Kavli IPMU, “Dark Matter Symposium FY2021”

Cosmological 21cm line observations to test scenarios of super-Eddington accretion on to seed BHs of high-z SMBHs

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

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Introduction

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

$10^{15}\ M_\odot$ to be PBH Dark matter
$10^{9}\ M_\odot$ observed at z=7.642 (PBH origins are excluded)

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

$M_{sBH}=10^2\ M_\odot$ at z~30 → accretions → $10^9\ M_\odot$ at z=7

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

- By 21cm data by EDGES, we can obtain upper bounds on emissions from accretions on to seed BHs and exclude the seed masses at z=17

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

Origin of seed BHs with $M_{sBH} = 10^2 - 10^6\ M_\odot$ at z>>7

- Astrophysical

Collapses of massive stars/gas clouds

Mergers of massive stars/ black holes

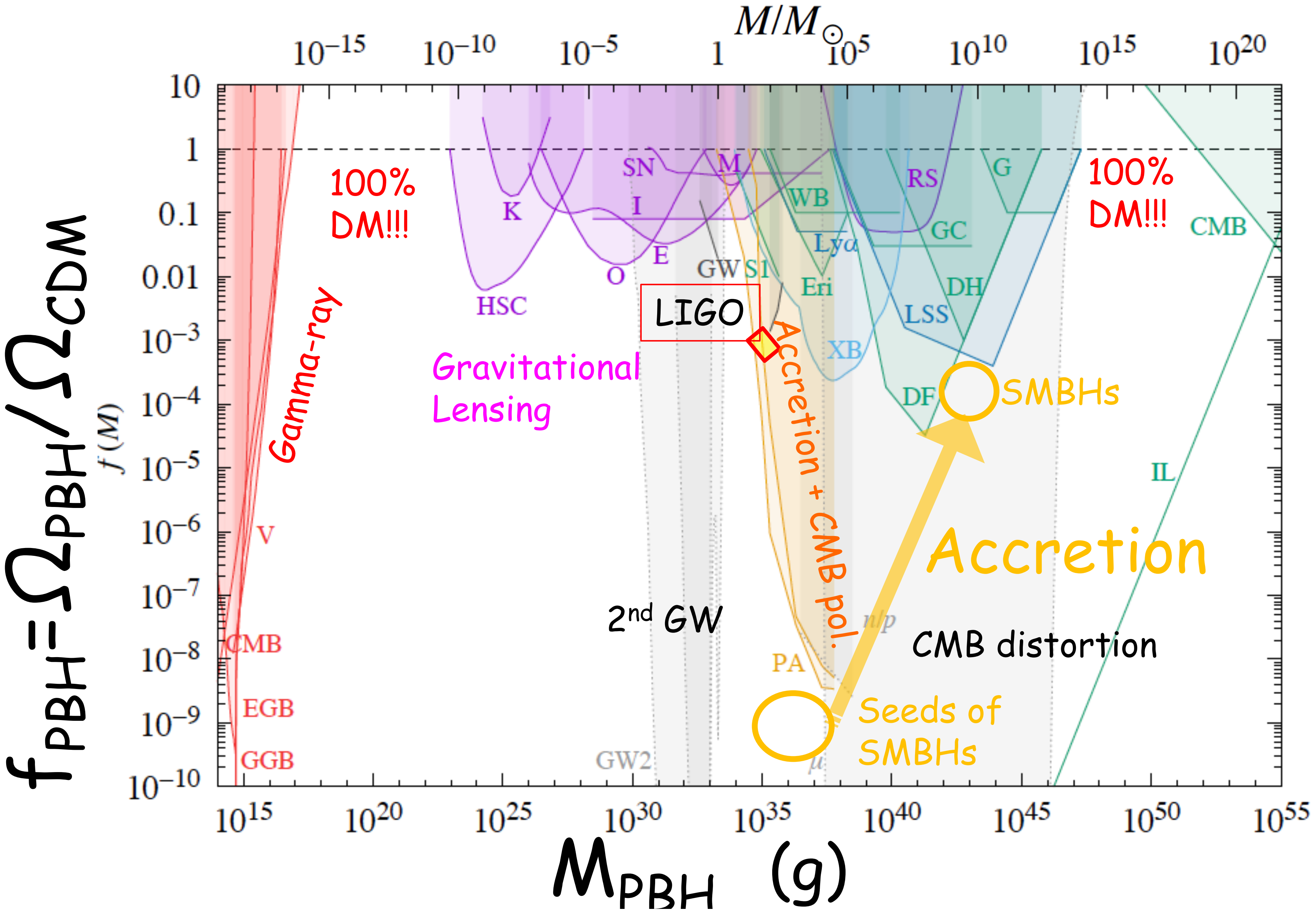
- Primordial

Formation temp. $T_{form} \sim O(10)$ MeV – $O(0.1)$ MeV

Curvature pertrurbation $P_\zeta \sim 10^{-1.5}$

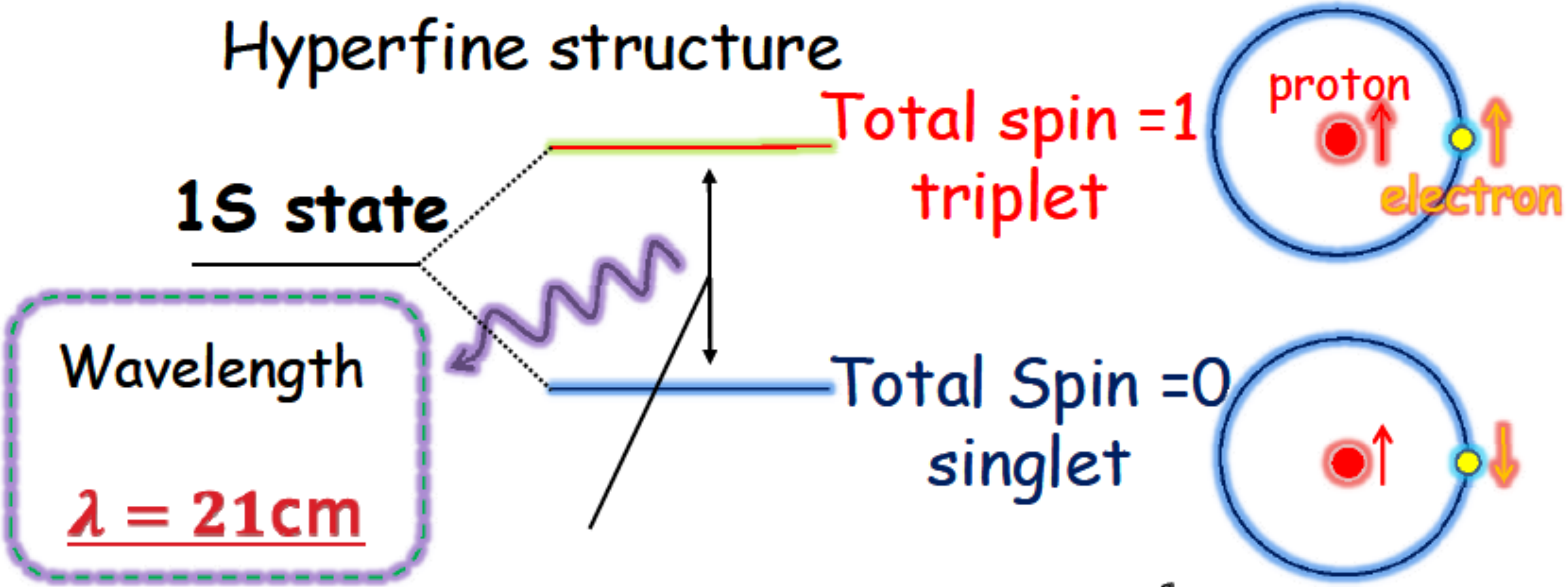
Upper bounds on the fraction of PBH to CDM

Carr, Kohri, Sendouda, J.Yokoyama (2010)(2021)



◇ 21cm line

◆**proton-electron's spin-spin interaction**



Hyperfine structure

1S state

Total spin =1

triplet

proton

electron

Total Spin =0

singlet

Wavelength

$\lambda = 21\text{cm}$

$$\Delta E = 2\pi\nu_{21} = 5.8\times10^{-6}\text{eV}$$

Spin temperature Ts

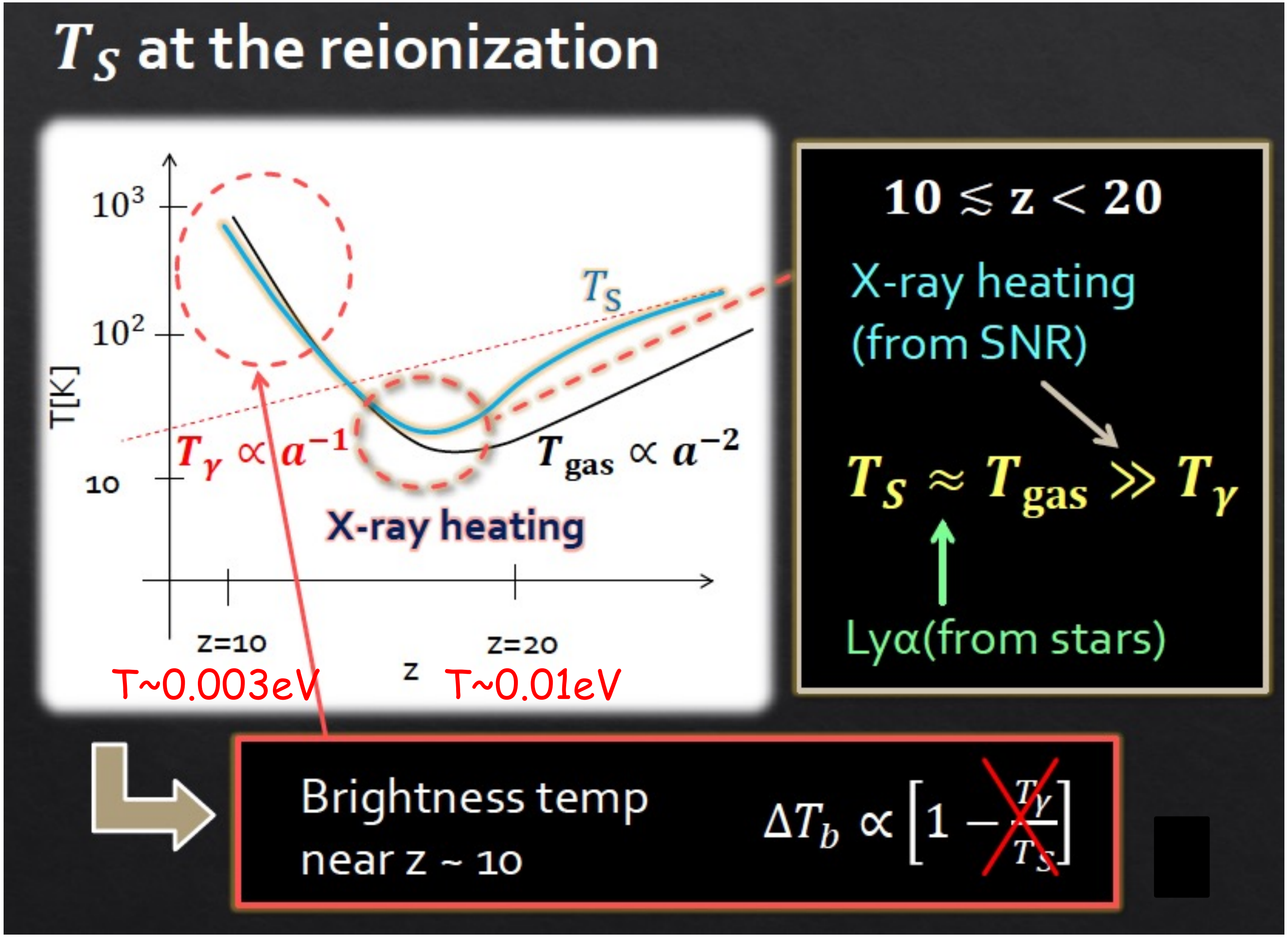
- Defined by the ratio of the occupation numbers in two states

