Title: Planckian discreteness as a solution of Hawking's information puzzle

Speakers: Alejandro Perez

Series: Quantum Gravity

Date: November 15, 2019 - 2:00 PM

URL: http://pirsa.org/19110052

Abstract: In approaches to quantum gravity, where smooth spacetime is an emergent approximation of a discrete Planckian fundamental structure, any standard effective field theoretical description will miss part of the degrees of freedom and thus break unitarity. Here we show that these expectations can be made precise in loop quantum cosmology. Concretely, even when loop quantum cosmology is unitary at the fundamental level, when microscopic degrees of freedom, irrelevant to low-energy cosmological observers, are suitably ignored, pure states in the effective description evolve into mixed states due to decoherence with the Planckian microscopic structure. When extrapolated to black hole formation and evaporation, this concrete example provides a key physical insight for a natural resolution of Hawking's information paradox.

Discreteness and the Hawking information loss puzzle

PI 2019

Work in collaboration with
Hongguang Liu and Lautaro Amadei

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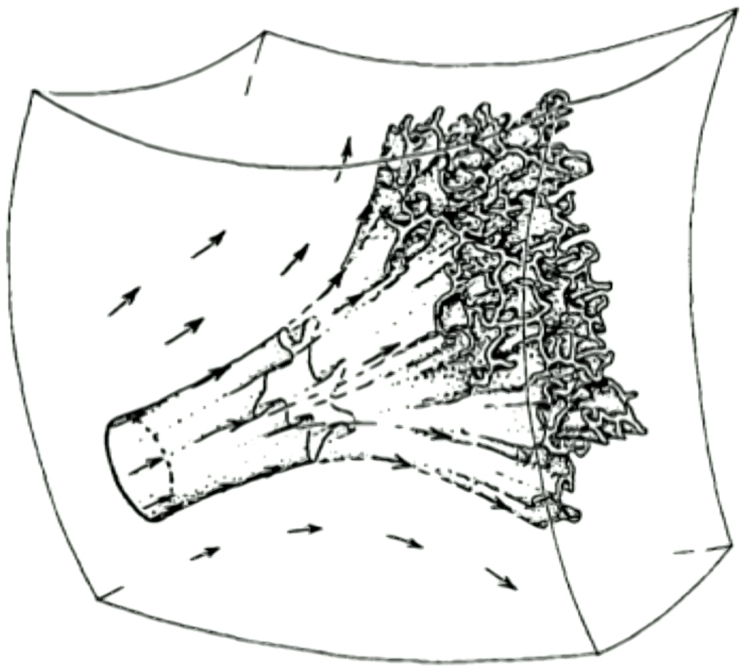
The arrow of time and gravitational collapse

complexity of the system + special initial conditions + coarse graining

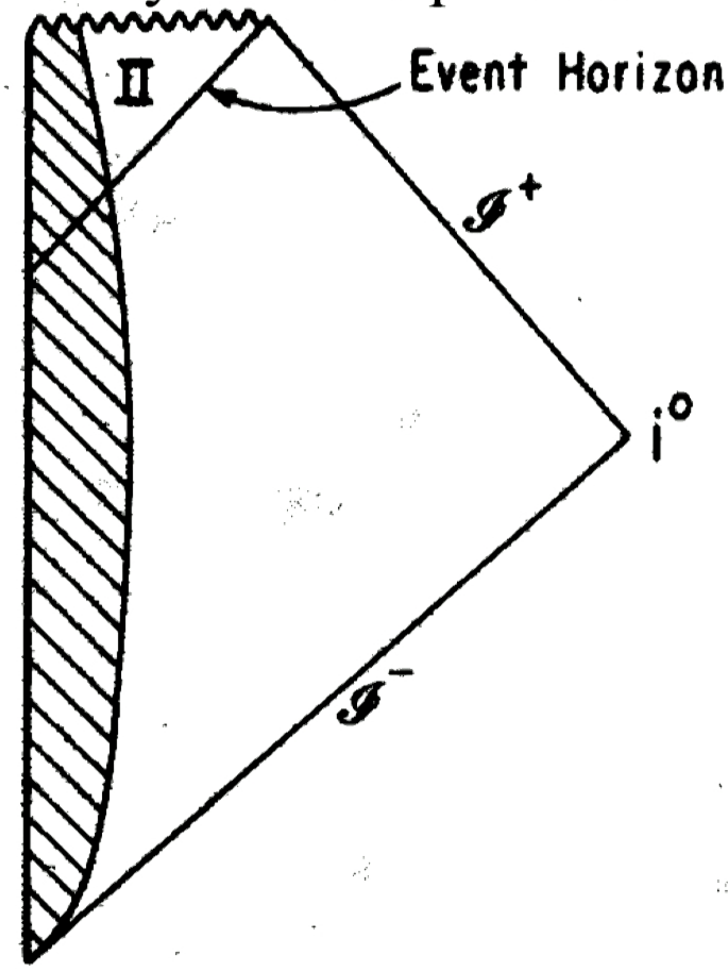


Picture by Penrose

Fig. 5.14. Despite the fact that Liouville's theorem tells us that phase-space volume does not change with time-evolution, this volume will normally *effectively* spread outwards because of the extreme complication of this evolution.

