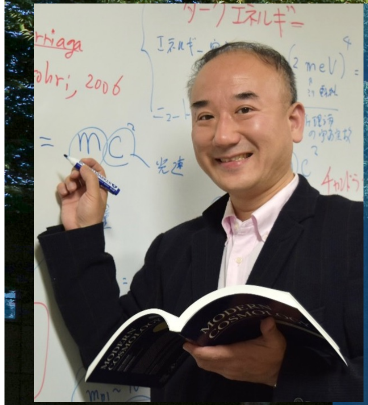
初代星・初代銀河研究会2023

高赤方偏移21cm線観測で迫る宇宙論の謎

―超巨大ブラックホールの起源・ニュートリノ質量・ダークマターの正体・小スケール密度ゆらぎ―



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Contents

1. NANOGrav15yr and Stochastic GWs

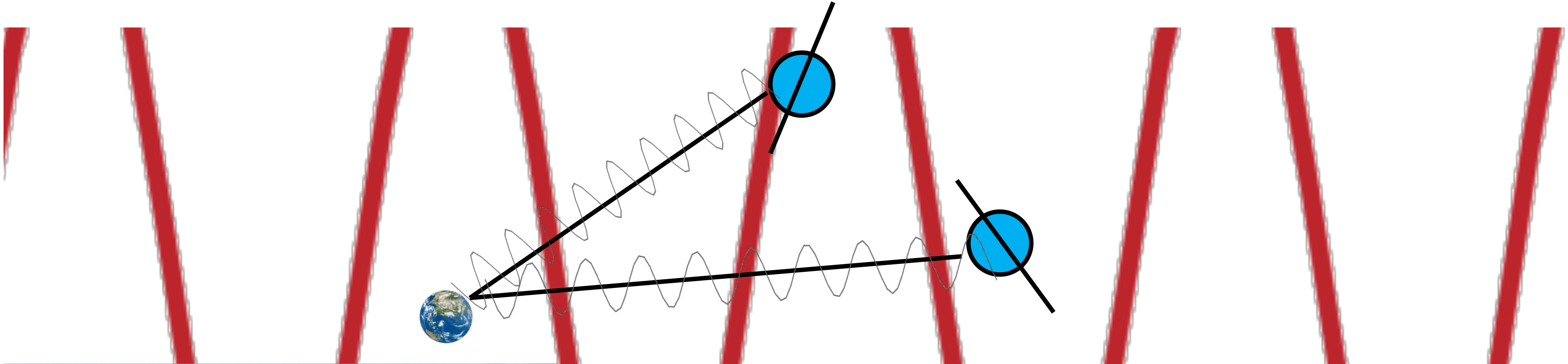
2. Cosmological 21cm and SMBHs, Neutrino mass, dark matter, density fluctuation

Gabriella Agazie, et al, The NANOGrav15yr collaboration, arXiv:2306.16213 [astro-ph.HE]

NANOGrav 15yr

(North American Nanohertz Observatory for Gravitational Waves)

found stochastic GWs through pulsar timing



The 305-meter dish of the William E. Gordon Telescope, The Arecibo Obs.

The 100-meter Green Bank Telescope

NANOGrav15yrの インフレーション/ダークマターへの示唆

Keisuke Inomata, Kazunori Kohri, Takahiro Terada, arXiv:2306.17834 [astro-ph.CO]

- 宇宙論的な非線形2次重力波の可能性

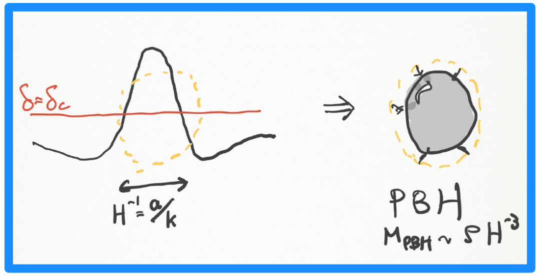
$\Omega_{GW} \sim 10^{-8} \propto \delta^2$ at $f \sim 10^{-8}$ Hz

他に、Inflationの大スケールゆらぎが作るモデル(S. Vagnozzi, arXiv:2306.16912)
cosmic string (J. Ellis etal, arXiv:2306.17147)
domain wall (Kitajima etal, 2306.17146)
phase transition (Fujikura etal, arXiv:2306.17086)
…

- 小スケールの大きな密度ゆらぎ$\langle\delta^2\rangle$を示唆

$\langle\delta^2\rangle \sim O(0.01) \gg 10^{-9}$ at $k \sim 10^{7}$ Mpc^{-1}

- 同じゆらぎは同時に原始ブラックホールを作る



$M_{PBH} \sim O(10^{-5})\, M_{\odot}$

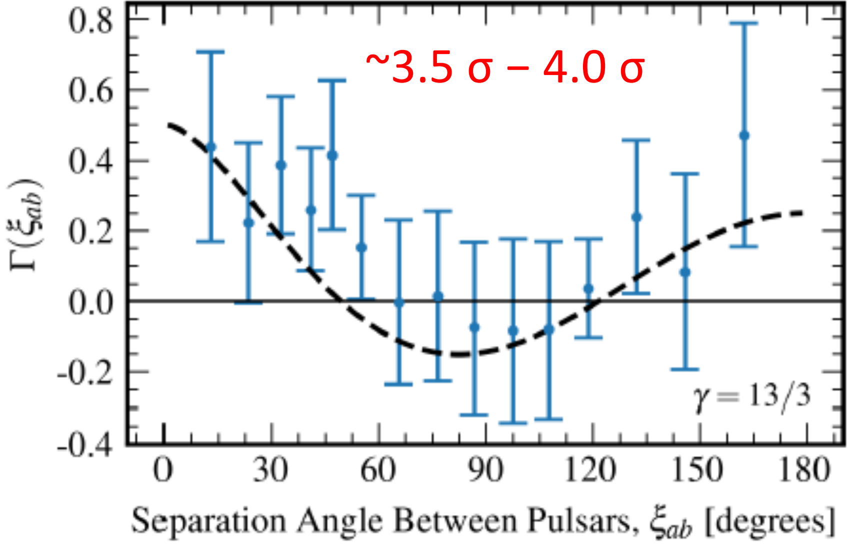
$f_{PBH} = \Omega_{PBH}/\Omega_{CDM} \sim O(0.01)$

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

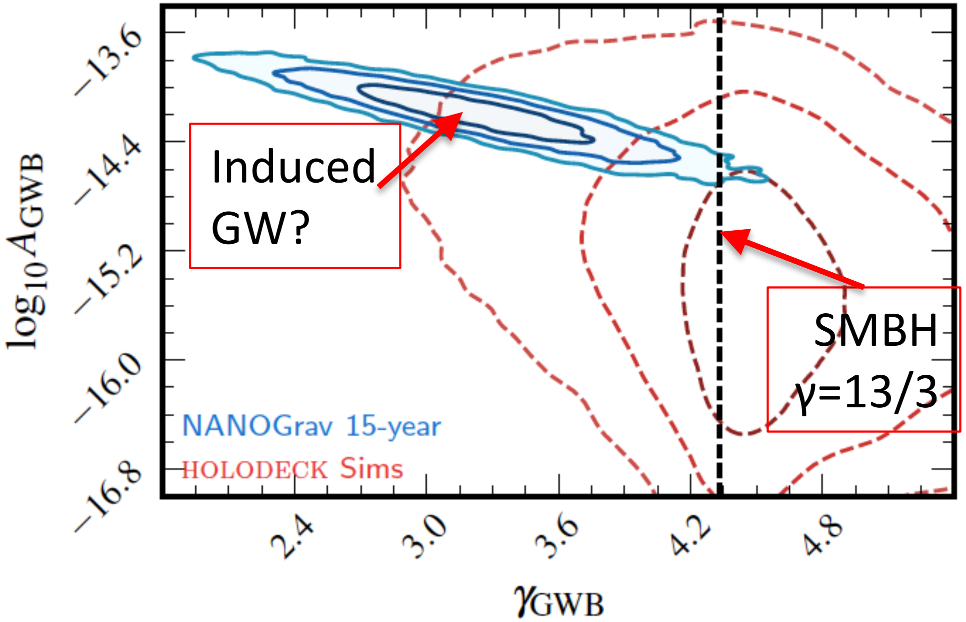
The NANOGrav 15-year Data Set: Evidence for a Gravitational-Wave Background

Gabriella Agazie, et al, The NANOGrav15yr collaboration, arXiv:2306.16213 [astro-ph.HE]

Hellings-Downs Curve



~3.5 σ – 4.0 σ



Induced GW?

SMBH
γ=13/3

$$h_c(f) = A_{\rm GWB}\left(\frac{f}{f_{\rm yr}}\right)^{\alpha}$$

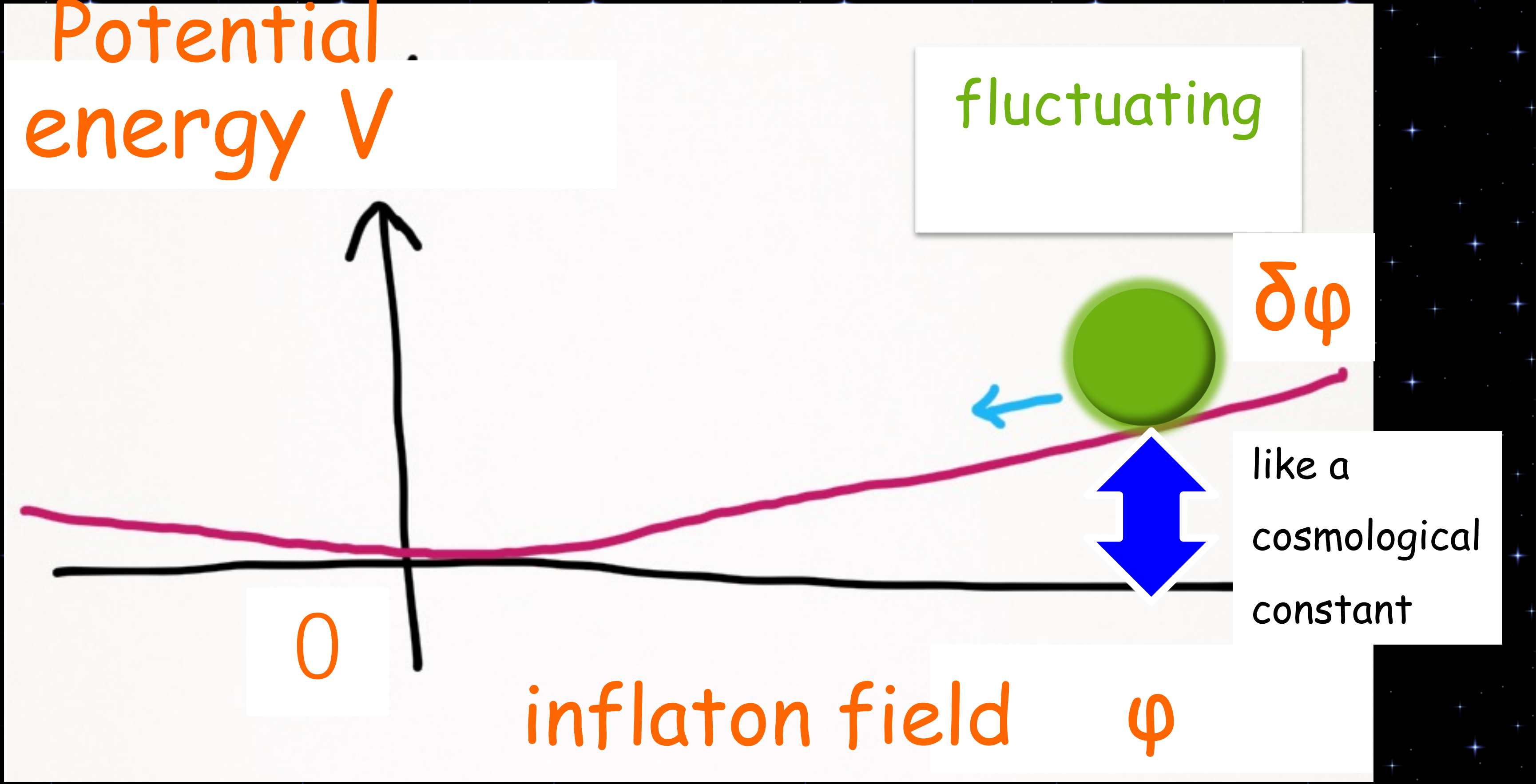
$$S_{ab}(f) = \Gamma_{ab}\,\frac{A_{\rm GWB}{}^2}{12\pi^2}\left(\frac{f}{f_{\rm yr}}\right)^{-\gamma} f_{\rm yr}^{-3}$$

$$\Omega(f) = \frac{2\pi}{3H_0^2} f^2 h_c(f)^2 = \Omega_{yr}\left(\frac{f}{f_{yr}}\right)^{\beta}$$

