# *Lecture 12: Black Holes*

- Old ideas for black holes
- Theory of black holes
- Real-life black holes
  - Stellar mass
  - Supermassive
- Speculative stuff

"The last I heard, Medwick was working on a model black hole in his lab."

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# *Quiz*

- Light travels through the shortest path in space-time. What is the name of the "shortest path" on a curved surface?

# I : OLD IDEAS FOR BLACK HOLES

- "What goes up must come down"… or must it?
- **Escape velocity**, $V_{esc}$
  - Critical velocity object must have to just escape the gravitational field of the Earth
    - $V<V_{esc}$ : object falls back to Earth
    - $V>V_{esc}$ : object never falls back to Earth
- In fact, escape velocity given in general by

$$V_{esc} = \sqrt{\frac{2GM}{R}}$$

when the mass of an object is M and the distance from the center is R

- Starting from Earth's surface, $V_{esc}$=11 km/s
- Starting from Sun's surface, $V_{esc}$= 616 km/s



# 18th Century ideas

- By making M larger and R smaller, $V_{esc}$ increases
- Idea of an object with gravity so strong that light cannot escape first suggested by Rev. John Mitchell in 1783

- Laplace (1798) – *"A luminous star, of the same density as the Earth, and whose diameter should be two hundred and fifty times larger than that of the Sun, would not, in consequence of its attraction, allow any of its rays to arrive at us; it is therefore possible that the largest luminous bodies in the universe may, through this cause, be invisible."*

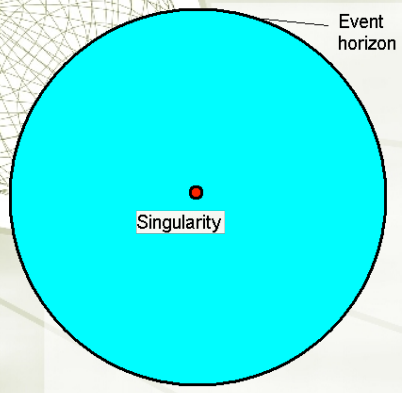
## II : MODERN IDEAS

- Karl Schwarzschild (1916)
  - First solution of Einstein's equations of GR
  - Describes gravitational field in (empty) space around a point mass
- Space-time interval in Schwarzschild's solution (radial displacements only) is

$$ds^2 = \left(1 - R_s / R\right)^{-1} dR^2$$

- Features of Schwarzschild's solution:
  - Yields Newton's law of gravity, with flat space, at large R
  - Space-time curvature becomes infinite at center (R=0; this is called a **space-time singularity**)
  - Gravitational time-dilation effect becomes infinite on a spherical surface known as the **event horizon**, where coefficient of $\Delta t$ is zero
  - Radius of the sphere representing the event horizon is called the **Schwarzschild radius,** $R_s$






•For a body of the Sun's mass, **Schwarzschild radius**

$$R_S = \frac{2GM}{c^2} \rightarrow 3\text{km}$$

• **Singularity** – spacetime curvature is infinite. Everything destroyed. Laws of GR break down.

• **Event horizon** – gravitational time-dilation is infinite as observed from large distance.

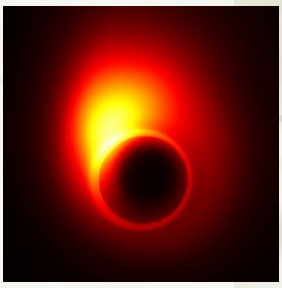
• Any light emitted at $R_s$ would be infinitely redshifted - hence could not be observed from outside

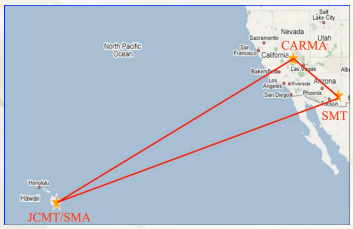
# More features of Schwarzschild black hole

