Photon axion enhancement around PBH

Ongoing working (2605.xxxx)

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The 8th Mini-Workshop on Chirality in the Universe Beyond the Electroweak Scale, 2026-04-25

Motivation

The search for PBH-ALP DM co-existence

- **Co-existence:** The dark matter (DM) can be composed of both *Primordial Black Holes (PBHs)* and *Axion-Like Particles (ALPs)*.

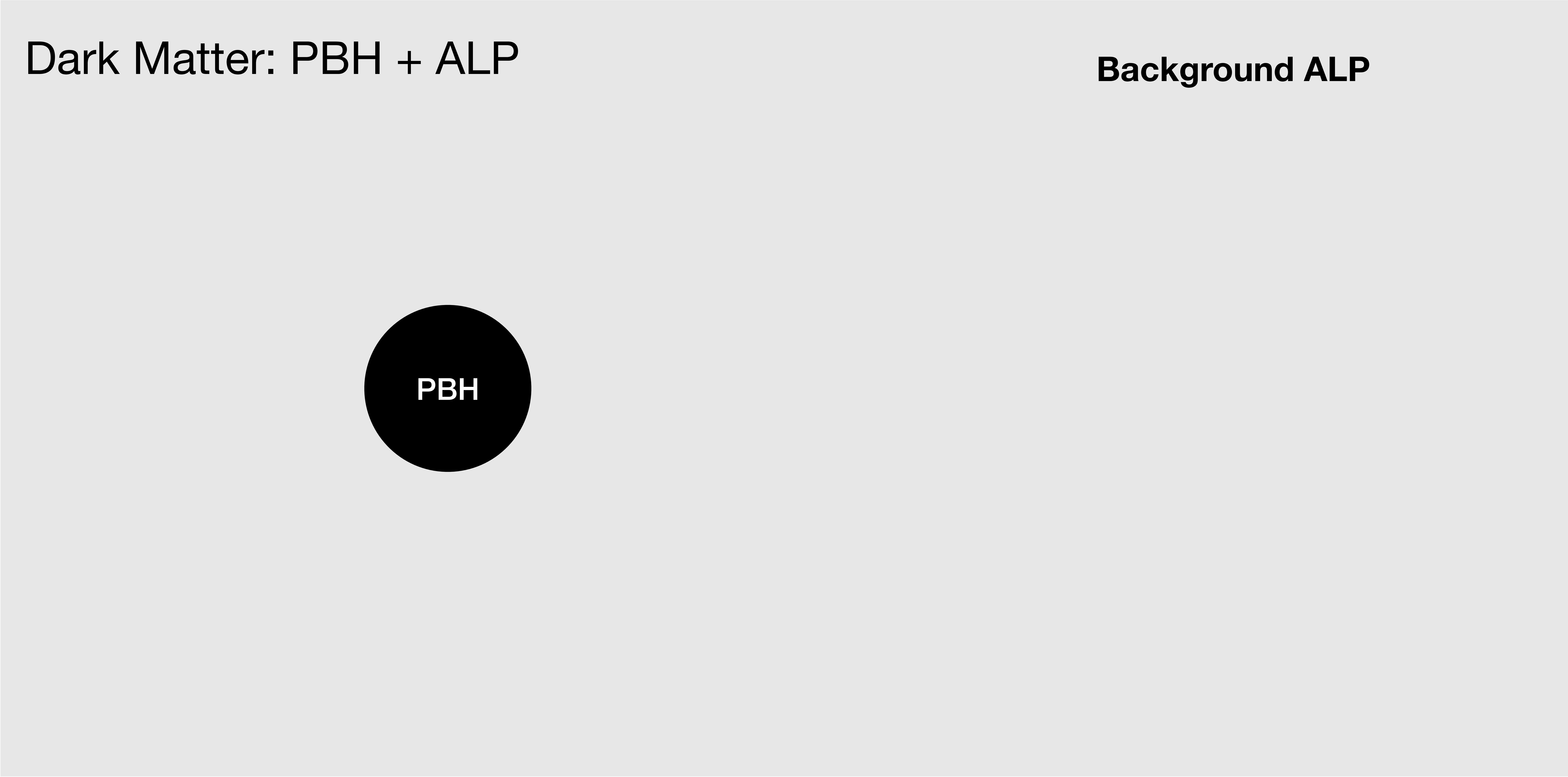
- **Gravitational Capture:** PBHs seeded by early density perturbations gravitationally capture surrounding ALPs, forming dense "*mini-halos*".

- **Density Contrast:** These PBH-induced halos are significantly denser than standard NFW profiles; they *scale as* $\sim r^{-9/4}$ in the inner regions, compared to the $\sim r^{-1}$ scaling of an NFW core.

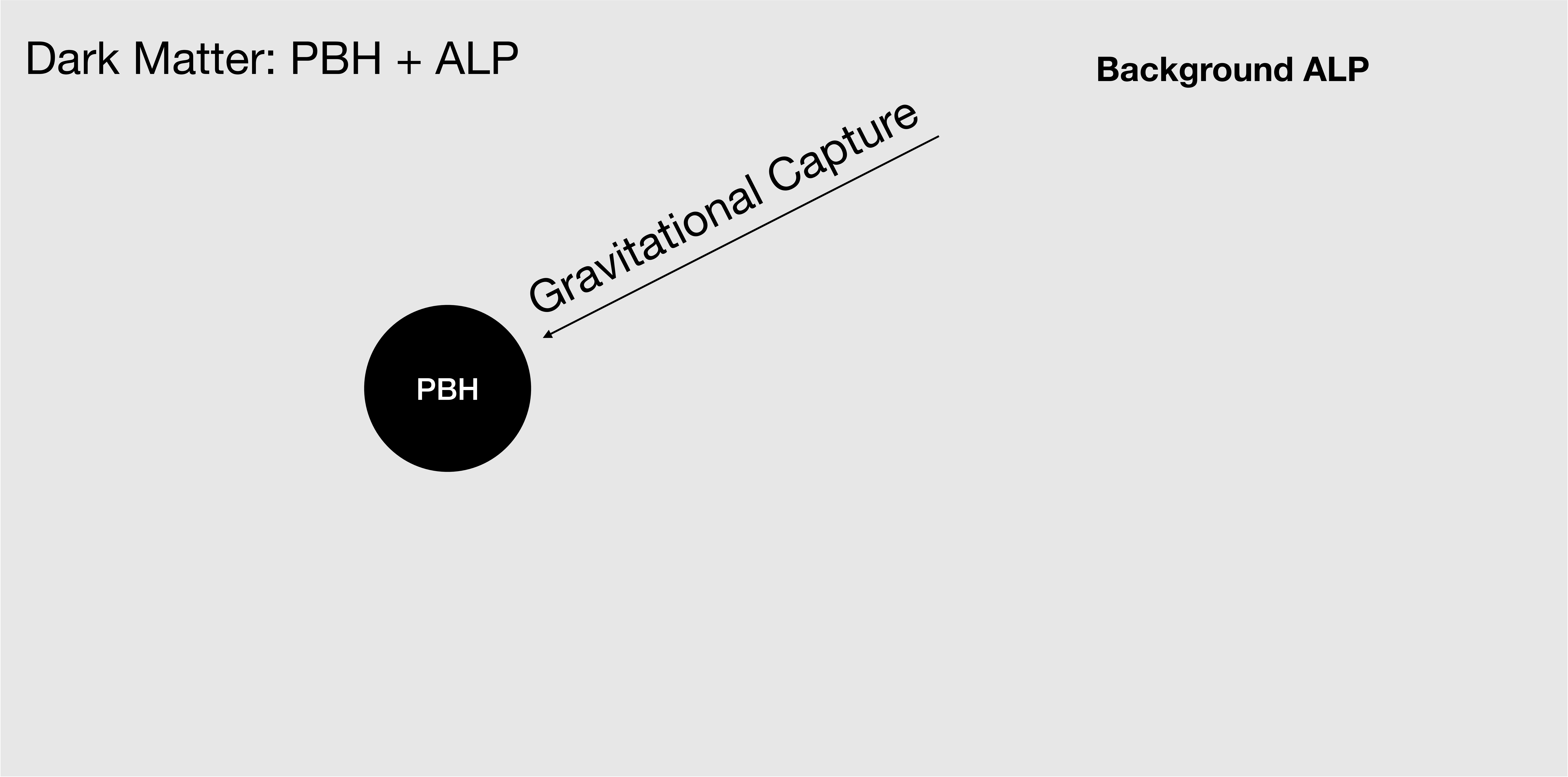
- **Photon Enhancement:** The density in these halos *enhances ALP decay.*

- **Observable Flux:** This enhancement produces a *detectable photon flux* that reaches Earth, providing a signature for searching for or constraining both PBHs and ALPs.

