NCTS-TCA Summer Student Program (SSP) 2025

Black Holes: Nature's Ultimate Mystery.

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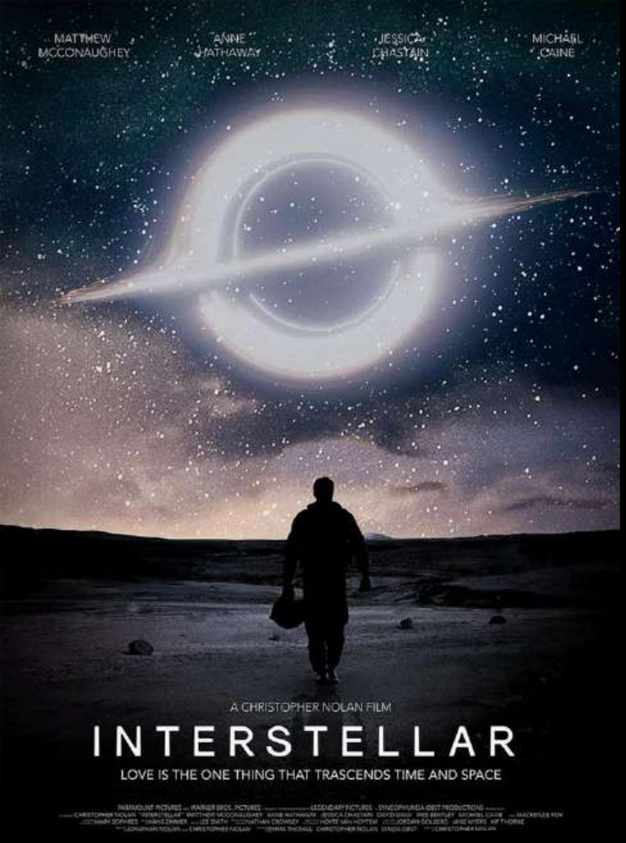
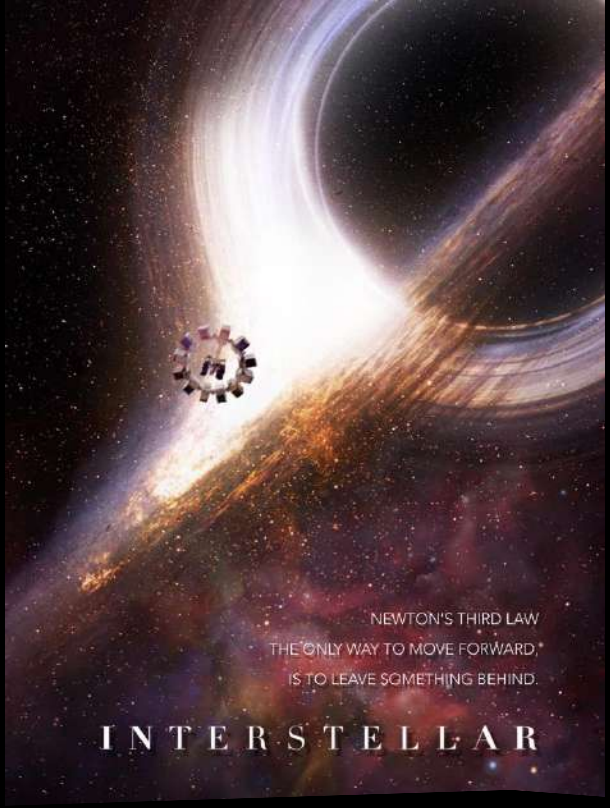
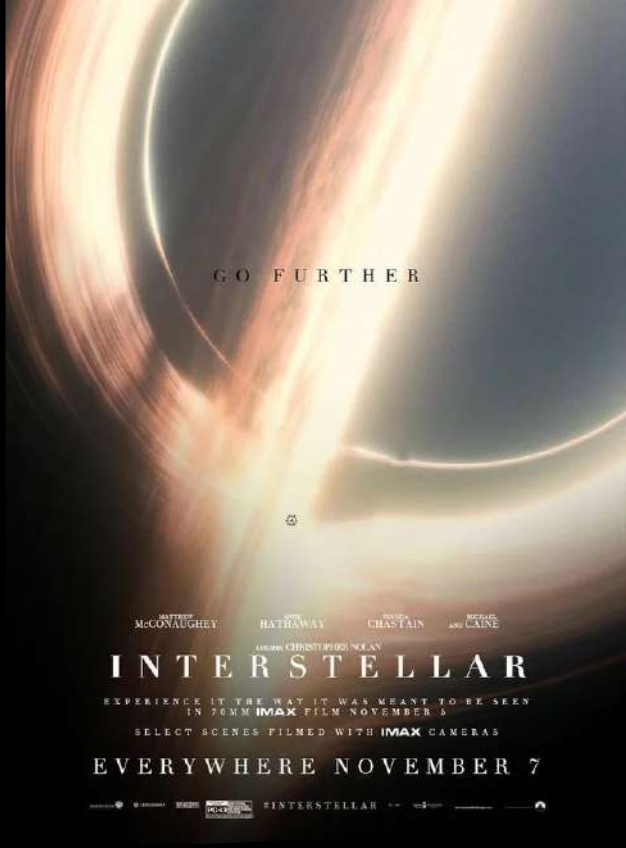
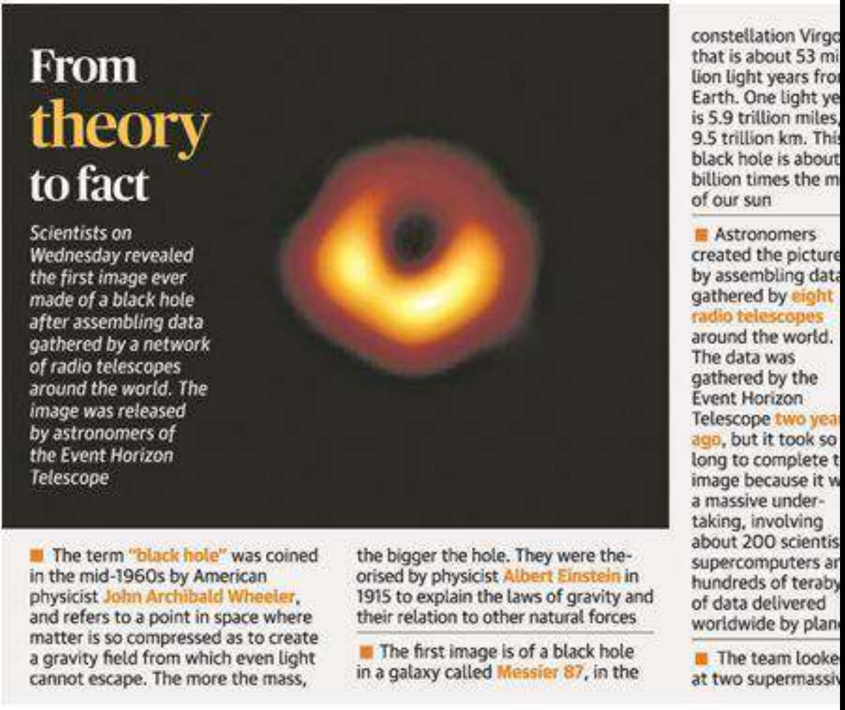
Black Holes:
Nature's Ultimate Mystery.







- Release date: November 7, 2014
- Director: Christopher Nolan


From theory to fact
Scientists on Wednesday revealed the first image ever made of a black hole after assembling data gathered by a network of radio telescopes around the world. The image was released by astronomers of the Event Horizon Telescope
constellation Virgo that is about 53 million light years from Earth. One light year is 5.9 trillion miles, 9.5 trillion km. This black hole is about billion times the mass of our sun
Astronomers created the picture by assembling data gathered by eight radio telescopes around the world. The data was gathered by the Event Horizon Telescope two years ago, but it took so long to complete the image because it was a massive undertaking, involving about 200 scientists, supercomputers and hundreds of terabytes of data delivered worldwide by plane
The term "black hole" was coined in the mid-1960s by American physicist John Archibald Wheeler, and refers to a point in space where matter is so compressed as to create a gravity field from which even light cannot escape. The more the mass, the bigger the hole. They were theorised by physicist Albert Einstein in 1915 to explain the laws of gravity and their relation to other natural forces
The first image of a black hole in a galaxy called Messier 87, in the
The team looked at two supermassive


for over-50s
No music, no hipster chefs
my guide to an 'attainable body'
Blackmailers threaten release of Assange embassy 'sex secrets'
May defies Tory rebels with pledge to stay on
I can still strike Brexit deal, PM tells EU leaders
... and here's another inescapable black hole


JOURNAL
The Washington
Barr to P 'Spying' Trump
A new horizon
n Gives U.K. Resolve Brexit

April 2019


The Washington Post
Barr thinks U.S. spied on Trump
WILL REVIEW 2016 DECISIONS IN RUSSIA PROBE
Treasury declines to release returns on time
A new horizon
Drawn from across the cosmos, the captivating first image of a black hole required a planet-size telescope

Q.1 What is a black hole?

Q.2 How are they formed?

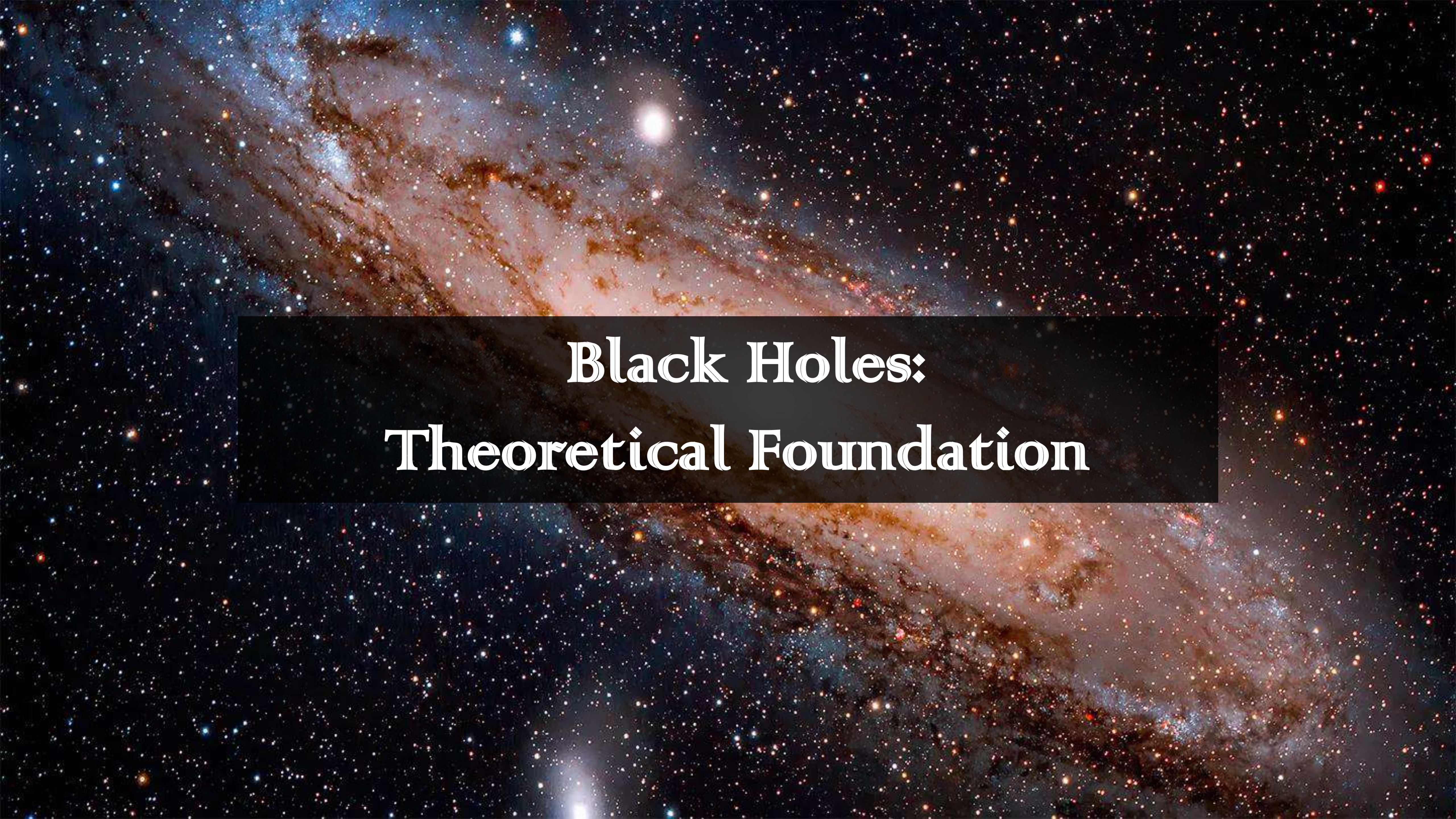
Q.3 How do we observe them?

Q.4 What happens to them over time?

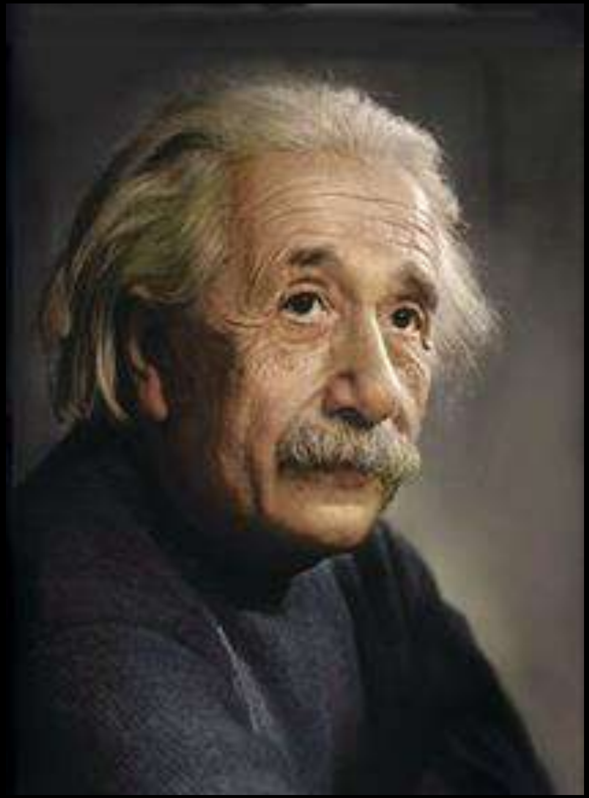
Black Holes:
Nature's Ultimate Mystery.

OUTLINE

- Introduction to Black Holes
- Theoretical Foundations
- Types of Astrophysical BHs
- Observational Evidence
- Formations & growth
- Open research questions
- Summary.



Black Holes: Theoretical Foundation

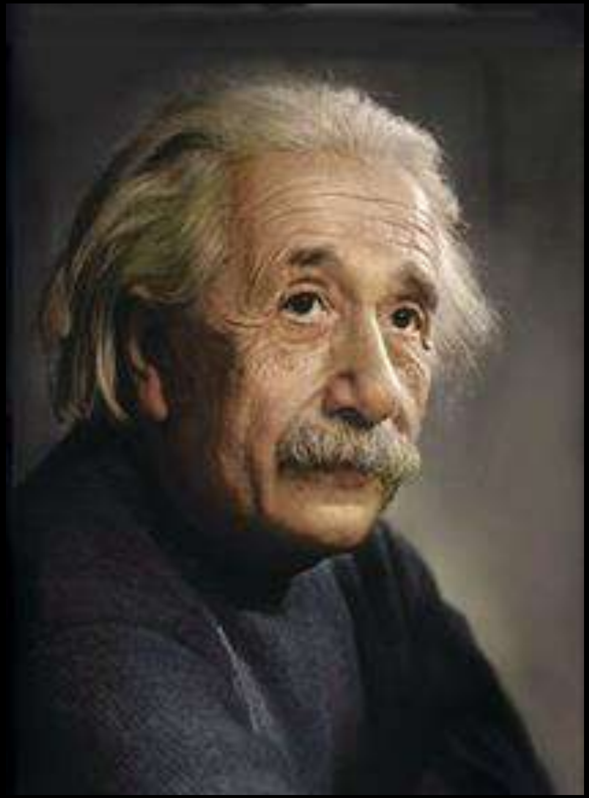


Weak Gravity
(Newton's law of gravity)

$$F = \frac{G\, M_1 M_2}{r^2}$$

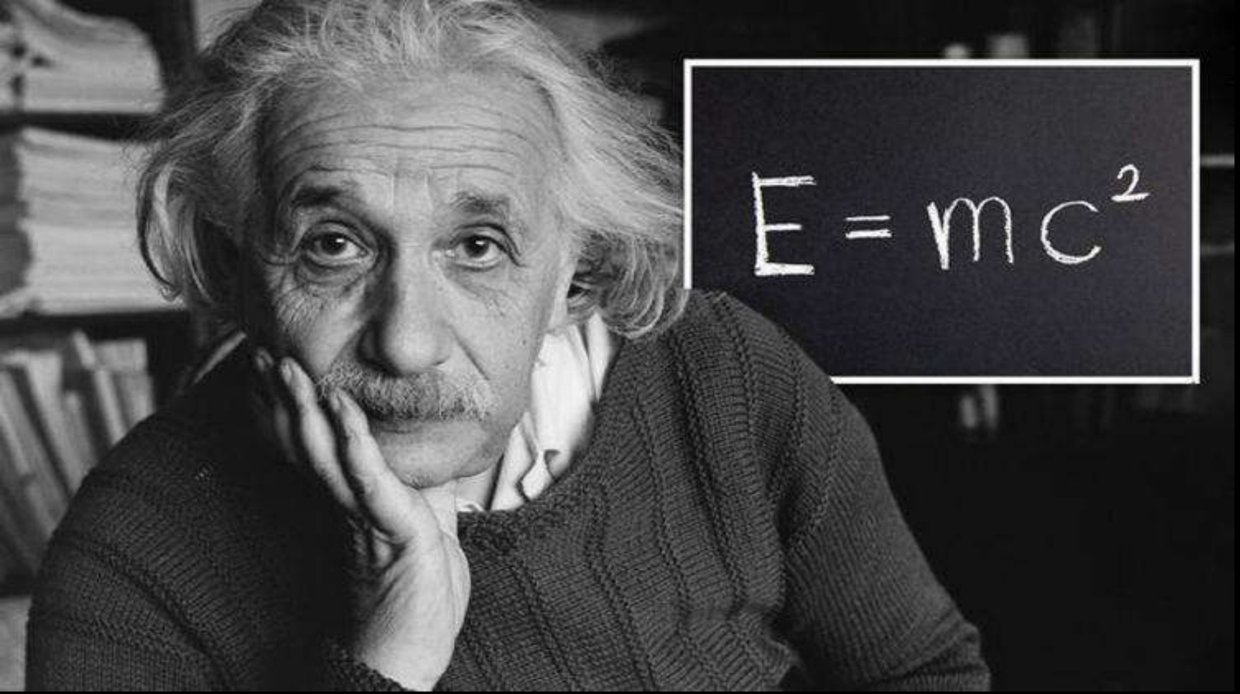
Strong Gravity
(General relativity)

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T\mu\nu$$



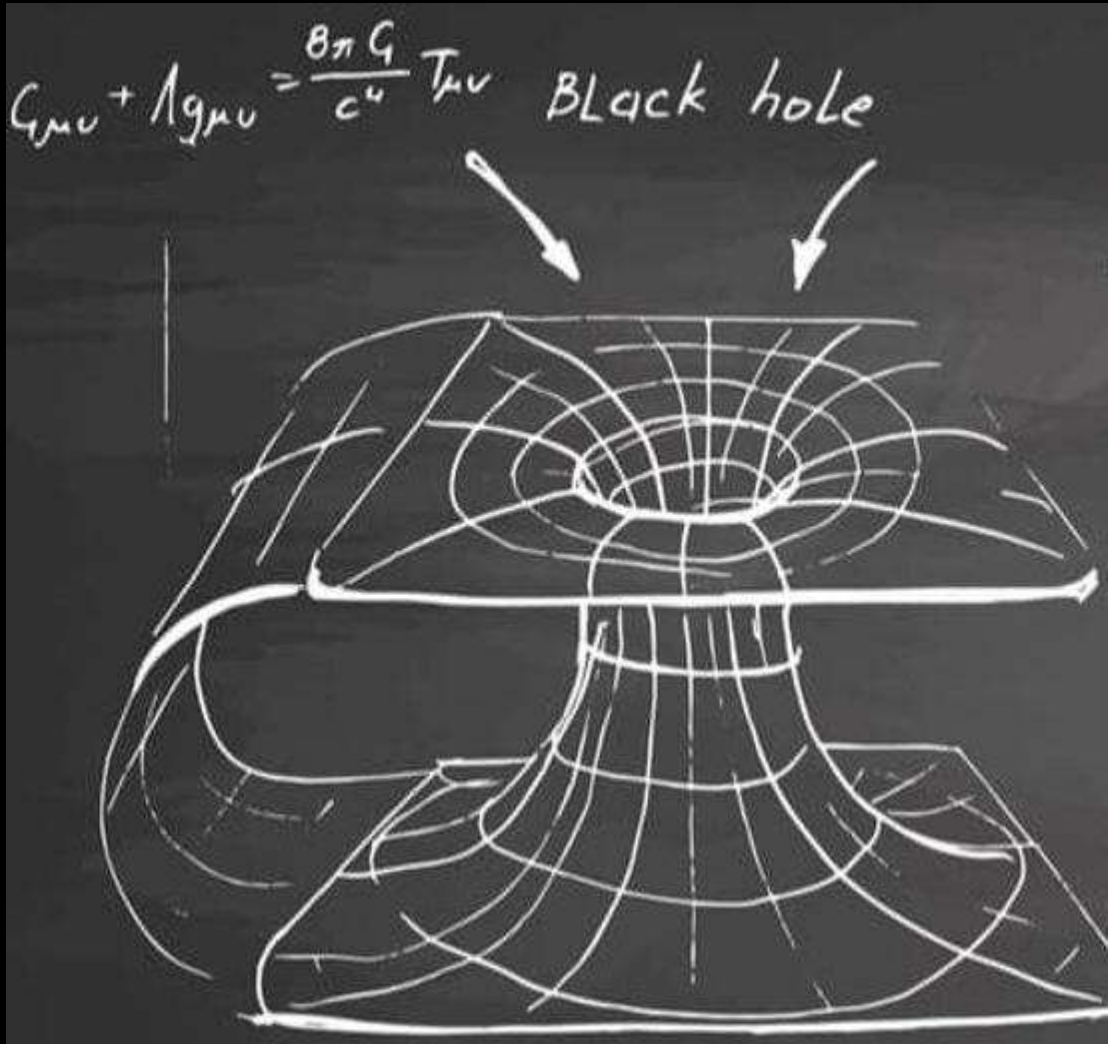
(**Newton's law of gravity**)

- ❌ No light bending prediction
- ❌ Fails to explain Mercury's orbit precession
- ❌ Breaks down in strong-field two-body systems
- ❌ Cannot describe black holes
- ❌ No prediction of gravitational waves

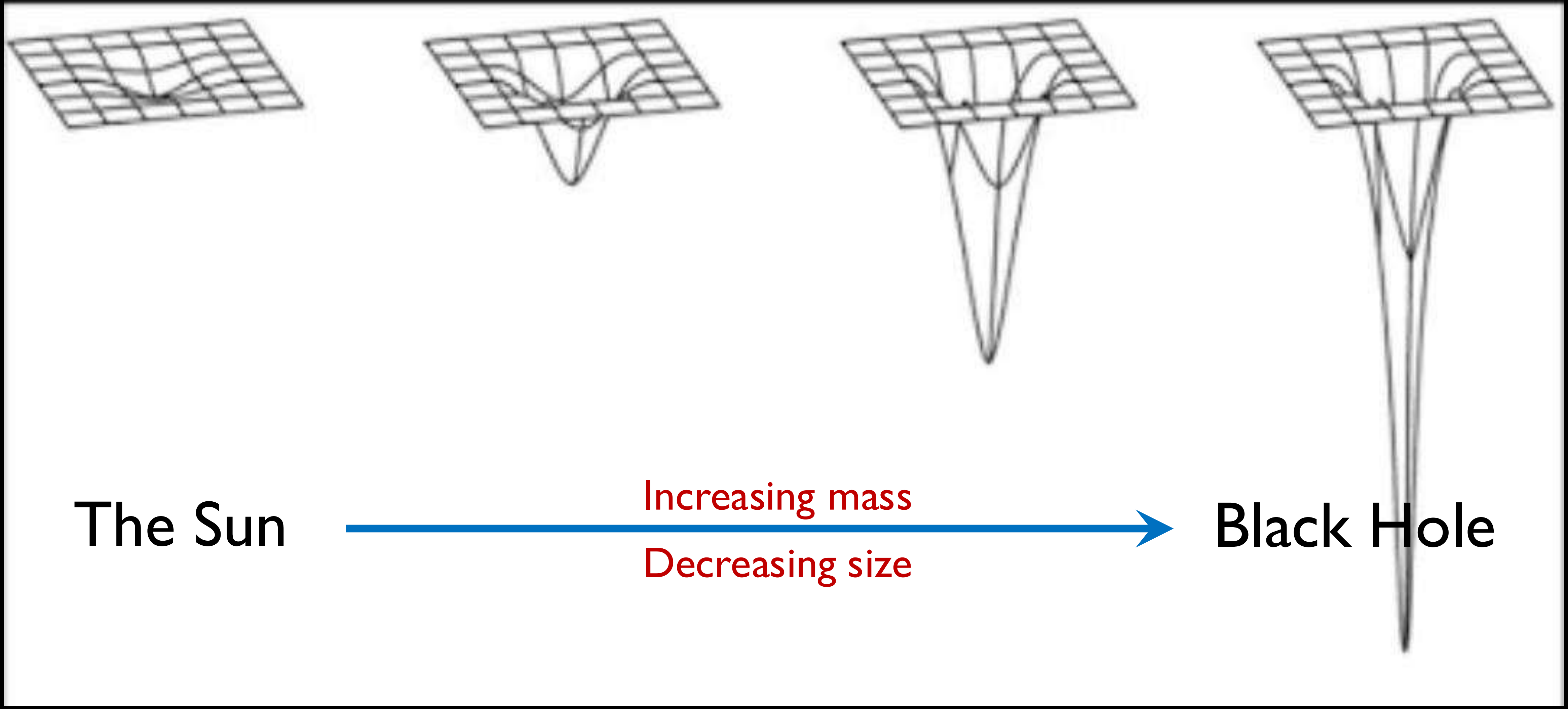


What is a Black Hole?

