BLACK HOLE COMPLEMENTARITY FROM MICROSTATE MODEL

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PLAN

1. Motivation for microstate models
2. Two toy models: (I) The trumpet and a qubit (ii) The trumpet and the quantum harmonic oscillator
3. A simple microstate model
4. The evaporating microstate
5. Conclusions and outlook

BASED ON

ONGOING WORKS WITH TANAY KIBE, PRABHA MANDAYAM, SUKRUT MONDKAR AND HARERAM SWAIN

KIBE, AM, SOLOVIEV, SWAIN; 2006.08644 (PHYS. REV. D 102 (2020) 8, 086008)

KIBE, MANDAYAM, AM: EPJC REVIEW

MOTIVATION

BLACK HOLE COMPLEMENTARITY AND THE PARADOX

Black hole complementarity principle for resolving information loss paradox: Information is both inside and outside an (old) black hole. No observer can verify both copies [Susskind, Thoraclius, Uglum 1993]

Is claimed to be a consequence of

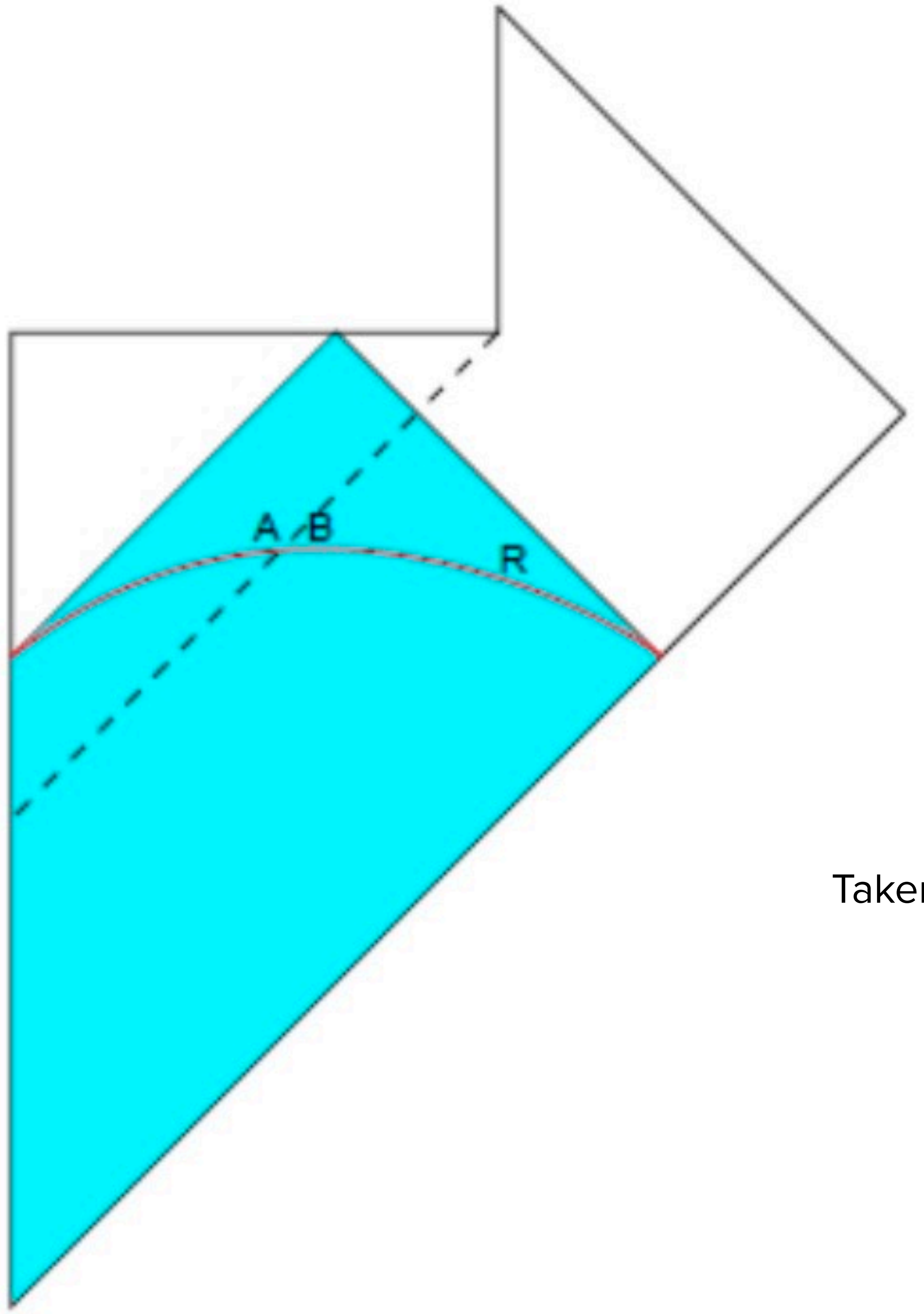
(i) Unitarity of evaporation process,

(ii) EFT and equivalence principle at the horizon

(iii) Fundamental Dogma: A distant observer sees the BH as a system with discrete energy spectrum, and

(iv) No Drama: Infalling observer sees a smooth horizon

The AMPS-Mathur Paradox: Strong subadditivity of entanglement entropy (considering three subsystems : early radiation + late radiation + interior implies that all four assumptions cannot be valid simultaneously



Taken from Daniel Harlow, Jerusalem Lectures

Two possible resolutions:

1. **Nyay (Principle): The Hilbert space cannot be factorized — the interior is encoded in a state-dependent way at the boundary [Papadodimas Raju 2012, Hayden Pennington 2018].**

2. **Neeti (Practice): Hayden and Harlow (2013) argued that it would take time exponential in the entropy (at the time of emission of B) to distill R_B from R needed to purify B. Kim, Tang and Preskill (2020) have made the argument more rigorous.**

Holographic reconstruction of black hole interior is state-dependent and complex.
[Papadodimas and Raju, Hayden and Pennington, Susskind, Engelhardt and Pennington, ……]

IN THIS TALK

How does "black hole complementarity principle" emerge from a microscopic description? Are there toy models?

Is there a microstate model from where within a local (but not necessarily global) semi-classical description, complementarity with an operationally smooth horizon emerges without paradoxes?

This will be similar to the recent understanding of Page curve from semi-classical black hole geometry.

Furthermore, is a black hole a special kind of coal after all?

TWO TOY MODELS

THE TRUMPET AND A CLASSICAL SYSTEM

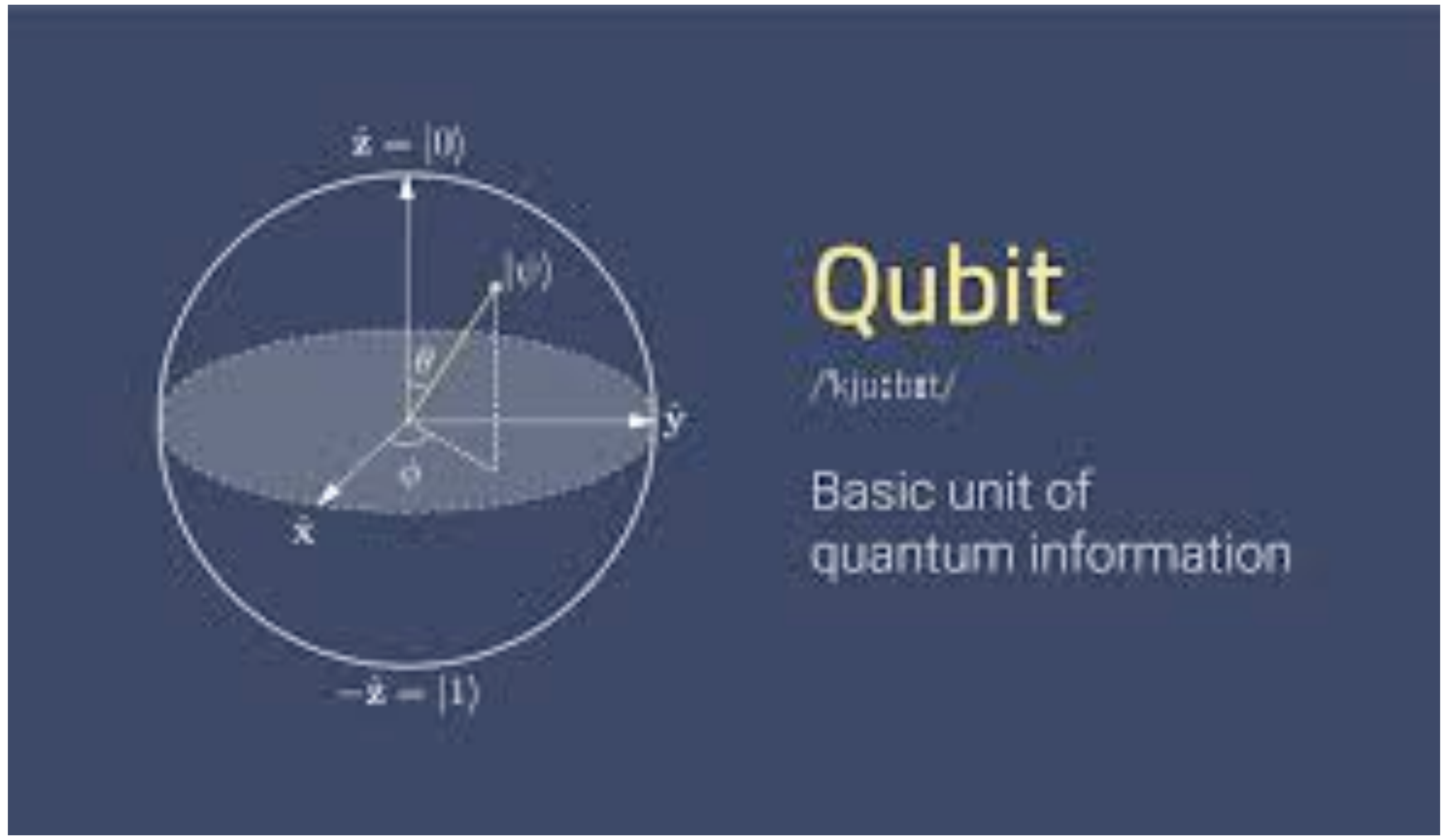
When we couple a classical system to a JT black hole (trumpet), the latter simply sucks away the energy of the classical system and typically drives it to the lowest energy equilibrium state.

The two systems decouple and we are left with no information of the initial state.

Not fully true if the classical system also has large number of degrees of freedom, etc.

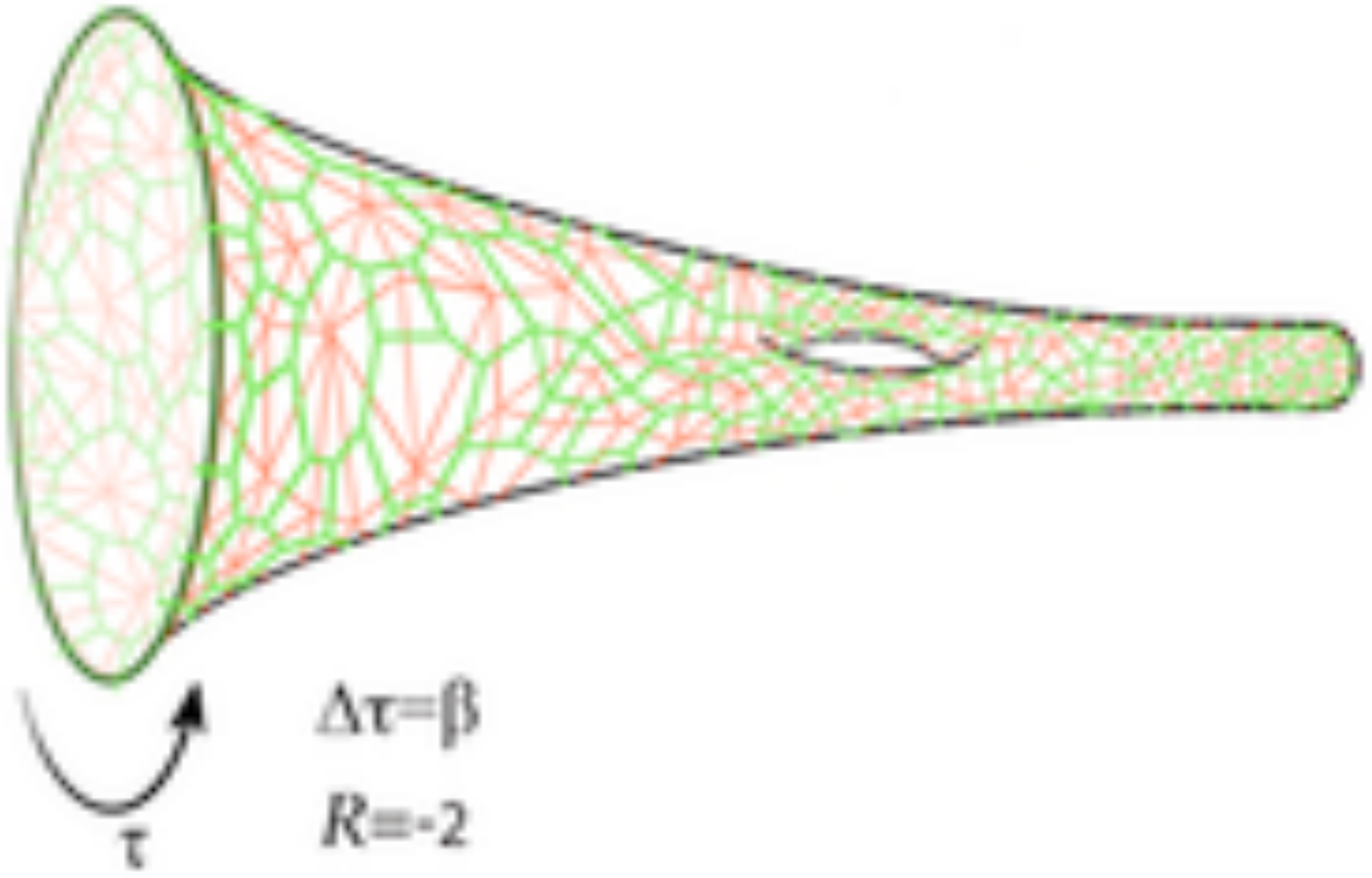
Decoupling leads to double copy of quantum information without cloning.

THE. TRUMPET. AND A QUBIT



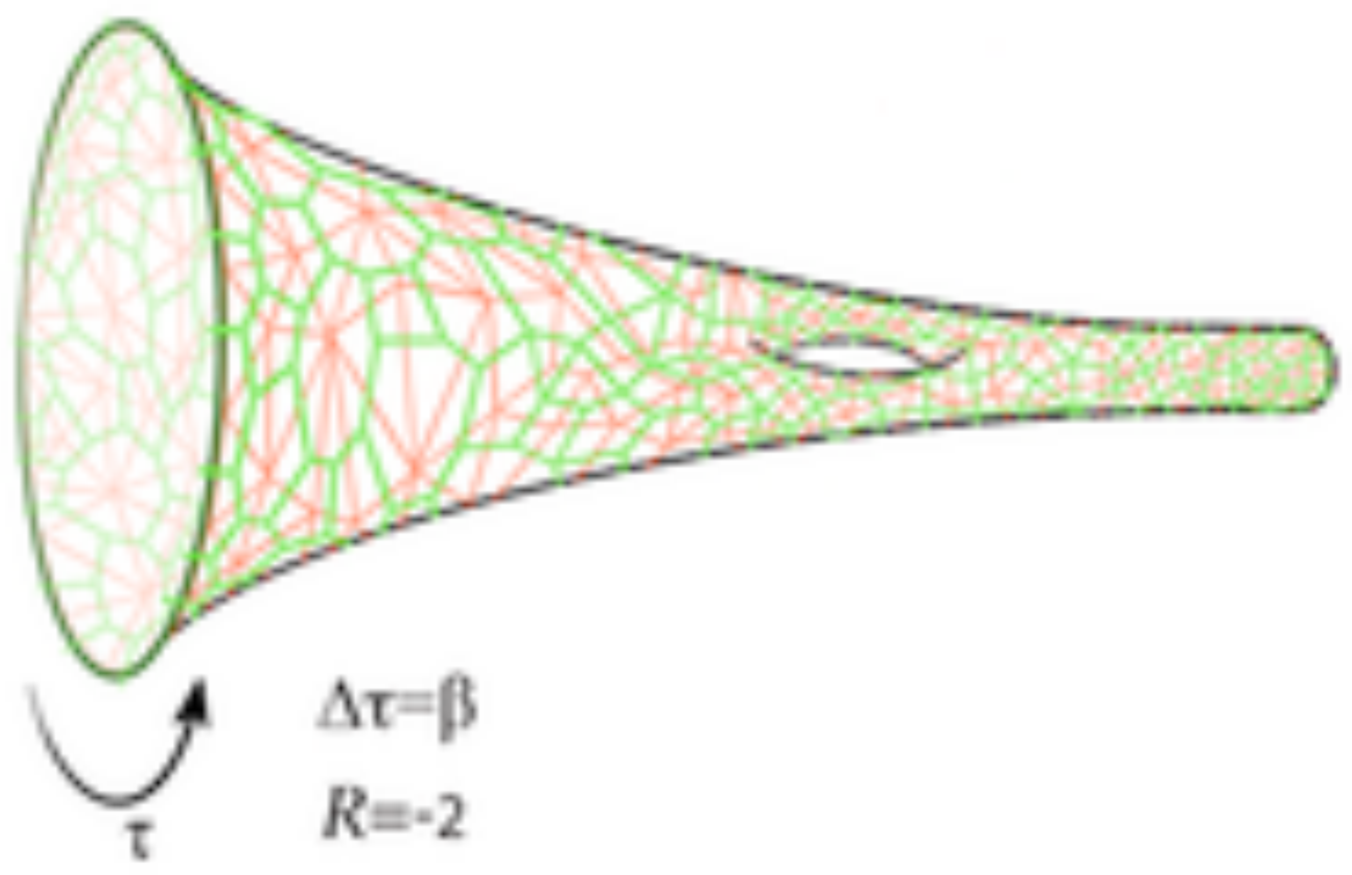
From Quantum Inspire

Jackie - Teitelboim GRAVITY
(THE TRUMPET)



From Phys. Rev. D 103, 046013 (The Trumpet)

$$t = t(u), \qquad \rho = \frac{t'(u) r}{1 - \frac{t''(u)}{t'(u)} r}$$



$$ds^2 = -\frac{2}{\rho^2} dt d\rho - \frac{1}{\rho^2} dt^2$$

GOES TO

THE TRUMPET HAS ONLY ONE DEGREE OF FREEDOM:

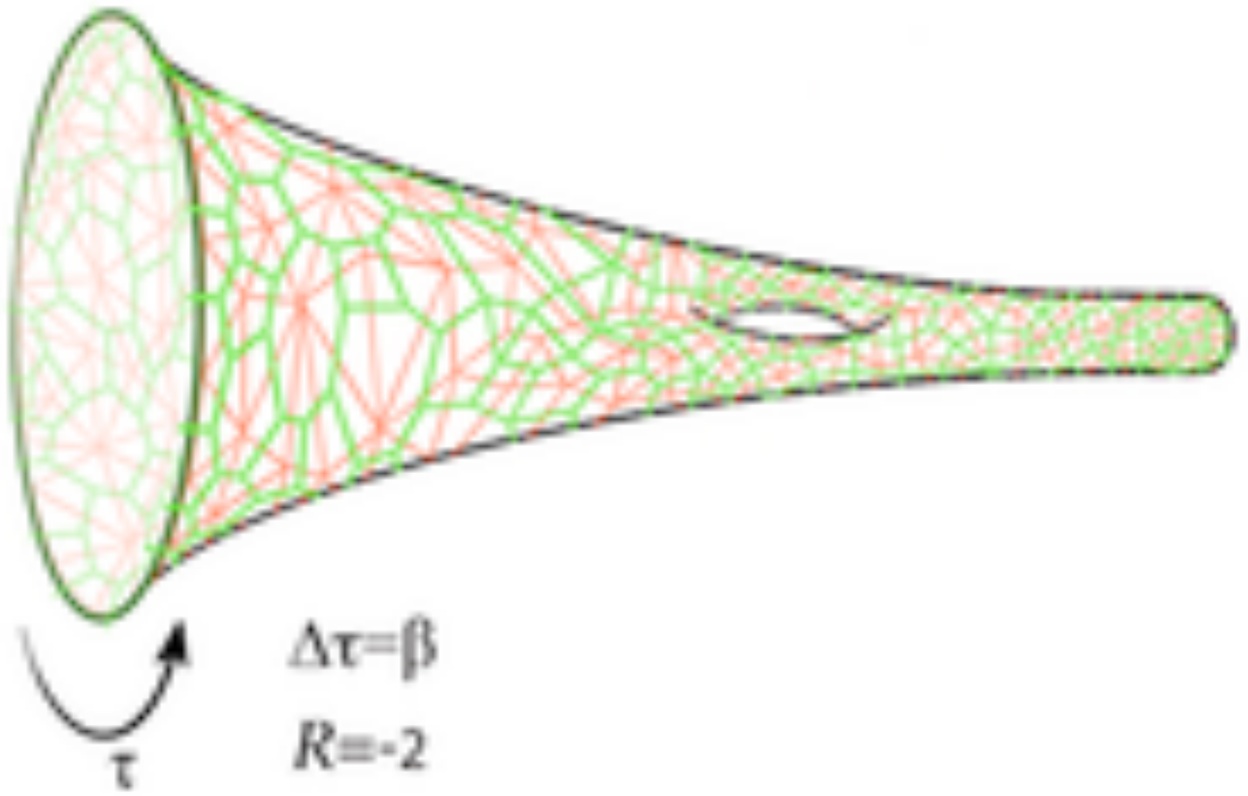
THE TIME REPARAMETRIZATION MODE

$$ds^2 = -\frac{2}{r^2} du dr - \left(\frac{1}{r^2} - M(u)\right) du^2$$

$$M(u) = -2\,\mathrm{Sch}(t(u), u) = -2\frac{t'''(u)}{t'(u)} + 3\left(\frac{t''(u)}{t'(u)}\right)^2$$

