Diffuse Emission from Black Hole Remnants

[arXiv 2207.06978]

Mateo Pascual

PhD student at Western University

Collaborators: S. Kazemian, C. Rovelli, F. Vidotto

email: mpascua@uwo.ca

Our Results

1. Non-stellar black hole population 

Planckian remnant Population

2. Explicit description of **diffuse emission** by remnant population, unveiling all information that **purifies** Hawking radiation mixed state.

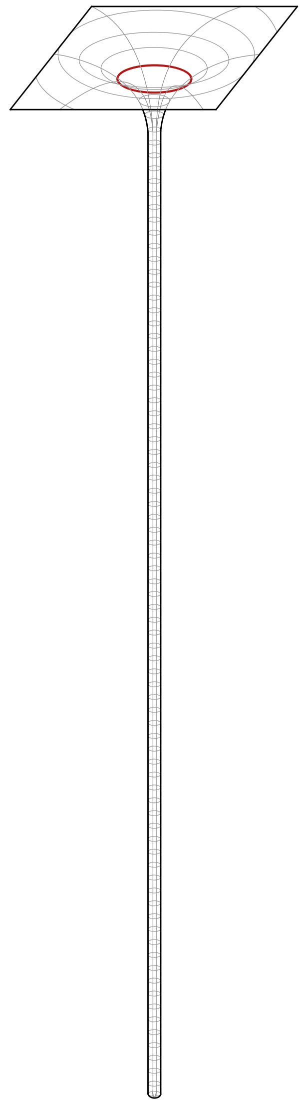
3. Confirm previous estimates of BH remnant's lifetime $\boxed{\tau \sim m^4}$.

4. **Amplitude** & **frequency** of observed radiation $\rightsquigarrow$ $\rho_{\textbf{remnants}}$.

5. QFT picture $\longrightarrow$ **stable remnants** are **extremely unlikely** in lab.

6. Remnants are the **ideal DM candidate**, now **observable** (indirectly).

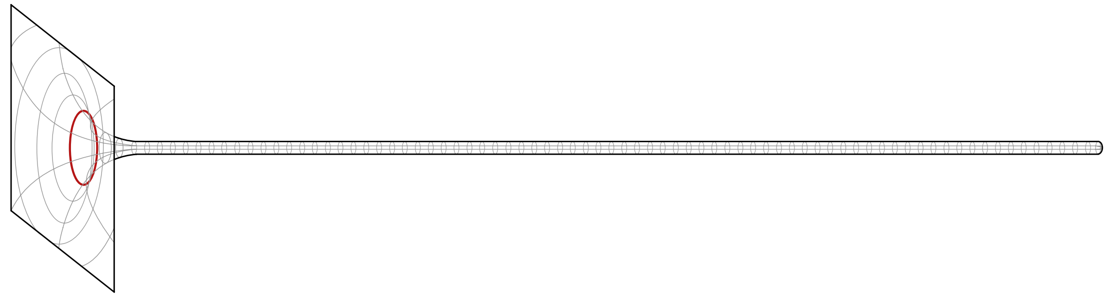
Introduction.



Long live the remnants!

INTRODUCTION.

Long live the remnants!



MOTIVATION FOR REMNANTS

GR & Non-pert. QG

(i) WH with **tiny horizon** and **huge interior volume** are exact classical solutions. [Haggard Rovelli '15]

(ii) Classical spacetimes with localised **BH → WH quantum tunneling** [Haggard Rovelli '15]

(iii) **LQG** shows **tunneling** is allowed, and **increasingly probable** at the end of Hawking evaporation. [Christodoulou Rovelli Speziale Vilensky '16] [Christodoulou D'Ambrosio '18] [D'Ambrosio Christodoulou Martin-Dussaud Rovelli Soltani '21] [Soltani Rovelli Martin-Dussaud '21]

(iv) QG **stabilises** Planck scale remnants. [Rovelli Vidotto '18]

(v) Old **objections** against remnants **don't apply**. [Bianchi Christodoulou D'Ambrosio Haggard Rovelli '18]

{from Banks, Giddings, Strominger '92 – '95}

Entropy from Interior Purifies Bekenstein-Hawking Radiation

- BH $\xrightarrow{\text{QTunnel}}$ WH $\Longrightarrow$ ~~event~~ horizon $\Longrightarrow$ ~~ergodic~~ system

- For non-ergodic systems,

$$\boxed{S_{vNeum} \geqslant S_{ThDyn}}$$

[Rovelli '17]
[Rovelli '19]

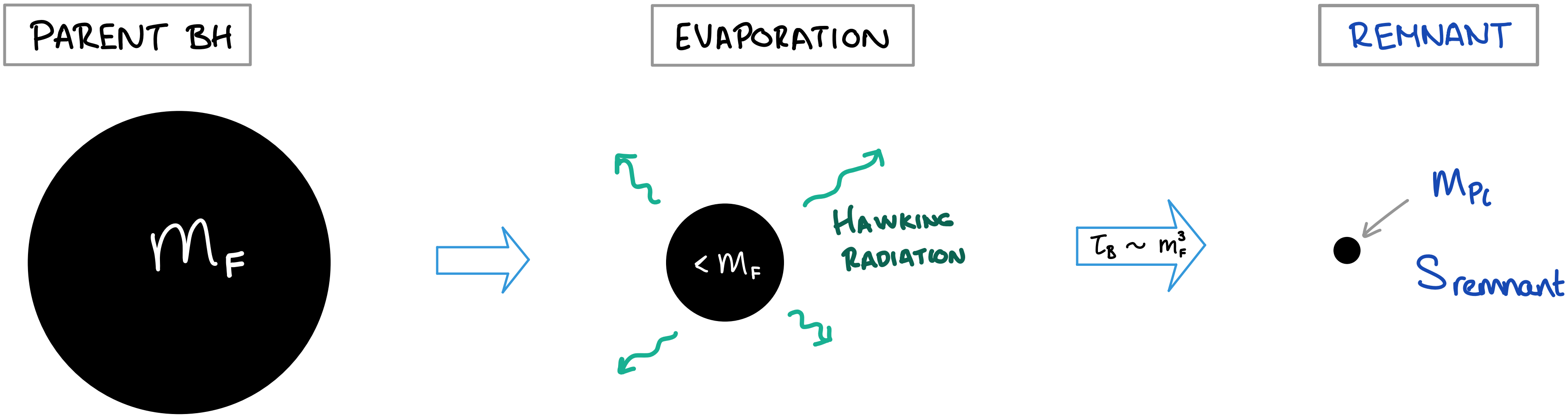
Interior state of BH is highly entangled with Hawking radiation.

