Dark Matter, Inflation, GW and Primordial Black Holes

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arXiv: 1705.05567
arXiv: 1705.06225
arXiv: 1707.01480

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The success of ΛCDM: DM does exist!

- ΛCDM – 5x more DM than baryons
    - CMB, BAO
    - Large scale structure
    - Bullet cluster
    - Galactic rotation curves, dwarf galaxies
    - Etc.
- All attempts to test the DM beyond gravity have failed
    - Direct detection experiments
    - Indirect detection
    - Colliders
    - Various dedicated laboratory experiments

Should we rethink our approaches?

- There is still plenty of room for discoveries
  - There are many generic DM production mechanism
  - Experimental programs are continuing

- May be Nature wants to tell us something?
  - Nervousness in our community from the experimental failures is there
  - People are looking for all sort of alternatives

Is the DM of purely gravitational origin?

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The minimal requirement:
the success of ΛCDM must be preserved.
Excludes MOND.

BGR: Is DM gravitational spin-2 field?

- Bimetric gravity – the only known consistent, ghost-free extension of GR with massive and interacting spin-2 fields

- Gravitational freeze-in via 2$\leftrightarrow$2 scatterings
  - Gravitational WIMP with TeV mass scale

arXiv: 1604.08564
arXiv: 1607.03497

- Coherently oscillating massive spin-2 field
  - Like gravitational ALPs in the 10^{-23} eV to 0.1 eV range
  - Predicts oscillation of electric charge, gravity becomes testable in lab. experiments

arXiv: 1708.04253

GR&LIGO: Can the DM be in the form of primordial black holes?

- Constraints on PBH for extended mass function
  - My background knowledge 6 months ago: PBHs as DM are excluded. Is it so?

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- Production of PBHs with inflation
  - Is this scenario consistent? What is the predicted mass function?

arXiv: 1705.06225

- PBH binary merger rate, gravity waves, CMB vs. supernova Hubble constant measurements
  - Can PBHs → GWs (dark radiation) explain the 3σ anomaly?

arXiv: 1707.01480

History and features of PBH DM

- Hawking (1971), Carr and Hawking (1974)
- 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)
- Provides new 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

See Garcia-Bellido, 1702.08275 for a shopping list

History of PBHs (cont.)

- Experimental constraints exist for large PBH mass window $10^{-18}M_{\odot}$ to $10^{4}M_{\odot}$
- 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 events triggered a big change

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

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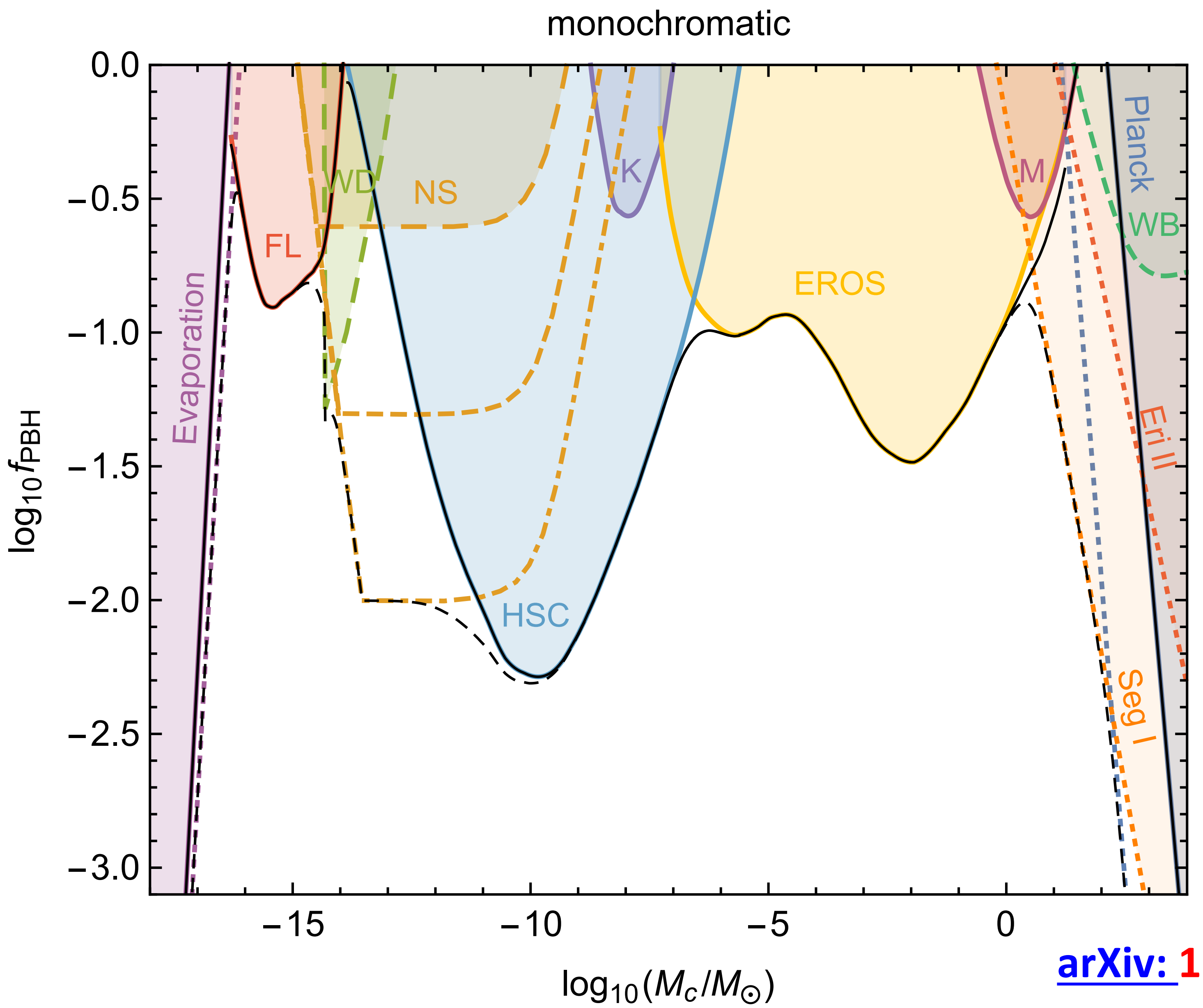
- Many systems constraining PBHs are not well understood (lot of wishful thinking in all directions)
  - Halo mass, profile and substructure (lensing, wide binaries), BH masses (SMBH), consistency of dwarfs
  - None of those features are properly studied in this context
- All constraints are for monochromatic mass
  - Not realistic for any physical PBH creation mechanism



