PBH: Cloud Cooling Bounds and High Temperature QCD PBH Formation

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KIAS HEP Seminar
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Lu et al., *ApJ Letters*,	arXiv:2007.02213
Laha **Lu** Takhistov, *PLB*,	arXiv:2009.11837
Takhistov **Lu** et al., *JCAP*,	arXiv:2105.06099
Takhistov **Lu** et al., *MNRAS*,	arXiv:2111.08699
Lu Takhistov Fuller, *PRL*,	arXiv: 2212.00156

Primordial Black Holes

Motivations

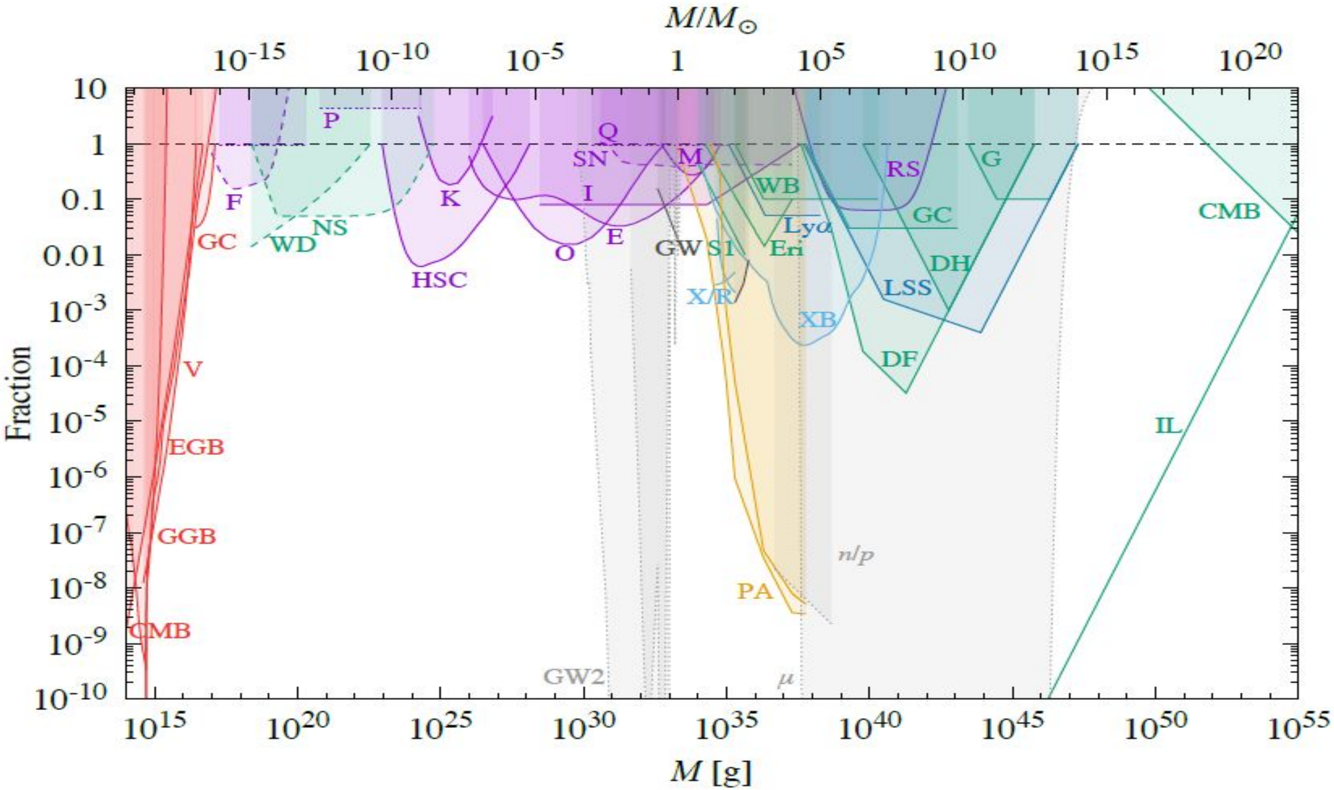
- Can comprise all of dark matter within the “mass window”
- Macroscopic dark matter candidate
- Formation scenarios usually result in gravitational waves
- Can seed supermassive black holes

Possible Signals

- Significant population of binary black hole mergers within the “mass gap”
- Microlensing candidate events from OGLE and HSC
- Observations of high redshift AGN ($z=10.6$?)

Primordial Black Hole Bounds from Gas Cooling

PBH Bounds



Carr et al. 2020

PBH Heating Constraint

Thermal Equilibrium

- Require heating rate equal to cooling rate
- Ignore heating from standard sources

Total heating (PBH) vs local heating (particle DM)

$$N_{\mathrm{PBH}}(M) = f_{\mathrm{PBH}} \frac{\rho_{\mathrm{DM}} V}{M}$$

PBH allowed fraction

$$f_{\mathrm{PBH}} < f_{\mathrm{bound}} = \frac{M\dot{C}}{\rho_{\mathrm{DM}} H(M)}$$

Lower limit

$$f_{\mathrm{bound}} > \frac{3M}{4\pi r_{\mathrm{sys}}^3 \rho_{\mathrm{DM}}}$$

Bhoonah et al. 2018
Wadekar and Farrar 2019

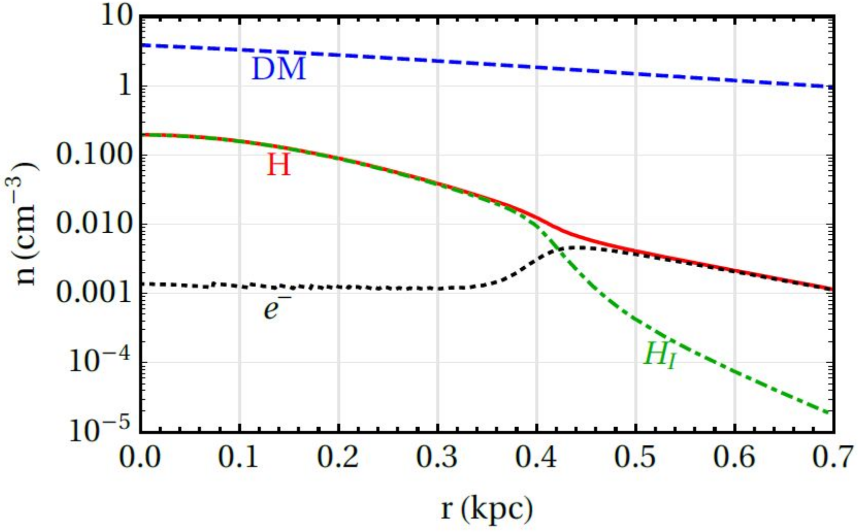
Target System: Leo T

Dwarf Galaxy

- Well-studied and modeled
- No significant star formation
- No coherent rotation detected

