HPNP2023

The 6th International Workshop on "Higgs as a Probe of New Physics 2023"

Recent topics on cosmology with primordial black holes and their implications for particle physics

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NAOJ from 1st July

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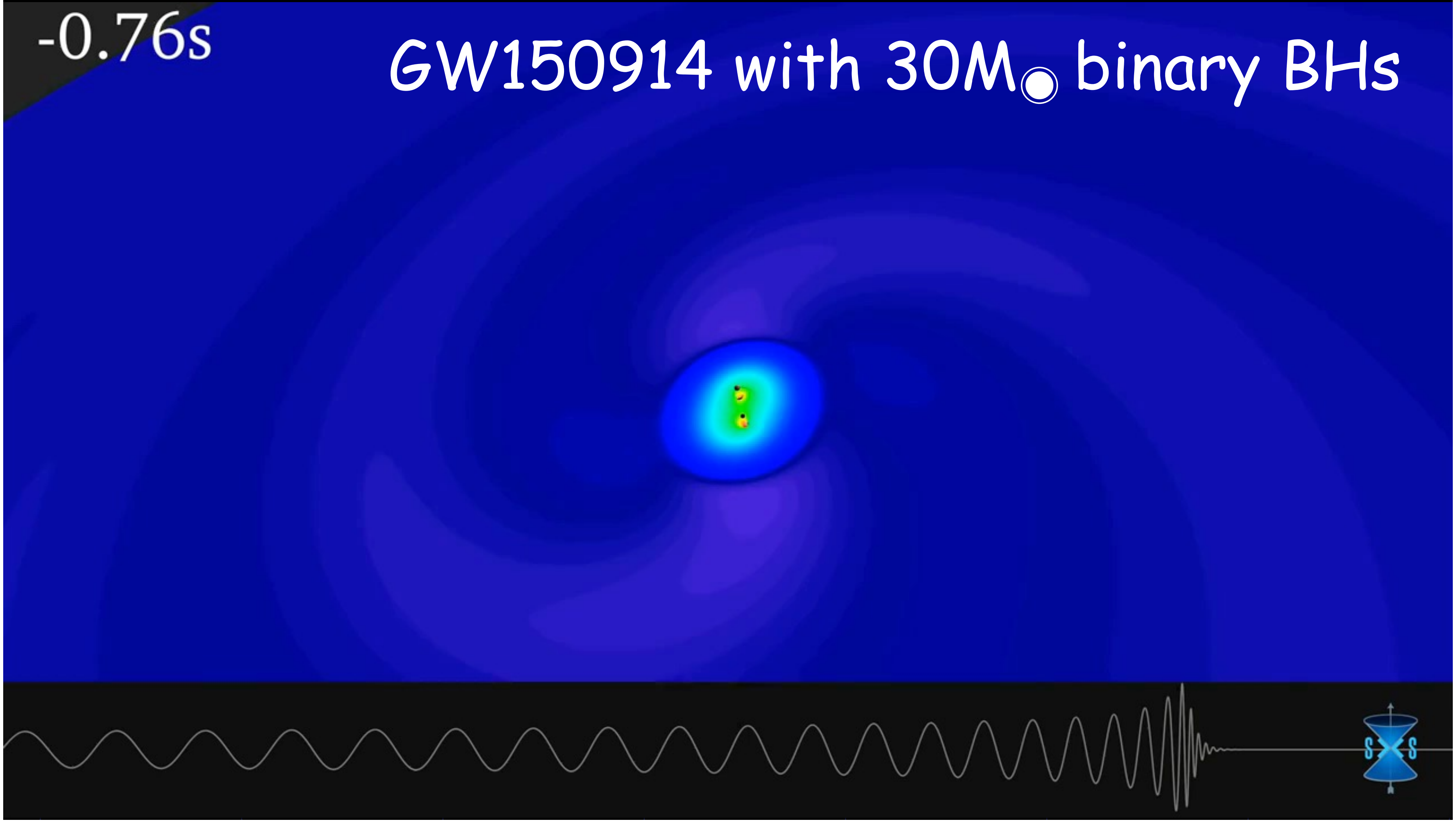
Detections of GWs from binary PBHs collide?

https://www.youtube.com/watch?v=1agm33iEAuo

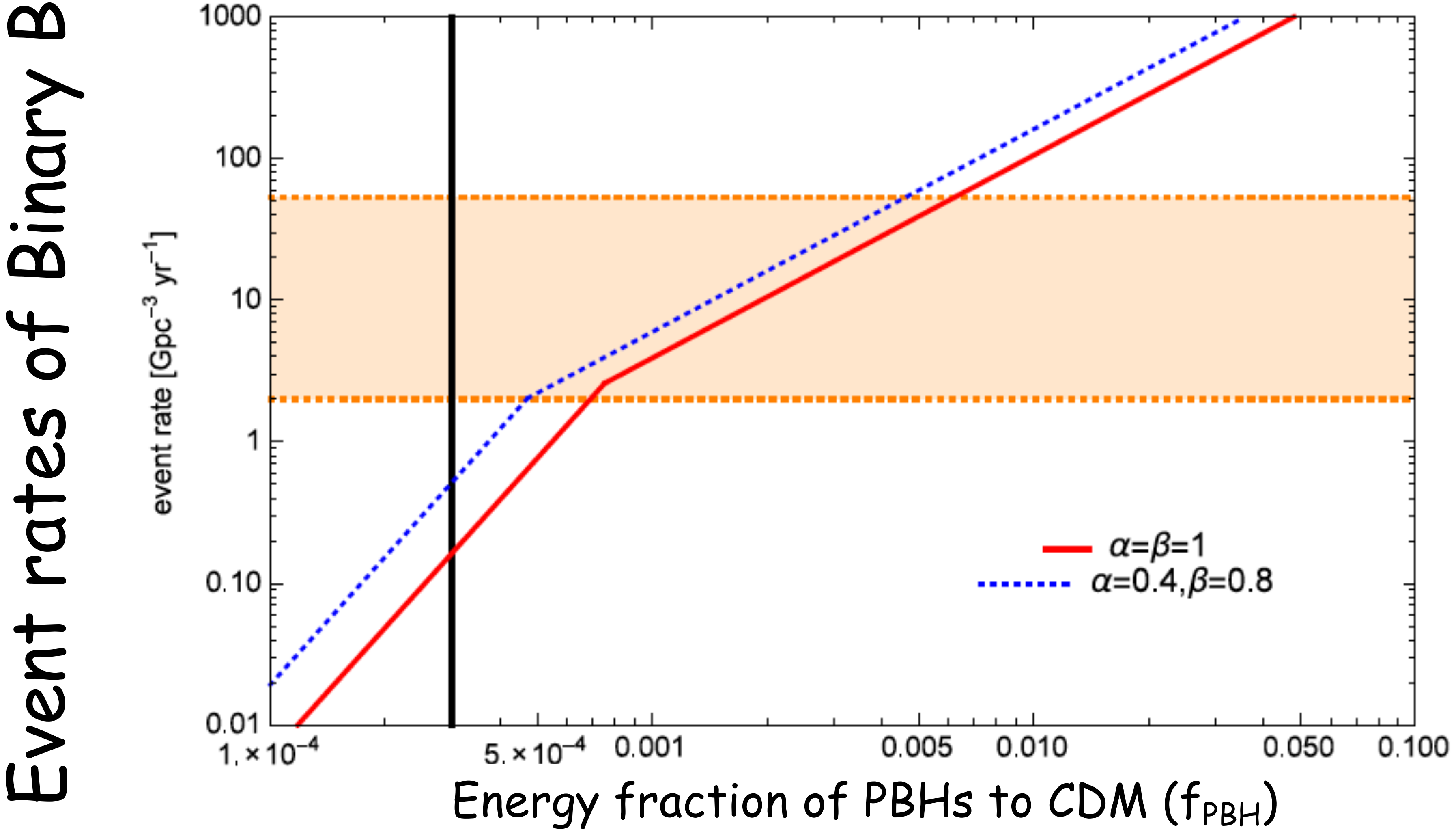


GW150914 with $30M_\odot$ binary BHs

GW150914 and its merger rates for $30\ M_{solar}$ masses BBH

M. Sasaki, T. Suyama, T. Tanaka and S. Yokoyama (2016).

A 3-body effect is important for the BBH formations



The attraction of primordial black holes (PBHs)

$1M_{\odot} \sim 2x10^{33}g$

- Possible sources of LIGO-Virgo-KAGRA binary merging gravitational waves ($\sim >$ $30M_{\odot}$)
- A good candidate of dark matter (10^{17}-10^{23}g)
- Seeds of supermassive BHs (SMBHs) ($< 10^{4}M_{\odot}$-$10^{5}M_{\odot}$ at $z >> 10$)
- Future MeV gamma ray observations hint at quantum gravity
- Verification of large quantum fluctuations on small scales created by inflation
- Simultaneously predicts the possibility of secondary generated background gravity waves (GWs)

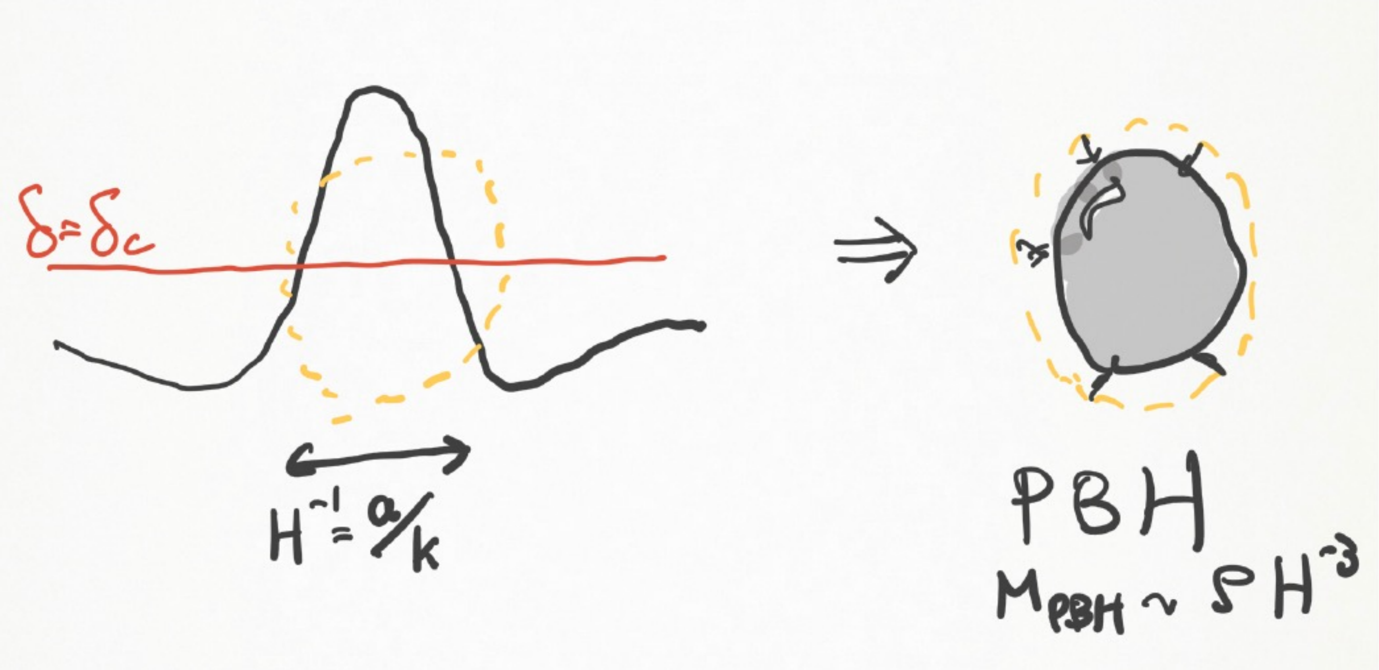
Conditions for a PBH formation in Radiation dominated (RD) Universe

