Title: Black Holes and Reversibility

Date: Apr 13, 2015 02:00 PM

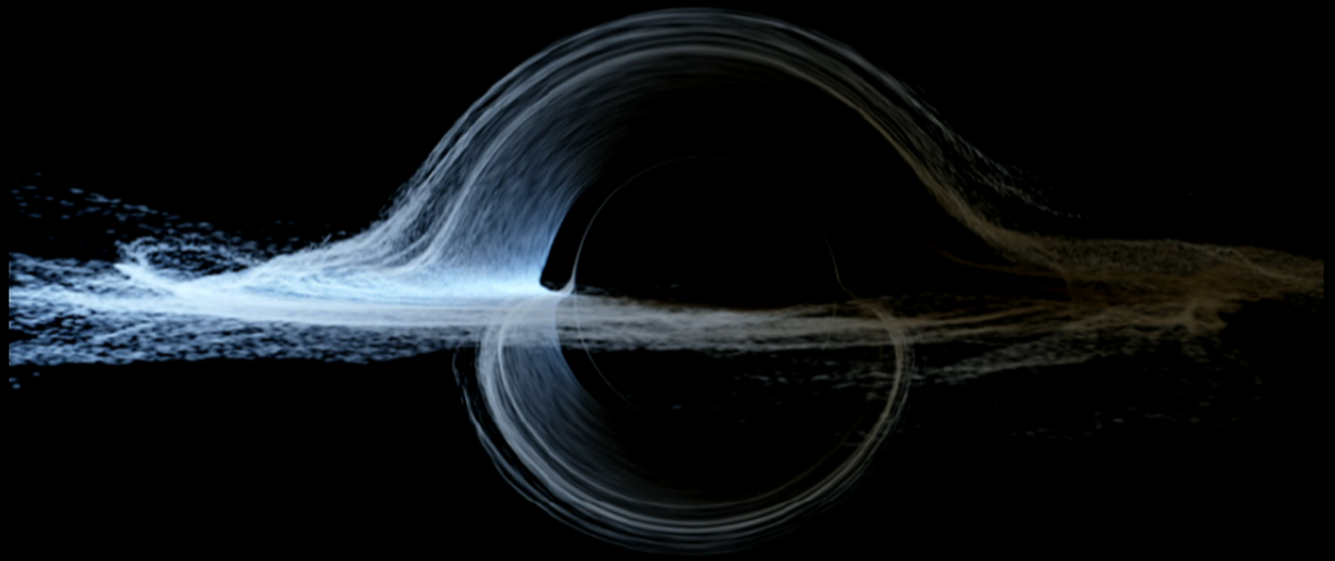
URL: http://pirsa.org/15040140

Abstract: It has become a platitute to say that black holes are fascinating objectsâ€”but they really are, in part because they challenge our understanding of the fundamental reversibility of physical processes.

In the first part of the talk, I will review some of the classical ways black holes behave as dissipative systems, such as the "hair lossâ€• phenomenon and the monotonic growth of horizon area. In the second part, I will explain how quantum mechanics (more precisely, the coupling of black holes to the quantum vacuum) affects the classical picture at late times, notably through particle creation and evaporation. I will argue that techniques from two-dimensional field theory can help bring clarity to the associated â€œinformation lossâ€•

problem, and perhaps also point to new, unexpected predictions. My approach will be as model-independent as possible; that is, rather than investigating a particular scenario for black hole evaporation, I will aim to derive generic consequences from basic assumptions regarding the reversibility of black hole evaporation.

THIS IS A BLACK HOLE



THORNE *ET AL.* 15

"[Black holes] are the most perfect macroscopic objects in the universe: the only elements in their construction are our concepts of space and time."

Chandrasekhar

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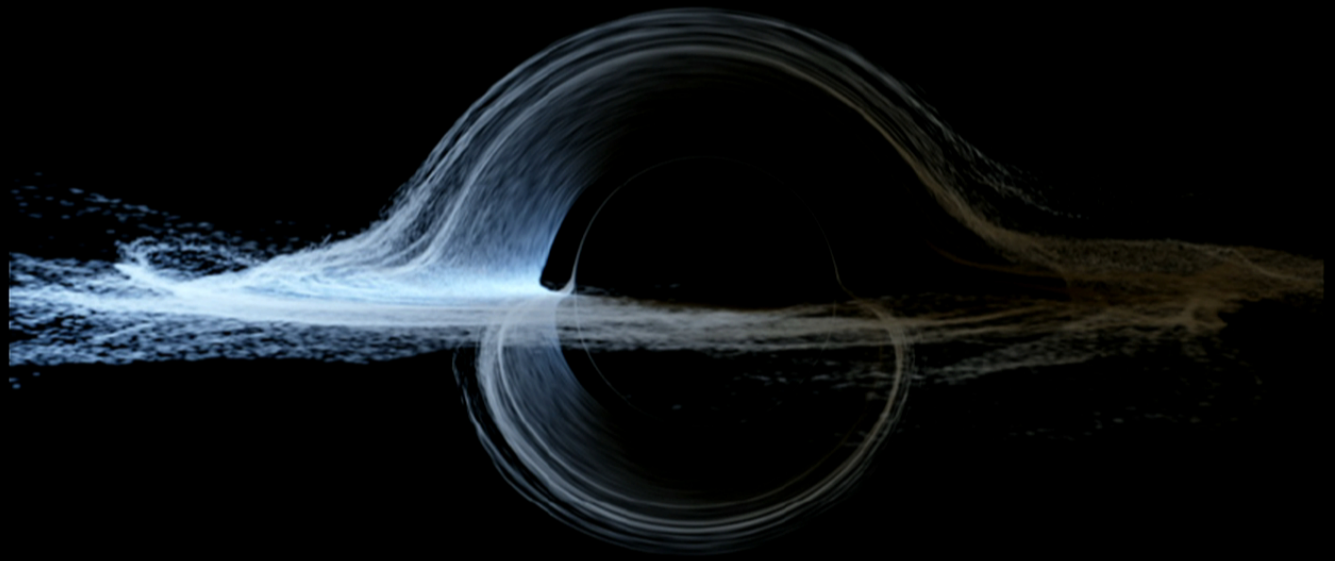

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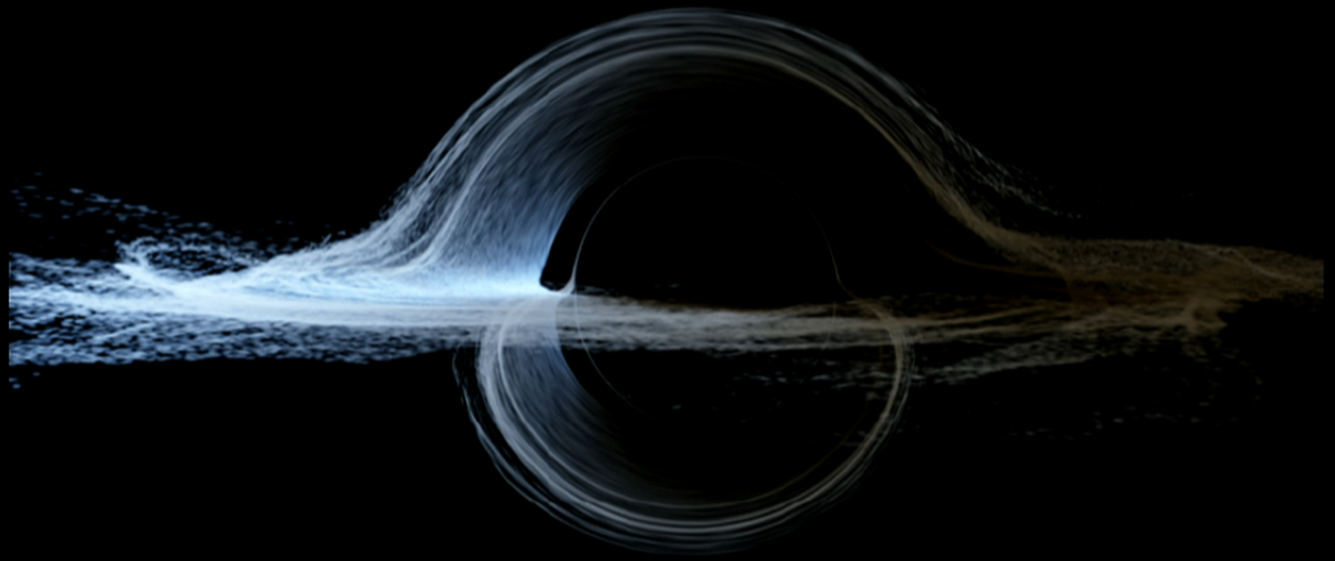

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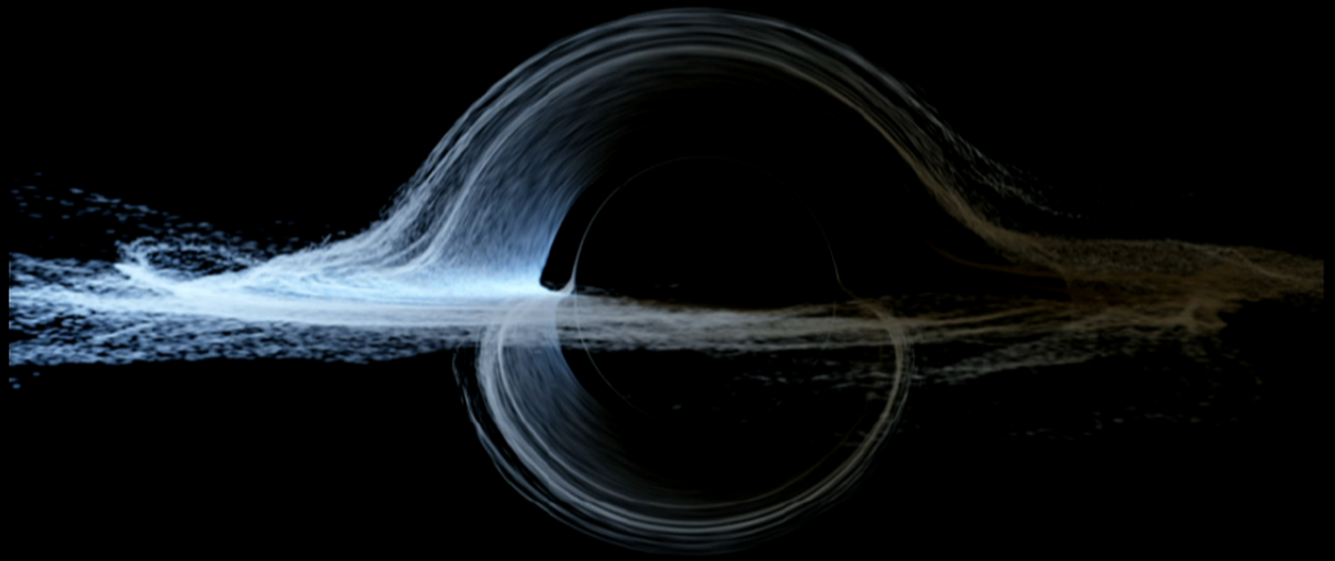

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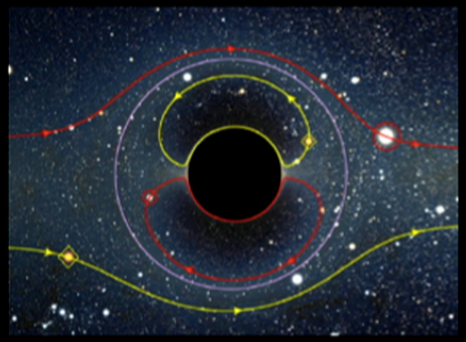
A SPACE ODDITY



RIAZUELO 14

- can go in, cannot come out
- hole is black, but see images of the entire sky near it
- a trip near a black hole is a trip to the future

$$\Delta t_r = (1 - r_s/r)^{1/2}\, \Delta t$$

- black hole are small outside, large inside

$$V(t) \sim 3\sqrt{3} M^2 t$$

- ...

