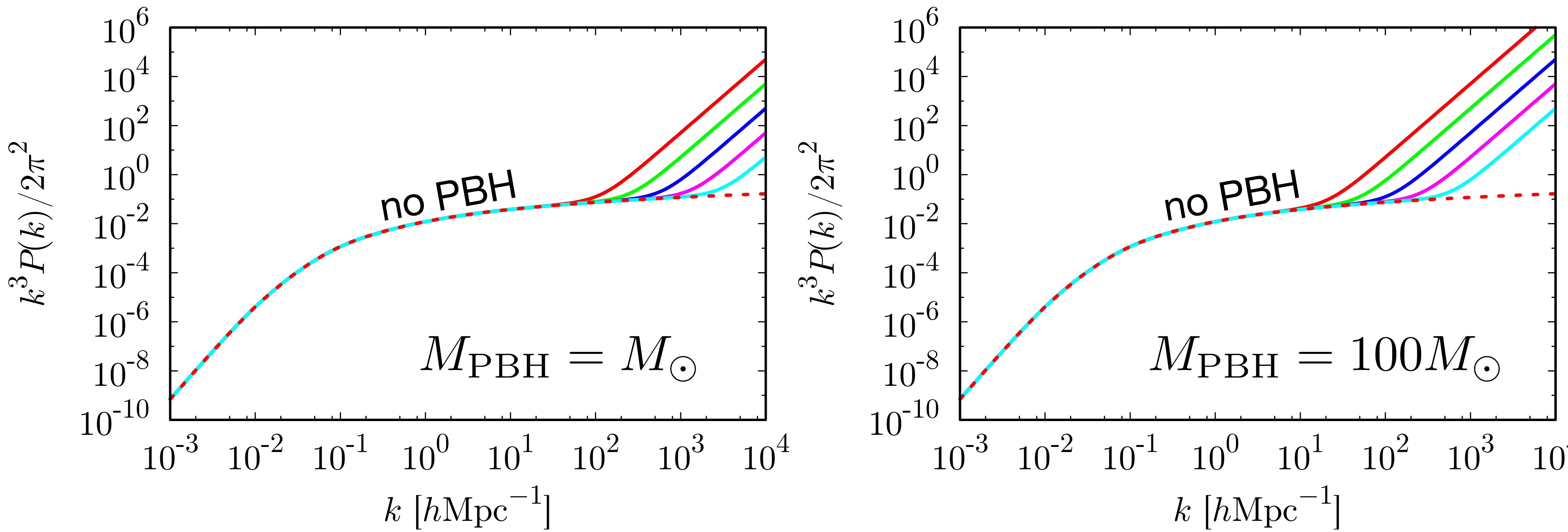
& CDM isocurvature perturbation : $S = \delta_{\rm DM} - \frac{3}{4}\delta_r = f_{\rm PBH}\delta_P$

Power spectrum of isocurvature perturbation : $P_{\rm iso}(k) = \frac{f_{\rm PBH}^2}{n_{\rm PBH}}$

