Distribution of primordial black holes and small-scale constraints

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Based on JG and N. Kitajima, to appear soon

Outline

What are primordial black holes (PBHs)?

BH formed in the early universe (Zel'dovich and Novikov 1967; Hawking 1971; Carr 1975...)

- A horizon-sized region with $\delta \gtrsim \delta_{\rm threshold}$
- Vast mass range: $m_{\rm Pl} \lesssim M_{\rm PBH} \lesssim 10^5 M_\odot$ or even larger
- Inflation, peculiar non-thermal histories, phase transitions...
- Pressureless matter component

Number of PBHs follows Poisson distribution:

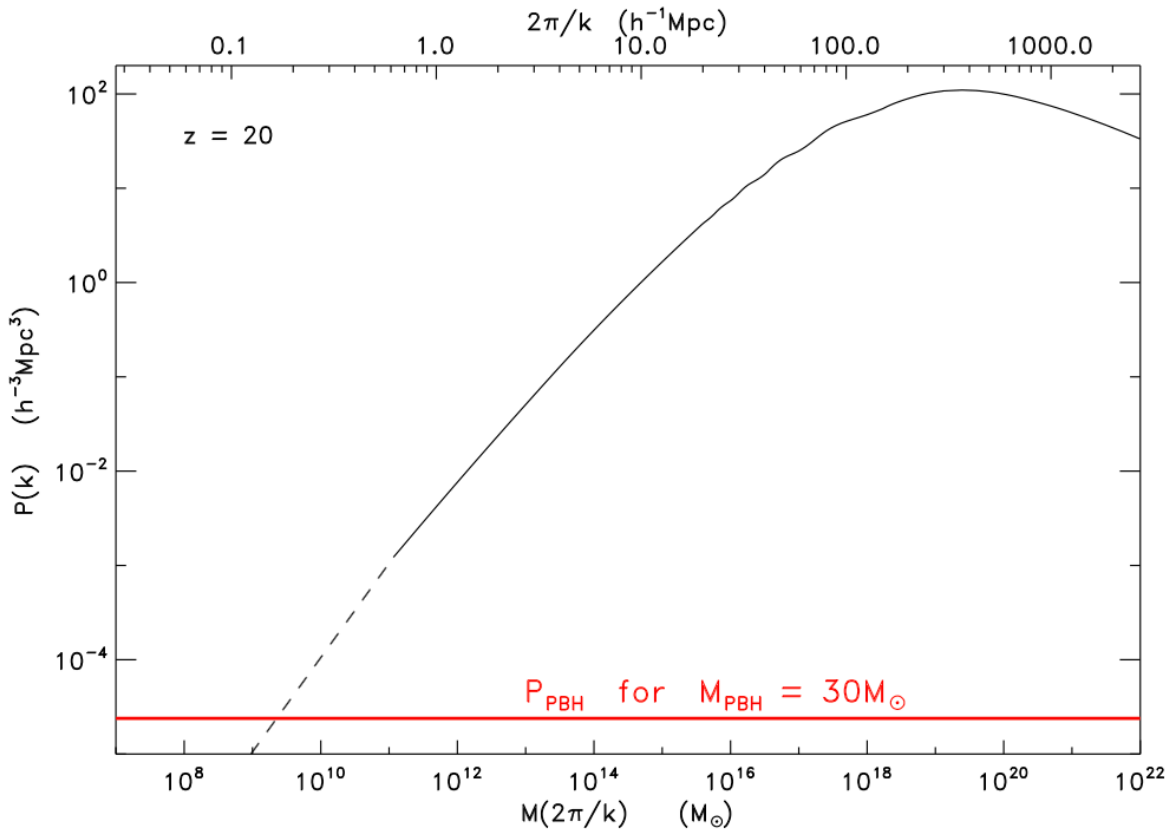
$$\mathbb{P}(N_{\rm PBH}) = \frac{\lambda^{N_{\rm PBH}} e^{-\lambda}}{N_{\rm PBH}!} \quad \text{with} \quad \lambda = \langle N_{\rm PBH} \rangle = \left\langle \delta N^2_{\rm PBH} \right\rangle$$

Formation of a PBH is a rare, discrete event

What is the contribution of PBHs to structure formation?

PBHs add scale-inv isocurvature perturbation: $P_{\rm PBH}(k) = 1/n_{\rm PBH}$

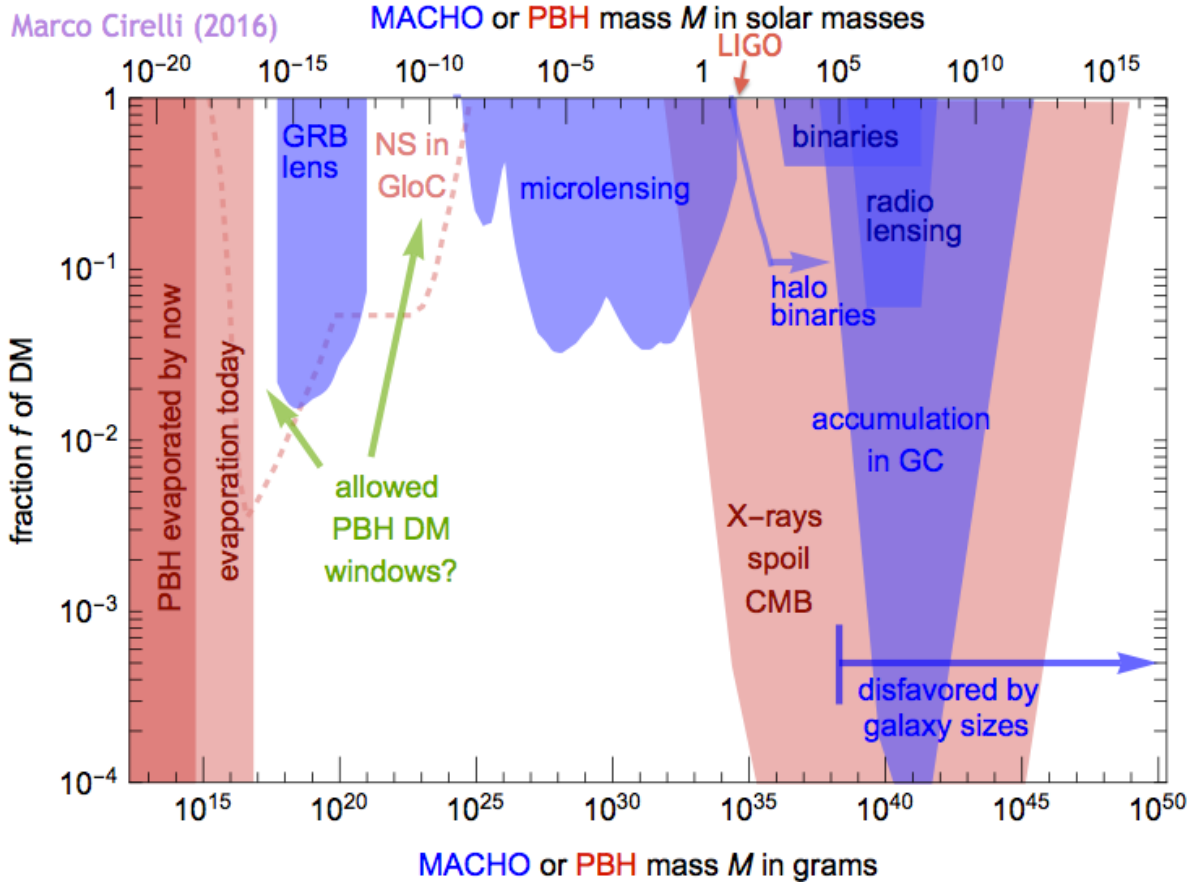
(Afshordi, McDonald and Spergel 2003; Kashlinsky 2016)



