TOWARDS EVENT HORIZON SCALE PHYSICS FROM MOVIES AND POLARIZATION MAPS

RICHARD ANANTUA

Event Horizon Telescope

CENTER FOR ASTROPHYSICS HARVARD & SMITHSONIAN

Black Hole Initiative Harvard University

x^0: 10/22/2021 5:30p EDT
x^i: At home

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PRESENTATION AT NSBP INNOVATIVE SEMINAR SERIES

TALK OUTLINE

- A Brief Introduction to Relativity
  - Electromagnetism
  - Special Relativity
  - General Relativity
- Observing Jet/Accretion Flow/Black Hole (JAB) Simulations
  - Terminology and Definitions
  - Application: M87
    - Observing JAB Simulations of M87
      - Comparison of images with VLBA (43 GHz) and polarized EHT (230 GHz) observations
- Future Horizons: Sgr A*
  - Observing JAB Simulations of Sgr A*
    - Comparison of images with EHT constraints
    - Classification of model parameter space movies

ELECTROMAGNETISM – MAXWELL'S EQUATIONS

- Maxwell's equations describe the dynamics of electric and magnetic fields

Gauss's Law

$$\oiint \vec{E} \cdot d\vec{A} = \frac{Q_{enc}}{\varepsilon_0}$$

Gauss's Law for Magnetism

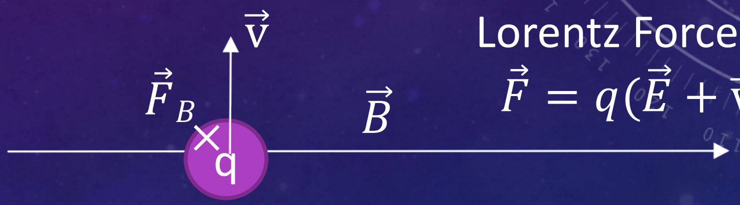
$$\oiint \vec{B} \cdot d\vec{A} = 0$$

Faraday's Law

$$\oint \vec{E} \cdot d\vec{l} = -\frac{\partial \Phi_B}{\partial t}$$

Ampère Law

$$\oint \vec{B} \cdot d\vec{l} = \mu_0 I_{enc} + \mu_0 \varepsilon_0 \frac{\partial \Phi_E}{\partial t}$$



Lorentz Force Law:

$$\vec{F} = q(\vec{E} + \vec{v} \times \vec{B})$$

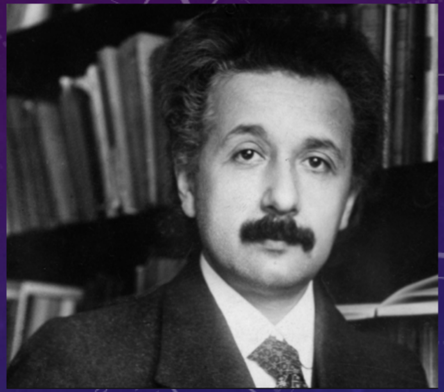
Now that we know these basic relationships between $\vec{E}$ and $\vec{B}$ … Let there be light!

Poynting flux (power per unit area):

$$\vec{S} = \frac{1}{\mu_0} \vec{E} \times \vec{B}$$

Let's also see Maxwell's Eqs. in integral form

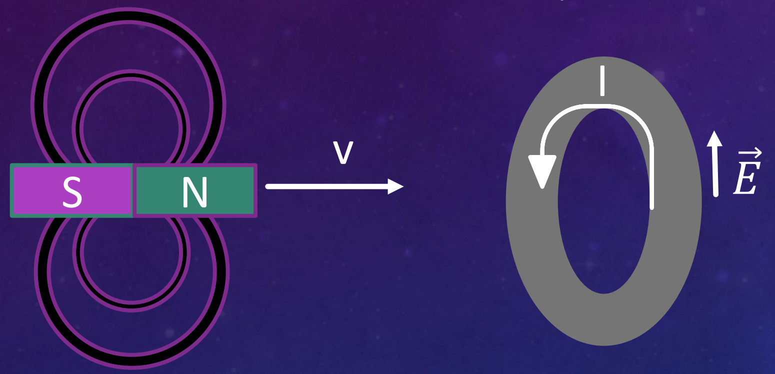
SPECIAL THEORY OF RELATIVITY – ON THE ELECTRODYNAMICS OF MOVING BODIES



- In 1905 Albert Einstein (1879-1955) wrote observations from a series of thought experiments and observations in *On the Electrodynamics of Moving Bodies:*
  - Relative, not absolute motion, establishes current in magnet-conductor system
  - Simultaneity depends on an observer's state of motion, or reference frame
  - Clocks synchronize if the difference in times (measured locally) from when light is emitted at A to when light arrives at B equals the corresponding difference for the reverse journey

RELATIVITY OF E AND B - MAGNET AND CONDUCTOR

- In the frame of the conductor, the moving magnet creates a changing magnetic flux that results in an electric field in the conductor, and subsequently a current

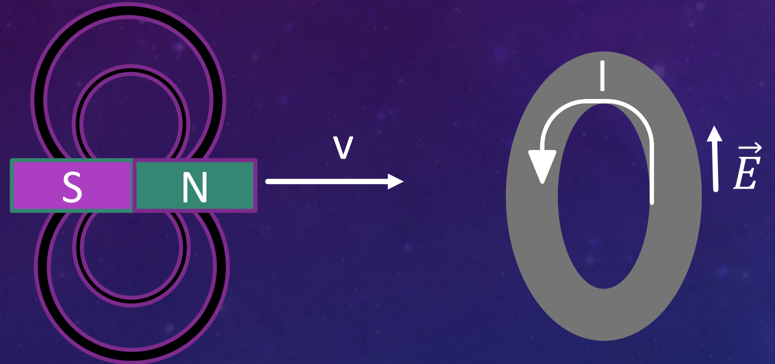


$$\oint \vec{E} \cdot d\vec{l} = -\frac{\partial \Phi_B}{\partial t}$$

- In the frame of the magnet…?

RELATIVITY OF E AND B - MAGNET AND CONDUCTOR

- In the frame of the conductor, the moving magnet creates a changing magnetic flux that results in an electric field in the conductor, and subsequently a current



$$\oint \vec{E} \cdot d\vec{l} = -\frac{\partial \Phi_B}{\partial t}$$

- In the frame of the magnet, the moving conductor's free charges are deflected by the magnetic field

$$\vec{F}_B = q\vec{v}\times\vec{B}$$

POSTULATES OF SPECIAL RELATIVITY

- Postulate 1: "The laws by which the states of physical systems undergo change are not affected, whether these changes of state be referred to the one or the other of two systems of co-ordinates in uniform translatory motion" (Einstein, 1905, p.4).

