Primordial Black Holes as the DM

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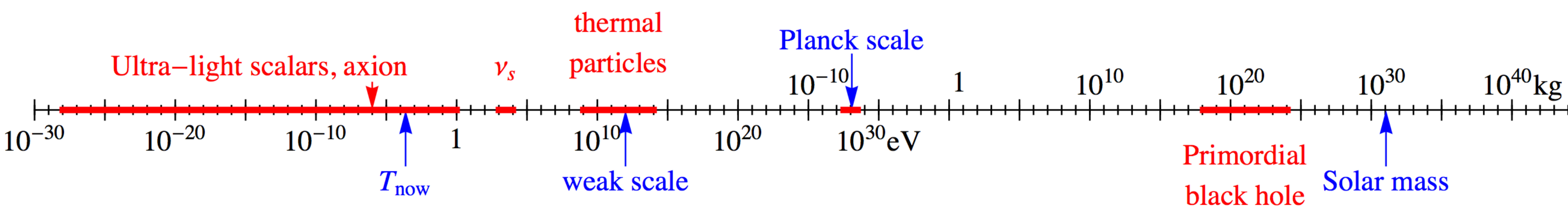
We still do not know the origin and properties of DM?

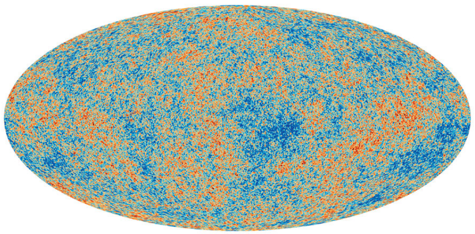


Spin-2 oscillations
arXiv: 1708.04253

Is the DM a manifestation of gravity?

PBHs – the oldest DM candidate

- Hawking (1971), Carr and Hawking (1974)
  - Primordial fluctuation of order 0.1 enter Universe at radiation era and collapse to BHs



PBHs -- frozen radiation energy density

- Hawking radiation (1974) changed the picture
  - Lower bound $M > 10^{-16}\, M_{\odot}$, macroscopic objects

The PBH cosmology

- At large scale PBHs are an ideal collisionless DM candidate, all the success of ΛCDM persists
- Predicts deviations from WIMPs at small scales
  - Seeds for galaxies and SMBHs, core vs. cusp, dwarf profiles, too big to fail (no stars by slingshot effect)
  - PBHs are the DM we want
- Provides new astrophysical probes of the DM
  - Stochastic GWs, reionisation and CMB, lensing, anomalous stars in Gaia, mass and spin of BHs, CR anomalies by accretion, predictions for inflation etc

Before the LIGO GW discovery – PBHs are ruled out as the dominant DM

- The only positive claim made by MACHO: $0.5M_{\odot}$ BHs observed. Later changed to

$$f_{\rm PBH} \equiv \Omega_{\rm PBH}/\Omega_{\rm DM} < 0.2$$

- The status before LIGO discovery of GWs was: the fraction of $1\ M_{\odot}$ PBH DM strongly constrained by the CMB measurements

LIGO discovery of GW changed physics: multi-messenger astronomy, tests of gravity with GW, tests of BH properties

