hi

today, 4 May

input:

the problems.

output:

final exam, experiment paper, course reviews

the modern families

back to "elementary"

$$\begin{pmatrix} u \\ d \\ s \end{pmatrix}$$ **"quarks"**

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix} \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}$$ **"leptons"**

γ **"Gauge Boson"**

1974: At Stanford and Brookhaven National Lab: new quark: "charm," c.

quarks $\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix}$

force propagators γ

leptons $\begin{pmatrix} \nu_e \\ e \end{pmatrix} \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}$

this lasted 1 years

1975: At Stanford new lepton: "tau," τ.

quarks $\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix}$

force propagators $\gamma,\ g$

leptons $\begin{pmatrix} \nu_e \\ e \end{pmatrix} \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix} \begin{pmatrix} \\ \tau \end{pmatrix}$

this lasted 0 years

1975: At Stanford new force carrier: "gluon," g.

quarks $\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix}$

force propagators $\gamma,\ g$

leptons $\begin{pmatrix} \nu_e \\ e \end{pmatrix} \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix} \begin{pmatrix} \\ \tau \end{pmatrix}$

this lasted 3 years

1978: At at Fermilab: new quark: "bottom," b.

quarks $\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} \\ b \end{pmatrix}$

force propagators $\gamma,\ g$

leptons $\begin{pmatrix} \nu_e \\ e \end{pmatrix} \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix} \begin{pmatrix} \\ \tau \end{pmatrix}$

this lasted 8 years

the modern quark families

back to "elementary"

1983: At CERN two new force carriers: W and Z bosons - precisely predicted

$$\text{quarks} \quad \begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} \\ b \end{pmatrix}$$

$$\text{force propagators } \gamma,\ g,\ W,\ Z$$

$$\text{leptons} \quad \begin{pmatrix} \nu_e \\ e \end{pmatrix} \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix} \begin{pmatrix} \\ \tau \end{pmatrix}$$

this lasted 11 years

1994: At at Fermilab: new quark: "top," t.

$$\text{quarks} \quad \begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix}$$

$$\text{force propagators } \gamma,\ g,\ W,\ Z$$

$$\text{leptons} \quad \begin{pmatrix} \nu_e \\ e \end{pmatrix} \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix} \begin{pmatrix} \\ \tau \end{pmatrix}$$

this lasted 6 years

2000: At Fermilab, finally the ν_τ lepton was found

$$\text{quarks} \quad \begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix}$$

$$\text{force propagators } \gamma,\ g,\ W,\ Z$$

$$\text{leptons} \quad \begin{pmatrix} \nu_e \\ e \end{pmatrix} \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix} \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}$$

Mmmm, Mmmm Good....

so, keep the magnet in mind

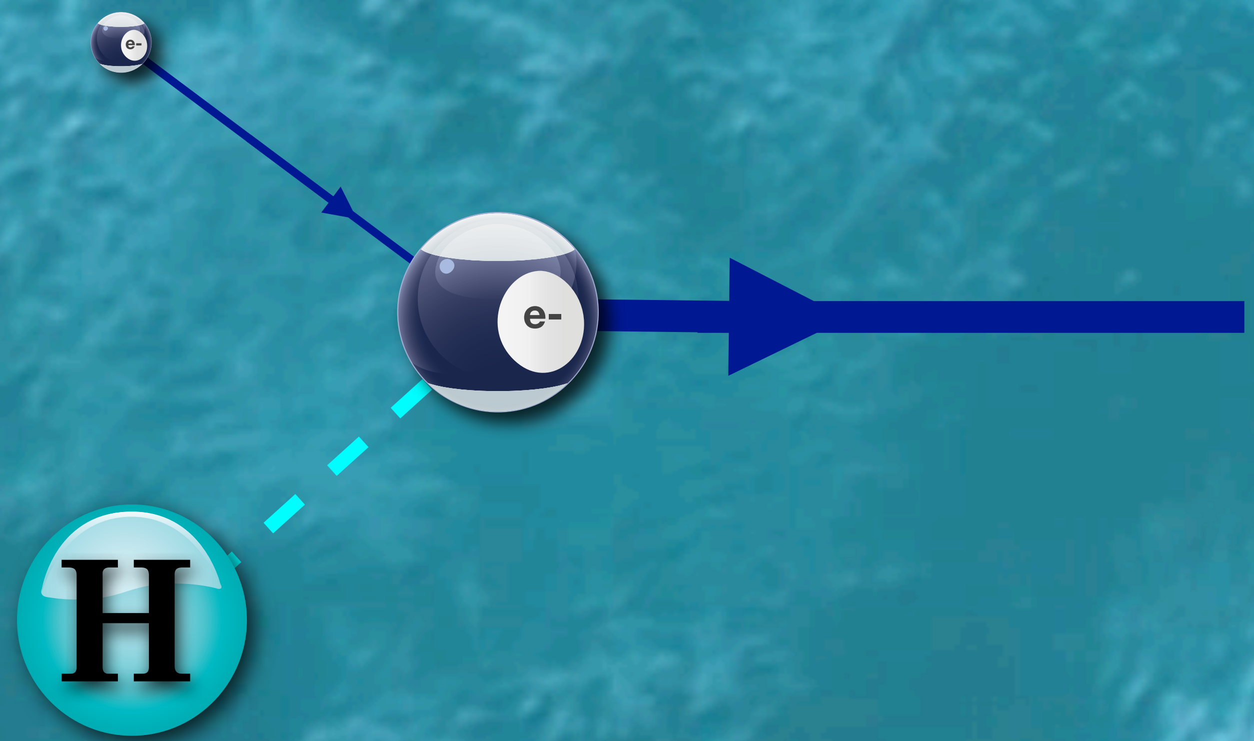
lower the temperature, create:

a phase transition

a lowered ground state energy

a spin zero, coherent excitation quantum state


Standard
Model



Higgs Boson

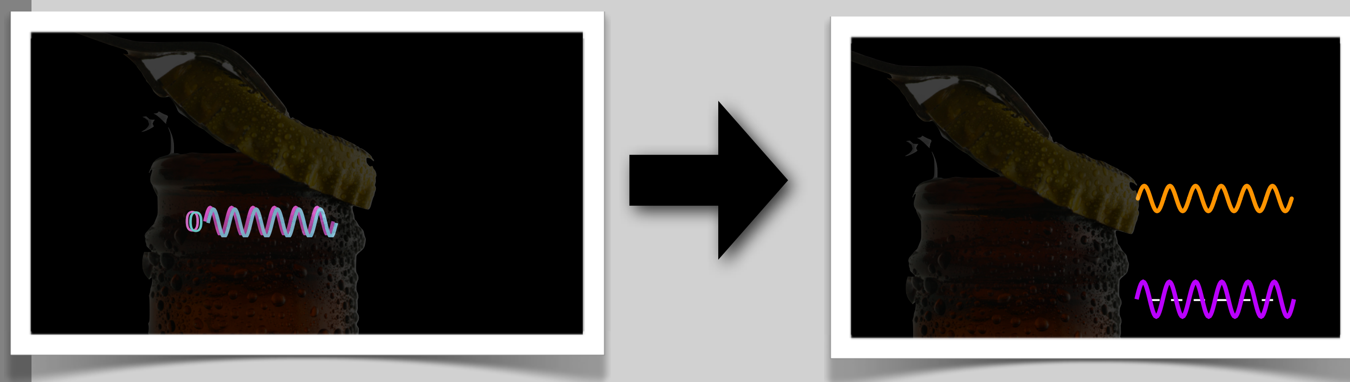
so, there were definite predictions of Weinberg's model

1. The *W* Boson should exist

2. The *Z* Boson should exist

Many physics reactions relate M_W to M_Z

3. The *Z* Boson and the γ are intimately related



4. The Higgs Boson should exist

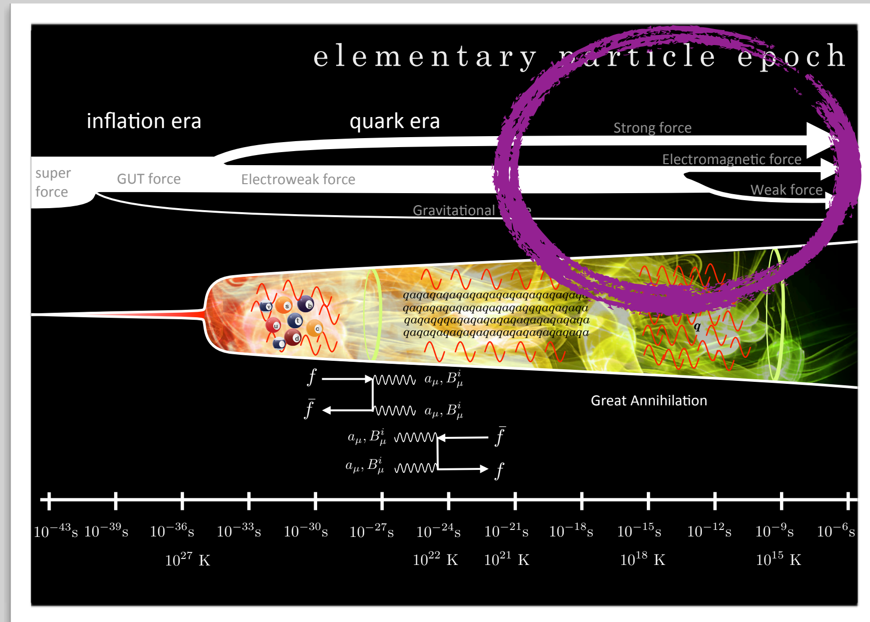
particle: **# *W* Boson**

symbol:	*W*
charge:	±1*e*
mass:	80.399 ± 0.023 GeV/c^2 = 80.4 p
spin:	1
category:	weak Vector Boson

particle: **_Z_ Boson**

symbol:	Z
charge:	0
mass:	91.1876 ± 0.0021 GeV/c^2 = 91.2 p
spin:	1
category:	weak Vector Boson

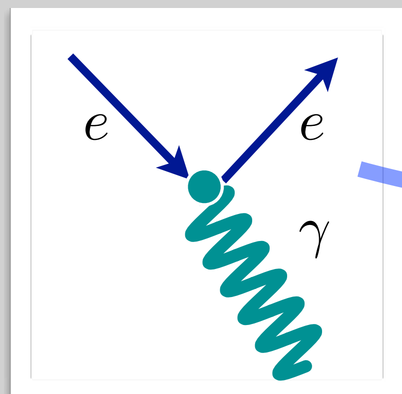
yup. unify

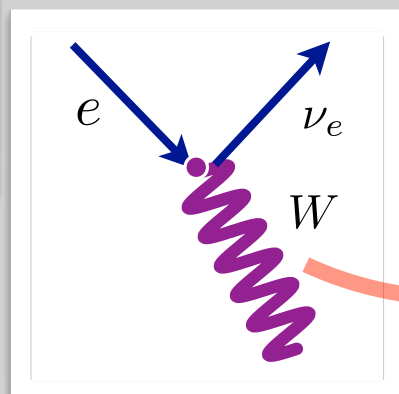


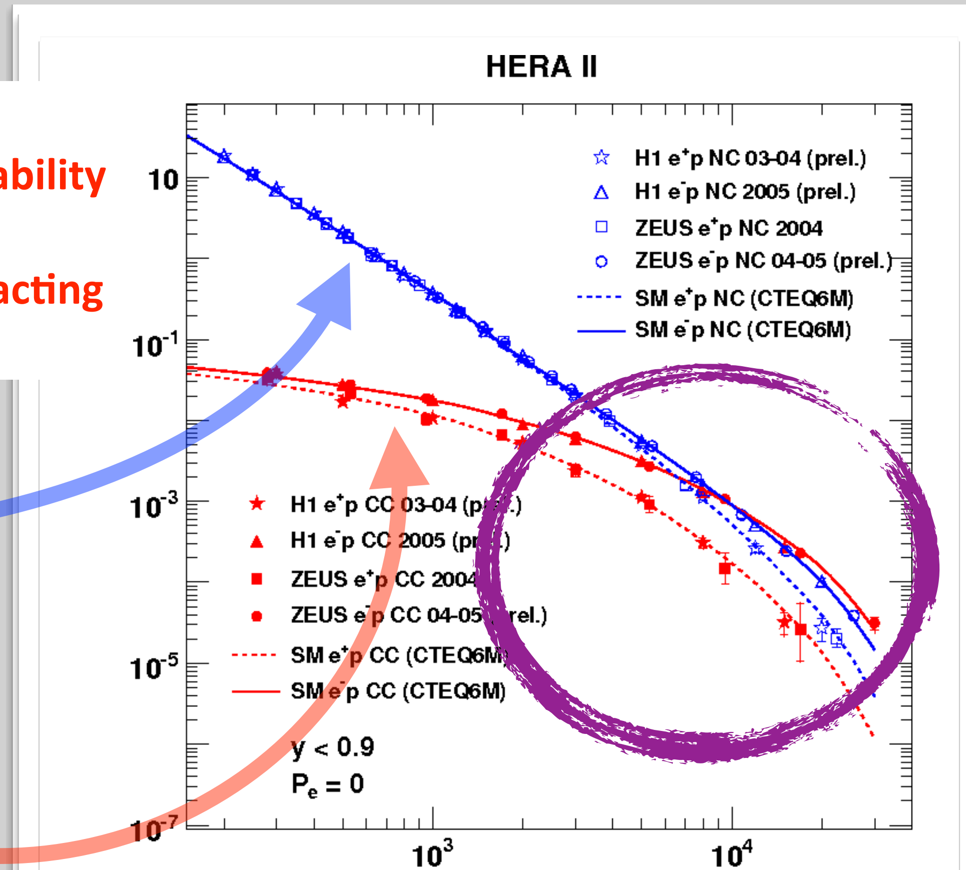
the higher the energies of the Messengers

the closer in strength the electromagnetic and weak interactions become

probability of interacting







Energy of photon or W

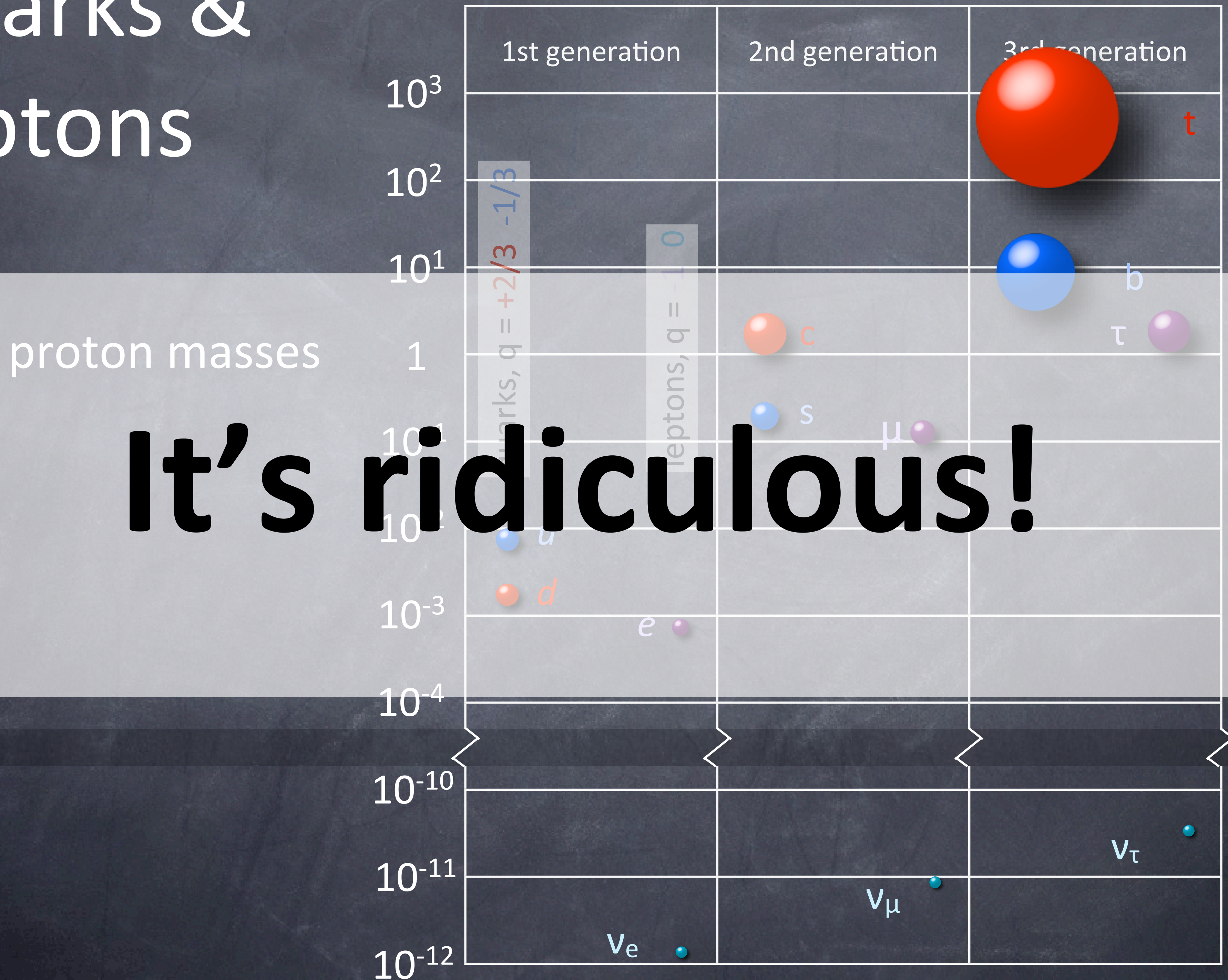
particle: **bottom quark**

symbol:	*b*
charge:	-1/3 e
mass:	4.5 GeV/c^2 = 4.5 p
spin:	1/2
category:	Fermion, quark

particle: **top quark**

symbol:	*t*
charge:	+2/3 e
mass:	172.0±2.2 GeV/c^2 = 172 p
spin:	1/2
category:	Fermion, quark

quarks & leptons

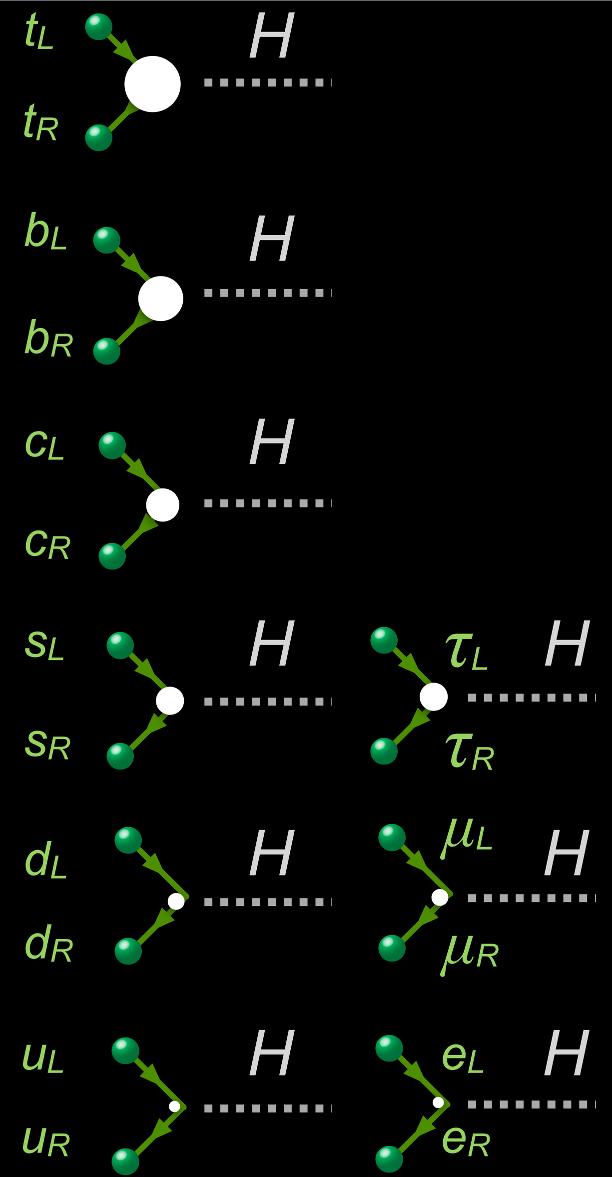


It's ridiculous!

this particle is strange

quantum numbers of the vacuum

distinguishes top, from bottom, from charm, from strange, etc.



a Higgs boson would be a chip of the vacuum.

