Cosmological 21cm bounds on annihilating DM, super-Eddington accretions onto SMBHs, or PBHs

Ryuichi Takahashi, Kazunori Kohri, arXiv:2107.00897 [astro-ph.CO]

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

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

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Advent of EDGES or SARAS 3

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

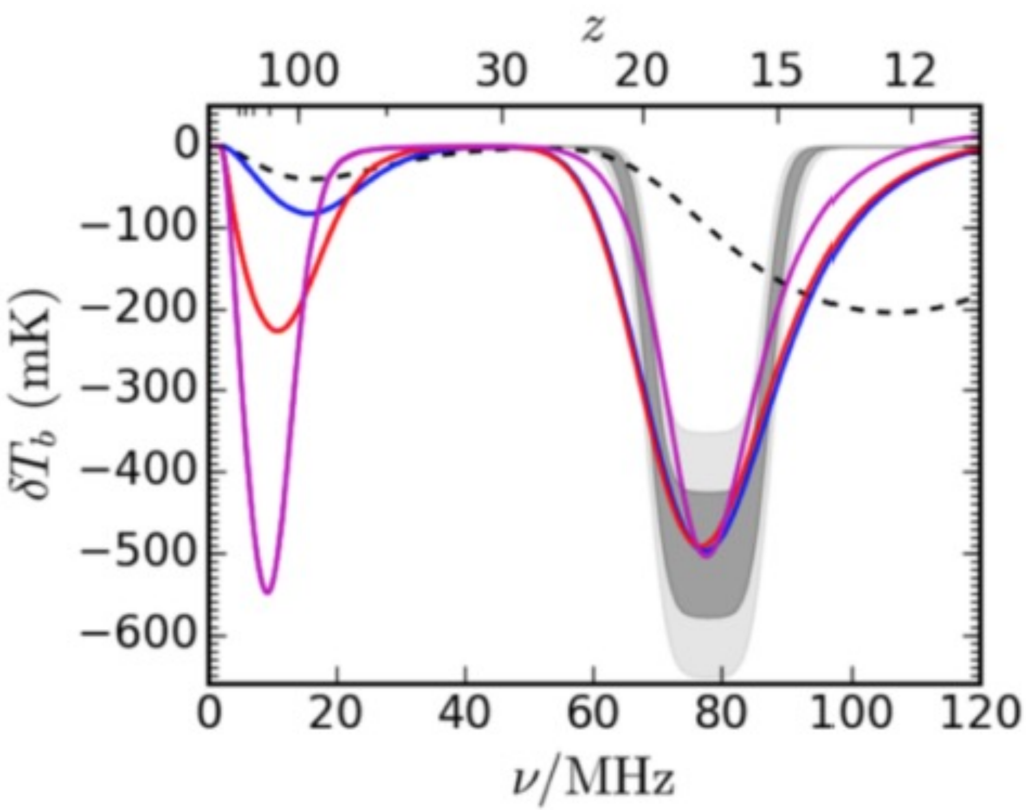


Figure 1: **The Dark Ages 21-cm absorption feature is a sensitive probe of cosmology.** The black dashed line shows the mean 21-cm brightness temperature (averaged across the sky) in a "standard" model of cosmology. The shape at $z \gtrsim 30$ is independent of astrophysical sources. The gray contours show schematically the reported EDGES absorption signal [4]. The solid curves are phenomenological models that invoke extra cooling to match the amplitude of the EDGES signal (as in [22]) but that also dramatically affect the Dark Ages absorption trough at $z > 50$.

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

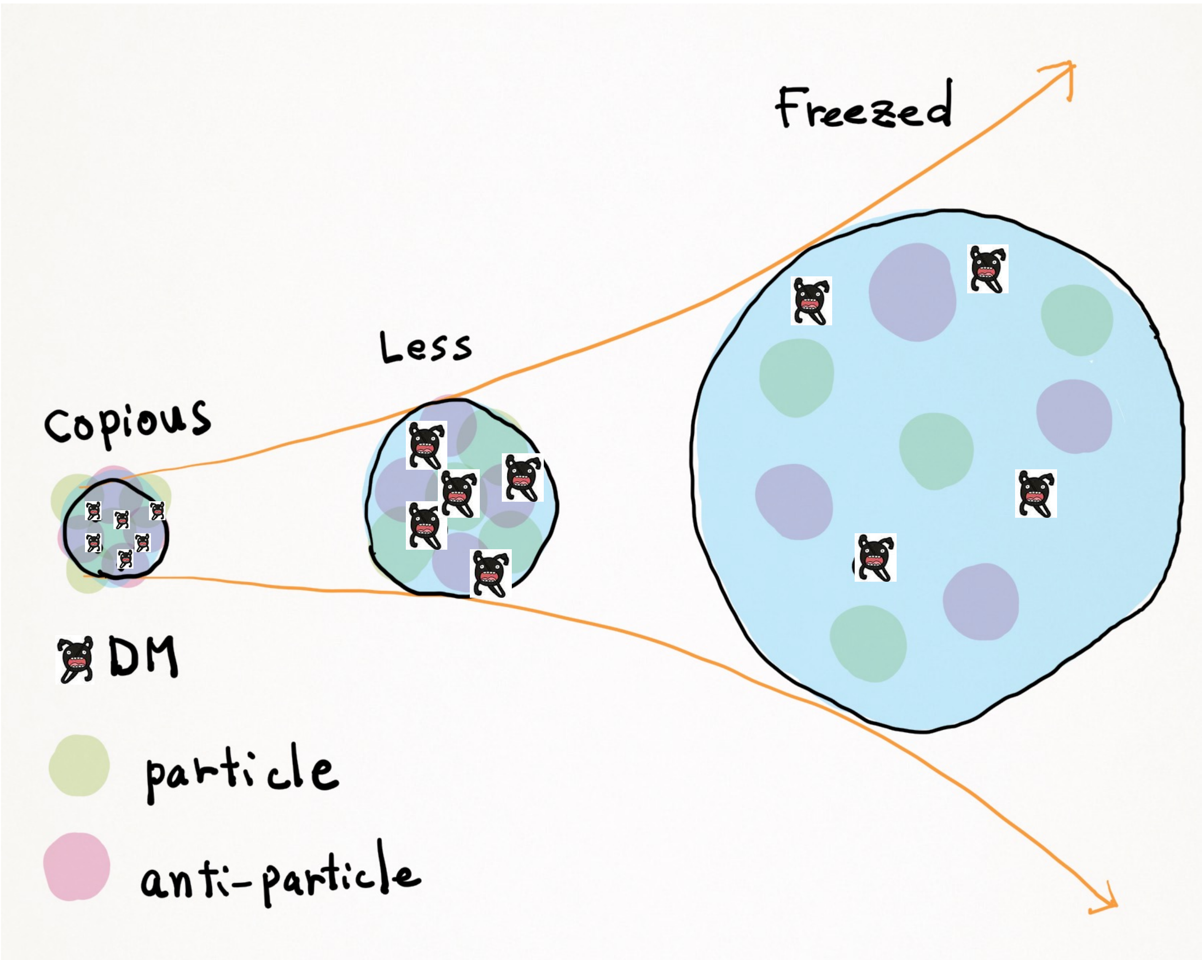
At least they did not report any emission lines!