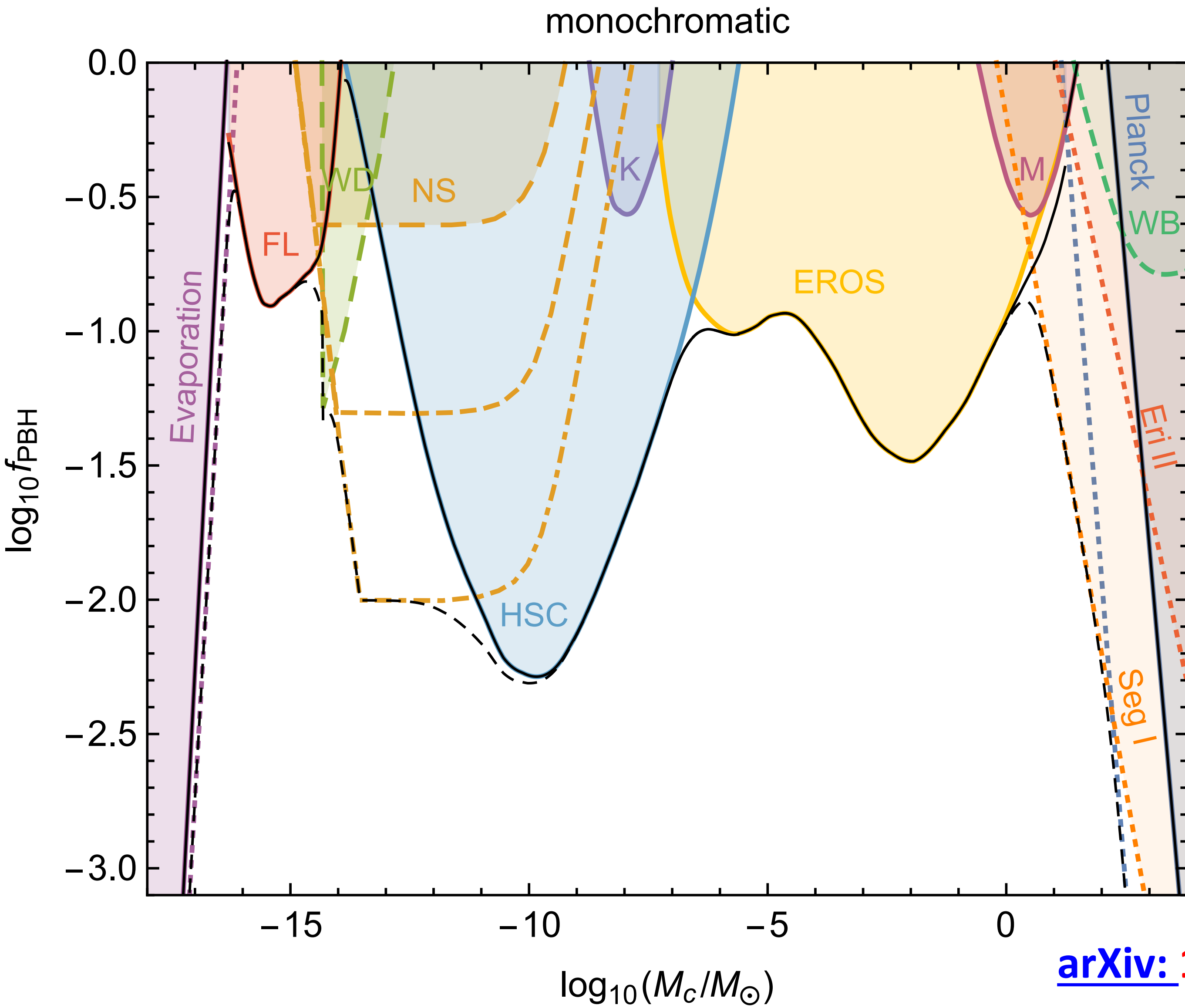
After LIGO:
10 $M_\odot$ PBH mass window opened

- Reanalysis of PBH accretion limits from CMB found $\sim 10^3$ cosmology error in previous papers

PRL 116 (2016) 201301

- All constraints are for monochromatic mass
  - Not realistic for any physical PBH creation mechanism

arXiv: 1705.05567



arXiv: 1705.05567

FIG. 1. *Upper left panel:* Constraints from different observations on the fraction of PBH DM, $f_{\rm PBH} \equiv \Omega_{\rm PBH}/\Omega_{\rm DM}$, as a function of the PBH mass M_c, assuming a monochromatic mass function. The purple region on the left is excluded by evaporations [8], the red region by femtolensing of gamma-ray bursts (FL) [40], the brown region by neutron star capture (NS) for different values of the dark matter density in the cores of globular clusters [41], the green region by white dwarf explosions (WD) [42], the blue, violet, yellow and purple regions by the microlensing results from Subaru (HSC) [43], Kepler (K) [44], EROS [45] and MACHO (M) [46], respectively. The dark blue, orange, red and green regions on the right are excluded by Planck data [36], survival of stars in Segue I (Seg I) [47] and Eridanus II (Eri II) [48], and the distribution of wide binaries (WB) [49], respectively.