The laws of physics are the same in any two inertial frames

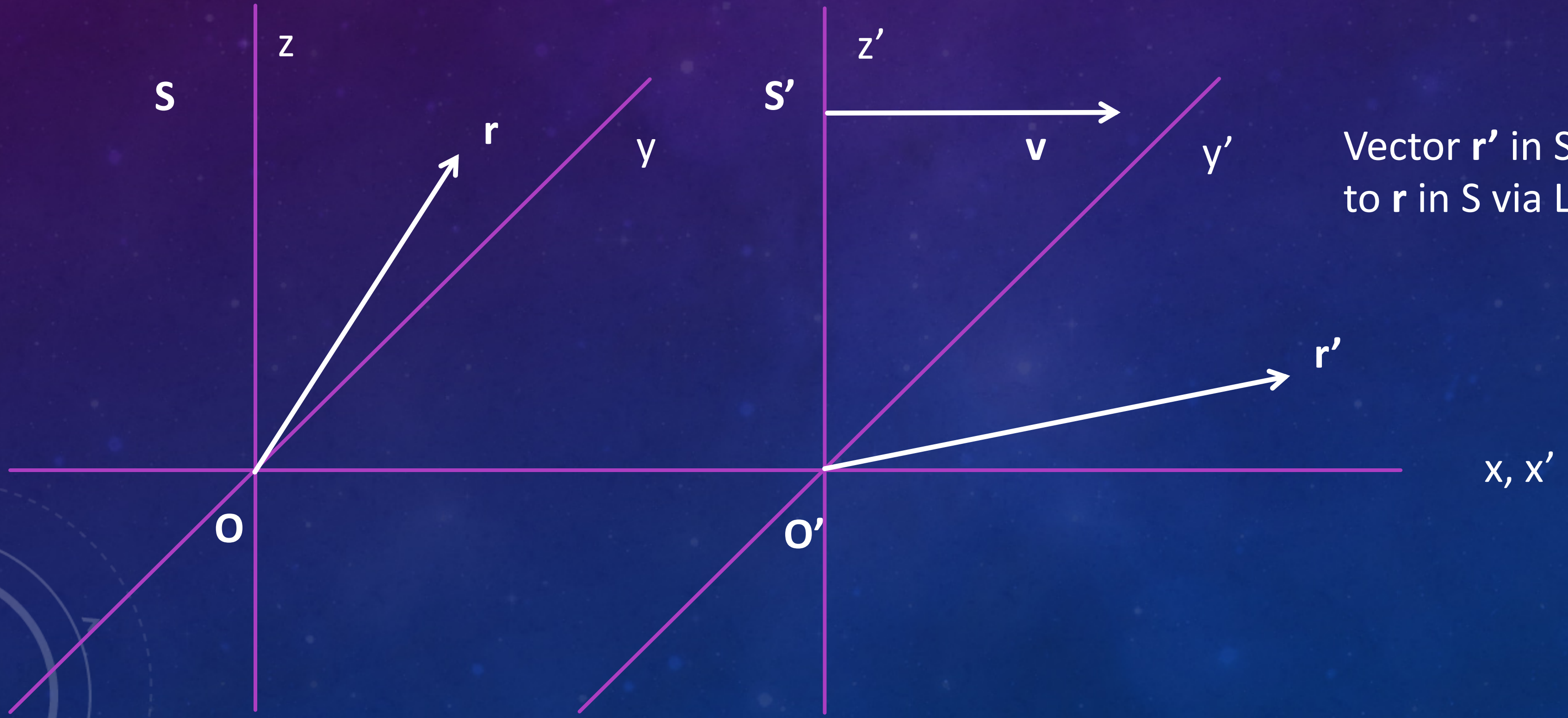
- Postulate 2: "Any ray of light moves in the 'stationary' system of co-ordinates with the determined velocity c, whether the ray be emitted by a stationary or by a moving body" (Einstein, 1905, p.4).

The speed of light in a vacuum is the constant c regardless of the motion of the emitting frame

$c = 299{,}792{,}458 \text{ m/s}$

LORENTZ TRANSFORMATIONS AND INERTIAL FRAMES

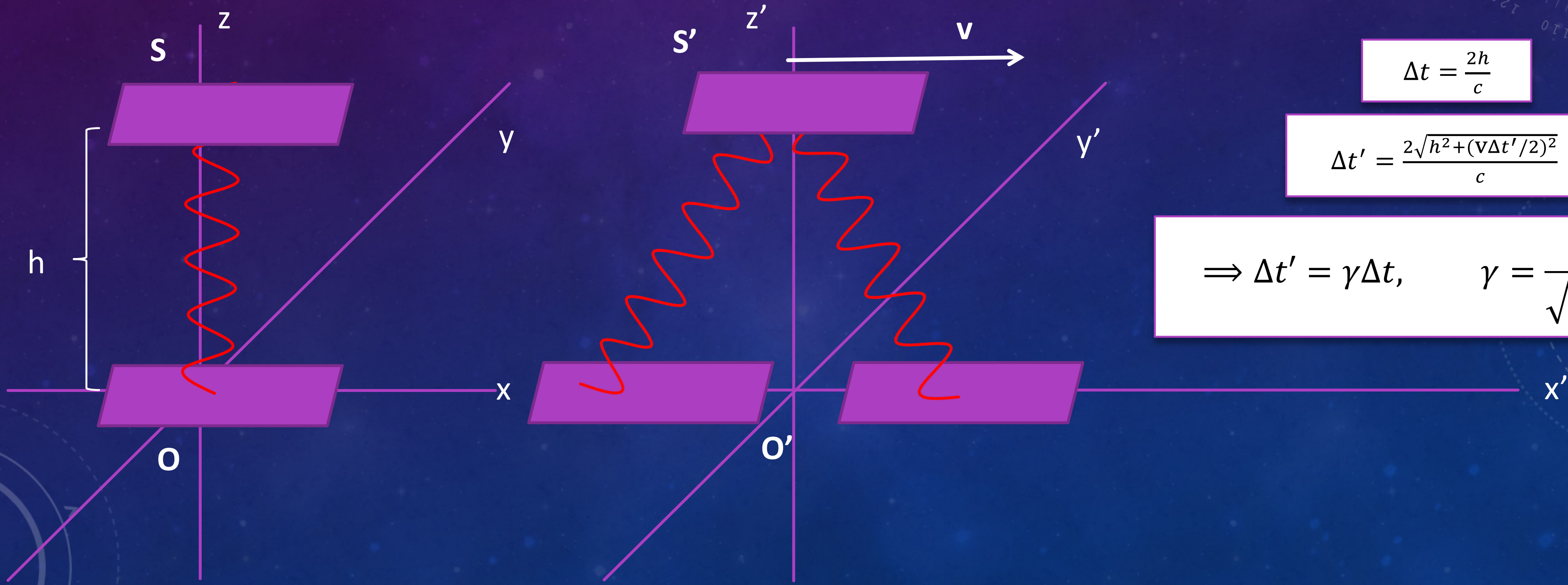
- Inertial frames move relative to each other at constant speed, without acceleration
- In relativity, space and time coordinates of an event observed in different inertial frames are related by Lorentz transformations t->t'(t,x,y,z), x->x'(t,x,y,z), y-> y'(t,x,y,z), z->z'(t,x,y,z)
- Frame S' is said to be "boosted" with velocity (v,0,0) with respect to S, and has Origin O' at (t',vt',0,0).



Vector **r'** in S' is related to **r** in S via Lorentz transformation

TIME DILATION

- Compare a light clock that undergoes a tick (round trip of a photon) in Frames S and S'
- Special relativity postulates the speed of light is the same in both stationary and moving clock
- During a tick $\Delta t'$ of the moving clock, the path length of light's worldline is longer in S' than in S



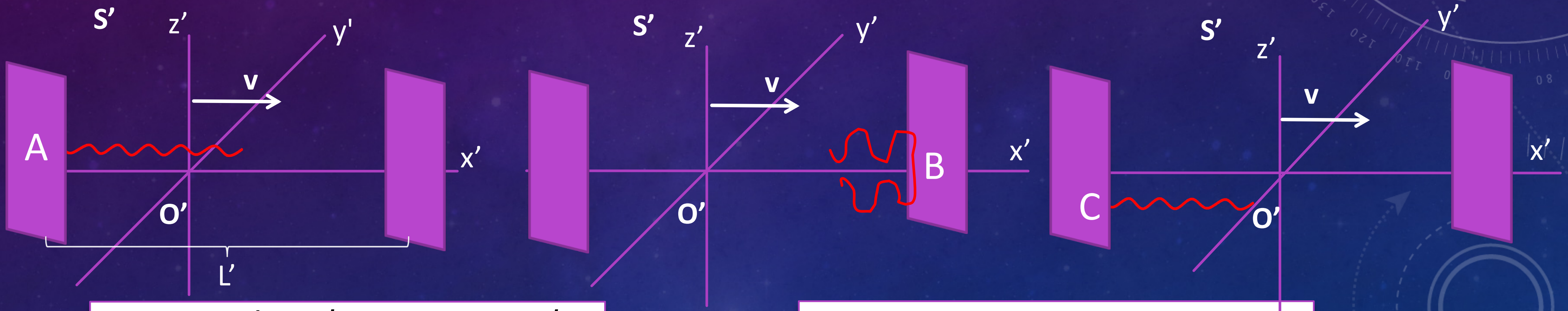
$$\Delta t = \frac{2h}{c}$$

$$\Delta t' = \frac{2\sqrt{h^2+(\mathrm{v}\Delta t'/2)^2}}{c}$$

$$\Longrightarrow \Delta t' = \gamma \Delta t, \qquad \gamma = \frac{1}{\sqrt{1-\mathrm{v}^2/c^2}}$$