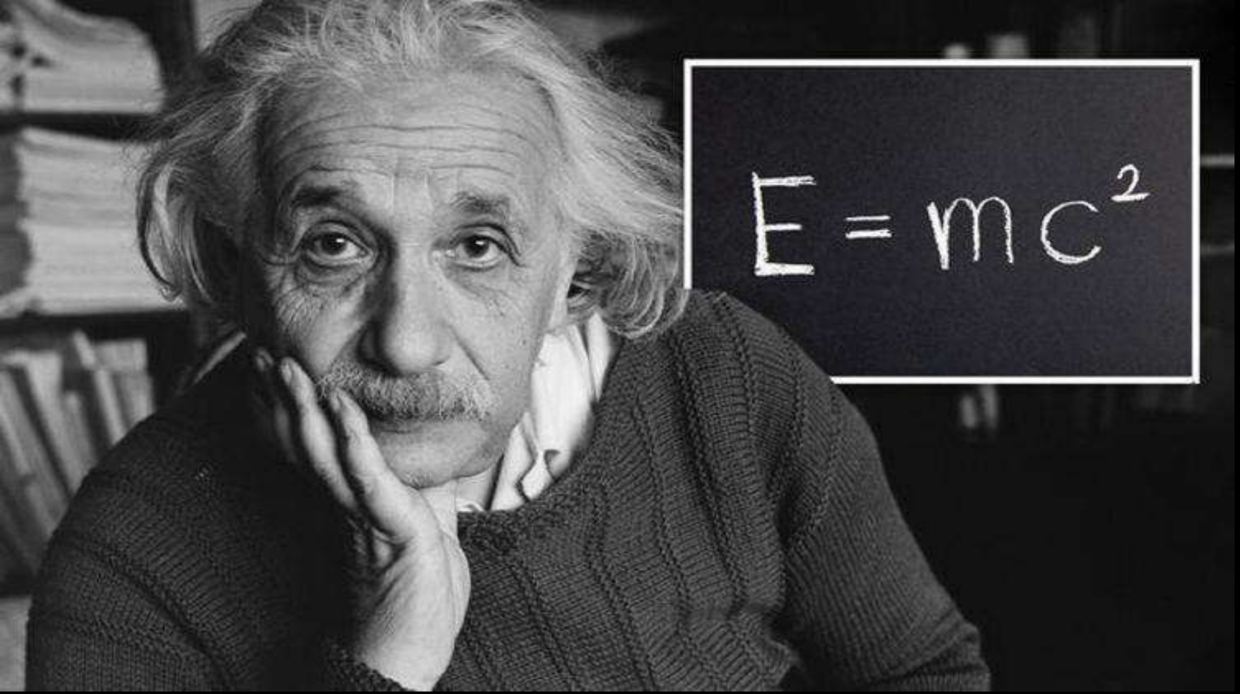
Theoretically, a black hole is a region in spacetime with a gravitational field so intense that nothing, not even light, can escape.



What is a Black Hole?

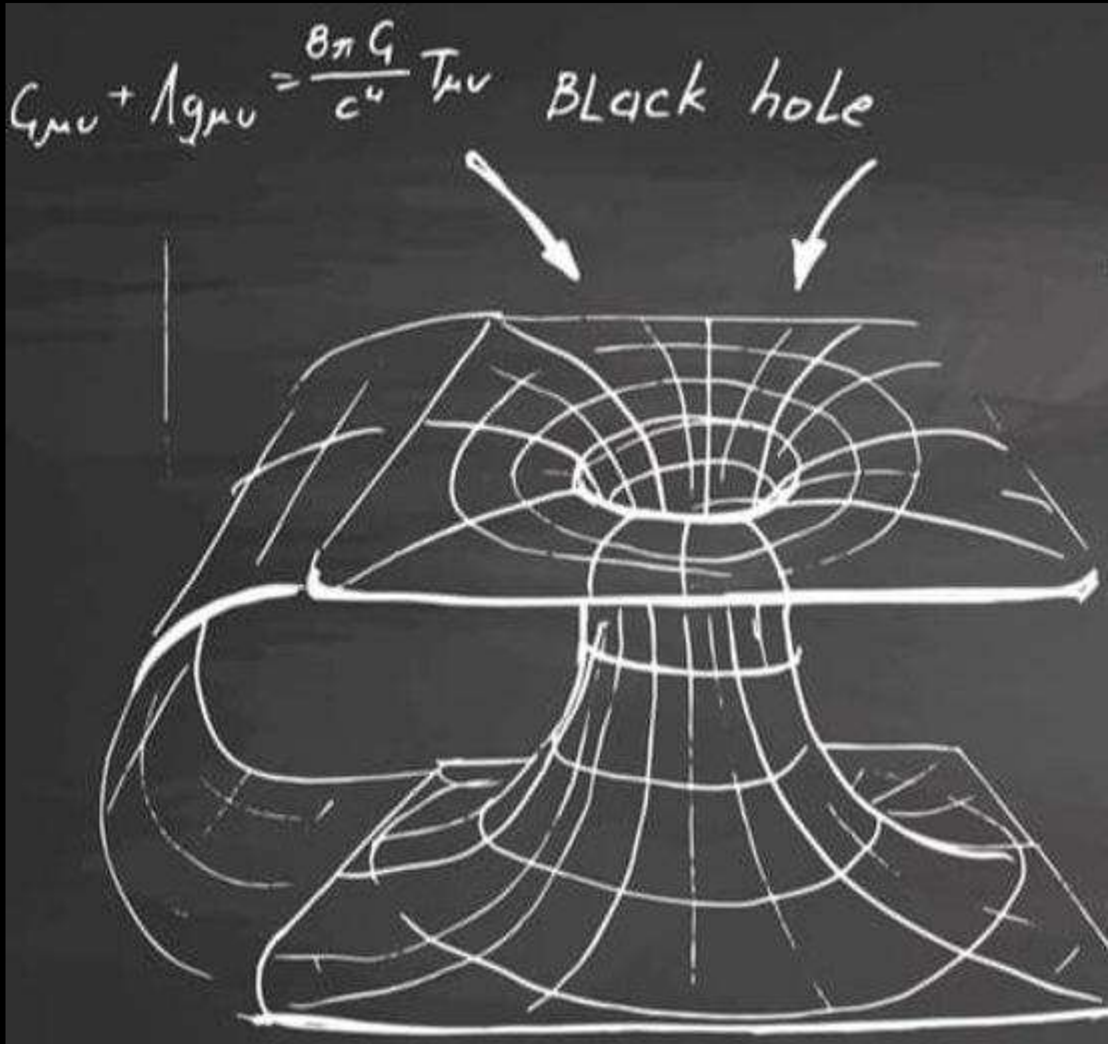


What is a Black Hole?



Einstein Field Equation

$$G_{\alpha\beta} = \frac{8\pi G}{c^4} T_{\alpha\beta}$$



What is a Black Hole?

- Black holes –Solution to the Einstein Field Equation
- Coupled nonlinear Partial differential equations.

Curvature of space

Distribution of mass/energy

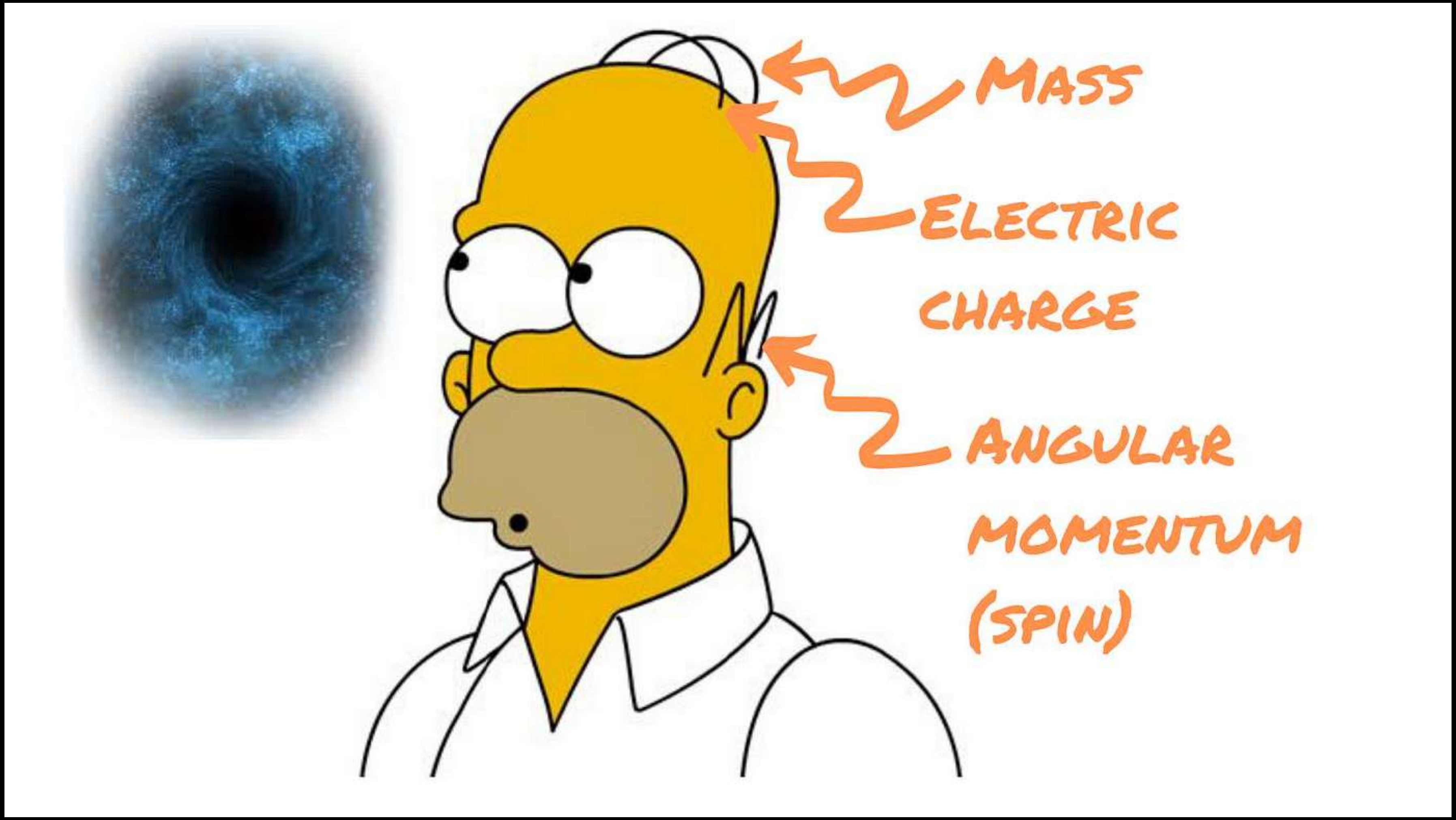
$$\boxed{G_{\alpha\beta} = \frac{8\pi G}{c^4} T_{\alpha\beta}}$$

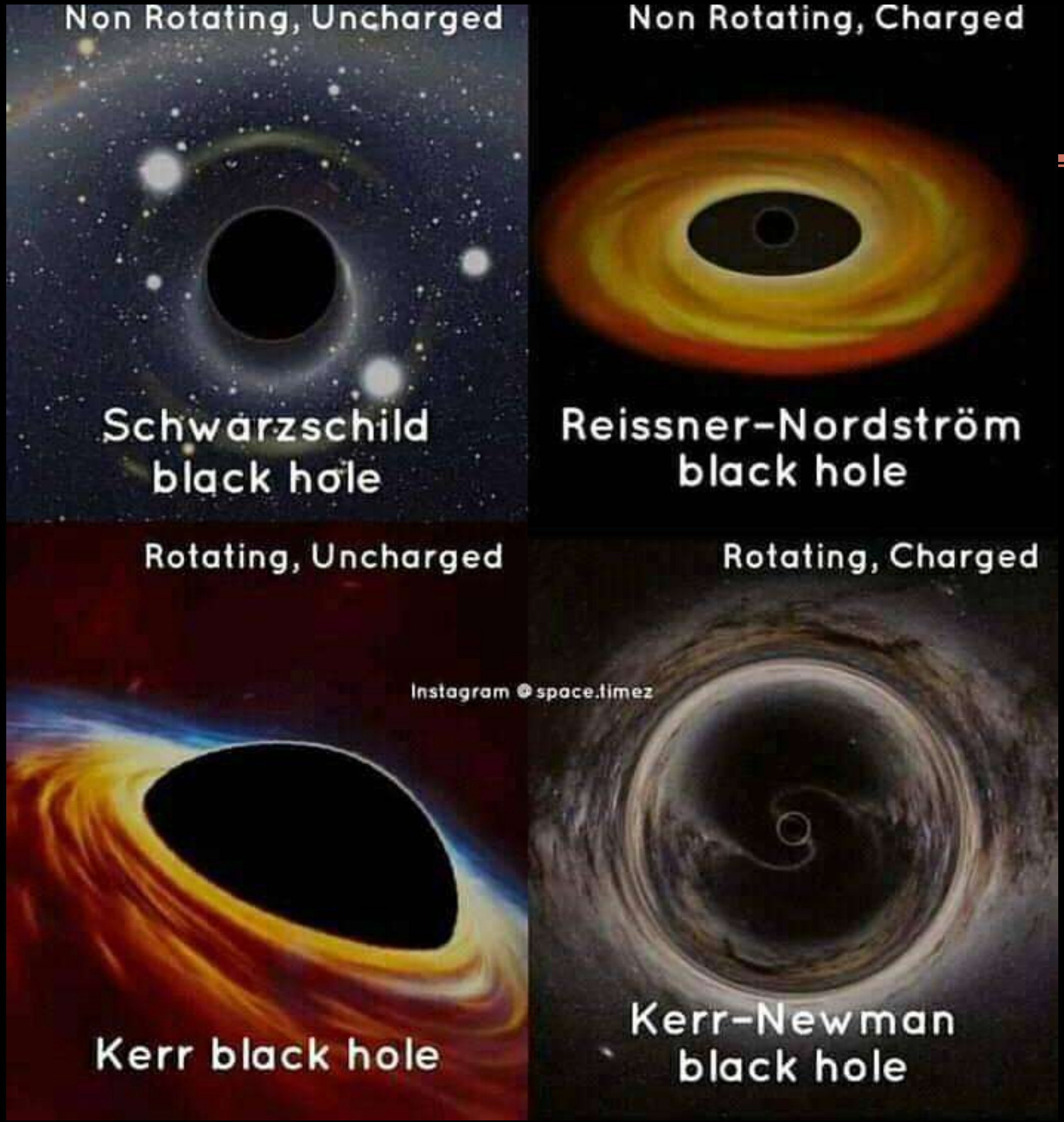
Some constants

GR naturally reduces to Newtonian gravity in the appropriate limit.

- **Correspondence Principle:** $v \ll c \quad \text{and} \quad \frac{\phi}{c^2} \ll 1$
- **Geodesic Equation → Newton's Second Law** $\frac{d^2\vec{r}}{dt^2} = -\nabla\phi,$
- **Poisson's Equation:** $\nabla^2\phi = 4\pi G\rho$

No hair Theorem

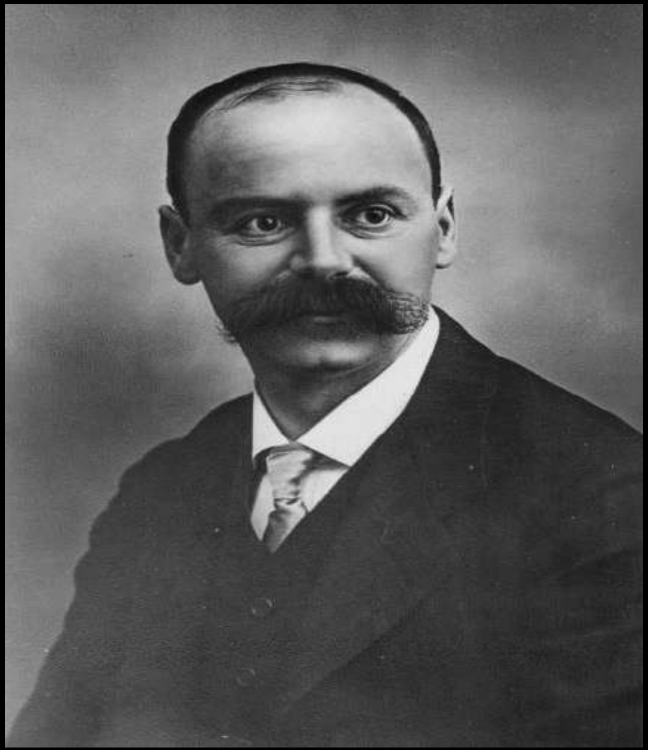


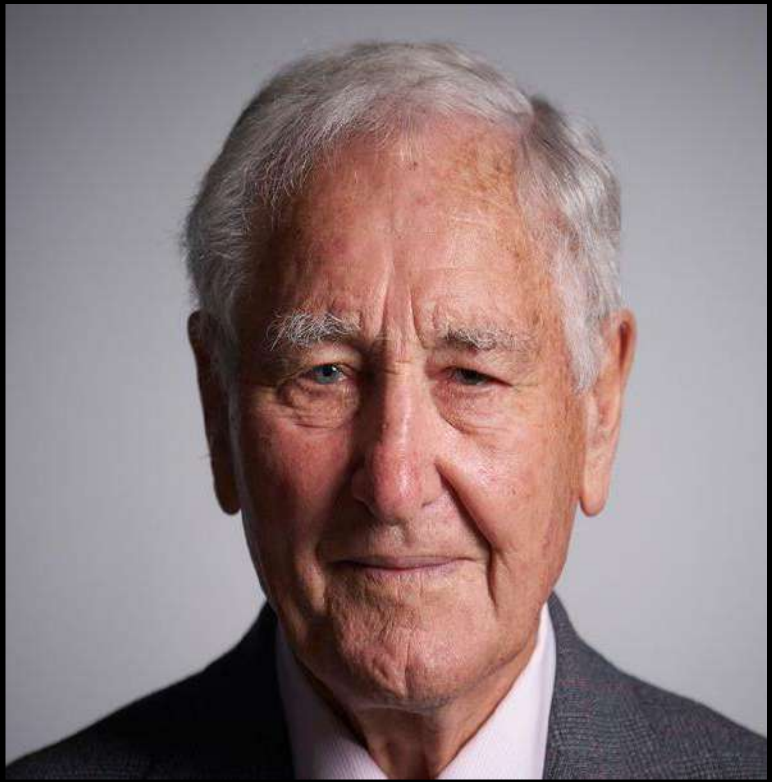


What is a Black Hole?

- Black holes can be characterized by – Mass, Spin & Angular momentum.

Black hole	Rotating	Charge
Schwarzschild	No	No
Reissner–Nordström	No	Yes
Kerr	Yes	No
Kerr-Newman	Yes	Yes



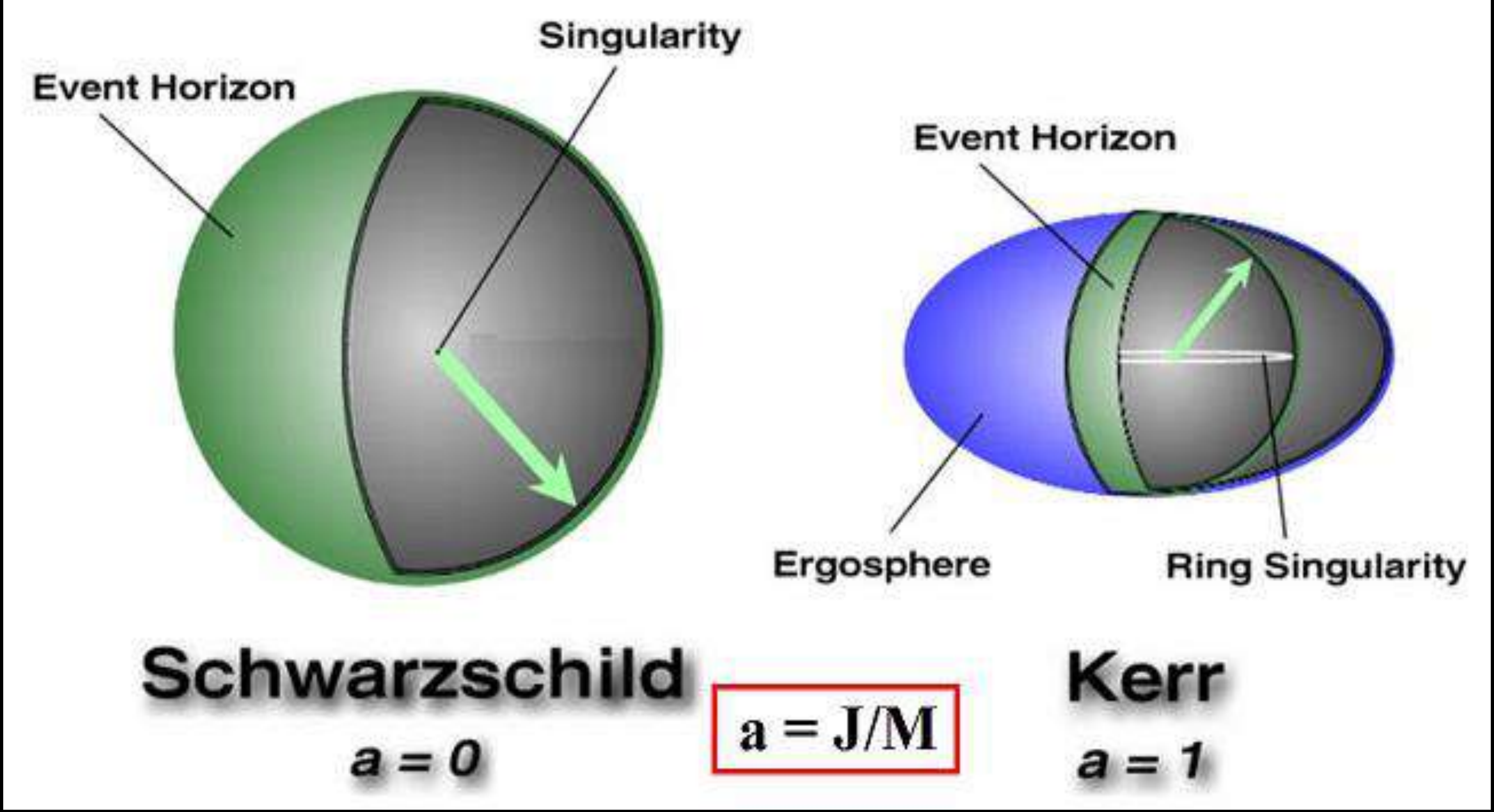


Schwarzschild

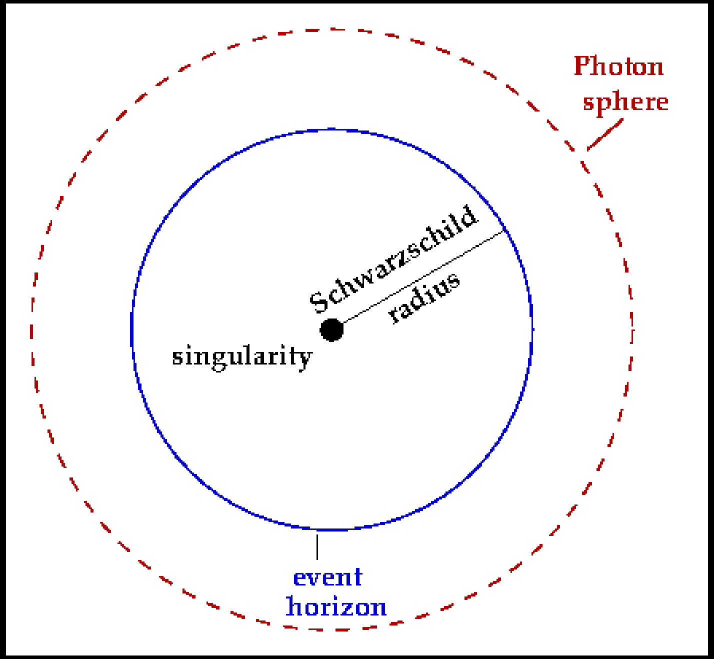
$a = 0$

Kerr

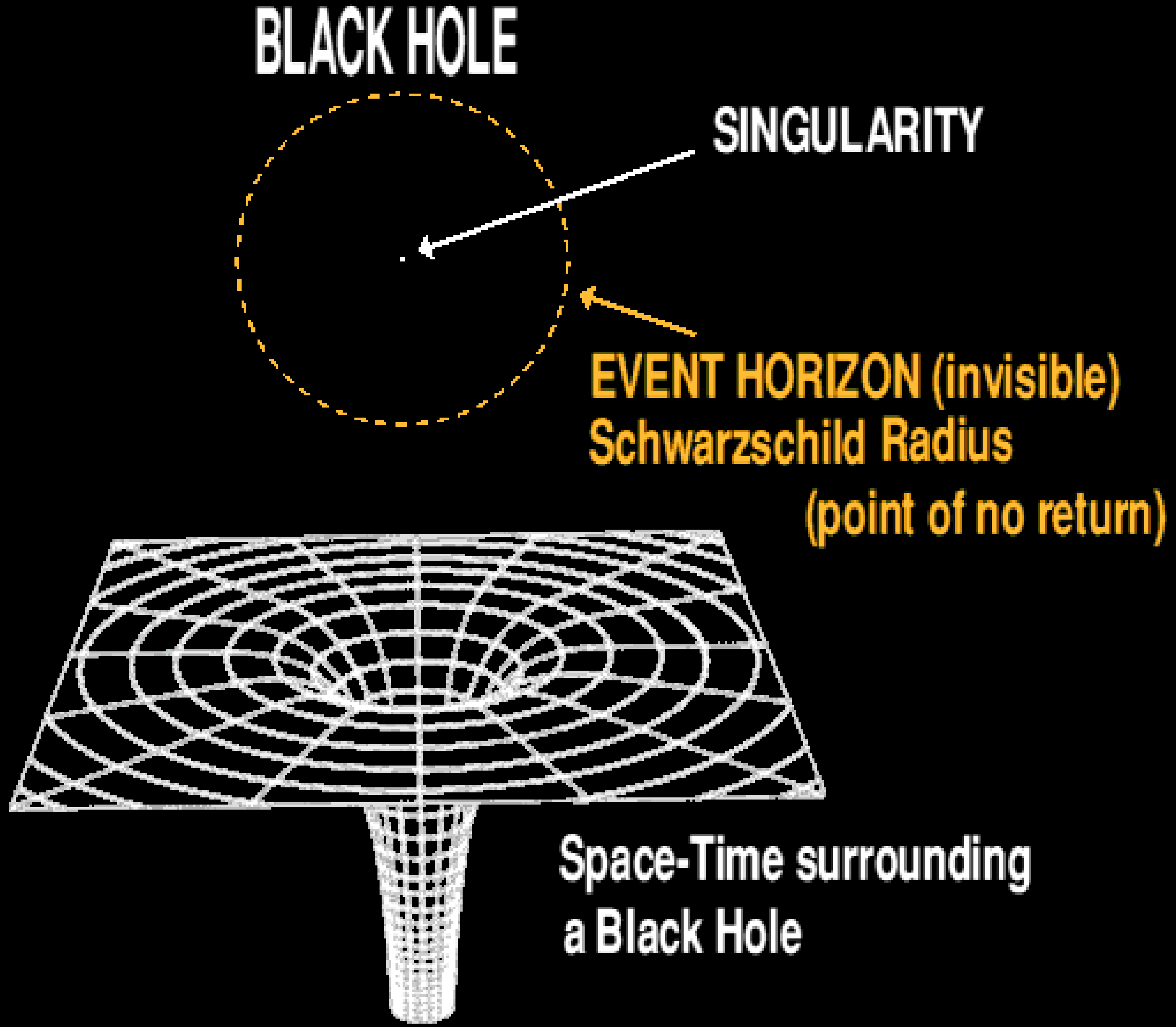
$a = 1$

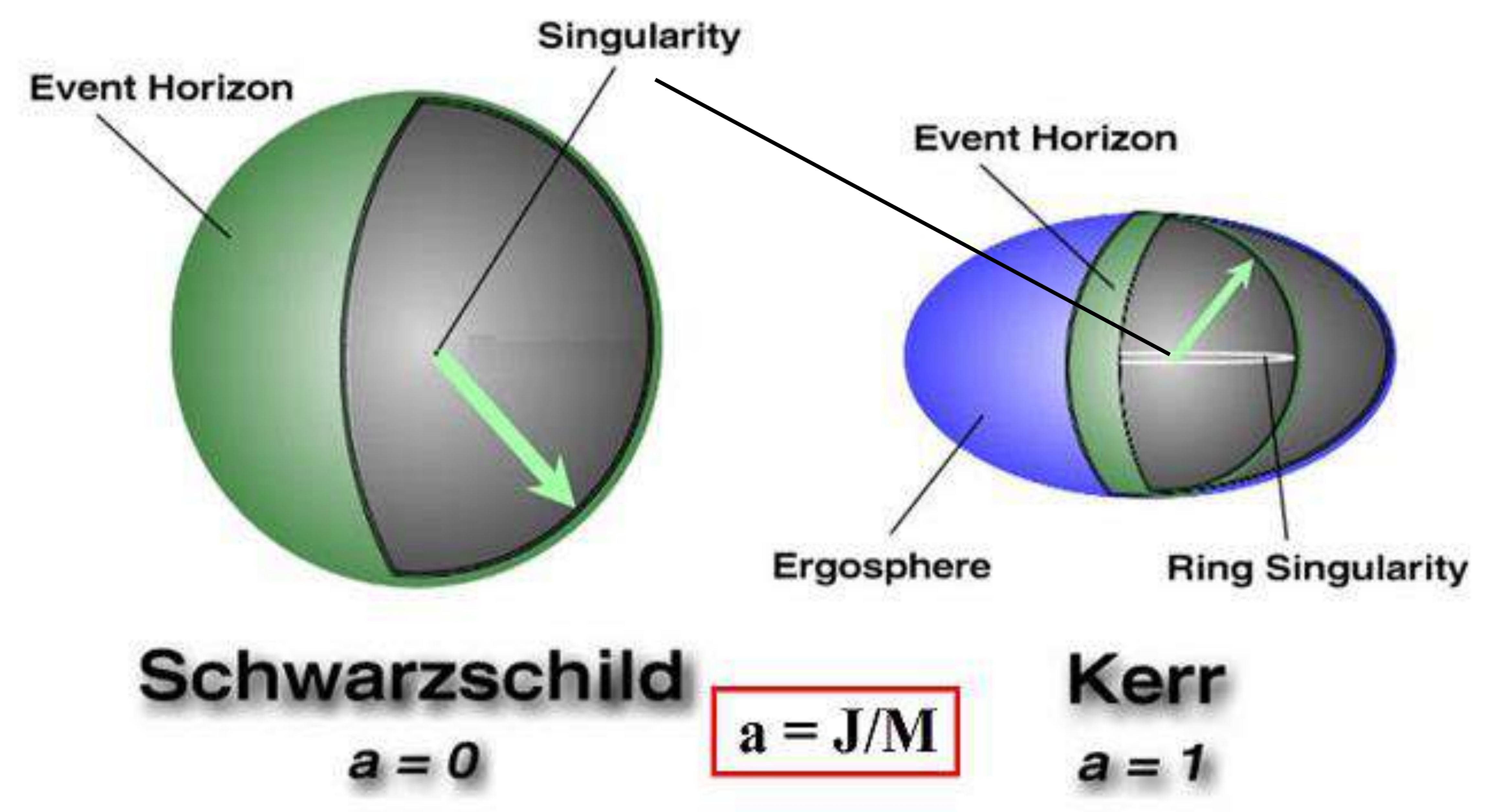

Singularity
Event Horizon
Event Horizon
Ergosphere
Ring Singularity
Schwarzschild
a = 0
a = J/M
Kerr
a = 1

