hi

Day 15, 12.03.2019

Einstein’s Special Theory of Relativity, 4.5

19 days until opening day

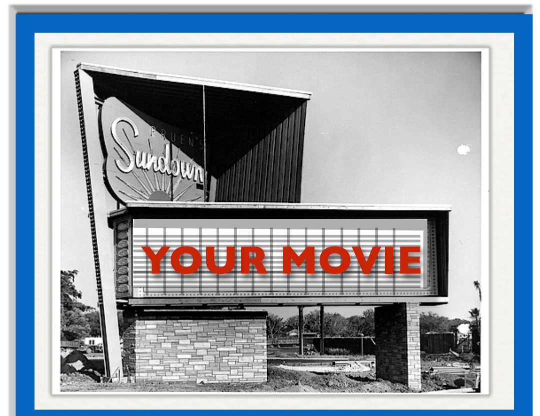
Kiss week

housekeeping

Gotta come to class

question about anything?

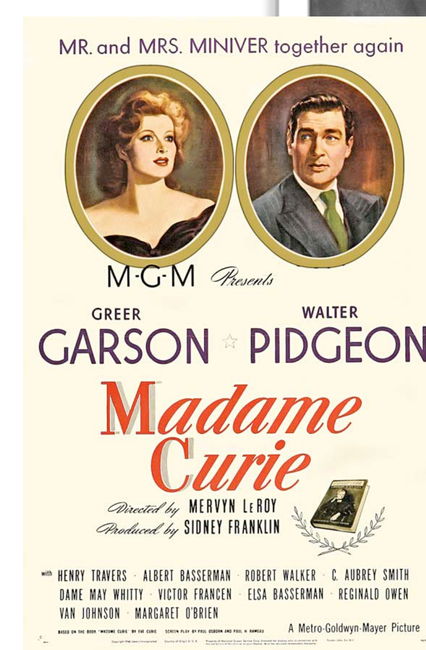
I'll make a movie for you:



Madame Curie movie - we have a quorum in favor

right now: looks like Monday, March 18

I'll remind you in FB to confirm that date



Section 2 folks:

Project has begun in phases:

Document 1: software, introduction, tutorial: due March 22

Document 2: your individual dataset and project instructions: due Final Exam

https://qstbb.pa.msu.edu/storage/QS&BB2019/Homework_Projects/honors_project_2019/MinervaInstructions1_2019.pages.pdf

MasteringAstronomy, finally after 3 emails and phone calls:

Course ID: MABROCK41459; free code: WSSPCT-BLIDA-INANE-TOGUE-RIGOT-UNRWA

check it! let me know if it is now working...

March 2019

Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
24	25	26	27	28	1	2
3	4 ←	5	6 spring break	7	8 →	9 HW6
10	11	12 lecture	13	14 lecture	15 HW6 due	16 HW7
17	18  ?	19 lecture	20	21 lecture	22 HW7 due	23 HW8
24	25	26 lecture	27	28 lecture	29 HW8 due	30 HW9
31	1	2 lecture	3	4 lecture	5 HW9 due	6

KEEP CALM AND LET'S REVIEW

Principle of Relativity

2 Postulates:

"inertial frame":

1. All laws of physics — mechanical and electromagnetic — are identical in co-moving inertial frames.

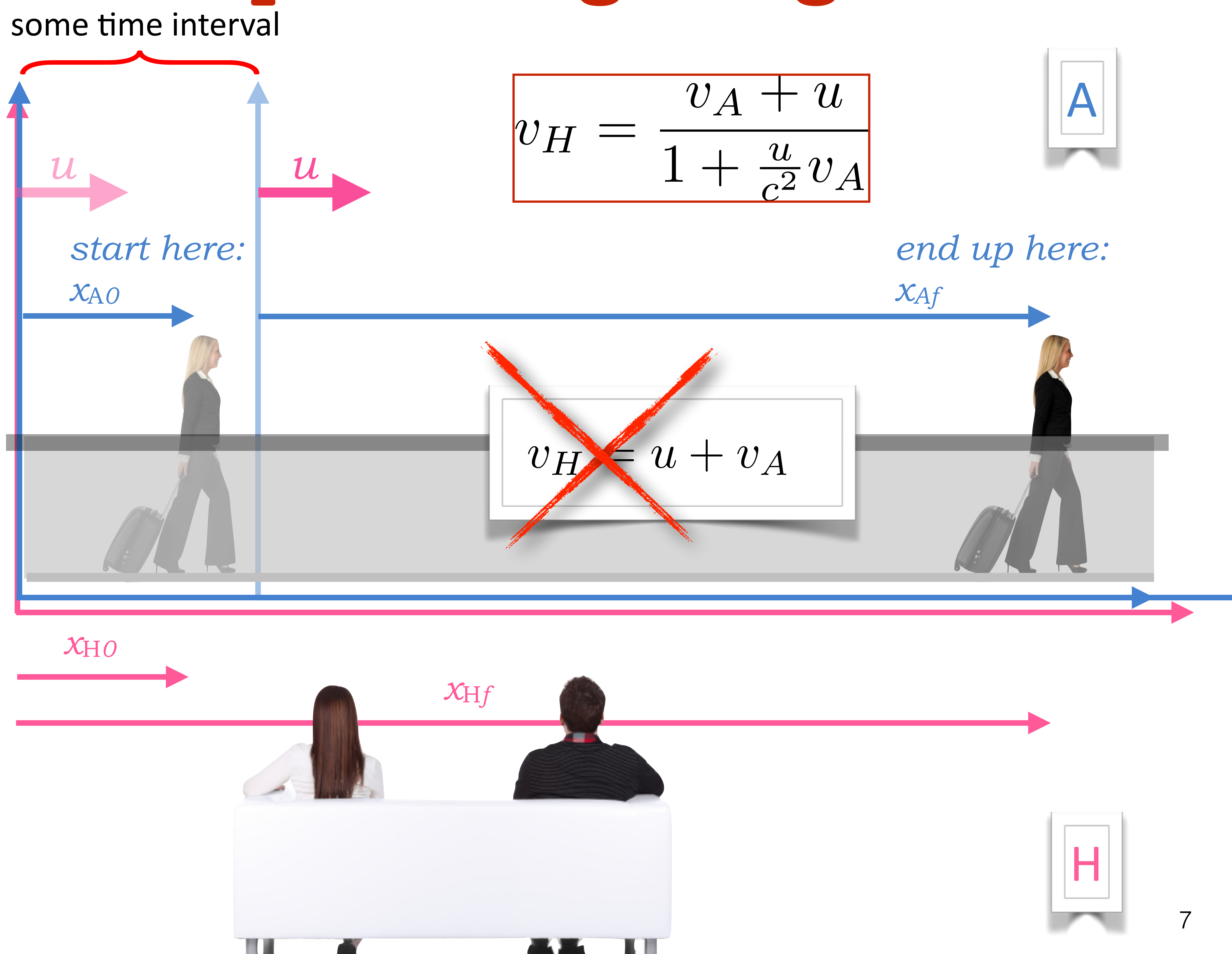
taking Galileo seriously, and then adding Maxwell

2. The speed of light is the same for all inertial observers.

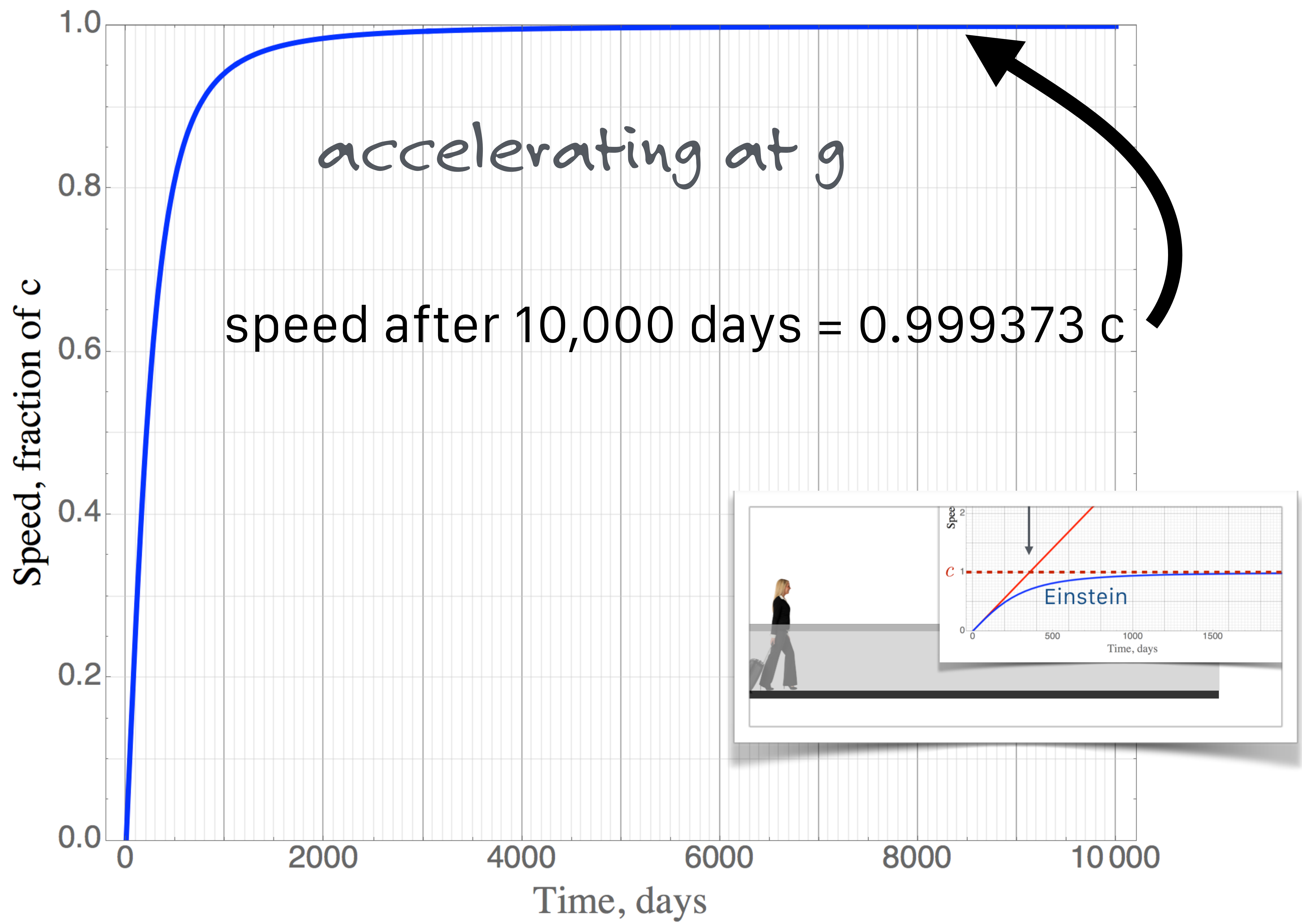
taking Maxwell seriously

a fact of nature

the airport, going fast



never get there



mass

&

energy

equivalent.

An object in its own rest frame:

has mass: m

has inherent energy: $E_m = mc^2$

speak of the "energy of mass"

and the "mass of energy"

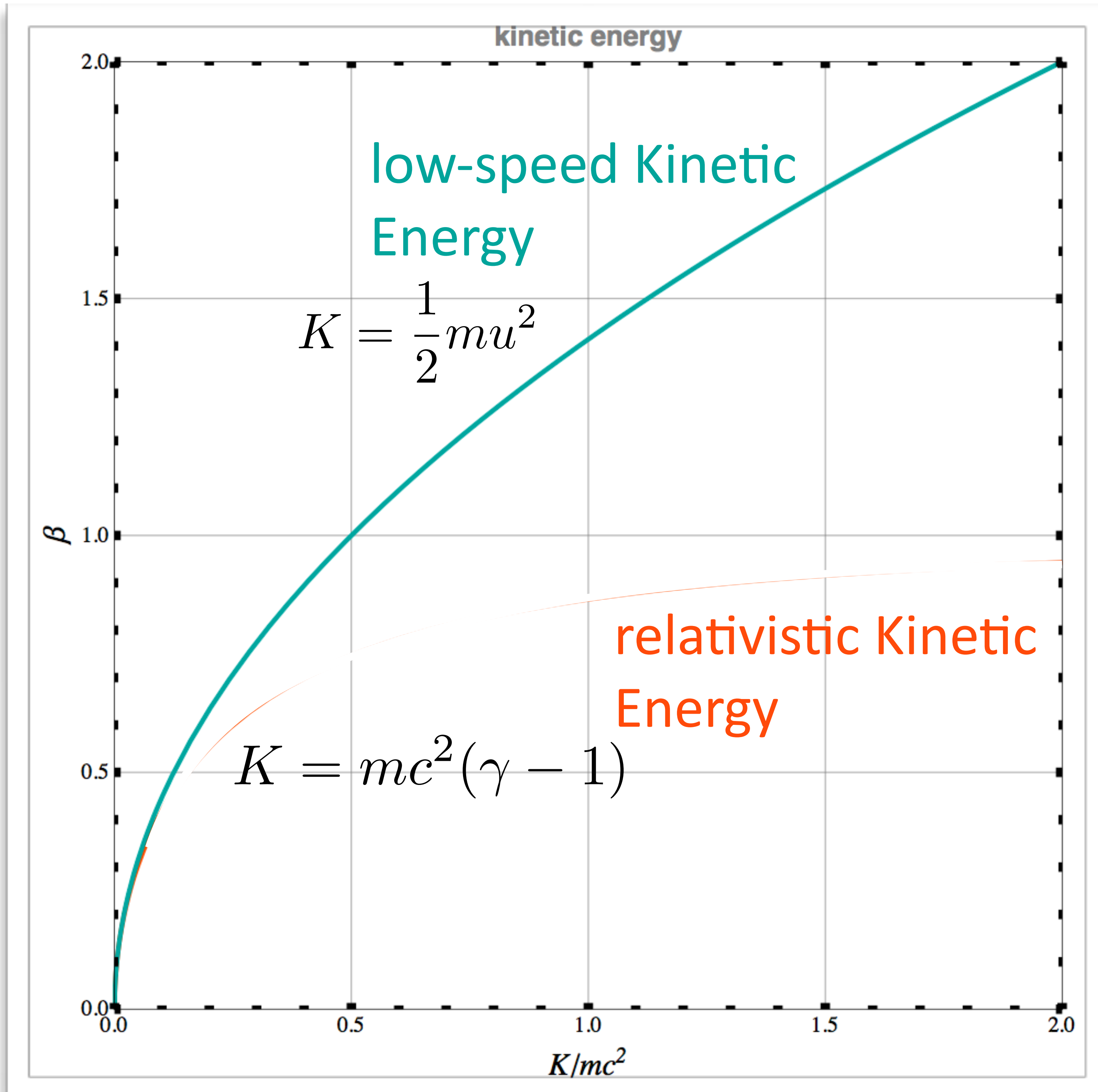
An object in an Away frame, u:

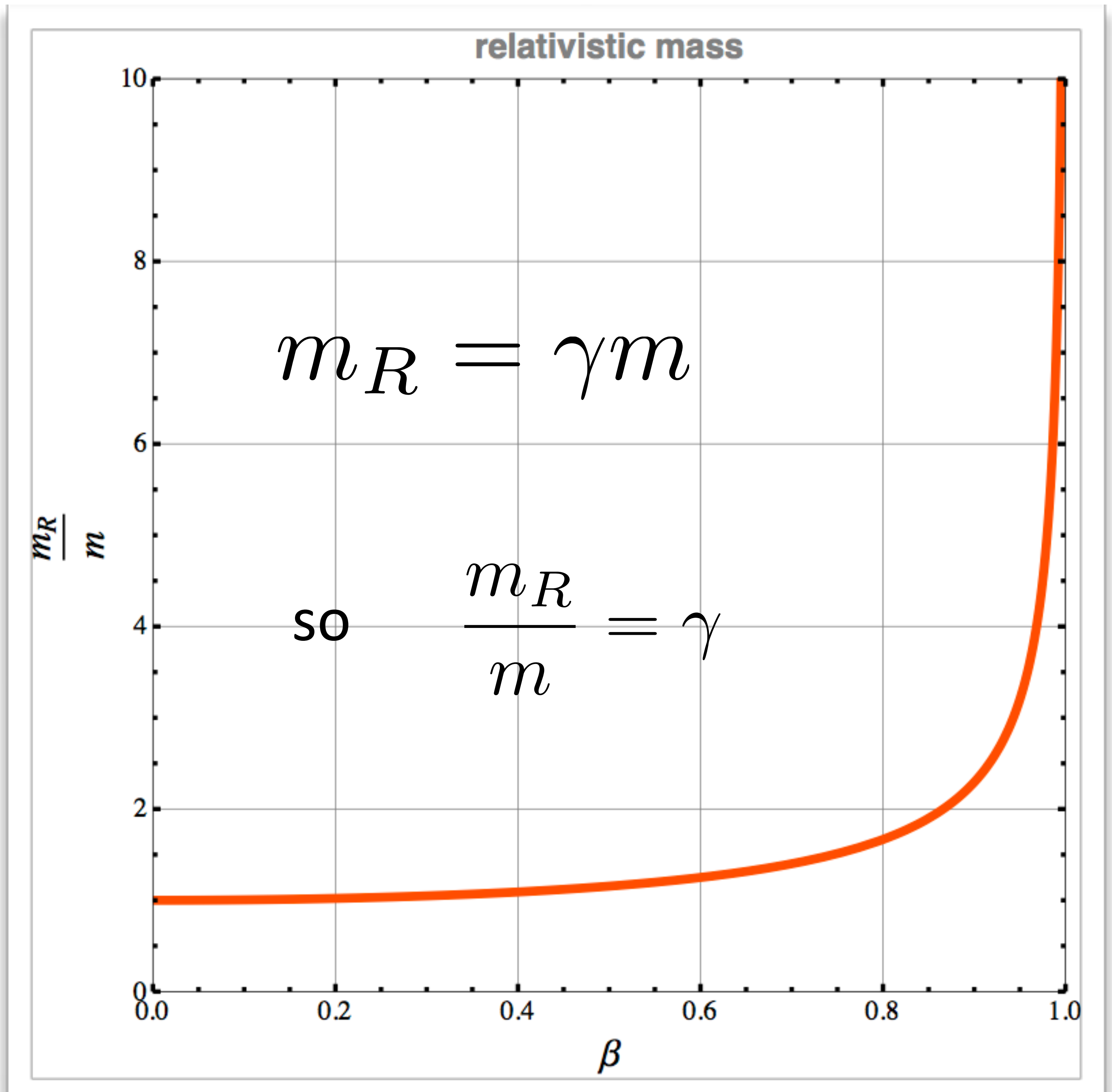
has mass for Home frame: $m_R = \gamma m$

has energy for Home frame: $E_T = m\gamma c^2$

total energy: $E_T = E_m + K$

Newton vs Einstein





a useful invariant

$$E_m = mc^2$$

$$E_T = m\gamma c^2$$

$$p = m\gamma v$$

and an important formal linkage

fun fact...just with a little algebra...

$$E_T^2 = (mc^2)^2 + (pc)^2$$

$$E_m^2 = E_T^2 - p^2c^2$$

$$m^2c^4 = E_m^2 = E_T^2 - p^2c^2$$

no velocity dependences, just a number...

"Energy-momentum relation"...

$$\boxed{E_T^2 = (mc^2)^2 + (pc)^2}$$

practical

Energy/momentum relations:

"rest mass"... m

the mass of an object in its own frame

"relativistic mass"... $m_R = m\gamma$

the mass of a moving object

"Energy"... $E_T = m\gamma c^2$

the total Energy of a moving object

"rest Energy"... $E = mc^2$

the mass-energy of an object in its own frame

Kinetic Energy... $K = mc^2(\gamma - 1)$

the energy due to motion

Relativistic momentum... $p = m\gamma u$

momentum for each component of space

Energy-momentum relation... $E_T^2 = \left(mc^2\right)^2 + (pc)^2$

an alternative, useful expression

You might want to remember this:

	energy of motion…	**Kinetic Energy**
+	energy of mass…	**Rest Energy**
	Total energy of an object	

there aren’t any other kinds of energy

completely inelastic collision

1 12 2

a collision from earlier

where mechanical energy was not conserved.

and they stick together

But we certainly would have said: $m_1 + m_2 = M_{12}$

Now...energy conservation is different:

$$E_{(\text{before})} = E_{(after)}$$

$$[E_{(\text{Object 1})}] + [E_{(\text{Object 2})}] = [E_{(\text{Object 12})}]$$

$$E_{m(1)} + K_1 + E_{m(2)} + K_2 = E_{m12} + K_{12}$$

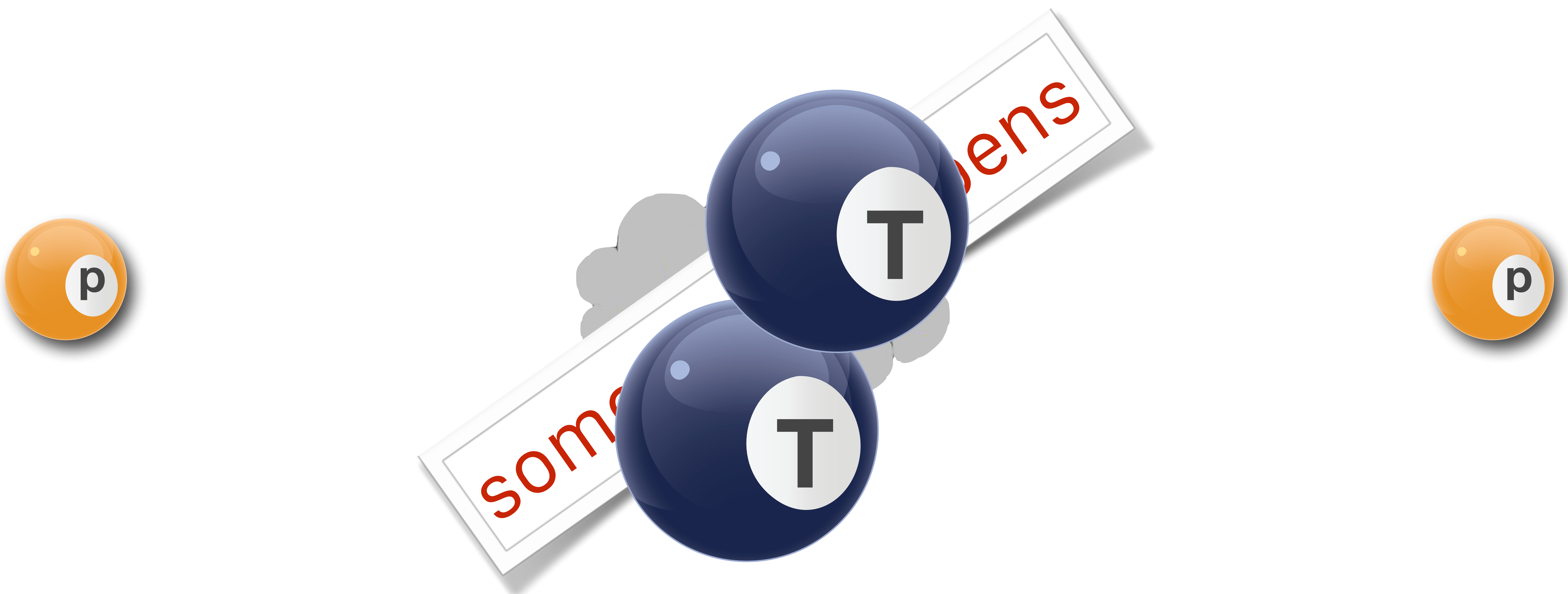
$$E_{m(1)}/c^2 + K_1/c^2 + E_{m(2)}/c^2 + K_2/c^2 = M_{12}$$

brand new thing!

this is how

we can take two protons, crash them together, and produce 2 “top quarks”…

each of which has the mass of 170 protons



particle colliding beam

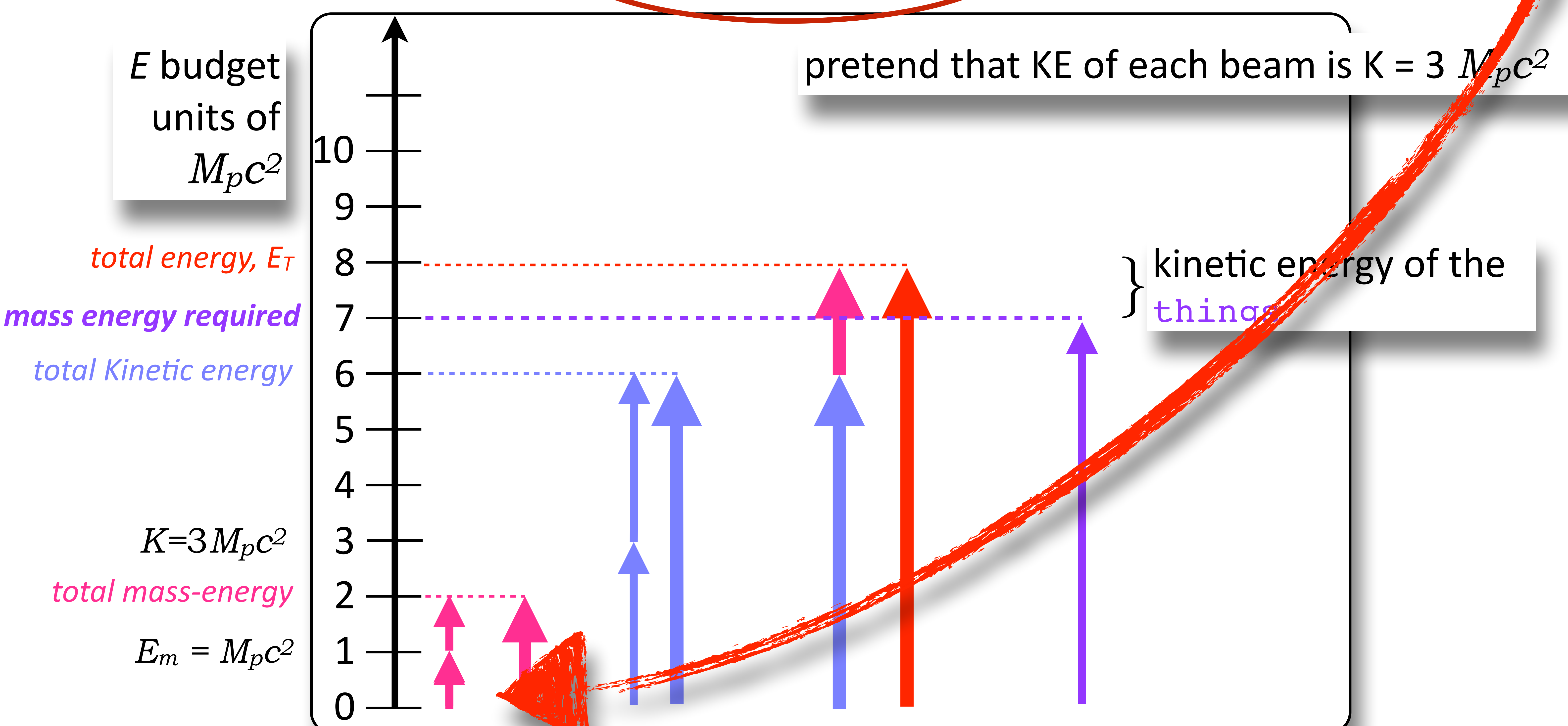
E_T = mass energy + kinetic energy + E_T = mass energy + kinetic energy

1 proton's mass = M_p

1 proton's mass energy = $M_p c^2$

Use head-on collisions to make objects more massive than protons.

