The extreme Universe viewed in very-high-energy gamma rays 2022

Gamma-ray Emission from Primordial Black Holes

Kazunori Kohri

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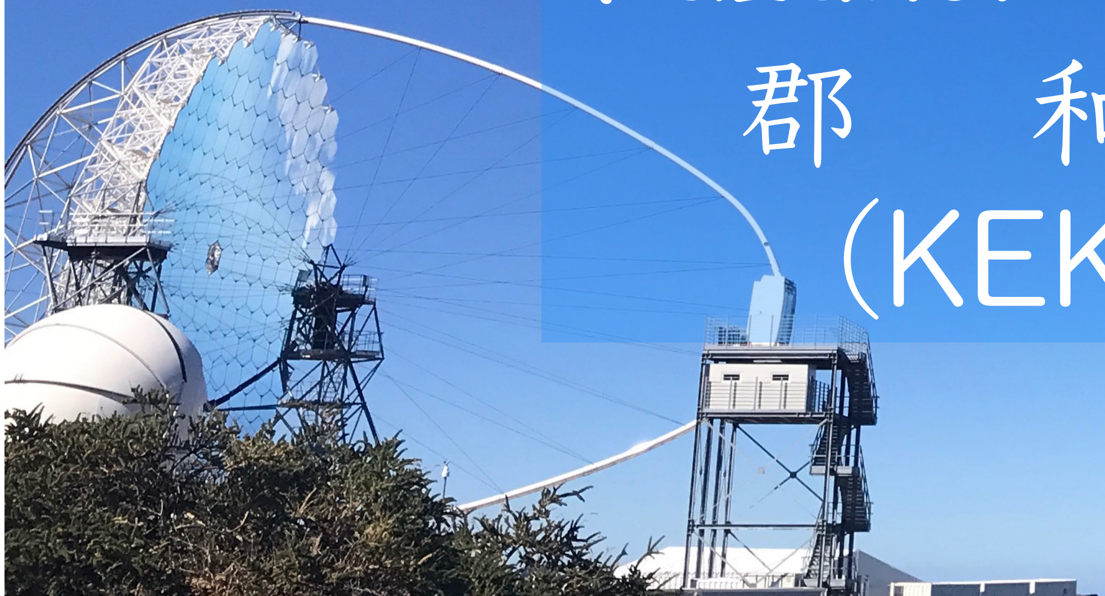
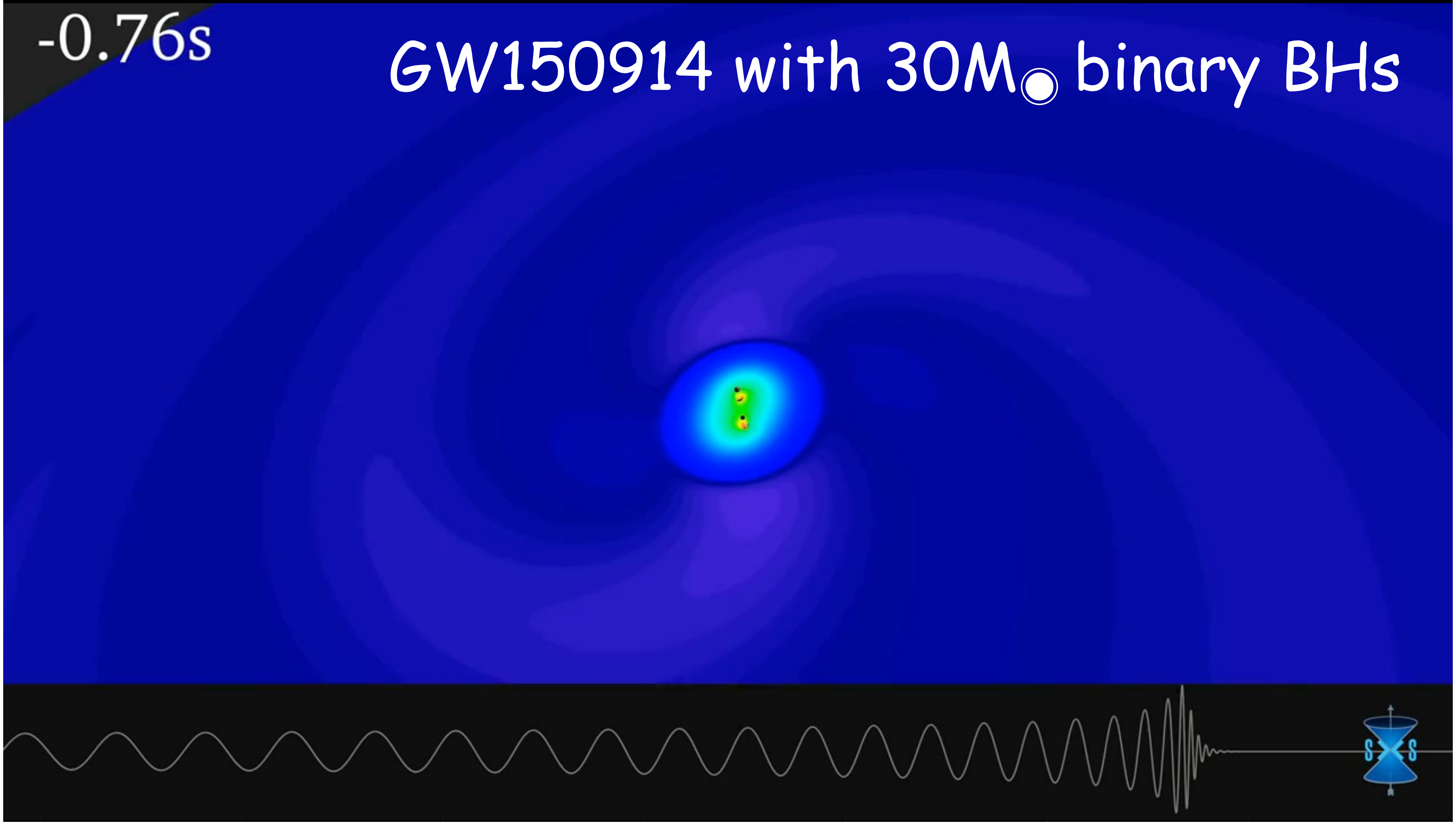
(KEK)



Detections of GWs from binary PBHs collide?

