INFRARED EFFECTS IN THE LATE STAGES OF BLACK HOLE EVAPORATION

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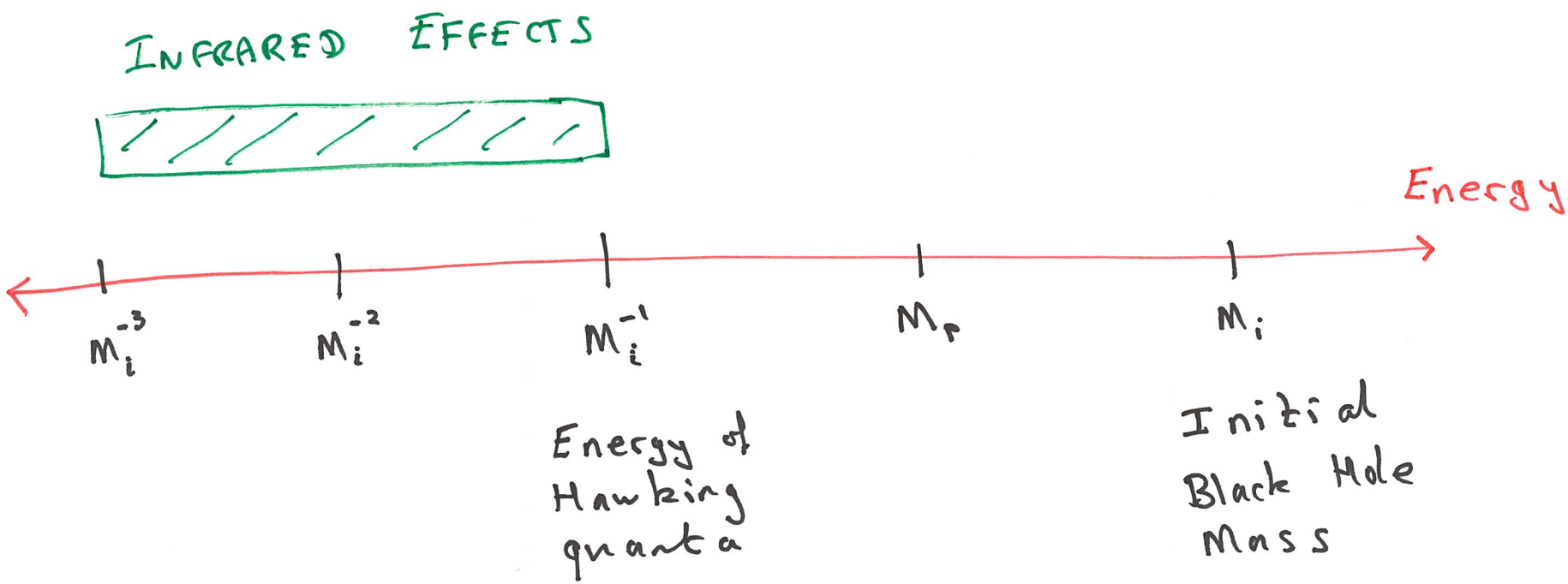
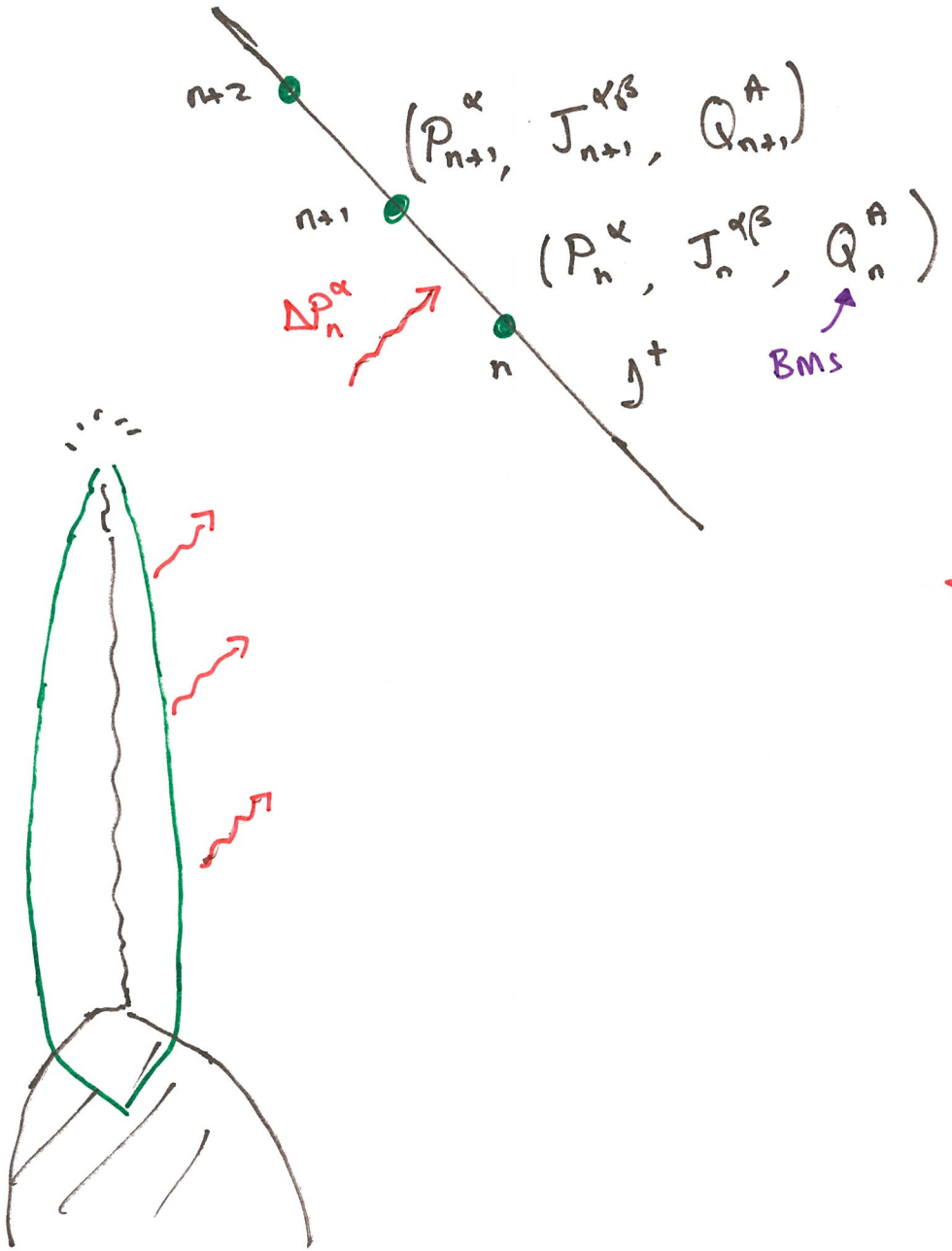
ENERGY SCALES



