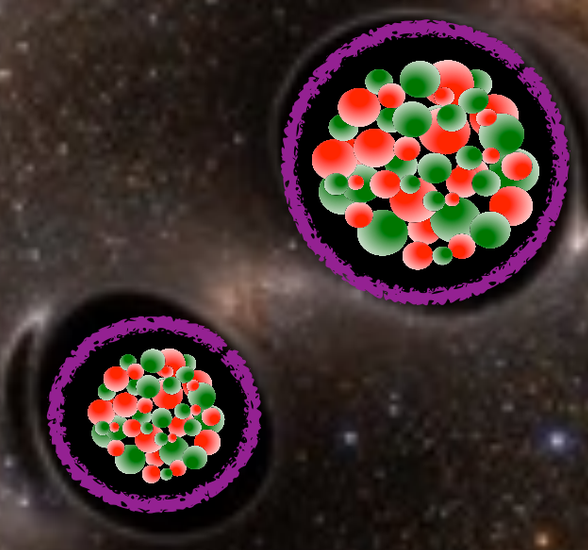
Black Hole Microstructure



“Tests de la relativité générale et théories alternatives”

Nick Warner, January 31, 2019

Research supported supported in part by ERC Grant number: 787320 - QBH Structure
DOE grant DE- SC0011687

Original photo credit: LIGO/Caltech

Why should you care about black hole microstates?

The Black-Hole Information Paradox

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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Bulk state functions (Mass (M), Charge (Q), Angular momentum (J))

uniquely specify the metric/solution outside the horizon

$\Rightarrow$ *Number of microstates measurable from outside = 1* $\Rightarrow$ *S = 0*

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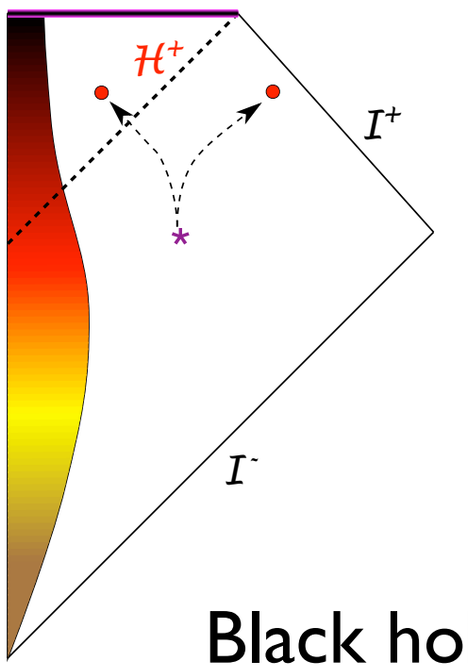
Hawking radiation



Black holes polarize the vacuum

→ Thermal "*Hawking*" radiation at infinity

$$T = \frac{\kappa}{2\pi} = \frac{\hbar c^3}{8\pi G k_B M}$$

Black holes evaporate into Hawking radiation over vast periods of time

In GR alone, Hawking Radiation Carries No Information

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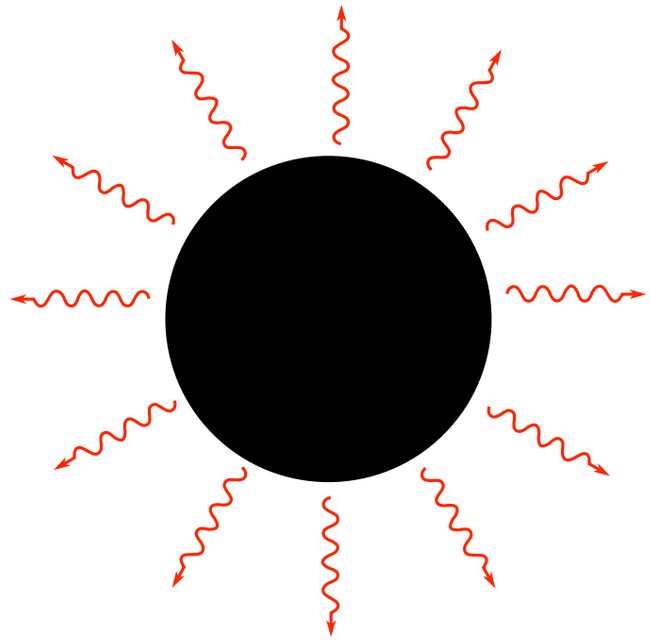
Hawking Radiation originates from quantum fluctuations in a region just outside the ***event horizon***



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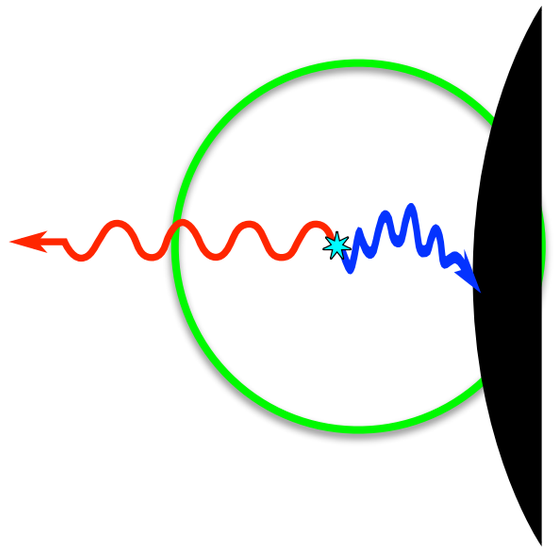

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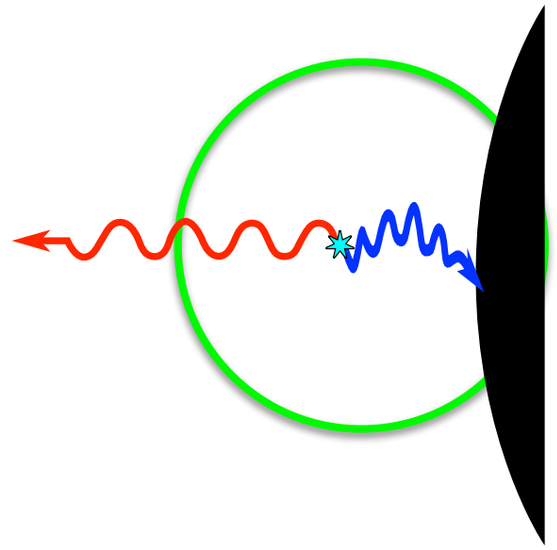

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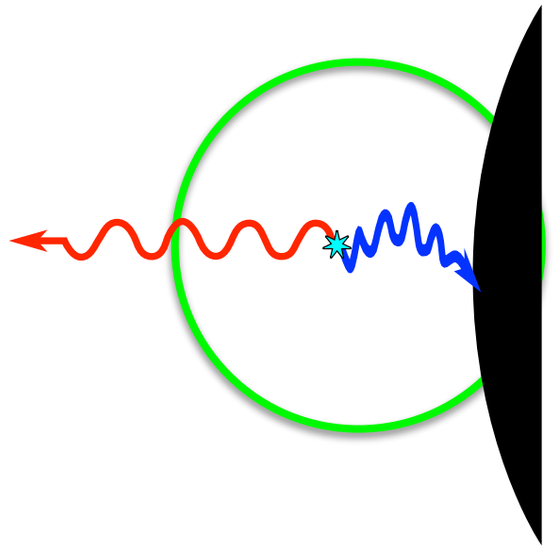

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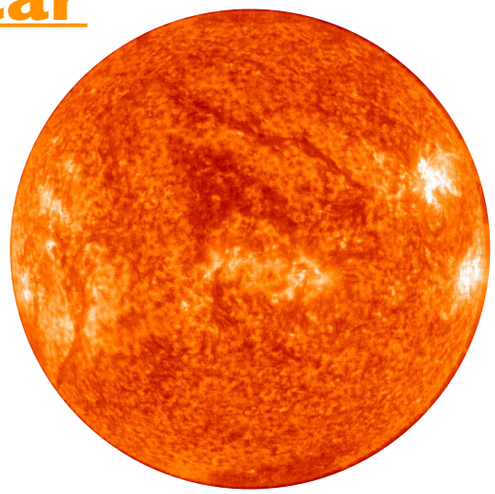
General Relativity + Quantum Mechanics
⇒ *Black holes, no matter how they form, evaporate into the same (largely featureless) cloud of Hawking Radiation*

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

A star



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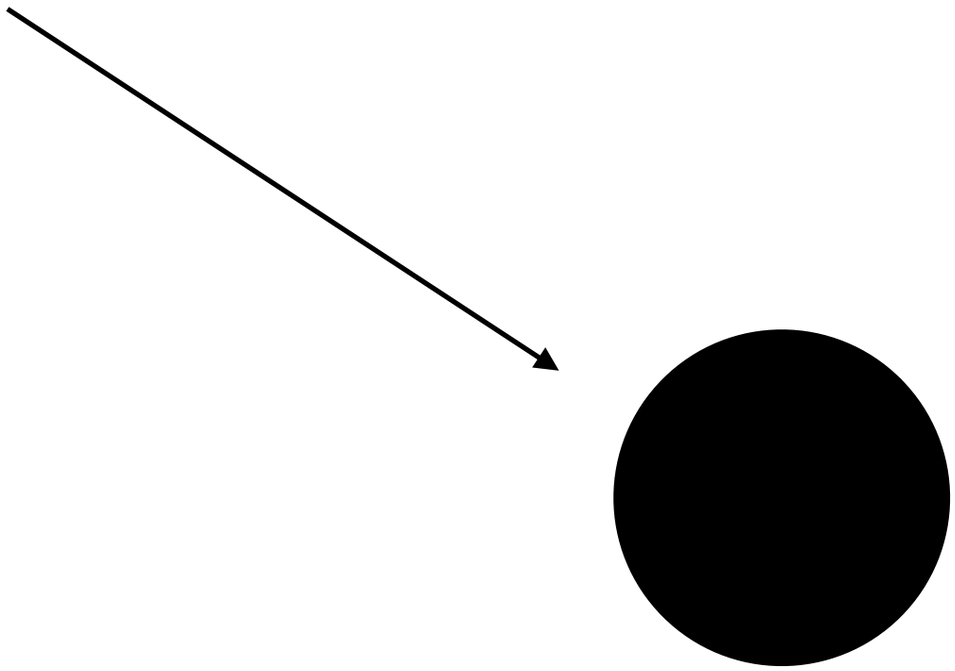

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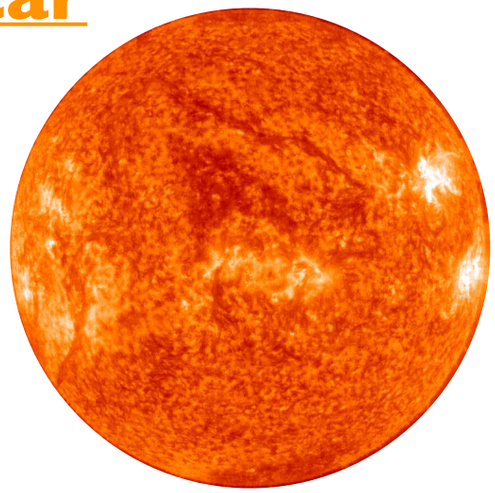

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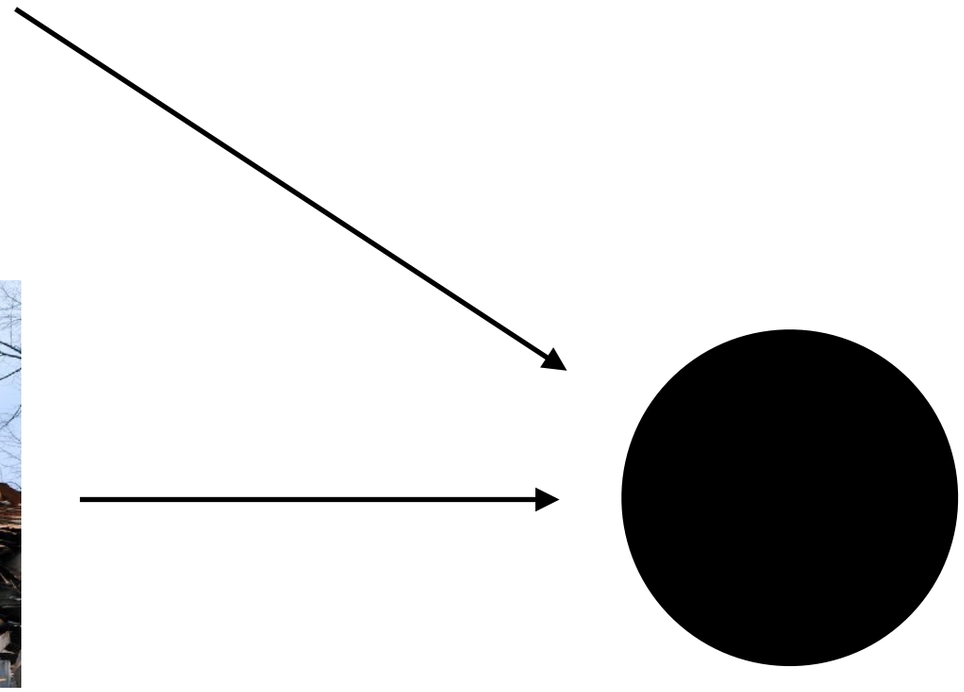