Schwarzschild radius



$$r_s = \frac{2GM}{c^2}$$

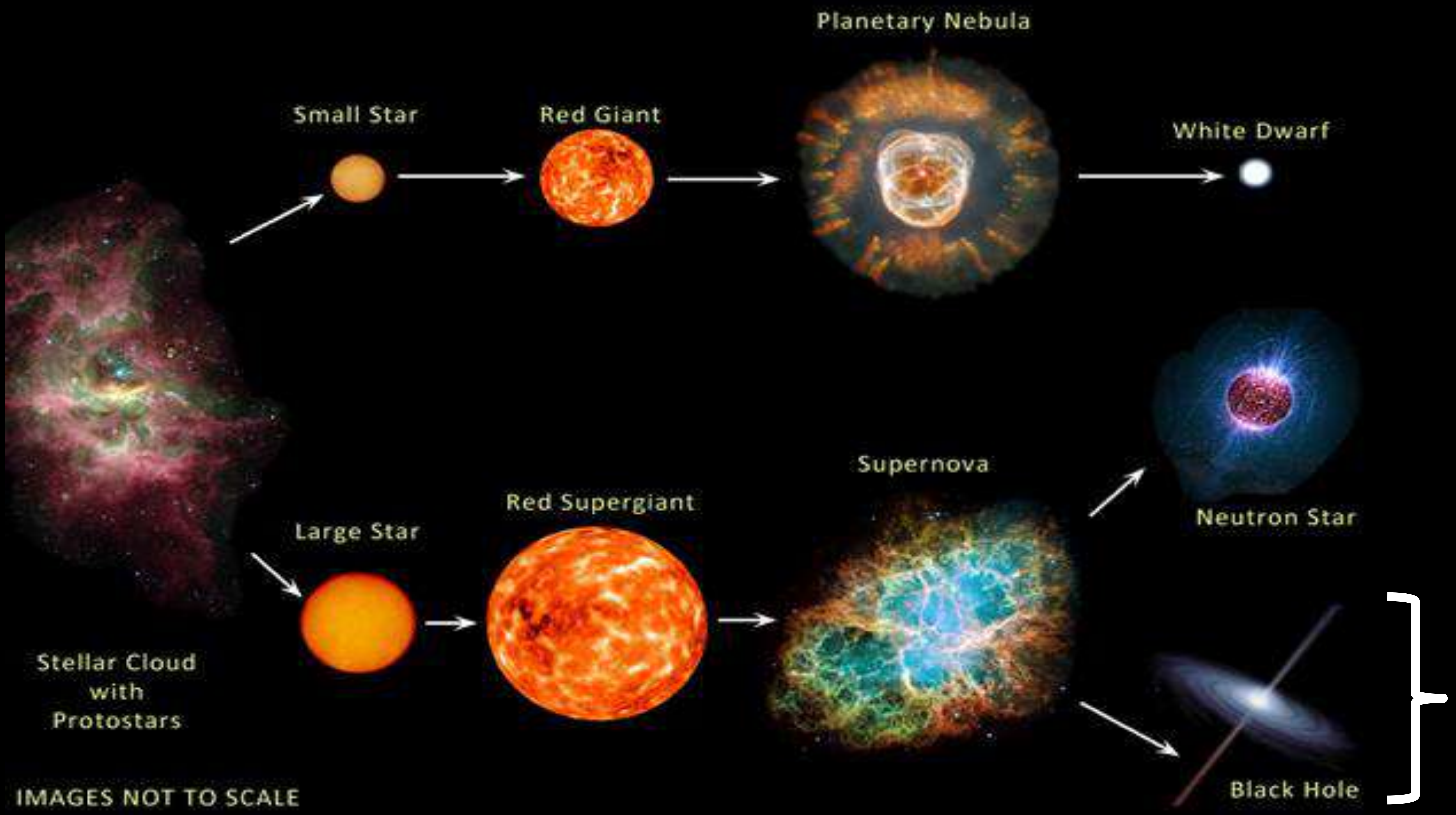




Singularity
Event Horizon
Event Horizon
Ergosphere
Ring Singularity
Schwarzschild
a = 0
a = J/M
Kerr
a = 1

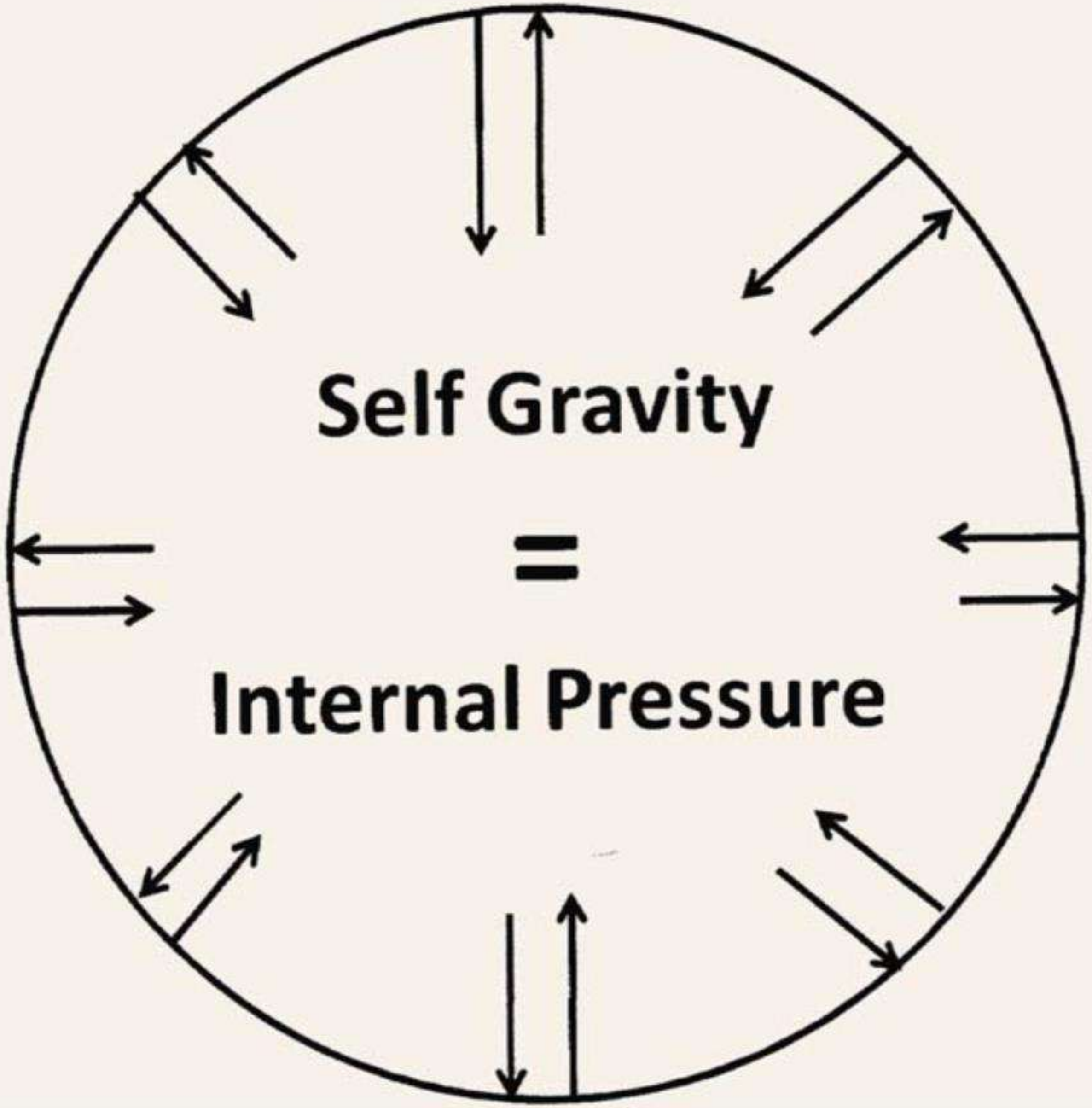
Black Holes:
Formation and Types

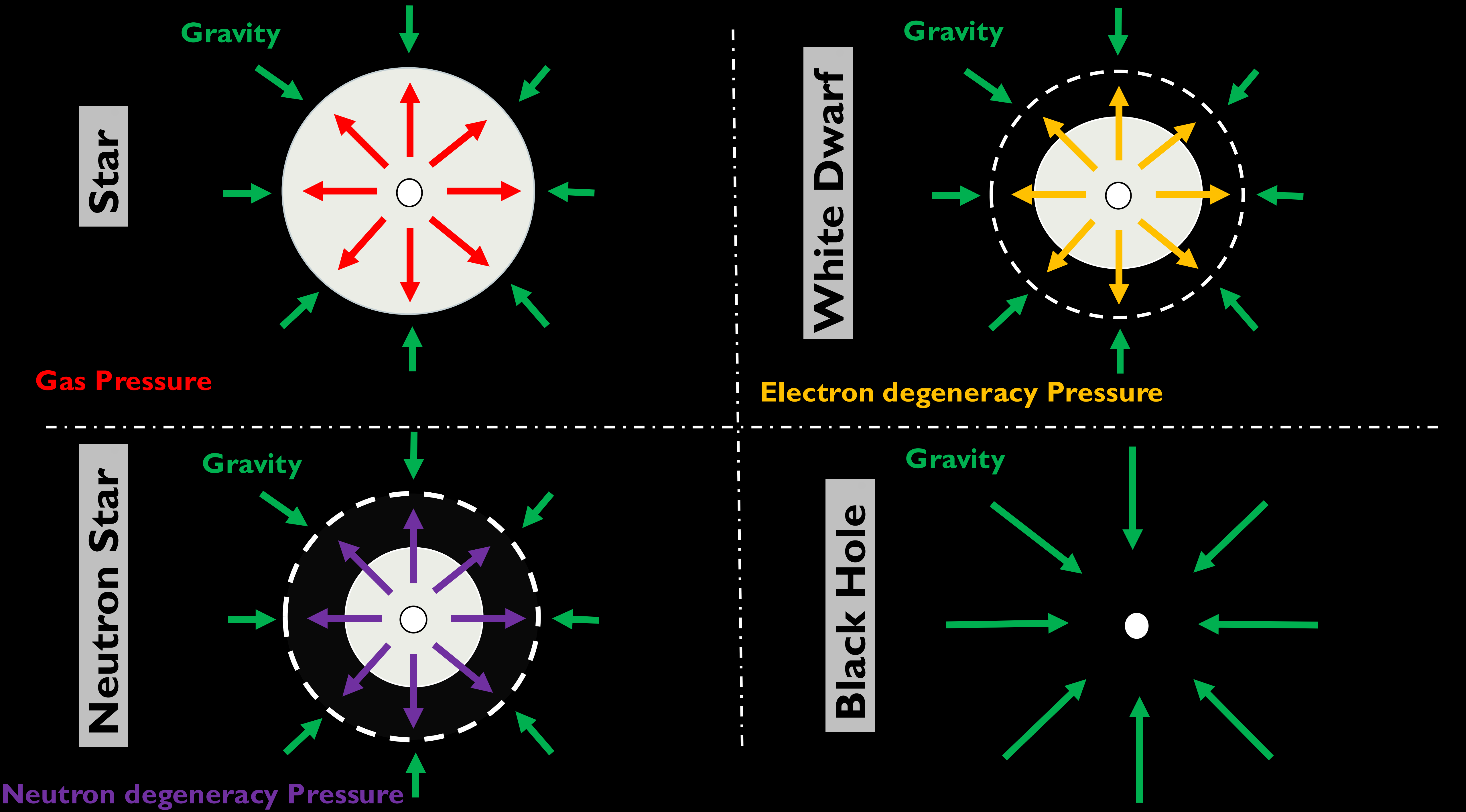
Astrophysical Black holes - Remnants of stellar evolution.



HYDROSTATIC EQUILIBRIUM

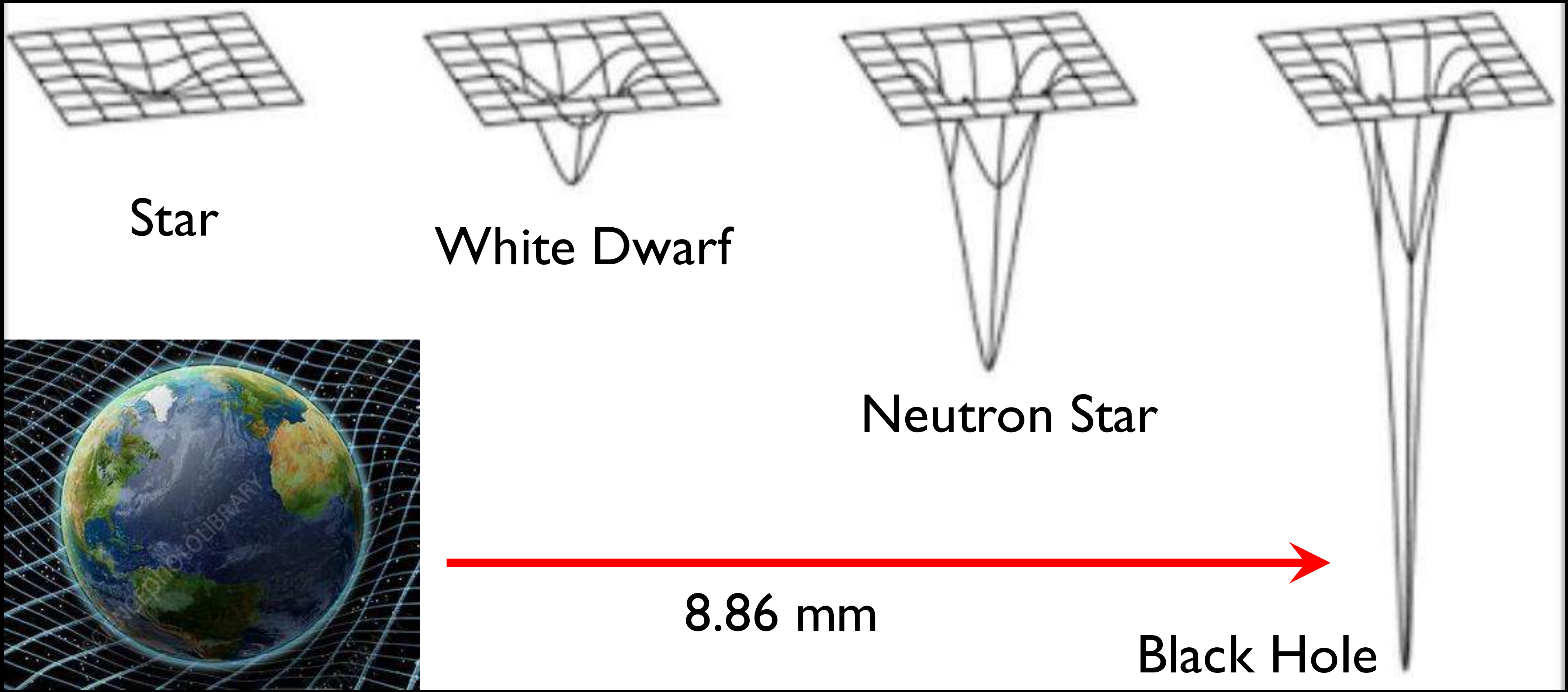
$$\frac{Gmdm}{r^2} = -4\pi r^2 dp$$




Star
Gravity
Gas Pressure
White Dwarf
Gravity
Electron degeneracy Pressure
Neutron Star
Gravity
Neutron degeneracy Pressure
Black Hole
Gravity

What is a Black Hole?

The Sun $\xrightarrow[\text{Decreasing size}]{\text{Increasing mass}}$ Black Hole

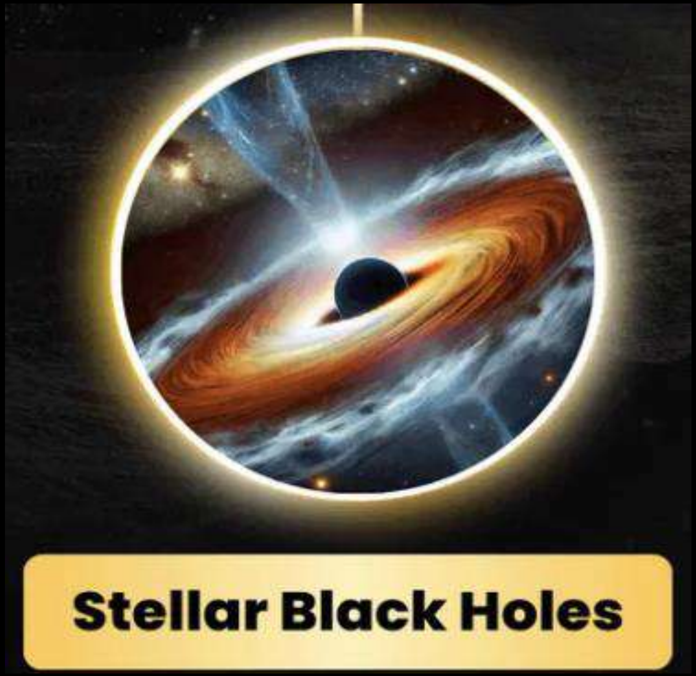


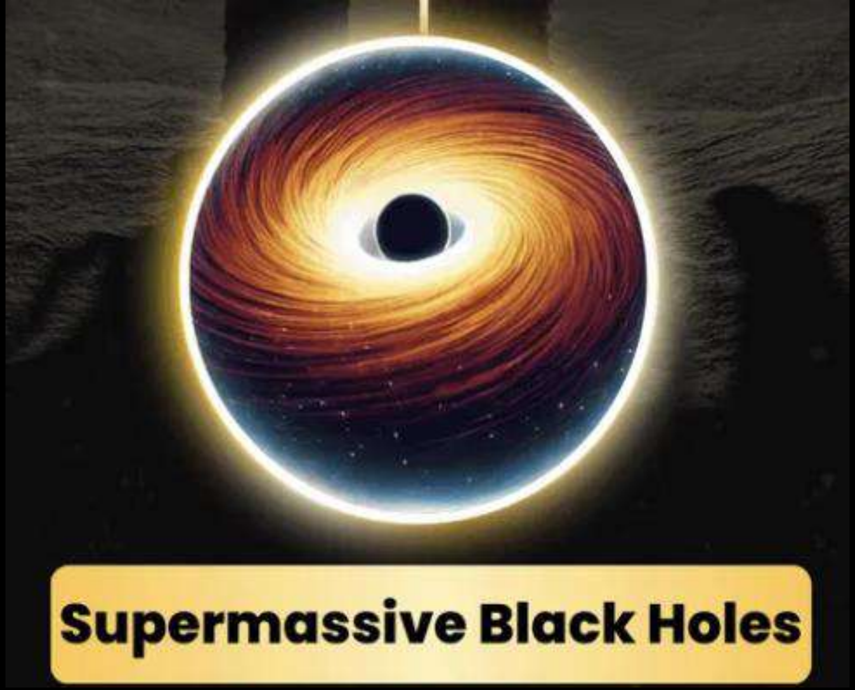
Object	Mass Range (in $M_\odot$)	Actual Radius (km)	Schwarzschild Radius (km)
Sun	~ 1 $M_\odot$	~ 696,340 km	~ 2.95 km
White Dwarf	~ 0.17 – 1.4 $M_\odot$ (Chandrasekhar limit)	~ 7,000 – 14,000 km	~ 0.5 – 4.1 km
Neutron Star	~ 1.1 – 2.3 $M_\odot$ (Tolman-Oppenheimer–Volkoff limit)	~ 10 – 15 km	~ 3.3 – 6.8 km
Black Hole	> ~ 2.3 $M_\odot$	Not defined (no surface); event horizon at Schwarzschild radius	> ~ 6.8 km