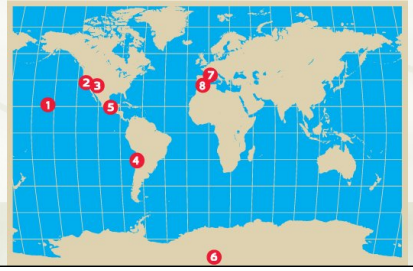
- Events inside the event horizon are causally-disconnected from events outside of the event horizon (i.e. no information can be sent from inside to outside the horizon)
- Observer who enters event horizon would only feel "strange" gravitational effects if the black hole mass is small, so that $R_s$ is comparable to observer's size
- Once inside the event horizon, future light cone always points toward singularity (any motion must be inward)
- Stable, circular orbits are not possible inside $3R_s$ : inside this radius, orbit must either be inward or outward but not steady
- Light ray passing BH tangentially at distance $1.5R_s$ would be bent around into a circle
- Thus black hole would produce "shadow" on sky



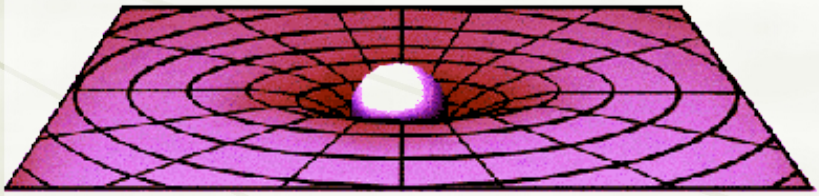
# Event horizon telescope





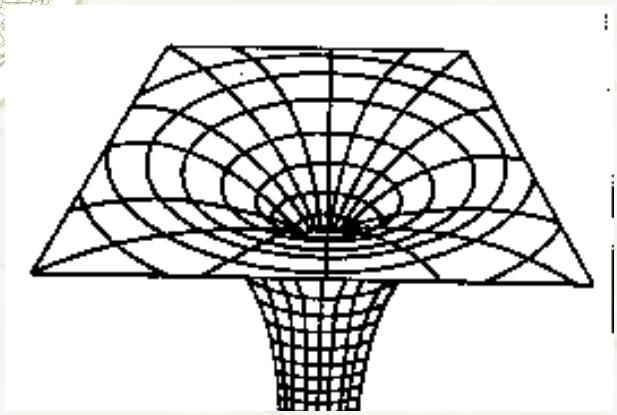
- Curved space around a star…



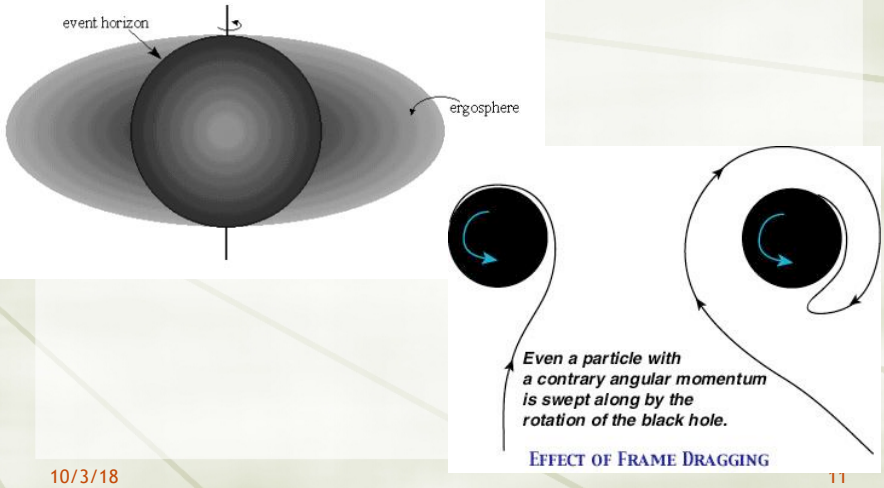
From web site of UCSD



## … and around a black hole



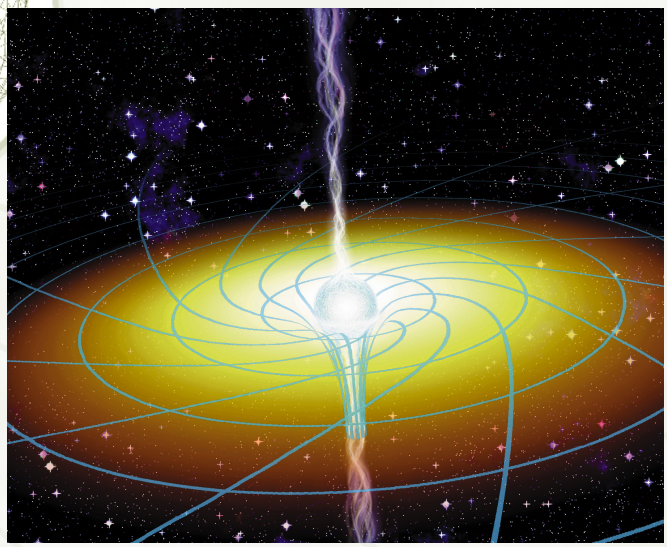
# Frame dragging by rotating black hole






Graphics: University of Winnipeg, Physics Dept.

