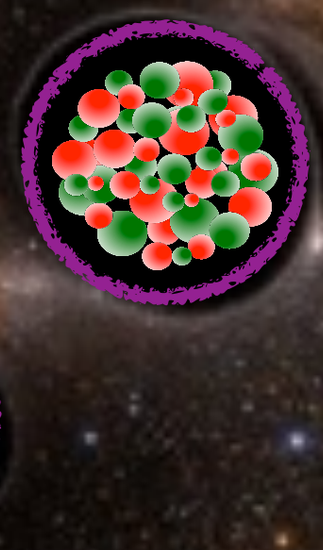
# *Microstate Geometries and the Microstructure of Black Holes*



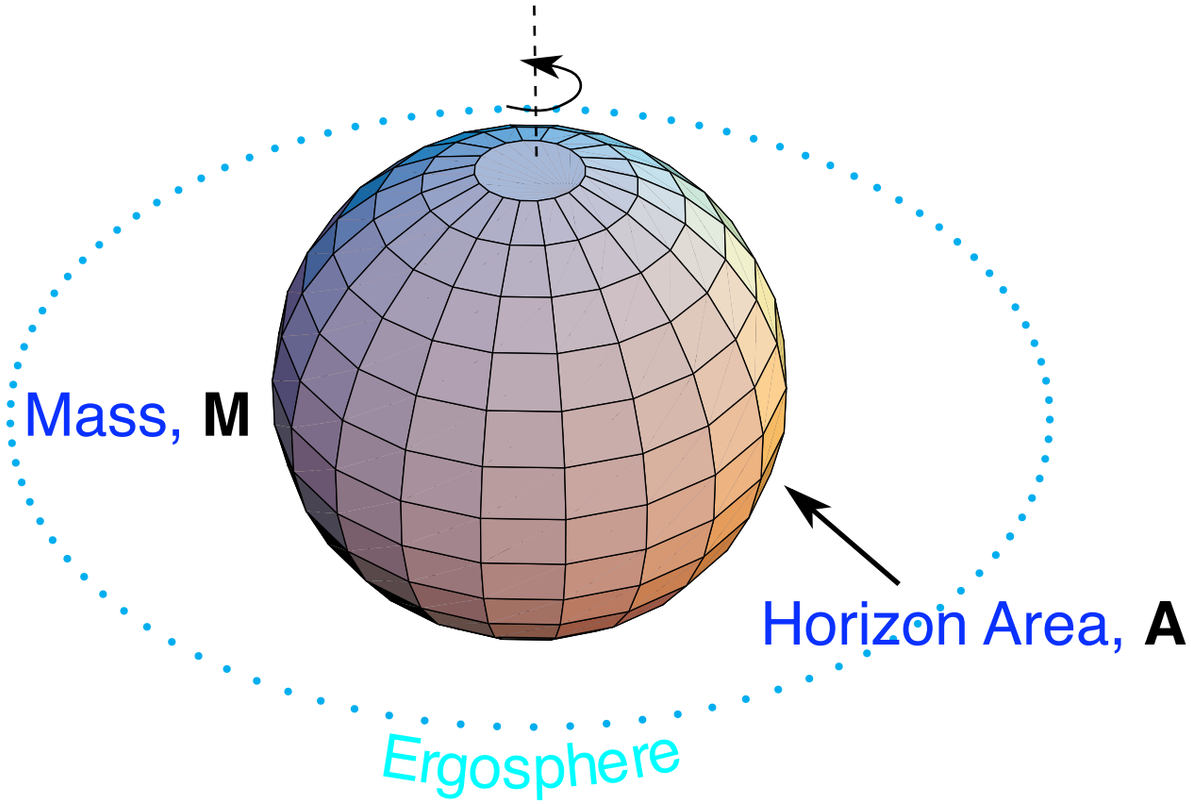
**IPhT colloquium**

**Nick Warner, October 15, 2018**

**Research supported supported in part by DOE grant DE- SC0011687**

**Original photo credit: LIGO/Caltech**

# Black-hole thermodynamics and the Penrose Process

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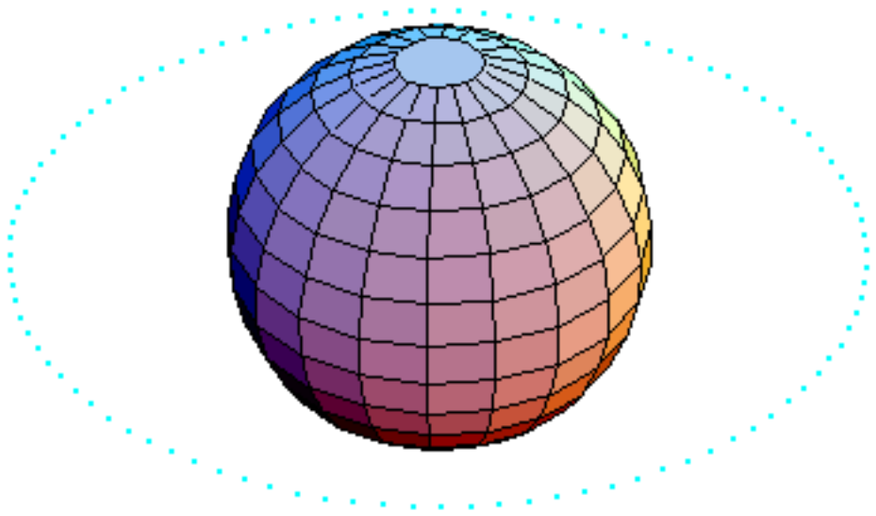

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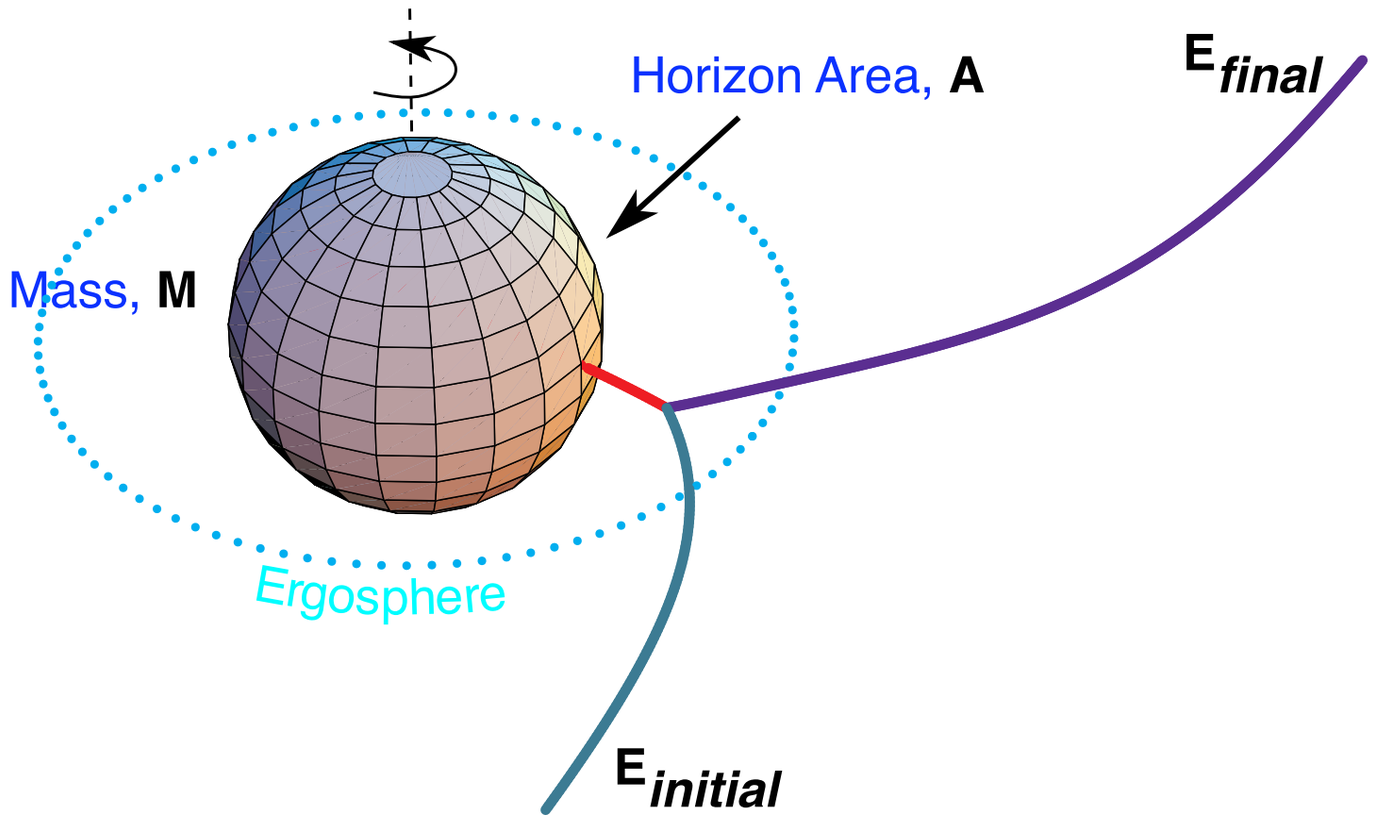


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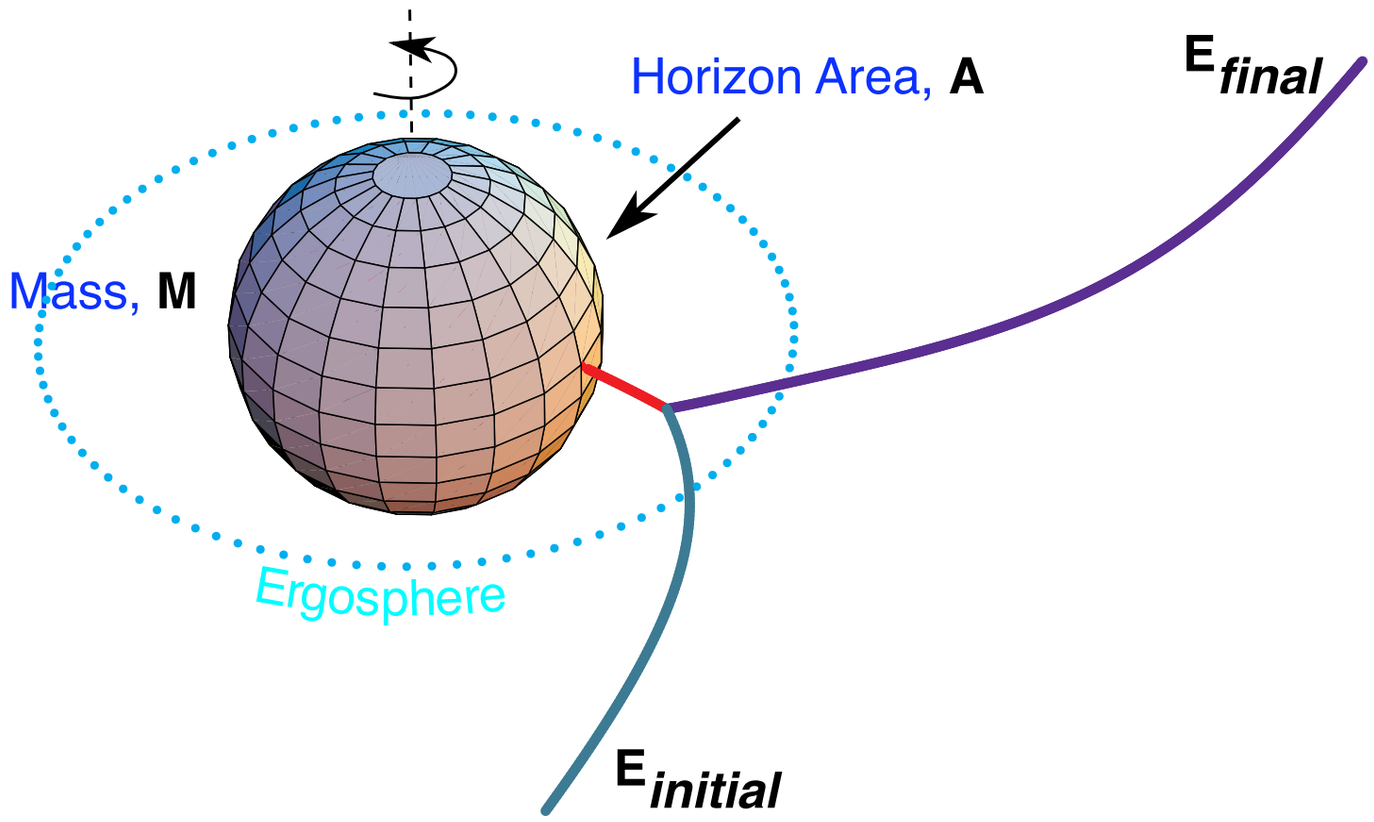


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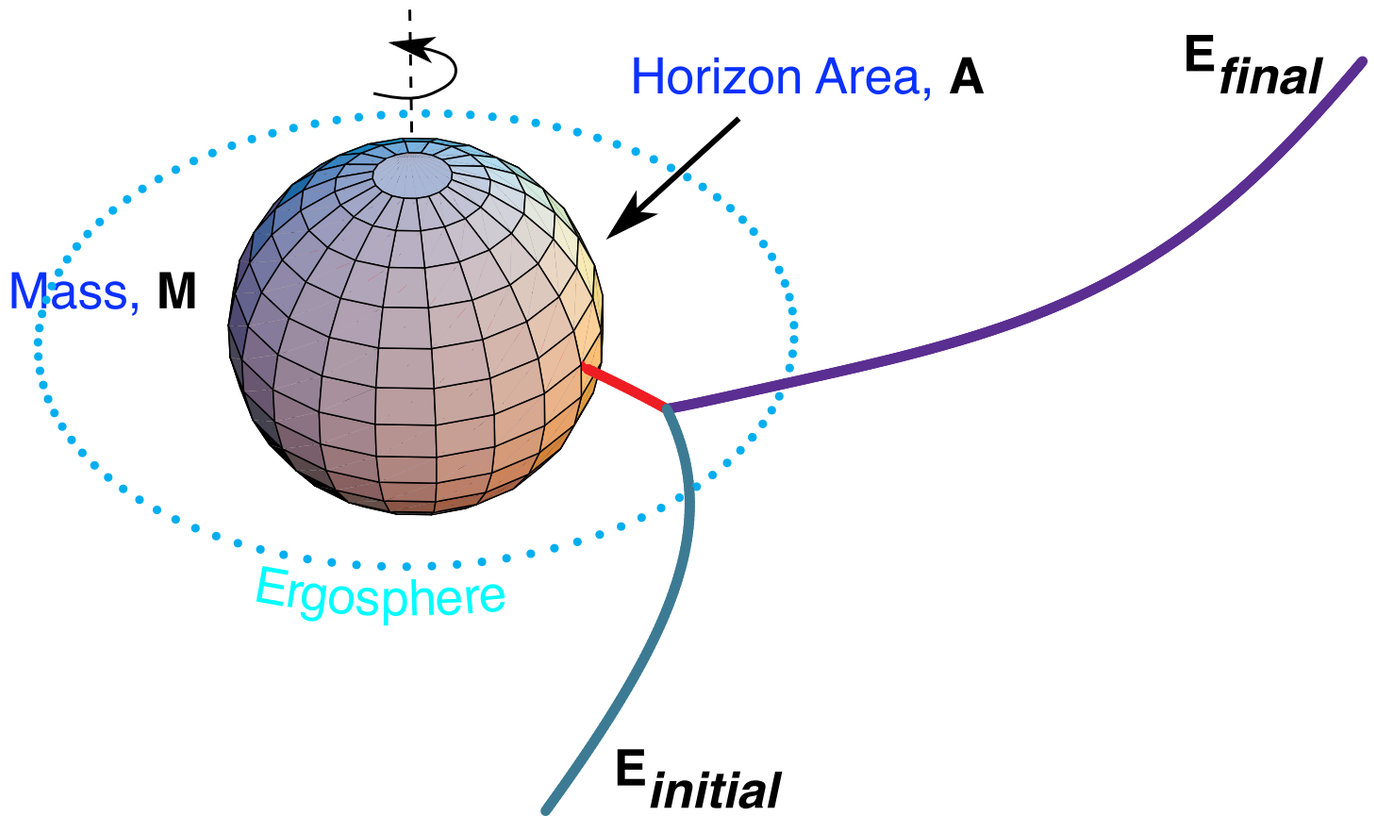


