

John Archibald Wheeler
American, 1911-

Q: What
is a black
hole?

A: An object
contained
within its own
event horizon.

Q: What 3
measurable
properties do
black holes
have?

A:

1. Mass

2. Angular momentum

3. Charge

Distance to origin $<$ Circumference/ 2π :

The river model of black holes

(Hamilton 2004)

**When you fall
in, how does it
look to your
friends?**

MIT Course 8.033, Fall 2006, Lecture 22

Max Tegmark

TODAY'S TOPICS:

- Astrophysical evidence for black holes
- Special relativity review for final exam
- Orbital equations in Schwarzschild metric

Evidence for
black holes,
part I

Astrophysical evidence for black holes:

1) Supermassive BH's in centers of most (all?) galaxies:

→ - existence of quasars, huge jets

- stellar motions $\Rightarrow 10^6 - 10^9$ solar masses

- orbiting gas disks \Rightarrow size less than 0.4 lightyears (can't be stars)

- devoured star incident \Rightarrow size less than 0.4 A.U.

- X-ray spectra reveal disk extending in to 6-20M!

M87
AGN

+

jet

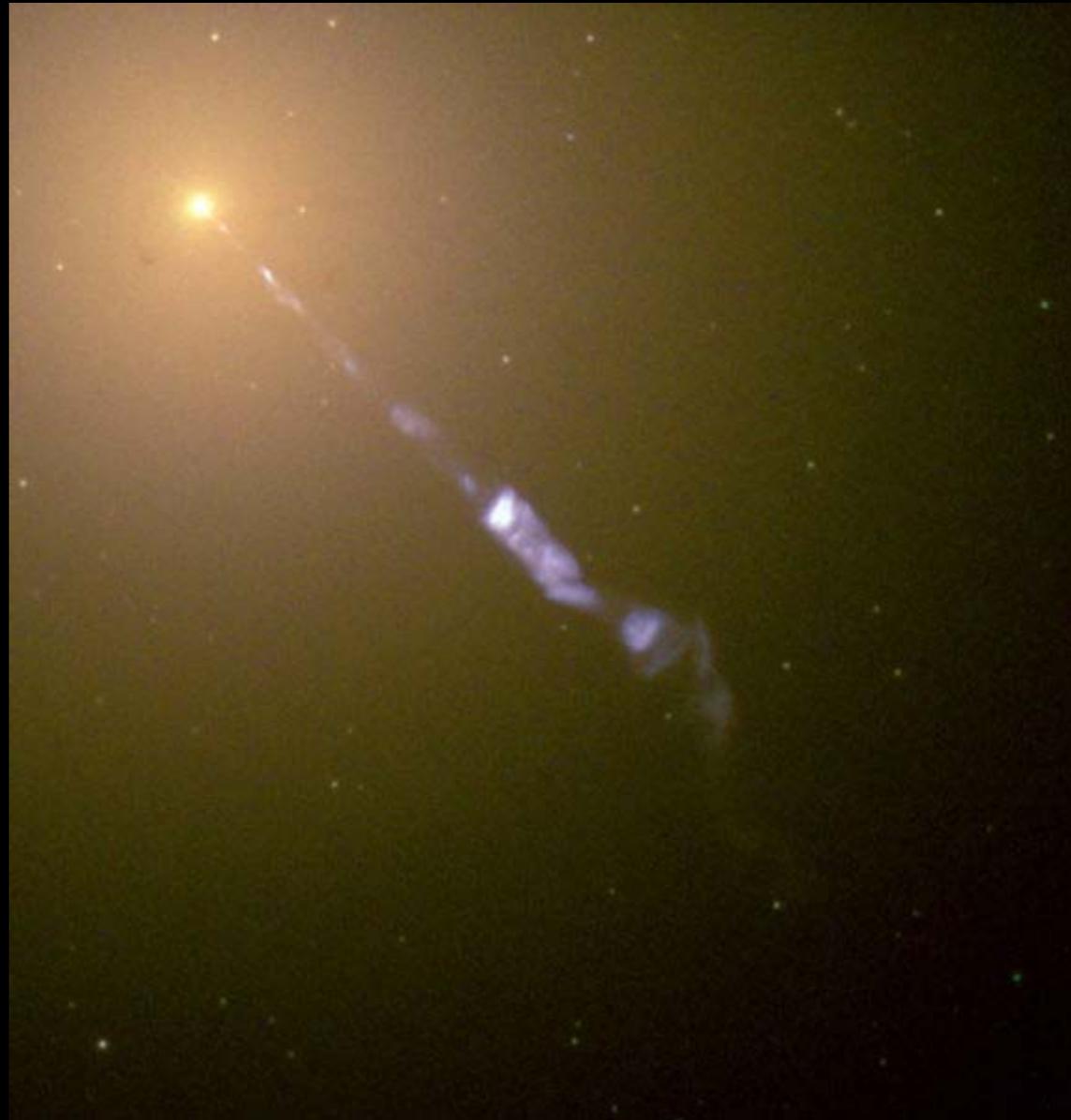


Image courtesy of NASA.