LENGTH CONTRACTION

- Now consider Events A, B and C for light bouncing parallel to the motion of a light clock in Frames S’



$$t'_{AB} = \frac{L' + vt'_{AB}}{c} \Longrightarrow t'_{AB} = \frac{L'}{c - v}$$

$$t'_{BC} = \frac{L' - vt'_{BC}}{c} \Longrightarrow t'_{BC} = \frac{L'}{c + v}$$

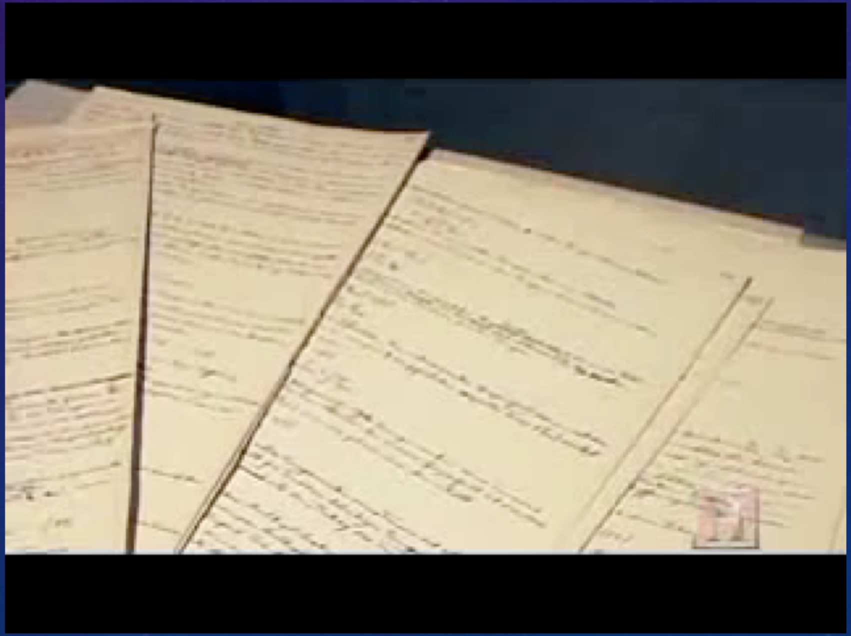
$$\Delta t' = t'_{AB} + t'_{BC} = \frac{2L'}{c\left(1 - \frac{v^2}{c^2}\right)} = \frac{2\gamma^2 L'}{c}$$

$$\Delta t' = \gamma \Delta t = \gamma \frac{2L}{c}$$

$$\Longrightarrow L' = \frac{L}{\gamma}$$

GENERAL THEORY OF RELATIVITY

- Einstein sought to extend his 1905 special theory of relativity to include non-inertial (accelerating) frames
- In strong gravitational fields, such as near black holes or neutron stars, classical+special relativistic predictions for lengths, times, frequencies, energy, etc. fail
- In a 1915 lecture at the Prussian Academy of Sciences in Berlin, Einstein unified gravity with special relativity in the general theory of relativity



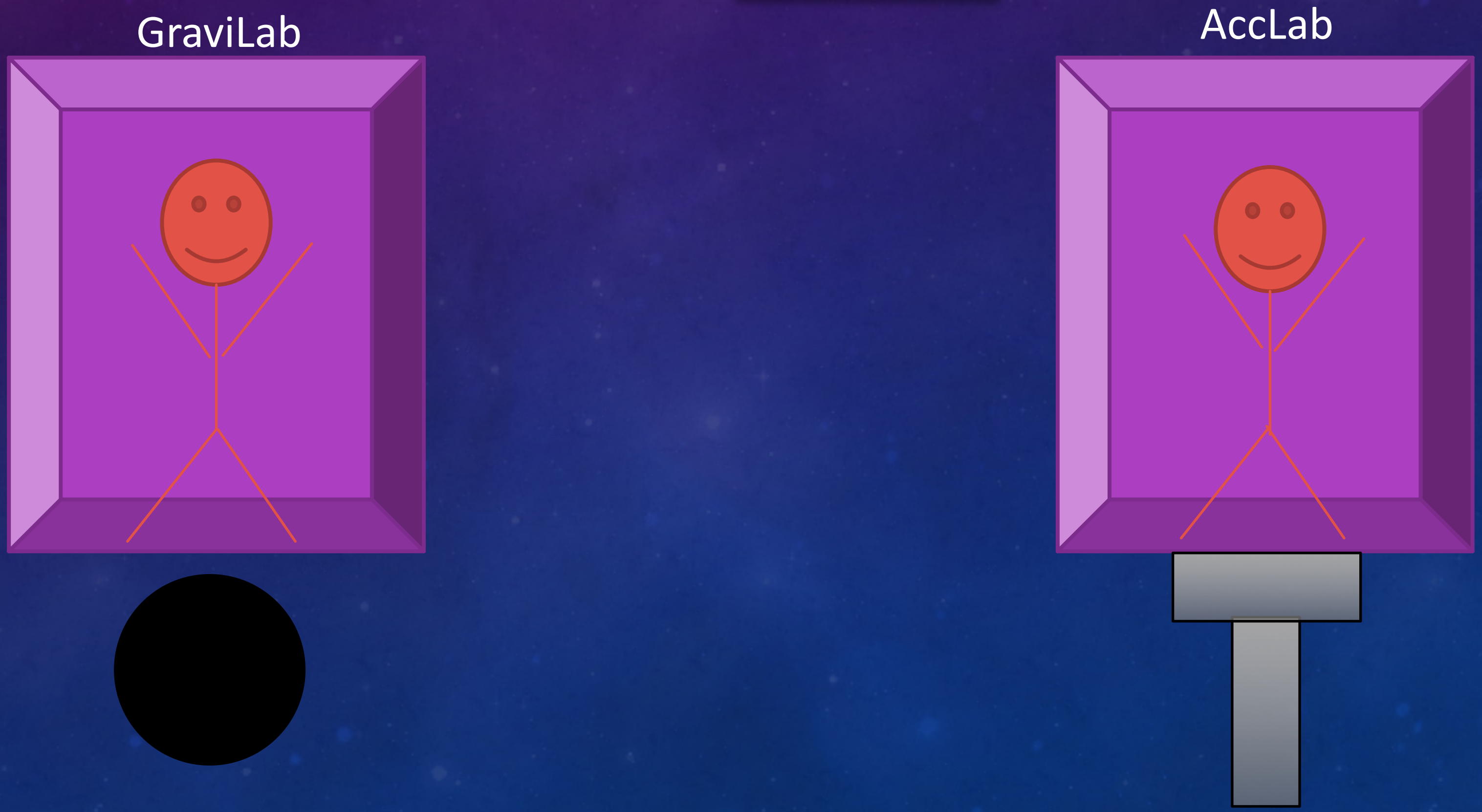
History Channel YouTube

EQUIVALENCE PRINCIPLE

- Consider two labs: GraviLab and AccLab
- Is there any experiment in either lab that can distinguish the black hole from the piston?

EQUIVALENCE PRINCIPLE - TIDAL FORCES

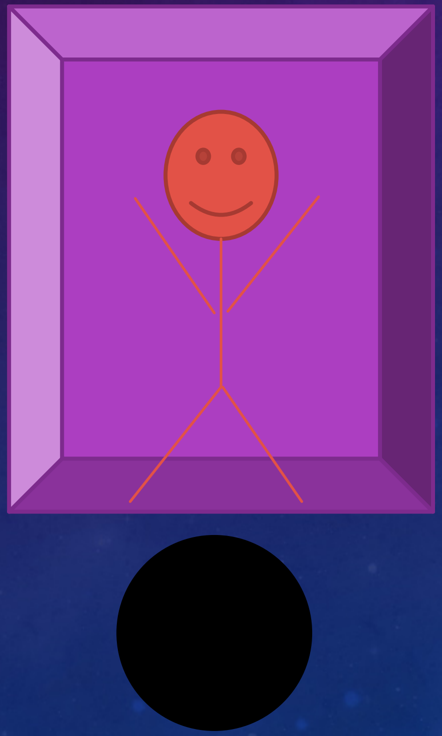
- Consider two labs: GraviLab and AccLab
- Tidal forces would affect only the person in GraviLab: $T \approx \frac{MH}{r^3}$