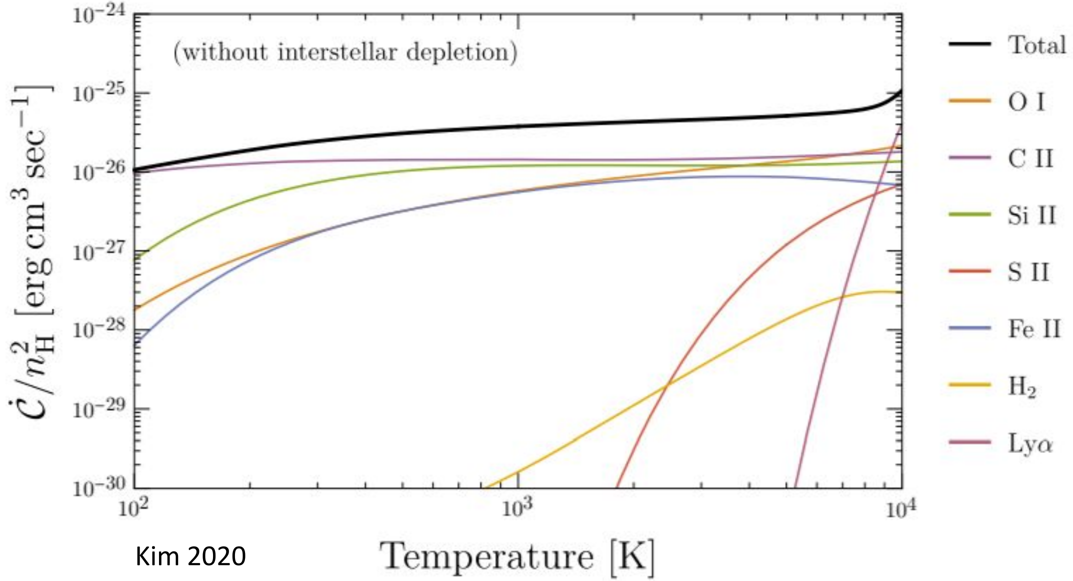
Properties

- Average DM density: 1.75 GeV/cm^3
- Average H1 density: 0.07 GeV/cm^3
- Velocity dispersion: 7 km/s
- Temperature: 6000 K



Wadekar and Farrar 2019
Faerman et al. 2013

Cloud Cooling



Kim 2020

Cooling rate:

$$\dot{C} = n^2 10^{[\mathrm{Fe/H}]} \Lambda(T)$$

$$= 2.28 \times 10^{-30} \text{ erg cm}^{-3} \text{ s}^{-1}$$

Cooling Function:

$$\Lambda(T) = 2.51 \times 10^{-28} T^{0.6}$$

Wadekar and Farrar 2019
Kim 2020

Cloud Heating Processes

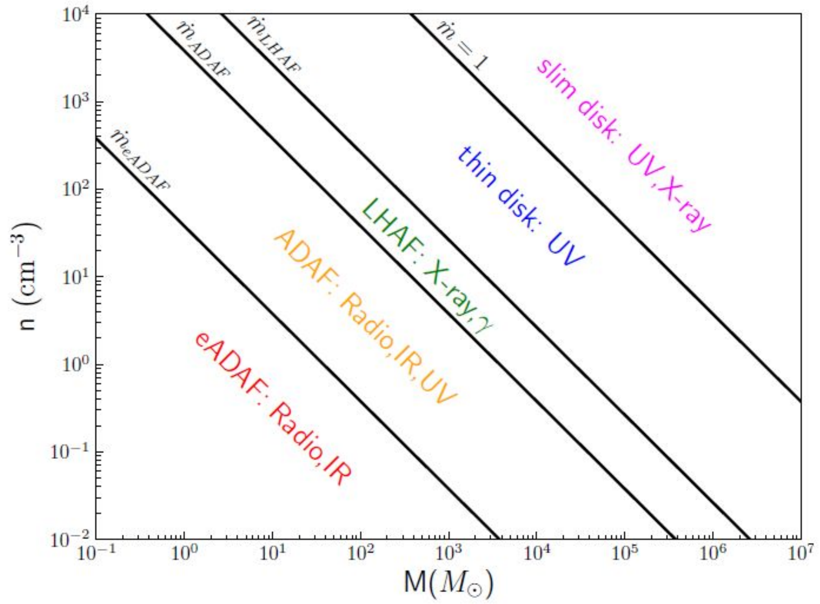
Accretion disk luminosity

- Bondi-Hoyle accretion
- ADAF
- Thin disk
- Optical Depth

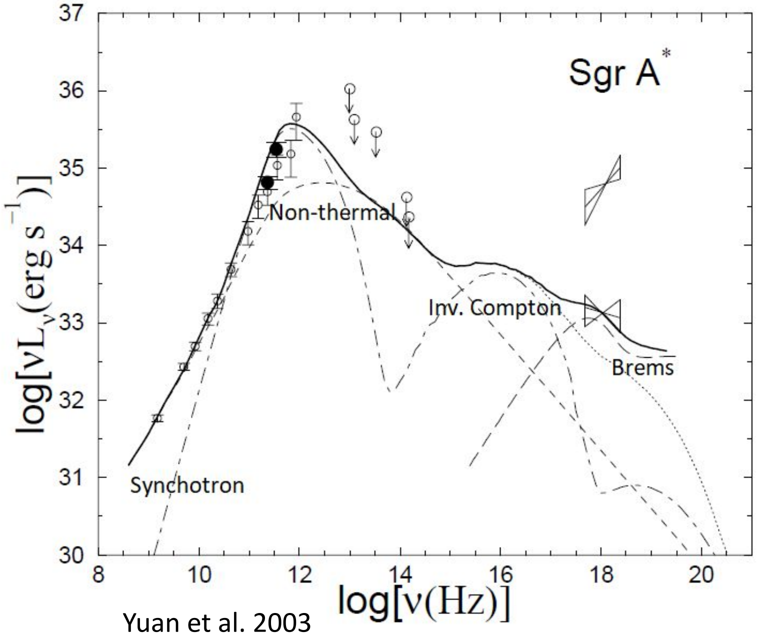
Winds

- Stopping Power

Dynamical Friction



Advection Dominated Accretion Flow (ADAF)



