PPC2023

The 16th International Conference on Interconnections between Particle Physics and Cosmology

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

Kazunori Kohri

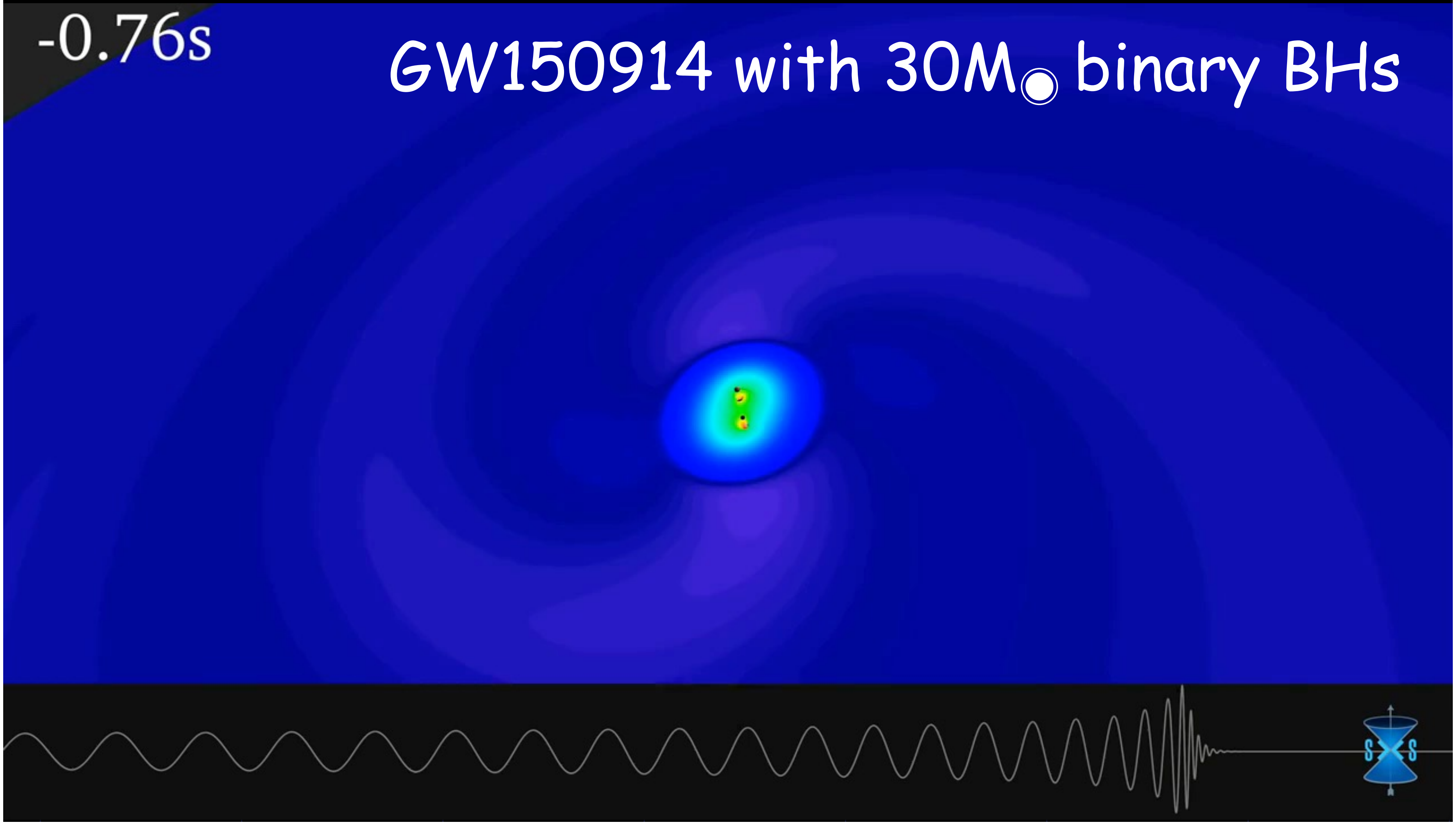
郡　和範

KEK → NAOJ from 1st July

Detections of GWs from binary PBHs collide?

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

GW150914 with $30M_\odot$ binary BHs

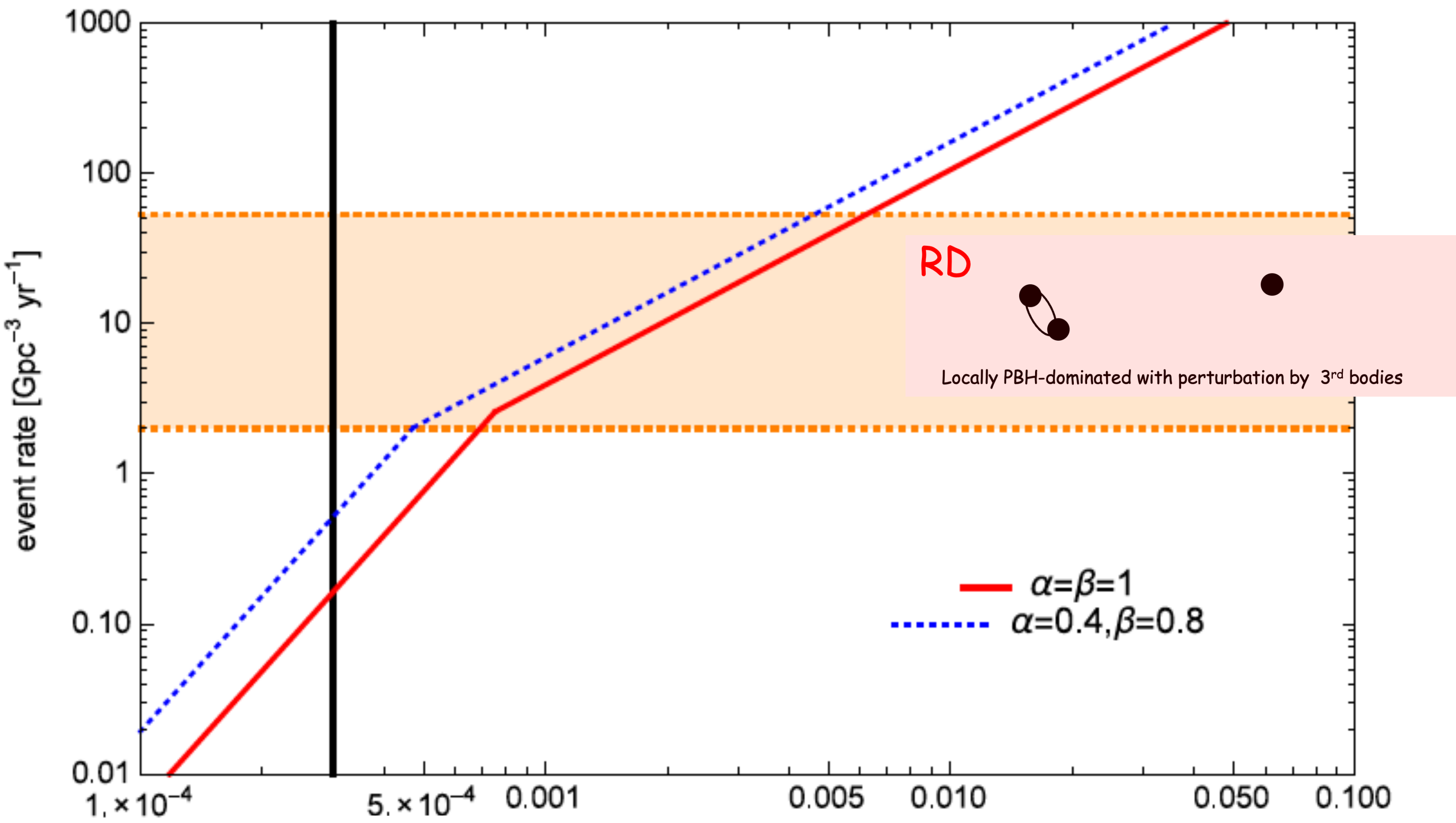


GW150914 and its merger rates for 30 $M_\odot$ masses BBH

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})

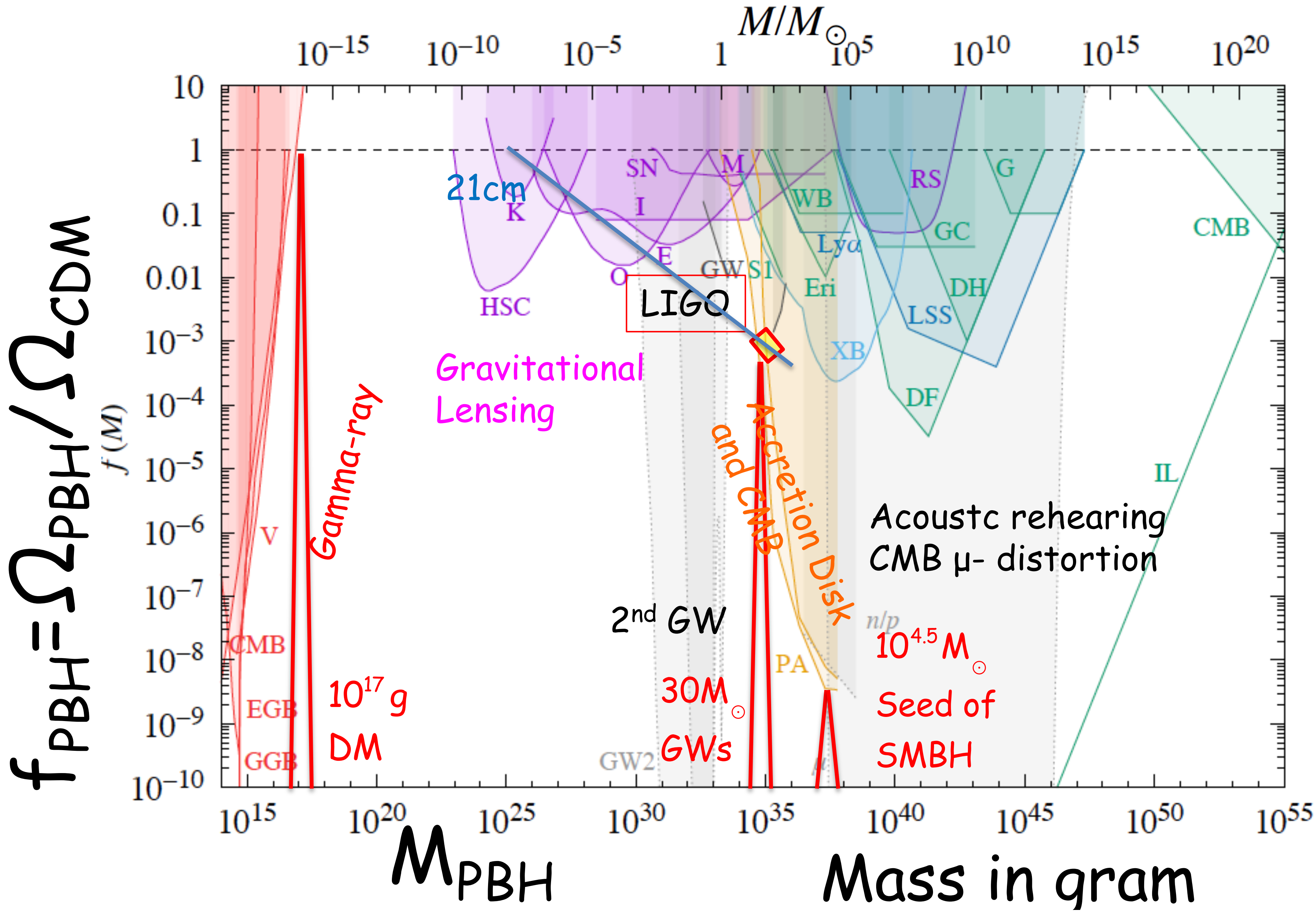
The attraction of primordial black holes (PBHs)

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

- Possible sources of LIGO-Virgo-KAGRA binary merging gravitational waves ($\sim> 30M_\odot$)
- A good candidate of dark matter (10^{17}-10^{23}g)
- Seeds of supermassive BHs (SMBHs) ($< 10^4M_\odot$-$10^6M_\odot$ 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)

Upper bounds on the fraction to CDM

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



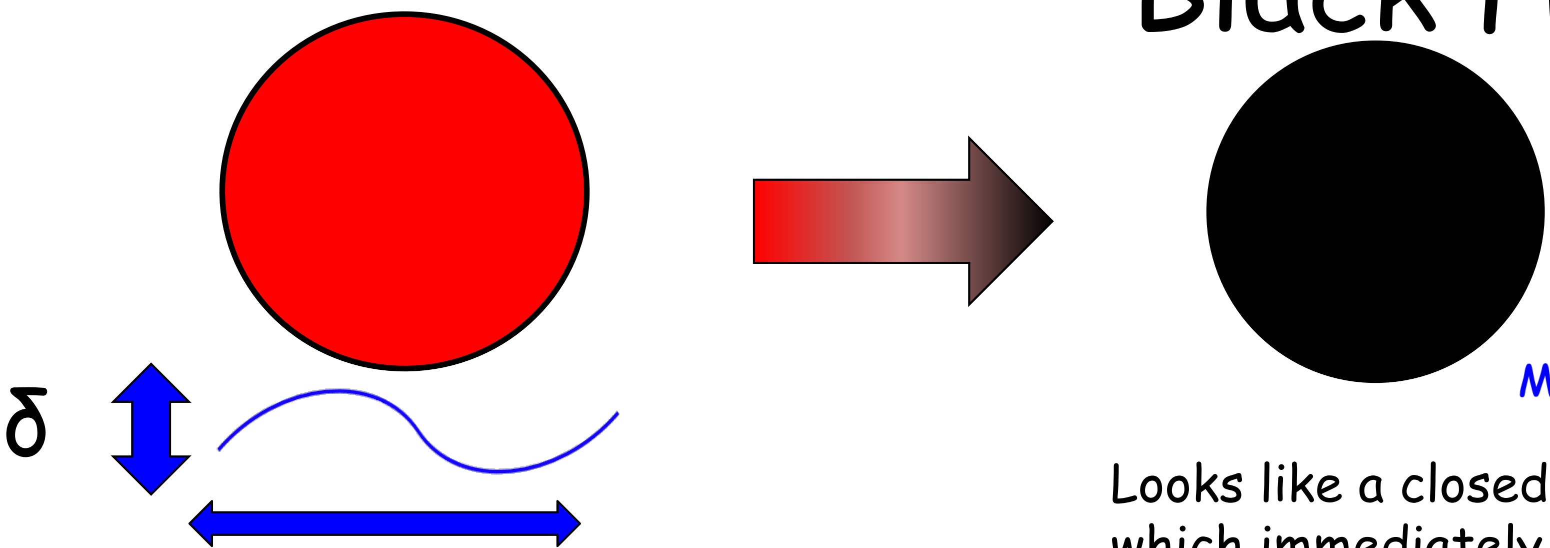
PBH formations in Radiation dominated (RD) Universe

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

- Gravity > pressure gradient (Jeans instability)

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

Black Hole



$H^{-1} = (a/k)$

k : wave number

$M_{PBH} \sim \rho (H_{form}^{-1})^3$

Looks like a closed Universe, which immediately collapses into a BH

Typical quantities of PBHs in RD

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

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

- Lifetime

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

- Hawking Temperature

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

- Wave number of horizon length

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

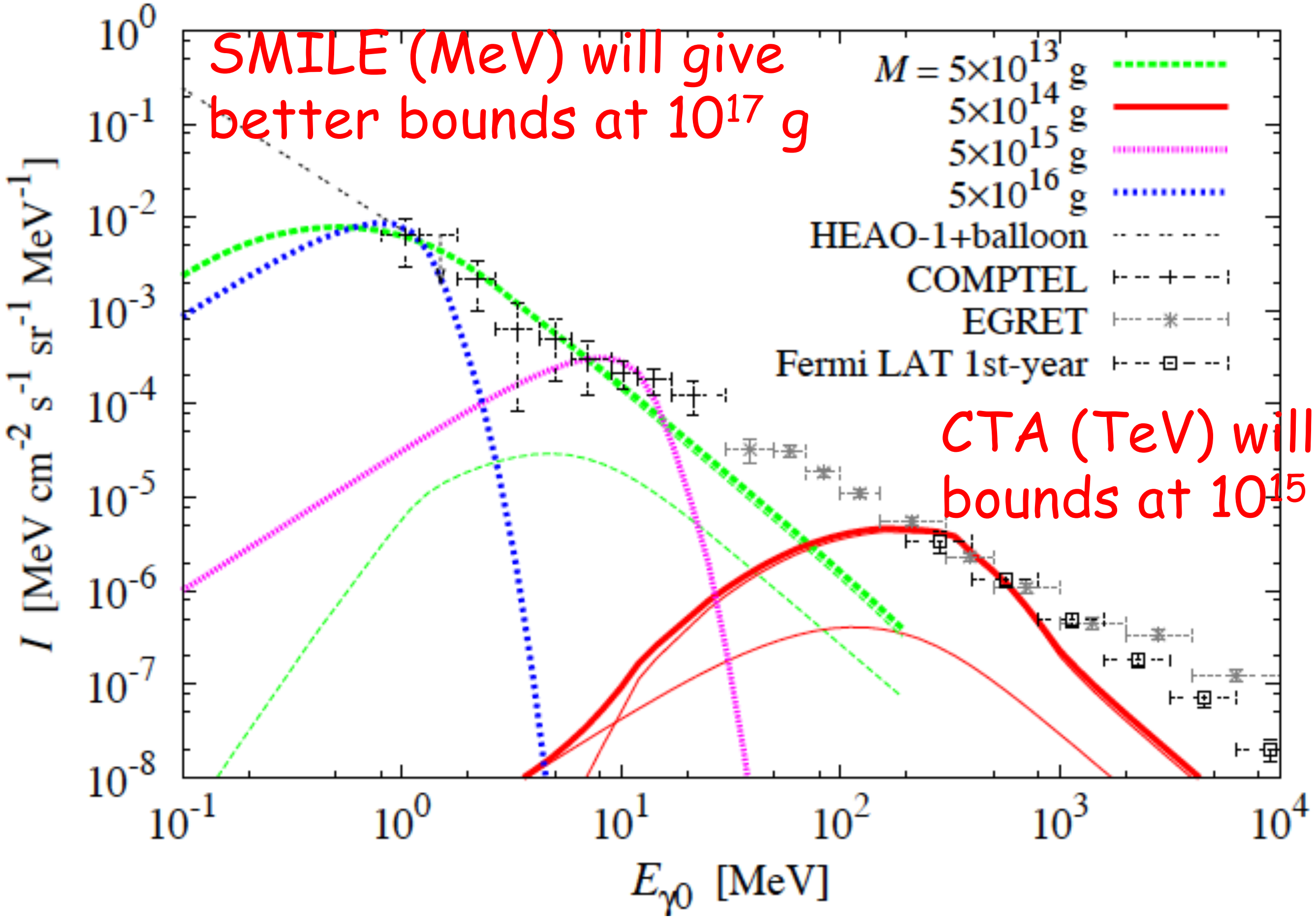
- Fraction to CDM

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

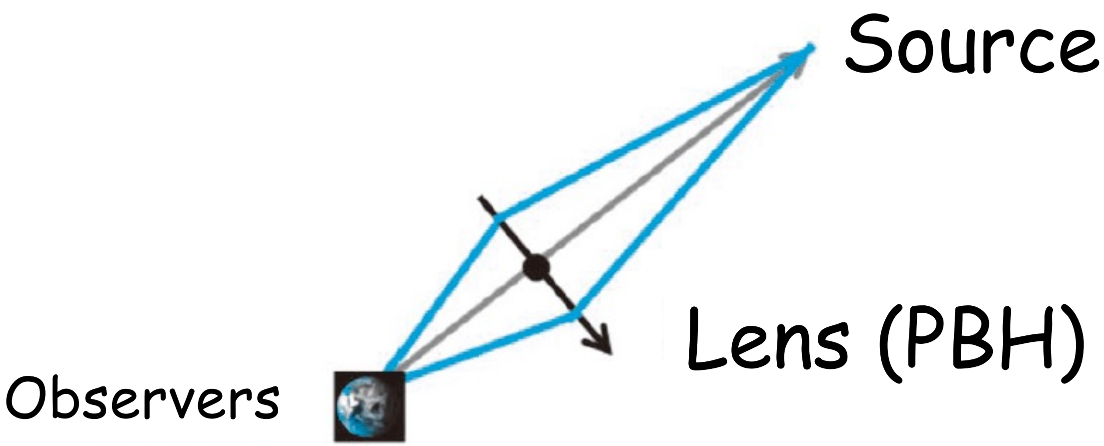
Evaporating PBHs through Hawking Process

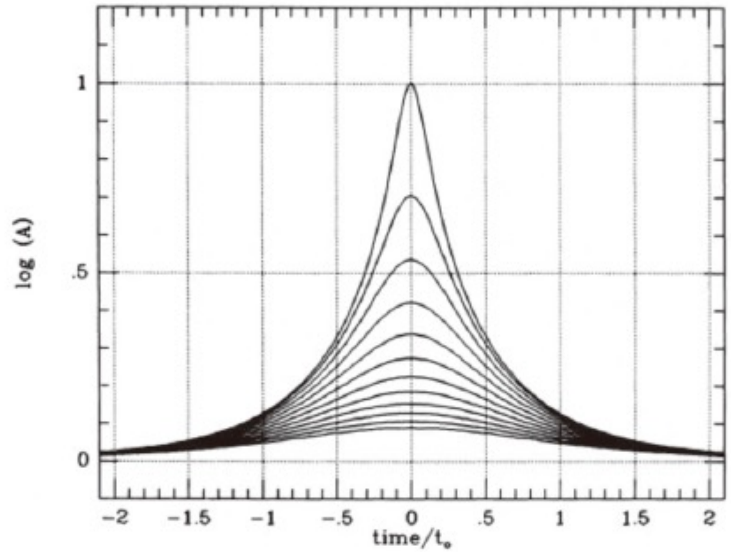
Carr, Kohri, Sendouda and Yokoyama (2010)