EQUIVALENCE PRINCIPLE

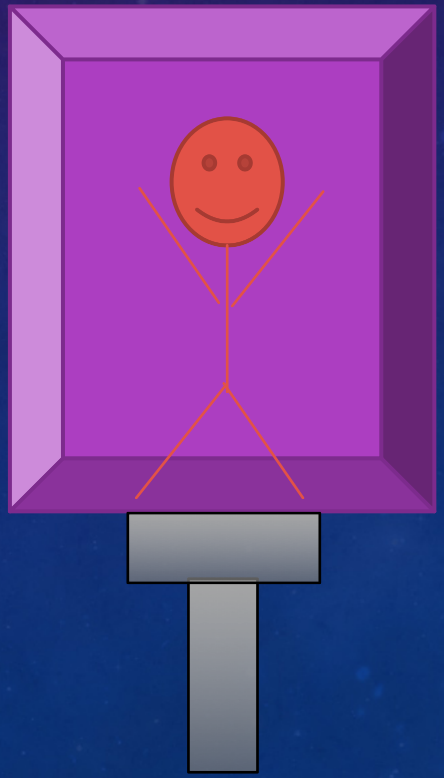
- Consider two labs: GraviLab and AccLab
- For sufficiently small labs, there is no experiment to distinguish them

GraviLab



Equivalence Principle: Local properties of curved spacetime are indistinguishable from flat spacetime

AccLab



POP QUIZ - RELATIVITY OF SIMULTANEITY

- A spaceship-bound individual synchronizes flashing lights for the spaceship. You are a reference frame in which the spaceship is moving at velocity **v**. Which source do you think the person in the spaceship first sees

a) Source A

b) Source B

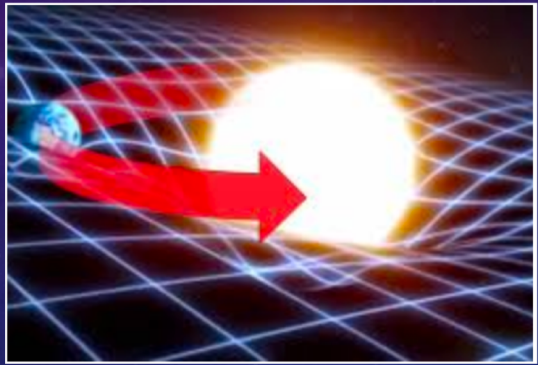
c) Both Sources A and B

BLACK HOLES - HISTORY

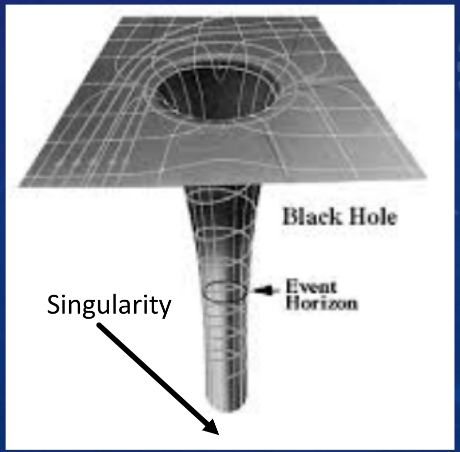
- In 1783 John Mitchell theorized that if a star's radius is >500R_{Sun}, light could not escape it
- In 1916, Karl Schwarszchild solved the Einstein field equations for the geometry outside a spherically symmetric, non-rotating mass
- In 1963, Roy Kerr solved the Einstein field equations for the geometry outside a spherically symmetric, rotating mass
- In the 1970's, black hole temperature was theorized by Hawking, among others

STRONG GRAVITY AND BLACK HOLES

- We have seen that Einstein's special relativity postulates can warp space and time
- Can gravity warp spacetime as well?
  - Yes! Dense objects change the spacetime distance formula from flat space



- STRONG gravity as one approaches singularity of infinite spacetime curvature

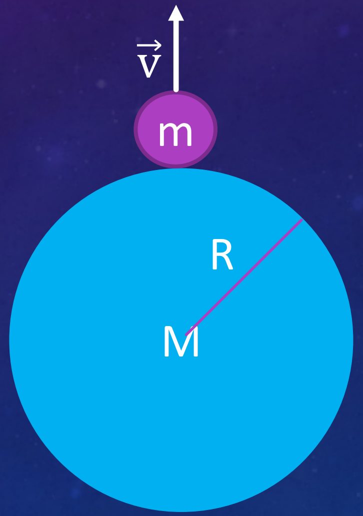


BLACK HOLES - CONCEPT

- Objects launched from massive bodies will fall back unless their kinetic energy is at least the magnitude of the potential energy binding them to the object:

$$\frac{m v_{esc}^2}{2} = \frac{GMm}{R}$$

$$\Rightarrow v_{esc} = \sqrt{\frac{2GM}{R}}$$



  - Note: The object's mass m does not enter the escape speed

- Exercise: Apply the escape speed condition to a massless photon traveling at the speed of light c to find the Schwarzschild radius r_S , i.e., the radius in which M would have to be contained so that light cannot escape.

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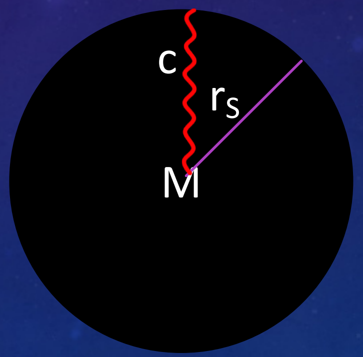


- Exercise: Apply the escape speed condition to a massless photon traveling at the speed of light c to find the Schwarzschild radius r_S , i.e., the radius in which M would have to be contained so that light cannot escape.

$$c = \sqrt{\frac{2GM}{R}}$$

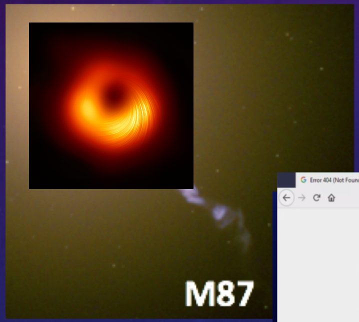
$$\Rightarrow r_S \equiv R = \frac{2GM}{c^2}$$

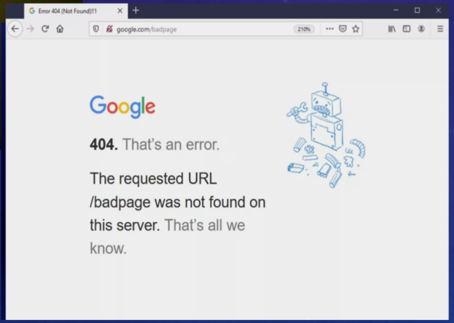
“OBSERVING” JAB SYSTEMS

1. Start with general relativistic magnetohydrodynamic (GRMHD) simulation or semi-analytic model of jet (or outflow)/accretion flow/black hole (JAB) system
2. Convert GRMHD variables to radiation prescriptions for emission, absorption, polarization, particle acceleration and/or dissipation to emulate sources
3. Add “observer” viewing sources, e.g., Event Horizon Telescope (EHT) targets:

   I. M87

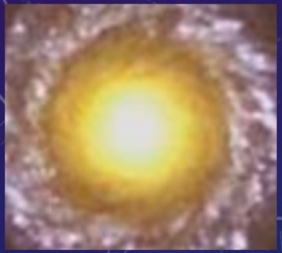
   II. Sgr A*



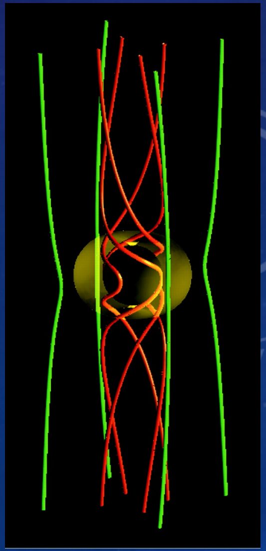


TERMINOLOGY AND DEFINITIONS

- Active Galactic Nucleus (AGN)– emitting region around a supermassive black hole (SMBH) appearing as a discrete source
- Accretion disk – inflowing, typically magnetized, plasma gravitationally bound to a central massive object
  - Magnetically Arrested Disk (MAD) – inflow inhibited by magnetic pressure near a black hole (contrast Standard and Normal Evolution (SANE))
- Stokes Parameters – total intensity I, two independent linear polarizations Q and U and circular polarization V
- Jet – a relativistic polar outflow emanating from about 10% of AGN SMBHs
  - Blandford-Znajek jets are powered by the interplay of black hole spin with magnetic fields yielding Poynting flux of electromagnetic energy
- Synchrotron radiation – polarized radiation occurring when relativistic charged particles gyrate around magnetic fieldlines