Yuan et al. 2003

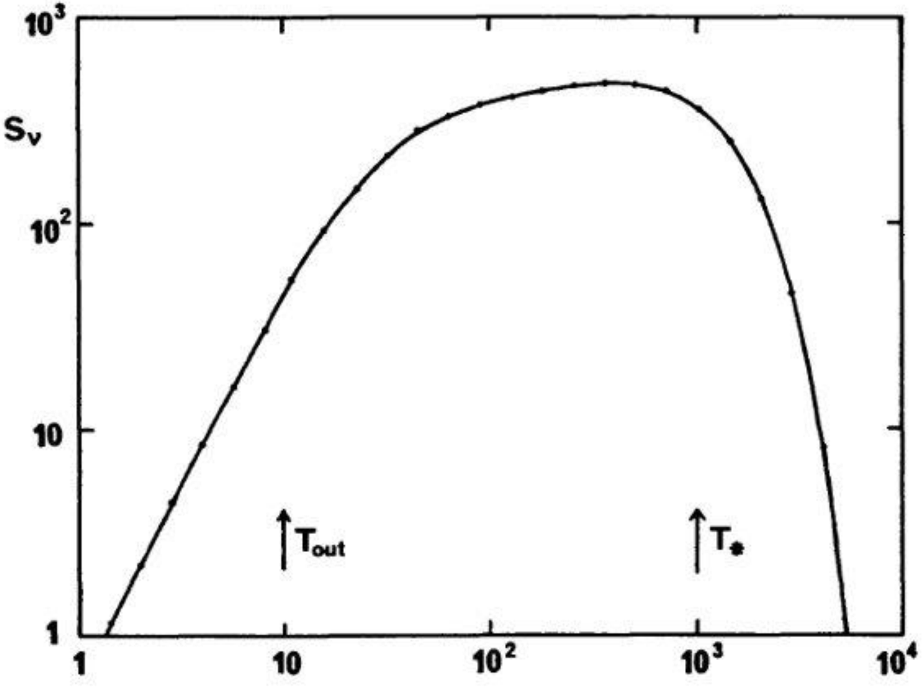
One Zone Model

Four components:

- Thermal synchrotron
- Non-thermal synchrotron
- Inverse Compton
- Bremsstrahlung

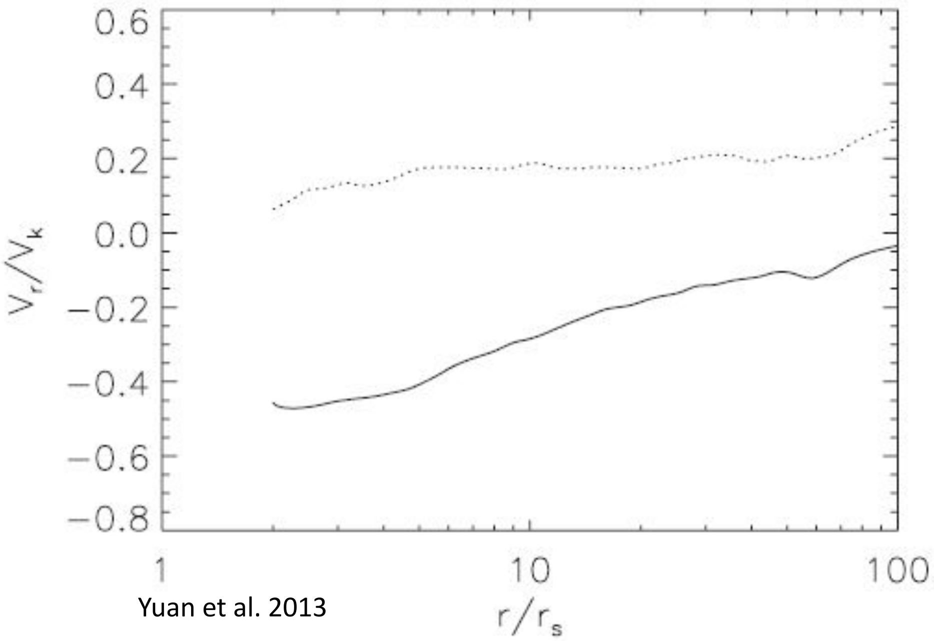
Thin disk (α-disk)

- Requires large accretion rate to form
- Efficient conversion of mass into radiation
- Bulk of emission between T_{out} and T_*
- Peaks at 10s of eV
- Analytically modeled



Pringle 1981

Winds



Yuan et al. 2013

Power-law inflow:

$$\dot{M}_{\rm in}(r) = \dot{M}_{\rm in}(r_{\rm out}) \left(\frac{r}{r_{\rm out}} \right)^{s}$$

Corresponding Outflow

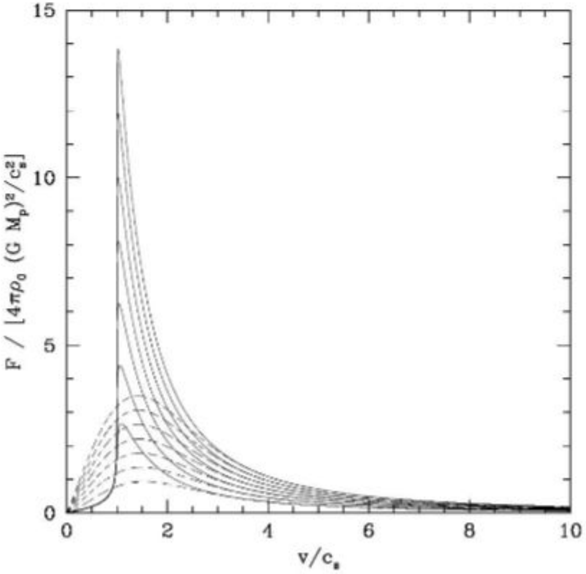
Estimate wind energy as fraction of binding energy