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



Gravitational Lensing

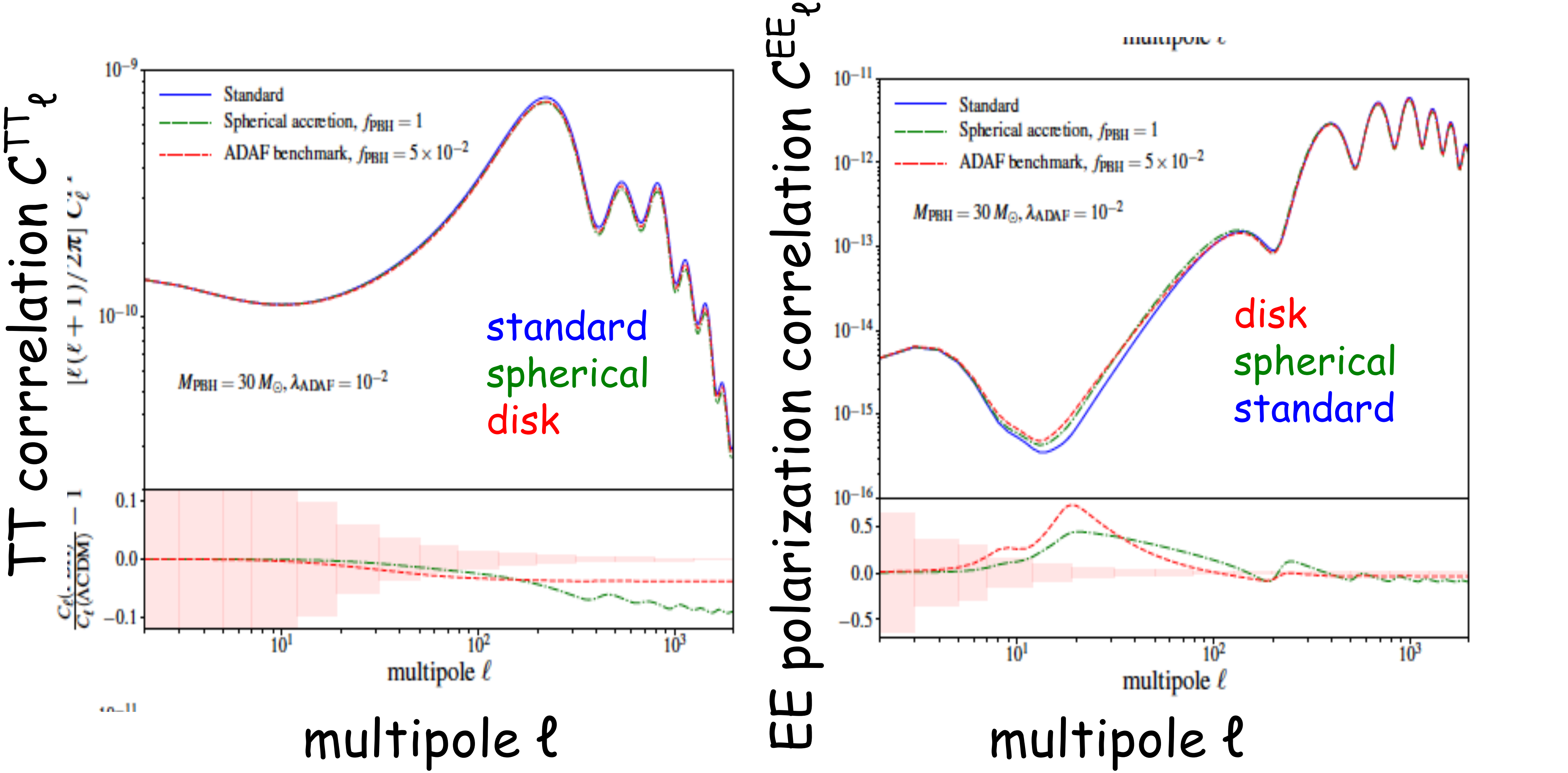




Hiroko Niikura, https://stg.asj.or.jp/jp/activities/geppou/item/113-1_6.pdf

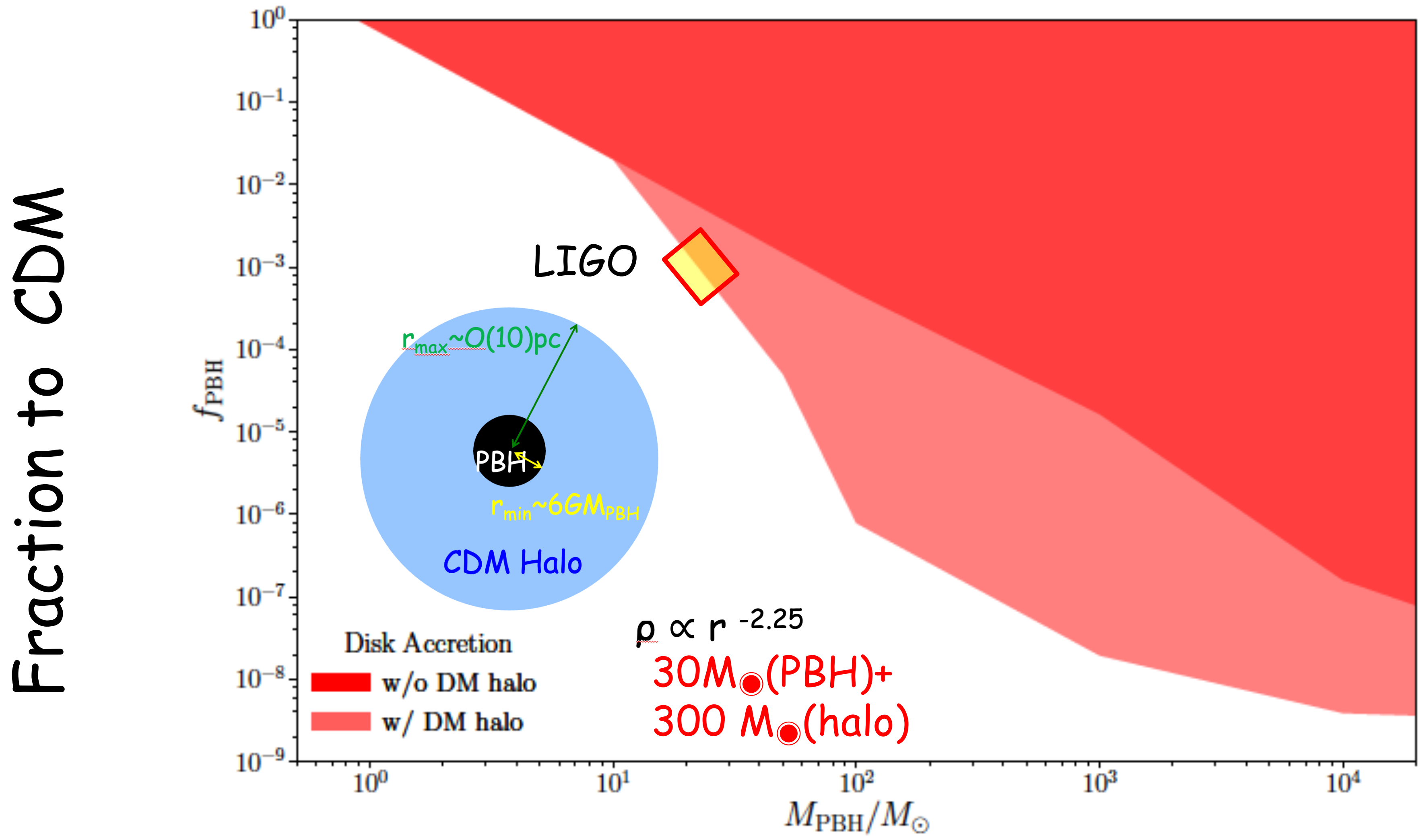
Modified CMB anisotropy and polarization

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



CMB bound by disk-accretion in the MD epoch

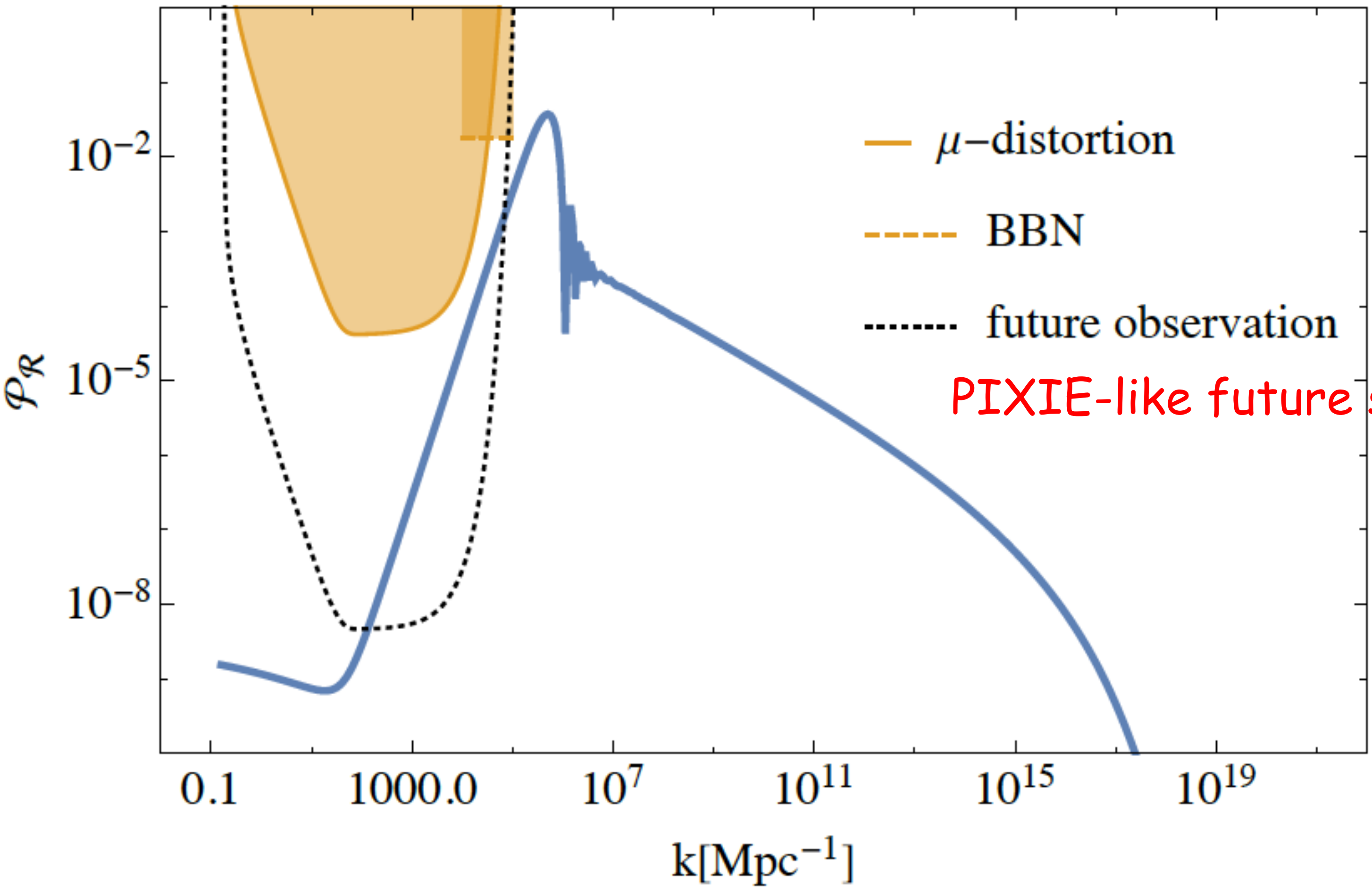
Serpico, Poulin, Calore, Clesse, Kohri (2017)



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

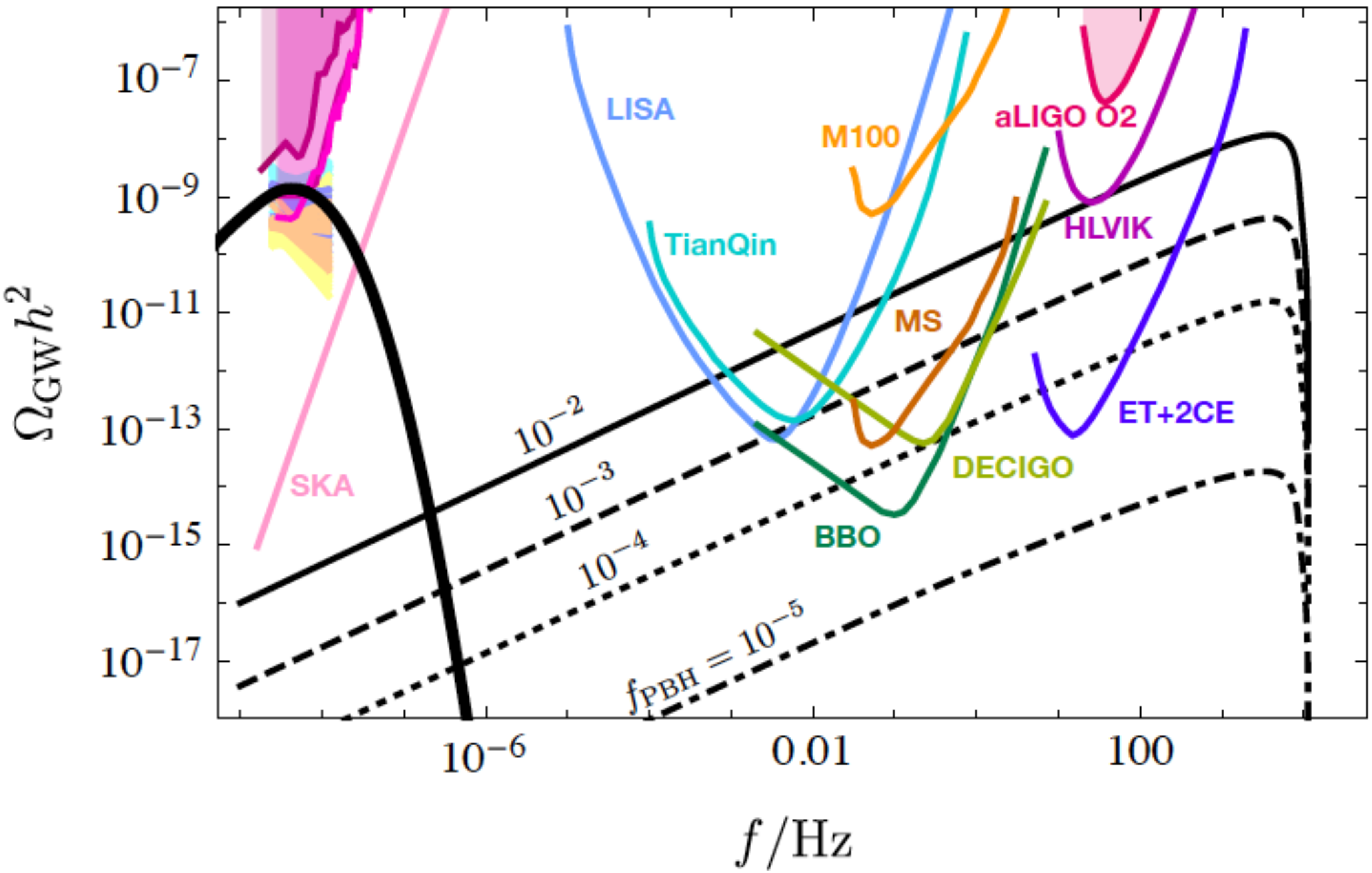
$$\Omega_{\mathrm{GW}}(k,\eta) = \frac{1}{3}\left(\frac{k}{\mathcal{H}}\right)^2 \mathcal{P}_h(k,\eta).$$

- Substituting the solution into this

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

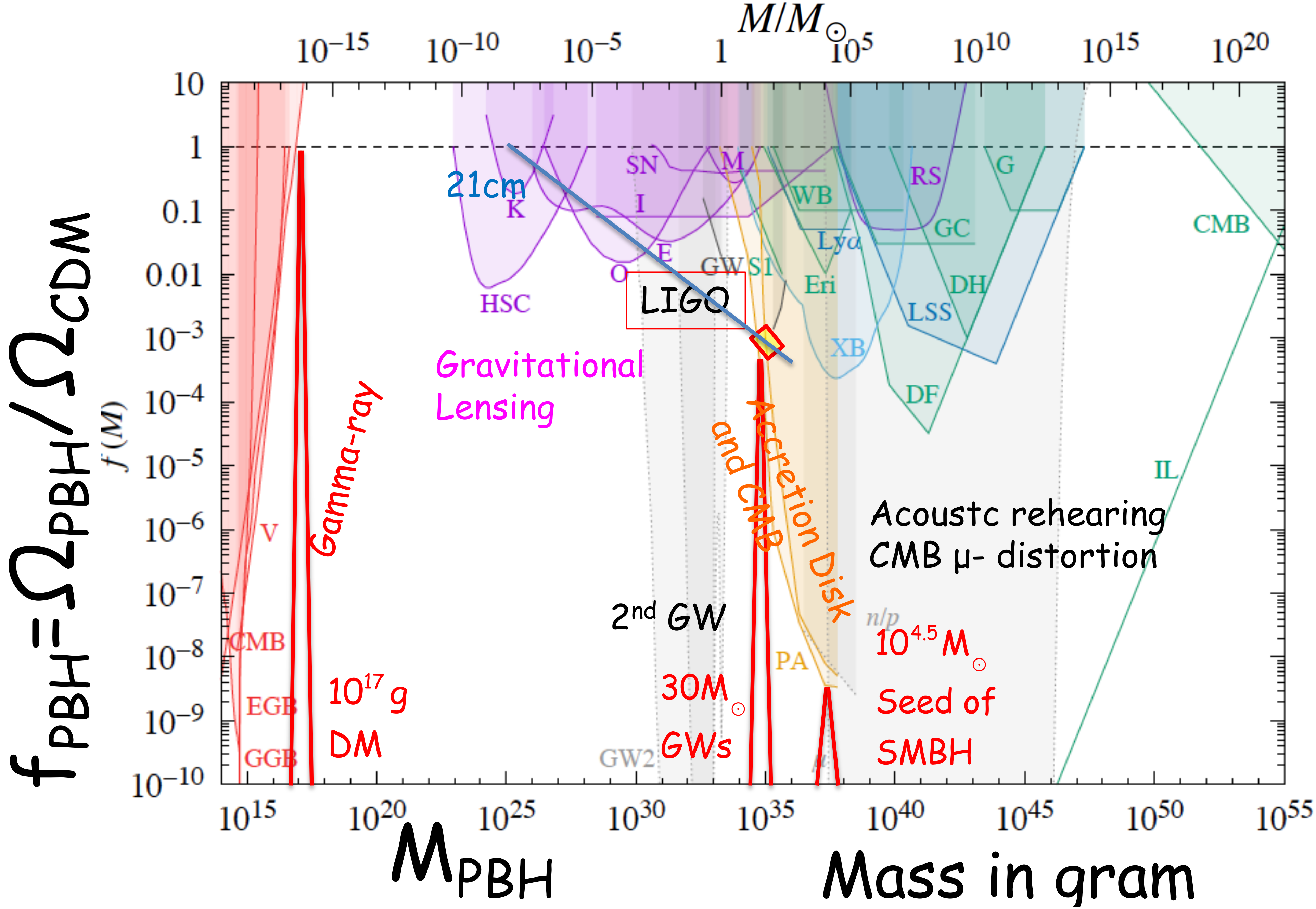
NANOGrav12.5yr and solar mass PBHs

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? –positive points -

1. LIGO events (～30 $M_\odot$)

   Strong lensing of FRBs

   Anisotropies and redshifts of GWs from PBHs

2. Seeds of SMBHs (～10^4 $M_\odot$ -10^6 $M_\odot$)

   Cosmological 21cm at z > ～O(10)

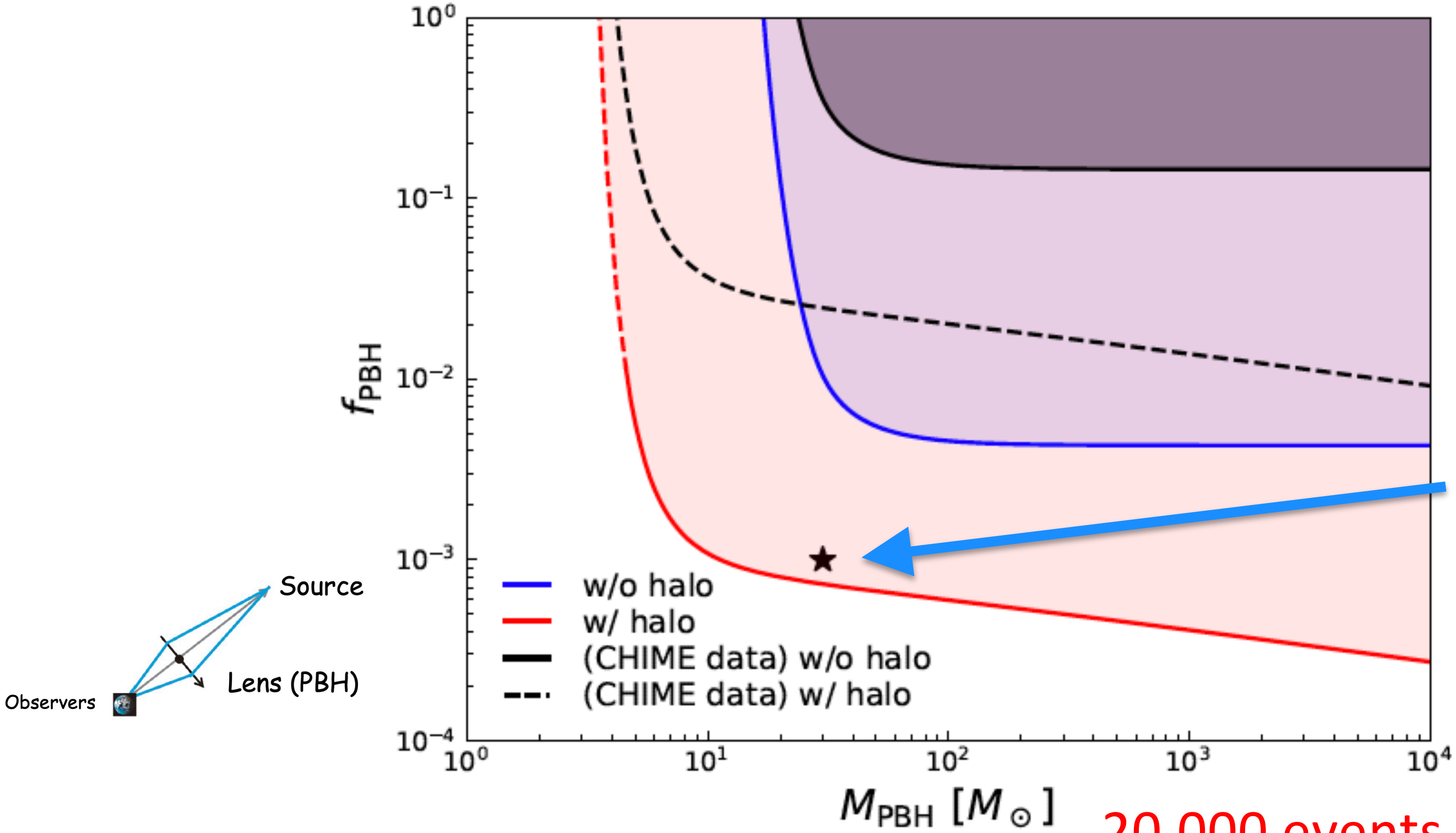
3. DM (10^{17}g – 10^{23}g)

