Reheating the Universe once more
-the dissipation of acoustic waves as a novel probe of primordial inhomogeneities on even smaller scales-

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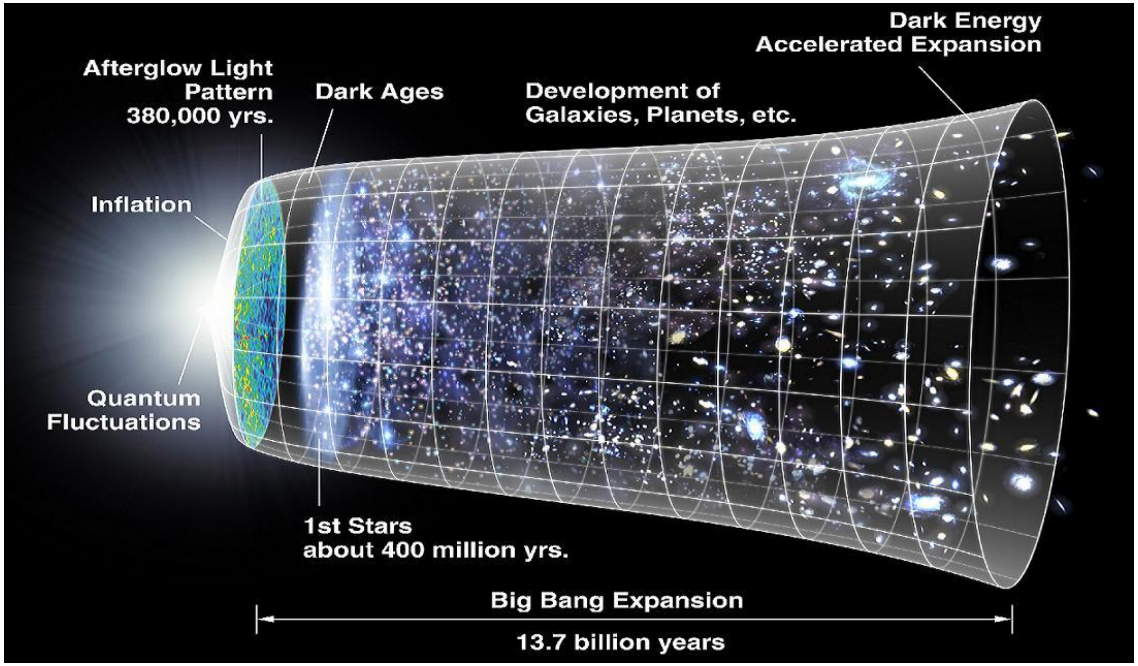
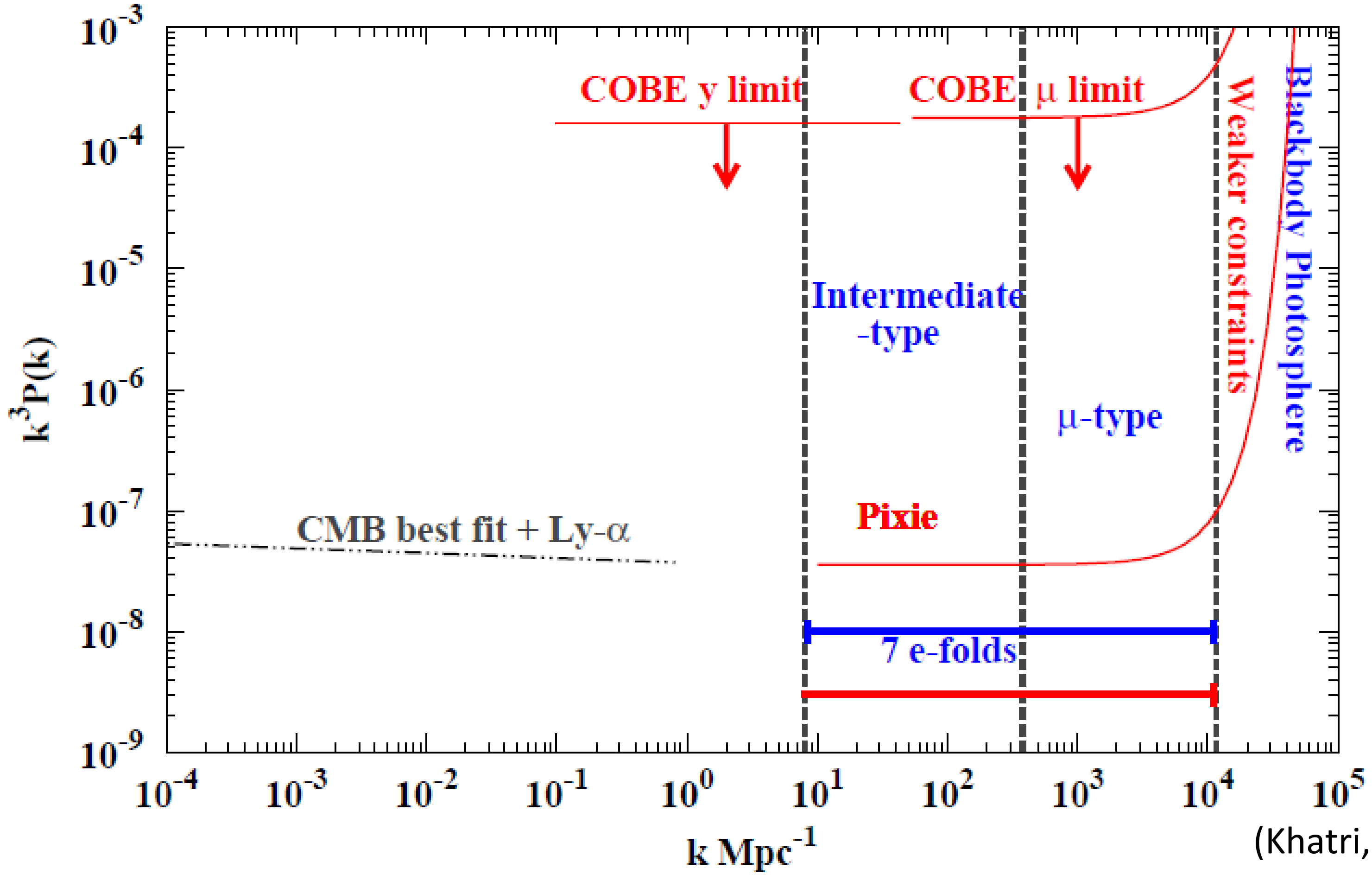


The rich structure of the Universe originates from the primordial perturbation which is ultimately related to physics of the early Universe (such as inflation).

Thus, we want information of the primordial perturbation as much as possible.

Our current knowledge



(Khatri, 2013)

For scales k<1 Mpc^{-1}, primordial perturbations are almost scale invariant.

For scales k<10^4 Mpc^{-1}, upper bound from the CMB distortion exists.

Various independent probes for the primordial perturbation are important.