Dynamical Friction

Friction force: $F_{\rm dyn} = -\frac{4\pi G^2 M^2 \rho}{v^2} I$

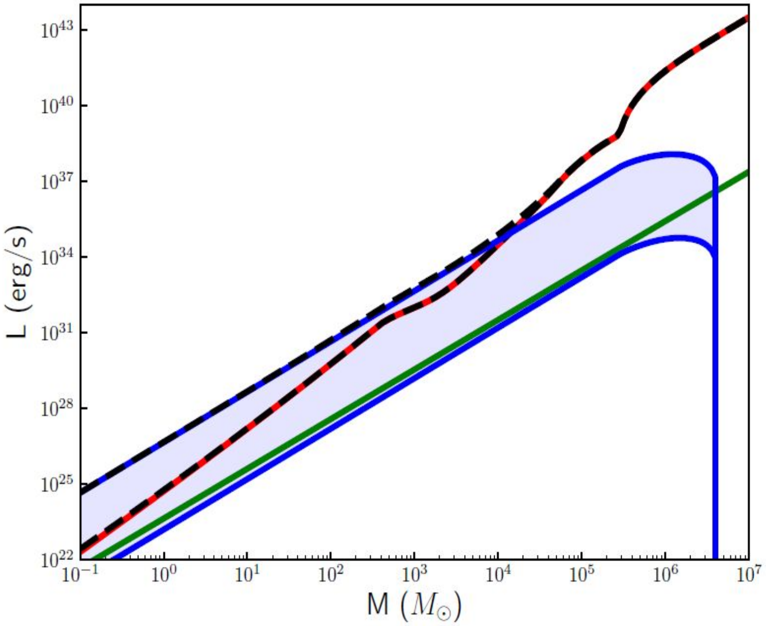
Gaseous medium vs collisionless

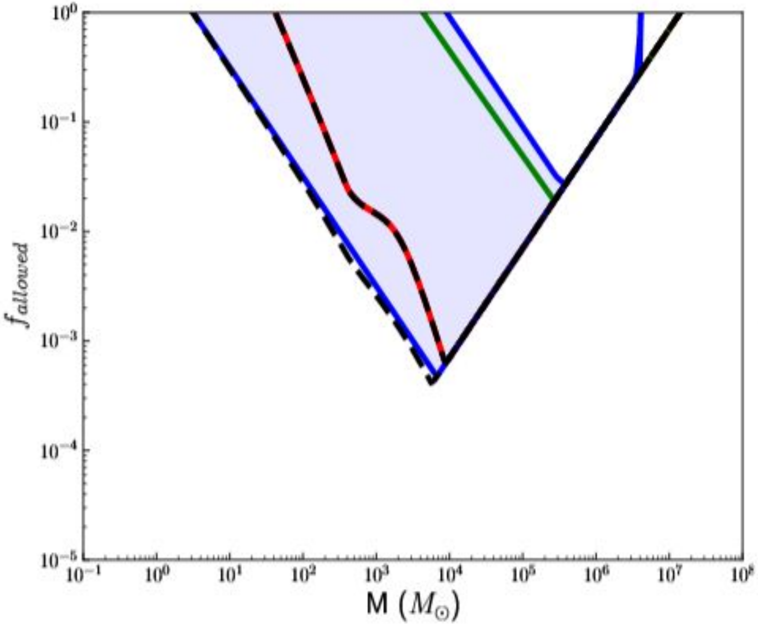
Simple but small contribution



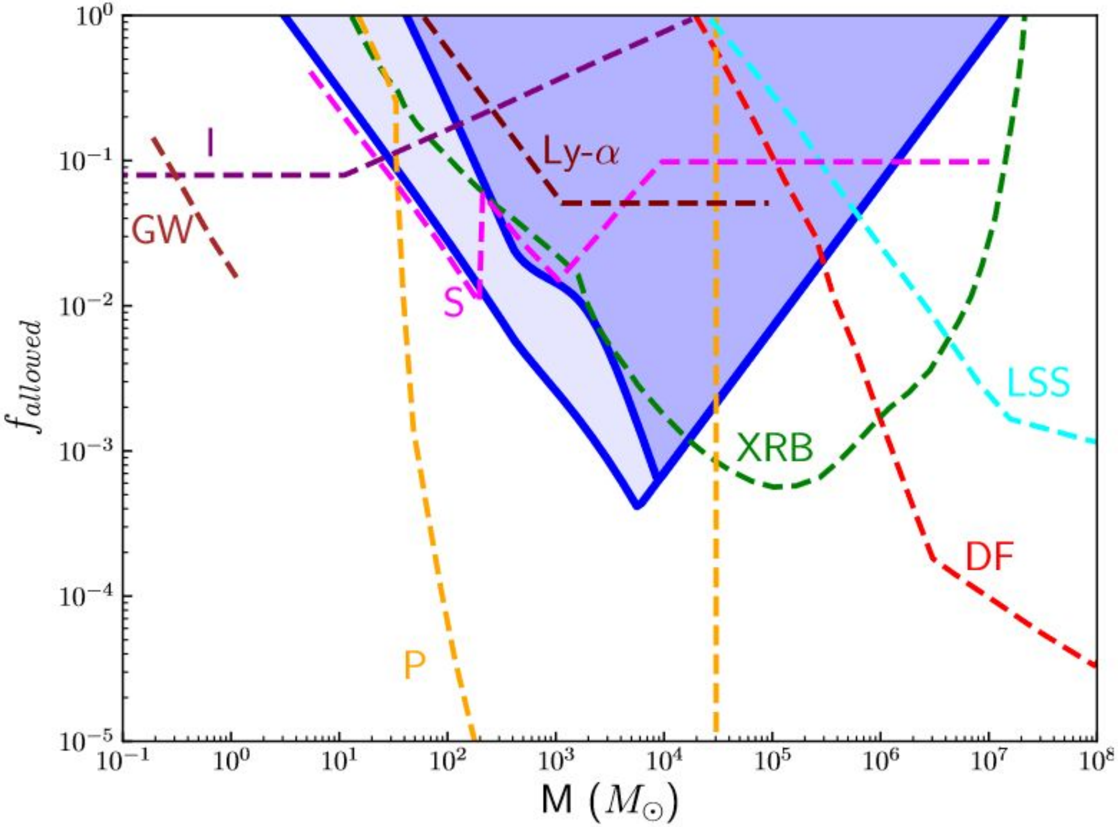
Ostriker 1999

Individual Heating Contributions





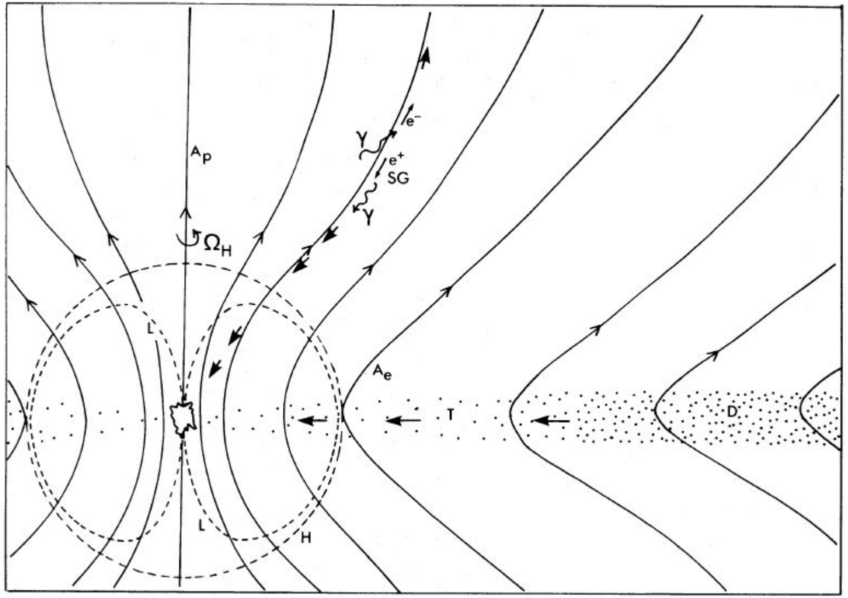
Initial Constraints



arXiv:2007.02213
arXiv:2009.11837

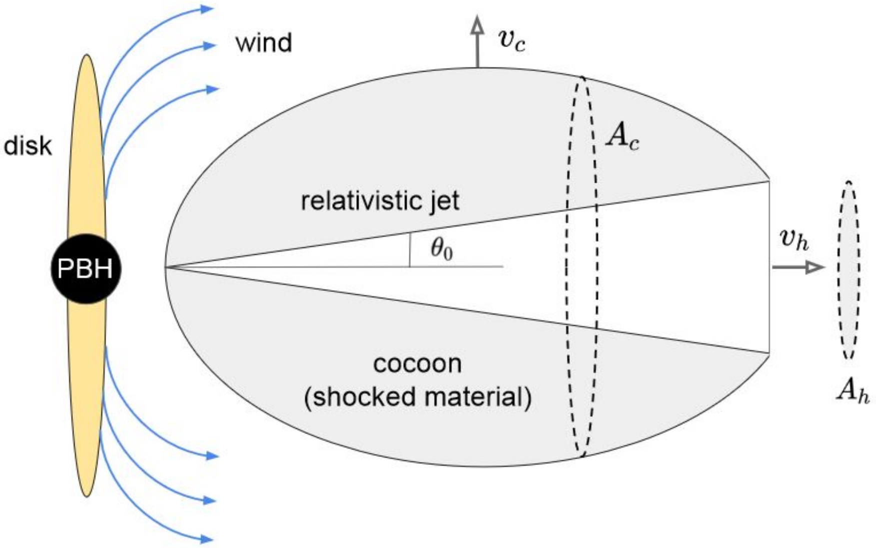
Spinning PBH

- Spin decreases Innermost Stable Circular Orbit (ISCO) radius
- Increased plasma temperature resulting in higher accretion disk emission
- Possibility of Blandford-Znajek jets