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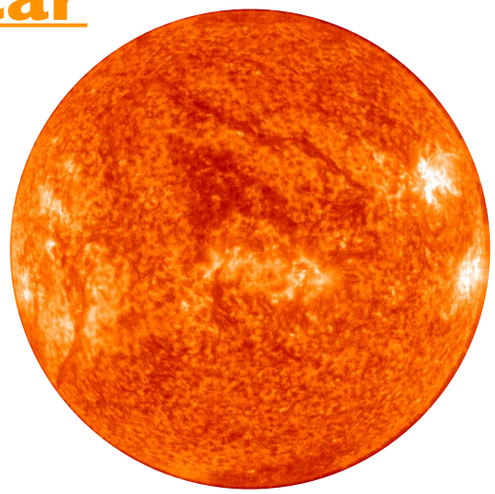

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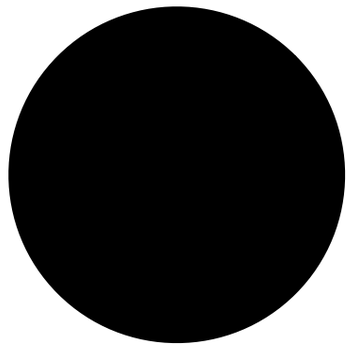
Politicians



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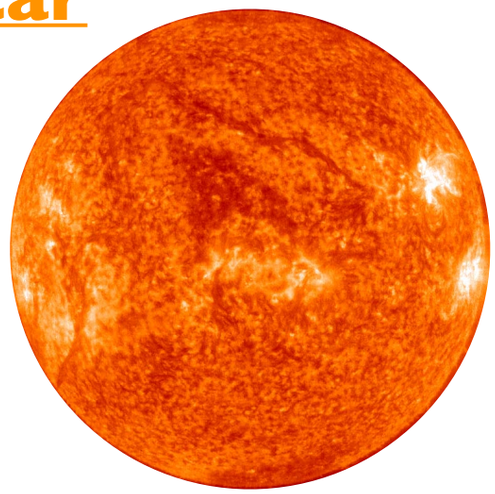

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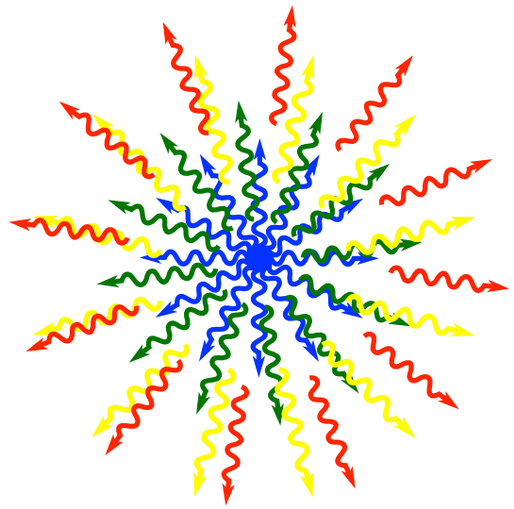

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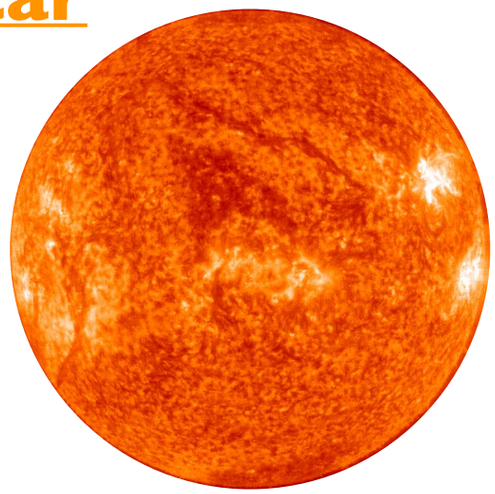

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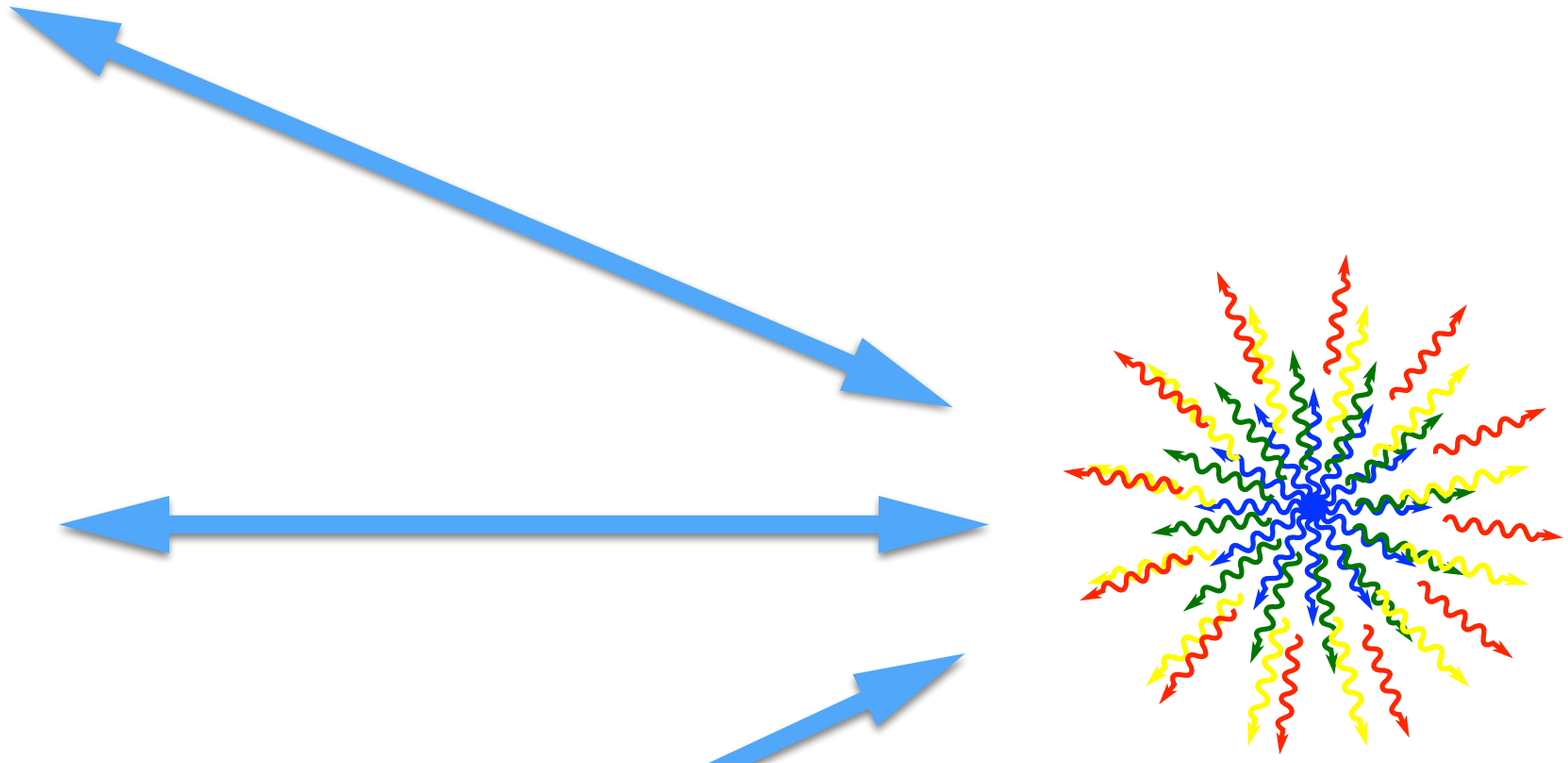

One (1) state

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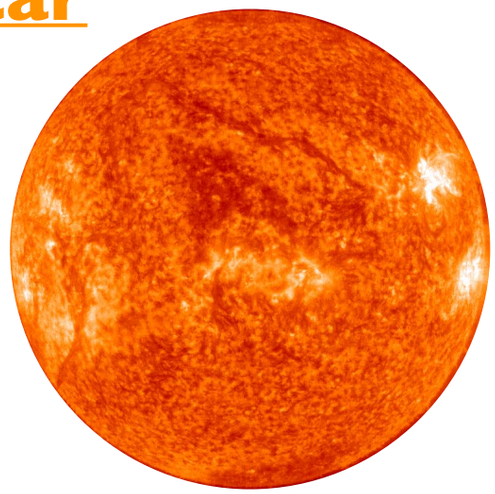

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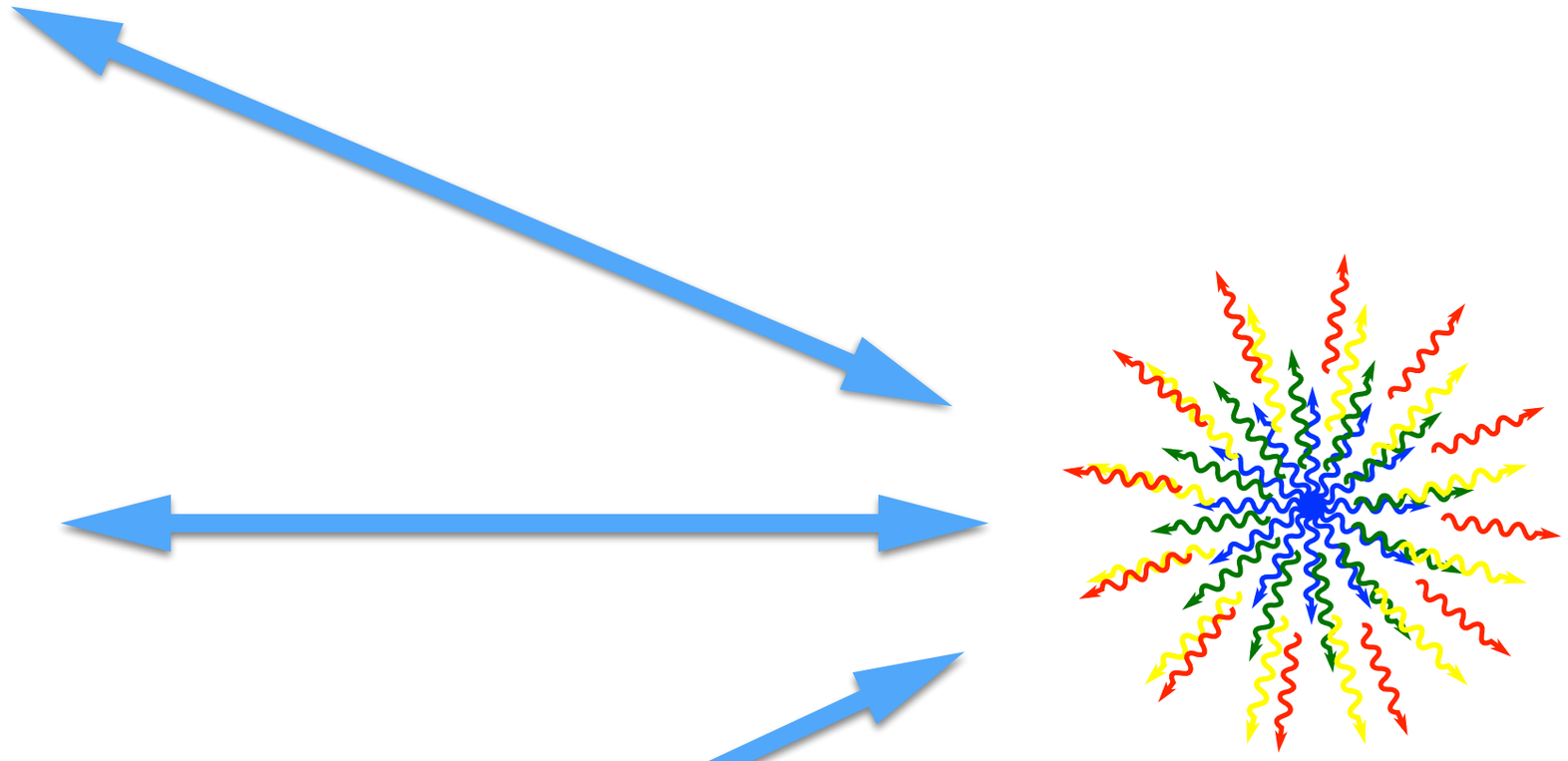