~~Holography "Central Dogma"~~

$$\cancel{S_{vNeum} = S_{ThDyn}}$$

[Maldacena '21]

Model: Entropy implies Lifetime of Remnants



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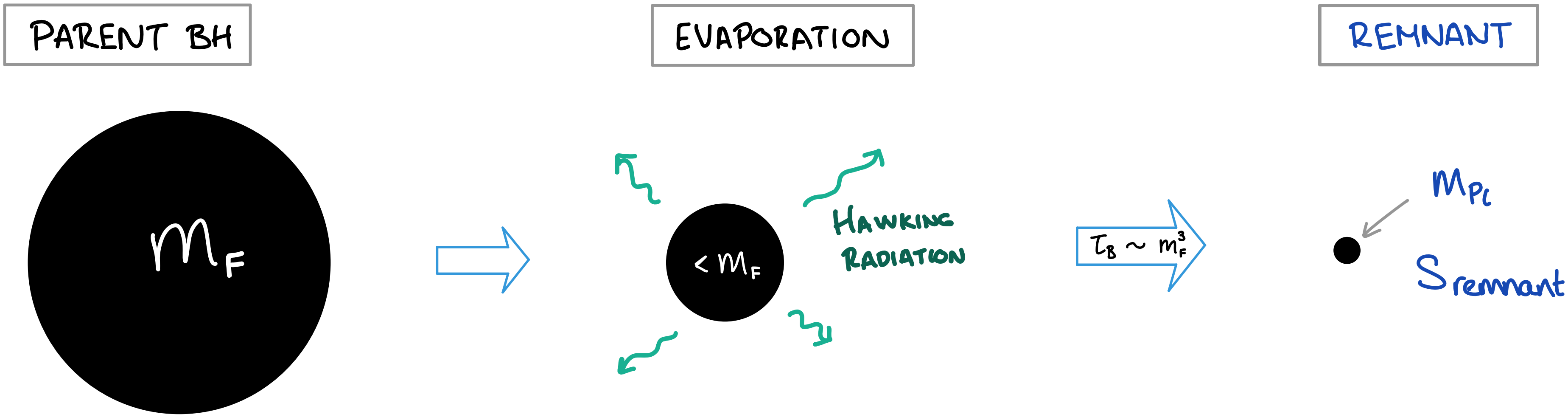

- Non-ergodic system → $$S_{remnant} \sim \frac{A}{4} = 4\pi m_F^2 \quad (1)$$ emmitted later as diffuse radiation

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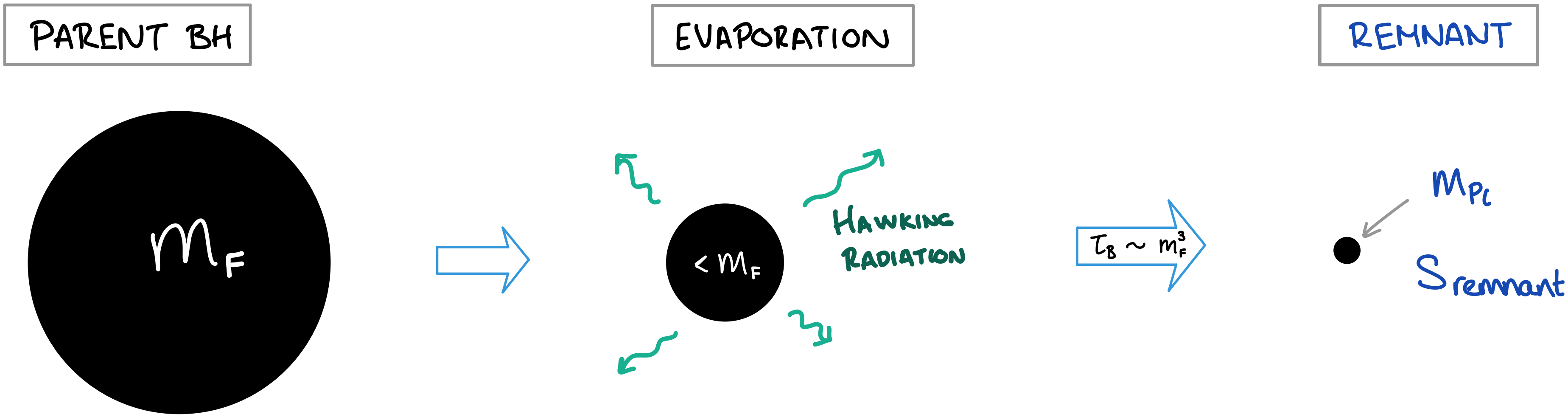