PBH Halo



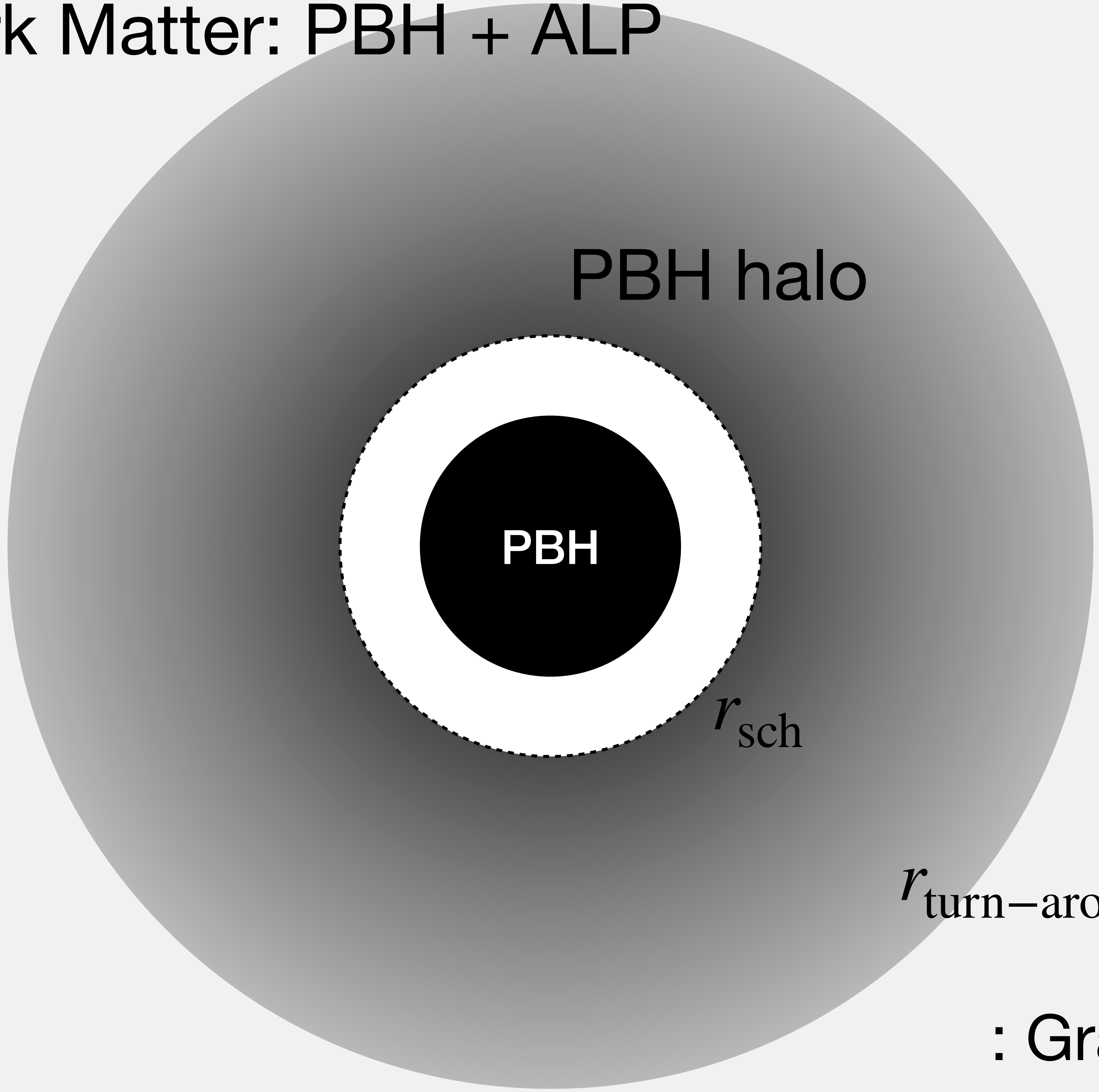
PBH Halo


Dark Matter: PBH + ALP
Background ALP
Gravitational Capture
PBH

PBH Halo

Dark Matter: PBH + ALP

Background ALP



$$r_{\text{turn-around}} \simeq (r_{\text{sch}} t^2)^{1/3}$$

Adamek et al., Phys.Rev.D 100 (2019) 2, 023506

: Gravity = Expansion

PBH Halo

Dark Matter: PBH + ALP

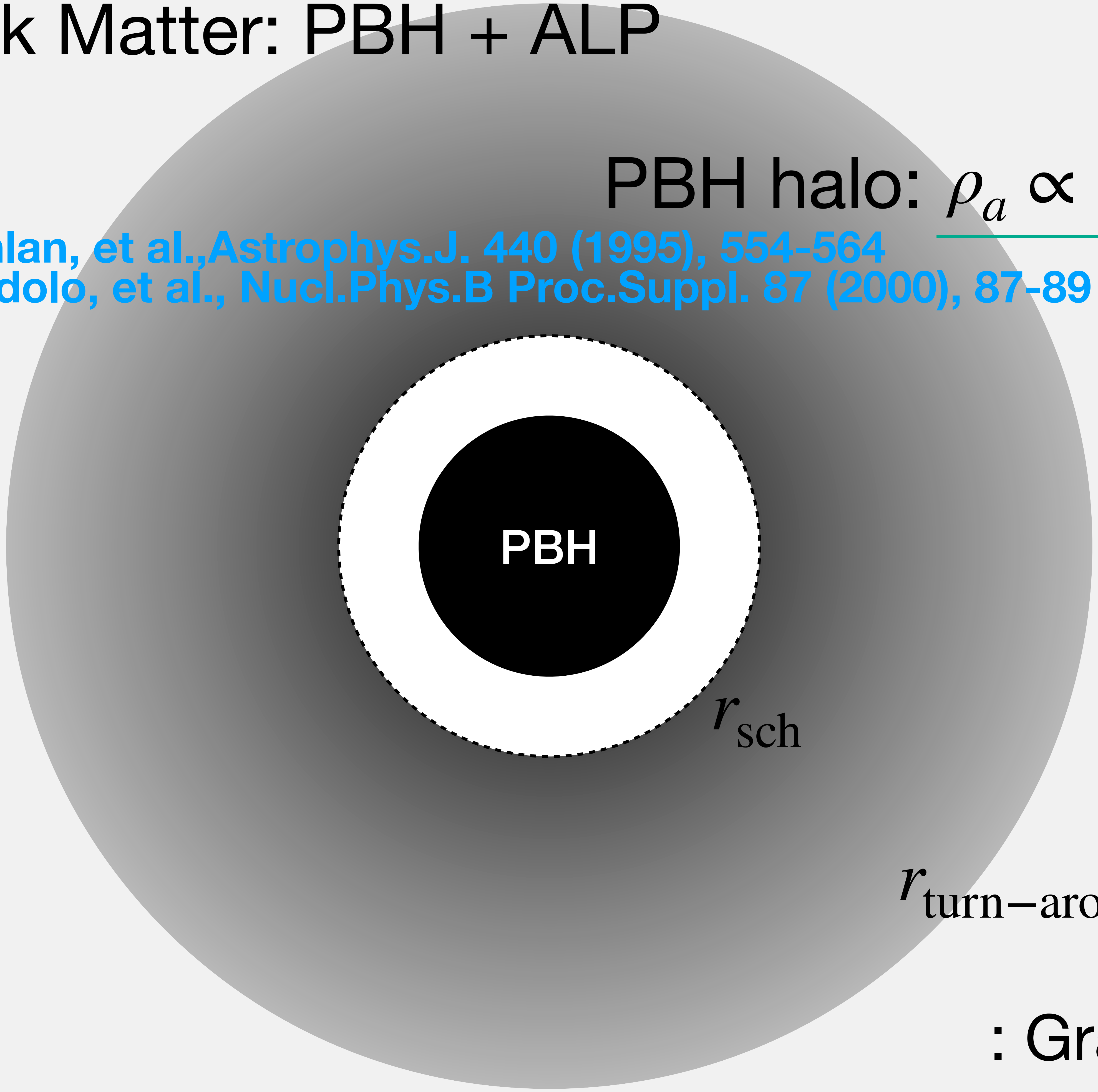
Background ALP

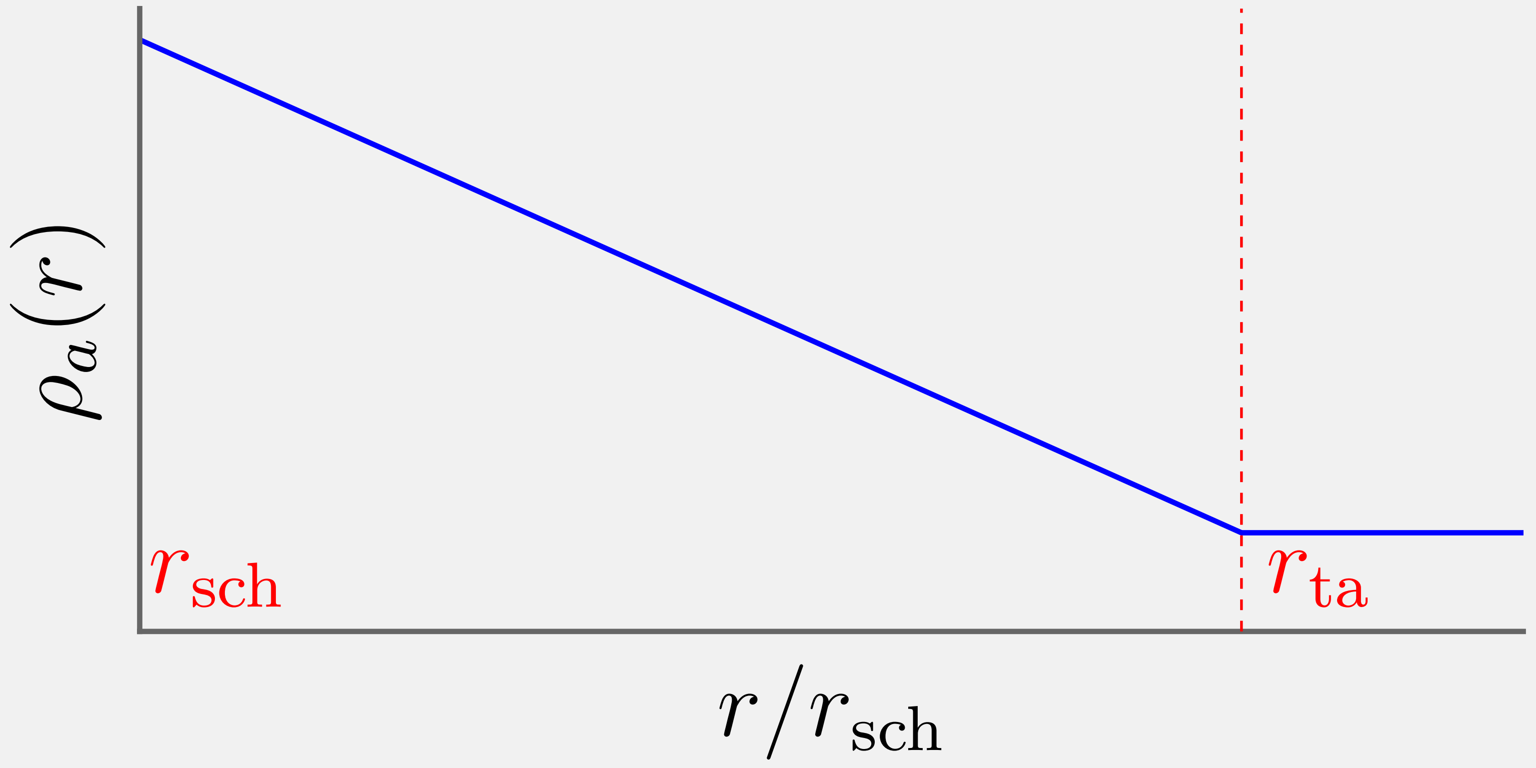
PBH halo: $\rho_a \propto r^{-9/4}$

Background: const.