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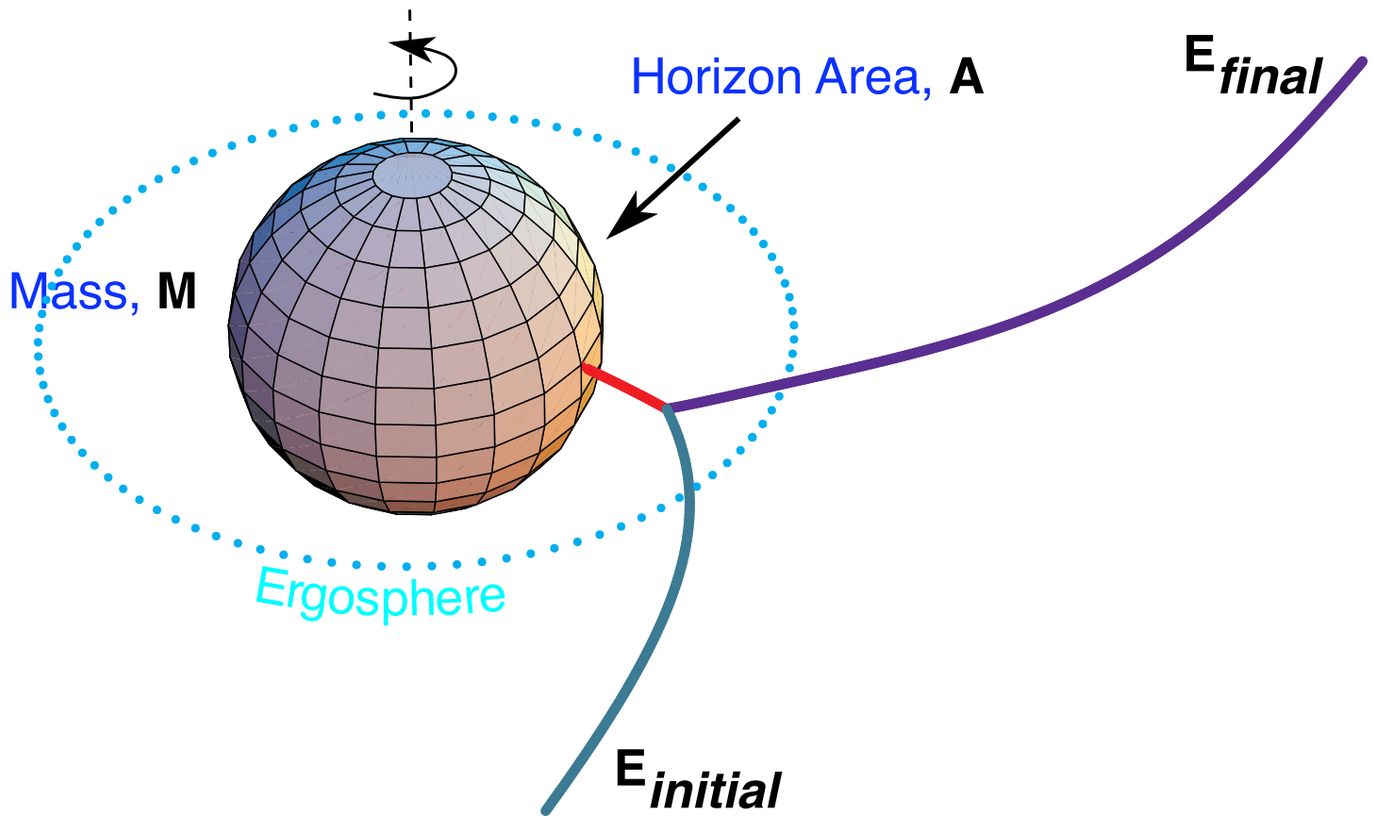


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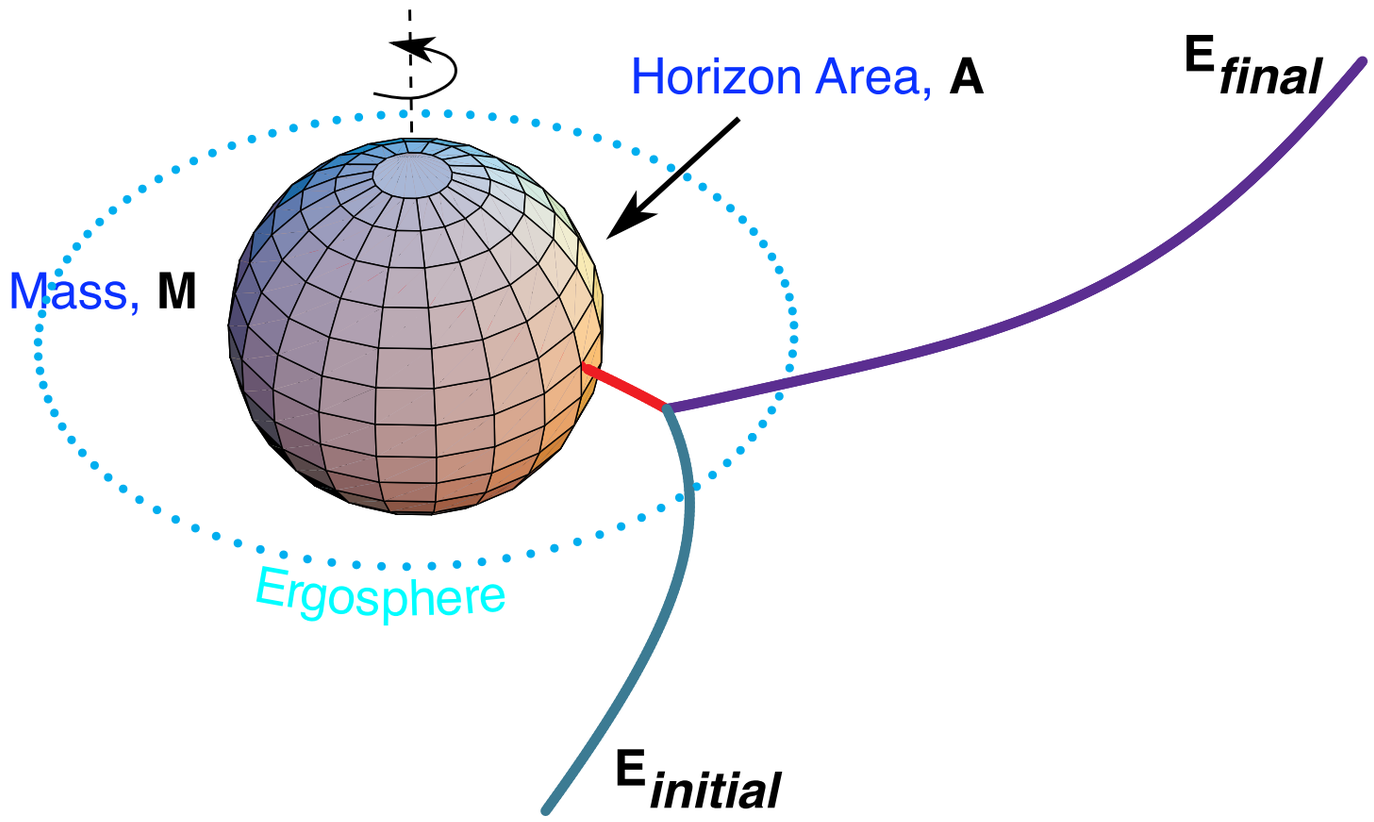


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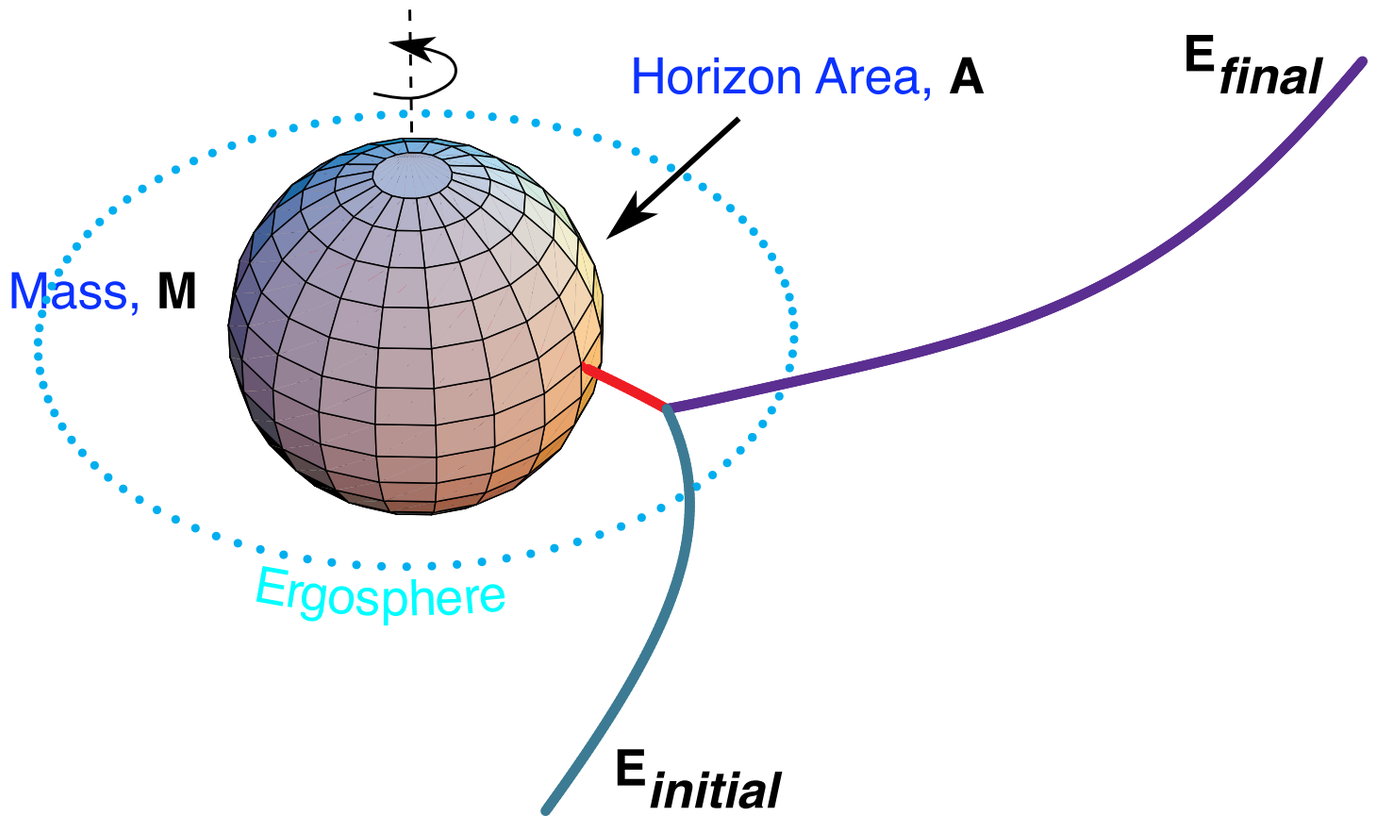


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Reversible, Carnot ideal: $dA = 0$ ⇔ Infalling particle grazes horizon

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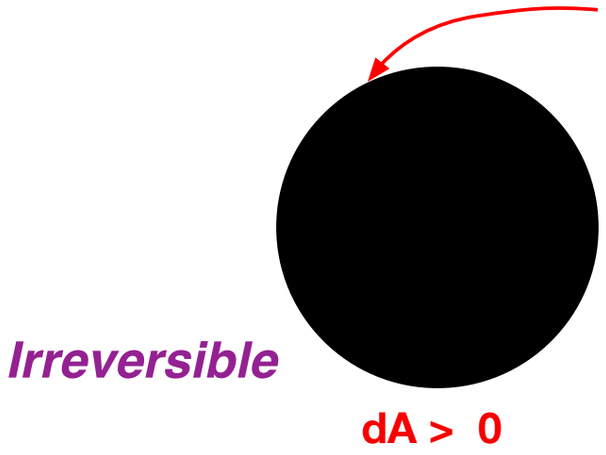


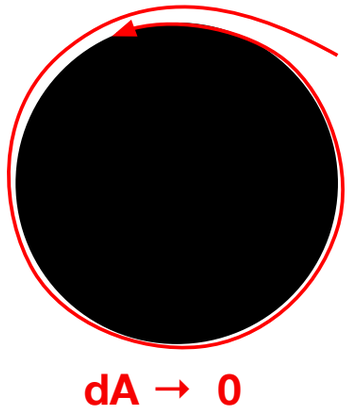

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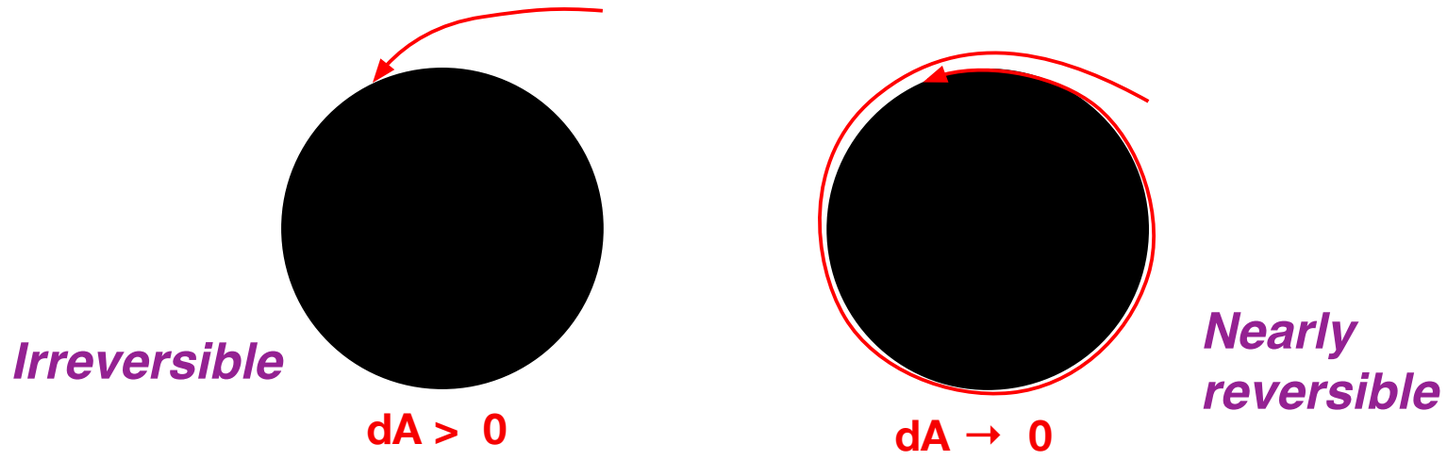


## Bekenstein:

- Particle must have finite size ~ Compton Wavelength ⇒ non-grazing ⇒ ***dA > 0***
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⇒ $S_{black\ hole.} \sim$ ***Area, A.*** (measured in Planck units)

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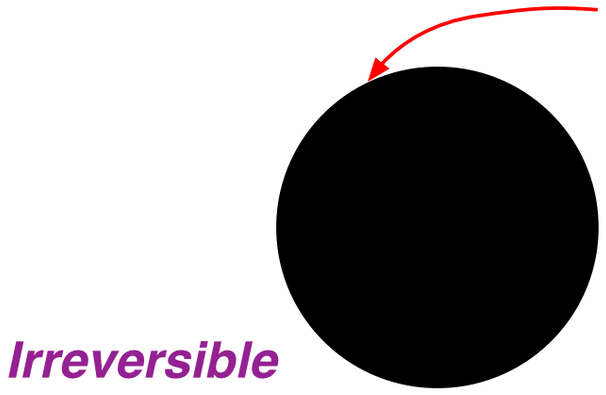

*Irreversible*

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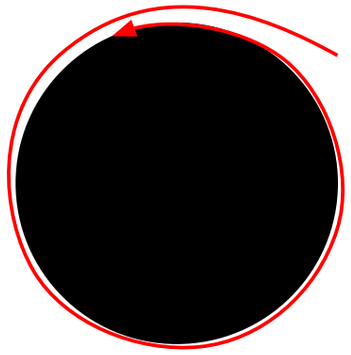

dA → 0

*Nearly reversible*

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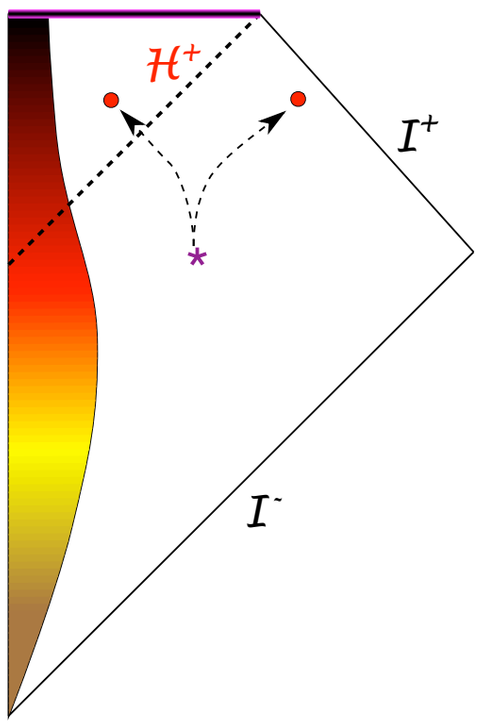


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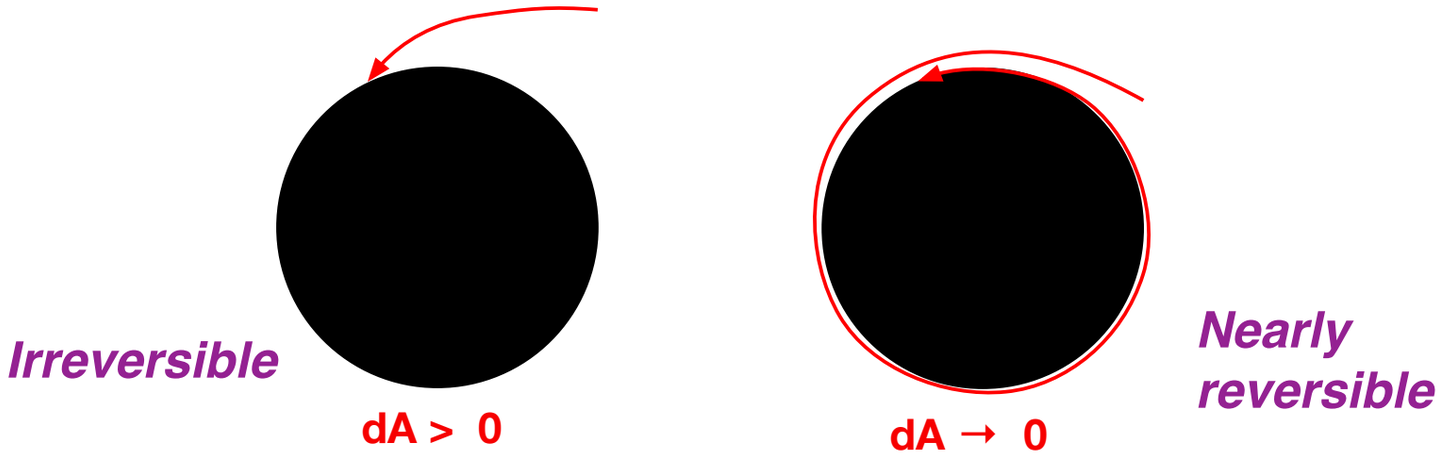