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

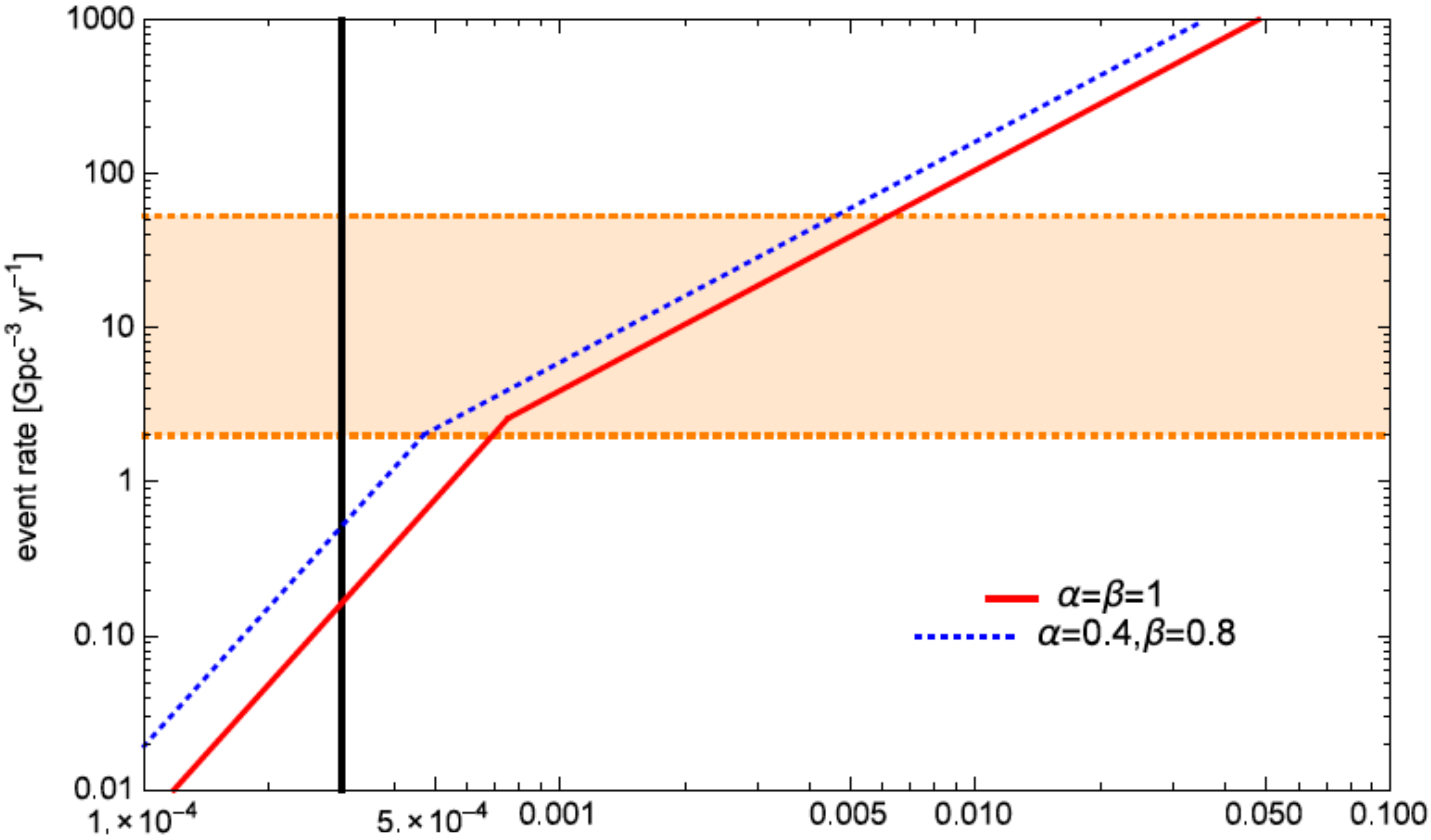


GW150914 and its merger rates for 30 M_{solar} masses BBH

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

A 3-body effect is important for the BBH formations

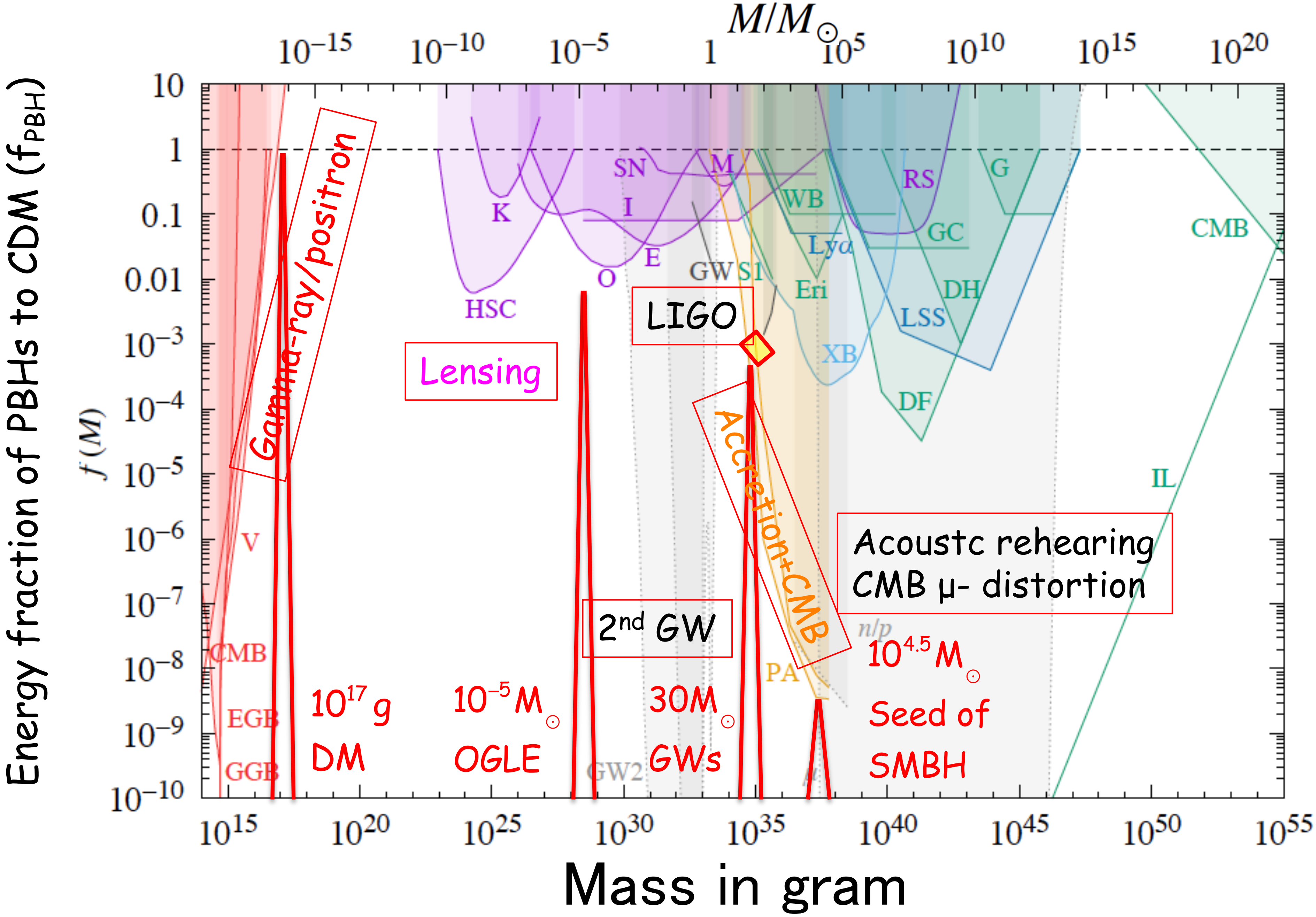
Event rates of Binary BH mergers



Energy fraction of PBHs to CDM (f_{PBH})

Observational bounds on PBHs

Carr, Kohri, Sendouda, J.Yokoyama (2009;2021)



Abstract

- PBHs are good candidates for dark matter with masses of 10^{17} - 10^{23} g .
- By future MeV-gamma-ray observations, we will test the PBH dark matter for m= 10^{17} g
- The 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 m = 10^{17} g
- By using the GeV-TeV gamma-ray observations, we can constrain possible bursts of PBHs to be a fraction of CDM

What is a PBH?

Primordial Black Hole (PBH)

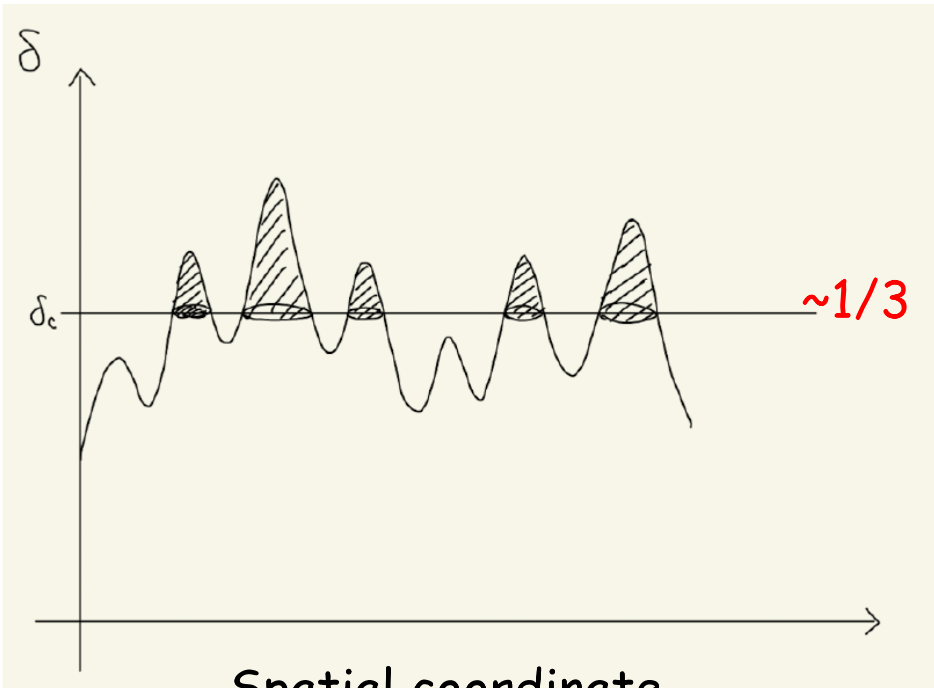
$1M_\odot \sim 2\times10^{33}g$

- Inflation origin fluctuations (large at small scales)