ADM MASS OF BLACK HOLE

$$S = N^2\left(\int \Phi(R+2) + \frac{1}{2}\int ((\partial\phi)^2 + m^2\phi^2) + S_{GH} + S_{qubit} \right)$$



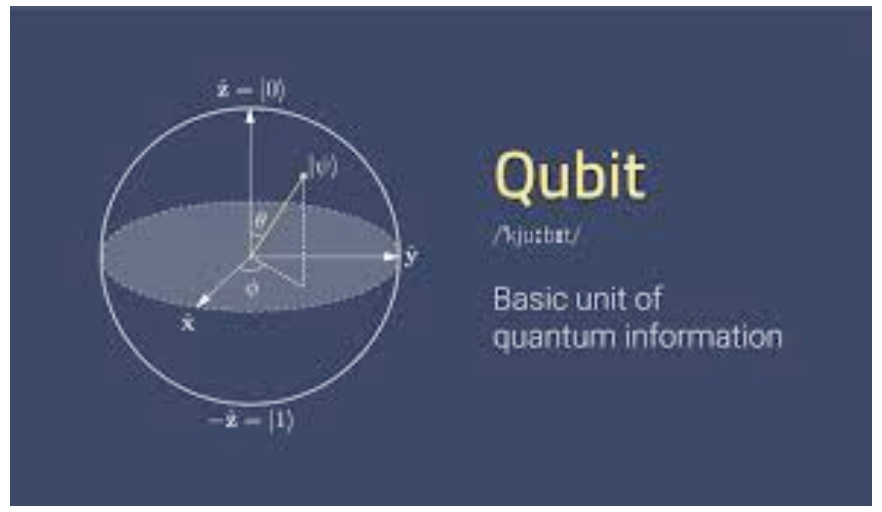
$$(\Box - m^2)\phi = 0 \qquad \Delta_O = \frac{1}{2} + \sqrt{\frac{1}{4} + m^2}$$

$$\lim_{r\to 0} r^{1-\Delta_O}\phi = \lambda\langle\sigma_x\rangle \qquad \lambda = \mathcal{O}(N)$$

$$\phi(r,u) = \lambda\langle\sigma_x\rangle r^{-1+\Delta_O} + \cdots + (O + \cdots)r^{\Delta_O} + \cdots$$

$$\frac{1}{2}\dot{M} = -\lambda\left(\Delta_O O\langle\dot{\sigma}_x\rangle + (\Delta_O - 1)\dot{O}\langle\sigma_x\rangle\right)$$

$$|\dot{\psi}\rangle = -i\left(h_0\sigma_z - \lambda O\sigma_x\right)|\psi\rangle \quad h_0 = \mathcal{O}(N^2)$$



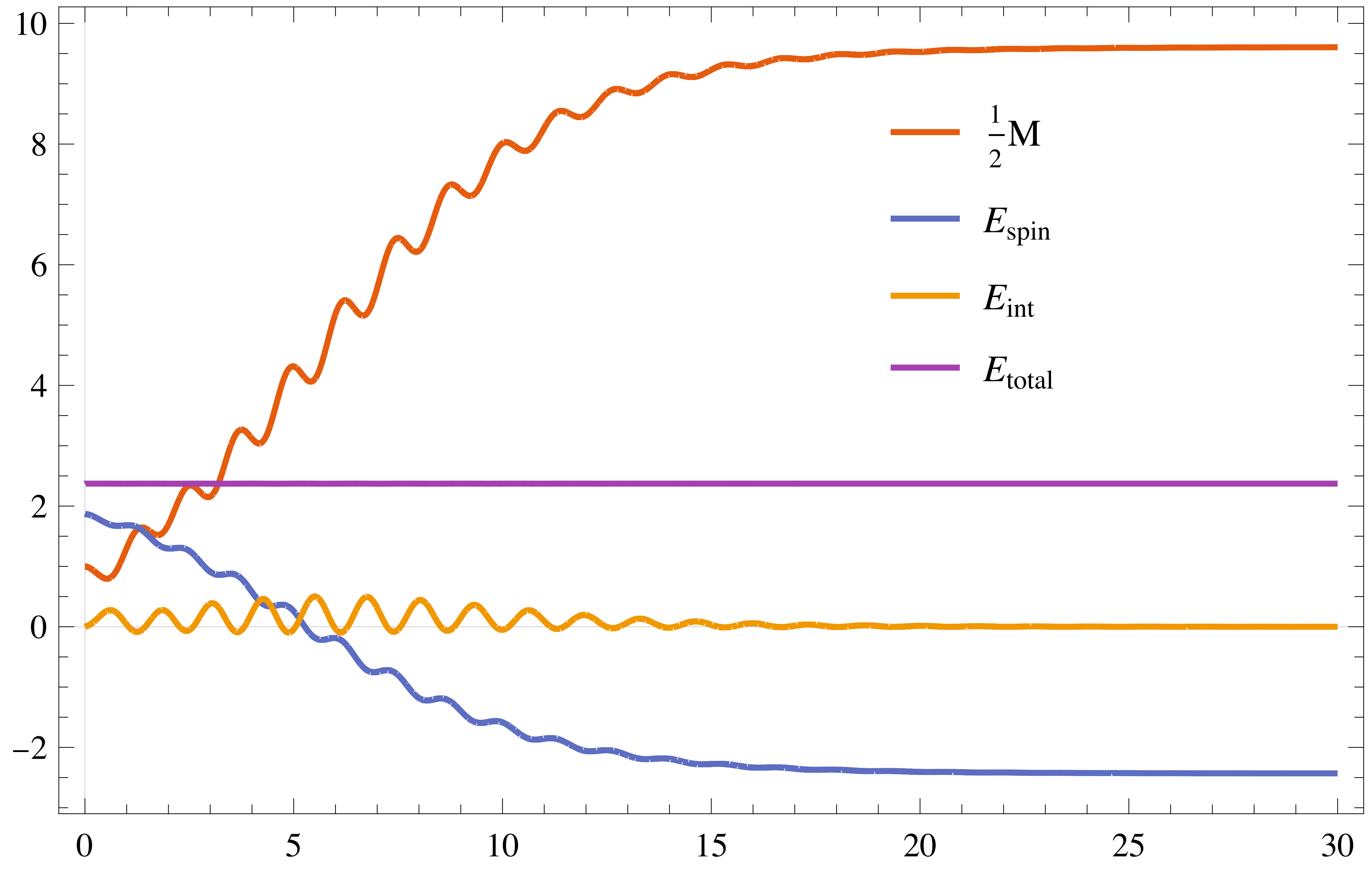
MORE GENERALLY

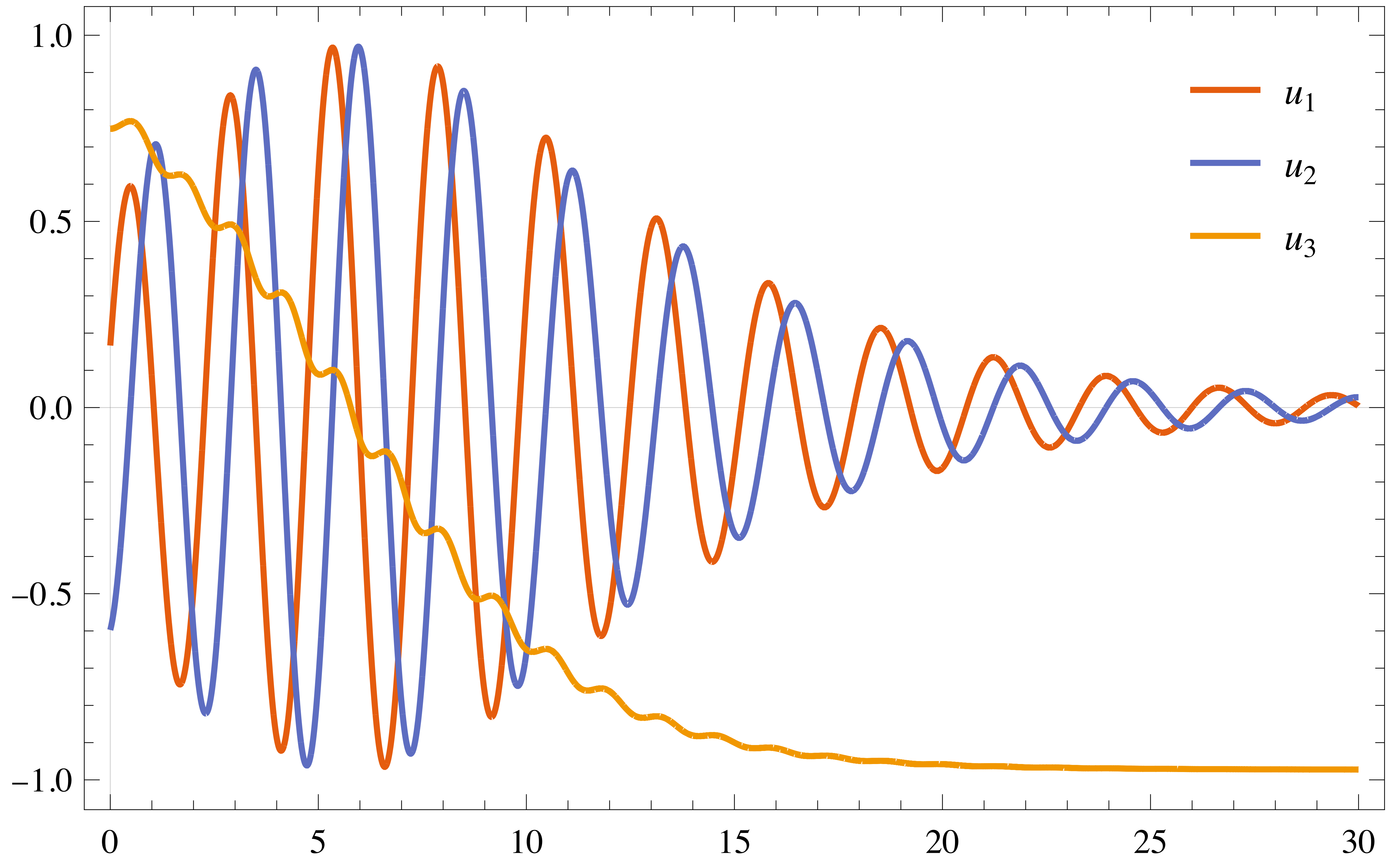
$$\hat{\rho} = \frac{1}{2}1 + u_1\sigma_1 + u_2\sigma_2 + u_3\sigma_3, \quad u_1^2 + u_2^2 + u_3^2 \leq \frac{1}{4}$$

$$\dot{u}_1 = -h_0u_2, \quad \dot{u}_2 = h_0u_1 + \lambda Ou_3, \quad \dot{u}_3 = -\lambda Ou_2$$

$$E = h_0\langle\sigma_z\rangle + \frac{1}{2}M + \Delta_O \lambda O\langle\sigma_x\rangle$$

is conserved





In the end we have decoupling as $\langle\sigma_x\rangle$ goes to zero

INPUT

$$\hat{\rho} = \frac{1}{2}1 + u_1\sigma_1 + u_2\sigma_2 + u_3\sigma_3, \quad u_1^2 + u_2^2 + u_3^2 \leq \frac{1}{4}$$

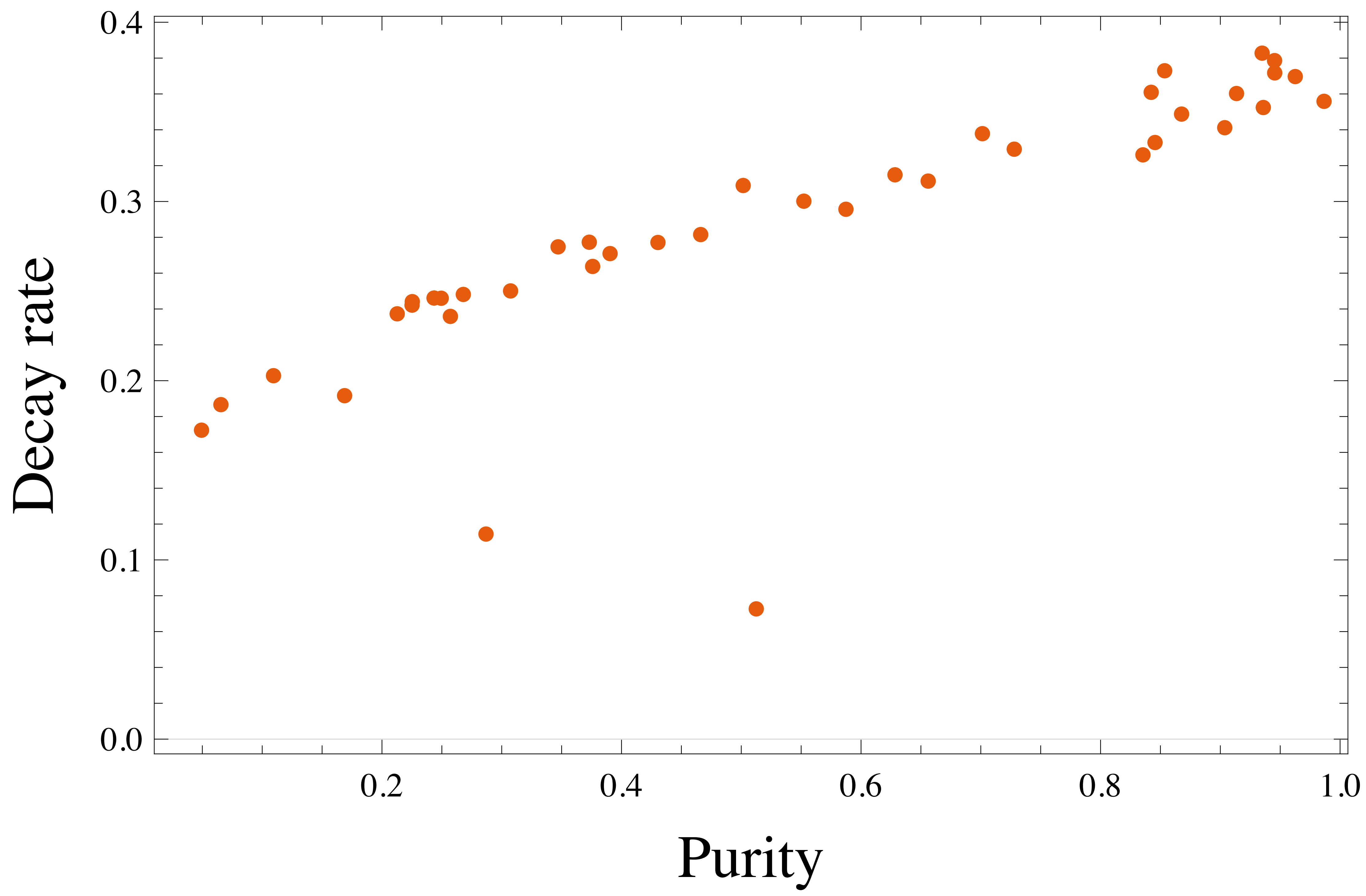
OUTPUT

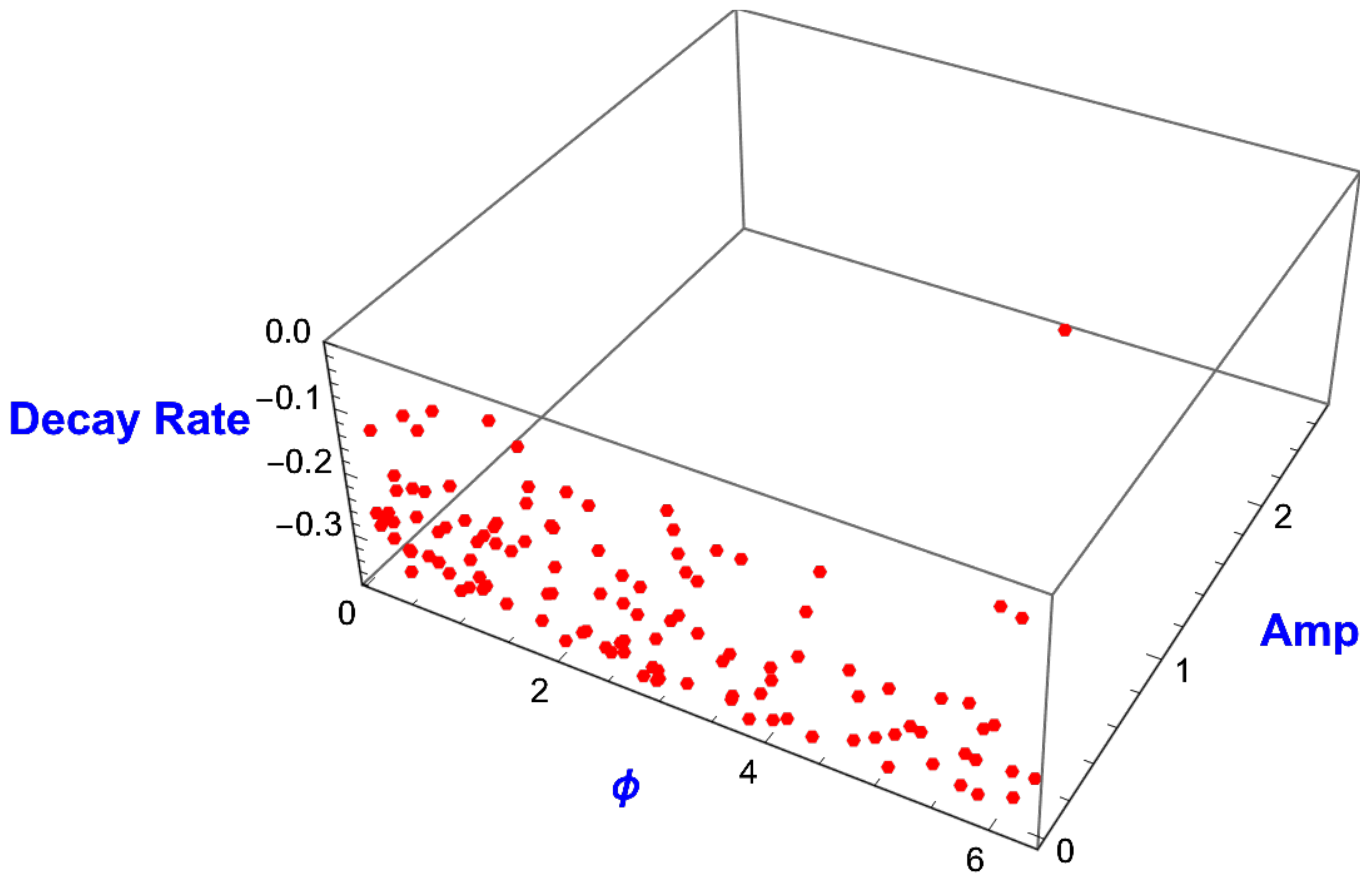
$$\hat{\rho} = \frac{1}{2}1 - \sqrt{u_1^2 + u_2^2 + u_3^2}\sigma_3$$

Eigenvalues of both input and output are $$\frac{1}{2} \pm \sqrt{u_1^2 + u_2^2 + u_3^2}$$

Purity of both input and output are $$\frac{1}{2} + 2(u_1^2 + u_2^2 + u_3^2)$$

Eigenvalues do not change. Purity does not change. Also von Neumann and Renyi Entropies are the same! Information is still lost