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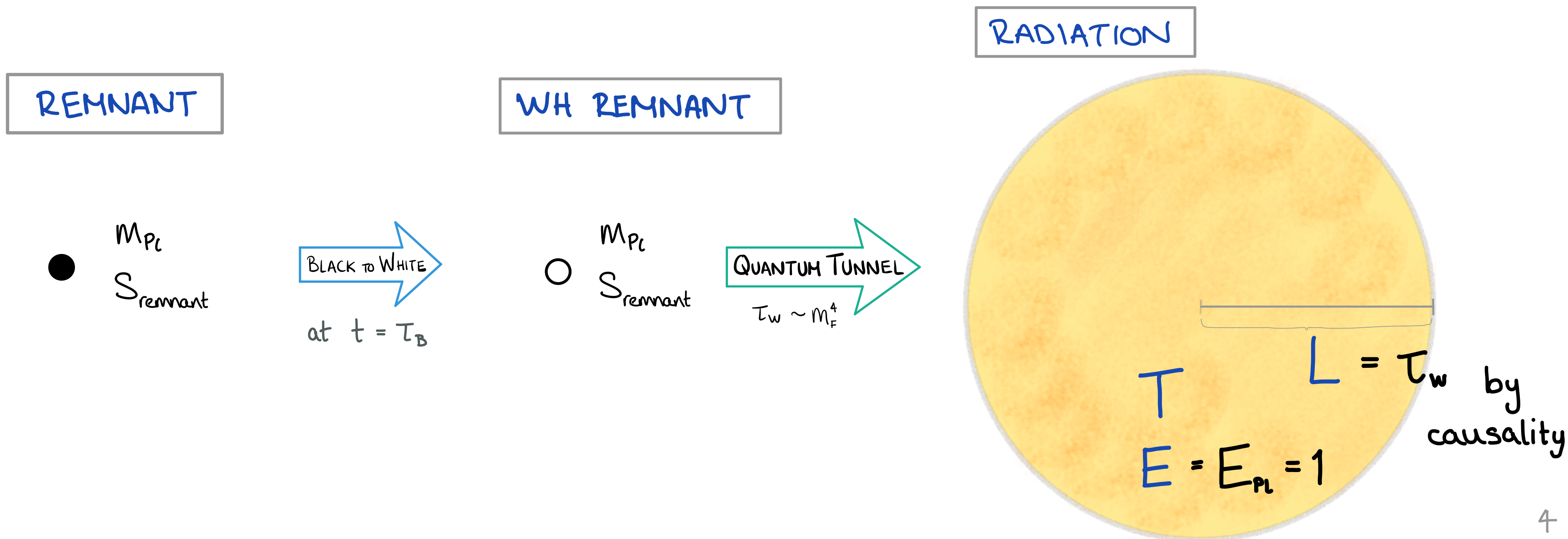
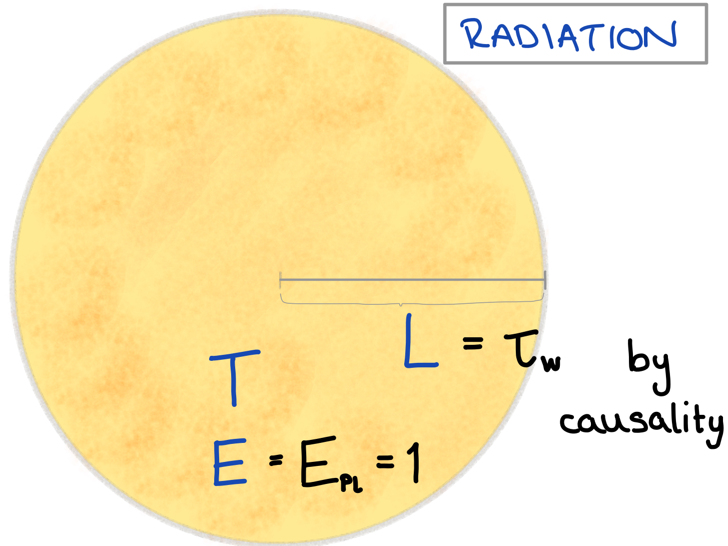


- Simple approx. model: [Preskill '92]

  uniform $\underbrace{\text{1-D}}_{\text{(radial)}}$ gas of radiation

  in equilibrium, for which:

- $S = \frac{2\pi}{3} L T$ & $E = \frac{1}{6} L T^2$ [Skobolev '13]



$\Rightarrow$ $$\boxed{L = \tau_w = 6 m_F^4} \quad (2) \qquad \boxed{T = \frac{1}{m_F^2}} \quad (3)$$

RADIATION

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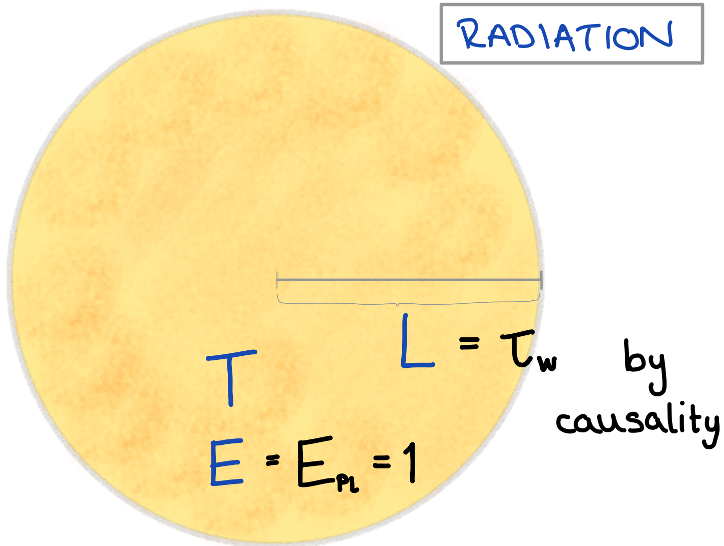