CIB, Ly-α forest, 21cm line...

Long-lived PBHs are also responsible for LIGO events?

Long-lived PBHs (with $M_{\rm PBH} \gtrsim 10^{15}{\rm g} \sim 10^{-18} M_\odot$) can survive today



LIGO events may mean PBHs with merging rate 9 - 240 $\mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$

(Bird et al. 2016; Clesse and García-Bellido 2016; Sasaki et al. 2016...)

Where are PBHs from?

Is PBH formation a random event, independent from each other?

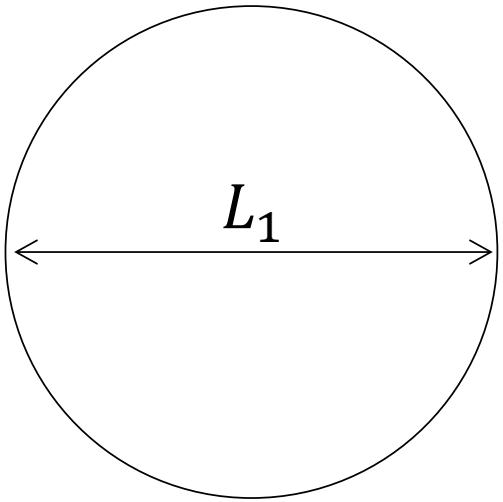
- From e.g. the collapse of cosmic string loops, yes
- From inflationary fluctuations, doubtful
- Statistical nature of pert seeding PBHs matters

If PBHs are from primordial perturbation with spectrum of the form

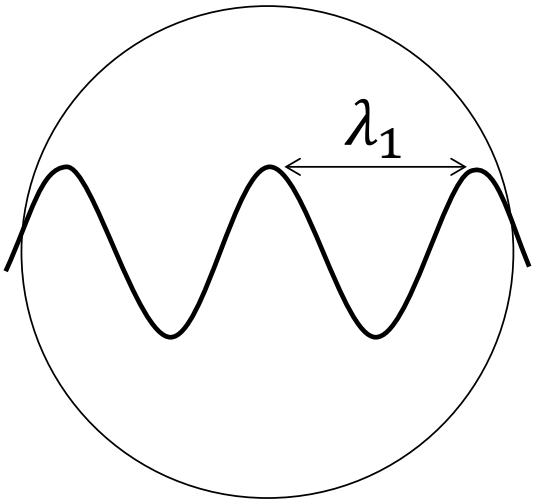
$$P_\delta(k) \sim k^{n_s-1}$$

what is the PBH distribution and observational consequences?

How to find PBHs



How to find PBHs



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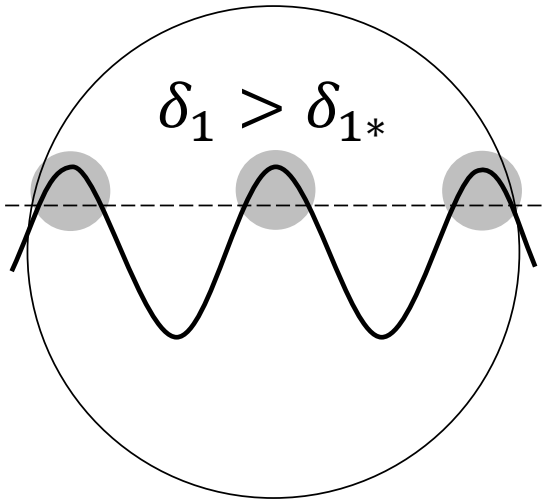

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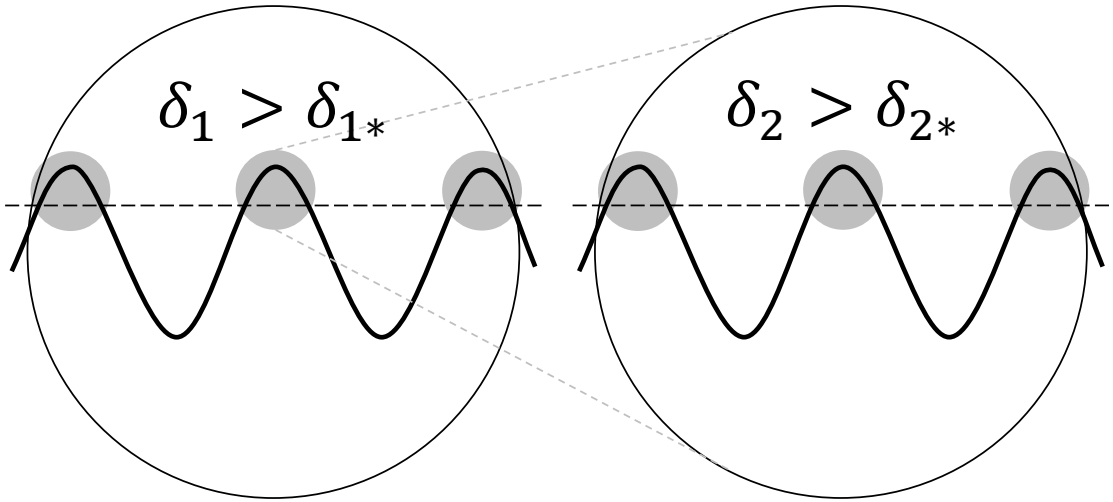