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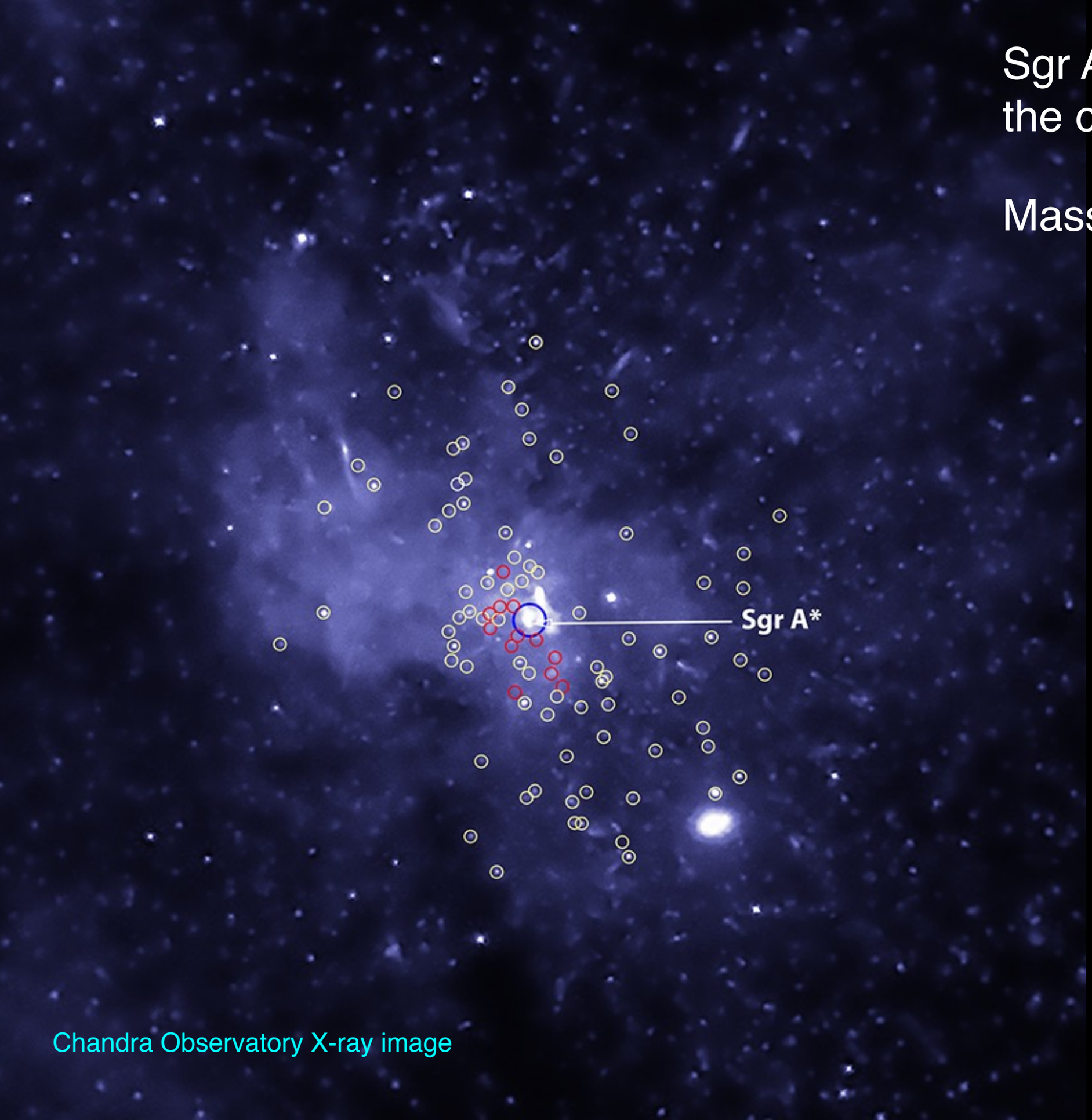
The Information Paradox:

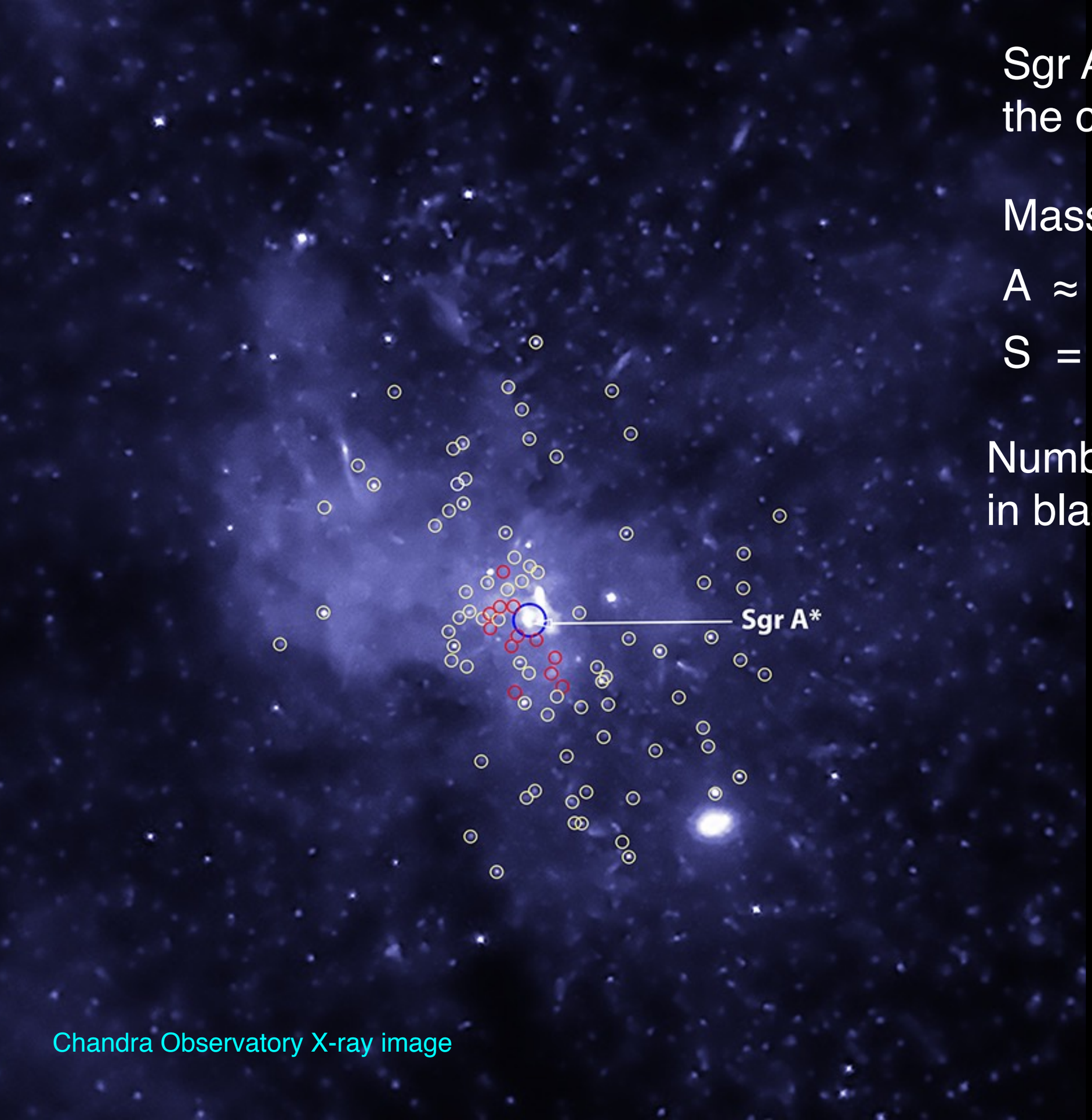
This process cannot be described by Unitary Evolution

Sgr A: Black hole at the core of Milky Way

Mass ≈ 4 × 10^6 $M_\odot$



Chandra Observatory X-ray image



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$A \approx 7 \times 10^{90}$ $\mathbf{L_{Planck}^2}$

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Number of microstates in black hole at Sgr A:

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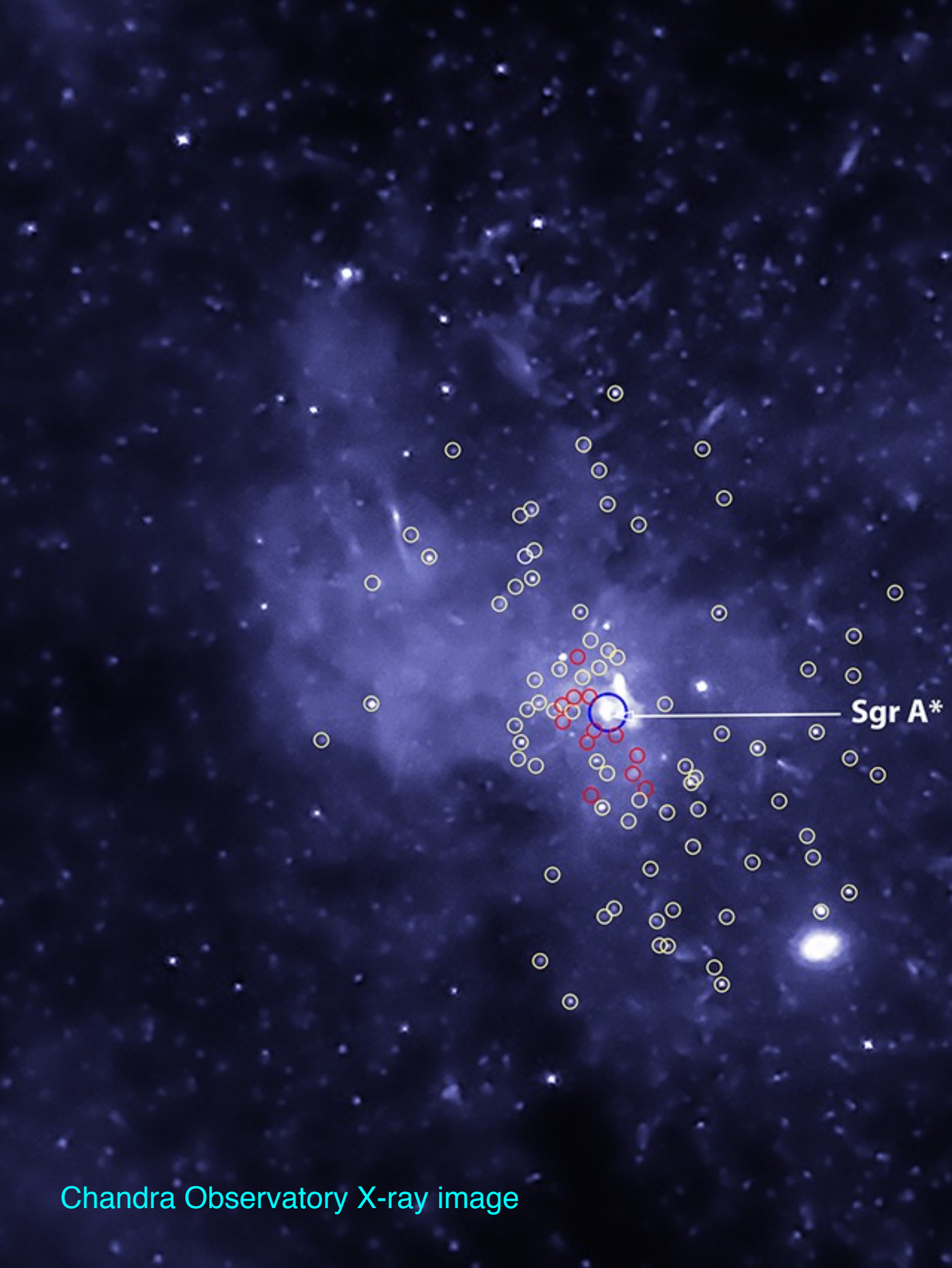

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Black hole uniqueness
⇒ End state of Hawking Radiation is ***unique***

The information problem:

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

An old conceit: Can be fixed by very slow leakage of information

Hawking evaporation is extremely slow:

$$t_{evap} = \frac{5120\,\pi\,G^2\,M_\odot^3}{\hbar\,c^4} \approx 6.6\times10^{74}s \approx 2.1\times10^{67}years$$

(for a one solar mass black hole)

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What is this new horizon-scale structure?