So:

The Higgs Boson is not just another particle.

there are embarrassments, incl.

the Higgs blows up

95% of the universe is missing

we’re off by 10^{120} in energy of vacuum

otherwise, things are great


problem #1

Where is the Higgs Boson?

the Higgs Boson has to exist

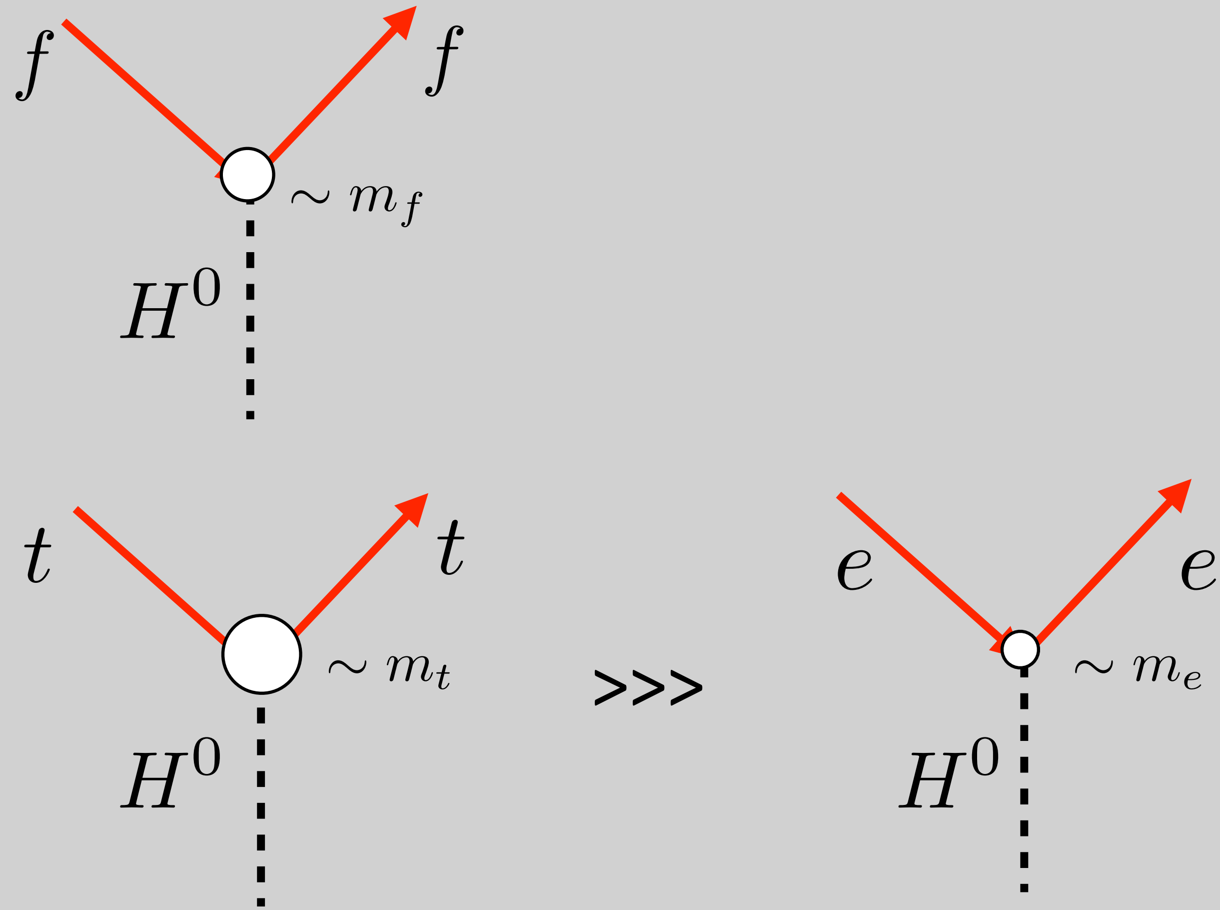
1. if we find it, that's great!

SM is a "part of the truth"

2. if we don't find it, that's great!

some seriously interesting new physics

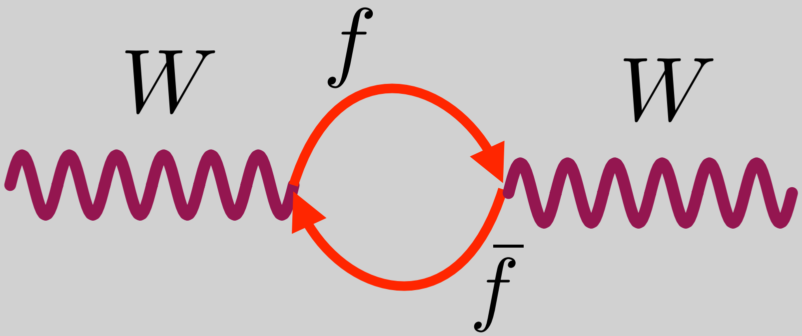
Remember, the Higgs Boson couples to the mass of Fermions



So, look for Higgs to decay into the heaviest thing it can!

loops help to pin it down

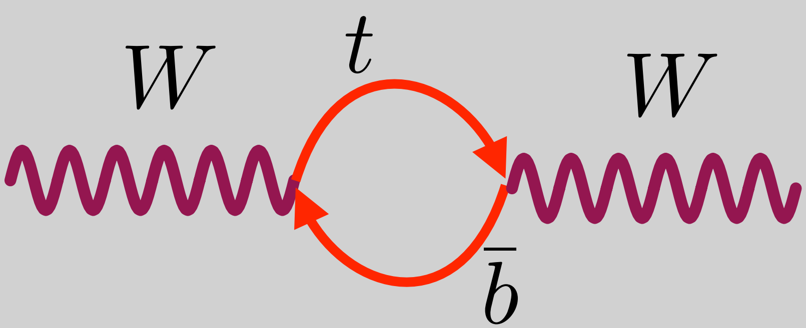
remember the loops for messengers and fermions



The W actually spends part of it's time as a fermion-antifermion pair

That affects its mass.

So...sometimes:

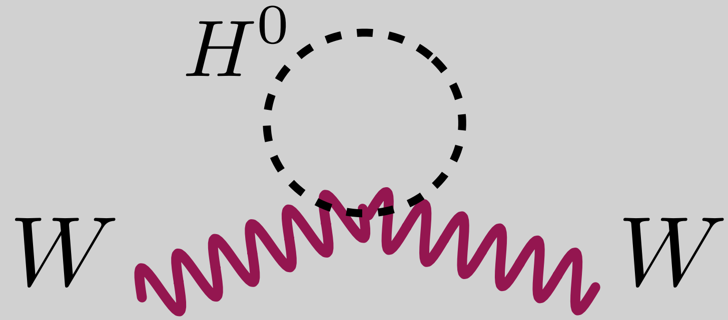


Rules of relativistic quantum field theory say that

M_W depends on the value of m_t

there are Higgs Boson loops also

another loop for the W and now Higgs:



Rules of relativistic quantum field theory say that

M_W depends on the value of M_H

calculate the effects

of the loops on the masses of:

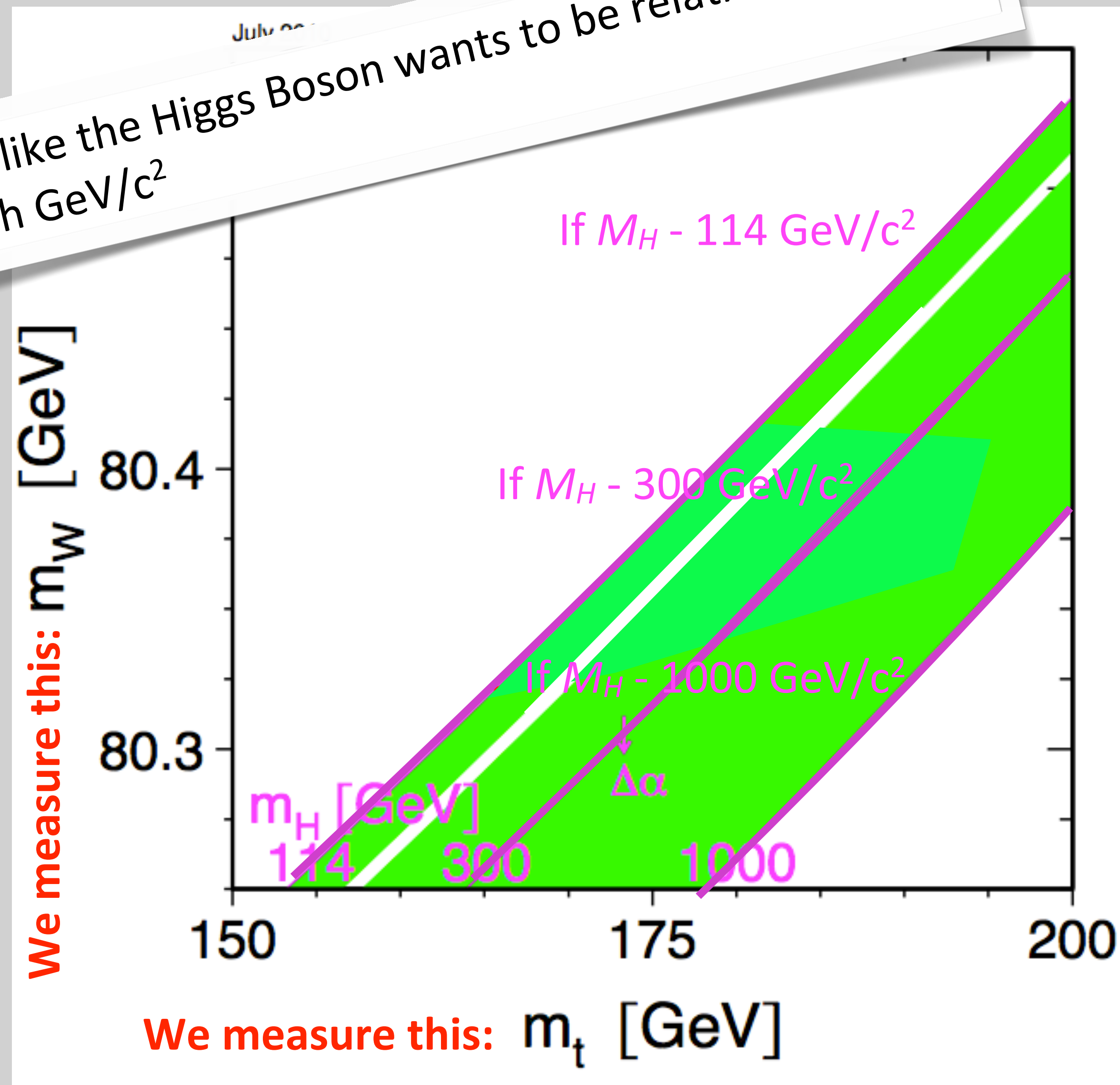
W boson

top quark

as a function of the mass of Higgs Boson

Predict the Higgs Boson Mass:

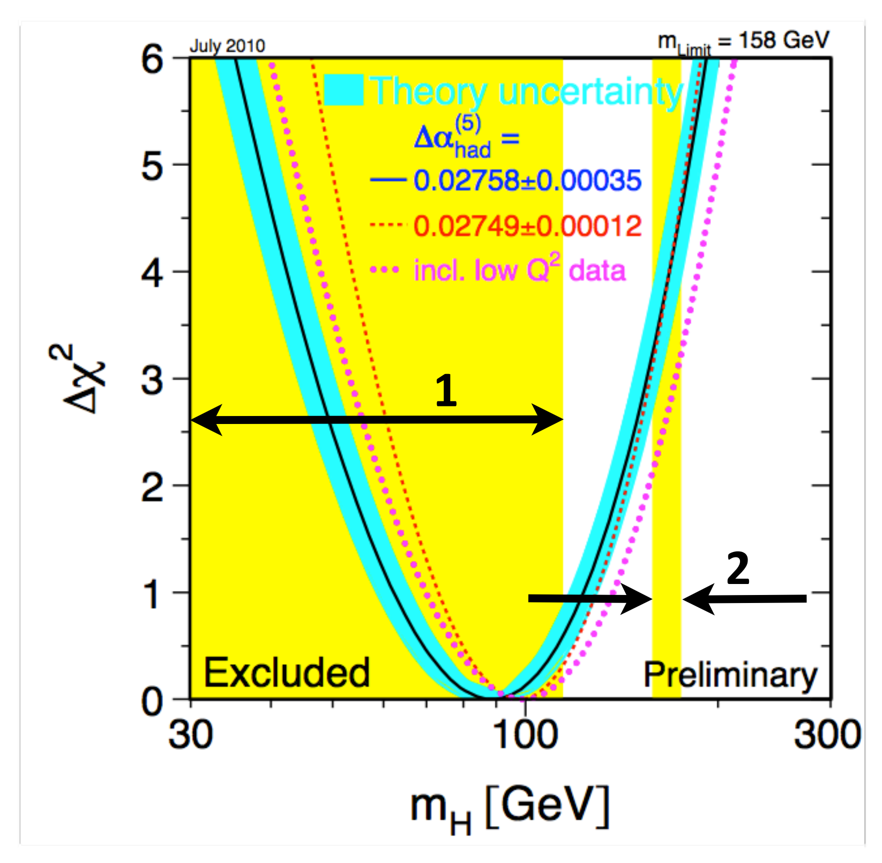
It looks like the Higgs Boson wants to be relatively light ~ 100ish GeV/c^2



but it’s not!

that’s why we’re excited

Predict the Higgs Boson Mass:



Higgs Boson mass:
should be something like 100-120ish GeV/c^2

But, our direct searches for it mean that it’s not:

in region 1 nor in region 2.

so, the Higgs Boson

is starting to be nearly missing-in-action

it will be found within 2 years at either Fermilab or LHC

period.

or not.

problem #2

infinities: The Standard Model is sick.

win-win?

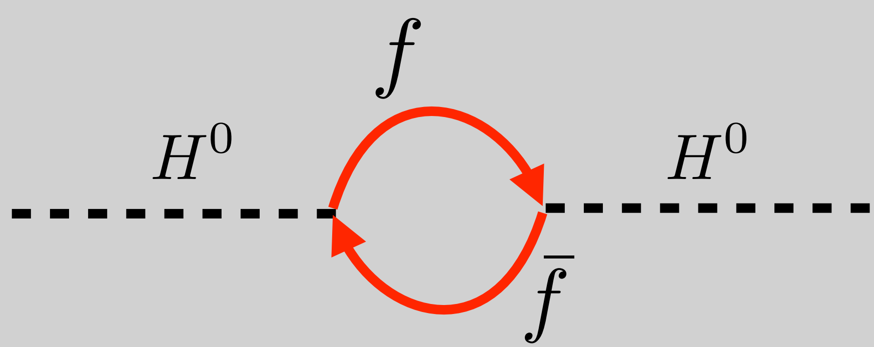
or lose-lose?

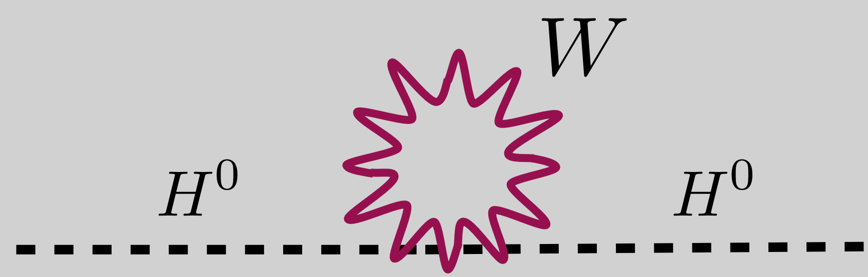
Suppose it is found...

that's great!

But, now our troubles really begin.

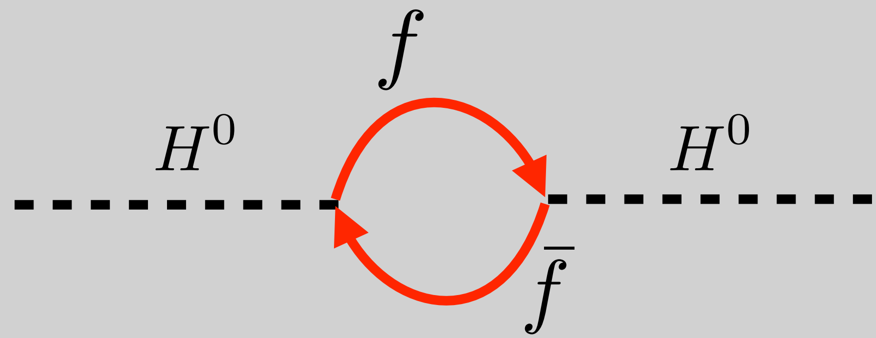
loops again.





here’s how loops work

the calculations require that you add up all possible energies of the particle in the loop



$$M_H + \delta M_H$$

loop calculation contributions

that could be big!

$$E(\text{loop}) \sim \sum_{E=0}^{E=\text{maximum amount}} (\text{energies of } f - \bar{f})$$

what is the highest energy conceivable?

gotta mix gravity with quantum mechanics.

Take the most violent gravitational bound:

the Schwarzchild radius

Take the most violent quantum mechanical bound:

the Compton wavelength

Relate them!

This would be the about the distance at which gravity needs to become quantum mechanical.

Said another way:

any length smaller and there is no theory that will work. None until there is a quantum mechanics of General Relativity.

$$R_S = \frac{2Gm}{c^2} \longleftrightarrow \lambda_C = \frac{h}{mc}$$

$$\frac{2Gm}{c^2} = \frac{h}{mc}$$

there are limits

fundamental.

limits.

to our theories

Called the "Planck Mass"...has all of the fundamental constants of our theories:

h: quantum mechanics

c: special relativity

G: gravity

$$M_P \sim 10^{19}\ \mathrm{GeV/c^2} \longrightarrow E_P \sim 10^{19}\mathrm{GeV}$$

an aside

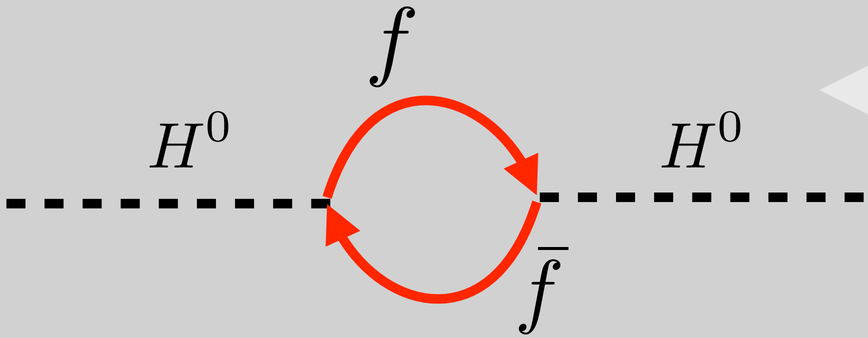
this corresponds to the shortest length possible

$$\ell_P = \sqrt{\frac{2hG}{c^3}}$$

The Planck Length...we cannot know anything smaller than that with current theories.

$$\ell_P \sim 10^{-35} \text{ m}$$

the Planck scale



$E_P \sim 10^{19}\text{GeV}$

not infinite...but enormous

$M_H + \delta M_H$

$$E(\text{loop}) \sim \sum_{E=0}^{E=\text{maximum amount}} (\text{energies of } f - \bar{f})$$

same thing as
...but contributes with opposite sign

could cancel! but more fermions than bosons

$$M_H + \delta M_H \sim M_H + E_{(\text{all fermions})} - E_{(\text{all bosons})}$$

desperately seeking SUSY

there's a theoretical dream

which may turn out to be true!

A new spacetime symmetry was theoretically "discovered" in the 1970's

"Supersymmetry"... "SUSY" – spin is the key parameter.