Warning!

- Orders of magnitude astrophysical and cosmological uncertainties

- Large theoretical uncertainties – GR is non-renormalizable, physics beyond GR is not well defined

Hawking radiation has never been observed

- Quantum gravity effects are expected to be of order few

- Gravity theories beyond GR predict the existence of horizonless objects that mimic BHs (Exotic Compact Objects, ECOs)

- Their radiation rate might be exponentially suppressed compared to BHs

- All DM can be in light wormholes or other ECOs

hep-ph/180207728

All DM can be in light wormholes or other ECOs

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1. Quantum Gravity effects:

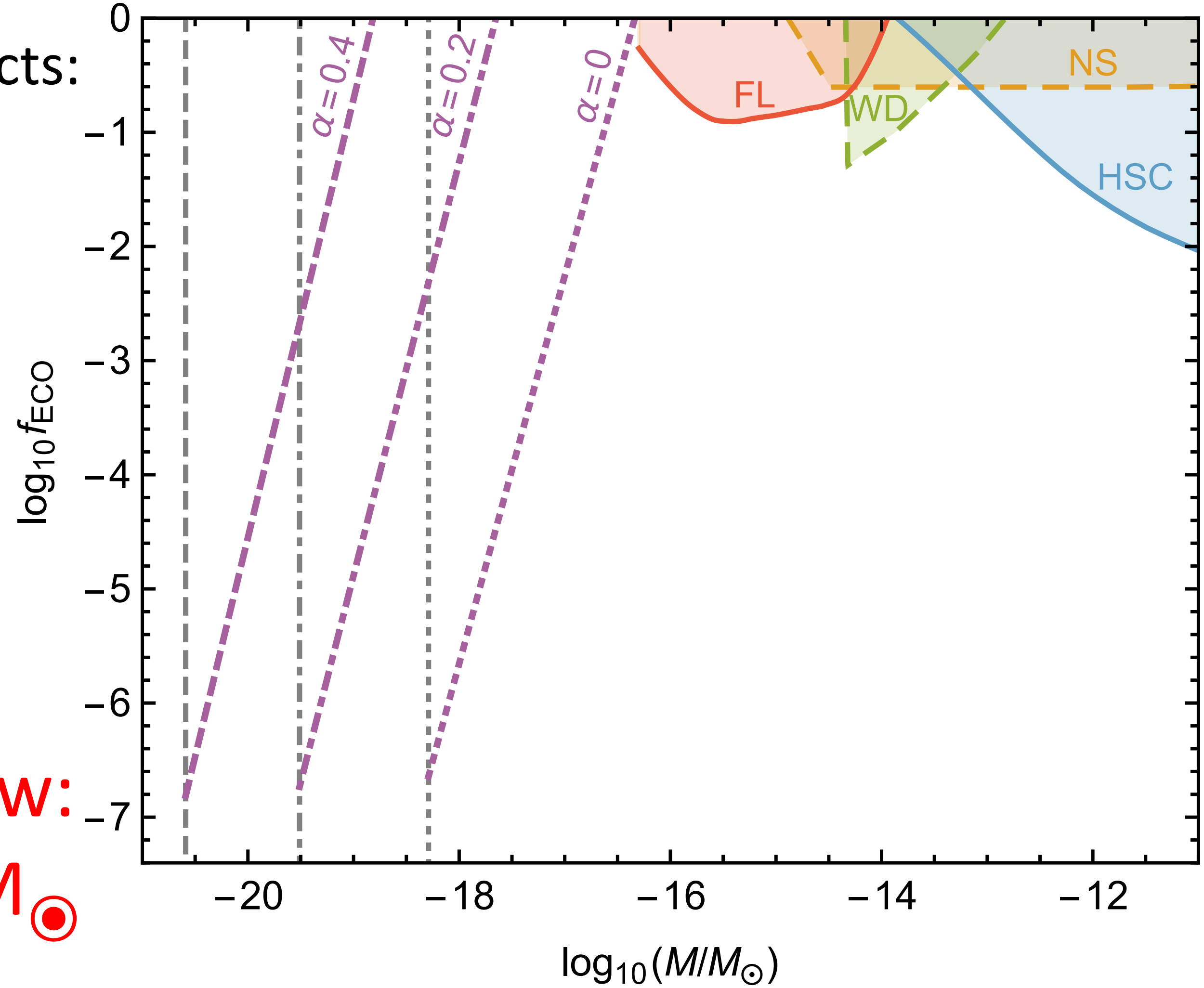
$$T \propto (M/\Lambda)^{\alpha}$$

2. THs beyond GR

$$T \propto \mathrm{Exp}(M/\Lambda)^{-1}$$

Scale of gravity:

$$10\ \mathrm{TeV} < \Lambda < M_P$$

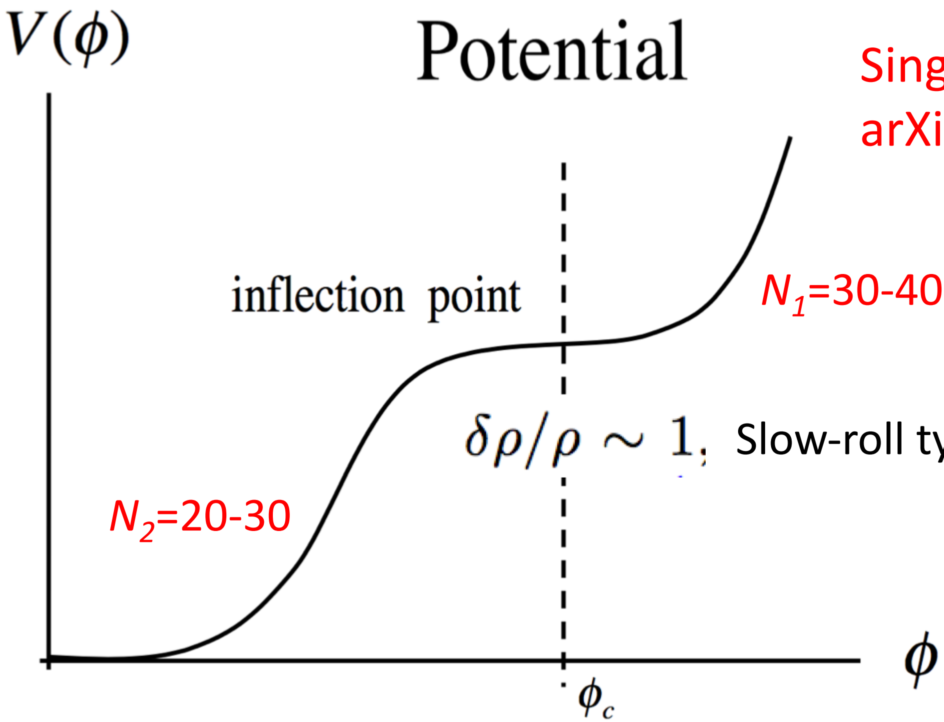


New mass window:

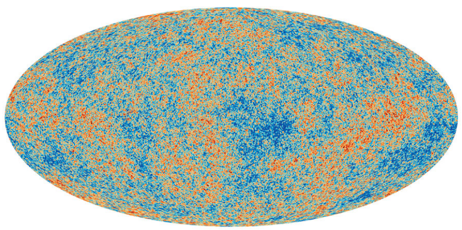
$$\Lambda < M_{ECO} < 10^{-16}\, M_{\odot}$$

How to produce the PBH population?

- Cartoon:



Single-field double inflation
arXiv:1705.06225



$$N = N_1 + N_2;$$

Slow-roll typically violated

- Potentials from the *Encyclopedia Inflationaris* are not usable – designed for *N*=50-60
- PBHs created at the end of inflation– must be light

Has LIGO observed the PBHs?