PBH comoving number density

Linear matter power spectrum

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

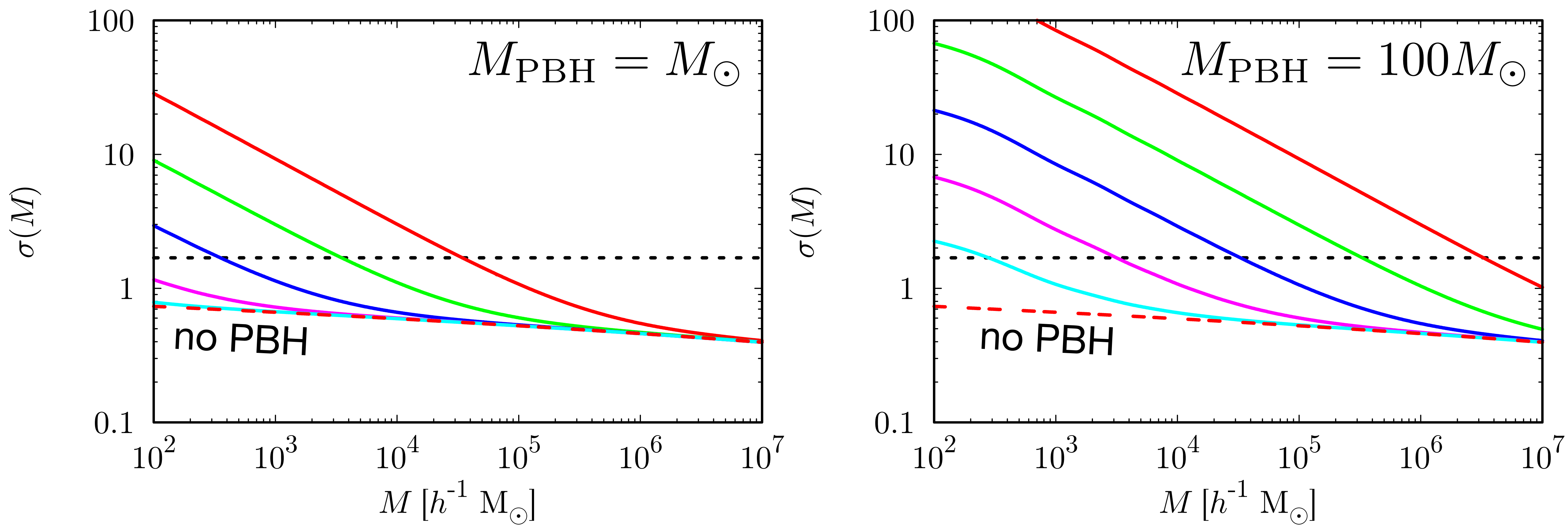


$$z = 20,\ \ f_{\rm PBH} = 10^{-1}, 10^{-2}, 10^{-3}, 10^{-4}, 10^{-5} \quad \text{from top to bottom}$$

Smoothed variance

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

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

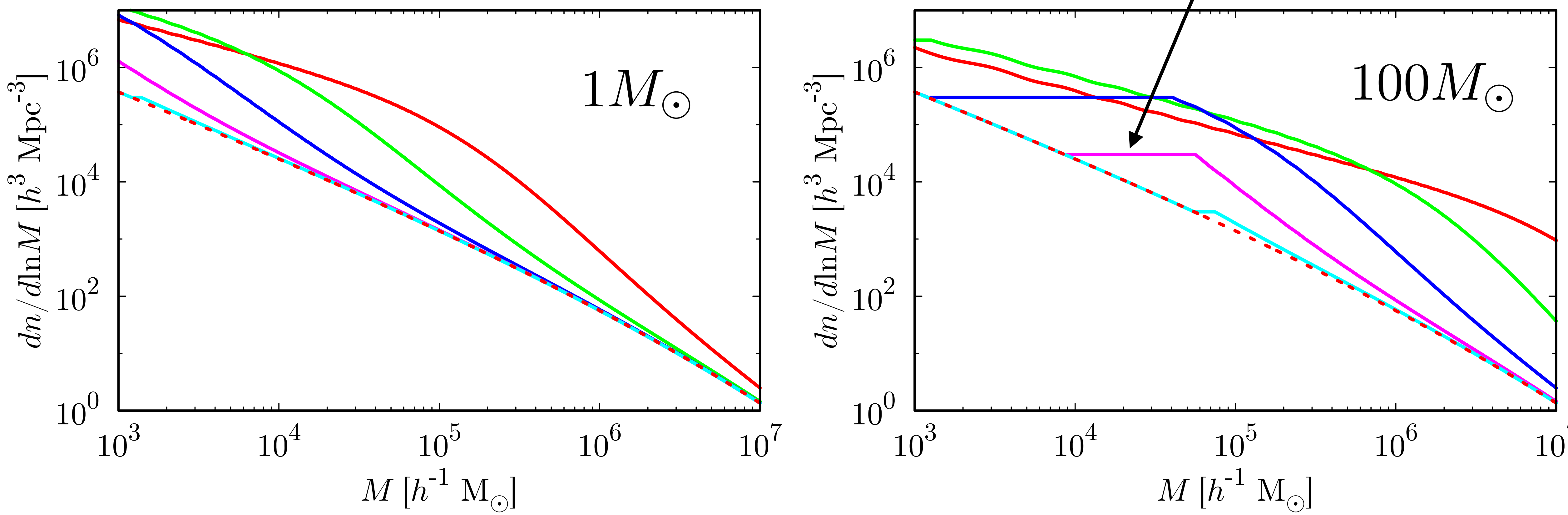


$$z = 20, \;\; f_{\rm PBH} = 10^{-1}, 10^{-2}, 10^{-3}, 10^{-4}, 10^{-5} \;\; \text{from top to bottom}$$