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.

Lognormal mass function

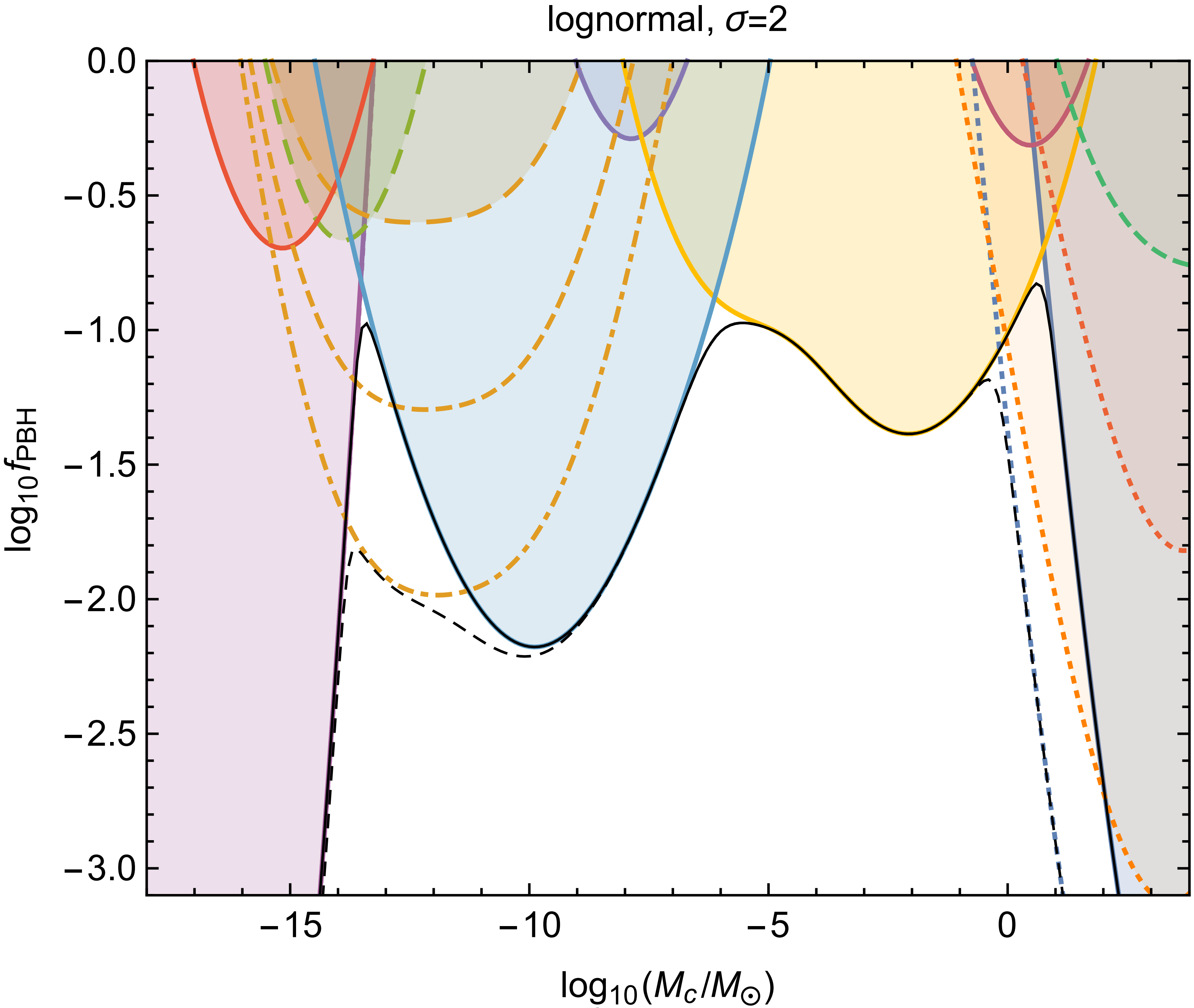
- Assume a mass function of the form