Quinlan, et al.,Astrophys.J. 440 (1995), 554-564
Gondolo, et al., Nucl.Phys.B Proc.Suppl. 87 (2000), 87-89

Denser than NFW profile ($\propto r^{-1}$)





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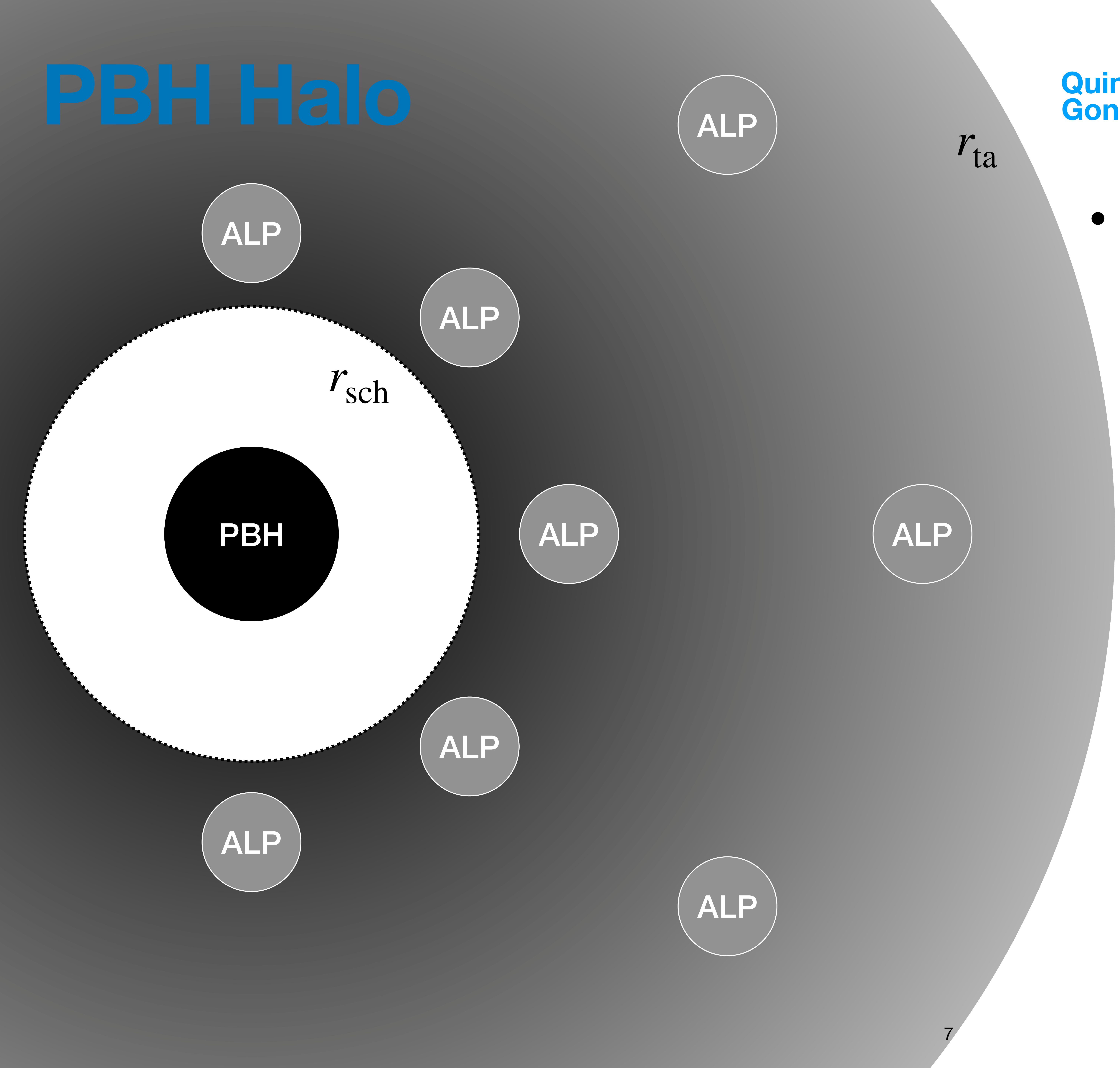

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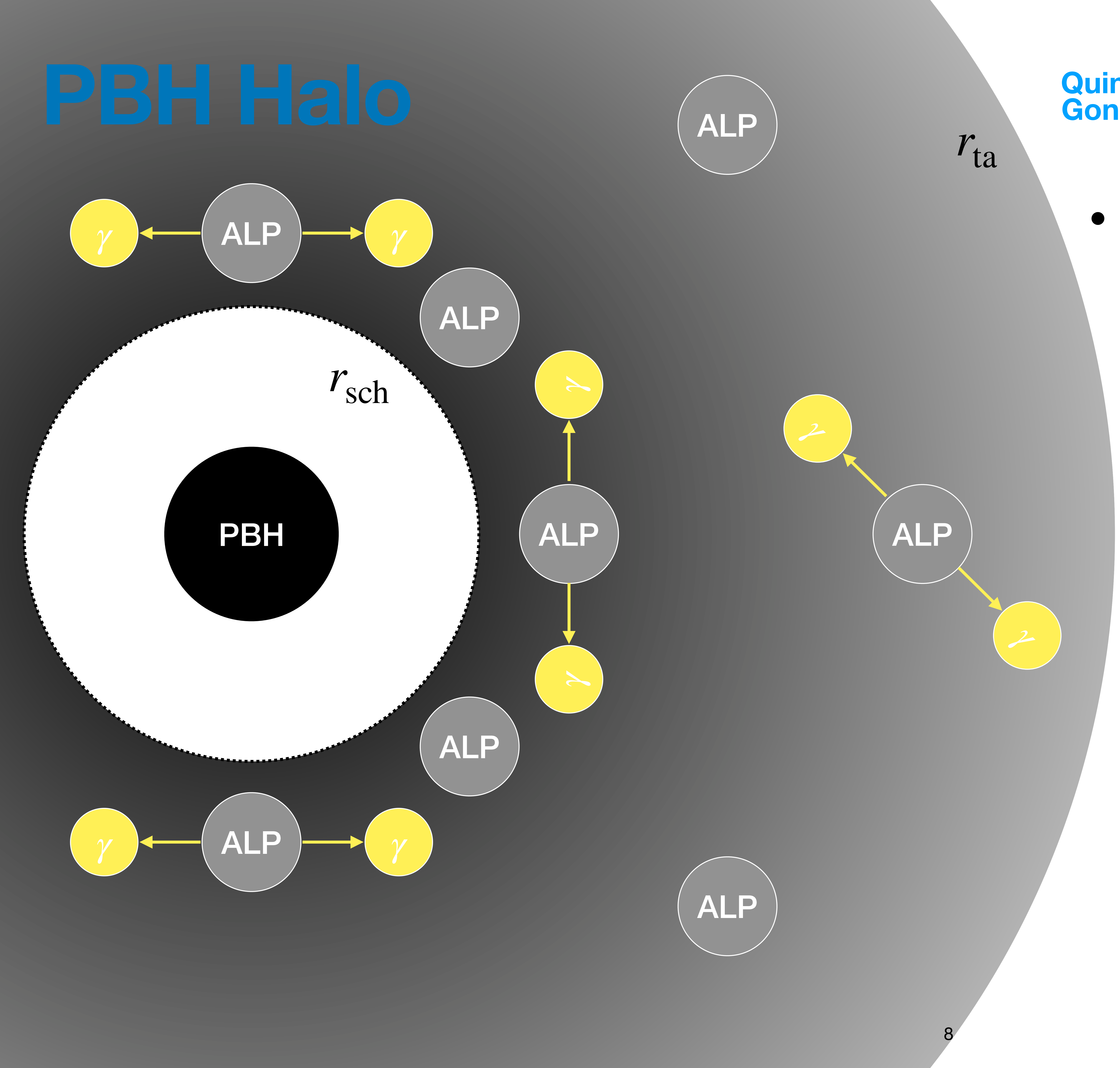
- $\rho(r) = f_{a/\rm DM} \frac{\rho_{\rm eq}}{2} \left(\frac{M_{\rm PBH}}{M_\odot} \right)^{3/4} \left(\frac{\tilde{r}}{r} \right)^{9/4}$

where $r_{\rm sch} \leq r < r_0(t)$

PBH Halo



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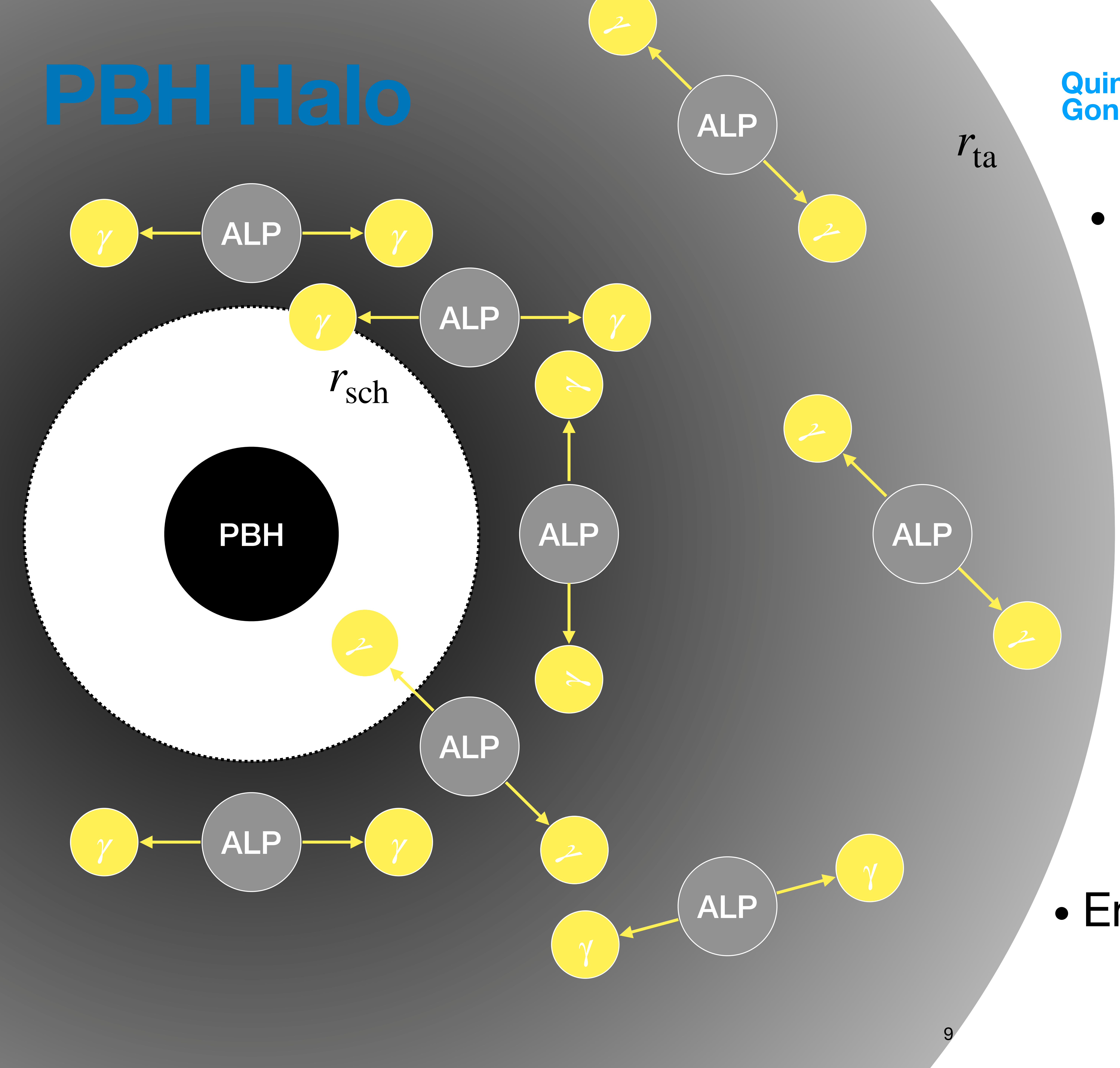
- $\mathscr{L}_{a\gamma\gamma} \supset \frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu}$