# Artist's conception of rotating black hole



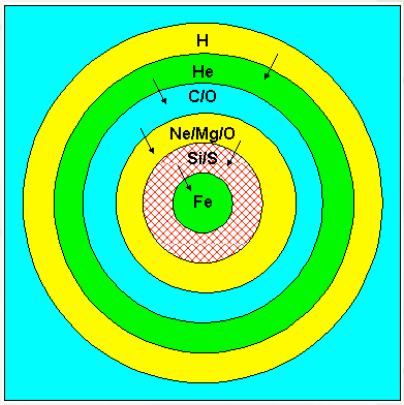
# III : Real-life black holes

- So much for theory – what about reality
- Thought to be two (maybe three?) classes of black hole in nature
  - **"Stellar mass black holes"** – left over from the collapse/implosion of a massive star (about 10 solar masses)
  - **"Supermassive black holes"** – giants that currently sit at the centers of galaxies (range from millions to billions of solar masses)
  - **"Intermediate-mass black holes"** – suggested by very recent observations (hundreds to thousand of solar masses)



# Stellar mass black holes

- End of massive star's life…
  - In core, fusion converts hydrogen to heavier elements (eventually, core converted to iron Fe).
  - Core collapses under its own weight
  - Huge energy release: Rest of star ejected – **Type II Supernova**
- Either a black hole or neutron star remains



# Rotating black holes

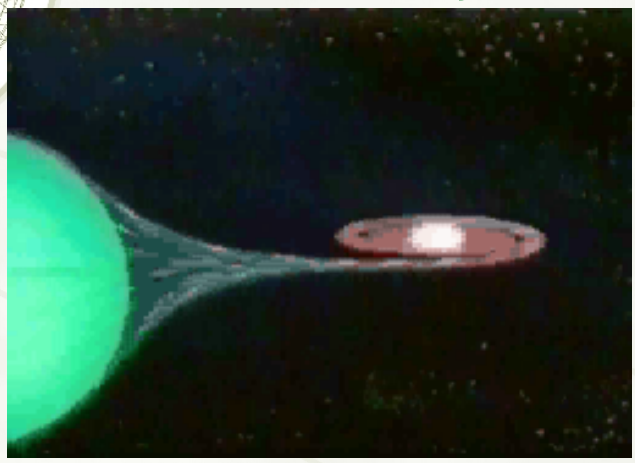
- Roy Kerr (1963)
  - Discovered solution to Einstein's equations corresponding to a rotating black hole
  - Kerr solution describes all black holes found in nature
- Features of the Kerr solution
  - Black Hole completely characterized by its mass and spin rate (no other features [except charge]; **no-hair theorem**)
  - Has space-time **singularity** and **event horizon** (like Schwarzschild solution)
  - Also has **"static surface"** inside of which nothing can remain motionless with respect to distant fixed coordinates
  - Space-time near rotating black hole is dragged around in the direction of rotation: **"frame dragging"**.
  - **Ergosphere** – region where space-time dragging is so intense that its impossible to resist rotation of black hole.



# Black holes in binary systems

- If black hole is formed in binary star system,
  - Tidal forces can rip matter of the other star
  - Matter goes into orbit around black hole – forms an **accretion disk**
  - As matter flows in towards the black hole, it gives up huge amount of energy
    - analogy to hydroelectric power derived when water falls over a dam
  - Energy is first converted to heat, raising gas temperature in accretion disk to millions of degrees
  - Hot accretion disk radiates away energy, emitted as X-rays
  - These systems are called **X-ray binaries**