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

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

g_i = 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)

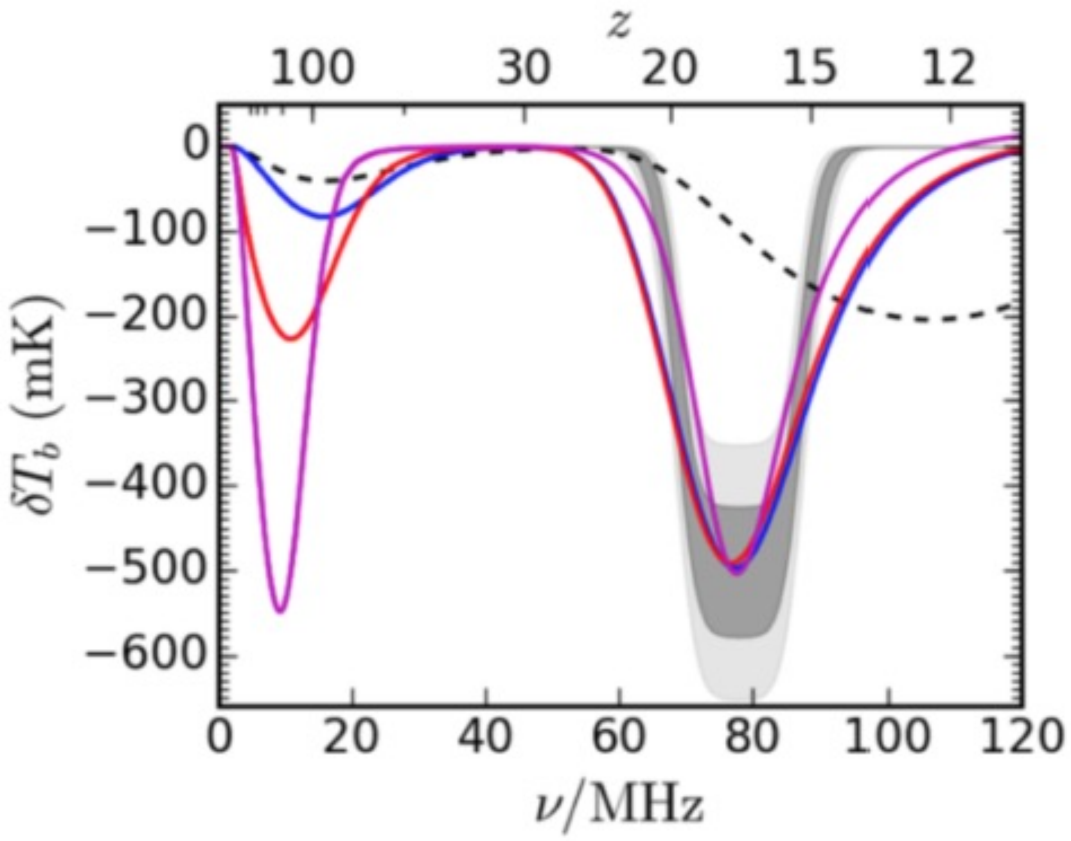
Brightness temp
near z ~ 10

$\Delta T_b \propto \left[1 - \cancel{\frac{T_\gamma}{T_S}}\right]$

21cm absorption by EDGES

Judd D. Bowman,et al., Nature 555 (2018) 67

Steven R. Furlanetto et al., arXiv:1903.06212



Absorption atZ ~ 17

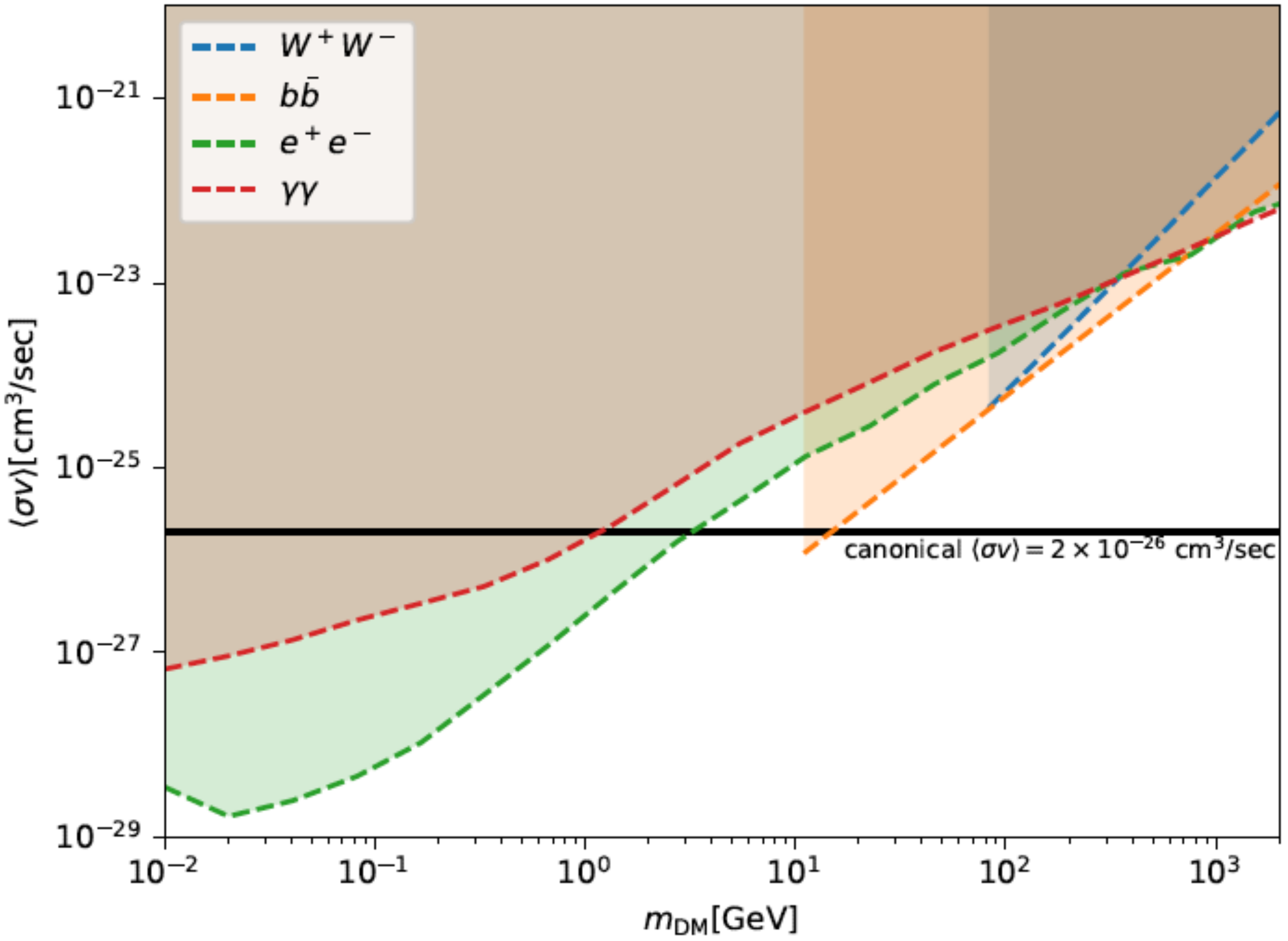
See also the talks by
Hiroyuki Tashiro (F10)
Ryuichi Takahashi (B02)