Zel'dovich and Novikov (1967), Hawking (1971), Carr (1975)

Harada,Yoo and KK (2013)

- Gravity could be stronger than pressure

$$\boxed{\delta > \delta_c \sim p/\rho \sim c_s^2 = w = 1/3}$$



wave number

Typical quantities of PBHs in RD

- Mass (horizon mass $=\rho(t_{\rm form})\, H(t_{\rm form})^{-3}$)

$$M_{\rm PBH} \sim \rho(H_{\rm form}^{-1})^3 \sim M_{pl}^2 t_{\rm from} \sim \frac{M_{pl}^3}{T_{\rm form}^2} \sim 10^{15} g \left(\frac{T_{\rm form}}{3\times 10^8 GeV}\right)^{-2} \sim 30 M_\odot \left(\frac{T_{\rm form}}{40 MeV}\right)^{-2}$$

- Lifetime

$$\tau_{\rm PBH} \sim \frac{M_{\rm PBH}^3}{M_{pl}^4} \sim 4\times 10^{17}\, {\rm sec} \left(\frac{M_{\rm PBH}}{10^{15} g}\right)^3 \sim 3\times 10^{68} {\rm yrs} \left(\frac{M_{\rm PBH}}{30 M_\odot}\right)^3$$

- Hawking Temperature

$$T_{\rm PBH} \sim \frac{M_{pl}^2}{M_{\rm PBH}} \sim 10 {\rm MeV} \left(\frac{M_{\rm PBH}}{10^{15} g}\right)^{-1} \sim 1\times 10^{-9}\ {\rm K} \left(\frac{M_{\rm PBH}}{30 M_\odot}\right)^{-1}$$

- Wave number of horizon length

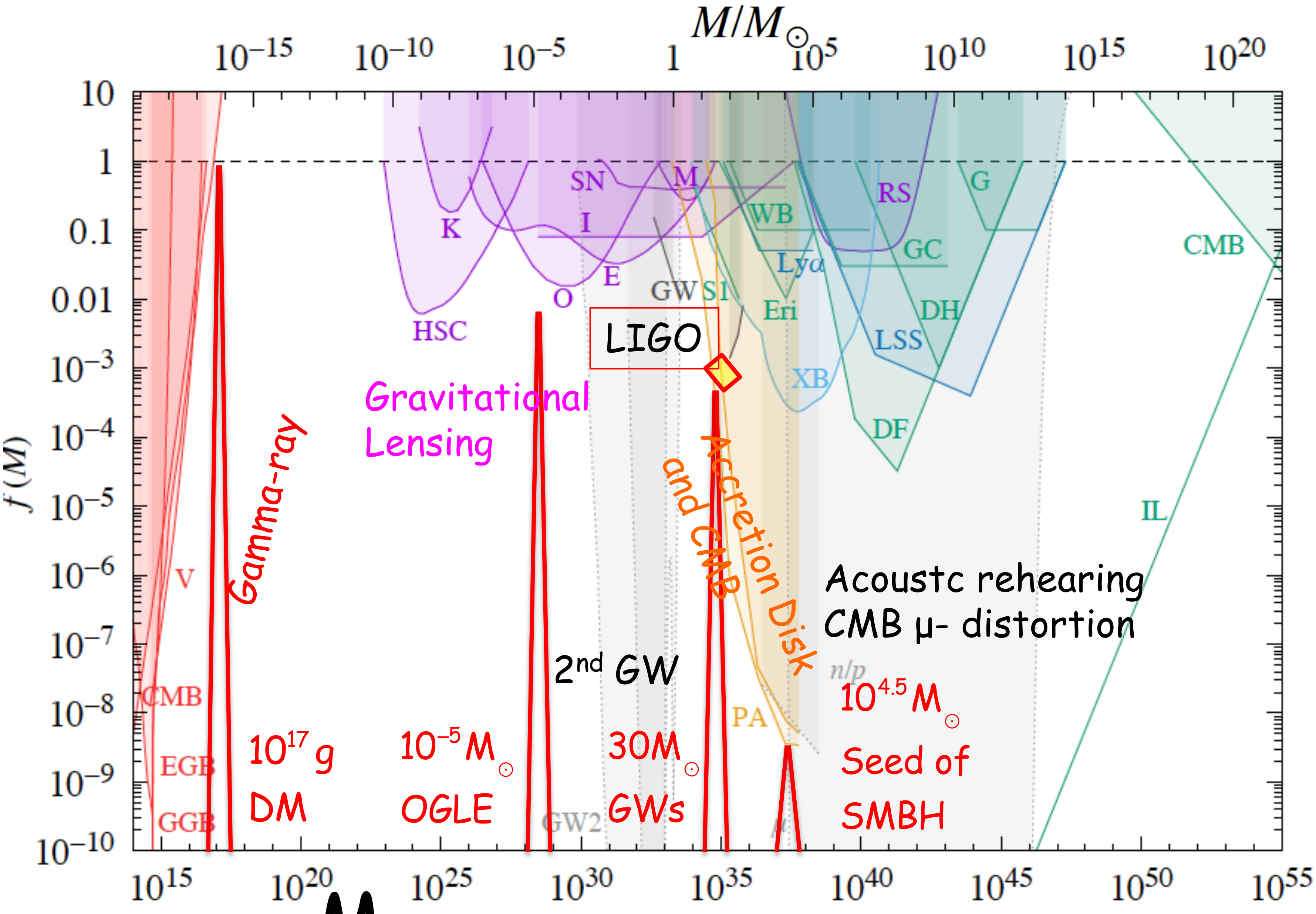
$$k = aH \sim 10^5 {\rm Mpc}^{-1} \left(\frac{M_{\rm PBH}}{10^4 M_\odot}\right)^{-1/2} \sim 10^5 {\rm Mpc}^{-1} \left(\frac{T_{\rm form}}{MeV}\right)^{+1}$$

- Fraction to CDM

$$f_{\rm fraction} \equiv \frac{\Omega_{PBH}}{\Omega_{CDM}} \sim 10^8 \left(\frac{M_{PBH}}{30 M_\odot}\right)^{-1/2} \sqrt{P_\delta} \exp\left[-\frac{1}{18 P_\delta}\right]$$

Upper bounds on the fraction to CDM

Carr, Kohri, Sendouda, J.Yokoyama (2009-2022)



$f_{PBH}=\Omega_{PBH}/\Omega_{CDM}$

Gamma-ray

Gravitational Lensing

LIGO

Accretion Disk and CMB

Acoustc rehearing
CMB μ- distortion

2^{nd} GW

10^{17} g
DM

$10^{-5} M_\odot$
OGLE

$30 M_\odot$
GWs

$10^{4.5} M_\odot$
Seed of
SMBH

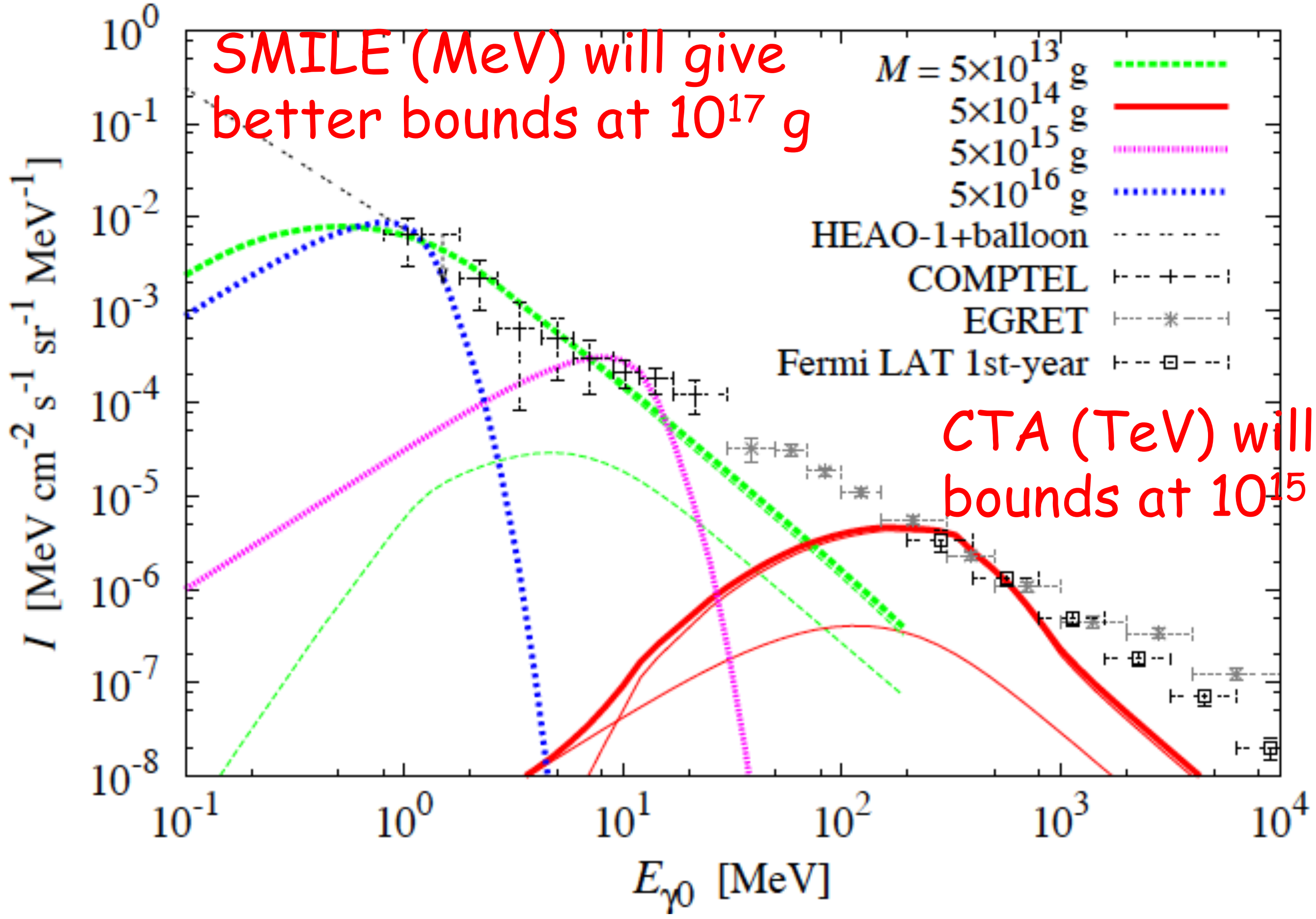
M_{PBH}

Mass in gram

Evaporating PBHs through Hawking Process

Carr, Kohri, Sendouda and Yokoyama (2010)