CHRISTODOULOU, ROVELLI 15

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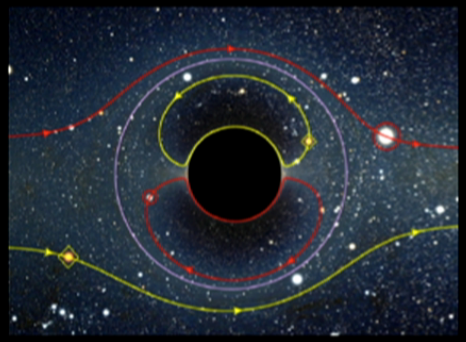

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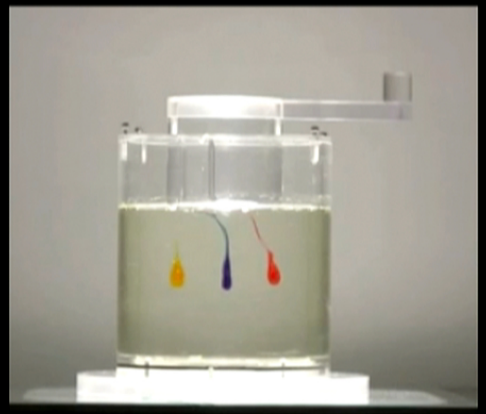
THE REVERSIBILITY PRINCIPLE

"Everything that can be done, can be undone."*



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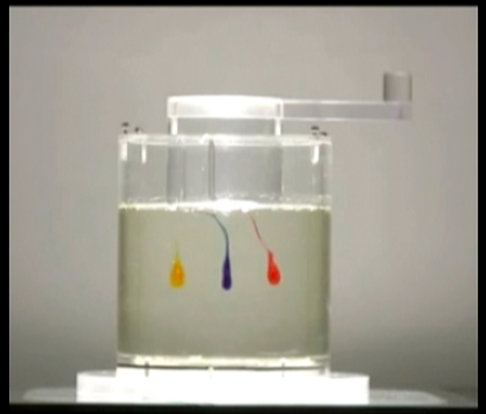

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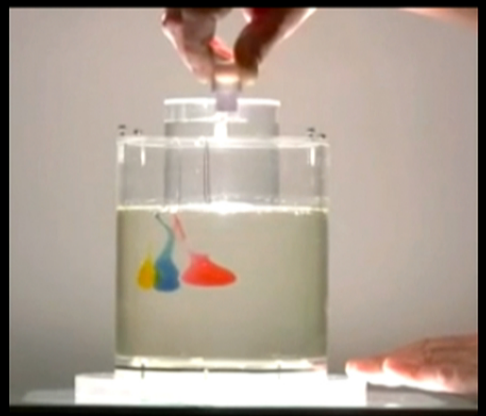

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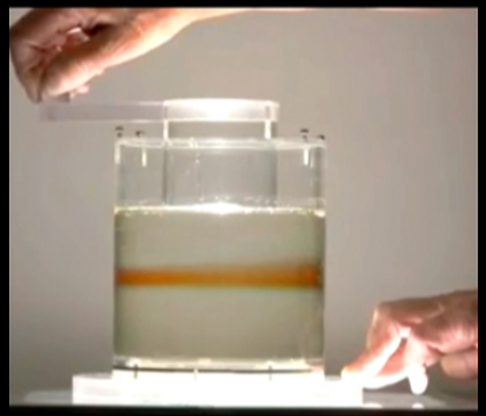

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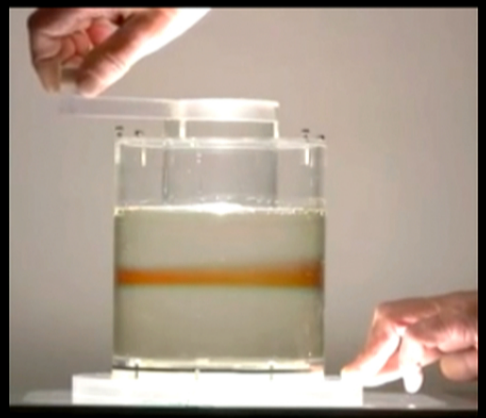

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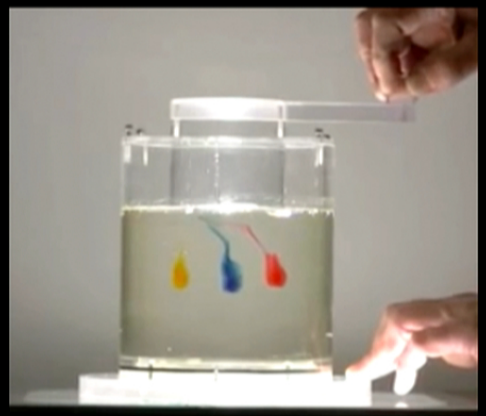

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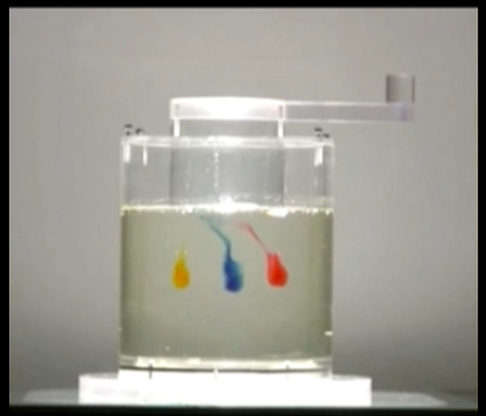


** in principle, if not in practice*

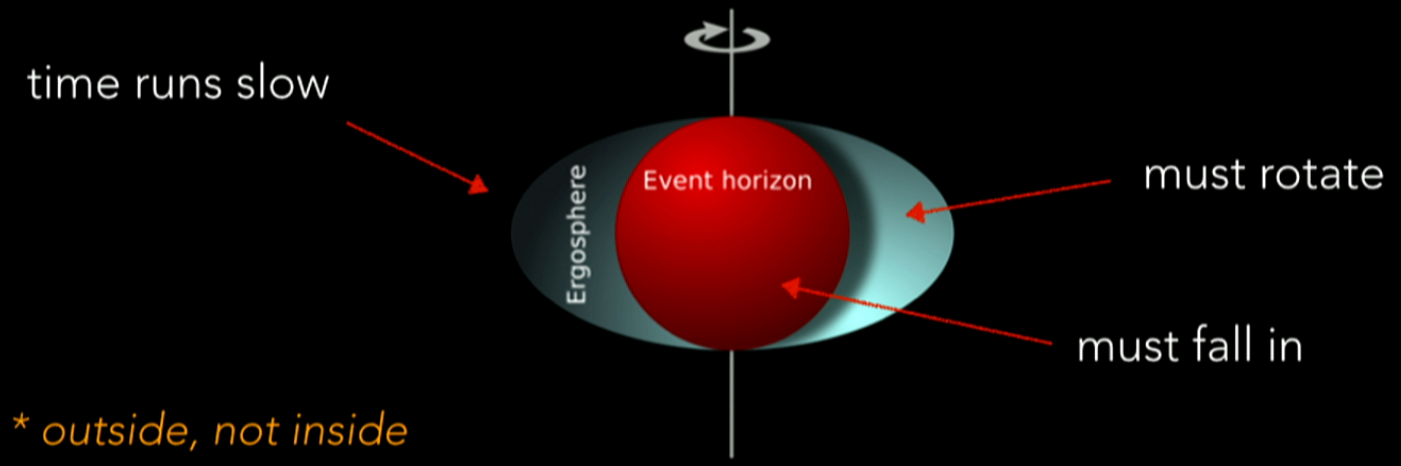
1. CLASSICAL IRREVERSIBILITY

$$R_{ab} - \frac{1}{2} R g_{ab} = \kappa T_{ab}$$

"BLACK HOLES HAVE NO HAIR"

NO HAIR THEOREM:
STATIONARY BLACK HOLES HAVE ONLY 2 PARAMETERS: M AND J*

This means that all stationary black holes can be described *exactly*, with no approximation: they are indeed "perfect".



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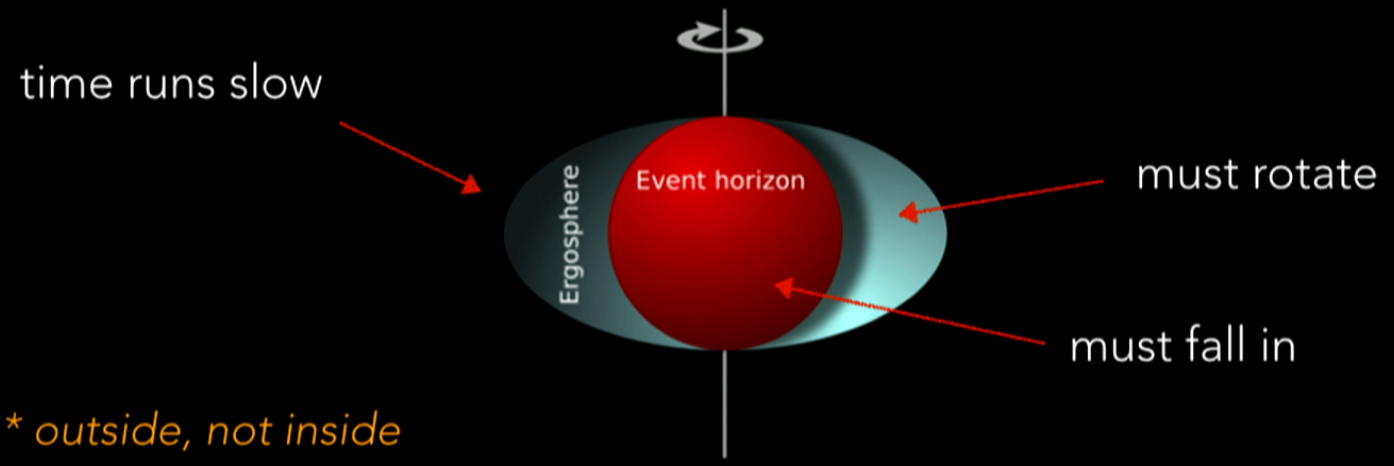

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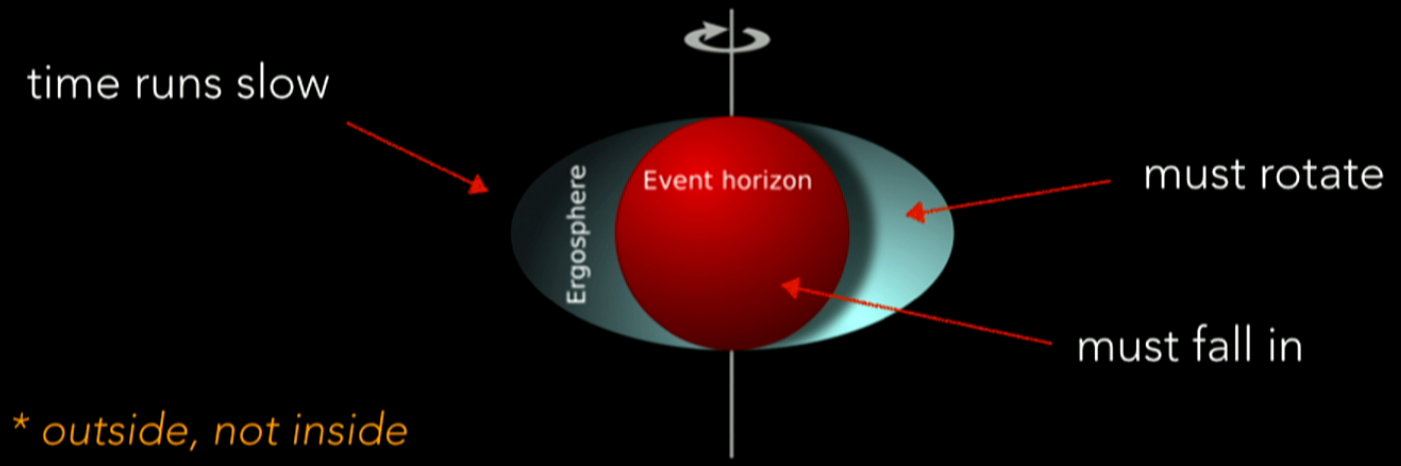