$$\delta \gg 10^{-5}$$

- Different from astrophysical BHs

$$1g < M < 10^{16}\ M_\odot$$



Density perturbation

~1/3 due to Jeans instability

Spatial coordinate

Y. Furuta's mster thesis, 2023

The attraction of primordial black holes (PBHs)

$1M_\odot \sim 2\times10^{33}g$

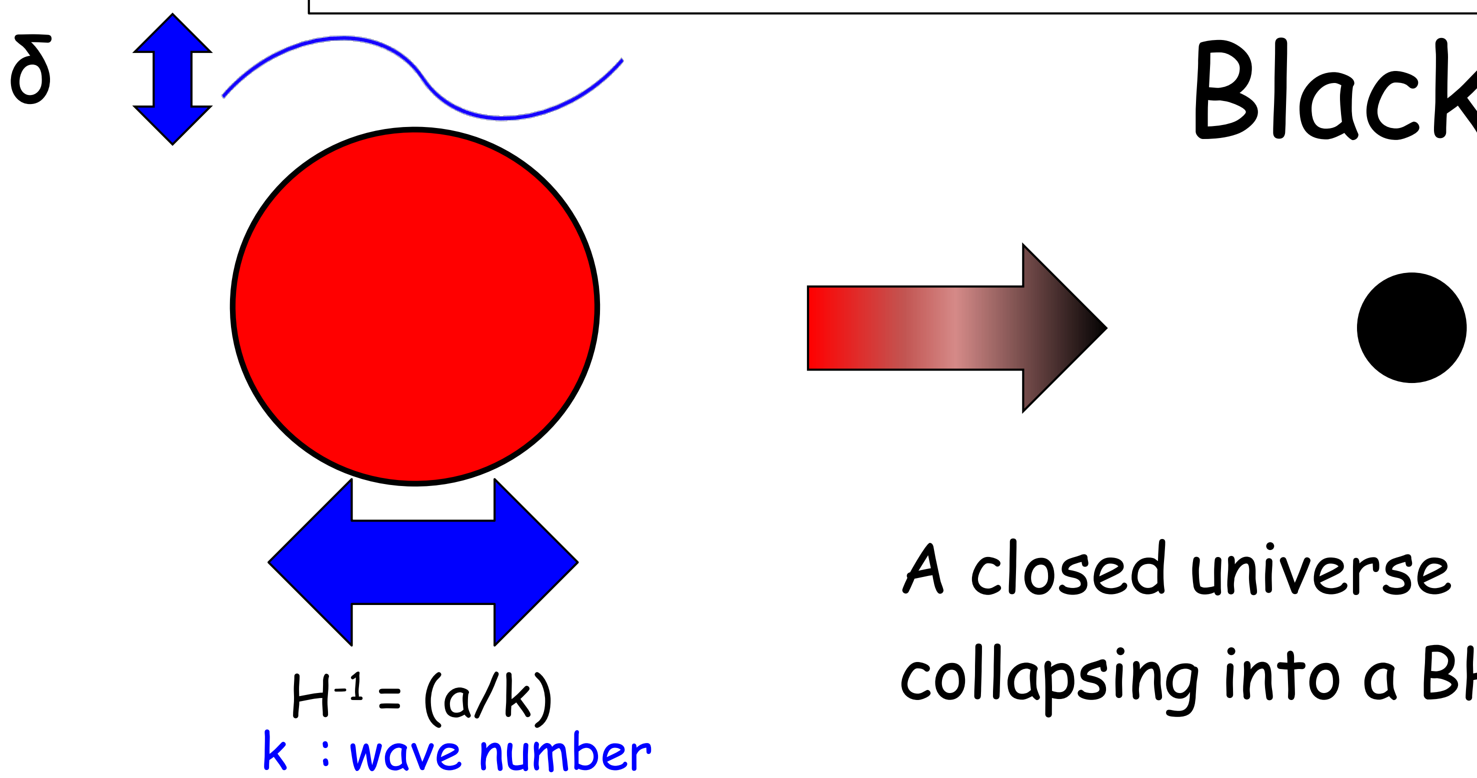
- Possible sources of LIGO-Virgo-KAGRA binary merging gravitational waves ($\sim> 30M_\odot$)
- Currently-evaporating PBH with *$m=10^{15}g$ is constrained by GeV- gamma-rays*
- A good candidate of dark matter (10^{17}-10^{23}g)
- Seeds of supermassive BHs (SMBHs) ($10^4M_\odot$-$10^5M_\odot$)
- Future 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)

PBH formations in Radiation dominated (RD) Universe

Zel'dovich and Novikov (1967), Hawking (1971), Carr (1975)
Harada,Yoo and KK (2013)

- Gravity > pressure gradient (Jeans instability)

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



Black Hole

A closed universe immediately collapsing into a BH

P_ζ (k) and PBH abundance β(M)

- Fraction of PBH to the total with Press Schechter(or Carr's) formalism

For Peak Statistics,
e.g., see Yoo, Harada, KK et al (2018)(2020)

$$\beta(M) \equiv \frac{\rho_{\rm PBH}(M)}{\rho_{\rm tot}} = \int_{\delta_{\rm th}}^{\infty} d\delta \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left(-\frac{\delta^2}{2\sigma^2}\right) = {\rm erfc}\left(\frac{\delta_{\rm th}}{\sqrt{2}\sigma}\right)$$

$\boxed{\sim 1/3 - 0.5}$

For analytical derivations, see Harada, Yoo, KK (2013)

0.43

$\sigma \sim \overline{\delta\rho/\rho}$

- Relation between β and fluctuation σ (or β and Ω)

$$\beta(M) \sim {\rm erfc}\left(\frac{\delta_{\rm th}}{\sqrt{2}\sigma}\right) \simeq \sqrt{\frac{2}{\pi}}\frac{\sigma}{\delta_{\rm th}} \exp\left(-\frac{\delta_{\rm th}^2}{2\sigma^2}\right)$$

$$= 1.5 \times 10^{-18} \left(\frac{m_{\rm PBH}}{10^{15} g}\right)^{1/2} \left(\frac{\Omega_{\rm PBH} h^2}{0.1}\right)$$

$\boxed{\sim P_\zeta}$

Curvature perturbation

Typical quantities of PBHs in RD

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

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

- Lifetime

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

- Hawking Temperature

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

- Fraction to CDM

$$\boxed{f_{\rm fraction} \equiv \frac{\Omega_{PBH}}{\Omega_{CDM}} \sim 10^{18}\left(\frac{M_{PBH}}{10^{15}{\rm g}}\right)^{-1/2}\sqrt{P_\delta}\exp\left[-\frac{1}{18 P_\delta}\right]}$$

Formations of PBHs in the inflationary Universe

- A blue-tilted perturbation with large running α_s and running-of-running β_s
- Tachyonic instability ($\text{mass}^2 < 0$)
- Ultra-slowroll inflation ($V' \sim 0$)?
- …

