Observational Constraints on the Primordial Curvature Power Spectrum

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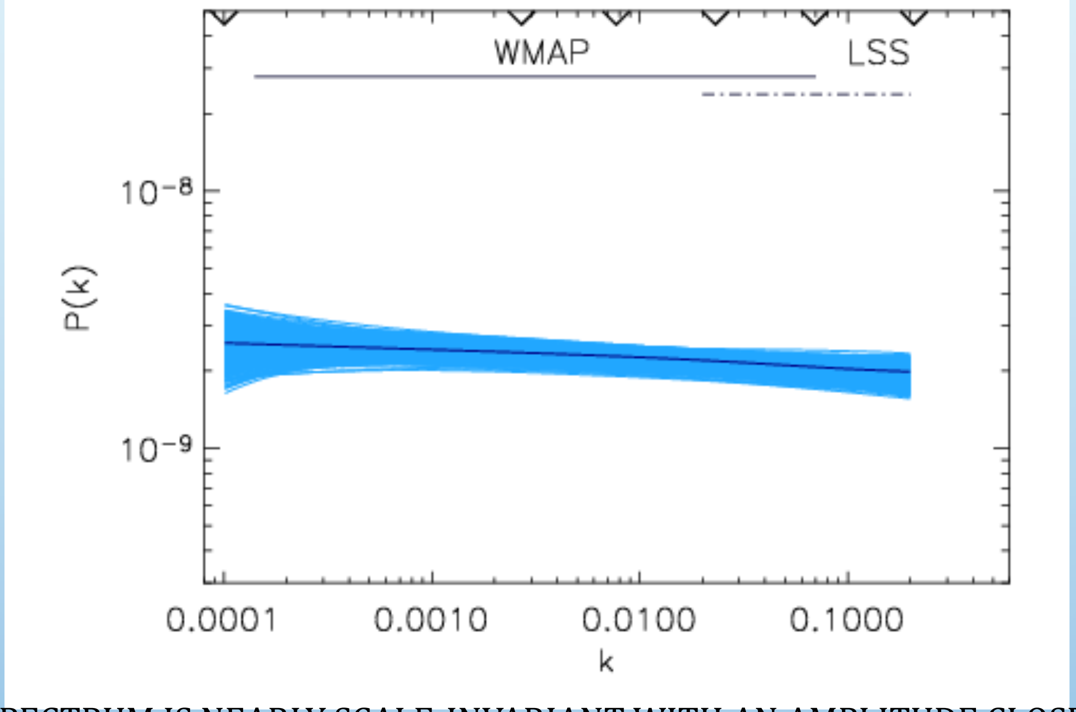
Based on :
arXiv:1705.09924, R. Emami, George F. Smoot

THE CMB & INFLATIONARY COSMOLOGY

CMB TEMPERATURE FLUCTUATION OBSERVATIONS PROVIDE A PRECISE MEASUREMENT OF THE PRIMORDIAL POWER SPECTRUM ON LARGE SCALES, CORRESPONDING TO WAVENUMBERS 10^{-3} MPC^{-1} $< K <$ 0.1 MPC^{-1}

LSS: LUMINOUS RED GALAXIES AND GALAXY CLUSTERS PROBE THE MATTER POWER SPECTRUM ON OVERLAPPING SCALES (0.02 MPC^{-1} $< K <$ 0.7 MPC^{-1}, WHILE THE LYMAN-ALPHA FOREST REACHES SLIGHTLY SMALLER SCALES (0.3 MPC^{-1} $< K <$ 3 MPC^{-1};



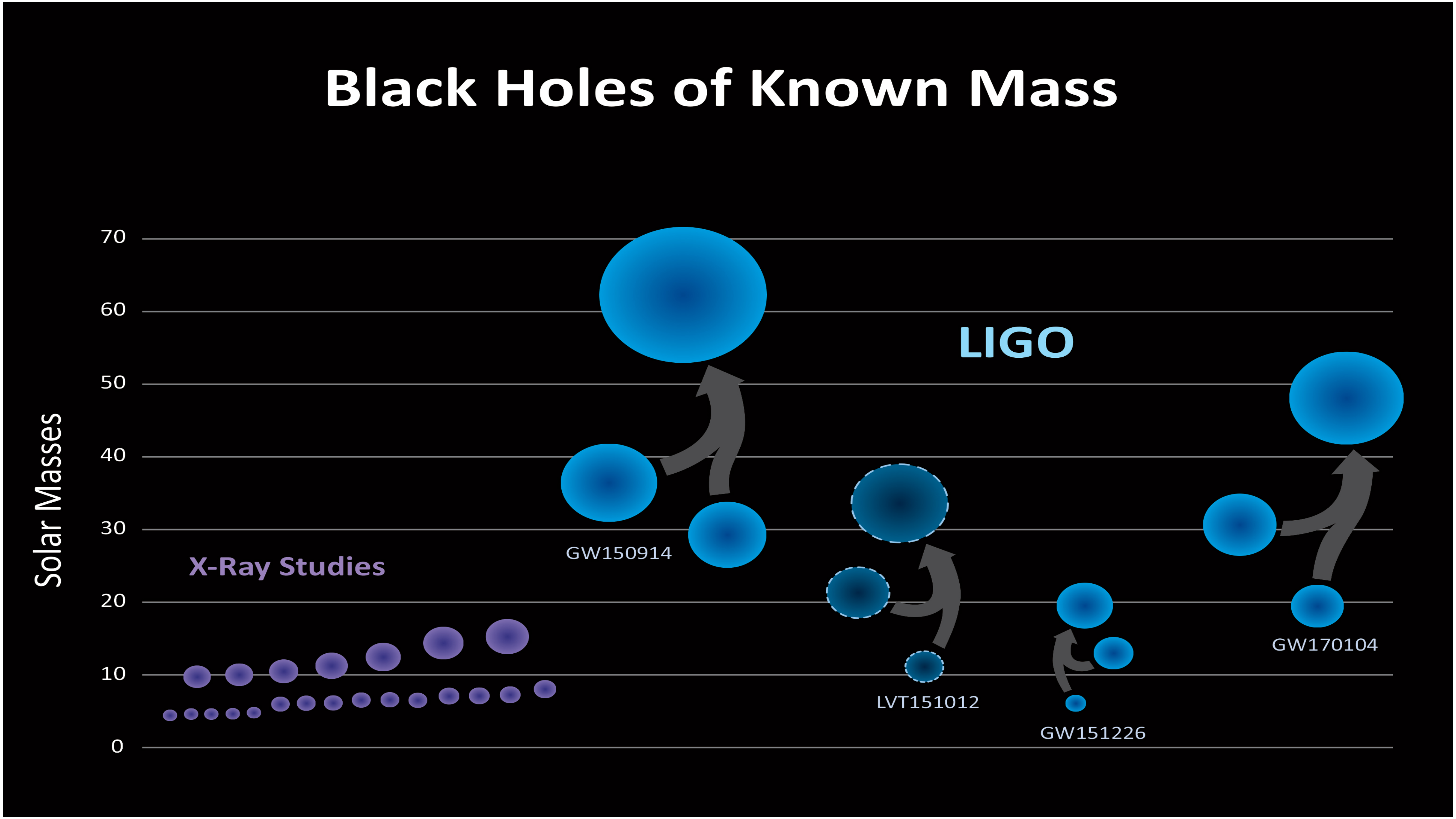
THE PRIMORDIAL POWER SPECTRUM IS NEARLY SCALE-INVARIANT WITH AN AMPLITUDE CLOSE TO 2×10^{-9}.

STRONGLY SUPPORT INFLATION AND MOTIVATE US TO OBTAIN OBSERVATIONS AND CONSTRAINTS REACHING TO SMALLER SCALES ON THE PRIMORDIAL CURVATURE POWER SPECTRUM AND BY IMPLICATION ON INFLATION.