Classical Gravitational Collapse

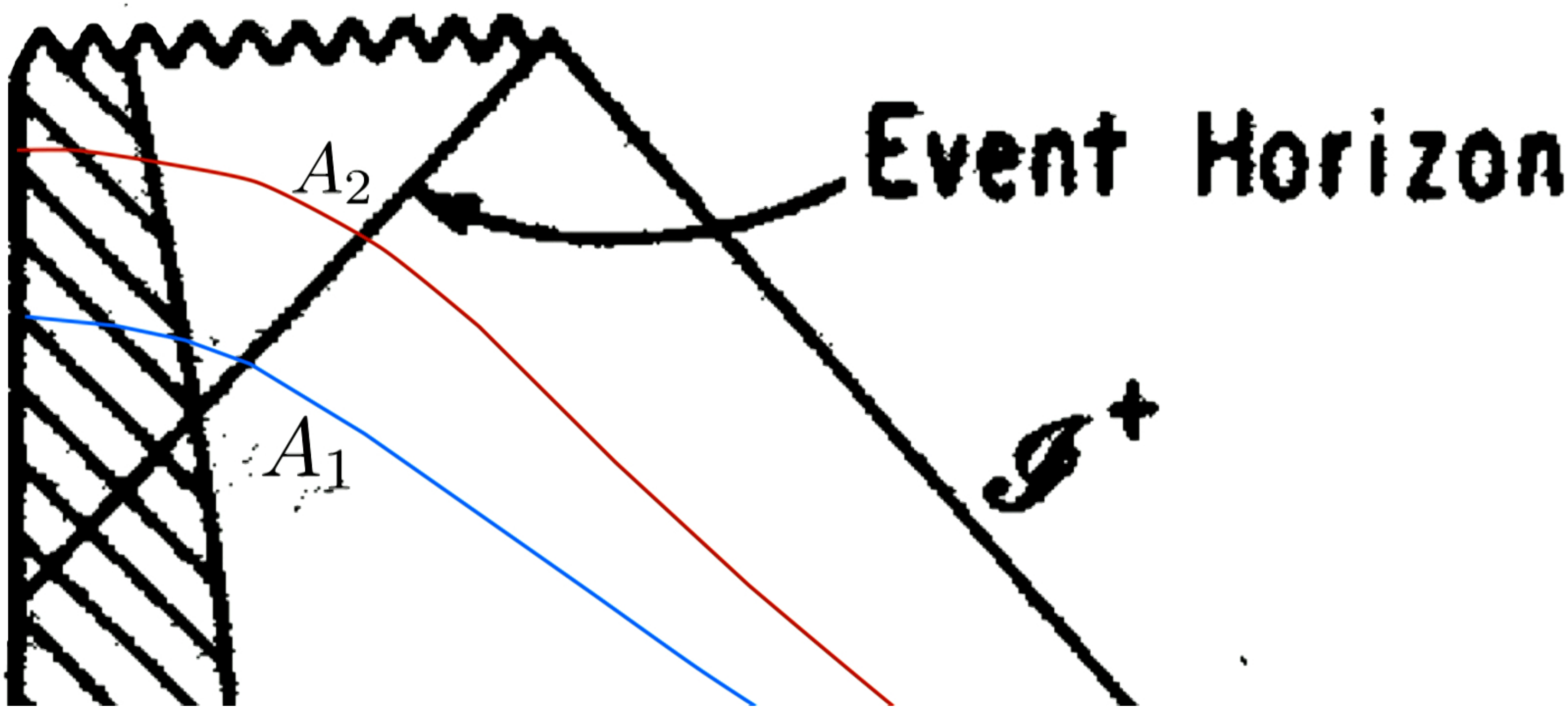
a time asymmetric process



Hawking area theorem

$$A_1 \leq A_2 \qquad \boxed{\delta A \geq 0}$$

Hawking 1971

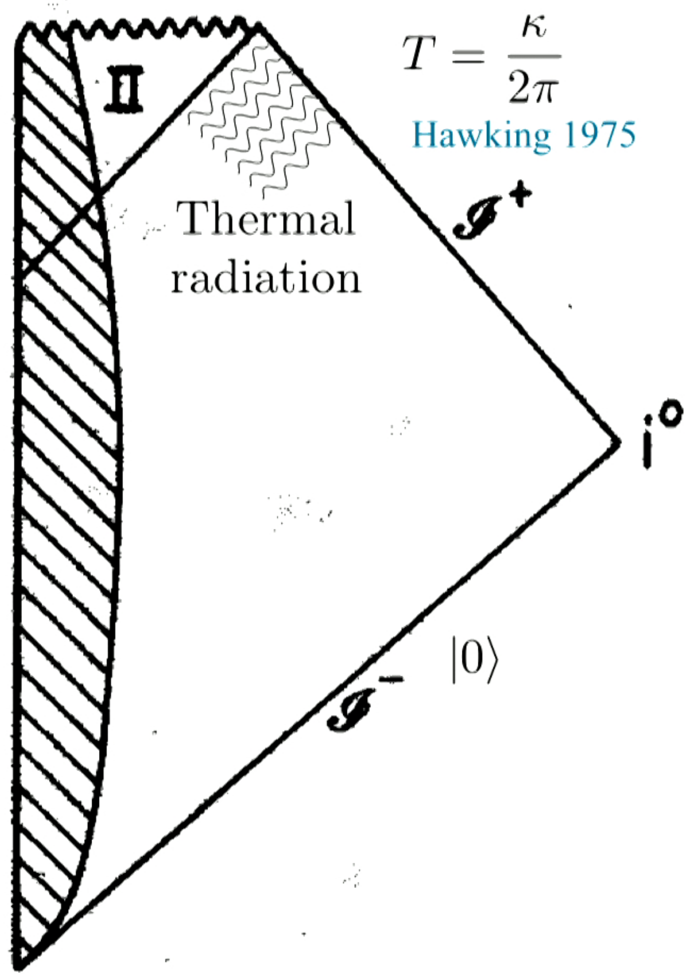


Semiclassical Gravitational Collapse

time asymmetry is accentuated

Hawking radiation

Quantum scattering
of a test quantum field



Black Hole thermodynamics

0th law: at thermal equilibrium (stationary BHs) the BH temperature $T = \frac{\kappa}{2\pi}$ is uniform.

1st law: when perturbed from equilibrium BHs return to equilibrium and satisfy the balance law

$$\delta M = T\frac{\delta A}{4} + \Omega\,\delta J + \Phi\,\delta e.$$

2nd law: $\delta S_{\text{total}} \equiv \delta S_{\text{BH}} + \delta S_{\text{matter}} \geq 0$ where $S_{\text{BH}} \equiv \frac{A}{4}$.

(This one is just Hawking's area theorem when matter can be neglected)

3rd law: The state $T = 0$, i.e., $\kappa = 0$ (extremal BHs) cannot be achieved from a $T \neq 0$ BH by a finite number of physical processes.

(cosmic censor conjecture)

The nature of BH entropy:
a key question for quantum gravity

0th law: at thermal equilibrium (stationary BHs) the BH temperature $T = \frac{\kappa}{2\pi}$ is uniform.

1st law: when perturbed from equilibrium BHs return to equilibrium and satisfy the balance law

heat! "molecular chaos"

$$\delta M = T\frac{\delta A}{4} + \Omega\,\delta J + \Phi\,\delta e.$$

Bekenstein 1974

2nd law: $\delta S_{\rm total} \equiv \delta S_{\rm BH} + \delta S_{\rm matter} \geq 0$ where $S_{\rm BH} \equiv \frac{A}{4}$.

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(cosmic censor conjecture)

Answer in loop quantum gravity

AP. Rept. Prog. Phys. **80** (2017)

Pure quantum geometry approach

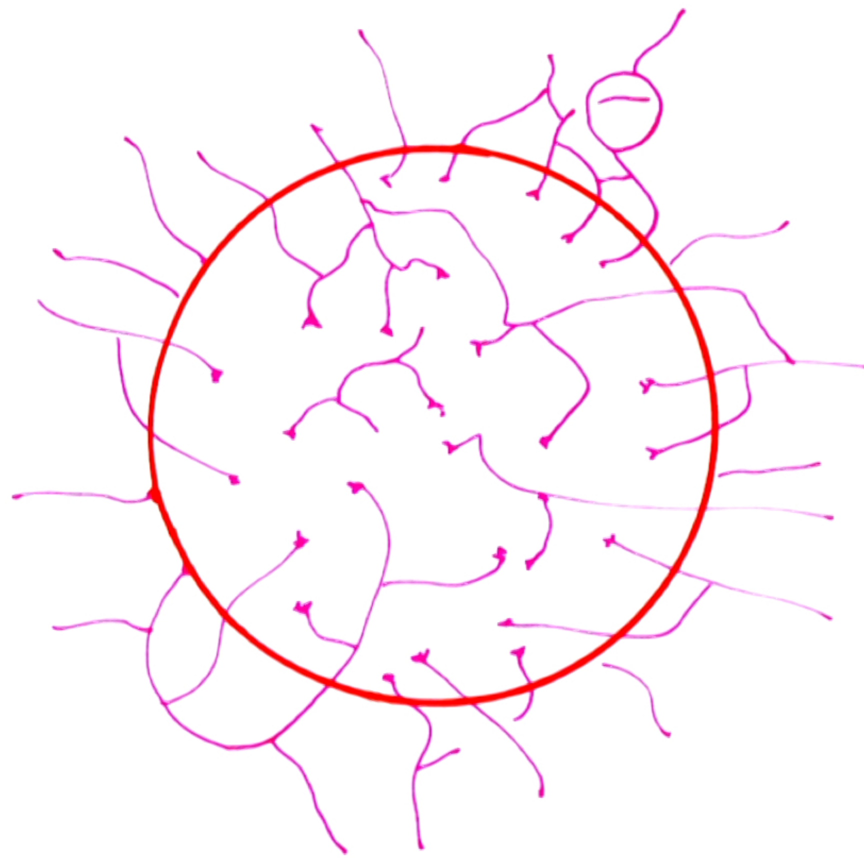
$$S_{bh} = \frac{\gamma_0}{\gamma}\frac{A}{4\ell_p^2}$$

Rovelli (1996),
Ashtekar-Baez-Krasnov-Corichi (1999),
etc

$$\gamma = \gamma_0$$

Barbero-Villasenor (2008)

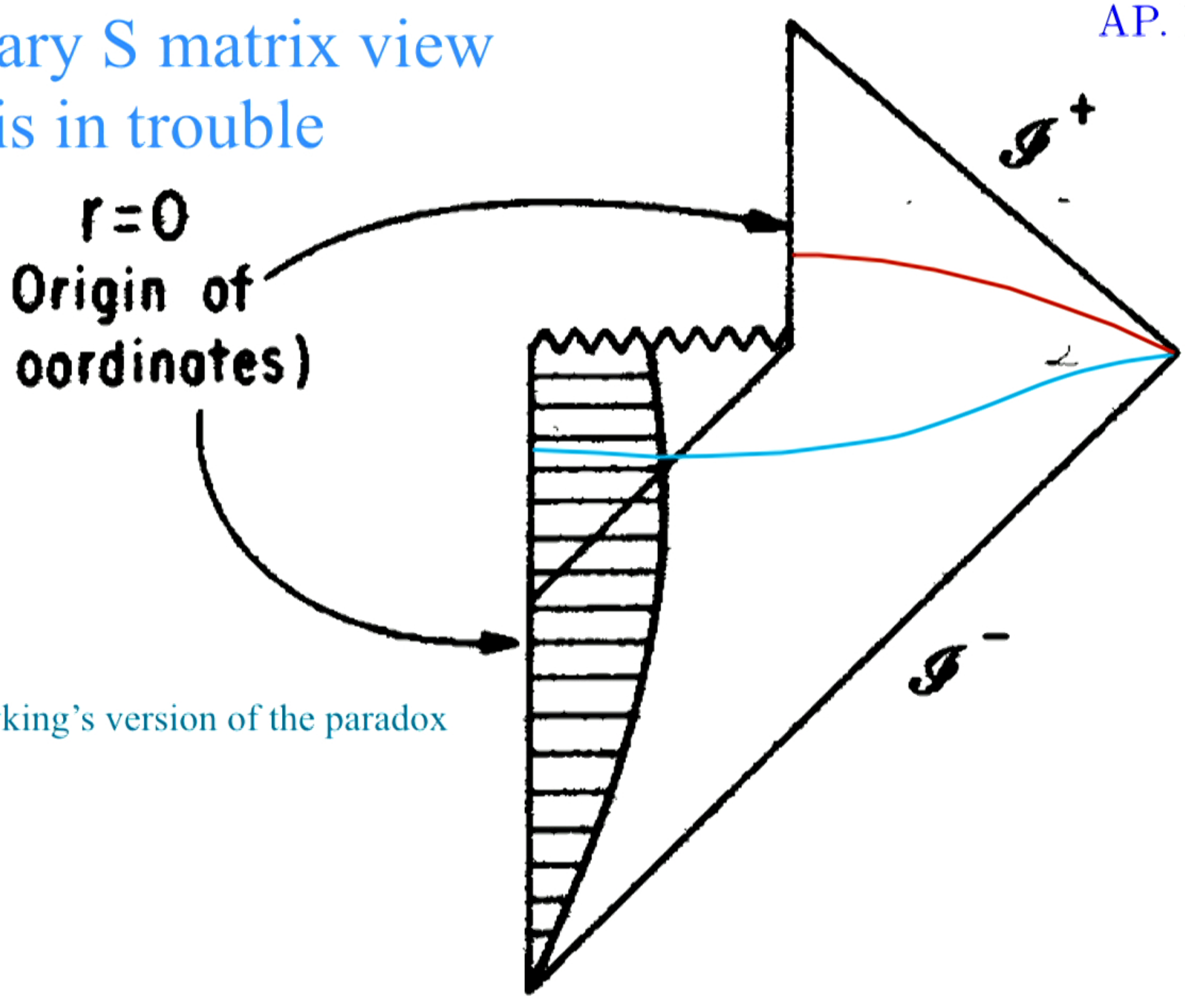
Key property: there is a multiplicity of microstates (quantum geometries) for each macroscopic classical black hole geometry.