Annihilating WIMP

https://commons.wikimedia.org

Neutralino χ, a candidate of WIMP (SUSY partner of photon/Z/Higgs)

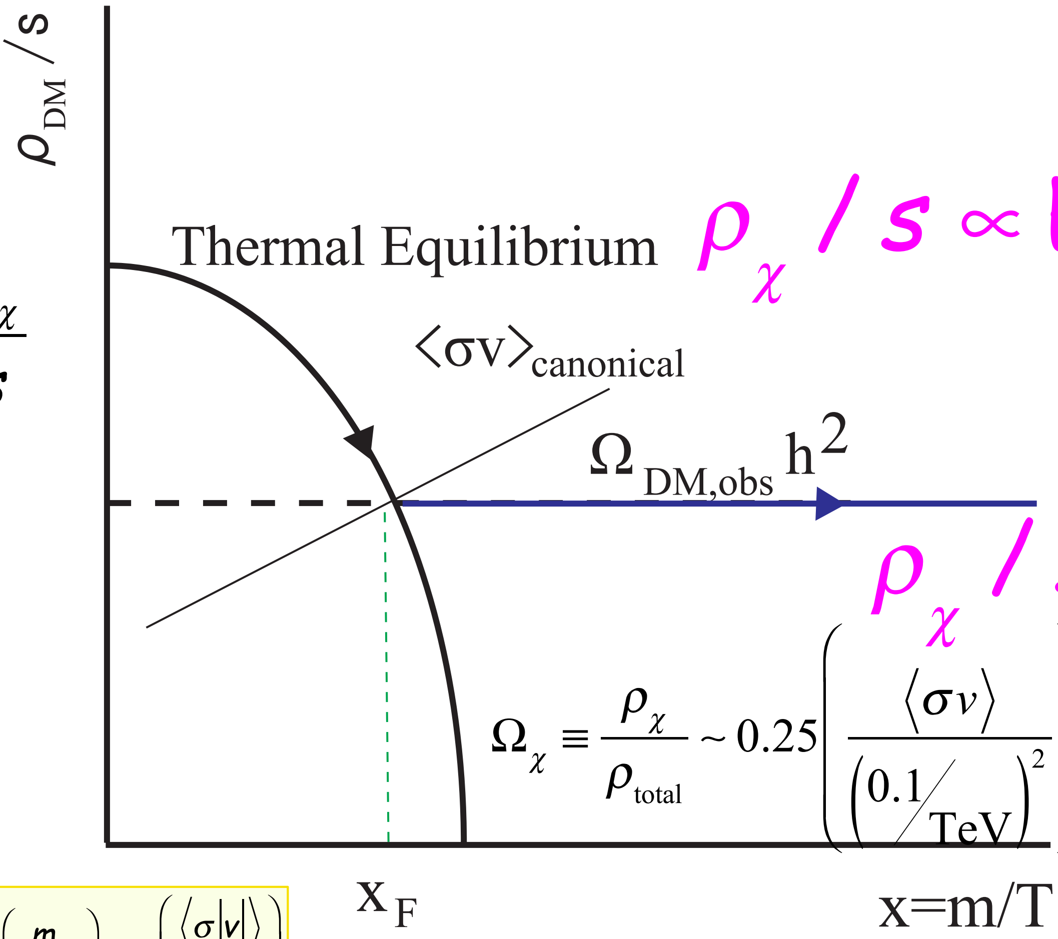
- Freezeout in the expanding Universe



Thermal freeze out of WIMP

$$\frac{\rho_{DM}}{s} = m\,\frac{n_\chi}{s}$$

($\rho_{DM} \propto a^3$, $s \propto a^3$)



$$\rho_\chi / s \propto \mathrm{Exp}[-m/T]$$

$$\rho_\chi / s \to \mathrm{const.}$$

$$\Omega_\chi \equiv \frac{\rho_\chi}{\rho_{total}} \sim 0.25\left(\frac{\langle\sigma v\rangle}{\left(0.1/\mathrm{TeV}\right)^2}\right)^{-1}$$

$$x_F \equiv \frac{m}{T_F} \sim 24 + \ln\left(\frac{m}{\mathrm{TeV}}\right) + \ln\left(\frac{\langle\sigma|v|\rangle}{\mathrm{TeV}^{-2}}\right)$$

Canonical cross section

$$\langle\sigma|v|\rangle_{canonical} = 3\times10^{-26}\,\frac{cm^3}{sec} \sim \frac{0.3^4}{(\mathrm{TeV})^2}$$

Energy injection by annihilating dark matter

- Injection rate

$$\frac{dE_{\rm inj}}{dV\,dt} = \bar{\rho}_{\rm DM}^2 B(z) \frac{\langle \sigma v \rangle}{m_{\rm DM}}$$

- Boost factor

$$B(z) = \langle \rho_{\rm DM}^2 \rangle / \bar{\rho}_{\rm DM}^2$$

- Thermal average cross section <σv> into SM+SM

$$\mathrm{DM} + \overline{\mathrm{DM}} \to \mathrm{SM} + \overline{\mathrm{SM}}$$

$$(\ W^+W^-,\ b\bar{b},\ e^+e^-,\ \gamma\gamma\ )$$

$$\frac{dE_{\rm inj}}{dV\,dt} \sim 10^{-21} \mathrm{eV/sec/cm^3}$$

$$\times \left(\frac{B(z)}{10^2}\right) \left(\frac{1+z}{18}\right)^6 \left(\frac{\langle \sigma v \rangle}{2 \times 10^{-26}\ \mathrm{cm^3/sec}}\right) \left(\frac{\Omega_{\rm DM} h^2}{0.12}\right)^2 \left(\frac{m_{\rm DM}}{10^2 \mathrm{GeV}}\right)^{-1}$$

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

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

$$T_{21{\rm cm}}(z) = \frac{T_s(z) - T_\gamma(z)}{1+z}\tau_{21{\rm cm}}(z) \qquad \Gamma_C = \frac{8\sigma_T a_r T_\gamma^4}{3m_e}\frac{x_e}{1+f_{\rm He}+x_e}$$

N-body simulation: Cosmological boost factor for dark matter annihilation at redshifts of z = 10–100 using the power spectrum approach

Ryuichi Takahashi, Kazunori Kohri, arXiv:2107.00897 [astro-ph.CO]