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

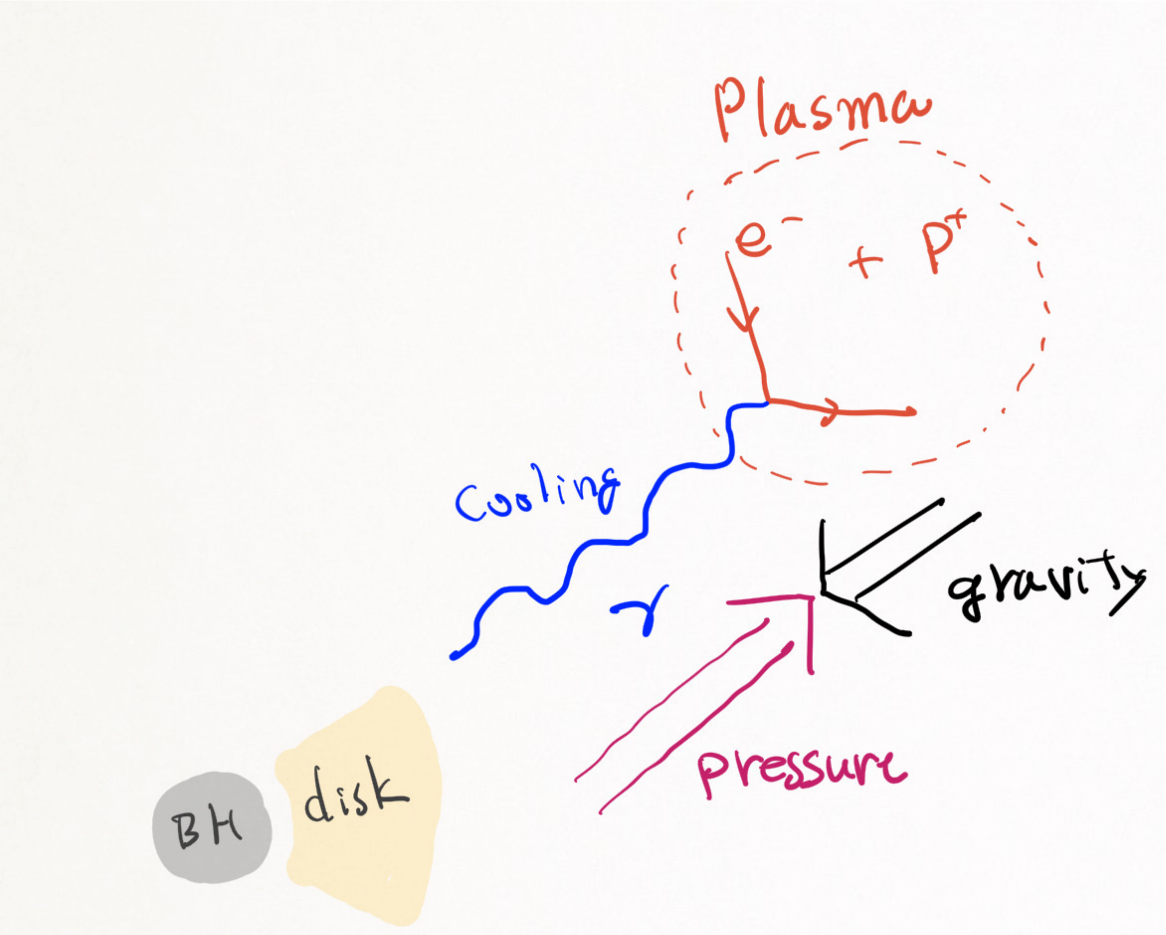
We can constrain any new heating mechanism at least such as accretions on to BHs or annihilating DMs at z~17

Impacts of new small-scale N-body simulations on dark matter annihilations constrained from cosmological 21cm line observations