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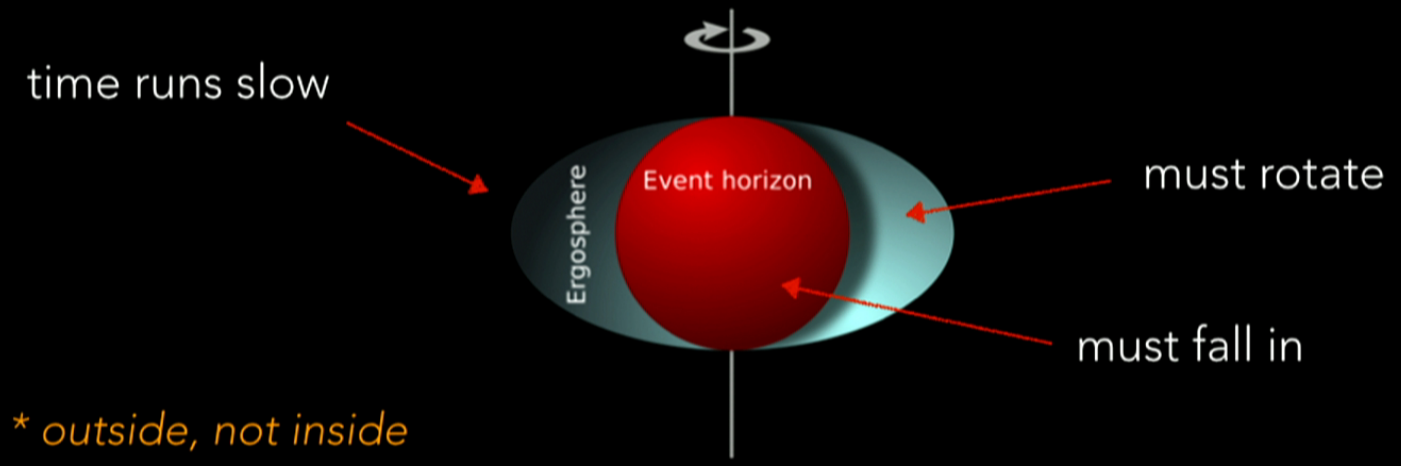
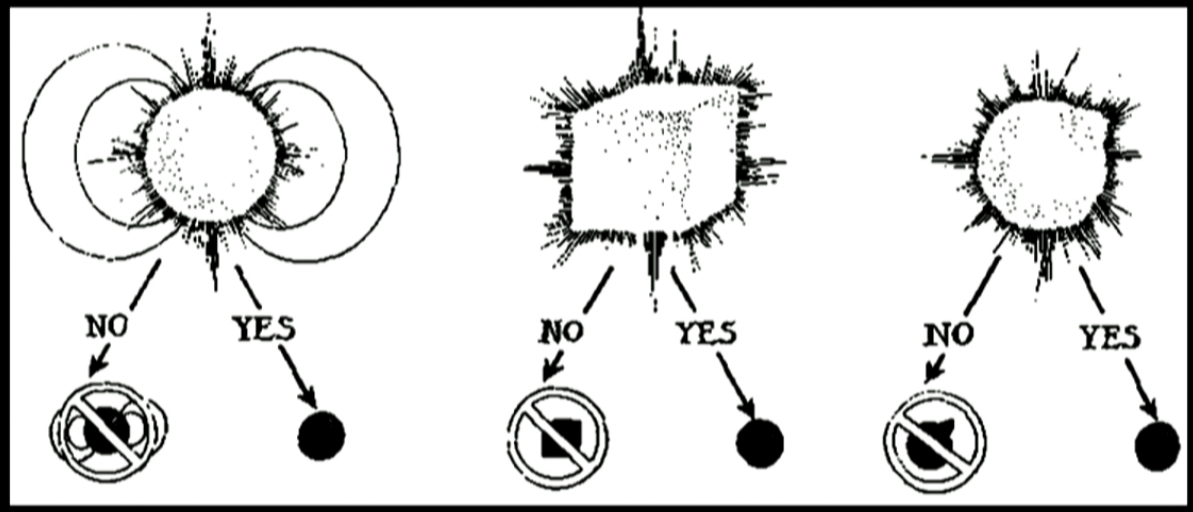


* *outside, not inside*

BLACK HOLE BALDING - OLD INSIGHTS

PRICE'S LAW:
WHATEVER CAN BE RADIATED IS RADIATED*



©THORNE

* *albeit slowly, i.e. with power law tails*

PRICE 72

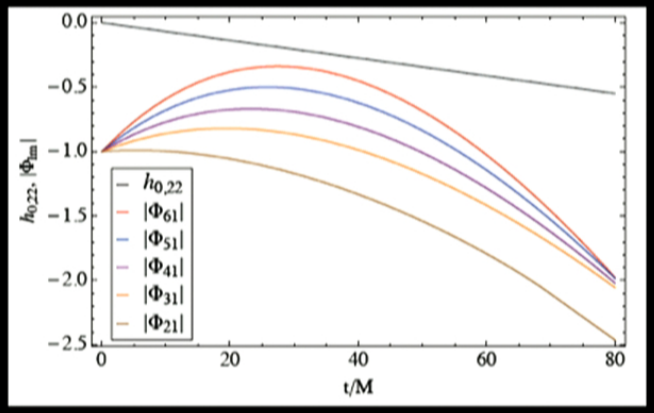
BLACK HOLE BALDING - NEW INSIGHTS

Turbulent balding

- parametric instability

$$\ddot{x} + \gamma\dot{x} + \omega(t)^2 x = 0$$

- inverse energy cascade
  small scales → large scales



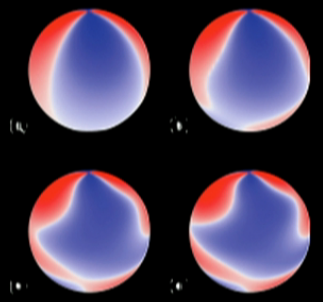
Gravitational Reynolds number:

$$Re_g = \frac{h_0}{m\gamma}$$

amplitude

azimuthal frequency

decay rate

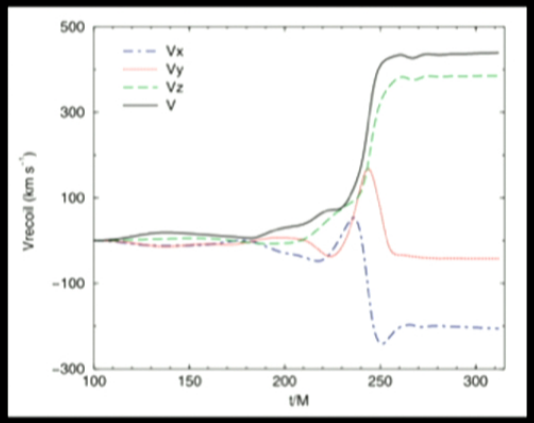


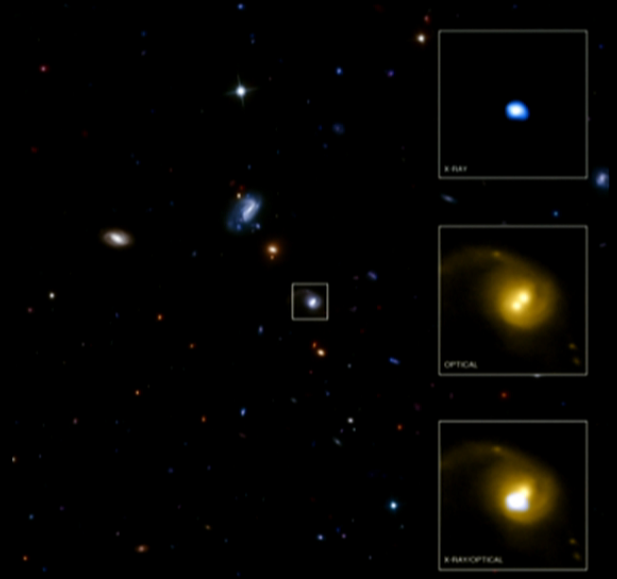
HUANG *ET AL.* 14

BLACK HOLE KICKS

Large recoil velocity (≃ 1% *c*) after merger:

- large spin orbit coupling
- focusing of gravitational waves





CID - 42

CAMPANELLI *ET AL.* 07

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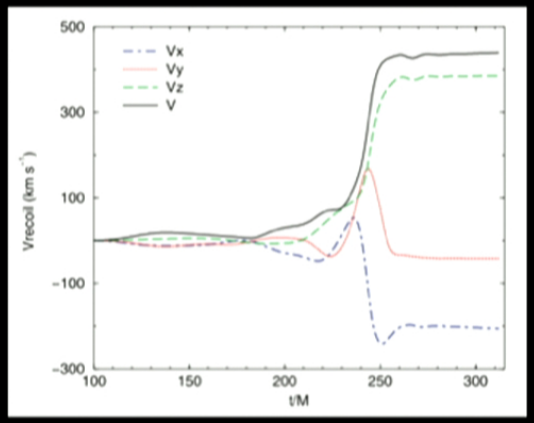

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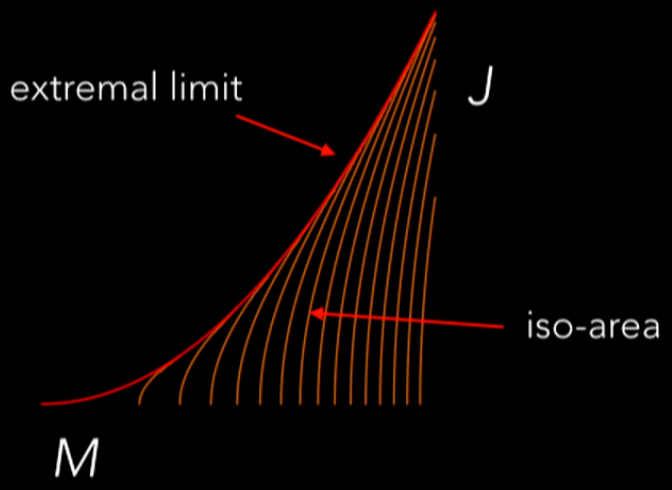
CAMPANELLI *ET AL.* 07