- Cosmological boost factor for DM annihilation

$$\rho(\boldsymbol{x};z) = \bar{\rho}(z)[1+\delta(\boldsymbol{x};z)]$$

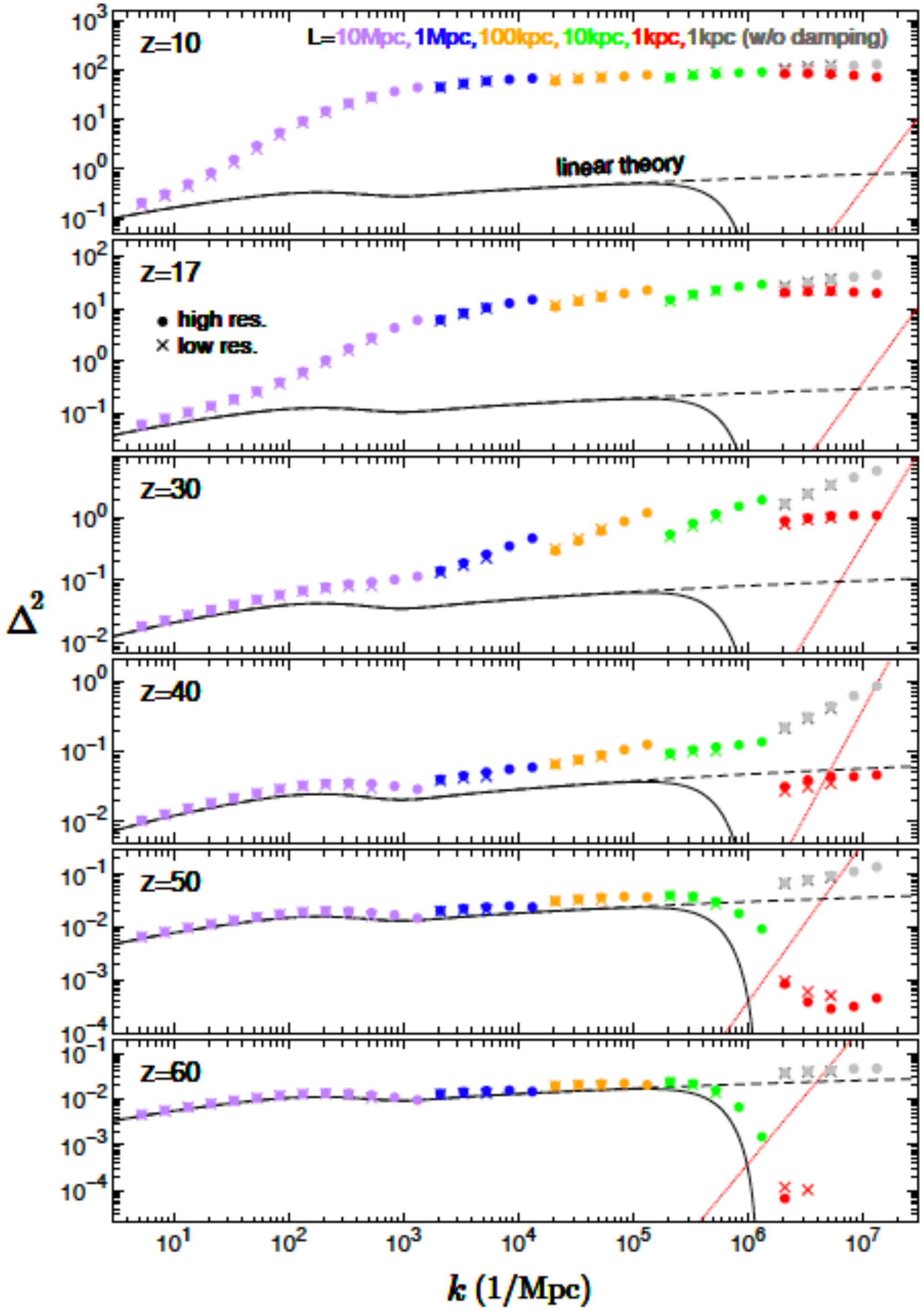
$$\langle\rho^2(\boldsymbol{x};z)\rangle = \bar{\rho}^2(z)B(z)$$

$$B(z) = 1 + \int_0^\infty d\ln k\,\Delta^2(k;z)$$

- Power spectrum $P_{\rm L}(k;z) = A\left(\frac{k}{k_*}\right)^{n_{\rm s}} D_+^2(z)\,T^2(k;z)\,D_{\rm fs}^2(k)$

L	$N_{\rm p}$	$2\pi/L$ [Mpc^{-1}]	$k_{\rm Ny}$ [Mpc^{-1}]	$m_{\rm p}$ [$M_\odot$]
10 Mpc	5120^3 (2560^3)	0.63	1.6×10^3 (800)	29 (230)
1 Mpc	5120^3 (2560^3)	6.3	1.6×10^4 (8.0×10^3)	2.9×10^{-2} (0.23)
100 kpc	5120^3 (2560^3)	63	1.6×10^5 (8.0×10^4)	2.9×10^{-5} (2.3×10^{-4})
10 kpc	5120^3 (2560^3)	630	1.6×10^6 (8.0×10^5)	2.9×10^{-8} (2.3×10^{-7})
1 kpc	5120^3 (2560^3)	6.3×10^3	1.6×10^7 (8.0×10^6)	2.9×10^{-11} (2.3×10^{-10})

$$\hat{P}(k;z) = \frac{1}{N_{\rm mode}}\sum_{|\boldsymbol{k}'|\in k}\left|\tilde{\delta}(\boldsymbol{k}';z)\right|^2$$

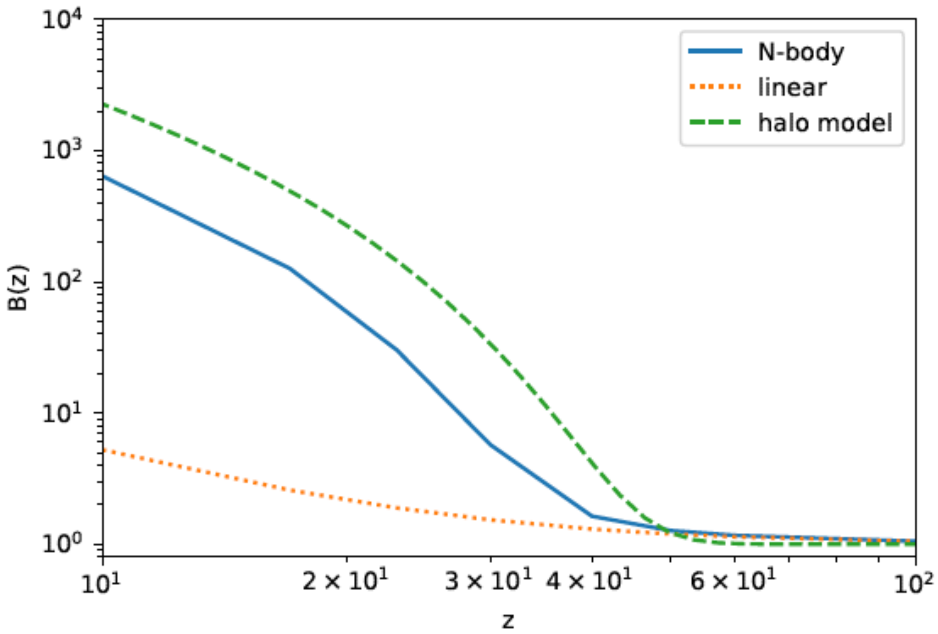


Ryuichi Takahashi, Kazunori Kohri, arXiv:2107.00897 [astro-ph.CO]