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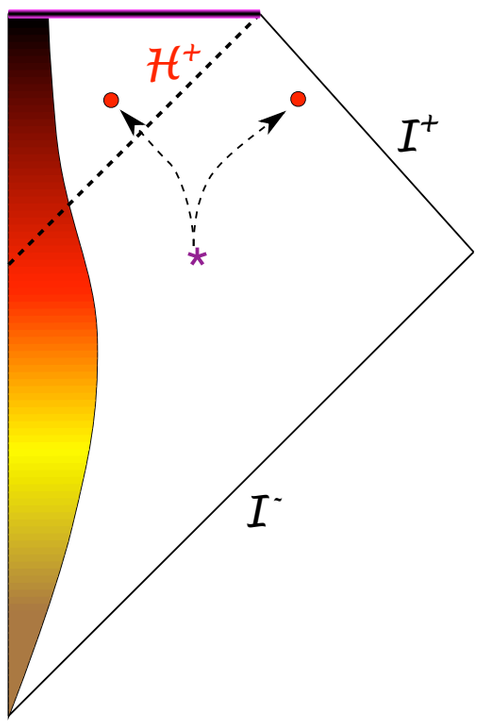


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→ Thermal "*Hawking*" radiation at infinity

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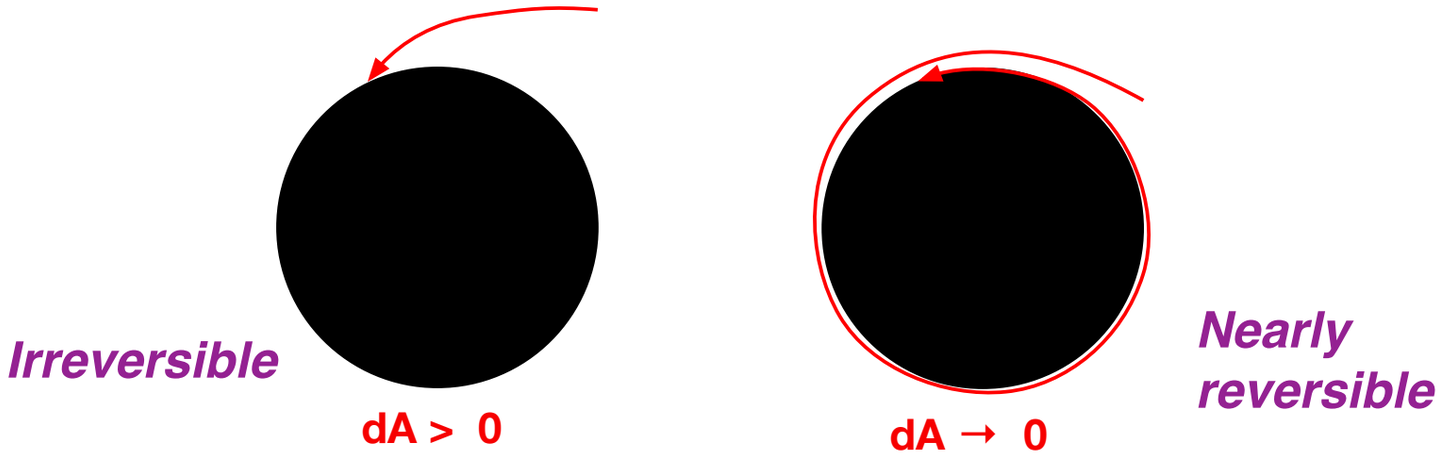


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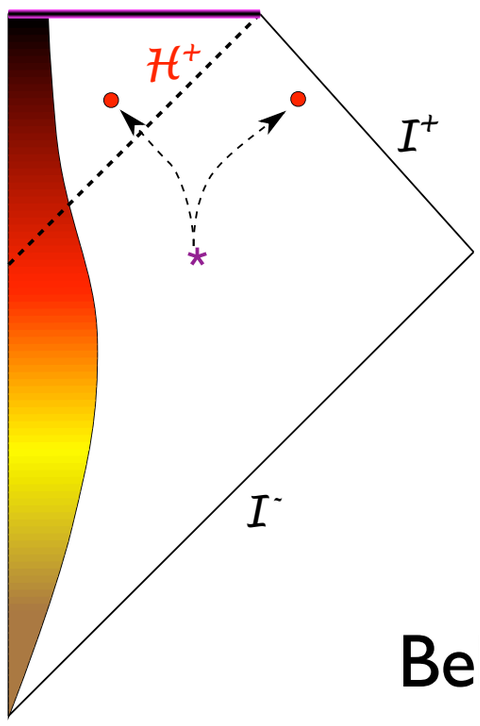


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Bekenstein-Hawking entropy: $$S = \frac{k_B c^3}{4 G \hbar} A = \frac{1}{4} \frac{A}{\ell_P^2}$$

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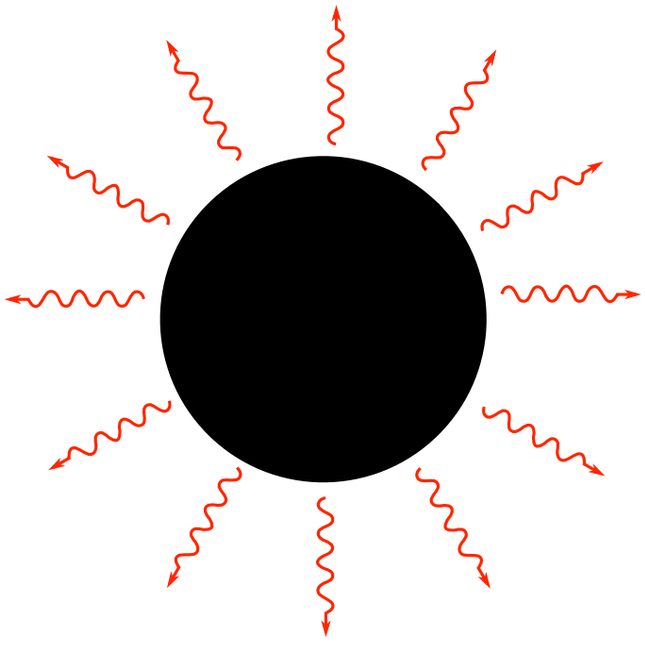

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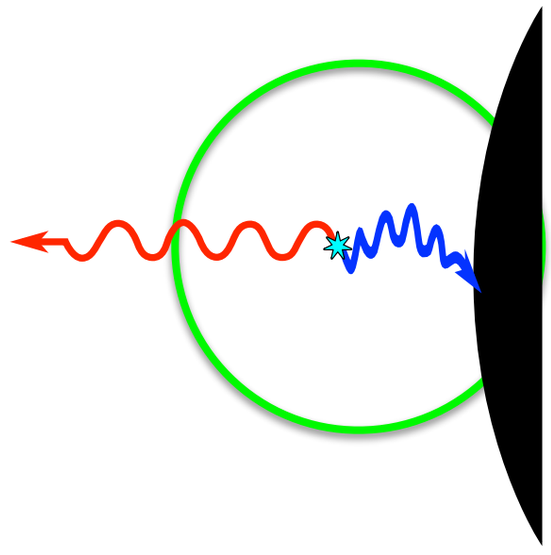

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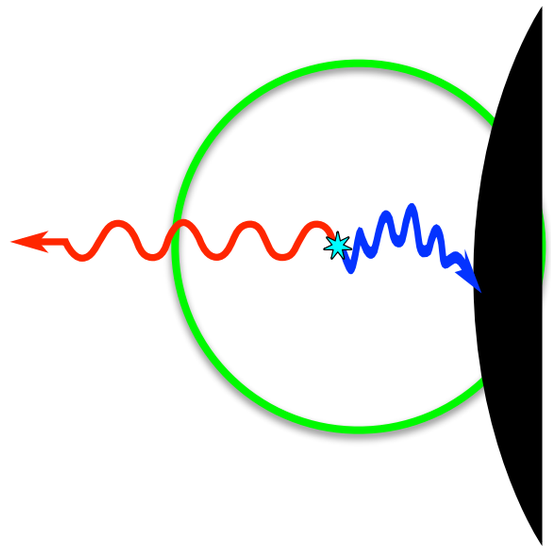

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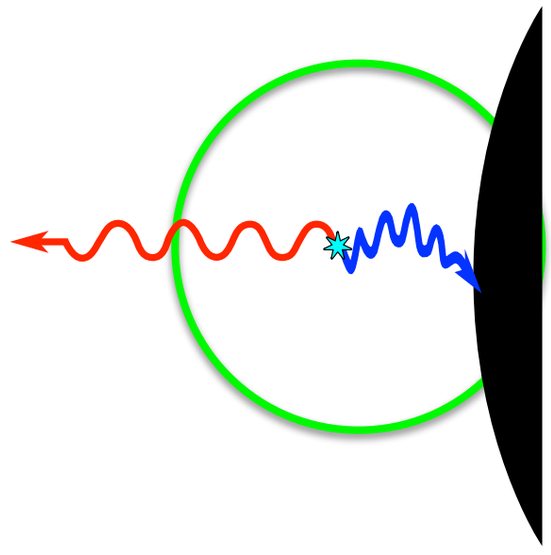

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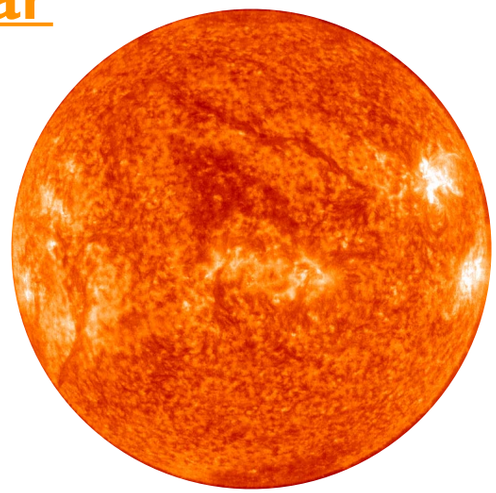
General Relativity + Quantum Mechanics

⇒ *Black holes, no matter how they form, evaporate into the same (largely featureless) cloud of Hawking Radiation*

The exterior structure of a black hole, and the *Hawking radiation* is unique

A star



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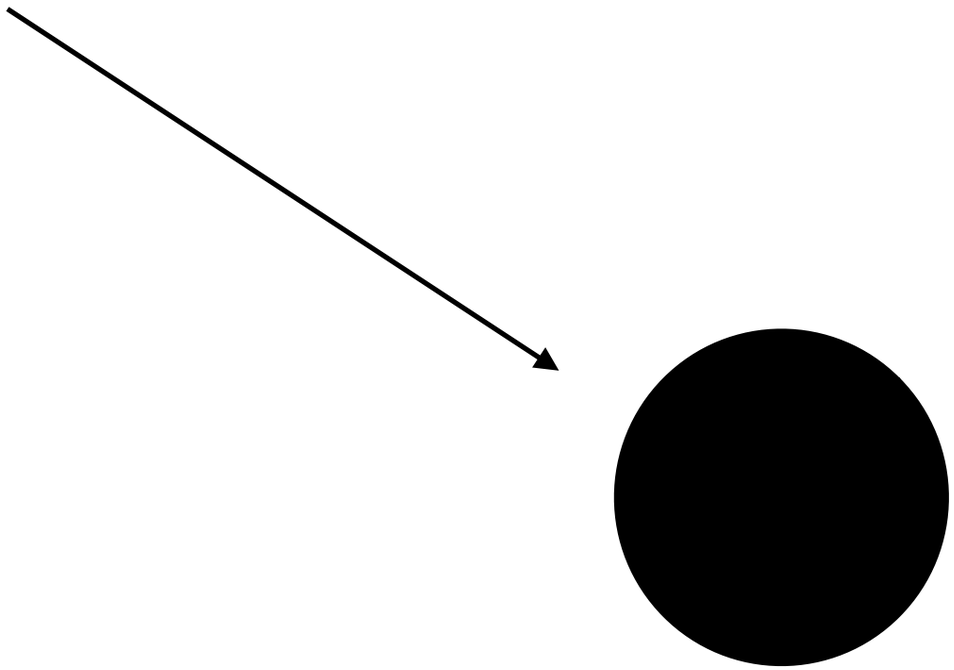

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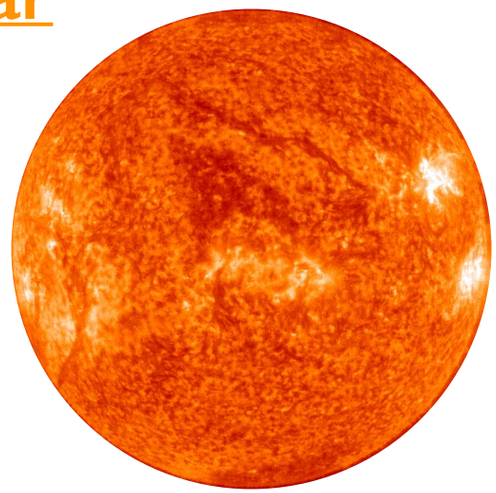

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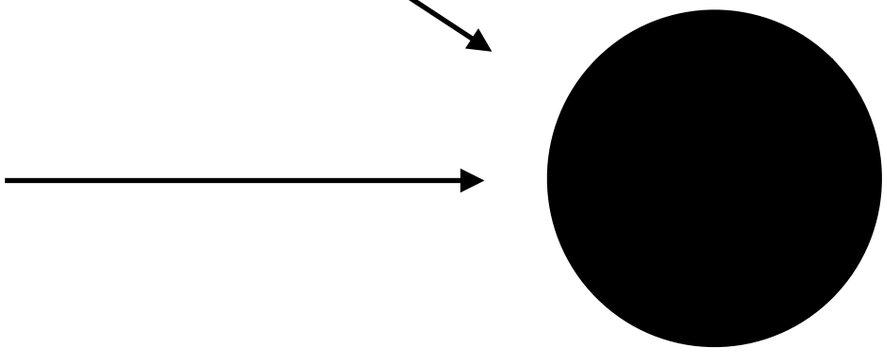

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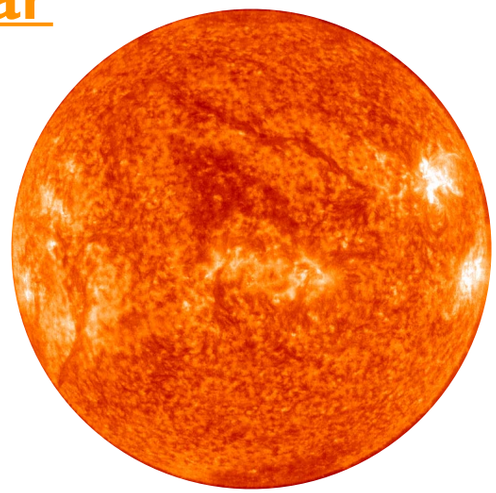

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Politicians

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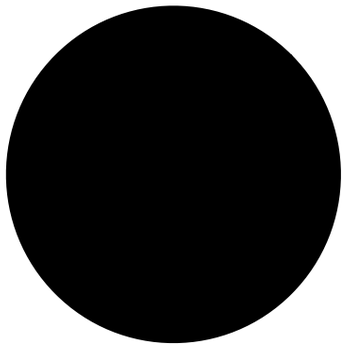

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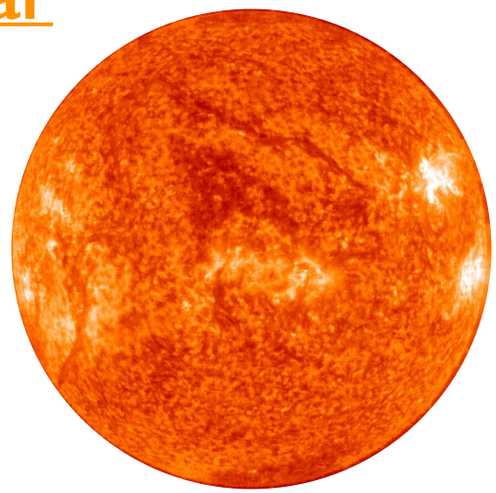

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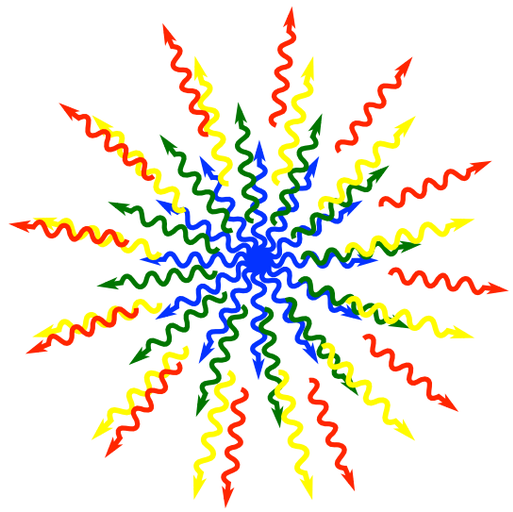

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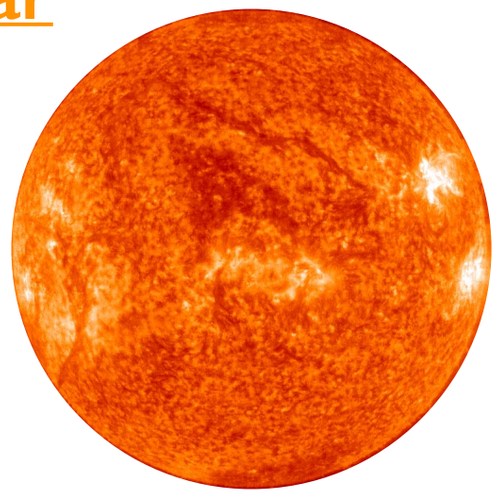

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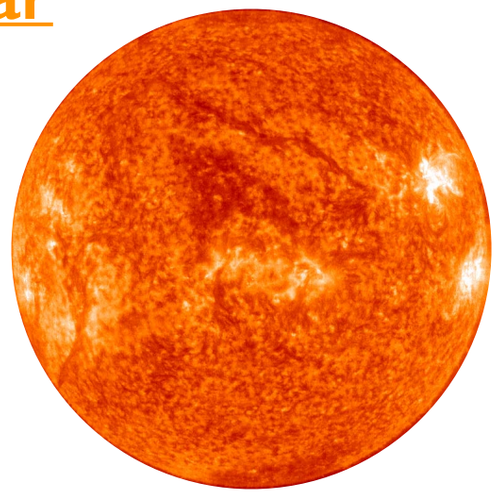