$\gamma = 3 - 2\alpha = 5 - \beta$

$\beta = 5 - \gamma\ (\sim 2)$

Inflation created quantum fluctuation



Potential energy V

fluctuating

$\delta\varphi$

like a cosmological constant

0

inflaton field φ

Accelerated expansion

quantum → classical

$P_\zeta \sim \delta^2$

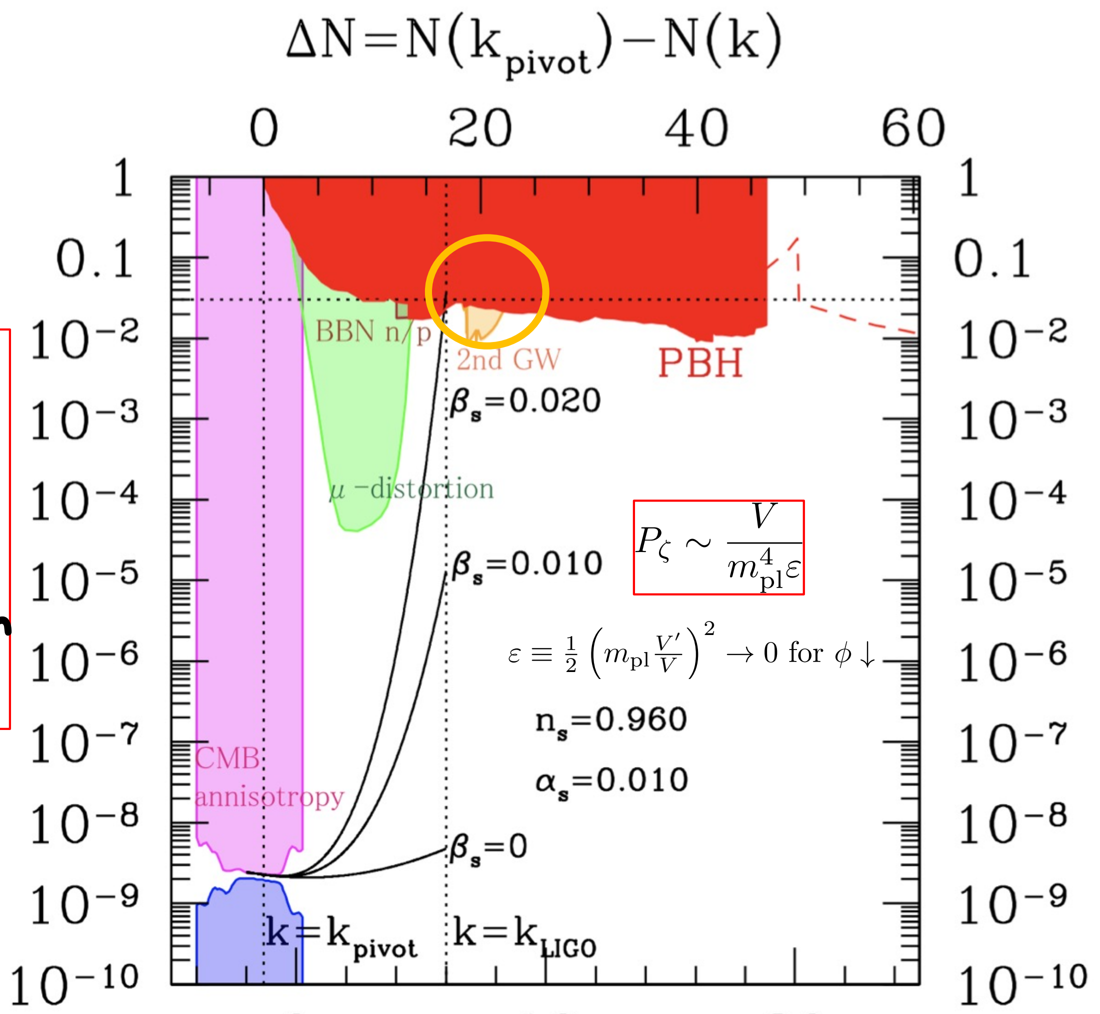
Curvature perturbation $P_\zeta(k)$

The δ-function like form

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

Amplitude of curvature perturbation

$P_\zeta \sim \langle\delta\rangle^2$



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

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

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

Secondary gravitational wave induced (IGW) from large curvature perturbation ($P_\zeta >> r$) 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

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

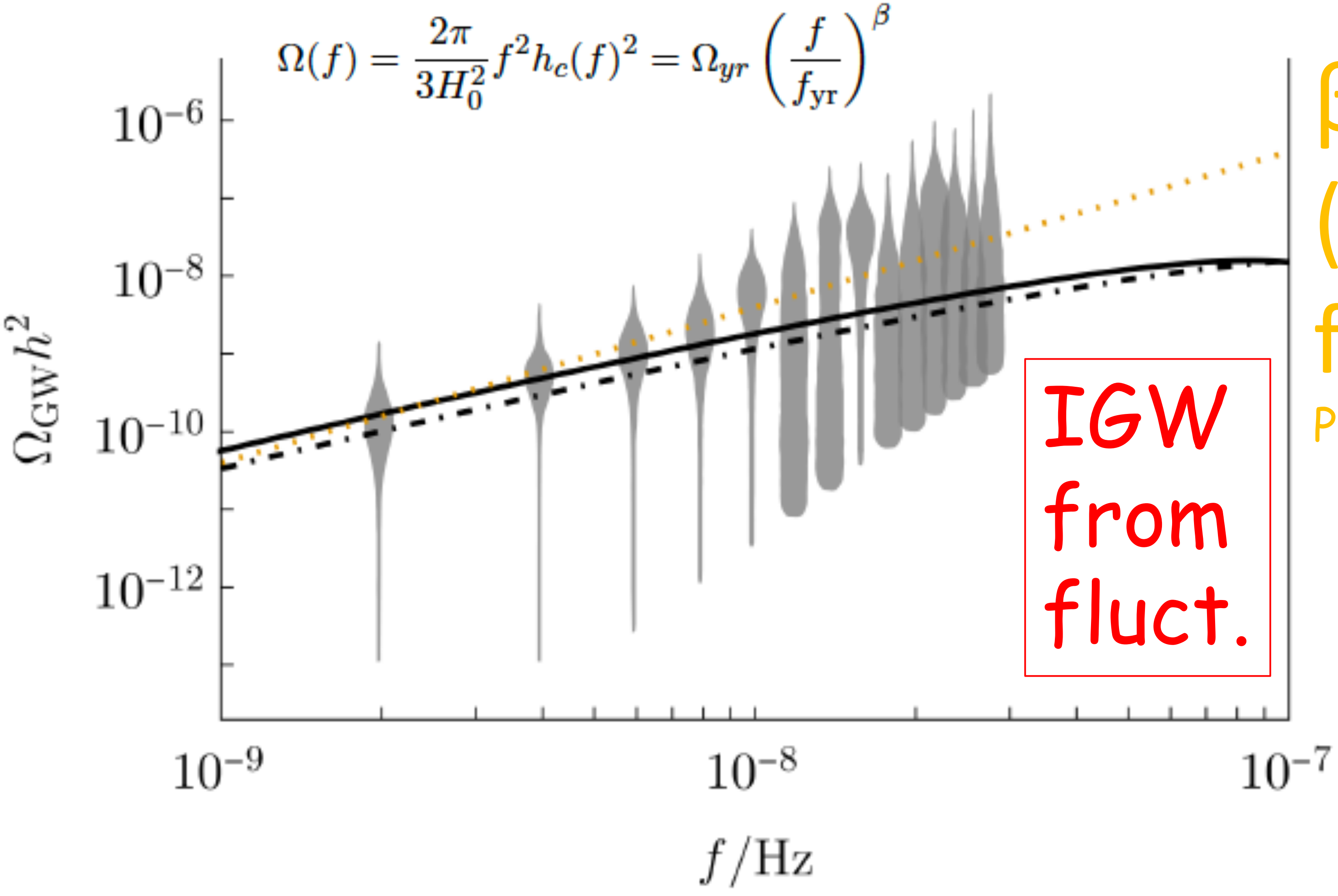
- Substituting the solution into this

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

$P_\zeta \sim \delta^2$

NANOGrav15yr by Induced GW and sub-solar PBHs

Keisuke Inomata, Kazunori Kohri, Takahiro Terada, arXiv:2306.17834 [astro-ph.CO]



$$\Omega(f) = \frac{2\pi}{3H_0^2} f^2 h_c(f)^2 = \Omega_{yr}\left(\frac{f}{f_{\rm yr}}\right)^{\beta}$$

β=2

(γ=3)

for

P_ζ~δ func.

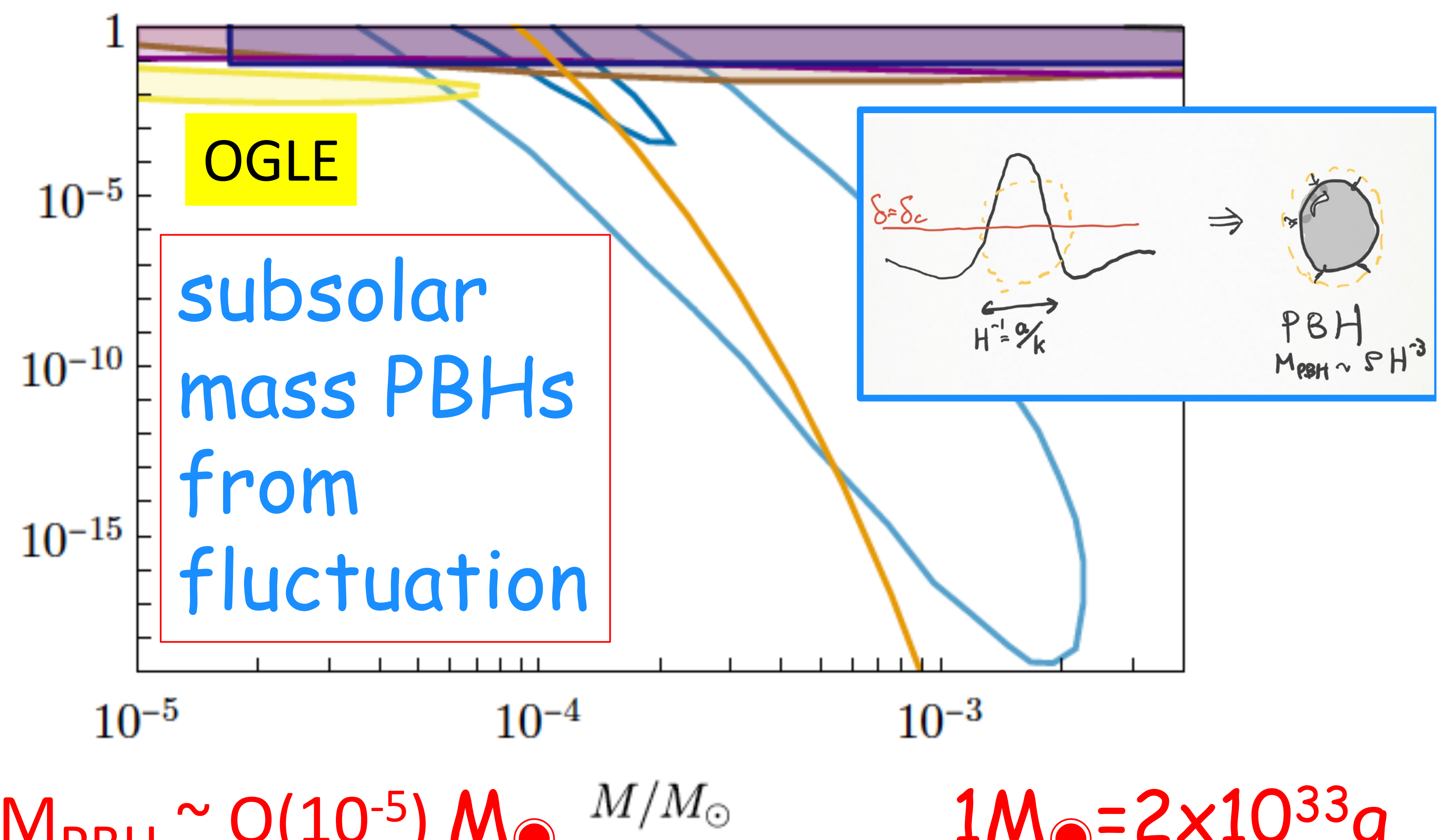
IGW from fluct.