Boost factor of small-scale halos

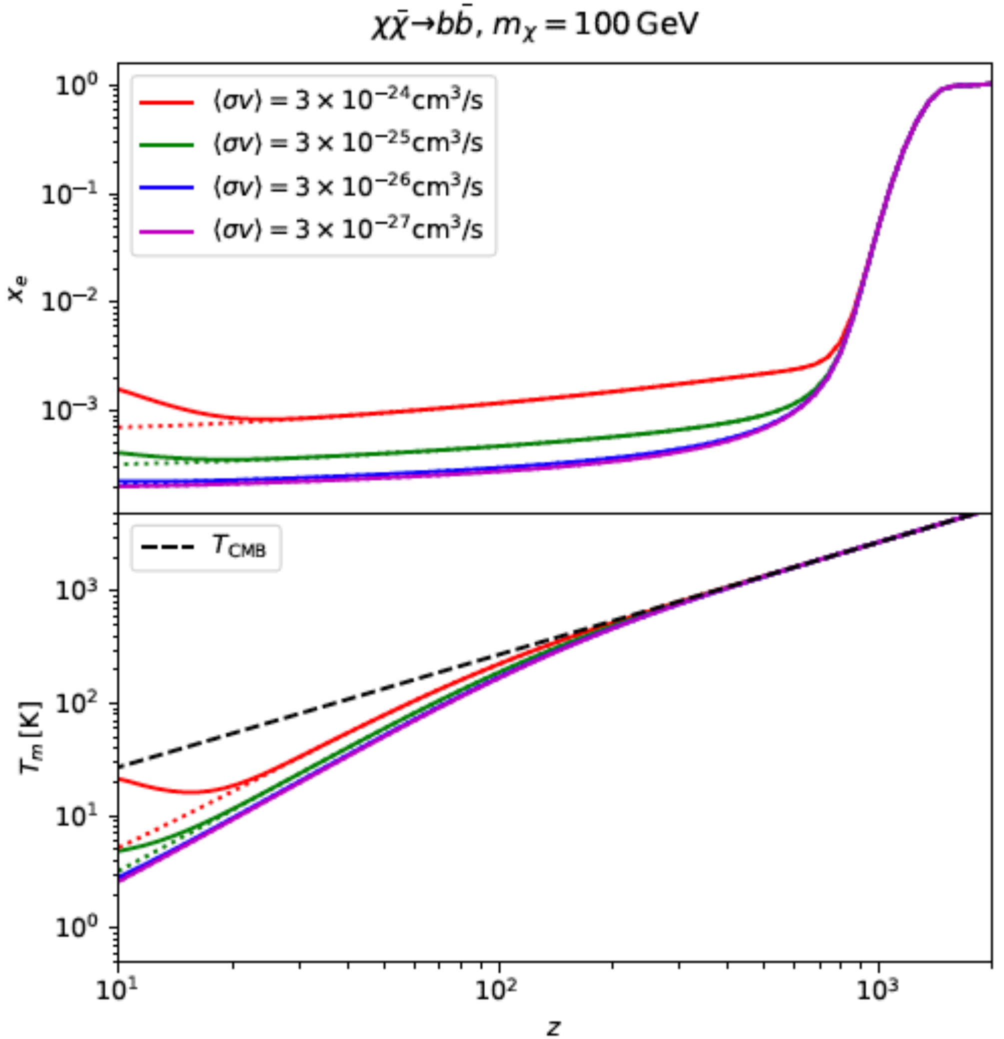
Ryuichi Takahashi, Kazunori Kohri, arXiv:2107.00897 [astro-ph.CO]

$$B(z) = 1 + \int_0^\infty \frac{dk}{k} \Delta^2(k; z)$$



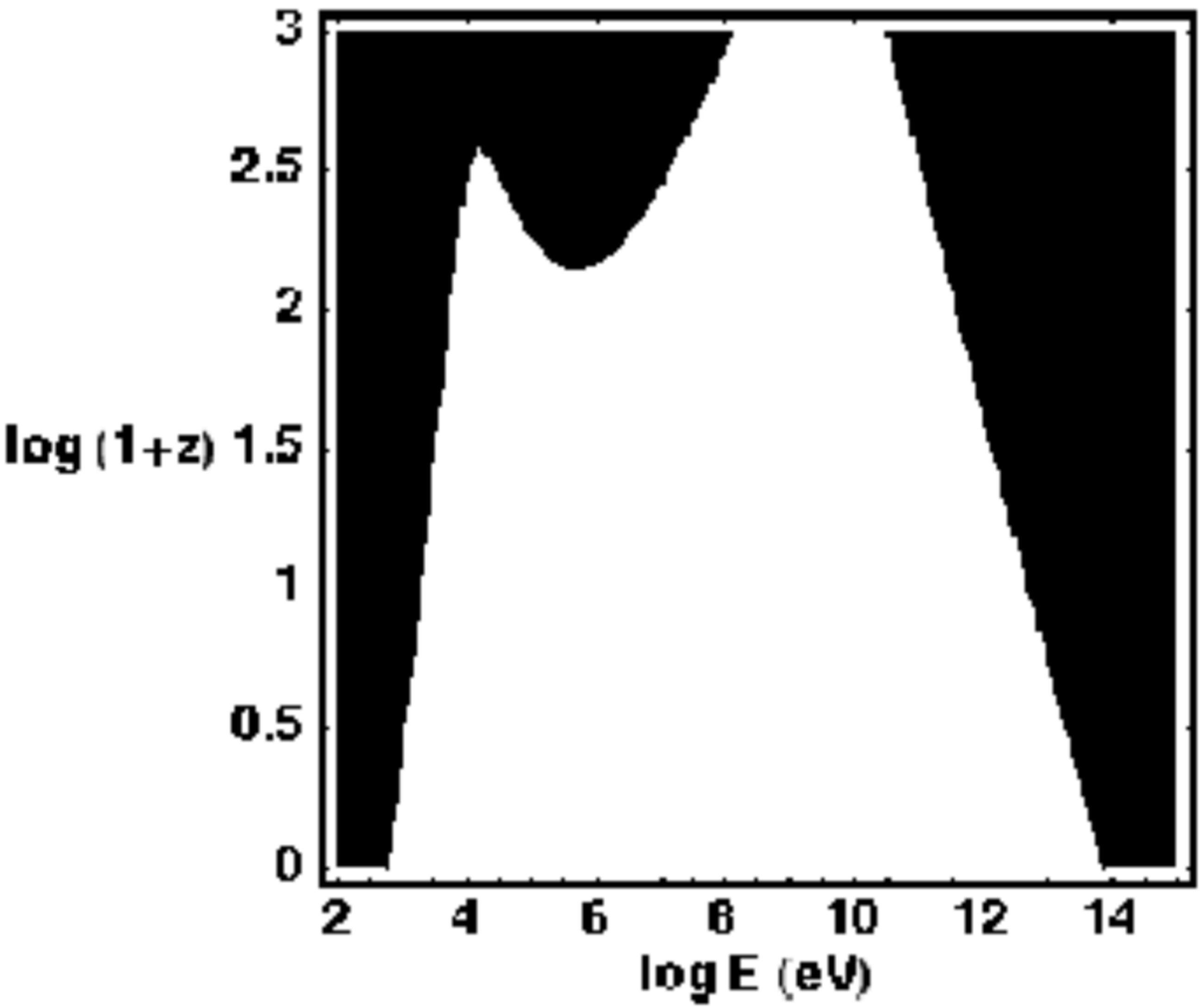
History of free electron ratio and temperature