Type-III Hilltop inflation models

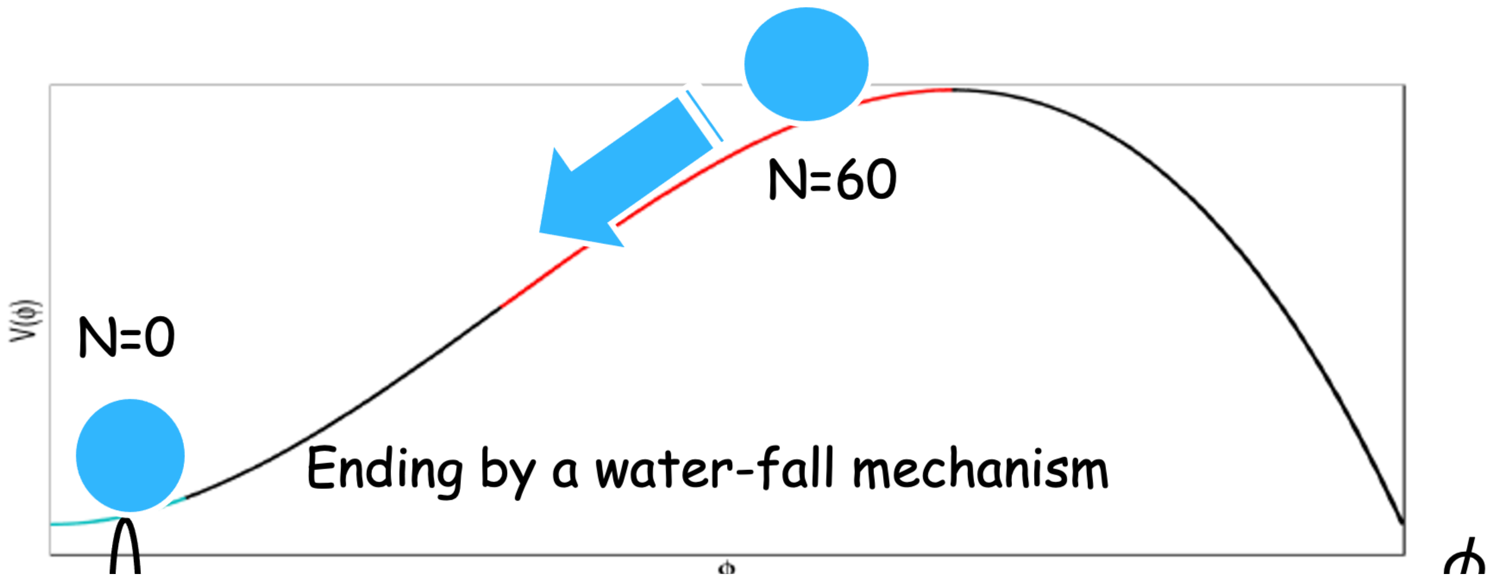
German, Ross, Sarkar (01)
Kohri, Lin and Lyth (07)

- Potential in supergravity, e.g.,

$$V(\phi) \;=\; V_0 + \frac{1}{2}m^2\phi^2 - \lambda\frac{\phi^p}{M_{\rm P}^{p-4}} + \cdots$$

$$W = C\frac{\phi^\rho}{M_{\rm pl}^{p-3}}, \quad \lambda \sim C m_{3/2}/M_{\rm pl}$$ in SUGRA

Allahverdi, Kusenko and Mazumdar (06)



Large running spectral index

Kohri, Lin and Lyth (07)

- Spectrum

$$P_\zeta \sim \frac{V}{m_{\rm pl}^4 \varepsilon}$$

- Enhanced curvature perturbation at small scales due to a large running of running

$$\varepsilon \equiv \frac{1}{2}\left(m_{\rm pl}\frac{V'}{V}\right)^2 \to 0 \text{ for } \phi\downarrow$$

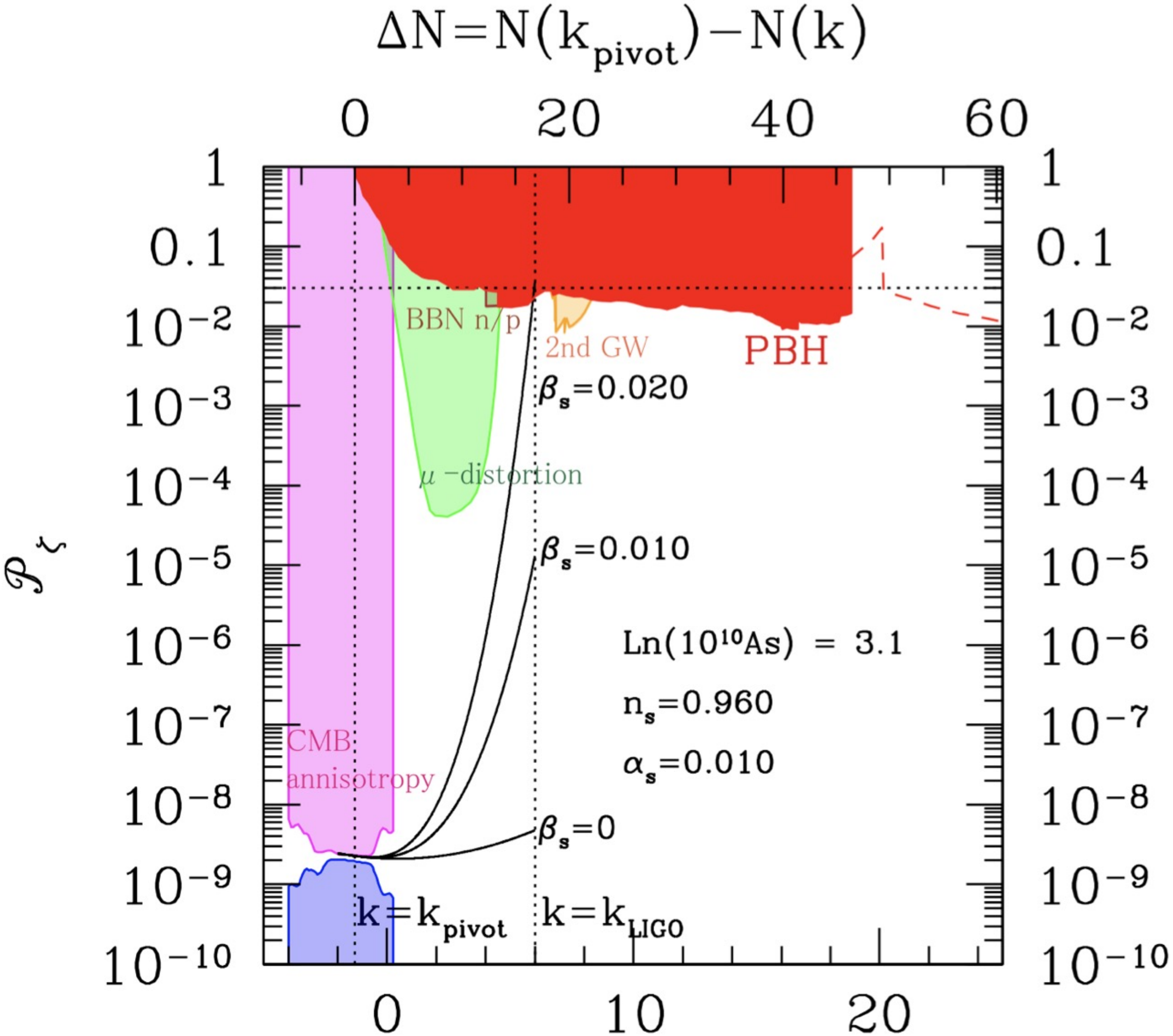
$$\beta_s = \frac{d^3 P_\zeta}{d(\ln k)^3} = 192\epsilon^3 + 192\epsilon^2\eta - 32\epsilon\eta^2 + (-24\epsilon + 2\eta)\boxed{\xi^{(2)}} + 2\boxed{\sigma^{(3)}}$$

Could be large!