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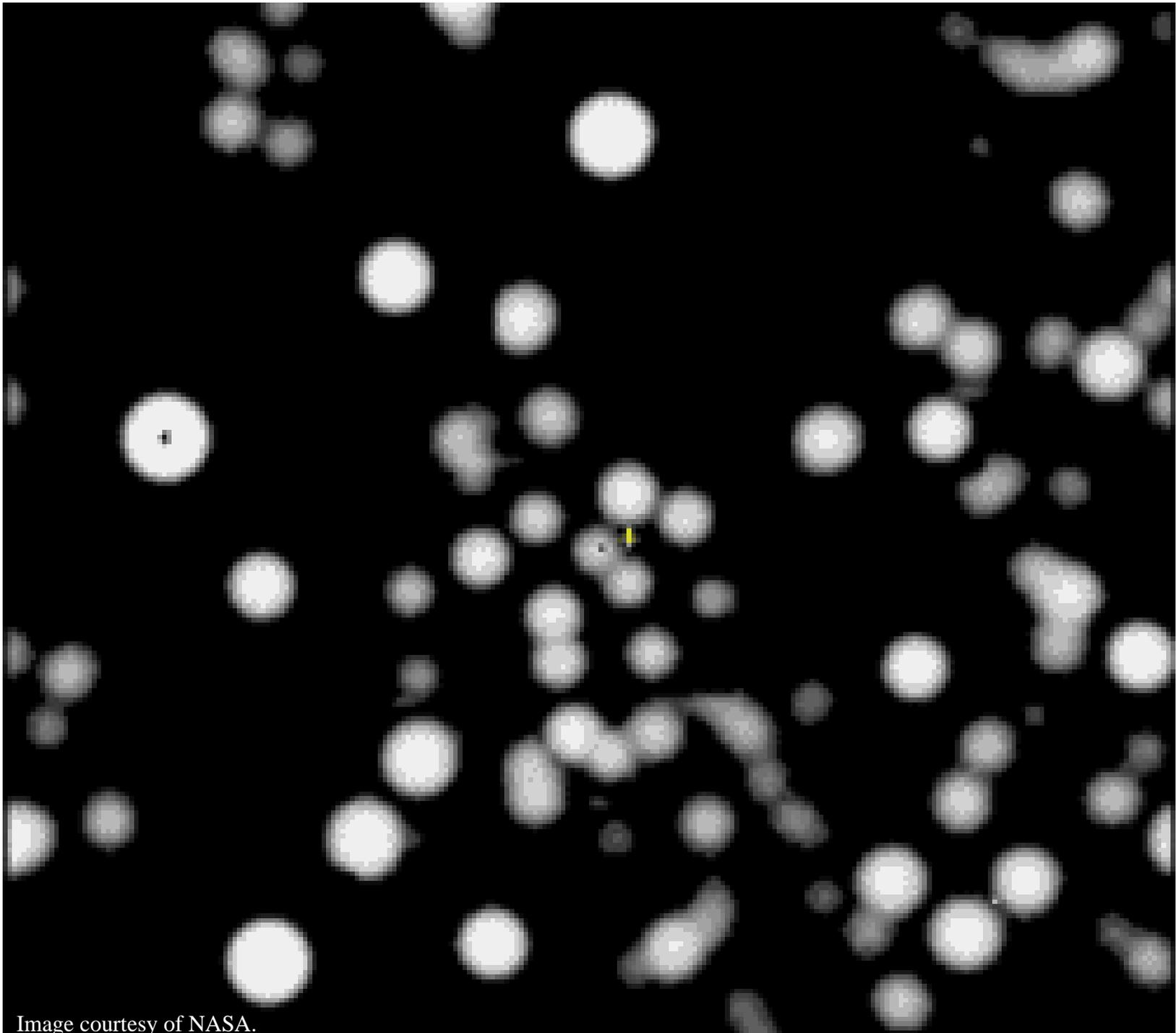


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Chandra x-ray satellite:

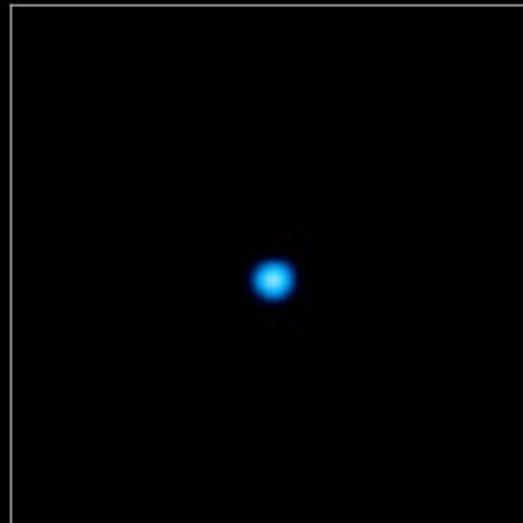


Image courtesy of NASA.

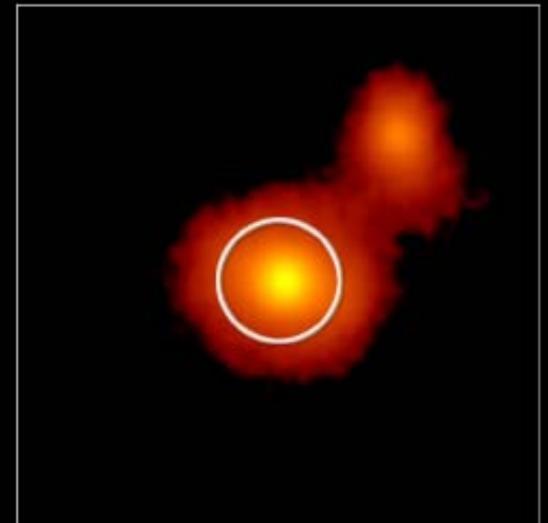
Star strays too close to Sagittarius A* supermassive black hole



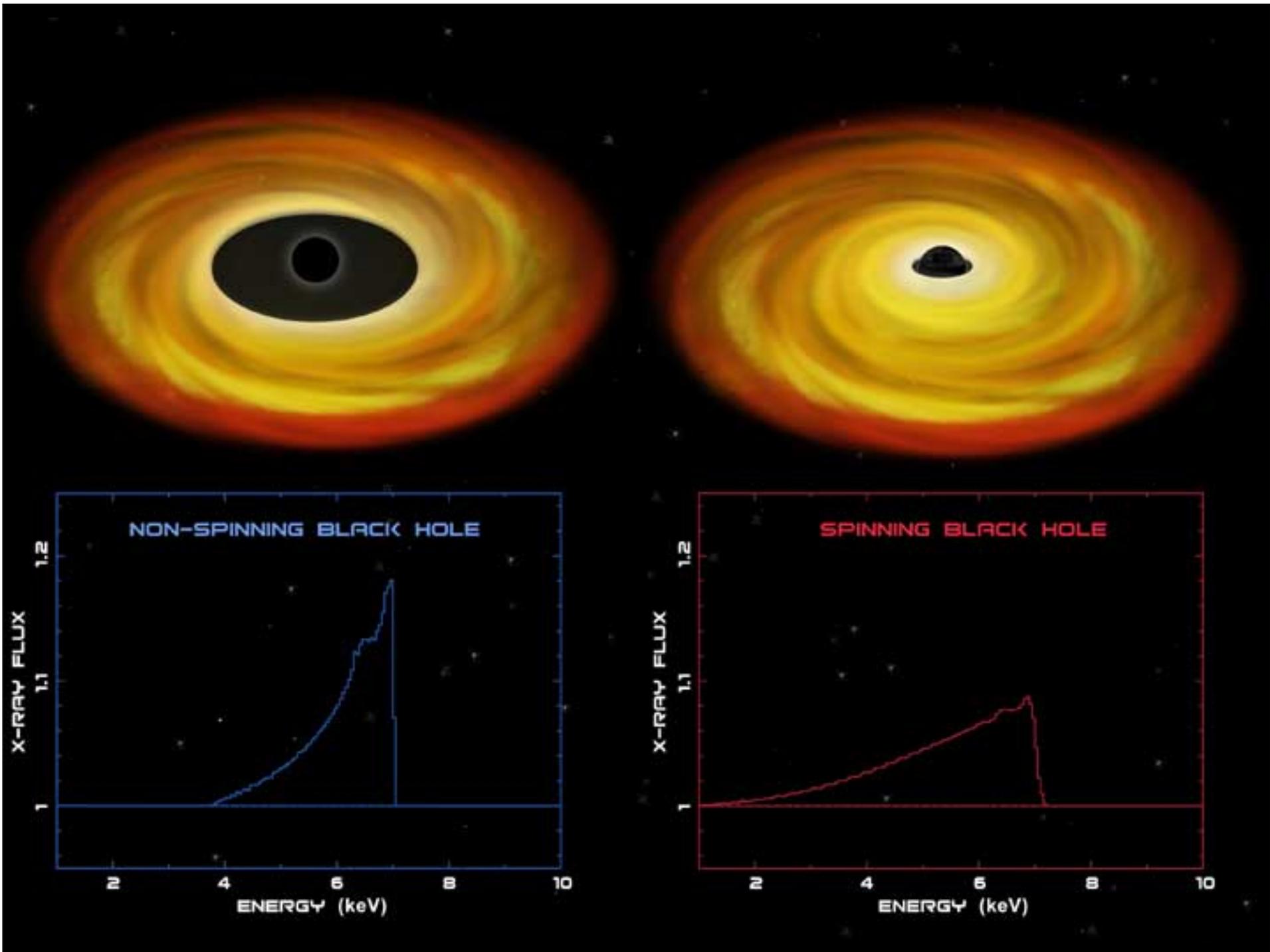
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CHANDRA X-RAY