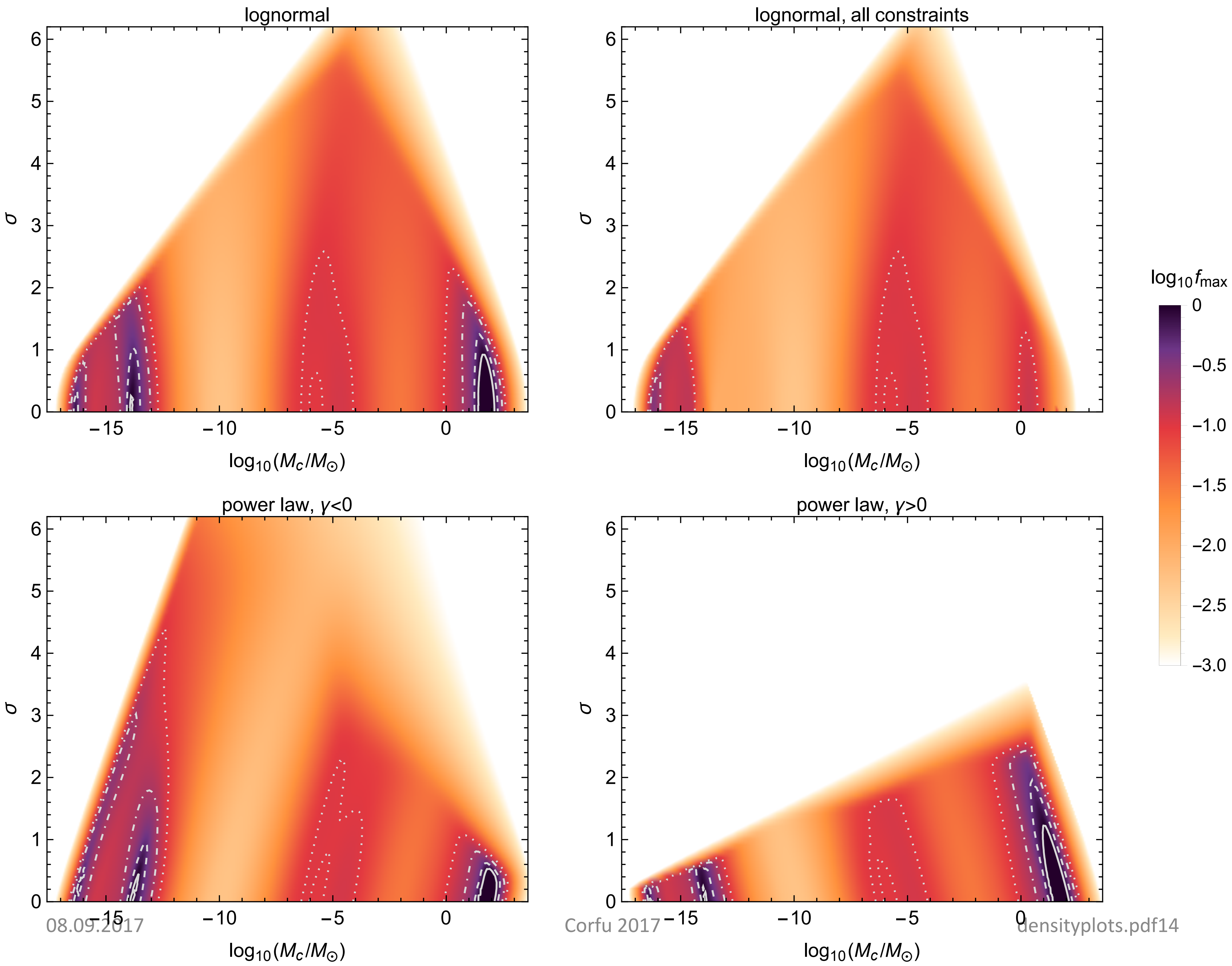
$$\psi(M) = \frac{f_{\rm PBH}}{\sqrt{2\pi}\sigma M} \exp\left(-\frac{\log^2(M/M_c)}{2\sigma^2}\right)$$