Halo mass function

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

$n_{\rm halo} \leq n_{\rm PBH}$

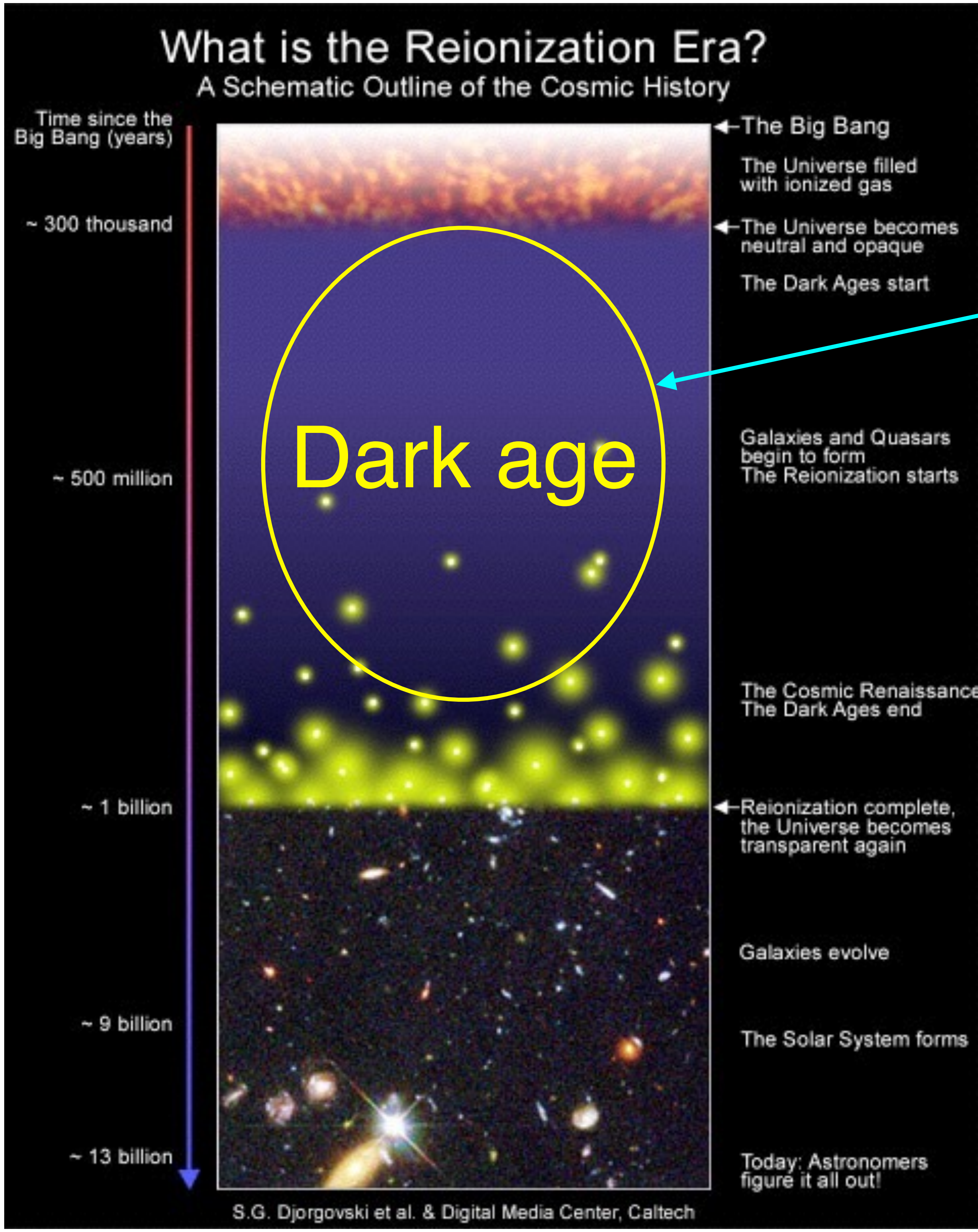


Gong, NK,1704.04132

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

21cm fluctuations from minihaloes

