BLACK HOLES: FROM STELLAR DEATH TO PRIMORDIAL ORIGINS

ERIC CANO
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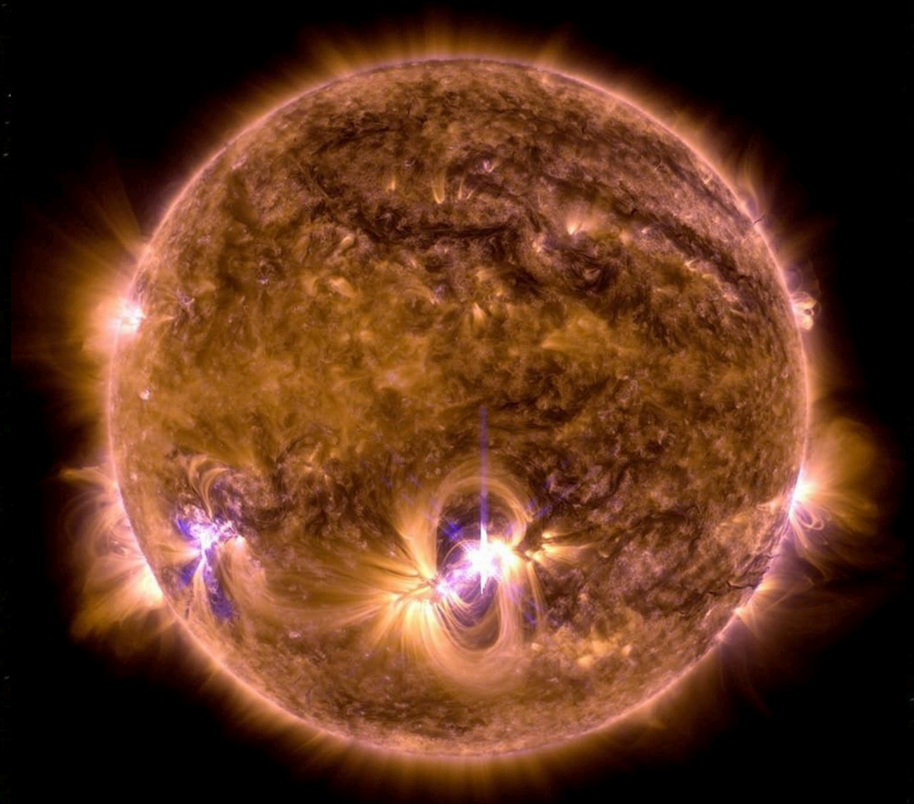
OUTLINE:

- Black Holes from Dying Stars
- Primordial Black Holes
- How We Study Black Holes
- Quantum Challenges
- What’s Next?