DON PAGE (1980): QUANTIZE SOME OF GRAVITATIONAL DEGREES OF FREEDOM



- Idealize as sequence of transitions one per quantum.
- Einsteins equations impose $P^{\alpha}_{n+1} = P^{\alpha}_{n} - \Delta P^{\alpha}_{n}$
- We will make order of magnitude estimates of fluctuations in ΔP^{α}_{n}, rather than first principle derivation.

PAGE MODEL : CLASSICAL STOCHASTIC PROCESS

★ Each Hawking quantum independent, order unity fluctuations

★ $\delta_n = \begin{cases} 0 & \text{no emission} \\ 2 & 1 \text{ quantum emitted} \end{cases}$

$\epsilon_n = \begin{cases} -1 & \text{left} \\ +1 & \text{right} \end{cases}$

★ Evolution :

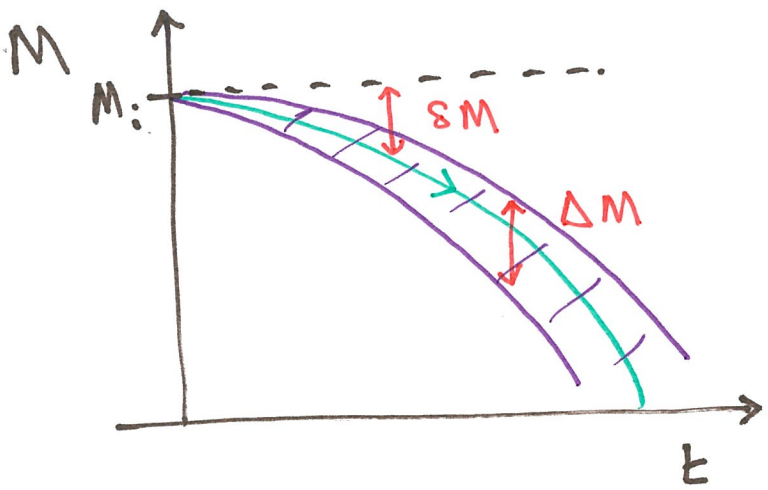
$$M_{n+1} = M_n - \delta_n M_n^{-1}$$

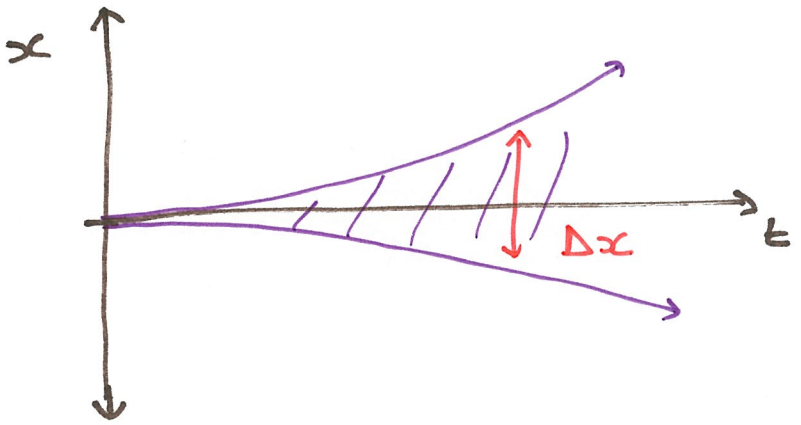
$$p_{n+1} = p_n + \epsilon_n \delta_n M_n^{-1}$$

$$t_{n+1} = t_n + M_n$$

$$x_{n+1} = x_n + \frac{p_n}{M_n}(t_{n+1} - t_n)$$

EVOLUTION OF BLACK HOLE CHARGES





★ Two regimes:

$\delta M << M_i$ (early)

$M << M_i$ (late)

★ Two approximation methods

$\delta M << M_i$ (Page)

$\Delta M << M$

★ Results:

$$\Delta x \sim \begin{cases} \delta M^{3/2} M_i^{1/2} \\ M_i^2 \end{cases}$$

$$\Delta M \sim \begin{cases} \sqrt{\delta M / M_i} \\ M_i^2 / M^2 \end{cases}$$

★ $\Delta M \sim M$ when $M \sim M_i^{2/3}$: macroscopic fluctuations

EXTENSION TO BMS CHARGES

★ Retarded Bondi coordinates (u, r, θ^A)

★ $$ds^2 = -\left[1 - 2\frac{m(u,\theta^A)}{r} + O(r^{-2})\right] du^2$$
$$- \left[1 + O(r^{-2})\right] du\, dr$$
$$+ r^2 \left[h_{AB}(\theta^C) + \frac{1}{r} C_{AB}(u,\theta^A) + \cdots\right] d\theta^A d\theta^B$$
$$+ \cdots$$