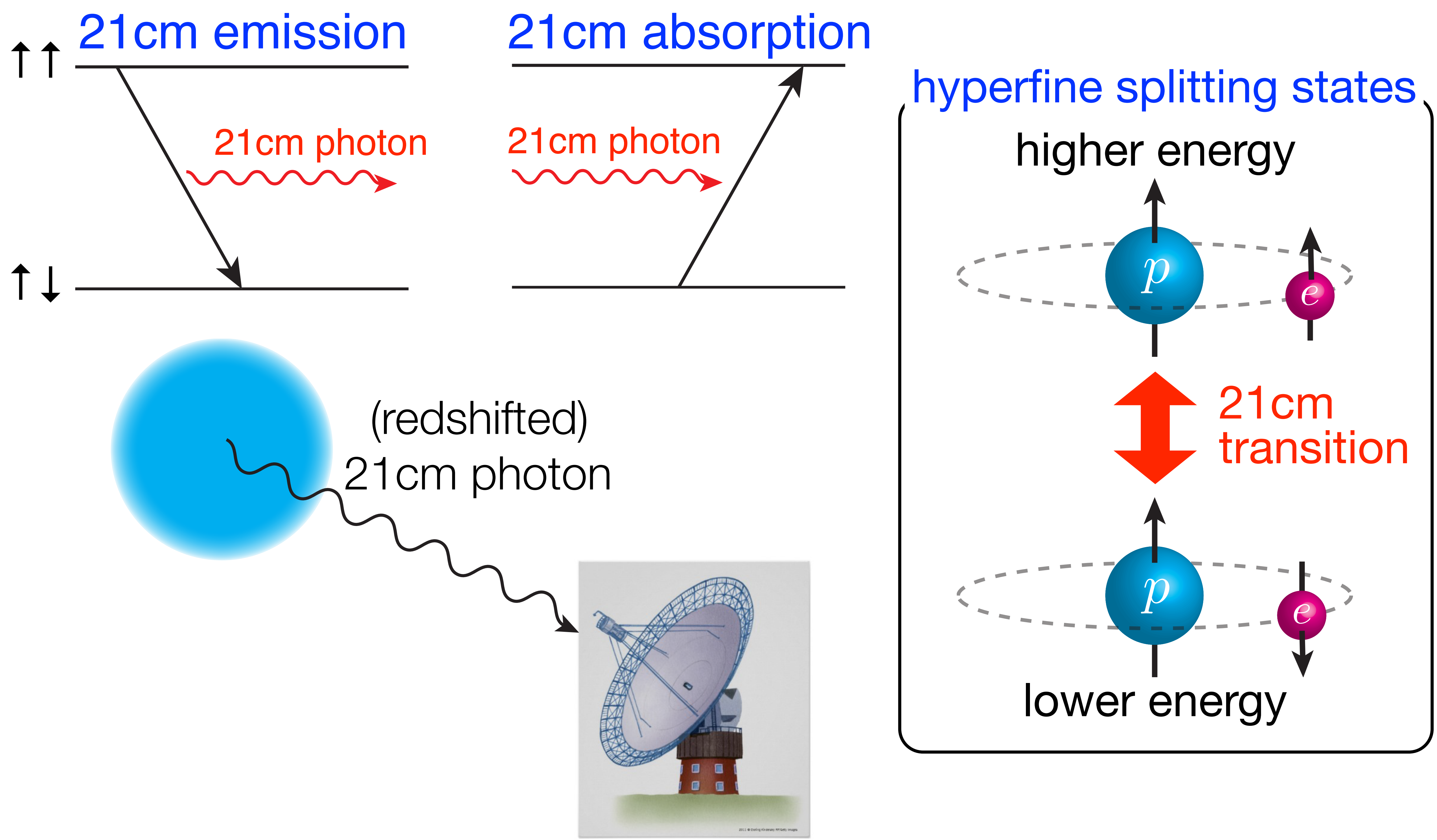
21cm Cosmology –probe of the DARK AGE–



- 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

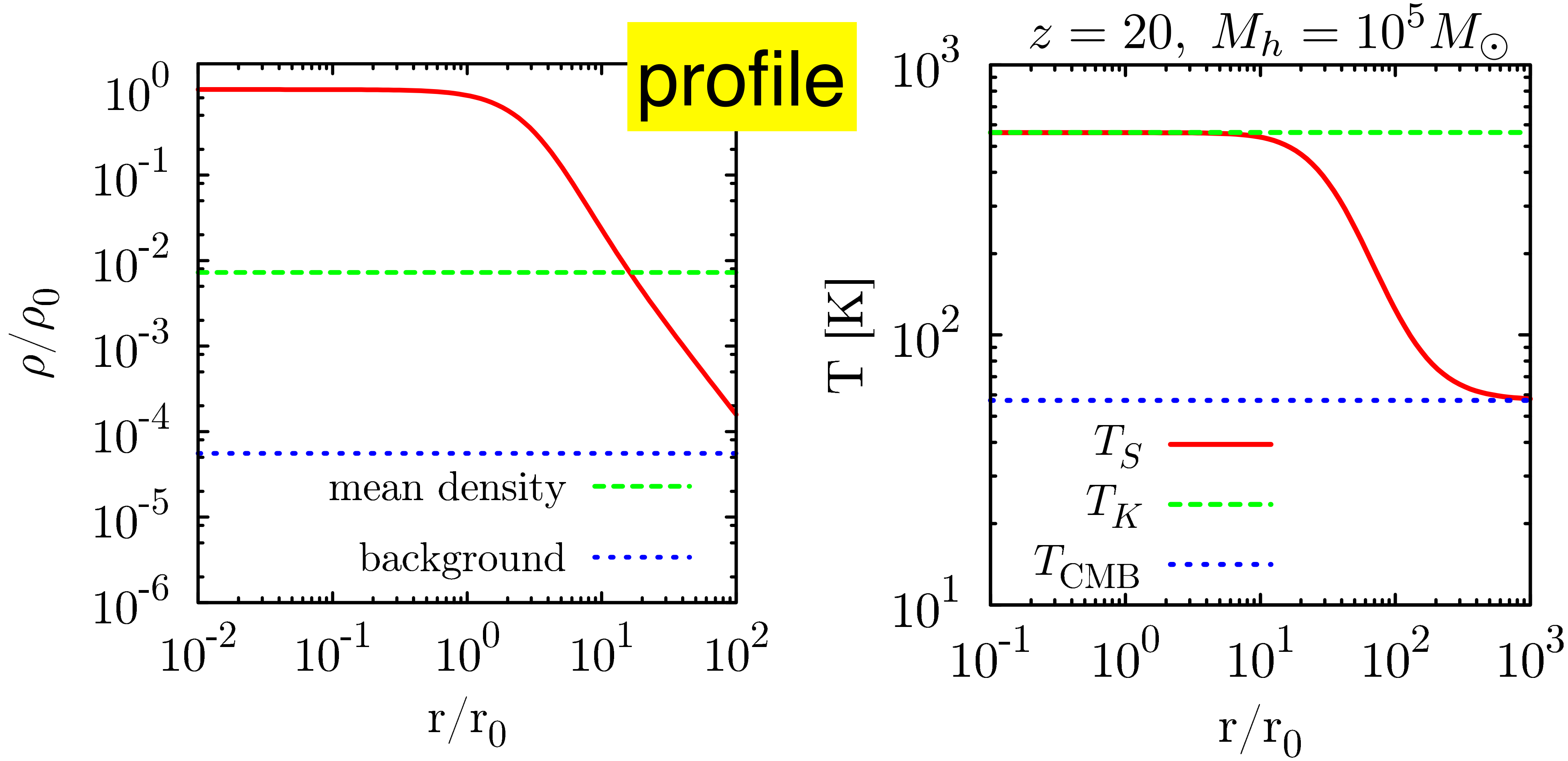


Density & temperature profile of minihalo (TIS model)