Types of Black Holes

Stellar Black Holes

Supermassive Black Holes

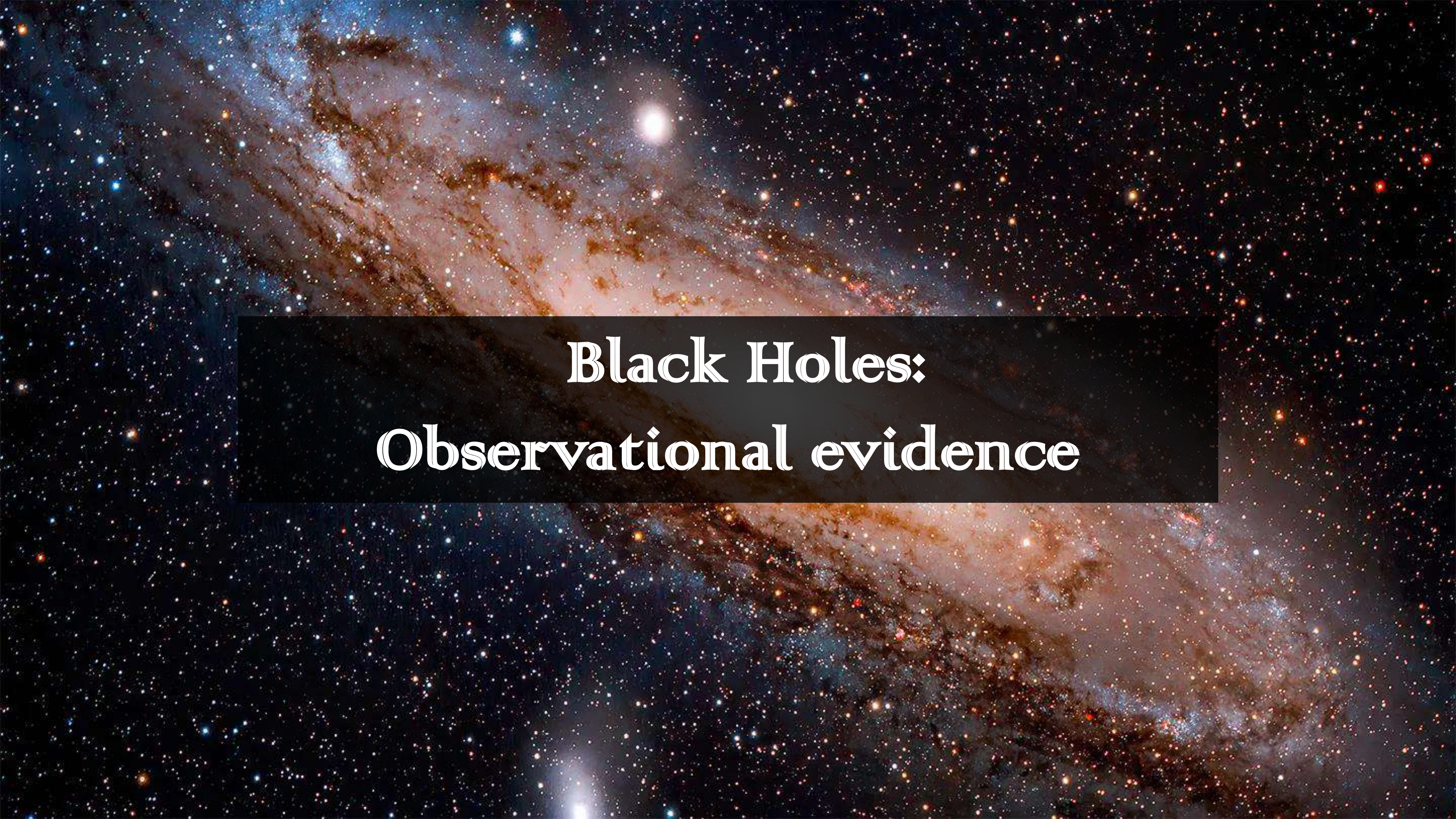


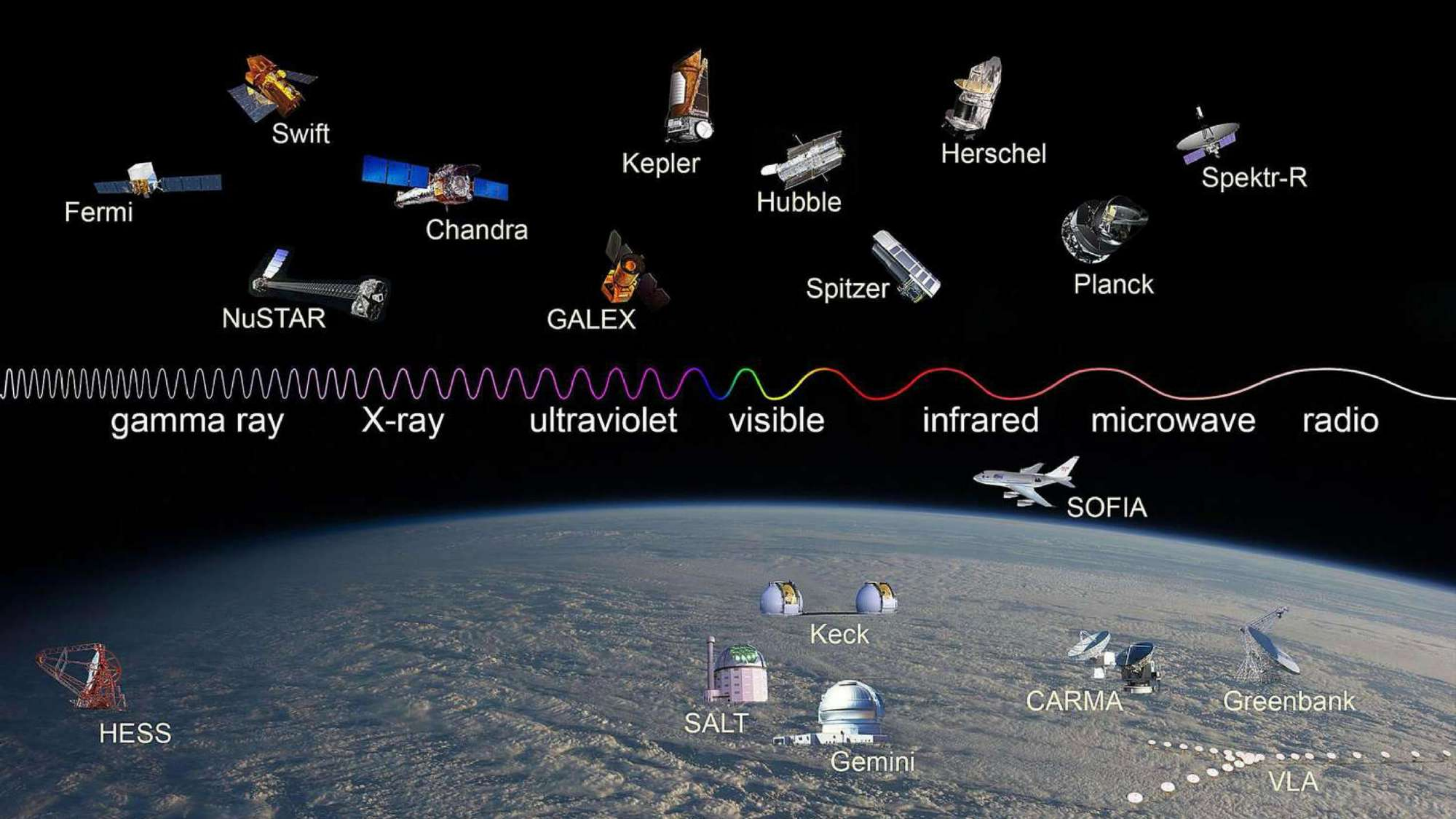


- Masses: ~ 3 - 100 M_{sun}
- Originating from the collapse of massive stars
- Distributed within galaxies
- Shine in X-ray when accreting from a companion star – X-ray binary

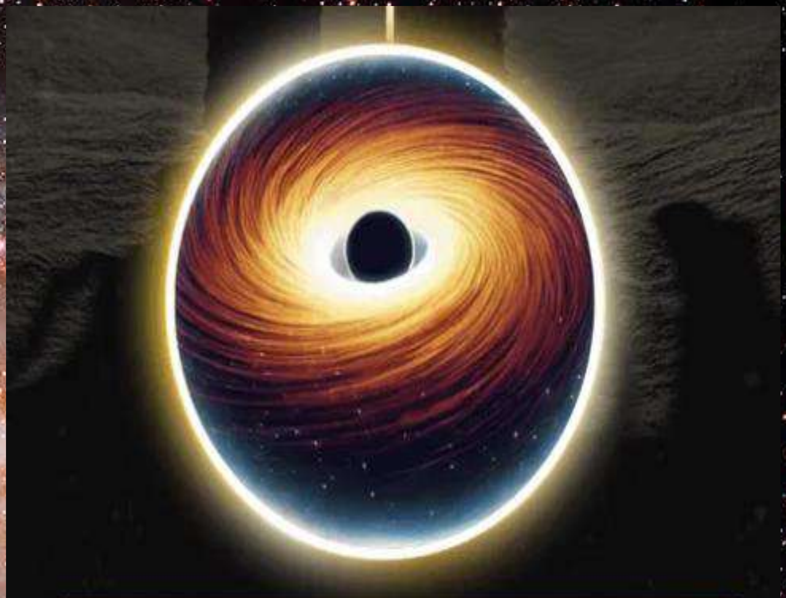
- Masses: ~10^6-10^{10} M_{sun}
- Origin – Unknown ???
- SMBHs are located at the center of galaxies
- Shine in optical/UV when accreting materials near the galactic centers -- AGN

Black Holes: Observational evidence




Swift
Fermi
Chandra
NuSTAR
Kepler
GALEX
Hubble
Spitzer
Herschel
Planck
Spektr-R
gamma ray
X-ray
ultraviolet
visible
infrared
microwave
radio
SOFIA
Keck
HESS
SALT
Gemini
CARMA
Greenbank
VLA

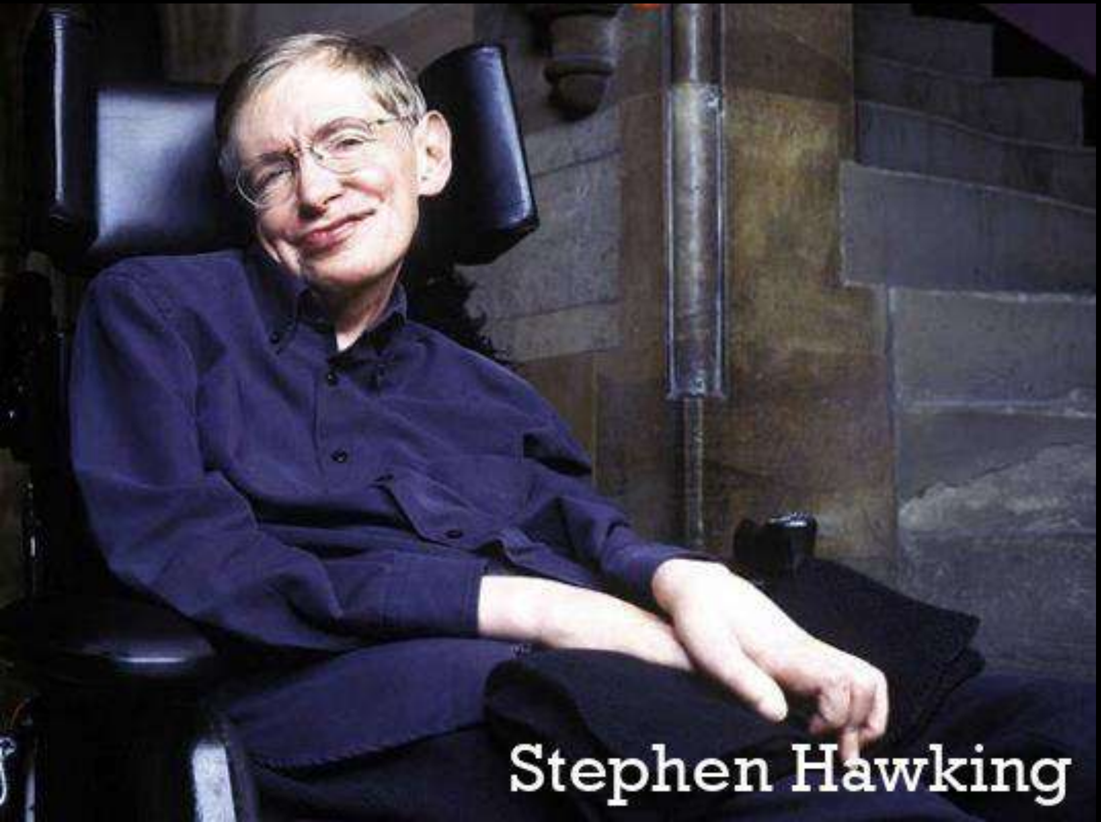
Stellar Black Holes



Supermassive Black Holes

First Stellar mass black hole observed

No, it's not a black hole

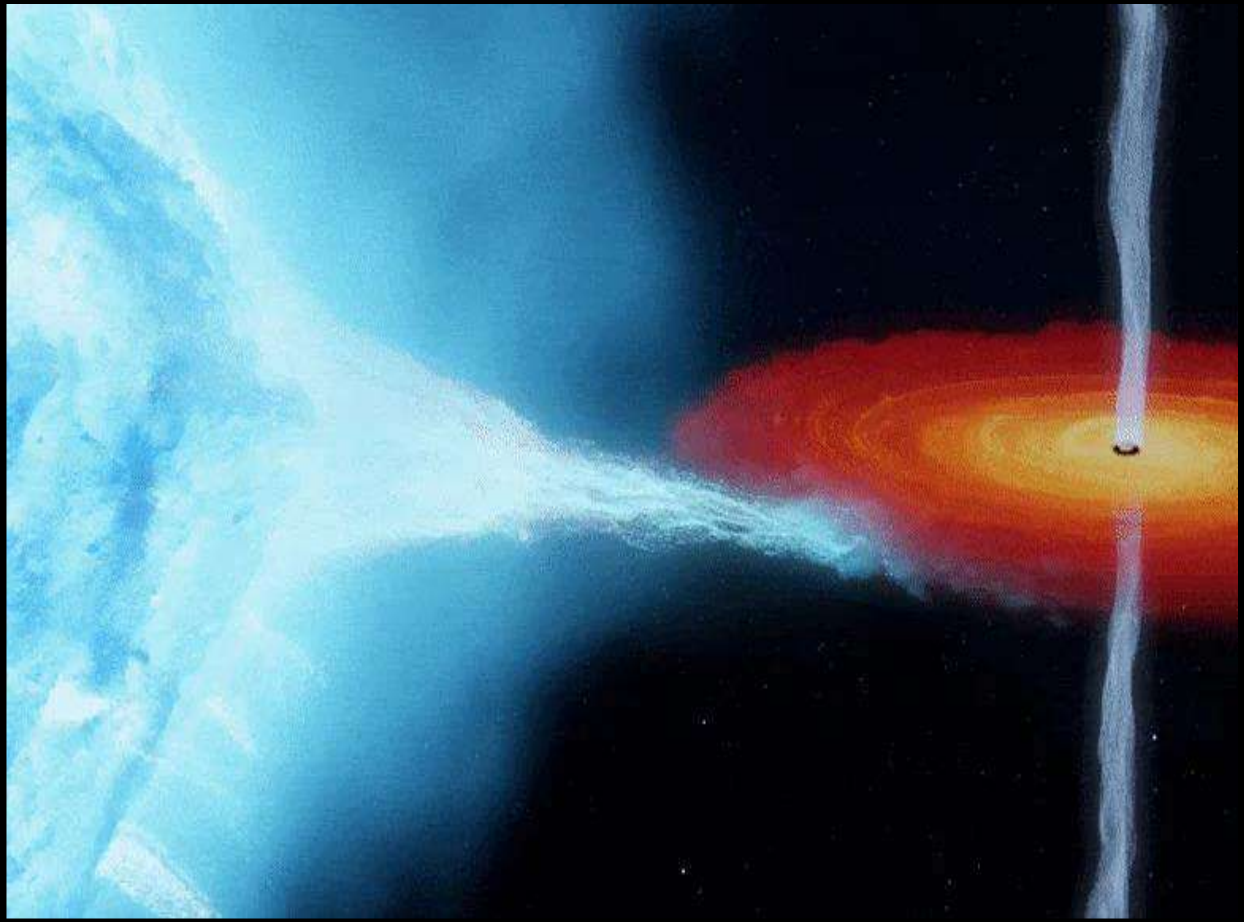


Yes, it is.
Let bet.

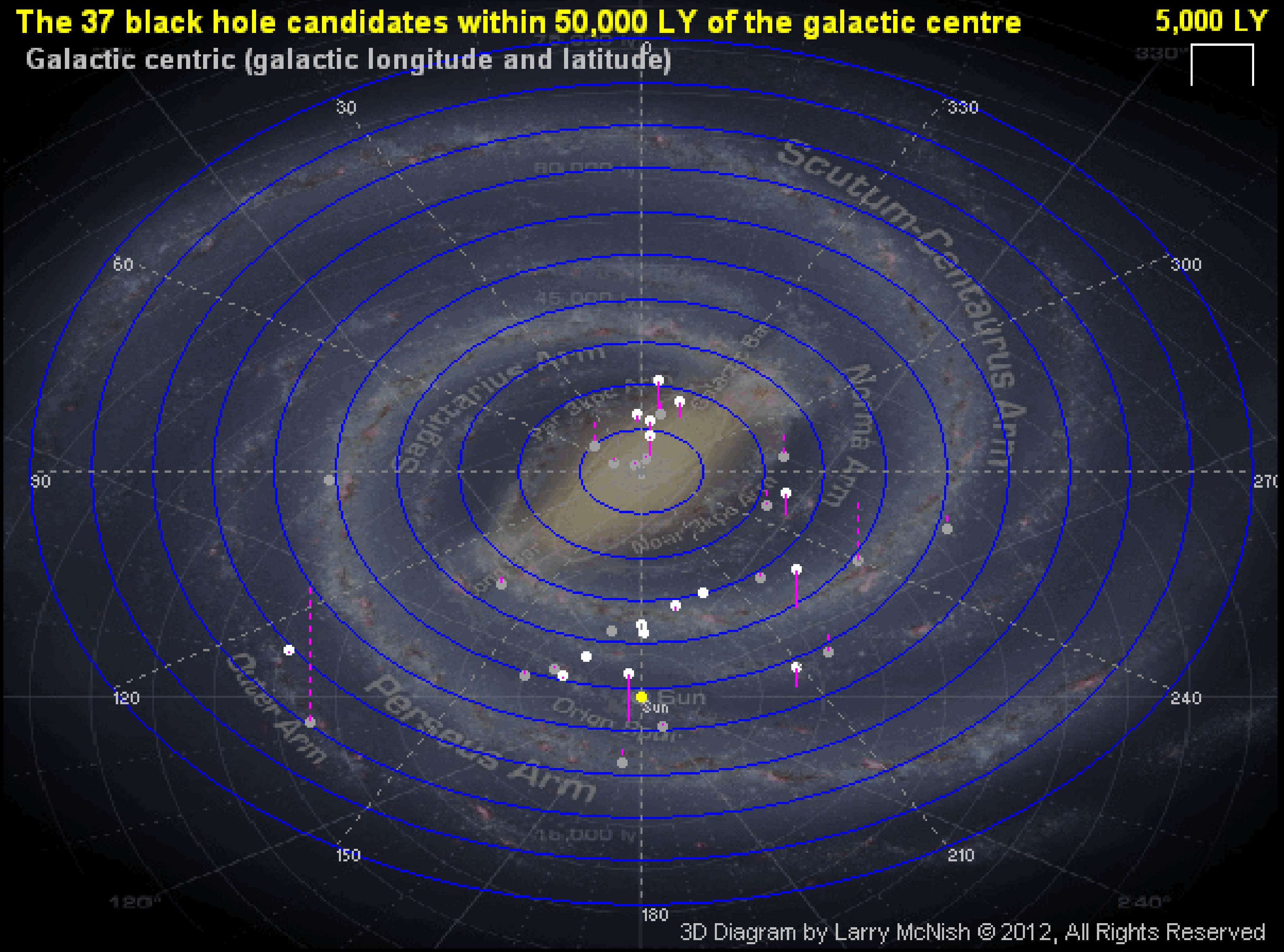

Cygnus X-1
Optical

Cygnus X-1 – X-ray Binary

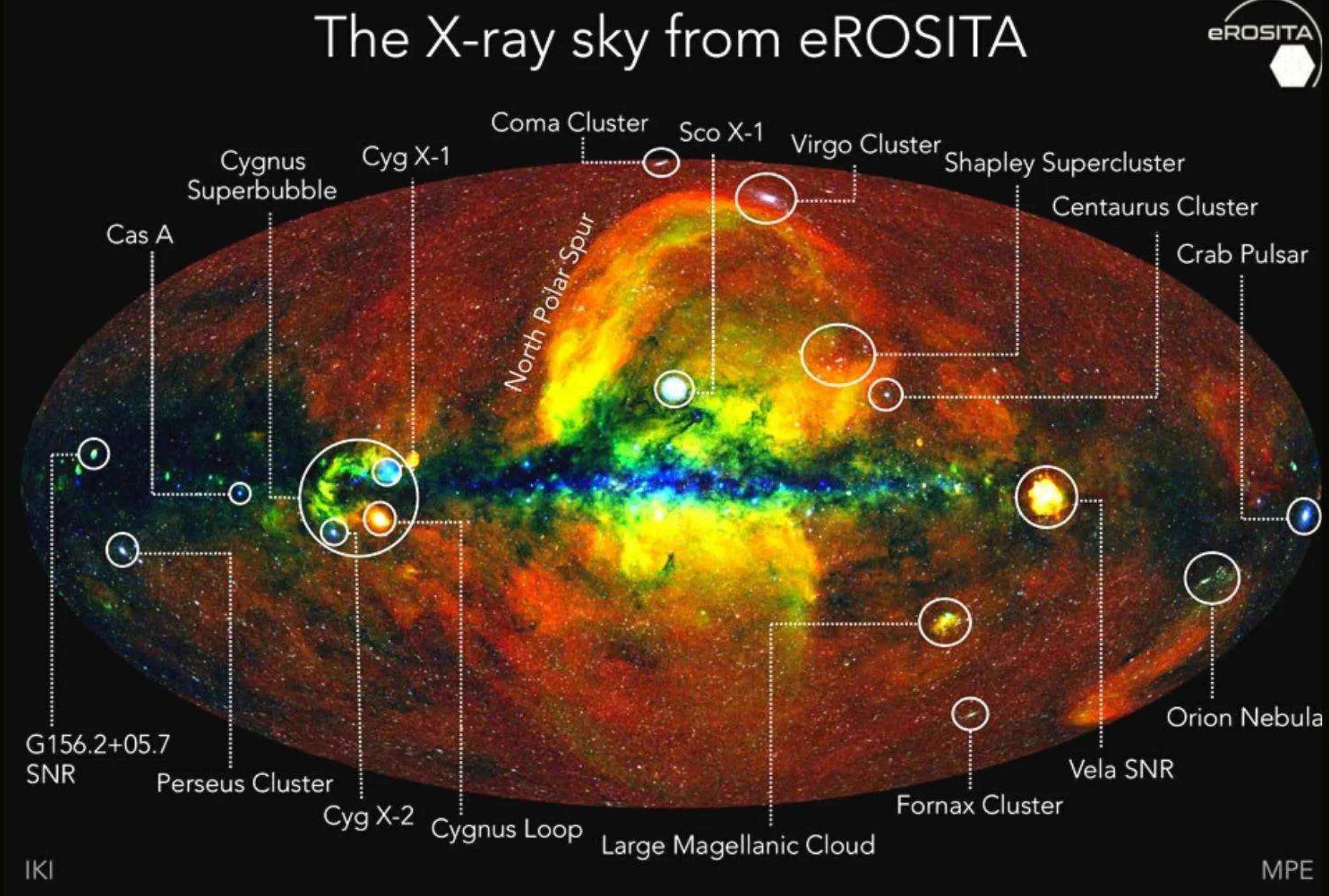
- Discovered in **1964** as a strong **X-ray source**
- Contains a **stellar-mass black hole** (~21 $M_\odot$) & a **massive companion star** (~40 $M_\odot$)
- Emits strongly in the **X-ray part of the spectrum**
- Helped confirm that **stellar-mass black holes exist**



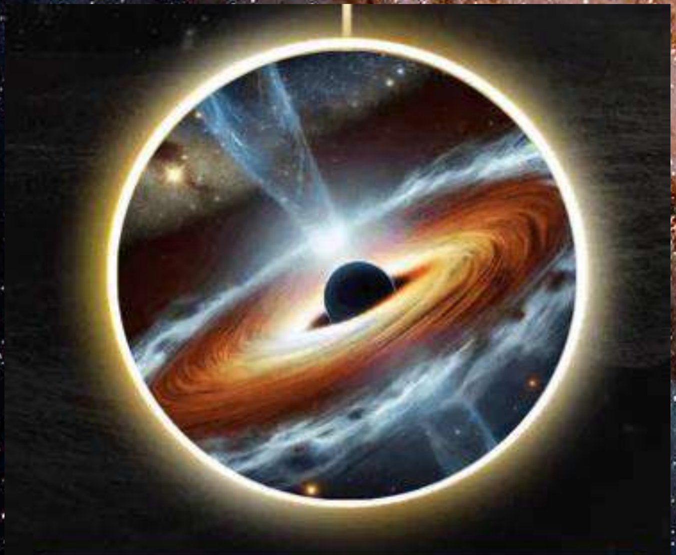
The 37 black hole candidates within 50,000 LY of the center of the Milky Way.



Every bright light is a neutron star or black hole.



Source: Jeremy Sanders, Hermann Brunner and the eSASS team (MPE) / Eugene Churazov, Marat Gilfanov (IKI)



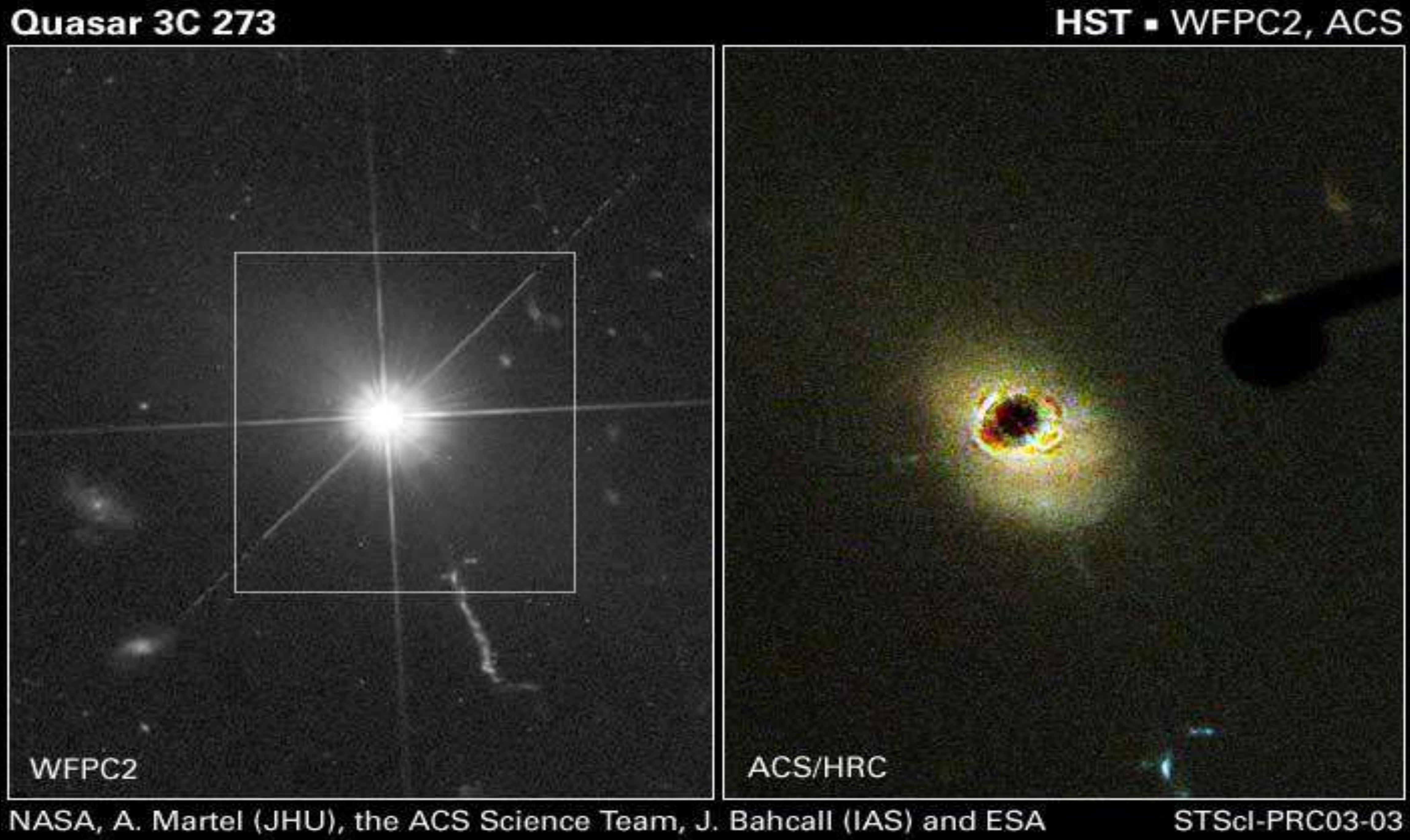
Stellar Black Holes

Supermassive Black Holes

Quasars: Discovery & Proof of Supermassive Black Holes

✅ Discovery of Quasars (1963) (Quasi Stellar radio sources)

- First identified as star-like radio sources with unusual spectra
- **Extreme distances → high luminosity (273 billion light yrs)**


Quasar 3C 273
HST ▪ WFPC2, ACS
WFPC2
ACS/HRC
NASA, A. Martel (JHU), the ACS Science Team, J. Bahcall (IAS) and ESA
STScI-PRC03-03

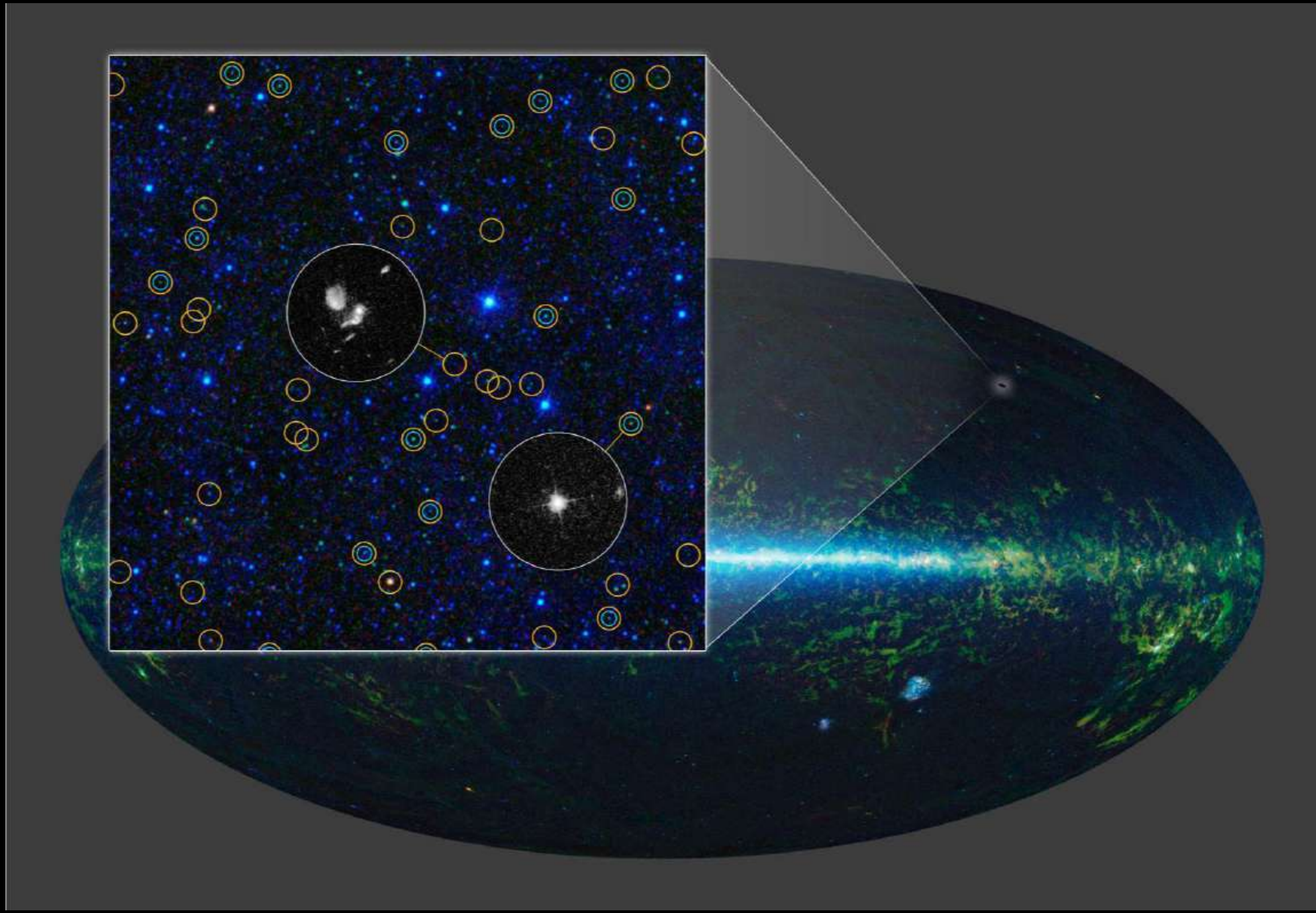
Quasars: Discovery & Proof of Supermassive Black Holes

✅ Indirect but Convincing Evidence

- Too compact and powerful to be star clusters or other known astrophysical objects
- Now understood as **active galactic nuclei** (AGN) powered by SMBHs

- ❖ Active galactic nuclei (AGN) = actively accreting SMBHs
- ❖ Physics similar to X-ray binaries, but emission peaks in the optical/UV bands

A zoomed-in view of quasars observed by NASA's Wide-field Infrared Survey Explorer.