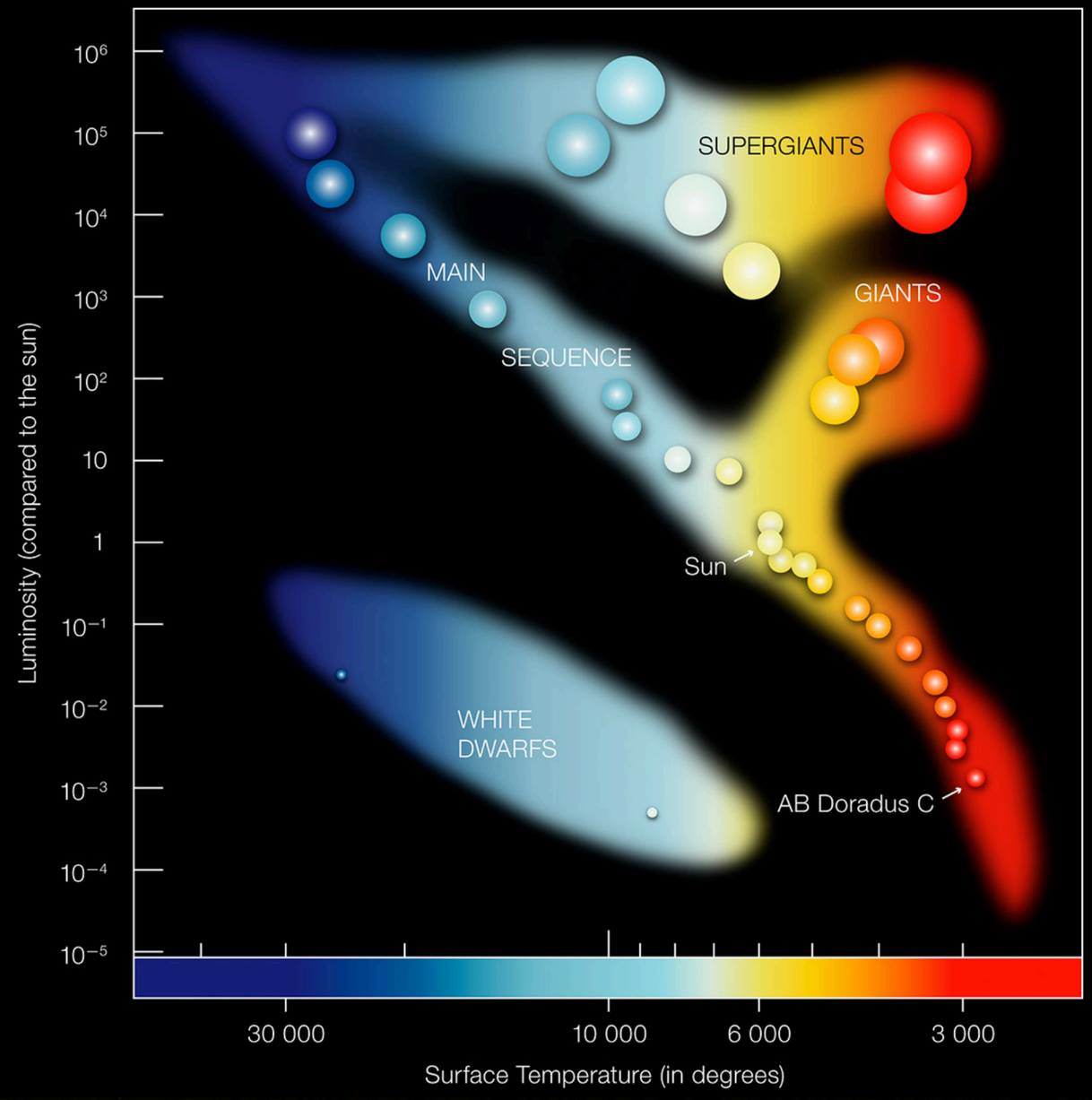
THE LIFE CYCLE OF A STAR:

- Stars are born from collapsing clouds of gas and dust.
- Fusion of hydrogen into helium provides outward pressure against gravity.
- When fusion ceases, the fate of the star depends on its mass:
- Less than 8 $M_\odot$: Becomes a white dwarf.
- From 8–25 $M_\odot$: Ends as a neutron star/pulsar.
- Greater than 25 $M_\odot$: Collapses into a black hole.



NASA's Solar Dynamics Observatory.

HR DIAGRAM:



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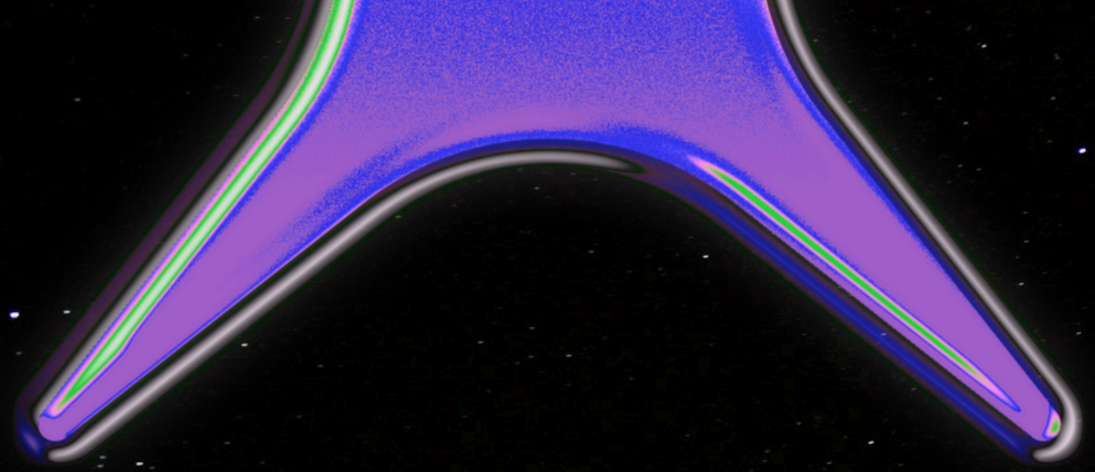
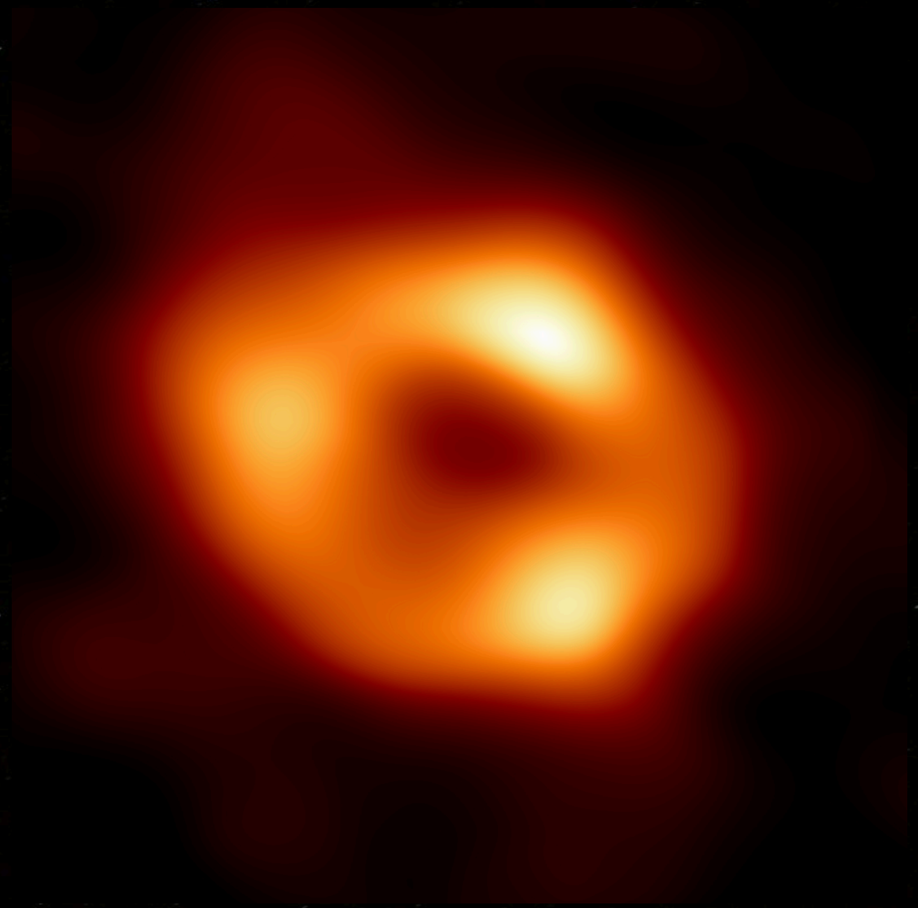


HOW BLACK HOLES FORM:

- When massive stars exhaust fuel, gravity wins, so the core collapses.
- If the remnant core is less than ~3 M⊙, neutron degeneracy pressure fails.
- Collapse continues into a singularity, forming a stellar-mass black hole.
- Surrounded by an event horizon: the point of no return.