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

energy splitting: $T_* = 0.068\ \mathrm{K}$

21cm differential brightness temperature



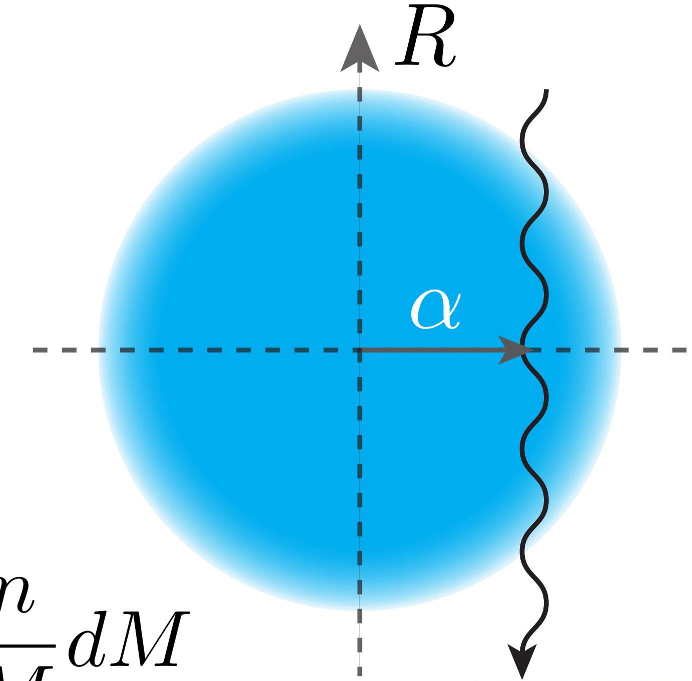
minihalo contribution ➢ $T_S \gg T_{\rm CMB}$ ➢ emission signal