Blandford and Znajek 1977

Winds and Jets as Outflows



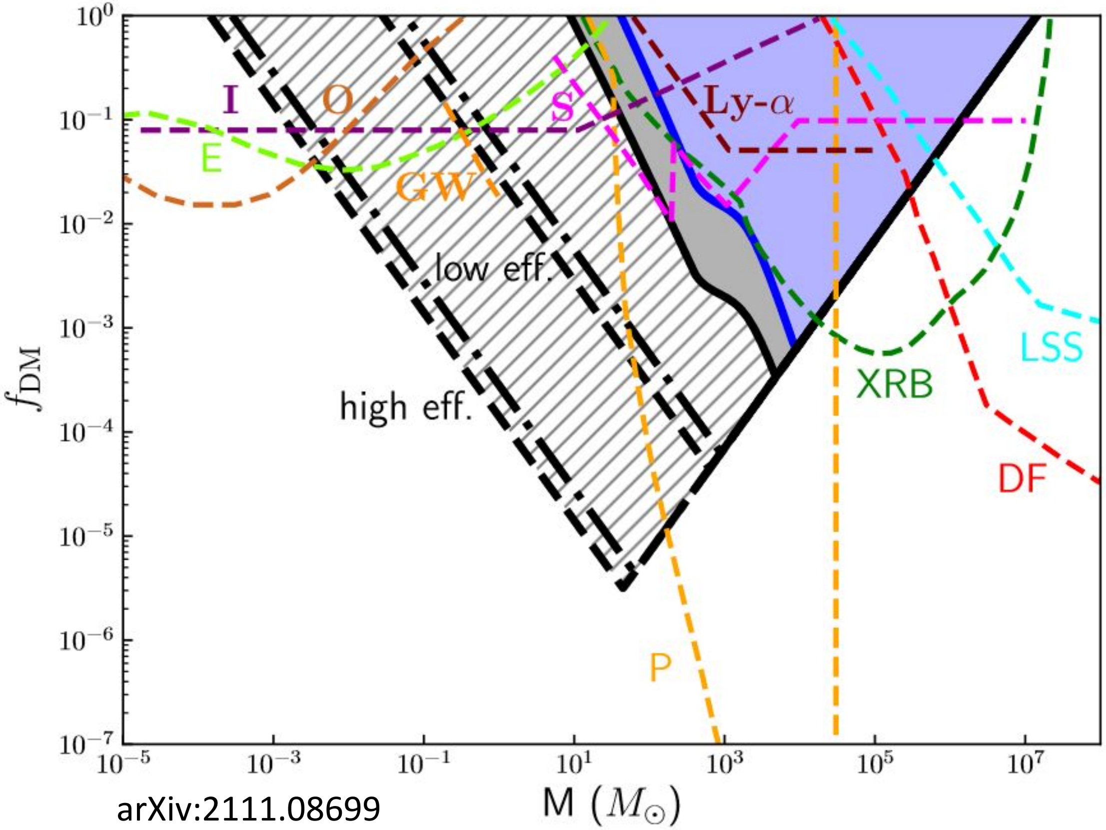
Volodymyr Takhistov

- Parameterized emission with efficiency factor

$$L_\mathrm{j} = \epsilon_j \dot{M}_\mathrm{acc}$$

- Magnetically Arrested Disk (MAD) suggest ϵ_j=1 (high eff.)
- Outflows from Quasars suggest ϵ_j=0.005 (low eff.)
- Additional factors from duty cycles, heating efficiency implicitly included

Shock Heating Limits



arXiv:2111.08699

Application to Evaporating PBHs

- Competitive bound for light PBH
- Uses similar cloud cooling argument
- Assumed positrons/electrons were permanently trapped
- We reanalyzed and included spin.

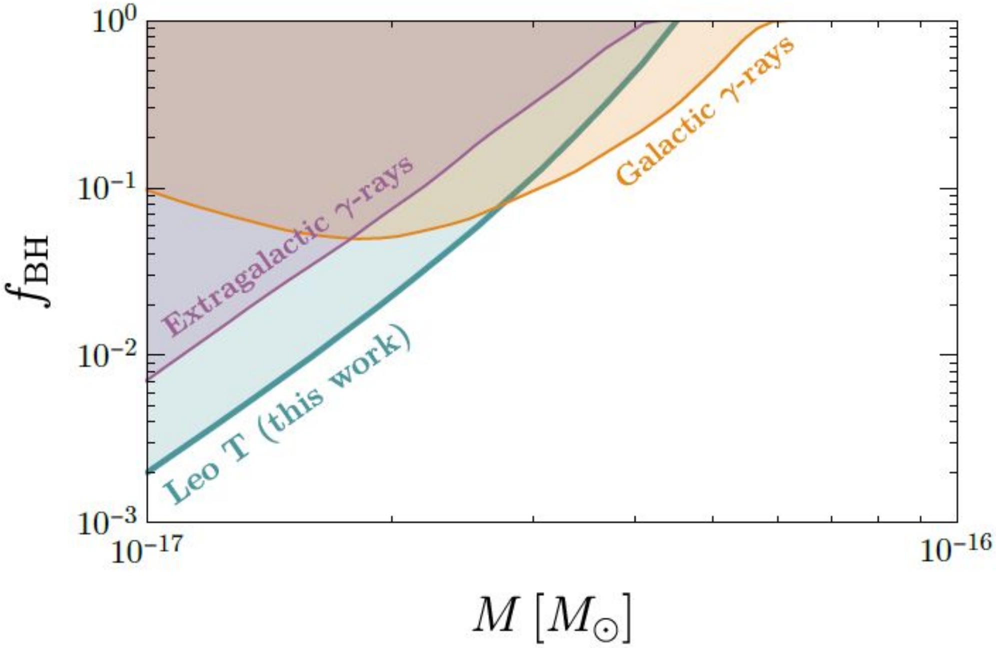
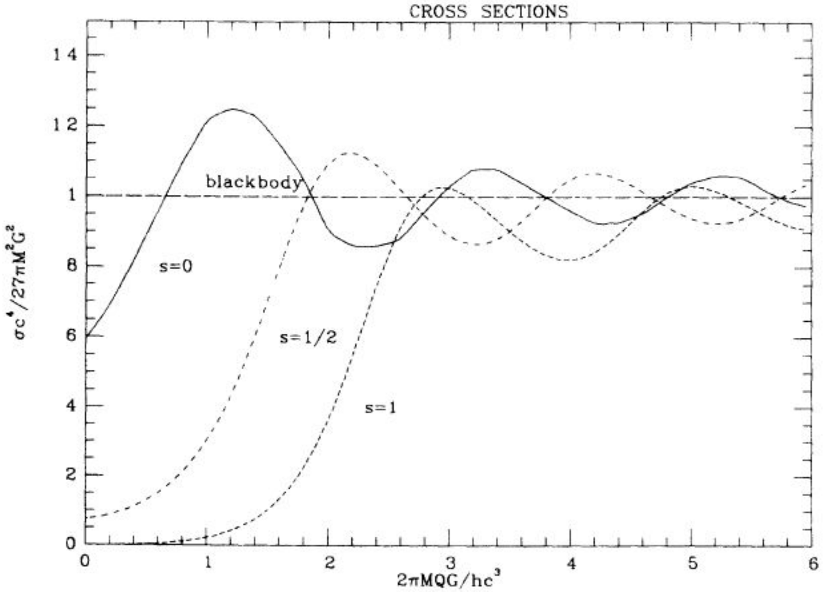