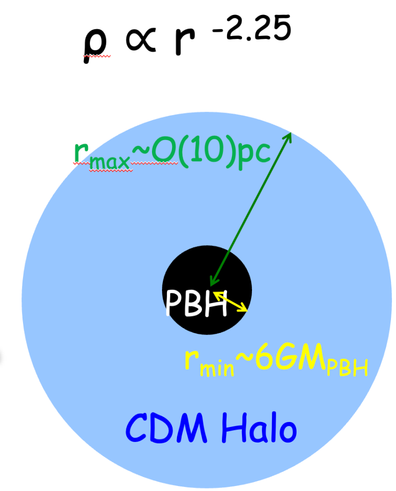
   Induced GWs

   MeV Gamma-ray

Point 1) Revealing Dark Matter Dress of Primordial Black Holes with 30 $M_\odot$ by Cosmological Strong Lensing

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



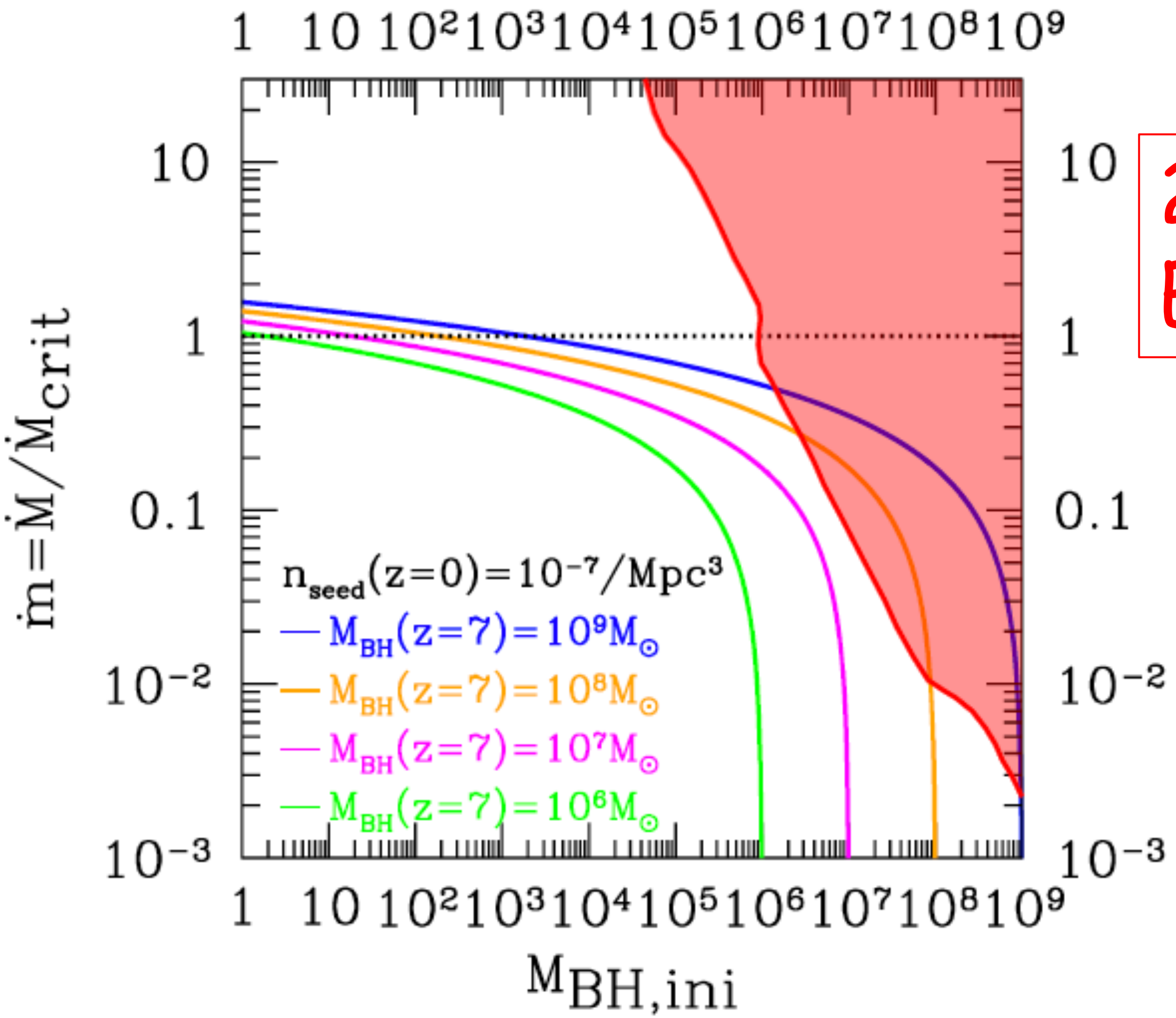


30$M_\odot$(PBH)+
300 $M_\odot$(halo)

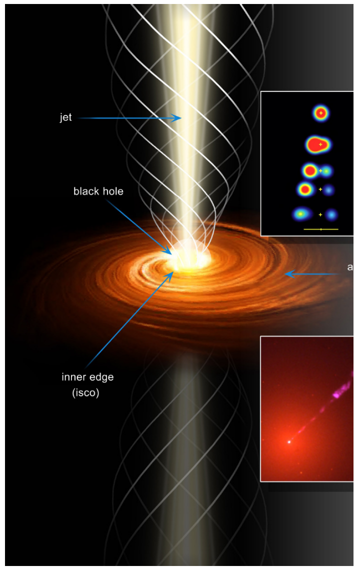
20,000 events by
CHIME collaboration

Point 2) Upper bounds (10^6 $M_\odot$) 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]



21cm
EDGES



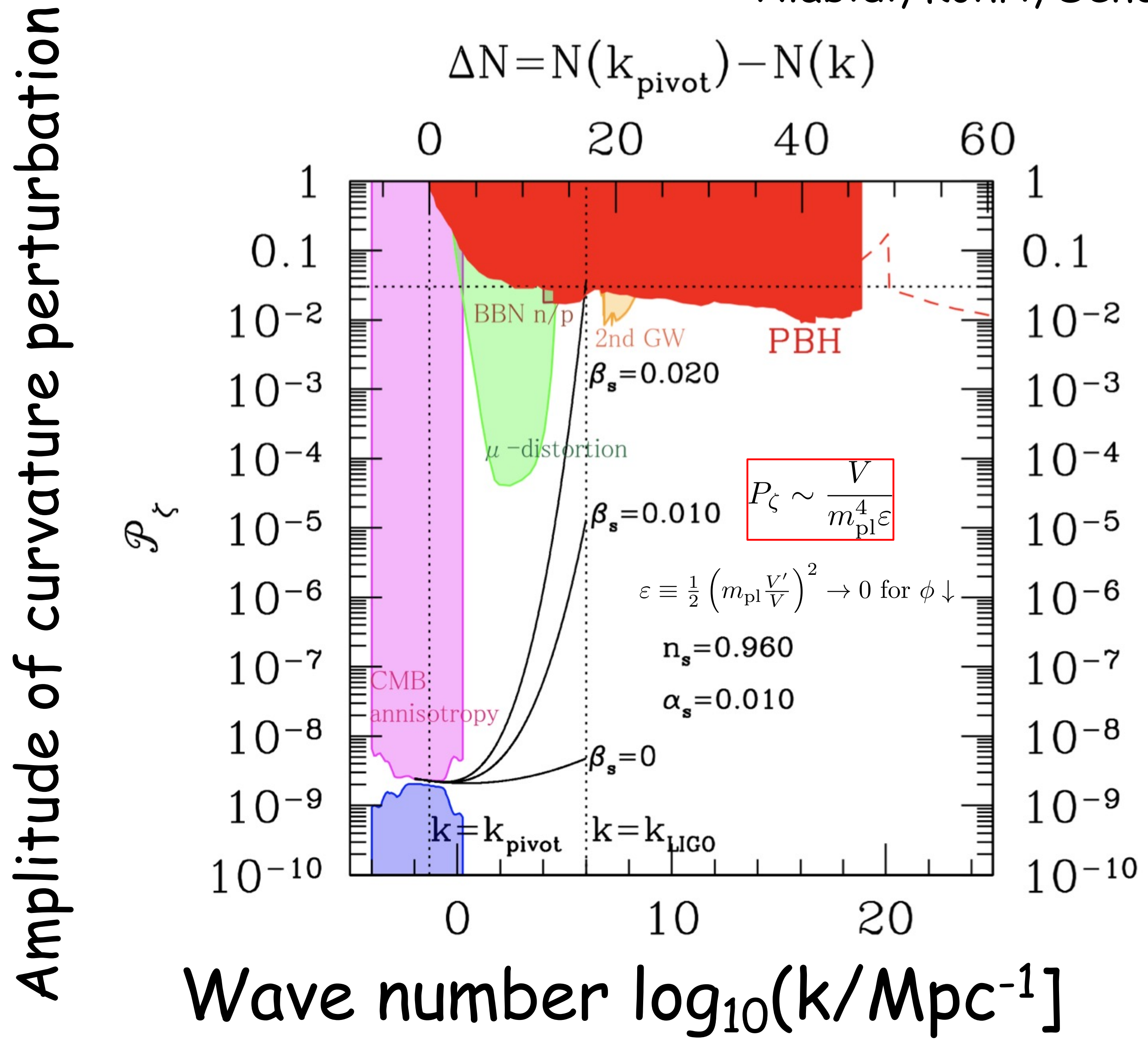
Point 3) dark matter

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



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

$$\alpha = M_P^2/12M^2$$

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

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

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

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

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

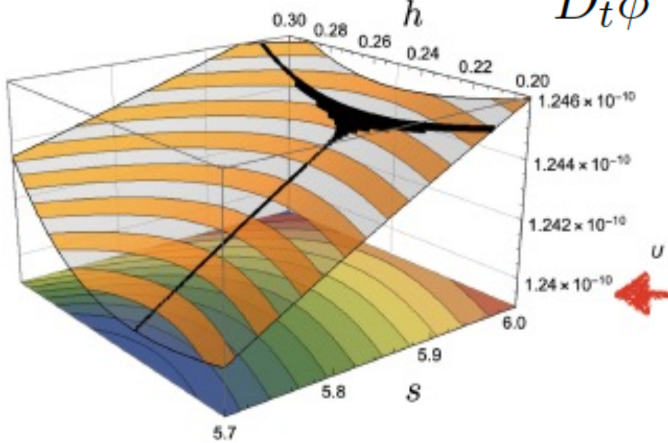
Motions on the potential of the Higgs-scalaron (s) system

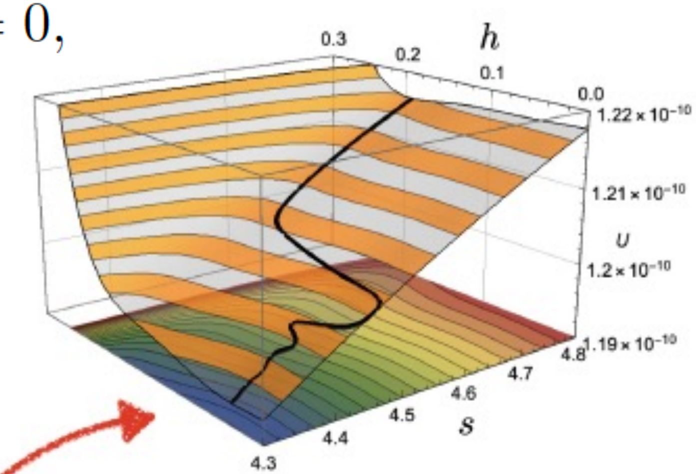
Dhong Yeon Cheong, Kazunori Kohri, Seong Chan Park, arXiv:2205.14813 [hep-ph]

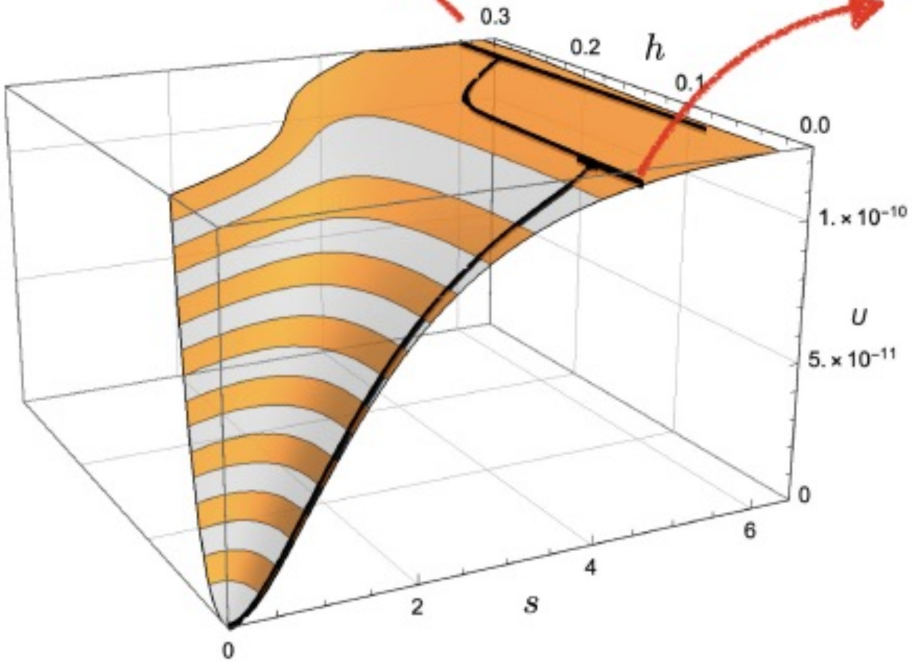
$$D_t \dot{\phi}^a + 3H\dot{\phi}^a + G^{ab} D_b U = 0,$$

$$\phi^s = s$$

$$\phi^h = h$$







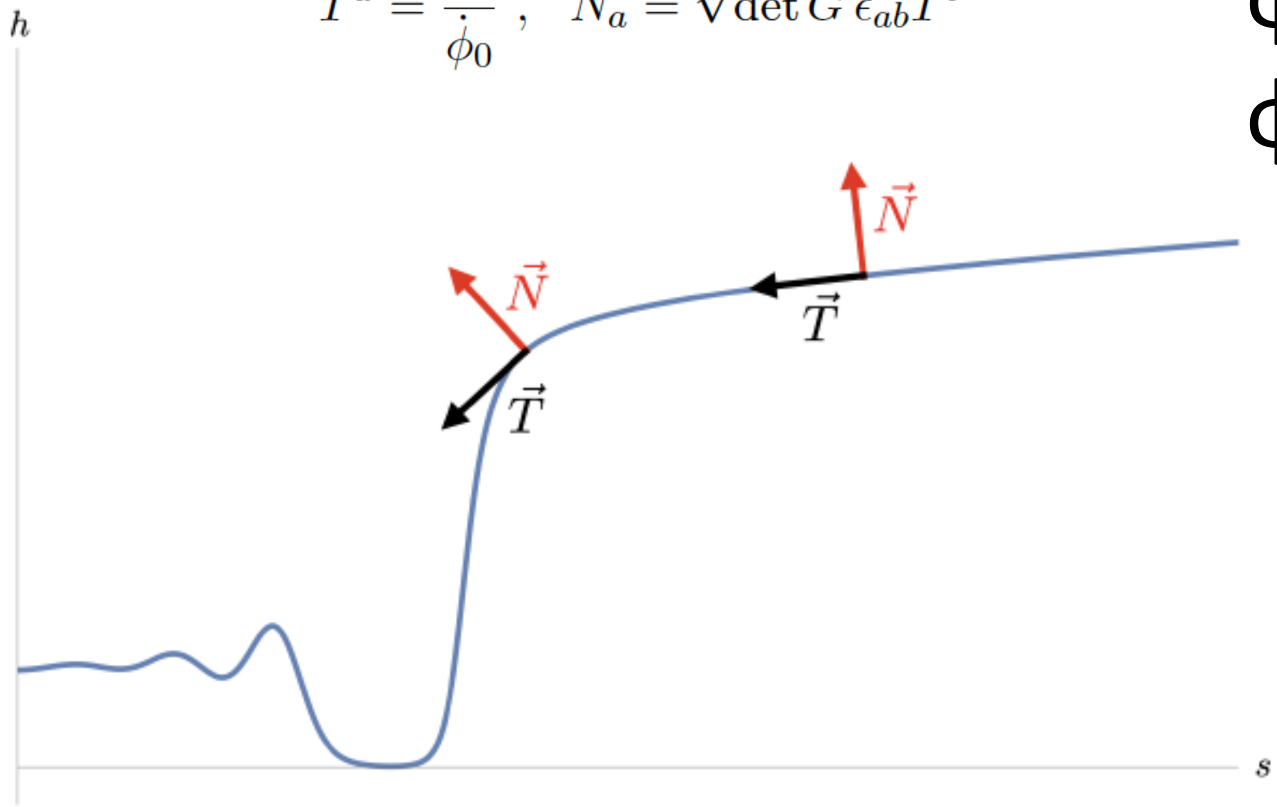
Adiabatic and is isocurvature perturbations in Higgs-R^2 Inflation

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

$$\phi^a(t,\vec{x}) = \phi_0^a(t) + \delta\phi^a(t,\vec{x}),$$

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

- Mukhanov-Sasaki variable

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

- Curvature and isocurvature perturbations

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

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

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

$$v_N = aN_a\delta\phi^a \equiv aN_aQ^a$$

Tachyonic Instability induced in Higgs-R^2 Inflation

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

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

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

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

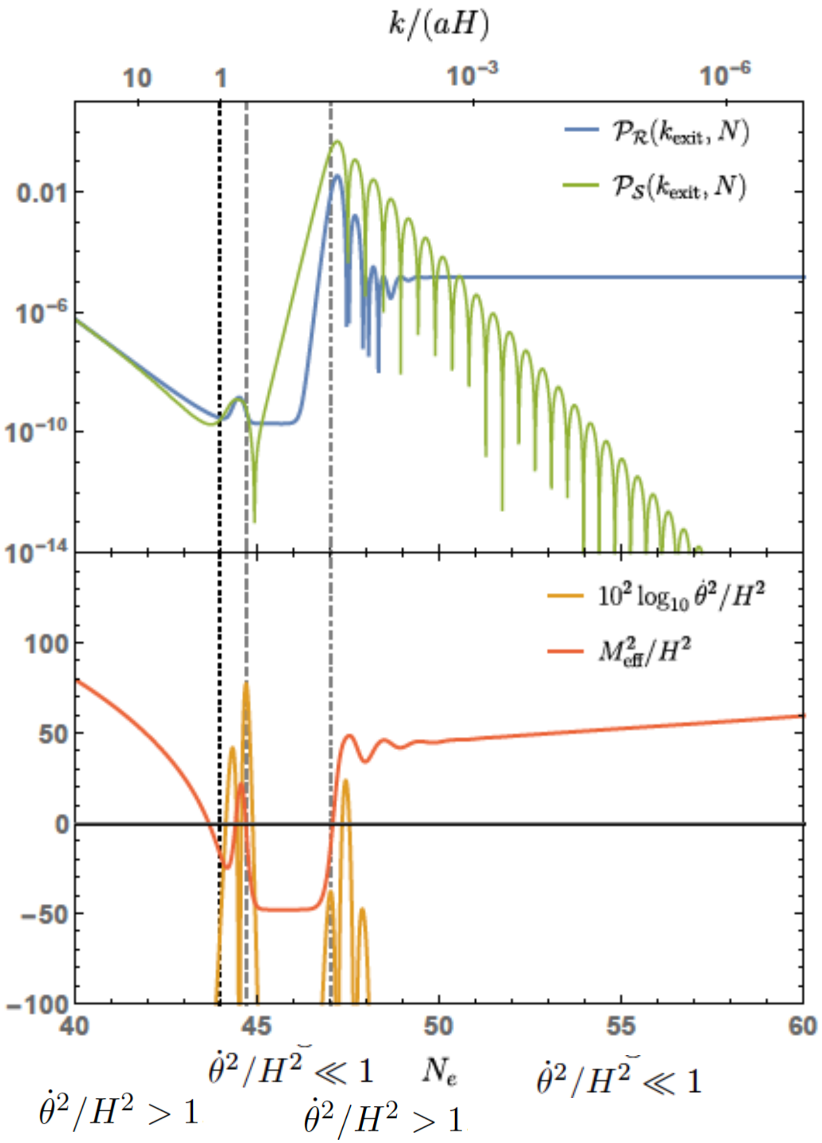
Hence Q_N can exhibit an *exponential* growth due to the tachyonic mass. This growth can be more rapid than cases implementing a USR phase.