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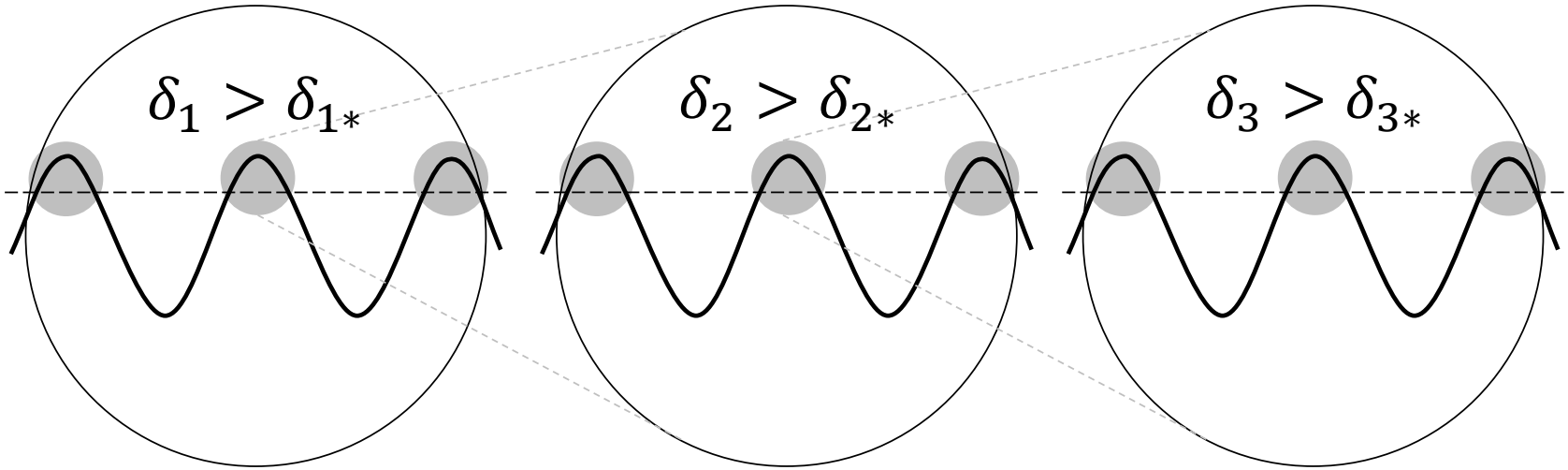
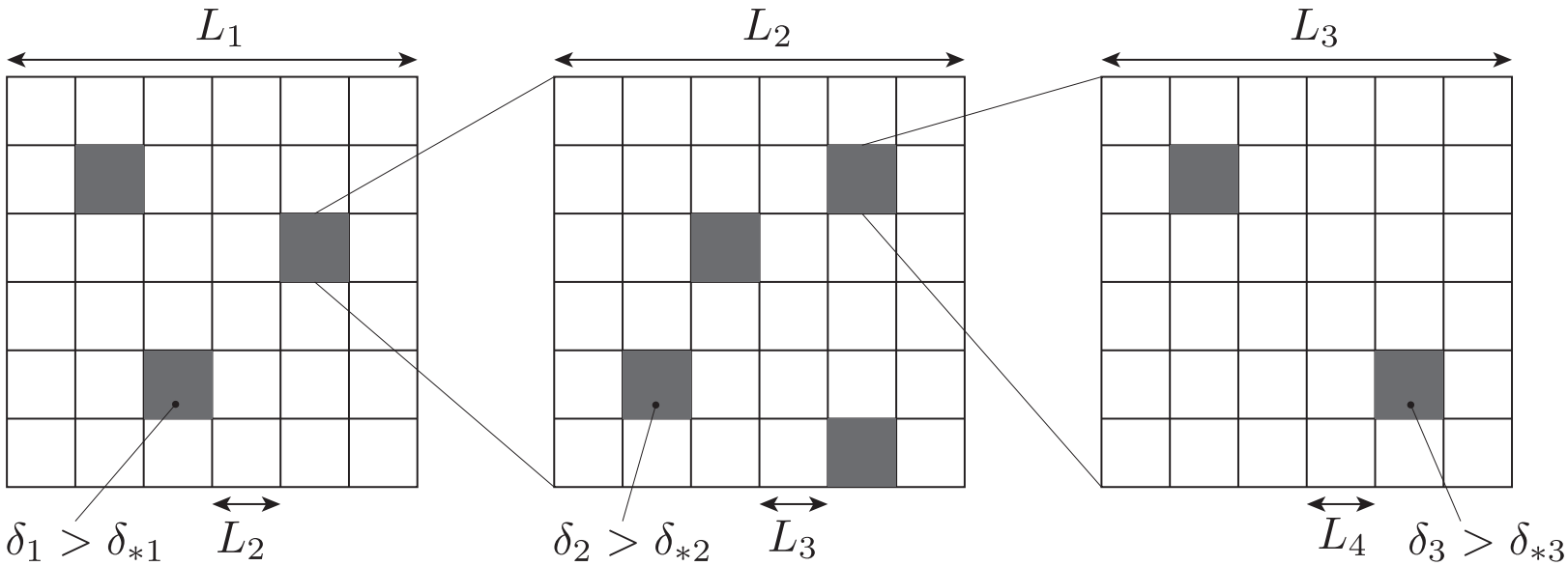


Accumulating peaks of longer wavelength modes onto shorter ones

(c.f. using curvature perturbation criteria for PBH formation needs caution, Young, Byrnes and Sasaki 2014)