- We converted the bounds for mass functions

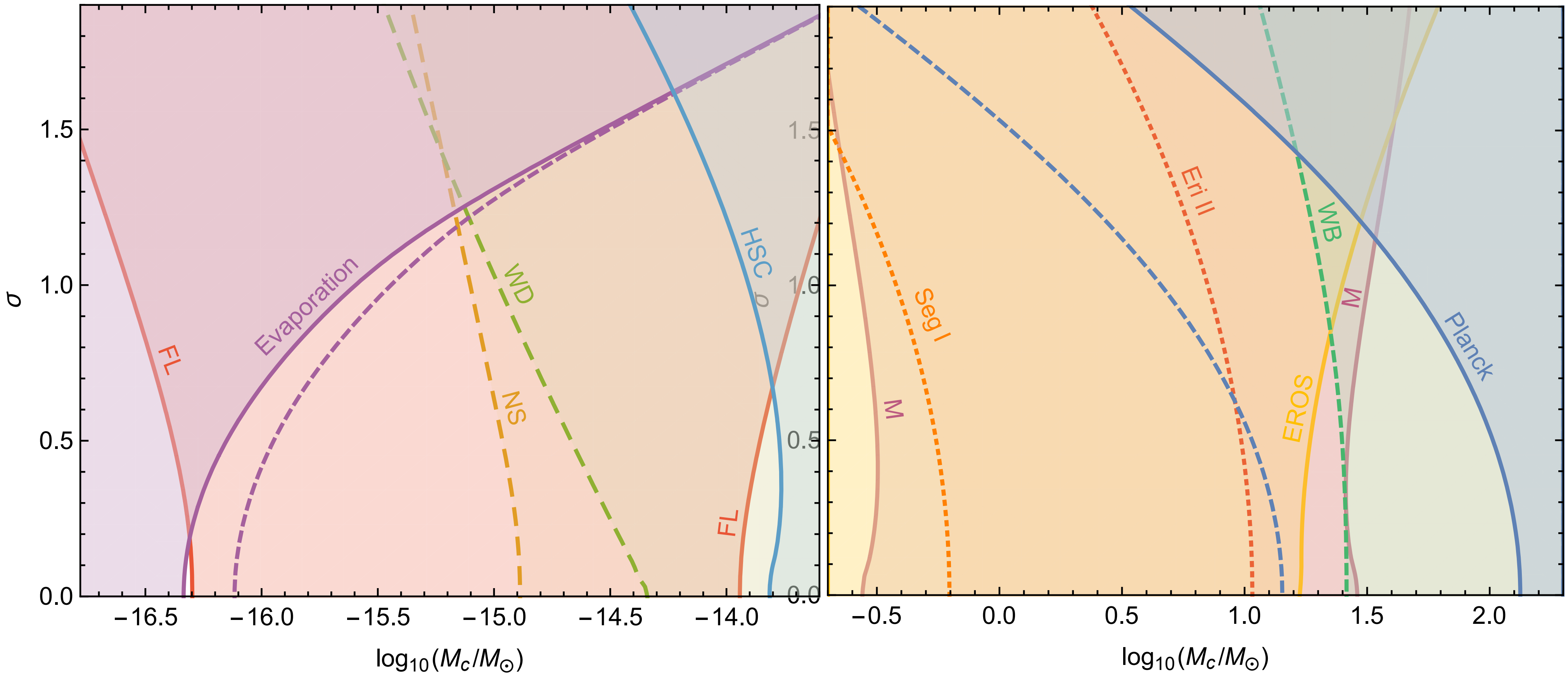
$$f_{\rm PBH} \equiv \frac{\Omega_{\rm PBH}}{\Omega_{\rm DM}} = \int {\rm d}M\, \psi(M)$$

- The effect: Wide distribution smears the bounds and closes the possible windows


lognormal, σ=2
0.0
−0.5
−1.0
−1.5
−2.0
−2.5
−3.0
−15
−10
−5
0
log10 fPBH
log10(Mc/M⊙)


lognormal
lognormal, all constraints
power law, γ<0
power law, γ>0
σ
log10(Mc/M⊙)
log10 fmax
0
−0.5
−1.0
−1.5
−2.0
−2.5
−3.0
−15
−10
−5
0
1
2
3
4
5
6