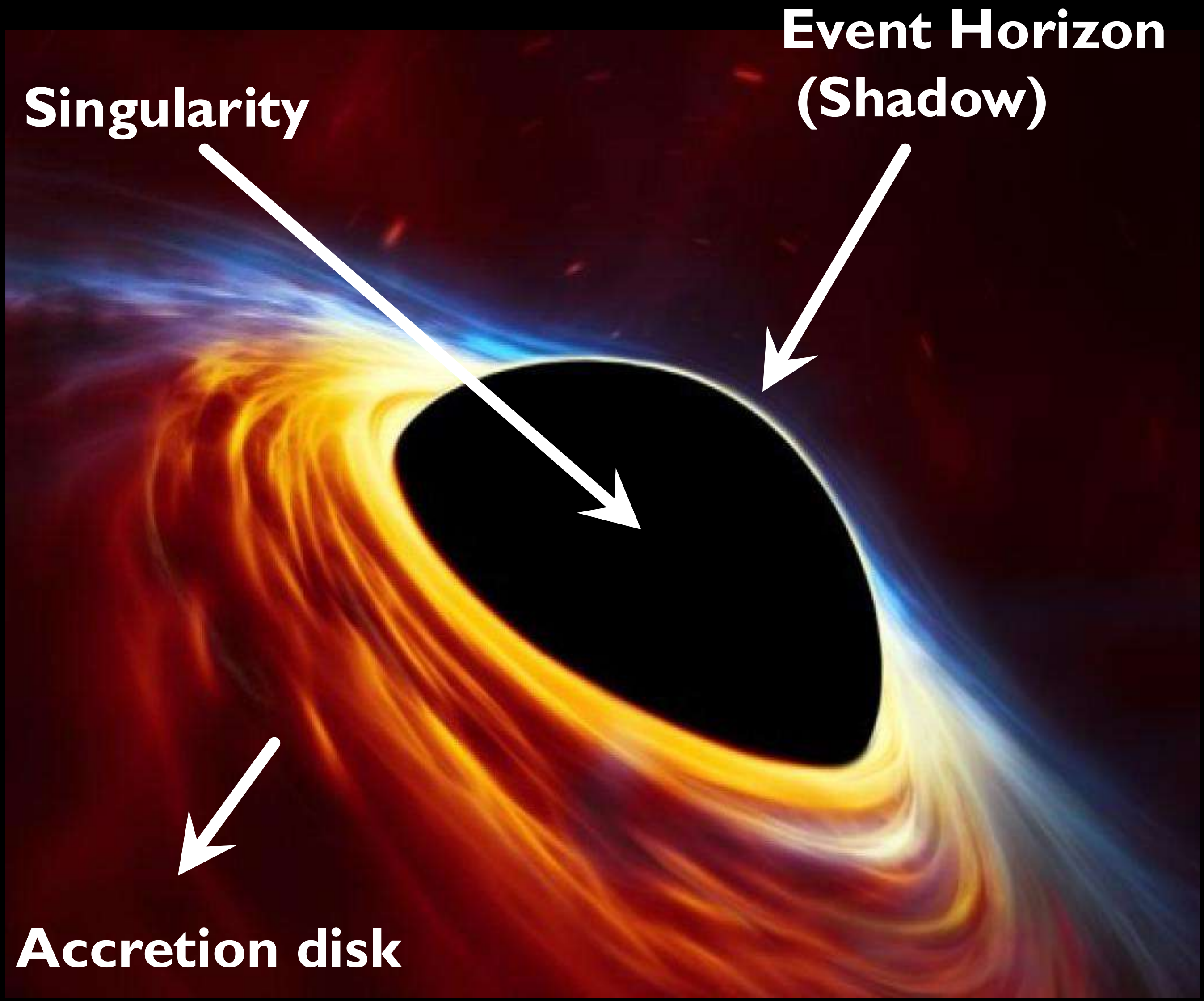


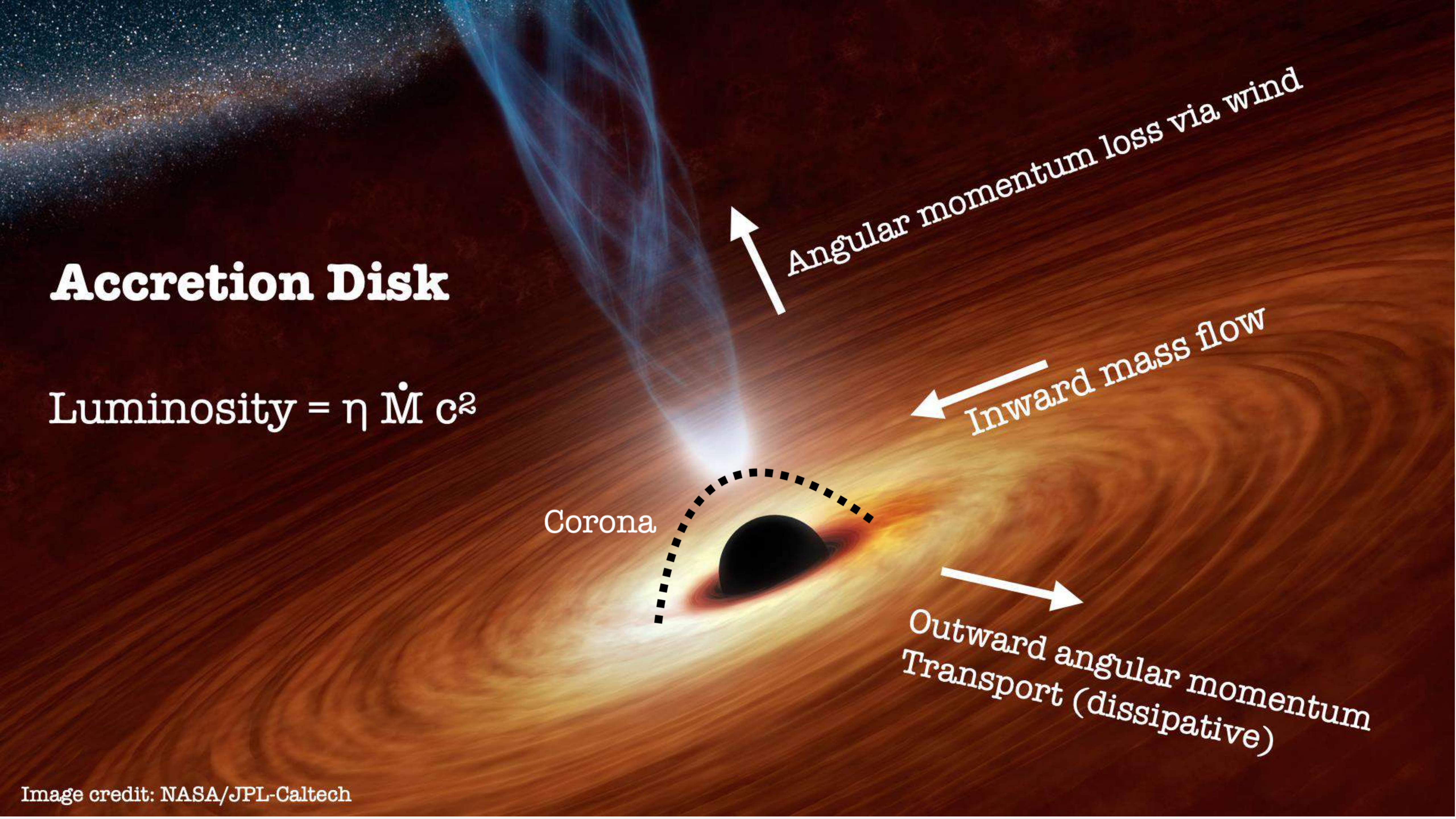
(Image credit: NASA/JPL-Caltech/UCLA/STScI)

Black Holes:
Growth & properties

Accretion Disk

Black hole accretion disk theory describes how matter, such as gas and dust, spirals into a black hole, forming a swirling disk.




Accretion Disk
Luminosity = $\eta \dot{M} c^2$
Angular momentum loss via wind
Inward mass flow
Corona
Outward angular momentum
Transport (dissipative)
Image credit: NASA/JPL-Caltech

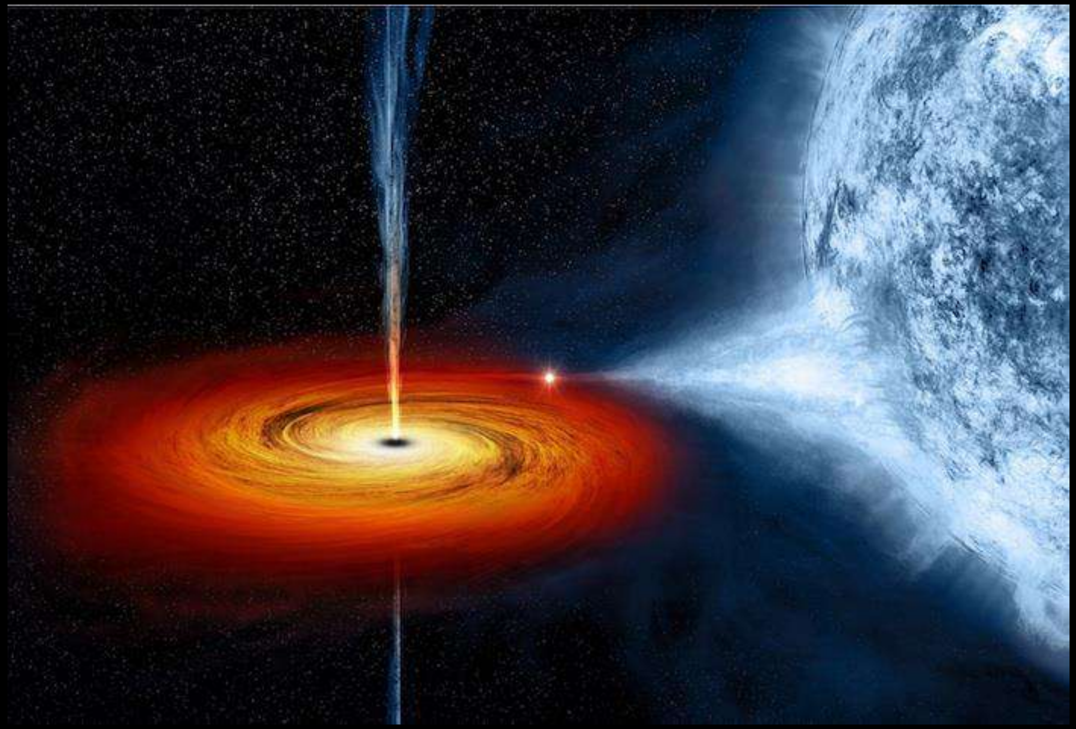
Eddington Luminosity

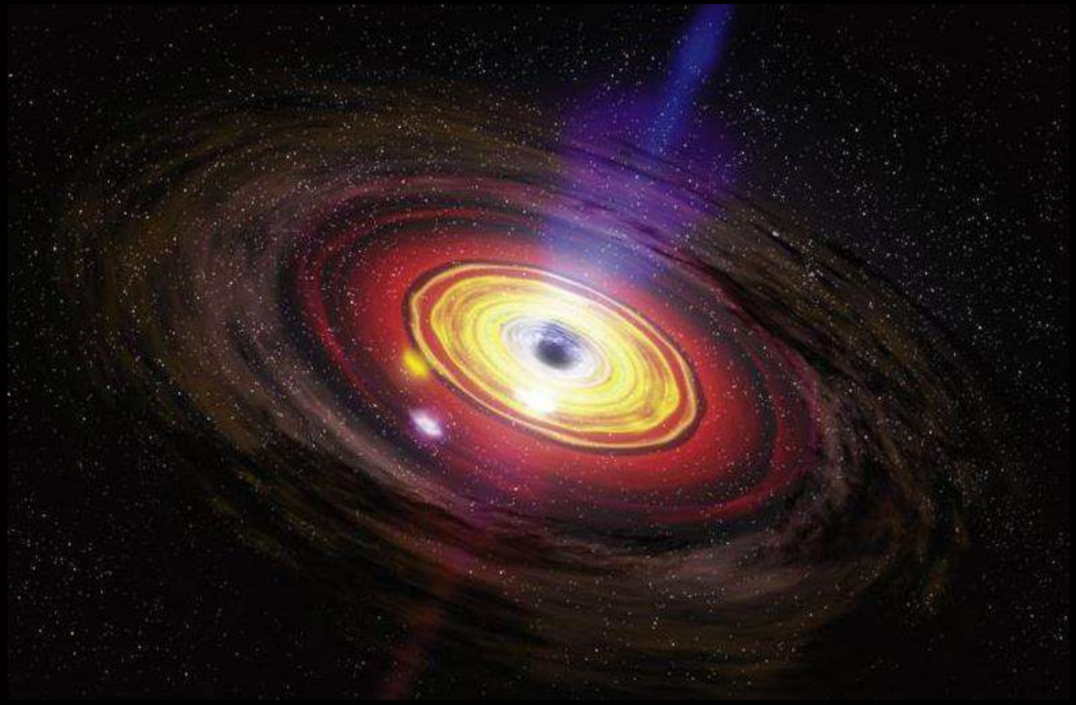
The Eddington limit, also known as the Eddington luminosity, is the maximum luminosity a star or accreting black hole can achieve when there's a balance between the outward force of radiation pressure and the inward force of gravity.

$$F_{rad} = F_{grav}$$

$$\frac{\sigma_T L}{4\Pi r^2 c} = \frac{GMm_p}{r^2}$$

$$L_{edd} = 3.2 \times 10^4 \left(\frac{M}{M_\odot}\right) L_\odot$$





Black Hole Accretion Disk

Many Kinds of Accreting BHs in the Universe :

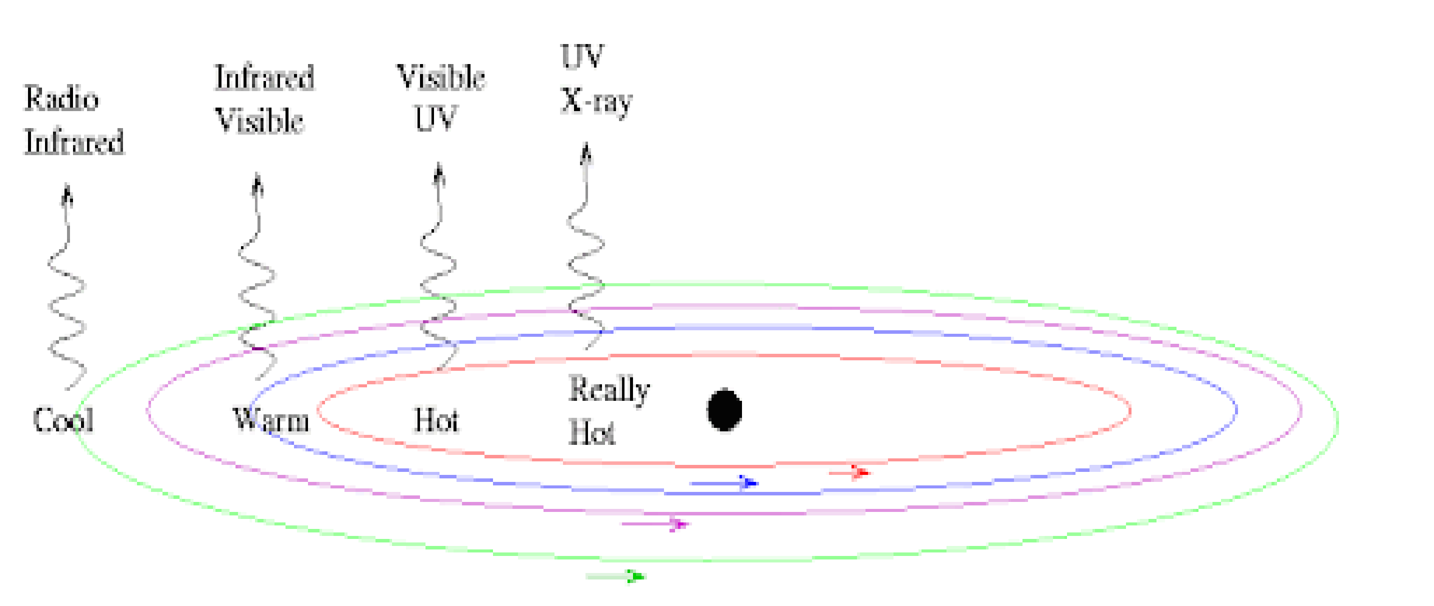
- ❖ Active Galactic Nuclei (AGNs)
- ❖ X-Ray Binaries (XRBs)

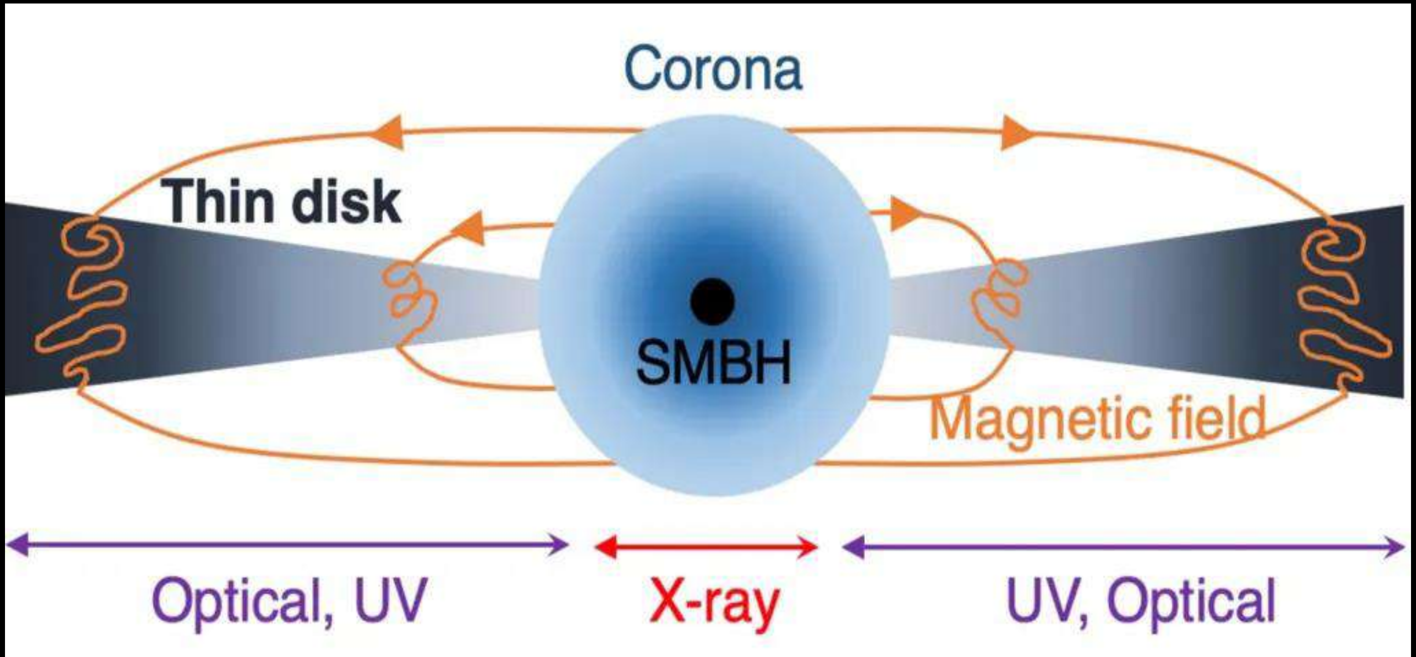
How do we see a BH?

- We observe **thermal and non-thermal radiation** emitted by hot gas in the **accretion disk**

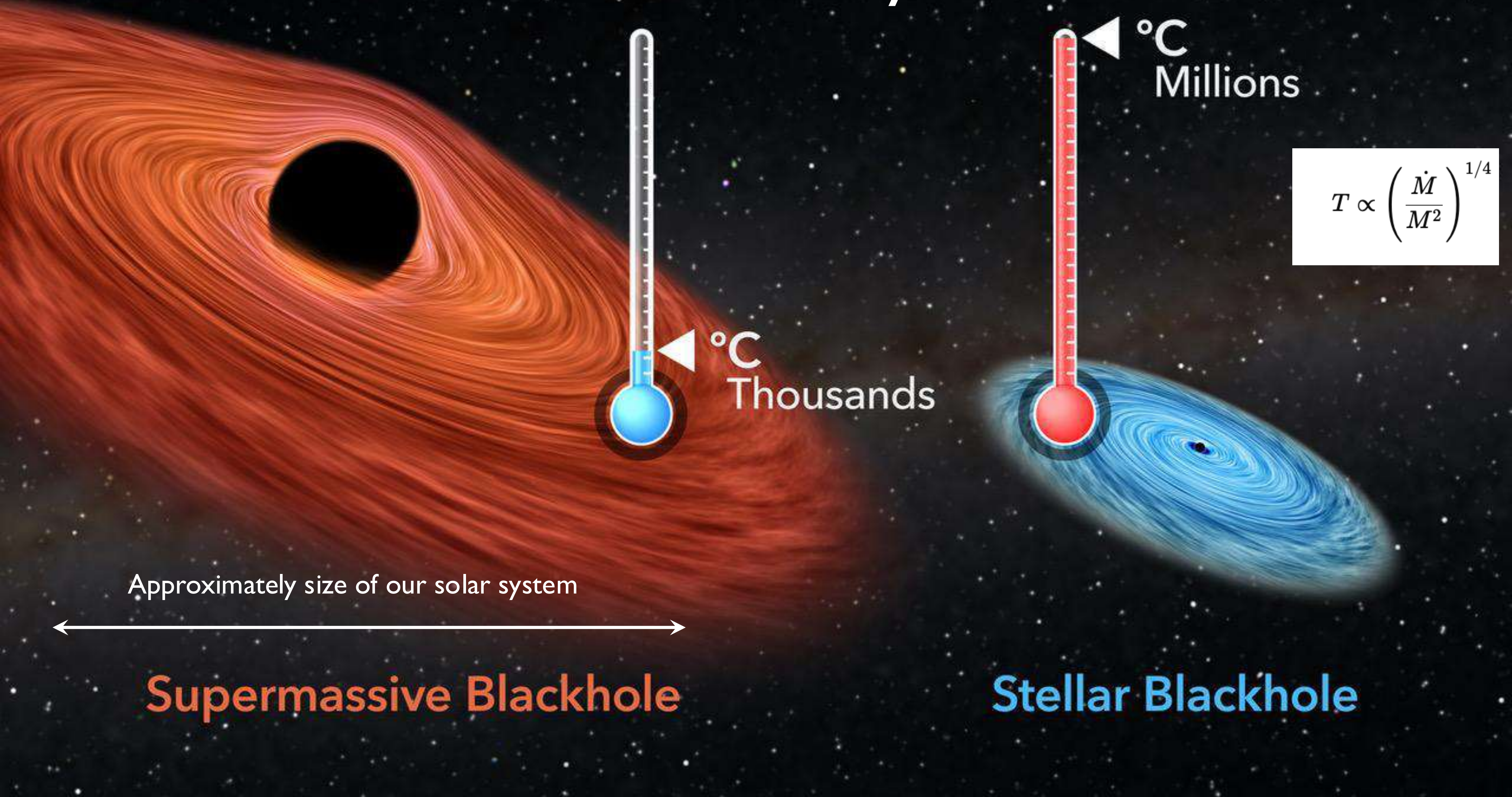
- Emission arises due to **friction (viscosity)** in the disk → heats the gas → it radiates

- **Temperature decreases with radius,** so **inner regions are hotter** than outer ones





The accretion disk scales linearly with the BH mass:



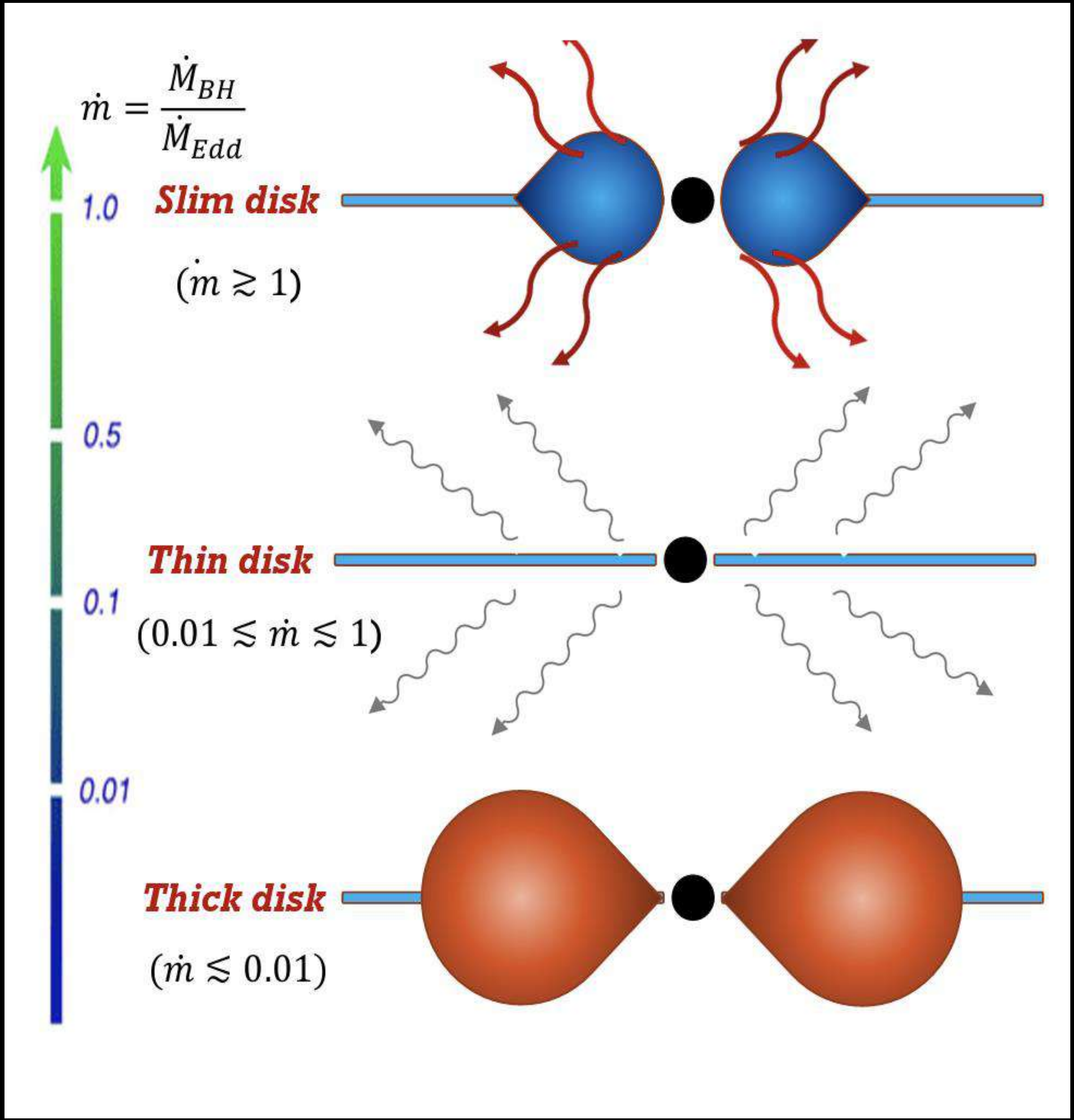
$$T \propto \left(\frac{\dot{M}}{M^2}\right)^{1/4}$$

Accretion disk solutions are achieved by solving the equations of fluid dynamics and gravity

🔧 1. Governing Equations

To model an accretion disk, we solve a set of coupled equations:

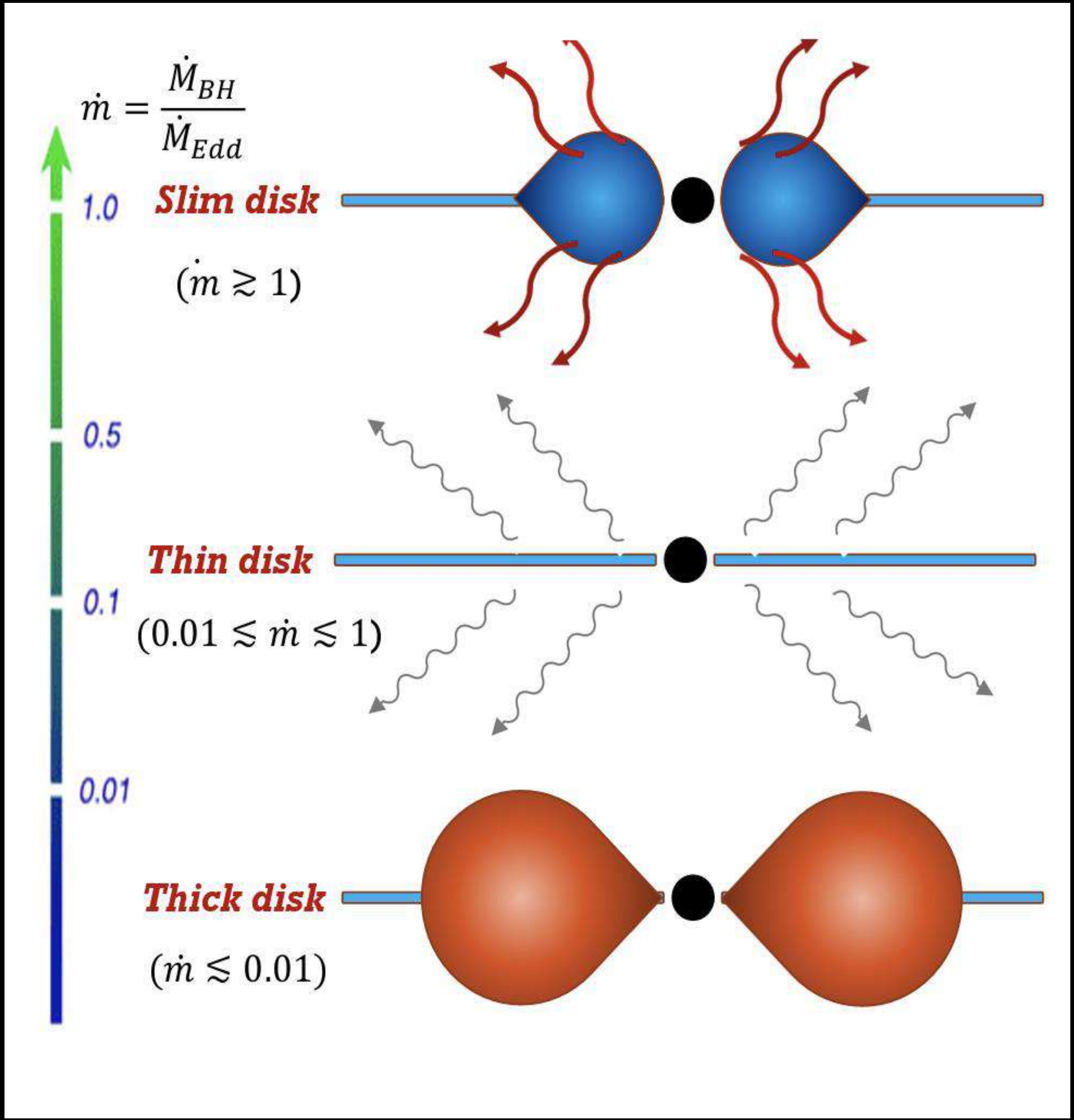
- **Continuity equation** (mass conservation
- **Momentum equations** (Euler or Navier-Stokes)
- **Energy equation**
- **Einstein's equations (GR)**



Accretion disk solutions

Slim Disks-

- Radiatively less efficient than thin disks.
- Radiation pressure-driven winds.
- Only occurs in rare cases.

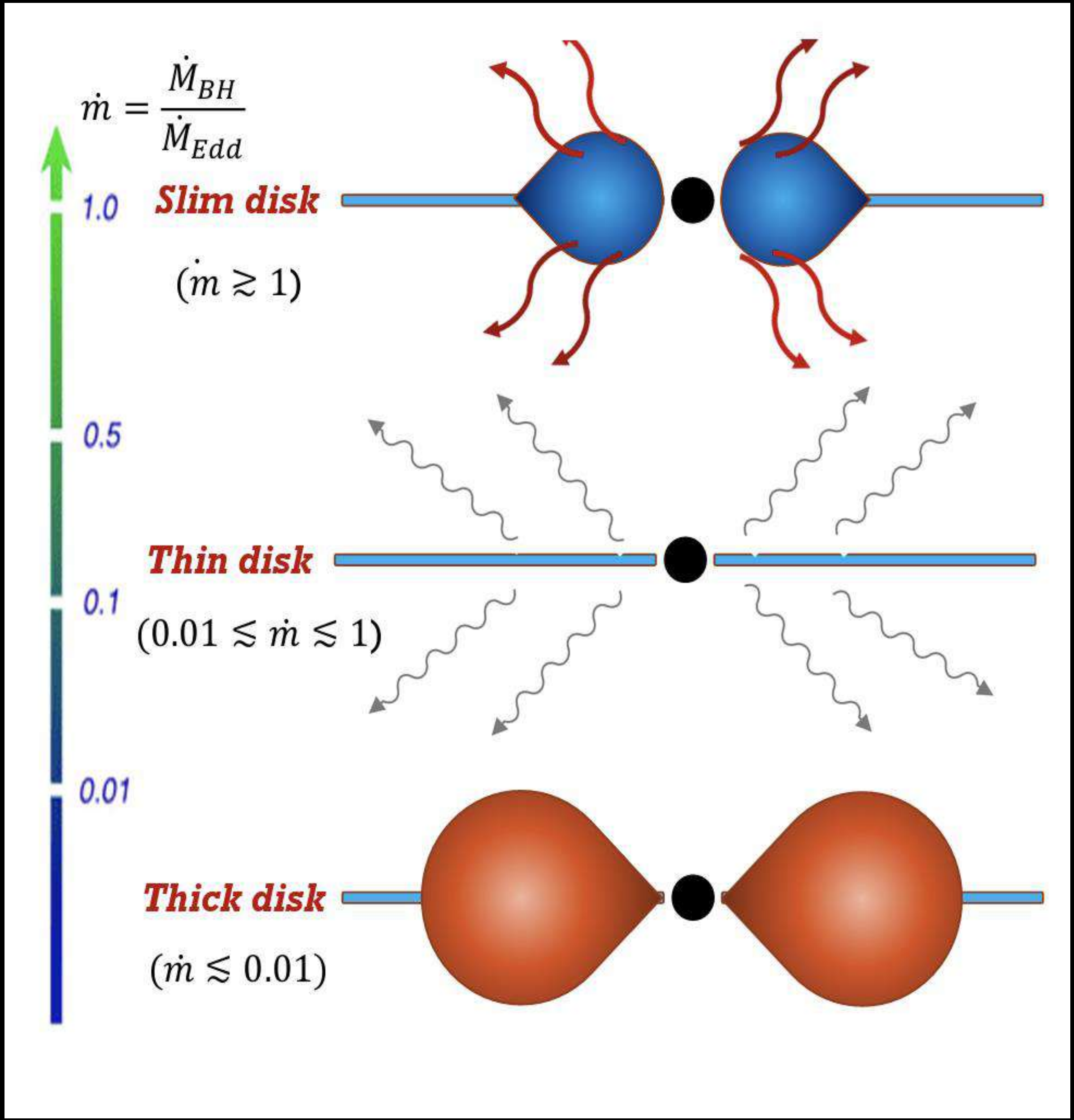


Accretion disk solutions

Thin Disks-

- Radiatively efficient
- Spectrum is well described by the superposition of black-body radiation
- Quasars, disk-dominated X-ray binaries

Accretion disk solutions

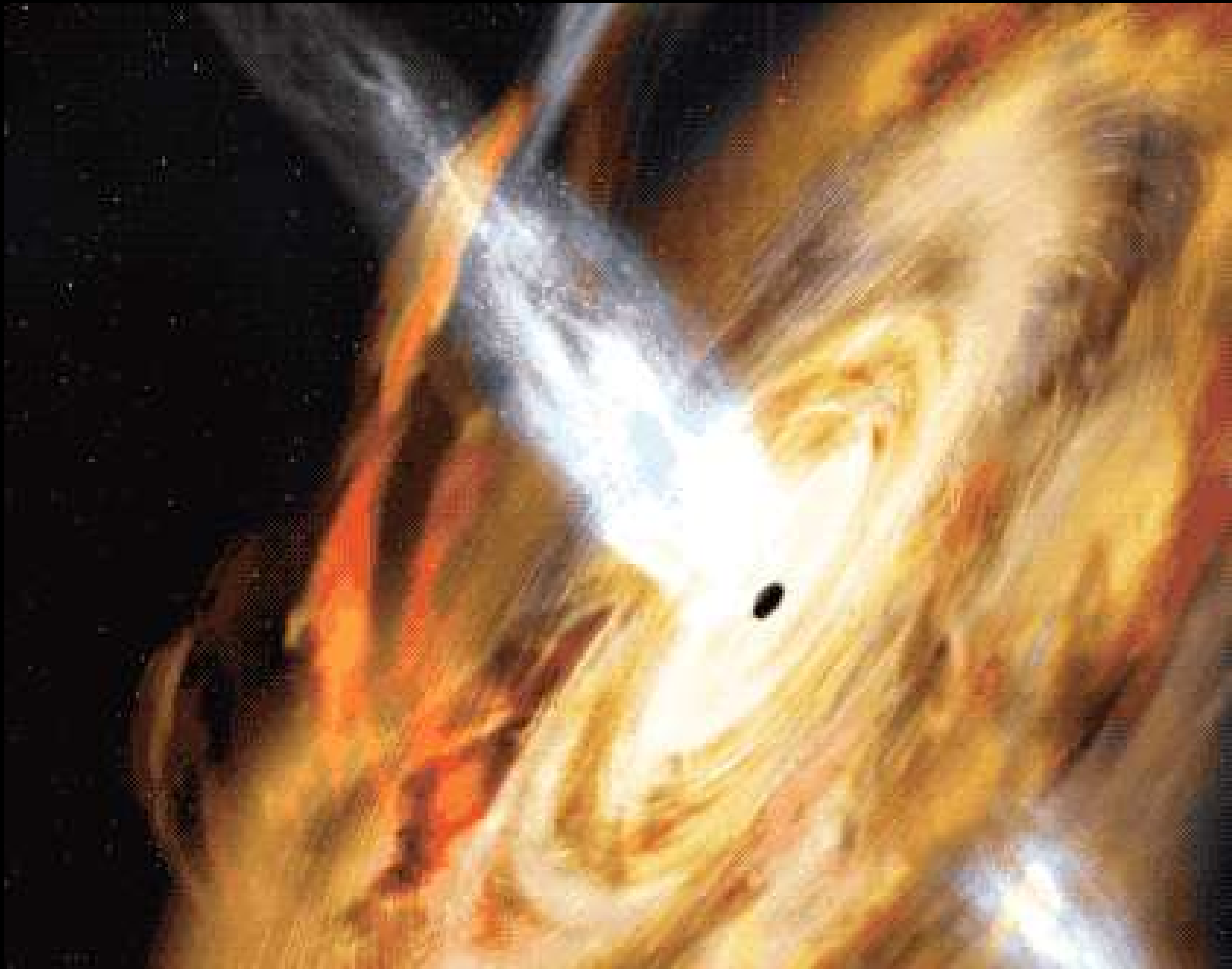


Thick Disks-

- Radiatively inefficient
- Accretion is from the hot corona
- Spectrum described by nonthermal processes.
- SgrA*, low-luminosity AGN, corona-dominated X-ray binaries

How Angular Momentum Gets Transferred?

Gravity pulls matter in, but angular momentum prevents direct infall. To accrete, the gas must lose angular momentum.



- ❖ Viscous Stresses
- ❖ Magnetic Fields
- ❖ Shocks or instabilities

How Angular Momentum Gets Transferred?

Accretion via angular momentum transport – Accretion disk

Vs

Accretion without angular momentum transport - Bondi

Without angular momentum transport

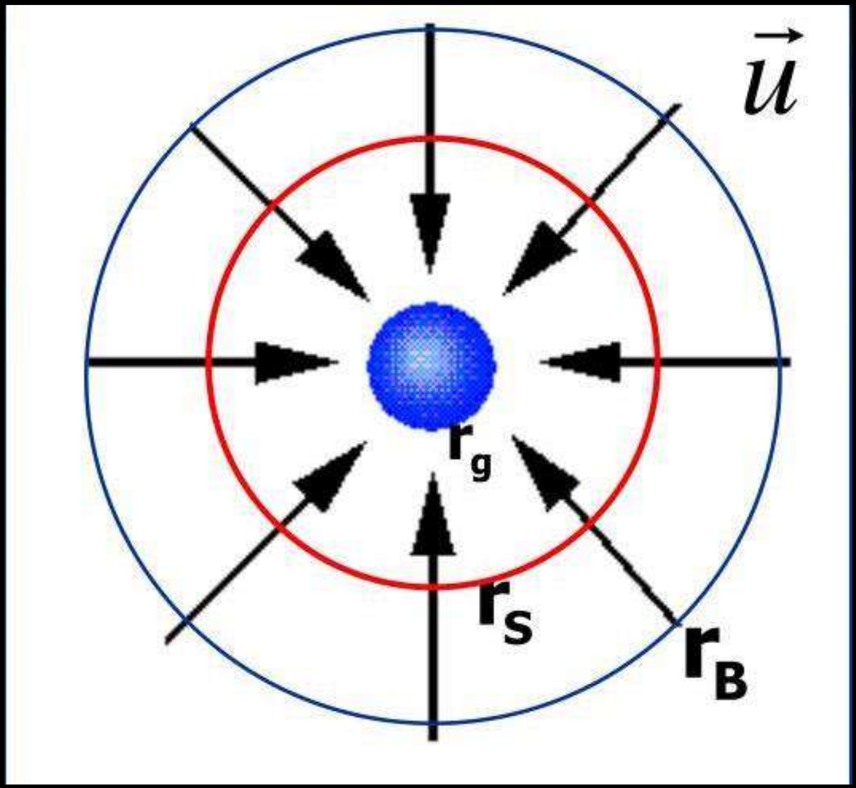
With angular momentum transport

Spherical accretion (Bondi, 1952)

Spherical, steady-state accretion of gas onto a compact object **without angular momentum**.

Assumes gas is **non-rotating** and falls radially inward under gravity.

- no angular momentum and no magnetic field



$$\dot{M}_{BH} = \frac{\pi G^2 M^2 \rho_\infty}{c_{s,\infty}^3}$$

$$r_{Bondi} = \frac{2GM}{c_{s,\infty}^2}$$

How Angular Momentum Gets Transferred?

Accretion via angular momentum transport = Forms an accretion disk

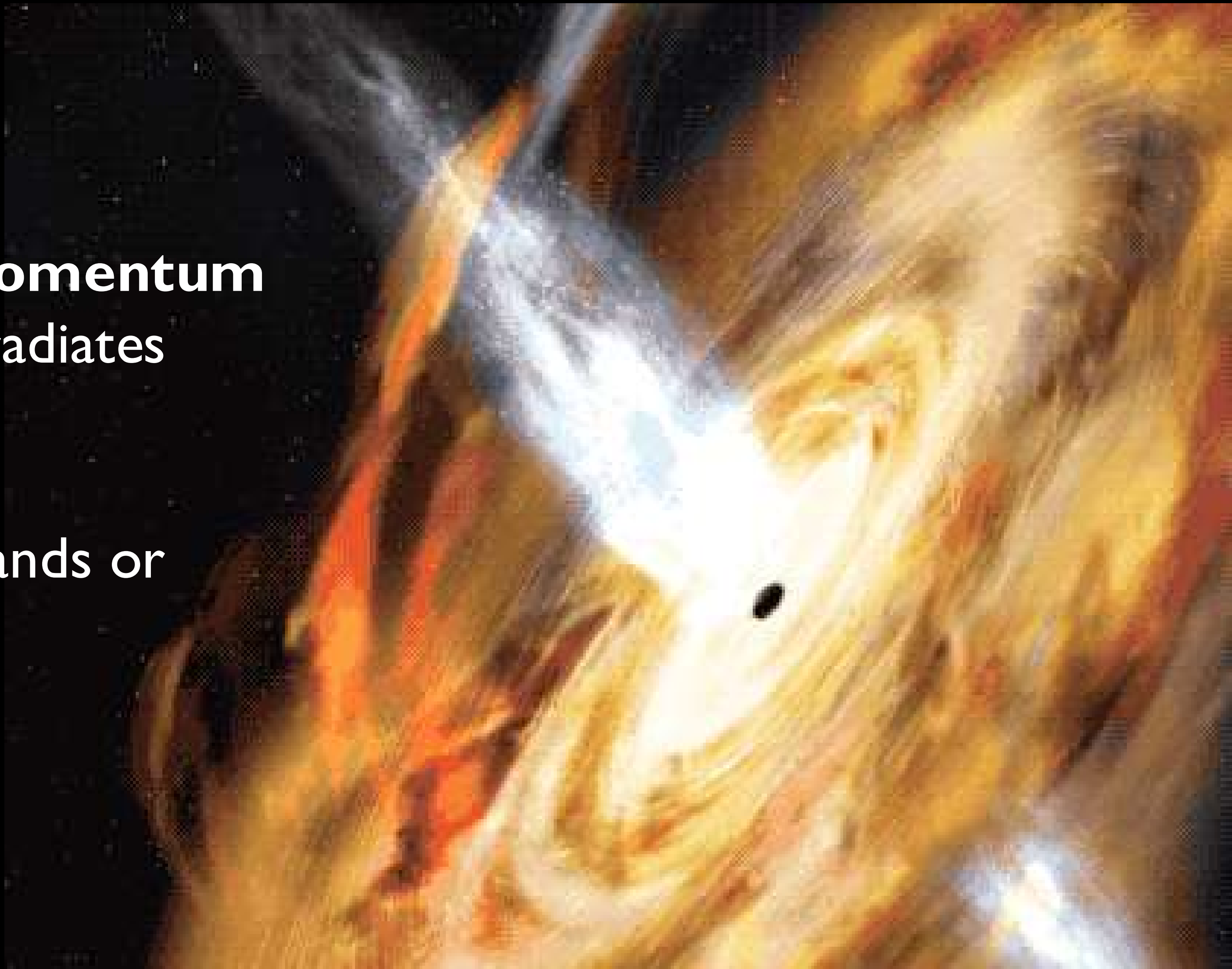
To accrete, gas must **lose angular momentum** via:

- Viscous/turbulent transport (α-viscosity)
- Magnetic torques (MRI or winds)
- Shocks or instabilities

How Angular Momentum Gets Transferred?

Net Effect

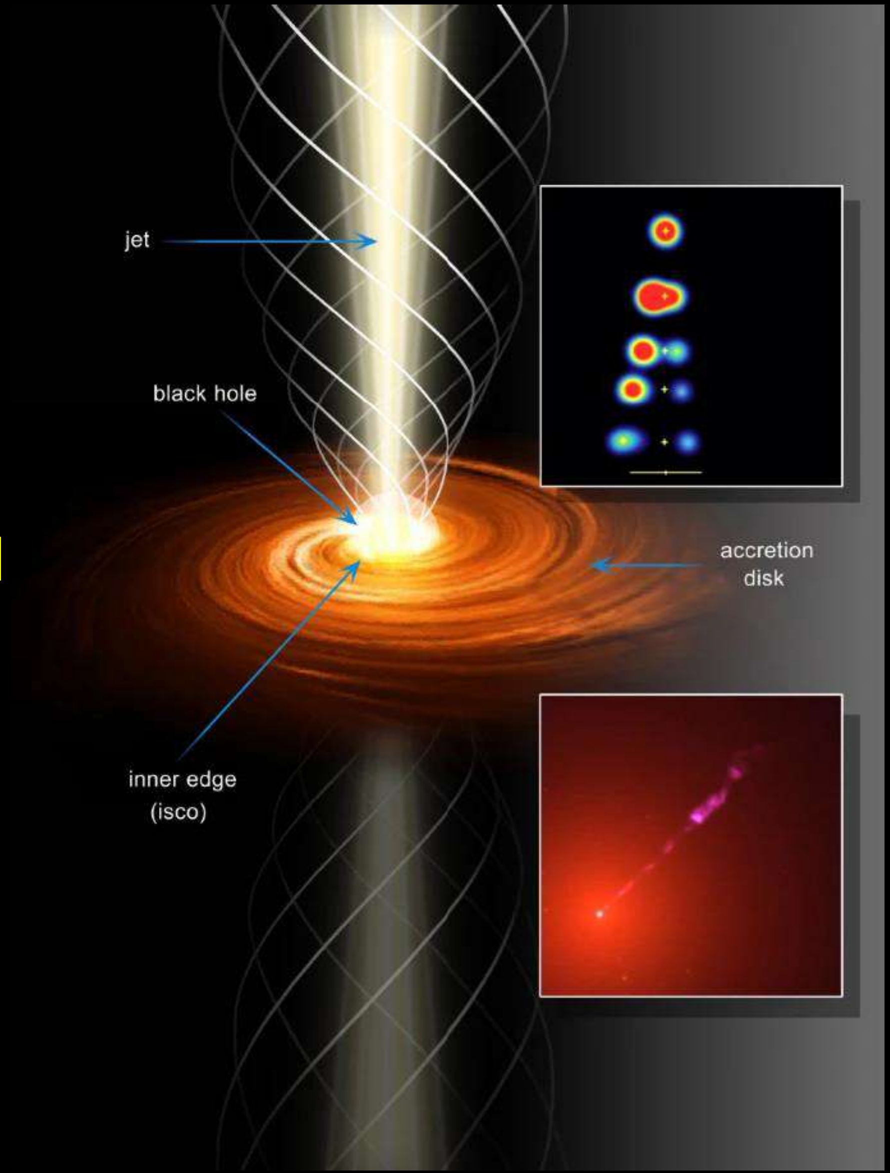
- Inner disk **loses angular momentum** → spirals in → heats up → radiates
- Outer disk **gains angular momentum** → slowly expands or drives outflows



Magnetic Field Geometry & Jet Formation

- launching and collimating **relativistic jets.**

- **Angular Momentum Transport**



Jets – powerful, narrow beams of matter and energy ejected along the rotation axis of a compact object

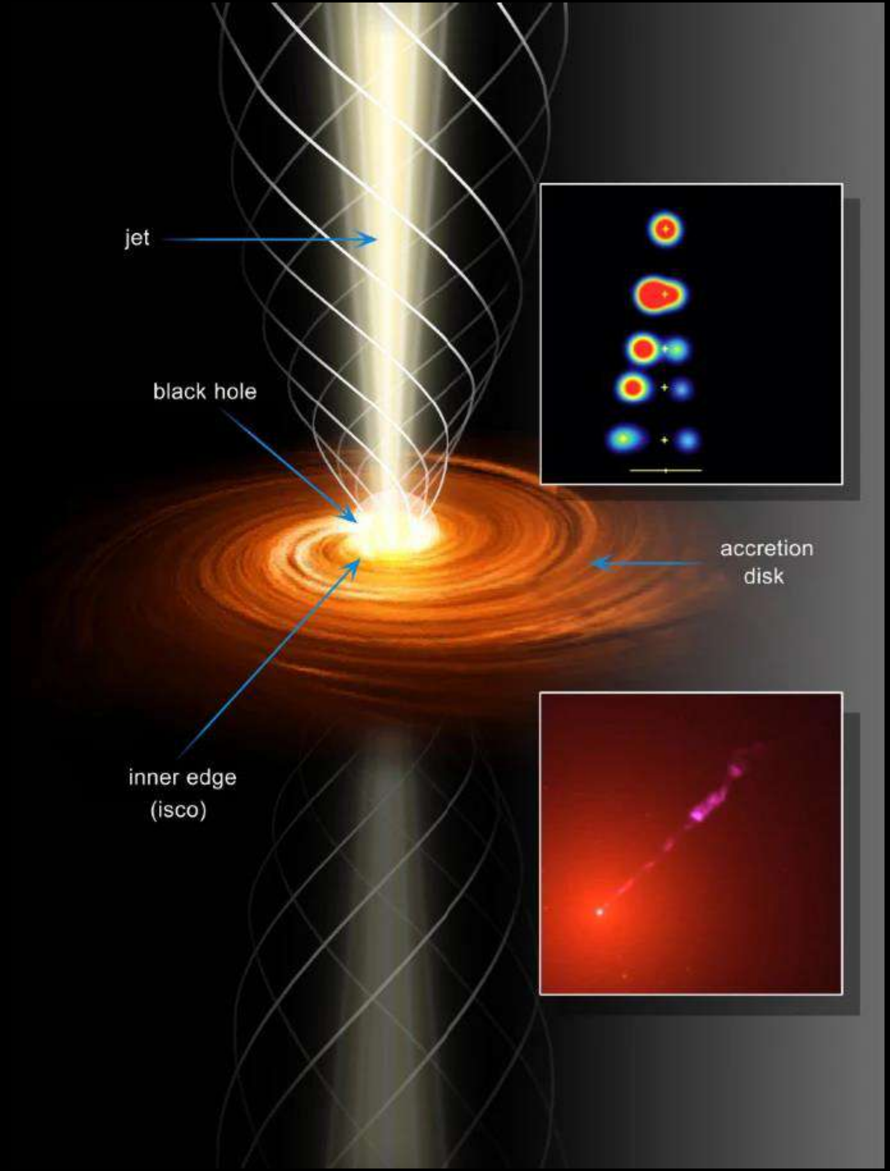
Astrophysical jets are collimated outflows of plasma moving at relativistic speeds.