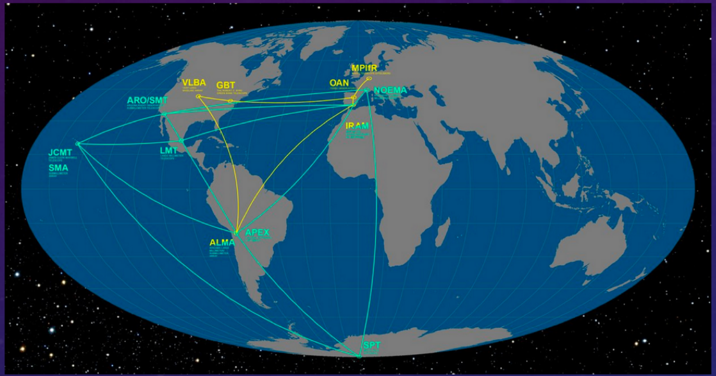
NGC 7742
AURA/STScI/NASA

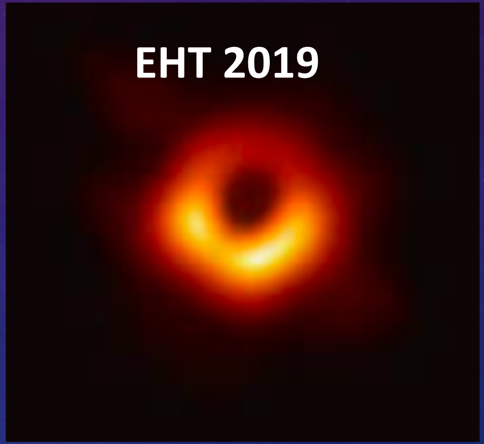


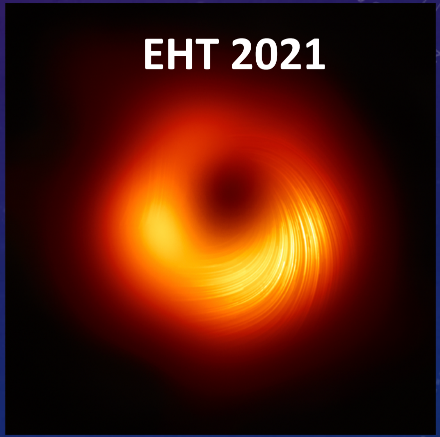
Koide et al. (2002)
Science **295**, 1688

BLACK HOLES - OBSERVATIONS

- The Event Horizon Telescope is a collection of radio antennae forming a network of intercontinental baselines to form mm-images







- Exercise: Can you explain why baselines of radio telescopes are so long in view of the angular resolution limit below?
  - The ability to distinguish two sources at smaller angular separation increases with aperture diameter

$$\Delta\theta_{\text{min}} = 1.22 \frac{\lambda}{D_{\text{aperture}}}$$

Zooming towards M87’s Jet and Central Black Hole

Courtesy of European Southern Observatory (ESO)

Emission Prescriptions for Radiative Transfer

- Critical Beta Electron Temperature Model (Anantua et al. 2020b (ARQ20)) – Turbulent Heating Physics (Howes 2010):
  1) Constant T_e/T_p at $\beta << \beta_c$
  2) T_e suppressed at $\beta >> \beta_c$

$$\frac{T_e}{T_p + T_e} = f \ \mathrm{Exp}[-\beta/\beta_c]$$

$$0 < f < 1, \qquad \beta = \frac{P_g}{P_B}, \qquad T_e = P_e/\rho$$

- R-Beta Model (EHTC Papers I-VIII)

$$R = \frac{T_i}{T_e} = \frac{1}{1+\beta^2} R_{\mathrm{low}} + \frac{\beta^2}{1+\beta^2} R_{\mathrm{high}}$$

- Constant β_e Model – Magnetic-to-Particle Energy Conversion:

$$\beta_e = \frac{P_e}{P_B} = \beta_{e0}$$

$$P_B = \frac{B^2}{2}$$

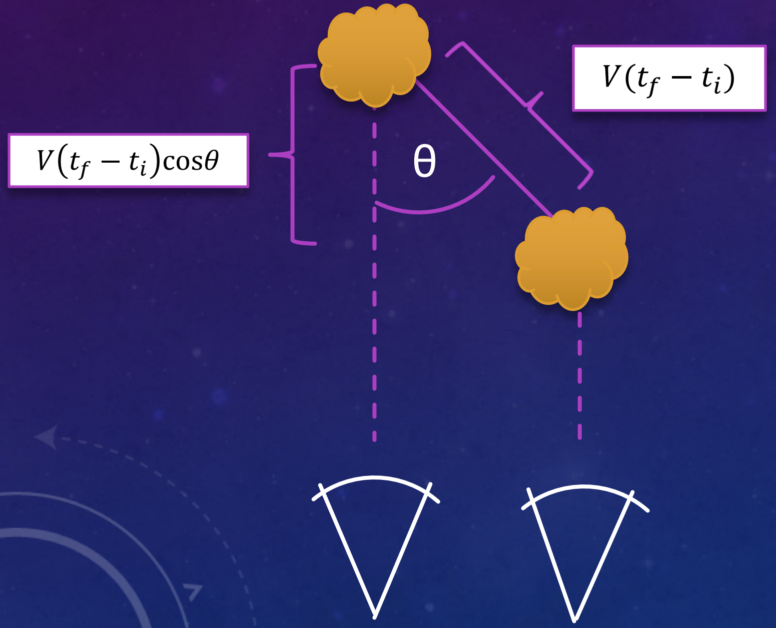
Equipartition for P_e~P_B

- Magnetic Bias Model

$$P_e = K_n P_B^n = K_N \left(\frac{B}{\sqrt{2}}\right)^N, \qquad n = N/2$$

JETS AND RELATIVISTIC BEAMING

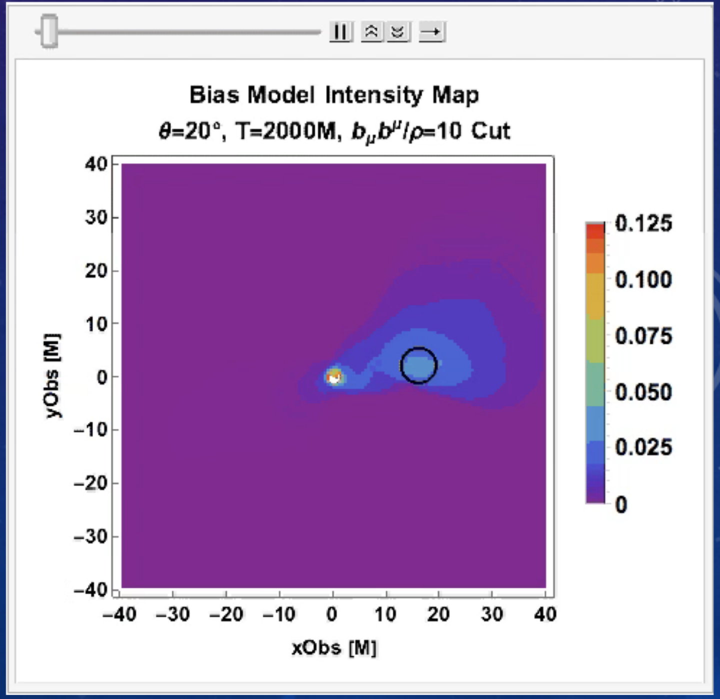
- Features moving with apparent speed 6c in M87 observed by Hubble (Biretta, J. A., Sparks, W. B., & Macchetto, F., 1999, ApJ 520, 621)
- Projection/finite c effect:



$$V_{t,app} = \frac{V(t_f - t_i)\sin\theta}{(t_f - t_i) - \tau}, \tau = \frac{V(t_f - t_i)\cos\theta}{c}$$

$$\Rightarrow V_{t,app} = \frac{V\sin\theta}{1 - \frac{V\cos\theta}{c}}$$

$(\theta_{Obs},\Phi_{Obs})$=(20°,0°), TObs=2000M,2056M,…,2560M
Emissivity: $j'_\nu \sim b'^{1.5}$
Disk subtraction: $b_\mu b^\mu/\rho$>10