SUSY:

all fermions → a boson partner

all bosons → a fermion partner

So: # fermions = # bosons

$$\sim M_H + \overbrace{E_{(\text{all fermions})} - E_{(\text{all bosons})}}^{\text{would cancel!}}$$

well motivated

supersymmetry must be "broken" at our epoch

since we don't see any supersymmetric particles

YET

Whole new set of particles to study:

(add an "s" to get their names...)

known fermion

electron
quark
top

SUSY

IF TRUE:

leads to a whole new set of particles to be found

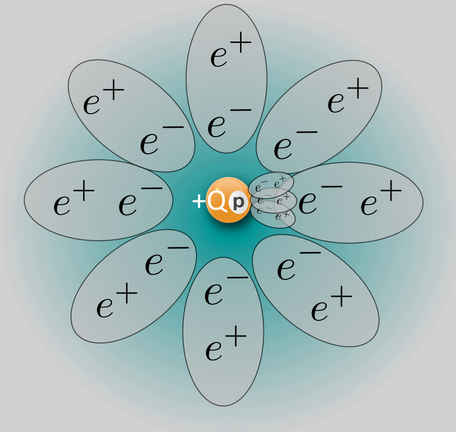
SUSY is a broken symmetry,

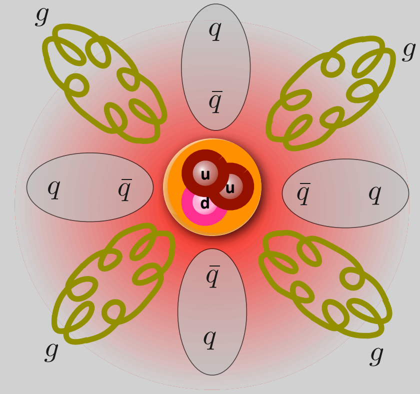
so the masses of sparticles must be higher than particles

Object of intense study by all experiments

SUSY offers a solution

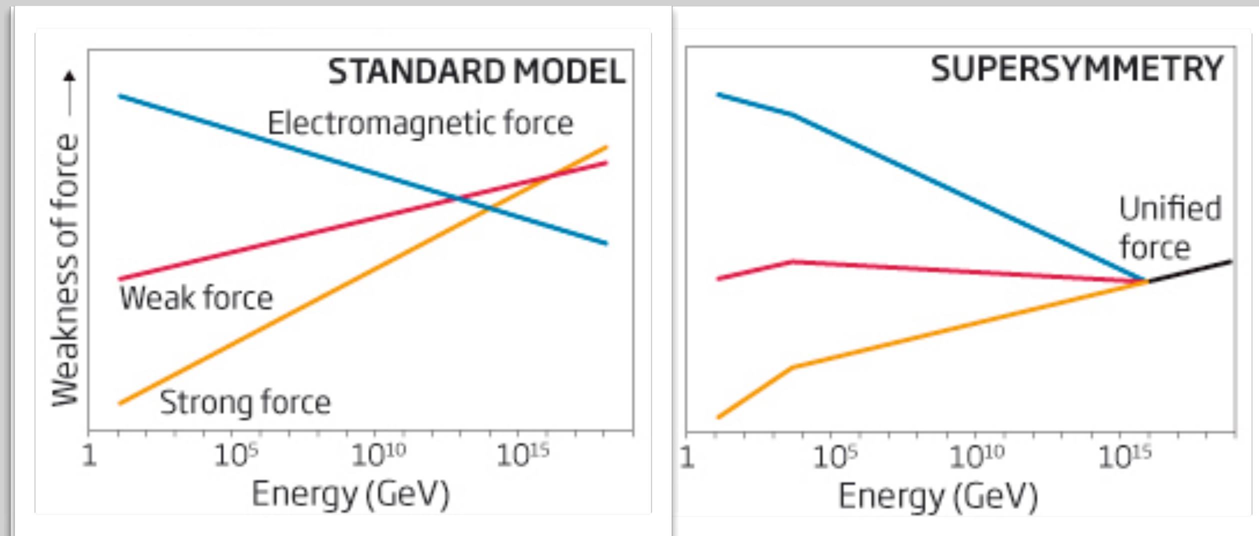
to unification of forces





electromagnetic force changes as we probe deeper

force changes as we probe deeper...the opposite way!



taken very seriously, otherwise the SM has serious problems

it's sick and in need of a theoretical and experimental cure

is it SUSY?

we don't know...but we're searching

If Higgs Boson is composite - made of other things...that helps

we don't know...but we're searching

problem #3

where is the antimatter?

a number:

1/2

the antimatter is missing.

either:

the universe created with only matter

or:

the antimatter disappeared

a number:

1 out of 10,000,000,000

to match what we see:

proportional excess of matter over antimatter

I mean, what are the odds?

this is what we observe

why? Dunno.

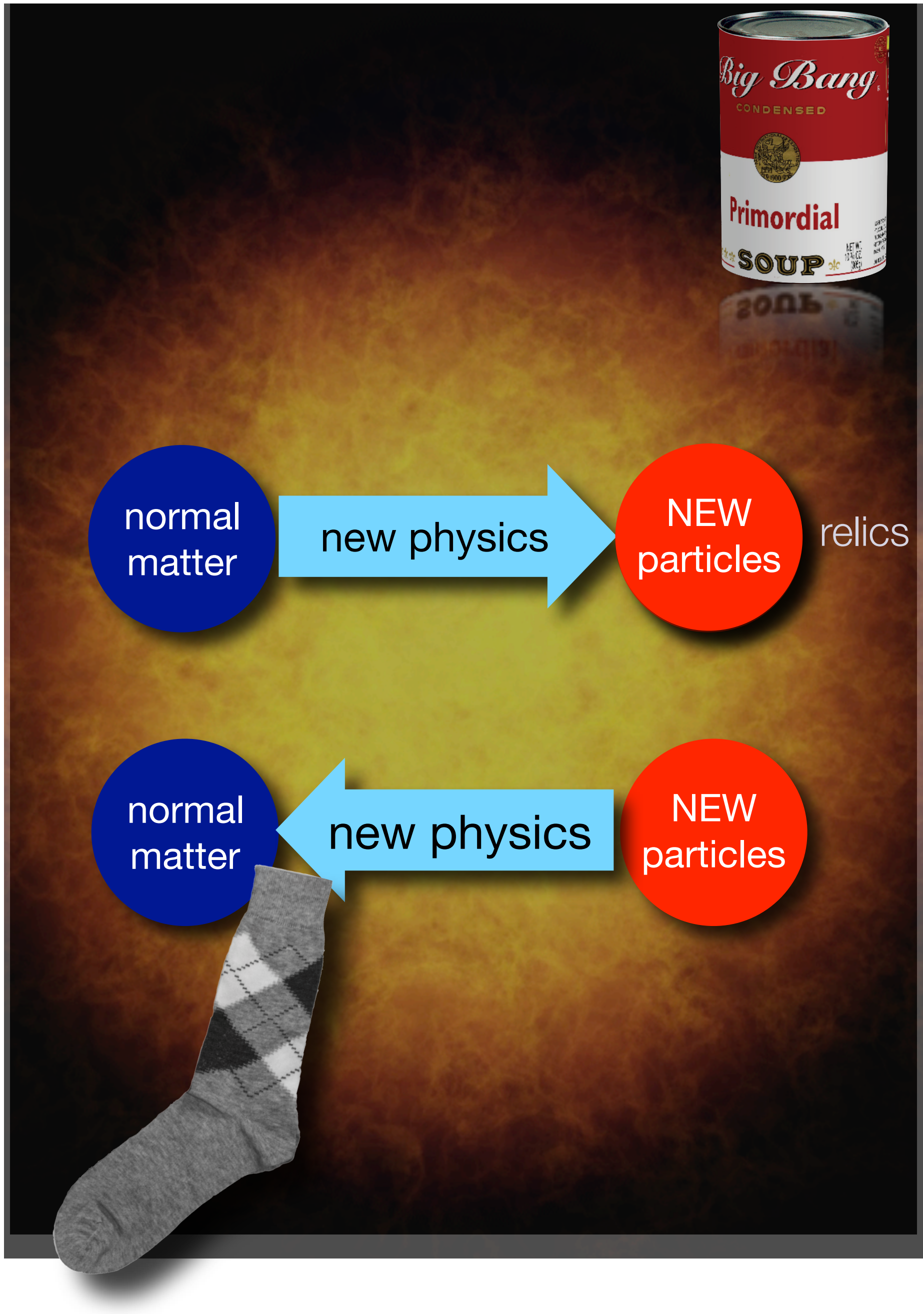
best explanation?

new particles that behave asymmetrically?

theories abound

theories are cheap.

testing them is not!



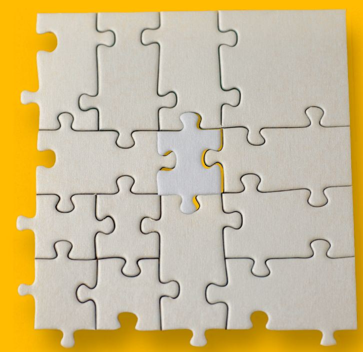
ideas for particles that:

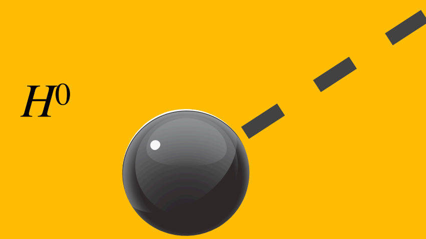
fix the Standard Model

require the Higgs Boson

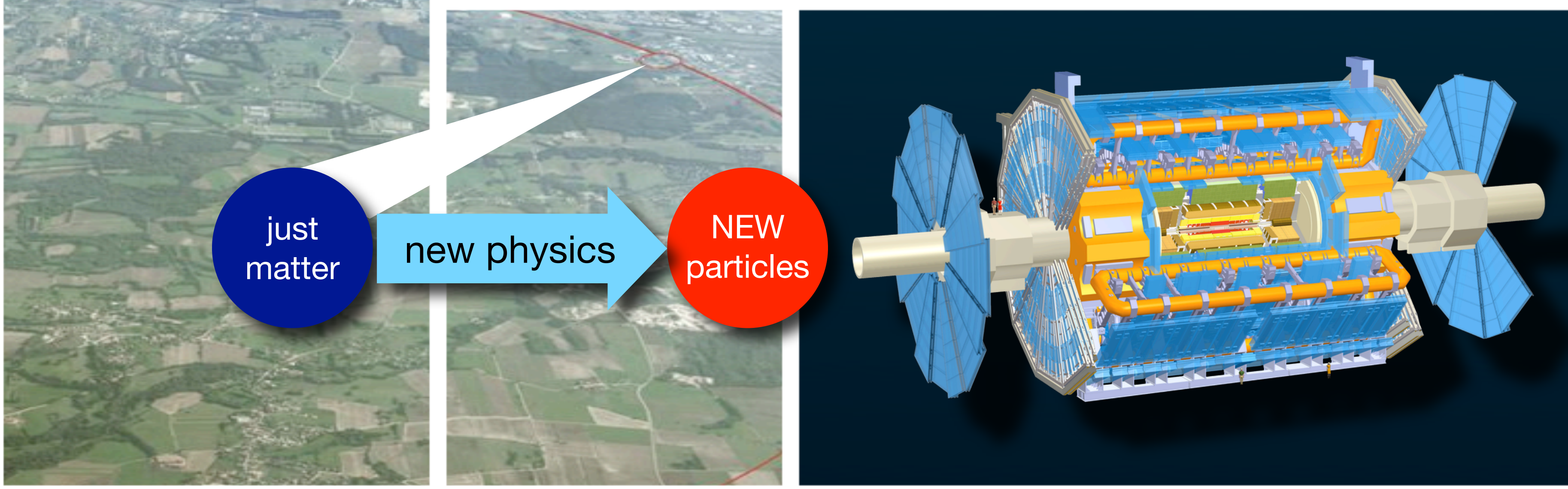
fix the antimatter problem

- **account for “dark matter**
- **unify the 4 forces of nature**
- **lead to extra dimensions**





Remember? We’re in the particle business



problem #4

what is dark matter?

There are two kinds of solutions

astrophysical

particles

Astrophysical solutions involve:

neutron stars	universe is too young to enough
black holes	universe is too young to enough
black dwarf stars	universe is too young to enough
brown dwarf stars	not seen near us
planets	not seen near us
rocks	not seen near us

particle physics solutions involve:

massive neutrinos	no evidence - mass is tiny
WIMPs	no evidence yet
cosmic strings	zero evidence, nor idea of how to find
some different GR	huh?

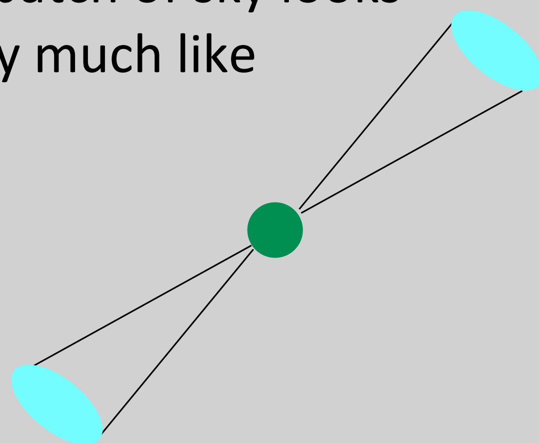
problem #5

the flatness problem. the horizon problem.

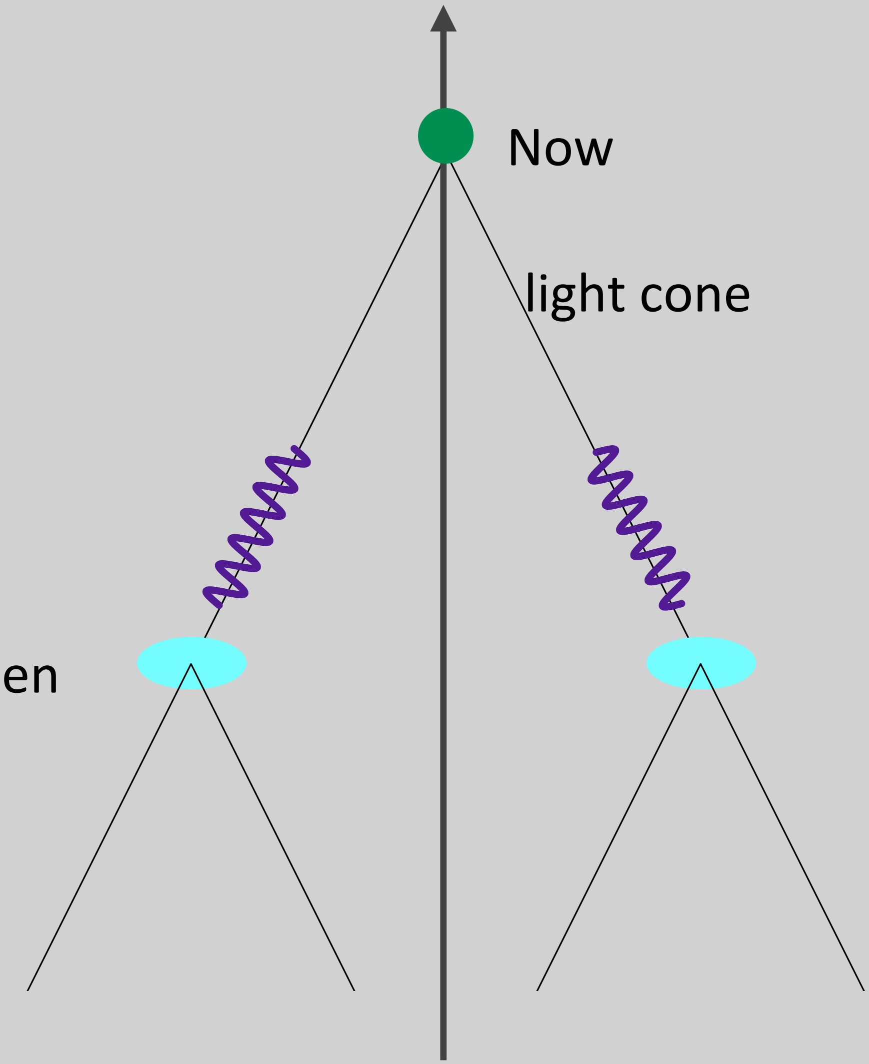
but wait...how come

the sky looks uniform? (“isotropic”)

that patch of sky looks
pretty much like



that
patch

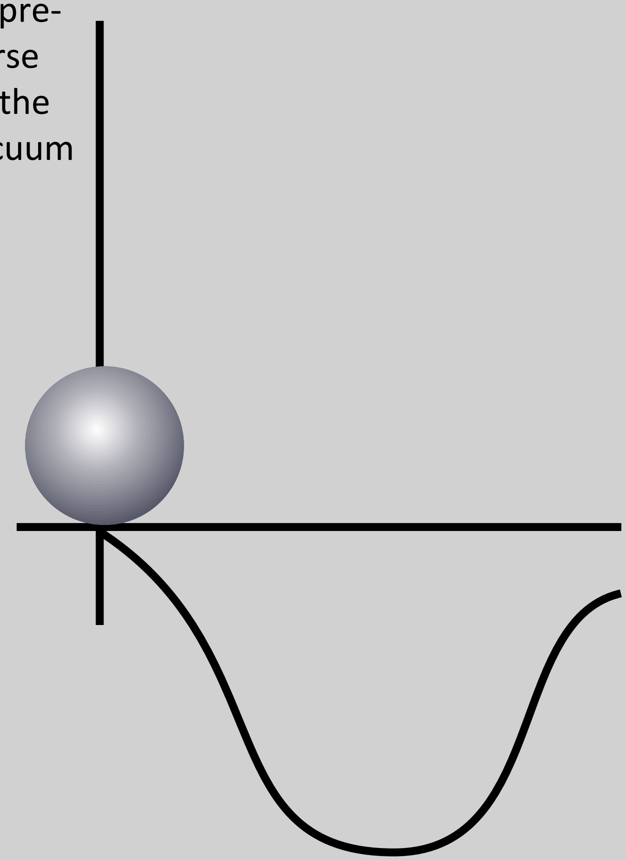


then

they would not have known
about one another...neither
would be in the other’s Past

another phase transition

the mother of all phase transitions



hypothetical!

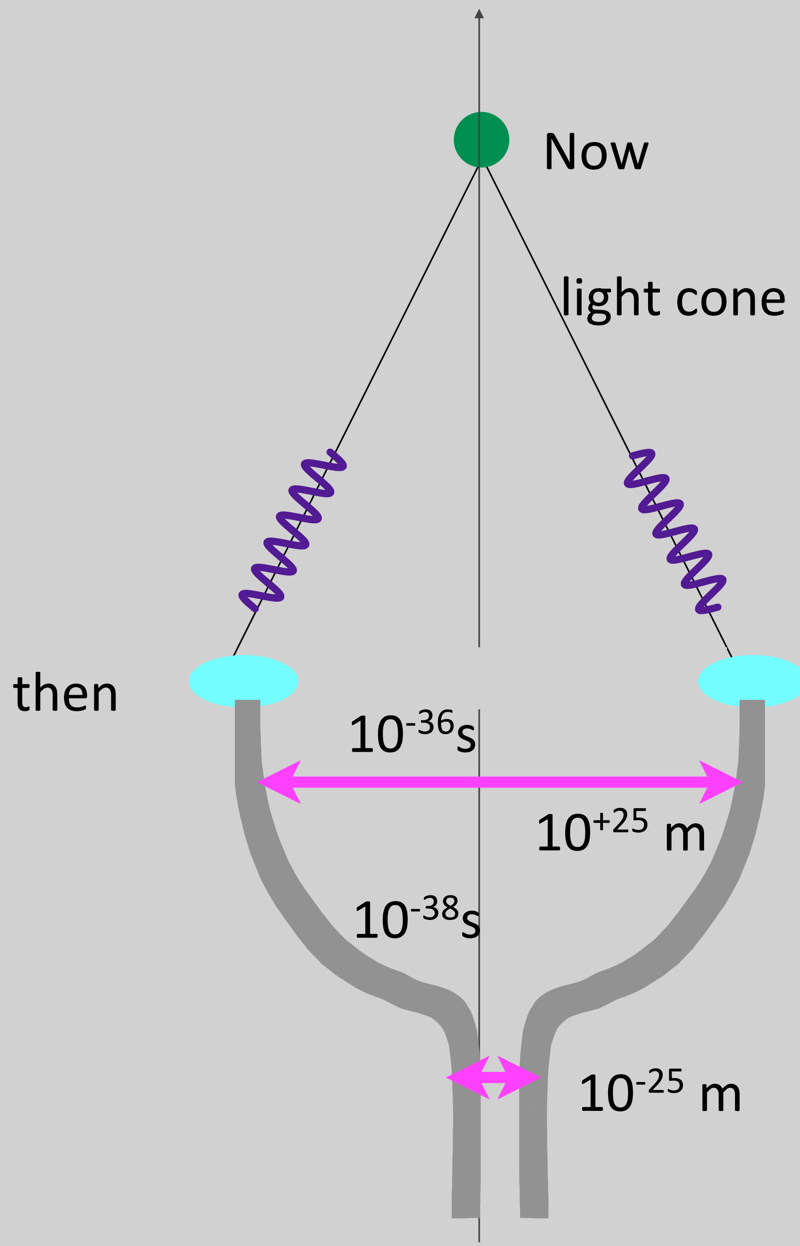
Yup...there is a spin 0 particle associated with this ^ phase transition...the “**inflaton**”

Energy liberation is so enormous – it exponentially increases the radius of the universe by 50 orders of magnitude!