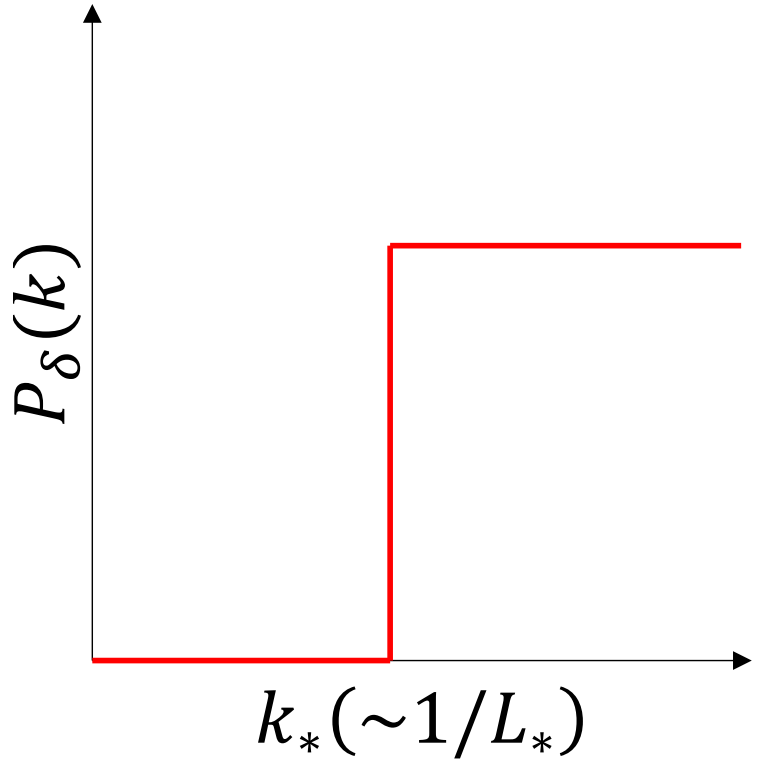
How to find PBHs



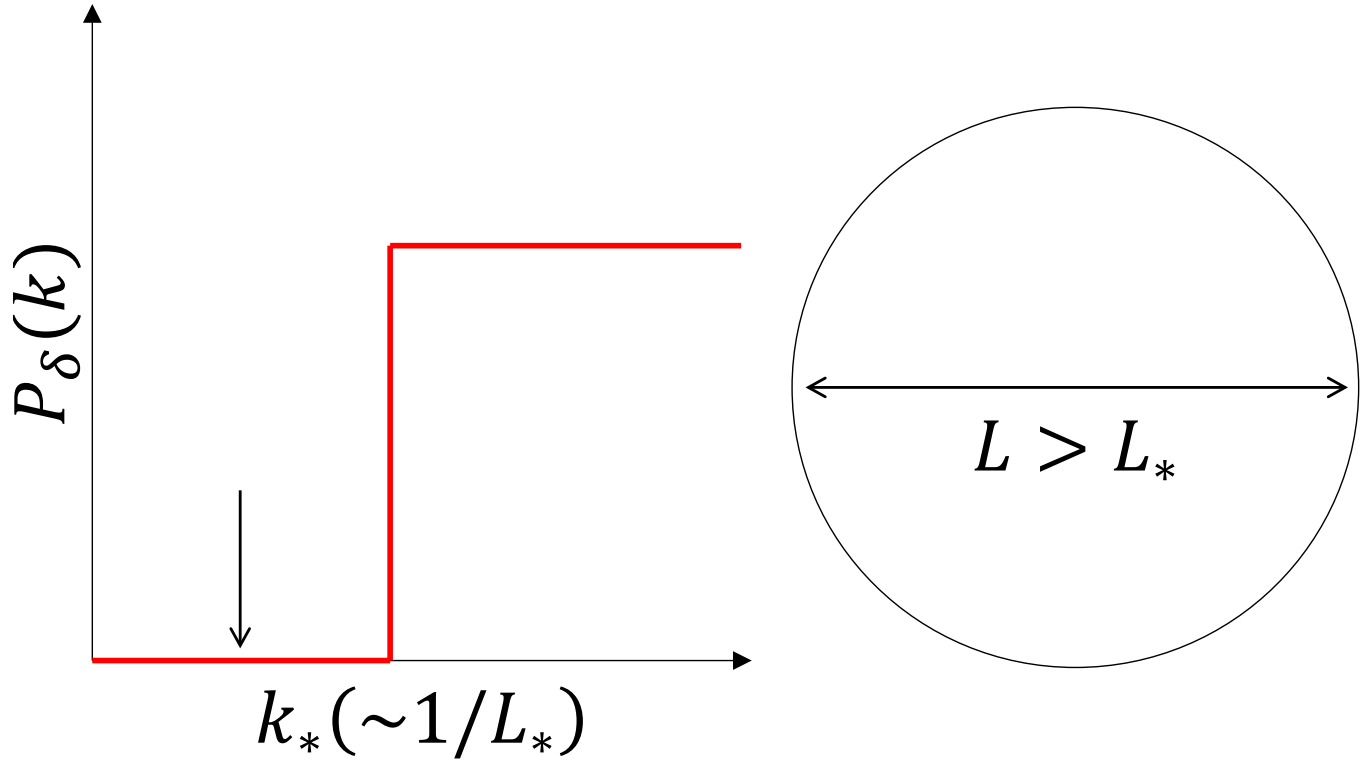
$$N_{\rm PBH} = N_{\delta_1>\delta_{*1}} \times N_{\delta_2>\delta_{*2}} \times \cdots \times N_{\delta_n>\delta_{*n}}$$