EHT COLLABORATION

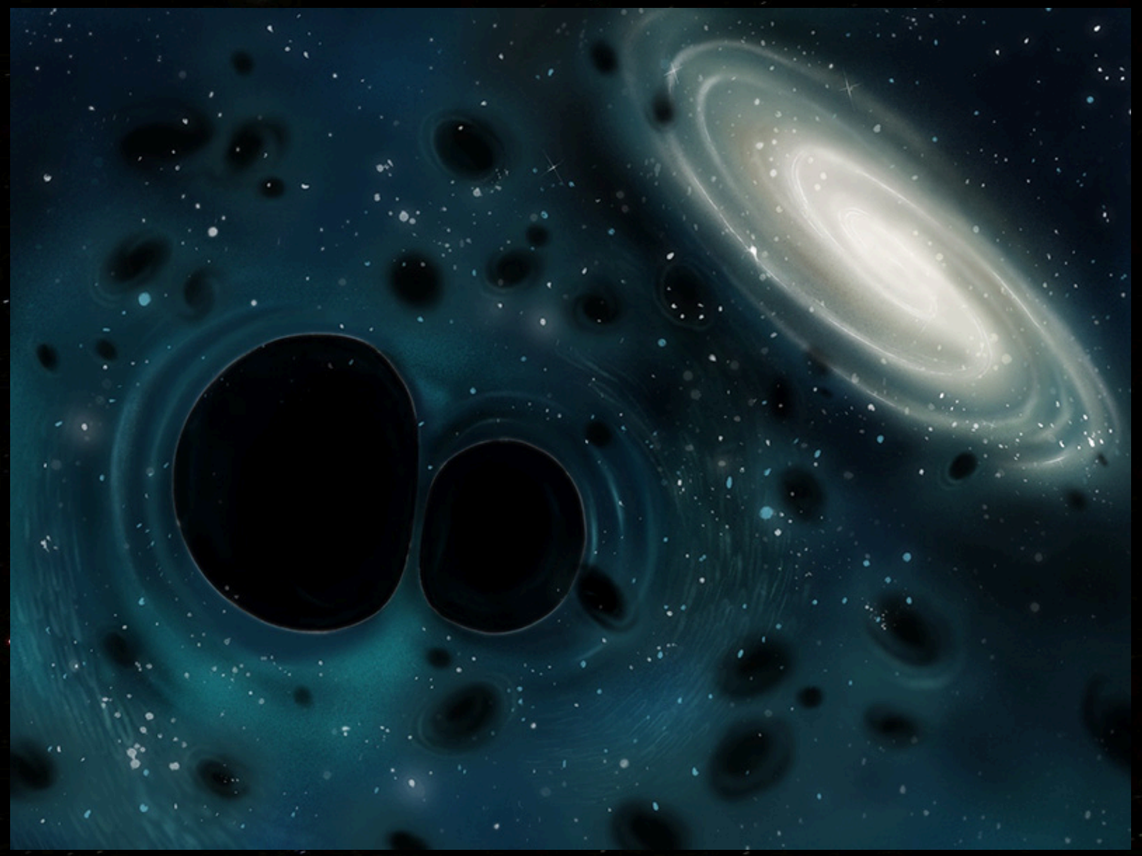
TYPES OF BLACK HOLES:

1. Stellar-Mass Black Holes (~3–20 $M_\odot$):
   - Formed via core collapse supernovae.
   - Detected in X-ray binaries.
2. Intermediate-Mass Black Holes (~100–1000 $M_\odot$):
   - Rare, may form via stellar mergers in dense star clusters.
3. Supermassive Black Holes (>10^6 $M_\odot$):
   - Found in galactic centers.
   - Origin unclear, possibly seeded by PBHs or rapid accretion.

INTERSTELLAR

WHAT ARE PRIMORDIAL BLACK HOLES (PBHS)?:

- Hypothetical black holes formed within the first second after the Big Bang.
- Not the result of star collapse, born from early universe density fluctuations.
- Mass could range from sub-atomic to thousands of solar masses.
- Could exist even before stars and galaxies formed.



PBS NEWS

HOW PRIMORDIAL BLACK HOLES MIGHT FORM

- During inflation or early universe phase transitions, some regions became over-dense.
- If density contrast > critical threshold, region collapses into a black hole.
- No need for stars, pure cosmological origin.