## *"X-ray" binary*

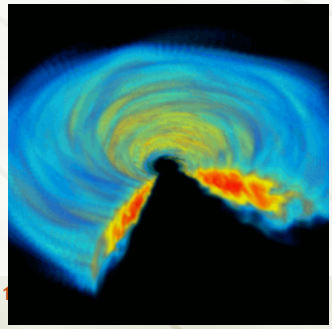


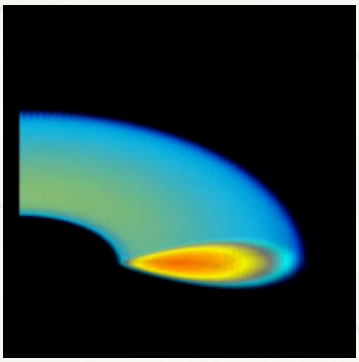
Outer layers of a nearby star are pulled off by tides, crash into accretion disk around BH



## *Accretion disk from numerical simulation*

- Turbulence develops and causes gas to accrete (flow inward) onto the black hole

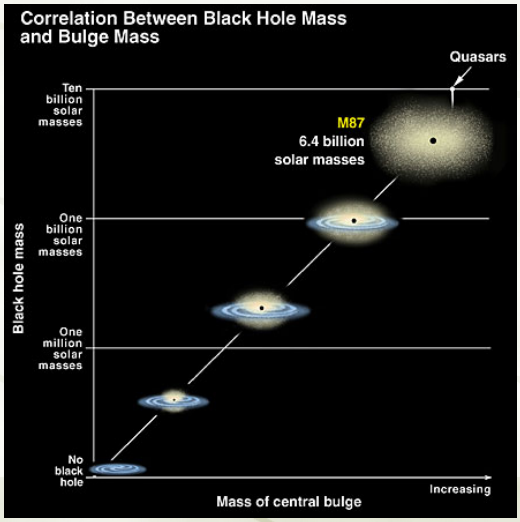




J. Hawley, U. Virginia

## Supermassive black holes (SMBHs)

- Found in the centers of galaxies



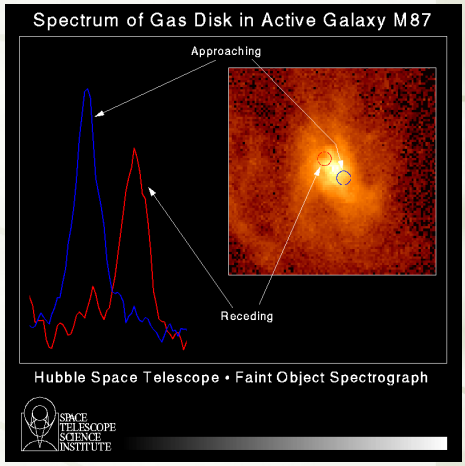



## Center of the Milky Way: Sgr A*

- The center of our own Galaxy
  - Can directly observe stars orbiting an unseen object
  - Need a black hole with mass of 3.7 million solar masses to explain stellar orbits
  - Best case yet of a black hole.

# M87

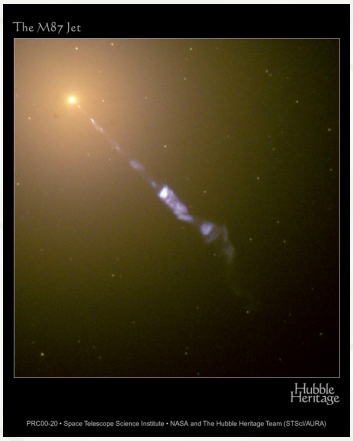
- Another example – the SMBH in the galaxy M87
  - Can see a gas disk orbiting galaxy's center
  - Measure velocities using the Doppler effect (red and blue shift of light from gas)
  - Need a 3 billion solar mass SMBH to explain gas disk velocities



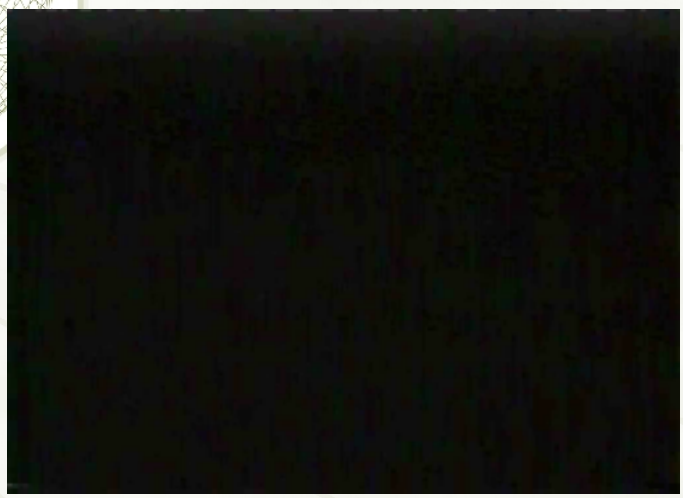



# Active Galactic Nuclei

- M87 shows signs of "central activity"
- The Jet
  - Jet of material squirted from vicinity of SMBH
  - Lorentz factor of >6
  - Powerful (probably as powerful as galaxy itself)
- What powers the jet?
  - Accretion power
  - Extraction of spin-energy of the black hole