Make Two things that each have $M(\text{thing}) = 3.5 \bullet M_p$

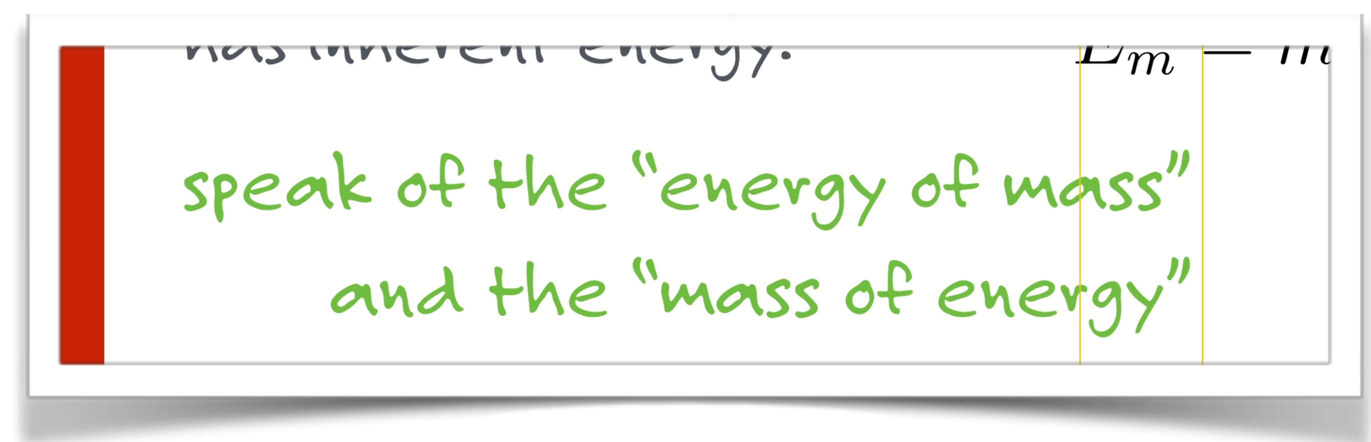


a hydrogen atom, take 2

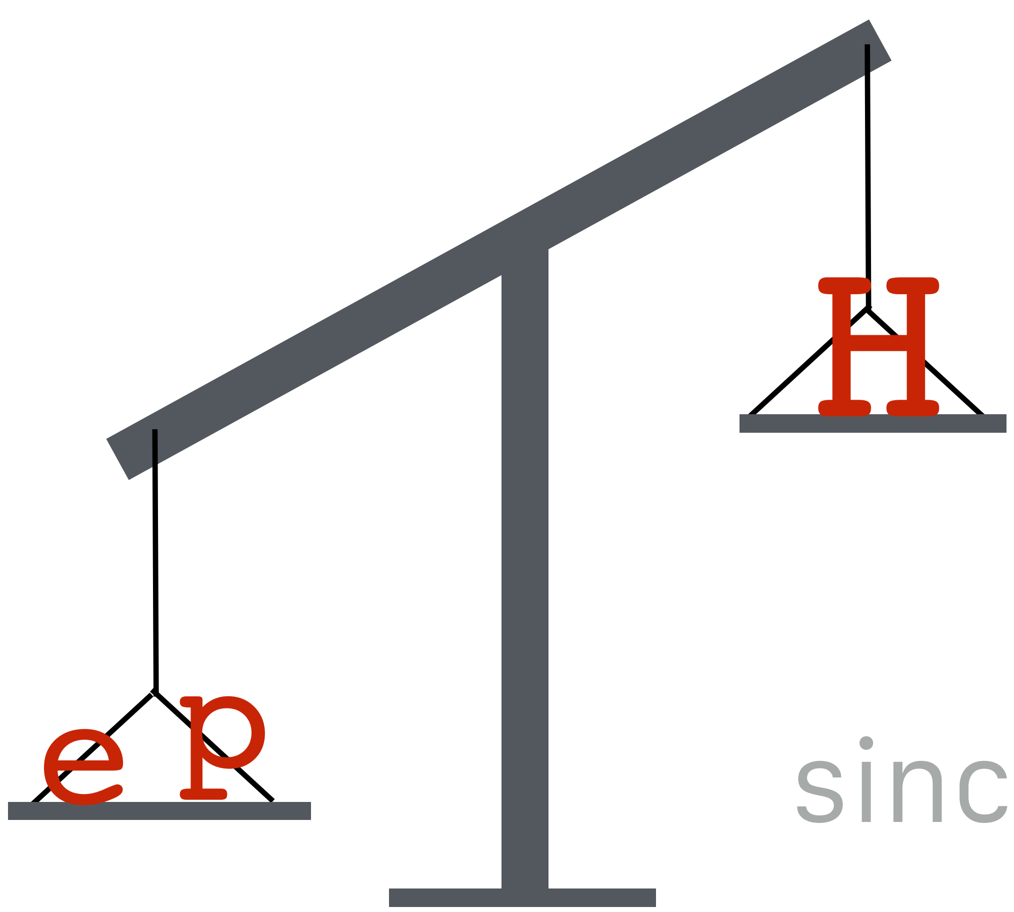
weighs less than the components of a hydrogen atom

so it can't fall apart into its components

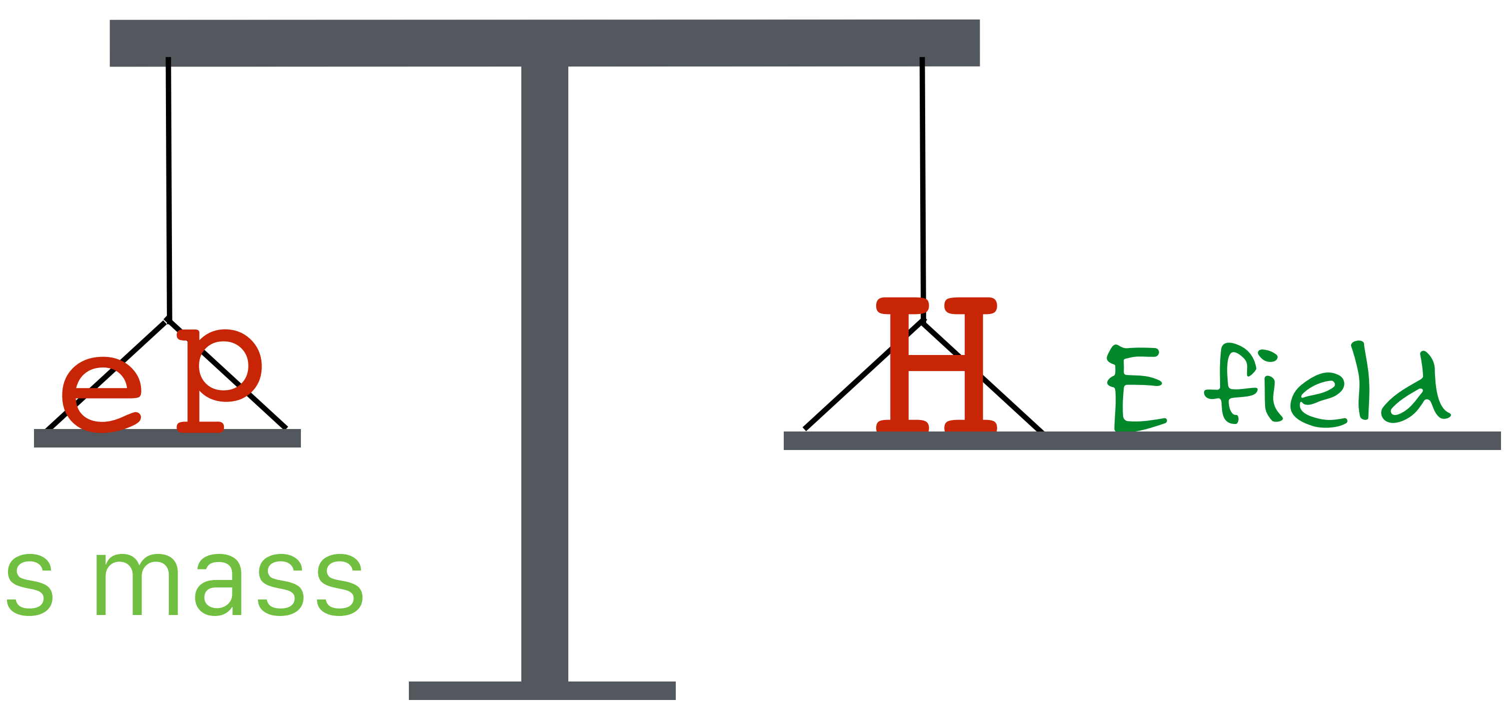
where is that "missing mass"?



in the energy of the Electric Field,



since Energy is mass



isn’t anything constant?

glad you asked

jargon alert: **invariant**

refers to: something that is unchanging under some transformation

entomology: *not*-variant

example: the spacetime interval

Can’t we agree on anything?

Is EVERYTHING RELATIVE?

no.

"The views of space and time which I wish to lay before you have sprung from the soil of experimental physics, and therein lies their strength. They are radical. Henceforth space by itself, and time by itself, are doomed to fade away into mere shadows, and only a kind of union of the two will preserve an independent reality.

Hermann Minkowski

ISP220: Quarks, Spacetime, and the Big Bang

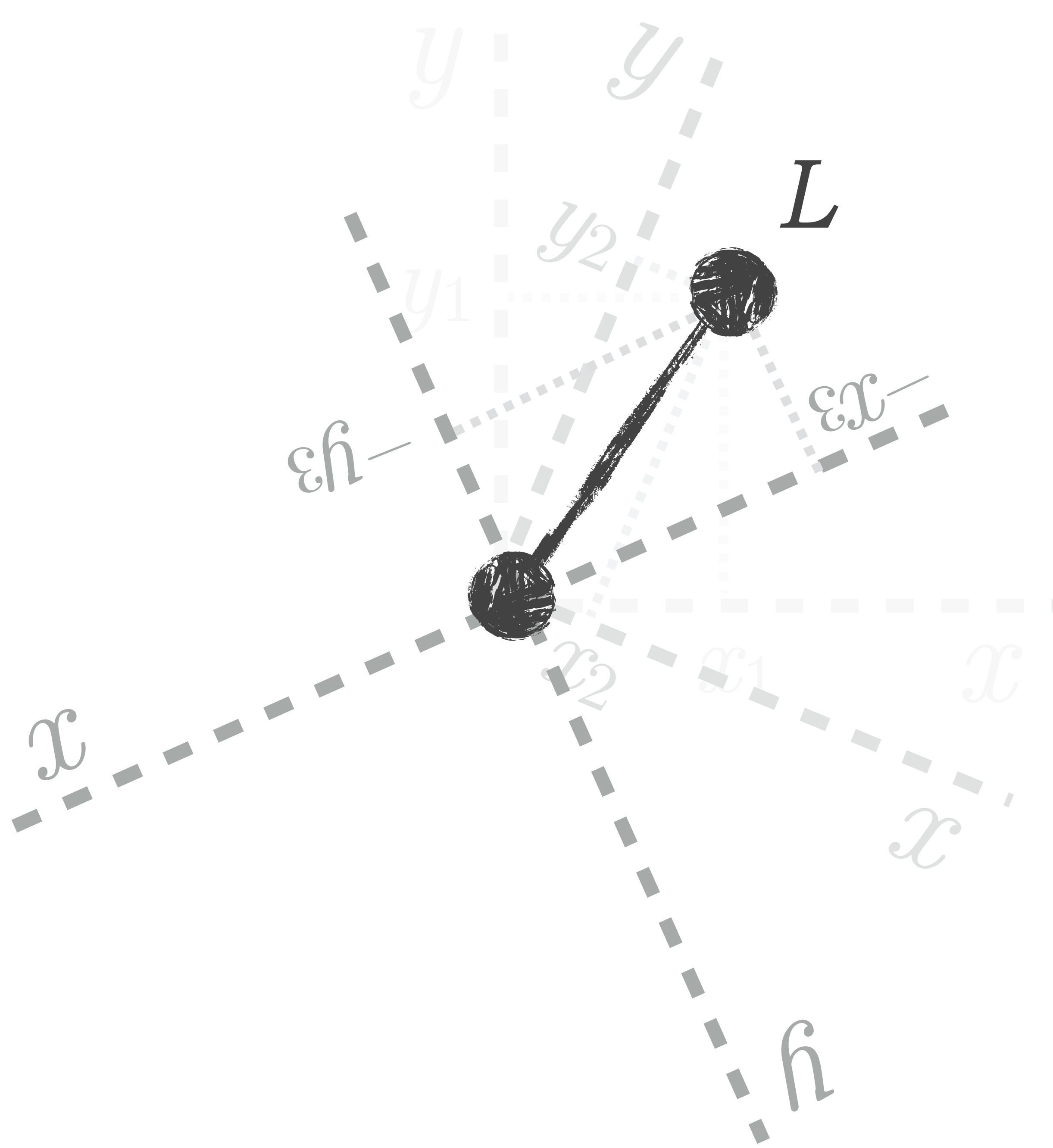
Space and time are mixed together and together become a single entity