The information paradox

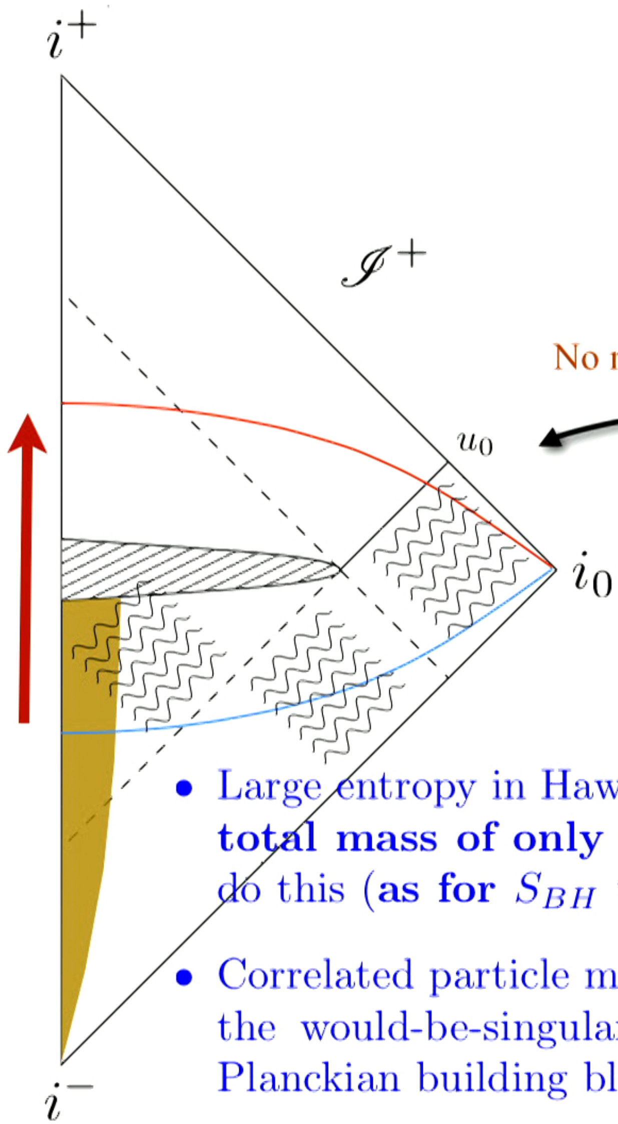
AP. Rept. Prog. Phys. 80 (2017)

A unitary S matrix view
is in trouble



Hawking's version of the paradox

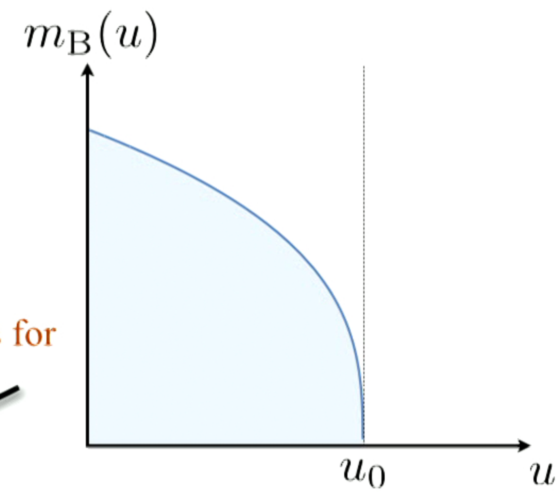
...but it cannot be the end of
the story either!



$\Delta S \neq 0$

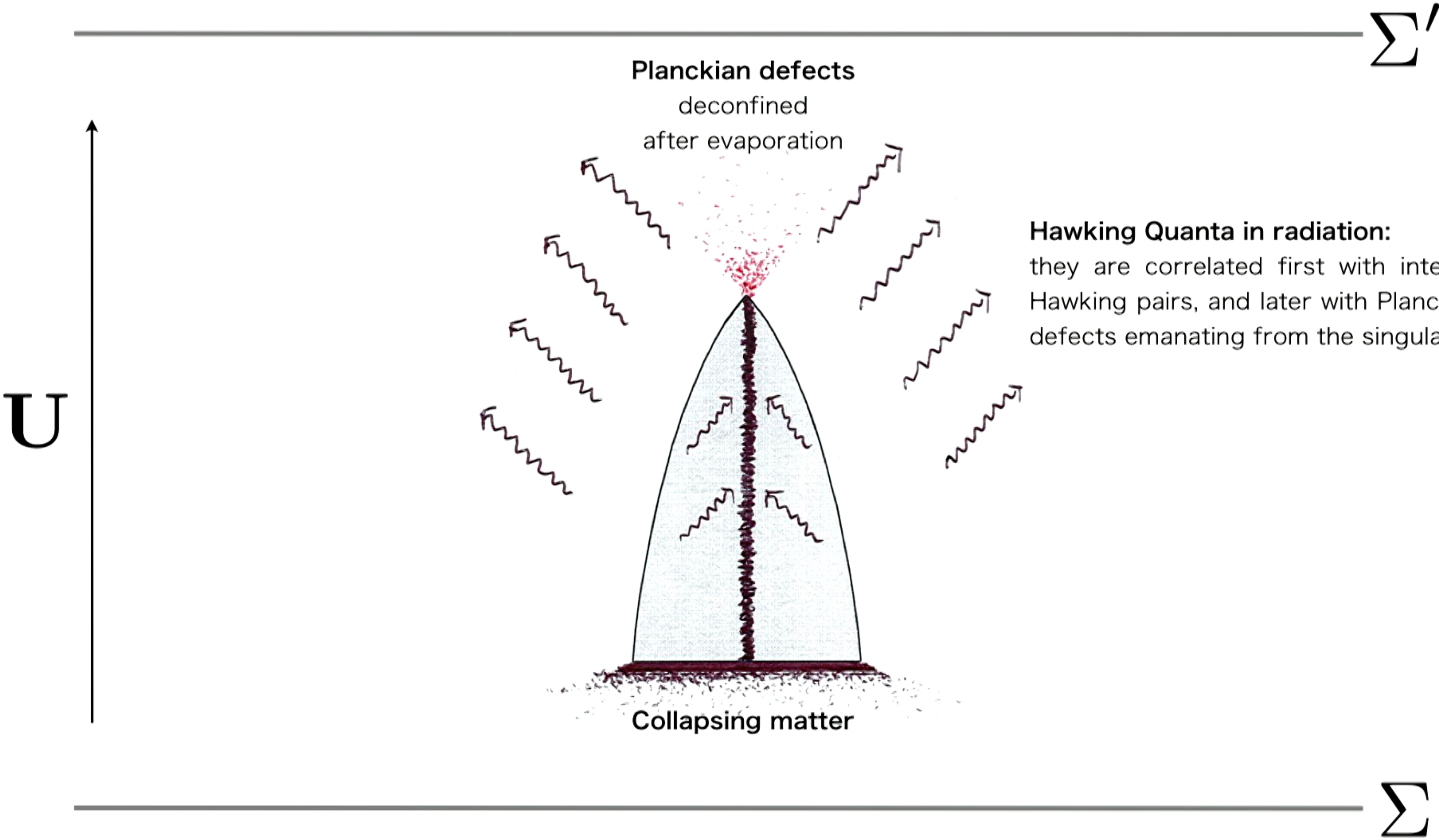
If only Hawking radiation
is considered
there an entropy jump.

No much energy remains for
purification.



- Large entropy in Hawking radiation needs a large number of $d.o.f.$ with a **total mass of only order m_p for purification**. Planckian defects can do this (**as for S_{BH} there is huge degeneracy in the $M = 0$ state**).