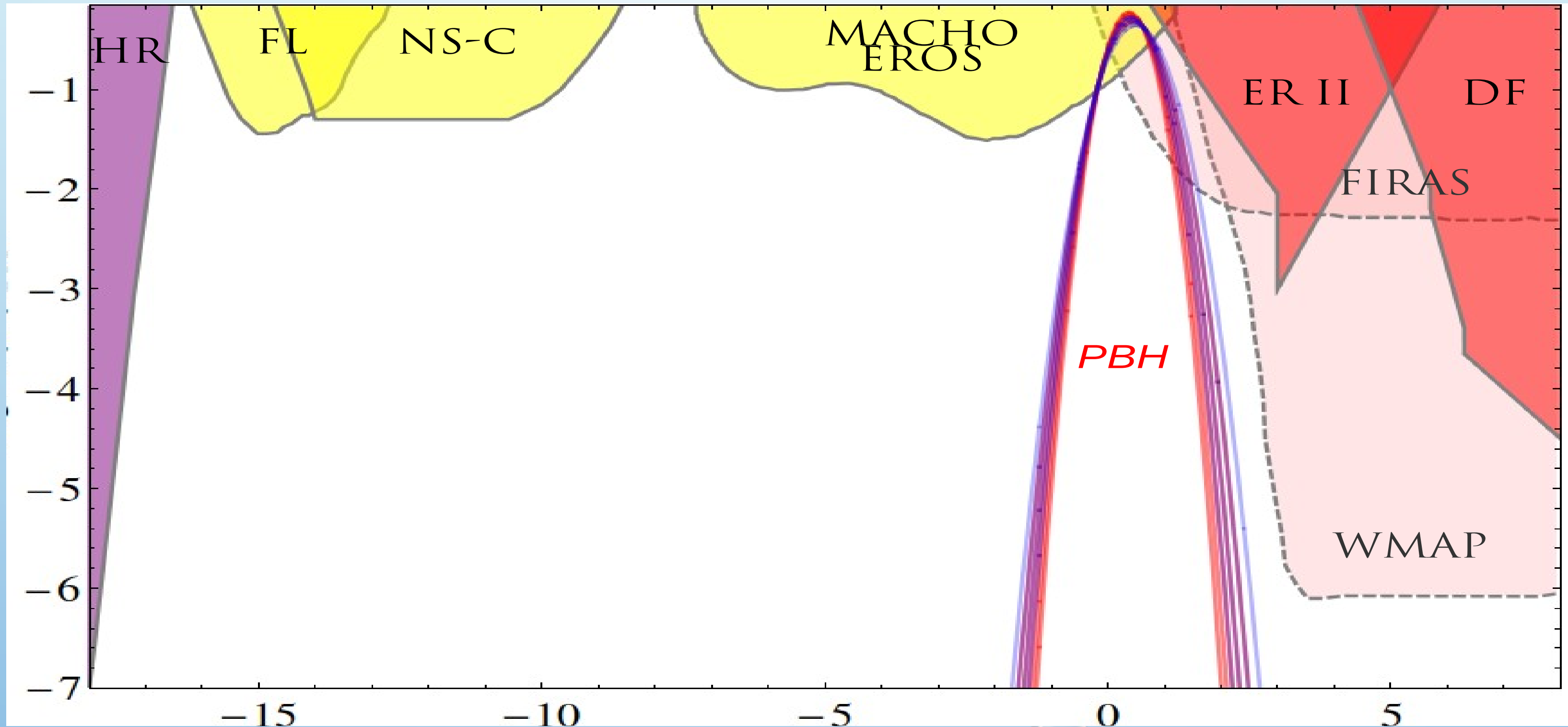
Outline:

- A quick introduction to Primordial Black Hole (PBH) as the Dark Matter,
- Observational Constraints on the primordial power-spectrum from PBHs,
- An introduction to Ultra Compact Mini-Halos (UCMH)
- Observational Constraints on the primordial power-spectrum from UCMH,
- Constraining the Dark Matter mass fraction for PBHs and UCMHs

“An Introduction to Primordial Black Holes (PBH)”


Black Holes of Known Mass
Solar Masses
70
60
50
40
30
20
10
0
X-Ray Studies
LIGO
GW150914
LVT151012
GW151226
GW170104