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- Planckian distribution : $\boxed{\nu_{peak} = \alpha T = \frac{\alpha}{m_F^2}}$ $\quad \alpha = 2.82 \quad (4)$

- For 1 photon, $\epsilon = \nu$: $\boxed{N_\gamma = \frac{E}{\epsilon} = \frac{m_F^2}{\alpha}}$ Total number of photons $\quad (5)$

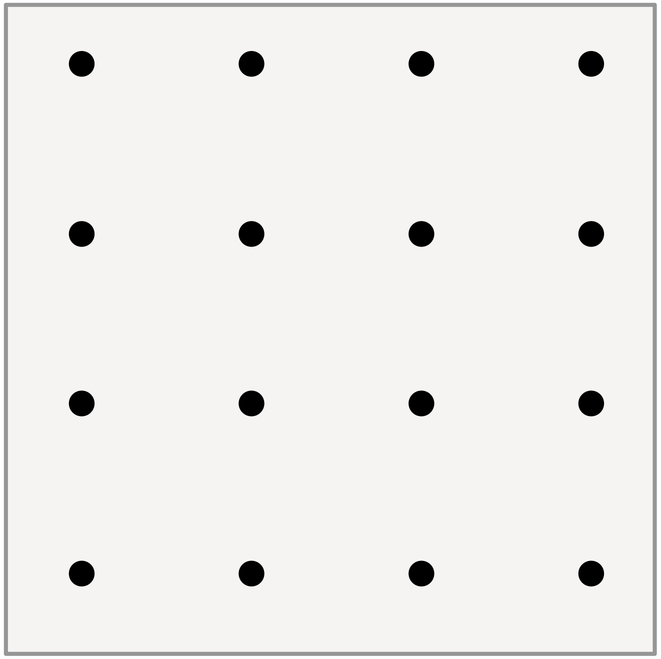
- Photon gas

  $V = \frac{4}{3}\pi L^3 \quad \rightarrow$

$$\boxed{\rho_0 = \frac{E}{V} = \frac{1}{288\pi} m_F^{-12}} \quad (6)$$

$$\boxed{n_\gamma = \frac{N_\gamma}{V} = \frac{1}{288\pi\alpha} m_F^{-10}} \quad (7)$$

Model: Ensemble Radiation



number density Ω

mass m_{PL}

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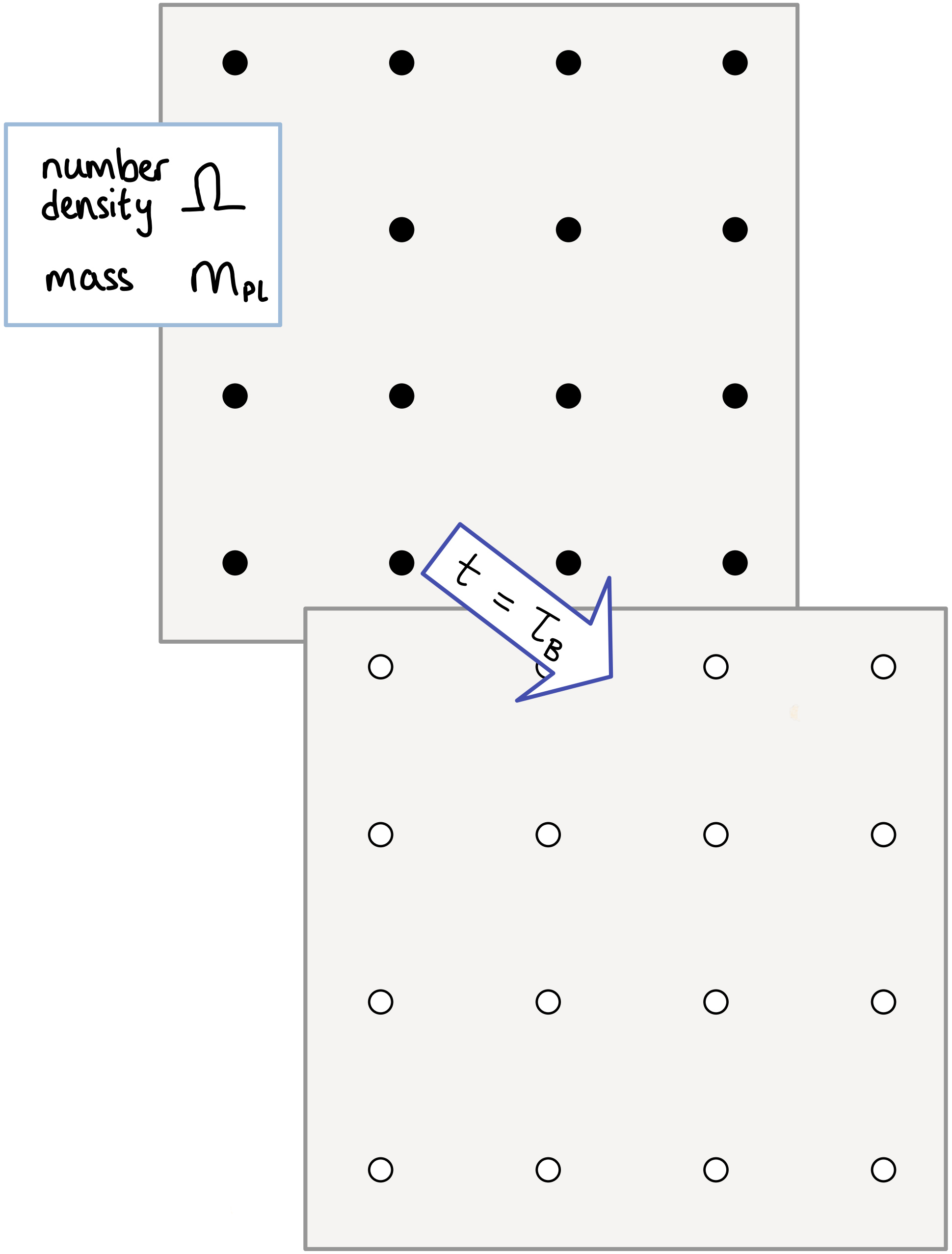