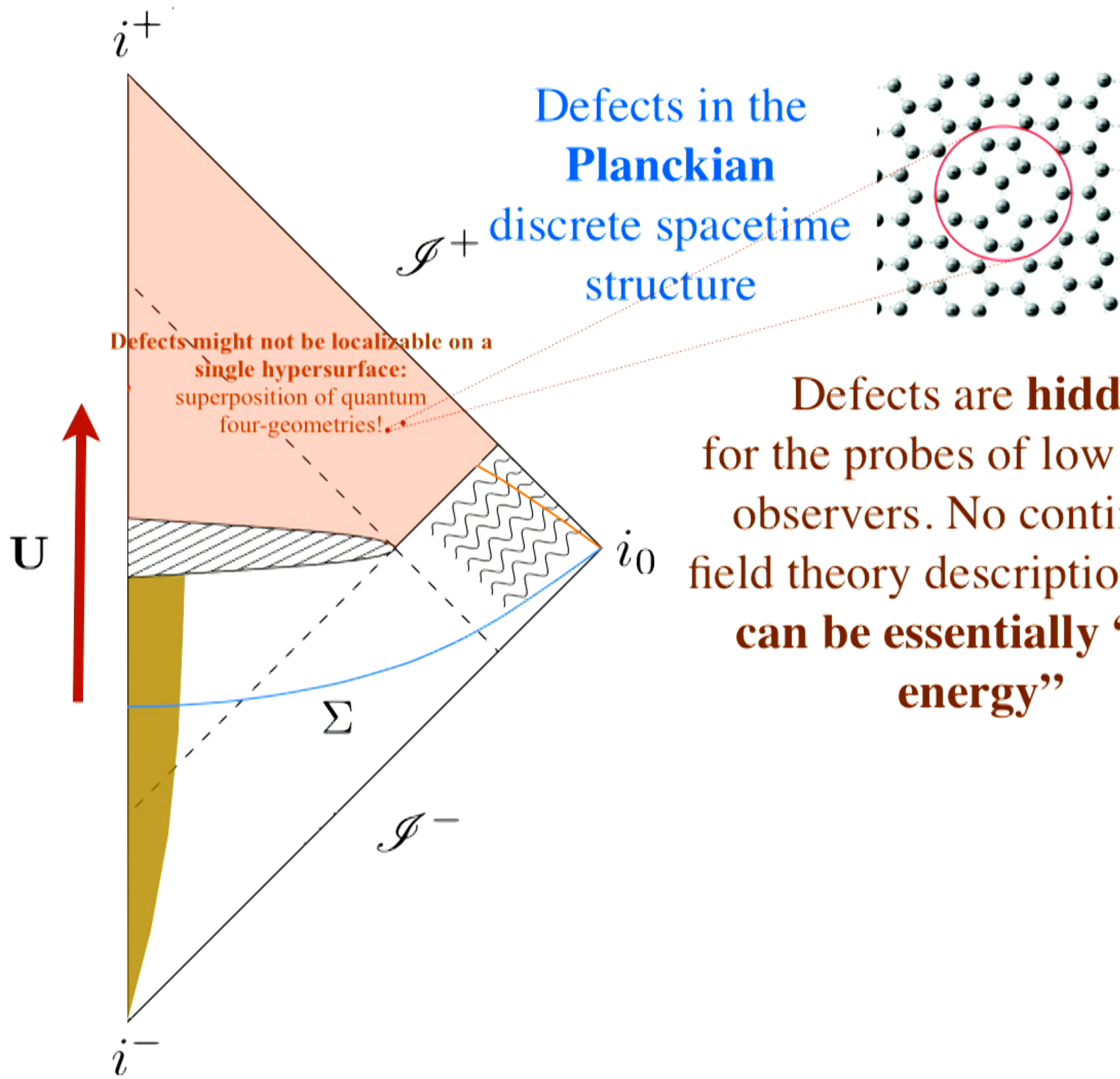
- Correlated particle modes with the Hawking radiation have gone thought the would-be-singularity region they must transfer correlations to the Planckian building blocks of geometry (**huge phase space available**).



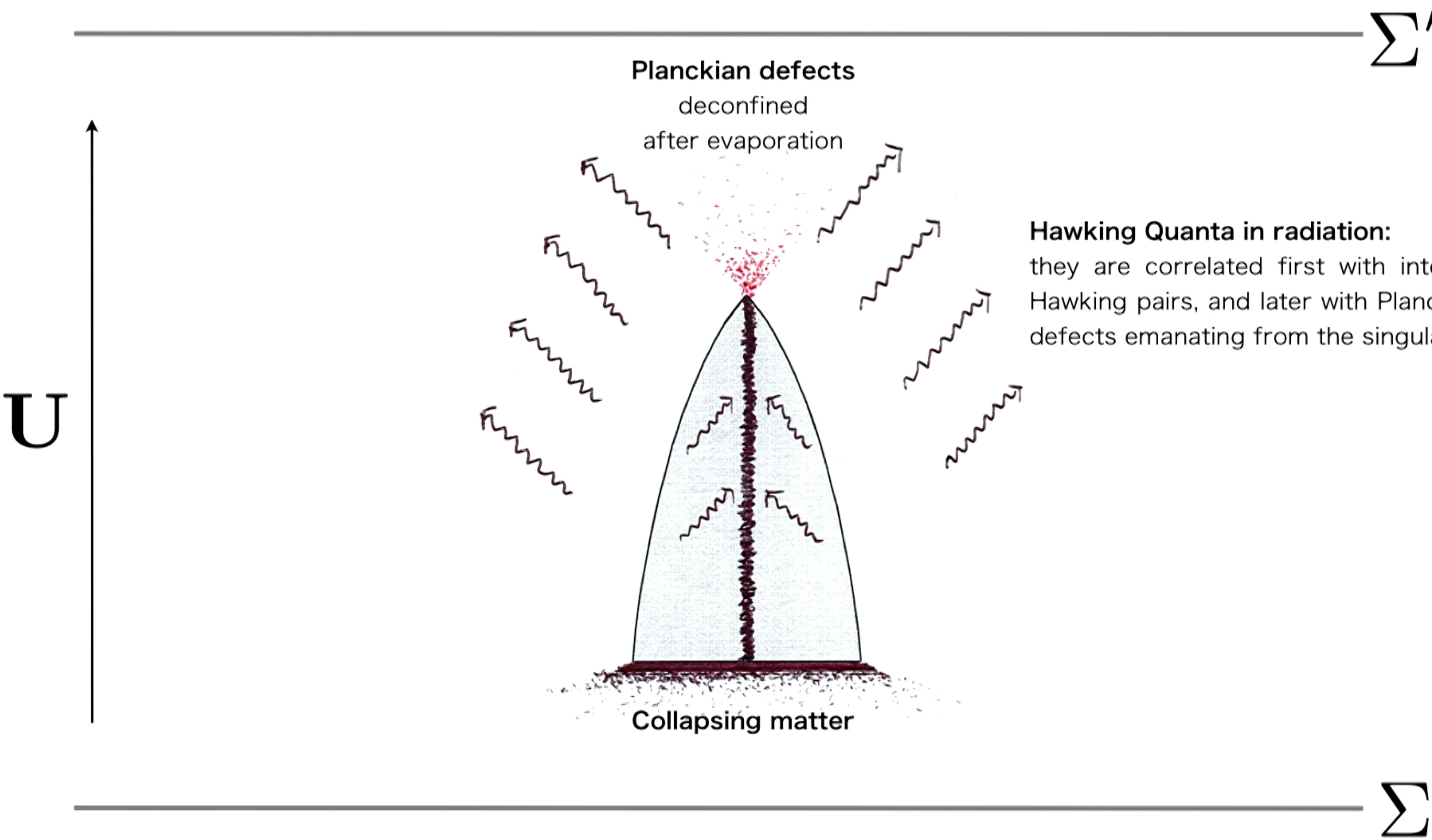
Hawking Quanta in radiation:
they are correlated first with internal Hawking pairs, and later with Planckian defects emanating from the singularity.

AP, *Class. Quant. Grav.* 32, 2015.

Evolution can be unitary in the fundamental theory if the Planckian quantum geometry degrees of freedom responsible for BH entropy in LQG, and not describable in terms of QFT, are appropriately taken into account.



Defects are **hidden** for the probes of low energy observers. No continuum field theory description. **They can be essentially "zero energy"**



Hawking Quanta in radiation:
they are correlated first with internal Hawking pairs, and later with Planckian defects emanating from the singularity.