Many proposals/Research Efforts

- ★ Fuzzballs — **Mathur + ...**
- ★ Microstate Geometries — **Bena, Guisto, Russo, Martinec, Shigemori, Turton, Warner + ...**
- ★ Firewalls — **Almheiri, Marolf, Polchinski, Sully ... Susskind ...**
- ★ Quantum Black Boxes — **"It from Qubit" collaboration**
- ★ BMS Hair — **Hawking, Perry and Strominger + ...**
- ★ ER=EPR Webs of Wormholes — **Maldacena, Susskind...**
- ★ (Quantum) "Pixie Dust"
  - ✦ Bose-Einstein Condensates — **Dvali, Lüst, Gomez + ...**
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With the *exception of Microstate Geometries* (and related Fuzzballs), all of these approaches fail to create anything that has a remote chance of actually looking and behaving like a black hole …

Many of these approaches work by ignoring gravity entirely …

Microstate Geometry Program

Goals:

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- ★ Remove horizons
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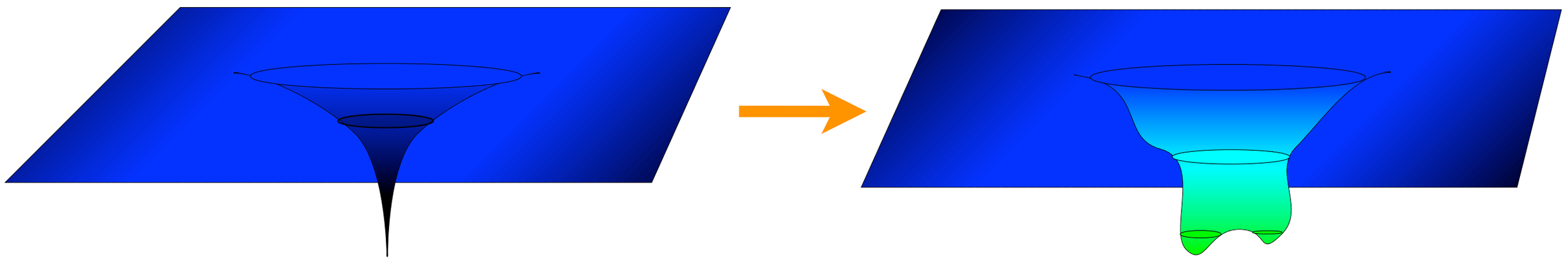
Microstate Geometries

- Smooth, horizonless "solitonic" 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



Looks exactly like a classical black hole until arbitrarily close to horizon scale

Why wasn't this done years ago?

An Old Story: Horizon-Scale Structure in GR

Is there anything that is "stiff enough" to support matter when it is *almost* a black hole? *Is there a mechanism for GR in 3+1 dimensions to support horizon-scale microstructure*?

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In General Relativity coupled to massless fields:

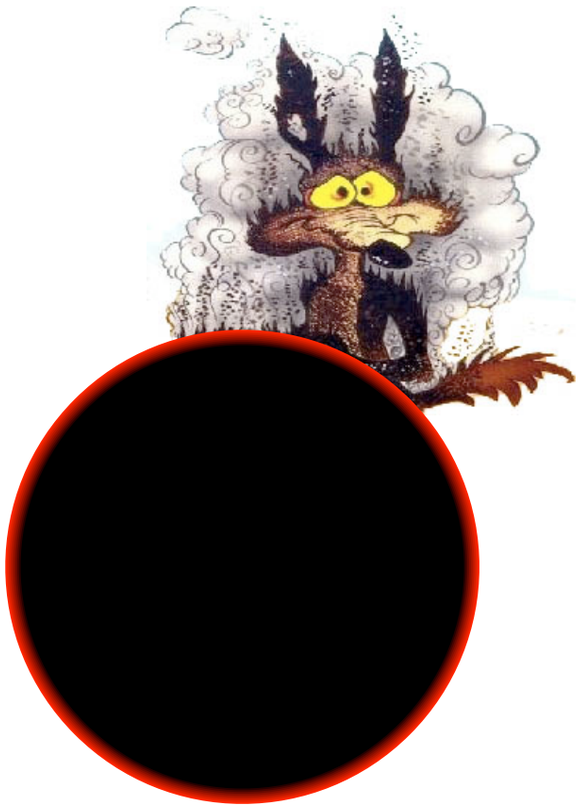
Time-independent solutions with time-independent matter
necessarily have horizons ⇒ *They must have singularities*

"No solitons without horizons"

The (almost) insurmountable difficulties of horizon-scale microstructure

The First Problem: A Black-Hole Correspondence Limit

Whatever structure you use to replace a black hole, close to the horizon scale, there must be a correspondence limit in which *classical GR re-emerges as the effective theory and the object must actually look and behave like an astrophysical black hole …*



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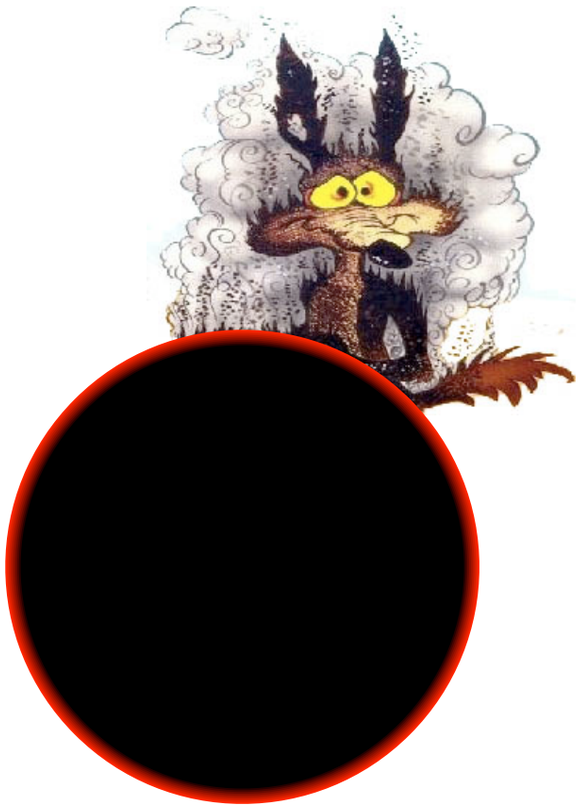

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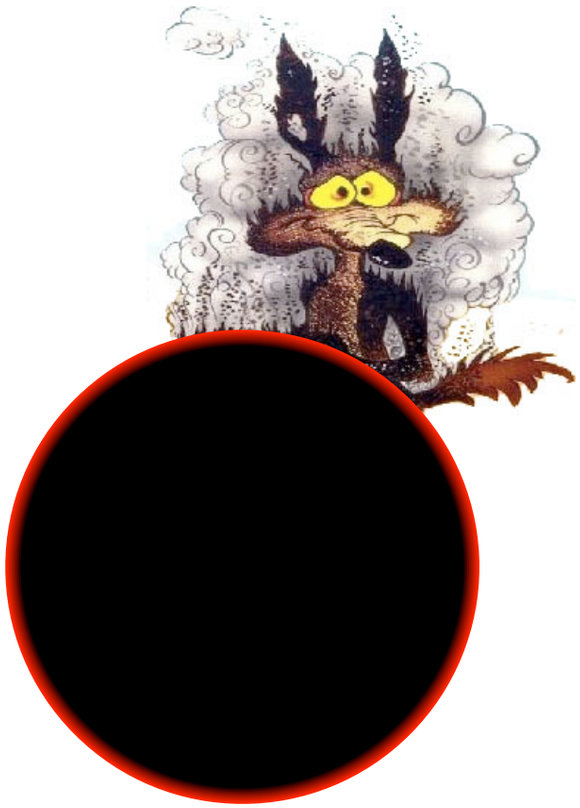

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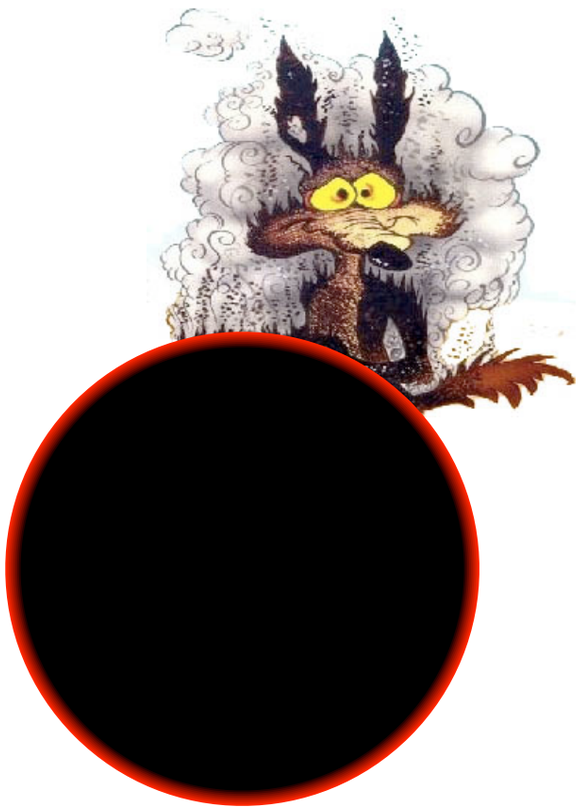
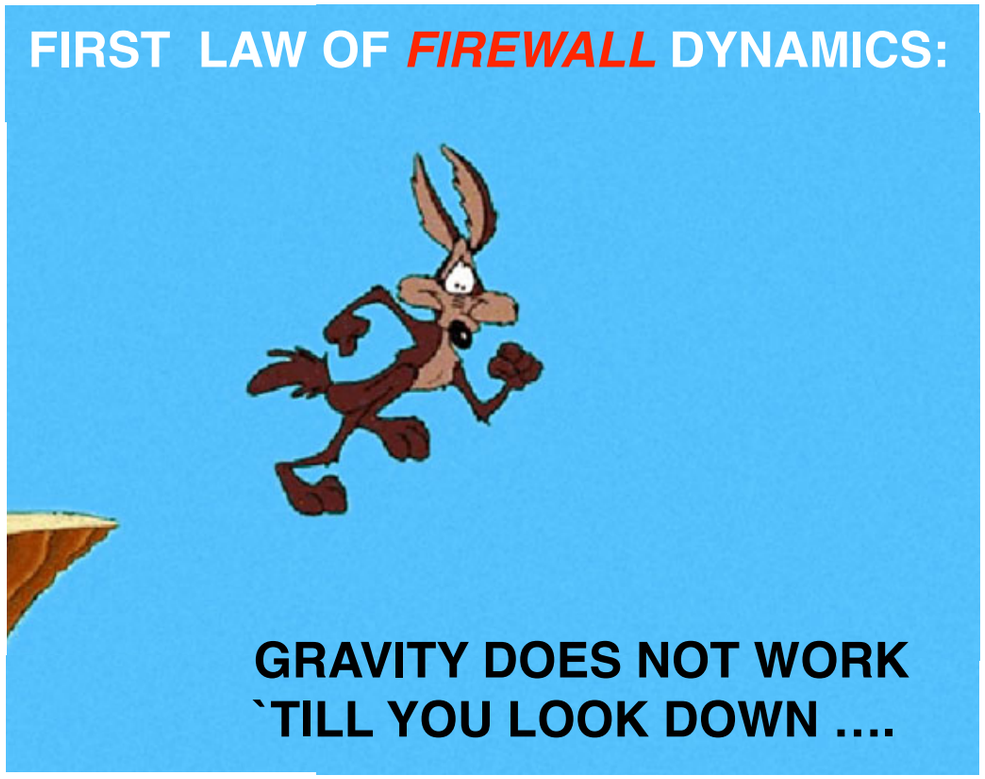
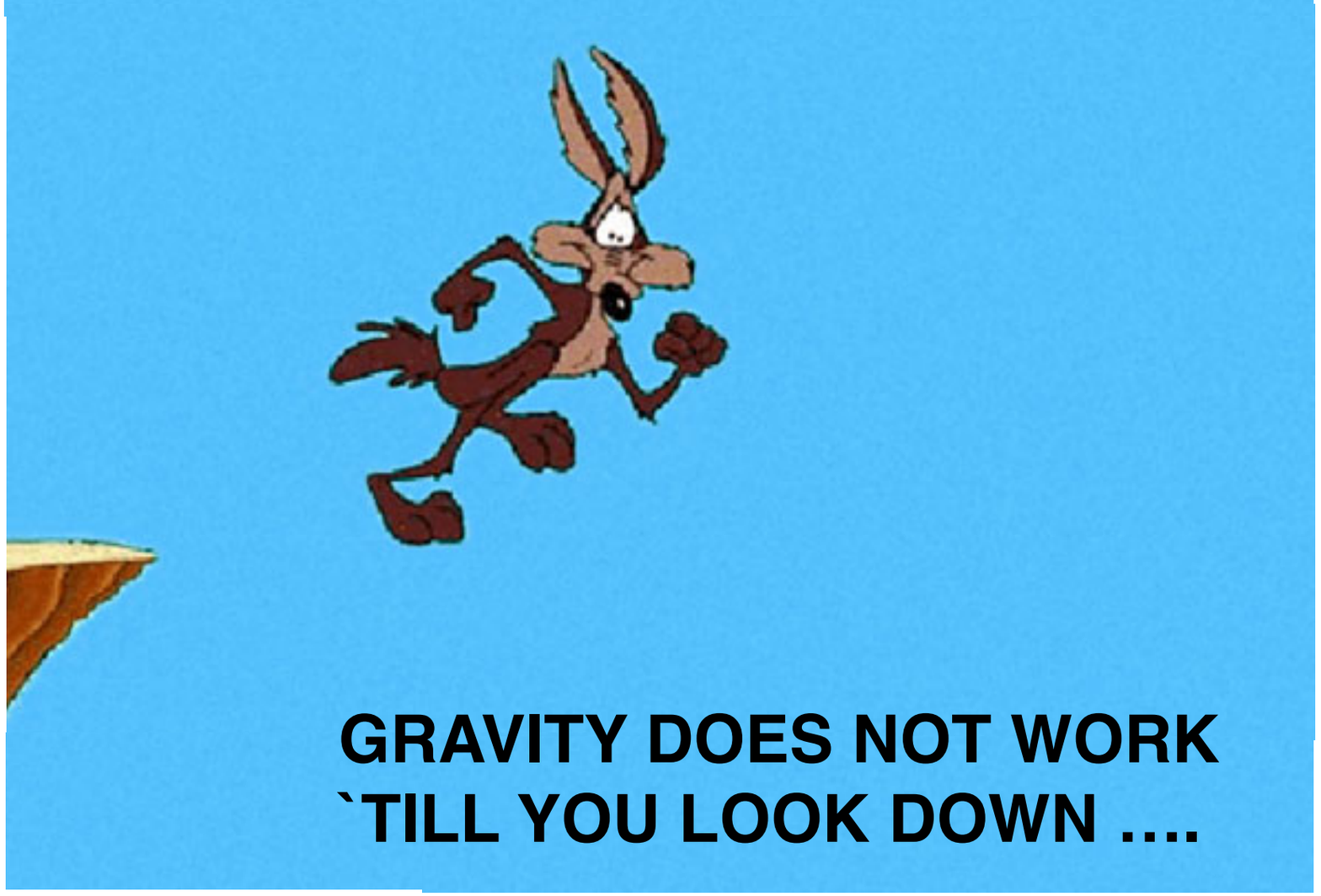