OBSERVATIONAL LIMITS ON COMPACT OBJECTS AS FRACTION OF DARK MATTER

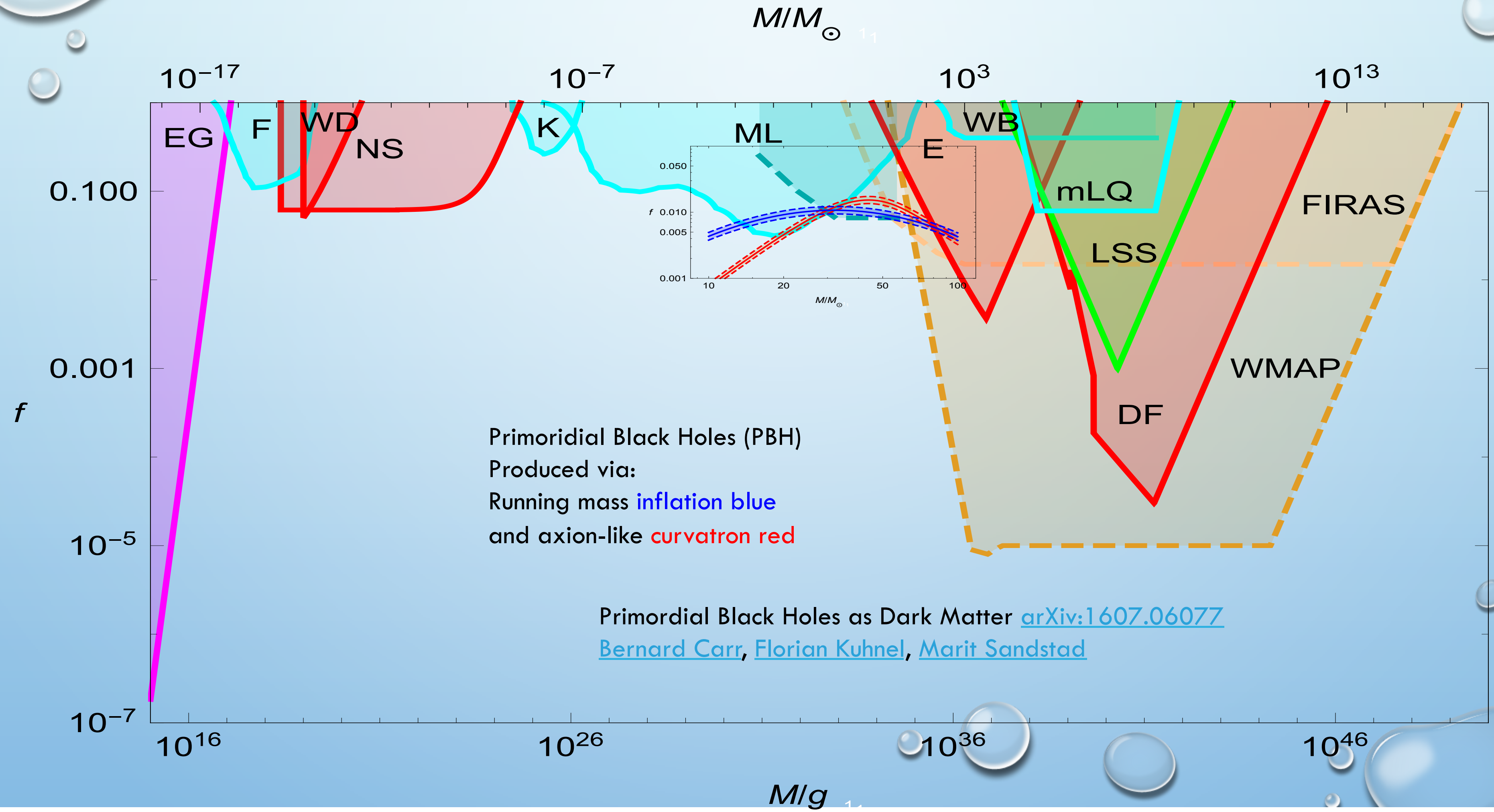


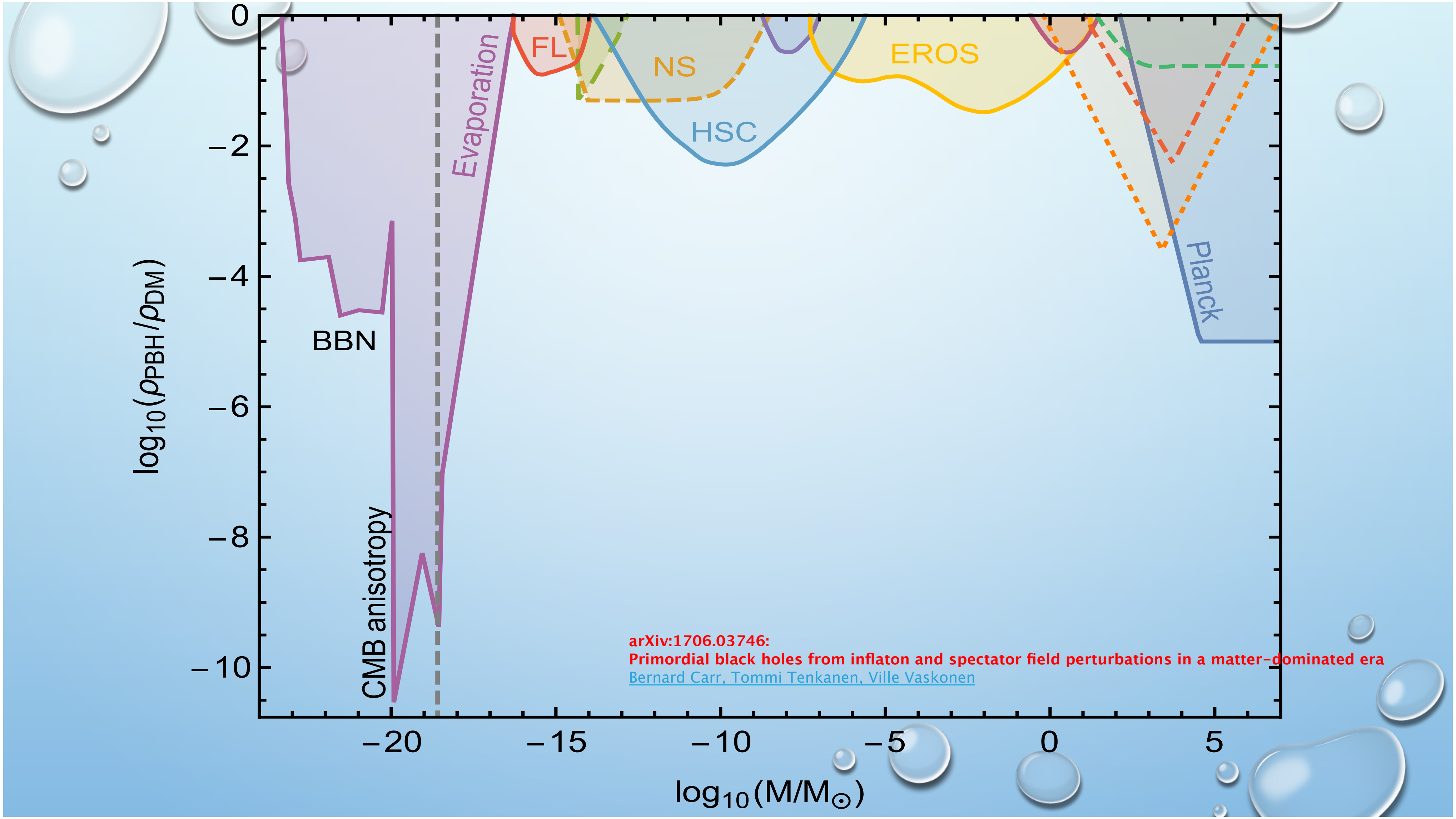
f_{DM}

Log (M/M_{Sun})

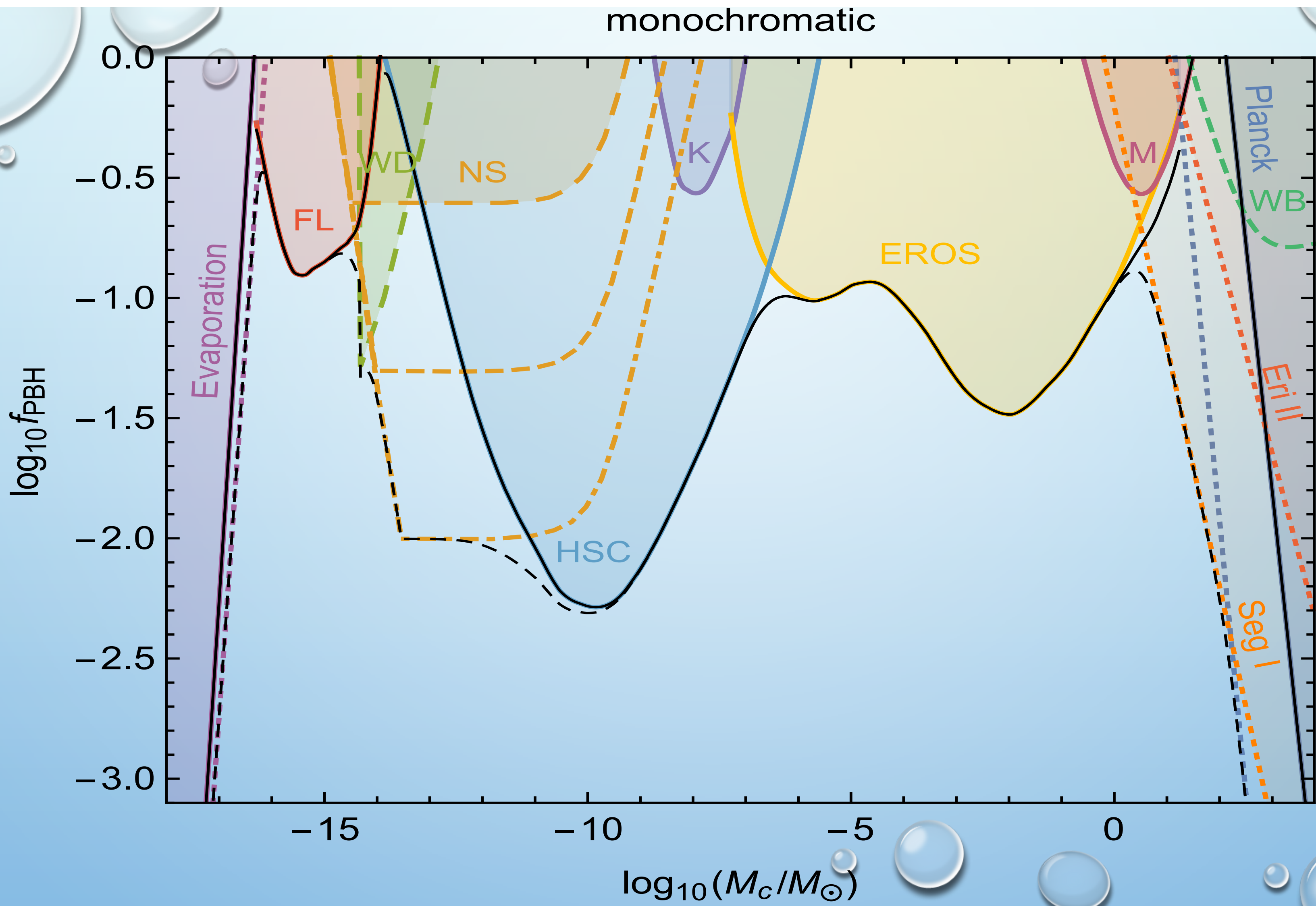
S. Blinnikov, A. Dolgov, N.K. Poraykoe, and K.Postnov arXiv:1611.00541