Curvature perturbation $P_\zeta(k)$

Kohri and T.Terada, 2018
Alabidi, Kohri, Sendouda, Sasaki, 2013

Amplitude of curvature perturbation



Wave number [1/Mpc]

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 (2007)

k = p x a

Motions on the potential of the Higgs-scalaron, two-fields system

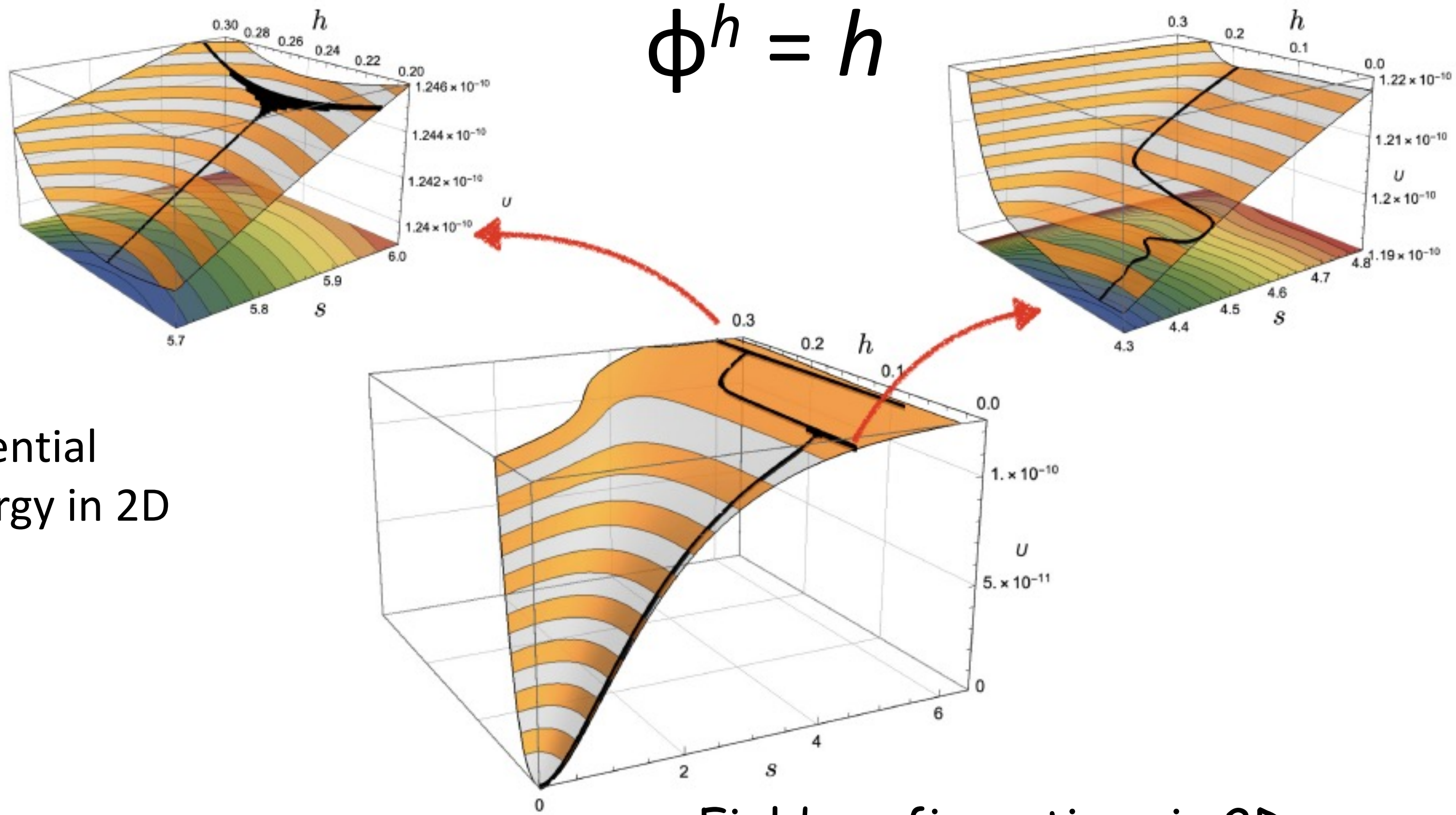
Dhong Yeon Cheong, Kazunori Kohri, Seong Chan Park, arXiv:2205.14813 [hep-ph]

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

$$\phi^s = s$$

$$\phi^h = h$$

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

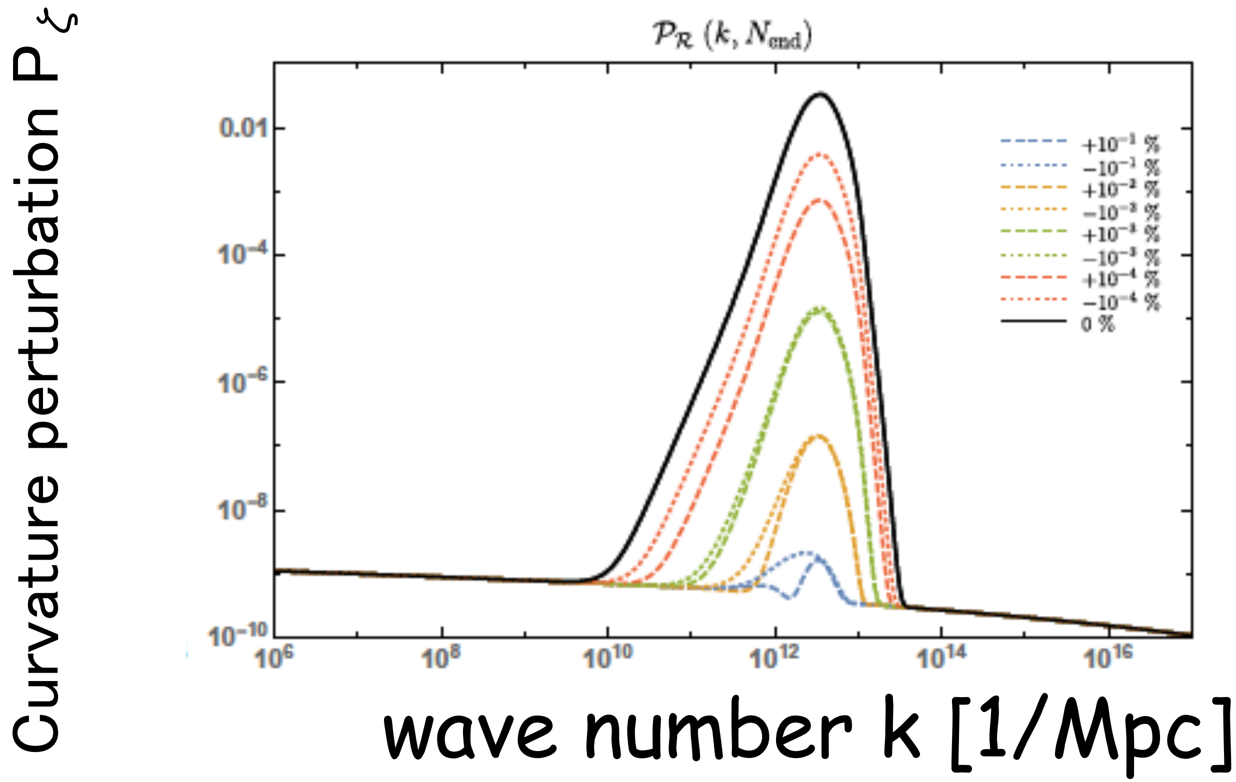


Potential
Energy in 2D

Field configurations in 2D

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]