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

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

Adiabatic and icocurvature modes in Higgs-R^2 Inflation

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

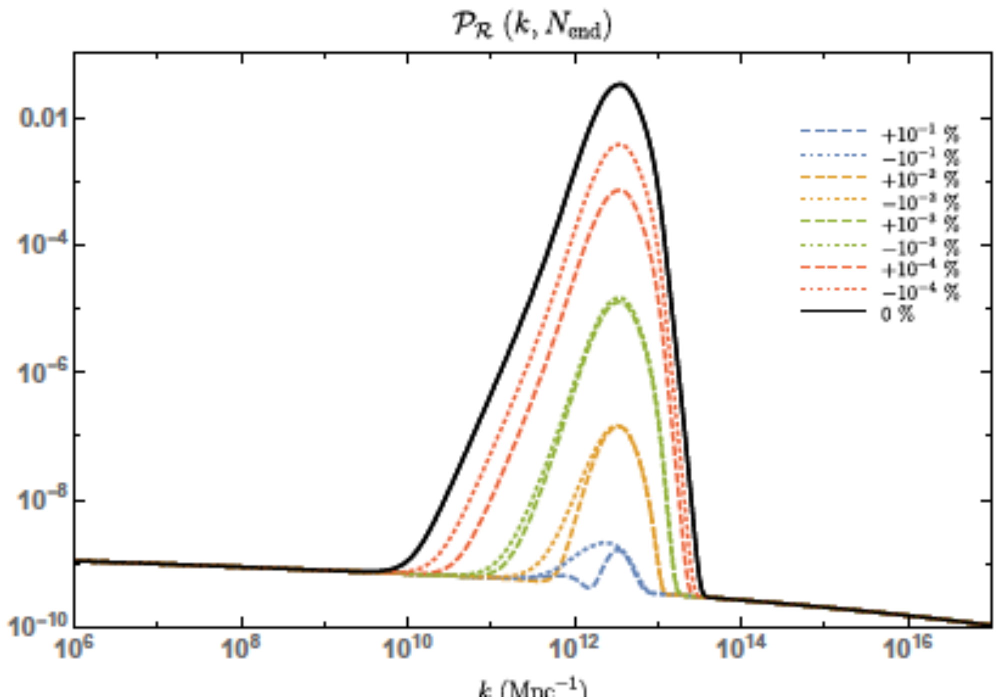


$$\mathcal{P}_\mathcal{S}(k_{\rm exit}, N_e) = \frac{k_{\rm exit}^3}{2\pi^2}\frac{H^2}{\dot\phi_0^2}\langle Q_{N,k}, Q_{N,k}\rangle$$

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

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]

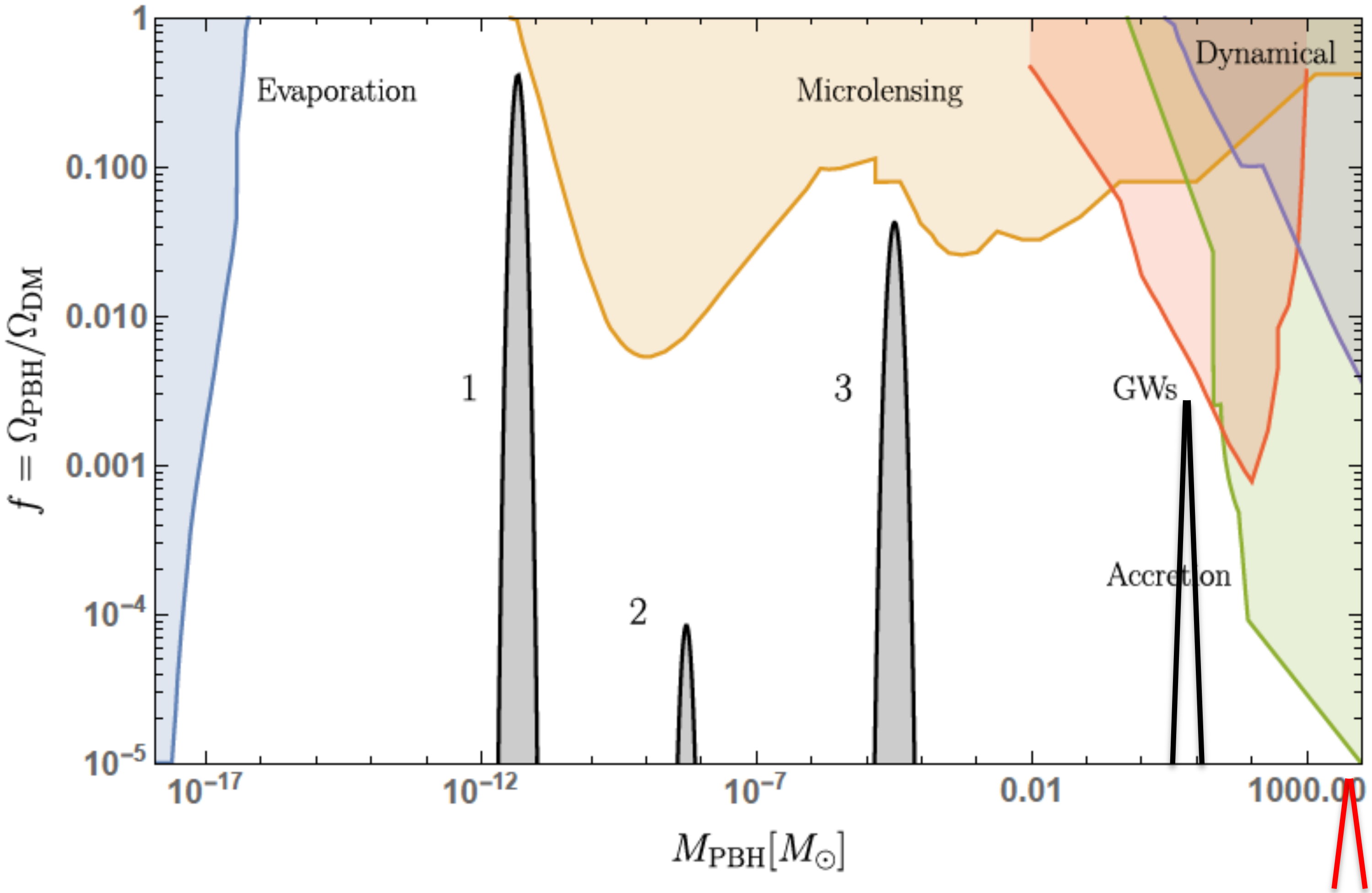


$\delta\lambda_m/\lambda_m$

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

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

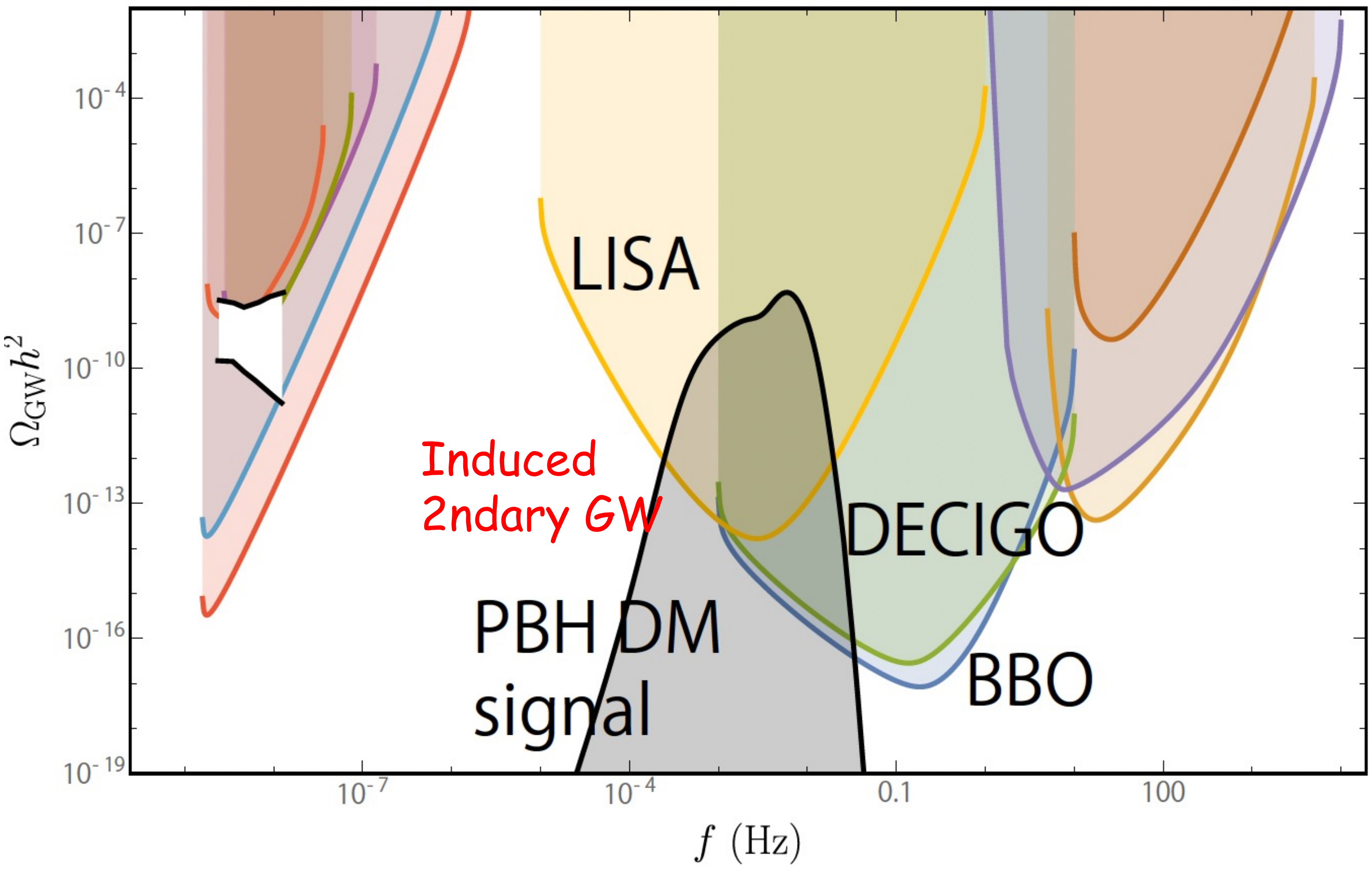
Dhong Yeon Cheong, Kazunori Kohri, Seong Chan Park, arXiv:2205.14813 [hep-ph]



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]

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 30 $M_{\odot}$ through strong gravitational lensing of FRBs due to PBH + Halo systems, which will be observed by CHIME
- Future 21cm observation can test accretions on to seed BHs to evolve to supermassive BHs (SMBHs) (< $10^4 M_{\odot}$-$10^6 M_{\odot}$ at z >>10)

My suggestions about how to enter PBH research in the future for non-expert people?

1. By a new (quantum) gravity theory, modifying gamma-ray spectrum differently from the one predicted by the Hawking process in the 4D Einstein gravity

2. Building of particle-theoretic and cosmological models of inflaton fields producing large curvature fluctuations on small scales

3. Scrutiny of a possible another mechanism for amplification of curvature fluctuations, such as strong first-order phase transitions in the early universe

4. …

M31 lensing on PBHs modified by size-distribution and finite-size effects on bright star sources

Nolan Smyth, Stefano Profumo, Samuel English, Tesla Jeltema, Kevin McKinnon, Puragra Guhathakurta, arXiv:1910.01285 [astro-ph.CO]

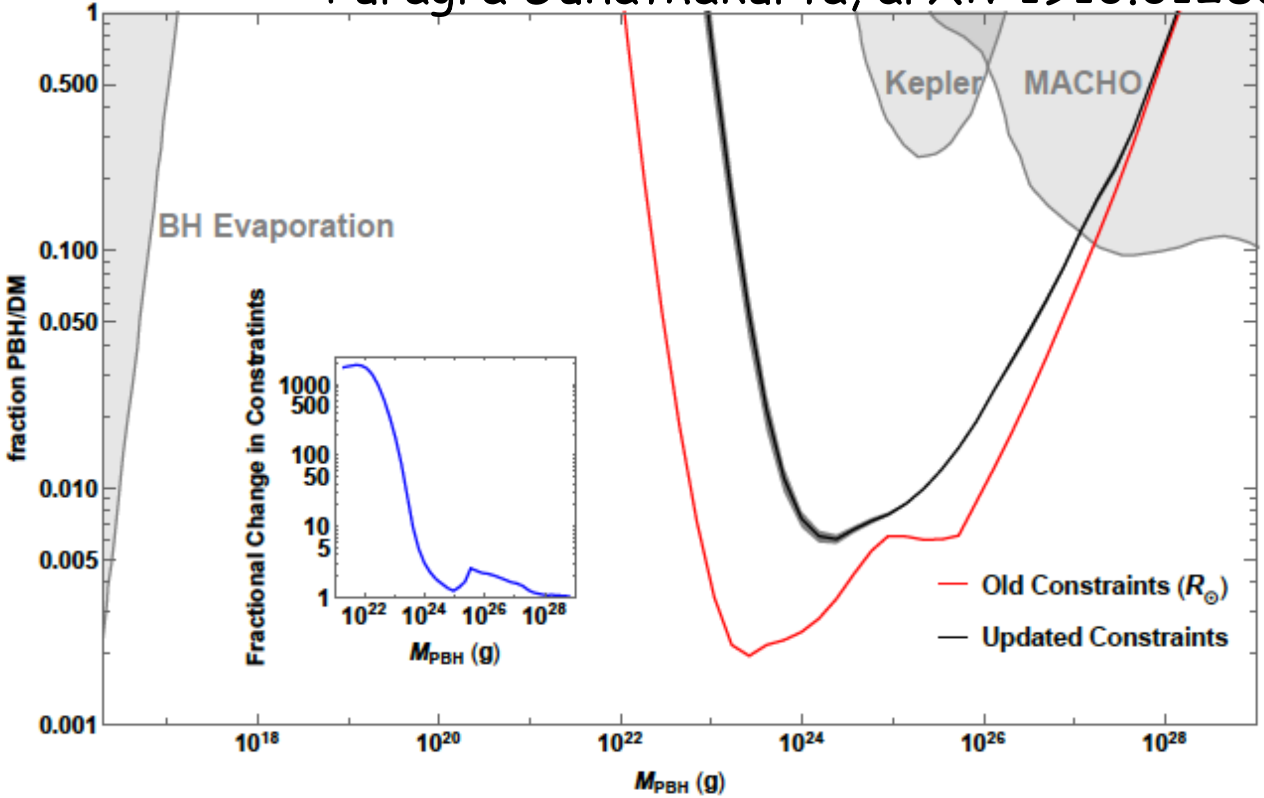


Figure 2. The constraints on primordial black holes as dark matter. The black line is the benchmark constraint and the primary result of this paper. The gray shading comes from the uncertainty in determining the stellar size distribution. The red line is

Observations of 21cm absorption line to test scenarios of super-Eddington accretion on to seed BHs ($\sim 10^4\ M_\odot$) of high-z SMBHs

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

We need a seed BH at z>>7

- We do not know origins of Super-Massive Black Holes

$10^9\ M_\odot$ observed at z=7.642 (PBHs are excluded)

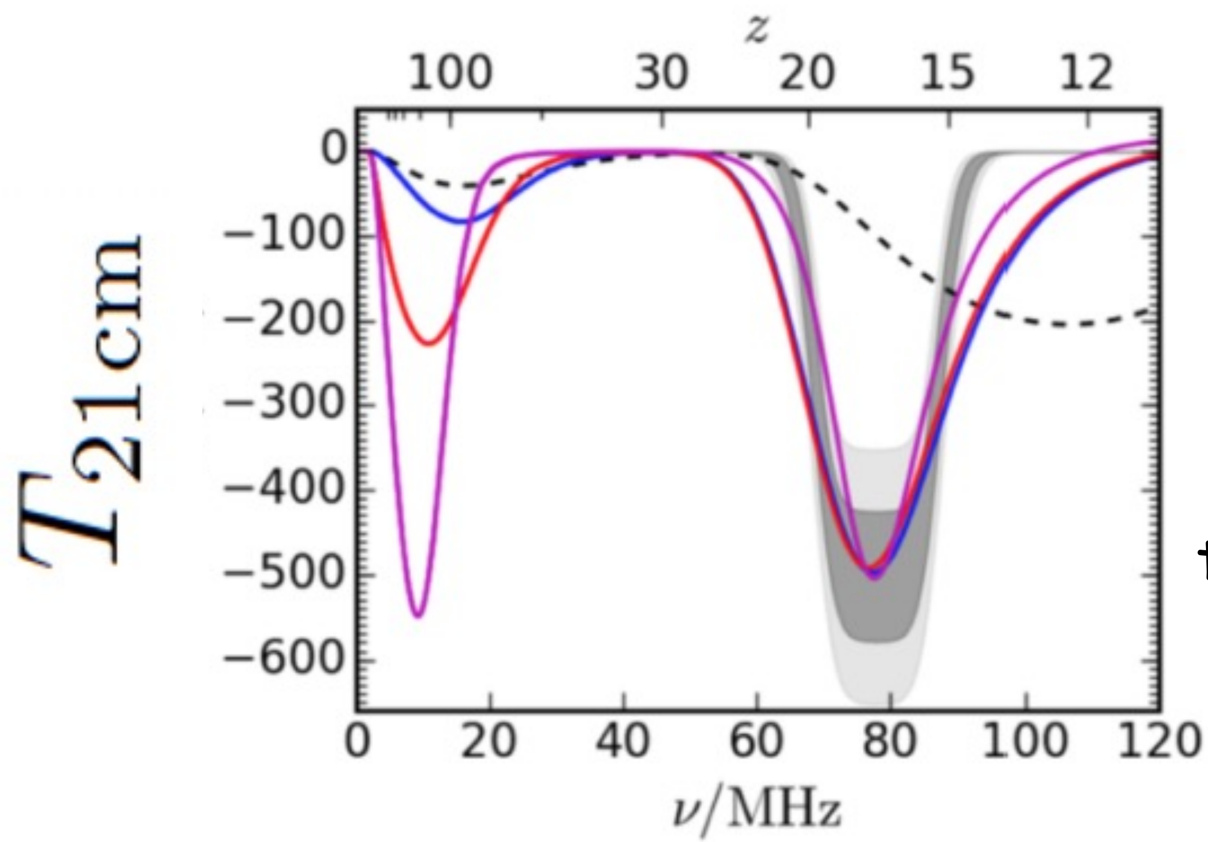
t(z=7.084) ~ 0.74Gyr

- We need seed (primordial) BHs before z >> 7 which had evolved to the SMBHs through accretions

$$\Omega_{\rm sBH}/\Omega_{\rm CDM} \sim 10^{-10} \left(\frac{n_{\rm seed,0}}{10^{-3}{\rm Mpc}^{-3}}\right)\left(\frac{M_{\rm BH,ini}}{10^2 M_\odot}\right)\left(\frac{M_{\rm SMBH}}{10^9 M_\odot}\right)\left(\frac{M_{\rm gal}}{10^{12} M_\odot}\right)^{-1}$$

Advent of EDGES

Judd D. Bowman, Alan E. E. Rogers, Raul A. Monsalve, Thomas J. Mozdzen &
Nivedita Mahesh, Nature 555 (2018) 67
Steven R. Furlanetto et al, arXiv:1903.06212



Absorption at Z ~ 17

t(z=17) ~ 0.22Gyr

$$\delta T_b = \quad T_{21cm} = -500^{+200}_{-500}\,\mathrm{mK} \quad (99\%\ \mathrm{CL})$$

Energy injection by accretion disks

- Injection rate $$\frac{dE_{\rm inj}}{dV\,dt}(z) = \int d\omega\; n_{\rm seed}(z)\frac{dL}{d\omega},$$

$$\frac{dE_{\rm inj}}{dV\,dt} \sim 10^{-20}\ {\rm eV\ sec^{-1}cm^{-3}} \times \left(\frac{n_{\rm seed,0}}{10^{-3}{\rm Mpc}^{-3}}\right)\left(\frac{1+z}{18}\right)^3\left(\frac{L}{10^{40}{\rm erg\ sec^{-1}}}\right)$$

- Accretion rate in unit of Eddington accretion $$\dot m = \frac{\dot M}{\dot M_{\rm crit}}$$

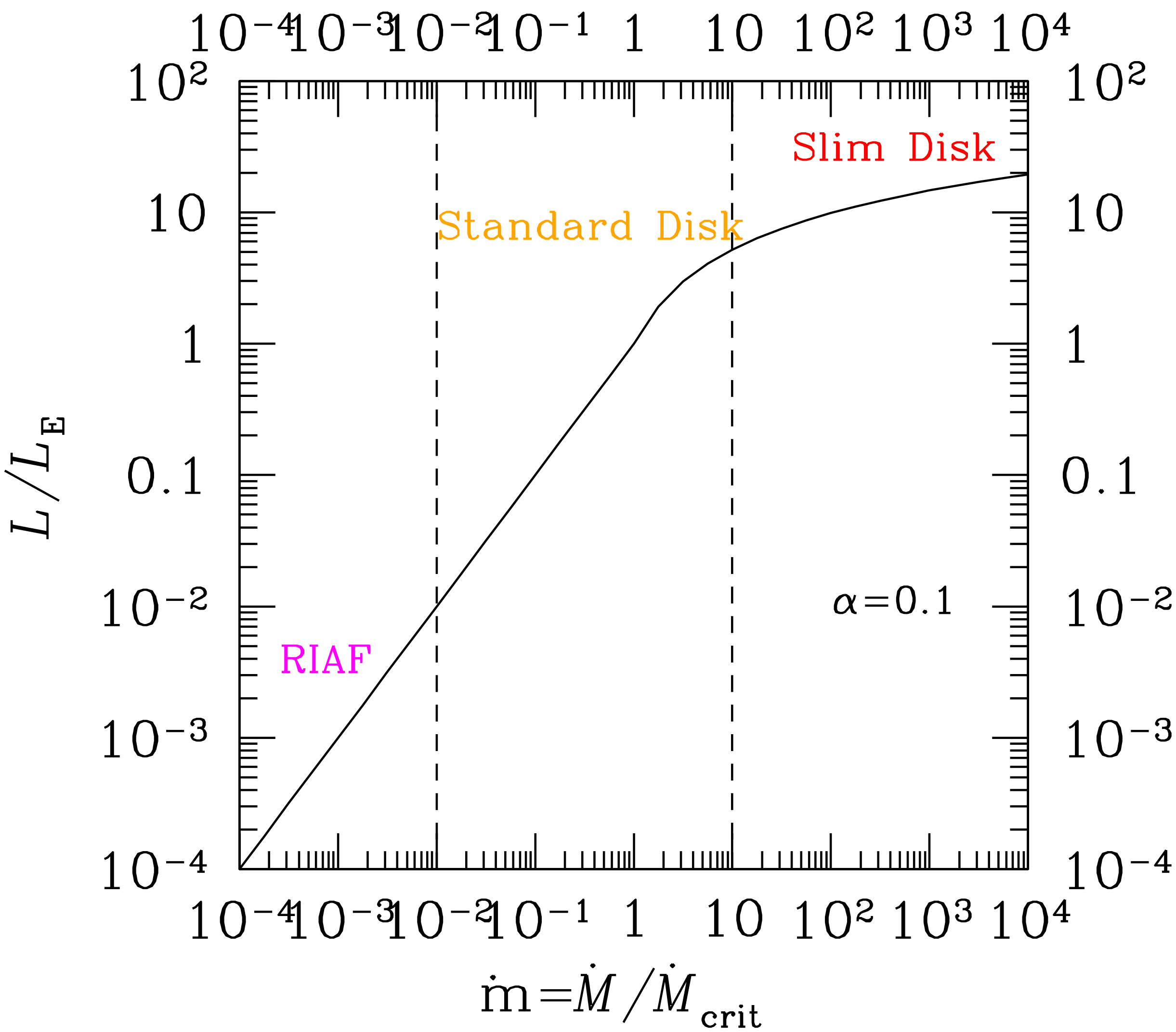
$$\dot M_{\rm crit} \equiv \eta_{\rm eff}^{-1} L_E \simeq 1.4\times 10^{18}\ {\rm g\ sec^{-1}}\left(\frac{\eta_{\rm eff}^{-1}}{10}\right)\left(\frac{M_{\rm BH}}{M_\odot}\right)$$