BLACK HOLE TRANSFORMATIONS

AREA LAW:
THE AREA OF A BLACK HOLE NEVER DECREASES*

HAWKING 71

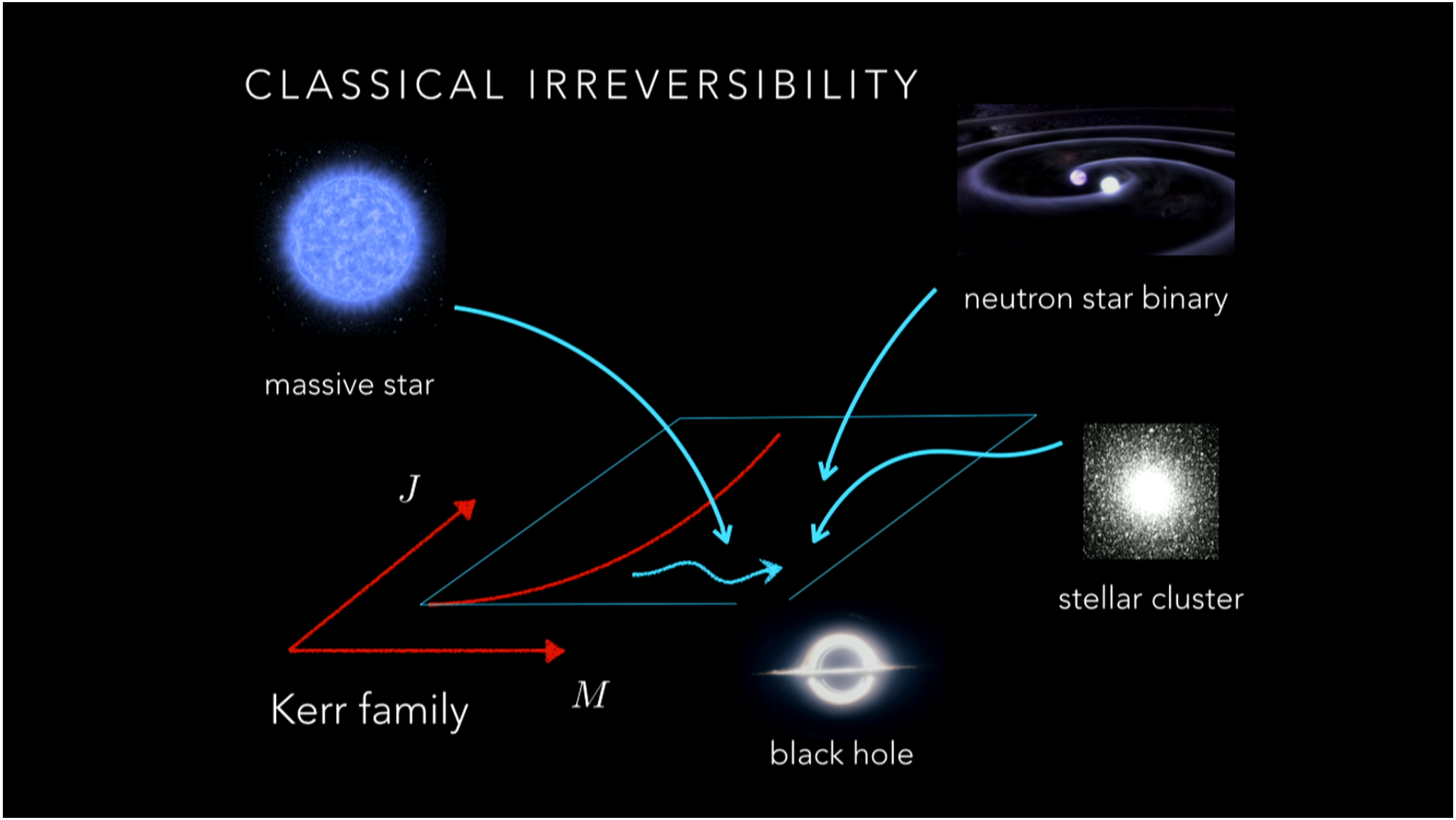


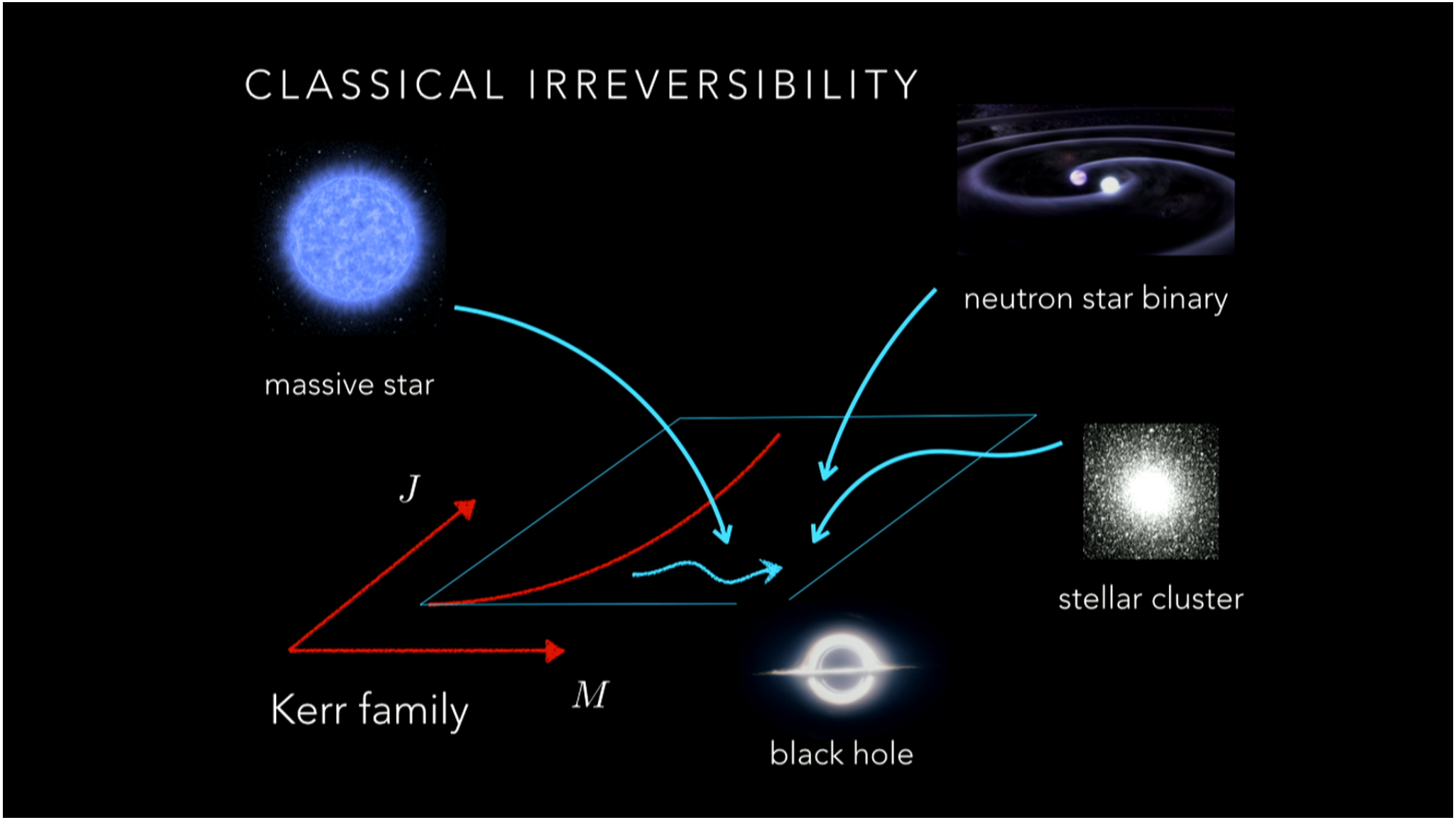
Two types of black hole transformations:

- reversible if $\delta A = 0$
  (≈ add/remove spin)
- irreversible if $\delta A > 0$
  (≈ add mass)

** when interacting with normal matter*

CHRISTODOULOU 70


CLASSICAL IRREVERSIBILITY
massive star
neutron star binary
stellar cluster
J
M
Kerr family
black hole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SINGULARITIES - OLD INSIGHTS

SINGULARITY THEOREM:
ALL BLACK HOLES CONTAIN SINGULARITIES*

PENROSE 65; HAWKING, PENROSE 70

An infalling observer will run into "trouble" in finite time.

The nature of this "trouble" is left unspecified.

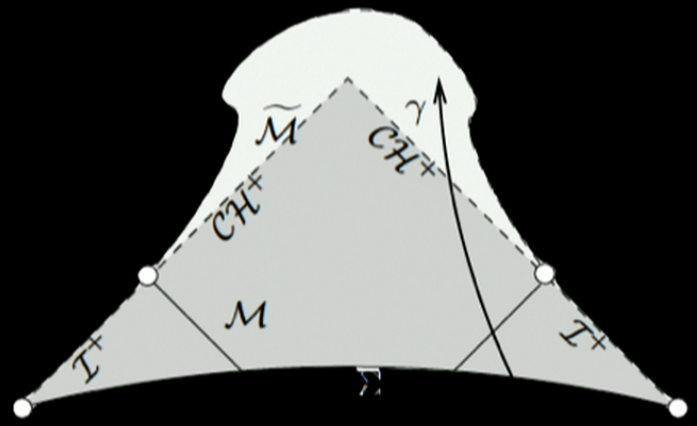
** if the black hole contains normal matter*

SINGULARITIES - NEW INSIGHTS

Old idea: time and space end at the (spacelike) singularity.

More careful computations suggest weak null singularities:

- spacetime can be extended continuously
- curvature blows up but not tidal disruptions
- unpredictable other universe?



ISRAEL, POISSON 89; DAFERMOS 13

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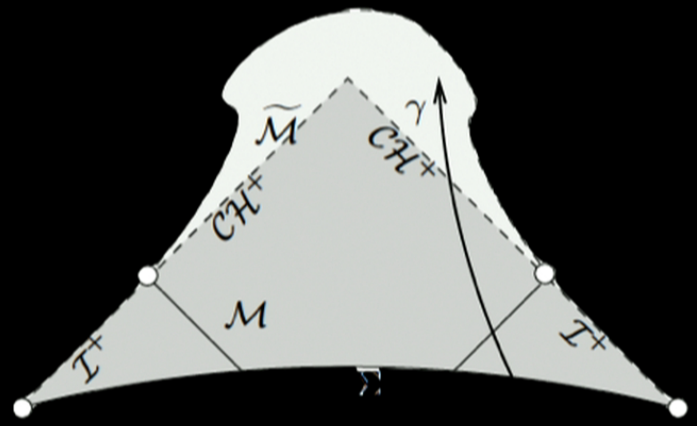

ISRAEL, POISSON 89; DAFERMOS 13

2. QUANTUM REVERSIBILITY?

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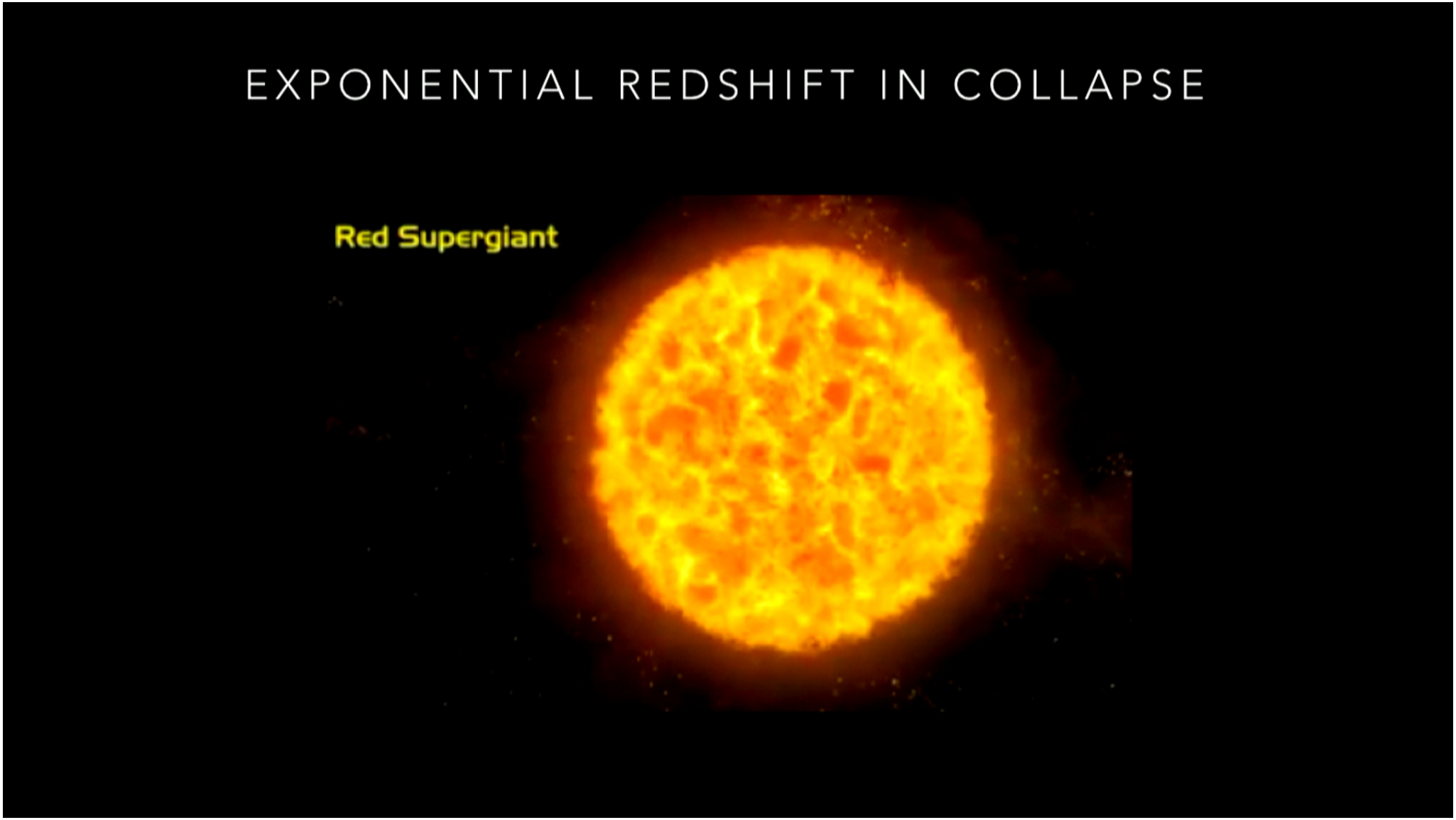
EXPONENTIAL REDSHIFT IN COLLAPSE