DARK MATTER MASS FRACTION LIMITS

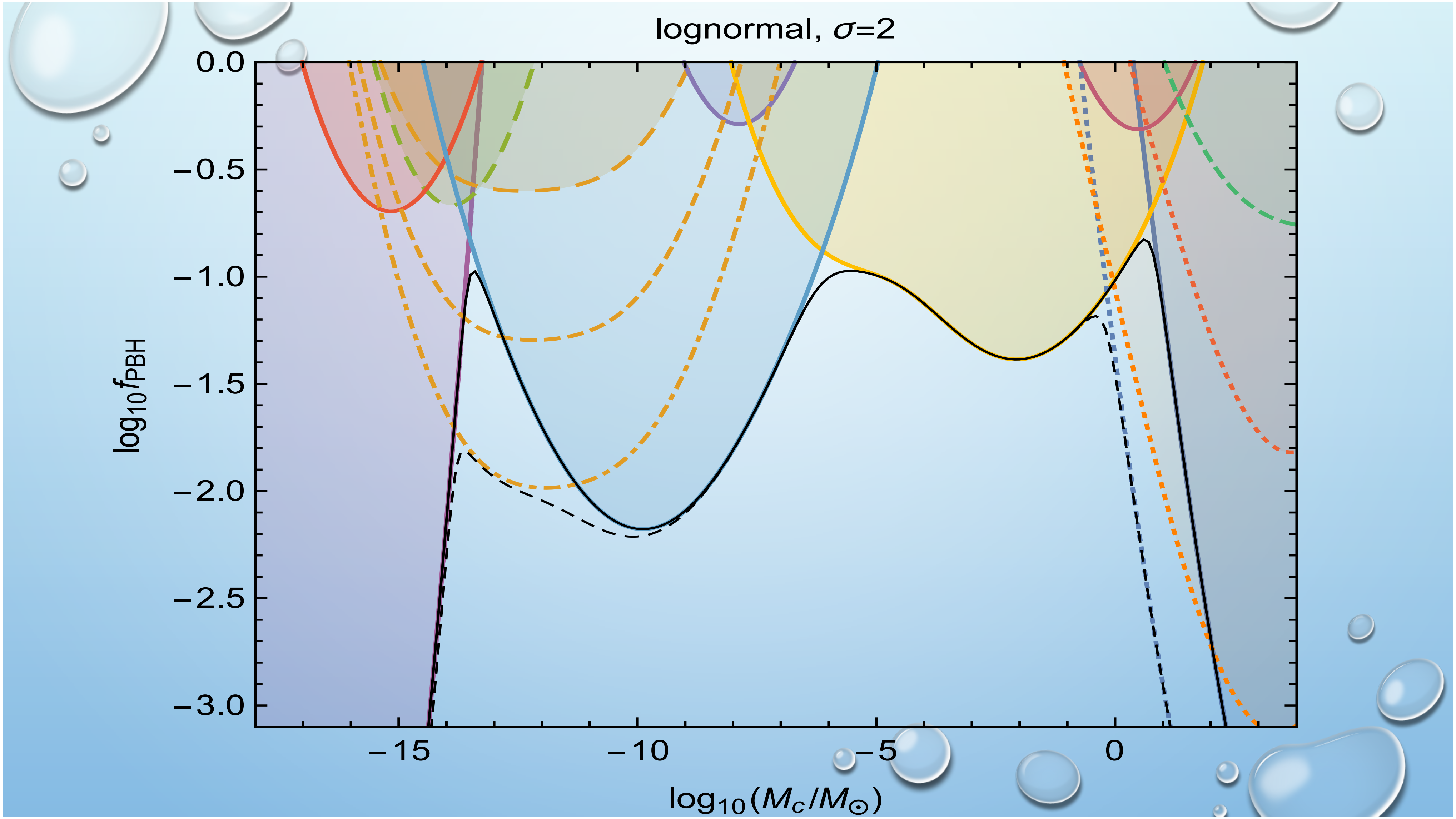




0
−2
−4
−6
−8
−10
−20
−15
−10
−5
0
5
$\log_{10}(\rho_{PBH}/\rho_{DM})$
$\log_{10}(M/M_\odot)$
BBN
CMB anisotropy
Evaporation
FL
NS
HSC
EROS
Planck
arXiv:1706.03746:
Primordial black holes from inflaton and spectator field perturbations in a matter-dominated era
Bernard Carr, Tommi Tenkanen, Ville Vaskonen



arXiv:1705.05567 [Primordial black hole constraints for extended mass functions Bernard Carr, Martti Raidal, Tommi Tenkanen, Ville Vaskonen, Hardi Veermäe



lognormal, σ=2
0.0
−0.5
−1.0
−1.5
−2.0
−2.5
−3.0
$\log_{10} f_{\mathrm{PBH}}$
−15
−10
−5
0
$\log_{10}(M_c/M_\odot)$

If the density perturbations at the stage of the horizon re-entry exceeds a threshold value, of order one, the gravity on that region will overcome the repulsive pressure and that area would be subjected to collapse and will form PBH.

$$M \simeq \frac{c^3 t}{G} \simeq 10^{15}\left(\frac{t}{10^{-23}}\right) g$$

Assuming that at every epoch, the mass of the PBH is a fixed fraction, f_M, of the horizon mass, we have,

$$\left(\frac{M}{M_{eq}}\right) \sim \left(\frac{g_{eq}}{g}\right)^{1/3}\left(\frac{k_{eq}}{k}\right)^2$$

Initial abundance of PBHs is given by:

$$\beta(M_{PBH}) \equiv \left(\frac{\rho^i_{PBH}}{\rho^i_{crit}}\right)$$

(Current) fraction of the mass of Milky Way halo in PBHs:

$$f_h = 4.11 \times 10^8 \left(\frac{M_{PBH}}{M_\odot}\right)^{-1/2}\left(\frac{g_{\star,i}}{106.75}\right)^{-1/4}\beta(M_{PBH})$$

Observational Constraints on the primordial power-spectrum form the PBH for Gaussian perturbations

For this purpose, we first figure out the observational constraints on the initial abundance of PBH. Then using the following formula, we could calculate the constraints on the primordial power-spectrum:

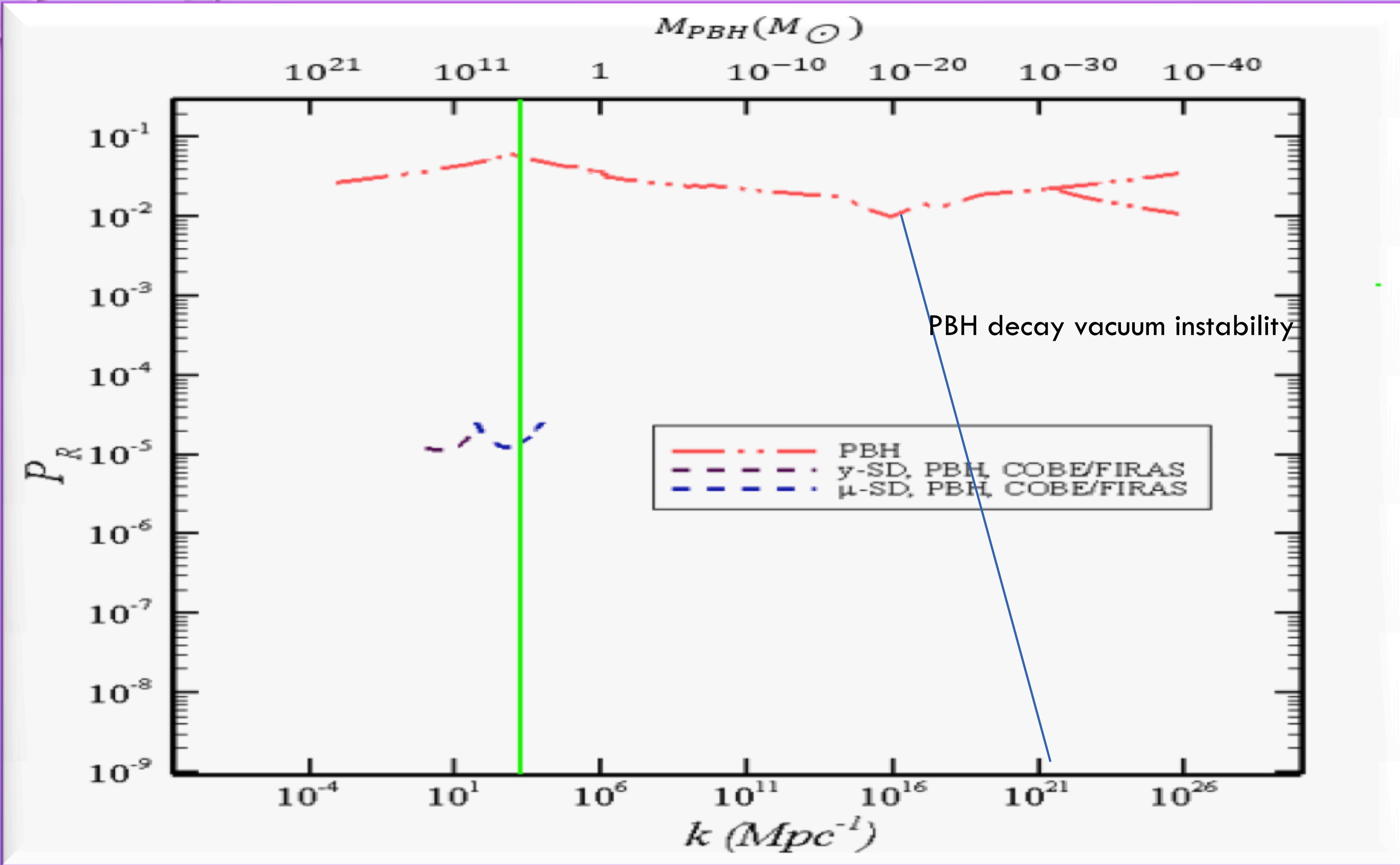
$$\beta(M_{PBH}) = 2f_M \int_{\delta_{crit}}^{1} P\left(\delta_{hor}(R)\right) d\delta_{hor}(R)$$