Zoom into the interesting regions

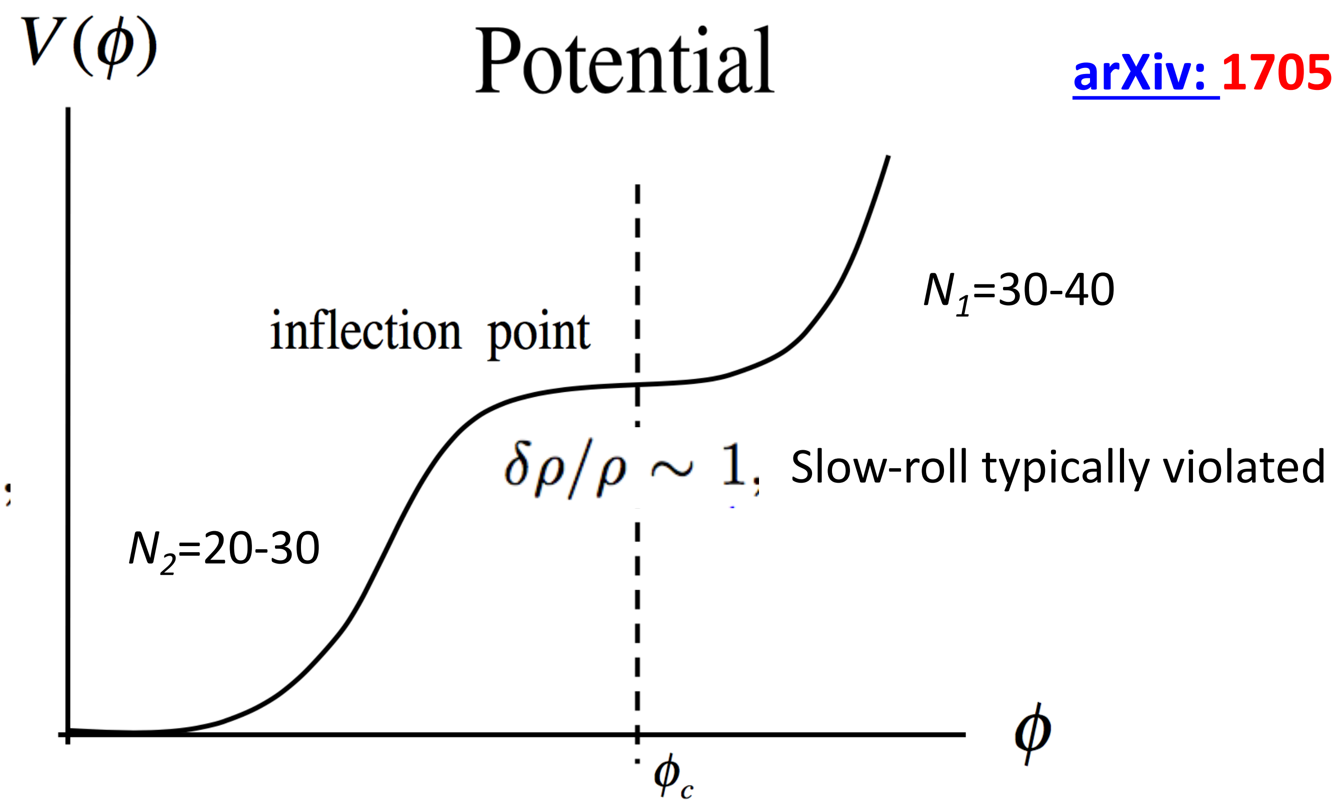


Narrow mass functions are phenomenologically preferred if f=1

How to produce the PBH population?

- Cartoon:

arXiv: 1705.06225



$$N = N_1 + N_2,$$

- Potentials from the *Encyclopedia Inflationaris* are not usable – designed for *N*=50-60

Single field double inflation

- Cosmology is consistent with single field inflation
- Most general Lagrangian for a single field:

$$\mathcal{L} = \sqrt{-g}\left(-\frac{1}{2}M_P^2\Omega(\sigma)R + \frac{1}{2}K(\sigma)(\partial\sigma)^2 - V(\sigma)\right)$$

$$\Omega(\sigma) = 1 + \frac{\xi}{M_P^2}\sigma^2, \quad V(\sigma) = \frac{1}{2}m^2(\sigma - v_1)^2 + \frac{1}{3}\mu(\sigma - v_1)^3 + \frac{1}{4}\lambda(\sigma - v_1)^4.$$

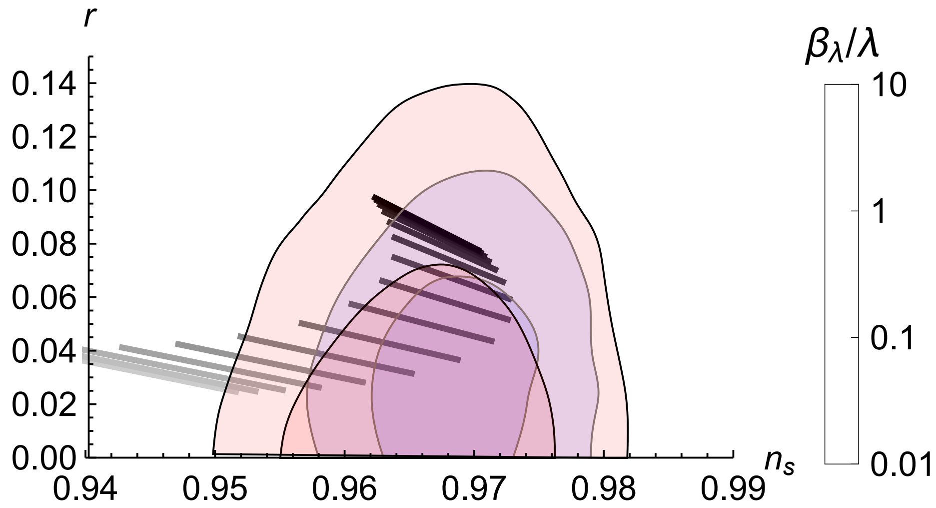
Assume renormalizability

- Higgs, Starobinsky inflations do not work
- We make it to work for N_1=40 with rad. correct.

$$\lambda_{\phi\Phi}\phi^2\Phi^2, \qquad \lambda(\sigma) = \lambda(m_\Phi) + \theta(\sigma - m_\Phi)\beta_\lambda \ln\frac{\sigma}{m_\Phi}$$