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



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

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

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

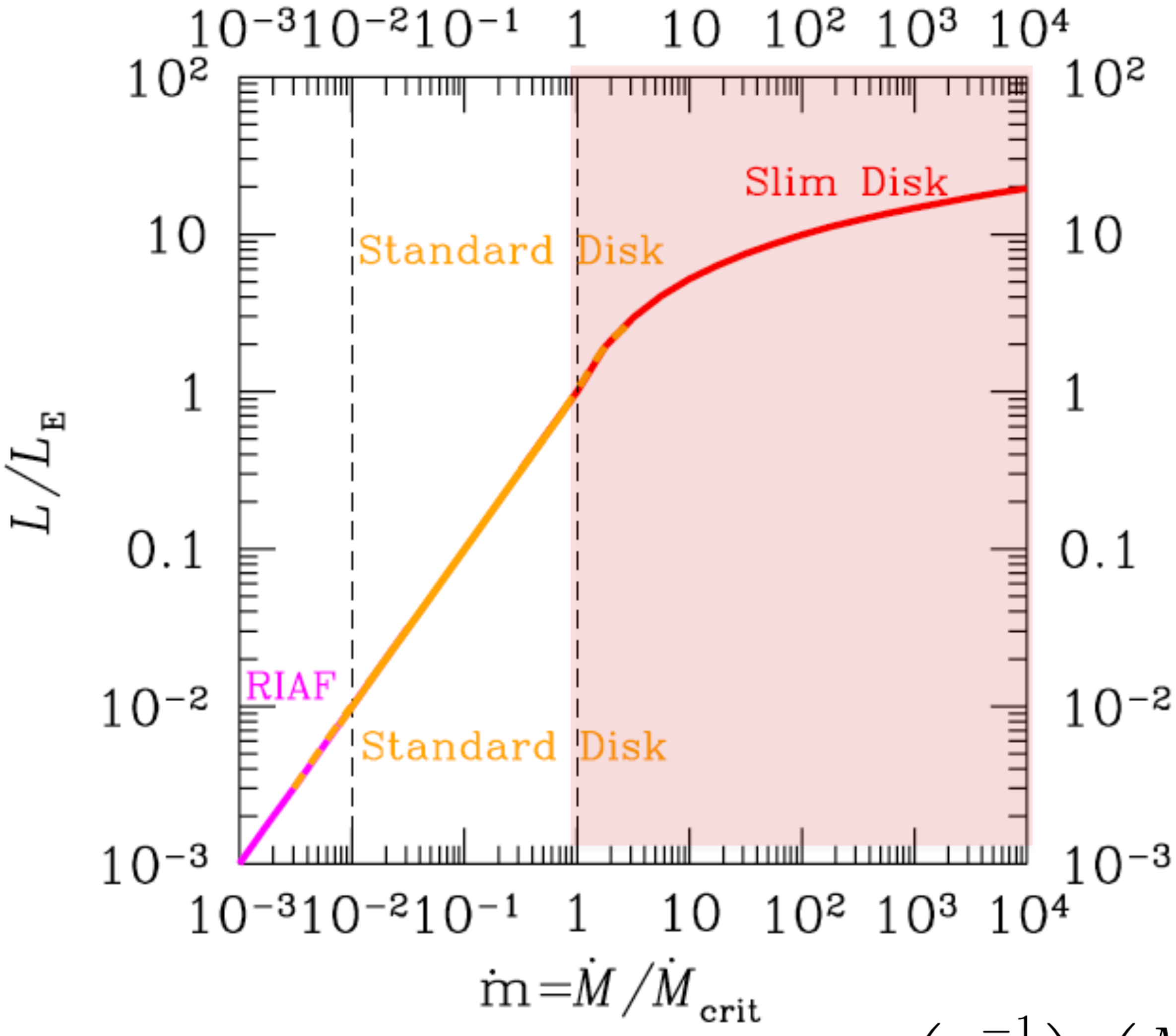
- Mass evolutions in the Eddington accretion

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

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

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]