CMB distortion by the Silk damping

Perturbation on super-Hubble scale $k \ll aH$

↓ Horizon re-entry

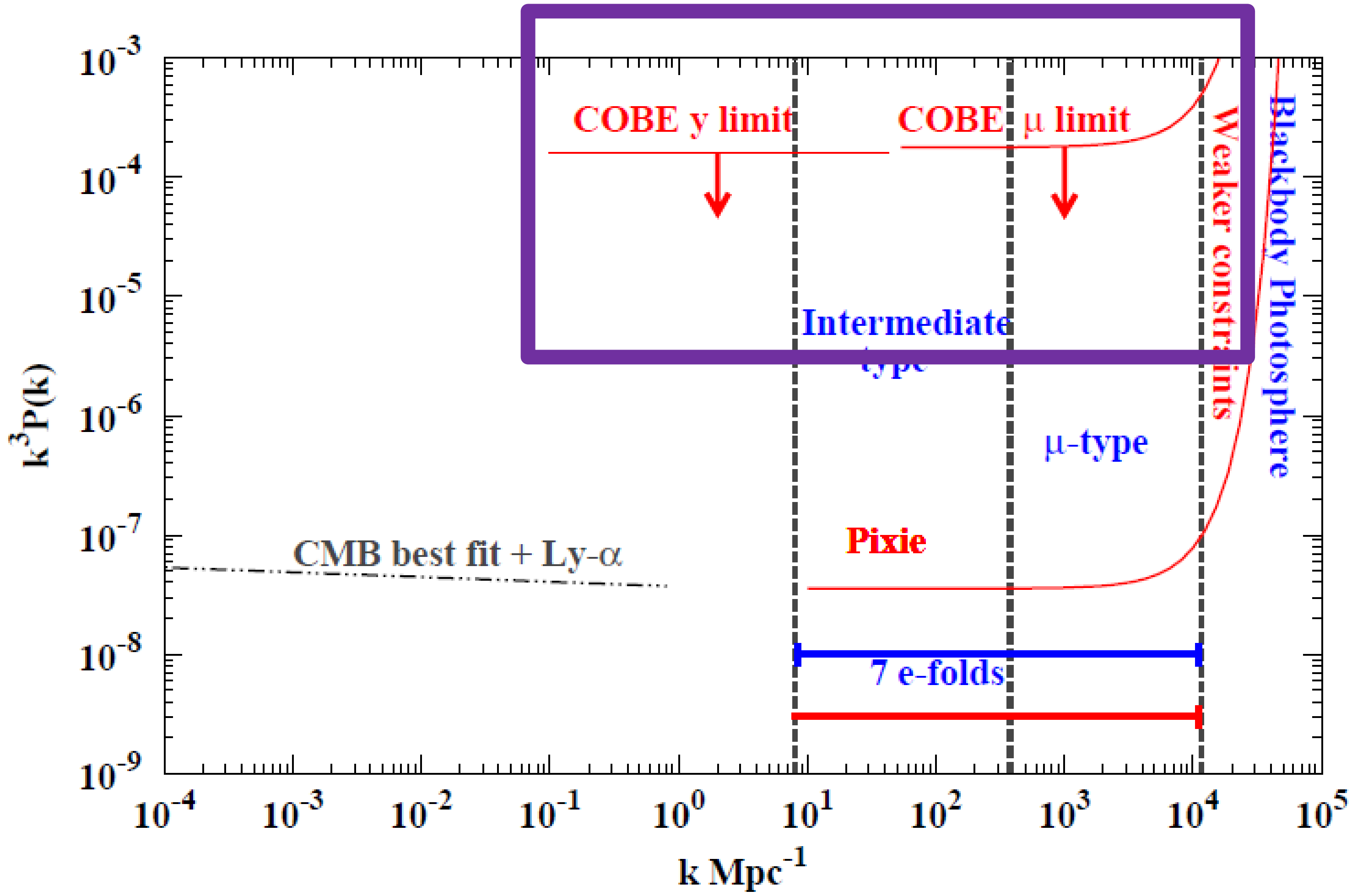
Acoustic oscillations

↓

Silk damping due to photon diffusion $k_D \simeq \sqrt{\frac{2H_0\Omega_m^{1/2} n_e \sigma_T}{c}(1+z)}$

↓

CMB distortion



COBE y limit
COBE μ limit
Weaker constraints
Blackbody Photosphere
Intermediate type
μ-type
Pixie
CMB best fit + Ly-α
7 e-folds
k³P(k)
k Mpc⁻¹
10⁻³
10⁻⁴
10⁻⁵
10⁻⁶
10⁻⁷
10⁻⁸
10⁻⁹
10⁻⁴
10⁻³
10⁻²
10⁻¹
10⁰
10¹
10²
10³
10⁴
10⁵

CMB distortion by the Silk damping

Perturbation on super-Hubble scale $k \ll aH$

Horizon re-entry

Acoustic oscillations

$k_{\rm D} \sim 4.0 \times 10^{-6}(1+z)^{3/2}{\rm Mpc}^{-1}$

Silk damping due to photon diffusion

$z < 2 \times 10^6$

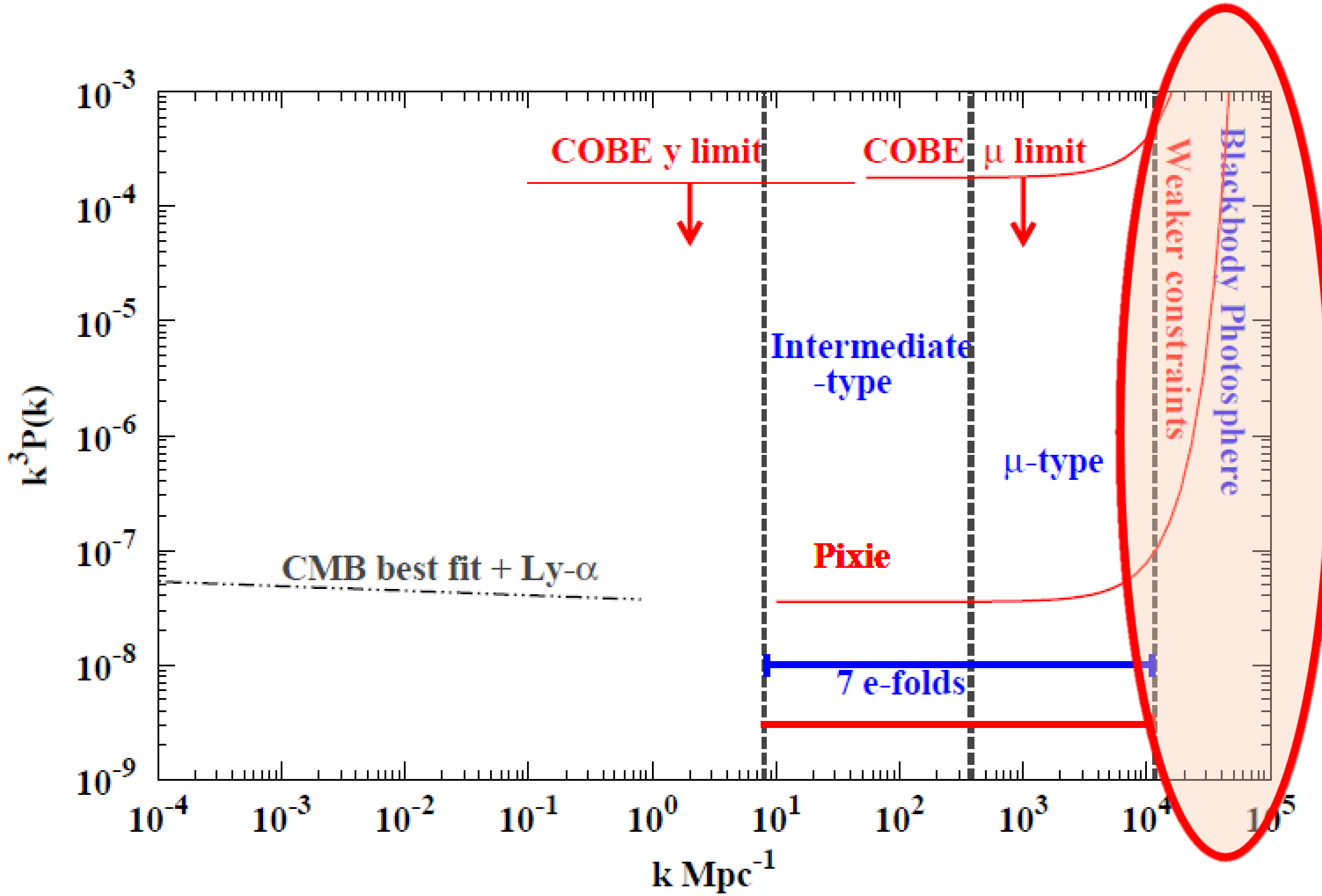
$k < 10^4\ Mpc^{-1}$

CMB distortion

$z > 2 \times 10^6$

$k > 10^4\ Mpc^{-1}$

New Planck distribution with larger temperature



However, measurement of the CMB distortion does not work for constraining primordial perturbation above $10^4\ Mpc^{-1}$.

It apparently looks that CMB is useless to probe those perturbations.

We have proposed a new method to constrain the perturbation in a range $10^4 Mpc^{-1}$<k< $10^5 Mpc^{-1}$.

(Very similar work, Jeong et al, 1403.3697)

Providing a new bound itself is of course interesting and important.

This range is also interesting in the context of PBHs as being seeds of SMBHs observed in many galaxies.

The idea

Perturbations in the above range dissipate into background CMB after BBN but before the CMB distortion era.

The baryon-photon ratio $\eta = n_b/n_\gamma$ at BBN era is larger than that in the era relevant to CMB observation.

$$\eta_{BBN} > \eta_{CMB}$$

Using two independent measurements of η thus allows us to impose constraint on the primordial perturbation.

Neutrino diffusion

Before neutrino decoupling, neutrino diffusion is much more efficient than the photon diffusion.

$$l_\nu = \frac{1}{{G_F}^2 T^2 n_l} \gg l_\gamma = \frac{1}{\sigma_T n_e}$$

$$k_\nu \approx 10^5 Mpc^{-1} \left(\frac{1+z}{1+z_{dec}} \right)^{-6}$$

$k > 10^5 Mpc^{-1}$ These modes have already dissipated due to the neutrino diffusion before BBN.