- $\omega_\gamma \simeq m_a/2$

PBH Halo



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- $\mathscr{L}_{a\gamma\gamma} \supset \frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu}\tilde{F}^{\mu\nu}$

- $\omega_\gamma \simeq m_a/2$

- Enhancement condition: $f_\gamma > 1$

Boltzmann Equation in PBH halo

- ALP energy distribution:

$$f_a(E_a, r) = \begin{cases} (2\pi)^3 \mathcal{N}(v_{\rm esc}) \dfrac{\rho_a(r)}{m_a} \dfrac{1}{2\pi m_a^2 \sigma_v^2}^{3/2} e^{-\frac{E_a^2 - m_a^2}{2m_a^2\sigma_v^2(r)}} & \text{where } \mathrm{E_a} \lesssim \mathrm{E_{max}}, \\ 0 & \text{where } E_a > E_{\max} \end{cases}$$

:Truncated Gaussian distribution

King, Astron.J. 71 (1966), 64
Eroshenko, Astron.Lett. 42 (2016) 6, 347-356

- ALP energy range:

$$|\vec{v}_a| \leq v_{\rm esc} = \sqrt{\frac{2GM_{\rm PBH}}{r}} \quad \Rightarrow \quad E_a \leq E_{a,\max} = \frac{m_a}{\sqrt{1 - v_{\rm esc}^2}}$$

- Photon energy range:

$$\omega_{\gamma,\min} \leq \omega_\gamma \leq \omega_{\gamma,\max} \quad \text{where } \omega_{\gamma,\max/\gamma,\min} = \frac{E_{a,\max} \pm \sqrt{E_{a,\max}^2 - m_a^2}}{2} = \frac{m_a(1 \pm v_{\rm esc})}{2\sqrt{1 - v_{\rm esc}^2}}$$

Boltzmann Equation in PBH halo

- Boltzmann equation for a photon with momentum ω:

$$\frac{df_\lambda(\omega)}{dt} = \frac{m_a\Gamma_a}{\omega^2}\int_{E_{\min}(\omega)}^{\infty} dE_a f_a(E_a)\left(1 + f_\lambda(\omega) + f_\lambda(E_a - \omega)\right) - \frac{m_a\Gamma_a}{\omega^2}\int_{m_a-\omega}^{\infty} d\omega'' f_\lambda(\omega) f_\lambda(\omega'') - \frac{3}{2r} f_\lambda(\omega)$$

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Production of photons

Loss of photons

Boltzmann Equation in PBH halo

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Production of photons

Stimulated decay

Spontaneous decay

Loss of photons

Back-reaction

Photon escape

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Range of ALP energy to produce photon with momentum ω

Range of photon momentum to produce ALP by annihilating with a photon ω

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Range of ALP energy to produce photon with momentum ω

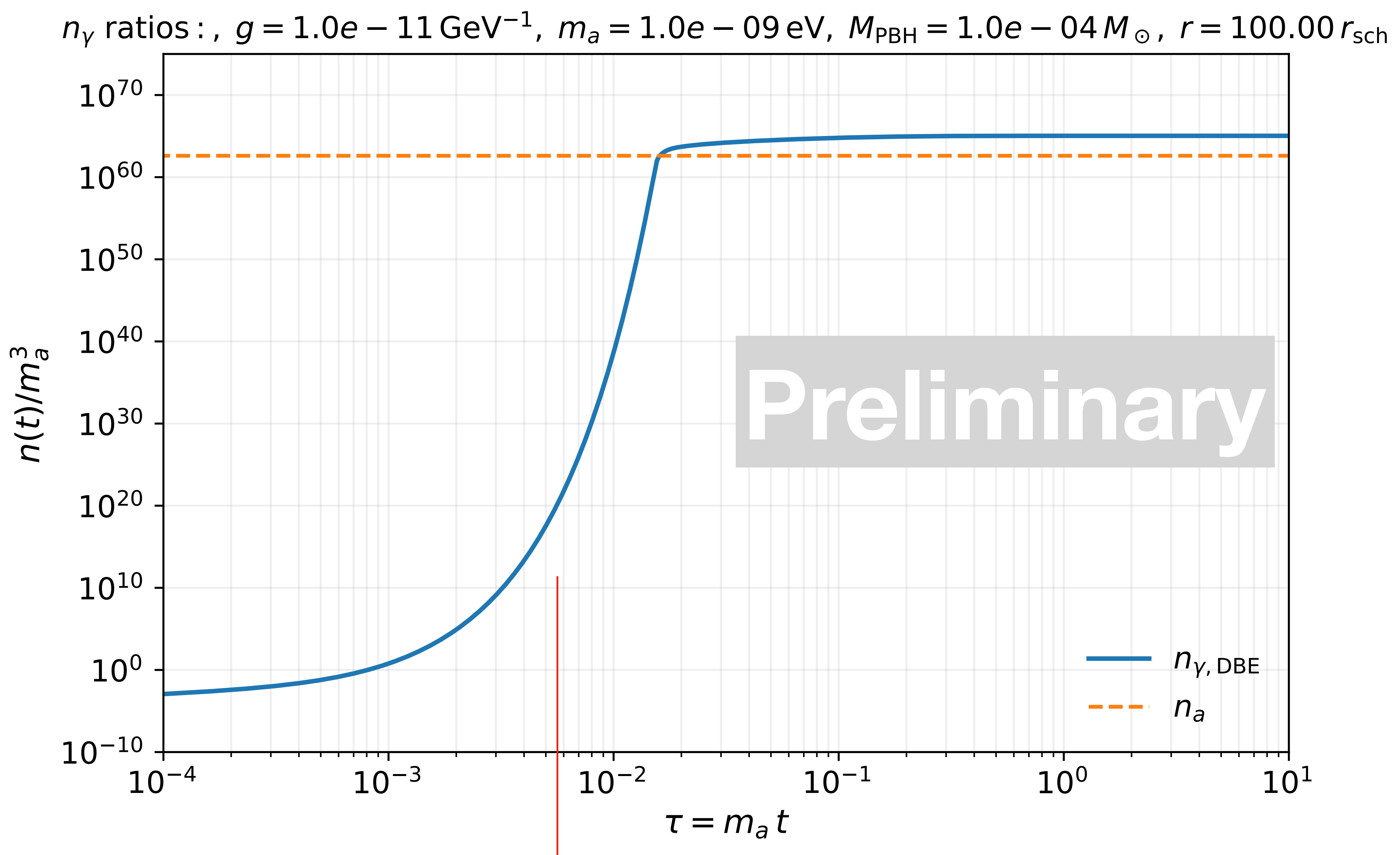
Range of photon momentum to produce ALP by annihilating with a photon ω

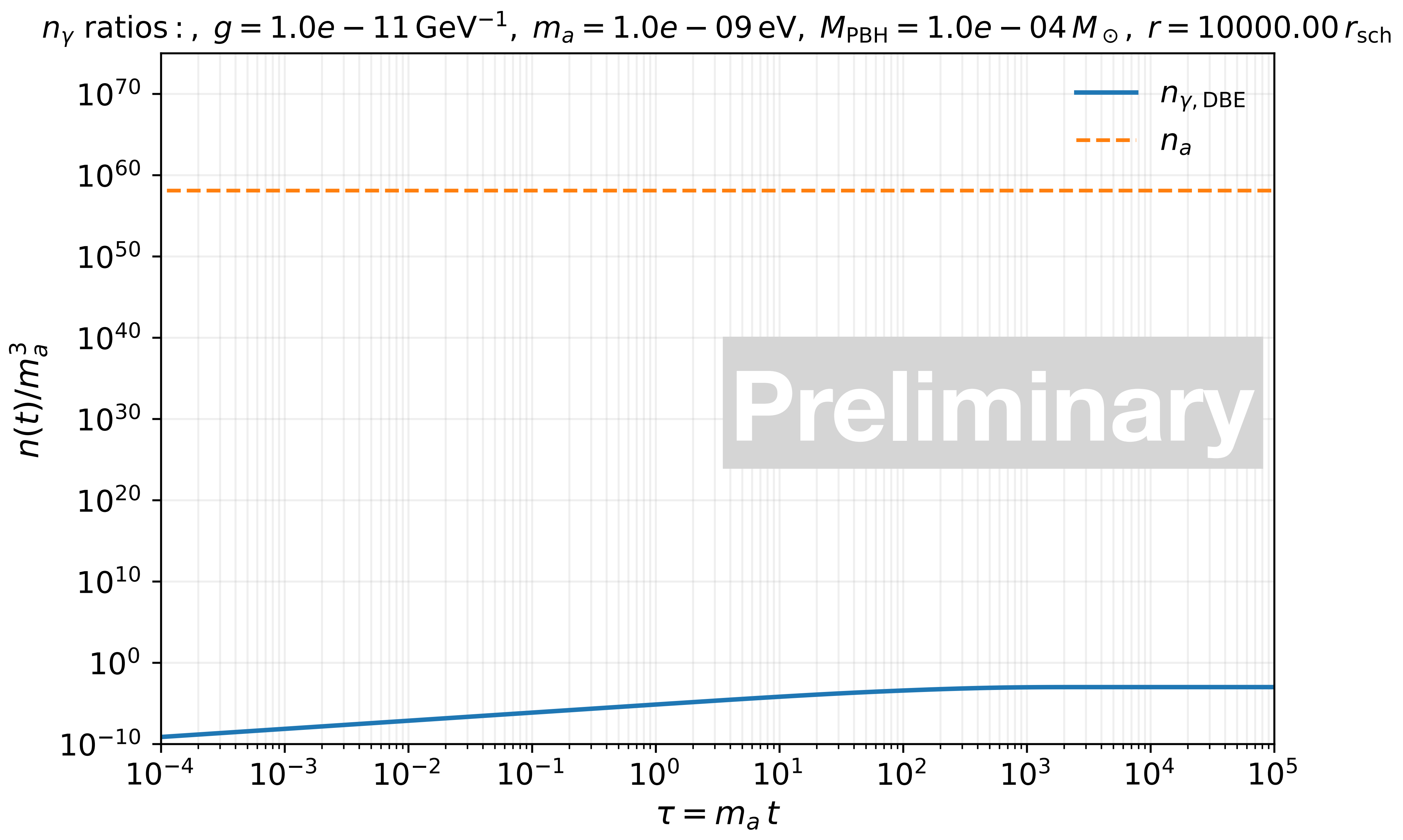
- Number density: $n_\gamma(r) = \sum_{\lambda=\pm} \frac{1}{(2\pi)^3}\int d^3\vec{\omega} f_\lambda(r,\vec{\omega}),\quad n_a(r) = \frac{\rho_a(r)}{m_a}$

Assumption:Constant on time

Results of Enhancement/Non-Enhancement

$$\frac{dn_\gamma}{dt} = \frac{m_a\Gamma_a}{\pi^2}\int_0^\infty d\omega \int_{E_{\min}}^\infty dE_a f_a(E_a)\left(1 + f_\lambda(\omega) + f_\lambda(E_a-\omega)\right) - \frac{m_a\Gamma_a}{\pi^2}\int_0^\infty d\omega \int_{m_a-\omega}^\infty d\omega'' f_\lambda(\omega) f_\lambda(\omega'') - \frac{3}{2r}n_\gamma,$$