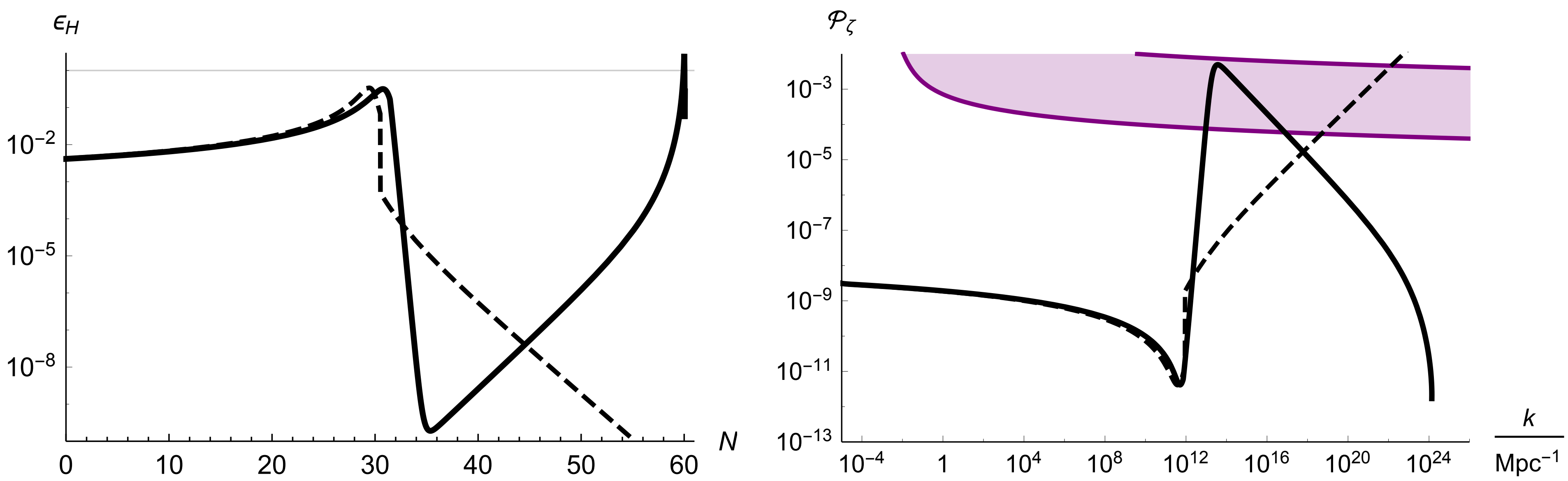
Results for the inflation

- 1[st] phase: Rad. corrected Higgs inflation, N_1=40



- 2[nd] phase: Hilltop inflation
- In general slow roll conditions are violated
- In general fine tuning is needed to glue the two phases together

Results for the inflation



- The observed DM abundance can be produced
- Predicts deviations from the lognormal PBH mass function

Have LIGO observed the PBHs?

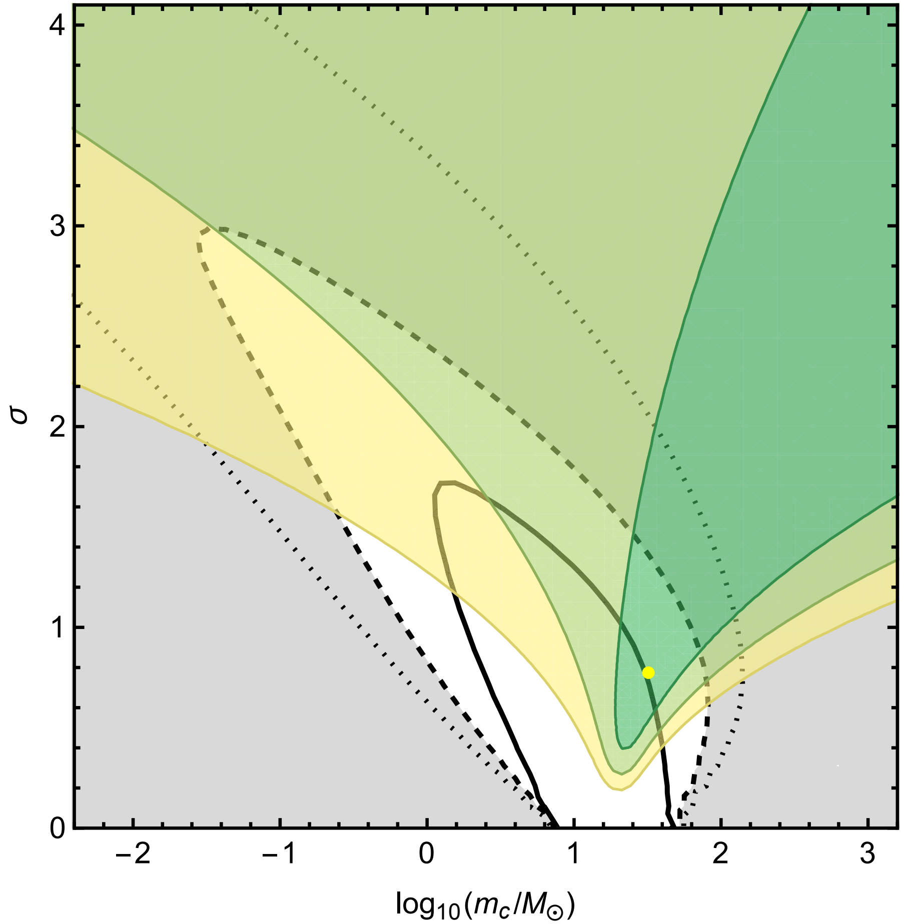
arXiv: 1707.01480

- 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]	$31.2^{+8.4}_{-6.0}$	$19.4^{+5.3}_{-5.9}$	$0.236^{+0.021}_{-0.020}$