Product of random vars: **Log-normal distribution**

Dependence on n_s

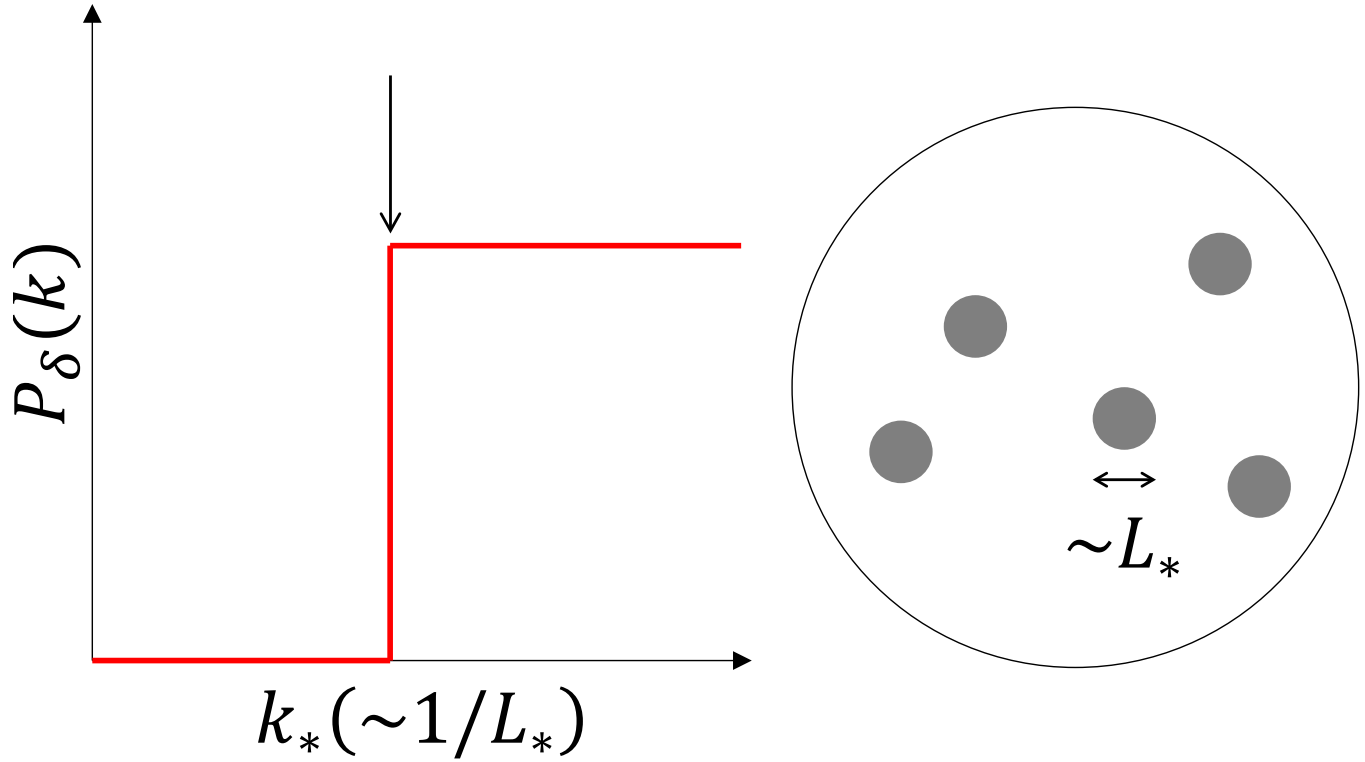


Dependence on n_s



Until L_* there is nothing,

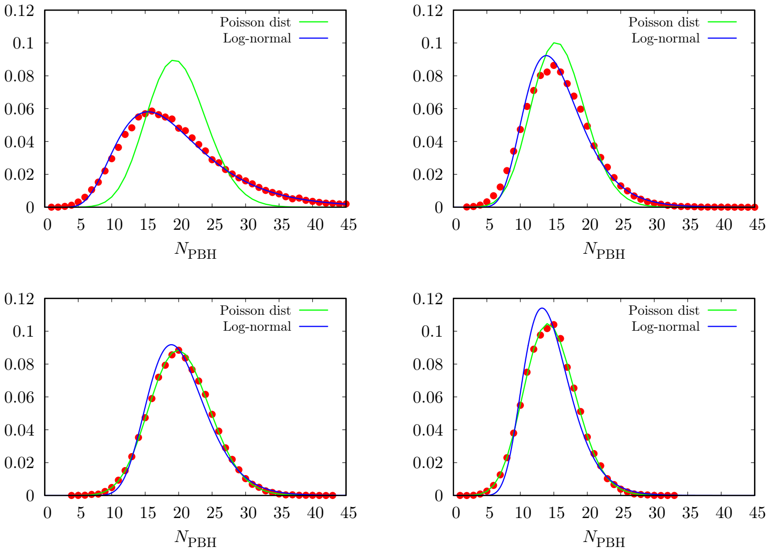
Dependence on n_s



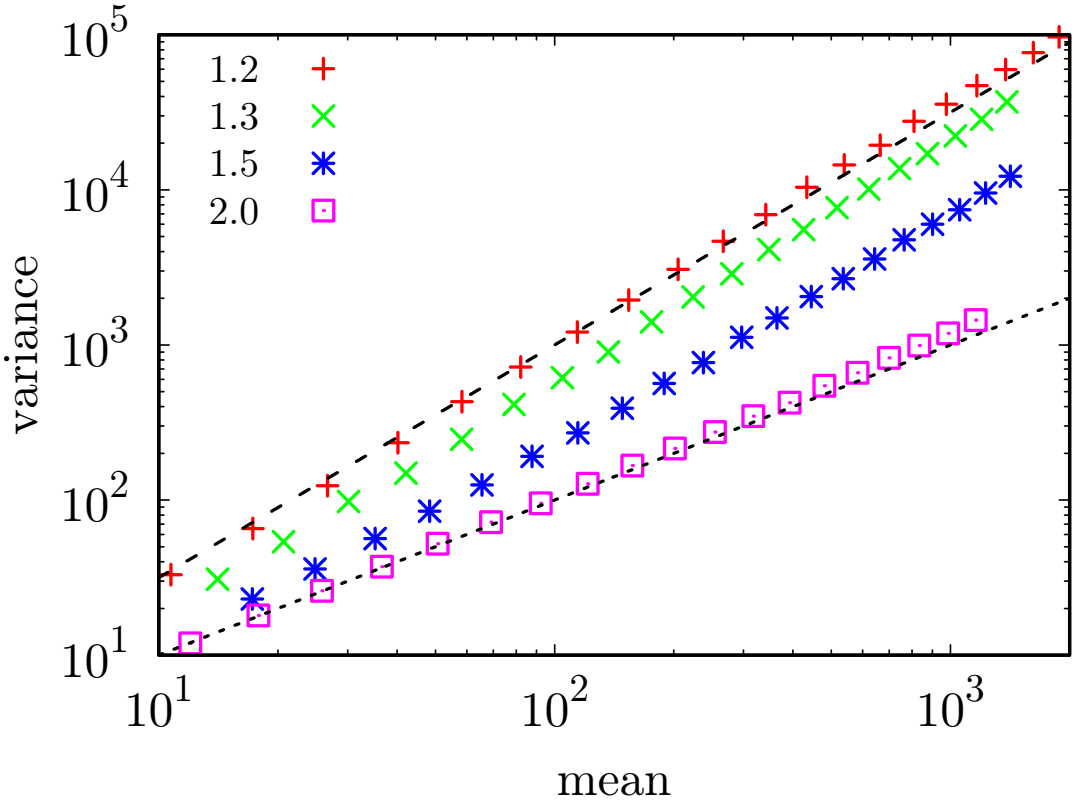
Until L_* there is nothing, only after then PBHs appear randomly