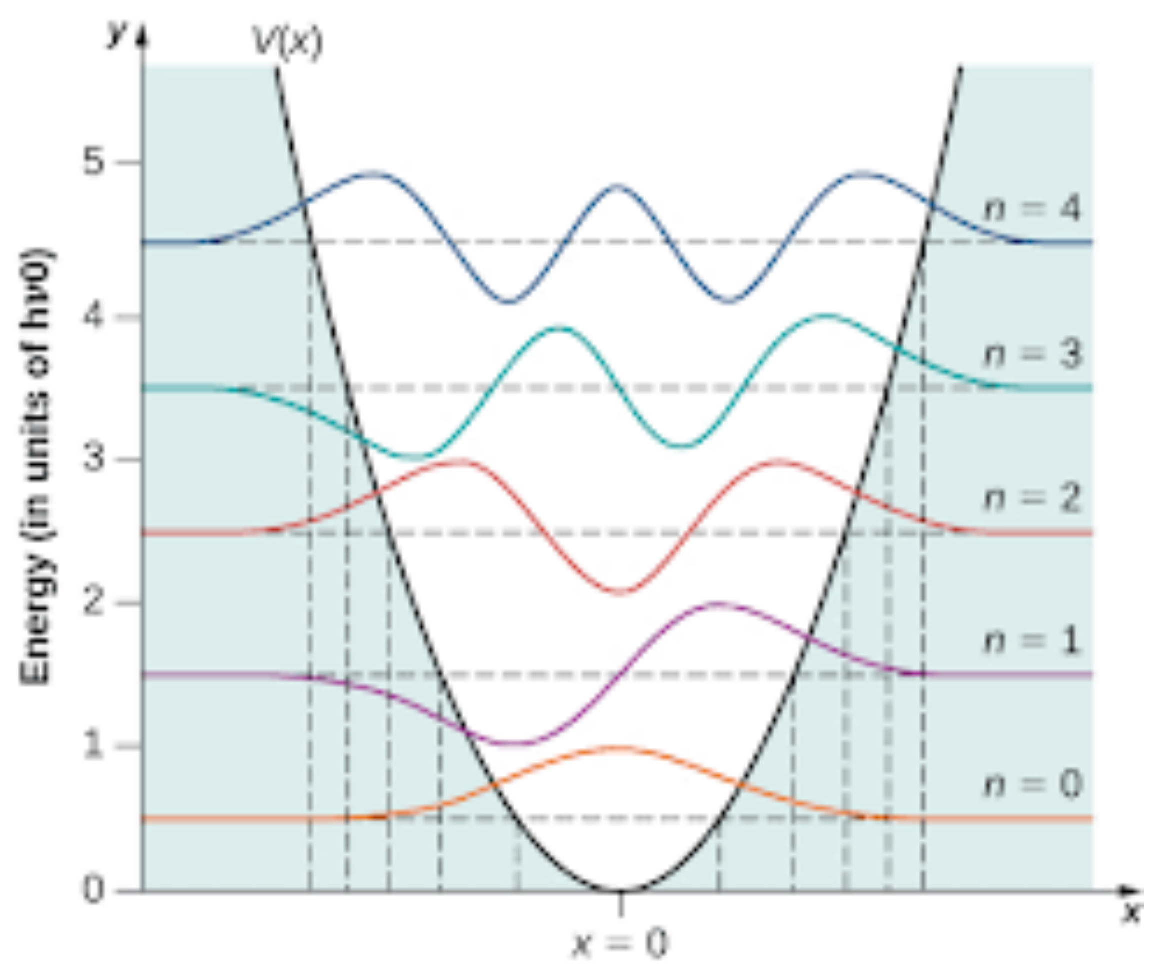


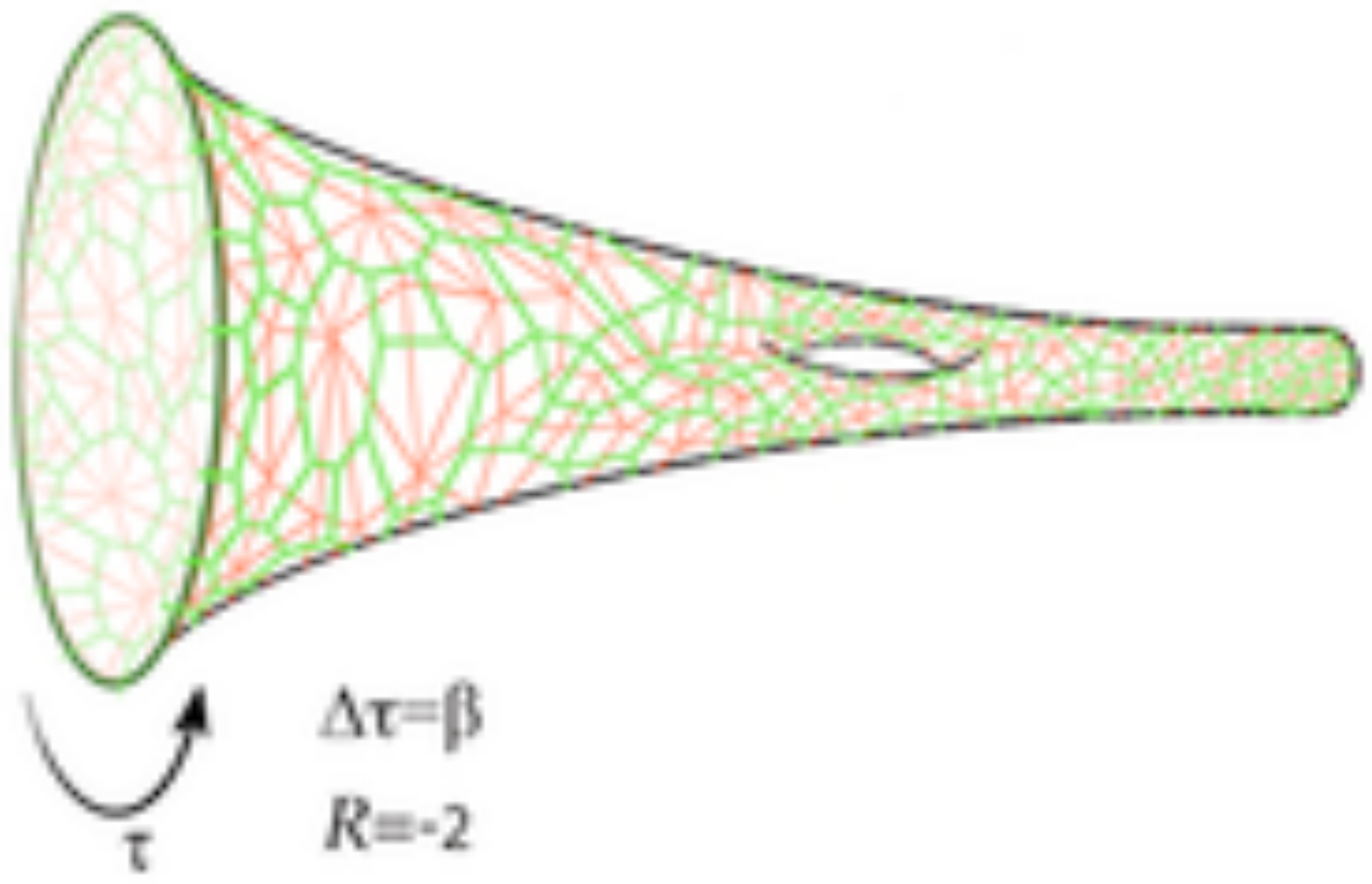


Purity and u_3 are encoded in the decay exponent and phase of the ringdown. The amplitude and frequency are independent of the input qubit.

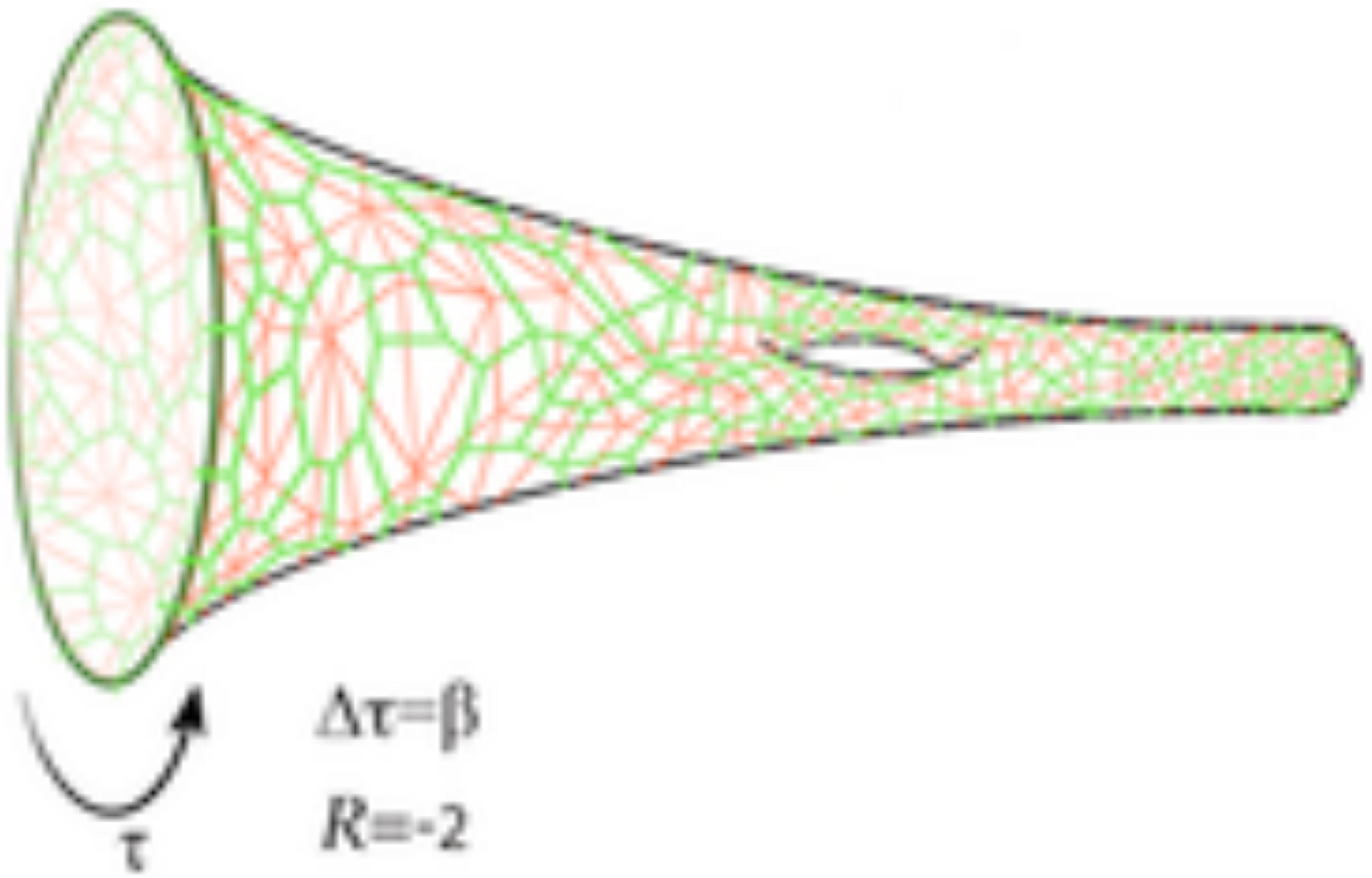
So the information of purity and u_3 of input qubit are encoded both in output state and black hole ringdown. Information is PARTLY copied TWICE.

THE. TRUMPET AND THE QUANTUM HARMONIC. OSCILLATOR

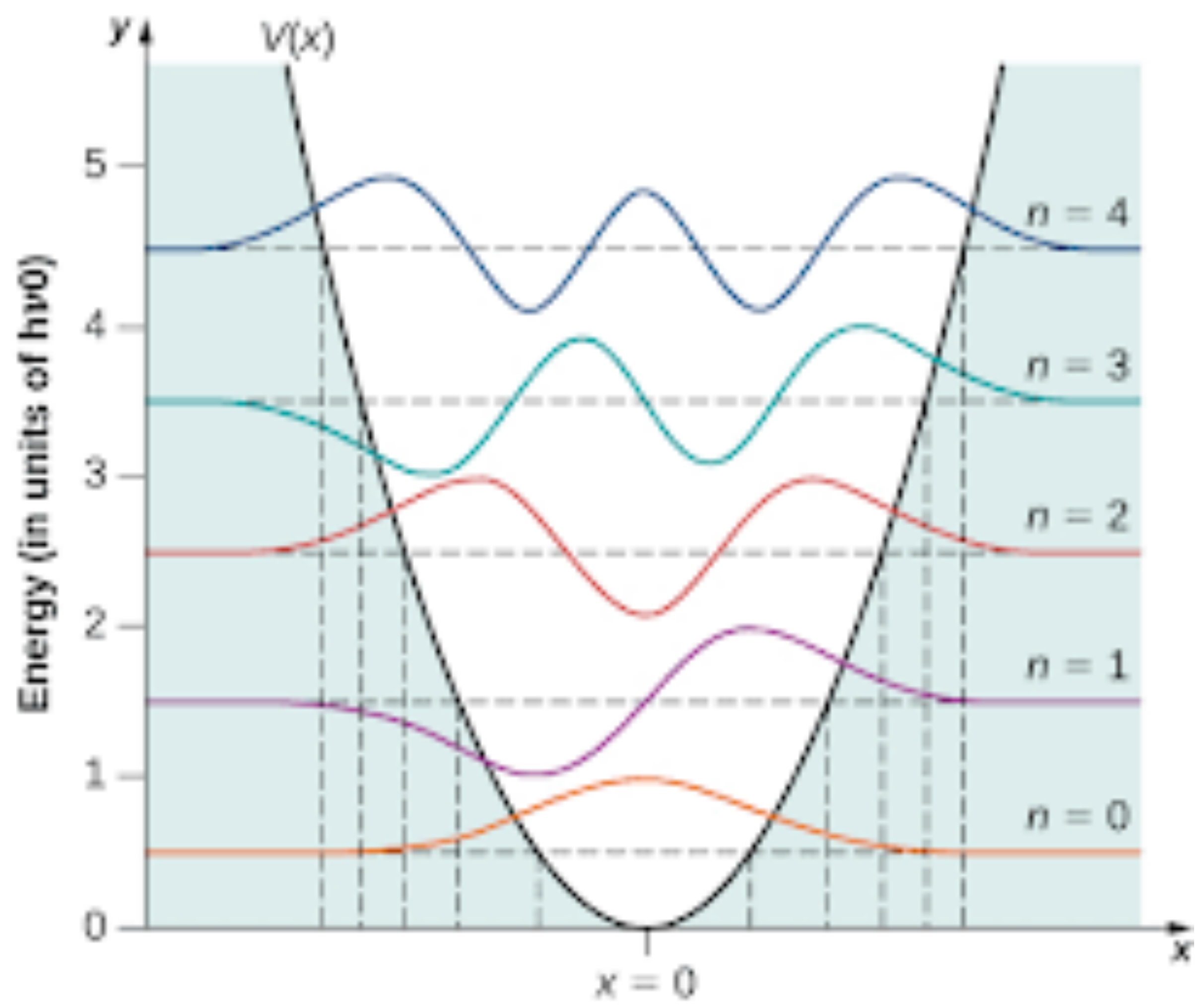




$$\frac{1}{2}\dot{M} = -\lambda\left(\Delta O\langle\dot{x}\rangle + (\Delta - 1)\dot{O}\langle x\rangle\right)$$



$$|\dot{\psi}\rangle = -i\left(\omega(a^\dagger a + \frac{1}{2}) - \lambda O\frac{a + a^\dagger}{\sqrt{2}}\right)|\psi\rangle$$



$$E = \frac{1}{2}\langle p^2\rangle + \frac{1}{2}\omega^2\langle x^2\rangle + \frac{1}{2}M + \lambda\Delta_O O\langle x\rangle$$

is conserved

$$\langle x | \Psi_n(t) \rangle = \left(\frac{\omega}{\pi}\right)^4 H_n\left(\sqrt{\omega}(x - x_p(t))\right) \exp\left(-\frac{\omega}{2}(x - x_p(t))^2 + i p_p(t) x\right)$$

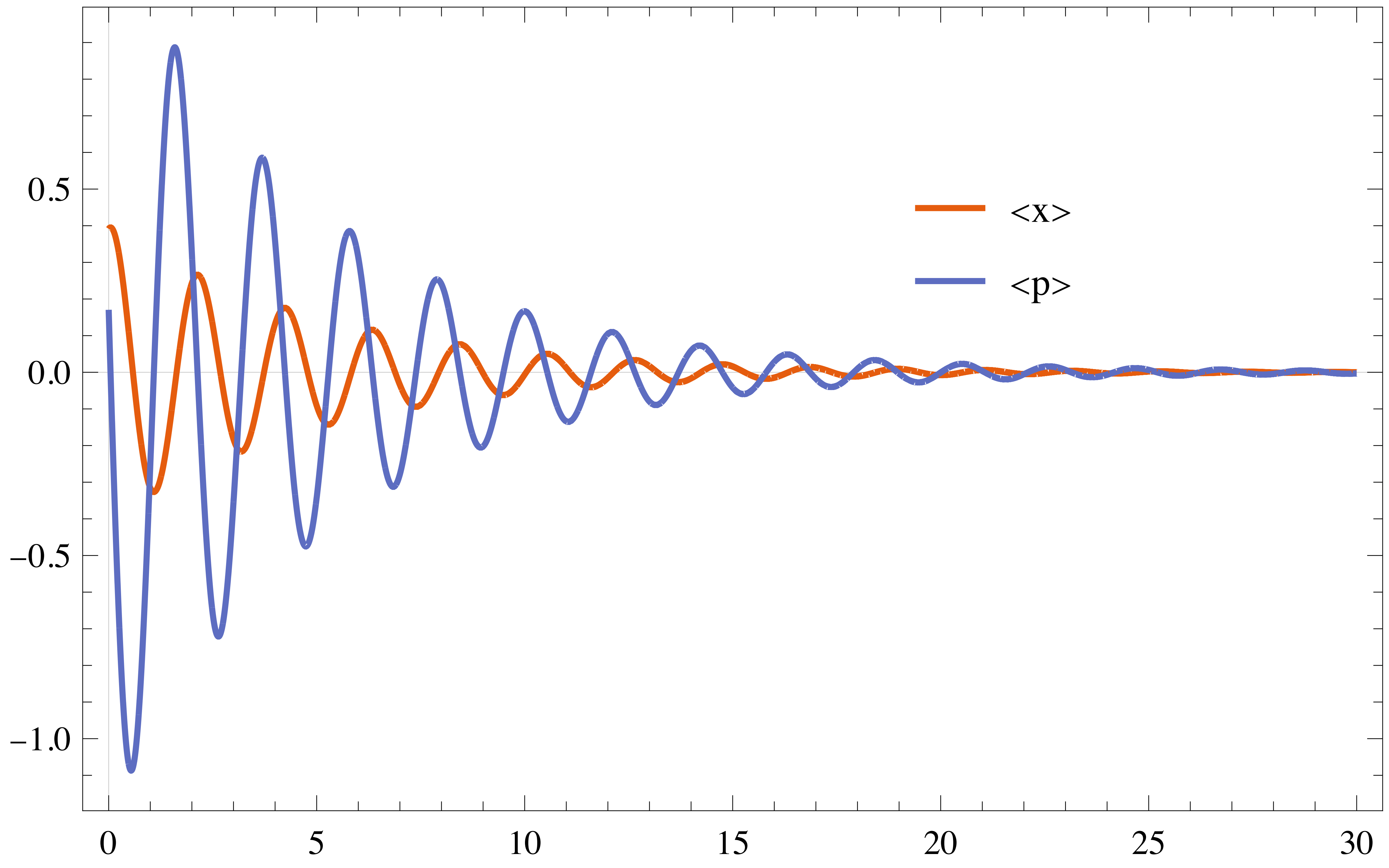
$$F_n(t) = \omega t \left(n + \frac{1}{2}\right) + \int_0^t \mathrm{d}t' \left(\frac{1}{2}\dot{x}_p^2(t') - \frac{1}{2}\omega^2 x_p^2(t')\right)$$