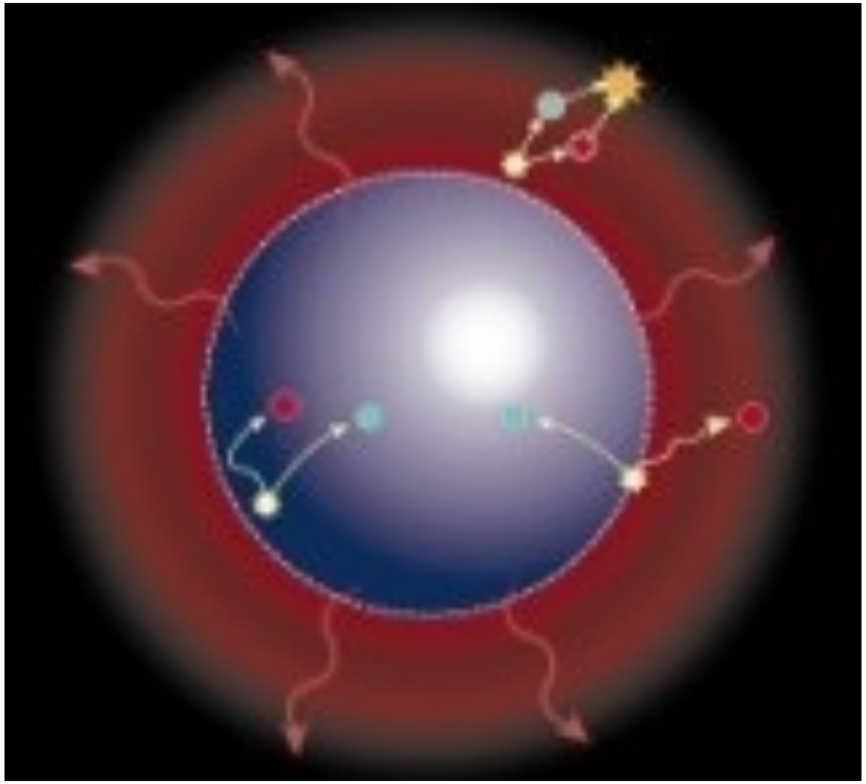
$$\delta\lambda_m/\lambda_m$$

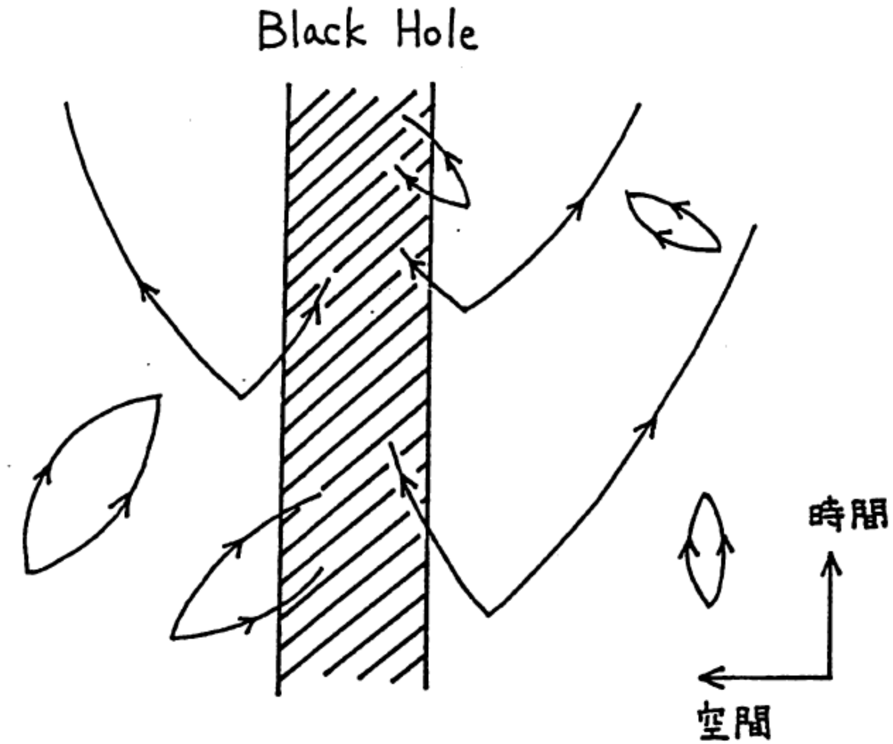
$$\delta\lambda_m/\lambda_m \equiv (\lambda_m^{dev} - \lambda_m)/\lambda_m \sim 10^{-4}\,\%$$

Black hole evaporation by the Hawking process

Finding a PBH in the Hawking process of evaporation with gamma rays

S.W. Hawking, 1974





牧晃司、東大理物理修士論文(1995)より

Emission rates by Hawking radiation

- Emission rate

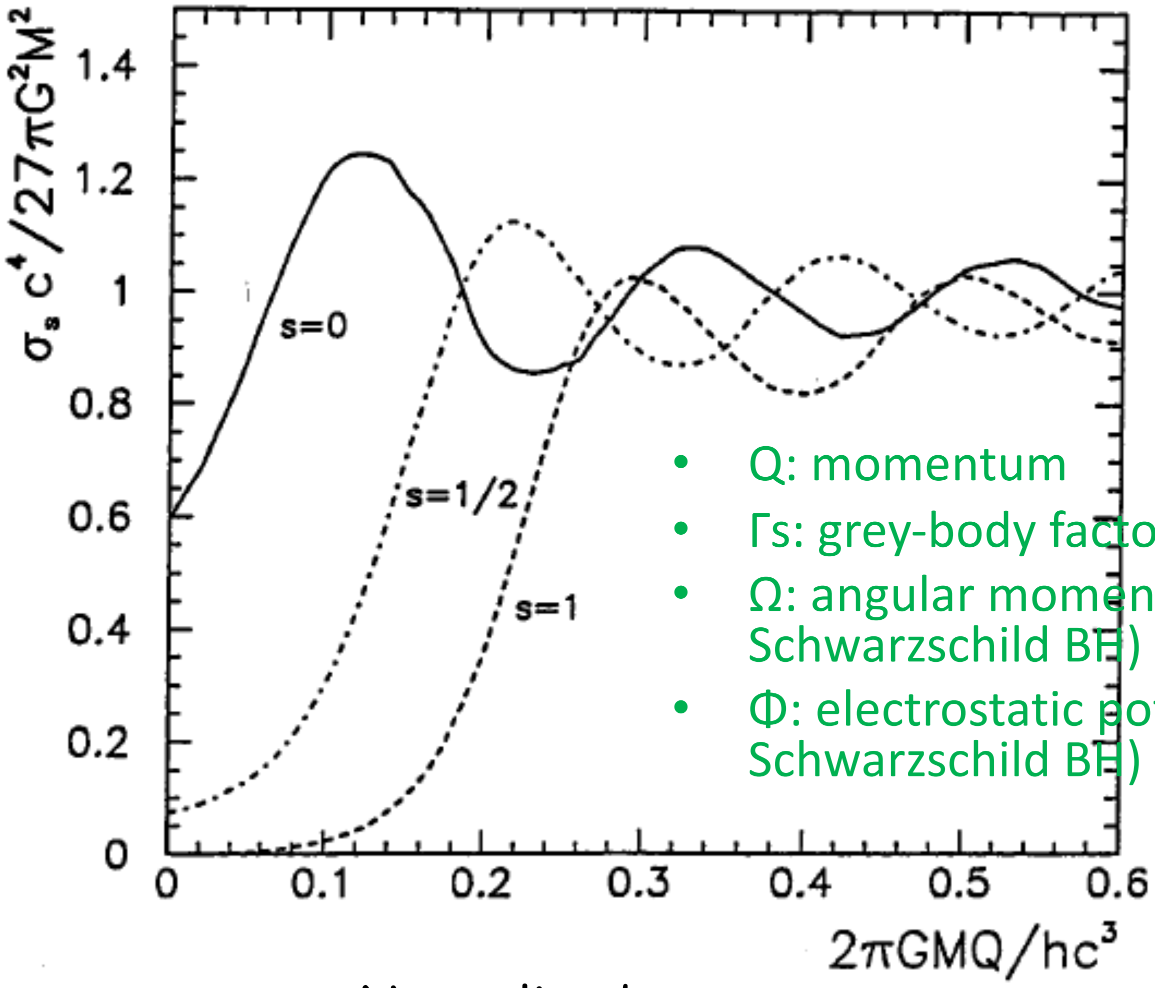
$$\mathrm{d}\dot{N}_s = \frac{\mathrm{d}E}{2\pi} \frac{\Gamma_s}{e^{E/T_{\mathrm{BH}}} - (-1)^{2\,s}}$$