“Inflation”

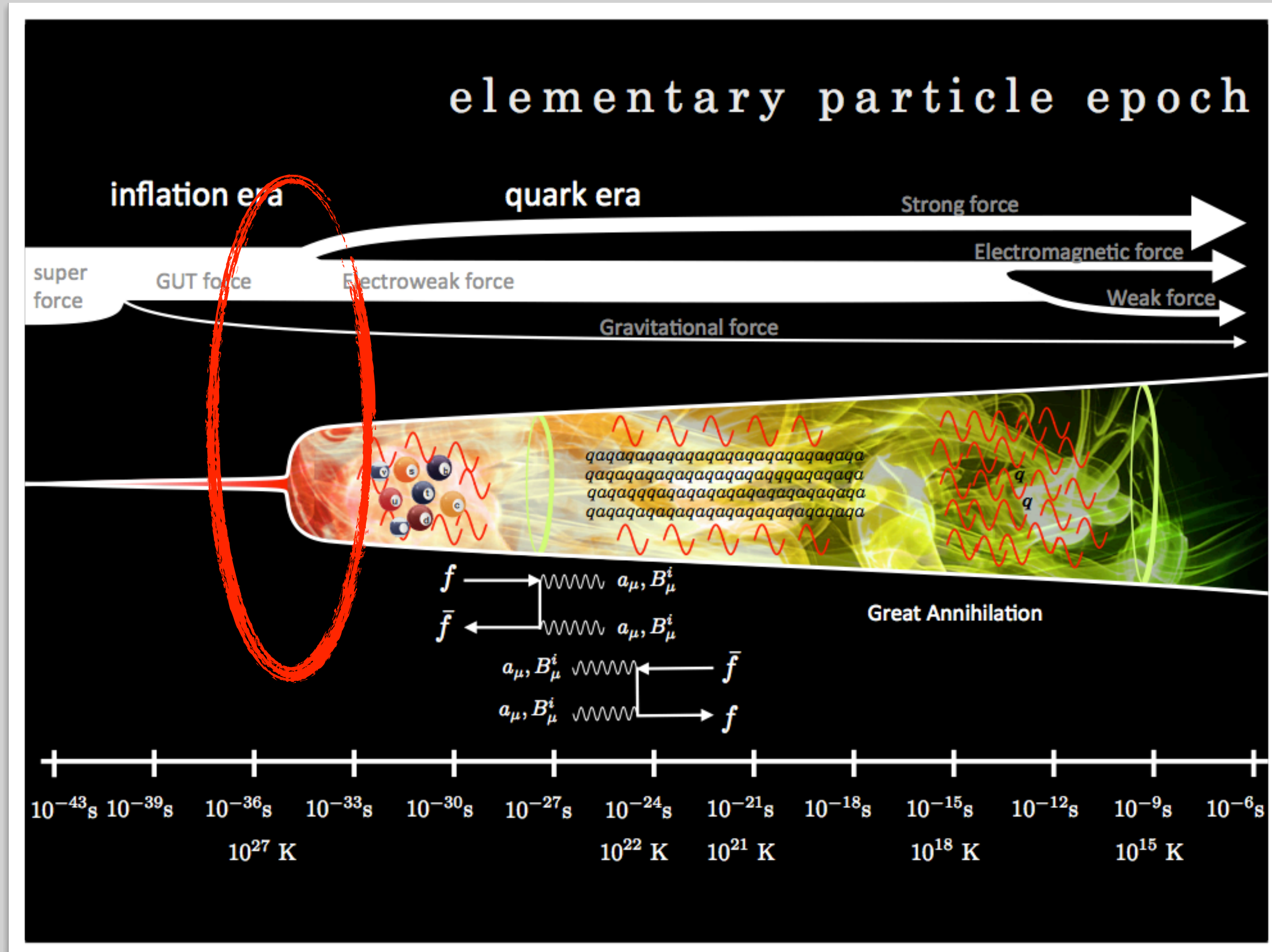
not an overheated economy...

another phase transition



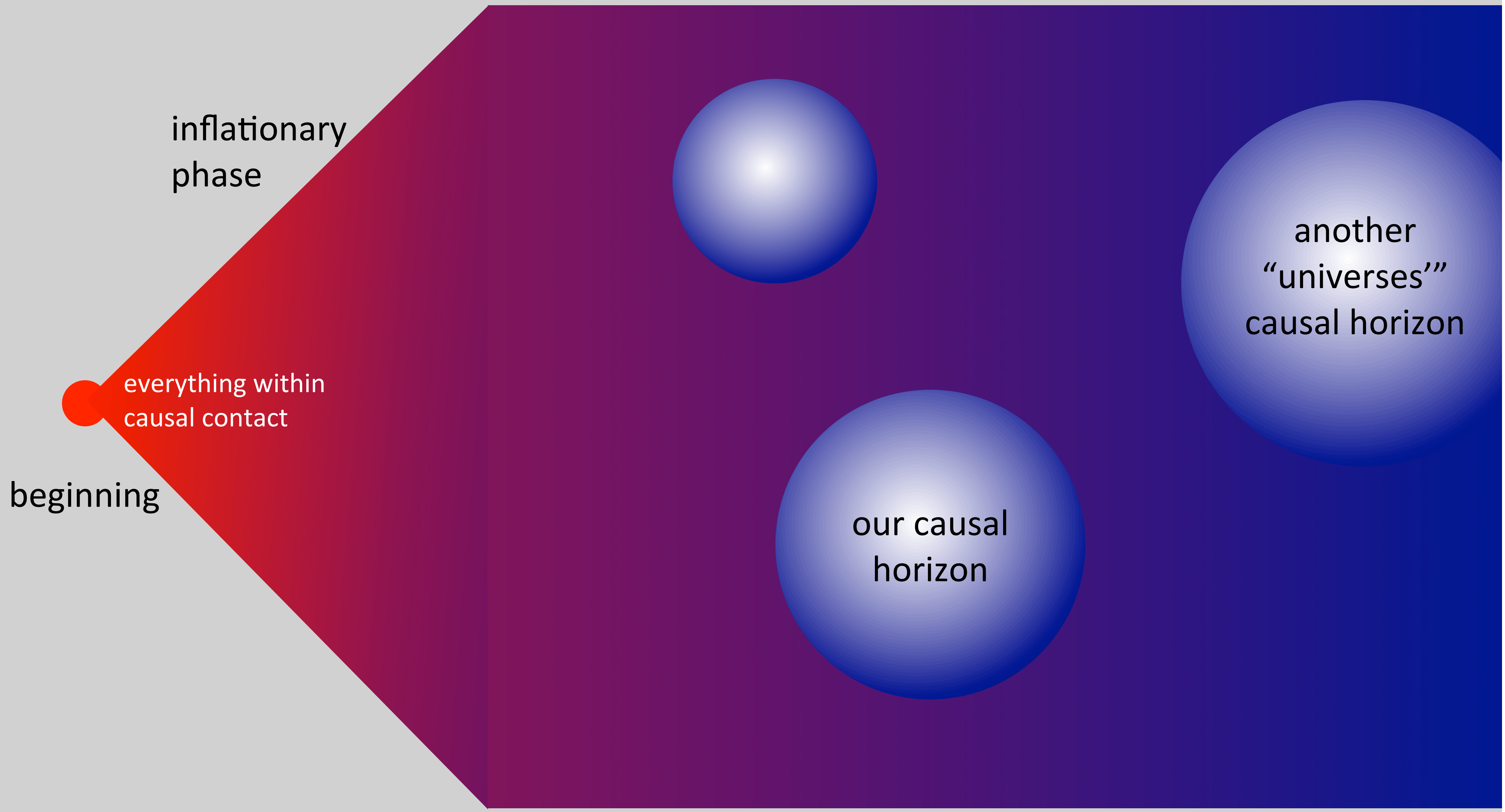
Inflation

the phase transition that was responsible for separating the strong from the electroweak, fueled the inflationary phase?



lost relatives?

the “multiverse” idea

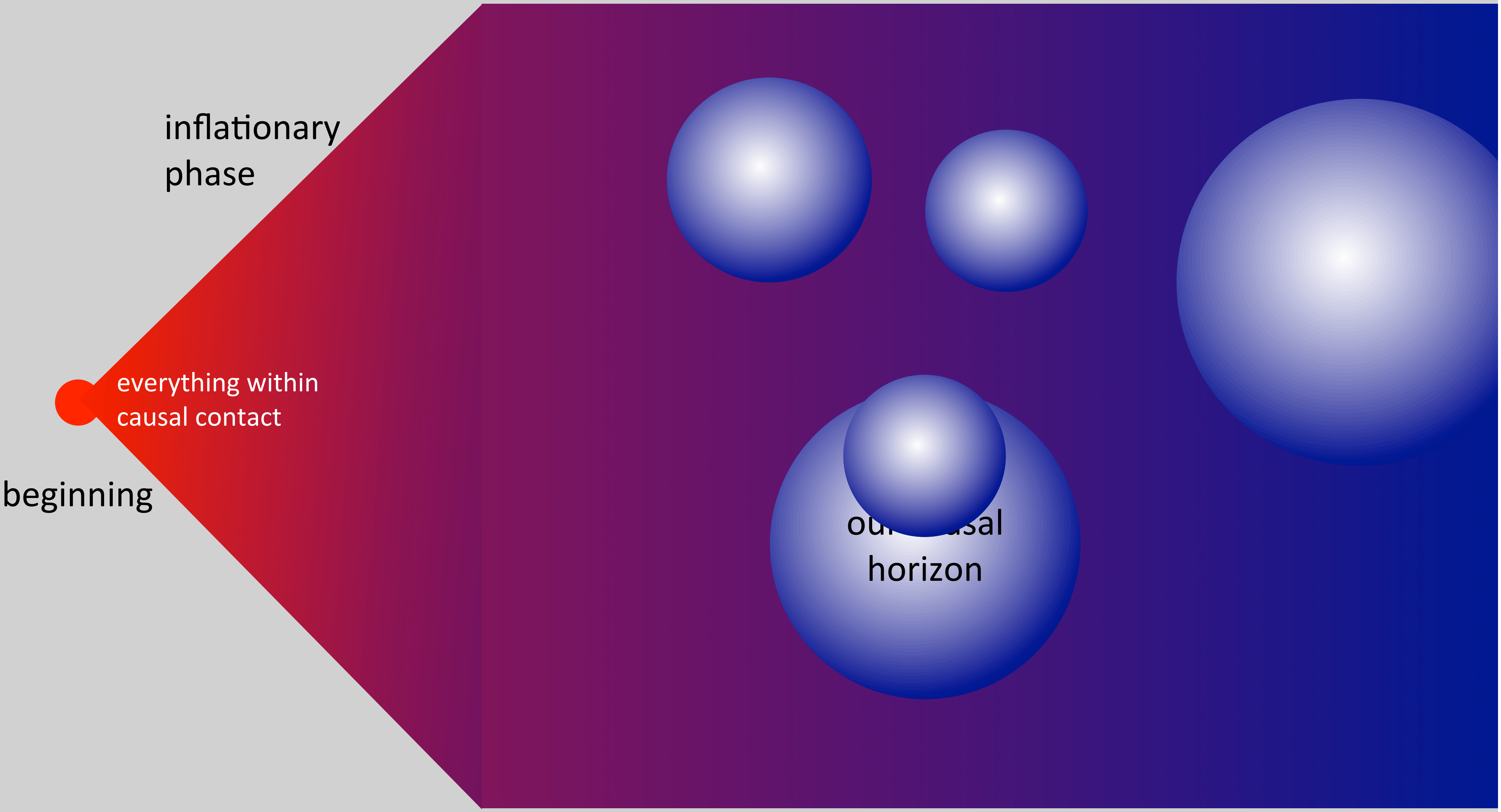


other “universes” might have different physics

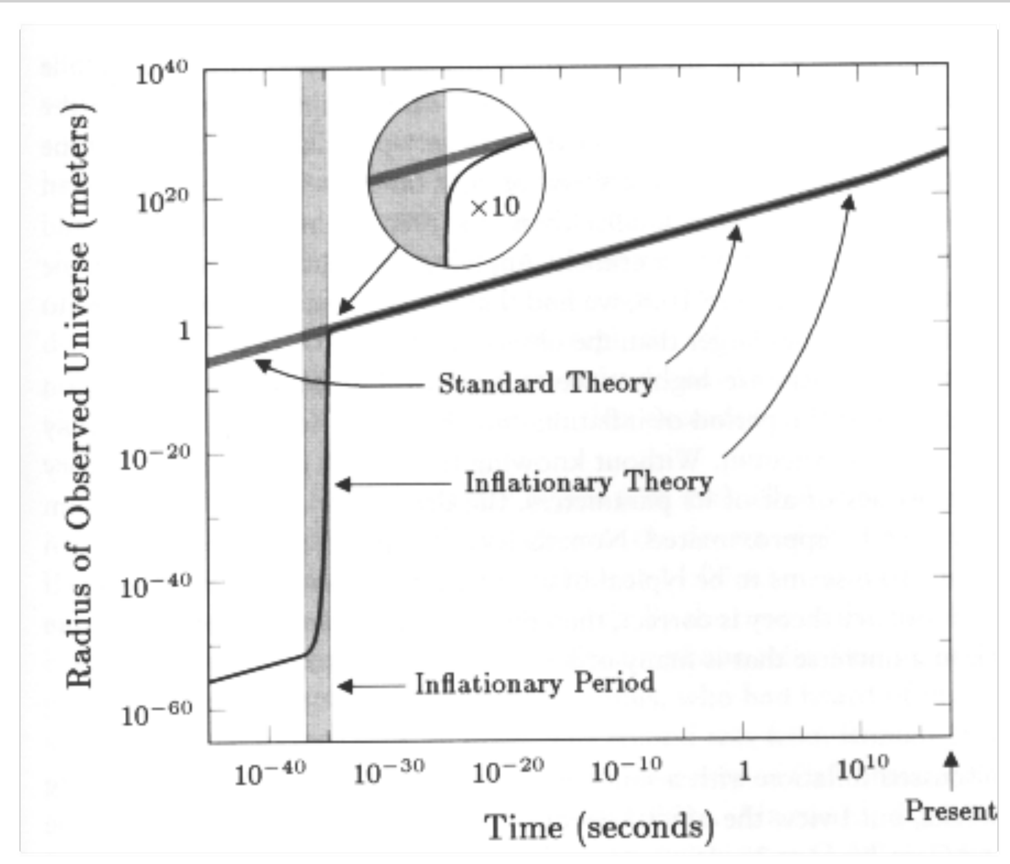
inflation is a quantum mechanical theory

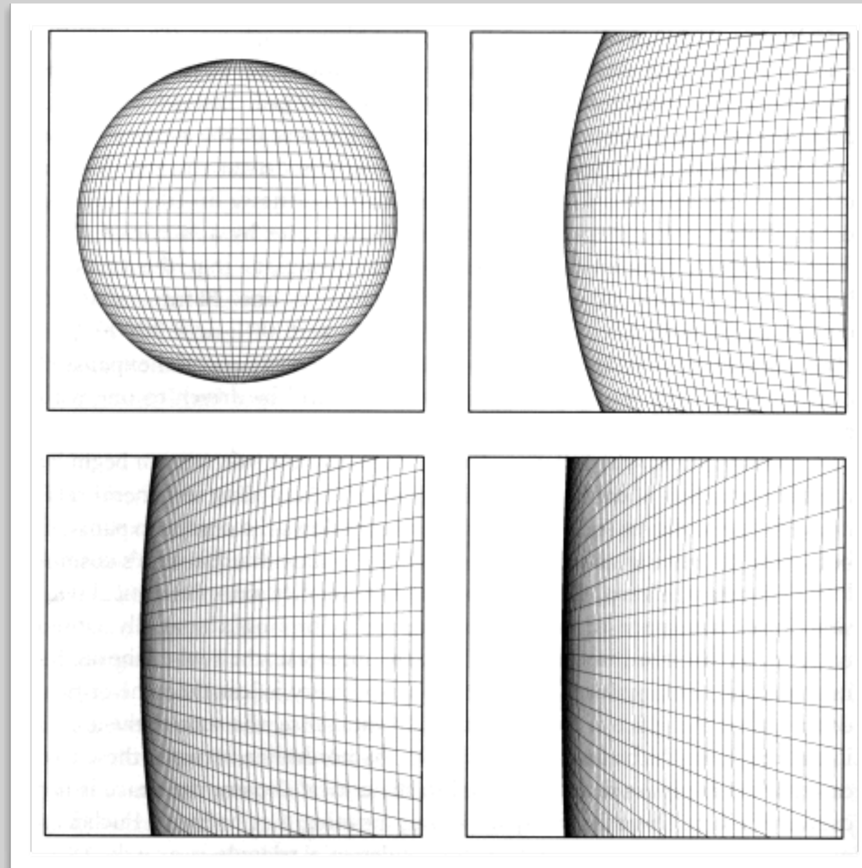
a blessing and a curse....

Inflation should still be happening....



inflated so fast, as to make our neighborhood locally flat?





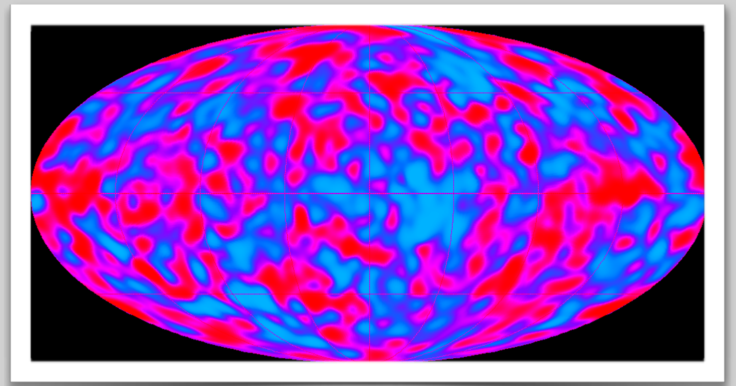
problem #6

what’s the geometry of the universe?

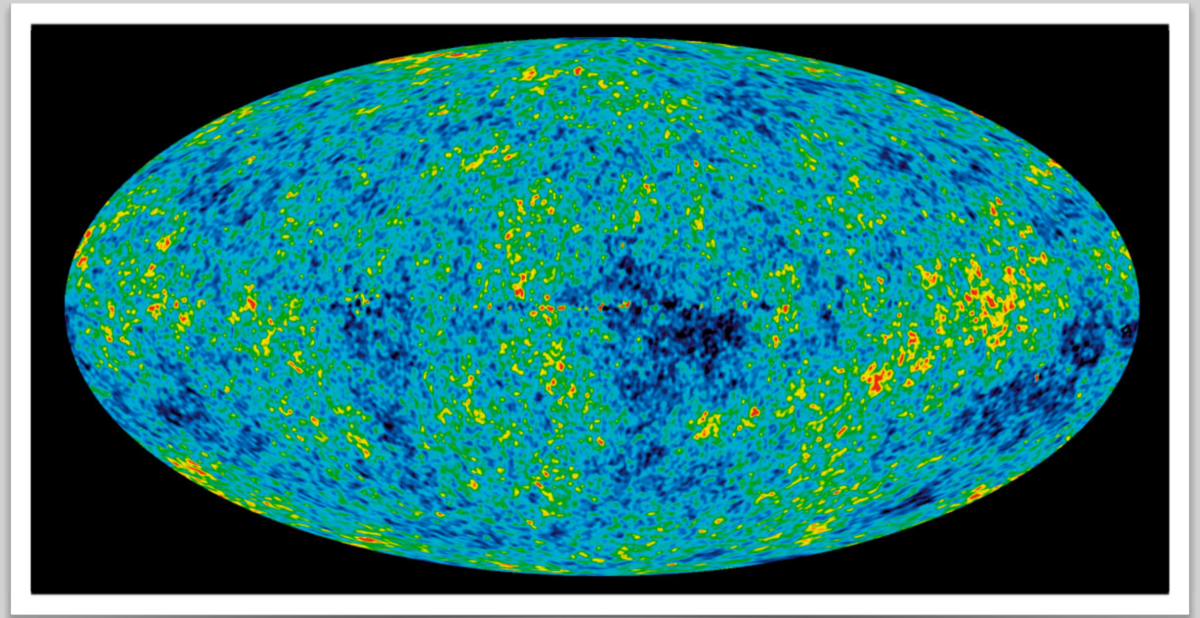
remember the CMB measurements?

COBE?

WMAP?