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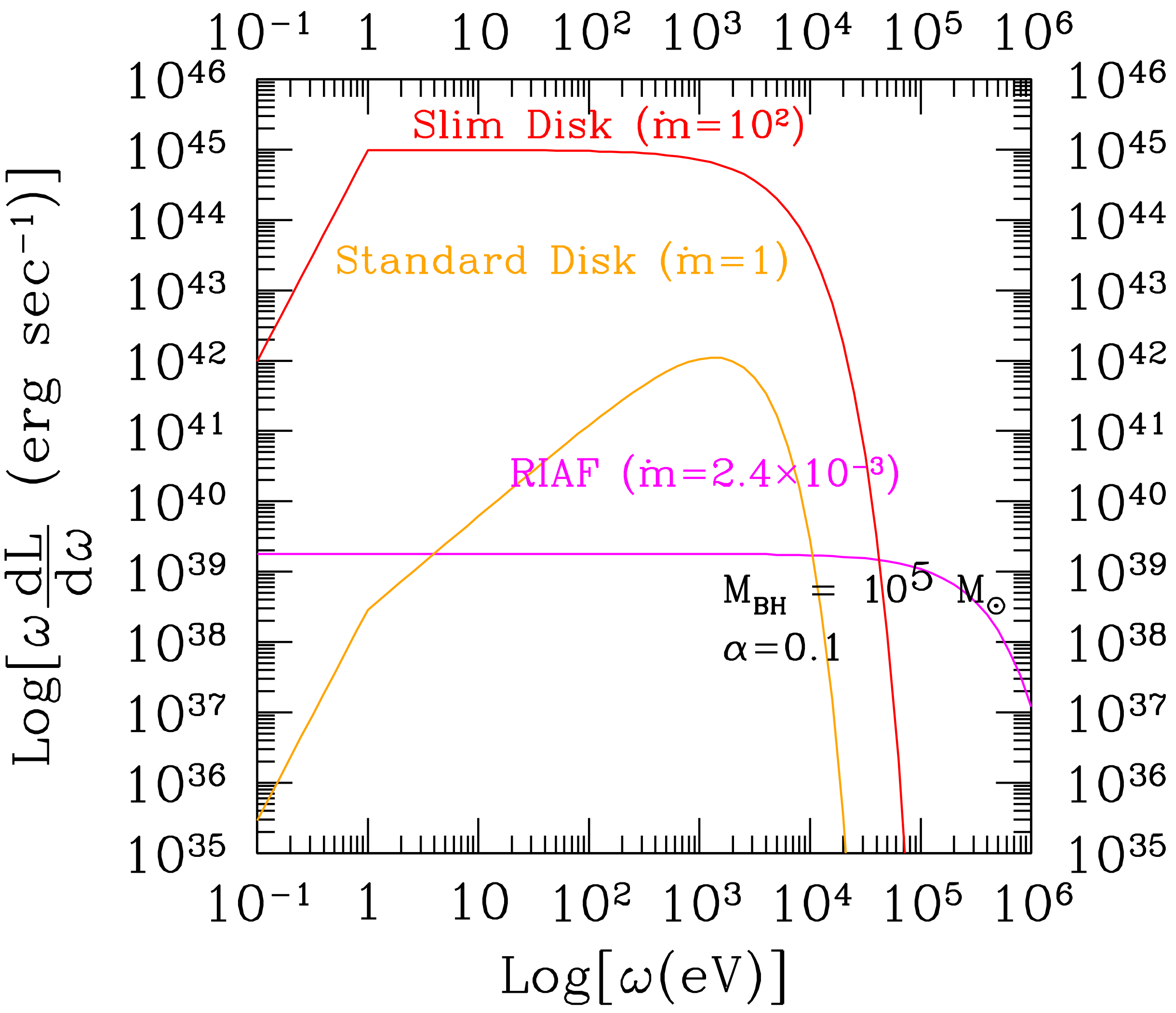
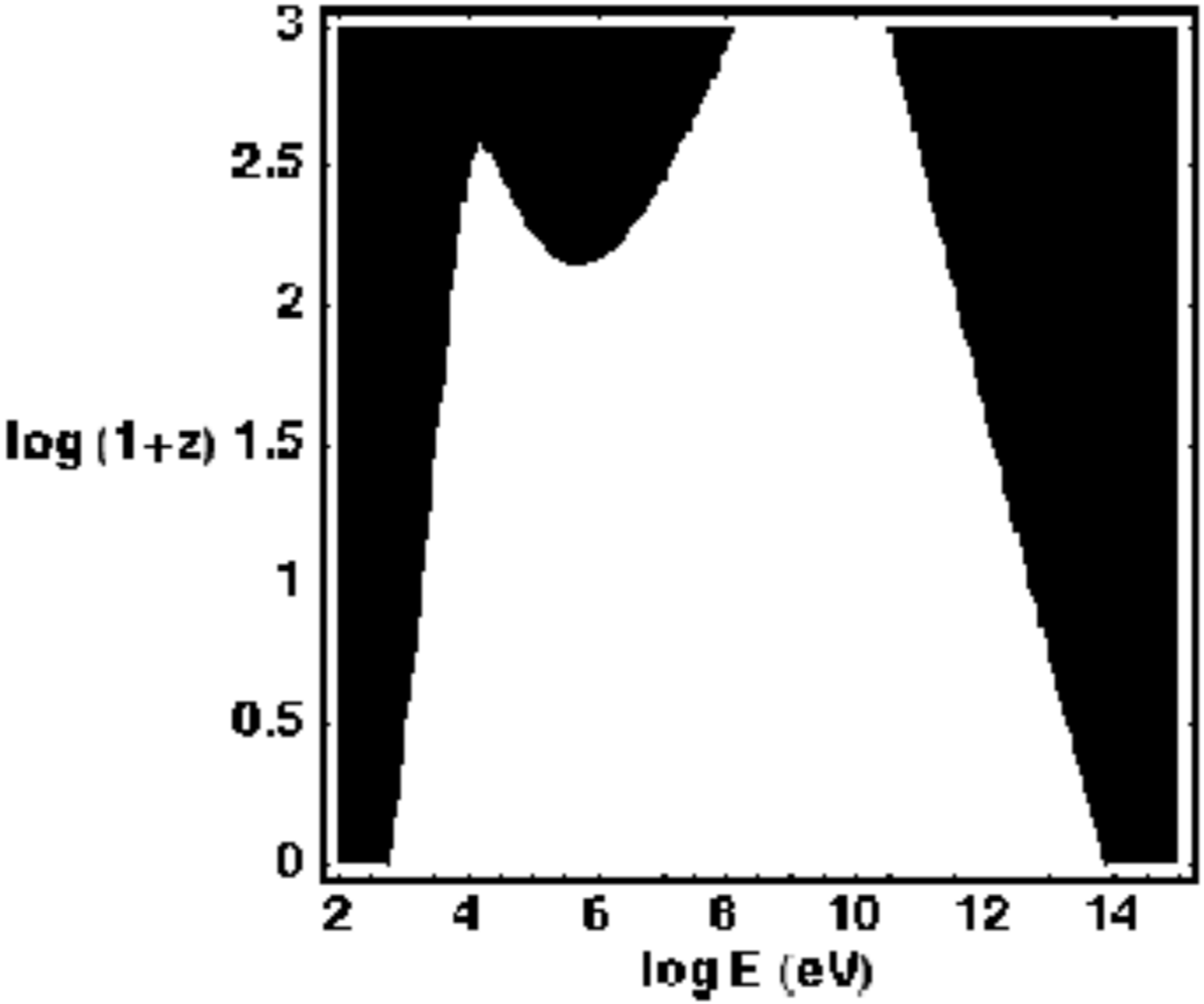
Photon spectrum from disks with $M_{BH} = 10^5\ M_\odot$

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



Optically thick?