‘‘coordinate systems’’

can mean “reference frames”

lengths are invariant

as viewed from all coordinate systems



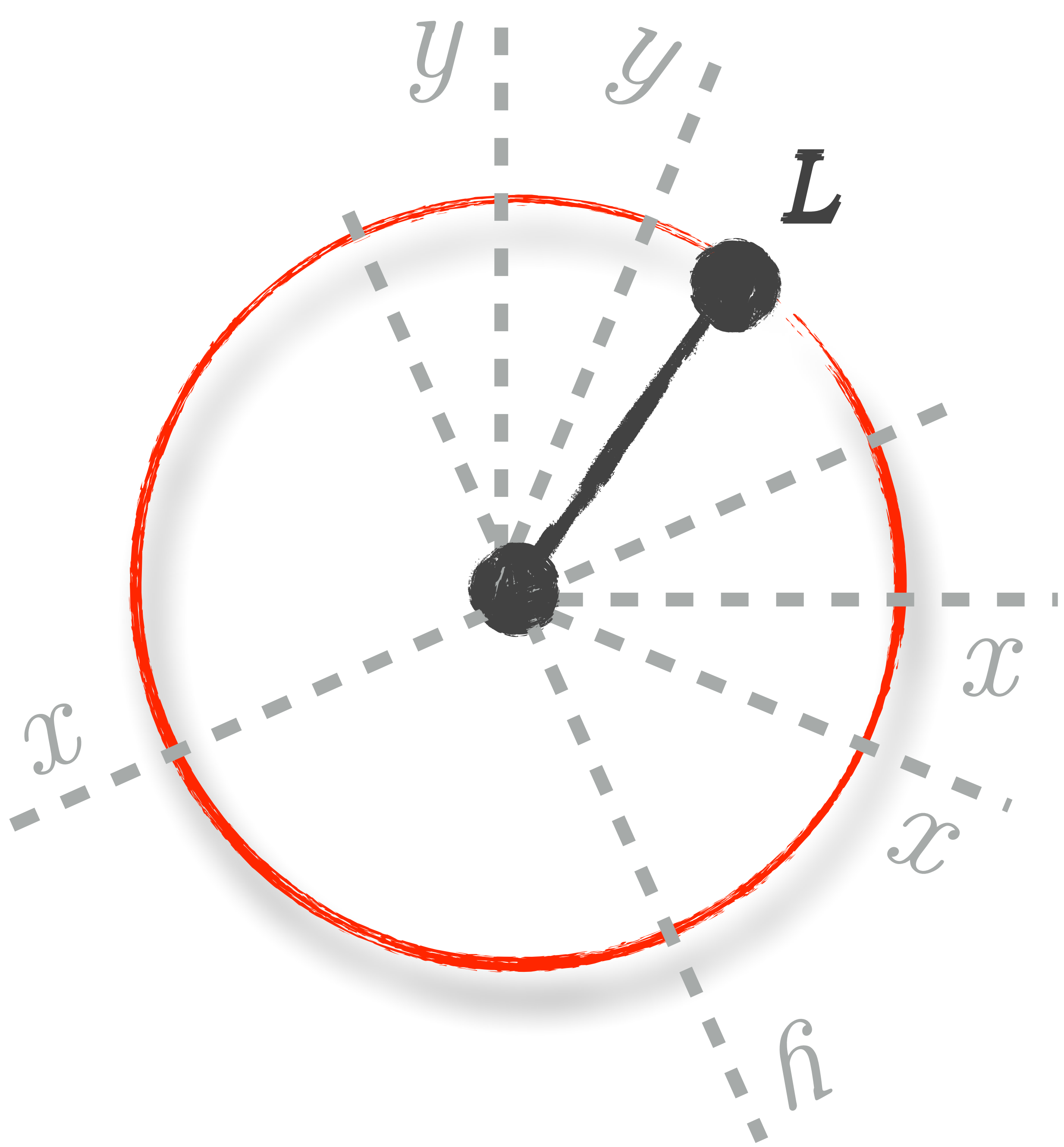
$$L^2 = x_1^2 + y_1^2$$

$$L^2 = x_2^2 + y_2^2$$

$$L^2 = x_3^2 + y_3^2$$

lengths are invariant

as viewed from all coordinate systems



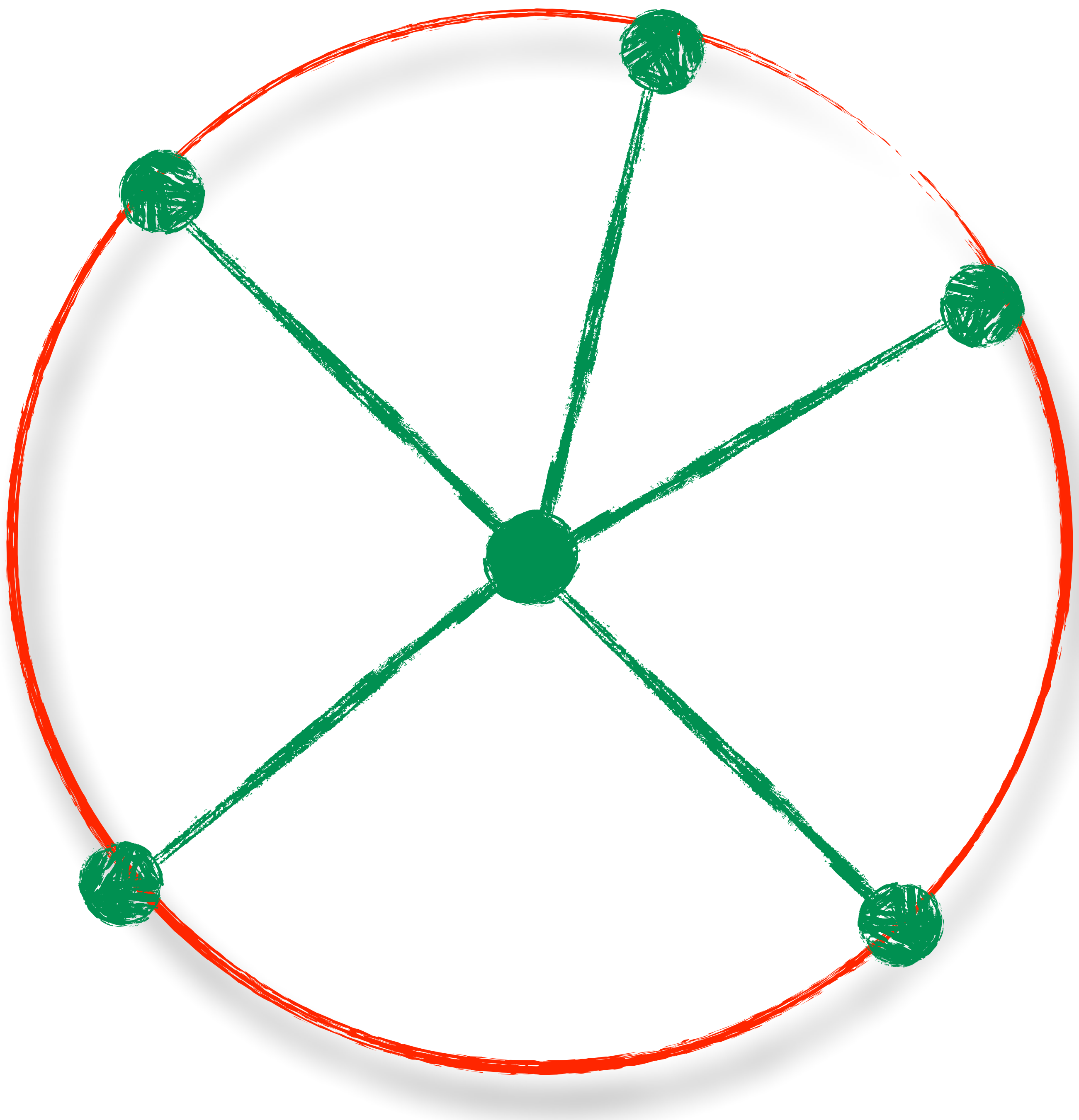
$$L^2 = x_1^2 + y_1^2$$

$$L^2 = x_2^2 + y_2^2$$

$$L^2 = x_3^2 + y_3^2$$

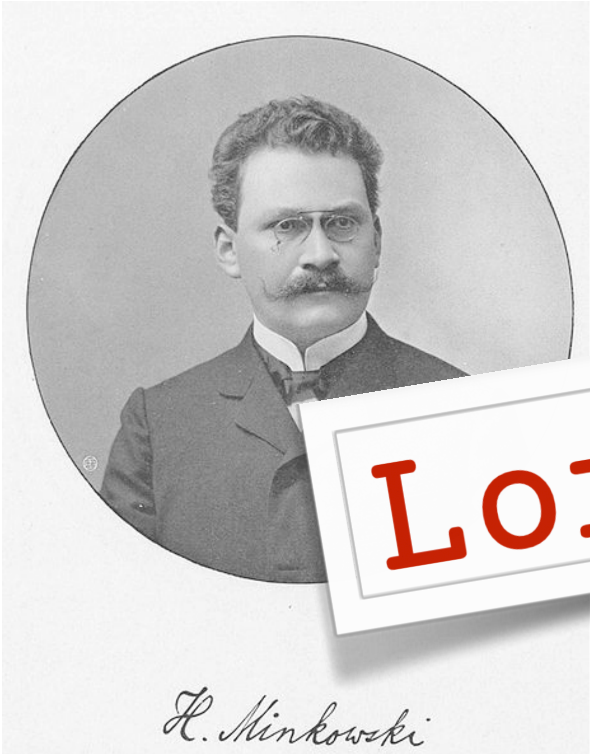
all coordinate systems in space

will place that point on the circle.



$$L^2 = x^2 + y^2 = x'^2 + y'^2 = x''^2 + y''^2 = x'''^2 + y'''^2$$

Let's call this: **the invariant curve**



Lorentz asked

What about SPACETIME?

what's constant? What's a Spacetime "Length"?