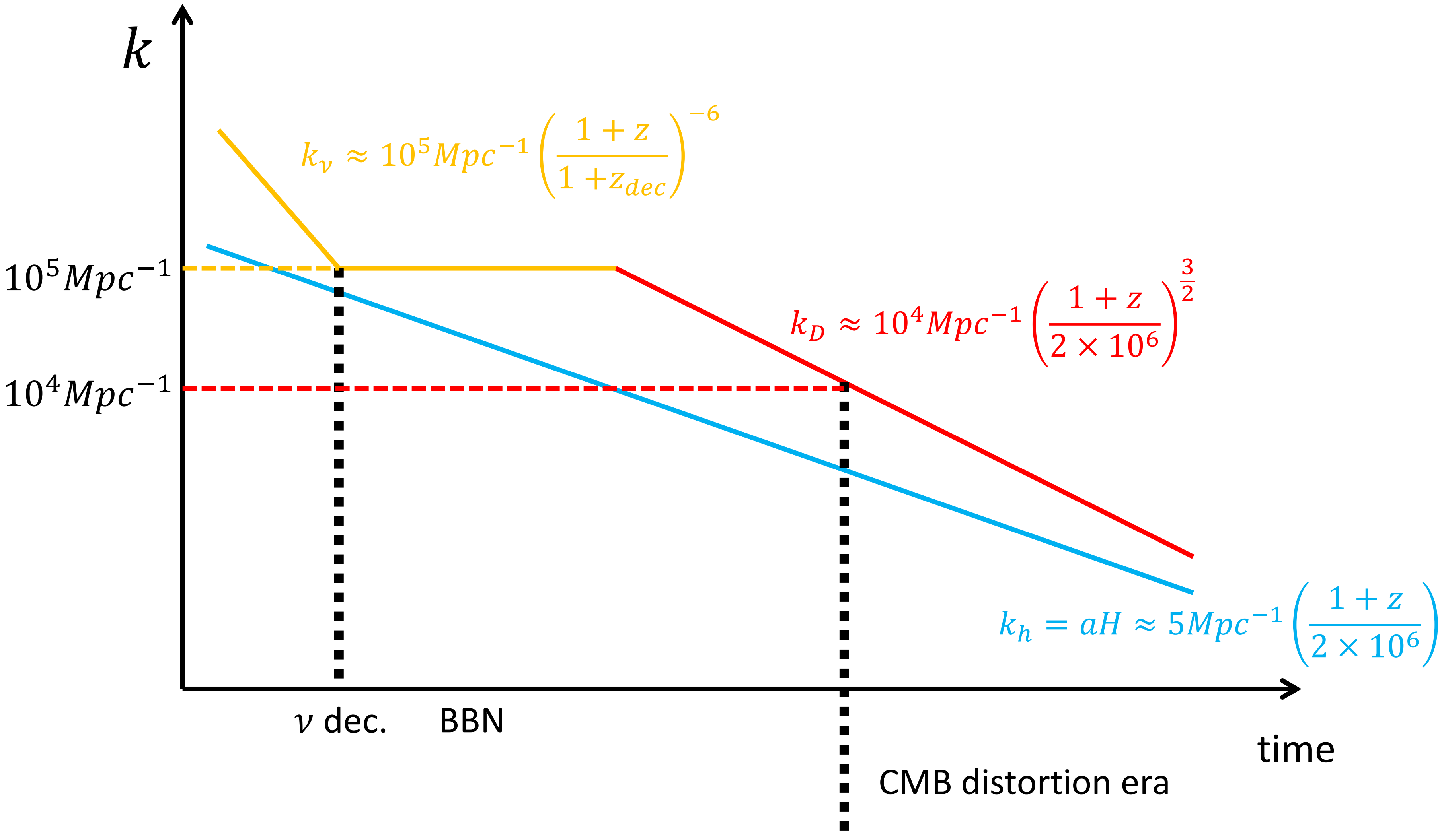
As a result, after BBN, only modes with $k < 10^5 Mpc^{-1}$ remain. Those modes dissipate due to the photon diffusion.

CMB distortion

$$10^4 Mpc^{-1} < \mathrm{k} < 10^5 Mpc^{-1}$$

Neutrino diffusion

Thermal history



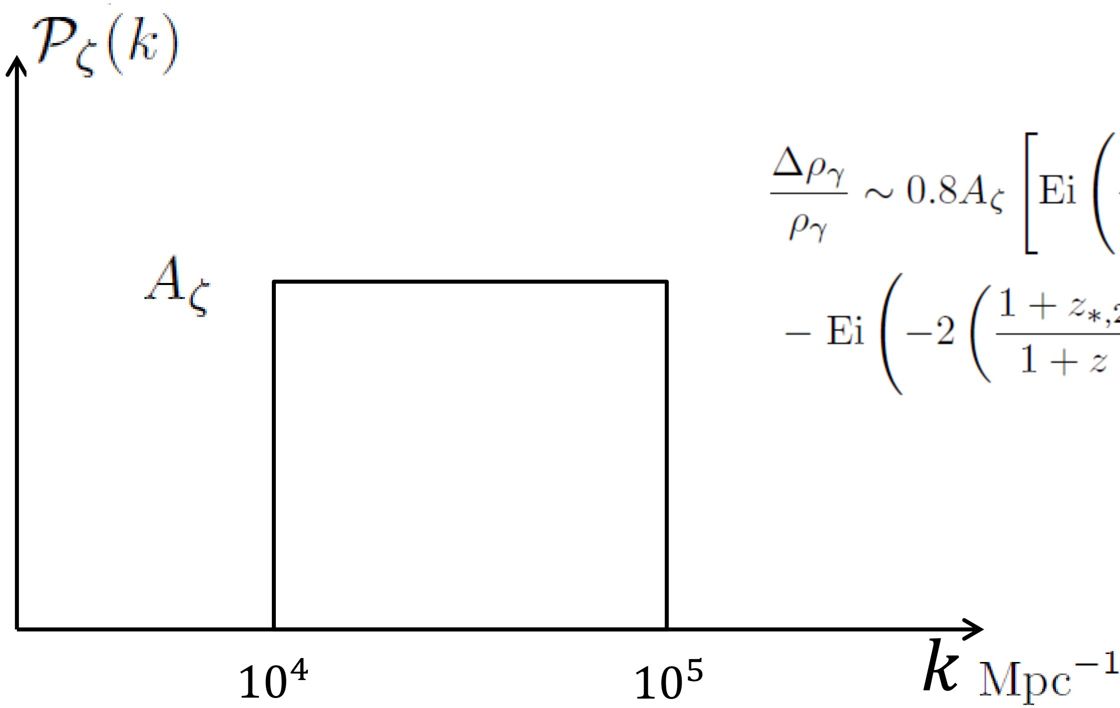
Energy injection

$$\frac{\Delta\rho_\gamma}{\rho_\gamma} = \int_{z_1}^{z_2} \frac{1}{a^4\rho_\gamma}\frac{d(a^4 Q_{\rm ac})}{dz}dz$$

$$\frac{1}{a^4\rho_\gamma}\frac{d(a^4 Q_{\rm ac})}{dz} \sim 9.4a\int \frac{kdk}{k_{\rm D}^2}\mathcal{P}_\zeta(k)2\sin^2(kr_{\rm s})e^{-2k^2/k_{\rm D}^2},$$

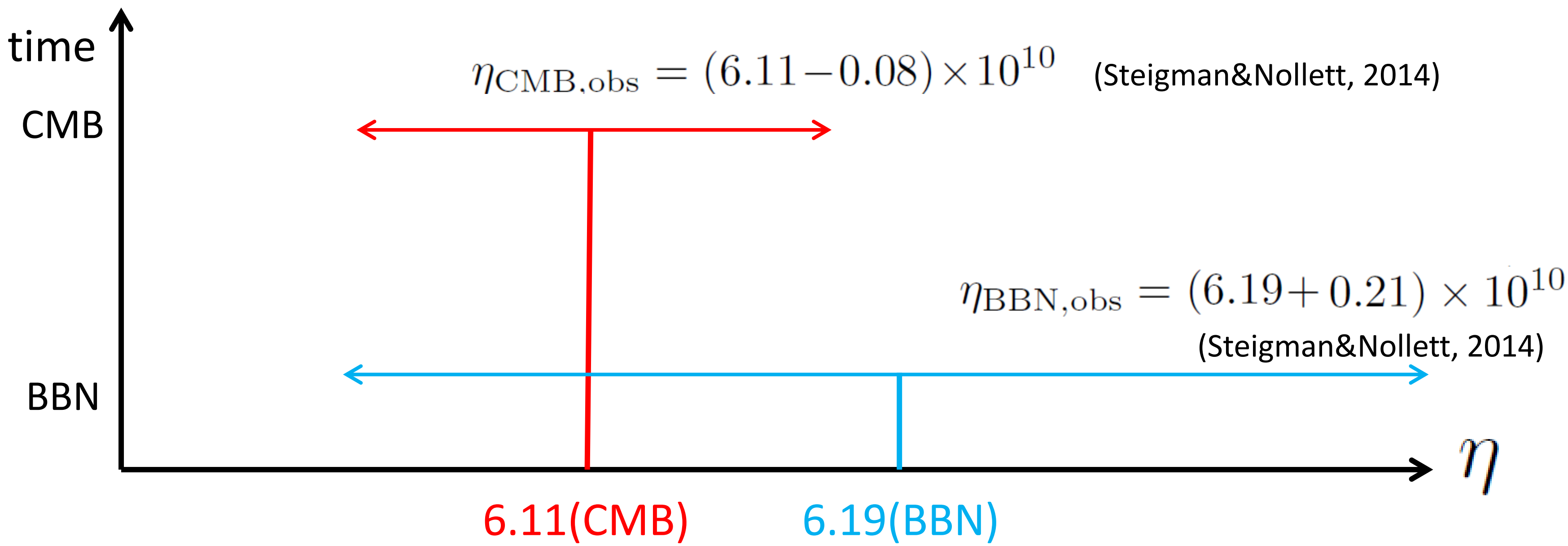
(Chluba et al, 2012)