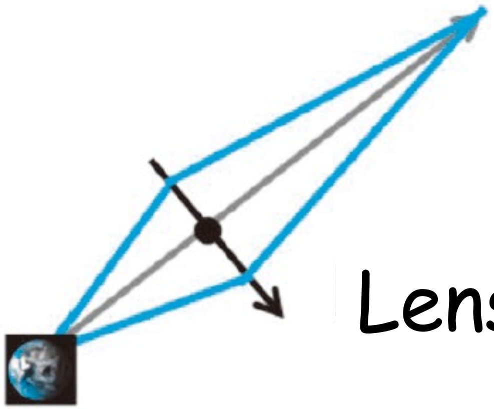
$$d\dot{N}_s = \frac{dE}{2\pi} \frac{\Gamma_s}{e^{E/T_{\rm BH}} - (-1)^{2s}}$$



SMILE (MeV) will give better bounds at 10^{17} g

CTA (TeV) will give better bounds at 10^{15} g

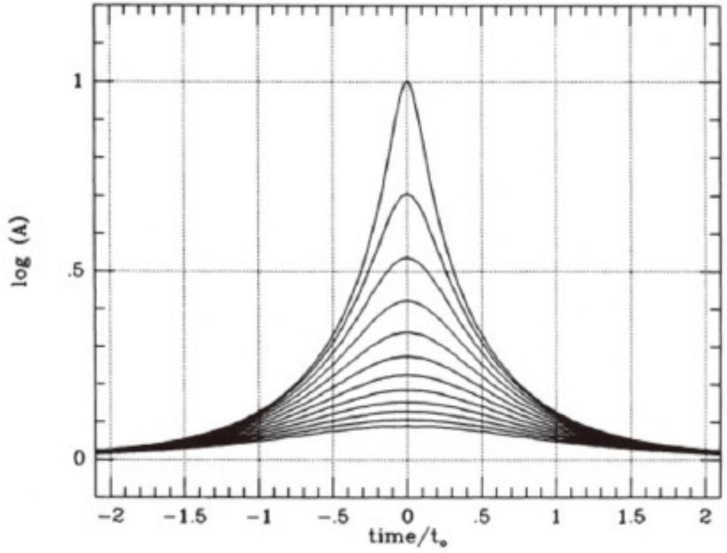
Gravitational Lensing



Source

Lens (PBH)

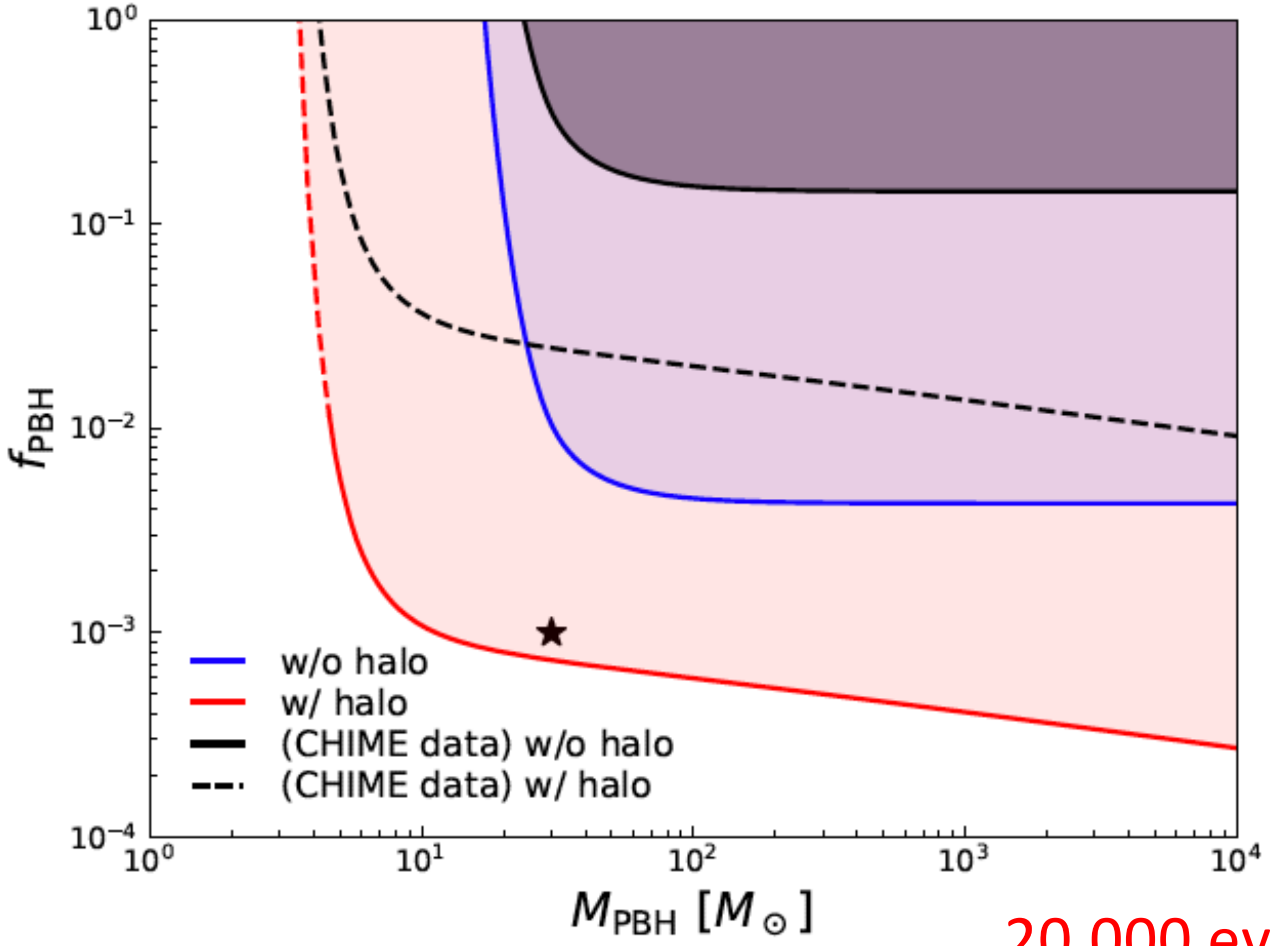
Observers



Hiroko Niikura, https://stg.asj.or.jp/jp/activities/geppou/item/113-1_6.pdf

Revealing Dark Matter Dress of Primordial Black Holes by Cosmological Strong Lensing

Masamune Oguri, Volodymyr Takhistov, Kazunori Kohri, arXiv:2208.05957 [astro-ph.CO]

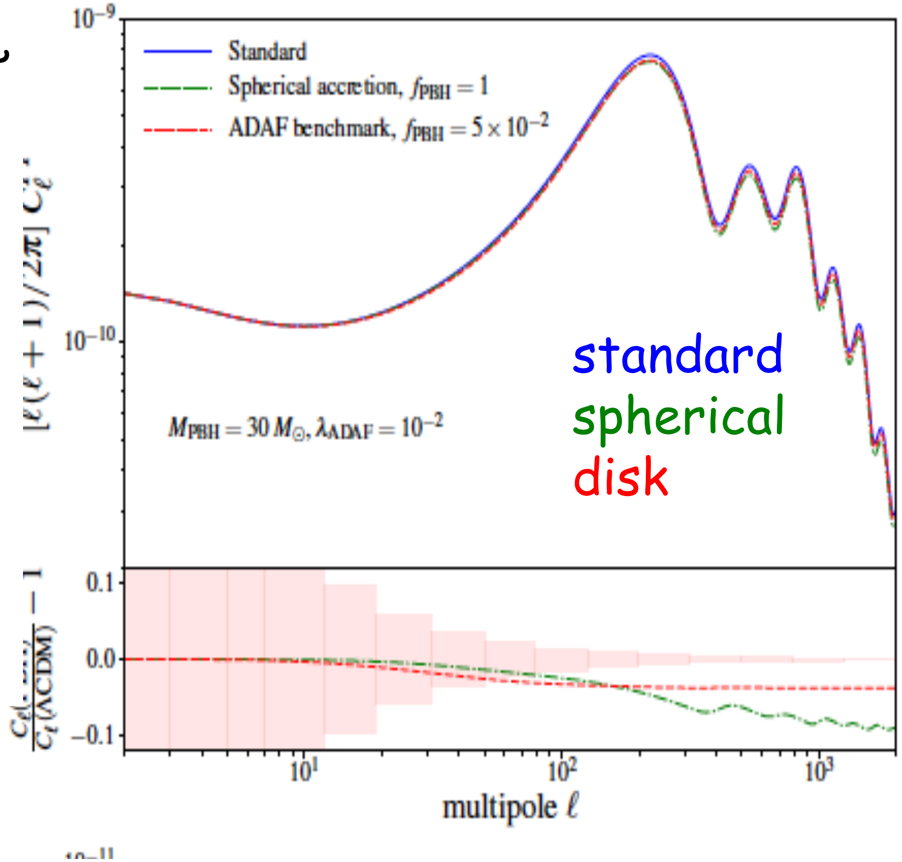


20,000 events by
CHIME collaboration

Modified CMB anisotropy and polarization

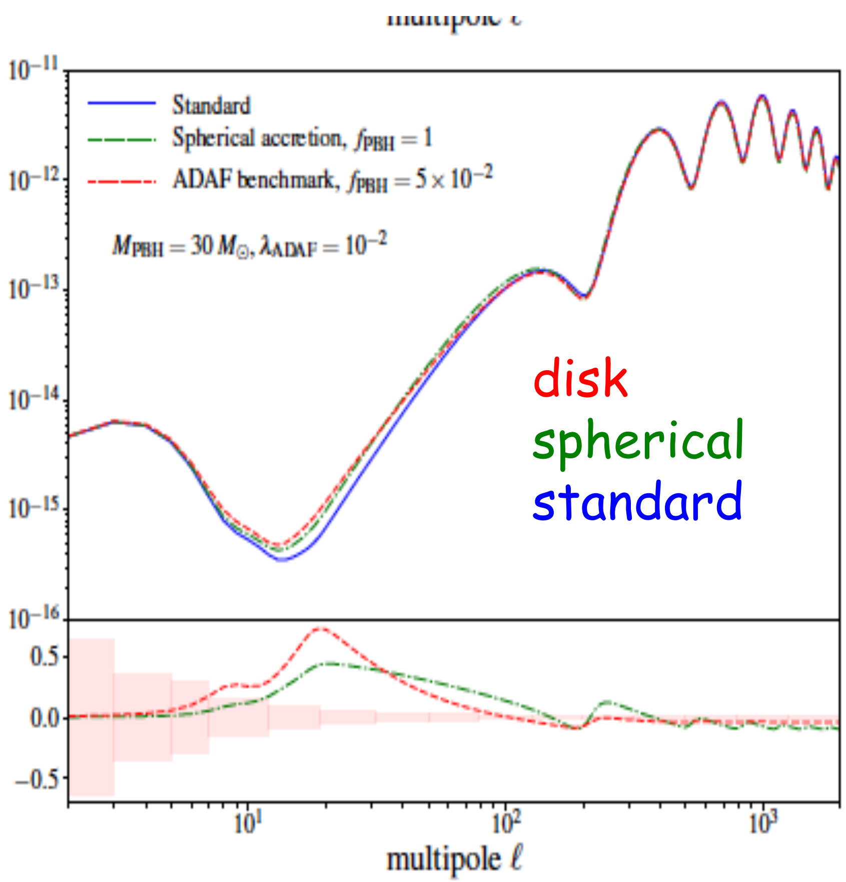
Serpico, Poulin, Calore, Clesse, Kohri (2017)