NANOGrav15yr by Induced GW and sub-solar PBHs

Keisuke Inomata, Kazunori Kohri, Takahiro Terada, arXiv:2306.17834 [astro-ph.CO]

$f_{PBH} = \Omega_{PBH}/\Omega_{CDM} \sim O(0.01) \text{ -- } O(0.1)$

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



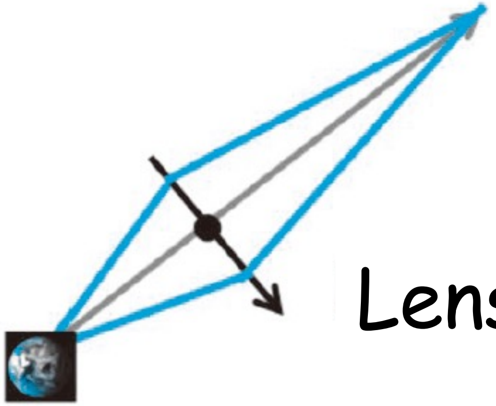
OGLE

subsolar mass PBHs from fluctuation

$M_{PBH} \sim O(10^{-5})\ M_\odot$

$1 M_\odot = 2 \times 10^{33} g$

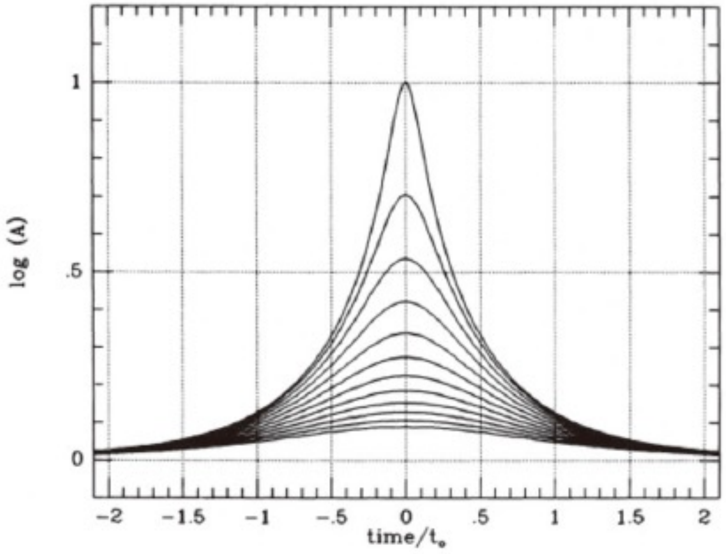
Gravitational Lensing



Source

Lens (PBH)

Observers



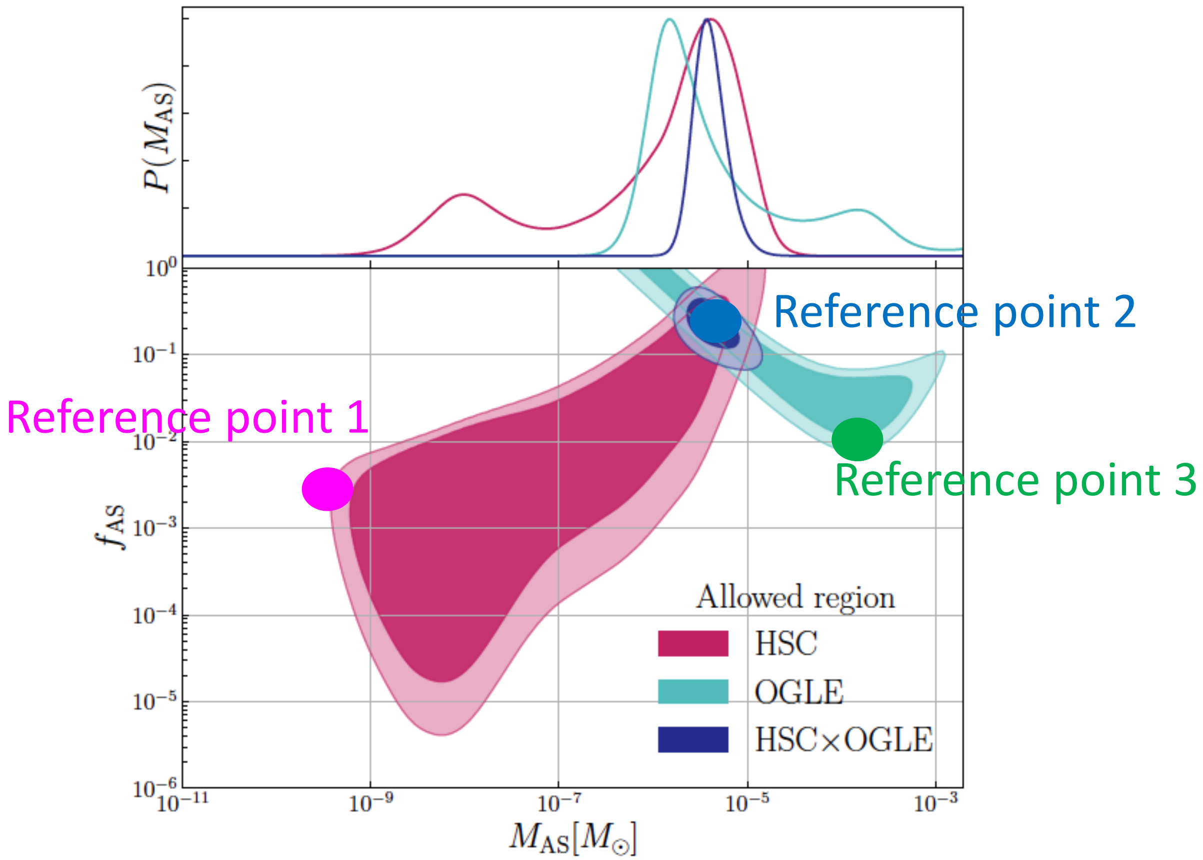
Hiroko Niikura, https://stg.asj.or.jp/jp/activities/geppou/item/113-1_6.pdf

HSC x OGLE events

Sunao Sugiyama, Masahiro Takada, Alexander Kusenko, arXiv:2108.03063 [hep-ph]

Hiroko Niikura, Masahiro Takada, Shuichiro Yokoyama, Takahiro Sumi, Shogo Masaki, arXiv:1901.07120 [astro-ph.CO]

Masahiro Takada, Naoki Yasuda, Robert H. Lupton, Takahiro Sumi, Surhud More, Toshiki Kurita, Sunao Sugiyama, Anupreeta More, Masamune Oguri, Masashi Chiba, arXiv:1701.02151 [astro-ph.CO]



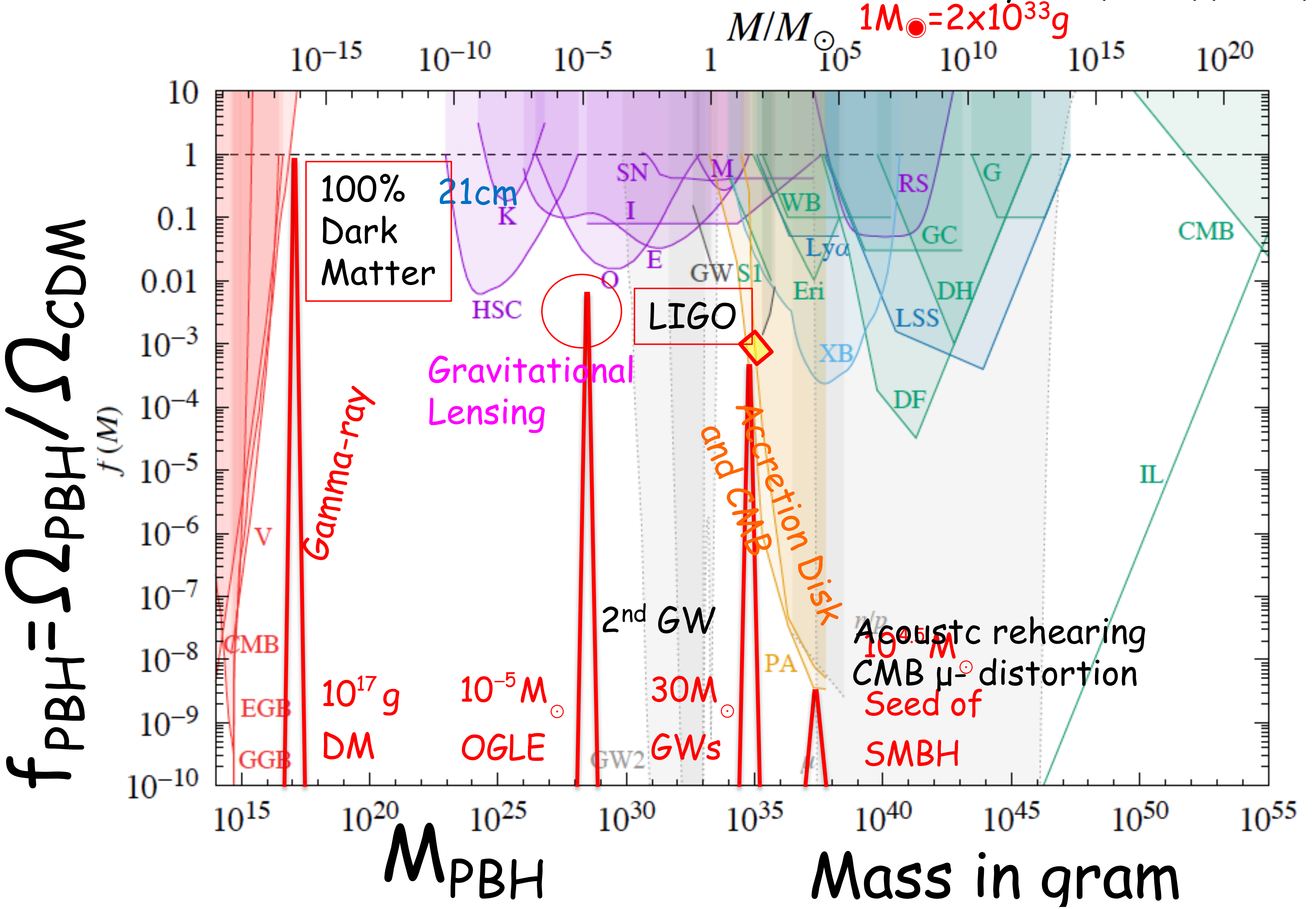
Reference point 1

Reference point 2

Reference point 3

Upper bounds on the fraction to CDM

Carr, Kohri, Sendouda, J.Yokoyama (2009)(2020)