Stimulated decay is dominant → Enhancement occurs

Results of Enhancement/Non-Enhancement

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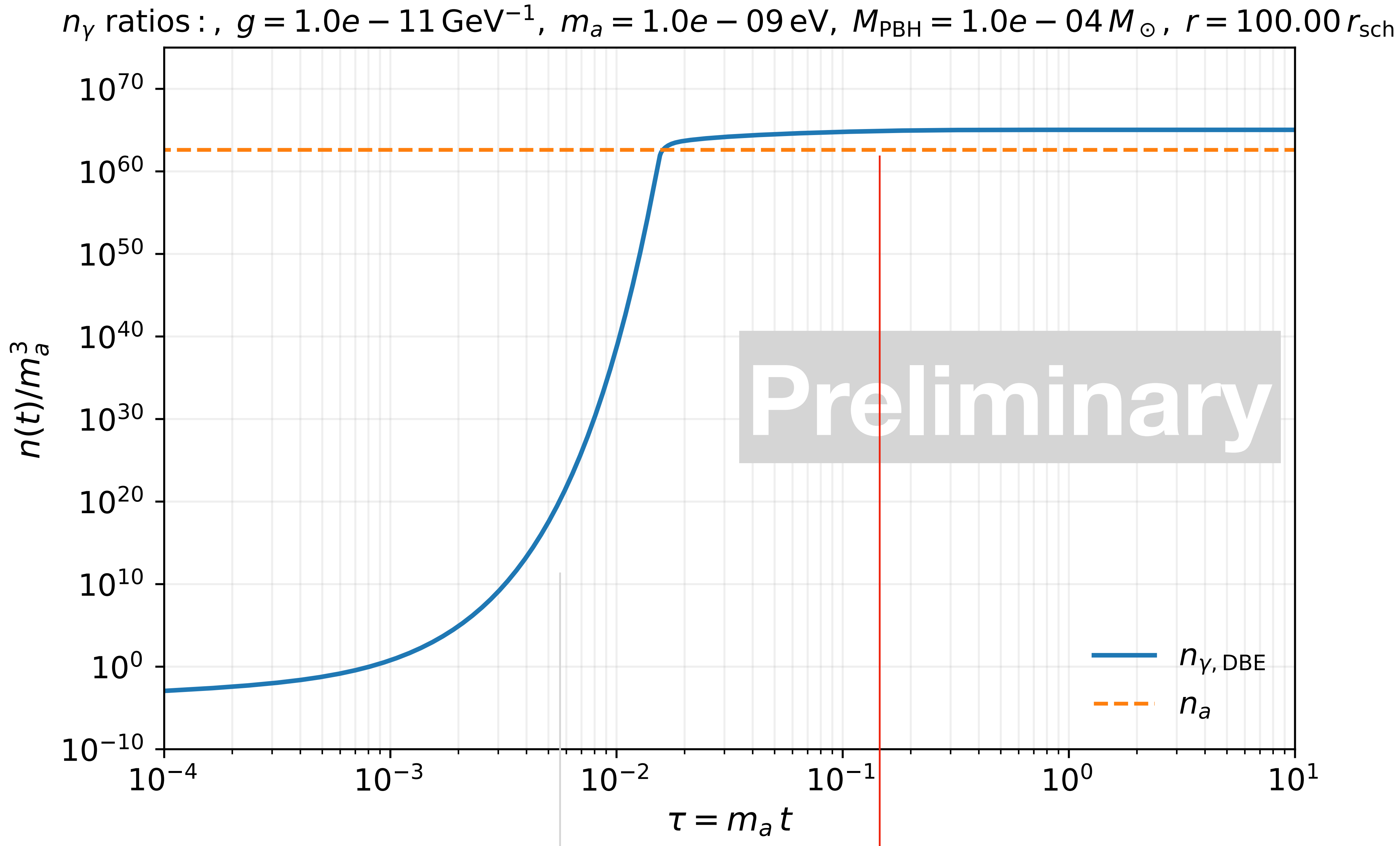
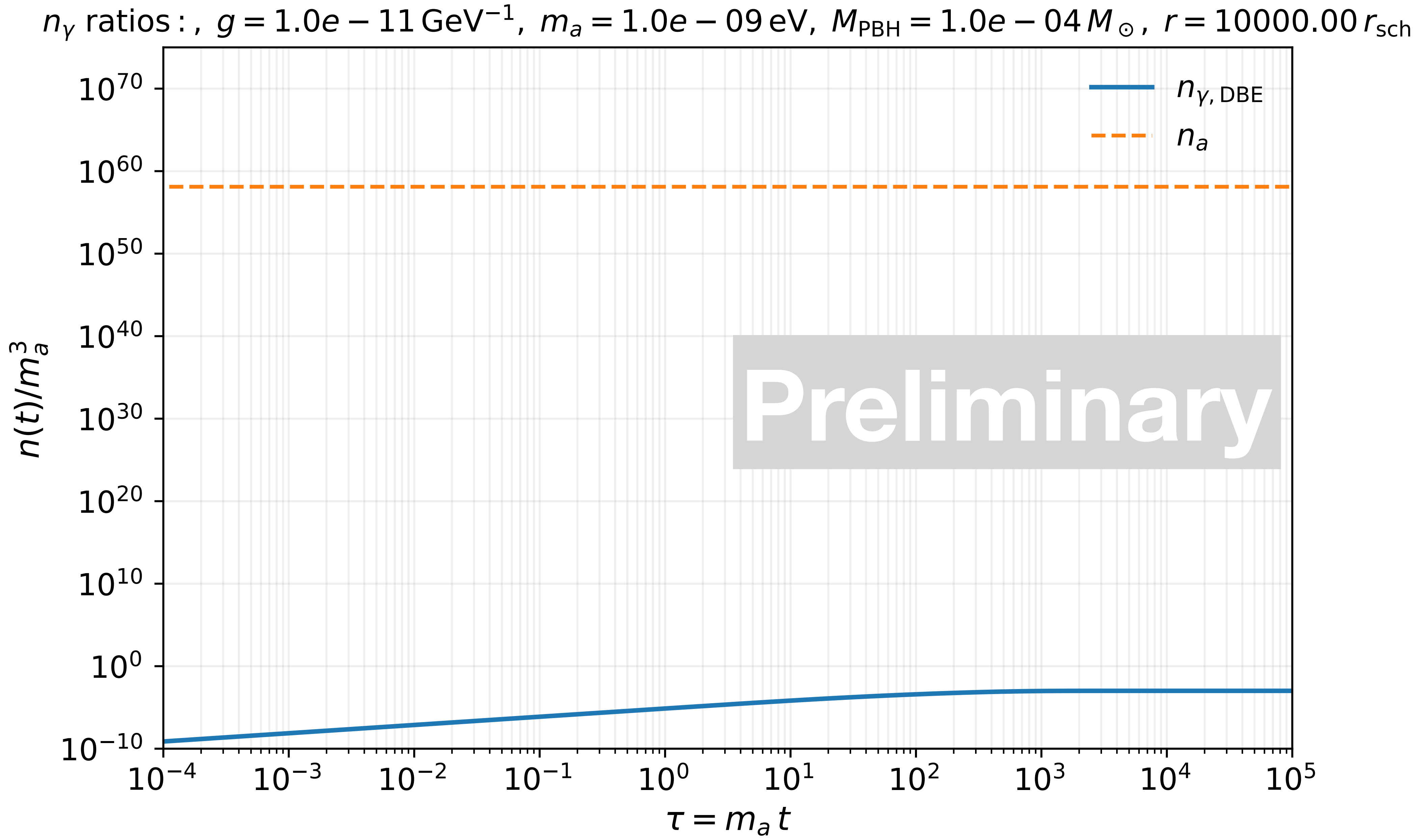