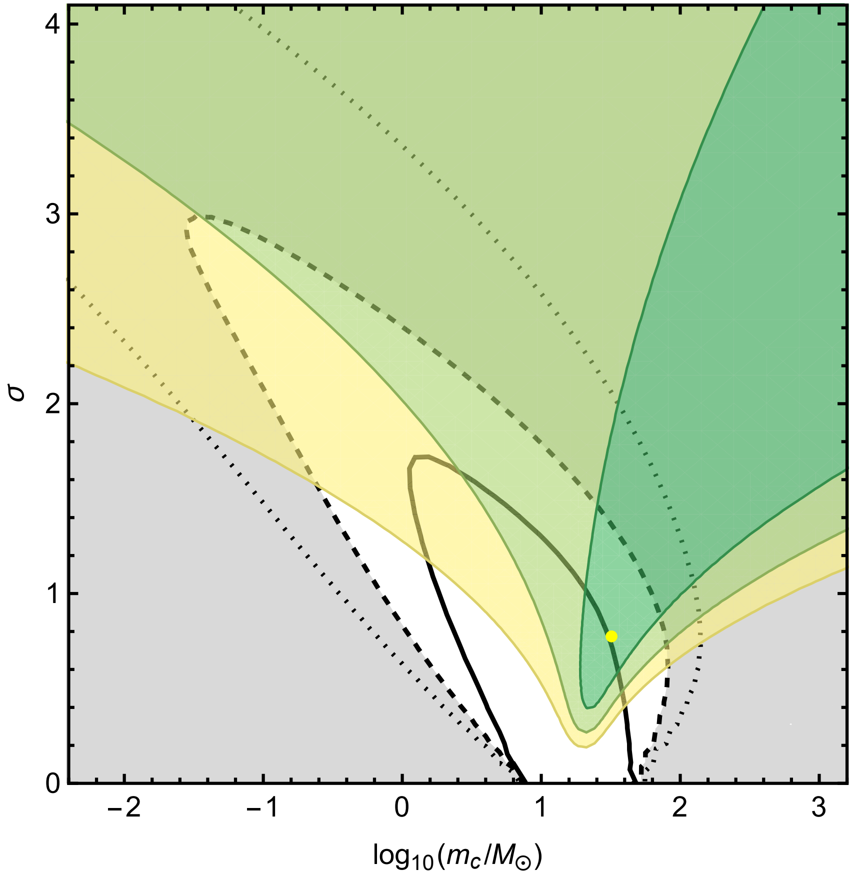
arXiv: 1707.01480

- To explain the LIGO rate with binaries forming today, enhancement of 10^8 is needed
- We compute the PBH binary formation and merger rate in the early Universe considering:
  - Three PBH approximation
  - Extended mass functions
  - Allowing for arbitrary PBH clustering, δ>>1

$$R_3(t_0) \approx 5.1 \times 10^4 \delta_{\rm dc}^{16/37} f_{\rm PBH}^{53/37} \left(\frac{m_c}{30 M_\odot}\right)^{-32/37} {\rm Gpc}^{-3}{\rm yr}^{-1}$$

LIGO rate: $12 - 213\,{\rm Gpc}^{-3}{\rm yr}^{-1}$

A fit to LIGO data assuming lognormal mass function for PBHs



	$m_1/M_\odot$	$m_2/M_\odot$	η
GW150914 [1]	36^{+5}_{-4}	29^{+4}_{-4}	$0.247^{+0.005}_{-0.005}$
GW151226 [2]	$14.2^{+8.3}_{-3.7}$	$7.5^{+2.3}_{-2.3}$	$0.226^{+0.046}_{-0.028}$
LVT151012 [3]	23^{+18}_{-6}	13^{+4}_{-5}	$0.231^{+0.054}_{-0.030}$
GW170104 [4]	$31.2^{+8.4}_{-6.0}$	$19.4^{+5.3}_{-5.9}$	$0.236^{+0.021}_{-0.020}$