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

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

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

Predictions for stochastic GW background

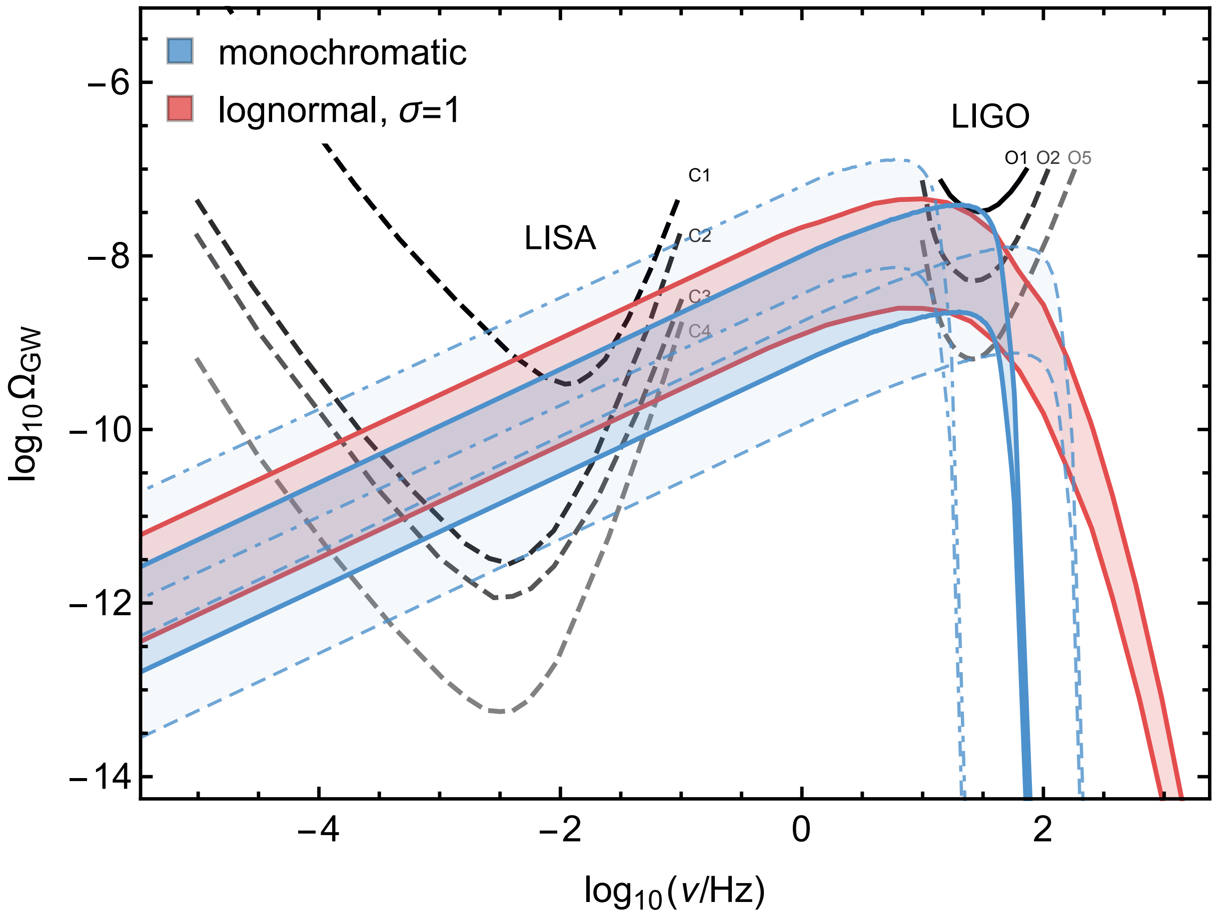
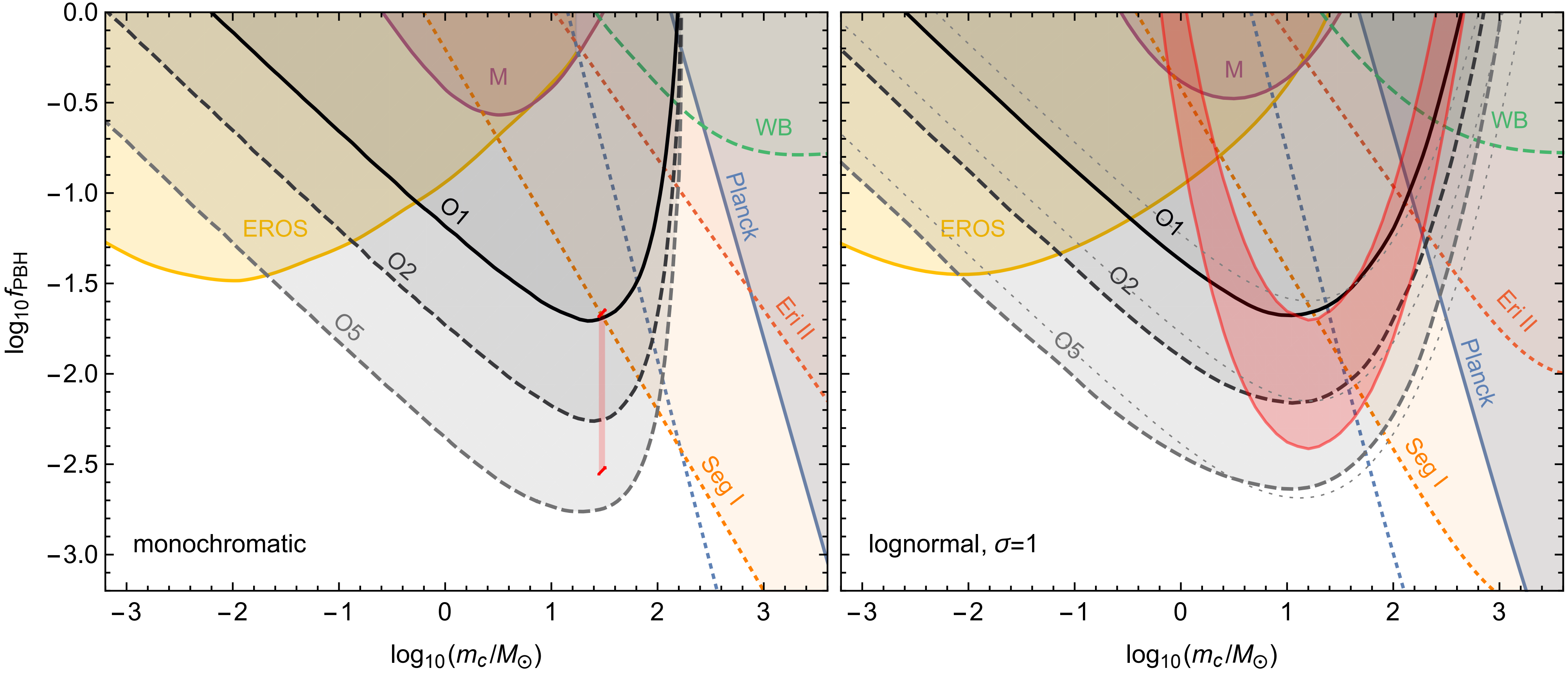