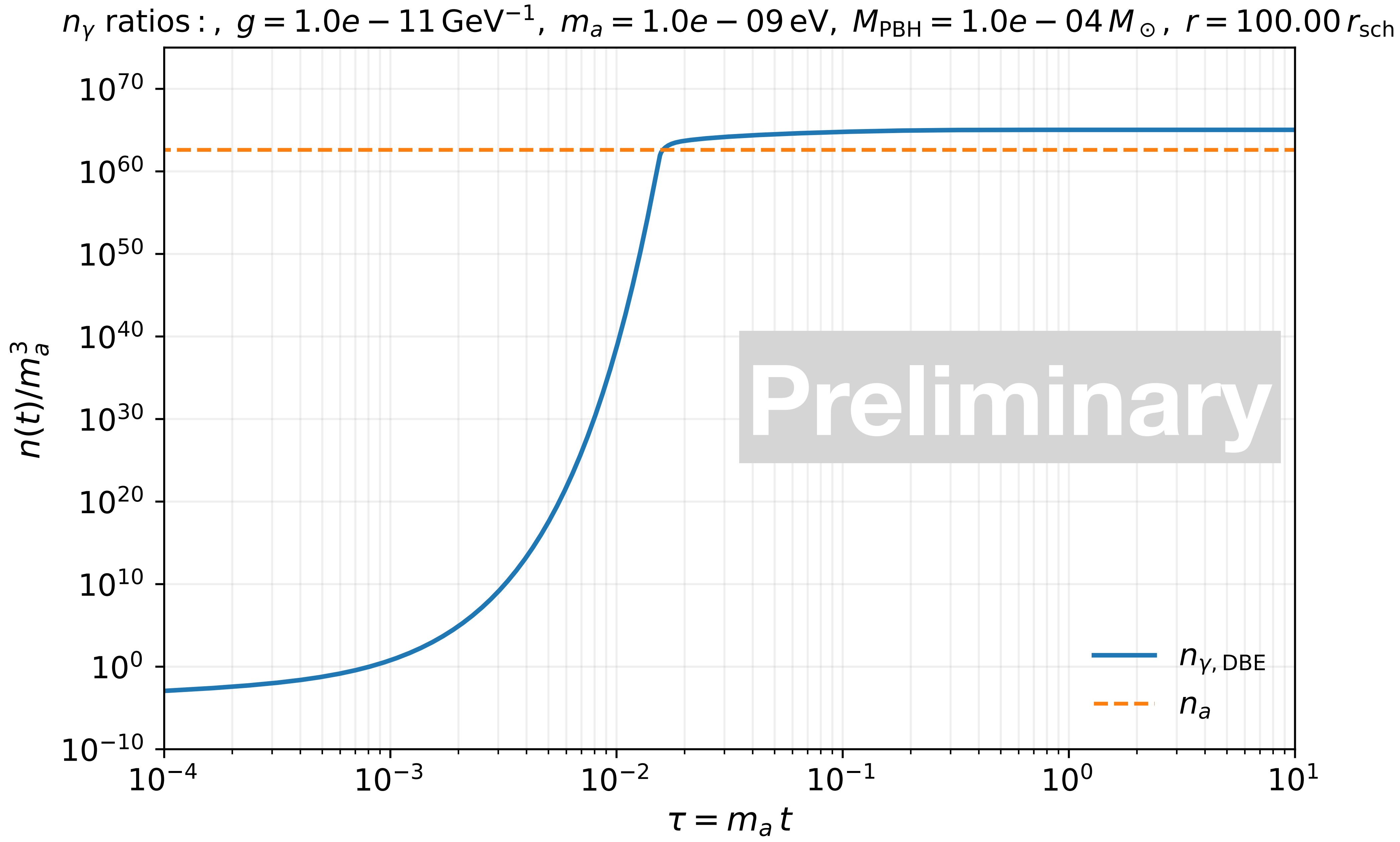


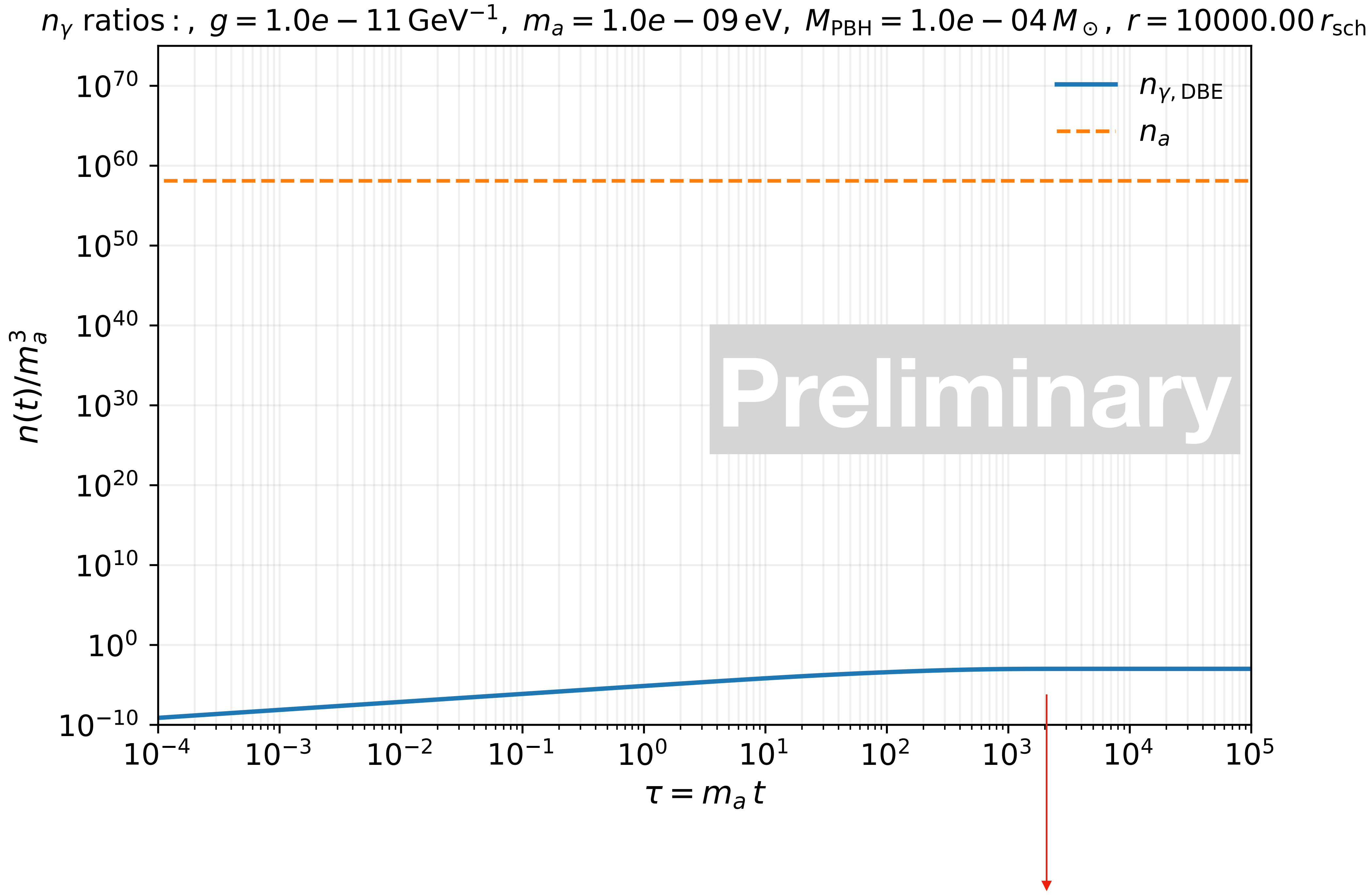
Stimulated decay is dominant → Enhancement occurs

Stimulated decay = Back-reaction → Number density reaches a constant

Results of Enhancement/Non-Enhancement

$$\frac{dn_\gamma}{dt} = \frac{m_a\Gamma_a}{\pi^2}\int_0^\infty d\omega \int_{E_{\min}}^\infty dE_a f_a(E_a)\left(1 + f_\lambda(\omega) + f_\lambda(E_a-\omega)\right) - \frac{m_a\Gamma_a}{\pi^2}\int_0^\infty d\omega \int_{m_a-\omega}^\infty d\omega'' f_\lambda(\omega) f_\lambda(\omega'') - \frac{3}{2r} n_\gamma,$$