$$\sim f_M erfc\left(\frac{\delta_{crit}}{\sqrt{2}\sigma_{hor}(R)}\right)$$

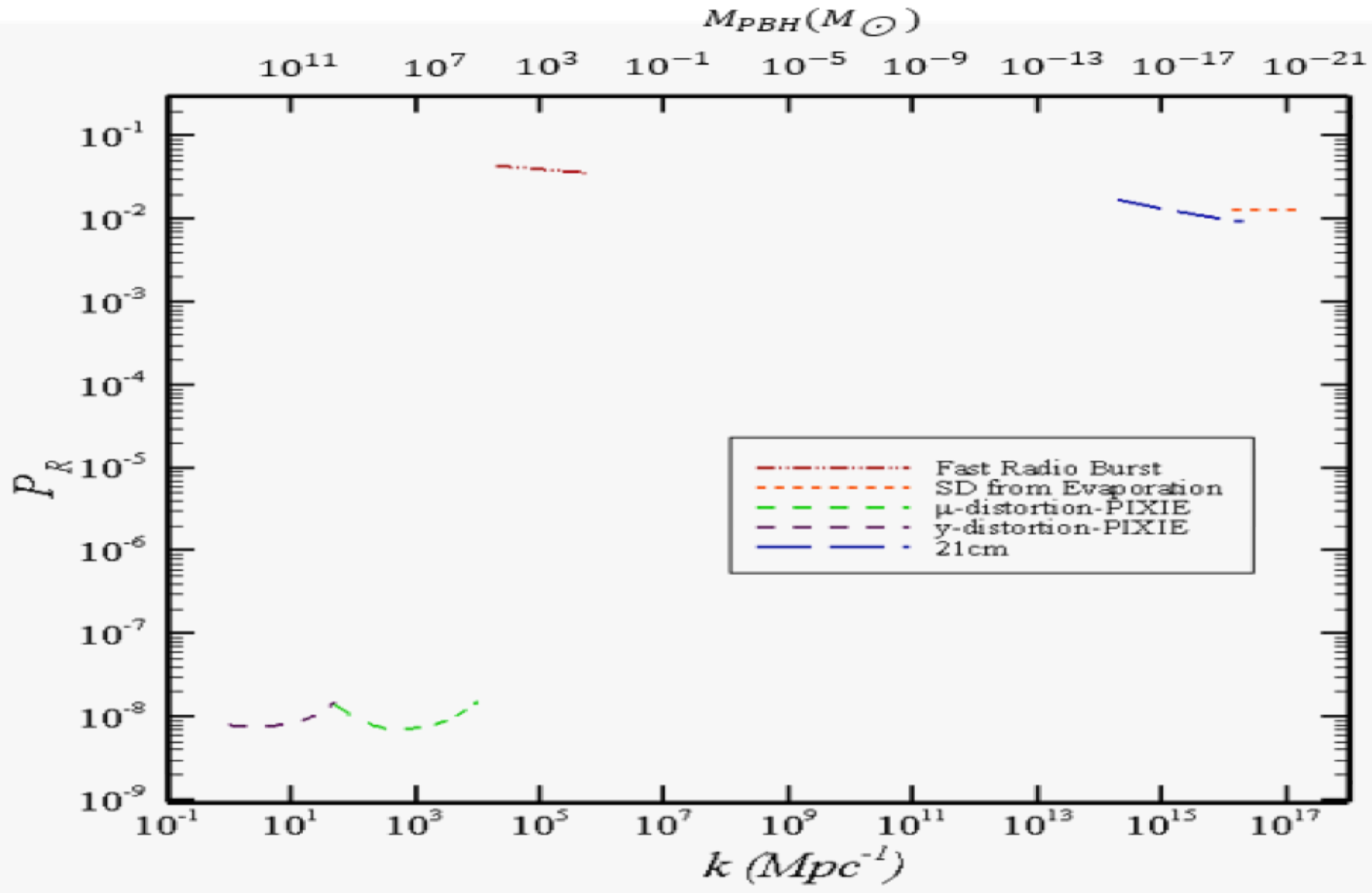
Constraints on the initial PBHs abundance, $\beta_{\rm PBH}$

description	wave number range	mass range	constraints on $\beta(M_{PBH})$
Disk heating	$10^{-3} \lesssim (k/Mpc^{-1}) \lesssim 10^{3}$	$10^{7} \lesssim (M_{PBH}/M_{\odot}) \lesssim 10^{18}$	$\lesssim 10^{-3}\left(f_M \frac{M_{PBH}}{M_{\odot}}\right)^{-1/2}$
Wide binary disruption	$800 \lesssim (k/Mpc^{-1}) \lesssim 10^{5}$	$10^{3} \lesssim (M_{PBH}/M_{\odot}) \lesssim 10^{8}$	$\lesssim 6 \times 10^{-11}\left(\frac{M_{PBH}}{f_M M_{\odot}}\right)^{1/2}$
Fast Radio Bursts	$2.9 \times 10^{4} \lesssim (k/Mpc^{-1}) \lesssim 9.2 \times 10^{5}$	$10 \lesssim (M_{PBH}/M_{\odot}) \lesssim 10^{4}$	$\lesssim 1.4 \times 10^{-9} F_D(M_{PBH})\left(\frac{M_{PBH}}{M_{\odot}}\right)^{1/2}$
Quasar microlensing	$1.2 \times 10^{5} \lesssim (k/Mpc^{-1}) \lesssim 6.5 \times 10^{7}$	$10^{-3} \lesssim (M_{PBH}/M_{\odot}) \lesssim 300$	$\lesssim 2 \times 10^{-10}\left(\frac{M_{PBH}}{f_M M_{\odot}}\right)^{1/2}$
Microlensing	$4.5 \times 10^{5} \lesssim (k/Mpc^{-1}) \lesssim 1.42 \times 10^{6}$ $1.42 \times 10^{6} \lesssim (k/Mpc^{-1}) \lesssim 1.4 \times 10^{9}$ $1.4 \times 10^{9} \lesssim (k/Mpc^{-1}) \lesssim 4.5 \times 10^{9}$	$1 \lesssim (M_{PBH}/M_{\odot}) \lesssim 10$ $10^{-6} \lesssim (M_{PBH}/M_{\odot}) \lesssim 1.0$ $10^{-7} \lesssim (M_{PBH}/M_{\odot}) \lesssim 10^{-6}$	$\lesssim 6 \times 10^{-11}\left(\frac{M_{PBH}}{f_M M_{\odot}}\right)^{1/2}$ $\lesssim 2 \times 10^{-11}\left(\frac{M_{PBH}}{f_M M_{\odot}}\right)^{1/2}$ $\lesssim \times 10^{-10}\left(\frac{M_{PBH}}{f_M M_{\odot}}\right)^{1/2}$
GRB femtolensing	$4.5 \times 10^{12} \lesssim (k/Mpc^{-1}) \lesssim 1.4 \times 10^{14}$	$10^{-16} \lesssim (M_{PBH}/M_{\odot}) \lesssim 10^{-13}$	$\lesssim 2 \times 10^{-10}\left(\frac{M_{PBH}}{f_M M_{\odot}}\right)^{1/2}$
Reionization and 21cm	$2 \times 10^{14} \lesssim (k/Mpc^{-1}) \lesssim 2 \times 10^{16}$	$10^{-20} \lesssim (M_{PBH}/M_{\odot}) \lesssim 10^{-16}$	$\lesssim 1.1 \times 10^{39}\left(\frac{M_{PBH}}{M_{\odot}}\right)^{7/2}$
CMB SD (COBE/FIRAS) CMB SD (PIXIE)	$2 \times 10^{16} \lesssim (k/Mpc^{-1}) \lesssim 2 \times 10^{17}$	$10^{-22} \lesssim (M_{PBH}/M_{\odot}) \lesssim 10^{-20}$	$\lesssim 10^{-21}$ $\lesssim 10^{-24}$
photodissociate D	$2 \times 10^{16} \lesssim (k/Mpc^{-1}) \lesssim 6.3 \times 10^{17}$	$10^{-24} \lesssim (M_{PBH}/M_{\odot}) \lesssim 10^{-21}$	$\lesssim 1.3 \times 10^{-10}\left(\frac{M_{PBH}}{f_M M_{\odot}}\right)^{1/2}$
Hadron injection	$6.3 \times 10^{17} \lesssim (k/Mpc^{-1}) \lesssim 6.3 \times 10^{18}$	$10^{-26} \lesssim (M_{PBH}/M_{\odot}) \lesssim 10^{-24}$	$\lesssim 10^{-20}$
Quasi-SMP	$3.7 \times 10^{16} \lesssim (k/Mpc^{-1}) \lesssim 6.3 \times 10^{18}$	$10^{-26} \lesssim (M_{PBH}/M_{\odot}) \lesssim 10^{-21}$	$\lesssim 7 \times 10^{-30}\left(\frac{M_{PBH}}{f_M M_{\odot}}\right)^{-1/2}$
LSP	$2 \times 10^{17} \lesssim (k/Mpc^{-1}) \lesssim 2 \times 10^{21}$	$10^{-31} \lesssim (M_{PBH}/M_{\odot}) \lesssim 10^{-25}$	$\lesssim 7 \times 10^{-30}\left(\frac{M_{PBH}}{f_M M_{\odot}}\right)^{-1/2}$
Planck relic	$2 \times 10^{21} \lesssim (k/Mpc^{-1}) \lesssim 7 \times 10^{25}$	$10^{-40} \lesssim (M_{PBH}/M_{\odot}) \lesssim 3 \times 10^{-31}$	$\lesssim 7 \times 10^{31}\left(\frac{M_{PBH}}{M_{\odot}}\right)^{3/2}$