FIRST LAW OF *FIREWALL* DYNAMICS:



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The Second Problem: Growth of Microstate Structure

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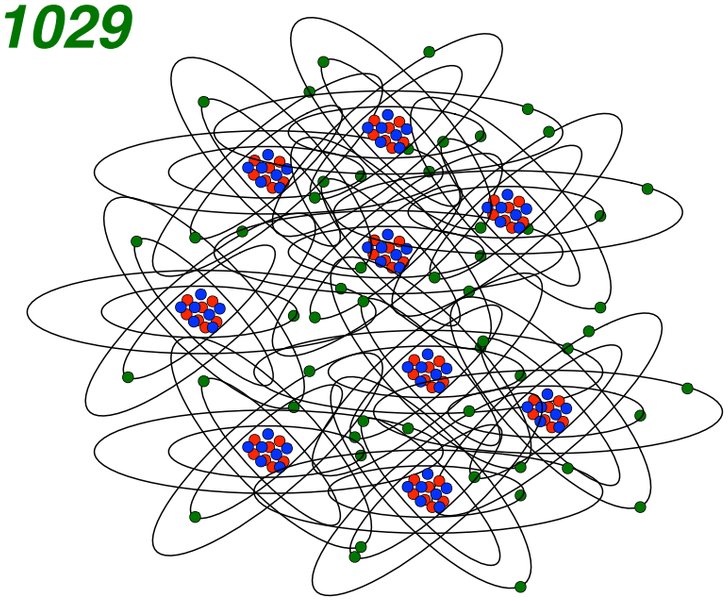
e.g. String theory: Strominger and Vafa: hep-th/9601029



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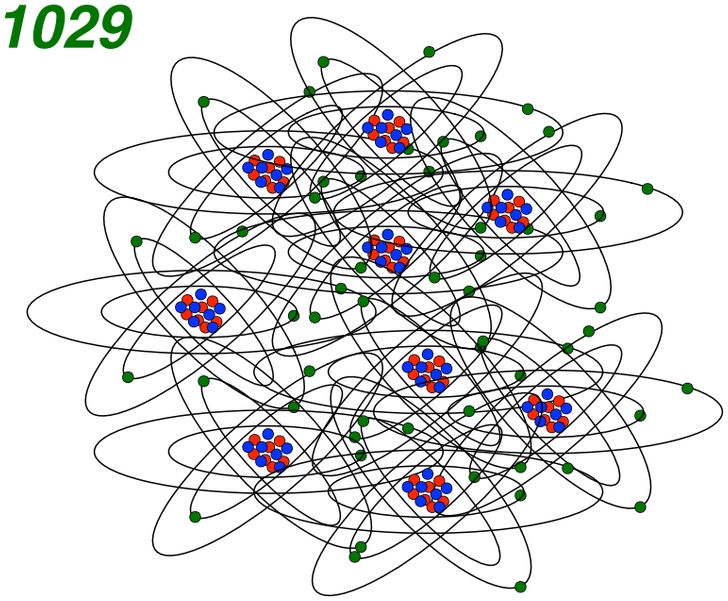

Increase G_{Newton}, (or string coupling, $\mathbf{g_s}$)

★ Perturbative matter/microstate structures ***shrink***

★ Horizon areas *grow*: $R_S = \frac{2\,G_{Newton}\,M}{c^2}$

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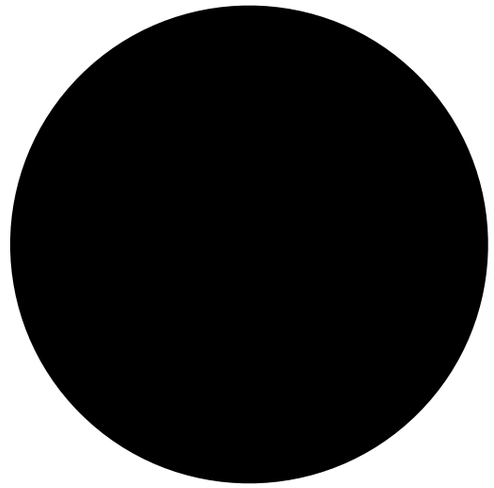

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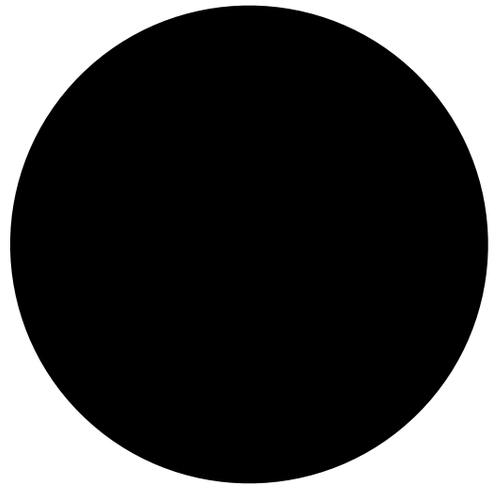

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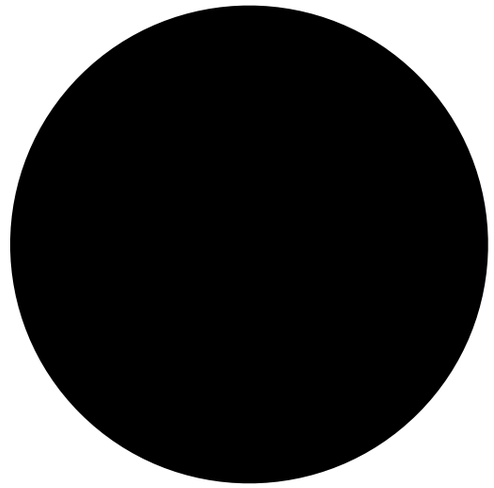

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★ The essential bottom lines:

- *Any proposed horizon-scale microstructure must grow in size ~ G_{Newton}*
- *Microstate structure cannot be supported by perturbative states/techniques, which necessarily shrink with G_{Newton}*

The Third Problem: Entropy and Black-Hole Formation

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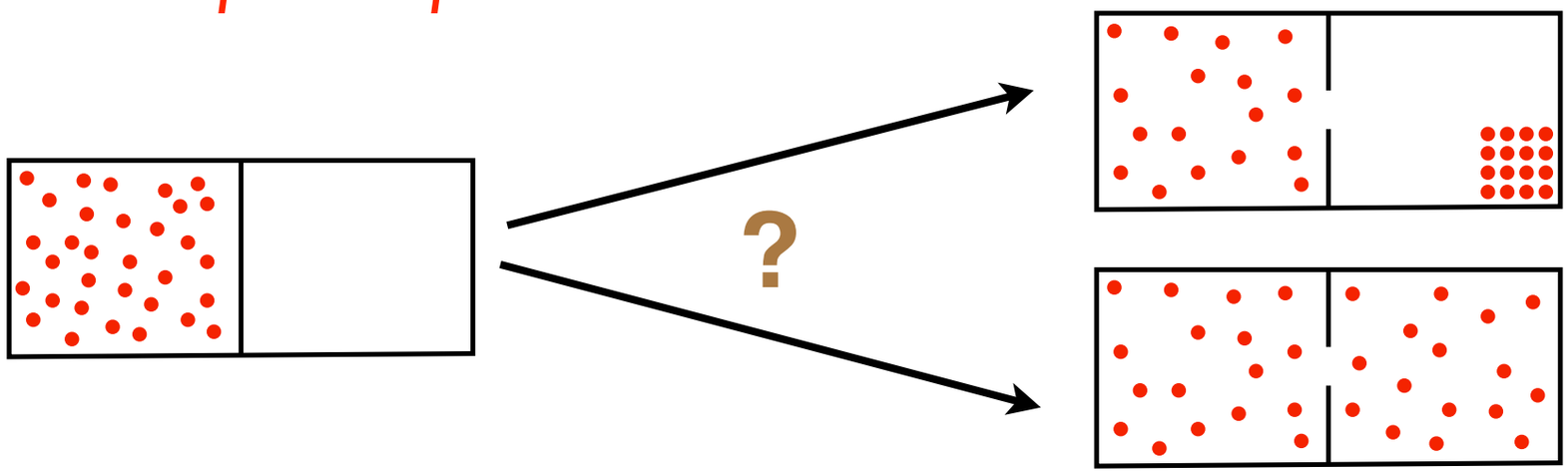

Some fine-tuned, "*atypical*" microstate

***Vast Families* of "*typical*" entropically favored microstate**

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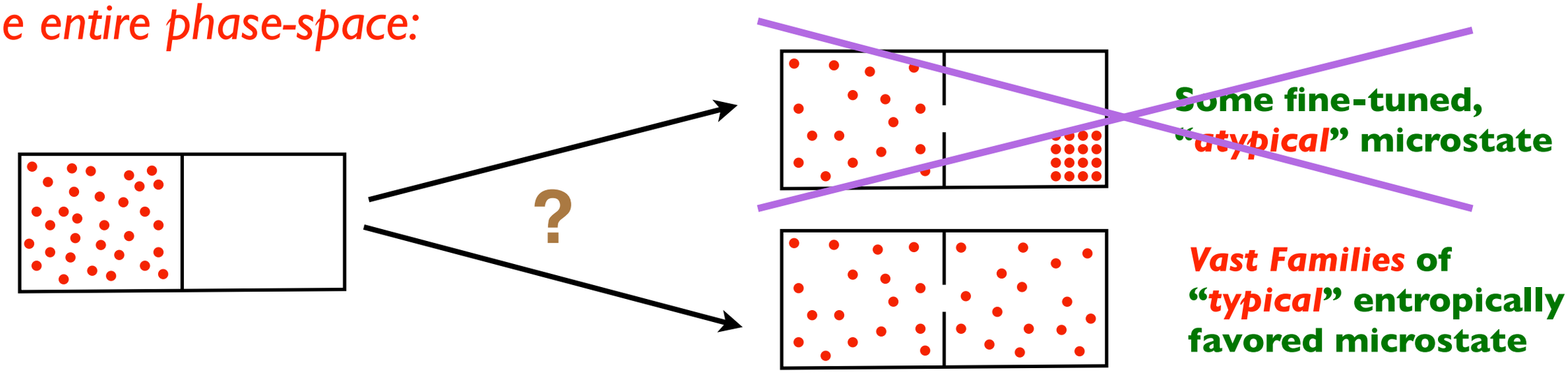