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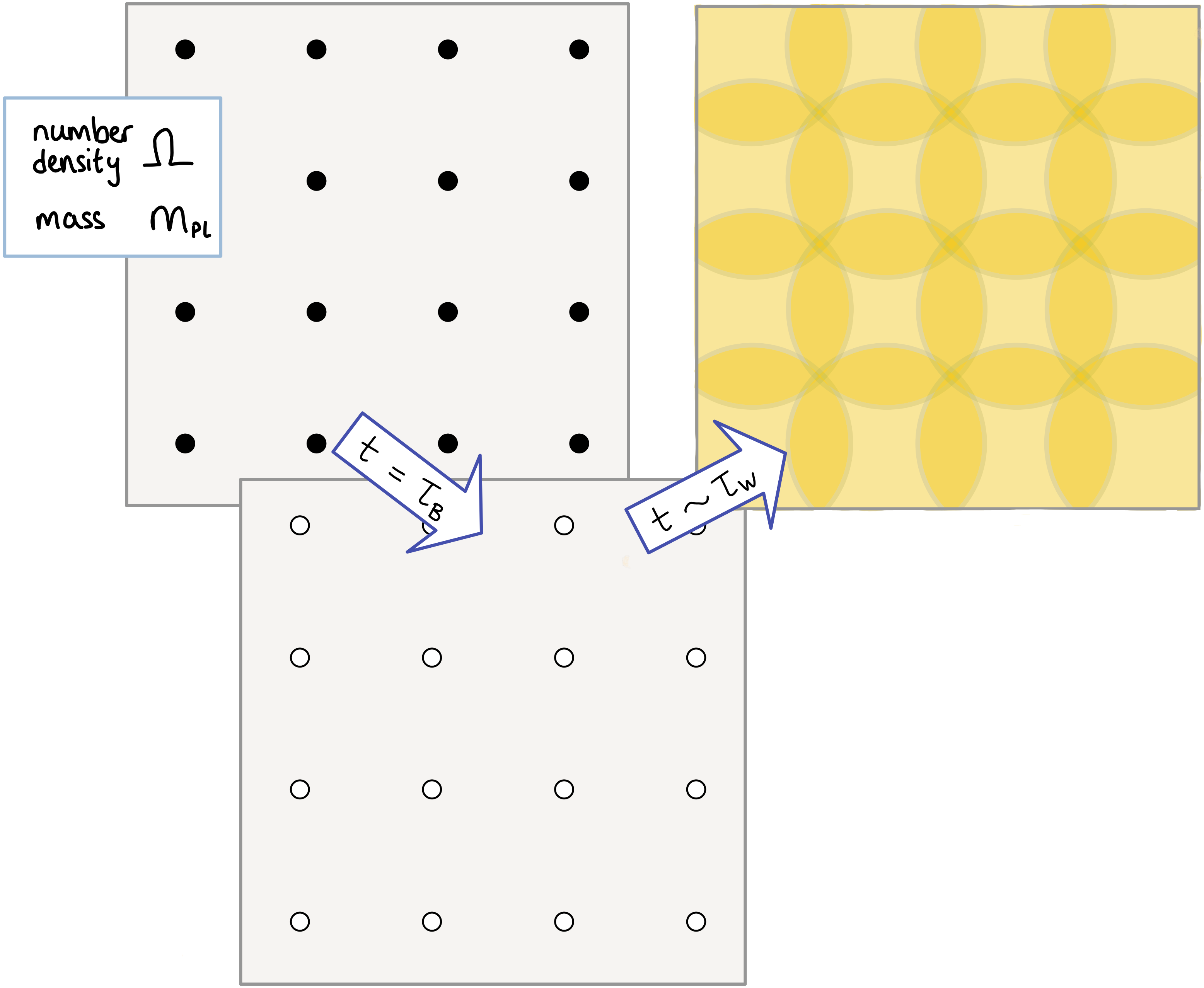