The action of pure gravity (unimodular)

$$S_0 = \int \frac{1}{2}\left[\dot{p}x + \frac{3p^2|x|}{2\gamma}N - \lambda\left(N|x| - \frac{2}{\gamma}\right)\right] dt$$

Chiou-Geiller (2010)

$t \equiv$ 4-volume elapsed by the fiducial cell
$x \equiv$ volume of the universe (fiducial cell) over ℓ_p^2
$p \equiv$ conjugate momentum

The Hamiltonian

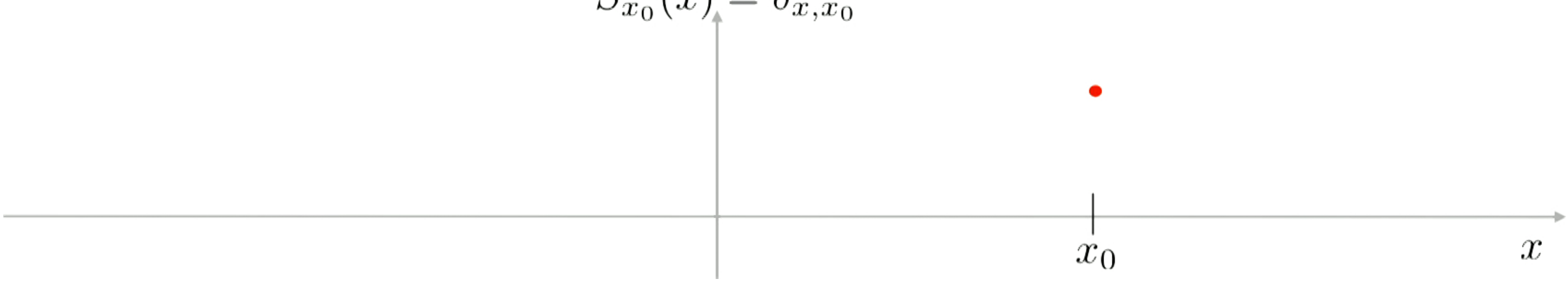
$$H = \Lambda = \frac{3}{\gamma^2}p^2$$

Loop quantization

$\Psi_1(x), \Psi_2(x) \in \mathscr{H}$

$$\langle \Psi_1(x)|\Psi_2(x)\rangle \equiv \sum_{x\in\mathbb{R}} \overline{\Psi}_1(x)\Psi_2(x)$$

$$S_{x_0}(x) = \delta_{x,x_0}$$



Loop quantization

$$\Psi_1(x), \Psi_2(x) \in \mathscr{H} \qquad \langle \Psi_1(x) | \Psi_2(x) \rangle \equiv \sum_{x \in \mathbb{R}} \overline{\Psi}_1(x) \Psi_2(x)$$

Shift operators

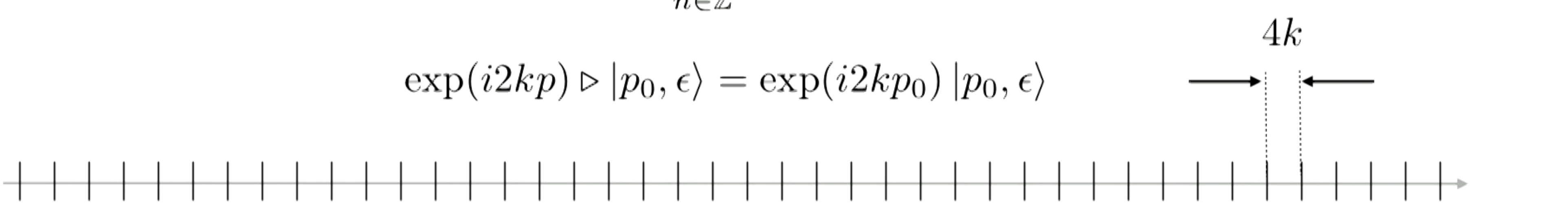
The p operator does not exist in this representation. Only finite translations do (holonomies in LQG)

$$\exp(i2kp)\Psi(x) = \Psi(x - 4k)$$

Eigenstates of the shift operator ('plane waves')

$$|p_0, \epsilon\rangle \equiv \sum_{n \in \mathbb{Z}} e^{-i \frac{p_0}{2} x} \delta_{x-\epsilon, 4nk}$$

$$\exp(i2kp) \triangleright |p_0, \epsilon\rangle = \exp(i2kp_0) \, |p_0, \epsilon\rangle$$



Quantization of the Hamiltonian

The Hamiltonian

$$H = \Lambda = \frac{3}{\gamma^2} p^2$$

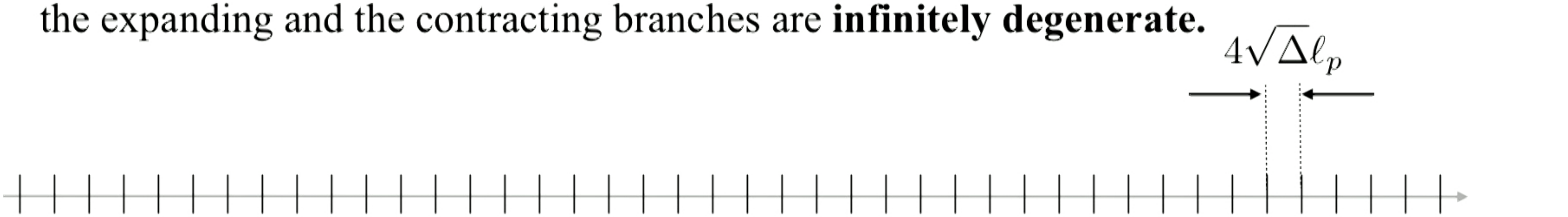
quantization → must use shift operators

$$\Lambda_\Delta \equiv \frac{3}{\gamma^2 \Delta \ell_p^2} \sin^2\left(\Delta^{\frac{1}{2}} \ell_p\, p\right)$$

Energy eigenstates are eigenstates of the cosmological constant

$$|p_0, \epsilon\rangle \equiv \sum_{n\in\mathbb{Z}} e^{-i\frac{p_0}{2}x} \delta_{x-\epsilon,4nk} \quad \text{for } k = \sqrt{\Delta}\ell_p \text{ and eigenvalue } \Lambda_\Delta(p_0) = 3\frac{\sin^2\left(\sqrt{\Delta}\ell_p\, p_0\right)}{\gamma^2 \Delta \ell_p^2}$$

In the Wheeler-DeWitt quantization eigenstates of the cosmological constant are two-fold degenerate: expanding or contracting universe. In the LQC representation both the expanding and the contracting branches are **infinitely degenerate.**



Matter: a scalar field as an example

$$(\hat{\Lambda}_0 - \frac{8\pi\ell_p^2}{V_0}\hat{H}_\phi) \triangleright |\psi\rangle = \Lambda\,|\psi\rangle$$

Pure gravity Hamiltonian

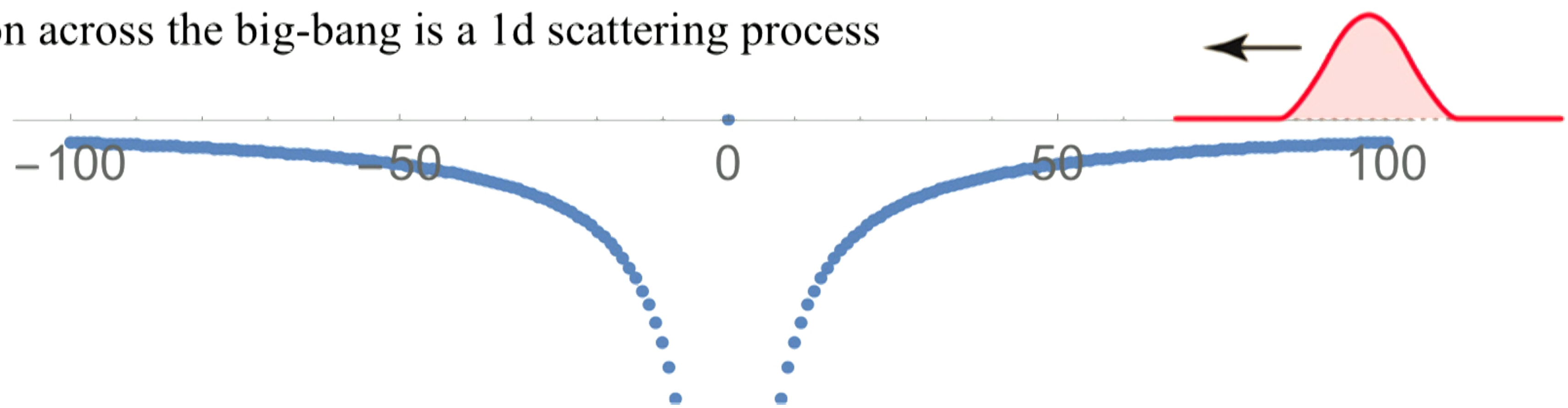
Massless scalar field

$$H_\phi = \frac{p_\phi^2}{8\pi\gamma^2\ell_p^4 x^2}$$

$$\hat{H}_\phi \triangleright |\psi\rangle = \frac{m p_\phi^2}{16\Delta^2\ell_p^4} \times$$

$$\times \sum_x |x\rangle \left(|x + 2\sqrt{\Delta}\ell_p|^{\frac{1}{2}} - |x - 2\sqrt{\Delta}\ell_p|^{\frac{1}{2}}\right)^4 \Psi(x,\phi)$$

Evolution across the big-bang is a 1d scattering process



Matter: a scalar field as an example

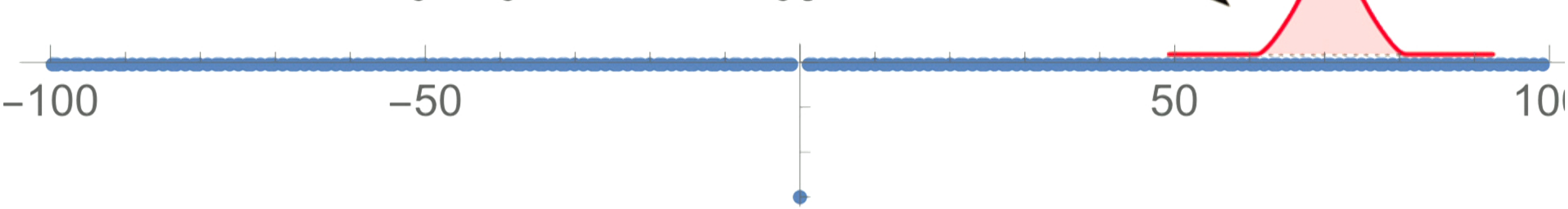
$$\hat{\Lambda} = \hat{\Lambda}_0 - \mu \frac{8\pi \ell_p^2}{V_0} \hat{H}_{\text{int}}$$

