PBH Formation in High Temperature QCD Transitions

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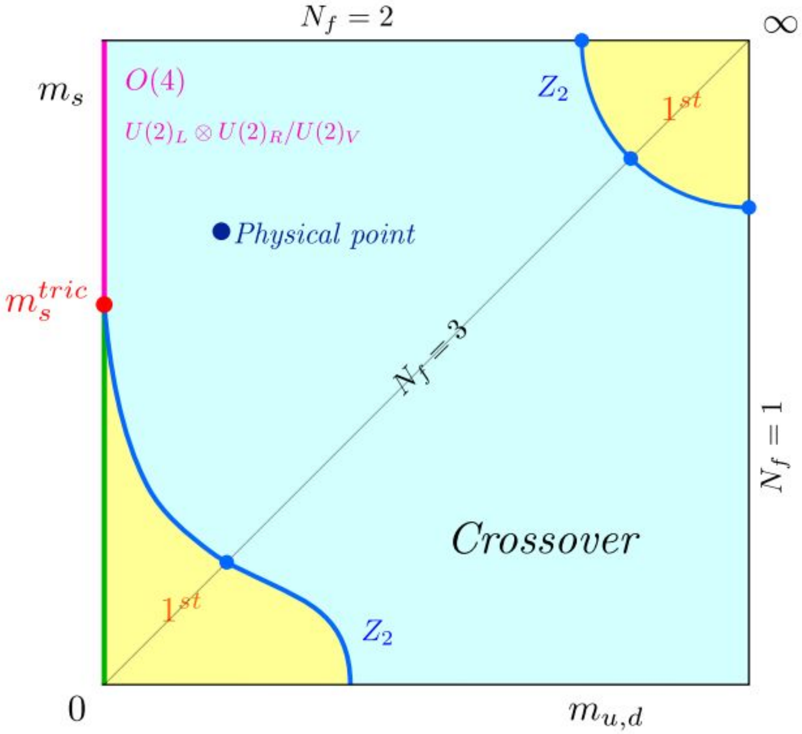
Why High Temperature QCD?

- Simulations have determined SM QCD to be second order/crossover
- First order transitions requires N≥3 massless quarks
- Need new physics to realize first order transition



Cuteri et al. 2017

Stronger Strong Coupling (Ipek and Tait)

New scalar φ coupled to gluons:

$$\mathcal{L} \supset -\frac{1}{4}\left(\frac{1}{g_{s0}^2} + \frac{\phi}{M_*}\right) G_{\mu\nu}G^{\mu\nu}$$

Non-zero (negative) vev: $V(\phi) = \alpha_1\phi + \alpha_2\phi^2 + \alpha_3\phi^3 + \alpha_4\phi^4$

Modified confinement scale

$$\Lambda(\langle\phi\rangle) = \Lambda_0 \ \mathrm{Exp}\left(\frac{24\pi^2}{2n_f - 33}\frac{\langle\phi\rangle}{M_*}\right)$$

Restoring SM QCD

1. Temperature-dependent VEV

2. Second scalar ψ coupled to gluon with opposite VEV

3. Second scalar ψ coupled to φ

$$V(\phi, \psi) = \alpha_1\phi + \alpha_2\phi^2 + \alpha_3\phi^3 + \alpha_4\phi^4 + \beta_1\psi^2 + \beta_2\psi^4 + \gamma_1\phi\psi^2 + \gamma_2\phi^2\psi^2$$