$$(m_c, \sigma) = (33M_\odot, 0.8)$$

$$f_{\rm PBH} = 0.0045 - 0.024.$$

- Just a small fraction $0.0027 - 0.018$ of PBH DM is in binaries

Predictions for stochastic GW background

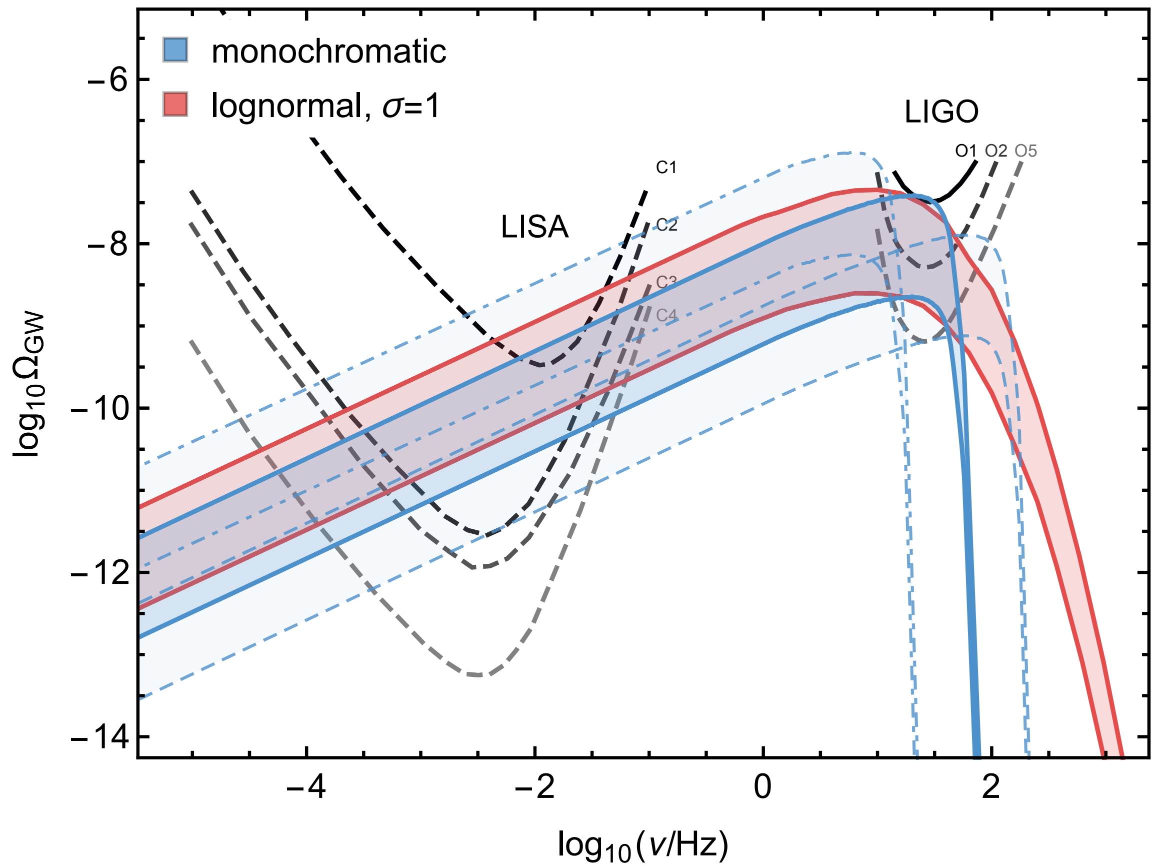
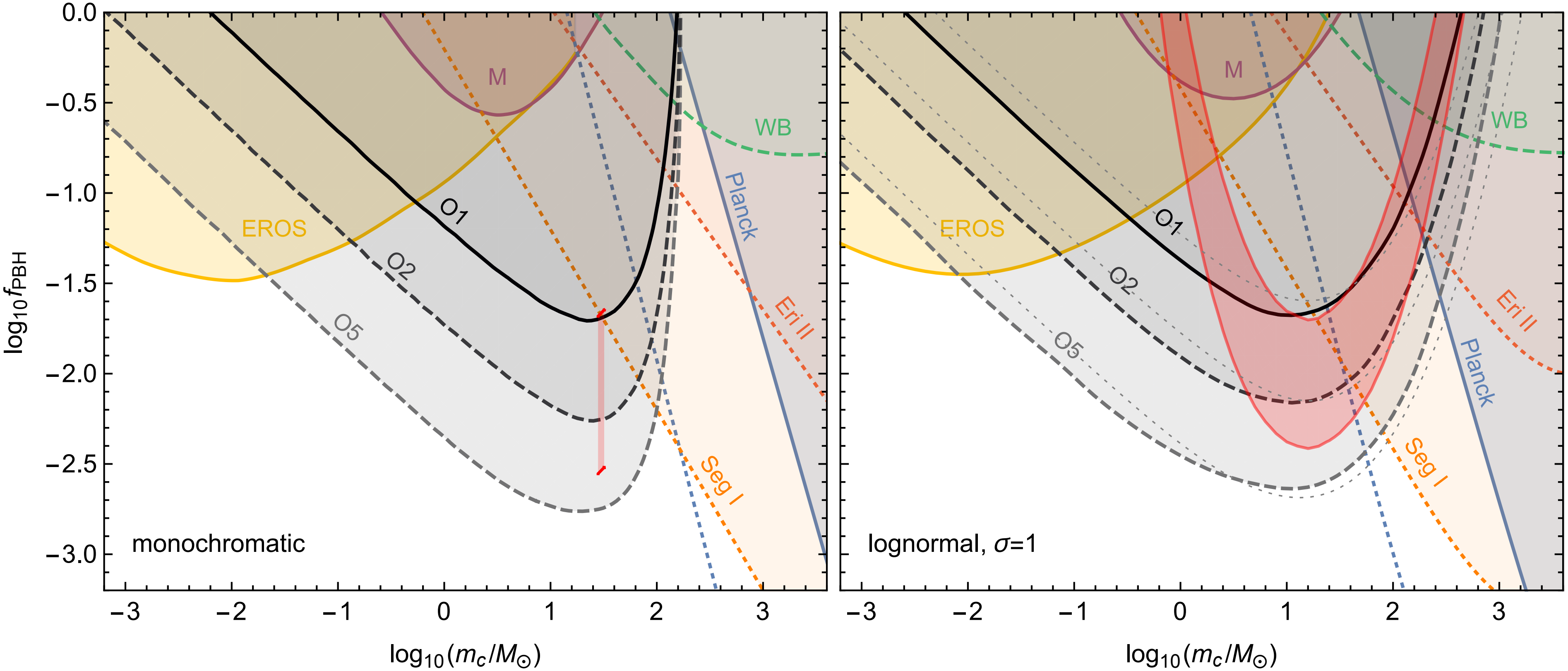