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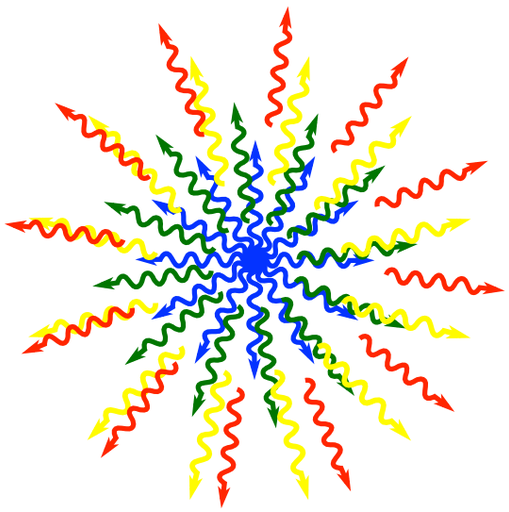
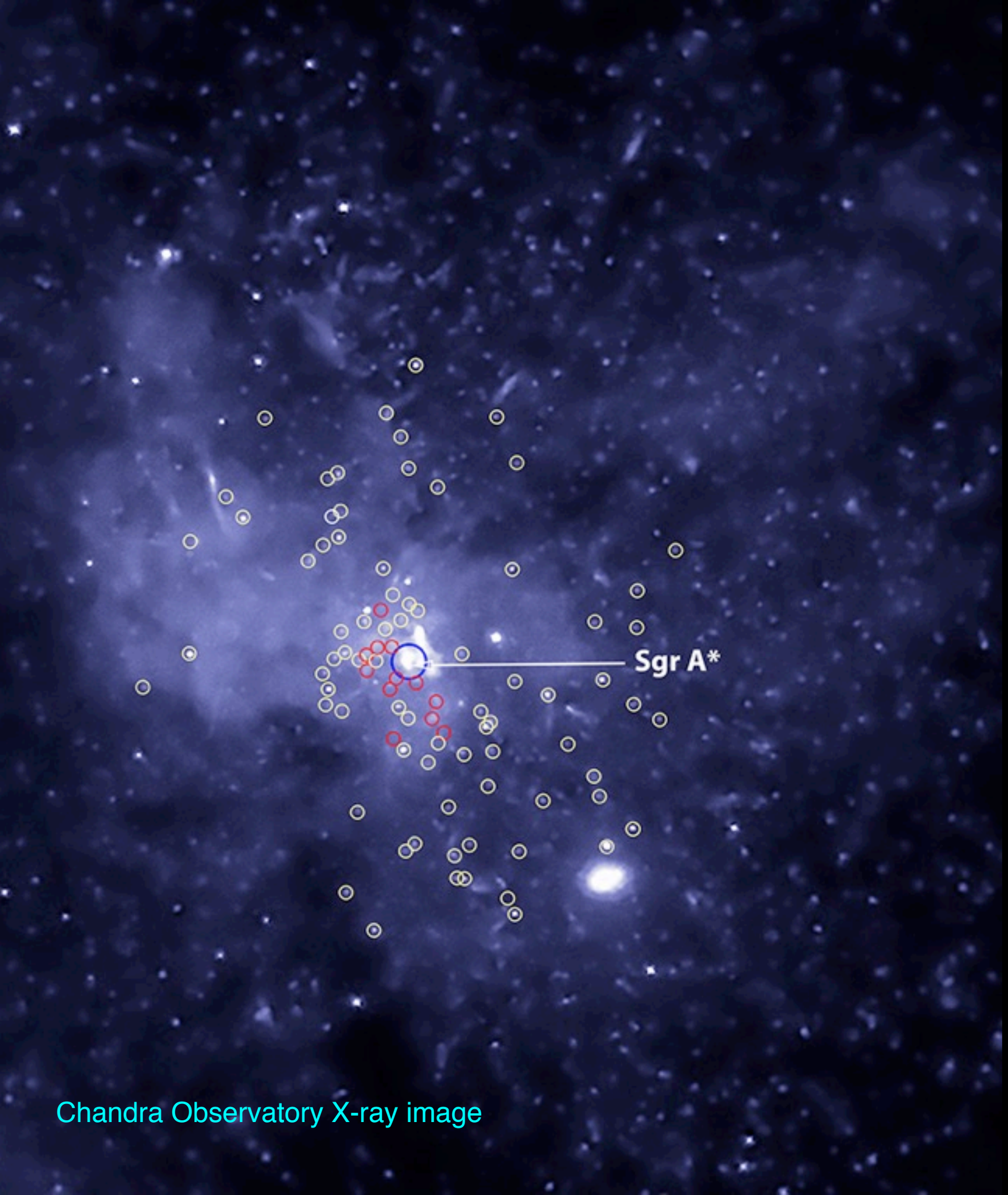


<u>The Information Paradox:</u>

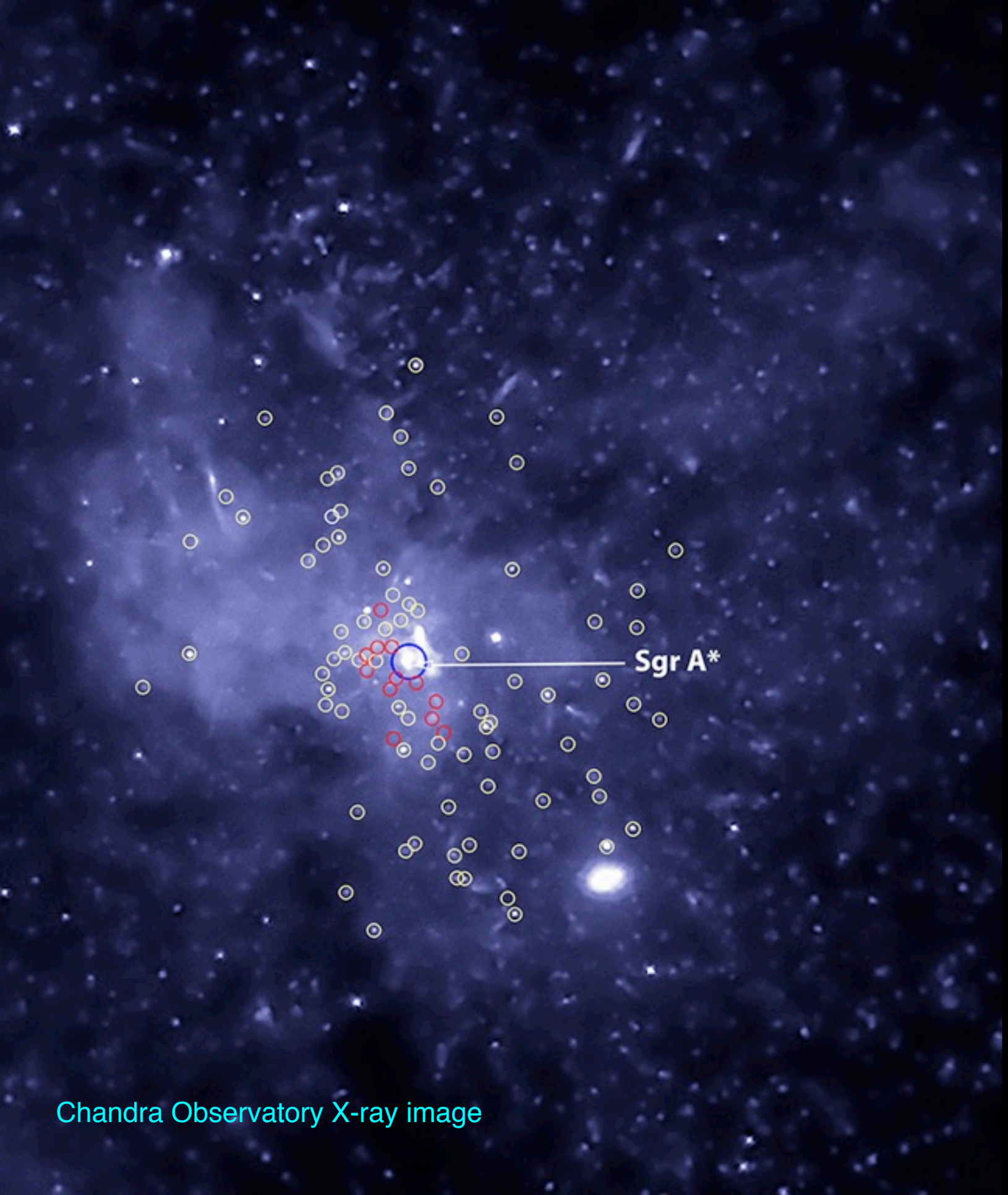
This process cannot be described by Unitary Evolution




Chandra Observatory X-ray image

Sgr A:  Black hole at the core of Milky Way

Mass $\approx 4 \times 10^6 M_\odot$

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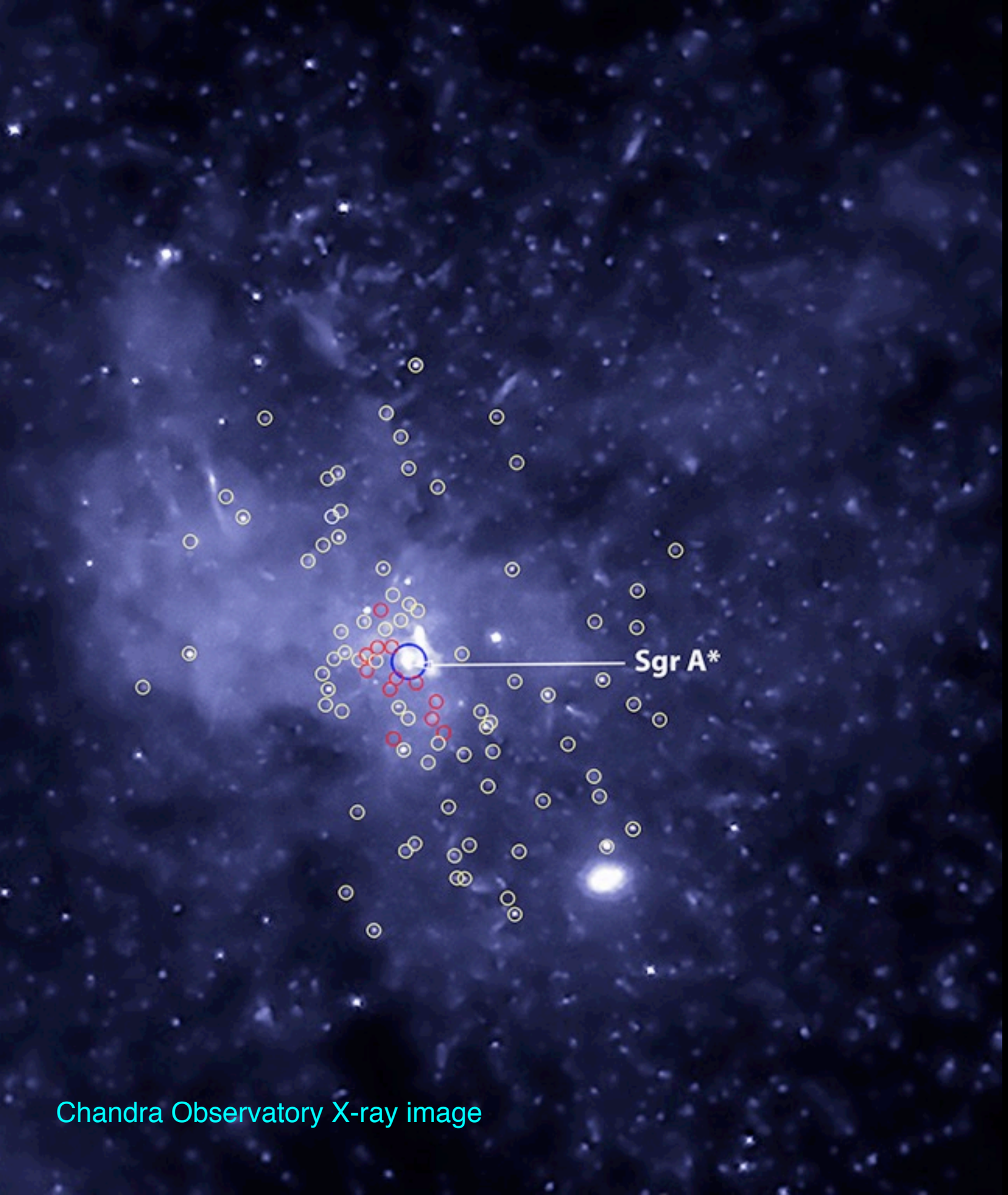


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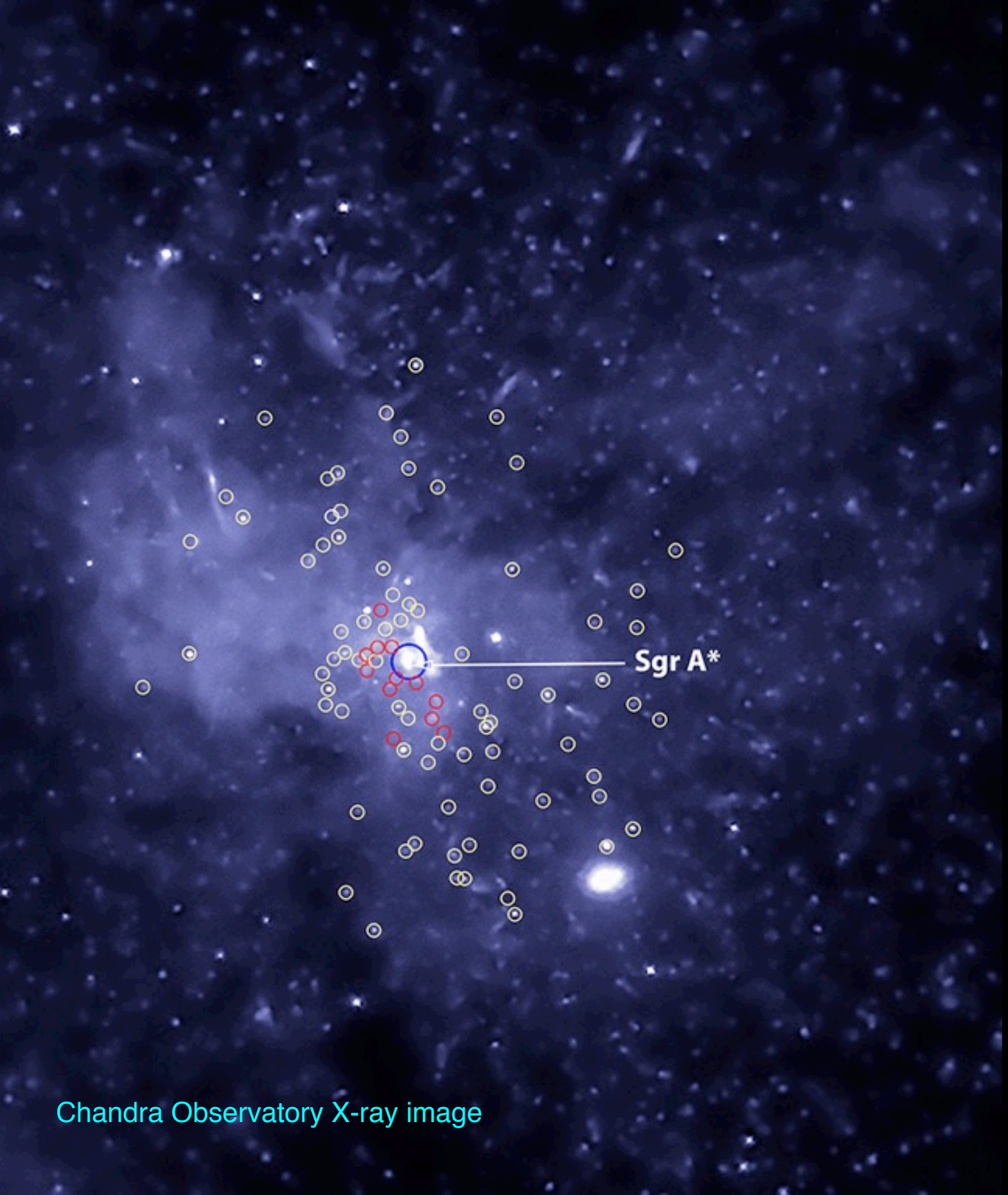


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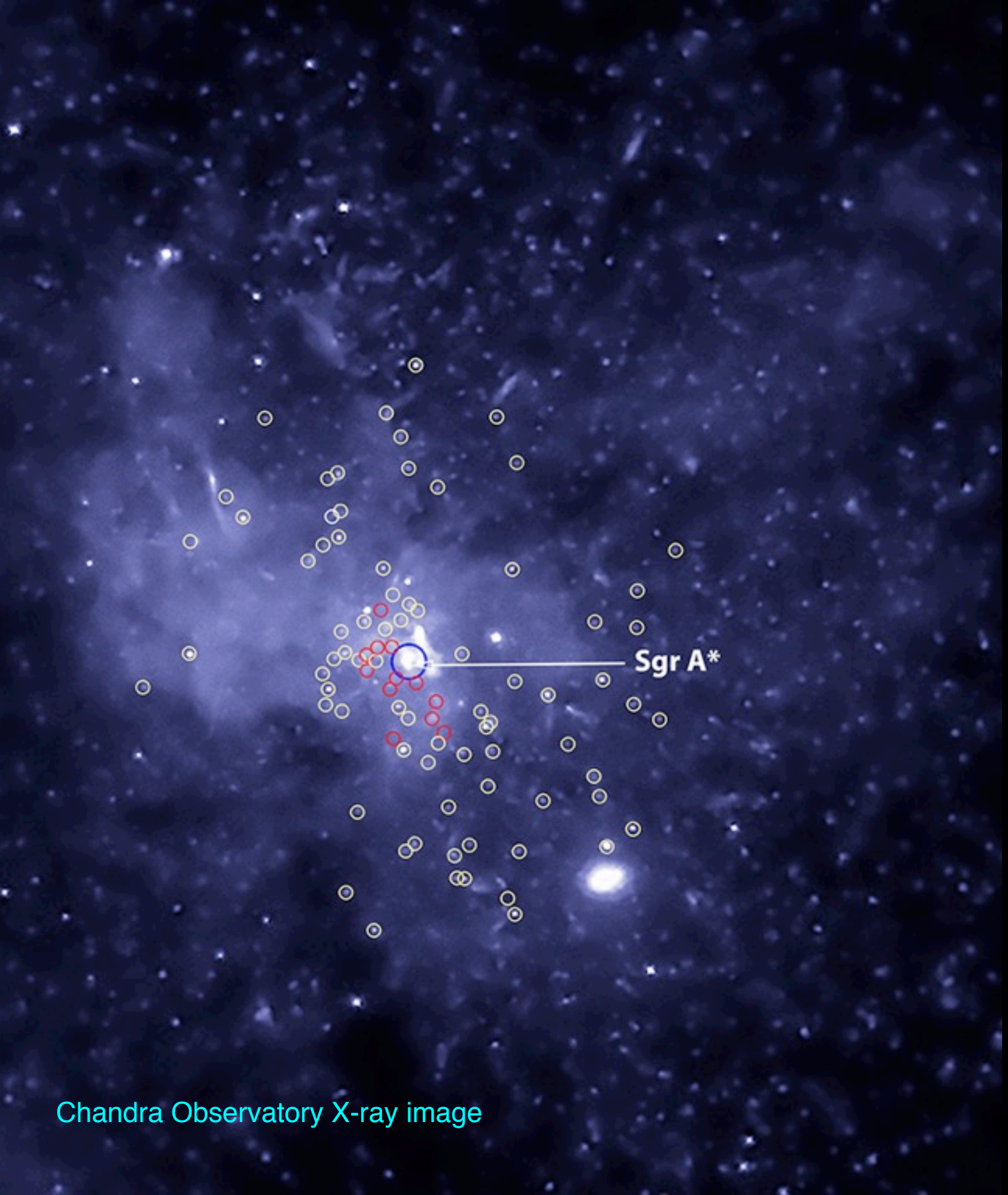
⇒ End state of Hawking Radiation is unique