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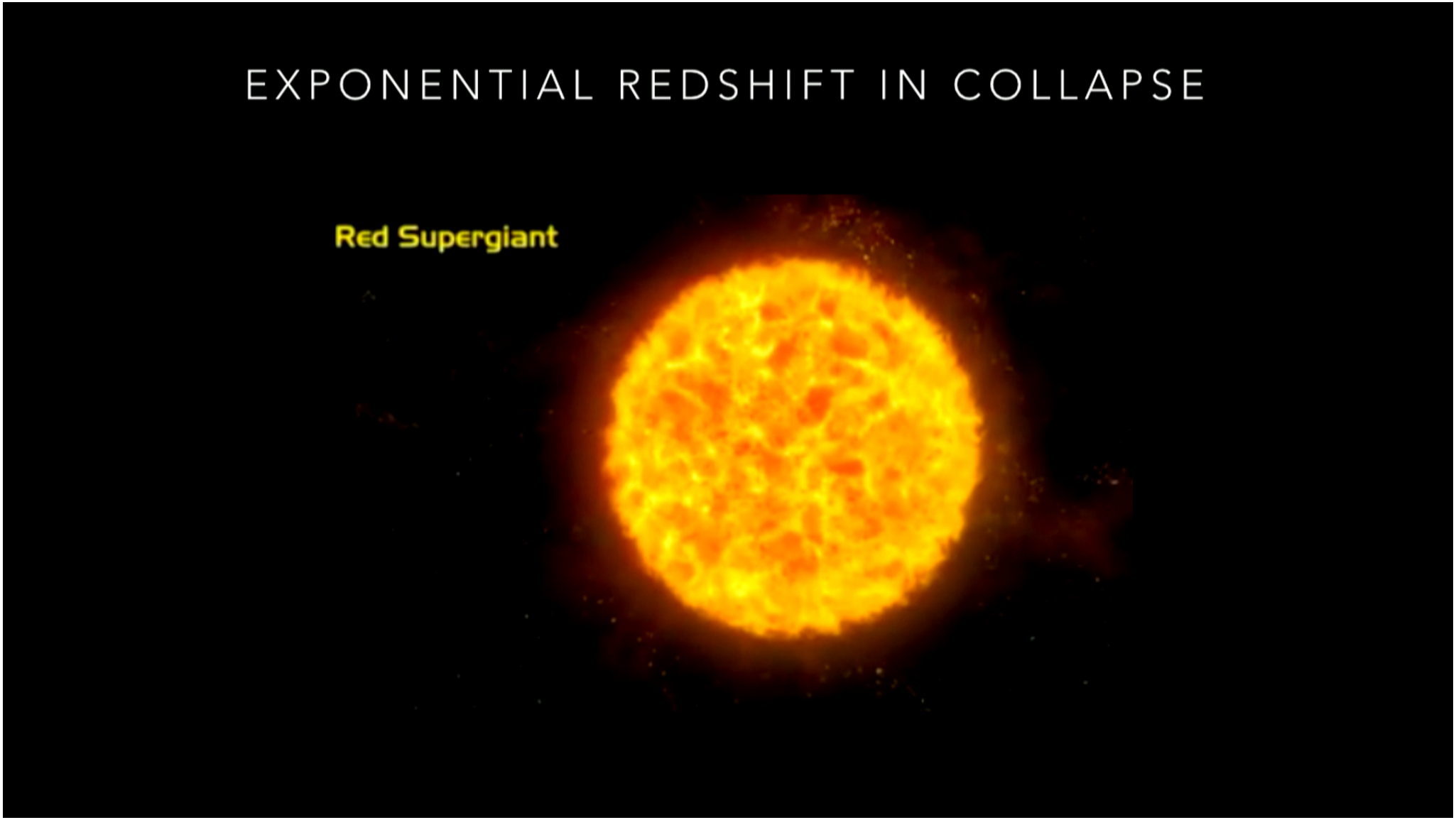

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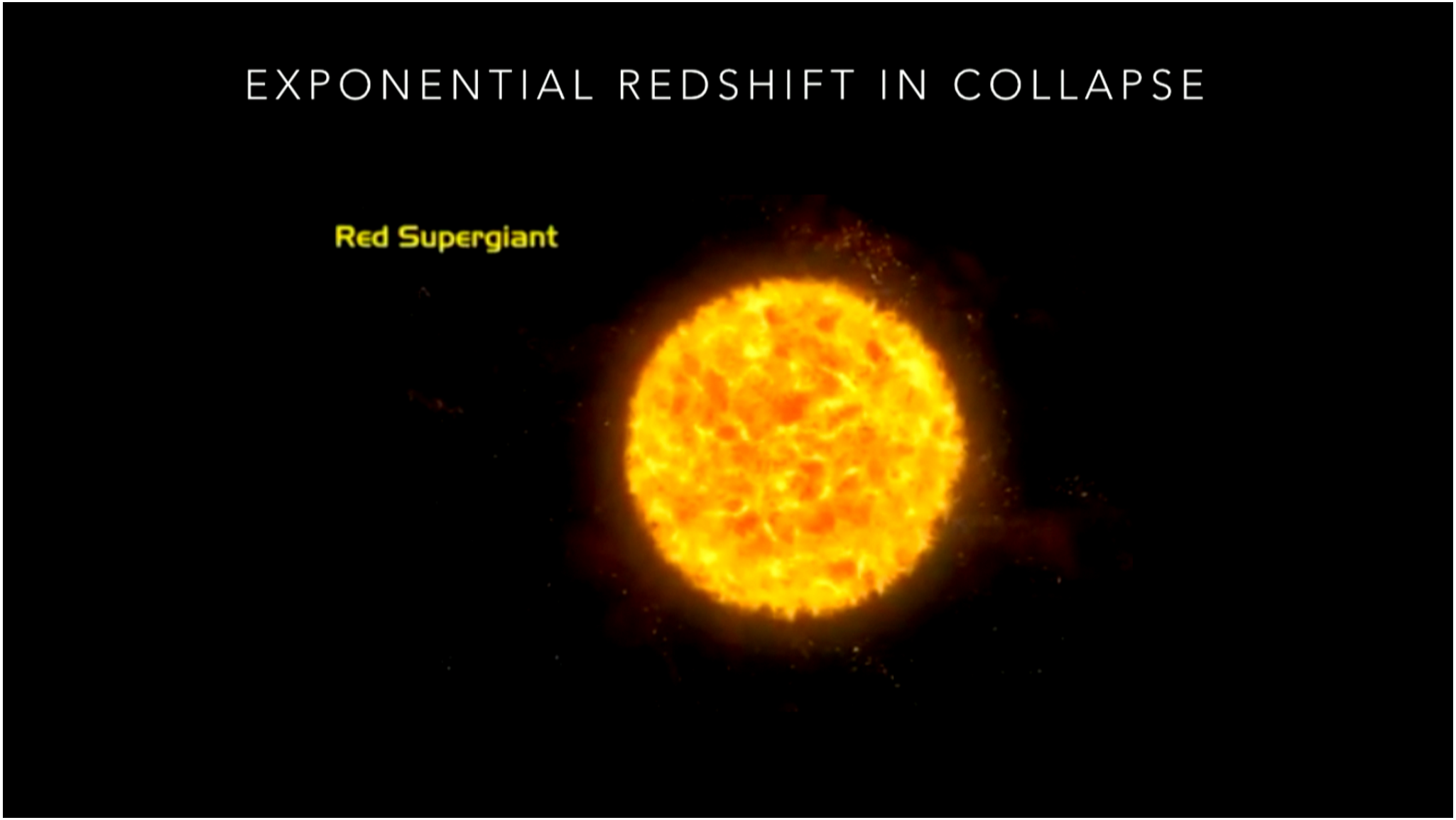

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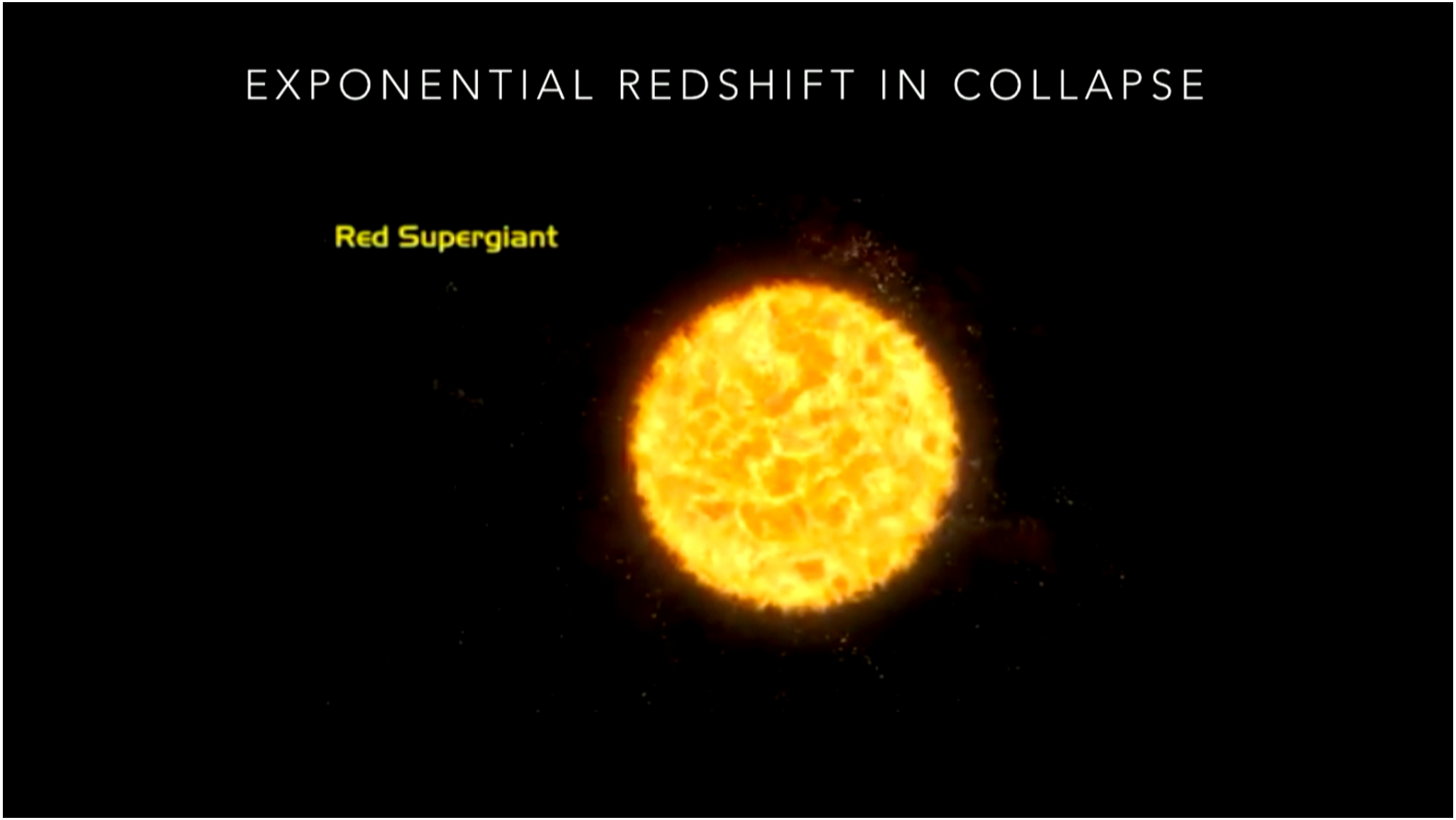