Figure from Kim 2020

Hawking Evaporation



MacGibbon and Webber 1990

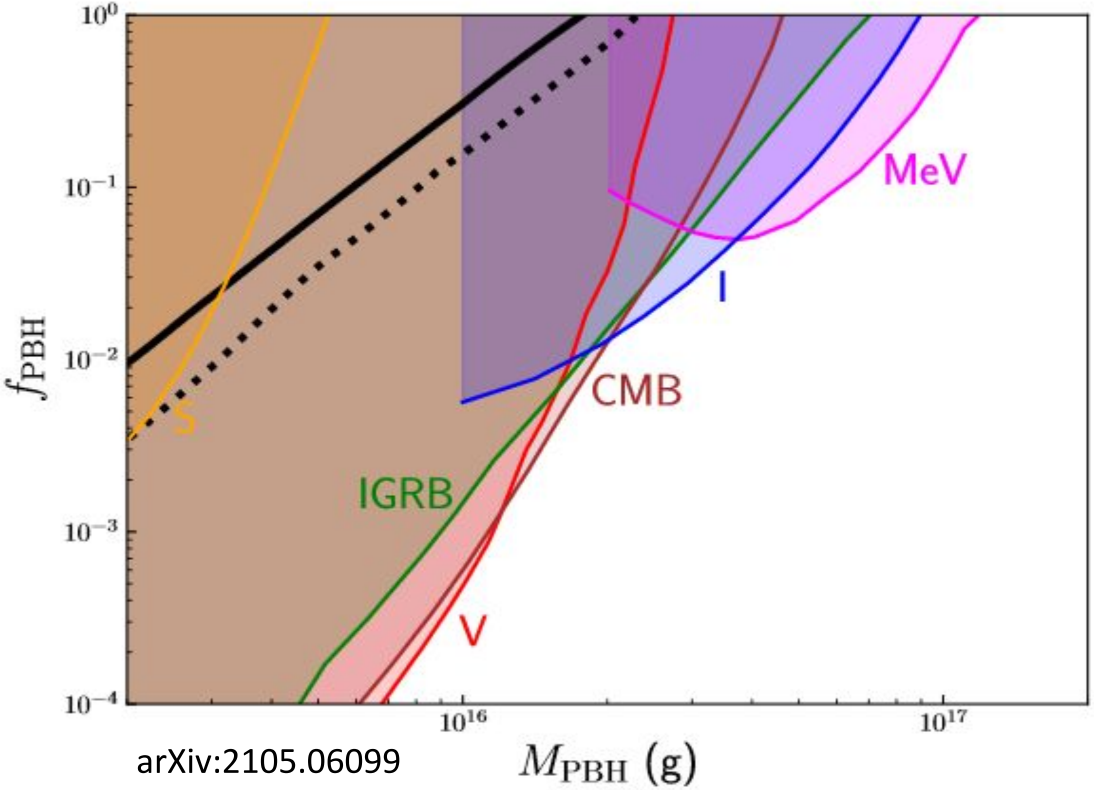
Approximate blackbody emission for non-spinning PBH

$$d\dot{N} = \frac{\Gamma_s dQ}{2\pi\hbar}\left[\exp\left[\frac{Q - n\hbar\Omega - q\Phi}{\hbar\kappa/2\pi c}\right] - (-1)^{2s}\right]^{-1}$$

Effective temperature:

$$kT = \frac{2\hbar GM}{c\mathcal{A}}\left[1 - \frac{c^2J^2}{G^2M^4} - \frac{q'^2}{GM^2}\right]^{1/2}$$

Light PBH Constraints



arXiv:2105.06099

Cooling Bound Conclusion

1. New competitive bound on intermediate mass black holes from cloud cooling. This bound is cosmology independent and complementary to other bounds.

2. Spinning black holes have increased emissions resulting in more stringent bounds

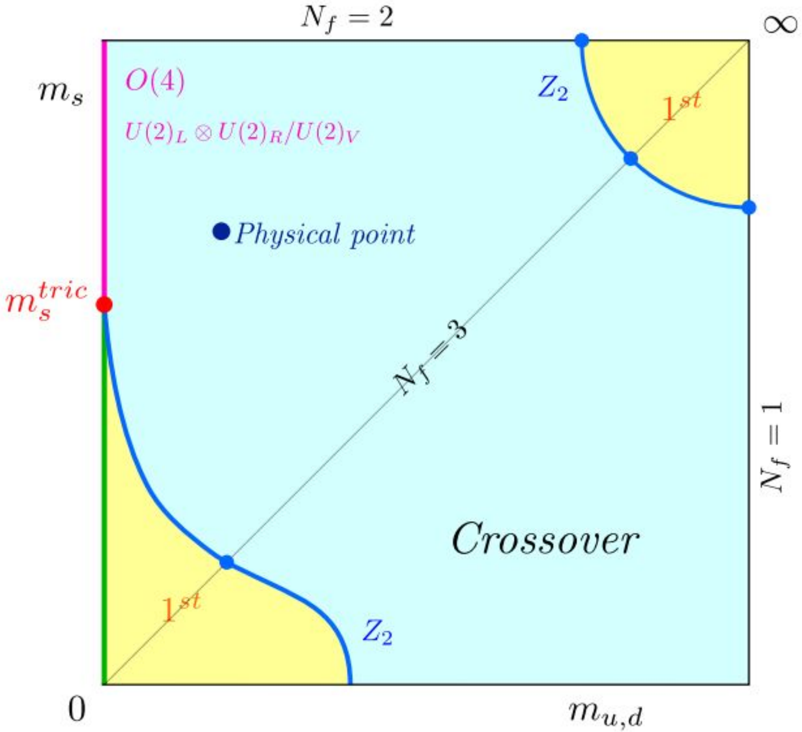
3. Outflows from winds or jets can form shocks, efficiently heating the jets.

4. Without the assumption of ion trapping, the bound on light PBH from Hawking evaporation is much weaker than previously claimed.