PNJL Model

- Effective description of QCD Transition

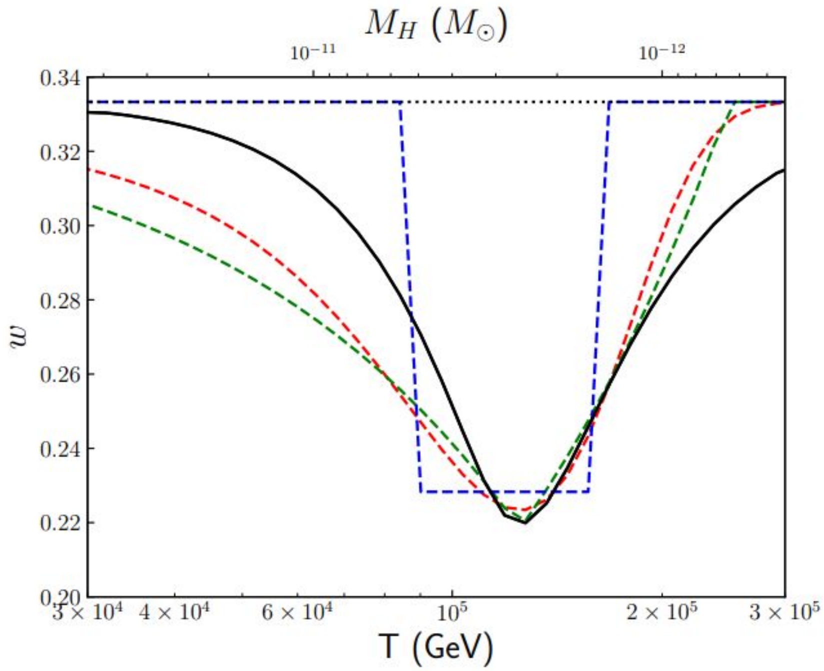
$$\mathcal{L}_{PNJL} = \bar{\chi}\left(i\gamma_\mu D^\mu - m_0\right)\chi + \frac{G}{2}\left[(\chi\bar{\chi})^2 + (\bar{\chi}i\gamma_5\vec{\tau}\chi)^2\right] - \mathcal{U}(\Phi, \bar{\Phi}, T)$$

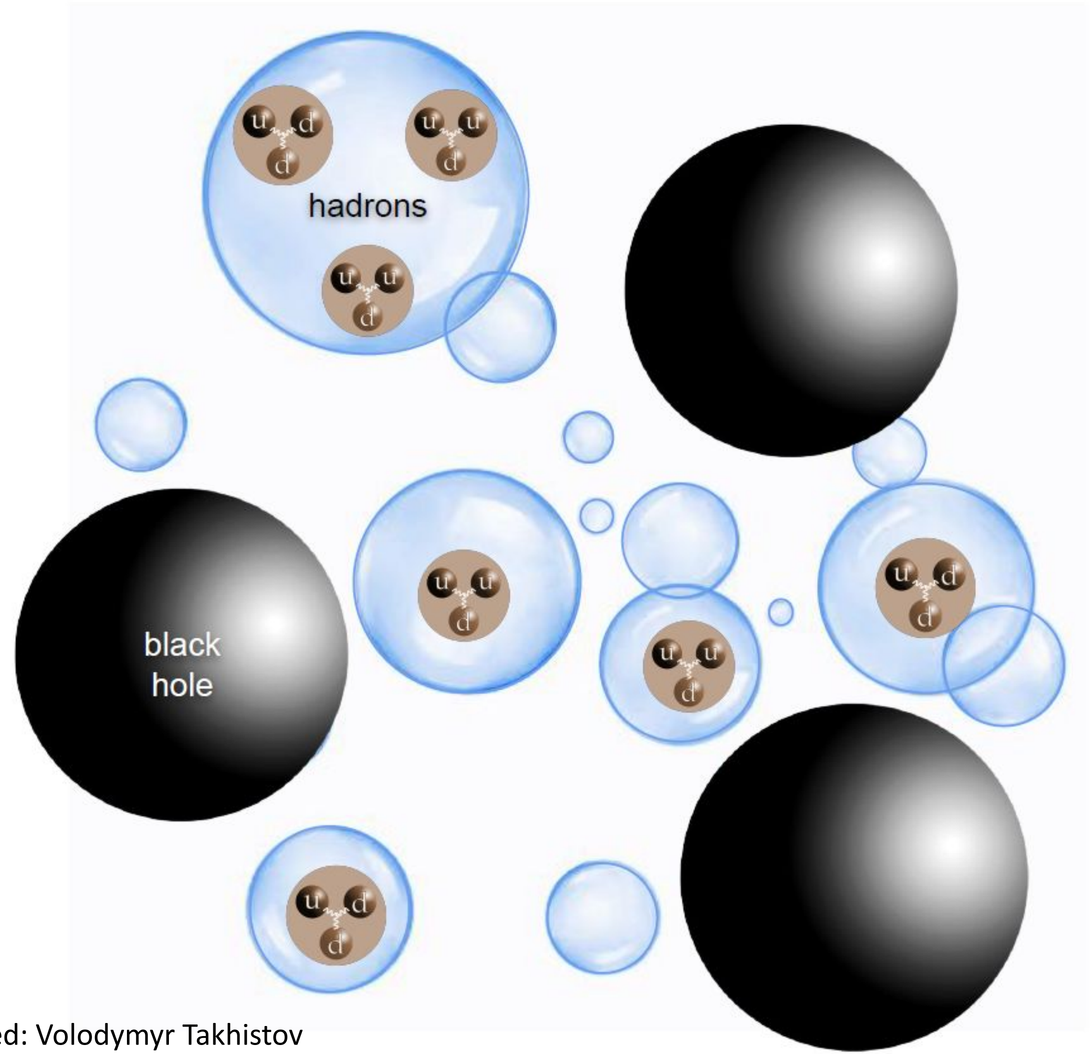
- Addition of Polyakov loop (gluons) to Nambu-Jona-Lasinio (quark) model