Xuelei Chen, Marc Kamionkowski, arXiv:astro-ph/0310473



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

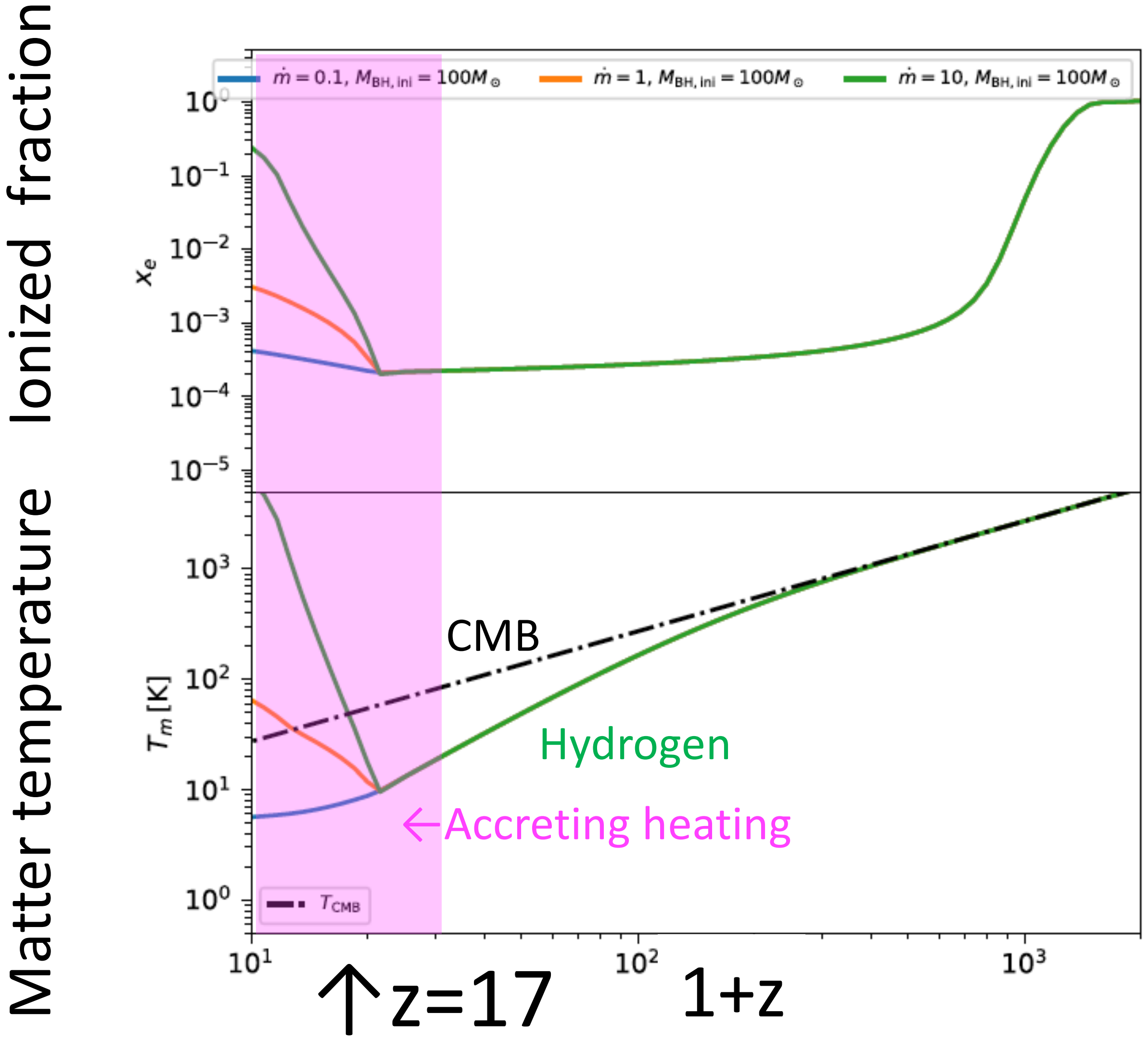
$$
\frac{dT_m}{dt} = -2H(t)T_m + \Gamma_C(T_\gamma - T_m) + \frac{dE_{\rm inj}}{dV\,dt}\frac{1}{n_{\rm H}}\frac{2f_{\rm heat}(z)}{3(1+x_e+f_{\rm He})}
$$