- Γ_s: Grey-body factor

Grey-body factor

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

Γ_s



Normalized momentum

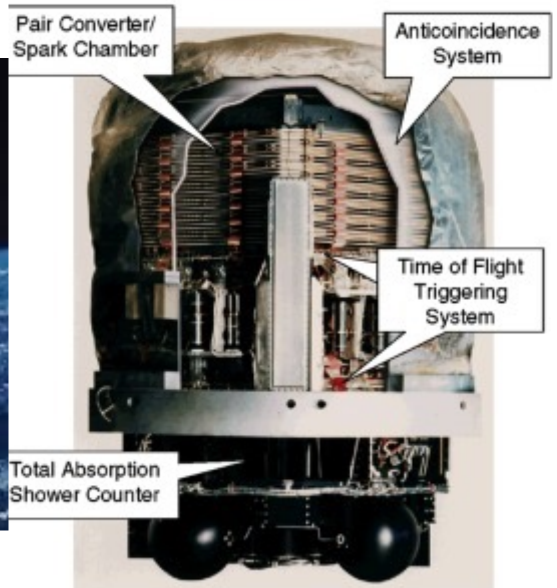
- Q: momentum
- Γs: grey-body factor
- Ω: angular momentum (n=0 for Schwarzschild BH)
- Φ: electrostatic potential (q=0 for Schwarzschild BH)

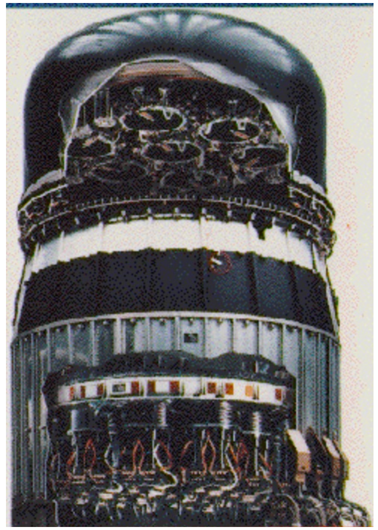
J. H. MacGibbon and B. R. Webber, Phys. Rev. D **41**, 3052 (1990)