The "Current" constraints on the primordial power-spectrum:



The “Futuristic” constraints on the primordial power-spectrum:



“An Introduction to UCMHs”
(Ultra Compact Mini-Halo objects)

UCMHs are dense dark matter structures, which can be formed from the larger over density perturbations right after the matter-radiation equality.

Density perturbations of the order 10^{-3} though its exact number is scale dependent as we will point it out in what follows, can collapse prior or right after the matter-radiation equality and therefore seed the formation of UCMHs.

$$M_i \simeq 1.3 \times 10^{11} \left(\frac{\Omega_\chi h^2}{0.112}\right)\left(\frac{Mpc^{-1}}{k}\right)^3 M_\odot$$

The Mass fraction of UCMHs is given by:

$$f_{UCMH} \equiv \frac{\Omega_{UCMh}(M^{(0)}_{UCMH})}{\Omega_{DM}} = \left[\frac{M_{UCMH}(z=0)}{M_{UCMH}(z_{eq}}\right]\beta(M_H(z_i)) = \left(\frac{400}{1.3}\right)\beta(M_H(z_i))$$

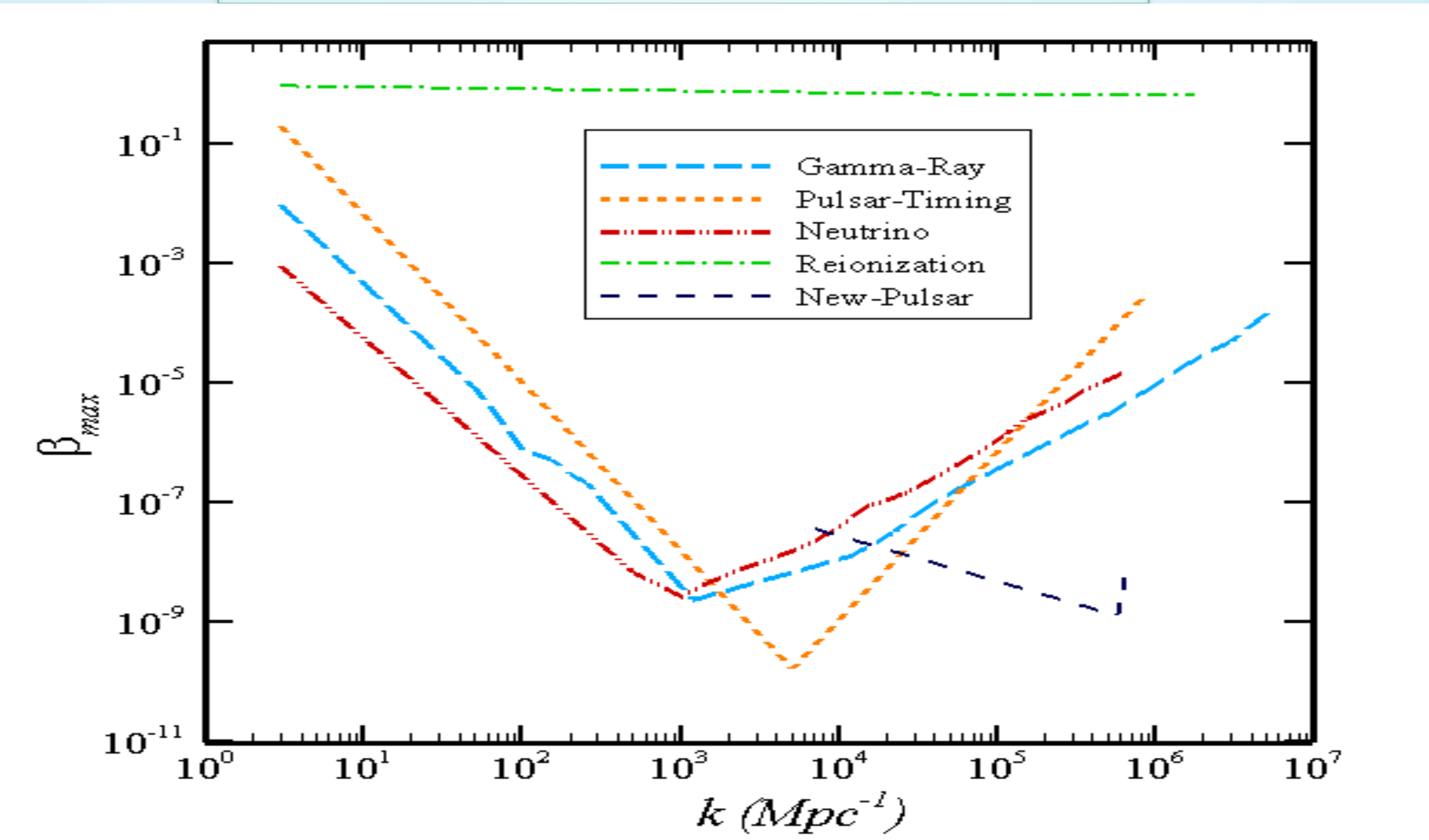
Observational Constraints on the primordial power-spectrum form the UCMHs

As for the PBHs, we first figure out the observational constraints on the initial abundance of UCMHs. Then, using the following formula, we calculate the constraints on the primordial power-spectrum:

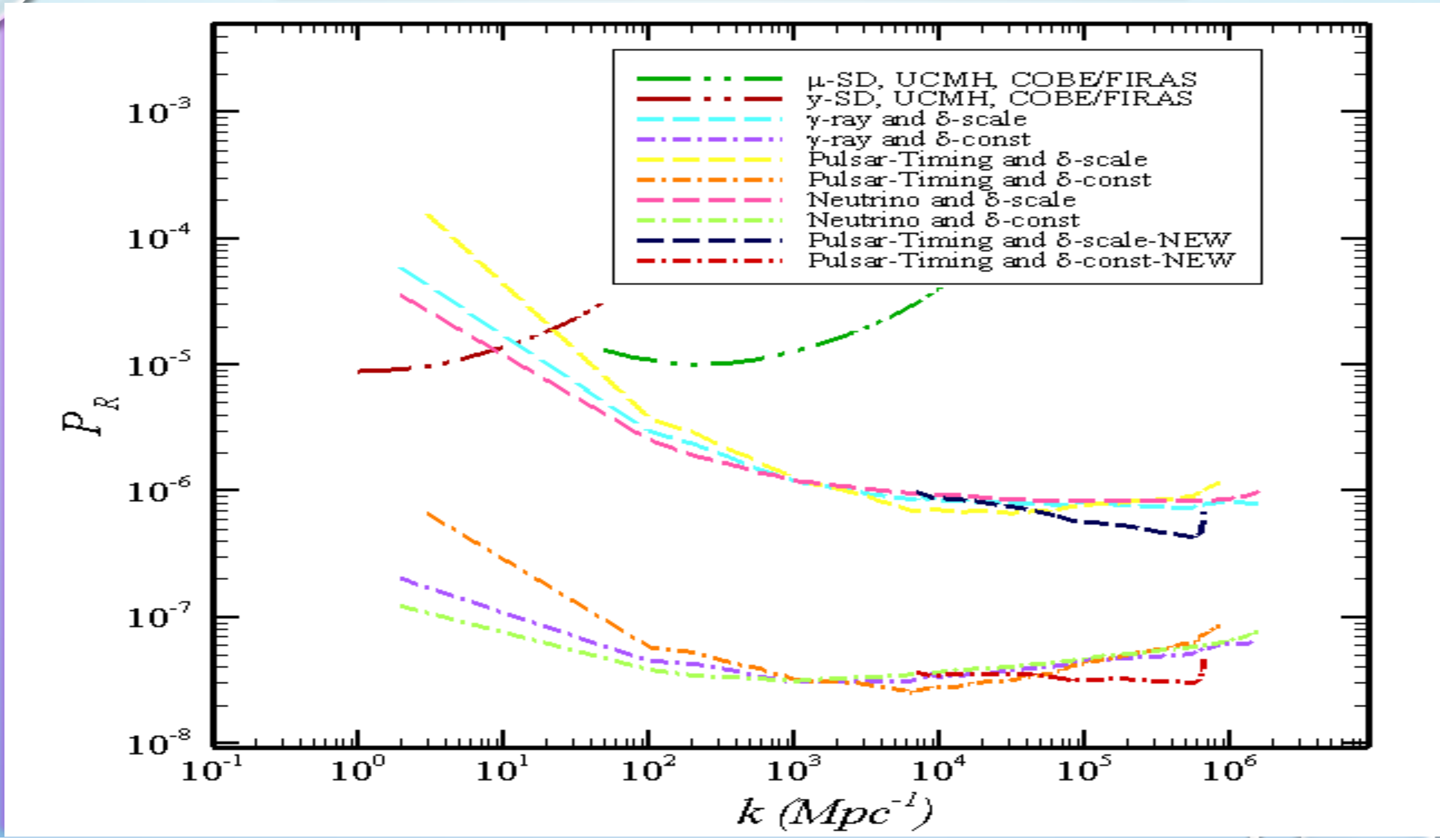
$$\beta(R) \simeq \left(\frac{\sigma_{hor}(R)}{\sqrt{2\pi}\delta_{min}}\right)\exp\left(-\frac{\delta_{min}^2}{2\sigma_{hor}^2(R)}\right)$$
$$\sim erfc\left(\frac{\delta_{min}}{\sqrt{2}\sigma_{hor}(R)}\right)$$