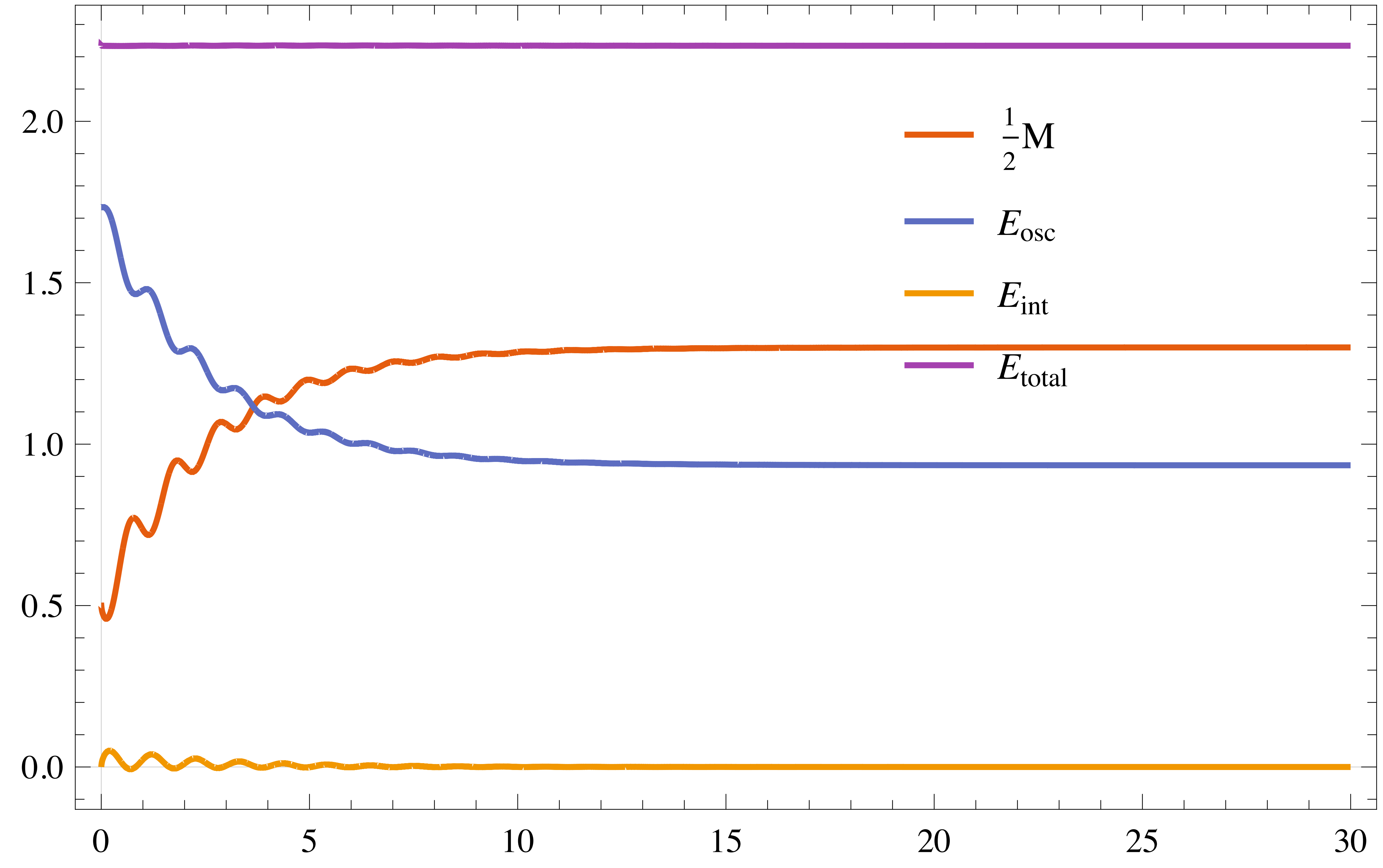
INPUT $$|\Psi(0)\rangle = \cos\theta e^{i\phi} |0\rangle + \sin\theta |1\rangle$$

SELF-CONSISTENT SOLUTION

$$|\Psi(t)\rangle = \cos\theta e^{i\phi} e^{-iF_0(t)} |\Psi_0(t)\rangle + \sin\theta e^{-iF_1(t)} |\Psi_1(t)\rangle$$

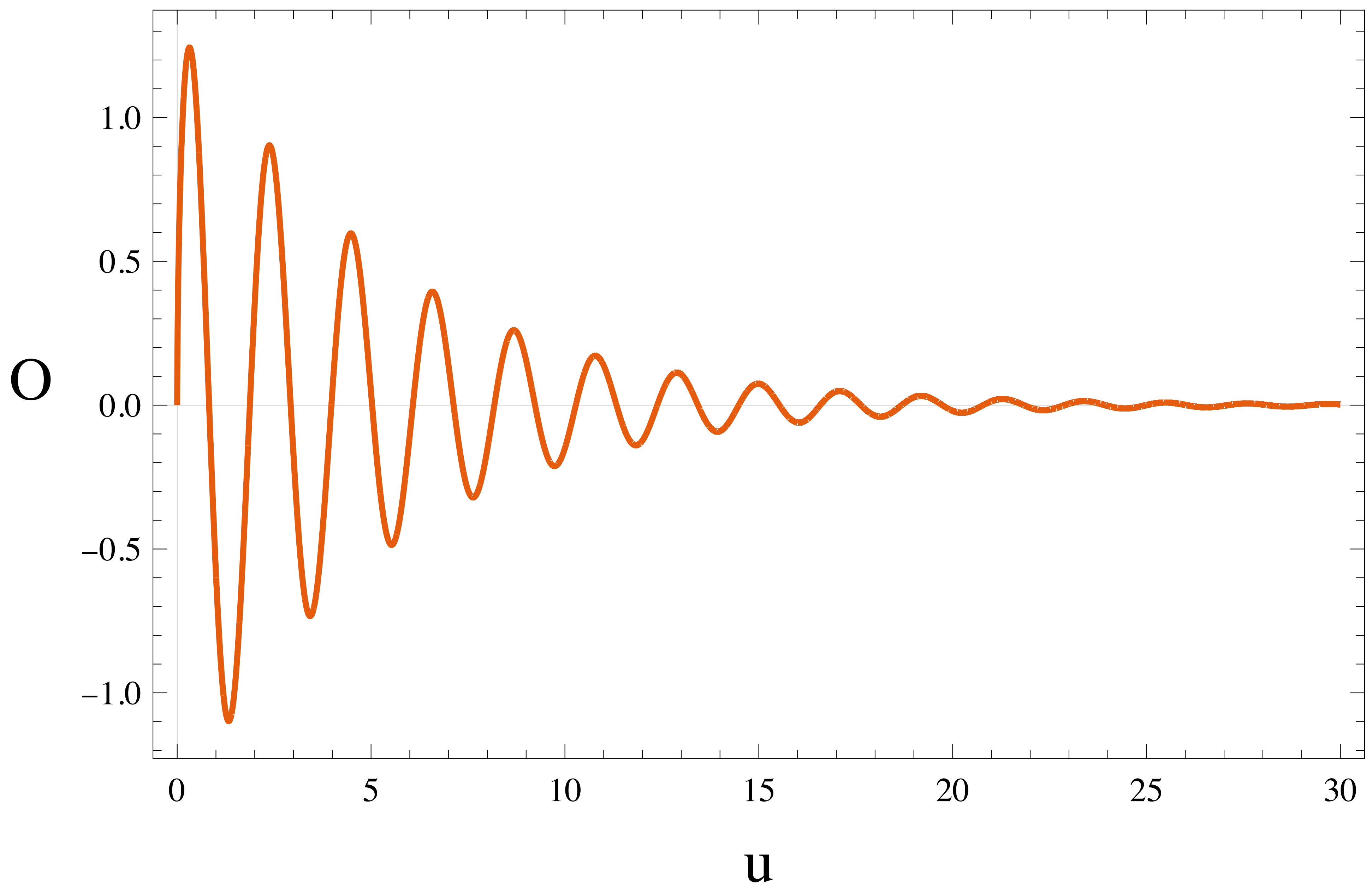
$$\ddot{x}_p(t) + \omega^2 x_p(t) = \lambda O(t), \quad p_p(t) = \dot{x}_p(t) \qquad x_p(0) = p_p(0) = 0$$





FINALLY WE HAVE DECOUPLING. ENERGY IS TRANSFERRED TO THE BLACK HOLE

HOWEVER THE QHO DOES NOT GO TO THE GROUND STATE.



FINALLY WE HAVE DECOUPLING. ENERGY IS TRANSFERRED TO THE BLACK HOLE

HOWEVER THE QHO DOES NOT GO TO THE GROUND STATE.

INPUT STATE

$$|\Psi\rangle = \cos\theta e^{i\phi}|0\rangle + \sin\theta|1\rangle$$

OUTPUT QUANTUM TRAJECTORY

$$|\Psi(t)\rangle = \cos\theta e^{i\phi}e^{-iF_0(t)}|\Psi_0(t)\rangle + \sin\theta e^{-iF_1(t)}|\Psi_1(t)\rangle$$

$$\ddot{x}_p(t) + \omega^2 x_p(t) = 0, \quad p_p(t) = \dot{x}_p(t) \qquad x_p(t) = A\cos(\omega t) + B\sin(\omega t)$$

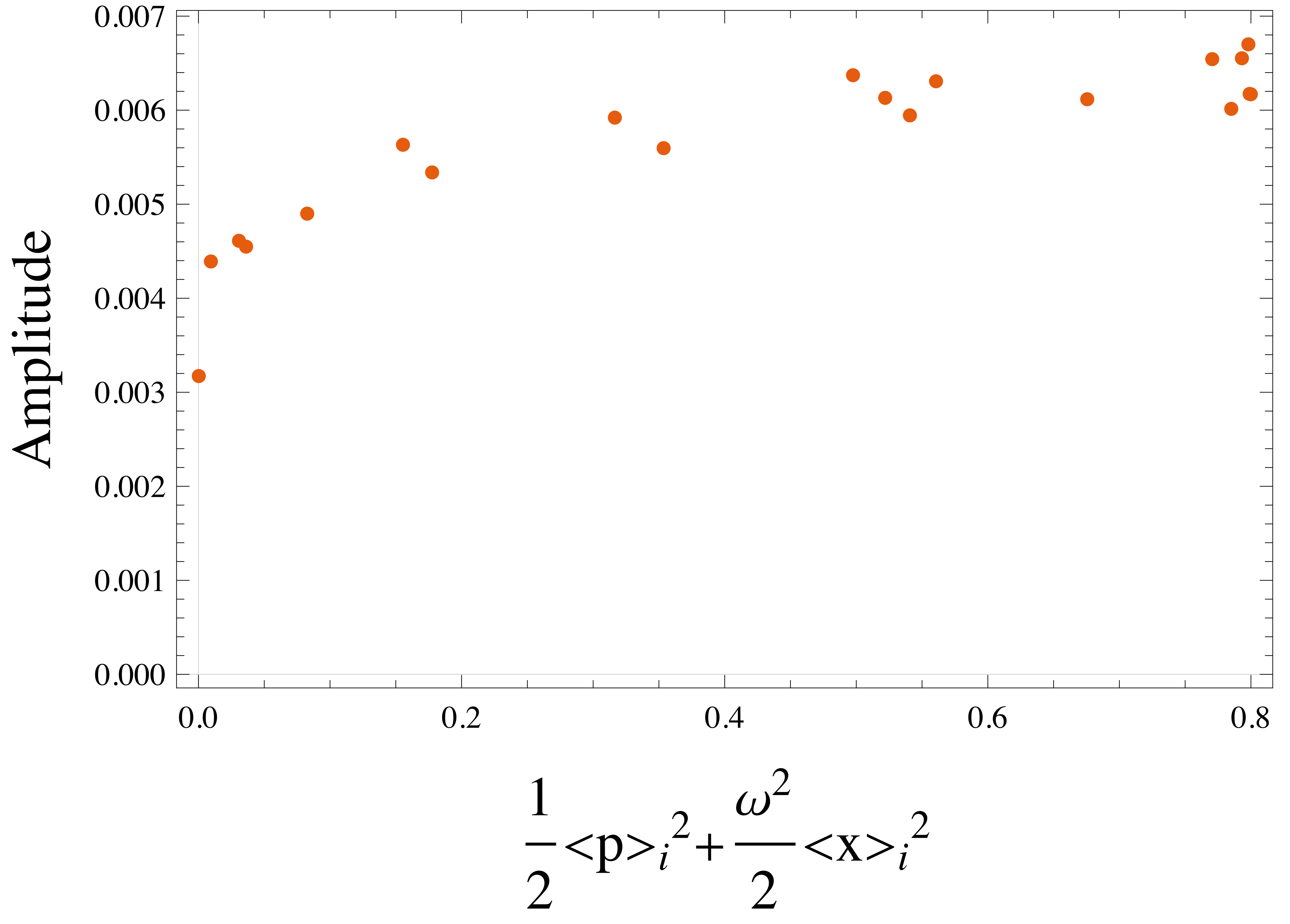
$$\langle x(t)\rangle = x_p(t) + \frac{1}{\sqrt{2\omega}}\sin(2\theta)\ \cos(\phi + \omega t) = 0 \qquad A = -\frac{1}{\sqrt{2\omega}}\sin(2\theta)\ \cos\phi, \ \ B = -\frac{1}{\sqrt{2\omega}}\sin(2\theta)\ \sin\phi$$

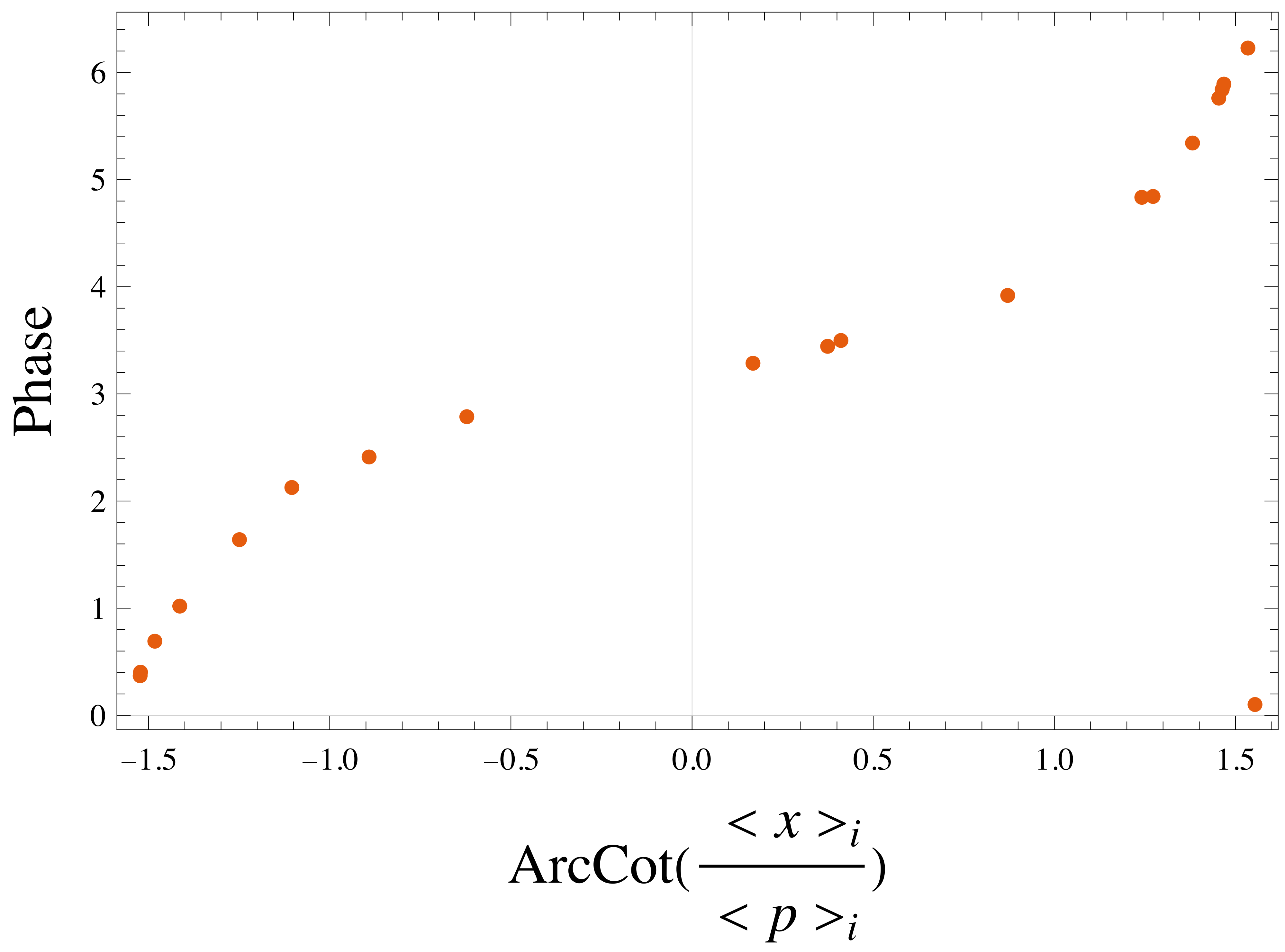
The amplitude and phase of the BH ringdown also carries complete information of the qubit.

The output quantum trajectory of the QHO maintains coherence after decoupling and is determined completely by the initial qubit.

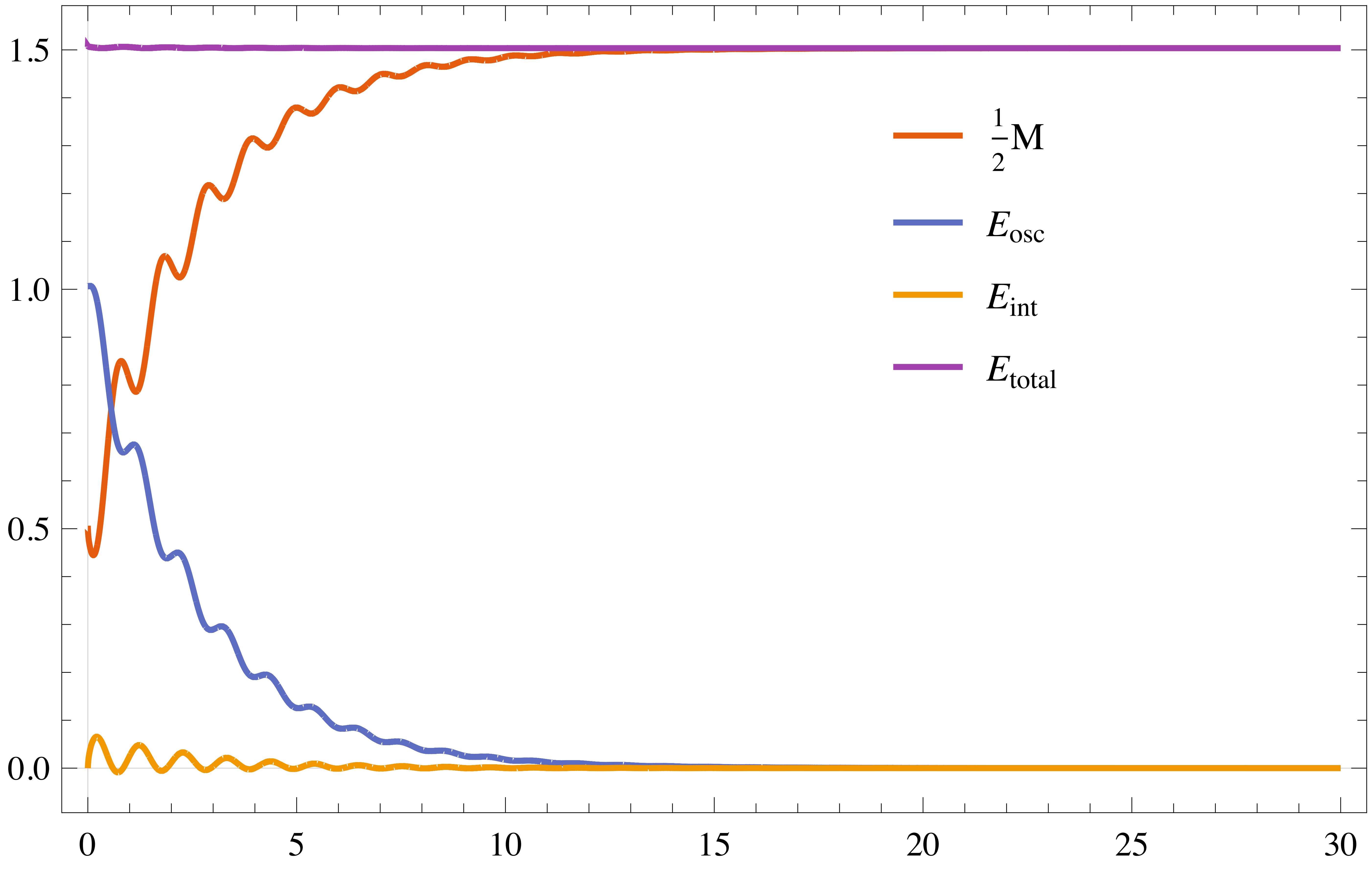
The output semi-classical ringdown of the BH after decoupling is also determined completely by the initial qubit and the final BH mass.

From both we can recover the initial qubit fully and independently. Information is copied fully twice.