Primordial perturbation we consider



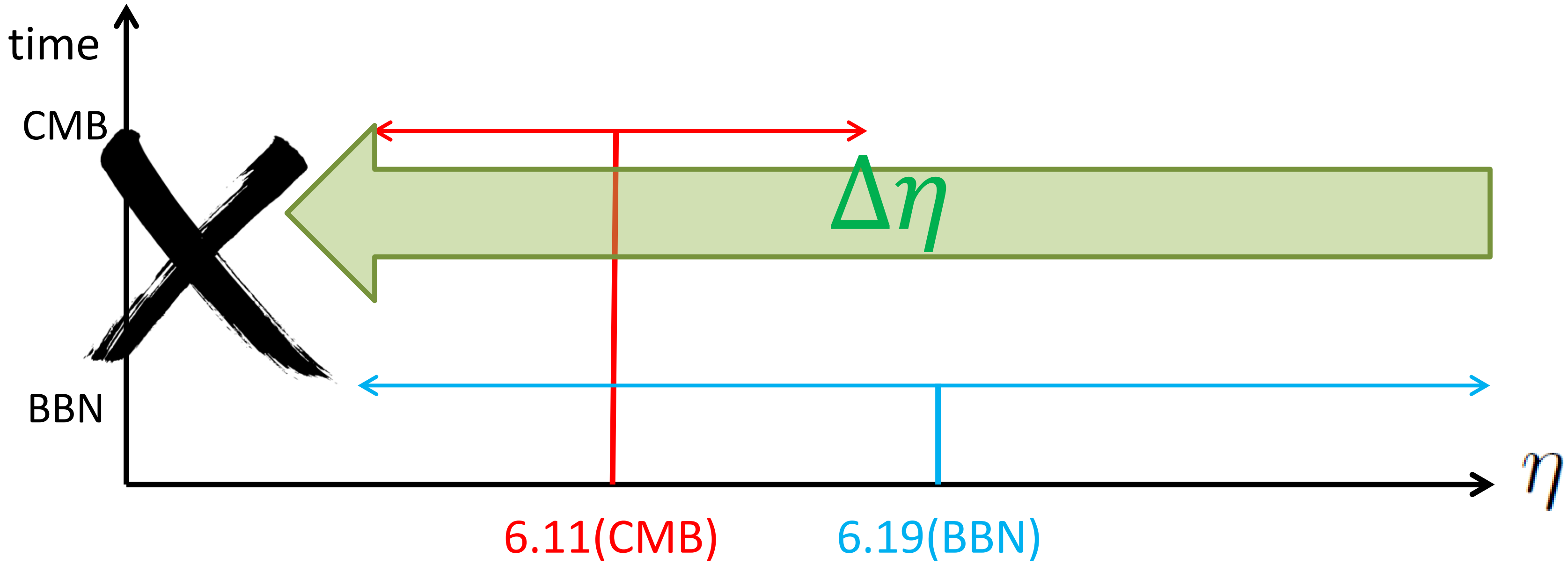
$$\frac{\Delta\rho_\gamma}{\rho_\gamma} \sim 0.8A_\zeta\left[{\rm Ei}\left(-2\left(\frac{1+z_{*,1}}{1+z}\right)^3\right) - {\rm Ei}\left(-2\left(\frac{1+z_{*,2}}{1+z}\right)^3\right)\right]_{z_2}^{z_1} \sim 2.3A_\zeta,$$

Method for our constraint



Intriguingly, $\eta_{\rm CMB,obs} < \eta_{\rm BBN,obs}$!?

Method for our constraint



$$\frac{\eta_{\rm CMB}}{\eta_{\rm BBN}} = \left(1 - \frac{3}{4}\frac{\Delta\rho_\gamma}{\rho_\gamma}\right) > \frac{\eta_{\rm CMB,obs}}{\eta_{\rm BBN,obs}}$$

$$A_\zeta \lesssim 0.6\left(1 - \frac{\eta_{\rm CMB,obs}}{\eta_{\rm BBN,obs}}\right)$$

This provides the most conservative bound on A_ζ.

Resultant bound on A_ζ

$$A_\zeta \lesssim 0.03(1\sigma), \quad 0.06(2\sigma)$$

- This competes the PBH bound.

$$10^3 M_\odot < M < 10^5 M_\odot$$
$$A_\zeta \lesssim 0.05.$$

Caution

- BH formation is very complex (critical phenomena, initial profile). This bound will change significantly if we consider non-Gaussianity of ζ.

- Our present bound is based on the perturbation theory and is relatively easy to quantify precisely as well as relate to observations.

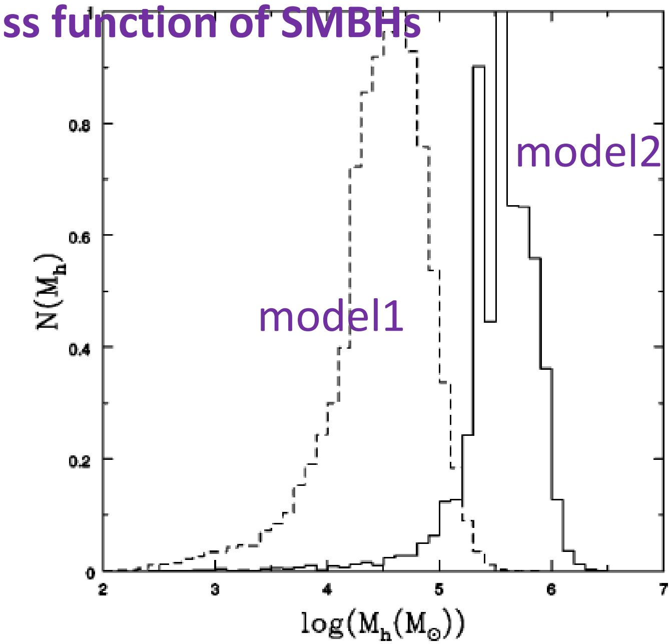
- Methodology for obtaining the bound is new.

- Contrary to the PBH case, potential reduction of the error bars in the future is linearly sensitive to the bound. Significant improvement of the bound may be achieved.

Primordial black holes $10^3 M_\odot < M < 10^5 M_\odot$

Primordial black holes in this mass range is interesting in the context of scenarios of PBHs as the seeds of super massive black holes($\sim 10^6 M_\odot$) observed in galaxies.

Initial PBH mass function explaining present mass function of SMBHs



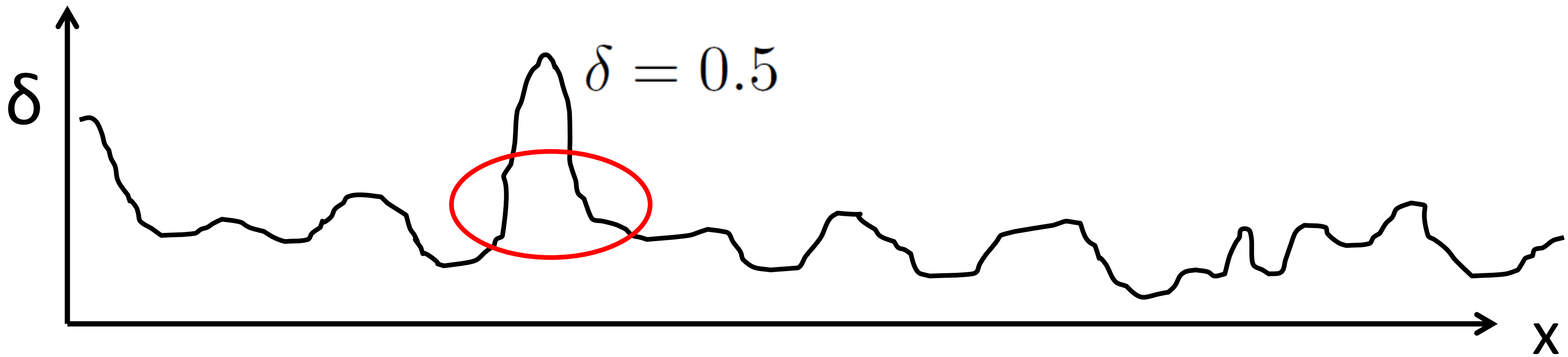
(Bean&Magueijo, 2002)

Future improved measurement of η may exclude PBHs in this mass range.

In the following, I will propose a new approach to probe PBHs in this mass range. (K.Kohri, T.Nakama and TS, to appear soon)

Primordial Black Holes

In the radiation dominated universe, if the density contrast exceeds a threshold value (=0.5) at the time of horizon crossing, BH forms.



$$M_{\rm peak} = 2 \times 10^4 \ M_\odot \left(\frac{k_*}{5 \times 10^4 \ {\rm Mpc}^{-1}} \right)^{-2}$$

PBH mass is related to the (comoving) wavenumber of perturbations.

Primordial Black Holes

Site of PBH formation must be rare, otherwise the universe becomes PBH dominated.

$$\sigma_{\bar{\delta}} = 0.06$$ (Gaussian PDF is assumed)

This value of the standard deviation must be realized in the corresponding scale if PBH scenario as seed of SMBHs is correct.