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

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

Time evolutions of temperature

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



Ionized fraction

Matter temperature

CMB

Hydrogen

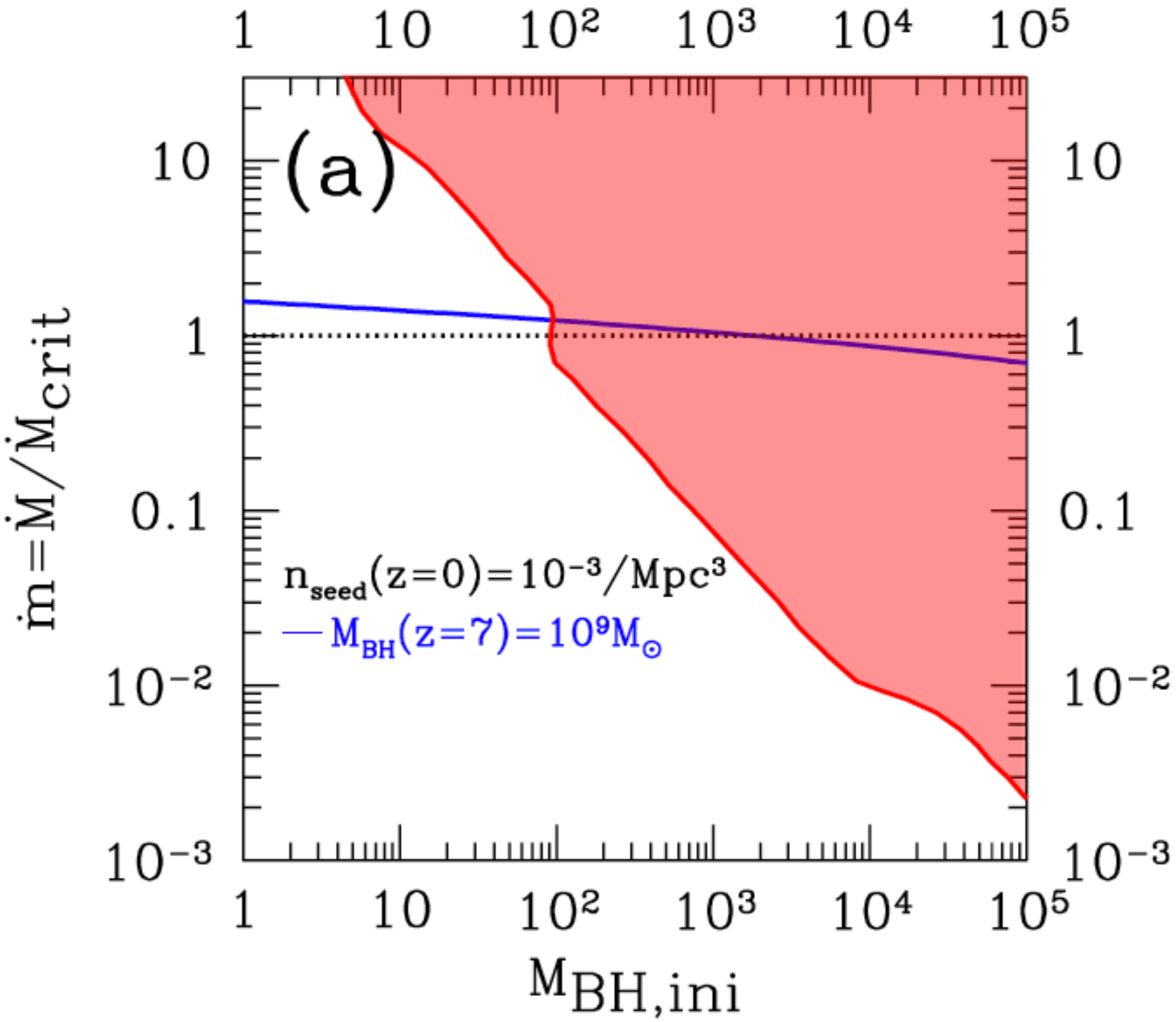
←Accreting heating

↑z=17

1+z

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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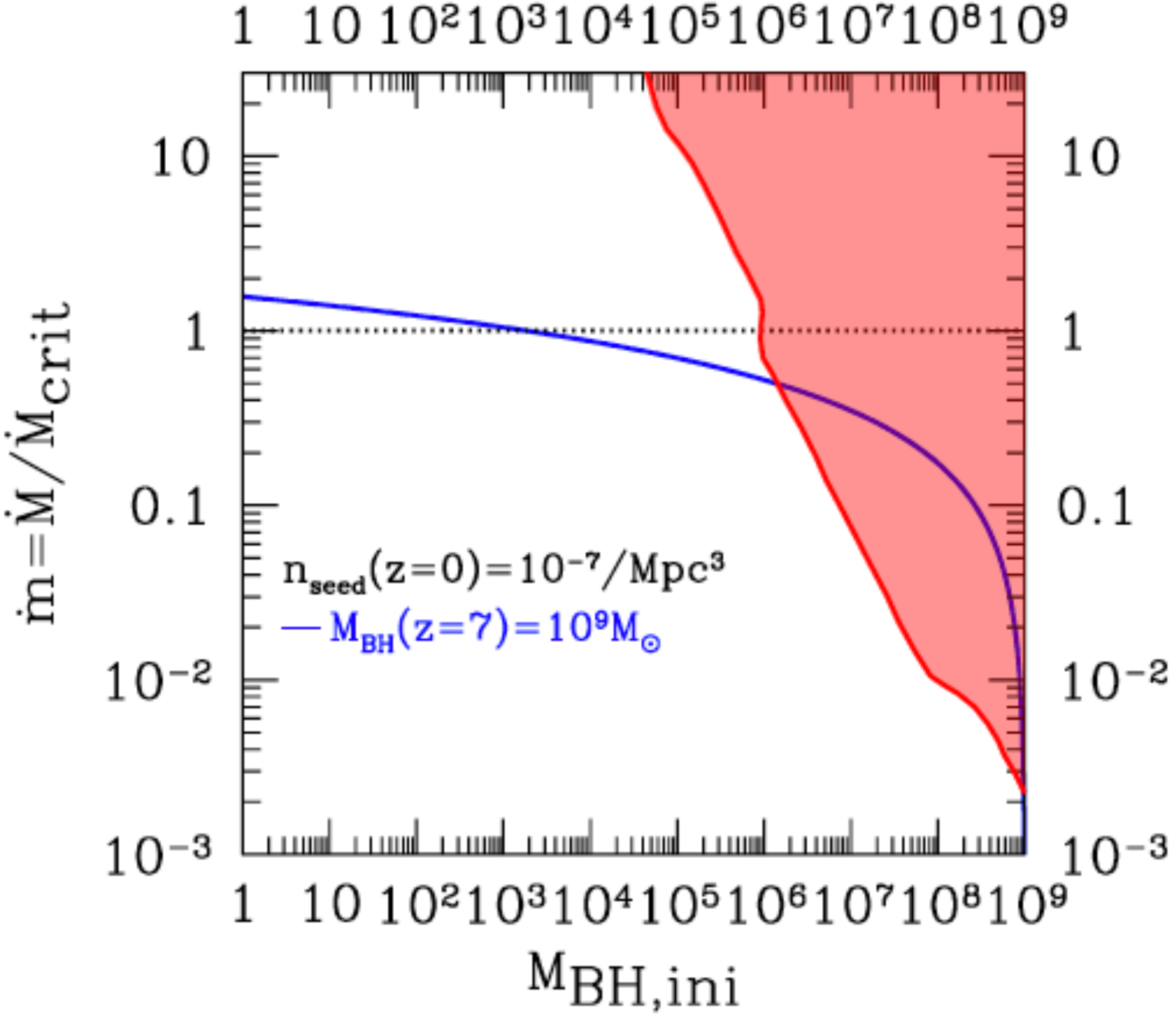

Conclusion

- 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)