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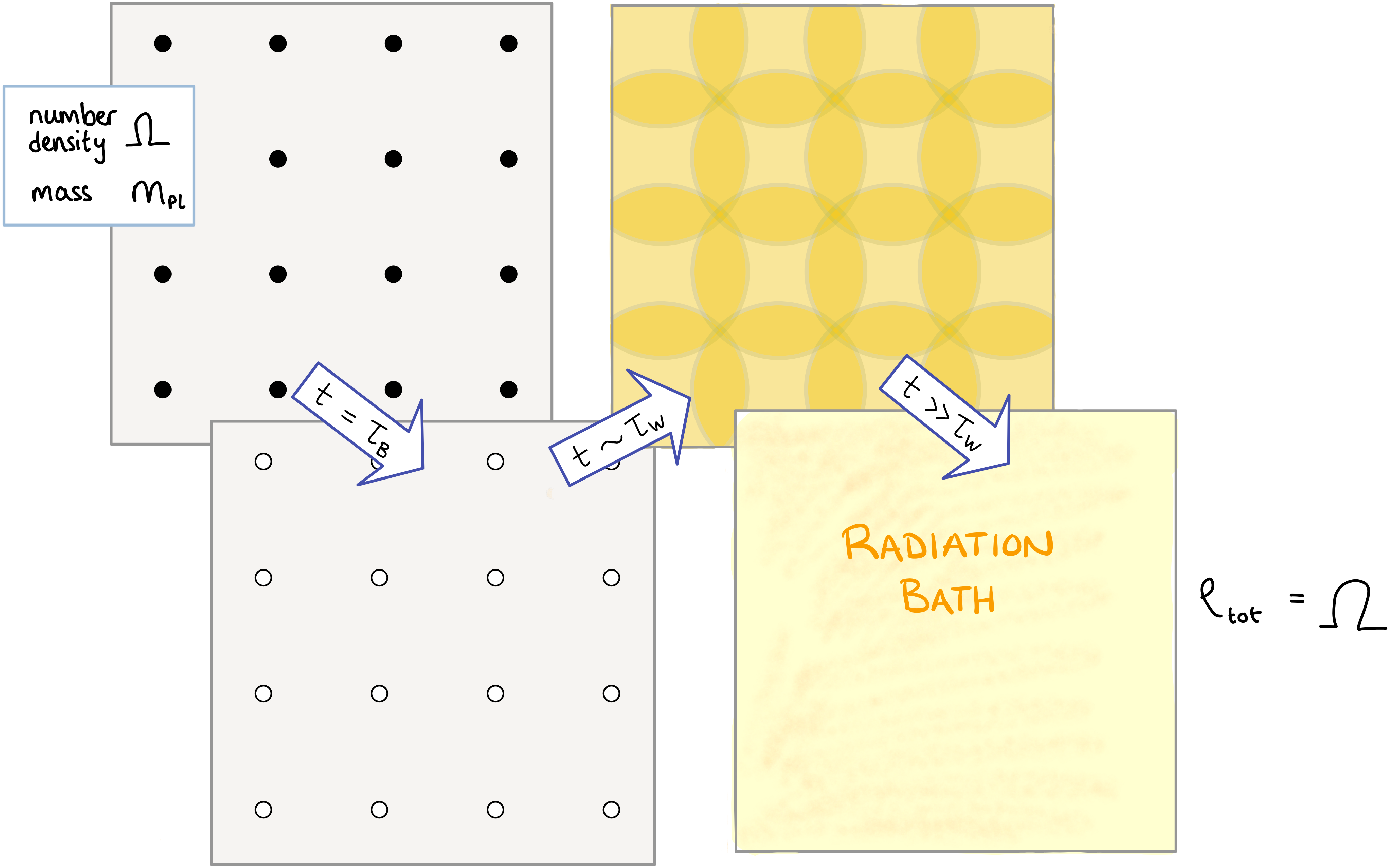

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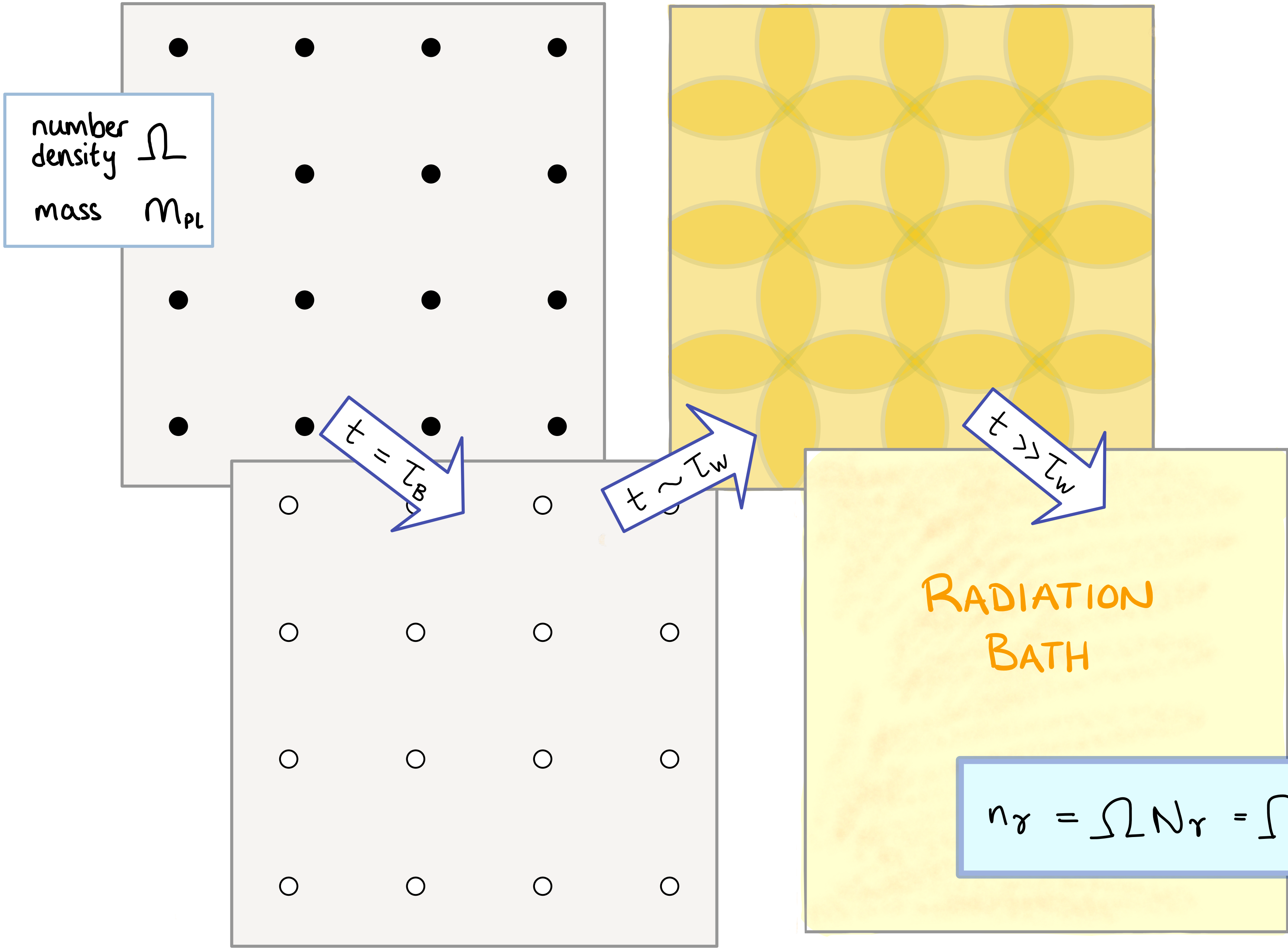