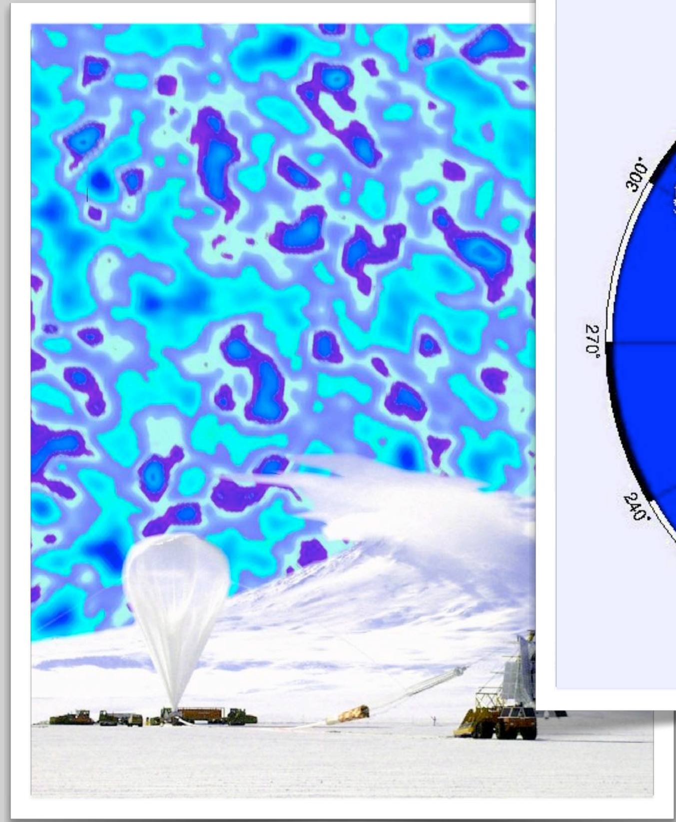


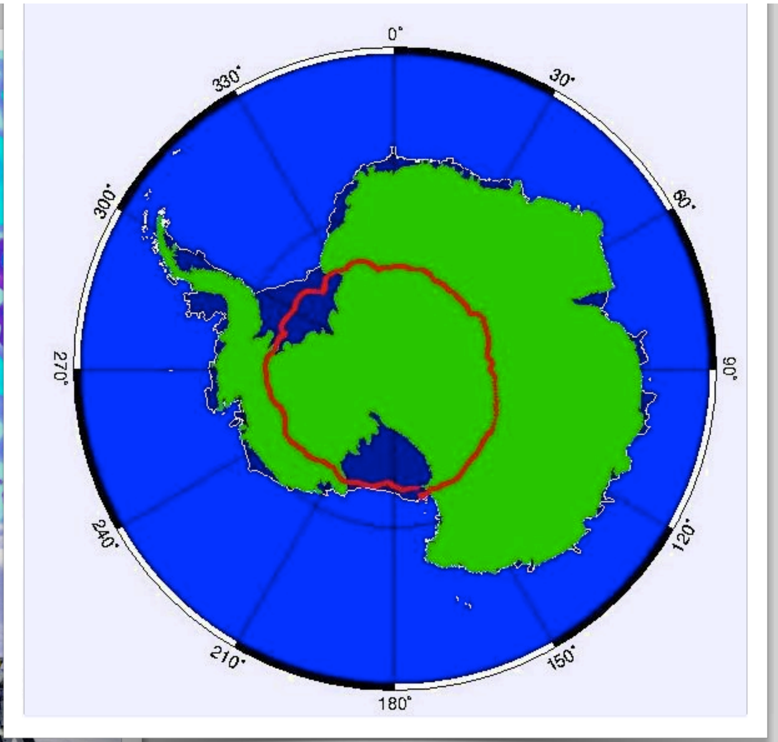
BOOMERANG

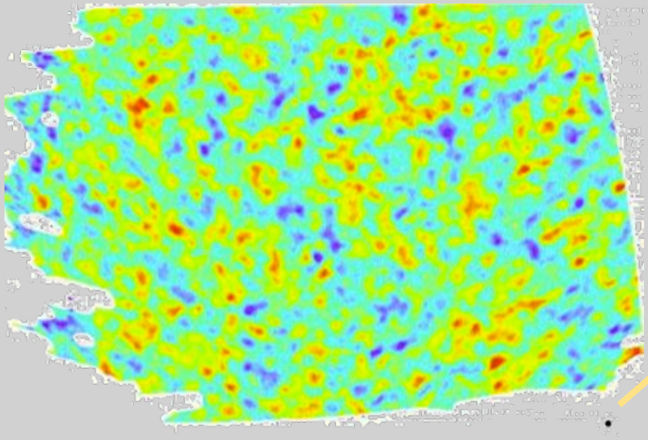


BOOMERanG (Balloon Observations of Millimetric Extragalactic Radiation and Geomagnetics)

Launched from the South Pole in 1998 has done even more precise measurements of the CMB







That's the moon's disk size for comparison

...on the balance between expansion and gravitation

how much mass/energy there is

Two general ways to determine that:

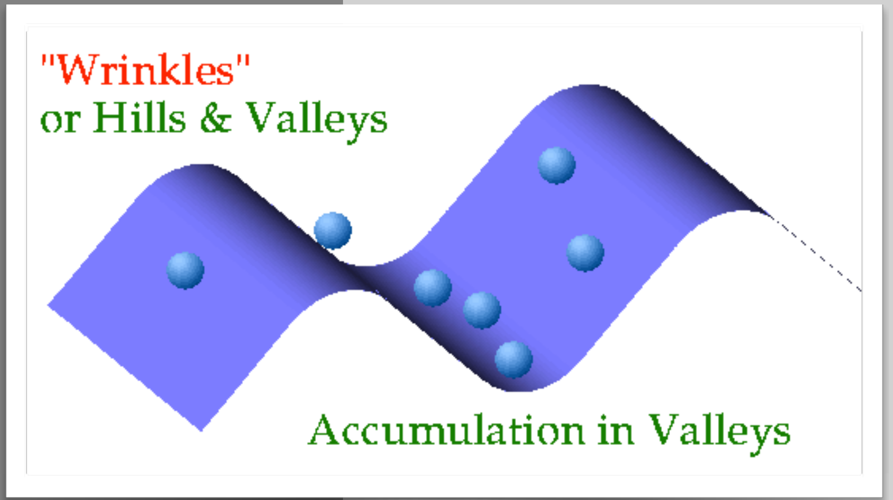
Count the stuff...how much stuff/light can we see and account for?

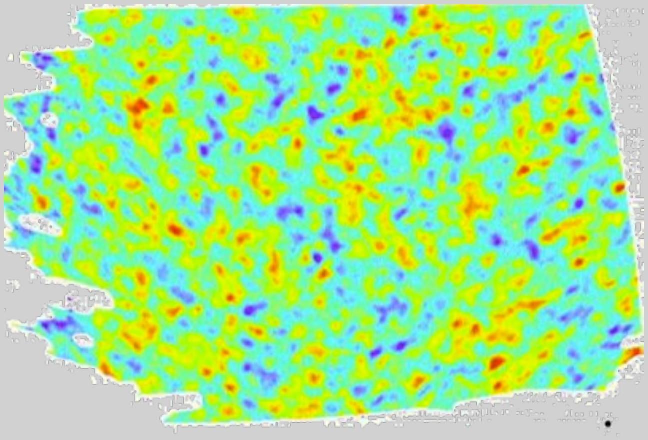
Measure spacetime...what clues do we have to the geometry of the universe?

BOOMERANG did that convincingly, first.

what is the fate of the universe?

That depends:



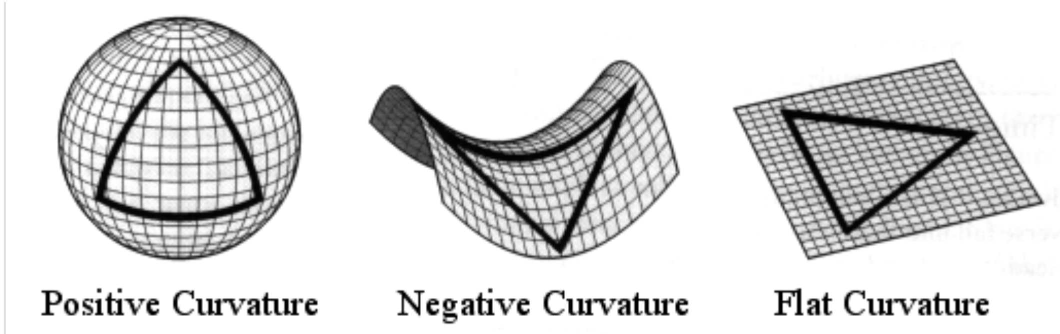


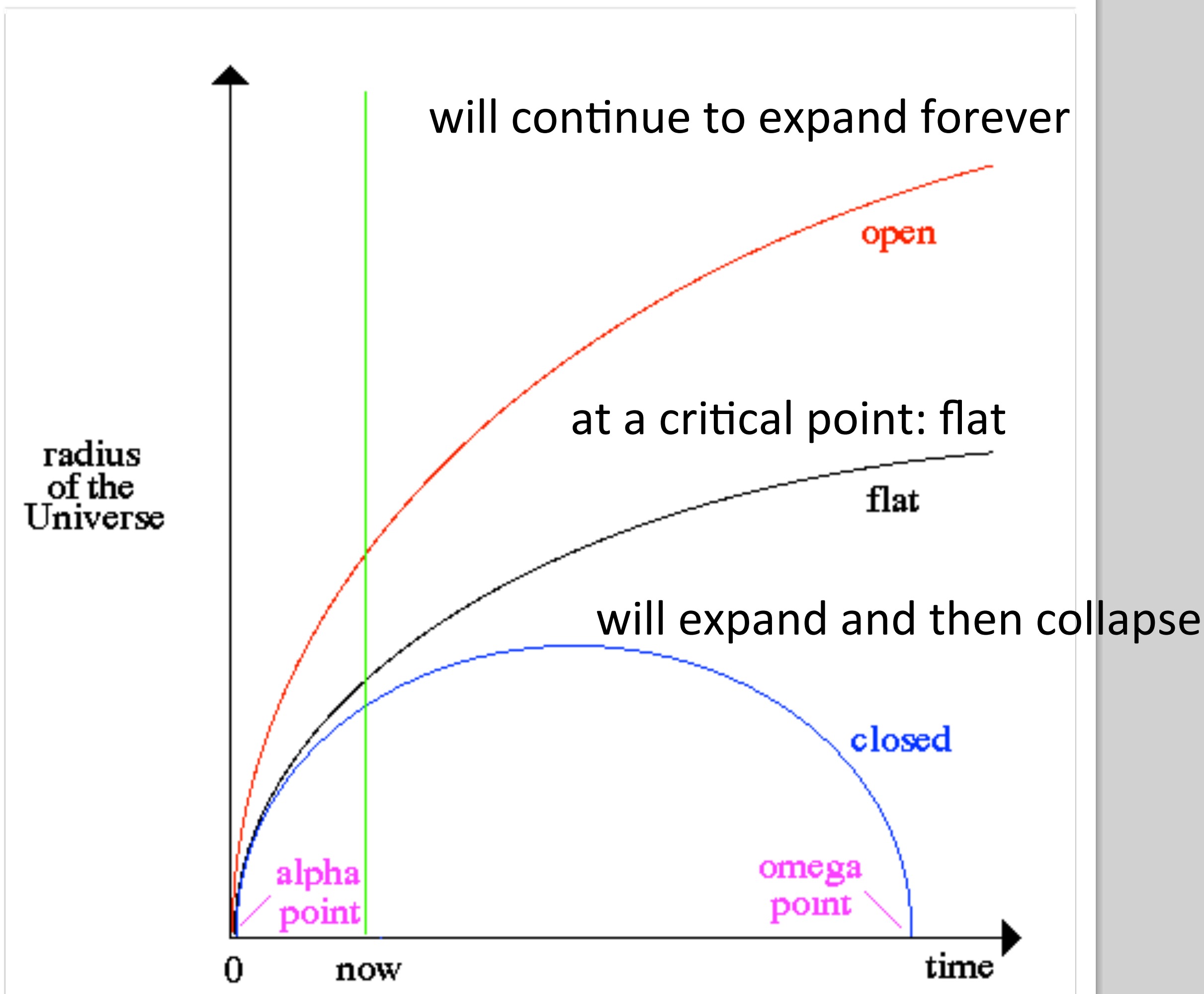
remember:

geometry ⟷ energy/mass

the geometry of spacetime can be of 3 sorts

“curvature”





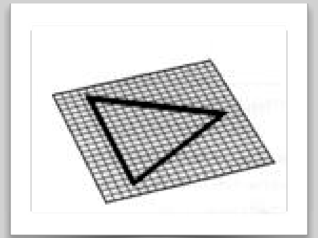
characterize the density (ρ) of matter per unit volume

"Omega"

$$\Omega = \frac{\rho}{\rho_{\text{critical}}}$$

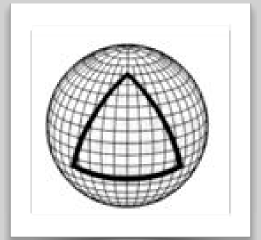
$\Omega = 1$ critical density

flat universe geometry
infinite



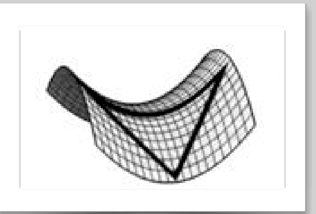
$\Omega \gg 1$ high density

closed universe geometry
finite

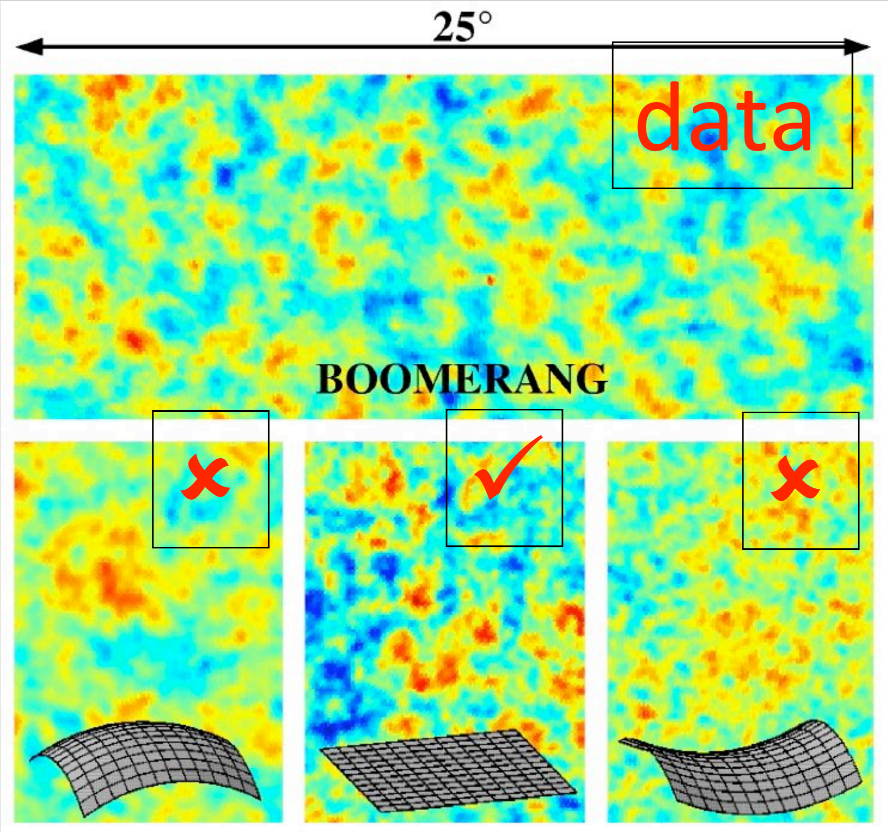


$\Omega \ll 1$ low density

open universe geometry
infinite



By comparing the anisotropy of the CMB to computer simulations



From these measurements,

$\Omega_{geometry} = 1$

But, it gets worse.

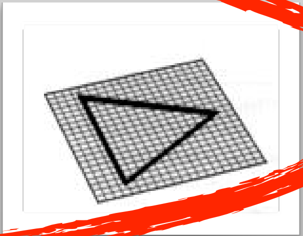
BOOMERANG SAYS:

characterize the amount of matter per unit volume

Omega

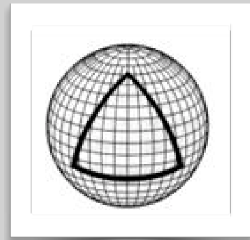
$\Omega = 1$ critical density

flat universe geometry
infinite



$\Omega \gg 1$ high density

closed universe geometry
finite



$\Omega \ll 1$ low density

open universe geometry
infinite

Here's the problem: measurements show that

whoa. 4% ?

$\Omega_B \sim 0.044$ "baryons"...stars and stuff made from protons

whoa. 30% ?

add dark matter:

$\Omega_M \sim 0.3$ matter= DM + B

recap

we're a little short this month

Add up everything that's visible:

$\Omega_{\text{luminous matter}}$

Visible stuff (stars, dust, gas) from telescopes

$\Omega_{\text{luminous matter}} \approx 0.01$

Other regular matter..He, deuterium, etc

$\Omega_{\text{luminous matter}} \approx 0.05$

$\Omega_{\text{dark matter}}$

$\Omega_{\text{dark matter}} \approx 0.25$

But: from measurements

$\Omega_{\text{geometry}} = 1$

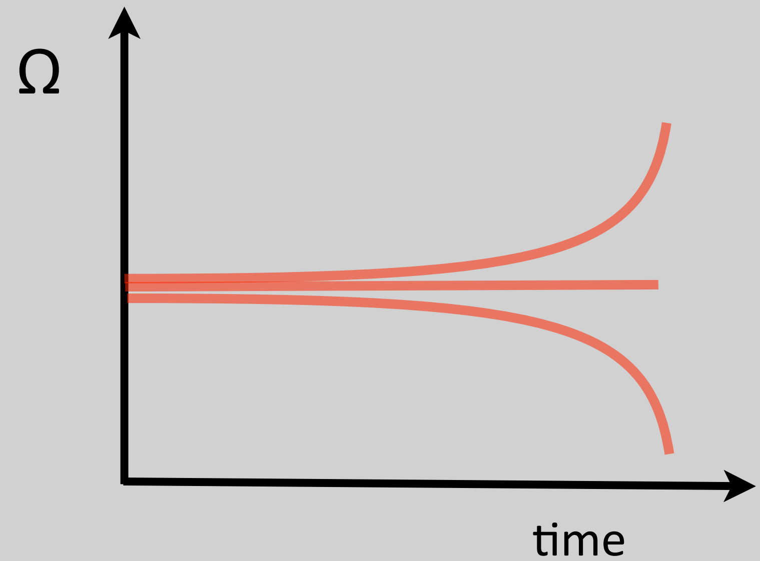
Meaning...that more than 94% of the mass/energy in the universe is unaccounted for by what we know as normal matter/radiation.

But, it gets worse.

there is a very, very strong prejudice

that Ω = 0.3 doesn't make sense

Because it evolves in time so fast:



If Ω is 0.3 now...it would have been 0.99999999999999999993 when the universe was 1 second old!

Too fine-tuned!

More satisfying if Ω = 1.0 for all times

But Ω = 0.3, not 1?

1a

1a supernovae are different

Typically stars not massive enough by themselves to nova

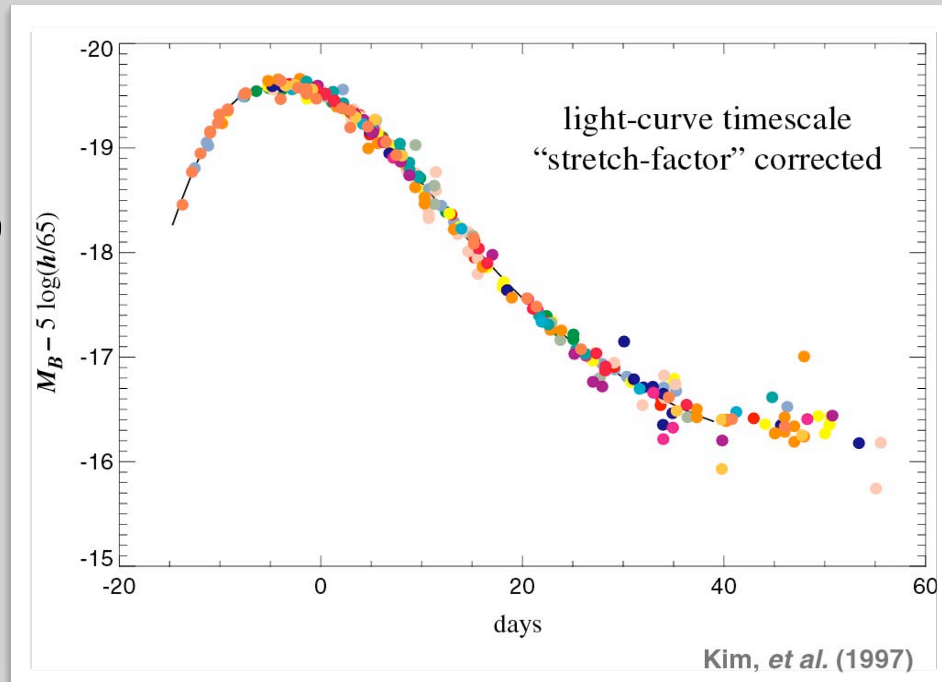
but:

in close proximity to another star which it siphons matter from, enough to cause a supernova explosion after all

Special events – they stay bright for a period of time **which is directly related to their magnitude** - So, like Cepheids, measure the time, deduce the brightness

with brightness, can determine the distance.

measure of brightness



But, it gets worse.