Unlike to the case of the PBHs, though, the minimal threshold for the over-density may be scale-dependent.

constraints on the initial UCMHs abundance, β_{UCMH} :



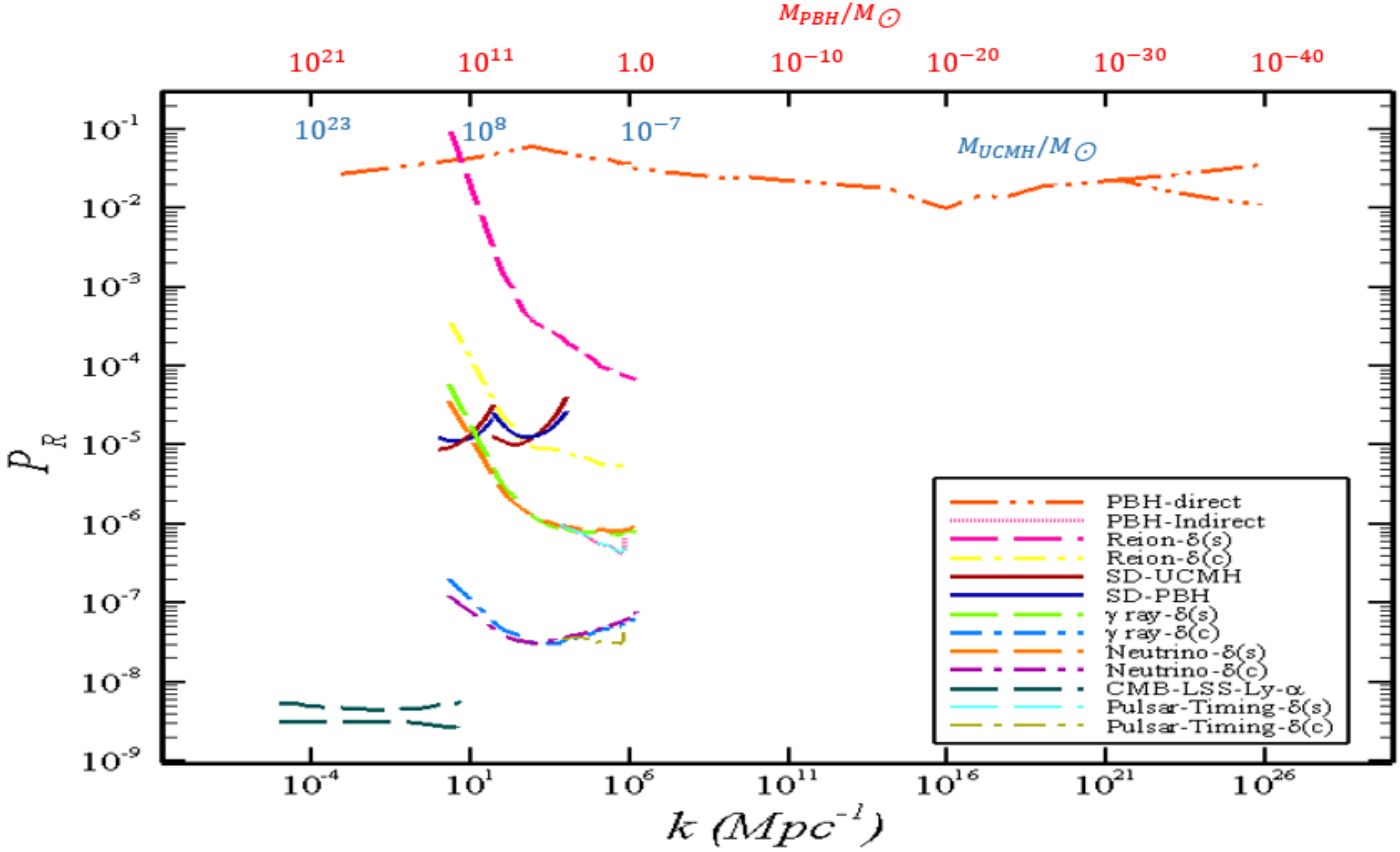
The observational constraints on the primordial power-spectrum:



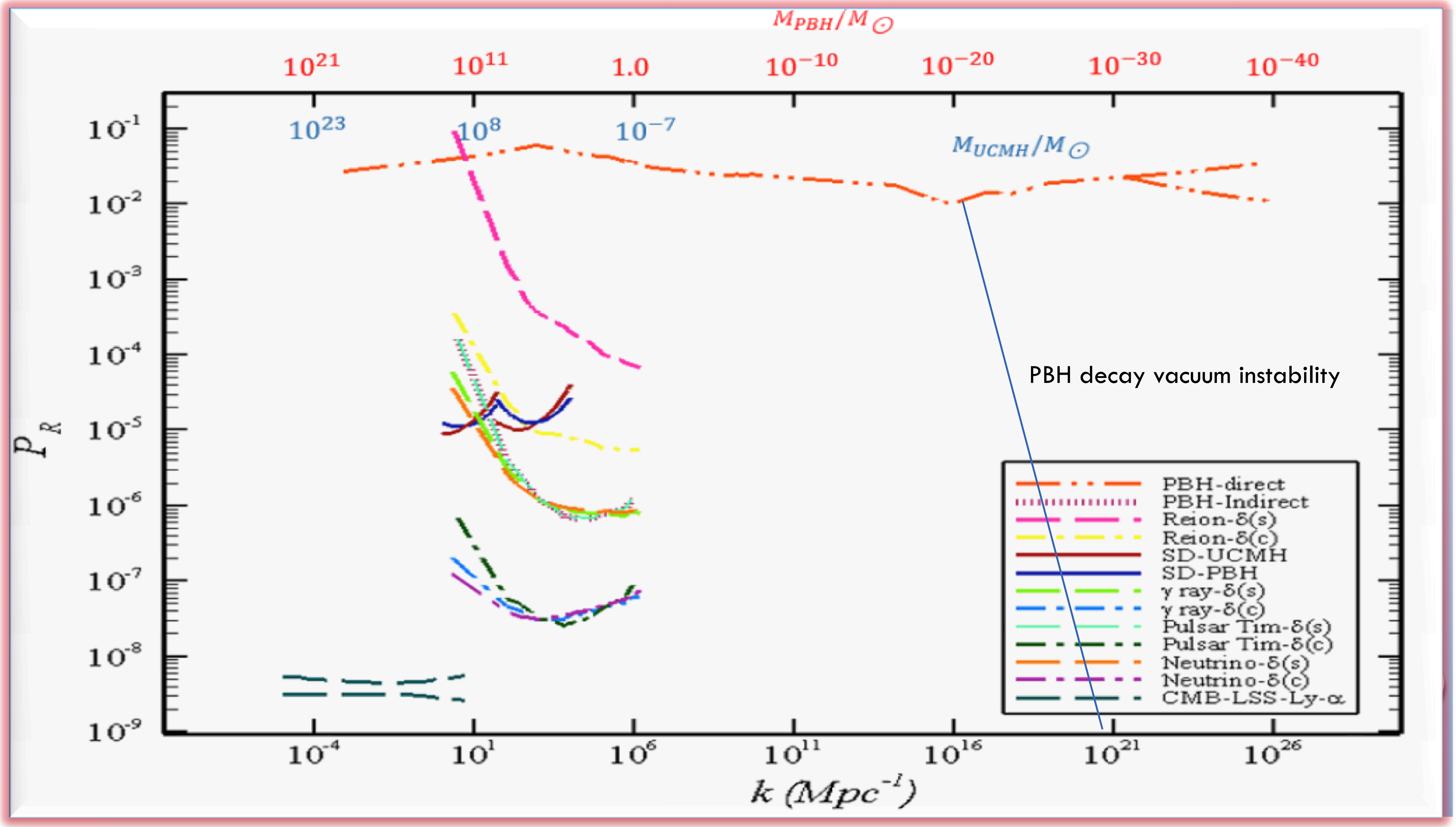
LACK OF UCMH OBJECTS IMPLIES LIMITS ON PBH