TT corrrelation C^{TT}_ℓ



multipole ℓ

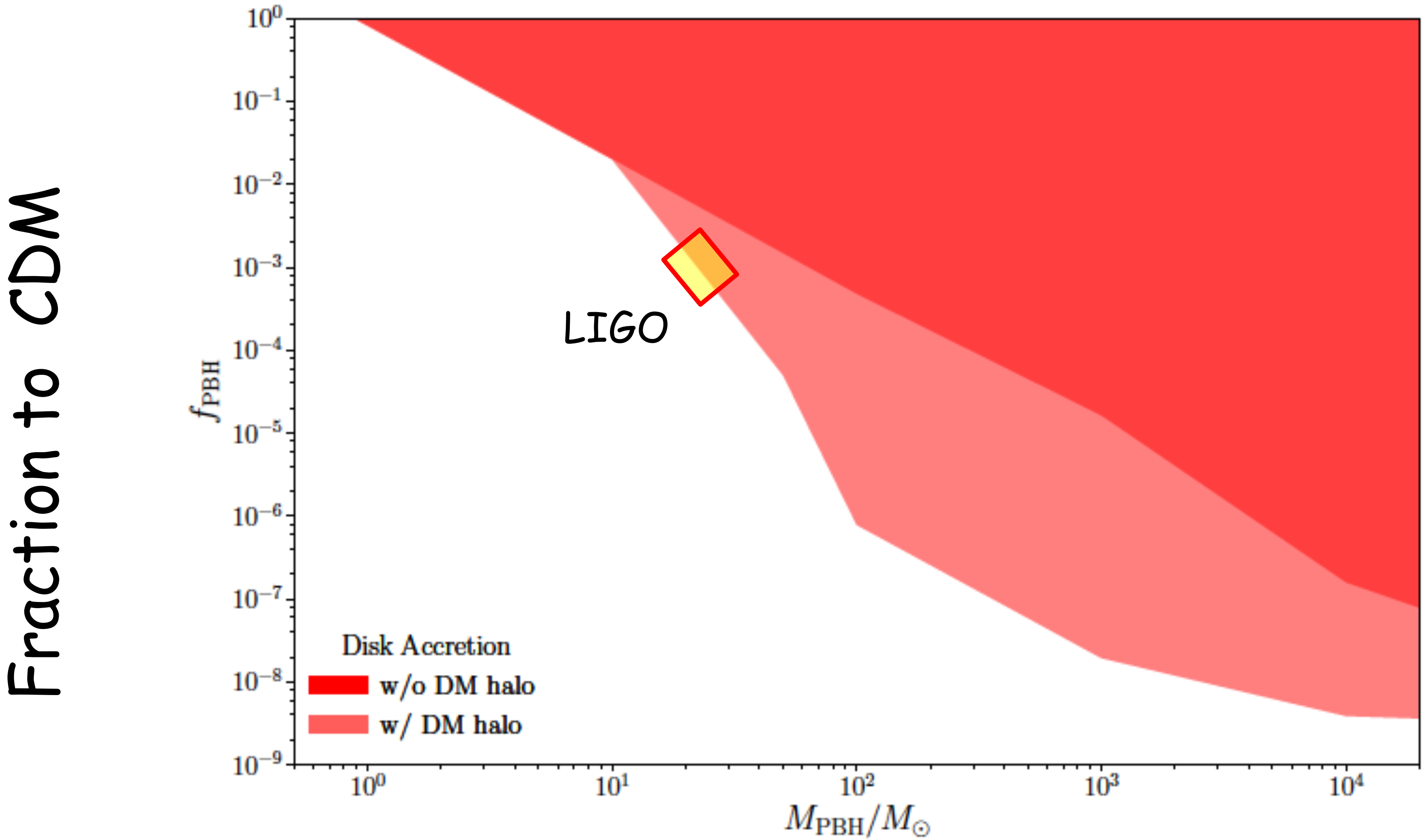
EE polarization correlation C^{EE}_ℓ



multipole ℓ

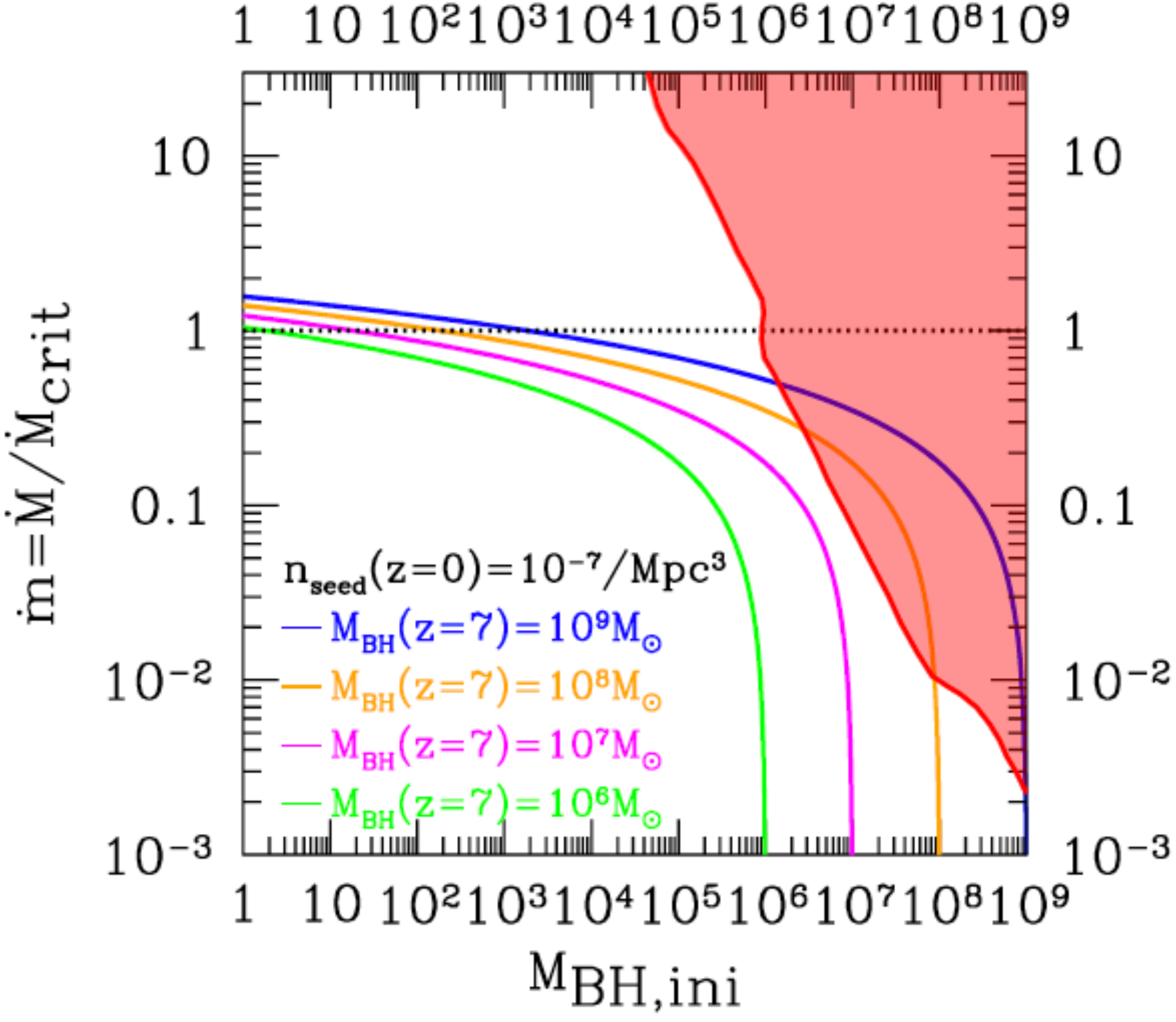
CMB bound by disk-accretion in the MD epoch

Serpico, Poulin, Calore, Clesse, Kohri (2017)



Upper bounds on accretion rates on seed BHs at z=17 evolved to SMBHs until z=7

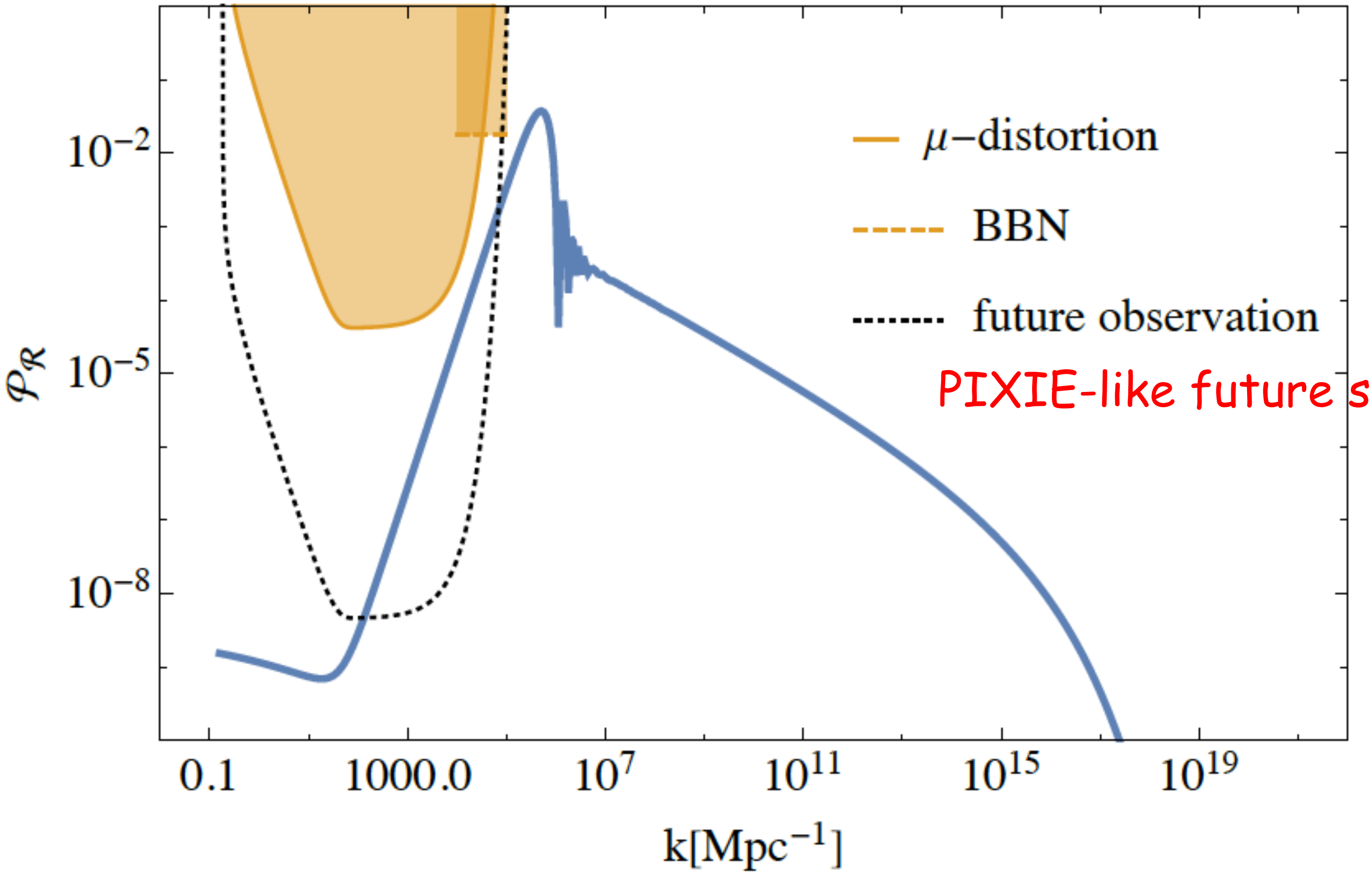
Kazunori Kohri, Toyokazu Sekiguchi, Sai Wang, arXiv:2201.05300 [astro-ph.CO]