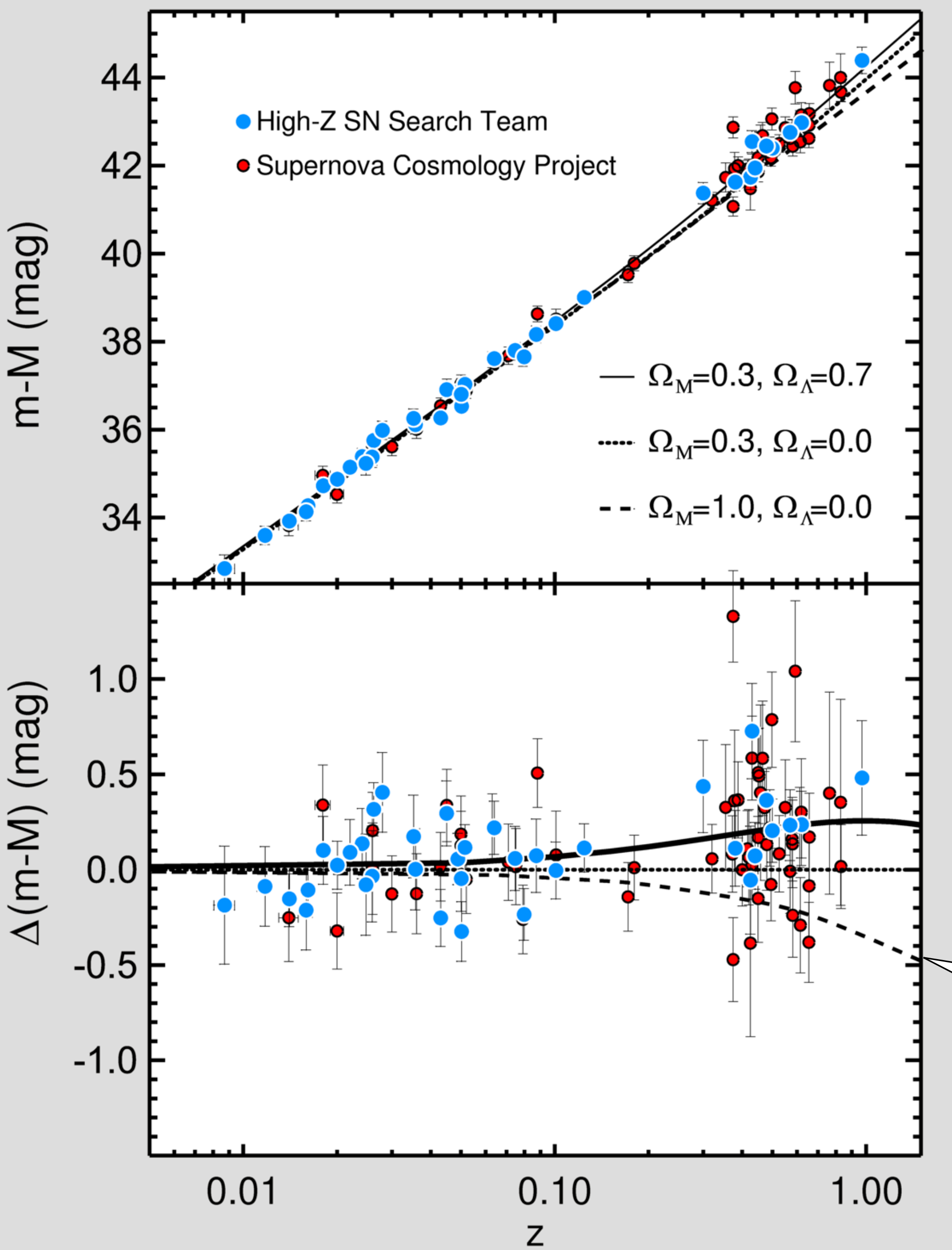
There are lots of these

– enough of these to have one about per second in deep galaxies

So, by searching one gets a wide range of distances

many, quite far away…at very "large redshifts"

enough of these to have one about per second in deep galaxies



Georg Raffelt, Max-Planck-Institut fur Physik

A flat matter-dominated universe would be the dashed line in the middle.

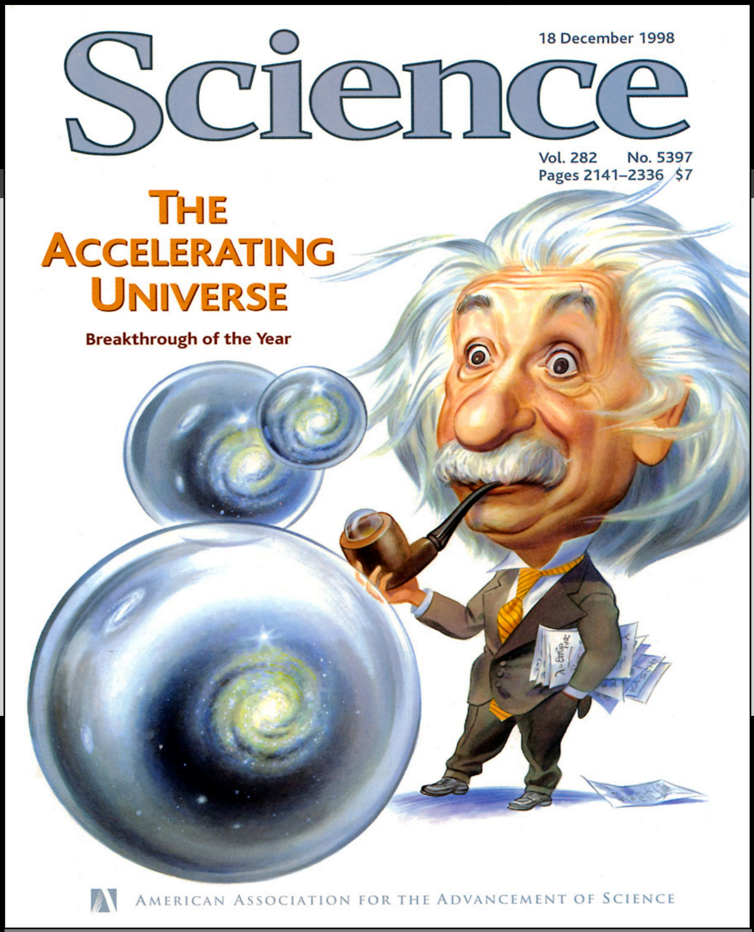
A decelerating (slowing down) universe one of the curves below that.

matter-dominated, decelerating universe

The data require an interpretation

that the Universe's expansion is

Accelerating



um...accelerating??

There has to be some "antigravity" kind of force at work to do this

What's more, there has to be a lot of it

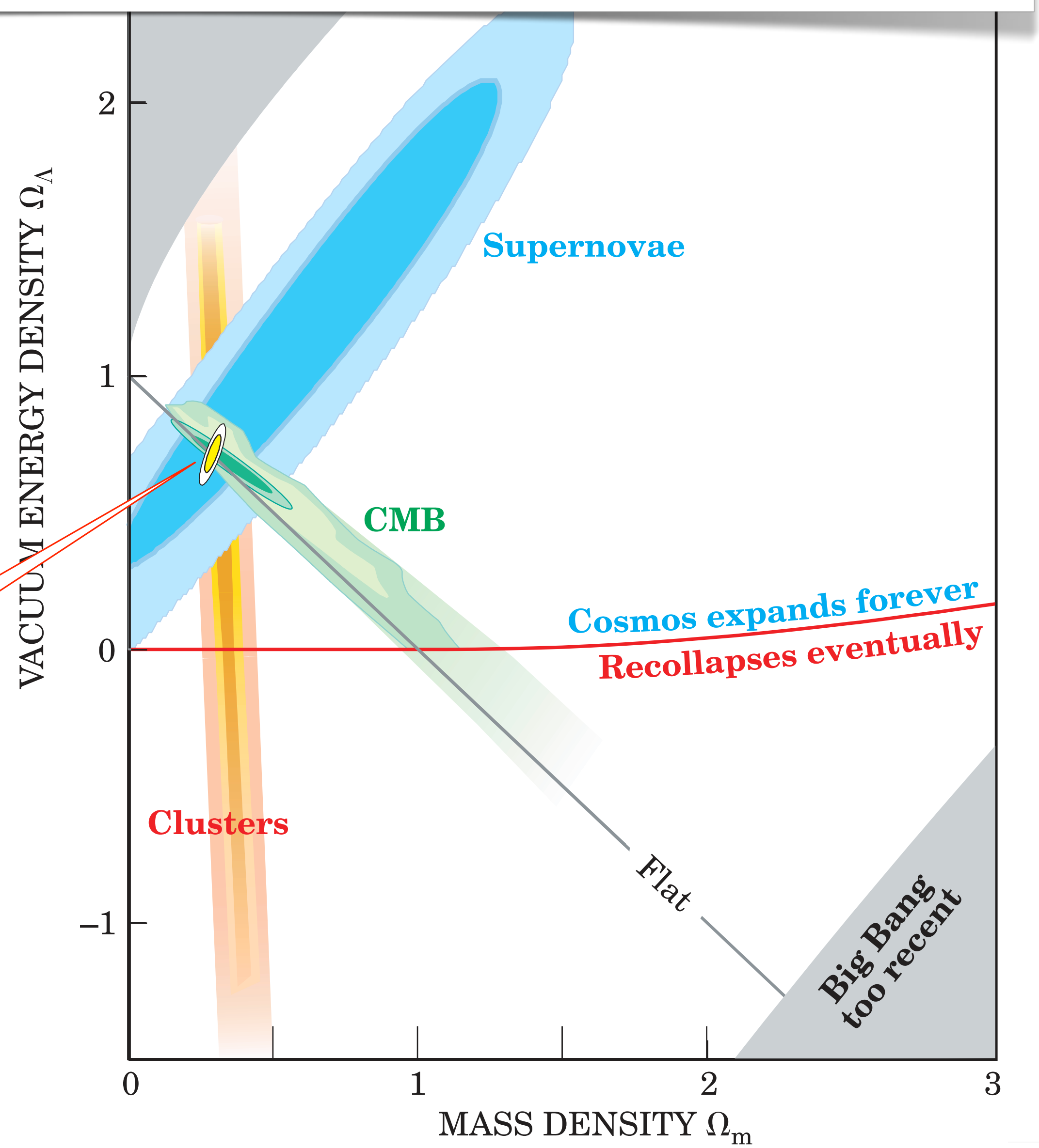
All observables (only some of which have been mentioned)
suggest a new contribution to Ω:

called Ω_Λ

$\Omega_{lum\ matter} + \Omega_{dark\ matter} + \Omega_\Lambda = \Omega(\text{total})$

$$\Omega_B + \Omega_{DM} + \Omega_\Lambda = 0.05 + 0.25 + 0.7 \sim 1$$

one of the most famous figures in astronomy



the best solution:

$\Omega_\Lambda = 0.7$

why “ Ω_Λ“

because it’s back.

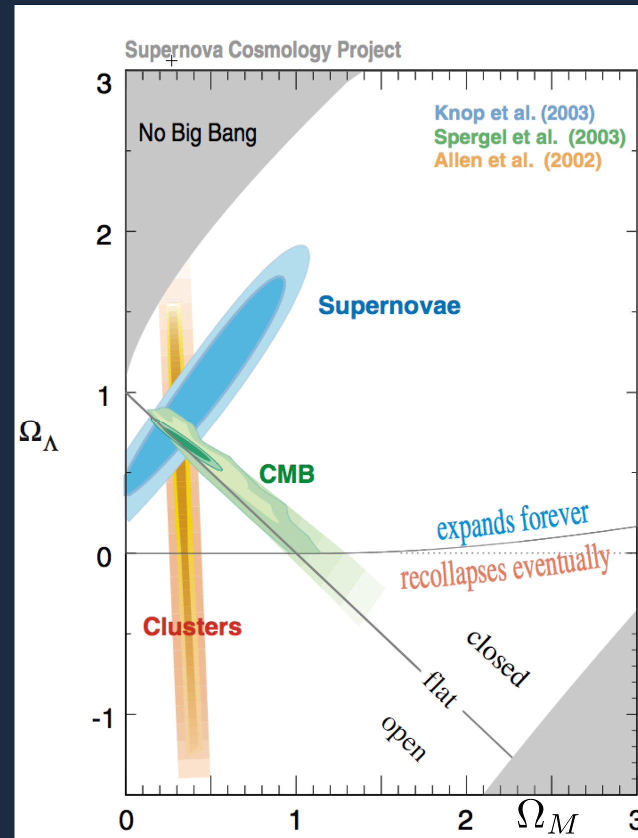
problem #7

the cosmological constant may have returned

interpreting dark energy

as a vacuum energy:

$$G + \Lambda = T$$



the pressure from vacuum energy

is negative

it will cause a spacetime expansion - increasing it from the BB's contribution

Λ acts like the energy of the vacuum

we think the vacuum belongs to us...particle physics

THE biggest problem in physical science

any missing mass/energy is presumably quantum mechanical

So, how's that working out for us?

vacuum energy

leads to virtual particles

borrowings and paying back

generations learned:

"It's never hard to find trouble in field theory...[we] subtract the vacuum expectation value...[giving]

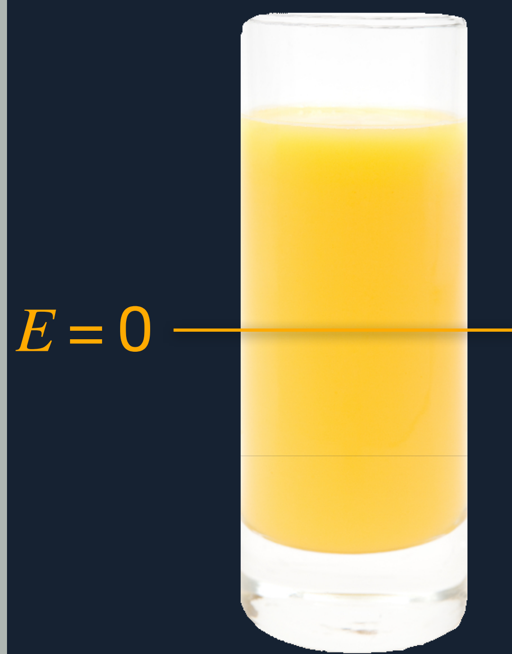
$\langle 0|H|0\rangle = 0$

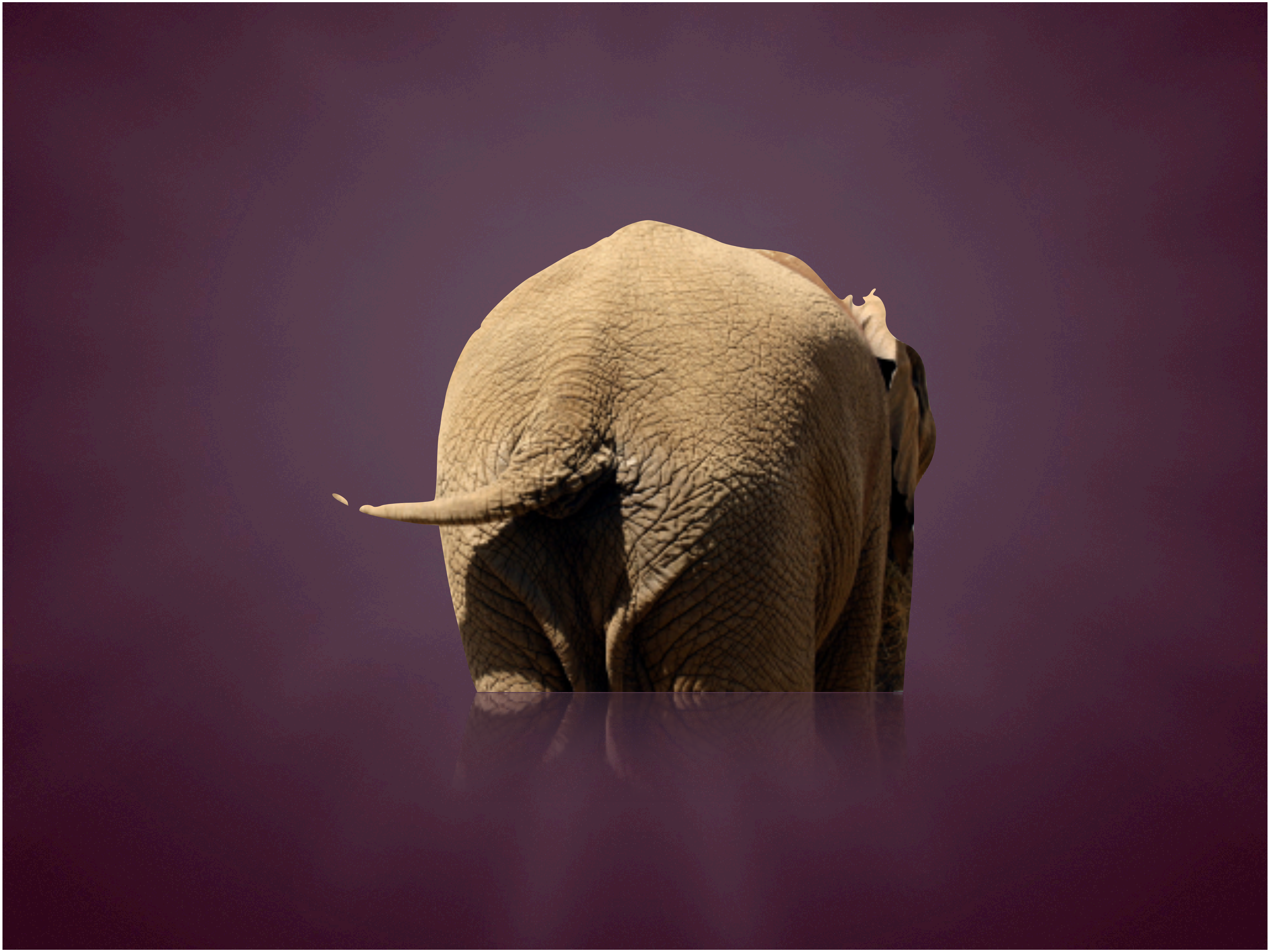
...[removing] the need of discussing several embarrassing divergences."

Bjorken and Drell, *Relativistic Quantum Fields*, 1965

"Only energy differences matter relative to the vacuum..."