Primordial Black Holes from High Temperature QCD Transitions

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

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

PNJL Model

- Effective description of QCD Transition

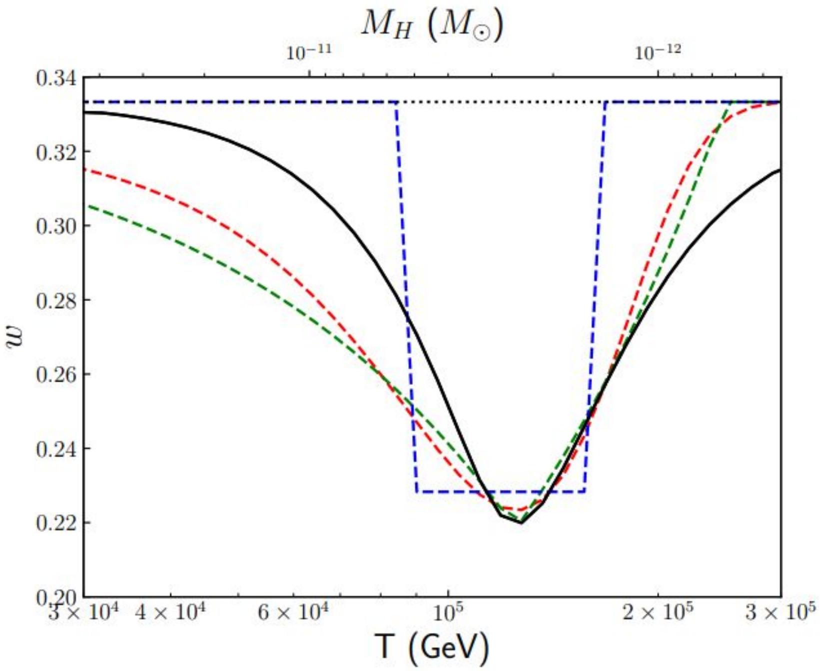
$$\mathcal{L}_{PNJL} = \bar{\chi}\left(i\gamma_\mu D^\mu - m_0\right)\chi + \frac{G}{2}\left[(\chi\bar{\chi})^2 + (\bar{\chi} i\gamma_5\vec{\tau}\chi)^2\right] - \mathcal{U}(\Phi, \bar{\Phi}, T)$$

- 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

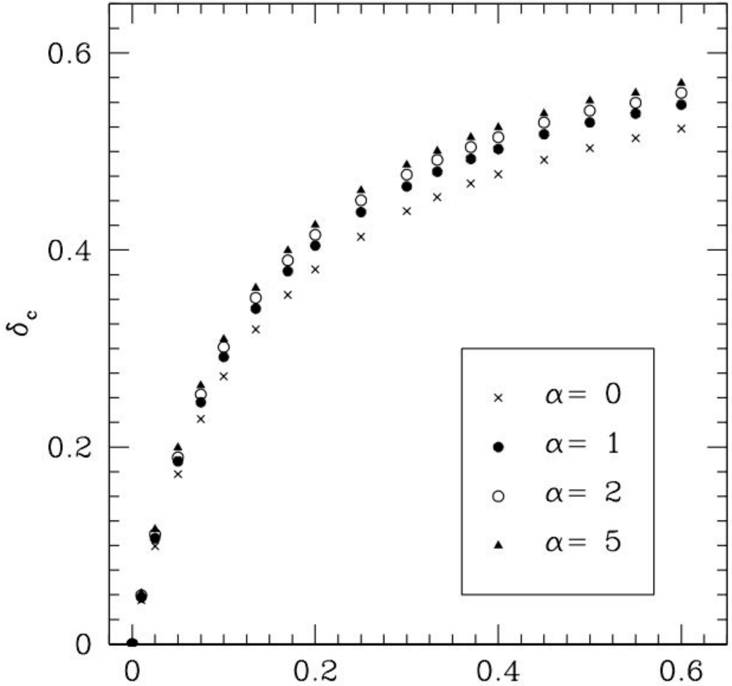


PBH Formation

- 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

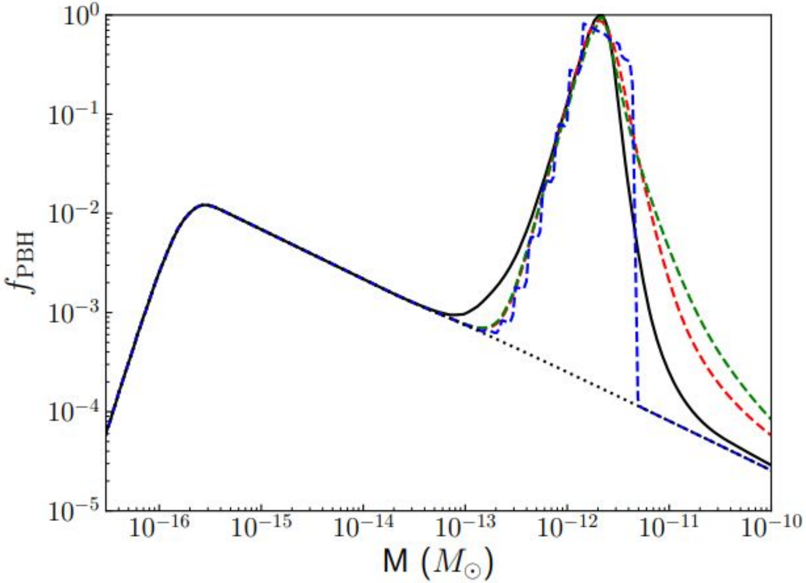
Enhanced PBH Formation

- Present day density scales with collapse probability

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

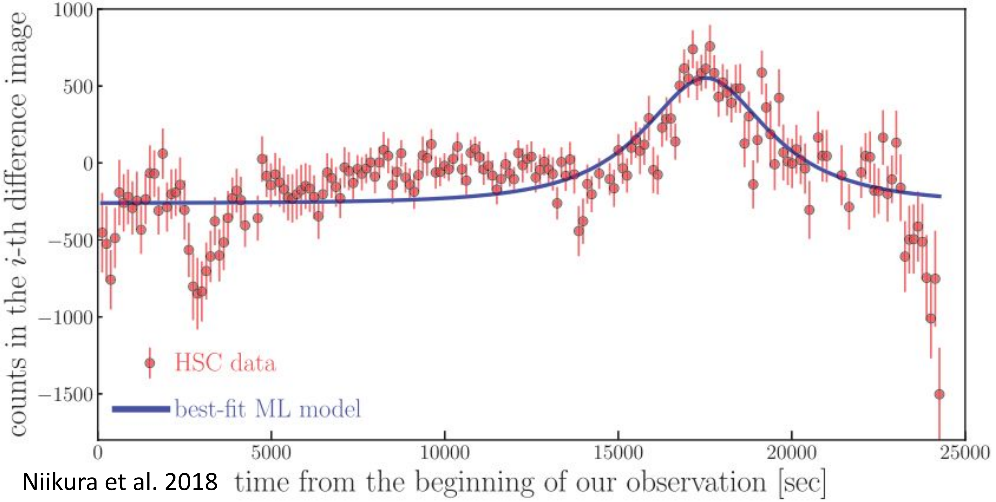
- Results hold irrespective of transition shape
- Mass depends on FOPT temperature