$$\rho_{tot} = \Omega$$

$$\boxed{n_\gamma = \Omega N_\gamma = \Omega \frac{m_F^2}{\alpha}} \qquad (8)$$

Linear Emission

- BH population forms at $t=0$, with mass m_F uniformly distributed with **number density** Ω.

- Emit radiation during WH phase.
  - approximate: steady linear emission. Find:

$$\rho_{rad}(t) = \begin{cases} 0 & \text{for } t < m_F^3 \\ \frac{(t-\tau_B)}{(\tau_W-\tau_B)}\Omega & \text{for } m_F^3 < t < 6m_F^4 \\ \Omega & \text{for } t > 6m_F^4 \end{cases} \tag{10}$$

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What about $\boxed{\text{Quantum Mechanics ?}}$ Area gap ?

Quantum Description of Emission

- LQG minimum 'area gap' $\sim A_{Pl}$ ⟹ Quantum leap from A_{Pl} to radiation state.
  [Rovelli Smolin '95]
  (analogous to conventional nuclear radioactivity)

- QFT perspective: remnant state $\cancel{|m\rangle}$ $|\mu, x_i\rangle$

energy quantum number
(Horizon $A = 16\pi\mu^2$)

interior configuration quantum numbers
($i \sim e^S = e^{M^2}$)

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- Quantum area gap implies $\mu_{min} \sim m_{Pl}$.

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$$\boxed{|\mu_{min}, x_i\rangle \longrightarrow |\gamma_1, \ldots, \gamma_n\rangle} \qquad (11)$$

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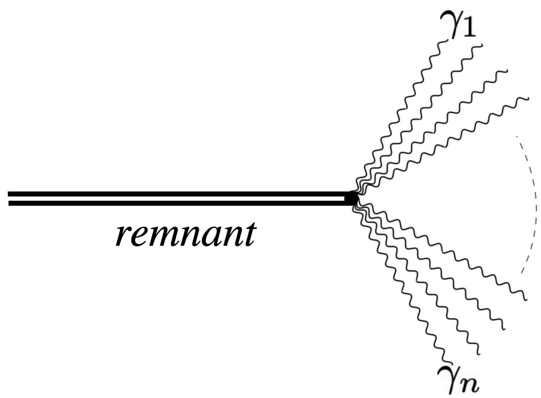

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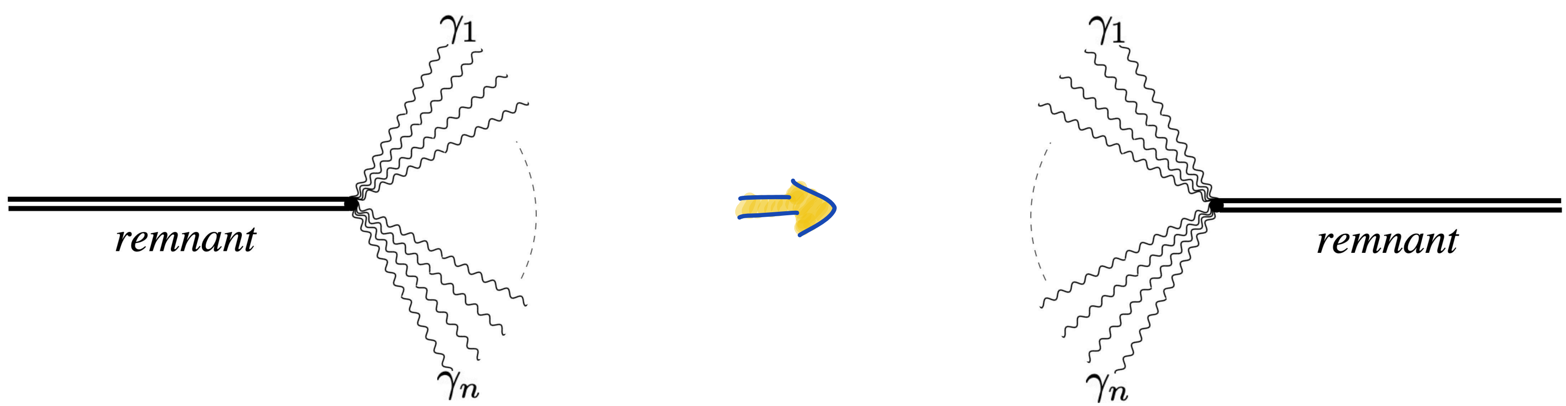