Encodes charges conjugate to supertranslations, trivial in stationary region of $\mathcal{I}^+$ → NO EXCITATION

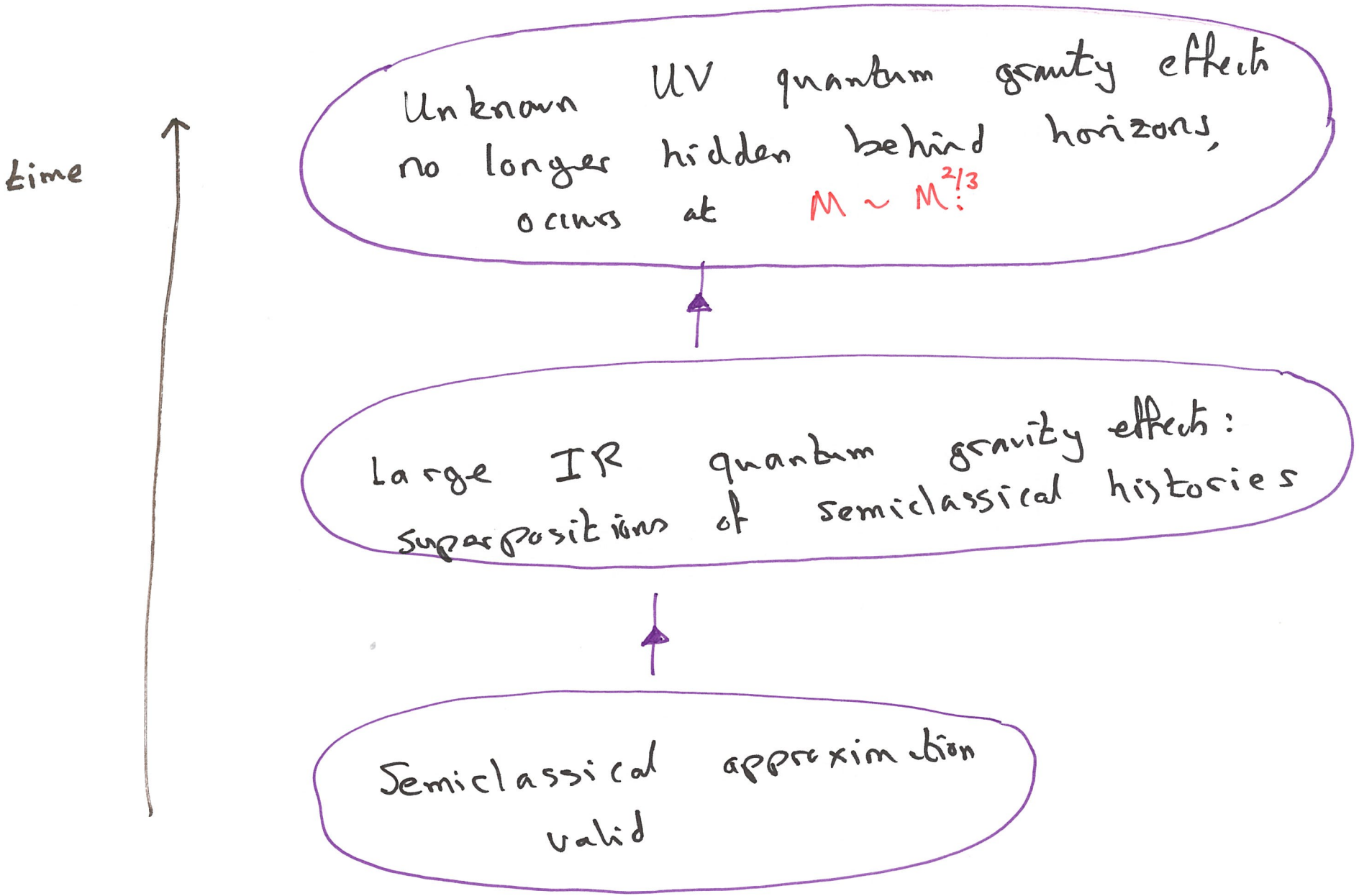
Encodes "super center of mass" charges conjugate to superrotations