Poisson distribution

Distribution of PBHs



Spectral index and PBH distribution



Simple scaling relation between var and mean

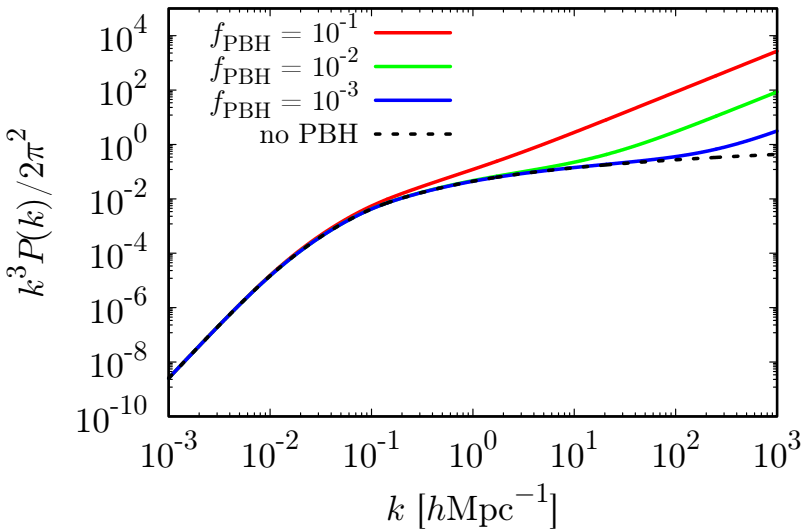
$$\mathrm{Var}[N_{\mathrm{PBH}}] \propto \begin{cases} \mathrm{Exp}[N_{\mathrm{PBH}}]^{3/2} & \text{for log-normal dist} \\ \mathrm{Exp}[N_{\mathrm{PBH}}] & \text{for Poisson dist} \end{cases}$$

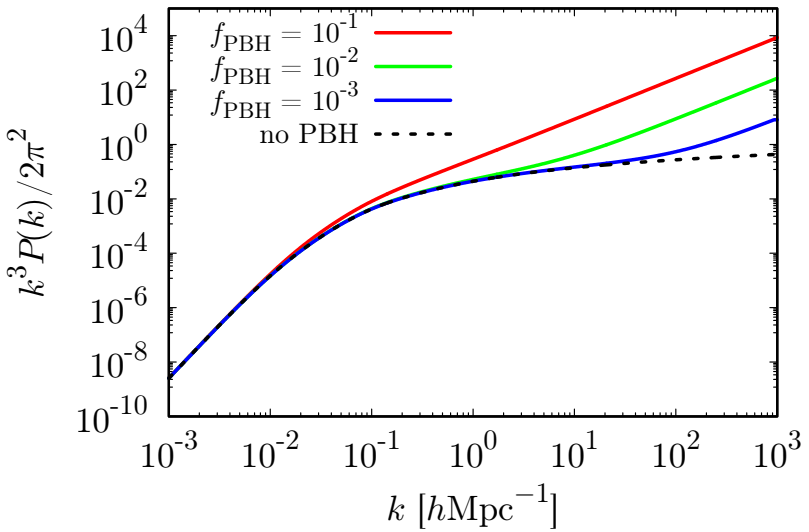
Matter power spectrum

For $k > k_{\rm eq}$, PBHs contribute to additional isocurvature pert:

$$P(k,z) = P_{\rm iso}(k)\,T^2_{\rm iso}(k)\,D^2(z)$$

$$= 8.6\times10^{-5}{\rm Mpc}^3\left(\frac{k}{\rm Mpc}\right)^{-3/2} f^{3/2}_{\rm PBH}\left(\frac{M_{\rm PBH}}{M_\odot}\right)^{1/2} T^2_{\rm iso}(k)\,D^2(z)$$