- Confinement transition before chiral transition

First Order QCD Transition

- High temperatures: 5-6 massless quarks
- Softening of equation of state parameter
- Additional energy changes phase rather than pressure





Cred: Volodymyr Takhistov

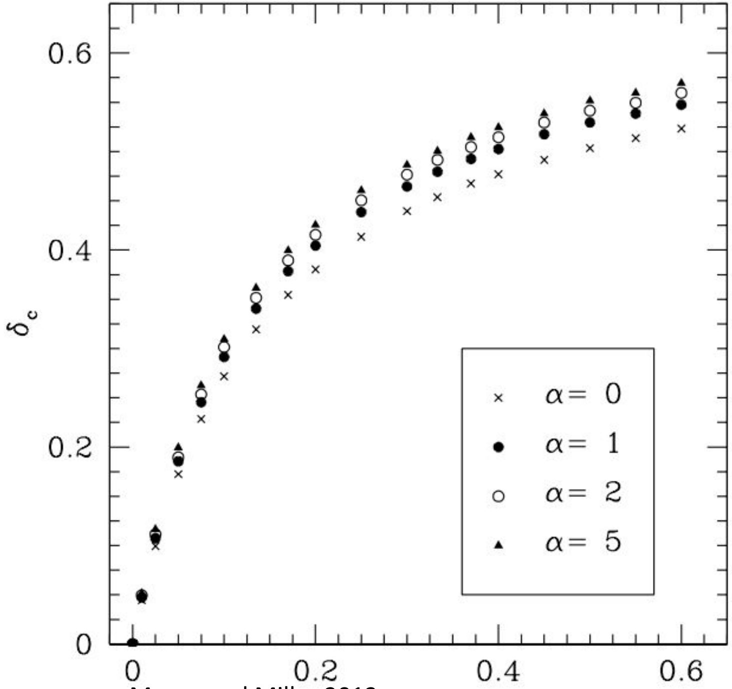
PBH Formation

- Horizon-sized perturbations above critical value:

$$\beta = 2 \int_{\delta_c}^{\infty} d\delta \frac{M_{\rm PBH}}{M_H} P(\delta, \sigma)$$

- Collapse facilitated by soft w (less pressure)