μ-distortion and acoustic reheating

Kohri, Nakama, Suyama (2014)

Inomata, Kawasaki, Mukaida, Tada, Yanagida (2017)



PIXIE-like future satelllite

Secondary gravitational wave induced from large curvature perturbation (P_ζ >> r) at small scales

K. N. Ananda, C. Clarkson, and D. Wands, 2006
D.Baumann, P.J.Steinhardt, K.Takahashi and K.Ichiki,2007
R.Saito and J.Yokoyama, 2008
KK and T.Terada, 2018
R.-G. Cai, S. Pi, and M. Sasaki, 2019

- Power spectrum of the tensor mode

$$\langle h^r_{\boldsymbol{k}}(\eta) h^s_{\boldsymbol{k}'}(\eta)\rangle = \frac{2\pi^2}{k^3}\mathcal{P}_h(k,\eta)\delta(\boldsymbol{k}+\boldsymbol{k}')\delta^{rs}, \qquad h_{ij}(\boldsymbol{x},\eta) = \int \frac{\mathrm{d}^3k}{(2\pi)^{3/2}} e^{i\boldsymbol{k}\cdot\boldsymbol{x}} \left[h^+_{\boldsymbol{k}}(\eta)\mathrm{e}^+_{ij}(\boldsymbol{k}) + h^\times_{\boldsymbol{k}}(\eta)\mathrm{e}^\times_{ij}(\boldsymbol{k})\right]$$

- Omega parameter well inside the horizon

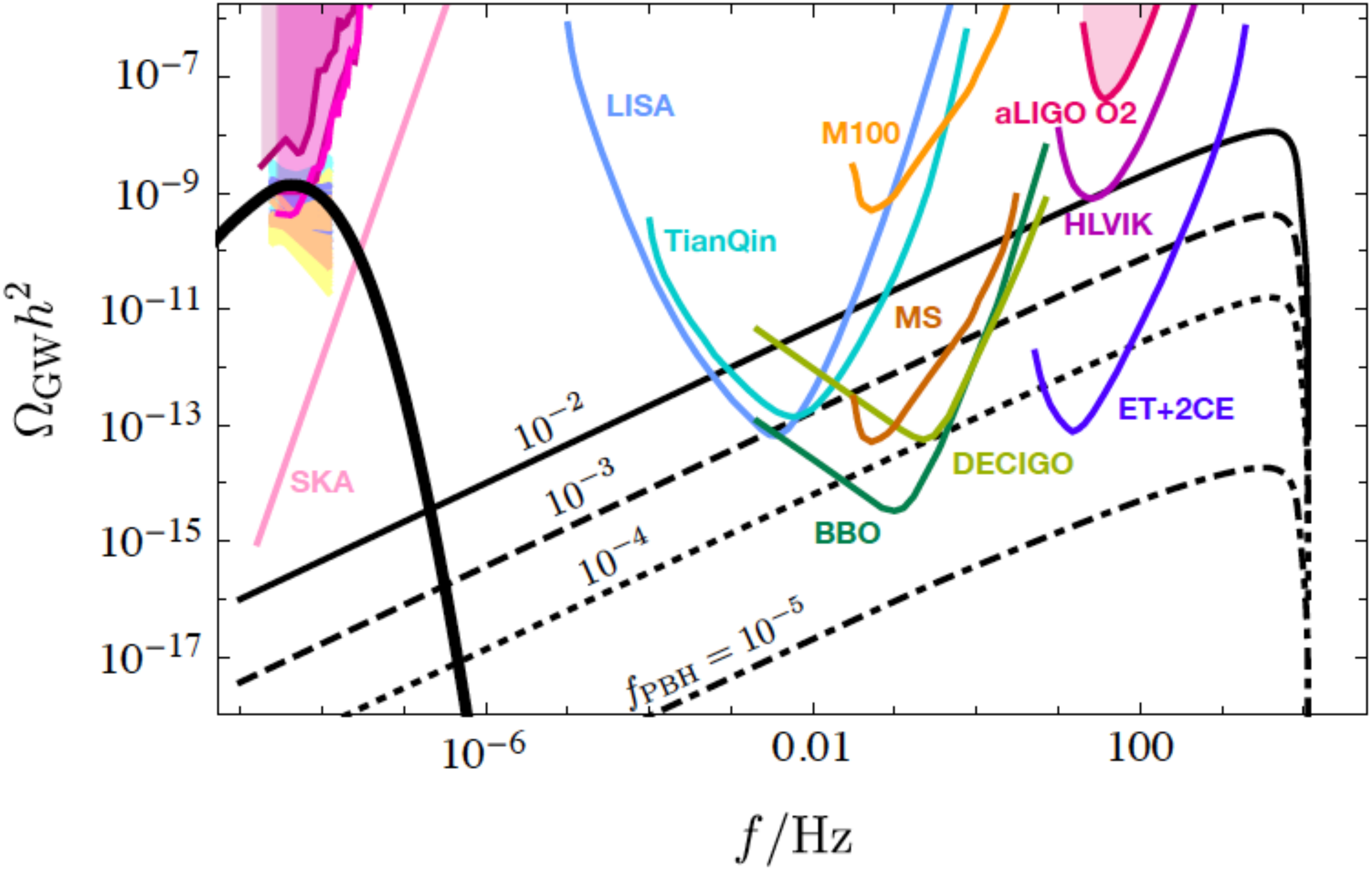
$$\Omega_{\rm GW}(k,\eta) = \frac{1}{3}\left(\frac{k}{\mathcal{H}}\right)^2 \mathcal{P}_h(k,\eta).$$

- Substituting the solution into this

$$\Omega_{\rm GW,c}(f) = \frac{1}{12}\left(\frac{f}{2\pi a H}\right)^2 \int_0^\infty \mathrm{d}t \int_{-1}^{1} \mathrm{d}s \left[\frac{t(t+2)(s^2-1)}{(t+s+1)(t-s+1)}\right]^2 \times \overline{I^2(t,s,k\eta_c)}\,\mathcal{P}_\zeta\left(\frac{(t+s+1)f}{4\pi}\right)\mathcal{P}_\zeta\left(\frac{(t-s+1)f}{4\pi}\right)$$

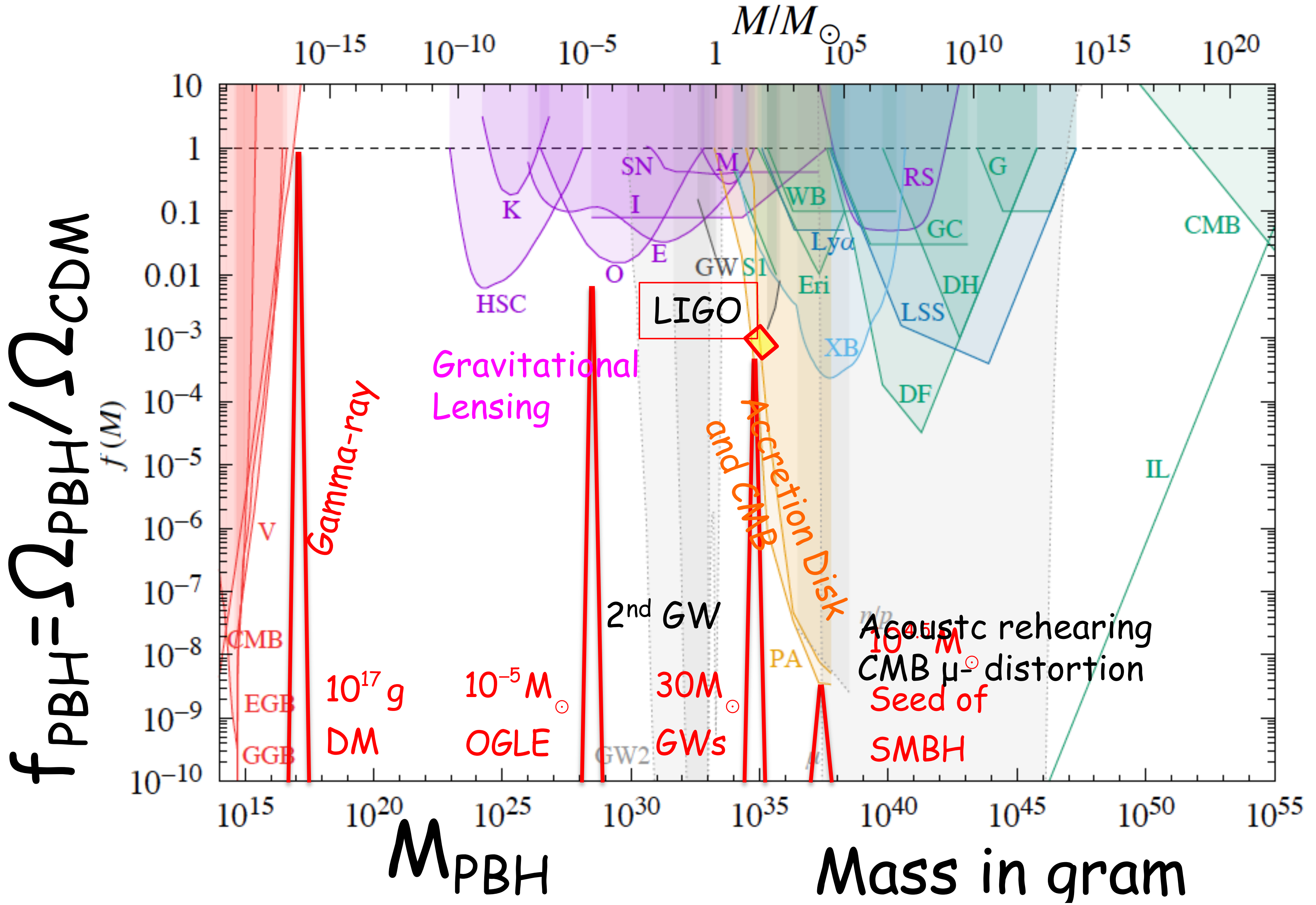
NANOGrav12.5yr and solar mass PBHs

K. Kohri and T. Terada, arXiv:arXiv:2009.11853



Upper bounds on the fraction to CDM

Carr, Kohri, Sendouda, J.Yokoyama (2009-2022)



How to test PBHs?