ESO OPTICAL



Review for final exam

Who knows a song with seven equations?

WE ALL BELIEVE IN RELATIVITY

Melody: Yellow Submarine, with italicized lines going like the chorus

Rømer measured the speed of light,
and something basic just wasn't right.

because Michaelson and Morley
showed that aether fit data poorly.

We jump to 1905.

In Einstein's brain, ideas thrive:

“The laws of nature must be the same
in every inertial frame.”

We all believe in relativity, relativity, relativity.

Yes we all believe in relativity, 8.033, relativity.

Einstein's postulates imply
that planes are shorter when they fly.
Their clocks are slowed by time dilation,
and look warped from aberration.

Cos theta-prime is cos theta minus beta ... over one minus beta cos theta.
Yes we all believe in relativity, 8.033, relativity.

With the Lorentz transformation,
we calculate the relation
between Chris's and Zoe's frame,
but all invariants, they are the same.

Like B dot E and B-squared minus E-squared,
... and the rest mass squared which is E-squared minus p-squared.
'cos we all believe in relativity, 8.033, relativity.

$$\cos \theta' = \frac{\cos \theta - \beta}{1 - \beta \cos \theta}$$

$$\mathbf{B}' \cdot \mathbf{E}' = \mathbf{B} \cdot \mathbf{E}$$

$$B'^2 - E'^2 = B^2 - E^2$$

$$m_0^2 = E^2 - p^2$$

Soon physicists had a proclivity
for using relativity.

But nukes made us all scared
because $E=mc^2$.

*Everything is relative, even simultaneity,
... and soon Einstein's become a de facto physics deity.
'cos we all believe in relativity, 8.033, relativity.*