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

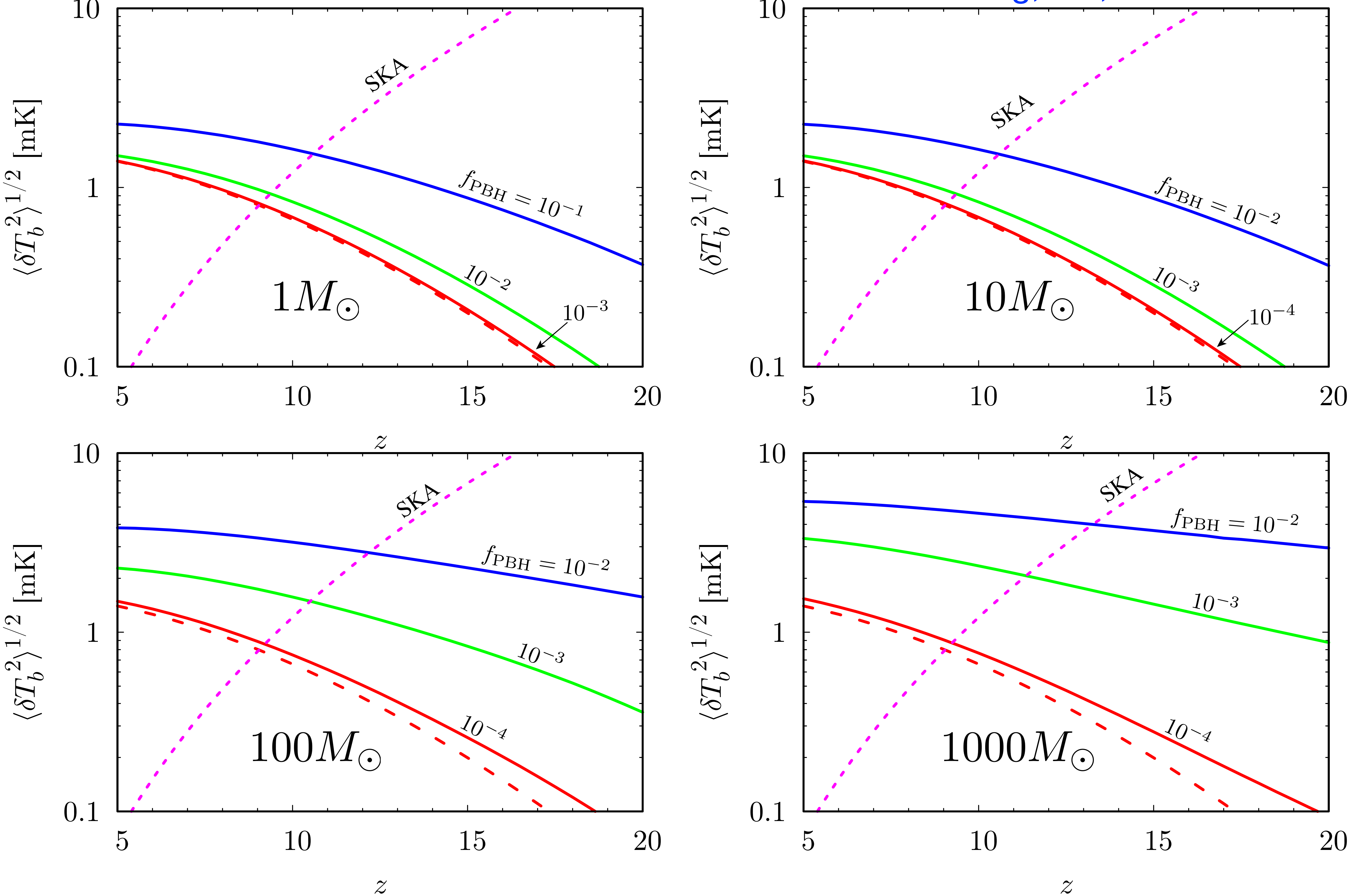
$A_{\rm tot} = 10^5\ {\rm m}^2$, $\Delta\theta_{\rm beam} = 9$ arcmin, $\Delta\nu_{\rm band} = 1$ MHz and $t_{\rm int} = 1000$ h