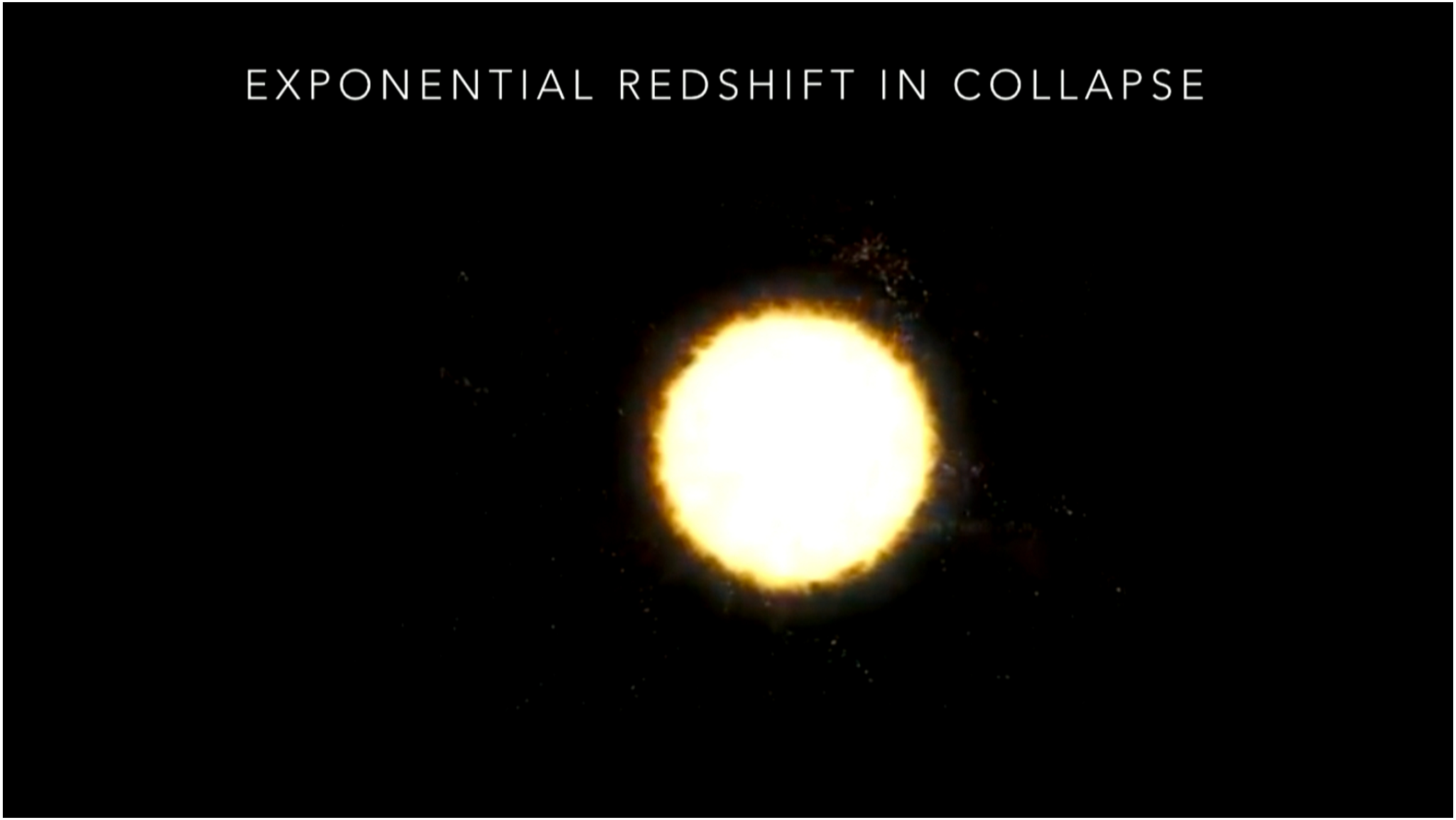
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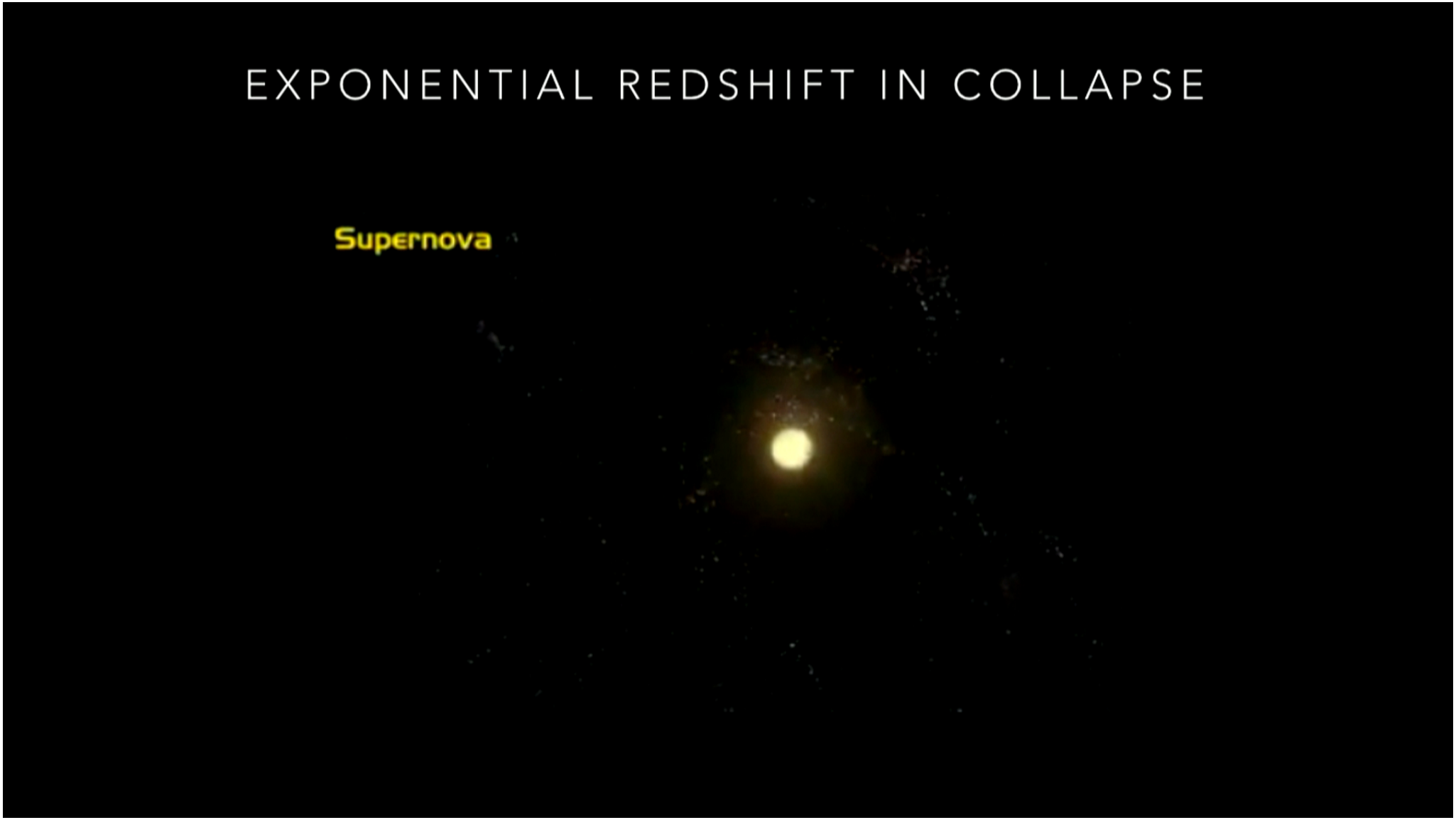
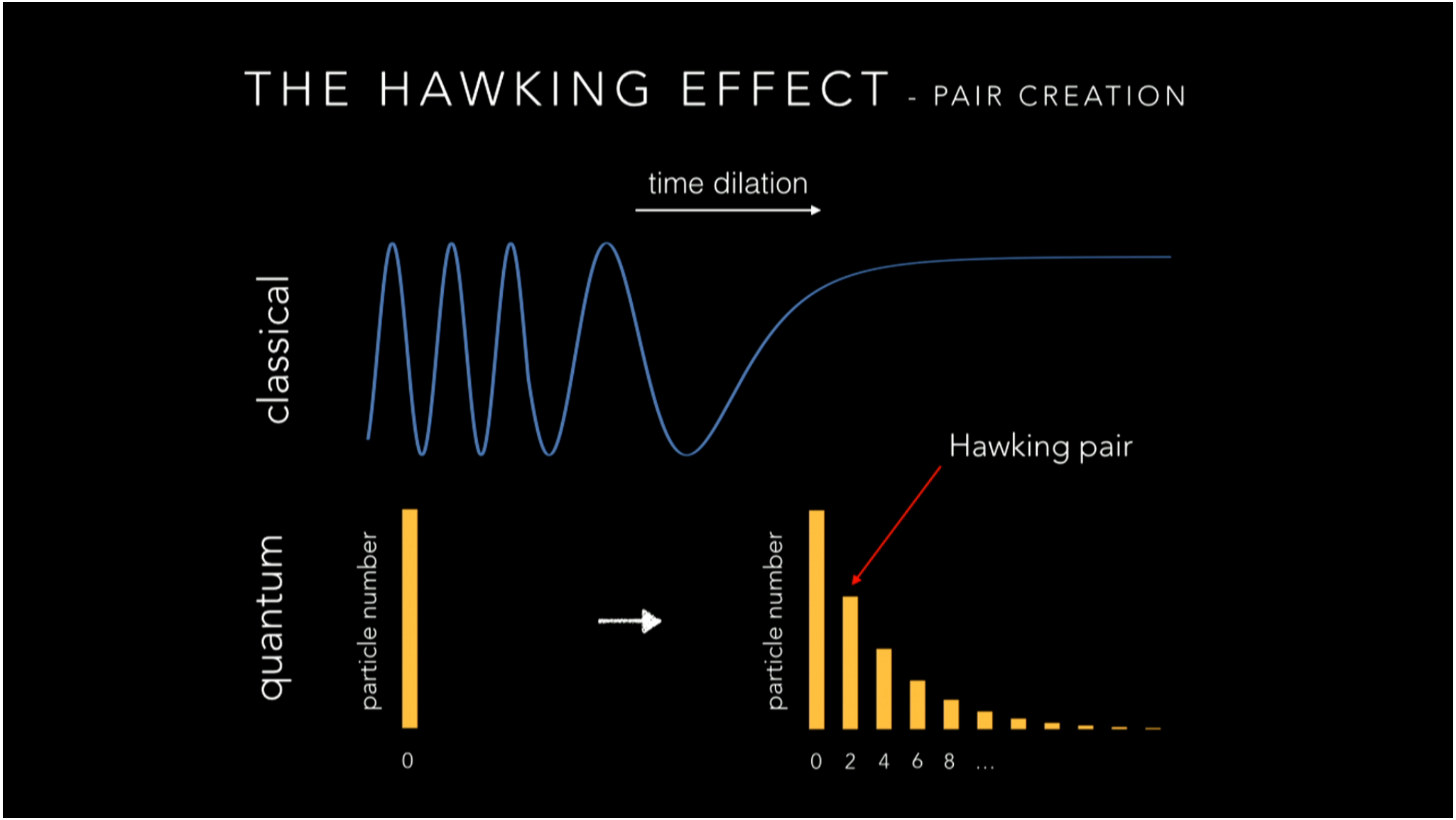
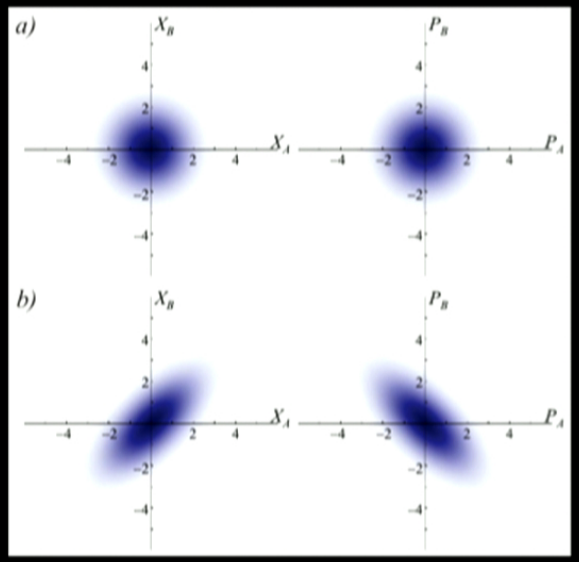



THE HAWKING EFFECT - PAIR CREATION
time dilation
classical
quantum
particle number
0
Hawking pair
particle number
0 2 4 6 8 ...

TWO-MODE SQUEEZED VACUUM STATE



squeezing parameter

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partial trace

$$\rho_A \propto \sum_{n=0}^{\infty} (\tanh r)^n |n\rangle\langle n|$$

Higher squeezing, higher temperature.