Try the same approach for spacetime as for space: Euclidean

construct the **Invariant Curve for spacetime**

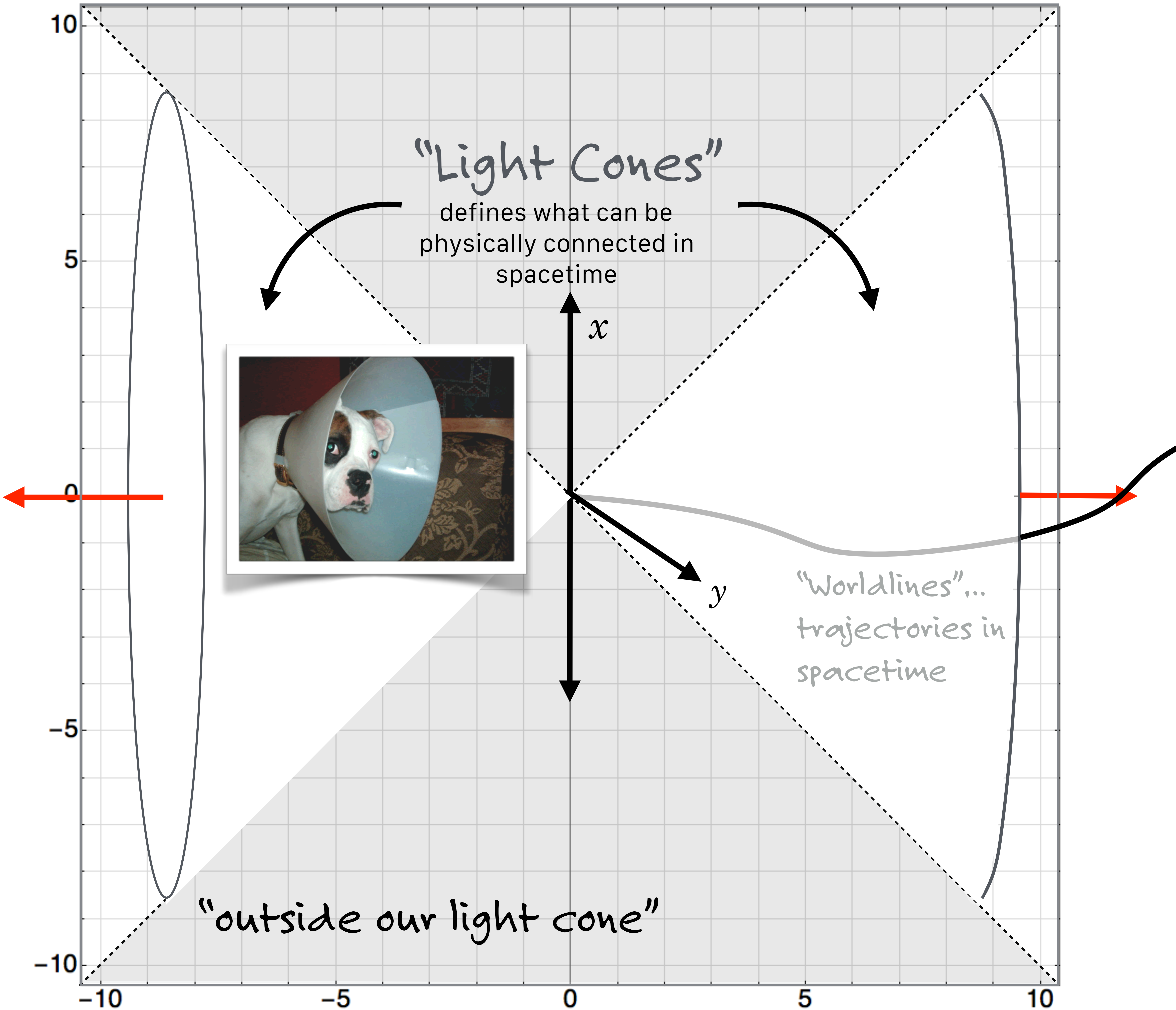
spacetime regions

collapse three space dimensions into 1

collapse one time dimension into...um...1

2 dimensional screen

substitutes for a 4 dimensional screen

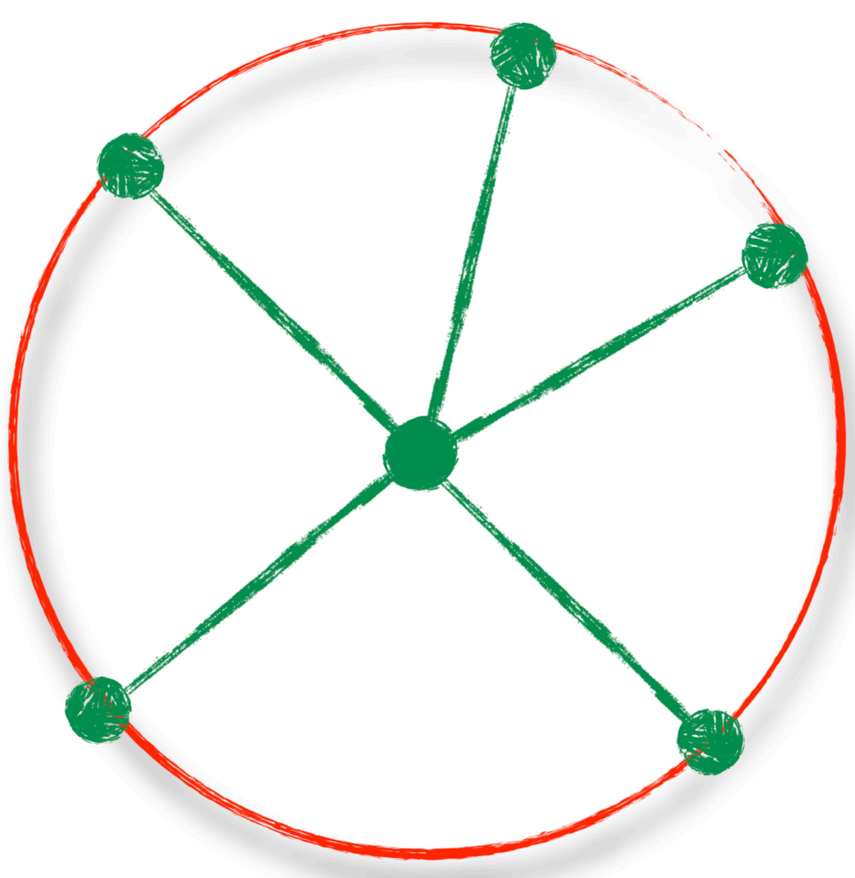

"Light Cones"
defines what can be physically connected in spacetime
x
y
"Worldlines"... trajectories in spacetime
"outside our light cone"
10
5
0
−5
−10
−10
−5
0
5
10

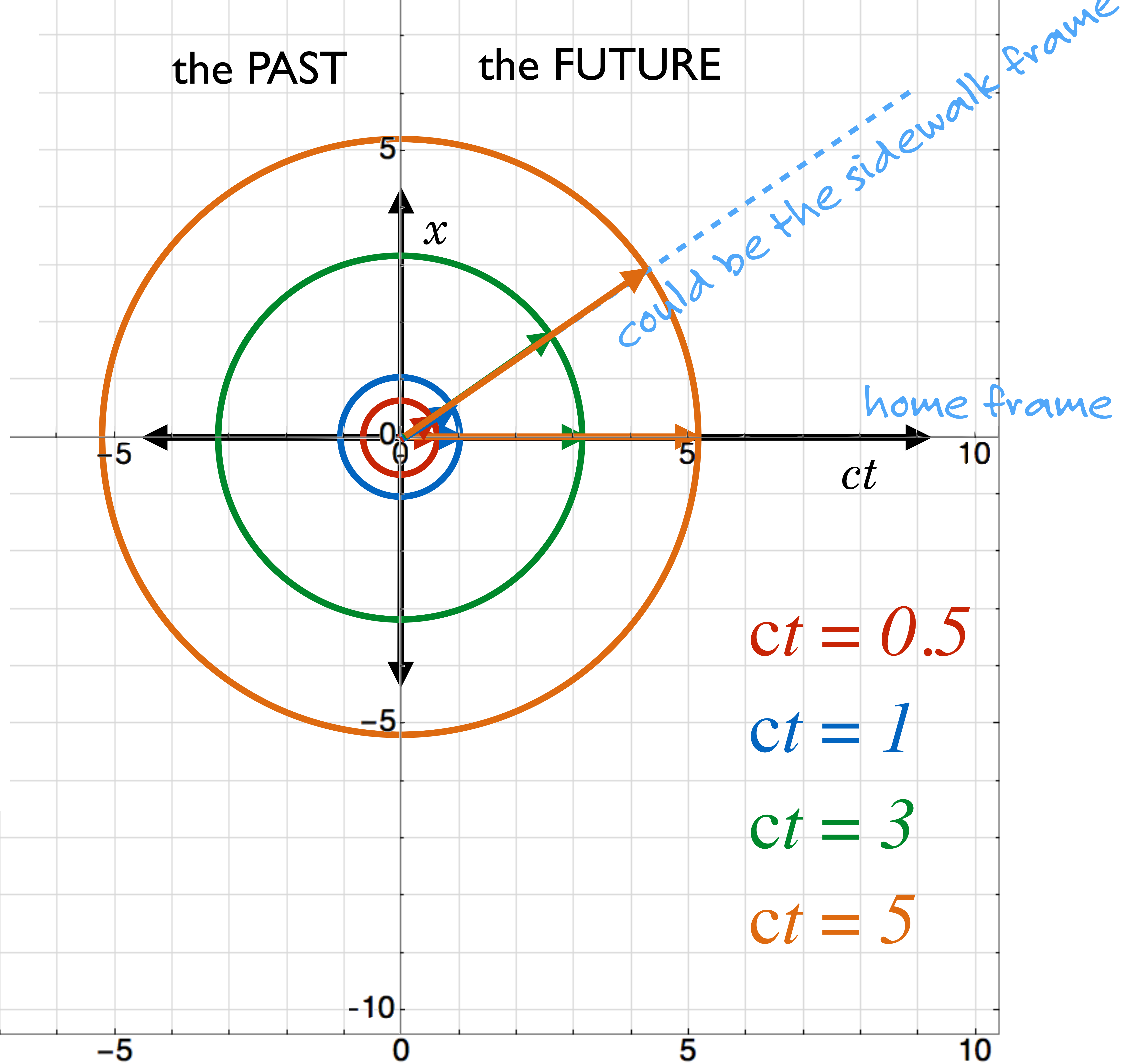
a trial invariant curve

for the airport

For two observers in two rest-frames:

Suppose invariant spacetime curve is like:





`make sense`

right?

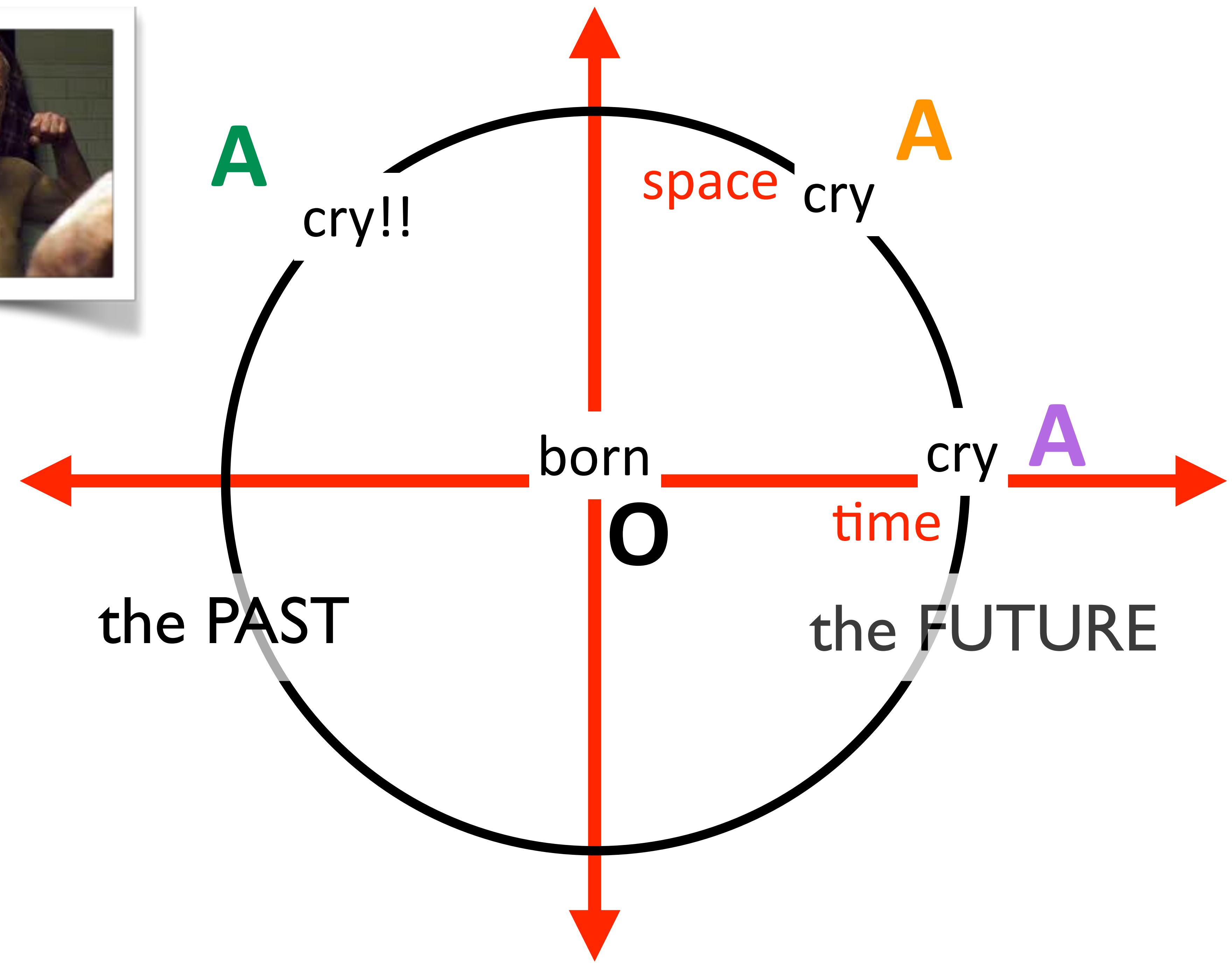
we're after

the invariant curve for spacetime

guess that it's a circle like "regular" geometry!

How about a hospital?