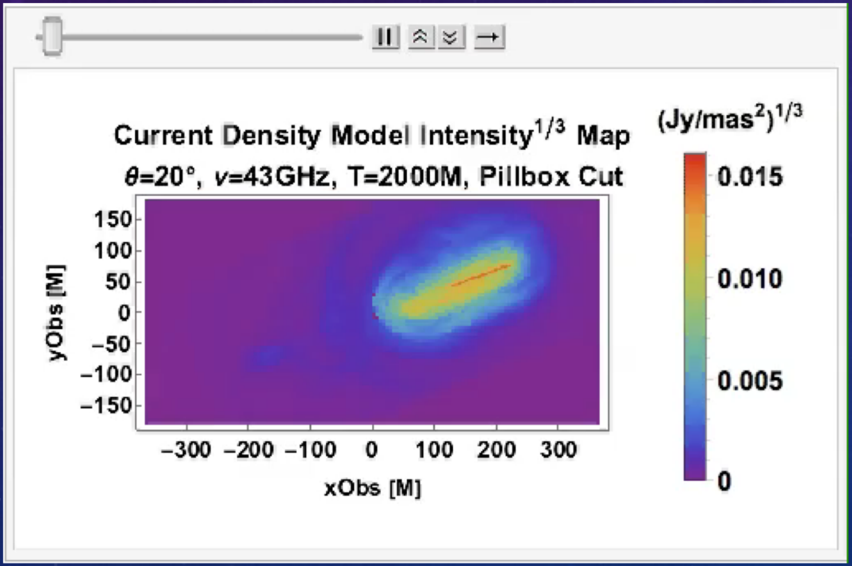


CONNECTING WITH OBSERVATIONS: M87 43 GHZ RADIO MAP TIME SERIES VS. CURRENT DENSITY MODEL

- Current density model based on having particles accelerated at current layers

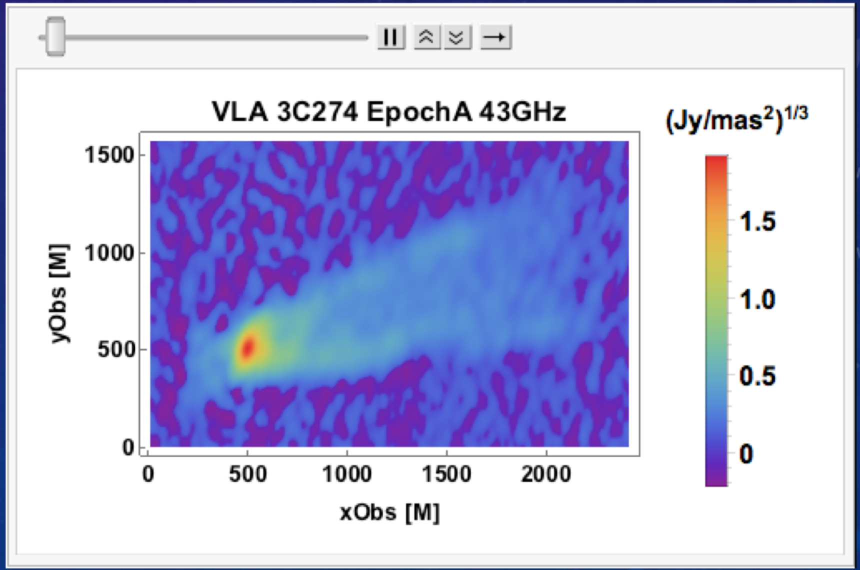
$$j_\nu \propto \widetilde{P}_e \propto j^2$$

$(\theta_{Obs},\Phi_{Obs})$=(20°,0°), T_{Obs}=2000M,2056M,…,2560M
Emissivity: Current Density Model
Disk subtraction: |z|>35M
L_{JSq}=1e4 M



Anantua, Blandford and Tchekhovskoy (2018) Galaxies, 6, 31

M87 43GHz (7mm) VLA maps
21-Day frame rate, Epochs A,B,D-L

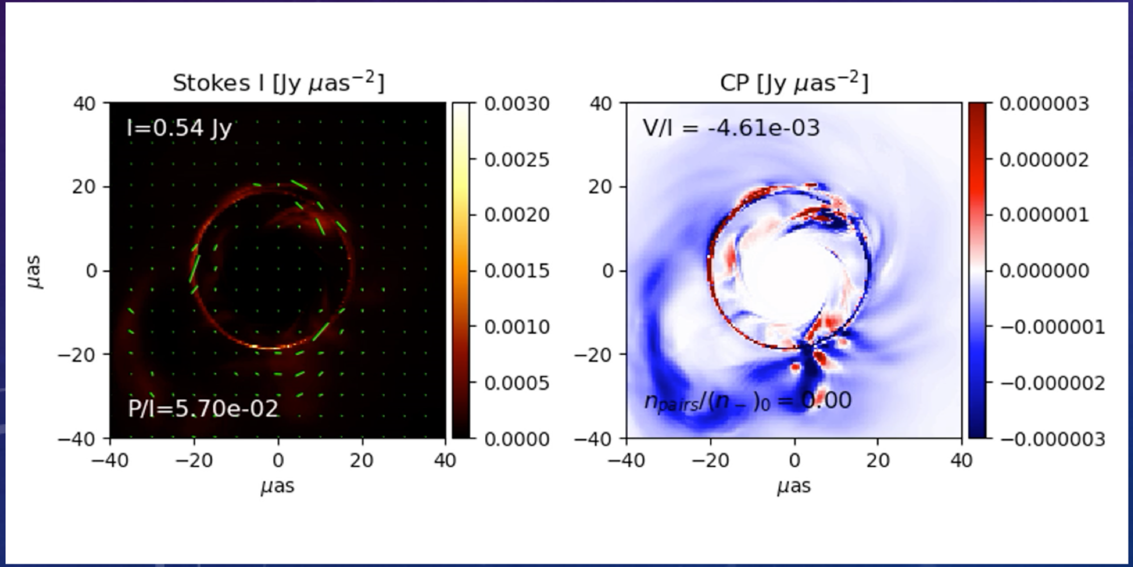


Courtesy of Craig Walker (NRAO), Chun Ly (UCLA), Bill Junor (Los Alamos), and Phil Hardee (U. Alabama)

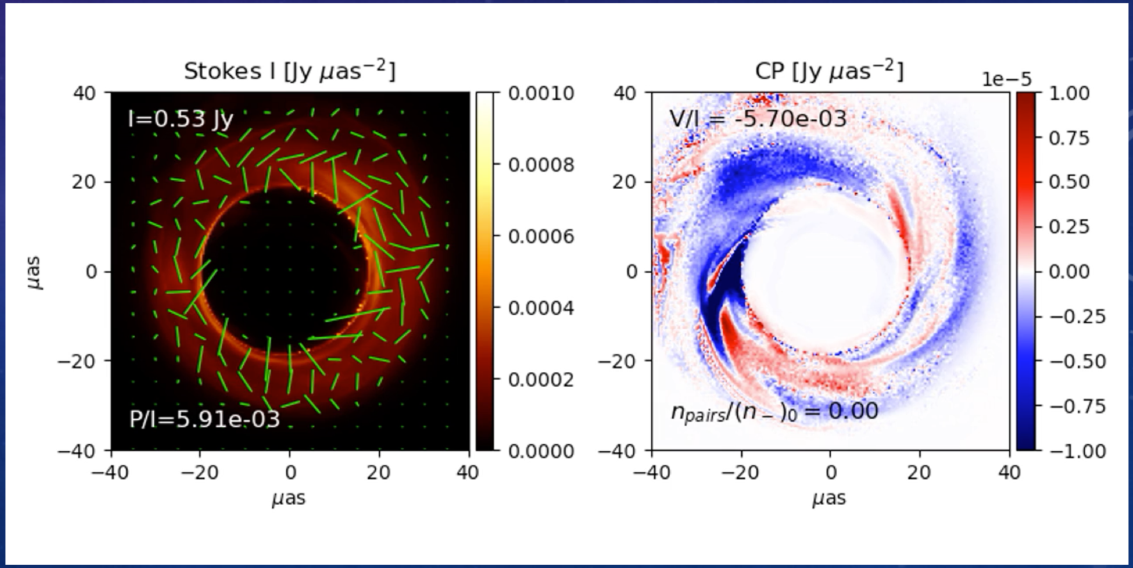
POSITRON EFFECTS ON "OBSERVING" GRMHD SIMULATIONS: MAD VS. SANE

- Using a HARM GRMHD simulation and adding e+/e- pairs so $n = n_p + (n_{e-})_0 + n_{\mathrm{Pairs}}$ in ray tracing at 230 GHz results in
  - Magnetically Arrested Disk (MAD) simulations with decreasing V/I with increasing $n_{e+} = \frac{n_{\mathrm{pairs}}}{2}$ due to positrons cancelling intrinsic circular polarization
  - MAD simulation models have lower Faraday depth than Standard and Normal Evolution (SANE), resulting in slower rates of EVPA rotation