Ultra compact mini halos (UCMHs)

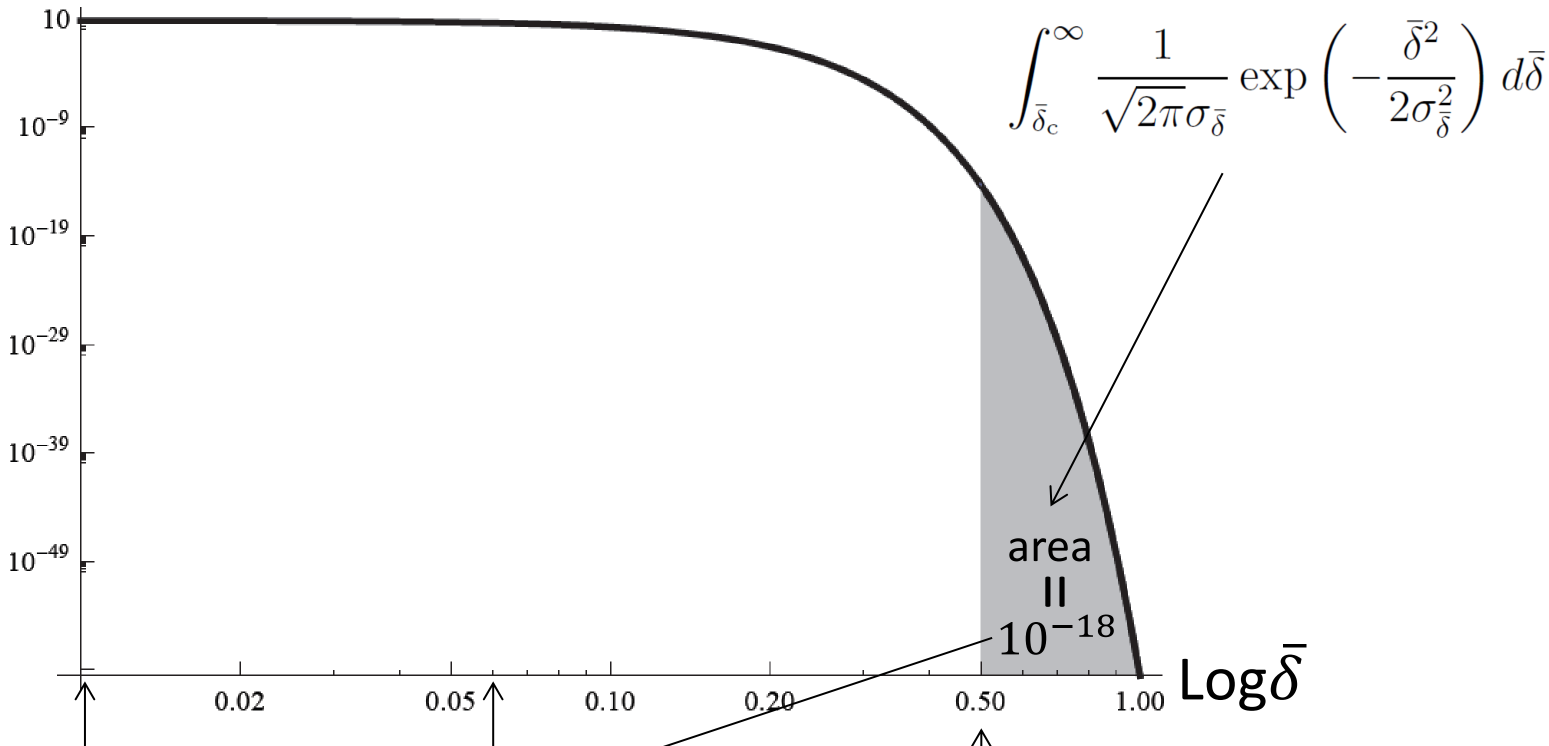
When the perturbations of the scale of interest cross the Hubble radius, dark matter perturbations continuously grow in the radiation dominated era and collapses at around the time of matter radiation equality.

The collapsed object is called ultra compact mini halos (UCMHs).

(Ricotti and Gould, 2009)

Ultra compact mini halos (UCMHs)

Logarithm of Gaussian PDF



$\bar{\delta}_{c,\mathrm{UCMH}} = 10^{-3} \ll \sigma_{\bar{\delta}} = 0.06$

Perturbations leading to UCMH formation are common.

⇩

Decent fraction of DM particles are contained in UCMHs!

Ultra compact mini halos (UCMHs)

Only dark matter forms UCMHs. Thus, the typical mass of UCMH is less than that of PBHs.

$$M_{\rm UCMH} = \ 3 \times 10^{-2} \ M_\odot \left(\frac{M_{\rm BH}}{10^4 \ M_\odot} \right)^{3/2}$$

$$R_{\rm UCMH} \simeq 2 \times 10^{11} \ {\rm km} \left(\frac{1 + z_{\rm eq}}{1 + z_{\rm turn}} \right) \left(\frac{M_{\rm BH}}{10^4 \ M_\odot} \right)^{1/2} .$$

Idea

If the PBH scenario as the SMBH seed is correct, substantial part of DM is in the form of UCMHs.

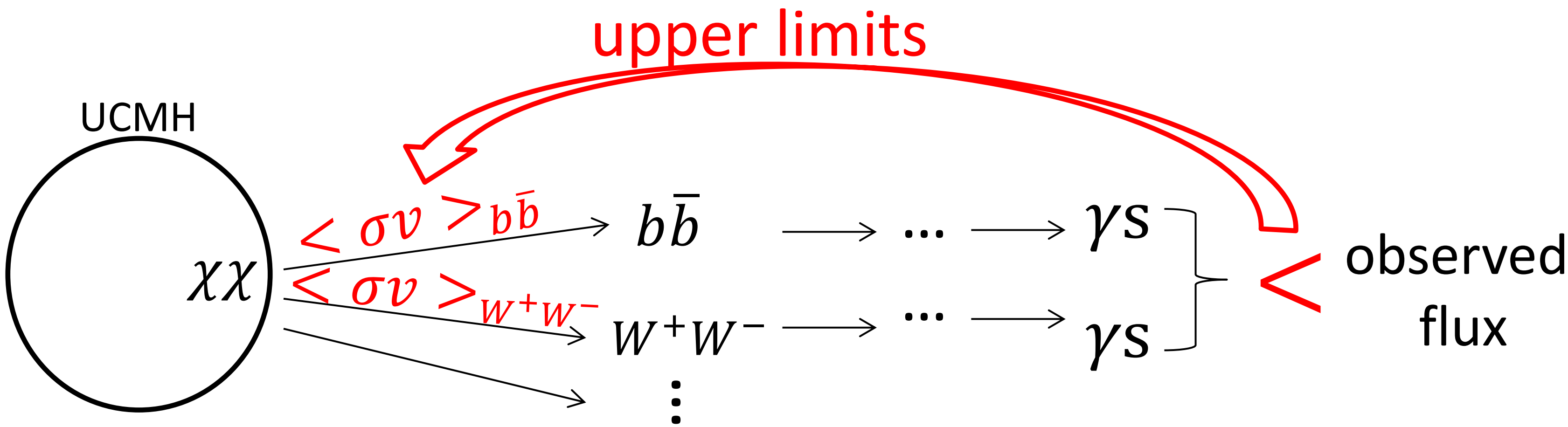
If dark matter particles annihilate and convert into standard model particles (such as photons), we expect some flux from UCMHs. We can then place upper bound on the annihilation cross section by using the observational data such as Fermi.

(Our hope)

Future experiments identify the nature of dark matter and determine annihilation cross sections. Those values turn out to exceed the upper bound set by the PBH scenario. -> PBH scenario is excluded.

Idea

- Assuming **PBHs (δ∼1)** are seeds of SMBHs, **numerous UCMHs ($\delta \sim 10^{-3}$)** should exist.

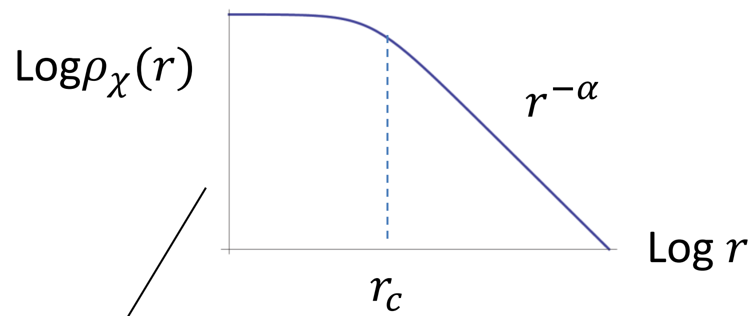


- The scenario of PBHs explaining SMBHs is INCOMPATIBLE with DM models in which the cross sections exceed these upper limits.

Method of calculation

Bringmann, Scott, Akrami, 2012

Kohri, Nakama, TS, in prep.



UCMH

$\downarrow \Phi_k$

Earth

earth↔UCMH

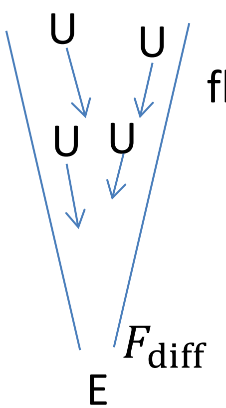
k-th mode

$$4\pi d^2 \Phi_k = \int_{\rm UCMH} d^3x N_k \frac{\rho_\chi^2 \langle \sigma v \rangle_k}{2 m_\chi^2}$$