Now, OA are event intervals, not just space-lengths



<u>If</u> spacetime's invariant curve is a circle...then

- if A is the event in one frame,
- then A is another viewpoint from another frame

But...so is A okay in a third frame. Uh oh.

the invariant "length" in spacetime

"the interval," s

Remember:

The invariant curve for space is the equation of a circle:

$$L^2 = x^2 + y^2 = x'^2 + y'^2 = x''^2 + y''^2 = x'''^2 + y'''^2$$

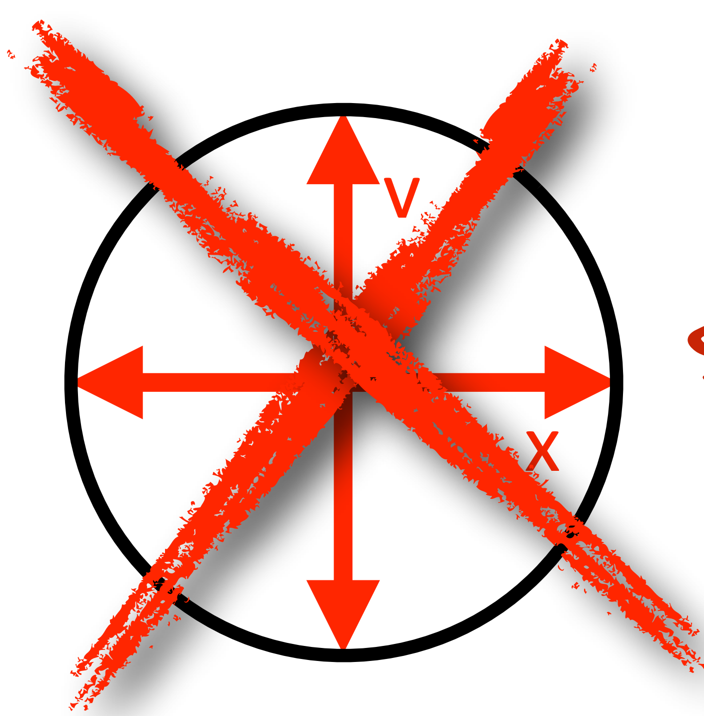
Minkowski's discovery was that the invariant curve for spacetime is

$$s^2 = c^2 t_H^2 - x_H^2$$

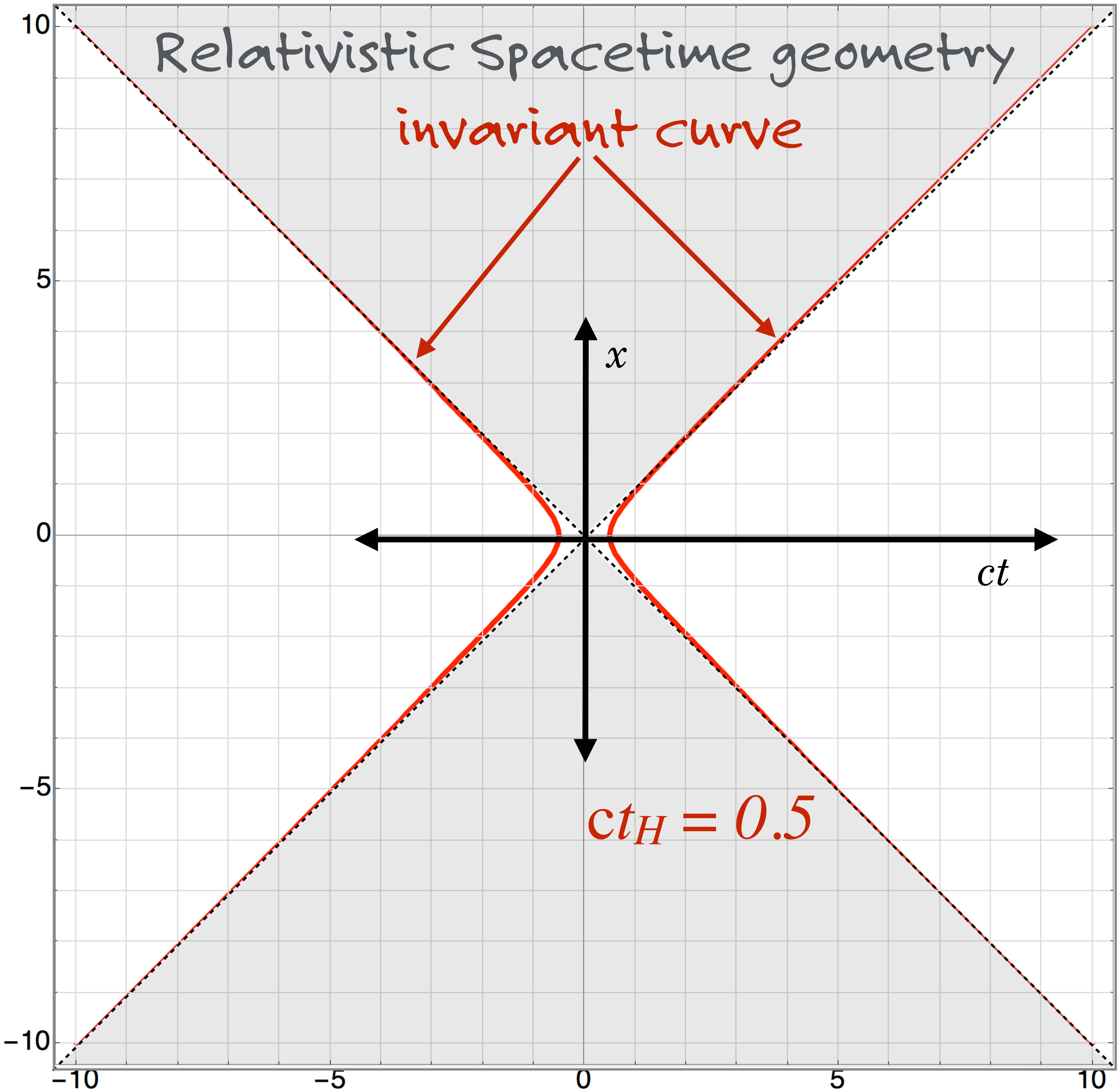
the equation of a hyperbola

This is the spacetime "length" that all inertial observers would agree on.

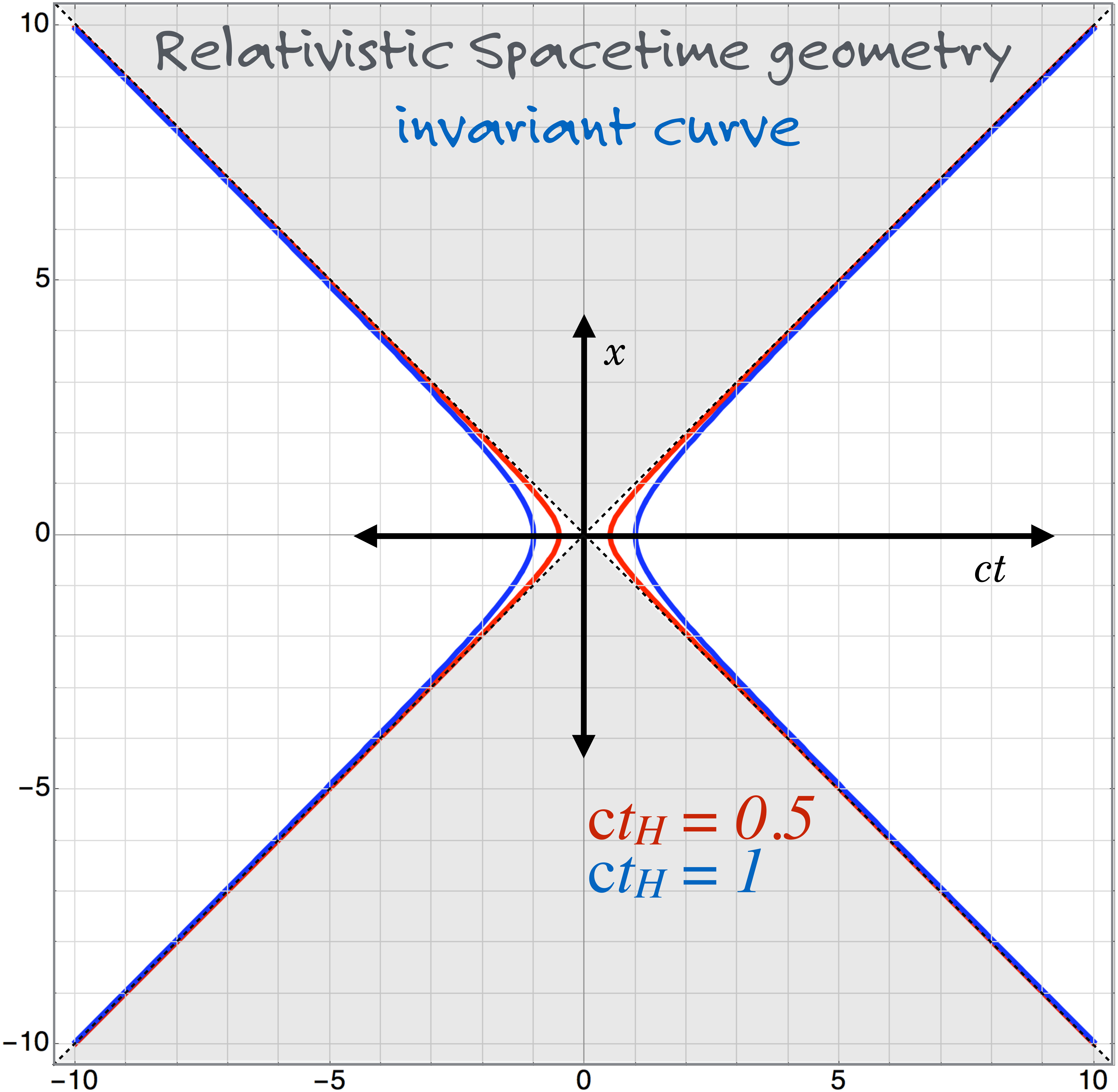
"s" is the "spacetime interval"