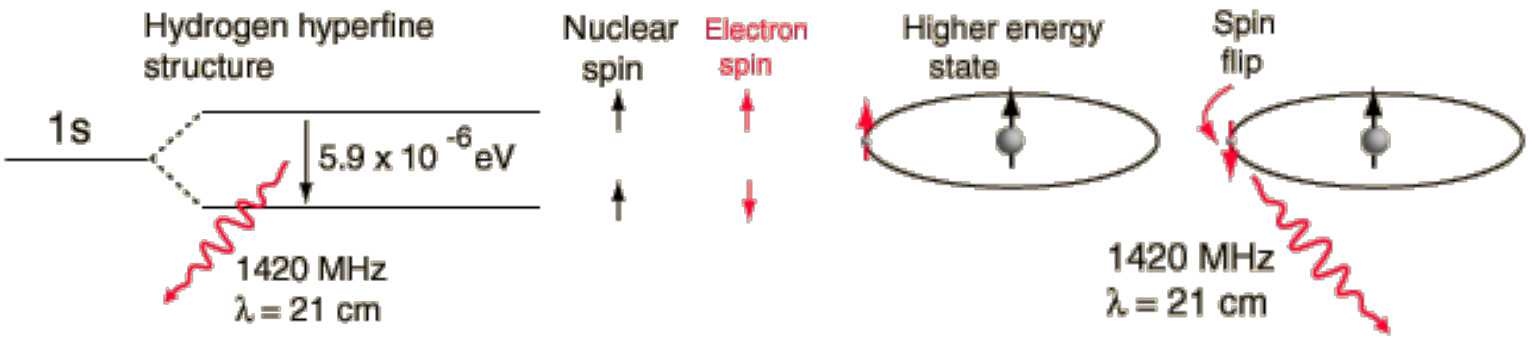




Small-scale power is enhanced, leading to larger number of haloes

Hydrogen 21cm line

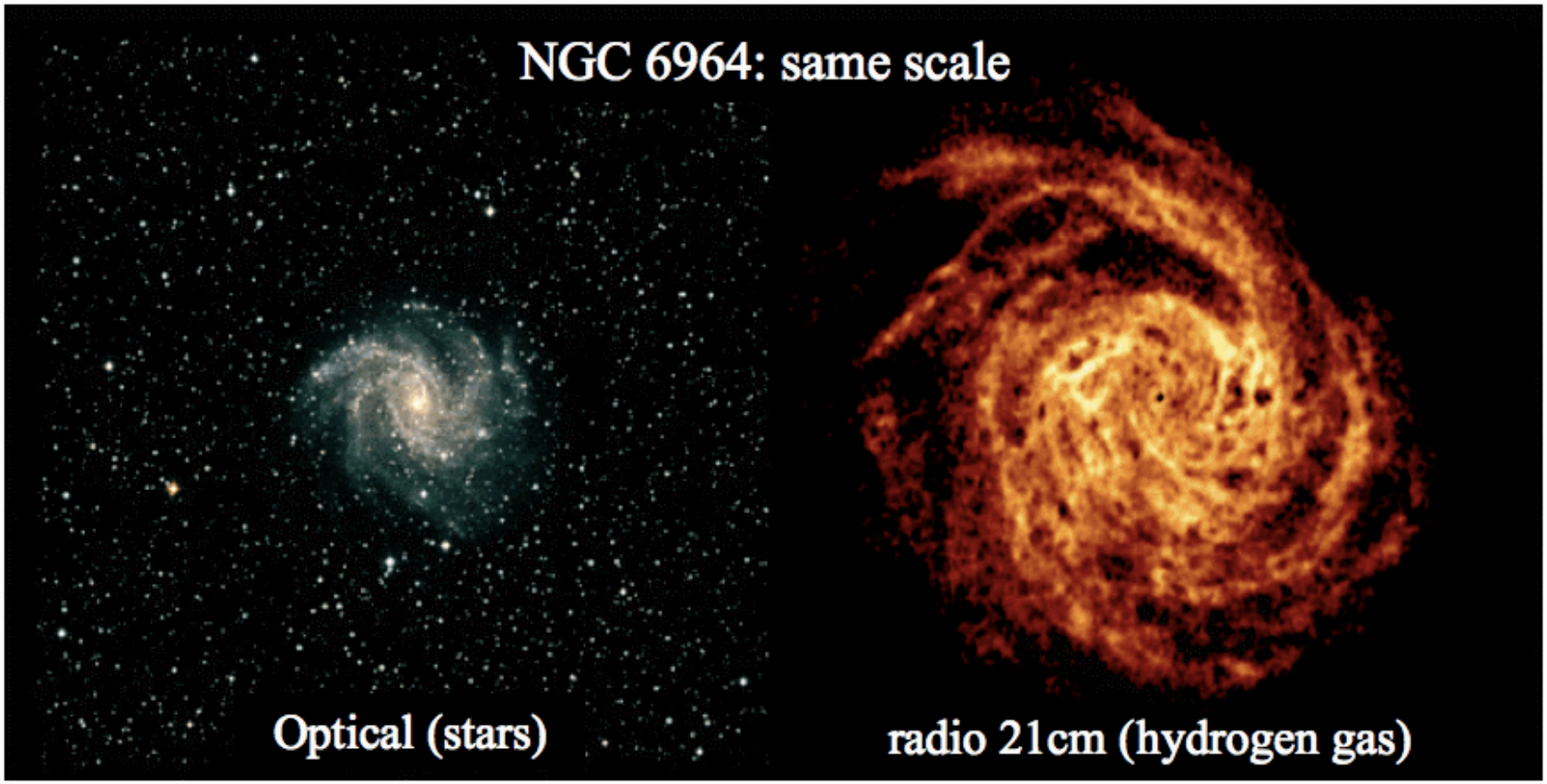
Hydrogen $1s$ ground state splitting due to the spin interaction (hyperfine structure)



Spin-parallel (higher energy) → spin-antiparallel (lower energy)