They emerge **perpendicular to the plane of the accretion disk**, often in **bipolar** pairs.

Magnetic Field Geometry & Jet Formation

- launching and collimating **relativistic jets.**
- **Angular Momentum Transport**

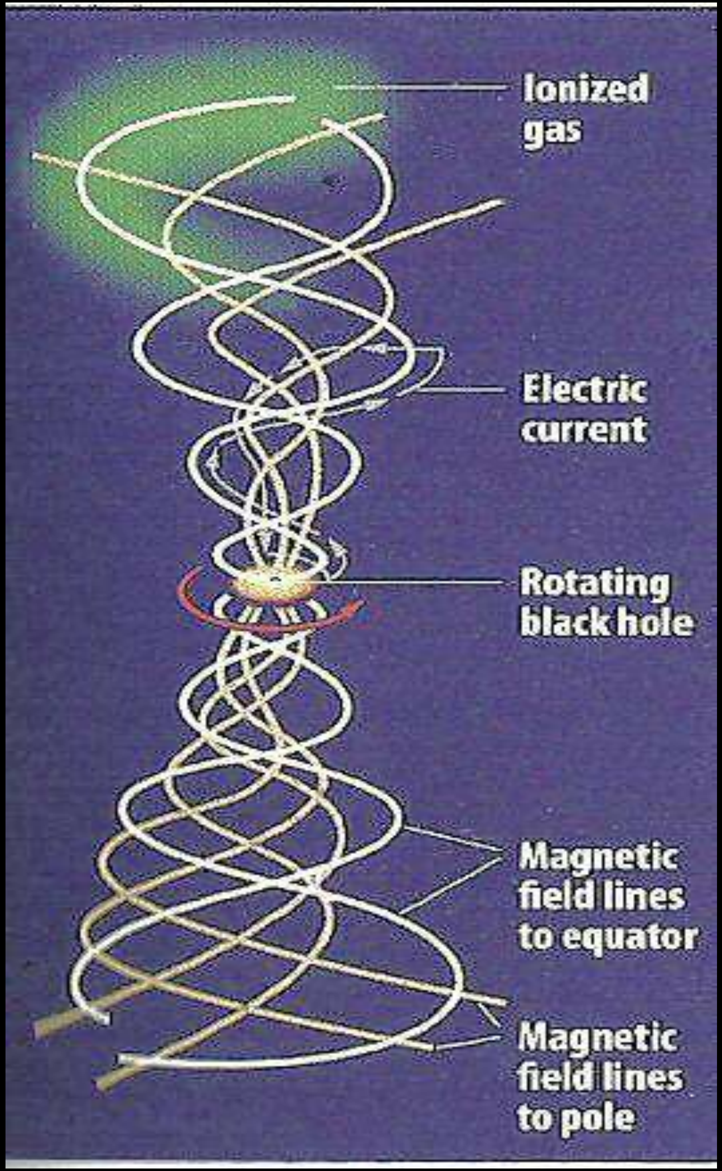
  - MRI (Magnetorotational Instability) amplifies fields in the disk
  - MRI is an **instability that arises in differentially rotating, weakly magnetized plasma.**
  - This feedback causes **runaway separation = instability = MRI**



Magnetic Field Geometry & Jet Formation

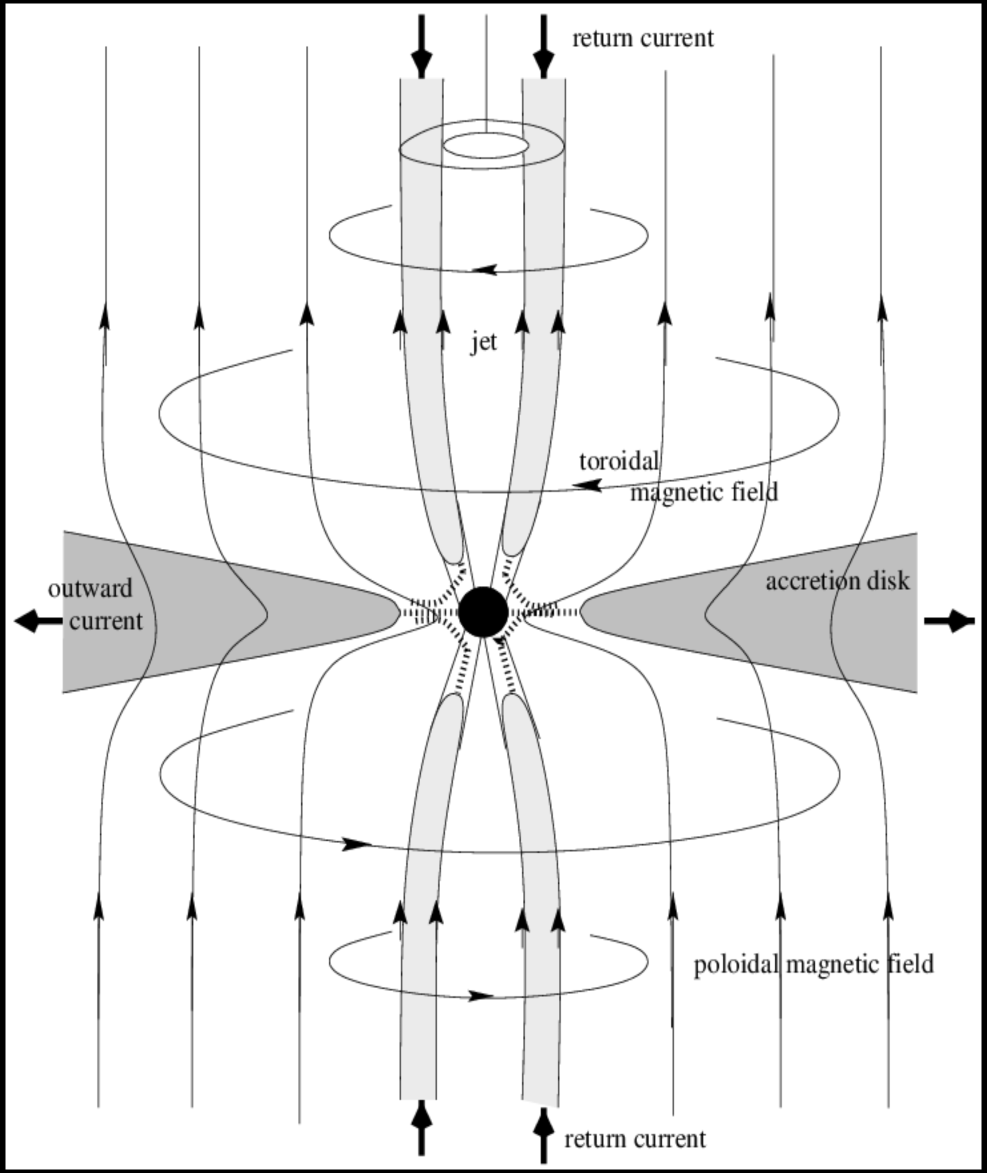
📊 Key Points

- ❖ **Jet power ∝ magnetic flux**
- ❖ Field geometry determines **launch, collimation, and stability**
- ❖ Simulations show **that ordered poloidal fields** are most efficient
- ❖ **Strong fields → structured, powerful jets**



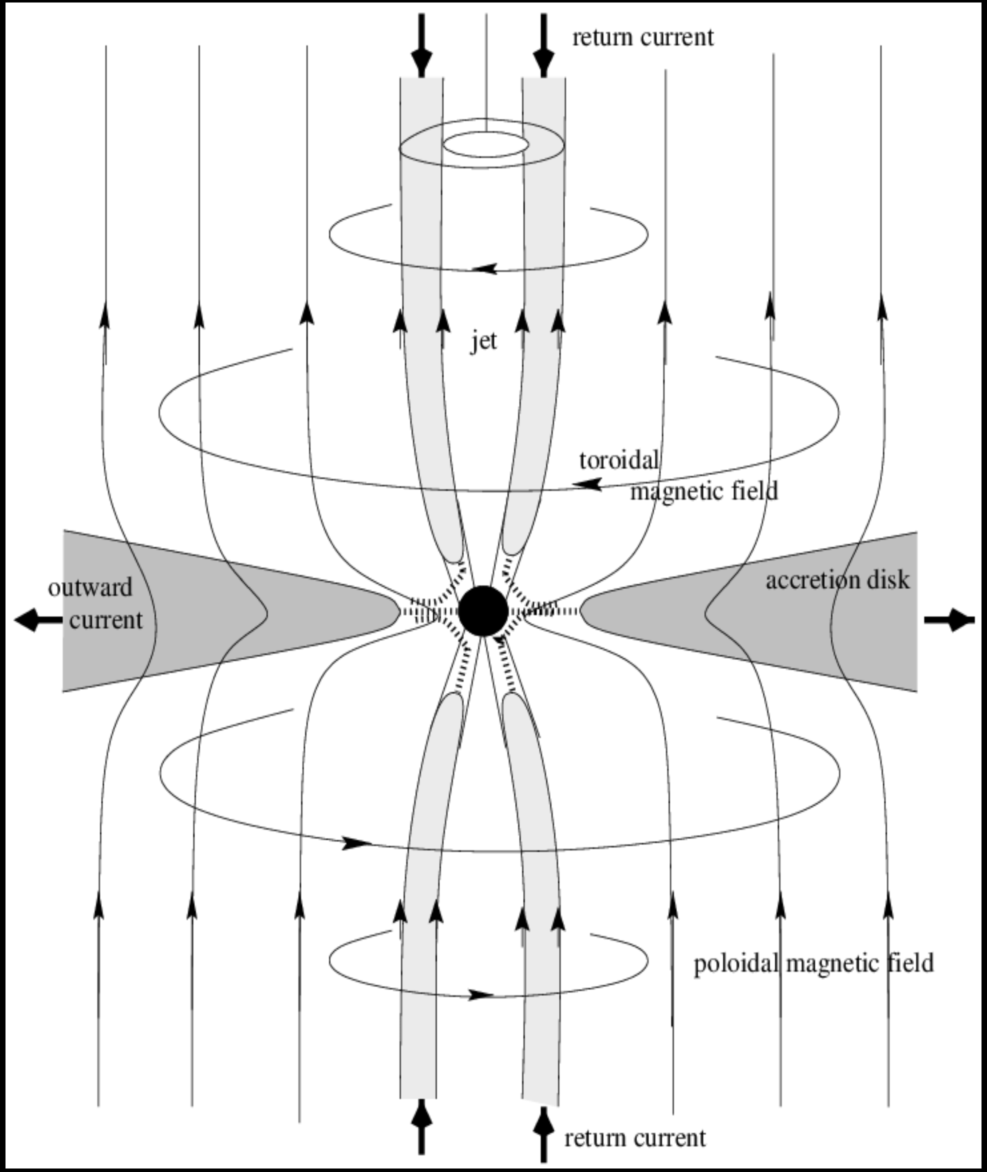
Blandford–Znajek (BZ) Mechanism

- A process that **extracts rotational energy** from a **spinning (Kerr) black hole.**
- Proposed by **Blandford & Znajek (1977)**



Blandford–Znajek (BZ) Mechanism

- **Magnetic field lines thread the black hole horizon.**
- Frame-dragging twists these field lines.
- This induces an **electric field** (Faraday induction).
- **Poynting flux** (electromagnetic energy) is launched outward.
- Result: **Powerful, collimated jet**

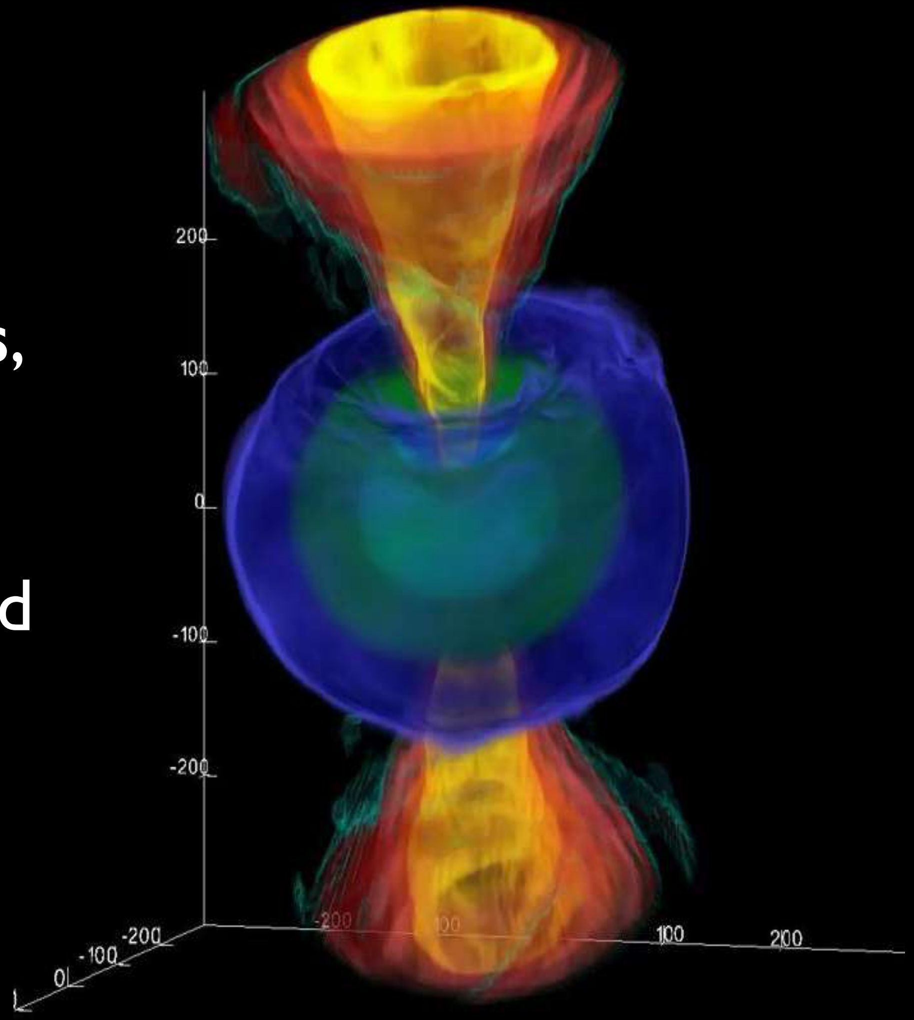


Role of GRMHD simulations

General Relativistic Magneto-Hydrodynamic Simulations

- Combine **general relativity**, **magnetic fields**, and **fluid dynamics.**

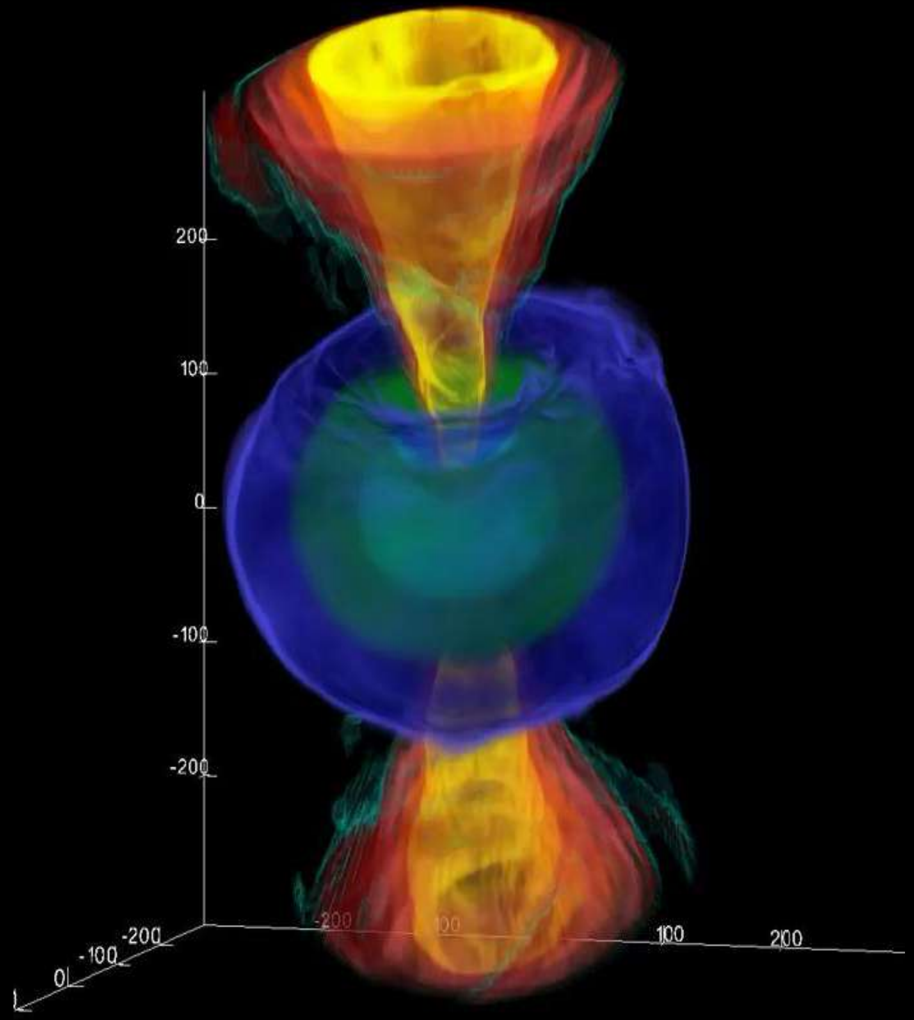
- Essential to model **strong gravity**, **plasma**, and **magnetically driven processes** near black holes



Role of GRMHD simulations

What Physics Is Included?

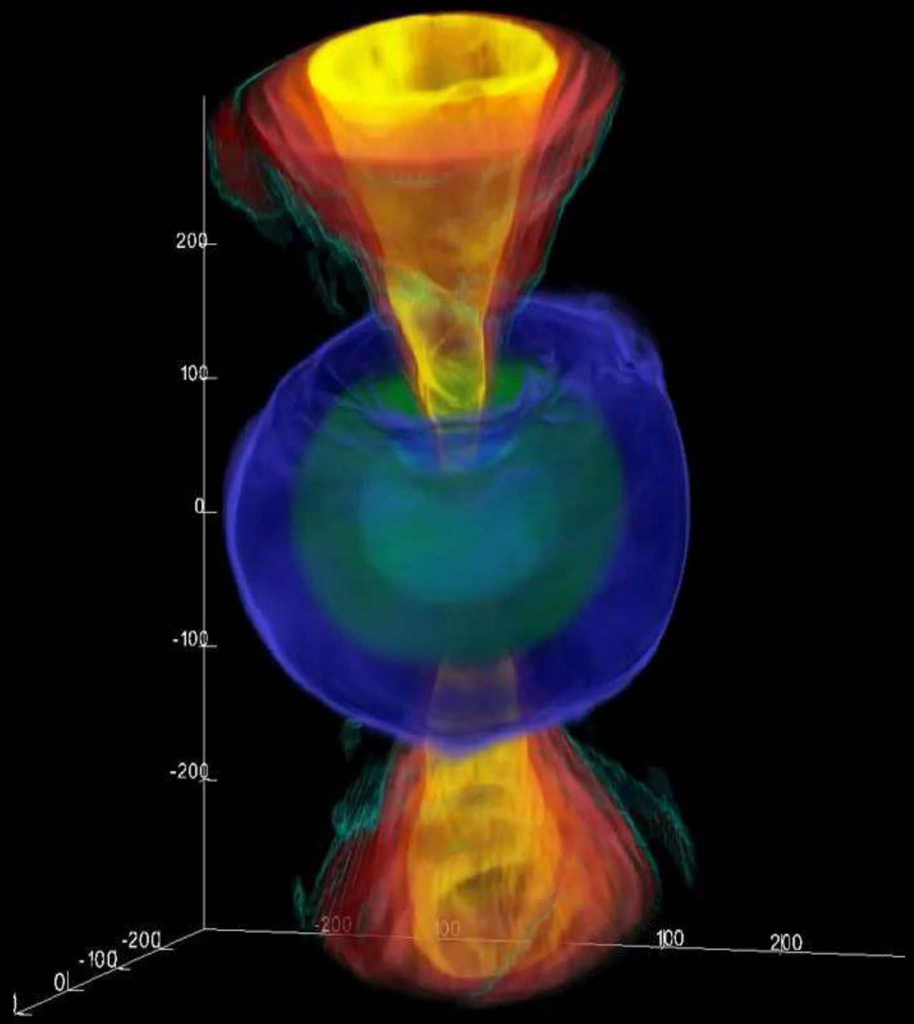
- Einstein's equations for gravity (fixed Kerr spacetime or dynamic in GR)
- MHD equations (mass, momentum, energy, magnetic induction)
- Microphysics: heating/cooling, radiation (in GRRMHD variants)



Role of GRMHD simulations

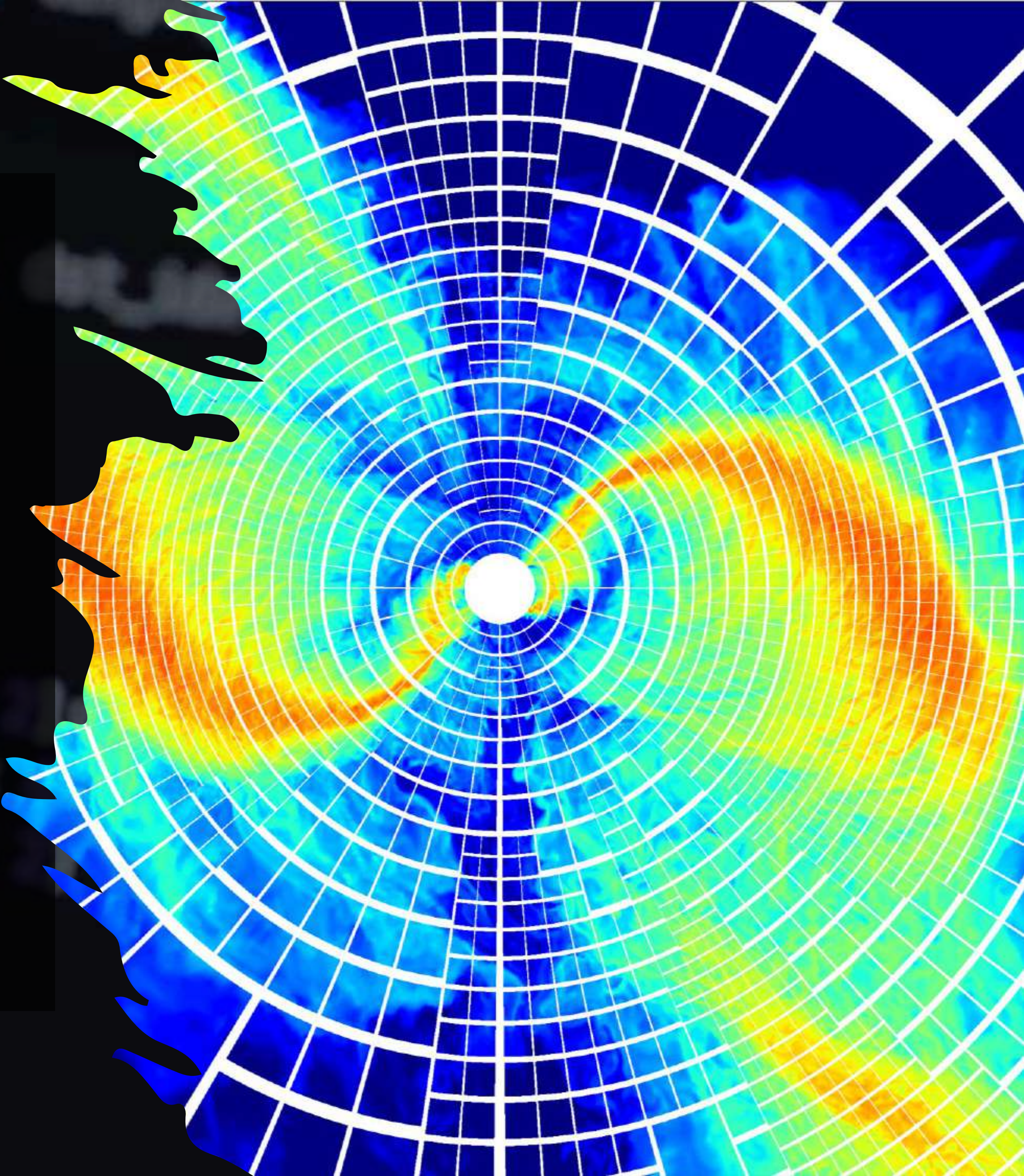
What Do GRMHD Simulations Model?