## *Artist's conception of M87 system*

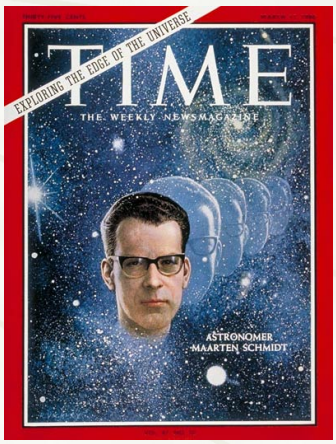


- MUSE: Supermassive Black Hole ("Black Holes and Revelations" 2009)



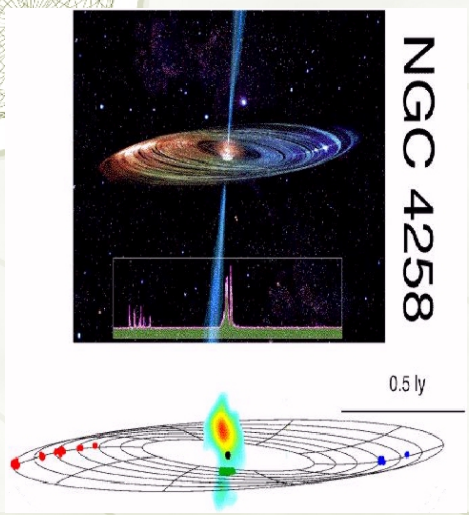
- M87 is example of an "active galactic nucleus"
  - Material flows (accretes) into black hole
  - Energy released by accretion of matter powers energetic phenomena
    - Emission from radio to gamma-rays
    - Jets
  - Supermassive black hole equivalent to the X-ray binaries systems
- Particularly powerful active galactic nuclei are sometimes called **Quasars**