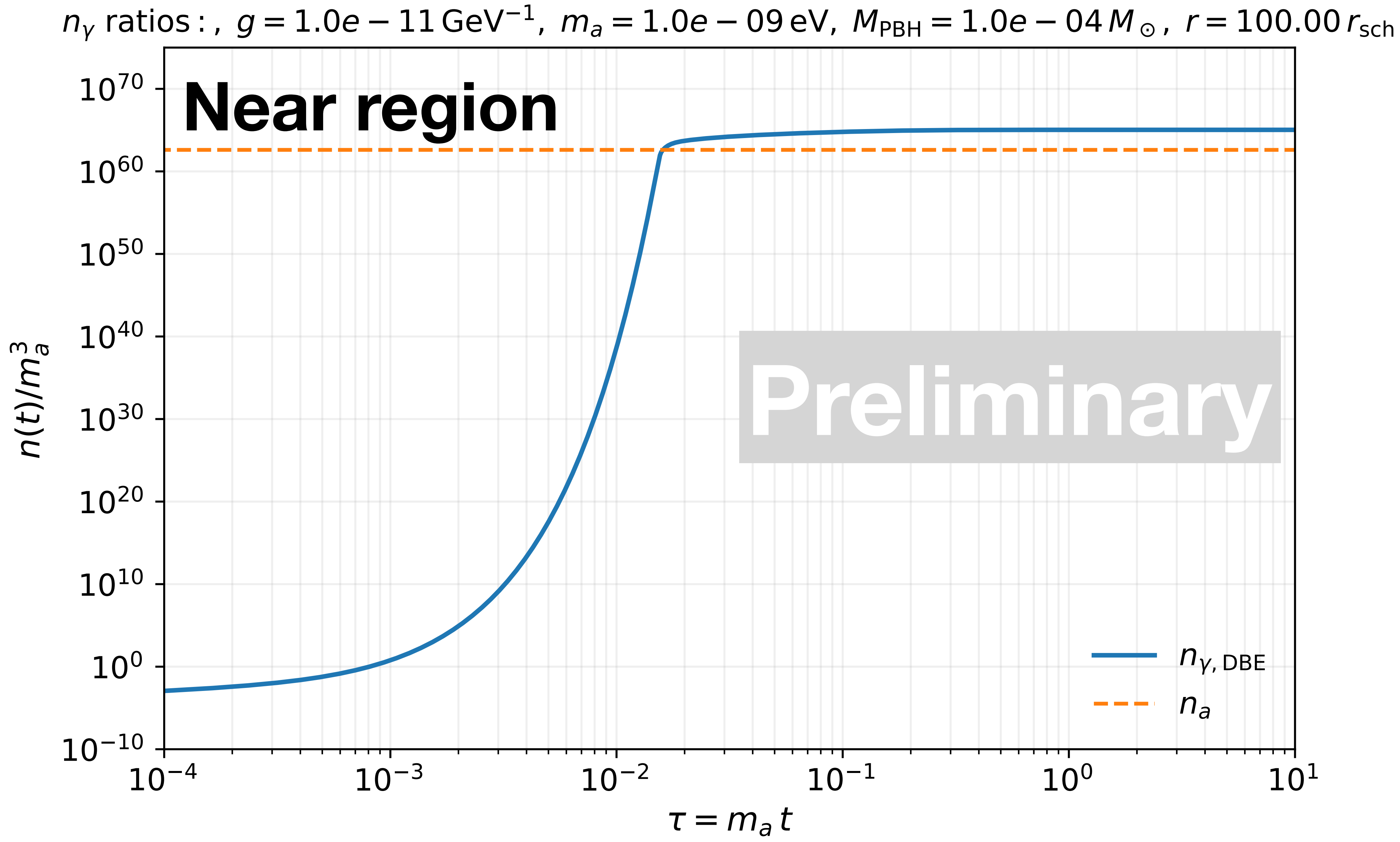


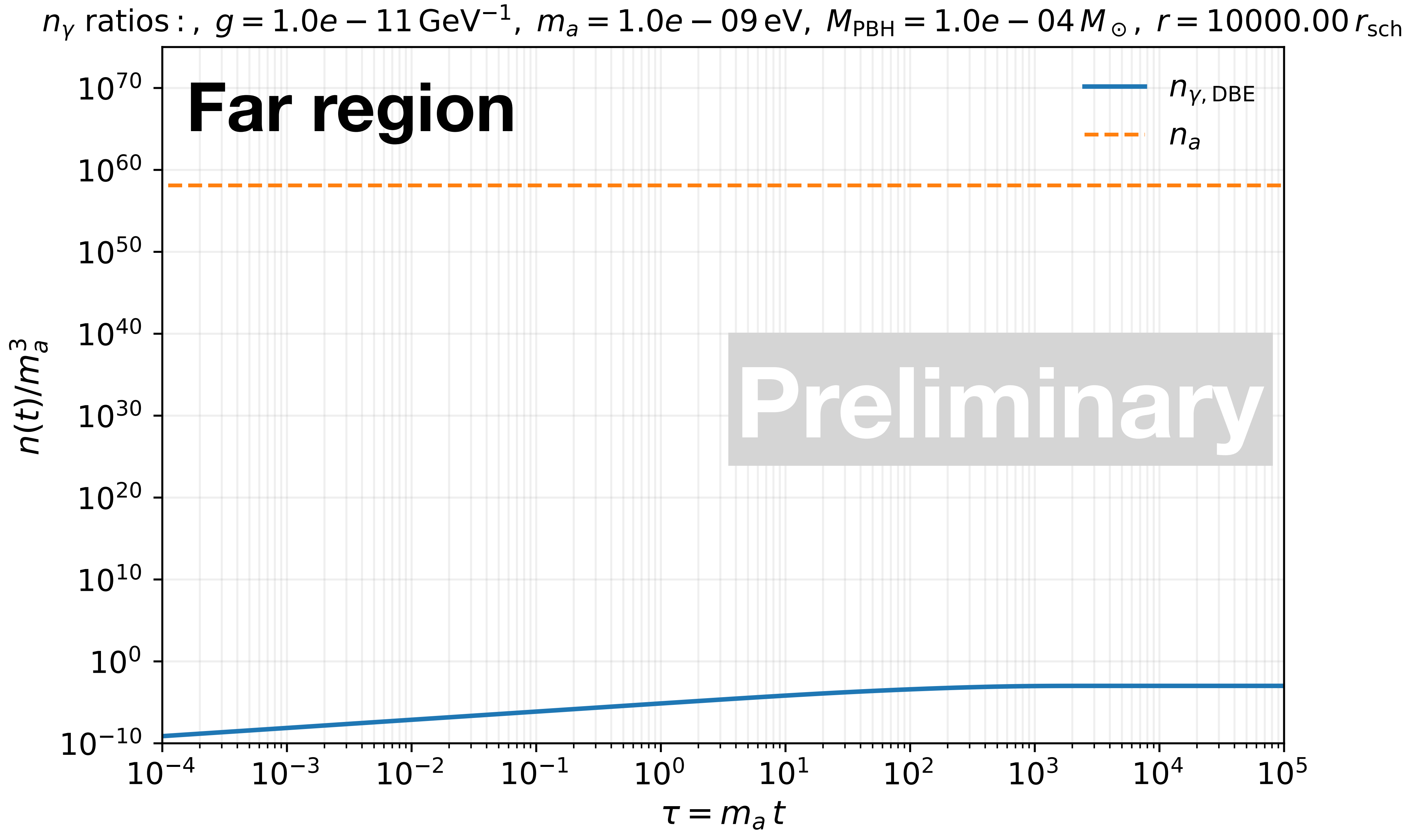
Escape is dominant → No enhancement occurs

Decay = Escape → Number density reaches a constant

Results of Enhancement/Non-Enhancement

$$\frac{dn_\gamma}{dt} = \frac{m_a\Gamma_a}{\pi^2}\int_0^\infty d\omega \int_{E_{\rm min}}^\infty dE_a f_a(E_a)\left(1 + f_\lambda(\omega) + f_\lambda(E_a-\omega)\right) - \frac{m_a\Gamma_a}{\pi^2}\int_0^\infty d\omega \int_{m_a-\omega}^\infty d\omega'' f_\lambda(\omega) f_\lambda(\omega'') - \frac{3}{2r} n_\gamma,$$



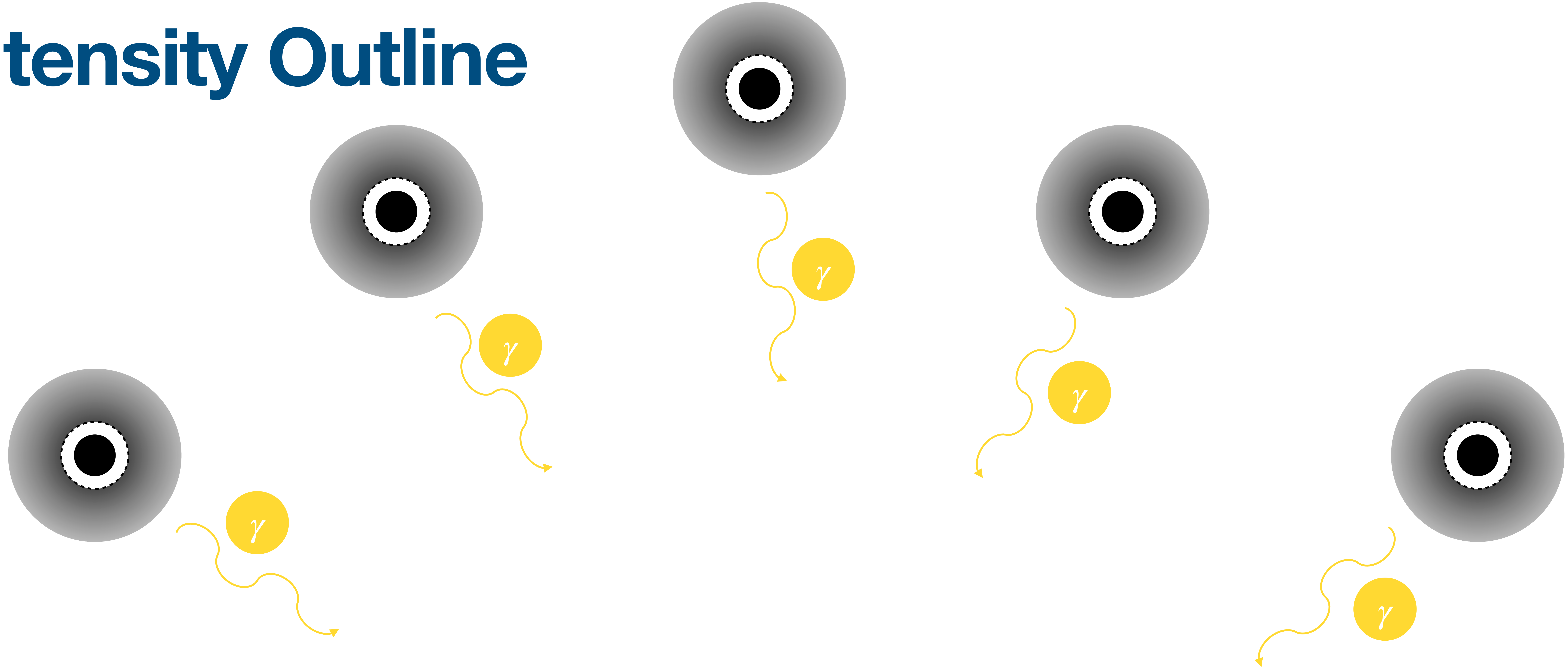


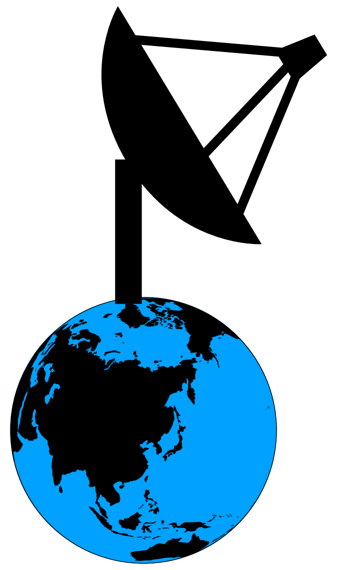
Stimulated decay > Photon escape

$r_{\rm enh}$

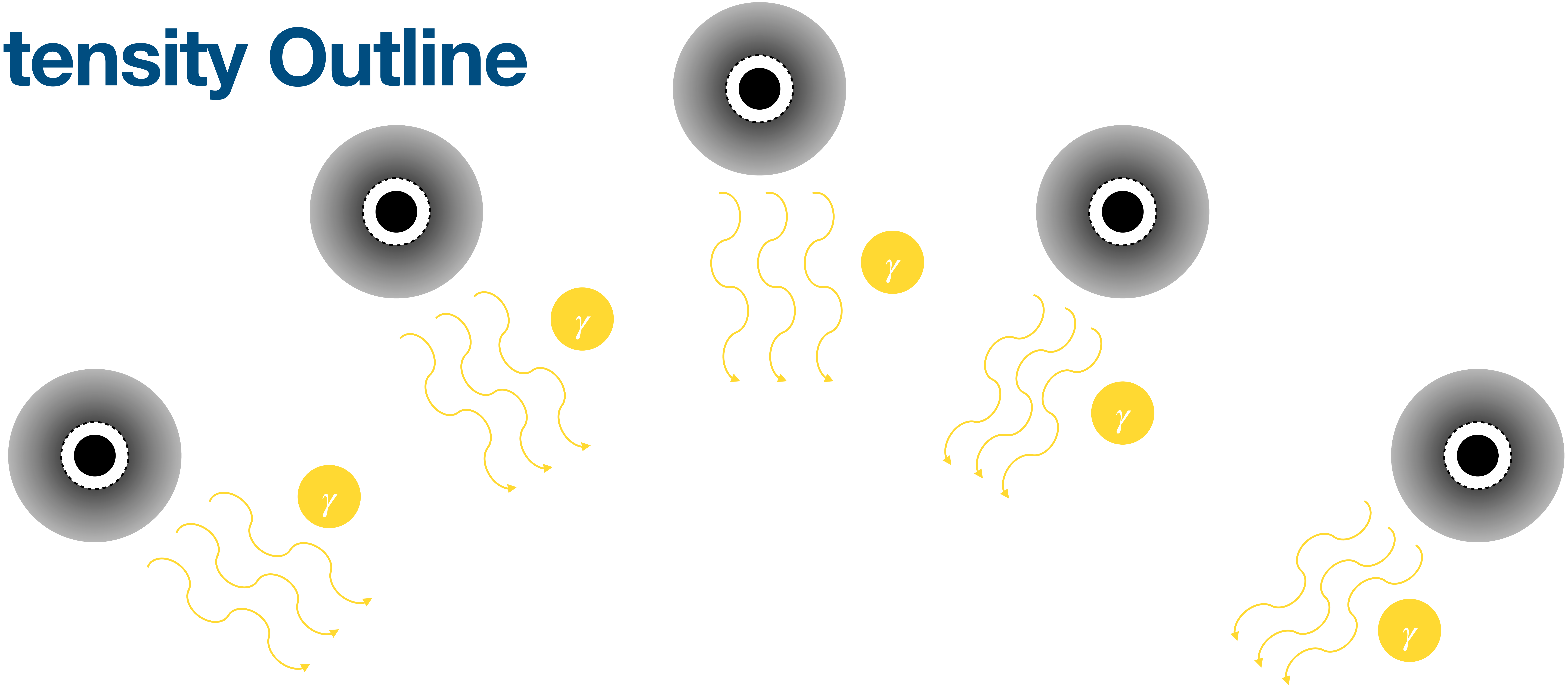
Stimulated decay < Photon escape

Intensity Outline

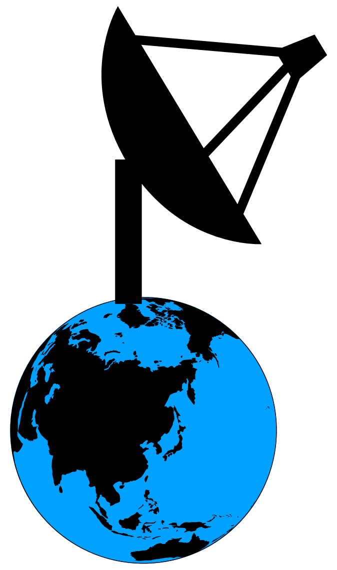


No enhancement,  Observable?

Intensity Outline



Enhancement,



Observable!