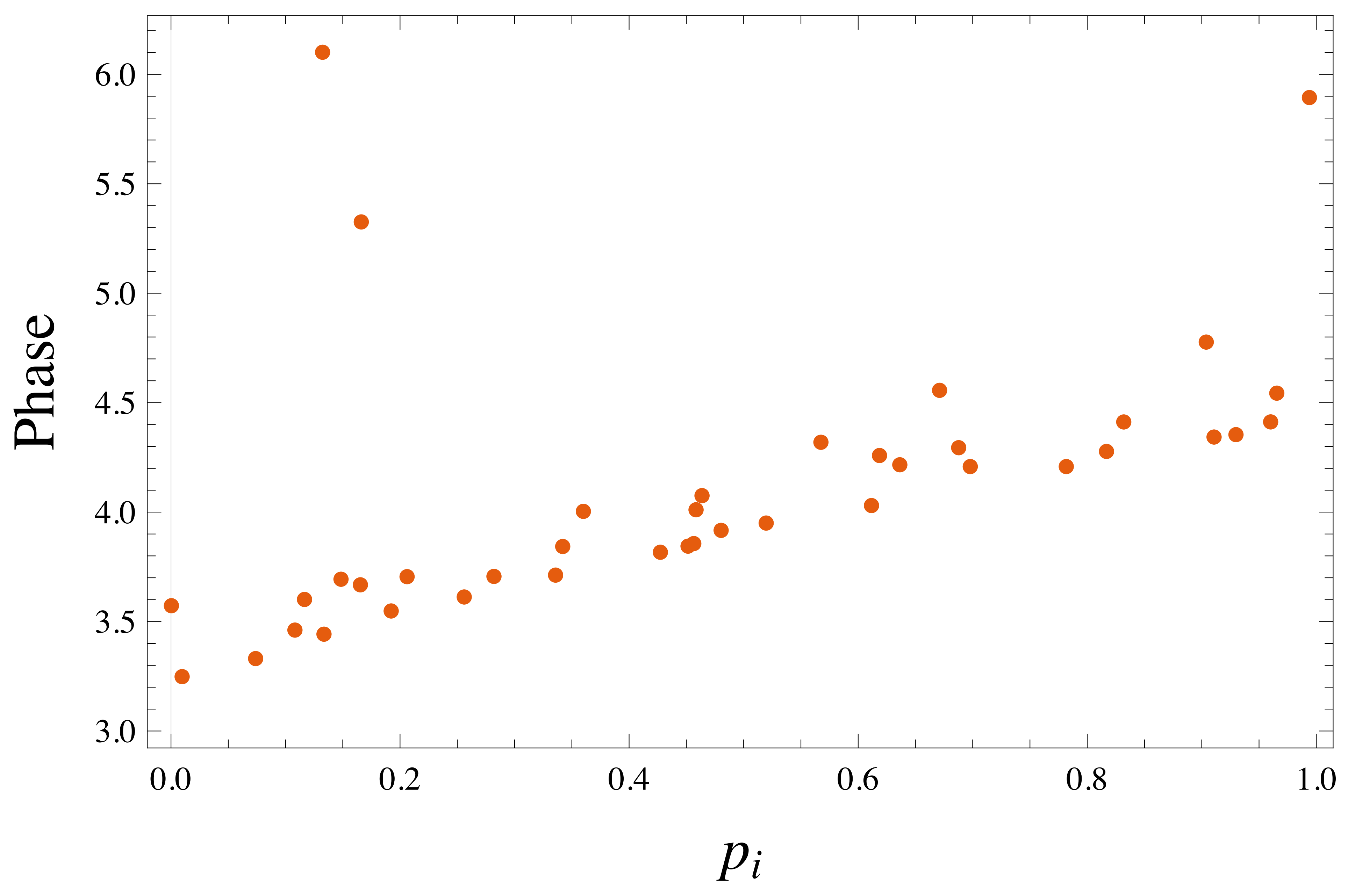


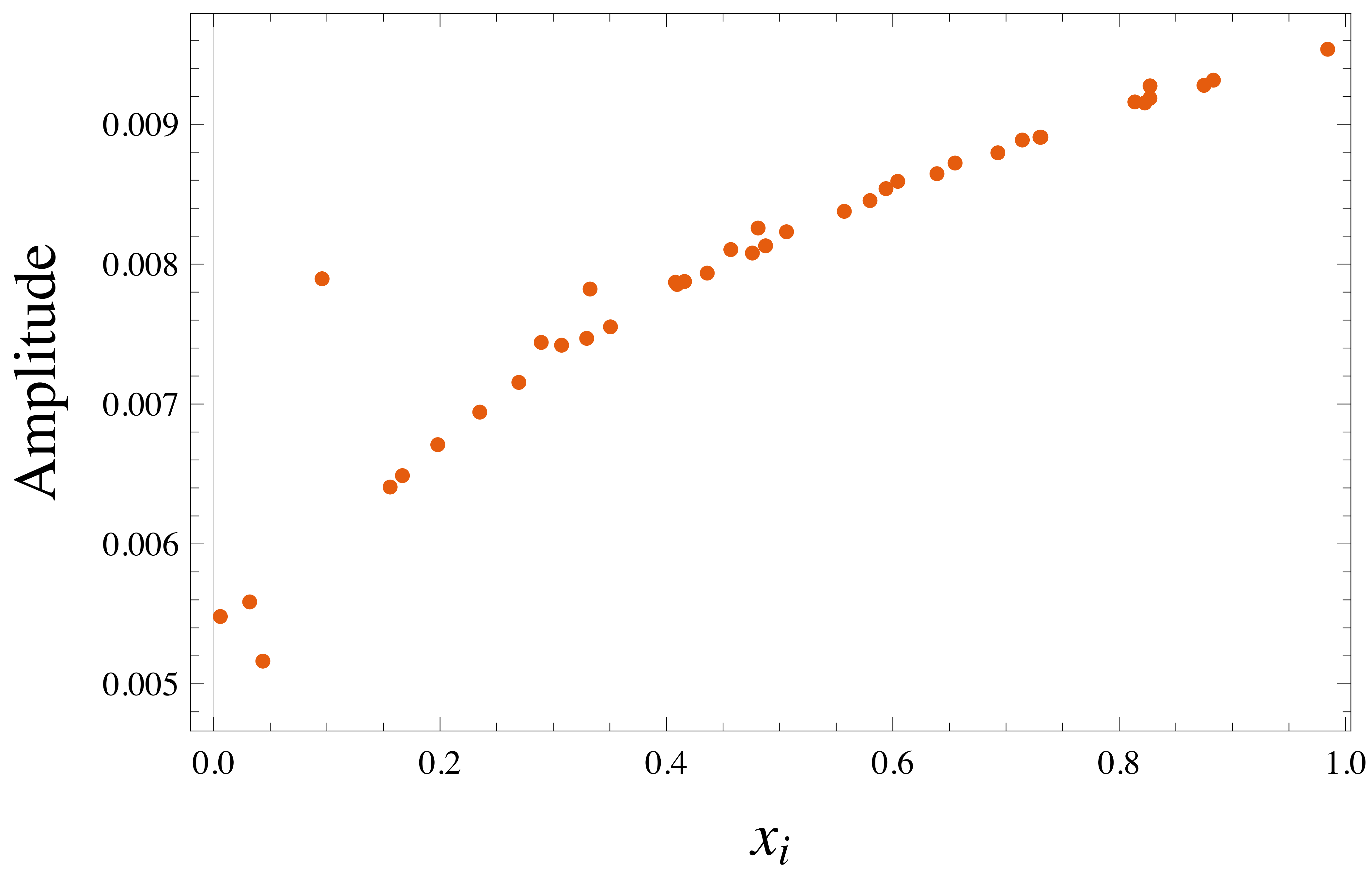


THE. CLASSICAL LIMIT



ALL ENERGY IS DRAINED TO THE BH





Phase of the ringdown gives the initial position and the amplitude of the ringdown gives the initial position.

However information is not copied twice.

QUANTUM. WEAK MEASUREMENT

Quantum Weak Measurement: Couple a qubit to an ancilla (environment). The intersystem coupling is switched off gradually and a strong measurement on the ancilla is performed.

One can then extract the expectation value of an operator of the qubit state efficiently while perturbing it only a little if the coupling is of the right kind.

Furthermore, one can control the quantum trajectory of the qubit by repeated measurements of the ancilla.

Needs to be revisited in the language of von-Neumann algebras to understand why the information can be copied twice. The algebra describing the BH ringdown is a type III_1 von Neumann algebra [Leutheusser and Liu 2021, Witten 2022]

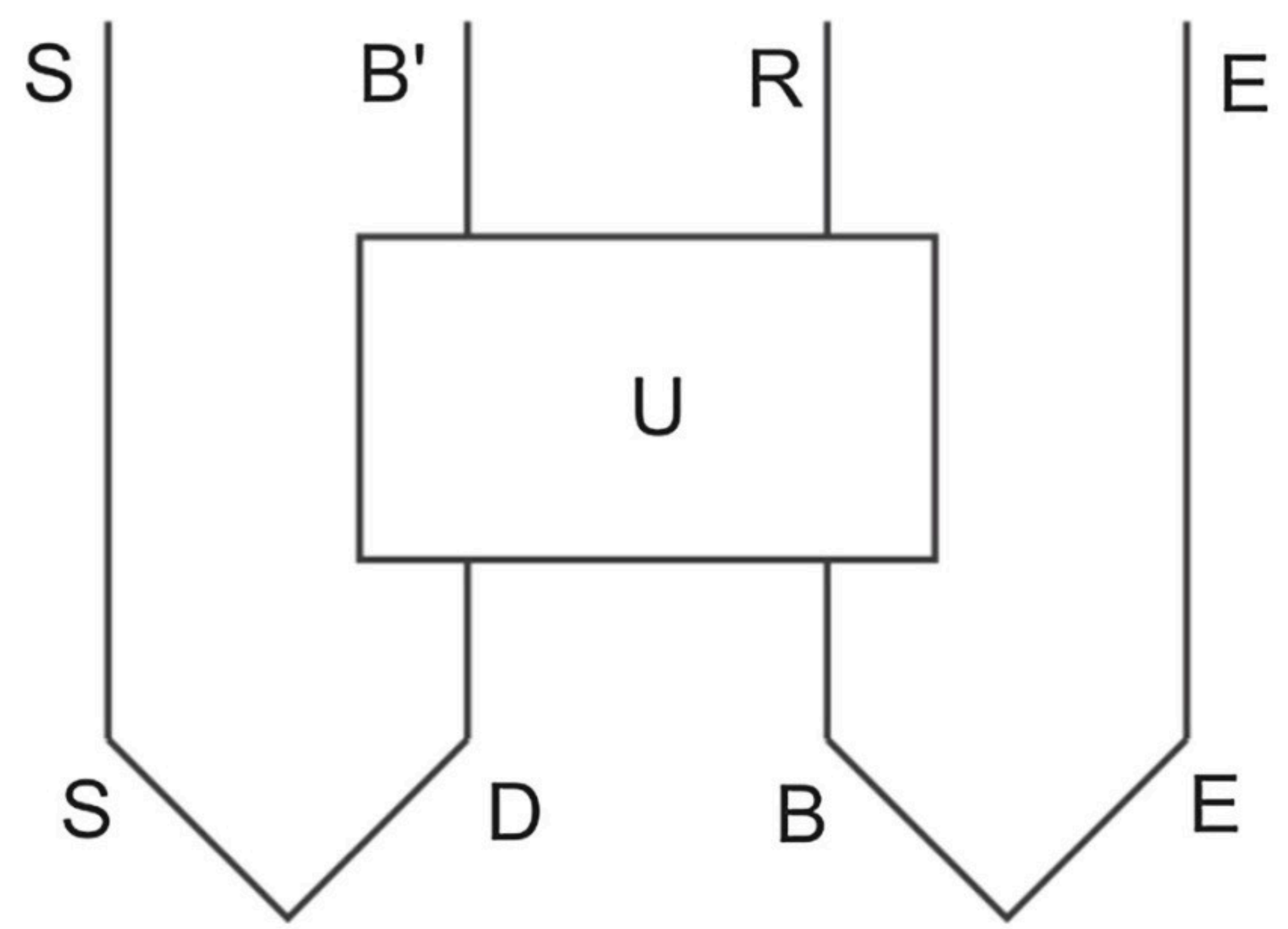
MORE SURPRISES

In the toy model, not only the input qubit but also the history of simple measurements can be encoded into the black hole ringdown.

If an entangled state is coupled to a two-sided trumpet, measurement can lead to opening up wormholes and new quantum channels, i.e. modes of information transfer [work under progress]

INFORMATION MIRRORING AND COMPLIMENTARITY

INFORMATION MIRRORING



Taken from Daniel Harlow, Jerusalem Lectures

A diary D entangled with reference S is thrown into an old black hole. For a scrambling unitary process of $D + B \to B' + R$ where R is emitted Hawking quanta, S and B' should have no mutual information. Therefore, the information of D is in $R \cup E$, where E is early radiation.

The scrambling time is $r_S \log S_{BH}$ [Hayden and Preskill 2007; Sekino and Susskind 2008]

If black hole complementarity is true and is consistent with unitarity, then the decoding of D from $R \cup E$ should be possible *without* the knowledge of the interior, i.e. B or B' and even the knowledge of U.

Can a microscopic model demonstrate this? (No known existing quantum circuit/code model exists which shows this possibility, see eg. Kitaev and Yoshida 2017)

If the semi-classical geometry can be trusted, it should be possible to decode a lot of information in D quickly from R and only a limited information of E much before R interacts with E fully.

How is such a decoding possible?

MORE QUESTIONS

1. Why simple observations see that the interior and exterior as decoupled and distinguishable if they are not?

2. How come we can decode some of the mirrored quantum information fast while the information of the interior is so well hidden in complexity?

3. More radically, can we only have observer dependent Hilbert spaces in quantum gravity and no global Hilbert space?

A SIMPLE MODEL

REF: KIBE, AM, SOLOVIEV, SWAIN; 2006.08644 (PHYS. REV. D 102 (2020) 8, 086008)

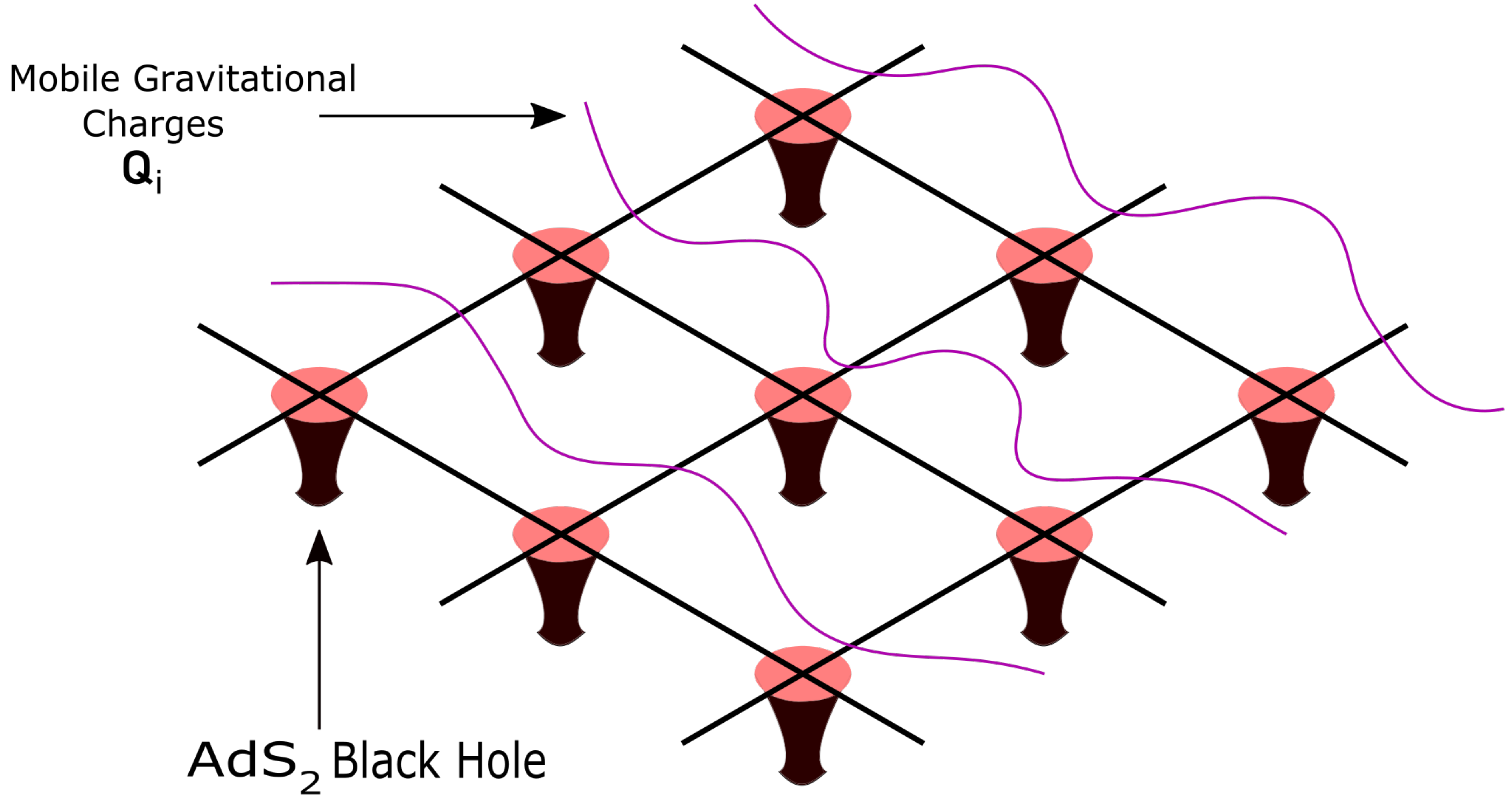
REF: KIBE, MANDAYAM AND AM; EPJC REVIEW

A CARTOON

The near-extremal horizon can fragment into multiple throats via instantons [Brill (1992); Maldacena, Michelson, Strominger (1999)]

There are abundant low energy modes at the boundaries of instanton moduli space where two or more throats are separated by sub-Planckian distance

This inspires a lattice model of fragmented throats with lattice dimensionality same as that of horizon. These "hard" degrees of freedom crystallize and interact via "soft" gravitational mobile charges.



CONCRETELY

INGREDIENTS OF A ONE-DIMENSIONAL HORIZON

1. **SYK type quantum dots dual to NAdS2 throats — degrees of freedom $t_i(u)$ where i is lattice site and u is the experimentalist's time. The reparametrized time $t_i(u)$ carries all information about the quantum dot's state.**

2. **The mobile gravitational hair which carries mobile Q_i gravitational charges which take values in SL(2,R).**

3. **Crucially the full system must have only one overall SL(2,R) symmetry corresponding to the original horizon geometry.**

The quantum dots do carry SL(2,R) charges too!

$$\mathcal{Q}_i^+ = \frac{t_i''}{t_i'^2} - \frac{t_i''^2}{t_i'^3} \qquad \mathcal{Q}_i^0 = t_i\left(\frac{t_i'''}{t_i'^2} - \frac{t_i''^2}{t_i'^3}\right) - \frac{t_i''}{t_i'}$$

$$\mathcal{Q}_i^- = t_i^2\left(\frac{t_i'''}{t_i'^2} - \frac{t_i''^2}{t_i'^3}\right) - 2t_i\left(\frac{t_i''}{t_i'} - \frac{t_i'}{t_i}\right)$$

The mass of the dual black hole is simply the Casimir of these charges

$$\mathcal{Q}_i \cdot \mathcal{Q}_j := -\mathcal{Q}_i^0\mathcal{Q}_j^0 + \frac{1}{2}\left(\mathcal{Q}_i^+\mathcal{Q}_j^- + \mathcal{Q}_i^-\mathcal{Q}_j^+\right)$$

SL(2,R) INVARIANT DOT PRODUCT

$$M_i = -\mathcal{Q}_i \cdot \mathcal{Q}_i = -2Sch(t_i(u), u) = -2\left(\frac{t_i'''}{t_i'} - \frac{3}{2}\frac{t_i''^2}{t_i'^2}\right)$$

OUR EQUATIONS

$$M_i' = -\lambda\left(\mathcal{Q}_{i-1} + \mathcal{Q}_{i+1} - 2\mathcal{Q}_i\right)\cdot \mathbf{Q}_i'$$

$$\mathbf{Q}_i'' = \frac{1}{\sigma^2}\left(\mathbf{Q}_{i-1} + \mathbf{Q}_{i+1} - 2\mathbf{Q}_i\right) + \frac{1}{\lambda^2}\left(\mathcal{Q}_{i-1} + \mathcal{Q}_{i+1} - 2\mathcal{Q}_i\right)$$

The first equation will turn out to be a diffusion type equation responsible for relaxation and decoupling for $\lambda > 0$

The second equation will ensure information mirroring. Non-trivially we will need to know only $\sum_i \mathbf{Q}_i'$ which is conserved (since $\sum_i \mathbf{Q}_i'' = 0$) analogous to primordial information in early radiation for the decoding of infalling qubits and not at all anything about the interior.

The hair should be quantized but let us carry on with a classical description for now.

The total conserved energy of the system is simply the sum of the black hole masses, the kinetic energy and gradient energy of the hair.

$$\mathscr{E} = \mathscr{E}_{\mathscr{Q}} + \mathscr{E}_{\mathrm{Q}}$$

$$\mathscr{E}_{\mathscr{Q}} = \sum_i M_i = M$$

$$\mathscr{E}_{\mathrm{Q}} = \frac{\lambda^3}{2} \sum_i \mathbf{Q}_i' \cdot \mathbf{Q}_i' + \frac{\lambda^3}{2\sigma^2} \sum_i \left(\mathbf{Q}_{i+1} - \mathbf{Q}_i\right) \cdot \left(\mathbf{Q}_{i+1} - \mathbf{Q}_i\right)$$

For a nice split between interior and exterior, crucially there is NO interaction term.