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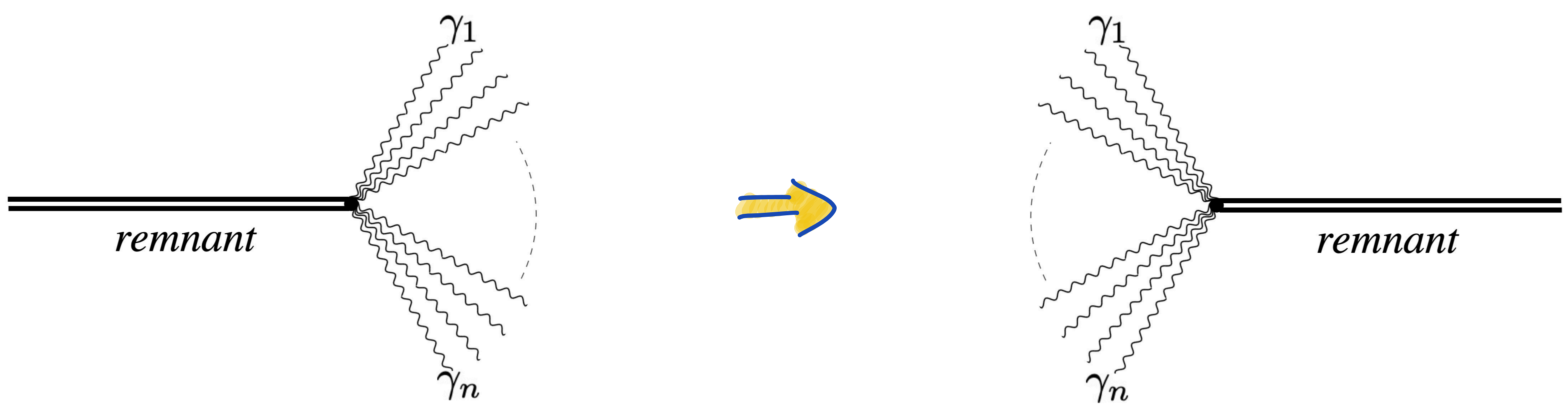

- Vast number of photons need to converge for Long-Living remnant in lab.

  e.g. PBH sized remnant in lab, $\underbrace{10^{38} < N_\gamma < 10^{48}}$.

Can't find remnants in lab? No wonder!!

Quantum Emission of Ensemble

For a population:

- Single decay + constant probability ⇒ "**radioactive**" decay.

$$\rho_{rem}(t) = \Omega e^{-\lambda(t-\tau_B)} \qquad \underbrace{\lambda \sim (\tau_\omega - \tau_B)^{-1}}_{} \qquad (13)$$

by Bohr's correspondance principle.

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- Recall $\nu_{peak} \sim m_F^{-2} \Rightarrow$ Find $\rho_{rad}(t, \nu_{peak})$

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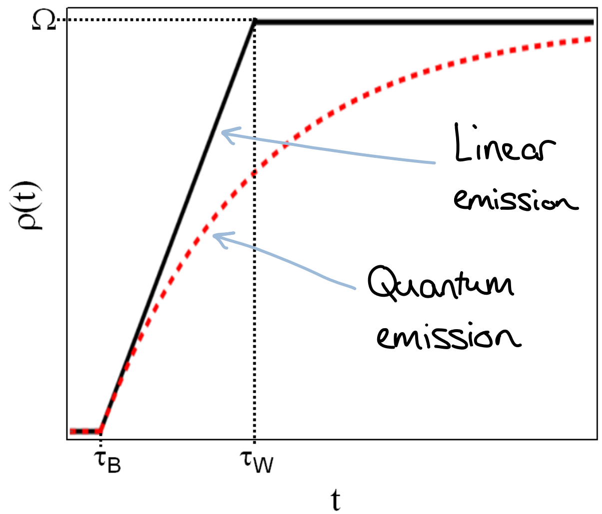

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Conclusion

- Area gap $\Rightarrow$ Planckian remnants.
- Unitarity $\Rightarrow$ remnant $\longrightarrow$ vast number of correlated photons.
  - **Extremely rare** in lab.
- BH population (e.g. PBH) $\longrightarrow$ **bath of diffuse emission**.
- Can **measure** $\boxed{\rho_{rad}(t, m_F) = \rho_{rem}\left[\exp\left(\frac{1-t m_F^{-3}}{1-6 m_F}\right) - 1\right]}$ for $t > m^3$ (14)
- Taking $t = t_H \sim 10^{60}\, t_{Pl}$, measurement of ρ_{rad} & ν_{peak} $\Rightarrow$ **measure ρ_{rem}**
- Inflationary scenarios (both big-bang and bouncing) pose strong constrains on abundance [Barrau Ferdinand Martineau Renevey '21]
- In **Matter-bounce** scenario, **remnants can account for DM**.
  (Emmanuel Frion's talk)

Planckian remnants originating before the cosmological bounce are observable Dark Matter candidates

arXiv:2207.06978

Questions?

arXiv:2207.06978

Thanks!

mpascua@uwo.ca

PBH REMNANTS

- Radiation bath today if $10^{15} m_{Pl} < M_{PBH} < 10^{20} m_{Pl}$ $\qquad m_{Pl} \sim 10^{-5} g$

$$\Big\downarrow \; \nu_{peak} \sim M^{-2}$$

$$10^{12}\,Hz > \nu_{peak} > 10^{2}\,Hz$$

⇒ Measure ρ_{rad} & ν_{peak}

→ value of ρ_{rem}

→ Does $\rho_{rem} \sim \rho_{DM}$?

NO !! ☹ → Not major component of DM

YES ! → PBH remnants are a component of DM