- LIGO events ($\sim 30\ M_\odot$)
    - Strong lensing of FRBs
    - Anisotropies of GWs from PBHs
- DM (10^{17}g – 10^{23}g)
    - Induced GWs
    - MeV Gamma-ray
- Seeds of SMBHs ($\sim 10^4\ M_\odot$)
    - Cosmological 21cm at $z > \sim O(10)$

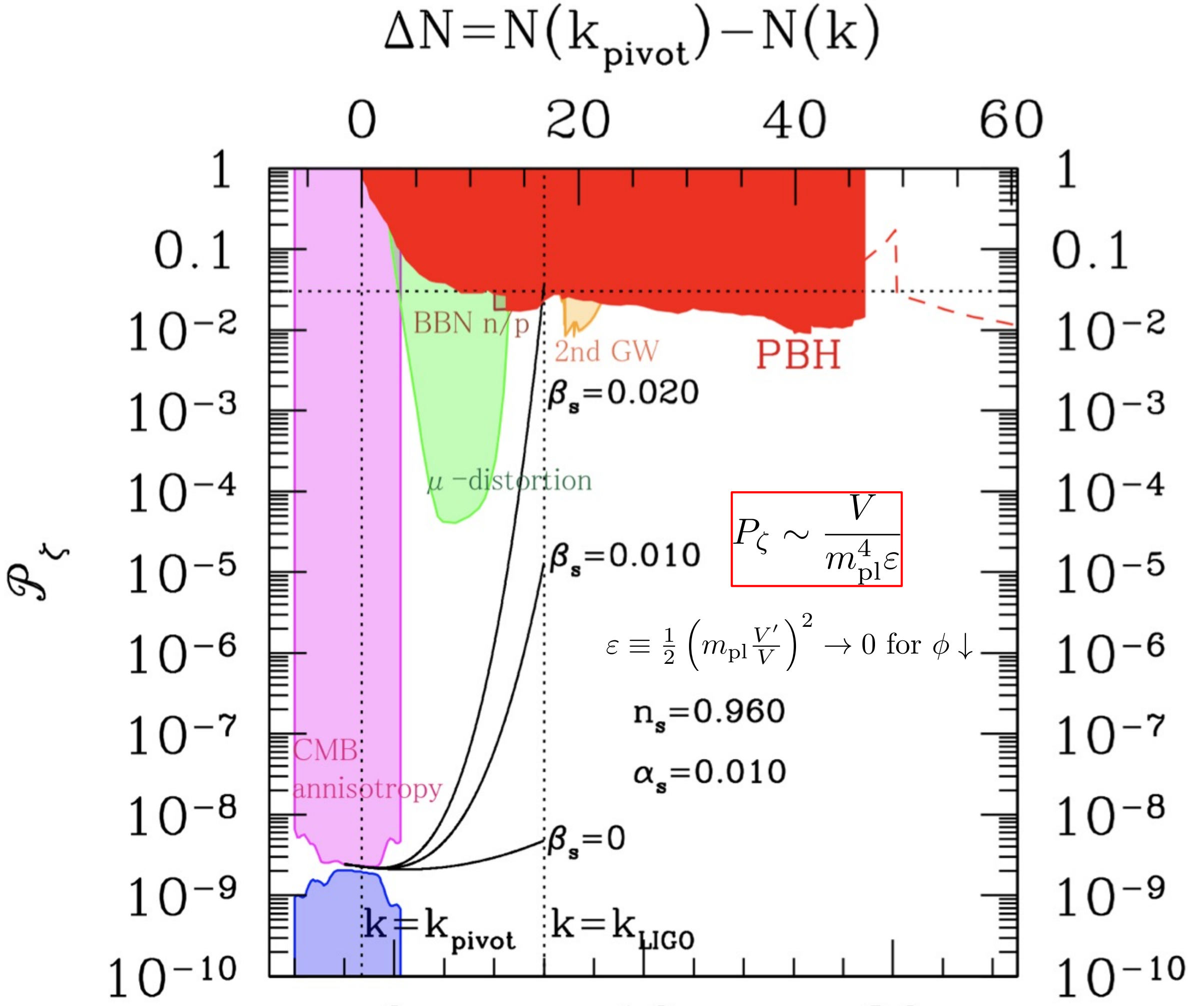
Mechanisms to produce PBHs

- Chaotic-New inflation: J. Yokoyama, 1998), Multi-field inflation (Kawasaki, Sugiyama, Yanagida, 1998, …
- At the end of inflation: Lyth, Malik, Sasaki, Zabarra (2006), Preheating: Green and Malik (1999), Taruya (1998) …
- Blue-tilted spectrum (perturbative) Leach Grivell and Liddle, 2001, Kohri, Lyth and Melchiorri, 2007, …
- Ultra-slowroll? see Kristiano and J.Yokoyama, 2023, A. Riotto, 2023, …
- Tachyonic instability : Dhong Yeon Cheong, Kazunori Kohri, Seong Chan Park, arXiv:2205.14813
- Curvaton: Kawasaki, Kitajima, Yanagida (2012), Kohri, Lin, Matsuda (2012), …
- 1st-order Phase transition (+ pre-existing large curvature perturbation A_s)
  Byrnes, Hindmarsh, Young, Hawkins, 2018, Abe, Tada, Ueda, 2020, Franciolini, Musco, Pani, Urbano, 2022, Hashino, Kanemura, Tomo Takahashi, and M. Tanaka, 2022, …
- Collapse of Q-balls or topological defects (monopole, cosmic string, domain wall):
  Cotner, Kusenko, Sasaki, Takhistov, 2019, Hasegawa and Kawasaki, 2018, …
- Extra attractive forces (Yukawa interaction, …) : Kawana and Xie, 2021, Lu, Kawana, Kusenko, 2023, …
- …

Curvature perturbation $P_\zeta(k)$

Kohri and T.Terada, 2018

Alabidi, Kohri, Sendouda, Sasaki, 2013



Amplitude of curvature perturbation

Wave number $\log_{10}(k/\mathrm{Mpc}^{-1})$

Planck (2018)

$$n_s = 0.9586 \pm 0.0056,$$
$$\alpha_s = 0.009 \pm 0.010,$$
$$\beta_s = 0.025 \pm 0.013.$$

at 68% C.L.

For inflation models with a big running, see Kohri, Lin Lyth (2008)

k = p x a

Higgs-R^2 Inflation

Dhong Yeon Cheong, Kazunori Kohri, Seong Chan Park, arXiv:2205.14813 [hep-ph]

- Action of Higgs and R^2

$$S_J = \int d^4x\sqrt{-g_J}\left[\frac{M_P^2}{2}\left(R_J + \frac{\xi h^2}{M_P^2}R_J + \frac{R_J^2}{6M^2}\right) - \frac{1}{2}g^{\mu\nu}\nabla_\mu h\nabla_\nu h - \frac{\lambda(\mu)}{4}h^4\right]$$

- Conformal transformation

$$\boxed{\alpha = M_P^2/12M^2}$$

$$\sqrt{\frac{2}{3}}\frac{s}{M_P} = \ln\left(1 + \frac{\xi h^2}{M_P^2} + \frac{R_J}{3M^2}\right) \equiv \Omega(s).$$

- Action of scalaron (s) and Higgs (h)

$$S = \int d^4x\sqrt{-g}\left[\frac{M_P^2}{2}R - \frac{1}{2}G_{ab}g^{\mu\nu}\nabla_\mu\phi^a\nabla_\nu\phi^b - U(\phi^a)\right]$$

$$U(\phi^a) \equiv e^{-2\Omega(s)}\left\{\frac{3}{4}M_P^2M^2\left(e^{\Omega(s)} - 1 - \frac{\xi h^2}{M_P^2}\right)^2 + \frac{\lambda\left(\mu\right)}{4}h^4\right\}$$

$$g_{\mu\nu} = e^{\Omega(s)}g_{\mu\nu}^J \qquad G_{ab} = \begin{pmatrix} 1 & 0 \\ 0 & e^{-\Omega(s)} \end{pmatrix}$$

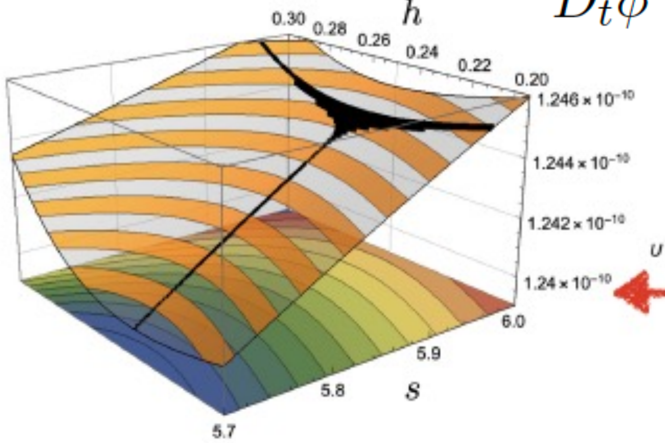
Motions on the potential of the Higgs-scalaron (s) system

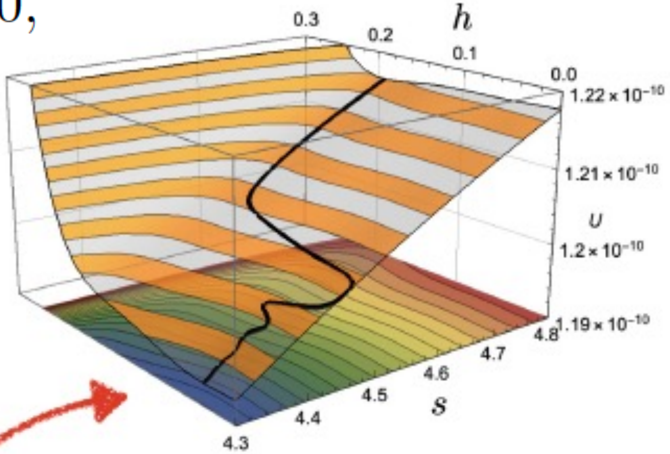
Dhong Yeon Cheong, Kazunori Kohri, Seong Chan Park, arXiv:2205.14813 [hep-ph]

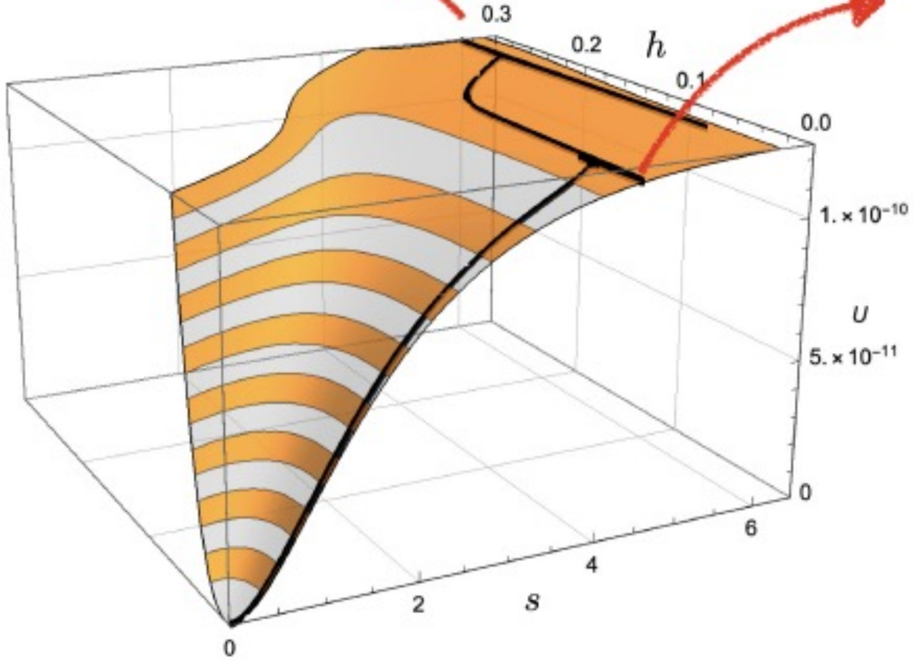
$$D_t\dot{\phi}^a + 3H\dot{\phi}^a + G^{ab}D_bU = 0,$$