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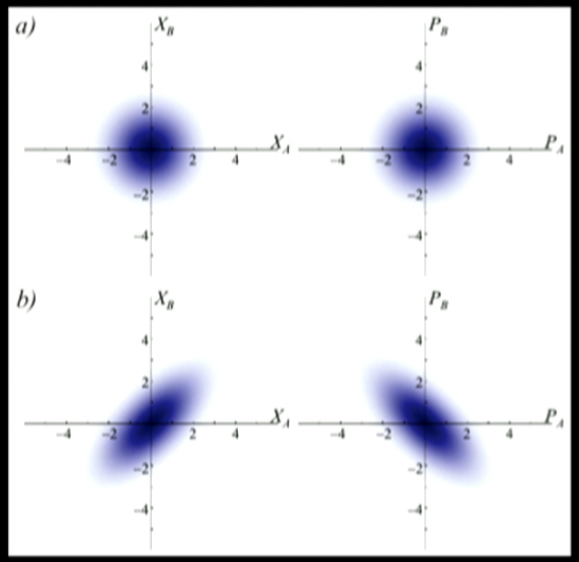

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LETTER

doi:10.1038/nature10561

Observation of the dynamical Casimir effect in a superconducting circuit

C. M. Wilson[1], G. Johansson[1], A. Pourkabirian[1], M. Simoen[1], J. R. Johansson[2], T. Duty[3], F. Nori[2,4] & P. Delsing[1]

SQUID

ARTICLES

nature physics

Observation of self-amplifying Hawking radiation in an analogue black-hole laser

Jeff Steinhauer

BEC

Selected for a Viewpoint in *Physics*

PRL **105,** 203901 (2010) PHYSICAL REVIEW LETTERS week ending 12 NOVEMBER 2010

Hawking Radiation from Ultrashort Laser Pulse Filaments

F. Belgiorno,[1] S. L. Cacciatori,[2,3] M. Clerici,[3] V. Gorini,[2,3] G. Ortenzi,[4] L. Rizzi,[3] E. Rubino,[3] V. G. Sala,[3] and D. Faccio[3,5,*]

nonlinear optics

PRL **106,** 021302 (2011) PHYSICAL REVIEW LETTERS week ending 14 JANUARY 2011

Measurement of Stimulated Hawking Emission in an Analogue System

Silke Weinfurtner,[1] Edmund W. Tedford,[2] Matthew C. J. Penrice,[1] William G. Unruh,[1] and Gregory A. Lawrence[2]

hydrodynamics

BLACK HOLE EVAPORATION

- Black hole excites radiation from the vacuum.
- The outgoing part of the flux is thermal:

$$T_H = \frac{\hbar c^3}{8\pi G M k_B}$$

- Mass loss rate:

$$\frac{dM}{dt} = -\frac{\hbar c^4}{15360\pi G^2 M^2}$$

Final fate?

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HAWKING 74

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EVAPORATION AND REVERSIBILITY

Quantum mechanics contradicts all classical lessons:

1. *No hair*: Hawking radiation is "hair"
2. *Area law*: area shrinks in time ("evaporation")
3. *Singularity*: quantum repulsion may resolve it

Does quantum mechanics restore reversibility?

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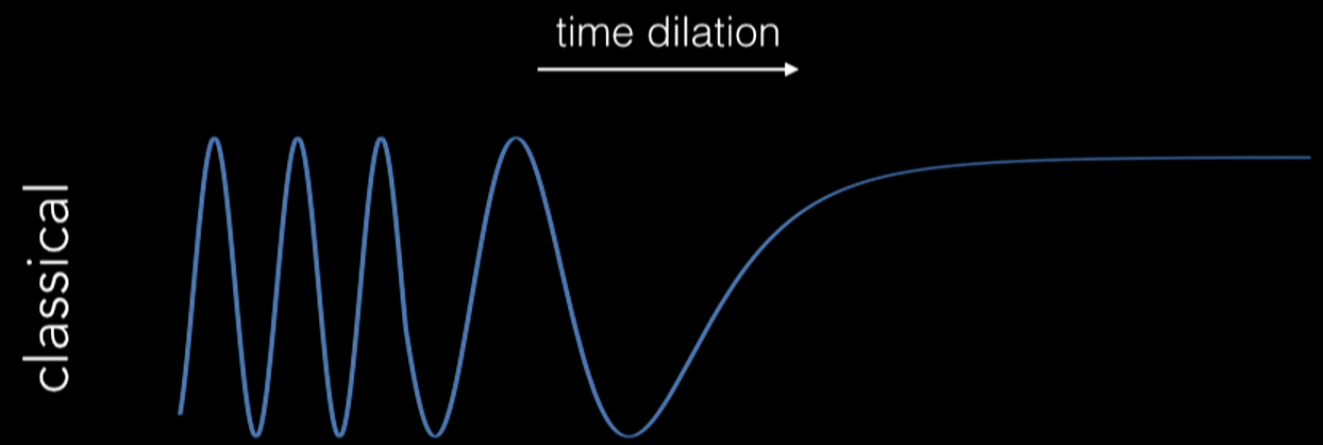
Does quantum mechanics restore reversibility?

THE HAWKING EFFECT - ENTANGLEMENT



quantum

short-range entanglement → long-range entanglement

(≃"quantum quench")

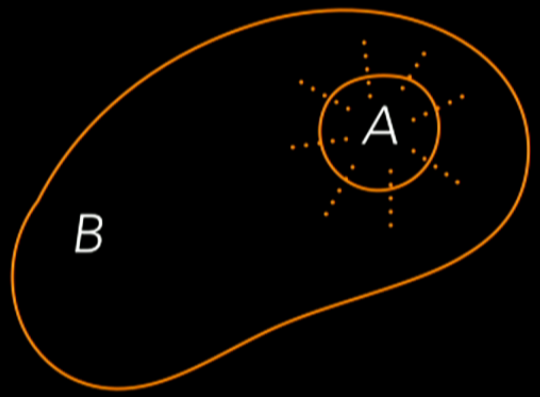
ENTANGLEMENT ENTROPY

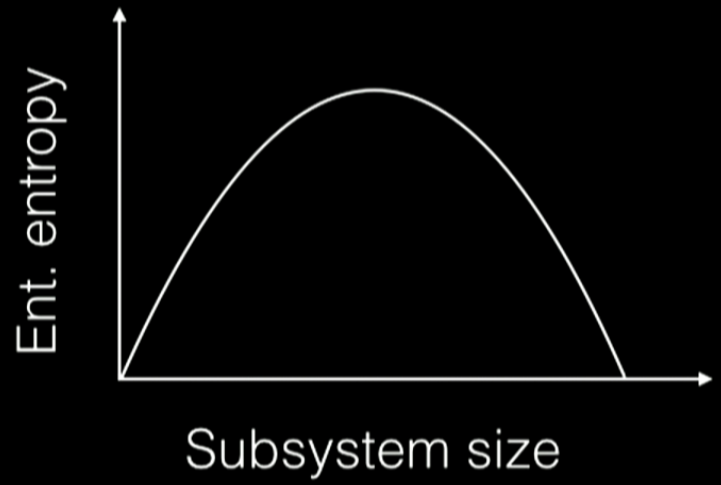
In quantum mechanics, entanglement entropy is

$$S[\rho_A] \equiv -\mathrm{tr}_A[\rho_A \ln \rho_A] \quad \text{with} \quad \rho_A \equiv \mathrm{tr}_B[\rho_{AB}]$$

with triangle inequality

$$|S[\rho_A] - S[\rho_B]| \leq S[\rho_{AB}] \leq S[\rho_A] + S[\rho_B]$$





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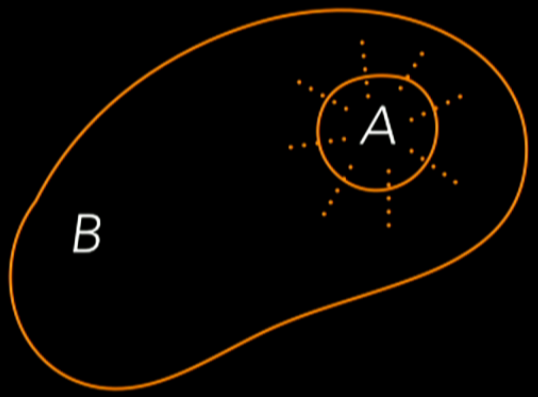

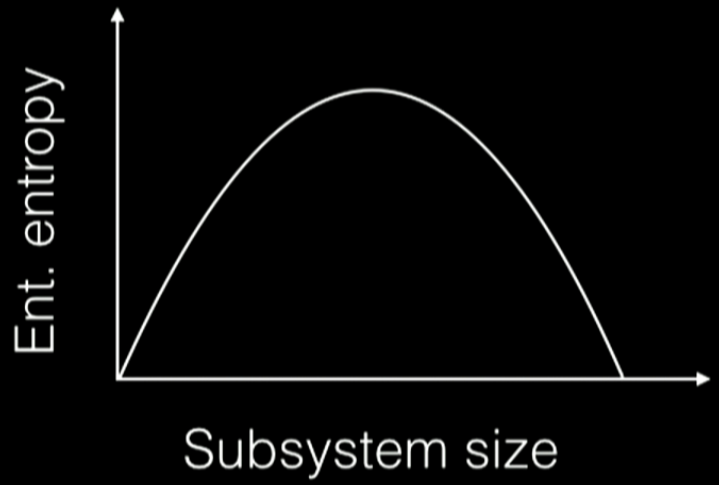

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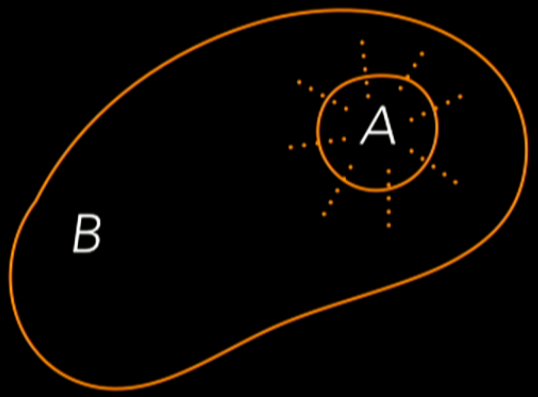
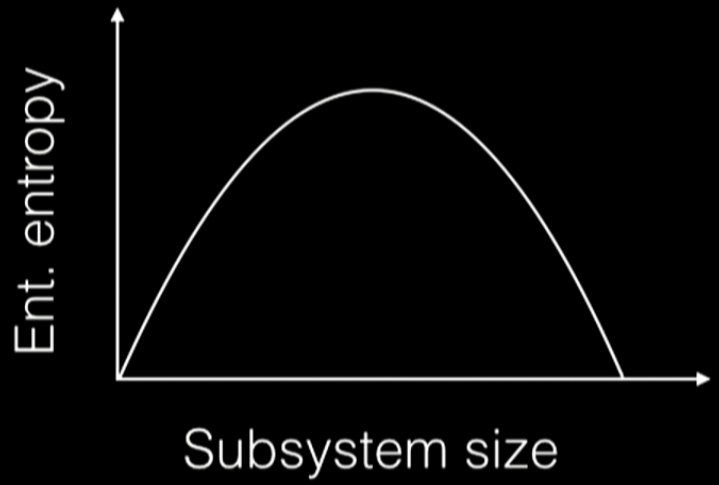
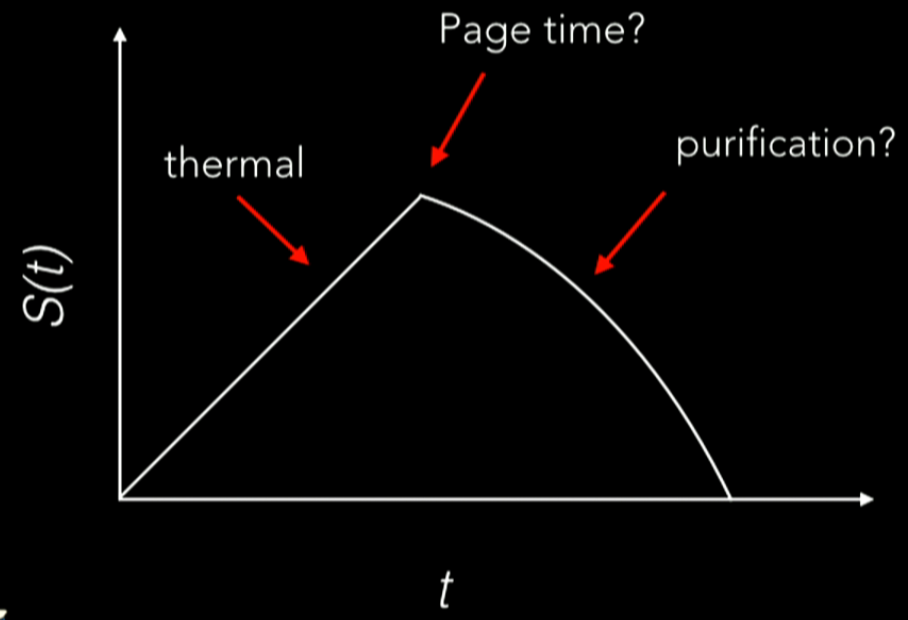