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



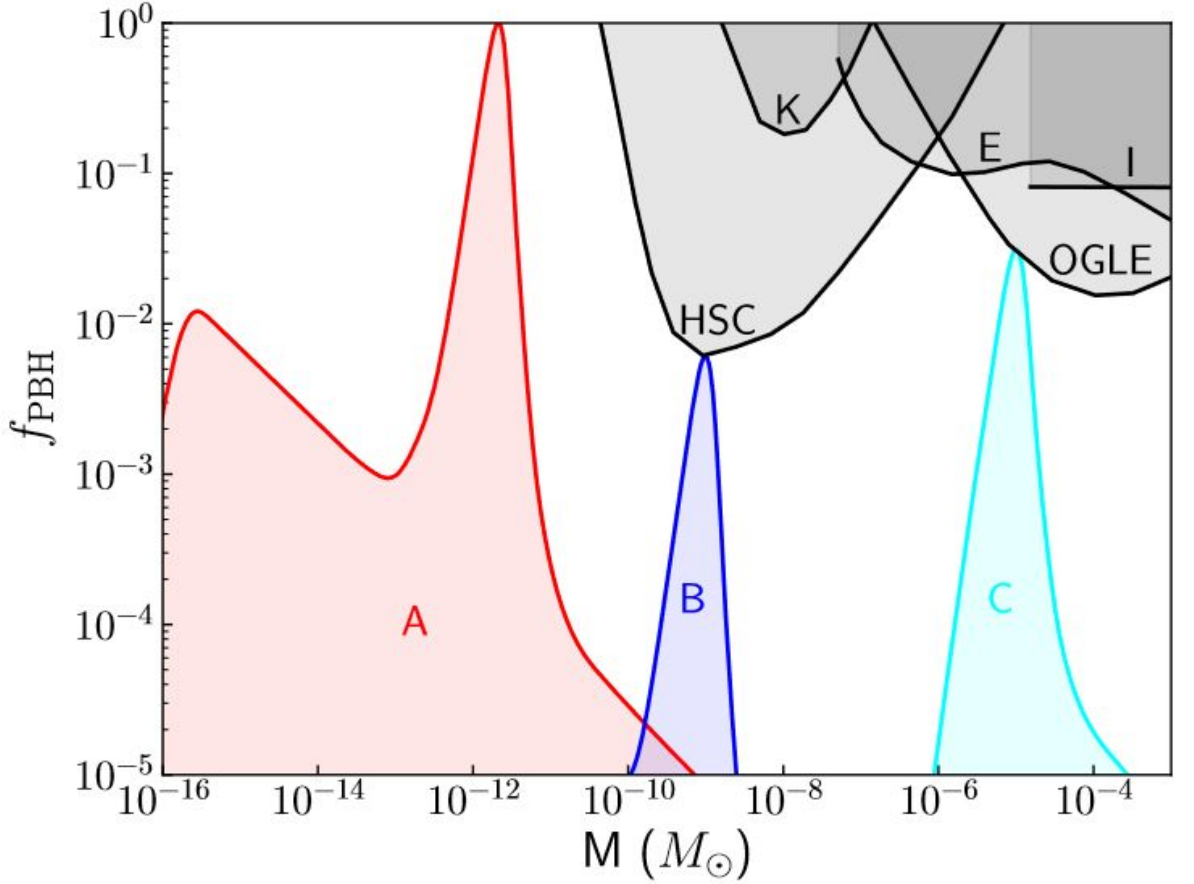
Target Populations

- 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



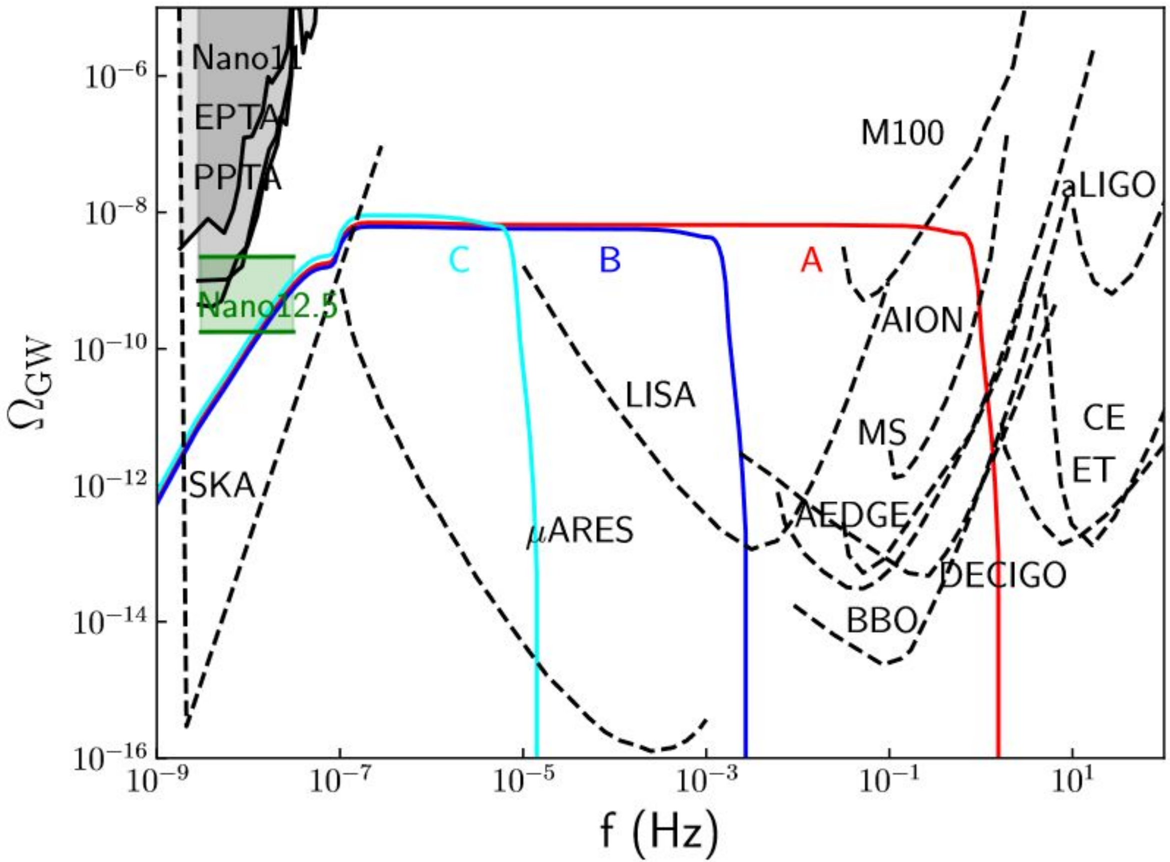
Gravitational Waves

- 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



High Temperature QCD Conclusion

- 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