NANOGrav15yr by Induced GW and sub-solar PBHs

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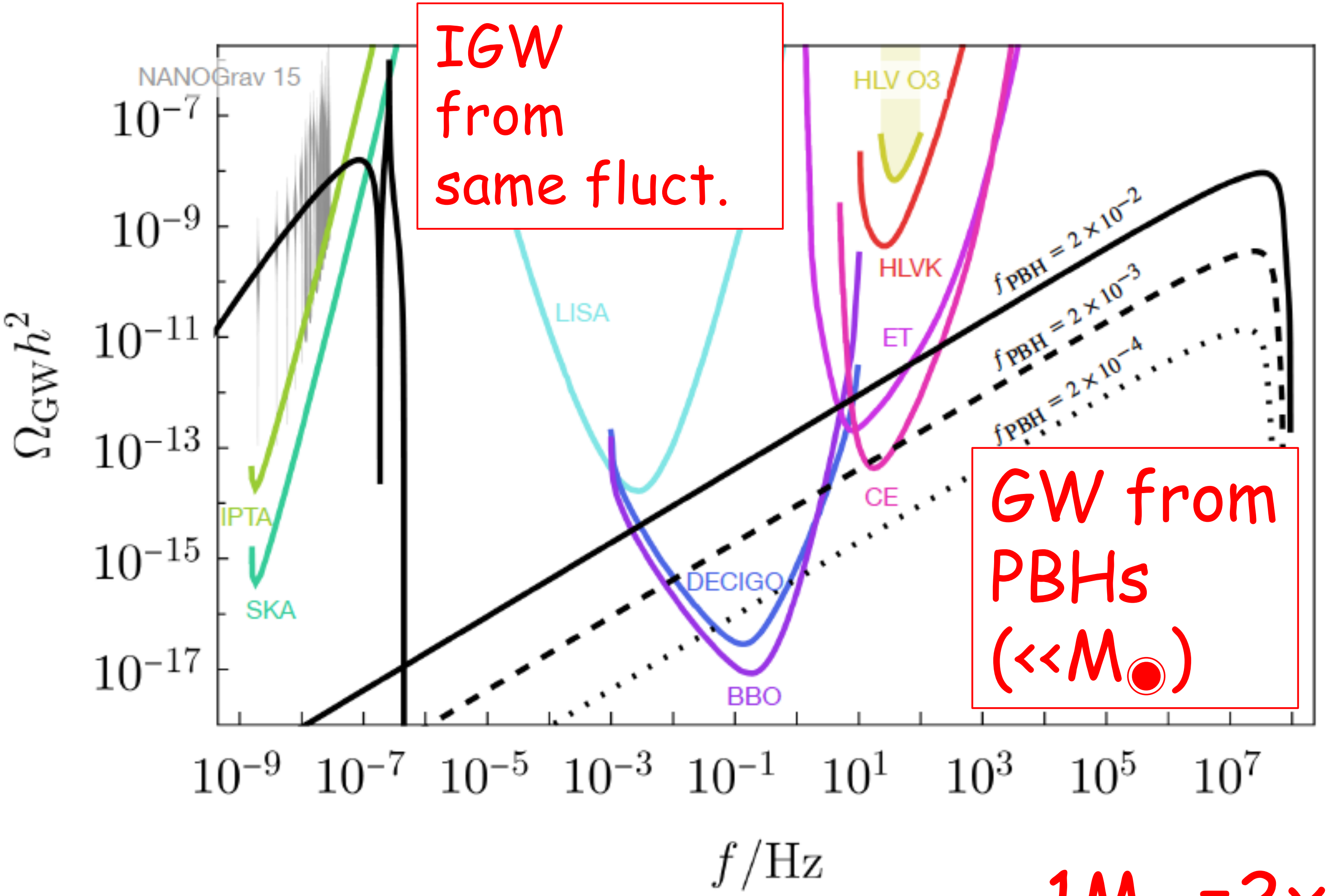


IGW from same fluct.

GW from PBHs ($\ll M_\odot$)

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

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

Summary of NANOGrav15yr

- 宇宙論的な非線形2次重力波の可能性

$\Omega_{GW}\sim10^{-8}\propto\delta^2$ at $f\sim10^{-8}$ Hz

- 小スケールの大きな密度ゆらぎ$\langle\delta^2\rangle$を示唆

$\langle\delta^2\rangle\sim O(0.01)\gg10^{-9}$ at $k\sim10^{7}$ Mpc^{-1}

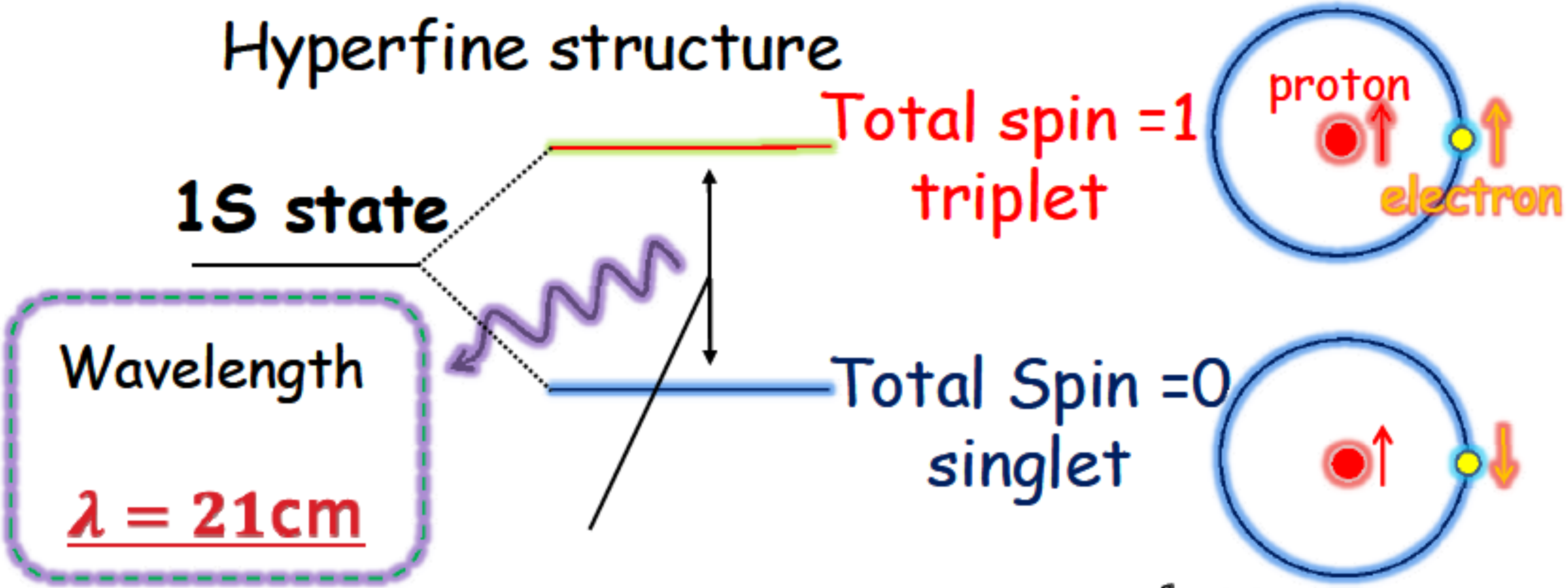
- 同じゆらぎは同時に原始ブラックホールを作る

$M_{BH}\sim O(10^{-5})\,M_\odot$

$f_{PBH}=\Omega_{PBH}/\Omega_{CDM}\sim O(0.01)$

◇ 21cm line

◆ proton-electron's spin-spin interaction



Hyperfine structure

1S state

Total spin =1
triplet

Total Spin =0
singlet

Wavelength

$\lambda = 21\mathrm{cm}$

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

Spin temperature Ts

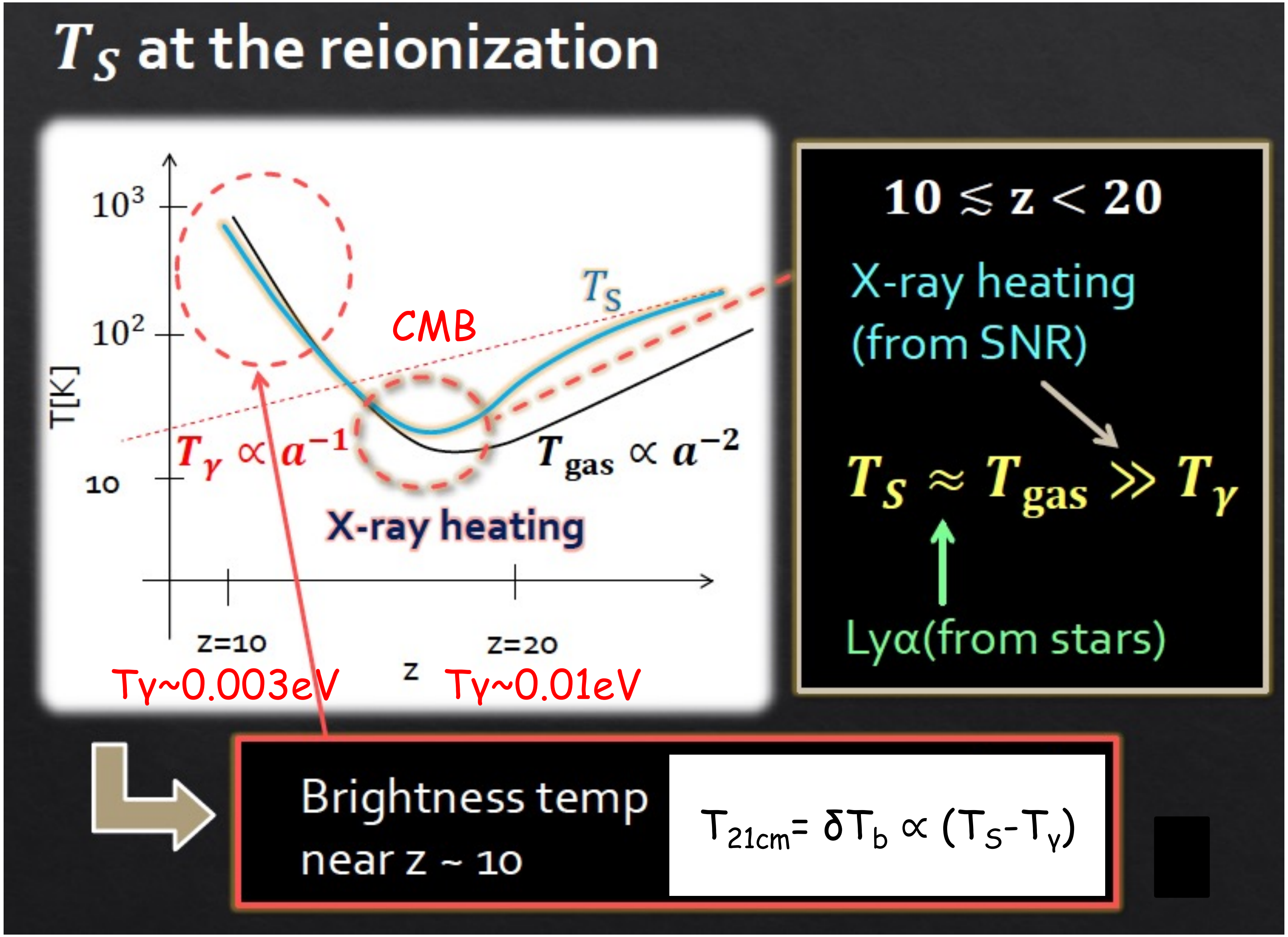
- Defined by the ratio of the occupation numbers in two states

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

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

$$g_i = \text{degree of reedom for a level "i"}$$

Cosmological 21cm emission line emitted at the reionization epoch



T_S at the reionization

$10 \lesssim z < 20$

X-ray heating (from SNR)