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$S = \frac{1}{4} A \approx 10^{90}$

Number of microstates in black hole at Sgr A:

$$e^{10^{90}}$$

Black hole uniqueness
⇒ End state of Hawking Radiation is unique

***The information problem:***

$$e^{10^{90}} \neq 1$$

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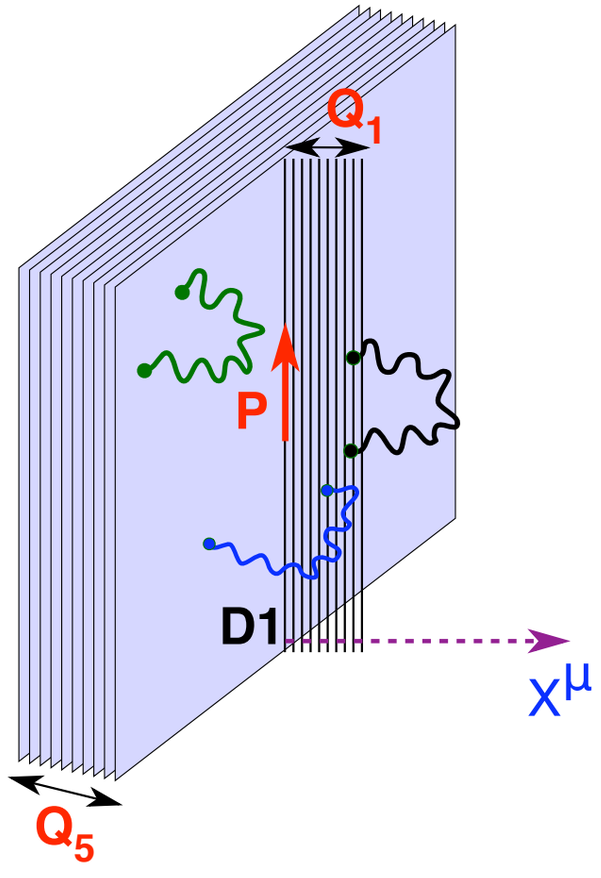

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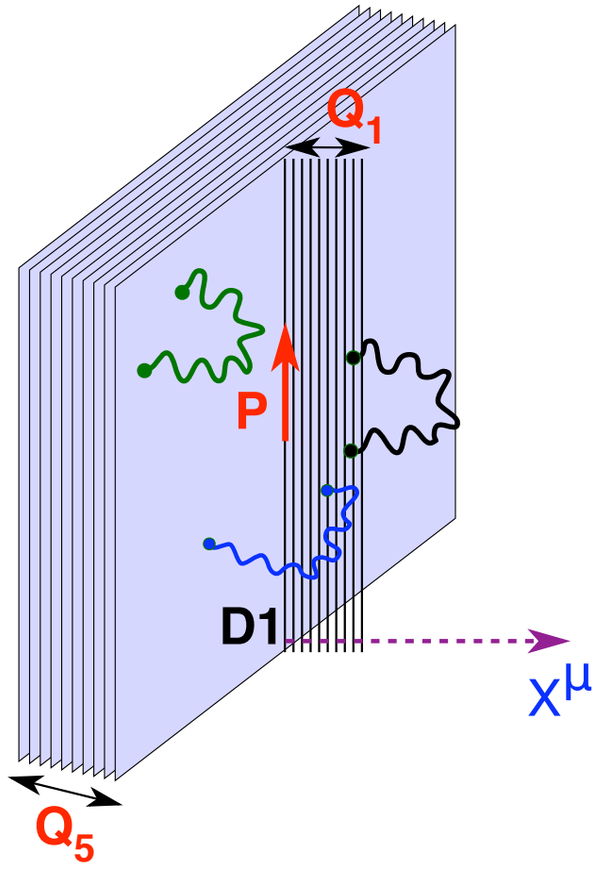

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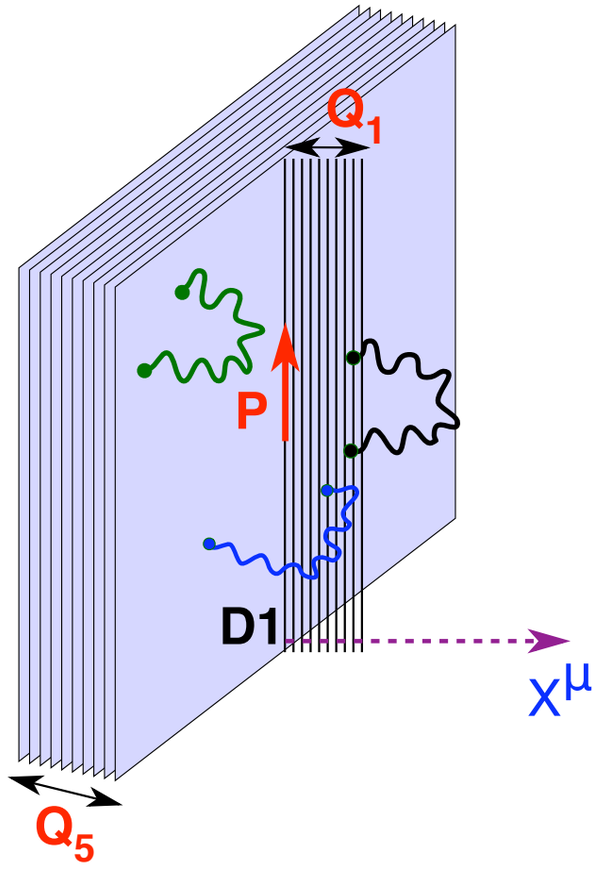

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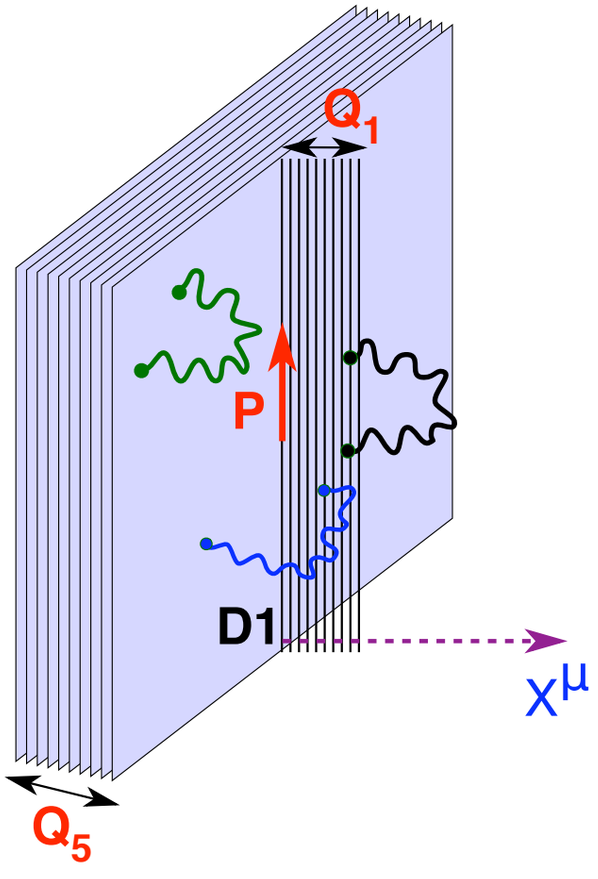

Goals since late 1990's:

(i) $G_{Newton}$, $g_{String} \neq 0$

(ii) No supersymmetry; broken supersymmetry

# State counting using a supersymmetric index

The perturbative microstates are supersymmetric index states and so should be preserved under deformations, including changes in $G_{Newton}$ and $g_{String}$.

*So what do these perturbative string states become at finite $G_{Newton}$, $g_{String}$?*

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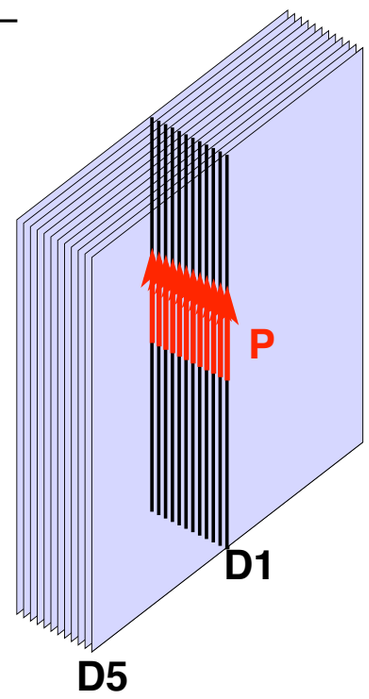

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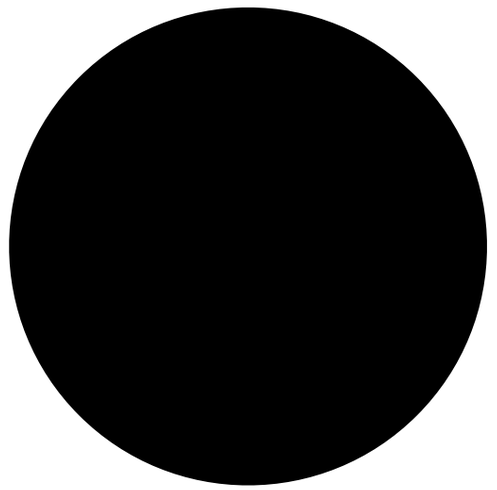

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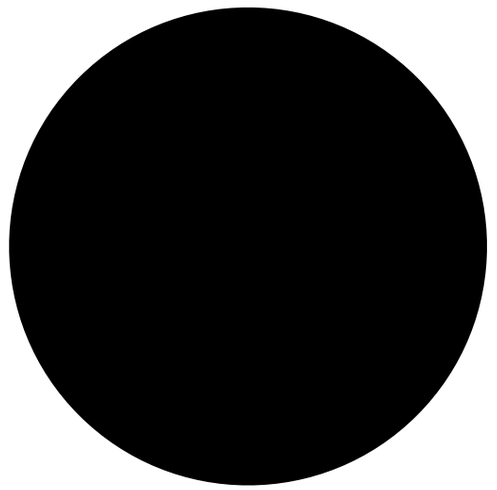

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*We seem to be back where we started …*

# ***Dodging the bullets***

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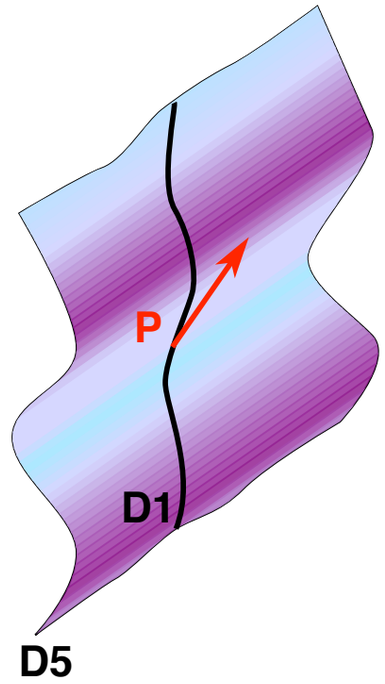
## Microstate scaling

D-brane tension ~ $g_s^{-1}$ + momentum, $P$

⇒ Branes spread out with increasing $g_s$

Can arrange brane configurations that grow in size with $g_s$ at exactly the same rate as the size of a black hole.

**Bena and Kraus, hep-th/0402144**



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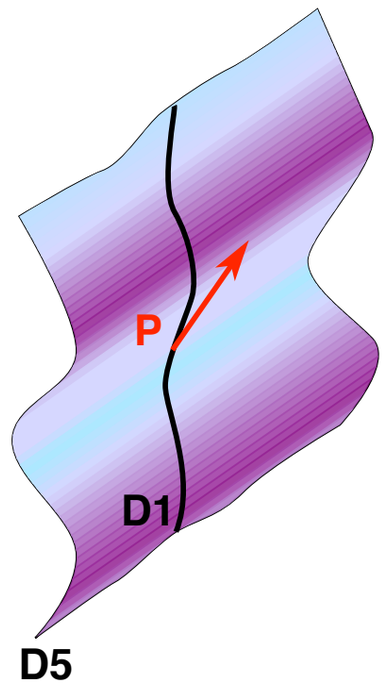


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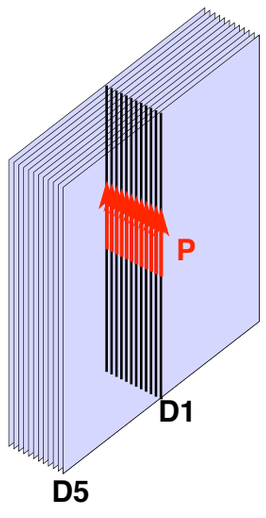
Dp-branes are electric charges of p-form Maxwell fields whose equations of motion typically involve Chern-Simons terms:

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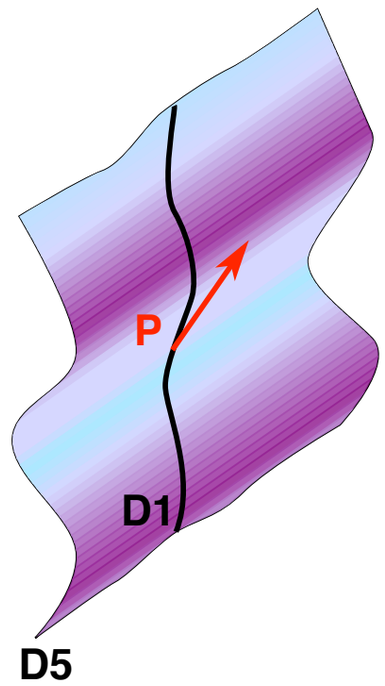


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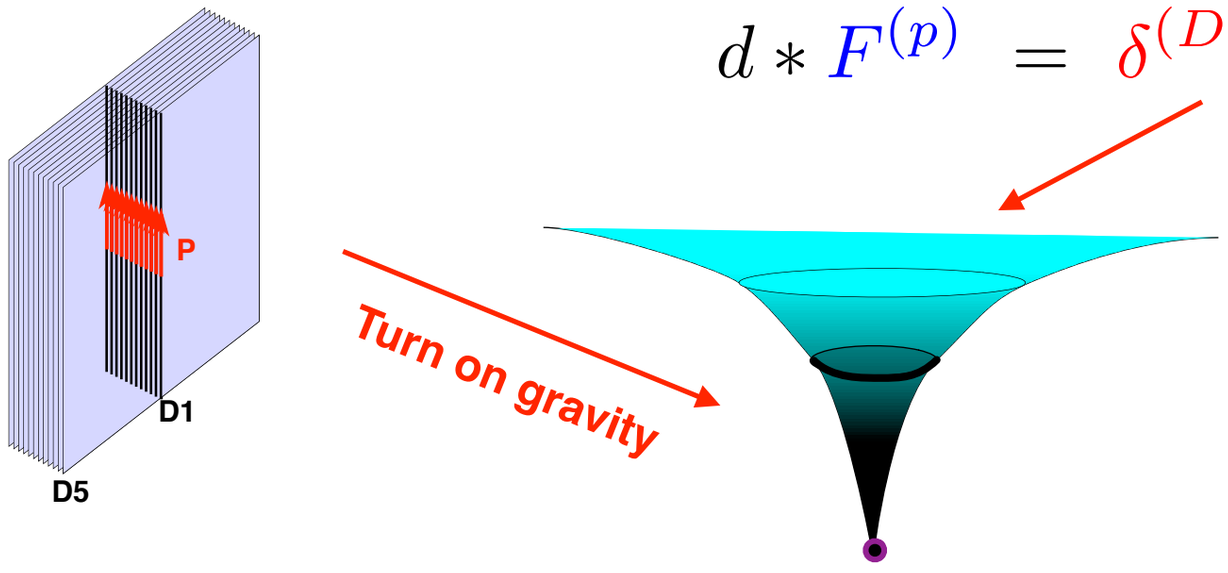


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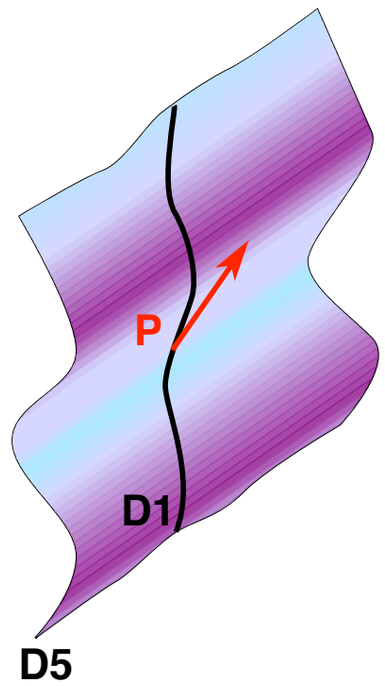