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



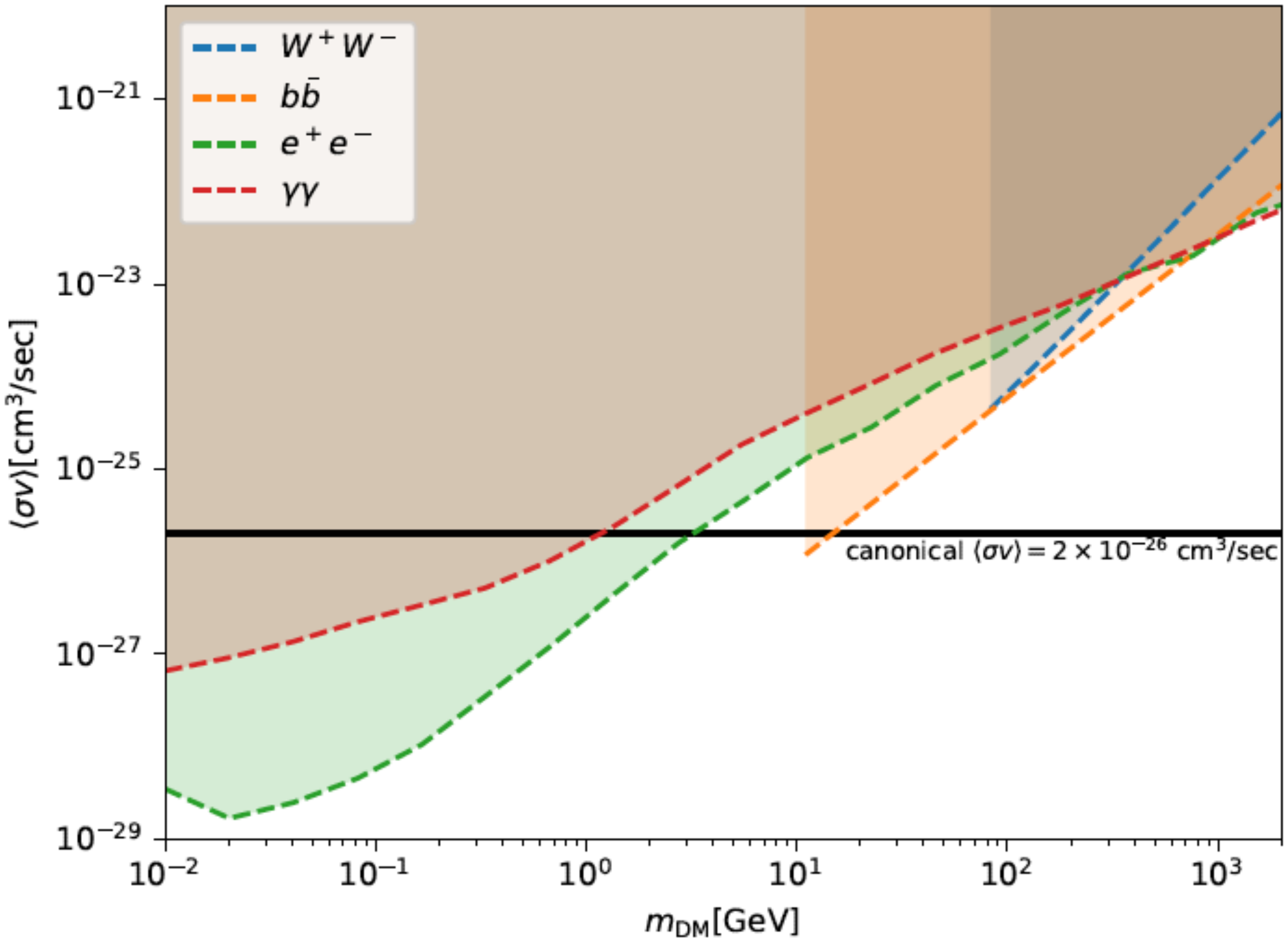
X-rays are absorbed by cosmological plasma at z > 10

X. Chen and M. Kamionkowski, 2003



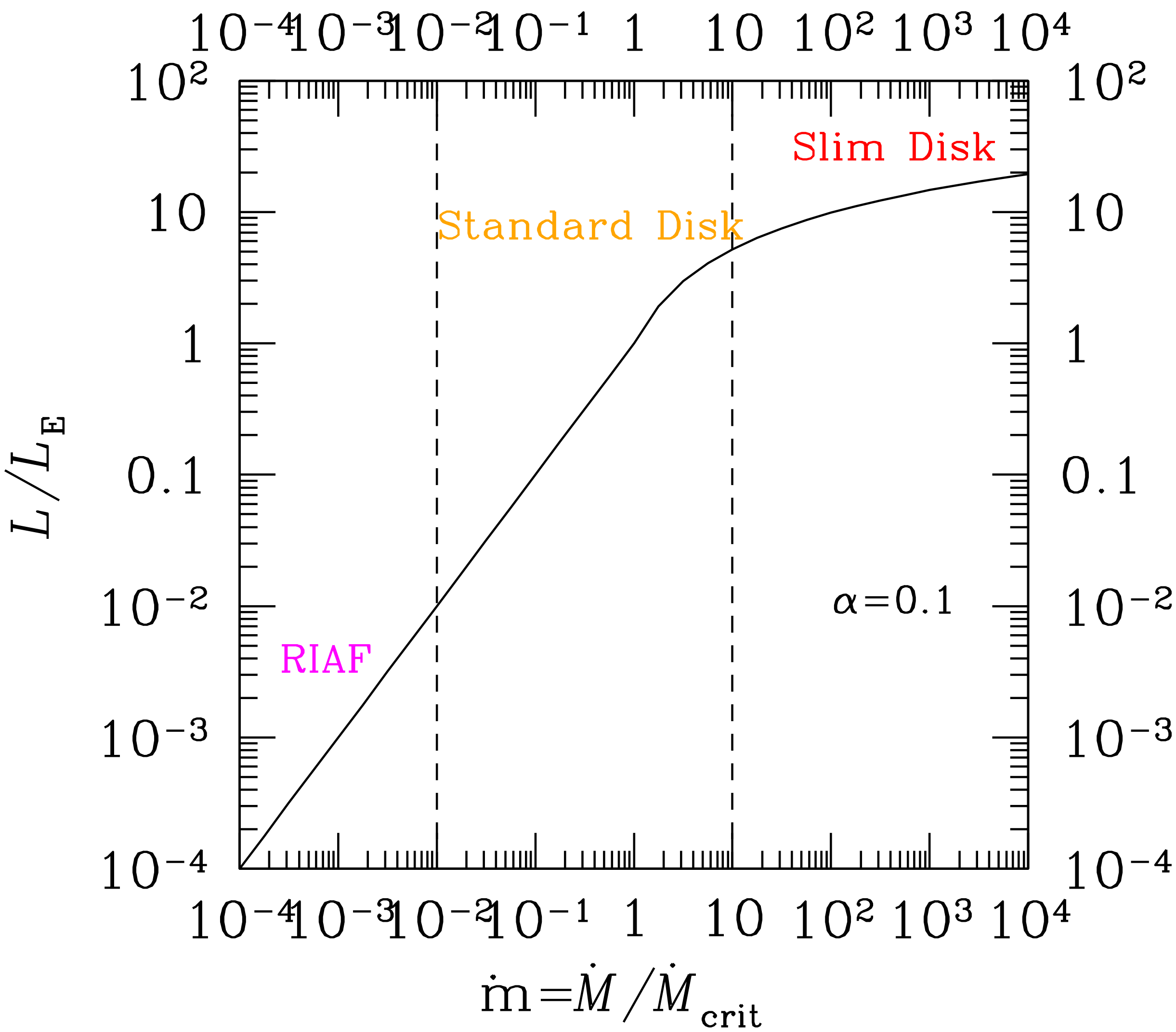
Upper bounds on annihilating cross section of dark matter