$\phi^s = s$

$\phi^h = h$







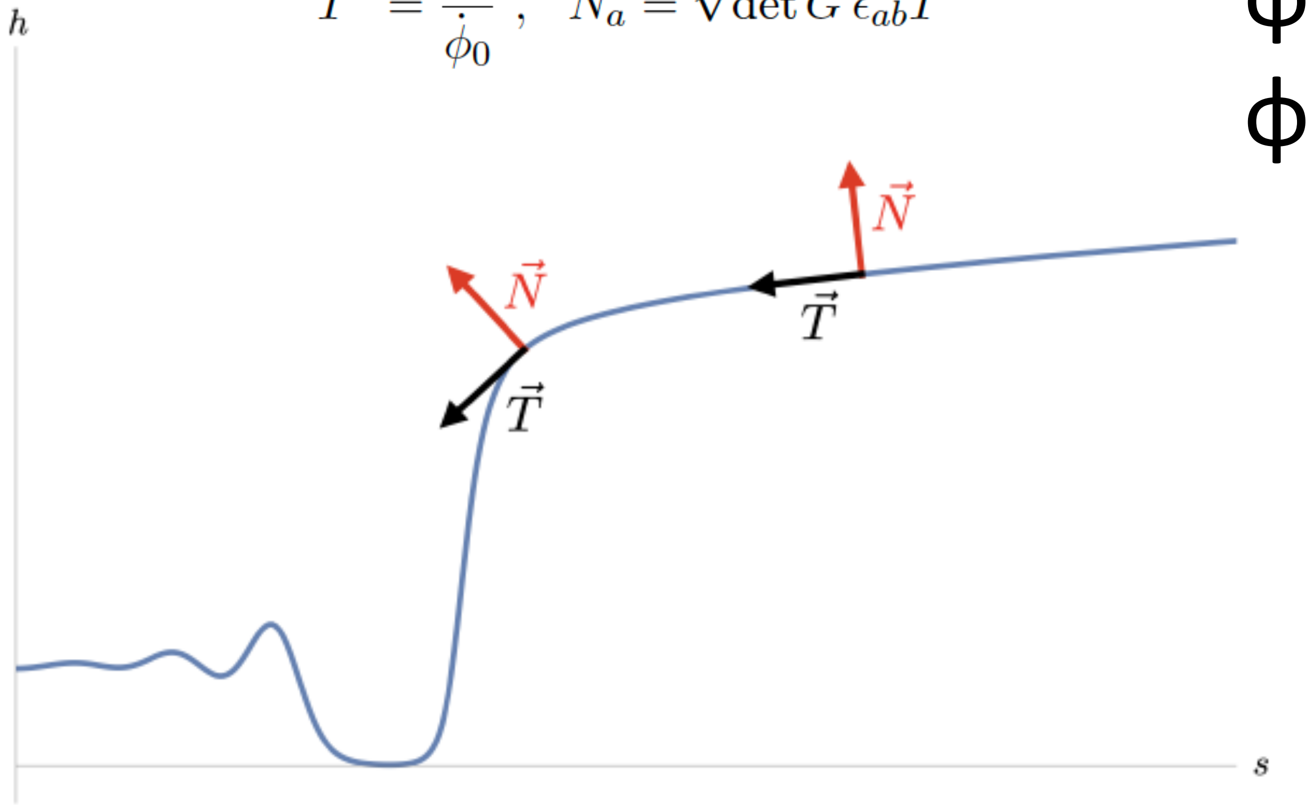
Adiabatic and is isocurvature perturbations in Higgs-R^2 Inflation

Dhong Yeon Cheong, Kazunori Kohri, Seong Chan Park, arXiv:2205.14813 [hep-ph]

$$T^a = \frac{\dot{\phi}^a}{\dot{\phi}_0}\ , \quad N_a = \sqrt{\det G}\,\epsilon_{ab}T^b$$

$\phi^s = s$

$\phi^h = h$



Curvature and isocurvature perturbations

$\phi^s = s$

$\phi^h = h$

- Metric

$$\phi^a(t,\vec{x}) = \phi^a_0(t) + \boxed{\delta\phi^a(t,\vec{x}),}$$

$$ds^2 = -(1+2\psi)dt^2 + a(t)^2(1-2\psi)\delta_{ij}dx^i dx^j$$

- Mukhanov-Sasaki variable

$$\boxed{Q^a} \equiv \delta\phi^a + \frac{\dot{\phi}^a}{H}\psi$$

- Curvature and isocurvature perturbations

$$\mathcal{R} = \frac{H}{a\dot{\phi}_0}v_T \equiv \frac{H}{\dot{\phi}_0}Q_T$$

$$\mathcal{S} = \frac{H}{a\dot{\phi}_0}v_N \equiv \frac{H}{\dot{\phi}_0}\boxed{Q_N.}$$

$$v_T = aT_a\delta\phi^a + a\frac{\dot{\phi}_0}{H}\psi \equiv aT_a\boxed{Q^a}$$

$$v_N = aN_a\delta\phi^a \equiv aN_a\boxed{Q^a}$$

Tachyonic Instability induced in Higgs-R^2 Inflation

Dhong Yeon Cheong, Kazunori Kohri, Seong Chan Park, arXiv:2205.14813 [hep-ph]

$$\ddot{Q}_N + 3H\dot{Q}_N + \left(\frac{k^2}{a^2} + M_{\rm eff}^2\right) Q_N = 2\dot{\phi}_0 \eta_\perp \dot{\mathcal{R}}$$

$$M_{\rm eff}^2 = U_{NN} + H^2\epsilon\mathbb{R} - \dot{\theta}^2 \qquad \boxed{U_{NN} \ < \ 0,}$$

$$M_{\rm eff}^2 \simeq \frac{1}{\dot{s}^2 + e^{-\sqrt{\frac{2}{3}}s}\dot{h}^2}\left(e^{\sqrt{\frac{2}{3}}s}\dot{s}^2\frac{\partial^2 U}{\partial h^2}\right) \simeq -3M^2\xi\left(1 - e^{-\sqrt{\frac{2}{3}}s}\right).$$

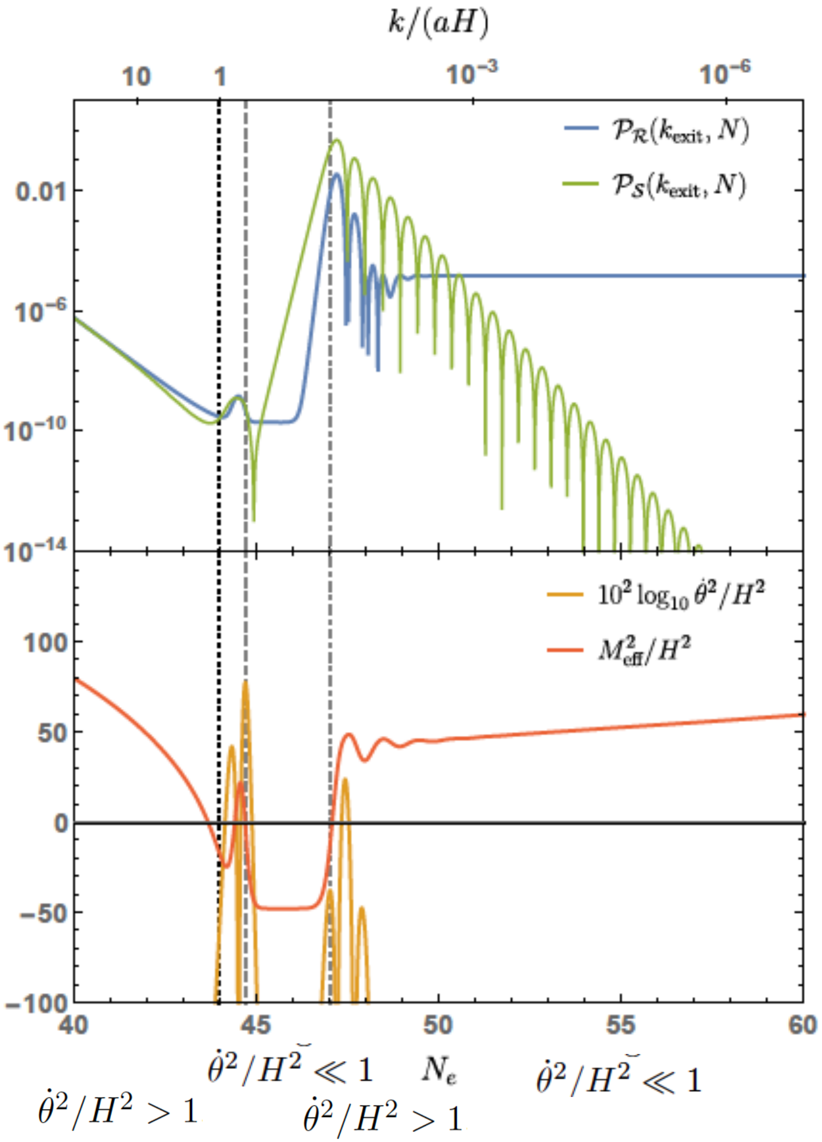
Hence Q_N can exhibit an *exponential* growth due to the tachyonic mass. This growth can be more rapid than cases implementing a USR phase.

$$Q_{N,k}(N_e) = e^{-\frac{3}{2}N_e}\left[d_3\, e^{-\frac{N_e}{2}\sqrt{9-4\frac{M_{\rm eff}^2}{H^2}-4\epsilon_k^2}} + d_4\, e^{\frac{N_e}{2}\sqrt{9-4\frac{M_{\rm eff}^2}{H^2}-4\epsilon_k^2}}\right]$$

$$\xrightarrow[|M_{\rm eff}^2| \gg H^2]{\epsilon_k^2 \ll 1} d_4\, e^{\left(\frac{|M_{\rm eff}|}{H} - \frac{3}{2}\right)N_e}$$

Adiabatic and icocurvature modes in Higgs-R^2 Inflation

Dhong Yeon Cheong, Kazunori Kohri, Seong Chan Park, arXiv:2205.14813 [hep-ph]