flux from a UCMH

# of photons per one annihilation

1 TeV



flux from several UCMHs

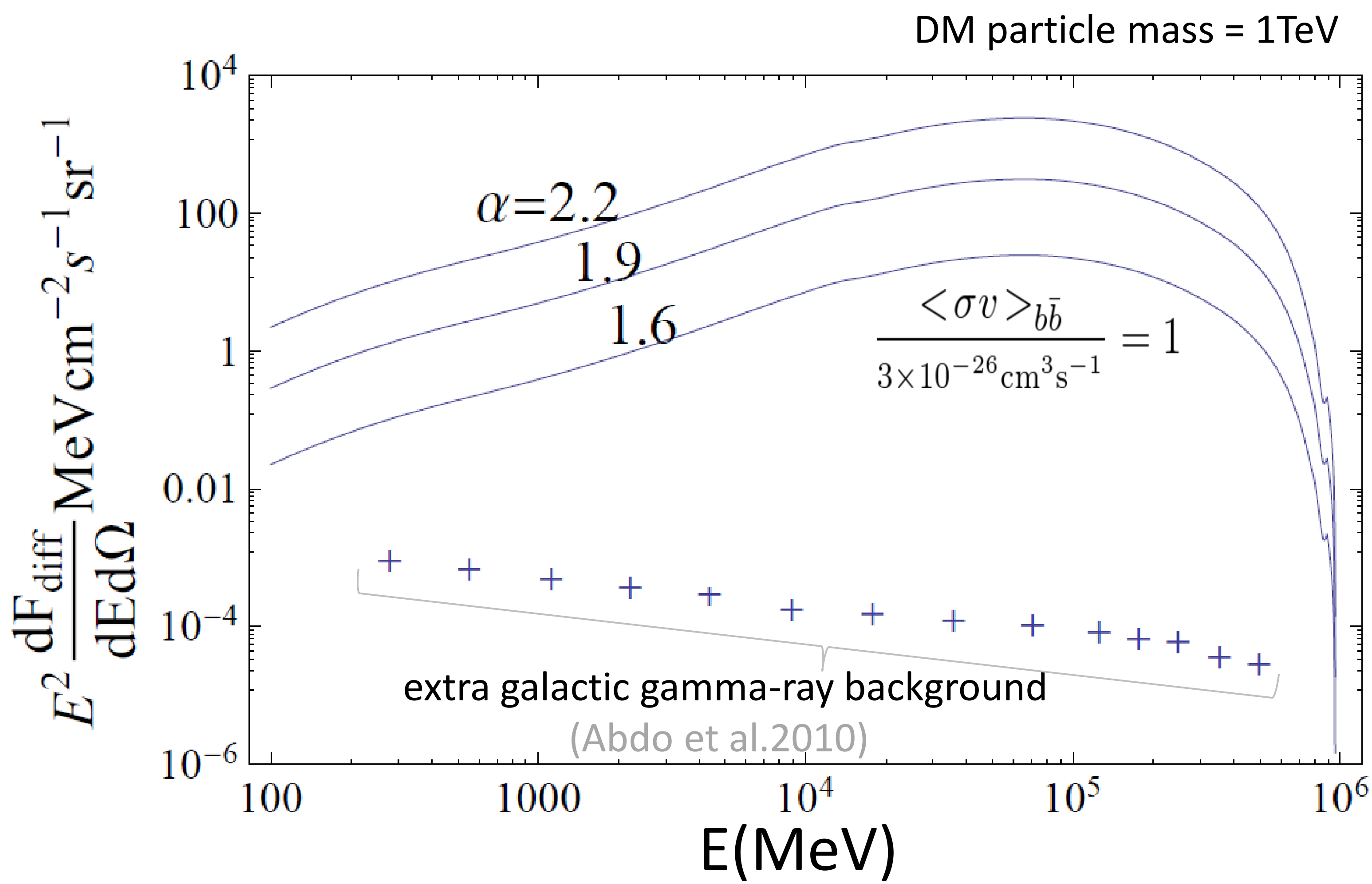
radius of Milky Way

$$E^2 \frac{dF_{\rm diff}}{dE d\Omega} = \frac{1}{2 M_{\rm UCMH}} \int_{d_{\rm E}}^{d_{\rm MW}} \rho_{\rm MW}(d') E^2 \frac{d\Phi(d')}{dE} d'^2 {\rm d}d'$$

center of Milky Way ↔earth

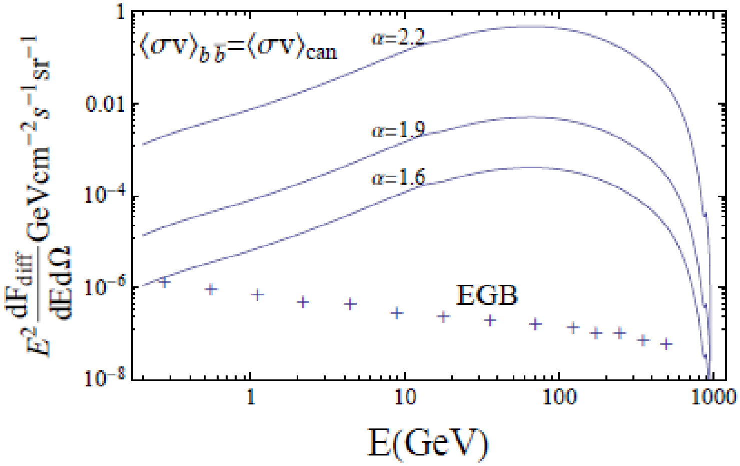
NFW profile

Comparison of γ-rays from UCMHs and observation

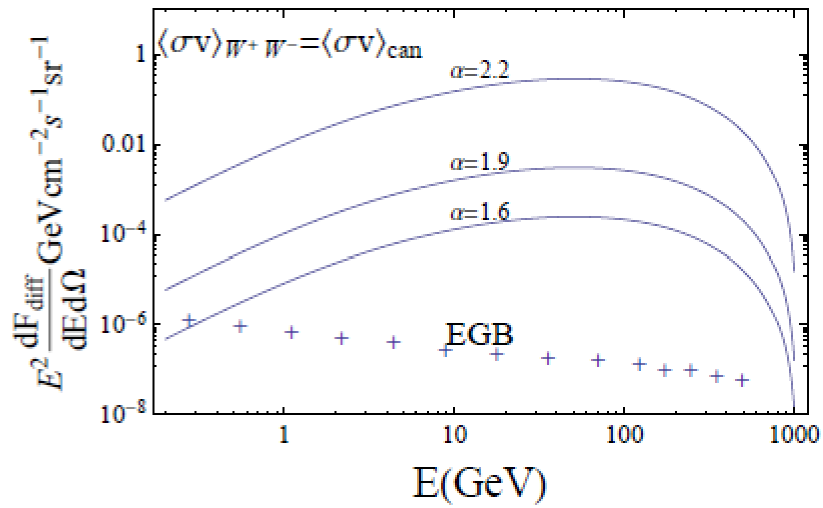


$\frac{<\sigma v>_{b\bar{b}}}{3\times10^{-26}\mathrm{cm}^3\mathrm{s}^{-1}} \lesssim 10^{-5}$ to be consistent with observation.