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



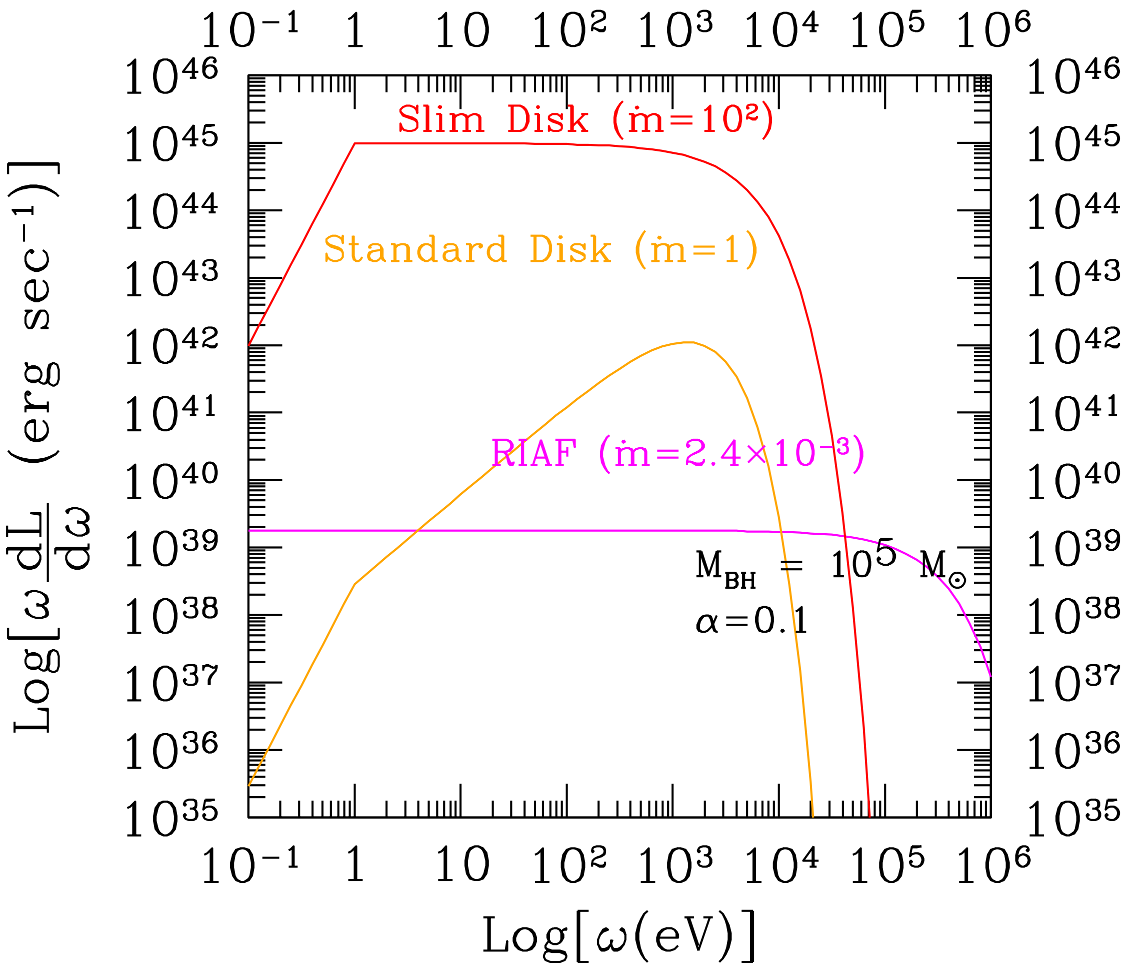
Emissions from
Super-Eddington accretion disks

Luminosity



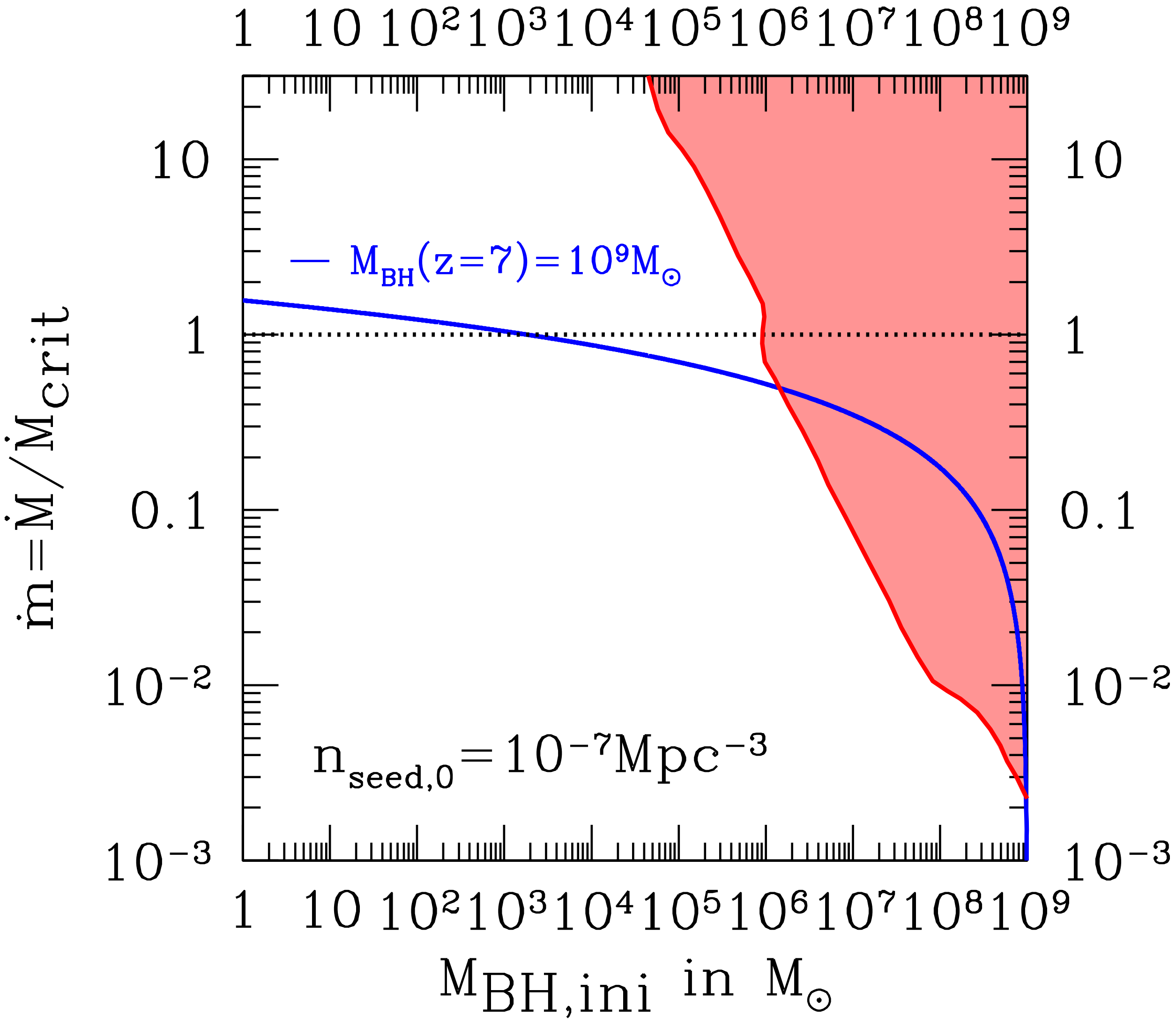
Slim Disk
Standard Disk
RIAF
α=0.1
L/L_E
$\dot{m}=\dot{M}/\dot{M}_{crit}$
10⁻⁴ 10⁻³ 10⁻² 10⁻¹ 1 10 10² 10³ 10⁴
10² 10 1 0.1 10⁻² 10⁻³ 10⁻⁴

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



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]



Primordial Black Holes (PBHs)?