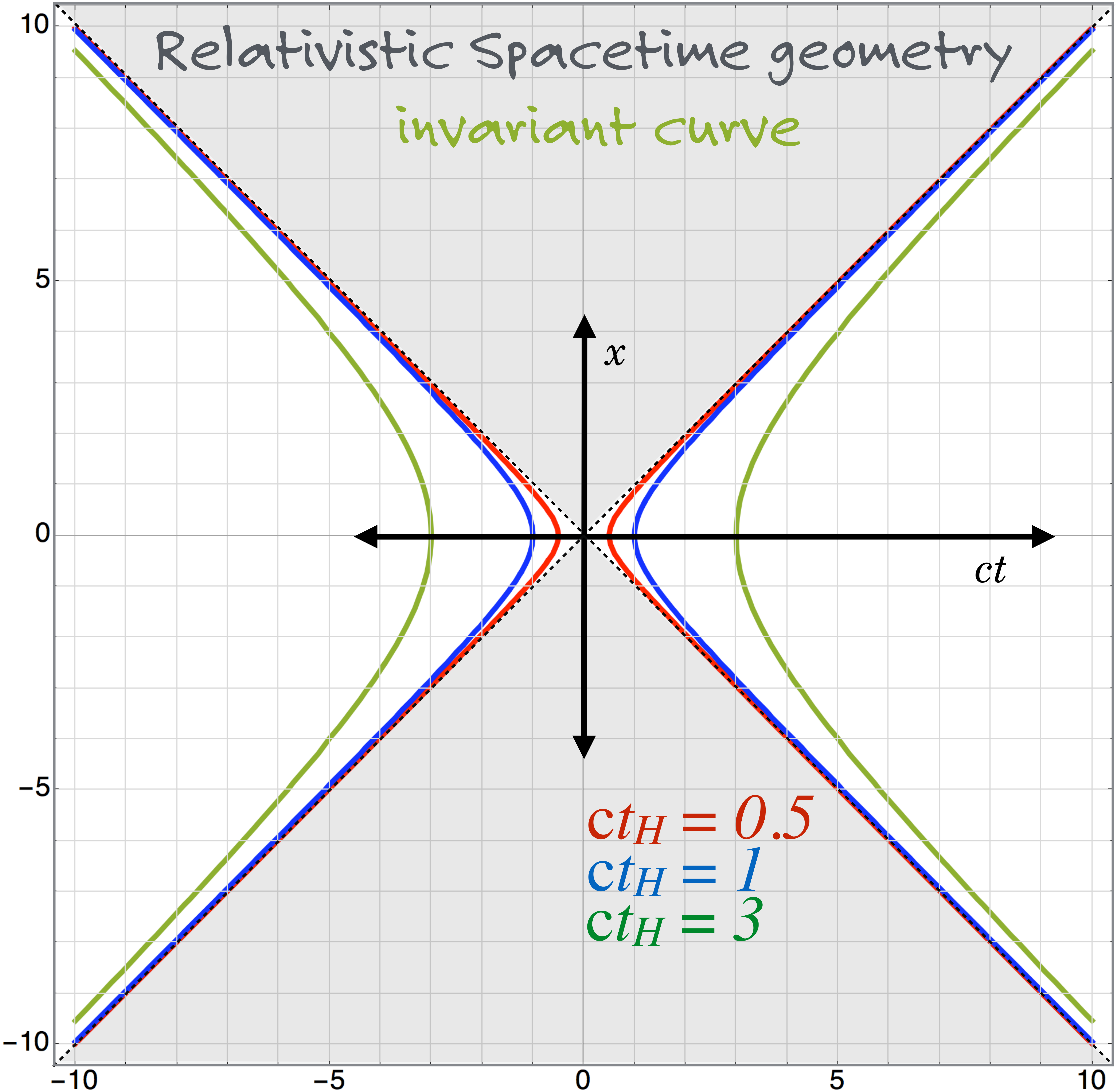


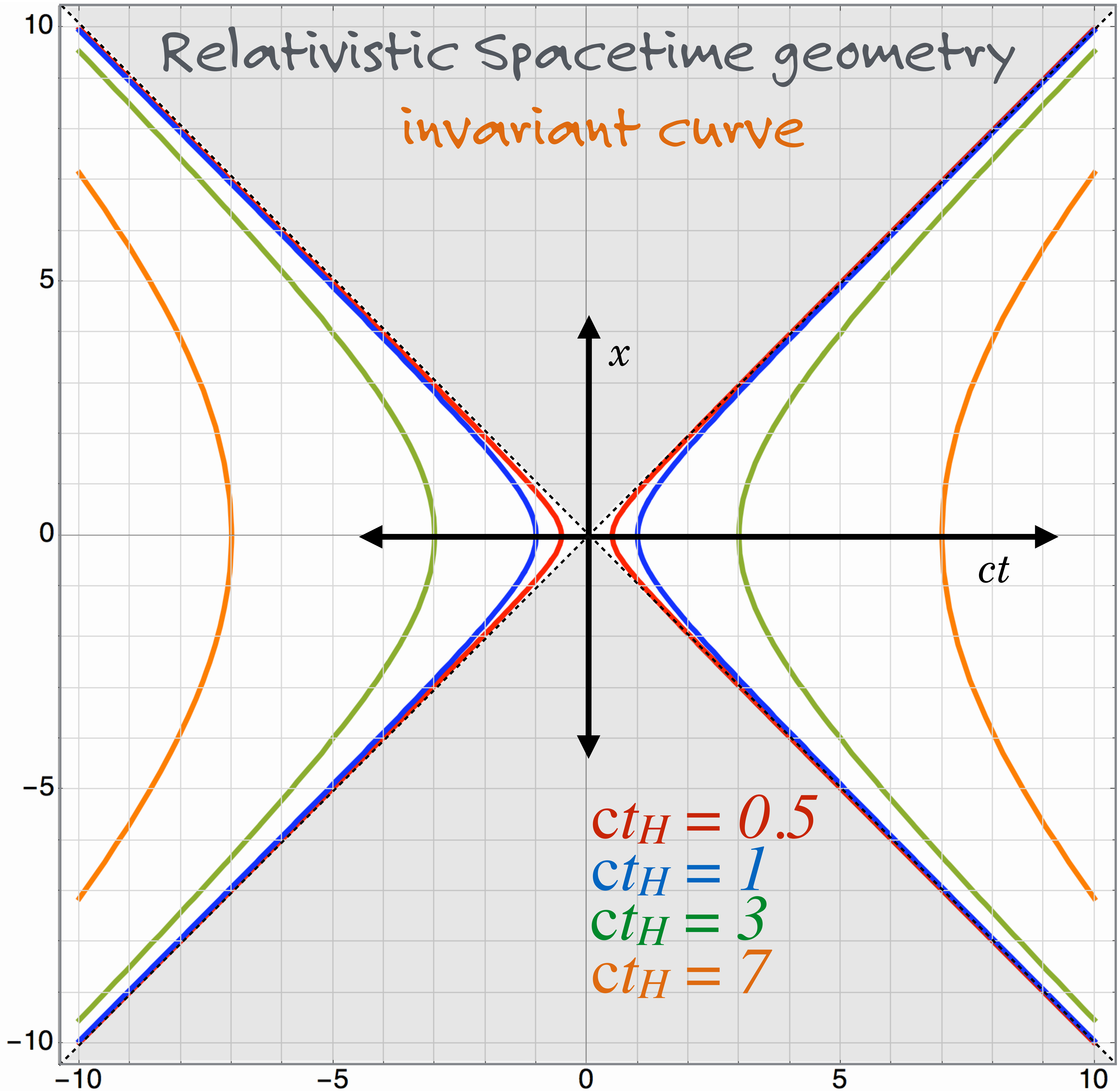
Spacetime is hyperbolic



Relativistic Spacetime geometry
invariant curve
x
ct
$ct_H = 0.5$
10
5
0
−5
−10
−10
−5
0
5
10

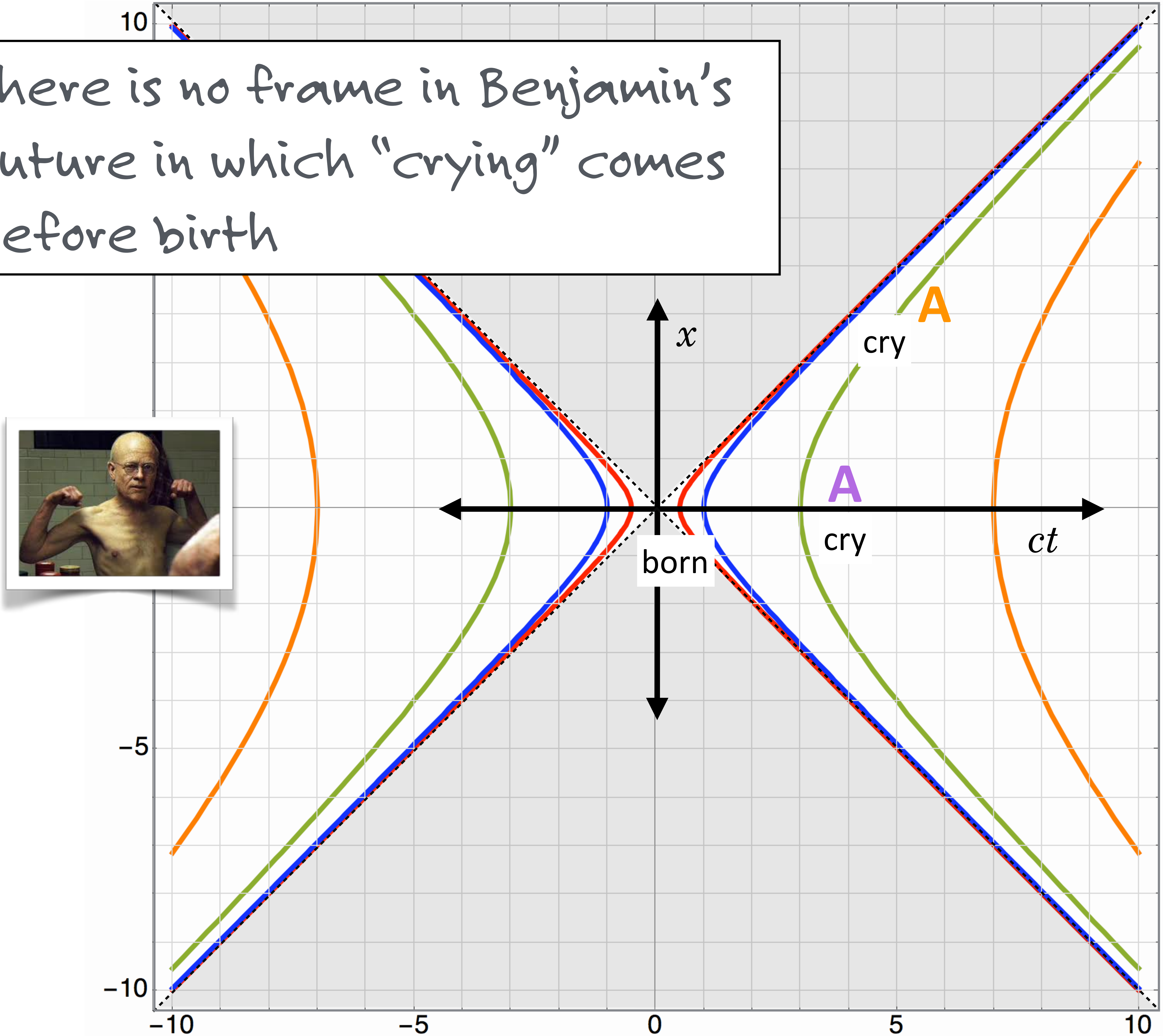

Relativistic Spacetime geometry
invariant curve
x
ct
$ct_H = 0.5$
$ct_H = 1$
10
5
0
−5
−10
−10
−5
0
5
10

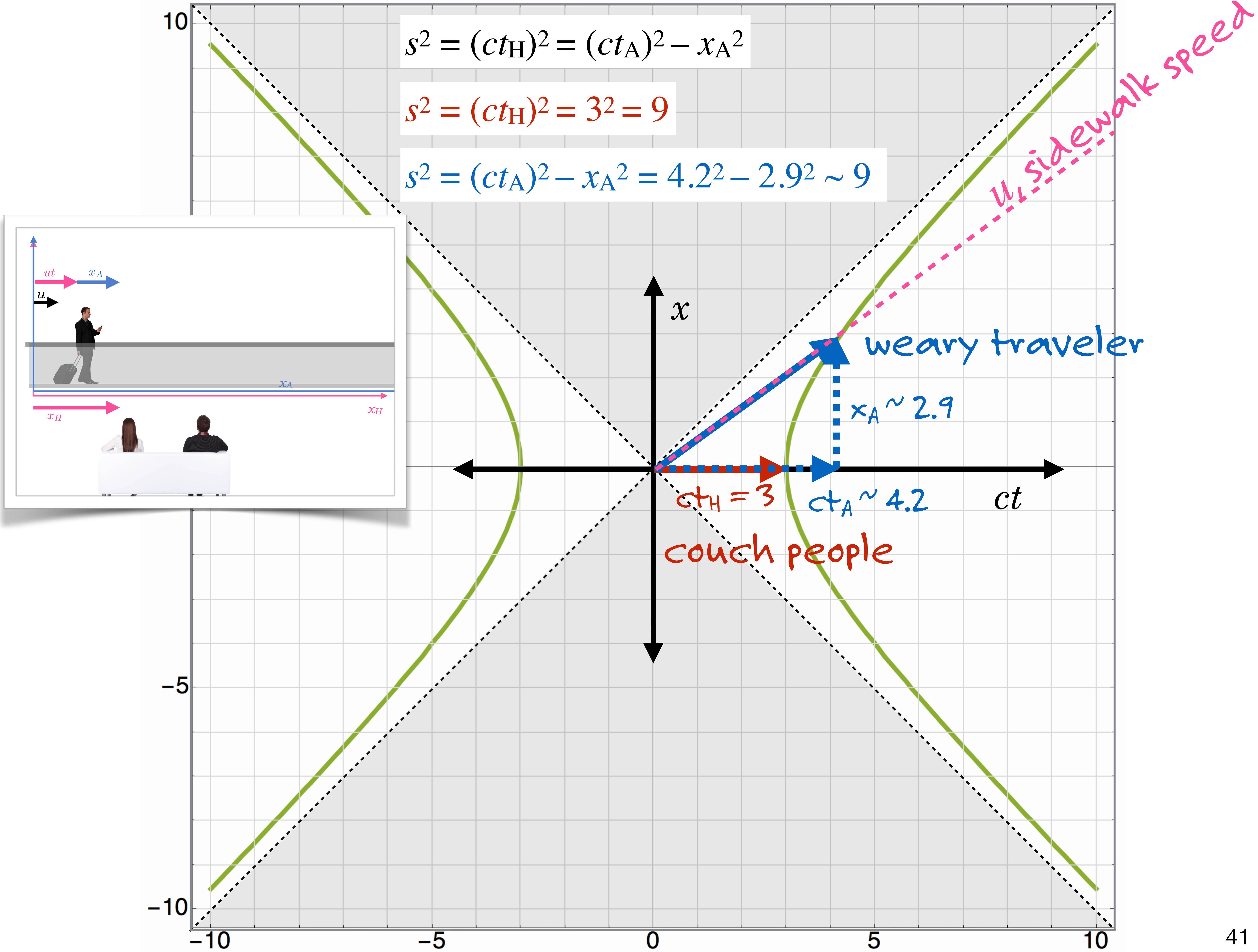

Relativistic Spacetime geometry
invariant curve
x
ct
10
5
0
−5
−10
−10
−5
0
5
10
$ct_H = 0.5$
$ct_H = 1$
$ct_H = 3$