- Mass evolutions in Eddington accretion

$$M_{\rm BH}(t) \sim M_{\rm BH,ini}\exp\left(10\dot m\frac{t}{\tau_E}\right)$$

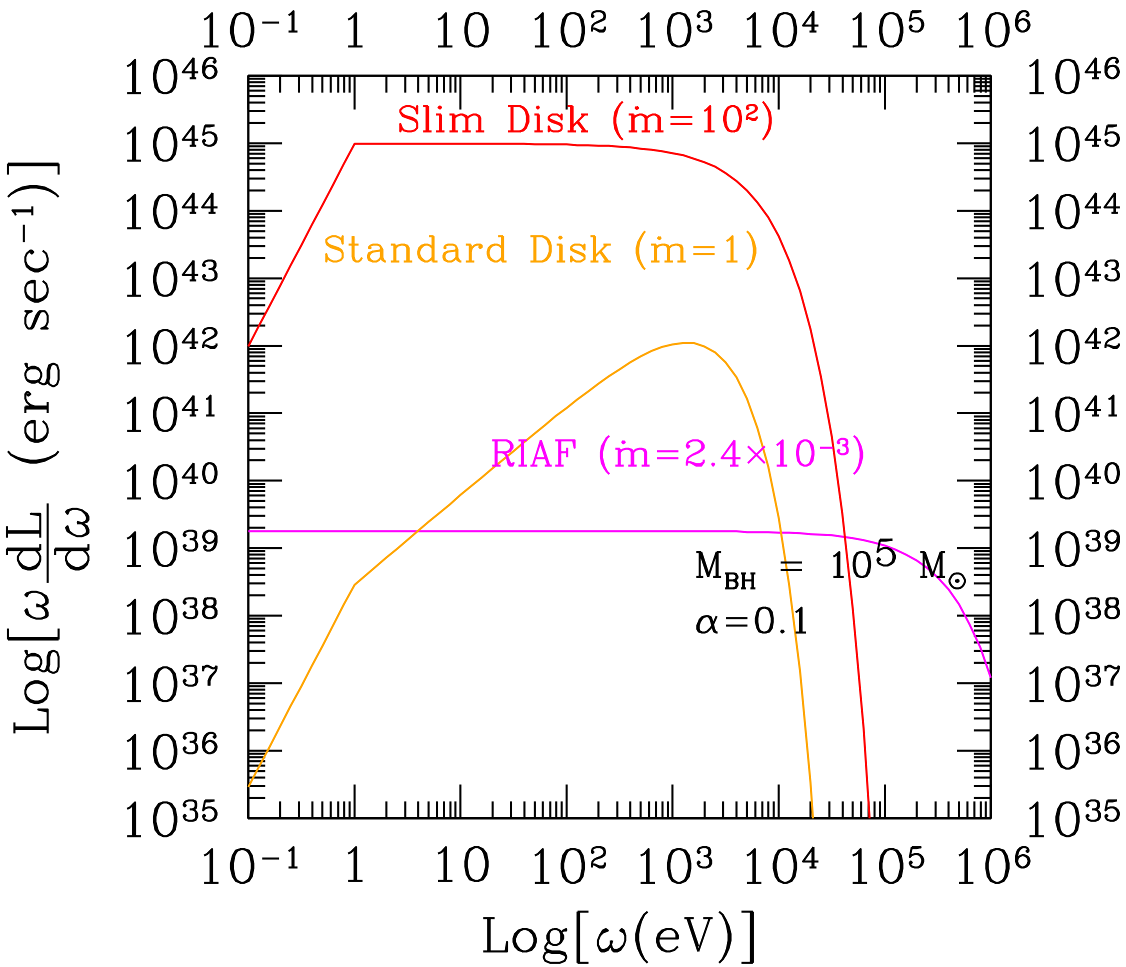
$$\tau_E \equiv \frac{M_{\rm BH}c^2}{L_E} = \frac{\sigma_T c}{4\pi\mu G m_p} \simeq 0.45{\rm Gyr}.$$

Luminosity



10^{-4} 10^{-3} 10^{-2} 10^{-1} 1 10 10^{2} 10^{3} 10^{4}
10^{2}
10
1
0.1
10^{-2}
10^{-3}
10^{-4}
L/L_E
Slim Disk
Standard Disk
RIAF
$\alpha=0.1$
$\dot{m}=\dot{M}/\dot{M}_{crit}$

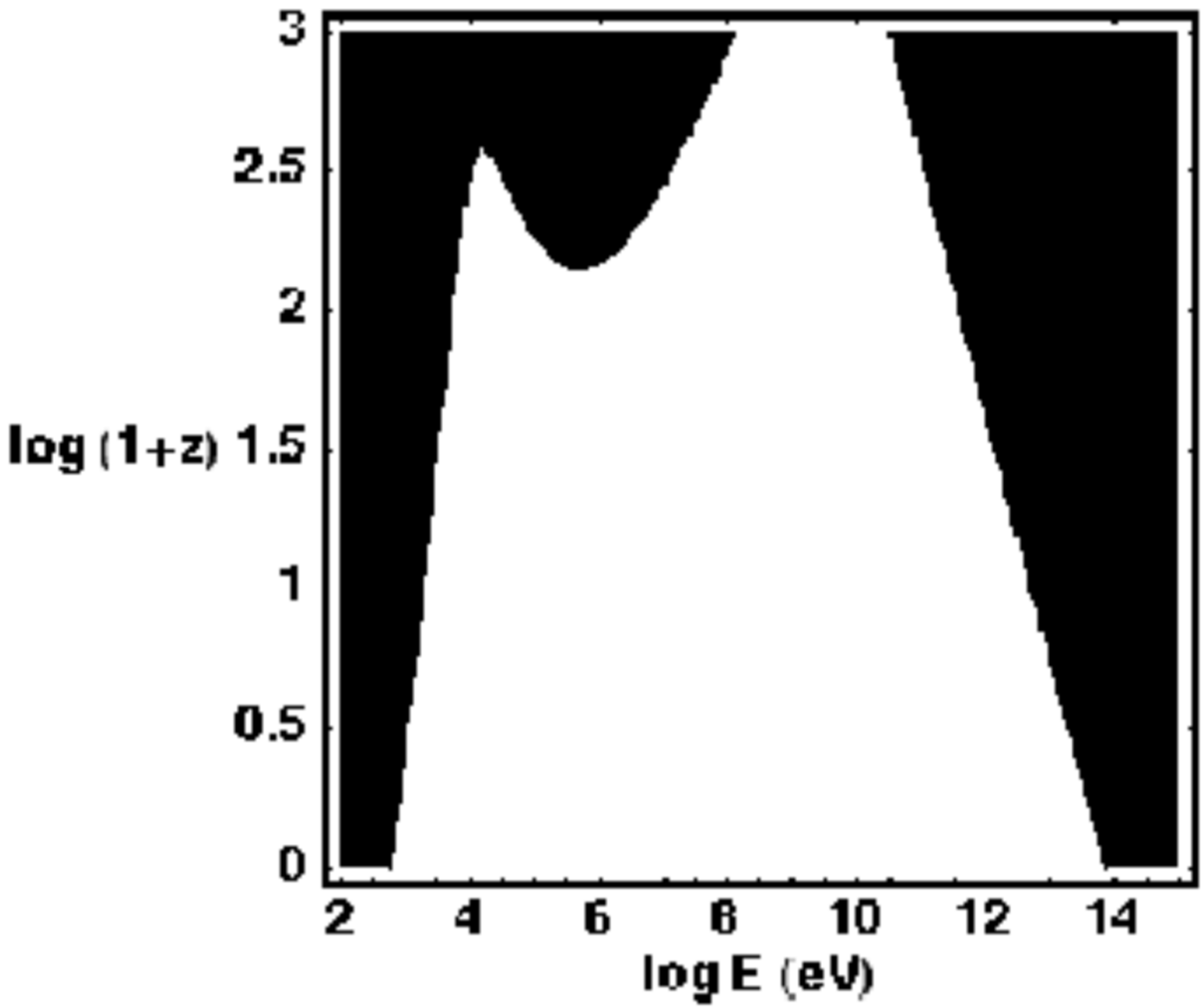
Spectrum $\omega\, dL/d\omega$ for a BH with $M_{BH} = 10^5\, M_\odot$



X-rays are absorbed by cosmological plasma at $z > 10$

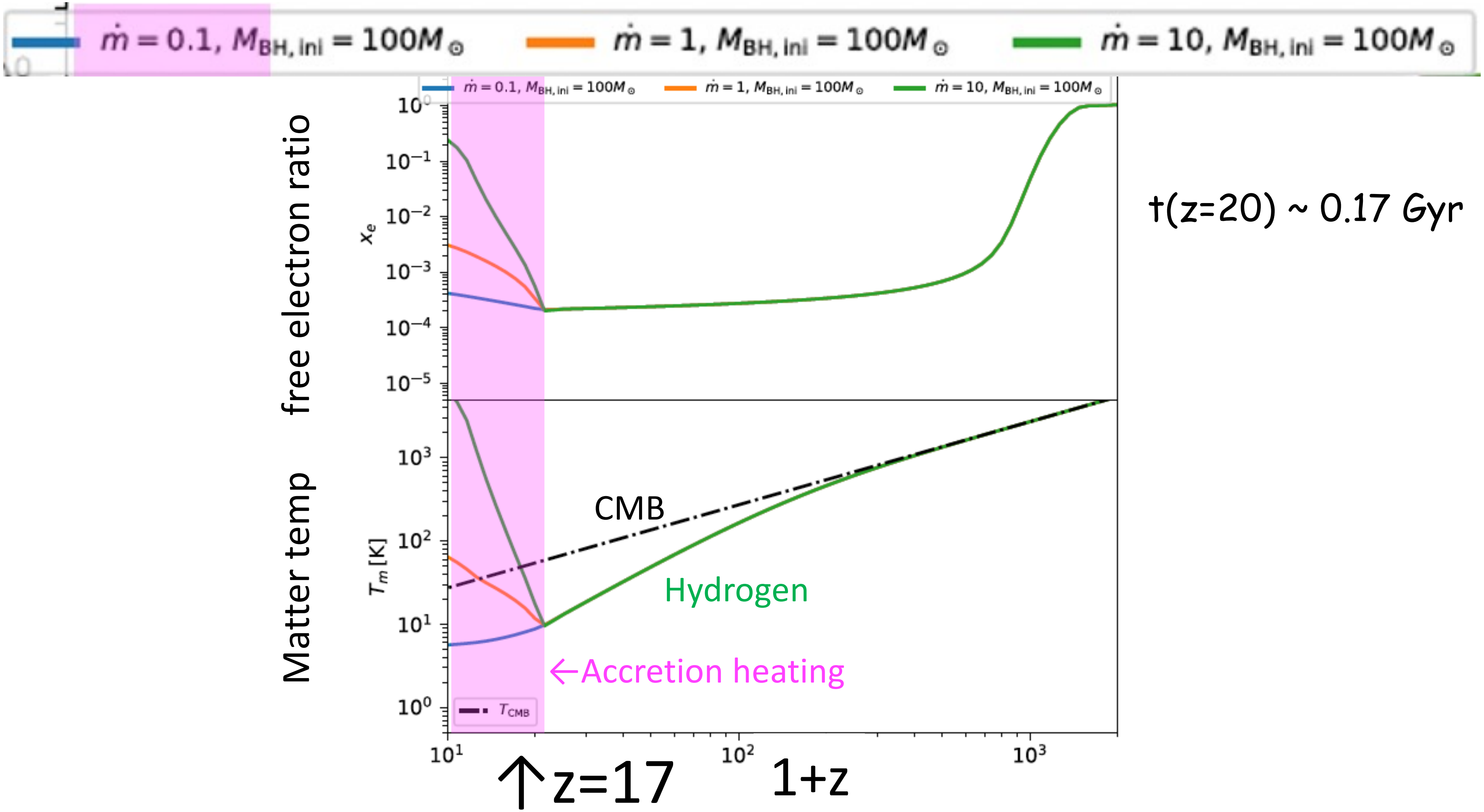
X-rays are absorbed by cosmological plasma at z > 10

X. Chen and M. Kamionkowski, 2003



Histories of free electron ratio and temperature

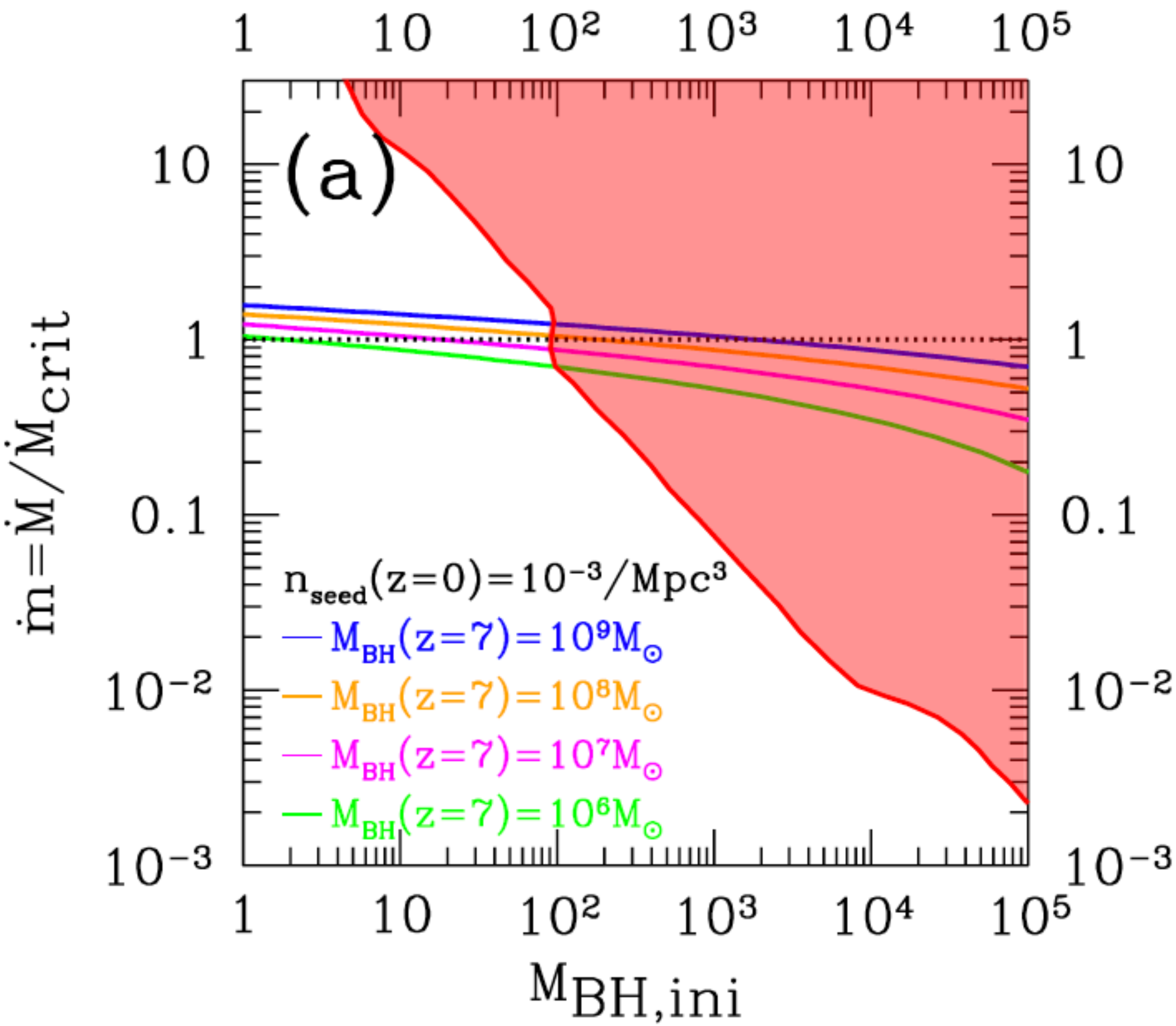
Kazunori Kohri, Toyokazu Sekiguchi, Sai Wang, arXiv:2201.05300 [astro-ph.CO]



t(z=20) ~ 0.17 Gyr

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]



Lower bounds on initial seed masses

- By the EDGES data, we can obtain upper bounds on accretion on to seed BHs, which evolved to high-z SMBHs

- We exclude the seed BHs with their masses

$$\mathrm{M_{BH,ini}} \gtrsim 10^2 M_\odot \text{ for } n_{\rm seed}(z=0) = 10^{-3}\mathrm{Mpc}^{-3}$$

Number counts of SMBHs at z=0 (the strongest assumption)

$$\mathrm{M_{BH,ini}} \gtrsim 10^6 M_\odot \text{ for } n_{\rm seed}(z=0) = 10^{-7}\mathrm{Mpc}^{-3}$$

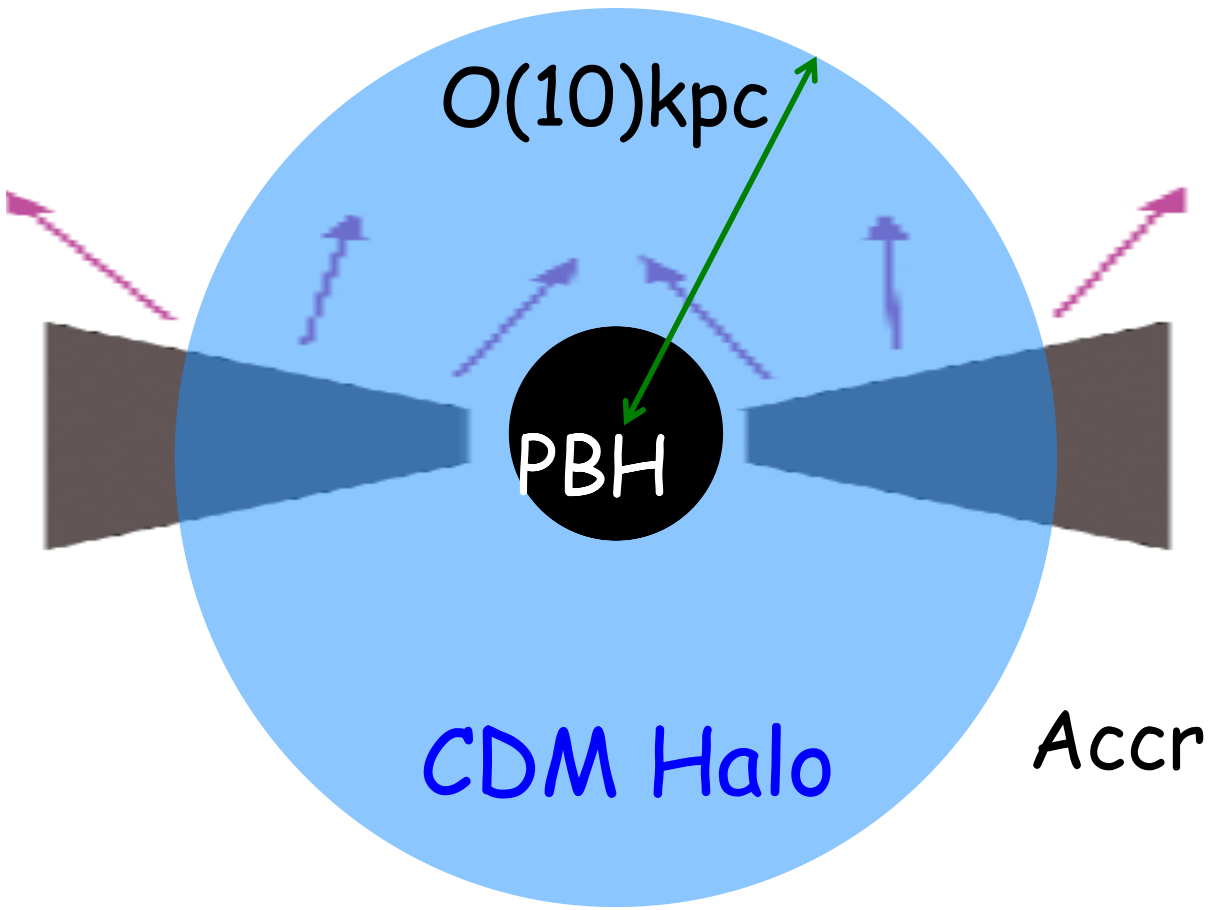
Observations of SMBHs at high-redshift at z=6 (conservative)

Revealing PBHs with $O(10)M_{\odot}$ by Cosmological Strong Lensing

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

Cosmological baryon accretion onto the PBH + CDM halo system

Poulin, Serpico, Inman, Kohri (2020)



$\rho \propto r^{-2.25}$

Accretion onto CDM + PBH

z ~30 -- 100

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

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

- Halo's Mass

$$M_{\rm h}(z_{\rm c}) = 3\Big(\frac{1000}{1+z_{\rm c}}\Big) M_{\rm PBH}$$

- Halo's radius

$$R_{\rm h}(z_{\rm c}) = 0.019\ {\rm pc}\Big(\frac{M_{\rm h}}{M_\odot}\Big)^{1/3}\Big(\frac{1000}{1+z_{\rm c}}\Big)$$