Chip Brock, multiple PHY853 lectures





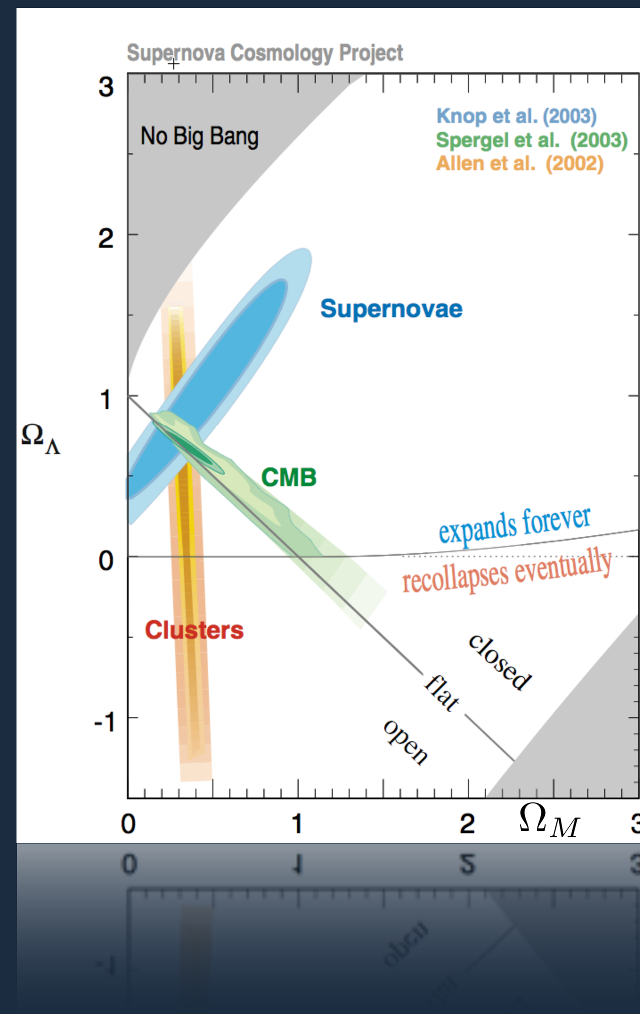
interpreting dark energy

as a vacuum energy:

$$G = T + \Lambda$$

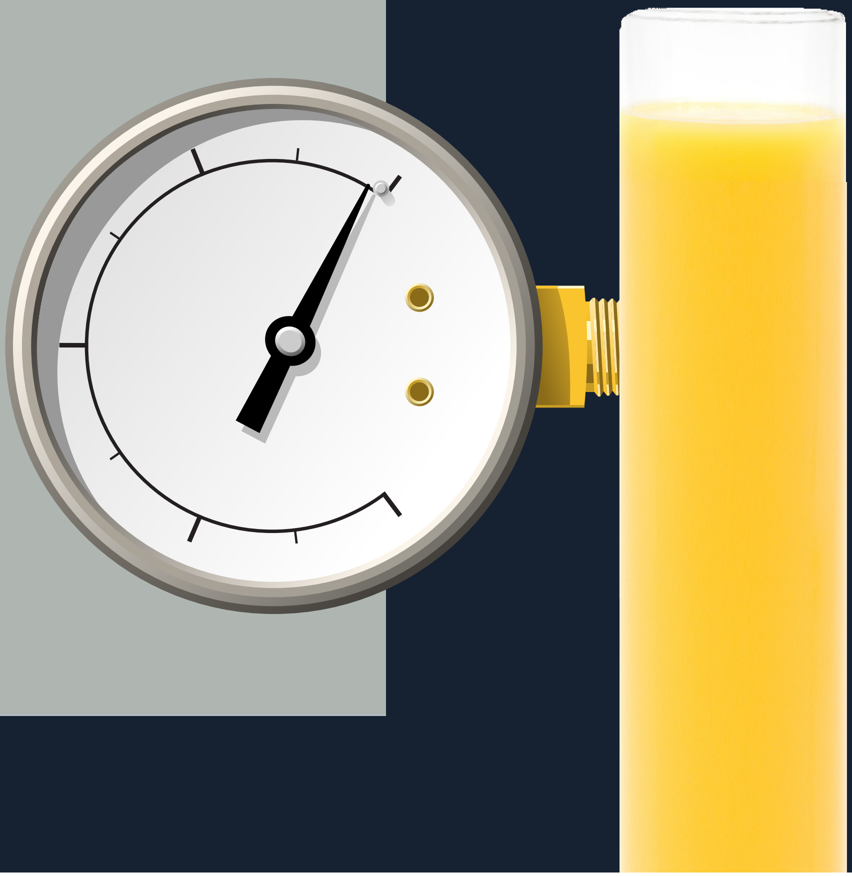
$$|\rho_{vac}(\text{cosmology})| < 10^{-9} \text{erg/cm}^3$$

Here, the vacuum energy absolute value matters!



the vacuum's back

how much?



Bj & D worry:

$$\therefore \rho \quad = \quad \infty$$

a cut-off:

The scale of gravity: the Planck scale...

$$E_P = \left(\frac{\hbar c^5}{G}\right)^{1/2} = 10^{19}\mathrm{GeV}$$

$$\rightarrow \rho_{vac}(\mathrm{Planck}) = 10^{114}\mathrm{erg/cm^3}$$

$$\rho_{vac}(\mathrm{RQFT}) = \infty$$

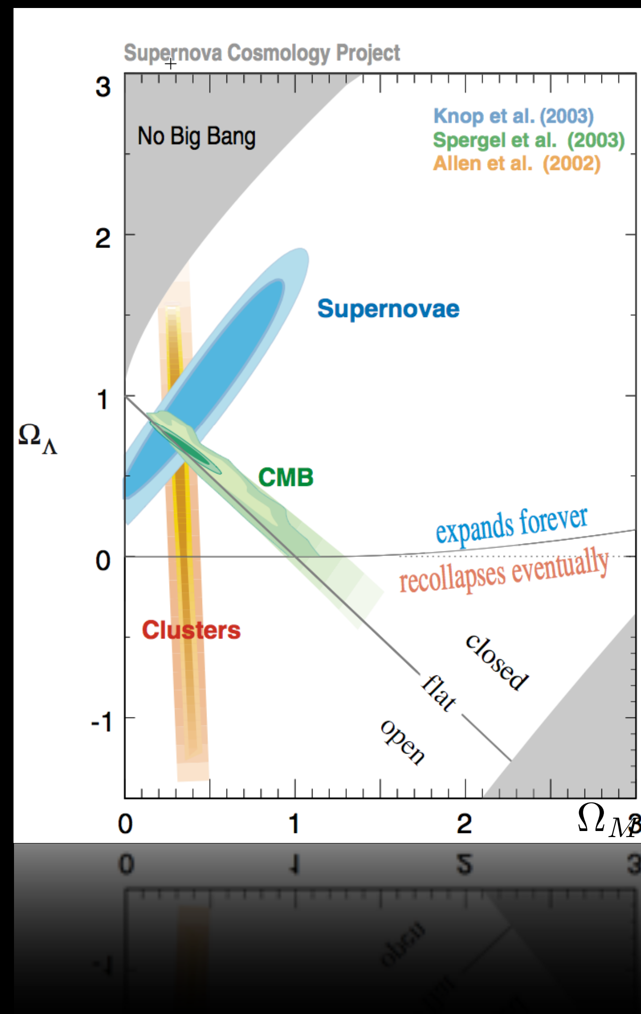
cosmological constant

Λ as a vacuum energy?

$$|\rho_{vac}(\text{cosmology})| < 10^{-9}\text{erg/cm}^3$$

vs.

$$\rho_{vac}(\text{Planck}) = 10^{114}\text{erg/cm}^3$$



vacuum embarrassment:

"...worst prediction in the history of physics."

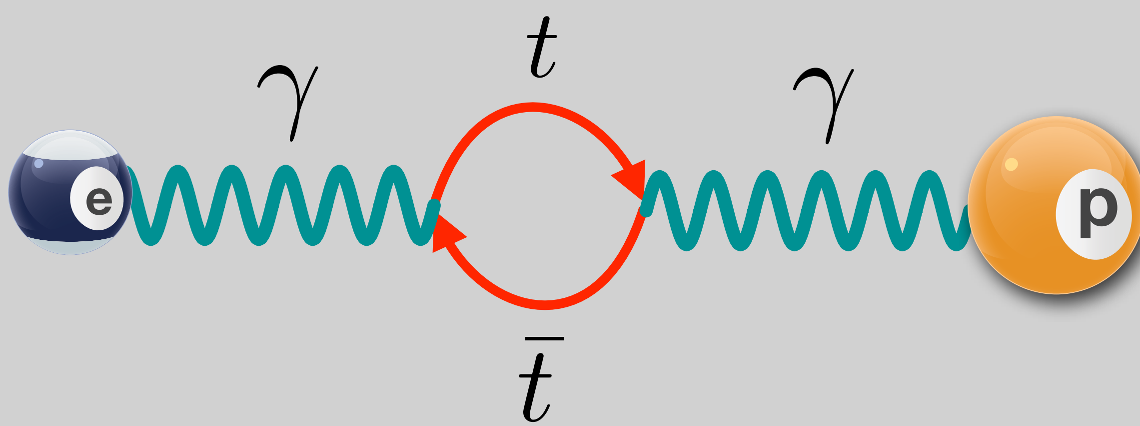
problem #8

that whole alpha to omega thing...the Big Issues?

some worry about the whole

Goldilocks thing

The conditions for our universe seem to be “just right”



If the top quark mass were just a little different?

or any of the fermions?

Their contributions to loops would result in a slightly larger or slightly smaller Bohr Radius

Chemistry would be entirely different!

any number of other

“coincidences” that make our world just right

(Victor Stenger)

The electromagnetic force is 39 orders of magnitude stronger than the gravitational force. If they were more comparable in strength, stars would have collapsed long before life had a chance to evolve.

The electron's mass is less than the difference in the masses of the neutron and proton. Thus, neutron beta decay can happen.

The neutron is heavier than the proton, but not so much heavier that neutrons cannot be bound in nuclei.

The carbon nucleus has an excited energy level at around 7.65 MeV. Without this state, insufficient carbon would be manufactured in stars.

you get the idea?

Science cannot function with “coincidence” as an ingredient.

Need to understand how ours is right.

“Anthropic Principle”

hugely controversial

skates on very thin ice for science

associated with:

John Barrow, Frank Tipler, Brandon Carter

“weak anthropic principle”: The observed values of all physical and cosmological quantities are not equally probable but take on values restricted by the requirement that there exist sites where carbon-based life can evolve and by the requirement that the Universe be old enough for it to have already done so.

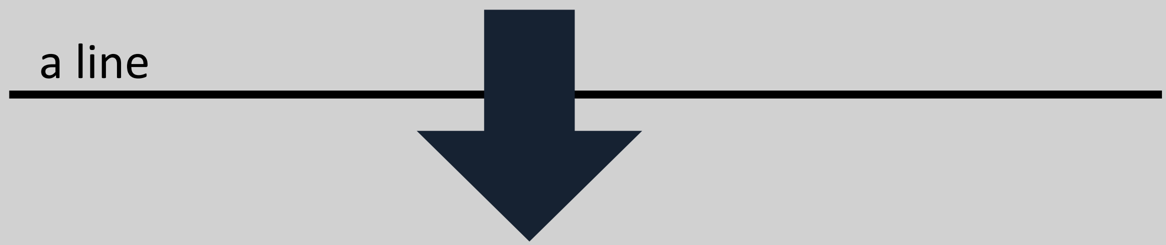
circular

“strong anthropic principle”: The Universe **must** have those properties which allow life to develop within it at some stage in its history.

“final anthropic principle”: Intelligent, information processing **must** come into evidence in the Universe, and, once it comes into existence, it will never die out.

implies purpose

These bug most of us...but they continue to be discussed



“extreme anthropic principle” = an explicit creator as a part of the science.

No science can go there.

The universe could be a fluke

how we deal with it

basically two ways:

1. it could be a cosmic accident

2. inflation can explain us

Of all the possible ways a universe could come into existence...that are the chances that our nicely tuned one might just occur as a quantum mechanical fluctuation?

you know...what're the odds?

not zero...but very tiny

People aren't very good at dealing with odds...

Suppose the lottery came out:

1 2 3 4 5 6 7 8

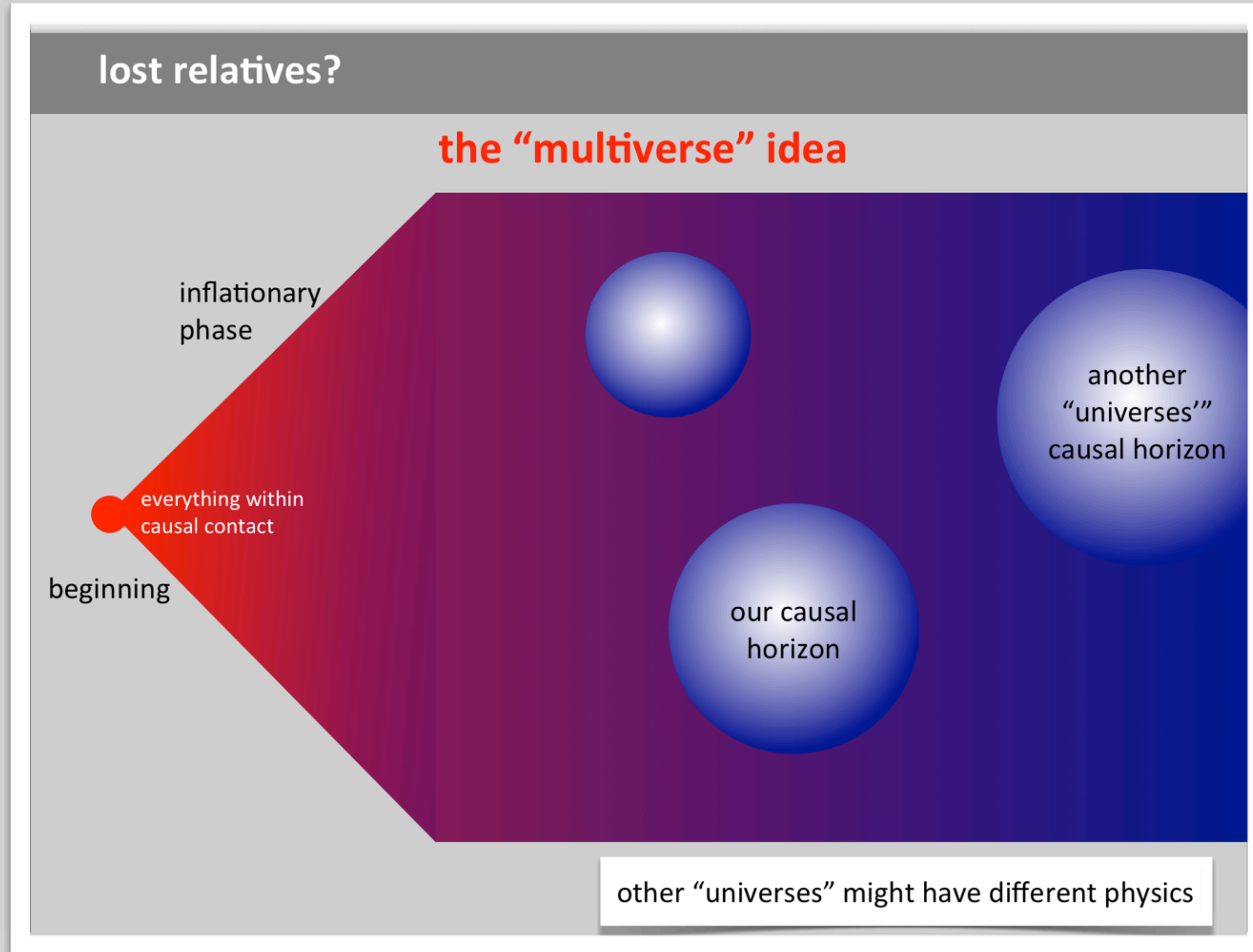
One's reaction might be: it's rigged!

same probability as:

6 5 2 4 1 8 3 7

most like the inflation solution

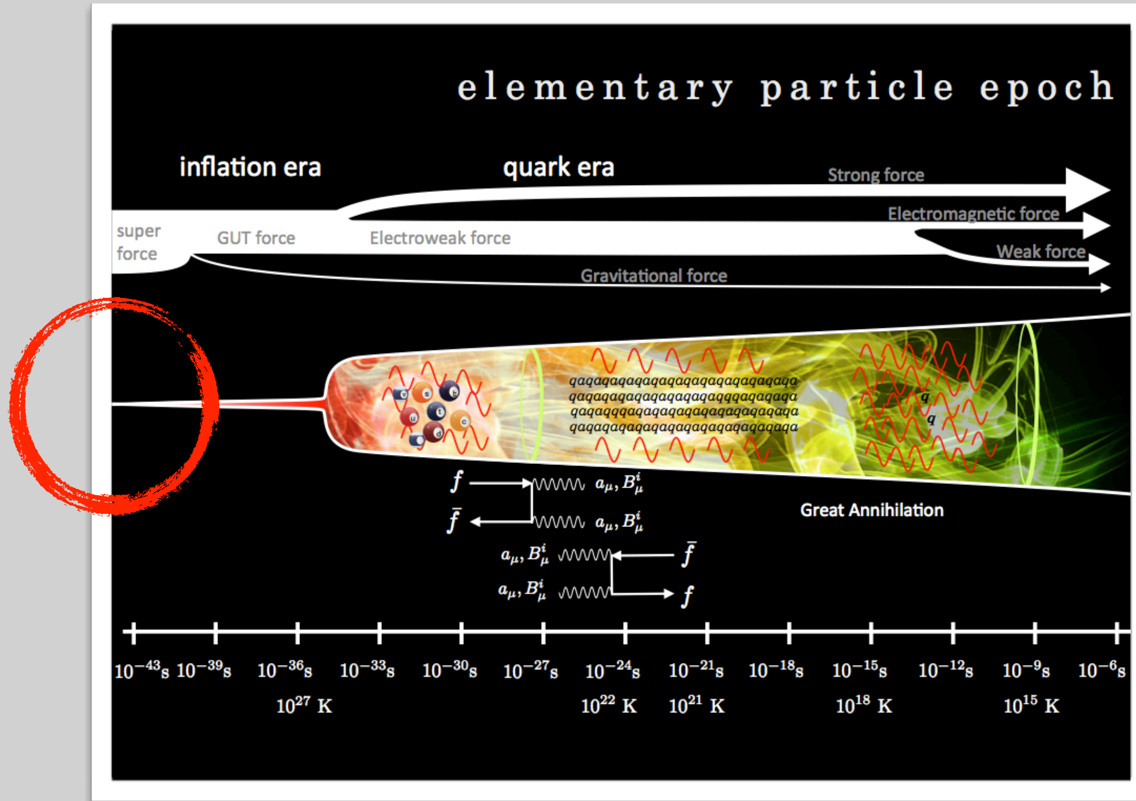
where ours is one of many



So, most would probably not sustain life and not live long or not support nucleosynthesis or even have the phase transitions that we've experienced.

the “Planck era”?

what could have existed?



Just geometry.

a spacetime foam - spacetime is so compressed and distorted...that it would be folded on itself, creating wormholes and mini-black holes

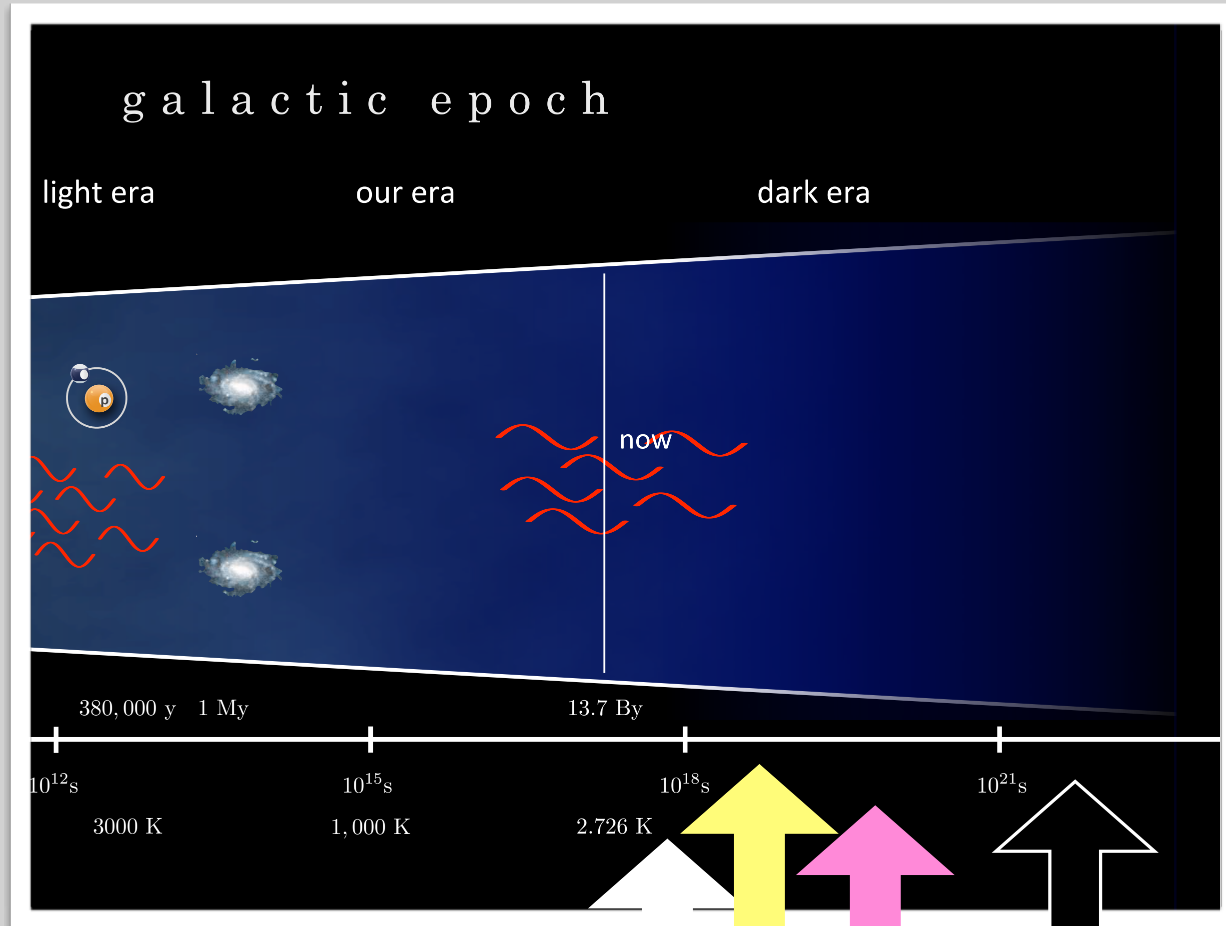
causality might not even exist

eventually, spacetime would rip and black holes would produce particle-antiparticle

how about the other end?

you know.