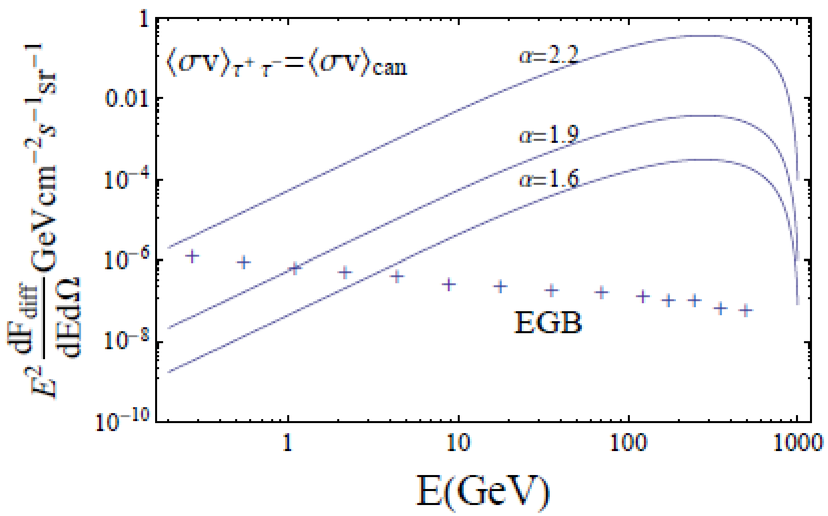
$b\bar{b}$



W^+W^-

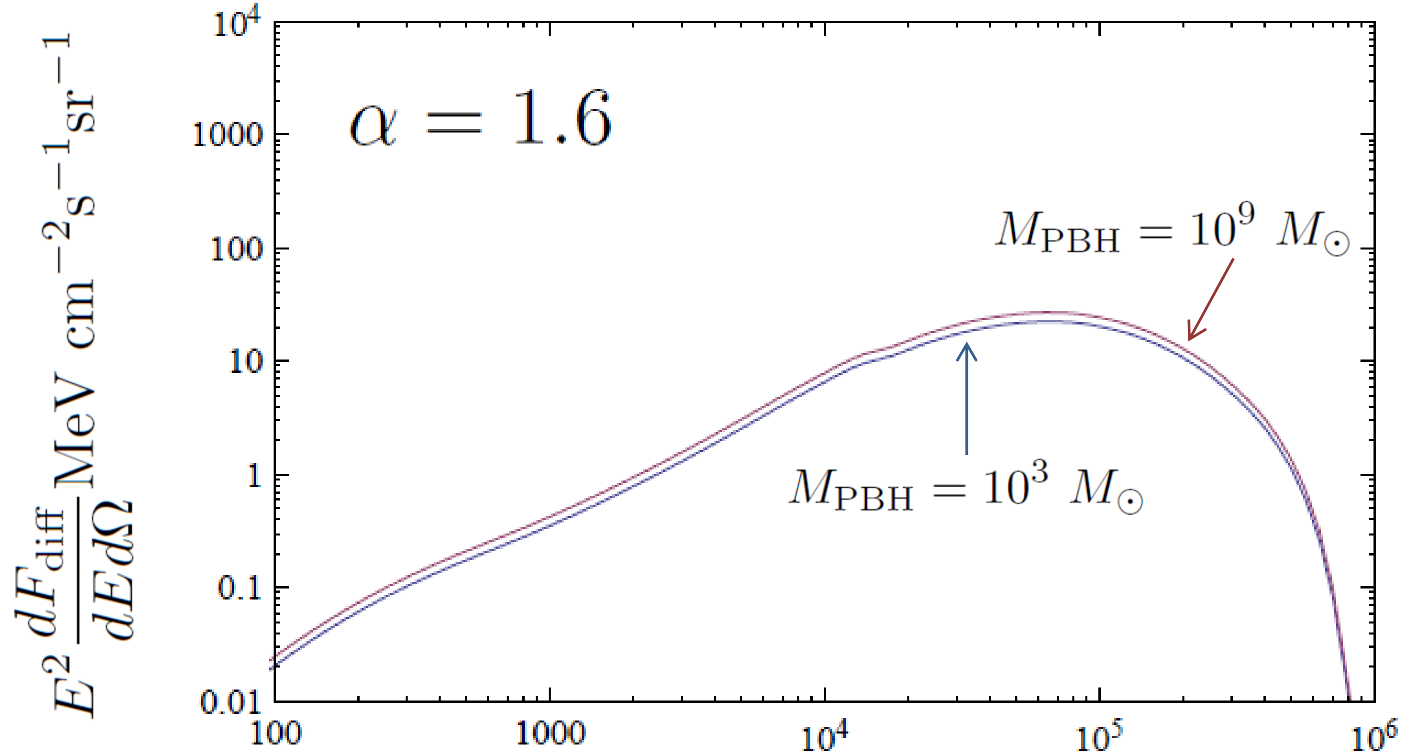


$\tau^+\tau^-$



Dependence of the flux on PBH mass

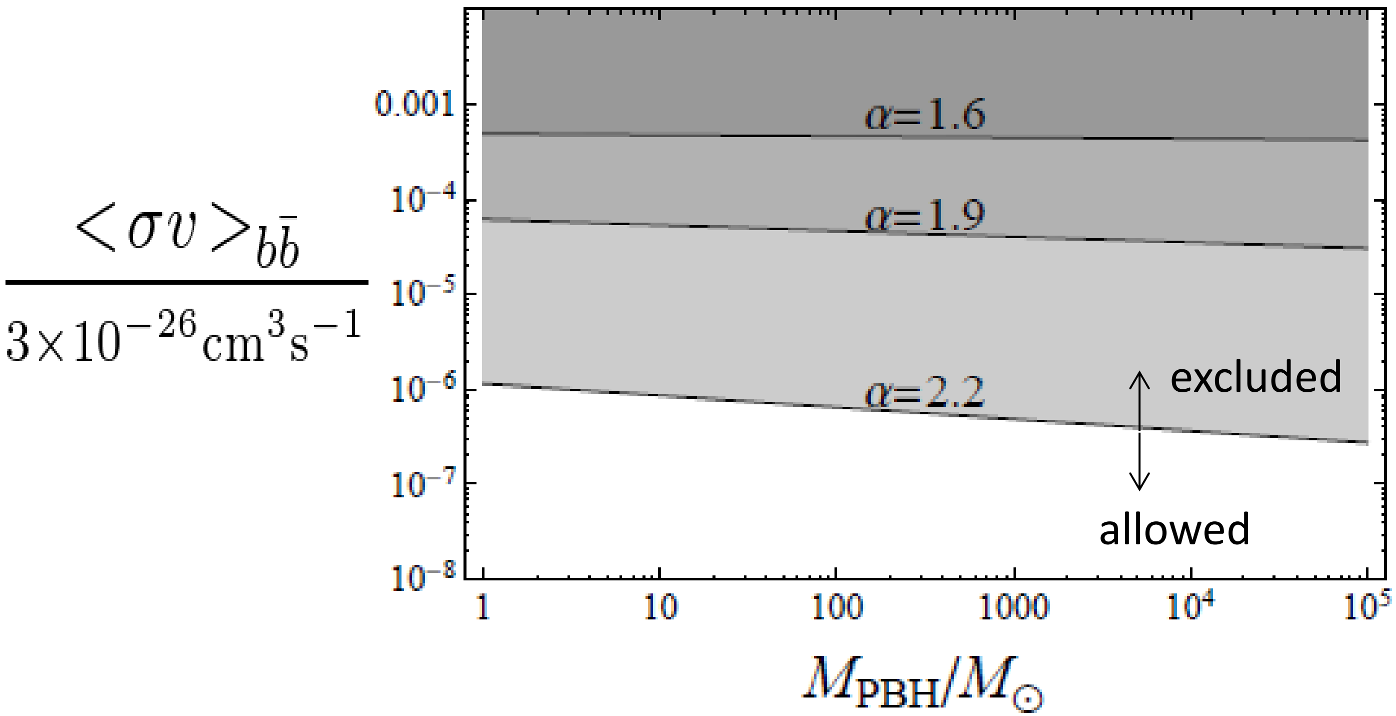
DM particle mass = 1TeV



E(MeV)

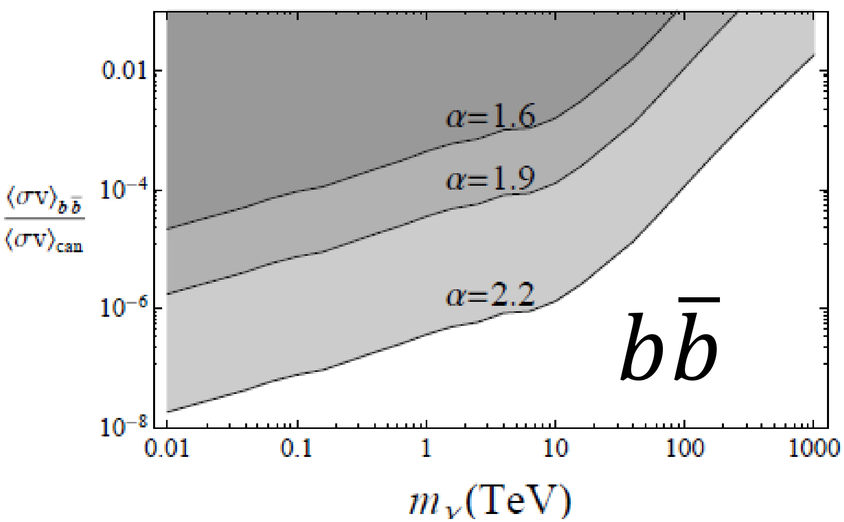
The flux is very insensitive to the PBH(UCMH) mass.

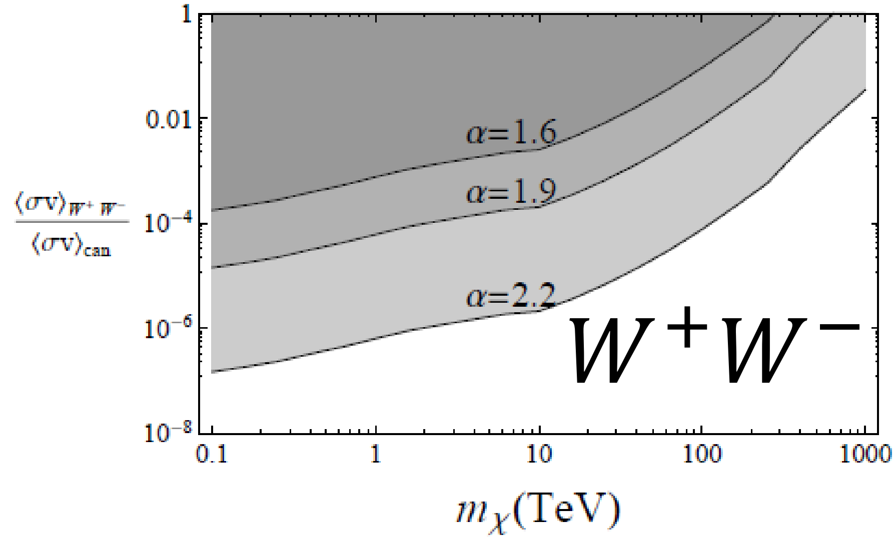
Upper limits on the cross section

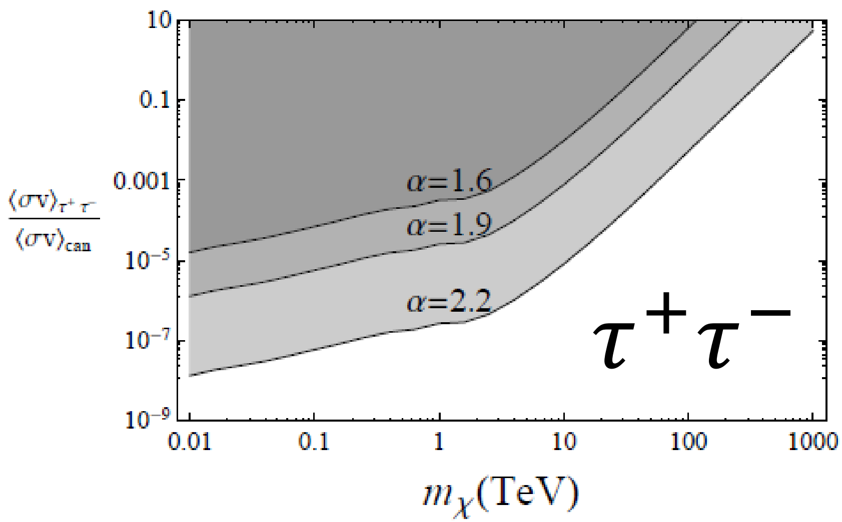


$$\frac{<\sigma v>_{b\bar{b}}}{3\times10^{-26}\mathrm{cm}^3\mathrm{s}^{-1}} \lesssim 10^{-5}$$ to be consistent with observation.