Future possible 21cm bounds on evaporating PBHs

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

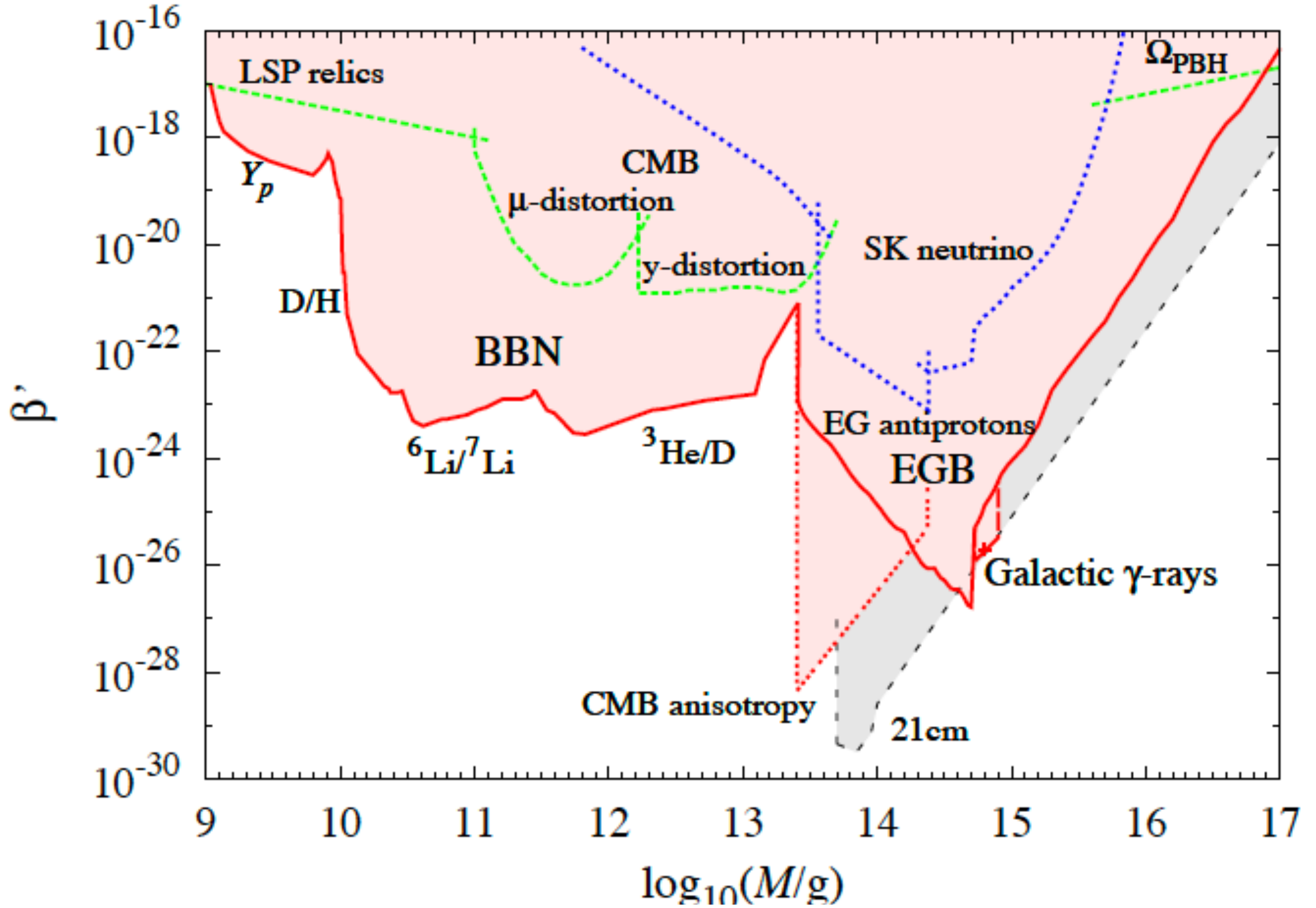


FIG. 6. Combined BBN and EGB limits (solid red), compared to other constraints on evaporating PBHs from LSP relics and CMB distortions (short-dashed green), extragalactic antiprotons and neutrinos (dotted blue), the Galactic γ-ray background, and CMB anisotropies (long-dashed and broken red), and the potential 21 cm limit (broken grey). The density limit from the smallest unevaporated black holes is also shown (short-dashed green) to show where it crosses the background photon limit. The solid red and dotted blue limits are original to this paper.

Lyman-alpha hearting by evaporating PBHs

Akash Kumar Saha, Abhijeet Singh, Priyank Parashari, Ranjan Laha, arXiv:2409.10617 [astro-ph.CO]