The. End.



6×10^{17} s, 20By: Andromeda and Milky Way will collide

3×10^{18} s, 100By: all galaxies are invisible - beyond all horizons

3×10^{19} s, 1Ty: the BB deuterium, Lithium will be gone

3×10^{21} s, 100Ty: the last star in the universe will go black

be happy. it's a long time 'till then.

scratch any of us hard-boiled physicists

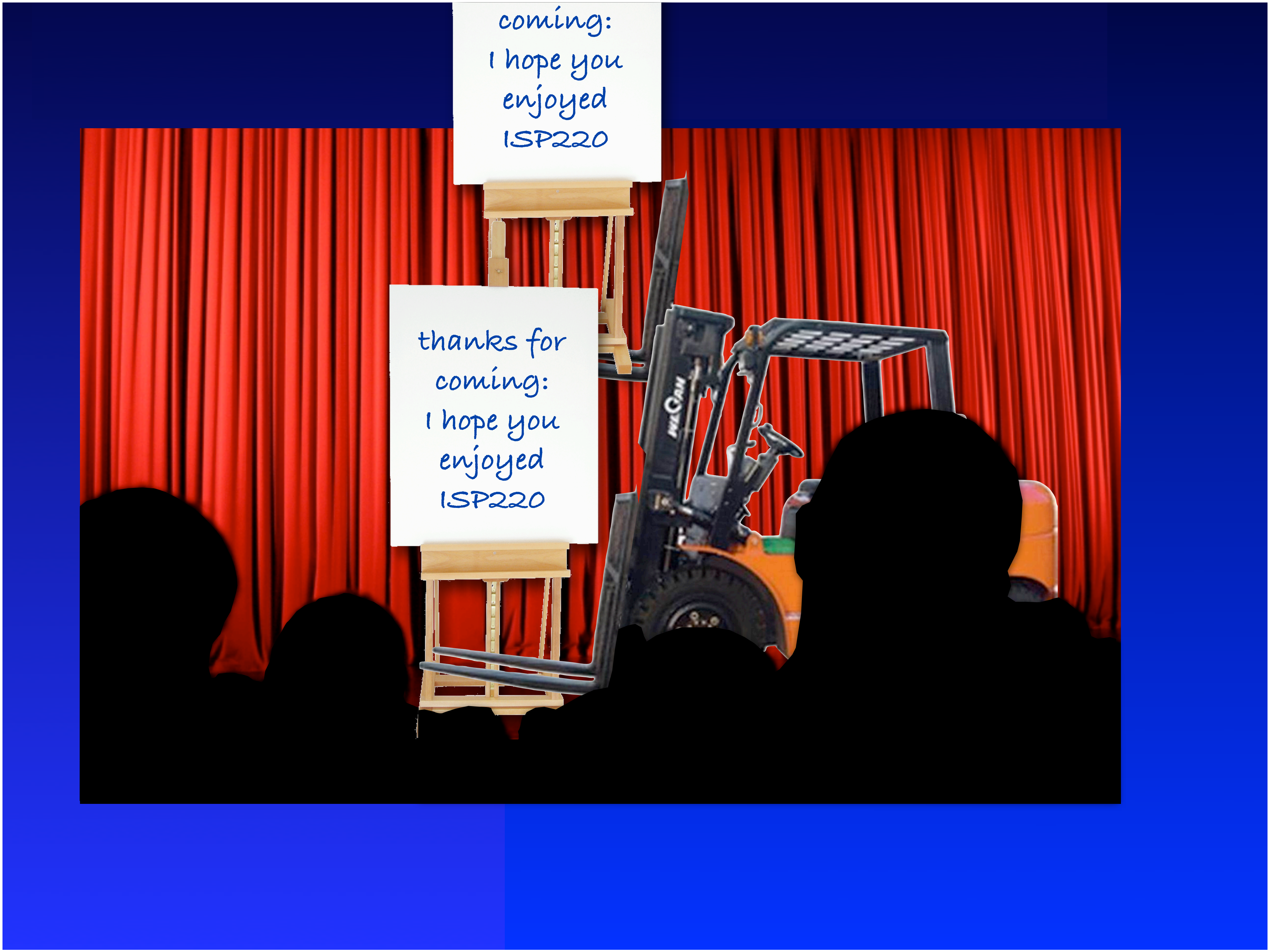
we are in awe of what we know

and how gorgeous it all is

problem #9

maybe the most important: the surprise. The unknown, unknowns.

That's where the fun happens. That's what makes science exciting!

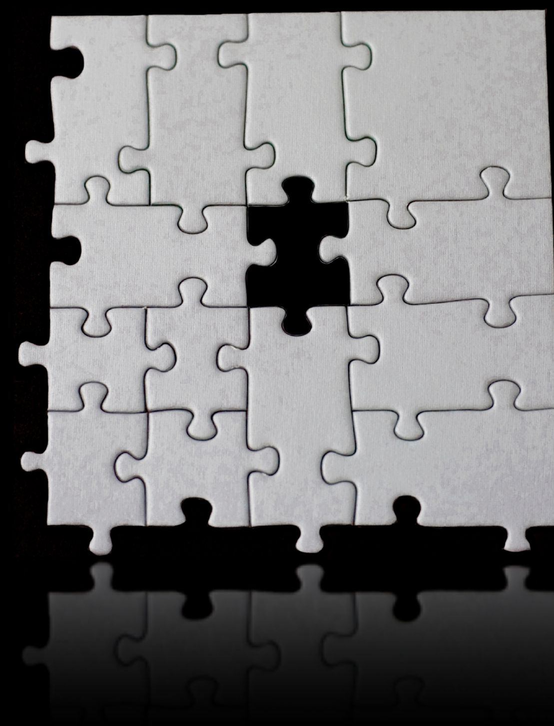

coming:
I hope you
enjoyed
ISP220
thanks for
coming:
I hope you
enjoyed
ISP220

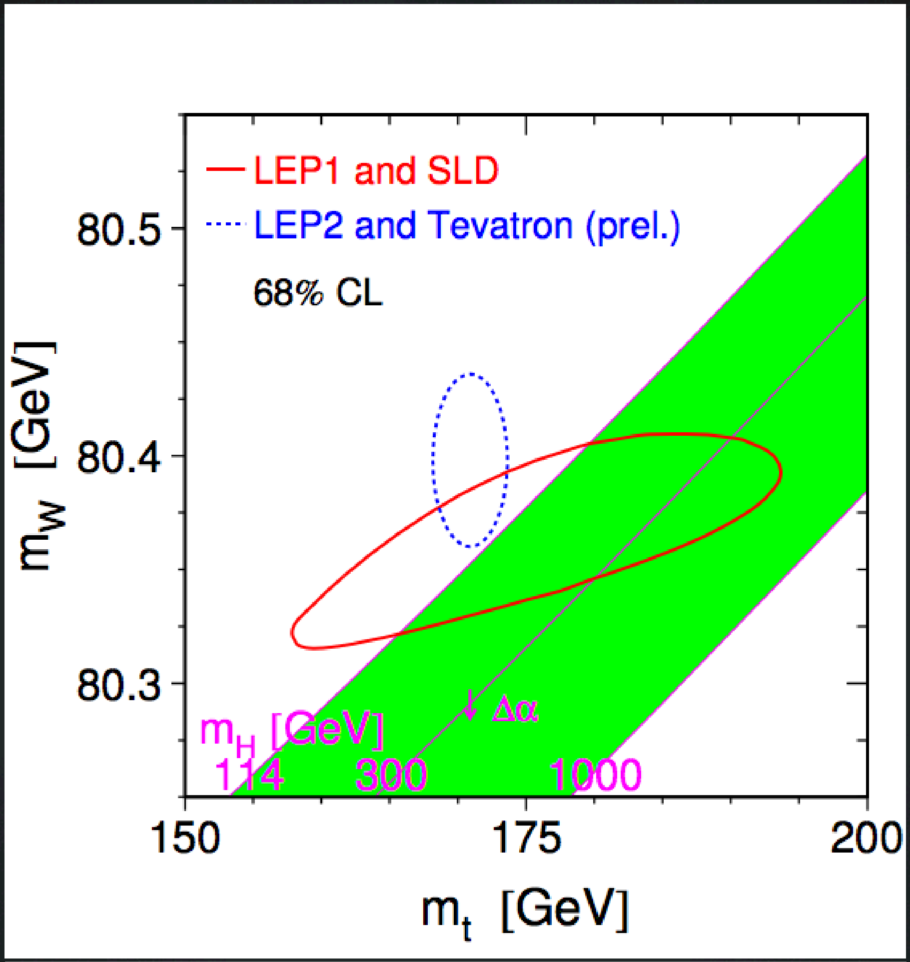
6

Incomplete.

...or worse

that's part of the game.





By constraining SM measurements:

{$M_H < 182$ GeV/c^2 ; > 114 GeV/c^2} and: $M_H = 76 +36 -24$ GeV/c^2

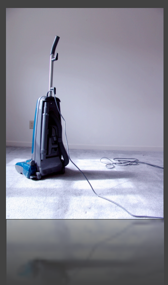
SM is a renormalizable theory

with issues... Higgs loops. and Gravity.

mass corrections

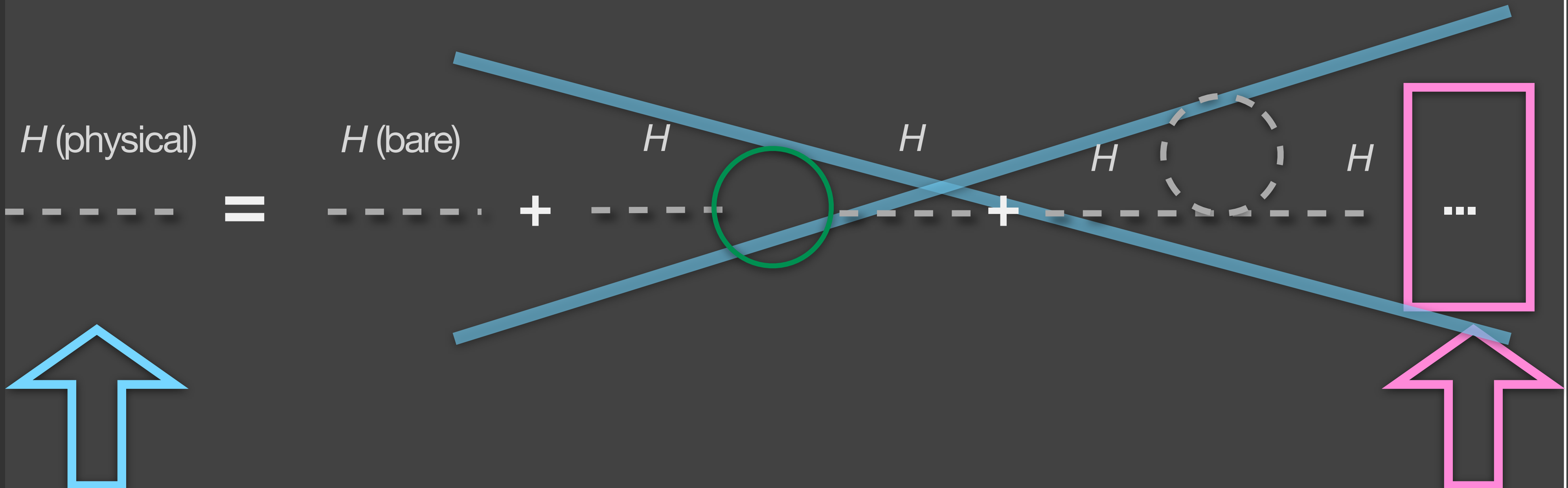
~ $(10^2\ \text{GeV})^2$?

$$m^2(p^2) = m_0^2 + Cg^2 \int_{p^2}^{\Lambda^2} \text{stuff } dk^2$$

$$m^2(p^2) \propto \Lambda^2$$ ← That same scale problem as with the  !

~ $(10^{19}\ \text{GeV})^2$?

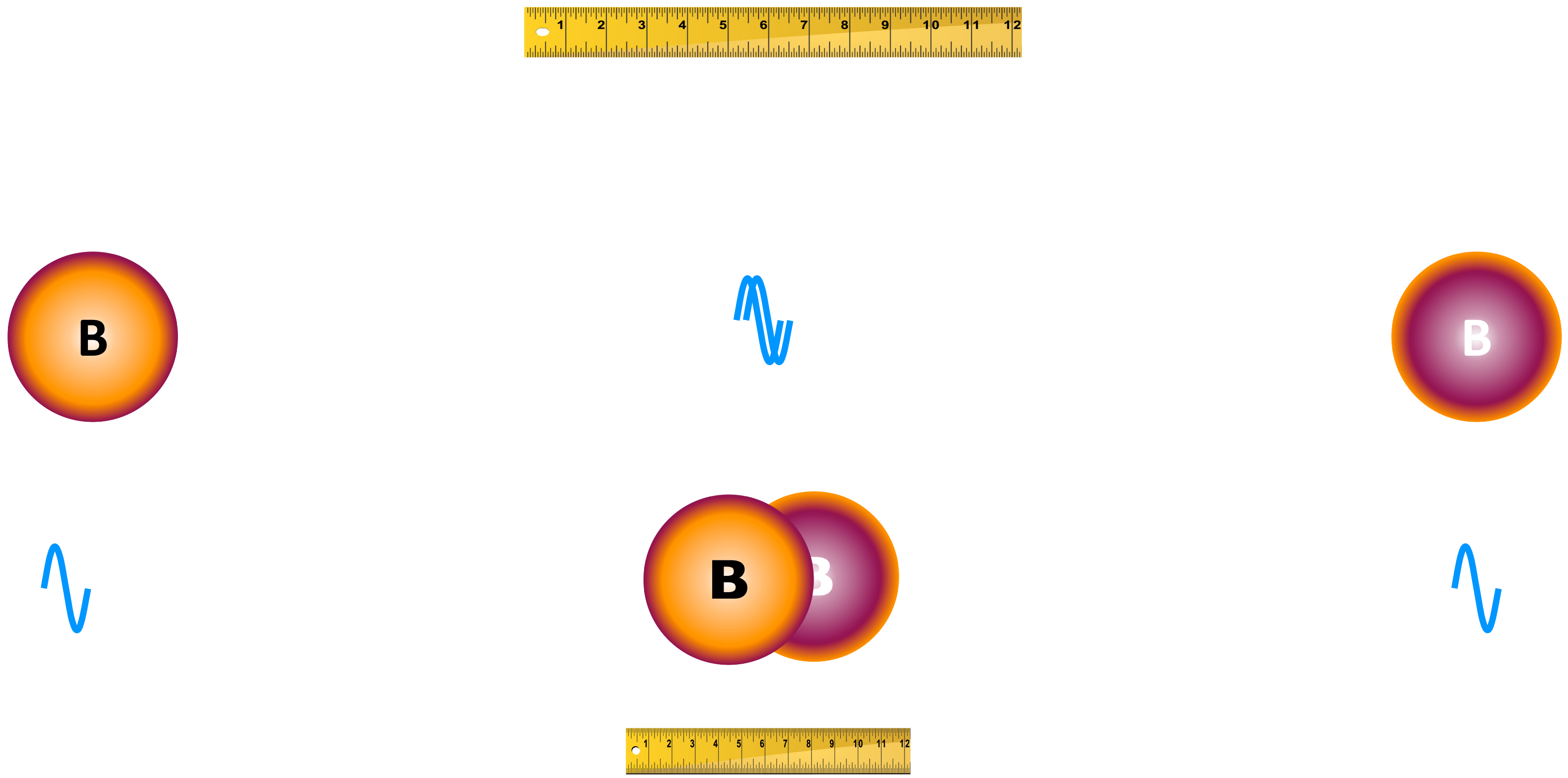
2 ways out?



Or, the "Higgs" is not an elementary particle after all

New physics causing a cancellation?

prior to 3 minutes: balance between radiation and particles.



Early moments: short wavelength photons = high frequency photons = high energy photons
lots of mc^2 available–can make heavy particles

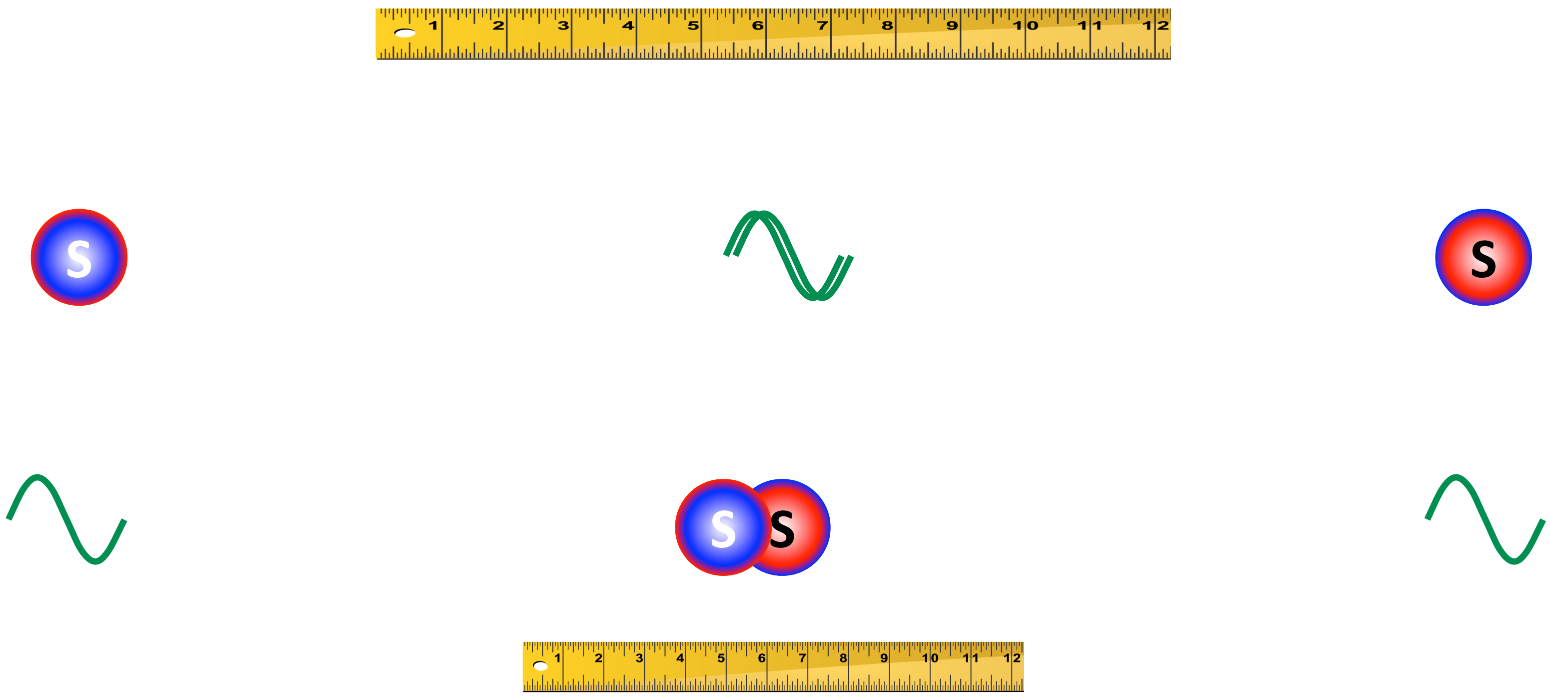
prior to 3 minutes: balance between radiation and particles.

Later moments:

spacetime has stretched!

longer wavelength, lower frequency = less high energy photons

less mc^2 available–can't make heaviest particles



heavy species "freeze out"