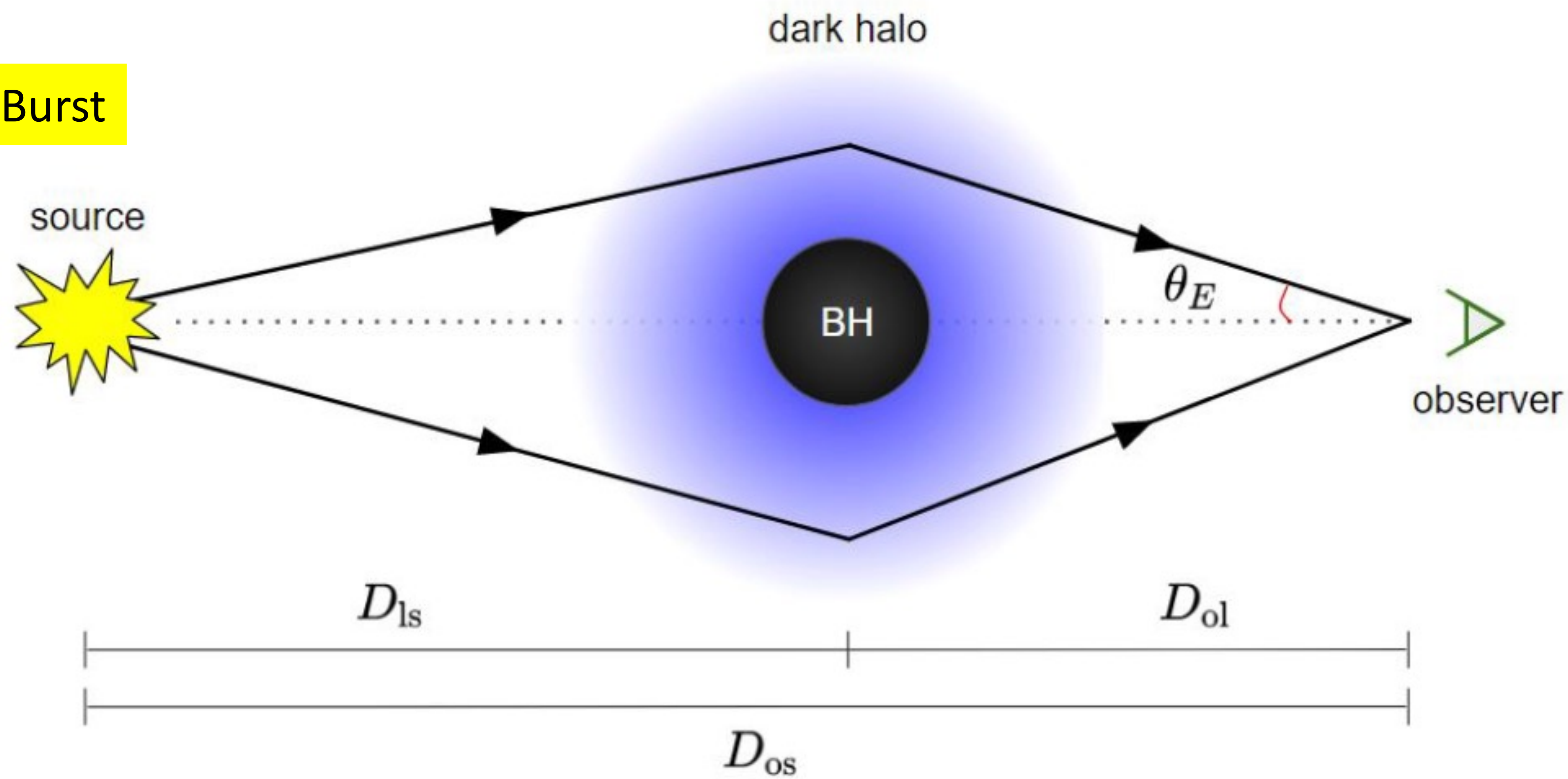
- Density profile of halo

$$\rho_{\rm h}(r) = \rho_0\Big(\frac{R_{\rm h}}{r}\Big)^{9/4}$$

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

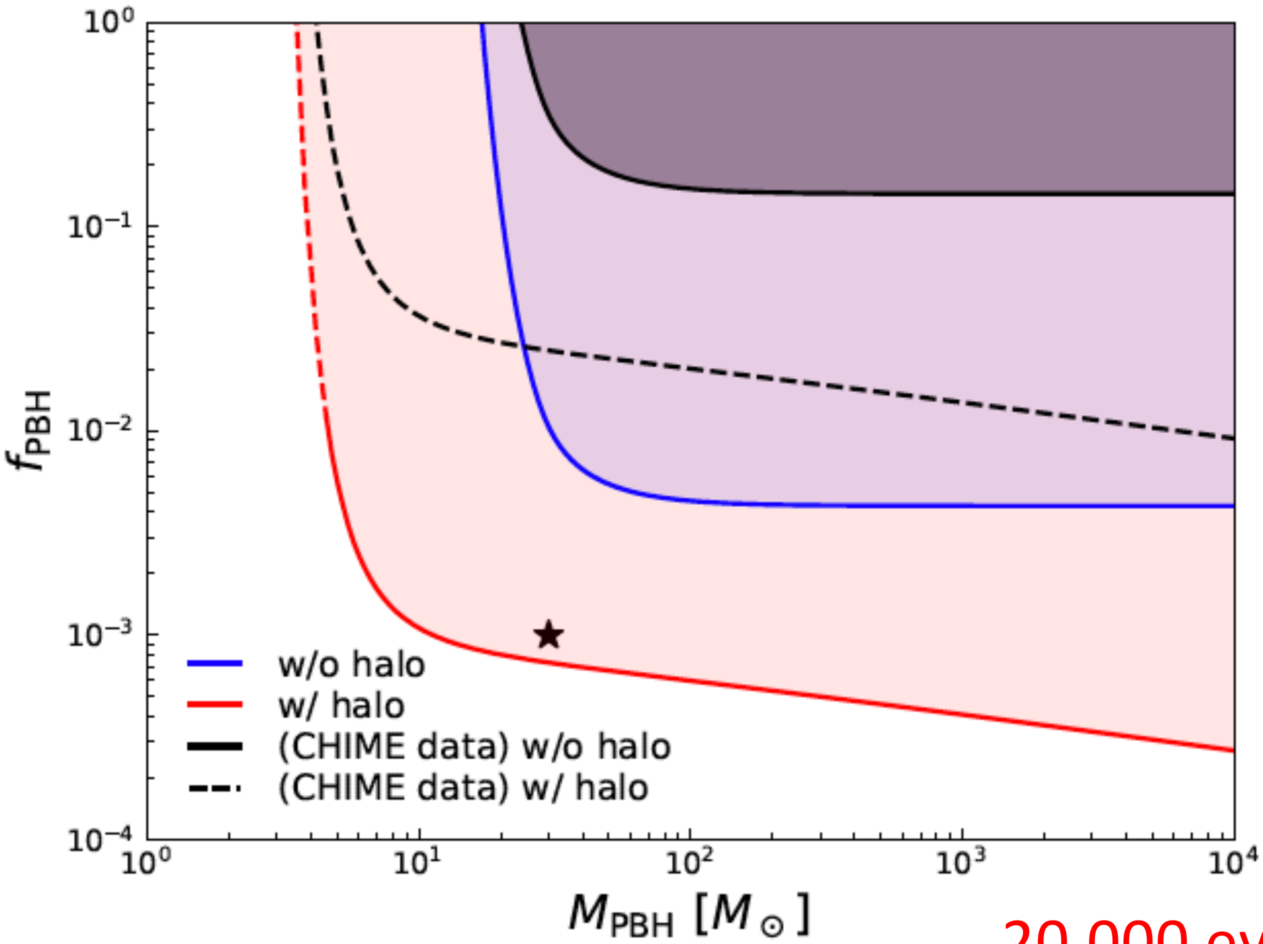
Masamune Oguri, Volodymyr Takhistov, Kazunori Kohri, arXiv:2208.05957 [astro-ph.CO]

Fast Radio Burst



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

Probing Primordial Black Holes with $O(10)M_\odot$ by using Angular Power Spectrum for Anisotropies in Stochastic Gravitational-Wave Background

Sai Wang, Kazunori Kohri, Valeri Vardanyan, arXiv:2107.01935 [gr-qc]

Merger rates

Sai Wang, Kazunori Kohri, Valeri Vardanyan, arXiv:2107.01935 [gr-qc]

- Merger rates of PBHs (multi-body effects)

Zu-Cheng Chen, Qing-Guo Huang, arXiv:1801.10327 [astro-ph.CO]

$$\mathcal{R}_{\mathrm{PBH}} = A \left(\frac{t_0}{t}\right)^{\frac{34}{37}} \frac{f^2}{(f^2+\sigma_{\mathrm{eq}}^2)^{\frac{21}{74}}} \left(\frac{m}{M_\odot}\right)^{-\frac{32}{37}} \qquad \sigma_{\mathrm{eq}} \simeq 0.005$$

- Merger rates of Astrophysical BHs (ABHs)

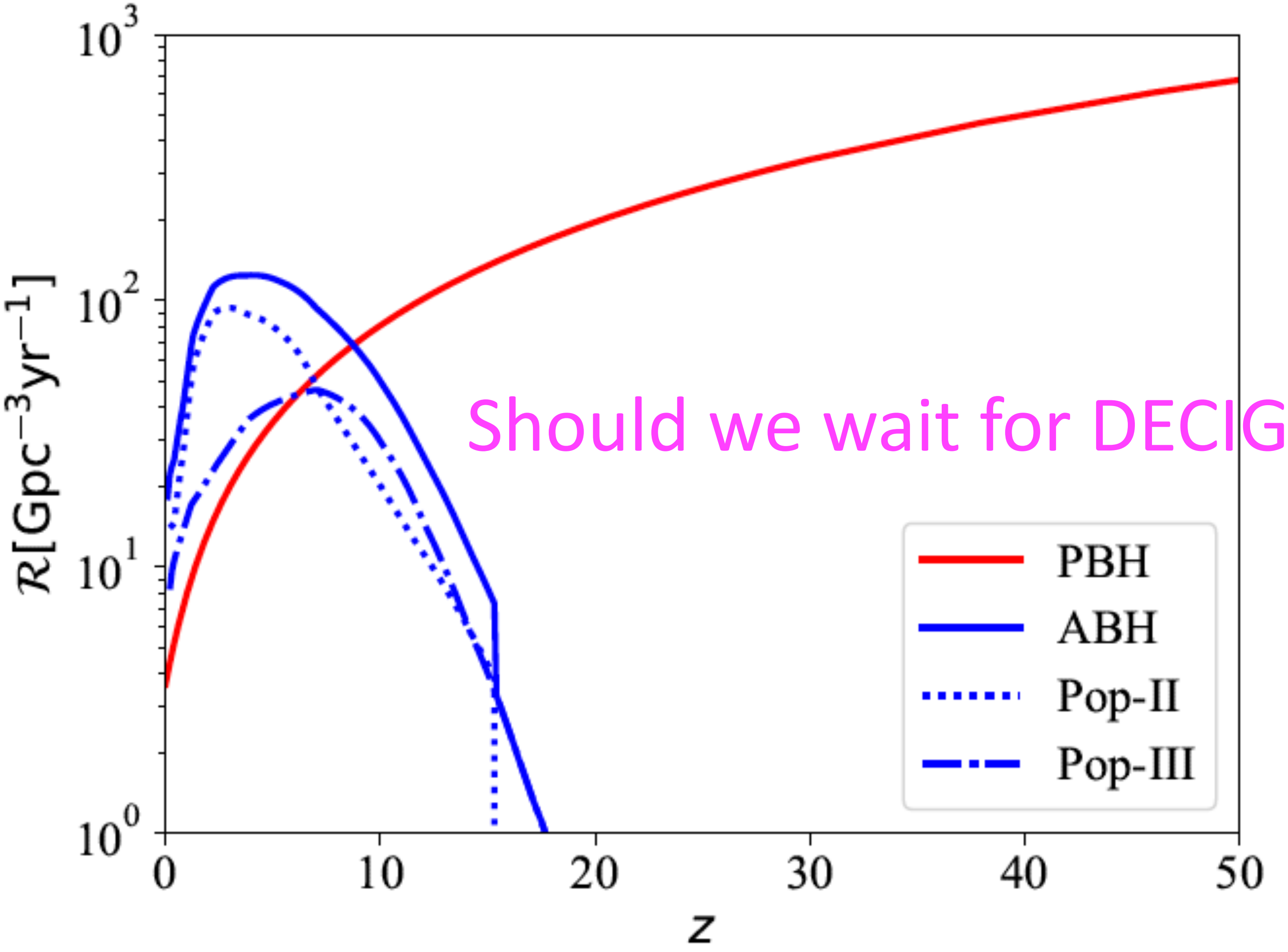
$$\mathcal{R}_{\mathrm{ABH}}(z) = A_{\mathrm{ABH}} \int_{50\mathrm{Myr}}^{t_c(z)} R_*(t_\mathrm{f}) P(t_\mathrm{d}) \frac{1+z}{1+z_\mathrm{f}} dt_\mathrm{d}$$

SFR $R_*(t_\mathrm{f})$

time delay distribution $P(t_\mathrm{d})$

Merger rates

Sai Wang, Kazunori Kohri, Valeri Vardanyan, arXiv:2107.01935 [gr-qc]



Should we wait for DECIGO/BBO?

Probing Primordial Black Holes with Angular Power Spectrum for Anisotropies in Stochastic Gravitational-Wave Background

Sai Wang, Kazunori Kohri, Valeri Vardanyan, arXiv:2107.01935 [gr-qc]

- Energy density

$$\Omega(\nu, \mathbf{e}) = \frac{1}{\rho_c} \frac{d^3 \rho(\nu, \mathbf{e})}{d \ln \nu d^2 \mathbf{e}} = \frac{\bar{\Omega}(\nu)}{4\pi} + \delta\Omega(\nu, \mathbf{e})$$

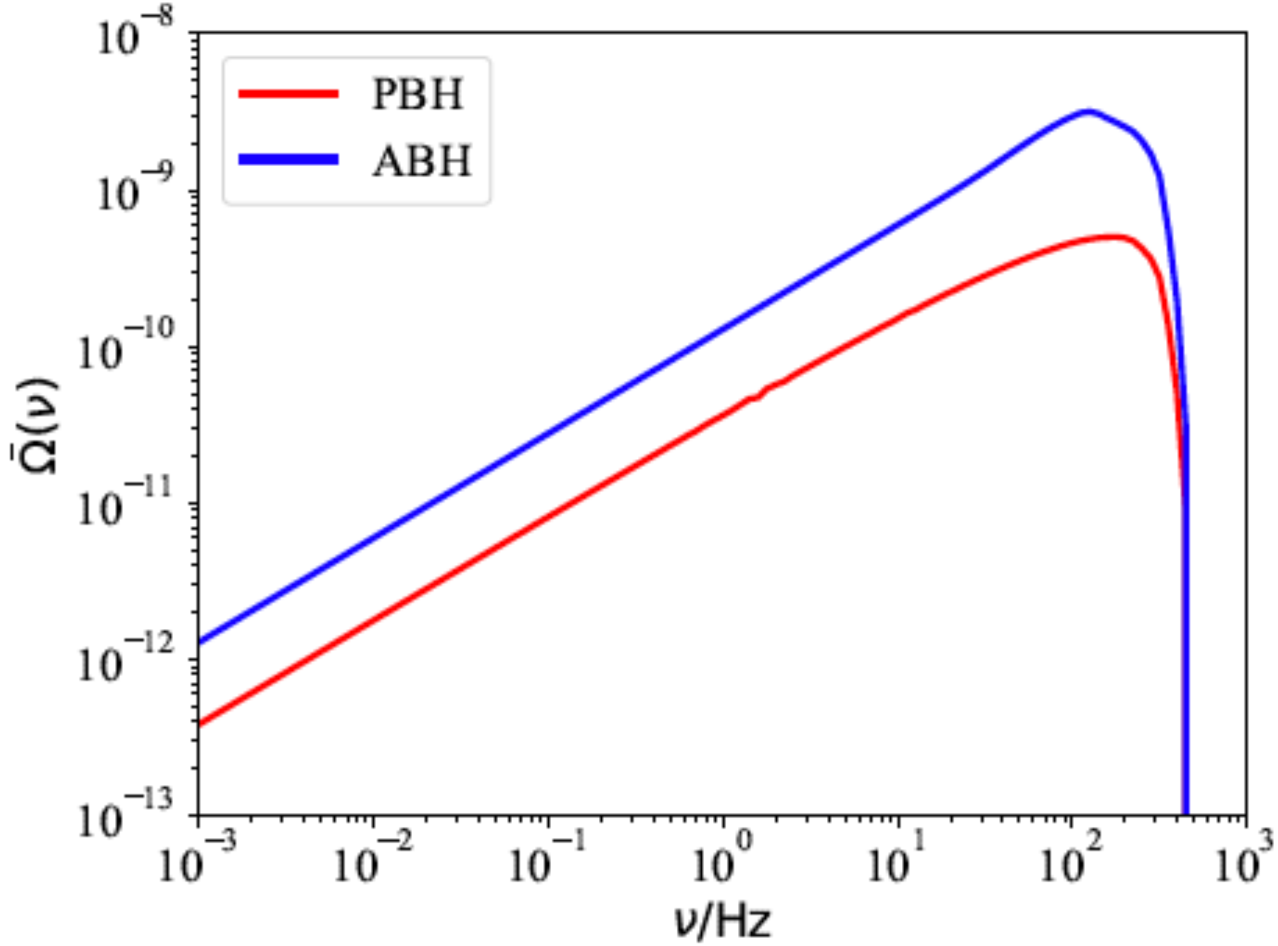
- Mean value

$$\bar{\Omega}(\nu) = \frac{\nu}{\rho_c} \int_0^{\eta_0} \mathrm{d}\eta\, a(\eta) \int \mathrm{d}\theta_s \mathcal{R}_X(\theta_s, t) \frac{dE_s}{\mathrm{d}\nu_s}(\nu_s, \theta_s)$$

X = PBH or ABH

Mean value of signals

Sai Wang, Kazunori Kohri, Valeri Vardanyan, arXiv:2107.01935 [gr-qc]



Angular power spectra of GWs from binary PBHs or binary ABHs

Sai Wang, Kazunori Kohri, Valeri Vardanyan, arXiv:2107.01935 [gr-qc]

- Anisotropy

X = PBH or ABH

$$\delta\Omega_\ell(\nu,k) = \frac{\nu}{4\pi\rho_c}\int_0^{\eta_0} d\eta \mathcal{A}_X(\nu;\eta)\times$$

$$b_X(\eta)\,\delta_m(\eta,k)(\eta) j_\ell(k\Delta\eta) + \cdots$$

$$\mathcal{A}_X(\eta,\nu) = a(\eta)\int d\theta_s \mathcal{R}_X(\theta_s,t)\frac{dE_s}{d\nu_s}(\nu_s,\theta_s)$$

$$b_{PBH} = 1$$

$$b_{ABH} = b_1 + b_2/D \qquad b_1 = b_2 = 1$$

Masamune Oguri, arXiv:1603.02356 [astro-ph.CO]

δm can be computed by CMBquick and Halofit

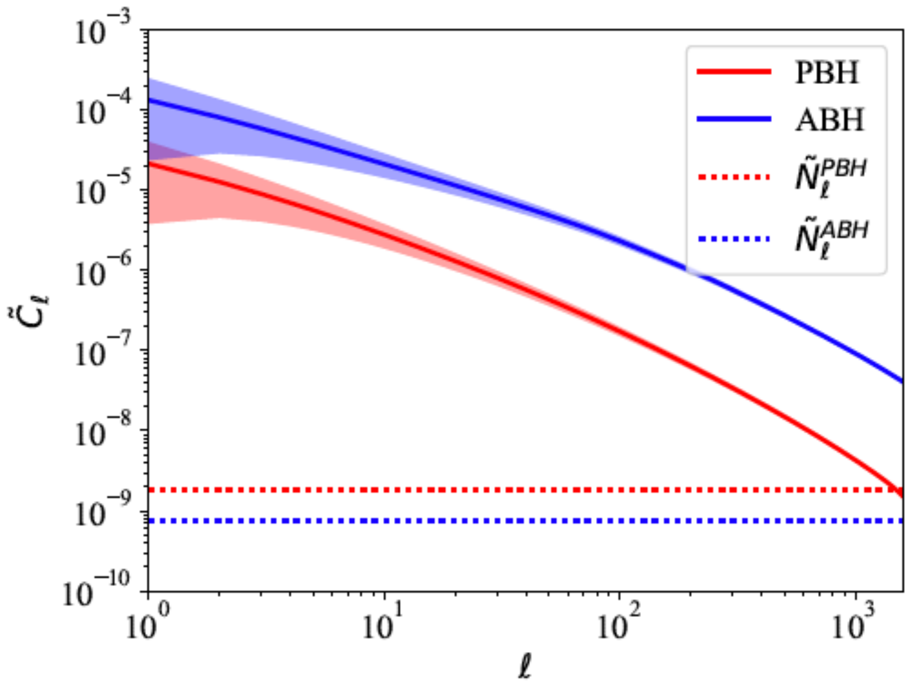
$$C_\ell(\nu) = \frac{2}{\pi}\int d\ln k\; k^3|\delta\Omega_\ell(\nu,k)|^2$$

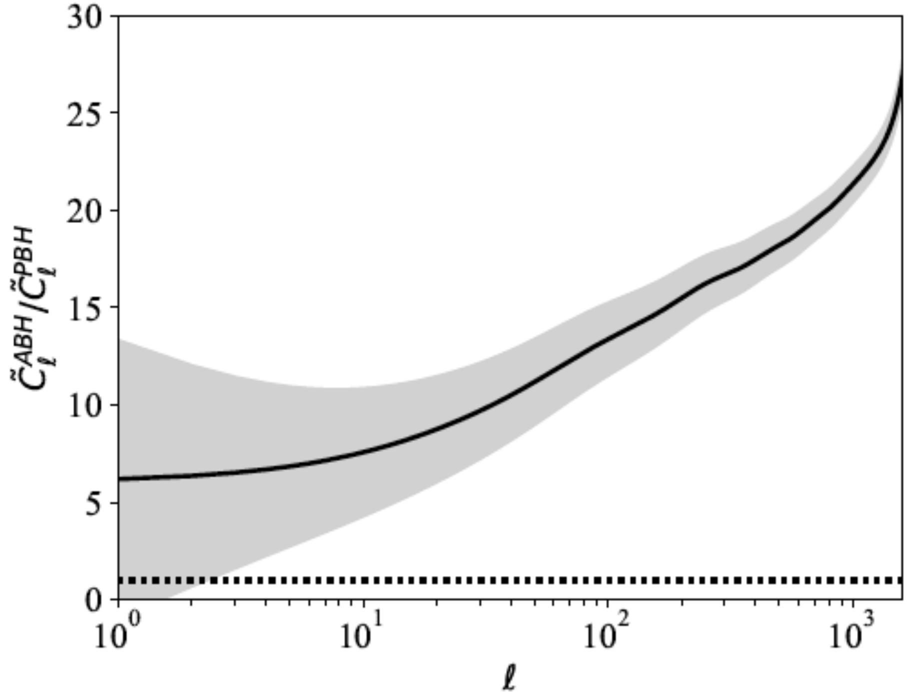
$$\widetilde{C}_\ell = C_\ell(\overline{\Omega}/4\pi)^{-2}$$