$T_S \approx T_{gas} \gg T_\gamma$

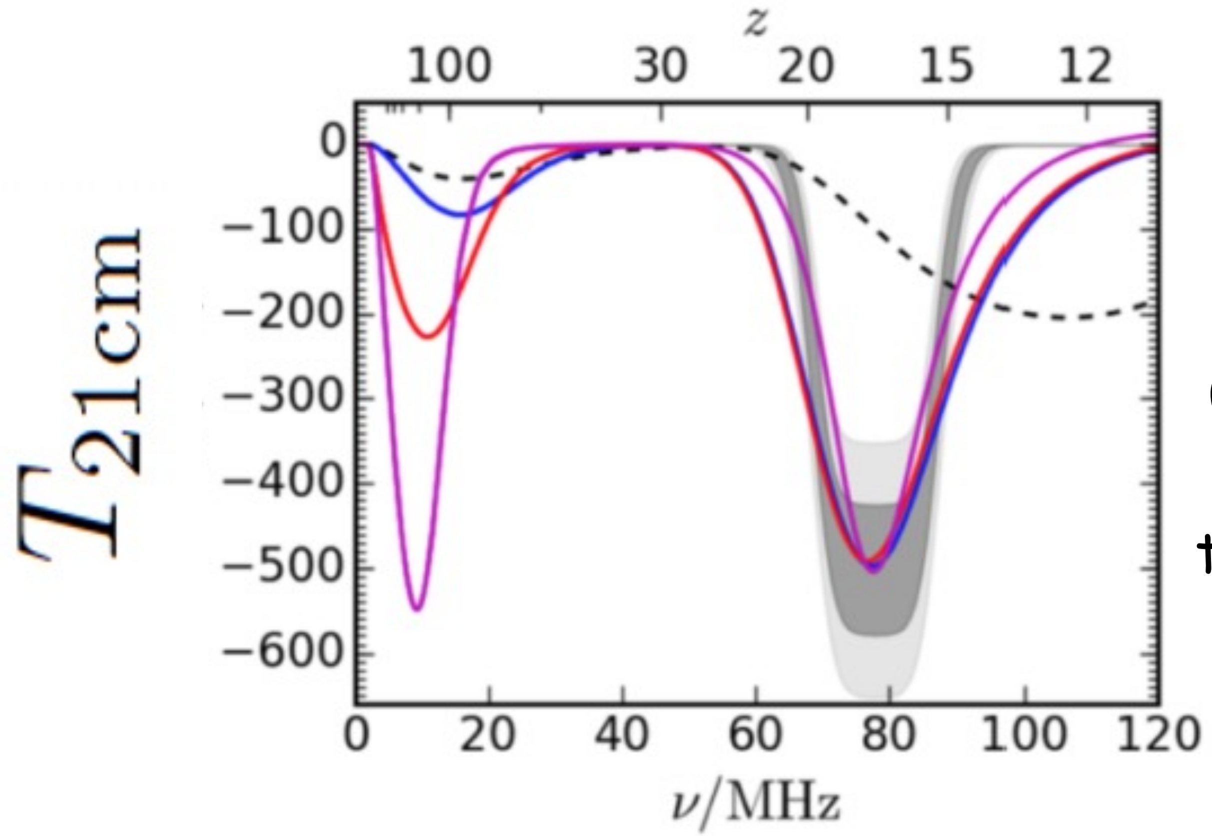
Lyα(from stars)

Brightness temp near z ~ 10

$T_{21cm} = \delta T_b \propto (T_S - T_\gamma)$

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



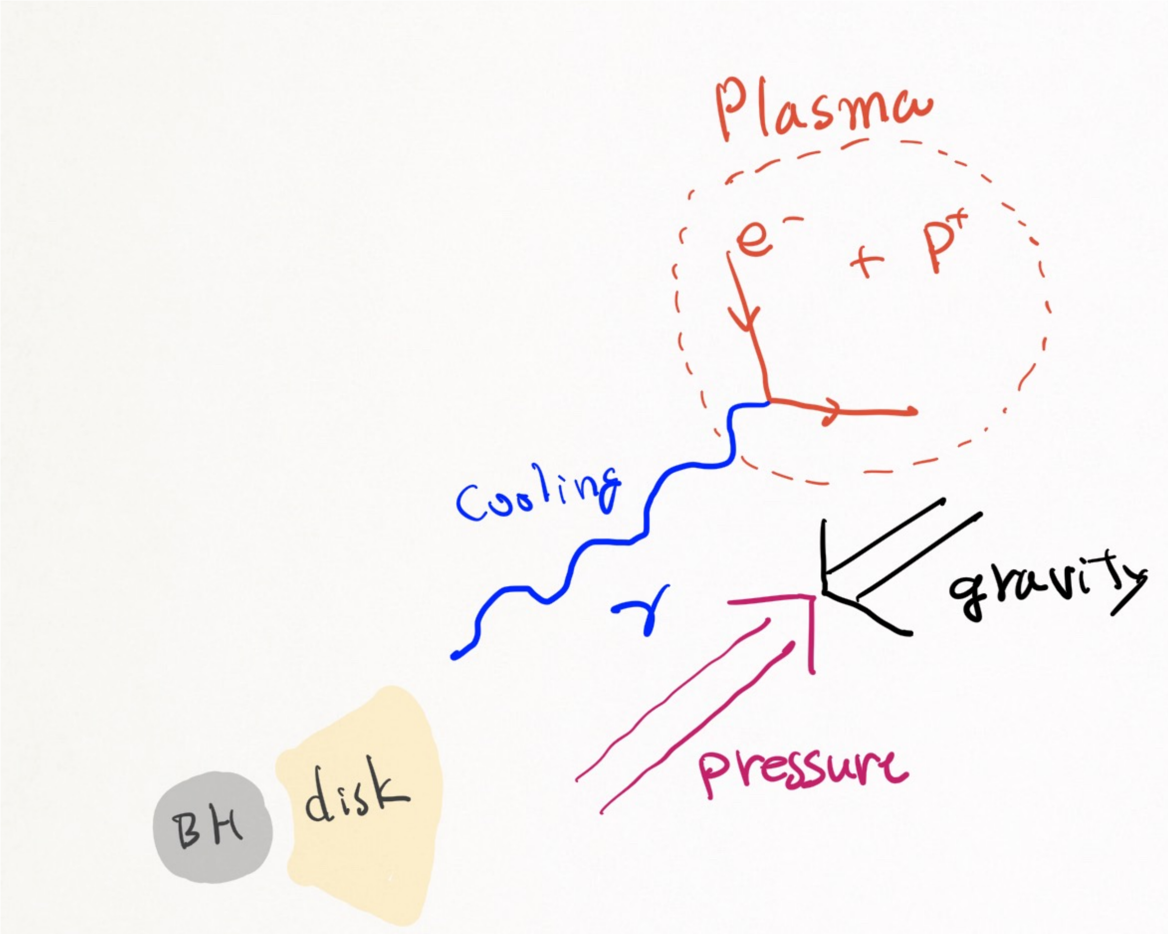
Absorption at Z ~ 17

t(z=17) ~ 0.22Gyr

δT_b =

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

The Eddington limit in accretions



$$L_{\rm E} \sim \frac{G_{\rm Newton} m_{\rm proton} M_{\rm BH}}{\sigma_{\rm Thomson}} \simeq 1.3 \times 10^{38}\,{\rm erg~~sec}^{-1} \left(\frac{M_{\rm BH}}{M_\odot}\right)$$

The Super-Eddington accretion

- Accretion rate in unit of the Eddington accretion

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

$$\dot{m} = \frac{\dot{M}}{\dot{M}_{\rm crit}}$$

- Mass evolutions in the Eddington accretion

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

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

Energy injection by accretion disks

- Injection rate

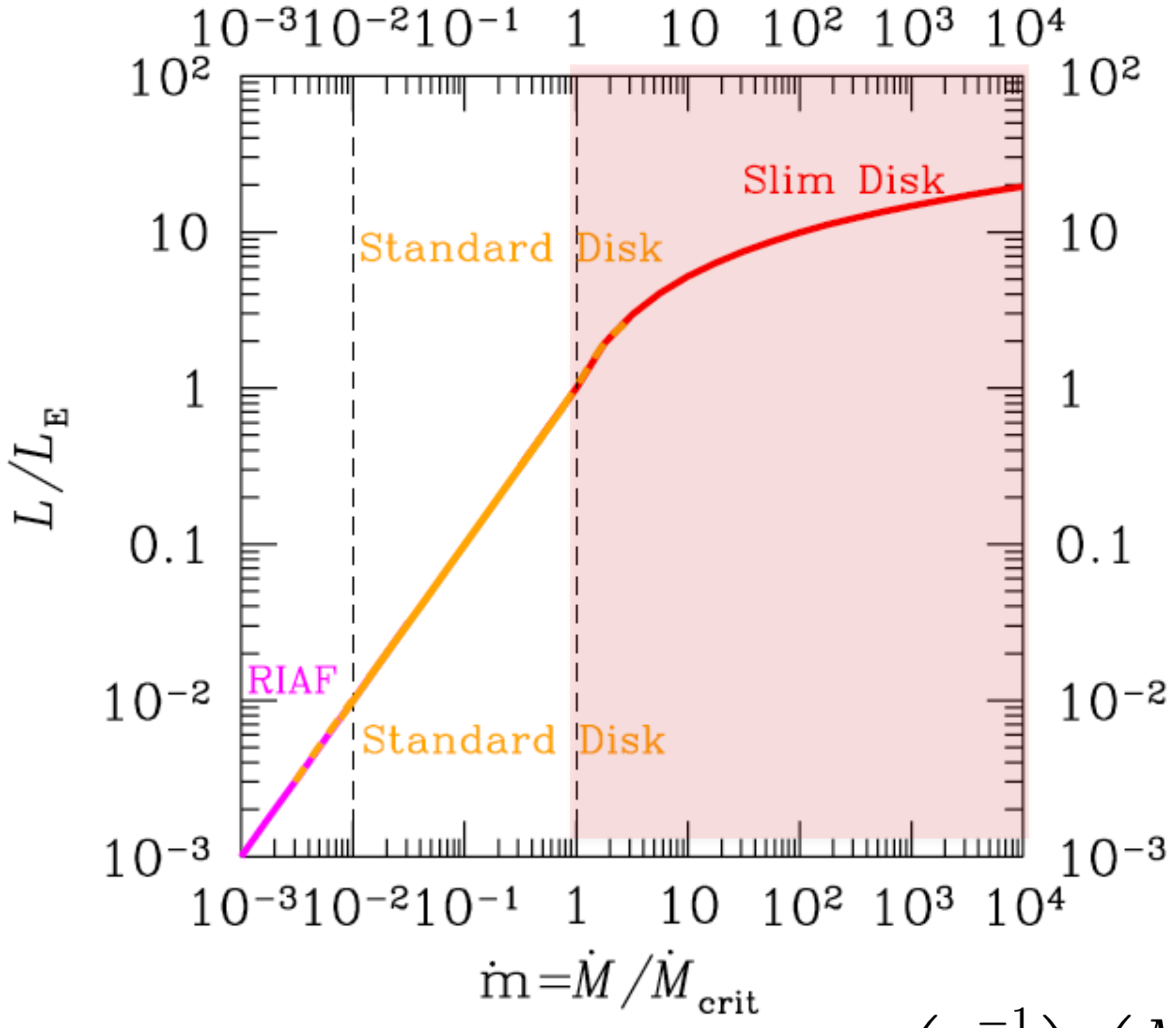
$$\frac{dE_{\rm inj}}{dV\,dt}(z) = \int d\omega \cdot n_{\rm seed}(z)\frac{dL}{d\omega},$$

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

This infjection rate is highly excluded by EDGES

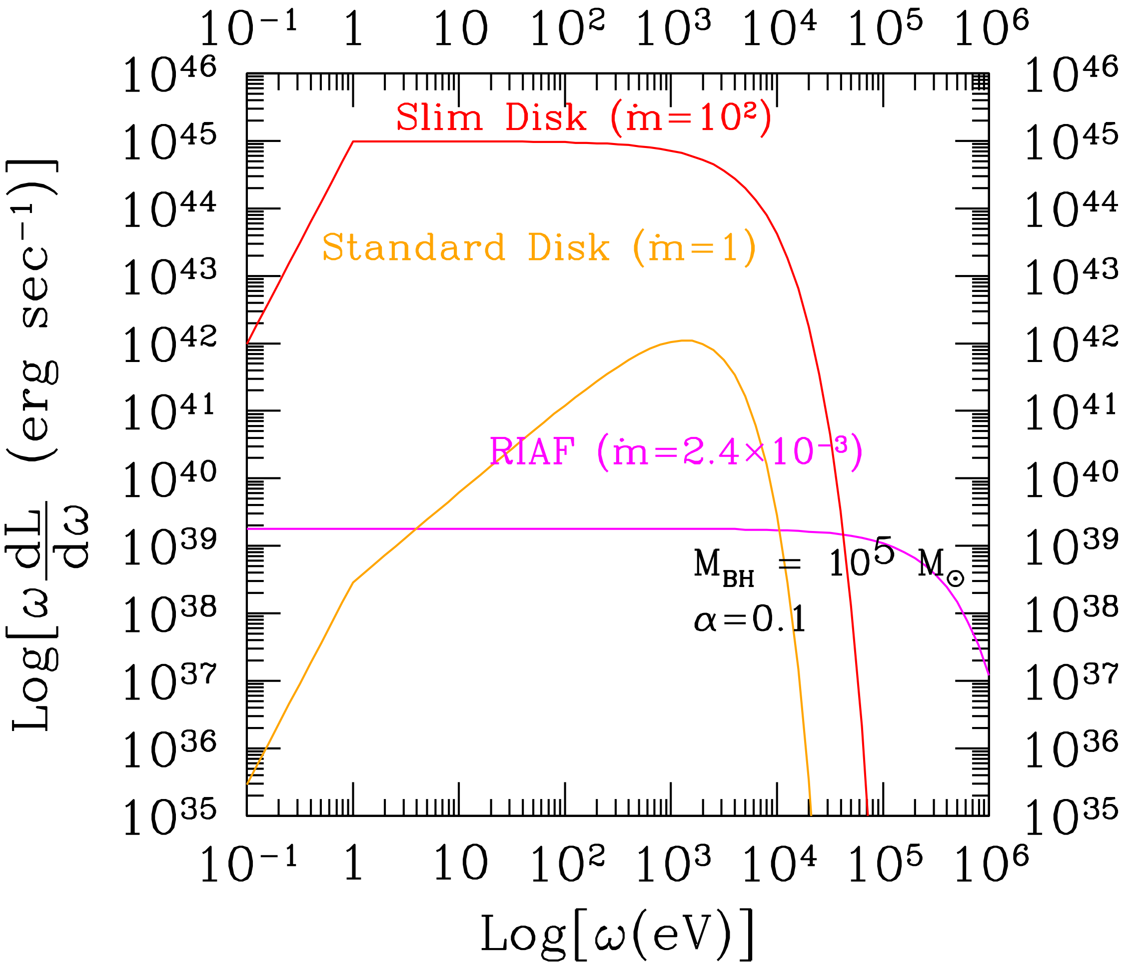
Luminosity of accretion disks

K. Watarai, J. Fukue, M. Takeuchi, S. Mineshige, PASJ., 52, 133 (2000)
Feng Yuan, Ramesh Narayan, arXiv:1401.0586 [astro-ph.HE]