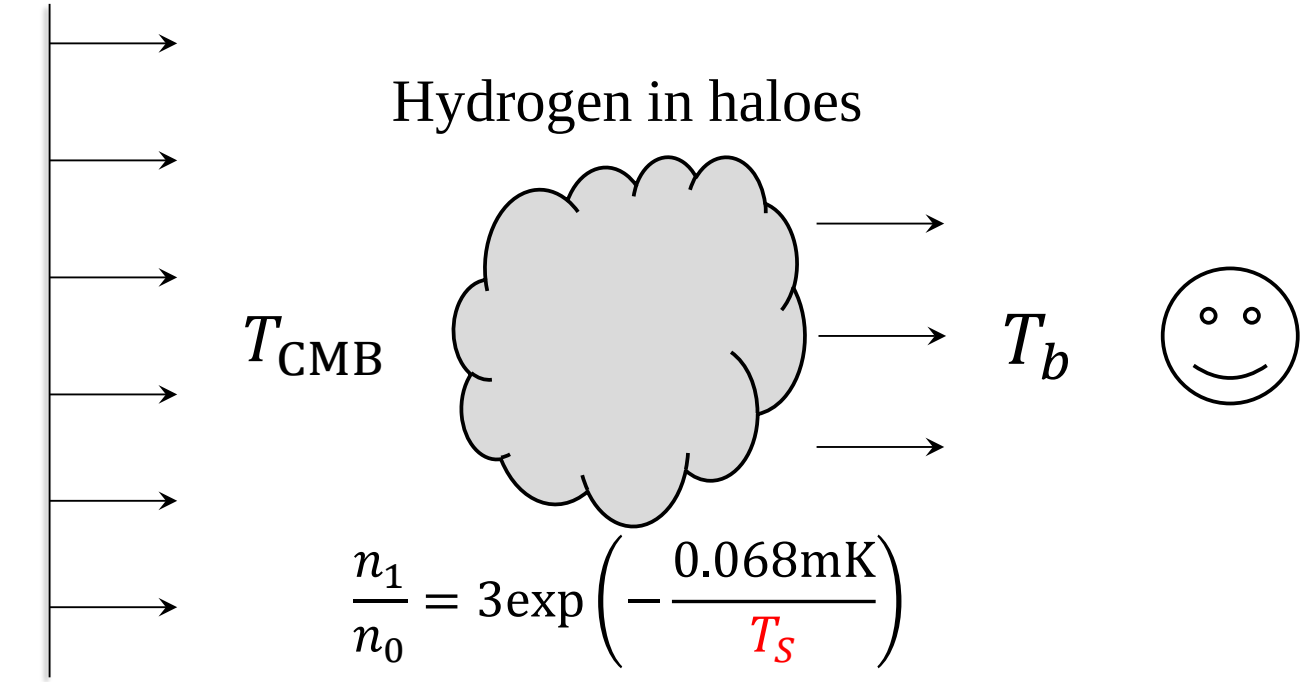
Mapping matter using 21cm signals

Hydrogen is most abundant element, so using 21cm signals we can map the distribution of matter (IGM) not optically visible



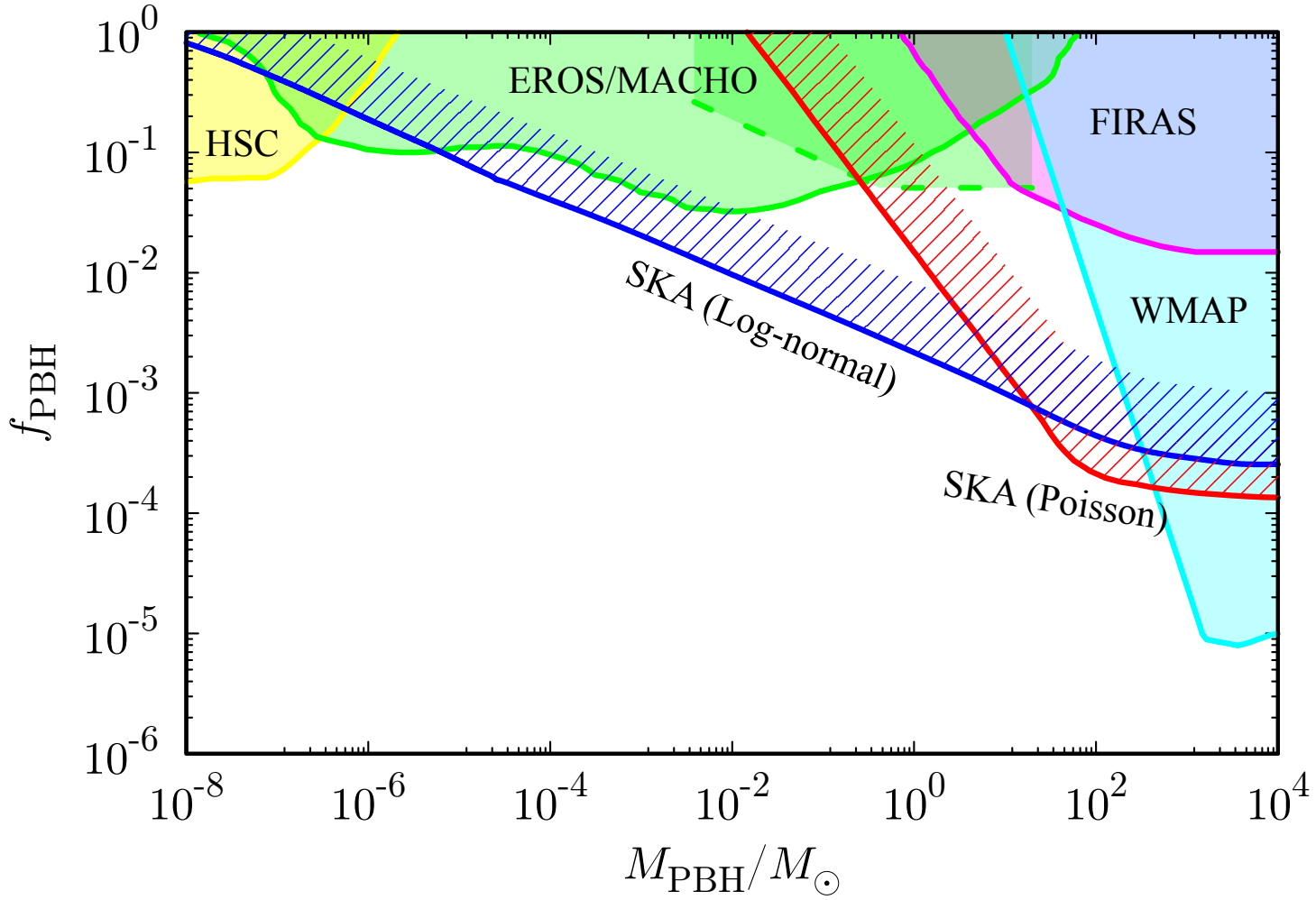
Differential brightness temperature from haloes

Haloes with masses $\lesssim 10^4 M_\odot - 10^8 M_\odot$ are filled with neutral hydrogen atoms and can be a detectable source of 21cm signals



Differential "brightness" temperature $\delta T_b \propto T_S - T_{\rm CMB}$

Improved forecast constraint on the PBH fraction



21cm constraint can cover ML window ($10^{-6}M_\odot \lesssim M_{\rm PBH} \lesssim 100M_\odot$)

Conclusions

- PBHs may hide around, still surviving today
- PBH formation can be well approximated as
  - Poisson dist as a totally random event
  - Log-normal dist from mild primordial spectrum
- Enhanced 21cm signals from haloes sourced by PBHs
  - Sensitive even if PBHs occupy sub-percent fraction of DM
  - $10^{-6} M_\odot \lesssim M_{\rm PBH} \lesssim 100 M_\odot$ can be strongly constrained