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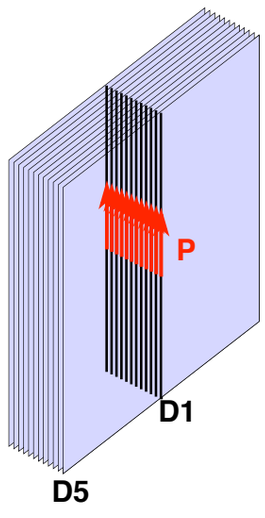


Turn on gravity

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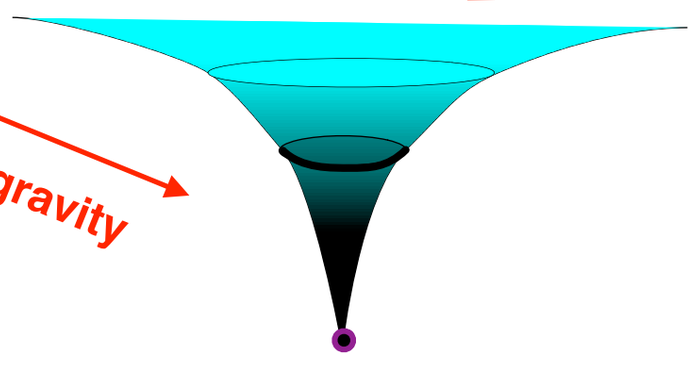

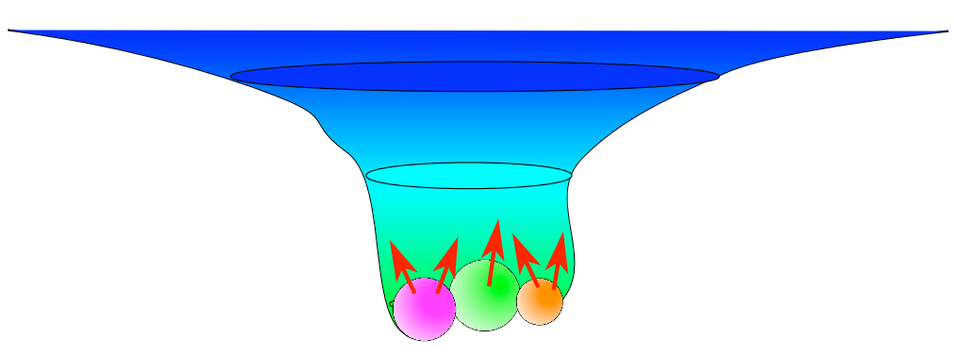

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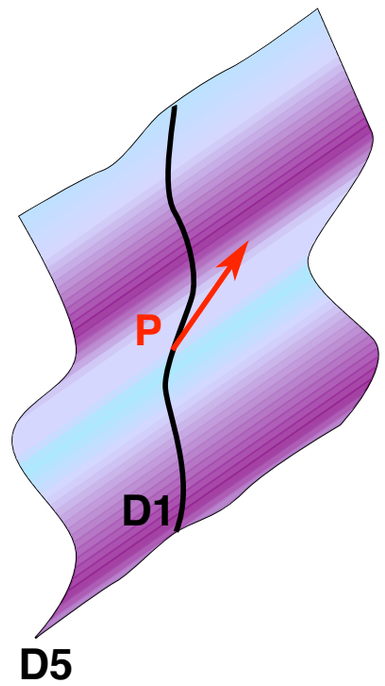


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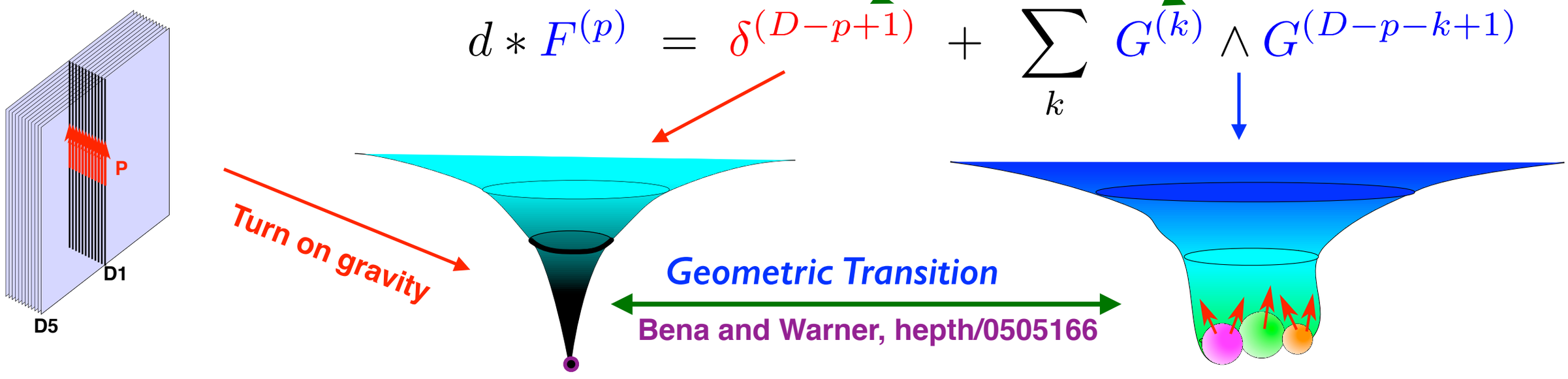


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***But it must do more***

**The information problem is caused by the presence of a horizon …**

⇒ *Event horizons must go!*

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Goals:

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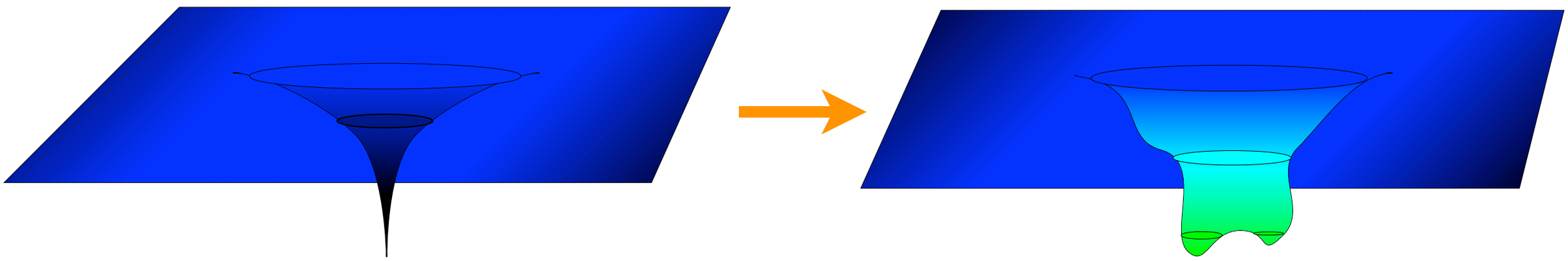
## Microstate Geometries

- Smooth, horizonless solutions to the bosonic sector of supergravity (the low-energy limit of string theory) *with the same asymptotic structure as a given black hole or black ring*

*Singularity resolved; Horizon removed*



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★ 2015-8: Precision holography of Microstate Geometries

Holographic duals of families of some Strominger-Vafa microstates

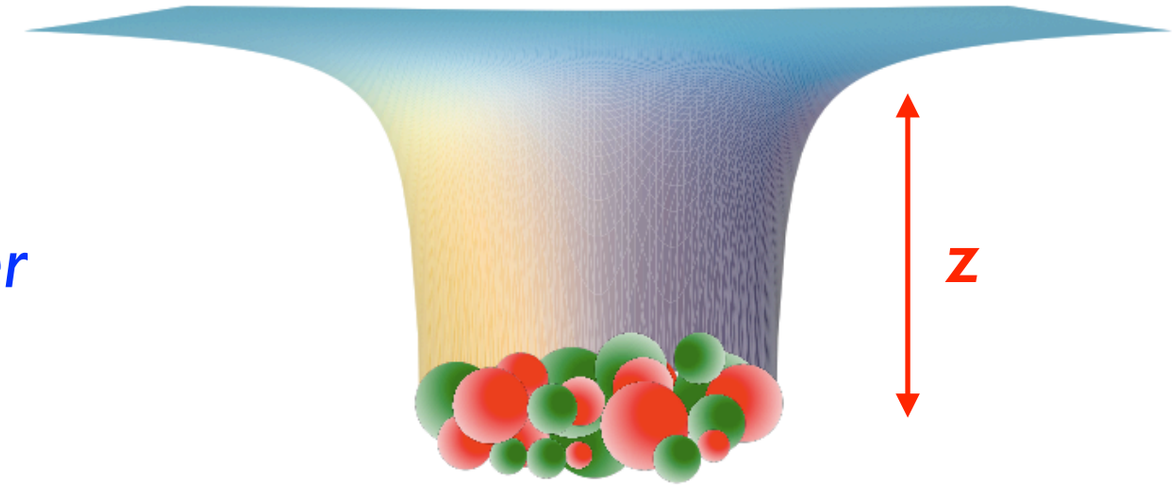
**Bena, Giusto, Martinec, Russo, Shigemori, Turton and Warner**
**arXiv:1503.01463, arXiv:1607.03908, arXiv:1711.10474**

# Scaling Microstate Geometries and Holography

## Scaling microstate geometries:

- Look like black holes until arbitrarily close to the horizon *but cap off smoothly*
- *Depth of throat,* **z**, *a free classical parameter*

  = *Red-shift to the cap*
- *Black-hole throat: AdS* ⇒ *Holographic field theory* of black-hole microstates



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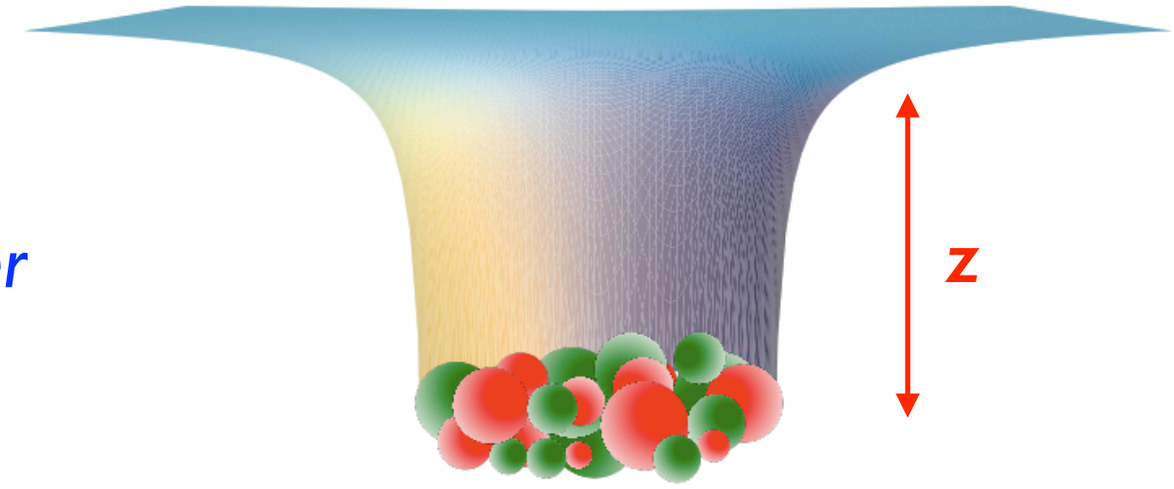
- Look like black holes until arbitrarily close to the horizon *but cap off smoothly*
- *Depth of throat,* **z**, *a free classical parameter*

  = *Red-shift to the cap*
- *Black-hole throat: AdS* ⇒ *Holographic field theory* of black-hole microstates

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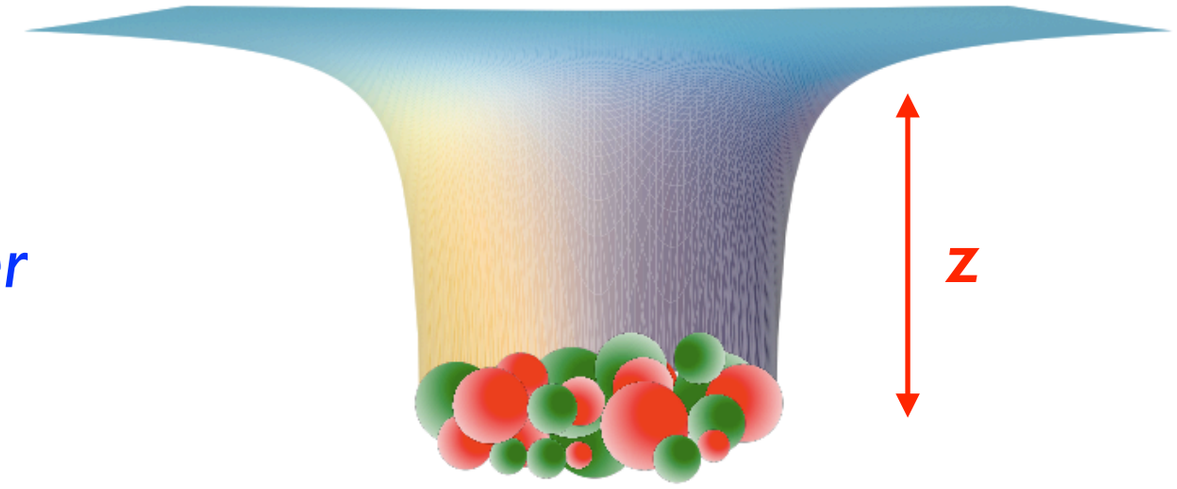


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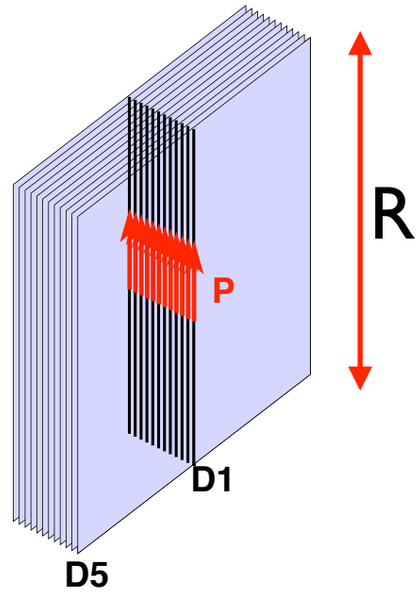
## The Dual CFT

In the system built with *momentum waves* on a system of D1 and D5 branes

Black-hole CFT: a marginal deformation of an orbifold (1+1)-dimensional CFT




Central charge

$$c = 6\, N_1\, N_5$$

Energy gap

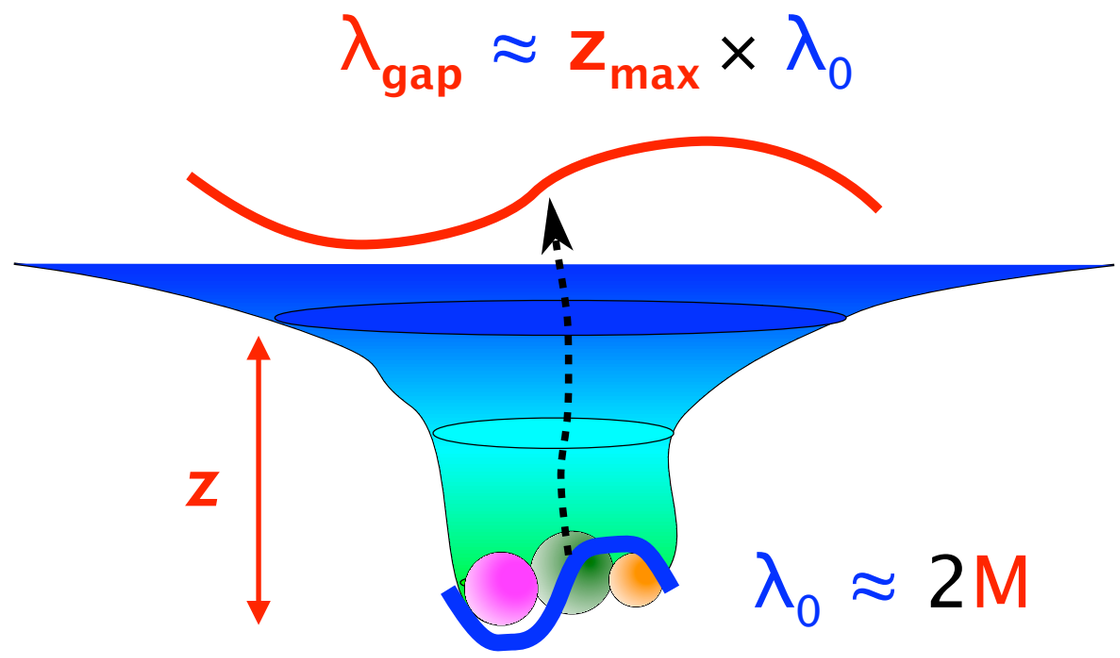
$$E_{gap} = \frac{1}{N_1\, N_5\, R}$$

# The Holographic Energy Gap

## New physics of microstate geometries:

$\lambda_{gap}$ = *maximally* redshifted wavelength, at infinity of lowest collective mode of bubbles at the bottom of the throat.