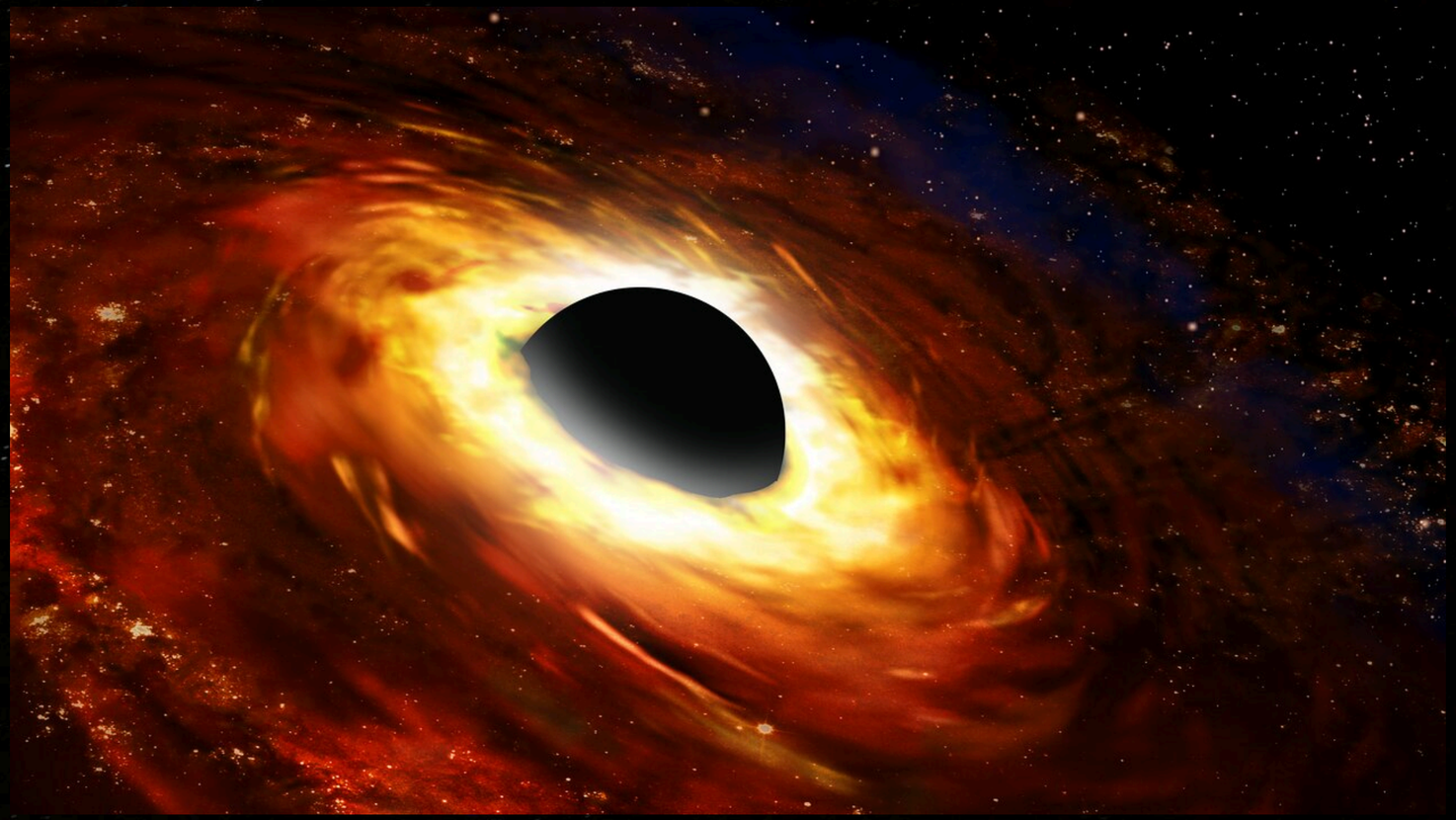
ADVANCED SCIENCE NEWS

WHY PRIMORDIAL BLACK HOLES MATTER:

- Could explain dark matter
- May have seeded early galaxy formation and even supermassive black holes.
- Contribute to gravitational wave events seen by LIGO/Virgo.
- Provide a probe of physics at energy scales unreachable by particle colliders.

DETECTING BLACK HOLES:

- Stellar black holes:
  - Accretion disks emit X-rays (X-ray binaries).
  - LIGO detects their mergers via gravitational waves.
- Primordial black holes:
  - Detected via microlensing, disruption of star orbits, or even evaporation (Hawking radiation) if small enough.
  - Current constraints come from CMB and galactic observations.