# 1966 Cover, discovery of QSOs





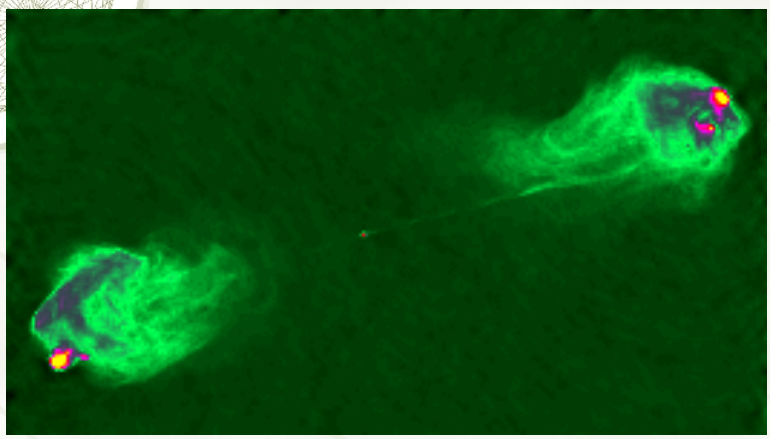

# Water masers and dynamics in NGC 4258




Masers reveal a tiny warped disk around a massive black hole

Miyoshi et al 1995; Greenhill et al 1996; Herrnstein et al. 1998

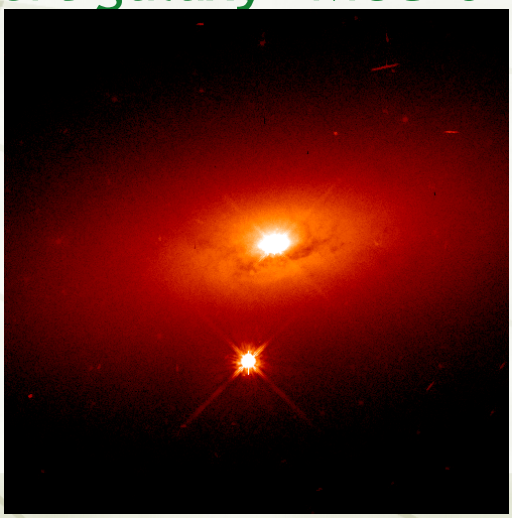
## The powerful radio-galaxy Cygnus-A



Radio image with the
Very Large Array in New Mexico

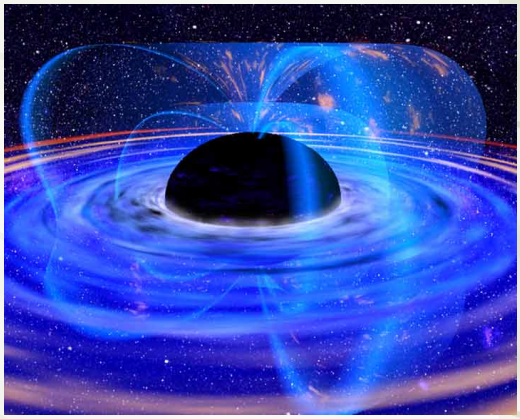


## Another example… the "Seyfert galaxy" MCG-6-30-15



Model for MCG-6-30-15 inferred on basis of X-ray data from XMM-Newton observatory:

magnetic fields transfer energy of spin from black hole to accretion disk!





## *What can come **out** of black hole?*

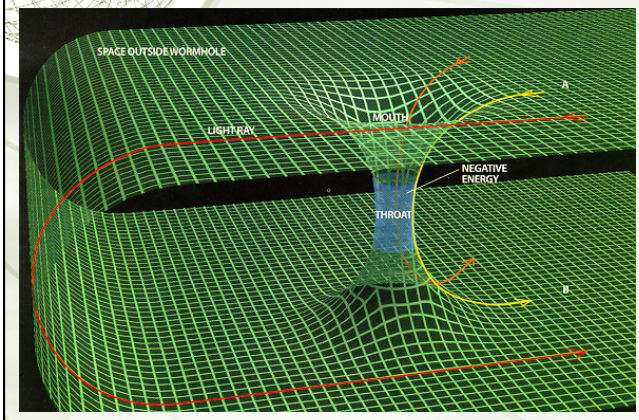
…more than you might think!

- Magnetic fields threading ergosphere can attach to and drag surrounding matter, reducing the black hole's spin and energy
- "Hawking Radiation": black hole slowly evaporates due to quantum mechanics effects
  - Particle/antiparticle pair is created near BH
  - One particle falls into horizon; the other escapes
  - Energy to create particles comes from gravity outside horizon

$$t_{evap} = 10^{10} yrs \times \left( \frac{M}{10^{12} kg} \right)^3$$

  - Solar-mass black hole would take $10^{65}$ years to evaporate!
  - Mini-black holes that could evaporate are not known to exist now, but possibly existed in early Universe

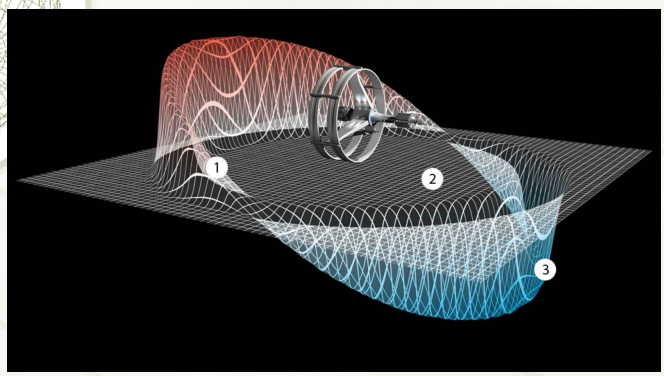
# White holes and Worm holes




- GR does not know about entropy: there is a symmetric solution for a BH known as a White-hole
- What if we can connect a BH and a WH to form a worm home?
- Shown by Rosen & Einstein for a Swartzschild BH, but it isn't stable and it cannot avoid the singularity
- Solution developed by K. Thorne, but requires exotic matter. Other solutions exist…



# Alcubierre drives




- Since we are on the topic, here is another "faster than light" trick
- Metric mathematically developed by Miguel Alcubierre, also needs "exotic matter"/"negative energy"