- Does not require peak in power spectrum



Musco and Miller 2012

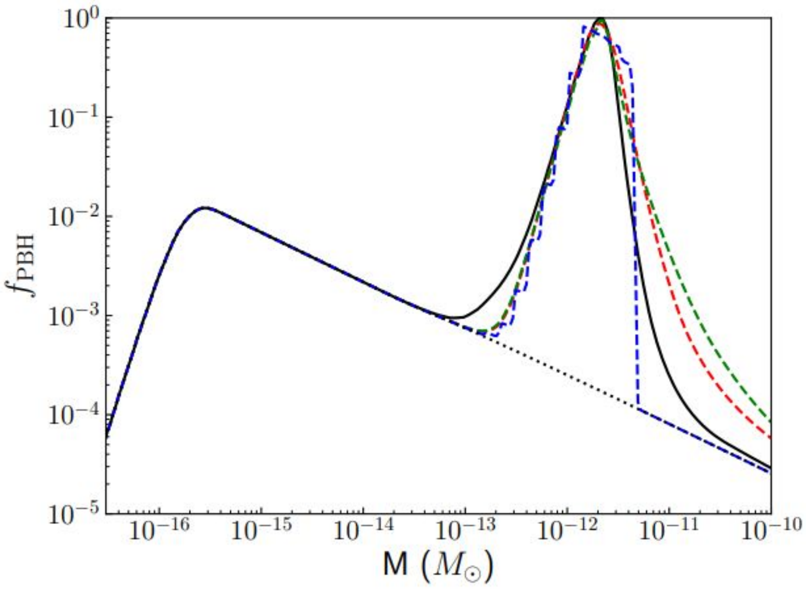
Enhanced PBH Formation

- Present day density scales with collapse probability

$$f_{\rm PBH} = \int \left(\frac{M}{M_{\rm eq}}\right)^{-1/2} \frac{\beta(M)}{\Omega_{\rm DM}} \frac{dM}{M}$$

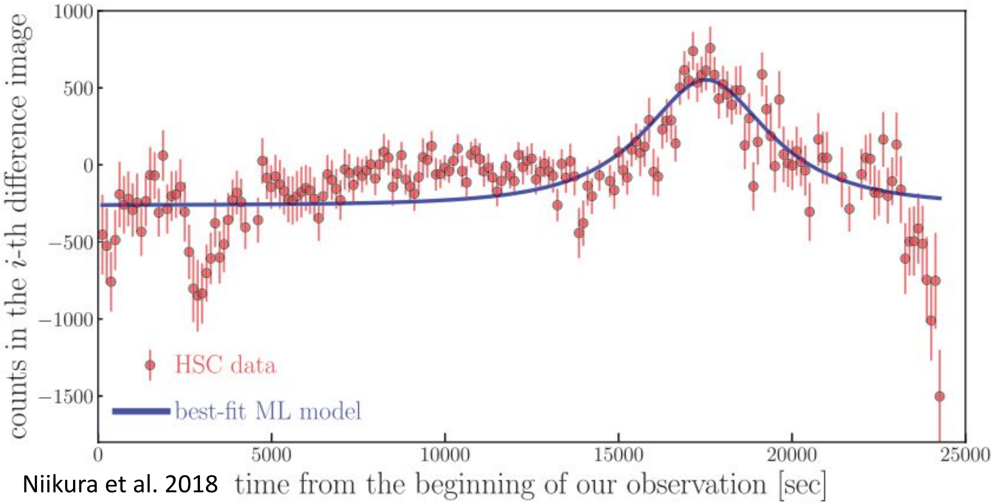
- Results hold irrespective of transition shape
- Mass depends on FOPT temperature

$$M_H \simeq 4.8 \times 10^{-10} M_\odot \left(\frac{T}{10\ \rm TeV}\right)^{-2} \left(\frac{g_*}{106.75}\right)^{-1/2}$$