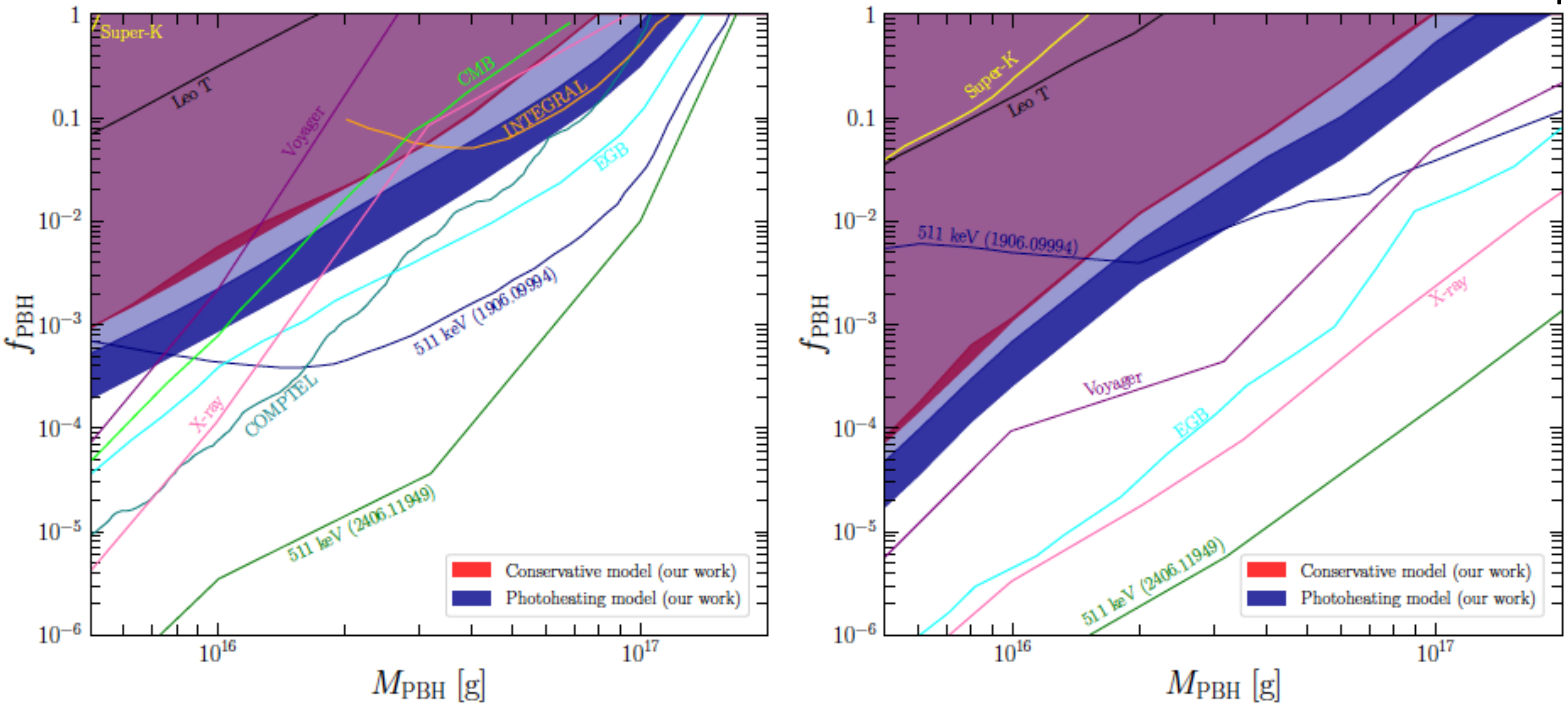
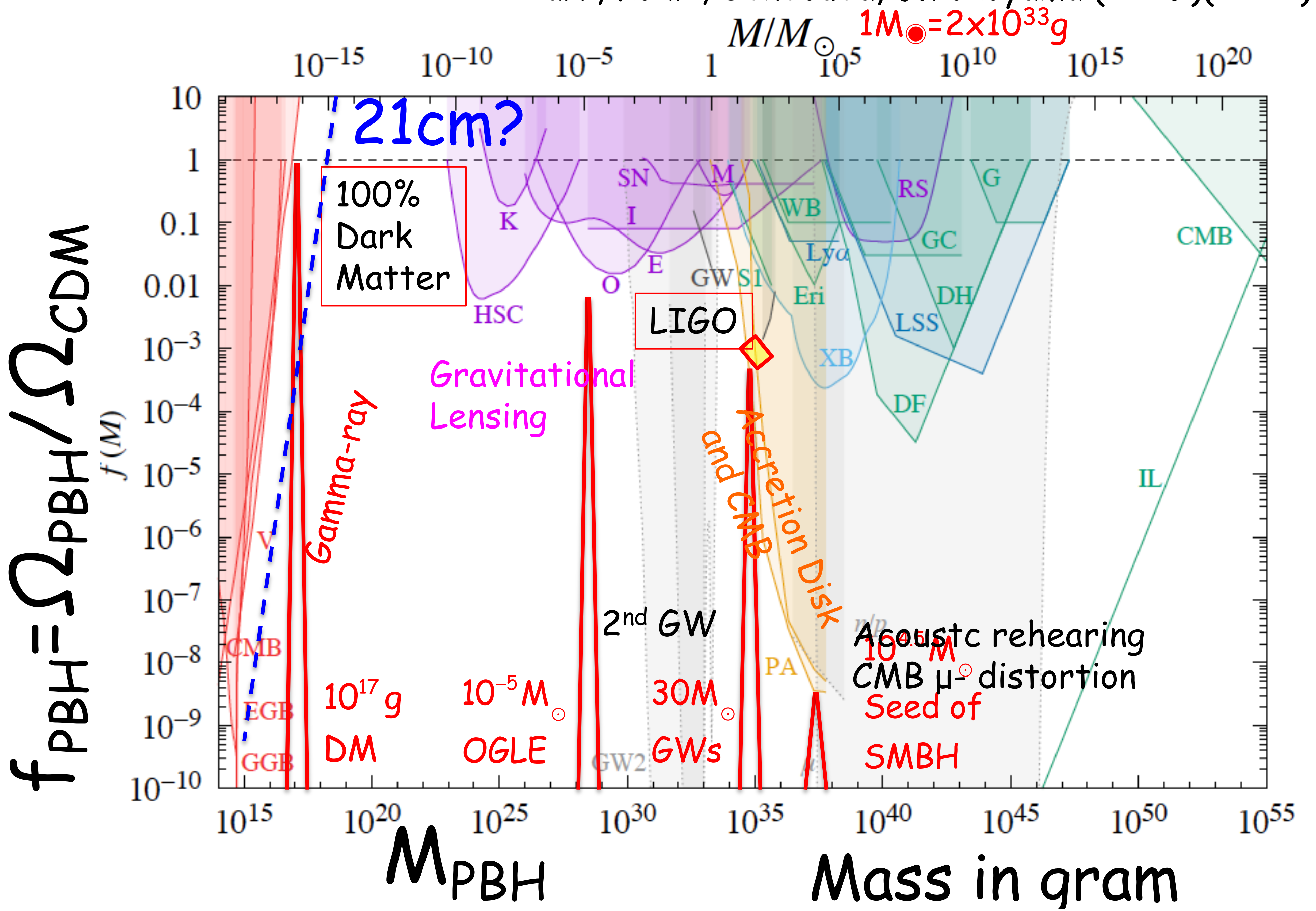


Figure 2. Constraints on non-spinning ($a_* = 0$) (left panel) and spinning ($a_* = 0.9999$) (right panel) PBH DM (monochromatic mass distribution). Constraints from the conservative model are shown in red (deep red and the shaded region above that), whereas the photoheating model limits are shown in blue (deep blue and the shaded region above that). The deep blue and deep red bands are obtained by varying over the photoheating models used in this work (FlexKnot [4], Tanh [4], and Trac [108, 109]). Previous constraints include low-energy positron measurements from Galactic Centre by INTEGRAL (navy [43] and green [112]), cosmic-ray flux measurement by Voyager (purple) [112], INTEGRAL (orange) and COMPTEL (teal) measurements of the Galactic gamma-ray flux [45, 46], Super-Kamiokande limit for diffuse supernovae neutrino background (yellow) [47], measurement of extra-Galactic gamma-ray emission (aqua) [48, 49], gas heating in Leo T (black) [50, 51], PLANCK measurement of CMB (lime) [54], and XMM-NEWTON measurement of Galactic diffuse X-ray emission (pink) [112]. Some of the bounds for non-spinning PBH DM are absent for spinning PBH DM simply because they have not been derived in the literature.

Upper bounds on the fraction to CDM

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



Conclusion

- We can conservatively exclude the masses of WIMP dark matter

  $m < 15$ GeV (quark-antiquark emission)

  $m < 3$ GeV (electron-positron emission)

- Cosmological 21cm can allow the super-Eddington accretions on to seed BHs ($m_{BH} < 10^6 M_\odot$) to be evolved to SMBHs until z=7

- 21cm global signals will potentially exclude 10^{18} g PBH dark mater