$$E_{gap} \sim (\lambda_{gap})^{-1}$$



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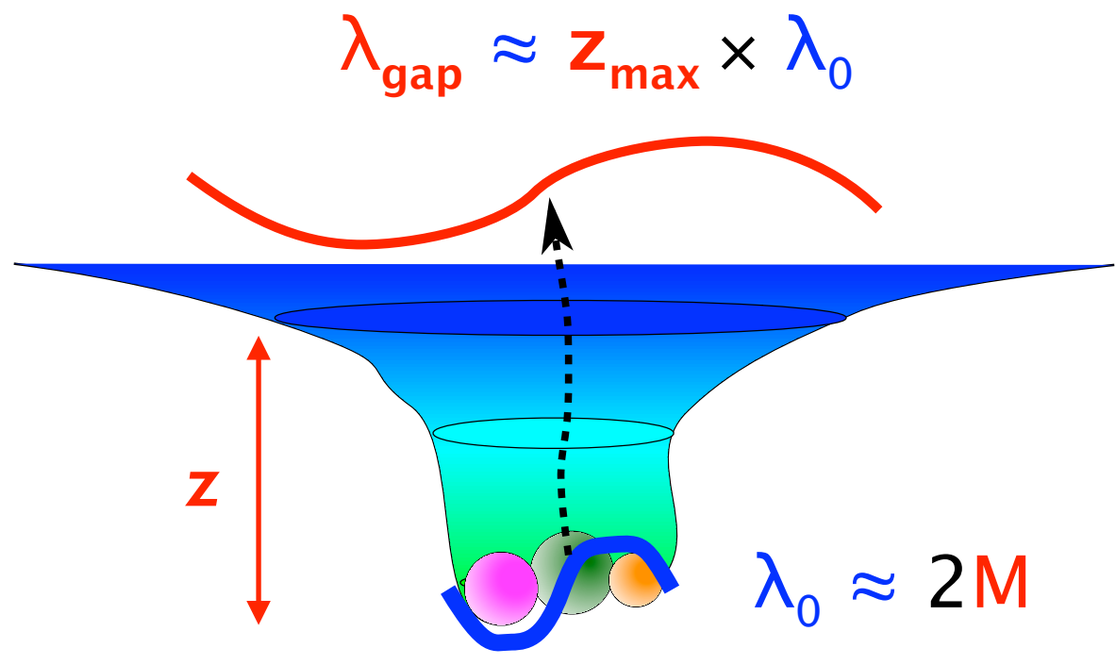

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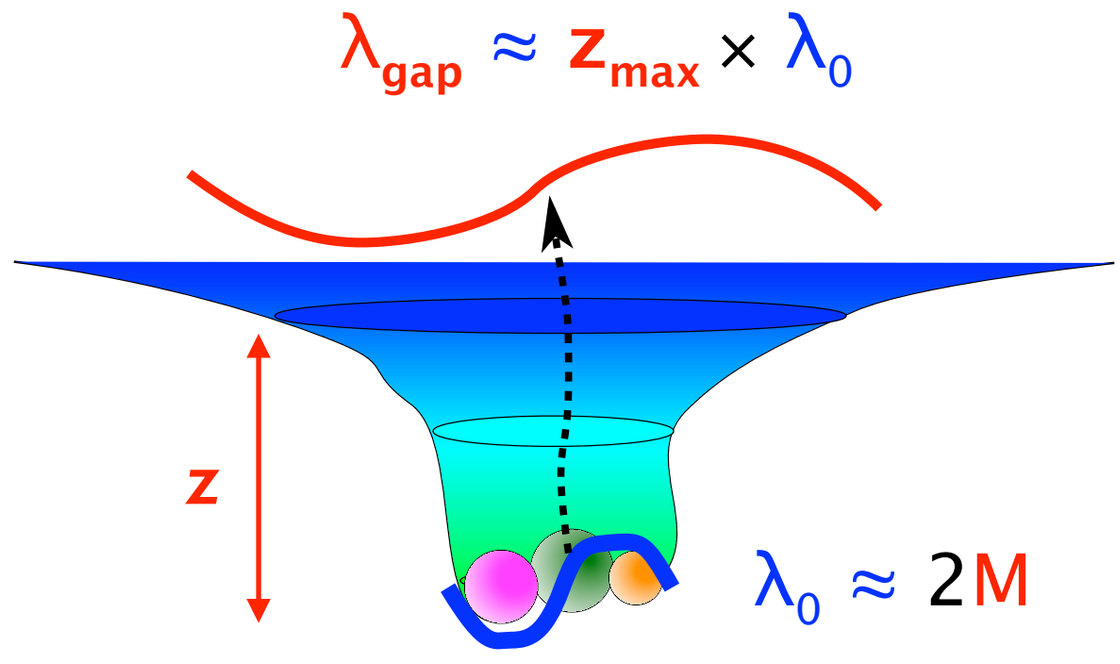


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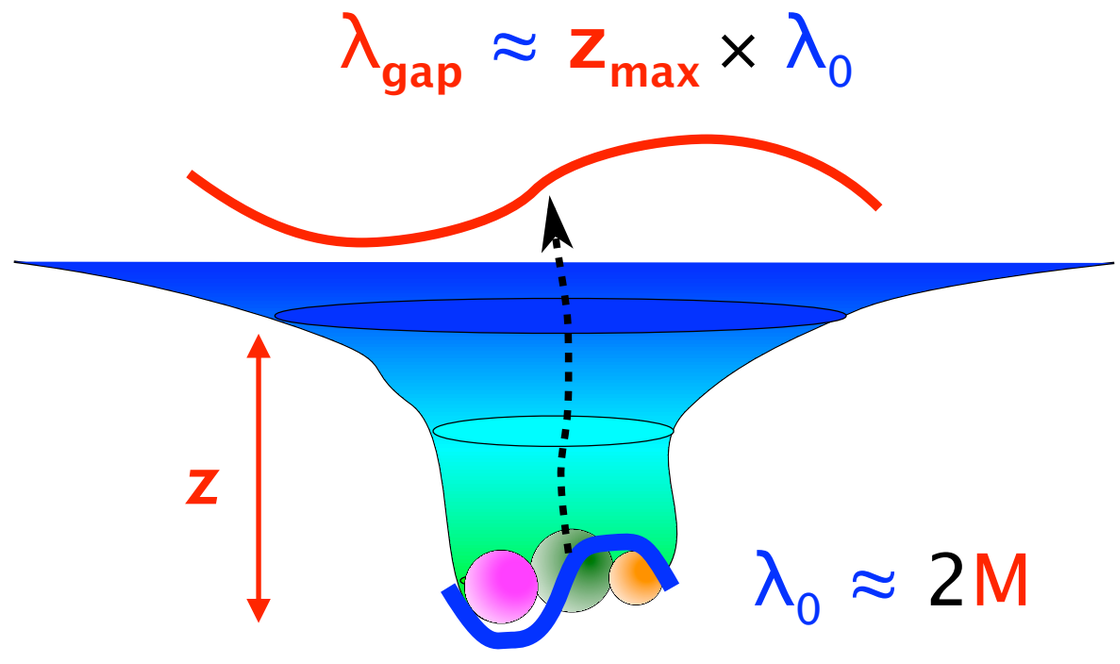


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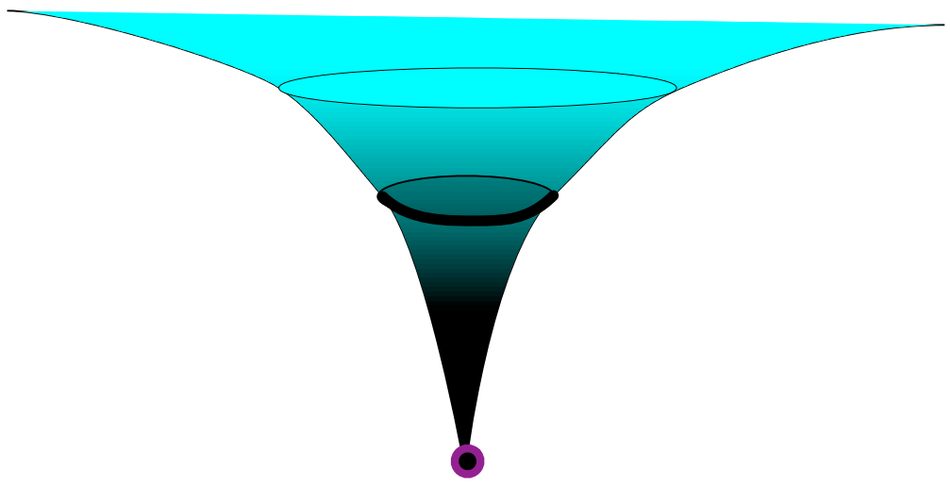
We found that this *exactly matches* $E_{gap} \sim (C_{cft})^{-1}$ for the *softest stringy excitations* underlying the original state counting of Strominger and Vafa .....

⇒ Excitations of scaling microstate geometries access the softest modes of the "*typical sector*" that provides the dominant contribution to the entropy ...

# The Holography of Topological Bubbles



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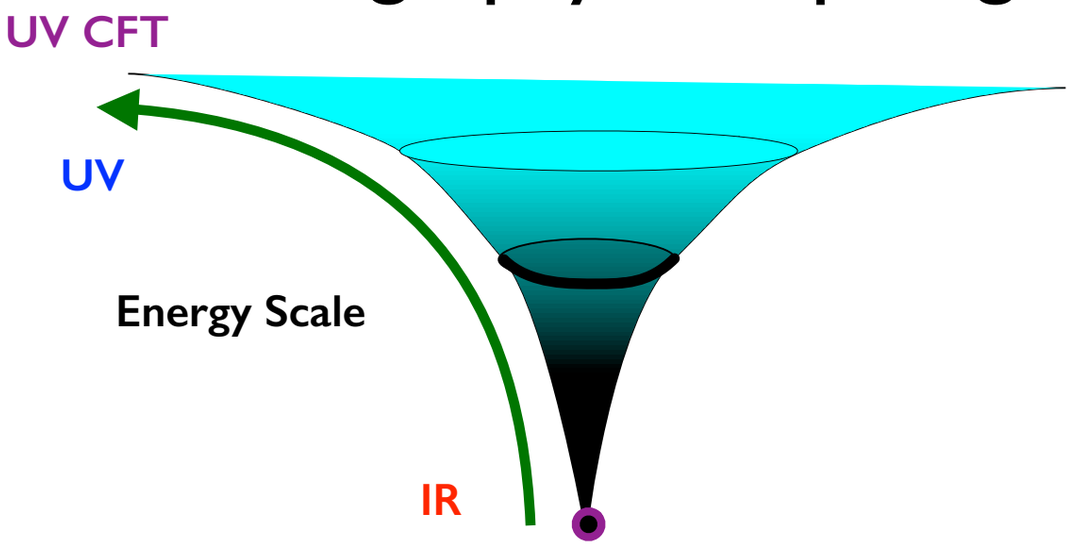

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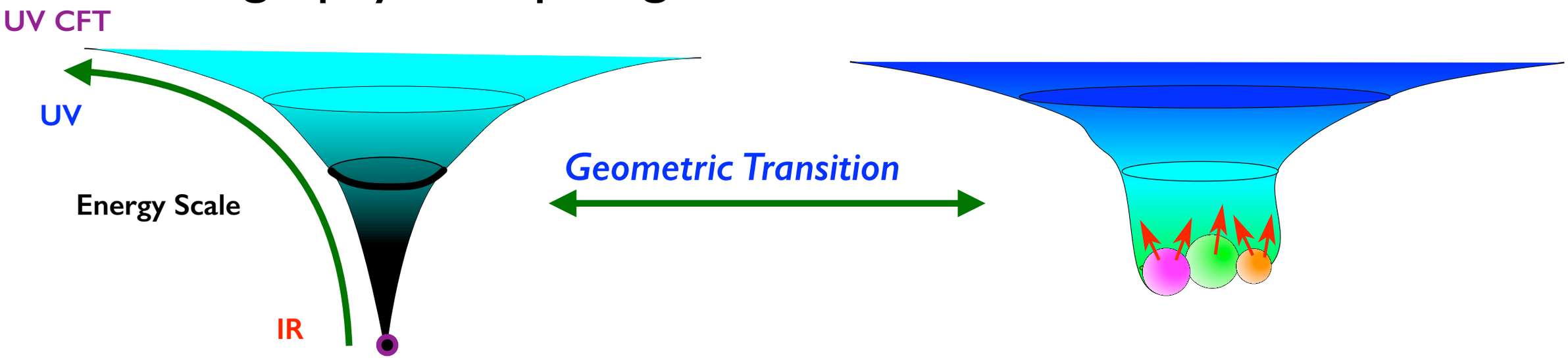

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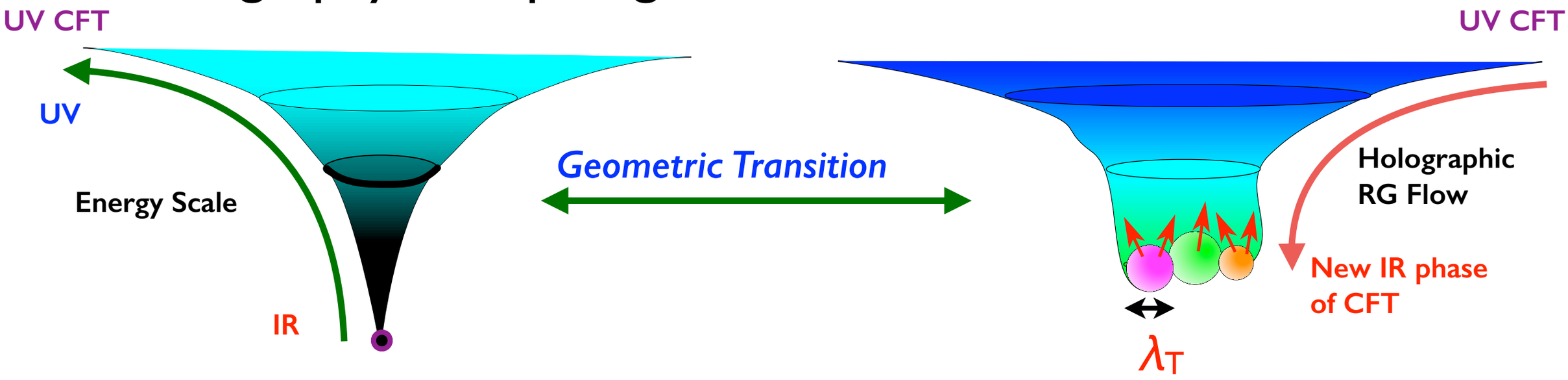

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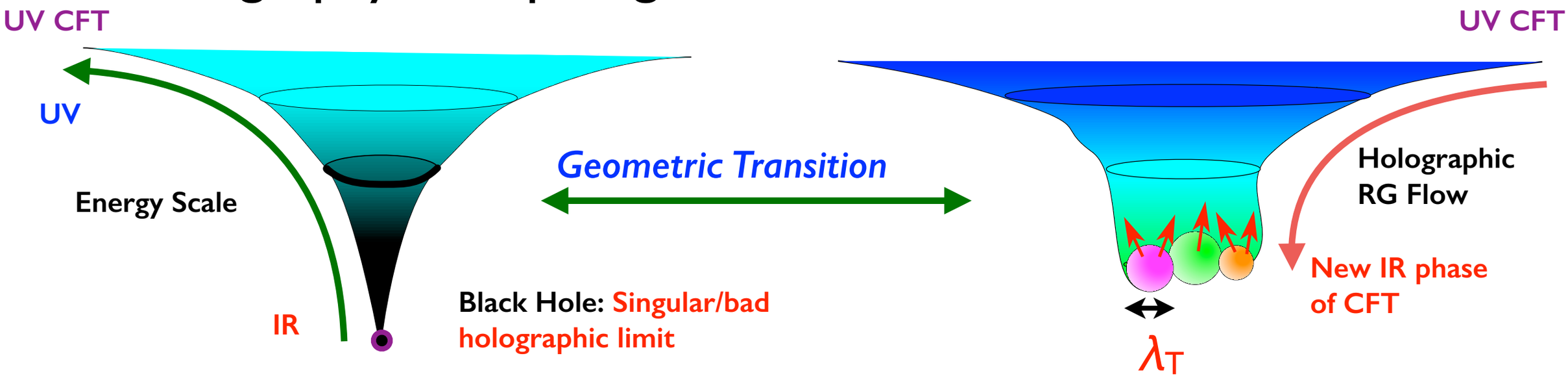


Holographic field theory:

- *Magnetic fluxes* $\longleftrightarrow$ *vevs of order parameters of new phases*
- *Scale,* $\lambda_T$*, of topological bubbles* $\longleftrightarrow$ *Magnitude of vevs*
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This was established in the holographic description of *confining gauge theories*

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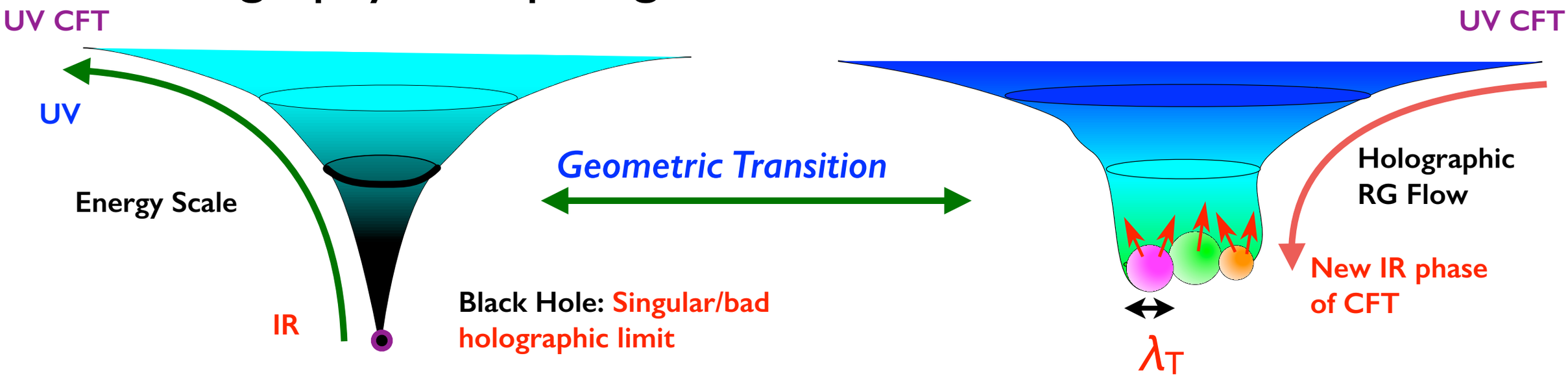


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Essential ideas:

- Microstate geometries $\longleftrightarrow$ *IR phases of the CFT*
- *Fluxes* $\longleftrightarrow$ *Order parameters*
- *New scales in the physics of black holes:*
  - *Order parameters:* $\lambda_T$
  - *Energy gap:* $E_{gap}$
- *Fluctuations of microstate geometries* $\longleftrightarrow$ *Excited states of the CFT*

# Current Foci of the Microstate Geometry Program

- How much of the microstate structure can be encoded semi-classically in the fluctuations spectrum of the fields and the geometry?
  - *Classify these states holographically*
  - *Classify the phase structure of the microstate geometries*

*Can these states sample phase space with enough fidelity to give a semi-classical description of black-hole thermodynamics?*

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- ✦ Use microstate geometries to study intrinsically stringy effects within given coherent phases of the black-hole system
  - *Stringy excitations within these geometries* **Martinec, Massai, Turton**
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- ✦ Study the holographic field theory of microstate geometries
  - *States and partition functions*
  - *Correlation functions in the CFT and the geometry*

**Giusto, Russo, Shigemori, Turton** **Raju, arXiv:1804.10616**

**IPhT: Bena, Guica, Heidemann, Monten, NPW arXiv:18XX.XXXX**

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- Can we use microstate geometries to model ideas of emergent space-time?