Sttionary solutions with(out) hair are microstate solutions

THROATS

$$\mathcal{Q}_i^0 = Q, \quad \mathcal{Q}_i^\pm \text{ random and constant}$$

HAIR

$$\mathbf{Q}_i^{0mon} = \alpha u$$

PRIMORDIAL FRAME

$$\mathbf{Q}_i^\pm = -\frac{\sigma^2}{\lambda^2}\mathcal{Q}_i^\pm + \mathcal{K}^\pm = \mathbf{Q}_i^{\pm loc}$$

LOCKED TO INTERIOR

$$\mathbf{Q}_i^0 = \mathbf{Q}_i^{0mon} + \mathbf{Q}_i^{0rad}, \qquad \mathbf{Q}_i^{0rad} = q_i(u)$$

FREE FROM INTERIOR

$$q_i'' - \frac{1}{\sigma^2}(q_{i+1} + q_{i-1} - 2q_i) = 0$$

Also, t_i, t_i', t_i'' need to be continuous for $-\infty < u < \infty$ and therefore

$$Q \leq -M_i, \qquad \mathcal{Q}_i^{\pm} \leq 0, \qquad \mathcal{Q}_i^{+} + \mathcal{Q}_i^{-} \geq 2Q$$

We choose this.

or

$$Q \geq -M_i, \qquad \mathcal{Q}_i^{\pm} \geq 0, \qquad \mathcal{Q}_i^{+} + \mathcal{Q}_i^{-} \leq 2Q$$

Remarkably these inequalities imply that $t_i' \geq 0$ or $t_i' \leq 0$ for all i.

The uniform arrow of time emerges from our model. We choose the future direction.

Recall that generally the total energy can be split into two parts

$$\mathcal{E} = \mathcal{E}_{\mathcal{Q}} + \mathcal{E}_{\mathrm{Q}} \qquad \mathcal{E}_{\mathcal{Q}} = \sum_i M_i = M$$

$$\mathcal{E}_{\mathrm{Q}} = \frac{\lambda^3}{2} \sum_i \mathbf{Q}_i^{'} \cdot \mathbf{Q}_i^{'} + \frac{\lambda^3}{2\sigma^2} \sum_i \left(\mathbf{Q}_{i+1} - \mathbf{Q}_i\right) \cdot \left(\mathbf{Q}_{i+1} - \mathbf{Q}_i\right)$$

But in the hairy microstates we have non-trivially (as a consequence of dynamics) neat split between interior and exterior components in the hair kinetic + gradient energy.

$$\mathcal{E}_{\mathrm{Q}} = \mathcal{E}_{\mathrm{Q}}^{pot} + \mathcal{E}_{\mathrm{Q}}^{mon} + \mathcal{E}_{\mathrm{Q}}^{rad}$$

$$\mathcal{E}_{\mathrm{Q}}^{pot} = -\frac{\sigma^2}{2\lambda} \sum_i \left(\mathcal{Q}_{i+1} - \mathcal{Q}_i\right) \cdot \left(\mathcal{Q}_{i+1} - \mathcal{Q}_i\right)$$

INTERIOR (LOCKED)

$$\mathcal{E}_{\mathrm{Q}}^{mon} = -\frac{1}{2}\lambda^3 \alpha^2$$

EXTERIOR (PRIMODIAL)

$$\mathcal{E}_{\mathrm{Q}}^{rad} = \frac{\lambda^3}{2} \sum_i q_i^{'2} + \frac{\lambda^3}{2\sigma^2} \sum_i \left(q_{i+1} - q_i\right)^2$$

EXTERIOR (DECOUPLED RADIATION)

<u>Ensemble of microstate solutions:</u>

Fix total mass M, Q and α.

Allocate M_i, $\mathcal{Q}_i^{\pm}$ subject to inequalities discussed.

<u>Adding hair on top:</u>

Each microstate solution supports hair oscillations $\mathbf{Q}_i^{rad}$ that can propagate freely over the lattice without affecting it

SHOCK AND VERIFY

Do our model reproduce energy absorption and relaxation properties of classical black hole?

If we cannot resolve the microstate and the horizon is the model indistinguishable from a classical black hole?

If yes, then when we perturb a random initial microstate with one or more sequence of shocks, then it will QUICKLY relax to another microstate absorbing all energy in the continuum limit.

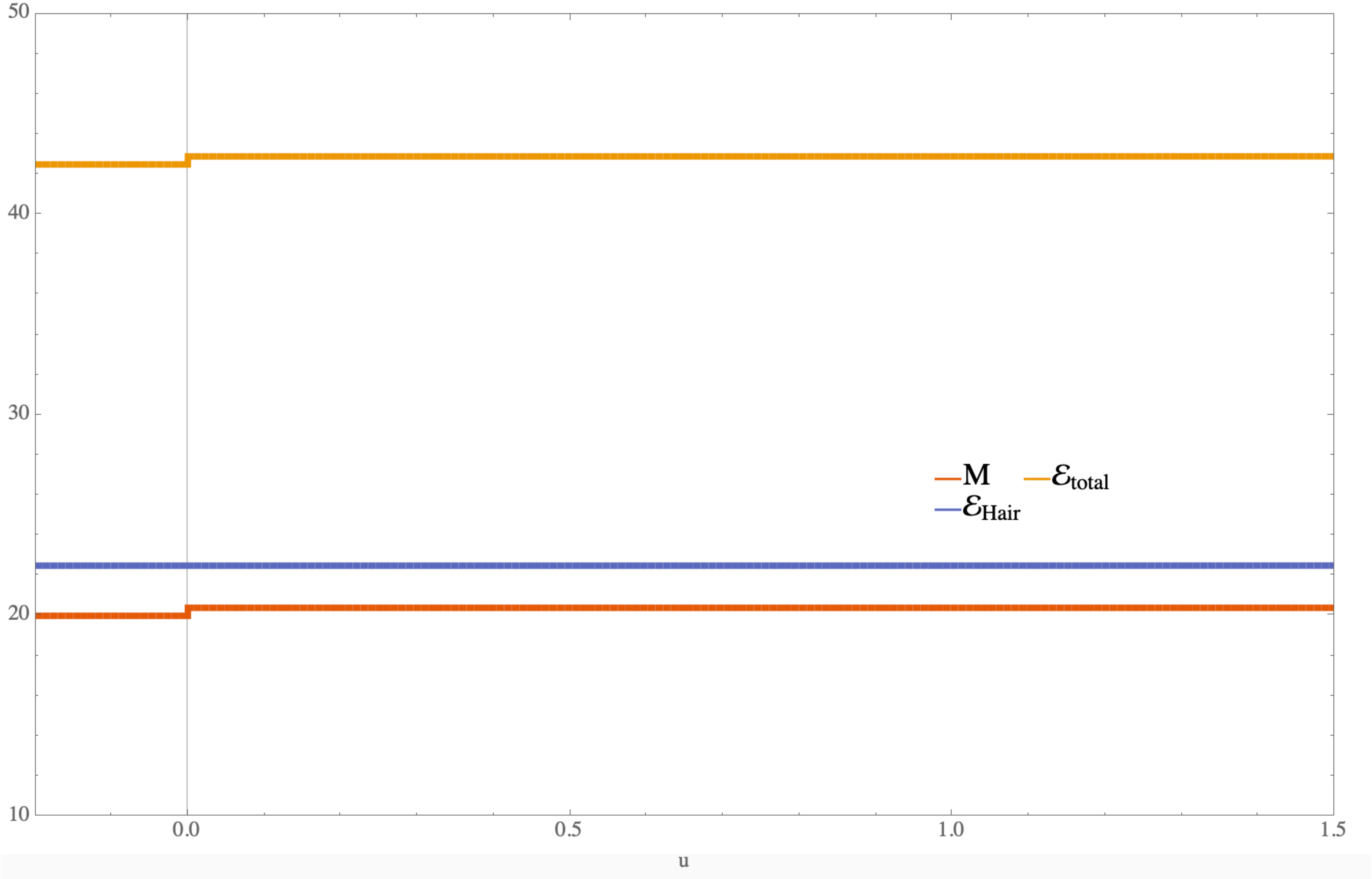
In presence of shocks, the equations of motion are:

$$M_i' = -\lambda\left(\mathcal{Q}_{i-1} + \mathcal{Q}_{i+1} - 2\mathcal{Q}_i\right)\cdot \mathbf{Q}_i' + \sum_A e_{i,A}\delta(u - u_{i,A})$$

$$\mathbf{Q}_i'' = \frac{1}{\sigma^2}\left(\mathbf{Q}_{i-1} + \mathbf{Q}_{i+1} - 2\mathbf{Q}_i\right) + \frac{1}{\lambda^2}\left(\mathcal{Q}_{i-1} + \mathcal{Q}_{i+1} - 2\mathcal{Q}_i\right)$$

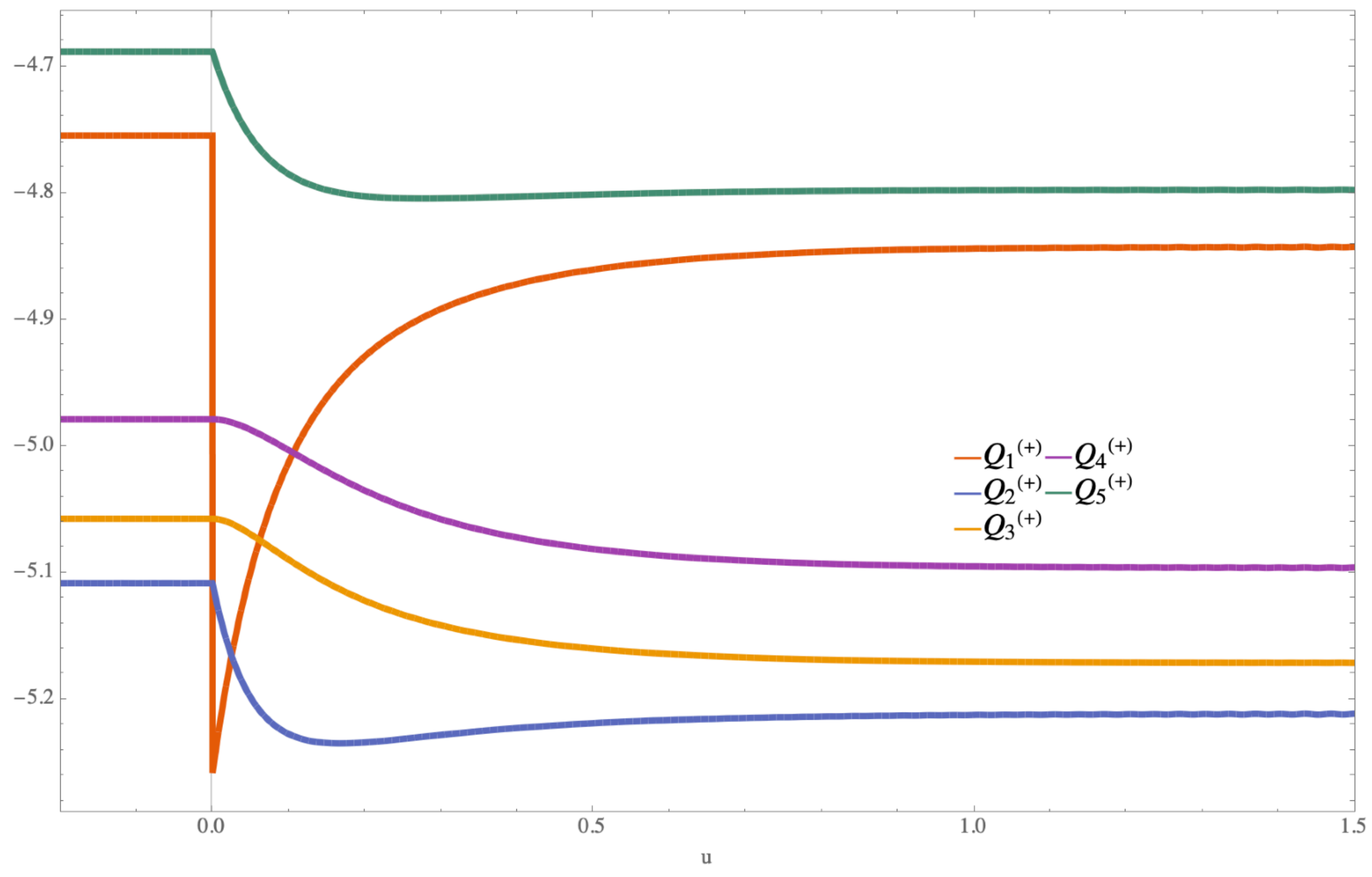
The shocks are produced by infalling null matter

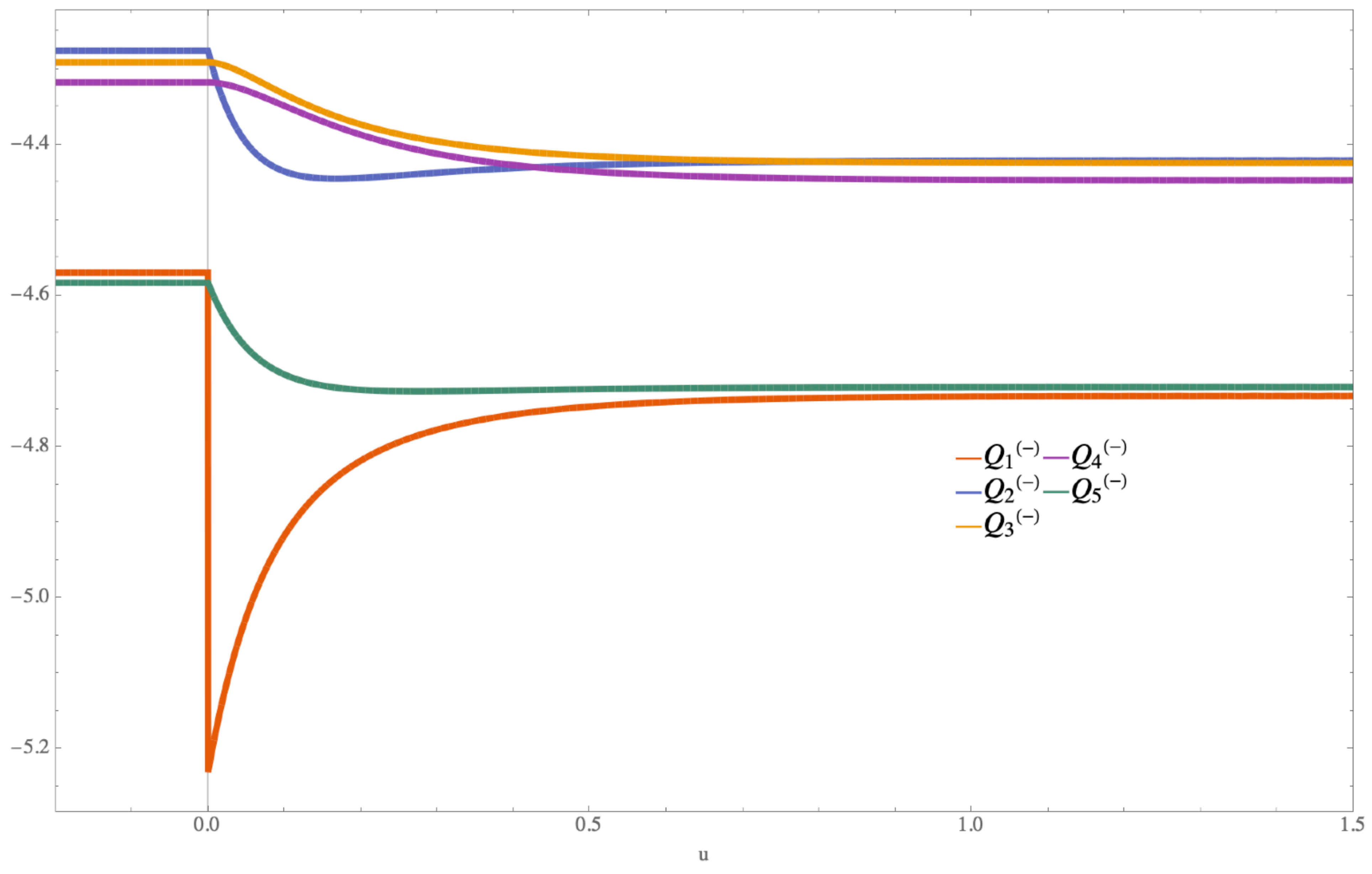
Results for a single shock



We shock a 5-site periodic chain at site 1. The initial microstate is always randomly chosen.

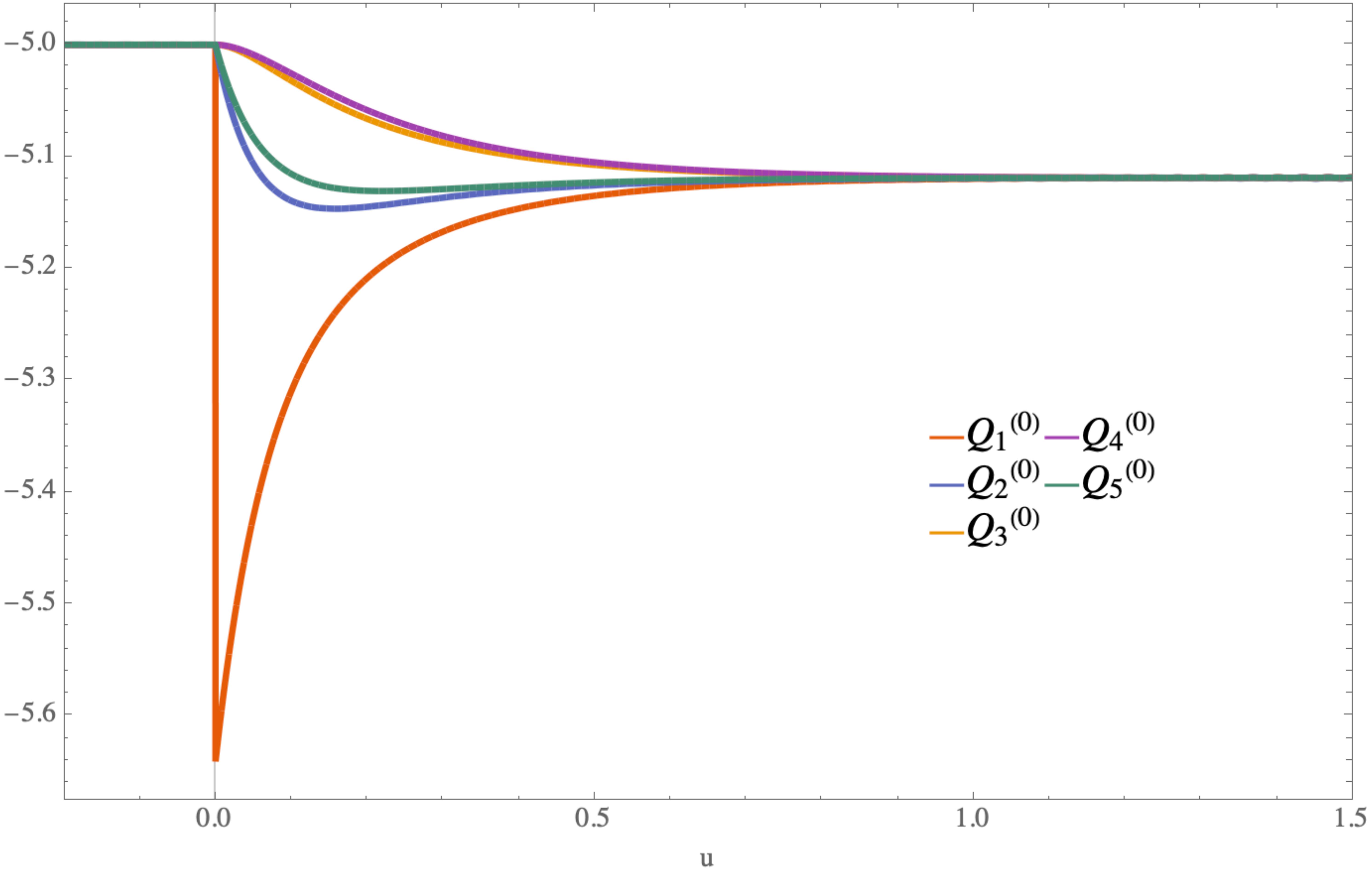
Note that the shock energy is almost totally (99.9 %) absorbed in the black hole mass





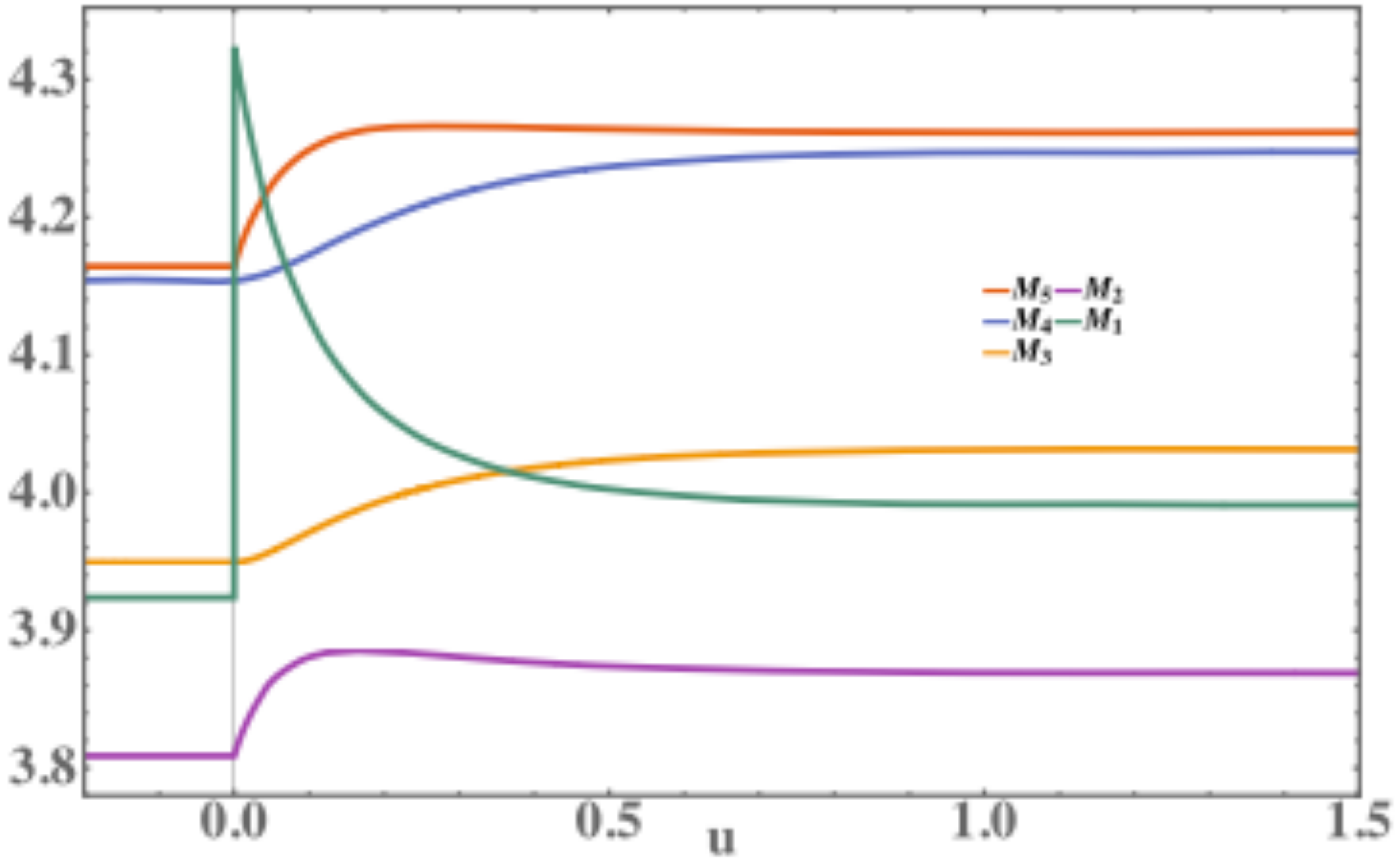
Also $\mathbb{Q}_i^{\pm}$ relax to constants as they should in a (final) microstate.