Dependence on dark matter mass



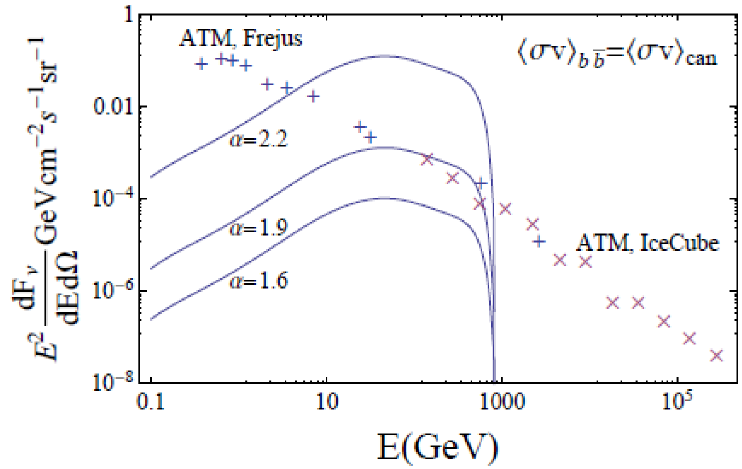




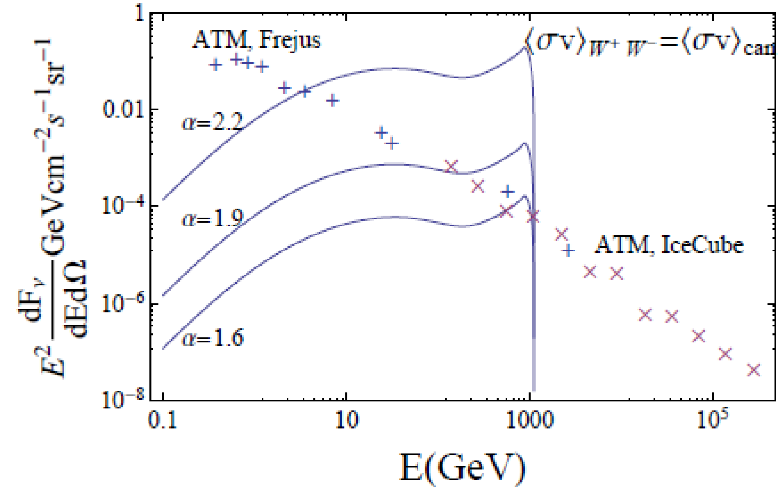
In most cases, the PBH scenario is not compatible with the canonical annihilation cross section for DM to SM particles.

Neutrino flux

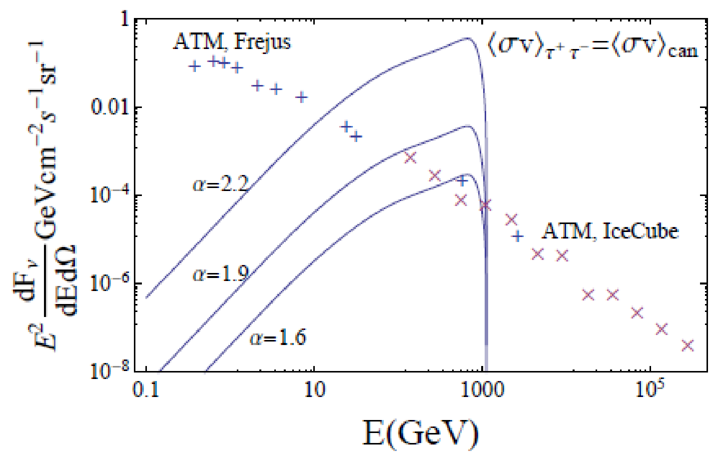
$b\bar{b}$



W^+W^-

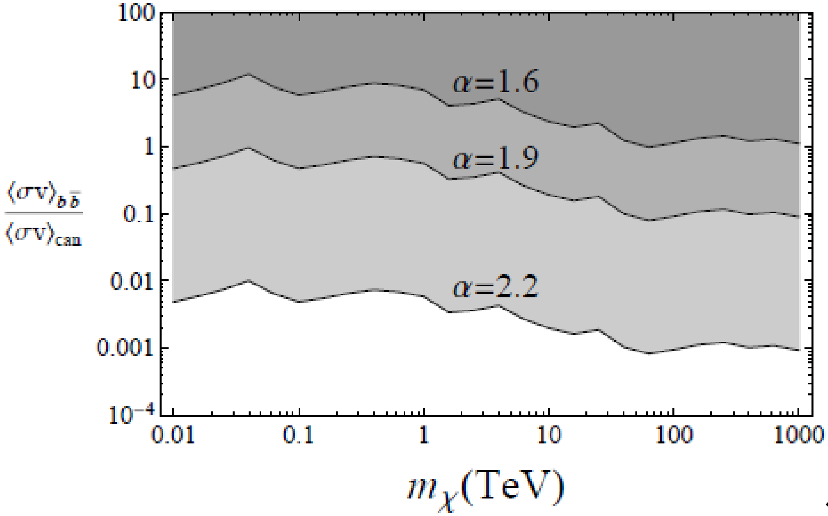


$\tau^+\tau^-$

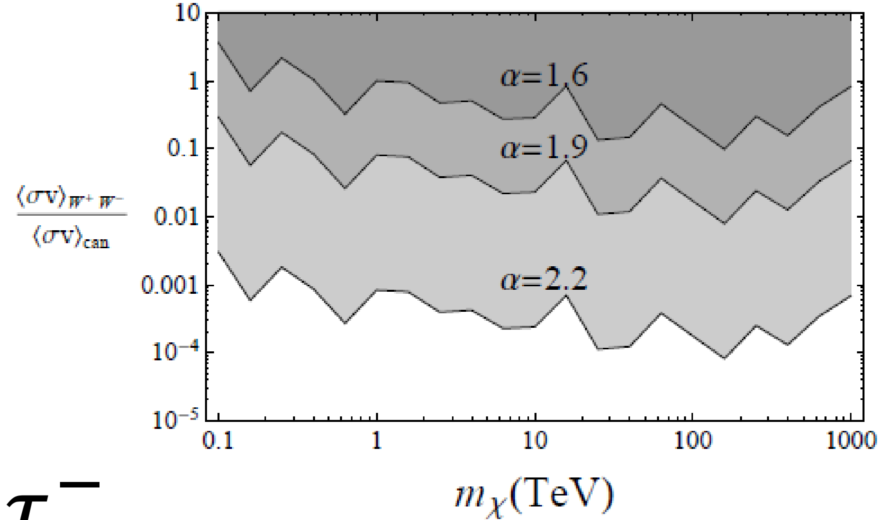


Constraints from neutrinos

$b\bar{b}$



W^+W^-



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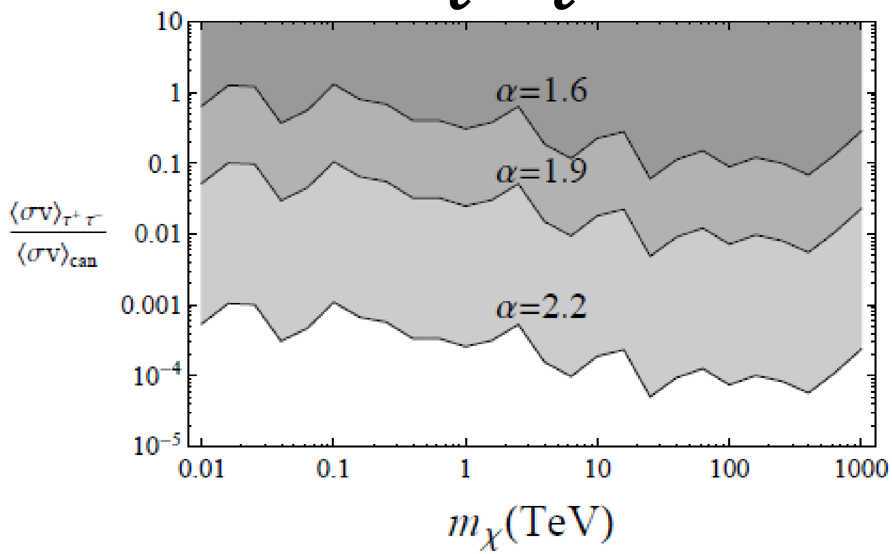

Constraints from neutrinos are weaker than those from photons.

Summary

We proposed a novel idea to probe primordial perturbations in a range $10^4 - 10^5 Mpc^{-1}$.

Use of the current data yields

$$A_\zeta \lesssim 0.03(1\sigma), \quad 0.06(2\sigma)$$

The scenario of PBHs explaining seeds of the SMBHs is INCOMPATIBLE with DM models in which the cross sections exceed these upper limits.

$$\frac{<\sigma v>_{b\bar{b}}}{3\times 10^{-26}\mathrm{cm}^3\mathrm{s}^{-1}} \lesssim 10^{-5}$$