SQUARE KILOMETRE ARRAY

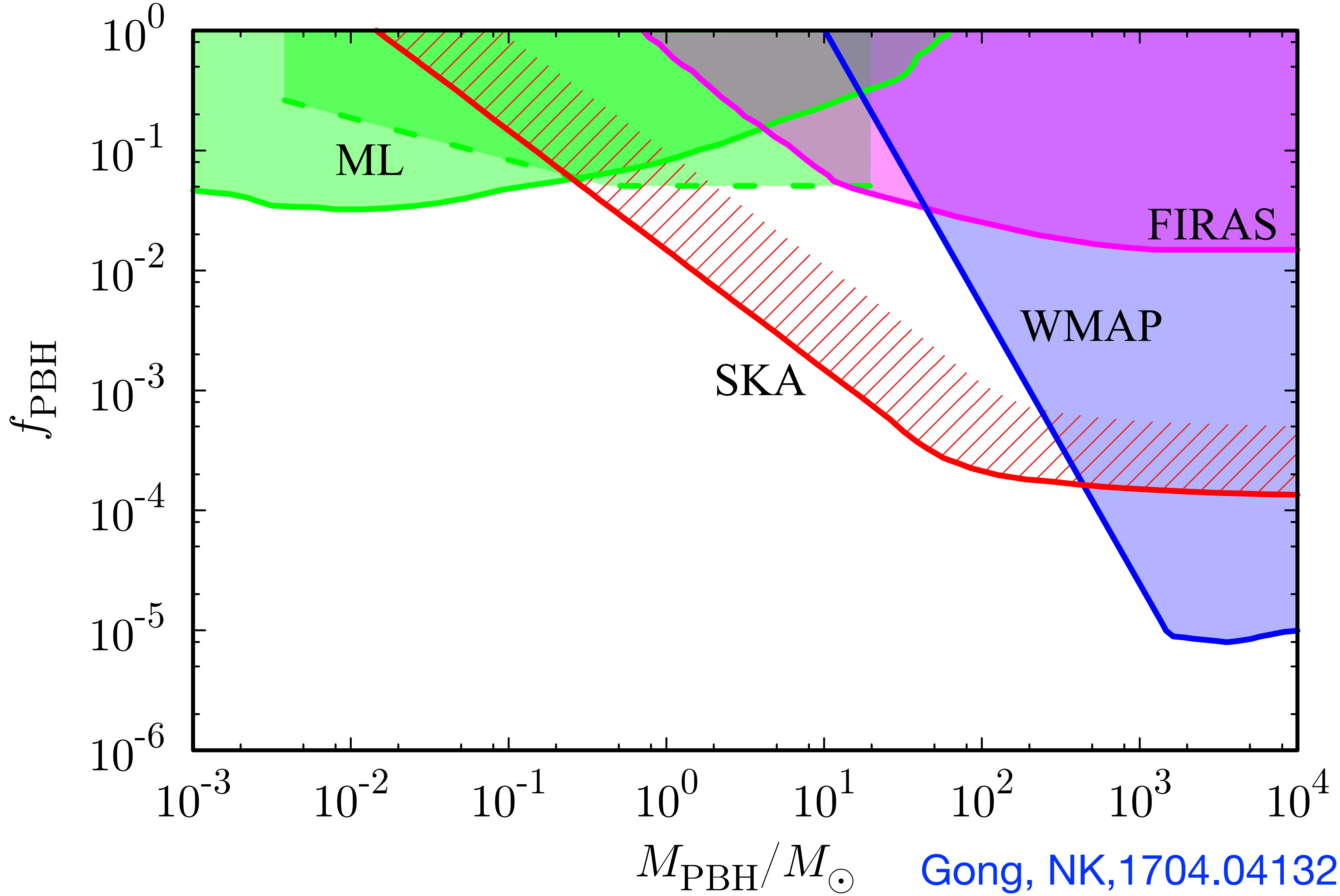
http://www.skatelescope.org

Fluctuation of brightness temperature

Gong, NK,1704.04132

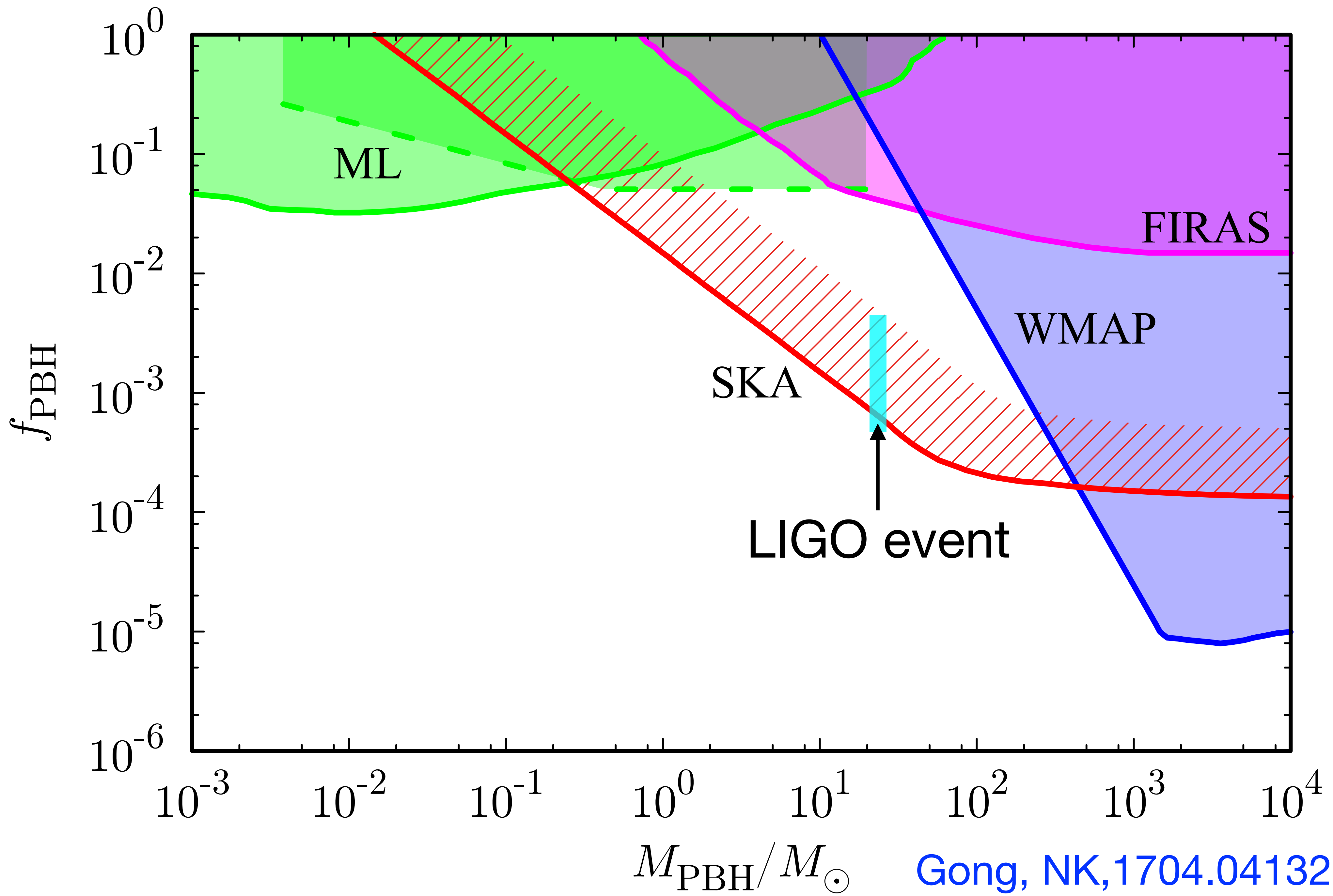


PBH constraint from SKA



Gong, NK,1704.04132

PBH constraint from SKA



Gong, NK,1704.04132

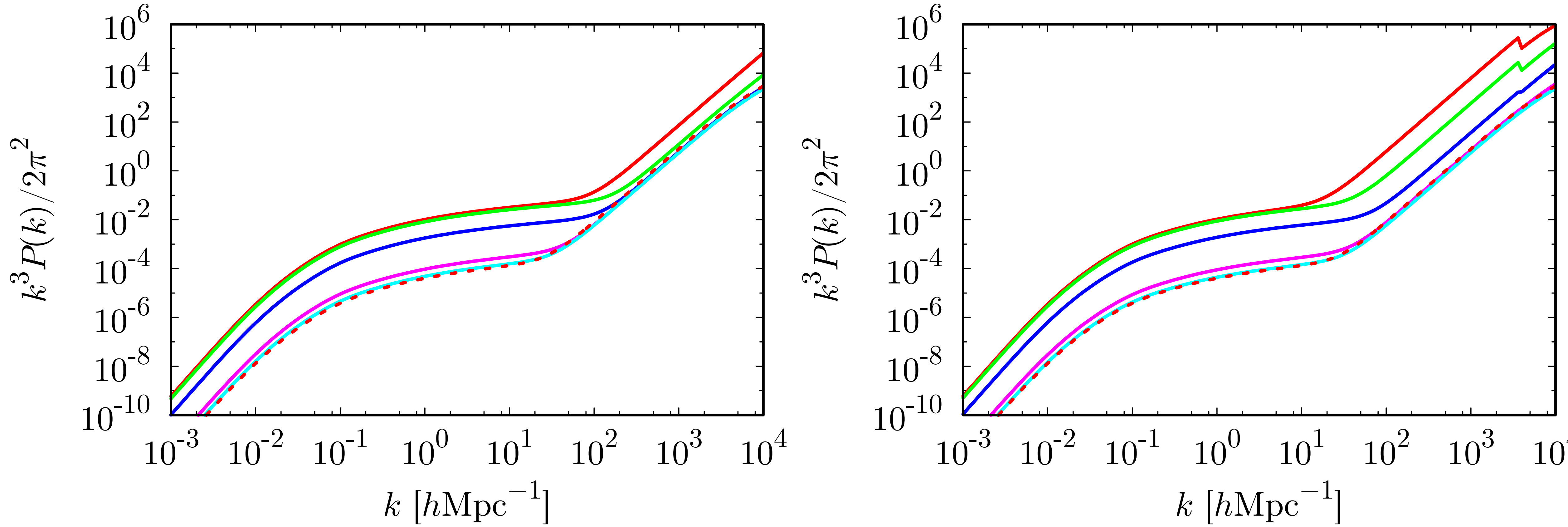
Summary

- PBH number fluctuates following the Poisson distribution and
  it contributes to the matter power spectrum as an isocurvature mode,
  which is dominant on small scales

- The Poisson fluctuation can change the halo mass function
  The number of small haloes can be significantly enhanced

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

Halo power spectrum



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