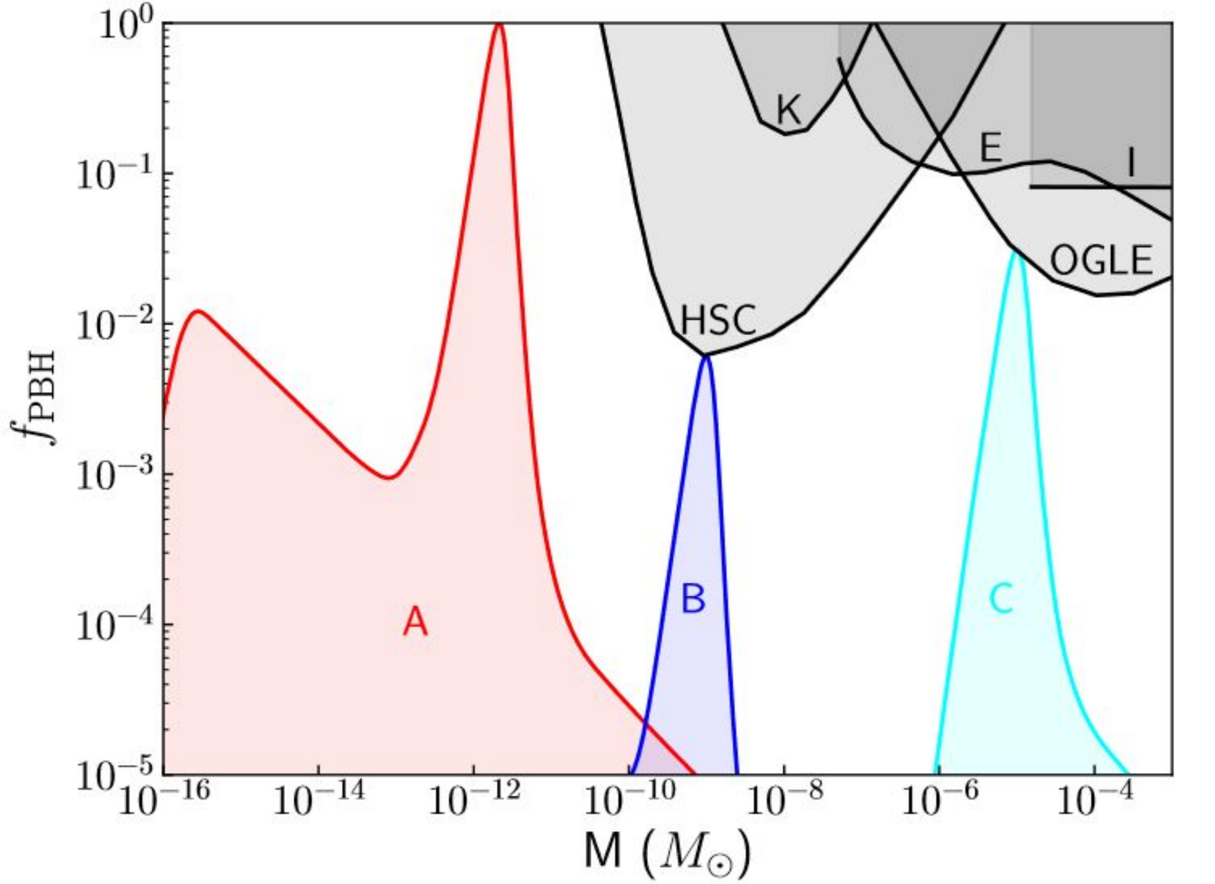
Target Populations

- Open DM mass window from 10^{17}-10^{23} g (10^{-16}-10^{-11} $M_\odot$)
- Candidate events from OGLE microlensing observations ~10^{-5} $M_\odot$
- Candidate event from Subaru Hyper-Suprime Cam (HSC) ~10^{-9} $M_\odot$