- Accretion disk structure and evolution
- Angular momentum transport (via MRI)
- Jet launching (Blandford–Znajek)
- Disk winds and outflows
- Variability and turbulence in disks



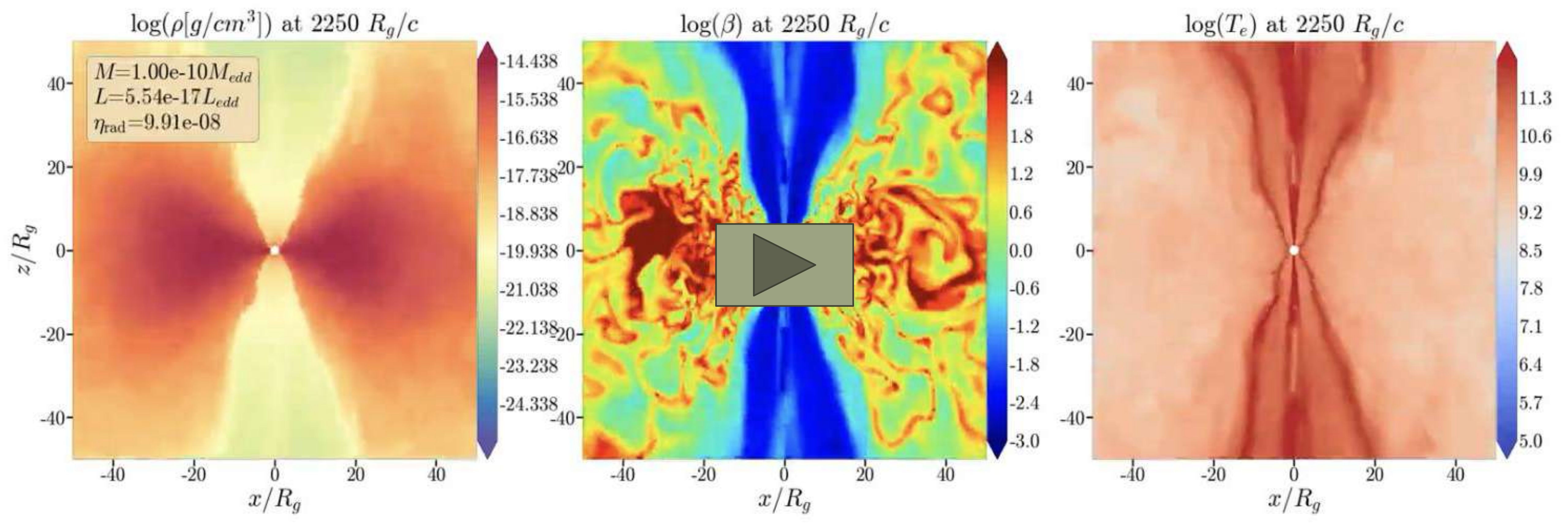
GRMHD codes -

- HARM,
- BHAC,
- KORAL,
- ATHENA++,
- H-AMR,
- Illinois GRMHD, etc.



GRMHD Simulation showing evolution of a Black Hole Accretion Disk

(Matthew Liska, 2023, H-AMR code)



🔧 1. Basic Terminology

- **Node**: A single physical machine in the cluster. Each node typically contains multiple CPU cores.
- **Core**: An individual processing unit in a CPU. More cores mean more parallel computation.
- **Wall-clock time**: Actual real-world time the simulation runs.
- **Core-hours**: Product of the number of cores used and the time (in hours) they were used. (standard billing/usage unit in HPC).

📐 2. Formula for Core-Hours

Core-hours = Number of Nodes × Cores per Node × Wall-clock Time (in hours)

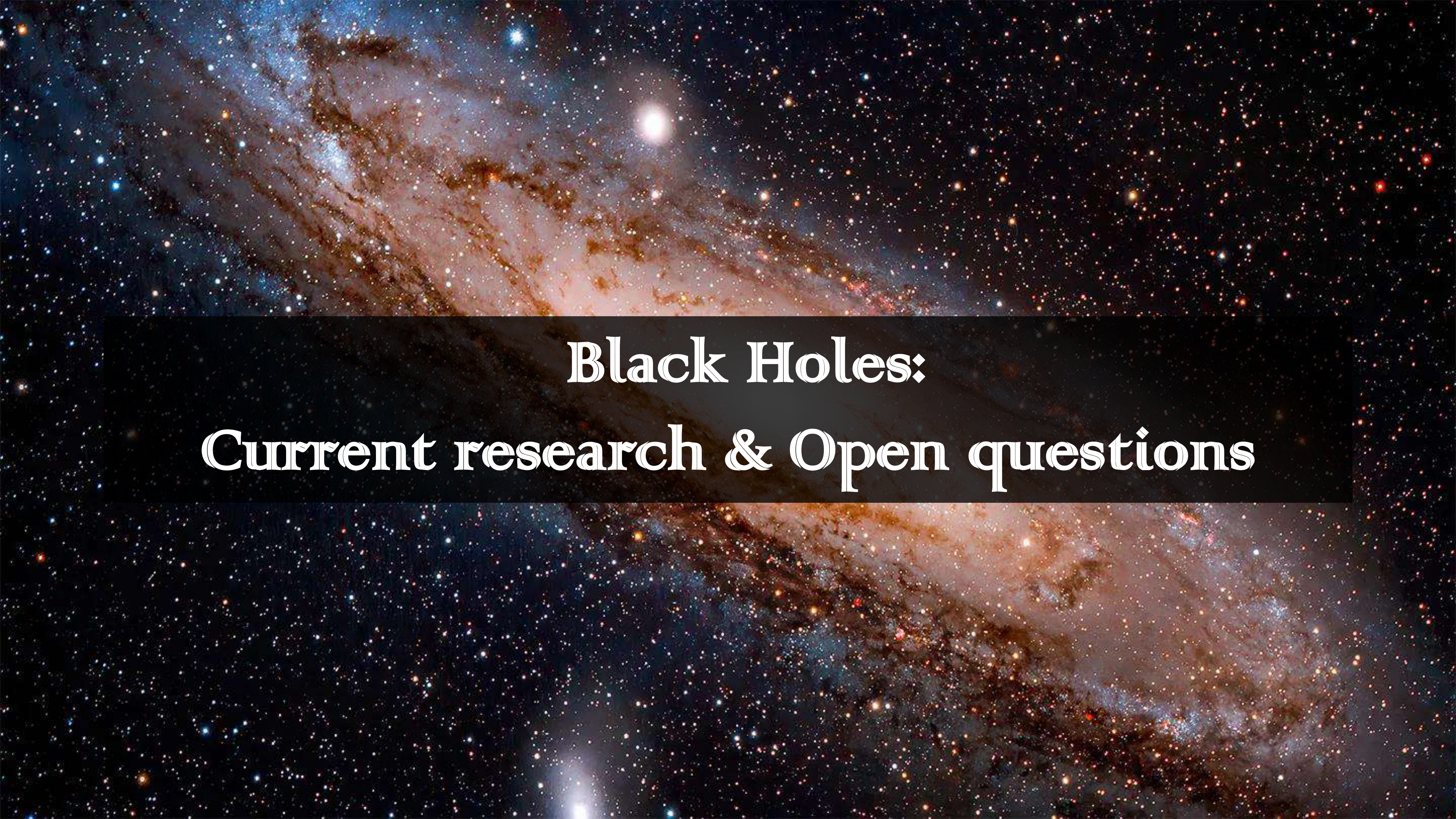
🧮 3. Example Calculation

Say your GRMHD simulation ran on:

- 16 nodes
- 64 cores per node
- for 10 wall-clock hours

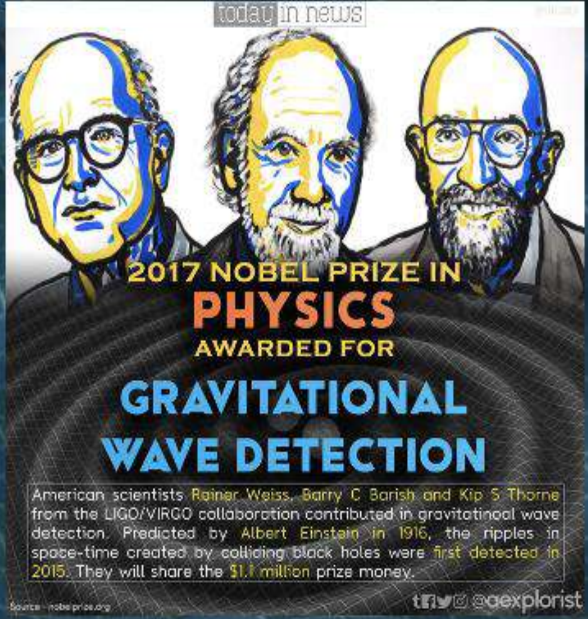
Then:

Core-hours = 16 × 64 × 10 = 10,240 core-hours



Black Holes:
Current research & Open questions

Discovery of Gravitational Waves – A New Era



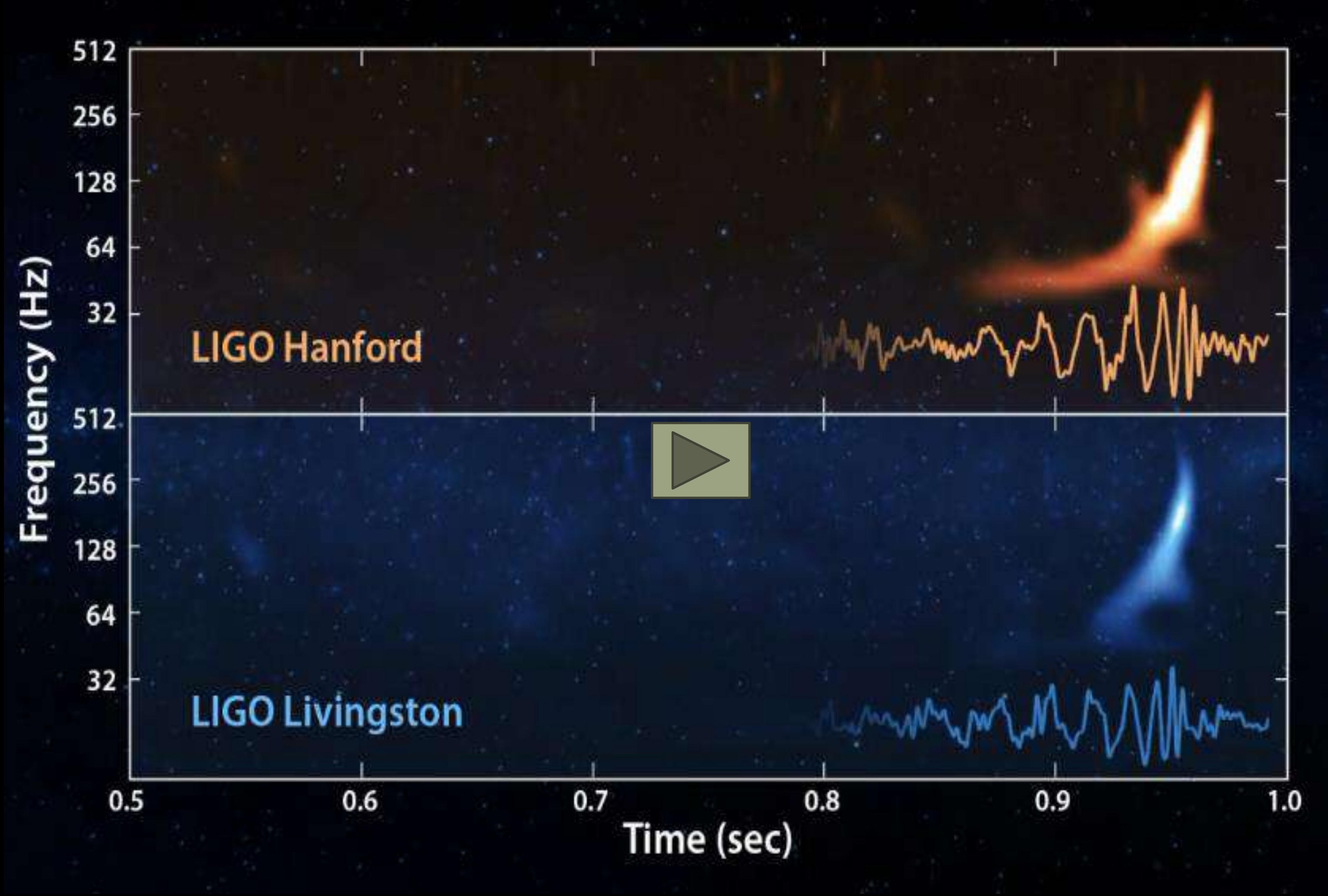
Discovery of Gravitational Waves – A New Era

📅 Historic Moment

- ❖ **February 11, 2016**: LIGO announced **first direct detection of gravitational waves**
- ❖ Event name: **GW150914**
- ❖ Detected from the merger of **two stellar-mass black holes** (~30 $M_\odot$ each)
- ❖ **Gravitational waves**: ripples in spacetime caused by **accelerating massive objects**

Discovery of Gravitational Waves – A New Era

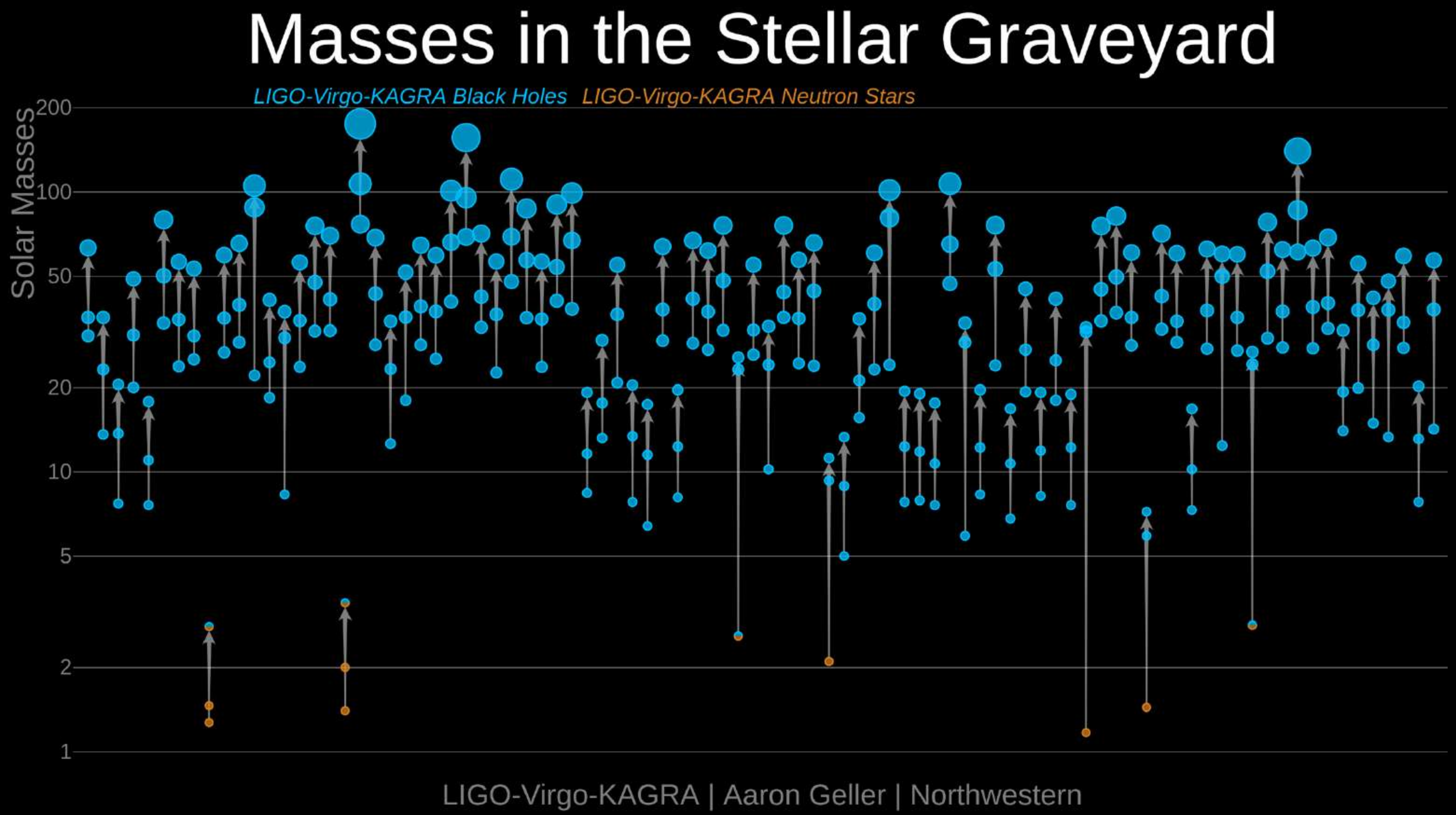
- LIGO observatories: Two detectors in the USA: **Hanford (WA)** and **Livingston (LA)**
- Use **laser interferometry** to detect incredibly small spacetime distortions
- Laser beams travel down **4 km arms** and reflect off mirrors
- A passing gravitational wave **alters the arm lengths by ~10^{-21} m**
- Produces **interference pattern** changes → signal recorded



Discovery of Gravitational Waves – A New Era

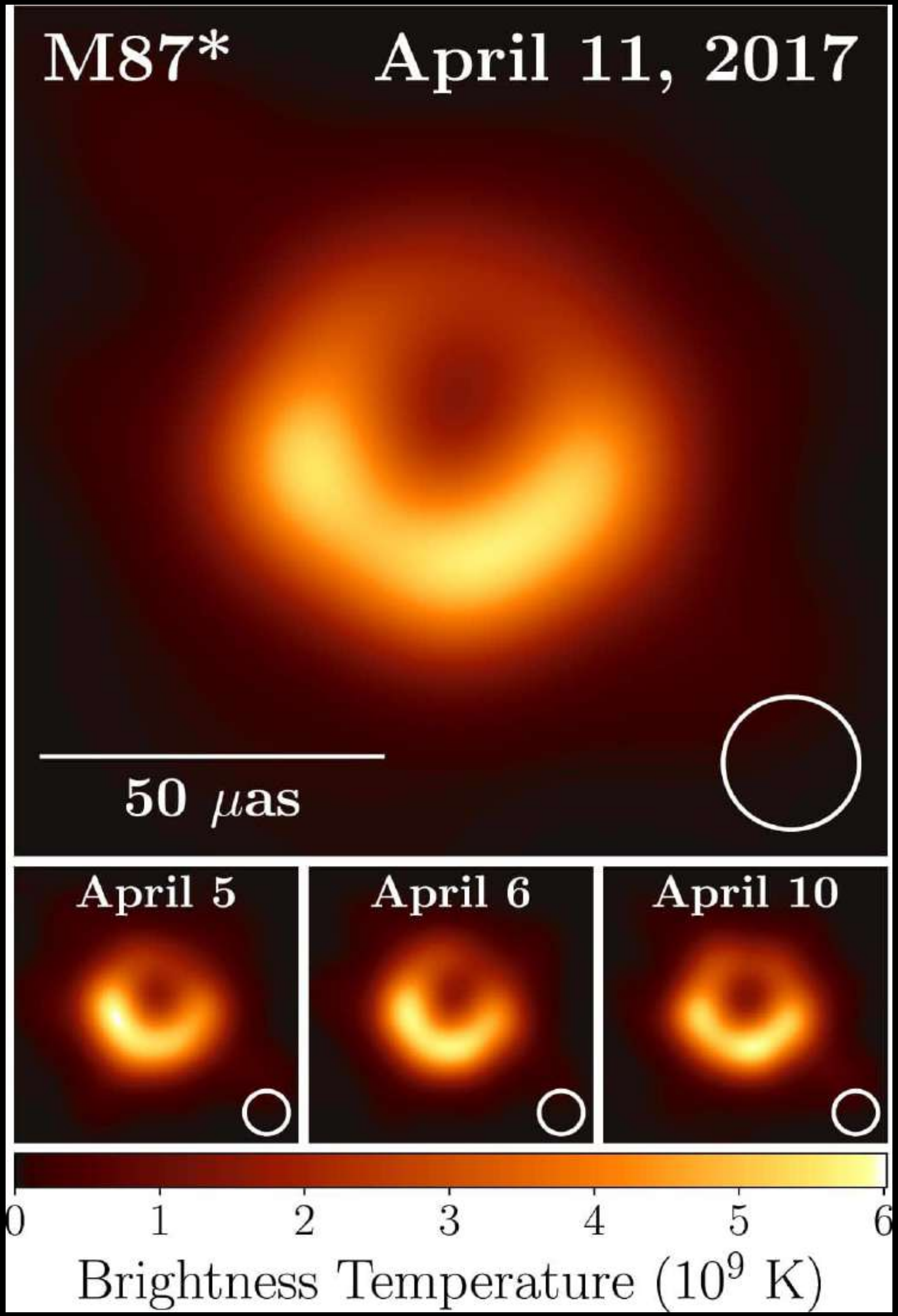
- **Opened a New Field: Gravitational Wave Astronomy - observe the universe through spacetime itself**, not just light
- Reveals events **invisible to telescopes** (e.g., black hole mergers)
- Measured properties of black holes (mass, spin, distance)
- Later events (e.g., **GW170817**) from **neutron star mergers**:
- Confirmed **origin of heavy elements**
- Linked **gravitational waves with electromagnetic signals**

On November 7, 2021, the LIGO-Virgo-KAGRA Collaboration released the largest catalog ever of collisions involving black holes and neutron stars.



The Historic Discovery – First Image of a Black Hole

- In **April 2019**, EHT released the **first-ever image of a black hole**
- Target: **M87*** — supermassive black hole in galaxy **Messier 87**
- **Direct visual confirmation** of black hole predictions from general relativity
- First glimpse of the **event horizon scale structure**



The Event Horizon Telescope (EHT) — a planet-scale array of eight ground-based radio telescopes forged through international collaboration

What Are We Seeing in the EHT Black Hole Image?

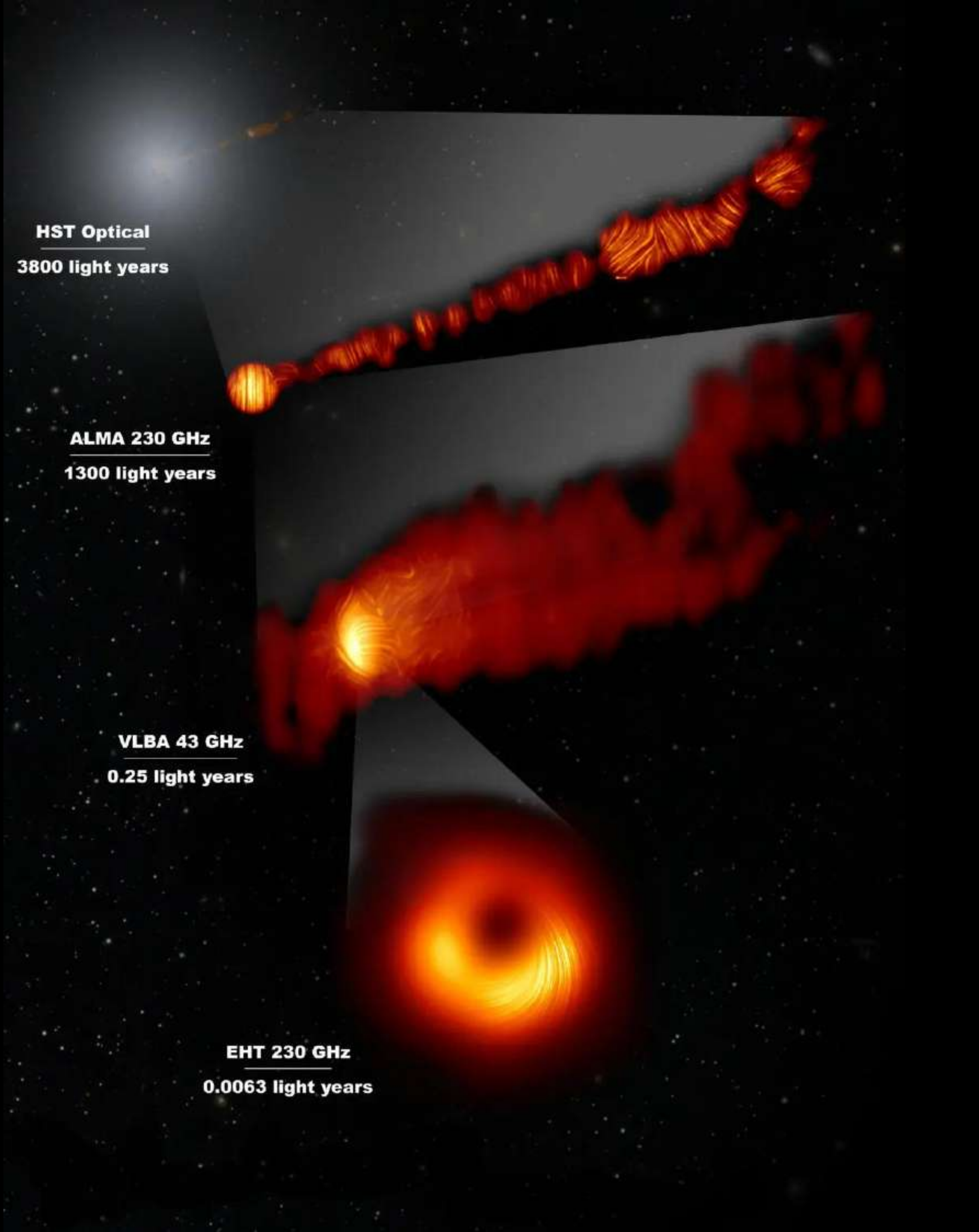
1. **Bright Ring of Emission ("Photon Ring")**

2. Dark Center – The Black Hole "Shadow"

3. **Asymmetry in Brightness**

4. **Not a Direct Image – It's a Reconstructed Signal**

5. Matches predictions from **General Relativity + GRMHD simulations**



New Windows Opened by EHT

🌌 Probing Extreme Gravity

- Tested **general relativity** in the **strong-field regime**
- Constrained black hole **mass, spin, and accretion geometry**

🧲 Jet–Disk Connection

- M87 has a **powerful relativistic jet** → The image helped locate **the launch region**
- Supports **the Blandford–Znajek mechanism** for jet formation

🔭 Toward Time-Resolved Imaging

- EHT now aims to create **movies** of black holes (time variability)
- Future targets: **Sgr A*** (Milky Way's SMBH), jet base studies, polarized imaging

Black Holes: Summary

Stellar-mass black holes are remnants of massive stars after supernova explosions.

Supermassive black holes reside at centers of most galaxies (origin, still mystery).

Black holes arise as exact solutions to Einstein's equations of general relativity.

Accretion disks - detect black holes by converting gravitational energy into radiation.

A central question in accretion theory is how angular momentum is transported outward.

These breakthroughs mark a new era of multi-messenger black hole astrophysics.

Magnetic fields are crucial for both angular momentum transport and jet formation.

GW detections - revolutionized our understanding of compact object mergers.

GRMHD simulations offer powerful insights -physics of accretion and jet dynamics.

Event Horizon Telescope (EHT) imaging - direct evidence of black hole shadows.

Thank you for listening