MAD R_{high}=20, a/M= -0.5



SANE R_{high}=20, a/M= -0.5



Antantua, Ricarte et al. et al. (in prep)

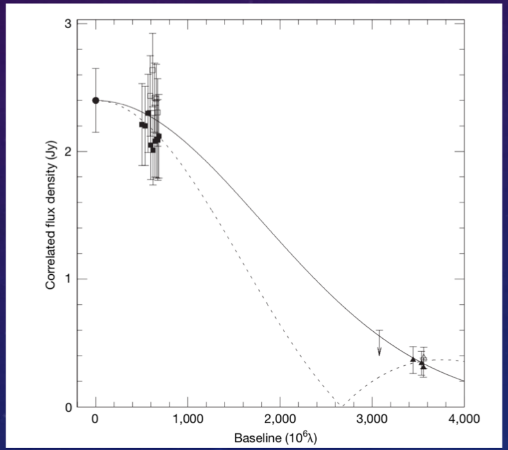
INTERSTELLAR - PHOTON RINGS

- Interstellar 2:13:24 – Shuttle approaches Gargantua with visible Einstein rings
- Quiz: What's missing?
  - A: Relativistic beaming

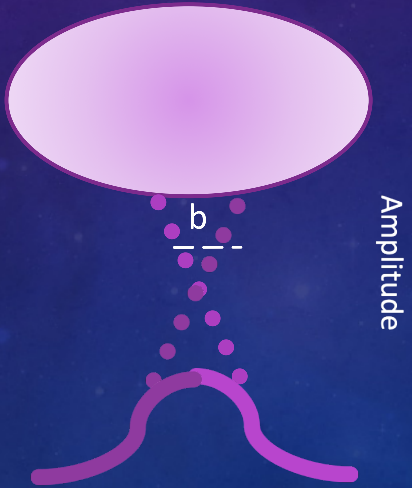
Zooming in on Milky Way’s Sgr A* Region
Courtesy of European Southern Observatory (ESO)

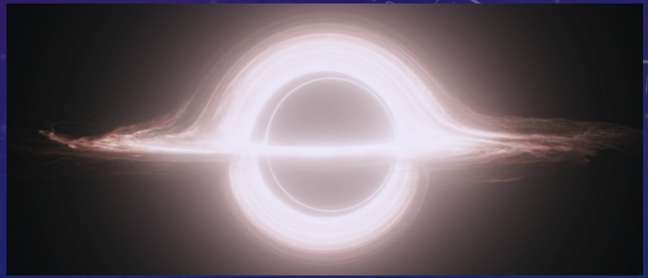
SGR A* IMAGE OBSERVATIONS

- Event Horizon Telescope (EHT) 230 GHz emitting region size constraints
  - Intrinsic size: $(\Delta\theta)_{\mathrm{FWHM}} = 37^{+16}_{-10}\mu as$ (isotropic); $(\Delta\theta_{\max})_{\mathrm{FWHM}}\ 56^{+7}_{-7}\mu as$ (anisotropic)
  - Scattering size: $43^{+14}_{-8}\mu as$ (isotropic)

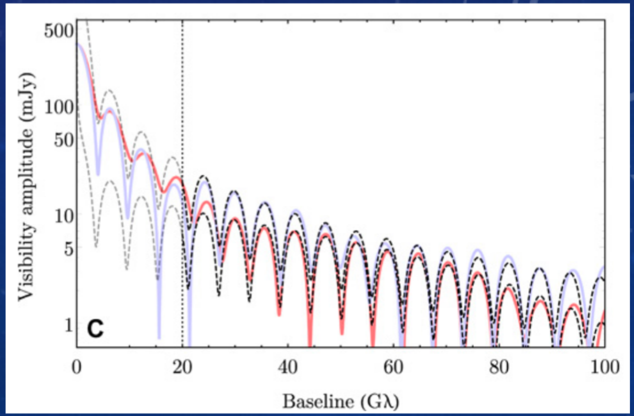


Doeleman et al. (2008)
Nature **455**, 78





Non-point symmetric (Fish et al. 2016; Johnson et al. 2018) ring more likely than circular Gaussian



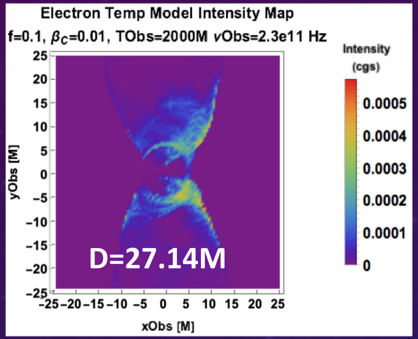
Johnson et al. (2020)
Science Adv. **6**, 1319

IMAGES IN PARAMETER SPACE

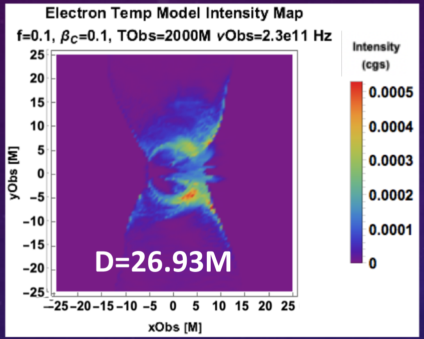
EHT Intrinsic Size Constraint for $I > 0.2 \times I_{Max}$:   8.2M < D <16.2M

$$M = \frac{GM_{\mathrm{BH}}}{c^2} \leftrightarrow 5\mu\mathrm{as}$$

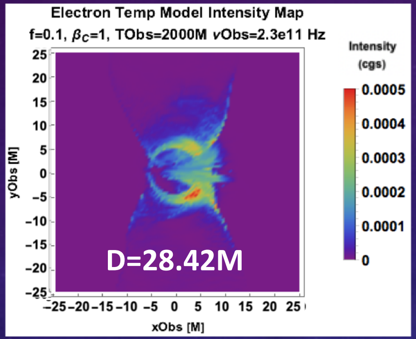
$(f, \beta_c) = (0.1, 0.01)$.