THE PAGE CURVE

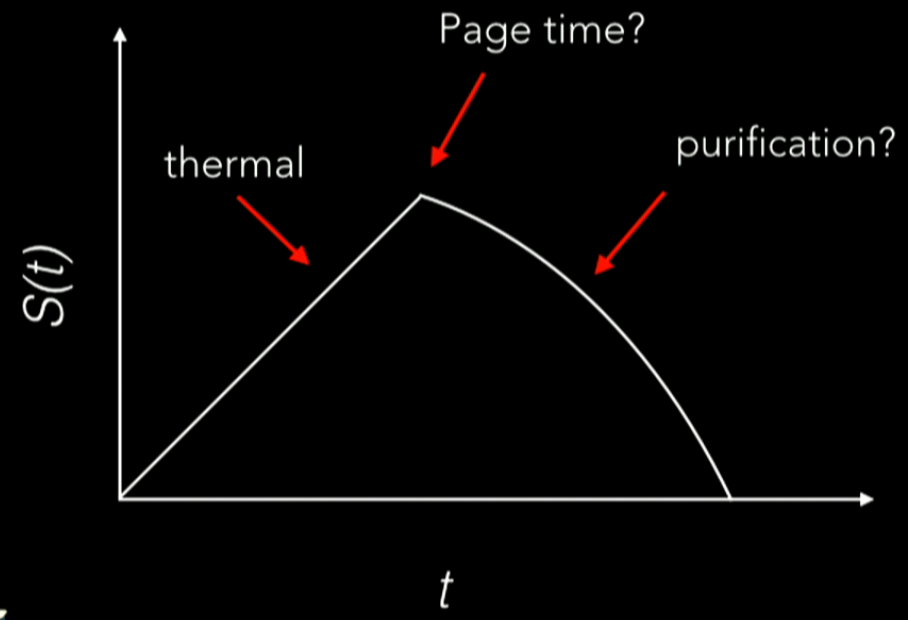
Outstanding open conjecture in semiclassical gravity:



PAGE 93,13

THE PAGE CURVE

Outstanding open conjecture in semiclassical gravity:



PAGE 93,13

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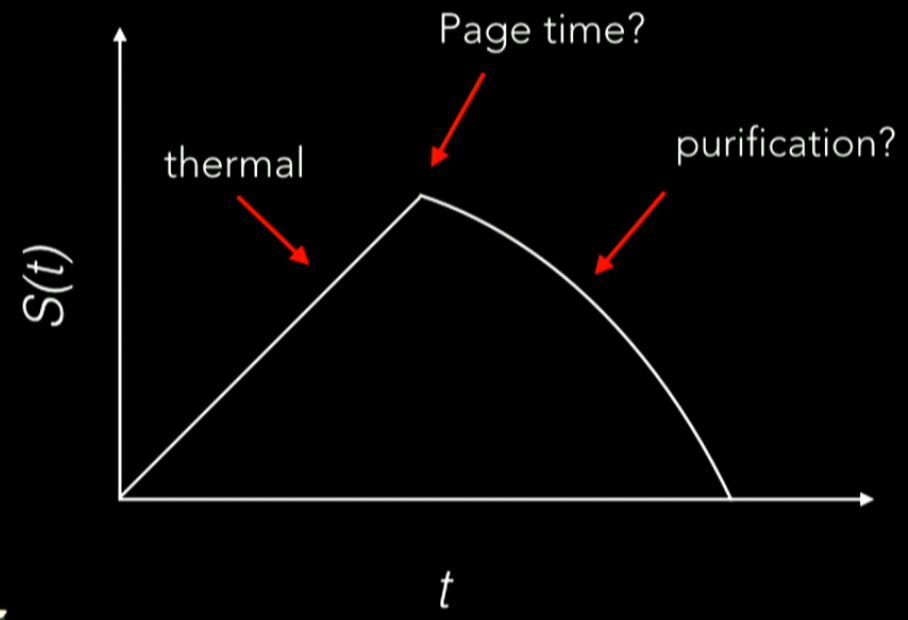

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RADIATION ENTROPY - THE 2D APPROXIMATION

Approximations of the field dynamics

1. neglect multipole moments *l > 0*
2. neglect "backscattering"

yields the geometric formula:

renormalized entropy

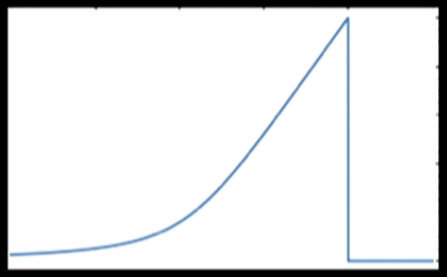
gravitational redshift

$$S(t) = \frac{1}{12} \ln \frac{\omega(t)}{\omega_0}$$

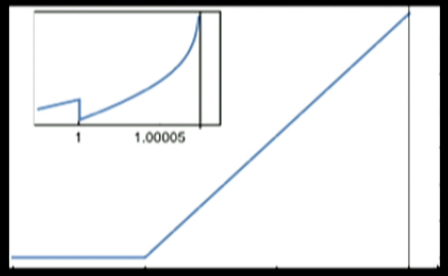
HOLZHEY *ET AL.* 94; BIANCHI, MS 14

FROM GEOMETRY TO ENTROPY

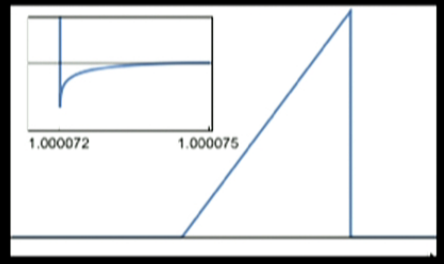
Direct probe of geometric vacuum deformations:



ϵ-star



monotonic evaporation



nonsingular hole

First *computations* of the Page curve.

BIANCHI, DE LORENZO, MS 14

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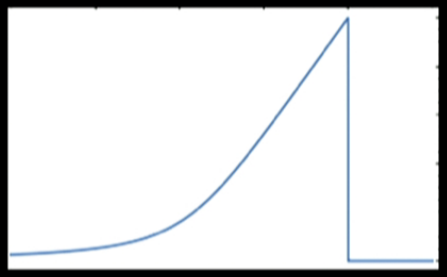
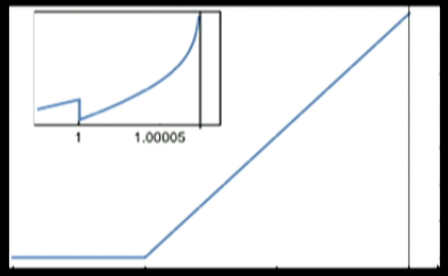


ϵ-star



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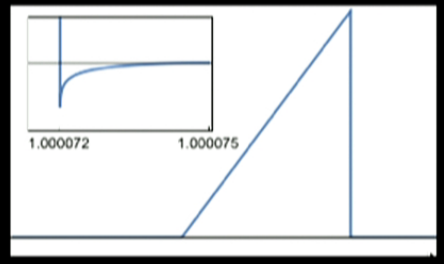

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BIANCHI, DE LORENZO, MS 14

REVERSIBILITY: THREE QUESTIONS

Is the evaporation process:

1. unitary, i.e. is purity of the vacuum preserved?

"information loss problem"

2. cyclic, i.e. is entanglement restored to its original value?

$$S(+\infty) = S(-\infty)?$$

(and conservative, i.e. do input and output energy match?)

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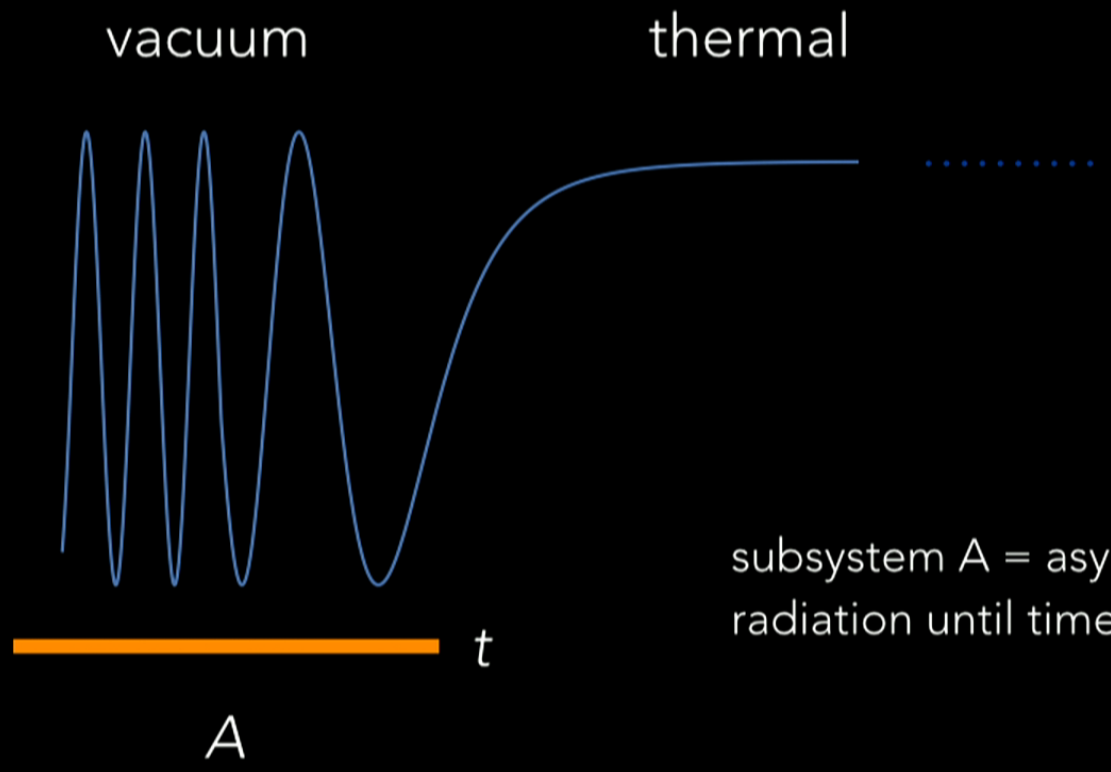
More importantly: what difference would it make?

RADIATION ENTROPY



subsystem A = asymptotic radiation until time *t*

FROM GEOMETRY TO ENTROPY

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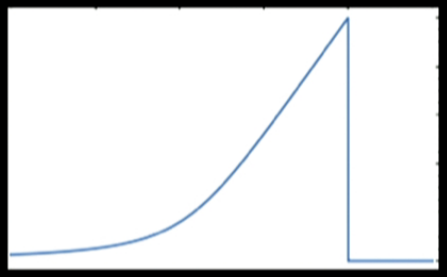

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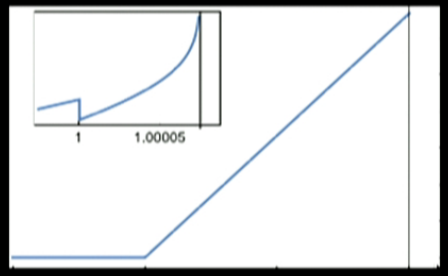

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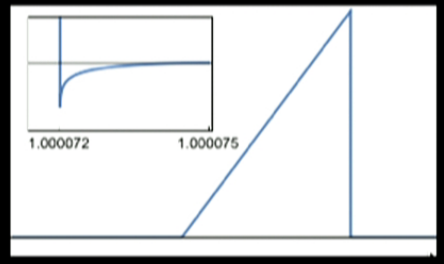

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First *computations* of the Page curve.

BIANCHI, DE LORENZO, MS 14

IT FROM BIT - AND THE GENERALIZED SECOND LAW

spacetime ⟵ quantum field

Entropy-flux identity:

$$2\pi F = 6\dot{S}^2 + \ddot{S}$$

BIANCHI, MS 14

Generalizes the "generalized second law":

- includes a non-adiabatic term (hence identity)
- does not require special causal structure (event horizon)
- implies the GSL in spherical symmetry

BEKENSTEIN 74

IT FROM BIT - CONSEQUENCES OF CYCLICITY

$$2\pi F = 6\dot{S}^2 + \ddot{S}$$

If evaporation is cyclic, then

1. the black hole must "gasp": $F(t_{\rm Page}) < 0$

3. purification must be slow:

initial mass

mass at the end of thermal phase

$$\tau_P \geq \xi \, \frac{(M_0^2 - M_1^2)^2}{M_1 m_P^2}$$

BIANCHI, MS 14

CONCLUSION: A TALE OF TWO THEORIES

Classical relativity suggests black holes break reversibility.

Quantum effects may resolve this, by enforcing

unitarity? cyclicity?

2d field theory helps us imagine what this might mean physically:

- black hole gasping
- slow purification

FOR MORE DETAILS

- International Loop Quantum Gravity Seminar (Mar. 15)
- References:
  - Bianchi, MS, PRD 90 (4), 041904(R) (2014)
  - Bianchi, de Lorenzo, MS, arXiv: 1409.0144
  - Bianchi, MS, GRG 46, 1809 (2014)

Thank you!