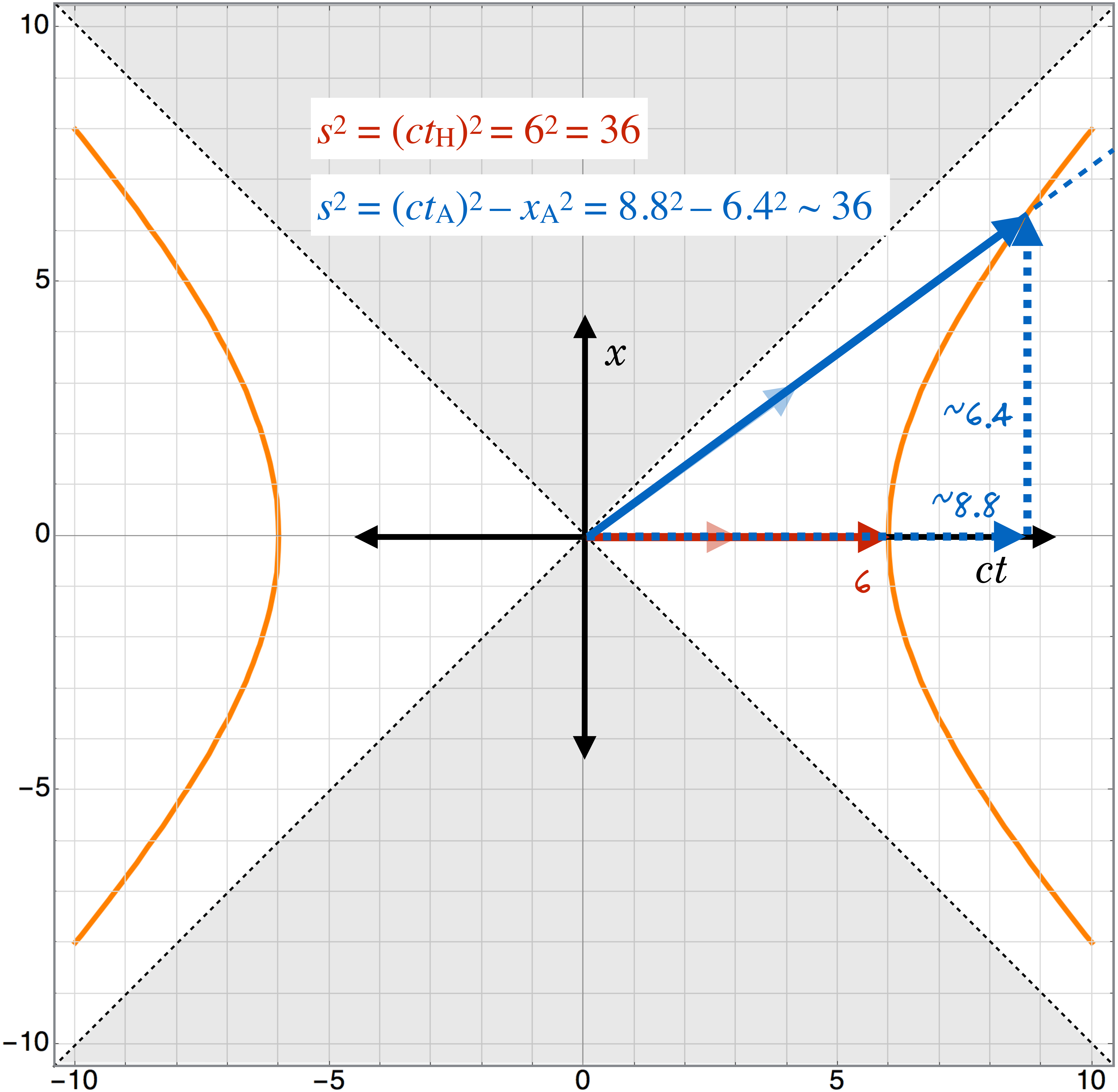
Relativistic Spacetime geometry
invariant curve
x
ct
$ct_H = 0.5$
$ct_H = 1$
$ct_H = 3$
$ct_H = 7$
10
5
0
−5
−10
−10
−5
0
5
10

there is no frame in Benjamin's future in which "crying" comes before birth





$s^2 = (ct_H)^2 = (ct_A)^2 - x_A^2$
$s^2 = (ct_H)^2 = 3^2 = 9$
$s^2 = (ct_A)^2 - x_A^2 = 4.2^2 - 2.9^2 \sim 9$
u, sidewalk speed
weary traveler
$x_A \sim 2.9$
$ct_H = 3$
$ct_A \sim 4.2$
couch people
x
ct
ut
x_A
u
x_H
10
−5
−10
−10
−5
0
5
10



s² = (ctH)² = 6² = 36
s² = (ctA)² − xA² = 8.8² − 6.4² ~ 36
x
ct
~6.4
~8.8
6
10
5
0
−5
−10
−10
−5
0
5
10

`causality is preserved`

in Minkowski spacetime

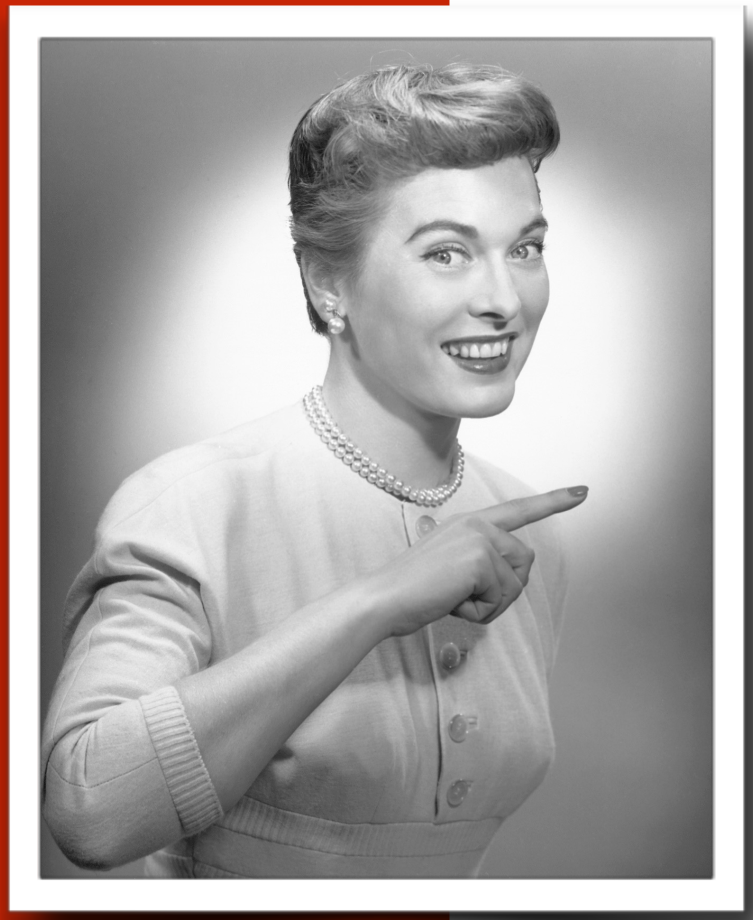
a useful invariant

$$E_m = mc^2$$

$$E_T = m\gamma c^2$$

$$p = m\gamma v$$

and an important formal linkage



fun fact...just with a little algebra...

$$m^2c^4 = E_m^2 = E_T^2 - p^2c^2$$

$$E_m^2 = E_T^2 - p^2c^2$$

another invariant...independent of the frame, just like:

$$s^2 = (ct)^2 - x^2$$

$$m^2c^4 = E_T^2 - p^2c^2$$

kinship:

t and E

x and p

three things are always, always constant

speed of light: c

spacetime interval: s

invariant mass: mc^2

Einstein preferred "Invariant Theory" to "Relativity"

Cousin Quantities!

- **Space and time** are not separate entities, but linked as spacetime
- **Electric and magnetic fields** are not separate entities, but linked as electromagnetism
- **Energy and momentum** are not separate entities, but linked as 4-momentum

so, how was this all received?

According to Einstein's sister,

...he anticipated a large reaction with much criticism

What he got at first was silence.

oh, a nice note from Max Planck asking for some clarification

then a seminar by Planck in Berlin which touched on Relativity...

- only then... a little professional attention, to "Prof. Einstein, University of Bern"

The first paper published on Relativity by not-Einstein:

also by Planck, who derived the relativistic momentum relation, $p = \gamma mv$

The 1908 Minkowski lecture, in which he worked out completely in modern form the mathematics of relativity and the spacetime view got people's attention

What about experiment?

so, how was this received?

According to E's sister: not well

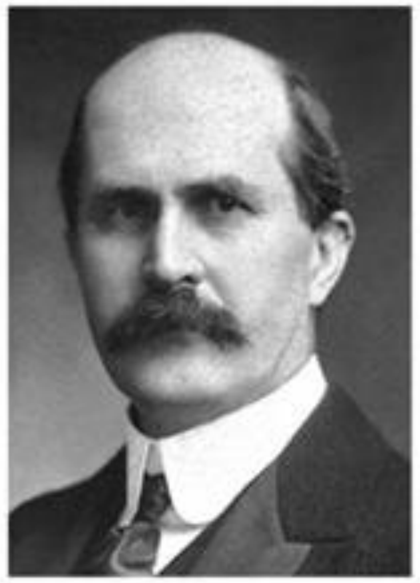
"Icy silence followed the publication"

Max Planck

editorial board member of Annalen der Physik

"immediately aroused my lively attention"

gave lecture at Berlin, published himself (1906), and began correspondence: ""Relativtheorie"



sent his assistant, Max Laue to visit in 1907

Laue published 8 papers on relativity himself in the next 4 years

Einstein was not Dr Einstein until 1905 at University of Zurich

promoted from 3rd class technical expert to 2nd class

not everyone liked Relativity

Antisemitism was in the fabric of European life

> “As remarkable as Einstein’s papers are…it still seems to me that something almost unhealthy lies in this unconstruable and impossible to visualize dogma. An Englishman would hardly have given us this theory. It might be here too, as in the case of Cohn, the abstract conceptual character of the Semite expresses itself.”
> Arnold Sommerfeld

incredibly proliforic

1906,07

- 17 papers published
- played in a string quartet weekly
- good father to 3 year old

commissioned to write a review

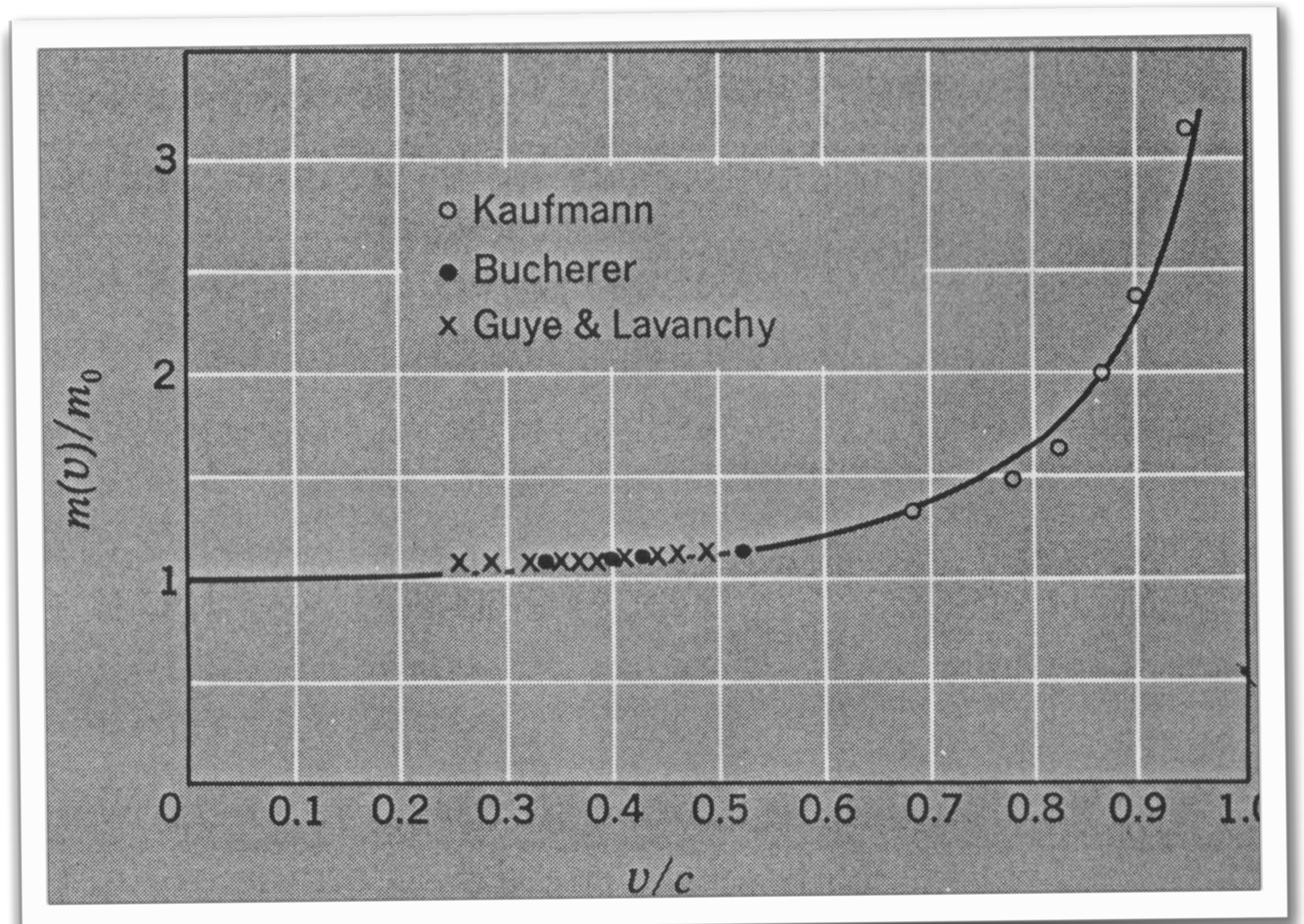
- had no library to do a literature search, "…closed during my free time."

Privatdozent position at Bern? A story ensues

the first experimental confirmation

New experiments were done,

and by 1910, the results were:



These results are from 1910 for three experiments, and the curve is the special relativity prediction

From this point on relativity has become a part of everyday scientific and engineering life

Kaufmann lost again...
Max Planck corrected his analysis