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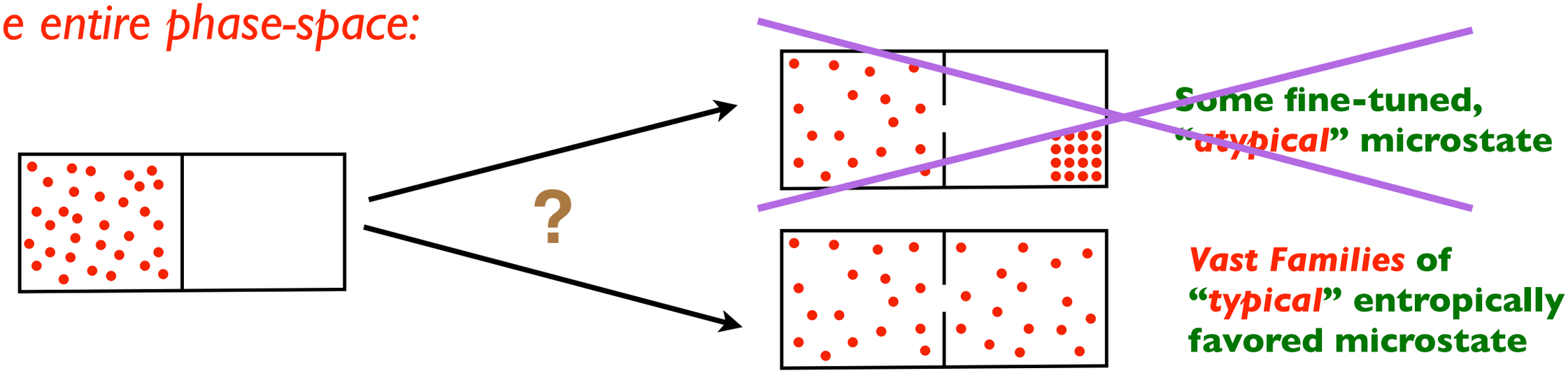

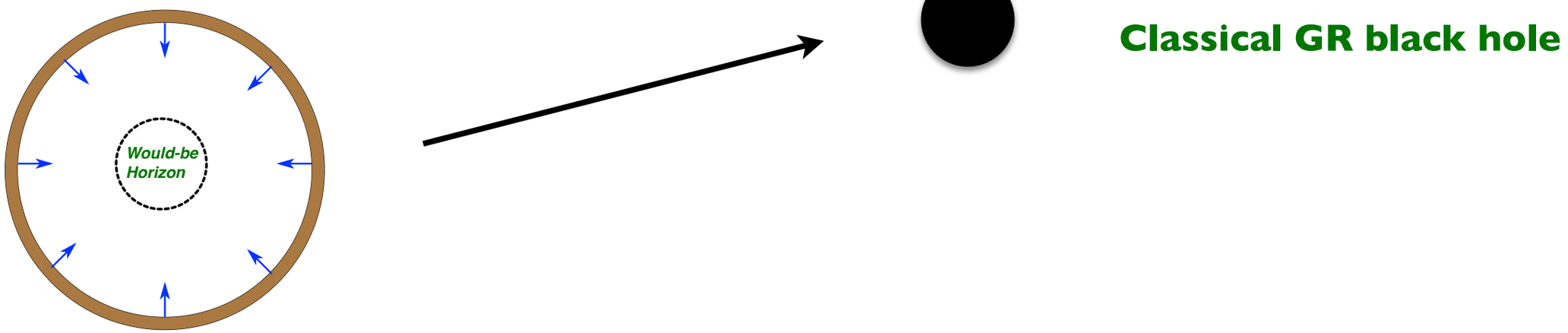

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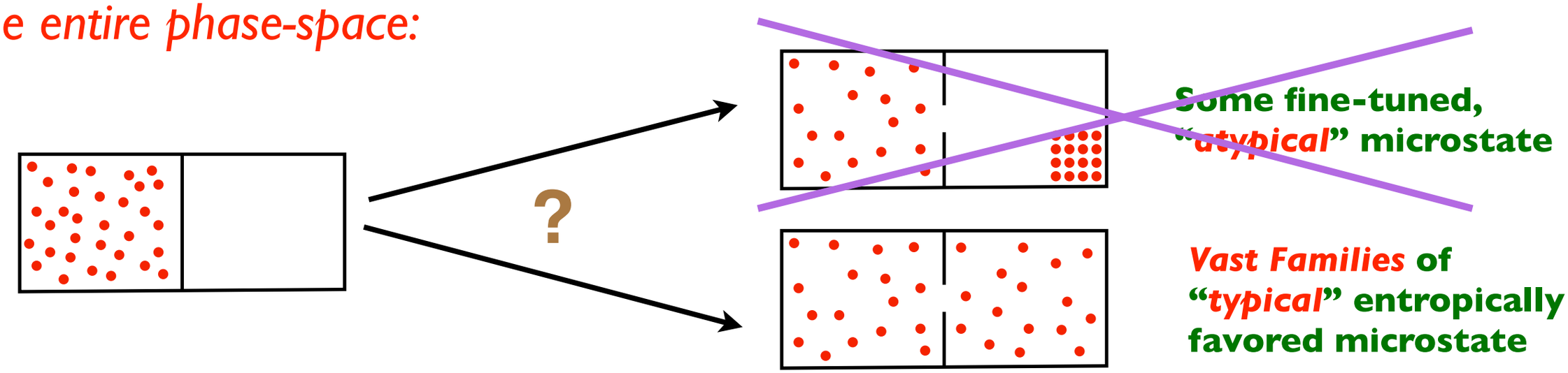

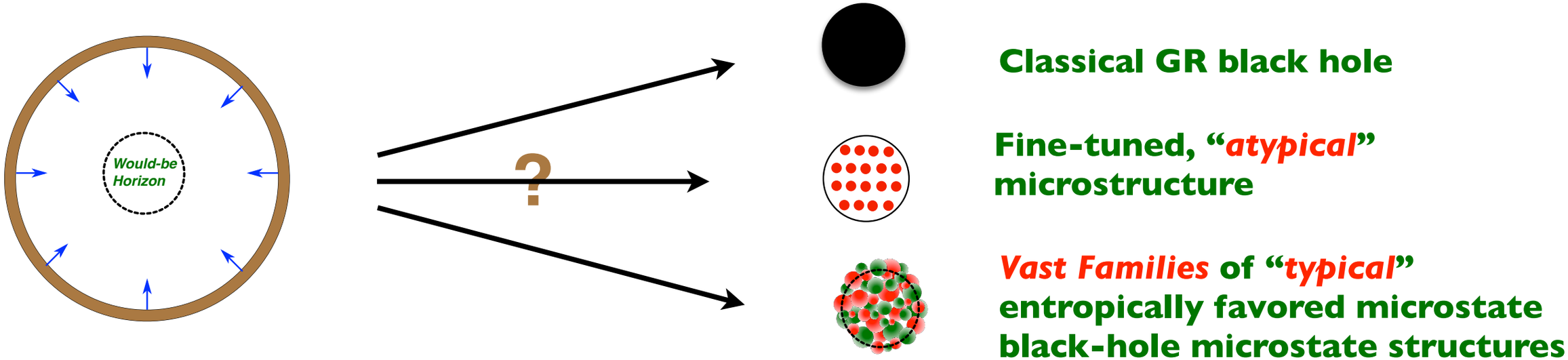

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$$N = e^{S} \sim e^{10^{90}}$$

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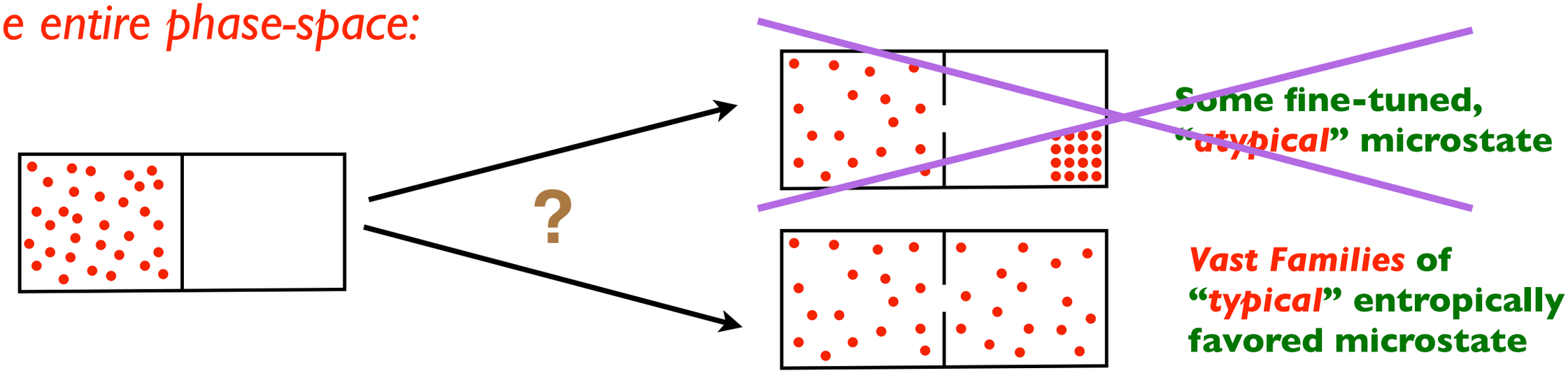

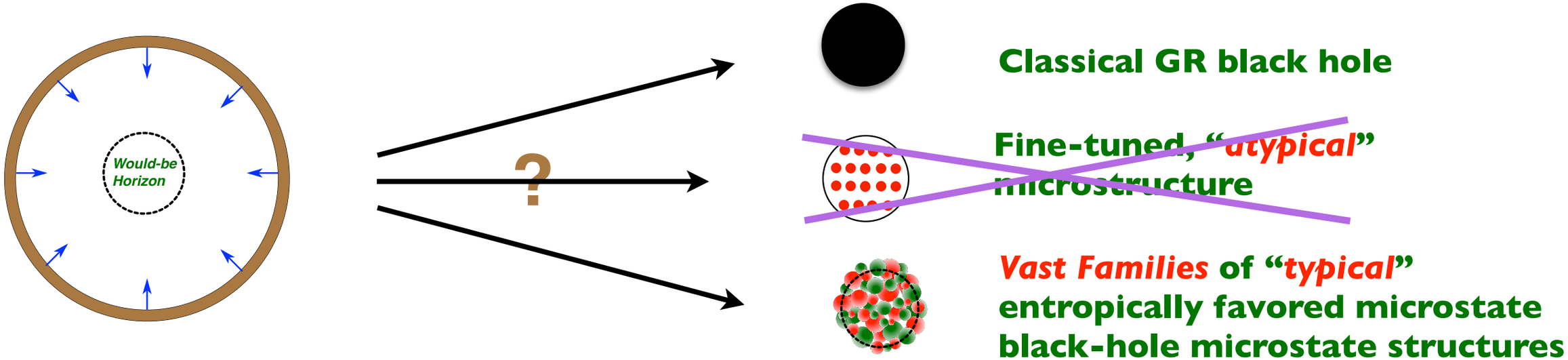

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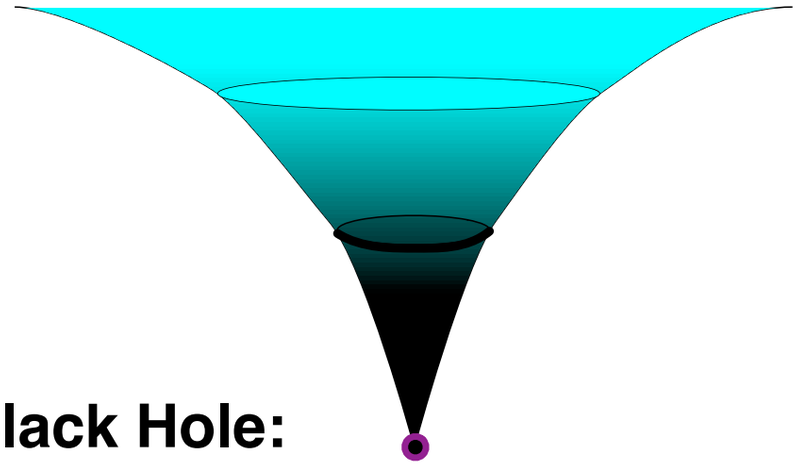
How do Microstate Geometries solve these problems?