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

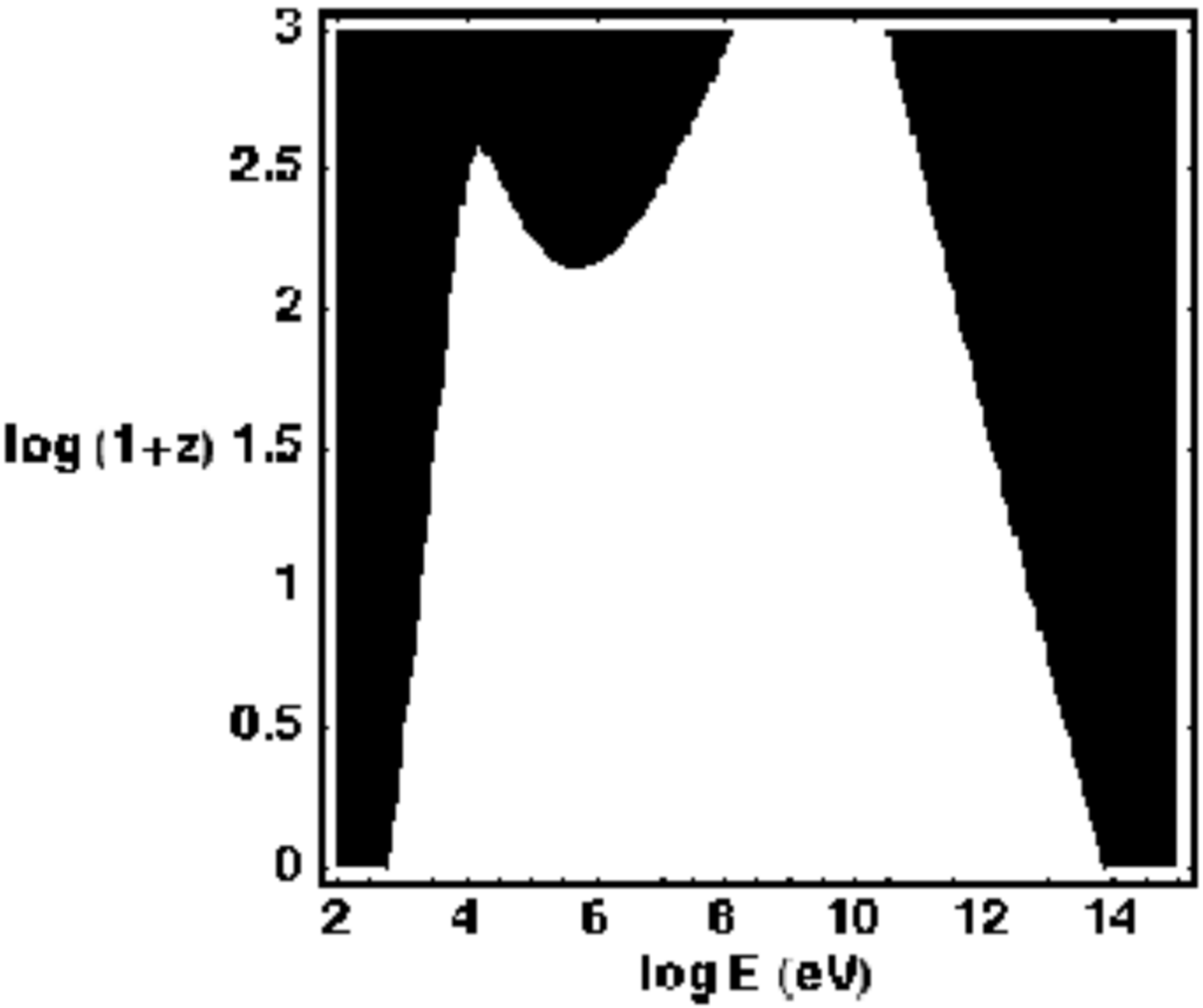
Spectrum ω dL/dω for a BH with $M_{BH} = 10^5\ M_\odot$



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



Ionization fraction x_e and the gas temperature T_m

- Ionization fraction

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

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

- Gas temperature

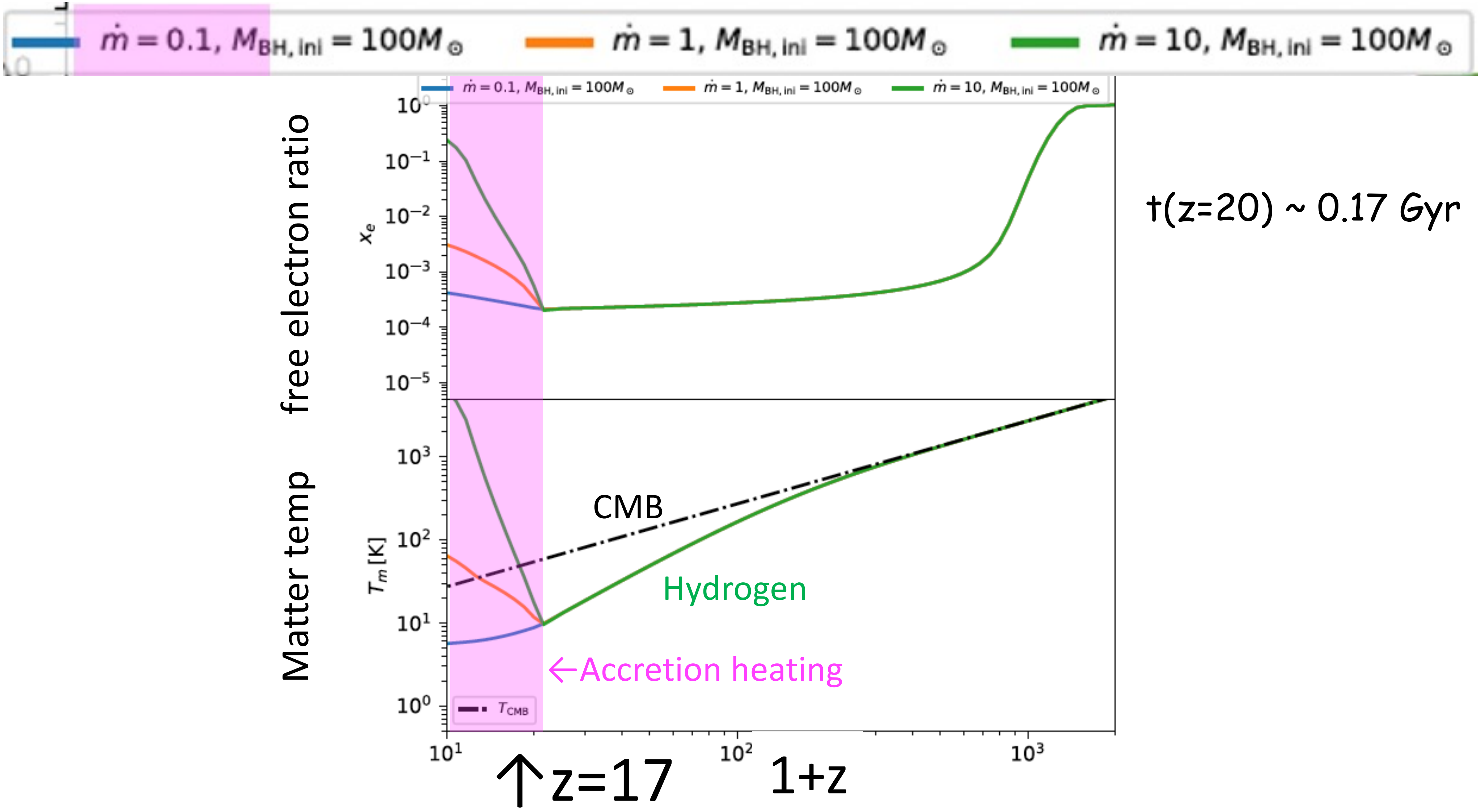
$$\frac{dT_m}{dt} = -2H(t)T_m + \Gamma_C(T_\gamma - T_m) + \frac{dE_{\rm inj}}{dV\,dt}\frac{1}{n_{\rm H}}\frac{2f_{\rm heat}(z)}{3(1+x_e+f_{\rm He})}$$

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

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

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

To obtain a conservative upper bound on accretions

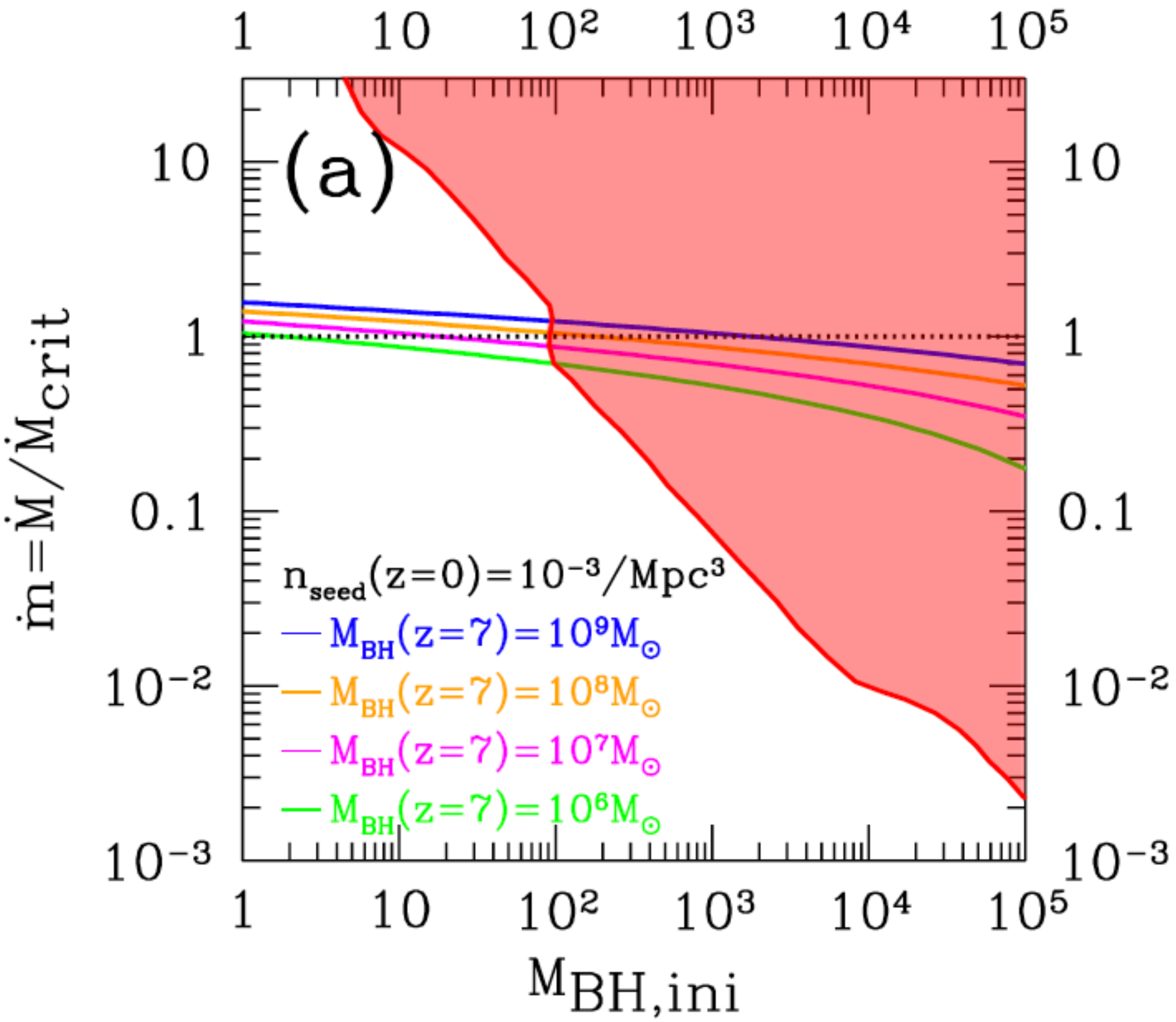
- We assume the prediction of mean value of T_{21} in the ΛCDM model, not the one of the EDGES