★ $$C_{AB} = \sum_{\ell \geq 2} C_\ell \, (\cdots)$$

$$\Delta C_\ell \sim \begin{cases} O(1) & \ell = O(1) \\ \ll 1 & \ell \gg 1 \end{cases}$$

★ Posit simple model for effect of a single quantum in n^{th} instantaneous Bondi frame, based on classical flux

IMPLICATIONS FOR INFORMATION LOSS PARADOX



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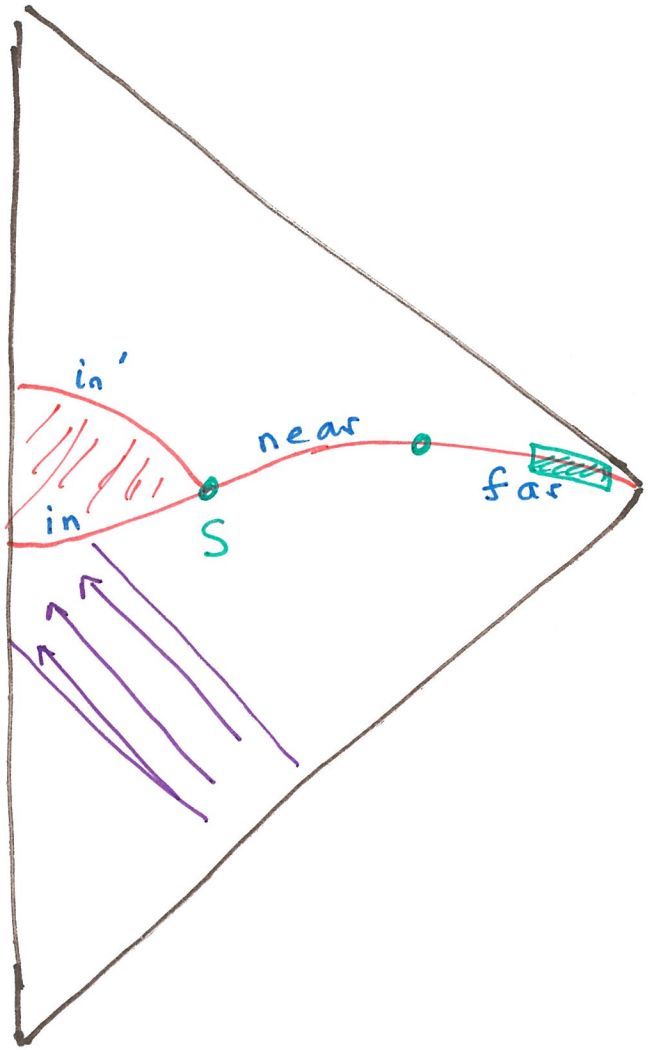

★ Far : distant matter maximally entangled with infalling matter

★ Near : Outgoing Hawking quanta

★ $S_{in}' = S_{near} + S_{far}$

$S_{near} \sim M_\odot^2$ $\quad S_{far} \sim M_\odot^2$

$\lesssim [M(S)\, R(S)]^{3/4} \sim \begin{cases} O(1) & \text{conventionally} \\ [M_\odot^{2/3}\, M_\odot^2]^{3/4} \sim M_\odot^2 & \text{now} \end{cases}$

★ ▨ = Superposition of masses, $0 \le M \le M_\odot^{2/3}$ at different locations

transition ??

Thermal state of mass $\sim M_\odot^{2/3}$ and extent $\sim M_\odot^2$

★ Paradox Robust : Resolution would require $O(1)$ fraction of energy in quanta of energy $\sim M_\odot^{-4/3}$, which

CONCLUSIONS

- There are dramatically large infrared fluctuations in the late stages of black hole evaporation

- The fluctuations do not affect the information loss paradox