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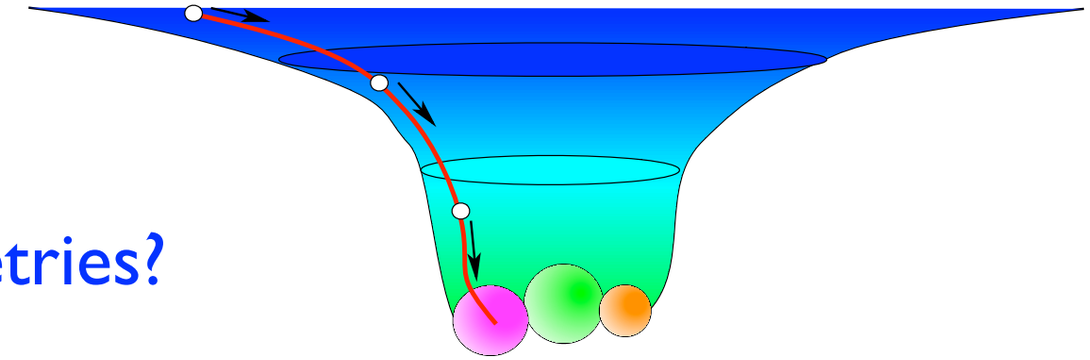
**Eperon, Reall and Santos: arXiv:1607.06828**

Matter gets trapped for long periods in microstate geometries ⇒

Non-linear instabilities of microstate geometries?



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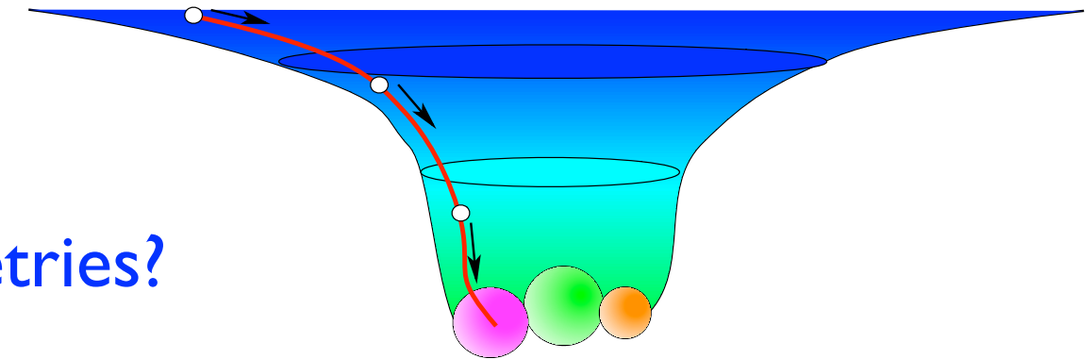

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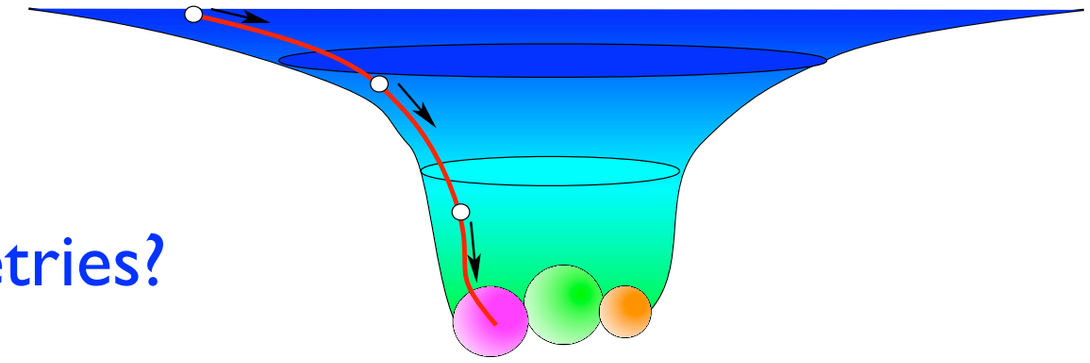

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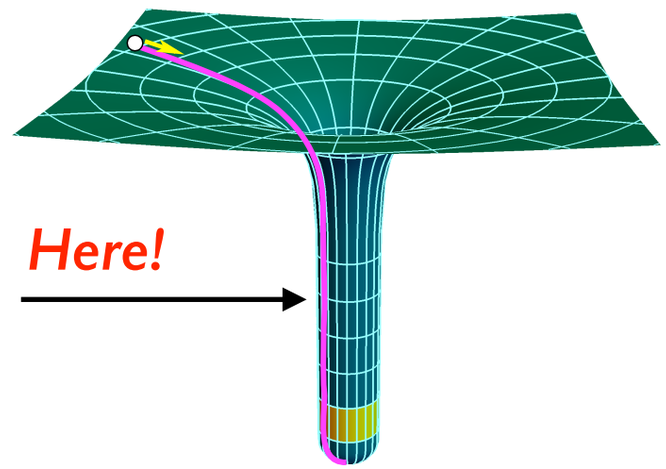

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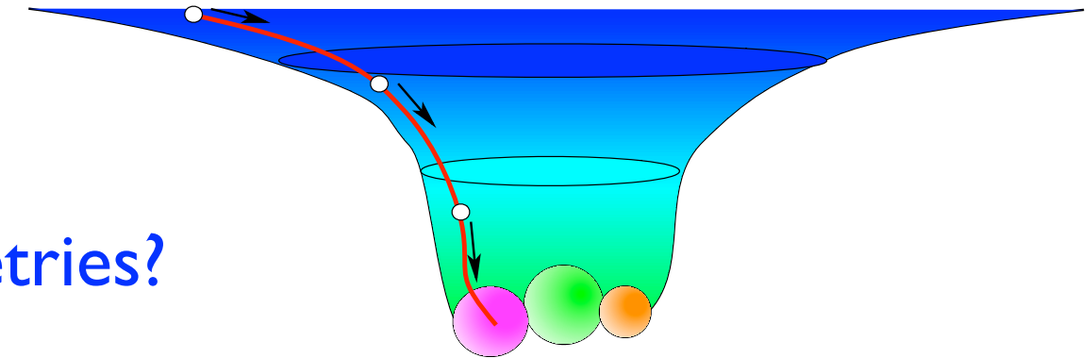

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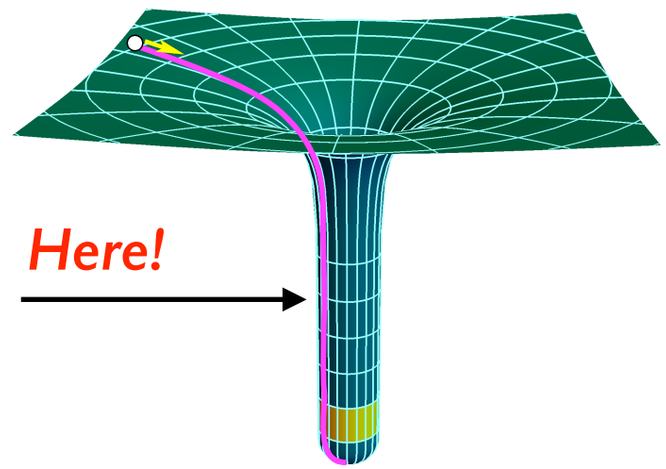


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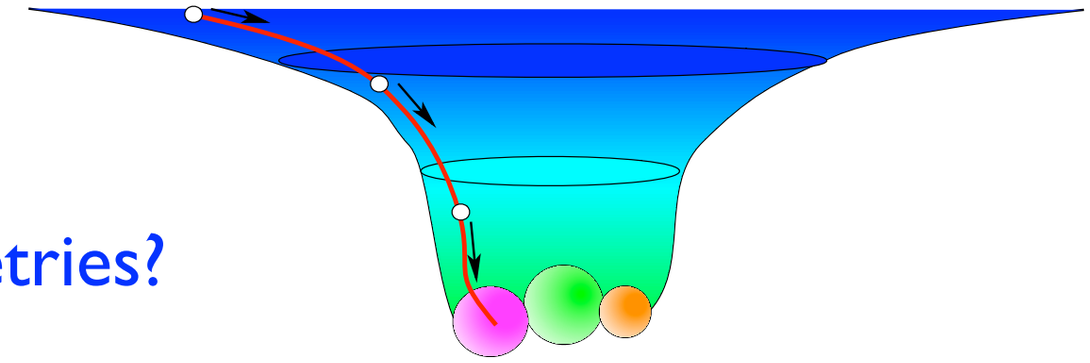

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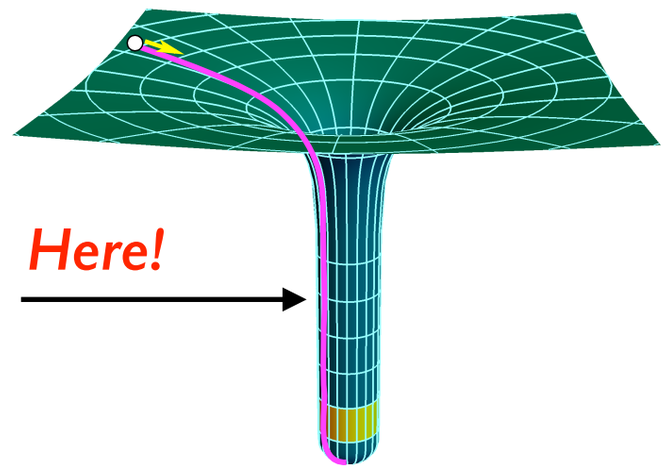


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What is the evolution of this scrambling? What is the back-reaction?
How is infalling matter incorporated into the microstate structure?

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- ✦ Perturbative methods
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  - *Topology of BPS microstate geometries make them robust under perturbation*
  - *BPS holographic dictionary: track the evolution in dual CFT*

# New horizon-scale physics?

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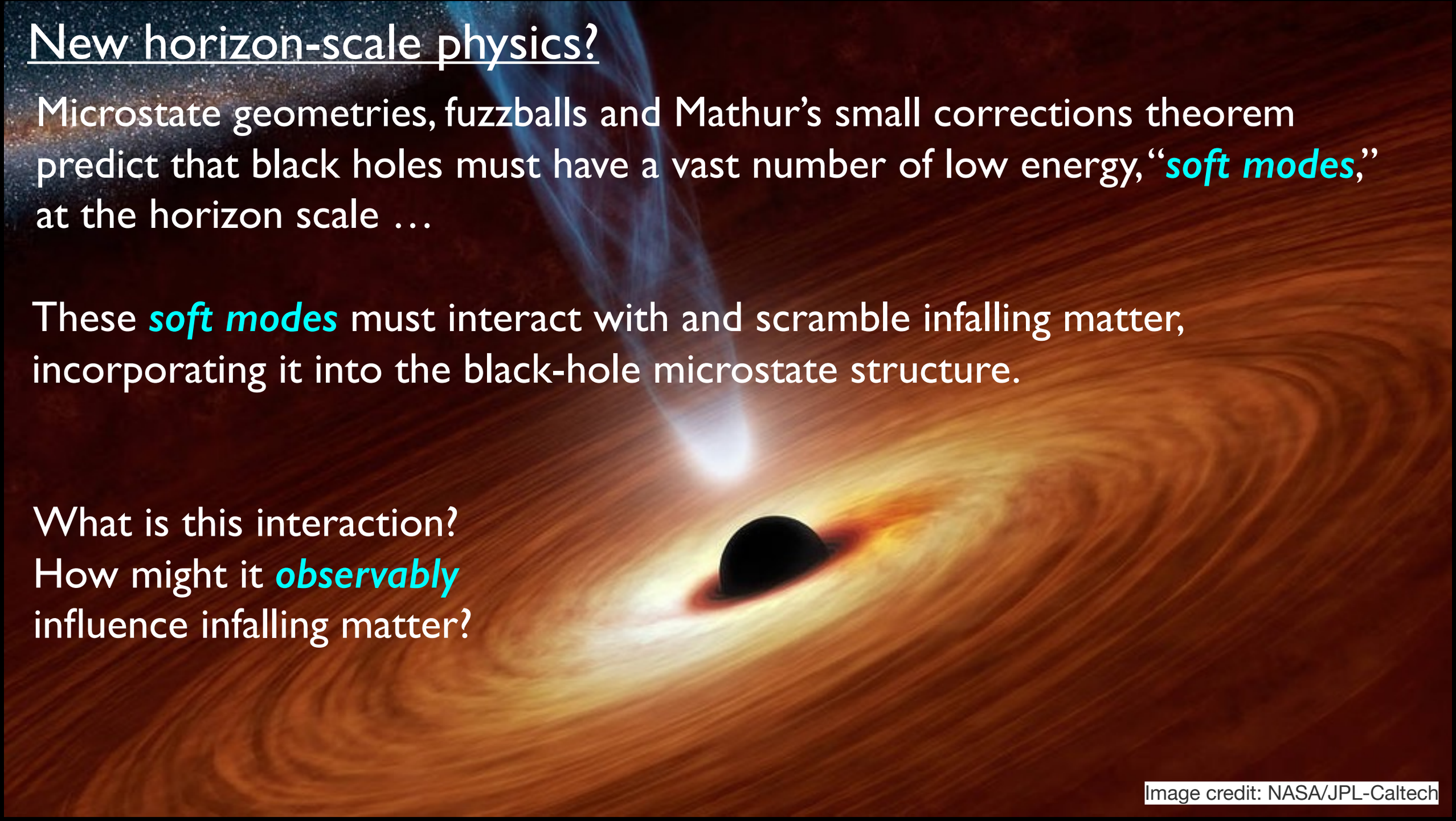

Image credit: NASA/JPL-Caltech

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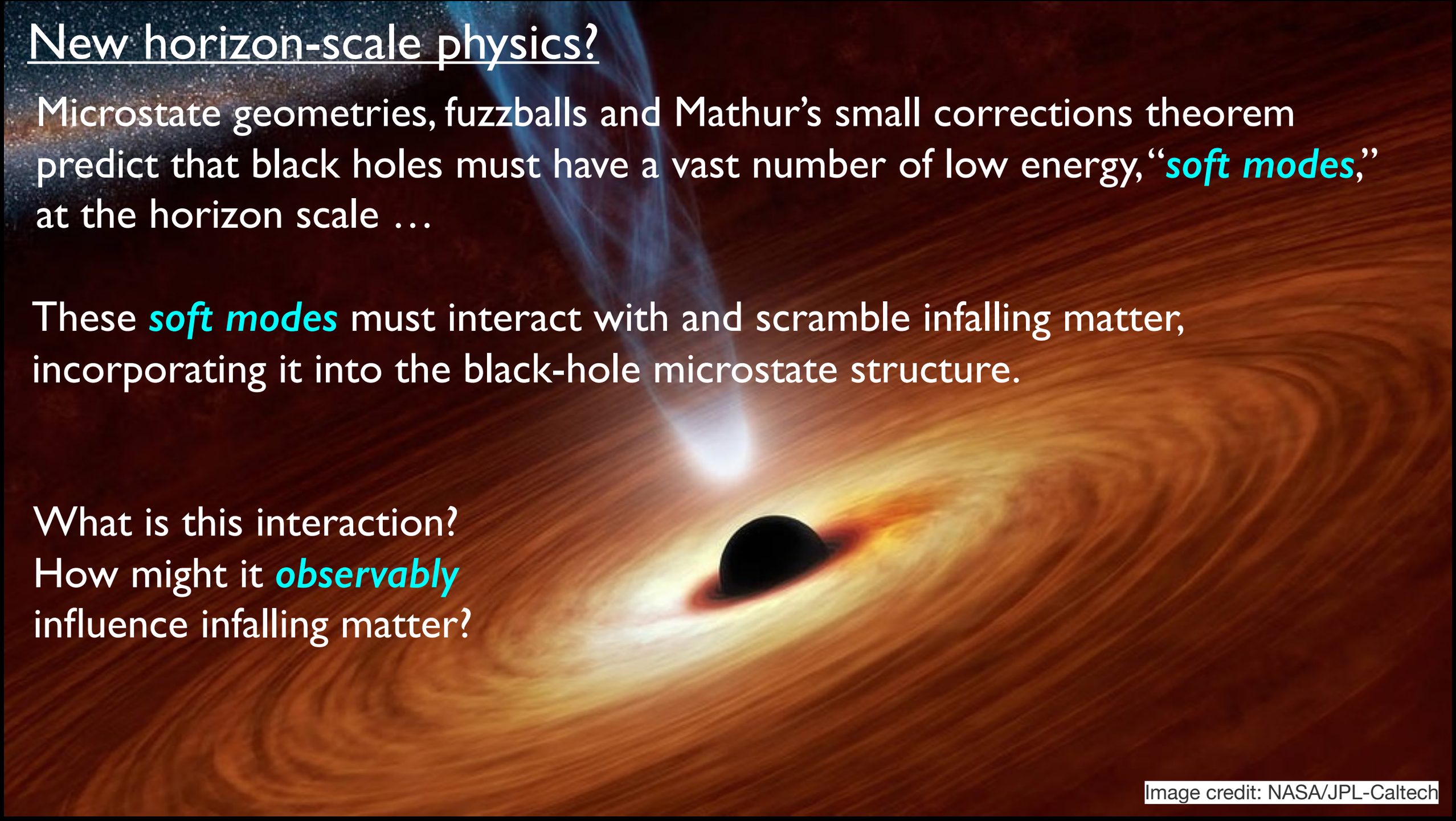

Image credit: NASA/JPL-Caltech

From RHIC and the study of quark-gluon plasmas:
Supergravity calculations in *Holographic Field Theories* are extremely good at giving *universal, effective hydrodynamics, like viscosity, coming from complex, strongly coupled quantum systems.*