Detecting gamma rays

GeV

MeV





Fermi

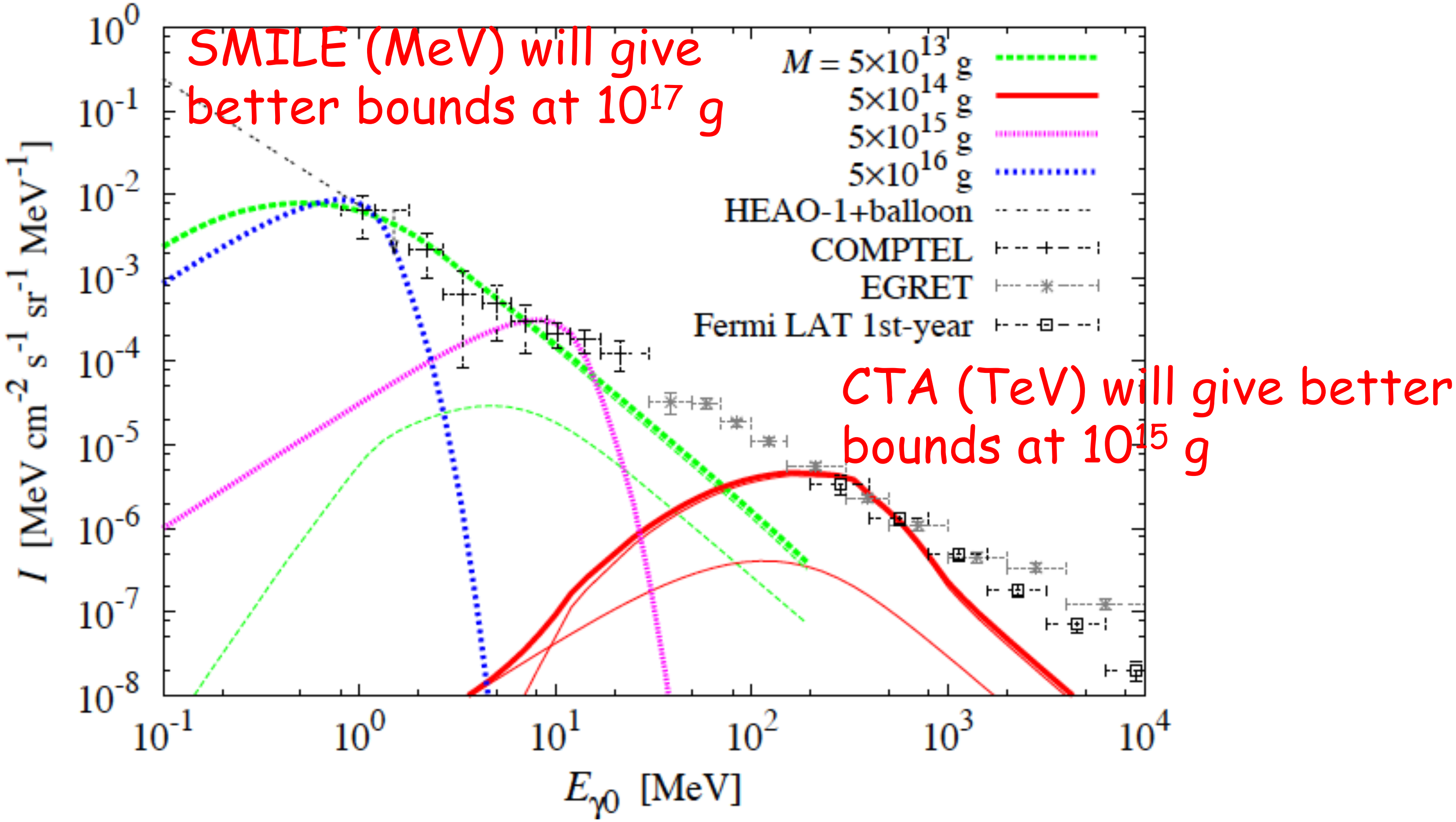
EGRET

COMPTEL

Evaporating PBHs through Hawking Process

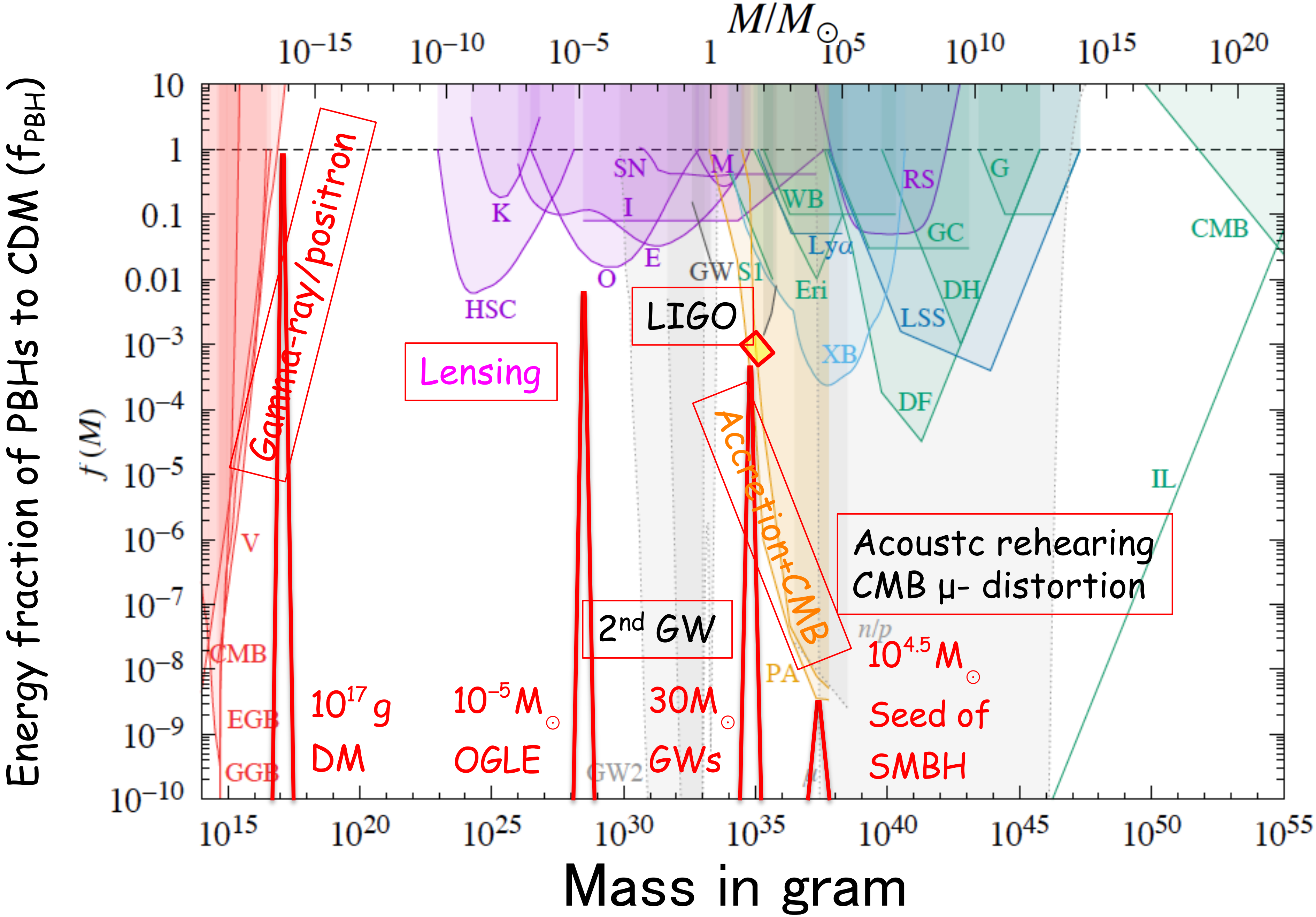
Carr, Kohri, Sendouda and Yokoyama (2010,2021)

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



Observational bounds on PBHs

Carr, Kohri, Sendouda, J.Yokoyama (2009,2021)



PBH burst?

HAWC observation for PBH bursts

A. Albert, et al, the HAWC collaboration, arXiv:1911.04356 [astro-ph.HE]

$$\dot{\rho}_{\rm PBH} < 3400^{+400}_{-100}\ \mathrm{pc}^{-3}\ \mathrm{yr}^{-1}$$

See Kanamori-kun's talk

Burst duration	**Burst Rate Upper Limit**
0.2 s	$3300\ ^{+300}_{-100}\ \mathrm{pc}^{-3}\mathrm{yr}^{-1}$
1 s	$3500\ ^{+400}_{-200}\ \mathrm{pc}^{-3}\mathrm{yr}^{-1}$
10 s	$3400\ ^{+400}_{-100}\ \mathrm{pc}^{-3}\mathrm{yr}^{-1}$

Experiment	**Burst Rate Upper Limit**	**Search Duration**	**Reference**
Milagro	$36000\ \mathrm{pc}^{-3}\mathrm{yr}^{-1}$	1 s	[27]
VERITAS	$22200\ \mathrm{pc}^{-3}\mathrm{yr}^{-1}$	30 s	[19]
H.E.S.S.	$14000\ \mathrm{pc}^{-3}\mathrm{yr}^{-1}$	30 s	[14]
Fermi-LAT	$7200\ \mathrm{pc}^{-3}\mathrm{yr}^{-1}$	1.26×10^8 s	[20]
HAWC 3 yr.	$\mathbf{3400\ pc^{-3}yr^{-1}}$	**10 s**	**This Work**

Secondary induced gravitational wave

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

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

- Substituting the solution into this

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

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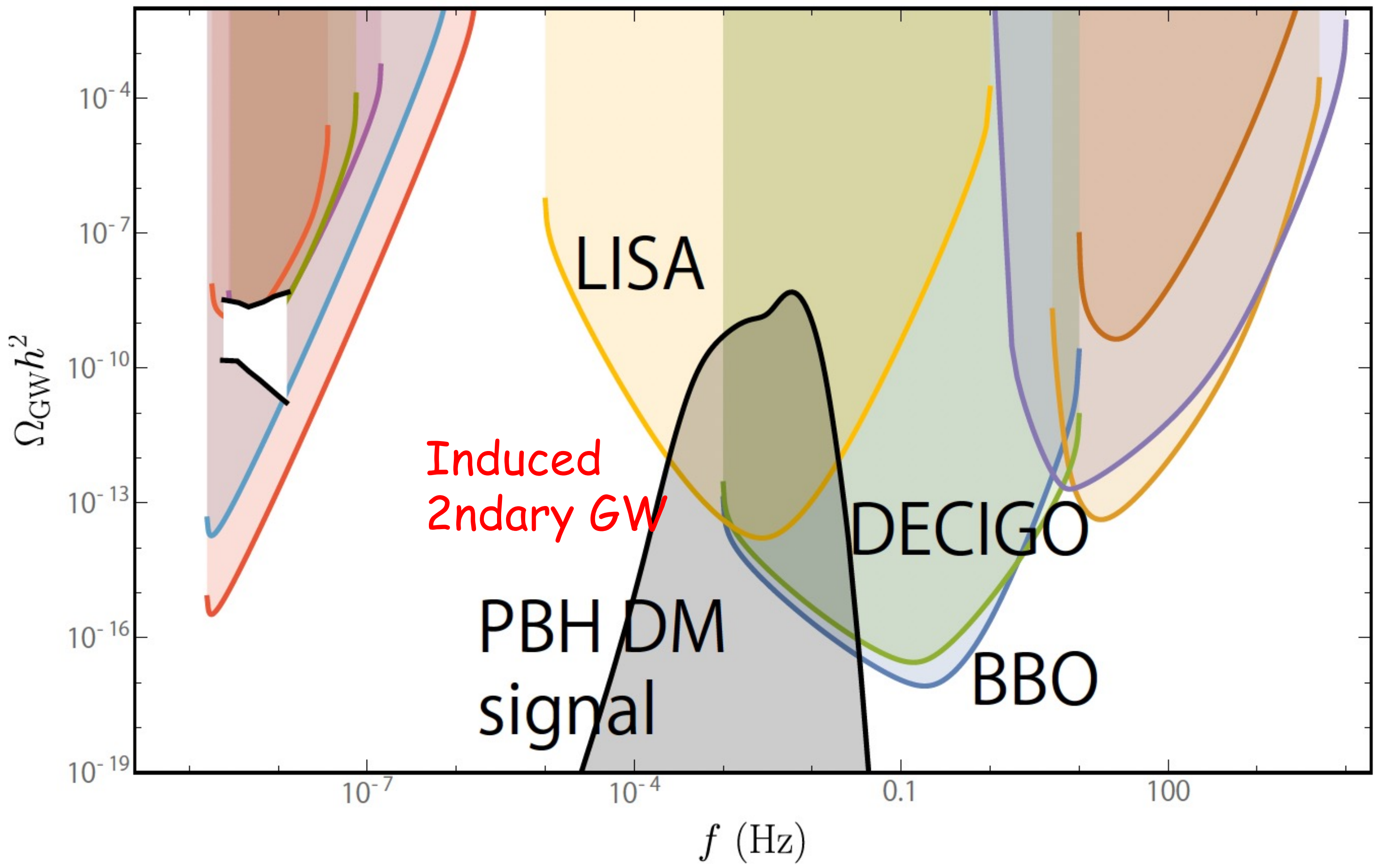
Dhong Yeon Cheong, Kazunori Kohri, Seong Chan Park, arXiv:2205.14813 [hep-ph]

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



Conclusions

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- The 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 m = 10^{17} g

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