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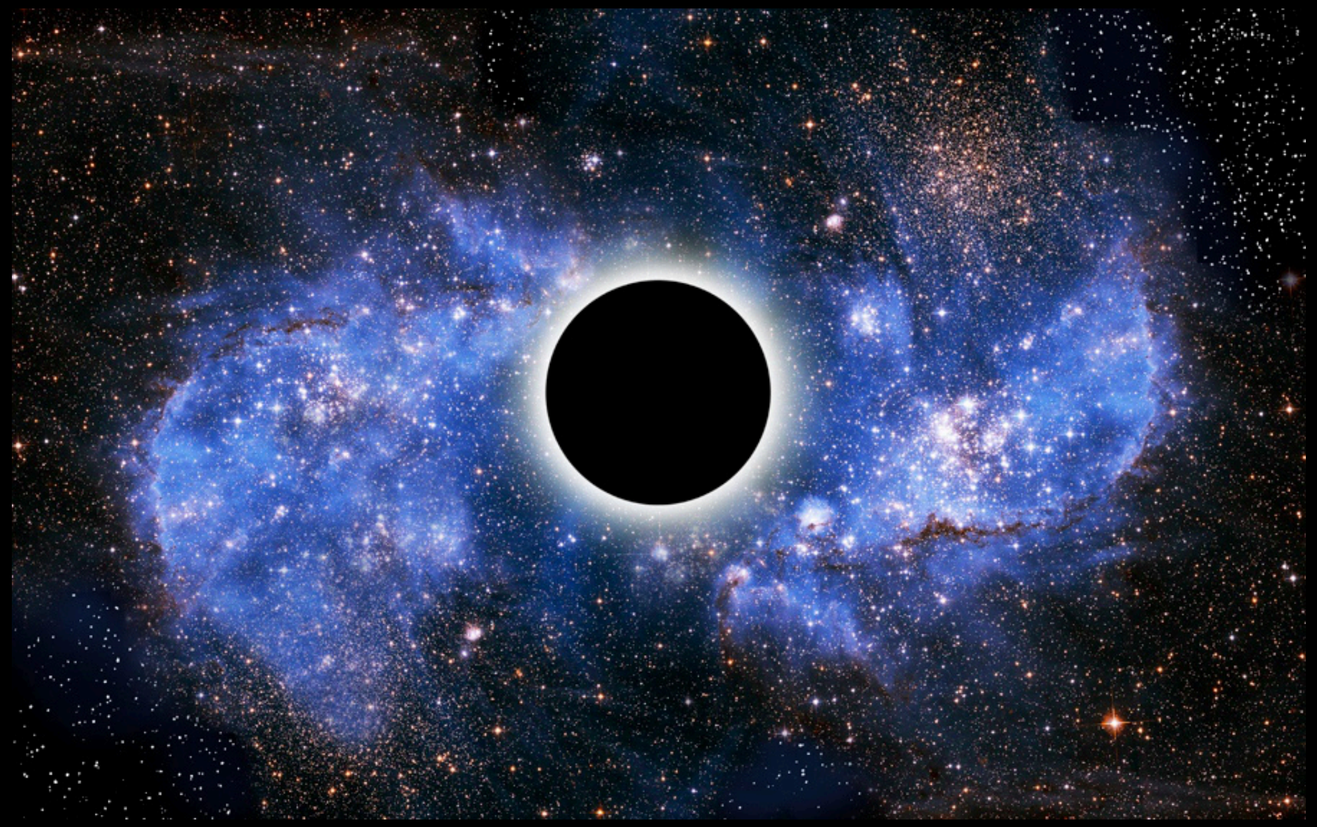
THE BLACK HOLE INFORMATION PARADOX

The Problem:

- Hawking radiation suggests black holes slowly lose mass and can eventually evaporate completely.
- If nothing escapes from within the event horizon, and the black hole disappears, then the information about the matter that fell in appears lost forever.
- This violates a key rule in quantum mechanics, which says that information must always be preserved, even if transformed.

Why It Matters:

- This paradox exposes a fundamental conflict between quantum mechanics and general relativity.
- It suggests that our current understanding of physics breaks down in extreme conditions like black holes.
- Solving it could lead to a breakthrough in quantum gravity, which is a theory that unifies the forces of nature and explains what happens at the center of a black hole or at the Big Bang.



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CONCLUSION

- Black holes, both regular and primordial, offer insight into gravity, quantum mechanics, and cosmology.
- PBHs could unlock secrets of dark matter, the early universe, and high-energy physics.
- Studying black holes connects us to the deepest questions about space, time, and the nature of reality.

CITATIONS

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