Pure gravity Hamiltonian (→ $\hat{\Lambda}_0$)

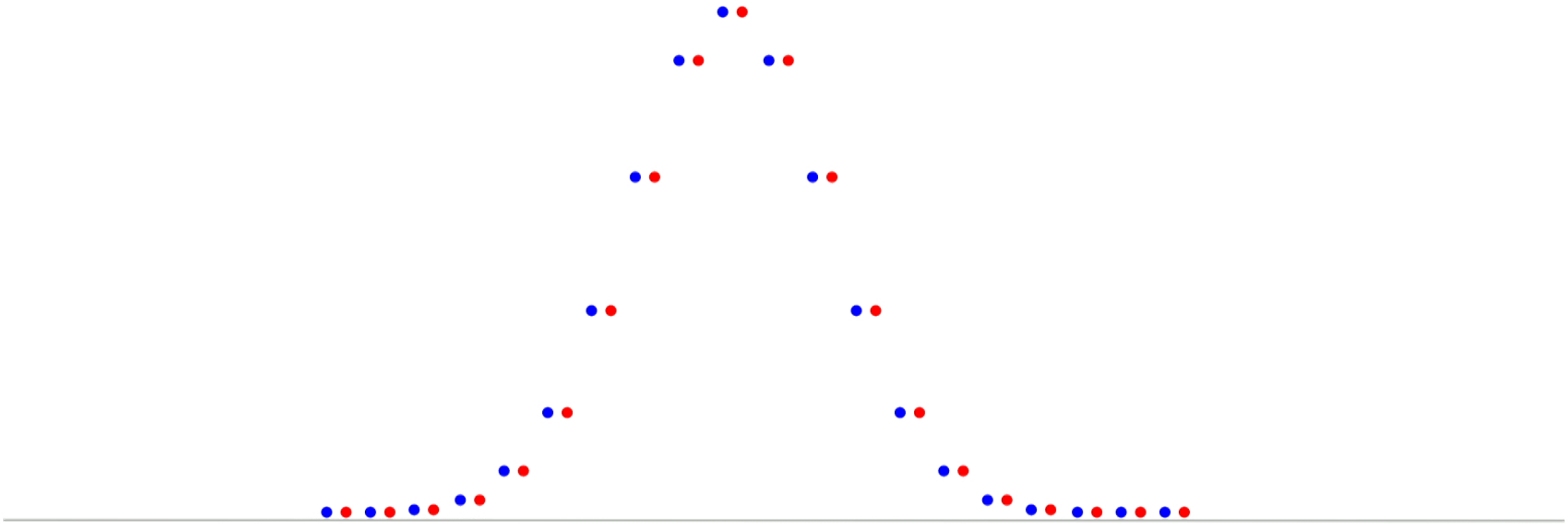
A toy solvable model

$$\hat{H}_{\text{int}} \triangleright |\psi\rangle \equiv \sum_x \left(\ell_p^{-4} \frac{V_0}{\sqrt{\Delta}} \right) |x\rangle \frac{\delta_{x,0}}{\sqrt{\Delta}} \Psi(0)$$

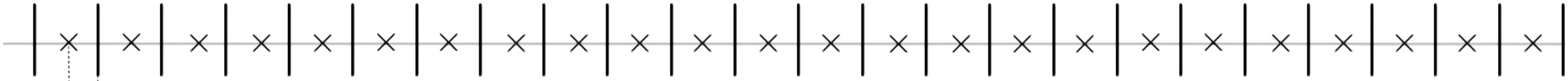
Evolution across the big-bang is a 1d scattering process

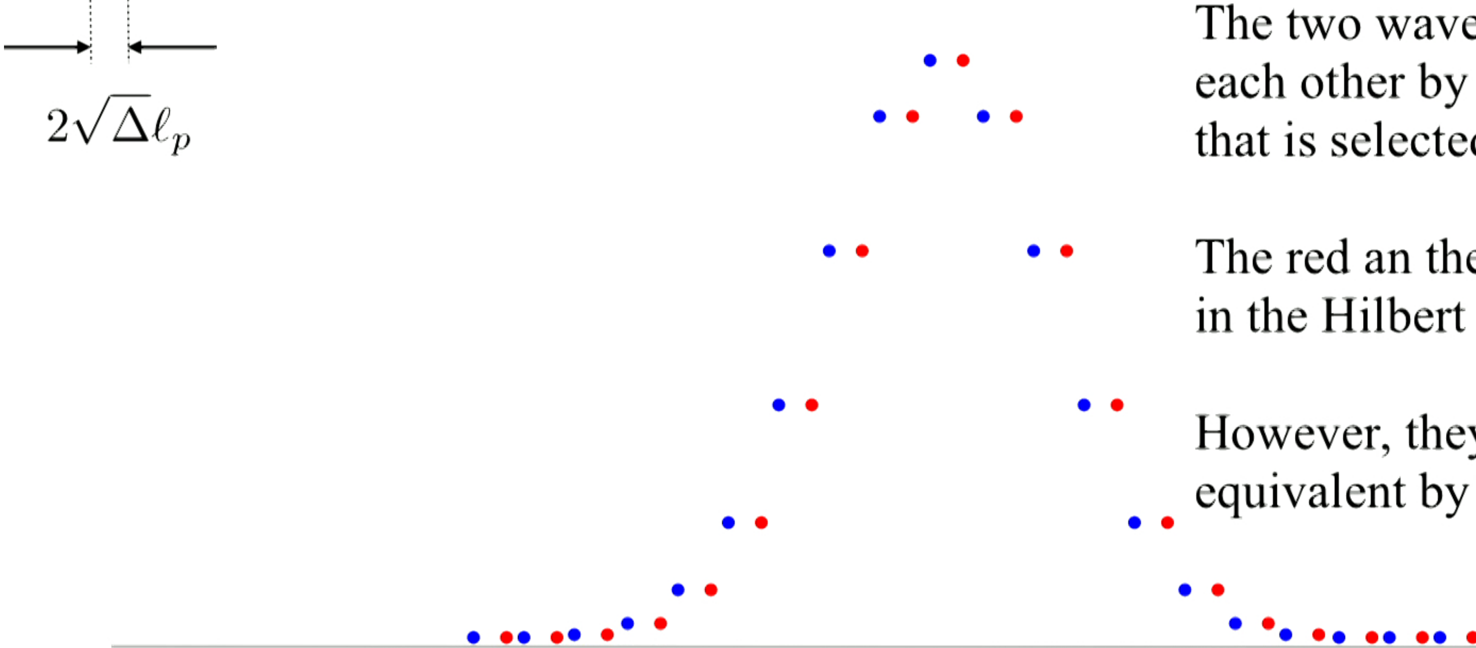


Shifting a wave packet



The superposition of these two is our initial state





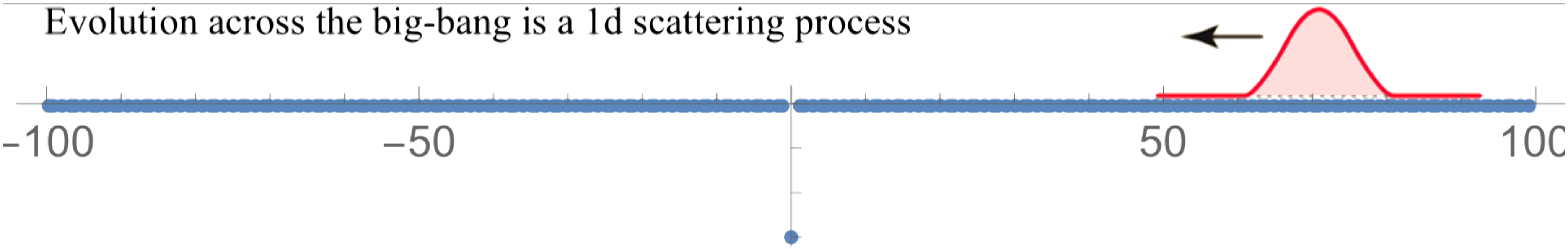
The two wave packets are shifted from each other by half of the lattice spacing that is selected by the free Hamiltonian.

The red an the blue are orthogonal states in the Hilbert space of LQC.