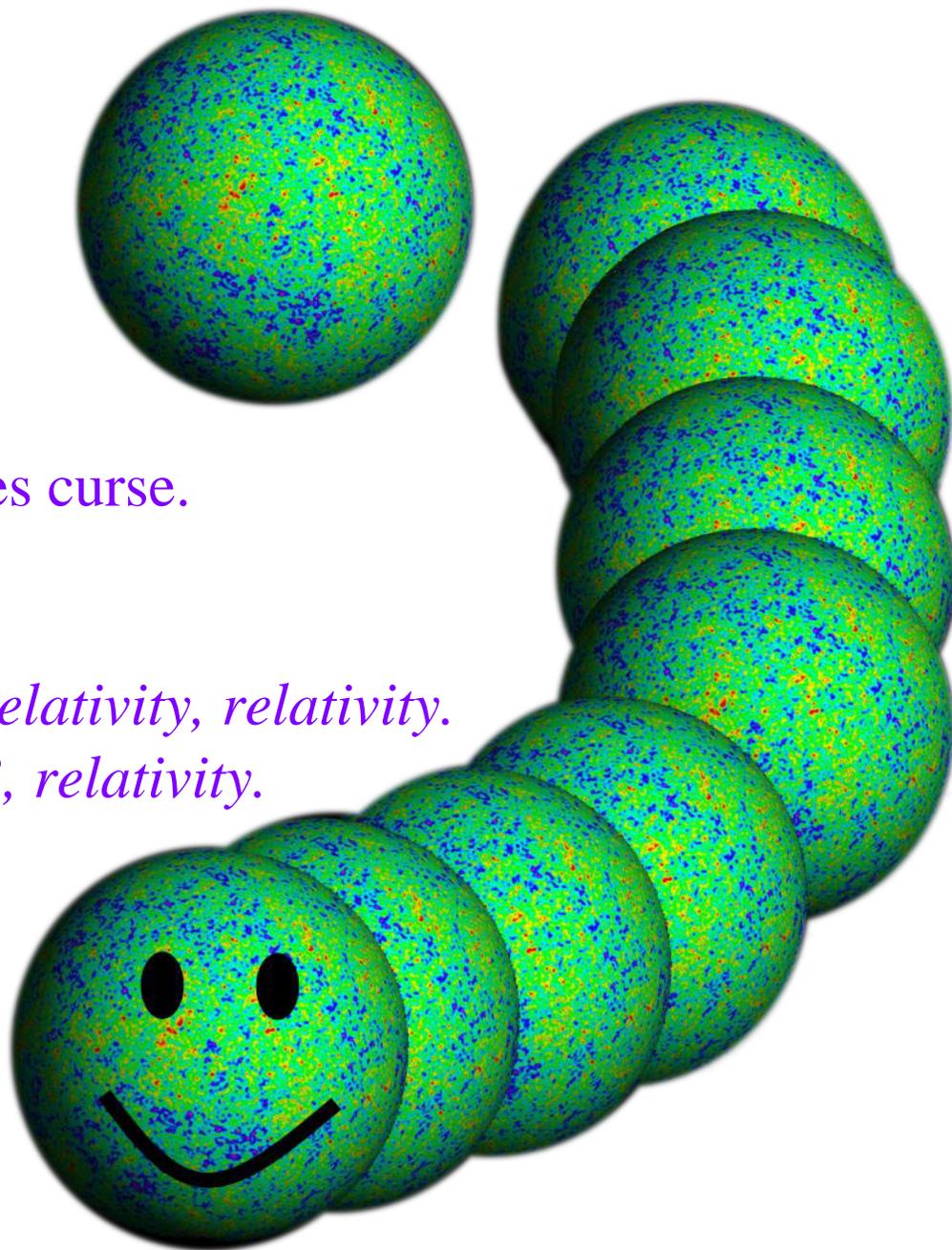
But Einstein had another dream,
and in nineteen sixteen
he made a deep unification
between gravity and acceleration.
He said physics ain't hard at all
as long as you are in free fall,
'cos our laws all stay the same
in a locally inertial frame.

*And he called it general relativity, relativity, relativity.
And we all believe in relativity, 8.033, relativity.*

If towards a black hole you fall
tides will make you slim tall,
but your friends won't see you enter
a singularity at the center,
because it will look to them
like you got stuck at radius $2M$.
But you get squished, despite this balking,
and then evaporate, says Stephen Hawking.
We all believe in relativity, relativity, relativity.
Yes we all believe in relativity, 8.033, relativity.

We're in an expanding space
with galaxies all over the place,
and we've learned from Edwin Hubble
that twice the distance makes redshift double
We can with confidence converse
about the age of our universe.
Rival theories are now moot
thanks to Penzias, Wilson, Mather & Smoot.
We all live in an expanding universe, expanding universe, expanding universe.
Yes we all live in an expanding universe, expanding universe, expanding universe.

But what's the physics of creation?
There's a theory called inflation
by Alan Guth and his friends,
but the catch is that it never ends,
making a fractal multiverse
which makes some of their colleagues curse.
Yes there's plenty left to figure out
like what reality is all about about.
but at least we believe in relativity, relativity, relativity.
Yes we all believe in relativity, 8.033, relativity.



How interesting did you find the various course components? (1-7)

25) Kinematics (special relativity basics, Lorentz transformations)

26) Dynamics, rockets

27) Electromagnetism

28) Particle physics

29) General relativity basics, metrics

30) Cosmology

31) Black holes

32) Historical background, the discoveries and the discoverers

Java orbit
simulator

Evidence for black holes, II

Astrophysical evidence for black holes:

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Astrophysical evidence for black holes:

2) Stellar mass BH's:

- Stars orbiting massive invisible companion
- Maximum neutron star mass is 3 solar masses
- Best example: V404 Cygni
partner mass = 12 ± 2 solar masses.
- Older example: Cygnus X1
- X-ray variability puts upper limit on size
- Appears that no “surface”