Niikura et al. 2018

Target Populations



Gravitational Waves

- Gravitational wave signal depends on power spectrum

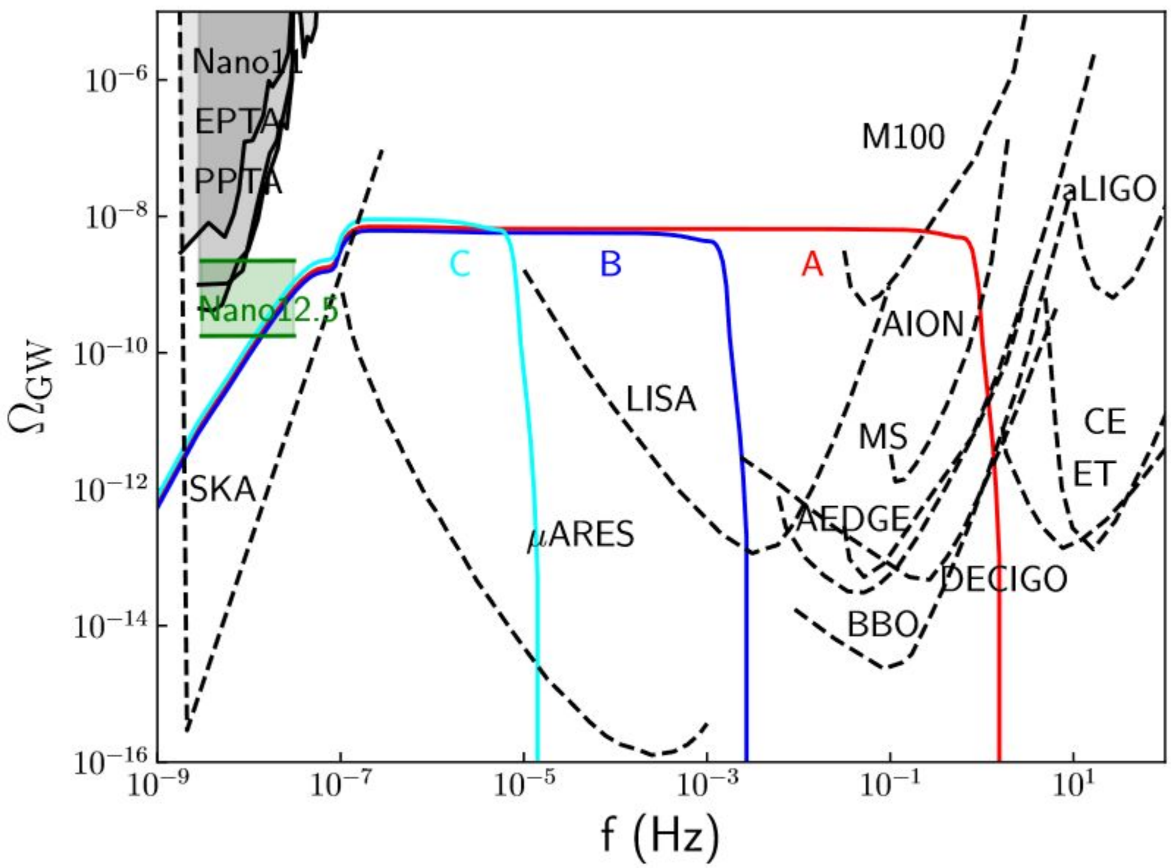
$$\Omega_{\mathrm{GW}} = \frac{c_g \Omega_{r,0}}{972} \int_0^\infty dx \int_{|1-x|}^{1+x} dy \frac{x^2}{y^2} \left[1 - \frac{(1 + x^2 - y^2)^2}{4x^2}\right]^2 \mathcal{P}_\zeta(kx) \mathcal{P}_\zeta(ky) \mathcal{I}^2(x, y)$$

- Interesting signal from Nanograv 12.5 yr data

- Range depends on power spectrum cut-off

- Additional GW from QCD transition

Gravitational Wave Signal



Conclusions

- We use PNJL to model the high temperature QCD transition
- Soft equation of state promotes PBH production
- Higher temperature transition -> Smaller masses
- Fits both the target PBH signals (DM, OGLE, HSC) as well as the Nanograv GW signal and could be detected by many upcoming experiments