Angular power spectra of GWs from binary PBHs or binary ABHs

Sai Wang, Kazunori Kohri, Valeri Vardanyan, arXiv:2107.01935 [gr-qc]

$$\widetilde{C}_\ell = C_\ell(\bar{\Omega}/4\pi)^{-2}$$





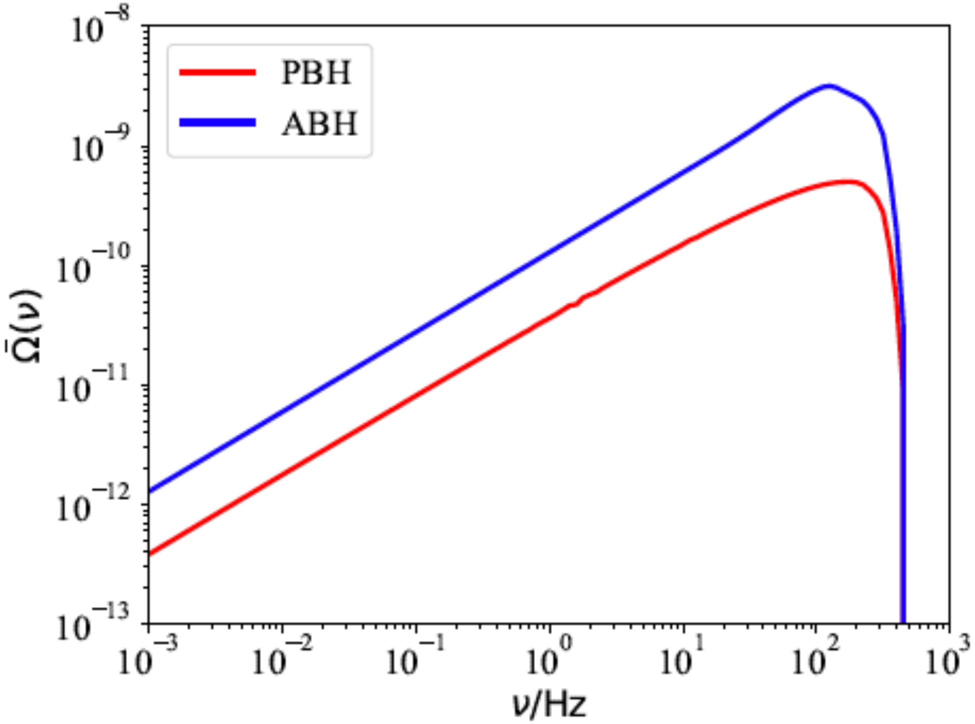
The reduced shot noise

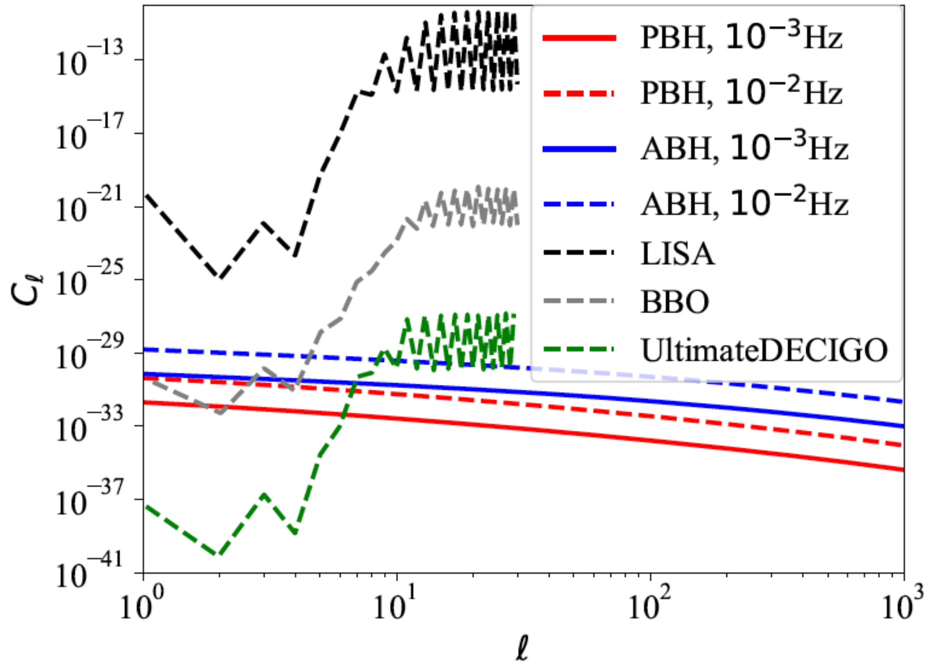
$$N_\ell \sim \frac{1}{(4\pi)^2}\frac{1}{\bar{n}t_0}\left(\frac{\nu\mathcal{A}_X}{\rho_c}\right)^2$$

$$\bar{\Omega} \sim t_0\nu\mathcal{A}_X/\rho_c, \text{ we obtain } \widetilde{N}_\ell \sim (t_0^3\bar{n})^{-1} \sim 10^{-8}.$$

Angular power spectra of GWs from binary PBHs or binary ABHs

Sai Wang, Kazunori Kohri, Valeri Vardanyan, arXiv:2107.01935 [gr-qc]





$$\nu = 10^{-2}\ \mathrm{Hz}$$

Primordial Black Holes (especially, M～ 10^{17}g – 10^{23}g) 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]

We need a seed BH at z>>7

- We do not know origins of Super-Massive Black Holes

$10^9\ M_\odot$ observed at z=7.642 (PBHs are excluded)

t(z=7.084) ~ 0.74Gyr

- We need seed (primordial) BHs before z >> 7 which had evolved to the SMBHs through accretions

$$\Omega_{\rm sBH}/\Omega_{\rm CDM} \sim 10^{-10} \left(\frac{n_{\rm seed,0}}{10^{-3}{\rm Mpc}^{-3}}\right)\left(\frac{M_{\rm BH,ini}}{10^2 M_\odot}\right)\left(\frac{M_{\rm SMBH}}{10^9 M_\odot}\right)\left(\frac{M_{\rm gal}}{10^{12} M_\odot}\right)^{-1}$$

- By EDGES' 21cm data, we can obtain upper bounds on accretion on to seed BHs and exclude the seed mass of SMBHs at z=17

$$\mathrm{M}_{\rm BH,ini} \gtrsim 10^2\ M_\odot \quad {\rm for} \quad n_{\rm seed}\ (z=0)/=10^{-3}{\rm Mpc}^{-3}$$

Number counts of SMBHs at z=0 (strong assumptions)

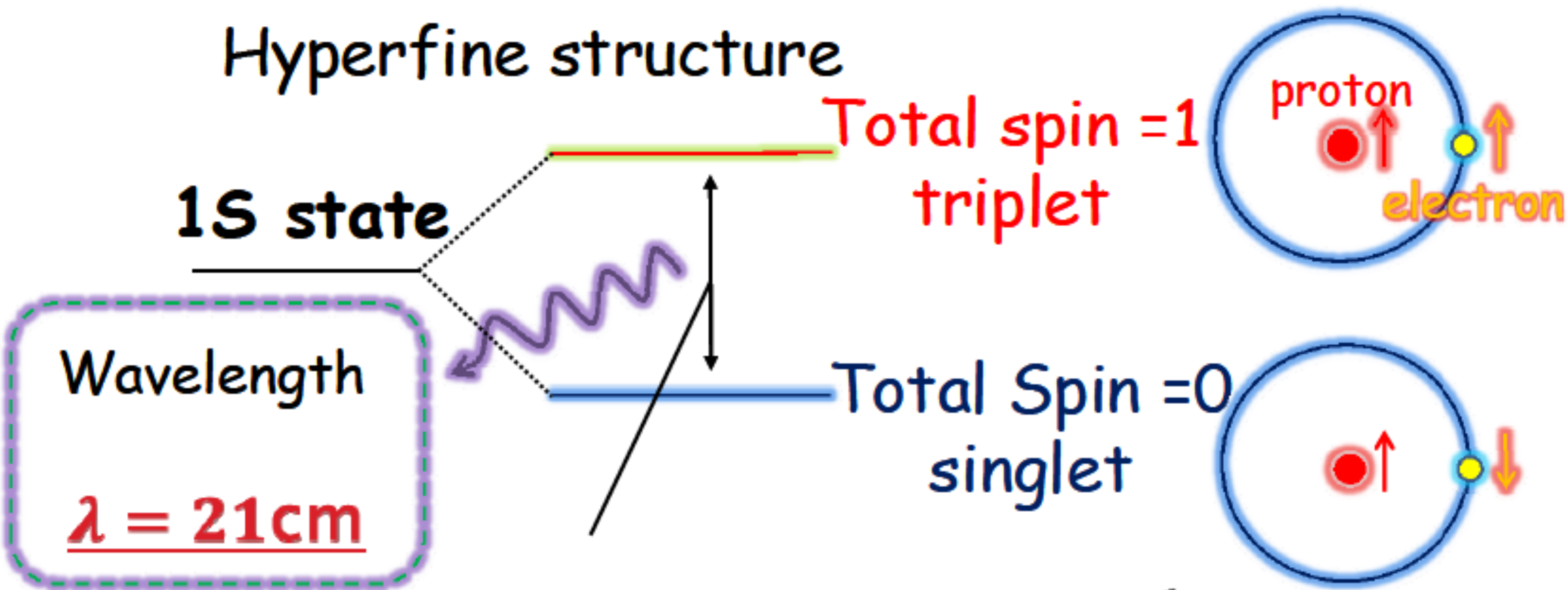
$$\mathrm{M}_{\rm BH,ini} \gtrsim 10^6\ M_\odot \quad {\rm for} \quad n_{\rm seed}\ (z=0)/=10^{-7}{\rm Mpc}^{-3}$$

Observations of SMBHs at z~6 (conservative)

t(z=6) ~ 0.96 Gyr

◇ 21cm line

◆proton-electron's spin-spin interaction



$$\Delta E = 2\pi\nu_{21} = 5.8 \times 10^{-6}\text{eV}$$

Spin temperature Ts

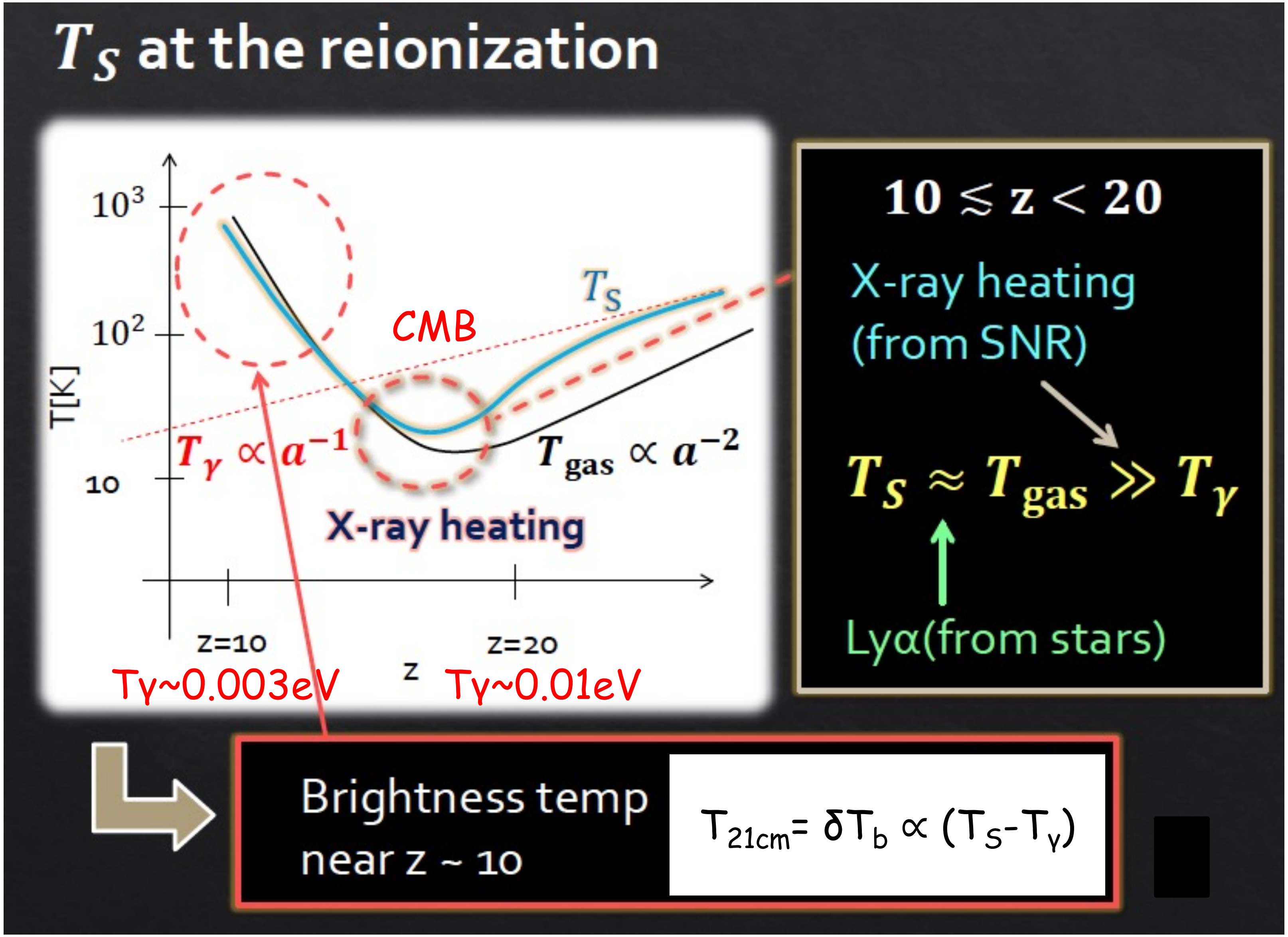
- Defined by the ratio of the occupation numbers in two states

$$\frac{n_{upper}}{n_{lower}} = \frac{g_{upper}}{g_{lower}} Exp\left[-\frac{\Delta E}{T_s}\right]$$

$$\Delta E = 2\pi\nu_{21} = 5.8 \times 10^{-6}\text{eV}$$

g_i = degree of reedom for a level "i"

Cosmological 21cm line around the reionization epoch



To obtain a conservative upper bound on accretions

- We assume the prediction of mean value of T_{21} in the ΛCDM model, not the one of the EDGES
- By adopting only the upper error of EDGES, we can exclude any heating sources such as accretions, not to exceed the mean value + EDGES's upper bound on T_{21}
- The recent claim by SARAS 3 does not change our results

Ionization fraction x_e and the gas temperature T_m

- Ionization fraction

$$\frac{dx_e}{dt} = -C\left[\alpha_{\rm H}(T_m)x_e^2 n_H - \beta_{\rm H}(T_\gamma)(1-x_e)e^{-E_\alpha/T_\gamma}\right] + \frac{dE_{\rm inj}}{dV\,dt}\frac{1}{n_{\rm H}}\left[\frac{f_{\rm ion}(t)}{E_0} + \frac{(1-C)f_{\rm exc}(t)}{E_\alpha}\right],$$

$$C = \frac{\Lambda n_{\rm H}(1-x_e) + \frac{1}{2\pi^2}E_\alpha^3 H(t)}{\Lambda n_{\rm H}(1-x_e) + \frac{1}{2\pi^2}E_\alpha^3 H(t) + \beta_H n_H(1-x_e)};$$

- Gas temperature

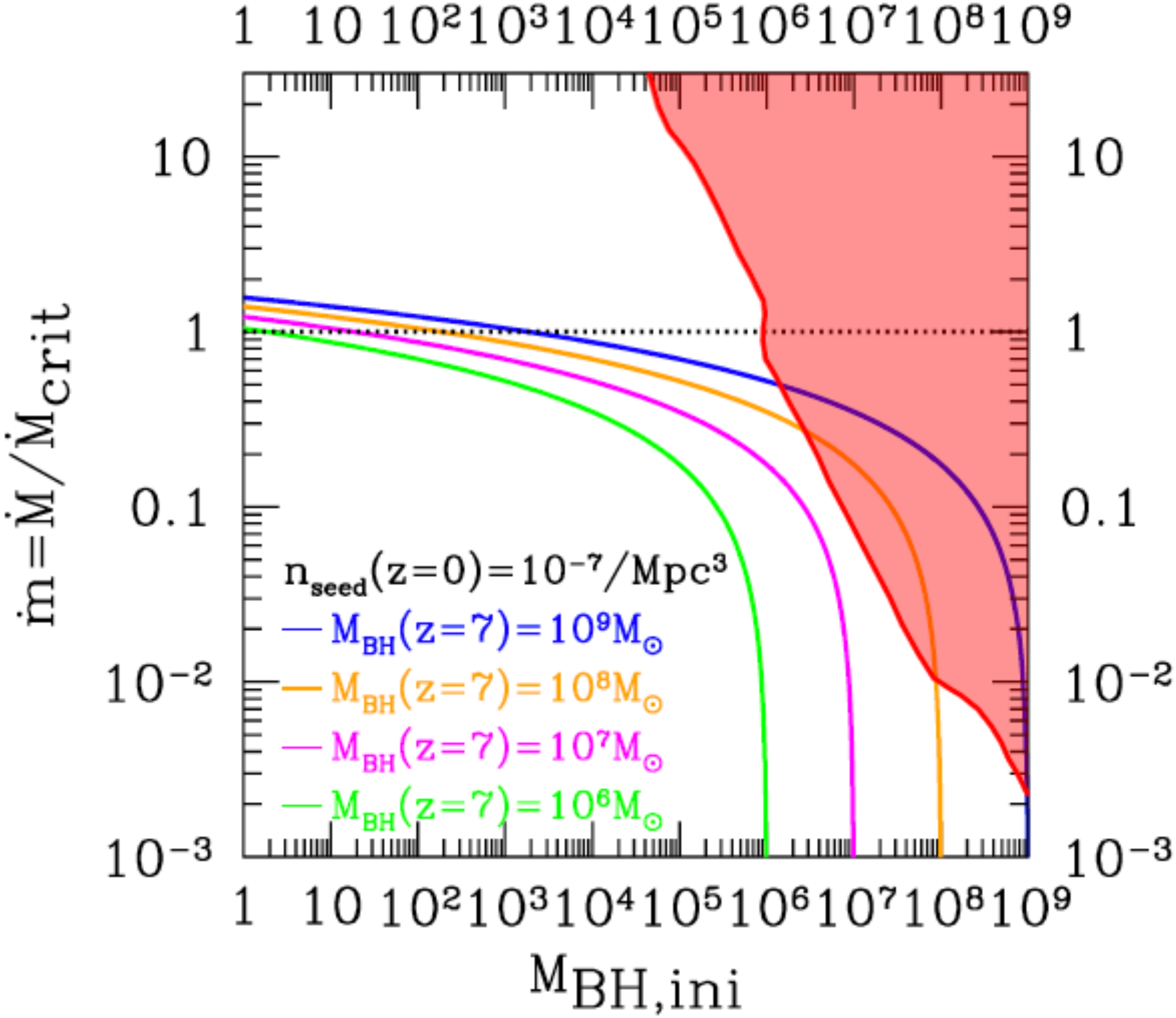
$$\frac{dT_m}{dt} = -2H(t)T_m + \Gamma_C(T_\gamma - T_m) + \frac{dE_{\rm inj}}{dV\,dt}\frac{1}{n_{\rm H}}\frac{2f_{\rm heat}(z)}{3(1+x_e+f_{\rm He})}$$

$$T_{21{\rm cm}}(z) = \frac{T_s(z)-T_\gamma(z)}{1+z}\tau_{21{\rm cm}}(z)$$

$$\Gamma_C = \frac{8\sigma_T a_r T_\gamma^4}{3m_e}\frac{x_e}{1+f_{\rm He}+x_e}$$

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]



Renormalization group equations in Higgs-R² Inflation

Yohei Ema, arXiv:1907.00993 [hep-ph]
Dhong Yeon Cheong, Kazunori Kohri, Seong Chan Park, arXiv:2205.14813 [hep-ph]

$A^{(ii\to jj)}_{\text{1-loop}} =$

the scalar loop to the graviton vacuum polarization

- Renormalization group

$$\beta(g) = \mu \frac{\partial g}{\partial \mu}$$

$$\alpha = M_P^2/12M^2$$

$$\beta_\alpha = -\frac{1}{16\pi^2}\frac{(1+6\xi)^2}{18},$$

$$\beta_\xi = -\frac{1}{16\pi^2}\left(\xi+\frac{1}{6}\right)\left(12\lambda+6y_t^2-\frac{3}{2}g'^2-\frac{9}{2}g^2\right)$$

$$\beta_\lambda = \beta_{\text{SM}} + \frac{1}{16\pi^2}\frac{2\xi^2(1+6\xi)^2 M^4}{M_P^4},$$

$$\lambda(\mu)|_{\mu=h} = \lambda_m + \frac{\beta_2^{\text{SM}}}{(16\pi^2)^2}\ln^2\left(\sqrt{\frac{h^2}{h_m^2}}\right) = \lambda_m + b\ln^2\left(\sqrt{\frac{h^2}{h_m^2}}\right)$$

$$\beta_2^{\text{SM}} \approx 0.5, \quad \mu_m = h_m \sim 10^{17} - 10^{18}\ \text{GeV}$$

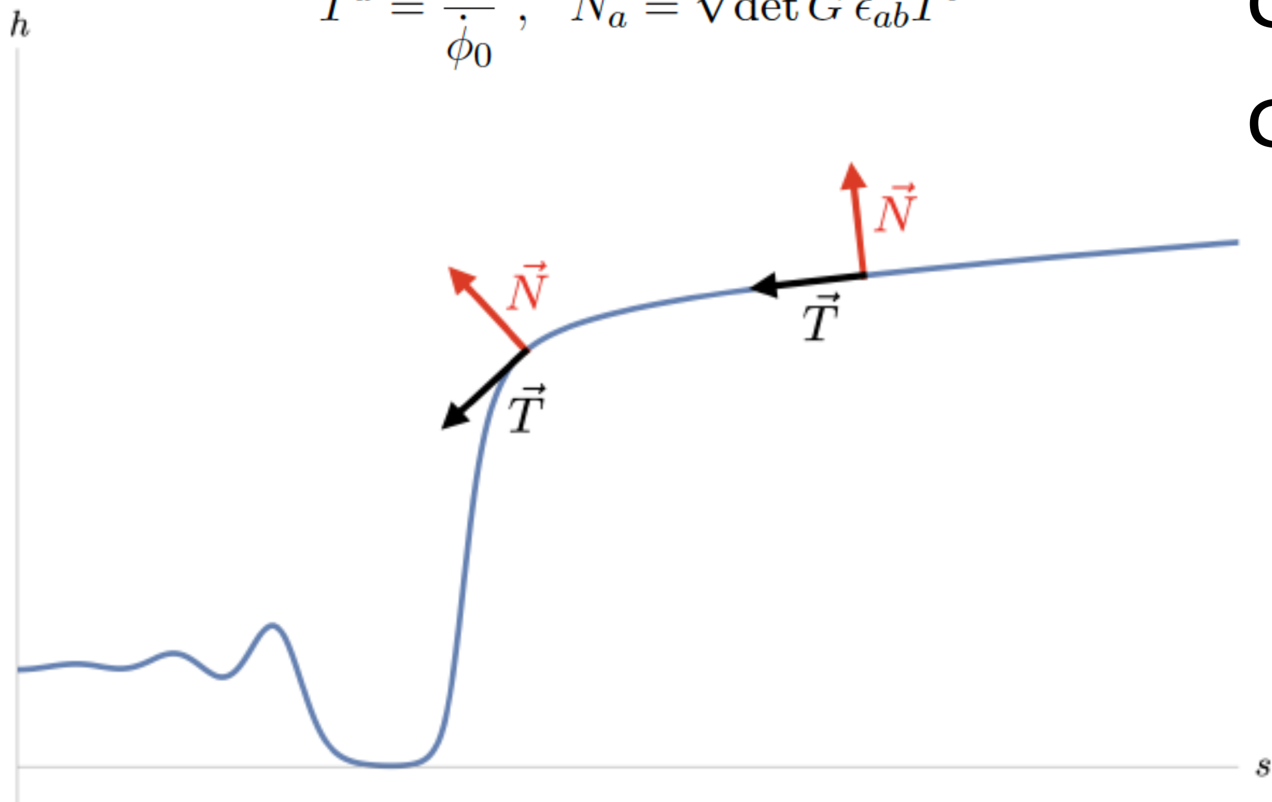
Adiabatic and is isocurvature perturbations in Higgs-R^2 Inflation