The dynamics is pseudo-random



Crucially the $\mathbb{Q}_i^0$ relaxes to a new homogeneous value in the microstate.

The conservation of the monopole charge implies that the final homogenous component should also be in same direction



(d) Evolution of M_i after the shock.

The dynamics is pseudorandom (necessary for Harlow-Hayden scenario)

The final microstate is hairy with decoupled q_i oscillations

The same happens with multiple shocks.

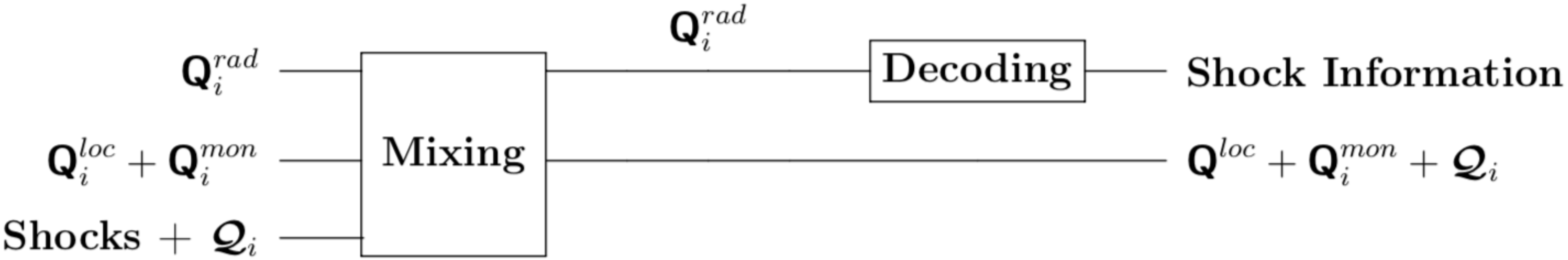
The dynamics has energy-absorption (exact in continuum limit) and quick relaxation properties.

It is pseudorandom (needs quantification).

Remarkably the decoupling of exterior and interior happens dynamically. The energy of the hair is conserved on its own in the continuum limit also.

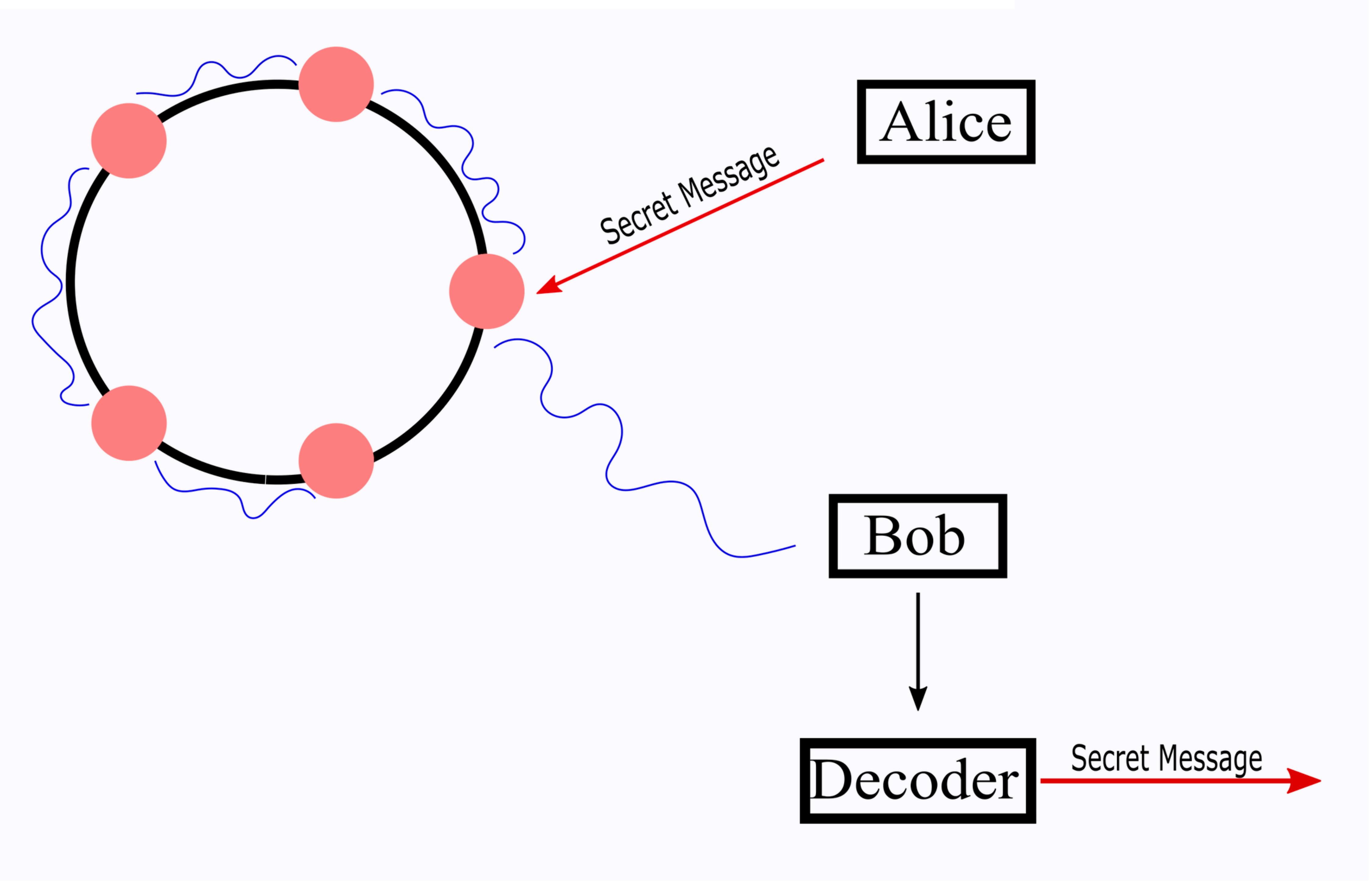
The final microstate always has decoupled hair oscillations.

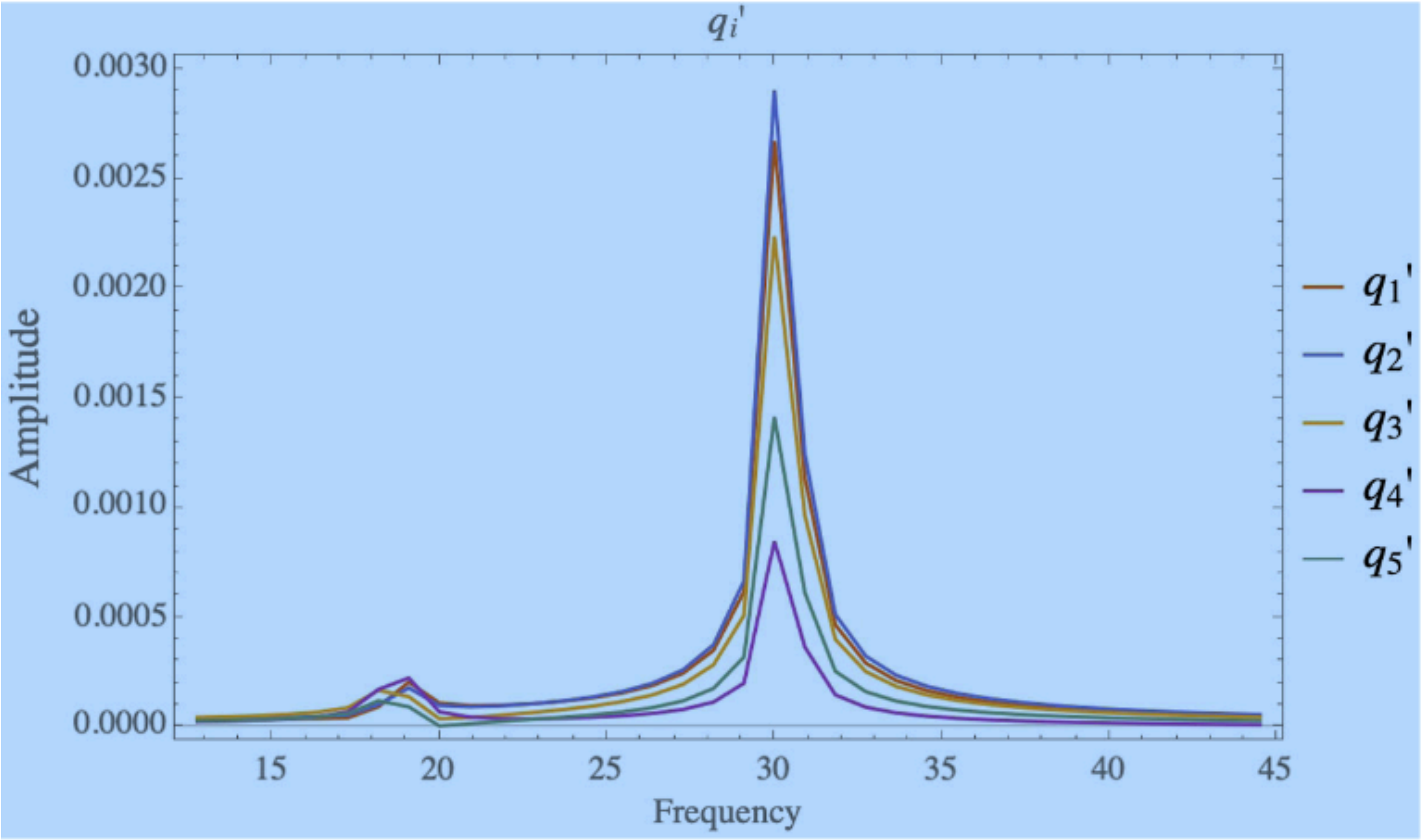
INFORMATION MIRRORING



Alice throws in her secret information into our BH in the form of an ordered list — time-sequence and locations of shocks.

Bob can decode the classical information from Q_i^{rad} as soon as it decouples from the final microstate. (Wait for the Hawking radiation story)



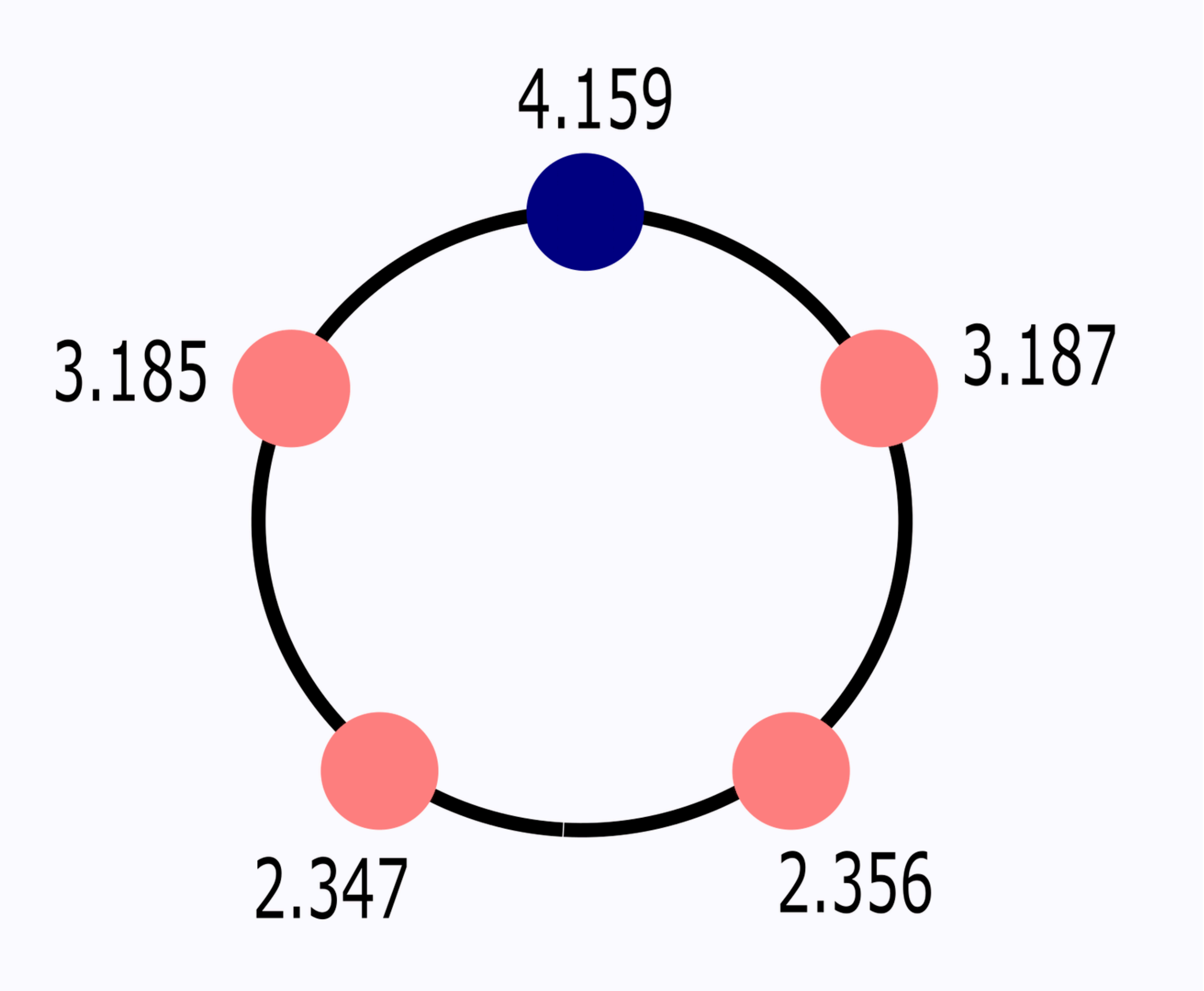


We explicitly see the two normal modes in the 5 site model after decoupling — the amplitudes (and phases) look random and encodes the interior in a complex way.

But wait for the phase differences! They mirror!

We need the primordial information of the monopole frame but nothing more

Decoding a single shock

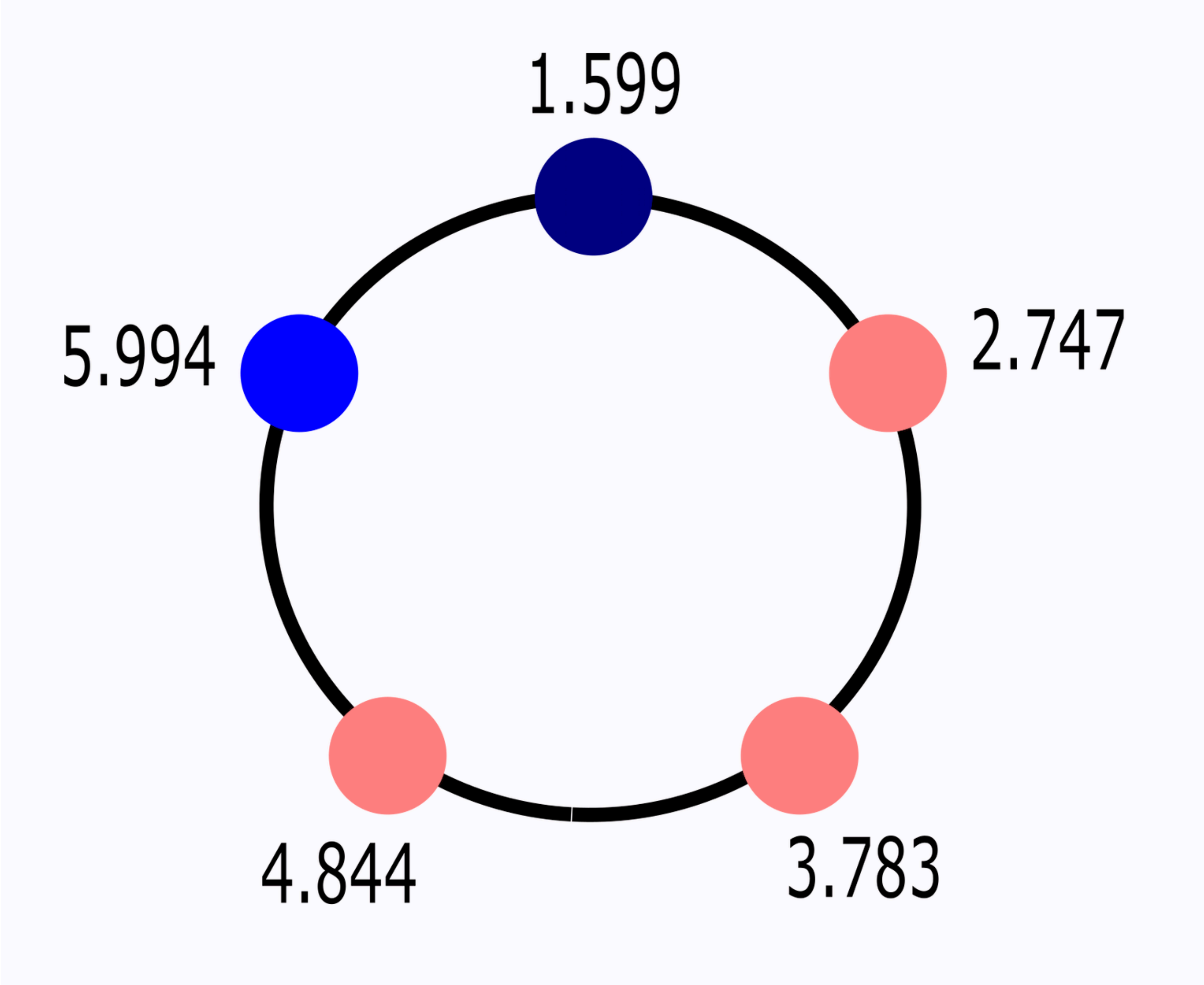


The symmetry in phase differences reveals which site was shocked

A highly non-trivial result because we start from highly asymmetric random initial conditions.