Figure 2. The stochastic GW background from the PBH mergers. The fraction of DM in PBHs is chosen such that the merger rate in the LIGO sensitivity range today is $12\,\mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$ for the lower lines and $213\,\mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$ for the upper lines, corresponding 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

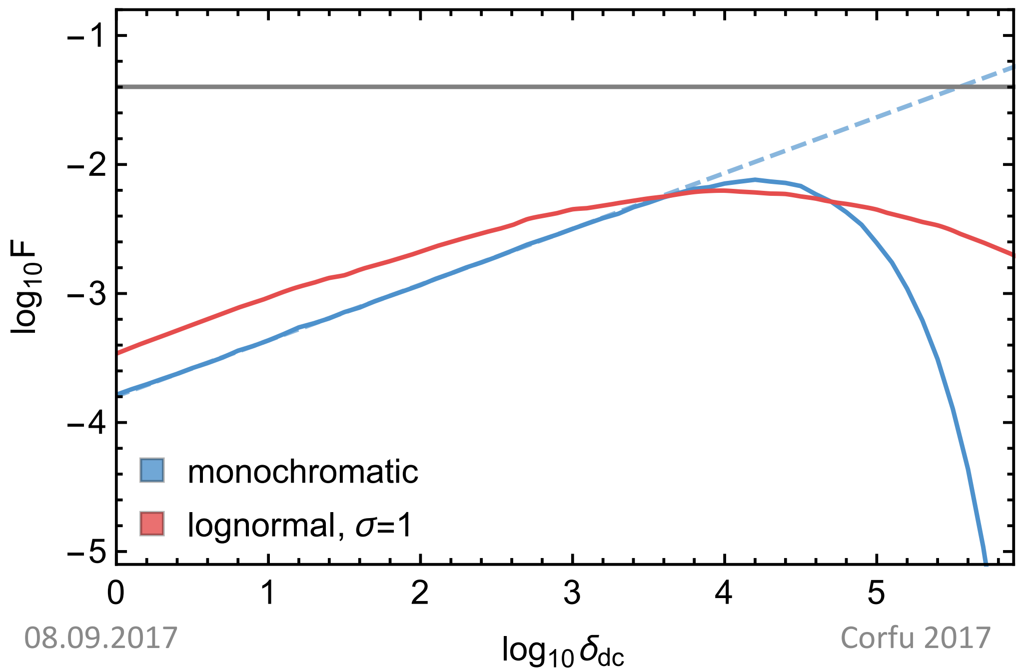


- Non-observation of the GW background by LISA will exclude the primordial origin of the LIGO events

3σ anomaly in low and high redshift measurements of H_0 and σ_8

- Generic solution: convert DM into DR
- This is precisely what PBH mergers are doing

$$F \approx 6.3 \times 10^{-4} \delta_{\rm dc}^{16/37} f_{\rm PBH}^{53/37} \left(\frac{m_c}{30 M_\odot}\right)^{5/37} \qquad F \approx 2-5\%$$



$$F \equiv \frac{\Delta\Omega_{\rm DM}}{\Omega_{\rm DM}(z_{\rm CMB})}$$

Conclusions

- PBHs may constitute a large fraction of the DM
  - Several bounds must be better understood
  - Future observations must see the PBH effects in astrophysics
- Single field double inflation may produce the PBH DM
  - Unusual potentials, slow roll approximation is usually violated, precise computations are needed
- PHB binaries may have been observed by LIGO
  - Fits suggest: just a small fraction of DM in PBHs, OK for structure
  - Explaining the low/high redshift H_0 anomaly is difficult without violating some common assumptions
  - PBH DM can be excluded by non-observation of the GW background by LIGO and LISA