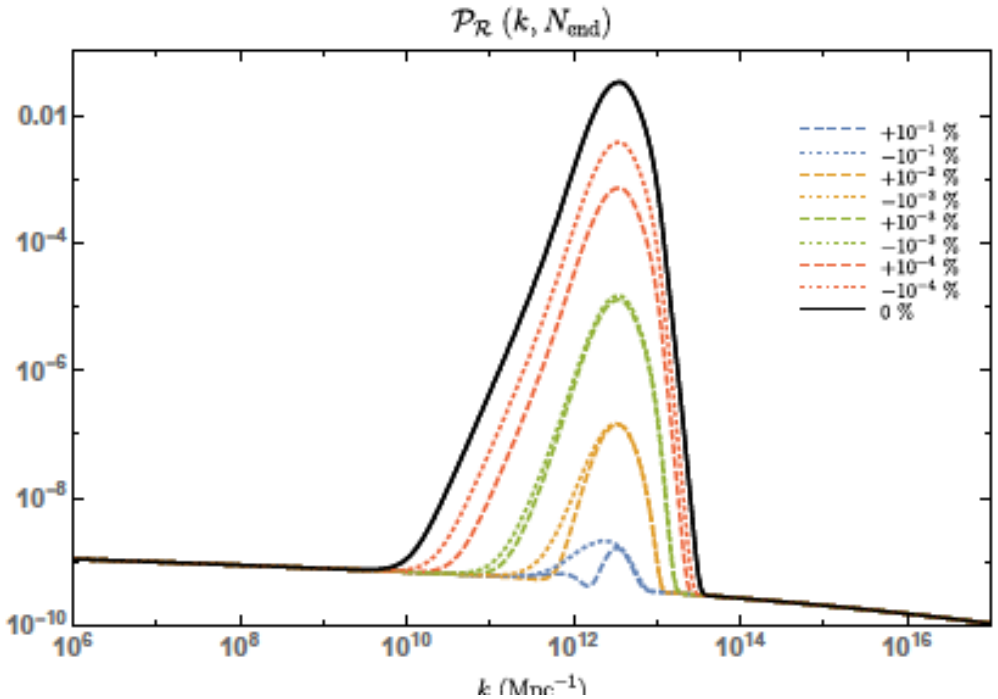


$$\mathcal{P}_S(k_{\rm exit}, N_e) = \frac{k_{\rm exit}^3}{2\pi^2}\frac{H^2}{\dot\phi_0^2}\langle Q_{N,k}, Q_{N,k}\rangle$$

$$= \mathcal{P}_S(k_{\rm exit}, N_1)\, e^{\left(\frac{2|M_{\rm eff}|}{H}-3\right)(N_e-N_1)}$$

Primordial Black Holes and Second Order Gravitational Waves from Tachyonic Instability induced in Higgs-R^2 Inflation

Dhong Yeon Cheong, Kazunori Kohri, Seong Chan Park, arXiv:2205.14813 [hep-ph]



$$\delta\lambda_m/\lambda_m$$

$$\delta\lambda_m/\lambda_m \equiv (\lambda_m^{dev} - \lambda_m)/\lambda_m \sim 10^{-4}\,\%$$

Primordial Black Holes and Second Order Gravitational Waves from Tachyonic Instability induced in Higgs-R^2 Inflation

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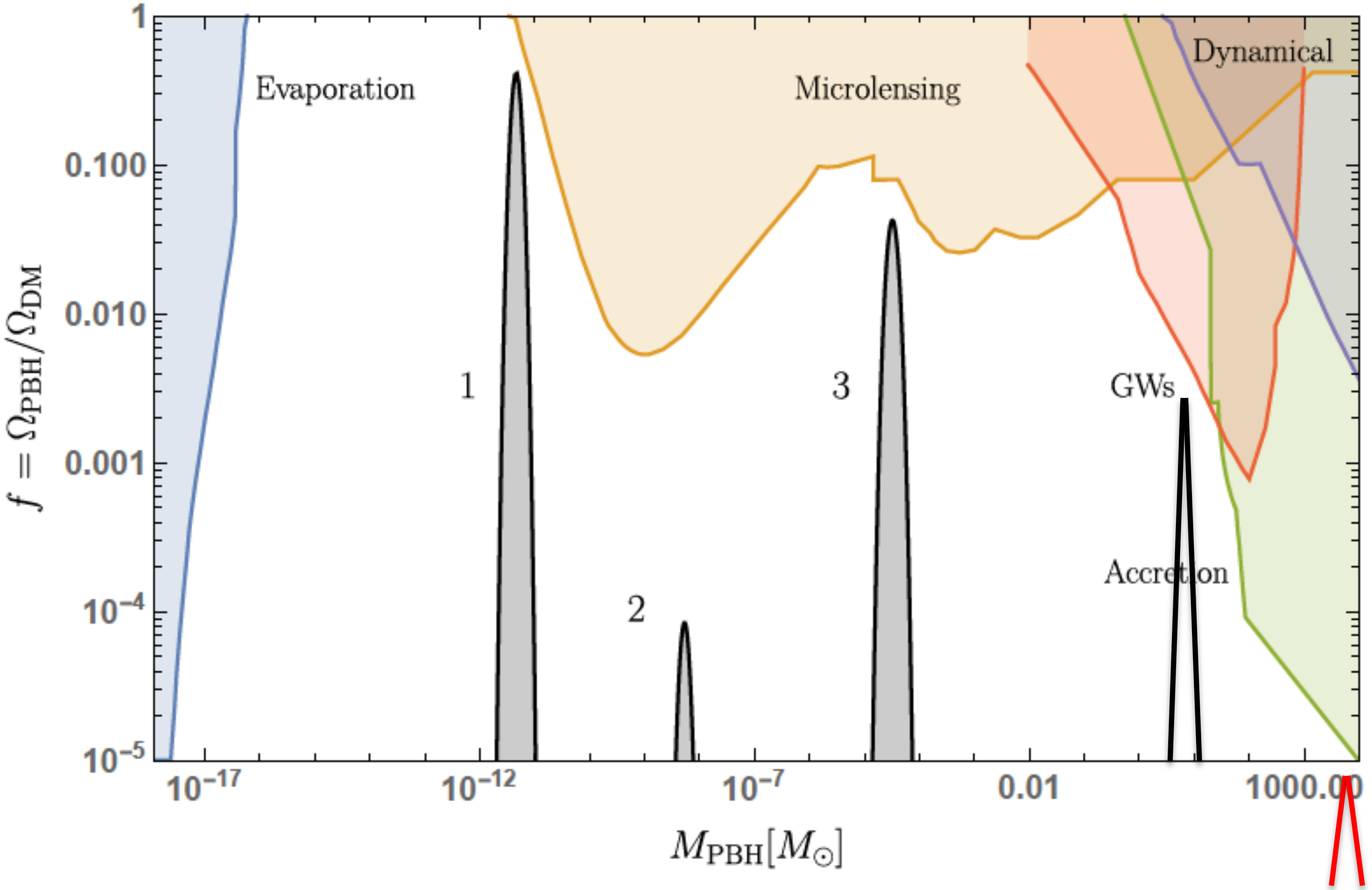

Primordial Black Holes and Second Order Gravitational Waves from Tachyonic Instability induced in Higgs-R^2 Inflation

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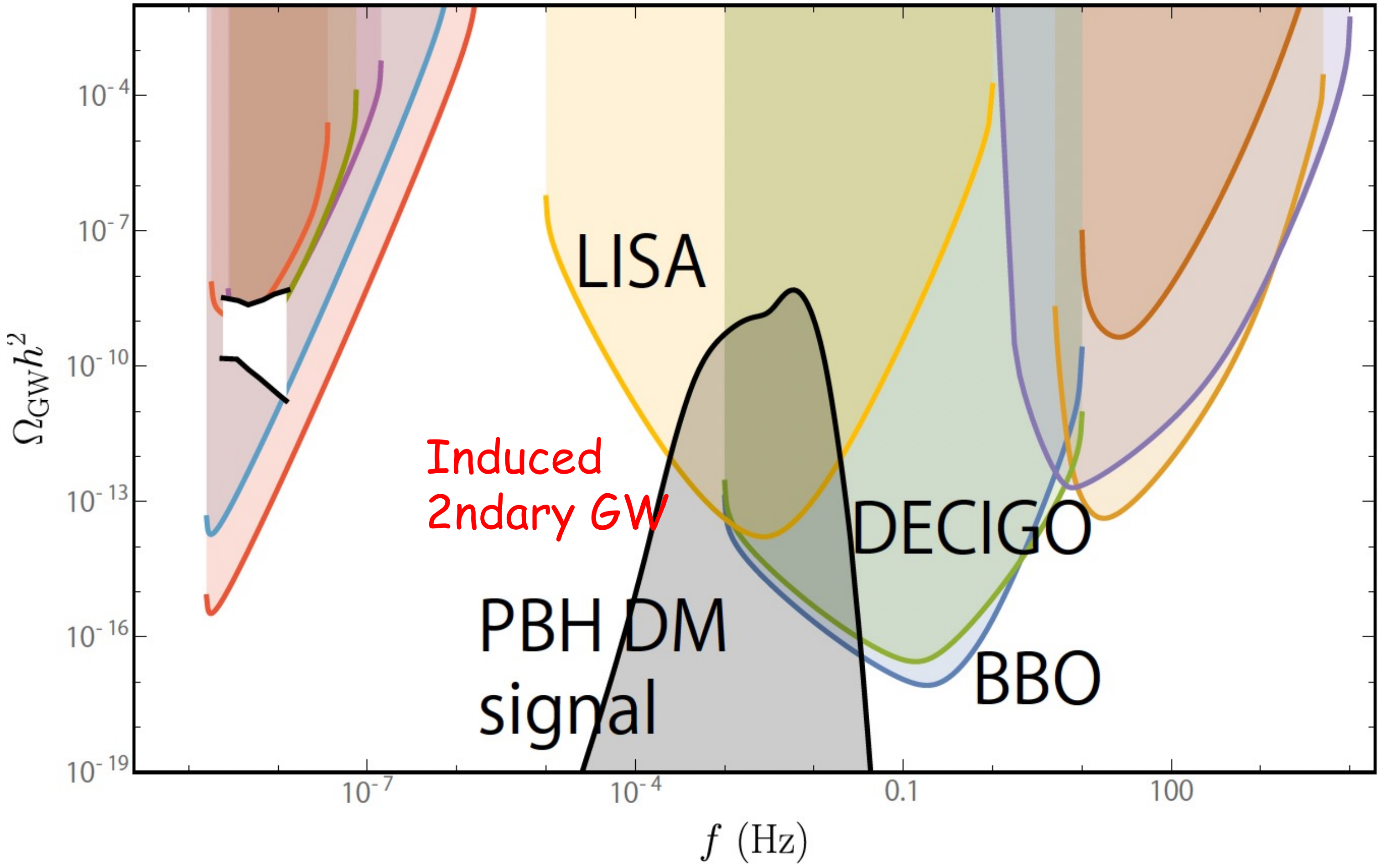
See also, K. Kohri and T. Terada, arXiv:2009.11853



Conclusion

- PBHs are good candidates for dark matter with masses of 10^{17} - 10^{23} g .
- By future MeV-gamma-ray observation, we will test the PBH dark matter with 10^{17} g
- A large curvature perturbation simultaneously predicts the possibility of 2ndary GWs at around 0.01 – 0.1 Hz to verify the PBH dark matter scenario with 10^{17} g
- In future, we may identify the sources of the LIGO events to be binary PBHs with O(10) $M_{\odot}$ through strong gravitational lensing of FRBs due to PBH + Halo systems, which will be observed by CHIME