Also not all features of Q_i^{rad} has this symmetry

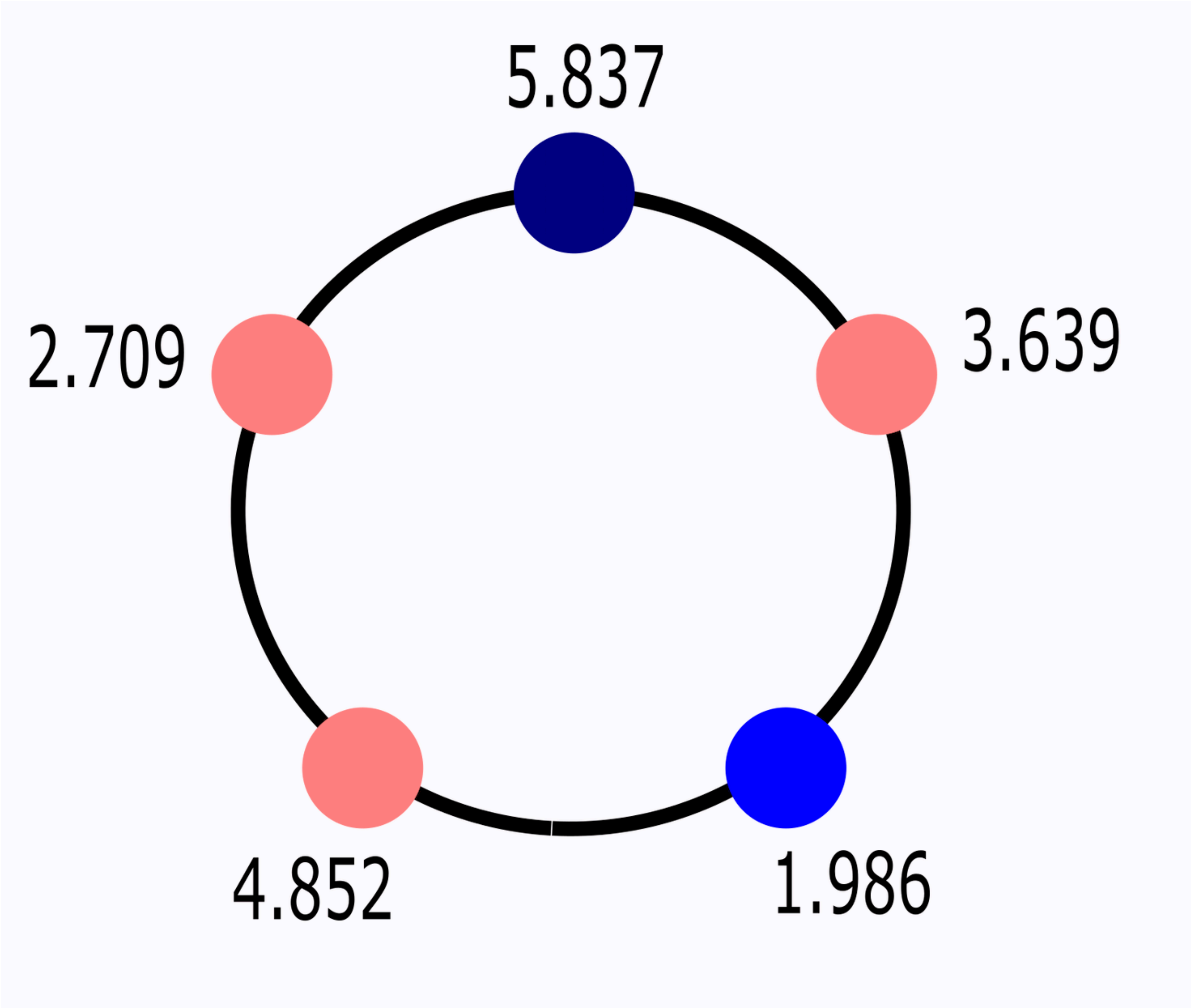
Decoding two shocks: 1



The maximum and minimum phase differences are the positions of the shocks

The minimum phase difference site was shocked first if the shocked sites are nearest neighbors

<u>Decoding two shocks: 2</u>



The maximum and minimum phase differences are the positions of the shocks

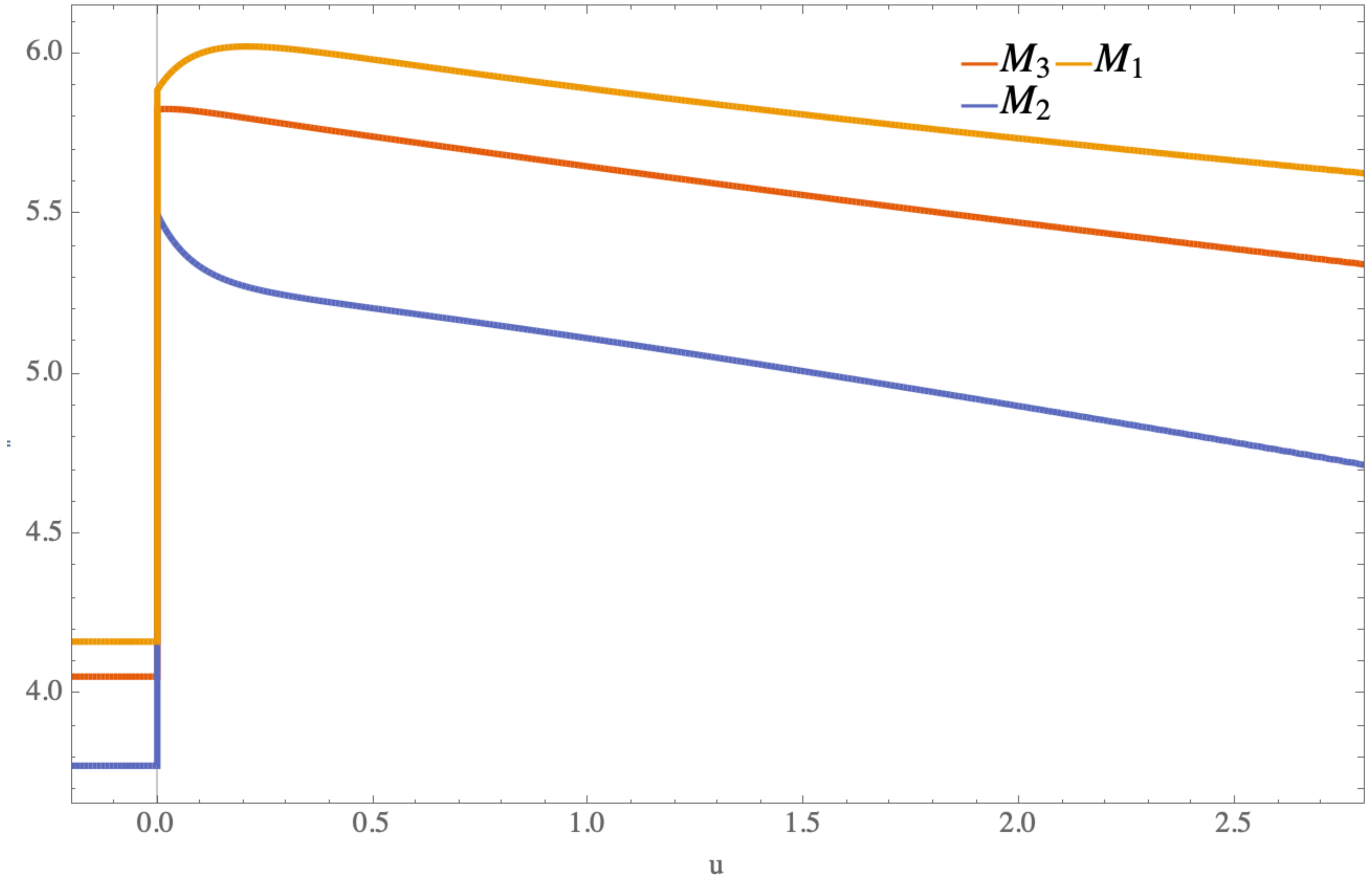
The minimum phase difference site was shocked <u>later</u> if the shocked sites are <u>not</u> nearest neighbors

ADDING HAWKING RADIATION

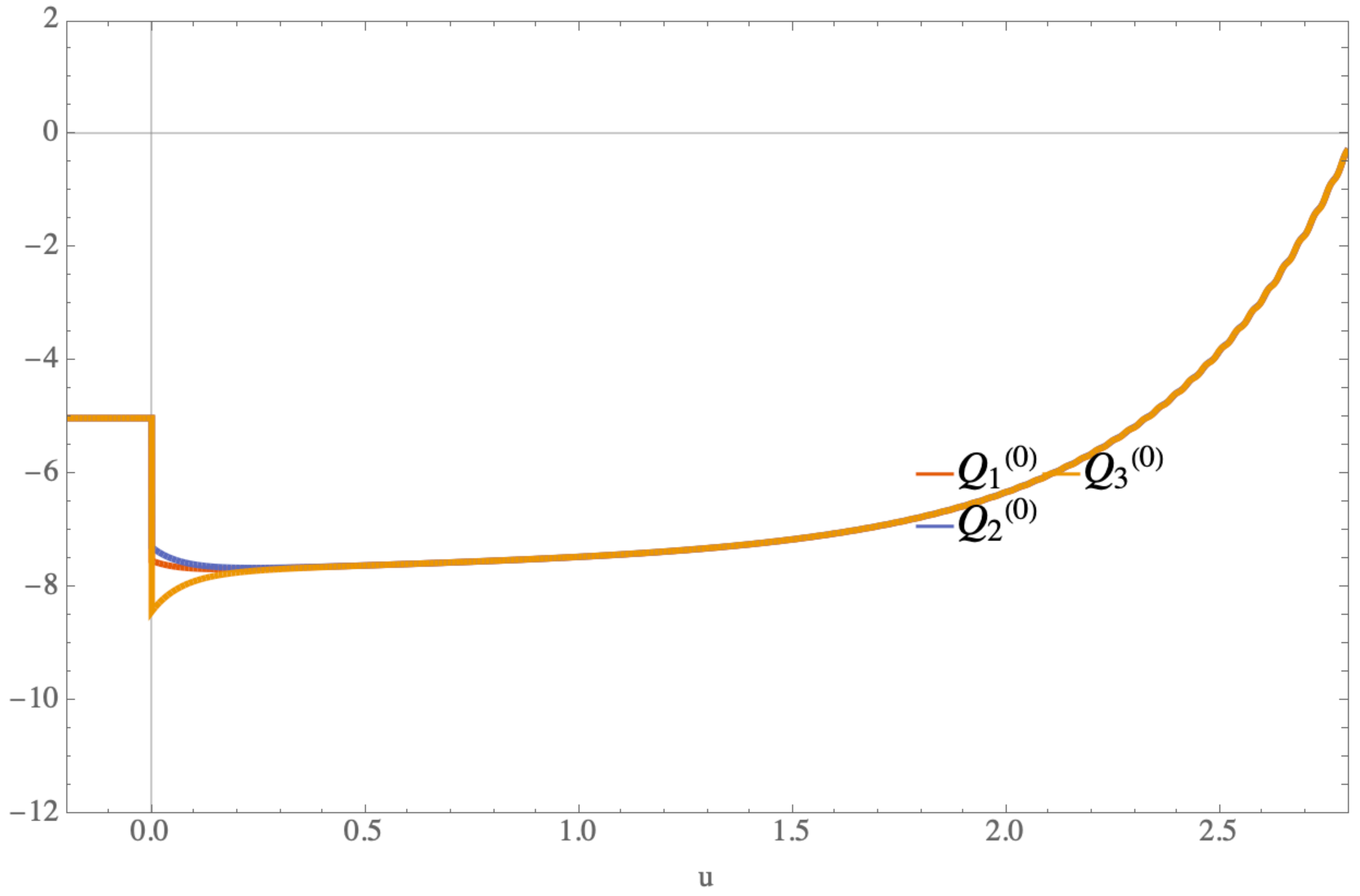
Let the 2D throats independently radiate Hawking quanta through a bulk CFT with transparent boundary conditions (as in Page curve models).

The Hawking quanta does not interact with hair directly. The Hawking quanta emitted from various throats also do not interact directly.

The masses of each throat evaporate.



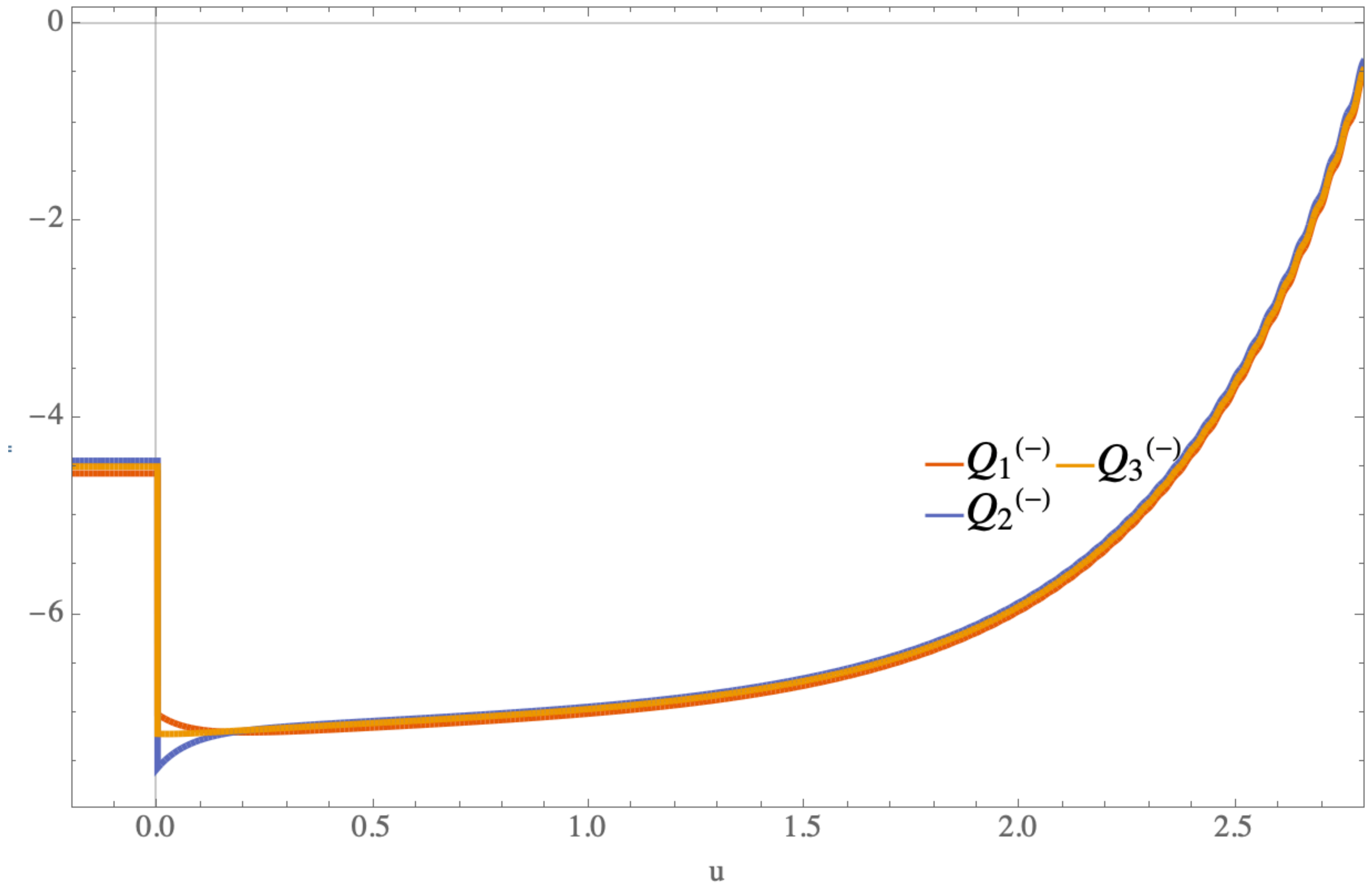
Very quickly the $\mathcal{Q}_i^0$ components of the throat homogenise. Depending on initial conditions, a decaying microstate is realized.



$\mathcal{Q}_i^+$ and $\mathcal{Q}_i^-$ components of the throat homogenise on a much much longer time-scale.

The SL(2,R) charges of all throats attain **a common null frame (stronger statement than all masses vanish). The overall scale is fixed by the pre-existing boundary condition for bulk Hawking quanta before transparency.**

Information is mirrored into both $\mathcal{Q}_i^0$ (on short timescales) and also in $\mathcal{Q}_i^\pm$ (on longer timescales)

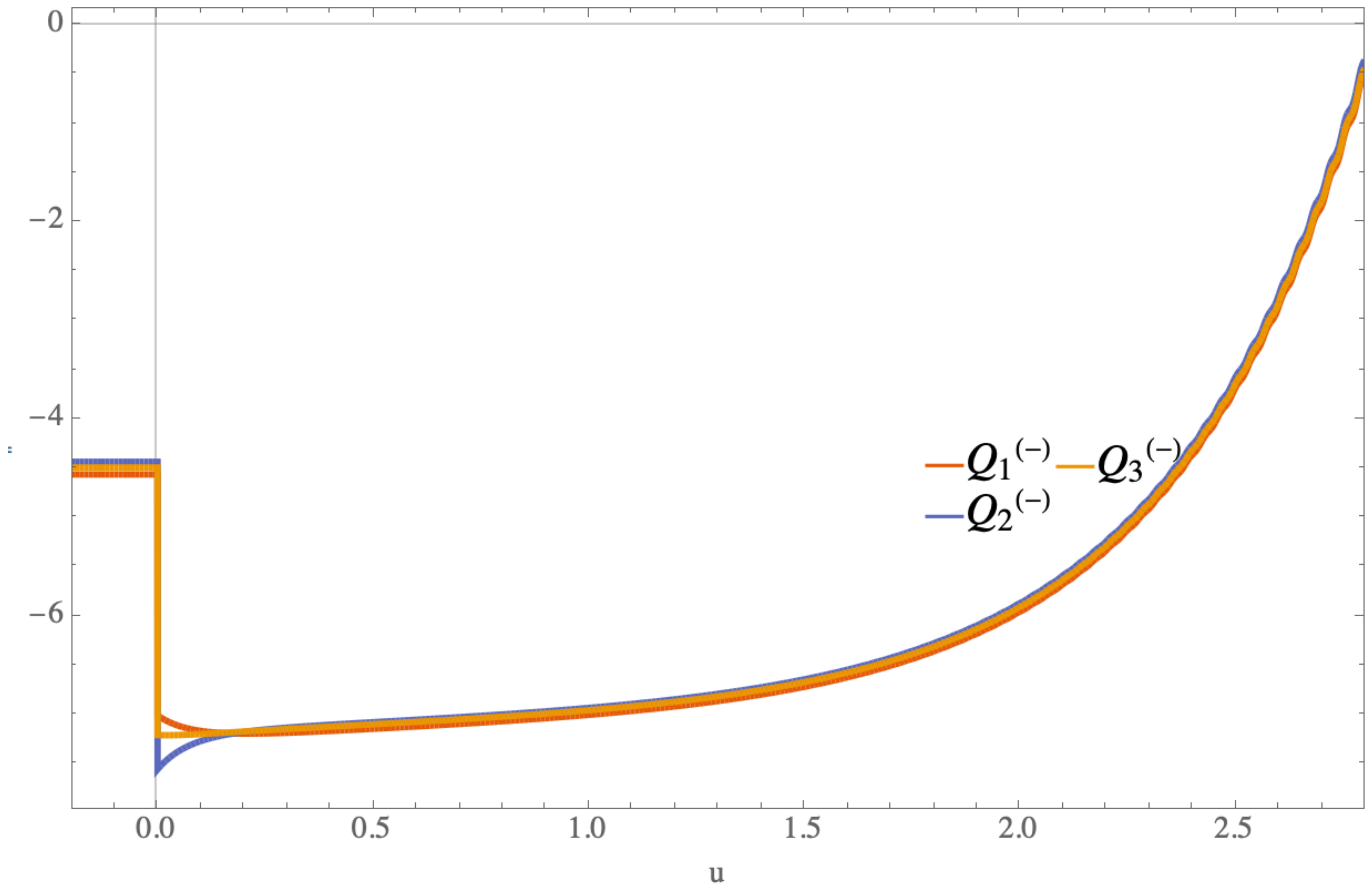


The throats decouple from each other asymptotically. They also decouple from hair.

This is precisely what we need for copying information. The ringdown of the throats will imprint the information into the Hawking quanta.

This imprinting is complex and conditioned on the history of the microstate. Can it be still partially reconstructed without decoding the interior?

However the decoding of the same information in the hair can be done rapidly and without the knowledge of the interior. We are explicitly understanding these issues with a 3-site model.



CONCLUSIONS AND OUTLOOK

We have a reasonably good phenomenological model of a quantum black hole that gives insights into origins of black hole complementarity while exhibiting right classical behaviour with horizon hair playing a very crucial role in factorisation.

The mutual decoupling of all degrees of freedom from each other copies information to the interior in very complex way via fantastic weak measurement of all other by the latter.

However, this requires NEW understanding of quantum weak measurement theory. This has fascinating consequences for quantum control, fault-tolerant quantum computing, etc. (resonates with our non-isometric erasure tolerant encoding)

Perhaps a strange metal is a black hole microstate? See my work with Doucot, Policastro, Samanta and Swain.

Black holes are indeed special objects. Black hole complementarity can be simulated.

THANK YOU

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