$(f, \beta_c) = (0.1, 0.1)$

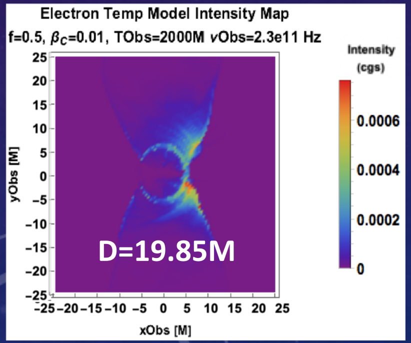


$(f, \beta_c) = (0.1, 1)$

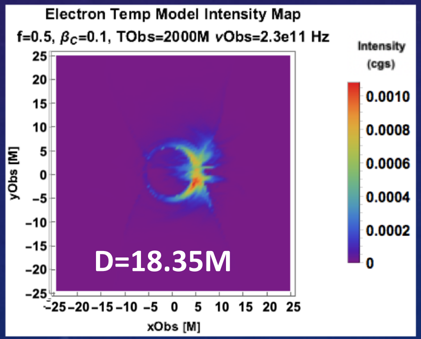


Increasing f, β_c

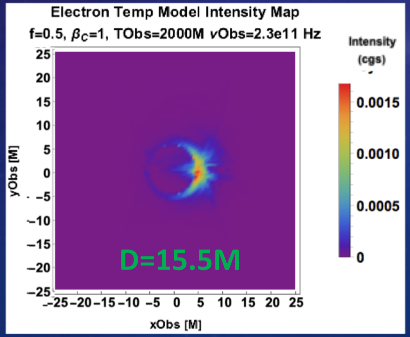
$(f, \beta_c) = (0.5, 0.01)$

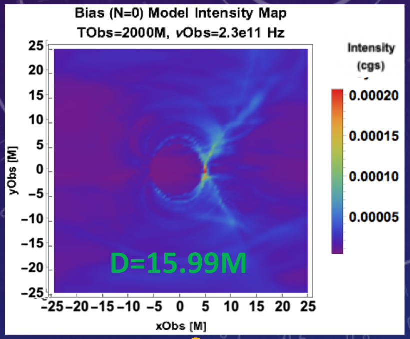


$(f, \beta_c) = (0.5, 0.1)$



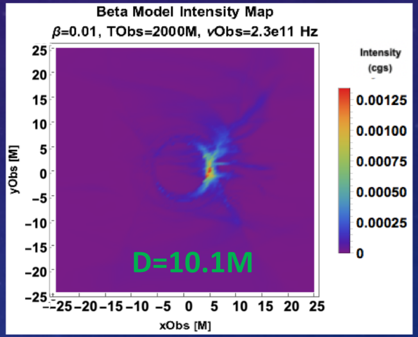
$(f, \beta_c) = (0.5, 1)$



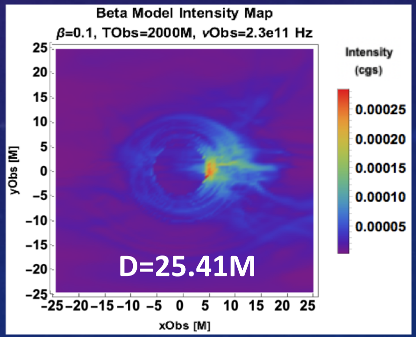


n=0

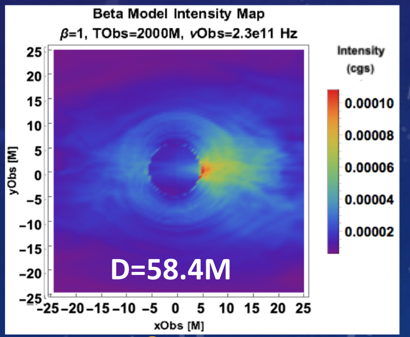
Decreasing β_{e0}



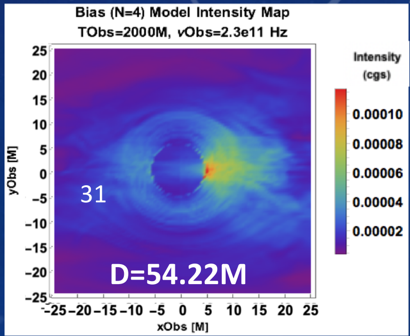
β_{e0}=0.01



β_{e0}=0.1



β_{e0} =1



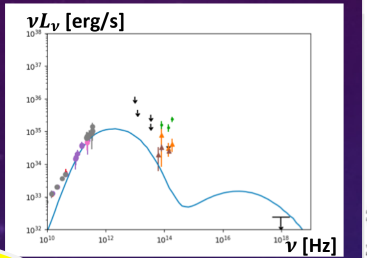
n=2

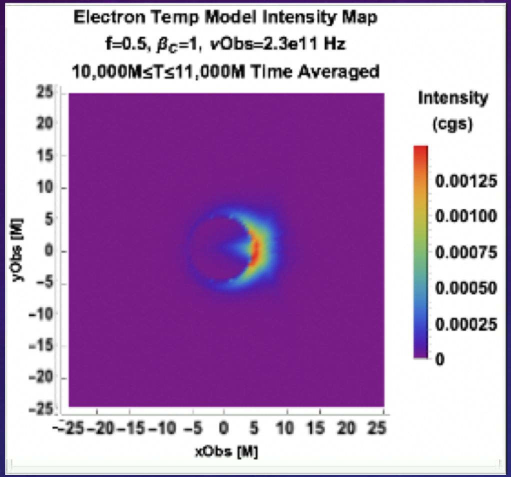
ARQ20

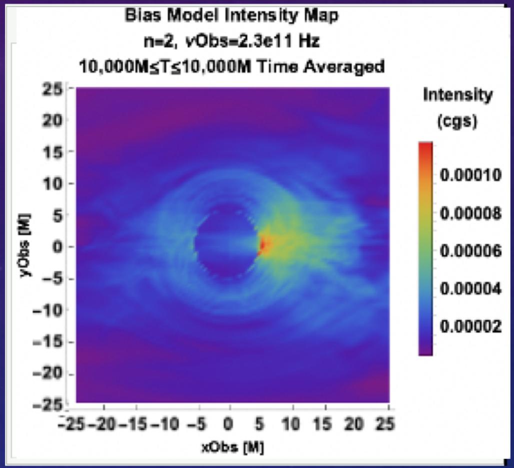
SGR A* MODEL CLASSIFICATION

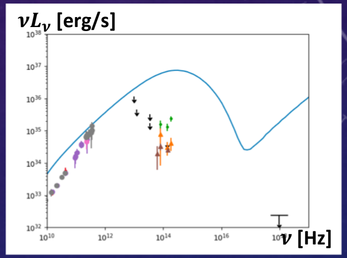
ARQ20 Model Movies

Tobs=10,000M,10,100M,…,11,000M





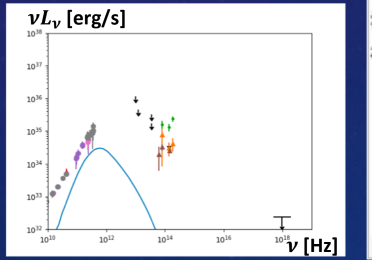


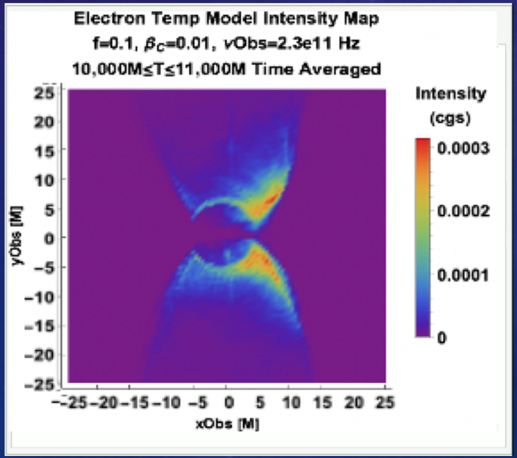


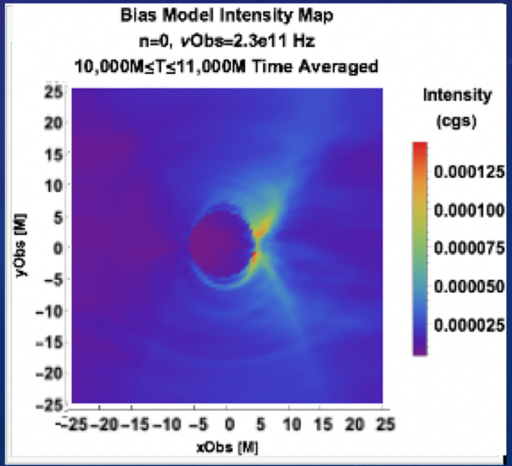
Type I a or b - Thin, Compact Asymmetric Photon Ring/Crescent; best fit spectrum or flat spectrum

Type III- Thick Photon Torus; spectral excesses at low and high frequency

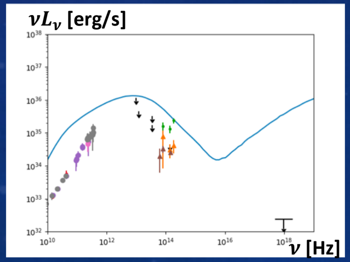
Type II - Inflow-Outflow Boundary + Thin Photon Ring; steep spectrum







Type IV - Extended Outflow; spectral excesses at low and high frequency and flat low frequency knee



ARQ20

CONCLUSIONS

- Special relativity unifies physical quantities classically thought distinct and independent
  - Electric and magnetic fields transform together as a tensor
  - Space and time transform as a 4-vector
- General relativity continues the unification by incorporating accelerating frames through the equivalence principle
  - Gravity can be identified with spacetime curvature, including for black holes in which spacetime approaches a singularity
- Observing Jet/Accretion Flow/Black Hole (JAB) Systems is a methodology that links intuitive e-/e+ emission models of phenomenological processes such as turbulent heating and conversion of magnetic to particle energy with discrete near-horizon AGN observations
  - M87
    - GRMHD simulations can be used to replicate near-horizon polarized features with R-Beta Model and observational signatures of AGN jets including limb brightening with Constant β_e , Magnetic Bias and Current Density Models
  - Sgr A*
    - 230 GHz synthetic intensity maps on the scale of tens of gravitational radii appear with:
      - Emitting region most compact for low β_{e0} and high (f, β_c); more asymmetry for low β_{e0} , n and high (f, β_c); preferred models may be uniquely determined by upcoming EHT results…
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