- 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

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]



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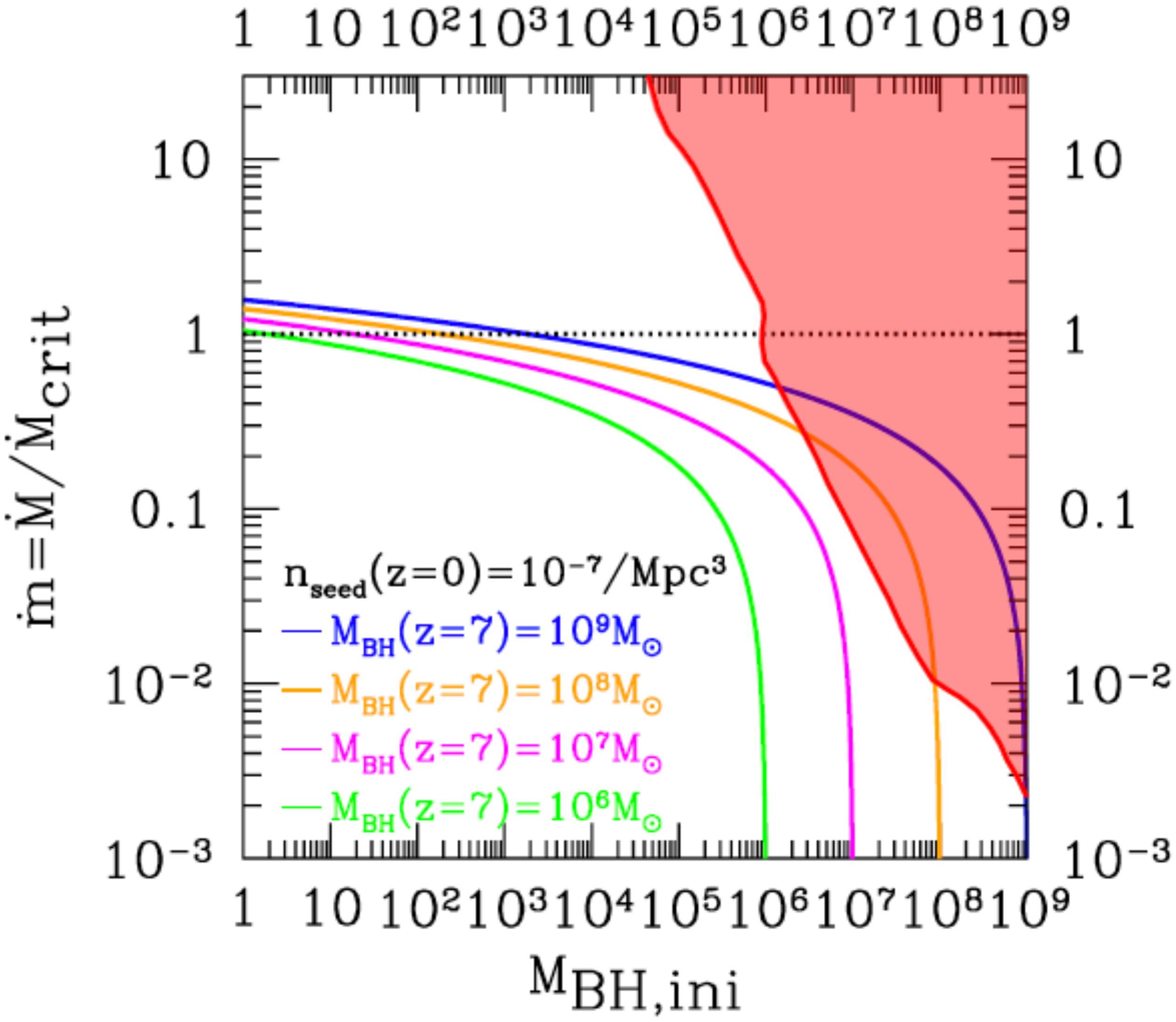


Summary of SMBHs

- 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

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

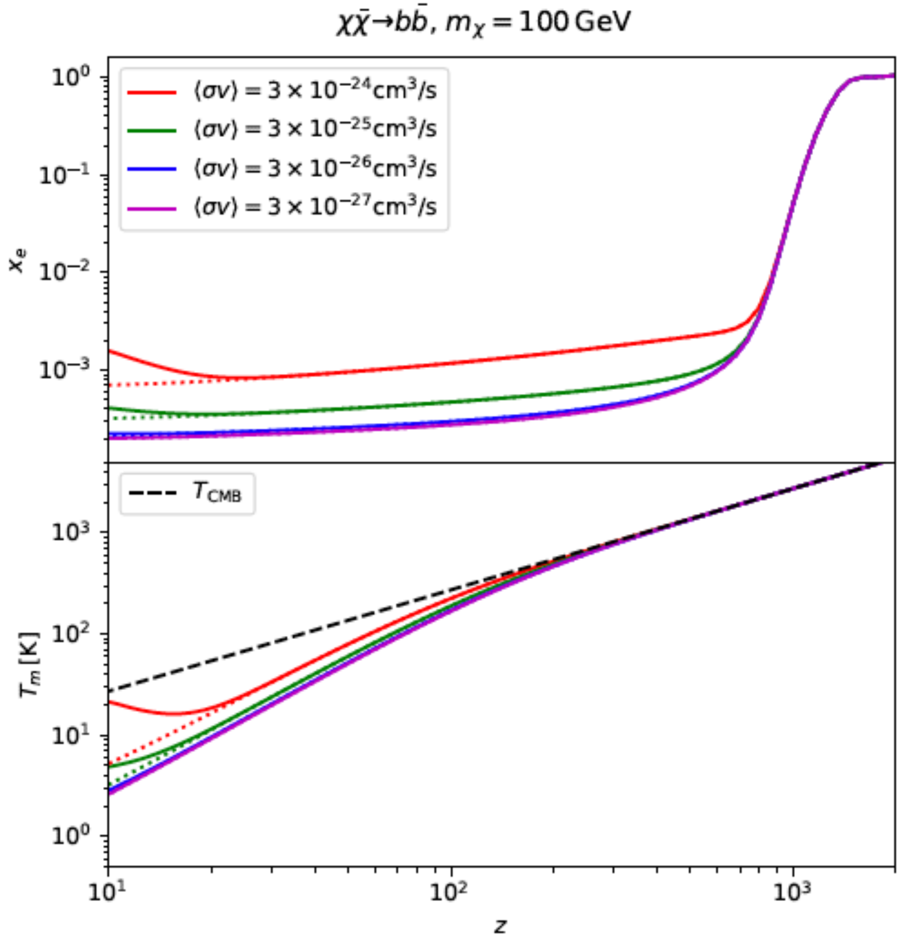
Number counts of SMBHs at z=0 (the strongest assumption)

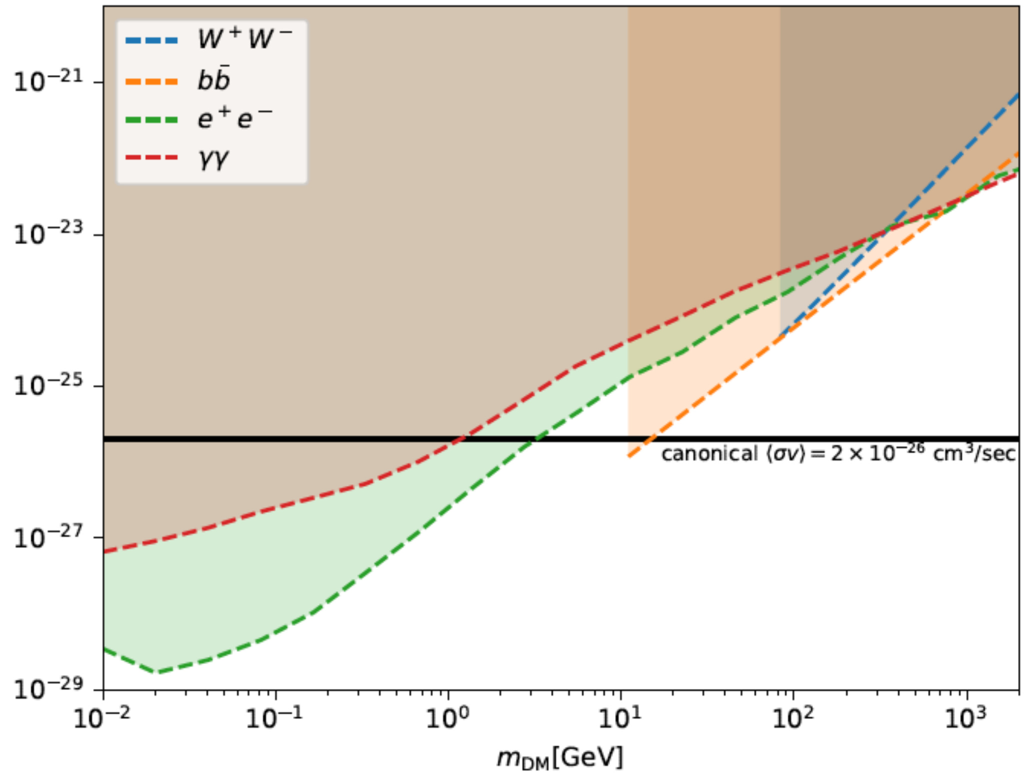
$$\mathrm{M}_{\mathrm{BH,ini}} \gtrsim 10^{6} M_{\odot} \text{ for } n_{\mathrm{seed}}(z=0) = 10^{-7}\mathrm{Mpc}^{-3}$$

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

EDGES's 21cm absorption bounds on annihilating dark matter

Nagisa Hiroshima, Kazunori Kohri, Toyokazu Sekiguchi, Ryuichi Takahashi, arXiv:2103.14810 [astro-ph.CO]