Summary

- **Verified Mechanism:** Using the *Boltzmann Equation*, we confirmed that the ultra-dense ALP halos ($\sim r^{-9/4}$) surrounding PBHs lead to significant *photon enhancement*.

- **Future Work:**

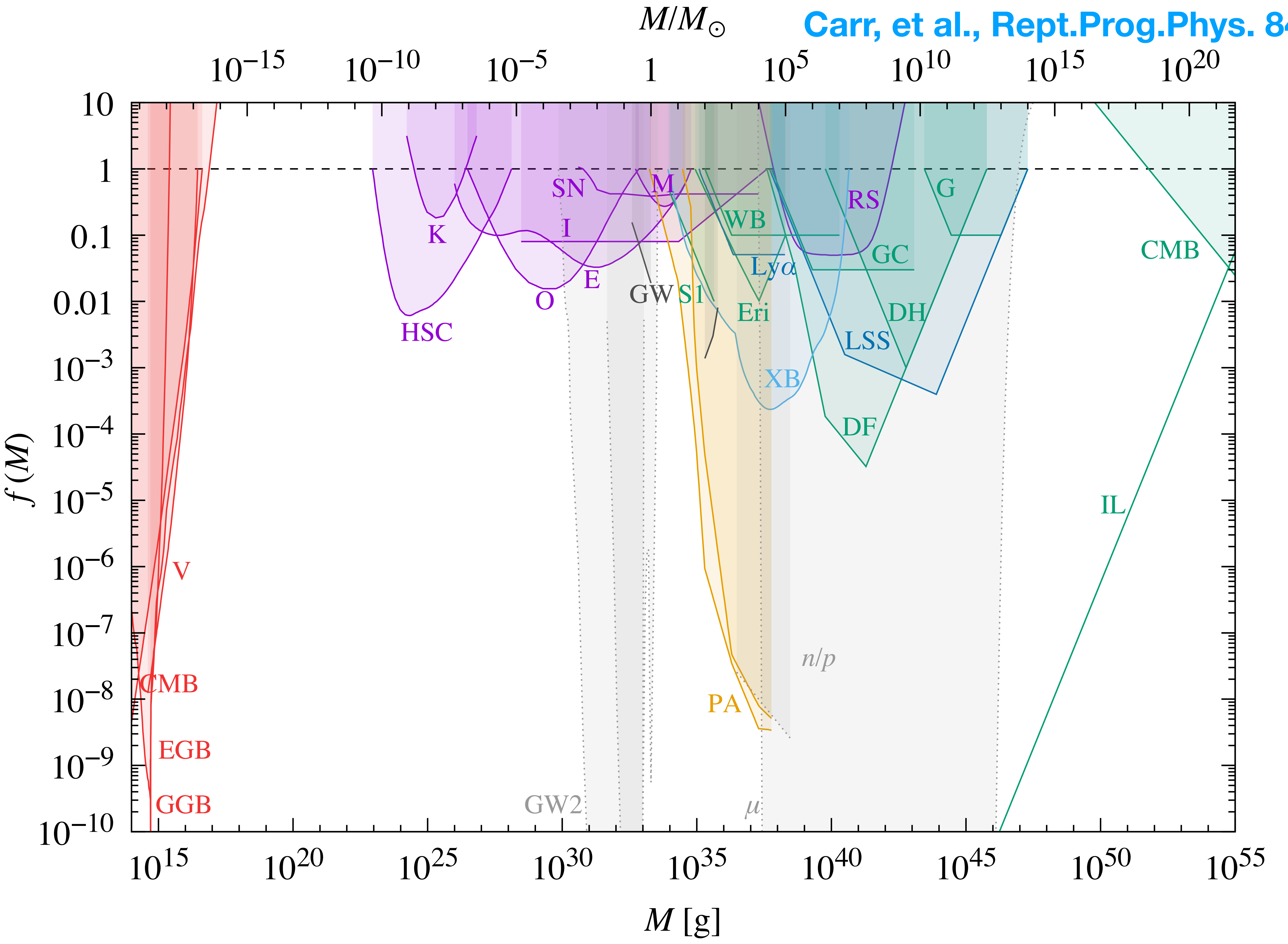
    - **PBH and ALP Phase Space:** Finding phase space where the photon enhances in the PBH halo.

    - **Observational Signature:** Calculating potentially detectable radio sources from the PBH halo with photon enhancement and finding constraints for PBH and ALPs.

Back-Up

PBH constraints

Carr, et al., Rept.Prog.Phys. 84 (2021) 11, 116902



Constant PBH halo

Dynamical time vs. decay time

- Dynamical time (time when background ALP enters the PBH halo):

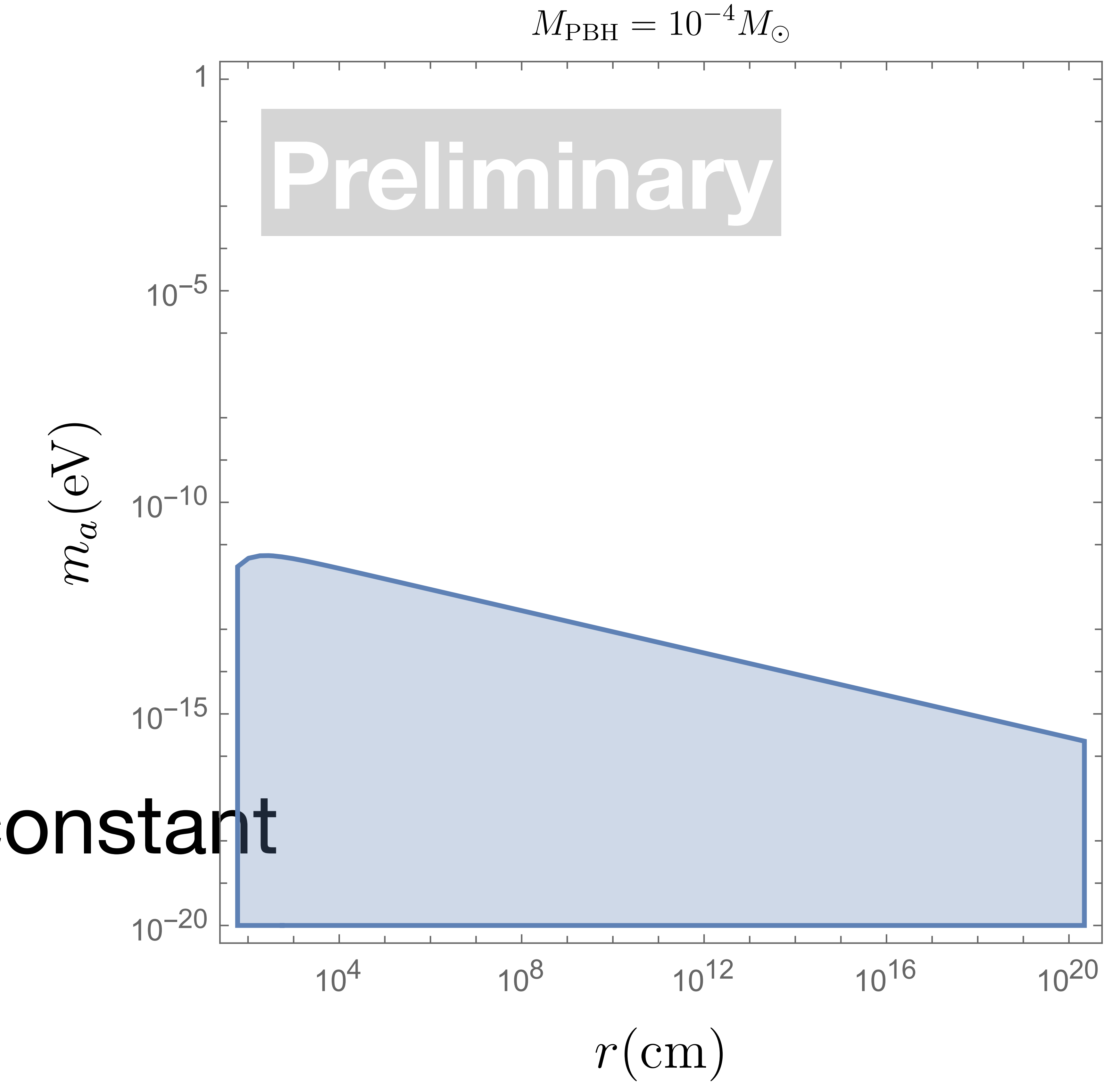
$$t_{\text{dynamics}} = \sqrt{\frac{r^3}{GM_{\text{PBH}}}}$$

- ALP decay time:

$$t_{\text{decay,eff}} \geq ((1+2f_\gamma)\Gamma_a)^{-1} \equiv \underline{\tau_{a,\min}}$$

Assumption: All the ALP decays to photon

- $t_{\text{dynamics}} < t_{\text{decay,eff}} \Rightarrow$ Axion number density is constant



Intensity

Carr, et al., Mon.Not.Roy.Astron.Soc. 506 (2021) 3, 3648-3661
Carr, et al.,Phys.Rev.D 81 (2010), 104019
Ferraz, et al., JCAP 07 (2022) 07, 026

- Photon number density:

$$\frac{dn_\gamma}{dt}(E_\gamma, t) = n_{\text{PBH}}(t)\frac{dN_\gamma}{dt}(E, t) \simeq n_{\text{PBH}}(t)E_\gamma\underline{\frac{d^2N_\gamma}{dtdE_\gamma}(E, t)}$$

Logarithmic binning approximation $\Delta E \simeq E$

- Intensity:

$$I \simeq \frac{dI}{dE}E = \frac{1}{4\pi}\rho_{c,0}\Omega_{\text{PBH},0}E_0\int_{t_{\text{rec}}}^{t_{\text{cloud}}} dt\frac{(1+z)}{M(t)}\frac{d^2N_\gamma}{dEdt}(E_0(1+z))$$

$$\simeq \frac{3}{4\pi^2}\rho_{c,0}\Omega_{\text{PBH},0}\frac{E_0^3}{M_{\text{PBH}}}\int_{t_i}^{t_f} dt(1+z)^3\int_{100r_{\text{sch}}}^{r_0(t)} drrf_\lambda(E_0(1+z), r)dr$$

Intensity

$$\frac{df_\lambda(\omega)}{dt} = \frac{m_a\Gamma_a}{\omega^2}\int_{E_{\min}(\omega)}^{\infty} dE_a f_a(E_a)\big(1 + f_\lambda(\omega) + f_\lambda(E_a-\omega)\big) - \frac{m_a\Gamma_a}{\omega^2}\int_{m_a-\omega}^{\infty} d\omega'' f_\lambda(\omega) f_\lambda(\omega'') - \frac{3}{2r} f_\lambda(\omega)$$

$$I \simeq \frac{3}{4\pi^2}\rho_{c,0}\Omega_{\mathrm{PBH},0}\frac{E_0^3}{M_{\mathrm{PBH}}}\int_{t_i}^{t_f} dt(1+z)^3\int_{100r_{\mathrm{sch}}}^{r_0(t)} drrf_\lambda(E_0(1+z), r)dr$$