However, they must be considered as equivalent by a coarse grained observer.

$$|\psi_{\rm in}, t\rangle = \frac{\pi}{\sqrt{2\Delta}\ell_p} \int dp \big(|p, 1\rangle\, \psi(p) + |p, 2\rangle\, \psi(p) \big) e^{-i\Lambda_\Delta(p) t}$$

Evolution across the big-bang is a 1d scattering process



Ansatz

$$|\psi_k\rangle = |x\rangle \begin{cases} e^{-i\frac{k}{2}x} + A(k)\, e^{i\frac{k}{2}x} & (x \geq 0) \\ B(k)\, e^{-i\frac{k}{2}x} & (x \leq 0) \end{cases}$$

Discrete Schroedinger equation

$$3\sum_x \frac{\Psi(x - 4\sqrt{\Delta}\ell_p) + \Psi(x + 4\sqrt{\Delta}\ell_p) - 2\Psi(x)}{2\gamma^2\Delta\ell_p^2} = \sum_x \left(\frac{8\pi\mu}{\Delta\ell_p^2}\delta_{x,0}\Psi(0) - \Lambda(k)\,\Psi(x)\,|x\rangle\right)$$

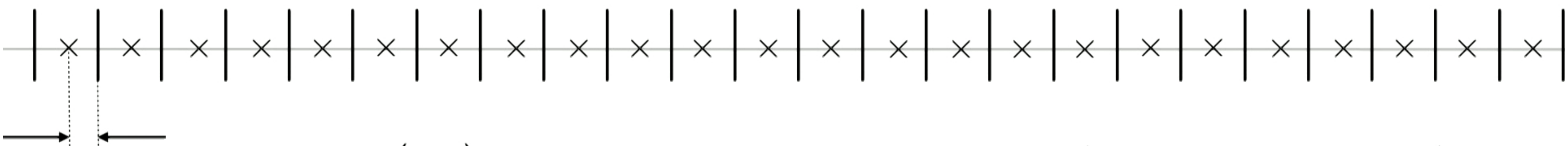
Solution

$$A(k) = \frac{-i\Theta(k)}{1 + i\Theta(k)} \qquad B(k) = \frac{1}{1 + i\Theta(k)} \qquad \Theta(k) \equiv \frac{16\pi\gamma^2}{3}\frac{\mu}{\sin(2k\sqrt{\Delta}\ell_p)}.$$

$$\boldsymbol{\rho}_{\text{in}} = \begin{pmatrix} \frac{1}{2} & 0 & \frac{1}{2} & 0 \\ 0 & 0 & 0 & 0 \\ \frac{1}{2} & 0 & \frac{1}{2} & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \longrightarrow \boldsymbol{\rho}_{\text{out}} = \frac{1}{2} \begin{pmatrix} |B(p_0)|^2 & \overline{A}(-p_0)B(p_0) & B(p_0) & 0 \\ A(-p_0)\overline{B(p_0)} & |A(-p_0)|^2 & A(-p_0) & 0 \\ \overline{B(p_0)} & \overline{A(-p_0)} & 1 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

Reduce density matrix
(coarse grained observers)

$$\langle p|\, \rho^{\text{R}}\, |p'\rangle \equiv \sum_{i=1}^{2} \langle p, i|\, \rho\, |p', i\rangle \qquad 1 \equiv \times \qquad 2 \equiv |$$



$2\sqrt{\Delta}\ell_p$

$$\boldsymbol{\rho}^{\text{R}}_{\text{in}} = \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} \longrightarrow \boldsymbol{\rho}^{\text{R}}_{\text{out}} = \frac{1}{2} \begin{pmatrix} 1+|B(p_0)|^2 & \overline{A}(-p_0)B(p_0) \\ A(-p_0)\overline{B(p_0)} & |A(-p_0)|^2 \end{pmatrix}$$

$$\delta S = \log(2) - \frac{3\Delta}{128\pi^2\gamma^2\mu^2}\Lambda\ell_p^2 + \mathscr{O}(\Lambda^2\ell_p^4)$$

Reduce density matrix
(coarse grained observers)

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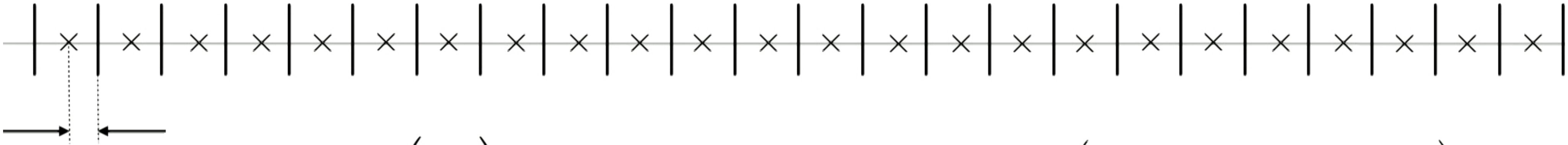

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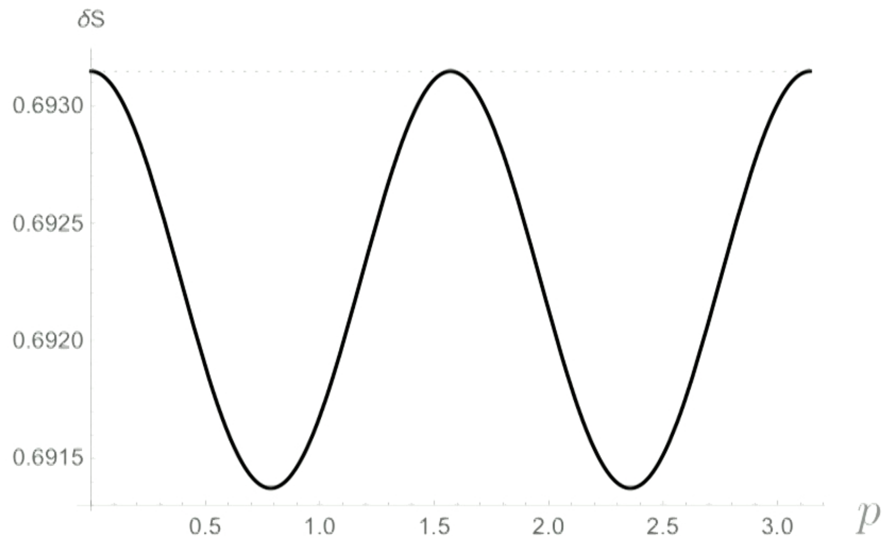

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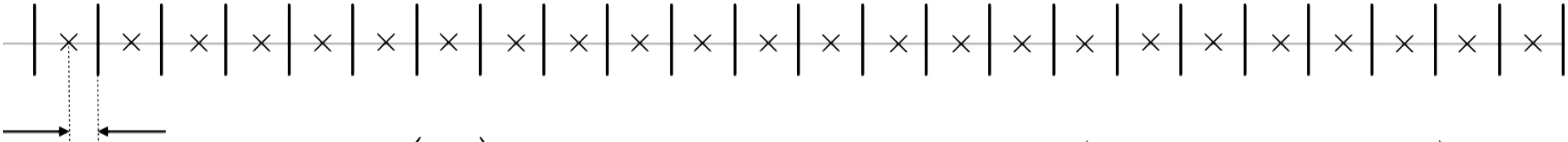
$$\langle p|\,\rho^{\mathrm{R}}\,|p'\rangle \equiv \sum_{i=1}^{2} \langle p, i|\,\rho\,|p', i\rangle \qquad 1 \equiv \times \qquad 2 \equiv |$$



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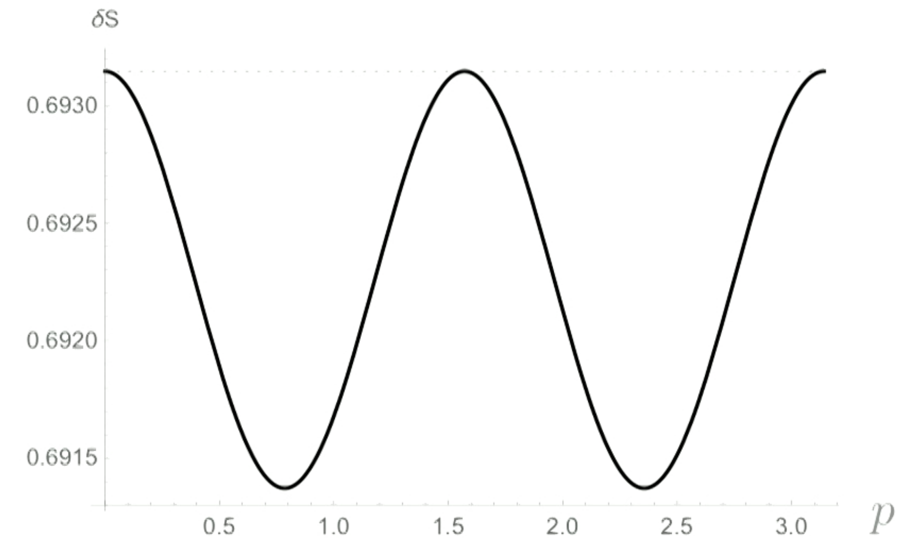
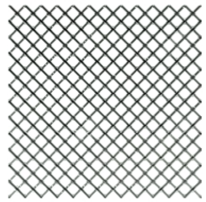