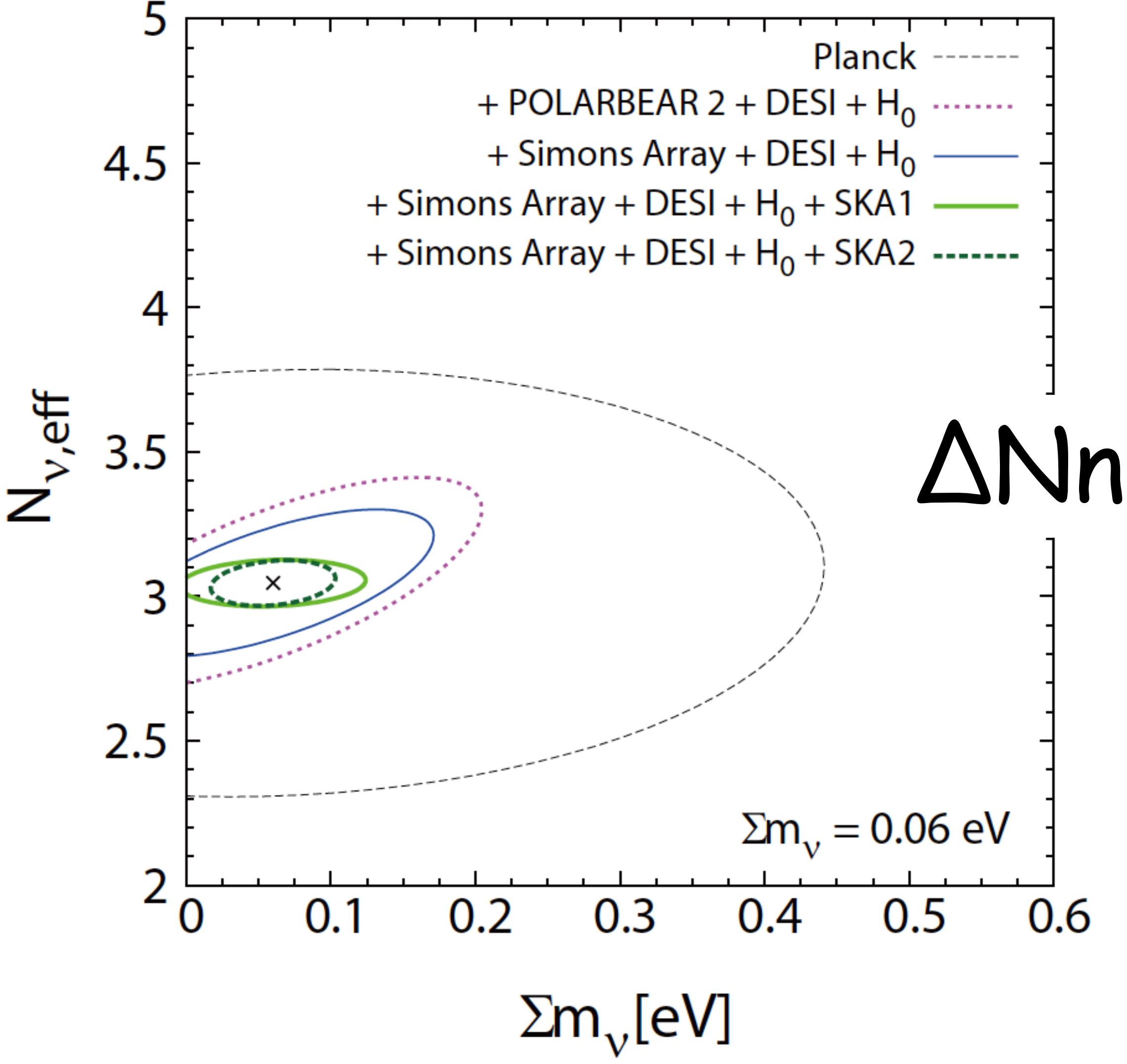


Annihilation cross section

mass of dark matter

Future constraints on neutrino species and mass by 21cm, CMB, and BAO

Oyama, Kohri, Hazumi (2015)



ΔNnu < 0.05

Power spectrum of curvature perturbation

- Parameterization

$$\mathcal{P}_\zeta(k) = \mathcal{P}_\zeta(k_{\rm ref}) \exp\left[(n_s-1)\ln\left(\frac{k}{k_{\rm ref}}\right) + \frac{1}{2}\alpha_s \ln^2\left(\frac{k}{k_{\rm ref}}\right) + \frac{1}{3!}\beta_s \ln^3\left(\frac{k}{k_{\rm ref}}\right)\right]$$

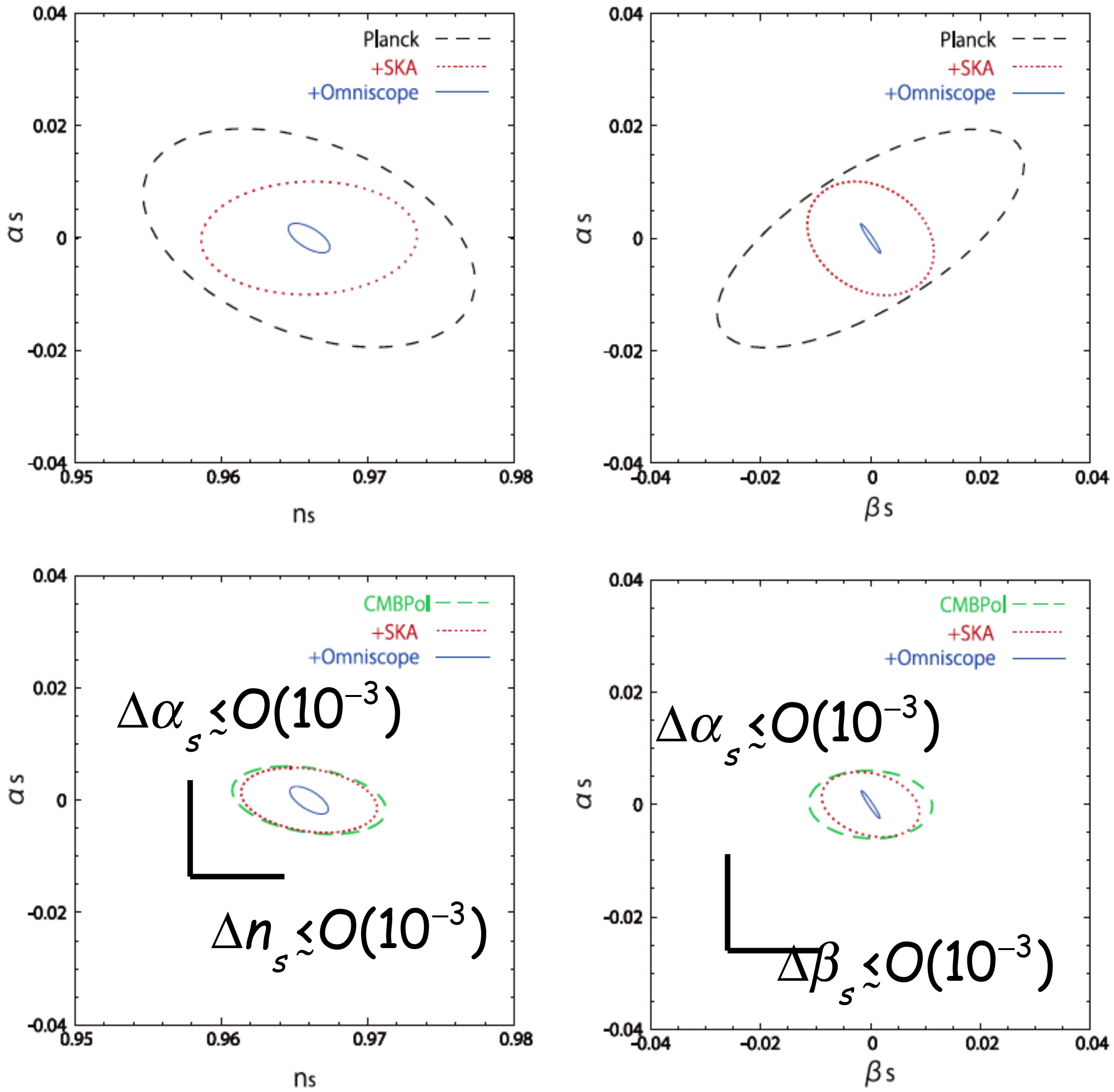
$$= \mathcal{P}_\zeta(k_{\rm ref}) \left(\frac{k}{k_{\rm ref}}\right)^{n_s-1+\frac{1}{2}\alpha_s \ln(k/k_{\rm ref})+\frac{1}{6}\beta_s \ln^2(k/k_{\rm ref})} ,$$

Forecasts of running and Running of Running

KK, Oyama, Sekiguchi, T.Takahashi (2013)

$$\alpha_s \equiv \frac{d\ln P_\zeta}{d\ln k}$$

$$\beta_s \equiv \frac{d\alpha_s}{d\ln k}$$



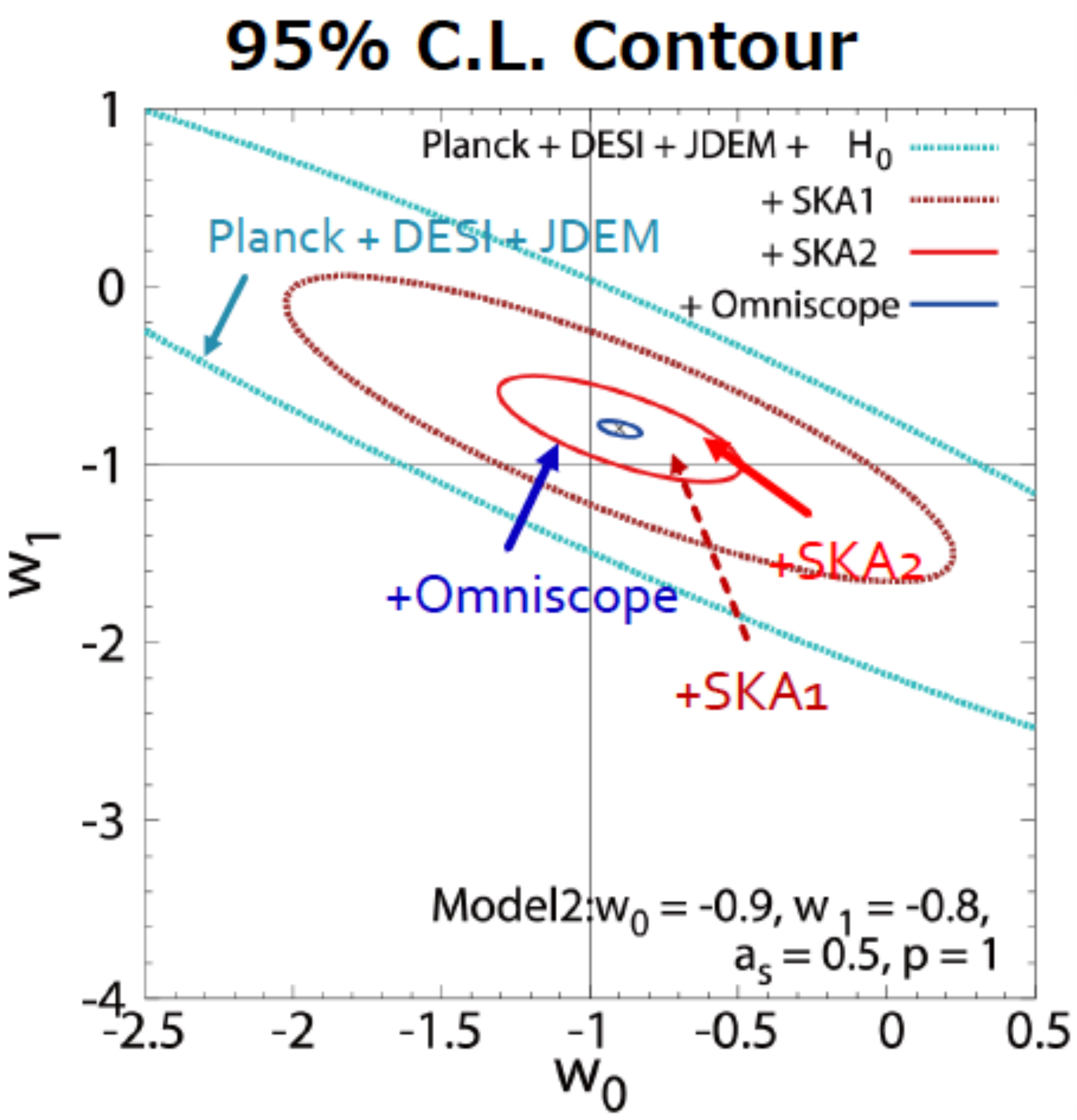
$\Delta\alpha_s \lesssim O(10^{-3})$

$\Delta n_s \lesssim O(10^{-3})$

$\Delta\alpha_s \lesssim O(10^{-3})$

$\Delta\beta_s \lesssim O(10^{-3})$

Forecast on dark energy in future experiments



Conclusion

1. NANOGrav15yr may observed the stochastic GWs, which can be fitted by secondary-induced GWs

2. Cosmological 21cm can give constraints on high-redshifted SMBHs, Neutrino mass, dark matter, dark energy or density fluctuation