Figure 2. The stochastic GW background from the PBH mergers. The fraction of DM in PBHs is chosen such that the merger rate in the LIGO sensitivity range today is $12\,{\rm Gpc}^{-3}{\rm yr}^{-1}$ for the lower lines and $213\,{\rm Gpc}^{-3}{\rm yr}^{-1}$ for the upper lines, corresponding to $f_{\rm PBH} \sim 0.001 - 0.01$. For the solid lines $m_c = 30M_{\odot}$, and for the dashed and dot-dashed lines $m_c = 10, 100M_{\odot}$, respectively. The black

Non-observation of the GW background implies bound on the PBH mass fraction



- Non-observation of the GW background by LISA will exclude the primordial origin of the LIGO events

Conclusions

- PBHs may constitute a fraction of the DM
  - Several bounds must be better understood
  - Future observations (Gaia) must see the PBH effects in astrophysics
- Single field double inflation may produce light PBHs
  - Unusual potentials, slow roll approximation is usually violated, precise computations are needed
- Stochastic GW bkg. offers most sensitive tests of PBHs
  - Fits suggest: just a small fraction of DM in PBHs
  - PBH DM can be excluded by non-observation of the GW background by LIGO and LISA
- However, all the DM can be in the form of light ECOs, requiring gravity theories beyond GR