Solving First Problem: Supporting Microstructure at the Horizon Scale



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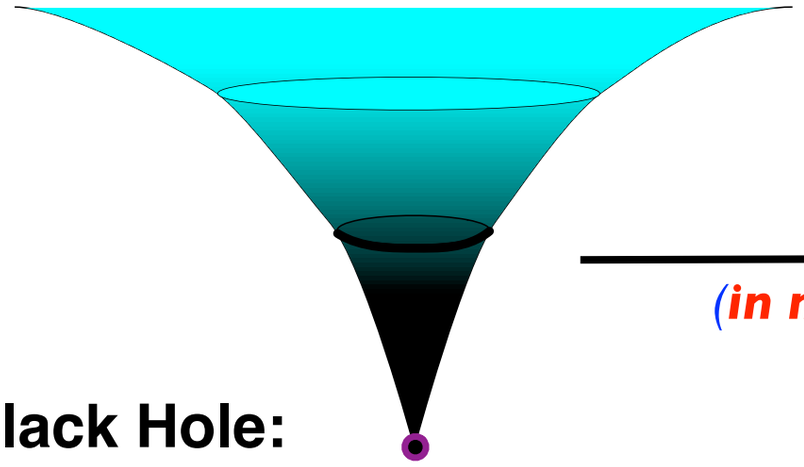

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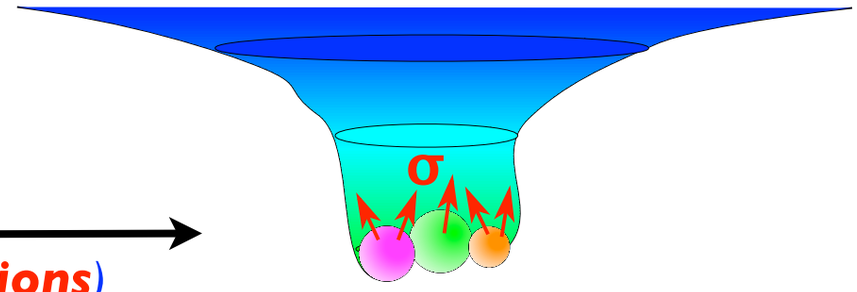
Blowing up
topological cycles

(in more than 3 spatial dimensions)



Smooth *horizonless*
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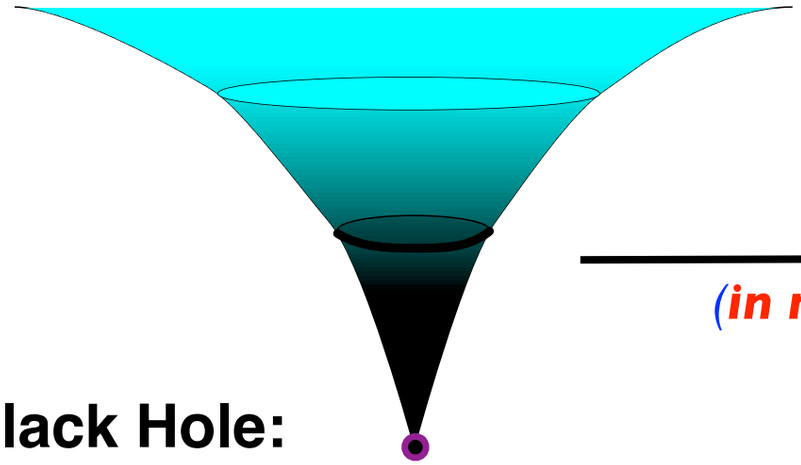

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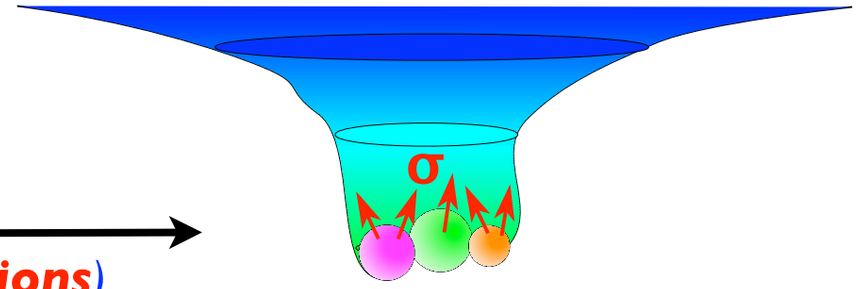

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A Transition driven by the Chern-Simons interaction

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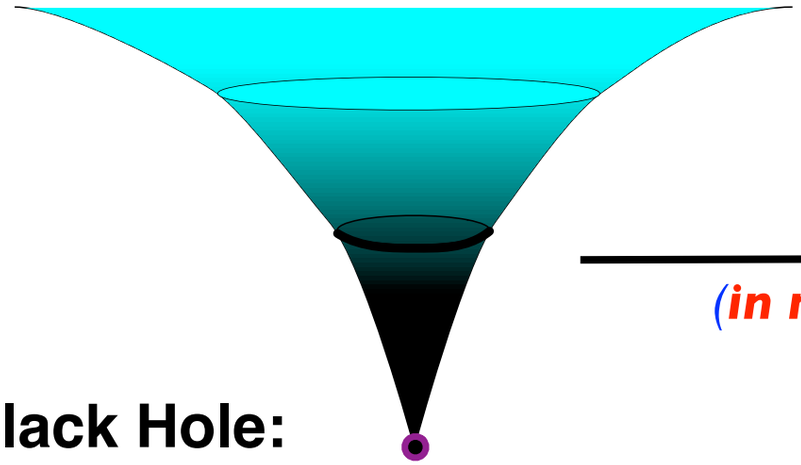

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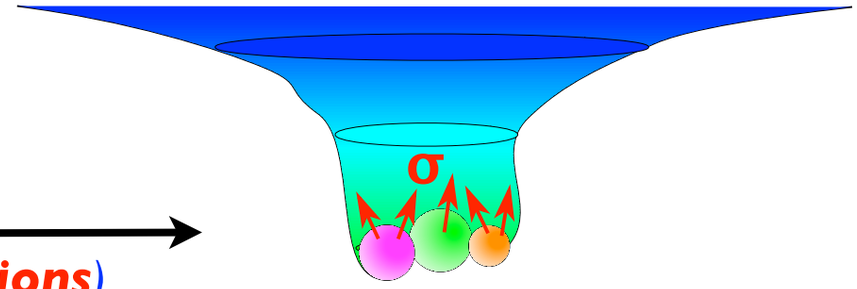

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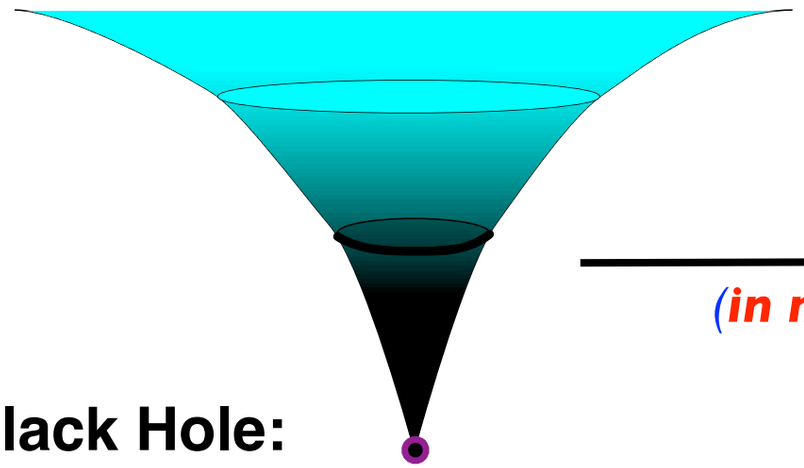

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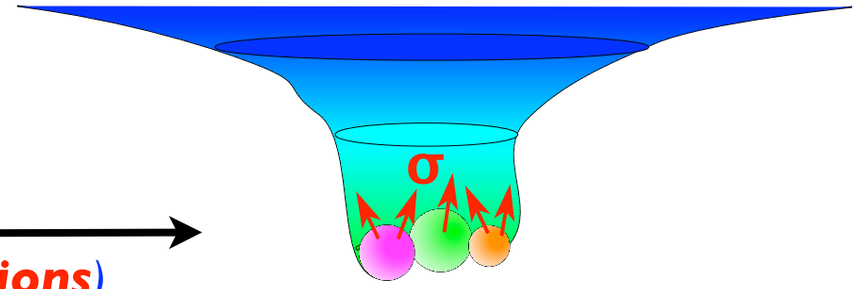

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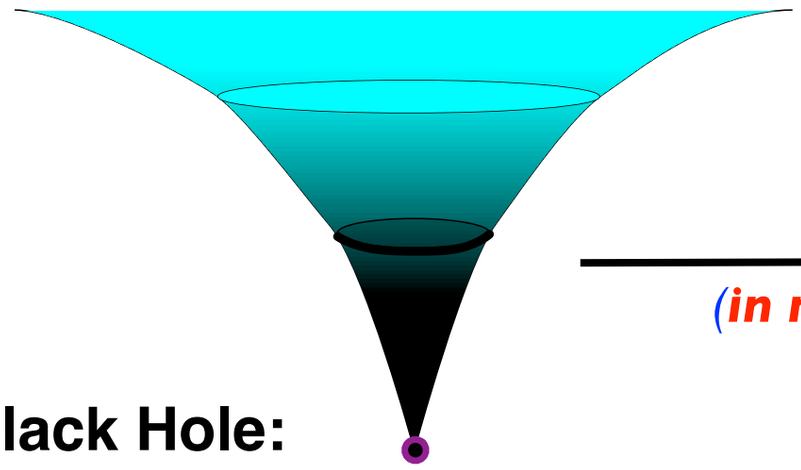

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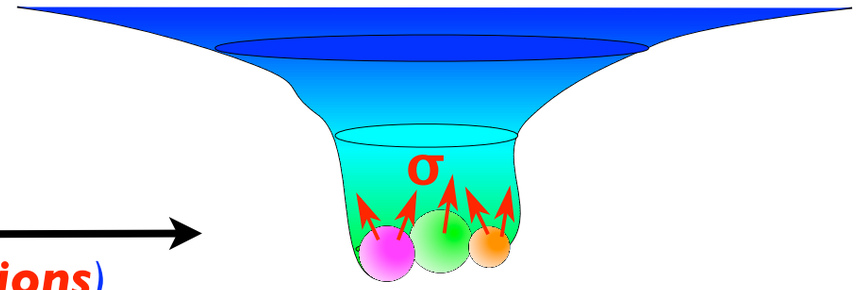

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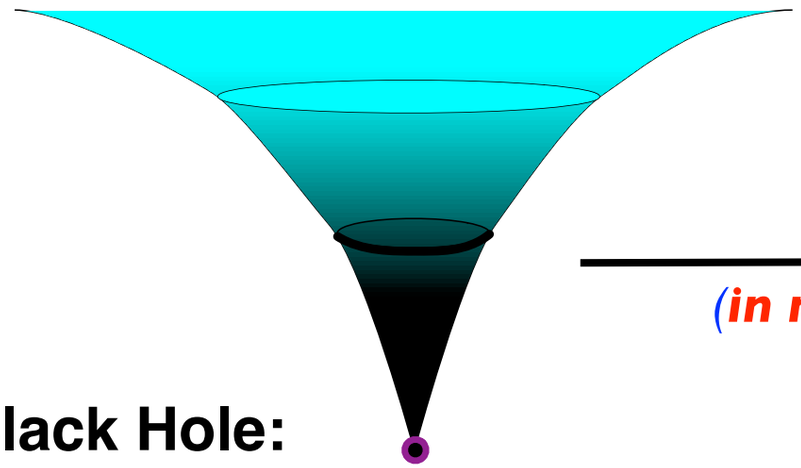

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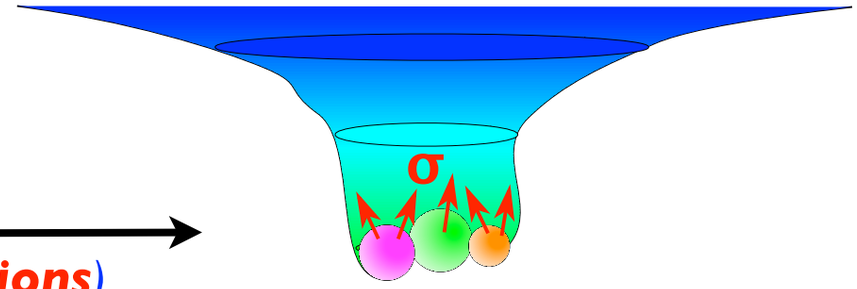

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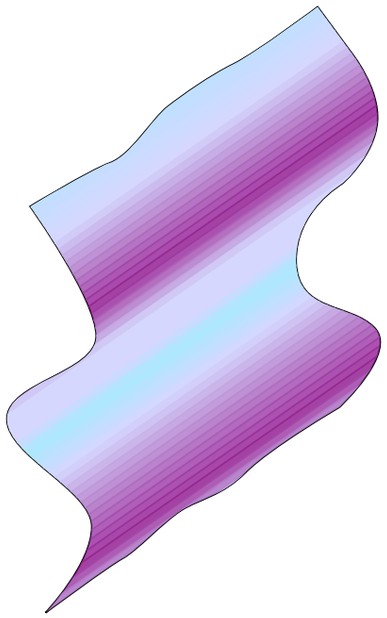