- LACK OF UCHM OBJECTS OBSERVATIONS IMPLIES STRONG LIMIT ON THE PRIMORDIAL POWER SPECTRUM
- IF THE PPS IS GAUSSIAN, THEN ESSENTIALLY NO FLUCTUATIONS OF STRENGTH TO PRODUCE PBH
  - IN THE RANGE $1 < K < 10^{6}$ MPC^{-1} OR IN ABOUT 1 $M_{SUN} < M_{PBH} < 10^{16}$ M_{SUN}
- THE PERTURBATION SPECTRUM WOULD HAVE TO BE NON-GAUSSIAN WITH A TINY FEATURE AT HIGH CURVATURE TO MAKE PBH

“Combined Constraints on the Primordial Power Spectrum from PBH as well as the UCMHs”



$M_{PBH}/M_{\odot}$
10^{21}
10^{11}
1.0
10^{-10}
10^{-20}
10^{-30}
10^{-40}
10^{23}
10^{8}
10^{-7}
$M_{UCMH}/M_{\odot}$
P_R
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-4}
10^{1}
10^{6}
10^{11}
10^{16}
10^{21}
10^{26}
$k\ (Mpc^{-1})$
PBH-direct
PBH-Indirect
Reion-δ(s)
Reion-δ(c)
SD-UCMH
SD-PBH
γ ray-δ(s)
γ ray-δ(c)
Neutrino-δ(s)
Neutrino-δ(c)
CMB-LSS-Ly-α
Pulsar-Timing-δ(s)
Pulsar-Timing-δ(c)



$M_{PBH}/M_{\odot}$
10^{21} 10^{11} 1.0 10^{-10} 10^{-20} 10^{-30} 10^{-40}
10^{23} 10^{8} 10^{-7}
$M_{UCMH}/M_{\odot}$
$P_{\mathcal{R}}$
10^{-1} 10^{-2} 10^{-3} 10^{-4} 10^{-5} 10^{-6} 10^{-7} 10^{-8} 10^{-9}
10^{-4} 10^{1} 10^{6} 10^{11} 10^{16} 10^{21} 10^{26}
$k\ (Mpc^{-1})$
PBH decay vacuum instability
PBH-direct
PBH-Indirect
Reion-δ(s)
Reion-δ(c)
SD-UCMH
SD-PBH
γ ray-δ(s)
γ ray-δ(c)
Pulsar Tim-δ(s)
Pulsar Tim-δ(c)
Neutrino-δ(s)
Neutrino-δ(c)
CMB-LSS-Ly-α

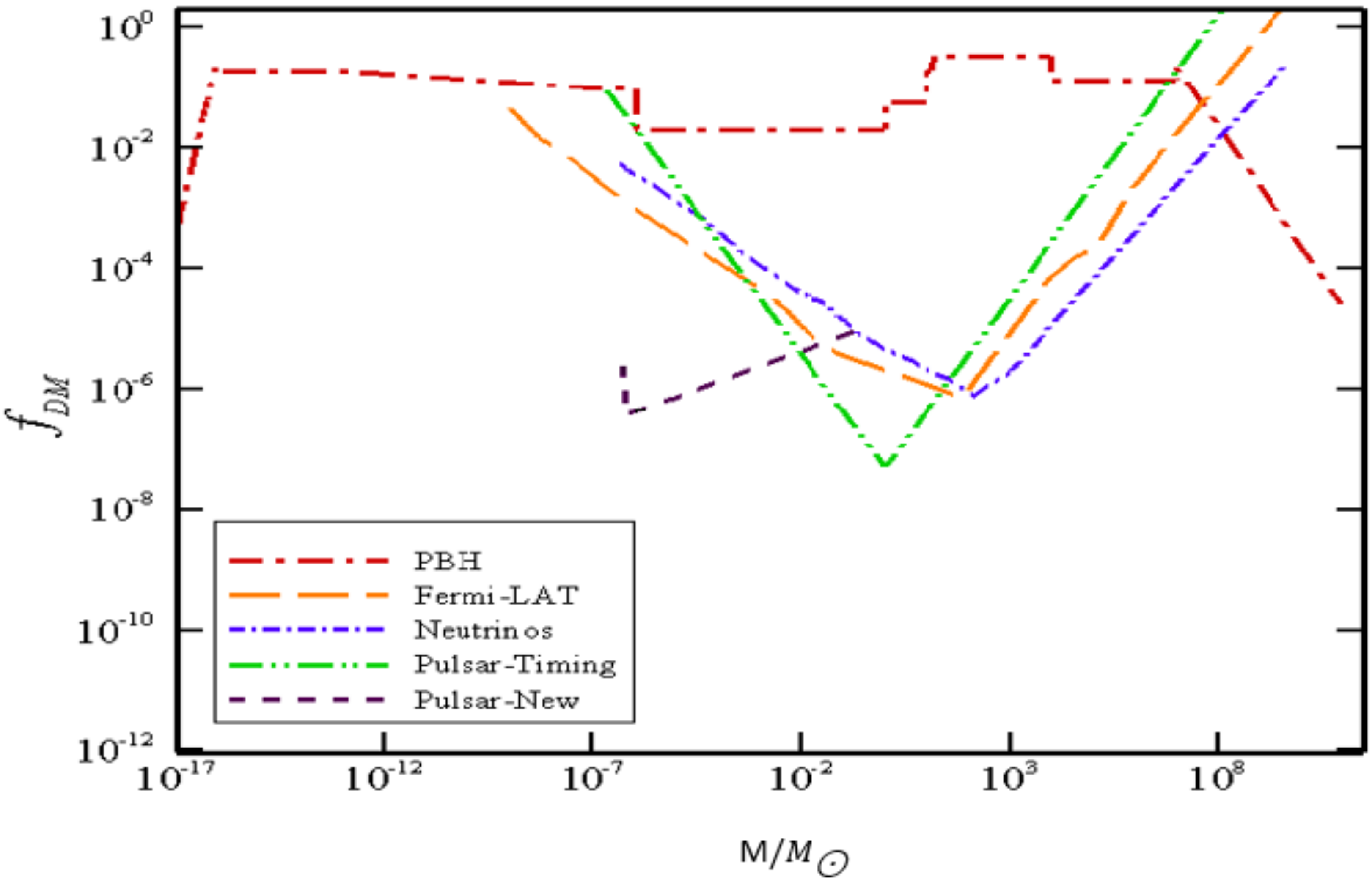
Conclusion:

- Introduced PBH and UCMHs as two examples of compact objects,

- Presented the observational constraints on the primordial power-spectrum from both of PBHs and UCMHs, Planck mass PBH decay and vacuum instability all leading to constraints on primordial perturbations and thus Inflation

- Finally, combining the constraints discussed the PBH abundance from the constraints coming from the UCMHs.

Thanks so much for your attention!



10^{0}
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
f_{DM}
PBH
Fermi-LAT
Neutrinos
Pulsar-Timing
Pulsar-New
10^{-17}
10^{-12}
10^{-7}
10^{-2}
10^{3}
10^{8}
$M/M_{\odot}$