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

$$\phi^a(t,\vec{x}) = \phi_0^a(t) + \delta\phi^a(t,\vec{x}),$$

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

- Mukhanov-Sasaki variable

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

- Curvature and isocurvature perturbations

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

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

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

$$v_N = aN_a\delta\phi^a \equiv aN_aQ^a$$

Tachyonic Instability induced in Higgs-R^2 Inflation

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

$$\epsilon \equiv -\frac{\dot{H}}{H^2} = \frac{\dot{\phi}_0^2}{2H^2}\,, \quad \eta^a \equiv -\frac{1}{H\dot{\phi}_0} D_t \dot{\phi}^a.$$

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

$$\eta^a = \eta_{\|} T^a + \eta_{\perp} N^a$$

$$\eta_{\|} \equiv -\frac{\ddot{\phi}_0}{H\dot{\phi}_0}\,, \quad \eta_{\perp} \equiv \frac{U_N}{\dot{\phi}_0 H}$$

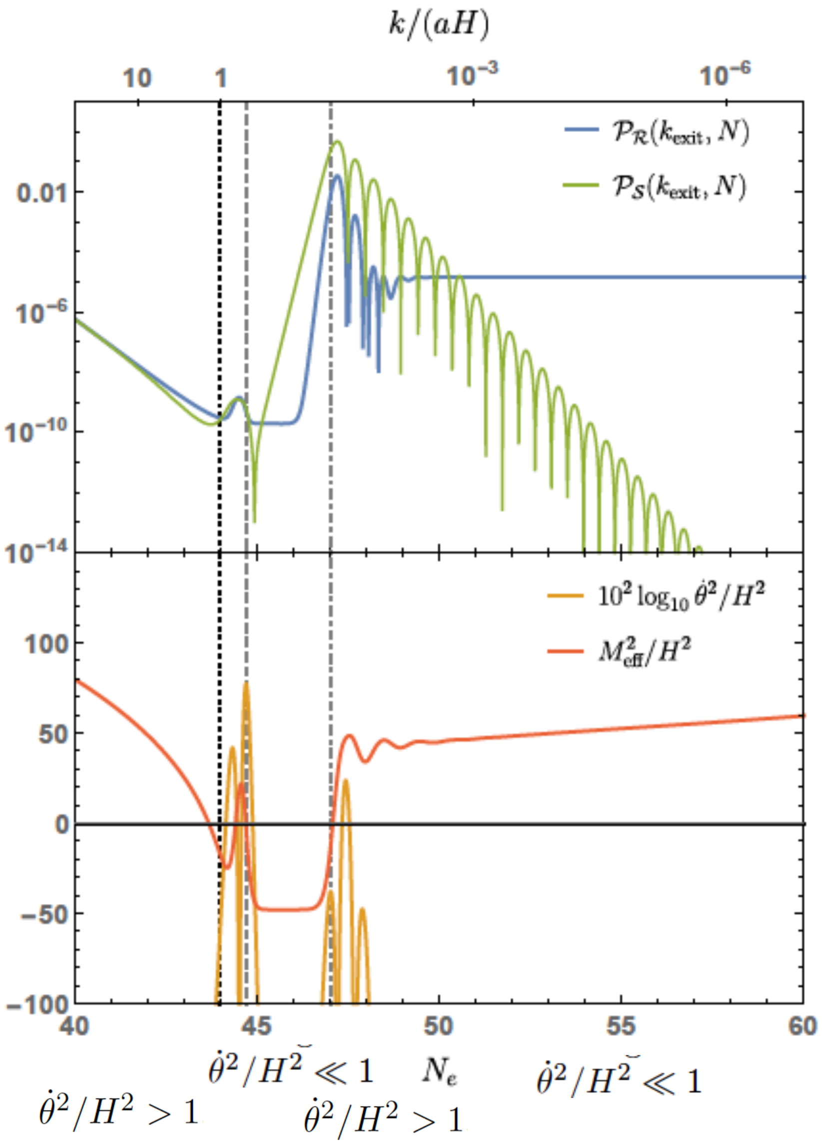
$$\ddot{Q}_N + 3H\dot{Q}_N + \left(\frac{k^2}{a^2} + M_{\rm eff}^2\right) Q_N = 2\dot{\phi}_0 \eta_{\perp} \dot{\mathcal{R}}$$

$$M_{\rm eff}^2 = U_{NN} + H^2 \epsilon \mathbb{R} - \dot{\theta}^2 \qquad \dot{\theta} \equiv H\eta_{\perp}$$

$$U_{NN} < 0,$$ during the tachyonic phase

Adiabatic and icocurvature modes in Higgs-R^2 Inflation

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

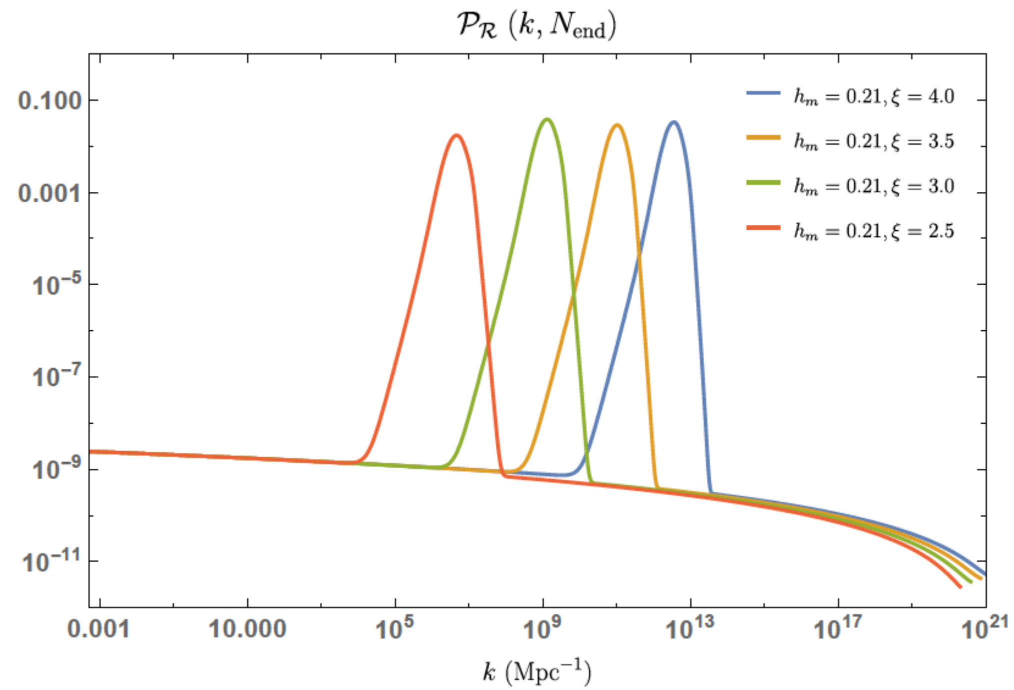


$$\mathcal{P}_{\mathcal{S}}(k_{\rm exit}, N_e) = \frac{k_{\rm exit}^3}{2\pi^2} \frac{H^2}{\dot{\phi}_0^2} \langle Q_{N,k}, Q_{N,k} \rangle$$

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

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

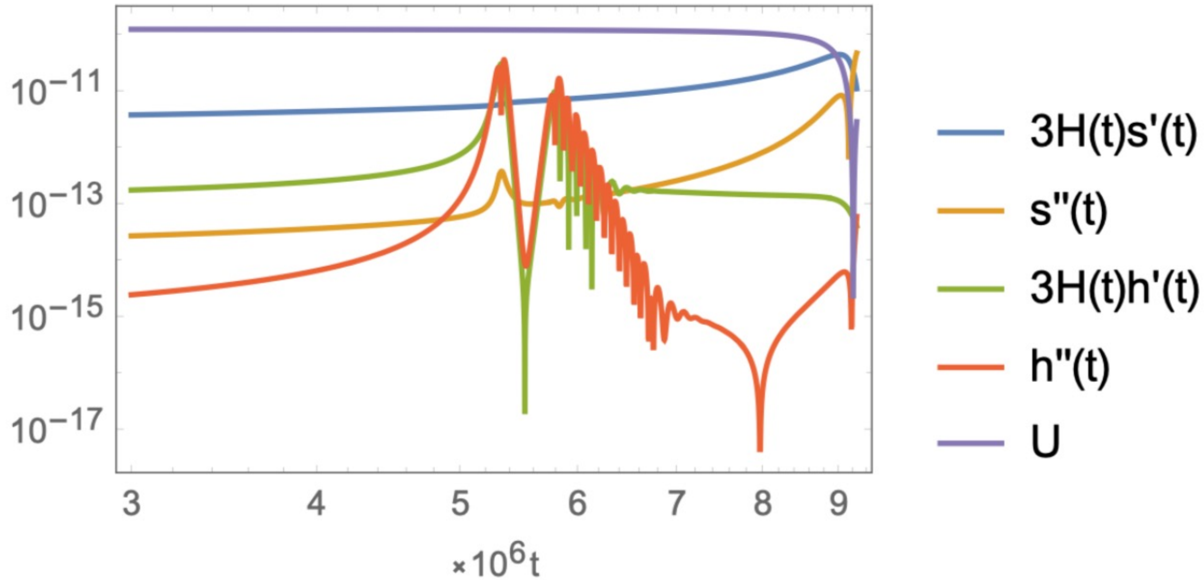
Dhong Yeon Cheong, Kazunori Kohri, Seong Chan Park, arXiv:2205.14813 [hep-ph]

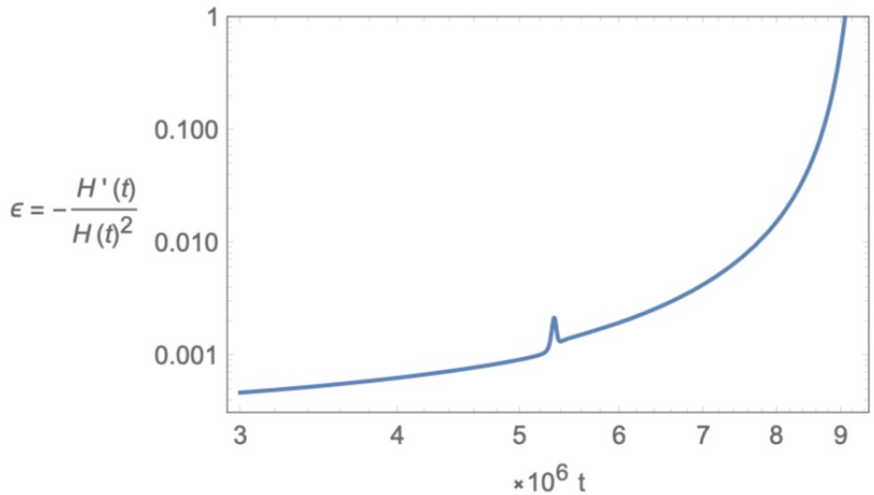


Set	$M(M_P)$	ξ	$\lambda_m(\times 10^{-6})$	β_2	$h_m\,(M_P)$	$k_{max}\,(\mathrm{Mpc}^{-1})$	$\mathcal{P}_{\mathcal{R},max}$
1	1.3×10^{-5}	4.0	4.1929792	0.5	0.21	3.6×10^{12}	0.033
2	1.3×10^{-5}	3.5	4.1209657	0.5	0.21	1.0×10^{11}	0.029
3	1.3×10^{-5}	3.0	4.0340269	0.5	0.21	1.1×10^{9}	0.036
4	1.3×10^{-5}	2.5	3.926196	0.5	0.21	4.5×10^{6}	0.02

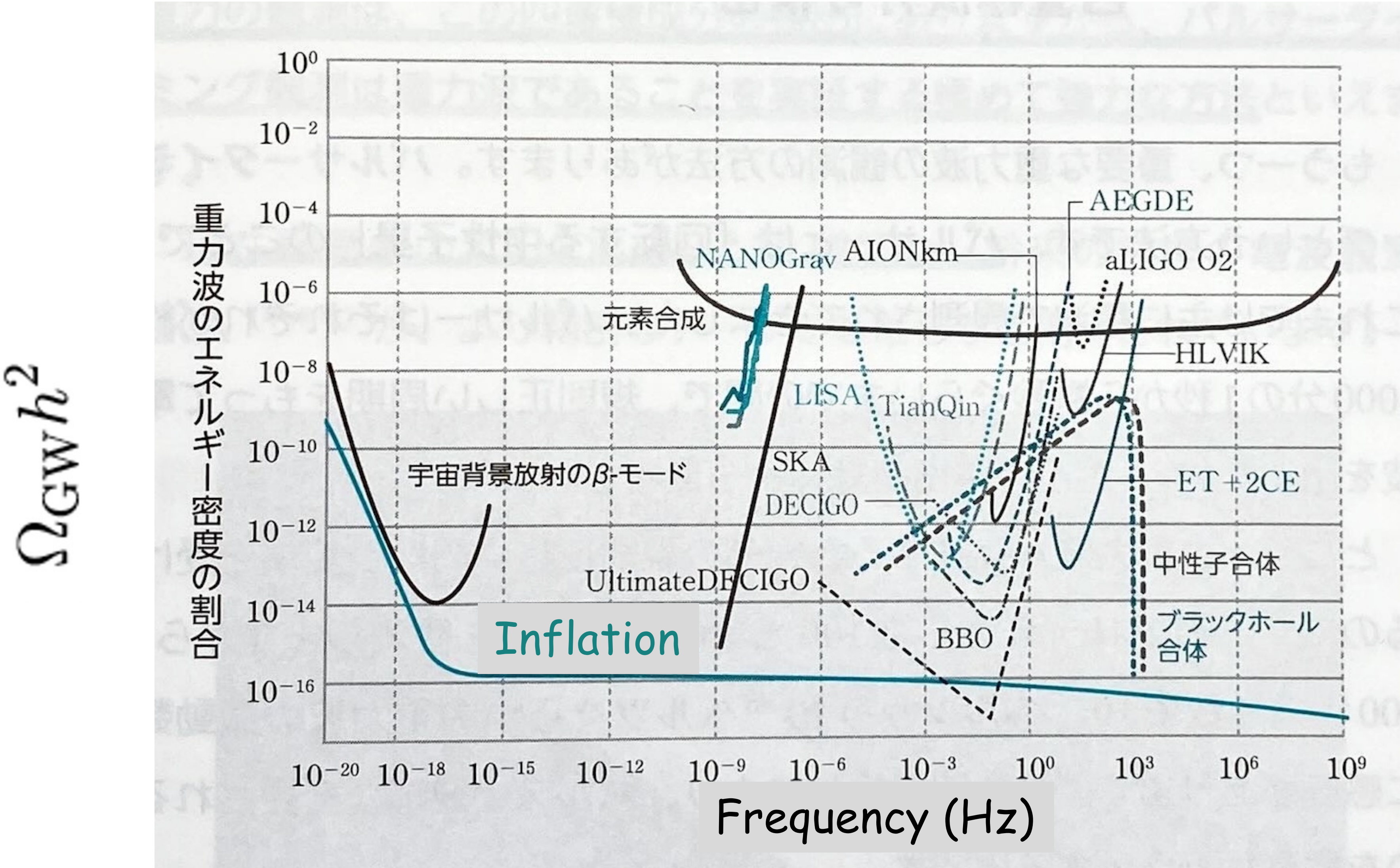
Velocities of s and h are small

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





The primordial GW of inflationary origin

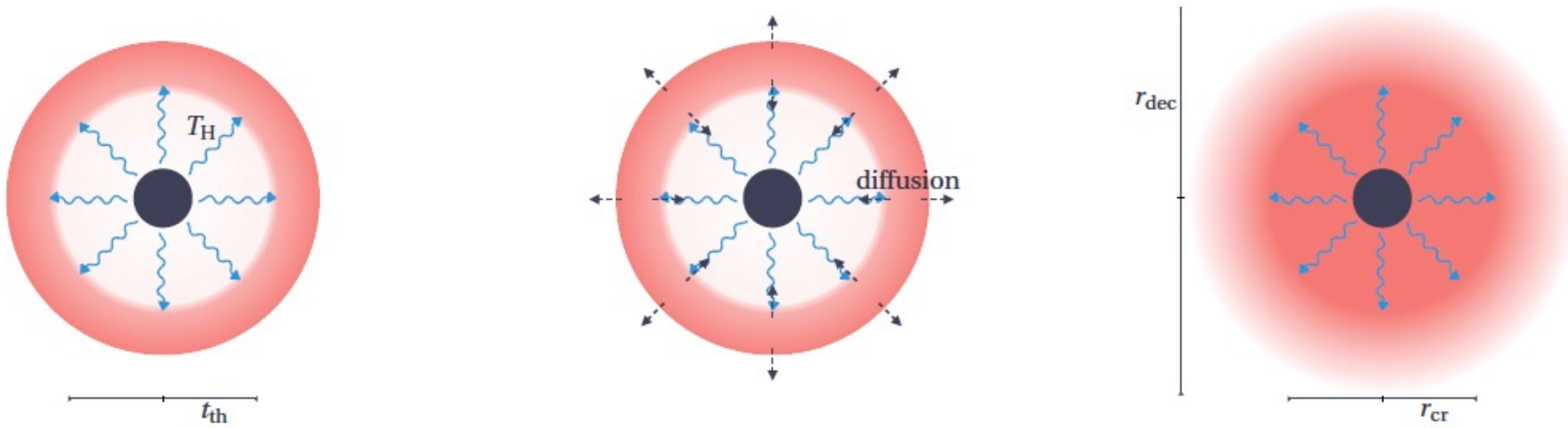


Kazunori Kohri, “Neutrinos and Gravitational Waves …” 2021, Beret Publishing

Possible baryogenesis by recovery of the sphaleron effect at hot spots around evaporating PBHs?

Minxi He, Kazunori Kohri, Kyohei Mukaida, Masaki Yamada, arXiv:2210.06238 [hep-ph]

- Hot spots were produced around PBHs



$$\Gamma_{\mathrm{Bethe}} \sim \alpha^2 T$$

$$\Gamma_{\mathrm{LPM}} \sim \alpha^2 T \sqrt{\frac{E}{k}}$$

$$\Gamma_{\mathrm{dittuse}} \sim \alpha^2 \frac{T^2 M_{\mathrm{BH}}}{m_{\mathrm{pl}}}$$

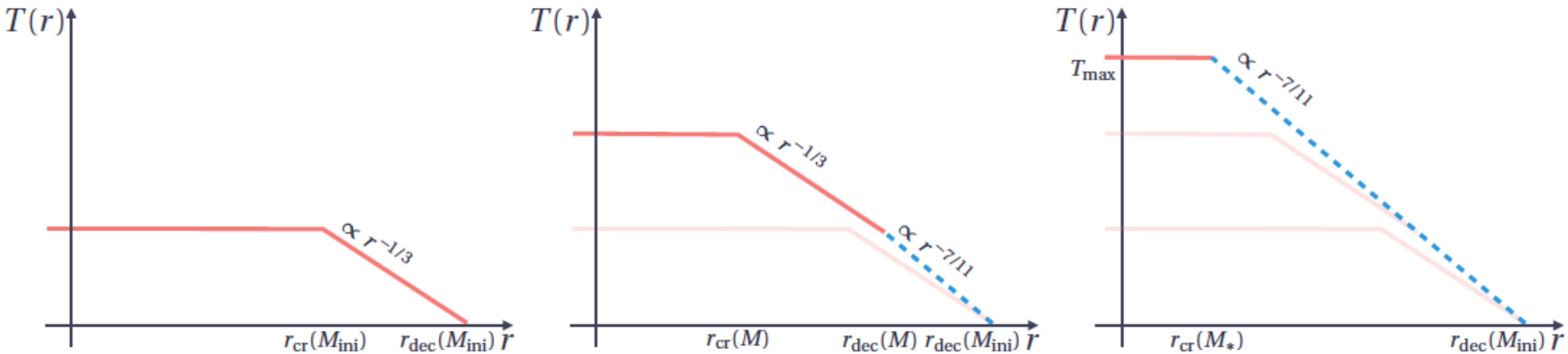
$$\Gamma_{\mathrm{evap}} \sim \frac{m_{\mathrm{pl}}^4}{M_{\mathrm{BH}}^3}$$

$$\Gamma_{\mathrm{evap}} \gg \Gamma_{\mathrm{diffuse}}$$

Possible baryogenesis by recovery of the sphaleron effect at hot spots around evaporating PBHs?

Minxi He, Kazunori Kohri, Kyohei Mukaida, Masaki Yamada, arXiv:2210.06238 [hep-ph]

- Temperature profile which exceeds the weak scale > 100 GeV



Possible baryogenesis by recovery of the sphaleron effect at hot spots around evaporating PBHs?

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- Maximum temperature

$$T_{\rm max} \equiv T(r < r_{\rm cr})|_{M_*} \simeq 0.02\, \alpha^{19/3} g_*^{-4/3} g_{H*}^{5/6}\, M_{\rm pl}\,,$$
$$\simeq 2 \times 10^9\,{\rm GeV} \left(\frac{\alpha}{0.1}\right)^{\frac{19}{3}} \left(\frac{g_*}{106.75}\right)^{-\frac{4}{3}} \left(\frac{g_{H*}}{108}\right)^{\frac{5}{6}}$$

GUT monopole cannot be produced!

- Volume fraction to realize T > 100 GeV

$$f_{\rm sph}(T_{\rm sph}) \sim 0.13\,{\rm Min}\left[1, \beta \frac{T_{\rm ini}}{T_{\rm ev}}\right] \left(\frac{\alpha}{0.1}\right)^{\frac{6}{7}} \left(\frac{g_*}{106.75}\right)^{-\frac{9}{7}} \left(\frac{g_{H*}}{108}\right)^{\frac{17}{7}} \left(\frac{M_{\rm ini}}{10^{5.5}\,{\rm g}}\right)^{-7}$$

Electroweak Sphaleron is locally revived, which can convert lepton # to baryon # even at a late Universe!

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
José Ramón Espinosa, Davide Racco, Antonio Riotto, 2018
Kohri 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

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