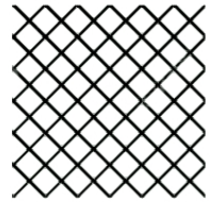
There is another way channel for information in LQC

$$\hat{H} \triangleright (|s\rangle \otimes \psi) = |s\rangle \otimes \ \hat{H}_{\Delta_s} \triangleright \psi$$

$$\Psi_{\text{in}} \equiv \Bigg(\tfrac{1}{\sqrt{2}}$$



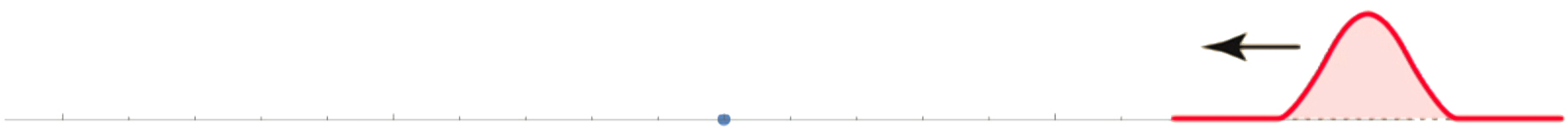
$$+ \tfrac{1}{\sqrt{2}}$$



$$\Bigg) \otimes \psi(p)$$

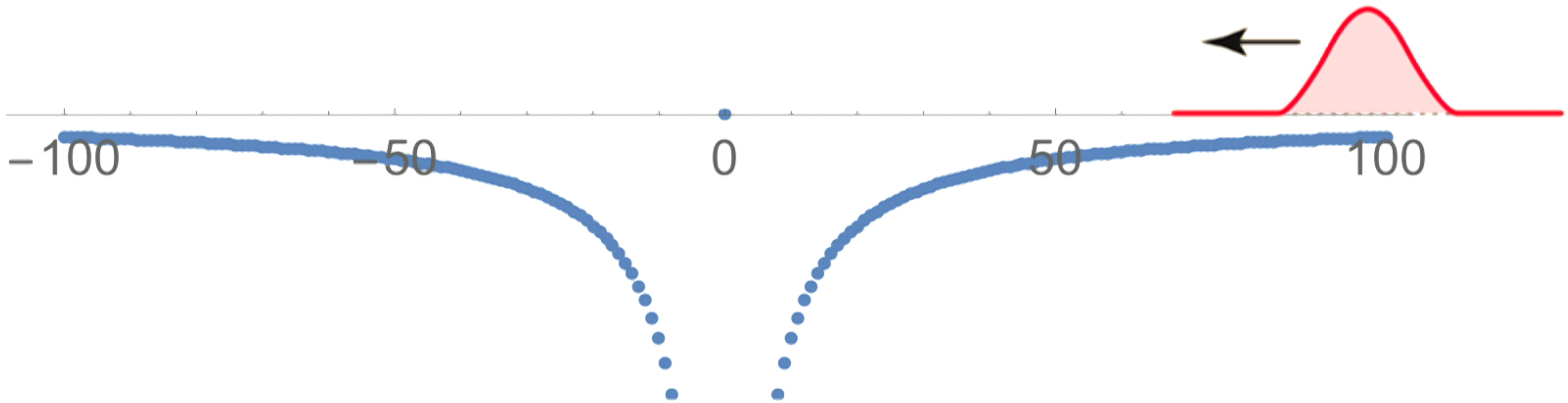
$$\Psi_{\text{in}}(t) = \sum_s \frac{1}{2\sqrt{2\Delta_s}\ell_p} \int dp\, |s\rangle \otimes |p\rangle\, \psi(p) e^{-i\frac{p}{2}\overline{\nu} - iE_s(p)t}$$

$$E_s(p) \propto \mathbf{R} \equiv \frac{12}{\gamma^2}\frac{1}{\Delta_s \ell_p^2}\left(\sin(\sqrt{\Delta_s}\ell_p p)\right)^2 = \frac{12}{\gamma^2}p^2 - \frac{4}{\gamma^2}\Delta_s \ell_p^2 p^4 + p^2 \mathscr{O}(\ell_p^4 p^4).$$



pure gravity case

Matter case (massless scalar here): The matter hamiltonian acts as a potential for the gravity part.



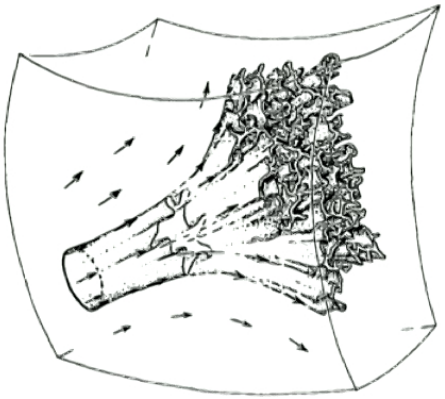
Asymptotic (free) state now

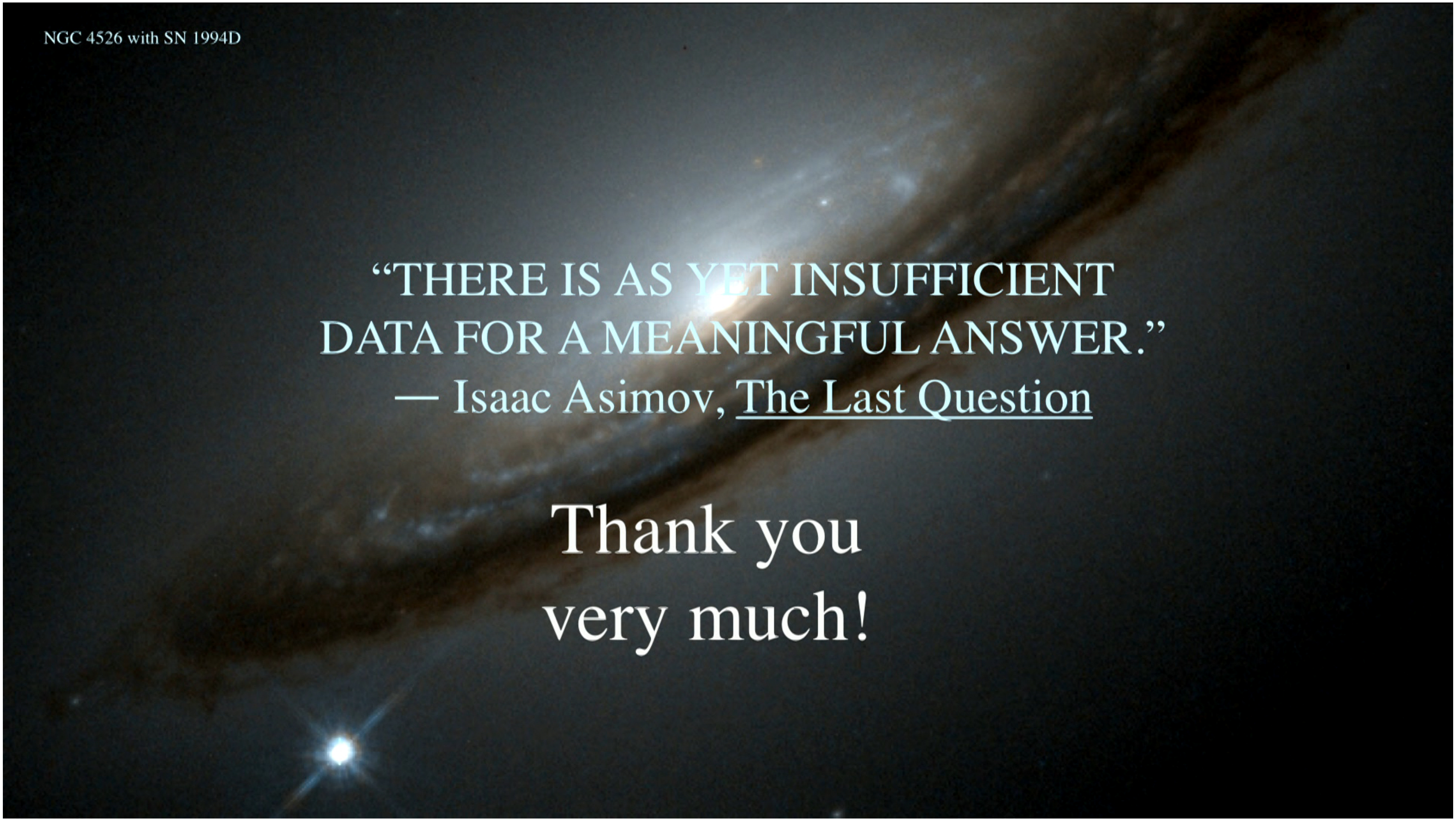
$$\Psi_{\rm in}(t) = \sum_s \frac{1}{2\sqrt{2\Delta_s}\ell_p} \int dp\, |s\rangle \otimes |p\rangle\, \psi(p) e^{-i\frac{p}{2}\overline{\nu} - iE_s(p)t}$$

Entropy jumps at the would-be-singularity, with **no energy dissipation**, just as required in the BH evaporation scenario proposed here!

Unruh 2012

Information is degraded but not destroyed in standard irreversible situations




NGC 4526 with SN 1994D
"THERE IS AS YET INSUFFICIENT
DATA FOR A MEANINGFUL ANSWER."
— Isaac Asimov, The Last Question
Thank you
very much!