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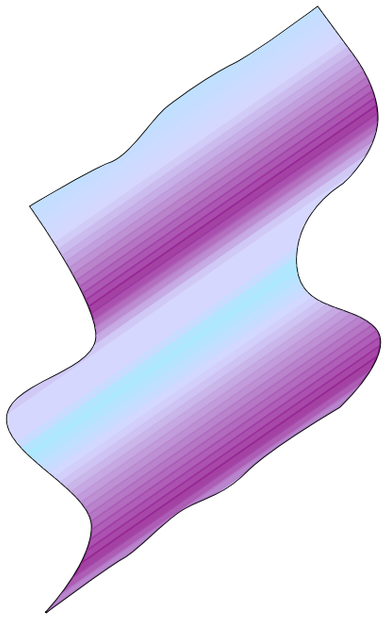
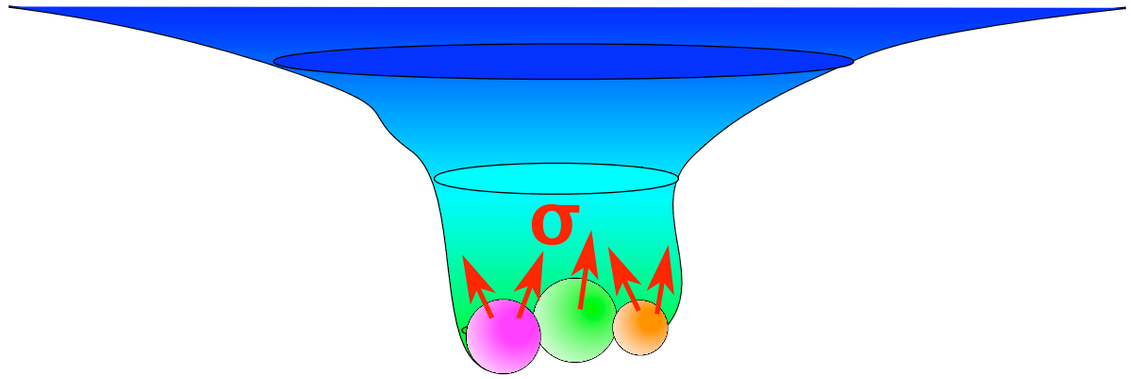


Cohomological Fluxes

Massless magnetic fluxes supported on non-trivial topology: Scale of cycles grows with G_{Newton}



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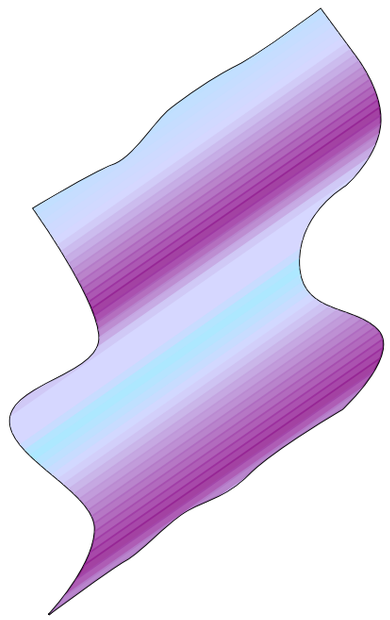

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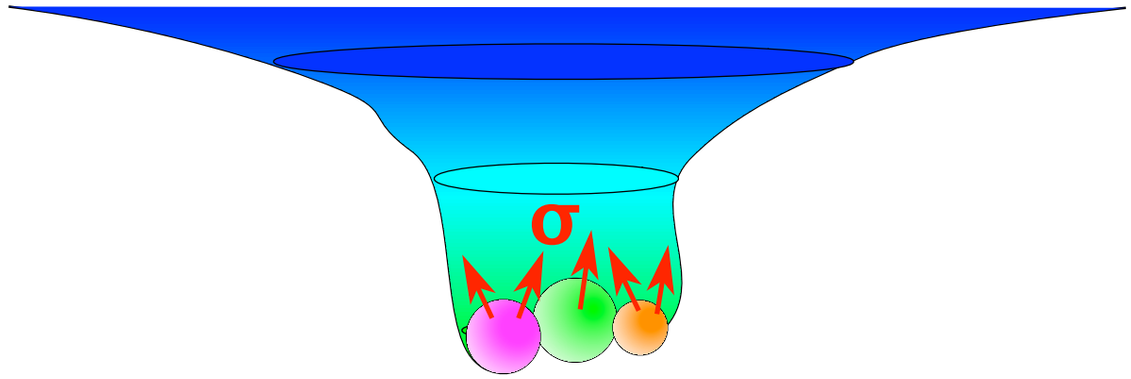

Solitons grow bigger as the (perturbative) coupling grows stronger:

Can arrange that these structures grow in size with G_{Newton} at exactly the same rate as the horizon of a black hole.

⇒ Back-reacted "*Microstate Geometries*" *extend to horizon scale*

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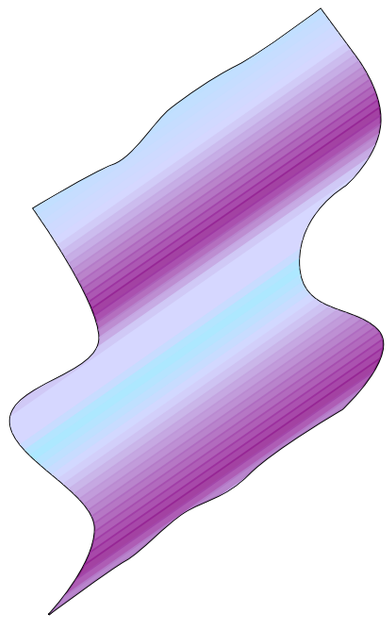

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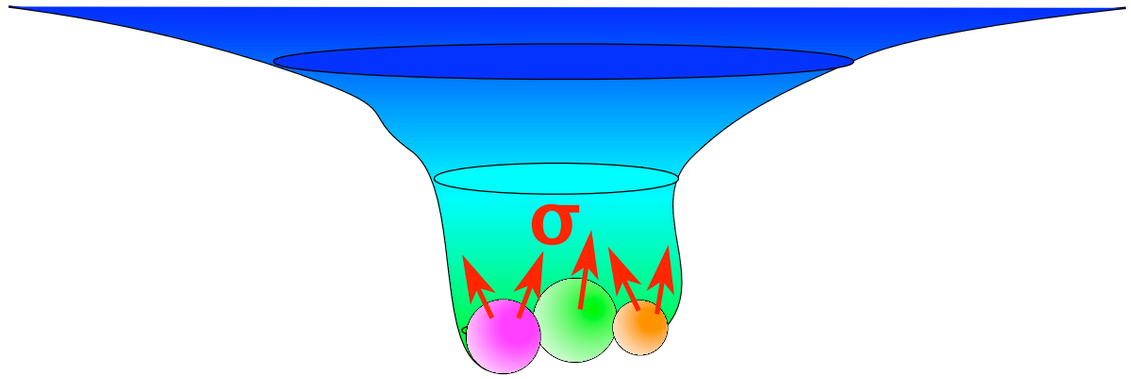

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Can only solve the growth problem with such ***solitonic*** structures …

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Strominger and Vafa: Supersymmetric black holes in string theory hep-th/9601029

- Take G_{Newton}, $g_{string} = 0$ and study configurations that gives rise to macroscopic black hole at finite G_{Newton}, g_{string}.
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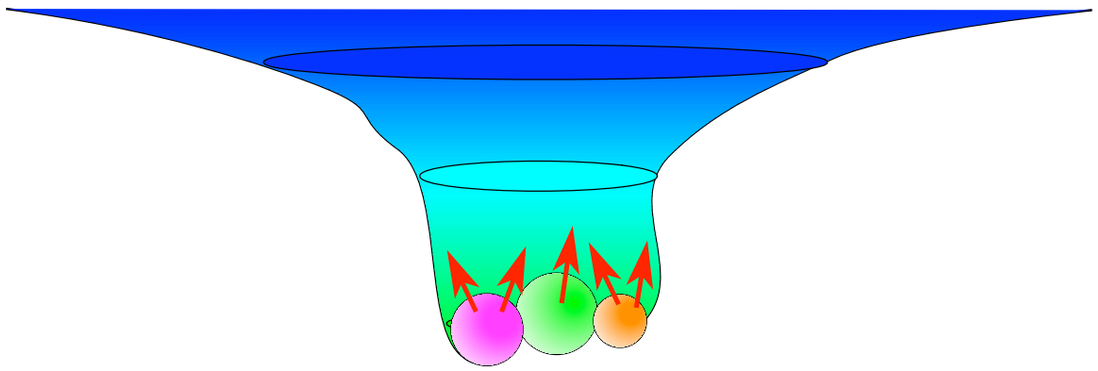
Microstate geometries play an essential role because they are the *only way* to support such structure against gravitational collapse …

Some New Black-Hole Physics

Schwarzschild black holes have *singular space-times* and depend on *only two scales*:
Mass, M and the Planck scale, ℓ_P



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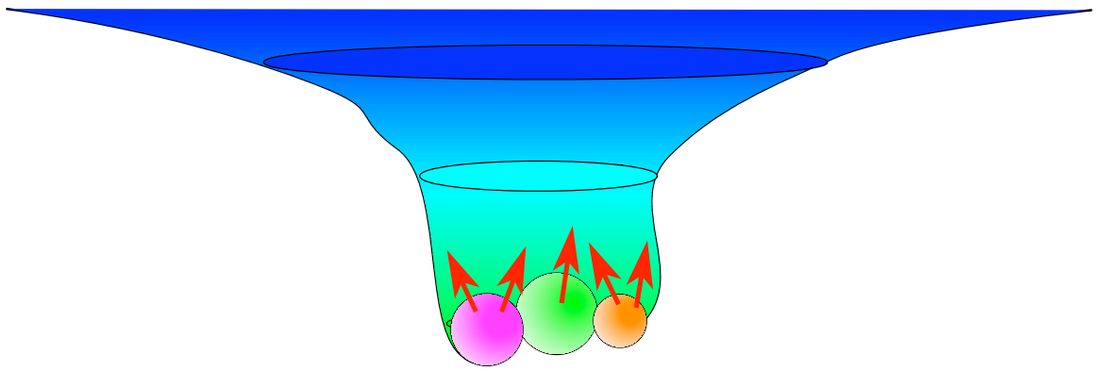

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★ Fluxes through cycles ↔ Order parameters of new phase

★ Fluctuations around the background ↔ microstate structure

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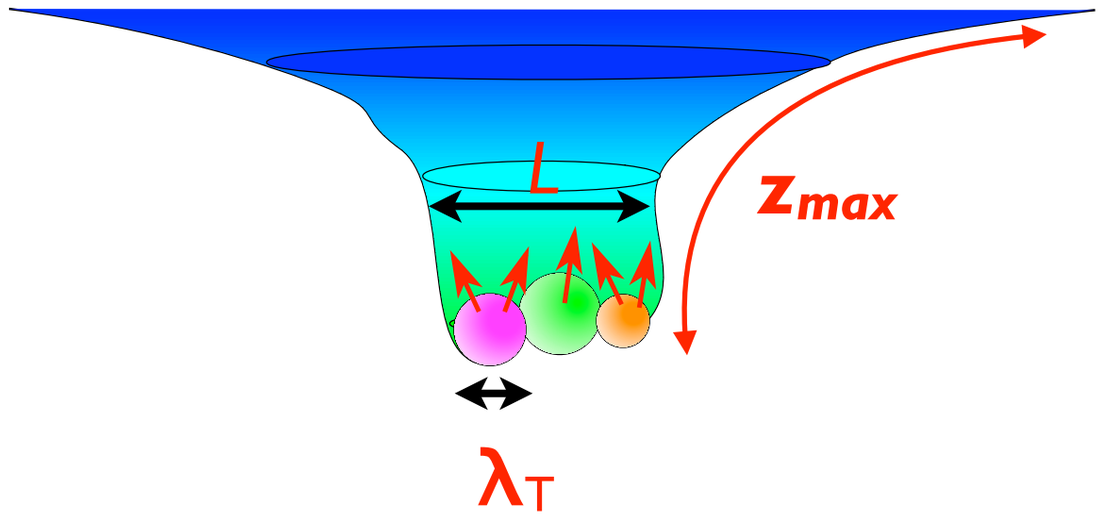
★ at least two *new* scales in black hole physics.



★ Fluxes through cycles ↔ Order parameters of new phase

★ Fluctuations around the background ↔ microstate structure

The new physical scales

★ Size, λ_T, of a typical cycle ↔ Scale of phase transition

★ *Energy Gap* = z_{max} × *(L = Horizon scale)*$^{-1}$ *defined by* z_{max} = *maximum redshift between infinity and the topology at the bottom that resolves the black hole*

Conclusions

- ★ *Microstate Geometries are the only viable, fully-back-reacted mechanism for supporting horizon-scale microstructure*
- ★ *Microstate Geometries represent a new state of matter that emerges at the horizon scale and prevents the collapse from forming a horizon or a singularity*
  - ✦ *Resolves the information problem by making all the microstate structure accessible from outside*
- ★ *Supergravity and stringy excitations of microstate geometries have the capacity to encode the vast number of microstates of a black hole*
  - ✦ *Entropically viable as end-state of collapse*

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- ★ Current Research:
  - ✦ *How these ideas extend to non-supersymmetric, astrophysical black holes.*
  - ✦ *Time-dependent phenomena: Evaporation, Accretion, Scrambling, Dynamics of Microstate Structure*